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

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## 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  $36.3 \text{ fb}^{-1}$ . 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.

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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  $503 \pm 16 \text{ MeV}$  [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  $499.0 \pm 1.5 \text{ MeV}$  [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  $36.3 \text{ fb}^{-1}$  [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,  $\Gamma_{\text{inv}}$ , 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 ( $p_T^{\text{miss}}$ ). 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 ( $\eta$ ) 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  $\tau$  decays ( $\tau_h$ ) 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  $\tau_h$  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  $\vec{p}_T^{\text{miss}}$  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  $p_T^{\text{miss}}$  [19]. The  $\vec{p}_T^{\text{miss}}$  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,  $\vec{p}_T^{\text{miss}}$  is replaced by the recoil vector  $\vec{U}$ , defined as the vector sum of  $\vec{p}_T^{\text{miss}}$  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  $p_T^{\text{miss}}$  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  $Z/\gamma^*$  in association with jets, where the  $Z/\gamma^*$  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  $p_T^{\text{miss}}$  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,  $\ell$ +jets, where  $\ell = e, \mu, \tau_h$  (hadronically decaying  $\tau$  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  $H_T^{\text{miss}}$  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  $p_T^{\text{miss}}$  and  $H_T^{\text{miss}}$  variables at the trigger level. This enables the same trigger to be used to select events for the  $p_T^{\text{miss}}$  plus jets region and the  $Z/\gamma^* \rightarrow \mu\mu$  and  $\mu$ +jets regions. This trigger is also used to select the  $\tau_h$ +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  $\phi$  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  $p_T^{\text{miss}}$ , 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  $p_T^{\text{miss}}$  measured only by the calorimeter systems and corrected for the presence of muons. To remove these events,  $\Delta$  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  $p_T^{\text{miss}}$  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  $\tau_h$  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  $\tau_h$  vetoes are applied.

The  $\mu$ +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  $\tau_h$ +jets region is selected by requiring one  $\tau_h$  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  $p_T^{\text{miss}}$ , is required to be in the range  $30 < m_T < 125$  GeV. In addition, for the e+jets region,  $p_T^{\text{miss}}$  is required to be  $> 100$  GeV to reduce the contribution from QCD multijet events.

The largest background contribution to the  $p_T^{\text{miss}}$  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  $\mu$ +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  $\mu$ +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  $p_T^{\text{miss}}$  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  $\mu$ +jets and e+jets regions. A simultaneous likelihood fit is performed to assess the consistency between the  $\mu$ +jets and e+jets channels by using the transfer factor method to predict the event yields in e+jets region from the  $\mu$ +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  $1.000 \pm 0.035$  and  $-0.019 \pm 0.020$  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  $\mu$ +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.

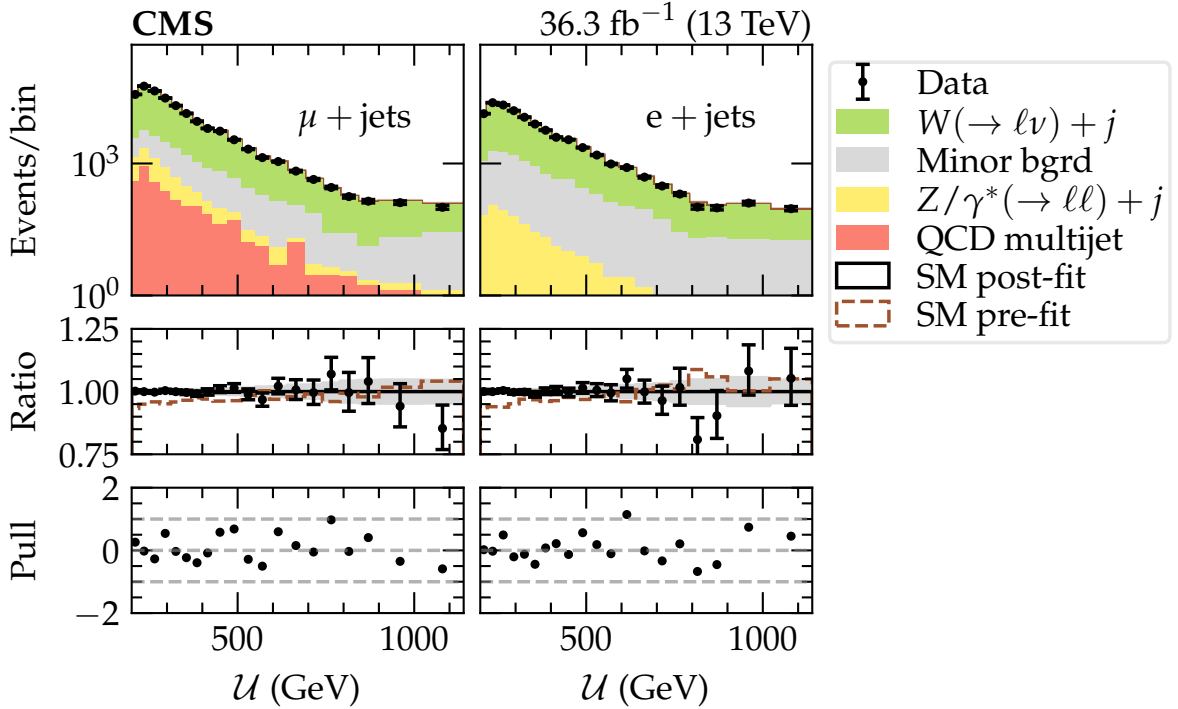


Figure 1: Distributions of  $\mathcal{U}$  in the regions of  $\mu$ +jets (left) and  $e$ +jets (right). Ratios are taken of the data with respect to both the SM post-fit and SM pre-fit results from a simultaneous likelihood fit performed to assess the consistency between the  $\mu$ +jets and  $e$ +jets 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  $\mu$ +jets and  $e$ +jets region with the  $\tau_h$ +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  $1.009 \pm 0.052$  and  $0.001 \pm 0.044$  for the normalization and shape parameters, respectively. Figure 2 shows the distributions of  $\mathcal{U}$  in the  $\mu$ +jets,  $e$ +jets and  $\tau_h$ +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  $\tau_h$  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

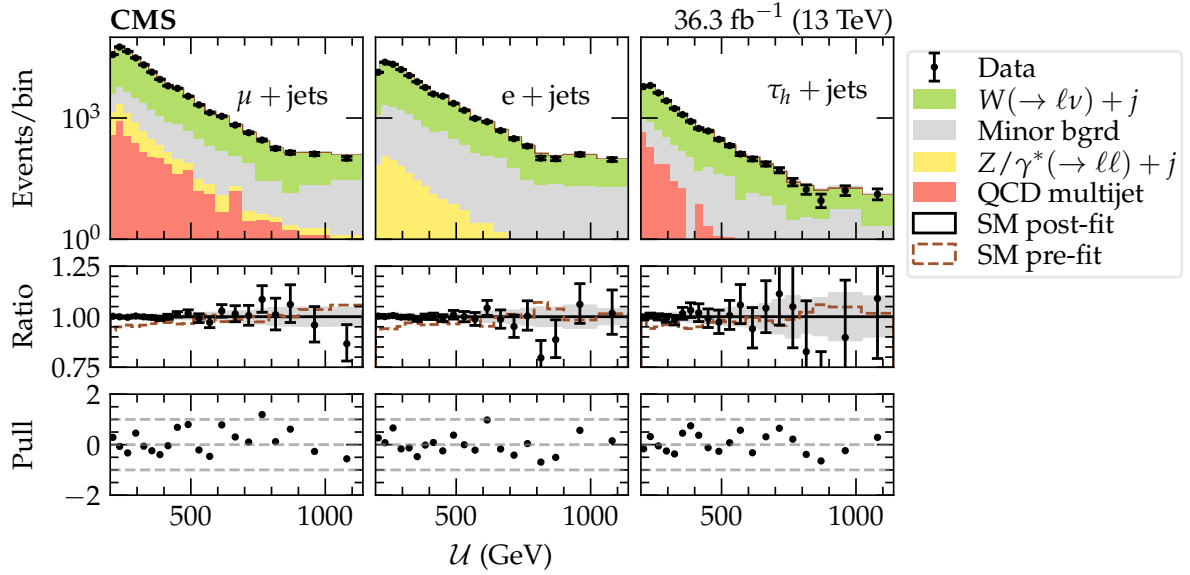


Figure 2: Distributions of  $\mathcal{U}$  in the regions of  $\mu$ +jets (left),  $e$ +jets (center), and  $\tau_h$ +jets (right). Ratios are taken of the data with respect to both the SM post-fit and SM pre-fit results from a likelihood fit performed to verify the consistency between the combined  $\mu$ +jets and  $e$ +jets region with the  $\tau_h$ +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  $p_T^{\text{miss}}$  and will have a direction closely aligned with  $\vec{p}_T^{\text{miss}}$ . 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  $p_T^{\text{miss}}$ -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  $p_T^{\text{miss}}$ -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  $1.11 \pm 0.08$  in the lowest  $\mathcal{U}$  bin to  $2.44 \pm 0.99$  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  $\tau_h$  veto efficiency is 0.7%. Experimental uncertainties from the  $p_T^{\text{miss}}$  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
$\tau_h$ veto efficiency	0.6–0.7
$p_T^{\text{miss}}$ trigger efficiency (jets plus $p_T^{\text{miss}}$ region)	0.7
$p_T^{\text{miss}}$ 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
$p_T^{\text{miss}}$ trigger efficiency ( $\mu$ +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,  $r_{\text{inv}}$ , 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  $r_{\text{inv}}$  is measured to be  $1.049 \pm 0.006$  (stat)  $\pm 0.032$  (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.

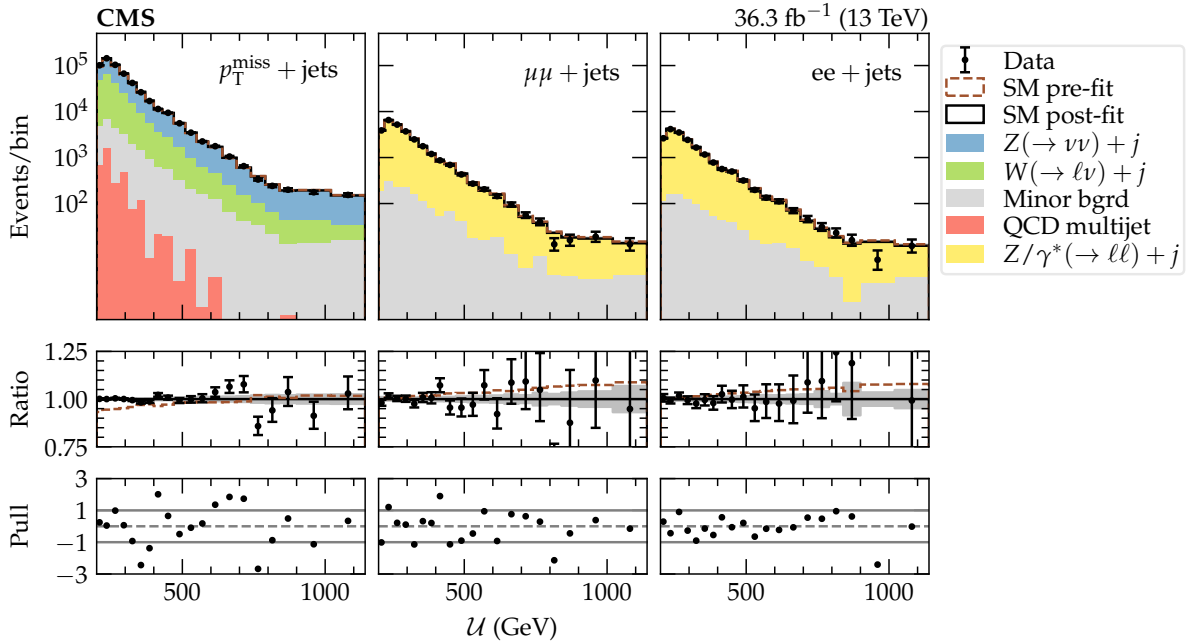


Figure 3: Distribution of  $\mathcal{U}$  for the  $p_T^{\text{miss}} + \text{jets}$  (left),  $Z/\gamma^* \rightarrow \mu\mu$  (center), and  $Z/\gamma^* \rightarrow ee$  (right) regions. Ratios are taken of the data with respect to both the SM post-fit and SM pre-fit results. The pulls are the difference 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  $r_{\text{inv}}$  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 ( $\Gamma_{\text{inv}}$ ) 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  $36.3 \text{ fb}^{-1}$  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  $\Gamma_{\text{inv}}$  to date and is competitive with the combined direct measurement from LEP and compatible with the value expected in the standard model.

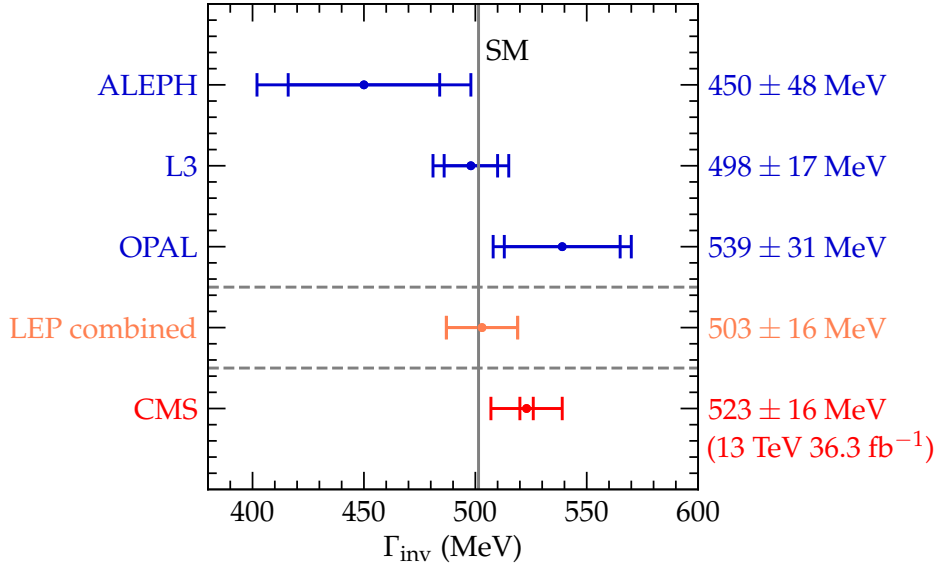


Figure 4: Direct measurements of the Z invisible width by the LEP experiments and the result from the CMS experiment presented here. Also shown is the prediction from the SM. The inner (outer) error bars show the statistical (total) uncertainty.

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















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







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

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















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














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









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

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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 

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










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E. Ayala 

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

E. Carrera Jarrin 











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

H. Abdalla<sup>14</sup> , S. Elgammal<sup>15</sup>






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

M.A. Mahmoud , Y. Mohammed 

















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S. Bhowmik , R.K. Dewanjee , K. Ehataht , M. Kadastik , S. Nandan , C. Nielsen ,  
J. Pata , M. Raidal , L. Tani , C. Veelken 

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


















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S. Bharthuar , E. Brücken , F. Garcia , J. Havukainen , M.S. Kim , R. Kinnunen,  
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























**Lappeenranta-Lahti University of Technology, Lappeenranta, Finland**

P. Luukka , H. Petrow , T. Tuuva











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B. Lenzi , E. Locci , J. Malcles , J. Rander, A. Rosowsky , M.Ö. Sahin , A. Savoy-  
Navarro<sup>16</sup> , M. Titov , G.B. Yu 


















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S. Ahuja , F. Beaudette , M. Bonanomi , A. Buchot Perraguin , P. Busson ,  
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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 ,  
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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,  
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





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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




























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C. Dziwok , G. Flügge , W. Haj Ahmad<sup>18</sup> , O. Hlushchenko, T. Kress , A. Nowack , C. Pistone, O. Pooth , D. Roy , H. Sert , A. Stahl<sup>19</sup> , T. Ziemons , 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. Borrás<sup>20</sup> , 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. Gallo<sup>21</sup> , A. Geiser , A. Giraldi , A. Grohsjean , M. Guthoff , A. Jafari<sup>22</sup> , N.Z. Jomhari , A. Kasem<sup>20</sup> , M. Kasemann , H. Kaveh , C. Kleinwort , D. Krücker , W. Lange, J. Lidrych , K. Lipka , W. Lohmann<sup>23</sup> , R. Mankel , I.-A. Melzer-Pellmann , 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. Scham<sup>24</sup> , V. Scheurer, S. Schnake , P. Schütze , C. Schwanenberger<sup>21</sup> , 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 




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





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

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










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

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










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









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




























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

S. Chenarani<sup>40</sup> , S.M. Etesami , M. Khakzad , M. Mohammadi Najafabadi 





























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M. Grunewald 







**INFN Sezione di Bari<sup>a</sup>, Università di Bari<sup>b</sup>, Politecnico di Bari<sup>c</sup>, Bari, Italy**

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
















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

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

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

S. Albergo<sup>a,b,43</sup> , S. Costa<sup>a,b,43</sup> , A. Di Mattia<sup>a</sup> , R. Potenza<sup>a,b</sup> , A. Tricomi<sup>a,b,43</sup> , C. Tuve<sup>a,b</sup> 






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

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


























**INFN Laboratori Nazionali di Frascati, Frascati, Italy**

L. Benussi , S. Bianco , D. Piccolo 






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

M. Bozzo<sup>a,b</sup> , F. Ferro<sup>a</sup> , R. Mulargia<sup>a,b</sup> , E. Robutti<sup>a</sup> , S. Tosi<sup>a,b</sup> 

**INFN Sezione di Milano-Bicocca<sup>a</sup>, Università di Milano-Bicocca<sup>b</sup>, Milano, Italy**


























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

**INFN Sezione di Napoli<sup>a</sup>, Università di Napoli 'Federico II'<sup>b</sup>, Napoli, Italy; Università della Basilicata<sup>c</sup>, Potenza, Italy; Università G. Marconi<sup>d</sup>, Roma, Italy**











S. Buontempo<sup>a</sup> , F. Carnevali<sup>a,b</sup> , N. Cavallo<sup>a,c</sup> , A. De Iorio<sup>a,b</sup> , F. Fabozzi<sup>a,c</sup> 

A.O.M. Iorio<sup>a,b</sup> , L. Lista<sup>a,b</sup> , S. Meola<sup>a,d,19</sup> , P. Paolucci<sup>a,19</sup> , B. Rossi<sup>a</sup> , C. Sciacca<sup>a,b</sup> 















**INFN Sezione di Padova<sup>a</sup>, Università di Padova<sup>b</sup>, Padova, Italy; Università di Trento<sup>c</sup>, Trento, Italy**

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

































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

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







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

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





































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







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






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



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




























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







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















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




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








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




















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







**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. Rumerio<sup>74</sup> , 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. Coubez<sup>20</sup> , D. Cutts , M. Hadley , U. Heintz , J.M. Hogan<sup>75</sup> , T. KWON , G. Landsberg , K.T. Lau , D. Li , M. Lukasik , J. Luo , M. Narain , N. Pervan , S. Sagir<sup>76</sup> , 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 



















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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. Pena<sup>77</sup> , 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. Elkafrawy<sup>78</sup> , 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. Dilsiz<sup>79</sup> , R.P. Gandrajula , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili<sup>80</sup> , J. Nachtman , H. Ogul<sup>81</sup> , Y. Onel , A. Penzo , C. Snyder, E. Tiras<sup>82</sup> 

**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 


















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



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





















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






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













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








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










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