



# Study of Z boson plus jets events using variables sensitive to double-parton scattering in pp collisions at 13 TeV

The CMS Collaboration\*

## Abstract

Double-parton scattering is investigated using events with a Z boson and jets. The Z boson is reconstructed using only the dimuon channel. The measurements are performed with proton-proton collision data recorded by the CMS experiment at the LHC at  $\sqrt{s} = 13$  TeV, corresponding to an integrated luminosity of  $35.9 \text{ fb}^{-1}$  collected in the year 2016. Differential cross sections of  $Z + \geq 1$  jet and  $Z + \geq 2$  jets are measured with transverse momentum of the jets above 20 GeV and pseudorapidity  $|\eta| < 2.4$ . Several distributions with sensitivity to double-parton scattering effects are measured as functions of the angle and the transverse momentum imbalance between the Z boson and the jets. The measured distributions are compared with predictions from several event generators with different hadronization models and different parameter settings for multiparton interactions. The measured distributions show a dependence on the hadronization and multiparton interaction simulation parameters, and are important input for future improvements of the simulations.

*Published in the Journal of High Energy Physics as doi:10.1007/JHEP10(2021)176.*



## 1 Introduction

Proton-proton (pp) collisions at high energies result in many events with a Z boson produced in association with jets at large transverse momentum  $p_T$ . The Z+jets process is an important background for many standard model (SM) measurements and searches for physics beyond the SM. Measurements of differential cross sections for Z boson production in association with jets can be used to test models of initial-state radiation, and multiparton interactions (MPI). Monte Carlo (MC) models are used to simulate collision processes and play a crucial role in understanding background for the new physics searches. The description of MPI is an important part of these simulations. However, MPI can not be completely described by perturbative quantum chromodynamics (QCD), so this requires a phenomenological description involving parameters that must be tuned with the help of data.

The ATLAS, CMS, and LHCb experiments have reported various measurements of Z+jets processes at centre-of-mass energies of 7 TeV [1–6], 8 TeV [7–9], and 13 TeV [10, 11]. Z boson production in association with jets is a process with a clean experimental signature and is well understood theoretically. In this paper, measurements of Z+jets events are performed to explore observables sensitive to the presence of MPI. A possible contribution could come from the simultaneous occurrence of two parton-parton interactions and is usually, when the involved scale is large, called double-parton scattering (DPS). This analysis explores new signatures sensitive to DPS in events with a Z boson and one or more jets, and compares the data with MC simulations, using a variety of event generators simulating Z+jets processes with different MPI and hadronization models.

The ATLAS, ALICE, CMS, and LHCb Collaborations have previously reported measurements of DPS in various topologies, such as WW [12], W+jets [13, 14], 4 jets [15], J/ $\psi$  production [16–19], double charm production [20, 21], but not in the Z+jets topology.

Figure 1 shows typical diagrams of single parton scattering (SPS) and DPS production of Z+2 jet events. In SPS, the Z boson decaying into two muons and the two jets come from the same parton-parton interaction, whereas in the case of DPS, the Z boson and the two jets originate from two independent interactions.

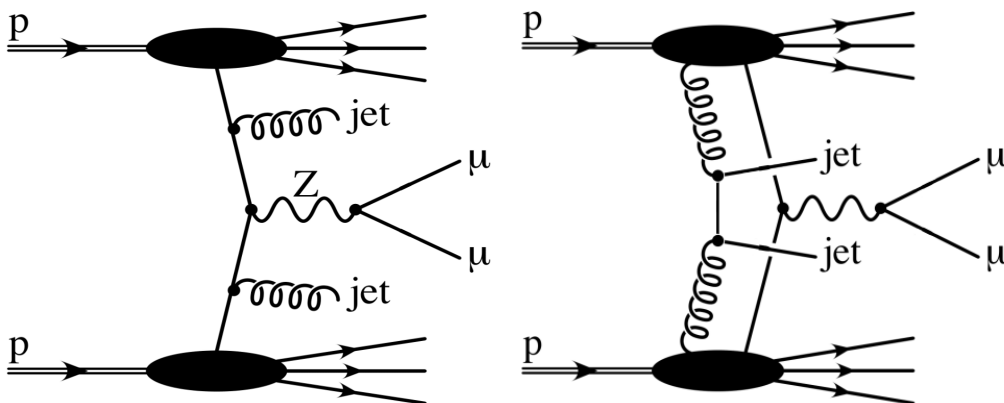


Figure 1: Typical diagrams for Z+2 jet production in a single (left) and double-parton (right) scattering process.

Events are categorized as  $Z + \geq 1$  jet and  $Z + \geq 2$  jets topologies, and the corresponding integrated cross sections are measured in a fiducial region. For consistency with previous DPS measurements at 7 TeV [13, 14], jets are required to have a  $p_T$  threshold of 20 GeV. Decreasing the jet  $p_T$  threshold would increase the DPS contribution, but will also lead to a significant

increase in the experimental uncertainties related to jet identification. With this threshold of 20 GeV, the DPS contribution is measured to be around 5.5% at 7 TeV [14] and, as estimated from simulation, at 13 TeV it is expected to increase by 20–30% because of the increased parton density. The differential cross sections are measured as functions of various observables based on the azimuthal ( $\phi$ , in radians) separation and the  $p_T$  balance between the Z boson and jets, as well as the  $p_T$  balance between two jets in case of  $Z + \geq 2$  jets events [13, 14, 22]. Since the two interactions in DPS are largely uncorrelated in the phase space studied, the shape of the distribution of these observables is expected to differ from that seen in SPS. Distributions of these observables normalized to the integrated cross section are measured because they have a lower systematic uncertainty due to the cancellation of the uncertainties correlated among bins. Previously measured distributions were used to extract parameters for DPS modelling in MC event generators [23, 24].

The measurement is performed using events where the Z boson decays into two oppositely charged muons. The pp collision data used in the analysis were collected in 2016 at  $\sqrt{s} = 13$  TeV, corresponding to an integrated luminosity of  $35.9 \text{ fb}^{-1}$ . Tabulated results are provided in the HEPDATA [25].

## 2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker covering a pseudorapidity region of  $|\eta| < 2.5$ , a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters, made of steel and quartz fibers, extend the  $\eta$  coverage provided by the barrel and endcap detectors to  $|\eta| < 5.0$ . Muons are measured in the range  $|\eta| < 2.4$ , with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers [26].

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of about 100 kHz within a latency of less than  $4 \mu\text{s}$  [27]. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [28].

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, is reported in Ref. [29].

## 3 Simulated event samples

MC event generators are used to simulate the signal and background contributions. These MC samples are employed to optimize the event selection, to validate simulated event samples, to estimate some background sources, and to extract the unfolding response matrices used to correct for detector effects in the measured distributions. In addition, MC generators with different MPI and hadronization models are used to compare with the measured distributions and to evaluate systematic uncertainties related to the model dependence.

The Z+jets events are simulated with MADGRAPH5\_aMC@NLO version 2.2.2 [30] (denoted MG5\_aMC). The calculation includes matrix elements (MEs) computed at next-to-leading-order (NLO) in perturbative QCD for the process  $pp \rightarrow Z + N$  jets,  $N = 0, 1, \text{ or } 2$ . The sample is

generated using the NNPDF 3.0 NLO parton distribution function (PDF) set [31]. An alternative simulation uses MG5\_aMC to calculate leading-order (LO) MEs for  $pp \rightarrow Z + N$  jets,  $N = 0, \dots, 4$ , and the NNPDF 3.0 LO PDF set.

The Z+jets process is also simulated with SHERPA v2.2 [32] with up to two additional parton emissions at NLO accuracy or up to four additional parton emissions at LO accuracy. The merging with the SHERPA parton shower is done via the MEPS@NLO prescription [33–35] using the five-flavour-number scheme, with a matching scale of 20 GeV. The NNPDF3.0 next-to-NLO (NNLO) set [31] and a dedicated set of tuned parton shower parameters [32] developed by the SHERPA authors are used.

Top quark-antiquark pair ( $t\bar{t}$ ) production, which forms the dominant background, is generated at NLO by MG5\_aMC. The diboson ( $WW, WZ, ZZ$ ) background processes are simulated at LO using PYTHIA8 v8.212 [36], and POWHEG 2.0 is used for the simulation of the single top quark processes ( $s$ -channel,  $t$ -channel, and  $tW$ ). The prediction for  $t\bar{t}$  production is normalized to NNLO in QCD including resummation of next-to-next-to-leading logarithmic soft-gluon terms with TOP++ 2.0 [37–43]. Diboson and single top quark background predictions are normalized to NLO [44] and NNLO [45] cross sections, respectively.

All samples, except those based on SHERPA, use PYTHIA8 to model the initial- and final-state parton showers and hadronization with the CUETP8M1 [24] or CUETP8M2T4 [46] tune. The CUETP8M1 tune includes the NNPDF 2.3 [47] LO PDF set with the strong coupling  $\alpha_S(m_Z)$  set to 0.1365 for space- and time-like shower simulation. The CUETP8M2T4 tune is based on the CUETP8M1 tune, which includes the NNPDF30\_lo\_as.0130 PDF set, but uses a lower value of  $\alpha_S = 0.1108$  for the initial-state radiation component of the parton shower. Matching between the ME generators and the parton shower is done using the  $k_T$ -MLM scheme [48, 49] with the matching scale set at 19 GeV for the LO MG5\_aMC sample, and the FxFx [50] scheme with the matching scale set to 30 GeV for the NLO MG5\_aMC events.

Generated events are processed through a full GEANT4-based [51] CMS detector simulation and trigger emulation. The simulated samples include the effects of multiple interactions in each bunch crossing, referred to as pileup. The simulated events are reconstructed with the same algorithm used for the data.

In addition to the Z+jets MG5\_aMC samples with the CUETP8M1 tune described above, the measurements are compared with simulations using different PYTHIA8 tunes, such as CP5 [23], CP5 without MPI, and CDPSTP8S1-Wj [24]. The CP5 tune uses NNPDF3.1 PDF set at NNLO, with  $\alpha_S$  values of 0.118, and running according to NLO evolution. The CP5 tune is chosen since it is the standard tune obtained by fitting a large number of 1.96, 7, and 13 TeV measurements sensitive to soft and semihard multipartonic interactions [23]. The W+dijet DPS tune, CDPSTP8S1-Wj is derived from the parameters of PYTHIA8 tune 4C, with a variation of the impact parameter dependence, i.e. matter overlap function, which is the convolution of the matter distributions of the two incoming hadrons. The DPS simulation in MC is usually quantified in terms of a parameter known as effective cross section  $\sigma_{\text{eff}}$ . In PYTHIA8, the value of  $\sigma_{\text{eff}}$  is calculated by dividing the nondiffractive (ND) cross section by the so-called “enhancement factor”, which depends on the parameters of the overlap matter distribution function and the limiting value of  $p_T$  at a reference energy [52]. For central collisions, the enhancement factor tends to be large, translating to a lower value of  $\sigma_{\text{eff}}$  and larger DPS contribution. For peripheral interactions, enhancement factors are small, giving large values of  $\sigma_{\text{eff}}$  and a small DPS contribution.

The Z+jets events calculated at NLO with MG5\_aMC are also interfaced with HERWIG7, apply-

Table 1: Summary of event generators with their k-factors (ratio of NNLO to NLO/LO cross section), PDF sets, and tunes used to produce both the signal and background event samples.

Process name	Event generator (k-factor)	Tune	PDF set
Z+jets	MG5_aMC (NLO) + PYTHIA8 (1.07)	CUETP8M1	NNPDF 3.0 NLO for matrix element NNPDF 2.3 LO for tune
Z+jets	MG5_aMC (LO) + PYTHIA8 (1.24)	CUETP8M1	NNPDF 3.0 LO for matrix element NNPDF 2.3 LO for tune
Z+jets	SHERPA (NLO) (0.97)	—	NNPDF 3.0 NNLO
Z+jets	MG5_aMC (NLO) + PYTHIA8 (1.07)	CP5	NNPDF 3.0 NLO for matrix element NNPDF 3.1 NNLO for tune
Z+jets	MG5_aMC (NLO) + PYTHIA8 MPI-OFF (1.07)	CP5	NNPDF 3.0 NLO for matrix element NNPDF 3.1 NNLO for tune
Z+jets	MG5_aMC (NLO) + PYTHIA8 (1.09)	CDPSTP8S1-Wj	NNPDF 3.0 NLO for matrix element CTEQ6L1 LO for tune
Z+jets	MG5_aMC (NLO) + HERWIG7 (1.02)	CH3	NNPDF 3.0 NLO for matrix element NNPDF 3.1 LO/NNLO for tune
t $\bar{t}$	MG5_aMC (NLO) + PYTHIA8 (—)	CUETP8M2T4	NNPDF 3.0 NLO for matrix element NNPDF30_lo_as_0130 for tune
Diboson	PYTHIA8 (LO) (—)	—	NNPDF 2.3 LO
Single top	POWHEG (NLO) + PYTHIA8 (—)	CUETP8M1	NNPDF 3.0 NLO for matrix element NNPDF 2.3 LO for tune

ing the CH3 tune for the underlying event description, hadronization, and showering [53–56]. The tune is derived by fitting measurements from pp collision data collected by the CMS experiment at  $\sqrt{s} = 0.9, 7, \text{ and } 13 \text{ TeV}$ . The CH3 tune makes use of the NNPDF3.1 LO PDF set with  $\alpha_S = 0.130$  for the simulation of MPI, but the NNLO PDF set with  $\alpha_S = 0.118$  for all other components. The cross sections of Z+jets events simulated with different MC event generators and configurations are normalized to NNLO calculations with FEWZ v3.1 [57]. Table 1 summarizes all the event generators, PDF sets, and tunes used to produce both signals (including alternative samples), and the background processes.

## 4 Event selection

The particle flow (PF) algorithm [58] is used to reconstruct and identify individual particle candidates in an event, with an optimized combination of information from the various elements of the CMS detector. Energy deposits are measured in the calorimeters and charged particles are identified in the central tracking and muon systems.

Events are selected with a single-muon trigger requiring at least one isolated muon candidate with  $p_T > 24 \text{ GeV}$ . The primary vertex is the vertex candidate with the largest value of summed physics-object  $p_T^2$ . The physics objects are the track-only jets, clustered using the jet finding anti- $k_T$  algorithm [59, 60] with the tracks assigned to candidate vertices as inputs, and the associated missing  $p_T$ , which is the negative vector  $p_T$  sum of all physics objects. Events are required to have at least two oppositely charged muons with  $p_T > 27 \text{ GeV}$  and  $|\eta| < 2.4$ . These muons are reconstructed by combining information from the inner tracker and the muon detector subsystems. The muon candidates are required to satisfy identification criteria based on the number of hits in each detector, the quality of the muon-track fit, and the consistency with the primary vertex, which is imposed by requiring the longitudinal and transverse impact parameters are less than 0.5 and 0.2 cm, respectively. The efficiency to reconstruct and identify the muons is greater than 96%. Matching muon candidates to tracks measured in the silicon tracker results in a relative  $p_T$  resolution for muons with  $20 < p_T < 100 \text{ GeV}$  of 1% in the barrel and 3% in the endcaps.

To suppress the multijet background, muons are required to be isolated. The relative isolation

variable,  $I_{\text{rel}}$ , for muons is defined as:

$$I_{\text{rel}} = \frac{[\sum p_{\text{T}}^{\text{charged}} + \max(0., \sum E_{\text{T}}^{\text{neutral}} + \sum E_{\text{T}}^{\gamma} - 0.5 \sum p_{\text{T}}^{\text{PU}})]}{p_{\text{T}}^{\mu}}. \quad (1)$$

Here  $\sum E_{\text{T}}^{\text{neutral}}$  and  $\sum E_{\text{T}}^{\gamma}$  are the transverse energy sums of neutral hadrons and photons, respectively, within a cone of radius  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$  around the muon track. The quantity  $\sum p_{\text{T}}^{\text{charged}}$  represents the  $p_{\text{T}}$  sum of the charged hadrons in the same cone around the muon associated with the selected vertex. Finally,  $\sum p_{\text{T}}^{\text{PU}}$  is the  $p_{\text{T}}$  sum of the charged hadrons in the same cone around the muon not associated with the selected vertex. A muon is considered isolated if  $I_{\text{rel}} < 0.2$ . There are small residual differences in the trigger, identification and isolation efficiencies between data and simulation, which are measured using the ‘‘tag-and-probe’’ method [61], and included by applying scale factors to simulated events [26].

To select Z boson candidate events, the invariant mass of the two oppositely charged muons with highest  $p_{\text{T}}$  is required to be close to the Z boson mass,  $70 < m_{\mu^+\mu^-} < 110$  GeV. The Z boson candidate is required to be accompanied by at least one jet with  $p_{\text{T}} > 20$  GeV and  $|\eta| < 2.4$ . The overlap between the muons from the Z boson decay and the jets is removed by requiring a minimum  $\Delta R$  distance of 0.4 between them.

Jets are clustered from PF candidates using the infrared- and collinear-safe anti- $k_{\text{T}}$  algorithm [59] with a distance parameter of 0.4, as implemented in the FASTJET package [60]. The jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5 to 10% of the true momentum over the entire  $p_{\text{T}}$  spectrum and detector acceptance. Pileup can contribute additional tracks and calorimetric energy depositions, increasing the apparent jet momentum. To mitigate the effects of pileup, tracks identified as originating from pileup vertices are discarded, and a factor [62] is applied to correct for the remaining contributions. Jet energy corrections are derived from simulation studies so that the average measured response of jets becomes identical to that of particle-level jets. In situ measurements of the momentum balance in dijet, multijet, photon+jet, and Z+jets events with the Z boson decaying leptonically are used to correct residual differences between the jet energy scales in data and simulation [63, 64]. The jet energy in simulation is spread to match the resolution observed in data. The jet energy resolution (JER) in data amounts typically to 15–20% at jet energy of 30 GeV, 10% at 100 GeV, and 5% at 1 TeV. Additional selection criteria are applied to remove jets potentially dominated by anomalous contributions from various subdetector components or reconstruction failures [65]. Jets identified as being likely to originate from pileup [66, 67] are also removed by using a pileup jet ID discriminator for jets with  $20 < p_{\text{T}} \leq 50$  GeV. No pileup jet ID is applied to jets with  $p_{\text{T}} \geq 50$  GeV, since here the pileup event contribution is negligible [67].

The selected events correspond to a sample of Z+jets events with a background of 2–5%, which is subtracted from the data before the unfolding. The dominant contribution is the production of  $t\bar{t}$  pairs. The simulation of  $t\bar{t}$  production is validated with data in a  $t\bar{t} \rightarrow e\mu + X$  control region. The  $t\bar{t}$  control region is constructed using data events by requiring an oppositely charged electron-muon pair with at least one jet. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track [68]. The longitudinal and transverse impact parameters for barrel (endcap) are required to be less than 0.10 (0.20) and 0.05 (0.10) cm, respectively. Electrons are required to have  $p_{\text{T}} > 27$  GeV and  $|\eta| < 2.4$ . The selection criteria for muons and jets are the same as discussed above. The invariant mass of

the oppositely charged  $e\mu$  pair is required to lie within the range of  $70 < m_{e\mu} < 110$  GeV. The difference in the data to simulation comparison in this control region is included as a part of the systematic uncertainty.

## 5 Observables and the unfolding

Events are categorized in the  $Z+ \geq 1$  jet and  $Z+ \geq 2$  jets subsets, and the differential cross sections are measured as function of the following observables:

### 1. $Z+ \geq 1$ jet events

- Azimuthal angle between the Z boson and the highest  $p_T$  (leading) jet:  $\Delta\phi(Z, j_1)$ . For SPS events, the Z boson and the leading jet will balance each other, hence this observable will peak around  $\pi$ , whereas for the DPS process the distribution is expected to be flat because of the absence of a correlation between the Z boson and the leading jet produced from the two different scatterings.
- Relative  $p_T$  imbalance between the Z boson and leading jet is

$$\Delta_{\text{rel}} p_T(Z, j_1) = \frac{|\vec{p}_T(Z) + \vec{p}_T(j_1)|}{|\vec{p}_T(Z)| + |\vec{p}_T(j_1)|}. \quad (2)$$

This observable is expected to be close to zero for SPS events, whereas in the case of DPS this observable will have higher values.

### 2. $Z+ \geq 2$ jets events

- Azimuthal angle between the Z boson and dijet system:  $\Delta\phi(Z, \text{dijet})$ . Here, dijet means the resulting three-momentum of the leading and subleading jets. For SPS events, the dijet system  $p_T$  will balance the Z boson  $p_T$ , therefore, this observable will peak around  $\pi$ . In the case of DPS production, the distribution is expected to be flat since the Z boson and the two jets are originating from two independent scatterings.
- Relative  $p_T$  imbalance between the Z boson and dijet system is

$$\Delta_{\text{rel}} p_T(Z, \text{dijet}) = \frac{|\vec{p}_T(Z) + \vec{p}_T(\text{dijet})|}{|\vec{p}_T(Z)| + |\vec{p}_T(\text{dijet})|}. \quad (3)$$

For SPS events this observable is expected to be 0, whereas for DPS events this observable will have higher values.

- Relative  $p_T$  imbalance between the leading ( $j_1$ ) and subleading ( $j_2$ ) jets is

$$\Delta_{\text{rel}} p_T(j_1, j_2) = \frac{|\vec{p}_T(j_1) + \vec{p}_T(j_2)|}{|\vec{p}_T(j_1)| + |\vec{p}_T(j_2)|}. \quad (4)$$

For DPS events, the two jets are expected to balance each other, therefore this observable will be around 0. For SPS events, the two jets are correlated with the Z boson and not expected to balance each other.

The reconstructed distributions are corrected for the event selection efficiency and detector resolution using an unfolding technique that employs a response matrix to map the reconstructed observables onto the particle-level values. The unfolding is done with 20 detector-level and 10



particle-level  $\Delta\phi$  or  $\Delta_{\text{rel}}p_{\text{T}}$  bins. The unfolding is performed using the TUNFOLD package [69], which is based on a least squares fit with a possible Tikhonov regularization term [70]. Since the effect of regularization is minimal on the reported observables, the unfolding is performed without regularization.

The Z+jets events simulated with MG5\_aMC + PYTHIA8 with tune CUETP8M1 are used to construct the response matrix. At particle level, events are required to have at least two oppositely charged muons with  $p_{\text{T}} > 27 \text{ GeV}$  and  $|\eta| < 2.4$ . The particle-level definition of a muon corresponds to a generator-level muon coming from the Z boson decay, “dressed” by adding the momenta of all photons within  $\Delta R < 0.1$  around both muon directions to account for the FSR effects [71]. The particle-level jets with  $p_{\text{T}} > 20 \text{ GeV}$  and  $|\eta| < 2.4$  are formed from stable particles ( $c\tau > 1 \text{ cm}$ ), except neutrinos, using the same anti- $k_{\text{T}}$  jet algorithm as for reconstructed jets. A possible overlap between particle-level jets and a pair of muons from the Z boson decay is removed by requiring a minimum distance of 0.4 between them. The distributions are unfolded to the particle level in the fiducial region defined in Table 2.

Table 2: Fiducial selections at particle level.

Object	Selections
Muons (dressed)	$p_{\text{T}} > 27 \text{ GeV},  \eta  < 2.4$
Z boson	$70 < m_{\mu^+\mu^-} < 110 \text{ GeV}$
At least 1 jet	$p_{\text{T}} > 20 \text{ GeV},  \eta  < 2.4$

In simulation, the reconstructed jets and a pair of muons are spatially matched to the corresponding particle-level objects by requiring that they are within  $\Delta R$  of 0.4 from one another. Events that have reconstructed objects without matched particle-level objects are included in the background category and are excluded from the sample. This contribution includes the events where the selected jets originate from pileup. The contribution of background with no jet at particle level, but at least one jet at the reconstructed level is about 4.1%. The contribution of background with no jet (1 jet) at particle level and at least 2 jets at the reconstruction level is around 1.1 (4.8)%. The simulation of pileup jets is validated in a control region enriched in pileup jets, obtained by inverting the criteria used to reject the pileup jets. The simulation describes the data well, within the uncertainties, in the pileup-enriched control region, validating the simulation of background events from pileup.

Events that have particle-level objects in the fiducial volume, but no matching reconstructed objects, are accounted for with acceptance and efficiency corrections. In addition, there may be events in which the particle-level jet passing the fiducial selection does not lead to a reconstructed level jet that passes the fiducial selection. Events of this type are considered as background at the reconstruction level and are not considered. However, at the generator level, these are genuine signal events missed because of the detector and reconstruction inefficiencies. These missed events are accounted for via a signal acceptance correction.

Finally, the unfolded distributions are scaled with the inverse of the integrated luminosity to obtain the differential cross section.

## 6 Systematic uncertainties

The measurements have various sources of systematic uncertainties.

- Jet energy resolution and scale: The effect of the uncertainty in jet energy scale (JES) or JER [63, 64] is evaluated by varying the JES or JER within the associated uncertainty and performing the unfolding procedure with the modified distribution. The

variations of JES corrections within their uncertainties change the differential cross sections by 2–8%, whereas the area-normalized distributions are affected by up to 4%. The variations of JER corrections within their uncertainty change the differential cross section distributions by 1–7% and area-normalized distributions up to 5%.

- Pileup jet identification: Simulated events are corrected for the differences in the jet identification efficiency between data and simulated events. The uncertainties in these corrections affect the measurements by up to 1–2% for differential cross section distributions and less than 0.5% for area-normalized distributions.
- Closure uncertainty: The effect of model dependence is evaluated by comparing unfolded results obtained using response matrices constructed with the MG5\_aMC + PYTHIA8 with tune CUETP8M1 and SHERPA generators having different ME and parton showering, as discussed in Section 3. The calculated uncertainty is then symmetrized.

The effect of scale uncertainties is estimated using a set of generator weights that correspond to variations of renormalization ( $\mu_F$ ) and factorization ( $\mu_R$ ) scales up and down by factors of 2 from their nominal values, excluding the pair of extreme variations. The unfolded distributions are obtained for all such combinations and their envelope is quoted as the uncertainty.

The uncertainty in the PDFs is estimated using the 100 replicas of the NNPDF 3.0 PDF set [72]. The unfolded distributions are reproduced using the weights of the replicas and a standard deviation is computed on a bin-by-bin basis [72].

These sources, added in quadrature, affect the differential cross section by 1–5% and area-normalized distributions up to 1–4% in the case of  $Z+ \geq 1$  jet events, whereas the effect is within 9% for the differential cross section and up to 7% for the area-normalized distribution in the case of  $Z+ \geq 2$  jet events.

- Integrated luminosity: It is determined with a 2.5% [73] uncertainty for differential cross section distributions, but completely cancels in the area normalized distributions.
- Pileup weighting: The distribution of the mean number of interactions per bunch crossing of the simulated samples is weighted to match that of the data. The uncertainty related to pileup weighting is estimated by varying the total inelastic cross section by  $\pm 4.6\%$  [74]. The effect is negligible for both the differential and area-normalized distributions. After the pileup weighting, the vertex multiplicity in simulation shows overall good agreement with data, but there is an overestimation of around 40% for high vertex multiplicities. To investigate the effect of this residual discrepancy, the simulated events are additionally corrected to reproduce the vertex multiplicity distributions observed in data. The data are unfolded with the weighted response matrix, and the results are compared with the unfolded results without weighting. These sources, added in quadrature, affect the differential cross section by 1.0–1.5% and area-normalized distributions up to 1%.
- Muon selection: The systematic uncertainty related to various muon selection criteria such as muon identification, isolation and trigger scale factors is less than 1% for both differential cross section and area-normalized distributions.

The effect of the muon momentum corrections on the measurement is very small ( $< 0.1\%$ ), therefore no additional systematic uncertainty is assigned.

- Background modelling: There is a small contribution from  $t\bar{t}$  events, whereas the contribution from other processes such as dibosons,  $W$ +jets, and QCD multijet pro-

duction is smaller than 1%. To calculate the systematic uncertainty related to the simulated background contribution, the cross sections of the background samples are varied by their uncertainties. The systematic uncertainty related to the  $t\bar{t}$  process is obtained from the differences between data and simulation in a  $t\bar{t} \rightarrow e\mu + X$  control region. The variation of the background contribution within the uncertainties affects the differential cross section less than 0.2% for  $Z+ \geq 1$  jet and less than 0.6% for  $Z+ \geq 2$  jets events. The effect of this variation on the area-normalized distributions is less than 0.2%.

Tables 3 and 4 summarize the effect of various systematic uncertainties for the differential cross section and the normalized distributions. These systematic uncertainties are considered uncorrelated and are added in quadrature.

Table 3: Uncertainty sources and their effect on the differential cross section distributions.

Observable/Uncertainty	$\Delta\phi(Z, j_1)$	$\Delta_{\text{rel}}p_T(Z, j_1)$	$\Delta\phi(Z, \text{dijet})$	$\Delta_{\text{rel}}p_T(Z, \text{dijet})$	$\Delta_{\text{rel}}p_T(j_1, j_2)$
JES	2.7–7.5%	2.4–7.4%	4.9–7.9%	4.5–8.4%	4.4–7.3%
JER	0.9–6.6%	1.4–5.8%	1.2–7.2%	2.1–5.1%	1.1–4.2%
Pileup jet identification	1.3–1.7%	0.9–1.6%	1.7–2.1%	1.6–2.1%	1.7–2.3%
Integrated luminosity	2.5%	2.5%	2.5%	2.5%	2.5%
Pileup modelling	0.1–0.7%	0.2–1.0%	0.2–1.4%	0.4–1.4%	0.8–1.4%
Closure uncertainty	0.6–4.0%	0.8–5.1%	2.7–6.1%	2.2–8.7%	2.2–8.7%
Muon selection	<1.0%	<1.0%	<1.0%	<1.0%	<1.0%
Background modelling	<0.2%	<0.2%	<0.6%	<0.6%	<0.4%
Total	4–11%	4–10%	8–14%	8–14%	7–11%

Table 4: Uncertainty sources and their effect on the area-normalized distributions.

Observable/Uncertainty	$\Delta\phi(Z, j_1)$	$\Delta_{\text{rel}}p_T(Z, j_1)$	$\Delta\phi(Z, \text{dijet})$	$\Delta_{\text{rel}}p_T(Z, \text{dijet})$	$\Delta_{\text{rel}}p_T(j_1, j_2)$
JES	0.1–3.8%	0.7–3.7%	0.6–4.0%	0.3–2.6%	0.3–1.5%
JER	0.3–4.6%	0.4–4.4%	1.3–4.4%	0.2–4.8%	0.2–1.7%
Pileup jet identification	0.1–0.2%	0.1–0.2%	0.1–0.2%	0.1–0.2%	0.1–0.4%
Pileup modelling	0.1–0.5%	0.1–0.5%	0.1–1%	0.1–0.8%	0.2–0.4%
Closure uncertainty	0.8–2.5%	0.9–3.6%	0.3–5.0%	0.4–6.7%	0.5–3.7%
Muon selection	<1.0%	<1.0%	<1.0%	<1.0%	<1.0%
Background modelling	<0.1%	<0.1%	<0.2%	<0.2%	<0.2%
Total	1–6%	1–6%	2–7%	1–7%	1–4%

## 7 Results

The production cross sections in the fiducial region defined in Table 2 are measured to be  $158.5 \pm 0.3$  (stat)  $\pm 7.0$  (syst)  $\pm 1.2$  (theo)  $\pm 4.0$  (lumi) pb for  $Z+ \geq 1$  jet events and  $44.8 \pm 0.4$  (stat)  $\pm 3.7$  (syst)  $\pm 0.5$  (theo)  $\pm 1.1$  (lumi) pb for  $Z+ \geq 2$  jet events. The measured cross sections are described, within the uncertainties, by different simulations, except for the MG5\_aMC + PYTHIA8 with CP5 tune MPIOFF and the DPS-specific CDPSTP8S1-WJ tune. The cross section of the DPS-specific tune is predicted to be 10% higher than the measured cross section. The cross section of CP5 tune without MPI underestimates the measured cross section up to 10% for  $Z+ \geq 1$  jet events and up to 16% for  $Z+ \geq 2$  jet events. Table 5 summarizes the measured and predicted cross sections for the  $Z+ \geq 1$  jet and  $Z+ \geq 2$  jet processes.

For  $Z+ \geq 1$  jet events, Fig. 2 (3) shows the differential cross section measurements (left) and the area-normalized distributions (right) as a function of  $\Delta\phi(Z, j_1)$  ( $\Delta_{\text{rel}}p_T(Z, j_1)$ ), respectively.

Table 5: Measured and predicted cross section for  $Z+ \geq 1$  jet and  $Z+ \geq 2$  jet production. Simulations are normalized to NNLO calculations (from FEWZ) and reported cross section values are extracted by applying fiducial selections. Predicted cross sections include statistical and theoretical uncertainties added in quadrature for MG5\_aMC + PYTHIA8 with CP5 tune, whereas the other predicted cross sections are reported with only statistical uncertainties.

Cross section (pb)	$Z+ \geq 1$ Jets	$Z+ \geq 2$ Jets	
Measured in data	$158.5 \pm 0.3$ (stat) $\pm 7.0$ (syst) $\pm 1.2$ (theo) $\pm 4.0$ (lumi) pb	$44.8 \pm 0.4$ (stat) $\pm 3.7$ (syst) $\pm 0.5$ (theo) $\pm 1.1$ (lumi) pb	
Predicted by MC			
MG5_aMC (NLO)	PYTHIA8, CP5 tune	$167.4 \pm 9.7$	$47.0 \pm 3.9$
	PYTHIA8, CP5 tune MPIOFF	$143.8 \pm 0.3$	$37.7 \pm 0.2$
	PYTHIA8, CDPSTP8S1-WJ tune	$178.4 \pm 0.3$	$50.5 \pm 0.2$
	HERWIG7, CH3 tune	$158.3 \pm 1.1$	$44.4 \pm 0.6$
MG5_aMC (LO) + PYTHIA8, CP5 tune	$161.2 \pm 0.1$	$45.3 \pm 0.1$	
SHERPA (NLO+LO)	$149.8 \pm 0.2$	$41.6 \pm 0.1$	

Different MC event generators (except for the MG5\_aMC + PYTHIA8 with the DPS-specific tune CDPSTP8S1-WJ) describe, within the uncertainties, the overall differential cross section as a function of  $\Delta\phi$  and  $\Delta_{\text{rel}}p_T$ , apart from a few discrepancies in some specific regions of these observables. MG5\_aMC + PYTHIA8 generator prediction with the DPS-specific tune CDPSTP8S1-WJ overestimates the cross section up to 10–20%, but correctly describe the shapes of the  $\Delta\phi$  and  $\Delta_{\text{rel}}p_T$  distributions. The MG5\_aMC + PYTHIA8 prediction (with CP5 tune) overestimates (up to 20%) the measurement in the lower- $\Delta_{\text{rel}}p_T$ , where SPS is expected to be dominant. The prediction of MG5\_aMC + HERWIG7 describes, within the uncertainties, the shape of the  $\Delta_{\text{rel}}p_T$  distribution, but deviates up to 15–20% in the lower- $\Delta\phi$  region where DPS is expected to contribute more.

The  $Z$ +jets calculation of MG5\_aMC + PYTHIA8 without MPI does not describe the measurement and is lower than the measurement by up to 50% in both the lower  $\Delta\phi$  and higher  $\Delta_{\text{rel}}p_T$  regions, where the MPI contribution is expected to be the largest.

For  $Z+ \geq 2$  jet events Fig. 4 (5) shows the differential cross section measurements (left) and the area-normalized distributions (right) as a function of  $\Delta\phi(Z, \text{dijet})$  ( $\Delta_{\text{rel}}p_T(Z, \text{dijet})$ ), respectively. The differential cross section, as a function of  $\Delta\phi$ , is reasonably well described by the different predictions. The predictions of MG5\_aMC + PYTHIA8 (with the CDPSTP8S1-WJ tune) and SHERPA best describe the shape of the measured distributions, whereas the MG5\_aMC + PYTHIA8 (with CP5 tune) prediction deviates by up to 15% in the lower- $\Delta\phi$  region, where DPS production of  $Z$ +jets is expected to contribute more. The shape of the  $\Delta_{\text{rel}}p_T$  distribution is best described by the predictions of MG5\_aMC + PYTHIA8 (with the CDPSTP8S1-WJ tune) and SHERPA. The MG5\_aMC + PYTHIA8 (with CP5 tune) prediction overestimates, up to 20%, in the lower- $\Delta_{\text{rel}}p_T$  region.

The differential cross section as a function of  $\Delta_{\text{rel}}p_T$  between two jets, as shown in Fig. 6, is well described by the different predictions except for MG5\_aMC + PYTHIA8 (with the CDPSTP8S1-WJ tune), which overestimates the differential cross section measurements up to 15%. The shape of the  $\Delta_{\text{rel}}p_T$  distribution is described well by the predictions presented, except some deviations shown by MG5\_aMC + HERWIG7 mainly in the higher region of the distribution. If MPI is not included in the simulation, predictions underestimate the differential cross section and fail to describe the shape of all the observables for  $Z+ \geq 2$  jet events with deviations up to

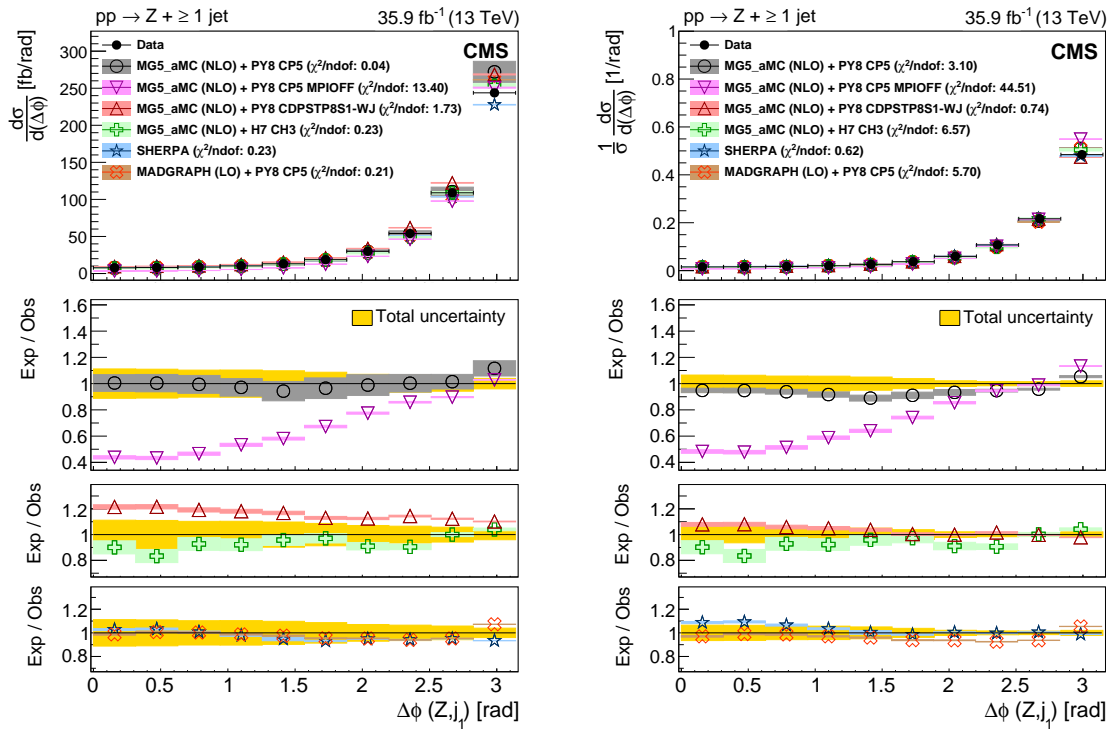


Figure 2: Differential cross sections (left) and area-normalized distributions (right) as functions of  $\Delta\phi$  between the Z boson and the leading jet for  $Z + \geq 1$  jet events. The uncertainties in the predictions are shown as coloured bands around the theoretical predictions including statistical, PDF, scale, and tune uncertainties for the NLO MG5\_aMC + PYTHIA8 (with CP5 tune) and the statistical uncertainty only for the LO MG5\_aMC + PYTHIA8 (with CP5 tune), NLO MG5\_aMC + PYTHIA8 (with CDPSTP8S1-WJ tune, CP5 tune with MPI-OFF), NLO MG5\_aMC + HERWIG7 (with tune CH3), and SHERPA predictions. In the top panel, the vertical bars on the data points represent statistical uncertainties, whereas in the bottom panels, the total uncertainty in data is indicated by the solid yellow band centred at 1. In the legend, the  $\chi^2$  per degree of freedom is given to quantify the goodness of fit of the model to the data.



50%.

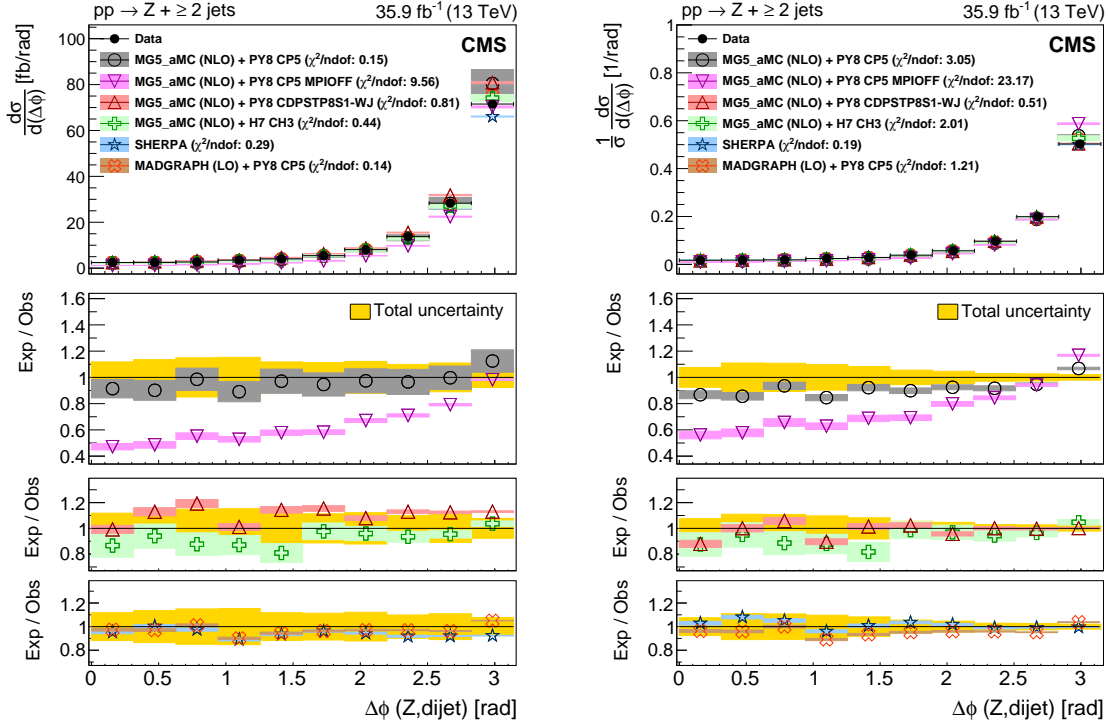


Figure 4: Differential cross sections (left) and area-normalized distributions (right) as functions of  $\Delta\phi$  between the Z boson and the dijet for  $Z + \geq 2$  jet events. The uncertainties in the predictions are shown as coloured bands around the theoretical predictions including statistical, PDF, scale and tune uncertainties for the NLO MG5\_aMC + PYTHIA8 (with CP5 tune) and the statistical uncertainty only for the LO MG5\_aMC + PYTHIA8 (with CP5 tune), NLO MG5\_aMC + PYTHIA8 (with CDPSTP8S1-WJ tune, CP5 tune with MPI-OFF), NLO MG5\_aMC + HERWIG7 (with tune CH3), and SHERPA predictions. In the top panel, the vertical bars on the data points represent statistical uncertainties, whereas in the bottom panels, the total uncertainty in data is indicated by the solid yellow band centred at 1. In the legend, the  $\chi^2$  per degree of freedom is given to quantify the goodness of fit of the model to the data.

The model parameters for different MPI and hadronization models are mostly derived by fitting minimum bias and low- $p_T$  ( $\lesssim 3$  GeV) MPI measurements. From the above data, it is clear that our measurements can test the accuracy of various predictions and the simulation of MPI. Most of the predictions follow a similar trend describing the differential cross sections and area-normalized distributions with a few exceptions.

The PYTHIA8 CP5 tune (with MPI) describes the differential cross section measurements within the uncertainty, but deviate (up to 15–20%) from the measurements in the lower-region of  $\Delta_{\text{rel}}p_T(Z, j_1)$  and  $\Delta_{\text{rel}}p_T(Z, \text{dijet})$ , where SPS is expected to be dominant. In the case of area-normalized distributions, the prediction from the MG5\_aMC + PYTHIA8 CP5 tune (with MPI) describes the shape of the  $\Delta_{\text{rel}}p_T(j_1, j_2)$  distribution within the uncertainty, but overestimates in the lower-region of  $\Delta_{\text{rel}}p_T(Z, j_1)$  and  $\Delta_{\text{rel}}p_T(Z, \text{dijet})$ , but underestimate otherwise. The LO calculations with MG5\_aMC + PYTHIA8 provide a similar agreement as obtained by the NLO calculation. The MG5\_aMC + HERWIG7 prediction describes the measurements within the uncertainty except some deviations in describing the shapes of the  $\Delta\phi(Z, j_1)$  and  $\Delta_{\text{rel}}p_T(j_1, j_2)$  distributions. The SHERPA prediction is in reasonable agreement with the measurements within the uncertainty.

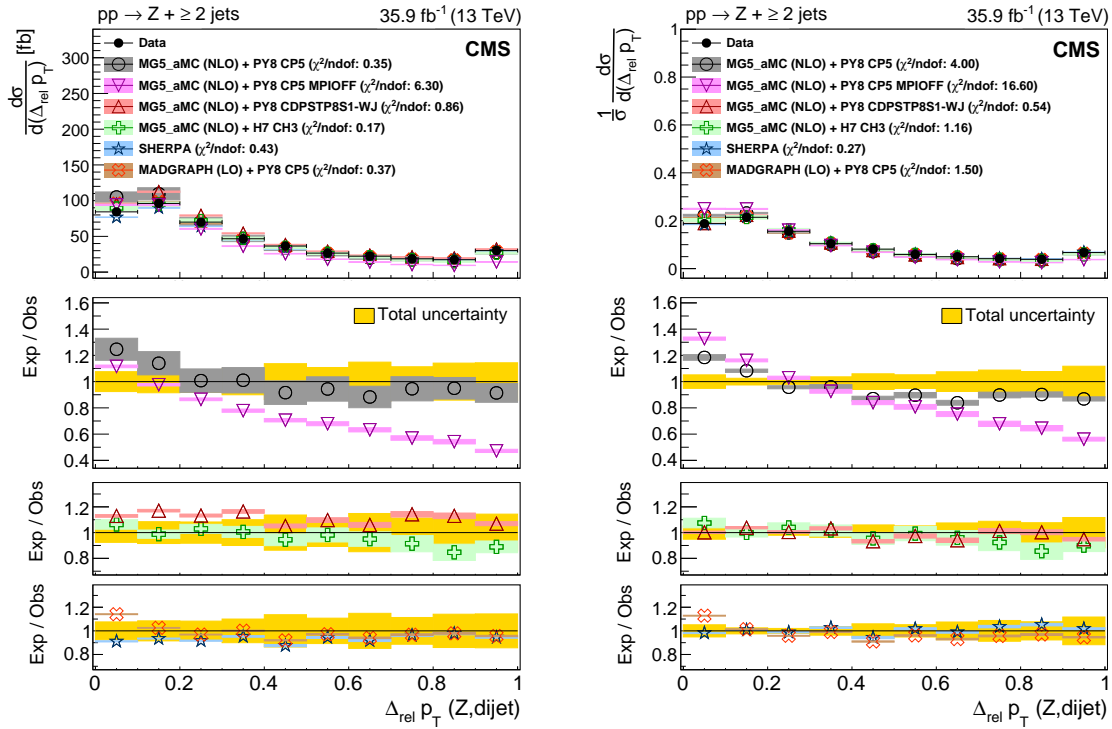


Figure 5: Differential cross sections (left) and area-normalized distributions (right) as functions of the  $p_T$  imbalance between the Z boson and the dijet for  $Z + \geq 2$  jet events. The uncertainties in the predictions are shown as coloured bands around the theoretical predictions including statistical, PDF, scale, and tune uncertainties for the NLO MG5\_aMC + PYTHIA8 (with CP5 tune) and the statistical uncertainty only for the LO MG5\_aMC + PYTHIA8 (with CP5 tune), NLO MG5\_aMC + PYTHIA8 (with CDPSTP8S1-WJ tune, CP5 tune with MPI-OFF), NLO MG5\_aMC + HERWIG7 (with tune CH3), and SHERPA predictions. In the top panel, the vertical bars on the data points represent statistical uncertainties, whereas in the bottom panels, the total uncertainty in data is indicated by the solid yellow band centred at 1. In the legend, the  $\chi^2$  per degree of freedom is given to quantify the goodness of fit of the model to the data.



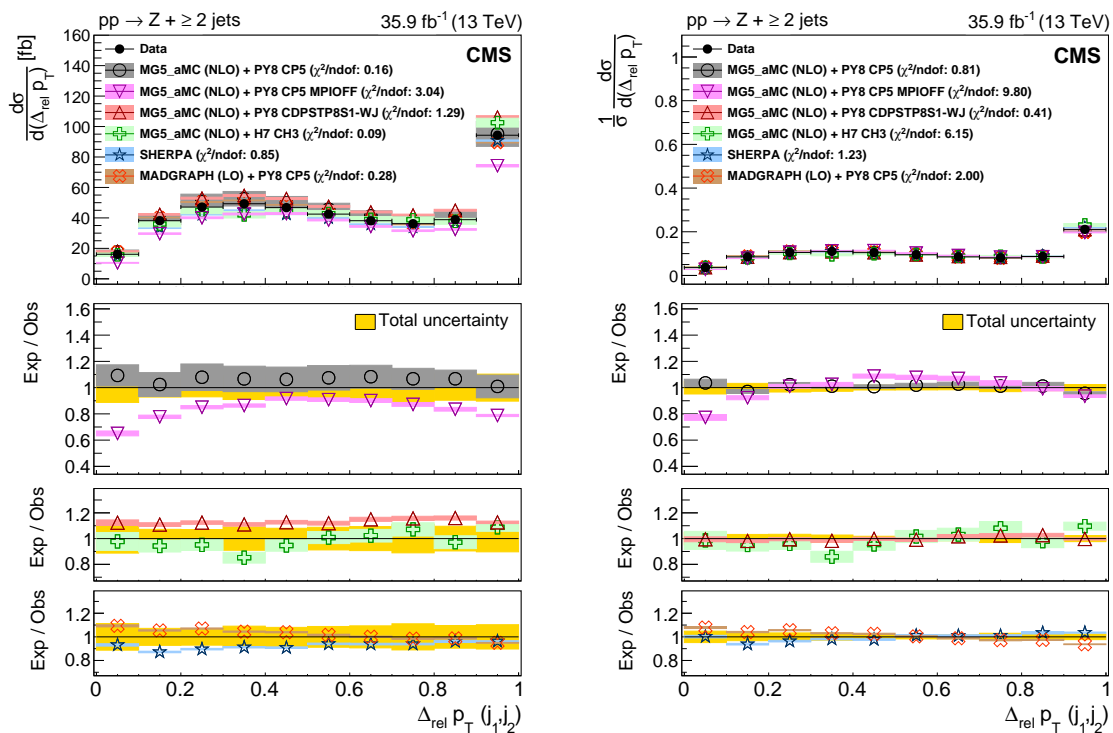


Figure 6: Differential cross sections (left) and area-normalized distributions (right) as functions of the  $p_T$  imbalance between leading and subleading jets for  $Z + \geq 2$  jet events. The uncertainties in the predictions are shown as coloured bands around the theoretical predictions including statistical, PDF, scale, and tune uncertainties for the NLO MG5\_aMC + PYTHIA8 (with CP5 tune) and the statistical uncertainty only for the LO MG5\_aMC + PYTHIA8 (with CP5 tune), NLO MG5\_aMC + PYTHIA8 (with CDPSTP8S1-WJ tune, CP5 tune with MPI-OFF), NLO MG5\_aMC + HERWIG7 (with tune CH3), and SHERPA predictions. In the top panel, the vertical bars on the data points represent statistical uncertainties, whereas in the bottom panels, the total uncertainty in data is indicated by the solid yellow band centred at 1. In the legend, the  $\chi^2$  per degree of freedom is given to quantify the goodness of fit of the model to the data.

The predictions based on the DPS-specific tune CDPSTP8S1-WJ describe the shape of the distributions within the uncertainty. Since the parameters were derived by fitting only 7 TeV measurements, this suggests that the collision energy dependence of the MPI parameters is well modelled in this tune.

## 8 Summary

The CMS Collaboration has measured the differential cross sections for  $Z + \geq 1$  jet and  $Z + \geq 2$  jet events using proton-proton collision data at  $\sqrt{s} = 13$  TeV, corresponding to an integrated luminosity of  $35.9 \text{ fb}^{-1}$  collected in the year 2016. The Z boson is reconstructed using the dimuon channel. This is the first measurement performed to explore observables sensitive to the presence of multi-parton interaction (MPI) using the Z+jets process at 13 TeV. Within the fiducial region, the production cross sections of  $Z + \geq 1$  jet and  $Z + \geq 2$  jet events are measured to be  $158.5 \pm 0.3$  (stat)  $\pm 7.0$  (syst)  $\pm 1.2$  (theo)  $\pm 4.0$  (lumi) pb and  $44.8 \pm 0.4$  (stat)  $\pm 3.7$  (syst)  $\pm 0.5$  (theo)  $\pm 1.1$  (lumi) pb, respectively. The measured integrated cross section in the fiducial region with jets is well described by the event generators SHERPA, MG5\_aMC + PYTHIA8, and MG5\_aMC + HERWIG7 predictions. The prediction obtained with MG5\_aMC + PYTHIA8 with the double-parton scattering (DPS) specific tune CDPSTP8S1-WJ overestimates the measurements by 10–15%, but correctly describes the shape of all the observables. The prediction from MG5\_aMC + PYTHIA8 with the CP5 tune, derived by fitting soft quantum chromodynamics (QCD) measurements, describes the differential cross section and area-normalized distributions. However, there are parts of the distributions that are not well described, such as single parton scattering that dominates lower regions of transverse momentum imbalance  $\Delta_{\text{rel}} p_{\text{T}}$  distributions. Predictions with other MPI models describe the measurements well (SHERPA) or reasonably well (MG5\_aMC + HERWIG7) except a few deviations in describing the shapes of the  $\Delta\phi(Z, j_1)$  and  $\Delta_{\text{rel}} p_{\text{T}}(j_1, j_2)$  distributions. The measured distributions show a significant sensitivity to MPI. A proper simulation of MPI is essential to describe the shape of the measured distributions and hence these results are a useful input to further improve DPS-specific tunes and a global tune in combination with other soft QCD measurements.

## Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid and other centres for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NK-FIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER

(Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThePCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 765710 and 824093 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 - GRK2497; the Lendület ("Momentum") Programme and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFIA research grants 123842, 123959, 124845, 124850, 125105, 128713, 128786, and 129058 (Hungary); the Council of Science and Industrial Research, India; the Latvian Council of Science; the Ministry of Science and Higher Education and the National Science Center, contracts Opus 2014/15/B/ST2/03998 and 2015/19/B/ST2/02861 (Poland); the National Priorities Research Program by Qatar National Research Fund; the Ministry of Science and Higher Education, project no. 0723-2020-0041 (Russia); the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalís and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

## References

- [1] ATLAS Collaboration, "Measurement of the production cross section of jets in association with a Z boson in pp collisions at  $\sqrt{s} = 7$  TeV with the ATLAS detector", *JHEP* **07** (2013) 032, doi:10.1007/JHEP07(2013)032, arXiv:1304.7098.
- [2] ATLAS Collaboration, "Measurement of the production cross section for  $Z/\gamma^*$  in association with jets in pp collisions at  $\sqrt{s} = 7$  TeV with the ATLAS detector.", *Phys. Rev. D* **85** (2011) 032009, doi:10.1103/PhysRevD.85.032009, arXiv:1111.2690.
- [3] CMS Collaboration, "Jet production rates in association with W and Z bosons in pp collisions at  $\sqrt{s} = 7$  TeV", *JHEP* **01** (2012) 010, doi:10.1007/JHEP01(2012)010, arXiv:1110.3226.
- [4] CMS Collaboration, "Measurements of jet multiplicity and differential production cross sections of Z+jets events in proton-proton collisions at  $\sqrt{s} = 7$  TeV", *Phys. Rev. D* **91** (2015) 052008, doi:10.1103/PhysRevD.91.052008, arXiv:1408.3104.
- [5] CMS Collaboration, "Event shapes and azimuthal correlations in Z+jets events in pp collisions at  $\sqrt{s} = 7$  TeV", *Phys. Lett. B* **722** (2013) 238, doi:10.1016/j.physletb.2013.04.025, arXiv:1301.1646.

- 
- [6] LHCb Collaboration, “Study of forward Z + jet production in pp collisions at  $\sqrt{s} = 7$  TeV”, *JHEP* **01** (2014) 033, doi:10.1007/JHEP01(2014)033, arXiv:1310.8197.
- [7] CMS Collaboration, “Comparison of the Z/ $\gamma^*$  + jets to  $\gamma$  + jets cross sections in pp collisions at  $\sqrt{s} = 8$  TeV”, *JHEP* **10** (2015) 128, doi:10.1007/JHEP04(2016)010, arXiv:1505.06520.
- [8] CMS Collaboration, “Measurements of differential production cross sections for a Z boson in association with jets in pp collisions at  $\sqrt{s} = 8$  TeV”, *JHEP* **04** (2017) 022, doi:10.1007/JHEP04(2017)022, arXiv:1611.03844.
- [9] LHCb Collaboration, “Measurement of forward W and Z boson production in association with jets in proton-proton collisions at  $\sqrt{s} = 8$  TeV”, *JHEP* **05** (2016) 131, doi:10.1007/JHEP05(2016)131, arXiv:1605.00951.
- [10] CMS Collaboration, “Measurement of differential cross sections for Z boson production in association with jets in proton-proton collisions at  $\sqrt{s} = 13$  TeV”, *Eur. Phys. J. C* **78** (2018) 965, doi:10.1140/epjc/s10052-018-6373-0, arXiv:1804.05252.
- [11] ATLAS Collaboration, “Measurements of the production cross-section for a Z boson in association with b-jets in proton-proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector”, *JHEP* **07** (2020) 044, doi:10.1007/JHEP07(2020)044, arXiv:2003.11960.
- [12] CMS Collaboration, “Constraints on the double-parton scattering cross section from same-sign W boson pair production in proton-proton collisions at  $\sqrt{s} = 8$  TeV”, *JHEP* **02** (2018) 032, doi:10.1007/JHEP02(2018)032, arXiv:1712.02280.
- [13] ATLAS Collaboration, “Measurement of hard double-parton interactions in  $W(\rightarrow l\nu) + 2$  jet events at  $\sqrt{s} = 7$  TeV with the ATLAS detector”, *New J. Phys.* **15** (2013) 033038, doi:10.1088/1367-2630/15/3/033038, arXiv:1301.6872.
- [14] CMS Collaboration, “Study of double parton scattering using W + 2-jet events in proton-proton collisions at  $\sqrt{s} = 7$  TeV”, *JHEP* **03** (2014) 032, doi:10.1007/JHEP03(2014)032, arXiv:1312.5729.
- [15] ATLAS Collaboration, “Study of the hard double-parton scattering contribution to inclusive four-lepton production in pp collisions at  $\sqrt{s} = 8$  TeV with the ATLAS detector”, *Phys. Lett. B* **790** (2019) 595, doi:10.1016/j.physletb.2019.01.062, arXiv:1811.11094.
- [16] ATLAS Collaboration, “Observation and measurements of the production of prompt and non-prompt J/ $\psi$  mesons in association with a Z boson in pp collisions at  $\sqrt{s} = 8$  TeV with the ATLAS detector”, *Eur. Phys. J. C* **75** (2015) 229, doi:10.1140/epjc/s10052-015-3406-9, arXiv:1412.6428.
- [17] LHCb Collaboration, “Observation of J/ $\psi$  pair production in pp collisions at  $\sqrt{s} = 7$  TeV”, *Phys. Lett. B* **707** (2012) 52, doi:10.1016/j.physletb.2011.12.015, arXiv:1109.0963.
- [18] LHCb Collaboration, “Measurement of the J/ $\psi$  pair production cross-section in pp collisions at  $\sqrt{s} = 13$  TeV”, *JHEP* **06** (2017) 047, doi:10.1007/JHEP06(2017)047, arXiv:1612.07451.

- [19] ALICE Collaboration, “ $J/\psi$  production as a function of charged particle multiplicity in pp collisions at  $\sqrt{s} = 7$  TeV”, *Phys. Lett. B* **712** (2012) 165, doi:10.1016/j.physletb.2012.04.052, arXiv:1202.2816.
- [20] LHCb Collaboration, “Observation of double charm production involving open charm in pp collisions at  $\sqrt{s} = 7$  TeV”, *JHEP* **06** (2012) 141, doi:10.1007/JHEP06(2012)141, arXiv:1205.0975.
- [21] LHCb Collaboration, “Observation of enhanced double parton scattering in proton-lead collisions at  $\sqrt{s_{NN}} = 8.16$  TeV”, *Phys. Rev. Lett.* **125** (2020) 212001, doi:10.1103/PhysRevLett.125.212001, arXiv:2007.06945.
- [22] D0 Collaboration, “Double parton interactions in  $\gamma+3$  jet events in  $p\bar{p}$  collisions  $\sqrt{s} = 1.96$  TeV”, *Phys. Rev. D* **81** (2010) 052012, doi:10.1103/PhysRevD.81.052012, arXiv:0912.5104.
- [23] CMS Collaboration, “Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements”, *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.
- [24] CMS Collaboration, “Event generator tunes obtained from underlying event and multiparton scattering measurements”, *Eur. Phys. J. C* **76** (2016) 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.
- [25] “HEPData record for this analysis”, 2021. doi:10.17182/hepdata.110665.
- [26] CMS Collaboration, “Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at  $\sqrt{s} = 13$  TeV”, *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.
- [27] CMS Collaboration, “Performance of the CMS Level-1 trigger in proton-proton collisions at  $\sqrt{s} = 13$  TeV”, *JINST* **15** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.
- [28] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [29] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [30] J. Alwall et al., “Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions”, *Eur. Phys. J. C* **53** (2008) 473, doi:10.1140/epjc/s10052-007-0490-5, arXiv:0706.2569.
- [31] NNPDF Collaboration, “Parton distributions for the LHC Run II”, *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.
- [32] Sherpa Collaboration, “Event generation with Sherpa 2.2”, *SciPost Phys.* **7** (2019) 034, doi:10.21468/SciPostPhys.7.3.034, arXiv:1905.09127.
- [33] S. Hoeche, F. Krauss, M. Schonherr, and F. Siegert, “QCD matrix elements + parton showers: The NLO case”, *JHEP* **04** (2013) 027, doi:10.1007/JHEP04(2013)027, arXiv:1207.5030.

- [34] T. Gehrmann et al., “NLO QCD matrix elements + parton showers in  $e^+e^- \rightarrow$  hadrons”, *JHEP* **01** (2013) 144, doi:10.1007/JHEP01(2013)144, arXiv:1207.5031.
- [35] S. Hoeche et al., “Triple vector boson production through Higgs-Strahlung with NLO multijet merging”, *Phys. Rev. D* **89** (2014) 093015, doi:10.1103/PhysRevD.89.093015, arXiv:1403.7516.
- [36] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
- [37] 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, doi:10.1103/PhysRevLett.110.252004, arXiv:1303.6254.
- [38] P. Bärnreuther, M. Czakon, and A. Mitov, “Percent level precision physics at the Tevatron: first genuine NNLO QCD corrections to  $q\bar{q} \rightarrow t\bar{t} + X$ ”, *Phys. Rev. Lett.* **109** (2012) 132001, doi:10.1103/PhysRevLett.109.132001, arXiv:1204.5201.
- [39] M. Beneke, P. Falgari, S. Klein, and C. Schwinn, “Hadronic top-quark pair production with NNLL threshold resummation”, *Nucl. Phys. B* **855** (2012) 695, doi:10.1016/j.nuclphysb.2011.10.021, arXiv:1109.1536.
- [40] M. Cacciari et al., “Top-pair production at hadron colliders with next-to-next-to-leading logarithmic soft-gluon resummation”, *Phys. Lett. B* **710** (2012) 612, doi:10.1016/j.physletb.2012.03.013, arXiv:1111.5869.
- [41] M. Czakon and A. Mitov, “NNLO corrections to top-pair production at hadron colliders: the all-fermionic scattering channels”, *JHEP* **12** (2012) 054, doi:10.1007/JHEP12(2012)054, arXiv:1207.0236.
- [42] M. Czakon and A. Mitov, “NNLO corrections to top pair production at hadron colliders: the quark-gluon reaction”, *JHEP* **01** (2013) 080, doi:10.1007/JHEP01(2013)080, arXiv:1210.6832.
- [43] 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, doi:10.1016/j.cpc.2014.06.021, arXiv:1112.5675.
- [44] J. M. Campbell, R. K. Ellis, and C. Williams, “Vector boson pair production at the LHC”, *JHEP* **07** (2011) 018, doi:10.1007/JHEP07(2011)018, arXiv:1105.0020.
- [45] N. Kidonakis, “Top Quark Production”, in *Proceedings, Helmholtz International Summer School on Physics of Heavy Quarks and Hadrons (HQ 2013): JINR, Dubna, Russia, July 15-28, 2013*, p. 139. (2014). arXiv:1311.0283. doi:10.3204/DESY-PROC-2013-03/Kidonakis.
- [46] CMS Collaboration, “Investigations of the impact of the parton shower tuning in PYTHIA 8 in the modelling of  $t\bar{t}$  at  $\sqrt{s} = 8$  and 13 TeV”, CMS Physics Analysis Summary CMS-PAS-TOP-16-021, 2016.
- [47] R. D. Ball et al., “Parton distributions with LHC data”, *Nucl. Phys. B* **867** (2013) 244, doi:10.1016/j.nuclphysb.2012.10.003, arXiv:1207.1303.
- [48] J. Alwall et al., “MadGraph 5: going beyond”, *JHEP* **06** (2011) 128, doi:10.1007/JHEP06(2011)128, arXiv:1106.0522.

- [49] J. Alwall, S. de Visscher, and F. Maltoni, “QCD radiation in the production of heavy colored particles at the LHC”, *JHEP* **02** (2009) 017, doi:10.1088/1126-6708/2009/02/017, arXiv:0810.5350.
- [50] R. Frederix and S. Frixione, “Merging meets matching in MC@NLO”, *JHEP* **12** (2012) 061, doi:10.1007/JHEP12(2012)061, arXiv:1209.6215.
- [51] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [52] T. Sjöstrand and M. van Zijl, “A multiple interaction model for the event structure in hadron collisions”, *Phys. Rev. D* **36** (1987) 2019, doi:10.1103/PhysRevD.36.2019.
- [53] M. Bahr et al., “Herwig++ physics and manual”, *Eur. Phys. J. C* **58** (2008) 639, doi:10.1140/epjc/s10052-008-0798-9, arXiv:0803.0883.
- [54] J. Bellm et al., “Herwig 7.0/Herwig++ 3.0 release note”, *Eur. Phys. J. C* **76** (2016) 196, doi:10.1140/epjc/s10052-016-4018-8, arXiv:1512.01178.
- [55] J. Bellm et al., “Herwig 7.1 release note”, CERN theory preprint CERN-PH-TH-2017-109, 2017. arXiv:1705.06919.
- [56] CMS Collaboration, “Development and validation of HERWIG 7 tunes from CMS underlying-event measurements”, *Eur. Phys. J. C* **81** (2021) 312, doi:10.1140/epjc/s10052-021-08949-5, arXiv:2011.03422.
- [57] K. Melnikov and F. Petriello, “Electroweak gauge boson production at hadron colliders through  $O(\alpha_s^2)$ ”, *Phys. Rev. D* **74** (2006) 114017, doi:10.1103/PhysRevD.74.114017, arXiv:hep-ph/0609070.
- [58] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
- [59] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- $k_T$  jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [60] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.
- [61] CMS Collaboration, “Measurement of the inclusive  $W$  and  $Z$  production cross sections in  $pp$  collisions at  $\sqrt{s} = 7$  TeV”, *JHEP* **10** (2011) 132, doi:10.1007/JHEP10(2011)132, arXiv:1107.4789.
- [62] M. Cacciari and G. P. Salam, “Pileup subtraction using jet areas”, *Phys. Lett. B* **659** (2008) 119, doi:10.1016/j.physletb.2007.09.077, arXiv:0707.1378.
- [63] CMS Collaboration, “Jet energy scale and resolution in the CMS experiment in  $pp$  collisions at 8 TeV”, *JINST* **12** (2017) P02014, doi:10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.
- [64] CMS Collaboration, “Jet energy scale and resolution performance with 13 TeV data collected by CMS in 2016”, CMS Detector Performance Summary CMS-DP-2018-028, 2018.

- [65] CMS Collaboration, “Jet performance in pp collisions at 7 TeV”, CMS Physics Analysis Summary CMS-PAS-JME-10-003, 2010.
- [66] CMS Collaboration, “Pileup jet identification”, CMS Physics Analysis Summary CMS-PAS-JME-13-005, 2013.
- [67] CMS Collaboration, “Pileup mitigation at CMS in 13 TeV data”, *JINST* **15** (2020) P09018, doi:10.1088/1748-0221/15/09/P09018, arXiv:2003.00503.
- [68] CMS Collaboration, “Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC”, *JINST* **16** (2021) P05014, doi:10.1088/1748-0221/16/05/P05014, arXiv:2012.06888.
- [69] S. Schmitt, “TUnfold: an algorithm for correcting migration effects in high energy physics”, *JINST* **7** (2012) T10003, doi:10.1088/1748-0221/7/10/T10003, arXiv:1205.6201.
- [70] A. N. Tikhonov, “Solution of incorrectly formulated problems and the regularization method”, *Soviet Math. Dokl.* **4** (1963) 1035.
- [71] CMS Collaboration, “Object definitions for top quark analyses at the particle level”, CMS Note 2017/004, 2017.
- [72] J. Butterworth et al., “PDF4LHC recommendations for LHC Run II”, *J. Phys. G* **43** (2016) 023001, doi:10.1088/0954-3899/43/2/023001, arXiv:1510.03865.
- [73] CMS Collaboration, “Precision luminosity measurement in proton-proton collisions at  $\sqrt{s} = 13$  TeV in 2015 and 2016 at CMS”, *Eur. Phys. J. C* **81** (2021) 800, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.
- [74] CMS Collaboration, “Measurement of the inelastic proton-proton cross section at  $\sqrt{s} = 13$  TeV”, *JHEP* **07** (2018) 161, doi:10.1007/JHEP07(2018)161, arXiv:1802.02613.



## A The CMS Collaboration

### Yerevan Physics Institute, Yerevan, Armenia

A. Tumasyan

### Institut für Hochenergiephysik, Wien, Austria

W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, M. Dragicevic, A. Escalante Del Valle, R. Frühwirth<sup>1</sup>, M. Jeitler<sup>1</sup>, N. Krammer, L. Lechner, D. Liko, I. Mikulec, P. Paulitsch, F.M. Pitters, J. Schieck<sup>1</sup>, R. Schöfbeck, M. Spanring, S. Templ, W. Waltenberger, C.-E. Wulz<sup>1</sup>

### Institute for Nuclear Problems, Minsk, Belarus

V. Chekhovsky, A. Litomin, V. Makarenko

### Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish<sup>2</sup>, E.A. De Wolf, X. Janssen, T. Kello<sup>3</sup>, A. Lelek, H. Rejeb Sfar, P. Van Mechelen, S. Van Putte, N. Van Remortel

### Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman, E.S. Bols, J. D'Hondt, J. De Clercq, M. Delcourt, H. El Faham, S. Lowette, S. Moortgat, A. Morton, D. Müller, A.R. Sahasransu, S. Tavernier, W. Van Doninck, P. Van Mulders

### Université Libre de Bruxelles, Bruxelles, Belgium

D. Beghin, B. Bilin, B. Clerboux, G. De Lentdecker, L. Favart, A. Grebenyuk, A.K. Kalsi, K. Lee, M. Mahdavihorrami, I. Makarenko, L. Moureaux, L. Pétré, A. Popov, N. Postiau, E. Starling, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer, D. Vannerom, L. Wezenbeek

### Ghent University, Ghent, Belgium

T. Cornelis, D. Dobur, J. Knolle, L. Lambrecht, G. Mestdach, M. Niedziela, C. Roskas, A. Samalan, K. Skovpen, T.T. Tran, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit

### Université Catholique de Louvain, Louvain-la-Neuve, Belgium

A. Bethani, G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, I.S. Donertas, A. Giammanco, K. Jaffel, V. Lemaître, K. Mondal, J. Prisciandaro, A. Taliércio, M. Teklishyn, P. Vischia, S. Wertz, S. Wuyckens

### Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

G.A. Alves, C. Hensel, A. Moraes

### Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

W.L. Aldá Júnior, M. Alves Gallo Pereira, M. Barroso Ferreira Filho, H. BRANDAO MALBOUISSON, W. Carvalho, J. Chinellato<sup>4</sup>, E.M. Da Costa, G.G. Da Silveira<sup>5</sup>, D. De Jesus Damiao, S. Fonseca De Souza, D. Matos Figueiredo, C. Mora Herrera, K. Mota Amarilo, L. Mundim, H. Nogima, P. Rebello Teles, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo, A. Vilela Pereira

### Universidade Estadual Paulista <sup>a</sup>, Universidade Federal do ABC <sup>b</sup>, São Paulo, Brazil

C.A. Bernardes<sup>a,a</sup>, L. Calligaris<sup>a</sup>, T.R. Fernandez Perez Tomei<sup>a</sup>, E.M. Gregores<sup>a,b</sup>, D.S. Lemos<sup>a</sup>, P.G. Mercadante<sup>a,b</sup>, S.F. Novaes<sup>a</sup>, Sandra S. Padula<sup>a</sup>

### Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

**University of Sofia, Sofia, Bulgaria**

A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov

**Beihang University, Beijing, China**

T. Cheng, W. Fang<sup>3</sup>, Q. Guo, T. Javaid<sup>6</sup>, M. Mittal, H. Wang, L. Yuan

**Department of Physics, Tsinghua University, Beijing, China**

M. Ahmad, G. Bauer, C. Dozen<sup>7</sup>, Z. Hu, J. Martins<sup>8</sup>, Y. Wang, K. Yi<sup>9,10</sup>

**Institute of High Energy Physics, Beijing, China**

E. Chapon, G.M. Chen<sup>6</sup>, H.S. Chen<sup>6</sup>, M. Chen, F. Iemmi, A. Kapoor, D. Leggat, H. Liao, Z.-A. LIU<sup>6</sup>, V. Milosevic, F. Monti, R. Sharma, J. Tao, J. Thomas-wilsker, J. Wang, H. Zhang, S. Zhang<sup>6</sup>, J. Zhao

**State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China**

A. Agapitos, Y. Ban, C. Chen, Q. Huang, A. Levin, Q. Li, X. Lyu, Y. Mao, S.J. Qian, D. Wang, Q. Wang, J. Xiao

**Sun Yat-Sen University, Guangzhou, China**

M. Lu, Z. You

**Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China**

X. Gao<sup>3</sup>, H. Okawa

**Zhejiang University, Hangzhou, China**

Z. Lin, M. Xiao

**Universidad de Los Andes, Bogota, Colombia**

C. Avila, A. Cabrera, C. Florez, J. Fraga, A. Sarkar, M.A. Segura Delgado

**Universidad de Antioquia, Medellin, Colombia**

J. Mejia Guisao, F. Ramirez, J.D. Ruiz Alvarez, C.A. Salazar González

**University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia**

D. Giljanovic, N. Godinovic, D. Lelas, I. Puljak

**University of Split, Faculty of Science, Split, Croatia**

Z. Antunovic, M. Kovac, T. Sculac

**Institute Rudjer Boskovic, Zagreb, Croatia**

V. Brigljevic, D. Ferencek, D. Majumder, M. Roguljic, A. Starodumov<sup>11</sup>, T. Susa

**University of Cyprus, Nicosia, Cyprus**

A. Attikis, E. Erodoutou, A. Ioannou, G. Kole, M. Kolosova, S. Konstantinou, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka

**Charles University, Prague, Czech Republic**

M. Finger<sup>12</sup>, M. Finger Jr.<sup>12</sup>, A. Kveton

**Escuela Politecnica Nacional, Quito, Ecuador**

E. Ayala

**Universidad San Francisco de Quito, Quito, Ecuador**

E. Carrera Jarrin

**Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt**

H. Abdalla<sup>13</sup>, S. Abu Zeid<sup>14</sup>

**Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt**

A. Lotfy, M.A. Mahmoud

**National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

**Department of Physics, University of Helsinki, Helsinki, Finland**

P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen

**Helsinki Institute of Physics, Helsinki, Finland**

S. Bharthuar, E. Brücken, F. Garcia, J. Havukainen, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, M. Lotti, L. Martikainen, J. Ott, H. Siikonen, E. Tuominen, J. Tuominiemi

**Lappeenranta University of Technology, Lappeenranta, Finland**

P. Luukka, H. Petrow, T. Tuuva

**IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France**

C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro<sup>15</sup>, M. Titov, G.B. Yu

**Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France**

S. Ahuja, F. Beaudette, M. Bonanomi, A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot, O. Davignon, B. Diab, G. Falmagne, S. Ghosh, R. Granier de Cassagnac, A. Hakimi, I. Kucher, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A. Zabi, A. Zghiche

**Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France**

J.-L. Agram<sup>16</sup>, J. Andrea, D. Apparau, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, D. Darej, J.-C. Fontaine<sup>16</sup>, U. Goerlach, C. Grimault, A.-C. Le Bihan, E. Nibigira, P. Van Hove

**Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France**

E. Asilar, S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, S. Perries, K. Shchablo, V. Sordini, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

**Georgian Technical University, Tbilisi, Georgia**

I. Lomidze, T. Toriashvili<sup>17</sup>, Z. Tsamalaidze<sup>12</sup>

**RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**

L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M.P. Rauch, N. Röwert, J. Schulz, M. Teroerde

**RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany**

D. Eliseev, M. Erdmann, P. Fackeldey, B. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, F. Ivone, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, G. Mocellin, S. Mondal, S. Mukherjee,

D. Noll, A. Novak, T. Pook, A. Pozdnyakov, Y. Rath, H. Reithler, J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma, S. Wiedenbeck, S. Zaleski

**RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany**

C. Dziwok, G. Flügge, W. Haj Ahmad<sup>18</sup>, O. Hlushchenko, T. Kress, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl<sup>19</sup>, T. Ziemons

**Deutsches Elektronen-Synchrotron, Hamburg, Germany**

H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, I. Babounikau, S. Baxter, O. Behnke, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borrás<sup>20</sup>, V. Botta, D. Brunner, A. Campbell, A. Cardini, C. Cheng, S. Consuegra Rodríguez, G. Correia Silva, V. Danilov, L. Didukh, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, O. Filatov, E. Gallo<sup>21</sup>, A. Geiser, A. Giraldi, A. Grohsjean, M. Guthoff, A. Jafari<sup>22</sup>, N.Z. Jomhari, H. Jung, A. Kasem<sup>20</sup>, M. Kasemann, H. Kaveh, C. Kleinwort, D. Krücker, W. Lange, J. Lidrych, K. Lipka, W. Lohmann<sup>23</sup>, R. Mankel, I.-A. Melzer-Pellmann, J. Metwally, A.B. Meyer, M. Meyer, J. Mnich, A. Mussgiller, Y. Otari, D. Pérez Adán, D. Pitzl, A. Raspereza, B. Ribeiro Lopes, J. Rübenach, A. Saggio, A. Saibel, M. Savitskyi, M. Scham, V. Scheurer, C. Schwanenberger<sup>21</sup>, A. Singh, R.E. Sosa Ricardo, D. Stafford, N. Tonon, O. Turkot, M. Van De Klundert, R. Walsh, D. Walter, Y. Wen, K. Wichmann, L. Wiens, C. Wissing, S. Wuchterl

**University of Hamburg, Hamburg, Germany**

R. Aggleton, S. Bein, L. Benato, A. Benecke, P. Connor, K. De Leo, M. Eich, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, P. Gunnellini, J. Haller, A. Hinzmann, G. Kasieczka, R. Klanner, R. Kogler, T. Kramer, V. Kutzner, J. Lange, T. Lange, A. Lobanov, A. Malara, A. Nigamova, K.J. Pena Rodriguez, O. Rieger, P. Schleper, M. Schröder, J. Schwandt, D. Schwarz, J. Sonneveld, H. Stadie, G. Steinbrück, A. Tews, B. Vormwald, I. Zoi

**Karlsruher Institut fuer Technologie, Karlsruhe, Germany**

J. Bechtel, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer<sup>†</sup>, A. Dierlamm, A. Droll, K. El Morabit, N. Faltermann, M. Giffels, J.o. Gosewisch, A. Gottmann, F. Hartmann<sup>19</sup>, C. Heidecker, U. Husemann, I. Katkov<sup>24</sup>, P. Keicher, R. Koppenhöfer, S. Maier, M. Metzler, S. Mitra, Th. Müller, M. Neukum, A. Nürnberg, G. Quast, K. Rabbertz, J. Rauser, D. Savoie, M. Schnepf, D. Seith, I. Shvetsov, H.J. Simonis, R. Ulrich, J. Van Der Linden, R.F. Von Cube, M. Wassmer, M. Weber, S. Wieland, R. Wolf, S. Wozniewski, S. Wunsch

**Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece**

G. Anagnostou, P. Asenov, G. Daskalakis, T. Gerasis, A. Kyriakis, D. Loukas, A. Stakia

**National and Kapodistrian University of Athens, Athens, Greece**

M. Diamantopoulou, D. Karasavvas, G. Karathanasis, P. Kontaxakis, C.K. Koraka, A. Manousakis-katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, E. Vourliotis

**National Technical University of Athens, Athens, Greece**

G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou

**University of Ioánnina, Ioánnina, Greece**

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, N. Manthos, I. Papadopoulos, J. Strologas

**MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University,**

**Budapest, Hungary**

M. Csanad, K. Farkas, M.M.A. Gadallah<sup>25</sup>, S. Lökös<sup>26</sup>, P. Major, K. Mandal, A. Mehta, G. Pasztor, A.J. Rádl, O. Surányi, G.I. Veres

**Wigner Research Centre for Physics, Budapest, Hungary**

M. Bartók<sup>27</sup>, G. Bencze, C. Hajdu, D. Horvath<sup>28</sup>, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>†</sup>

**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**

S. Czellar, J. Karancsi<sup>27</sup>, J. Molnar, Z. Szillasi, D. Teyssier

**Institute of Physics, University of Debrecen, Debrecen, Hungary**

P. Raics, Z.L. Trocsanyi<sup>29</sup>, B. Ujvari

**Karoly Robert Campus, MATE Institute of Technology**

T. Csorgo<sup>30</sup>, F. Nemes<sup>30</sup>, T. Novak

**Indian Institute of Science (IISc), Bangalore, India**

J.R. Komaragiri, D. Kumar, L. Panwar, P.C. Tiwari

**National Institute of Science Education and Research, HBNI, Bhubaneswar, India**

S. Bahinipati<sup>31</sup>, D. Dash, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu<sup>32</sup>, A. Nayak<sup>32</sup>, P. Saha, N. Sur, S.K. Swain, D. Vats<sup>32</sup>

**Panjab University, Chandigarh, India**

S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra<sup>33</sup>, R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Meena, K. Sandeep, J.B. Singh, A.K. Viridi

**University of Delhi, Delhi, India**

A. Ahmed, A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, A. Kumar, M. Naimuddin, P. Priyanka, K. Ranjan, A. Shah

**Saha Institute of Nuclear Physics, HBNI, Kolkata, India**

M. Bharti<sup>34</sup>, R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, S. Dutta, B. Gomber<sup>35</sup>, M. Maity<sup>36</sup>, S. Nandan, P. Palit, P.K. Rout, G. Saha, B. Sahu, S. Sarkar, M. Sharan, B. Singh<sup>34</sup>, S. Thakur<sup>34</sup>

**Indian Institute of Technology Madras, Madras, India**

P.K. Behera, S.C. Behera, P. Kalbhor, A. Muhammad, R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar

**Bhabha Atomic Research Centre, Mumbai, India**

D. Dutta, V. Jha, V. Kumar, D.K. Mishra, K. Naskar<sup>37</sup>, P.K. Netrakanti, L.M. Pant, P. Shukla

**Tata Institute of Fundamental Research-A, Mumbai, India**

T. Aziz, S. Dugad, M. Kumar, U. Sarkar

**Tata Institute of Fundamental Research-B, Mumbai, India**

S. Banerjee, S. Bhattacharya, R. Chudasama, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee

**Indian Institute of Science Education and Research (IISER), Pune, India**

K. Alpana, S. Dube, B. Kansal, S. Pandey, A. Rane, A. Rastogi, S. Sharma

**Department of Physics, Isfahan University of Technology, Isfahan, Iran**

H. Bakhshiansohi<sup>38</sup>, M. Zeinali<sup>39</sup>

**Institute for Research in Fundamental Sciences (IPM), Tehran, Iran**S. Chenarani<sup>40</sup>, S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi**University College Dublin, Dublin, Ireland**

M. Grunewald

**INFN Sezione di Bari <sup>a</sup>, Università di Bari <sup>b</sup>, Politecnico di Bari <sup>c</sup>, Bari, Italy**M. Abbrescia<sup>a,b</sup>, R. Aly<sup>a,b,41</sup>, C. Aruta<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, N. De Filippis<sup>a,c</sup>, M. De Palma<sup>a,b</sup>, A. Di Florio<sup>a,b</sup>, A. Di Pilato<sup>a,b</sup>, W. Elmetenawee<sup>a,b</sup>, L. Fiore<sup>a</sup>, A. Gelmi<sup>a,b</sup>, M. Gul<sup>a</sup>, G. Iaselli<sup>a,c</sup>, M. Ince<sup>a,b</sup>, S. Lezki<sup>a,b</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, I. Margjeka<sup>a,b</sup>, V. Mastrapasqua<sup>a,b</sup>, J.A. Merlin<sup>a</sup>, S. My<sup>a,b</sup>, S. Nuzzo<sup>a,b</sup>, A. Pellecchia<sup>a,b</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, A. Ranieri<sup>a</sup>, G. Selvaggi<sup>a,b</sup>, L. Silvestris<sup>a</sup>, F.M. Simone<sup>a,b</sup>, R. Venditti<sup>a</sup>, P. Verwilligen<sup>a</sup>**INFN Sezione di Bologna <sup>a</sup>, Università di Bologna <sup>b</sup>, Bologna, Italy**G. Abbiendi<sup>a</sup>, C. Battilana<sup>a,b</sup>, D. Bonacorsi<sup>a,b</sup>, L. Borghonovi<sup>a</sup>, L. Brigliadori<sup>a</sup>, R. Campanini<sup>a,b</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, T. Diotallevi<sup>a,b</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, P. Giacomelli<sup>a</sup>, L. Giommi<sup>a,b</sup>, C. Grandi<sup>a</sup>, L. Guiducci<sup>a,b</sup>, S. Lo Meo<sup>a,42</sup>, L. Lunerti<sup>a,b</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, F.L. Navarra<sup>a,b</sup>, A. Perrotta<sup>a</sup>, F. Primavera<sup>a,b</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G.P. Siroli<sup>a,b</sup>**INFN Sezione di Catania <sup>a</sup>, Università di Catania <sup>b</sup>, Catania, Italy**S. Albergo<sup>a,b,43</sup>, S. Costa<sup>a,b,43</sup>, A. Di Mattia<sup>a</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b,43</sup>, C. Tuve<sup>a,b</sup>**INFN Sezione di Firenze <sup>a</sup>, Università di Firenze <sup>b</sup>, Firenze, Italy**G. Barbagli<sup>a</sup>, A. Cassese<sup>a</sup>, R. Ceccarelli<sup>a,b</sup>, V. Ciulli<sup>a,b</sup>, C. Civinini<sup>a</sup>, R. D'Alessandro<sup>a,b</sup>, E. Focardi<sup>a,b</sup>, G. Latino<sup>a,b</sup>, P. Lenzi<sup>a,b</sup>, M. Lizzo<sup>a,b</sup>, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, R. Seidita<sup>a,b</sup>, G. Sguazzoni<sup>a</sup>, L. Viliani<sup>a</sup>**INFN Laboratori Nazionali di Frascati, Frascati, Italy**

L. Benussi, S. Bianco, D. Piccolo

**INFN Sezione di Genova <sup>a</sup>, Università di Genova <sup>b</sup>, Genova, Italy**M. Bozzo<sup>a,b</sup>, F. Ferro<sup>a</sup>, R. Mulargia<sup>a,b</sup>, E. Robutti<sup>a</sup>, S. Tosi<sup>a,b</sup>**INFN Sezione di Milano-Bicocca <sup>a</sup>, Università di Milano-Bicocca <sup>b</sup>, Milano, Italy**A. Benaglia<sup>a</sup>, F. Brivio<sup>a,b</sup>, F. Cetorelli<sup>a,b</sup>, V. Ciriolo<sup>a,b,19</sup>, F. De Guio<sup>a,b</sup>, M.E. Dinardo<sup>a,b</sup>, P. Dini<sup>a</sup>, S. Gennai<sup>a</sup>, A. Ghezzi<sup>a,b</sup>, P. Govoni<sup>a,b</sup>, L. Guzzi<sup>a,b</sup>, M. Malberti<sup>a</sup>, S. Malvezzi<sup>a</sup>, A. Massironi<sup>a</sup>, D. Menasce<sup>a</sup>, L. Moroni<sup>a</sup>, M. Paganoni<sup>a,b</sup>, D. Pedrini<sup>a</sup>, S. Ragazzi<sup>a,b</sup>, N. Redaelli<sup>a</sup>, T. Tabarelli de Fatis<sup>a,b</sup>, D. Valsecchi<sup>a,b,19</sup>, D. Zuolo<sup>a,b</sup>**INFN Sezione di Napoli <sup>a</sup>, Università di Napoli 'Federico II' <sup>b</sup>, Napoli, Italy, Università della Basilicata <sup>c</sup>, Potenza, Italy, Università G. Marconi <sup>d</sup>, Roma, Italy**S. Buontempo<sup>a</sup>, F. Carnevali<sup>a,b</sup>, N. Cavallo<sup>a,c</sup>, A. De Iorio<sup>a,b</sup>, F. Fabozzi<sup>a,c</sup>, A.O.M. Iorio<sup>a,b</sup>, L. Lista<sup>a,b</sup>, S. Meola<sup>a,d,19</sup>, P. Paolucci<sup>a,19</sup>, B. Rossi<sup>a</sup>, C. Sciacca<sup>a,b</sup>**INFN Sezione di Padova <sup>a</sup>, Università di Padova <sup>b</sup>, Padova, Italy, Università di Trento <sup>c</sup>, Trento, Italy**P. Azzi<sup>a</sup>, N. Bacchetta<sup>a</sup>, D. Bisello<sup>a,b</sup>, P. Bortignon<sup>a</sup>, A. Bragagnolo<sup>a,b</sup>, R. Carlin<sup>a,b</sup>, P. Checchia<sup>a</sup>, P. De Castro Manzano<sup>a</sup>, T. Dorigo<sup>a</sup>, U. Dosselli<sup>a</sup>, F. Gasparini<sup>a,b</sup>, U. Gasparini<sup>a,b</sup>, S.Y. Hoh<sup>a,b</sup>, L. Layer<sup>a,44</sup>, M. Margoni<sup>a,b</sup>, A.T. Meneguzzo<sup>a,b</sup>, J. Pazzini<sup>a,b</sup>, M. Presilla<sup>a,b</sup>, P. Ronchese<sup>a,b</sup>, R. Rossin<sup>a,b</sup>, F. Simonetto<sup>a,b</sup>, G. Strong<sup>a</sup>, M. Tosi<sup>a,b</sup>, H. YARAR<sup>a,b</sup>, M. Zanetti<sup>a,b</sup>, P. Zotto<sup>a,b</sup>, A. Zucchetta<sup>a,b</sup>, G. Zumerle<sup>a,b</sup>

**INFN Sezione di Pavia <sup>a</sup>, Università di Pavia <sup>b</sup>, Pavia, Italy**

C. Aime<sup>a,b</sup>, A. Braghieri<sup>a</sup>, S. Calzaferri<sup>a,b</sup>, D. Fiorina<sup>a,b</sup>, P. Montagna<sup>a,b</sup>, S.P. Ratti<sup>a,b</sup>, V. Re<sup>a</sup>, M. Ressegotti<sup>a,b</sup>, C. Riccardi<sup>a,b</sup>, P. Salvini<sup>a</sup>, I. Vai<sup>a</sup>, P. Vitulo<sup>a,b</sup>

**INFN Sezione di Perugia <sup>a</sup>, Università di Perugia <sup>b</sup>, Perugia, Italy**

G.M. Bilei<sup>a</sup>, D. Ciangottini<sup>a,b</sup>, L. Fanò<sup>a,b</sup>, P. Lariccia<sup>a,b</sup>, M. Magherini<sup>b</sup>, G. Mantovani<sup>a,b</sup>, V. Mariani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, F. Moscatelli<sup>a</sup>, A. Piccinelli<sup>a,b</sup>, A. Rossi<sup>a,b</sup>, A. Santocchia<sup>a,b</sup>, D. Spiga<sup>a</sup>, T. Tedeschi<sup>a,b</sup>

**INFN Sezione di Pisa <sup>a</sup>, Università di Pisa <sup>b</sup>, Scuola Normale Superiore di Pisa <sup>c</sup>, Pisa Italy, Università di Siena <sup>d</sup>, Siena, Italy**

P. Azzurri<sup>a</sup>, G. Bagliesi<sup>a</sup>, V. Bertacchi<sup>a,c</sup>, L. Bianchini<sup>a</sup>, T. Boccali<sup>a</sup>, E. Bossini<sup>a,b</sup>, R. Castaldi<sup>a</sup>, M.A. Ciocci<sup>a,b</sup>, R. Dell'Orso<sup>a</sup>, M.R. Di Domenico<sup>a,d</sup>, S. Donato<sup>a</sup>, A. Giassi<sup>a</sup>, M.T. Grippo<sup>a</sup>, F. Ligabue<sup>a,c</sup>, E. Manca<sup>a,c</sup>, G. Mandorli<sup>a,c</sup>, A. Messineo<sup>a,b</sup>, F. Palla<sup>a</sup>, S. Parolia<sup>a,b</sup>, G. Ramirez-Sanchez<sup>a,c</sup>, A. Rizzi<sup>a,b</sup>, G. Rolandi<sup>a,c</sup>, S. Roy Chowdhury<sup>a,c</sup>, A. Scribano<sup>a</sup>, N. Shafiei<sup>a,b</sup>, P. Spagnolo<sup>a</sup>, R. Tenchini<sup>a</sup>, G. Tonelli<sup>a,b</sup>, N. Turini<sup>a,d</sup>, A. Venturi<sup>a</sup>, P.G. Verdini<sup>a</sup>

**INFN Sezione di Roma <sup>a</sup>, Sapienza Università di Roma <sup>b</sup>, Rome, Italy**

M. Campana<sup>a,b</sup>, F. Cavallari<sup>a</sup>, M. Cipriani<sup>a,b</sup>, D. Del Re<sup>a,b</sup>, E. Di Marco<sup>a</sup>, M. Diemoz<sup>a</sup>, E. Longo<sup>a,b</sup>, P. Meridiani<sup>a</sup>, G. Organtini<sup>a,b</sup>, F. Pandolfi<sup>a</sup>, R. Paramatti<sup>a,b</sup>, C. Quaranta<sup>a,b</sup>, S. Rahatlou<sup>a,b</sup>, C. Rovelli<sup>a</sup>, F. Santanastasio<sup>a,b</sup>, L. Soffia<sup>a</sup>, R. Tramontano<sup>a,b</sup>

**INFN Sezione di Torino <sup>a</sup>, Università di Torino <sup>b</sup>, Torino, Italy, Università del Piemonte Orientale <sup>c</sup>, Novara, Italy**

N. Amapane<sup>a,b</sup>, R. Arcidiacono<sup>a,c</sup>, S. Argiro<sup>a,b</sup>, M. Arneodo<sup>a,c</sup>, N. Bartosik<sup>a</sup>, R. Bellan<sup>a,b</sup>, A. Bellora<sup>a,b</sup>, J. Berenguer Antequera<sup>a,b</sup>, C. Biino<sup>a</sup>, N. Cartiglia<sup>a</sup>, S. Cometti<sup>a</sup>, M. Costa<sup>a,b</sup>, R. Covarelli<sup>a,b</sup>, N. Demaria<sup>a</sup>, B. Kiani<sup>a,b</sup>, F. Legger<sup>a</sup>, C. Mariotti<sup>a</sup>, S. Maselli<sup>a</sup>, E. Migliore<sup>a,b</sup>, E. Monteil<sup>a,b</sup>, M. Monteno<sup>a</sup>, M.M. Obertino<sup>a,b</sup>, G. Ortona<sup>a</sup>, L. Pacher<sup>a,b</sup>, N. Pastrone<sup>a</sup>, M. Pelliccioni<sup>a</sup>, G.L. Pinna Angioni<sup>a,b</sup>, M. Ruspa<sup>a,c</sup>, R. Salvatico<sup>a,b</sup>, K. Shchelina<sup>a,b</sup>, F. Siviero<sup>a,b</sup>, V. Sola<sup>a</sup>, A. Solano<sup>a,b</sup>, D. Soldi<sup>a,b</sup>, A. Staiano<sup>a</sup>, M. Tornago<sup>a,b</sup>, D. Trocino<sup>a,b</sup>, A. Vagnerini

**INFN Sezione di Trieste <sup>a</sup>, Università di Trieste <sup>b</sup>, Trieste, Italy**

S. Belforte<sup>a</sup>, V. Candelise<sup>a,b</sup>, M. Casarsa<sup>a</sup>, F. Cossutti<sup>a</sup>, A. Da Rold<sup>a,b</sup>, G. Della Ricca<sup>a,b</sup>, G. Sorrentino<sup>a,b</sup>, F. Vazzoler<sup>a,b</sup>

**Kyungpook National University, Daegu, Korea**

S. Dogra, C. Huh, B. Kim, D.H. Kim, G.N. Kim, J. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, B.C. Radburn-Smith, S. Sekmen, Y.C. Yang

**Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea**

H. Kim, D.H. Moon

**Hanyang University, Seoul, Korea**

B. Francois, T.J. Kim, J. Park

**Korea University, Seoul, Korea**

S. Cho, S. Choi, Y. Go, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, J. Yoo

**Kyung Hee University, Department of Physics, Seoul, Republic of Korea**

J. Goh, A. Gurtu

**Sejong University, Seoul, Korea**

H.S. Kim, Y. Kim

**Seoul National University, Seoul, Korea**

J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, S. Ko, H. Kwon, H. Lee, S. Lee, B.H. Oh, M. Oh, S.B. Oh, H. Seo, U.K. Yang, I. Yoon

**University of Seoul, Seoul, Korea**

W. Jang, D. Jeon, D.Y. Kang, Y. Kang, J.H. Kim, S. Kim, B. Ko, J.S.H. Lee, Y. Lee, I.C. Park, Y. Roh, D. Song, I.J. Watson, S. Yang

**Yonsei University, Department of Physics, Seoul, Korea**

S. Ha, H.D. Yoo

**Sungkyunkwan University, Suwon, Korea**

Y. Jeong, H. Lee, Y. Lee, I. Yu

**College of Engineering and Technology, American University of the Middle East (AUM), Egaila, Kuwait**

T. Beyrouthy, Y. Maghrbi

**Riga Technical University, Riga, Latvia**

V. Veckalns<sup>45</sup>

**Vilnius University, Vilnius, Lithuania**

M. Ambrozas, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis, A. Vaitkevicius

**National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia**

N. Bin Norjoharuddeen, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

**Universidad de Sonora (UNISON), Hermosillo, Mexico**

J.F. Benitez, A. Castaneda Hernandez, M. León Coello, J.A. Murillo Quijada, A. Sehrawat, L. Valencia Palomo

**Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico**

G. Ayala, H. Castilla-Valdez, I. Heredia-De La Cruz<sup>46</sup>, R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sanchez-Hernandez

**Universidad Iberoamericana, Mexico City, Mexico**

S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**

I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

**University of Montenegro, Podgorica, Montenegro**

J. Mijuskovic<sup>47</sup>, N. Raicevic

**University of Auckland, Auckland, New Zealand**

D. Krofcheck

**University of Canterbury, Christchurch, New Zealand**

S. Bheesette, P.H. Butler

**National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan**

A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

**AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland**

V. Avati, L. Grzanka, M. Malawski



**National Centre for Nuclear Research, Swierk, Poland**

H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szeleper, P. Zalewski

**Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland**

K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Walczak

**Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal**

M. Araujo, P. Bargassa, D. Bastos, A. Boletti, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, M. Pisano, J. Seixas, O. Toldaiev, J. Varela

**Joint Institute for Nuclear Research, Dubna, Russia**

S. Afanasiev, D. Budkouski, I. Golutvin, I. Gorbunov, V. Karjavine, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev<sup>48,49</sup>, V. Palichik, V. Perelygin, M. Savina, D. Seitova, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, B.S. Yuldashev<sup>50</sup>, A. Zarubin, I. Zhizhin

**Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia**

G. Gavrillov, V. Golovtsov, Y. Ivanov, V. Kim<sup>51</sup>, E. Kuznetsova<sup>52</sup>, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Volkov, A. Vorobyev

**Institute for Nuclear Research, Moscow, Russia**

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, D. Kirpichnikov, M. Kirsanov, N. Krasnikov, A. Pashenkov, G. Pivovarov, D. Tlisov<sup>†</sup>, A. Toropin

**Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia**

V. Epshteyn, V. Gavrillov, N. Lychkovskaya, A. Nikitenko<sup>53</sup>, V. Popov, A. Spiridonov, A. Steppenov, M. Toms, E. Vlasov, A. Zhokin

**Moscow Institute of Physics and Technology, Moscow, Russia**

T. Aushev

**National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia**

M. Chadeeva<sup>54</sup>, A. Oskin, P. Parygin, E. Popova, V. Rusinov

**P.N. Lebedev Physical Institute, Moscow, Russia**

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

**Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia**

A. Belyaev, E. Boos, M. Dubinin<sup>55</sup>, L. Dudko, A. Ershov, V. Klyukhin, O. Kodolova, I. Lokhtin, O. Lukina, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

**Novosibirsk State University (NSU), Novosibirsk, Russia**

V. Blinov<sup>56</sup>, T. Dimova<sup>56</sup>, L. Kardapoltsev<sup>56</sup>, A. Kozyrev<sup>56</sup>, I. Ovtin<sup>56</sup>, Y. Skovpen<sup>56</sup>

**Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia**

I. Azhgirey, I. Bayshev, D. Elumakhov, V. Kachanov, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

**National Research Tomsk Polytechnic University, Tomsk, Russia**

A. Babaev, V. Okhotnikov

**Tomsk State University, Tomsk, Russia**

V. Borchsh, V. Ivanchenko, E. Tcherniaev

**University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia**

P. Adzic<sup>57</sup>, M. Dordevic, P. Milenovic, J. Milosevic

**Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain**

M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, Cristina F. Bedoya, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. León Holgado, D. Moran, Á. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, L. Urda Gómez, C. Willmott

**Universidad Autónoma de Madrid, Madrid, Spain**

J.F. de Trocóniz, R. Reyes-Almanza

**Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain**

B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, C. Ramón Álvarez, J. Ripoll Sau, V. Rodríguez Bouza, A. Trapote, N. Trevisani

**Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain**

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, C. Fernandez Madrazo, P.J. Fernández Manteca, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, J.M. Vizán Garcia

**University of Colombo, Colombo, Sri Lanka**

MK Jayananda, B. Kailaspathy<sup>58</sup>, D.U.J. Sonnadara, DDC Wickramarathna

**University of Ruhuna, Department of Physics, Matara, Sri Lanka**

W.G.D. Dharmaratna, K. Liyanage, N. Perera, N. Wickramage

**CERN, European Organization for Nuclear Research, Geneva, Switzerland**

T.K. Aarrestad, D. Abbaneo, J. Alimena, E. Auffray, G. Auzinger, J. Baechler, P. Baillon<sup>†</sup>, D. Barney, J. Bendavid, M. Bianco, A. Bocchi, T. Camporesi, M. Capeans Garrido, G. Cerminara, S.S. Chhibra, L. Cristella, D. d'Enterria, A. Dabrowski, N. Daci, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita<sup>59</sup>, D. Fasanella, S. Fiorendi, A. Florent, G. Franzoni, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Haranko, J. Hegeman, Y. Iiyama, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, M. Komm, N. Kratochwil, C. Lange, S. Laurila, P. Lecoq, K. Long, C. Lourenço, L. Malgeri, S. Mallios, M. Mannelli, A.C. Marini, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, S. Orfanelli, L. Orsini, F. Pantaleo, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, M. Pitt, H. Qu, T. Quast, D. Rabadý, A. Racz, G. Reales Gutiérrez, M. Rieger, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas<sup>60</sup>, S. Summers, V.R. Tavolaro, D. Treille, A. Tsiros, G.P. Van Onsem, M. Verzetti, J. Wanczyk<sup>61</sup>, K.A. Wozniak, W.D. Zeuner

**Paul Scherrer Institut, Villigen, Switzerland**

L. Caminada<sup>62</sup>, A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, M. Missiroli, T. Rohe

**ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland**

K. Androsov<sup>61</sup>, M. Backhaus, P. Berger, A. Calandri, N. Chernyavskaya, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, F. Eble, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, C. Martin Perez, M.T. Meinhard, F. Micheli, F. Nessi-Tedaldi, J. Niedziela, F. Pauss, V. Perovic, G. Perrin, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, V. Stampf, J. Steggemann<sup>61</sup>, R. Wallny, D.H. Zhu

**Universität Zürich, Zurich, Switzerland**

C. Amsler<sup>63</sup>, P. Bäertschi, C. Botta, D. Brzhechko, M.F. Canelli, K. Cormier, A. De Wit, R. Del Burgo, J.K. Heikkilä, M. Huwiler, A. Jofrehei, B. Kilminster, S. Leontsinis, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, G. Rauco, A. Reimers, P. Robmann, S. Sanchez Cruz, K. Schweiger, Y. Takahashi

**National Central University, Chung-Li, Taiwan**

C. Adloff<sup>64</sup>, C.M. Kuo, W. Lin, A. Roy, T. Sarkar<sup>36</sup>, S.S. Yu

**National Taiwan University (NTU), Taipei, Taiwan**

L. Ceard, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, H.y. Wu, E. Yazgan, P.r. Yu

**Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand**

B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas

**Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey**

F. Boran, S. Damarseckin<sup>65</sup>, Z.S. Demiroglu, F. Dolek, I. Dumanoglu<sup>66</sup>, E. Eskut, Y. Guler, E. Gurpinar Guler<sup>67</sup>, I. Hos<sup>68</sup>, C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir<sup>69</sup>, A. Polatoz, A.E. Simsek, B. Tali<sup>70</sup>, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

**Middle East Technical University, Physics Department, Ankara, Turkey**

B. Isildak<sup>71</sup>, G. Karapinar<sup>72</sup>, K. Ocalan<sup>73</sup>, M. Yalvac<sup>74</sup>

**Bogazici University, Istanbul, Turkey**

B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya<sup>75</sup>, O. Kaya<sup>76</sup>, Ö. Özçelik, S. Tekten<sup>77</sup>, E.A. Yetkin<sup>78</sup>

**Istanbul Technical University, Istanbul, Turkey**

A. Cakir, K. Cankocak<sup>66</sup>, Y. Komurcu, S. Sen<sup>79</sup>

**Istanbul University, Istanbul, Turkey**

S. Cerci<sup>70</sup>, B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci<sup>70</sup>

**Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine**

B. Grynyov

**National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine**

L. Levchuk

**University of Bristol, Bristol, United Kingdom**

D. Anthony, E. Bhal, S. Bologna, J.J. Brooke, A. Bundock, E. Clement, D. Cussans, H. Flacher,

J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou<sup>80</sup>, R. White

**Rutherford Appleton Laboratory, Didcot, United Kingdom**

K.W. Bell, A. Belyaev<sup>81</sup>, C. Brew, R.M. Brown, D.J.A. Cockerill, K.V. Ellis, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, T. Williams

**Imperial College, London, United Kingdom**

R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, V. Cepaitis, G.S. Chahal<sup>82</sup>, D. Colling, P. Dauncey, G. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, J. Nash<sup>83</sup>, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, A. Tapper, K. Uchida, T. Virdee<sup>19</sup>, N. Wardle, S.N. Webb, D. Winterbottom, A.G. Zecchinelli

**Brunel University, Uxbridge, United Kingdom**

K. Coldham, J.E. Cole, A. Khan, P. Kyberd, I.D. Reid, L. Teodorescu, S. Zahid

**Baylor University, Waco, USA**

S. Abdullin, A. Brinkerhoff, B. Caraway, J. Dittmann, K. Hatakeyama, A.R. Kanuganti, B. McMaster, N. Pastika, S. Sawant, C. Sutantawibul, J. Wilson

**Catholic University of America, Washington, DC, USA**

R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

**The University of Alabama, Tuscaloosa, USA**

A. Buccilli, S.I. Cooper, D. Di Croce, S.V. Gleyzer, C. Henderson, C.U. Perez, P. Rumerio<sup>84</sup>, C. West

**Boston University, Boston, USA**

A. Akpinar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, E. Fontanesi, D. Gastler, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, S. Yuan, D. Zou

**Brown University, Providence, USA**

G. Benelli, B. Burkle, X. Coubez<sup>20</sup>, D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan<sup>85</sup>, G. Landsberg, K.T. Lau, J. Lee, M. Lukasik, J. Luo, M. Narain, S. Sagir<sup>86</sup>, E. Usai, W.Y. Wong, X. Yan, D. Yu, W. Zhang

**University of California, Davis, Davis, USA**

J. Bonilla, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, P.T. Cox, R. Erbacher, G. Haza, F. Jensen, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, B. Regnery, D. Taylor, Y. Yao, F. Zhang

**University of California, Los Angeles, USA**

M. Bachtis, R. Cousins, A. Datta, D. Hamilton, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, N. Mccoll, W.A. Nash, S. Regnard, D. Saltzberg, B. Stone, V. Valuev

**University of California, Riverside, Riverside, USA**

K. Burt, Y. Chen, R. Clare, J.W. Gary, M. Gordon, G. Hanson, G. Karapostoli, O.R. Long, N. Manganeli, M. Olmedo Negrete, W. Si, S. Wimpenny, Y. Zhang

**University of California, San Diego, La Jolla, USA**

J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, J. Duarte, R. Gerosa, L. Giannini, D. Gilbert, J. Guiang, R. Kansal, V. Krutelyov, R. Lee, J. Letts, M. Masciovecchio, S. May,

M. Pieri, B.V. Sathia Narayanan, V. Sharma, M. Tadel, A. Vartak, F. Würthwein, Y. Xiang, A. Yagil

**University of California, Santa Barbara - Department of Physics, Santa Barbara, USA**

N. Amin, C. Campagnari, M. Citron, A. Dorsett, V. Dutta, J. Incandela, M. Kilpatrick, J. Kim, B. Marsh, H. Mei, M. Oshiro, M. Quinnan, J. Richman, U. Sarica, D. Stuart, S. Wang

**California Institute of Technology, Pasadena, USA**

A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, J. Ngadiuba, T.Q. Nguyen, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, Z. Zhang, R.Y. Zhu

**Carnegie Mellon University, Pittsburgh, USA**

J. Alison, S. An, M.B. Andrews, P. Bryant, T. Ferguson, A. Harilal, T. Mudholkar, M. Paulini, A. Sanchez

**University of Colorado Boulder, Boulder, USA**

J.P. Cumalat, W.T. Ford, E. MacDonald, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

**Cornell University, Ithaca, USA**

J. Alexander, Y. Cheng, J. Chu, D.J. Cranshaw, K. McDermott, J. Monroy, J.R. Patterson, D. Quach, J. Reichert, A. Ryd, W. Sun, S.M. Tan, Z. Tao, J. Thom, P. Wittich, M. Zientek

**Fermi National Accelerator Laboratory, Batavia, USA**

M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, K.F. Di Petrillo, V.D. Elvira, Y. Feng, J. Freeman, Z. Gecse, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, D. Lincoln, R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena<sup>55</sup>, O. Prokofyev, F. Ravera, A. Reinsvold Hall, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, H.A. Weber

**University of Florida, Gainesville, USA**

D. Acosta, P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, F. Errico, R.D. Field, D. Guerrero, B.M. Joshi, M. Kim, E. Koenig, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, K. Shi, J. Sturdy, J. Wang, E. Yigitbasi, X. Zuo

**Florida State University, Tallahassee, USA**

T. Adams, A. Askew, D. Diaz, R. Habibullah, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, H. Prosper, C. Schiber, R. Yohay, J. Zhang

**Florida Institute of Technology, Melbourne, USA**

M.M. Baarmand, S. Butalla, T. Elkafrawy<sup>14</sup>, M. Hohlmann, R. Kumar Verma, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

**University of Illinois at Chicago (UIC), Chicago, USA**

M.R. Adams, H. Becerril Gonzalez, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, A.H. Merrit, C. Mills, G. Oh, T. Roy, S. Rudrabhatla, M.B. Tonjes, N. Varelas, J. Viinikainen, X. Wang, Z. Wu, Z. Ye

**The University of Iowa, Iowa City, USA**

M. Alhousseini, K. Dilsiz<sup>87</sup>, R.P. Gandrajula, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili<sup>88</sup>, J. Nachtman, H. Ogul<sup>89</sup>, Y. Onel, A. Penzo, C. Snyder, E. Tiras<sup>90</sup>

**Johns Hopkins University, Baltimore, USA**

O. Amram, B. Blumenfeld, L. Corcodilos, J. Davis, M. Eminizer, A.V. Gritsan, S. Kyriacou, P. Maksimovic, J. Roskes, M. Swartz, T.Á. Vámi

**The University of Kansas, Lawrence, USA**

J. Anguiano, C. Baldenegro Barrera, P. Baringer, A. Bean, A. Bylinkin, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, C. Lindsey, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, C. Smith, J.D. Tapia Takaki, Q. Wang, J. Williams, G. Wilson

**Kansas State University, Manhattan, USA**

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, T. Mitchell, A. Modak, K. Nam

**Lawrence Livermore National Laboratory, Livermore, USA**

F. Rebassoo, D. Wright

**University of Maryland, College Park, USA**

E. Adams, A. Baden, O. Baron, A. Belloni, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, A.C. Mignerey, S. Nabili, M. Seidel, A. Skuja, L. Wang, K. Wong

**Massachusetts Institute of Technology, Cambridge, USA**

D. Abercrombie, G. Andreassi, R. Bi, S. Brandt, W. Busza, I.A. Cali, Y. Chen, M. D'Alfonso, J. Eysermans, G. Gomez Ceballos, M. Goncharov, P. Harris, M. Hu, M. Klute, D. Kovalskyi, J. Krupa, Y.-J. Lee, B. Maier, C. Mironov, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, K. Tatar, J. Wang, Z. Wang, B. Wyslouch

**University of Minnesota, Minneapolis, USA**

R.M. Chatterjee, A. Evans, P. Hansen, J. Hiltbrand, Sh. Jain, M. Krohn, Y. Kubota, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

**University of Nebraska-Lincoln, Lincoln, USA**

K. Bloom, M. Bryson, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, J.R. González Fernández, C. Joo, I. Kravchenko, M. Musich, I. Reed, J.E. Siado, G.R. Snow<sup>†</sup>, W. Tabb, F. Yan

**State University of New York at Buffalo, Buffalo, USA**

G. Agarwal, H. Bandyopadhyay, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, J. Pekkanen, S. Rappoccio, A. Williams

**Northeastern University, Boston, USA**

G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, J. Li, G. Madigan, B. Marzocchi, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

**Northwestern University, Evanston, USA**

S. Bhattacharya, J. Bueghly, Z. Chen, A. Gilbert, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, M. Velasco

**University of Notre Dame, Notre Dame, USA**

R. Band, R. Bucci, A. Das, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, K. Lannon, N. Loukas, N. Marinelli, I. Mcalister, T. McCauley, F. Meng, K. Mohrman,

---

Y. Musienko<sup>48</sup>, R. Ruchti, P. Siddireddy, M. Wayne, A. Wightman, M. Wolf, M. Zarucki, L. Zygala

**The Ohio State University, Columbus, USA**

B. Bylsma, B. Cardwell, L.S. Durkin, B. Francis, C. Hill, M. Nunez Ornelas, K. Wei, B.L. Winer, B.R. Yates

**Princeton University, Princeton, USA**

F.M. Addesa, B. Bonham, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, G. Kopp, S. Kwan, D. Lange, M.T. Lucchini, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, D. Stickland, C. Tully

**University of Puerto Rico, Mayaguez, USA**

S. Malik, S. Norberg

**Purdue University, West Lafayette, USA**

A.S. Bakshi, V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, S. Karmarkar, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, C.C. Peng, S. Piperov, A. Purohit, J.F. Schulte, M. Stojanovic<sup>15</sup>, J. Thieman, F. Wang, R. Xiao, W. Xie

**Purdue University Northwest, Hammond, USA**

J. Dolen, N. Parashar

**Rice University, Houston, USA**

A. Baty, M. Decaro, S. Dildick, K.M. Ecklund, S. Freed, P. Gardner, F.J.M. Geurts, A. Kumar, W. Li, B.P. Padley, R. Redjimi, W. Shi, A.G. Stahl Leitton, S. Yang, L. Zhang, Y. Zhang

**University of Rochester, Rochester, USA**

A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, E. Ranken, R. Taus

**Rutgers, The State University of New Jersey, Piscataway, USA**

B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, O. Karacheban<sup>23</sup>, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

**University of Tennessee, Knoxville, USA**

H. Acharya, A.G. Delannoy, S. Spanier

**Texas A&M University, College Station, USA**

O. Bouhali<sup>91</sup>, M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon<sup>92</sup>, H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, D. Rathjens, A. Safonov

**Texas Tech University, Lubbock, USA**

N. Akchurin, J. Damgov, V. Hegde, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, I. Volobouev, Z. Wang, A. Whitbeck

**Vanderbilt University, Nashville, USA**

E. Appelt, S. Greene, A. Gurrola, W. Johns, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska

**University of Virginia, Charlottesville, USA**

M.W. Arenton, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, A. Li, C. Neu, B. Tannenwald, S. White, E. Wolfe

**Wayne State University, Detroit, USA**

N. Poudyal, P. Thapa

**University of Wisconsin - Madison, Madison, WI, USA**

K. Black, T. Bose, J. Buchanan, C. Caillol, S. Dasu, I. De Bruyn, P. Everaerts, F. Fienga, C. Galloni, H. He, M. Herndon, A. Hervé, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, A. Mohammadi, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, S. Trembath-reichert, W. Vetens

†: Deceased

1: Also at TU Wien, Wien, Austria

2: Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt, Alexandria, Egypt

3: Also at Université Libre de Bruxelles, Bruxelles, Belgium

4: Also at Universidade Estadual de Campinas, Campinas, Brazil

5: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

6: Also at University of Chinese Academy of Sciences, Beijing, China

7: Also at Department of Physics, Tsinghua University, Beijing, China, Beijing, China

8: Also at UFMS, Nova Andradina, Brazil

9: Also at Nanjing Normal University Department of Physics, Nanjing, China

10: Now at The University of Iowa, Iowa City, USA

11: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia

12: Also at Joint Institute for Nuclear Research, Dubna, Russia

13: Also at Cairo University, Cairo, Egypt

14: Also at Ain Shams University, Cairo, Egypt

15: Also at Purdue University, West Lafayette, USA

16: Also at Université de Haute Alsace, Mulhouse, France

17: Also at Tbilisi State University, Tbilisi, Georgia

18: Also at Erzincan Binali Yildirim University, Erzincan, Turkey

19: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

20: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

21: Also at University of Hamburg, Hamburg, Germany

22: Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran, Isfahan, Iran

23: Also at Brandenburg University of Technology, Cottbus, Germany

24: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

25: Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt

26: Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary

27: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary

28: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary

29: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary, Budapest, Hungary

30: Also at Wigner Research Centre for Physics, Budapest, Hungary

31: Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India

32: Also at Institute of Physics, Bhubaneswar, India

33: Also at G.H.G. Khalsa College, Punjab, India

34: Also at Shoolini University, Solan, India



- 
- 35: Also at University of Hyderabad, Hyderabad, India  
36: Also at University of Visva-Bharati, Santiniketan, India  
37: Also at Indian Institute of Technology (IIT), Mumbai, India  
38: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany  
39: Also at Sharif University of Technology, Tehran, Iran  
40: Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran  
41: Now at INFN Sezione di Bari <sup>a</sup>, Università di Bari <sup>b</sup>, Politecnico di Bari <sup>c</sup>, Bari, Italy  
42: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy  
43: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy  
44: Also at Università di Napoli 'Federico II', NAPOLI, Italy  
45: Also at Riga Technical University, Riga, Latvia, Riga, Latvia  
46: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico  
47: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France  
48: Also at Institute for Nuclear Research, Moscow, Russia  
49: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia  
50: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan  
51: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia  
52: Also at University of Florida, Gainesville, USA  
53: Also at Imperial College, London, United Kingdom  
54: Also at P.N. Lebedev Physical Institute, Moscow, Russia  
55: Also at California Institute of Technology, Pasadena, USA  
56: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia  
57: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia  
58: Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka  
59: Also at INFN Sezione di Pavia <sup>a</sup>, Università di Pavia <sup>b</sup>, Pavia, Italy, Pavia, Italy  
60: Also at National and Kapodistrian University of Athens, Athens, Greece  
61: Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland  
62: Also at Universität Zürich, Zurich, Switzerland  
63: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria  
64: Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France  
65: Also at Şırnak University, Sırnak, Turkey  
66: Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey  
67: Also at Konya Technical University, Konya, Turkey  
68: Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey  
69: Also at Piri Reis University, Istanbul, Turkey  
70: Also at Adiyaman University, Adiyaman, Turkey  
71: Also at Ozyegin University, Istanbul, Turkey  
72: Also at Izmir Institute of Technology, Izmir, Turkey  
73: Also at Necmettin Erbakan University, Konya, Turkey  
74: Also at Bozok Universititesi Rektörlüğü, Yozgat, Turkey, Yozgat, Turkey  
75: Also at Marmara University, Istanbul, Turkey  
76: Also at Milli Savunma University, Istanbul, Turkey  
77: Also at Kafkas University, Kars, Turkey

78: Also at Istanbul Bilgi University, Istanbul, Turkey

79: Also at Hacettepe University, Ankara, Turkey

80: Also at Vrije Universiteit Brussel, Brussel, Belgium

81: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom

82: Also at IPPP Durham University, Durham, United Kingdom

83: Also at Monash University, Faculty of Science, Clayton, Australia

84: Also at Università di Torino, TORINO, Italy

85: Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA

86: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey

87: Also at Bingol University, Bingol, Turkey

88: Also at Georgian Technical University, Tbilisi, Georgia

89: Also at Sinop University, Sinop, Turkey

90: Also at Erciyes University, KAYSERI, Turkey

91: Also at Texas A&M University at Qatar, Doha, Qatar

92: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea