Physics Letters B 766 (2017) 268–290

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Measurement of the WZ production cross section in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration [*]

CERN, Switzerland

A R T I C L E   I N F O

Article history:
Received 23 July 2016
Received in revised form 10 December 2016
Accepted 7 January 2017
Available online 11 January 2017
Editor: M. Doser

Keywords:
CMS
Physics
Electroweak

A B S T R A C T

The WZ production cross section in proton–proton collisions at $\sqrt{s} = 13$ TeV is measured with the CMS experiment at the LHC using a data sample corresponding to an integrated luminosity of 2.3 fb^{-1}. The measurement is performed in the leptonic decay modes $\text{WZ} \to \ell\nu\ell'\ell'$, where $\ell, \ell' = \text{e}, \mu$. The measured cross section for the range $60 < m_{\ell'\ell'} < 120$ GeV is $\sigma(\text{pp} \to \text{WZ}) = 39.9 \pm 3.2(\text{stat})\,^{+2.9}_{-3.1}(\text{syst}) \pm 0.4(\text{theo}) \pm 1.3(\text{lumi})$ pb, consistent with the standard model prediction.

1. Introduction

Measurements of the cross sections for massive gauge boson pair production in proton–proton collisions provide an essential test of the electroweak sector of the standard model (SM). The electroweak interaction in the SM is determined by the non-Abelian $SU(2)_\text{L} \times U(1)_\text{Y}$ gauge group. The non-Abelian nature of the electroweak gauge group leads to gauge boson self-interactions via triple gauge couplings (TGCs) and quartic gauge couplings (QGCs). The weak gauge boson pair production includes TGC interactions as well as QGC interactions via vector boson scattering. Thus, the study of diboson production can directly test both the weak interaction and the non-Abelian nature of the electroweak gauge group. The next-to-leading order (NLO) and next-to-next-to-leading order (NNLO) perturbative QCD corrections for the boson pair production have substantial impact on the predicted cross sections due to the addition of the gluon-initiated processes that are enhanced at energies available at the CERN LHC. The increase in the cross section is significant compared to the experimental uncertainties, allowing LHC boson pair cross section measurements to directly validate higher-order perturbative QCD calculations.

The observation of WZ production in proton–antiproton collisions at the Tevatron collider was reported by the CDF [1,2] and D0 [3] experiments. The WZ production cross section in proton–proton collisions has been measured at the LHC by the CMS experiment at $\sqrt{s} = 8$ TeV [4] and the ATLAS experiment at $\sqrt{s} = 7, 8,$ and 13 TeV [5–7]. All measurements are in good agreement with SM predictions.

This paper reports the CMS measurement of the WZ production cross section in proton–proton collisions at $\sqrt{s} = 13$ TeV. The measurement is performed using the leptonic decay modes $\text{WZ} \to \ell\nu\ell'\ell'$, where $\ell, \ell' = \text{e}, \mu$.

2. The CMS detector

The CMS detector is described in detail elsewhere [8]. The key components for this analysis are summarized here. 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 superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, which provide the pseudorapidity coverage $|\eta| < 1.479$ in a barrel section and $1.479 < |\eta| < 3.0$ in two endcap sections. Forward calorimeters extend the coverage to $|\eta| < 5.0$. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

The first level of the CMS trigger system, composed of custom hardware processors, is designed to select the most interesting events in less than 4 μs using information from the calorimeters and muon detectors. The high-level-trigger processor farm decreases the event rate from almost 100 kHz to around 1 kHz, before data storage.

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[*] *E-mail address:* cms-publication-committee-chair@cern.ch.

http://dx.doi.org/10.1016/j.physletb.2017.01.011

3. Data and Monte Carlo samples

This measurement uses a sample of proton–proton collisions collected in 2015 at $\sqrt{s} = 13$ TeV. The integrated luminosity of the sample is 2.3 fb^{-1}. Several Monte Carlo (MC) event generators are used to simulate the signal and background processes.

The WZ signal is generated at NLO in perturbative QCD with POWHEG2.0 [9–12]. The ZZ production via $\text{q}\bar{\text{q}}$ annihilation is generated at NLO using POWHEG2.0, while the $\text{gg} \to \text{ZZ}$ process is simulated at leading-order with MCFM 7.0 [13]. The $\text{Z}\gamma$, $\text{t}\bar{\text{t}}\text{V}$ ($\text{t}\bar{\text{t}}\text{W}$, $\text{t}\bar{\text{t}}\text{Z}$), tZ, and triboson events VVV (WWZ, WZZ, ZZZ) are generated at NLO with MADGRAPH5_aMC@NLO [14]. The ZZ samples are scaled to the cross section calculated at NNLO for $\text{q}\bar{\text{q}} \to \text{ZZ}$ [15] (scaling k factor 1.1) and at NLO for $\text{gg} \to \text{ZZ}$ [16] (scaling k factor 1.7). The PYTHIA 8.175 [17] program is used for parton showering, hadronization, and underlying event simulation using the CUETP8M1 tune [18]. The NNPDF3.0 [19] set of parton distribution functions (PDFs) is used, unless otherwise specified.

For all processes, the detector response is simulated using a detailed description of the CMS detector, based on the GEANT4 package [20], and the event reconstruction is performed with the same algorithms used for data. The simulated samples include additional interactions per bunch crossing (pileup) taken from minimum-bias events generated with PYTHIA. The simulated events are weighted so that the pileup distribution matches the measured one, with an average of about 11 pileup interactions per bunch crossing.

4. Event reconstruction

Using the information from all CMS subdetectors, a particle-flow (PF) technique is employed to identify and reconstruct the individual particles emerging from each collision event [21,22]. The particles are classified into mutually exclusive categories: charged hadrons, neutral hadrons, photons, muons, and electrons.

Electrons are reconstructed within the geometrical acceptance $|\eta^{\text{e}}| < 2.5$. The reconstruction combines the information from clusters of energy deposits in the ECAL and the trajectory in the tracker [23]. Electron identification relies on the electromagnetic shower shape and other observables based on tracker and calorimeter information. The selection criteria depend on the transverse momentum, p_{T}, and $|\eta|$, and on a categorization according to observables that are sensitive to the amount of bremsstrahlung emitted along the trajectory in the tracker. Two working points are defined: *tight* and *very tight*.

Muons are reconstructed within $|\eta^{\mu}| < 2.4$ [24]. The reconstruction combines the information from both the tracker and the muon spectrometer. The muons are selected from among the reconstructed muon track candidates by applying minimal quality requirements on the track components in the muon system and by ensuring that muons are associated to small energy deposits in the calorimeters. A single *tight* working point is defined.

The electrons and muons are required to originate from the primary vertex, which is chosen to be the vertex with the highest sum of p_{T}^2 of its constituent tracks [25]. For each lepton track the distance of closest approach to the primary vertex in the transverse plane, d_{xy}, is required to be less than 0.01 (0.07) cm for electrons in the barrel (endcap) region and 0.01 cm for muons with p_{T} less than 20 GeV and 0.02 cm for muons with p_{T} greater than 20 GeV. The distance along the beamline, d_z, must be less than 0.4 (0.6) cm for electrons in the barrel (endcap) and 0.1 cm for muons. For the *very tight* electron working point, electrons must pass $d_{xy} \leq 0.01\,(0.04)$ cm and $d_z \leq 0.05\,(0.4)$ cm in the barrel (endcap) region.

Jets are reconstructed using PF objects. The anti-k_{T} jet clustering algorithm [26] with $R = 0.4$ is used. The standard method for jet energy corrections [27] is applied. These include corrections to the pileup contribution that keep the jet energy correction and the corresponding uncertainty almost independent of the number of pileup interactions. To exclude electrons and muons from the jet sample, the jets are required to be separated from the identified leptons by $\Delta R > 0.3$. In order to reject jets coming from pileup collisions (pileup jets), a multivariate-based jet identification algorithm [28] is applied. This algorithm takes advantage of differences in the shape of energy deposits in a jet cone between hard-scatter and pileup jets. The jets are required to have $p_{\text{T}} > 20$ GeV and $|\eta| < 5.0$. To identify the top quark background contribution in its decay to b quarks, the CSVv2 b tagging algorithm [29] with the *tight* working point is used [30]. The efficiency for selecting b quark jets is ≈49% with a misidentification probability of ≈4% for c quark jets and ≈0.1% for light quark jets.

The isolation of individual electrons or muons is defined relative to their transverse momentum p_{T}^{ℓ} by summing over the transverse momenta of charged hadrons and neutral particles within a cone with radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$ around the lepton direction at the interaction vertex:

$$I^{\ell} = \left(\sum p_{\text{T}}^{\text{charged}} + \max\left[0, \sum p_{\text{T}}^{\text{neutral}} + \sum p_{\text{T}}^{\gamma} - p_{\text{T}}^{\text{PU}}\right]\right) \Big/ p_{\text{T}}^{\ell}. \tag{1}$$

Here, $\sum p_{\text{T}}^{\text{charged}}$ is the scalar sum of the transverse momenta of charged hadrons originating from the primary vertex. The $\sum p_{\text{T}}^{\text{neutral}}$ and $\sum p_{\text{T}}^{\gamma}$ are the scalar sums of the transverse momenta for neutral hadrons and photons, respectively. The neutral contribution to the isolation from pileup events, p_{T}^{PU}, is estimated differently for electrons and muons. For electrons, $p_{\text{T}}^{\text{PU}} \equiv \rho\, A_{\text{eff}}$, where the average transverse momentum flow density ρ is calculated in each event using the "jet area" method [31], which defines ρ as the median of the ratio of the jet transverse momentum to the jet area, $p_{\text{T}}^{\text{jet}}/A_{\text{jet}}$, for all pileup jets in the event. The effective area A_{eff} is the geometric area of the isolation cone times an η-dependent correction factor that accounts for the residual dependence of the isolation on the pileup. For muons, $p_{\text{T}}^{\text{PU}} \equiv 0.5 \sum_i p_{\text{T}}^{\text{PU},i}$, where i runs over the charged hadrons originating from pileup vertices and the factor 0.5 corrects for the ratio of charged to neutral particle contributions in the isolation cone. Electrons are considered isolated if $I^{\text{e}} < 0.08\,(0.07)$ for the barrel (endcap) region, while muons are considered isolated if $I^{\mu} < 0.15$. For the *very tight* electron working point, the electrons must pass $I^{\text{e}} < 0.04\,(0.06)$ for the barrel (endcap) region.

The missing transverse momentum vector $\vec{p}_{\text{T}}^{\text{miss}}$ is defined as the projection onto the plane perpendicular to the beams of the negative vector sum of the momenta of all reconstructed PF objects in an event, corrected for the pileup contribution. Its magnitude is referred to as $E_{\text{T}}^{\text{miss}}$.

The overall efficiencies of the reconstruction, identification, and isolation requirements for the prompt e or μ are measured in data in several bins of p_{T}^{ℓ} and $|\eta^{\ell}|$ using a "tag-and-probe" technique [32] applied to an inclusive sample of Z events. The efficiency for selecting electrons in the ECAL barrel (endcaps) varies from about 85% (77%) at $p_{\text{T}}^{\text{e}} \approx 10$ GeV to about 95% (89%) for $p_{\text{T}}^{\text{e}} > 20$ GeV. It is about 85% in the transition region between the ECAL barrel and endcaps, $1.44 < |\eta| < 1.57$, averaging over the whole p_{T} range. Muons are reconstructed and identified with efficiency above 98% in the full $|\eta^{\mu}| < 2.4$ range. These efficiencies are measured in data and simulation. The data/MC efficiency ratios are used as scale factors to correct the simulated event yields.

5. Event selection

Collision events are selected by triggers that require the presence of one or two electrons or muons. The p_T threshold for the single lepton is 23 (20) GeV for the electron (muon) trigger. For the dilepton triggers, with the same or different flavors, the minimum p_T of the leading and subleading leptons are 17 (17) and 12 (8) GeV for electrons (muons), respectively. The trigger efficiency for events within the acceptance of this analysis is greater than 99%.

A selected event is required to have three lepton candidates $\ell\ell'\ell'$. The $\ell'\ell'$ pair has two leptons with opposite charge and the same flavor, as expected for a Z boson candidate. One of the leptons from the Z boson candidate is required to have $p_T > 20$ GeV and the other $p_T > 10$ GeV. If more than one combination is possible, the one with invariant mass closest to the Z boson mass is selected. The lepton associated with the W boson must have $p_T > 20$ GeV. All leptons must pass the *tight* identification and isolation requirements. To further reduce the contribution from Z+jets in events with an electron associated with the W boson, this electron must pass the requirements of the *very tight* working point.

There must be no other isolated leptons with $p_T > 10$ GeV in the events. To reduce contributions from $t\bar{t}$ events, the two leptons constituting the Z boson candidate are required to have an invariant mass satisfying $76 < m_{\ell\ell} < 106$ GeV, and there must be no jets with $p_T > 20$ GeV and $|\eta| < 2.4$ that pass a b tagging requirement. The WZ events are expected to have missing transverse energy consistent with the presence of a neutrino in the final state, therefore $E_T^{\text{miss}} > 30$ GeV is required. The invariant mass of any dilepton pair must be greater than 4 GeV. This requirement prevents problems with collinear emission of same-flavor opposite-sign dilepton pairs in theoretical calculations. The selection is extended to all dilepton pairs at the detector level to reduce backgrounds from low mass resonances with a negligible effect on signal efficiency. The trilepton invariant mass, $m_{3\ell}$, is required to be more than 100 GeV to exclude a region where production of Z bosons with final-state radiation is expected to contribute.

6. Background estimation

The background contributions in this analysis are divided into two categories: background processes with prompt isolated leptons, e.g., ZZ, Zγ, $t\bar{t}$Z; and background processes from nonprompt leptons from hadrons decaying to leptons inside jets or jets misidentified as isolated leptons, primarily Z+jets and $t\bar{t}$. The background processes with prompt leptons are estimated from simulation. The processes with at least one nonprompt lepton are estimated from data.

The major background contributions with nonprompt leptons arise from the production of Z bosons in association with jets and from $t\bar{t}$, whereas smaller contributions come from W boson production in association with jets and multijet processes. The nonprompt background contribution is evaluated using the "*tight*-to-*loose*" method. The method estimates the probability that a *loose* candidate is misidentified as a *tight* lepton and applies this probability to control regions with *loose* candidates to estimate the resulting contribution to the signal region. These *loose* candidates are selected with relaxed lepton identification and isolation requirements.

The misidentification probability is measured from a sample of dijet events enriched in nonprompt leptons. The sample is selected with one jet passing the relaxed lepton identification requirements matched to a single lepton trigger, defined as the probe lepton. The probe lepton and the second jet must be separated by $\Delta R > 1$. The misidentification ratio for each lepton flavor is defined in bins of lepton p_T and η as the ratio of the number of probe leptons that pass the final isolation and identification requirements to the number of probe leptons that do not pass the *tight* requirements. The contamination from W+jets is suppressed by requiring a transverse mass $m_T < 20$ GeV, where $m_T = \sqrt{2E_T^{\text{miss}} p_T^{\ell}(1-\cos(\Delta\phi))}$ and $\Delta\phi$ is the azimuthal angle between the vectors $\vec{p}_T^{\text{miss}}$ and $\vec{p}_T^{\ell}$. The contamination from Z boson events is suppressed by requiring the invariant mass of each pair of leptons composed of the probe lepton and of any other lepton candidate in the event to be outside of the window 60–120 GeV. Contributions from low mass resonances decaying into pairs of leptons are suppressed by requiring the dilepton mass to be greater than 20 GeV. The transverse momentum spectrum of the probe lepton in dijet events is different from the spectrum in Z and $t\bar{t}$ events. We have verified in data that one can make them similar with a requirement on the minimum transverse momentum of the second jet of 20 (35) GeV for the dijet events with one probe muon (electron).

A set of control regions with events containing three leptons is then used to estimate the background from nonprompt leptons. Zero, one, or two leptons are required to pass the signal region requirements, while the remaining leptons must pass the *loose* requirements and fail the signal region requirements. The misidentification ratio is applied to the *loose* leptons failing the *tight* identification requirements to estimate the corresponding contribution to the signal region. The total background is calculated as a sum of contributions from different regions. This method is validated in nonoverlapping data samples enriched in Drell–Yan and $t\bar{t}$ contributions. The Drell–Yan region is defined by inverting the selection requirement in E_T^{miss} and the $t\bar{t}$ region is defined by requiring at least one b-tagged jet and rejecting events with $76 < m_{\ell\ell} < 106$ GeV while keeping all other requirements for the signal region. The overall yield predicted with the "*tight*-to-*loose*" method agrees with that measured in the control region within 5%, with a maximum deviation of 30% in a single decay channel. The observed deviations are used as systematic uncertainties in the predicted background yields in the signal region.

7. Systematic uncertainties

Systematic uncertainties are less than 1% for the trigger efficiency and 2–4% for the lepton identification and isolation requirements, depending on the lepton flavors. Other systematic uncertainties are related to the use of simulated samples: 1% for the effects of pileup and 1–2% for the E_T^{miss} reconstruction, which is estimated by varying the energies of the PF objects within their uncertainties. The uncertainty in the b quark jet content in WZ events is 2% and accounts for differences in b-tagging efficiencies between data and MC as well as differences in b quark jet content between Z+jets and WZ+jets events. The uncertainty in the integrated luminosity of the data sample is 2.7% [33]. This uncertainty affects both the signal and the simulated portion of the background estimation and does not affect the background estimation from data; the total effect of the luminosity uncertainty on the cross section is 3.2%.

Uncertainties in prompt background sources are estimated from the theoretical uncertainties in the cross sections. For the ZZ background the uncertainty is 4% [15,34], and it contributes to the WZ cross section with an uncertainty of 0.4%. The uncertainties are 15% for $t\bar{t}$V [14,35,36] and 6% for triboson and Zγ [13]; their contribution to the uncertainty in the WZ cross section is much less than 1%.

The uncertainties in background contributions from both flavors of nonprompt leptons are determined by combining the uncertainties in the measured values of the misidentification probabilities and the statistical uncertainties due to the limited number

Table 1
The contributions of each systematic uncertainty source to the combined uncertainty in the cross section measurement. The integrated luminosity as well as the PDF and scale uncertainties are reported separately in Equations (2) and (3) as (lumi) and (theo), respectively, while the other uncertainties are combined into a single systematic uncertainty (syst).

Source of uncertainty	Uncertainty in the cross section
Background with nonprompt μ	5.4%
Background with nonprompt e	3.9%
b tagging	2.1%
$E_{\mathrm{T}}^{\mathrm{miss}}$	2.0%
Electron efficiency	1.9%
Muon efficiency	1.5%
Pileup	0.8%
ZZ cross section	0.4%
$\mathrm{t\bar{t}V}$ cross section	negligible
$\mathrm{Z}\gamma$ cross section	negligible
VVV cross section	negligible
Integrated luminosity	3.2%
PDF and scales	1.0%

of events in the control regions. The systematic uncertainty in the misidentification probability is 30% for both electrons and muons. It covers the largest difference observed between the estimated and measured numbers of events in data control samples enriched in $\mathrm{t\bar{t}}$ and Drell–Yan contributions. The uncertainties are uncorrelated between electrons and muons. The contribution to the uncertainty in the cross section measurement is 5.4% (3.9%) from muons (electrons).

Theoretical uncertainties in the $\mathrm{WZ} \to \ell\nu\ell'\ell'$ acceptance are evaluated using POWHEG and MCFM by varying dynamic renormalization and factorization scales independently up and down by a factor of two with respect to the default values $\mu_R = \mu_F = m_{\mathrm{WZ}}$ with the condition that $0.5 \leq \mu_R/\mu_F \leq 2$, where m_{WZ} is the mass of the WZ system at the generator level. The uncertainty in the acceptance due to the scale variations can be neglected. Phenomenological uncertainties (PDF+α_s) are estimated using the CT14 [37], NNPDF3.0, and MMHT2014 [38] PDF sets according to their individual prescriptions. The largest variation among the sets defines an envelope of about 1%, which is taken as the theoretical uncertainty in the measured cross section.

A summary of each systematic uncertainty and its contribution to the final uncertainty in the cross section measurement is presented in Table 1.

8. Results

The observed and expected event yields for all decay channels are summarized in Table 2. The invariant mass distributions for all channels combined are shown in Fig. 1 and compared to the SM expectations and to the backgrounds estimated from data. The two upper plots show distributions for events after all the selection requirements are applied except the one displayed. The two lower plots show distributions with the full WZ selection requirements. Kinematic distributions of the selected events are shown in Fig. 2. Overall, the simulated signal combined with the background contributions are in agreement with the data within uncertainties.

The measured yields, corrected for the efficiency of the event selections and the acceptance of the fiducial phase space, are used to evaluate the WZ production cross section.

The fiducial $\mathrm{WZ} \to \ell\nu\ell'\ell'$ phase space is defined by the requirement of two leptons from the Z boson decay to have $p_{\mathrm{T}} > 20$ and 10 GeV, the charged lepton from W boson decay to have $p_{\mathrm{T}} >$ 20 GeV, all leptons to be within $|\eta| < 2.5$, $60 < m_{\ell'\ell'} < 120$ GeV, and invariant mass of any same-flavor opposite-sign lepton pair is above 4 GeV. All the leptons are considered before final-state radiation (FSR). The difference between the cross section calculation with leptons before FSR and the cross section with "dressed" leptons, which are obtained by summing the lepton momentum and the momenta of radiated photons within a cone of $\Delta R < 0.1$ around the lepton, is found to be less than 1%.

The correction between the fiducial definition and the selection requirements takes into account the effect of the $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement, the reduced $m_{\ell'\ell'}$ mass window in the selection with respect to the fiducial definition, and the requirements of exactly three isolated leptons and no b-tagged jets in the event. A small contribution from WZ events where the W or Z boson decays via τ into an electron or muon is considered as signal at the detector level, but not at the generator level. Thus the correction for τ lepton decays is also taken into account in the selection efficiency.

The efficiency of the selection requirements with respect to the fiducial requirements varies with the channel, from 55% in $\mu\mu\mu$ to 25% in eee. It includes a 70% correction for the $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement at the reconstruction level, a 7% correction for the contribution from tau decays and the effects of the lepton identification requirements. The difference in the Z boson mass window definition at the selection level and in the fiducial definition has a 2% effect. The theoretical uncertainties in these corrections are estimated by checking differences between the various POWHEG, MADGRAPH, and MCFM predictions and are found to be much less than 1% so they are neglected in the fiducial cross section measurement. The major difference between the channels is the tighter identification and isolation requirements on the electrons.

To include all final states in the cross section calculation, the number of expected signal and background events is fitted to the number of observed events simultaneously in all decay channels. The likelihood is written as a combination of individual channel likelihoods for the signal and background hypotheses. The statistical and systematic uncertainties are included as scaling nuisance parameters and the correlation between different sources of uncertainties across channels is taken into account.

Table 2
The expected yields of WZ events and the estimated yields of background events, consisting of the prompt leptons estimated from simulation and nonprompt background from data, compared to the number of observed events for each decay channel. The first uncertainty is statistical and the second is systematic.

Decay channel	Expected WZ	Background		Total expected	Observed
		Nonprompt	Prompt		
eee	$35.9 \pm 0.6^{+1.8}_{-1.8}$	$10.6 \pm 1.7^{+3.2}_{-2.5}$	$6.6 \pm 0.6^{+0.5}_{-0.5}$	$53.1 \pm 1.9^{+3.9}_{-3.3}$	49
eeμ	$50.2 \pm 0.8^{+2.4}_{-2.4}$	$14.8 \pm 3.6^{+3.9}_{-3.0}$	$8.3 \pm 0.5^{+0.6}_{-0.6}$	$73.3 \pm 3.7^{+4.8}_{-4.1}$	78
$\mu\mu$e	$56.0 \pm 0.8^{+2.5}_{-2.4}$	$21.5 \pm 3.2^{+5.0}_{-3.9}$	$9.3 \pm 0.6^{+0.8}_{-0.7}$	$86.8 \pm 3.4^{+5.8}_{-4.8}$	83
$\mu\mu\mu$	$84.0 \pm 1.0^{+3.4}_{-3.3}$	$20.0 \pm 4.9^{+6.1}_{-4.7}$	$12.4 \pm 0.5^{+0.8}_{-0.7}$	$116.3 \pm 5.0^{+7.2}_{-6.0}$	108
Total	$226 \pm 2^{+10}_{-9}$	$67 \pm 7^{+14}_{-11}$	$37 \pm 1^{+3}_{-2}$	$330 \pm 7^{+18}_{-16}$	318

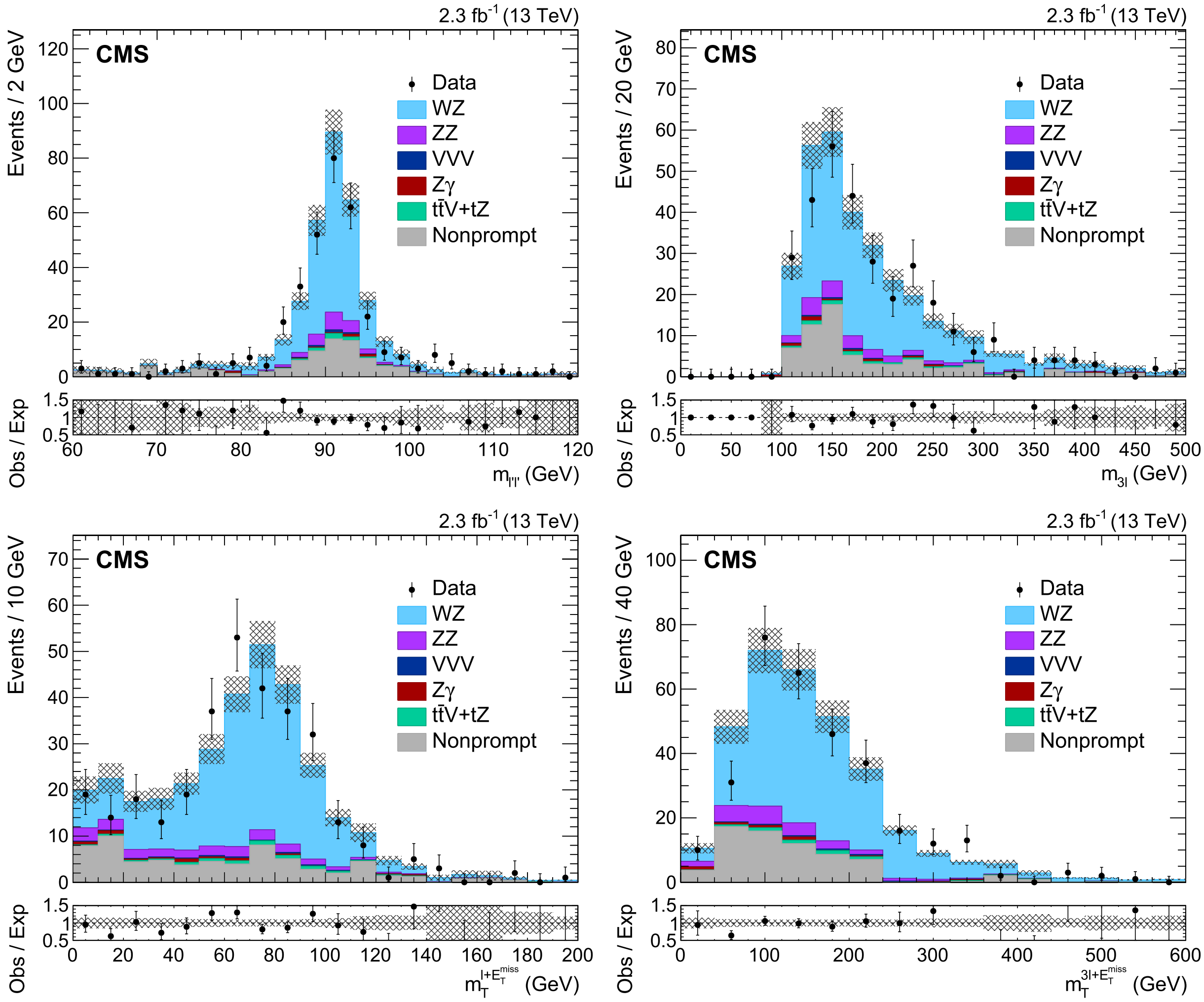

Fig. 1. (upper left) Distribution of the reconstructed $\ell'\ell'$ pair mass summed for all decay channels with the $m_{\ell'\ell'}$ selection extended to 60–120 GeV. (upper right) Distribution of the $\ell\ell'\ell'$ reconstructed mass summed for all decay channels with the $m_{3\ell} > 100$ GeV selection requirement removed. (lower left) The transverse mass of the lepton from the W boson and the $E_{\mathrm{T}}^{\mathrm{miss}}$ system. (lower right) The transverse mass of the three leptons and the $E_{\mathrm{T}}^{\mathrm{miss}}$ system. Solid symbols represent the data with Poisson statistical uncertainties, while histograms represent the expected WZ signal and backgrounds. The shaded band represents the uncertainties in the signal and background estimated yields and includes systematic, theoretical, and integrated luminosity uncertainties in addition to the statistical uncertainty. The background shapes are taken from simulation or data, as described in the text. A ratio of the observed (Obs) and expected (Exp) distributions is also included.

The fiducial $\mathrm{WZ} \to \ell\nu\ell'\ell'$ cross section for $p_{\mathrm{T}}^{\ell'} > 20, 10$ GeV, $p_{\mathrm{T}}^{\ell} > 20$ GeV, all leptons within $|\eta| < 2.5$, $60 < m_{\ell'\ell'} < 120$ GeV, and invariant mass of any same-flavor opposite-sign lepton pair above 4 GeV is

$$\sigma_{\mathrm{fid}}(\mathrm{pp} \to \mathrm{WZ} \to \ell\nu\ell'\ell') = 258 \pm 21\,(\mathrm{stat}) \\ {}^{+19}_{-20}(\mathrm{syst}) \pm 8(\mathrm{lumi})\ \mathrm{fb}, \qquad (2)$$

corresponding to a total cross section for the range $60 < m_{\ell'\ell'} < 120$ GeV of

$$\sigma(\mathrm{pp} \to \mathrm{WZ}) = 39.9 \pm 3.2(\mathrm{stat}) \\ {}^{+2.9}_{-3.1}(\mathrm{syst}) \pm 0.4(\mathrm{theo}) \pm 1.3(\mathrm{lumi})\ \mathrm{pb}. \qquad (3)$$

The acceptance of the fiducial phase space, $(45.0 \pm 0.4)\%$, is calculated with POWHEG. The nominal Z to dilepton branching fraction $\mathcal{B}(\mathrm{Z} \to \ell'\ell')$ is $(3.3658 \pm 0.0023)\%$ for each lepton flavor, while for the W boson the average branching fraction to each lepton flavor, $(10.67 \pm 0.16)\%$, is derived from $(10.71 \pm 0.16)\%$ for the electron channel and $(10.63 \pm 0.15)\%$ for the muon channel [39].

The measured cross sections can be compared to the theoretical values of $274^{+11}_{-8}\,(\mathrm{scale}) \pm 4\,(\mathrm{PDF})$ fb for the fiducial cross section and $42.3^{+1.4}_{-1.1}\,(\mathrm{scale}) \pm 0.6\,(\mathrm{PDF})$ pb for the total cross section calculated with MCFM at NLO with NNPDF3.0 PDFs, with dynamic renormalization and factorization scales set to $\mu_R = \mu_F = m_{\mathrm{WZ}}$. The uncertainty is obtained by varying the factorization and renormalization scales independently up and down by a factor of two with the condition that $0.5 \le \mu_R/\mu_F \le 2$. The MCFM and POWHEG predicted cross sections agree within the statistical uncertainties of the generated samples.

The measured total cross section can also be compared to the theoretical value of $50.0^{+1.1}_{-1.0}\,(\mathrm{scale})$ pb, available at NNLO via MATRIX [40] with fixed QCD scales set to $\mu_R = \mu_F = \frac{1}{2}(m_{\mathrm{Z}} + m_{\mathrm{W}})$ and NNPDF3.0 PDFs. Uncertainties in this calculation take into account only renormalization and factorization scale variations. The variations are done independently with the condition that $0.5 \le \mu_R/\mu_F \le 2$. The values from MCFM with this scale choice are $291^{+16}_{-13}\,(\mathrm{scale}) \pm 4\,(\mathrm{PDF})$ fb for the fiducial and $44.9^{+2.2}_{-1.8}\,(\mathrm{scale}) \pm 0.7\,(\mathrm{PDF})$ pb for the total cross sections.

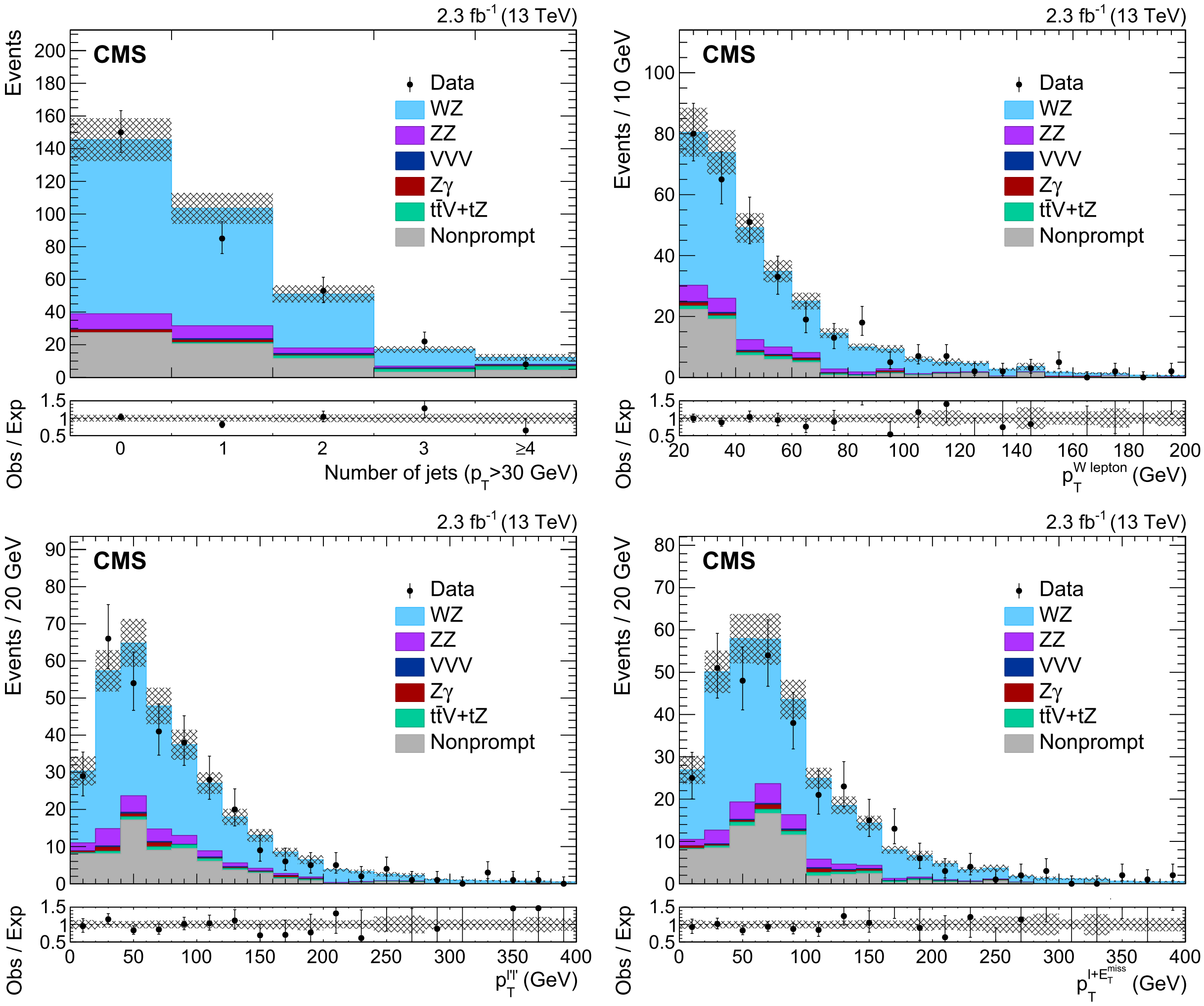

Fig. 2. (upper left) Distribution of the number of jets with $p_T > 30$ GeV in the event. (upper right) Transverse momentum of the lepton associated with the W boson. (lower left) Transverse momentum of selected Z boson candidates. (lower right) Transverse momentum of selected W boson candidates. Solid symbols represent the data with Poisson statistical uncertainties, while histograms represent the expected WZ signal and backgrounds. The shaded band represents the uncertainties in the signal and background estimated yields and includes systematic, theoretical, and integrated luminosity uncertainties in addition to the statistical uncertainty. The background shapes are taken from simulation or data, as described in the text. A ratio of the observed (Obs) and expected (Exp) distributions is also included.

9. Summary

The WZ production cross section in proton–proton collisions at $\sqrt{s} = 13$ TeV has been measured with the CMS experiment at the LHC using a data sample corresponding to an integrated luminosity of 2.3 fb^{-1}. The measurement is performed in the leptonic decay modes $\text{WZ} \to \ell\nu\ell'\ell'$, where $\ell, \ell' = \text{e}, \mu$. The measured fiducial $\text{WZ} \to \ell\nu\ell'\ell'$ cross section for two leptons from the Z boson decay with $p_T > 20$ and 10 GeV, the charged lepton from the W boson decay with $p_T > 20$ GeV, all leptons within $|\eta| < 2.5$, and $60 < m_{\ell'\ell'} < 120$ GeV is $\sigma_{\text{fid}}(\text{pp} \to \text{WZ} \to \ell\nu\ell'\ell') = 258 \pm 21(\text{stat})^{+19}_{-20}(\text{syst}) \pm 8(\text{lumi})$ fb. The corresponding total cross section is $\sigma(\text{pp} \to \text{WZ}) = 39.9 \pm 3.2(\text{stat})^{+2.9}_{-3.1}(\text{syst}) \pm 0.4(\text{theo}) \pm 1.3(\text{lumi})$ pb for the dilepton mass range $60 < m_{\ell'\ell'} < 120$ GeV. For both cross sections, the invariant mass of any same-flavor opposite-sign lepton pair is required to be above 4 GeV. This measurement is compared with the theoretical values of $274^{+11}_{-8}(\text{scale}) \pm 4(\text{PDF})$ fb for the fiducial cross section and $42.3^{+1.4}_{-1.1}(\text{scale}) \pm 0.6(\text{PDF})$ pb for the total cross section calculated with MCFM at NLO with NNPDF3.0 PDFs, with dynamic renormalization and factorization scales set to $\mu_R = \mu_F = m_{\text{WZ}}$, and with the NNLO prediction from MATRIX.

Acknowledgements

We thank Massimiliano Grazzini and his collaborators for providing the NNLO cross section calculations. We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid 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 and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CIN-

VESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A.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 Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus programme of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2013/11/B/ST2/04202, 2014/13/B/ST2/02543 and 2014/15/B/ST2/03998, Sonata-bis 2012/07/E/ST2/01406; the Thalis and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the National Priorities Research Program by Qatar National Research Fund; the Programa Clarín-COFUND del Principado de Asturias; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); and the Welch Foundation, contract C-1845.

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The CMS Collaboration

V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth[1], V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler[1], A. König, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady, N. Rad, B. Rahbaran, H. Rohringer, J. Schieck[1], J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz[1]

Institut für Hochenergiephysik der OeAW, Wien, Austria

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

National Centre for Particle and High Energy Physics, Minsk, Belarus

S. Alderweireldt, E.A. De Wolf, X. Janssen, J. Lauwers, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Universiteit Antwerpen, Antwerpen, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, N. Heracleous, S. Lowette, S. Moortgat, L. Moreels, A. Olbrechts, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Vrije Universiteit Brussel, Brussel, Belgium

H. Brun, C. Caillol, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang[2]

Université Libre de Bruxelles, Bruxelles, Belgium

A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, G. Garcia, M. Gul, D. Poyraz, S. Salva, R. Schöfbeck, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

Ghent University, Ghent, Belgium

H. Bakhshiansohi, C. Beluffi[3], O. Bondu, S. Brochet, G. Bruno, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, L. Forthomme, B. Francois, A. Giammanco, A. Jafari, P. Jez, M. Komm, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, C. Nuttens, K. Piotrzkowski, L. Quertenmont, M. Selvaggi, M. Vidal Marono, S. Wertz

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

N. Beliy

Université de Mons, Mons, Belgium

W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato[4], A. Custódio, E.M. Da Costa, G.G. Da Silveira, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson,

D. Matos Figueiredo, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote[4], A. Vilela Pereira

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

S. Ahuja[a], C.A. Bernardes[b], S. Dogra[a], T.R. Fernandez Perez Tomei[a], E.M. Gregores[b], P.G. Mercadante[b], C.S. Moon[a], S.F. Novaes[a], Sandra S. Padula[a], D. Romero Abad[b], J.C. Ruiz Vargas

[a] *Universidade Estadual Paulista, São Paulo, Brazil*
[b] *Universidade Federal do ABC, São Paulo, Brazil*

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

W. Fang[5]

Beihang University, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen[6], T. Cheng, C.H. Jiang, D. Leggat, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, H. Zhang, J. Zhao

Institute of High Energy Physics, Beijing, China

Y. Ban, G. Chen, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

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

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, C.F. González Hernández, J.D. Ruiz Alvarez, J.C. Sanabria

Universidad de Los Andes, Bogota, Colombia

N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano

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

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, S. Micanovic, L. Sudic, T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

University of Cyprus, Nicosia, Cyprus

M. Finger[7], M. Finger Jr.[7]

Charles University, Prague, Czechia

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

A.A. Abdelalim[8,9], Y. Mohammed[10], E. Salama[11,12]

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

B. Calpas, M. Kadastik, M. Murumaa, L. Perrini, M. Raidal, A. Tiko, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, J. Pekkanen, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

J. Härkönen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Peltola, J. Tuominiemi, E. Tuovinen, L. Wendland

Helsinki Institute of Physics, Helsinki, Finland

J. Talvitie, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri, S. Ganjour, S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, I. Kucher, E. Locci, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

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

A. Abdulsalam, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, O. Davignon, R. Granier de Cassagnac, M. Jo, S. Lisniak, P. Miné, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

J.-L. Agram [13], J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte [13], X. Coubez, J.-C. Fontaine [13], D. Gelé, U. Goerlach, A.-C. Le Bihan, J.A. Merlin [14], K. Skovpen, P. Van Hove

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

S. Gadrat

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France

S. Beauceron, C. Bernet, G. Boudoul, E. Bouvier, C.A. Carrillo Montoya, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov [15], D. Sabes, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

T. Toriashvili [16]

Georgian Technical University, Tbilisi, Georgia

Z. Tsamalaidze [7]

Tbilisi State University, Tbilisi, Georgia

C. Autermann, S. Beranek, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, S. Schael, C. Schomakers, J.F. Schulte, J. Schulz, T. Verlage, H. Weber, V. Zhukov [15]

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

M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, M. Hamer, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer,

P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teyssier, S. Thüer

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

V. Cherepanov, G. Flügge, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, A. Nehrkorn, A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl [14]

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

M. Aldaya Martin, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A.A. Bin Anuar, K. Borras [17], A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Dolinska, G. Eckerlin, D. Eckstein, E. Eren, E. Gallo [18], J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, P. Gunnellini, A. Harb, J. Hauk, M. Hempel [19], H. Jung, A. Kalogeropoulos, O. Karacheban [19], M. Kasemann, J. Keaveney, J. Kieseler, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann [19], R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M.Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, C. Seitz, S. Spannagel, N. Stefaniuk, K.D. Trippkewitz, G.P. Van Onsem, R. Walsh, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

V. Blobel, M. Centis Vignali, A.R. Draeger, T. Dreyer, E. Garutti, K. Goebel, D. Gonzalez, J. Haller, M. Hoffmann, A. Junkes, R. Klanner, R. Kogler, N. Kovalchuk, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, J. Ott, F. Pantaleo [14], T. Peiffer, A. Perieanu, J. Poehlsen, C. Sander, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

University of Hamburg, Hamburg, Germany

C. Barth, C. Baus, J. Berger, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, S. Fink, R. Friese, M. Giffels, A. Gilbert, P. Goldenzweig, D. Haitz, F. Hartmann [14], S.M. Heindl, U. Husemann, I. Katkov [15], P. Lobelle Pardo, B. Maier, H. Mildner, M.U. Mozer, T. Müller, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

G. Anagnostou, G. Daskalakis, T. Geralis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, I. Topsis-Giotis

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

A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

National and Kapodistrian University of Athens, Athens, Greece

I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Loukas, N. Manthos, I. Papadopoulos, E. Paradas

University of Ioánnina, Ioánnina, Greece

N. Filipovic

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

G. Bencze, C. Hajdu, P. Hidas, D. Horvath [20], F. Sikler, V. Veszpremi, G. Vesztergombi [21], A.J. Zsigmond

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi [22], A. Makovec, J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

M. Bartók[21], P. Raics, Z.L. Trocsanyi, B. Ujvari

University of Debrecen, Debrecen, Hungary

S. Bahinipati, S. Choudhury[23], P. Mal, K. Mandal, A. Nayak[24], D.K. Sahoo, N. Sahoo, S.K. Swain

National Institute of Science Education and Research, Bhubaneswar, India

S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, U. Bhawandeep, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, A. Mehta, M. Mittal, J.B. Singh, G. Walia

Panjab University, Chandigarh, India

Ashok Kumar, A. Bhardwaj, B.C. Choudhary, R.B. Garg, S. Keshri, S. Malhotra, M. Naimuddin, N. Nishu, K. Ranjan, R. Sharma, V. Sharma

University of Delhi, Delhi, India

R. Bhattacharya, S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

Saha Institute of Nuclear Physics, Kolkata, India

P.K. Behera

Indian Institute of Technology Madras, Madras, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty[14], P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Dugad, G. Kole, B. Mahakud, S. Mitra, G.B. Mohanty, B. Parida, N. Sur, B. Sutar

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhowmik[25], R.K. Dewanjee, S. Ganguly, M. Guchait, Sa. Jain, S. Kumar, M. Maity[25], G. Majumder, K. Mazumdar, T. Sarkar[25], N. Wickramage[26]

Tata Institute of Fundamental Research-B, Mumbai, India

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, A. Rane, S. Sharma

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

H. Behnamian, S. Chenarani[27], E. Eskandari Tadavani, S.M. Etesami[27], A. Fahim[28], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh[29], M. Zeinali

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia[a,b], C. Calabria[a,b], C. Caputo[a,b], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], N. De Filippis[a,c], M. De Palma[a,b], L. Fiore[a], G. Iaselli[a,c], G. Maggi[a,c], M. Maggi[a], G. Miniello[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a,b], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a,14], R. Venditti[a,b], P. Verwilligen[a]

[a] *INFN Sezione di Bari, Bari, Italy*
[b] *Università di Bari, Bari, Italy*
[c] *Politecnico di Bari, Bari, Italy*

G. Abbiendi[a], C. Battilana, D. Bonacorsi[a,b], S. Braibant-Giacomelli[a,b], L. Brigliadori[a,b], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], S.S. Chhibra[a,b], G. Codispoti[a,b], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a,b], P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], S. Marcellini[a], G. Masetti[a], A. Montanari[a], F.L. Navarria[a,b], A. Perrotta[a], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b], N. Tosi[a,b,14]

[a] *INFN Sezione di Bologna, Bologna, Italy*
[b] *Università di Bologna, Bologna, Italy*

S. Albergo[a,b], M. Chiorboli[a,b], S. Costa[a,b], A. Di Mattia[a], F. Giordano[a,b], R. Potenza[a,b], A. Tricomi[a,b], C. Tuve[a,b]

[a] *INFN Sezione di Catania, Catania, Italy*
[b] *Università di Catania, Catania, Italy*

G. Barbagli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], V. Gori[a,b], P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], G. Sguazzoni[a], L. Viliani[a,b,14]

[a] *INFN Sezione di Firenze, Firenze, Italy*
[b] *Università di Firenze, Firenze, Italy*

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera[14]

INFN Laboratori Nazionali di Frascati, Frascati, Italy

V. Calvelli[a,b], F. Ferro[a], M. Lo Vetere[a,b], M.R. Monge[a,b], E. Robutti[a], S. Tosi[a,b]

[a] *INFN Sezione di Genova, Genova, Italy*
[b] *Università di Genova, Genova, Italy*

L. Brianza, M.E. Dinardo[a,b], S. Fiorendi[a,b], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], S. Malvezzi[a], R.A. Manzoni[a,b,14], B. Marzocchi[a,b], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Pigazzini, S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b]

[a] *INFN Sezione di Milano-Bicocca, Milano, Italy*
[b] *Università di Milano-Bicocca, Milano, Italy*

S. Buontempo[a], N. Cavallo[a,c], G. De Nardo, S. Di Guida[a,d,14], M. Esposito[a,b], F. Fabozzi[a,c], A.O.M. Iorio[a,b], G. Lanza[a], L. Lista[a], S. Meola[a,d,14], P. Paolucci[a,14], C. Sciacca[a,b], F. Thyssen

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

P. Azzi[a,14], N. Bacchetta[a], L. Benato[a,b], D. Bisello[a,b], A. Boletti[a,b], R. Carlin[a,b], A. Carvalho Antunes De Oliveira[a,b], P. Checchia[a], M. Dall'Osso[a,b], P. De Castro Manzano[a], T. Dorigo[a], U. Dosselli[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], S. Lacaprara[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], J. Pazzini[a,b,14], N. Pozzobon[a,b], P. Ronchese[a,b], F. Simonetto[a,b], E. Torassa[a], M. Zanetti, P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

[a] *INFN Sezione di Padova, Padova, Italy*
[b] *Università di Padova, Padova, Italy*
[c] *Università di Trento, Trento, Italy*

A. Braghieri[a], A. Magnani[a,b], P. Montagna[a,b], S.P. Ratti[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

[a] *INFN Sezione di Pavia, Pavia, Italy*
[b] *Università di Pavia, Pavia, Italy*

L. Alunni Solestizi[a,b], G.M. Bilei[a], D. Ciangottini[a,b], L. Fanò[a,b], P. Lariccia[a,b], R. Leonardi[a,b], G. Mantovani[a,b], M. Menichelli[a], A. Saha[a], A. Santocchia[a,b]

[a] *INFN Sezione di Perugia, Perugia, Italy*
[b] *Università di Perugia, Perugia, Italy*

K. Androsov [a,30], P. Azzurri [a,14], G. Bagliesi [a], J. Bernardini [a], T. Boccali [a], R. Castaldi [a], M.A. Ciocci [a,30], R. Dell'Orso [a], S. Donato [a,c], G. Fedi, A. Giassi [a], M.T. Grippo [a,30], F. Ligabue [a,c], T. Lomtadze [a], L. Martini [a,b], A. Messineo [a,b], F. Palla [a], A. Rizzi [a,b], A. Savoy-Navarro [a,31], P. Spagnolo [a], R. Tenchini [a], G. Tonelli [a,b], A. Venturi [a], P.G. Verdini [a]

[a] *INFN Sezione di Pisa, Pisa, Italy*
[b] *Università di Pisa, Pisa, Italy*
[c] *Scuola Normale Superiore di Pisa, Pisa, Italy*

L. Barone [a,b], F. Cavallari [a], M. Cipriani [a,b], G. D'imperio [a,b,14], D. Del Re [a,b,14], M. Diemoz [a], S. Gelli [a,b], C. Jorda [a], E. Longo [a,b], F. Margaroli [a,b], P. Meridiani [a], G. Organtini [a,b], R. Paramatti [a], F. Preiato [a,b], S. Rahatlou [a,b], C. Rovelli [a], F. Santanastasio [a,b]

[a] *INFN Sezione di Roma, Roma, Italy*
[b] *Università di Roma, Roma, Italy*

N. Amapane [a,b], R. Arcidiacono [a,c,14], S. Argiro [a,b], M. Arneodo [a,c], N. Bartosik [a], R. Bellan [a,b], C. Biino [a], N. Cartiglia [a], F. Cenna [a,b], M. Costa [a,b], R. Covarelli [a,b], A. Degano [a,b], N. Demaria [a], L. Finco [a,b], B. Kiani [a,b], C. Mariotti [a], S. Maselli [a], E. Migliore [a,b], V. Monaco [a,b], E. Monteil [a,b], M.M. Obertino [a,b], L. Pacher [a,b], N. Pastrone [a], M. Pelliccioni [a], G.L. Pinna Angioni [a,b], F. Ravera [a,b], A. Romero [a,b], M. Ruspa [a,c], R. Sacchi [a,b], K. Shchelina [a,b], V. Sola [a], A. Solano [a,b], A. Staiano [a], P. Traczyk [a,b]

[a] *INFN Sezione di Torino, Torino, Italy*
[b] *Università di Torino, Torino, Italy*
[c] *Università del Piemonte Orientale, Novara, Italy*

S. Belforte [a], M. Casarsa [a], F. Cossutti [a], G. Della Ricca [a,b], C. La Licata [a,b], A. Schizzi [a,b], A. Zanetti [a]

[a] *INFN Sezione di Trieste, Trieste, Italy*
[b] *Università di Trieste, Trieste, Italy*

D.H. Kim, G.N. Kim, M.S. Kim, S. Lee, S.W. Lee, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

Kyungpook National University, Daegu, Republic of Korea

A. Lee

Chonbuk National University, Jeonju, Republic of Korea

J.A. Brochero Cifuentes, T.J. Kim

Hanyang University, Seoul, Republic of Korea

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, Y. Kim, B. Lee, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Korea University, Seoul, Republic of Korea

J. Almond, J. Kim, S.B. Oh, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

Seoul National University, Seoul, Republic of Korea

M. Choi, H. Kim, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, G. Ryu, M.S. Ryu

University of Seoul, Seoul, Republic of Korea

Y. Choi, J. Goh, C. Hwang, J. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

V. Dudenas, A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali[32], F. Mohamad Idris[33], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[34], A. Hernandez-Almada, R. Lopez-Fernandez, R. Magaña Villalba, J. Mejia Guisao, A. Sanchez-Hernandez

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

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

D. Krofcheck

University of Auckland, Auckland, New Zealand

P.H. Butler

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

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

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, A. Byszuk[35], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak

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

P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadruccio, J. Varela, P. Vischia

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

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev[36,37], P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

L. Chtchipounov, V. Golovtsov, Y. Ivanov, V. Kim[38], E. Kuznetsova[39], V. Murzin, V. Oreshkin, V. Sulimov, A. Vorobyev

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

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, M. Toms, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

A. Bylinkin[37]

Moscow Institute of Physics and Technology, Russia

M. Chadeeva[40], M. Danilov[40], O. Markin

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

V. Andreev, M. Azarkin[37], I. Dremin[37], M. Kirakosyan, A. Leonidov[37], S.V. Rusakov, A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, M. Dubinin[41], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

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

V. Blinov[42], Y. Skovpen[42]

Novosibirsk State University (NSU), Novosibirsk, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

P. Adzic[43], P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

J. Alcaraz Maestre, M. Barrio Luna, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

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

J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad Autónoma de Madrid, Madrid, Spain

J. Cuevas, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, I. Suárez Andrés, J.M. Vizan Garcia

Universidad de Oviedo, Oviedo, Spain

I.J. Cabrillo, A. Calderon, J.R. Castiñeiras De Saa, E. Curras, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, F. Matorras, J. Piedra Gomez, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, P. Bloch, A. Bocci, A. Bonato, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, M. D'Alfonso, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, F. De Guio, A. De Roeck, E. Di Marco[44], M. Dobson, B. Dorney, T. du Pree, D. Duggan, M. Dünser, N. Dupont, A. Elliott-Peisert, S. Fartoukh, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, M. Girone, F. Glege, D. Gulhan, S. Gundacker, M. Guthoff, J. Hammer, P. Harris, J. Hegeman, V. Innocente, P. Janot, H. Kirschenmann, V. Knünz, A. Kornmayer[14], M.J. Kortelainen, K. Kousouris, M. Krammer[1], P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi[45], M. Rovere, M. Ruan, H. Sakulin, J.B. Sauvan, C. Schäfer, C. Schwick, M. Seidel, A. Sharma, P. Silva, M. Simon, P. Sphicas[46], J. Steggemann, M. Stoye, Y. Takahashi, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns[47], G.I. Veres[21], N. Wardle, A. Zagozdzinska[35], W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, P. Eller, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, P. Lecomte[†], W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Rossini, M. Schönenberger, A. Starodumov[48], V.R. Tavolaro, K. Theofilatos, R. Wallny

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler[49], L. Caminada, M.F. Canelli, V. Chiochia, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, Y. Yang

Universität Zürich, Zurich, Switzerland

V. Candelise, T.H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C.M. Kuo, W. Lin, Y.J. Lu, A. Pozdnyakov, S.S. Yu

National Central University, Chung-Li, Taiwan

Arun Kumar, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, F. Fiori, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Paganis, A. Psallidas, J.f. Tsai, Y.M. Tzeng

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, G. Singh, N. Srimanobhas, N. Suwonjandee

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

A. Adiguzel, S. Damarseckin, Z.S. Demiroglu, C. Dozen, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal[50], O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut[51], K. Ozdemir[52], S. Ozturk[53], A. Polatoz, B. Tali[54], S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Cukurova University, Adana, Turkey

B. Bilin, S. Bilmis, B. Isildak[55], G. Karapinar[56], M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, M. Kaya[57], O. Kaya[58], E.A. Yetkin[59], T. Yetkin[60]

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak, S. Sen[61]

Istanbul Technical University, Istanbul, Turkey

B. Grynyov

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

L. Levchuk, P. Sorokin

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

R. Aggleton, F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, D.M. Newbold [62], S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev [63], C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, P. Dunne, A. Elwood, D. Futyan, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, R. Lucas [62], L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, J. Nash, A. Nikitenko [48], J. Pela, B. Penning, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, C. Seez, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta [64], T. Virdee [14], J. Wright, S.C. Zenz

Imperial College, London, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leslie, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Brunel University, Uxbridge, United Kingdom

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika

Baylor University, Waco, USA

O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

The University of Alabama, Tuscaloosa, USA

D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Boston University, Boston, USA

G. Benelli, E. Berry, D. Cutts, A. Garabedian, J. Hakala, U. Heintz, J.M. Hogan, O. Jesus, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, E. Spencer, R. Syarif

Brown University, Providence, USA

R. Breedon, G. Breto, D. Burns, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, F. Ricci-Tam, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

University of California, Davis, Davis, USA

R. Cousins, P. Everaerts, A. Florent, J. Hauser, M. Ignatenko, D. Saltzberg, E. Takasugi, V. Valuev, M. Weber

University of California, Los Angeles, USA

K. Burt, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, M. Malberti, M. Olmedo Negrete, M.I. Paneva, A. Shrinivas, H. Wei, S. Wimpenny, B.R. Yates

University of California, Riverside, Riverside, USA

J.G. Branson, G.B. Cerati, S. Cittolin, M. Derdzinski, R. Gerosa, A. Holzner, D. Klein, V. Krutelyov, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech [65], C. Welke, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, San Diego, La Jolla, USA

R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, N. Mccoll, S.D. Mullin, A. Ovcharova, J. Richman, D. Stuart, I. Suarez, C. West, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA

D. Anderson, A. Apresyan, J. Bendavid, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, J.M. Lawhorn, A. Mott, H.B. Newman, C. Pena, M. Spiropulu, J.R. Vlimant, S. Xie, R.Y. Zhu

California Institute of Technology, Pasadena, USA

M.B. Andrews, V. Azzolini, B. Carlson, T. Ferguson, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, T. Mulholland, K. Stenson, S.R. Wagner

University of Colorado Boulder, Boulder, USA

J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Cornell University, Ithaca, USA

D. Winn

Fairfield University, Fairfield, USA

S. Abdullin, M. Albrow, G. Apollinari, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir, M. Cremonesi, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, D. Hare, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, J. Linacre, D. Lincoln, R. Lipton, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, C. Newman-Holmes[†], V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, S. Das, R.D. Field, I.K. Furic, J. Konigsberg, A. Korytov, P. Ma, K. Matchev, H. Mei, P. Milenovic[66], G. Mitselmakher, D. Rank, L. Shchutska, D. Sperka, L. Thomas, J. Wang, S. Wang, J. Yelton

University of Florida, Gainesville, USA

S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida International University, Miami, USA

A. Ackert, J.R. Adams, T. Adams, A. Askew, S. Bein, B. Diamond, S. Hagopian, V. Hagopian, K.F. Johnson, A. Khatiwada, H. Prosper, A. Santra, M. Weinberg

Florida State University, Tallahassee, USA

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi[67], M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, P. Kurt, C. O'Brien, I.D. Sandoval Gonzalez, P. Turner, N. Varelas, H. Wang, Z. Wu, M. Zakaria, J. Zhang

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

B. Bilki[68], W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya[69], A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok[70], A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

The University of Iowa, Iowa City, USA

I. Anderson, B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, M. Osherson, J. Roskes, U. Sarica, M. Swartz, M. Xiao, Y. Xin, C. You

Johns Hopkins University, Baltimore, USA

A. Al-bataineh, P. Baringer, A. Bean, J. Bowen, C. Bruner, J. Castle, R.P. Kenny III, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, S. Sanders, R. Stringer, J.D. Tapia Takaki, Q. Wang

The University of Kansas, Lawrence, USA

A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Kansas State University, Manhattan, USA

D. Lange, F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, J.A. Gomez, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Kolberg, J. Kunkle, Y. Lu, A.C. Mignerey, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

University of Maryland, College Park, USA

D. Abercrombie, B. Allen, A. Apyan, R. Barbieri, A. Baty, R. Bi, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, Z. Demiragli, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Hsu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, K. Krajczar, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Sumorok, K. Tatar, M. Varma, D. Velicanu, J. Veverka, J. Wang, T.W. Wang, B. Wyslouch, M. Yang, V. Zhukova

Massachusetts Institute of Technology, Cambridge, USA

A.C. Benvenuti, R.M. Chatterjee, A. Evans, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S.C. Kao, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

E. Avdeeva, R. Bartek, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, D. Knowlton, I. Kravchenko, A. Malta Rodrigues, F. Meier, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

University of Nebraska-Lincoln, Lincoln, USA

M. Alyari, J. Dolen, J. George, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, A. Parker, S. Rappoccio, B. Roozbahani

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, D. Baumgartel, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood

Northeastern University, Boston, USA

S. Bhattacharya, K.A. Hahn, A. Kubik, A. Kumar, J.F. Low, N. Mucia, N. Odell, B. Pollack, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

Northwestern University, Evanston, USA

N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Marinelli, F. Meng, C. Mueller, Y. Musienko[36], M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, N. Valls, M. Wayne, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, USA

J. Alimena, L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, R. Hughes, W. Ji, B. Liu, W. Luo, D. Puigh, B.L. Winer, H.W. Wulsin

The Ohio State University, Columbus, USA

S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, J. Luo, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully, A. Zuranski

Princeton University, Princeton, USA

S. Malik

University of Puerto Rico, Mayaguez, USA

A. Barker, V.E. Barnes, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, K. Jung, D.H. Miller, N. Neumeister, B.C. Radburn-Smith, X. Shi, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu

Purdue University, West Lafayette, USA

N. Parashar, J. Stupak

Purdue University Calumet, Hammond, USA

A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, Z. Tu, J. Zabel

Rice University, Houston, USA

B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, M. Verzetti

University of Rochester, Rochester, USA

J.P. Chou, E. Contreras-Campana, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, K. Nash, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

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

M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

University of Tennessee, Knoxville, USA

O. Bouhali[71], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, E. Juska, T. Kamon[72], R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Rose, A. Safonov, A. Tatarinov, K.A. Ulmer

Texas A&M University, College Station, USA

N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Dudero, J. Faulkner, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, S. Undleeb, I. Volobouev, Z. Wang

Texas Tech University, Lubbock, USA

A.G. Delannoy, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

Vanderbilt University, Nashville, USA

M.W. Arenton, P. Barria, B. Cox, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, F. Xia

University of Virginia, Charlottesville, USA

C. Clarke, R. Harr, P.E. Karchin, P. Lamichhane, J. Sturdy

Wayne State University, Detroit, USA

D.A. Belknap, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, T. Ruggles, A. Savin, A. Sharma, N. Smith, W.H. Smith, D. Taylor, N. Woods

University of Wisconsin – Madison, Madison, WI, USA

[†] Deceased.
[1] Also at Vienna University of Technology, Vienna, Austria.
[2] Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.
[3] Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.
[4] Also at Universidade Estadual de Campinas, Campinas, Brazil.
[5] Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[6] Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
[7] Also at Joint Institute for Nuclear Research, Dubna, Russia.
[8] Also at Helwan University, Cairo, Egypt.
[9] Now at Zewail City of Science and Technology, Zewail, Egypt.
[10] Now at Fayoum University, El-Fayoum, Egypt.
[11] Also at British University in Egypt, Cairo, Egypt.
[12] Now at Ain Shams University, Cairo, Egypt.
[13] Also at Université de Haute Alsace, Mulhouse, France.
[14] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[15] Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
[16] Also at Tbilisi State University, Tbilisi, Georgia.
[17] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[18] Also at University of Hamburg, Hamburg, Germany.
[19] Also at Brandenburg University of Technology, Cottbus, Germany.
[20] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[21] Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
[22] Also at University of Debrecen, Debrecen, Hungary.
[23] Also at Indian Institute of Science Education and Research, Bhopal, India.
[24] Also at Institute of Physics, Bhubaneswar, India.
[25] Also at University of Visva-Bharati, Santiniketan, India.
[26] Also at University of Ruhuna, Matara, Sri Lanka.
[27] Also at Isfahan University of Technology, Isfahan, Iran.
[28] Also at University of Tehran, Department of Engineering Science, Tehran, Iran.
[29] Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[30] Also at Università degli Studi di Siena, Siena, Italy.
[31] Also at Purdue University, West Lafayette, USA.
[32] Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
[33] Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
[34] Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
[35] Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
[36] Also at Institute for Nuclear Research, Moscow, Russia.
[37] Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
[38] Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[39] Also at University of Florida, Gainesville, USA.
[40] Also at P.N. Lebedev Physical Institute, Moscow, Russia.
[41] Also at California Institute of Technology, Pasadena, USA.

[42] Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
[43] Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[44] Also at INFN Sezione di Roma; Università di Roma, Roma, Italy.
[45] Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
[46] Also at National and Kapodistrian University of Athens, Athens, Greece.
[47] Also at Riga Technical University, Riga, Latvia.
[48] Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
[49] Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
[50] Also at Mersin University, Mersin, Turkey.
[51] Also at Cag University, Mersin, Turkey.
[52] Also at Piri Reis University, Istanbul, Turkey.
[53] Also at Gaziosmanpasa University, Tokat, Turkey.
[54] Also at Adiyaman University, Adiyaman, Turkey.
[55] Also at Ozyegin University, Istanbul, Turkey.
[56] Also at Izmir Institute of Technology, Izmir, Turkey.
[57] Also at Marmara University, Istanbul, Turkey.
[58] Also at Kafkas University, Kars, Turkey.
[59] Also at Istanbul Bilgi University, Istanbul, Turkey.
[60] Also at Yildiz Technical University, Istanbul, Turkey.
[61] Also at Hacettepe University, Ankara, Turkey.
[62] Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[63] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[64] Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
[65] Also at Utah Valley University, Orem, USA.
[66] Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[67] Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
[68] Also at Argonne National Laboratory, Argonne, USA.
[69] Also at Erzincan University, Erzincan, Turkey.
[70] Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
[71] Also at Texas A&M University at Qatar, Doha, Qatar.
[72] Also at Kyungpook National University, Daegu, Korea.