CERN-EP-2022-088
2023/06/02

CMS-SMP-18-014

Precision measurement of the Z boson invisible width in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

A precise measurement of the invisible width of the Z boson produced in proton-proton collisions at a center-of-mass energy of 13 TeV is presented using data recorded by the CMS experiment at the LHC, corresponding to an integrated luminosity of 36.3 fb^{-1} . The result is obtained from a simultaneous fit to kinematic distributions for two data samples of Z boson plus jets: one dominated by Z boson decays to invisible particles and the other by Z boson decays to muon and electron pairs. The invisible width is measured to be $523 \pm 3 \text{ (stat)} \pm 16 \text{ (syst)} \text{ MeV}$. This result is the first precise measurement of the invisible width of the Z boson at a hadron collider, and is the single most precise direct measurement to date, competitive with the combined result of the direct measurements from the LEP experiments.

Published in Physics Letters B as doi:10.1016/j.physletb.2022.137563.

Precision measurements of Z boson properties at the CERN LHC enable important tests of the standard model (SM). Deviations from the SM predictions could reveal signs of new physics beyond the SM. Among the physical observables describing the Z boson, the ‘invisible width’ corresponds to Z boson decays to particles that are not detected, such as neutrino-antineutrino pairs, and can be translated into a constraint on the number of light neutrino species coupling to the Z boson. A precise measurement of this quantity could reveal non-SM contributions from new-physics scenarios [1].

Experiments at the CERN Large Electron-Positron Collider (LEP) measured the invisible width of the Z boson using both direct and indirect approaches. The direct method is based on the associated production of an initial-state photon with a Z boson that subsequently decays invisibly. Direct measurements have been made by the OPAL [2], ALEPH [3], and L3 [4] experiments, yielding the LEP combined measurement of 503 ± 16 MeV [5]. The indirect method uses the total Z boson width extracted from the Z boson lineshape, and subtracts the measured partial decay widths to all known visible final states. This method is the most precise, with a combined indirect measurement of 499.0 ± 1.5 MeV [5] from the LEP experiments. A previous measurement by the UA2 experiment used the W boson and Z boson widths to deduce a limit on the number of light neutrino generations [6].

This Letter presents the first direct measurement of the invisible width of the Z boson at a hadron collider. The direct and indirect measurements could be sensitive to different new-physics scenarios [7] motivating the goal to reduce the total uncertainty in the direct measurement. We use data recorded by the CMS experiment from proton-proton (pp) collisions at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 36.3 fb^{-1} [8]. This measurement exploits the similarity in kinematic characteristics between the decay of the Z boson to neutrinos and its decay to charged leptons (in this case, electrons and muons), and is based on the ratio of branching fractions between these decay modes, as given by the following:

$$\Gamma(Z \rightarrow \nu\bar{\nu}) = \frac{\sigma(Z+\text{jets})\mathcal{B}(Z \rightarrow \nu\bar{\nu})}{\sigma(Z+\text{jets})\mathcal{B}(Z \rightarrow \ell\ell)}\Gamma(Z \rightarrow \ell\ell) \quad (1)$$

where $\sigma(Z+\text{jets})$ is the cross section to produce a Z boson in association with jets, $\Gamma(Z \rightarrow \nu\bar{\nu})$ and $\mathcal{B}(Z \rightarrow \nu\bar{\nu})$ are the partial width and branching fraction of the Z boson to neutrinos. Similarly, for the charged leptons the partial width and branching fraction are $\Gamma(Z \rightarrow \ell\ell)$ and $\mathcal{B}(Z \rightarrow \ell\ell)$. The invisible width, Γ_{inv} , is extracted from a simultaneous fit to kinematic distributions for two data samples: one dominated by Z boson decays to invisible particles and the other by Z boson decays to muon and electron pairs. Since the invisible particles cannot be detected, invisible Z boson decays can only be identified when the Z boson has a significant transverse momentum (p_T) leading to large missing transverse momentum (p_T^{miss}). In this analysis, therefore, only Z bosons produced in association with jets are considered. Tabulated results are available in the HepData database [9]. A previous measurement by CMS of the differential production cross section of the invisible decay of the Z boson is presented in [10].

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, 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 extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. Events of interest are selected using a two-tiered trigger system [11]. A detailed description of the CMS detector and relevant kinematic variables is reported in Ref. [12].

The particle-flow (PF) algorithm [13] reconstructs and identifies individual particles in an event with an optimized combination of information from the various elements of the CMS detector. It identifies these particles as charged or neutral hadrons, photons, and charged leptons. The energy of electrons is determined from a combination of the electron momentum measured by the tracker and the cluster of energy deposition in the ECAL. Muons are identified as tracks in the central tracker consistent with either a track or several hits in the muon system, and associated with energy deposits in the calorimeter compatible with the muon hypothesis. The momentum of muons is obtained from the curvature of the corresponding track. The primary vertex (PV) is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in Section 9.4.1 of [14].

For each event, hadronic jets are clustered from these reconstructed particles using the infrared- and collinear-safe anti- k_T algorithm [15, 16] with a distance parameter of 0.4. Jet energy corrections are derived from simulation studies so that the average measured response of jets match that of particle-level jets. In situ measurements of the momentum balance in dijet, photon+jet, Z+jet, and multijet events are used to determine any residual differences between the jet energy scale (JES) in data and simulation, and appropriate corrections are made [17]. The jet energy resolution (JER) typically amounts to 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV.

Hadronic τ decays (τ_h) are reconstructed using the hadrons-plus-strips algorithm [18], which combines 1 or 3 tracks with energy deposits in the calorimeters, to identify the tau decay modes. To distinguish genuine τ_h decays from jets originating from the hadronization of quarks or gluons, and from electrons, a discriminant based on a multivariate analysis is used [18].

The vector \vec{p}_T^{miss} is computed as the negative vector sum of the p_T of all particle candidates from the PF algorithm in an event, and its magnitude is denoted as p_T^{miss} [19]. The \vec{p}_T^{miss} vector is modified to account for corrections to the energy scale of the reconstructed jets in the event. For the leptonic data sets selected in this analysis, \vec{p}_T^{miss} is replaced by the recoil vector \vec{U} , defined as the vector sum of \vec{p}_T^{miss} and \vec{p}_T of the charged leptons passing the object selection in each event. This parameter acts as a proxy for the boson p_T . Henceforth $\mathcal{U} = |\vec{U}|$ is used to denote p_T^{miss} for events with no leptons and \mathcal{U} for events containing leptons.

The signal process of a Z boson decaying to neutrinos produced in association with jets is simulated at next-to-leading order (NLO) using the Monte Carlo (MC) event generator MADGRAPH5_aMC@NLO 2.3.2 [20] interfaced with PYTHIA (v8.212) [21] for parton shower (PS) and hadronization. The matrix element (ME) calculation includes up to three final-state partons generated from quantum chromodynamics (QCD) interactions and the ME-PS matching is performed following the FxFx [22] prescription. The Drell–Yan production of Z/γ^* in association with jets, where the Z/γ^* decays to charged leptons, and the production of a W boson in association with jets are simulated in the same way. Corrections are applied to the cross sections for these processes as a function of the boson p_T to account for higher-order effects from next-to-next-to-leading order (NNLO) in QCD and NLO in electroweak (EW) [23] interactions. The impact of the NLO EW corrections is particularly significant since they become large and negative at high p_T , leading to a 20–30% correction for Z+jets and W+jets production cross sections at 1 TeV in boson p_T [23].

Top quark pair events are generated with MADGRAPH5_aMC@NLO and normalized to the inclusive cross section calculated at NNLO matched to next-to-next-to-leading logarithmic accuracy [24, 25]. Single top quark processes are generated at leading order (LO) with POWHEG [26–28] and normalized to the NLO cross sections for tW and t-channel production [29], whereas the s-channel production is generated at NLO with MADGRAPH5_aMC@NLO. The production of diboson processes is simulated using a combination of MADGRAPH5_aMC@NLO and

POWHEG at NLO accuracy. The photon+jets process is generated using the MADGRAPH5_aMC@NLO generator at NLO with up to one parton in the final state and the ME-PS matching is performed following the FxFx prescription. QCD multijet production is generated with PYTHIA at LO.

The NNPDF3.0 LO and NLO [30] parton distribution functions (PDFs) are used, respectively, with the LO and NLO generators described above. The PYTHIA program with the CUETP8M1 underlying event tune [31] is used to describe parton showering and hadronization for all simulated samples. The full detector response is simulated using the GEANT4 [32] package for all background and signal samples.

Additional pp interactions within the same or nearby bunch crossings (pileup) are included in the simulated samples, with the multiplicity weighted to match the pileup distribution measured in data.

The events used in this analysis can be categorized into three main regions: the p_T^{miss} plus jets region that is composed predominantly of $Z \rightarrow \nu\bar{\nu}$ events; a dilepton plus jets region with $Z/\gamma^* \rightarrow \mu\mu$ and $Z/\gamma^* \rightarrow ee$ events; and a single-lepton plus jets region, ℓ +jets, where $\ell = e, \mu, \tau_h$ (hadronically decaying τ lepton), that is enriched in W +jets events.

Events are selected using an unprescaled trigger that requires $p_T^{\text{miss}} > 90 \text{ GeV}$ and $H_T^{\text{miss}} > 90 \text{ GeV}$, where H_T^{miss} is the magnitude of the vectorial p_T sum of all jets with $p_T > 20 \text{ GeV}$ and $|\eta| < 5.0$. Muons are not included in the calculation of the p_T^{miss} and H_T^{miss} variables at the trigger level. This enables the same trigger to be used to select events for the p_T^{miss} plus jets region and the $Z/\gamma^* \rightarrow \mu\mu$ and μ +jets regions. This trigger is also used to select the τ_h +jets region. Events for the $Z/\gamma^* \rightarrow ee$ and e +jets regions are selected using a trigger that requires at least one reconstructed electron passing a tight identification selection [33] and with $p_T > 27 \text{ GeV}$.

Muon candidates are required to be reconstructed in the fiducial region of pseudorapidity $|\eta| < 2.4$ of the muon system. Electron candidates are required to be reconstructed within $|\eta| < 2.4$, excluding the barrel-to-endcap $1.444 < |\eta| < 1.566$ transition regions of the ECAL. The leptons are required to be isolated, where the isolation is calculated from PF candidates and corrected for pileup on an event-by-event basis. The scalar p_T sum over all particle candidates reconstructed in an isolation cone with radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ (0.3), where ϕ is the azimuthal angle, around the momentum vector of the muon (electron) must be $< 15\%$ (6%) of the lepton p_T . Jets are required to have $p_T > 40 \text{ GeV}$ and $|\eta| < 2.4$.

A set of ‘baseline’ selection criteria are applied to all regions. It requires \mathcal{U} to be $> 200 \text{ GeV}$, which ensures that the trigger efficiency is high ($> 98\%$), and the leading jet in the event to have $p_T > 200 \text{ GeV}$. An event is vetoed if there are jets with $p_T > 40 \text{ GeV}$ and $|\eta| > 2.4$ to reduce the contribution from vector boson scattering processes. Misidentified high- p_T muons can produce p_T^{miss} , leading to a mismodeling that is particularly apparent at large values of the distribution of $\Delta = |p_{T,\text{Calo.}}^{\text{miss}} - \mathcal{U}|/\mathcal{U}$. This quantity tests the difference, relative to \mathcal{U} , between the particle-based \mathcal{U} and $p_{T,\text{Calo.}}^{\text{miss}}$, which is p_T^{miss} measured only by the calorimeter systems and corrected for the presence of muons. To remove these events, Δ is required to be less than 0.5. Events are also vetoed if they contain an isolated photon passing loose identification criteria [33] and with $p_T > 25 \text{ GeV}$ and $|\eta| < 2.5$. This requirement suppresses events from EW processes with an initial-state photon and from multijet production. Backgrounds from top-quark processes are reduced by vetoing any event containing b-tagged jets, defined as jets originating from the hadronization of b quarks using a combined secondary vertex discriminator with the medium working point [34]. Further reduction of the QCD multijet background is achieved by requiring the azimuthal separation between each of the four leading jets and \vec{U} ($\Delta\phi_{\text{min}}$) to be greater than

0.5. Additional selection requirements for each region on top of this baseline selection are described in the following.

For the p_T^{miss} plus jets region, backgrounds from W and Z bosons decaying via charged leptons are suppressed by vetoing events containing one or more isolated muon or electron passing a loose identification selection [33, 35] with $p_T > 10$ GeV and $|\eta| < 2.5$ or a τ_h with $p_T > 20$ GeV and $|\eta| < 2.3$.

The dilepton region is selected by requiring exactly one pair of isolated muons or electrons having opposite electric charges, such that the invariant mass ($m_{\ell\ell}$) of the pair is compatible with the Z boson mass ($71 < m_{\ell\ell} < 111$ GeV). The muons and electrons are required to have $p_T > 25$ and > 30 GeV respectively, and pass a medium identification selection [33, 35]. For $Z/\gamma^* \rightarrow \mu\mu$ ($Z/\gamma^* \rightarrow ee$) events, electron (muon) and τ_h vetoes are applied.

The μ +jets region is selected by requiring exactly one well identified and isolated muon with $p_T > 25$ GeV and $|\eta| < 2.4$. The corresponding p_T requirement for electrons in the e+jets region is 30 GeV. The τ_h +jets region is selected by requiring one τ_h lepton passing a tight identification selection [18] with $p_T > 40$ GeV and $|\eta| < 2.3$. The transverse mass, defined as $m_T = \sqrt{2p_T^{\text{miss}}p_T^\ell(1 - \cos \Delta\phi)}$, where $\Delta\phi$ is the azimuthal angle between the lepton and p_T^{miss} , is required to be in the range $30 < m_T < 125$ GeV. In addition, for the e+jets region, p_T^{miss} is required to be > 100 GeV to reduce the contribution from QCD multijet events.

The largest background contribution to the p_T^{miss} plus jets region comes from W+jets events, accounting for 37% of the events in this region. This includes events where the W boson decays via electrons (6.6%), muons (9.6%), hadronically decaying taus (13.1%), and leptonically decaying taus (7.3%). This background is estimated using the control regions of μ +jets and e+jets events that are independent of the signal region, but have similar kinematic requirements. These control regions select events where there is a single muon or electron in the final state, from both a W boson decaying directly to an electron or muon or indirectly via a leptonically decaying tau lepton.

The estimation of this background proceeds by defining a transfer factor (t_W) as the ratio of the number of W+jets events in the signal region to that in the control region, as predicted by simulation. This t_W is determined as a function of \mathcal{U} and used to extrapolate from the event yields in data in the μ +jets and e+jets control regions to obtain the number of expected W+jets events in the signal region. Systematic uncertainties in t_W associated with the muon and electron reconstruction, identification, and isolation requirements are included, and contribute at the 2% level for muons and electrons. Uncertainties in t_W associated with the JES and JER, the p_T^{miss} trigger and electron trigger efficiencies, pileup, and b-tagged jet veto are also included. The jet energy scale uncertainty does not completely cancel in the transfer factor and has a residual effect of a few percent at low \mathcal{U} . Theoretical uncertainties in the corrections applied to account for NNLO QCD and NLO EW contributions, and from PDFs are also included; however, these mostly cancel in the ratio of W+jets events in the signal and control regions. The contributions from all these sources of uncertainties on t_W are included in Table 1

Studies are performed to validate the transfer factor method and to further test the extrapolation involved in predicting W+jets events in the signal region from the combined μ +jets and e+jets regions. A simultaneous likelihood fit is performed to assess the consistency between the μ +jets and e+jets channels by using the transfer factor method to predict the event yields in e+jets region from the μ +jets region. The fit has two unconstrained parameters that are used to extract differences in the overall normalization and shape of the \mathcal{U} distribution with all systematic uncertainties included as nuisance parameters. The post-fit values for these parameters

are 1.000 ± 0.035 and -0.019 ± 0.020 for the normalization and shape parameters, respectively. The shape parameter is constructed as a dimensionless parameter that varies the shape of the \mathcal{U} distribution in one region linearly with respect to the other, effectively giving the value of the slope for the ratio of the \mathcal{U} distribution in the two regions. Values of 1.0 for the normalization parameter, and 0.0 for the shape parameter signify perfect consistency between the two regions. Hence, the post-fit values are in agreement within uncertainties with the expectation for consistent electron and muon channels. Figure 1 shows the distributions of \mathcal{U} in the μ +jets and e +jets regions before and after the likelihood fit. The dominant uncertainties are from the electron trigger efficiency, followed by the muon and electron identification efficiencies.

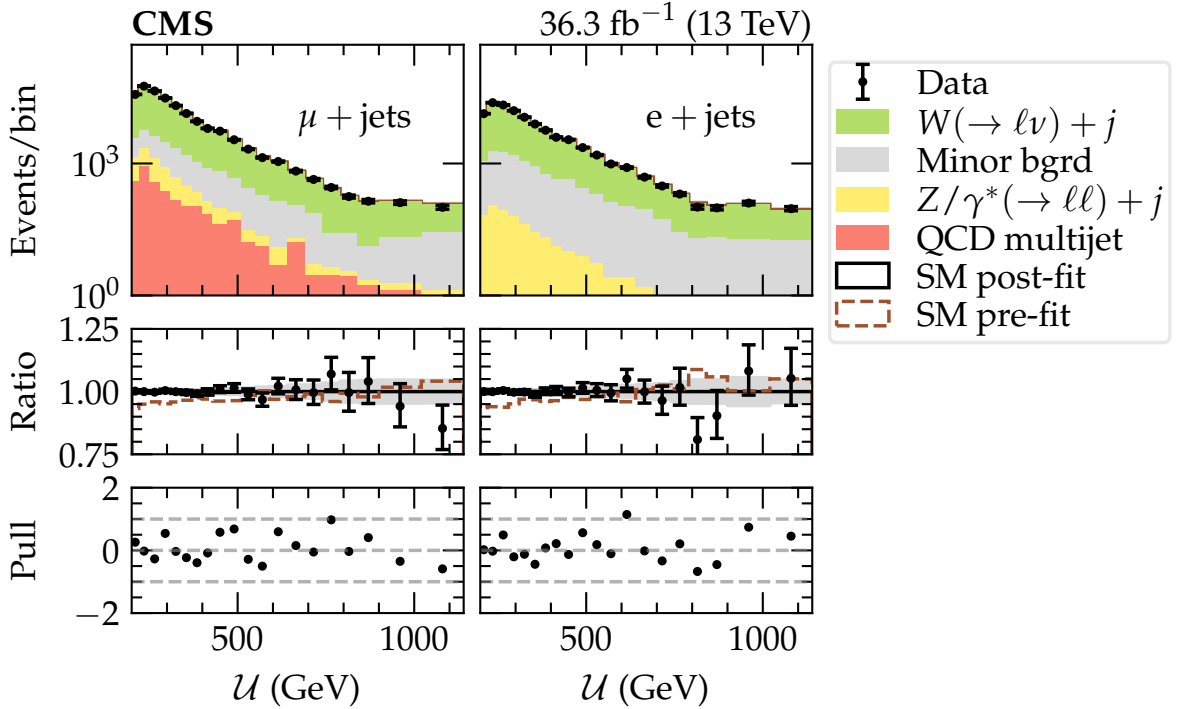


Figure 1: Distributions of \mathcal{U} in the regions of μ +jets (left) and e +jets (right). Ratios are taken of the data with respect to both the SM post-fit and SM pre-fit results from a simultaneous likelihood fit performed to assess the consistency between the μ +jets and e +jets channels. Pull is the difference between the data and the SM post-fit results, normalized by their uncertainties summed in quadrature. The ‘Minor’ background includes the sum of all the contributions from processes such as diboson events, top pair production, and single top production.

A similar likelihood fit is performed to verify the consistency between the combined μ +jets and e +jets region with the τ_h +jets region with two unconstrained parameters to extract differences in the normalization and shape of the \mathcal{U} distribution. Again, the post-fit values of these parameters show consistency within the uncertainties among all three regions, with values of 1.009 ± 0.052 and 0.001 ± 0.044 for the normalization and shape parameters, respectively. Figure 2 shows the distributions of \mathcal{U} in the μ +jets, e +jets and τ_h +jets regions before and after the likelihood fit. All systematic uncertainties are included as nuisance parameters in the fit, with the largest uncertainty coming from the τ_h selection efficiency and subdominant sources of uncertainty from the muon identification and electron trigger efficiencies.

The contribution to the signal region from QCD multijet events is estimated from a control region that is selected by applying the same criteria as to the signal region but inverting the

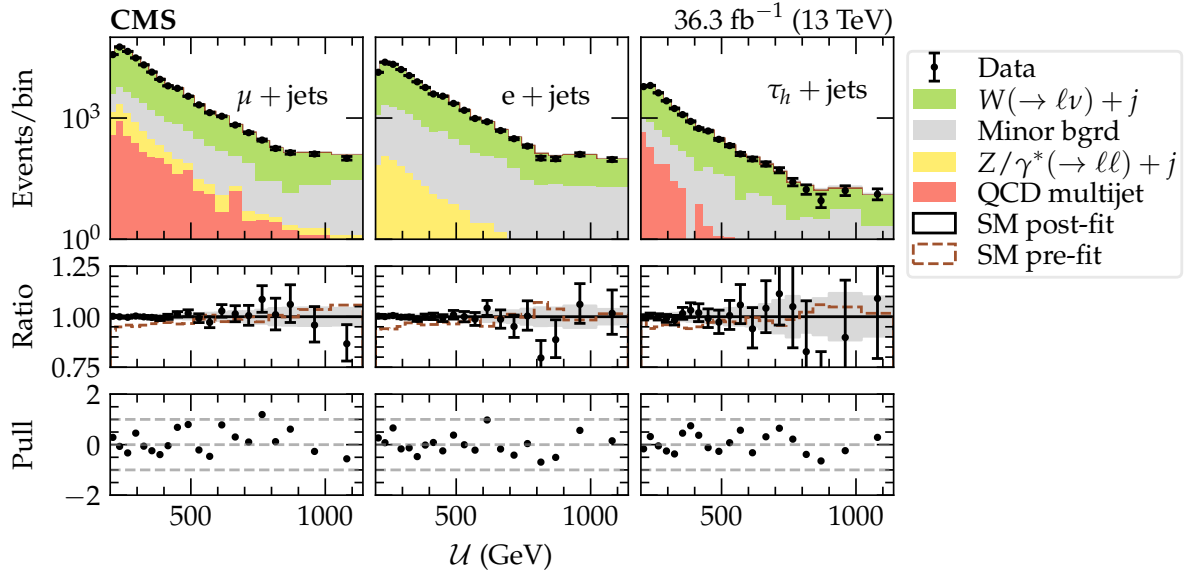


Figure 2: Distributions of \mathcal{U} in the regions of μ +jets (left), e +jets (center), and τ_h +jets (right). Ratios are taken of the data with respect to both the SM post-fit and SM pre-fit results from a likelihood fit performed to verify the consistency between the combined μ +jets and e +jets region with the τ_h +jets region. The pulls are the difference between the data and the SM post-fit results, normalized by their uncertainties summed in quadrature. The ‘Minor’ background includes the sum of all the contributions from processes such as diboson events, top pair production, and single top production.

requirement on $\Delta\phi_{\min}$. A jet from a QCD multijet event that is severely mismeasured results in significant p_T^{miss} and will have a direction closely aligned with \vec{p}_T^{miss} . If there are one or more jets with $\Delta\phi_{\min} < 0.5$, and if at least one of those jets has $p_T > 40$ GeV, then the event falls into the QCD control region. Most events in the QCD control region have just one jet with $\Delta\phi_{\min} < 0.5$ and $p_T > 40$ GeV. A fit to the p_T distribution of this p_T^{miss} -aligned jet is used to extrapolate the event yields for QCD multijet events from the control region to the signal one. An overall disagreement of 17% is seen in the normalization in this QCD control region between data and simulation, attributed to the mismodelling of the QCD process in simulation. A likelihood fit is performed where this disagreement is parameterised as a linear fit to the p_T distribution of this p_T^{miss} -aligned jet in each \mathcal{U} bin and extrapolated to the signal region for $p_T < 40$ GeV. This linear fit parameterisation significantly improves the agreement between data and simulation and is used to extract a normalization scale factor for the QCD multijet process in the signal region. This scale factor ranges from 1.11 ± 0.08 in the lowest \mathcal{U} bin to 2.44 ± 0.99 for the last \mathcal{U} bin. The total uncertainty in this normalization scale factor includes contributions from the jet energy scale and resolution, pileup, and lepton-related uncertainties. An additional systematic uncertainty is also assigned from the difference between a linear fit and a quadratic fit to extrapolate from the multijet-enriched control region to the signal region. The overall contribution of the uncertainty on the QCD multijet background on the final result is negligible.

Other backgrounds from top quark pair, single top quark, diboson, and photon+jets production are taken from simulation. Since most of these processes are generated at NLO, the simulation is considered to be a reliable estimation of their contributions to the various signal and control regions.

The contributions of virtual photon exchange must be corrected to extract a value for the invisible width. This requires estimates of the contributions from $\gamma^* \rightarrow \ell\ell$ and its interference with $Z \rightarrow \ell\ell$. These are determined from MADGRAPH5_aMC@NLO where the pure $Z \rightarrow \ell\ell$ process and $\gamma^* \rightarrow \ell\ell$ is generated and the ratio of the cross sections of these processes with respect to $Z/\gamma^* \rightarrow \ell\ell$, within the invariant mass region $71 < m_{\ell\ell} < 111$ GeV, is used to determine the contribution from $\gamma^* \rightarrow \ell\ell$ and the interference term. Systematic uncertainties from PDFs, renormalization and factorization scales, and limited size of MC samples are included. The contribution from $\gamma^* \rightarrow \ell\ell$ is 1.5% and is subtracted as a background to the $Z/\gamma^* \rightarrow \ell\ell$ process, whereas the interference is 0.6% and is used to scale the cross section for $Z/\gamma^* \rightarrow \ell\ell$ to account for the interference term appearing in the $Z \rightarrow \ell\ell$ amplitude.

The main systematic uncertainties affecting the measurement of the Z invisible width are described in the following. Systematic uncertainties from the muon and electron identification efficiencies, obtained from Ref. [36], are among the dominant uncertainties, contributing 2.1 and 1.6%, respectively. The uncertainty in the jet energy scale is the second-largest uncertainty, at 1.9%. The statistical uncertainty in the electron identification efficiency and the uncertainty from pileup both contribute at the 1% level, whereas the uncertainty from the τ_h veto efficiency is 0.7%. Experimental uncertainties from the p_T^{miss} and electron trigger efficiencies are at the 0.7% level, whereas other experimental uncertainties from the jet energy resolution, QCD multijet background, and the b-tagged jet veto efficiency are negligible. Theoretical uncertainties from higher-order QCD and EW corrections applied to the Z+jets and W+jets processes are estimated using the prescription of Ref. [23] and implemented as five parameters. The final impact on the result is 0.5%. Uncertainties in PDFs mostly cancel, with a residual contribution of 0.2%. The combined statistical and systematic uncertainty in the measurement is 3.2%, with the statistical uncertainty contributing 0.6%. The main sources of systematic uncertainty and their relative contribution (in %) are shown in Table 1.

Table 1: Relative uncertainties (in %) on the final measurement from different sources.

Source of systematic uncertainty	Uncertainty (%)
Muon identification efficiency (syst.)	2.1
Jet energy scale	1.8–1.9
Electron identification efficiency (syst.)	1.6
Electron identification efficiency (stat.)	1.0
Pileup	0.9–1.0
Electron trigger efficiency	0.7
τ_h veto efficiency	0.6–0.7
p_T^{miss} trigger efficiency (jets plus p_T^{miss} region)	0.7
p_T^{miss} trigger efficiency ($Z/\gamma^* \rightarrow \mu\mu$ region)	0.6
Boson p_T dependence of QCD corrections	0.5
Jet energy resolution	0.3–0.5
p_T^{miss} trigger efficiency (μ +jets region)	0.4
Muon identification efficiency (stat.)	0.3
Electron reconstruction efficiency (syst.)	0.3
Boson p_T dependence of EW corrections	0.3
PDFs	0.2
Renormalization/factorization scale	0.2
Electron reconstruction efficiency (stat.)	0.2
Overall	3.2

The invisible width of the Z boson is extracted from a simultaneous likelihood fit to the \mathcal{U} dis-

tributions in the $p_T^{\text{miss}} + \text{jets}$, $Z/\gamma^*(\mu\mu) + \text{jets}$, $Z/\gamma^*(ee) + \text{jets}$, $\mu + \text{jets}$, and $e + \text{jets}$ regions. The \mathcal{U} distribution is divided into 20 bins to exploit the signal-to-background ratios and the dependence of systematic uncertainties on \mathcal{U} . The bin widths are chosen to be roughly equivalent to the \mathcal{U} resolution and with a maximum statistical uncertainty of 30% for the $Z/\gamma^*(\mu\mu) + \text{jets}$ and $Z/\gamma^*(ee) + \text{jets}$ regions. The transfer factor estimating the $W + \text{jets}$ background is implemented as a global unconstrained parameter scaling the $W + \text{jets}$ process in the $p_T^{\text{miss}} + \text{jets}$ and $\ell + \text{jets}$ regions and an additional free parameter is used to scale the normalisation of both the $Z \rightarrow \ell\ell$ and $Z \rightarrow \nu\bar{\nu}$ processes. Systematic uncertainties are treated as nuisance parameters, modeled with Gaussian constraints. The post-fit distributions from the simultaneous fit are shown in Fig. 3. The total number of events observed in data and from the the post-fit simulation results for the $p_T^{\text{miss}} + \text{jets}$, $Z/\gamma^*(\mu\mu) + \text{jets}$, and $Z/\gamma^*(ee) + \text{jets}$ regions are shown in Table 2.

The parameter of interest, r_{inv} , is defined as $\Gamma_{\text{inv}}/\Gamma^{\text{MC}}(Z \rightarrow \nu\bar{\nu})$, using the ratio of Eq. 1 with its expectation from simulation and assuming that the value of $\Gamma(Z \rightarrow \ell\ell)$ in data is the same as simulation. The value of r_{inv} is measured to be 1.049 ± 0.006 (stat) ± 0.032 (syst). This is translated into a measurement of the width using the $Z \rightarrow \nu\bar{\nu}$ partial width from simulation ($\Gamma^{\text{MC}}(Z \rightarrow \nu\bar{\nu})$), which is calculated from the branching fraction of $Z \rightarrow \nu\bar{\nu}$ in MADGRAPH5_aMC@NLO [20] for an invariant mass range of 71–111 GeV and the total Z boson width of 2.4988 GeV. The value of $\Gamma^{\text{MC}}(Z \rightarrow \nu\bar{\nu})$ is 498.7 MeV and the $Z \rightarrow \ell\ell$ partial width to one charged lepton flavor is 84.2 MeV.

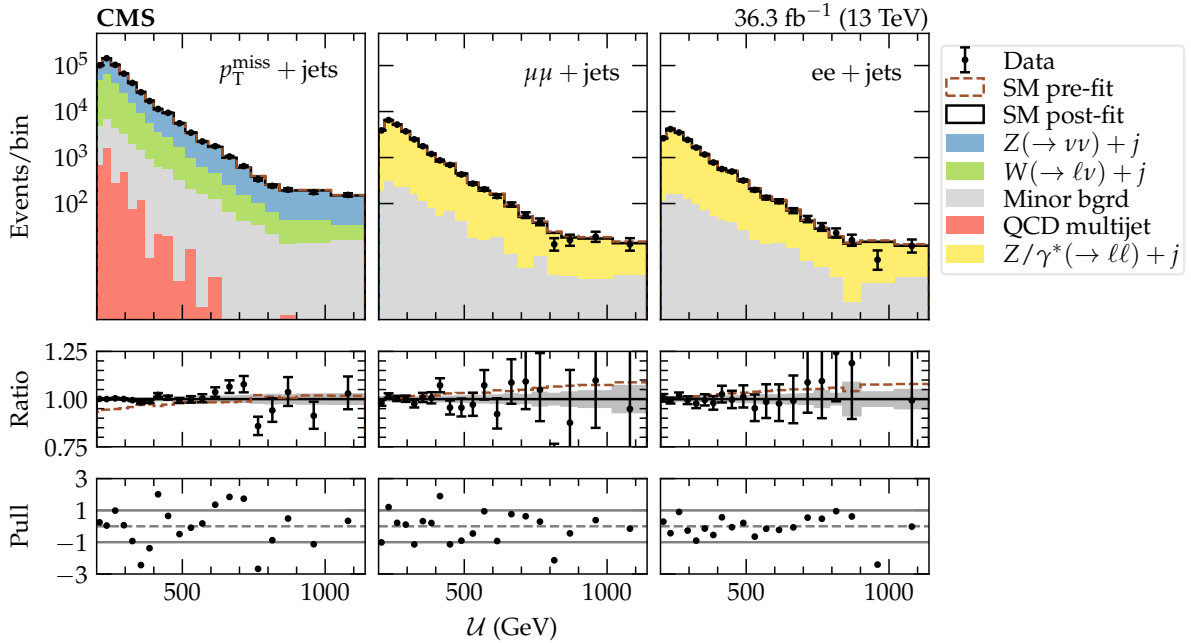


Figure 3: Distribution of \mathcal{U} for the $p_T^{\text{miss}} + \text{jets}$ (left), $Z/\gamma^* \rightarrow \mu\mu$ (center), and $Z/\gamma^* \rightarrow ee$ (right) regions. Ratios are taken of the data with respect to both the SM post-fit and SM pre-fit results. The pulls are the difference between the data and the SM post-fit results, normalized by their uncertainties summed in quadrature. The ‘Minor’ background includes the sum of all the contributions from processes such as diboson events, top pair production, single top production that are determined from simulation.

The measured Z boson invisible width value (Eq. 1) is obtained by multiplying r_{inv} by $\Gamma^{\text{MC}}(Z \rightarrow \nu\bar{\nu})$:

$$\Gamma_{\text{inv}} = 523 \pm 3 \text{ (stat)} \pm 16 \text{ (syst)} \text{ MeV.} \quad (2)$$

Table 2: SM post-fit predictions for the $p_T^{\text{miss}} + \text{jets}$, $Z/\gamma^* \rightarrow \mu\mu$, and $Z/\gamma^* \rightarrow ee$ regions and the total number of events measured in data.

	$p_T^{\text{miss}} + \text{jets}$	$Z/\gamma^* \rightarrow \mu\mu$	$Z/\gamma^* \rightarrow ee$
$Z(\nu\nu) + \text{jets}$	310000	—	—
$Z/\gamma^* \rightarrow \ell\ell$	2680	25900	17300
$W(\ell\nu) + \text{jets}$	195000	—	—
QCD multijet	3360	—	—
Minor	25600	1720	1090
Total SM	537000	27600	18400
Data	537326	27631	18326

A comparison with the direct measurements from the LEP experiments ALEPH, OPAL, and L3, as well as with the LEP combined measurement is shown in Fig. 4. Also shown is the standard model prediction for $\Gamma(Z \rightarrow \nu\bar{\nu})$ of $501.44 \pm 0.04 \text{ MeV}$ [5, 37]. With an uncertainty of 16 MeV, this measurement of the Z boson invisible width at CMS is comparable in precision to the LEP combined result and is compatible with the value expected in the SM.

In summary, this Letter presents the first precise measurement of the invisible width (Γ_{inv}) of the Z boson at a hadron collider. The measurement is performed using proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$ and data corresponding to an integrated luminosity of 36.3 fb^{-1} recorded with the CMS detector, yielding a result of $\Gamma_{\text{inv}} = 523 \pm 3 \text{ (stat)} \pm 16 \text{ (syst)} \text{ MeV}$. It represents the single most precise direct measurement of Γ_{inv} to date and is competitive with the combined direct measurement from LEP and compatible with the value expected in the standard model.

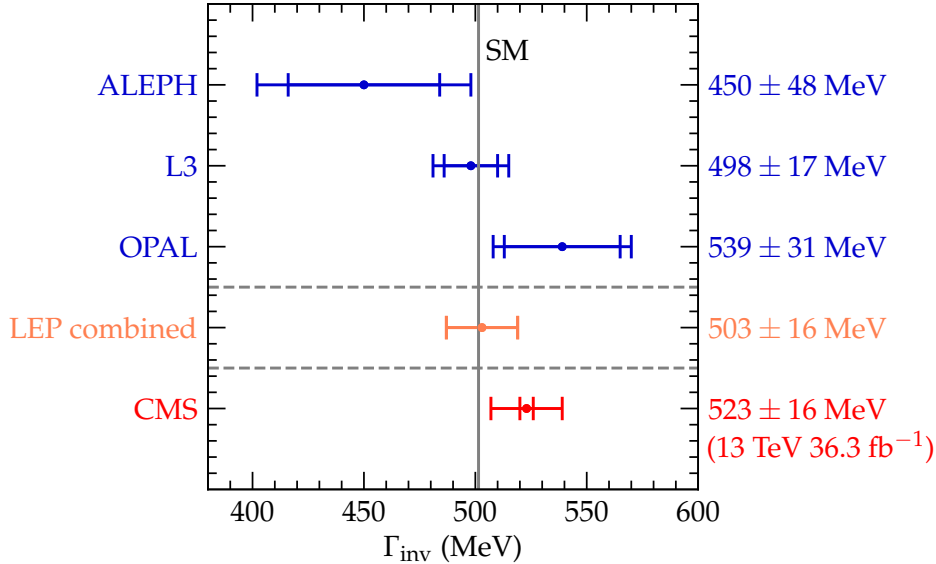


Figure 4: Direct measurements of the Z invisible width by the LEP experiments and the result from the CMS experiment presented here. Also shown is the prediction from the SM. The inner (outer) error bars show the statistical (total) uncertainty.

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 centers and personnel of the Worldwide LHC Computing Grid and other centers 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 and BNSF (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); GSRI (Greece); NKFIH (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); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 884104, and COST Action CA16108 (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 Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 - GRK2497; the Hungarian Academy of Sciences, the New National Excellence Program - ÚNKP, the NKFIH research grants K 124845, K 124850, K 128713, K 128786, K 129058, K 131991, K 133046, K 138136, K 143460, K 143477, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF "a way of making Europe", and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B05F650021 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References


- [1] CMS Collaboration, “Search for new particles in events with energetic jets and large missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **11** (2021) 153, doi:10.1007/JHEP11(2021)153, arXiv:2107.13021.
- [2] OPAL Collaboration, “Measurement of single photon production in e^+e^- collisions near the Z^0 resonance”, *Z. Phys. C* **65** (1995) 47, doi:10.1007/BF01571303.
- [3] ALEPH Collaboration, “A direct measurement of the invisible width of the Z from single photon counting”, *Phys. Lett. B* **313** (1993) 520, doi:10.1016/0370-2693(93)90027-F.
- [4] L3 Collaboration, “Determination of the number of light neutrino species from single photon production at LEP”, *Phys. Lett. B* **431** (1998) 199, doi:10.1016/S0370-2693(98)00519-X.
- [5] Particle Data Group, P. A. Zyla et al., “Review of particle physics”, *Prog. Theor. Exp. Phys.* **2020** (2020) 083C01, doi:10.1093/ptep/ptaa104.
- [6] UA2 Collaboration, “Measurement of the standard model parameters from a study of W and Z bosons”, *Phys. Lett. B* **186** (1987) 440, doi:10.1016/0370-2693(87)90324-8.
- [7] M. Carena, A. de Gouvea, A. Freitas, and M. Schmitt, “Invisible Z boson decays at e^+e^- colliders”, *Phys. Rev. D.* **68** (2003) 113007, doi:10.1103/PhysRevD.68.113007, arXiv:hep-ph/0308053.
- [8] 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.
- [9] HEPData record for this analysis, 2022. doi:10.17182/hepdata.130965.
- [10] CMS Collaboration, “Measurement of the Z boson differential production cross section using its invisible decay mode ($Z\nu\bar{\nu}$) in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **05** (2021) 205, doi:10.1007/JHEP05(2021)205, arXiv:2012.09254.
- [11] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [12] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [13] 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.
- [14] D. Contardo et al., “Technical proposal for the Phase-II upgrade of the CMS detector”, technical report, 2015. doi:10.17181/CERN.VU8I.D59J.
- [15] 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.
- [16] 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.

-
- [17] 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.
- [18] CMS Collaboration, “Performance of reconstruction and identification of τ leptons decaying to hadrons and ν_τ in pp collisions at $\sqrt{s} = 13$ TeV”, *JINST* **13** (2018) P10005, doi:10.1088/1748-0221/13/10/P10005, arXiv:1809.02816.
- [19] CMS Collaboration, “Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector”, *JINST* **14** (2019) P07004, doi:10.1088/1748-0221/14/07/P07004, arXiv:1903.06078.
- [20] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.
- [21] 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.
- [22] R. Frederix and S. Frixione, “Merging meets matching in MC@NLO”, *JHEP* **12** (2012) 061, doi:10.1007/JHEP12(2012)061, arXiv:1209.6215.
- [23] J. M. Lindert et al., “Precise predictions for V+jets dark matter backgrounds”, *Eur. Phys. J. C.* **77** (2017) 829, doi:10.1140/epjc/s10052-017-5389-1, arXiv:1705.04664.
- [24] N. Kidonakis, “Differential and total cross sections for top pair and single top production”, in *Proceedings, 20th International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS 2012): Bonn, Germany*, p. 831. 2012. arXiv:1205.3453. doi:10.3204/DESY-PROC-2012-02/251.
- [25] M. Czakon, P. Fiedler, and A. Mitov, “Total top-quark pair-production cross section at hadron colliders through $\mathcal{O}(\alpha_s^4)$ ”, *Phys. Rev. Lett.* **110** (2013) 252004, doi:10.1103/PhysRevLett.110.252004, arXiv:1303.6254.
- [26] P. Nason, “A new method for combining NLO QCD with shower Monte Carlo algorithms”, *JHEP* **11** (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.
- [27] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with parton shower simulations: the POWHEG method”, *JHEP* **11** (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.
- [28] S. Alioli, P. Nason, C. Oleari, and E. Re, “A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX”, *JHEP* **06** (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.
- [29] E. Re, “Single-top Wt -channel production matched with parton showers using the POWHEG method”, *Eur. Phys. J. C.* **71** (2011) 1547, doi:10.1140/epjc/s10052-011-1547-z, arXiv:1009.2450.
- [30] NNPDF Collaboration, “Parton distributions for the LHC Run II”, *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.



















- [31] 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.
- [32] GEANT4 Collaboration, “GEANT4 — a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [33] 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.
- [34] CMS Collaboration, “Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV”, *JINST* **13** (2018) P05011, doi:10.1088/1748-0221/13/05/P05011, arXiv:1712.07158.
- [35] CMS Collaboration, “Performance of the reconstruction and identification of high-momentum muons in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **15** (2020) P02027, doi:10.1088/1748-0221/15/02/P02027, arXiv:1912.03516.
- [36] CMS Collaboration, “Measurements of differential Z boson production cross sections in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **12** (2019) 061, doi:10.1007/JHEP12(2019)061, arXiv:1909.04133.
- [37] ALEPH, DELPHI, L3, OPAL, and SLD Collaborations, LEP Electroweak Working Group, SLD Electroweak Group, and SLD Heavy Flavour Group Collaboration, “Precision electroweak measurements on the Z resonance”, *Phys. Rept.* **427** (2006) 257, doi:10.1016/j.physrep.2005.12.006, arXiv:hep-ex/0509008.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A. Tumasyan¹ 




Institut für Hochenergiephysik, Vienna, Austria

W. Adam , J.W. Andrejkovic, T. Bergauer , S. Chatterjee , K. Damanakis , M. Dragicevic , A. Escalante Del Valle , R. Frühwirth² , M. Jeitler² , N. Krammer , L. Lechner , D. Liko , I. Mikulec , P. Paulitsch, F.M. Pitters, J. Schieck² , R. Schöfbeck , D. Schwarz , S. Templ , W. Waltenberger , C.-E. Wulz² 
















Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish³ , E.A. De Wolf, T. Janssen , T. Kello⁴, 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 , M. Delcourt , H. El Faham , S. Lowette , S. Moortgat , A. Morton , D. Müller , A.R. Sahasransu , S. Tavernier , W. Van Doninck


















Université Libre de Bruxelles, Bruxelles, Belgium

D. Beghin, B. Bilin , B. Clerbaux , 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 

Ghent University, Ghent, Belgium

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





















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

A. Benecke , A. Bethani , G. Bruno , F. Bury , C. Caputo , P. David , C. Delaere , I.S. Donertas , A. Giammanco , K. Jaffel , Sa. Jain , V. Lemaître, K. Mondal , J. Prisciandaro, A. Taliencio , M. Teklishyn , T.T. Tran , P. Vischia , S. Wertz 

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. Chinellato⁵, E.M. Da Costa , G.G. Da Silveira⁶ , D. De Jesus Damiao , S. Fonseca De Souza , 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 Araujo⁷ , A. Vilela Pereira 

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil

C.A. Bernardes⁶ , L. Calligaris , T.R. Fernandez Perez Tomei , E.M. Gregores , D. S. Lemos , P.G. Mercadante , S.F. Novaes , Sandra S. Padula 




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 , T. Javaid⁸, M. Mittal , L. Yuan 










Department of Physics, Tsinghua University, Beijing, China

M. Ahmad , G. Bauer, C. Dozen , Z. Hu , J. Martins⁹ , Y. Wang, K. Yi^{10,11}

Institute of High Energy Physics, Beijing, China

E. Chapon , G.M. Chen⁸ , H.S. Chen⁸ , M. Chen , F. Iemmi , A. Kapoor , D. Leggat, H. Liao , Z.-A. Liu¹² , V. Milosevic , F. Monti , R. Sharma , J. Tao , J. Thomas-Wilsker , J. Wang , H. Zhang , J. Zhao 




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

A. Agapitos , Y. An , Y. Ban , C. Chen, 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. Gao⁴ , H. Okawa , Y. Zhang 





Zhejiang University, Hangzhou, Zhejiang, China

Z. Lin , M. Xiao 

Universidad de Los Andes, Bogota, Colombia

C. Avila , A. Cabrera , C. Florez , J. Fraga 

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. Starodumov¹³ , T. Susa 

University of Cyprus, Nicosia, Cyprus

A. Attikis , K. Christoforou , 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. Finger¹³ , M. Finger Jr.¹³ , 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. Abdalla¹⁴ , S. Elgammal¹⁵






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

M.A. Mahmoud , Y. Mohammed 
















National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

S. Bhowmik , R.K. Dewanjee , K. Ehataht , M. Kadastik , S. Nandan , 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 ,
M. Myllymäki , J. Ott , H. Siikonen , E. Tuominen , J. Tuominiemi 



























Lappeenranta-Lahti 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-
Navarro¹⁶ , 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 , J. Motta , M. Nguyen ,
C. Ochando , P. Paganini , J. Rembser , R. Salerno , U. Sarkar , J.B. Sauvan ,
Y. Sirois , A. Tarabini , A. Zabi , A. Zghiche 




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

J.-L. Agram¹⁷ , J. Andrea, D. Apparù , D. Bloch , G. Bourgatte, J.-M. Brom ,
E.C. Chabert , C. Collard , D. Darej, J.-C. Fontaine¹⁷, 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 , 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

A. Khvedelidze¹³ , I. Lomidze , Z. Tsamalaidze¹³ 

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

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

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





A. Dodonova , D. Eliseev , M. Erdmann , P. Fackeldey , B. Fischer , S. Ghosh ,
T. Hebbeker , K. Hoepfner , F. Ivone , 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 , L. Vigilante, S. Wiedenbeck , S. Zaleski




























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

C. Dziwok , G. Flügge , W. Haj Ahmad¹⁸ , O. Hlushchenko, T. Kress , A. Nowack , C. Pistone, O. Pooth , D. Roy , H. Sert , A. Stahl¹⁹ , T. Ziemons , A. Zotz 






























Deutsches Elektronen-Synchrotron, Hamburg, Germany

H. Aarup Petersen, M. Aldaya Martin , P. Asmuss, S. Baxter , M. Bayatmakou , O. Behnke, A. Bermúdez Martínez , S. Bhattacharya , A.A. Bin Anuar , K. Borrás²⁰ , D. Brunner , A. Campbell , A. Cardini , C. Cheng, F. Colombina, S. Consuegra Rodríguez , G. Correia Silva , V. Danilov, M. De Silva , L. Didukh , G. Eckerlin, D. Eckstein, L.I. Estevez Banos , O. Filatov , E. Gallo²¹ , A. Geiser , A. Giraldi , A. Grohsjean , M. Guthoff , A. Jafari²² , N.Z. Jomhari , A. Kasem²⁰ , M. Kasemann , H. Kaveh , C. Kleinwort , D. Krücker , W. Lange, J. Lidrych , K. Lipka , W. Lohmann²³ , R. Mankel , I.-A. Melzer-Pellmann , M. Mendizabal Morentin , J. Metwally, A.B. Meyer , M. Meyer , J. Mnich , A. Mussgiller , Y. Otariid, D. Pérez Adán , D. Pitzl, A. Raspereza, B. Ribeiro Lopes , J. Rübenach, A. Saggio , A. Saibel , M. Savitskyi , M. Scham²⁴ , V. Scheurer, S. Schnake , P. Schütze , C. Schwanenberger²¹ , M. Shchedrolosiev , R.E. Sosa Ricardo , D. Stafford, N. Tonon , 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. Albrecht , S. Bein , L. Benato , P. Connor , K. De Leo , M. Eich, F. Feindt, A. Fröhlich, C. Garbers , E. Garutti , P. Gunnellini, M. Hajheidari, 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 , J. Sonneveld , H. Stadie , G. Steinbrück , A. Tews, I. Zoi 











Karlsruher Institut fuer Technologie, Karlsruhe, Germany

J. Bechtel , S. Brommer , M. Burkart, E. Butz , R. Caspart , T. Chwalek , W. De Boer[†], A. Dierlamm , A. Droll, K. El Morabit , N. Faltermann , M. Giffels , J.o. Gosewisch, A. Gottmann , F. Hartmann¹⁹ , C. Heidecker, U. Husemann , P. Keicher, R. Koppenhöfer , S. Maier , M. Metzler, S. Mitra , Th. Müller , M. Neukum, A. Nürnberg , G. Quast , K. Rabbertz , J. Rauser, D. Savoieu , 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. Wozniowski , S. Wunsch




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

G. Anagnostou, G. Daskalakis , T. Gerasis , A. Kyriakis, 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

K. Adamidis, I. Bestintzanos, I. Evangelou , C. Foudas, P. Giannelios , 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. Csanád , K. Farkas , M.M.A. Gadallah²⁵ , S. Lökös²⁶ , P. Major , K. Mandal , A. Mehta , G. Pásztor , A.J. Rádl , O. Surányi , G.I. Veres 



Wigner Research Centre for Physics, Budapest, Hungary

M. Bartók²⁷ , G. Bencze, C. Hajdu , D. Horvath²⁸ , F. Sikler , V. Veszpremi 




Institute of Nuclear Research ATOMKI, Debrecen, Hungary

S. Czellar, J. Karancsi²⁷ , J. Molnar, Z. Szillasi, D. Teyssier 





Institute of Physics, University of Debrecen, Debrecen, Hungary

P. Raics, Z.L. Trocsanyi²⁹ , B. Ujvari 














Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary

T. Csorgo³⁰ , F. Nemes³⁰ , T. Novak 










Indian Institute of Science (IISc), Bangalore, India

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










Panjab University, Chandigarh, India

S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra³¹ , 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 , M. Gola, S. Keshri , A. Kumar , M. Naimuddin , P. Priyanka , K. Ranjan , A. Shah 





Saha Institute of Nuclear Physics, HBNI, Kolkata, India

M. Bharti³², R. Bhattacharya , S. Bhattacharya , D. Bhowmik, S. Dutta , S. Dutta, B. Gomber³³ , M. Maity³⁴, P. Palit , P.K. Rout , G. Saha , B. Sahu , S. Sarkar, M. Sharan, B. Singh³², S.Thakur³² 



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. Naskar³⁵ , P.K. Netrakanti, L.M. Pant, P. Shukla 










Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, S. Dugad, M. Kumar , G.B. Mohanty 

Tata Institute of Fundamental Research-B, Mumbai, India

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

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India

S. Bahinipati³⁶ , C. Kar , P. Mal , T. Mishra , V.K. Muraleedharan Nair Bindhu³⁷ , A. Nayak³⁷ , P. Saha , N. Sur , S.K. Swain, D. Vats³⁷ 

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

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

Isfahan University of Technology, Isfahan, Iran

H. Bakhshiansohi³⁸ , E. Khazaie , M. Zeinali³⁹ 

































Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

S. Chenarani⁴⁰ , S.M. Etesami , M. Khakzad , M. Mohammadi Najafabadi 





























University College Dublin, Dublin, Ireland

M. Grunewald 







INFN Sezione di Bari^a, Università di Bari^b, Politecnico di Bari^c, Bari, Italy

M. Abbrescia^{a,b} , R. Aly^{a,c,41} , C. Aruta^{a,b} , A. Colaleo^a , D. Creanza^{a,c} , N. De Filippis^{a,c} , M. De Palma^{a,b} , A. Di Florio^{a,b} , A. Di Pilato^{a,b} , W. Elmetenawee^{a,b} , L. Fiore^a , A. Gelmi^{a,b} , M. Gul^a , G. Iaselli^{a,c} , M. Ince^{a,b} , S. Lezki^{a,b} , G. Maggi^{a,c} , M. Maggi^a , I. Margjeka^{a,b} , V. Mastrapasqua^{a,b} , S. My^{a,b} , S. Nuzzo^{a,b} , A. Pellecchia^{a,b} , A. Pompili^{a,b} , G. Pugliese^{a,c} , D. Ramos^a , A. Ranieri^a , G. Selvaggi^{a,b} , L. Silvestris^a , F.M. Simone^{a,b} , R. Venditti^a , P. Verwilligen^a 
















INFN Sezione di Bologna^a, Università di Bologna^b, Bologna, Italy

G. Abbiendi^a , C. Battilana^{a,b} , D. Bonacorsi^{a,b} , L. Borgonovi^a , L. Brigliadori^a , R. Campanini^{a,b} , P. Capiluppi^{a,b} , A. Castro^{a,b} , F.R. Cavallo^a , M. Cuffiani^{a,b} , G.M. Dallavalle^a , T. Diotallevi^{a,b} , F. Fabbri^a , A. Fanfani^{a,b} , P. Giacomelli^a , L. Giommi^{a,b} , C. Grandi^a , L. Guiducci^{a,b} , S. Lo Meo^{a,42} , L. Lunerti^{a,b} , S. Marcellini^a , G. Masetti^a , F.L. Navarria^{a,b} , A. Perrotta^a , F. Primavera^{a,b} , A.M. Rossi^{a,b} , T. Rovelli^{a,b} , G.P. Siroli^{a,b} 

INFN Sezione di Catania^a, Università di Catania^b, Catania, Italy

S. Albergo^{a,b,43} , S. Costa^{a,b,43} , A. Di Mattia^a , R. Potenza^{a,b} , A. Tricomi^{a,b,43} , C. Tuve^{a,b} 

INFN Sezione di Firenze^a, Università di Firenze^b, Firenze, Italy

G. Barbagli^a , A. Cassese^a , R. Ceccarelli^{a,b} , V. Ciulli^{a,b} , C. Cividini^a , R. D'Alessandro^{a,b} , E. Focardi^{a,b} , G. Latino^{a,b} , P. Lenzi^{a,b} , M. Lizzo^{a,b} , M. Meschini^a , S. Paoletti^a , R. Seidita^{a,b} , G. Sguazzoni^a , L. Viliani^a 


























INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi , S. Bianco , D. Piccolo 






INFN Sezione di Genova^a, Università di Genova^b, Genova, Italy

M. Bozzo^{a,b} , F. Ferro^a , R. Mulargia^{a,b} , E. Robutti^a , S. Tosi^{a,b} 

INFN Sezione di Milano-Bicocca^a, Università di Milano-Bicocca^b, Milano, Italy









A. Benaglia^a , G. Boldrini^a , F. Brivio^{a,b} , F. Cetorelli^{a,b} , F. De Guio^{a,b} , M.E. Dinardo^{a,b} , P. Dini^a , S. Gennai^a , A. Ghezzi^{a,b} , P. Govoni^{a,b} , L. Guzzi^{a,b} , M.T. Lucchini^{a,b} , M. Malberti^a , S. Malvezzi^a , A. Massironi^a , D. Menasce^a , L. Moroni^a , M. Paganoni^{a,b} , D. Pedrini^a , B.S. Pinolini^a , S. Ragazzi^{a,b} , N. Redaelli^a , T. Tabarelli de Fatis^{a,b} , D. Valsecchi^{a,b,19} , D. Zuolo^{a,b} 

INFN Sezione di Napoli^a, Università di Napoli 'Federico II'^b, Napoli, Italy; Università della Basilicata^c, Potenza, Italy; Università G. Marconi^d, Roma, Italy









S. Buontempo^a , F. Carnevali^{a,b} , N. Cavallo^{a,c} , A. De Iorio^{a,b} , F. Fabozzi^{a,c} 

A.O.M. Iorio^{a,b} , L. Lista^{a,b} , S. Meola^{a,d,19} , P. Paolucci^{a,19} , B. Rossi^a , C. Sciacca^{a,b} 









INFN Sezione di Padova^a, Università di Padova^b, Padova, Italy; Università di Trento^c, Trento, Italy

P. Azzi^a , N. Bacchetta^a , D. Bisello^{a,b} , P. Bortignon^a , A. Bragagnolo^{a,b} , R. Carlin^{a,b} , P. Checchia^a , T. Dorigo^a , U. Dosselli^a , F. Gasparini^{a,b} , U. Gasparini^{a,b} , G. Grosso^a, S.Y. Hoh^{a,b} , L. Layer^{a,44}, E. Lusiani^a , M. Margoni^{a,b} , A.T. Meneguzzo^{a,b} , J. Pazzini^{a,b} , P. Ronchese^{a,b} , R. Rossin^{a,b} , F. Simonetto^{a,b} , G. Strong^a , M. Tosi^{a,b} , H. Yarar^{a,b}, M. Zanetti^{a,b} , P. Zotto^{a,b} , A. Zucchetta^{a,b} , G. Zumerle^{a,b}









INFN Sezione di Pavia^a, Università di Pavia^b, Pavia, Italy

C. Aime^{a,b} , A. Braghieri^a , S. Calzaferri^{a,b} , D. Fiorina^{a,b} , P. Montagna^{a,b} , S.P. Ratti^{a,b}, V. Re^a , C. Riccardi^{a,b} , P. Salvini^a , I. Vai^a , P. Vitulo^{a,b}



INFN Sezione di Perugia^a, Università di Perugia^b, Perugia, Italy

P. Asenov^{a,45} , G.M. Bilei^a , D. Ciangottini^{a,b} , L. Fanò^{a,b} , P. Lariccia^{a,b}, M. Magherini^{a,b} , G. Mantovani^{a,b}, V. Mariani^{a,b} , M. Menichelli^a , F. Moscatelli^{a,45} , A. Piccinelli^{a,b} , M. Presilla^{a,b} , A. Rossi^{a,b} , A. Santocchia^{a,b} , D. Spiga^a , T. Tedeschi^{a,b}









INFN Sezione di Pisa^a, Università di Pisa^b, Scuola Normale Superiore di Pisa^c, Pisa, Italy; Università di Siena^d, Siena, Italy

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









INFN Sezione di Roma^a, Sapienza Università di Roma^b, Roma, Italy

P. Barria^a , M. Campana^{a,b} , F. Cavallari^a , D. Del Re^{a,b} , E. Di Marco^a , M. Diemoz^a , E. Longo^{a,b} , P. Meridiani^a , G. Organtini^{a,b} , F. Pandolfi^a , R. Paramatti^{a,b} , C. Quaranta^{a,b} , S. Rahatlou^{a,b} , C. Rovelli^a , F. Santanastasio^{a,b} , L. Soffi^a , R. Tramontano^{a,b}














INFN Sezione di Torino^a, Università di Torino^b, Torino, Italy; Università del Piemonte Orientale^c, Novara, Italy

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

INFN Sezione di Trieste^a, Università di Trieste^b, Trieste, Italy

S. Belforte^a , V. Candelise^{a,b} , M. Casarsa^a , F. Cossutti^a , A. Da Rold^{a,b} , G. Della Ricca^{a,b} , G. Sorrentino^{a,b} , F. Vazzoler^{a,b} 

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, 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.Y. Kang, Y. Kang , S. Kim , B. Ko, J.S.H. Lee , Y. Lee , J.A. Merlin, I.C. Park , Y. Roh, M.S. Ryu , D. Song, Watson, I.J. , S. Yang 


Yonsei University, Department of Physics, Seoul, Korea

S. Ha , H.D. Yoo 

Sungkyunkwan University, Suwon, Korea

M. Choi , H. Lee, Y. Lee , I. Yu 

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

T. Beyrouthy, Y. Maghrbi 


Riga Technical University, Riga, Latvia

K. Dreimanis , V. Veckalns 



Vilnius University, Vilnius, Lithuania

M. Ambrozias , A. Carvalho Antunes De Oliveira , A. Juodagalvis , A. Rinkevicius , G. Tamulaitis 








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 , E. De La Cruz-Burelo , I. Heredia-De La Cruz⁴⁶ , R. Lopez-Fernandez , C.A. Mondragon Herrera, D.A. Perez Navarro , A. Sánchez Hernández 


Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera , 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. Mijuskovic⁴⁷, N. Raicevic 







University of Auckland, Auckland, New Zealand

D. Krofcheck 

University of Canterbury, Christchurch, New Zealand

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. Szeper , P. Zalewski 

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

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


























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 



VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

P. Adzic⁴⁸ , 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 , C. Perez Dengra , 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 , J.R. González Fernández , E. Palencia Cortezon , C. Ramón Álvarez , V. Rodríguez Bouza , A. Soto Rodríguez , A. Trapote , N. Trevisani , C. Vico Villalba 

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

J.A. Brochero Cifuentes , I.J. Cabrillo , A. Calderon , 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. Vizan Garcia 

















University of Colombo, Colombo, Sri Lanka

M.K. Jayananda , B. Kailasapathy⁴⁹ , D.U.J. Sonnadara , D.D.C. 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[†], D. Barney , J. Bendavid , M. Bianco , A. Bocci , T. Camporesi , M. Capeans Garrido , G. Cerminara , N. Chernyavskaya , S.S. Chhibra , M. Cipriani , L. Cristella , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defran- chis , M. Deile , M. Dobson , M. Dünser , N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita⁵⁰, D. Fasanella , A. Florent , G. Franzoni , W. Funk , S. Giani, D. Gigi, K. Gill, F. Glege , L. Gouskos , M. Haranko , J. Hegeman , V. Innocente , T. James , P. Janot , J. Kaspar , J. Kieseler , M. Komm , N. Kratochwil , C. Lange , S. Laurila , P. Lecoq , A. Lintuluoto , K. Long , C. Lourenço , B. Maier , 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. Rabady , A. Racz, G. Reales Gutiérrez, M. Rieger , M. Rovere , H. Sakulin , J. Salfeld-Nebgen , S. Scarfi, C. Schäfer, M. Selvaggi , A. Sharma , P. Silva , W. Snoeys , P. Sphicas⁵¹ , S. Summers , K. Tatar , V.R. Tavolaro , D. Treille , P. Tropea , A. Tsirou, G.P. Van Onsem , J. Wanczyk⁵² , K.A. Wozniak , W.D. Zeuner
























Paul Scherrer Institut, Villigen, Switzerland

L. Caminada⁵³ , A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli , D. Kotlinski , M. Missiroli⁵³ , L. Noehte⁵³ , T. Rohe 




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

K. Androsov⁵² , M. Backhaus , P. Berger, A. Calandri , A. De Cosa , G. Dissertori , M. Dittmar, M. Donegà , C. Dorfer , F. Eble , K. Gedia , F. Glessgen , T.A. Gómez Es- pinosa , C. Grab , D. Hits , W. Lustermann , A.-M. Lyon , R.A. Manzoni , L. Marchese , C. Martin Perez , M.T. Meinhard , F. Nessi-Tedaldi , J. Niedziela , F. Pauss , V. Perovic , S. Pigazzini , M.G. Ratti , M. Reichmann , C. Reissel , T. Reitenspiess , B. Ristic , D. Ruini, D.A. Sanz Becerra , V. Stampf, J. Steggemann⁵² , R. Wallny , D.H. Zhu 










Universität Zürich, Zurich, Switzerland

C. Amsler⁵⁴ , P. Bäertschi , C. Botta , D. Brzdechko, M.F. Canelli , K. Cormier , A. De Wit , R. Del Burgo, J.K. Heikkilä , M. Huwiler , W. Jin , A. Jofre- hei , B. Kilminster , S. Leontsinis , S.P. Liechi , A. Macchiolo , P. Meiring , V.M. Mikuni , U. Molinatti , I. Neutelings , A. Reimers , P. Robmann, S. Sanchez Cruz , K. Schweiger , M. Senger , Y. Takahashi 




National Central University, Chung-Li, Taiwan

C. Adloff⁵⁵, C.M. Kuo, W. Lin, A. Roy , T. Sarkar³⁴ , 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. Damarseekin⁵⁶ , Z.S. Demiroglu , F. Dolek , I. Dumanoglu⁵⁷ , E. Eskut,
Y. Guler⁵⁸ , E. Gurpinar Guler⁵⁸ , C. Isik , O. Kara, A. Kayis Topaksu , U. Kiminsu ,
G. Onengut , K. Ozdemir⁵⁹ , A. Polatoz , A.E. Simsek , B. Tali⁶⁰ , U.G. Tok ,
S. Turkcapar , I.S. Zorbakir 

Middle East Technical University, Physics Department, Ankara, Turkey

B. Isildak⁶¹ , G. Karapinar, K. Ocalan⁶² , M. Yalvac⁶³ 

Bogazici University, Istanbul, Turkey

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya⁶⁴ , O. Kaya⁶⁵ , Ö. Özçelik ,
S. Tekten⁶⁶ , E.A. Yetkin⁶⁷ 


Istanbul Technical University, Istanbul, Turkey

A. Cakir , K. Cankocak⁵⁷ , Y. Komurcu , S. Sen⁶⁸ 

Istanbul University, Istanbul, Turkey

S. Cerci⁶⁰ , I. Hos⁶⁹ , B. Kaynak , S. Ozkorucuklu , D. Sunar Cerci⁶⁰ , C. Zorbilmez 
















Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine

B. Grynyov 
















National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, 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. Stylianou⁷⁰ ,
K. Walkingshaw Pass, R. White 





Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell , A. Belyaev⁷¹ , C. Brew , R.M. Brown , D.J.A. Cockerill , C. Cooke ,
K.V. Ellis, K. Harder , S. Harper , M.-L. Holmberg , 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. Chahal⁷² , 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 , D.G. Monk , J. Nash⁷³ , M. Pesaresi, D.M. Raymond,
A. Richards, A. Rose , E. Scott , C. Seez , A. Shtipliyski, A. Tapper , K. Uchida ,
T. Virdee¹⁹ , M. Vojinovic , N. Wardle , S.N. Webb , D. Winterbottom

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, Texas, USA

S. Abdullin , A. Brinkerhoff , B. Caraway , J. Dittmann , K. Hatakeyama , A.R. Kanuganti , B. McMaster , N. Pastika , M. Saunders , 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, Alabama, USA

A. Buccilli , S.I. Cooper , D. Di Croce , S.V. Gleyzer , C. Henderson , C.U. Perez , P. Rumerio⁷⁴ , C. West 



















Boston University, Boston, Massachusetts, USA

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














Brown University, Providence, Rhode Island, USA

G. Benelli , B. Burkle , X. Coubez²⁰ , D. Cutts , M. Hadley , U. Heintz , J.M. Hogan⁷⁵ , T. KWON , G. Landsberg , K.T. Lau , D. Li , M. Lukasik , J. Luo , M. Narain , N. Pervan , S. Sagir⁷⁶ , F. Simpson , E. Usai , W.Y. Wong , X. Yan , D. Yu , W. Zhang

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

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



















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

J.G. Branson , P. Chang , S. Cittolin , S. Cooperstein , N. Deelen , D. Diaz , J. Duarte , R. Gerosa , L. Giannini , J. Guiang , R. Kansal , V. Krutelyov , R. Lee , J. Letts , M. Masciovecchio , F. Mokhtar , 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, California, 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 , F. Setti , J. Sheplock , D. Stuart , S. Wang 

California Institute of Technology, Pasadena, California, USA

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

















Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

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


University of Colorado Boulder, Boulder, Colorado, USA

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

























Cornell University, Ithaca, New York, USA

J. Alexander , S. Bright-Thonney , X. Chen , Y. Cheng , D.J. Cranshaw , S. Hogan , J. Monroy , J.R. Patterson , D. Quach , J. Reichert , M. Reid , A. Ryd , W. Sun , J. Thom , P. Wittich , R. Zou 









Fermi National Accelerator Laboratory, Batavia, Illinois, USA

M. Albrow , M. Alyari , G. Apollinari , A. Apresyan , A. Apyan , S. Banerjee , L.A.T. Bauerick , D. Berry , J. Berryhill , P.C. Bhat , K. Burkett , J.N. Butler , A. Canepa , G.B. Cerati , H.W.K. Cheung , F. Chlebana , 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 , J. Ngadiuba , V. O'Dell, V. Papadimitriou , K. Pedro , C. Pena⁷⁷ , O. Prokofyev, F. Ravera , A. Reinsvold Hall , L. Ristori , E. Sexton-Kennedy , N. Smith , A. Soha , W.J. Spalding , L. Spiegel , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , H.A. Weber 








University of Florida, Gainesville, Florida, 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 , J. Rotter , K. Shi , J. Sturdy , J. Wang , E. Yigitbasi , X. Zuo 




















Florida State University, Tallahassee, Florida, USA

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











Florida Institute of Technology, Melbourne, Florida, USA

M.M. Baarmand , S. Butalla , T. Elkafrawy⁷⁸ , M. Hohmann , R. Kumar Verma , D. Noonan , M. Rahmani, F. Yumiceva 












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

M.R. Adams , H. Becerril Gonzalez , R. Cavanaugh , 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, Iowa, USA























M. Alhusseini , K. Dilsiz⁷⁹ , R.P. Gandrajula , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili⁸⁰ , J. Nachtman , H. Ogul⁸¹ , Y. Onel , A. Penzo , C. Snyder, E. Tiras⁸² 

Johns Hopkins University, Baltimore, Maryland, 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, Kansas, USA

A. Abreu , J. Anguiano , C. Baldenegro Barrera , P. Baringer , A. Bean , A. Bylinkin 

Z. Flowers , T. Isidori , S. Khalil , J. King , G. Krintiras , A. Kropivnitskaya , M. Lazarovits , C. Le Mahieu , C. Lindsey, J. Marquez , N. Minafra , M. Murray , M. Nickel , C. Rogan , C. Royon , R. Salvatico , S. Sanders , E. Schmitz , C. Smith , J.D. Tapia Takaki , Q. Wang , Z. Warner, J. Williams , G. Wilson 




Kansas State University, Manhattan, Kansas, USA

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






















Lawrence Livermore National Laboratory, Livermore, California, USA

F. Rebassoo , D. Wright 

University of Maryland, College Park, Maryland, 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 , C. Palmer , M. Seidel , A. Skuja , L. Wang , K. Wong 















Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

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

University of Minnesota, Minneapolis, Minnesota, USA

R.M. Chatterjee, A. Evans , 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, Nebraska, USA

K. Bloom , M. Bryson, S. Chauhan , D.R. Claes , C. Fangmeier , L. Finco , F. Golf , C. Joo , I. Kravchenko , M. Musich , I. Reed , J.E. Siado , G.R. Snow[†], W. Tabb , F. Yan , A.G. Zecchinelli 









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

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























Northeastern University, Boston, Massachusetts, USA

G. Alverson , E. Barberis , 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, Illinois, USA

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




















University of Notre Dame, Notre Dame, Indiana, USA

R. Band , R. Bucci, M. Cremonesi, A. Das , N. Dev , R. Goldouzian , M. Hildreth , K. Hurtado Anampa , C. Jessop , K. Lannon , J. Lawrence , N. Loukas , L. Lutton , N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady , K. Mohrman , C. Moore , Y. Musienko¹³ , R. Ruchti , P. Siddireddy, A. Townsend , M. Wayne , A. Wightman , M. Zarucki , L. Zygala 

The Ohio State University, Columbus, Ohio, 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, New Jersey, 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 , D. Marlow , K. Mei , I. Ojalvo , J. Olsen , D. Stickland ,
C. Tully 



University of Puerto Rico, Mayaguez, Puerto Rico, USA

S. Malik , S. Norberg

Purdue University, West Lafayette, Indiana, USA

A.S. Bakshi , V.E. Barnes , R. Chawla , S. Das , L. Gutay, M. Jones , A.W. Jung ,
S. Karmarkar , D. Kondratyev , M. Liu , G. Negro , N. Neumeister , G. Paspalaki ,
S. Piperov , A. Purohit , J.F. Schulte , M. Stojanovic , J. Thieman , F. Wang ,
R. Xiao , W. Xie 











Purdue University Northwest, Hammond, Indiana, USA

J. Dolen , N. Parashar 
















Rice University, Houston, Texas, USA

A. Baty , T. Carnahan , 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 Leiton ,
S. Yang , L. Zhang⁸³, Y. Zhang 

University of Rochester, Rochester, New York, 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, New Jersey, USA

B. Chiarito, J.P. Chou , A. Gandrakota , Y. Gershtein , E. Halkiadakis , A. Hart ,
M. Heindl , O. Karacheban²³ , 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, Tennessee, USA

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










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

O. Bouhali⁸⁴ , M. Dalchenko , A. Delgado , R. Eusebi , J. Gilmore , T. Huang ,
T. Kamon⁸⁵ , H. Kim , S. Luo , S. Malhotra, R. Mueller , D. Overton , D. Rathjens ,
A. Safonov 














Texas Tech University, Lubbock, Texas, 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, Tennessee, 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, Virginia, USA

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

Wayne State University, Detroit, Michigan, USA

N. Poudyal 

University of Wisconsin - Madison, Madison, Wisconsin, USA

K. Black , T. Bose , 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 

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN

S. Afanasiev, V. Andreev , Yu. Andreev , T. Aushev , M. Azarkin , A. Babaev , A. Belyaev , V. Blinov⁸⁶, E. Boos , V. Borshch , D. Budkouski , O. Bychkova, V. Chekhovsky, R. Chistov⁸⁶ , M. Danilov⁸⁶ , A. Dermenev , T. Dimova⁸⁶ , I. Dremin , M. Dubinin⁷⁷ , L. Dudko , V. Epshteyn , A. Ershov , G. Gavrillov , V. Gavrillov , S. Gninenko , V. Golovtcov , N. Golubev , I. Golutvin, I. Gorbunov , A. Gribushin , V. Ivanchenko , Y. Ivanov , V. Kachanov , L. Kardapoltsev⁸⁶ , V. Karjavine , A. Karneyeu , V. Kim⁸⁶ , M. Kirakosyan, D. Kirpichnikov , M. Kirsanov , V. Klyukhin , O. Kodolova⁸⁷ , D. Konstantinov , V. Korenkov , A. Kozyrev⁸⁶ , N. Krasnikov , E. Kuznetsova⁸⁸, A. Lanev , A. Litomin, N. Lychkovskaya , V. Makarenko , A. Malakhov , V. Matveev⁸⁶ , V. Murzin , A. Nikitenko⁸⁹ , S. Obraztsov , V. Okhotnikov , V. Oreshkin , A. Oskin, I. Ovtin⁸⁶ , V. Palichik , P. Parygin , A. Pashenkov, V. Perelygin , S. Petrushanko , G. Pivovarov , S. Polikarpov⁸⁶ , V. Popov, O. Radchenko⁸⁶ , M. Savina , V. Savrin , D. Seitova, V. Shalaev , S. Shmatov , S. Shulha , Y. Skovpen⁸⁶ , S. Slabospitskii , I. Smirnov, V. Smirnov , A. Snigirev , D. Sosnov , A. Stepenov , V. Sulimov , E. Tcherniaev , A. Terkulov , O. Teryaev , M. Toms , A. Toropin , L. Uvarov , A. Uzunian , E. Vlasov , S. Volkov, A. Vorobyev, N. Voytishin , B.S. Yuldashev⁹⁰, A. Zarubin , I. Zhizhin , A. Zhokin 

†: Deceased

¹Also at Yerevan State University, Yerevan, Armenia

²Also at TU Wien, Vienna, Austria

³Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt

⁴Also at Université Libre de Bruxelles, Bruxelles, Belgium

⁵Also at Universidade Estadual de Campinas, Campinas, Brazil

⁶Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

⁷Also at The University of the State of Amazonas, Manaus, Brazil

⁸Also at University of Chinese Academy of Sciences, Beijing, China

⁹Also at UFMS, Nova Andradina, Brazil

¹⁰Also at Nanjing Normal University Department of Physics, Nanjing, China

¹¹Now at The University of Iowa, Iowa City, Iowa, USA

¹²Also at University of Chinese Academy of Sciences, Beijing, China

¹³Also at an institute or an international laboratory covered by a cooperation agreement with CERN

¹⁴Also at Cairo University, Cairo, Egypt

¹⁵Now at British University in Egypt, Cairo, Egypt

¹⁶Also at Purdue University, West Lafayette, Indiana, USA

¹⁷Also at Université de Haute Alsace, Mulhouse, France

¹⁸Also at Erzincan Binali Yildirim University, Erzincan, Turkey

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

-
- ²⁰Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- ²¹Also at University of Hamburg, Hamburg, Germany
- ²²Also at Isfahan University of Technology, Isfahan, Iran
- ²³Also at Brandenburg University of Technology, Cottbus, Germany
- ²⁴Also at Forschungszentrum Jülich, Juelich, Germany
- ²⁵Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- ²⁶Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
- ²⁷Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- ²⁸Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- ²⁹Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- ³⁰Also at Wigner Research Centre for Physics, Budapest, Hungary
- ³¹Also at Punjab Agricultural University, Ludhiana, India
- ³²Also at Shoolini University, Solan, India
- ³³Also at University of Hyderabad, Hyderabad, India
- ³⁴Also at University of Visva-Bharati, Santiniketan, India
- ³⁵Also at Indian Institute of Technology (IIT), Mumbai, India
- ³⁶Also at IIT Bhubaneswar, Bhubaneswar, India
- ³⁷Also at Institute of Physics, Bhubaneswar, India
- ³⁸Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- ³⁹Also at Sharif University of Technology, Tehran, Iran
- ⁴⁰Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- ⁴¹Also at Helwan University, Cairo, Egypt
- ⁴²Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- ⁴³Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- ⁴⁴Also at Università di Napoli 'Federico II', Napoli, Italy
- ⁴⁵Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- ⁴⁶Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- ⁴⁷Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- ⁴⁸Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- ⁴⁹Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- ⁵⁰Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
- ⁵¹Also at National and Kapodistrian University of Athens, Athens, Greece
- ⁵²Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- ⁵³Also at Universität Zürich, Zurich, Switzerland
- ⁵⁴Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- ⁵⁵Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- ⁵⁶Also at Şirnak University, Sirnak, Turkey
- ⁵⁷Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
- ⁵⁸Also at Konya Technical University, Konya, Turkey
- ⁵⁹Also at Izmir Bakircay University, Izmir, Turkey
- ⁶⁰Also at Adiyaman University, Adiyaman, Turkey
- ⁶¹Also at Yildiz Technical University, Istanbul, Turkey
- ⁶²Also at Necmettin Erbakan University, Konya, Turkey
- ⁶³Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey

⁶⁴Also at Marmara University, Istanbul, Turkey

⁶⁵Also at Milli Savunma University, Istanbul, Turkey

⁶⁶Also at Kafkas University, Kars, Turkey

⁶⁷Also at Istanbul Bilgi University, Istanbul, Turkey

⁶⁸Also at Hacettepe University, Ankara, Turkey

⁶⁹Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey

⁷⁰Also at Vrije Universiteit Brussel, Brussel, Belgium

⁷¹Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom

⁷²Also at IPPP Durham University, Durham, United Kingdom

⁷³Also at Monash University, Faculty of Science, Clayton, Australia

⁷⁴Also at Università di Torino, Torino, Italy

⁷⁵Also at Bethel University, St. Paul, Minnesota, USA

⁷⁶Also at Karamanoğlu Mehmetbey University, Karaman, Turkey

⁷⁷Also at California Institute of Technology, Pasadena, California, USA

⁷⁸Also at Ain Shams University, Cairo, Egypt

⁷⁹Also at Bingol University, Bingol, Turkey

⁸⁰Also at Georgian Technical University, Tbilisi, Georgia

⁸¹Also at Sinop University, Sinop, Turkey

⁸²Also at Erciyes University, Kayseri, Turkey

⁸³Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China

⁸⁴Also at Texas A&M University at Qatar, Doha, Qatar

⁸⁵Also at Kyungpook National University, Daegu, Korea

⁸⁶Also at another institute or international laboratory covered by a cooperation agreement with CERN

⁸⁷Also at Yerevan Physics Institute, Yerevan, Armenia

⁸⁸Also at University of Florida, Gainesville, Florida, USA

⁸⁹Also at Imperial College, London, United Kingdom

⁹⁰Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan