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(ALICE Collaboration) Acharya, S.; ...; Erhardt, Filip; ...; Gotovac, Sven; ...; Jerčić, M.; ...; Karatović, David; ...; ...

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

S. Acharya *et al.**
(ALICE Collaboration)

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The production cross section of inclusive J/ψ pairs in pp collisions at a center-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 $p_T > 0$. The production cross section of inclusive J/ψ pairs is reported to be 10.3 ± 2.3 (stat.) ± 1.3 (syst.) nb in this kinematic interval. The contribution from nonprompt J/ψ (i.e., originated from beauty-hadron decays) to the inclusive sample is evaluated. The effective double-parton scattering cross section is computed, neglecting the single-parton scattering contribution.

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I. 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 color 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 CERN Large Hadron Collider (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 progress 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 ($\hat{\sigma}$)

divided by an effective cross section (σ_{eff}) [12,13,34]

$$\sigma_{A,B}^{\text{DPS}} = \frac{m}{2} \frac{\hat{\sigma}^A \hat{\sigma}^B}{\sigma_{\text{eff}}}, \quad (1)$$

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 nonexhaustive 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, multijets [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 40 years of study, and considered a longstanding puzzle of QCD. The color-singlet model (CSM), which assumes the formation of an intermediate $Q\bar{Q}$ state with the quantum numbers of the final state, underestimates the production cross section at high p_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]. Nonrelativistic QCD (NRQCD) calculations consider both color-singlet (CS) and color-octet (CO) states of the $Q\bar{Q}$ pair [60], but fail to predict at the same time the production cross section and polarization [61–65]. The selection rules for pair production in the CS process of LO NRQCD forbid the feed-down from cascade decays of excited

*Full author list given at the end of the article.

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charge-conjugate-even states, e.g., $\chi_c \rightarrow J/\psi \gamma$, whose contribution is significant in single quarkonium production, and makes the comparison of data to model calculations difficult. As a consequence, quarkonium-pair production provides stringent tests of model calculations.

In this article 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 nonprompt contribution, stemming 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.

II. 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 $p_T = 0$ 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 analyzed 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 center of the SPD detector along the beam direction are discarded according to the requirement $|v_z| \leq 10$ cm.

These selections allowed us to keep the pile-up below 0.3% for the analyzed events, also for events with two muon pairs with an invariant mass above 2 GeV/c². 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 ± 0.01 (stat.) ± 0.80 (syst.) pb⁻¹.

III. 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

$$\sigma(J/\psi J/\psi) = \frac{N}{\mathcal{L}_{\text{int}} \times \epsilon \times B^2(J/\psi \rightarrow \mu^+ \mu^-)}, \quad (2)$$

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

The J/ψ pair signal is evaluated from a fit to the two-dimensional invariant mass distribution. A two-step procedure was chosen. The first step exploits the one-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 normalization 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 two-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 via $F(m_1, m_2)$:

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

where N and R are the corresponding normalisation parameters. The $\psi(2S)$ contribution is neglected in the two-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

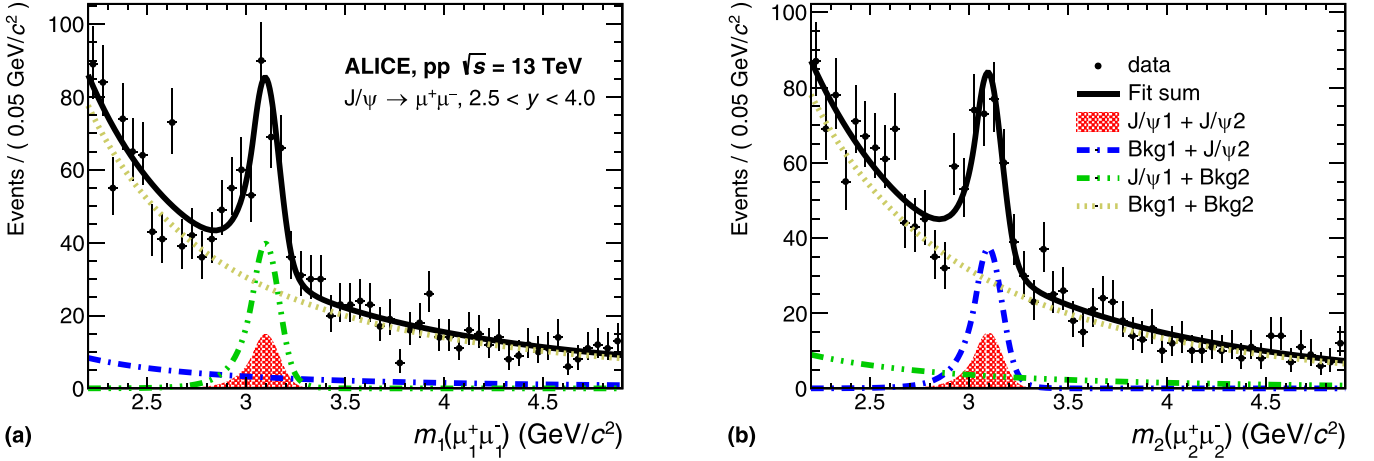


FIG. 1. Projections of a fit to the two-dimensional invariant mass distribution for inclusive J/ψ pair candidates for (a) $m_1(\mu_1^+\mu_1^-)$ and (b) $m_2(\mu_2^+\mu_2^-)$. The (black) markers show data. The (black) solid line represents the total fit function. The (blue and green) dashed-dotted lines 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.

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 $N = 59.3 \pm 13.5$ (stat.) ± 4.4 (syst.).

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

$$\epsilon(J/\psi J/\psi) = \epsilon(J/\psi) \times \epsilon(J/\psi). \quad (4)$$

The J/ψ ϵ , $\epsilon(J/\psi)$, 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 factorization approach for the efficiency calculation was tested. The invariant mass distribution was compared with the corresponding one after applying a two-dimensional (y , p_T) acceptance-times-efficiency correction per J/ψ candidate. The shapes of the two-dimensional invariant mass distribution, and their projections are not modified by the correction, confirming the validity of our assumption. In addition, a toy Monte Carlo was developed to study the possible influence of angular correlations between the two J/ψ of the pair. Two J/ψ were simulated per event, according to a (y , p_T) distribution extracted from single J/ψ measurements. To mimic possible correlations among the J/ψ , their rapidity difference was forced to follow either a triangular or a flat distribution. The average pair efficiency was computed for both cases. The

resultant pair efficiency was found to be in agreement with the calculation from the factorisation approach for both cases.

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 normalization, and (iv) the acceptance-times-efficiency correction.

Details on the signal extraction procedure were given previously in this article. 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_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_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 two-dimensional $\epsilon(p_T, y)$ 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].

TABLE I. Sources of systematic uncertainty on the J/ψ pair production cross section measurement.

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

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 I summarizes the systematic uncertainties on the measurement of the J/ψ pair production cross section.

IV. RESULTS

The inclusive J/ψ pair production cross section in the kinematic interval $2.5 < y < 4.0$ and $p_T > 0$ is measured to be

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

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

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

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

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

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 nonprompt components to the measured inclusive J/ψ cross section, where the nonprompt contribution originates from beauty-hadron decays.

The contamination from beauty-hadron decays to the J/ψ pair cross section is evaluated to assess the impact on the measurement according to

$$\sigma_{\text{nonprompt}}(J/\psi J/\psi) = \sigma_{bb}^{\text{total}} \times \alpha \times B^2(h_b \rightarrow J/\psi + X). \quad (5)$$

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

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

in Ref. [79]. The branching ratio of a beauty hadron into a J/ψ is $B(h_b \rightarrow J/\psi + X) = (1.16 \pm 0.10)\%$ [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 $b\bar{b}$ 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 $\alpha = 0.044_{-0.007}^{+0.005}$ 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 nonprompt contribution of

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

and, correspondingly, the prompt J/ψ pair cross section is

$$\begin{aligned} \sigma_{\text{prompt}}(J/\psi J/\psi) &= \sigma(J/\psi J/\psi) - \sigma_{\text{nonprompt}}(J/\psi J/\psi) \\ &= 7.3 \pm 1.7 \text{ (stat.)}_{-2.1}^{+1.9} \text{ (syst.) nb.} \end{aligned}$$

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 $\beta = 0.121_{-0.002}^{+0.001}$. Thus, the nonprompt contribution to the J/ψ production cross section is

$$\begin{aligned} \sigma_{\text{nonprompt}}(J/\psi) &= 2 \times \sigma_{bb}^{\text{total}} \times \beta \times B(h_b \rightarrow J/\psi + X) \\ &= 1.41 \pm 0.04 \text{ (stat.)} \pm 0.19 \text{ (syst.)} \mu\text{b,} \end{aligned}$$

and the prompt component is evaluated to be

$$\begin{aligned} \sigma_{\text{prompt}}(J/\psi) &= \sigma(J/\psi) - \sigma_{\text{nonprompt}}(J/\psi) \\ &= 9.89 \pm 0.32 \text{ (stat.)}_{-1.48}^{+1.47} \text{ (syst.)} \mu\text{b.} \end{aligned}$$

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

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

and the ratio related to the effective DPS cross section becomes

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

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 $p_T < 10 \text{ GeV}/c$ [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 σ_{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-flavor 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].

V. 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 ± 2.3 (stat.) ± 1.3 (syst.) nb, for J/ψ in the rapidity interval $2.5 < y < 4.0$ and for $p_T > 0$. The effective double-parton scattering cross section is evaluated neglecting the single-parton scattering contribution. 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 nonprompt contributions. This will also enable studying the kinematics of these events and probe model calculations.

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Fedichio²⁹, A. Feliciello⁵⁵, G. Feofilov¹⁴⁰, A. Fernández Téllez⁴⁴, L. Ferrandi¹¹⁰, M. B. Ferrer³², A. Ferrero¹²⁸, C. Ferrero⁵⁵, A. Ferretti²⁴, V. J. G. Feuillard⁹⁴, V. Filova³⁵, D. Finogeev¹⁴⁰, F. M. Fionda⁵¹, F. Flor¹¹⁴, A. N. Flores¹⁰⁸, S. Foertsch⁶⁷, I. Fokin⁹⁴, S. Fokin¹⁴⁰, E. Fragiaco⁵⁶, E. Frajna¹³⁶, U. Fuchs³², N. Funicello²⁸, C. Fuget⁷³, A. Furs¹⁴⁰, T. Fusayas⁹⁸, J. J. Gaardhøje⁸³, M. Gagliardi²⁴, A. M. Gago¹⁰¹, C. D. Galvan¹⁰⁹, D. R. Gangadharan¹¹⁴, P. Ganoti⁷⁸, C. Garabatos⁹⁷, J. R. A. Garcia⁴⁴, E. Garcia-Solis⁹, C. Gargiulo³², A. Garibli⁸¹, K. Garner¹³⁵, P. Gasik⁹⁷, A. Gautam¹¹⁶, M. B. Gay Ducati⁶⁵, M. Germain¹⁰³, A. Ghimouz¹²³, C. Ghosh¹³², M. Giacalone^{50,25}, P. Giubellino^{97,55}, P. Giubilato²⁷, A. M. C. Glaenger¹²⁸, P. Glässel⁹⁴, E. Glimos¹²⁰, D. J. Q. Goh⁷⁶, V. Gonzalez¹³⁴, S. Gorbunov³⁸, M. Gorgon², K. Goswami⁴⁷, S. Gotovac³³, V. Grabski⁶⁶, L. K. Graczykowski¹³³, E. Grecka⁸⁶, A. Grelli⁵⁸, C. Grigoras³², V. Grigoriev¹⁴⁰, S. S. Grigoryan^{141,1}, F. Grosa³², J. F. Grosse-Oetringhaus³², R. Grosso⁹⁷, D. Grund³⁵, G. G. Guardiano¹¹¹, R. Guernane⁷³, M. Guilbaud¹⁰³, K. Gulbrandsen⁸³, T. Gundem⁶³

A. Riabov¹⁴⁰, V. Riabov¹⁴⁰, R. Ricci²⁸, M. Richter¹⁹, A. A. Riedel⁹⁵, W. Riegler³², C. Ristea⁶², M. V. Rodriguez³², M. Rodríguez Cahuantzi⁴⁴, K. Røed¹⁹, R. Rogalev¹⁴⁰, E. Rogochaya¹⁴¹, T. S. Rogoschinski⁶³, D. Rohr³², D. Röhrich²⁰, P. F. Rojas⁴⁴, S. Rojas Torres³⁵, P. S. Rokita¹³³, G. Romanenko¹⁴¹, F. Ronchetti⁴⁸, A. Rosano^{30,52}, E. D. Rosas⁶⁴, K. Roslon¹³³, A. Rossi⁵³, A. Roy⁴⁷, S. Roy⁴⁶, N. Rubini²⁵, O. V. Rueda¹¹⁴, D. Ruggiano¹³³, R. Rui²³, P. G. Russek², R. Russo⁸⁴, A. Rustamov⁸¹, E. Ryabinkin¹⁴⁰, Y. Ryabov¹⁴⁰, A. Rybicki¹⁰⁷, H. Rytönen¹¹⁵, J. Ryu¹⁶, W. Rzeska¹³³, O. A. M. Saariäki⁴³, R. Sadek¹⁰³, S. Sadhu³¹, S. Sadowsky¹⁴⁰, J. Saetre²⁰, K. Šafařík³⁵, P. Saha⁴¹, S. K. Saha⁴, S. Saha⁸⁰, B. Sahoo⁴⁶, B. Sahoo⁴⁷, R. Sahoo⁴⁷, S. Sahoo⁶⁰, D. Sahu⁴⁷, P. K. Sahu⁶⁰, J. Saini¹³², K. Sajdakova³⁷, S. Sakai¹²³, M. P. Salvan⁹⁷, S. Sambyal⁹¹, I. Sanna^{32,95}, T. B. Saramela¹¹⁰, D. Sarkar¹³⁴, N. Sarkar¹³², P. Sarma⁴¹, V. Sarritzu²², V. M. Sarti⁹⁵, M. H. P. Sas¹³⁷, J. Schambach⁸⁷, H. S. Scheid⁶³, C. Schiaua⁴⁵, R. Schicker⁹⁴, A. Schmah⁹⁴, C. Schmidt⁹⁷, H. R. Schmidt⁹³, M. O. Schmidt³², M. Schmidt⁹³, N. V. Schmidt⁸⁷, A. R. Schmier¹²⁰, R. Schotter¹²⁷, A. Schröter³⁸, J. Schukraft³², K. Schwarz⁹⁷, K. Schweda⁹⁷, G. Scioli²⁵, E. Scomarini⁵⁵, J. E. Seger¹⁴, Y. Sekiguchi¹²², D. Sekihata¹²², I. Selyuzhenkov⁹⁷, S. Senyukov¹²⁷, J. J. Seo⁵⁷, D. Serebryakov¹⁴⁰, L. Šerkšnytė⁹⁵, A. Sevcenco⁶², T. J. Shaba⁶⁷, A. Shabetai¹⁰³, R. Shahoyan³², A. Shangaraev¹⁴⁰, A. Sharma⁹⁰, B. Sharma⁹¹, D. Sharma⁴⁶, H. Sharma^{53,107}, M. Sharma⁹¹, S. Sharma⁷⁶, S. Sharma⁹¹, U. Sharma⁹¹, A. Shatat⁷², O. Sheibani¹¹⁴, K. Shigaki⁹², M. Shimomura⁷⁷, J. Shin¹¹, S. Shirinkin¹⁴⁰, Q. Shou³⁹, Y. Sibiriak¹⁴⁰, S. Siddhanta⁵¹, T. Siemarczuk⁷⁹, T. F. Silva¹¹⁰, D. Silvermyr⁷⁵, T. Simantathammakul¹⁰⁵, R. Simeonov³⁶, B. Singh⁹¹, B. Singh⁹⁵, K. Singh⁴⁷, R. Singh⁸⁰, R. Singh⁹¹, R. Singh⁴⁷, S. Singh¹⁵, V. K. Singh¹³², V. Singhal¹³², T. Sinha⁹⁹, B. Sitar¹², M. Sitta^{130,55}, T. B. Skaali¹⁹, G. Skorodumovs⁹⁴, M. Slupecki⁴³, N. Smirnov¹³⁷, R. J. M. Snellings⁵⁸, E. H. Solheim¹⁹, J. Song¹¹⁴, A. Songmoolnak¹⁰⁵, C. Sonnabend^{32,97}, F. Soramel²⁷, A. B. Soto-hernandez⁸⁸, R. Spijkers⁸⁴, I. Sputowska¹⁰⁷, J. Staa⁷⁵, J. Stachel⁹⁴, I. Stan⁶², P. J. Steffanic¹²⁰, S. F. Stiefelmaier⁹⁴, D. Stocco¹⁰³, I. Storehaug¹⁹, P. Stratmann¹³⁵, S. Strazzi²⁵, C. P. Stylianidis⁸⁴, A. A. P. Suaide¹¹⁰, C. Suire⁷², M. Sukhanov¹⁴⁰, M. Suljic³², R. Sultanov¹⁴⁰, V. Sumberia⁹¹, S. Sumowidagdo⁸², S. Swain⁶⁰, I. Szarka¹², M. Szymkowski¹³³, S. F. Taghavi⁹⁵, G. Taillepied⁹⁷, J. Takahashi¹¹¹, G. J. Tambave⁸⁰, S. Tang⁶, Z. Tang¹¹⁸, J. D. Tapia Takaki¹¹⁶, N. Tapus¹²⁴, L. A. Tarasovicova¹³⁵, M. G. Tazila⁴⁵, G. F. Tassielli³¹, A. Tauro³², G. Tejada Muñoz⁴⁴, A. Telesca³², L. Terlizzi²⁴, C. Terrevoli¹¹⁴, S. Thakur⁴, D. Thomas¹⁰⁸, A. Tikhonov¹⁴⁰, A. R. Timmins¹¹⁴, M. Tkacik¹⁰⁶, T. Tkacik¹⁰⁶, A. Toia⁶³, R. Tokumoto⁹², N. Topilskaya¹⁴⁰, M. Toppi⁴⁸, T. Tork⁷², A. G. Torres Ramos³¹, A. Trifiró^{30,52}, A. S. Triolo^{32,30,52}, S. Tripathy⁵⁰, T. Tripathy⁴⁶, S. Trogolo³², V. Trubnikov³, W. H. Trzaska¹¹⁵, T. P. Trzcinski¹³³, A. Tumkin¹⁴⁰, R. Turrisi⁵³, T. S. Tveter¹⁹, K. Ullaland²⁰, B. Ulukutlu⁹⁵, A. Uras¹²⁶, M. Urioni^{54,131}, G. L. Usai²², M. Vala³⁷, N. Valle²¹, L. V. R. van Doremalen⁵⁸, M. van Leeuwen⁸⁴, C. A. van Veen⁹⁴, R. J. G. van Weelden⁸⁴, P. Vande Vyvre³², D. Varga¹³⁶, Z. Varga¹³⁶, M. Vasileiou⁷⁸, A. Vasiliev¹⁴⁰, O. Vázquez Doce⁴⁸, V. Vechernin¹⁴⁰, E. Vercellin²⁴, S. Vergara Limón⁴⁴, L. Vermunt⁹⁷, R. Vértesi¹³⁶, M. Verweij⁵⁸, L. Vickovic³³, Z. Vilakazi¹²¹, O. Villalobos Baillie¹⁰⁰, A. Villani²³, G. Vino⁴⁹, A. Vinogradov¹⁴⁰, T. Virgili²⁸, M. M. O. Virta¹¹⁵, V. Vislavicius⁷⁵, A. Vodopyanov¹⁴¹, B. Volkel³², M. A. Völkl⁹⁴, K. Voloshin¹⁴⁰, S. A. Voloshin¹³⁴, G. Volpe³¹, B. von Haller³², I. Vorobyev⁹⁵, N. Vozniuk¹⁴⁰, J. Vrláková³⁷, J. Wan³⁹, C. Wang³⁹, D. Wang³⁹, Y. Wang³⁹, A. Wegrzynek³², F. T. Weighofer³⁸, S. C. Wenzel³², J. P. Wessels¹³⁵, S. L. Weyhmiller¹³⁷, J. Wiechula⁶³, J. Wikne¹⁹, G. Wilk⁷⁹, J. Wilkinson⁹⁷, G. A. Willems¹³⁵, B. Windelband⁹⁴, M. Winn¹²⁸, J. R. Wright¹⁰⁸, W. Wu³⁹, Y. Wu¹¹⁸, R. Xu⁶, A. Yadav⁴², A. K. Yadav¹³², S. Yalcin⁷¹, Y. Yamaguchi⁹², S. Yang²⁰, S. Yano⁹², Z. Yin⁶, I.-K. Yoo¹⁶, J. H. Yoon⁵⁷, H. Yu¹¹, S. Yuan²⁰, A. Yuncu⁹⁴, V. Zaccolo²³, C. Zampolli³², F. Zanone⁹⁴, N. Zardoshti³², A. Zarochentsev¹⁴⁰, P. Závada⁶¹, N. Zaviyalov¹⁴⁰, M. Zhalov¹⁴⁰, B. Zhang⁶, L. Zhang³⁹, S. Zhang³⁹, X. Zhang⁶, Y. Zhang¹¹⁸, Z. Zhang⁶, M. Zhao¹⁰, V. Zhrebchevskii¹⁴⁰, Y. Zhi¹⁰, D. Zhou⁶, Y. Zhou⁸³, J. Zhu^{97,6}, Y. Zhu⁶, S. C. Zugeravel⁵⁵ and N. Zurlo^{131,54}

(ALICE Collaboration)

¹A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia²AGH University of Science and Technology, Cracow, Poland³Bogolyubov Institute for Theoretical Physics, National Academy of Sciences of Ukraine, Kiev, Ukraine⁴Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India⁵California Polytechnic State University, San Luis Obispo, California, USA⁶Central China Normal University, Wuhan, China⁷Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba⁸Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico⁹Chicago State University, Chicago, Illinois, USA¹⁰China Institute of Atomic Energy, Beijing, China¹¹Chungbuk National University, Cheongju, Republic of Korea¹²Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics, Bratislava, Slovak Republic¹³COMSATS University Islamabad, Islamabad, Pakistan

- ¹⁴Creighton University, Omaha, Nebraska, USA
- ¹⁵Department of Physics, Aligarh Muslim University, Aligarh, India
- ¹⁶Department of Physics, Pusan National University, Pusan, Republic of Korea
- ¹⁷Department of Physics, Sejong University, Seoul, Republic of Korea
- ¹⁸Department of Physics, University of California, Berkeley, California, USA
- ¹⁹Department of Physics, University of Oslo, Oslo, Norway
- ²⁰Department of Physics and Technology, University of Bergen, Bergen, Norway
- ²¹Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- ²²Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy
- ²³Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy
- ²⁴Dipartimento di Fisica dell'Università and Sezione INFN, Turin, Italy
- ²⁵Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Bologna, Italy
- ²⁶Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Catania, Italy
- ²⁷Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Padova, Italy
- ²⁸Dipartimento di Fisica 'E.R. Caianiello' dell'Università and Gruppo Collegato INFN, Salerno, Italy
- ²⁹Dipartimento DISAT del Politecnico and Sezione INFN, Turin, Italy
- ³⁰Dipartimento di Scienze MIFT, Università di Messina, Messina, Italy
- ³¹Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy
- ³²European Organization for Nuclear Research (CERN), Geneva, Switzerland
- ³³Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, Croatia
- ³⁴Faculty of Engineering and Science, Western Norway University of Applied Sciences, Bergen, Norway
- ³⁵Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
- ³⁶Faculty of Physics, Sofia University, Sofia, Bulgaria
- ³⁷Faculty of Science, P.J. Šafárik University, Košice, Slovak Republic
- ³⁸Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
- ³⁹Fudan University, Shanghai, China
- ⁴⁰Gangneung-Wonju National University, Gangneung, Republic of Korea
- ⁴¹Gauhati University, Department of Physics, Guwahati, India
- ⁴²Helmholtz-Institut für Strahlen- und Kernphysik, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn, Germany
- ⁴³Helsinki Institute of Physics (HIP), Helsinki, Finland
- ⁴⁴High Energy Physics Group, Universidad Autónoma de Puebla, Puebla, Mexico
- ⁴⁵Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
- ⁴⁶Indian Institute of Technology Bombay (IIT), Mumbai, India
- ⁴⁷Indian Institute of Technology Indore, Indore, India
- ⁴⁸INFN, Laboratori Nazionali di Frascati, Frascati, Italy
- ⁴⁹INFN, Sezione di Bari, Bari, Italy
- ⁵⁰INFN, Sezione di Bologna, Bologna, Italy
- ⁵¹INFN, Sezione di Cagliari, Cagliari, Italy
- ⁵²INFN, Sezione di Catania, Catania, Italy
- ⁵³INFN, Sezione di Padova, Padova, Italy
- ⁵⁴INFN, Sezione di Pavia, Pavia, Italy
- ⁵⁵INFN, Sezione di Torino, Turin, Italy
- ⁵⁶INFN, Sezione di Trieste, Trieste, Italy
- ⁵⁷Inha University, Incheon, Republic of Korea
- ⁵⁸Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University/Nikhef, Utrecht, Netherlands
- ⁵⁹Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovak Republic
- ⁶⁰Institute of Physics, Homi Bhabha National Institute, Bhubaneswar, India
- ⁶¹Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
- ⁶²Institute of Space Science (ISS), Bucharest, Romania
- ⁶³Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
- ⁶⁴Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
- ⁶⁵Instituto de Física, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Brazil
- ⁶⁶Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
- ⁶⁷iThemba LABS, National Research Foundation, Somerset West, South Africa
- ⁶⁸Jeonbuk National University, Jeonju, Republic of Korea
- ⁶⁹Johann-Wolfgang-Goethe Universität Frankfurt Institut für Informatik, Fachbereich Informatik und Mathematik, Frankfurt, Germany
- ⁷⁰Korea Institute of Science and Technology Information, Daejeon, Republic of Korea
- ⁷¹KTO Karatay University, Konya, Turkey
- ⁷²Laboratoire de Physique des 2 Infinis, Irène Joliot-Curie, Orsay, France

- ⁷³Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3, Grenoble, France
- ⁷⁴Lawrence Berkeley National Laboratory, Berkeley, California, USA
- ⁷⁵Lund University Department of Physics, Division of Particle Physics, Lund, Sweden
- ⁷⁶Nagasaki Institute of Applied Science, Nagasaki, Japan
- ⁷⁷Nara Women's University (NWU), Nara, Japan
- ⁷⁸National and Kapodistrian University of Athens, School of Science, Department of Physics, Athens, Greece
- ⁷⁹National Centre for Nuclear Research, Warsaw, Poland
- ⁸⁰National Institute of Science Education and Research, Homi Bhabha National Institute, Jatni, India
- ⁸¹National Nuclear Research Center, Baku, Azerbaijan
- ⁸²National Research and Innovation Agency - BRIN, Jakarta, Indonesia
- ⁸³Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- ⁸⁴Nikhef, National institute for subatomic physics, Amsterdam, Netherlands
- ⁸⁵Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom
- ⁸⁶Nuclear Physics Institute of the Czech Academy of Sciences, Husinec-Řež, Czech Republic
- ⁸⁷Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA
- ⁸⁸Ohio State University, Columbus, Ohio, USA
- ⁸⁹Physics department, Faculty of science, University of Zagreb, Zagreb, Croatia
- ⁹⁰Physics Department, Panjab University, Chandigarh, India
- ⁹¹Physics Department, University of Jammu, Jammu, India
- ⁹²Physics Program and International Institute for Sustainability with Knotted Chiral Meta Matter (SKCM2), Hiroshima University, Hiroshima, Japan
- ⁹³Physikalisches Institut, Eberhard-Karls-Universität Tübingen, Tübingen, Germany
- ⁹⁴Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- ⁹⁵Physik Department, Technische Universität München, Munich, Germany
- ⁹⁶Politecnico di Bari and Sezione INFN, Bari, Italy
- ⁹⁷Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
- ⁹⁸Saga University, Saga, Japan
- ⁹⁹Saha Institute of Nuclear Physics, Homi Bhabha National Institute, Kolkata, India
- ¹⁰⁰School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
- ¹⁰¹Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
- ¹⁰²Stefan Meyer Institut für Subatomare Physik (SMI), Vienna, Austria
- ¹⁰³SUBATECH, IMT Atlantique, Nantes Université, CNRS-IN2P3, Nantes, France
- ¹⁰⁴Sungkyunkwan University, Suwon City, Republic of Korea
- ¹⁰⁵Suranaree University of Technology, Nakhon Ratchasima, Thailand
- ¹⁰⁶Technical University of Košice, Košice, Slovak Republic
- ¹⁰⁷The Henryk Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland
- ¹⁰⁸The University of Texas at Austin, Austin, Texas, USA
- ¹⁰⁹Universidad Autónoma de Sinaloa, Culiacán, Mexico
- ¹¹⁰Universidade de São Paulo (USP), São Paulo, Brazil
- ¹¹¹Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
- ¹¹²Universidade Federal do ABC, Santo Andre, Brazil
- ¹¹³University of Cape Town, Cape Town, South Africa
- ¹¹⁴University of Houston, Houston, Texas, USA
- ¹¹⁵University of Jyväskylä, Jyväskylä, Finland
- ¹¹⁶University of Kansas, Lawrence, Kansas, USA
- ¹¹⁷University of Liverpool, Liverpool, United Kingdom
- ¹¹⁸University of Science and Technology of China, Hefei, China
- ¹¹⁹University of South-Eastern Norway, Kongsberg, Norway
- ¹²⁰University of Tennessee, Knoxville, Tennessee, USA
- ¹²¹University of the Witwatersrand, Johannesburg, South Africa
- ¹²²University of Tokyo, Tokyo, Japan
- ¹²³University of Tsukuba, Tsukuba, Japan
- ¹²⁴University Politehnica of Bucharest, Bucharest, Romania
- ¹²⁵Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
- ¹²⁶Université de Lyon, CNRS/IN2P3, Institut de Physique des 2 Infinis de Lyon, Lyon, France
- ¹²⁷Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France, Strasbourg, France
- ¹²⁸Université Paris-Saclay Centre d'Etudes de Saclay (CEA), IRFU, Département de Physique Nucléaire (DPhN), Saclay, France
- ¹²⁹Università degli Studi di Foggia, Foggia, Italy
- ¹³⁰Università 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, USA*
- ¹³⁵*Westfälische Wilhelms-Universität Münster, Institut für Kernphysik, Münster, Germany*
- ¹³⁶*Wigner Research Centre for Physics, Budapest, Hungary*
- ¹³⁷*Yale University, New Haven, Connecticut, USA*
- 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*

*Also at: Max-Planck-Institut für Physik, Munich, Germany.

†Also at: Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Bologna, Italy.

‡Deceased.

§Also at: An institution covered by a cooperation agreement with CERN.

||Also at: Department of Applied Physics, Aligarh Muslim University, Aligarh, India.

¶Also at: Institute of Theoretical Physics, University of Wrocław, Poland.