

CERN-EP/2016-174
2016/11/10

CMS-SMP-16-001

Measurement of the ZZ production cross section and $Z \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$ branching fraction in pp collisions at $\sqrt{s} = 13 \text{ TeV}$

The CMS Collaboration*

Abstract

Four-lepton production in proton-proton collisions, $pp \rightarrow (Z/\gamma^*)(Z/\gamma^*) \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$, where $\ell, \ell' = e$ or μ , is studied at a center-of-mass energy of 13 TeV with the CMS detector at the LHC. The data sample corresponds to an integrated luminosity of 2.6 fb^{-1} . The ZZ production cross section, $\sigma(pp \rightarrow ZZ) = 14.6^{+1.9}_{-1.8} (\text{stat})^{+0.5}_{-0.3} (\text{syst}) \pm 0.2 (\text{theo}) \pm 0.4 (\text{lumi}) \text{ pb}$, is measured for events with two opposite-sign, same-flavor lepton pairs produced in the mass region $60 < m_{\ell^+ \ell^-}, m_{\ell'^+ \ell'^-} < 120 \text{ GeV}$. The Z boson branching fraction to four leptons is measured to be $\mathcal{B}(Z \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-) = 4.9^{+0.8}_{-0.7} (\text{stat})^{+0.3}_{-0.2} (\text{syst})^{+0.2}_{-0.1} (\text{theo}) \pm 0.1 (\text{lumi}) \times 10^{-6}$ for the four-lepton invariant mass in the range $80 < m_{\ell^+ \ell^- \ell'^+ \ell'^-} < 100 \text{ GeV}$ and dilepton mass $m_{\ell^+ \ell^-} > 4 \text{ GeV}$ for all opposite-sign, same-flavor lepton pairs. The results are in agreement with standard model predictions.

Published in Physics Letters B as doi:10.1016/j.physletb.2016.10.054.

1 Introduction

Measurements of diboson production at the CERN LHC allow precision studies of the standard model (SM). These measurements are important for testing predictions that were recently made available at next-to-next-to-leading-order (NNLO) in quantum chromodynamics (QCD) [1]. Comparing these predictions to data at a range of center-of-mass energies gives insight into the structure of the electroweak gauge sector of the SM, and new proton-proton collision data at $\sqrt{s} = 13$ TeV allow diboson measurements at the highest energies to date. Any deviations from expected values could be an indication of physics beyond the SM.

Previous measurements of the ZZ production cross section from CMS were performed in the $ZZ \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$ and $ZZ \rightarrow \ell^+ \ell^- \nu \nu$ decay channels, where $\ell = e, \mu$ and $\ell' = e, \mu, \tau$ for both Z bosons produced on-shell, in the dilepton mass range 60–120 GeV [2–4]. These measurements were made with data sets corresponding to integrated luminosities of 5.1 fb^{-1} at $\sqrt{s} = 7$ TeV and 19.6 fb^{-1} at $\sqrt{s} = 8$ TeV, and agree with SM predictions. The ATLAS Collaboration produced similar results at $\sqrt{s} = 7, 8$, and 13 TeV [5–7], which also agree with the SM.

Extending the mass window for the dilepton candidates to lower values allows measurements of $(Z/\gamma^*)(Z/\gamma^*)$ production, where “Z” may indicate an on-shell Z boson or an off-shell Z^* boson. The resulting sample includes Higgs boson events in the “golden channel” $H \rightarrow ZZ^* \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$, where $\ell' = e, \mu$, and rare Z boson decays to four leptons. The $Z \rightarrow \ell^+ \ell^- \gamma^* \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$ decay was studied in detail at LEP [8] and was observed in pp collisions by CMS [9] and by ATLAS [10]. Though the branching fraction for this decay is orders of magnitude smaller than that for the $Z \rightarrow \ell^+ \ell^-$ decay, the precisely known mass of the Z boson makes the four-lepton mode useful for calibrating mass measurements of the nearby Higgs resonance.

This letter reports a study of four-lepton production ($pp \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$, where ℓ and ℓ' indicate electrons or muons) at $\sqrt{s} = 13$ TeV with a data set corresponding to an integrated luminosity of $2.62 \pm 0.07 \text{ fb}^{-1}$ recorded in 2015. From this study, cross sections are inferred for nonresonant production of pairs of Z bosons, $pp \rightarrow ZZ$, where both Z bosons are produced on-shell, defined as the mass range 60–120 GeV, and resonant $pp \rightarrow Z \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$ production. Discussion of resonant Higgs boson production is beyond the scope of this letter.

2 The CMS detector

A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [11].

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 (HCAL), which provide coverage in pseudorapidity $|\eta| < 1.479$ in a barrel and $1.479 < |\eta| < 3.0$ in two endcap regions. Forward calorimeters extend the coverage provided by the barrel and endcap detectors to $|\eta| < 5.0$. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid in the range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers.

Electron momenta are estimated by combining energy measurements in the ECAL with momentum measurements in the tracker. The momentum resolution for electrons with transverse momentum $p_T \approx 45 \text{ GeV}$ from $Z \rightarrow e^+ e^-$ decays ranges from 1.7% for nonshowering

electrons in the barrel region to 4.5% for showering electrons in the endcaps [12]. Matching muons to tracks measured in the silicon tracker results in a p_T resolution for muons with $20 < p_T < 100$ GeV of 1.3–2.0% in the barrel and better than 6% in the endcaps. The p_T resolution in the barrel is better than 10% for muons with p_T up to 1 TeV [13].

3 Signal and background simulation

Signal events are generated with POWHEG 2.0 [14–16] at next-to-leading-order (NLO) in QCD for quark-antiquark processes and leading-order (LO) for quark-gluon processes. This includes ZZ , $Z\gamma^*$, Z , and $\gamma^*\gamma^*$ production with a constraint of $m_{\ell^+\ell^-} > 4$ GeV applied between all pairs of oppositely charged leptons at the generator level to avoid infrared divergences. The $gg \rightarrow ZZ$ process is simulated at LO with MCFM v7.0 [17]. These samples are scaled to correspond to cross sections calculated at NNLO for $q\bar{q} \rightarrow ZZ$ [1] (scaling K factor 1.1) and at NLO for $gg \rightarrow ZZ$ [18] (K factor 1.7). The $gg \rightarrow ZZ$ process is calculated to $\mathcal{O}(\alpha_s^5)$, where α_s is the strong coupling constant, while the other contributing processes are calculated to $\mathcal{O}(\alpha_s^4)$; this higher-order correction is included because the effect is known to be large [18].

A sample of Higgs boson events is produced in the gluon-gluon fusion process with POWHEG 2.0 in the NLO QCD approximation. The Higgs boson decay is modeled with JHUGEN 3.1.8 [19–21]. The $q\bar{q} \rightarrow WZ$ process is generated with POWHEG 2.0.

The PYTHIA v8.175 [22–24] package is used for parton showering, hadronization, and the underlying event simulation, with parameters set by the CUETP8M1 tune [25]. The NNPDF3.0 [26] set is used as the default set of parton distribution functions (PDFs). For all simulated event samples, the PDFs are calculated to the same order in QCD as the process in the sample.

The detector response is simulated using a detailed description of the CMS detector implemented with the GEANT4 package [27]. The event reconstruction is performed with the same algorithms used for data. The simulated samples include additional interactions per bunch crossing, referred to as “pileup.” The simulated events are weighted so that the pileup distribution matches the data, with an average of about 11 interactions per bunch crossing.

4 Event reconstruction

All long-lived particles in each collision event — electrons, muons, photons, and charged and neutral hadrons — are identified and reconstructed with the CMS particle-flow (PF) algorithm [28, 29] from a combination of the signals from all subdetectors. Reconstructed electrons [12] and muons [13] are candidates for inclusion in four-lepton final states if they have $p_T^e > 7$ GeV and $|\eta^e| < 2.5$ or $p_T^\mu > 5$ GeV and $|\eta^\mu| < 2.4$. These are designated “signal leptons.”

Signal leptons are also required to originate from the event vertex, defined as the proton-proton interaction vertex whose associated charged particles have the highest sum of p_T^2 . The distance of closest approach between each lepton track and the event vertex is required to be less than 0.5 cm in the plane transverse to the beam axis, and less than 1 cm in the direction along the beam axis. Furthermore, the significance of the three-dimensional impact parameter relative to the event vertex, SIP_{3D} , is required to satisfy $SIP_{3D} \equiv |IP/\sigma_{IP}| < 4$ for each lepton, where IP is the distance of closest approach of each lepton track to the event vertex and σ_{IP} is its associated uncertainty.

Signal leptons are required to be isolated from other particles in the event. The relative isolation

is defined as

$$R_{\text{iso}} = \left[\sum_{\text{charged hadrons}} p_T + \max\left(0, \sum_{\text{neutral hadrons}} p_T + \sum_{\text{photons}} p_T - p_T^{\text{PU}}\right) \right] / p_T^\ell, \quad (1)$$

where the sums run over the charged and neutral hadrons, and photons, in a cone defined by $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ around the lepton trajectory, where ϕ is the azimuthal angle in radians. To minimize the contribution of charged particles from pileup to the isolation calculation, charged hadrons are included only if they originate from the event vertex. The contribution of neutral particles from pileup is p_T^{PU} . For electrons, p_T^{PU} is evaluated with the “jet area” method described in Ref. [30]; for muons, it is taken to be half the sum of the p_T of all charged particles in the cone originating from pileup vertices. The factor one-half accounts for the expected ratio of charged to neutral particle energy in hadronic interactions. A lepton is considered isolated if $R_{\text{iso}} < 0.35$.

Emission of final-state radiation (FSR) photons by the signal leptons may degrade the performance of the isolation requirements and Z boson mass reconstruction. These photons are omitted from the isolation determination for signal leptons and are implicitly included in dilepton kinematic calculations. Photons are FSR candidates if $p_T^\gamma > 2 \text{ GeV}$, $|\eta^\gamma| < 2.4$, their relative isolation (defined as in Eq. (1) with $p_T^{\text{PU}} = 0$) is less than 1.8, and $\Delta R(\ell, \gamma) < 0.5$ with respect to the nearest signal lepton. To avoid double counting of bremsstrahlung photons that are already included in electron reconstruction, photons are not FSR candidates if there is any signal electron within $\Delta R(\gamma, e) < 0.15$ or within $|\Delta\phi(\gamma, e)| < 2$ and $|\Delta\eta(\gamma, e)| < 0.05$. Because FSR photons have a higher average energy than photons from pileup and are expected to be mostly collinear with the emitting lepton, a photon candidate is accepted as FSR if $\Delta R(\ell, \gamma) / (p_T^\gamma)^2 < 0.012 \text{ GeV}^{-2}$.

In simulated $ZZ \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$ events, the efficiency to select generated FSR photons is around 55%, and roughly 85% of selected photons are matched to FSR photons. At least one FSR photon is identified in approximately 2%, 5%, and 8% of simulated events in the $4e$, $2e2\mu$, and 4μ channels, respectively. In data events with two on-shell Z bosons, no FSR photons are selected in the $4e$ decay channel, while at least one FSR photon is selected in three and five events in the $2e2\mu$ and 4μ decay channels, respectively.

The lepton reconstruction, identification, and isolation efficiencies are measured with a tag-and-probe technique [31] applied to a sample of $Z \rightarrow \ell^+ \ell^-$ data events. The measurements are performed in several bins of p_T^ℓ and $|\eta^\ell|$. The electron reconstruction and selection efficiency in the ECAL barrel (endcaps) varies from about 85% (77%) at $p_T^e \approx 10 \text{ GeV}$ to about 95% (89%) for $p_T^e \geq 20 \text{ GeV}$, while in the barrel-endcap transition region this efficiency is about 85% averaged over all electrons with $p_T^e > 7 \text{ GeV}$. The muons are reconstructed and identified with efficiencies above $\sim 98\%$ within $|\eta^\mu| < 2.4$.

5 Event selection

The primary triggers for this analysis require the presence of a pair of loosely isolated leptons of the same or different flavors. The highest p_T lepton must have $p_T^\ell > 17 \text{ GeV}$, and the subleading lepton must have $p_T^e > 12 \text{ GeV}$ if it is an electron or $p_T^\mu > 8 \text{ GeV}$ if it is a muon. The dielectron and dimuon triggers require that the tracks corresponding to the leptons originate from within 2 mm of each other in the plane transverse to the beam axis. Triggers requiring a triplet of lower- p_T leptons with no isolation criterion, or a single high- p_T electron without an isolation

requirement, are also used. An event is used if it passes any trigger regardless of the decay channel. The total trigger efficiency for events within the acceptance of this analysis is greater than 98%.

A signal event must contain at least two Z/γ^* candidates, each formed from an oppositely charged pair of isolated signal electrons or muons. Among the four leptons, the highest p_T lepton must have $p_T > 20$ GeV, and the second-highest p_T lepton must have $p_T^e > 12$ GeV if it is an electron or $p_T^\mu > 10$ GeV if it is a muon. All leptons are required to be separated by $\Delta R(\ell_1, \ell_2) > 0.02$, and electrons are required to be separated from muons by $\Delta R(e, \mu) > 0.05$.

Within each event, all permutations of leptons giving a valid pair of Z/γ^* candidates are considered separately. Within each $\ell^+\ell^-\ell'^+\ell'^-$ candidate, the dilepton candidate with an invariant mass closest to 91.2 GeV, taken as the nominal Z boson mass, is denoted Z_1 and is required to have a mass greater than 40 GeV. The other dilepton candidate is denoted Z_2 . Both m_{Z_1} and m_{Z_2} are required to be less than 120 GeV. All pairs of oppositely charged leptons in the candidate are required to have $m_{\ell\ell'} > 4$ GeV regardless of flavor.

If multiple $\ell^+\ell^-\ell'^+\ell'^-$ candidates within an event pass all selections, the passing candidate with m_{Z_1} closest to the nominal Z boson mass is chosen. In the rare case of further ambiguity, which may arise in events with five or more signal leptons, the Z_2 candidate that maximizes the scalar p_T sum of the four leptons is chosen.

Additional requirements are applied to select events for measurements of specific processes. The $pp \rightarrow ZZ$ cross section is measured using events where both m_{Z_1} and m_{Z_2} are greater than 60 GeV. The $Z \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ branching fraction is measured using events with $80 < m_{\ell+\ell-\ell'+\ell'-} < 100$ GeV, a range chosen to retain most of the decays in the resonance while removing most other processes with four-lepton final states.

6 Background estimate

The major background contributions arise from Z boson and WZ diboson production in association with jets and from $t\bar{t}$ production. In all these cases, particles from jet fragmentation satisfy both lepton identification and isolation criteria, and are thus misidentified as signal leptons.

The probability for such objects to be selected is measured from a sample of $Z + \ell_{\text{candidate}}$ events, where Z is a pair of oppositely charged, same-flavor leptons that pass all analysis requirements and satisfy $|m_{\ell+\ell-} - m_Z| < 10$ GeV, where m_Z is the nominal Z boson mass. Each event in this sample must have exactly one additional object $\ell_{\text{candidate}}$ that passes relaxed identification requirements with no isolation requirements applied. The misidentification probability for each lepton flavor is defined as a ratio of the number of candidates that pass the final isolation and identification requirements to the total number in the sample, measured in bins of lepton candidate p_T and η . The number of $Z + \ell_{\text{candidate}}$ events is corrected for contamination from WZ production, or ZZ production in which one lepton is not reconstructed. These events have a third genuine, isolated lepton that must be excluded from the misidentification probability calculation. The WZ contamination is suppressed by requiring the missing transverse energy E_T^{miss} to be below 25 GeV. The E_T^{miss} is defined as the magnitude of the missing transverse momentum vector $\vec{p}_T^{\text{miss}}$, the projection onto the plane transverse to the beams of the negative vector sum of the momenta of all reconstructed particles in the event. Additionally, the transverse mass $m_T \equiv \sqrt{(E_T^\ell + E_T^{\text{miss}})^2 - (\vec{p}_T^\ell + \vec{p}_T^{\text{miss}})^2}$ of $\ell_{\text{candidate}}$ and the missing transverse momentum vector is required to be less than 30 GeV. The residual contribution of WZ and ZZ events, which may be up to a few percent of the events with $\ell_{\text{candidate}}$ passing all selection criteria, is estimated

from simulation and subtracted.

To account for all sources of background events, two control samples are used to estimate the number of background events in the signal regions. Both are defined to contain events with a dilepton candidate satisfying all requirements (Z_1) and two additional lepton candidates $\ell'^+ \ell'^-$. In one control sample, enriched in WZ events, one ℓ' candidate is required to satisfy the full identification and isolation criteria and the other must fail the full criteria and instead satisfy only relaxed ones; in the other, enriched in Z+jets events, both ℓ' candidates must satisfy the relaxed criteria, but fail the full criteria. The additional leptons must have opposite charge and the same flavor ($e^\pm e^\mp, \mu^\pm \mu^\mp$). From this set of events, the expected number of background events in the signal region is obtained by scaling the number of observed $Z_1 + \ell'^+ \ell'^-$ events by the misidentification probability for each lepton failing the selection. Low-mass dileptons may be sufficiently collinear that their isolation cones overlap, and their misidentification probabilities are therefore correlated. To mitigate the effect of these correlations, only the control sample in which both additional leptons fail the full selection is used if $\Delta R(\ell'^+, \ell'^-) < 0.6$. The background contributions to the signal regions of $Z \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$ and $ZZ \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$ are summarized in Section 8.

7 Systematic uncertainties

Systematic uncertainties are summarized in Table 1. In both data and simulated event samples, trigger efficiencies are evaluated with a tag-and-probe technique. The ratio between data and simulation is applied to simulated events, and the size of the resulting change in expected yield is taken as the uncertainty for the determination of the trigger efficiency. This uncertainty is around 2% of the final estimated yield. For $Z \rightarrow e^+ e^- e^+ e^-$ events, the uncertainty increases to 4%.

Table 1: The contributions of each source of signal systematic uncertainty in the cross section measurements. The integrated luminosity uncertainty and the PDF and scale uncertainties are considered separately. All other uncertainties are added in quadrature into a single systematic uncertainty. Uncertainties that vary by decay channel are listed as a range.

Uncertainty	$Z \rightarrow 4\ell$	$ZZ \rightarrow 4\ell$
ID efficiency	2–6%	0.4–0.9%
Isolation efficiency	1–6%	0.3–1.1%
Trigger efficiency	2–4%	2%
MC statistics	1–2%	1%
Background	0.7–1.4%	0.7–2%
Pileup	0.4–0.8%	0.2%
PDF	1%	1%
QCD Scales	1%	1%
Integrated luminosity	2.7%	2.7%

The lepton identification and isolation efficiencies in simulation are corrected with scaling factors derived with a tag-and-probe method and applied as a function of lepton p_T and η . To estimate the uncertainties associated with the tag-and-probe technique, the total yield is re-computed with the scaling factors varied up and down by the tag-and-probe fit uncertainties. The uncertainties associated with the identification efficiency in the $ZZ \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$ ($Z \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$) signal regions are found to be 0.9% (6%) in the $4e$ final state, 0.7% (4%) in the $2e2\mu$ final state, and 0.4% (2%) in the 4μ final state. The corresponding uncertainties associated with the isolation efficiency are 1.1% (6%) in the $4e$ final state, 0.7% (3%) in the $2e2\mu$ final

state, and 0.3% (1%) in the 4μ final state. These uncertainties are higher for $Z \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ events because the leptons generally have lower p_T , and the samples used in the tag-and-probe method have fewer events and more contamination from nonprompt leptons in this low- p_T region.

Uncertainties due to the effect of factorization (μ_F) and renormalization (μ_R) scale choice on the $ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ acceptance are evaluated with POWHEG and MCFM by varying the scales up and down by a factor of two with respect to the default values $\mu_F = \mu_R = m_{ZZ}$. These variations are much smaller than 1% and are neglected. Parametric uncertainties (PDF+ α_s) are evaluated using the CT10 [32] and NNPDF3.0 sets and are found to be less than 1%. The largest difference between predictions from POWHEG and MCFM with different scales and PDF sets, 1.5%, is considered to be the theoretical uncertainty in the acceptance calculation. An additional theoretical uncertainty arises from scaling the POWHEG $q\bar{q} \rightarrow ZZ$ simulated sample from its NLO cross section to the NNLO prediction, and the MCFM $gg \rightarrow ZZ$ samples from their LO cross sections to the NLO predictions. The change in the acceptance corresponding to this scaling procedure is found to be 1.1%. All theoretical uncertainties are added in quadrature.

The largest uncertainty in the estimated background yield arises from differences in sample composition between the $Z + \ell$ control sample used to calculate the lepton misidentification probability and the $Z + \ell^+\ell^-$ control sample. A further uncertainty arises from the limited number of events in the $Z + \ell$ sample. A systematic uncertainty of 40% of the estimated background yield is applied to cover both effects. The size of this uncertainty varies by channel, but is less than 1% of the total expected yield.

The uncertainty in the integrated luminosity of the data sample is 2.7% [33].

8 Cross section measurements

The distributions of the four-lepton mass and the masses of the Z_1 and Z_2 candidates are shown in Fig. 1. The SM predictions include nonresonant ZZ predictions normalized using the NNLO cross section, production of the SM Higgs boson with mass 125 GeV [34], and resonant $Z \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ production. The background estimated from data is also shown. The reconstructed invariant mass of the Z_1 candidates, and a scatter plot showing the correlation between m_{Z_2} and m_{Z_1} in data events, are shown in Fig. 2. In the scatter plot, clusters of events corresponding to $ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-$, $Z\gamma^* \rightarrow \ell^+\ell^-\ell'^+\ell'^-$, and $Z \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ production can be seen.

The four-lepton invariant mass distribution below 110 GeV is shown in Fig. 3 (left). Figure 3 (right) shows m_{Z_2} plotted against m_{Z_1} for events with $m_{\ell^+\ell^-\ell'^+\ell'^-}$ between 80 and 100 GeV, and the observed and expected event yields in this mass region are given in Table 2.

Table 2: The observed and expected yields of four-lepton events in the mass region $80 < m_{\ell^+\ell^-\ell'^+\ell'^-} < 100$ GeV and estimated yields of background events evaluated from data, shown for each final state and summed in the total expected yield. The first uncertainty is statistical, the second one is systematic.

Final state	Expected $N_{\ell^+\ell^-\ell'^+\ell'^-}$	Background	Total expected	Observed
4μ	$16.88 \pm 0.14 \pm 0.62$	$0.31 \pm 0.30 \pm 0.12$	$17.19 \pm 0.33 \pm 0.63$	17
$2e2\mu$	$15.88 \pm 0.14 \pm 0.87$	$0.37 \pm 0.27 \pm 0.15$	$16.25 \pm 0.31 \pm 0.88$	16
$4e$	$5.58 \pm 0.08 \pm 0.53$	$0.21 \pm 0.10 \pm 0.08$	$5.78 \pm 0.13 \pm 0.53$	6
Total	$38.33 \pm 0.21 \pm 1.19$	$0.89 \pm 0.42 \pm 0.22$	$39.22 \pm 0.47 \pm 1.21$	39

The reconstructed four-lepton invariant mass is shown in Fig. 4 (left) for events with two on-

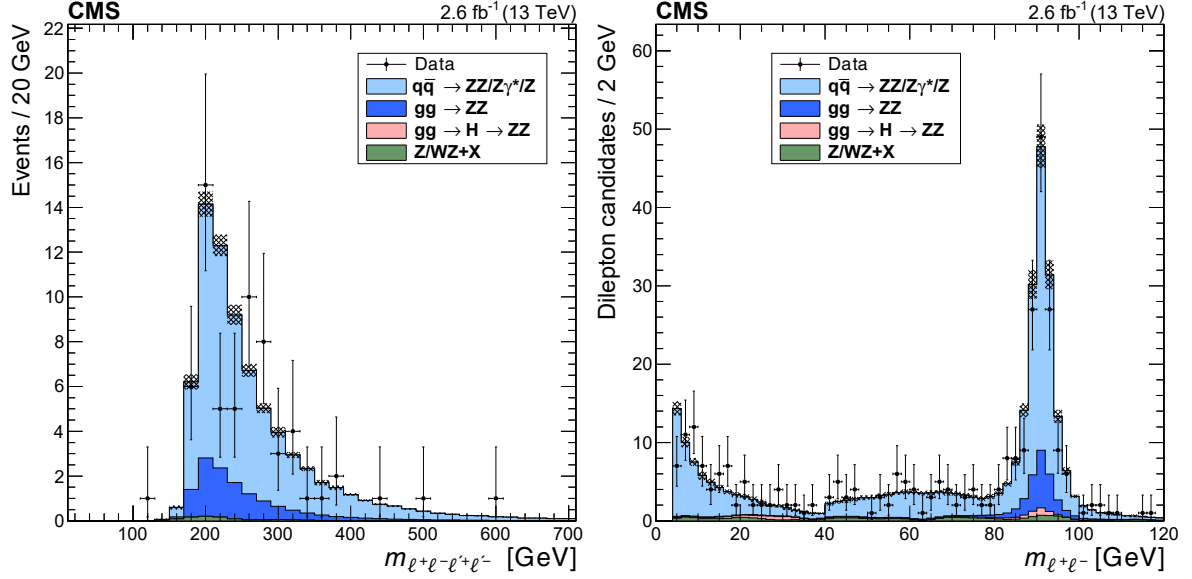


Figure 1: Distributions of (left) the four-lepton invariant mass $m_{\ell+\ell-\ell'+\ell'-}$ and (right) the invariant mass of the dilepton candidates in all selected four-lepton events, including both Z_1 and Z_2 in each event. Points represent the data, while shaded histograms represent the SM prediction and background estimate. Hatched regions around the predicted yield represent combined statistical, systematic, theoretical, and integrated luminosity uncertainties.

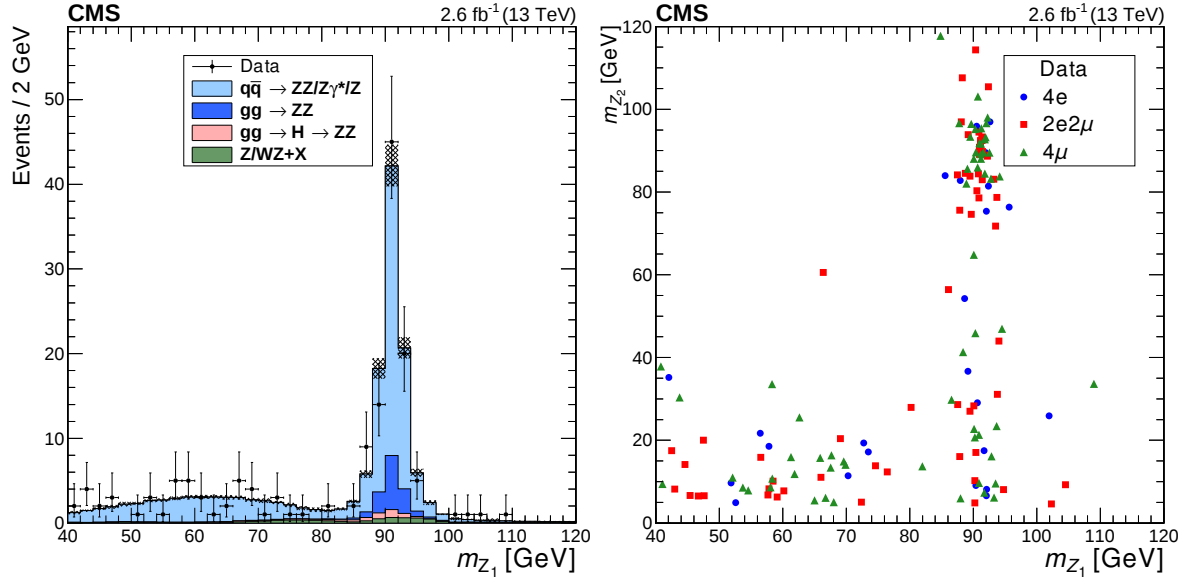


Figure 2: (left) The distribution of the reconstructed mass of the Z_1 candidate. Points represent the data, while shaded histograms represent the SM prediction and background estimate. Hatched regions around the predicted yield represent combined statistical, systematic, theoretical, and integrated luminosity uncertainties. (right) The reconstructed m_{Z_2} plotted against the reconstructed m_{Z_1} in data events, with distinctive markers for each final state.

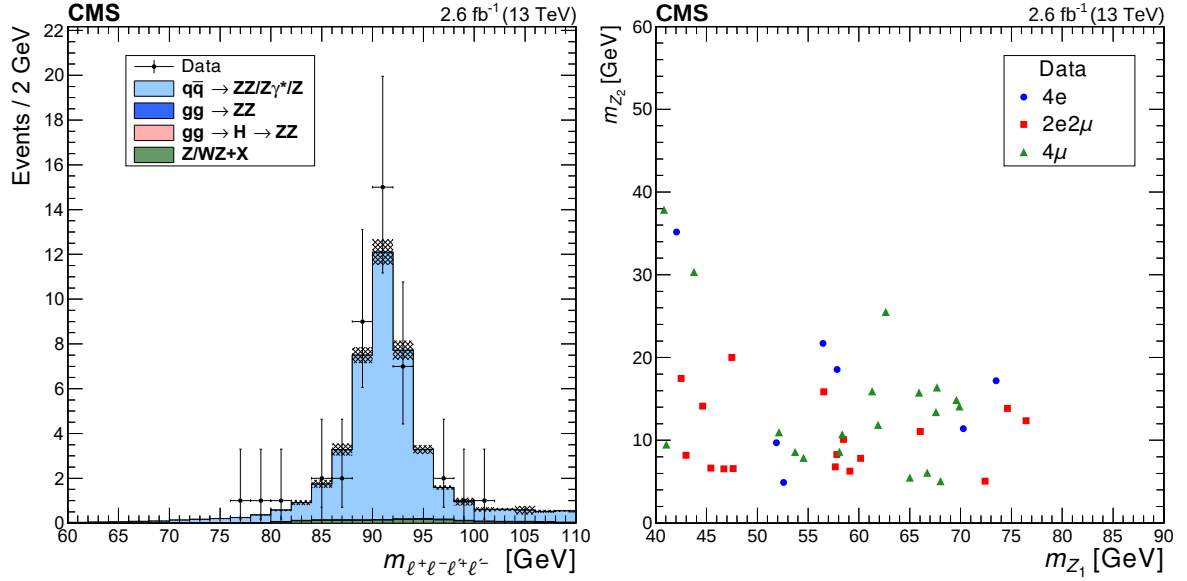


Figure 3: (left) The distribution of the reconstructed four-lepton mass $m_{\ell^+\ell^-\ell'^+\ell'^-}$ for events selected with $m_{\ell^+\ell^-\ell'^+\ell'^-} < 110$ GeV. Points represent the data, while shaded histograms represent the SM prediction and background estimate. Hatched regions around the predicted yield represent combined statistical, systematic, theoretical, and integrated luminosity uncertainties. (right) The reconstructed m_{Z_2} plotted against the reconstructed m_{Z_1} in data events selected with $m_{\ell^+\ell^-\ell'^+\ell'^-}$ between 80 and 100 GeV, with distinctive markers for each final state.

shell Z bosons. Figure 4 (right) shows the invariant mass distribution for all Z candidates in these events. The corresponding observed and expected yields are given in Table 3.

Table 3: The observed and expected yields of ZZ events, and estimated yields of background events evaluated from data, shown for each final state and summed in the total expected yield. The first uncertainty is statistical, the second one is systematic.

Final state	Expected $N_{\ell^+\ell^-\ell'^+\ell'^-}$	Background	Total expected	Observed
4μ	$21.80 \pm 0.15 \pm 0.46$	$0.00^{+0.24+0.10}_{-0.00-0.00}$	$21.80^{+0.28+0.47}_{-0.15-0.46}$	26
$2e2\mu$	$36.15 \pm 0.20 \pm 0.81$	$0.60 \pm 0.34 \pm 0.24$	$36.75 \pm 0.34 \pm 0.85$	30
$4e$	$14.87 \pm 0.12 \pm 0.36$	$0.81 \pm 0.26 \pm 0.33$	$15.68 \pm 0.26 \pm 0.48$	8
Total	$72.82 \pm 0.27 \pm 1.00$	$1.42^{+0.49+0.42}_{-0.43-0.41}$	$74.23^{+0.56+1.08}_{-0.45-1.08}$	64

The observed yields are used to evaluate the $pp \rightarrow Z \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ and $pp \rightarrow ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ production cross sections from a combined fit to the number of observed events in all the final states. The likelihood is a combination of individual channel likelihoods for the signal and background hypotheses with the statistical and systematic uncertainties in the form of scaling nuisance parameters. The ratio of the measured cross section to the SM cross section given by this fit including all channels is scaled by the cross section used in the simulation to find the measured fiducial cross section.

The definitions for the fiducial phase spaces for the $Z \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ and $ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ cross section measurements are given in Table 4.

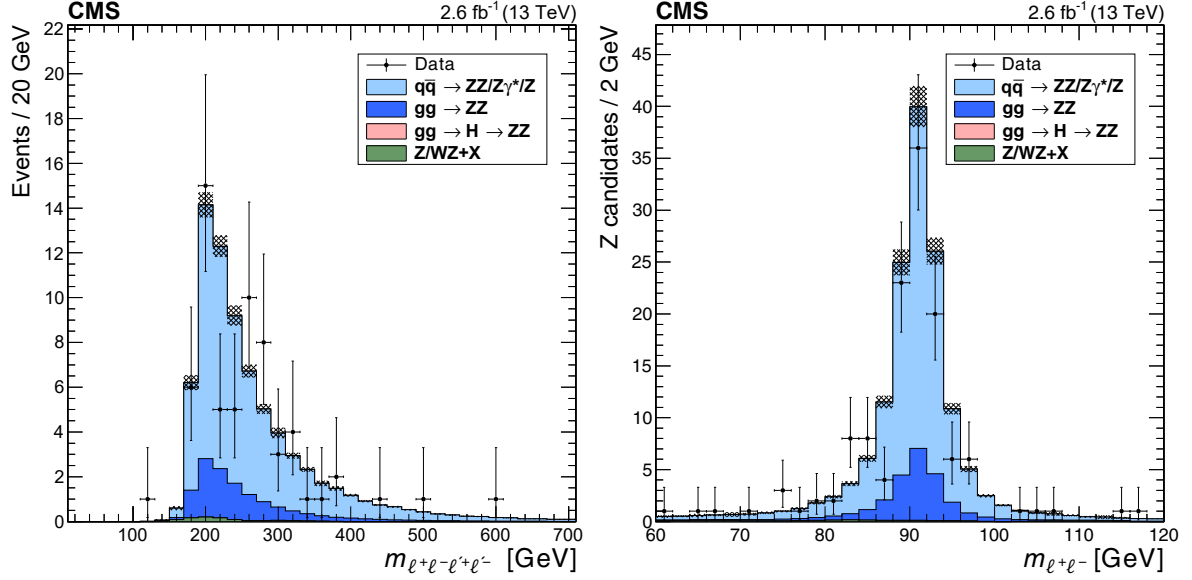


Figure 4: Distributions of (left) the four-lepton invariant mass $m_{\ell^+\ell^-\ell'^+\ell'^-}$ and (right) dilepton candidate mass for four-lepton events selected with both Z bosons on-shell. Points represent the data, while shaded histograms represent the SM prediction and background estimate. Hatched regions around the predicted yield represent combined statistical, systematic, theoretical, and integrated luminosity uncertainties.

Table 4: Fiducial definitions for the reported cross sections. The common requirements are applied for both measurements.

Cross section measurement	Fiducial requirements
Common requirements	$p_T^{\ell_1} > 20 \text{ GeV}$, $p_T^{\ell_2} > 10 \text{ GeV}$, $p_T^{\ell_{3,4}} > 5 \text{ GeV}$, $ \eta^\ell < 2.5$, $m_{\ell^+\ell^-} > 4 \text{ GeV}$ (any opposite-sign same-flavor pair)
$Z \rightarrow \ell^+\ell^-\ell'^+\ell'^-$	$m_{Z_1} > 40 \text{ GeV}$ $80 < m_{\ell^+\ell^-\ell'^+\ell'^-} < 100 \text{ GeV}$
$ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-$	$60 < m_{Z_1}, m_{Z_2} < 120 \text{ GeV}$

The measured cross sections are

$$\begin{aligned}\sigma_{\text{fid}}(\text{pp} \rightarrow \text{Z} \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-) &= 30.5^{+5.2}_{-4.7} (\text{stat})^{+1.8}_{-1.4} (\text{syst}) \pm 0.8 (\text{lumi}) \text{ fb}, \\ \sigma_{\text{fid}}(\text{pp} \rightarrow \text{ZZ} \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-) &= 34.8^{+4.6}_{-4.2} (\text{stat})^{+1.2}_{-0.8} (\text{syst}) \pm 0.9 (\text{lumi}) \text{ fb}.\end{aligned}$$

The $\text{pp} \rightarrow \text{Z} \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$ fiducial cross section can be compared to $27.9^{+1.0}_{-1.5} \pm 0.6 \text{ fb}$ calculated at NLO in QCD with POWHEG using the same settings as used for the simulated sample described in Section 3, with dynamic scales $\mu_F = \mu_R = m_{\ell^+ \ell^- \ell'^+ \ell'^-}$. The uncertainties are for scale and PDF variations, respectively. The ZZ fiducial cross section can be compared to $34.4^{+0.7}_{-0.6} \pm 0.5 \text{ fb}$ calculated with POWHEG and MCFM using the same settings as the simulated samples, with dynamic scales $\mu_F = \mu_R = 0.5 m_{\ell^+ \ell^- \ell'^+ \ell'^-}$ for the contribution from MCFM.

The $\text{pp} \rightarrow \text{Z} \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$ fiducial cross section is scaled to $\sigma(\text{pp} \rightarrow \text{Z})\mathcal{B}(\text{Z} \rightarrow 4\ell)$ using the acceptance correction factor $\mathcal{A} = 0.122 \pm 0.002$, estimated with POWHEG. This factor corrects the fiducial $\text{Z} \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$ cross section to the phase space with only the 80–100 GeV mass window and $m_{\ell^+ \ell^-} > 4 \text{ GeV}$ requirements, and also includes a correction, 0.96 ± 0.01 , for the contribution of nonresonant four-lepton production to the signal region. The measured cross section is

$$\sigma(\text{pp} \rightarrow \text{Z})\mathcal{B}(\text{Z} \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-) = 250^{+43}_{-39} (\text{stat})^{+15}_{-11} (\text{syst}) \pm 4 (\text{theo}) \pm 7 (\text{lumi}) \text{ fb}. \quad (2)$$

The branching fraction for the $\text{Z} \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$ decay, $\mathcal{B}(\text{Z} \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-)$, is measured by comparing the cross section given by Eq. (2) with the $\text{Z} \rightarrow \ell^+ \ell^-$ cross section, and is computed as

$$\mathcal{B}(\text{Z} \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-) = \frac{\sigma(\text{pp} \rightarrow \text{Z} \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-)}{\mathcal{C}_{80-100}^{60-120} \sigma(\text{pp} \rightarrow \text{Z} \rightarrow \ell^+ \ell^-) / \mathcal{B}(\text{Z} \rightarrow \ell^+ \ell^-)},$$

where $\sigma(\text{pp} \rightarrow \text{Z} \rightarrow \ell^+ \ell^-) = 1870^{+50}_{-40} \text{ pb}$ is the $\text{Z} \rightarrow \ell^+ \ell^-$ cross section times branching fraction calculated at NNLO with FEWZ v2.0 [35] in the mass range 60–120 GeV. Its uncertainty includes PDF uncertainties and uncertainties in α_s , the charm and bottom quark masses, and the effect of neglected higher-order corrections to the calculation. The factor $\mathcal{C}_{80-100}^{60-120} = 0.926 \pm 0.001$ corrects for the difference in Z mass windows and is estimated using POWHEG. Its uncertainty includes scale and PDF variations. The nominal Z to dilepton branching fraction $\mathcal{B}(\text{Z} \rightarrow \ell^+ \ell^-)$ is 0.03366 [36]. The measured value is

$$\mathcal{B}(\text{Z} \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-) = 4.9^{+0.8}_{-0.7} (\text{stat})^{+0.3}_{-0.2} (\text{syst})^{+0.2}_{-0.1} (\text{theo}) \pm 0.1 (\text{lumi}) \times 10^{-6},$$

where the theoretical uncertainty includes the uncertainties in $\mathcal{A}$, $\mathcal{C}_{80-100}^{60-120}$, and $\sigma(\text{pp} \rightarrow \text{Z})\mathcal{B}(\text{Z} \rightarrow \ell^+ \ell^-)$. This can be compared with 4.6×10^{-6} , computed with MADGRAPH5_AMC@NLO [37], and is consistent with the CMS and ATLAS measurements at $\sqrt{s} = 7$ and 8 TeV [9, 10].

The total ZZ production cross section for both dileptons produced in the mass range 60–120 GeV and $m_{\ell^+ \ell'^-} > 4 \text{ GeV}$ is found to be

$$\sigma(\text{pp} \rightarrow \text{ZZ}) = 14.6^{+1.9}_{-1.8} (\text{stat})^{+0.5}_{-0.3} (\text{syst}) \pm 0.2 (\text{theo}) \pm 0.4 (\text{lumi}) \text{ pb}.$$

The measured total cross section can be compared to the theoretical value of $14.5^{+0.5}_{-0.4} \pm 0.2 \text{ pb}$ calculated with a combination of POWHEG and MCFM with the same settings as described for $\sigma_{\text{fid}}(\text{pp} \rightarrow \text{ZZ} \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-)$. It can also be compared to $16.2^{+0.6}_{-0.4} \text{ pb}$, calculated at NNLO in QCD via MATRIX [1, 38], or $15.0^{+0.7}_{-0.6} \pm 0.2 \text{ pb}$, calculated with MCFM at NLO in QCD with additional contributions from LO $g g \rightarrow \text{ZZ}$ diagrams. Both values are calculated with the NNPDF3.0 PDF sets, at NNLO and NLO respectively, and fixed scales set to $\mu_F = \mu_R = m_Z$.

The total ZZ cross section is shown in Fig. 5 as a function of the proton-proton center-of-mass energy. Results from the CMS [2–4] and ATLAS [5–7] experiments are compared to predictions from MATRIX and MCFM with the NNPDF3.0 PDF sets and fixed scales $\mu_F = \mu_R = m_Z$. The MATRIX prediction uses PDFs calculated at NNLO, while the MCFM prediction uses NLO PDFs. The uncertainties are statistical (inner bars) and statistical and systematic added in quadrature (outer bars). The band around the MATRIX predictions reflects scale uncertainties, while the band around the MCFM predictions reflects both scale and PDF uncertainties. The theoretical predictions and all CMS measurements are performed in the dilepton mass range 60–120 GeV. All ATLAS measurements are in the mass window 66–116 GeV. The smaller mass window is estimated to cause a 1.6% reduction in the measured cross section.

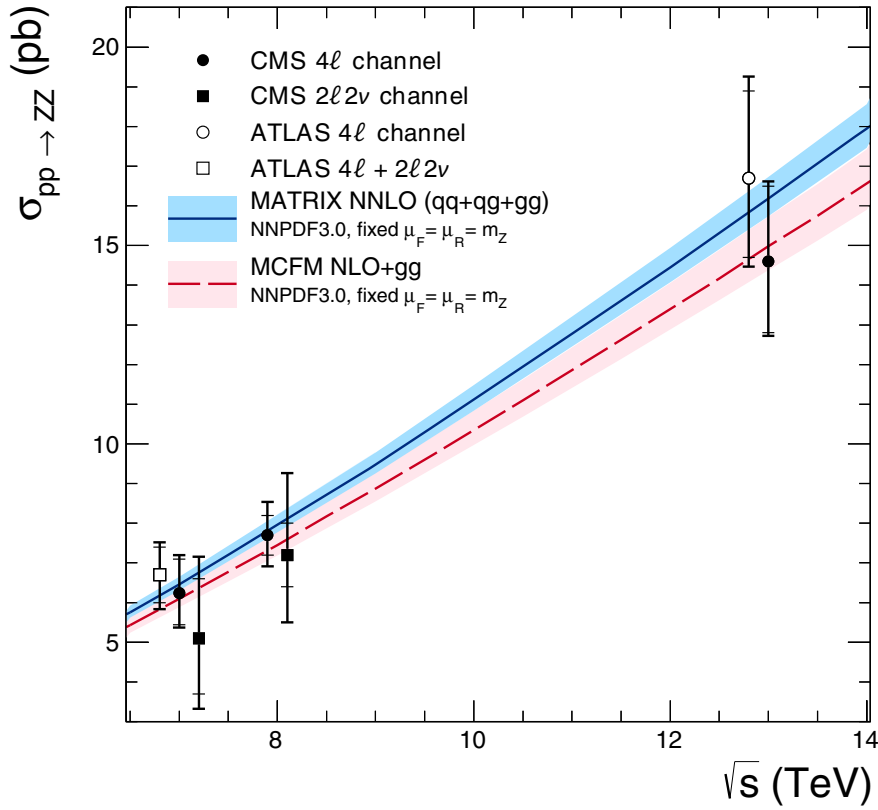


Figure 5: The total ZZ cross section as a function of the proton-proton center-of-mass energy. Results from the CMS and ATLAS experiments are compared to predictions from MATRIX and MCFM with NNPDF3.0 PDF sets and fixed scales $\mu_F = \mu_R = m_Z$. Details of the calculations and uncertainties are given in the text. Measurements at the same center-of-mass energy are shifted slightly along the x-axis for clarity.

9 Summary

Results have been presented for a study of four-lepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV with the CMS detector at the LHC. The $pp \rightarrow ZZ$ cross section has been measured to be $\sigma(pp \rightarrow ZZ) = 14.6^{+1.9}_{-1.8}(\text{stat})^{+0.5}_{-0.3}(\text{syst}) \pm 0.2(\text{theo}) \pm 0.4(\text{lumi})$ pb for Z boson masses in the range $60 < m_Z < 120$ GeV. The branching fraction for Z boson decays to four leptons has been measured to be $\mathcal{B}(Z \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-) = 4.9^{+0.8}_{-0.7}(\text{stat})^{+0.3}_{-0.2}(\text{syst})^{+0.2}_{-0.1}(\text{theo}) \pm 0.1(\text{lumi}) \times 10^{-6}$ for four-lepton mass in the range $80 < m_{\ell^+ \ell^- \ell'^+ \ell'^-} < 100$ GeV and dilepton mass $m_{\ell^+ \ell^-} >$

4 GeV for all oppositely charged same-flavor lepton pairs. The results are consistent with SM predictions.

Acknowledgments

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 centers 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, CINVESTAV, 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 program 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 program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program 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 Thalís and Aristeia programs 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.

References

- [1] F. Cascioli et al., “ZZ production at hadron colliders in NNLO QCD”, *Phys. Lett. B* **735** (2014) 311, doi:10.1016/j.physletb.2014.06.056, arXiv:1405.2219.

- [2] CMS Collaboration, “Measurement of the ZZ production cross section and search for anomalous couplings in $2\ell 2\ell'$ final states in pp collisions at $\sqrt{s} = 7$ TeV”, *JHEP* **01** (2013) 063, doi:10.1007/JHEP01(2013)063, arXiv:1211.4890.
- [3] CMS Collaboration, “Measurement of the $pp \rightarrow ZZ$ production cross section and constraints on anomalous triple gauge couplings in four-lepton final states at $\sqrt{s} = 8$ TeV”, *Phys. Lett. B* **740** (2015) 250, doi:10.1016/j.physletb.2016.04.010, arXiv:1406.0113. [Erratum: doi:10.1016/j.physletb.2014.11.059].
- [4] CMS Collaboration, “Measurements of the ZZ production cross sections in the $2\ell 2\nu$ channel in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV and combined constraints on triple gauge couplings”, *Eur. Phys. J. C* **75** (2015) 511, doi:10.1140/epjc/s10052-015-3706-0, arXiv:1503.05467.
- [5] ATLAS Collaboration, “Measurement of ZZ production in pp collisions at $\sqrt{s} = 7$ TeV and limits on anomalous ZZZ and $ZZ\gamma$ couplings with the ATLAS detector”, *JHEP* **03** (2013) 128, doi:10.1007/JHEP03(2013)128, arXiv:1211.6096.
- [6] ATLAS Collaboration, “Measurements of four-lepton production in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector”, *Phys. Lett. B* **753** (2016) 552, doi:10.1016/j.physletb.2015.12.048, arXiv:1509.07844.
- [7] ATLAS Collaboration, “Measurement of the ZZ Production Cross Section in pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector”, *Phys. Rev. Lett.* **116** (2016) 101801, doi:10.1103/PhysRevLett.116.101801, arXiv:1512.05314.
- [8] ALEPH Collaboration, “Study of the four fermion final state at the Z resonance”, *Z. Phys. C* **66** (1995) 3, doi:10.1007/BF01496576.
- [9] CMS Collaboration, “Observation of Z decays to four leptons with the CMS detector at the LHC”, *JHEP* **12** (2012) 034, doi:10.1007/JHEP12(2012)034, arXiv:1210.3844.
- [10] ATLAS Collaboration, “Measurements of Four-Lepton Production at the Z Resonance in pp Collisions at $\sqrt{s} = 7$ and 8 TeV with ATLAS”, *Phys. Rev. Lett.* **112** (2014) 231806, doi:10.1103/PhysRevLett.112.231806, arXiv:1403.5657.
- [11] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [12] CMS Collaboration, “Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *JINST* **10** (2015) P06005, doi:10.1088/1748-0221/10/06/P06005, arXiv:1502.02701.
- [13] CMS Collaboration, “Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV”, *JINST* **7** (2012) P10002, doi:10.1088/1748-0221/7/10/P10002, arXiv:1206.4071.
- [14] S. Alioli, P. Nason, C. Oleari, and E. Re, “NLO vector-boson production matched with shower in POWHEG”, *JHEP* **07** (2008) 060, doi:10.1088/1126-6708/2008/07/060, arXiv:0805.4802.
- [15] P. Nason, “A new method for combining NLO QCD with shower Monte Carlo algorithms”, *JHEP* **11** (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.

- [16] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with parton shower simulations: the POWHEG method”, *JHEP* **11** (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.
- [17] J. M. Campbell and R. K. Ellis, “MCFM for the Tevatron and the LHC”, *Nucl. Phys. Proc. Suppl.* **205–206** (2010) 10, doi:10.1016/j.nuclphysbps.2010.08.011, arXiv:1007.3492.
- [18] F. Caola, K. Melnikov, R. Rötsch, and L. Tancredi, “QCD corrections to ZZ production in gluon fusion at the LHC”, *Phys. Rev. D* **92** (2015) 094028, doi:10.1103/PhysRevD.92.094028, arXiv:1509.06734.
- [19] Y. Gao et al., “Spin determination of single-produced resonances at hadron colliders”, *Phys. Rev. D* **81** (2010) 075022, doi:10.1103/PhysRevD.81.075022, arXiv:1001.3396.
- [20] S. Bolognesi et al., “On the spin and parity of a single-produced resonance at the LHC”, *Phys. Rev. D* **86** (2012) 095031, doi:10.1103/PhysRevD.86.095031, arXiv:1208.4018.
- [21] I. Anderson et al., “Constraining anomalous HVV interactions at proton and lepton colliders”, *Phys. Rev. D* **89** (2014) 035007, doi:10.1103/PhysRevD.89.035007, arXiv:1309.4819.
- [22] T. Sjöstrand, S. Mrenna, and P. Skands, “PYTHIA 6.4 physics and manual”, *JHEP* **05** (2006) 026, doi:10.1088/1126-6708/2006/05/026, arXiv:hep-ph/0603175.
- [23] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
- [24] S. Alioli, P. Nason, C. Oleari, and E. Re, “A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX”, *JHEP* **06** (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.
- [25] CMS Collaboration, “Event generator tunes obtained from underlying event and multiparton scattering measurements”, *Eur. Phys. J. C* **76** (2016) 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.
- [26] NNPDF Collaboration, “Parton distributions for the LHC Run II”, *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.
- [27] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [28] CMS Collaboration, “Particle-Flow Event Reconstruction in CMS and Performance for Jets, Taus, and E_T^{miss} ”, CMS Physics Analysis Summary CMS-PAS-PFT-09-001, 2009.
- [29] CMS Collaboration, “Commissioning of the Particle-flow Event Reconstruction with the first LHC collisions recorded in the CMS detector”, CMS Physics Analysis Summary CMS-PAS-PFT-10-001, 2010.
- [30] M. Cacciari and G. P. Salam, “Pileup subtraction using jet areas”, *Phys. Lett. B* **659** (2008) 119, doi:10.1016/j.physletb.2007.09.077, arXiv:0707.1378.

- [31] CMS Collaboration, “Measurement of the Inclusive W and Z Production Cross Sections in pp Collisions at $\sqrt{s} = 7$ TeV”, *JHEP* **10** (2011) 132, doi:10.1007/JHEP10(2011)132, arXiv:1107.4789.
- [32] H.-L. Lai et al., “New parton distributions for collider physics”, *Phys. Rev. D* **82** (2010) 074024, doi:10.1103/PhysRevD.82.074024, arXiv:1007.2241.
- [33] CMS Collaboration, “CMS Luminosity Measurement for the 2015 Data Taking Period”, Technical Report CMS-PAS-LUM-15-001, CERN, 2016.
- [34] ATLAS and CMS Collaborations, “Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments”, *Phys. Rev. Lett.* **114** (2015) 191803, doi:10.1103/PhysRevLett.114.191803, arXiv:1503.07589.
- [35] R. Gavin, Y. Li, F. Petriello, and S. Quackenbush, “FEWZ 2.0: A code for hadronic Z production at next-to-next-to-leading order”, *Comput. Phys. Commun.* **182** (2011) 2388, doi:10.1016/j.cpc.2011.06.008, arXiv:1011.3540.
- [36] Particle Data Group, K. A. Olive et al., “Review of particle physics”, *Chin. Phys. C* **38** (2014) 090001, doi:10.1088/1674-1137/38/9/090001.
- [37] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.
- [38] M. Grazzini, S. Kallweit, and D. Rathlev, “ZZ production at the LHC: fiducial cross sections and distributions in NNLO QCD”, *Phys. Lett. B* **750** (2015) 407, doi:10.1016/j.physletb.2015.09.055, arXiv:1507.06257.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

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

Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth¹, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler¹, A. König, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabadý, N. Rad, B. Rahbaran, H. Rohringer, J. Schieck¹, J. Strauss, W. Treberer-Treberspur, W. Waltenberger, C.-E. Wulz¹

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

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

Universiteit Antwerpen, Antwerpen, Belgium

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

Vrije Universiteit Brussel, Brussel, 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

Université Libre de Bruxelles, Bruxelles, 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. Zhang²

Ghent University, Ghent, 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

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

H. Bakhshiansohi, C. Beluffi³, 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. Piotrkowski, L. Quertenmont, M. Selvaggi, M. Vidal Marono, S. Wertz

Université de Mons, Mons, Belgium

N. Bely

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

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

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

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato⁴, A. Custódio, E.M. Da Costa, G.G. Da Silveira⁵, 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 Manganote⁴, A. Vilela Pereira

Universidade Estadual Paulista ^a, Universidade Federal do ABC ^b, São Paulo, 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

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

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

University of Sofia, Sofia, Bulgaria

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

Beihang University, Beijing, China

W. Fang⁶

Institute of High Energy Physics, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen⁷, 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

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

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

Universidad de Los Andes, Bogota, Colombia

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

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

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

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

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

Charles University, Prague, Czech Republic

M. Finger⁸, M. Finger Jr.⁸

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

A. Ellithi Kamel⁹, M.A. Mahmoud^{10,11}, A. Radi^{11,12}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

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

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, 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

Lappeenranta University of Technology, Lappeenranta, Finland

J. Talvitie, T. Tuuva

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

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

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

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

J.-L. Agram¹³, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte¹³, X. Coubez, J.-C. Fontaine¹³, D. Gelé, U. Goerlach, A.-C. Le Bihan, J.A. Merlin¹⁴, K. Skovpen, P. Van Hove

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

S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, 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. Popov¹⁵, D. Sabes, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret

Georgian Technical University, Tbilisi, Georgia

T. Toriashvili¹⁶

Tbilisi State University, Tbilisi, Georgia

Z. Tsamalaidze⁸

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

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. Zhukov¹⁵

RWTH Aachen University, III. Physikalisches Institut A, 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 B, 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. Stahl¹⁴

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A.A. Bin Anuar, K. Borras¹⁷, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez

Pardos, G. Dolinska, G. Eckerlin, D. Eckstein, E. Eren, E. Gallo¹⁸, J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, P. Gunnellini, A. Harb, J. Hauk, M. Hempel¹⁹, H. Jung, A. Kalogeropoulos, O. Karacheban¹⁹, M. Kasemann, J. Keaveney, J. Kieseler, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann¹⁹, 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

University of Hamburg, 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. Pantaleo¹⁴, 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

Institut für Experimentelle Kernphysik, Karlsruhe, 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. Hartmann¹⁴, S.M. Heindl, U. Husemann, I. Katkov¹⁵, 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

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

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

National and Kapodistrian University of Athens, Athens, Greece

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

University of Ioánnina, Ioánnina, Greece

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

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

N. Filipovic

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, P. Hidas, D. Horvath²⁰, F. Sikler, V. Veszpremi, G. Vesztergombi²¹, A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi²², A. Makovec, J. Molnar, Z. Szillasi

University of Debrecen, Debrecen, Hungary

M. Bartók²¹, P. Raics, Z.L. Trocsanyi, B. Ujvari

National Institute of Science Education and Research, Bhubaneswar, India

S. Bahinipati, S. Choudhury²³, P. Mal, K. Mandal, A. Nayak²⁴, D.K. Sahoo, N. Sahoo, S.K. Swain

Panjab University, Chandigarh, 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

University of Delhi, Delhi, 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

Saha Institute of Nuclear Physics, Kolkata, 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

Indian Institute of Technology Madras, Madras, India

P.K. Behera

Bhabha Atomic Research Centre, Mumbai, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty¹⁴, P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

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

S. Banerjee, S. Bhowmik²⁵, R.K. Dewanjee, S. Ganguly, M. Guchait, Sa. Jain, S. Kumar, M. Maity²⁵, G. Majumder, K. Mazumdar, T. Sarkar²⁵, N. Wickramage²⁶

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

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

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

H. Behnamian, S. Chenarani²⁷, E. Eskandari Tadavani, S.M. Etesami²⁷, A. Fahim²⁸, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh²⁹, M. Zeinali

University College Dublin, Dublin, Ireland

M. Felcini, M. Grunewald

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

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

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

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

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

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera¹⁴

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

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

L. Brianza¹⁴, 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}

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

S. Buontempo^a, 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

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

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

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

INFN Sezione di Pisa ^a, Università di Pisa ^b, Scuola Normale Superiore di Pisa ^c, Pisa, 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

INFN Sezione di Roma ^a, Università di Roma ^b, Roma, 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}

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

N. Ampane^{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}

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

Kyungpook National University, Daegu, Korea

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

Chonbuk National University, Jeonju, Korea

A. Lee

Hanyang University, Seoul, Korea

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

Korea University, Seoul, 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

Seoul National University, Seoul, Korea

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

University of Seoul, Seoul, Korea

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

Sungkyunkwan University, Suwon, Korea

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

Vilnius University, Vilnius, Lithuania

V. Dudenas, A. Juodagalvis, J. Vaitkus

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

I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali³², F. Mohamad Idris³³, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz³⁴, A. Hernandez-Almada, R. Lopez-Fernandez, R. Magaña Villalba, J. Mejia Guisao, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

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

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

A. Morelos Pineda

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

P.H. Butler

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

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

National Centre for Nuclear Research, Swierk, Poland

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

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

K. Bunkowski, A. Byszuk³⁵, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak

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

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. Vadrucio, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia

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

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

L. Chtchipounov, V. Golovtsov, Y. Ivanov, V. Kim³⁸, E. Kuznetsova³⁹, V. Murzin, V. Oreshkin, V. Sulimov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

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

Moscow Institute of Physics and Technology

A. Bylinkin³⁷

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

M. Chadeeva⁴⁰, E. Popova, E. Tarkovskii

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin³⁷, I. Dremin³⁷, M. Kirakosyan, A. Leonidov³⁷, S.V. Rusakov, A. Terkulov

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

A. Baskakov, A. Belyaev, E. Boos, M. Dubinin⁴¹, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia

V. Blinov⁴², Y. Skovpen⁴²

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

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

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

P. Adzic⁴³, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Milosevic, V. Rekovic

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

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

Universidad Autónoma de Madrid, Madrid, Spain

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

Universidad de Oviedo, Oviedo, Spain

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

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

CERN, European Organization for Nuclear Research, Geneva, Switzerland

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 Marco⁴⁴, 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. Kornmayer¹⁴, M.J. Kortelainen, K. Kousouris, M. Krammer¹, 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. Rolandi⁴⁵, M. Rovere, M. Ruan, H. Sakulin, J.B. Sauvan, C. Schäfer, C. Schwick, M. Seidel, A. Sharma, P. Silva, M. Simon, P. Sphicas⁴⁶, J. Steggemann, M. Stoye, Y. Takahashi, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckals⁴⁷, G.I. Veres²¹, N. Wardle, A. Zagozdinska³⁵, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

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

Institute for Particle Physics, ETH Zurich, Zurich, 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. Starodumov⁴⁸, V.R. Tavolaro, K. Theofilatos, R. Wallny

Universität Zürich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler⁴⁹, L. Caminada, M.F. Canelli, 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

National Central University, Chung-Li, Taiwan

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 Taiwan University (NTU), Taipei, 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

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

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

Cukurova University, Adana, Turkey

A. Adiguzel, S. Cerci⁵⁰, S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal⁵¹, O. Kara, U. Kiminsu, M. Oglakci, G. Onengut⁵², K. Ozdemir⁵³, D. Sunar Cerci⁵⁰, B. Tali⁵⁰, H. Topakli⁵⁴, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

B. Bilin, S. Bilmis, B. Isildak⁵⁵, G. Karapinar⁵⁶, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

E. Gülmez, M. Kaya⁵⁷, O. Kaya⁵⁸, E.A. Yetkin⁵⁹, T. Yetkin⁶⁰

Istanbul Technical University, Istanbul, Turkey

A. Cakir, K. Cankocak, S. Sen⁶¹

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

B. Grynyov

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

L. Levchuk, P. Sorokin

University of Bristol, Bristol, United Kingdom

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. Newbold⁶², S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev⁶³, 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

Imperial College, London, 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. Lucas⁶², L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, J. Nash, A. Nikitenko⁴⁸, J. Pela, B. Penning,

M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, C. Seez, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta⁶⁴, T. Virdee¹⁴, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, USA

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

The University of Alabama, Tuscaloosa, USA

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

Boston University, Boston, USA

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

Brown University, Providence, 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

University of California, Davis, Davis, 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, Los Angeles, USA

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

University of California, Riverside, Riverside, 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, San Diego, La Jolla, 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. Wasserbaech⁶⁵, C. Welke, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara, Santa Barbara, 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

California Institute of Technology, Pasadena, 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

Carnegie Mellon University, Pittsburgh, USA

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

University of Colorado Boulder, Boulder, USA

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

Cornell University, Ithaca, 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

Fairfield University, Fairfield, USA

D. Winn

Fermi National Accelerator Laboratory, Batavia, 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

University of Florida, Gainesville, 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. Milenovic⁶⁶, G. Mitselmakher, D. Rank, L. Shchutska, D. Sperka, L. Thomas, J. Wang, S. Wang, J. Yelton

Florida International University, Miami, USA

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

Florida State University, Tallahassee, 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 Institute of Technology, Melbourne, USA

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi⁶⁷, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, 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

The University of Iowa, Iowa City, USA

B. Bilki⁶⁸, W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁶⁹, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok⁷⁰, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, 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

The University of Kansas, Lawrence, 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

Kansas State University, Manhattan, USA

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

Lawrence Livermore National Laboratory, Livermore, USA

F. Rebassoo, D. Wright

University of Maryland, College Park, 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

Massachusetts Institute of Technology, Cambridge, 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

University of Minnesota, Minneapolis, 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 Mississippi, Oxford, USA

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, 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

State University of New York at Buffalo, Buffalo, 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

Northeastern University, Boston, USA

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

Northwestern University, Evanston, 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

University of Notre Dame, Notre Dame, USA

N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³⁶, M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, N. Valls, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, 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

Princeton University, Princeton, USA

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

University of Puerto Rico, Mayaguez, USA

S. Malik

Purdue University, West Lafayette, 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 Calumet, Hammond, USA

N. Parashar, J. Stupak

Rice University, Houston, 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

University of Rochester, Rochester, 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

Rutgers, The State University of New Jersey, Piscataway, 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

University of Tennessee, Knoxville, USA

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

Texas A&M University, College Station, USA

O. Bouhali⁷¹, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, E. Juska, T. Kamon⁷², R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Rose, A. Safonov, A. Tatarinov, K.A. Ulmer

Texas Tech University, Lubbock, USA

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

Vanderbilt University, Nashville, 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

University of Virginia, Charlottesville, 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

Wayne State University, Detroit, USA

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

University of Wisconsin - Madison, Madison, WI, 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

†: 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 Universidade Federal de Pelotas, Pelotas, Brazil
- 6: Also at Université Libre de Bruxelles, Bruxelles, Belgium
- 7: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- 8: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 9: Also at Cairo University, Cairo, Egypt
- 10: Also at Fayoum University, El-Fayoum, Egypt
- 11: Now 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 Adiyaman University, Adiyaman, Turkey
- 51: Also at Mersin University, Mersin, Turkey
- 52: Also at Cag University, Mersin, Turkey
- 53: Also at Piri Reis University, Istanbul, Turkey
- 54: Also at Gaziosmanpasa University, Tokat, 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