Observation of the $Z \rightarrow \psi \ell^+ \ell^-$ decay in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

This Letter presents the observation of the rare $Z$ boson decay $Z \rightarrow \psi \ell^+ \ell^-$. Here, $\psi$ represents contributions from direct $J/\psi$ and $\psi(2S) \rightarrow J/\psi X$, $\ell^+ \ell^-$ is a pair of electrons or muons, and the $J/\psi$ meson is detected via its decay to $\mu^+ \mu^-$. The sample of proton-proton collision data, collected by the CMS experiment at the LHC at a center-of-mass energy of 13 TeV, corresponds to an integrated luminosity of 35.9 fb$^{-1}$. The signal is observed with a significance in excess of 5 standard deviations. After subtraction of the $\psi(2S) \rightarrow J/\psi X$ contribution, the ratio of the branching fraction of the exclusive decay $Z \rightarrow J/\psi \ell^+ \ell^-$ to the decay $Z \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ within a fiducial phase space is measured to be $B(Z \rightarrow J/\psi \ell^+ \ell^-)/B(Z \rightarrow \mu^+ \mu^- \mu^+ \mu^-) = 0.67 \pm 0.18$ (stat) $\pm 0.05$ (syst).

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*See Appendix A for the list of collaboration members
Although the Z boson was discovered more than 30 years ago [11], only one exclusive decay channel with leptons, \( Z \rightarrow 4\ell \) [2–6], has been observed apart from the dilepton final states. In particular, for radiative dilepton decays, experiments have reported only upper limits on the branching fraction for \( Z \rightarrow \ell^+ \ell^- \gamma \), where \( \ell = e, \mu \) [7–9]. No resonant structure in the four-lepton decay has yet been observed. The high rate of Z boson production at the CERN LHC facilitates the study of rare decay channels such as \( Z \rightarrow V\gamma \), \( Z \rightarrow V\ell^+ \ell^- \), and \( Z \rightarrow VV \), where \( V \) is a vector meson with \( J^{PC} = 1^{--} \). In this paper, we present the observation of the decay of the Z boson to a final state with a \( J/\psi \) meson and two oppositely charged same-flavor leptons.

The \( Z \rightarrow V\ell^+ \ell^- \) process has been described and studied in various theoretical papers [10–16]. For the case where \( V = J/\psi \), the branching fraction \( B(Z \rightarrow J/\psi \ell^+ \ell^-) \) is calculable within the standard model. The dominant diagram is the quantum electrodynamics radiative process illustrated in Fig. 1 with the \( \gamma^* - V \) transition strength derived from the measured \( V \rightarrow \ell^+ \ell^- \) electromagnetic decays [17]. The theoretical estimates of the branching fraction cover the range \( (6.7–7.7) \times 10^{-7} \) [10, 11]. Although this branching fraction is small, the dileptons and vector meson in the final state offer a clean signature. The measurement of this branching fraction is valuable for the calculation of the fragmentation function for a virtual photon to split into a \( J/\psi \) meson. Rare Higgs boson decays, such as those to quarkonia [18, 19], will become accessible in the future, making it possible to search for non-standard model signatures in these decays, including, e.g., anomalous couplings or new exotic light states [20]. Accurate knowledge of potential backgrounds from Z decays to quarkonia will be essential for these measurements.

![Figure 1: Feynman diagram for the dominant production process and leading-order decay of the \( Z \rightarrow J/\psi \ell^+ \ell^- \).](image)

This analysis uses proton-proton (pp) collision data recorded by the CMS experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 35.9 fb\(^{-1}\). We report the observation of the \( Z \rightarrow \psi \ell^+ \ell^- \) decay channel, where \( \psi \) represents the contributions from direct \( J/\psi \) and \( J/\psi \) mesons from \( \psi(2S) \) decays, and the \( J/\psi \) is detected via its \( \mu^+ \mu^- \) decay channel. We measure the ratio of the branching fraction of this decay to that of the \( Z \rightarrow \mu^+ \mu^- \mu^+ \mu^- \) decay, to take advantage of a partial cancellation of systematic uncertainties.

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator...
hadron calorimeter, each composed of a barrel and two endcap sections. Muons are detected in
gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid, in
the pseudorapidity range $|\eta| < 2.4$ [21]. Electrons are reconstructed using information from
the ECAL and the tracker, in the $|\eta| < 2.5$ range [22]. A more 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. [23].

Events of the $Z \rightarrow \mu^+\mu^-\mu^+\mu^-$ process are simulated with the next-to-leading-order
Monte Carlo (MC) generator POWHEG [24], interfaced with PYTHIA 8.175 [25] [26] with parameters set
by the CUETP8M1 tune [27] for parton showering, hadronization, and the underlying event.
The parton distribution functions are taken from the NNPDF 3.0 [28] set. For the $Z \rightarrow J/\psi \ell^+\ell^-$
signal we use PYTHIA 8.175 (same tune as for $Z \rightarrow \mu^+\mu^-\mu^+\mu^-$) to simulate the production of Z
bosons, with an unpolarized phase-space model for the $Z \rightarrow J/\psi \ell^+\ell^-$ decay. Matrix-element
effects are evaluated by comparison with data and treated as systematic uncertainties. The
detector response is simulated with a model of the CMS detector implemented in the GEANT4
package [29]. We measure the fiducial branching fraction restricted to a region of phase space
covered by the acceptance of the measurement, as described below.

The trigger and offline selection criteria closely follow the previous CMS analysis of $Z \rightarrow 4\ell$
decays [24]. Triggers requiring one, two, or three charged leptons, with varying $p_T$ require-
ments, are used. The combined efficiency of the triggers, within the acceptance of this analysis
defined below, is greater than 99%.

Among the multiple pp collisions within the time resolution of the data acquisition, the primary
vertex is taken to be the reconstructed vertex with the largest sum of $p_T^2$ over the physics objects
in the event. These objects include the jets, clustered using the jet finding algorithm [30] [31],
with the tracks assigned to the vertex as inputs, and the associated missing transverse momen-
tum, taken as the negative vector sum of the $p_T$ of those jets. The primary vertex is required
to lie within 24 cm of the center of the detector along the beam axis and 2 cm perpendicular
to that axis. Charged particle tracks associated with vertices other than the primary vertex are
ignored.

We require all lepton candidate trajectories to pass within 1 (0.5) cm of the primary vertex in the
direction along (perpendicular to) the beam axis. The lepton candidates from Z boson decay are
required to be isolated from the hadronic activity in the event. To satisfy this requirement, the
scalar sum of transverse energy deposits in the calorimeters and the $p_T$ of tracks is computed
in a cone of radius $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ in $\eta-\phi$ around the lepton trajectory, where $\phi$ is
the azimuthal angle in radians. The sum is corrected for other leptons from Z boson decay that
fall within the isolation cone and for the average hadronic activity in an event. The ratio of this
corrected sum to the lepton $p_T$ is required to be smaller than 0.35. Leptons are required to be
separated by $\Delta R > 0.02$ (0.05) for same- (different-) flavor pairs.

We select events with two oppositely charged reconstructed muons consistent with the dimuon
decay of a $J/\psi$ meson that, in combination with two additional oppositely charged electrons or
muons (prompt leptons, $\ell$), is consistent with the decay $Z \rightarrow J/\psi \ell^+\ell^-$. Specifically, the invariant
mass of the $\psi$ muon pair must satisfy $2.6 < m_{\mu^+\mu^-} < 3.6$ GeV and that of the four leptons must satisfy
$|m_{\mu^+\mu^-\ell^+\ell^-} - m_Z| < 25$ GeV, where $m_Z = 91.2$ GeV [17]. Each of the muons from $J/\psi$
decay are required to have $p_T > 3.5$ GeV and $|\eta| < 2.4$, and the $p_T$ of the $J/\psi$ candidate must exceed
8.5 GeV. We require the highest- and second-highest-$p_T$ prompt leptons to have $p_T > 30$
and 15 GeV, respectively, satisfy $|\eta| < 2.5$ (2.4) for $\ell = e$ ($\mu$), and have a dilepton invariant mass
$m_{\ell^+\ell^-} < 80$ GeV. The lepton $p_T$ thresholds ensure high trigger efficiency, and the invariant mass
requirement suppresses the background from events in which a dilepton from $Z$ boson decay
is combined with a dimuon from an uncorrelated J/$\psi$ decay or a nonresonant muon pair.

The four leptons, and separately the two muons from the J/$\psi$ decay, are fitted to common vertices, with each vertex fit required to have a $\chi^2$ probability greater than 5%. The significance of the three-dimensional impact parameter relative to the primary vertex is required to satisfy $|d_{IP}/\sigma_{IP}| < 4$ for each lepton, where $d_{IP}$ is the distance of closest approach of the lepton track to the event vertex and $\sigma_{IP}$ is the associated uncertainty.

Following the application of the selection criteria described above, 29 (18) events remain in the $\psi \mu^+\mu^-$ ($\psi e^+e^-$) sample. Figure 2 shows a two-dimensional plot of the $\mu^+\mu^-$ versus $\mu^+\mu^-\ell^+\ell^-$ invariant masses for the candidate events. The signal appears as a concentration of events in the overlap region of the J/$\psi$ meson and Z boson masses. The events outside the central cluster along the Z boson mass band indicate contributions from the $Z \rightarrow (\text{continuum } \mu^+\mu^-)\ell^+\ell^-$ decay, and along the J/$\psi$ meson mass band, nonresonant $J/\psi \ell^+\ell^-$ production.

Figure 2: Distribution of invariant masses $m_{\mu^+\mu^-}$ vs. $m_{\mu^+\mu^-\ell^+\ell^-}$ for the selected candidates. The values in the legend give the numbers of candidates per bin.

We measure the branching fraction of the $Z \rightarrow \psi \ell^+\ell^-$ decay mode relative to that of $Z \rightarrow \mu^+\mu^-\mu^+\mu^-$. The selection criteria for the $Z \rightarrow \mu^+\mu^-\mu^+\mu^-$ events are the same as for the signal events, except that the vertex and $p_T$ requirements specific to the J/$\psi$ meson are removed, and the required mass ranges of the two oppositely charged muon pairs become $4 \,(40) < m(\mu^+\mu^-) < 80 \text{ GeV}$, where the 40 GeV threshold applies to the pair with the larger invariant mass.

The signal yield is obtained from unbinned extended maximum-likelihood fits [32] of the distributions in the two invariant mass variables $m_{\mu^+\mu^-}$ and $m_{\mu^+\mu^-\ell^+\ell^-}$, separately for the dimuon and dielectron channels. The probability density function (pdf) is a sum of four terms, each of which is a yield parameter multiplying a component pdf of the form $f(m_{\mu^+\mu^-})g(m_{\mu^+\mu^-\ell^+\ell^-})$. 
Figure 3: Invariant mass distributions for the $\psi$ muon pairs (left) and for $\psi\ell^+\ell^-$ (right), for $Z \to \psi\mu^+\mu^-$ (upper) and $Z \to \psi e^+e^-$ (lower) candidates. In each histogram the data are represented by the points, with the vertical bars showing the statistical uncertainties, and the solid curve is the overall fit to the data. The shaded region corresponds to the signal yield, while the dashed lines are the $\psi$ meson signal from the Z boson background (left) and the Z boson signal from the $\psi$ meson background (right). The dotted line represents the combinatorial background.

The four terms account for the $Z \to \psi\ell^+\ell^-$ signal and the backgrounds from: $Z \to \ell^+\ell^-$ with nonresonant $\mu^+\mu^-$; nonresonant $J/\psi\ell^+\ell^-$; and nonresonant $\mu^+\mu^-\ell^+\ell^-$. The pdf for the $J/\psi \to \mu^+\mu^-$ invariant mass distribution is a Gaussian function of $m_{\mu^+\mu^-}$ with the mean fixed to the $J/\psi$ meson mass [17] and the width as a free parameter of the fit. The $Z \to \mu^+\mu^-\ell^+\ell^-$ pdf is a Breit–Wigner function of $m_{\mu^+\mu^-\ell^+\ell^-}$ with its central value and width fixed to the mass and width of the Z boson [17], convolved with a Gaussian function whose width is a free parameter. The pdfs for the continuum background in each dimension of the fit, representing backgrounds that are both peaking and nonpeaking in the orthogonal dimension, are exponential functions with free decay parameters. The projections in each variable are shown in Fig. 3 along with...
the pdf components resulting from the fits.

The yields resulting from the fit are 13.0 ± 3.9 events for the \( Z \rightarrow \psi \mu^+\mu^- \) mode and 11.2 ± 3.4 events for \( Z \rightarrow \psi e^+e^- \), where the uncertainties are statistical only. The yields of the two decay modes agree within uncertainties, as expected, since the reconstruction efficiencies of the prompt electrons and muons in this \( p_T \) range are similar. The \( Z \rightarrow \mu^+\mu^-\mu^+\mu^- \) reference signal is extracted with a separate extended unbinned maximum-likelihood fit to the \( m_{\mu^+\mu^-\mu^+\mu^-} \) distribution, using the same parametrization as for \( Z \rightarrow \psi e^+e^- \). The fit yields 250 ± 20 events.

We evaluate the signal significance for both \( \psi \mu^+\mu^- \) and \( \psi e^+e^- \) by generating random pseudo-experiments with dimuon and four-lepton invariant mass distributions drawn from the background-only pdf and then fitted with the background-only and signal-plus-background hypotheses. From the pseudo-experiments the likelihood ratio of the two hypotheses is calculated and compared with the likelihood ratio of the data. Taking into account the systematic uncertainties (discussed below), the background-only hypothesis is excluded at 4.0 and 4.3 standard deviations for \( \psi \mu^+\mu^- \) and \( \psi e^+e^- \), respectively. The combination of the two significances based on the Fisher formalism \[33\] results in the observation of the \( Z \rightarrow \psi \ell^+\ell^- \) decay mode with a significance of 5.7 standard deviations.

From the observed signal yield we compute a ratio of branching fractions defined over the fiducial phase space of the measurement defined in Table 1. The entries consist of the kinematical requirements of the event selection given above, plus the additional requirement \( m_{\ell^+\ell^-} > 40 \text{ GeV} \) for the \( Z \rightarrow \psi \ell^+\ell^- \) candidates, which is added to match the selection of the \( Z \rightarrow \mu^+\mu^-\mu^+\mu^- \) candidates and to avoid regions of the decay phase space in which the acceptance is steeply falling. This requirement removes 2 (0) events from the \( Z \rightarrow \psi e^+e^- \) \((Z \rightarrow \psi \mu^+\mu^-)\) sample, and 0.95 events from the fitted \( Z \rightarrow \psi e^+e^- \) yield. The ratio of the fiducial branching fractions for lepton flavor \( \ell \) is

\[
R_{\psi \ell^+\ell^-} = \frac{B(Z \rightarrow J/\psi \ell^+\ell^-)}{B(Z \rightarrow \mu^+\mu^-\mu^+\mu^-)} = \left( \frac{1}{2} \sum_{i=\mu,e} N_{Z \rightarrow J/\psi \ell_i^+\ell_i^-} \right) \frac{e_{Z \rightarrow \mu^+\mu^-\mu^+\mu^-}}{N_{Z \rightarrow \mu^+\mu^-\mu^+\mu^-}} \frac{1}{B(J/\psi \rightarrow \mu^+\mu^-)},
\]

where the branching fraction \( B(J/\psi \rightarrow \mu^+\mu^-) = (5.961 \pm 0.033)\% \) \[17\], \( N_{Z \rightarrow J/\psi \ell_i^+\ell_i^-} \) is the signal yield excluding the \( \psi(2S) \rightarrow J/\psi X \) contribution, and \( N_{Z \rightarrow \mu^+\mu^-\mu^+\mu^-} \) is the reference-channel yield. The experimental efficiencies to reconstruct events within the fiducial phase space are determined from simulation to be \( \epsilon_{Z \rightarrow J/\psi \mu^+\mu^-} = 81\% \), \( \epsilon_{Z \rightarrow J/\psi e^+e^-} = 80\% \), and \( \epsilon_{Z \rightarrow \mu^+\mu^-\mu^+\mu^-} = 81\% \).

Table 1: Definition of the fiducial phase space for the measurement of the ratio of branching fractions. Here, \( \ell \) refers to a prompt muon or electron from the signal decay, or to either of the two muons from the higher invariant-mass pair in the reference-channel decay, and \( \mu \) refers to a \( J/\psi \) daughter or a member of the lower invariant-mass pair in the reference-channel decay. The symbol \( \ell_1 (\ell_2) \) refers to the prompt lepton having the higher (lower) value of \( p_T \). The \( p_T^{J/\psi} \) threshold is applied to the signal and the \( m(\mu^+\mu^-) \) requirement to the reference channel.

| Fiducial requirement                                                                                                                                            |
|---------------------------------------------------------------------------------------------------------|
| 40 < \( m_{\ell^+\ell^-} \) < 80 GeV                                                               |
| \( \vert \eta(\text{electrons}) \vert < 2.5, \ \vert \eta(\text{muons}) \vert < 2.4 \)                |
| \( p_T(\ell_1, \ell_2, \mu, \mu) > (30, 15, 3.5, 3.5) \) GeV                                          |
| Signal: \( p_T^{J/\psi} > 8.5 \) GeV                                                                |
| Reference channel: \( 4 < m(\mu^+\mu^-) < 80 \) GeV                                               |

Calculated contributions from \( \psi(2S) \rightarrow J/\psi X \) decays, the dominant feed-down source of \( J/\psi \)
mesons, are subtracted from the signal yields, since the natural width of the Z boson does not allow the separation of the process \( \psi(2S) \rightarrow J/\psi X \) from direct \( J/\psi \) production. The predicted production ratio of \( Z \rightarrow \psi(2S) \ell^+ \ell^- \) to \( Z \rightarrow \psi(2S) \ell^+ \ell^- \) is 3.5 \( \pm \) 1.1. Taking into account the branching fraction of \( \psi(2S) \rightarrow J/\psi X \) \( \pm \) 17, the ratio of \( N (Z \rightarrow J/\psi \ell^+ \ell^-) \) to \( N (Z \rightarrow \psi(2S) \rightarrow J/\psi X \ell^+ \ell^-) \) is \( 5.7 \pm 0.1 \). Using this scale factor, we subtract 1.9 (1.7) events from the \( N_{Z \rightarrow \psi \mu^+ \mu^-} \) yield, considering them as \( J/\psi \) events from \( \psi(2S) \) meson decays.

Since the signal and reference-channel events are recorded with the same triggers, and the topologies are similar, many systematic uncertainties cancel in the ratio. The uncertainties \( \mathcal{R}_{J/\psi \ell^+ \ell^-} \) are shown for the two signal decay modes in columns 2 and 3 of Table 2 and are combined in quadrature as uncorrelated, unless stated otherwise, in column 4.

Systematic uncertainties arising from the choice of fit model are calculated by varying the pdfs used for the signal (Z and \( J/\psi \)) and combinatorial background. Substitution of a double-Gaussian function for the Z boson signal leads to differences in the signal yields of 0.02, 0.05, and 1.88 events in \( Z \rightarrow \psi \mu^+ \mu^- \), \( Z \rightarrow \psi e^+ e^- \), and \( Z \rightarrow \mu^+ \mu^- \), respectively. The corresponding changes from using a first-order polynomial instead of an exponential function for the \( Z \) boson combinatorial background are 0.9, 0.1, and 0.4 events.

A similar approach was followed for the \( J/\psi \) meson signal and background pdfs. The maximum difference observed in the signal yields resulting from the substitution of the sum of a double-Gaussian and a Crystal Ball \( \pm \) 34 function for the signal pdf is 0.6 events for the \( \psi \mu^+ \mu^- \) and 0.2 events for the \( \psi e^+ e^- \) final state. The background pdf was replaced by a first-order polynomial to estimate the background model uncertainty, where a difference of 0.2 events is found in both decay modes.

To measure the uncertainty from the fitting procedure, 1000 random pseudo-samples were generated with the number of events of each drawn from a Poisson distribution having a mean equal to the number of events observed in the data. The absolute value of the average deviation of the fit yields from the nominal yield is taken as the systematic uncertainty.

The reconstruction efficiencies of the muons from \( J/\psi \) decay and prompt leptons (electrons and muons) are checked with \( Z \rightarrow \mu^+ \mu^- \), \( Z \rightarrow e^+ e^- \), and \( J/\psi \rightarrow \mu^+ \mu^- \) decay data using the “tag-and-probe” method \( \pm \) 21 \( \pm \) 35, as functions of the lepton \( \eta \) and \( p_T \). To calculate the systematic uncertainty in \( \mathcal{R}_{J/\psi \ell^+ \ell^-} \), these efficiencies are varied within their uncertainty, with the uncertainties from the lepton efficiencies treated as correlated in the ratio. In addition, we assign an uncertainty associated with the finite number of MC signal and reference-channel events used to obtain the reconstruction efficiencies.

We test the three-body Z boson decay model implemented in the MC simulation by comparing distributions from the simulation with those from signal-weighted data, obtained from the fit model by the \( \chi \)Plot method \( \pm \) 36. The most sensitive observable was found to be the azimuthal separation between the \( J/\psi \) candidate and the highest- and second-highest-\( p_T \) prompt leptons. We apply the observed shape differences to the simulation and reevaluate the reconstruction efficiency to extract the decay model uncertainty.

The uncertainty in the fraction of \( J/\psi \) events that potentially originate from \( \psi(2S) \) is propagated from the uncertainty of the \( N (Z \rightarrow J/\psi \ell^+ \ell^-) \) to \( N (Z \rightarrow \psi(2S) \rightarrow J/\psi X \ell^+ \ell^-) \) ratio.

The total systematic uncertainty of 7.6\% for \( \mathcal{R}_{J/\psi \ell^+ \ell^-} \) is calculated by adding the sources of uncertainty given in the last column of Table 2 in quadrature.

After subtracting the \( \psi(2S) \) feed-down we extract from Eq. (1) the branching fraction ratio
Table 2: The contributions to the systematic uncertainty in the ratio of branching fractions for the prompt muon, prompt electron, and combined samples, in percent. The last row gives the sum in quadrature of all components.

| Source of uncertainty                  | $R_{J/\psi \ell^+\ell^-}$ | $R_{J/\psi e^+e^-}$ | $R_{J/\psi e^+e^-}$ |
|----------------------------------------|----------------------------|---------------------|---------------------|
| Z boson signal shape                   | 0.8                        | 0.8                 | 0.8                 |
| Z boson background shape               | 6.9                        | 0.5                 | 3.7                 |
| $J/\psi$ meson signal shape           | 4.8                        | 2.0                 | 2.8                 |
| $J/\psi$ meson background shape       | 1.5                        | 1.5                 | 1.1                 |
| Fit procedure                          | 3.0                        | 8.4                 | 4.2                 |
| Reconstruction efficiency              | 0.9                        | 5.9                 | 4.0                 |
| MC sample size                         | 0.7                        | 0.8                 | 0.5                 |
| Z boson decay model                    | 0.7                        | 1.6                 | 0.8                 |
| $\psi(2S)$ feed-down                   | 0.3                        | 0.3                 | 0.3                 |
| Total                                  | 9.2                        | 10.8                | 7.6                 |

$R_{J/\psi \ell^+\ell^-}$ for the phase-space region defined in Table 1

$R_{J/\psi \ell^+\ell^-} = 0.67 \pm 0.18 \text{ (stat)} \pm 0.05 \text{ (syst)}.$

Assuming that the factors applied to extrapolate the signal and reference-channel branching fractions from the phase space defined in Table 1 to the full phase space approximately cancel in the ratio, we use the measured value of $B(Z \rightarrow \mu^+\mu^-\mu^+\mu^-) = (1.20 \pm 0.08) \times 10^{-6}$ for $m(\mu^+\mu^-) > 4 \text{ GeV}$ to obtain an estimate for $B(Z \rightarrow J/\psi \ell^+\ell^-)$ of $8 \times 10^{-7}$. This result is consistent with standard model predictions of $(6.7 \pm 0.7) \times 10^{-7}$ and $7.7 \times 10^{-7}$.

The factors that extrapolate the fiducial measurements to the full phase space depend on the Z boson decay matrix element, which determines the angular distributions of the $\psi$ muons and prompt leptons. Computing those factors assuming that the $\psi$ is transversely or longitudinally polarized in the helicity frame ($\lambda_\psi = \pm 1$) leads to a full phase space branching fraction ratio that differs by less than 25% from the unpolarized result.

In summary, a new decay mode of the Z boson into a $\psi$ meson, where $\psi$ represents the contributions from direct $J/\psi$ and $\psi(2S) \rightarrow J/\psi X$, and an additional pair of leptons (muons or electrons), is observed with a statistical significance greater than 5 standard deviations. Using data from proton-proton collisions collected with the CMS detector at $\sqrt{s} = 13 \text{ TeV}$, corresponding to an integrated luminosity of 35.9 fb$^{-1}$, 13.0 $\pm$ 3.9 events of the $Z \rightarrow \psi \mu^+\mu^-$ and 11.2 $\pm$ 3.4 events of the $Z \rightarrow \psi e^+e^-$ decay are obtained. This is the first observed Z boson decay to a vector meson and two oppositely charged same-flavor leptons. The ratio of the branching fraction for this decay to the one for the reference channel $Z \rightarrow \mu^+\mu^-\mu^+\mu^-$ in the fiducial phase space of the measurement, as defined in Table 1 after subtracting the $\psi(2S)$ feed-down, is $R_{J/\psi \ell^+\ell^-} = 0.67 \pm 0.18 \text{ (stat)} \pm 0.05 \text{ (syst)}$. Using the known branching fraction for $Z \rightarrow \mu^+\mu^-\mu^+\mu^-$ results in a branching fraction for $Z \rightarrow J/\psi \ell^+\ell^-$ consistent with standard model predictions.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria
W. Adam, F. Ambroggi, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth¹, V.M. Ghete, J. Hrubec, M. Jeitler¹, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, H. Rohringer, J. Schieck¹, R. Schöfbeck, M. Spanring, D. Spitzbart, A. Taurok, W. Waltenberger, J. Wittmann, C.-E. Wulz¹, M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus
V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, M. Pieters, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium
S. Abu Zeid, F. Blekman, J. D’Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lovette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium
D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, A.K. Kalsi, T. Lenzi, J. Luetic, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, Q. Wang

Ghent University, Ghent, Belgium
T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov², D. Poyraz, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, G. Krintiras, V. Lemaître, A. Magitteri, A. Mertens, M. Musich, K. Piotrzkowski, A. Saggio, M. Vidal Marono, S. Wertz, J. Zobec

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
F.L. Alves, G.A. Alves, L. Brito, G. Correia Silva, 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. Chinellato³, E. Coelho, E.M. Da Costa, G.G. Da Silveira⁴, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote³, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista a, Universidade Federal do ABC b, São Paulo, Brazil
S. Ahuja⁵, C.A. Bernardes⁴, L. Calligaris⁴, T.R. Fernandez Perez Tomei⁵, E.M. Gregores⁵, P.G. Mercadante b, S.F. Novaes⁵, SandraS. Padula a, D. Romero Abad b

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia,
Bulgaria
A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria
A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China
W. Fang\textsuperscript{5}, X. Gao\textsuperscript{5}, L. Yuan

Institute of High Energy Physics, Beijing, China
M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Z. Xu

Tsinghua University, Beijing, China
Y. Wang

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
B. Courbon, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov\textsuperscript{6}, T. Susa

University of Cyprus, Nicosia, Cyprus
M.W. Ather, A. Attikis, M. Kolosova, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

Charles University, Prague, Czech Republic
M. Finger\textsuperscript{7}, M. Finger Jr.\textsuperscript{7}

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran\textsuperscript{8,9}, A. Mahrous\textsuperscript{10}, Y. Mohammed\textsuperscript{11}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken
Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland
T. Tuuva

IRFU, CEA, Université Paris-Saclay, GIF-sur-Yvette, France
M. Besançon, F. Coudert, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France
A. Abdulsalam, C. Amendola, I. Antropov, F. Beaudette, P. Busson, C. Charlot, R. Granier de Cassagnac, I. Kucher, S. Lisiak, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Pigard, R. Salerno, J.B. Sauvan, Y. Siros, A.G. Stahl Leiton, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram, J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, V. Cherepanov, C. Collard, E. Conte, J.-C. Fontaine, D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, 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, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov, V. Sordini, M. Vander Donckt, S. Viret, S. Zhang

Georgian Technical University, Tbilisi, Georgia
A. Khvedelidze

Tbilisi State University, Tbilisi, Georgia
Z. Tsamaladze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer, V. Zhukov

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
A. Albert, D. Duchardt, M. Endres, M. Erdmann, T. Esch, R. Fischer, S. Ghosh, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, H. Keller, S. Knutzen, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, A. Schmidt, D. Teyssier
RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
G. Flügge, O. Hlushchenko, B. Kargoll, T. Kress, A. Künsken, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, H. Sert, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, I. Babounikau, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borras, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, T. Eichhorn, A. Elwood, E. Eren, E. Gallo, A. Geiser, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, M. Haranko, A. Harb, J. Hauk, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, A. Lelek, T. Lenz, K. Lipka, W. Lohmann, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, V. Myronenko, S.K. Pfìltisch, D. Pitzl, A. Raspereza, M. Savitskyi, P. Saxena, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, N. Stefaniuk, H. Tholen, A. Vagnerini, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

University of Hamburg, Hamburg, Germany
R. Aggleton, S. Bein, L. Benato, A. Benecke, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, D. Marconi, J. Multhaup, M. Niedziela, D. Nowatschin, A. Perieanu, A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, D. Troendle, A. Vanhoefer, B. Vormwald

Karlsruher Institut fuer Technology
M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, N. Faltermann, B. Freund, M. Giffels, M.A. Harrendorf, F. Hartmann, S.M. Heindl, U. Husemann, F. Kassel, I. Katkov, S. Kudella, H. Mildner, S. Mitra, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrrmann, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki, I. Topsis-Giotis

National and Kapodistrian University of Athens, Athens, Greece
G. Karathanasis, S. Kesisoglou, P. Kontaxakis, A. Panagiotou, N. Saoulidou, E. Tziaferi, K. Vellidis

National Technical University of Athens, Athens, Greece
K. Kousouris, I. Papakrivopoulos, G. Tsiapolitis

University of Ioánina, Ioánina, Greece
I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Trianitis, D. Tsitsonis

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Óttvös Loránd University, Budapest, Hungary
M. Bartók, M. Csanad, N. Filipovic, P. Major, M.I. Nagy, G. Pasztor, O. Sura, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horvath, A. Hunyadi, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi
Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi, A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, Z.L. Töcsanyi, B. Ujvari

Indian Institute of Science (IISc), Bangalore, India
S. Choudhury, J.R. Komaragiri, P.C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, India
S. Bahinipati, C. Kar, P. Mal, K. Mandal, A. Nayak, D.K. Sahoo, S.K. Swain

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, A. Kaur, M. Kaur, S. Kaur, R. Kumar, P. Kumari, M. Lohan, A. Mehta, K. Sandeep, S. Sharma, J.B. Singh, G. Walia

University of Delhi, Delhi, India
A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, Ashok Kumar, S. Malhotra, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
R. Bhardwaj, M. Bharti, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep, D. Bhowmik, S. Dey, S. Dutta, S. Ghosh, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, B. Singh, 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, P.K. Netrakanti, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, B. Sutar, Ravindra Kumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Karmakar, S. Kumar, M. Maity, G. Majumder, K. Mazumdar, N. Sahoo, T. Sarkar

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani, E. Eskandari Tadavani, S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseini, B. Safarzadeh, M. Zeinali

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
M. Abbrescia, C. Calabria, A. Colaleo, D. Creanza, L. Cristella, N. De Filippis, M. De Palma, A. Di Florio, F. Errico, L. Fiore, A. Gelmi, G. Iaselli, S. Lezzi, G. Maggi, M. Maggi, G. Miniello, S. My, S. Nuzzo, A. Pompili, G. Pugliese, R. Radogna, A. Ranieri, G. Selvaggi, A. Sharma, L. Silvestris, R. Venditti, P. Verwilligen, G. Zito
INFN Sezione di Bologna, Università di Bologna, Bologna, Italy
G. Abbiendi, C. Battilana, B. Bonacorsi, L. Bordigoni, S. Braibant-Giacomelli, R. Campanini, P. Capiluppi, A. Castro, F.R. Cavallo, S.S. Chhibra, C. Ciocca, G. Codispoti, M. Cuffiani, G.M. Dallavalle, F. Fabbri, A. Fanfani, P. Giacomelli, C. Grandi, L. Guiducci, F. Iemmi, S. Marcellini, G. Masetti, A. Montanari, F.L. Navarria, A. Perrotta, F. Primavera, A.M. Rossi, T. Rovelli, G.P. Siroli, N. Tosi

INFN Sezione di Catania, Università di Catania, Catania, Italy
S. Albergo, A. Di Mattia, R. Potenza, A. Tricomi, C. Tuve

INFN Sezione di Firenze, Università di Firenze, Firenze, Italy
G. Barbaglia, K. Chatterjee, V. Ciulli, C. Civinini, R. D’Alessandro, E. Focardi, G. Latino, P. Lenzi, M. Meschini, S. Paoletti, L. Russo, G. Sguazzoni, D. Strom, L. Viliba

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

INFN Sezione di Genova, Università di Genova, Genova, Italy
F. Ferro, F. Ravera, E. Robutti, N. Tosi

INFN Sezione di Milano-Bicocca, Università di Milano-Bicocca, Milano, Italy
A. Benaglia, A. Beschi, B. Brianza, F. Brivio, V. Ciriolo, S. Di Guida, M.E. Dinardo, S. Fiorendi, S. Gennai, A. Ghezzi, P. Govoni, M. Malberti, S. Malvezzi, A. Massironi, D. Menasse, L. Moroni, M. Paganoni, D. Pedrini, S. Ragazzi, T. Tabarelli de Fatis

INFN Sezione di Napoli, Università di Napoli ‘Federico II’, Napoli, Italy, Università della Basilicata, Potenza, Italy, Università G. Marconi, Roma, Italy
S. Buontempo, N. Cavallo, A. Di Crescenzo, F. Fabozzi, F. Fienga, G. Galati, A.O.M. Iorio, W.A. Khan, L. Lista, S. Meola, P. Paolucci, C. Sciaccia, E. Voevodina

INFN Sezione di Padova, Università di Padova, Padova, Italy, Università di Trento, Trento, Italy
P. Azzi, N. Bacchetta, M. Bellato, A. Boletti, A. Bragagnolo, R. Carlin, P. Checchia, M. Dall’Osso, P. De Castro Manzano, T. Dorigo, U. Dosselli, F. Gasparini, U. Gasparini, A. Gozzelino, S. Lacaparra, P. Lujan, M. Marconi, A.T. Meneguzzo, N. Pozzobon, P. Ronchese, R. Rossin, F. Simonetto, A. Tiko, E. Torassa, M. Zanetti, P. Zotto

INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
A. Braghieri, A. Magnani, P. Montagna, S.P. Ratti, V. Re, M. Ressegotti, C. Riccardi, P. Salvini, I. Vai, P. Vitulà, P. Zanotti

INFN Sezione di Perugia, Università di Perugia, Perugia, Italy
L. Alunni Solestizi, M. Biasini, G.M. Bilei, C. Cecchi, D. Ciangottini, L. Fanò, P. Lariccia, E. Manoni, G. Mantovani, V. Mariani, M. Menichelli, A. Rossi, A. Santocchia, D. Spiga

INFN Sezione di Pisa, Università di Pisa, Scuola Normale Superiore di Pisa, Pisa, Italy
K. Androsov, P. Azzurri, G. Bagliesi, L. Bianchini, T. Boccali, L. Borrello, R. Castaldi, M.A. Ciocci, R. Dell’Orso, G. Fedi, F. Fiori, L. Giannini, A. Giassi, M.T. Grippo

INFN Sezione di Roma, Università di Roma ‘La Sapienza’, Roma, Italy
A. Arena, A. Cardini, A. De Filippo, A. Gardi, M. Gatti, F. Gatto, G. Giorgetti, A. Grandi, R. Guadagno, S. Guidi, M. Haro, G. Lazzaro, M. Longhi, S. Lupi, A. Malizia, S. Mazzanti, M. Nardelli, I. Nastasi, C. Nocera, L. Occhialini, M. Passarino, M. Passi, P. Pellegrini, O. Pistone, M. Polcari, S. Rauch, S. Riccaboni, L. Segre, D. Seminara, M. Tosi, G. Tosi, M. Tonello, E. Voevodina, L. Viliba, A. Viti, C. Vitulli, A. Zanetti
Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, M.C. Duran-Osuna, I. Heredia-De La Cruz, R. Lopez-Fernandez, J. Mejia Guisao, R.I. Rabadan-Trejo, G. Ramirez-Sanchez, R Reyes-Almanza, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
J. Eysermans, 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
S. Bheesette, P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, M.I. Asghar, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoib, M. Waqas

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, M. Szleper, P. Traczyk, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, 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, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Seixas, G. Strong, O. Toldaiev, D. Vadruccio, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
A. Golunov, I. Golutvin, V. Karjavin, V. Korenkov, G. Kozlov, A. Lanev, A. Malakhov, V. Matveev, V.V. Mitsyn, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, V. Smirnov, V. Trofimov, B.S. Yuldashev, A. Zarubin, V. Zhiltsov

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
V. Golovtsov, Y. Ivanov, V. Kim, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermeniev, 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. Gavrilov, N. Lyakhovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, V. Stolin, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev
National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI),
Moscow, Russia
R. Chistov, M. Danilov, P. Parygin, D. Philippov, S. Polikarpov, E. Tarkovskii

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, S.V. Rusakov, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Baskakov, A. Belyaev, E. Boos, M. Dubinin, 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. Blinov, T. Dimova, L. Kardapoltsev, D. Shtol, Y. Skovpen

State Research Center of Russian Federation, Institute for High Energy Physics of NRC “Kurchatov Institute”, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, A. Godizov, V. Kachanov, A. Kalinin, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, T. Troshin, N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia
A. Babaev, S. Baidali

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, A. Álvez Fernández, I. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, M.S. Soares, A. Triossi

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain
J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. Gonzalez Fernández, E. Palencia Cortezon, V. Rodríguez Bouza, S. Sanchez Cruz, P. Vischia, J.M. Vizan García

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, J. García-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, B. Akgun, E. Auffray, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Boci, C. Botta, T. Camporesi, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, G. Cucciati, D. d’Enterria, A. Dabrowski, V. Daponte, A. David, A. De Roeck, N. Deelen, M. Dobson,
T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita, D. Fasanella, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, M. Guibaud, D. Gulhan, J. Hegeman, V. Innocente, A. Jafari, P. Janot, O. Karacheban, J. Kieseler, A. Kornmayer, C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, F. Meijers, J. A. Merlin, S. Mersi, E. Meschi, P. Milenovic, F. Moortgat, M. Mulders, J. Ngadiuba, S. Orfanelli, L. Orsini, F. Pantaleo, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F. M. Pitters, D. Rabady, A. Racz, T. Reis, G. Rolandi, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas, A. Stakia, J. Steggemann, M. Tosi, D. Treille, L. Veckalns, W. D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

L. Caminada, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H. C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S. A. Wiederkehr

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

M. Backhaus, L. Bäni, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, C. Grab, C. Heidegger, D. Hits, J. Hoss, T. Klijnsma, W. Listermann, R. A. Manzoni, M. Marionneau, M. T. Meinhard, F. Michel, P. Musella, F. Nessi-Tedaldi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, P. Pigazzini, M. Quittnat, D. Ruini, D. A. Sanz Becerra, M. Schönenberger, L. Schultska, V. R. Tavolaro, K. Theofilatos, M. L. Vesterbacka Olsson, R. Wallny, D. H. Zhu

Universität Zürich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler, D. Brzhechko, M. F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, I. Neutelings, D. Pinna, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

National Central University, Chung-Li, Taiwan

Y.-H. Chang, K.-Y. Cheng, T.-H. Doan, Sh. Jain, R. Khurana, C. M. Kuo, W. Lin, A. Pozdnyakov, S. S. Yu

National Taiwan University (NTU), Taipei, Taiwan

P. Chang, Y. Chao, K. F. Chen, P. H. Chen, W. - S. Hou, Arun Kumar, Y. - Y. Li, R. - S. Lu, E. Paganis, A. Psallidas, A. Steen, J. F. Tsai

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

B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

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

A. Bat, F. Boran, S. Cerci, S. Damarseckin, Z. S. Demiroglu, F. Dolek, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, C. Isik, E. E. Kangal, O. Kara, A. Kayis Topaksu, U. Kimalsu, M. Oglakci, G. Onengut, K. Ozdemir, S. Ozturk, D. Sunar Cerci, B. Tali, U. G. Tok, S. Turkcapar, I. S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

B. Isildak, G. Karapinar, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

I. O. Atakisi, E. Gülmez, M. Kaya, O. Kaya, S. Tekten, E. A. Yetkin

Istanbul Technical University, Istanbul, Turkey

M. N. Agaras, S. Atay, A. Cakir, K. Cankocak, Y. Komurcu, S. Seń

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

B. Grynyov
National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold, S. Paramesvaran, B. Penning, T. Sakuma, D. Smith, V.J. Smith, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev, C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Imperial College, London, United Kingdom
G. Auzinger, R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, D. Colling, L. Corpe, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, Y. Haddad, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, J. Nash, A. Nikitenko, V. Palladino, M. Pesaresi, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, G. Singh, M. Stoye, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee, N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, A. Morton, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, USA
K. Call, J. Dittmann, K. Hatakeyama, H. Liu, C. Madrid, B. Mcmaster, N. Pastika, C. Smith

Catholic University of America, Washington DC, USA
R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, USA
A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA
D. Arcaro, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Brown University, Providence, USA
G. Benelli, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, J. Pazzini, S. Piperov, S. Sagir, E. Usai, D. Yu

University of California, Davis, Davis, USA
R. Band, C. Brainerd, R. Breeden, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, W. Ko, O. Kukral, R. Lander, C. Mclean, M. Muhlhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, D. Stolp, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

University of California, Los Angeles, USA
M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schnaible, V. Valuev

University of California, Riverside, Riverside, USA
E. Bouvier, K. Burt, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli,
E. Kennedy, E. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B.R. Yates

University of California, San Diego, La Jolla, USA
J.G. Branson, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA
N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, M. Citron, A. Dishaw, V. Dutta, M. Franco Sevilla, L. Gouskos, R. Heller, J. Incandela, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, S. Wang, J. Yoo

California Institute of Technology, Pasadena, USA
D. Anderson, A. Bornheim, J.M. Lawhorn, H.B. Newman, T.Q. Nguyen, M. Spiropulu, J.R. Vlimant, R. Wilkinson, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, USA
J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, S. Leontsinis, E. MacDonald, T. Mulholland, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA
J. Alexander, J. Chaves, Y. Cheng, J. Chu, A. Datta, K. Mcdermott, N. Mirman, J.R. Patterson, D. Quach, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Ayyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla†, K. Berkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, G. Gess, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris, S. Hasagawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahm, V. O’Dell, K. Pedro, C. Pena, O. Prokofyev, G. Rakness, L. Ristori, A. Savoy-Navarro, B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, 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. Bertignou, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, M. Carver, D. Curry, R.D. Field, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, K. Shi, D. Sperka, J. Wang, S. Wang

Florida International University, Miami, USA
Y.R. Joshi, S. Linn

Florida State University, Tallahassee, USA
A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, A. Santra, V. Sharma, R. Yohay
Northeastern University, Boston, USA
G. Alverson, E. Barberis, C. Freer, A. Hortiangtham, D.M. Morse, T. Orimoto, R. Teixeira De Lima, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, USA
S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA
R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko, M. Planer, A. Reinsvold, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA
J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, T.Y. Ling, W. Luo, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, USA
S. Cooperstein, P. Elmer, J. Hardenbrook, P. Hebda, S. Higginbotham, A. Kalogeropoulos, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, USA
S. Malik, S. Norberg

Purdue University, West Lafayette, USA
A. Barker, V.E. Barnes, S. Das, L. Gutay, M. Jones, A.W. Jung, A. Khatiwada, B. Mahakud, D.H. Miller, N. Neumeister, C.C. Peng, H. Qiu, J.F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, USA
T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, USA
Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, W. Li, B. Michlin, B.P. Padley, J. Roberts, J. Rorie, W. Shi, Z. Tu, J. Zabel, A. Zhang

University of Rochester, Rochester, USA
A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, R. Taus, M. Verzetti

Rutgers, The State University of New Jersey, Piscataway, USA
A. Agapitos, J.P. Chou, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzler, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA
A.G. Delannoy, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

Texas A&M University, College Station, USA
O. Bouhali, A. Castaneda Hernandez, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon, S. Luo, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov
Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, F. De Guio, P.R. Dudero, S. Kunori, K. Lamiuchane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Vanderbilt University, Nashville, USA
S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, J.D. Ruiz Alvarez, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij, Q. Xu

University of Virginia, Charlottesville, USA
M.W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA
R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

University of Wisconsin - Madison, Madison, WI, USA
M. Brodski, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, T. Ruggles, A. Savin, N. Smith, W.H. Smith, N. Woods

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
3: Also at Universidade Estadual de Campinas, Campinas, Brazil
4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
5: Also at Université Libre de Bruxelles, Bruxelles, Belgium
6: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
7: Also at Joint Institute for Nuclear Research, Dubna, Russia
8: Also at Suez University, Suez, Egypt
9: Now at British University in Egypt, Cairo, Egypt
10: Now at Helwan University, Cairo, Egypt
11: Now at Fayoum University, El-Fayoum, Egypt
12: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia
13: Also at Université de Haute Alsace, Mulhouse, France
14: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
15: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
16: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
17: Also at University of Hamburg, Hamburg, Germany
18: Also at Brandenburg University of Technology, Cottbus, Germany
19: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
20: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
21: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
22: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
23: Also at Institute of Physics, Bhubaneswar, India
24: Also at Shoolini University, Solan, India
25: Also at University of Visva-Bharati, Santiniketan, India
26: Also at Isfahan University of Technology, Isfahan, Iran
27: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
28: Also at Università degli Studi di Siena, Siena, Italy
29: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
30: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
31: Also at Consejo Nacional de Ciencia y Tecnologia, Mexico city, Mexico
32: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
33: Also at Institute for Nuclear Research, Moscow, Russia
34: Now at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
35: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
36: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
37: Also at University of Florida, Gainesville, USA
38: Also at P.N. Lebedev Physical Institute, Moscow, Russia
39: Also at California Institute of Technology, Pasadena, USA
40: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
41: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
42: Also at INFN Sezione di Pavia a, Università di Pavia b, Pavia, Italy
43: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
44: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
45: Also at National and Kapodistrian University of Athens, Athens, Greece
46: Also at Riga Technical University, Riga, Latvia
47: Also at Universität Zürich, Zurich, Switzerland
48: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
49: Also at Adiyaman University, Adiyaman, Turkey
50: Also at Istanbul Aydin University, Istanbul, Turkey
51: Also at Mersin University, Mersin, Turkey
52: Also at Piri Reis University, Istanbul, Turkey
53: Also at Gaziosmanpasa University, Tokat, Turkey
54: Also at Ozyegin University, Istanbul, Turkey
55: Also at Izmir Institute of Technology, Izmir, Turkey
56: Also at Marmara University, Istanbul, Turkey
57: Also at Kafkas University, Kars, Turkey
58: Also at Istanbul Bilgi University, Istanbul, Turkey
59: Also at Hacettepe University, Ankara, Turkey
60: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
61: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
62: Also at Monash University, Faculty of Science, Clayton, Australia
63: Also at Bethel University, St. Paul, USA
64: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
65: Also at Utah Valley University, Orem, USA
66: Also at Purdue University, West Lafayette, USA
67: Also at Beykent University, Istanbul, Turkey
68: Also at Bingol University, Bingol, Turkey
69: Also at Sinop University, Sinop, 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