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Upsilon (nS) polarizations versus particle multiplicity in pp collisions at $\sqrt{s}=7$ TeV

Khachatryan, V.

2016-10-10

Khachatryan , V , Eerola , P , Pekkanen , J , Voutilainen , M , Härkönen , J , Karimäki , V , Kinnunen , R , Lampén , T , Lassila-Perini , K , Lehti , S , Lindén , T , Luukka , P , Peltola , T , Tuominiemi , J , Tuovinen , E , Wendland , L , Talvitie , J , Tuuva , T & The CMS Collaboration 2016 , ' Upsilon (nS) polarizations versus particle multiplicity in pp collisions at $\sqrt{s}=7$ TeV ' , Physics Letters B , vol. 761 , pp. 31-52 . <https://doi.org/10.1016/j.physletb.2016.07.065>

<http://hdl.handle.net/10138/174825>

<https://doi.org/10.1016/j.physletb.2016.07.065>

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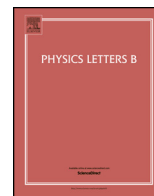
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$\Upsilon(nS)$ polarizations versus particle multiplicity in pp collisions at $\sqrt{s} = 7$ TeV



The CMS Collaboration ^{*}

CERN, Switzerland

ARTICLE INFO

Article history:

Received 9 March 2016

Received in revised form 5 July 2016

Accepted 26 July 2016

Available online 2 August 2016

Editor: M. Doser

Keywords:

CMS

Physics

Quarkonium production

Quarkonium polarization

QCD medium effects

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 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) [1]. Quarkonium production is expected to proceed in two steps [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 are functions of the $Q\bar{Q}$ momentum and are calculated in perturbative QCD [3–6], 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 $^1S_0^{[8]}$, $^3S_1^{[8]}$ and $^3P_J^{[8]}$ 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 [3–7]. Polarization data play a central role in these

analyses [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 $^3S_1^{[8]}$ 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

^{*} E-mail address: cms-publication-committee-chair@cern.ch.

nuclear collisions (see Ref. [8] and references therein) and of their relation to signatures of quark–gluon plasma formation [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 $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ 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 [12]: the $\Upsilon(nS)$ cross sections, normalised by their N_{ch} -integrated values, increase with N_{ch} ; the $\Upsilon(2S)$ and $\Upsilon(3S)$ cross sections, normalised by the $\Upsilon(1S)$ value, decrease with N_{ch} .

The measurements are performed using a dimuon data sample collected in 2011 by the CMS experiment at the CERN LHC, corresponding to an integrated luminosity of 4.9 fb^{-1} , and follow the analysis method used in the N_{ch} -integrated measurement [13]. The dimuon mass distribution is used to separate the $\Upsilon(nS)$ signals from each other and from muon pairs due to other processes, such as decays of heavy flavour mesons. The $\Upsilon(nS)$ polarizations are characterized through three parameters, $\vec{\lambda} = (\lambda_{\vartheta}, \lambda_{\varphi}, \lambda_{\vartheta\varphi})$, reflecting the anisotropy of the angular distribution of the decay muons [14],

$$W(\cos \vartheta, \varphi | \vec{\lambda}) \propto \frac{1}{(3 + \lambda_{\vartheta})} (1 + \lambda_{\vartheta} \cos^2 \vartheta + \lambda_{\varphi} \sin^2 \vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos \varphi), \quad (1)$$

where ϑ and φ are the polar and azimuthal angles, respectively, of the μ^+ . These $\vec{\lambda}$ parameters, as well as the frame-invariant parameter $\tilde{\lambda} = (\lambda_{\vartheta} + 3\lambda_{\varphi}) / (1 - \lambda_{\varphi})$ [15], are measured in the centre-of-mass helicity frame (HX), where the z axis coincides with the direction of the Υ momentum. The y axis of the polarization frame is reversed between positive and negative rapidity, a definition that avoids the cancellation of $\lambda_{\vartheta\varphi}$ when integrating events over a symmetrical range in rapidity. This is explained in Ref. [16], which provides a pedagogical introduction to quarkonium polarization physics. As in the previous CMS quarkonium polarization measurements [13,17], the analysis is exclusively based on measured data: the 3-momentum vectors of the two muons (containing the spin alignment information of the decaying $\Upsilon(nS)$ mesons) and the muon detection efficiencies.

2. CMS detector and data analysis

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 $8.5 < M < 11.5 \text{ GeV}$, $|y| < 1.25$ and $p_T > 5$ or 7 GeV (depending on the instantaneous luminosity); the dimuon vertex fit χ^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

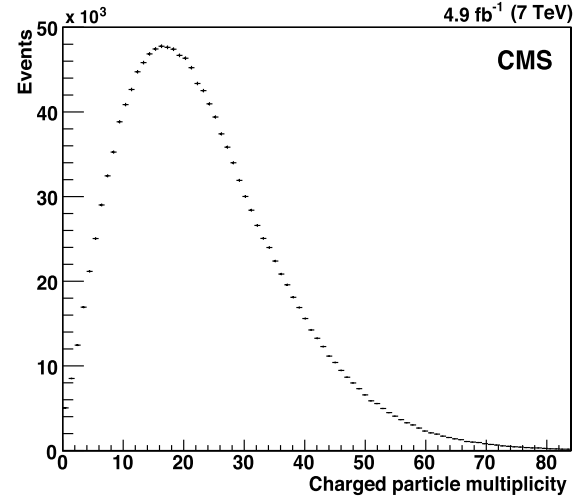


Fig. 1. Charged particle multiplicity distribution of the events selected for the analysis.

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 χ^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 line is selected. The N_{ch} variable is computed by counting “high purity” [19] charged tracks, excluding the two muons, of $|\eta| < 2.4$, $p_T > 500 \text{ MeV}$, 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_{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. Fig. 1 shows the N_{ch} distribution of the events selected in this 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 $\sigma \approx 80 \text{ MeV}$, slightly dependent on p_T . The $\Upsilon(nS)$ signal mass regions are defined as the $\pm 1\sigma$ 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_{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 $\Upsilon(nS)$ p_T ranges, 10–15 and 15–35 GeV. The dimuons are integrated within $|y| < 1.2$. The lower p_T $\Upsilon(3S)$ polarization

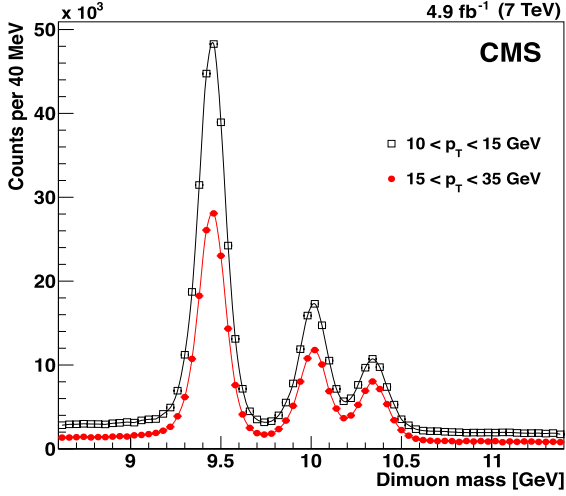


Fig. 2. Dimuon mass distributions in the $\Upsilon(nS)$ region for two p_T ranges.

measurement merges the two highest N_{ch} bins, to reduce the background-related systematic uncertainties. In the lowest N_{ch} bin, the background fractions in the signal mass regions, f_{Bg} , are approximately 3%, 7%, and 10% for the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$, respectively. The corresponding values in the highest N_{ch} bin are ~ 4 and ~ 2.5 times higher in the 10–15 and 15–35 GeV p_T ranges, respectively. All analysis bins have signal yields sufficiently high for a reliable measurement, the worst case being the 2300 $\Upsilon(3S)$ events in the highest N_{ch} bin at high p_T . All signal yields and background fractions are tabulated in the supplemental material.

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 $|\eta|$ 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 $\Upsilon(nS)$ 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 $\cos\vartheta$ 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 $\cos\vartheta$ and φ , of the background corresponding to a given $\Upsilon(nS)$ state is evaluated as a weighted average of the distributions measured in the two mass sidebands, the weights reflecting (linearly) the differences between the $\Upsilon(nS)$ mass and the median masses of the sidebands. The background component is subtracted on an event-by-event basis using a likelihood-ratio criterion, randomly selecting and removing a fraction f_{Bg} of events distributed according to the $(p_T, |y|, M, \cos\vartheta, \varphi)$ distribution of the background model [13]. The posterior probability density (PPD) for the average values of the $\Upsilon(nS)$ polarization parameters ($\vec{\lambda}$) inside a particular

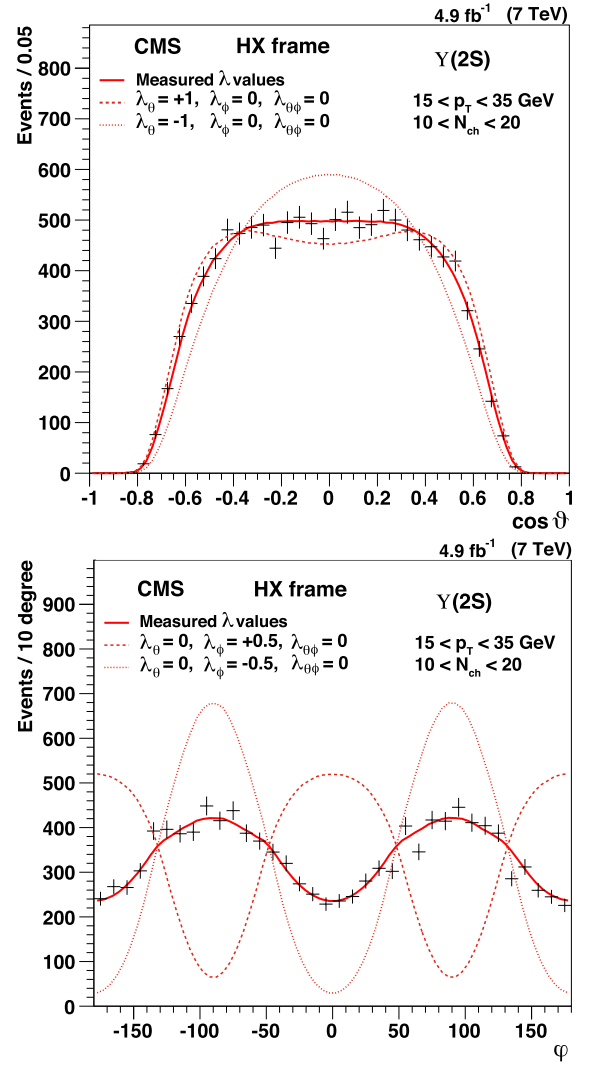


Fig. 3. Distributions of $\cos\vartheta$ (top) and φ (bottom), for the $\Upsilon(2S)$ in a representative analysis bin. The curves represent two polarization scenarios (dashed and dotted lines, defined in the legends) and the measured case (solid lines): $\lambda_\vartheta = 0.237$, $\lambda_\varphi = -0.027$, $\lambda_{\vartheta\varphi} = -0.025$.

bin is then defined as a product over the remaining (signal-like) events i ,

$$\mathcal{P}(\vec{\lambda}) = \prod_i \mathcal{E}(\vec{p}_1^{(i)}, \vec{p}_2^{(i)}), \quad (2)$$

where \mathcal{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 $(\cos\vartheta, \varphi)$ acceptance maps; each event is attributed a probability reflecting the full event kinematics (not only $\cos\vartheta$ and φ) and the values of the polarization parameters,

$$\mathcal{E}(\vec{p}_1, \vec{p}_2) = \frac{1}{\mathcal{N}(\vec{\lambda})} W(\cos\vartheta, \varphi|\vec{\lambda}) \epsilon(\vec{p}_1, \vec{p}_2), \quad (3)$$

where $\epsilon(\vec{p}_1, \vec{p}_2)$ is the measured detection efficiency. The normalization factor $\mathcal{N}(\vec{\lambda})$ is calculated by integrating $W \cdot \epsilon$ over $\cos\vartheta$ 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.

Fig. 3 compares the $\cos\vartheta$ and φ distributions measured for $\Upsilon(2S)$ 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 φ 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 ~ 0.1 for λ_ϑ and ~ 0.03 – 0.05 for λ_φ and $\lambda_{\vartheta\varphi}$, slightly increasing with N_{ch} . The corresponding $\Upsilon(2S)$ and $\Upsilon(3S)$ values are slightly larger: ~ 0.2 for λ_ϑ , ~ 0.04 for λ_φ , and ~ 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 λ parameters are measured with negligible correlations, as illustrated by Fig. 4, which shows the two-dimensional marginals of the PPD in the λ_φ vs. λ_ϑ and $\lambda_{\vartheta\varphi}$ vs. λ_φ planes, for a representative analysis bin.

Fig. 5 shows the λ_ϑ , λ_φ , $\lambda_{\vartheta\varphi}$, and $\tilde{\lambda}$ values measured in the HX frame for the three $\Upsilon(nS)$ states, in both p_T ranges. The corresponding numerical results are tabulated in the supplemental material. 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 Υ 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 $\Upsilon(1S)$ results, all the λ 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 $\Upsilon(1S)$ production between low- and high-multiplicity pp collisions. The measurements are compatible with a non-negligible fraction of $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons being produced via the transversely polarized $^3S_1^{[8]}$ octet term. Given the present uncertainties,

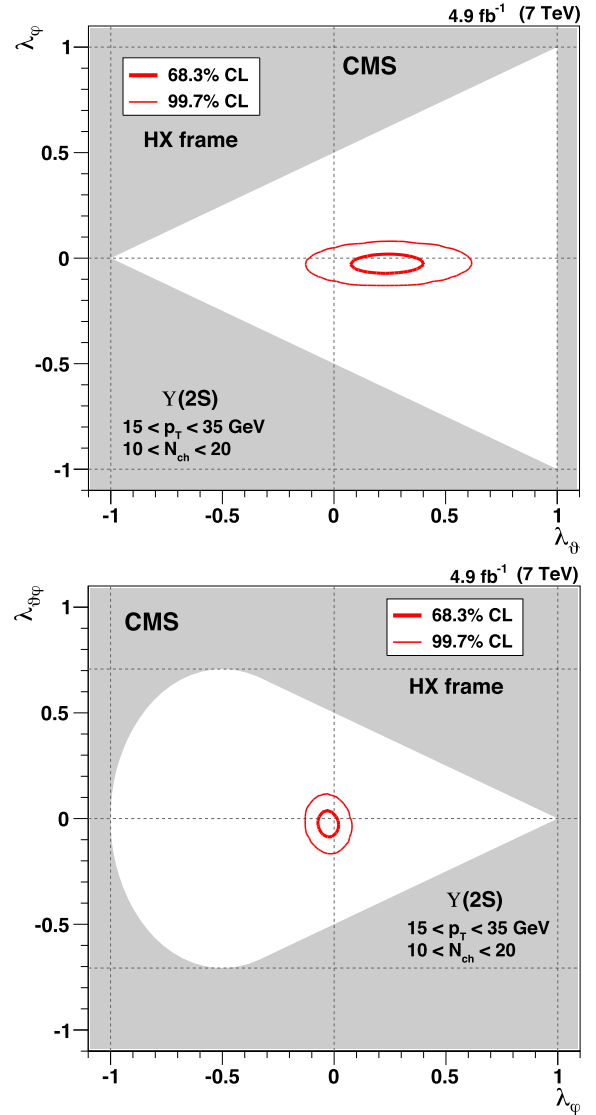


Fig. 4. Two-dimensional marginals of the PPD for the HX frame in the λ_φ vs. λ_ϑ (top) and $\lambda_{\vartheta\varphi}$ vs. λ_φ (bottom) planes, for $\Upsilon(2S)$ with $15 < p_T < 35$ GeV and $10 < N_{\text{ch}} < 20$, displaying the 68.3% and 99.7% CL total uncertainties. The shaded areas represent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

no clear trends can be seen regarding changes of their polarizations with N_{ch} .

To place these results into context, Fig. 6-top illustrates how the λ_ϑ parameter would change as a function of N_{ch} if quarkonium production would be dominated by two processes, one unpolarized ($\lambda_\vartheta = 0$, as is the case for the $^1S_0^{[8]}$ octet) and the other fully transversely polarized in the HX frame ($\lambda_\vartheta = +1$, as for the $^3S_1^{[8]}$ octet, at high enough p_T). The four curves represent different variations with N_{ch} (linearly in the $0 < N_{\text{ch}} < 60$ 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 different processes, of polarizations λ_0 and λ_1 , depends on f as [25]

$$\lambda(f) = \left[\frac{(1-f)\lambda_0}{3+\lambda_0} + \frac{f\lambda_1}{3+\lambda_1} \right] / \left[\frac{1-f}{3+\lambda_0} + \frac{f}{3+\lambda_1} \right]. \quad (4)$$

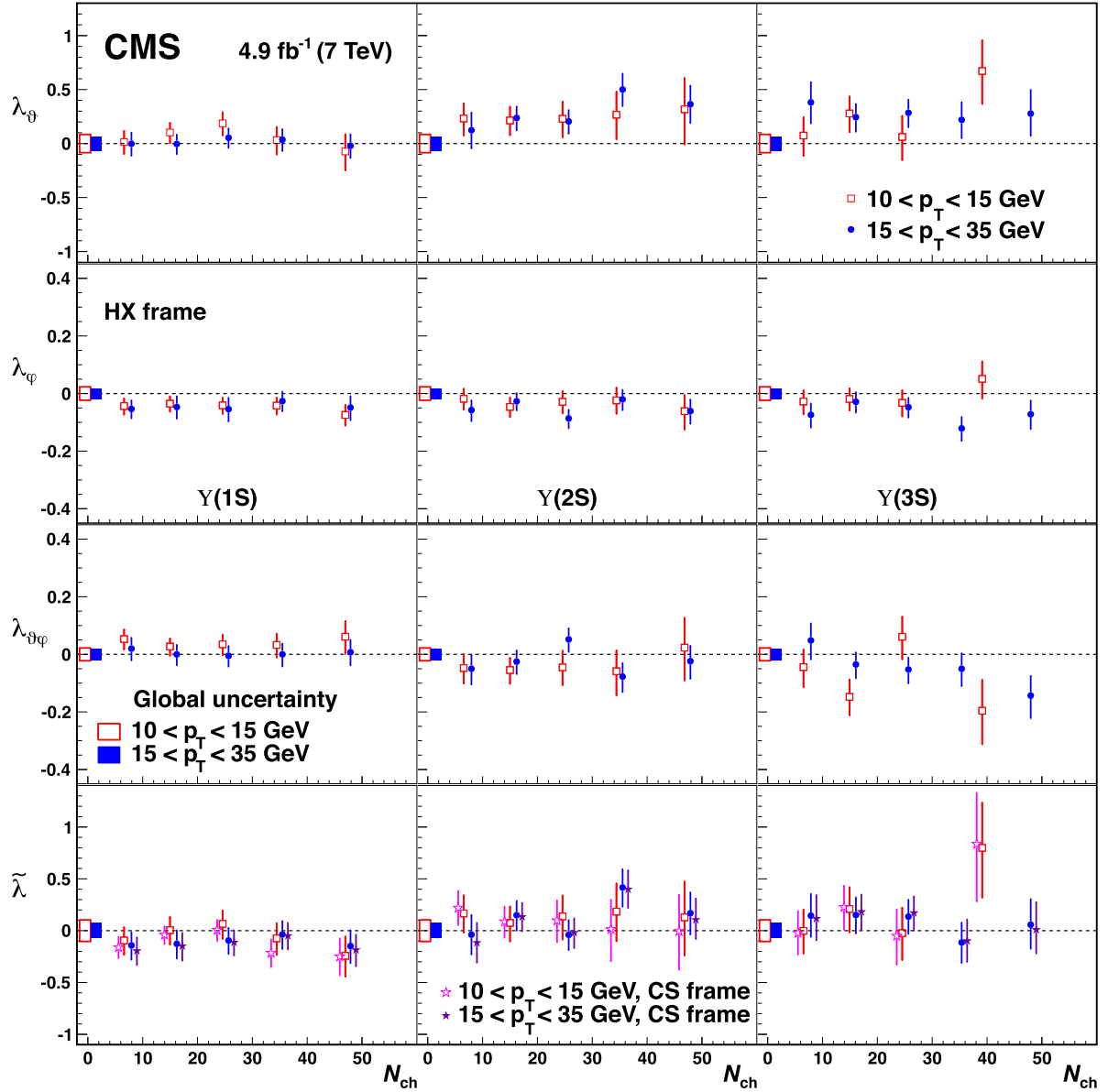


Fig. 5. The λ_θ , λ_ϕ , $\lambda_{\theta\phi}$, and $\tilde{\lambda}$ parameters (top to bottom) for the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ states (left to right), in the HX frame, as a function of N_{ch} , for both p_T ranges. The $\tilde{\lambda}$ values are also shown for the CS frame; 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.

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 $\Upsilon(nS)$ λ 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 $\Upsilon(nS)$ 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 $\Upsilon(1S)$ 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 $\Upsilon(nS)$ polarizations, for lack of information regarding the χ_b polarizations and their feed-down fractions. Fig. 6-bottom shows how the measured (inclusive) polarization is expected to change as a function of N_{ch} if the directly-produced component (of polarization λ_0) is complemented by a feed-down component (of polarization λ_1) that contributes with a fraction f , decreasing linearly with N_{ch} from 50% to 0 in the $0 < N_{ch} < 60$ range. The six curves correspond to different assumptions for λ_0 and λ_1 , reported in the legends, with λ_1 representing an effective average of the χ_{b1} and χ_{b2} polarizations (the χ_{b1} and χ_{b2} λ_θ 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_{ch} , where the inclusive λ_θ tends to the direct λ_0 value. At low N_{ch} , where the feed-down contribution is, hypothetically, the highest, the inclusive λ_θ parameter crucially depends on the assumed χ_b polarization.

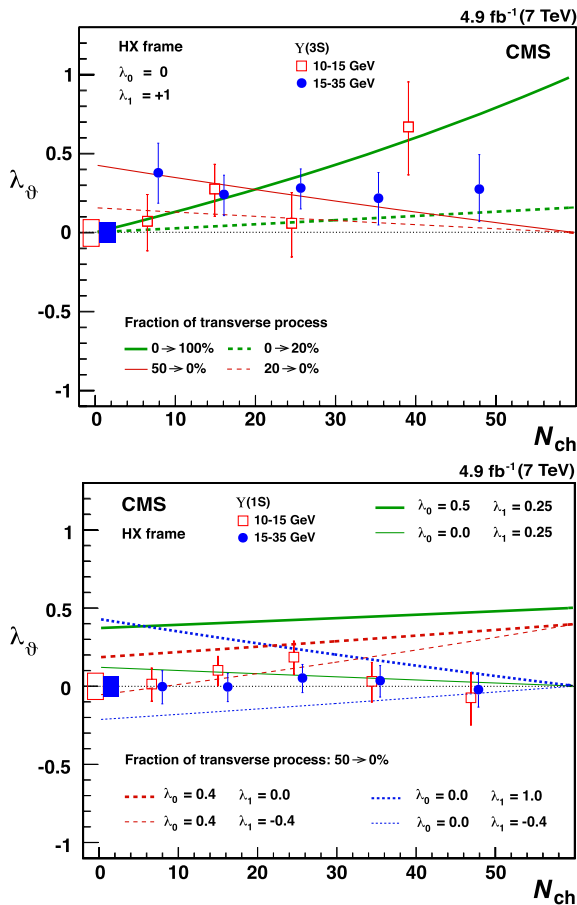


Fig. 6. Expected N_{ch} -dependences of the λ_{θ} parameter for the sum of two processes, of polarizations λ_0 and λ_1 , of relative fractions changing linearly with N_{ch} (see text for details). The measured λ_{θ} values are also shown, for the $\Upsilon(3S)$ (top) and $\Upsilon(1S)$ (bottom).

5. Summary

The polarizations of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ 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 $p\text{Pb}$ 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.

Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses.

Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); F.R.S. - FNRS and FWO (Belgium); CNPQ, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MOST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); MoER, ERC IUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEC (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Research Council and ELPLANET (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund; the OPUS programme of the National Science Center (Poland); the Compagnia di San Paolo (Torino); MIUR project 20108T4XTM (Italy); the Thalís and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the National Priorities Research Program by Qatar National Research Fund; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University (Thailand); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); and the Welch Foundation, contract C-1845.

Appendix A. Supplementary material

Supplementary material related to this article can be found online at <http://dx.doi.org/10.1016/j.physletb.2016.07.065>.

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The CMS Collaboration

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

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, 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. Schöffbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz¹

Institut für Hochenergiephysik der OeAW, Wien, Austria

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

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

S. Alderweireldt, 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 Spilbeek

Universiteit Antwerpen, Antwerpen, 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

Vrije Universiteit Brussel, Brussel, 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

Université Libre de Bruxelles, Bruxelles, Belgium

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

Ghent University, Ghent, Belgium

S. Basegmez, C. Beluffi⁴, O. Bondu, S. Brochet, G. Bruno, A. Caudron, L. Ceard, C. Delaere, D. Favart, L. Forthomme, A. Giammanco, A. Jafari, P. Jez, M. Komm, V. Lemaître, A. Mertens, M. Musich, C. Nuttens, L. Perrini, K. Piotrkowski, A. Popov⁵, L. Quertenmont, M. Selvaggi, M. Vidal Marono

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

N. Belyi, G.H. Hammad

Université de Mons, Mons, Belgium

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

Centro Brasileiro de Pesquisas Físicas, 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 do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

S. Ahuja^a, C.A. Bernardes^b, A. De Souza Santos^b, S. Dogra^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, C.S. Moon^{a,7}, S.F. Novaes^a, Sandra S. Padula^a, D. Romero Abad^b, J.C. Ruiz Vargas

^a Universidade Estadual Paulista, São Paulo, Brazil

^b Universidade Federal do ABC, São Paulo, Brazil

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

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

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

University of Sofia, Sofia, Bulgaria

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, D. Leggat, R. Plestina⁸, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, H. Zhang

Institute of High Energy Physics, Beijing, China

C. Asawatrangkuldee, Y. Ban, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

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

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

Universidad de Los Andes, Bogota, Colombia

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

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

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, K. Kadija, J. Luetic, S. Micanovic, L. Sudic

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

M. Bodlak, M. Finger⁹, M. Finger Jr.⁹

Charles University, Prague, Czech Republic

A.A. Abdelalim^{10,11}, A. Awad, A. Mahrous¹⁰, A. Radi^{12,13}

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

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

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, J. Pekkanen, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

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

Helsinki Institute of Physics, Helsinki, Finland

J. Talvitie, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

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

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

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

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

J.-L. Agram¹⁴, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte¹⁴, X. Coubez, J.-C. Fontaine¹⁴, D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, J.A. Merlin², K. Skovpen, P. Van Hove

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

S. Gadrat

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

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

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

T. Toriashvili¹⁵

Georgian Technical University, Tbilisi, Georgia

Z. Tsamalaidze⁹

Tbilisi State University, Tbilisi, Georgia

C. Autermann, S. Beranek, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, S. Schael, J.F. Schulte, T. Verlage, H. Weber, V. Zhukov⁵

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

M. Ata, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, P. Kreuzer, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, P. Papacz, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teyssier, S. Thüer

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

V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, F. Hoehle, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, A. Nehrkorn, A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl

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

M. Aldaya Martin, I. Asin, N. Bartosik, O. Behnke, U. Behrens, K. Borras¹⁶, A. Burgmeier, A. Campbell, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Dolinska, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, E. Gallo¹⁷, J. Garay Garcia, A. Geiser, A. Gizhko, P. Gunnellini, J. Hauk, M. Hempel¹⁸, H. Jung, A. Kalogeropoulos, O. Karacheban¹⁸, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann¹⁸, R. Mankel, I.-A. Melzer-Pellmann, 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

Deutsches Elektronen-Synchrotron, 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. Scharf, P. Schleper, E. Schlieckau, A. Schmidt, S. Schumann, J. Schwandt, V. Sola, H. Stadie, G. Steinbrück, F.M. Stober, H. Tholen, D. Troendle, E. Usai, L. Vanelderden, A. Vanhoefer, B. Vormwald

University of Hamburg, Hamburg, 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. Frensch, 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. Schröder, G. Sieber, H.J. Simonis, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

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

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

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

National and Kapodistrian University of Athens, Athens, Greece

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

University of Ioánnina, Ioánnina, Greece

G. Bencze, C. Hajdu, A. Hazi, P. Hidas, D. Horvath¹⁹, F. Sikler, V. Veszpremi, G. Vesztergombi²⁰, A.J. Zsigmond

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi²¹, J. Molnar, Z. Szillasi²

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

M. Bartók²², A. Makovec, P. Raics, Z.L. Trocsanyi, B. Ujvari

University of Debrecen, Debrecen, Hungary

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

National Institute of Science Education and Research, Bhubaneswar, India

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

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, 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

Saha Institute of Nuclear Physics, Kolkata, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty², L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Banerjee, S. Bhowmik²⁴, R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu²⁵, Sa. Jain, G. Kole, S. Kumar, B. Mahakud, M. Maity²⁴, G. Majumder, K. Mazumdar, S. Mitra, G.B. Mohanty, B. Parida, T. Sarkar²⁴, N. Sur, B. Sutar, N. Wickramage²⁶

Tata Institute of Fundamental Research, Mumbai, India

S. Chauhan, S. Dube, A. Kapoor, K. Kotheekar, S. Sharma

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

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

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia^{a,b}, C. Calabria^{a,b}, C. Caputo^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, G. Maggi^{a,c}, M. Maggi^a, G. Miniello^{a,b}, S. My^{a,c}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^{a,b}, A. Ranieri^a, G. Selvaggi^{a,b}, L. Silvestris^{a,2}, R. Venditti^{a,b}

^a INFN Sezione di Bari, Bari, Italy

^b Università di Bari, Bari, Italy

^c Politecnico di Bari, Bari, Italy

G. Abbiendi^a, C. Battilana², D. Bonacorsi^{a,b}, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, S.S. Chhibra^{a,b}, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b},

S. Marcellini^a, G. Masetti^a, A. Montanari^a, F.L. Navarria^{a,b}, A. Perrotta^a, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^{a,b,2}

^a INFN Sezione di Bologna, Bologna, Italy

^b Università di Bologna, Bologna, Italy

G. Cappello^b, M. Chiorboli^{a,b}, S. Costa^{a,b}, A. Di Mattia^a, F. Giordano^{a,b}, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

^a INFN Sezione di Catania, Catania, Italy

^b Università di Catania, Catania, Italy

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, V. Gori^{a,b}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, L. Viliani^{a,b,2}

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera²

INFN Laboratori Nazionali di Frascati, Frascati, Italy

V. Calvelli^{a,b}, F. Ferro^a, M. Lo Vetere^{a,b}, M.R. Monge^{a,b}, E. Robutti^a, S. Tosi^{a,b}

^a INFN Sezione di Genova, Genova, Italy

^b Università di Genova, Genova, Italy

L. Brianza, M.E. Dinardo^{a,b}, S. Fiorendi^{a,b}, S. Gennai^a, R. Gerosa^{a,b}, A. Ghezzi^{a,b}, P. Govoni^{a,b}, S. Malvezzi^a, R.A. Manzoni^{a,b,2}, B. Marzocchi^{a,b}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, N. Redaelli^a, T. Tabarelli de Fatis^{a,b}

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

^b Università di Milano-Bicocca, Milano, Italy

S. Buontempo^a, N. Cavallo^{a,c}, S. Di Guida^{a,d,2}, M. Esposito^{a,b}, F. Fabozzi^{a,c}, A.O.M. Iorio^{a,b}, G. Lanza^a, L. Lista^a, S. Meola^{a,d,2}, M. Merola^a, P. Paolucci^{a,2}, C. Sciacca^{a,b}, F. Thyssen

^a INFN Sezione di Napoli, Napoli, Italy

^b Università di Napoli "Federico II", Napoli, Italy

^c Università della Basilicata, Potenza, Italy

^d Università G. Marconi, Roma, Italy

P. Azzi^{a,2}, N. Bacchetta^a, L. Benato^{a,b}, D. Bisello^{a,b}, A. Boletti^{a,b}, R. Carlin^{a,b}, P. Checchia^a, M. Dall'Osso^{a,b,2}, T. Dorigo^a, U. Dosselli^a, F. Fanzago^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, F. Gonella^a, A. Gozzelino^a, S. Lacaprara^a, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, M. Michelotto^a, J. Pazzini^{a,b,2}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Tosi^{a,b}, M. Zanetti, P. Zotto^{a,b}, A. Zucchetta^{a,b,2}, G. Zumerle^{a,b}

^a INFN Sezione di Padova, Padova, Italy

^b Università di Padova, Padova, Italy

^c Università di Trento, Trento, Italy

A. Braghieri^a, A. Magnani^{a,b}, P. Montagna^{a,b}, S.P. Ratti^{a,b}, V. Re^a, C. Riccardi^{a,b}, P. Salvini^a, I. Vai^{a,b}, P. Vitulo^{a,b}

^a INFN Sezione di Pavia, Pavia, Italy

^b Università di Pavia, Pavia, Italy

L. Alunni Solestizi^{a,b}, G.M. Bilei^a, D. Ciangottini^{a,b,2}, L. Fanò^{a,b}, P. Lariccia^{a,b}, G. Mantovani^{a,b}, M. Menichelli^a, A. Saha^a, A. Santocchia^{a,b}

^a INFN Sezione di Perugia, Perugia, Italy

^b Università di Perugia, Perugia, Italy

K. Androsov^{a,30}, P. Azzurri^{a,2}, G. Bagliesi^a, J. Bernardini^a, T. Boccali^a, R. Castaldi^a, M.A. Ciocci^{a,30}, R. Dell'Orso^a, S. Donato^{a,c,2}, G. Fedi, L. Foà^{a,c,†}, A. Giassi^a, M.T. Grippo^{a,30}, F. Ligabue^{a,c}, T. Lomtadze^a

L. Martini ^{a,b}, A. Messineo ^{a,b}, F. Palla ^a, A. Rizzi ^{a,b}, A. Savoy-Navarro ^{a,31}, A.T. Serban ^a, P. Spagnolo ^a, R. Tenchini ^a, G. Tonelli ^{a,b}, A. Venturi ^a, P.G. Verdini ^a

^a INFN Sezione di Pisa, Pisa, Italy

^b Università di Pisa, Pisa, Italy

^c Scuola Normale Superiore di Pisa, Pisa, Italy

L. Barone ^{a,b}, F. Cavallari ^a, G. D'imperio ^{a,b,2}, D. Del Re ^{a,b,2}, M. Diemoz ^a, S. Gelli ^{a,b}, C. Jorda ^a, E. Longo ^{a,b}, F. Margaroli ^{a,b}, P. Meridiani ^a, G. Organtini ^{a,b}, R. Paramatti ^a, F. Preiato ^{a,b}, S. Rahatlou ^{a,b}, C. Rovelli ^a, F. Santanastasio ^{a,b}, P. Traczyk ^{a,b,2}

^a INFN Sezione di Roma, Roma, Italy

^b Università di Roma, Roma, Italy

N. Amapane ^{a,b}, R. Arcidiacono ^{a,c,2}, S. Argiro ^{a,b}, M. Arneodo ^{a,c}, R. Bellan ^{a,b}, C. Biino ^a, N. Cartiglia ^a, M. Costa ^{a,b}, R. Covarelli ^{a,b}, A. Degano ^{a,b}, N. Demaria ^a, L. Finco ^{a,b,2}, B. Kiani ^{a,b}, C. Mariotti ^a, S. Maselli ^a, E. Migliore ^{a,b}, V. Monaco ^{a,b}, E. Monteil ^{a,b}, M.M. Obertino ^{a,b}, L. Pacher ^{a,b}, N. Pastrone ^a, M. Pelliccioni ^a, G.L. Pinna Angioni ^{a,b}, F. Ravera ^{a,b}, A. Romero ^{a,b}, M. Ruspa ^{a,c}, R. Sacchi ^{a,b}, A. Solano ^{a,b}, A. Staiano ^a

^a INFN Sezione di Torino, Torino, Italy

^b Università di Torino, Torino, Italy

^c Università del Piemonte Orientale, Novara, Italy

S. Belforte ^a, V. Candelise ^{a,b}, M. Casarsa ^a, F. Cossutti ^a, G. Della Ricca ^{a,b}, B. Gobbo ^a, C. La Licata ^{a,b}, M. Marone ^{a,b}, A. Schizzi ^{a,b}, A. Zanetti ^a

^a INFN Sezione di Trieste, Trieste, Italy

^b Università di Trieste, Trieste, Italy

A. Kropivnitskaya, S.K. Nam

Kangwon National University, Chunchon, Republic of Korea

D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, A. Sakharov, D.C. Son

Kyungpook National University, Daegu, Republic of Korea

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

Chonbuk National University, Jeonju, Republic of Korea

S. Song

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Republic of 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

Korea University, Seoul, Republic of Korea

H.D. Yoo

Seoul National University, Seoul, Republic of Korea

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

University of Seoul, Seoul, Republic of Korea

Y. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

V. Dudenias, A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

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

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

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

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

S. Carrillo Moreno, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

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

D. Krofcheck

University of Auckland, Auckland, New Zealand

P.H. Butler

University of Canterbury, Christchurch, New Zealand

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

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

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

National Centre for Nuclear Research, Swierk, Poland

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

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

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

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

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

Joint Institute for Nuclear Research, Dubna, Russia

V. Golovtsov, Y. Ivanov, V. Kim³⁸, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

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

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

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

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

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

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

P.N. Lebedev Physical Institute, Moscow, Russia

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

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

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

P. Adzic³⁹, P. Cirkovic, D. Devetak, J. Milosevic, V. Rekovic

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

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

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

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

Universidad Autónoma de Madrid, Madrid, Spain

J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, J.M. Vizán García

Universidad de Oviedo, Oviedo, Spain

I.J. Cabrillo, A. Calderon, J.R. Castiñeiras 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. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, G.M. Berruti, P. Bloch, A. Bocci, 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 Marco⁴⁰, 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. Glege, 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. Orfanelli⁴¹, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, A. Racz, T. Reis, G. Rolandi⁴², M. Rovere, M. Ruan, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, A. Sharma, P. Silva, M. Simon,

P. Sphicas⁴³, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Triossi, A. Tsirou, G.I. Veres²⁰, N. Wardle, H.K. Wöhri, A. Zagozdzińska³⁵, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

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

Paul Scherrer Institut, Villigen, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, P. Eller, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, P. Lecomte[†], W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, L. Perrozzi, M. Quittnat, M. Rossini, M. Schönenberger, A. Starodumov⁴⁴, M. Takahashi, V.R. Tavolaro, K. Theofilatos, R. Wallny

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

T.K. Aarrestad, C. AMSler⁴⁵, L. Caminada, M.F. Canelli, V. Chiochia, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, Y. Yang

Universität Zürich, Zurich, Switzerland

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

National Central University, Chung-Li, Taiwan

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

National Taiwan University (NTU), Taipei, Taiwan

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

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

A. Adiguzel, S. Cerci⁴⁶, S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal⁴⁷, A. Kayis Topaksu, G. Onengut⁴⁸, K. Ozdemir⁴⁹, A. Polatoz, B. Tali⁴⁶, H. Topakli⁵⁰, C. Zorbilmez

Cukurova University, Adana, Turkey

B. Bilin, S. Bilmis, B. Isildak⁵¹, G. Karapinar⁵², M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, M. Kaya⁵³, O. Kaya⁵⁴, E.A. Yetkin⁵⁵, T. Yetkin⁵⁶

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak, S. Sen⁵⁷, F.I. Vardarli

Istanbul Technical University, Istanbul, Turkey

B. Grynyov

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

L. Levchuk, P. Sorokin

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

R. Aggleton, F. Ball, L. Beck, J.J. Brooke, 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. Newbold⁵⁸, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, D. Smith, V.J. Smith

University of Bristol, Bristol, United Kingdom

A. Belyaev⁵⁹, C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, S.D. Worm

Rutherford Appleton Laboratory, Didcot, United Kingdom

M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, P. Dunne, A. Elwood, D. Futyan, G. Hall, G. Iles, R. Lane, R. Lucas⁵⁸, L. Lyons, A.-M. Magnan, S. Malik, J. Nash, A. Nikitenko⁴⁴, J. Pela, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, C. Seez, A. Tapper, K. Uchida, M. Vazquez Acosta⁶⁰, T. Virdee, S.C. Zenz

Imperial College, London, United Kingdom

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

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, USA

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

The University of Alabama, Tuscaloosa, USA

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

Boston University, Boston, USA

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

Brown University, Providence, USA

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

University of California, Davis, Davis, USA

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

University of California, Los Angeles, USA

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

University of California, Riverside, Riverside, USA

J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D'Agnolo, M. Derdzinski, A. Holzner, R. Kelley, D. Klein, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech⁶¹, C. Welke, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, San Diego, La Jolla, USA

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

University of California, Santa Barbara, Santa Barbara, USA

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

California Institute of Technology, Pasadena, USA

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

Carnegie Mellon University, Pittsburgh, USA

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

University of Colorado Boulder, Boulder, USA

J. Alexander, A. Chatterjee, J. Chaves, J. Chu, S. Dittmer, N. Eggert, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, W. Sun, S.M. Tan, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, P. Wittich

Cornell University, Ithaca, USA

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

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, S. Das, R.D. Field, I.K. Furic, J. Konigsberg, A. Korytov, 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

University of Florida, Gainesville, USA

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

Florida International University, Miami, USA

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

Florida State University, Tallahassee, USA

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi⁶³, M. Hohlmann, H. Kalakhety, D. Noonan, T. Roy, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

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

University of Illinois at Chicago (UIC), Chicago, 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

The University of Iowa, Iowa City, 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

Johns Hopkins University, Baltimore, 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

The University of Kansas, Lawrence, USA

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

Kansas State University, Manhattan, USA

D. Lange, F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

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

University of Maryland, College Park, USA

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

Massachusetts Institute of Technology, Cambridge, 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 Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

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

University of Nebraska–Lincoln, Lincoln, USA

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

State University of New York at Buffalo, Buffalo, 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

Northeastern University, Boston, 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

Northwestern University, Evanston, USA

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

University of Notre Dame, Notre Dame, 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

The Ohio State University, Columbus, 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

Princeton University, Princeton, USA

S. Malik

University of Puerto Rico, Mayaguez, 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, West Lafayette, USA

N. Parashar, J. Stupak

Purdue University Calumet, Hammond, USA

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

Rice University, Houston, USA

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

University of Rochester, Rochester, USA

J.P. Chou, E. Contreras-Campana, D. Ferencek, Y. Gershtein, E. Halkiadakis, 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

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

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

University of Tennessee, Knoxville, 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 A&M University, College Station, USA

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

Texas Tech University, Lubbock, 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

Vanderbilt University, Nashville, 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

University of Virginia, Charlottesville, USA

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

Wayne State University, Detroit, 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

University of Wisconsin–Madison, Madison, WI, USA

† 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, Republic of Korea.