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Observation of double J/ψ meson production in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV

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The first observation of the concurrent production of two J/ψ mesons in proton-nucleus collisions is presented. The analysis is based on a proton-lead (pPb) data sample recorded at a nucleon-nucleon center-of-mass energy of 8.16 TeV by the CMS experiment at the CERN LHC and corresponding to an integrated luminosity of 174.6 nb^{-1}. The two J/ψ mesons are reconstructed in their $\mu^+\mu^-$ decay channels with transverse momenta $p_{\mathrm{T}} > 6.5$ GeV and rapidity $|y| < 2.4$. Events where one of the J/ψ mesons is reconstructed in the dielectron channel are also considered in the search. The $p\mathrm{Pb} \to J/\psi J/\psi + X$ process is observed with a significance of 5.3 standard deviations. The measured inclusive fiducial cross section, using the four-muon channel alone, is $\sigma(p\mathrm{Pb} \to J/\psi J/\psi + X) = 22.0 \pm 8.9(\mathrm{stat}) \pm 1.5(\mathrm{syst})$ nb. A fit of the data to the expected rapidity separation for pairs of J/ψ mesons produced in single (SPS) and double (DPS) parton scatterings yields $\sigma_{\mathrm{SPS}}^{p\mathrm{Pb}\to J/\psi J/\psi+X} = 16.5 \pm 10.8(\mathrm{stat}) \pm 0.1(\mathrm{syst})$ nb and $\sigma_{\mathrm{DPS}}^{p\mathrm{Pb}\to J/\psi J/\psi+X} = 5.4 \pm 6.2(\mathrm{stat}) \pm 0.4(\mathrm{syst})$ nb, respectively. This latter result can be transformed into a lower bound on the effective DPS cross section, closely related to the squared average interparton transverse separation in the collision, of $\sigma_{\mathrm{eff}} > 1.0$ mb at 95% confidence level.

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I. INTRODUCTION

High-energy collisions of protons and nuclei at the CERN LHC are characterized by multiple interactions of their underlying partonic constituents (quarks and gluons). Such multiple parton interactions can lead to the simultaneous production of several particles with values of transverse momentum and/or mass above a few GeV, much larger than the typical nonperturbative $\mathcal{O}(0.2\ \mathrm{GeV})$ scale of quantum chromodynamics (QCD). Research on multiparton interactions has attracted an increasing interest at hadron colliders as a means to probe the generalized parton densities of the proton, to determine the unknown energy evolution of the partonic transverse profile of the proton, and to study the role of partonic correlations (in position and momentum phase space, as well as in flavor, color, and spin quantum numbers) in the hadronic wave functions [1,2]. A good understanding of multiple hard scatterings of partons is also crucial to describe the continuum backgrounds in studies of rare standard model resonance decays, as well as in searches for new physics, in final states where various heavy particles are produced [3–5].

Following a purely geometric approach, i.e., ignoring any parton correlations, the probability to produce n high-p_{T} particles in a given hadron-hadron collision is proportional to the nth product of the probabilities to independently produce each of them [6]. Thus, the probability to produce two high-p_{T} particles in a double parton scattering (DPS) would scale with the square of the corresponding single parton scattering (SPS) probabilities. The occurrence of DPS processes is therefore more likely for final states with large SPS cross sections, as is the case for quarkonium mesons compared to rarer heavy particles such as electroweak bosons [7]. Under this approximation, the cross section to produce two charmonium mesons, ψ_1 and ψ_2, via DPS in a proton-proton (pp) collision can be expressed as the product of the SPS cross sections for the production of each individual meson (calculated using perturbative QCD or directly measured using collision data) normalized by an effective cross section (σ_{eff}) to ensure the proper units of the ratio,

$$\sigma_{\mathrm{DPS}}^{pp\to\psi_1\psi_2+X} = \left(\frac{\mathfrak{m}}{2}\right)\frac{\sigma_{\mathrm{SPS}}^{pp\to\psi_1+X}\sigma_{\mathrm{SPS}}^{pp\to\psi_2+X}}{\sigma_{\mathrm{eff}}}. \quad (1)$$

Here, $\mathfrak{m}$ is a combinatorial factor to avoid double counting the same process, $\mathfrak{m} = 1(2)$ if $\psi_1 = \psi_2$ $(\psi_1 \neq \psi_2)$. In a

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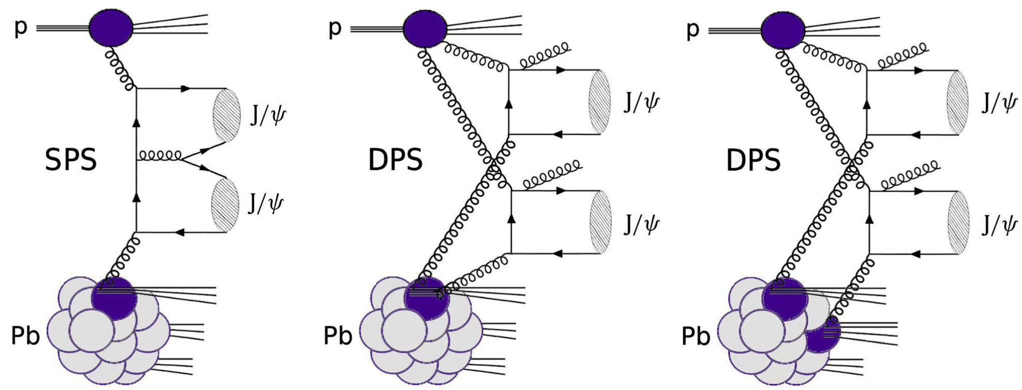

FIG. 1. Representative diagrams of SPS (left) and DPS (center and right) contributions to the production of two J/ψ mesons in pPb collisions.

purely geometric approach, the σ_{eff} value can be determined via

$$\sigma_{\text{eff}} = \left[\int d^2\mathbf{b}T^2(\mathbf{b})\right]^{-1}, \quad (2)$$

where $T(\mathbf{b})$ is the pp transverse overlap function at the vector impact parameter $\mathbf{b}$ of the collision [6]. In terms of the transverse parton density of the proton, $\rho(\mathbf{b})$, the overlap function is given by $T(\mathbf{b}) = \int \rho(\mathbf{b_1})\rho(\mathbf{b_1} - \mathbf{b})d^2\mathbf{b_1}$, and the σ_{eff} parameter can be interpreted as the squared average interparton distance in the pp collision where the two hard scatterings take place. Thus, a smaller value of σ_{eff} implies larger DPS yields. For the typical proton transverse density profiles implemented in common Monte Carlo (MC) event generators used at collider energies, e.g., PYTHIA [8] or Herwig++ [9], $\sigma_{\text{eff}} \approx 20$–$30$ mb. These values are about a factor of 2 larger than those experimentally derived via Eq. (1) for a variety of different pairs of particles measured at the Tevatron and the LHC [2]. This discrepancy points to the presence of various types of parton correlations in the proton [10] not accounted for in the purely geometrical approach, as represented in Eq. (2). In addition, the experimentally extracted values of σ_{eff} seemingly depend on the particular final state under consideration, with multiquarkonium production processes yielding lower values, $\sigma_{\text{eff}} \approx 5$–$10$ mb from $J/\psi J/\psi$ [11–15], $J/\psi J/\psi J/\psi$ [16], $J/\psi \Upsilon$ [17], and $\Upsilon\Upsilon$ [4,18] studies, than the $\sigma_{\text{eff}} \approx 15$ mb obtained from final states involving pairs of high-p_{T} jets and/or electroweak bosons [19–26]. Such process-dependent σ_{eff} determinations appear consistent with flavor-dependent correlations that follow the different quark or gluon densities in the parton distribution functions (PDFs) probed at varying values of the momentum fraction by each scattering [27].

To advance understanding of multiple hard scatterings, it has been suggested to study DPS processes in proton-nucleus (pA) collisions [28–30] in which the large transverse parton density of the nucleus significantly enhances the DPS contributions compared to the pp case. Measurements of DPS processes in pA collisions have also been proposed as a means to shed light on the impact-parameter dependence of nuclear PDFs (nPDFs) [31]. For pPb collisions, the equivalent of Eq. (1) for the inclusive production of two J/ψ mesons is

$$\sigma_{\text{DPS}}^{p\text{Pb}\to J/\psi J/\psi+X} = \left(\frac{1}{2}\right)\frac{\sigma_{\text{SPS}}^{p\text{Pb}\to J/\psi+X}\sigma_{\text{SPS}}^{p\text{Pb}\to J/\psi+X}}{\sigma_{\text{eff},p\text{Pb}}}, \quad (3)$$

where the effective pPb cross section in the denominator accounts now for two possible DPS contributions coming from collisions of partons of the "projectile" proton with partons of one or two nucleons of the "target" lead ion (center and right diagrams of Fig. 1, respectively). Under the same assumptions of factorization of hard-scattering probabilities that lead to Eq. (2) in the pp case, the value of $\sigma_{\text{eff},p\text{Pb}}$ can be connected to that of σ_{eff} through the relationship [6,30]

$$\sigma_{\text{eff},p\text{Pb}} = \frac{A\sigma_{\text{eff}}}{1 + \sigma_{\text{eff}}F_{p\text{Pb}}/A}, \quad (4)$$

where $A = 208$ is the Pb mass number, and the quantity $F_{p\text{Pb}} = (A-1)/A\int d^2\mathbf{b}T^2(\mathbf{b}) \approx A^{1/3}/14\pi\ \text{mb}^{-1}$, similarly to Eq. (2), is the integral over impact parameter of the squared pPb transverse profile, which can be determined through a Glauber MC model [32]. In this approximation, the value of $\sigma_{\text{eff},p\text{Pb}}$ is expected to be about half the total hadronic pPb cross section that amounts to $\sigma_{p\text{Pb}} \approx 2$ b at the LHC [33,34]. Using Eq. (4), measurements of the DPS cross sections in pPb collisions can therefore provide alternative extractions of the σ_{eff} parameter, independently of pp data. Such studies with pPb collisions extend the physics reach of the heavy ion program at the LHC [35].

A first study of DPS in pPb collisions was carried out by the LHCb experiment through measurements of the simultaneous production of different pairs of charmed hadrons at nucleon-nucleon center-of-mass energy

TABLE I. Definition of the fiducial phase space for the $p\mathrm{Pb} \to J/\psi J/\psi + X$ cross section measurement in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV.

Particle	Fiducial requirement
Muons	$p_{\mathrm{T}} > 3.4$ GeV for $\lvert\eta\rvert < 0.3$
	$p_{\mathrm{T}} > 3.3$ GeV for $0.3 < \lvert\eta\rvert < 1.1$
	$p_{\mathrm{T}} > 5.5 - 2.0\lvert\eta\rvert$ GeV for $1.1 < \lvert\eta\rvert < 2.1$
	$p_{\mathrm{T}} > 1.3$ GeV for $2.1 < \lvert\eta\rvert < 2.4$
J/ψ mesons	$p_{\mathrm{T}} > 6.5$ GeV and $\lvert y\rvert < 2.4$

$\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV [36]. This paper reports the measurement of the concurrent production of two J/ψ vector mesons in pPb collisions at the same center-of-mass energy. This process has not been previously observed and is of interest to clarify the SPS production of multiple quarkonium states [7,37], to improve our understanding of DPS processes [6,10], as well as to study nPDF properties [31]. The generic types of partonic scatterings contributing to prompt $J/\psi J/\psi + X$ production are schematically shown in Fig. 1. In SPS processes (Fig. 1, left), the two vector mesons are produced by a single pair of interacting partons, whereas two different pairs of partons produce the final $J/\psi J/\psi + X$ state in DPS (Fig. 1, center and right). The relatively high mass ($m_{J/\psi} = 3.1$ GeV), combined with the experimental requirement of ${p_{\mathrm{T}}}^{J/\psi} > 6.5$ GeV, ensure that both charmonium mesons are produced in hard partonic scatterings with virtualities above $Q \approx \sqrt{m^2_{J/\psi} + p^2_{\mathrm{T}}} \approx 7$ GeV, which can be well described theoretically with perturbative calculations based, e.g., on the nonrelativistic QCD approach [38].

This analysis studies DPS in double charmonium production in pPb collisions at the LHC, following an approach similar to that used in the triple-J/ψ observation in pp collisions [16]. Exploiting the pPb data sample collected at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV in 2016, we measure the fiducial cross section for the rare final state of interest. The $J/\psi J/\psi + X$ cross section is measured in the fiducial volume of the detector, defined in Table I, correcting for experimental inefficiencies. There is no extrapolation of the cross section for the final state beyond the fiducial acceptance, thus avoiding potential systematic uncertainties coming, e.g., from the polarization of the J/ψ mesons. The tabulated results of this study are provided in a HEPData record [39].

II. THE CMS DETECTOR AND DATA SELECTION

The CMS apparatus [40] is a multipurpose, nearly hermetic detector, designed to trigger on [41,42] and identify electrons, muons, photons, and charged and neutral hadrons [43–45]. A global "particle-flow" algorithm [46] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon inner tracker and by the crystal electromagnetic and brass-scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. The silicon tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$. During the LHC running period when the data used in this article were recorded, the silicon tracker consisted of 1440 silicon pixel and 15 148 silicon strip detector modules. For nonisolated particles of $1 < p_{\mathrm{T}} < 10$ GeV and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_{T} and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [45]. The electromagnetic calorimeter (ECAL) consists of 75 848 lead tungstate crystals, which provide coverage in pseudorapidity $|\eta| < 1.48$ in a barrel region and $1.48 < |\eta| < 3.0$ in two end cap regions. Muons are measured in the pseudorapidity range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. The forward hadron (HF) calorimeter extends the pseudorapidity coverage provided by the barrel and end cap detectors, and uses steel as an absorber and quartz fibers as the sensitive material. The two halves of the HF are located 11.2 m from the interaction region, one on each end, and together they provide coverage in the range $3.0 < |\eta| < 5.2$. They also serve as luminosity monitors. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [40].

Events are filtered using a two-tiered trigger system [42]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors [41]. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [42].

The events are collected with a trigger requiring two muon candidates found in the muon detectors at level-1. In order to maximize the detection efficiency [47], no explicit selection is made on their transverse momentum or pseudorapidity. During the 2016 pPb run, this trigger was operated without any prescale, recording an integrated luminosity of 174.6 nb^{-1}.

For the offline analysis, events have to pass a set of selection criteria designed to reject events from background processes (beam-gas collisions) as described in Ref. [48]. Events are required to have at least one reconstructed interaction vertex, formed by two or more associated tracks, with a distance from the center of the nominal interaction region of less than 25 cm along the beam direction and 0.2 cm in the plane transverse to the beam direction. The primary vertex is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking

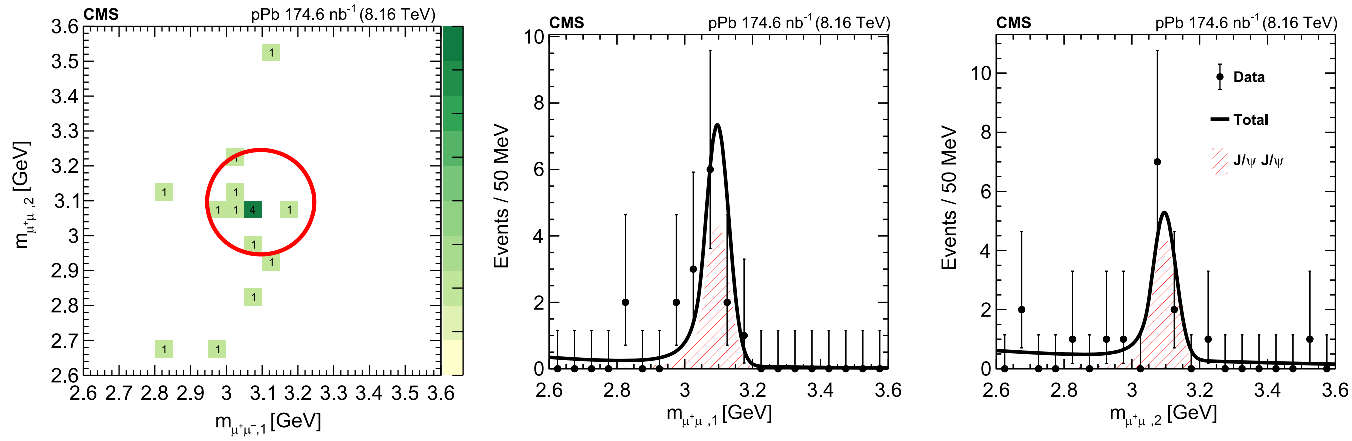

FIG. 2. Dimuon invariant mass distributions of the pPb events passing all selection criteria, shown as a 2D map (left panel, with the numbers indicating the counts per bin and the red circle indicating the double J/ψ meson signal region) and its 1D projections for each pair (center and right panels). In the 1D projections, the measured data are represented by the points (with vertical bars showing their Poisson statistical uncertainties), the solid curve shows the overall signal + background fit to the data, and the red hashed area shows the signal yields for the $J/\psi J/\psi + X$ process.

information alone, as described in Sec. 9.4.1 of Ref. [49]. In order to select inelastic hadronic collisions, the pPb events are also required to have at least one tower in each of the HF detectors with energy deposits of more than 3 GeV per tower. Any potential event containing more than one pPb interaction (pileup) is removed by the offline requirement of a common vertex for the four selected muons, as described below.

III. EVENT RECONSTRUCTION AND EFFICIENCY

Muons are reconstructed by combining information from the silicon tracker and the muon system composed of four layers of detectors (muon "stations") [44]. The matching between tracks reconstructed in each of the subsystems proceeds either outside-in, starting from a track in the muon system, or inside-out, starting from a track provided by the silicon tracker. In the latter case, charged particles in the tracker that match track segments in only one or two muon stations are also considered in the analysis to collect low-p_T muons that may not have sufficient energy to traverse the entire muon system. The muons are selected from the reconstructed track candidates that match with at least one segment in any muon station in both x and y coordinates. Furthermore, the muon candidates are required to be identified as "soft," as defined in Ref. [44]. Matching muons to tracks measured in the silicon tracker results in a relative transverse momentum resolution, for muons with p_T up to 100 GeV, of 1% in the barrel and 3% in the end caps [44,47].

All muons are required to pass a variable minimum p_T value based on their pseudorapidity, as described in Table I. Muons with opposite-sign charge are combined into pairs with invariant masses $2.6 < m_{\mu\mu} < 3.6$ GeV to form a J/ψ candidate. No pair ambiguities (namely, cases where the two J/ψ mesons can be simultaneously reconstructed with two different combinations of the four muons), nor events with more than four muons satisfying the selection criteria, are found in data. The reconstructed J/ψ candidates are required to have $p_T > 6.5$ GeV and $|y| < 2.4$. The four muons are fit to a common vertex, and the χ^2 probability of the fit is required to be larger than 0.1% [50]. A total of 16 candidate di-J/ψ events pass all selection criteria (Fig. 2). The requirement of the four muons to share the same vertex suppresses contributions from nonprompt J/ψ mesons originating from the decays of b quark hadrons. All selected events have vertices consistent with the primary vertex within 100 μm and, therefore, the nonprompt single J/ψ meson contribution is expected to be, at most, a few percent of the prompt one within the selected kinematical range [51,52]. This feature further confirms that the J/ψ mesons considered in this analysis are promptly produced.

Simulations based on the PYTHIA 8.303 [53] and EPOS-LHC [54] MC event generators are used to determine the overall efficiency of the analysis including the impact of the dimuon triggers, as well as of the single muon and J/ψ meson reconstruction within the fiducial volume defined in Table I. The generated prompt J/ψ mesons are produced unpolarized in agrement with LHC data [55–57]. Generated PYTHIA-8 $pp \to J/\psi + X$ events are embedded into pPb events simulated with EPOS-LHC that replicate the hadronic activity from the underlying event. To improve the agreement between the simulated and measured charged particle multiplicities, a weighting procedure based on the number of tracks per event is applied when combining both MC samples. The generated events are then processed through a detailed simulation of the CMS detector based on the Geant4 [58] package. The overall reconstruction efficiency is calculated as the ratio of the number of reconstructed events in the MC simulation (after all selection criteria are applied) to the number of generated events (after generator-level filters) within the fiducial phase space of the analysis.

IV. SIGNAL EXTRACTION

The signal is extracted from all events passing the fiducial requirements listed in Table I, with a two-dimensional (2D) unbinned extended maximum likelihood fit that exploits the invariant masses of the two J/ψ meson candidates as variables. The signal J/ψ mass distribution is modeled with a Crystal Ball function [59] and the combinatorial background is described by an exponential function. Both probability density functions (pdfs) are used twice, for the J/ψ_1 and J/ψ_2 states, per event, where the indices 1 and 2 indicate, respectively, the leading (i.e., highest p_T) and subleading J/ψ meson. The parameters describing the Crystal Ball J/ψ signal model are fixed (for both J/ψ mesons) to values obtained from fits of the simulated distributions, the mean being essentially identical to the world-average J/ψ mass, $m_{J/\psi} = 3.1$ GeV [60], and the relative dimuon mass resolution being close to 1% ($\delta m_{J/\psi} \approx 30$ MeV). The parameters of the exponential background are left free in the fit. The per-event 2D map of the two measured dimuon invariant mass distributions is shown in Fig. 2 (left) with the red circle indicating the double-J/ψ signal region within $\pm 5\delta m_{J/\psi}$ around the two J/ψ meson masses.

In total, four parameters representing the four combination of yields, $N(J/\psi_1{}^{\mathrm{sig,bkg}}, J/\psi_2{}^{\mathrm{sig,bkg}})$ for each of the two J/ψ meson candidates to be either signal or background, are incorporated into the likelihood fit. The number of signal and background events derived from the fit procedure are listed in Table II.

The projection of the result of the 2D fit in the two variables, $m_{\mu\mu,1}$ and $m_{\mu\mu,2}$, is shown in Fig. 2 (center and right panels). The data points indicate the measured counts, and the red hashed area shows the fitted signal component. The derived signal yield is $N_{\mathrm{sig}} \equiv N(J/\psi_1{}^{\mathrm{sig}}, J/\psi_2{}^{\mathrm{sig}}) = 8.5 \pm 3.4$ events. The difference between the red area and the fit (solid black curve) indicates the size of the backgrounds, listed in Table II, from events with four uncorrelated muons (mostly filling the area to the left of the J/ψ peaks) and with two uncorrelated muons coming from the $J/\psi_{1,2} + \mu^+\mu^-$ combination (filling the empty area below the peaks).

The signal has a significance of 4.9 standard deviations, obtained from the likelihood ratio of the default signal-plus-background fit and the background-only fit (imposing $N_{\mathrm{sig}} = 0$), using the standard asymptotic formula [61] assuming that the Wilks theorem conditions apply [62]. As discussed below, the systematic uncertainties are small (6.1%, with a fraction of them impacting equally signal and background) and do not alter the statistical significance evaluation. This significance was also validated with MC pseudoexperiments.

TABLE II. Signal and background yields obtained from the likelihood fit procedure in the four-muon and dimuon-dielectron analyses over the $m_{\mu\mu,ee} = 2.6$–3.6 GeV mass range.

	Final state	
Yield	$\mu^+\mu^-\mu^+\mu^-$	$\mu^+\mu^-e^+e^-$
$N(J/\psi_1^{\mathrm{sig}}, J/\psi_2^{\mathrm{sig}})$	8.5 ± 3.4	5.7 ± 4.0
$N(J/\psi_1^{\mathrm{bkg}}, J/\psi_2^{\mathrm{sig}})$	0.9 ± 1.6	4.9 ± 3.8
$N(J/\psi_1^{\mathrm{sig}}, J/\psi_2^{\mathrm{bkg}})$	5.2 ± 3.0	4.5 ± 3.4
$N(J/\psi_1^{\mathrm{bkg}}, J/\psi_2^{\mathrm{bkg}})$	1.4 ± 1.9	6.0 ± 3.5

To fully confirm the observation of the double-J/ψ process, events are also analyzed where the leading J/ψ meson is reconstructed in its $\mu^+\mu^-$ decay mode and the other decays via $J/\psi \to e^+e^-$. This channel has a larger background than the 4-muon one, but increases the total size of the data sample and provides a cross-check of the latter. The electron momentum is estimated by combining the ECAL energy measurement (including the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron trajectory) with the momentum measurement in the tracker. The momentum resolution is typically smaller than 5% for electrons in the range $2 < p_T < 10$ GeV. It is generally better in the barrel region than in the end caps, and also depends on the fraction of the electron energy emitted through bremsstrahlung (f_{brem}) as it traverses the material in front of the ECAL [43,63]. Both electrons are required to have $f_{\mathrm{brem}} > 0.01$ (to remove any potential charged-pion contamination) and to be of opposite-sign charge.

For the $\mu^+\mu^- + e^+e^-$ channel, the selection of the dimuon candidates remains the same as for the double-$\mu^+\mu^-$ analysis, and the candidate $e^\pm$ are required to have $p_T > 2.5$ GeV and $|\eta| < 2.5$ and to share the same common vertex. The parameters of the Crystal Ball J/ψ meson signal are derived from the MC simulation, with the resulting mass resolution of the dielectron decay mode being $\delta m_{J/\psi} \approx 70$ MeV. A total number of 21 events pass the $(\mu^+\mu^-, e^+e^-)$ criteria with both dileptons having invariant masses over $m_{\mu\mu,ee} = 2.6$–3.6 GeV. No events passing the selection criteria of the dimuon-dielectron channel are present in the double-dimuon sample.

The fit procedure followed is the same as for the four-muon final state. The per-event 2D map of the dimuon-dielectron invariant mass distributions is shown in Fig. 3 (left) with the red circle indicating the double-J/ψ signal region within $\pm 5\delta m_{J/\psi}$ around the masses of the two J/ψ mesons. The projection of the result of the 2D fit in the two variables, $m_{\mu\mu,1}$ and $m_{ee,2}$, is shown in Fig. 3 (center and right panels). The signal yield (red hashed area) is 5.7 ± 4.0 events.

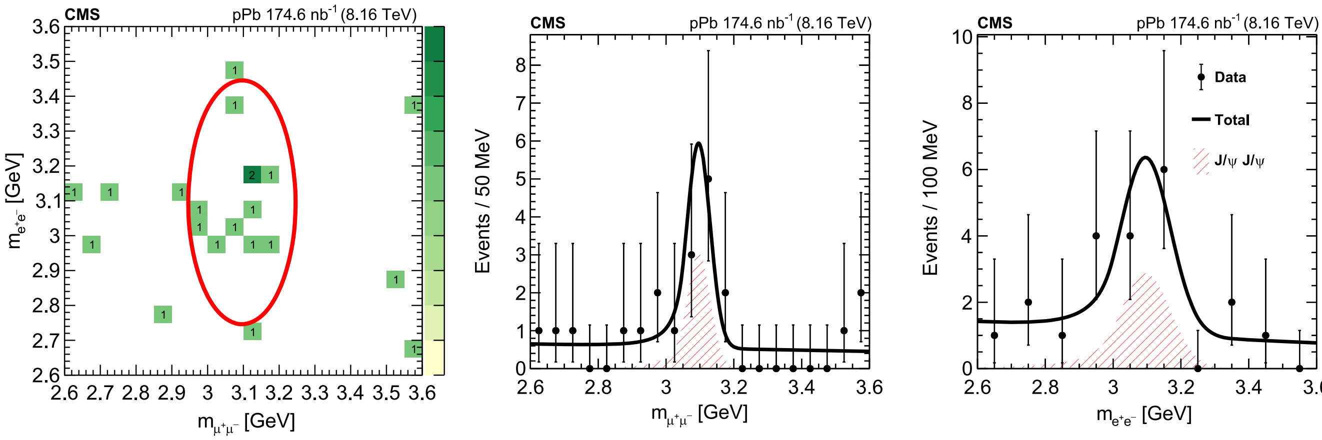

FIG. 3. Dilepton invariant mass distributions of the pPb events passing all selection criteria, shown as a 2D map (left panel, with the numbers indicating the counts per bin and the red circle indicating the double J/ψ meson signal region) and its 1D projections for each pair (center and right panels). In the 1D projections, the measured data are represented by the points (vertical bars showing their Poisson statistical uncertainties), the solid curve shows the overall signal + background fit to the data, and the red hashed area shows the signal yields for the $J/\psi J/\psi + X$ process.

The significance of the $(J/\psi \to e^+e^- + J/\psi \to \mu^+\mu^-)$ mode, calculated in the same way as for the $(J/\psi \to \mu^+\mu^- + J/\psi \to \mu^+\mu^-)$ channel, is 2.3 standard deviations. The combination of the two decay modes, using the Fisher formalism [64] with $p^{\text{value}} = p_1^{\text{value}} p_2^{\text{value}}(1 - \log(p_1^{\text{value}} p_2^{\text{value}}))$, where the $p_{1,2}^{\text{values}}$ are the p values of each independent analysis, gives a total statistical significance of 5.3 standard deviations.

V. RESULTS

The cross section of the double-J/ψ production reconstructed in the four-muon decay mode is obtained through the expression

$$\sigma(p\text{Pb} \to J/\psi J/\psi + X) = \frac{N_{\text{sig}}}{\epsilon \mathcal{L}_{\text{int}} \mathcal{B}^2_{J/\psi \to \mu^+\mu^-}}, \qquad (5)$$

where $N_{\text{sig}} = 8.5 \pm 3.4$ is the number of signal events reconstructed with an overall efficiency ϵ in the fiducial region defined in Table I, $\mathcal{L} = 174.6 \pm 6.1\ \text{nb}^{-1}$ is the total integrated luminosity, and $\mathcal{B}_{J/\psi \to \mu^+\mu^-} = (5.961 \pm 0.033)\%$ is the dimuon decay branching fraction [60]. We do not compute the cross section corresponding to the $(J/\psi \to e^+e^- + J/\psi \to \mu^+\mu^-)$ decay mode because it has much larger backgrounds and is not precise enough to quantitatively improve the overall cross section extraction. To determine the number of signal events corrected for the reconstruction efficiency, we use the expression $N_{\text{sig}}/\epsilon = \sum_i {N_{\text{sig}}}^i/\epsilon^i$, where N^i_{sig} are statistical per-event weights (having a value between 1 and 0, indicating events being more or less signal-like) obtained using the sPlot technique [65]. Based on the kinematics of each J/ψ meson in the p_{T} and rapidity plane, the ϵ^i values are calculated from a 2D efficiency map obtained from the simulated signal. At central rapidities ($|y| < 1$), the efficiency is approximately constant at $\approx$90%, decreasing towards higher rapidities. The p_{T} dependence of ϵ^i features a fast rise at low p_{T}, becoming unity at $p_{\text{T}} \approx 15$ GeV. Any mismatches on the reconstruction and trigger efficiency observed between the MC simulation and the measured data are corrected by applying the scale factors described in Ref. [44]. The double-J/ψ efficiency is $\epsilon = 62.1\%$, consistent with the squared single-J/ψ efficiency, as expected, given that it is driven by the kinematics of the two individual J/ψ mesons.

The systematic uncertainties in the cross section determined with Eq. (5) are listed in Table III. The dependence of the measured cross section on the modeling of the J/ψ meson signal and background subtraction is examined by replacing the Crystal Ball pdf of the nominal model by a Crystal-Ball-plus-Gaussian function, as well as the exponential background by a first-order polynomial distribution. The differences observed in the signal yields are 4.0 and 2.5%, for the variations of the signal and background pdfs,

TABLE III. Relative contributions to the systematic uncertainty in the $\sigma(p\text{Pb} \to J/\psi J/\psi + X)$ measurement. The last row lists the sum in quadrature of all components.

Source of uncertainty	$\sigma(p\text{Pb} \to J/\psi J/\psi + X)$ (%)
J/ψ meson signal shape	4.0
Dimuon continuum background shape	2.5
Integrated luminosity	3.5
Efficiency scale factors	1.3
Branching fraction	1.1
Total	6.1

respectively. Releasing the constraint of the J/ψ signal mean and width parameters from the MC simulation results in a negligible difference (0.1%) and is not considered as a source of systematic uncertainty. A 3.5% uncertainty is added from the integrated luminosity measurement [66,67]. The uncertainty in the scale factors applied to the MC simulation to correct for possible data/MC differences amounts to 1.3%. Finally, the uncertainty of $\mathcal{B}_{J/\psi\to\mu^+\mu^-}$ propagates into an uncertainty of 1.1% in the cross section measurement.

The resulting fiducial cross section is $\sigma(p\mathrm{Pb}\to J/\psi J/\psi) = 22.0\pm8.9(\mathrm{stat})\pm1.5(\mathrm{syst})\,\mathrm{nb}$. Such a cross section contains in principle contributions from the SPS and DPS production channels shown in Fig. 1. Namely, the result is $\sigma(p\mathrm{Pb}\to J/\psi J/\psi + X) = \sigma_{\mathrm{SPS}}^{p\mathrm{Pb}\to J/\psi J/\psi+X} + \sigma_{\mathrm{DPS}}^{p\mathrm{Pb}\to J/\psi J/\psi+X}$, and the size of each contribution is estimated from theoretical calculations (matched to existing LHC experimental J/ψ data) and the measured double J/ψ meson differential distributions, as explained in the next section.

VI. DISCUSSION

In the simplest factorized approach represented by Eq. (1), the DPS double J/ψ meson cross section can be derived from the squared single J/ψ meson cross section divided by σ_{eff}. The single-J/ψ cross sections in pPb and pp collisions are well understood both experimentally and theoretically thanks to multiple measurements and calculations that agree with each other within less than 10% [7]. We use here the perturbative QCD calculation at next-to-leading order (NLO) accuracy from HELAC-Onia [68,69] using the CT14NLO PDF [70] for the proton and the EPPS16 nPDF for the Pb nucleus [71], reweighted as discussed in Refs. [72,73]. The predicted SPS cross section (Table IV, first row) is normalized so as to reproduce the inclusive J/ψ measurements in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV [74], and thus it does not have any theoretical scale uncertainties assigned but only a ≈6% data normalization uncertainty. The proton-nucleon (pN) cross section (obtained by dividing the pPb cross section by $A = 208$) within the fiducial requirements of Table I amounts to $\sigma_{\mathrm{SPS}}^{p\mathrm{Pb}\to J/\psi+X}\mathcal{B}(J/\psi\to\mu^+\mu^-)/A = 21.7\pm1.4(\mathrm{nPDF})\pm1.4(\mathrm{norm})$ nb, to be compared with the corresponding pp cross section of $\sigma_{\mathrm{SPS}}^{pp\to J/\psi+X}\mathcal{B}(J/\psi\to\mu^+\mu^-) = 25.0\pm1.8(\mathrm{PDF})$ nb, indicating a ≈10% reduction due to nPDF shadowing. The theoretical prediction for the prompt double J/ψ meson SPS cross section (Table IV, second row) is obtained using the color singlet model at approximately NLO accuracy [75,76] computed with HELAC-Onia using the CT14NLO proton PDF and the reweighted EPPS16 nPDF for the Pb nucleus. The double J/ψ meson SPS cross section in pN collisions within the fiducial phase space of Table I amounts to $\sigma_{\mathrm{SPS}}^{p\mathrm{Pb}\to J/\psi J/\psi+X}\mathcal{B}^2(J/\psi\to\mu^+\mu^-)/A = 0.097^{+0.185}_{-0.063}(\mathrm{scale})\pm0.004(\mathrm{nPDF})\,\mathrm{pb}$, to be compared with a pp cross section of $\sigma_{\mathrm{SPS}}^{pp\to J/\psi J/\psi+X}\mathcal{B}^2(J/\psi\to\mu^+\mu^-) = 0.105^{+0.200}_{-0.068}(\mathrm{scale})\pm0.004(\mathrm{PDF})$ pb, indicating about 8% nPDF shadowing corrections.

TABLE IV. Predictions for single and double J/ψ meson production cross sections in SPS processes in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV within the fiducial phase space of Table I, obtained with the HELAC-Onia code using the CT14NLO proton PDF and the reweighted EPPS16 lead nPDF, as explained in the text. The quoted uncertainty of the single (double) J/ψ meson cross section includes nPDF and normalization (nPDF and scale) uncertainties, added in quadrature.

Process	Theoretical cross section
$\sigma_{\mathrm{SPS}}^{p\mathrm{Pb}\to J/\psi+X}\mathcal{B}(J/\psi\to\mu^+\mu^-)$	4.51 ± 0.42 μb
$\sigma_{\mathrm{SPS}}^{p\mathrm{Pb}\to J/\psi J/\psi+X}\mathcal{B}^2(J/\psi\to\mu^+\mu^-)$	$20.2^{+38.5}_{-13.1}$ pb

The theoretical SPS single J/ψ meson cross section has an overall uncertainty of ±9%, and thus so will have the corresponding DPS cross section (for a given σ_{eff}). However, the SPS double J/ψ meson cross section is poorly constrained, and can vary within a +200%, −65% range [76]. Therefore, we use our own data in order to constrain the SPS and DPS contributions to the measured double-J/ψ cross section. The most discriminating variables to distinguish SPS from DPS processes are the separation in azimuth $\Delta\phi$ and rapidity Δy between the two produced particles [2]. The J/ψ mesons produced by DPS processes are expected to be completely decorrelated in their production and, thus, should feature flatter distributions in their relative azimuthal and rapidity separations (blue histograms in Fig. 4). On the other hand, the SPS mechanism leads to a correlated production of both J/ψ mesons that prefer to be produced closer in rapidity and with a small or a maximum separation in azimuthal angle. Theoretical expectations based on contributions from multiple SPS channels, computed up to $\mathcal{O}(\alpha_S^6)$ perturbative accuracy and cross-checked with existing data [76], indicate that the distributions of the two J/ψ mesons from SPS processes tend to have a rapidity separation peaked at $\Delta y = 0$ and maxima at $\Delta\phi \approx 0, \pi$ (Fig. 4).

Due to the limited size of our signal data sample, it is not possible to perform a 2D template fit of the measured $\Delta\phi - \Delta y$ distributions with shapes dictated by the theoretical expectations to extract the absolute normalization of the poorly known SPS double J/ψ meson yields. Instead, we identify a phase space region where the SPS contribution is expected to be minimal, and constrain there the expected size of the DPS yield. For this purpose, we use the predicted shape of the Δy distribution, which shows that the $\Delta y \gtrsim 2$ region is free from SPS contributions (red histogram in Fig. 4, left) and, therefore, any signal count measured there is dominated by DPS production.

To extract the number of DPS events, we perform a 1D fit to the Δy variable. Using a DPS template built by

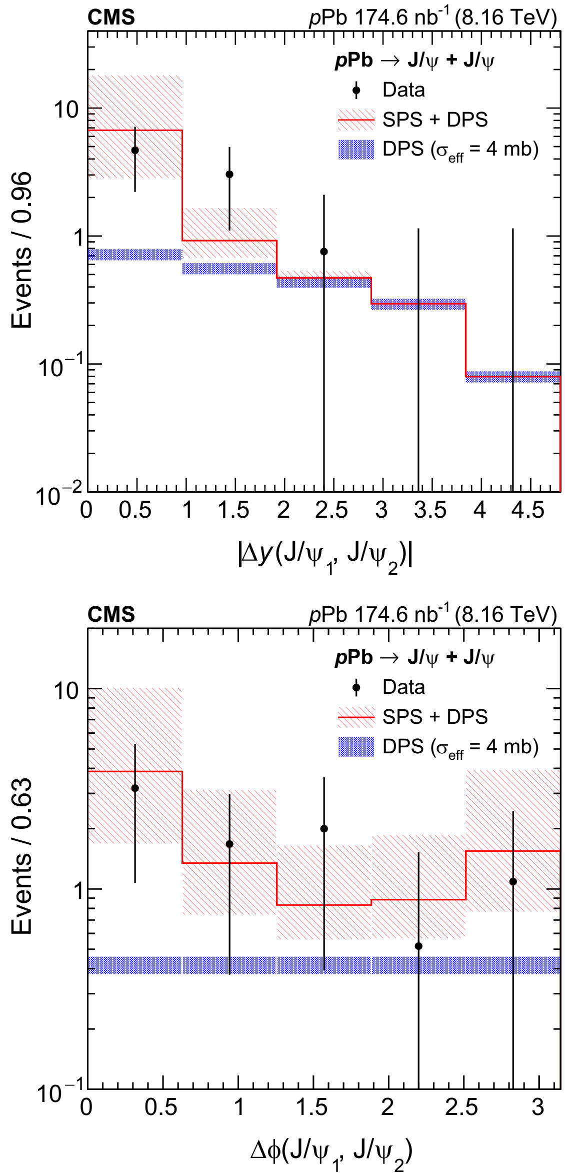

FIG. 4. Distribution of rapidity separation (top) between the two J/ψ mesons in data (black markers), fitted template of the expected DPS contribution (blue histogram) normalized to the data outside of the SPS-dominated region (as described in the text), and fitted SPS + DPS distribution (red histogram). Distribution of azimuthal separation (bottom) between the two J/ψ mesons measured in data (black markers) and expected DPS contribution (blue histogram), and SPS + DPS sum (red histogram), with the relative normalization derived from the Δy distribution (left panel), as explained in the text.

combining J/ψ mesons from different events, we fit the weighted data in the DPS dominated region of $\Delta y > 2$. The fit results in a yield of 2.1 DPS events and $\sigma_{\text{eff}} = 4.0$ mb, as explained in more detail below, shown as a blue histogram in Fig. 4. The left plot shows the fit result of the Δy distribution compared with the data (markers). We also overlay the combined SPS + DPS distribution shown with the red histogram (and hashed uncertainty bands in red). Figure 4 (right) shows the corresponding $\Delta\phi$ distribution, with the DPS and SPS + DPS distributions having the same normalization as in the left plot.

This fit procedure allows the extraction of the number of SPS and DPS signal counts: $N_{\text{SPS}} = 6.4 \pm 4.2$ and $N_{\text{DPS}} = 2.1 \pm 2.4$, respectively. The corresponding SPS and DPS fiducial cross sections, derived using Eq. (5), amount to $\sigma_{\text{SPS}}^{p\text{Pb}\to J/\psi J/\psi+X} = 16.5 \pm 10.8(\text{stat}) \pm 0.1(\text{syst})$ nb and $\sigma_{\text{DPS}}^{p\text{Pb}\to J/\psi J/\psi+X} = 5.4 \pm 6.2(\text{stat}) \pm 0.4(\text{syst})$ nb. From this latter value, we can extract the effective $\sigma_{\text{eff},p\text{Pb}}$ cross section via Eq. (3). Using the theoretical predictions (constrained by existing data) for $\sigma_{\text{SPS}}^{p\text{Pb}\to J/\psi+X}$ from Table IV, we obtain $\sigma_{\text{eff},p\text{Pb}} = 0.53^{+\infty}_{-0.2}$ b. The extracted $\sigma_{\text{eff},p\text{Pb}}$ value has an arbitrarily large upper uncertainty that indicates that the SPS yield alone would be compatible with the data.

By neglecting parton correlations, and assuming that the double PDF of the nucleons can be factorized in longitudinal and transverse components, the effective DPS cross section for pPb collisions can be converted into a pp equivalent σ_{eff} one, through Eq. (4). Using $A = 208$ for a Pb nucleus and a factor $F_{p\text{Pb}} = 29.5$ mb^{-1} derived from the pPb thickness function with a Glauber MC model, a value $\sigma_{\text{eff}} = 4.0^{+\infty}_{-1.5}$ mb is obtained, where the unbound upper uncertainty indicates that the double J/ψ meson yields could in principle be produced without DPS contributions. Therefore, the final result is better expressed as a limit on the maximum amount of DPS allowed by the data, which translates into a lower limit on the effective DPS cross section of $\sigma_{\text{eff}} > 1.0$ mb at 95% confidence level (CL).

In Fig. 5, the lower σ_{eff} bound determined in this work is compared with other extractions of the effective DPS cross section derived from double- and triple-quarkonium production measurements [12,12,14,14,15,15–17,37,77–80] (blue circles), as well as from processes with jets, photons, and W bosons [19,26,81–84] (black squares). A few of the quarkonium σ_{eff} values plotted (indicated with an asterisk in the legend) are those derived by more recent phenomenological studies [37,77,79,80] of the experimental data, with an improved evaluation of the SPS contributions. Overall, the effective cross sections obtained from multiquarkonium production favor a smaller value of $\sigma_{\text{eff}} \approx 3$–10 mb compared with the $\sigma_{\text{eff}} \approx 10$–20 mb result of the other types of multiple hard scattering processes. Our measurement of $\sigma_{\text{eff}} > 1.0$ mb at 95% CL calls for larger pPb datasets to confirm, or not, its consistency with the σ_{eff} values derived from pp data and, eventually, better constrain the average effective interparton distance squared (σ_{eff}) involved in the production of a pair of quarkonium mesons in hadronic collisions.

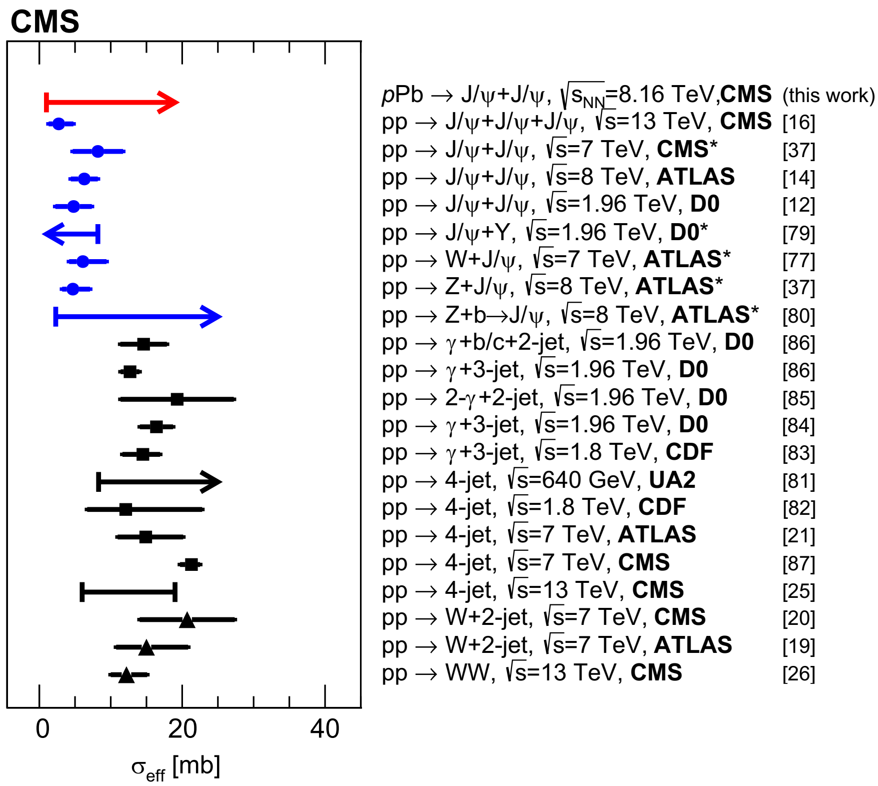

FIG. 5. Comparison of the effective DPS cross sections σ_{eff} extracted in this work (red arrow lower limit) with the same parameter derived in pp measurements of double- and triple-quarkonium production [12,14–16,37,77,79,80] (blue circles), as well as in final states with jets [81,82,85], γ + jets [83,84,86], W + jets [19,20], and double W bosons [26] (black squares). The asterisk shown in a few legend entries indicates that the result has been obtained by more recent phenomenological analyses of the experimental data.

VII. SUMMARY

The first observation of the concurrent production of two J/ψ mesons in proton-lead (pPb) collisions has been reported. Events with two J/ψ mesons, each decaying into two muons, have been reconstructed in pPb collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{\text{NN}}} = 8.16$ TeV. The data sample corresponds to an integrated luminosity of 174.6 nb^{-1} collected by the CMS experiment at the CERN LHC. After all selection requirements, 8.5 ± 3.4 events are found that confirm the production of the $J/\psi J/\psi + X$ final state. Events where the least energetic J/ψ meson is reconstructed in the dielectron channel are also considered in the search, leading to a signal yield of 5.7 ± 4.0 events. The statistical significance of the signal, relative to the background-only expectation, corresponds to 5.3 standard deviations (4.9 standard deviations in the four-muon channel alone). The fiducial cross section for $J/\psi J/\psi + X$ production is $\sigma(p\text{Pb} \to J/\psi J/\psi + X) = 22.0 \pm 8.9(\text{stat}) \pm 1.5(\text{syst})$ nb. This result is compared with the theoretical expectations for $J/\psi J/\psi + X$ production via the sum of contributions from single- and double-parton scatterings (SPS and DPS, respectively). Under the simplest assumption of factorization of multiple hard scattering probabilities in terms of SPS cross sections, the measured $J/\psi J/\psi + X$ cross section is consistent with the production of SPS + DPS processes with fiducial cross sections $\sigma_{\text{SPS}}^{p\text{Pb}\to J/\psi J/\psi + X} = 16.5 \pm 10.8(\text{stat}) \pm 0.1(\text{syst})$ nb and $\sigma_{\text{DPS}}^{p\text{Pb}\to J/\psi J/\psi + X} = 5.4 \pm 6.2(\text{stat}) \pm 0.4(\text{syst})$ nb. The derived DPS cross section can be transformed into a lower bound on the effective DPS cross section parameter (σ_{eff}) that is closely related to the squared average interparton transverse separation in the collision. A limit of $\sigma_{\text{eff}} > 1.0$ mb at 95% confidence level is set, which is consistent with σ_{eff} values obtained from double and triple quarkonium measurements in pp collisions. The present analysis supports the interest of exploiting the production of multiple heavy and/or high-p_{T} particles in pPb collisions at the LHC as a novel means to study the dynamics of multiple independent hard scatterings.

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