



Precise measurements of W^- and Z -boson transverse momentum spectra with the ATLAS detector using pp collisions at $\sqrt{s} = 5.02$ TeV and 13 TeV

The ATLAS Collaboration

This paper describes measurements of the transverse momentum spectra of W and Z bosons produced in proton–proton collisions at centre-of-mass energies of $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 13$ TeV with the ATLAS experiment at the Large Hadron Collider. Measurements are performed in the electron and muon channels, $W \rightarrow \ell\nu$ and $Z \rightarrow \ell\ell$ ($\ell = e$ or μ), and for W events further separated by charge. The data were collected in 2017 and 2018, in dedicated runs with reduced instantaneous luminosity, and correspond to 255 pb^{-1} and 338 pb^{-1} at $\sqrt{s} = 5.02$ TeV and 13 TeV, respectively. These conditions optimise the reconstruction of the W -boson transverse momentum. The distributions observed in the electron and muon channels are unfolded, combined, and compared to QCD calculations based on parton shower Monte Carlo event generators and analytical resummation. The description of the transverse momentum distributions by Monte Carlo event generators is imperfect and shows significant differences largely common to W^- , W^+ and Z production. The agreement is better at $\sqrt{s} = 5.02$ TeV, especially for predictions that were tuned to Z production data at $\sqrt{s} = 7$ TeV. Higher-order, resummed predictions based on DYTURBO generally match the data best across the spectra. Distribution ratios are also presented and test the understanding of differences between the production processes.

Contents

1	Introduction	3
2	The ATLAS detector and datasets	4
2.1	ATLAS detector	4
2.2	Data sets	5
2.3	Signal and background simulation	5
3	Lepton and event selection	6
3.1	Electrons	6
3.2	Muons	6
3.3	Primary vertex reconstruction	7
3.4	Selection of W - and Z -boson candidate events	7
4	Hadronic recoil reconstruction and calibration	8
4.1	Hadronic recoil reconstruction	8
4.2	Hadronic recoil calibration	9
5	Background estimates and event yields	11
5.1	Background in the $W \rightarrow \ell\nu$ selection	11
5.2	Background in the $Z \rightarrow \ell\ell$ selection	15
5.3	Detector-level event yields and distributions	16
6	Cross-section measurement	28
6.1	Unfolding	28
6.2	Systematic uncertainties	31
6.3	Validation of recoil-based measurement with Z dilepton	32
7	Results	32
7.1	Combination of electron and muon channels	32
7.2	Integrated cross sections and distribution ratios	34
7.3	Comparison to predictions	36
8	Conclusion	45
	Appendix	48
A	Measurement uncertainty breakdown for all channels	48
B	Comparisons to RADISH predictions and DYTURBO uncertainty composition	51
C	Comparisons to multijet-merged predictions	55
D	Total integrated W and Z cross sections and ratios	57

1 Introduction

Measurements of W - and Z -boson production in proton–proton (pp) collisions at the LHC constitute a sensitive test of Quantum Chromodynamics (QCD). The transverse momentum (p_T^V) of the gauge bosons V (W , Z) with respect to the initial proton beam arises from higher order corrections to the leading order Drell–Yan processes, and from non-perturbative effects such as the primordial k_T of the incoming partons. Precise measurements and predictions of the spectra in the region $p_T^V \lesssim 30$ GeV are of particular interest for the measurement of the W -boson mass at hadron colliders [1–4].

Over the last years, theoretical predictions have been calculated including increasingly higher order corrections. These comprise the fixed-order corrections, known up to third order in the strong coupling α_S [5–7], and the resummation of logarithmic terms from soft and collinear emissions using complex formalisms to obtain reliable predictions in the low p_T^V region. Analytic approaches based *e.g.* on transverse momentum resummation [8] have been extended up to fourth order [9–11]. Parton shower and hadronisation models, such as those implemented in PYTHIA [12], HERWIG [13] or SHERPA [14] provide an alternative approach and predict the complete event topology.

Experimentally, a measurement of the Z -boson p_T spectrum (p_T^Z) is relatively straightforward through the transverse momentum of the pair of charged decay leptons, $p_T^{\ell\ell}$. It was measured previously in pp collisions at the Large Hadron Collider (LHC) by the ATLAS Collaboration at centre-of-mass energies of $\sqrt{s} = 7$, 8, and 13 TeV [15–17]. Similar measurements were performed by CMS [18–20] and LHCb [21–23].

Even though precise data on p_T^Z spectra exist, these can only be employed in a measurement of the W -boson mass (m_W) through a theoretical modelling of the differences between the W and Z production processes, *e.g.* those induced by different energy scales, couplings, and flavour and momentum fractions of the initial-state quarks. A direct measurement of the W -boson p_T distribution (p_T^W) is therefore of significant interest to test this modelling and reduce the related uncertainties in a measurement of m_W . While samples of W -boson events are easily selected using the leptonic decays $W \rightarrow \ell\nu$, a measurement of the p_T^W spectrum is a much more significant challenge, as the decay neutrino escapes direct detection. The measurement requires the reconstruction of the hadronic system the boson recoils against, the *hadronic recoil*. Additional pp interactions occurring in the same bunch crossing as the signal (pile-up), degrade the resolution and constitute the main limitation in this measurement. Consequently, previous measurements at the LHC used relatively small, low pile-up datasets, at $\sqrt{s} = 7$ TeV by ATLAS [24] and at $\sqrt{s} = 8$ TeV by CMS [25], with integrated luminosities of 31 pb^{-1} and 18 pb^{-1} , respectively.

This paper presents measurements of the W - and Z -boson p_T^V distributions in pp collisions, using data collected in dedicated LHC runs with low instantaneous luminosity at centre-of-mass energies of $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 13$ TeV. These datasets respectively correspond to about 255 and 338 pb^{-1} ; two inelastic pp collisions take place on average in the same bunch crossing. The clean experimental conditions optimise the resolution on the hadronic recoil while maintaining high yields of signal events, allowing a precise measurement of the p_T^W distribution. The required calibrations for the detector response to electrons, muons and the hadronic recoil are derived or cross-checked with $Z \rightarrow \ell\ell$ events in the same datasets.

The analysis is performed in leptonic final states, where lepton refers to electrons and muons ($\ell = e, \mu$). The W -boson measurement is performed separately for W^- and W^+ production, and p_T^W is unfolded from the hadronic recoil, \vec{u}_T , reconstructed in the plane transverse to the beam using charged-particle tracks and energy deposits in the calorimeter. For $Z \rightarrow \ell\ell$ events, the p_T^Z spectrum is primarily measured through the dilepton system, $p_T^{\ell\ell}$. An alternative measurement, based on \vec{u}_T , is compared to the $p_T^{\ell\ell}$ result and used to

validate the reconstruction and measurement techniques. The measurements in the electron and muon channels are combined accounting for correlations of statistical and systematic uncertainties.

2 The ATLAS detector and datasets

2.1 ATLAS detector

The ATLAS detector [26] at the LHC covers nearly the entire solid angle around the collision point.¹ It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting air-core toroidal magnets.

The inner-detector system (ID) is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the range $|\eta| < 2.5$. The high-granularity silicon pixel detector covers the vertex region and typically provides four measurements per track, the first hit generally being in the insertable B-layer (IBL) installed before Run 2 [27, 28]. It is followed by the SemiConductor Tracker (SCT), which usually provides eight measurements per track. These silicon detectors are complemented by the transition radiation tracker (TRT), which enables radially extended track reconstruction up to $|\eta| = 2.0$. The TRT also provides electron identification information based on the fraction of hits (typically 30 in total) above a higher energy-deposit threshold corresponding to transition radiation.

The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. Within the region $|\eta| < 3.2$, electromagnetic calorimetry is provided by barrel and endcap high-granularity lead/liquid-argon (LAr) calorimeters, with an additional thin LAr presampler covering $|\eta| < 1.8$ to correct for energy loss in material upstream of the calorimeters. Hadronic calorimetry is provided by the steel/scintillator-tile calorimeter, segmented into three barrel structures within $|\eta| < 1.7$, and two copper/LAr hadronic endcap calorimeters. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules optimised for electromagnetic and hadronic energy measurements respectively.

The muon spectrometer (MS) comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field generated by the superconducting air-core toroidal magnets. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. Three layers of precision chambers, each consisting of layers of monitored drift tubes, cover the region $|\eta| < 2.7$, complemented by cathode-strip chambers in the forward region, where the background is highest. The muon trigger system covers the range $|\eta| < 2.4$ with resistive-plate chambers in the barrel, and thin-gap chambers in the endcap regions.

The luminosity is measured mainly by the LUCID-2 [29] detector that records Cherenkov light produced in the quartz windows of photomultipliers located close to the beampipe.

Events are selected by the first-level trigger system implemented in custom hardware, followed by selections made by algorithms implemented in software in the high-level trigger [30]. The first-level trigger accepts

¹ ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z -axis along the beam pipe. The x -axis points from the IP to the centre of the LHC ring, and the y -axis points upwards. Polar coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z -axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$ and is equal to the rapidity $y = \frac{1}{2} \ln \left(\frac{E+p_z}{E-p_z} \right)$ in the relativistic limit. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$.

events from the 40 MHz bunch crossings at a rate below 100 kHz, which the high-level trigger further reduces in order to record complete events to disk at about 1 kHz.

A software suite [31] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

2.2 Data sets

The analysis is conducted using datasets corresponding to integrated luminosities of $254.9 \pm 2.6 \text{ pb}^{-1}$ at $\sqrt{s} = 5.02 \text{ TeV}$ and $338.1 \pm 3.1 \text{ pb}^{-1}$ at $\sqrt{s} = 13 \text{ TeV}$ [32]. They were collected in 2017 and 2018 during dedicated LHC low pile-up runs with an average number of pp interactions, $\langle\mu\rangle$, of about two, as compared to $\langle\mu\rangle \sim 34$ for the nominal LHC Run 2 operation between 2015 and 2018. To fully exploit these conditions, the thresholds applied to suppress noise in the reconstruction of clusters of energy in the calorimeters were lowered, optimising the reconstruction of the hadronic recoil as described in Section 4. The data was collected with triggers that require at least one electron or muon with transverse momentum thresholds of $p_{\text{T}}^e > 15 \text{ GeV}$ and $p_{\text{T}}^\mu > 14 \text{ GeV}$, respectively [30, 33, 34]. Loose identification criteria are applied at the trigger level for electron or muon candidates.

2.3 Signal and background simulation

Samples of Monte Carlo (MC) simulated events are used to model the signal and background processes. All MC samples were processed through the full ATLAS detector simulation [35] based on GEANT4 [36] using settings specific to the low pile-up run conditions. The effects of pile-up collisions in the same or neighbouring bunch crossings were included in the MC simulation by overlaying inelastic pp interactions produced using PYTHIA 8 with the NNPDF2.3LO set of parton distribution functions (PDFs) [37] and the A3 set of tuned parameters [38].

The main signal event samples for W and Z production were generated using the POWHEG event generator at next-to-leading order in QCD (NLO) [39–42] using the CT10 PDF [43], interfaced to PYTHIA 8 [12] using the AZNLO tune [15]. These POWHEG+PYTHIA 8 samples were interfaced to PHOTOS++ [44] to simulate the effect of final-state QED radiation. The effective sample size is typically 10–20 times larger than the data to minimise the impact of MC statistical uncertainties. Alternative signal samples were prepared with SHERPA 2.2.1 ($\sqrt{s} = 13 \text{ TeV}$) and 2.2.5 ($\sqrt{s} = 5.02 \text{ TeV}$) [14] using the NNPDF3.0 NNLO PDFs [45] and merging matrix element calculations from Comix [46] and OPENLOOPS [47–49] for $V + 0, 1, 2$ partons at NLO accuracy with $V + 3, 4$ partons at leading order (LO) accuracy in the MEPS@NLO scheme [50–54]. These samples are used to evaluate the uncertainty arising from the choice of the program used to simulate the signal events. The W and Z samples are normalised to next-to-next-to-leading (NNLO) calculations performed using the DYTURBO [55] program, an optimised version of DYNNLO [56, 57] using the MMHT2014 NNLO PDF set [58]. A conservative total uncertainty of 5% is taken as normalisation uncertainty in background predictions or control regions, covering the uncertainties in PDFs, α_S and missing higher order corrections.

Backgrounds from top-antitop-quark pair ($t\bar{t}$) production and single-top-quark production (Wt associated production, t -channel, s -channel) were generated with POWHEG+PYTHIA 8 [59] and normalised to the NNLO predictions with resummation at next-to-next-to-leading-logarithmic (NNLL) accuracy [60–66]. Diboson production VV ($V = W, Z$) was generated with SHERPA in all decay channels with at least one real lepton in the final state and treated as background [67].

3 Lepton and event selection

This analysis relies on the reconstruction and selection of electrons and muons. The calibrations and efficiency measurements used for the low pile-up datasets are briefly summarised in this section. The methodology closely follows that established for the full ATLAS Run 2 dataset [68, 69], referred to as the high pile-up dataset. A full set of corrections are determined from the low pile-up datasets. However, where possible, corrections determined from the large high pile-up dataset are used instead to benefit from their better statistical precision. Corrections derived from the high pile-up dataset are complemented by additional corrections or uncertainties reflecting the extrapolation to the low pile-up regime.

The W - and Z -boson event selections are also described in this section, as well as the determination of the primary vertex reconstruction efficiency. The hadronic recoil, \vec{u}_T , is a detector-level measure of p_T^W , and is used to infer the transverse momentum of the decay neutrino. Its reconstruction and calibration are specific to this analysis and are described in Section 4.

3.1 Electrons

Electron candidates are reconstructed from clusters of energy deposited in the electromagnetic calorimeter and associated with at least one track in the ID. Electrons are required to be within the coverage of the ID and the precision region of the EM calorimeter, $|\eta| < 2.47$. Electrons in the transition region between the barrel and endcap calorimeters, $1.37 < |\eta| < 1.52$, are excluded. Electron candidates are required to have a transverse momentum of $p_T^\ell > 25$ GeV and pass the *Medium* likelihood identification requirements [68]. They are also required to be isolated from nearby activity, as measured by tracks in a cone of size $\Delta R < 0.2$ around the candidate. The scalar sum of the p_T of these tracks is required to be less than 10% of the electron p_T^ℓ and may not exceed 5 GeV for electrons with $p_T^\ell > 50$ GeV, i.e. $p_T^{\text{cone20}}/\min(p_T^\ell, 50 \text{ GeV}) < 0.1$.

Corrections and uncertainties in the electron energy calibration are estimated by using a combination of simulation-based and data-driven procedures as described in Ref. [68]. The energy scale and resolution differences between data and simulation are determined in the low pile-up datasets using $Z \rightarrow ee$ decays and the statistical uncertainties are dominant. Smaller systematic uncertainties on the simulation of the material and on the relative calibration of the calorimeter layers are taken from the analysis of the high pile-up dataset instead.

Corrections to the electron trigger, identification and isolation efficiencies are determined separately in the 13 TeV and 5.02 TeV low pile-up data from Z -boson events using tag-and-probe methods [68]. The electron reconstruction efficiency corrections are instead extrapolated from the high pile-up dataset.

3.2 Muons

The muon reconstruction is performed independently in the ID and in the MS, and a muon candidate is formed from the combination of a muon spectrometer track with an ID track. The muon candidates are required to have an absolute pseudorapidity of $|\eta| < 2.4$, a transverse momentum of $p_T^\ell > 25$ GeV and to satisfy the *Medium* identification criteria [69]. Muons are required to be isolated from nearby activity with the same criterion as electrons.

Corrections are applied to the reconstructed muon momentum in simulation to precisely match the data. The corrections to the simulated momentum resolution and momentum scale are determined using both

$Z \rightarrow \mu\mu$ and $J/\psi \rightarrow \mu\mu$ events in the high pile-up dataset as described in Ref. [69]. They are cross-checked with the low pile-up dataset and good agreement is found. A dedicated correction for charge-dependent momentum biases in data is determined in situ and applied as a function of muon η using a combination of different methods [69, 70]. These correlated systematic biases can be introduced either by detector deformations to which the alignment procedure has little sensitivity or by the procedure used to determine the alignment parameters [71].

The efficiency of the selection criteria for muon candidates is measured using tag-and-probe methods [69] in $Z \rightarrow \mu\mu$ events separately for the 13 TeV and 5.02 TeV data. Efficiency correction factors for muon trigger and isolation are evaluated as a function of muon η and p_T in the low pile-up dataset with a precision limited by the size of the $Z \rightarrow \mu\mu$ data samples. The muon reconstruction efficiency correction is instead determined with the high pile-up dataset and extrapolated to low pileup.

3.3 Primary vertex reconstruction

Primary vertices are reconstructed requiring at least two charged-particle tracks [72] and the hard-scatter vertex is chosen as the one with the largest sum of squared track transverse momenta. Lepton candidates are required to originate from this vertex. The significance of the track's transverse impact parameter calculated relative to the beam line, $|d_0/\sigma_{d_0}|$, must be smaller than three for muons and smaller than five for electrons. Furthermore, the longitudinal impact parameter, z_0 (the difference between the z -coordinate of the point on the track at which d_0 is defined and the longitudinal position of the primary vertex), is required to satisfy $|z_0 \cdot \sin(\theta)| < 0.5$ mm.

The efficiency of this requirement in $Z \rightarrow \ell\ell$ events is generally above 99% and included in the tag-and-probe procedures described above. However, for W -boson events at low p_T , the reconstruction of the correct primary vertex is more challenging as it requires at least one additional charged-particle track from hadronic activity in addition to the lepton. A dedicated measurement of this efficiency is therefore derived. It is performed in $Z \rightarrow \ell\ell$ events as function of the number of reconstructed additional tracks, i.e. excluding the leptons, and the boson p_T . The data measurement can then be applied to the $W \rightarrow \ell\nu$ simulation. The vertex reconstruction inefficiency in W -boson events with $p_T^W < 5$ GeV at $\sqrt{s} = 5.02$ TeV (13 TeV) is found to be about 5% (3%) for the electron channels and 3% (2%) for the muon channels. It decreases towards higher p_T^W , and asymptotically reaches about 1% in the electron channel and 0.5% in the muon channel.

3.4 Selection of W - and Z -boson candidate events

The $W \rightarrow \ell\nu$ event selection requires exactly one reconstructed and isolated electron or muon satisfying the criteria described in Sections 3.1 or 3.2, respectively. Events with additional leptons of the same flavour with transverse momentum $p_T^\ell > 20$ GeV are discarded to reduce the Z background; the identification requirement for these veto leptons is loosened with respect to the nominal selection to make the veto more effective. There are no requirements on the number of leptons with flavour different than the channel under study. The missing transverse momentum, \vec{p}_T^{miss} , and its magnitude E_T^{miss} are defined from \vec{p}_T^ℓ and \vec{u}_T following $\vec{p}_T^{\text{miss}} = -(\vec{p}_T^\ell + \vec{u}_T)$, and represent a measure of the transverse momentum of the neutrino. The background from QCD multijet events is reduced by the requirement $E_T^{\text{miss}} > 25$ GeV. Furthermore, the W -boson transverse mass $m_T = \sqrt{2p_T^\ell E_T^{\text{miss}}(1 - \cos \Delta\phi_{\ell\nu})}$ must exceed 50 GeV, where $\Delta\phi_{\ell\nu}$ is the azimuthal angle between \vec{p}_T^ℓ and \vec{p}_T^{miss} . After all selections, a total number of 7.1×10^5 (2.2×10^6) W -boson

candidate events are selected in the $W \rightarrow e\nu$ channel and 7.5×10^5 (2.2×10^6) in the $W \rightarrow \mu\nu$ channel for the 5.02 TeV (13 TeV) data.

$Z \rightarrow \ell\ell$ events are selected by requiring exactly two same-flavour, opposite-charge leptons. The same reconstruction and isolation criteria as discussed above are applied, and the lepton-pair invariant mass is restricted to the range $66 < m_{\ell\ell} < 116$ GeV. A total of 5.2×10^4 (1.7×10^5) Z-boson candidates are found in the electron channel and 7.0×10^4 (2.1×10^5) in the muon channel for the 5.02 TeV (13 TeV) data.

4 Hadronic recoil reconstruction and calibration

The final state of a $W \rightarrow \ell\nu$ or $Z \rightarrow \ell\ell$ event naturally separates into the leptonic system and the associated QED radiation, and the hadronic recoil, \vec{u}_T , defined from the remaining reconstructed particles in the event. Up to the detector resolution, the transverse momentum of the hadronic recoil is equal in magnitude to the vector boson transverse momentum and points in the opposite direction, $\vec{u}_T = -\vec{p}_T^V$.

In $Z \rightarrow \ell\ell$ events, the Z-boson transverse momentum can be estimated from both the lepton pair $p_T^{\ell\ell}$ and u_T . The well-measured dilepton system can thus be used to calibrate the hadronic recoil response, and the unfolded $p_T^{\ell\ell}$ distribution provides a cross-check of the p_T^Z spectrum measured from u_T .

4.1 Hadronic recoil reconstruction

The hadronic recoil was used successfully in ATLAS analyses with $\sqrt{s} = 7$ TeV data [24, 70]. For these measurements, the reconstruction was based on calorimetric energy deposits reconstructed using a topological clustering algorithm [73]. In this analysis, the hadronic recoil is reconstructed from *Particle Flow Objects* (PFOs) [74, 75] that combine information from ID tracks and the calorimeters in an optimal way and avoid double counting. Compared to the calorimeter-based measurement, the particle flow technique improves the recoil resolution by 3% at low p_T^V , increasing to 15% at $p_T^V \approx 50$ GeV.

The recoil vector \vec{u}_T is computed from the vector sum of all charged and neutral PFO momenta. PFOs within $\Delta R = 0.2$ around identified electrons and muons are not included in the recoil, to avoid energy deposits originating from charged leptons and accompanying photons. This procedure also removes small underlying event and pile-up contributions. To compensate this bias, the PFO momentum measured in a region at the same η as the lepton, and randomly chosen ϕ , with the constraint of being separated from the lepton and recoil directions by $\Delta\phi > 0.4$, is rotated to the lepton axis and added to the recoil.

The resolution of u_T primarily depends on the event activity variable ΣE_T , the scalar sum of the transverse energies of all PFOs included in the recoil. The quantity $\Sigma \vec{E}_T = \Sigma E_T - u_T$ is a modified event activity variable with reduced correlation to the vector boson dynamics, and that mostly represents the underlying event and pile-up. Events are characterised by the vector boson transverse momentum and $\Sigma \vec{E}_T$.

In $Z \rightarrow \ell\ell$ events, the projections of the hadronic recoil on the axes parallel and perpendicular to the momentum of the lepton pair are denoted u_{\parallel} and u_{\perp} , respectively. These projections are used to calibrate the hadronic recoil scale and resolution. The perpendicular component u_{\perp} is expected to have a mean of zero and a width given by the resolution. The sum of u_{\parallel} and $p_T^{\ell\ell}$ is also called *bias*,

$$b = u_{\parallel} + p_T^{\ell\ell}, \quad (1)$$

and would ideally be close to zero. However, $b > 0$ is observed on average, due to particles escaping detection, energy losses in passive detector material and the non-compensating nature of the calorimeters.

4.2 Hadronic recoil calibration

The hadronic recoil scale, resolution and direction need to be calibrated before the measurement is performed. The $Z \rightarrow \ell\ell$ final state is the primary reference, since the final-state kinematics are fully determined through the precise reconstruction of the decay lepton pair. The calibration derived from the Z -boson sample at a given value of dilepton transverse momentum $p_T^{\ell\ell}$, is applied to the $W \rightarrow \ell\nu$ simulation at the same value in the generated transverse momentum $p_T^{\text{true},V}$ of the W -boson. This replacement is possible as the lepton resolution is better than that of the hadronic recoil by about one order of magnitude. The corrections are derived in four sequential steps:

- the modelling of the modified event activity $\Sigma\vec{E}_T$ in the signal simulation is corrected, separately in W - and Z -boson events;
- the simulated azimuthal distribution of the recoil is corrected to that observed in data;
- the simulated recoil scale and core resolution are corrected to those observed in data, using the u_\perp and u_\parallel projections in Z -boson events;
- residual corrections for non-Gaussian resolution tails are derived in data and applied to the simulation.

All corrections are obtained separately for $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 13$ TeV data. As the recoil response is independent of the decay lepton flavour, the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ samples are merged to derive the corrections. The corrections are then applied to the $W \rightarrow \ell\nu$ MC samples, and the closure of the calibration is verified by application to $Z \rightarrow \ell\ell$ samples. Small differences in the hadronic activity between W and Z bosons, for example induced by the different initial-state quark flavours and momentum fractions, are accounted for by dedicated corrections or systematic uncertainties, as explained at the end of this section.

Modelling of $\Sigma\vec{E}_T$

Three event weights are obtained for the POWHEG+PYTHIA 8 MC samples to model the observed $\Sigma\vec{E}_T$ distribution and its correlation with the p_T^V distribution. A first two-dimensional reweighting of the $(\Sigma\vec{E}_T, p_T^{\ell\ell})$ distribution is derived from the ratio of data and simulation for the Z -boson sample. The weights are applied to the W simulation as a function of $p_T^{\text{true},V}$, as explained above. After this correction, the $\Sigma\vec{E}_T$ distributions in W -boson data and simulation agree at the percent level.

The residual disagreement in the W -boson sample remaining after the first reweighting using the Z -boson data, is removed using a second event weight obtained from the W -boson sample itself. This correction is performed separately for each charge, as a function of $\Sigma\vec{E}_T$ and in bins of u_T after a first calibration of u_T in the simulation using the resolution and response corrections discussed below.

The application of these weights to the Z and W samples modifies the generated transverse momentum spectrum of the bosons in the simulation. The initial spectrum is restored using a third, one-dimensional weight as a function of $p_T^{\text{true},V}$. The total weight applied to simulated $W \rightarrow \ell\nu$ events is the product of the three weights described above. Only the first and third weight are applied to Z events.

A closure test is performed using simulated SHERPA Z and W events as pseudo-data, to verify that the correlation between $\Sigma\bar{E}_T$ and $p_T^{\text{true},V}$ in POWHEG+PYTHIA8 is corrected to that present in SHERPA. A good closure is observed and the small residual non-closure is taken as a systematic uncertainty.

Azimuthal correction

The azimuthal direction of the recoil, $\phi(\vec{u}_T)$, is not uniformly distributed due to effects not fully modelled by the simulation, such as non-uniformity in the calorimeter response, the calorimeter mechanical deformation, the beam displacement from the nominal beam line in (x, y) , or the beam-crossing angle. An empirical correction is obtained from the differences between the mean values of the x and y components of the recoil in Z events in data and in the simulation ($\langle u_x \rangle$ and $\langle u_y \rangle$). A small dependence on $\Sigma\bar{E}_T$ is observed and included in the correction. The components of the recoil in the simulation are then corrected accordingly.

The impact of this stage of the calibration on the measured u_T distribution in W simulated events is at most 0.5%, giving confidence that the correlation between the direction and the magnitude of the recoil is weak.

Resolution and response corrections

The data-to-MC resolution correction for u_\perp is derived as a ratio of $\sigma(u_\perp)$ values following

$$r(\Sigma\bar{E}_T, p_T^{\ell\ell}) = \frac{\sigma_{u_\perp}(\Sigma\bar{E}_T, p_T^{\ell\ell})^{\text{data}}}{\sigma_{u_\perp}(\Sigma\bar{E}_T, p_T^{\ell\ell})^{\text{MC}}}, \quad (2)$$

where σ_{u_\perp} is derived from Gaussian fits to the u_\perp distributions in $Z \rightarrow \ell\ell$ events, in bins of $\Sigma\bar{E}_T$ and $p_T^{\ell\ell}$. The distribution of u_\perp in the W -boson simulation is then corrected following

$$u_\perp^{\text{MC,corr}} = u_\perp^{\text{MC}} \cdot r(\Sigma\bar{E}_T, p_T^{\text{true},V}). \quad (3)$$

The data-to-MC corrections for u_\parallel (r') use the standard deviation and mean of the *bias* defined in Eq. (1) that relate to the resolution and scale, respectively. The corrections are extracted in $Z \rightarrow \ell\ell$ events, $r'(\Sigma\bar{E}_T, p_T^{\ell\ell})$, and transferred to the W -boson MC, $r'(\Sigma\bar{E}_T, p_T^{\text{true},V})$, as:

$$u_\parallel^{\text{MC,corr}} = \langle u_\parallel^{\text{data}} \rangle + (\langle b^{\text{data}} \rangle - \langle b^{\text{MC}} \rangle) \cdot r' + (u_\parallel^{\text{MC}} - \langle u_\parallel^{\text{data}} \rangle) \cdot r'. \quad (4)$$

Tail correction

The resolution corrections discussed above only correct the core Gaussian parts of the u_\parallel and u_\perp distributions. Non-Gaussian effects appear in the tails, mostly driven by hadronic activity out of the detector acceptance. A final step in the recoil calibration therefore corrects the resolution tails in simulation to that in data after applying all previous corrections. The correction is derived in bins of $p_T^{\ell\ell}$ from the cumulants of the u_\parallel and u_\perp distributions in data and simulation with an inverse transform sampling (*Smirnoff transform*). The full transformation is parameterised by empirical functions with two (four) parameters for u_\perp (u_\parallel). The transformation gives corrected values as of u_\parallel and u_\perp as a function of these same variables for each event. For u_\perp this results in a symmetric stretching around zero and for u_\parallel in an asymmetric stretching around the median of the distribution.

Summary of recoil calibration

Figure 1 shows the comparison of σ_{u_\perp} and $\langle b \rangle$ as a function of $p_T^{\ell\ell}$ in the $Z \rightarrow \mu\mu$ simulated and data samples. Good closure is observed. Similar results are obtained in the $Z \rightarrow ee$ samples. The uncertainty in the extrapolation from the Z to the W is estimated from the differences between the standard deviation and mean of the u_\perp and u_\parallel distributions in the simulation, at given values of $(\Sigma \bar{E}_T, p_T^{\text{true},V})$, to derive alternative sets of resolution and response corrections r and r' .

A final systematic uncertainty in the recoil calibration is estimated by using SHERPA signal events as pseudo data in the calibration procedure. The POWHEG+PYTHIA 8 sample is calibrated to SHERPA, the full analysis described in Section 6 is performed and the difference between the measured p_T^V distribution and the generated spectrum gives the closure of the correction. To simplify the procedure and avoid double-counting the extrapolation from Z to W , the calibration of each process uses only the corresponding signal sample from both event generators. The p_T^V spectrum of SHERPA is also reweighted to POWHEG+PYTHIA 8 to avoid double-counting the unfolding prior uncertainty. The difference between the two generators in observables relevant to the description of the recoil is larger than the one between data and POWHEG+PYTHIA 8 in Z events, which gives confidence that this uncertainty component is not accidentally underestimated.

5 Background estimates and event yields

5.1 Background in the $W \rightarrow \ell\nu$ selection

Background contributions from single-boson and diboson production (electroweak background) and $t\bar{t}$ and single-top-quark production (top-quark background) are directly estimated from the MC simulated samples described earlier. They are dominated by $W \rightarrow \tau\nu$ events with $\tau \rightarrow \ell\nu\nu$ at low u_T and top-quark pair production at higher u_T . In the electron channels there is an additional background contribution from $W \rightarrow e\nu$ events where the reconstructed electron charge is mismeasured.

Background from QCD multijet (MJ) production cannot be reliably simulated and has to be derived from data. Depending on the lepton flavour, the MJ background has significant contributions from leptons produced in semileptonic decays of heavy quarks, pion and kaon decays, or photon conversions, and is referred to as fake leptons below. The multijet yields in the electron and muon selections of the W -boson analysis are estimated separately for positively and negatively charged samples. As multijet production is concentrated at lower values of p_T^ℓ , E_T^{miss} and m_T as compared to the signal, this background is estimated with a template fit in these kinematic distributions in a phase-space region with relaxed E_T^{miss} and m_T selections, called the *fit region*. The p_T^ℓ , E_T^{miss} and m_T templates in the fit region for the $W \rightarrow \ell\nu$ signal and electroweak and top-quark backgrounds are obtained using simulation. The multijet templates are built from events passing the same kinematic selections as the nominal selection except that the lepton isolation requirement is inverted. In the final step, the multijet yields in the signal region are determined by multiplying the fit region yields by a transfer factor that corrects for the acceptance of the E_T^{miss} and m_T selections and the impact of the inverted isolation requirements needed to extract the multijet background templates.

The multijet yield is estimated three times using the p_T^ℓ , E_T^{miss} and m_T distributions separately and the results are found to be compatible and averaged for the final result. As the shape of the multijet templates depends on the anti-isolation criterion, mutually exclusive intervals in the isolation variable are chosen to

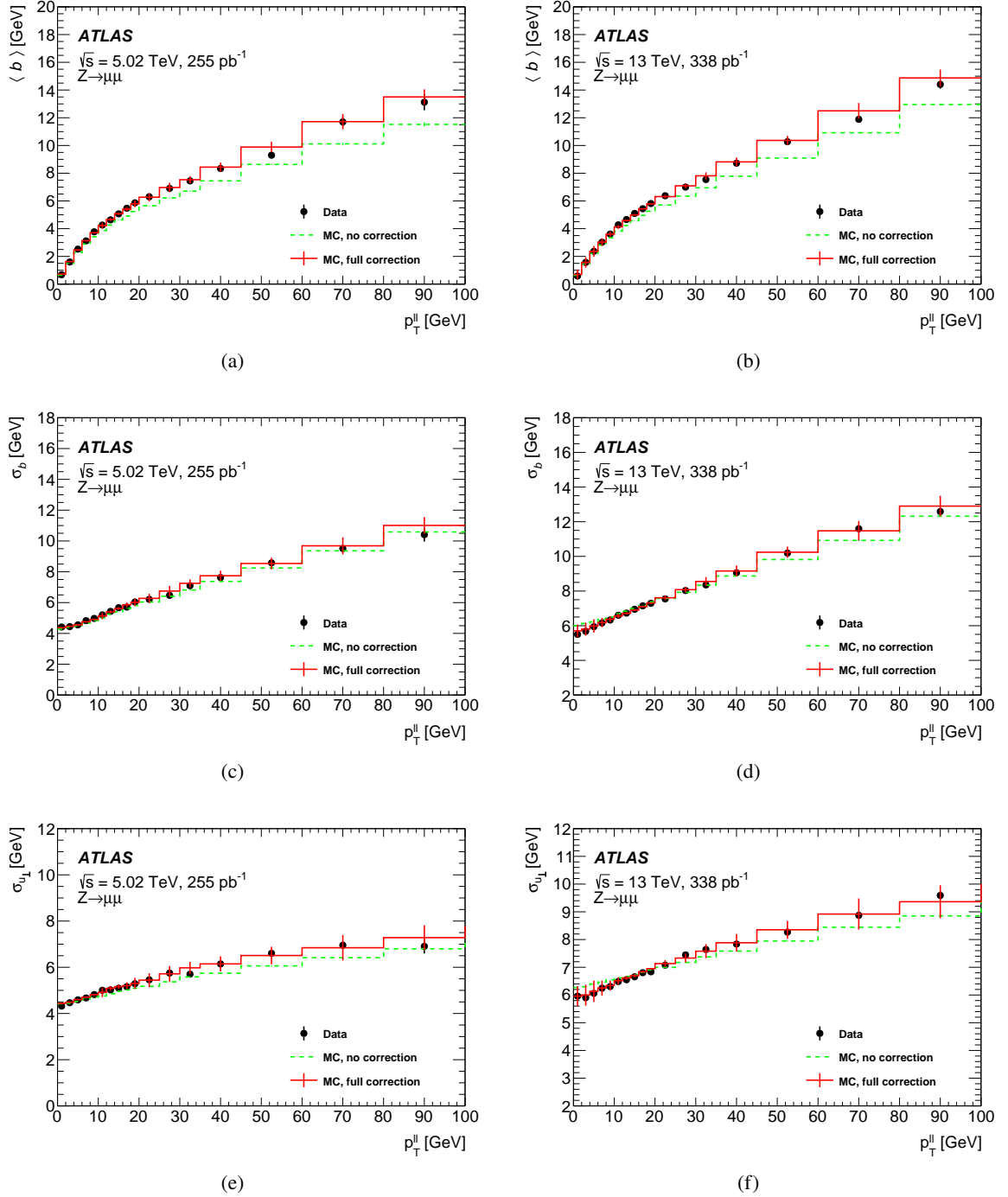


Figure 1: Mean value for the bias $b = u_{\parallel} + p_T^{\ell\ell}$ at (a) $\sqrt{s} = 5.02$ TeV and (b) $\sqrt{s} = 13$ TeV, standard deviation of the bias at (c) $\sqrt{s} = 5.02$ TeV and (d) $\sqrt{s} = 13$ TeV, and standard deviation of u_{\perp} at (e) $\sqrt{s} = 5.02$ TeV and (f) $\sqrt{s} = 13$ TeV in $Z \rightarrow \mu\mu$ events. Data (black dots) are compared to the simulation before (green dotted histograms) and after (red histograms) correction. The values are shown as a function of $p_T^{\ell\ell}$. Error bars show the sum of statistical uncertainties and systematic uncertainties from recoil calibration and from the choice of event generator (the difference between SHERPA and POWHEG+PYTHIA 8).

create statistically independent multijet templates. These samples are designed to be progressively closer to the signal-candidate selection and are used to study the dependence of the multijet extraction on the considered isolation.

Several improvements are included in this background estimate with respect to a similar method described in Ref. [70]. In particular, the removal of all energy in the cone around lepton candidates from the hadronic recoil calculation, as described in Section 4.1, is problematic for the case where leptons are required to fail the isolation selection. The correct properties in the multijet-enriched sample are restored by adding back a fraction of the hadronic activity around the lepton candidate and recalculating the kinematic variables u_T , E_T^{miss} , and m_T accordingly. Another significant improvement on the MJ yield estimate is the use of MJ templates in the fits that have their shapes corrected. This correction is achieved by combining the shapes from different anti-isolation intervals to extrapolate into the fit region. Instead of repeating the template fit in different anti-isolation intervals, it is carried out only once for a given kinematic distribution, and the corresponding dependence of the measured multijet yield is entirely located in the transfer factor. Example results of template fits in the electron and muon channels are shown in Figure 2. In Figure 3, the transfer factors accounting for the efficiency of the kinematic cuts and the isolation requirements to extrapolate from the *fit region* to the signal region are shown as a function of anti-isolation intervals.

The final MJ background yield and total uncertainty is presented in Table 1. The dominant MJ yield uncertainties arise from: the statistical uncertainty from the limited data and MC events in the fit region, the linear extrapolation procedure to the average isolation value in the signal region, and the possible mis-modelling of the jet activity in the anti-isolated regions. The uncertainty arising from the latter effect is studied by categorising events in broad bins of u_T .

Corrections to the shape of the multijet background contributions and corresponding uncertainties in the distributions used in the final measurement are estimated with a similar procedure. The MJ kinematic distributions in the signal region are determined by linearly extrapolating the shape of the distributions observed in the mutually exclusive anti-isolation intervals into the isolated region. Uncertainties in the extrapolated distributions are dominated by the statistical uncertainty. The resulting multijet background distribution is propagated to the final analysis. A smoothing is applied to the MJ u_T spectra for $u_T > 100$ GeV to avoid large fluctuations due to low event counts in the data samples.

The estimated multijet background fractions in the 5.02 TeV dataset represent 0.8% and 0.1% of the total number of observed W^- candidate events in the electron and muon channels, respectively. In the 13 TeV dataset the corresponding fractions are larger at 2.9% and 0.6% because the gluon-induced multijet production rises faster with \sqrt{s} than the quark-induced signal. For W^+ candidate events the background yields are found to be similar to the W^- channels within uncertainties, and the relative fractions are lower by the size of the W^+/W^- cross-section ratio. The different sources of the MJ uncertainty components in yield and shape are treated as correlated across the channels, while the statistical uncertainties are uncorrelated.

The total impact of the uncertainties in the background estimation on the cross-section measurements is shown in Figures 24 and 25 in Appendix A, and is at the level of 0.1%–1% in the low $p_T^W < 63$ GeV region, depending on the channel.

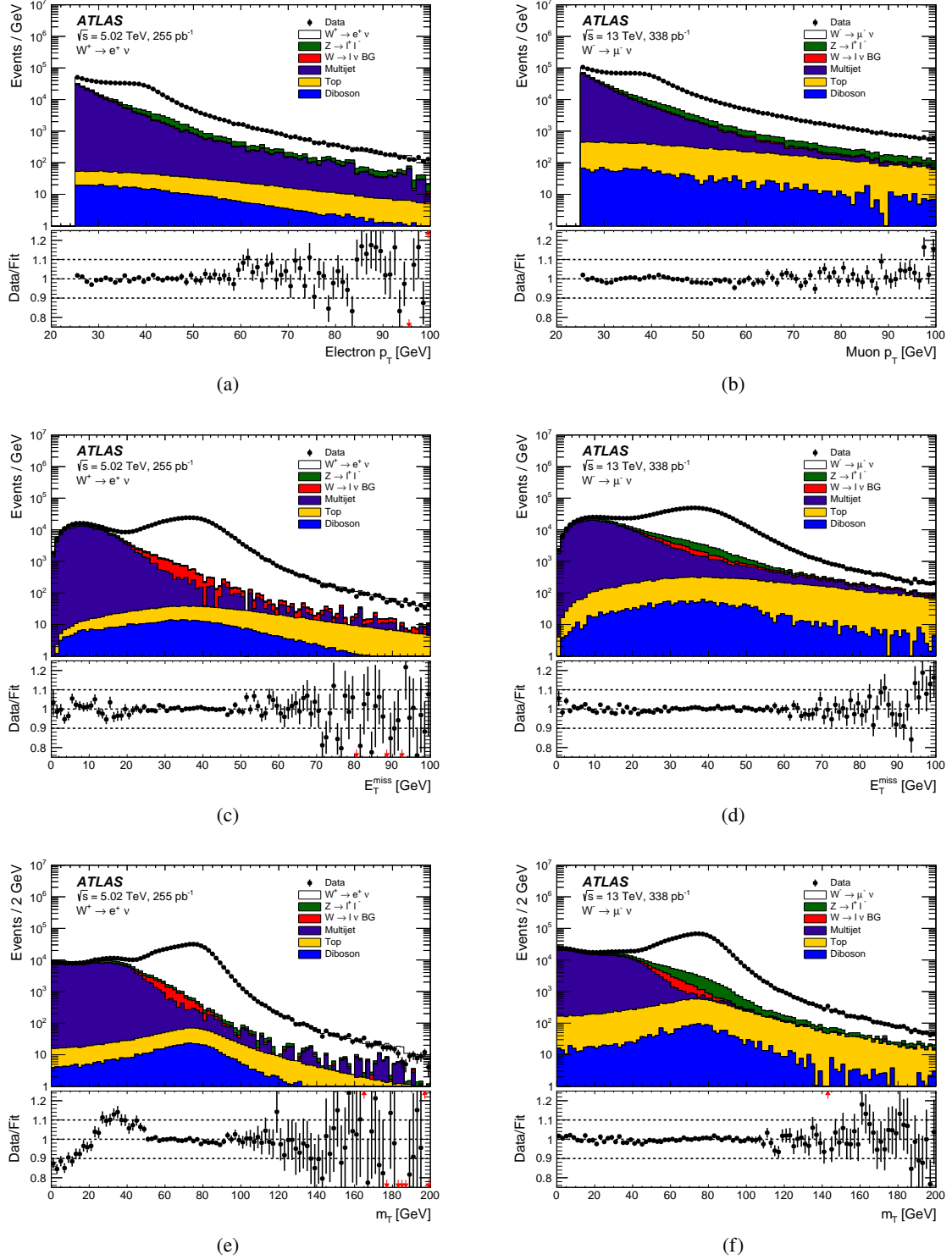


Figure 2: Distributions of (a,b) p_T^ℓ , (c,d) E_T^{miss} and (e,f) m_T in a phase-space region without E_T^{miss} and m_T selections (*fit region*) used to extract multijet yields in template fits in the $W^+ \rightarrow e^+ \nu$ in the (a,c,e) $\sqrt{s} = 5.02$ TeV dataset and $W^+ \rightarrow \mu^+ \nu$ in the (b,d,f) $\sqrt{s} = 13$ TeV dataset. Multijet templates are derived from the data combining the shape information from different anti-isolation intervals. The data are compared to the simulation including signal and background contributions. The category $W \rightarrow \ell \nu$ BG refers to background from $W \rightarrow \tau \nu$ and charge misidentification in the electron channels.

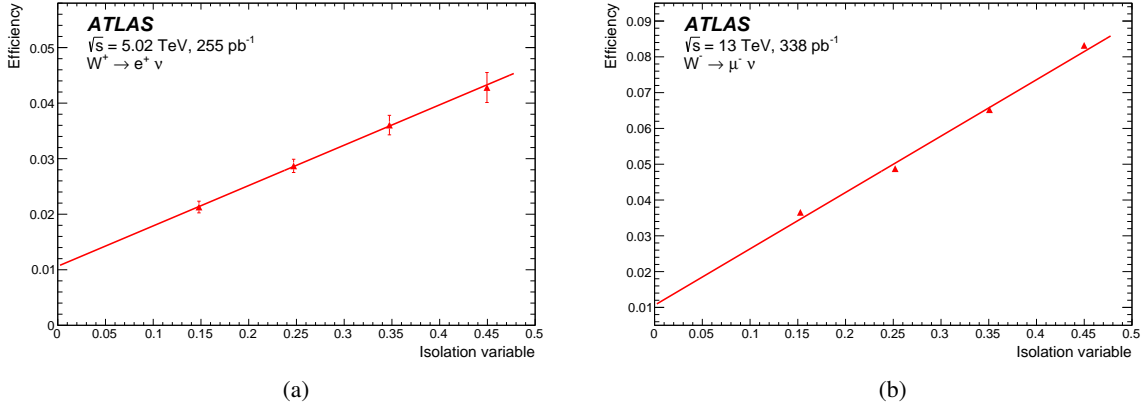


Figure 3: Illustration of the multijet yield transfer factors to account for the different kinematic selections in E_T^{miss} and m_T and isolation requirements from the *fit region* to the signal region. The transfer factors are shown as a function of the lower bound of the range of the isolation variable $p_T^{\text{cone20}} / \min(p_T^\ell, 50 \text{ GeV})$ used to define the anti-isolation intervals, for (a) the $W^+ \rightarrow e^+ \nu$ channel at $\sqrt{s} = 5.02$ TeV and (b) the $W^- \rightarrow \mu^- \nu$ channel at $\sqrt{s} = 13$ TeV. The data points are reasonably described by the linear fits indicated by the solid lines. The uncertainties in the data points are statistical only.

5.2 Background in the $Z \rightarrow \ell\ell$ selection

As in the $W \rightarrow \ell \nu$ analysis, the electroweak and top-quark backgrounds are directly estimated from the MC simulated samples described earlier. They are dominated by diboson and top-quark pair production at higher u_T , but very small overall.

A data-driven two-dimensional sideband method is employed to estimate MJ background. The signal region A is complemented by three orthogonal control regions B , C , and D enriched in events produced from background processes with fake leptons. For both channels, events in region B have the nominal requirements except that the subleading lepton is required to fail the isolation selection. For events to be registered in region C in the electron channel, the primary requirement is to fail the *Medium* identification requirement, but pass the *Loose* criteria. In addition, only same-charge pairs are selected and the p_T^ℓ requirement is loosened to 20 GeV. For the muon channel, region C is defined to contain only same-charge muon pairs and also here the p_T^ℓ requirement is loosened to 20 GeV. Finally, for region D events are selected with the modifications of the B and C regions applied at the same time.

Multijet event yields N_{MJ} in each control region are estimated from data by subtracting the contribution from prompt leptons predicted by the simulation. Because of the very high signal contamination in the background-enriched regions in the $Z \rightarrow ee$ channel, the events with $80 < m_{\ell\ell} < 100$ GeV are excluded. The total MJ yield in the signal region is then estimated through $N_{\text{MJ}}^A = N_{\text{MJ}}^B \cdot N_{\text{MJ}}^C / N_{\text{MJ}}^D$. In the electron channel the final MJ yield is also scaled back to the full $m_{\ell\ell}$ range.

The final MJ event yield and uncertainty for each channel are summarised in Table 2. In all channels, the MJ event estimate is below 0.1% with respect to the expected signal. In the $Z \rightarrow ee$ channel at 5.02 TeV the final MJ event estimate was found to be consistent with zero. An upper limit on the MJ yield in this channel is derived from the statistical uncertainties of the yields in the background-enriched regions.

Table 1: Observed and expected event yield comparison for the W -boson selections in the $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 13$ TeV datasets for the electron and muon channels split by the charge of the reconstructed lepton. The uncertainties in the multijet background correspond to the total uncertainties, while for backgrounds estimated from MC simulation only statistical uncertainties are given. The category $W \rightarrow \ell\nu$ BG refers to background from $W \rightarrow \tau\nu$ as well as charge misidentification in the electron channels.

Channel	Observed	Signal	$W \rightarrow \ell\nu$ BG	$Z \rightarrow \ell\ell$	Top	Diboson	Multijet
$\sqrt{s} = 5.02$ TeV $W \rightarrow \ell\nu$							
$W^- \rightarrow e^-\nu$	274375	264510 \pm 170	7303 \pm 29	1031 \pm 6	862.7 \pm 2.1	340.5 \pm 2.9	2200 \pm 700
$W^+ \rightarrow e^+\nu$	430662	417090 \pm 210	9064 \pm 32	1102 \pm 7	951.4 \pm 2.9	376.2 \pm 2.3	2300 \pm 900
$W^- \rightarrow \mu^-\nu$	288026	273900 \pm 170	5160 \pm 25	8517 \pm 21	799.0 \pm 2.0	339.1 \pm 1.9	300 \pm 340
$W^+ \rightarrow \mu^+\nu$	457223	438020 \pm 210	7854 \pm 30	9773 \pm 22	890.6 \pm 2.8	384.6 \pm 2.3	500 \pm 400
$\sqrt{s} = 13$ TeV $W \rightarrow \ell\nu$							
$W^- \rightarrow e^-\nu$	949297	876490 \pm 270	22360 \pm 60	6546 \pm 21	12780 \pm 50	1720 \pm 50	27000 \pm 5000
$W^+ \rightarrow e^+\nu$	1207652	1116800 \pm 300	24680 \pm 60	6883 \pm 21	13260 \pm 50	1720 \pm 50	29000 \pm 5000
$W^- \rightarrow \mu^-\nu$	964514	897400 \pm 270	14650 \pm 50	33940 \pm 40	11950 \pm 50	1620 \pm 40	6000 \pm 2000
$W^+ \rightarrow \mu^+\nu$	1245755	1153400 \pm 300	18390 \pm 50	37690 \pm 40	12520 \pm 50	1720 \pm 50	6000 \pm 2000

Table 2: Observed and expected event yield comparison for Z -boson selections in the $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 13$ TeV datasets for the electron and muon channels. The uncertainties in the multijet background correspond to the total uncertainties, while for backgrounds estimated from MC simulation only statistical uncertainties are given.

Channel	Observed	Signal	$Z \rightarrow \tau\tau$	Top	Diboson	Multijet
$\sqrt{s} = 5.02$ TeV $Z \rightarrow \ell\ell$						
$Z \rightarrow ee$	51772	51310 \pm 40	23 \pm 4	35.5 \pm 0.4	109.1 \pm 2.0	0 \pm 100
$Z \rightarrow \mu\mu$	70447	69820 \pm 60	39 \pm 5	44.0 \pm 0.4	144.9 \pm 2.1	16 \pm 8
$\sqrt{s} = 13$ TeV $Z \rightarrow \ell\ell$						
$Z \rightarrow ee$	165027	158000 \pm 100	80 \pm 8	500 \pm 10	324 \pm 15	110 \pm 70
$Z \rightarrow \mu\mu$	214035	207900 \pm 100	80 \pm 8	554 \pm 9	414 \pm 17	180 \pm 40

The shape of the MJ events is taken from the corresponding distributions in the background-enriched regions. To suppress statistical fluctuations for the $p_T^{\ell\ell}$ and u_T distributions, the templates are smoothed with a Landau function and normalised to the inclusive number of MJ events for each channel.

The total impact of the background estimation on the unfolded $p_T^{\ell\ell}$ and u_T distributions for the 5.02 TeV and 13 TeV datasets is provided in Figures 26 – 27 in Appendix A and is generally well below 0.1%.

5.3 Detector-level event yields and distributions

The final observed and expected event yields for the full W and Z selections obtained in the electron and muon channels for both datasets are summarised in Tables 1 and 2. All calibrations and efficiency corrections discussed in Sections 3 and 4 are applied.

Detector-level distributions for the 5.02 TeV dataset and for the 13 TeV dataset are provided in Figures 4–7 and Figures 8–11 for the W -boson analyses and in Figure 12 and Figure 13 for the Z -boson analyses. To

better visualise the agreement in the shapes, the MC predictions are normalised to the integral of the data distribution. The underlying $p_T^{\text{true},V}$ distributions have been reweighted with a smooth function as described in detail in Section 6.1 to match the data as closely as possible in the p_T^V range of 0 – 100 GeV.

In the ratio panels, the grey band is the total systematic uncertainty, while for the brown band the typically small statistical uncertainty in the MC simulation is added in quadrature. The systematic uncertainty shown is the experimental uncertainty excluding luminosity, since the MC simulation is normalised to the data integral, and excluding the uncertainty derived from the alternative signal simulation using `SHERPA`. The χ^2/dof shown includes all shown uncertainties and is calculated with the corresponding covariance matrix taking into account bin-to-bin correlations of the systematic uncertainties.

Overall, good agreement is observed between the data and the MC simulation estimates in all the kinematic distributions. Several channels at 13 TeV show a modest mismodelling of the high p_T tails by a few percent, such as the lepton p_T distributions for the W boson (Figure 10). These are due to imperfections in the $p_T^{\text{true},V}$ reweighting. However, the spectra are sufficiently well modelled to perform the p_T^V measurements and corresponding uncertainties are assessed in the unfolding.

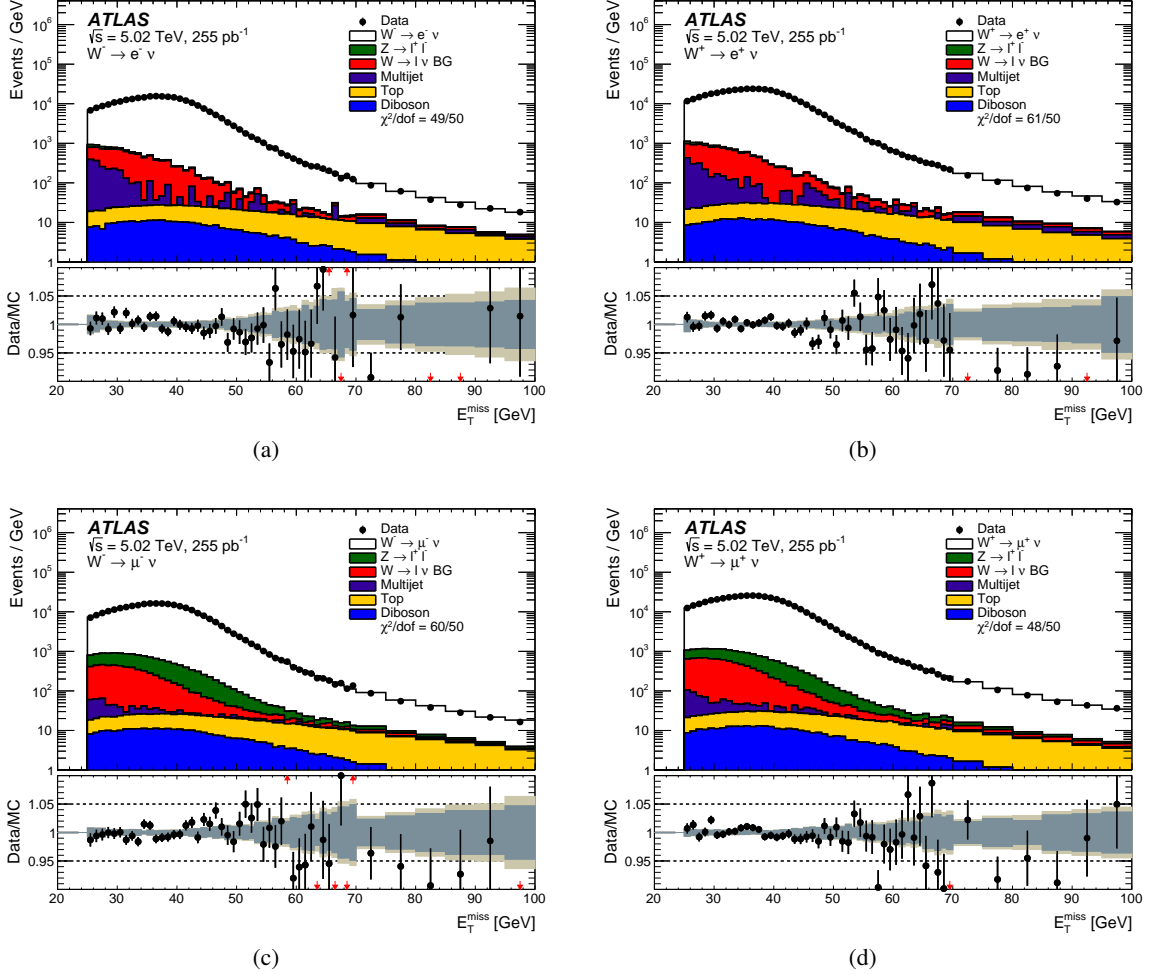


Figure 4: Missing transverse momentum E_T^{miss} distributions in the (a) $W^- \rightarrow e^- \nu$, (b) $W^+ \rightarrow e^+ \nu$, (c) $W^- \rightarrow \mu^- \nu$ and (d) $W^+ \rightarrow \mu^+ \nu$ channels for the $\sqrt{s} = 5.02$ TeV dataset. The data (black points) is compared to the sum of all expected background and signal contributions, shown as a solid line, normalised to the total data yield. The lower panel shows the ratio of the data to the full prediction (black points) as well as the prediction uncertainties around 1 excluding (including) the MC simulation statistical component as dark (light) band. The prediction uncertainties shown exclude those from the luminosity measurement and the alternative signal modelling, see text. The χ^2/dof is computed using the full covariance matrix of all shown statistical and systematic uncertainties. The category $W \rightarrow \ell \nu$ BG refers to background from $W \rightarrow \tau \nu$ and charge misidentification in the electron channels.

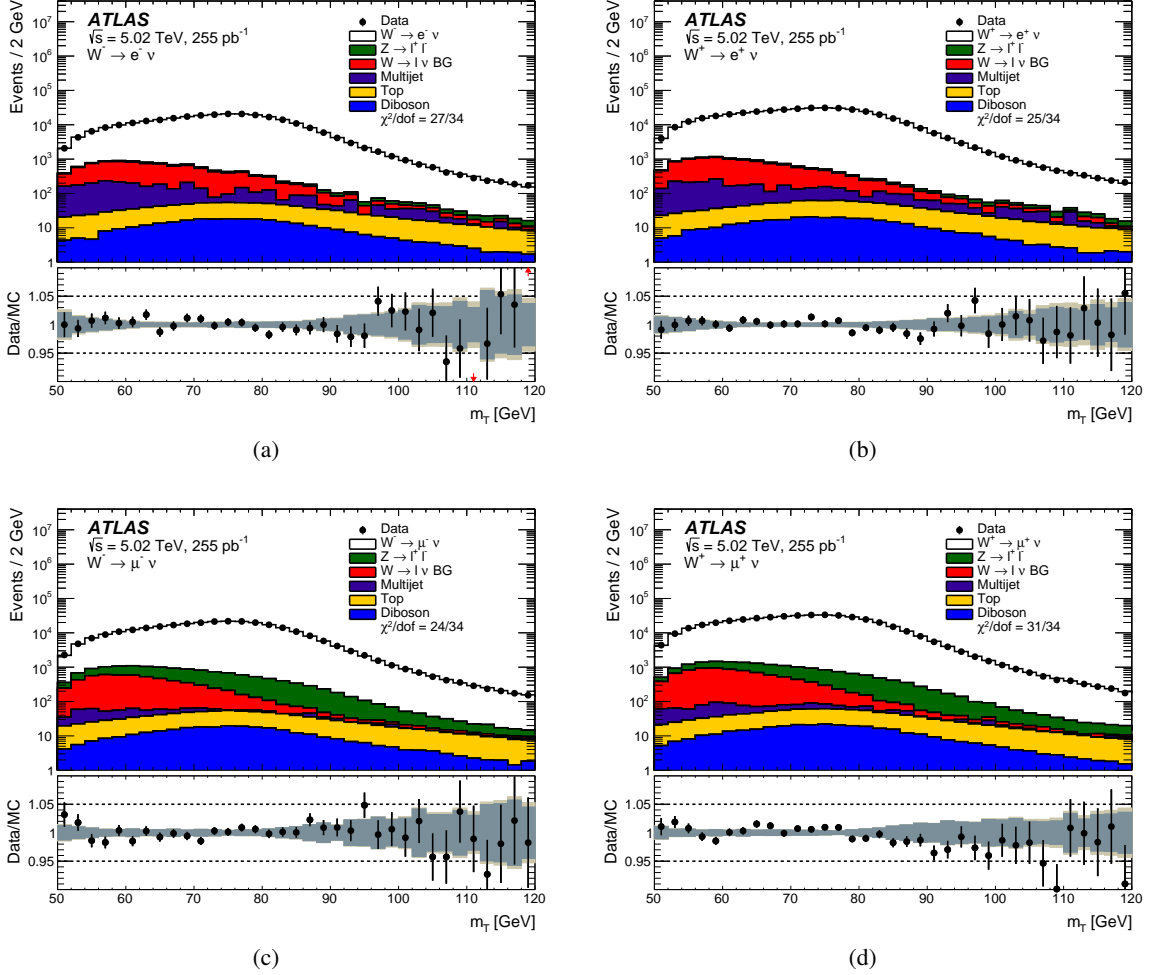


Figure 5: Transverse mass m_T distribution of the W boson in the (a) $W^- \rightarrow e^- \nu$, (b) $W^+ \rightarrow e^+ \nu$, (c) $W^- \rightarrow \mu^- \nu$ and (d) $W^+ \rightarrow \mu^+ \nu$ channels for the $\sqrt{s} = 5.02 \text{ TeV}$ dataset. The data (black points) is compared to the sum of all expected background and signal contributions, shown as a solid line, normalised to the total data yield. The lower panel shows the ratio of the data to the full prediction (black points) as well as the prediction uncertainties around 1 excluding (including) the MC simulation statistical component as dark (light) band. The prediction uncertainties shown exclude those from the luminosity measurement and the alternative signal modelling, see text. The χ^2/dof is computed using the full covariance matrix of all shown statistical and systematic uncertainties. The category $W \rightarrow \ell \nu$ BG refers to background from $W \rightarrow \tau \nu$ and charge misidentification in the electron channels.

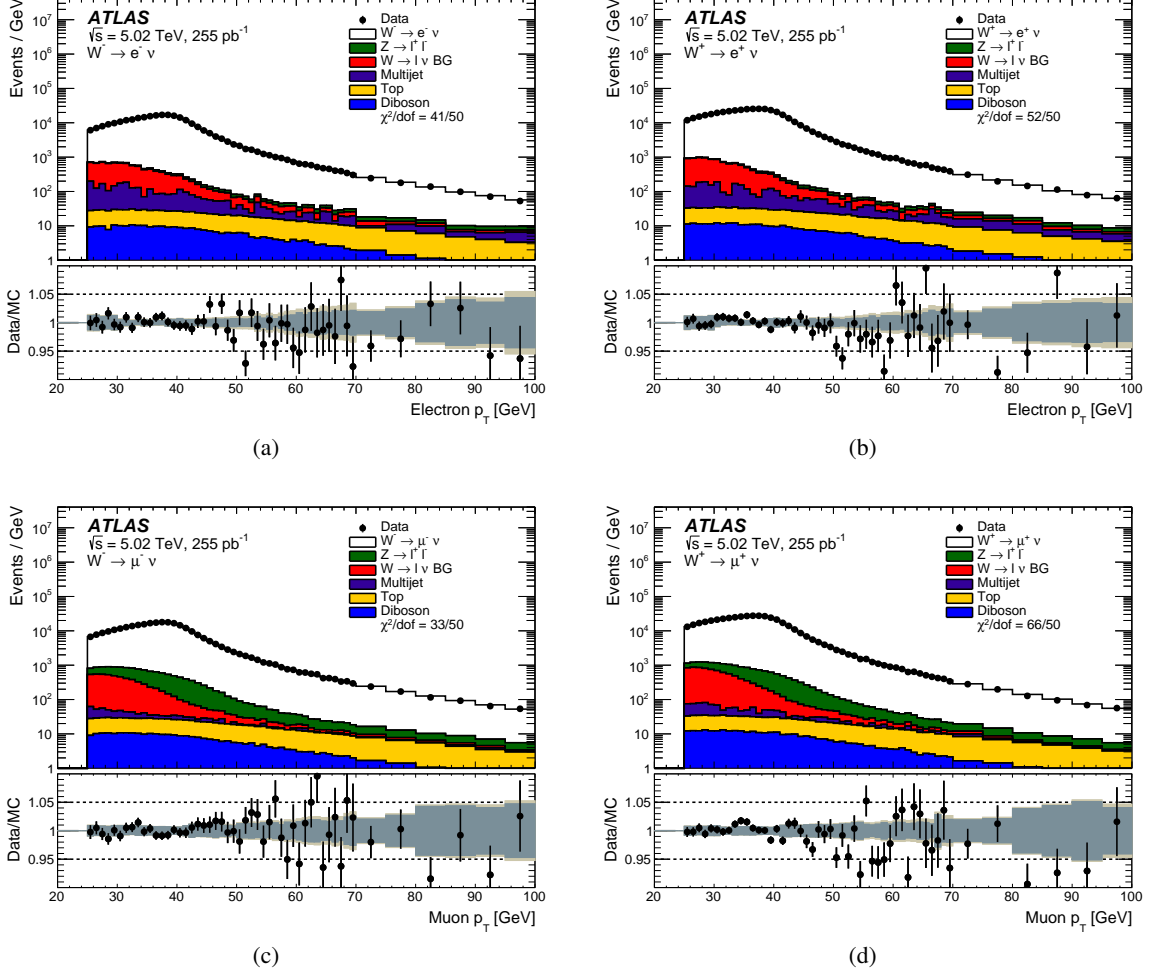


Figure 6: Lepton transverse momentum p_T distributions in the (a) $W^- \rightarrow e^- \nu$, (b) $W^+ \rightarrow e^+ \nu$, (c) $W^- \rightarrow \mu^- \nu$ and (d) $W^+ \rightarrow \mu^+ \nu$ channels for the $\sqrt{s} = 5.02$ TeV dataset. The data (black points) is compared to the sum of all expected background and signal contributions, shown as a solid line, normalised to the total data yield. The lower panel shows the ratio of the data to the full prediction (black points) as well as the prediction uncertainties around 1 excluding (including) the MC simulation statistical component as dark (light) band. The prediction uncertainties shown exclude those from the luminosity measurement and the alternative signal modelling, see text. The χ^2/dof is computed using the full covariance matrix of all shown statistical and systematic uncertainties. The category $W \rightarrow \ell \nu$ BG refers to background from $W \rightarrow \tau \nu$ and charge misidentification in the electron channels.

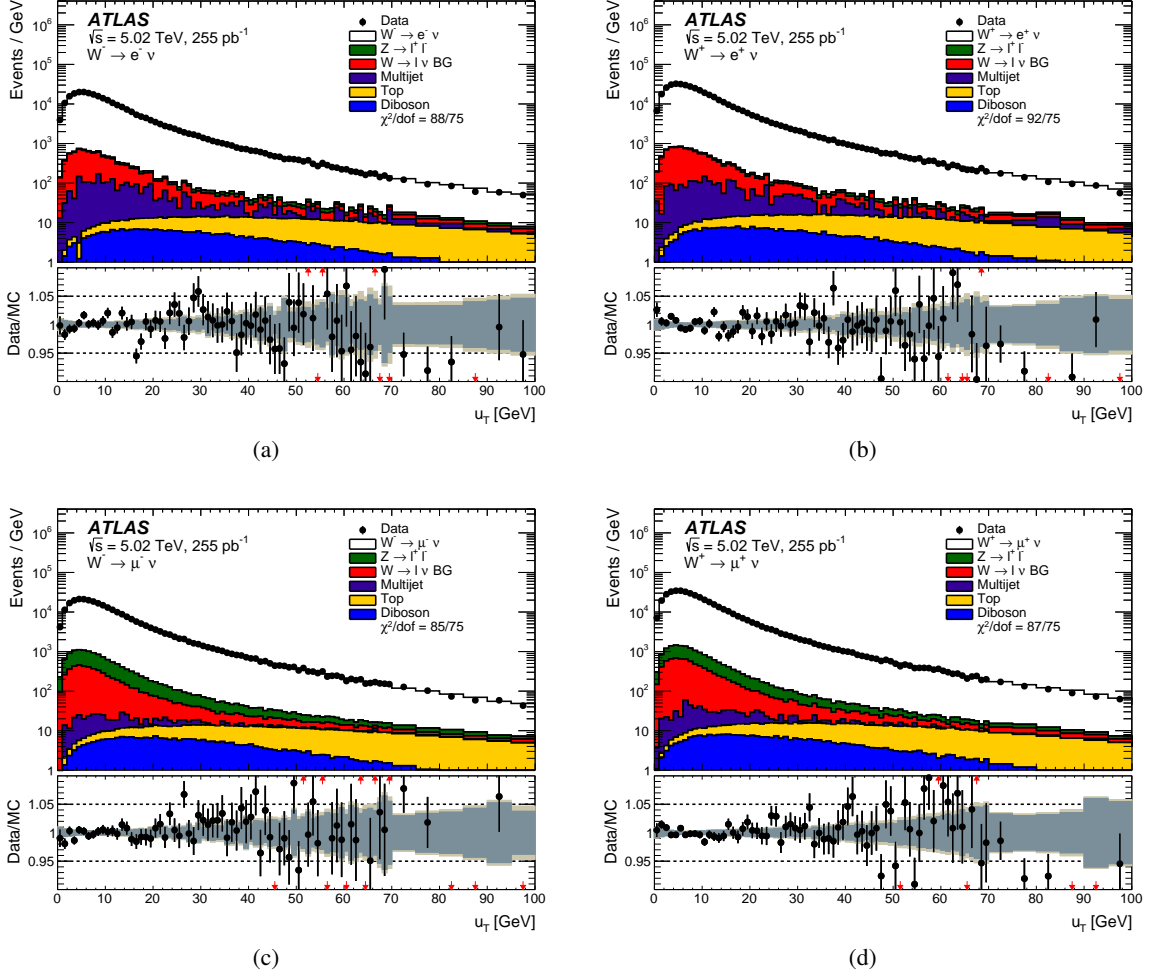


Figure 7: Hadronic recoil u_T distributions (boson transverse momentum) in the (a) $W^- \rightarrow e^- \nu$, (b) $W^+ \rightarrow e^+ \nu$, (c) $W^- \rightarrow \mu^- \nu$ and (d) $W^+ \rightarrow \mu^+ \nu$ channels for the $\sqrt{s} = 5.02$ TeV dataset. The data (black points) is compared to the sum of all expected background and signal contributions, shown as a solid line, normalised to the total data yield. The lower panel shows the ratio of the data to the full prediction (black points) as well as the prediction uncertainties around 1 excluding (including) the MC simulation statistical component as dark (light) band. The prediction uncertainties shown exclude those from the luminosity measurement and the alternative signal modelling, see text. The χ^2/dof is computed using the full covariance matrix of all shown statistical and systematic uncertainties. The category $W \rightarrow \ell \nu$ BG refers to background from $W \rightarrow \tau \nu$ and charge misidentification in the electron channels.

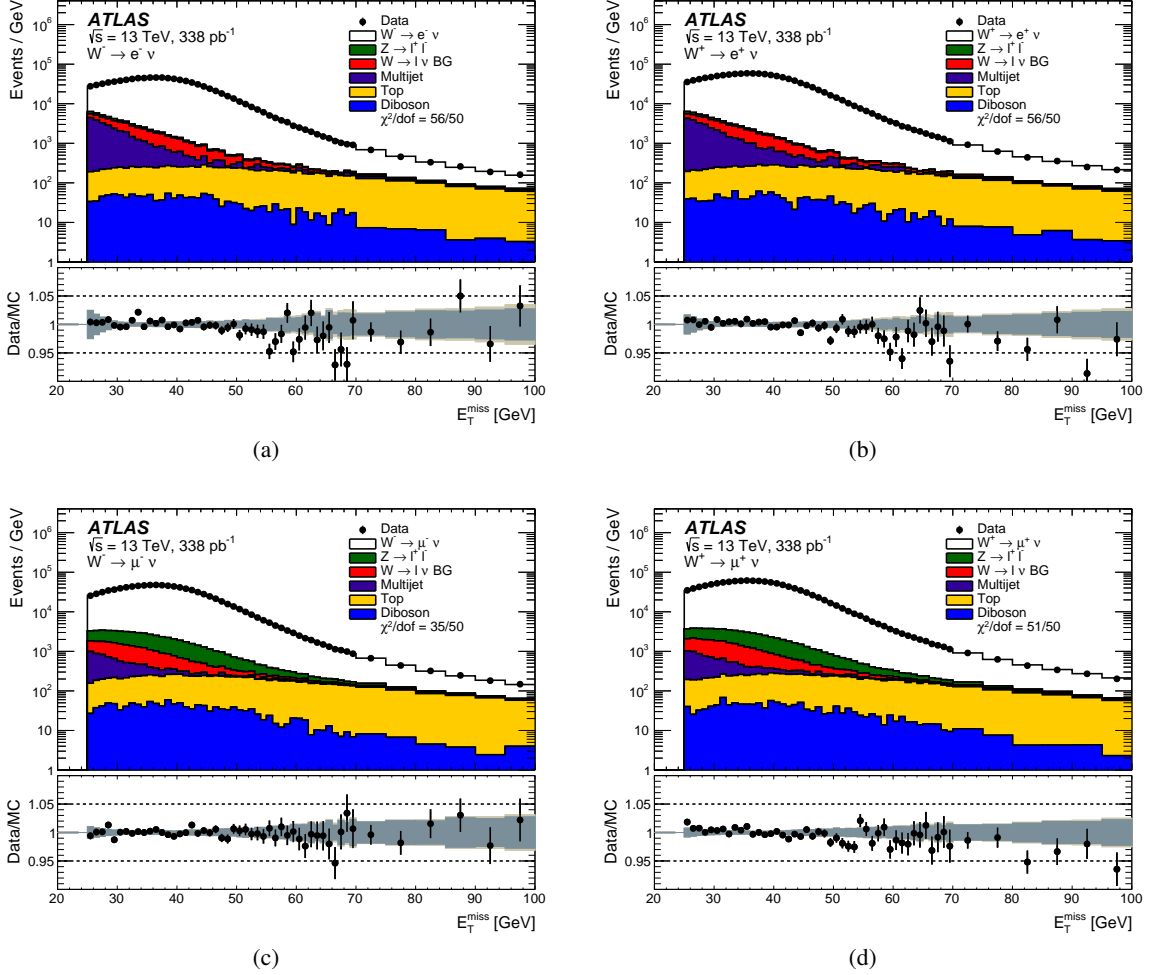


Figure 8: Missing transverse momentum E_T^{miss} distributions in the (a) $W^- \rightarrow e^- \nu$, (b) $W^+ \rightarrow e^+ \nu$, (c) $W^- \rightarrow \mu^- \nu$ and (d) $W^+ \rightarrow \mu^+ \nu$ channels for the $\sqrt{s} = 13 \text{ TeV}$ dataset. The data (black points) is compared to the sum of all expected background and signal contributions, shown as a solid line, normalised to the total data yield. The lower panel shows the ratio of the data to the full prediction (black points) as well as the prediction uncertainties around 1 excluding (including) the MC simulation statistical component as dark (light) band. The prediction uncertainties shown exclude those from the luminosity measurement and the alternative signal modelling, see text. The χ^2/dof is computed using the full covariance matrix of all shown statistical and systematic uncertainties. The category $W \rightarrow \ell \nu$ BG refers to background from $W \rightarrow \tau \nu$ and charge misidentification in the electron channels.

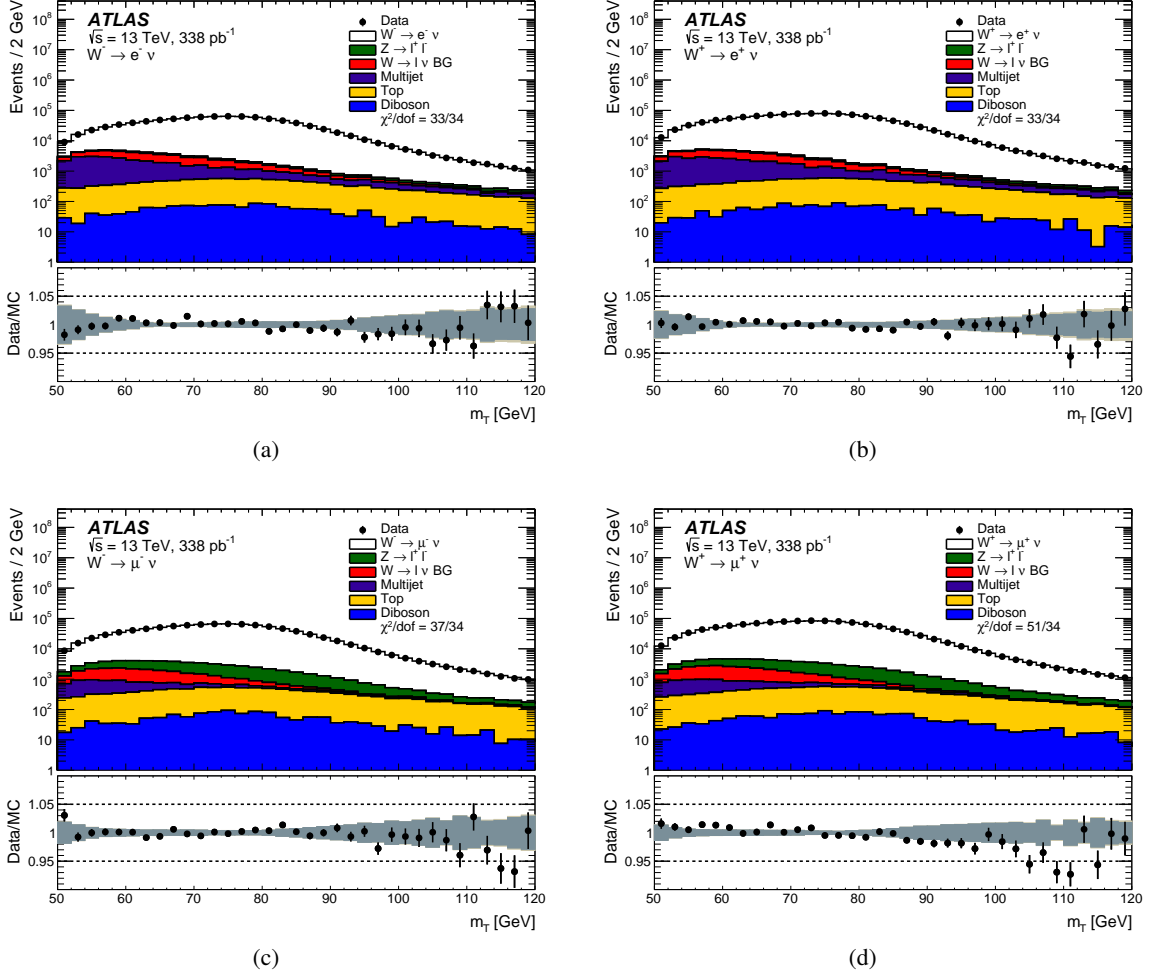


Figure 9: Transverse mass m_T distributions of the W boson in the (a) $W^- \rightarrow e^- \nu$, (b) $W^+ \rightarrow e^+ \nu$, (c) $W^- \rightarrow \mu^- \nu$ and (d) $W^+ \rightarrow \mu^+ \nu$ channels for the $\sqrt{s} = 13$ TeV dataset. The data (black points) is compared to the sum of all expected background and signal contributions, shown as a solid line, normalised to the total data yield. The lower panel shows the ratio of the data to the full prediction (black points) as well as the prediction uncertainties around 1 excluding (including) the MC simulation statistical component as dark (light) band. The prediction uncertainties shown exclude those from the luminosity measurement and the alternative signal modelling, see text. The χ^2/dof is computed using the full covariance matrix of all shown statistical and systematic uncertainties. The category $W \rightarrow \ell \nu$ BG refers to background from $W \rightarrow \tau \nu$ and charge misidentification in the electron channels.

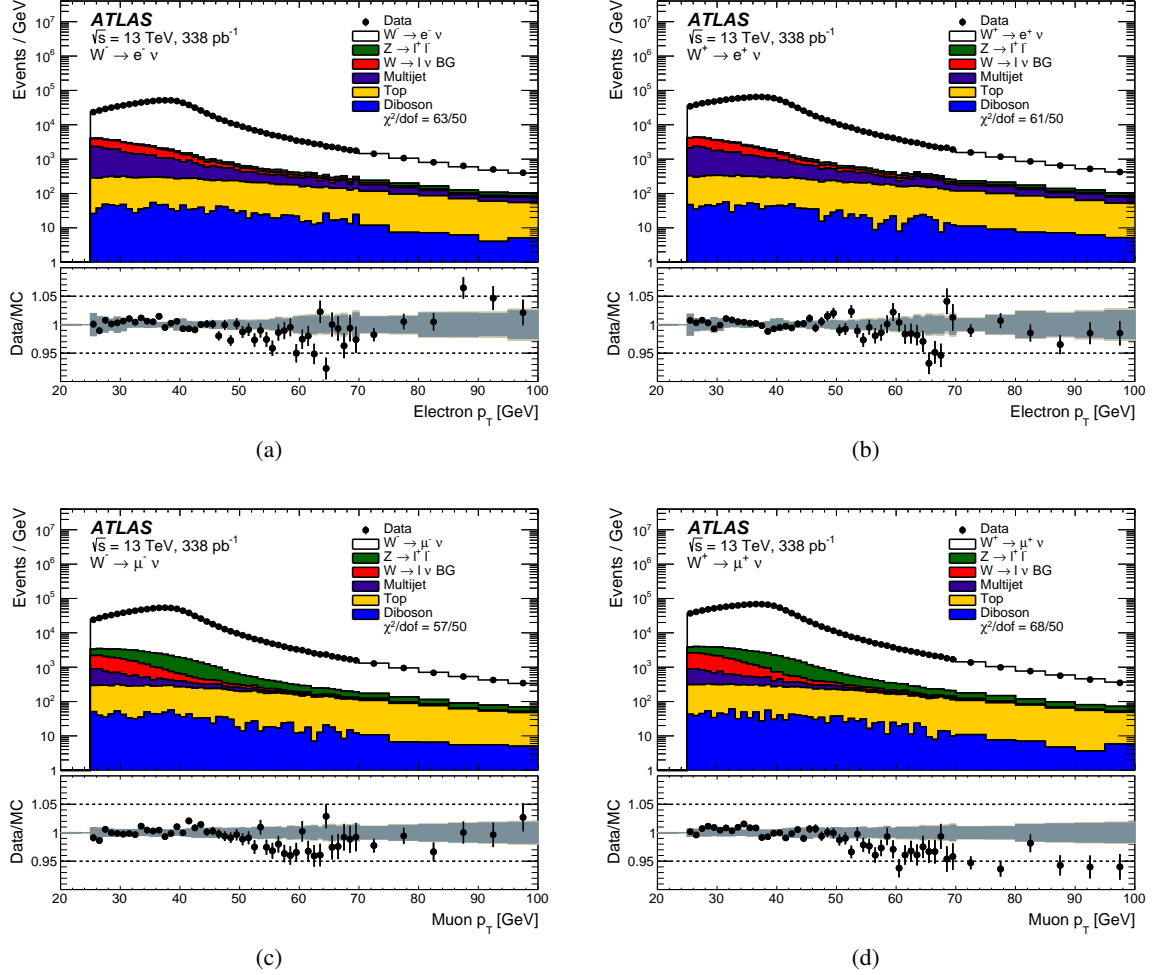


Figure 10: Lepton transverse momentum p_T distributions in the (a) $W^- \rightarrow e^- \nu$, (b) $W^+ \rightarrow e^+ \nu$, (c) $W^- \rightarrow \mu^- \nu$ and (d) $W^+ \rightarrow \mu^+ \nu$ channels for the $\sqrt{s} = 13$ TeV dataset. The data (black points) is compared to the sum of all expected background and signal contributions, shown as a solid line, normalised to the total data yield. The lower panel shows the ratio of the data to the full prediction (black points) as well as the prediction uncertainties around 1 excluding (including) the MC simulation statistical component as dark (light) band. The prediction uncertainties shown exclude those from the luminosity measurement and the alternative signal modelling, see text. The χ^2/dof is computed using the full covariance matrix of all shown statistical and systematic uncertainties. The category $W \rightarrow \ell \nu$ BG refers to background from $W \rightarrow \tau \nu$ and charge misidentification in the electron channels.

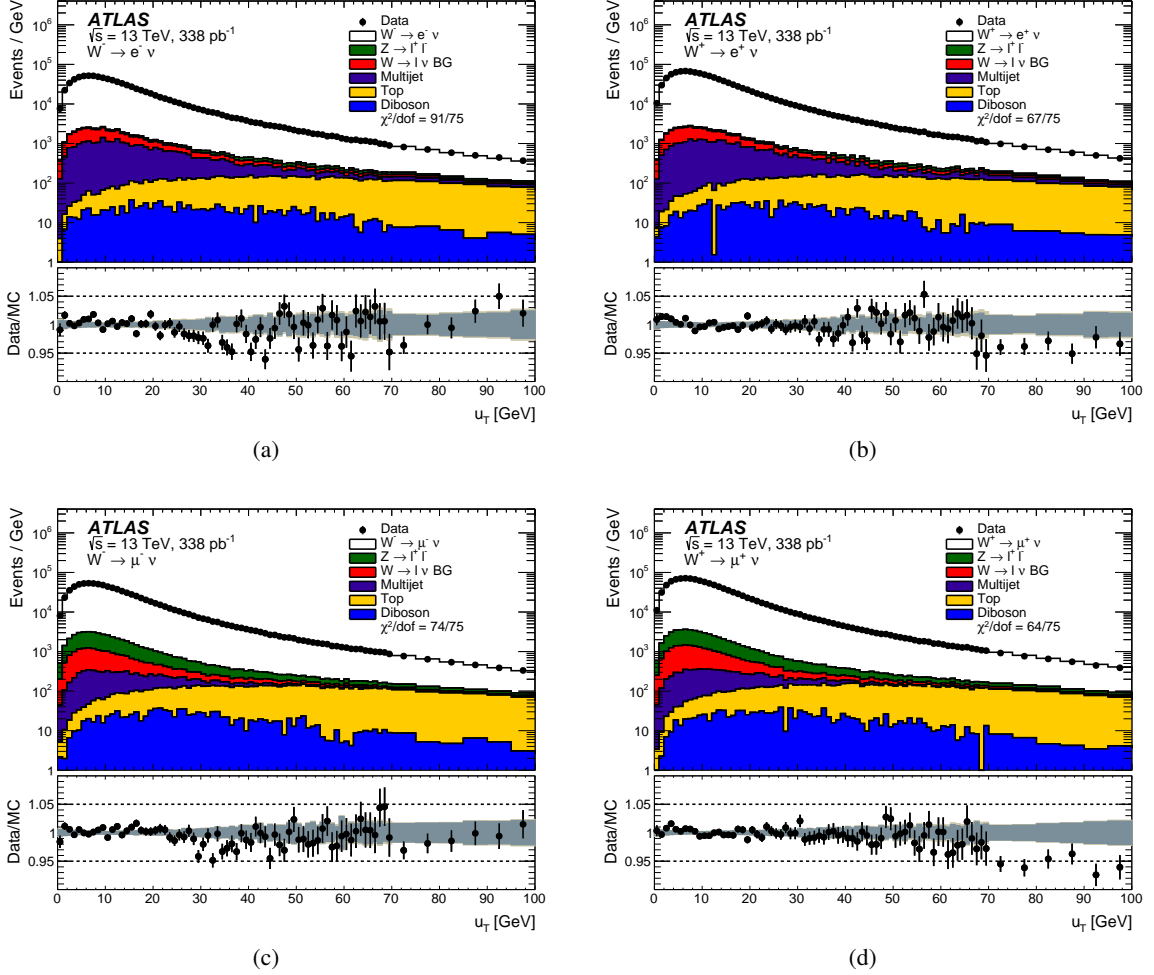


Figure 11: Hadronic recoil u_T distributions (boson transverse momentum) in the (a) $W^- \rightarrow e^- \nu$, (b) $W^+ \rightarrow e^+ \nu$, (c) $W^- \rightarrow \mu^- \nu$ and (d) $W^+ \rightarrow \mu^+ \nu$ channels for the $\sqrt{s} = 13$ TeV dataset. The data (black points) is compared to the sum of all expected background and signal contributions, shown as a solid line, normalised to the total data yield. The lower panel shows the ratio of the data to the full prediction (black points) as well as the prediction uncertainties around 1 excluding (including) the MC simulation statistical component as dark (light) band. The prediction uncertainties shown exclude those from the luminosity measurement and the alternative signal modelling, see text. The χ^2/dof is computed using the full covariance matrix of all shown statistical and systematic uncertainties. The category $W \rightarrow \ell \nu$ BG refers to background from $W \rightarrow \tau \nu$ and charge misidentification in the electron channels.

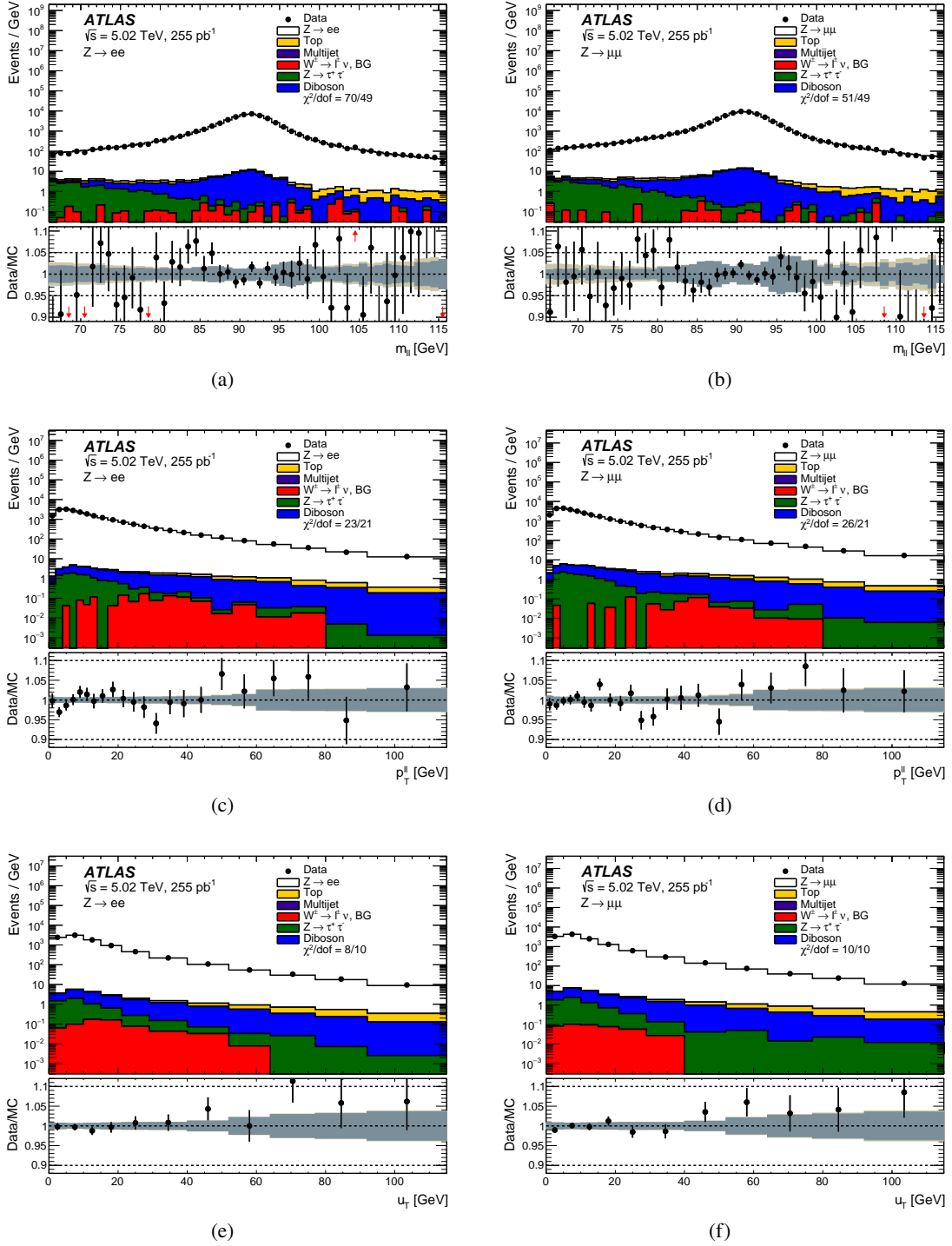


Figure 12: Distributions of dilepton mass $m_{\ell\ell}$ in the (a) $Z \rightarrow ee$ and (b) $Z \rightarrow \mu\mu$ channels, of dilepton transverse momentum $p_T^{\ell\ell}$ in the (c) $Z \rightarrow ee$ and (d) $Z \rightarrow \mu\mu$ channels, and of hadronic recoil u_T in the (e) $Z \rightarrow ee$ and (f) $Z \rightarrow \mu\mu$ channels in the $\sqrt{s} = 5.02$ TeV analysis. The data (black points) is compared to the sum of all expected background and signal contributions, shown as a solid line, normalised to the total data yield. The lower panel shows the ratio of the data to the full prediction (black points) and the prediction uncertainties around 1 excluding (including) the MC simulation statistical component as dark grey (light brown) band. The prediction uncertainties shown exclude those from the luminosity measurement and the alternative signal modelling, see text. The χ^2/dof is computed using the full covariance matrix of all shown statistical and systematic uncertainties.

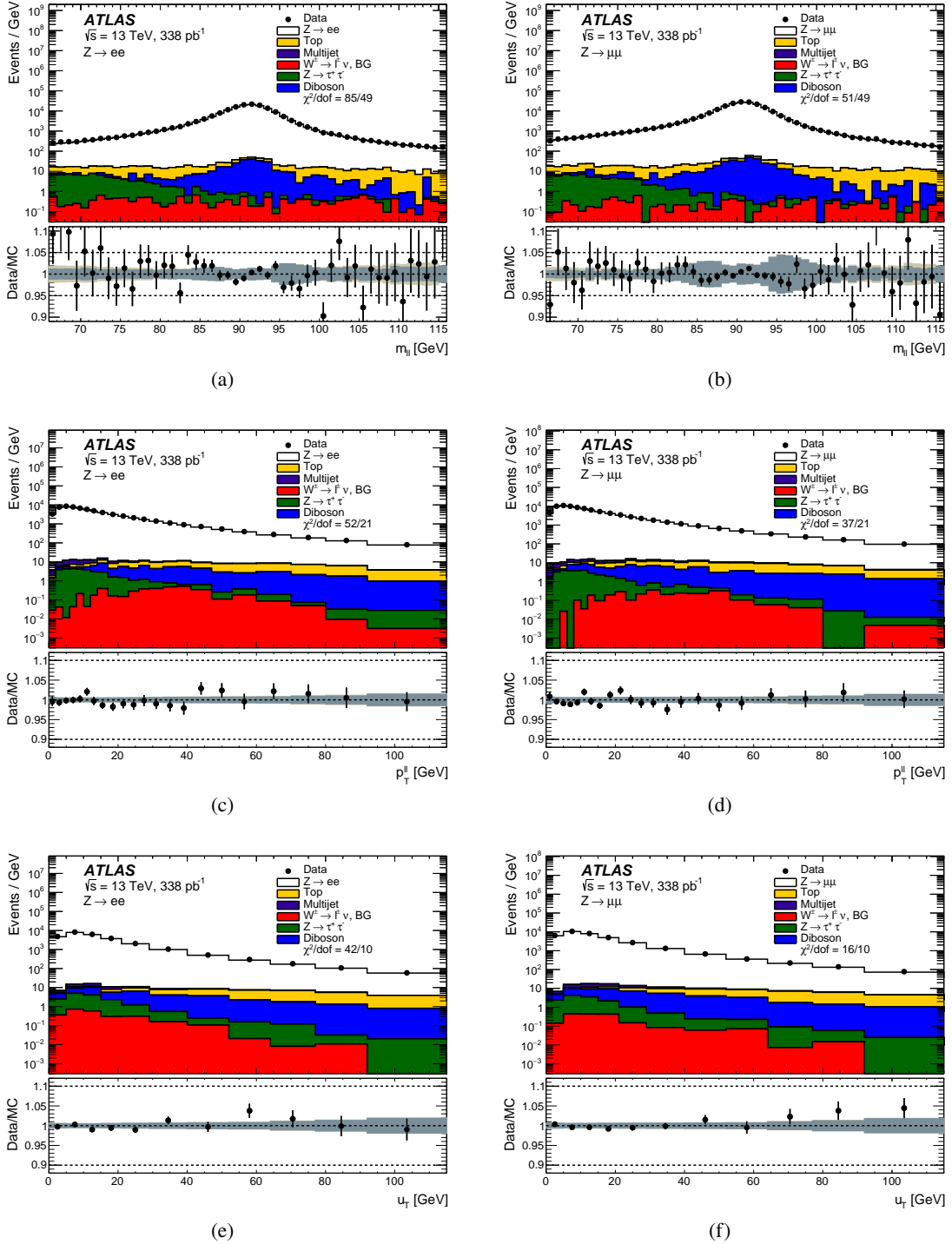


Figure 13: Distributions of dilepton mass $m_{\ell\ell}$ in the (a) $Z \rightarrow ee$ and (b) $Z \rightarrow \mu\mu$ channels, of dilepton transverse momentum $p_T^{\ell\ell}$ in the (c) $Z \rightarrow ee$ and (d) $Z \rightarrow \mu\mu$ channels, and of hadronic recoil u_T in the (e) $Z \rightarrow ee$ and (f) $Z \rightarrow \mu\mu$ channels in the $\sqrt{s} = 13$ TeV analysis. The data (black points) is compared to the sum of all expected background and signal contributions, shown as a solid line, normalised to the total data yield. The lower panel shows the ratio of the data to the full prediction (black points) and the prediction uncertainties around 1 excluding (including) the MC simulation statistical component as dark grey (light brown) band. The prediction uncertainties shown exclude those from the luminosity measurement and the alternative signal modelling, see text. The χ^2/dof is computed using the full covariance matrix of all shown statistical and systematic uncertainties.

6 Cross-section measurement

The W^- , W^+ and Z -boson transverse momentum distributions are measured separately for the electron and muon decay channels. Results are reported in a fiducial phase space close to the experimental acceptance, and defined by particle-level kinematics as follows:

- $W \rightarrow \ell\nu$: $p_T^\ell > 25$ GeV, $|\eta^\ell| < 2.5$, $p_T^\nu > 25$ GeV, and $m_T > 50$ GeV;
- $Z \rightarrow \ell\ell$: $p_T^\ell > 25$ GeV, $|\eta^\ell| < 2.5$, and 66 GeV $< m_{\ell\ell} < 116$ GeV.

The lepton kinematics used in the definition of the cross sections corresponds to the Born level for QED final-state radiation effects. The Z -boson measurements include the small virtual photon contributions, i.e. the full $Z/\gamma^* \rightarrow \ell\ell$ process is measured. The measured differential cross sections are also used to derive integrated cross sections and ratios.

The measurement bins are chosen by taking into consideration competing demands on the analysis, namely sensitivity to the underlying physics, the statistical precision in each bin, and detector resolution effects. The latter are particularly important for the hadronic recoil observable at low boson transverse momentum and require a minimum bin size of 7 GeV at low p_T^V to ensure that the unfolding systematic uncertainties are around 1% or lower. The measurement is performed in $p_T^{\text{true},V}$ bins with bin edges as follows:

- p_T^W at 5.02 TeV: [0, 7, 14, 21, 28, 35, 42, 49, 56, 63, 77, 92, 115, 145, 175, 220] GeV;
- p_T^W at 13 TeV : [0, 7, 14, 21, 28, 35, 42, 49, 56, 63, 77, 92, 115, 145, 175, 220, 310, 600] GeV;
- p_T^Z at 5.02 TeV: [0, 2, 4, 6, 8, 10, 12, 14, 17, 20, 23, 26, 29, 33, 37, 41, 47, 53, 60, 70, 80, 92, 115, 145, 175, 220] GeV;
- p_T^Z at 13 TeV : [0, 2, 4, 6, 8, 10, 12, 14, 17, 20, 23, 26, 29, 33, 37, 41, 47, 53, 60, 70, 80, 92, 115, 145, 175, 220, 310, 600] GeV.

The p_T^Z distribution is measured separately using the u_T and the $p_T^{\ell\ell}$ observables. The former is used to validate the measurement procedures in the same bins as the respective p_T^W measurements, as discussed in Section 6.3, while the latter is used in the main p_T^Z measurements with the finer binning given above. For the differential W/Z ratio measurements, the Z boson distribution is also measured using the $p_T^{\ell\ell}$ observable in the same bins as the W distributions.

6.1 Unfolding

The distributions observed after analysis selections and background subtraction are corrected for detector effects using an iterative Bayesian unfolding method [76, 77]. First, the data are corrected for events that pass the detector-level selection but not the particle-level selection. The iterative Bayesian unfolding technique is then used to correct for the finite detector acceptance, resolution and reconstruction efficiency and estimate the true underlying distribution.

Simulated events are used to determine the response matrices needed to correct for the migration between bins in the detector- and particle-level distributions. The hadronic recoil resolution leads to significant migrations in u_T . The effect of the detector resolution on the event migrations is illustrated in Figure 14, which compares the observed $p_T^{\ell\ell}$ and u_T distributions for given intervals in $p_T^{\text{true},V}$, in simulated $Z \rightarrow \mu\mu$ events at 13 TeV. Significant differences are observed in the corresponding reconstructed distributions.

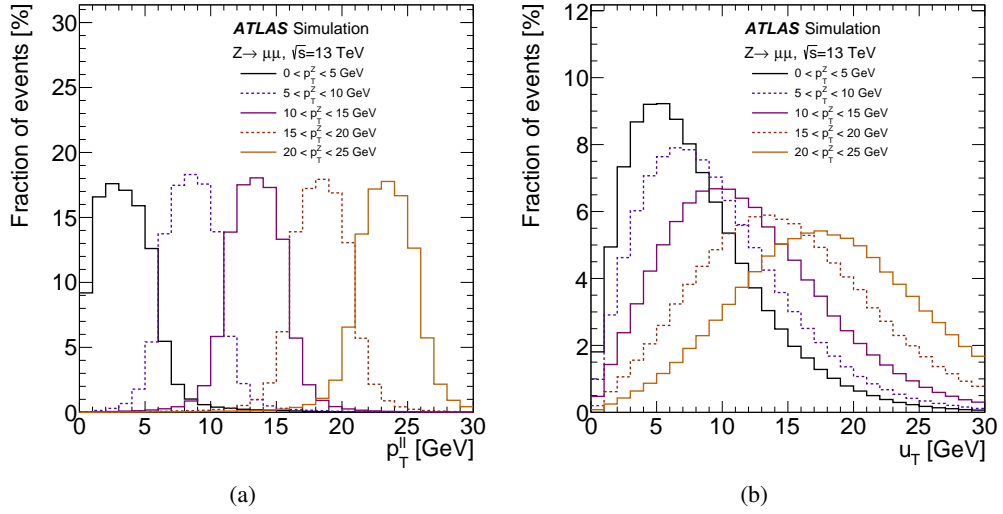


Figure 14: The detector response in five intervals in the true boson transverse momentum p_T^Z are shown for $Z \rightarrow \mu\mu$ events at $\sqrt{s} = 13$ TeV, using the observables built from (a) the dilepton system $p_T^{\ell\ell}$ and (b) the hadronic recoil u_T .

The particle-level binning is therefore optimised separately for each observable. The number of iterations in the unfolding procedure is optimised to minimise the total measurement uncertainty, and specifically the uncertainty related to possible biases induced by the unfolding prior. Methods to estimate the unfolding bias and the optimisation of the number of iterations are discussed further in this section.

After calibration corrections, the detector-level transverse momentum distributions in data and MC are found to disagree, *i.e.* the difference is found to be significantly larger than the experimental sensitivity, especially at 13 TeV. To minimise the related uncertainties, the simulation is reweighted in $p_T^{\text{true},V}$ to optimise the agreement between data and MC for the reconstructed u_T (or $p_T^{\ell\ell}$) distributions for W (and Z) analyses.² This procedure ensures that the unfolding bias is kept as low as possible.

The agreement between data and simulation is optimised for the u_T distribution by minimising the following χ^2 :

$$\chi^2 = \sum_{ij} \Delta_i (C^{-1})_{ij} \Delta_j, \quad (5)$$

$$\Delta_i = (D_i - B_i) - \sum_k T_{ik} \times w_k. \quad (6)$$

Here $(C^{-1})_{ij}$ denotes the inverted total covariance between detector-level bins i and j , including statistical and systematic uncertainties in the observed and simulated u_T distributions; Δ_i is the difference between the background-subtracted data distribution in bin i , $D_i - B_i$, and the corresponding reconstruction-level simulated distribution. The latter is obtained from the product between a generator-level weighting coefficient w_k and the transfer matrix T_{ik} that is filled with the number of entries in bins i, k at detector and particle level, respectively. The weight, w_k , is the average in particle-level bin k of a continuous weighting function $w(p_T^{\text{true},V})$ that modifies the p_T^W distribution in the MC sample. The parameters of $w(p_T^{\text{true},V})$ are

² To achieve this, the analysis including some background estimates is iterated. Object calibrations, including the hadronic recoil are performed such that they are to first order insensitive to the p_T^V modelling in the MC simulation.

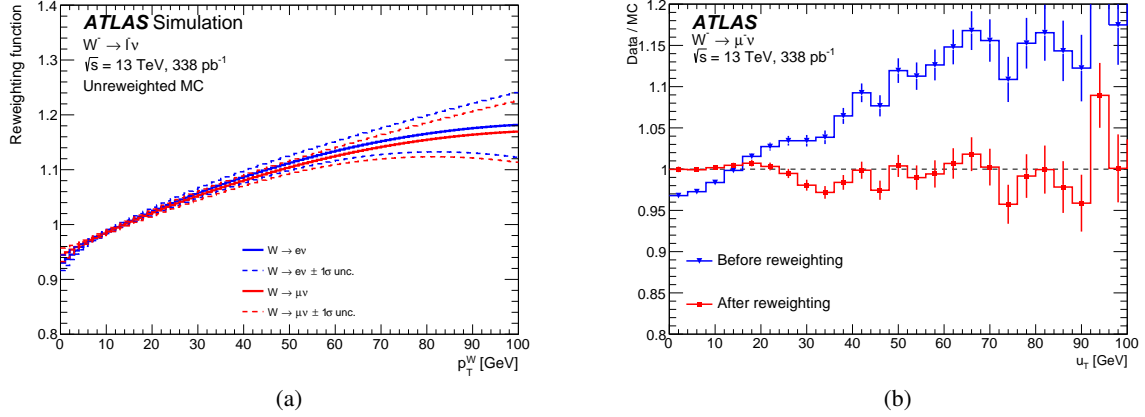


Figure 15: (a) Fitted truth reweighting functions w_T in the electron and muon channels (full lines) for $W^- \rightarrow \ell^- \nu$ at $\sqrt{s} = 13$ TeV. The dashed lines represent the uncertainty on the reweighting functions from the fit. (b) The data-to-simulation ratios of the reconstructed u_T distributions before (blue triangles) and after (red squares) the reweighting. Error bars are statistical only.

the degrees of freedom in the minimisation procedure. A satisfactory agreement is obtained using the empirical function

$$w(p_T) = N \left[\left(1 + a p_T^{\text{true},V} + b \left(p_T^{\text{true},V} \right)^2 \right) \times \left(1 - c + c \times r_{\text{NNPDF/CT10}}(p_T^{\text{true},V}) \right) \right], \quad (7)$$

where N is an overall normalisation factor and $r_{\text{NNPDF/CT10}}(p_T^{\text{true},V})$ represents the ratio of DYTURBO predictions obtained using NNPDF3.0 and CT10NLO in the full phase space. The additional parameters (a, b, c) provide more flexibility to minimise the χ^2 of Eq. (5).

The reweighting functions are optimised separately for each process and each centre-of-mass energy. They are derived over the $p_T^{\text{true},V}$ range of 0 – 100 GeV where a good modelling of the spectrum is critical. The value of the correction at $p_T^{\text{true},V} = 100$ GeV is used for $p_T^{\text{true},V} > 100$ GeV, as the impact on the final results in this region is found to be negligible. Using the $W^- \rightarrow \ell^- \nu$ at 13 TeV as example, the two reweighting functions for the electron and muon channels are shown in Figure 15(a). Since the e and μ channel are compatible for all final states, the averages of the respective two reweighting functions are later applied to both channels. The corresponding effect of this p_T^V reweighting on the reconstructed u_T distributions is shown in Figure 15(b).

The reweighted simulation is used to determine the response matrix used in the unfolding. Both the bin size at low p_T^W and the number of unfolding iterations are optimised given the considerations discussed above. As statistical uncertainties are generally smaller than the estimate of the unfolding bias, a large number of 25 iterations is found to be optimal for the 13 TeV analysis to minimise the total uncertainties. In the smaller 5.02 TeV samples the optimal number of iterations is found to be nine.

For the Z process the same approach is used, with the addition that separate reweightings are derived using the $p_T^{\ell\ell}$ and u_T distributions for the respective measurements.³ Because of the far better resolution in $p_T^{\ell\ell}$,

³ The measurement of p_T^Z using the u_T distribution is only used in the validation of the measurement procedure, presented in Section 6.3.

only two unfolding iterations are used. Uncertainties related to the assumed prior for the p_T^V spectrum in the unfolding are discussed in the next section.

6.2 Systematic uncertainties

The present measurement is affected by statistical uncertainties as well as systematic uncertainties related to detector calibration, the background estimate, the definition of the response matrix and to the unfolding procedure. For each uncertainty, the corresponding source of uncertainty is varied to estimate the effect on the final result. A graphical representation of the uncertainties is given in Appendix A.

The effect on the measurement from the finite size of the data and MC simulated samples is estimated by generating pseudo-experiment variations of the respective samples [78]. The resulting statistical uncertainties are uncorrelated between channels, but partially correlated between bins due to the unfolding. In the p_T^W measurement at 5.02 TeV, where the event samples are smaller than at 13 TeV, the statistical uncertainty of the data is the co-dominant uncertainty beyond $p_T^W = 20$ GeV, going from about 0.5% below this region to $\approx 2.5\%$ at $p_T^W = 60$ GeV. At 13 TeV, it becomes dominant around $p_T^W = 60$ GeV. For the p_T^Z measurements, the statistical uncertainty of the data is the dominant source of uncertainty.

Uncertainties in the scale and resolution of the hadronic recoil are among the dominant uncertainties in the p_T^W measurement. They are estimated by propagating the statistical uncertainties in the calibration procedure and systematic effects as discussed in Section 4. In the first p_T^W bin these are usually the largest or second-largest systematic uncertainties reaching typically 0.6%. They grow moderately with p_T^W depending on the boson charge and on the centre of mass energy. In the p_T^W range of 30–50 GeV, the uncertainty in the measurement for W^- events is slightly higher than for W^+ events, due to observed differences between the extrapolation uncertainties from the Z -boson. In the 5.02 TeV data, it reaches 1.5% at 50 GeV, and goes up to $\approx 3\%$ at 100 GeV. At 13 TeV, since more Z events are available for the calibration, the uncertainty is smaller, and increases slowly to reach 1.5% at 100 GeV.

Lepton-related systematic uncertainties due to energy scale and resolution as well as reconstruction and selection efficiency corrections are propagated considering the statistical and systematic uncertainties in the procedures described in Sections 3.1 and 3.2. They have only a small effect on both the p_T^W and the p_T^Z measurements.

Uncertainties in the background estimation are only significant in the W analysis. Uncertainties induced by the simulated backgrounds are obtained by independently varying the corresponding cross sections. The uncertainty in the multijet background is dominant in the electron channel. The estimated multijet background yields are treated as correlated between the channels since the same techniques are used.

The uncertainty assigned to the unfolding procedure itself is estimated from the dependence of the results on the assumed priors for the p_T^V distributions. The nominal particle-level spectrum, obtained from the reweighting procedure described in Section 6.1, is varied within the fit uncertainties, taking correlations between the fit parameters into account. Alternative functional forms are used to test the influence of the p_T^V distribution at low values. The baseline particle-level distribution at a given rapidity is modified using alternative predictions. Four alternative predictions are chosen: DYTURBO with the NNPDF3.1 and CT10 PDF sets; POWHEG+HERWIG 7, and PYTHIA 8, described in more detail in Section 7.3. The SHERPA samples introduced in Section 2.3 are considered but discarded due to the poor description of the data below 20 GeV.

The closure of the unfolding procedure is further tested using the alternative SHERPA model for the signal MC simulation, as discussed at the end of Section 4. The SHERPA samples represent a completely independent implementation of the physics of vector boson production and decay as compared to POWHEG+PYTHIA 8. In many respects, such as the vertex efficiency (Section 3.3) and the modelling of quantities relevant for the hadronic recoil (Section 4.2), the predictions of the two generators bracket the data. At 5.02 TeV, the resulting uncertainty stays subdominant in the region $p_T^W < 30$ GeV, whereas at 13 TeV, it is the largest or second-to-largest systematic uncertainty, reaching more than 1% in the second bin.

The uncertainties in the integrated luminosities are 1.0% and 0.92% for the 5.02 TeV and 13 TeV datasets, following the methodology discussed in Ref. [32], using the LUCID-2 detector [29] for the primary luminosity measurements, complemented by measurements using the inner detector and calorimeters.

6.3 Validation of recoil-based measurement with Z dilepton

In the Z samples, the transverse momentum spectra can be inferred either from the $p_T^{\ell\ell}$ or from the u_T distributions. As shown in Figure 14, a sizeable difference is observed between the resolutions of the two observables. Therefore a comparison of the corresponding unfolded distributions is a powerful tool to validate the recoil calibration and the measurement of p_T^W .

For the validation, the p_T^Z spectra are unfolded from the $p_T^{\ell\ell}$ and u_T distributions using the same binning as used for the p_T^W measurement. The uncertainty in the difference can be represented in covariance matrix form, accounting for correlations where relevant. Since the two measurements are extracted from the same events, the statistical correlation is estimated by using the bootstrap method. The compatibility is estimated evaluating the χ^2 computed for the differences of the unfolded distributions. The electron and muon-channel measurements in a given bin are added. The leading uncertainties arise from data statistical uncertainties, hadronic recoil calibration and components of the unfolding uncertainty. Lepton calibrations are only significant at 13 TeV. The number of degrees of freedom is one less than the number of bins due to the additional constraint of the same total cross section extracted from the two observables. Figure 16 compares both measured spectra at each centre-of-mass energy. The χ^2/dof values computed with the 5.02 TeV and 13 TeV datasets are 14.9/14 and 8.7/16, respectively, which represents an excellent compatibility.

7 Results

7.1 Combination of electron and muon channels

The electron and muon channel cross sections are combined assuming Gaussian uncertainties, following the best linear unbiased estimator prescription (BLUE) [79, 80]. The χ^2 to be minimised is:

$$\chi^2 = \sum_{i,j=1}^{2N} (m_i - \bar{m}_i) (C^{-1})_{ij} (m_j - \bar{m}_j), \quad (8)$$

where m_i are the measurements in the $i = 1 \dots N$ bins of the distributions in the electron and muon channels, i.e the $2N$ -sized vector $\mathbf{m} = \{m_1^e, \dots, m_N^e; m_1^\mu, \dots, m_N^\mu\}$, $\bar{\mathbf{m}} = \{\bar{m}_1, \dots, \bar{m}_N; \bar{m}_1, \dots, \bar{m}_N\}$ is the

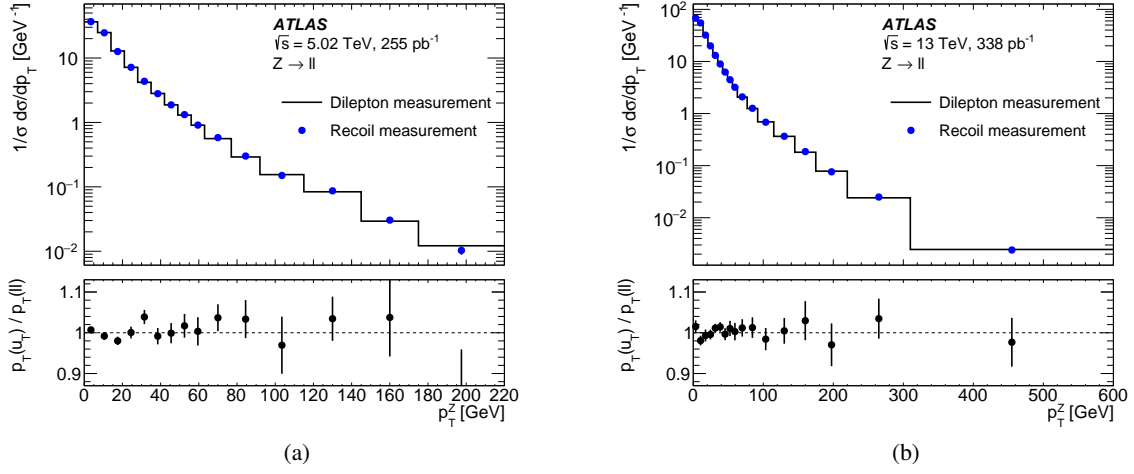


Figure 16: Spectra of p_T^Z measured using either $p_T^{\ell\ell}$ (black line) or u_T (blue points), at (a) $\sqrt{s} = 5.02$ TeV and (b) $\sqrt{s} = 13$ TeV. The respective measurements, shown in the top panel, largely overlap. The lower panel shows the ratio of the u_T over the $p_T^{\ell\ell}$ measurements with the uncertainties estimated from the square root of the diagonal elements of the total covariance matrix used to compute the compatibility between them.

vector of averages to be determined, and C^{-1} is the inverse of the $2N \times 2N$ measurement covariance matrix. The covariance matrix C is constructed as

$$C_{ij} = C_{ij}^{\text{stat}} + \sum_k C_{ij}^{\text{syst},k}, \quad (9)$$

where C^{stat} is the statistical covariance and can be written as

$$C^{\text{stat}} = \begin{pmatrix} C_e^{\text{stat}} & 0 \\ 0 & C_\mu^{\text{stat}} \end{pmatrix}, \quad (10)$$

and $C_{e(\mu)}^{\text{stat}}$ are non-diagonal, $N \times N$ covariance matrices resulting from the unfolding of the electron- and muon-channel distributions. For each systematic source of uncertainty k ,

$$C_{ij}^{\text{syst},k} = \Gamma_i^k \Gamma_j^k \quad (11)$$

is the product of the effects of varying source k in bins i and j .

The vector $\bar{\mathbf{m}}$ that minimises the χ^2 is:

$$\bar{\mathbf{m}} = (H^T C^{-1} H)^{-1} H^T C^{-1} \mathbf{m}, \quad (12)$$

where H is a $2N \times N$ matrix such that $H_{ij} = 1$ when measurement bin $i = 1 \cdots 2N$ contributes to the combined value $j = 1 \cdots N$, and $H_{ij} = 0$ otherwise. The covariance matrix of the combined measurement is given by:

$$\bar{C} = (H^T C^{-1} H)^{-1}. \quad (13)$$

This procedure is correct in the Gaussian limit and when the uncertainties do not depend on the value of the measured quantity. Many sources of uncertainty are, however, defined relative to the measurement; for example, luminosity or efficiency uncertainties are fixed fractions of the measured cross section. Such

uncertainties are then smaller for lower measured values, biasing the average towards the lowest measured cross section. The combination procedure is therefore iterated and the covariance matrix elements are rescaled according to the combined uncertainties of the previous iteration [81]. Stable results are obtained after four iterations.

The uncertainty model is detailed, with about 1800 systematic sources. Lepton-related uncertainties are treated as uncorrelated between measurements at a given \sqrt{s} , but fully correlated within one \sqrt{s} sample. Recoil uncertainties are similarly correlated between the W^- , W^+ and Z measurements at a given \sqrt{s} , with the exception of the $\Sigma\bar{E}_T$ modelling that is only correlated for a type of vector boson. Background uncertainties are treated as fully correlated across all channels, except for the QCD multijet between W and Z samples. Unfolding uncertainties are treated as correlated across a given spectrum as well as between the electron and muons channels, but uncorrelated otherwise. The generator uncertainties are separately correlated between all W and all Z analyses across both \sqrt{s} datasets, but uncorrelated between W and Z . Finally, the luminosity systematic uncertainty is correlated among all analyses using a given \sqrt{s} data sample, but treated as uncorrelated between the 5.02 TeV and 13 TeV datasets.

Combinations are performed for absolute and normalised differential cross sections. The compatibility of the electron and muon channel measurements is generally good, as evidenced by combination χ^2 values close to the number of degrees of freedom. The combined uncertainties on the normalised spectra are shown as a function of p_T^W and p_T^Z in Figure 17, with an overall precision of about 1% at low p_T , reaching about 10% towards the end of the spectrum. The W -boson uncertainties are dominated by unfolding systematic uncertainties at low p_T^W , and statistical uncertainties at high p_T^W . The generator dependence of the recoil calibration procedure is sizeable at 13 TeV. The Z -boson uncertainties are fully dominated by statistical uncertainties.

7.2 Integrated cross sections and distribution ratios

Integrated fiducial cross sections are obtained by summing the measured distributions over a given spectrum, and the corresponding uncertainty is given by summing the corresponding covariance matrix elements. The definition of the fiducial volume is given in Section 6, and the results are summarised in Table 3. Experimental systematic uncertainties excluding the luminosity are at the level of 0.4% and 0.5% for W -boson production at 5.02 TeV and 13 TeV, respectively. The corresponding numbers for the Z -boson cross sections are 0.7% and 0.9%. The luminosity uncertainty is 1.0% at 5.02 TeV, and 0.9% at 13 TeV.

Similar measurements at 5.02 TeV previously published by ATLAS in Ref. [82] are not directly comparable to the new results due to small differences in the fiducial volume definition. However, the relative uncertainties are improved by about a factor of two due to the larger dataset and improved experimental calibrations, including the luminosity measurement. The measurements at 13 TeV are compatible with those performed by ATLAS with the very early Run 2 data with a luminosity of just 81 pb^{-1} [83] and improve the precision by a factor of 3.5 for the W measurement and a factor of 1.7 for the Z measurement. The 13 TeV Z -boson measurement is also compatible with the improved ATLAS measurement of Ref. [84] that has a slightly lower precision because of the preliminary luminosity calibration used then.

The measured ratios of integrated fiducial cross sections are given in Tables 4 and 5. As expected, all cross sections rise with \sqrt{s} , as lower parton momentum fractions x are probed and the densities of sea quarks and antiquarks rise towards low x . The increase in the W^+ cross section is the smallest because it has the largest contribution from higher x valence quarks that contribute less to the phase space measured at higher \sqrt{s} .

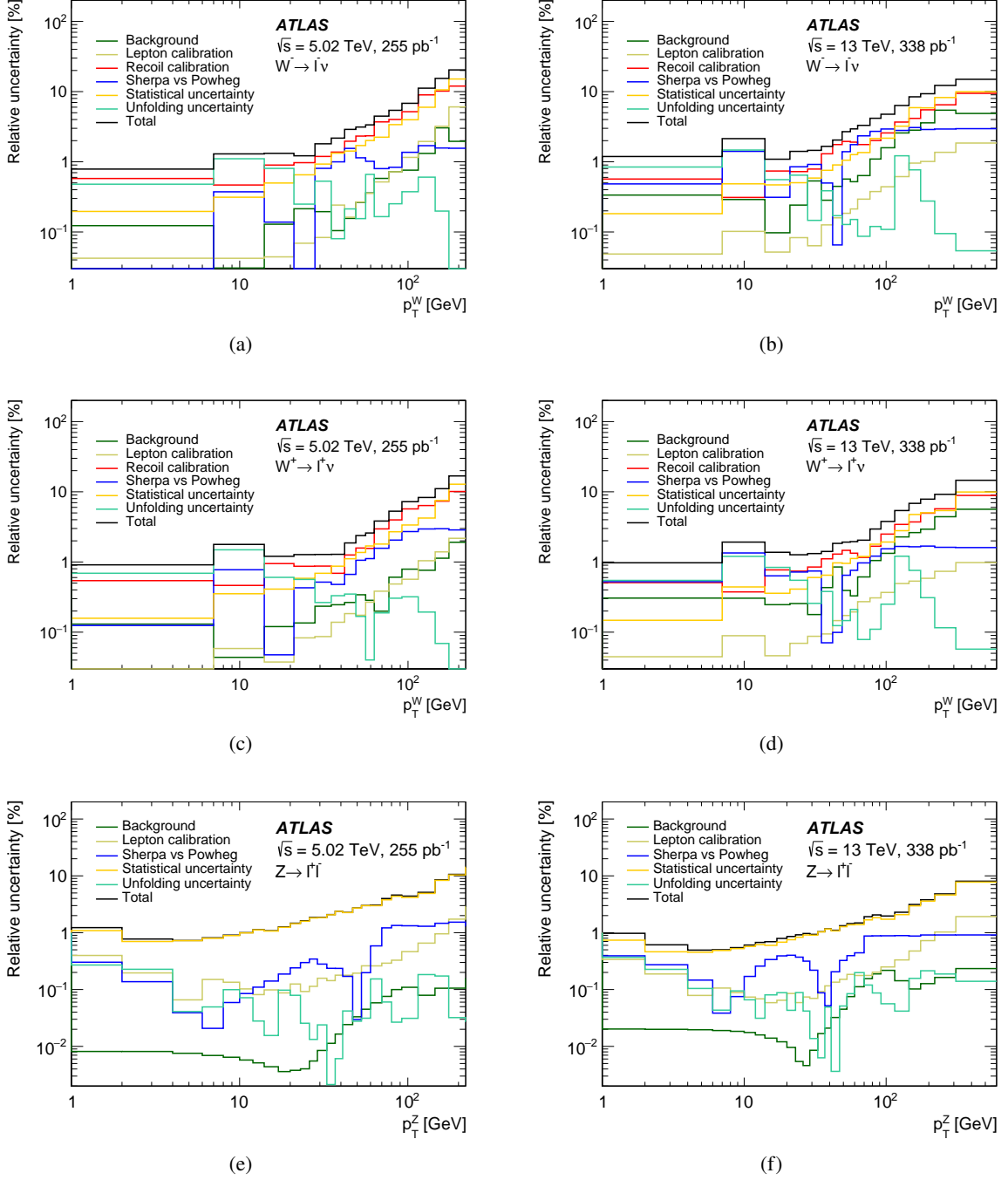


Figure 17: Uncertainty contributions in the combined normalised p_T distributions for W^- at (a) $\sqrt{s} = 5.02$ TeV and (b) $\sqrt{s} = 13$ TeV, W^+ at (c) $\sqrt{s} = 5.02$ TeV and (d) $\sqrt{s} = 13$ TeV, and Z at (e) $\sqrt{s} = 5.02$ TeV and (f) $\sqrt{s} = 13$ TeV.

Table 3: Integrated fiducial cross sections for W^- , W^+ and Z production at $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 13$ TeV.

Process	$\sigma_{\text{fid}}(\sqrt{s} = 5.02 \text{ TeV})$ [pb]	$\sigma_{\text{fid}}(\sqrt{s} = 13 \text{ TeV})$ [pb]
$W^- \rightarrow \ell^- \nu$	$1384 \pm 2 \text{ (stat.)} \pm 5 \text{ (syst.)} \pm 15 \text{ (lumi.)}$	$3486 \pm 3 \text{ (stat.)} \pm 18 \text{ (syst.)} \pm 34 \text{ (lumi.)}$
$W^+ \rightarrow \ell^+ \nu$	$2228 \pm 3 \text{ (stat.)} \pm 8 \text{ (syst.)} \pm 23 \text{ (lumi.)}$	$4571 \pm 3 \text{ (stat.)} \pm 21 \text{ (syst.)} \pm 44 \text{ (lumi.)}$
$Z \rightarrow \ell\ell$	$333.0 \pm 1.2 \text{ (stat.)} \pm 2.2 \text{ (syst.)} \pm 3.3 \text{ (lumi.)}$	$780.3 \pm 2.6 \text{ (stat.)} \pm 7.1 \text{ (syst.)} \pm 7.1 \text{ (lumi.)}$

Table 4: Ratio of integrated fiducial cross sections at $\sqrt{s} = 13$ TeV and $\sqrt{s} = 5.02$ TeV.

Process	$\sigma_{\text{fid}}(\sqrt{s} = 13 \text{ TeV})/\sigma_{\text{fid}}(\sqrt{s} = 5.02 \text{ TeV})$
$W^- \rightarrow \ell^- \nu$	$2.516 \pm 0.005 \text{ (stat.)} \pm 0.010 \text{ (syst.)} \pm 0.036 \text{ (lumi.)}$
$W^+ \rightarrow \ell^+ \nu$	$2.050 \pm 0.003 \text{ (stat.)} \pm 0.008 \text{ (syst.)} \pm 0.029 \text{ (lumi.)}$
$Z \rightarrow \ell\ell$	$2.344 \pm 0.011 \text{ (stat.)} \pm 0.011 \text{ (syst.)} \pm 0.032 \text{ (lumi.)}$

Table 5: Integrated fiducial cross sections ratios at $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 13$ TeV.

Processes	Cross-section ratio at $\sqrt{s} = 5.02 \text{ TeV}$	Cross-section ratio at $\sqrt{s} = 13 \text{ TeV}$
W^+/W^-	$1.609 \pm 0.003 \text{ (stat.)} \pm 0.004 \text{ (syst.)}$	$1.308 \pm 0.003 \text{ (stat.)} \pm 0.004 \text{ (syst.)}$
W^-/Z	$4.16 \pm 0.02 \text{ (stat.)} \pm 0.03 \text{ (syst.)}$	$4.46 \pm 0.02 \text{ (stat.)} \pm 0.05 \text{ (syst.)}$
W^+/Z	$6.69 \pm 0.02 \text{ (stat.)} \pm 0.05 \text{ (syst.)}$	$5.84 \pm 0.02 \text{ (stat.)} \pm 0.06 \text{ (syst.)}$
W^\pm/Z	$10.85 \pm 0.04 \text{ (stat.)} \pm 0.07 \text{ (syst.)}$	$10.30 \pm 0.04 \text{ (stat.)} \pm 0.10 \text{ (syst.)}$

Cross-section ratios are also formed of the absolute and normalised differential distributions, both between different processes at a given \sqrt{s} and between the same processes at different \sqrt{s} . Theoretically, ratios probe specific aspects of the modelling of W and Z production. The W^+/W^- and W^\pm/Z ratios are expected to be relatively insensitive to universal resummation effects, but the low- p_T range is sensitive to the different initial quark flavours and specifically the contribution of heavy quarks. Experimentally, some of these ratios benefit from a partial cancellation of systematic uncertainties. Most notably, the recoil calibration at a given \sqrt{s} is strongly correlated between the W^+ and W^- measurements as it stems from the same calibration, mostly using Z events. Figure 18(a) and 18(b) illustrates how the associated uncertainties largely cancel in the W^+/W^- ratios, resulting in a measurement uncertainty of around 1% at low p_T . By contrast, since this calibration is obtained independently at $\sqrt{s} = 5.02$ TeV and 13 TeV, the related uncertainty increases in a ratio, as shown in Figures 18(c) and 18(d) and the typical precision is around 2% at lower p_T , increasing significantly towards higher p_T . The electron–muon combination of these ratios have generally very good χ^2/dof .

7.3 Comparison to predictions

The final measurements, obtained from the combination of electron and muon channels, are compared to an extensive list of predictions from higher-order resummed predictions and MC event generators. As a representative example of resummation predictions, calculations from DYTURBO v1.2.3 are presented. These predictions are computed by performing the resummation of logarithmically-enhanced contributions in the small q_T region of the lepton pairs at NNLL accuracy and also include the corresponding finite-order

Table 6: Measured integrated fiducial cross sections for W^- , W^+ and Z production at $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 13$ TeV with total uncertainties (‘Data’) are compared to DYTURBO predictions at NNLO+NNLL using three different NNLO PDF sets: CT18, MSHT20 and NNPDF3.1. Uncertainties in the theoretical predictions correspond to those obtained by variations of the factorisation and renormalisation scales (‘scale’) and those computed from the variations in each PDF given by eigenvector or replica variations (‘PDF’).

PDF set	$W^- \rightarrow \ell^- \nu$	$W^+ \rightarrow \ell^+ \nu$	$Z \rightarrow \ell\ell$
$\sigma_{\text{fid}}(\sqrt{s} = 5.02 \text{ TeV})$ [pb]			
Data	1384 ± 16	2228 ± 25	333.0 ± 4.1
CT18	1360 ± 10 (scale) $^{+30}_{-40}$ (PDF)	2200 ± 10 (scale) $^{+40}_{-70}$ (PDF)	320 ± 1 (scale) $^{+5}_{-9}$ (PDF)
MSHT20	1351^{+5}_{-6} (scale) $^{+22}_{-23}$ (PDF)	2180 ± 10 (scale) $^{+30}_{-40}$ (PDF)	324 ± 1 (scale) $^{+4}_{-5}$ (PDF)
NNPDF31	1381 ± 6 (scale) ± 16 (PDF)	2232^{+8}_{-9} (scale) ± 25 (PDF)	329 ± 1 (scale) ± 4 (PDF)
$\sigma_{\text{fid}}(\sqrt{s} = 13 \text{ TeV})$ [pb]			
Data	3486 ± 38	4571 ± 49	780.3 ± 10.4
CT18	3410^{+40}_{-20} (scale) $^{+60}_{-100}$ (PDF)	4460^{+40}_{-30} (scale) $^{+80}_{-130}$ (PDF)	748^{+5}_{-4} (scale) $^{+18}_{-25}$ (PDF)
MSHT20	3400^{+40}_{-20} (scale) $^{+40}_{-60}$ (PDF)	4460^{+40}_{-30} (scale) $^{+60}_{-70}$ (PDF)	763^{+6}_{-4} (scale) $^{+9}_{-12}$ (PDF)
NNPDF31	3450^{+40}_{-20} (scale) ± 30 (PDF)	4510^{+40}_{-30} (scale) ± 40 (PDF)	769^{+6}_{-4} (scale) ± 7 (PDF)

QCD contributions at NNLO (corrections up to α_s^2). Three different NNLO PDF sets are used: CT18 [85], MSHT20 [86] and NNPDF3.1 [87]. Theoretical uncertainties are estimated through variations of the nominal factorisation, renormalisation and resummation scales by a factor of two up and down, excluding variations in opposite directions, and taking the envelope of all variations. The PDF uncertainties for each set are estimated by calculating the variations for all eigenvector or replicas and combining the results following the prescriptions relevant for each PDF set. When computing the uncertainties in ratios or across differential spectra, the effect of a certain PDF eigenvector or replica variation is taken as correlated. Similarly, the effect of each scale variation is treated as fully correlated between all vector bosons, \sqrt{s} and across spectra. Additional comparisons at $\sqrt{s} = 13$ TeV to predictions by the RADISH program are presented in Appendix B.

The integrated cross-section measurements and ratios presented in Section 7.2 are compared to the integrated DYTURBO predictions in Table 6. Good agreement with the central values of the NNPDF3.1 already within the experimental uncertainties is seen, while the CT18 and MSHT20 predictions tend to underestimate the cross sections, similar to previous observations [82, 84]. When considering the dominant PDF uncertainties, the agreement with all PDF sets is satisfactory. Table 7 compares the measured ratios of cross sections at $\sqrt{s} = 13$ TeV and $\sqrt{s} = 5.02$ TeV to the predictions. The increases in cross section are well predicted by all PDF sets. Table 8 then presents ratios at fixed \sqrt{s} , which are again generally compatible with the predictions. The W^\pm/Z ratios predicted by CT18 are 1–2 standard deviations above the data, which is similar to an observation at $\sqrt{s} = 7$ TeV attributed to the strange-quark density [88].

Differential predictions are also obtained from MC event generators that combine LO or NLO matrix elements and match them to parton showers and models for underlying event, hadronisation and particle decay. The MC samples already described in Section 2.3, namely POWHEG+PYTHIA 8 with the AZNLO tune and SHERPA 2.2.1/2.2.5, are included, however without the reweighting to match the reconstruction-level

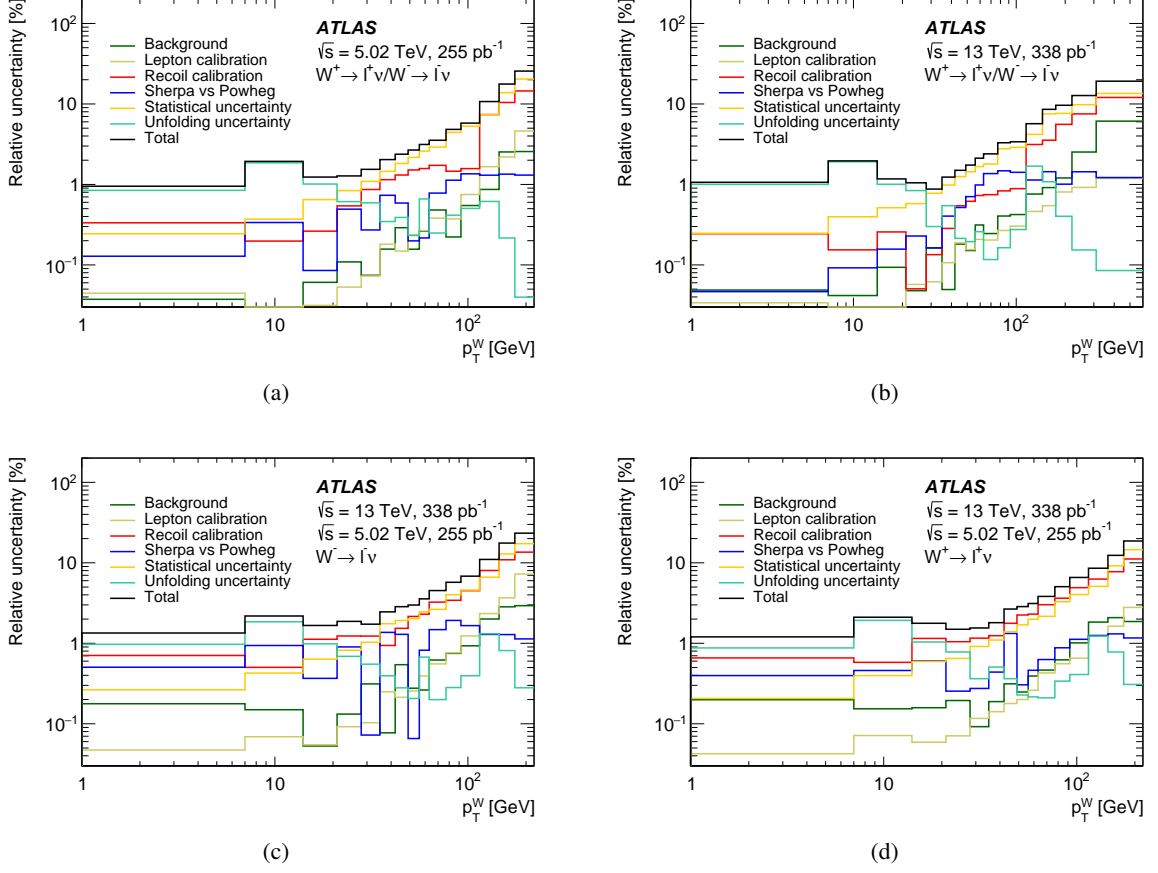


Figure 18: Uncertainty contributions in the ratios of combined normalised p_T distributions for W^+/W^- at (a) $\sqrt{s} = 5.02$ TeV and (b) $\sqrt{s} = 13$ TeV as well as the ratios of measurements at different centre-of-mass energies $\sqrt{s} = 13$ TeV to $\sqrt{s} = 5.02$ TeV for (c) W^- and (d) W^+ .

Table 7: Ratios of measured integrated fiducial cross sections at $\sqrt{s} = 13$ TeV and $\sqrt{s} = 5.02$ TeV for W^- , W^+ and Z production with total uncertainties ('Data') are compared to DYTURBO predictions at NNLO+NNLL using three different NNLO PDF sets: CT18, MSHT20 and NNPDF3.1.

PDF set	$W^- \rightarrow \ell^- \nu$	$W^+ \rightarrow \ell^+ \nu$	$Z \rightarrow \ell \ell$
$\sigma_{\text{fid}}(\sqrt{s} = 13 \text{ TeV}) / \sigma_{\text{fid}}(\sqrt{s} = 5.02 \text{ TeV})$			
Data	2.516 ± 0.038	2.050 ± 0.030	2.344 ± 0.036
CT18	$2.499^{+0.017}_{-0.005}$ (scale) $+0.043_{-0.046}$ (PDF)	$2.029^{+0.010}_{-0.007}$ (scale) $+0.029_{-0.023}$ (PDF)	$2.335^{+0.012}_{-0.009}$ (scale) $+0.049_{-0.038}$ (PDF)
MSHT20	$2.515^{+0.017}_{-0.005}$ (scale) $+0.018_{-0.020}$ (PDF)	$2.040^{+0.010}_{-0.007}$ (scale) $+0.014_{-0.015}$ (PDF)	$2.358^{+0.012}_{-0.009}$ (scale) $+0.018_{-0.022}$ (PDF)
NNPDF31	$2.500^{+0.017}_{-0.005}$ (scale) ± 0.031 (PDF)	$2.022^{+0.010}_{-0.007}$ (scale) ± 0.029 (PDF)	$2.335^{+0.012}_{-0.009}$ (scale) ± 0.026 (PDF)

Table 8: Ratios of measured integrated fiducial cross sections of W^+/W^- and W^\pm/Z for the $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 13$ TeV data with total uncertainties (‘Data’) are compared to DYTURBO predictions at NNLO+NNLL using three different NNLO PDF sets: CT18, MSHT20 and NNPDF3.1.

PDF set	W^+/W^-	W^\pm/Z
Cross-section ratio at $\sqrt{s} = 5.02$ TeV		
Data	1.609 ± 0.005	10.85 ± 0.08
CT18	$1.612^{+0.001}_{-0.003}$ (scale) $^{+0.018}_{-0.028}$ (PDF)	$11.13^{+0.04}_{-0.06}$ (scale) ± 0.11 (PDF)
MSHT20	$1.618^{+0.001}_{-0.003}$ (scale) ± 0.008 (PDF)	$10.92^{+0.04}_{-0.06}$ (scale) $^{+0.07}_{-0.05}$ (PDF)
NNPDF31	$1.616^{+0.001}_{-0.003}$ (scale) ± 0.018 (PDF)	$10.98^{+0.04}_{-0.06}$ (scale) ± 0.15 (PDF)
Cross-section ratio at $\sqrt{s} = 13$ TeV		
Data	1.308 ± 0.005	10.30 ± 0.11
CT18	$1.309^{+0.000}_{-0.003}$ (scale) $^{+0.012}_{-0.007}$ (PDF)	10.53 ± 0.03 (scale) $^{+0.13}_{-0.15}$ (PDF)
MSHT20	$1.312^{+0.000}_{-0.003}$ (scale) $^{+0.005}_{-0.004}$ (PDF)	10.29 ± 0.03 (scale) $^{+0.07}_{-0.05}$ (PDF)
NNPDF31	$1.307^{+0.000}_{-0.003}$ (scale) ± 0.003 (PDF)	10.37 ± 0.03 (scale) ± 0.06 (PDF)

data described in Section 6.1. A POWHEG+HERWIG 7 sample is simulated using a similar set-up as POWHEG+PYTHIA 8, but using HERWIG 7 [13, 89] for the parton shower, hadronisation and underlying event using the default tune. A prediction with PYTHIA 8 alone matches LO matrix elements to a parton shower with the CTEQ6L1 PDF set and the AZ parameter set tuned to describe 7 TeV $p_T^{\ell\ell}$ and ϕ^* measurements [15]. Further predictions at 13 TeV with multijet-merged predictions at NLO as described in Ref. [90] are prepared with SHERPA 2.2.11 and MADGRAPH_AMC@NLO FxFx+PYTHIA 8 [91, 92] and presented in Appendix C. The fiducial predictions are extracted with the RIVET toolkit [93].

To separate overall normalisation and shape effects, all differential comparisons are shown using normalised spectra. Figures 19 and 20 compare the measurements and some ratios at $\sqrt{s} = 5.02$ TeV to DYTURBO and the MC predictions, respectively. The equivalent comparisons at $\sqrt{s} = 13$ TeV are given in Figures 21 and 22.

As expected, many features are broadly observed across all final states and in both \sqrt{s} datasets. First, the data is precise and discriminating up to about $p_T^V = 100$ GeV at 5.02 TeV and $p_T^V = 200$ GeV at 13 TeV. The DYTURBO resummed predictions show the best agreement across the spectrum and generally match the data at the percent level. When focusing on the lower $p_T^V < 30$ GeV region, the W^+ measurements show overall the largest deviation from the DYTURBO predictions. The three investigated PDF sets produce only small differences in the shapes of the distributions, but theoretical uncertainties at higher p_T^V are significant, dominated by the scale variations.

The MC predictions that were tuned to $\sqrt{s} = 7$ TeV data, POWHEG+PYTHIA 8 AZNLO and PYTHIA 8 AZ, describe reasonably well the low- p_T^V region that is relevant for the measurement of the W -boson mass. However, they show worse agreement for $p_T^V > 40$ GeV. The POWHEG+HERWIG 7 predictions does not perform well across the whole spectrum. The SHERPA 2.2.1/2.2.5 predictions match the data best at higher p_T^V , but they deviate significantly in the region $p_T^V \lesssim 20$ GeV, a behaviour that was improved in SHERPA 2.2.11 by optimising the matching conditions [90], see also Appendix C.

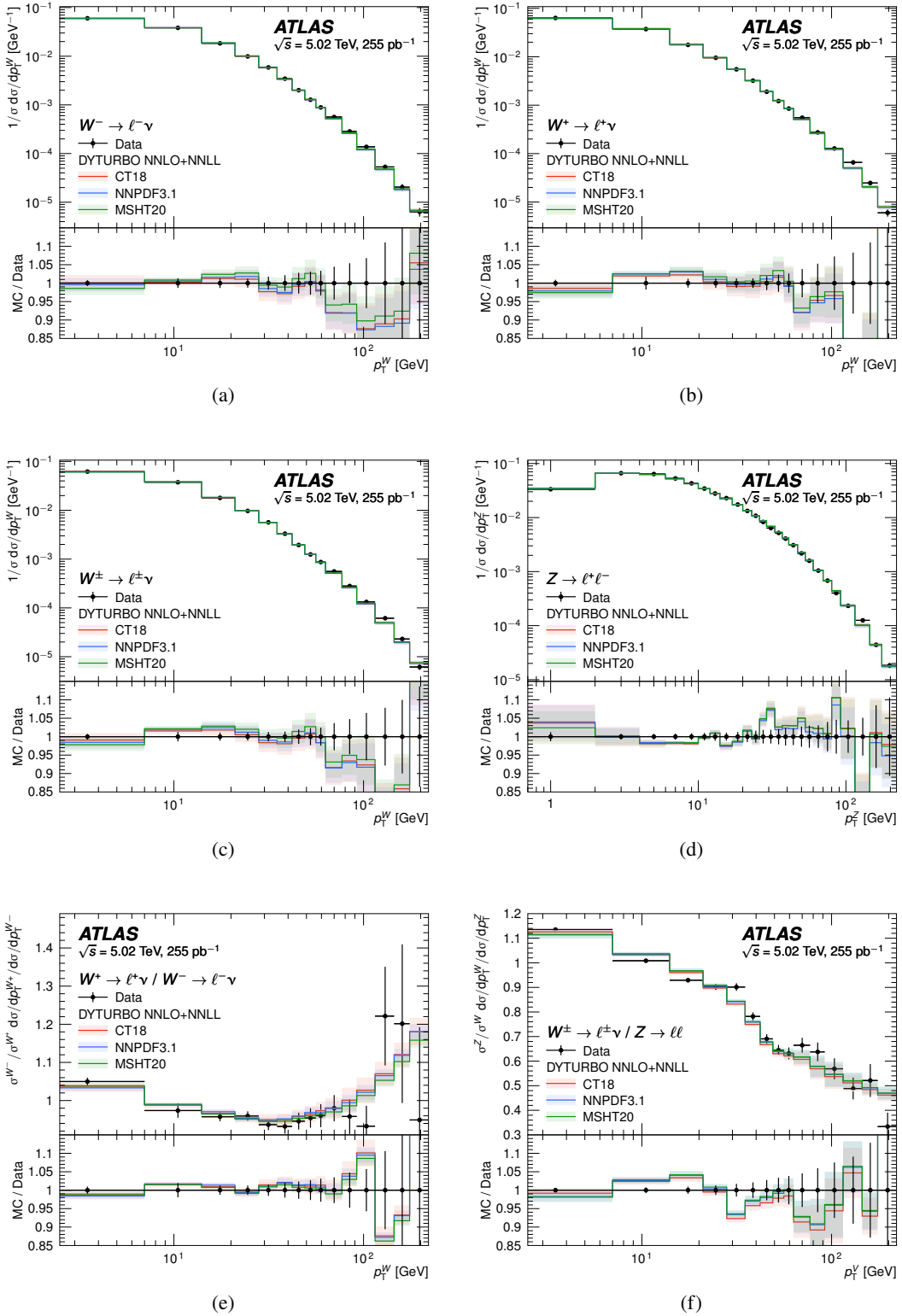


Figure 19: Measurements of normalised differential distributions at $\sqrt{s} = 5.02$ TeV (black points) for (a) W^- , (b) W^+ , (c) the sum W^\pm , (d) Z as well as the ratios (e) W^+/W^- and (f) W^\pm/Z compared to DYTURBO predictions with different PDF sets (coloured lines and PDF and scale uncertainties as shaded band) as described in the text. The lower panels show the ratio of prediction to data with data markers centred at one and error bars giving the size of the total measurement uncertainties.

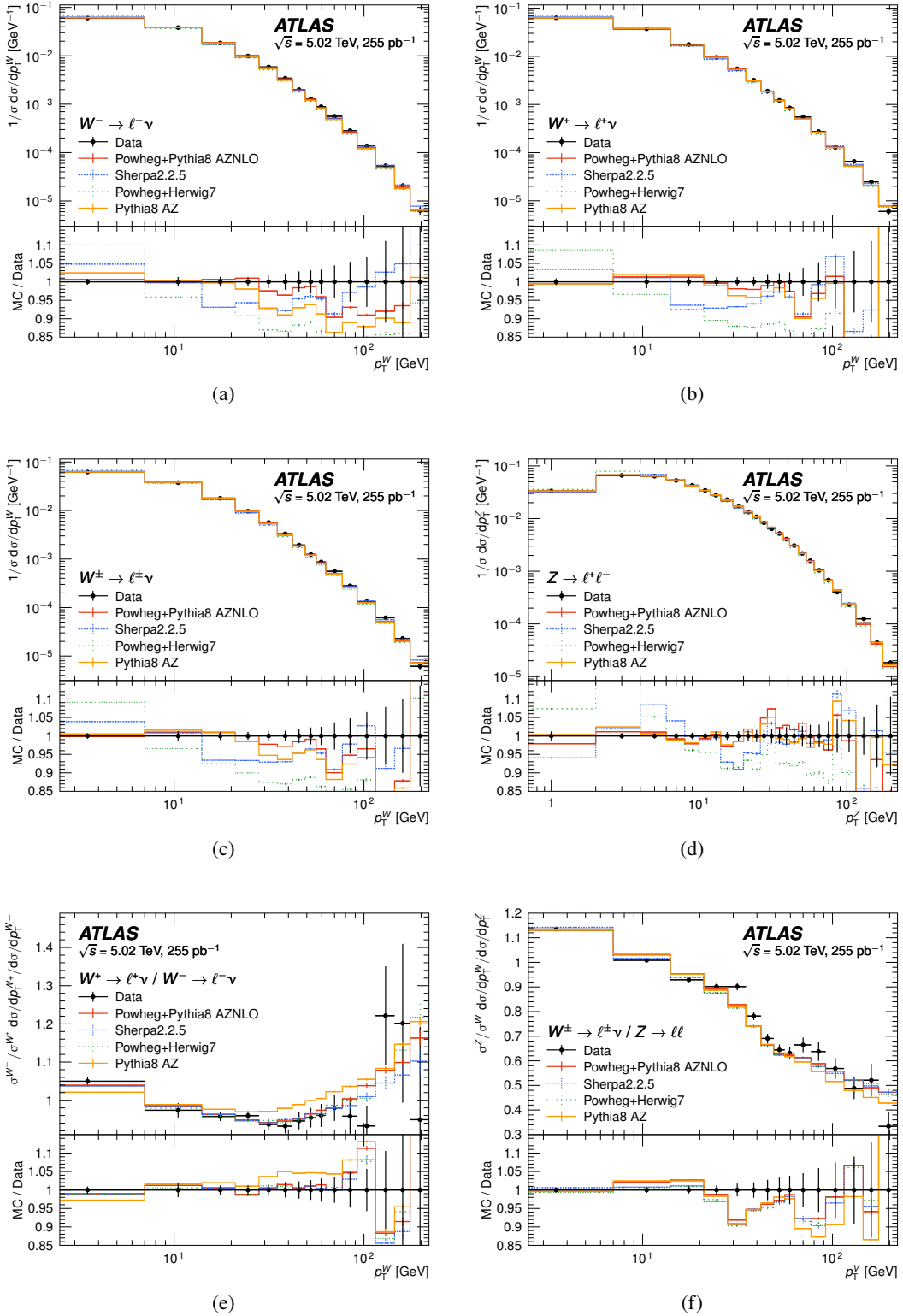


Figure 20: Measurements of normalised differential distributions at $\sqrt{s} = 5.02$ TeV (black points) for (a) W^- , (b) W^+ , (c) the sum W^\pm , (d) Z as well as the ratios (e) W^+/W^- and (f) W^\pm/Z compared to a variety of MC predictions (coloured lines) as described in the text. The lower panels show the ratio of prediction to data with data markers centred at one and error bars giving the size of the total measurement uncertainties.

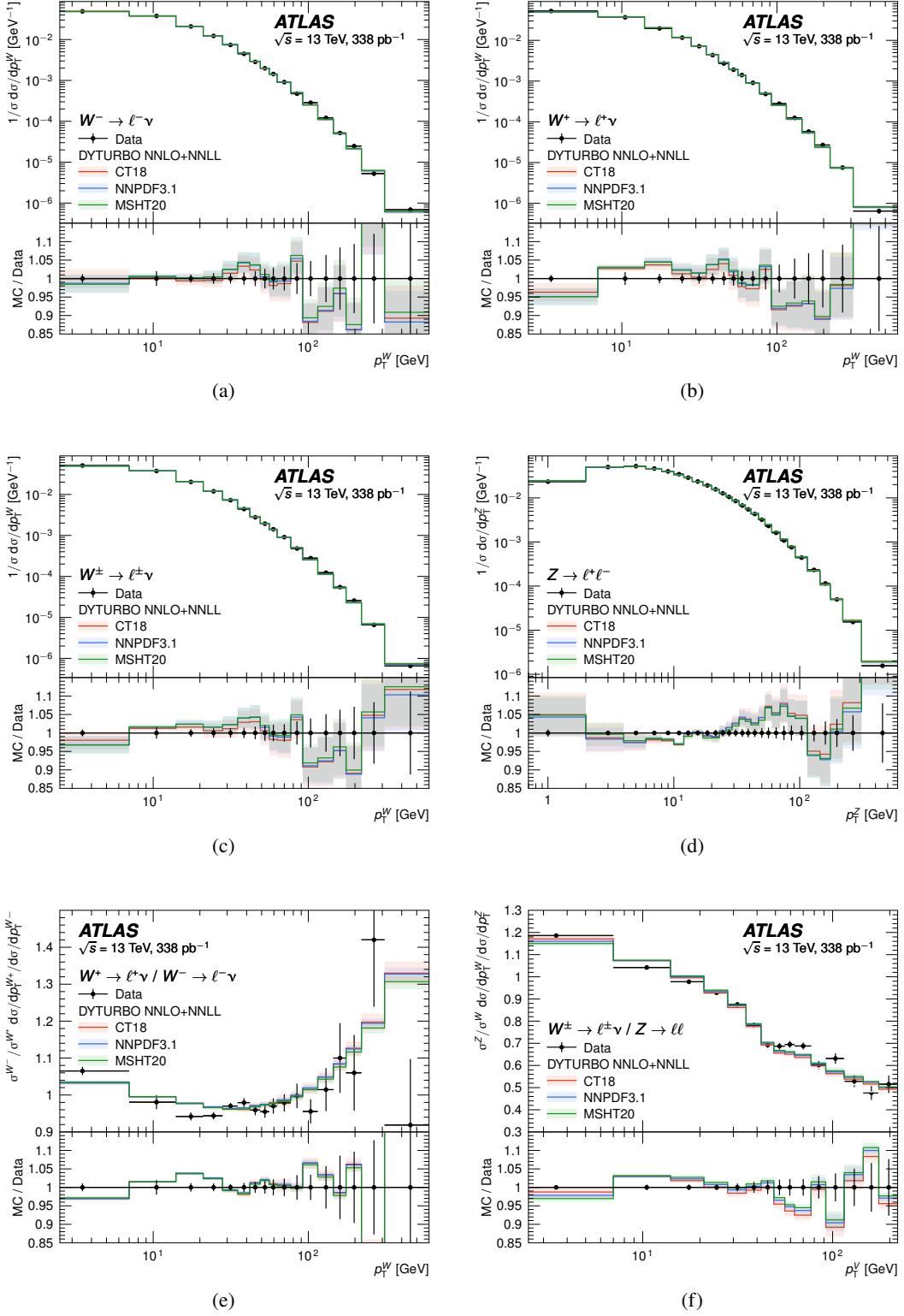


Figure 21: Measurements of normalised differential distributions at $\sqrt{s} = 13$ TeV (black points) for (a) W^- , (b) W^+ , (c) the sum W^\pm , (d) Z as well as the ratios (e) W^+/W^- and (f) W^\pm/Z compared to DYTURBO predictions with different PDF sets (coloured lines and PDF and scale uncertainties as shaded band) as described in the text. The lower panels show the ratio of prediction to data with data markers centred at one and error bars giving the size of the total measurement uncertainties.

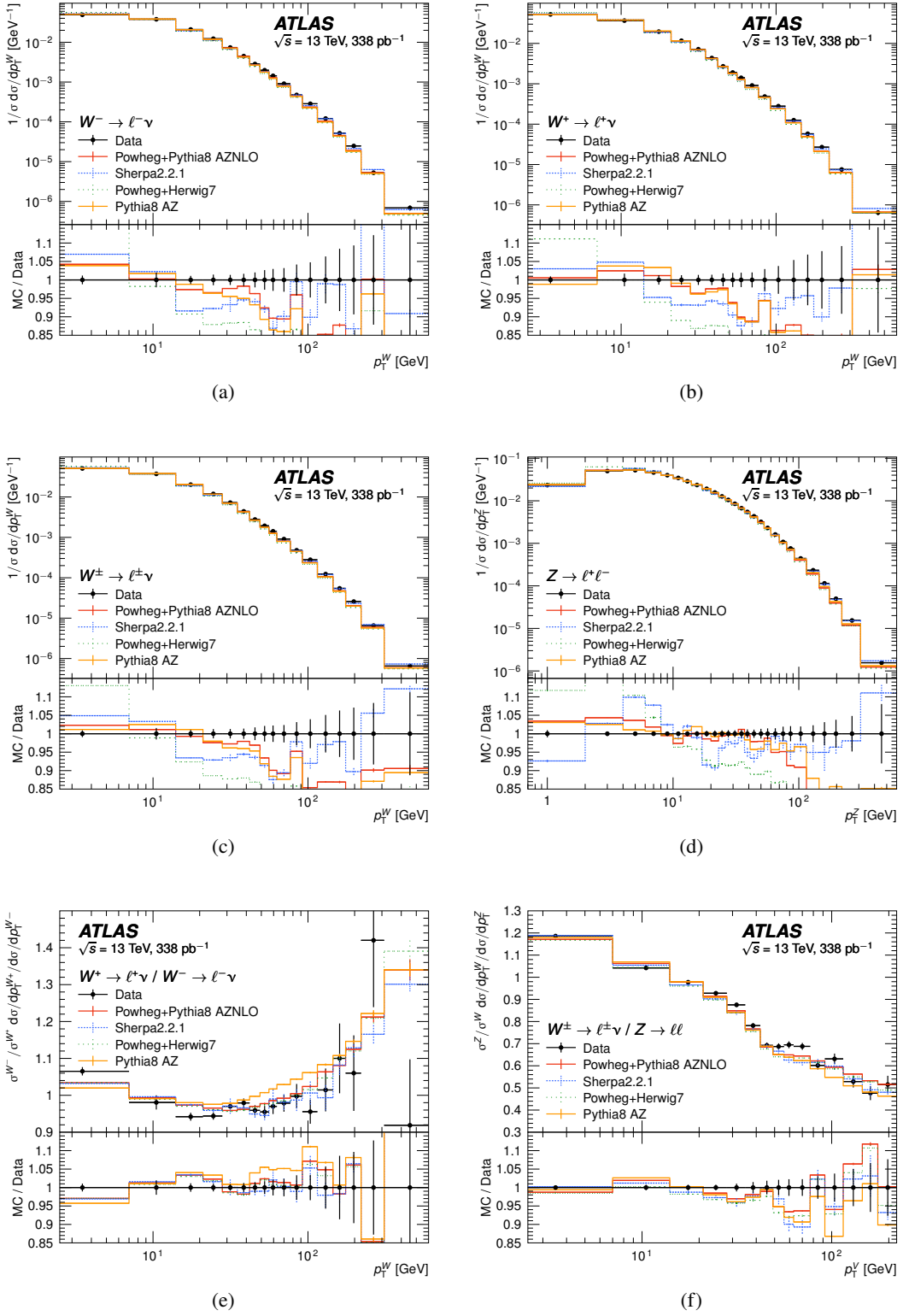


Figure 22: Measurements of normalised differential distributions at $\sqrt{s} = 13$ TeV (black points) for (a) W^- , (b) W^+ , (c) the sum W^\pm , (d) Z as well as the ratios (e) W^+/W^- and (f) W^\pm/Z compared to a variety of MC predictions (coloured lines) as described in the text. The lower panels show the ratio of prediction to data with data markers centred at one and error bars giving the size of the total measurement uncertainties.

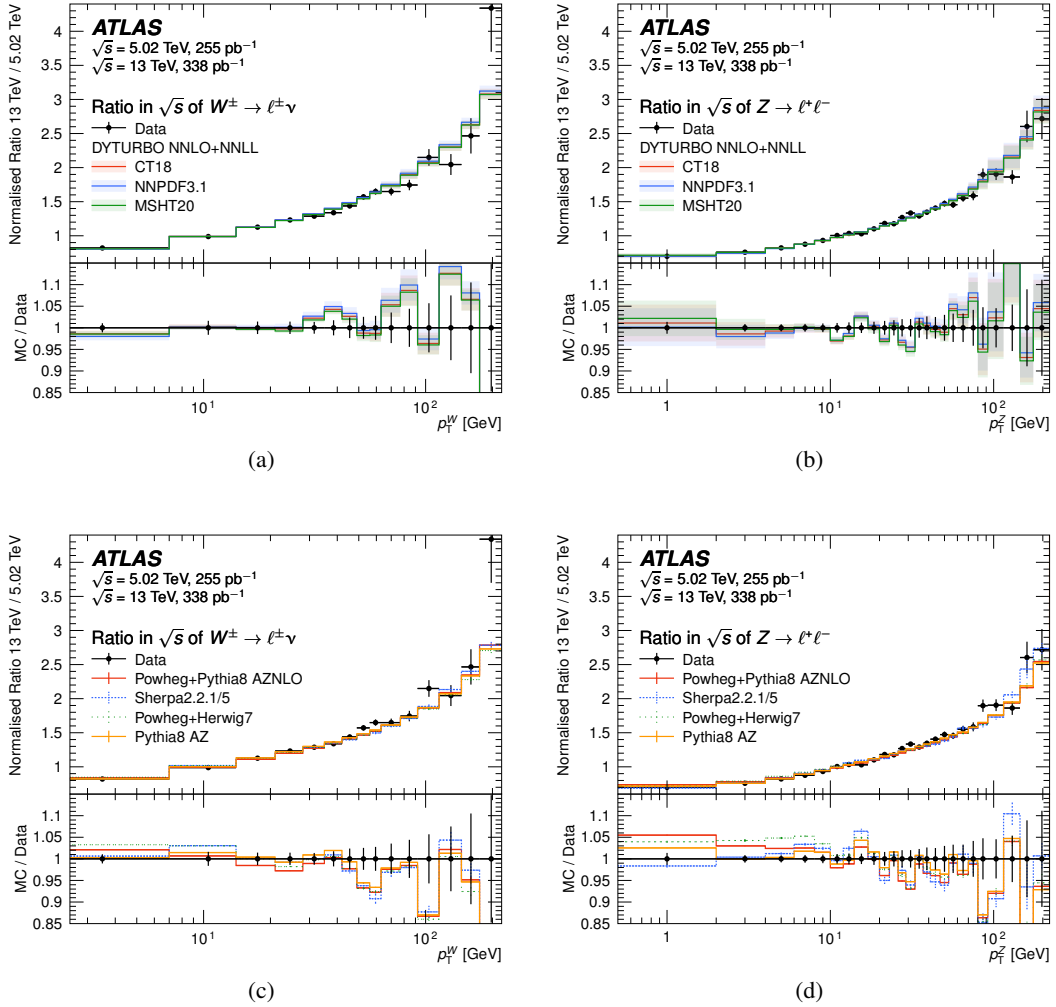


Figure 23: Ratios of normalised differential distributions at $\sqrt{s} = 13$ TeV to $\sqrt{s} = 5.02$ TeV (black points) for (a,c) W^\pm and (b,d) Z compared to (a,b) DYTURBO predictions with different PDF sets or (b,d) a variety of MC predictions (coloured lines, PDF and scale uncertainties as shaded band for DYTURBO) as described in the text. The lower panels show the ratio of prediction to data with data markers centred at one and error bars giving the size of the total measurement uncertainties.

The ratios W^+/W^- and W^\pm/Z are measured to percent-level precision and show some interesting features at both \sqrt{s} values. The differences between the predictions and uncertainties shrink in these ratios. The PYTHIA 8 AZ prediction is clearly ruled out by the data in the W^+/W^- ratio. However, this is an effect of mismodelled angular decay distributions and thus the fiducial acceptance. The ratios at $\sqrt{s} = 13$ GeV show the largest differences between data and predictions at lower $p_T^V < 30$ GeV.

The ratios of normalised differential distributions at $\sqrt{s} = 13$ TeV to $\sqrt{s} = 5.02$ TeV are shown in Figure 23. Here DYTURBO is in excellent agreement with the data, while several MC predictions fail to follow the energy dependence in the low p_T^V region correctly.

8 Conclusion

This paper presented an extensive set of measurements of W^- and Z -boson p_T distributions at two centre-of-mass energies: $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 13$ TeV. The measurements were performed with pp collision data delivered by the LHC and recorded by the ATLAS detector in special low pile-up conditions in 2017 and 2018.

While the p_T^Z distribution had been measured in great detail previously using the dilepton system produced in Z -boson decays, the direct measurement of the p_T^W distribution relies on the full reconstruction of the hadronic recoil in W -boson events. The dedicated datasets, reconstruction and calibration techniques allowed an unprecedented granularity of about 7 GeV in p_T^W and a final precision at the level of 1 – 2%. All measurements have been performed in the electron and muon decays of the bosons and the results are combined.

A unique feature of the analysis presented is the wide coverage of six high-precision absolute and normalised cross section distributions for the three vector boson final states W^- , W^+ and Z at two well separated centre-of-mass energies. In addition, integrated fiducial cross sections and a variety of ratios are presented. The integrated results in particular profit from the very precise luminosity measurement with an uncertainty of 0.9 – 1.0%, leading to improvements in the precision compared to existing results by a factor of two or more. The integrated results and ratios are generally compatible with DYTURBO predictions at order NNLO+NNLL.

The comparison of differential spectra to different MC simulations shows a variety of deficiencies in the description of the transverse momentum distribution; many are common for all vector bosons. The agreement is better at $\sqrt{s} = 5.02$ TeV, especially for those predictions that were tuned to Z -boson measurements at $\sqrt{s} = 7$ TeV. The ratios show generally a better agreement as expected due to the similarity in the processes. The higher-order resummed predictions from DYTURBO match the data best across the spectrum. All predictions show similar disagreements with the data in the W^+/W^- and W^\pm/Z ratios, especially at $\sqrt{s} = 13$ TeV.

These detailed measurements are of great importance for future measurements of the W -boson mass that rely on a good modelling of the p_T^W spectrum. The results can be used to test and constrain various theoretical uncertainties affecting the predictions. Different contributions may be understood from the different ranges of parton momentum fractions and initial parton flavours that are probed by W^- , W^+ and Z production at $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 13$ TeV.

Acknowledgements

We thank CERN for the very successful operation of the LHC and its injectors, as well as the support staff at CERN and at our institutions worldwide without whom ATLAS could not be operated efficiently.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF/SFU (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [94].

We gratefully acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; Minciencias, Colombia; MEYS CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MEiN, Poland; FCT, Portugal; MNE/IFA, Romania; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DSI/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taipei; TENMAK, Türkiye; STFC, United Kingdom; DOE and NSF, United States of America.

Individual groups and members have received support from BCKDF, CANARIE, CRC and DRAC, Canada; COST, ERC, ERDF, Horizon 2020, ICSC-NextGenerationEU and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex, Investissements d’Avenir IDEX and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and MINERVA, Israel; Norwegian Financial Mechanism 2014-2021, Norway; NCN and NAWA, Poland; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom.

In addition, individual members wish to acknowledge support from Chile: Agencia Nacional de Investigación y Desarrollo (FONDECYT 1190886, FONDECYT 1210400, FONDECYT 1230987); China: National Natural Science Foundation of China (NSFC - 12175119, NSFC 12275265); European Union: European Research Council (ERC - 948254), Horizon 2020 Framework Programme (MUCCA - CHIST-ERA-19-XAI-00), Italian Center for High Performance Computing, Big Data and Quantum Computing (ICSC, NextGenerationEU), Marie Skłodowska-Curie Actions (EU H2020 MSC IF GRANT NO 101033496); France: Agence Nationale de la Recherche (ANR-20-CE31-0013, ANR-21-CE31-0013, ANR-21-CE31-0022), Investissements d’Avenir IDEX (ANR-11-LABX-0012), Investissements d’Avenir Labex (ANR-11-LABX-0012); Germany: Baden-Württemberg Stiftung (BW Stiftung-Postdoc Eliteprogramme), Deutsche Forschungsgemeinschaft (DFG - CR 312/5-1); Italy: Istituto Nazionale di Fisica Nucleare (FELLINI G.A. n. 754496, ICSC, NextGenerationEU); Japan: Japan Society for the Promotion of Science (JSPS KAKENHI 22H01227, JSPS KAKENHI JP21H05085, JSPS KAKENHI JP22H04944); Netherlands: Netherlands Organisation for Scientific Research (NWO Veni 2020 - VI.Veni.202.179); Norway: Research Council of Norway (RCN-314472); Poland: Polish National Agency for Academic Exchange (PPN/PPO/2020/1/00002/U/00001), Polish National Science Centre (NCN 2021/42/E/ST2/00350, NCN UMO-2019/34/E/ST2/00393, UMO-2020/37/B/ST2/01043, UMO-2021/40/C/ST2/00187); Slovenia: Slovenian Research Agency (ARIS grant J1-3010); Spain: BBVA Foundation (LEO22-1-603), Generalitat Valenciana (Artemisa, FEDER,

IDIFEDER/2018/048), La Caixa Banking Foundation (LCF/BQ/PI20/11760025), Ministry of Science and Innovation (RYC2019-028510-I, RYC2020-030254-I), PROMETEO and GenT Programmes Generalitat Valenciana (CIDEAGENT/2019/023, CIDEAGENT/2019/027); Sweden: Swedish Research Council (VR 2022-03845, VR 2022-04683), Knut and Alice Wallenberg Foundation (KAW 2017.0100, KAW 2018.0157, KAW 2019.0447); Switzerland: Swiss National Science Foundation (SNSF - PCEFP2_194658); United Kingdom: Leverhulme Trust (Leverhulme Trust RPG-2020-004); United States of America: Neubauer Family Foundation.

Appendix

A Measurement uncertainty breakdown for all channels

The uncertainty contributions in the unfolded, normalised p_T^W and p_T^Z spectra for each decay channel are given in Figures 24 (25) and 26 (27) for the W -boson and Z -boson analyses on the 5.02 TeV (13 TeV) datasets.

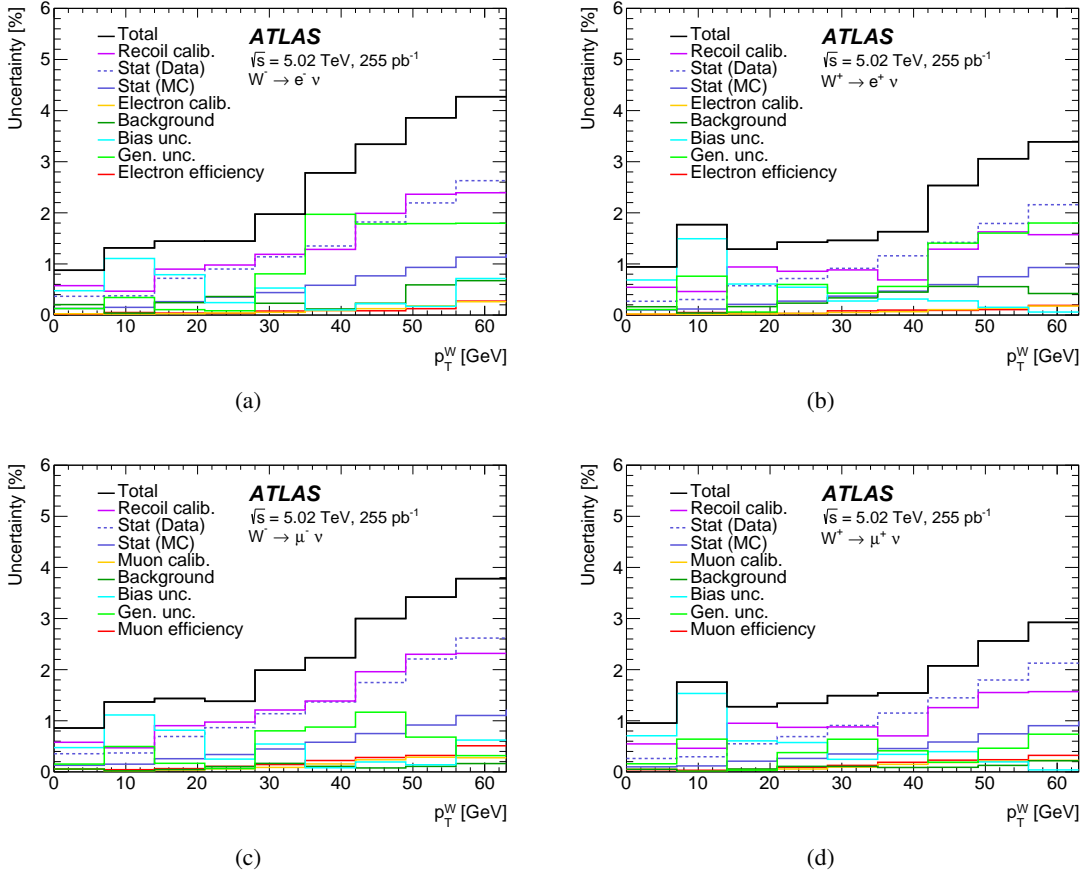


Figure 24: Uncertainty contributions in the normalised p_T^W distribution in the (a) $W^- \rightarrow e^- \nu$, (b) $W^+ \rightarrow e^+ \nu$, (c) $W^- \rightarrow \mu^- \nu$ and (d) $W^+ \rightarrow \mu^+ \nu$ channels for the $\sqrt{s} = 5.02$ TeV dataset, focusing on the low $p_T^W < 63$ GeV region. The ‘Background’ component refers to the sum of uncertainties in the normalisation of the simulated background samples and the uncertainties in the yield and shape of the multijet background estimate. The ‘Electron efficiency’ and ‘Muon efficiency’ components refer to the total uncertainty in the lepton efficiency scale factors : electron trigger, reconstruction, identification, isolation (electron channel) and muon trigger, identification, track-to-vertex association, isolation (muon channel). The uncertainties are shown as a percentage of the unfolded data per p_T bin.

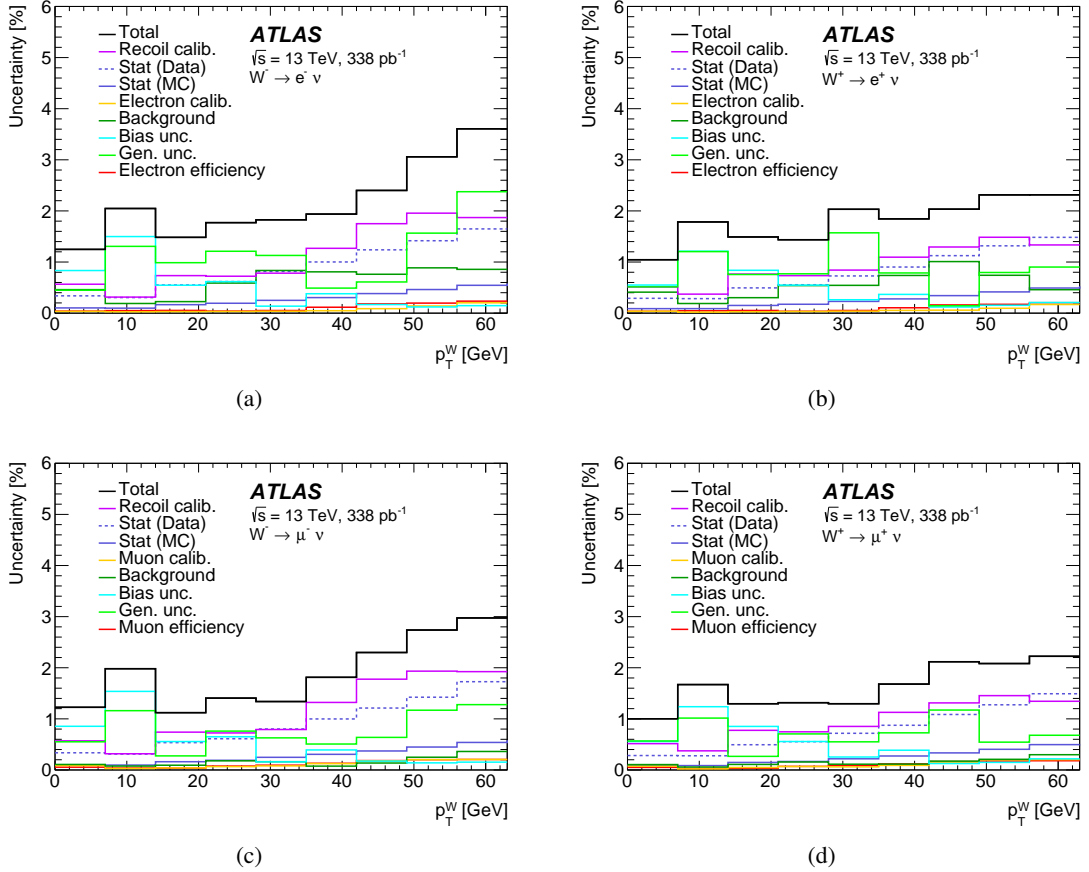


Figure 25: Uncertainty contributions in the normalised p_T^W distribution in the (a) $W^- \rightarrow e^- \nu$, (b) $W^+ \rightarrow e^+ \nu$, (c) $W^- \rightarrow \mu^- \nu$ and (d) $W^+ \rightarrow \mu^+ \nu$ channels for the $\sqrt{s} = 13$ TeV dataset, focusing on the low $p_T^W < 63$ GeV region. The ‘Background’ component refers to the sum of uncertainties in the normalisation of the simulated background samples and the uncertainties in the yield and shape of the multijet background estimate. The ‘Electron efficiency’ and ‘Muon efficiency’ components refer to the total uncertainty in the lepton efficiency scale factors : electron trigger, reconstruction, identification, isolation (electron channel) and muon trigger, identification, track-to-vertex association, isolation (muon channel). The uncertainties are shown as a percentage of the unfolded data per p_T bin.

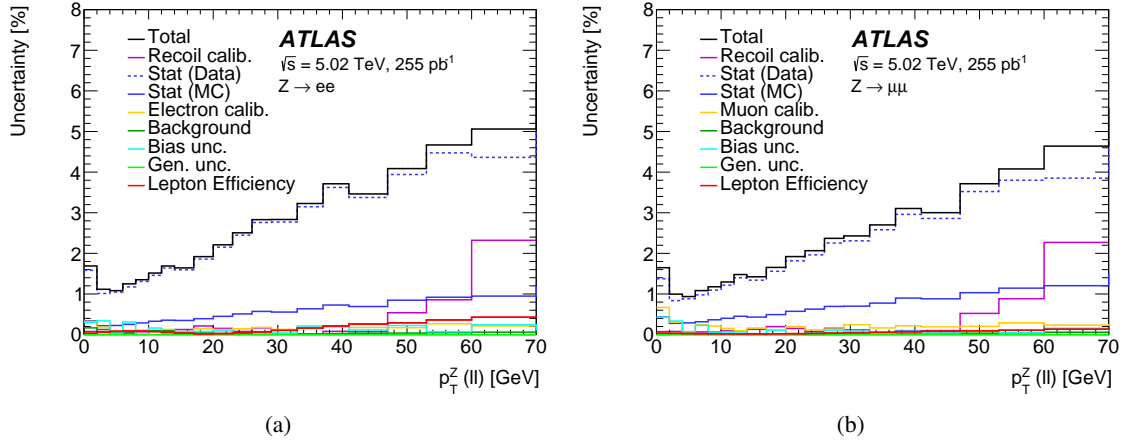


Figure 26: Uncertainty contributions in the normalised p_T^Z distribution in the (a) $Z \rightarrow ee$ and (b) $Z \rightarrow \mu\mu$ decay channels for the $\sqrt{s} = 5.02$ TeV dataset. The ‘Background’ component refers to the sum of uncertainties in the normalisation of the simulated background samples and the uncertainties in the yield and shape of the multijet background estimate. The ‘SF tot.’ component refers to the total uncertainty in the lepton efficiency scale factors: electron trigger, reconstruction, identification, isolation (electron channel) and muon trigger, identification, track-to-vertex association, isolation (muon channel). The uncertainties are shown as a percentage of the unfolded data per p_T bin.

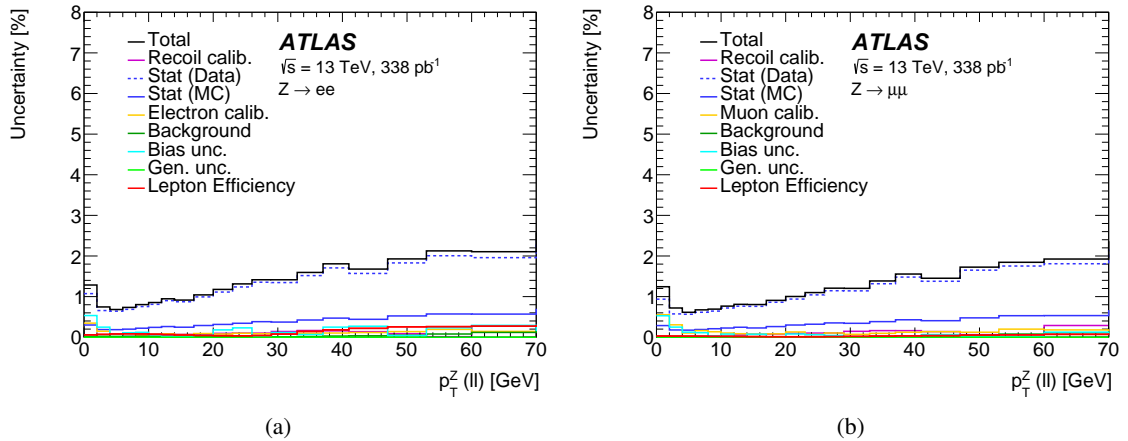


Figure 27: Uncertainty contributions in the normalised p_T^Z distribution in the (a) $Z \rightarrow ee$ and (b) $Z \rightarrow \mu\mu$ decay channels for the $\sqrt{s} = 13$ TeV dataset. The ‘Background’ component refers to the sum of uncertainties in the normalisation of the simulated background samples and the uncertainties in the yield and shape of the multijet background estimate. The ‘SF tot.’ component refers to the total uncertainty in the lepton efficiency scale factors: electron trigger, reconstruction, identification, isolation (electron channel) and muon trigger, identification, track-to-vertex association, isolation (muon channel). The uncertainties are shown as a percentage of the unfolded data per p_T bin.

B Comparisons to RADISH predictions and DYTURBO uncertainty composition

Figure 28 compares the measurements at $\sqrt{s} = 13$ TeV to predictions obtained by the RADISH program [9, 95]. Compared to the DYTURBO predictions shown in the main body, these were computed at a higher perturbative accuracy by matching to a NNLO prediction of Z+jet production ($O(\alpha_s^3)$) from NNLOJET [96] with resummation of $\log(m_{\ell\ell}/p_T)$ terms at next-to-next-to-next-to-leading-logarithm (N³LL) accuracy [97]. The NNPDF3.1 set of PDFs is used with QCD scales set to $\mu_r = \mu_f = \sqrt{(m_{\ell\ell})^2 + (p_T^V)^2}$ and the resummation scale set to $Q = m_{\ell\ell}/2$. Uncertainties in this prediction are derived from variations of μ_r and μ_f and two variations of Q by a factor of two up and down. As comparison, the DYTURBO predictions are shown as computed with the same PDF set and the uncertainty decomposed into those originating from the PDF variations and the scale variations.

At $\sqrt{s} = 5.02$ TeV the RADISH predictions were not available, therefore Figures 29 and 30 repeat the DYTURBO predictions as shown in the main body, but provide the same decomposition of the uncertainties into those estimated by QCD scale variations and those from PDFs.

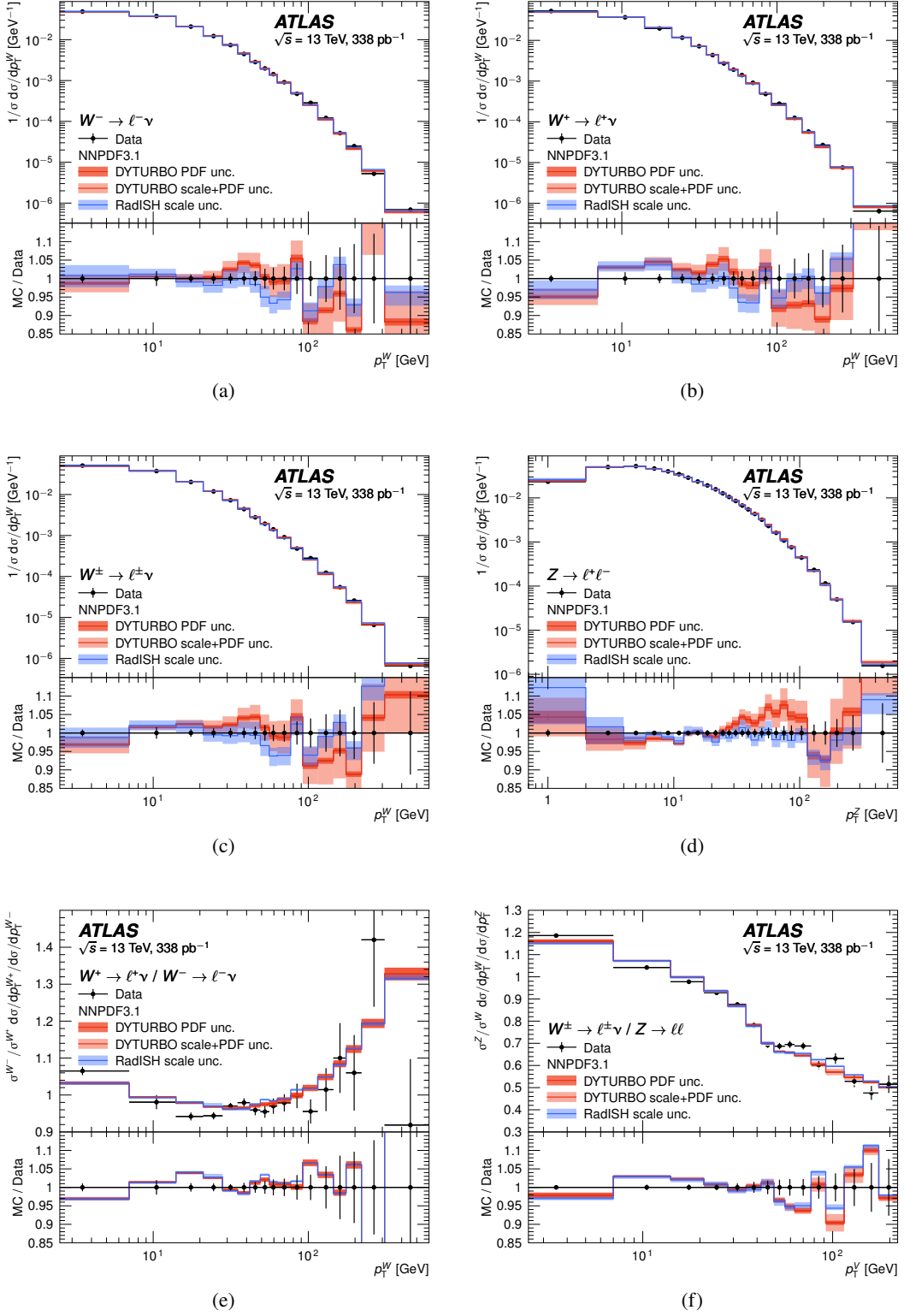


Figure 28: Measurements of normalised differential distributions at $\sqrt{s} = 13$ TeV (black points) for (a) W^- , (b) W^+ , (c) the sum W^\pm , (d) Z as well as (e) the ratios W^+/W^- and (f) W^\pm/Z compared to RADISH and DYTURBO predictions with the NNPDF3.1 PDF set as described in the text. The shaded areas show the theoretical uncertainties derived from variations of the QCD scales and PDFs, the latter only for the DYTURBO predictions. The lower panels show the ratio of prediction to data with data markers centred at one and error bars giving the total measurement uncertainties.

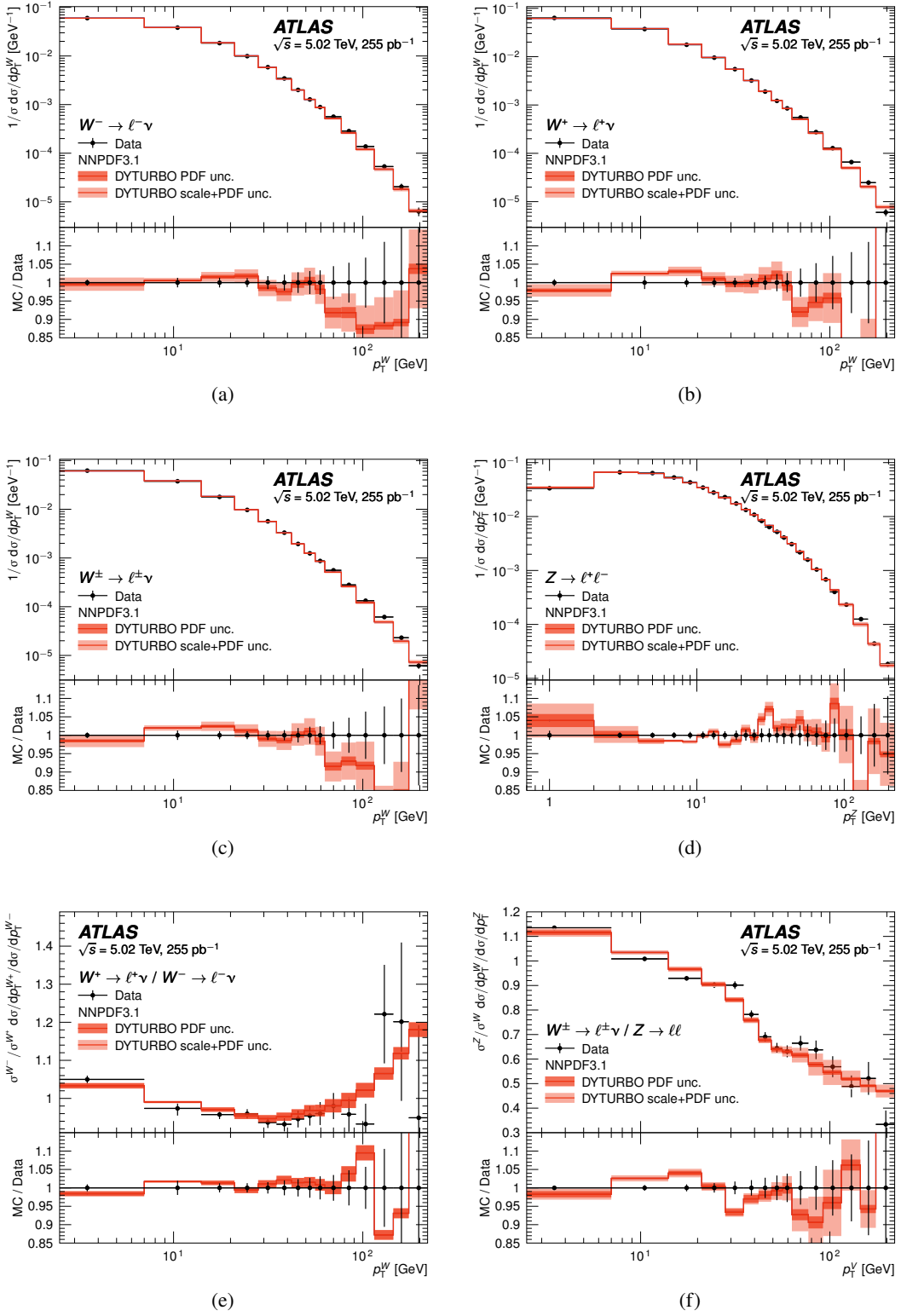


Figure 29: Measurements of normalised differential distributions at $\sqrt{s} = 5.02$ TeV (black points) for (a) W^- , (b) W^+ , (c) the sum W^\pm , (d) Z as well as (e) the ratios W^+/W^- and (f) W^\pm/Z compared to DYTURBO predictions with different PDF sets (coloured lines) as described in the text. The lower panels show the ratio of prediction to data with data markers centred on one and error bars giving the total measurement uncertainties.

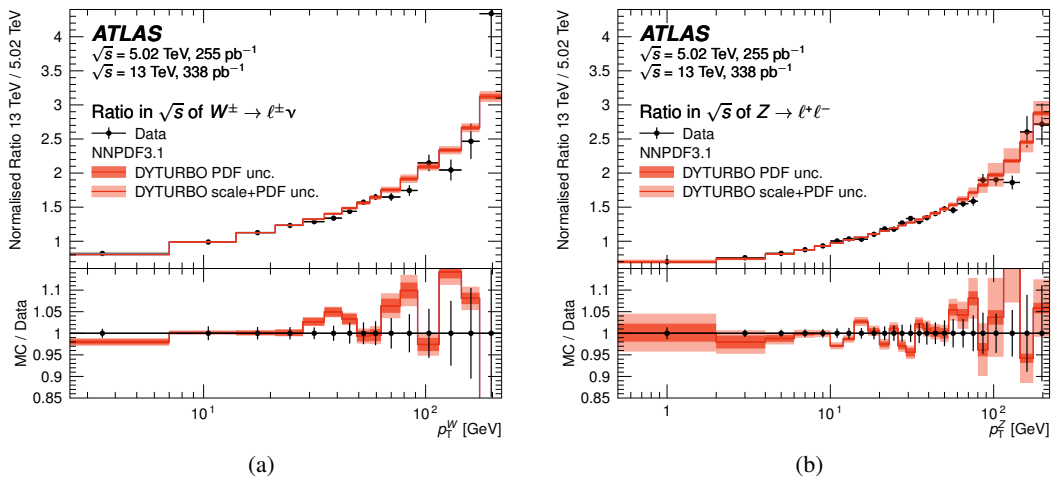


Figure 30: Ratios of normalised differential distributions at $\sqrt{s} = 13$ TeV to $\sqrt{s} = 5.02$ TeV (black points) for (a,c) W^\pm and (b,d) Z compared to (a,b) DYTURBO predictions with different PDF sets or (b,d) a variety of MC predictions (coloured lines) as described in the text. The lower panels show the ratio of prediction to data with data markers centred at one and error bars giving the size of the total measurement uncertainties.

C Comparisons to multijet-merged predictions

Figure 31 compares the measurements at $\sqrt{s} = 13$ TeV to three multijet-merged predictions that were discussed in detail in Ref. [90]. All samples show a similar behaviour across the W^- , W^+ , Z measurements and are very close to the data for the W^+/W^- ratio. The SHERPA 2.2.11 sample improves the behaviour of the SHERPA 2.2.1 sample in the region $p_T = 20$ GeV, where matrix-element and parton shower emissions are matched. Both SHERPA samples have some room for improvement in the region of lowest $p_T \lesssim 10$ GeV. The MADGRAPH_AMC@NLO FxFX+PYTHIA 8 is very close to SHERPA 2.2.11 at higher $p_T > 40$ GeV and appears to behave better at low $p_T < 10$ GeV. It shows, however, some excess over data for $p_T = 20\text{--}30$ GeV.

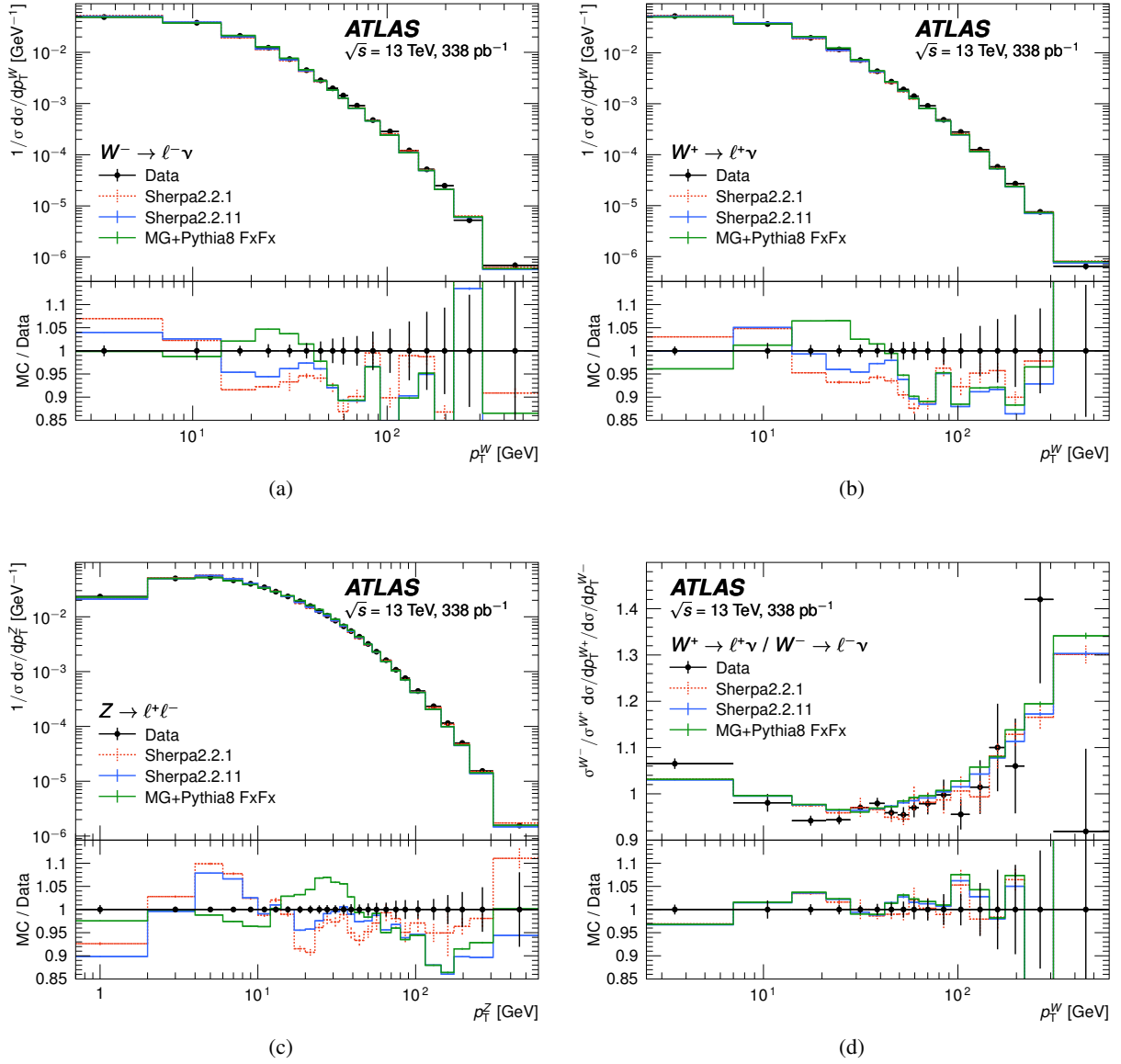


Figure 31: Measurements of normalised differential distributions at $\sqrt{s} = 13$ TeV (black points) for (a) W^- , (b) W^+ , (c) Z as well as (d) the W^+/W^- ratio compared to a variety MC predictions of multijet-merged NLO SHERPA and MADGRAPH_AMC@NLO FxFx+PYTHIA 8 samples (coloured lines) as described in the text. The lower panels show the ratio of prediction to data with data markers centred at one and error bars giving the size of the total measurement uncertainties.

D Total integrated W and Z cross sections and ratios

The total production cross section for $pp \rightarrow W \rightarrow \ell\nu$ and $pp \rightarrow Z/\gamma^* \rightarrow \ell\ell$ may be obtained from the fiducial measurements presented in this paper in Table 3 through theoretically calculated acceptance factors A as $\sigma_{\text{tot}} = \sigma_{\text{fid}}/A$. For the Z/γ^* case, the total phase space retains the invariant mass range of $66 < m_{\ell\ell} < 116$ GeV. Table 9 summarises the A values as computed from the nominal POWHEG+PYTHIA 8 samples using the CT18 PDF set. The uncertainties are estimated from variations of QCD scales, PDFs and the difference to the alternative SHERPA samples. The corresponding total cross sections are given as well. The typical uncertainty on the acceptance correction is 2%. The equivalent computations for cross-section ratios are presented in Table 10.

Tables 11 and 12 display extrapolation factors E that may be used to translate the measured fiducial cross sections and ratios, respectively, to the fiducial phase space of the CMS analysis [98]:

- $W \rightarrow \ell\nu$: $p_{\text{T}}^{\ell} > 25$ GeV, $|\eta^{\ell}| < 2.4$, $p_{\text{T}}^{\nu} > 0$, and $m_{\text{T}} > 40$ GeV;
- $Z \rightarrow \ell\ell$: $p_{\text{T}}^{\ell} > 25$ GeV, $|\eta^{\ell}| < 2.4$, and 60 GeV $< m_{\ell\ell} < 120$ GeV.

As the phase spaces are similar, these factors are generally close to unity (within about 10%) and the theoretical uncertainties, computed in the same way as for A factors, are small.

Table 9: Acceptance factors A to derive total production cross sections for W^- , W^+ and Z production at 5.02 TeV and 13 TeV with total theory uncertainties. The measured fiducial cross sections and ratios are repeated from Table 3 and the resulting total cross sections are given.

	$W^- \rightarrow \ell\nu$	$W^+ \rightarrow \ell\nu$	$W^\pm \rightarrow \ell\nu$	$Z \rightarrow \ell\ell$
$\sqrt{s} = 5.02 \text{ TeV}$				
A	0.475 ± 0.004	0.506 ± 0.008	0.494 ± 0.006	0.492 ± 0.006
$\sigma_{\text{fid}} [\text{pb}]$	1384 ± 16	2228 ± 25	3612 ± 40	333.0 ± 4.1
$\sigma_{\text{tot}} [\text{pb}]$	2913 ± 41	4401 ± 85	7316 ± 124	677 ± 12
$\sqrt{s} = 13 \text{ TeV}$				
A	0.399 ± 0.006	0.386 ± 0.009	0.391 ± 0.008	0.393 ± 0.011
$\sigma_{\text{fid}} [\text{pb}]$	3486 ± 38	4571 ± 49	8057 ± 88	780.3 ± 10.4
$\sigma_{\text{tot}} [\text{pb}]$	8740 ± 160	11850 ± 310	20580 ± 460	1986 ± 59

Table 10: Acceptance factors A to derive total production cross-section ratios at 5.02 TeV and 13 TeV with total theory uncertainties. The measured fiducial ratios are repeated from Table 5 and the resulting total cross-section ratios are given.

	W^+/W^-	W^\pm/Z
$\sqrt{s} = 5.02 \text{ TeV}$		
$A^V/A^{V'}$	1.065 ± 0.012	1.003 ± 0.008
$\sigma_{\text{fid}}^V/\sigma_{\text{fid}}^{V'}$	1.609 ± 0.005	10.85 ± 0.08
$\sigma_{\text{tot}}^V/\sigma_{\text{tot}}^{V'}$	1.511 ± 0.017	10.82 ± 0.12
$\sqrt{s} = 13 \text{ TeV}$		
$A^V/A^{V'}$	0.968 ± 0.011	0.996 ± 0.010
$\sigma_{\text{fid}}^V/\sigma_{\text{fid}}^{V'}$	1.308 ± 0.005	10.30 ± 0.11
$\sigma_{\text{tot}}^V/\sigma_{\text{tot}}^{V'}$	1.351 ± 0.017	10.34 ± 0.15

Table 11: Extrapolation factors E to translate the fiducial integrated cross sections to the phase space of the analysis performed by the CMS Collaboration [98]. The measured fiducial cross sections are repeated from Table 3 and the resulting extrapolated cross sections in the CMS fiducial volume are given.

Experiment	$W^- \rightarrow \ell\nu$	$W^+ \rightarrow \ell\nu$	$Z \rightarrow \ell\ell$
$\sqrt{s} = 5.02 \text{ TeV}$			
E	1.0951 ± 0.0053	1.1009 ± 0.0042	0.9637 ± 0.0008
ATLAS	1384 ± 16	2228 ± 25	333.0 ± 4.1
ATLAS@CMSfid	1516 ± 19	2453 ± 29	320.9 ± 4.0
$\sqrt{s} = 13 \text{ TeV}$			
E	1.1156 ± 0.0031	1.1154 ± 0.0014	0.9621 ± 0.0011
ATLAS	3486 ± 38	4571 ± 49	780.3 ± 10.4
ATLAS@CMSfid	3889 ± 44	5099 ± 55	750.7 ± 10.0

Table 12: Extrapolation factors E to translate the fiducial integrated cross-section ratios to the phase space of the analysis performed by the CMS Collaboration [98]. The measured fiducial cross-section ratios are repeated from Table 5 and the resulting extrapolated cross-section ratios in the CMS fiducial volume are given.

Experiment	W^+/W^-	W^\pm/Z
$\sqrt{s} = 5.02 \text{ TeV}$		
$E^V/E^{V'}$	1.0052 ± 0.0013	1.1401 ± 0.0050
ATLAS	1.609 ± 0.005	10.85 ± 0.08
ATLAS@CMSfid	1.617 ± 0.005	12.37 ± 0.11
$\sqrt{s} = 13 \text{ TeV}$		
$E^V/E^{V'}$	0.9998 ± 0.0033	1.1594 ± 0.0009
ATLAS	1.308 ± 0.005	10.30 ± 0.11
ATLAS@CMSfid	1.308 ± 0.007	11.94 ± 0.13

References

- [1] ATLAS Collaboration, *Measurement of the W-boson mass and width with the ATLAS detector using proton-proton collisions at $\sqrt{s} = 7$ TeV*, (2024), arXiv: [2403.15085 \[hep-ex\]](#).
- [2] CDF Collaboration, *High-precision measurement of the W boson mass with the CDF II detector*, *Science* **376** (2022) 170.
- [3] D0 Collaboration, *Measurement of the W boson mass with the D0 detector*, *Phys. Rev. D* **89** (2014) 012005, arXiv: [1310.8628 \[hep-ex\]](#).
- [4] LHCb Collaboration, *Measurement of the W boson mass*, *JHEP* **01** (2022) 036, arXiv: [2109.01113 \[hep-ex\]](#).
- [5] R. Boughezal et al., *Z-boson production in association with a jet at next-to-next-to-leading order in perturbative QCD*, *Phys. Rev. Lett.* **116** (2016) 152001, arXiv: [1512.01291 \[hep-ph\]](#).
- [6] A. Gehrmann-De Ridder, T. Gehrmann, E. W. N. Glover, A. Huss and T. A. Morgan, *Precise QCD predictions for the production of a Z boson in association with a hadronic jet*, *Phys. Rev. Lett.* **117** (2016) 022001, arXiv: [1507.02850 \[hep-ph\]](#).
- [7] R. Boughezal, X. Liu and F. Petriello, *W-boson plus jet differential distributions at NNLO in QCD*, *Phys. Rev. D* **94** (2016) 113009, arXiv: [1602.06965 \[hep-ph\]](#).
- [8] G. Bozzi, S. Catani, D. de Florian and M. Grazzini, *Transverse-momentum resummation and the spectrum of the Higgs boson at the LHC*, *Nucl. Phys. B* **737** (2006) 73, arXiv: [hep-ph/0508068 \[hep-ph\]](#).
- [9] W. Bizoń et al., *The transverse momentum spectrum of weak gauge bosons at N^3 LL + NNLO*, *Eur. Phys. J. C* **79** (2019) 868, arXiv: [1905.05171 \[hep-ph\]](#).
- [10] T. Neumann and J. Campbell, *Fiducial Drell-Yan production at the LHC improved by transverse-momentum resummation at N^4 LL_p + N^3 LO*, *Phys. Rev. D* **107** (2023) L011506, arXiv: [2207.07056 \[hep-ph\]](#).
- [11] S. Camarda, L. Cieri and G. Ferrera, *Drell-Yan lepton-pair production: q_T resummation at N4LL accuracy*, *Phys. Lett. B* **845** (2023) 138125, arXiv: [2303.12781 \[hep-ph\]](#).
- [12] T. Sjöstrand, S. Mrenna and P. Skands, *A brief introduction to PYTHIA 8.1*, *Comput. Phys. Commun.* **178** (2008) 852, arXiv: [0710.3820 \[hep-ph\]](#).
- [13] J. Bellm et al., *Herwig 7.0/Herwig++ 3.0 release note*, *Eur. Phys. J. C* **76** (2016) 196, arXiv: [1512.01178 \[hep-ph\]](#).
- [14] E. Bothmann et al., *Event generation with Sherpa 2.2*, *SciPost Phys.* **7** (2019) 034, arXiv: [1905.09127 \[hep-ph\]](#).
- [15] ATLAS Collaboration, *Measurement of the Z/ γ^* boson transverse momentum distribution in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, *JHEP* **09** (2014) 145, arXiv: [1406.3660 \[hep-ex\]](#).
- [16] ATLAS Collaboration, *Measurement of the transverse momentum and ϕ_η^* distributions of Drell-Yan lepton pairs in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, *Eur. Phys. J. C* **76** (2016) 291, arXiv: [1512.02192 \[hep-ex\]](#).

- [17] ATLAS Collaboration, *Measurement of the transverse momentum distribution of Drell–Yan lepton pairs in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *Eur. Phys. J. C* **80** (2020) 616, arXiv: [1912.02844 \[hep-ex\]](#).
- [18] CMS Collaboration, *Measurement of the rapidity and transverse momentum distributions of Z bosons in pp collisions at $\sqrt{s} = 7$ TeV*, *Phys. Rev. D* **85** (2012) 032002, arXiv: [1110.4973 \[hep-ex\]](#).
- [19] CMS Collaboration, *Measurement of the Z boson differential cross section in transverse momentum and rapidity in proton–proton collisions at 8 TeV*, *Phys. Lett. B* **749** (2015) 187, arXiv: [1504.03511 \[hep-ex\]](#).
- [20] CMS Collaboration, *Measurement of the mass dependence of the transverse momentum of lepton pairs in Drell–Yan production in proton–proton collisions at $\sqrt{s} = 13$ TeV*, *Eur. Phys. J. C* **83** (2023) 628, arXiv: [2205.04897 \[hep-ex\]](#).
- [21] LHCb Collaboration, *Measurement of the forward Z boson production cross-section in pp collisions at $\sqrt{s} = 7$ TeV*, *JHEP* **08** (2015) 039, arXiv: [1505.07024 \[hep-ex\]](#).
- [22] LHCb Collaboration, *Measurement of forward W and Z boson production in pp collisions at $\sqrt{s} = 8$ TeV*, *JHEP* **01** (2016) 155, arXiv: [1511.08039 \[hep-ex\]](#).
- [23] LHCb Collaboration, *Precision measurement of forward Z boson production in proton-proton collisions at $\sqrt{s} = 13$ TeV*, *JHEP* **07** (2022) 026, arXiv: [2112.07458 \[hep-ex\]](#).
- [24] ATLAS Collaboration, *Measurement of the transverse momentum distribution of W bosons in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, *Phys. Rev. D* **85** (2012) 012005, arXiv: [1108.6308 \[hep-ex\]](#).
- [25] CMS Collaboration, *Measurement of the transverse momentum spectra of weak vector bosons produced in proton–proton collisions at $\sqrt{s} = 8$ TeV*, *JHEP* **02** (2017) 096, arXiv: [1606.05864 \[hep-ex\]](#).
- [26] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, *JINST* **3** (2008) S08003.
- [27] ATLAS Collaboration, *ATLAS Insertable B-Layer: Technical Design Report*, ATLAS-TDR-19; CERN-LHCC-2010-013, 2010, URL: <https://cds.cern.ch/record/1291633>, Addendum: ATLAS-TDR-19-ADD-1; CERN-LHCC-2012-009, 2012, URL: <https://cds.cern.ch/record/1451888>.
- [28] B. Abbott et al., *Production and integration of the ATLAS Insertable B-Layer*, *JINST* **13** (2018) T05008, arXiv: [1803.00844 \[physics.ins-det\]](#).
- [29] G. Avoni et al., *The new LUCID-2 detector for luminosity measurement and monitoring in ATLAS*, *JINST* **13** (2018) P07017.
- [30] ATLAS Collaboration, *Performance of the ATLAS trigger system in 2015*, *Eur. Phys. J. C* **77** (2017) 317, arXiv: [1611.09661 \[hep-ex\]](#).
- [31] ATLAS Collaboration, *The ATLAS Collaboration Software and Firmware*, ATL-SOFT-PUB-2021-001, 2021, URL: <https://cds.cern.ch/record/2767187>.

- [32] ATLAS Collaboration, *Luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC*, *Eur. Phys. J. C* **83** (2023) 982, arXiv: [2212.09379 \[hep-ex\]](#).
- [33] ATLAS Collaboration, *Performance of electron and photon triggers in ATLAS during LHC Run 2*, *Eur. Phys. J. C* **80** (2020) 47, arXiv: [1909.00761 \[hep-ex\]](#).
- [34] ATLAS Collaboration, *Performance of the ATLAS muon triggers in Run 2*, *JINST* **15** (2020) P09015, arXiv: [2004.13447 \[physics.ins-det\]](#).
- [35] ATLAS Collaboration, *The ATLAS Simulation Infrastructure*, *Eur. Phys. J. C* **70** (2010) 823, arXiv: [1005.4568 \[physics.ins-det\]](#).
- [36] S. Agostinelli et al., *GEANT4 – a simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250.
- [37] NNPDF Collaboration, R. D. Ball et al., *Parton distributions with LHC data*, *Nucl. Phys. B* **867** (2013) 244, arXiv: [1207.1303 \[hep-ph\]](#).
- [38] ATLAS Collaboration, *The Pythia 8 A3 tune description of ATLAS minimum bias and inelastic measurements incorporating the Donnachie–Landshoff diffractive model*, ATL-PHYS-PUB-2016-017, 2016, URL: <https://cds.cern.ch/record/2206965>.
- [39] P. Nason, *A new method for combining NLO QCD with shower Monte Carlo algorithms*, *JHEP* **11** (2004) 040, arXiv: [hep-ph/0409146](#).
- [40] S. Frixione, P. Nason and C. Oleari, *Matching NLO QCD computations with parton shower simulations: the POWHEG method*, *JHEP* **11** (2007) 070, arXiv: [0709.2092 \[hep-ph\]](#).
- [41] S. Alioli, P. Nason, C. Oleari and E. Re, *NLO vector-boson production matched with shower in POWHEG*, *JHEP* **07** (2008) 060, arXiv: [0805.4802 \[hep-ph\]](#).
- [42] S. Alioli, P. Nason, C. Oleari and E. Re, *A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX*, *JHEP* **06** (2010) 043, arXiv: [1002.2581 \[hep-ph\]](#).
- [43] H.-L. Lai et al., *New parton distributions for collider physics*, *Phys. Rev. D* **82** (2010) 074024, arXiv: [1007.2241 \[hep-ph\]](#).
- [44] P. Golonka and Z. Was, *PHOTOS Monte Carlo: a precision tool for QED corrections in Z and W decays*, *Eur. Phys. J. C* **45** (2006) 97, arXiv: [hep-ph/0506026](#).
- [45] NNPDF Collaboration, R. D. Ball et al., *Parton distributions for the LHC run II*, *JHEP* **04** (2015) 040, arXiv: [1410.8849 \[hep-ph\]](#).
- [46] T. Gleisberg and S. Höche, *Comix, a new matrix element generator*, *JHEP* **12** (2008) 039, arXiv: [0808.3674 \[hep-ph\]](#).
- [47] F. Buccioni et al., *OpenLoops 2*, *Eur. Phys. J. C* **79** (2019) 866, arXiv: [1907.13071 \[hep-ph\]](#).
- [48] F. Cascioli, P. Maierhöfer and S. Pozzorini, *Scattering Amplitudes with Open Loops*, *Phys. Rev. Lett.* **108** (2012) 111601, arXiv: [1111.5206 \[hep-ph\]](#).
- [49] A. Denner, S. Dittmaier and L. Hofer, *COLLIER: A fortran-based complex one-loop library in extended regularizations*, *Comput. Phys. Commun.* **212** (2017) 220, arXiv: [1604.06792 \[hep-ph\]](#).

- [50] S. Schumann and F. Krauss,
A parton shower algorithm based on Catani–Seymour dipole factorisation, *JHEP* **03** (2008) 038,
arXiv: [0709.1027 \[hep-ph\]](#).
- [51] S. Höche, F. Krauss, M. Schönherr and F. Siegert,
A critical appraisal of NLO+PS matching methods, *JHEP* **09** (2012) 049,
arXiv: [1111.1220 \[hep-ph\]](#).
- [52] S. Höche, F. Krauss, M. Schönherr and F. Siegert,
QCD matrix elements + parton showers. The NLO case, *JHEP* **04** (2013) 027,
arXiv: [1207.5030 \[hep-ph\]](#).
- [53] S. Catani, F. Krauss, B. R. Webber and R. Kuhn, *QCD Matrix Elements + Parton Showers*,
JHEP **11** (2001) 063, arXiv: [hep-ph/0109231](#).
- [54] S. Höche, F. Krauss, S. Schumann and F. Siegert, *QCD matrix elements and truncated showers*,
JHEP **05** (2009) 053, arXiv: [0903.1219 \[hep-ph\]](#).
- [55] S. Camarda, L. Cieri and G. Ferrera, *Drell–Yan lepton-pair production: q_T resummation at N^3LL accuracy and fiducial cross sections at N^3LO* , *Phys. Rev. D* **104** (2021) L111503,
arXiv: [2103.04974 \[hep-ph\]](#).
- [56] S. Catani and M. Grazzini, *Next-to-Next-to-Leading-Order Subtraction Formalism in Hadron Collisions and its Application to Higgs-boson Production at the Large Hadron Collider*,
Phys. Rev. Lett. **98** (2007) 222002, arXiv: [hep-ph/0703012 \[hep-ph\]](#).
- [57] S. Catani, L. Cieri, G. Ferrera, D. de Florian and M. Grazzini, *Vector Boson Production at Hadron Colliders: A Fully Exclusive QCD Calculation at Next-to-Next-to-Leading Order*,
Phys. Rev. Lett. **103** (2009) 082001, arXiv: [0903.2120 \[hep-ph\]](#).
- [58] L. A. Harland-Lang, A. D. Martin, P. Motylinski and R. S. Thorne,
Parton distributions in the LHC era: MMHT 2014 PDFs, *Eur. Phys. J. C* **75** (2015) 204,
arXiv: [1412.3989 \[hep-ph\]](#).
- [59] ATLAS Collaboration,
Study of top-quark pair modelling and uncertainties using ATLAS measurements at $\sqrt{s} = 13$ TeV,
ATL-PHYS-PUB-2020-023, 2020, URL: <https://cds.cern.ch/record/2730443>.
- [60] M. Beneke, P. Falgari, S. Klein and C. Schwinn,
Hadronic top-quark pair production with NNLL threshold resummation,
Nucl. Phys. B **855** (2012) 695, arXiv: [1109.1536 \[hep-ph\]](#).
- [61] M. Cacciari, M. Czakon, M. Mangano, A. Mitov and P. Nason, *Top-pair production at hadron colliders with next-to-next-to-leading logarithmic soft-gluon resummation*,
Phys. Lett. B **710** (2012) 612, arXiv: [1111.5869 \[hep-ph\]](#).
- [62] P. Bärnreuther, M. Czakon and A. Mitov, *Percent-Level-Precision Physics at the Tevatron: Next-to-Next-to-Leading Order QCD Corrections to $q\bar{q} \rightarrow t\bar{t} + X$* ,
Phys. Rev. Lett. **109** (2012) 132001, arXiv: [1204.5201 \[hep-ph\]](#).
- [63] M. Czakon and A. Mitov,
NNLO corrections to top-pair production at hadron colliders: the all-fermionic scattering channels,
JHEP **12** (2012) 054, arXiv: [1207.0236 \[hep-ph\]](#).
- [64] M. Czakon and A. Mitov,
NNLO corrections to top pair production at hadron colliders: the quark-gluon reaction,
JHEP **01** (2013) 080, arXiv: [1210.6832 \[hep-ph\]](#).

- [65] M. Czakon, P. Fiedler and A. Mitov,
Total Top-Quark Pair-Production Cross Section at Hadron Colliders Through $O(\alpha_S^4)$,
Phys. Rev. Lett. **110** (2013) 252004, arXiv: 1303.6254 [hep-ph].
- [66] M. Czakon and A. Mitov,
Top++: A program for the calculation of the top-pair cross-section at hadron colliders,
Comput. Phys. Commun. **185** (2014) 2930, arXiv: 1112.5675 [hep-ph].
- [67] ATLAS Collaboration, *Multi-Boson Simulation for 13 TeV ATLAS Analyses*,
ATL-PHYS-PUB-2017-005, 2017, URL: <https://cds.cern.ch/record/2261933>.
- [68] ATLAS Collaboration, *Electron and photon performance measurements with the ATLAS detector using the 2015–2017 LHC proton–proton collision data*, *JINST* **14** (2019) P12006,
arXiv: 1908.00005 [hep-ex].
- [69] ATLAS Collaboration, *Studies of the muon momentum calibration and performance of the ATLAS detector with pp collisions at $\sqrt{s} = 13$ TeV*, *Eur. Phys. J. C* **83** (2023) 686,
arXiv: 2212.07338 [hep-ex].
- [70] ATLAS Collaboration,
Measurement of the W-boson mass in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector,
Eur. Phys. J. C **78** (2018) 110, arXiv: 1701.07240 [hep-ex],
Erratum: *Eur. Phys. J. C* **78** (2018) 898.
- [71] ATLAS Collaboration, *Alignment of the ATLAS Inner Detector in Run 2*,
Eur. Phys. J. C **80** (2020) 1194, arXiv: 2007.07624 [hep-ex].
- [72] ATLAS Collaboration, *Vertex Reconstruction Performance of the ATLAS Detector at $\sqrt{s} = 13$ TeV*,
ATL-PHYS-PUB-2015-026, 2015, URL: <https://cds.cern.ch/record/2037717>.
- [73] ATLAS Collaboration,
Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1,
Eur. Phys. J. C **77** (2017) 490, arXiv: 1603.02934 [hep-ex].
- [74] ATLAS Collaboration,
Jet reconstruction and performance using particle flow with the ATLAS Detector,
Eur. Phys. J. C **77** (2017) 466, arXiv: 1703.10485 [hep-ex].
- [75] ATLAS Collaboration, *Jet energy scale and resolution measured in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *Eur. Phys. J. C* **81** (2021) 689,
arXiv: 2007.02645 [hep-ex].
- [76] G. D’Agostini, *A multidimensional unfolding method based on Bayes’ theorem*,
Nucl. Instrum. Meth. A **362** (1995) 487.
- [77] G. D’Agostini, *Improved iterative Bayesian unfolding*, (2010),
arXiv: 1010.0632 [physics.data-an].
- [78] ATLAS Collaboration,
Evaluating statistical uncertainties and correlations using the bootstrap method,
ATL-PHYS-PUB-2021-011, 2021, URL: <https://cds.cern.ch/record/2759945>.
- [79] L. Lyons, D. Gibaut and P. Clifford,
How to Combine Correlated Estimates of a Single Physical Quantity,
Nucl. Instrum. Meth. A **270** (1988) 110.

- [80] A. Valassi, *Combining correlated measurements of several different physical quantities*, *Nucl. Instrum. Meth. A* **500** (2003) 391.
- [81] H. Dembinski, M. Schmelling and R. Waldi, *Application of the Iterated Weighted Least-Squares Fit to counting experiments*, *Nucl. Instrum. Meth. A* **940** (2019) 135, arXiv: [1807.07911 \[physics.data-an\]](#).
- [82] ATLAS Collaboration, *Measurements of W and Z boson production in pp collisions at $\sqrt{s} = 5.02$ TeV with the ATLAS detector*, *Eur. Phys. J. C* **79** (2019) 128, arXiv: [1810.08424 \[hep-ex\]](#), Erratum: *Eur. Phys. J. C* **79** (2019) 374.
- [83] ATLAS Collaboration, *Measurement of W^\pm and Z -boson production cross sections in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *Phys. Lett. B* **759** (2016) 601, arXiv: [1603.09222 \[hep-ex\]](#).
- [84] ATLAS Collaboration, *Measurements of top-quark pair to Z -boson cross-section ratios at $\sqrt{s} = 13, 8, 7$ TeV with the ATLAS detector*, *JHEP* **02** (2017) 117, arXiv: [1612.03636 \[hep-ex\]](#).
- [85] T.-J. Hou et al., *New CTEQ global analysis of quantum chromodynamics with high-precision data from the LHC*, *Phys. Rev. D* **103** (2021) 014013, arXiv: [1912.10053 \[hep-ph\]](#).
- [86] S. Bailey, T. Cridge, L. A. Harland-Lang, A. D. Martin and R. S. Thorne, *Parton distributions from LHC, HERA, Tevatron and fixed target data: MSHT20 PDFs*, *Eur. Phys. J. C* **81** (2021) 341, arXiv: [2012.04684 \[hep-ph\]](#).
- [87] NNPDF Collaboration, R. D. Ball et al., *Parton distributions from high-precision collider data*, *Eur. Phys. J. C* **77** (2017) 663, arXiv: [1706.00428 \[hep-ph\]](#).
- [88] ATLAS Collaboration, *Precision measurement and interpretation of inclusive W^+ , W^- and Z/γ^* production cross sections with the ATLAS detector*, *Eur. Phys. J. C* **77** (2017) 367, arXiv: [1612.03016 \[hep-ex\]](#).
- [89] J. Bellm et al., *Herwig 7.1 Release Note*, (2017), arXiv: [1705.06919 \[hep-ph\]](#).
- [90] ATLAS Collaboration, *Modelling and computational improvements to the simulation of single vector-boson plus jet processes for the ATLAS experiment*, *JHEP* **08** (2022) 089, arXiv: [2112.09588 \[hep-ex\]](#).
- [91] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, *JHEP* **07** (2014) 079, arXiv: [1405.0301 \[hep-ph\]](#).
- [92] R. Frederix and S. Frixione, *Merging meets matching in MC@NLO*, *JHEP* **12** (2012) 061, arXiv: [1209.6215 \[hep-ph\]](#).
- [93] C. Bierlich et al., *Robust Independent Validation of Experiment and Theory: Rivet version 3*, *SciPost Phys.* **8** (2020) 026, arXiv: [1912.05451 \[hep-ph\]](#).
- [94] ATLAS Collaboration, *ATLAS Computing Acknowledgements*, ATL-SOFT-PUB-2023-001, 2023, URL: <https://cds.cern.ch/record/2869272>.
- [95] W. Bizoń et al., *Fiducial distributions in Higgs and Drell-Yan production at $N^3LL+NNLO$* , *JHEP* **12** (2018) 132, arXiv: [1805.05916 \[hep-ph\]](#).
- [96] A. Gehrmann-De Ridder, T. Gehrmann, E. W. N. Glover, A. Huss and T. A. Morgan, *NNLO QCD corrections for Drell-Yan p_T^Z and ϕ_η^* observables at the LHC*, *JHEP* **11** (2016) 094, arXiv: [1610.01843 \[hep-ph\]](#), Erratum: *JHEP* **10** (2018) 126.

- [97] W. Bizoń, P. F. Monni, E. Re, L. Rottoli and P. Torrielli,
Momentum-space resummation for transverse observables and the Higgs p_{\perp} at $N^3LL+NNLO$,
JHEP **02** (2018) 108, arXiv: [1705.09127](https://arxiv.org/abs/1705.09127) [[hep-ph](#)].
- [98] CMS Collaboration,
Measurement of W and Z boson inclusive cross sections in pp collisions at 5.02 and 13 TeV, (2023),
URL: <https://cds.cern.ch/record/2868090>.

The ATLAS Collaboration

G. Aad ¹⁰², B. Abbott ¹²⁰, K. Abeling ⁵⁵, N.J. Abicht ⁴⁹, S.H. Abidi ²⁹, A. Aboulhorma ^{35e}, H. Abramowicz ¹⁵¹, H. Abreu ¹⁵⁰, Y. Abulaiti ¹¹⁷, B.S. Acharya ^{69a,69b,m}, C. Adam Bourdarios ⁴, L. Adamczyk ^{86a}, L. Adamek ¹⁵⁵, S.V. Addepalli ²⁶, M.J. Addison ¹⁰¹, J. Adelman ¹¹⁵, A. Adiguzel ^{21c}, T. Adye ¹³⁴, A.A. Affolder ¹³⁶, Y. Afik ³⁶, M.N. Agaras ¹³, J. Agarwala ^{73a,73b}, A. Aggarwal ¹⁰⁰, C. Agheorghiesei ^{27c}, A. Ahmad ³⁶, F. Ahmadov ^{38,y}, W.S. Ahmed ¹⁰⁴, S. Ahuja ⁹⁵, X. Ai ^{62a}, G. Aielli ^{76a,76b}, A. Aikot ¹⁶³, M. Ait Tamlah ^{35e}, B. Aitbenchikh ^{35a}, I. Aizenberg ¹⁶⁹, M. Akbiyik ¹⁰⁰, T.P.A. Åkesson ⁹⁸, A.V. Akimov ³⁷, D. Akiyama ¹⁶⁸, N.N. Akolkar ²⁴, K. Al Khoury ⁴¹, G.L. Alberghi ^{23b}, J. Albert ¹⁶⁵, P. Albicocco ⁵³, G.L. Albouy ⁶⁰, S. Alderweireldt ⁵², M. Aleksa ³⁶, I.N. Aleksandrov ³⁸, C. Alexa ^{27b}, T. Alexopoulos ¹⁰, F. Alfonsi ^{23b}, M. Algren ⁵⁶, M. Alhroob ¹²⁰, B. Ali ¹³², H.M.J. Ali ⁹¹, S. Ali ¹⁴⁸, S.W. Alibocus ⁹², M. Aliev ¹⁴⁵, G. Alimonti ^{71a}, W. Alkakhri ⁵⁵, C. Allaire ⁶⁶, B.M.M. Allbrooke ¹⁴⁶, J.F. Allen ⁵², C.A. Allendes Flores ^{137f}, P.P. Allport ²⁰, A. Aloisio ^{72a,72b}, F. Alonso ⁹⁰, C. Alpigiani ¹³⁸, M. Alvarez Estevez ⁹⁹, A. Alvarez Fernandez ¹⁰⁰, M. Alves Cardoso ⁵⁶, M.G. Alviggi ^{72a,72b}, M. Aly ¹⁰¹, Y. Amaral Coutinho ^{83b}, A. Ambler ¹⁰⁴, C. Amelung ³⁶, M. Amerl ¹⁰¹, C.G. Ames ¹⁰⁹, D. Amidei ¹⁰⁶, S.P. Amor Dos Santos ^{130a}, K.R. Amos ¹⁶³, V. Ananiev ¹²⁵, C. Anastopoulos ¹³⁹, T. Andeen ¹¹, J.K. Anders ³⁶, S.Y. Andrean ^{47a,47b}, A. Andreazza ^{71a,71b}, S. Angelidakis ⁹, A. Angerami ^{41,ab}, A.V. Anisenkov ³⁷, A. Annovi ^{74a}, C. Antel ⁵⁶, M.T. Anthony ¹³⁹, E. Antipov ¹⁴⁵, M. Antonelli ⁵³, F. Anulli ^{75a}, M. Aoki ⁸⁴, T. Aoki ¹⁵³, J.A. Aparisi Pozo ¹⁶³, M.A. Aparo ¹⁴⁶, L. Aperio Bella ⁴⁸, C. Appelt ¹⁸, A. Apyan ²⁶, N. Aranzabal ³⁶, C. Arcangeletti ⁵³, A.T.H. Arce ⁵¹, E. Arena ⁹², J-F. Arguin ¹⁰⁸, S. Argyropoulos ⁵⁴, J.-H. Arling ⁴⁸, O. Arnaez ⁴, H. Arnold ¹¹⁴, G. Artoni ^{75a,75b}, H. Asada ¹¹¹, K. Asai ¹¹⁸, S. Asai ¹⁵³, N.A. Asbah ⁶¹, K. Assamagan ²⁹, R. Astalos ^{28a}, S. Atashi ¹⁶⁰, R.J. Atkin ^{33a}, M. Atkinson ¹⁶², H. Atmani ^{35f}, P.A. Atlasidha ¹⁰⁶, K. Augsten ¹³², S. Auricchio ^{72a,72b}, A.D. Auriol ²⁰, V.A. Austrup ¹⁰¹, G. Avolio ³⁶, K. Axiotis ⁵⁶, G. Azuelos ^{108,ag}, D. Babal ^{28b}, H. Bachacou ¹³⁵, K. Bachas ^{152,p}, A. Bachiu ³⁴, F. Backman ^{47a,47b}, A. Badea ⁶¹, P. Bagnaia ^{75a,75b}, M. Bahmani ¹⁸, A.J. Bailey ¹⁶³, V.R. Bailey ¹⁶², J.T. Baines ¹³⁴, L. Baines ⁹⁴, C. Bakalis ¹⁰, O.K. Baker ¹⁷², E. Bakos ¹⁵, D. Bakshi Gupta ⁸, V. Balakrishnan ¹²⁰, R. Balasubramanian ¹¹⁴, E.M. Baldin ³⁷, P. Balek ^{86a}, E. Ballabene ^{23b,23a}, F. Balli ¹³⁵, L.M. Baltes ^{63a}, W.K. Balunas ³², J. Balz ¹⁰⁰, E. Banas ⁸⁷, M. Bandieramonte ¹²⁹, A. Bandyopadhyay ²⁴, S. Bansal ²⁴, L. Barak ¹⁵¹, M. Barakat ⁴⁸, E.L. Barberio ¹⁰⁵, D. Barberis ^{57b,57a}, M. Barbero ¹⁰², M.Z. Barel ¹¹⁴, K.N. Barends ^{33a}, T. Barillari ¹¹⁰, M-S. Barisits ³⁶, T. Barklow ¹⁴³, P. Baron ¹²², D.A. Baron Moreno ¹⁰¹, A. Baroncelli ^{62a}, G. Barone ²⁹, A.J. Barr ¹²⁶, J.D. Barr ⁹⁶, L. Barranco Navarro ^{47a,47b}, F. Barreiro ⁹⁹, J. Barreiro Guimarães da Costa ^{14a}, U. Barron ¹⁵¹, M.G. Barros Teixeira ^{130a}, S. Barsov ³⁷, F. Bartels ^{63a}, R. Bartoldus ¹⁴³, A.E. Barton ⁹¹, P. Bartos ^{28a}, A. Basan ¹⁰⁰, M. Baselga ⁴⁹, A. Bassalat ^{66,b}, M.J. Basso ^{156a}, C.R. Basson ¹⁰¹, R.L. Bates ⁵⁹, S. Batlamous ^{35e}, J.R. Batley ³², B. Batool ¹⁴¹, M. Battaglia ¹³⁶, D. Battulga ¹⁸, M. Bauge ^{75a,75b}, M. Bauer ³⁶, P. Bauer ²⁴, L.T. Bazzano Hurrell ³⁰, J.B. Beacham ⁵¹, T. Beau ¹²⁷, P.H. Beauchemin ¹⁵⁸, F. Becherer ⁵⁴, P. Bechtel ²⁴, H.P. Beck ^{19,o}, K. Becker ¹⁶⁷, A.J. Beddall ⁸², V.A. Bednyakov ³⁸, C.P. Bee ¹⁴⁵, L.J. Beemster ¹⁵, T.A. Beermann ³⁶, M. Begalli ^{83d}, M. Begel ²⁹, A. Behera ¹⁴⁵, J.K. Behr ⁴⁸, J.F. Beirer ⁵⁵, F. Beisiegel ²⁴, M. Belfkir ¹⁵⁹, G. Bella ¹⁵¹, L. Bellagamba ^{23b}, A. Bellerive ³⁴, P. Bellos ²⁰, K. Beloborodov ³⁷, D. Benchebroun ^{35a}, F. Bendebba ^{35a}, Y. Benhammou ¹⁵¹, M. Benoit ²⁹, J.R. Bensinger ²⁶, S. Bentvelsen ¹¹⁴, L. Beresford ⁴⁸, M. Beretta ⁵³, E. Bergeas Kuutmann ¹⁶¹,

N. Berger ⁴, B. Bergmann ¹³², J. Beringer ^{17a}, G. Bernardi ⁵, C. Bernius ¹⁴³,
 F.U. Bernlochner ²⁴, F. Bernon ^{36,102}, T. Berry ⁹⁵, P. Berta ¹³³, A. Berthold ⁵⁰, I.A. Bertram ⁹¹,
 S. Bethke ¹¹⁰, A. Betti ^{75a,75b}, A.J. Bevan ⁹⁴, M. Bhamjee ^{33c}, S. Bhatta ¹⁴⁵,
 D.S. Bhattacharya ¹⁶⁶, P. Bhattarai ¹⁴³, V.S. Bhopatkar ¹²¹, R. Bi ^{29,ai}, R.M. Bianchi ¹²⁹,
 G. Bianco ^{23b,23a}, O. Biebel ¹⁰⁹, R. Bielski ¹²³, M. Biglietti ^{77a}, M. Bindi ⁵⁵, A. Bingul ^{21b},
 C. Bini ^{75a,75b}, A. Biondini ⁹², C.J. Birch-sykes ¹⁰¹, G.A. Bird ^{20,134}, M. Birman ¹⁶⁹,
 M. Biros ¹³³, S. Biryukov ¹⁴⁶, T. Bisanz ⁴⁹, E. Bisceglie ^{43b,43a}, J.P. Biswal ¹³⁴, D. Biswas ¹⁴¹,
 A. Bitadze ¹⁰¹, K. Bjørke ¹²⁵, I. Bloch ⁴⁸, C. Blocker ²⁶, A. Blue ⁵⁹, U. Blumenschein ⁹⁴,
 J. Blumenthal ¹⁰⁰, G.J. Bobbink ¹¹⁴, V.S. Bobrovnikov ³⁷, M. Boehler ⁵⁴, B. Boehm ¹⁶⁶,
 D. Bogavac ³⁶, A.G. Bogdanchikov ³⁷, C. Bohm ^{47a}, V. Boisvert ⁹⁵, P. Bokan ⁴⁸, T. Bold ^{86a},
 M. Bomben ⁵, M. Bona ⁹⁴, M. Boonekamp ¹³⁵, C.D. Booth ⁹⁵, A.G. Borbély ⁵⁹,
 I.S. Bordulev ³⁷, H.M. Borecka-Bielska ¹⁰⁸, G. Borissov ⁹¹, D. Bortoletto ¹²⁶, D. Boscherini ^{23b},
 M. Bosman ¹³, J.D. Bossio Sola ³⁶, K. Bouaouda ^{35a}, N. Bouchhar ¹⁶³, J. Boudreau ¹²⁹,
 E.V. Bouhova-Thacker ⁹¹, D. Boumediene ⁴⁰, R. Bouquet ⁵, A. Boveia ¹¹⁹, J. Boyd ³⁶,
 D. Boye ²⁹, I.R. Boyko ³⁸, J. Bracinek ²⁰, N. Brahimi ^{62d}, G. Brandt ¹⁷¹, O. Brandt ³²,
 F. Braren ⁴⁸, B. Brau ¹⁰³, J.E. Brau ¹²³, R. Brenner ¹⁶⁹, L. Brenner ¹¹⁴, R. Brenner ¹⁶¹,
 S. Bressler ¹⁶⁹, D. Britton ⁵⁹, D. Britzger ¹¹⁰, I. Brock ²⁴, G. Brooijmans ⁴¹, W.K. Brooks ^{137f},
 E. Brost ²⁹, L.M. Brown ¹⁶⁵, L.E. Bruce ⁶¹, T.L. Bruckler ¹²⁶, P.A. Bruckman de Renstrom ⁸⁷,
 B. Brüers ⁴⁸, A. Bruni ^{23b}, G. Bruni ^{23b}, M. Bruschi ^{23b}, N. Bruscino ^{75a,75b}, T. Buanes ¹⁶,
 Q. Buat ¹³⁸, D. Buchin ¹¹⁰, A.G. Buckley ⁵⁹, O. Bulekov ³⁷, B.A. Bullard ¹⁴³, S. Burdin ⁹²,
 C.D. Burgard ⁴⁹, A.M. Burger ⁴⁰, B. Burghgrave ⁸, O. Burlayenko ⁵⁴, J.T.P. Burr ³²,
 C.D. Burton ¹¹, J.C. Burzynski ¹⁴², E.L. Busch ⁴¹, V. Büscher ¹⁰⁰, P.J. Bussey ⁵⁹,
 J.M. Butler ²⁵, C.M. Buttar ⁵⁹, J.M. Butterworth ⁹⁶, W. Buttinger ¹³⁴, C.J. Buxo Vazquez ¹⁰⁷,
 A.R. Buzykaev ³⁷, S. Cabrera Urbán ¹⁶³, L. Cadamuro ⁶⁶, D. Caforio ⁵⁸, H. Cai ¹²⁹,
 Y. Cai ^{14a,14e}, V.M.M. Cairo ³⁶, O. Cakir ^{3a}, N. Calace ³⁶, P. Calafiura ^{17a}, G. Calderini ¹²⁷,
 P. Calfayan ⁶⁸, G. Callea ⁵⁹, L.P. Caloba ^{83b}, D. Calvet ⁴⁰, S. Calvet ⁴⁰, T.P. Calvet ¹⁰²,
 M. Calvetti ^{74a,74b}, R. Camacho Toro ¹²⁷, S. Camarda ³⁶, D. Camarero Munoz ²⁶,
 P. Camarri ^{76a,76b}, M.T. Camerlingo ^{72a,72b}, D. Cameron ³⁶, C. Camincher ¹⁶⁵, M. Campanelli ⁹⁶,
 A. Camplani ⁴², V. Canale ^{72a,72b}, A. Canesse ¹⁰⁴, J. Cantero ¹⁶³, Y. Cao ¹⁶², F. Capocasa ²⁶,
 M. Capua ^{43b,43a}, A. Carbone ^{71a,71b}, R. Cardarelli ^{76a}, J.C.J. Cardenas ⁸, F. Cardillo ¹⁶³,
 T. Carli ³⁶, G. Carlino ^{72a}, J.I. Carlotto ¹³, B.T. Carlson ^{129,q}, E.M. Carlson ^{165,156a},
 L. Carminati ^{71a,71b}, A. Carnelli ¹³⁵, M. Carnesale ^{75a,75b}, S. Caron ¹¹³, E. Carquin ^{137f},
 S. Carrá ^{71a}, G. Carratta ^{23b,23a}, F. Carrio Argos ^{33g}, J.W.S. Carter ¹⁵⁵, T.M. Carter ⁵²,
 M.P. Casado ^{13,i}, M. Caspar ⁴⁸, E.G. Castiglia ¹⁷², F.L. Castillo ⁴, L. Castillo Garcia ¹³,
 V. Castillo Gimenez ¹⁶³, N.F. Castro ^{130a,130e}, A. Catinaccio ³⁶, J.R. Catmore ¹²⁵, V. Cavaliere ²⁹,
 N. Cavalli ^{23b,23a}, V. Cavalinni ^{74a,74b}, Y.C. Cekmecelioglu ⁴⁸, E. Celebi ^{21a}, F. Celli ¹²⁶,
 M.S. Centonze ^{70a,70b}, V. Cepaitis ⁵⁶, K. Cerny ¹²², A.S. Cerqueira ^{83a}, A. Cerri ¹⁴⁶,
 L. Cerrito ^{76a,76b}, F. Cerutti ^{17a}, B. Cervato ¹⁴¹, A. Cervelli ^{23b}, G. Cesarini ⁵³, S.A. Cetin ⁸²,
 Z. Chadi ^{35a}, D. Chakraborty ¹¹⁵, J. Chan ¹⁷⁰, W.Y. Chan ¹⁵³, J.D. Chapman ³², E. Chapon ¹³⁵,
 B. Chargeishvili ^{149b}, D.G. Charlton ²⁰, T.P. Charman ⁹⁴, M. Chatterjee ¹⁹, C. Chauhan ¹³³,
 S. Chekanov ⁶, S.V. Chekulaev ^{156a}, G.A. Chelkov ^{38,a}, A. Chen ¹⁰⁶, B. Chen ¹⁵¹, B. Chen ¹⁶⁵,
 H. Chen ^{14c}, H. Chen ²⁹, J. Chen ^{62c}, J. Chen ¹⁴², M. Chen ¹²⁶, S. Chen ¹⁵³, S.J. Chen ^{14c},
 X. Chen ^{62c,135}, X. Chen ^{14b,af}, Y. Chen ^{62a}, C.L. Cheng ¹⁷⁰, H.C. Cheng ^{64a}, S. Cheong ¹⁴³,
 A. Cheplakov ³⁸, E. Cheremushkina ⁴⁸, E. Cherepanova ¹¹⁴, R. Cherkaoui El Moursli ^{35e},
 E. Cheu ⁷, K. Cheung ⁶⁵, L. Chevalier ¹³⁵, V. Chiarella ⁵³, G. Chiarelli ^{74a}, N. Chiedde ¹⁰²,
 G. Chiodini ^{70a}, A.S. Chisholm ²⁰, A. Chitan ^{27b}, M. Chitishvili ¹⁶³, M.V. Chizhov ³⁸,
 K. Choi ¹¹, A.R. Chomont ^{75a,75b}, Y. Chou ¹⁰³, E.Y.S. Chow ¹¹⁴, T. Chowdhury ^{33g},

K.L. Chu [id](#)¹⁶⁹, M.C. Chu [id](#)^{64a}, X. Chu [id](#)^{14a,14e}, J. Chudoba [id](#)¹³¹, J.J. Chwastowski [id](#)⁸⁷, D. Cieri [id](#)¹¹⁰,
 K.M. Ciesla [id](#)^{86a}, V. Cindro [id](#)⁹³, A. Ciocio [id](#)^{17a}, F. Ciroto [id](#)^{72a,72b}, Z.H. Citron [id](#)^{169,k}, M. Citterio [id](#)^{71a},
 D.A. Ciubotaru [id](#)^{27b}, B.M. Ciungu [id](#)¹⁵⁵, A. Clark [id](#)⁵⁶, P.J. Clark [id](#)⁵², J.M. Clavijo Columbie [id](#)⁴⁸,
 S.E. Clawson [id](#)⁴⁸, C. Clement [id](#)^{47a,47b}, J. Clercx [id](#)⁴⁸, Y. Coadou [id](#)¹⁰², M. Cobal [id](#)^{69a,69c},
 A. Cocco [id](#)^{57b}, R.F. Coelho Barrue [id](#)^{130a}, R. Coelho Lopes De Sa [id](#)¹⁰³, S. Coelli [id](#)^{71a}, H. Cohen [id](#)¹⁵¹,
 A.E.C. Coimbra [id](#)^{71a,71b}, B. Cole [id](#)⁴¹, J. Collot [id](#)⁶⁰, P. Conde Muiño [id](#)^{130a,130g}, M.P. Connell [id](#)^{33c},
 S.H. Connell [id](#)^{33c}, I.A. Connelly [id](#)⁵⁹, E.I. Conroy [id](#)¹²⁶, F. Conventi [id](#)^{72a,ah}, H.G. Cooke [id](#)²⁰,
 A.M. Cooper-Sarkar [id](#)¹²⁶, A. Cordeiro Oudot Choi [id](#)¹²⁷, F. Cormier [id](#)¹⁶⁴, L.D. Corpe [id](#)⁴⁰,
 M. Corradi [id](#)^{75a,75b}, F. Corriveau [id](#)^{104,w}, A. Cortes-Gonzalez [id](#)¹⁸, M.J. Costa [id](#)¹⁶³, F. Costanza [id](#)⁴,
 D. Costanzo [id](#)¹³⁹, B.M. Cote [id](#)¹¹⁹, G. Cowan [id](#)⁹⁵, K. Cranmer [id](#)¹⁷⁰, D. Cremonini [id](#)^{23b,23a},
 S. Crépe-Renaudin [id](#)⁶⁰, F. Crescioli [id](#)¹²⁷, M. Cristinziani [id](#)¹⁴¹, M. Cristoforetti [id](#)^{78a,78b}, V. Croft [id](#)¹¹⁴,
 J.E. Crosby [id](#)¹²¹, G. Crosetti [id](#)^{43b,43a}, A. Cueto [id](#)⁹⁹, T. Cuhadar Donszelmann [id](#)¹⁶⁰, H. Cui [id](#)^{14a,14e},
 Z. Cui [id](#)⁷, W.R. Cunningham [id](#)⁵⁹, F. Curcio [id](#)^{43b,43a}, P. Czodrowski [id](#)³⁶, M.M. Czurylo [id](#)^{63b},
 M.J. Da Cunha Sargedas De Sousa [id](#)^{57b,57a}, J.V. Da Fonseca Pinto [id](#)^{83b}, C. Da Via [id](#)¹⁰¹,
 W. Dabrowski [id](#)^{86a}, T. Dado [id](#)⁴⁹, S. Dahbi [id](#)^{33g}, T. Dai [id](#)¹⁰⁶, D. Dal Santo [id](#)¹⁹, C. Dallapiccola [id](#)¹⁰³,
 M. Dam [id](#)⁴², G. D'amen [id](#)²⁹, V. D'Amico [id](#)¹⁰⁹, J. Damp [id](#)¹⁰⁰, J.R. Dandoy [id](#)¹²⁸, M.F. Daneri [id](#)³⁰,
 M. Danninger [id](#)¹⁴², V. Dao [id](#)³⁶, G. Darbo [id](#)^{57b}, S. Darmora [id](#)⁶, S.J. Das [id](#)^{29,ai}, S. D'Auria [id](#)^{71a,71b},
 C. David [id](#)^{156b}, T. Davidek [id](#)¹³³, B. Davis-Purcell [id](#)³⁴, I. Dawson [id](#)⁹⁴, H.A. Day-hall [id](#)¹³², K. De [id](#)⁸,
 R. De Asmundis [id](#)^{72a}, N. De Biase [id](#)⁴⁸, S. De Castro [id](#)^{23b,23a}, N. De Groot [id](#)¹¹³, P. de Jong [id](#)¹¹⁴,
 H. De la Torre [id](#)¹¹⁵, A. De Maria [id](#)^{14c}, A. De Salvo [id](#)^{75a}, U. De Sanctis [id](#)^{76a,76b}, A. De Santo [id](#)¹⁴⁶,
 J.B. De Vivie De Regie [id](#)⁶⁰, D.V. Dedovich [id](#)³⁸, J. Degens [id](#)¹¹⁴, A.M. Deiana [id](#)⁴⁴, F. Del Corso [id](#)^{23b,23a},
 J. Del Peso [id](#)⁹⁹, F. Del Rio [id](#)^{63a}, F. Deliot [id](#)¹³⁵, C.M. Delitzsch [id](#)⁴⁹, M. Della Pietra [id](#)^{72a,72b},
 D. Della Volpe [id](#)⁵⁶, A. Dell'Acqua [id](#)³⁶, L. Dell'Asta [id](#)^{71a,71b}, M. Delmastro [id](#)⁴, P.A. Delsart [id](#)⁶⁰,
 S. Demers [id](#)¹⁷², M. Demichev [id](#)³⁸, S.P. Denisov [id](#)³⁷, L. D'Eramo [id](#)⁴⁰, D. Derendarz [id](#)⁸⁷, F. Derue [id](#)¹²⁷,
 P. Dervan [id](#)⁹², K. Desch [id](#)²⁴, C. Deutsch [id](#)²⁴, F.A. Di Bello [id](#)^{57b,57a}, A. Di Ciaccio [id](#)^{76a,76b},
 L. Di Ciaccio [id](#)⁴, A. Di Domenico [id](#)^{75a,75b}, C. Di Donato [id](#)^{72a,72b}, A. Di Girolamo [id](#)³⁶,
 G. Di Gregorio [id](#)³⁶, A. Di Luca [id](#)^{78a,78b}, B. Di Micco [id](#)^{77a,77b}, R. Di Nardo [id](#)^{77a,77b}, C. Diaconu [id](#)¹⁰²,
 M. Diamantopoulou [id](#)³⁴, F.A. Dias [id](#)¹¹⁴, T. Dias Do Vale [id](#)¹⁴², M.A. Diaz [id](#)^{137a,137b},
 F.G. Diaz Capriles [id](#)²⁴, M. Didenko [id](#)¹⁶³, E.B. Diehl [id](#)¹⁰⁶, L. Diehl [id](#)⁵⁴, S. Díez Cornell [id](#)⁴⁸,
 C. Díez Pardos [id](#)¹⁴¹, C. Dimitriadi [id](#)^{161,24,161}, A. Dimitrievska [id](#)^{17a}, J. Dingfelder [id](#)²⁴, I-M. Dinu [id](#)^{27b},
 S.J. Dittmeier [id](#)^{63b}, F. Dittus [id](#)³⁶, F. Djama [id](#)¹⁰², T. Djobava [id](#)^{149b}, J.I. Djuvslund [id](#)¹⁶,
 C. Doglioni [id](#)^{101,98}, A. Dohnalova [id](#)^{28a}, J. Dolejsi [id](#)¹³³, Z. Dolezal [id](#)¹³³, K.M. Dona [id](#)³⁹,
 M. Donadelli [id](#)^{83c}, B. Dong [id](#)¹⁰⁷, J. Donini [id](#)⁴⁰, A. D'Onofrio [id](#)^{77a,77b}, M. D'Onofrio [id](#)⁹²,
 J. Dopke [id](#)¹³⁴, A. Doria [id](#)^{72a}, N. Dos Santos Fernandes [id](#)^{130a}, P. Dougan [id](#)¹⁰¹, M.T. Dova [id](#)⁹⁰,
 A.T. Doyle [id](#)⁵⁹, M.A. Draguet [id](#)¹²⁶, E. Dreyer [id](#)¹⁶⁹, I. Drivas-koulouris [id](#)¹⁰, A.S. Drobac [id](#)¹⁵⁸,
 M. Drozdova [id](#)⁵⁶, D. Du [id](#)^{62a}, T.A. du Pree [id](#)¹¹⁴, F. Dubinin [id](#)³⁷, M. Dubovsky [id](#)^{28a}, E. Duchovni [id](#)¹⁶⁹,
 G. Duckeck [id](#)¹⁰⁹, O.A. Ducu [id](#)^{27b}, D. Duda [id](#)⁵², A. Dudarev [id](#)³⁶, E.R. Duden [id](#)²⁶, M. D'uffizi [id](#)¹⁰¹,
 L. Dufflot [id](#)⁶⁶, M. Dührssen [id](#)³⁶, C. Dülsen [id](#)¹⁷¹, A.E. Dumitriu [id](#)^{27b}, M. Dunford [id](#)^{63a}, S. Dungs [id](#)⁴⁹,
 K. Dunne [id](#)^{47a,47b}, A. Duperrin [id](#)¹⁰², H. Duran Yildiz [id](#)^{3a}, M. Düren [id](#)⁵⁸, A. Durglishvili [id](#)^{149b},
 B.L. Dwyer [id](#)¹¹⁵, G.I. Dyckes [id](#)^{17a}, M. Dyndal [id](#)^{86a}, S. Dysch [id](#)¹⁰¹, B.S. Dziedzic [id](#)⁸⁷,
 Z.O. Earnshaw [id](#)¹⁴⁶, G.H. Eberwein [id](#)¹²⁶, B. Eckerova [id](#)^{28a}, S. Eggebrecht [id](#)⁵⁵,
 E. Egidio Purcino De Souza [id](#)¹²⁷, L.F. Ehrke [id](#)⁵⁶, G. Eigen [id](#)¹⁶, K. Einsweiler [id](#)^{17a}, T. Ekelof [id](#)¹⁶¹,
 P.A. Ekman [id](#)⁹⁸, S. El Farkh [id](#)^{35b}, Y. El Ghazali [id](#)^{35b}, H. El Jarrari [id](#)^{35e,148}, A. El Moussaouy [id](#)¹⁰⁸,
 V. Ellajosyula [id](#)¹⁶¹, M. Ellert [id](#)¹⁶¹, F. Ellinghaus [id](#)¹⁷¹, A.A. Elliot [id](#)⁹⁴, N. Ellis [id](#)³⁶, J. Elmsheuser [id](#)²⁹,
 M. Elsing [id](#)³⁶, D. Emelianov [id](#)¹³⁴, Y. Enari [id](#)¹⁵³, I. Ene [id](#)^{17a}, S. Epari [id](#)¹³, J. Erdmann [id](#)⁴⁹,
 P.A. Erland [id](#)⁸⁷, M. Errenst [id](#)¹⁷¹, M. Escalier [id](#)⁶⁶, C. Escobar [id](#)¹⁶³, E. Etzion [id](#)¹⁵¹, G. Evans [id](#)^{130a},
 H. Evans [id](#)⁶⁸, L.S. Evans [id](#)⁹⁵, M.O. Evans [id](#)¹⁴⁶, A. Ezhilov [id](#)³⁷, S. Ezzarqtouni [id](#)^{35a}, F. Fabbri [id](#)⁵⁹,

L. Fabbri [ID23b,23a](#), G. Facini [ID96](#), V. Fadeyev [ID136](#), R.M. Fakhruddinov [ID37](#), S. Falciano [ID75a](#),
 L.F. Falda Ulhoa Coelho [ID36](#), P.J. Falke [ID24](#), J. Faltova [ID133](#), C. Fan [ID162](#), Y. Fan [ID14a](#), Y. Fang [ID14a,14e](#),
 M. Fanti [ID71a,71b](#), M. Faraj [ID69a,69b](#), Z. Farazpay [ID97](#), A. Farbin [ID8](#), A. Farilla [ID77a](#), T. Farooque [ID107](#),
 S.M. Farrington [ID52](#), F. Fassi [ID35e](#), D. Fassouliotis [ID9](#), M. Faucci Giannelli [ID76a,76b](#), W.J. Fawcett [ID32](#),
 L. Fayard [ID66](#), P. Federic [ID133](#), P. Federicova [ID131](#), O.L. Fedin [ID37,a](#), G. Fedotov [ID37](#), M. Feickert [ID170](#),
 L. Feligioni [ID102](#), D.E. Fellers [ID123](#), C. Feng [ID62b](#), M. Feng [ID14b](#), Z. Feng [ID114](#), M.J. Fenton [ID160](#),
 A.B. Fenyuk [ID37](#), L. Ferencz [ID48](#), R.A.M. Ferguson [ID91](#), S.I. Fernandez Luengo [ID137f](#), M.J.V. Fernoux [ID102](#),
 J. Ferrando [ID48](#), A. Ferrari [ID161](#), P. Ferrari [ID114,113](#), R. Ferrari [ID73a](#), D. Ferrere [ID56](#), C. Ferretti [ID106](#),
 F. Fiedler [ID100](#), P. Fiedler [ID132](#), A. Filipčič [ID93](#), E.K. Filmer [ID1](#), F. Filthaut [ID113](#),
 M.C.N. Fiolhais [ID130a,130c,c](#), L. Fiorini [ID163](#), W.C. Fisher [ID107](#), T. Fitschen [ID101](#), P.M. Fitzhugh [ID135](#),
 I. Fleck [ID141](#), P. Fleischmann [ID106](#), T. Flick [ID171](#), M. Flores [ID33d,ac](#), L.R. Flores Castillo [ID64a](#),
 L. Flores Sanz De Acedo [ID36](#), F.M. Follega [ID78a,78b](#), N. Fomin [ID16](#), J.H. Foo [ID155](#), B.C. Forland [ID68](#),
 A. Formica [ID135](#), A.C. Forti [ID101](#), E. Fortin [ID36](#), A.W. Fortman [ID61](#), M.G. Foti [ID17a](#), L. Fountas [ID9j](#),
 D. Fournier [ID66](#), H. Fox [ID91](#), P. Francavilla [ID74a,74b](#), S. Francescato [ID61](#), S. Franchellucci [ID56](#),
 M. Franchini [ID23b,23a](#), S. Franchino [ID63a](#), D. Francis [ID36](#), L. Franco [ID113](#), V. Franco Lima [ID36](#),
 L. Franconi [ID48](#), M. Franklin [ID61](#), G. Frattari [ID26](#), A.C. Freegard [ID94](#), W.S. Freund [ID83b](#), Y.Y. Frid [ID151](#),
 J. Friend [ID59](#), N. Fritzsche [ID50](#), A. Froch [ID54](#), D. Froidevaux [ID36](#), J.A. Frost [ID126](#), Y. Fu [ID62a](#),
 M. Fujimoto [ID118,ad](#), E. Fullana Torregrosa [ID163,*](#), K.Y. Fung [ID64a](#), E. Furtado De Simas Filho [ID83b](#),
 M. Furukawa [ID153](#), J. Fuster [ID163](#), A. Gabrielli [ID23b,23a](#), A. Gabrielli [ID155](#), P. Gadow [ID36](#),
 G. Gagliardi [ID57b,57a](#), L.G. Gagnon [ID17a](#), E.J. Gallas [ID126](#), B.J. Gallop [ID134](#), K.K. Gan [ID119](#),
 S. Ganguly [ID153](#), J. Gao [ID62a](#), Y. Gao [ID52](#), F.M. Garay Walls [ID137a,137b](#), B. Garcia [ID29](#), C. García [ID163](#),
 A. Garcia Alonso [ID114](#), A.G. Garcia Caffaro [ID172](#), J.E. García Navarro [ID163](#), M. Garcia-Sciveres [ID17a](#),
 G.L. Gardner [ID128](#), R.W. Gardner [ID39](#), N. Garelli [ID158](#), D. Garg [ID80](#), R.B. Garg [ID143,n](#), J.M. Gargan [ID52](#),
 C.A. Garner [ID155](#), C.M. Garvey [ID33a](#), S.J. Gasiorowski [ID138](#), P. Gaspar [ID83b](#), G. Gaudio [ID73a](#), V. Gautam [ID13](#),
 P. Gauzzi [ID75a,75b](#), I.L. Gavrilenko [ID37](#), A. Gavrilyuk [ID37](#), C. Gay [ID164](#), G. Gaycken [ID48](#), E.N. Gazis [ID10](#),
 A.A. Geanta [ID27b](#), C.M. Gee [ID136](#), C. Gemme [ID57b](#), M.H. Genest [ID60](#), S. Gentile [ID75a,75b](#),
 A.D. Gentry [ID112](#), S. George [ID95](#), W.F. George [ID20](#), T. Gerialis [ID46](#), P. Gessinger-Befurt [ID36](#),
 M.E. Geyik [ID171](#), M. Ghani [ID167](#), M. Ghneimat [ID141](#), K. Ghorbanian [ID94](#), A. Ghosal [ID141](#),
 A. Ghosh [ID160](#), A. Ghosh [ID7](#), B. Giacobbe [ID23b](#), S. Giagu [ID75a,75b](#), T. Giani [ID114](#), P. Giannetti [ID74a](#),
 A. Giannini [ID62a](#), S.M. Gibson [ID95](#), M. Gignac [ID136](#), D.T. Gil [ID86b](#), A.K. Gilbert [ID86a](#), B.J. Gilbert [ID41](#),
 D. Gillberg [ID34](#), G. Gilles [ID114](#), N.E.K. Gillwald [ID48](#), L. Ginabat [ID127](#), D.M. Gingrich [ID2,ag](#),
 M.P. Giordani [ID69a,69c](#), P.F. Giraud [ID135](#), G. Giugliarelli [ID69a,69c](#), D. Giugni [ID71a](#), F. Giuli [ID36](#),
 I. Gkialas [ID9j](#), L.K. Gladilin [ID37](#), C. Glasman [ID99](#), G.R. Gledhill [ID123](#), G. Glemža [ID48](#), M. Glisic [ID123](#),
 I. Gnesi [ID43b,f](#), Y. Go [ID29,ai](#), M. Goblirsch-Kolb [ID36](#), B. Gocke [ID49](#), D. Godin [ID108](#), B. Gokturk [ID21a](#),
 S. Goldfarb [ID105](#), T. Golling [ID56](#), M.G.D. Gololo [ID33g](#), D. Golubkov [ID37](#), J.P. Gombas [ID107](#),
 A. Gomes [ID130a,130b](#), G. Gomes Da Silva [ID141](#), A.J. Gomez Delegido [ID163](#), R. Gonçalo [ID130a,130c](#),
 G. Gonella [ID123](#), L. Gonella [ID20](#), A. Gongadze [ID149c](#), F. Gonnella [ID20](#), J.L. Gonski [ID41](#),
 R.Y. González Andana [ID52](#), S. González de la Hoz [ID163](#), S. Gonzalez Fernandez [ID13](#),
 R. Gonzalez Lopez [ID92](#), C. Gonzalez Renteria [ID17a](#), M.V. Gonzalez Rodrigues [ID48](#),
 R. Gonzalez Suarez [ID161](#), S. Gonzalez-Sevilla [ID56](#), G.R. Gonzalvo Rodriguez [ID163](#), L. Goossens [ID36](#),
 B. Gorini [ID36](#), E. Gorini [ID70a,70b](#), A. Gorišek [ID93](#), T.C. Gosart [ID128](#), A.T. Goshaw [ID51](#), M.I. Gostkin [ID38](#),
 S. Goswami [ID121](#), C.A. Gottardo [ID36](#), S.A. Gotz [ID109](#), M. Goughri [ID35b](#), V. Goumarre [ID48](#),
 A.G. Goussiou [ID138](#), N. Govender [ID33c](#), I. Grabowska-Bold [ID86a](#), K. Graham [ID34](#), E. Gramstad [ID125](#),
 S. Grancagnolo [ID70a,70b](#), M. Grandi [ID146](#), C.M. Grant [ID1,135](#), P.M. Gravila [ID27f](#), F.G. Gravili [ID70a,70b](#),
 H.M. Gray [ID17a](#), M. Greco [ID70a,70b](#), C. Grefe [ID24](#), I.M. Gregor [ID48](#), P. Grenier [ID143](#), C. Grieco [ID13](#),
 A.A. Grillo [ID136](#), K. Grimm [ID31](#), S. Grinstein [ID13,s](#), J.-F. Grivaz [ID66](#), E. Gross [ID169](#),
 J. Grosse-Knetter [ID55](#), C. Grud [ID106](#), J.C. Grundy [ID126](#), L. Guan [ID106](#), W. Guan [ID29](#), C. Gubbels [ID164](#),

J.G.R. Guerrero Rojas [ID163](#), G. Guerrieri [ID69a,69c](#), F. Guescini [ID110](#), R. Gugel [ID100](#), J.A.M. Guhit [ID106](#), A. Guida [ID18](#), T. Guillemain [ID4](#), E. Guilloton [ID167,134](#), S. Guindon [ID36](#), F. Guo [ID14a,14e](#), J. Guo [ID62c](#), L. Guo [ID48](#), Y. Guo [ID106](#), R. Gupta [ID48](#), S. Gurbuz [ID24](#), S.S. Gurdasani [ID54](#), G. Gustavino [ID36](#), M. Guth [ID56](#), P. Gutierrez [ID120](#), L.F. Gutierrez Zagazeta [ID128](#), C. Gutschow [ID96](#), C. Gwenlan [ID126](#), C.B. Gwilliam [ID92](#), E.S. Haaland [ID125](#), A. Haas [ID117](#), M. Habedank [ID48](#), C. Haber [ID17a](#), H.K. Hadavand [ID8](#), A. Hadeef [ID100](#), S. Hadzic [ID110](#), J.J. Hahn [ID141](#), E.H. Haines [ID96](#), M. Haleem [ID166](#), J. Haley [ID121](#), J.J. Hall [ID139](#), G.D. Hallewell [ID102](#), L. Halser [ID19](#), K. Hamano [ID165](#), M. Hamer [ID24](#), G.N. Hamity [ID52](#), E.J. Hampshire [ID95](#), J. Han [ID62b](#), K. Han [ID62a](#), L. Han [ID14c](#), L. Han [ID62a](#), S. Han [ID17a](#), Y.F. Han [ID155](#), K. Hanagaki [ID84](#), M. Hance [ID136](#), D.A. Hangal [ID41,ab](#), H. Hanif [ID142](#), M.D. Hank [ID128](#), R. Hankache [ID101](#), J.B. Hansen [ID42](#), J.D. Hansen [ID42](#), P.H. Hansen [ID42](#), K. Hara [ID157](#), D. Harada [ID56](#), T. Harenberg [ID171](#), S. Harkusha [ID37](#), M.L. Harris [ID103](#), Y.T. Harris [ID126](#), J. Harrison [ID13](#), N.M. Harrison [ID119](#), P.F. Harrison [ID167](#), N.M. Hartman [ID110](#), N.M. Hartmann [ID109](#), Y. Hasegawa [ID140](#), R. Hauser [ID107](#), C.M. Hawkes [ID20](#), R.J. Hawkings [ID36](#), Y. Hayashi [ID153](#), S. Hayashida [ID111](#), D. Hayden [ID107](#), C. Hayes [ID106](#), R.L. Hayes [ID114](#), C.P. Hays [ID126](#), J.M. Hays [ID94](#), H.S. Hayward [ID92](#), F. He [ID62a](#), M. He [ID14a,14e](#), Y. He [ID154](#), Y. He [ID48](#), N.B. Heatley [ID94](#), V. Hedberg [ID98](#), A.L. Heggelund [ID125](#), N.D. Hehir [ID94,*](#), C. Heidegger [ID54](#), K.K. Heidegger [ID54](#), W.D. Heidorn [ID81](#), J. Heilman [ID34](#), S. Heim [ID48](#), T. Heim [ID17a](#), J.G. Heinlein [ID128](#), J.J. Heinrich [ID123](#), L. Heinrich [ID110,ae](#), J. Hejbal [ID131](#), L. Helary [ID48](#), A. Held [ID170](#), S. Hellesund [ID16](#), C.M. Helling [ID164](#), S. Hellman [ID47a,47b](#), R.C.W. Henderson [ID91](#), L. Henkelmann [ID32](#), A.M. Henriques Correia [ID36](#), H. Herde [ID98](#), Y. Hernández Jiménez [ID145](#), L.M. Herrmann [ID24](#), T. Herrmann [ID50](#), G. Herten [ID54](#), R. Hertenberger [ID109](#), L. Hervas [ID36](#), M.E. Hespings [ID100](#), N.P. Hessey [ID156a](#), H. Hibi [ID85](#), E. Hill [ID155](#), S.J. Hillier [ID20](#), J.R. Hinds [ID107](#), F. Hinterkeuser [ID24](#), M. Hirose [ID124](#), S. Hirose [ID157](#), D. Hirschbuehl [ID171](#), T.G. Hitchings [ID101](#), B. Hiti [ID93](#), J. Hobbs [ID145](#), R. Hobincu [ID27e](#), N. Hod [ID169](#), M.C. Hodgkinson [ID139](#), B.H. Hodgkinson [ID32](#), A. Hoecker [ID36](#), J. Hofer [ID48](#), T. Holm [ID24](#), M. Holzbock [ID110](#), L.B.A.H. Hommels [ID32](#), B.P. Honan [ID101](#), J. Hong [ID62c](#), T.M. Hong [ID129](#), B.H. Hooberman [ID162](#), W.H. Hopkins [ID6](#), Y. Horii [ID111](#), S. Hou [ID148](#), A.S. Howard [ID93](#), J. Howarth [ID59](#), J. Hoya [ID6](#), M. Hrabovsky [ID122](#), A. Hrynevich [ID48](#), T. Hryn'ova [ID4](#), P.J. Hsu [ID65](#), S.-C. Hsu [ID138](#), Q. Hu [ID62a](#), Y.F. Hu [ID14a,14e](#), S. Huang [ID64b](#), X. Huang [ID14c](#), Y. Huang [ID139](#), Y. Huang [ID14a](#), Z. Huang [ID101](#), Z. Hubacek [ID132](#), M. Huebner [ID24](#), F. Huegging [ID24](#), T.B. Huffman [ID126](#), C.A. Hugli [ID48](#), M. Huhtinen [ID36](#), S.K. Huiberts [ID16](#), R. Hulsken [ID104](#), N. Huseynov [ID12](#), J. Huston [ID107](#), J. Huth [ID61](#), R. Hyneman [ID143](#), G. Iacobucci [ID56](#), G. Iakovidis [ID29](#), I. Ibragimov [ID141](#), L. Iconomidou-Fayard [ID66](#), P. Iengo [ID72a,72b](#), R. Iguchi [ID153](#), T. Iizawa [ID126](#), Y. Ikegami [ID84](#), N. Ilic [ID155](#), H. Imam [ID35a](#), M. Ince Lezki [ID56](#), T. Ingebretsen Carlson [ID47a,47b](#), G. Introzzi [ID73a,73b](#), M. Iodice [ID77a](#), V. Ippolito [ID75a,75b](#), R.K. Irwin [ID92](#), M. Ishino [ID153](#), W. Islam [ID170](#), C. Issever [ID18,48](#), S. Istin [ID21a,ak](#), H. Ito [ID168](#), J.M. Iturbe Ponce [ID64a](#), R. Iuppa [ID78a,78b](#), A. Ivina [ID169](#), J.M. Izen [ID45](#), V. Izzo [ID72a](#), P. Jacka [ID131,132](#), P. Jackson [ID1](#), R.M. Jacobs [ID48](#), B.P. Jaeger [ID142](#), C.S. Jagfeld [ID109](#), G. Jain [ID156a](#), P. Jain [ID54](#), G. Jäkel [ID171](#), K. Jakobs [ID54](#), T. Jakoubek [ID169](#), J. Jamieson [ID59](#), K.W. Janas [ID86a](#), M. Javurkova [ID103](#), F. Jeanneau [ID135](#), L. Jeanty [ID123](#), J. Jejelava [ID149a,z](#), P. Jenni [ID54,g](#), C.E. Jessiman [ID34](#), S. Jézéquel [ID4](#), C. Jia [ID62b](#), J. Jia [ID145](#), X. Jia [ID61](#), X. Jia [ID14a,14e](#), Z. Jia [ID14c](#), Y. Jiang [ID62a](#), S. Jiggins [ID48](#), J. Jimenez Pena [ID13](#), S. Jin [ID14c](#), A. Jinaru [ID27b](#), O. Jinnouchi [ID154](#), P. Johansson [ID139](#), K.A. Johns [ID7](#), J.W. Johnson [ID136](#), D.M. Jones [ID32](#), E. Jones [ID48](#), P. Jones [ID32](#), R.W.L. Jones [ID91](#), T.J. Jones [ID92](#), H.L. Joos [ID55,36](#), R. Joshi [ID119](#), J. Jovicevic [ID15](#), X. Ju [ID17a](#), J.J. Junggeburth [ID103](#), T. Junkermann [ID63a](#), A. Juste Rozas [ID13,s](#), M.K. Juzek [ID87](#), S. Kabana [ID137e](#), A. Kaczmarska [ID87](#), M. Kado [ID110](#), H. Kagan [ID119](#), M. Kagan [ID143](#), A. Kahn [ID41](#), A. Kahn [ID128](#), C. Kahra [ID100](#), T. Kaji [ID153](#), E. Kajomovitz [ID150](#), N. Kakati [ID169](#), I. Kalaitzidou [ID54](#), C.W. Kalderon [ID29](#), A. Kamenshchikov [ID155](#), N.J. Kang [ID136](#), D. Kar [ID33g](#), K. Karava [ID126](#), M.J. Kareem [ID156b](#), E. Karentzos [ID54](#), I. Karknias [ID152](#), O. Karkout [ID114](#), S.N. Karpov [ID38](#), Z.M. Karpova [ID38](#), V. Kartvelishvili [ID91](#), A.N. Karyukhin [ID37](#),

E. Kasimi ¹⁵², J. Katzy ⁴⁸, S. Kaur ³⁴, K. Kawade ¹⁴⁰, M.P. Kawale ¹²⁰, C. Kawamoto ⁸⁸,
 T. Kawamoto ¹³⁵, E.F. Kay ³⁶, F.I. Kaya ¹⁵⁸, S. Kazakos ¹⁰⁷, V.F. Kazanin ³⁷, Y. Ke ¹⁴⁵,
 J.M. Keaveney ^{33a}, R. Keeler ¹⁶⁵, G.V. Kehris ⁶¹, J.S. Keller ³⁴, A.S. Kelly ⁹⁶, J.J. Kempster ¹⁴⁶,
 K.E. Kennedy ⁴¹, P.D. Kennedy ¹⁰⁰, O. Kepka ¹³¹, B.P. Kerridge ¹⁶⁷, S. Kersten ¹⁷¹,
 B.P. Kerševan ⁹³, S. Keshri ⁶⁶, L. Keszeghova ^{28a}, S. Ketabchi Haghghat ¹⁵⁵, M. Khandoga ¹²⁷,
 A. Khanov ¹²¹, A.G. Kharlamov ³⁷, T. Kharlamova ³⁷, E.E. Khoda ¹³⁸, M. Kholodenko ³⁷,
 T.J. Khoo ¹⁸, G. Khoriali ¹⁶⁶, J. Khubua ^{149b}, Y.A.R. Khwaira ⁶⁶, A. Kilgallon ¹²³,
 D.W. Kim ^{47a,47b}, Y.K. Kim ³⁹, N. Kimura ⁹⁶, M.K. Kingston ⁵⁵, A. Kirchhoff ⁵⁵, C. Kirfel ²⁴,
 F. Kirfel ²⁴, J. Kirk ¹³⁴, A.E. Kiryunin ¹¹⁰, C. Kitsaki ¹⁰, O. Kivernyk ²⁴, M. Klassen ^{63a},
 C. Klein ³⁴, L. Klein ¹⁶⁶, M.H. Klein ¹⁰⁶, M. Klein ⁹², S.B. Klein ⁵⁶, U. Klein ⁹²,
 P. Klimek ³⁶, A. Klimentov ²⁹, T. Klioutchnikova ³⁶, P. Kluit ¹¹⁴, S. Kluth ¹¹⁰, E. Kneringer ⁷⁹,
 T.M. Knight ¹⁵⁵, A. Knue ⁴⁹, R. Kobayashi ⁸⁸, D. Kobylanski ¹⁶⁹, S.F. Koch ¹²⁶,
 M. Kocian ¹⁴³, P. Kodyš ¹³³, D.M. Koeck ¹²³, P.T. Koenig ²⁴, T. Koffas ³⁴, M. Kolb ¹³⁵,
 I. Koletsou ⁴, T. Komarek ¹²², K. Köneke ⁵⁴, A.X.Y. Kong ¹, T. Kono ¹¹⁸, N. Konstantinidis ⁹⁶,
 B. Konya ⁹⁸, R. Kopeliansky ⁶⁸, S. Koperny ^{86a}, K. Korcyl ⁸⁷, K. Kordas ^{152,e}, G. Koren ¹⁵¹,
 A. Korn ⁹⁶, S. Korn ⁵⁵, I. Korolkov ¹³, N. Korotkova ³⁷, B. Kortman ¹¹⁴, O. Kortner ¹¹⁰,
 S. Kortner ¹¹⁰, W.H. Kostecka ¹¹⁵, V.V. Kostyukhin ¹⁴¹, A. Kotsokechagia ¹³⁵, A. Kotwal ⁵¹,
 A. Koulouris ³⁶, A. Kourkoumeli-Charalampidi ^{73a,73b}, C. Kourkoumelis ⁹, E. Kourlitis ^{110,ae},
 O. Kovanda ¹⁴⁶, R. Kowalewski ¹⁶⁵, W. Kozanecki ¹³⁵, A.S. Kozhin ³⁷, V.A. Kramarenko ³⁷,
 G. Kramberger ⁹³, P. Kramer ¹⁰⁰, M.W. Krasny ¹²⁷, A. Krasnahorkay ³⁶, J.W. Kraus ¹⁷¹,
 J.A. Kremer ⁴⁸, T. Kresse ⁵⁰, J. Kretschmar ⁹², K. Kreul ¹⁸, P. Krieger ¹⁵⁵,
 S. Krishnamurthy ¹⁰³, M. Krivos ¹³³, K. Krizka ²⁰, K. Kroeninger ⁴⁹, H. Kroha ¹¹⁰, J. Kroll ¹³¹,
 J. Kroll ¹²⁸, K.S. Krowpman ¹⁰⁷, U. Kruchonak ³⁸, H. Krüger ²⁴, N. Krumnack ⁸¹, M.C. Kruse ⁵¹,
 J.A. Krzysiak ⁸⁷, O. Kuchinskaia ³⁷, S. Kuday ^{3a}, S. Kuehn ³⁶, R. Kuesters ⁵⁴, T. Kuhl ⁴⁸,
 V. Kukhtin ³⁸, Y. Kulchitsky ^{37,a}, S. Kuleshov ^{137d,137b}, M. Kumar ^{33g}, N. Kumari ⁴⁸,
 A. Kupco ¹³¹, T. Kupfer ⁴⁹, A. Kupich ³⁷, O. Kuprash ⁵⁴, H. Kurashige ⁸⁵, L.L. Kurchaninov ^{156a},
 O. Kurdysh ⁶⁶, Y.A. Kurochkin ³⁷, A. Kurova ³⁷, M. Kuze ¹⁵⁴, A.K. Kvam ¹⁰³, J. Kvitka ¹²²,
 T. Kwan ¹⁰⁴, N.G. Kyriacou ¹⁰⁶, L.A.O. Laatu ¹⁰², C. Lacasta ¹⁶³, F. Lacava ^{75a,75b},
 H. Lacker ¹⁸, D. Lacour ¹²⁷, N.N. Lad ⁹⁶, E. Ladygin ³⁸, B. Laforge ¹²⁷, T. Lagouri ^{137e},
 F.Z. Lahbabi ^{35a}, S. Lai ⁵⁵, I.K. Lakomic ^{86a}, N. Lalloue ⁶⁰, J.E. Lambert ¹⁶⁵, S. Lammers ⁶⁸,
 W. Lampl ⁷, C. Lampoudis ^{152,e}, A.N. Lancaster ¹¹⁵, E. Lançon ²⁹, U. Landgraf ⁵⁴,
 M.P.J. Landon ⁹⁴, V.S. Lang ⁵⁴, R.J. Langenberg ¹⁰³, O.K.B. Langrekken ¹²⁵, A.J. Lankford ¹⁶⁰,
 F. Lanni ³⁶, K. Lantzsch ²⁴, A. Lanza ^{73a}, A. Lapertosa ^{57b,57a}, J.F. Laporte ¹³⁵, T. Lari ^{71a},
 F. Lasagni Manghi ^{23b}, M. Lassnig ³⁶, V. Latonova ¹³¹, A. Laudrain ¹⁰⁰, A. Laurier ¹⁵⁰,
 S.D. Lawlor ¹³⁹, Z. Lawrence ¹⁰¹, M. Lazzaroni ^{71a,71b}, B. Le ¹⁰¹, E.M. Le Boulicaut ⁵¹,
 B. Leban ⁹³, A. Lebedev ⁸¹, M. LeBlanc ¹⁰¹, F. Ledroit-Guillon ⁶⁰, A.C.A. Lee ⁹⁶, S.C. Lee ¹⁴⁸,
 S. Lee ^{47a,47b}, T.F. Lee ⁹², L.L. Leeuw ^{33c}, H.P. Lefebvre ⁹⁵, M. Lefebvre ¹⁶⁵, C. Leggett ^{17a},
 G. Lehmann Miotto ³⁶, M. Leigh ⁵⁶, W.A. Leight ¹⁰³, W. Leinonen ¹¹³, A. Leisos ^{152,r},
 M.A.L. Leite ^{83c}, C.E. Leitgeb ⁴⁸, R. Leitner ¹³³, K.J.C. Leney ⁴⁴, T. Lenz ²⁴, S. Leone ^{74a},
 C. Leonidopoulos ⁵², A. Leopold ¹⁴⁴, C. Leroy ¹⁰⁸, R. Les ¹⁰⁷, C.G. Lester ³²,
 M. Levchenko ³⁷, J. Levêque ⁴, D. Levin ¹⁰⁶, L.J. Levinson ¹⁶⁹, M.P. Lewicki ⁸⁷, D.J. Lewis ⁴,
 A. Li ⁵, B. Li ^{62b}, C. Li ^{62a}, C-Q. Li ^{62c}, H. Li ^{62a}, H. Li ^{62b}, H. Li ^{14c}, H. Li ^{14b}, H. Li ^{62b},
 K. Li ¹³⁸, L. Li ^{62c}, M. Li ^{14a,14e}, Q.Y. Li ^{62a}, S. Li ^{14a,14e}, S. Li ^{62d,62c,d}, T. Li ⁵, X. Li ¹⁰⁴,
 Z. Li ¹²⁶, Z. Li ¹⁰⁴, Z. Li ⁹², Z. Li ^{14a,14e}, S. Liang ^{14a,14e}, Z. Liang ^{14a}, M. Liberatore ¹³⁵,
 B. Liberti ^{76a}, K. Lie ^{64c}, J. Lieber Marin ^{83b}, H. Lien ⁶⁸, K. Lin ¹⁰⁷, R.E. Lindley ⁷,
 J.H. Lindon ², E. Lipeles ¹²⁸, A. Lipniacka ¹⁶, A. Lister ¹⁶⁴, J.D. Little ⁴, B. Liu ^{14a},
 B.X. Liu ¹⁴², D. Liu ^{62d,62c}, J.B. Liu ^{62a}, J.K.K. Liu ³², K. Liu ^{62d,62c}, M. Liu ^{62a},

M.Y. Liu ^{62a}, P. Liu ^{14a}, Q. Liu ^{62d,138,62c}, X. Liu ^{62a}, Y. Liu ^{14d,14e}, Y.L. Liu ^{62b}, Y.W. Liu ^{62a},
J. Llorente Merino ¹⁴², S.L. Lloyd ⁹⁴, E.M. Lobodzinska ⁴⁸, P. Loch ⁷, S. Loffredo ^{76a,76b},
T. Lohse ¹⁸, K. Lohwasser ¹³⁹, E. Loiacono ⁴⁸, M. Lokajicek ^{131,*}, J.D. Lomas ²⁰,
J.D. Long ¹⁶², I. Longarini ¹⁶⁰, L. Longo ^{70a,70b}, R. Longo ¹⁶², I. Lopez Paz ⁶⁷,
A. Lopez Solis ⁴⁸, J. Lorenz ¹⁰⁹, N. Lorenzo Martinez ⁴, A.M. Lory ¹⁰⁹,
G. Löschcke Centeno ¹⁴⁶, O. Loseva ³⁷, X. Lou ^{47a,47b}, X. Lou ^{14a,14e}, A. Lounis ⁶⁶, J. Love ⁶,
P.A. Love ⁹¹, G. Lu ^{14a,14e}, M. Lu ⁸⁰, S. Lu ¹²⁸, Y.J. Lu ⁶⁵, H.J. Lubatti ¹³⁸, C. Luci ^{75a,75b},
F.L. Lucio Alves ^{14c}, A. Lucotte ⁶⁰, F. Luehring ⁶⁸, I. Luise ¹⁴⁵, O. Lukianchuk ⁶⁶,
O. Lundberg ¹⁴⁴, B. Lund-Jensen ¹⁴⁴, N.A. Luongo ¹²³, M.S. Lutz ¹⁵¹, A.B. Lux ²⁵, D. Lynn ²⁹,
H. Lyons ⁹², R. Lysak ¹³¹, E. Lytken ⁹⁸, V. Lyubushkin ³⁸, T. Lyubushkina ³⁸, M.M. Lyukova ¹⁴⁵,
H. Ma ²⁹, K. Ma ^{62a}, L.L. Ma ^{62b}, Y. Ma ¹²¹, D.M. Mac Donell ¹⁶⁵, G. Maccarrone ⁵³,
J.C. MacDonald ¹⁰⁰, P.C. Machado De Abreu Farias ^{83b}, R. Madar ⁴⁰, W.F. Mader ⁵⁰,
T. Madula ⁹⁶, J. Maeda ⁸⁵, T. Maeno ²⁹, H. Maguire ¹³⁹, V. Maiboroda ¹³⁵,
A. Maio ^{130a,130b,130d}, K. Maj ^{86a}, O. Majersky ⁴⁸, S. Majewski ¹²³, N. Makovec ⁶⁶,
V. Maksimovic ¹⁵, B. Malaescu ¹²⁷, Pa. Malecki ⁸⁷, V.P. Maleev ³⁷, F. Malek ⁶⁰, M. Mali ⁹³,
D. Malito ⁹⁵, U. Mallik ⁸⁰, S. Maltezos ¹⁰, S. Malyukov ³⁸, J. Mamuzic ¹³, G. Mancini ⁵³,
G. Manco ^{73a,73b}, J.P. Mandalia ⁹⁴, I. Mandić ⁹³, L. Manhaes de Andrade Filho ^{83a},
I.M. Maniatis ¹⁶⁹, J. Manjarres Ramos ^{102,aa}, D.C. Mankad ¹⁶⁹, A. Mann ¹⁰⁹, B. Mansoulie ¹³⁵,
S. Manzoni ³⁶, A. Marantis ^{152,r}, G. Marchiori ⁵, M. Marcisovsky ¹³¹, C. Marcon ^{71a},
M. Marinescu ²⁰, M. Marjanovic ¹²⁰, E.J. Marshall ⁹¹, Z. Marshall ^{17a}, S. Marti-Garcia ¹⁶³,
T.A. Martin ¹⁶⁷, V.J. Martin ⁵², B. Martin dit Latour ¹⁶, L. Martinelli ^{75a,75b}, M. Martinez ^{13,s},
P. Martinez Agullo ¹⁶³, V.I. Martinez Outschoorn ¹⁰³, P. Martinez Suarez ¹³, S. Martin-Haugh ¹³⁴,
V.S. Martoiu ^{27b}, A.C. Martyniuk ⁹⁶, A. Marzin ³⁶, D. Mascione ^{78a,78b}, L. Masetti ¹⁰⁰,
T. Mashimo ¹⁵³, J. Masik ¹⁰¹, A.L. Maslennikov ³⁷, L. Massa ^{23b}, P. Massarotti ^{72a,72b},
P. Mastrandrea ^{74a,74b}, A. Mastroberardino ^{43b,43a}, T. Masubuchi ¹⁵³, T. Mathisen ¹⁶¹,
J. Matousek ¹³³, N. Matsuzawa ¹⁵³, J. Maurer ^{27b}, B. Maček ⁹³, D.A. Maximov ³⁷, R. Mazini ¹⁴⁸,
I. Maznas ¹⁵², M. Mazza ¹⁰⁷, S.M. Mazza ¹³⁶, E. Mazzeo ^{71a,71b}, C. Mc Ginn ²⁹,
J.P. Mc Gowan ¹⁰⁴, S.P. Mc Kee ¹⁰⁶, E.F. McDonald ¹⁰⁵, A.E. McDougall ¹¹⁴, J.A. Mcfayden ¹⁴⁶,
R.P. McGovern ¹²⁸, G. Mchedlidze ^{149b}, R.P. Mckenzie ^{33g}, T.C. Mclachlan ⁴⁸,
D.J. McLaughlin ⁹⁶, S.J. McMahon ¹³⁴, P.C. McNamara ¹⁰⁵, C.M. Mcpartland ⁹²,
R.A. McPherson ^{165,w}, S. Mehlhase ¹⁰⁹, A. Mehta ⁹², D. Melini ¹⁵⁰, B.R. Mellado Garcia ^{33g},
A.H. Melo ⁵⁵, F. Meloni ⁴⁸, A.M. Mendes Jacques Da Costa ¹⁰¹, H.Y. Meng ¹⁵⁵, L. Meng ⁹¹,
S. Menke ¹¹⁰, M. Mentink ³⁶, E. Meoni ^{43b,43a}, C. Merlassino ¹²⁶, L. Merola ^{72a,72b},
C. Meroni ^{71a,71b}, G. Merz ¹⁰⁶, O. Meshkov ³⁷, J. Metcalfe ⁶, A.S. Mete ⁶, C. Meyer ⁶⁸,
J-P. Meyer ¹³⁵, R.P. Middleton ¹³⁴, L. Mijović ⁵², G. Mikenberg ¹⁶⁹, M. Mikestikova ¹³¹,
M. Mikuž ⁹³, H. Mildner ¹⁰⁰, A. Milic ³⁶, C.D. Milke ⁴⁴, D.W. Miller ³⁹, L.S. Miller ³⁴,
A. Milov ¹⁶⁹, D.A. Milstead ^{47a,47b}, T. Min ^{14c}, A.A. Minaenko ³⁷, I.A. Minashvili ^{149b}, L. Mince ⁵⁹,
A.I. Mincer ¹¹⁷, B. Mindur ^{86a}, M. Mineev ³⁸, Y. Mino ⁸⁸, L.M. Mir ¹³, M. Miralles Lopez ¹⁶³,
M. Mironova ^{17a}, A. Mishima ¹⁵³, M.C. Missio ¹¹³, A. Mitra ¹⁶⁷, V.A. Mitsou ¹⁶³,
Y. Mitsumori ¹¹¹, O. Miu ¹⁵⁵, P.S. Miyagawa ⁹⁴, T. Mkrtchyan ^{63a}, M. Mlinarevic ⁹⁶,
T. Mlinarevic ⁹⁶, M. Mlynarikova ³⁶, S. Mobius ¹⁹, P. Moder ⁴⁸, P. Mogg ¹⁰⁹,
A.F. Mohammed ^{14a,14e}, S. Mohapatra ⁴¹, G. Mokgatitwane ^{33g}, L. Moleri ¹⁶⁹, B. Mondal ¹⁴¹,
S. Mondal ¹³², K. Mönig ⁴⁸, E. Monnier ¹⁰², L. Monsonis Romero ¹⁶³, J. Montejo Berlingen ¹³,
M. Montella ¹¹⁹, F. Montekali ^{77a,77b}, F. Monticelli ⁹⁰, S. Monzani ^{69a,69c}, N. Morange ⁶⁶,
A.L. Moreira De Carvalho ^{130a}, M. Moreno Llácer ¹⁶³, C. Moreno Martinez ⁵⁶, P. Morettini ^{57b},
S. Morgenstern ³⁶, M. Morii ⁶¹, M. Morinaga ¹⁵³, A.K. Morley ³⁶, F. Morodei ^{75a,75b},
L. Morvaj ³⁶, P. Moschovakos ³⁶, B. Moser ³⁶, M. Mosidze ^{149b}, T. Moskalets ⁵⁴,

P. Moskvitina ¹¹³, J. Moss ^{31,1}, E.J.W. Moyse ¹⁰³, O. Mtintsilana ^{33g}, S. Muanza ¹⁰²,
 J. Mueller ¹²⁹, D. Muenstermann ⁹¹, R. Müller ¹⁹, G.A. Mullier ¹⁶¹, A.J. Mullin³², J.J. Mullin¹²⁸,
 D.P. Mungo ¹⁵⁵, D. Munoz Perez ¹⁶³, F.J. Munoz Sanchez ¹⁰¹, M. Murin ¹⁰¹, W.J. Murray ^{167,134},
 A. Murrone ^{71a,71b}, J.M. Muse ¹²⁰, M. Muškinja ^{17a}, C. Mwewa ²⁹, A.G. Myagkov ^{37,a},
 A.J. Myers ⁸, A.A. Myers¹²⁹, G. Myers ⁶⁸, M. Myska ¹³², B.P. Nachman ^{17a}, O. Nackenhorst ⁴⁹,
 A. Nag ⁵⁰, K. Nagai ¹²⁶, K. Nagano ⁸⁴, J.L. Nagle ^{29,ai}, E. Nagy ¹⁰², A.M. Nairz ³⁶,
 Y. Nakahama ⁸⁴, K. Nakamura ⁸⁴, K. Nakkalil ⁵, H. Nanjo ¹²⁴, R. Narayan ⁴⁴,
 E.A. Narayanan ¹¹², I. Naryshkin ³⁷, M. Naseri ³⁴, S. Nasri ¹⁵⁹, C. Nass ²⁴, G. Navarro ^{22a},
 J. Navarro-Gonzalez ¹⁶³, R. Nayak ¹⁵¹, A. Nayaz ¹⁸, P.Y. Nechaeva ³⁷, F. Nechansky ⁴⁸,
 L. Nedic ¹²⁶, T.J. Neep ²⁰, A. Negri ^{73a,73b}, M. Negrini ^{23b}, C. Nellist ¹¹⁴, C. Nelson ¹⁰⁴,
 K. Nelson ¹⁰⁶, S. Nemecek ¹³¹, M. Nessi ^{36,h}, M.S. Neubauer ¹⁶², F. Neuhaus ¹⁰⁰,
 J. Neundorf ⁴⁸, R. Newhouse ¹⁶⁴, P.R. Newman ²⁰, C.W. Ng ¹²⁹, Y.W.Y. Ng ⁴⁸, B. Ngair ^{35e},
 H.D.N. Nguyen ¹⁰⁸, R.B. Nickerson ¹²⁶, R. Nicolaidou ¹³⁵, J. Nielsen ¹³⁶, M. Niemeyer ⁵⁵,
 J. Niermann ^{55,36}, N. Nikiforou ³⁶, V. Nikolaenko ^{37,a}, I. Nikolic-Audit ¹²⁷, K. Nikolopoulos ²⁰,
 P. Nilsson ²⁹, I. Ninca ⁴⁸, H.R. Nindhito ⁵⁶, G. Ninio ¹⁵¹, A. Nisati ^{75a}, N. Nishu ²,
 R. Nisius ¹¹⁰, J-E. Nitschke ⁵⁰, E.K. Nkadimeng ^{33g}, T. Nobe ¹⁵³, D.L. Noel ³²,
 T. Nommensen ¹⁴⁷, M.B. Norfolk ¹³⁹, R.R.B. Norisam ⁹⁶, B.J. Norman ³⁴, J. Novak ⁹³,
 T. Novak ⁴⁸, L. Novotny ¹³², R. Novotny ¹¹², L. Nozka ¹²², K. Ntekas ¹⁶⁰,
 N.M.J. Nunes De Moura Junior ^{83b}, E. Nurse⁹⁶, J. Ocariz ¹²⁷, A. Ochi ⁸⁵, I. Ochoa ^{130a},
 S. Oerdek ^{48,i}, J.T. Offermann ³⁹, A. Ogrodnik ¹³³, A. Oh ¹⁰¹, C.C. Ohm ¹⁴⁴, H. Oide ⁸⁴,
 R. Oishi ¹⁵³, M.L. Ojeda ⁴⁸, M.W. O'Keefe⁹², Y. Okumura ¹⁵³, L.F. Oleiro Seabra ^{130a},
 S.A. Olivares Pino ^{137d}, D. Oliveira Damazio ²⁹, D. Oliveira Goncalves ^{83a}, J.L. Oliver ¹⁶⁰,
 A. Olszewski ⁸⁷, Ö.O. Öncel ⁵⁴, A.P. O'Neill ¹⁹, A. Onofre ^{130a,130e}, P.U.E. Onyisi ¹¹,
 M.J. Oreglia ³⁹, G.E. Orellana ⁹⁰, D. Orestano ^{77a,77b}, N. Orlando ¹³, R.S. Orr ¹⁵⁵,
 V. O'Shea ⁵⁹, L.M. Osojnak ¹²⁸, R. Ospanov ^{62a}, G. Otero y Garzon ³⁰, H. Otono ⁸⁹,
 P.S. Ott ^{63a}, G.J. Ottino ^{17a}, M. Ouchrif ^{35d}, J. Ouellette ²⁹, F. Ould-Saada ¹²⁵, M. Owen ⁵⁹,
 R.E. Owen ¹³⁴, K.Y. Oyulmaz ^{21a}, V.E. Ozcan ^{21a}, N. Ozturk ⁸, S. Ozturk ⁸², H.A. Pacey ¹²⁶,
 A. Pacheco Pages ¹³, C. Padilla Aranda ¹³, G. Padovano ^{75a,75b}, S. Pagan Griso ^{17a},
 G. Palacino ⁶⁸, A. Palazzo ^{70a,70b}, S. Palestini ³⁶, J. Pan ¹⁷², T. Pan ^{64a}, D.K. Panchal ¹¹,
 C.E. Pandini ¹¹⁴, J.G. Panduro Vazquez ⁹⁵, H.D. Pandya ¹, H. Pang ^{14b}, P. Pani ⁴⁸,
 G. Panizzo ^{69a,69c}, L. Paolozzi ⁵⁶, C. Papadatos ¹⁰⁸, S. Parajuli ⁴⁴, A. Paramonov ⁶,
 C. Paraskevopoulos ¹⁰, D. Paredes Hernandez ^{64b}, T.H. Park ¹⁵⁵, M.A. Parker ³², F. Parodi ^{57b,57a},
 E.W. Parrish ¹¹⁵, V.A. Parrish ⁵², J.A. Parsons ⁴¹, U. Parzefall ⁵⁴, B. Pascual Dias ¹⁰⁸,
 L. Pascual Dominguez ¹⁵¹, E. Pasqualucci ^{75a}, S. Passaggio ^{57b}, F. Pastore ⁹⁵, P. Pasuwan ^{47a,47b},
 P. Patel ⁸⁷, U.M. Patel ⁵¹, J.R. Pater ¹⁰¹, T. Pauly ³⁶, J. Parkes ¹⁴³, M. Pedersen ¹²⁵,
 R. Pedro ^{130a}, S.V. Peleganchuk ³⁷, O. Penc ³⁶, E.A. Pender ⁵², H. Peng ^{62a}, K.E. Pensi ¹⁰⁹,
 M. Penzin ³⁷, B.S. Peralva ^{83d}, A.P. Pereira Peixoto ⁶⁰, L. Pereira Sanchez ^{47a,47b},
 D.V. Perepelitsa ^{29,ai}, E. Perez Codina ^{156a}, M. Perganti ¹⁰, L. Perini ^{71a,71b,*}, H. Pernegger ³⁶,
 O. Perrin ⁴⁰, K. Peters ⁴⁸, R.F.Y. Peters ¹⁰¹, B.A. Petersen ³⁶, T.C. Petersen ⁴², E. Petit ¹⁰²,
 V. Petousis ¹³², C. Petridou ^{152,e}, A. Petrukhin ¹⁴¹, M. Pettee ^{17a}, N.E. Pettersson ³⁶,
 A. Petukhov ³⁷, K. Petukhova ¹³³, R. Pezoa ^{137f}, L. Pezzotti ³⁶, G. Pezzullo ¹⁷², T.M. Pham ¹⁷⁰,
 T. Pham ¹⁰⁵, P.W. Phillips ¹³⁴, G. Piacquadio ¹⁴⁵, E. Pianori ^{17a}, F. Piazza ^{71a,71b}, R. Piegai ³⁰,
 D. Pietreanu ^{27b}, A.D. Pilkington ¹⁰¹, M. Pinamonti ^{69a,69c}, J.L. Pinfeld ²,
 B.C. Pinheiro Pereira ^{130a}, A.E. Pinto Pinoargote ^{100,135}, L. Pintucci ^{69a,69c}, K.M. Piper ¹⁴⁶,
 A. Pirttikoski ⁵⁶, D.A. Pizzi ³⁴, L. Pizzimento ^{64b}, A. Pizzini ¹¹⁴, M.-A. Pleier ²⁹, V. Plesanovs⁵⁴,
 V. Pleskot ¹³³, E. Plotnikova³⁸, G. Poddar ⁴, R. Poettgen ⁹⁸, L. Poggioli ¹²⁷, I. Pokharel ⁵⁵,
 S. Polacek ¹³³, G. Polesello ^{73a}, A. Poley ^{142,156a}, R. Polifka ¹³², A. Polini ^{23b}, C.S. Pollard ¹⁶⁷,

Z.B. Pollock ¹¹⁹, V. Polychronakos ²⁹, E. Pompa Pacchi ^{75a,75b}, D. Ponomarenko ¹¹³,
L. Pontecorvo ³⁶, S. Popa ^{27a}, G.A. Popeneciu ^{27d}, A. Poreba ³⁶, D.M. Portillo Quintero ^{156a},
S. Pospisil ¹³², M.A. Postill ¹³⁹, P. Postolache ^{27c}, K. Potamianos ¹⁶⁷, P.A. Potepa ^{86a},
I.N. Potrap ³⁸, C.J. Potter ³², H. Potti ¹, T. Poulsen ⁴⁸, J. Poveda ¹⁶³, M.E. Pozo Astigarraga ³⁶,
A. Prades Ibanez ¹⁶³, J. Pretel ⁵⁴, D. Price ¹⁰¹, M. Primavera ^{70a}, M.A. Principe Martin ⁹⁹,
R. Privara ¹²², T. Procter ⁵⁹, M.L. Proffitt ¹³⁸, N. Proklova ¹²⁸, K. Prokofiev ^{64c}, G. Proto ¹¹⁰,
S. Protopopescu ²⁹, J. Proudfoot ⁶, M. Przybycien ^{86a}, W.W. Przygoda ^{86b}, J.E. Puddefoot ¹³⁹,
D. Pudzha ³⁷, D. Pyatiizbyantseva ³⁷, J. Qian ¹⁰⁶, D. Qichen ¹⁰¹, Y. Qin ¹⁰¹, T. Qiu ⁵²,
A. Quadt ⁵⁵, M. Queitsch-Maitland ¹⁰¹, G. Quetant ⁵⁶, R.P. Quinn ¹⁶⁴, G. Rabanal Bolanos ⁶¹,
D. Rafanoharana ⁵⁴, F. Ragusa ^{71a,71b}, J.L. Rainbolt ³⁹, J.A. Raine ⁵⁶, S. Rajagopalan ²⁹,
E. Ramakoti ³⁷, K. Ran ^{48,14e}, N.P. Rapheeha ^{33g}, H. Rasheed ^{27b}, V. Raskina ¹²⁷,
D.F. Rassloff ^{63a}, S. Rave ¹⁰⁰, B. Ravina ⁵⁵, I. Ravinovich ¹⁶⁹, M. Raymond ³⁶, A.L. Read ¹²⁵,
N.P. Readioff ¹³⁹, D.M. Rebutzi ^{73a,73b}, G. Redlinger ²⁹, A.S. Reed ¹¹⁰, K. Reeves ²⁶,
J.A. Reidelsturz ¹⁷¹, D. Reikher ¹⁵¹, A. Rej ¹⁴¹, C. Rembser ³⁶, A. Renardi ⁴⁸, M. Renda ^{27b},
M.B. Rendel ¹¹⁰, F. Renner ⁴⁸, A.G. Rennie ¹⁶⁰, A.L. Rescia ⁴⁸, S. Resconi ^{71a},
M. Ressegotti ^{57b,57a}, S. Rettie ³⁶, J.G. Reyes Rivera ¹⁰⁷, E. Reynolds ^{17a}, O.L. Rezanova ³⁷,
P. Reznicek ¹³³, N. Ribaric ⁹¹, E. Ricci ^{78a,78b}, R. Richter ¹¹⁰, S. Richter ^{47a,47b},
E. Richter-Was ^{86b}, M. Ridel ¹²⁷, S. Ridouani ^{35d}, P. Rieck ¹¹⁷, P. Riedler ³⁶, E.M. Riefel ^{47a,47b},
M. Rijssenbeek ¹⁴⁵, A. Rimoldi ^{73a,73b}, M. Rimoldi ⁴⁸, L. Rinaldi ^{23b,23a}, T.T. Rinn ²⁹,
M.P. Rinnagel ¹⁰⁹, G. Ripellino ¹⁶¹, I. Riu ¹³, P. Rivadeneira ⁴⁸, J.C. Rivera Vergara ¹⁶⁵,
F. Rizatdinova ¹²¹, E. Rizvi ⁹⁴, B.A. Roberts ¹⁶⁷, B.R. Roberts ^{17a}, S.H. Robertson ^{104,w},
D. Robinson ³², C.M. Robles Gajardo ^{137f}, M. Robles Manzano ¹⁰⁰, A. Robson ⁵⁹, A. Rocchi ^{76a,76b},
C. Roda ^{74a,74b}, S. Rodriguez Bosca ^{63a}, Y. Rodriguez Garcia ^{22a}, A. Rodriguez Rodriguez ⁵⁴,
A.M. Rodríguez Vera ^{156b}, S. Roe ³⁶, J.T. Roemer ¹⁶⁰, A.R. Roepe-Gier ¹³⁶, J. Roggel ¹⁷¹,
O. Røhne ¹²⁵, R.A. Rojas ¹⁰³, C.P.A. Roland ⁶⁸, J. Roloff ²⁹, A. Romaniouk ³⁷,
E. Romano ^{73a,73b}, M. Romano ^{23b}, A.C. Romero Hernandez ¹⁶², N. Rompotis ⁹², L. Roos ¹²⁷,
S. Rosati ^{75a}, B.J. Rosser ³⁹, E. Rossi ¹²⁶, E. Rossi ^{72a,72b}, L.P. Rossi ^{57b}, L. Rossini ⁵⁴,
R. Rosten ¹¹⁹, M. Rotaru ^{27b}, B. Rottler ⁵⁴, C. Rougier ^{102,aa}, D. Rousseau ⁶⁶, D. Rousso ³²,
A. Roy ¹⁶², S. Roy-Garand ¹⁵⁵, A. Rozanov ¹⁰², Y. Rozen ¹⁵⁰, X. Ruan ^{33g},
A. Rubio Jimenez ¹⁶³, A.J. Ruby ⁹², V.H. Ruelas Rivera ¹⁸, T.A. Ruggeri ¹, A. Ruggiero ¹²⁶,
A. Ruiz-Martinez ¹⁶³, A. Rummler ³⁶, Z. Rurikova ⁵⁴, N.A. Rusakovich ³⁸, H.L. Russell ¹⁶⁵,
G. Russo ^{75a,75b}, J.P. Rutherford ⁷, S. Rutherford Colmenares ³², K. Rybacki ⁹¹, M. Rybar ¹³³,
E.B. Rye ¹²⁵, A. Ryzhov ⁴⁴, J.A. Sabater Iglesias ⁵⁶, P. Sabatini ¹⁶³, L. Sabetta ^{75a,75b},
H.F-W. Sadrozinski ¹³⁶, F. Safai Tehrani ^{75a}, B. Safarzadeh Samani ¹³⁴, M. Safdari ¹⁴³,
S. Saha ¹⁶⁵, M. Sahinsoy ¹¹⁰, M. Saimpert ¹³⁵, M. Saito ¹⁵³, T. Saito ¹⁵³, D. Salamani ³⁶,
A. Salnikov ¹⁴³, J. Salt ¹⁶³, A. Salvador Salas ¹³, D. Salvatore ^{43b,43a}, F. Salvatore ¹⁴⁶,
A. Salzburger ³⁶, D. Sammel ⁵⁴, D. Sampsonidis ^{152,e}, D. Sampsonidou ¹²³, J. Sánchez ¹⁶³,
A. Sanchez Pineda ⁴, V. Sanchez Sebastian ¹⁶³, H. Sandaker ¹²⁵, C.O. Sander ⁴⁸,
J.A. Sandesara ¹⁰³, M. Sandhoff ¹⁷¹, C. Sandoval ^{22b}, D.P.C. Sankey ¹³⁴, T. Sano ⁸⁸,
A. Sansoni ⁵³, L. Santi ^{75a,75b}, C. Santoni ⁴⁰, H. Santos ^{130a,130b}, S.N. Santpur ^{17a}, A. Santra ¹⁶⁹,
K.A. Saoucha ^{116b}, J.G. Saraiva ^{130a,130d}, J. Sardain ⁷, O. Sasaki ⁸⁴, K. Sato ¹⁵⁷, C. Sauer ^{63b},
F. Sauerburger ⁵⁴, E. Sauvan ⁴, P. Savard ^{155,ag}, R. Sawada ¹⁵³, C. Sawyer ¹³⁴, L. Sawyer ⁹⁷,
I. Sayago Galvan ¹⁶³, C. Sbarra ^{23b}, A. Sbrizzi ^{23b,23a}, T. Scanlon ⁹⁶, J. Schaarschmidt ¹³⁸,
P. Schacht ¹¹⁰, U. Schäfer ¹⁰⁰, A.C. Schaffer ^{66,44}, D. Schaile ¹⁰⁹, R.D. Schamberger ¹⁴⁵,
C. Scharf ¹⁸, M.M. Schefer ¹⁹, V.A. Schegelsky ³⁷, D. Scheirich ¹³³, F. Schenck ¹⁸,
M. Schernau ¹⁶⁰, C. Scheulen ⁵⁵, C. Schiavi ^{57b,57a}, E.J. Schioppa ^{70a,70b}, M. Schioppa ^{43b,43a},
B. Schlag ^{143,n}, K.E. Schleicher ⁵⁴, S. Schlenker ³⁶, J. Schmeing ¹⁷¹, M.A. Schmidt ¹⁷¹,

K. Schmieden ¹⁰⁰, C. Schmitt ¹⁰⁰, S. Schmitt ⁴⁸, L. Schoeffel ¹³⁵, A. Schoening ^{63b},
 P.G. Scholer ⁵⁴, E. Schopf ¹²⁶, M. Schott ¹⁰⁰, J. Schovancova ³⁶, S. Schramm ⁵⁶,
 F. Schroeder ¹⁷¹, T. Schroer ⁵⁶, H-C. Schultz-Coulon ^{63a}, M. Schumacher ⁵⁴, B.A. Schumm ¹³⁶,
 Ph. Schune ¹³⁵, A.J. Schuy ¹³⁸, H.R. Schwartz ¹³⁶, A. Schwartzman ¹⁴³, T.A. Schwarz ¹⁰⁶,
 Ph. Schwemling ¹³⁵, R. Schwienhorst ¹⁰⁷, A. Sciandra ¹³⁶, G. Sciolla ²⁶, F. Scuri ^{74a},
 C.D. Sebastiani ⁹², K. Sedlaczek ¹¹⁵, P. Seema ¹⁸, S.C. Seidel ¹¹², A. Seiden ¹³⁶,
 B.D. Seidlitz ⁴¹, C. Seitz ⁴⁸, J.M. Seixas ^{83b}, G. Sekhniaidze ^{72a}, S.J. Sekula ⁴⁴, L. Selem ⁶⁰,
 N. Semprini-Cesari ^{23b,23a}, D. Sengupta ⁵⁶, V. Senthilkumar ¹⁶³, L. Serin ⁶⁶, L. Serkin ^{69a,69b},
 M. Sessa ^{76a,76b}, H. Severini ¹²⁰, F. Sforza ^{57b,57a}, A. Sfyrta ⁵⁶, E. Shabalina ⁵⁵, R. Shaheen ¹⁴⁴,
 J.D. Shahinian ¹²⁸, D. Shaked Renous ¹⁶⁹, L.Y. Shan ^{14a}, M. Shapiro ^{17a}, A. Sharma ³⁶,
 A.S. Sharma ¹⁶⁴, P. Sharma ⁸⁰, S. Sharma ⁴⁸, P.B. Shatalov ³⁷, K. Shaw ¹⁴⁶, S.M. Shaw ¹⁰¹,
 A. Shcherbakova ³⁷, Q. Shen ^{62c,5}, P. Sherwood ⁹⁶, L. Shi ⁹⁶, X. Shi ^{14a}, C.O. Shimmin ¹⁷²,
 J.D. Shinner ⁹⁵, I.P.J. Shipsey ¹²⁶, S. Shirabe ^{56,h}, M. Shiyakova ^{38,u}, J. Shlomi ¹⁶⁹,
 M.J. Shochet ³⁹, J. Shojaii ¹⁰⁵, D.R. Shope ¹²⁵, B. Shrestha ¹²⁰, S. Shrestha ^{119,aj},
 E.M. Shrif ^{33g}, M.J. Shroff ¹⁶⁵, P. Sicho ¹³¹, A.M. Sickles ¹⁶², E. Sideras Haddad ^{33g},
 A. Sidoti ^{23b}, F. Siegert ⁵⁰, Dj. Sijacki ¹⁵, R. Sikora ^{86a}, F. Sili ⁹⁰, J.M. Silva ²⁰,
 M.V. Silva Oliveira ²⁹, S.B. Silverstein ^{47a}, S. Simion ⁶⁶, R. Simoniello ³⁶, E.L. Simpson ⁵⁹,
 H. Simpson ¹⁴⁶, L.R. Simpson ¹⁰⁶, N.D. Simpson ⁹⁸, S. Simsek ⁸², S. Sindhu ⁵⁵, P. Sinervo ¹⁵⁵,
 S. Singh ¹⁵⁵, S. Sinha ⁴⁸, S. Sinha ¹⁰¹, M. Sioli ^{23b,23a}, I. Siral ³⁶, E. Sitnikova ⁴⁸,
 S.Yu. Sivoklov ^{37,*}, J. Sjölin ^{47a,47b}, A. Skaf ⁵⁵, E. Skorda ²⁰, P. Skubic ¹²⁰, M. Slawinska ⁸⁷,
 V. Smakhtin ¹⁶⁹, B.H. Smart ¹³⁴, J. Smiesko ³⁶, S.Yu. Smirnov ³⁷, Y. Smirnov ³⁷,
 L.N. Smirnova ^{37,a}, O. Smirnova ⁹⁸, A.C. Smith ⁴¹, E.A. Smith ³⁹, H.A. Smith ¹²⁶,
 J.L. Smith ⁹², R. Smith ¹⁴³, M. Smizanska ⁹¹, K. Smolek ¹³², A.A. Snesarev ³⁷, S.R. Snider ¹⁵⁵,
 H.L. Snoek ¹¹⁴, S. Snyder ²⁹, R. Sobie ^{165,w}, A. Soffer ¹⁵¹, C.A. Solans Sanchez ³⁶,
 E.Yu. Soldatov ³⁷, U. Soldevila ¹⁶³, A.A. Solodkov ³⁷, S. Solomon ²⁶, A. Soloshenko ³⁸,
 K. Solovieva ⁵⁴, O.V. Solovyanov ⁴⁰, V. Solovyev ³⁷, P. Sommer ³⁶, A. Sonay ¹³,
 W.Y. Song ^{156b}, J.M. Sonneveld ¹¹⁴, A. Sopczak ¹³², A.L. Soppio ⁹⁶, F. Sopkova ^{28b},
 V. Sothilingam ^{63a}, S. Sottocornola ⁶⁸, R. Soualah ^{116b}, Z. Soumami ^{35e}, D. South ⁴⁸,
 N. Soybelman ¹⁶⁹, S. Spagnolo ^{70a,70b}, M. Spalla ¹¹⁰, D. Sperlich ⁵⁴, G. Spigo ³⁶, S. Spinali ⁹¹,
 D.P. Spiteri ⁵⁹, M. Spousta ¹³³, E.J. Staats ³⁴, A. Stabile ^{71a,71b}, R. Stamen ^{63a}, A. Stampekis ²⁰,
 M. Standke ²⁴, E. Stanecka ⁸⁷, M.V. Stange ⁵⁰, B. Stanislaus ^{17a}, M.M. Stanitzki ⁴⁸, B. Stapf ⁴⁸,
 E.A. Starchenko ³⁷, G.H. Stark ¹³⁶, J. Stark ^{102,aa}, D.M. Starko ^{156b}, P. Staroba ¹³¹,
 P. Starovoitov ^{63a}, S. Stärz ¹⁰⁴, R. Staszewski ⁸⁷, G. Stavropoulos ⁴⁶, J. Steentoft ¹⁶¹,
 P. Steinberg ²⁹, B. Stelzer ^{142,156a}, H.J. Stelzer ¹²⁹, O. Stelzer-Chilton ^{156a}, H. Stenzel ⁵⁸,
 T.J. Stevenson ¹⁴⁶, G.A. Stewart ³⁶, J.R. Stewart ¹²¹, M.C. Stockton ³⁶, G. Stoicea ^{27b},
 M. Stolarski ^{130a}, S. Stonjek ¹¹⁰, A. Straessner ⁵⁰, J. Strandberg ¹⁴⁴, S. Strandberg ^{47a,47b},
 M. Stratmann ¹⁷¹, M. Strauss ¹²⁰, T. Strebler ¹⁰², P. Strizenec ^{28b}, R. Ströhmer ¹⁶⁶,
 D.M. Strom ¹²³, L.R. Strom ⁴⁸, R. Stroynowski ⁴⁴, A. Strubig ^{47a,47b}, S.A. Stucci ²⁹,
 B. Stugu ¹⁶, J. Stupak ¹²⁰, N.A. Styles ⁴⁸, D. Su ¹⁴³, S. Su ^{62a}, W. Su ^{62d}, X. Su ^{62a,66},
 K. Sugizaki ¹⁵³, V.V. Sulin ³⁷, M.J. Sullivan ⁹², D.M.S. Sultan ^{78a,78b}, L. Sultanaliev ³⁷,
 S. Sultansoy ^{3b}, T. Sumida ⁸⁸, S. Sun ¹⁰⁶, S. Sun ¹⁷⁰, O. Sunneborn Gudnadottir ¹⁶¹, N. Sur ¹⁰²,
 M.R. Sutton ¹⁴⁶, H. Suzuki ¹⁵⁷, M. Svatos ¹³¹, M. Swiatlowski ^{156a}, T. Swirski ¹⁶⁶, I. Sykora ^{28a},
 M. Sykora ¹³³, T. Sykora ¹³³, D. Ta ¹⁰⁰, K. Tackmann ^{48,t}, A. Taffard ¹⁶⁰, R. Tafirout ^{156a},
 J.S. Tafoya Vargas ⁶⁶, E.P. Takeva ⁵², Y. Takubo ⁸⁴, M. Talby ¹⁰², A.A. Talyshev ³⁷,
 K.C. Tam ^{64b}, N.M. Tamir ¹⁵¹, A. Tanaka ¹⁵³, J. Tanaka ¹⁵³, R. Tanaka ⁶⁶, M. Tanasini ^{57b,57a},
 Z. Tao ¹⁶⁴, S. Tapia Araya ^{137f}, S. Tapprogge ¹⁰⁰, A. Tarek Abouelfadl Mohamed ¹⁰⁷,
 S. Tarem ¹⁵⁰, K. Tariq ^{14a}, G. Tarna ^{102,27b}, G.F. Tartarelli ^{71a}, P. Tas ¹³³, M. Tasevsky ¹³¹,

E. Tassi [id^{43b,43a}](#), A.C. Tate [id¹⁶²](#), G. Tatenò [id¹⁵³](#), Y. Tayalati [id^{35e,v}](#), G.N. Taylor [id¹⁰⁵](#), W. Taylor [id^{156b}](#),
 H. Teagle [id⁹²](#), A.S. Tee [id¹⁷⁰](#), R. Teixeira De Lima [id¹⁴³](#), P. Teixeira-Dias [id⁹⁵](#), J.J. Teoh [id¹⁵⁵](#),
 K. Terashi [id¹⁵³](#), J. Terron [id⁹⁹](#), S. Terzo [id¹³](#), M. Testa [id⁵³](#), R.J. Teuscher [id^{155,w}](#), A. Thaler [id⁷⁹](#),
 O. Theiner [id⁵⁶](#), N. Themistokleous [id⁵²](#), T. Thevenaux-Pelzer [id¹⁰²](#), O. Thielmann [id¹⁷¹](#), D.W. Thomas [id⁹⁵](#),
 J.P. Thomas [id²⁰](#), E.A. Thompson [id^{17a}](#), P.D. Thompson [id²⁰](#), E. Thomson [id¹²⁸](#), Y. Tian [id⁵⁵](#),
 V. Tikhomirov [id^{37,a}](#), Yu.A. Tikhonov [id³⁷](#), S. Timoshenko [id³⁷](#), D. Timoshyn [id¹³³](#), E.X.L. Ting [id¹](#),
 P. Tipton [id¹⁷²](#), S.H. Tlou [id^{33g}](#), A. Tnourji [id⁴⁰](#), K. Todome [id¹⁵⁴](#), S. Todorova-Nova [id¹³³](#), S. Todt [id⁵⁰](#),
 M. Togawa [id⁸⁴](#), J. Tojo [id⁸⁹](#), S. Tokár [id^{28a}](#), K. Tokushuku [id⁸⁴](#), O. Toldaiev [id⁶⁸](#), R. Tombs [id³²](#),
 M. Tomoto [id^{84,111}](#), L. Tompkins [id^{143,n}](#), K.W. Topolnicki [id^{86b}](#), E. Torrence [id¹²³](#), H. Torres [id^{102,aa}](#),
 E. Torró Pastor [id¹⁶³](#), M. Toscani [id³⁰](#), C. Toscirci [id³⁹](#), M. Tost [id¹¹](#), D.R. Tovey [id¹³⁹](#), A. Traet [id¹⁶](#),
 I.S. Trandafir [id^{27b}](#), T. Trefzger [id¹⁶⁶](#), A. Tricoli [id²⁹](#), I.M. Trigger [id^{156a}](#), S. Trincaz-Duvoid [id¹²⁷](#),
 D.A. Trischuk [id²⁶](#), B. Trocmé [id⁶⁰](#), C. Troncon [id^{71a}](#), L. Truong [id^{33c}](#), M. Trzebinski [id⁸⁷](#), A. Trzupiek [id⁸⁷](#),
 F. Tsai [id¹⁴⁵](#), M. Tsai [id¹⁰⁶](#), A. Tsiamis [id^{152,e}](#), P.V. Tsiarehka [id³⁷](#), S. Tsigaridas [id^{156a}](#), A. Tsirigotis [id^{152,r}](#),
 V. Tsiskaridze [id¹⁵⁵](#), E.G. Tskhadadze [id^{149a}](#), M. Tsopoulou [id^{152,e}](#), Y. Tsujikawa [id⁸⁸](#), I.I. Tsukerman [id³⁷](#),
 V. Tsulaia [id^{17a}](#), S. Tsuno [id⁸⁴](#), O. Tsur [id¹⁵⁰](#), K. Tsurii [id¹¹⁸](#), D. Tsybychev [id¹⁴⁵](#), Y. Tu [id^{64b}](#),
 A. Tudorache [id^{27b}](#), V. Tudorache [id^{27b}](#), A.N. Tuna [id³⁶](#), S. Turchikhin [id^{57b,57a}](#), I. Turk Cakir [id^{3a}](#),
 R. Turra [id^{71a}](#), T. Turtuvshin [id^{38,x}](#), P.M. Tuts [id⁴¹](#), S. Tzamarias [id^{152,e}](#), P. Tzanis [id¹⁰](#), E. Tzovara [id¹⁰⁰](#),
 F. Ukegawa [id¹⁵⁷](#), P.A. Ulloa Poblete [id^{137c,137b}](#), E.N. Umaka [id²⁹](#), G. Unal [id³⁶](#), M. Unal [id¹¹](#),
 A. Undrus [id²⁹](#), G. Unel [id¹⁶⁰](#), J. Urban [id^{28b}](#), P. Urquijo [id¹⁰⁵](#), G. Usai [id⁸](#), R. Ushioda [id¹⁵⁴](#),
 M. Usman [id¹⁰⁸](#), Z. Uysal [id^{21b}](#), L. Vacavant [id¹⁰²](#), V. Vacek [id¹³²](#), B. Vachon [id¹⁰⁴](#), K.O.H. Vadla [id¹²⁵](#),
 T. Vafeiadis [id³⁶](#), A. Vaitkus [id⁹⁶](#), C. Valderanis [id¹⁰⁹](#), E. Valdes Santurio [id^{47a,47b}](#), M. Valente [id^{156a}](#),
 S. Valentinetti [id^{23b,23a}](#), A. Valero [id¹⁶³](#), E. Valiente Moreno [id¹⁶³](#), A. Vallier [id^{102,aa}](#),
 J.A. Valls Ferrer [id¹⁶³](#), D.R. Van Arneman [id¹¹⁴](#), T.R. Van Daalen [id¹³⁸](#), A. Van Der Graaf [id⁴⁹](#),
 P. Van Gemmeren [id⁶](#), M. Van Rijnbach [id^{125,36}](#), S. Van Stroud [id⁹⁶](#), I. Van Vulpen [id¹¹⁴](#),
 M. Vanadia [id^{76a,76b}](#), W. Vandelli [id³⁶](#), M. Vandenbroucke [id¹³⁵](#), E.R. Vandewall [id¹²¹](#), D. Vannicola [id¹⁵¹](#),
 L. Vannoli [id^{57b,57a}](#), R. Vari [id^{75a}](#), E.W. Varnes [id⁷](#), C. Varni [id^{17b}](#), T. Varol [id¹⁴⁸](#), D. Varouchas [id⁶⁶](#),
 L. Varriale [id¹⁶³](#), K.E. Varvell [id¹⁴⁷](#), M.E. Vasile [id^{27b}](#), L. Vaslin [id⁴⁰](#), G.A. Vasquez [id¹⁶⁵](#), A. Vasyukov [id³⁸](#),
 F. Vazeille [id⁴⁰](#), T. Vazquez Schroeder [id³⁶](#), J. Veatch [id³¹](#), V. Vecchio [id¹⁰¹](#), M.J. Veen [id¹⁰³](#),
 I. Veliscek [id¹²⁶](#), L.M. Veloce [id¹⁵⁵](#), F. Veloso [id^{130a,130c}](#), S. Veneziano [id^{75a}](#), A. Ventura [id^{70a,70b}](#),
 S. Ventura Gonzalez [id¹³⁵](#), A. Verbytskyi [id¹¹⁰](#), M. Verducci [id^{74a,74b}](#), C. Vergis [id²⁴](#),
 M. Verissimo De Araujo [id^{83b}](#), W. Verkerke [id¹¹⁴](#), J.C. Vermeulen [id¹¹⁴](#), C. Vernieri [id¹⁴³](#),
 M. Vessella [id¹⁰³](#), M.C. Vetterli [id^{142,ag}](#), A. Vgenopoulos [id^{152,e}](#), N. Viaux Maira [id^{137f}](#), T. Vickey [id¹³⁹](#),
 O.E. Vickey Boeriu [id¹³⁹](#), G.H.A. Viehhauser [id¹²⁶](#), L. Vigani [id^{63b}](#), M. Villa [id^{23b,23a}](#),
 M. Villaplana Perez [id¹⁶³](#), E.M. Villhauer [id⁵²](#), E. Vilucchi [id⁵³](#), M.G. Vincter [id³⁴](#), G.S. Virdee [id²⁰](#),
 A. Vishwakarma [id⁵²](#), A. Visibile [id¹¹⁴](#), C. Vittori [id³⁶](#), I. Vivarelli [id¹⁴⁶](#), E. Voevodina [id¹¹⁰](#), F. Vogel [id¹⁰⁹](#),
 P. Vokac [id¹³²](#), Yu. Volkotrub [id^{86a}](#), J. Von Ahnen [id⁴⁸](#), E. Von Toerne [id²⁴](#), B. Vormwald [id³⁶](#),
 V. Vorobel [id¹³³](#), K. Vorobev [id³⁷](#), M. Vos [id¹⁶³](#), K. Voss [id¹⁴¹](#), J.H. Vossebeld [id⁹²](#), M. Vozak [id¹¹⁴](#),
 L. Vozdecky [id⁹⁴](#), N. Vranjes [id¹⁵](#), M. Vranjes Milosavljevic [id¹⁵](#), M. Vreeswijk [id¹¹⁴](#), R. Vuillermet [id³⁶](#),
 O. Vujinovic [id¹⁰⁰](#), I. Vukotic [id³⁹](#), S. Wada [id¹⁵⁷](#), C. Wagner [id¹⁰³](#), J.M. Wagner [id^{17a}](#), W. Wagner [id¹⁷¹](#),
 S. Wahdan [id¹⁷¹](#), H. Wahlberg [id⁹⁰](#), M. Wakida [id¹¹¹](#), J. Walder [id¹³⁴](#), R. Walker [id¹⁰⁹](#), W. Walkowiak [id¹⁴¹](#),
 A. Wall [id¹²⁸](#), T. Wamorkar [id⁶](#), A.Z. Wang [id¹⁷⁰](#), C. Wang [id¹⁰⁰](#), C. Wang [id^{62c}](#), H. Wang [id^{17a}](#),
 J. Wang [id^{64a}](#), R.-J. Wang [id¹⁰⁰](#), R. Wang [id⁵¹](#), R. Wang [id⁶](#), S.M. Wang [id¹⁴⁸](#), S. Wang [id^{62b}](#),
 T. Wang [id^{62a}](#), W.T. Wang [id⁸⁰](#), W. Wang [id^{14a}](#), X. Wang [id^{14c}](#), X. Wang [id¹⁶²](#), X. Wang [id^{62c}](#),
 Y. Wang [id^{62d}](#), Y. Wang [id^{14c}](#), Z. Wang [id¹⁰⁶](#), Z. Wang [id^{62d,51,62c}](#), Z. Wang [id¹⁰⁶](#), A. Warburton [id¹⁰⁴](#),
 R.J. Ward [id²⁰](#), N. Warrack [id⁵⁹](#), A.T. Watson [id²⁰](#), H. Watson [id⁵⁹](#), M.F. Watson [id²⁰](#), E. Watton [id^{59,134}](#),
 G. Watts [id¹³⁸](#), B.M. Waugh [id⁹⁶](#), C. Weber [id²⁹](#), H.A. Weber [id¹⁸](#), M.S. Weber [id¹⁹](#), S.M. Weber [id^{63a}](#),
 C. Wei [id^{62a}](#), Y. Wei [id¹²⁶](#), A.R. Weidberg [id¹²⁶](#), E.J. Weik [id¹¹⁷](#), J. Weingarten [id⁴⁹](#), M. Weirich [id¹⁰⁰](#),

C. Weiser ⁵⁴, C.J. Wells ⁴⁸, T. Wenaus ²⁹, B. Wendland ⁴⁹, T. Wengler ³⁶, N.S. Wenke ¹¹⁰, N. Wermes ²⁴, M. Wessels ^{63a}, A.M. Wharton ⁹¹, A.S. White ⁶¹, A. White ⁸, M.J. White ¹, D. Whiteson ¹⁶⁰, L. Wickremasinghe ¹²⁴, W. Wiedenmann ¹⁷⁰, C. Wiel ⁵⁰, M. Wielers ¹³⁴, C. Wiglesworth ⁴², D.J. Wilbern ¹²⁰, H.G. Wilkens ³⁶, D.M. Williams ⁴¹, H.H. Williams ¹²⁸, S. Williams ³², S. Willocq ¹⁰³, B.J. Wilson ¹⁰¹, P.J. Windischhofer ³⁹, F.I. Winkel ³⁰, F. Winklmeier ¹²³, B.T. Winter ⁵⁴, J.K. Winter ¹⁰¹, M. Wittgen ¹⁴³, M. Wobisch ⁹⁷, Z. Wolffs ¹¹⁴, J. Wollrath ¹⁶⁰, M.W. Wolter ⁸⁷, H. Wolters ^{130a,130c}, A.F. Wongel ⁴⁸, S.D. Worm ⁴⁸, B.K. Wosiek ⁸⁷, K.W. Woźniak ⁸⁷, S. Wozniowski ⁵⁵, K. Wraight ⁵⁹, C. Wu ²⁰, J. Wu ^{14a,14e}, M. Wu ^{64a}, M. Wu ¹¹³, S.L. Wu ¹⁷⁰, X. Wu ⁵⁶, Y. Wu ^{62a}, Z. Wu ¹³⁵, J. Wuerzinger ^{110,ae}, T.R. Wyatt ¹⁰¹, B.M. Wynne ⁵², S. Xella ⁴², L. Xia ^{14c}, M. Xia ^{14b}, J. Xiang ^{64c}, M. Xie ^{62a}, X. Xie ^{62a}, S. Xin ^{14a,14e}, A. Xiong ¹²³, J. Xiong ^{17a}, D. Xu ^{14a}, H. Xu ^{62a}, L. Xu ^{62a}, R. Xu ¹²⁸, T. Xu ¹⁰⁶, Y. Xu ^{14b}, Z. Xu ⁵², Z. Xu ^{14a}, B. Yabsley ¹⁴⁷, S. Yacoob ^{33a}, Y. Yamaguchi ¹⁵⁴, E. Yamashita ¹⁵³, H. Yamauchi ¹⁵⁷, T. Yamazaki ^{17a}, Y. Yamazaki ⁸⁵, J. Yan ^{62c}, S. Yan ¹²⁶, Z. Yan ²⁵, H.J. Yang ^{62c,62d}, H.T. Yang ^{62a}, S. Yang ^{62a}, T. Yang ^{64c}, X. Yang ^{62a}, X. Yang ^{14a}, Y. Yang ⁴⁴, Y. Yang ^{62a}, Z. Yang ^{62a}, W-M. Yao ^{17a}, Y.C. Yap ⁴⁸, H. Ye ^{14c}, H. Ye ⁵⁵, J. Ye ^{14a}, S. Ye ²⁹, X. Ye ^{62a}, Y. Yeh ⁹⁶, I. Yeletsikh ³⁸, B.K. Yeo ^{17b}, M.R. Yexley ⁹⁶, P. Yin ⁴¹, K. Yorita ¹⁶⁸, S. Younas ^{27b}, C.J.S. Young ³⁶, C. Young ¹⁴³, C. Yu ^{14a,14e}, Y. Yu ^{62a}, M. Yuan ¹⁰⁶, R. Yuan ^{62b}, L. Yue ⁹⁶, M. Zaazoua ^{62a}, B. Zabinski ⁸⁷, E. Zaid ⁵², T. Zakareishvili ^{149b}, N. Zakharchuk ³⁴, S. Zambito ⁵⁶, J.A. Zamora Saa ^{137d,137b}, J. Zang ¹⁵³, D. Zanzi ⁵⁴, O. Zaplatilek ¹³², C. Zeitnitz ¹⁷¹, H. Zeng ^{14a}, J.C. Zeng ¹⁶², D.T. Zenger Jr ²⁶, O. Zenin ³⁷, T. Ženiš ^{28a}, S. Zenz ⁹⁴, S. Zerradi ^{35a}, D. Zerwas ⁶⁶, M. Zhai ^{14a,14e}, B. Zhang ^{14c}, D.F. Zhang ¹³⁹, J. Zhang ^{62b}, J. Zhang ⁶, K. Zhang ^{14a,14e}, L. Zhang ^{14c}, P. Zhang ^{14a,14e}, R. Zhang ¹⁷⁰, S. Zhang ¹⁰⁶, T. Zhang ¹⁵³, X. Zhang ^{62c}, X. Zhang ^{62b}, Y. Zhang ^{62c,5}, Y. Zhang ⁹⁶, Z. Zhang ^{17a}, Z. Zhang ⁶⁶, H. Zhao ¹³⁸, P. Zhao ⁵¹, T. Zhao ^{62b}, Y. Zhao ¹³⁶, Z. Zhao ^{62a}, A. Zhemchugov ³⁸, J. Zheng ^{14c}, K. Zheng ¹⁶², X. Zheng ^{62a}, Z. Zheng ¹⁴³, D. Zhong ¹⁶², B. Zhou ¹⁰⁶, H. Zhou ⁷, N. Zhou ^{62c}, Y. Zhou ⁷, C.G. Zhu ^{62b}, J. Zhu ¹⁰⁶, Y. Zhu ^{62c}, Y. Zhu ^{62a}, X. Zhuang ^{14a}, K. Zhukov ³⁷, V. Zhulanov ³⁷, N.I. Zimine ³⁸, J. Zinsser ^{63b}, M. Ziolkowski ¹⁴¹, L. Živković ¹⁵, A. Zoccoli ^{23b,23a}, K. Zoch ⁶¹, T.G. Zorbas ¹³⁹, O. Zormpa ⁴⁶, W. Zou ⁴¹, L. Zwalinski ³⁶.

¹Department of Physics, University of Adelaide, Adelaide; Australia.

²Department of Physics, University of Alberta, Edmonton AB; Canada.

³(^a)Department of Physics, Ankara University, Ankara; (^b)Division of Physics, TOBB University of Economics and Technology, Ankara; Türkiye.

⁴LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France.

⁵APC, Université Paris Cité, CNRS/IN2P3, Paris; France.

⁶High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America.

⁷Department of Physics, University of Arizona, Tucson AZ; United States of America.

⁸Department of Physics, University of Texas at Arlington, Arlington TX; United States of America.

⁹Physics Department, National and Kapodistrian University of Athens, Athens; Greece.

¹⁰Physics Department, National Technical University of Athens, Zografou; Greece.

¹¹Department of Physics, University of Texas at Austin, Austin TX; United States of America.

¹²Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.

¹³Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain.

¹⁴(^a)Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (^b)Physics Department, Tsinghua University, Beijing; (^c)Department of Physics, Nanjing University, Nanjing; (^d)School of Science,

Shenzhen Campus of Sun Yat-sen University;^(e)University of Chinese Academy of Science (UCAS), Beijing; China.

¹⁵Institute of Physics, University of Belgrade, Belgrade; Serbia.

¹⁶Department for Physics and Technology, University of Bergen, Bergen; Norway.

¹⁷^(a)Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA;^(b)University of California, Berkeley CA; United States of America.

¹⁸Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany.

¹⁹Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland.

²⁰School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom.

²¹^(a)Department of Physics, Bogazici University, Istanbul;^(b)Department of Physics Engineering, Gaziantep University, Gaziantep;^(c)Department of Physics, Istanbul University, Istanbul; Türkiye.

²²^(a)Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá;^(b)Departamento de Física, Universidad Nacional de Colombia, Bogotá; Colombia.

²³^(a)Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna;^(b)INFN Sezione di Bologna; Italy.

²⁴Physikalisches Institut, Universität Bonn, Bonn; Germany.

²⁵Department of Physics, Boston University, Boston MA; United States of America.

²⁶Department of Physics, Brandeis University, Waltham MA; United States of America.

²⁷^(a)Transilvania University of Brasov, Brasov;^(b)Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest;^(c)Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi;^(d)National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca;^(e)National University of Science and Technology Politehnica, Bucharest;^(f)West University in Timisoara, Timisoara;^(g)Faculty of Physics, University of Bucharest, Bucharest; Romania.

²⁸^(a)Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava;^(b)Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic.

²⁹Physics Department, Brookhaven National Laboratory, Upton NY; United States of America.

³⁰Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires; Argentina.

³¹California State University, CA; United States of America.

³²Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom.

³³^(a)Department of Physics, University of Cape Town, Cape Town;^(b)iThemba Labs, Western Cape;^(c)Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg;^(d)National Institute of Physics, University of the Philippines Diliman (Philippines);^(e)University of South Africa, Department of Physics, Pretoria;^(f)University of Zululand, KwaDlangezwa;^(g)School of Physics, University of the Witwatersrand, Johannesburg; South Africa.

³⁴Department of Physics, Carleton University, Ottawa ON; Canada.

³⁵^(a)Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca;^(b)Faculté des Sciences, Université Ibn-Tofail, Kénitra;^(c)Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech;^(d)LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda;^(e)Faculté des sciences, Université Mohammed V, Rabat;^(f)Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.

³⁶CERN, Geneva; Switzerland.

³⁷Affiliated with an institute covered by a cooperation agreement with CERN.

³⁸Affiliated with an international laboratory covered by a cooperation agreement with CERN.

³⁹Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America.

- ⁴⁰LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France.
- ⁴¹Nevis Laboratory, Columbia University, Irvington NY; United States of America.
- ⁴²Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark.
- ⁴³(^a)Dipartimento di Fisica, Università della Calabria, Rende;(^b)INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy.
- ⁴⁴Physics Department, Southern Methodist University, Dallas TX; United States of America.
- ⁴⁵Physics Department, University of Texas at Dallas, Richardson TX; United States of America.
- ⁴⁶National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece.
- ⁴⁷(^a)Department of Physics, Stockholm University;(^b)Oskar Klein Centre, Stockholm; Sweden.
- ⁴⁸Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany.
- ⁴⁹Fakultät Physik , Technische Universität Dortmund, Dortmund; Germany.
- ⁵⁰Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany.
- ⁵¹Department of Physics, Duke University, Durham NC; United States of America.
- ⁵²SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom.
- ⁵³INFN e Laboratori Nazionali di Frascati, Frascati; Italy.
- ⁵⁴Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
- ⁵⁵II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.
- ⁵⁶Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
- ⁵⁷(^a)Dipartimento di Fisica, Università di Genova, Genova;(^b)INFN Sezione di Genova; Italy.
- ⁵⁸II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany.
- ⁵⁹SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom.
- ⁶⁰LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France.
- ⁶¹Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America.
- ⁶²(^a)Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei;(^b)Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao;(^c)School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai;(^d)Tsung-Dao Lee Institute, Shanghai; China.
- ⁶³(^a)Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg;(^b)Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany.
- ⁶⁴(^a)Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong;(^b)Department of Physics, University of Hong Kong, Hong Kong;(^c)Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China.
- ⁶⁵Department of Physics, National Tsing Hua University, Hsinchu; Taiwan.
- ⁶⁶IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France.
- ⁶⁷Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona; Spain.
- ⁶⁸Department of Physics, Indiana University, Bloomington IN; United States of America.
- ⁶⁹(^a)INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine;(^b)ICTP, Trieste;(^c)Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy.
- ⁷⁰(^a)INFN Sezione di Lecce;(^b)Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy.
- ⁷¹(^a)INFN Sezione di Milano;(^b)Dipartimento di Fisica, Università di Milano, Milano; Italy.
- ⁷²(^a)INFN Sezione di Napoli;(^b)Dipartimento di Fisica, Università di Napoli, Napoli; Italy.
- ⁷³(^a)INFN Sezione di Pavia;(^b)Dipartimento di Fisica, Università di Pavia, Pavia; Italy.
- ⁷⁴(^a)INFN Sezione di Pisa;(^b)Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.
- ⁷⁵(^a)INFN Sezione di Roma;(^b)Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy.
- ⁷⁶(^a)INFN Sezione di Roma Tor Vergata;(^b)Dipartimento di Fisica, Università di Roma Tor Vergata,

Roma; Italy.

^{77(a)}INFN Sezione di Roma Tre; ^(b)Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy.

^{78(a)}INFN-TIFPA; ^(b)Università degli Studi di Trento, Trento; Italy.

⁷⁹Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria.

⁸⁰University of Iowa, Iowa City IA; United States of America.

⁸¹Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America.

⁸²Istinye University, Sariyer, Istanbul; Türkiye.

^{83(a)}Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora; ^(b)Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; ^(c)Instituto de Física, Universidade de São Paulo, São Paulo; ^(d)Rio de Janeiro State University, Rio de Janeiro; Brazil.

⁸⁴KEK, High Energy Accelerator Research Organization, Tsukuba; Japan.

⁸⁵Graduate School of Science, Kobe University, Kobe; Japan.

^{86(a)}AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow; ^(b)Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland.

⁸⁷Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland.

⁸⁸Faculty of Science, Kyoto University, Kyoto; Japan.

⁸⁹Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka ; Japan.

⁹⁰Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina.

⁹¹Physics Department, Lancaster University, Lancaster; United Kingdom.

⁹²Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom.

⁹³Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia.

⁹⁴School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom.

⁹⁵Department of Physics, Royal Holloway University of London, Egham; United Kingdom.

⁹⁶Department of Physics and Astronomy, University College London, London; United Kingdom.

⁹⁷Louisiana Tech University, Ruston LA; United States of America.

⁹⁸Fysiska institutionen, Lunds universitet, Lund; Sweden.

⁹⁹Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain.

¹⁰⁰Institut für Physik, Universität Mainz, Mainz; Germany.

¹⁰¹School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom.

¹⁰²CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.

¹⁰³Department of Physics, University of Massachusetts, Amherst MA; United States of America.

¹⁰⁴Department of Physics, McGill University, Montreal QC; Canada.

¹⁰⁵School of Physics, University of Melbourne, Victoria; Australia.

¹⁰⁶Department of Physics, University of Michigan, Ann Arbor MI; United States of America.

¹⁰⁷Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.

¹⁰⁸Group of Particle Physics, University of Montreal, Montreal QC; Canada.

¹⁰⁹Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany.

¹¹⁰Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany.

¹¹¹Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan.

¹¹²Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America.

¹¹³Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands.

- ¹¹⁴Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands.
- ¹¹⁵Department of Physics, Northern Illinois University, DeKalb IL; United States of America.
- ¹¹⁶(^a)New York University Abu Dhabi, Abu Dhabi;(^b)University of Sharjah, Sharjah; United Arab Emirates.
- ¹¹⁷Department of Physics, New York University, New York NY; United States of America.
- ¹¹⁸Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.
- ¹¹⁹Ohio State University, Columbus OH; United States of America.
- ¹²⁰Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America.
- ¹²¹Department of Physics, Oklahoma State University, Stillwater OK; United States of America.
- ¹²²Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic.
- ¹²³Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America.
- ¹²⁴Graduate School of Science, Osaka University, Osaka; Japan.
- ¹²⁵Department of Physics, University of Oslo, Oslo; Norway.
- ¹²⁶Department of Physics, Oxford University, Oxford; United Kingdom.
- ¹²⁷LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France.
- ¹²⁸Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America.
- ¹²⁹Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America.
- ¹³⁰(^a)Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa;(^b)Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa;(^c)Departamento de Física, Universidade de Coimbra, Coimbra;(^d)Centro de Física Nuclear da Universidade de Lisboa, Lisboa;(^e)Departamento de Física, Universidade do Minho, Braga;(^f)Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain);(^g)Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal.
- ¹³¹Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic.
- ¹³²Czech Technical University in Prague, Prague; Czech Republic.
- ¹³³Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic.
- ¹³⁴Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom.
- ¹³⁵IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.
- ¹³⁶Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America.
- ¹³⁷(^a)Departamento de Física, Pontificia Universidad Católica de Chile, Santiago;(^b)Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago;(^c)Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena;(^d)Universidad Andres Bello, Department of Physics, Santiago;(^e)Instituto de Alta Investigación, Universidad de Tarapacá, Arica;(^f)Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile.
- ¹³⁸Department of Physics, University of Washington, Seattle WA; United States of America.
- ¹³⁹Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.
- ¹⁴⁰Department of Physics, Shinshu University, Nagano; Japan.
- ¹⁴¹Department Physik, Universität Siegen, Siegen; Germany.
- ¹⁴²Department of Physics, Simon Fraser University, Burnaby BC; Canada.
- ¹⁴³SLAC National Accelerator Laboratory, Stanford CA; United States of America.
- ¹⁴⁴Department of Physics, Royal Institute of Technology, Stockholm; Sweden.
- ¹⁴⁵Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of

America.

¹⁴⁶Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom.

¹⁴⁷School of Physics, University of Sydney, Sydney; Australia.

¹⁴⁸Institute of Physics, Academia Sinica, Taipei; Taiwan.

¹⁴⁹^(a)E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; ^(b)High Energy Physics Institute, Tbilisi State University, Tbilisi; ^(c)University of Georgia, Tbilisi; Georgia.

¹⁵⁰Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel.

¹⁵¹Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel.

¹⁵²Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece.

¹⁵³International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan.

¹⁵⁴Department of Physics, Tokyo Institute of Technology, Tokyo; Japan.

¹⁵⁵Department of Physics, University of Toronto, Toronto ON; Canada.

¹⁵⁶^(a)TRIUMF, Vancouver BC; ^(b)Department of Physics and Astronomy, York University, Toronto ON; Canada.

¹⁵⁷Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan.

¹⁵⁸Department of Physics and Astronomy, Tufts University, Medford MA; United States of America.

¹⁵⁹United Arab Emirates University, Al Ain; United Arab Emirates.

¹⁶⁰Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America.

¹⁶¹Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden.

¹⁶²Department of Physics, University of Illinois, Urbana IL; United States of America.

¹⁶³Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain.

¹⁶⁴Department of Physics, University of British Columbia, Vancouver BC; Canada.

¹⁶⁵Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.

¹⁶⁶Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany.

¹⁶⁷Department of Physics, University of Warwick, Coventry; United Kingdom.

¹⁶⁸Waseda University, Tokyo; Japan.

¹⁶⁹Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel.

¹⁷⁰Department of Physics, University of Wisconsin, Madison WI; United States of America.

¹⁷¹Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany.

¹⁷²Department of Physics, Yale University, New Haven CT; United States of America.

^a Also Affiliated with an institute covered by a cooperation agreement with CERN.

^b Also at An-Najah National University, Nablus; Palestine.

^c Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America.

^d Also at Center for High Energy Physics, Peking University; China.

^e Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki; Greece.

^f Also at Centro Studi e Ricerche Enrico Fermi; Italy.

^g Also at CERN, Geneva; Switzerland.

^h Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.

ⁱ Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona; Spain.

^j Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.

^k Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva; Israel.

- ^l Also at Department of Physics, California State University, Sacramento; United States of America.
- ^m Also at Department of Physics, King's College London, London; United Kingdom.
- ⁿ Also at Department of Physics, Stanford University, Stanford CA; United States of America.
- ^o Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
- ^p Also at Department of Physics, University of Thessaly; Greece.
- ^q Also at Department of Physics, Westmont College, Santa Barbara; United States of America.
- ^r Also at Hellenic Open University, Patras; Greece.
- ^s Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
- ^t Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
- ^u Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.
- ^v Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
- ^w Also at Institute of Particle Physics (IPP); Canada.
- ^x Also at Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar; Mongolia.
- ^y Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
- ^z Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
- ^{aa} Also at L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France.
- ^{ab} Also at Lawrence Livermore National Laboratory, Livermore; United States of America.
- ^{ac} Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.
- ^{ad} Also at Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.
- ^{ae} Also at Technical University of Munich, Munich; Germany.
- ^{af} Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
- ^{ag} Also at TRIUMF, Vancouver BC; Canada.
- ^{ah} Also at Università di Napoli Parthenope, Napoli; Italy.
- ^{ai} Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.
- ^{aj} Also at Washington College, Chestertown, MD; United States of America.
- ^{ak} Also at Yeditepe University, Physics Department, Istanbul; Türkiye.
- * Deceased