EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2018-056
2019/02/14

CMS-HIN-16-015

Measurement of prompt $\psi(2S)$ production cross sections in proton-lead and proton-proton collisions at $\sqrt{s_{NN}} = 5.02$ TeV

The CMS Collaboration*

Abstract

Measurements of prompt $\psi(2S)$ meson production cross sections in proton-lead (pPb) and proton-proton (pp) collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{NN}}$ = 5.02 TeV are reported. The results are based on pPb and pp data collected by the CMS experiment at the LHC, corresponding to integrated luminosities of 34.6 nb^{-1} and 28.0 pb^{-1}, respectively. The nuclear modification factor R_{pPb} is measured for prompt $\psi(2S)$ in the transverse momentum range $4 < p_T < 30$ GeV/c and the center-of-mass rapidity range $-2.4 < y_{CM} < 1.93$. The results on $\psi(2S)$ R_{pPb} are compared to the corresponding modification factor for prompt J/ψ mesons. The results point to different nuclear effects at play in the production of the excited charmonium state compared to the ground state, in the region of backward rapidity and for $p_T < 10$ GeV/c.

Published in Physics Letters B as doi:10.1016/j.physletb.2019.01.058.

*See Appendix A for the list of collaboration members

1 Introduction

The study of quarkonium production in nuclear collisions has a long and rich history, dating back to the original proposal by Matsui and Satz predicting J/ψ suppression in heavy ion collisions due to Debye screening in the quark-gluon plasma (QGP) [1]. After this proposal, the first J/ψ measurements in heavy ion collisions were performed in fixed target experiments at the CERN SPS, at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{_{\mathrm{NN}}}} \approx 20\,\mathrm{GeV}$ [2, 3]. A similar level of suppression was later observed in gold-gold collisions at the BNL RHIC, at $\sqrt{s_{_{\mathrm{NN}}}} = 200\,\mathrm{GeV}$ [4, 5]. At the CERN LHC, the production of charmonium (J/ψ, $\psi(2S)$) and bottomonium ($\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$) states has been studied in lead-lead (PbPb) collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 2.76$ and $5.02\,\mathrm{TeV}$ [6–12], bringing new elements for the understanding of the medium produced in high-energy heavy ion collisions.

The quarkonium yields can be modified in heavy ion collisions because of several effects [13], including suppression [1] and recombination of charm quark pairs [14] inside the hot matter (QGP), and cold nuclear matter effects. An unambiguous interpretation of the nucleus-nucleus LHC results requires a quantitative understanding of cold nuclear matter effects. The nuclear parton distribution functions (nPDFs) are known to be different from those in a free proton [15, 16]. In addition, gluon radiation induced by multiple parton scattering in the nucleus leads to transverse momentum (p_{T}) broadening and coherent energy loss, resulting in a significant quarkonium suppression in nuclear collisions at all available energies [17, 18]. These phenomena are best studied in proton-nucleus collisions, in which hot medium effects, such as those due to the QGP, are likely to be limited.

Many charmonium production measurements have been performed in proton-induced collisions, on several nuclei, at the SPS [19–22], HERA [23], and Tevatron [24]. A global analysis of the fixed-target measurements can be found in Ref. [25]. At RHIC, J/ψ and $\psi(2S)$ data in deuteron-gold collisions have been reported by the PHENIX [26] and STAR [27] Collaborations. At the LHC, the cross section of J/ψ in proton-lead (pPb) collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$ has been measured by the ALICE [28, 29], ATLAS [30], CMS [31], and LHCb [32] Collaborations. A significant suppression of the prompt J/ψ yield in pPb collisions has been observed at forward rapidity (y) and low p_{T}, while no strong nuclear effects are reported at backward rapidity, where forward and backward indicate, respectively, the directions of the proton and Pb beams. Measurements of the $\Upsilon(1S)$ in pPb collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$ have also been performed by the ALICE [33], ATLAS [34], and LHCb [35] experiments, indicating that the $\Upsilon(1S)$ state is less suppressed than the J/ψ.

Additional information can be obtained by studying the behavior of the excited states, which are less tightly bound compared to the ground states and might suffer stronger suppression in heavy ion collisions. At the LHC, the ALICE [36] and CMS [11] Collaborations have reported a stronger suppression of the $\psi(2S)$ state compared to the J/ψ in PbPb collisions. In pPb collisions, ALICE [37], ATLAS [34], and LHCb [38] data show that $\psi(2S)$ suppression, integrated over transverse momentum, is more pronounced than that of the J/ψ. This observation suggests final-state effects for the excited states, possibly due to inelastic interactions with the medium produced in pPb collisions [39]. In the bottomonium sector, the double yield ratios $\Upsilon(3S)/\Upsilon(1S)$ and $\Upsilon(2S)/\Upsilon(1S)$ in pPb relative to pp collisions have been measured by CMS [40] and found to be less than unity, again indicating stronger final-state effects in the production of excited quarkonium states.

This Letter reports measurements of the cross sections for prompt $\psi(2S)$ production in pp and pPb collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$, with the $\psi(2S)$ decaying to $\mu^+\mu^-$, over the p_{T} range 4–30 GeV/c and center-of-mass rapidity range $-2.4 < y_{\mathrm{CM}} < 1.93$. The data were collected with the CMS detector at the LHC, in 2013 for the pPb sample and in 2015 for the pp sample, corresponding to integrated luminosities of $34.6 \pm 1.2\,\mathrm{nb}^{-1}$ [41] and $28.0 \pm 0.6\,\mathrm{pb}^{-1}$ [42], respectively. In addition, the modification of quarkonium production in pPb collisions is quantified by the nuclear modification factor, R_{pPb}, which is defined as the ratio of the cross sections in pPb and pp collisions divided by the Pb mass number, $A = 208$. The $\psi(2S)$ R_{pPb} is determined as a function of y_{CM} and p_{T}, and is compared to that of the J/ψ mesons measured at the same center-of-mass energy [31]. This is the first measurement of $\psi(2S)$ R_{pPb} at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$ in differential bins of p_{T} and y_{CM} that uses the pp data measured at the same center-of-mass energy.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume there are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. The forward hadron (HF) calorimeter uses steel as absorber and quartz fibers as the sensitive material. The two halves of the HF are located at $\pm 11.2\,\mathrm{m}$ from the nominal interaction point. Together they provide coverage in the range $3.0 < |\eta| < 5.2$ and also serve as luminosity monitors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid, in the range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers. Matching muons to tracks measured in the silicon tracker results in a relative p_{T} resolution for typical muons in this analysis of 1.3–2.0% in the barrel and better than 6% in the endcaps [43]. 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. [44].

3 Event selection

The pPb collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$ correspond to a proton beam energy of 4 TeV and a lead beam energy of 1.58 TeV per nucleon. The proton beam traveled in the $-\eta$ direction (in the detector coordinate system) in the first part of the run, corresponding to an integrated luminosity $\mathcal{L}_{\mathrm{int}} = 20.7\,\mathrm{nb}^{-1}$, and in the opposite direction in the second part of the run, corresponding to $\mathcal{L}_{\mathrm{int}} = 13.9\,\mathrm{nb}^{-1}$. Particles emitted at $|\eta_{CM}| = 0$ in the nucleon-nucleon center-of-mass frame are detected in the laboratory frame at $\eta_{\mathrm{lab}} = \pm 0.465$ depending on the proton beam direction. In this paper, data for half of the run were reflected so that positive η always corresponds to the direction of the proton beam. The pp data set, collected at the same collision energy as the pPb sample, corresponds to $\mathcal{L}_{\mathrm{int}} = 28.0\,\mathrm{pb}^{-1}$. In the pp sample, the dimuons from $\psi(2S)$ decays are reconstructed within $|y_{\mathrm{CM}}| < 2.4$ and in the same p_{T} range as the pPb data, $4 < p_{\mathrm{T}} < 30\,\mathrm{GeV}/c$.

Inelastic hadronic collisions are selected by requiring at least one HF tower with more than 3 GeV of total energy in each of the two HF calorimeters. This is not required in pp collisions, which suffer less from photon-induced interactions compared to pPb collisions. The pp and pPb events are further selected to have at least one reconstructed primary vertex composed of two or more associated tracks, excluding the two muons, within 25 cm from the nominal interaction point along the beam axis and within 2 cm in the transverse plane. To reject the beam-gas background events, the fraction of good-quality tracks associated with the primary vertex is required to be larger than 25% when there are more than 10 tracks per event.

The dimuon events are selected by the level-1 trigger, a hardware-based trigger system requiring two muon candidates in the muon detectors with no explicit limitations on their p_{T} or η. In the offline analysis, muons are required to be within the following kinematic regions, which ensure single-muon reconstruction efficiencies above 10%:

$$\begin{aligned} p_{\mathrm{T}}^{\mu} &> 3.3\,\mathrm{GeV}/c && \text{for } |\eta^{\mu}_{\mathrm{lab}}| < 1.2, \\ p_{\mathrm{T}}^{\mu} &> (4 - [1.1\,|\eta^{\mu}_{\mathrm{lab}}|])\,\mathrm{GeV}/c && \text{for } 1.2 < |\eta^{\mu}_{\mathrm{lab}}| < 2.1, \\ p_{\mathrm{T}}^{\mu} &> 1.3\,\mathrm{GeV}/c && \text{for } 2.1 < |\eta^{\mu}_{\mathrm{lab}}| < 2.4. \end{aligned} \tag{1}$$

The oppositely charged muon pairs are further selected to originate from a common vertex with a χ^2 probability greater than 1%, and to survive standard identification criteria [43]. In order to remove cosmic-ray muons, the transverse and longitudinal distances of closest approach between the muon trajectory and the reconstructed primary vertex are required to be less than 0.3 cm and 20 cm, respectively. All of these selections are common to both the pp and the pPb data sets.

4 Yield extraction

The prompt ψ(2S) signal extraction procedure is similar to that in previous CMS analyses [8, 11], and is the same for the pp and pPb data sets. The dimuon mass distribution is fitted with signal (including both the J/ψ and ψ(2S) resonances) and background contributions using an extended unbinned maximum likelihood procedure [45]. While the scope of the present Letter is the measurement of the prompt ψ(2S) production, the J/ψ resonance was included in the ψ(2S) fit to increase the peak fitting stability. It has been checked that the prompt J/ψ results obtained in this analysis agree with the ones in Ref. [31], which used a different method for separating prompt from nonprompt charmonia. The prompt J/ψ results of Ref. [31] are the ones used in this Letter for comparison with the new analysis of ψ(2S) production. Both resonance shapes are modeled by the weighted sum of a Crystal Ball (CB) [46] and a Gaussian function. The CB function, $g_{\mathrm{CB}}(m)$, combines a Gaussian core and a power law tail with exponent n, accounting for energy loss due to final-state photon radiation, with a parameter α defining the transition between the Gaussian and the power law functions:

$$g_{\mathrm{CB}}(m) = \begin{cases} \dfrac{N}{\sqrt{2\pi}\,\sigma_{\mathrm{CB}}} \exp\!\left(-\dfrac{(m-m_0)^2}{2\,\sigma^2_{\mathrm{CB}}}\right), & \text{for } \dfrac{m-m_0}{\sigma_{\mathrm{CB}}} > -\alpha; \\ \dfrac{N}{\sqrt{2\pi}\,\sigma_{\mathrm{CB}}} \left(\dfrac{n}{|\alpha|}\right)^{n} \exp\!\left(-\dfrac{|\alpha|^2}{2}\right) \left(\dfrac{n}{|\alpha|} - |\alpha| - \dfrac{m-m_0}{\sigma_{\mathrm{CB}}}\right)^{-n}, & \text{for } \dfrac{m-m_0}{\sigma_{\mathrm{CB}}} < -\alpha. \end{cases} \tag{2}$$

The CB and Gaussian functions have independent widths, σ_{CB} and σ_{G}, to accommodate the dependence of the dimuon invariant mass resolution on the dimuon rapidity and p_{T}, but share a common mean m_0 representing the J/ψ mass. The signal models used for the ψ(2S) and J/ψ share the same α and n parameters. The mean and the width of the Gaussian model for the ψ(2S) are obtained from those of the J/ψ, scaled by their mass ratio ($m_{\psi(2S)}/m_{\mathrm{J}/\psi} = 1.1903$ [47]). The following parameters are left free in the fit: m_0, σ_{CB}, σ_{G}, $N_{\mathrm{J}/\psi}$ (the J/ψ yield), $N_{\psi(2S)}$ (the ψ(2S) yield), f (the relative contribution of the Gaussian and CB functions), and α. Based on simulation studies, the value of the parameter n is fixed to 2.1. The parameter α is left free, covering the variation of signal shapes in each of the p_{T} and rapidity bins. The same value for f is used in the definition of the ψ(2S) and J/ψ signal shapes. The underlying background is described by a Chebyshev polynomial of degree N ($1 \le N \le 3$). The degree of the Chebyshev polynomial is obtained in each $(p_{\mathrm{T}}, y_{\mathrm{CM}})$ bin of the analysis using a log-likelihood ratio test.

Several alternative fitting procedures have been tested, and the yield variations with respect to the nominal result are included as a systematic uncertainty, as explained in Section 6. The two pPb data sets, corresponding to each proton beam direction, are merged and analyzed together after having verified that the independent results are compatible with each other.

The J/ψ and ψ(2S) coming from b hadron decays (nonprompt charmonia) are evaluated using the displacement of the $\mu^+\mu^-$ vertex from the primary collision vertex. This secondary $\mu^+\mu^-$ vertex is characterized by the pseudo-proper decay length,

$$\ell_{\mathrm{J}/\psi} = L_{xy}\,\frac{m_{\mathrm{J}/\psi}}{p_{\mathrm{T}}}, \tag{3}$$

where L_{xy} is the transverse distance between the primary and dimuon vertices, $m_{\mathrm{J}/\psi}$ is the mass of the J/ψ [47] (assumed for all muon pairs), and p_{T} is the transverse momentum of the dimuon. Prompt charmonia are selected by requiring $\ell_{\mathrm{J}/\psi}$ to be smaller than a threshold value l_0, which is tuned using simulation separately for the pp and pPb collisions systems, in order to keep 90% of the total prompt charmonia [11]. Since the $\ell_{\mathrm{J}/\psi}$ resolution improves with increasing dimuon p_{T}, the l_0 values also depend on p_{T}. The l_0 values used remove between 70% and 90% (80% and 90%) of the nonprompt ψ(2S) in pPb (pp) collisions, from low- to high-p_{T}.

The yields so obtained have a small nonprompt contamination, which is corrected using the number of simulated events passing and failing the $\ell_{\mathrm{J}/\psi}$ threshold criteria [11]. The full value of this correction is also propagated as a source of systematic uncertainty.

Figure 1 shows the dimuon invariant mass distributions with the J/ψ and ψ(2S) peaks in pPb and pp data, for one of the bins with the smallest signal-to-background ratio (lowest p_{T} and most backward y), after applying the $\ell_{\mathrm{J}/\psi}$ selection, together with the curves resulting from the fits. The raw prompt ψ(2S) yield extracted in these bins is $\sim$300 for the pPb, and twice as much for the pp samples.

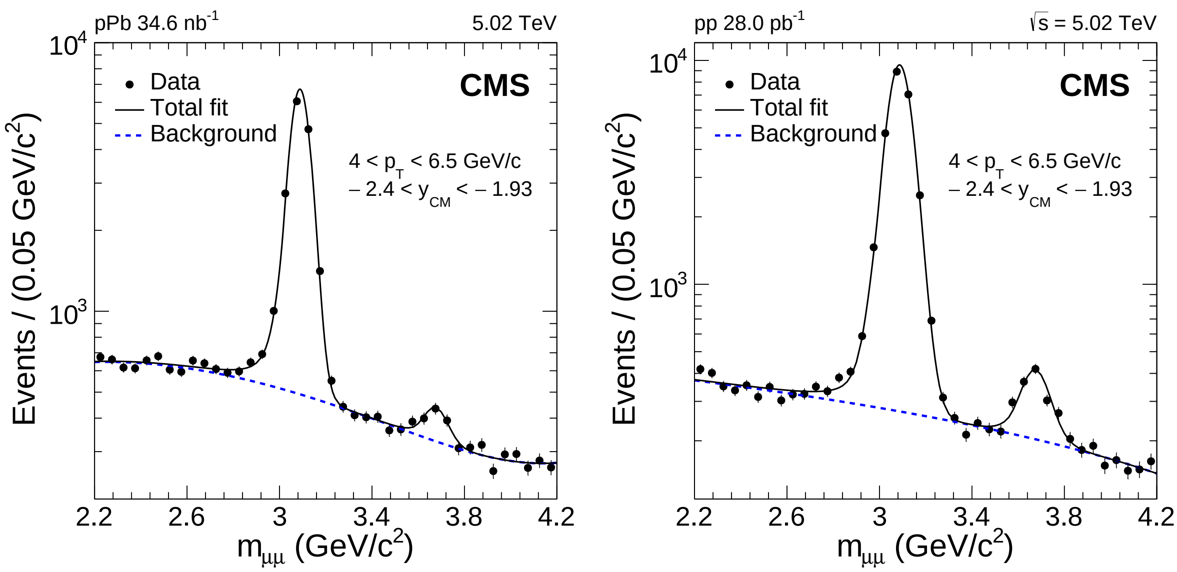

Figure 1: Dimuon invariant mass distribution showing the J/ψ and ψ(2S) peaks in pPb (left panel) and pp (right panel) data, after applying the $\ell_{\mathrm{J}/\psi}$ selection, for $-2.4 < y_{\mathrm{CM}} < -1.93$ and $4 < p_{\mathrm{T}} < 6.5\,\mathrm{GeV}/c$. The fits to the distributions are also shown.

5 Acceptance and efficiency corrections

Simulated events are used to obtain the acceptance and efficiency correction factors for the measured $\psi(2S)$ yields. The events are generated using PYTHIA 6.424 [48] for pPb collisions and PYTHIA 8.209 [49] for pp collisions. The generated particles in the pPb Monte Carlo (MC) are boosted by the β of the center-of-mass system in the laboratory frame, resulting in $\Delta y = \pm 0.465$. The prompt J/ψ and $\psi(2S)$ are assumed to be produced unpolarized in both pp and pPb collisions, which is supported by measurements in pp collisions at $\sqrt{s} = 7\,\text{TeV}$ [50, 51]. The final-state QED radiation of the decay muons is simulated using PHOTOS 215.5 [52]. Finally, the CMS detector response is simulated using GEANT4 [53].

The acceptance in a given (p_T, y_{CM}) bin is defined as the fraction of generated $\psi(2S)$ mesons resulting in a detectable muon pair, i.e., passing the single muon selection criteria defined in Eq. (1). The efficiency is given by the fraction of generated and detectable muon pairs that result in a reconstructed muon pair, also passing the trigger and offline selections. The combined $\psi(2S)$ acceptance and efficiency for pPb (pp) results ranges between 13% (14%) in the lowest p_T region ($4.0 < p_T < 6.5\,\text{GeV}/c$) and 66% (67%) in the highest p_T region ($10.0 < p_T < 30.0\,\text{GeV}/c$). It is maximum in the overlap region between barrel and endcap detectors, and decreases to minimum values for $|y_{CM}| > 2$.

The individual components of the simulation-based dimuon efficiency (track reconstruction, muon identification and selection, and triggering) are probed using single muons from J/ψ meson decays in both simulated and collision data, with the *tag-and-probe* (T&P) method [31, 54]. The data-to-simulation ratios of single muon efficiencies obtained from T&P, calculated as a function of muon η and p_T, are used as weights (*scale factors*) to correct event-by-event the dimuon efficiency. The effect of this correction on the dimuon efficiency is similar for pp and pPb events and ranges from 0.99 to 1.33, with larger corrections at lower p_T and more forward/backward rapidities.

6 Systematic uncertainties

The following sources of point-to-point systematic uncertainties are considered for both pp and pPb data: the yield extraction method, given the choice of signal and background models; acceptance and efficiency corrections, including T&P scale factors and the possible difference in the dimuon p_T spectrum between data and simulation; and the nonprompt charmonia contamination. The evaluation of these systematic uncertainties is described below.

- **Signal shape variation.** This systematic uncertainty is obtained by changing the fitting constraints on the CB shape parameters. In the nominal fits, the CB parameter n is fixed from simulation, $n = 2.1$, and the parameter α is left free. In a first variation, the parameter α is fixed to the MC-based value 1.7, and n is left free. A second variation consists in fixing both parameters to the values extracted from MC, $n = 2.1$ and $\alpha = 1.7$. The maximum difference, in each analysis bin, between the yields extracted with the nominal fit and either of these variations, is taken as a systematic uncertainty.
- **Background shape variation.** The degree N of the Chebyshev polynomial is changed to $N + 1$ if $N < 3$, and to $N - 1$ if $N = 3$. The systematic uncertainty is estimated as the absolute difference in the yields with respect to the nominal case.
- **Simulated dimuon p_T spectrum.** The acceptance and efficiency correction factors depend on the shape of the simulated $\psi(2S)$ p_T distribution; the difference between

data and simulation is a source of systematic uncertainty. The ratio of the corrected yields in data and simulation is evaluated as a function of p_T, for each rapidity bin. Continuous weighting factors are obtained by fitting these data-to-simulation ratios with a linear function in p_T. The acceptance and efficiency values are evaluated again after weighting the p_T distribution of the generated $\psi(2S)$ mesons in the simulation by the function obtained. The difference between the reweighed simulation and the nominal yields is taken as a systematic uncertainty.

- **T&P scale factors.** The statistical uncertainty on the T&P scale factors, as well as systematic uncertainties in their derivation, are accounted for as a systematic uncertainty. These uncertainties are further described in Ref. [31].
- **Nonprompt contamination.** The difference between the prompt meson yields with and without the correction for the residual nonprompt contamination is propagated as a systematic uncertainty.

The systematic uncertainty in the yield extraction, determined by summing the uncertainties from the signal and background shape variations in quadrature, is in the range 1.0–22% and 0.4–6.5% for the pPb and pp results, respectively. This large range is mostly driven by the variation of the signal over background ratio across the analysis bins. The dominant part in this uncertainty is from background modeling, with an average over all the p_T and y_{CM} bins of 3.9 (2.4)% and a maximum of 22 (4.9)% for the pPb (pp) results. The average signal modeling contribution is 1.9% and 1.4%, for the pPb and pp results, respectively.

The systematic uncertainty in the acceptance and efficiency correction factors, combining the dimuon p_T spectrum reweighting and T&P uncertainties, lies within 2.0–7.4% and 1.9–8.1% for the pPb and pp results, respectively. The prompt selection method induces an uncertainty of 4.5–15% (0.2–8.0%) for the pPb (pp) results, with the maximum value in the lowest p_T bin in the backward y region. The total systematic uncertainty, calculated as the sum in quadrature of the individual uncertainties, is in the range 5–26% (4–11%) for the pPb (pp) cross section measurements. In general, the uncertainty is minimum in the highest p_T bins in the central y region, and increases when going to lower p_T and forward/backward y regions. For the R_{pPb} measurement, the pp and pPb uncertainties are considered independent and added in quadrature point-by-point. The total systematic uncertainty in this case is in the range 5.0–22.6%.

The global (common to all points) systematic uncertainty due to the uncertainty in the integrated luminosity of the pPb and pp data sets is 3.5% [41] and 2.3% [42], respectively. For the cross section results, this uncertainty is not included to the point-to-point uncertainties, while for the R_{pPb} results the two numbers are added in quadrature and displayed as a box around $R_{pPb} = 1$. The dominant source of uncertainty for the R_{pPb} measurement is the statistical uncertainty in the pPb data.

7 Results

The prompt $\psi(2S)$ production cross section (multiplied by the $\psi(2S)$ branching fraction to $\mu^+\mu^-$, $\mathcal{B}(\psi(2S) \to \mu^+\mu^-)$) in the dimuon decay channel is determined as

$$\mathcal{B}(\psi(2S) \to \mu^+\mu^-) \frac{d^2\sigma}{dp_T\, dy_{CM}} = \frac{N_{fit}^{\psi(2S)} / (\mathrm{acc}\,\varepsilon)}{\mathcal{L}_{int}\, \Delta p_T\, \Delta y_{CM}}, \quad (4)$$

where $N_{fit}^{\psi(2S)}$ is the extracted raw yield of prompt $\psi(2S)$ mesons in a given (p_T, y_{CM}) bin, $(\mathrm{acc}\,\varepsilon)$ is the product of the dimuon acceptance and efficiency described in Section 5, and Δp_T and

Δy_{CM} are the widths of the kinematic bin considered.

Figures 2 and 3 show the production cross sections of prompt $\psi(2S)$ mesons in pPb and pp collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$, respectively. The results are given as a function of p_{T} and in four rapidity bins, separately for forward (the direction of the proton beam) and backward (the direction of the Pb beam) rapidities in the case of the pPb measurements.

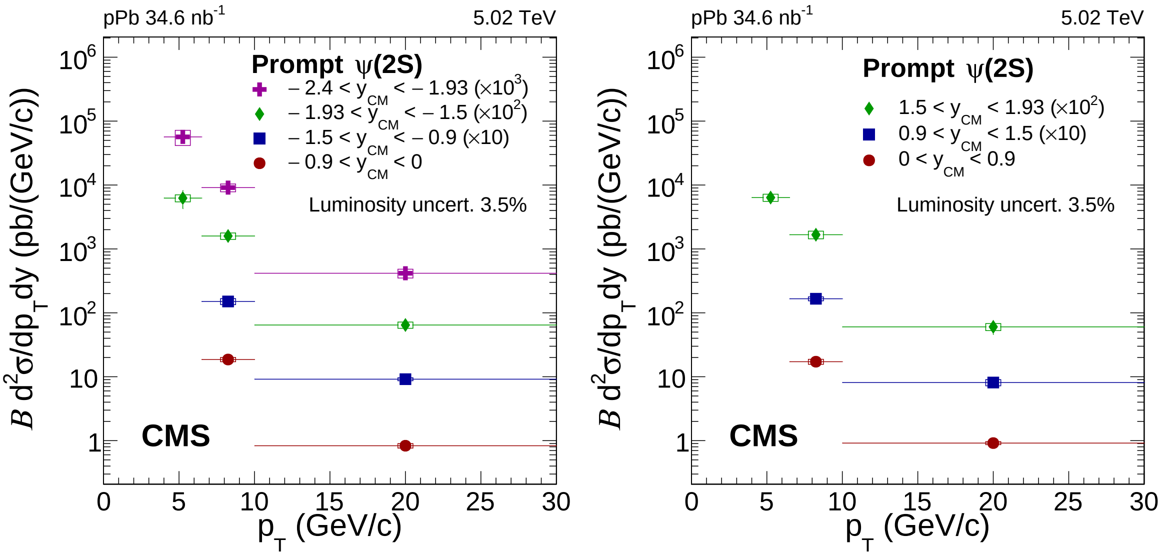

Figure 2: Differential cross section (multiplied by the dimuon branching fraction) of prompt $\psi(2S)$ production in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$, as a function of p_{T}, in several rapidity bins and separately for backward (left panel) and forward (right panel) rapidity regions. Statistical and systematic uncertainties are represented with error bars and boxes, respectively. The fully correlated luminosity uncertainty of 3.5% is not included in the point-by-point uncertainties.

The second observable considered is the nuclear modification factor, defined as

$$R_{\mathrm{pPb}}(p_{\mathrm{T}}, y_{\mathrm{CM}}) \equiv \frac{(\mathrm{d}^2\sigma/\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}y_{\mathrm{CM}})_{\mathrm{pPb}}}{\mathrm{A}(\mathrm{d}^2\sigma/\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}y_{\mathrm{CM}})_{\mathrm{pp}}}. \tag{5}$$

In the absence of any nuclear effects the measured yield in pPb collisions would be just a superposition of $A = 208$ (the number of nucleons in the Pb nucleus) pp collisions, and the R_{pPb} would be one.

Figure 4 shows the rapidity dependence of the prompt $\psi(2S)$ R_{pPb} in three p_{T} ranges: 4–6.5, 6.5–10, and 10–30 GeV/c. In the backward rapidity region, the prompt $\psi(2S)$ mesons are suppressed in the intermediate p_{T} region, and compatible with unity in the rest. In the forward rapidity region, the R_{pPb} is consistent with unity for all p_{T} bins (although systematically smaller). For comparison, the prompt J/ψ nuclear modification factor [31] is also shown in Fig. 4. The measured value of R_{pPb} for prompt $\psi(2S)$ mesons, when integrated over p_{T} and rapidity ($6.5 < p_{\mathrm{T}} < 30\,\mathrm{GeV}/c$, $|y| < 1.6$), is $0.852 \pm 0.037\,(\mathrm{stat}) \pm 0.062\,(\mathrm{syst})$. The prompt J/$\psi$ R_{pPb} in the same kinematic range is $1.108 \pm 0.021\,(\mathrm{stat}) \pm 0.055\,(\mathrm{syst})$. The R_{pPb} for prompt J/ψ mesons lies systematically above that of the $\psi(2S)$ state. The difference between the two sets of results was quantified, separately for the backward and forward regions, by comparing the two distributions with a χ^2-test, removing the correlated uncertainties from the integrated luminosity. The p-values are < 0.05 for the lowest two p_{T} ranges in the backward rapidity region, and > 0.37 in all the other rapidity and p_{T} intervals. This shows that, with a p-value cutoff of

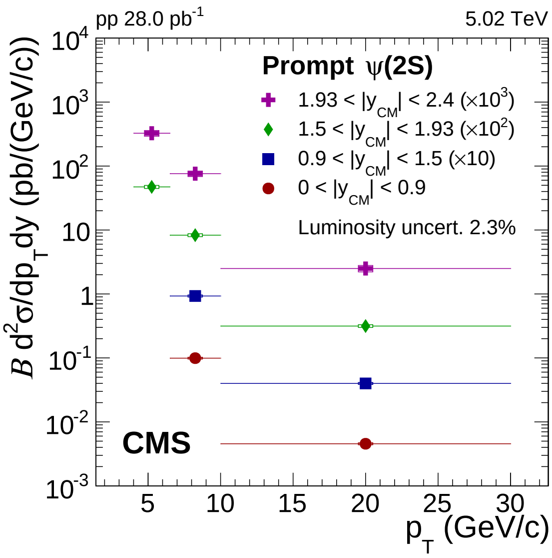

Figure 3: Differential cross section (multiplied by the dimuon branching fraction) of prompt $\psi(2S)$ production in pp collisions at $\sqrt{s} = 5.02$ TeV as a function of p_T, in four y_{CM} bins. Statistical and systematic uncertainties are represented with error bars and boxes, respectively. The fully correlated luminosity uncertainty of 2.3% is not included in the point-by-point uncertainties.

0.05, the two sets of results are incompatible with each other in the backward rapidity region for $p_T < 10\,\text{GeV}/c$, but are compatible in the rest. This suggests the presence of different nuclear effects at play in the production of the excited charmonium state compared to the ground state, in the region of backward rapidity and for $p_T < 10\,\text{GeV}/c$.

Figure 5 shows the p_T dependence of the prompt $\psi(2S)$ R_{pPb} in seven rapidity bins, from the most backward $-2.4 < y_{CM} < -1.93$ to the most forward $1.5 < y_{CM} < 1.93$ accessible regions. Also in this case, a χ^2-test was used to quantify the significance of the difference of the results from unity, in which the fully correlated global uncertainty, displayed as a box around $R_{pPb} = 1$, was not included. The p-values are below 0.05 only in the most backward region. This points to the presence of nuclear effects affecting the $\psi(2S)$ production in the most backward region that persists at large transverse momentum.

The suppression of prompt $\psi(2S)$ mesons as compared to prompt J/ψ mesons, seen in Fig. 4, is compatible with what was measured by the ALICE [37], ATLAS [34], and LHCb [38] Collaborations for p_T integrated charmonium production in pPb collisions at the same collision energy. While nPDFs [15, 16] and coherent energy loss [17, 18] are the most discussed effects to explain prompt J/ψ meson suppression, these two phenomena are expected to affect the R_{pPb} of prompt J/ψ and $\psi(2S)$ mesons by a similar amount. On the contrary, the final-state interaction with hadrons moving along with the produced charmonium might lead to a stronger suppression of the $\psi(2S)$ meson, due to its larger size [39, 55]. The present measurements, covering wide transverse momentum ($4 < p_T < 30\,\text{GeV}/c$) and rapidity ($-2.4 < y_{CM} < 1.93$) ranges, will help understand the origin of the suppression of excited quarkonium states in pPb collisions at the LHC.

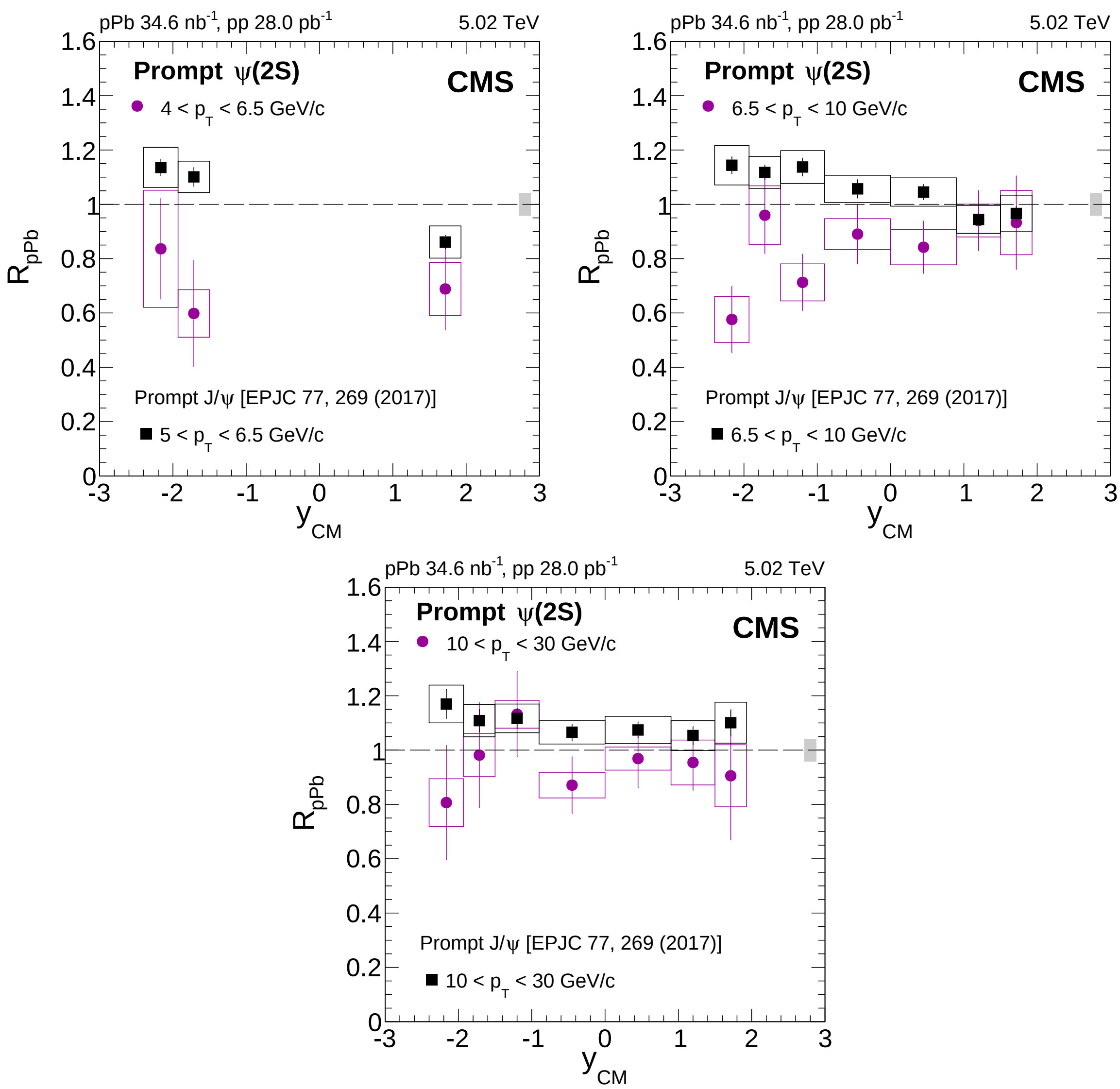

Figure 4: Rapidity dependence of the prompt $\psi(2S)$ R_{pPb} in three p_T ranges. For comparison, the prompt J/ψ nuclear modification factor [31] is also shown. Statistical and systematic uncertainties are represented with error bars and boxes, respectively. The fully correlated global uncertainty of 4.2% (that affects both charmonia) is displayed as a box around $R_{pPb} = 1$.

8 Summary

The data collected by CMS in pp and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are used to investigate prompt $\psi(2S)$ meson production. The results are based on data samples corresponding to integrated luminosities of 28.0 pb^{-1} for pp collisions and 34.6 nb^{-1} for pPb collisions. The nuclear modification factor (R_{pPb}) of prompt $\psi(2S)$, in the kinematic range $4 < p_T < 30$ GeV/c and $-2.4 < y_{CM} < 1.93$, is determined and compared to that of prompt J/ψ mesons, reported in Ref. [31]. The prompt $\psi(2S)$ production is suppressed in the intermediate 6.5–10 GeV/c p_T interval in the region of backward rapidity. The R_{pPb} is consistent with unity everywhere else (although systematically smaller). The R_{pPb} values of prompt J/ψ when compared to those of prompt $\psi(2S)$ mesons, point to different nuclear effects at play in the production of the excited charmonium state compared to the ground state, in the region of backward rapidity and for $p_T < 10$ GeV/c. The effects of nuclear parton distribution functions or coherent energy loss

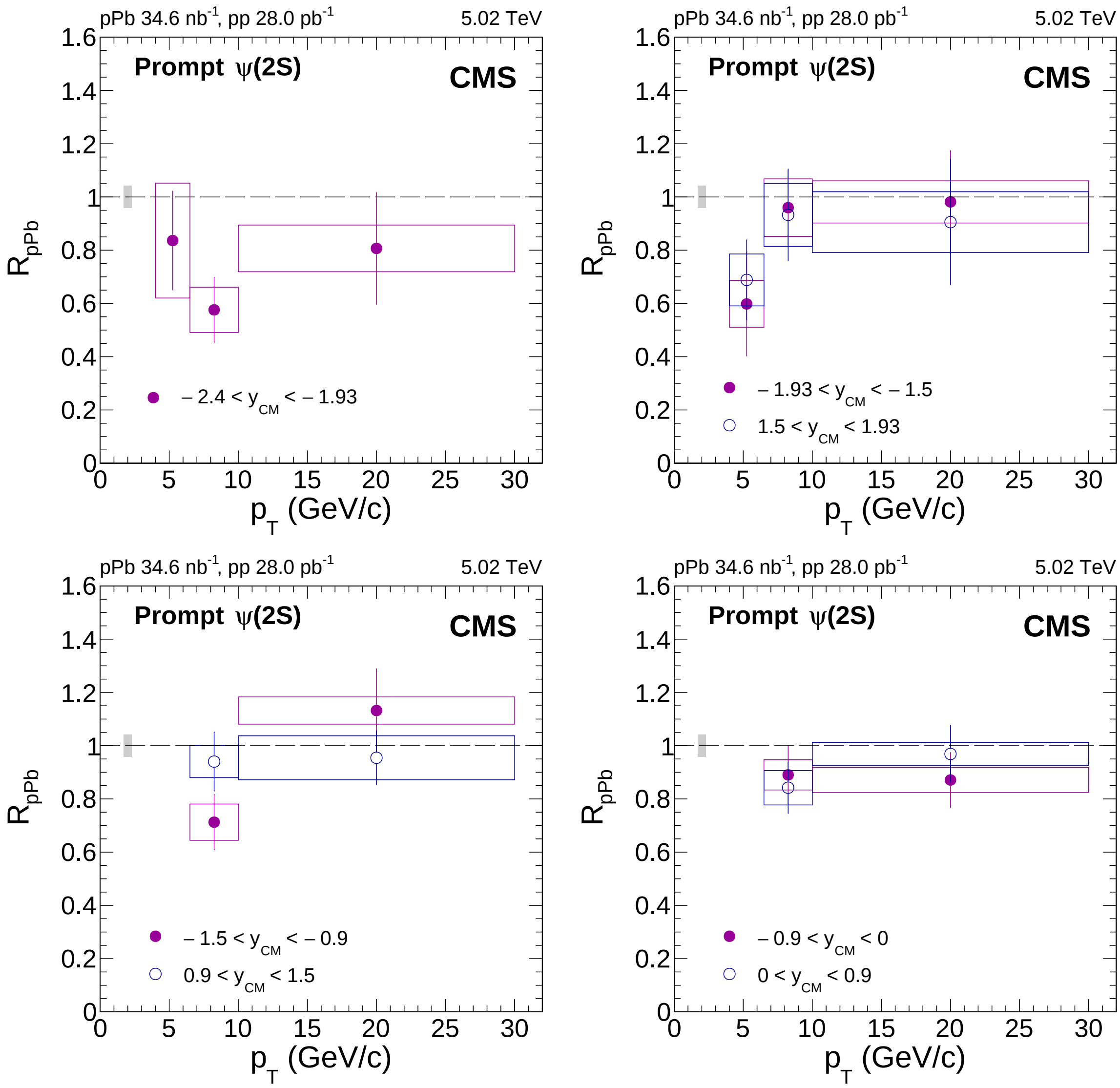

Figure 5: Transverse momentum dependence of the prompt $\psi(2S)$ R_{pPb} in four rapidity ranges. Statistical and systematic uncertainties are represented with error bars and boxes, respectively. The fully correlated global uncertainty of 4.2% is displayed as a box around $R_{pPb} = 1$.

are expected to affect the R_{pPb} of prompt J/ψ and ψ(2S) by a similar amount, thus the results hint the presence of final-state interactions with the medium (partonic or hadronic) produced in pPb collisions.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract No. 675440 (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science - EOS" - be.h project n. 30820817; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Lendület ("Momentum") Program and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFIA research grants 123842, 123959, 124845, 124850 and 125105 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalis and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

[1] 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.

[2] NA38 Collaboration, "The production of J/ψ in 200 GeV/nucleon oxygen-uranium interactions", *Phys. Lett. B* **220** (1989) 471, doi:10.1016/0370-2693(89)90905-2.

[3] NA50 Collaboration, "Anomalous J/ψ suppression in PbPb interactions at 158 GeV/c per nucleon", *Phys. Lett. B* **410** (1997) 337, doi:10.1016/S0370-2693(97)00915-5.

[4] PHENIX Collaboration, "J/ψ production versus centrality, transverse momentum, and rapidity in AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV", *Phys. Rev. Lett.* **98** (2007) 232301, doi:10.1103/PhysRevLett.98.232301, arXiv:nucl-ex/0611020.

[5] PHENIX Collaboration, "J/ψ suppression at forward rapidity in AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV", *Phys. Rev. C* **84** (2011) 054912, doi:10.1103/PhysRevC.84.054912, arXiv:1103.6269.

[6] ALICE Collaboration, "Centrality, rapidity and transverse momentum dependence of J/ψ suppression in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV", *Phys. Lett. B* **734** (2014) 314, doi:10.1016/j.physletb.2014.05.064, arXiv:1311.0214.

[7] CMS Collaboration, "Suppression and azimuthal anisotropy of prompt and nonprompt J/ψ production in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV", *Eur. Phys. J. C* **77** (2017) 252, doi:10.1140/epjc/s10052-017-4781-1, arXiv:1610.00613.

[8] CMS Collaboration, "Measurement of prompt ψ(2S) to J/ψ yield ratios in PbPb and pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV", *Phys. Rev. Lett.* **113** (2014) 262301, doi:10.1103/PhysRevLett.113.262301, arXiv:1410.1804.

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

[10] CMS Collaboration, "Suppression of Υ(1S), Υ(2S) and Υ(3S) production in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV", *Phys. Lett. B* **770** (2017) 357, doi:10.1016/j.physletb.2017.04.031, arXiv:1611.01510.

[11] CMS Collaboration, "Relative modification of prompt ψ(2S) and J/ψ yields from pp to PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV", *Phys. Rev. Lett.* **118** (2017) 162301, doi:10.1103/PhysRevLett.118.162301, arXiv:1611.01438.

[12] CMS Collaboration, "Suppression of excited Υ states relative to the ground state in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV", *Phys. Rev. Lett.* **120** (2018) 142301, doi:10.1103/PhysRevLett.120.142301, arXiv:1706.05984.

[13] V. Kumar, P. Shukla, and R. Vogt, "Quarkonia suppression in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV", *Phys. Rev. C* **92** (2015) 024908, doi:10.1103/PhysRevC.92.024908, arXiv:1410.3299.

[14] P. Braun-Munzinger, V. Koch, T. Schäfer, and J. Stachel, "Properties of hot and dense matter from relativistic heavy ion collisions", *Phys. Rept.* **621** (2016) 76, doi:10.1016/j.physrep.2015.12.003, arXiv:1510.00442.

[15] E. G. Ferreiro, F. Fleuret, J. P. Lansberg, and A. Rakotozafindrabe, "Impact of the nuclear modification of the gluon densities on J/ψ production in pPb collisions at $\sqrt{s_{NN}} = 5$ TeV", *Phys. Rev. C* **88** (2013) 047901, `doi:10.1103/PhysRevC.88.047901`, `arXiv:1305.4569`.

[16] R. Vogt, "Shadowing effects on J/ψ and Y production at energies available at the CERN Large Hadron Collider", *Phys. Rev. C* **92** (2015) 034909, `doi:10.1103/PhysRevC.92.034909`, `arXiv:1507.04418`.

[17] F. Arleo and S. Peigné, "J/ψ suppression in pA collisions from parton energy loss in cold QCD matter", *Phys. Rev. Lett.* **109** (2012) 122301, `doi:10.1103/PhysRevLett.109.122301`, `arXiv:1204.4609`.

[18] F. Arleo, R. Kolevatov, S. Peigné, and M. Rustamova, "Centrality and p_T dependence of J/ψ suppression in proton-nucleus collisions from parton energy loss", *JHEP* **05** (2013) 155, `doi:10.1007/JHEP05(2013)155`, `arXiv:1304.0901`.

[19] NA3 Collaboration, "Experimental J/ψ hadronic production from 150- GeV/c to 280- GeV/c", *Z. Phys. C* **20** (1983) 101, `doi:10.1007/BF01573213`.

[20] NA38 Collaboration, "Charmonia production in 450- GeV/c proton induced reactions", *Phys. Lett. B* **444** (1998) 516, `doi:10.1016/S0370-2693(98)01398-7`.

[21] NA50 Collaboration, "Charmonium production and nuclear absorption in pA interactions at 450- GeV", *Eur. Phys. J. C* **33** (2004) 31, `doi:10.1140/epjc/s2003-01539-y`.

[22] NA60 Collaboration, "J/ψ production in proton-nucleus collisions at 158 and 400 GeV", *Phys. Lett. B* **706** (2012) 263, `doi:10.1016/j.physletb.2011.11.042`, `arXiv:1004.5523`.

[23] HERA-B Collaboration, "Kinematic distributions and nuclear effects of J/ψ production in 920 GeV fixed-target proton-nucleus collisions", *Eur. Phys. J. C* **60** (2009) 525, `doi:10.1140/epjc/s10052-009-0965-7`, `arXiv:0812.0734`.

[24] FNAL E866 / NuSea Collaboration, "Measurement of J/ψ and $\psi(2S)$ suppression in pA collisions at 800 GeV/c", *Phys. Rev. Lett.* **84** (2000) 3256, `doi:10.1103/PhysRevLett.84.3256`, `arXiv:nucl-ex/9909007`.

[25] C. Lourenco, R. Vogt, and H. K. Woehri, "Energy dependence of J/ψ absorption in proton-nucleus collisions", *JHEP* **02** (2009) 014, `doi:10.1088/1126-6708/2009/02/014`, `arXiv:0901.3054`.

[26] PHENIX Collaboration, "J/ψ production and nuclear effects for d+au and pp collisions at $\sqrt{s_{NN}} = 200$ GeV", *Phys. Rev. Lett.* **96** (2006) 012304, `doi:10.1103/PhysRevLett.96.012304`, `arXiv:nucl-ex/0507032`.

[27] STAR Collaboration, "Suppression of Y production in d+Au and AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV", *Phys. Lett. B* **735** (2014) 127, `doi:10.1016/j.physletb.2014.06.028`, `arXiv:1312.3675`. [Erratum: Phys. Lett.B743,537(2015)].

[28] ALICE Collaboration, "J/ψ production and nuclear effects in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV", *JHEP* **02** (2014) 073, `doi:10.1007/JHEP02(2014)073`, `arXiv:1308.6726`.

[29] ALICE Collaboration, "Rapidity and transverse momentum dependence of the inclusive J/ψ nuclear modification factor in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$", *JHEP* **06** (2015) 055, doi:10.1007/JHEP06(2015)055, arXiv:1503.07179.

[30] ATLAS Collaboration, "Measurement of differential J/ψ production cross sections and forward-backward ratios in pPb collisions with the ATLAS detector", *Phys. Rev. C* **92** (2015) 034904, doi:10.1103/PhysRevC.92.034904, arXiv:1505.08141.

[31] CMS Collaboration, "Measurement of prompt and nonprompt J/ψ production in pp and pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$", *Eur. Phys. J. C* **77** (2017) 269, doi:10.1140/epjc/s10052-017-4828-3, arXiv:1702.01462.

[32] LHCb Collaboration, "Study of J/ψ production and cold nuclear matter effects in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5\,\mathrm{TeV}$", *JHEP* **02** (2014) 072, doi:10.1007/JHEP02(2014)072, arXiv:1308.6729.

[33] ALICE Collaboration, "Production of inclusive $\Upsilon(1S)$ and $\Upsilon(2S)$ in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$", *Phys. Lett. B* **740** (2015) 105, doi:10.1016/j.physletb.2014.11.041, arXiv:1410.2234.

[34] ATLAS Collaboration, "Measurement of quarkonium production in proton-lead and proton-proton collisions at 5.02 TeV with the ATLAS detector", *Eur. Phys. J. C* **78** (2018) 171, doi:10.1140/epjc/s10052-018-5624-4, arXiv:1709.03089.

[35] LHCb Collaboration, "Study of Υ production and cold nuclear matter effects in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5\,\mathrm{TeV}$", *JHEP* **07** (2014) 094, doi:10.1007/JHEP07(2014)094, arXiv:1405.5152.

[36] ALICE Collaboration, "Differential studies of inclusive J/ψ and $\psi(2S)$ production at forward rapidity in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$", *JHEP* **05** (2016) 179, doi:10.1007/JHEP05(2016)179, arXiv:1506.08804.

[37] ALICE Collaboration, "Suppression of $\psi(2S)$ production in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$", *JHEP* **12** (2014) 073, doi:10.1007/JHEP12(2014)073, arXiv:1405.3796.

[38] LHCb Collaboration, "Study of $\psi(2S)$ production and cold nuclear matter effects in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5\,\mathrm{TeV}$", *JHEP* **03** (2016) 133, doi:10.1007/JHEP03(2016)133, arXiv:1601.07878.

[39] E. G. Ferreiro, "Excited charmonium suppression in proton-nucleus collisions as a consequence of comovers", *Phys. Lett. B* **749** (2015) 98, doi:10.1016/j.physletb.2015.07.066, arXiv:1411.0549.

[40] CMS Collaboration, "Event activity dependence of Υ(nS) production in $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ pPb and $\sqrt{s} = 2.76\,\mathrm{TeV}$ pp collisions", *JHEP* **04** (2014) 103, doi:10.1007/JHEP04(2014)103, arXiv:1312.6300.

[41] CMS Collaboration, "Luminosity calibration for the 2013 proton-lead and proton-proton data taking", CMS Physics Analysis Summary CMS-PAS-LUM-13-002, 2014.

[42] CMS Collaboration, "CMS luminosity calibration for the pp reference run at $\sqrt{s} = 5.02\,\mathrm{TeV}$", CMS Physics Analysis Summary CMS-PAS-LUM-16-001, 2016.

[43] CMS Collaboration, "Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7\,\mathrm{TeV}$", *JINST* **7** (2012) P10002, doi:10.1088/1748-0221/7/10/P10002, arXiv:1206.4071.

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

[45] W. Verkerke and D. P. Kirkby, "The ROOFIT toolkit for data modeling", in *13th International Conference for Computing in High-Energy and Nuclear Physics (CHEP 2003)*. La Jolla, California, 2003. arXiv:physics/0306116. eConf C0303241 (2003) MOLT007.

[46] M. J. Oreglia, "A study of the reactions $\psi' \to \gamma\gamma\psi$". PhD thesis, Stanford University, 1980. SLAC Report SLAC-R-236.

[47] Particle Data Group, C. Patrignani et al., "Review of particle physics", *Chin. Phys. C* **40** (2016) 100001, doi:10.1088/1674-1137/40/10/100001.

[48] T. Sjöstrand, S. Mrenna, and P. Skands, "PYTHIA 6.4 physics and manual", *JHEP* **05** (2006) 026, doi:10.1088/1126-6708/2006/05/026, arXiv:hep-ph/0603175.

[49] T. Sjöstrand et al., "An introduction to PYTHIA 8.2", *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[50] CMS Collaboration, "Measurement of the prompt J/ψ and ψ(2S) polarizations in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$", *Phys. Lett. B* **727** (2013) 381, doi:10.1016/j.physletb.2013.10.055, arXiv:1307.6070.

[51] CMS Collaboration, "Υ(nS) polarizations versus particle multiplicity in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$", *Phys. Lett. B* **761** (2016) 31, doi:10.1016/j.physletb.2016.07.065, arXiv:1603.02913.

[52] E. Barberio and Z. Wąs, "PHOTOS: a universal Monte Carlo for QED radiative corrections. version 2.0", *Comput. Phys. Commun.* **79** (1994) 291, doi:10.1016/0010-4655(94)90074-4.

[53] GEANT4 Collaboration, "GEANT4—a simulation toolkit", *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.

[54] CMS Collaboration, "Measurements of inclusive W and Z cross sections in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$", *JHEP* **01** (2011) 080, doi:10.1007/JHEP01(2011)080, arXiv:1012.2466.

[55] Y.-Q. Ma, R. Venugopalan, K. Watanabe, and H.-F. Zhang, "ψ(2S) versus J/ψ suppression in proton-nucleus collisions from factorization violating soft color exchanges", *Phys. Rev. C* **97** (2018) 014909, doi:10.1103/PhysRevC.97.014909, arXiv:1707.07266.

A The CMS Collaboration

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

Institut für Hochenergiephysik, Wien, Austria
W. Adam, F. Ambrogi, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, M. Friedl, V.M. Ghete, J. Hrubec, M. Jeitler[1], N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, H. Rohringer, J. Schieck[1], R. Schöfbeck, M. Spanring, D. Spitzbart, A. Taurok, W. Waltenberger, J. Wittmann, C.-E. Wulz[1], M. Zarucki

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

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

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

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

Ghent University, Ghent, Belgium
T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov[2], D. Poyraz, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

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

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
F.L. Alves, G.A. Alves, L. Brito, G. Correia Silva, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato[3], E. Coelho, E.M. Da Costa, G.G. Da Silveira[4], D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote[3], F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista [a], Universidade Federal do ABC [b], São Paulo, Brazil
S. Ahuja[a], C.A. Bernardes[a], L. Calligaris[a], T.R. Fernandez Perez Tomei[a], E.M. Gregores[b], P.G. Mercadante[b], S.F. Novaes[a], SandraS. Padula[a], D. Romero Abad[b]

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

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

Beihang University, Beijing, China
W. Fang[5], X. Gao[5], L. Yuan

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

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

Tsinghua University, Beijing, China
Y. Wang

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

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

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

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov[6], T. Susa

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

Charles University, Prague, Czech Republic
M. Finger[7], M. Finger Jr.[7]

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

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

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran[8,9], M.A. Mahmoud[10,9], Y. Mohammed[10]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, L. Perrini, M. Raidal, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

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

Lappeenranta University of Technology, Lappeenranta, Finland
T. Tuuva

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

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France
A. Abdulsalam[11], C. Amendola, I. Antropov, F. Beaudette, P. Busson, L. Cadamuro, C. Charlot, R. Granier de Cassagnac, I. Kucher, S. Lisniak, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Pigard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, Y. Yilmaz, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
J.-L. Agram[12], J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, V. Cherepanov, C. Collard, E. Conte[12], F. Drouhin[12], J.-C. Fontaine[12], D. Gelé, U. Goerlach, M. Jansová, P. Juillot, A.-C. Le Bihan, N. Tonon, P. Van Hove

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

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, C. Bernet, G. Boudoul, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov[13], V. Sordini, M. Vander Donckt, S. Viret, S. Zhang

Georgian Technical University, Tbilisi, Georgia
T. Toriashvili[14]

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze[7]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer, V. Zhukov[13]

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
A. Albert, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, S. Ghosh, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, A. Schmidt, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
G. Flügge, O. Hlushchenko, B. Kargoll, T. Kress, A. Künsken, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, H. Sert, A. Stahl[15]

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, I. Babounikau, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borras[16], V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, T. Eichhorn, A. Elwood, E. Eren, E. Gallo[17], A. Geiser, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, A. Harb, J. Hauk, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, A. Lelek, T. Lenz, K. Lipka, W. Lohmann[18], R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, S.K. Pflitsch, D. Pitzl, A. Raspereza, M. Savitskyi, P. Saxena, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, N. Stefaniuk, H. Tholen, A. Vagnerini, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

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

Institut für Experimentelle Teilchenphysik, Karlsruhe, Germany
M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, N. Faltermann, B. Freund, M. Giffels, M.A. Harrendorf, F. Hartmann[15], S.M. Heindl, U. Husemann, F. Kassel[15], I. Katkov[13], S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

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

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

National Technical University of Athens, Athens, Greece
K. Kousouris, I. Papakrivopoulos, Y. Tsipolitis

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

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanad, N. Filipovic, G. Pasztor, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horvath[19], Á. Hunyadi, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi[†]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi[21], A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary
M. Bartók[20], P. Raics, Z.L. Trocsanyi, B. Ujvari

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

National Institute of Science Education and Research, HBNI, Bhubaneswar, India
S. Bahinipati[22], P. Mal, K. Mandal, A. Nayak[23], D.K. Sahoo[22], S.K. Swain

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

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
R. Bhardwaj[24], M. Bharti, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep[24], D. Bhowmik, S. Dey, S. Dutt[24], S. Dutta, S. Ghosh, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, B. Singh, S. Thakur[24]

Indian Institute of Technology Madras, Madras, India
P.K. Behera

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

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

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity[25], G. Majumder, K. Mazumdar, N. Sahoo, T. Sarkar[25]

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

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[26], E. Eskandari Tadavani, S.M. Etesami[26], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh[27], M. Zeinali

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

INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], C. Calabria[a,b], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], F. Errico[a,b], L. Fiore[a], A. Gelmi[a,b], G. Iaselli[a,c], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], G. Miniello[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a], A. Ranieri[a], G. Selvaggi[a,b], A. Sharma[a], L. Silvestris[a,15], R. Venditti[a], P. Verwilligen[a], G. Zito[a]

INFN Sezione di Bologna [a], Università di Bologna [b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a,b], S. Braibant-Giacomelli[a,b],

R. Campanini[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], P. Giacomelli[a], L. Guiducci[a,b], S. Marcellini[a], G. Masetti[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]

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

INFN Sezione di Firenze [a], Università di Firenze [b], Firenze, Italy
G. Barbagli[a], K. Chatterjee[a,b], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], G. Latino, P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], L. Russo[a,28], G. Sguazzoni[a], D. Strom[a], L. Viliani[a]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera[15]

INFN Sezione di Genova [a], Università di Genova [b], Genova, Italy
F. Ferro[a], F. Ravera[a,b], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
A. Benaglia[a], A. Beschi[b], L. Brianza[a,b], F. Brivio[a,b], V. Ciriolo[a,b,15], M.E. Dinardo[a,b], S. Fiorendi[a,b], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], M. Malberti[a,b], S. Malvezzi[a], R.A. Manzoni[a,b], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Pigazzini[a,b,29], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli [a], Università di Napoli 'Federico II' [b], Napoli, Italy, Università della Basilicata [c], Potenza, Italy, Università G. Marconi [d], Roma, Italy
S. Buontempo[a], N. Cavallo[a,c], A. Di Crescenzo[a,b], S. Di Guida[a,d,15], F. Fabozzi[a,c], F. Fienga[a,b], G. Galati[a,b], A.O.M. Iorio[a,b], W.A. Khan[a], L. Lista[a], S. Meola[a,d,15], P. Paolucci[a,15], C. Sciacca[a,b], E. Voevodina[a,b]

INFN Sezione di Padova [a], Università di Padova [b], Padova, Italy, Università di Trento [c], Trento, Italy
P. Azzi[a], N. Bacchetta[a], L. Benato[a,b], D. Bisello[a,b], A. Boletti[a,b], A. Bragagnolo, R. Carlin[a,b], P. Checchia[a], M. Dall'Osso[a,b], P. De Castro Manzano[a], T. Dorigo[a], U. Dosselli[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], S. Lacaprara[a], P. Lujan, M. Margoni[a,b], A.T. Meneguzzo[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], A. Tiko, E. Torassa[a], M. Zanetti[a,b], P. Zotto[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
A. Braghieri[a], A. Magnani[a], P. Montagna[a,b], S.P. Ratti[a,b], V. Re[a], M. Ressegotti[a,b], C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

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

INFN Sezione di Pisa [a], Università di Pisa [b], Scuola Normale Superiore di Pisa [c], Pisa, Italy
K. Androsov[a], P. Azzurri[a], G. Bagliesi[a], L. Bianchini[a], T. Boccali[a], L. Borrello, R. Castaldi[a], M.A. Ciocci[a,b], R. Dell'Orso[a], G. Fedi[a], L. Giannini[a,c], A. Giassi[a], M.T. Grippo[a], F. Ligabue[a,c], T. Lomtadze[a], E. Manca[a,c], G. Mandorli[a,c], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma [a], Sapienza Università di Roma [b], Rome, Italy
L. Barone[a,b], F. Cavallari[a], M. Cipriani[a,b], N. Daci[a], D. Del Re[a,b], E. Di Marco[a,b], M. Diemoz[a],

S. Gelli[a,b], E. Longo[a,b], B. Marzocchi[a,b], P. Meridiani[a], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], F. Preiato[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b]

INFN Sezione di Torino [a], Università di Torino [b], Torino, Italy, Università del Piemonte Orientale [c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[a,b], C. Biino[a], N. Cartiglia[a], F. Cenna[a,b], M. Costa[a,b], R. Covarelli[a,b], A. Degano[a,b], N. Demaria[a], B. Kiani[a,b], C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], E. Monteil[a,b], M. Monteno[a], M.M. Obertino[a,b], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G.L. Pinna Angioni[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], K. Shchelina[a,b], V. Sola[a], A. Solano[a,b], A. Staiano[a]

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], G. Della Ricca[a,b], F. Vazzoler[a,b], A. Zanetti[a]

Kyungpook National University
D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S. Sekmen, Y.C. Yang

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
H. Kim, D.H. Moon, G. Oh

Hanyang University, Seoul, Korea
J. Goh, T.J. Kim

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

Sejong University, Seoul, Korea
H. Kim

Seoul National University, Seoul, Korea
J. Almond, J. Kim, J.S. Kim, H. Lee, K. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

University of Seoul, Seoul, Korea
H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

Sungkyunkwan University, Suwon, Korea
Y. Choi, C. Hwang, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania
V. Dudenas, A. Juodagalvis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali[30], F. Mohamad Idris[31], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
M.C. Duran-Osuna, H. Castilla-Valdez, E. De La Cruz-Burelo, G. Ramirez-Sanchez, I. Heredia-De La Cruz[32], R.I. Rabadan-Trejo, R. Lopez-Fernandez, J. Mejia Guisao, R Reyes-Almanza, A. Sanchez-Hernandez

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
A. Morelos Pineda

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
S. Bheesette, P.H. Butler

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

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

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk[33], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Seixas, G. Strong, O. Toldaiev, D. Vadruccio, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
A. Baginyan, P. Bunin, I. Golutvin, V. Karjavin, V. Korenkov, G. Kozlov, A. Lanev, A. Malakhov, V. Matveev[34,35], V.V. Mitsyn, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov, V. Trofimov, B.S. Yuldashev[36], A. Zarubin, V. Zhiltsov

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
V. Golovtsov, Y. Ivanov, V. Kim[37], E. Kuznetsova[38], P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. 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, A. Stepennov, V. Stolin, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev, A. Bylinkin[35]

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
R. Chistov[39], M. Danilov[39], P. Parygin, D. Philippov, S. Polikarpov, E. Tarkovskii

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin[35], I. Dremin[35], M. Kirakosyan[35], S.V. Rusakov, A. Terkulov

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

Novosibirsk State University (NSU), Novosibirsk, Russia
V. Blinov[40], T. Dimova[40], L. Kardapoltsev[40], D. Shtol[40], Y. Skovpen[40]

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

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

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[41], P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

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

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

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

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

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, B. Akgun, E. Auffray, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, T. Camporesi, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, G. Cucciati, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, A. De Roeck, N. Deelen, M. Dobson, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita[42], G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, D. Gulhan, J. Hegeman, V. Innocente, A. Jafari, P. Janot, O. Karacheban[18], J. Kieseler, V. Knünz, A. Kornmayer, M. Krammer[1], C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, F. Meijers, J.A. Merlin,

S. Mersi, E. Meschi, P. Milenovic[43], F. Moortgat, M. Mulders, H. Neugebauer, J. Ngadiuba, S. Orfanelli, L. Orsini, F. Pantaleo[15], L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, T. Reis, G. Rolandi[44], M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas[45], A. Stakia, J. Steggemann, M. Tosi, D. Treille, A. Tsirou, V. Veckalns[46], M. Verweij, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl[†], L. Caminada[47], K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
M. Backhaus, L. Bäni, P. Berger, B. Casal, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, C. Grab, C. Heidegger, D. Hits, J. Hoss, T. Klijnsma, W. Lustermann, M. Marionneau, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Reichmann, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland
T.K. Aarrestad, C. Amsler[48], D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, I. Neutelings, D. Pinna, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

National Central University, Chung-Li, Taiwan
Y.H. Chang, K.y. Cheng, T.H. Doan, Sh. Jain, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Arun Kumar, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, J.f. Tsai

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
A. Bat, F. Boran, S. Cerci[49], S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos[50], E.E. Kangal[51], O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir[52], S. Ozturk[53], D. Sunar Cerci[49], B. Tali[49], U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
B. Isildak[54], G. Karapinar[55], M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey
I.O. Atakisi, E. Gülmez, M. Kaya[56], O. Kaya[57], S. Tekten, E.A. Yetkin[58]

Istanbul Technical University, Istanbul, Turkey
M.N. Agaras, S. Atay, A. Cakir, K. Cankocak, Y. Komurcu, S. Sen[59]

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

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

University of Bristol, Bristol, United Kingdom
T. Alexander, F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold[60], S. Paramesvaran, B. Penning, T. Sakuma, D. Smith, V.J. Smith, J. Taylor

Rutherford Appleton Laboratory, Didcot, United Kingdom
A. Belyaev[61], C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Imperial College, London, United Kingdom
G. Auzinger, R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, D. Colling, L. Corpe, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, Y. Haddad, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, J. Nash[62], A. Nikitenko[6], V. Palladino, M. Pesaresi, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, T. Strebler, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta[63], T. Virdee[15], N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

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

Baylor University, Waco, USA
A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika, C. Smith

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

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

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

Brown University, Providence, USA
G. Benelli, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan[64], K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, J. Pazzini, S. Piperov, S. Sagir, R. Syarif, D. Yu

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

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

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

University of California, San Diego, La Jolla, USA
J.G. Branson, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein,

G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech[65], J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

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

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

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

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

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

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla[†], K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, C. Pena, O. Prokofyev, G. Rakness, L. Ristori, A. Savoy-Navarro[66], B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck, W. Wu

University of Florida, Gainesville, USA
D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, R.D. Field, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, K. Shi, D. Sperka, L. Thomas, J. Wang, S. Wang

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

Florida State University, Tallahassee, USA
A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, A. Santra, V. Sharma, R. Yohay

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, C. Mills, I.D. Sandoval Gonzalez, M.B. Tonjes, N. Varelas, H. Wang, Z. Wu, J. Zhang

The University of Iowa, Iowa City, USA
B. Bilki[67], W. Clarida, K. Dilsiz[68], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya[69], A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul[70], Y. Onel, F. Ozok[71], A. Penzo, C. Snyder, E. Tiras, J. Wetzel

Johns Hopkins University, Baltimore, USA
B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, W.T. Hung, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

The University of Kansas, Lawrence, USA
A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Rogan, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang

Kansas State University, Manhattan, USA
A. Ivanov, K. Kaadze, Y. Maravin, A. Modak, A. Mohammadi, L.K. Saini, N. Skhirtladze

Lawrence Livermore National Laboratory, Livermore, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, USA
A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar

Massachusetts Institute of Technology, Cambridge, USA
D. Abercrombie, B. Allen, V. Azzolini, R. Barbieri, A. Baty, G. Bauer, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.-J. Lee, A. Levin, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch, S. Zhaozhong

University of Minnesota, Minneapolis, USA
A.C. Benvenuti, R.M. Chatterjee, A. Evans, P. Hansen, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, J. Turkewitz, M.A. Wadud

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA
E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, USA
A. Godshalk, C. Harrington, I. Iashvili, A. Kharchilava, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA
E. Barberis, C. Freer, A. Hortiangtham, A. Massironi, D.M. Morse, T. Orimoto, R. Teixeira De Lima, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

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

University of Notre Dame, Notre Dame, USA
R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko[34], M. Planer, A. Reinsvold, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

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

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

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

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

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

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

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

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

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

Texas A&M University, College Station, USA
O. Bouhali[72], A. Castaneda Hernandez[72], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[73], R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, F. De Guio, P.R. Dudero, J. Faulkner, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

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

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

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

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

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
3: Also at Universidade Estadual de Campinas, Campinas, Brazil
4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
5: Also at Université Libre de Bruxelles, Bruxelles, Belgium
6: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
7: Also at Joint Institute for Nuclear Research, Dubna, Russia
8: Also at Suez University, Suez, Egypt
9: Now at British University in Egypt, Cairo, Egypt
10: Also at Fayoum University, El-Fayoum, Egypt
11: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia
12: Also at Université de Haute Alsace, Mulhouse, France
13: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
14: Also at Tbilisi State University, Tbilisi, Georgia
15: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
16: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
17: Also at University of Hamburg, Hamburg, Germany
18: Also at Brandenburg University of Technology, Cottbus, Germany
19: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
20: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
21: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
22: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
23: Also at Institute of Physics, Bhubaneswar, India
24: Also at Shoolini University, Solan, India
25: Also at University of Visva-Bharati, Santiniketan, India
26: Also at Isfahan University of Technology, Isfahan, Iran
27: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
28: Also at Università degli Studi di Siena, Siena, Italy
29: Also at INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
30: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
31: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia

32: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
33: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
34: Also at Institute for Nuclear Research, Moscow, Russia
35: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
36: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
37: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
38: Also at University of Florida, Gainesville, USA
39: Also at P.N. Lebedev Physical Institute, Moscow, Russia
40: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
41: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
42: Also at INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
43: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
44: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
45: Also at National and Kapodistrian University of Athens, Athens, Greece
46: Also at Riga Technical University, Riga, Latvia
47: Also at Universität Zürich, Zurich, Switzerland
48: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
49: Also at Adiyaman University, Adiyaman, Turkey
50: Also at Istanbul Aydin University, Istanbul, Turkey
51: Also at Mersin University, Mersin, Turkey
52: Also at Piri Reis University, Istanbul, Turkey
53: Also at Gaziosmanpasa University, Tokat, Turkey
54: Also at Ozyegin University, Istanbul, Turkey
55: Also at Izmir Institute of Technology, Izmir, Turkey
56: Also at Marmara University, Istanbul, Turkey
57: Also at Kafkas University, Kars, Turkey
58: Also at Istanbul Bilgi University, Istanbul, Turkey
59: Also at Hacettepe University, Ankara, Turkey
60: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
61: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
62: Also at Monash University, Faculty of Science, Clayton, Australia
63: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
64: Also at Bethel University, St. Paul, USA
65: Also at Utah Valley University, Orem, USA
66: Also at Purdue University, West Lafayette, USA
67: Also at Beykent University, Istanbul, Turkey
68: Also at Bingol University, Bingol, Turkey
69: Also at Erzincan University, Erzincan, Turkey
70: Also at Sinop University, Sinop, Turkey
71: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
72: Also at Texas A&M University at Qatar, Doha, Qatar
73: Also at Kyungpook National University, Daegu, Korea