EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP-2023-053
22 March 2023

Measurement of inclusive J/ψ pair production cross section in pp collisions at $\sqrt{s} = 13$ TeV

ALICE Collaboration*

Abstract

The production cross section of inclusive J/ψ pairs in pp collisions at a centre-of-mass energy $\sqrt{s} = 13$ TeV is measured with ALICE. The measurement is performed for J/ψ in the rapidity interval $2.5 < y < 4.0$ and for transverse momentum $p_{\rm T} > 0$. The production cross section of inclusive J/ψ pairs is reported to be $10.3 \pm 2.3\,(\text{stat.}) \pm 1.3\,(\text{syst.})$ nb in this kinematic interval. The contribution from non-prompt J/ψ (i.e. originated from beauty-hadron decays) to the inclusive sample is evaluated. The results are discussed and compared with data.

*See Appendix A for the list of collaboration members

1 Introduction

In the quantum chromodynamics (QCD) parton model [1], hadrons are composed of elementary constituents, the partons. Due to the composite nature of hadrons, multiple parton hard scatterings can occur in a hadron–hadron collision. Thus, it is possible to have two or more hard parton interactions simultaneously. Multiple parton interactions (MPI) have been studied since the introduction of the parton model [2, 3]. Further studies included the generalization of the QCD evolution equations into multiparton distribution and fragmentation functions [4, 5], and a discussion on the possible correlations in the colour and spin degrees of freedom [6]. Double-parton scatterings (DPS) are the simplest case of MPI, and were found to play the most important role in processes with final states such as four jets, four leptons or n-jet + W/γ measurements [7–15]. These studies were complemented by several measurements in hadron collisions at center-of-mass energies ($\sqrt{s}$) ranging from 63 GeV to 1.96 TeV [16–22].

At the LHC energies, the probability to have multiple parton interactions increases: as with the increase of collision energy, partons with smaller momentum fraction x are probed, with larger fluxes. Recent measurements have shown the relevance of MPI at the LHC [23–28], and have contributed to stimulate recent progresses in the theoretical understanding of MPI [29–33]. Nevertheless, a quantitative estimate of the DPS impact on observables remains challenging. Neglecting the parton correlations in the proton, the DPS contribution to a final state $A+B$ can be evaluated as the product of the parton level cross sections ($\widehat{\sigma}$) divided by an effective cross section ($\sigma_{\rm eff}$) [12, 13, 34]

$$\sigma^{\rm DPS}_{A,B} = \frac{m}{2}\,\frac{\widehat{\sigma}^{A}\,\widehat{\sigma}^{B}}{\sigma_{\rm eff}}, \tag{1}$$

where the parameter m is a symmetry factor, $m = 1$ if $A = B$, and 2 otherwise. The effective cross section is a phenomenological parameter related to the transverse overlap function between the partons of the proton, and is thought to be universal. It was found to range between 2 and 25 mb [18, 20, 22–25, 27, 35–42].

Double particle production is typically exploited to study DPS. A non exhaustive list of these studies are the measurements of the production cross sections of double quarkonium, i.e. J/ψ pairs [22, 35, 36, 43–46], Υ pairs [47], or J/$\psi + \Upsilon$ [37], electroweak boson plus quarkonium [22, 26, 27, 38, 39, 48], double charm production [23], charmed hadrons plus quarkonium [23, 27], electroweak boson plus open charm [23, 49], as well as measurements with jets in the final state, multi-jets [16–18, 50], $\gamma+$3-jets [19–21], $2\gamma+$2-jets [51], and W + 2-jets [25]. The recent observation of triple J/ψ production proposes an additional channel to study double and triple parton scatterings [52].

In the quarkonium sector, quarkonium-pair production is a golden tool to probe the production mechanism of heavy quarkonia [53–55]. The production mechanism of heavy quarkonia is not fully understood after more than forty years of study, and considered a long-standing puzzle of QCD. The colour-singlet model (CSM), which assumes the formation of an intermediate $\mathrm{Q\overline{Q}}$ state with the quantum numbers of the final state, underestimates the production cross section at high $p_{\rm T}$ both at leading-order (LO) and next-to-leading-order (NLO) [56–58]. The recent CSM next-to-next-to-leading-order NNLO* calculations have reduced the discrepancies [56, 59]. Non-relativistic QCD (NRQCD) calculations consider both colour-singlet (CS) and colour-octet (CO) states of the $\mathrm{Q\overline{Q}}$ pair [60], but fail to predict at the same time the production cross section and polarisation [61–65]. The selection rules for pair production in the CS process of LO NRQCD forbid the feed-down from cascade decays of excited charge-conjugate-even states, e.g. $\chi_{\rm c} \rightarrow {\rm J}/\psi\,\gamma$, whose contribution is significant in single quarkonium production, and makes difficult the comparison of data to model calculations. As a consequence, quarkonium-pair production provides stringent tests of model calculations.

In this letter we report the measurement of inclusive J/ψ pair production cross section in pp collisions at $\sqrt{s} = 13$ TeV at large rapidity ($2.5 < y < 4.0$) with ALICE. Inclusive J/ψ results correspond to the sum two contributions: the prompt contribution, originated from direct charm decays or decays of higher-mass excited states; and the non-prompt contribution, steaming from beauty decays. The results corroborate analogous measurements performed in a similar rapidity interval by LHCb [36]. They constitute a probe to study quarkonium production mechanisms and the DPS contribution.

2 Experimental apparatus and data sample

A description of the ALICE detector and its performances can be found in Refs. [66, 67]. At forward rapidity ($2.5 < y < 4.0$) the production of quarkonium states is measured in the muon spectrometer down to $p_{\mathrm{T}} = 0$ via their dimuon decay channel. The muon spectrometer of ALICE consists of a ten interaction length thick front absorber to filter muons, five tracking stations of two planes of cathode pad chambers each (MCH), a dipole magnet with a field integral of 3 Tm surrounding the third tracking station, a 1.2 m thick iron wall to absorb secondary hadrons escaping from the front absorber and low momentum muons coming mainly from π and K decays, and two trigger stations made of two planes of resistive plate chambers each (MTR) [68]. The silicon pixel detector (SPD) and scintillator arrays (V0) are also used in this analysis. The V0 counters, two arrays of 32 scintillator tiles each, cover $2.8 \leq \eta \leq 5.1$ (V0A) and $-3.7 \leq \eta \leq -1.7$ (V0C) and provide trigger information. The minimum bias (MB) trigger requirement consists of a logical AND of a signal in V0A and in V0C. The SPD, two cylindrical layers covering $|\eta| \leq 2.0$ and $|\eta| \leq 1.4$ for the inner and outer layers, respectively, is dedicated to the vertex reconstruction and allows estimating pile-up. The maximum interaction rate for the analysed data sample is 260 kHz, and the maximum pile-up probability is about 5×10^{-3}, negligible for this measurement.

The J/ψ pair analysis is performed using data from pp collisions at $\sqrt{s}$ = 13 TeV collected from 2016 to 2018. The event sample was selected using the dimuon trigger condition, which is defined as the coincidence between the MB requirement and two opposite-charge sign track segments in the muon spectrometer trigger stations. Each track segment in the trigger stations is required to have a transverse momentum, evaluated online, larger than about 0.5 GeV/c. Only events passing a selection criterion to remove beam–background collisions contamination, based on the timing information from the V0 arrays, are considered in the analysis.

When multiple primary vertices are reconstructed by the SPD, the event is tagged as pile-up and removed from this analysis. In order to avoid acceptance biases on the reconstructed SPD tracklets, events with a displaced vertex with respect to centre of the SPD detector along the beam direction are discarded according to the requirement $|v_z| \leq 10$ cm. Considering the above selections, the total number of dimuon triggered events in the sample sums up to 587.4×10^6 events and corresponds to an integrated luminosity of $24.11 \pm 0.01(\text{stat.}) \pm 0.80(\text{syst.})\,\text{pb}^{-1}$.

3 Analysis

J/ψ candidates are built from muon pairs of opposite-charge sign. Muons are identified by requiring that selected tracks in the MCH have a matching track segment in MTR. Only muon tracks within the detector acceptance are kept for analysis. Tracks are required to be within $-4.0 < \eta^{\mu} < -2.5$, and the radial distance from the beam axis at the end of the front absorber, R_{abs}, is limited to $17.6 < R_{\text{abs}} <$ 89.5 cm [69]. J/ψ pair candidates are reconstructed from all combinations of double dimuon pairs (each dimuon consisting of an opposite-charge sign muon pair) per event.

The production cross section of inclusive J/ψ pairs is determined as

$$\sigma(\mathrm{J}/\psi\,\mathrm{J}/\psi) = \frac{N}{\mathscr{L}_{\text{int}} \times \varepsilon \times B^2(\mathrm{J}/\psi \to \mu^+\mu^-)}\,, \tag{2}$$

where N is the signal estimate, ε is the acceptance-times-efficiency correction, $B(\mathrm{J}/\psi \to \mu^+\mu^-) = (5.961 \pm 0.033)\%$ is the branching fraction of $\mathrm{J}/\psi \to \mu^+\mu^-$ [70], and $\mathscr{L}_{\text{int}}$ is the integrated luminosity.

The J/ψ pair signal is evaluated from a fit to the 2-dimensional invariant mass distribution. A two-step procedure was chosen. The first step exploits the 1-dimensional distribution of all J/ψ candidates in the data sample analysed, to obtain a good description of the J/ψ line shape from data. A fit is performed with a superposition of J/ψ and $\psi(2S)$ signal functions and a background function. The J/ψ mass, width, and normalisation are left free in the procedure. Instead, the $\psi(2S)$ mass and width are bound to those of J/ψ as described in Ref. [71]. The 2-dimensional invariant mass distribution of J/ψ pair candidates $(m_1(\mu_1^+\mu_1^-), m_2(\mu_2^+\mu_2^-))$ is fit in the second step.

$$\begin{aligned} F(m_1,m_2) \quad = \quad & N \times S_1(m_1) \times S_2(m_2) + R_{B_1,S_2} \times B_1(m_1) \times S_2(m_2) \\ & + R_{S_1,B_2} \times S_1(m_1) \times B_2(m_2) + R_{B_1,B_2} \times B_1(m_1) \times B_2(m_2)\,, \end{aligned} \tag{3}$$

where N and R are the corresponding normalisation parameters. The $\psi(2S)$ contribution is neglected in the 2-dimensional fit. The J/ψ pole mass and width determined from the first step are fixed in the second step of the fit, the rest of the fit parameters are left free. Different combinations of functional forms are used to determine the raw yield and its uncertainties. The signal S is modelled by a Crystal Ball function including a Gaussian core and two asymmetric power-law tails [72]. The power-law tail parameters are obtained both from data or Monte Carlo and fixed in the fits [69]. The background B contribution is described by either the sum of two exponentials, an exponential of a second order polynomial, or the ratio of a first-order to a second-order polynomials. The mass distribution is fit in two different mass intervals to test the results stability, i.e. [2.0, 4.5] and [2.2, 4.9] GeV/c^2. As the candidates were assigned randomly, the fit function is symmetric under exchange of m_1 and m_2. The projections of one of the fits on $m_1(\mu_1^+\mu_1^-)$ and $m_2(\mu_2^+\mu_2^-)$ are shown in Fig. 1. The J/ψ pair signal and statistical uncertainty are evaluated as the average of the values obtained in the twelve fit configurations. The systematic uncertainty is given by their standard deviation. The raw yield is $N = 59.3 \pm 13.5\,(\text{stat}) \pm 4.4\,(\text{syst})$.

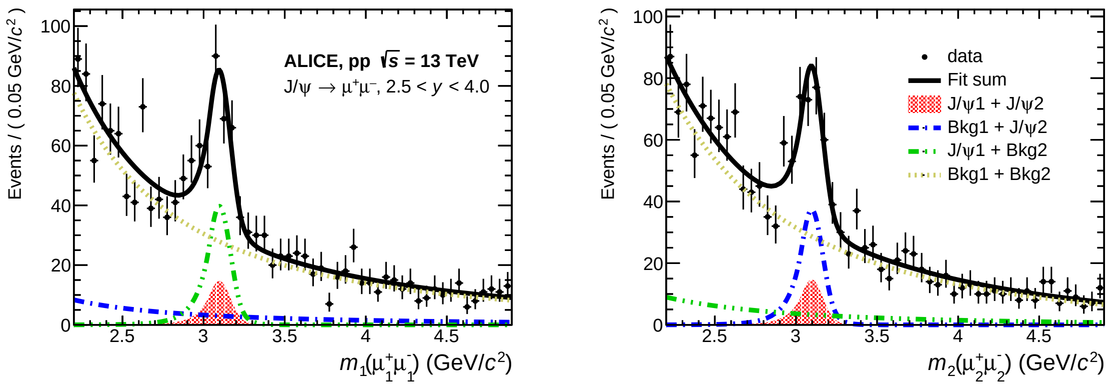

Figure 1: Projections of a fit to the 2-dimensional invariant mass distribution for inclusive J/ψ pair candidates for (left) $m_1(\mu_1^+\mu_1^-)$ and (right) $m_2(\mu_2^+\mu_2^-)$. The (black) markers show data. The (black) solid line represents the total fit function. The (blue and green) dashed-dotted lines indicate the background contribution from a combination of a real J/ψ signal with a combinatorial candidate. The (yellow) dotted line represents muon pairs from combinatorial background.

The acceptance, reconstruction and selection efficiency is evaluated assuming factorisation of the corrections of the J/ψ pair as

$$\varepsilon(\mathrm{J}/\psi\,\mathrm{J}/\psi) = \varepsilon(\mathrm{J}/\psi) \times \varepsilon(\mathrm{J}/\psi)\,. \tag{4}$$

The J/ψ ε is computed from Monte Carlo simulations as described in Ref. [69]. An iterative procedure is used to generate input rapidity (y) and transverse momentum (p_{T}) distributions from data. The J/ψ are decayed into pairs of muons using EVTGEN [73] and PHOTOS [74]. A GEANT3 [75] simulation is performed to transport the decay muons through the apparatus including a realistic description of the detector conditions during data taking. The validity of the factorisation approach for the efficiency calculation was tested. The invariant mass distribution was compared with the corresponding one after applying a 2-dimensional (y, $p_{\rm T}$) acceptance-times-efficiency correction per J/ψ candidate. The shapes of the 2-dimensional invariant mass distribution, and their projections are not modified by the correction, confirming the validity of our assumption.

Various sources of systematic uncertainties on the J/ψ pair production cross section are considered: (i) the signal extraction, (ii) the branching fraction uncertainty, (iii) the luminosity normalisation, and (iv) the acceptance-times-efficiency correction. Details on the signal extraction procedure were given previously in this Letter. The systematic uncertainty on the signal extraction, obtained as described above, amounts to 7.4%. The branching fraction uncertainty is 0.6% for single J/ψ [70], thus 1.1% for J/ψ pairs. The influence of the luminosity normalisation factor is evaluated by computing the equivalent number of minimum-bias events in the analysed dimuon sample with different methods as described in Ref. [76], which amounts to 2.9%. The uncertainty on the minimum bias cross section, evaluated in a van der Meer scan (1.6%), is also taken into account in the calculation [77]. These two sources lead to a 3.3% systematic uncertainty for the luminosity. The systematic uncertainty on the acceptance-times-efficiency correction contains contributions from (i) the input $p_{\rm T}$ and y distributions, (ii) the tracking efficiency in the MCH, (iii) the MTR trigger efficiency, and (iv) the matching of the reconstructed tracks in the MCH with the track segments in the MTR. The influence of the simulated J/ψ $p_{\rm T}$ and y distributions is tested by comparing the corrected yield obtained via the iterative procedure, with the one obtained from an efficiency-corrected invariant mass distribution. For this exercise, a 2-dimensional $\varepsilon(p_{\rm T}, y)$ correction is applied to each J/ψ candidate in order to build the efficiency-corrected invariant mass distribution, which was then fit to obtain the corresponding corrected yield. A 0.5% uncertainty is assigned to the MC input for J/ψ [69]. The systematic uncertainties on the tracking efficiency in the MCH, the MTR trigger efficiency and the matching between the MCH and MTR are evaluated comparing single muon data and MC, as described in Ref. [78]. The differences are then propagated to the dimuon case, being 4%, 2% and 1% respectively for the J/ψ [69]. This results in a 4.6% acceptance-times-efficiency uncertainty for J/ψ, and is propagated to a 9.2% uncertainty for J/ψ pairs. The analysis requirement that all selected tracks in the MCH should match track segments in the MTR removes any possible dependence on which pair of tracks activated the trigger. Table 1 summarises the systematic uncertainties on the measurement of the J/ψ pair production cross section.

Table 1: Sources of systematic uncertainty on the J/ψ pair production cross section measurement.

Source	Uncertainty (%)
Signal extraction	7.4
Acceptance-times-efficiency	9.2
$B(\mathrm{J}/\psi \to \mu^+\mu^-)$	1.1
Luminosity	3.3
Total	12.3

4 Results

The inclusive J/ψ pair production cross section in the kinematic interval $2.5 < y < 4.0$ and $p_{\rm T} > 0$ is measured to be

$$\sigma(\mathrm{J}/\psi\,\mathrm{J}/\psi) = 10.3 \pm 2.3\,(\mathrm{stat.}) \pm 1.3\,(\mathrm{syst.})\ \mathrm{nb}.$$

The ratio of the production cross section of the inclusive J/ψ pair to that of the inclusive J/ψ is

$$\frac{\sigma(\mathrm{J}/\psi\,\mathrm{J}/\psi)}{\sigma(\mathrm{J}/\psi)} = (9.1 \pm 2.0\,(\mathrm{stat.}) \pm 1.3\,(\mathrm{syst.})) \times 10^{-4}\,,$$

considering $\mathrm{d}\sigma(\mathrm{J}/\psi)/\mathrm{d}y = (7533.3 \pm 26.7\,(\mathrm{stat.}) \pm 491.6\,(\mathrm{syst.}))$ nb for $p_{\mathrm{T}} > 0$ and $2.5 < y < 4.0$ [69], and assuming the systematic uncertainties to be uncorrelated. Likewise, the ratio

$$\frac{1}{2}\frac{\sigma(\mathrm{J}/\psi)^2}{\sigma(\mathrm{J}/\psi\,\mathrm{J}/\psi)} = 6.2 \pm 1.4\,(\mathrm{stat.}) \pm 1.1\,(\mathrm{syst.})\ \mathrm{mb},$$

can be calculated and interpreted as an effective cross section, according to Eq. (1). This interpretation assumes that all J/ψ pairs are produced via DPS processes. The relative contribution of SPS and DPS processes to J/ψ pair production is a topic of debate and intense studies, see e.g. Ref. [36]. In addition, the understanding of this ratio gets challenged by the contribution of both the prompt and non-prompt components to the measured inclusive J/ψ cross section, where the non-prompt contribution originates from beauty-hadron decays.

The contamination from beauty-hadron decays to the J/ψ pair cross section is evaluated to get a grasp of its influence to the measurement according to

$$\sigma_{\mathrm{non-prompt}}(\mathrm{J}/\psi\,\mathrm{J}/\psi) = \sigma_{\mathrm{b\bar{b}}}^{\mathrm{total}} \times \alpha \times B^2(h_b \rightarrow \mathrm{J}/\psi\ \ + \mathrm{X})\,.$$

The total beauty-hadron production cross section was measured to be

$$\sigma_{\mathrm{b\bar{b}}}^{\mathrm{total}} = 502 \pm 16\ (\mathrm{stat.}) \pm 51\ (\mathrm{syst.})^{+2}_{-3}\ (\mathrm{extr.})\ \mu\mathrm{b}$$

in Ref. [79]. The branching ratio of a beauty hadron into a J/ψ is $B(h_b \rightarrow \mathrm{J}/\psi + \mathrm{X}) = (1.16 \pm 0.10)\%$ [70], and the acceptance correction factor α is estimated using PYTHIA 8.3 [80] simulations. Beauty hadrons are simulated according to three different configurations and forced to decay into J/ψ. The three configurations use the Monash 2013 tune for the calculation [81]. Two of them also include a tuning of the parameters to get a good agreement with the NLO calculation by Mangano, Nason, and Ridolfi for the $\mathrm{b\bar{b}}$ single and double differential distributions [82]. The difference between the latter two is that one of them adds the ATLAS tune settings for multiple parton interactions [83]. The α factor is obtained from the ratio of the J/ψ pair counts in the acceptance to the number of all J/ψ pairs in the simulation. The value of $\alpha = 0.044^{+0.005}_{-0.007}$ is determined as the average of the factors obtained with all configurations, and the systematic uncertainty is conservatively set to the full spread of the values. This gives a non-prompt contribution of

$$\sigma_{\text{non-prompt}}(\mathrm{J}/\psi\,\mathrm{J}/\psi) = 2.97 \pm 0.09\,(\mathrm{stat.})^{+0.68}_{-0.76}(\mathrm{syst.})\ \mathrm{nb},$$

and correspondingly the prompt J/ψ pair cross section is

$$\sigma_{\mathrm{prompt}}(\mathrm{J}/\psi\,\mathrm{J}/\psi) = \sigma(\mathrm{J}/\psi\,\mathrm{J}/\psi) - \sigma_{\text{non-prompt}}(\mathrm{J}/\psi\,\mathrm{J}/\psi) = 7.3 \pm 1.7\,(\mathrm{stat.})^{+1.9}_{-2.1}(\mathrm{syst.})\ \mathrm{nb}.$$

Analogously, for the single J/ψ case, the computed extrapolation factor to account for the number of J/ψ from beauty decays in the acceptance is $\beta = 0.121^{+0.001}_{-0.002}$. Thus, the non-prompt contribution to the J/ψ production cross section is

$$\sigma_{\text{non-prompt}}(\mathrm{J}/\psi) = 2 \times \sigma_{\mathrm{b\bar{b}}}^{\mathrm{total}} \times \beta \times B(h_{\mathrm{b}} \rightarrow \mathrm{J}/\psi\ \ + \mathrm{X}) = 1.41 \pm 0.04\,(\mathrm{stat.}) \pm 0.19(\mathrm{syst.})\ \mu\mathrm{b},$$

and the prompt component is evaluated to be

$$\sigma_{\mathrm{prompt}}(\mathrm{J}/\psi) = \sigma(\mathrm{J}/\psi) - \sigma_{\text{non-prompt}}(\mathrm{J}/\psi) = 9.89 \pm 0.32\,(\mathrm{stat.})^{+1.47}_{-1.48}(\mathrm{syst.})\ \mu\mathrm{b}.$$

Therefore, the ratios discussed earlier in this section can be evaluated for the prompt case. The ratio of the prompt J/ψ pair production cross section to that of J/ψ equals

$$\frac{\sigma_{\mathrm{prompt}}(\mathrm{J}/\psi\,\mathrm{J}/\psi)}{\sigma_{\mathrm{prompt}}(\mathrm{J}/\psi)} = (7.4 \pm 1.7\,(\mathrm{stat.}) \pm 2.2\,(\mathrm{syst.})) \times 10^{-4}\,,$$

and the ratio related to the effective DPS cross section becomes

$$\frac{1}{2}\frac{\sigma_{\rm prompt}(J/\psi)^2}{\sigma_{\rm prompt}(J/\psi\, J/\psi)} = 6.7 \pm 1.6\,(\text{stat.}) \pm 2.7\,(\text{syst.})\ \text{mb}.$$

A differential measurement of the prompt J/ψ pair production cross section and the corresponding ratios were previously reported by the LHCb collaboration in a slightly different kinematic interval, $2.0 < y < 4.5$ and $p_T < 10$ GeV/c [36, 46]. The results presented here are in agreement with the LHCb ones within uncertainties.

Despite the caveat caused by the calculation of this effective value considering both the SPS and DPS contributions to the production cross section, this value is consistent with the values obtained from quarkonium-pair production measurements, with $\sigma_{\rm eff}$ values ranging from 2.2 to 12.5 mb [22, 35–37], and with the values obtained for quarkonium associated production at central rapidity (in the range 2.3–6.1 mb) [38, 39, 59]. It is smaller than the values obtained for associated heavy-flavour production at large rapidity by LHCb (ranging from 12.8 to 18.0 mb) [23, 27], or those from jet or electroweak associated production (whose values are between 12.0 and 21.3 mb) [18, 20, 24, 25, 40–42].

5 Conclusion

The production cross section of J/ψ pairs at large rapidity in pp collisions at $\sqrt{s} = 13$ TeV was studied by ALICE. The measurement exploits the full Run 2 data sample collected by ALICE. The production cross section of inclusive J/ψ pairs is reported to be $10.3 \pm 2.3\,(\text{stat.}) \pm 1.3\,(\text{syst.})$ nb, for J/ψ in the rapidity interval $2.5 < y < 4.0$ and for $p_T > 0$. The results are compatible with analogous measurements performed by the LHCb collaboration in a similar kinematic interval [36, 46].

The Run 3 data taking, with the upgraded ALICE detector and the larger accumulated luminosity [84], will allow us to perform this measurement with increased precision and separating the prompt and non-prompt contributions. This will also enable studying the kinematics of these events and probe model calculations.

Acknowledgements

The ALICE Collaboration would like to thank all its engineers and technicians for their invaluable contributions to the construction of the experiment and the CERN accelerator teams for the outstanding performance of the LHC complex. The ALICE Collaboration gratefully acknowledges the resources and support provided by all Grid centres and the Worldwide LHC Computing Grid (WLCG) collaboration. The ALICE Collaboration acknowledges the following funding agencies for their support in building and running the ALICE detector: A. I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation (ANSL), State Committee of Science and World Federation of Scientists (WFS), Armenia; Austrian Academy of Sciences, Austrian Science Fund (FWF): [M 2467-N36] and Nationalstiftung für Forschung, Technologie und Entwicklung, Austria; Ministry of Communications and High Technologies, National Nuclear Research Center, Azerbaijan; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Financiadora de Estudos e Projetos (Finep), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and Universidade Federal do Rio Grande do Sul (UFRGS), Brazil; Bulgarian Ministry of Education and Science, within the National Roadmap for Research Infrastructures 2020¿2027 (object CERN), Bulgaria; Ministry of Education of China (MOEC) , Ministry of Science & Technology of China (MSTC) and National Natural Science Foundation of China (NSFC), China; Ministry of Science and Education and Croatian Science Foundation, Croatia; Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Cubaenergía, Cuba; Ministry of Education, Youth and Sports of the Czech Republic, Czech Republic; The Danish Council for Independent Research | Natural Sciences, the VILLUM FONDEN and Danish National Research Foundation (DNRF), Denmark; Helsinki Institute of Physics (HIP), Finland; Commissariat à l'Energie Atomique (CEA) and Institut National de Physique Nucléaire et de Physique des Particules (IN2P3) and Centre National de la Recherche Scientifique (CNRS), France; Bundesministerium für Bildung und Forschung (BMBF) and GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany; General Secretariat for Research and Technology, Ministry of Education, Research and Religions, Greece; National Research, Development and Innovation Office, Hungary; Department of Atomic Energy Government of India (DAE), Department of Science and Technology, Government of India (DST), University Grants Commission, Government of India (UGC) and Council of Scientific and Industrial Research (CSIR), India; National Research and Innovation Agency - BRIN, Indonesia; Istituto Nazionale di Fisica Nucleare (INFN), Italy; Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) and Japan Society for the Promotion of Science (JSPS) KAKENHI, Japan; Consejo Nacional de Ciencia (CONACYT) y Tecnología, through Fondo de Cooperación Internacional en Ciencia y Tecnología (FONCICYT) and Dirección General de Asuntos del Personal Academico (DGAPA), Mexico; Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), Netherlands; The Research Council of Norway, Norway; Commission on Science and Technology for Sustainable Development in the South (COMSATS), Pakistan; Pontificia Universidad Católica del Perú, Peru; Ministry of Education and Science, National Science Centre and WUT ID-UB, Poland; Korea Institute of Science and Technology Information and National Research Foundation of Korea (NRF), Republic of Korea; Ministry of Education and Scientific Research, Institute of Atomic Physics, Ministry of Research and Innovation and Institute of Atomic Physics and University Politehnica of Bucharest, Romania; Ministry of Education, Science, Research and Sport of the Slovak Republic, Slovakia; National Research Foundation of South Africa, South Africa; Swedish Research Council (VR) and Knut & Alice Wallenberg Foundation (KAW), Sweden; European Organization for Nuclear Research, Switzerland; Suranaree University of Technology (SUT), National Science and Technology Development Agency (NSTDA), Thailand Science Research and Innovation (TSRI) and National Science, Research and Innovation Fund (NSRF), Thailand; Turkish Energy, Nuclear and Mineral Research Agency (TENMAK), Turkey; National Academy of Sciences of Ukraine, Ukraine; Science and Technology Facilities Council (STFC), United Kingdom; National Science Foundation of the United States of America (NSF) and United States Department of Energy, Office of Nuclear Physics (DOE NP), United States of America. In addition, individual groups or members have received support from: European Research Council, Strong 2020 - Horizon 2020 (grant nos. 950692, 824093), European Union; Academy of Finland (Center of Excellence in Quark Matter) (grant nos. 346327, 346328), Finland; Programa de Apoyos para la Superación del Personal Académico, UNAM, Mexico.

References

[1] J. D. Bjorken and E. A. Paschos, "Inelastic Electron Proton and gamma Proton Scattering, and the Structure of the Nucleon", *Phys. Rev.* **185** (1969) 1975–1982.

[2] F. Takagi, "Multiple Production of Quark Jets Off Nuclei", *Phys. Rev. Lett.* **43** (1979) 1296.

[3] C. Goebel, F. Halzen, and D. M. Scott, "Double Drell-Yan Annihilations in Hadron Collisions: Novel Tests of the Constituent Picture", *Phys. Rev. D* **22** (1980) 2789.

[4] R. Kirschner, "Generalized Lipatov-Altarelli-Parisi Equations and Jet Calculus Rules", *Phys. Lett. B* **84** (1979) 266–270.

[5] V. P. Shelest, A. M. Snigirev, and G. M. Zinovev, "The Multiparton Distribution Equations in QCD", *Phys. Lett. B* **113** (1982) 325.

[6] M. Mekhfi, "Correlations in Color and Spin in Multiparton Processes", *Phys. Rev. D* **32** (1985) 2380.

[7] N. Paver and D. Treleani, "Multi - Quark Scattering and Large p_T Jet Production in Hadronic Collisions", *Nuovo Cim. A* **70** (1982) 215.

[8] N. Paver and D. Treleani, "Multiple Parton Interactions and Multi - Jet Events at Collider and Tevatron Energies", *Phys. Lett. B* **146** (1984) 252–256.

[9] M. Mekhfi, "Multiparton processes: an application to double Drell-Yan", *Phys. Rev. D* **32** (1985) 2371.

[10] B. Humpert, "Are there multi - quark interactions?", *Phys. Lett. B* **131** (1983) 461–467.

[11] B. Humpert, "The production of gauge boson pairs by p anti-p colliders", *Phys. Lett. B* **135** (1984) 179–186.

[12] B. Humpert and R. Odorico, "Multiparton Scattering and QCD Radiation as Sources of Four Jet Events", *Phys. Lett. B* **154** (1985) 211.

[13] L. Ametller, N. Paver, and D. Treleani, "Possible Signature of Multiple Parton Interactions in Collider Four Jet Events", *Phys. Lett. B* **169** (1986) 289–292.

[14] F. Halzen, P. Hoyer, and W. J. Stirling, "Evidence for Multiple Parton Interactions From the Observation of Multi - Muon Events in Drell-Yan Experiments", *Phys. Lett. B* **188** (1987) 375–378.

[15] R. M. Godbole, S. Gupta, and J. Lindfors, "Doudlbe parton scattering contribution to W + jets", *Z. Phys. C* **47** (1990) 69–74.

[16] **Axial Field Spectrometer** Collaboration, T. Åkesson *et al.*, "Double Parton Scattering in pp Collisions at $\sqrt{s} = 63$ GeV", *Z. Phys. C* **34** (1987) 163.

[17] **UA2** Collaboration, J. Alitti *et al.*, "A Study of multi - jet events at the CERN anti-p p collider and a search for double parton scattering", *Phys. Lett. B* **268** (1991) 145–154.

[18] **CDF** Collaboration, F. Abe *et al.*, "Study of four jet events and evidence for double parton interactions in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV", *Phys. Rev. D* **47** (1993) 4857–4871.

[19] **CDF** Collaboration, F. Abe *et al.*, "Measurement of double parton scattering in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV", *Phys. Rev. Lett.* **79** (1997) 584–589.

[20] **D0** Collaboration, V. M. Abazov *et al.*, "Double parton interactions in γ+3 jet events in pp^- bar collisions $\sqrt{s} = 1.96$ TeV.", *Phys. Rev. D* **81** (2010) 052012, arXiv:0912.5104 [hep-ex].

[21] **D0** Collaboration, V. M. Abazov *et al.*, "Double Parton Interactions in $\gamma + 3$ Jet and $\gamma + b/c jet + 2$ Jet Events in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV", *Phys. Rev. D* **89** (2014) 072006, arXiv:1402.1550 [hep-ex].

[22] **D0** Collaboration, V. M. Abazov *et al.*, "Observation and Studies of Double J/ψ Production at the Tevatron", *Phys. Rev. D* **90** (2014) 111101, arXiv:1406.2380 [hep-ex].

[23] **LHCb** Collaboration, R. Aaij *et al.*, "Observation of double charm production involving open charm in pp collisions at $\sqrt{s}$ = 7 TeV", *JHEP* **06** (2012) 141, arXiv:1205.0975 [hep-ex]. [Addendum: JHEP 03, 108 (2014)].

[24] **ATLAS** Collaboration, G. Aad *et al.*, "Measurement of hard double-parton interactions in $W(\rightarrow l\nu)$+ 2 jet events at $\sqrt{s}$=7 TeV with the ATLAS detector", *New J. Phys.* **15** (2013) 033038, arXiv:1301.6872 [hep-ex].

[25] **CMS** Collaboration, S. Chatrchyan *et al.*, "Study of Double Parton Scattering Using W + 2-Jet Events in Proton-Proton Collisions at $\sqrt{s}$ = 7 TeV", *JHEP* **03** (2014) 032, arXiv:1312.5729 [hep-ex].

[26] **ATLAS** Collaboration, G. Aad *et al.*, "Observation and measurements of the production of prompt and non-prompt J/ψ mesons in association with a Z boson in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector", *Eur. Phys. J. C* **75** (2015) 229, arXiv:1412.6428 [hep-ex].

[27] **LHCb** Collaboration, R. Aaij *et al.*, "Production of associated Y and open charm hadrons in pp collisions at $\sqrt{s} = 7$ and 8 TeV via double parton scattering", *JHEP* **07** (2016) 052, arXiv:1510.05949 [hep-ex].

[28] **ALICE** Collaboration, "The ALICE experiment – A journey through QCD", arXiv:2211.04384 [nucl-ex].

[29] B. Blok, Y. Dokshitser, L. Frankfurt, and M. Strikman, "pQCD physics of multiparton interactions", *Eur. Phys. J. C* **72** (2012) 1963, arXiv:1106.5533 [hep-ph].

[30] M. Diehl, D. Ostermeier, and A. Schafer, "Elements of a theory for multiparton interactions in QCD", *JHEP* **03** (2012) 089, arXiv:1111.0910 [hep-ph]. [Erratum: JHEP 03, 001 (2016)].

[31] J. R. Gaunt, "Glauber Gluons and Multiple Parton Interactions", *JHEP* **07** (2014) 110, arXiv:1405.2080 [hep-ph].

[32] M. Diehl, T. Kasemets, and S. Keane, "Correlations in double parton distributions: effects of evolution", *JHEP* **05** (2014) 118, arXiv:1401.1233 [hep-ph].

[33] J. R. Gaunt, R. Maciula, and A. Szczurek, "Conventional versus single-ladder-splitting contributions to double parton scattering production of two quarkonia, two Higgs bosons and $c\bar{c}c\bar{c}$", *Phys. Rev. D* **90** (2014) 054017, arXiv:1407.5821 [hep-ph].

[34] A. Del Fabbro and D. Treleani, "Scale factor in double parton collisions and parton densities in transverse space", *Phys. Rev. D* **63** (2001) 057901, arXiv:hep-ph/0005273.

[35] **ATLAS** Collaboration, M. Aaboud *et al.*, "Measurement of the prompt J/ ψ pair production cross-section in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector", *Eur. Phys. J. C* **77** (2017) 76, arXiv:1612.02950 [hep-ex].

[36] **LHCb** Collaboration, R. Aaij *et al.*, "Measurement of the J/ψ pair production cross-section in pp collisions at $\sqrt{s} = 13$ TeV", *JHEP* **06** (2017) 047, arXiv:1612.07451 [hep-ex]. [Erratum: JHEP 10, 068 (2017)].

[37] **D0** Collaboration, V. M. Abazov *et al.*, "Evidence for simultaneous production of J/ψ and Υ mesons", *Phys. Rev. Lett.* **116** (2016) 082002, arXiv:1511.02428 [hep-ex].

[38] J.-P. Lansberg and H.-S. Shao, "Phenomenological analysis of associated production of $Z^0 + b$ in the $b \to J/\psi X$ decay channel at the LHC", *Nucl. Phys. B* **916** (2017) 132–142, arXiv:1611.09303 [hep-ph].

[39] J.-P. Lansberg, H.-S. Shao, and N. Yamanaka, "Indication for double parton scatterings in $W+$ prompt J/ψ production at the LHC", *Phys. Lett. B* **781** (2018) 485–491, arXiv:1707.04350 [hep-ph].

[40] **CDF** Collaboration, F. Abe *et al.*, "Double parton scattering in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV", *Phys. Rev. D* **56** (1997) 3811–3832.

[41] **CMS** Collaboration, V. Khachatryan *et al.*, "Event generator tunes obtained from underlying event and multiparton scattering measurements", *Eur. Phys. J. C* **76** (2016) 155, arXiv:1512.00815 [hep-ex].

[42] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Evidence for WW production from double-parton interactions in proton–proton collisions at $\sqrt{s} = 13$ TeV", *Eur. Phys. J. C* **80** (2020) 41, arXiv:1909.06265 [hep-ex].

[43] **NA3** Collaboration, J. Badier *et al.*, "Evidence for $\psi\psi$ Production in π^- Interactions at 150 GeV/c and 280 GeV/c", *Phys. Lett. B* **114** (1982) 457–460.

[44] J. Badier *et al.*, "$\psi\psi$ production and limits on beauty meson production from 400 GeV/c protons", *Physics Letters B* **158** (1985) 85–91.

[45] **CMS** Collaboration, V. Khachatryan *et al.*, "Measurement of Prompt J/ψ Pair Production in pp Collisions at $\sqrt{s}$ = 7 TeV", *JHEP* **09** (2014) 094, arXiv:1406.0484 [hep-ex].

[46] **LHCb** Collaboration, R. Aaij *et al.*, "Observation of J/ψ pair production in pp collisions at $\sqrt{s} = 7$ TeV", *Phys. Lett. B* **707** (2012) 52–59, arXiv:1109.0963 [hep-ex].

[47] **CMS** Collaboration, V. Khachatryan *et al.*, "Observation of Υ(1S) pair production in proton-proton collisions at $\sqrt{s} = 8$ TeV", *JHEP* **05** (2017) 013, arXiv:1610.07095 [hep-ex].

[48] **ATLAS** Collaboration, G. Aad *et al.*, "Measurement of the production of a W boson in association with a charm quark in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector", *JHEP* **05** (2014) 068, arXiv:1402.6263 [hep-ex].

[49] **LHCb** Collaboration, R. Aaij *et al.*, "Observation of associated production of a Z boson with a D meson in the forward region", *JHEP* **04** (2014) 091, arXiv:1401.3245 [hep-ex].

[50] **ATLAS** Collaboration, M. Aaboud *et al.*, "Study of hard double-parton scattering in four-jet events in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS experiment", *JHEP* **11** (2016) 110, arXiv:1608.01857 [hep-ex].

[51] **D0** Collaboration, V. M. Abazov *et al.*, "Study of double parton interactions in diphoton + dijet events in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV", *Phys. Rev. D* **93** (2016) 052008, arXiv:1512.05291 [hep-ex].

[52] **CMS** Collaboration, A. Tumasyan *et al.*, "Observation of triple J/ψ meson production in proton-proton collisions at $\sqrt{s}$ = 13 TeV", arXiv:2111.05370 [hep-ex].

[53] P. Ko, C. Yu, and J. Lee, "Inclusive double-quarkonium production at the Large Hadron Collider", *JHEP* **01** (2011) 070, arXiv:1007.3095 [hep-ph].

[54] L.-P. Sun, H. Han, and K.-T. Chao, "Impact of J/ψ pair production at the LHC and predictions in nonrelativistic QCD", *Phys. Rev. D* **94** (2016) 074033, arXiv:1404.4042 [hep-ph].

[55] S. P. Baranov and A. H. Rezaeian, "Prompt double J/ψ production in proton-proton collisions at the LHC", *Phys. Rev. D* **93** (2016) 114011, arXiv:1511.04089 [hep-ph].

[56] J. P. Lansberg, "J/ψ production at $\sqrt{s} = 1.96$ and 7 TeV: Color-Singlet Model, NNLO* and polarisation", *J. Phys. G* **38** (2011) 124110, arXiv:1107.0292 [hep-ph].

[57] J. M. Campbell, F. Maltoni, and F. Tramontano, "QCD corrections to J/psi and Upsilon production at hadron colliders", *Phys. Rev. Lett.* **98** (2007) 252002, arXiv:hep-ph/0703113.

[58] B. Gong and J.-X. Wang, "Next-to-leading-order QCD corrections to J/ψ polarization at Tevatron and Large-Hadron-Collider energies", *Phys. Rev. Lett.* **100** (2008) 232001, arXiv:0802.3727 [hep-ph].

[59] J.-P. Lansberg, "New Observables in Inclusive Production of Quarkonia", *Phys. Rept.* **889** (2020) 1–106, arXiv:1903.09185 [hep-ph].

[60] G. T. Bodwin, E. Braaten, and G. P. Lepage, "Rigorous QCD analysis of inclusive annihilation and production of heavy quarkonium", *Phys. Rev. D* **51** (1995) 1125–1171, arXiv:hep-ph/9407339. [Erratum: Phys.Rev.D 55, 5853 (1997)].

[61] **LHCb** Collaboration, R. Aaij *et al.*, "Measurement of J/ψ polarization in *pp* collisions at $\sqrt{s} = 7$ TeV", *Eur. Phys. J. C* **73** (2013) 2631, arXiv:1307.6379 [hep-ex].

[62] **LHCb** Collaboration, R. Aaij *et al.*, "Measurement of $\psi(2S)$ polarisation in *pp* collisions at $\sqrt{s} = 7$ TeV", *Eur. Phys. J. C* **74** (2014) 2872, arXiv:1403.1339 [hep-ex].

[63] **CMS** Collaboration, S. Chatrchyan *et al.*, "Measurement of the $Y(1S), Y(2S)$ and $Y(3S)$ Polarizations in *pp* Collisions at $\sqrt{s} = 7$ TeV", *Phys. Rev. Lett.* **110** (2013) 081802, arXiv:1209.2922 [hep-ex].

[64] **CMS** Collaboration, S. Chatrchyan *et al.*, "Measurement of the Prompt J/ψ and ψ(2S) Polarizations in *pp* Collisions at $\sqrt{s}$ = 7 TeV", *Phys. Lett. B* **727** (2013) 381–402, arXiv:1307.6070 [hep-ex].

[65] **ALICE** Collaboration, B. Abelev *et al.*, "J/ψ polarization in *pp* collisions at $\sqrt{s} = 7$ TeV", *Phys. Rev. Lett.* **108** (2012) 082001, arXiv:1111.1630 [hep-ex].

[66] **ALICE** Collaboration, K. Aamodt *et al.*, "The ALICE experiment at the CERN LHC", *JINST* **3** (2008) S08002.

[67] **ALICE** Collaboration, B. B. Abelev *et al.*, "Performance of the ALICE Experiment at the CERN LHC", *Int. J. Mod. Phys. A* **29** (2014) 1430044, arXiv:1402.4476 [nucl-ex].

[68] **ALICE** Collaboration, K. Aamodt *et al.*, "Rapidity and transverse momentum dependence of inclusive J/ψ production in *pp* collisions at $\sqrt{s} = 7$ TeV", *Phys. Lett. B* **704** (2011) 442–455, arXiv:1105.0380 [hep-ex]. [Erratum: Phys.Lett.B 718, 692–698 (2012)].

[69] **ALICE** Collaboration, S. Acharya *et al.*, "Energy dependence of forward-rapidity J/ψ and ψ(2S) production in pp collisions at the LHC", *Eur. Phys. J. C* **77** (2017) 392, arXiv:1702.00557 [hep-ex].

[70] **Particle Data Group** Collaboration, R. L. Workman and Others, "Review of Particle Physics", *PTEP* **2022** (2022) 083C01.

[71] **ALICE** Collaboration, J. Adam *et al.*, "Inclusive quarkonium production at forward rapidity in pp collisions at $\sqrt{s} = 8$ TeV", *Eur. Phys. J. C* **76** (2016) 184, arXiv:1509.08258 [hep-ex].

[72] **ALICE** Collaboration, "Quarkonium signal extraction in ALICE", ALICE-PUBLIC-2015-006. https://cds.cern.ch/record/2060096.

[73] D. J. Lange, "The EvtGen particle decay simulation package", *Nucl. Instrum. Meth. A* **462** (2001) 152–155.

[74] E. Barberio and Z. Was, "PHOTOS: A Universal Monte Carlo for QED radiative corrections. Version 2.0", *Comput. Phys. Commun.* **79** (1994) 291–308.

[75] R. Brun, F. Bruyant, F. Carminati, S. Giani, M. Maire, A. McPherson, G. Patrick, and L. Urban, "GEANT: Detector Description and Simulation Tool; Oct 1994",. https://cds.cern.ch/record/1082634. Long Writeup W5013.

[76] **ALICE** Collaboration, "Measurement of ψ(2S) production as a function of charged-particle pseudorapidity density in pp collisions at $\sqrt{s}$ = 13 TeV and p-Pb collisions at $\sqrt{s_{\rm NN}}$ = 8.16 TeV with ALICE at the LHC", arXiv:2204.10253 [nucl-ex].

[77] **ALICE** Collaboration, "ALICE 2016-2017-2018 luminosity determination for pp collisions at $\sqrt{s}$ = 13 TeV", ALICE-PUBLIC-2021-005. https://cds.cern.ch/record/2776672.

[78] **ALICE** Collaboration, B. B. Abelev *et al.*, "Measurement of quarkonium production at forward rapidity in *pp* collisions at $\sqrt{s} = 7$ TeV", *Eur. Phys. J. C* **74** (2014) 2974, arXiv:1403.3648 [nucl-ex].

[79] **ALICE** Collaboration, S. Acharya *et al.*, "Prompt and non-prompt J/ψ production cross sections at midrapidity in proton-proton collisions at $\sqrt{\rm s}$ = 5.02 and 13 TeV", *JHEP* **03** (2022) 190, arXiv:2108.02523 [nucl-ex].

[80] C. Bierlich *et al.*, "A comprehensive guide to the physics and usage of PYTHIA 8.3", arXiv:2203.11601 [hep-ph].

[81] P. Skands, S. Carrazza, and J. Rojo, "Tuning PYTHIA 8.1: the Monash 2013 Tune", *Eur. Phys. J. C* **74** (2014) 3024, arXiv:1404.5630 [hep-ph].

[82] M. L. Mangano, P. Nason, and G. Ridolfi, "Heavy quark correlations in hadron collisions at next-to-leading order", *Nucl. Phys. B* **373** (1992) 295–345.

[83] **ATLAS** Collaboration, "ATLAS Pythia 8 tunes to 7 TeV data", ATL-PHYS-PUB-2014-021. https://cds.cern.ch/record/1966419.

[84] **ALICE** Collaboration, "ALICE upgrades during the LHC Long Shutdown 2", arXiv:2302.01238 [physics.ins-det].

A The ALICE Collaboration

S. Acharya [125], D. Adamová [86], A. Adler[69], G. Aglieri Rinella [32], M. Agnello [29], N. Agrawal [50], Z. Ahammed [132], S. Ahmad [15], S.U. Ahn [70], I. Ahuja [37], A. Akindinov [140], M. Al-Turany [97], D. Aleksandrov [140], B. Alessandro [55], H.M. Alfanda [6], R. Alfaro Molina [66], B. Ali [15], A. Alici [25], N. Alizadehvandchali [114], A. Alkin [32], J. Alme [20], G. Alocco [51], T. Alt [63], I. Altsybeev [140], M.N. Anaam [6], C. Andrei [45], A. Andronic [135], V. Anguelov[94], F. Antinori [53], P. Antonioli [50], N. Apadula [74], L. Aphecetche [103], H. Appelshäuser [63], C. Arata [73], S. Arcelli [25], M. Aresti [51], R. Arnaldi [55], J.G.M.C.A. Arneiro [110], I.C. Arsene [19], M. Arslandok [137], A. Augustinus [32], R. Averbeck [97], S. Aziz [72], M.D. Azmi [15], A. Badalà [52], J. Bae [104], Y.W. Baek [40], X. Bai [118], R. Bailhache [63], Y. Bailung [47], A. Balbino [29], A. Baldisseri [128], B. Balis [2], D. Banerjee [4], Z. Banoo [91], R. Barbera [26], F. Barile [31], L. Barioglio [95], M. Barlou[78], G.G. Barnaföldi [136], L.S. Barnby [85], V. Barret [125], L. Barreto [110], C. Bartels [117], K. Barth [32], E. Bartsch [63], N. Bastid [125], S. Basu [75], G. Batigne [103], D. Battistini [95], B. Batyunya [141], D. Bauri[46], J.L. Bazo Alba [101], I.G. Bearden [83], C. Beattie [137], P. Becht [97], D. Behera [47], I. Belikov [127], A.D.C. Bell Hechavarria [135], F. Bellini [25], R. Bellwied [114], S. Belokurova [140], G. Bencedi [136], S. Beole [24], A. Bercuci [45], Y. Berdnikov [140], A. Berdnikova [94], L. Bergmann [94], M.G. Besoiu [62], L. Betev [32], P.P. Bhaduri [132], A. Bhasin [91], M.A. Bhat [4], B. Bhattacharjee [41], L. Bianchi [24], N. Bianchi [48], J. Bielčík [35], J. Bielčíková [86], J. Biernat [107], A.P. Bigot [127], A. Bilandzic [95], G. Biro [136], S. Biswas [4], N. Bize [103], J.T. Blair [108], D. Blau [140], M.B. Blidaru [97], N. Bluhme[38], C. Blume [63], G. Boca [21,54], F. Bock [87], T. Bodova [20], A. Bogdanov[140], S. Boi [22], J. Bok [57], L. Boldizsár [136], M. Bombara [37], P.M. Bond [32], G. Bonomi [131,54], H. Borel [128], A. Borissov [140], H. Bossi [137], E. Botta [24], Y.E.M. Bouziani [63], L. Bratrud [63], P. Braun-Munzinger [97], M. Bregant [110], M. Broz [35], G.E. Bruno [96,31], M.D. Buckland [23], D. Budnikov[140], H. Buesching [63], S. Bufalino [29], P. Buhler [102], Z. Buthelezi [67,121], A. Bylinkin [20], S.A. Bysiak[107], M. Cai [6], H. Caines [137], A. Caliva [28], E. Calvo Villar [101], J.M.M. Camacho [109], P. Camerini [23], F.D.M. Canedo [110], M. Carabas [124], A.A. Carballo [32], A.G.B. Carcamo [94], F. Carnesecchi [32], R. Caron [126], L.A.D. Carvalho [110], J. Castillo Castellanos [128], F. Catalano [32,24], C. Ceballos Sanchez [141], I. Chakaberia [74], P. Chakraborty [46], S. Chandra [132], S. Chapeland [32], M. Chartier [117], S. Chattopadhyay [132], S. Chattopadhyay [99], T.G. Chavez [44], T. Cheng [97,6], C. Cheshkov [126], B. Cheynis [126], V. Chibante Barroso [32], D.D. Chinellato [111], E.S. Chizzali [95], J. Cho [57], S. Cho [57], P. Chochula [32], P. Christakoglou [84], C.H. Christensen [83], P. Christiansen [75], T. Chujo [123], M. Ciacco [29], C. Cicalo [51], F. Cindolo [50], M.R. Ciupek[97], G. Clai[II,50], F. Colamaria [49], J.S. Colburn[100], D. Colella [96,31], M. Colocci [25], G. Conesa Balbastre [73], Z. Conesa del Valle [72], G. Contin [23], J.G. Contreras [35], M.L. Coquet [128], T.M. Cormier[I,87], P. Cortese [130,55], M.R. Cosentino [112], F. Costa [32], S. Costanza [21,54], C. Cot [72], J. Crkovská [94], P. Crochet [125], R. Cruz-Torres [74], P. Cui [6], A. Dainese [53], M.C. Danisch [94], A. Danu [62], P. Das [80], P. Das [4], S. Das [4], A.R. Dash [135], S. Dash [46], A. De Caro [28], G. de Cataldo [49], J. de Cuveland[38], A. De Falco [22], D. De Gruttola [28], N. De Marco [55], C. De Martin [23], S. De Pasquale [28], R. Deb[131], S. Deb [47], K.R. Deja[133], R. Del Grande [95], L. Dello Stritto [28], W. Deng [6], P. Dhankher [18], D. Di Bari [31], A. Di Mauro [32], B. Diab [128], R.A. Diaz [141,7], T. Dietel [113], Y. Ding [6], R. Divià [32], D.U. Dixit [18], Ø. Djuvsland[20], U. Dmitrieva [140], A. Dobrin [62], B. Dönigus [63], J.M. Dubinski[133], A. Dubla [97], S. Dudi [90], P. Dupieux [125], M. Durkac[106], N. Dzalaiova[12], T.M. Eder [135], R.J. Ehlers [74], F. Eisenhut [63], D. Elia [49], B. Erazmus [103], F. Ercolessi [25], F. Erhardt [89], M.R. Ersdal[20], B. Espagnon [72], G. Eulisse [32], D. Evans [100], S. Evdokimov [140], L. Fabbietti [95], M. Faggin [27], J. Faivre [73], F. Fan[6], W. Fan [74], A. Fantoni [48], M. Fasel [87], P. Fecchio[29], A. Feliciello [55], G. Feofilov [140], A. Fernández Téllez [44], L. Ferrandi [110], M.B. Ferrer [32], A. Ferrero [128], C. Ferrero [55], A. Ferretti [24], V.J.G. Feuillard [94], V. Filova[35], D. Finogeev [140], F.M. Fionda [51], F. Flor [114], A.N. Flores [108], S. Foertsch [67], I. Fokin [94], S. Fokin [140], E. Fragiacomo [56], E. Frajna [136], U. Fuchs [32], N. Funicello [28], C. Furget[73], A. Furs [140], T. Fusayasu [98], J.J. Gaardhøje [83], M. Gagliardi [24], A.M. Gago [101], C.D. Galvan [109], D.R. Gangadharan [114], P. Ganoti [78], C. Garabatos [97], J.R.A. Garcia[44], E. Garcia-Solis [9], C. Gargiulo [32], A. Garibli[81], K. Garner[135], P. Gasik [97], A. Gautam [116], M.B. Gay Ducati [65], M. Germain [103], A. Ghimouz[123], C. Ghosh[132], M. Giacalone [50,25], P. Giubellino [97,55], P. Giubilato [27], A.M.C. Glaenzer [128], P. Glässel [94], E. Glimos[120], D.J.Q. Goh[76], V. Gonzalez [134], S. Gorbunov[38], M. Gorgon [2], K. Goswami [47], S. Gotovac[33], V. Grabski [66], L.K. Graczykowski [133], E. Grecka [86], A. Grelli [58], C. Grigoras [32], V. Grigoriev[140], S. Grigoryan [141,1], F. Grosa [32], J.F. Grosse-Oetringhaus [32], R. Grosso [97], D. Grund [35], G.G. Guardiano [111], R. Guernane [73], M. Guilbaud [103], K. Gulbrandsen [83], T. Gundem [63], T. Gunji [122], W. Guo [6], A. Gupta [91], R. Gupta [91], R. Gupta [47], S.P. Guzman[44], K. Gwizdziel [133], L. Gyulai [136], M.K. Habib[97], C. Hadjidakis[72], F.U. Haider[91], H. Hamagaki[76], A. Hamdi[74], M. Hamid[6], Y. Han[138], B.G. Hanley[134], R. Hannigan[108], J. Hansen[75], M.R. Haque[133], J.W. Harris[137], A. Harton[9], H. Hassan[87], D. Hatzifotiadou[50], P. Hauer[42], L.B. Havener[137], S.T. Heckel[95], E. Hellbär[97], H. Helstrup[34], M. Hemmer[63], T. Herman[35], G. Herrera Corral[8], F. Herrmann[135], S. Herrmann[126], K.F. Hetland[34], B. Heybeck[63], H. Hillemanns[32], B. Hippolyte[127], F.W. Hoffmann[69], B. Hofman[58], B. Hohlweger[84], G.H. Hong[138], M. Horst[95], A. Horzyk[2], Y. Hou[6], P. Hristov[32], C. Hughes[120], P. Huhn[63], L.M. Huhta[115], T.J. Humanic[88], L.A. Husova[135], A. Hutson[114], R. Ilkaev[140], H. Ilyas[13], M. Inaba[123], G.M. Innocenti[32], M. Ippolitov[140], A. Isakov[86], T. Isidori[116], M.S. Islam[99], M. Ivanov[12], M. Ivanov[97], V. Ivanov[140], K.E. Iversen[75], M. Jablonski[2], B. Jacak[74], N. Jacazio[25], P.M. Jacobs[74], S. Jadlovska[106], J. Jadlovsky[106], S. Jaelani[82], C. Jahnke[111], M.J. Jakubowska[133], M.A. Janik[133], T. Janson[69], M. Jercic[89], S. Ji[16], S. Jia[10], A.A.P. Jimenez[64], F. Jonas[87], J.M. Jowett[32,97], J. Jung[63], M. Jung[63], A. Junique[32], A. Jusko[100], M.J. Kabus[32,133], J. Kaewjai[105], P. Kalinak[59], A.S. Kalteyer[97], A. Kalweit[32], V. Kaplin[140], A. Karasu Uysal[71], D. Karatovic[89], O. Karavichev[140], T. Karavicheva[140], P. Karczmarczyk[133], E. Karpechev[140], U. Kebschull[69], R. Keidel[139], D.L.D. Keijdener[58], M. Keil[32], B. Ketzer[42], S.S. Khade[47], A.M. Khan[6], S. Khan[15], A. Khanzadeev[140], Y. Kharlov[140], A. Khatun[116], A. Khuntia[107], M.B. Kidson[113], B. Kileng[34], B. Kim[104], C. Kim[16], D.J. Kim[115], E.J. Kim[68], J. Kim[138], J.S. Kim[40], J. Kim[57], J. Kim[68], M. Kim[18], S. Kim[17], T. Kim[138], K. Kimura[92], S. Kirsch[63], I. Kisel[38], S. Kiselev[140], A. Kisiel[133], J.P. Kitowski[2], J.L. Klay[5], J. Klein[32], S. Klein[74], C. Klein-Bösing[135], M. Kleiner[63], T. Klemenz[95], A. Kluge[32], A.G. Knospe[114], C. Kobdaj[105], T. Kollegger[97], A. Kondratyev[141], N. Kondratyeva[140], E. Kondratyuk[140], J. Konig[63], S.A. Konigstorfer[95], P.J. Konopka[32], G. Kornakov[133], S.D. Koryciak[2], A. Kotliarov[86], V. Kovalenko[140], M. Kowalski[107], V. Kozhuharov[36], I. Králik[59], A. Kravčáková[37], L. Krcal[32,38], M. Krivda[100,59], F. Krizek[86], K. Krizkova Gajdosova[32], M. Kroesen[94], M. Krüger[63], D.M. Krupova[35], E. Kryshen[140], V. Kučera[57], C. Kuhn[127], P.G. Kuijer[84], T. Kumaoka[123], D. Kumar[132], L. Kumar[90], N. Kumar[90], S. Kumar[31], S. Kundu[32], P. Kurashvili[79], A. Kurepin[140], A.B. Kurepin[140], A. Kuryakin[140], S. Kushpil[86], J. Kvapil[100], M.J. Kweon[57], Y. Kwon[138], S.L. La Pointe[38], P. La Rocca[26], A. Lakrathok[105], M. Lamanna[32], R. Langoy[119], P. Larionov[32], E. Laudi[32], L. Lautner[32,95], R. Lavicka[102], R. Lea[131,54], H. Lee[104], I. Legrand[45], G. Legras[135], J. Lehrbach[38], T.M. Lelek[2], R.C. Lemmon[85], I. León Monzón[109], M.M. Lesch[95], E.D. Lesser[18], P. Lévai[136], X. Li[10], X.L. Li[6], J. Lien[119], R. Lietava[100], I. Likmeta[114], B. Lim[24], S.H. Lim[16], V. Lindenstruth[38], A. Lindner[45], C. Lippmann[97], A. Liu[18], D.H. Liu[6], J. Liu[117], G.S.S. Liveraro[111], I.M. Lofnes[20], C. Loizides[87], S. Lokos[107], J. Lomker[58], P. Loncar[33], J.A. Lopez[94], X. Lopez[125], E. López Torres[7], P. Lu[97,118], J.R. Luhder[135], M. Lunardon[27], G. Luparello[56], Y.G. Ma[39], M. Mager[32], A. Maire[127], M.V. Makariev[36], M. Malaev[140], G. Malfattore[25], N.M. Malik[91], Q.W. Malik[19], S.K. Malik[91], L. Malinina[VI,141], D. Mallick[80], N. Mallick[47], G. Mandaglio[30,52], S.K. Mandal[79], V. Manko[140], F. Manso[125], V. Manzari[49], Y. Mao[6], R.W. Marcjan[2], G.V. Margagliotti[23], A. Margotti[50], A. Marín[97], C. Markert[108], P. Martinengo[32], M.I. Martínez[44], G. Martínez García[103], M.P.P. Martins[110], S. Masciocchi[97], M. Masera[24], A. Masoni[51], L. Massacrier[72], A. Mastroserio[129,49], O. Matonoha[75], S. Mattiazzo[27], P.F.T. Matuoka[110], A. Matyja[107], C. Mayer[107], A.L. Mazuecos[32], F. Mazzaschi[24], M. Mazzilli[32], J.E. Mdhluli[121], A.F. Mechler[63], Y. Melikyan[43,140], A. Menchaca-Rocha[66], E. Meninno[102,28], A.S. Menon[114], M. Meres[12], S. Mhlanga[113,67], Y. Miake[123], L. Micheletti[32], L.C. Migliorin[126], D.L. Mihaylov[95], K. Mikhaylov[141,140], A.N. Mishra[136], D. Miśkowiec[97], A. Modak[4], A.P. Mohanty[58], B. Mohanty[80], M. Mohisin Khan[III,15], M.A. Molander[43], Z. Moravcova[83], C. Mordasini[95], D.A. Moreira De Godoy[135], I. Morozov[140], A. Morsch[32], T. Mrnjavac[32], V. Muccifora[48], S. Muhuri[132], J.D. Mulligan[74], A. Mulliri[22], M.G. Munhoz[110], R.H. Munzer[63], H. Murakami[122], S. Murray[113], L. Musa[32], J. Musinsky[59], J.W. Myrcha[133], B. Naik[121], A.I. Nambrath[18], B.K. Nandi[46], R. Nania[50], E. Nappi[49], A.F. Nassirpour[17,75], A. Nath[94], C. Nattrass[120], M.N. Naydenov[36], A. Neagu[19], A. Negru[124], L. Nellen[64], G. Neskovic[38], B.S. Nielsen[83], E.G. Nielsen[83], S. Nikolaev[140], S. Nikulin[140], V. Nikulin[140], F. Noferini[50], S. Noh[11], P. Nomokonov[141], J. Norman[117], N. Novitzky[123], P. Nowakowski[133], A. Nyanin[140], J. Nystrand[20], M. Ogino[76], A. Ohlson[75], V.A. Okorokov[140], J. Oleniacz[133], A.C. Oliveira Da Silva[120], M.H. Oliver[137], A. Onnerstad[115], C. Oppedisano[55], A. Ortiz Velasquez[64], J. Otwinowski[107], M. Oya[92], K. Oyama[76], Y. Pachmayer[94], S. Padhan[46], D. Pagano[131,54], G. Paić[64], A. Palasciano[49], S. Panebianco[128], H. Park[123], H. Park[104], J. Park[57], J.E. Parkkila[32], R.N. Patra[91], B. Paul[22], H. Pei[6], T. Peitzmann[58], X. Peng[6], M. Pennisi[24],

D. Peresunko [140], G.M. Perez [7], S. Perrin [128], Y. Pestov[140], V. Petrov [140], M. Petrovici [45], R.P. Pezzi [103,65], S. Piano [56], M. Pikna [12], P. Pillot [103], O. Pinazza [50,32], L. Pinsky[114], C. Pinto [95], S. Pisano [48], M. Płoskoń [74], M. Planinic[89], F. Pliquett[63], M.G. Poghosyan [87], B. Polichtchouk [140], S. Politano [29], N. Poljak [89], A. Pop [45], S. Porteboeuf-Houssais [125], V. Pozdniakov [141], I.Y. Pozos[44], K.K. Pradhan [47], S.K. Prasad [4], S. Prasad [47], R. Preghenella [50], F. Prino [55], C.A. Pruneau [134], I. Pshenichnov [140], M. Puccio [32], S. Pucillo [24], Z. Pugelova[106], S. Qiu [84], L. Quaglia [24], R.E. Quishpe[114], S. Ragoni [14], A. Rakotozafindrabe [128], L. Ramello [130,55], F. Rami [127], S.A.R. Ramirez[44], T.A. Rancien[73], M. Rasa [26], S.S. Räsänen [43], R. Rath [50], M.P. Rauch[20], I. Ravasenga [84], K.F. Read [87,120], C. Reckziegel[112], A.R. Redelbach [38], K. Redlich [IV,79], C.A. Reetz [97], A. Rehman[20], F. Reidt [32], H.A. Reme-Ness [34], Z. Rescakova[37], K. Reygers [94], A. Riabov [140], V. Riabov [140], R. Ricci [28], M. Richter[19], A.A. Riedel [95], W. Riegler [32], C. Ristea [62], M.V. Rodriguez [32], M. Rodríguez Cahuantzi [44], K. Røed [19], R. Rogalev [140], E. Rogochaya [141], T.S. Rogoschinski [63], D. Rohr [32], D. Röhrich [20], P.F. Rojas[44], S. Rojas Torres [35], P.S. Rokita [133], G. Romanenko [141], F. Ronchetti [48], A. Rosano [30,52], E.D. Rosas[64], K. Roslon [133], A. Rossi [53], A. Roy [47], S. Roy[46], N. Rubini [25], O.V. Rueda [114], D. Ruggiano[133], R. Rui [23], P.G. Russek [2], R. Russo [84], A. Rustamov [81], E. Ryabinkin [140], Y. Ryabov [140], A. Rybicki [107], H. Rytkonen [115], J. Ryu [16], W. Rzesa[133], O.A.M. Saarimaki [43], R. Sadek [103], S. Sadhu [31], S. Sadovsky [140], J. Saetre [20], K. Šafařík [35], P. Saha[41], S.K. Saha [4], S. Saha [80], B. Sahoo [46], B. Sahoo [47], R. Sahoo [47], S. Sahoo[60], D. Sahu [47], P.K. Sahu [60], J. Saini [132], K. Sajdakova[37], S. Sakai [123], M.P. Salvan [97], S. Sambyal [91], I. Sanna [32,95], T.B. Saramela[110], D. Sarkar [134], N. Sarkar[132], P. Sarma[41], V. Sarritzu [22], V.M. Sarti [95], M.H.P. Sas [137], J. Schambach [87], H.S. Scheid [63], C. Schiaua [45], R. Schicker [94], A. Schmah[94], C. Schmidt [97], H.R. Schmidt[93], M.O. Schmidt [32], M. Schmidt[93], N.V. Schmidt [87], A.R. Schmier [120], R. Schotter [127], A. Schröter [38], J. Schukraft [32], K. Schwarz[97], K. Schweda [97], G. Scioli [25], E. Scomparin [55], J.E. Seger [14], Y. Sekiguchi[122], D. Sekihata [122], I. Selyuzhenkov [97], S. Senyukov [127], J.J. Seo [57], D. Serebryakov [140], L. Šerkšnytė [95], A. Sevcenco [62], T.J. Shaba [67], A. Shabetai [103], R. Shahoyan[32], A. Shangaraev [140], A. Sharma[90], B. Sharma [91], D. Sharma[46], H. Sharma[53,107], M. Sharma [91], S. Sharma [76], S. Sharma [91], U. Sharma [91], A. Shatat [72], O. Sheibani[114], K. Shigaki [92], M. Shimomura[77], J. Shin[11], S. Shirinkin [140], Q. Shou [39], Y. Sibiriak [140], S. Siddhanta [51], T. Siemiarczuk [79], T.F. Silva [110], D. Silvermyr [75], T. Simantathammakul[105], R. Simeonov [36], B. Singh[91], B. Singh [95], K. Singh [47], R. Singh [80], R. Singh [91], R. Singh [47], S. Singh [15], V.K. Singh [132], V. Singhal [132], T. Sinha [99], B. Sitar [12], M. Sitta [130,55], T.B. Skaali[19], G. Skorodumovs [94], M. Slupecki [43], N. Smirnov [137], R.J.M. Snellings [58], E.H. Solheim [19], J. Song [114], A. Songmoolnak[105], C. Sonnabend [32,97], F. Soramel [27], A.B. Soto-hernandez[88], R. Spijkers [84], I. Sputowska [107], J. Staa [75], J. Stachel [94], I. Stan [62], P.J. Steffanic [120], S.F. Stiefelmaier [94], D. Stocco [103], I. Storehaug [19], P. Stratmann [135], S. Strazzi [25], C.P. Stylianidis[84], A.A.P. Suaide [110], C. Suire [72], M. Sukhanov [140], M. Suljic [32], R. Sultanov [140], V. Sumberia [91], S. Sumowidagdo [82], S. Swain[60], I. Szarka [12], M. Szymkowski[133], S.F. Taghavi [95], G. Taillepied [97], J. Takahashi [111], G.J. Tambave [80], S. Tang [6], Z. Tang [118], J.D. Tapia Takaki [V,116], N. Tapus[124], M.G. Tarzila[45], G.F. Tassielli [31], A. Tauro [32], G. Tejeda Muñoz [44], A. Telesca [32], L. Terlizzi [24], C. Terrevoli [114], S. Thakur [4], D. Thomas [108], A. Tikhonov [140], A.R. Timmins [114], M. Tkacik[106], T. Tkacik [106], A. Toia [63], R. Tokumoto[92], N. Topilskaya [140], M. Toppi [48], T. Tork [72], A.G. Torres Ramos [31], A. Trifiró [30,52], A.S. Triolo [32,30,52], S. Tripathy [50], T. Tripathy [46], S. Trogolo [32], V. Trubnikov[3], W.H. Trzaska [115], T.P. Trzcinski [133], A. Tumkin[140], R. Turrisi [53], T.S. Tveter [19], K. Ullaland [20], B. Ulukutlu [95], A. Uras [126], M. Urioni [54,131], G.L. Usai [22], M. Vala[37], N. Valle [21], L.V.R. van Doremalen[58], M. van Leeuwen [84], C.A. van Veen [94], R.J.G. van Weelden [84], P. Vande Vyvre [32], D. Varga [136], Z. Varga [136], M. Vasileiou [78], A. Vasiliev [140], O. Vázquez Doce [48], V. Vechernin [140], E. Vercellin [24], S. Vergara Limón[44], L. Vermunt [97], R. Vértesi [136], M. Verweij [58], L. Vickovic[33], Z. Vilakazi[121], O. Villalobos Baillie [100], A. Villani [23], G. Vino [49], A. Vinogradov [140], T. Virgili [28], M.M.O. Virta [115], V. Vislavicius[75], A. Vodopyanov [141], B. Volkel [32], M.A. Völkl [94], K. Voloshin[140], S.A. Voloshin [134], G. Volpe [31], B. von Haller [32], I. Vorobyev [95], N. Vozniuk [140], J. Vrláková [37], J. Wan[39], C. Wang [39], D. Wang[39], Y. Wang [39], A. Wegrzynek [32], F.T. Weiglhofer[38], S.C. Wenzel [32], J.P. Wessels [135], S.L. Weyhmiller [137], J. Wiechula [63], J. Wikne [19], G. Wilk [79], J. Wilkinson [97], G.A. Willems[135], B. Windelband[94], M. Winn [128], J.R. Wright [108], W. Wu[39], Y. Wu [118], R. Xu [6], A. Yadav [42], A.K. Yadav [132], S. Yalcin[71], Y. Yamaguchi[92], S. Yang[20], S. Yano[92], Z. Yin [6], I.-K. Yoo [16], J.H. Yoon [57], H. Yu[11], S. Yuan[20], A. Yuncu [94], V. Zaccolo [23], C. Zampolli [32], F. Zanone [94], N. Zardoshti [32], A. Zarochentsev [140], P. Závada [61], N. Zaviyalov[140], M. Zhalov [140], B. Zhang [6], L. Zhang [39], S. Zhang [39], X. Zhang [6], Y. Zhang[118], Z. Zhang [6], M. Zhao [10], V. Zherebchevskii [140],

Y. Zhi[10], D. Zhou[6], Y. Zhou[83], J. Zhu[97,6], Y. Zhu[6], S.C. Zugravel[55], N. Zurlo[131,54]

Affiliation Notes

[I] Deceased
[II] Also at: Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Bologna, Italy
[III] Also at: Department of Applied Physics, Aligarh Muslim University, Aligarh, India
[IV] Also at: Institute of Theoretical Physics, University of Wroclaw, Poland
[V] Also at: University of Kansas, Lawrence, Kansas, United States
[VI] Also at: An institution covered by a cooperation agreement with CERN

Collaboration Institutes

[1] A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia
[2] AGH University of Science and Technology, Cracow, Poland
[3] Bogolyubov Institute for Theoretical Physics, National Academy of Sciences of Ukraine, Kiev, Ukraine
[4] Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India
[5] California Polytechnic State University, San Luis Obispo, California, United States
[6] Central China Normal University, Wuhan, China
[7] Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba
[8] Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico
[9] Chicago State University, Chicago, Illinois, United States
[10] China Institute of Atomic Energy, Beijing, China
[11] Chungbuk National University, Cheongju, Republic of Korea
[12] Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics, Bratislava, Slovak Republic
[13] COMSATS University Islamabad, Islamabad, Pakistan
[14] Creighton University, Omaha, Nebraska, United States
[15] Department of Physics, Aligarh Muslim University, Aligarh, India
[16] Department of Physics, Pusan National University, Pusan, Republic of Korea
[17] Department of Physics, Sejong University, Seoul, Republic of Korea
[18] Department of Physics, University of California, Berkeley, California, United States
[19] Department of Physics, University of Oslo, Oslo, Norway
[20] Department of Physics and Technology, University of Bergen, Bergen, Norway
[21] Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[22] Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy
[23] Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy
[24] Dipartimento di Fisica dell'Università and Sezione INFN, Turin, Italy
[25] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Bologna, Italy
[26] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Catania, Italy
[27] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Padova, Italy
[28] Dipartimento di Fisica 'E.R. Caianiello' dell'Università and Gruppo Collegato INFN, Salerno, Italy
[29] Dipartimento DISAT del Politecnico and Sezione INFN, Turin, Italy
[30] Dipartimento di Scienze MIFT, Università di Messina, Messina, Italy
[31] Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy
[32] European Organization for Nuclear Research (CERN), Geneva, Switzerland
[33] Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, Croatia
[34] Faculty of Engineering and Science, Western Norway University of Applied Sciences, Bergen, Norway
[35] Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
[36] Faculty of Physics, Sofia University, Sofia, Bulgaria
[37] Faculty of Science, P.J. Šafárik University, Košice, Slovak Republic
[38] Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[39] Fudan University, Shanghai, China

[40] Gangneung-Wonju National University, Gangneung, Republic of Korea
[41] Gauhati University, Department of Physics, Guwahati, India
[42] Helmholtz-Institut für Strahlen- und Kernphysik, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn, Germany
[43] Helsinki Institute of Physics (HIP), Helsinki, Finland
[44] High Energy Physics Group, Universidad Autónoma de Puebla, Puebla, Mexico
[45] Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
[46] Indian Institute of Technology Bombay (IIT), Mumbai, India
[47] Indian Institute of Technology Indore, Indore, India
[48] INFN, Laboratori Nazionali di Frascati, Frascati, Italy
[49] INFN, Sezione di Bari, Bari, Italy
[50] INFN, Sezione di Bologna, Bologna, Italy
[51] INFN, Sezione di Cagliari, Cagliari, Italy
[52] INFN, Sezione di Catania, Catania, Italy
[53] INFN, Sezione di Padova, Padova, Italy
[54] INFN, Sezione di Pavia, Pavia, Italy
[55] INFN, Sezione di Torino, Turin, Italy
[56] INFN, Sezione di Trieste, Trieste, Italy
[57] Inha University, Incheon, Republic of Korea
[58] Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University/Nikhef, Utrecht, Netherlands
[59] Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovak Republic
[60] Institute of Physics, Homi Bhabha National Institute, Bhubaneswar, India
[61] Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
[62] Institute of Space Science (ISS), Bucharest, Romania
[63] Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[64] Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
[65] Instituto de Física, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Brazil
[66] Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
[67] iThemba LABS, National Research Foundation, Somerset West, South Africa
[68] Jeonbuk National University, Jeonju, Republic of Korea
[69] Johann-Wolfgang-Goethe Universität Frankfurt Institut für Informatik, Fachbereich Informatik und Mathematik, Frankfurt, Germany
[70] Korea Institute of Science and Technology Information, Daejeon, Republic of Korea
[71] KTO Karatay University, Konya, Turkey
[72] Laboratoire de Physique des 2 Infinis, Irène Joliot-Curie, Orsay, France
[73] Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3, Grenoble, France
[74] Lawrence Berkeley National Laboratory, Berkeley, California, United States
[75] Lund University Department of Physics, Division of Particle Physics, Lund, Sweden
[76] Nagasaki Institute of Applied Science, Nagasaki, Japan
[77] Nara Women's University (NWU), Nara, Japan
[78] National and Kapodistrian University of Athens, School of Science, Department of Physics , Athens, Greece
[79] National Centre for Nuclear Research, Warsaw, Poland
[80] National Institute of Science Education and Research, Homi Bhabha National Institute, Jatni, India
[81] National Nuclear Research Center, Baku, Azerbaijan
[82] National Research and Innovation Agency - BRIN, Jakarta, Indonesia
[83] Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[84] Nikhef, National institute for subatomic physics, Amsterdam, Netherlands
[85] Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom
[86] Nuclear Physics Institute of the Czech Academy of Sciences, Husinec-Řež, Czech Republic
[87] Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States
[88] Ohio State University, Columbus, Ohio, United States
[89] Physics department, Faculty of science, University of Zagreb, Zagreb, Croatia
[90] Physics Department, Panjab University, Chandigarh, India
[91] Physics Department, University of Jammu, Jammu, India
[92] Physics Program and International Institute for Sustainability with Knotted Chiral Meta Matter (SKCM2),

Hiroshima University, Hiroshima, Japan
[93] Physikalisches Institut, Eberhard-Karls-Universität Tübingen, Tübingen, Germany
[94] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[95] Physik Department, Technische Universität München, Munich, Germany
[96] Politecnico di Bari and Sezione INFN, Bari, Italy
[97] Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[98] Saga University, Saga, Japan
[99] Saha Institute of Nuclear Physics, Homi Bhabha National Institute, Kolkata, India
[100] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[101] Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
[102] Stefan Meyer Institut für Subatomare Physik (SMI), Vienna, Austria
[103] SUBATECH, IMT Atlantique, Nantes Université, CNRS-IN2P3, Nantes, France
[104] Sungkyunkwan University, Suwon City, Republic of Korea
[105] Suranaree University of Technology, Nakhon Ratchasima, Thailand
[106] Technical University of Košice, Košice, Slovak Republic
[107] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland
[108] The University of Texas at Austin, Austin, Texas, United States
[109] Universidad Autónoma de Sinaloa, Culiacán, Mexico
[110] Universidade de São Paulo (USP), São Paulo, Brazil
[111] Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
[112] Universidade Federal do ABC, Santo Andre, Brazil
[113] University of Cape Town, Cape Town, South Africa
[114] University of Houston, Houston, Texas, United States
[115] University of Jyväskylä, Jyväskylä, Finland
[116] University of Kansas, Lawrence, Kansas, United States
[117] University of Liverpool, Liverpool, United Kingdom
[118] University of Science and Technology of China, Hefei, China
[119] University of South-Eastern Norway, Kongsberg, Norway
[120] University of Tennessee, Knoxville, Tennessee, United States
[121] University of the Witwatersrand, Johannesburg, South Africa
[122] University of Tokyo, Tokyo, Japan
[123] University of Tsukuba, Tsukuba, Japan
[124] University Politehnica of Bucharest, Bucharest, Romania
[125] Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
[126] Université de Lyon, CNRS/IN2P3, Institut de Physique des 2 Infinis de Lyon, Lyon, France
[127] Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France, Strasbourg, France
[128] Université Paris-Saclay Centre d'Etudes de Saclay (CEA), IRFU, Départment de Physique Nucléaire (DPhN), Saclay, France
[129] Università degli Studi di Foggia, Foggia, Italy
[130] Università del Piemonte Orientale, Vercelli, Italy
[131] Università di Brescia, Brescia, Italy
[132] Variable Energy Cyclotron Centre, Homi Bhabha National Institute, Kolkata, India
[133] Warsaw University of Technology, Warsaw, Poland
[134] Wayne State University, Detroit, Michigan, United States
[135] Westfälische Wilhelms-Universität Münster, Institut für Kernphysik, Münster, Germany
[136] Wigner Research Centre for Physics, Budapest, Hungary
[137] Yale University, New Haven, Connecticut, United States
[138] Yonsei University, Seoul, Republic of Korea
[139] Zentrum für Technologie und Transfer (ZTT), Worms, Germany
[140] Affiliated with an institute covered by a cooperation agreement with CERN
[141] Affiliated with an international laboratory covered by a cooperation agreement with CERN.