Abstract

The polarizations of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons are measured as a function of the charged particle multiplicity in proton-proton collisions at $\sqrt{s} = 7$ TeV. The measurements are performed with a dimuon data sample collected in 2011 by the CMS experiment, corresponding to an integrated luminosity of $4.9\text{ fb}^{-1}$. The results are extracted from the dimuon decay angular distributions, in two ranges of $\Upsilon(nS)$ transverse momentum (10–15 and 15–35 GeV), and in the rapidity interval $|y| < 1.2$. The results do not show significant changes from low- to high-multiplicity pp collisions, although large uncertainties preclude definite statements in the $\Upsilon(2S)$ and $\Upsilon(3S)$ cases.

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1 Introduction

Studies of heavy-quarkonium production contribute to an improved understanding of hadron formation within the context of quantum chromodynamics (QCD) \cite{1}. Quarkonium production is expected to proceed in two steps \cite{2}. First, a heavy quark-antiquark pair, $Q\bar{Q}$, is produced, with angular momentum $L$ and spin $S$. Then this “pre-resonance” binds into the measured quarkonium state through a nonperturbative evolution that may change $L$ and/or $S$. The short-distance $Q\bar{Q}$ production cross sections (SDCs) are functions of the $Q\bar{Q}$ momentum and are calculated in perturbative QCD \cite{3–5}, while the probabilities that $Q\bar{Q}$ pairs of different quantum properties form the observed quarkonium state are parametrized by momentum-independent long-distance matrix elements (LDMEs). Since they are expected to scale with powers of the heavy-quark velocity squared, $v^2$, in the nonrelativistic limit ($v^2 \ll 1$) most LDMEs are negligible and $S$-wave vector quarkonia should be dominantly formed from $Q\bar{Q}$ pairs produced as colour-singlet, $3S^1_{[1]}$, or as one of the $1S^0_{[8]}$, $3S^8_{[1]}$ and $3P^8_{[1]}$ colour-octet states. While the colour-singlet LDME can be calculated with potential models, the others, reflecting the complexity of the evolution of a coloured QCD system into a formed hadron, are determined through phenomenological analyses of quarkonium production data \cite{3–7}. Polarization data play a central role in these analyses \cite{7}, which are performed in the zero-momentum frame of the quarkonium state (and, approximately, of the $Q\bar{Q}$ pair) and can directly reveal the quantum properties of the $Q\bar{Q}$, relying in most cases only on basic angular-momentum analysis. For example, $1S^0_{[8]}$ $Q\bar{Q}$ states evolve into unpolarized $3S^1$ quarkonia, while $3S^8_{[1]}$ states, with quantum numbers identical to those of a gluon, lead to transversely polarized $3S^1$ quarkonia.

The factorization hypothesis of nonrelativistic QCD implicitly assumes that the LDMEs are universal constants, independent of the short-distance process that created the $Q\bar{Q}$: the same LDMEs should be extracted from proton-(anti)proton and $e^+e^-$ data, for example. However, cross section and polarization measurements at high transverse momentum, $p_T$, are currently limited to pp collisions, so that the LDME universality hypothesis remains a nontrivial assumption requiring direct experimental investigation. Since the nonperturbative quarkonium formation process involves interactions with the QCD medium surrounding the $Q\bar{Q}$ state, allowing it to neutralize its net colour through emission or absorption of soft gluons, it is important to verify if the polarizations (directly related to the LDMEs) depend on the complexity of the hadronic environment created by the collision. Probing if the polarizations are affected by an increase in the multiplicity of particles produced in pp collisions, the topic of the present analysis, is a first step in such a study, to be followed by analogous investigations using proton-nucleus and nucleus-nucleus data collected at different collision centralities. Such studies are crucial for a reliable interpretation of the quarkonium suppression patterns seen in high-energy nuclear collisions (see Ref. \cite{8} and references therein) and of their relation to signatures of quark-gluon plasma formation \cite{9–11}. While changes in integrated yields or in $p_T$ and rapidity, $y$, distributions can be caused by effects such as modified parton densities in the nucleus or parton energy loss, the observation of changes in quarkonium polarization would be a direct signal of a modification in the bound-state formation mechanism.

This Letter reports how the polarizations of the $Y(1S)$, $Y(2S)$, and $Y(3S)$ mesons produced in pp collisions at a centre-of-mass energy of 7 TeV change as a function of charged particle multiplicity, $N_{ch}$. It complements two observations made for pp and pPb collisions \cite{12}: the $Y(nS)$ cross sections, normalised by their $N_{ch}$-integrated values, increase with $N_{ch}$; the $Y(2S)$ and $Y(3S)$ cross sections, normalised by the $Y(1S)$ value, decrease with $N_{ch}$.

The measurements are performed using a dimuon data sample collected in 2011 by the CMS ex-
The CMS apparatus is based on a superconducting solenoid of 6 m internal diameter, providing a 3.8 T field. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter. Muons are measured with drift tubes, cathode strip chambers, and resistive-plate chambers. The main detectors used in this analysis are the silicon tracker and the muon system, which enable the measurement of muon momenta over the pseudorapidity range $|\eta| < 2.4$. 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. [18]. The events were collected using a two-level trigger system. The first level uses custom hardware processors to select events with two muons. The high-level trigger, adding information from the silicon tracker, selects opposite-sign muon pairs of invariant mass $8.5 < M < 11.5 \text{ GeV}$, $|\eta| < 1.25$ and $p_T > 5$ or $7 \text{ GeV}$ (depending on the instantaneous luminosity); the dimuon vertex fit $\chi^2$ probability must exceed 0.5% and the two muons must have a distance of closest approach smaller than 5 mm. Although the trigger logic does not reject events on the basis of the $p_T$ of the single muons, at mid-rapidity the bending induced by the magnetic field prevents muons of $p_T$ smaller than $\sim 3 \text{ GeV}$ from reaching the muon stations.

The offline analysis selects muon tracks with hits in more than ten tracker layers, at least two of which are in the pixel layers, and matched with segments in the muon system. They must have a good track fit quality, point to the interaction region, and match the muon objects that triggered the event. The selected muons are required to satisfy $|\eta| < 1.6$ and to have $p_T$ above 4.5, 3.5, and 3 GeV for $|\eta| < 1.2$, $1.2 < |\eta| < 1.4$, and $1.4 < |\eta| < 1.6$, respectively, to ensure reliable detection and trigger efficiencies. The combinatorial background from uncorrelated muons is suppressed by requiring a dimuon vertex fit $\chi^2$ probability larger than 1% and by rejecting events where the distance between the dimuon vertex and the primary vertex is larger than twice its resolution. In events with multiple reconstructed primary vertices (pileup), the one nearest to the point of closest approach between the trajectory of the dimuon and the beam
The $N_{\text{ch}}$ variable is computed by counting “high purity” charged tracks, excluding the two muons, of $|\eta| < 2.4$, $p_T > 500$ MeV, and $p_T$ measured with better than 10% relative accuracy. Acceptance and reconstruction efficiencies are not corrected for. Each track is assigned a weight reflecting the likelihood that it belongs to the primary vertex [19]; tracks consistent with the vertex have a weight close to unity. The migration of events from one $N_{\text{ch}}$ bin to the next, caused by inadvertently counting spurious tracks produced in near-by pileup vertices, is kept negligible by rejecting events with more than 16 vertices. Figure 1 shows the $N_{\text{ch}}$ distribution of the events selected in this analysis.

![Charged particle multiplicity distribution](image)

**Figure 1:** Charged particle multiplicity distribution of the events selected for the analysis.

The dimuon mass distribution, shown in Fig. 2, is well described by three Crystal-Ball functions [20], one per $\Upsilon(nS)$ peak, and a second-order polynomial function representing the underlying continuum, determined from the mass sidebands, 8.6–8.9 and 10.6–11.4 GeV. The dimuon mass resolution is $\sigma \approx 80$ MeV, slightly dependent on $p_T$. The $Y(nS)$ signal mass regions are defined as the ±1 $\sigma$ windows around the fitted means of the Crystal-Ball functions. The corresponding cross-feed between the three peaks is negligible. The analysis is performed in five $N_{\text{ch}}$ bins, 0–10, 10–20, 20–30, 30–40, and 40–60, sufficiently numerous and narrow to probe potential variations of the polarizations, and in two $Y(nS)$ $p_T$ ranges, 10–15 and 15–35 GeV. The dimuons are integrated within $|y| < 1.2$. The lower $p_T$ $\Upsilon(3S)$ polarization measurement merges the two
The single-muon detection efficiencies are measured with a “tag-and-probe” technique [21], using event samples collected with triggers specifically designed for this purpose, including a sample enriched in dimuons from J/ψ decays where a muon is combined with another track and the pair is required to have an invariant mass within 2.8–3.4 GeV. The procedure was validated with detailed Monte Carlo simulation studies. The measured efficiencies are parametrized as a function of muon p_T, in eight |η| bins. Their uncertainties, ~2–3%, reflecting the statistical precision of the calibration samples and possible imperfections of the parametrization, are independent of N_{ch} and identical for the three Y(nS) states. These global uncertainties do not affect the search for potential variations of the polarizations from low- to high-multiplicity events. The trigger and the selection criteria could potentially introduce differences between the dimuon detection efficiencies and the product of the efficiencies of the two single muons. Simulation studies reveal that such correlations have a negligible dependence on cos θ and φ, in the phase space of this analysis [13]. The residual angular dependences are accounted for in the evaluation of the global systematic uncertainties.

3 Extraction of the polarization parameters

The two-dimensional angular distribution, in cos θ and φ, of the background corresponding to a given Y(nS) state is evaluated as a weighted average of the distributions measured in the two mass sidebands, the weights reflecting (linearly) the differences between the Y(nS) mass and the median masses of the sidebands. The background component is subtracted on an event-by-event basis using a likelihood-ratio criterium, randomly selecting and removing a fraction f_{Bg} of events distributed according to the (p_T, |y|, M, cos θ, φ) distribution of the background model [13]. The posterior probability density (PPD) for the average values of the polarization parameters (\tilde{λ}) inside a particular bin is then defined as a product over the remaining (signal-like) events i,

$$P(\tilde{λ}) = \prod_i E(\vec{p}_{1(i)}, \vec{p}_{2(i)})$$

(2)

where E represents the event probability distribution as a function of the muon momenta \vec{p}_{1,2} in event i. This analysis method does not use model-dependent (cos θ, φ) acceptance maps; each event is attributed a probability reflecting the full event kinematics (not only cos θ and φ) and the values of the polarization parameters,

$$E(\vec{p}_1, \vec{p}_2) = \frac{1}{N(\tilde{λ})} W(\cos θ, φ|\tilde{λ}) \epsilon(\vec{p}_1, \vec{p}_2)$$

(3)

where \epsilon(\vec{p}_1, \vec{p}_2) is the measured detection efficiency. The normalization factor N(\tilde{λ}) is calculated by integrating W · ε over cos θ and φ uniformly, using (p_T, |y|, M) distributions determined from the background-subtracted data. To account for the statistical fluctuations related to its random nature, the background subtraction procedure is repeated 50 times.

Figure 3 compares the cos θ and φ distributions measured for Y(2S) signal events of 15 < p_T < 35 GeV and 10 < N_{ch} < 20 with curves representing the “best fit”. For illustration, curves
reflecting extreme polarization scenarios are also shown: fully transverse ($\lambda_{\vartheta} = +1$) and fully longitudinal ($\lambda_{\vartheta} = -1$) in the $\cos \vartheta$ panel, and $\lambda_{\varphi} = \pm 0.5$ in the $\varphi$ panel ($|\lambda_{\varphi}|$ must be smaller than 0.5 if $\lambda_{\vartheta} = 0$ [14]).

Each of the systematic uncertainties on the polarization parameters caused by the analysis framework and the detection efficiencies is individually evaluated through 50 statistically independent pseudo-experiments. For each effect, the systematic uncertainty is the difference between the injected and resulting parameters. The robustness of the framework to measure the signal polarization is validated for several signal and background polarization scenarios. The impact of residual biases that could be caused by uncertainties on the muon or dimuon efficiencies is evaluated by extracting the polarization parameters after applying corresponding variations to the input efficiencies. The background model uncertainty is evaluated by modifying the relative weights of the low- and high-mass sidebands when building the background distributions. A broad range of hypotheses is considered, including the assumption that the background under the $\Upsilon(1S)$ ($\Upsilon(3S)$) peak resembles exclusively the low-mass (high-mass) sideband, or assuming that it is reproduced by an equal mixture of the two sideband distributions. Several systematic uncertainties have similar levels, except in the highest $N_{ch}$ bins and the lowest $p_T$ range, where the background model uncertainty dominates, especially for the $\Upsilon(2S)$ and $\Upsilon(3S)$ states. For the $\Upsilon(1S)$ state and in the HX frame, the $N_{ch}$-dependent systematic uncertainties are $\sim 0.1$ for $\lambda_{\vartheta}$ and $\sim 0.03$–$0.05$ for $\lambda_{\varphi}$ and $\lambda_{\vartheta\varphi}$, slightly increasing with $N_{ch}$. The corresponding $\Upsilon(2S)$ and $\Upsilon(3S)$ values are slightly larger: $\sim 0.2$ for $\lambda_{\vartheta}$, $\sim 0.04$ for $\lambda_{\varphi}$, and $\sim 0.05$–$0.08$ for $\lambda_{\vartheta\varphi}$. The statistical uncertainties are negligible for the $\Upsilon(1S)$ state and become dominant for the $\Upsilon(2S)$ and $\Upsilon(3S)$ states, as $N_{ch}$ increases.

## 4 Results

The final PPD of the polarization parameters is an envelope of the PPDs corresponding to all hypotheses considered in the evaluation of the systematic uncertainties. In each analysis bin, the central values and 68.3% confidence level (CL) uncertainties of each polarization parameter are evaluated from the corresponding one-dimensional marginal posterior, calculated by
numerical integration. In the HX frame, the $\lambda$ parameters are measured with negligible correlations, as illustrated by Fig. 4, which shows the two-dimensional marginals of the PPD in the $\lambda_\varphi$ vs. $\lambda_\theta$ and $\lambda_\varphi \varphi$ vs. $\lambda_\varphi$ planes, for a representative analysis bin.

![Diagram of two-dimensional marginals of the PPD](image)

Figure 4: Two-dimensional marginals of the PPD for the HX frame in the $\lambda_\varphi$ vs. $\lambda_\theta$ (left) and $\lambda_\varphi \varphi$ vs. $\lambda_\varphi$ (right) planes, for $Y(2S)$ with $15 < p_T < 35$ GeV and $10 < N_{ch} < 20$, displaying the 68.3% and 99.7% CL total uncertainties. The shaded areas represent physically forbidden regions of parameter space for the decay of a $J = 1$ particle [14].

Figure 5 shows the $\lambda_\theta$, $\lambda_\varphi$, $\lambda_\varphi \varphi$, and $\tilde{\lambda}$ values measured in the HX frame for the three $Y(nS)$ states, in both $p_T$ ranges. The corresponding numerical results are tabulated in Appendix A. The $\tilde{\lambda}$ values have also been measured in the Collins–Soper frame (CS) [22], whose $z$ axis is the average of the two beam directions in the $Y$ rest frame, and in the perpendicular helicity frame (PX) [23], orthogonal to the CS frame. The three measurements agree with each other, within systematic uncertainties (similar in all frames), as required in the absence of unaccounted systematic effects [24].

Regarding the $Y(1S)$ results, all the $\lambda$ parameters are close to zero, indicating essentially unpolarized production, as expected if the mesons included in this analysis would be dominantly produced through the unpolarized $^1S_0^{[8]}$ pre-resonant octet state. The trend as a function of $N_{ch}$ does not indicate any strong changes in $Y(1S)$ production between low- and high-multiplicity pp collisions. The measurements are compatible with a non-negligible fraction of $Y(2S)$ and $Y(3S)$ mesons being produced via the transversely polarized $^3S_1^{[8]}$ octet term. Given the present uncertainties, no clear trends can be seen regarding changes of their polarizations with $N_{ch}$.

To place these results into context, Fig. 6-left illustrates how the $\lambda_\theta$ parameter would change as a function of $N_{ch}$ if quarkonium production would be dominated by two processes, one unpolarized ($\lambda_\theta = 0$, as is the case for the $^1S_0^{[8]}$ octet) and the other fully transversely polarized in the HX frame ($\lambda_\theta = +1$, as for the $^3S_1^{[8]}$ octet, at high enough $p_T$). The four curves represent different variations with $N_{ch}$ (linearly in the $0 < N_{ch} < 60$ range) of the fraction of events, $f$, produced through the latter process (defined in the legends). These curves were computed knowing that the polarization of a sample of quarkonium states produced through two differ-
Figure 5: The $\lambda_{\phi}$, $\lambda_{\varphi}$, $\lambda_{\phi\varphi}$, and $\bar{\lambda}$ parameters (top to bottom) for the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ states (left to right), in the HX frame, as a function of $N_{ch}$, for both $p_T$ ranges. The $\bar{\lambda}$ values are also shown for the CS frame; the HX and CS uncertainties are strongly correlated. The vertical bars represent the $N_{ch}$-dependent total uncertainties (at 68.3% CL), while the boxes at the zero horizontal line represent the global uncertainties. The points are placed at the average $N_{ch}$ of each bin, with a small offset for easier viewing.
ent processes, of polarizations $\lambda_0$ and $\lambda_1$, depends on $f$ as [25]

$$\lambda(f) = \left[ \frac{1 - f}{3 + \lambda_0} + \frac{f \lambda_1}{3 + \lambda_1} \right] \left[ \frac{1 - f}{3 + \lambda_0} + \frac{f}{3 + \lambda_1} \right].$$

(4)

Figure 6: Expected $N_{\text{ch}}$-dependences of the $\lambda_\theta$ parameter for the sum of two processes, of polarizations $\lambda_0$ and $\lambda_1$, of relative fractions changing linearly with $N_{\text{ch}}$ (see text for details). The measured $\lambda_\theta$ values are also shown, for the $Y(3S)$ (left) and $Y(1S)$ (right).

Changes in the LDMEs, in particular of the dominant $^1S^0_8$ and $^3S^1_8$ octet terms [7], are not the only possible cause of variations in the measured $Y(nS)$ $\lambda$ parameters between low- and high-multiplicity pp collisions; the effects of feed-down decays from heavier quarkonia should also be considered. In fact, the polarizations reported here correspond to inclusive $Y(nS)$ samples, not distinguishing mesons emitted in the decays of $S$- and $P$-wave bottomonium states from the directly-produced ones. Assuming that all directly-produced $S$-wave states have identical polarizations, their decays to lighter $S$-wave states do not induce differences between the measured (inclusive) polarizations and those of the directly-produced mesons. On the contrary, feed-down decays from $P$-wave states can significantly affect the measured values, especially for the $Y(1S)$ state, presumably the one affected by the largest feed-down fraction. It is presently not possible to reliably evaluate the influence of the feed-down decays on the measured $Y(nS)$ polarizations, for lack of information regarding the $\lambda_\theta$ polarizations and their feed-down fractions. Figure 6-right shows how the measured (inclusive) polarization is expected to change as a function of $N_{\text{ch}}$ if the directly-produced component (of polarization $\lambda_0$) is complemented by a feed-down component (of polarization $\lambda_1$) that contributes with a fraction $f$, decreasing linearly with $N_{\text{ch}}$ from 50% to 0 in the $0 < N_{\text{ch}} < 60$ range. The six curves correspond to different assumptions for $\lambda_0$ and $\lambda_1$, reported in the legends, with $\lambda_1$ representing an effective average of the $\chi_{b1}$ and $\chi_{b2}$ polarizations (the $\chi_{b1}$ and $\chi_{b2}$ $\lambda_\theta$ values must verify $\lambda_\theta > -1/3$ and $\lambda_\theta > -3/5$, respectively [25]). In these scenarios the feed-down fraction is assumed to become negligible at high $N_{\text{ch}}$, where the inclusive $\lambda_\theta$ tends to the direct $\lambda_0$ value. At low $N_{\text{ch}}$, where the feed-down contribution is, hypothetically, the highest, the inclusive $\lambda_\theta$ parameter crucially depends on the assumed $\chi_{b}$ polarization.

5 Summary

The polarizations of the $Y(1S)$, $Y(2S)$, and $Y(3S)$ mesons produced in pp collisions at $\sqrt{s} = 7$ TeV have been determined as functions of the charged particle multiplicity of the event in
two $\Upsilon(nS)$ $p_T$ ranges. The measurements do not show significant variations as a function of $N_{ch}$, even though the large $\Upsilon(2S)$ and $\Upsilon(3S)$ uncertainties preclude definite statements in these cases. This study opens the way for analogous measurements extending to the charmonium family, particularly interesting for the $\psi(2S)$, which is unaffected by feed-down decays and, therefore, provides a more direct probe of LDME universality. Equivalent analyses should also be performed in pPb and PbPb event samples, in view of evaluating how quark-antiquark bound-state formation is influenced by the surrounding medium, which is an essential input for the interpretation of quarkonium suppression patterns in nuclear collisions.

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References

[1] N. Brambilla et al., “Heavy quarkonium: progress, puzzles, and opportunities”, Eur. Phys. J. C 71 (2011) 1534, \texttt{doi:10.1140/epjc/s10052-010-1534-9}
[2] G. Bodwin, E. Braaten, and P. Lepage, “Rigorous QCD analysis of inclusive annihilation and production of heavy quarkonium”, *Phys. Rev. D* **51** (1995) 1125, doi:10.1103/PhysRevD.51.1125, arXiv:hep-ph/9407339

[3] M. Butenschön and B. Kniehl, “J/ψ polarization at Tevatron and LHC: NRQCD factorization at the crossroads”, *Phys. Rev. Lett.* **108** (2012) 172002, doi:10.1103/PhysRevLett.108.172002, arXiv:1201.1872

[4] B. Gong, L.-P. Wan, J.-X. Wang, and H.-F. Zhang, “Polarization for prompt J/ψ, ψ(2S) production at the Tevatron and LHC”, *Phys. Rev. Lett.* **110** (2013) 042002, doi:10.1103/PhysRevLett.110.042002, arXiv:1205.6682

[5] K.-T. Chao et al., “J/ψ polarization at hadron colliders in NRQCD”, *Phys. Rev. Lett.* **108** (2012) 242004, doi:10.1103/PhysRevLett.108.242004, arXiv:1201.2675

[6] B. Gong, L.-P. Wan, J.-X. Wang, and H.-F. Zhang, “Complete next-to-leading-order study on the yield and polarization of Y(1S,2S,3S) at the Tevatron and LHC”, *Phys. Rev. Lett.* **112** (2014) 032001, doi:10.1103/PhysRevLett.112.032001, arXiv:1305.0748

[7] P. Faccioli et al., “Quarkonium production in the LHC era: a polarized perspective”, *Phys. Lett. B* **736** (2014) 98, doi:10.1016/j.physletb.2014.07.006, arXiv:1403.3970

[8] CMS Collaboration, “Observation of sequential Y suppression in PbPb collisions”, *Phys. Rev. Lett.* **109** (2012) 222301, doi:10.1103/PhysRevLett.109.222301, arXiv:1208.2826

[9] T. Matsui and H. Satz, “J/ψ suppression by Quark-Gluon Plasma formation”, *Phys. Lett. B* **178** (1986) 416, doi:10.1016/0370-2693(86)91404-8

[10] F. Karsch, D. Kharzeev, and H. Satz, “Sequential charmonium dissociation”, *Phys. Lett. B* **637** (2006) 75, doi:10.1016/j.physletb.2006.03.078, arXiv:hep-ph/0512239

[11] A. Andronic et al., “Heavy-flavour and quarkonium production in the LHC era: from proton-proton to heavy-ion collisions”, *Eur. Phys. J. C* **76** (2015) 107, doi:10.1140/epjc/s10052-015-3819-5, arXiv:1506.03981

[12] CMS Collaboration, “Event activity dependence of Y(nS) production in √s_{NN} = 5.02 TeV pPb and √s = 2.76 TeV pp collisions”, *JHEP* **04** (2014) 103, doi:10.1007/JHEP04(2014)103, arXiv:1312.6300

[13] CMS Collaboration, “Measurement of the Y(1S), Y(2S), and Y(3S) polarizations in pp collisions at √s = 7 TeV”, *Phys. Rev. Lett.* **110** (2013) 081802, doi:10.1103/PhysRevLett.110.081802, arXiv:1209.2922

[14] P. Faccioli, C. Lourenço, J. Seixas, and H. Wöhri, “Model-independent constraints on the shape parameters of dilepton angular distributions”, *Phys. Rev. D* **83** (2011) 056008, doi:10.1103/PhysRevD.83.056008, arXiv:1102.3946

[15] P. Faccioli, C. Lourenço, and J. Seixas, “Rotation-invariant relations in vector meson decays into fermion pairs”, *Phys. Rev. Lett.* **105** (2010) 061601, doi:10.1103/PhysRevLett.105.061601, arXiv:1005.2601
[16] P. Faccioli, C. Lourenc¸o, J. Seixas, and H. W¨ohri, “Towards the experimental clarification of quarkonium polarization”, Eur. Phys. J. C 69 (2010) 657, doi:10.1140/epjc/s10052-010-1420-5, arXiv:1006.2738.

[17] CMS Collaboration, “Measurement of the prompt J/ψ and ψ(2S) polarizations in pp collisions at √s = 7 TeV”, Phys. Lett. B 727 (2013) 381, doi:10.1016/j.physletb.2013.10.055, arXiv:1307.6070.

[18] CMS Collaboration, “The CMS experiment at the CERN LHC”, JINST 3 (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[19] CMS Collaboration, “Description and performance of track and primary-vertex reconstruction with the CMS tracker”, JINST 9 (2014) P10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.

[20] M. J. Oreglia, “A study of the reactions ψ′ → γγψ” PhD thesis, Stanford University, 1980. SLAC Report R-236.

[21] CMS Collaboration, “Measurements of inclusive W and Z cross sections in pp collisions at √s = 7 TeV”, JHEP 01 (2011) 080, doi:10.1007/JHEP01(2011)080.

[22] J. Collins and D. Soper, “Angular Distribution of Dileptons in High-Energy Hadron Collisions”, Phys. Rev. D 16 (1977) 2219, doi:10.1103/PhysRevD.16.2219.

[23] E. Braaten, D. Kang, J. Lee, and C. Yu, “Optimal spin quantization axes for the polarization of dileptons with large transverse momentum”, Phys. Rev. D 79 (2009) 014025, doi:10.1103/PhysRevD.79.014025, arXiv:0810.4506.

[24] P. Faccioli, C. Lourenc¸o, and J. Seixas, “New approach to quarkonium polarization studies”, Phys. Rev. D 81 (2010) 111502(R), doi:10.1103/PhysRevD.81.111502, arXiv:1005.2855.

[25] P. Faccioli, C. Lourenc¸o, J. Seixas, and H. W¨ohri, “Determination of χc and χb polarizations from dilepton angular distributions in radiative decays”, Phys. Rev. D 83 (2011) 096001, doi:10.1103/PhysRevD.83.096001, arXiv:1103.4882.
### Supplemental material

Table 1: Signal yields, $N$, and background fractions, $f_{bg}$ (in %), within $1\sigma$ windows around the nominal $\Upsilon(nS)$ masses for the considered $N_{ch}$ and $p_T$ ranges.

| $p_T$ [GeV] | $N_{ch}$ | $\Upsilon(1S)$ | $\Upsilon(2S)$ | $\Upsilon(3S)$ |
|------------|---------|---------------|---------------|---------------|
|            | $N$     | $f_{bg}$      | $N$           | $f_{bg}$      | $N$           | $f_{bg}$ |
| 0–10       | 26900   | 3             | 10200         | 7             | 6500          | 10      |
| 10–20      | 51300   | 5             | 18200         | 12            | 10800         | 18      |
| 10–15      | 39200   | 7             | 13000         | 18            | 7500          | 26      |
| 20–30      | 20100   | 9             | 6300          | 24            | 5200          | 40      |
| 30–40      | 11300   | 12            | 3400          | 31            |               |         |
| 40–60      | 10600   | 3             | 4500          | 7             | 3200          | 9       |
| 10–20      | 27900   | 4             | 12100         | 9             | 8200          | 12      |
| 15–35      | 25700   | 5             | 10900         | 11            | 7200          | 15      |
| 20–30      | 15100   | 6             | 6300          | 14            | 3800          | 20      |
| 30–40      | 9500    | 7             | 3400          | 17            | 2300          | 24      |
Table 2: Y(nS) polarization parameters in the HX frame. The global uncertainties, independent of state and $N_{ch}$ bin, are also indicated.

| State | $p_T$ [GeV] | $N_{ch}$ | $\lambda_\phi$ | $\lambda_\varphi$ | $\lambda_{\phi\varphi}$ | $\lambda$ |
|-------|-------------|----------|-----------------|-------------------|-------------------|--------|
| Y(1S) | 10–15       |          |   |                  |                  |        |
| 0–10  | +0.014±0.102 | −0.110   | −0.044±0.026 | +0.053±0.033 | −0.094±0.126 | −0.138 |
| 10–20 | +0.103±0.089 | −0.098   | −0.035±0.025 | +0.027±0.028 | +0.005±0.126 | +0.139 |
| 20–30 | +0.187±0.102 | −0.110   | −0.041±0.026 | +0.035±0.033 | +0.066±0.128 | +0.145 |
| 30–40 | +0.032±0.121 | −0.132   | −0.042±0.031 | +0.033±0.039 | −0.074±0.159 |        |
| 40–60 | −0.073±0.159 | −0.174   | −0.074±0.034 | +0.061±0.054 | −0.243±0.186 |        |
| Y(2S) | 10–15       |          |   |                  |                  |        |
| 0–10  | +0.232±0.140 | −0.156   | −0.018±0.035 | −0.048±0.054 | +0.166±0.174 | +0.183 |
| 10–20 | +0.214±0.126 | −0.136   | −0.047±0.032 | −0.055±0.048 | +0.075±0.158 | +0.178 |
| 20–30 | +0.230±0.158 | −0.171   | −0.028±0.036 | −0.045±0.057 | +0.137±0.201 | +0.224 |
| 30–40 | +0.267±0.213 | −0.226   | −0.024±0.044 | −0.059±0.084 | +0.183±0.272 | +0.284 |
| 40–60 | +0.317±0.289 | −0.325   | −0.061±0.055 | −0.063±0.113 | +0.128±0.345 |        |
| Y(3S) | 10–15       |          |   |                  |                  |        |
| 0–10  | +0.074±0.169 | −0.187   | −0.028±0.038 | −0.044±0.061 | −0.009±0.205 | −0.219 |
| 10–20 | +0.279±0.156 | −0.173   | −0.019±0.037 | −0.148±0.060 | +0.208±0.209 | +0.223 |
| 20–30 | +0.061±0.194 | −0.213   | −0.032±0.043 | −0.061±0.078 | −0.023±0.259 |        |
| 30–60 | +0.672±0.285 | −0.304   | +0.051±0.061 | −0.196±0.116 | +0.798±0.435 | −0.479 |
| global unc. | ±0.085 | ±0.023 | ±0.022 | ±0.104 | |
| Y(1S) | 15–35       |          |   |                  |                  |        |
| 0–10  | −0.002±0.102 | −0.110   | −0.054±0.029 | +0.020±0.038 | −0.142±0.128 | −0.138 |
| 10–20 | −0.004±0.087 | −0.094   | −0.047±0.037 | −0.000±0.033 | −0.127±0.130 | −0.142 |
| 20–30 | +0.053±0.087 | −0.093   | −0.054±0.042 | −0.005±0.037 | −0.095±0.121 |        |
| 30–40 | +0.036±0.097 | −0.105   | −0.026±0.033 | −0.000±0.042 | −0.037±0.128 | −0.139 |
| 40–60 | −0.021±0.106 | −0.112   | −0.049±0.039 | +0.007±0.043 | −0.148±0.151 |        |
| Y(2S) | 15–35       |          |   |                  |                  |        |
| 0–10  | +0.124±0.163 | −0.168   | −0.058±0.034 | −0.050±0.048 | −0.039±0.189 | −0.190 |
| 10–20 | +0.237±0.105 | −0.114   | −0.027±0.028 | −0.025±0.043 | +0.149±0.138 | +0.148 |
| 20–30 | +0.205±0.113 | −0.113   | −0.086±0.034 | +0.052±0.043 | −0.040±0.141 |        |
| 30–40 | +0.501±0.147 | −0.153   | −0.020±0.033 | −0.078±0.053 | +0.416±0.177 | +0.184 |
| 40–60 | +0.364±0.210 | −0.172   | −0.061±0.044 | −0.024±0.061 | +0.169±0.206 |        |
| Y(3S) | 15–35       |          |   |                  |                  |        |
| 0–10  | +0.381±0.188 | −0.193   | −0.074±0.039 | +0.048±0.059 | +0.144±0.210 | +0.203 |
| 10–20 | +0.244±0.121 | −0.134   | −0.029±0.033 | −0.035±0.041 | +0.151±0.169 | +0.177 |
| 20–30 | +0.028±0.121 | −0.132   | −0.048±0.032 | −0.053±0.041 | +0.135±0.162 | +0.165 |
| 30–40 | +0.220±0.163 | −0.121+0.039 | −0.050±0.054 | −0.014±0.191 |        |
| 40–60 | +0.278±0.218 | −0.206   | −0.072±0.048 | −0.143±0.068 | +0.057±0.246 | −0.231 |
| global unc. | ±0.066 | ±0.019 | ±0.020 | ±0.073 | |
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, C. Fabjan¹, M. Flechl, M. Friedl, R. Frühwirth¹, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler¹, V. Knünz, A. König, M. Krammer¹, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady², N. Rad, B. Rahbaran, H. Rohringer, J. Schieck¹, R. Schönbeck, J. Strauss, W. Treberer-Treberspurg, 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, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, J. Lauwers, S. Luyckx, 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, J. Keaveney, S. Lowette, L. Moreels, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium
P. Barria, H. Brun, C. Caillol, B. Clerbaux, G. De Lentdecker, W. Fang, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, T. Maerschalk, A. Marinov, L. Perniè, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang³

Ghent University, Ghent, Belgium
K. Beernaert, L. Benucci, A. Cimmino, S. Cruycy, D. Dobur, A. Fagot, G. Garcia, M. Gul, J. McCarrian, A.A. Ocampo Rios, D. Poyraz, D. Ryckbosch, S. Salva, M. Sigamani, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Bassegmez, C. Beluffi⁴, O. Bondu, S. Brochet, G. Bruno, A. Caudron, L. Cear, C. Delaere, D. Favart, L. Forthomme, A. Giammanco, A. Jafari, P. Jez, M. Komm, V. Lemaitre, A. Mertens, M. Musich, C. Nuttens, L. Perrini, K. Piotrzkowski, A. Popov⁵, L. Quertenmont, M. Selvaggi, M. Vidal Marono

Université de Mons, Mons, Belgium
N. Beliy, G.H. Hammad

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, M. Correa Martins Junior, M. Hamer, 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. Chinellato⁶, A. Custódio, E.M. Da Costa, 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 Manganote⁶, A. Vilela Pereira
Universidade Estadual Paulista \textsuperscript{a}, Universidade Federal do ABC \textsuperscript{b}, S\~{a}o Paulo, Brazil
S. Ahuja\textsuperscript{b}, C.A. Bernardes\textsuperscript{b}, A. De Souza Santos\textsuperscript{b}, S. Dogra\textsuperscript{a}, T.R. Fernandez Perez Tomei\textsuperscript{a}, E.M. Gregores\textsuperscript{b}, P.G. Mercadante\textsuperscript{b}, C.S. Moon\textsuperscript{a,7}, S.F. Novaes\textsuperscript{a}, Sandra S. Padula\textsuperscript{a}, D. Romero Abad\textsuperscript{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

Institute of High Energy Physics, Beijing, China
M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, D. Leggat, R. Plestina\textsuperscript{a}, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, H. Zhang

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
C. Asawatangtrakuldee, Y. Ban, 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, B. Gomez Moreno, J.C. Sanabria

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
N. Godinovic, D. Lesla, 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, K. Kadija, J. Luetic, S. Micanovic, L. Sudic

University of Cyprus, Nicosia, Cyprus
A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolau, F. Ptochos, P.A. Razis, H. Rykaczewski

Charles University, Prague, Czech Republic
M. Bodlak, M. Finger\textsuperscript{9}, M. Finger Jr.\textsuperscript{9}

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
A.A. Abdelalim\textsuperscript{10,11}, A. Awad, A. Mahrous\textsuperscript{10}, A. Radi\textsuperscript{12,13}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
B. Calpas, M. Kadastik, M. Murumaa, M. Raidal, A. Tiko, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, J. Peikkanen, 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

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
M. Besancon, F. Coudenc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri,
A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, S. Naumann-Emme, A. Nayak, E. Ntomari, H. Perrey, 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, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany
V. Blobel, M. Centis Vignali, A.R. Draeger, J. Erfle, E. Garutti, K. Goebel, D. Gonzalez, M. Görner, J. Haller, M. Hoffmann, R.S. Höing, A. Junkes, R. Klanner, R. Kogler, N. Kovalchuk, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, M. Meyer, D. Nowatschin, J. Ott, F. Pantaleo², T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, D. Rathjens, C. Sander, C. Schleppe, E. Schlieckau, A. Schmidt, S. Schumann, J. Schwandt, V. Sola, H. Stadie, G. Steinbrück, F.M. Stober, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

Institut für Experimentelle Kernphysik, Karlsruhe, Germany
C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Descroix, A. Dierlamm, S. Fink, F. French, R. Friese, M. Giffels, A. Gilbert, D. Haitz, F. Hartmann², S.M. Heindl, U. Husemann, I. Katkov⁵, A. Kornmayer², 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. Scharf, G. Sieber, H.J. Simonis, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wohrmann, 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, A. Psallidas, 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, J. Strologas

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, A. Hazi, P. Hidas, D. Horváth¹⁹, F. Sikler, V. Veszpremi, G. Vesztergombi²⁰, A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi²¹, J. Molnar, Z. Szillasi²

University of Debrecen, Debrecen, Hungary
M. Bartók²², A. Makovec, P. Raics, Z.L. Trocsanyi, B. Ujvari

National Institute of Science Education and Research, Bhubaneswar, India
S. Choudhury²³, P. Mal, K. Mandal, D.K. Sahoo, N. Sahoo, S.K. Swain

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, R. Gupta, 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. Malhotra, M. Naimuddin, N. Nishu, K. Ranjan, R. Sharma, V. Sharma
Saha Institute of Nuclear Physics, Kolkata, India
S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutta, N. Majumdar, A. Modak, K. Mondal,
S. Mukhopadhyay, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan

Bhabha Atomic Research Centre, Mumbai, India
R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty, L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research, Mumbai, India
T. Aziz, S. Banerjee, S. Bhowmik, R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly,
S. Ghosh, M. Guchait, A. Gurtu, S. Jain, G. Kole, S. Kumar, B. Mahakud, M. Majumder,
G. Mazumdar, K. Mazumdar, S. Mitra, G.B. Mohanty, B. Parida, T. Sarkar, N. Sur, B. Sutar,
N. Wickramage

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

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
H. Bakhshiansohi, H. Behnamian, S.M. Etesami, F. Fahim, M. Khakzad, M. Mohammadi
Najafabadi, M. Naseri, S. Paknejad Mehdiaabadi, F. Rezaei Hosseinabadi, 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, C. Caputo, A. Colaleo, D. Creanza, L. Cristella, N. De Filippis,
M. De Palma, L. Fiore, G. Iaselli, G. Maggi, M. Maggi, G. Miniello, S. My, S. Nuzzo,
A. Pompili, G. Pugliese, R. Radogna, L. Silvestris, R. Venditti

INFN Sezione di Bologna, Università di Bologna, Bologna, Italy
G. Abbiendi, C. Battilana, D. Bonacorsì, S. Braibant-Giacomelli, L. Brigliadori,
R. Campanini, P. Capiluppi, A. Castro, F.R. Cavallo, S.S. Chhibra, G. Codispoti,
M. Cuffiani, G.M. Dallavalle, F. Fabbrì, A. Fanfani, D. Fasanella, P. Giacomelli,
C. Grandi, L. Guiducci, S. Marcellini, G. Masetti, A. Montanari, L.M. Pant,
A. Perrottà, A.M. Rossi, T. Rovelli, G.P. Siroli, N. Tosi

INFN Sezione di Catania, Università di Catania, Catania, Italy
G. Cappello, M. Chiorboli, S. Costa, A. Di Mattia, F. Giordano, R. Potenza,
A. Tricomi, C. Tuve

INFN Sezione di Firenze, Università di Firenze, Firenze, Italy
G. Barbagli, V. Ciulli, C. Civenini, R. D’Alessandro, E. Focardi, V. Gori, P. Lenzi,
M. Meschini, S. Paololetti, G. Sguazzoni, L. Viliani

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

INFN Sezione di Genova, Università di Genova, Genova, Italy
V. Calvelli, F. Ferro, M. Lo Vetere, M.R. Monge, E. Robutti, S. Tosi

INFN Sezione di Milano-Bicocca, Università di Milano-Bicocca, Milano, Italy
L. Brianza, M.E. Dinardo, S. Fioretti, S. Gennai, R. Gerosa, A. Ghezzi, P. Govoni,
S. Malvezzi, R.A. Manzoni, B. Marzocchi, D. Menasce, L. Moroni, M. Paganoni,
D. Pedrini, S. Ragazzi, N. Redaelli, T. Tabarelli de Fatis
Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
S. Song

Korea University, Seoul, Korea
S. Cho, S. Choi, Y. Go, D. Gyun, B. Hong, H. Kim, Y. Kim, B. Lee, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Seoul National University, Seoul, Korea
H.D. Yoo

University of Seoul, Seoul, Korea
M. Choi, 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, D. Kim, E. Kwon, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania
V. Dudenius, 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 Ali, F. Mohamad Idris, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz, A. Hernandez-Almada, R. Lopez-Fernandez, J. Mejia Guisao, A. Sanchez-Hernandez

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
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, T. Khurshid, M. Shoai, 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
G. Brona, K. Bunkowski, A. Byyszuk, 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, F. Nguyen, 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, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, A. Zarubin

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

V. Golovtsov, Y. Ivanov, V. Kim, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, 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. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, E. Vlasov, A. Zhokin

**National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia**

M. Chadeeva, R. Chistov, M. Danilov, V. Rusinov, E. Tarkovskii

**P.N. Lebedev Physical Institute, Moscow, Russia**

P. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov

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

A. Baskakov, A. Belyaev, E. Boos, A. Demiyanov, A. Ershov, A. Gribushin, O. Kodolova, V. Korotkikh, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan

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

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

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

P. Adzic, P. Cirkovic, D. Devetak, J. Milosevic, V. Rekovic

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

J. Alcaraz Maestre, 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, J. Santaolalla, M.S. Soares

**Universidad Autónoma de Madrid, Madrid, Spain**

C. Albajar, J.F. de Trocóniz, M. Missiroli, D. Moran
Universidad de Oviedo, Oviedo, Spain
J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I.J. Cabrillo, A. Calderon, J.R. Castañeiras De Saa, E. Curras, P. De Castro Manzano, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, J. Piedra Gomez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellarò, 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, A. Benaglia, J. Bendavid, L. Benhabib, G.M. Berrutti, P. Bloch, A. Boci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, R. Castello, G. Cerminara, M. D’Alfonso, D. d’Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, F. De Guio, A. De Roeck, S. De Visscher, E. Di Marco, M. Dobson, M. Dordevic, B. Dorney, T. du Pree, D. Duggan, M. Dünser, N. Dupont, A. Elliott-Peisert, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Gele, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, P. Harris, J. Hegeman, V. Innocente, P. Janot, H. Kirschenmann, M.J. Kortelainen, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, M.T. Lucchini, N. Magini, L. Malgeri, M. Mannelli, A. Martelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, M.V. Nemallapudi, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrolli, G. Petracciani, A. Pfeiffer, M. Pierini, D. Piparo, A. Racz, T. Reis, G. Rolandì, M. Rovere, M. Ruan, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, A. Sharma, P. Silva, M. Simon, P. Sphicas, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Triossi, A. Tsirou, G.I. Veres, N. Wardle, H.K. Wöhri, A. Zagozdzinska, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl, K. Deiters, W. Erdmann, 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, L. Perrozzi, M. Quittnat, M. Rossini, M. Schönberger, A. Starodumov, M. Takahashi, V.R. Tavolaro, K. Theofilatos, R. Wällny

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

National Central University, Chung-Li, Taiwan
M. Cardaci, K.H. Chen, T.H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C.M. Kuo, W. Lin, Y.J. Lu, A. Pozdynakov, 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, U. Grundler, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Petrakou, J.f. Tsai, Y.M. Tzeng
Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimanobhas, N. Suwonjandee

Cukurova University, Adana, Turkey
A. Adiguzel, S. Cerci, S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal, A. Kayis Topaksu, G. Onengut, K. Ozdemir, A. Polatoz, B. Tali, H. Topakti, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
B. Bilin, S. Bilmis, B. Isildak, G. Karapinar, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey
E. Gulmez, M. Kaya, O. Kaya, E.A. Yetkin, T. Yetkin

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak, S. Sen, F.I. Vardarlı

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
L. Levchuk, P. Sorokin

University of Bristol, Bristol, United Kingdom
R. Aggleton, F. Ball, L. Beck, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, D. Smith, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom
A. Belyaev, C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cocke, J.A. Coughlan, K. Harder, S. Harper, E. Olaïya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, S.D. Worm

Imperial College, London, United Kingdom
M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauence, G. Davies, A. De Wit, M. Della Negra, P. Dunne, A. Elwood, D. Fuyan, G. Hall, G. Iles, R. Lane, R. Lucas, L. Lyons, A.-M. Magnan, S. Malik, J. Nash, A. Nikitenko, J. Pela, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, C. Seez, A. Tapper, K. Uchida, M. Vazquez Acosta, T. Virdee, 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
G. Rakness, 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, K. Kotov, P. Ma, K. Matchev, H. Mei, P. Milenovic62, G. Mitselmakher, D. Rank, R. Rossin, L. Shchutska, M. Snowball, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

Florida International University, Miami, USA
S. Hewamanage, 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, J. Bochenek, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, A. Khatiwada, H. Prosper, M. Weinberg

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, V. Bhopatkar, S. Colafranceschi63, M. Hohlmann, H. Kalakhety, 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, Z. Wu, M. Zakaria, J. Zhang

The University of Iowa, Iowa City, USA
B. Bilki64, W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya65, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok66, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, USA
I. Anderson, B.A. Barnett, 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
P. Baringer, A. Bean, C. Bruner, R.P. Kenny III, D. Majumder, M. Malek, W. Mcbrayer, M. Murray, S. Sanders, R. Stringer, 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
D. Lange, 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
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. Gulhan, Y. Iiyama, G.M. Innocenti,
M. Klute, D. Kovalskyi, 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, B. Dahmes, A. Evans, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S.C. Kao, K. Klapoetke, 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, F. Meier, J. Monroy, F. Ratnikov, J.E. Siado, G.R. Snow

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, S. Rappoccio, B. Roozbahani

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

Northwestern University, Evanston, USA
S. Bhattacharya, K.A. Hahn, A. Kubik, J.F. Low, N. Mucia, N. Odell, B. Pollack, M. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA
N. Dev, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Marinelli, F. Meng, C. Mueller, Y. Musienko, M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, N. Valls, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA
L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, A. Hart, C. Hill, R. Hughes, W. Ji, T.Y. Ling, B. Liu, W. Luo, D. Puigh, M. Rodenburg, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, USA
O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, 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, D. Benedetti, D. Bortoletto, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, K. Jung, A. Kumar, D.H. Miller, N. Neumeister, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, 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. Eshaq, 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, D. Ferencek, Y. Gershtein, M. Heindl, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, 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, G. Riley, K. Rose, S. Spanier, K. Thapa

Texas A&M University, College Station, USA
O. Bouhali67, A. Castaneda Hernandez67, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon68, V. Krutelyov, R. Mueller, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, A. Rose, A. Safonov, A. Tatarinov, K.A. Ulmer2

Texas Tech University, Lubbock, USA
N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Dudero, J. Faulkner, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, S. Undleeb, I. Volobouev

Vanderbilt University, Nashville, USA
E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, Y. Mao, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, USA
M.W. Arenton, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, J. Wood, F. Xia

Wayne State University, Detroit, USA
C. Clarke, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

University of Wisconsin - Madison, Madison, WI, USA
D.A. Belknap, D. Carlsmith, M. Cepeda, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, T. Ruggles, T. Sarangi, A. Savin, A. Sharma, N. Smith, W.H. Smith, D. Taylor, P. Verwilligen, N. Woods

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
3: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
4: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
5: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
6: Also at Universidade Estadual de Campinas, Campinas, Brazil
7: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France
8: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
9: Also at Joint Institute for Nuclear Research, Dubna, Russia
10: Also at Helwan University, Cairo, Egypt
11: Now at Zewail City of Science and Technology, Zewail, Egypt
12: Also at British University in Egypt, Cairo, Egypt
13: Now at Ain Shams University, Cairo, Egypt
14: Also at Université de Haute Alsace, Mulhouse, France
15: Also at Tbilisi State University, Tbilisi, Georgia
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 Institute of Nuclear Research ATOMKI, Debrecen, Hungary
20: Also at Eötvös Loránd University, Budapest, Hungary
21: Also at University of Debrecen, Debrecen, Hungary
22: Also at Wigner Research Centre for Physics, Budapest, Hungary
23: Also at Indian Institute of Science Education and Research, Bhopal, India
24: Also at University of Visva-Bharati, Santiniketan, India
25: Now at King Abdulaziz University, Jeddah, Saudi Arabia
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 Faculty of Physics, University of Belgrade, Belgrade, Serbia
40: Also at INFN Sezione di Roma; Università di Roma, Roma, Italy
41: Also at National Technical University of Athens, Athens, Greece
42: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
43: Also at National and Kapodistrian University of Athens, Athens, Greece
44: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
45: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
46: Also at Adiyaman University, Adiyaman, Turkey
47: Also at Mersin University, Mersin, Turkey
48: Also at Cag University, Mersin, Turkey
49: Also at Piri Reis University, Istanbul, Turkey
50: Also at Gaziosmanpasa University, Tokat, Turkey
51: Also at Ozyegin University, Istanbul, Turkey
52: Also at Izmir Institute of Technology, Izmir, Turkey
53: Also at Marmara University, Istanbul, Turkey
54: Also at Kafkas University, Kars, Turkey
55: Also at Istanbul Bilgi University, Istanbul, Turkey
56: Also at Yildiz Technical University, Istanbul, Turkey
57: Also at Hacettepe University, Ankara, Turkey
58: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
59: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
60: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
61: Also at Utah Valley University, Orem, USA
62: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
63: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
64: Also at Argonne National Laboratory, Argonne, USA
65: Also at Erzincan University, Erzincan, Turkey
66: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
67: Also at Texas A&M University at Qatar, Doha, Qatar
68: Also at Kyungpook National University, Daegu, Korea