Measurement of inclusive J/ψ pair production cross section in pp collisions at √s=13 TeV

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

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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 $10.3 \pm 2.3\,(\text{stat.}) \pm 1.3\,(\text{syst.})$ 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 $+ W/\gamma$ 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 ($\widehat{\sigma}$) divided by an effective cross section (σ_{eff}) [12,13,34]

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

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 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], γ + 3-jets [19–21], 2γ + 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 $Q\overline{Q}$ 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 $Q\overline{Q}$ 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

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charge-conjugate-even states, e.g., $\chi_c \to J/\psi\,\gamma$, 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 $2.8 \leqslant \eta \leqslant 5.1$ (V0A) and $-3.7 \leqslant \eta \leqslant -1.7$ (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 $|\eta| \leqslant 2.0$ and $|\eta| \leqslant 1.4$ 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 $|v_z| \leqslant 10$ 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/c^2. 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 $24.11 \pm 0.01\,(\text{stat.}) \pm 0.80\,(\text{syst.})\,\text{pb}^{-1}$.

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

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

where N is the signal estimate, ϵ is the acceptance-times-efficiency correction, $B(J/\psi \to \mu^+\mu^-) = (5.961 \pm 0.033)\%$ is the branching fraction of $J/\psi \to \mu^+\mu^-$ [70], and $\mathcal{L}_{\text{int}}$ 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 $F(m_1, m_2)$:

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

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

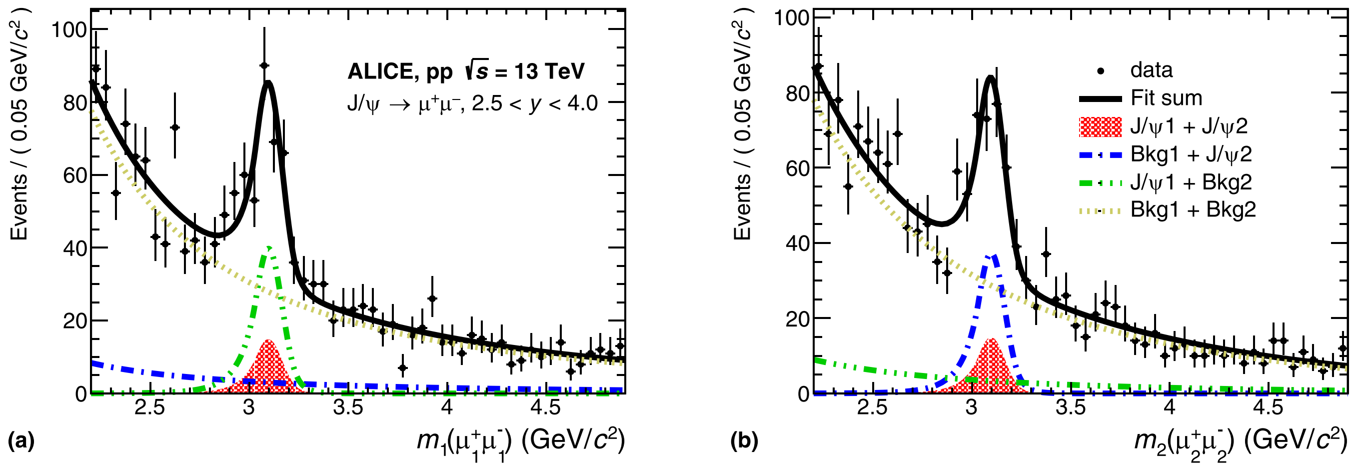

FIG. 1. Projections of a fit to the two-dimensional invariant mass distribution for inclusive J/ψ pair candidates for (a) $m_1(\mu_1^+\mu_1^-)$ and (b) $m_2(\mu_2^+\mu_2^-)$. The (black) markers show data. The (black) solid line represents the total fit function. The (blue and green) dashed-dotted lines 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 $N = 59.3 \pm 13.5\,(\text{stat.}) \pm 4.4\,(\text{syst.})$.

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
$B(\mathrm{J}/\psi \to \mu^+\mu^-)$	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

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

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

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

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

$$\sigma_{\text{nonprompt}}(J/\psi\ J/\psi) = \sigma_{b\bar{b}}^{\text{total}} \times \alpha \times B^2(h_b \to J/\psi + X). \tag{5}$$

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

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

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

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

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

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

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

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

and the prompt component is evaluated to be

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

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

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

and the ratio related to the effective DPS cross section becomes

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

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 $p_T < 10\,\text{GeV}/c$ [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 $10.3 \pm 2.3\,(\text{stat.}) \pm 1.3\,(\text{syst.})$ nb, for J/ψ in the rapidity interval $2.5 < y < 4.0$ and for $p_T > 0$. The 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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