


## Fraction of $\chi_c$ Decays in Prompt $J/\psi$ Production Measured in $p\text{Pb}$ Collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV

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The fraction of  $\chi_{c1}$  and  $\chi_{c2}$  decays in the prompt  $J/\psi$  yield,  $F_{\chi_c \rightarrow J/\psi} = \sigma_{\chi_c \rightarrow J/\psi} / \sigma_{J/\psi}$ , is measured by the LHCb detector in  $p\text{Pb}$  collisions at  $\sqrt{s_{\text{NN}}} = 8.16$  TeV. The study covers the forward ( $1.5 < y^* < 4.0$ ) and backward ( $-5.0 < y^* < -2.5$ ) rapidity regions, where  $y^*$  is the  $J/\psi$  rapidity in the nucleon-nucleon center-of-mass system. Forward and backward rapidity samples correspond to integrated luminosities of  $13.6 \pm 0.3$  and  $20.8 \pm 0.5$  nb $^{-1}$ , respectively. The result is presented as a function of the  $J/\psi$  transverse momentum  $p_{\text{T},J/\psi}$  in the range  $1 < p_{\text{T},J/\psi} < 20$  GeV/ $c$ . The  $F_{\chi_c \rightarrow J/\psi}$  fraction at forward rapidity is compatible with the LHCb measurement performed in  $pp$  collisions at  $\sqrt{s} = 7$  TeV, whereas the result at backward rapidity is  $2.4\sigma$  larger than in the forward region for  $1 < p_{\text{T},J/\psi} < 3$  GeV/ $c$ . The increase of  $F_{\chi_c \rightarrow J/\psi}$  at low  $p_{\text{T},J/\psi}$  at backward rapidity is compatible with the suppression of the  $\psi(2S)$  contribution to the prompt  $J/\psi$  yield. The lack of in-medium dissociation of  $\chi_c$  states observed in this study sets an upper limit of 180 MeV on the free energy available in these  $p\text{Pb}$  collisions to dissociate or inhibit charmonium state formation.

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Heavy ion collisions in the relativistic regime provide an opportunity to release quarks and gluons from hadrons and form a hot and dense quark-gluon plasma (QGP), the same state of matter theorized to exist microseconds after the big bang and to compose the core of neutron stars [1]. While there are many indications of QGP formation in nucleus-nucleus collisions at RHIC and the LHC, its formation in small systems such as proton-nucleus collisions is not firmly established. The observation of collective particle flow in  $p\text{Pb}$  collisions at the LHC, and  $pA$  and  $dA$  collisions at RHIC, suggests the existence of QGP droplets in these collisions (see, for example, [2]), but a lack of other signatures prevents a conclusion. Quarkonium states have a broad range of binding energies [3] of the same order of magnitude as the freeze-out temperature, the minimum temperature needed to form a QGP [4–6]. The spectrum of quarkonium states that survive nucleus collisions is a powerful tool to determine the free energy and temperature reached by the initial stage of heavy ion collisions. However, a quarkonium state can also be broken by its interaction with comoving particles if the particle multiplicity is high enough, as observed in the nucleus-going direction in proton- and deuteron-nucleus collisions [7].

The nuclear modification factor, defined as the ratio between the particle yield per nucleon interaction measured in heavy ion and  $pp$  collisions, is the most commonly used observable to quantify nuclear effects. The spin-1 ground-state charmonium meson  $J/\psi$ , with a binding energy of 640 MeV, has a nuclear modification factor similar to the open charm meson  $D^0$  at forward and backward rapidity ranges in  $p\text{Pb}$  collisions [8]. This observation indicates that the nuclear modification factor observed in  $J/\psi$  yields in these collisions can be attributed solely to nuclear modification of parton densities before the formation of the  $c\bar{c}$  pair. The charmonium state  $\psi(2S)$ , with a binding energy of 50 MeV, has a suppression stronger than the  $J/\psi$  state at backward rapidity in  $p(d)A$  collisions at RHIC [9] and the LHC [10–12], indicating that this weakly bound state is also suppressed by final-state nuclear effects.

Additional constraints on the free local energy produced in  $pA$  collisions, which would dissociate or prevent charmonium state formation, can be provided by the  $\chi_{c1}$  and  $\chi_{c2}$  states. These have binding energies of 220 and 180 MeV, respectively. The  $P$ -wave charmonium states  $\chi_{cn}$  are mainly reconstructed from the radiative decay  $\chi_{cn} \rightarrow J/\psi\gamma$  with branching ratios 1.4%, 34%, and 19% for  $n = 0, 1$ , and 2 [13]. The production of  $\chi_{c0}$  mesons is rarely studied in this decay mode, due to its small branching ratio. Measurements of  $\chi_c$  production typically require high detection efficiency for low-energy photons, and effective discrimination against the overwhelming  $\pi^0$  decay sources producing large combinatorial backgrounds in the  $J/\psi\gamma$  mass distribution. For these reasons,  $\chi_c$  measurements in

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heavy ion collisions are rare. There are two  $\chi_c$  measurements in nucleus collisions: (i) HERA-B measured the fraction of  $\chi_c$  decays in  $J/\psi$  production in proton on C and W targets at  $\sqrt{s_{NN}} = 41.6$  GeV [14], showing no dependence on the target material and (ii) PHENIX measured the  $\chi_c/J/\psi$  fraction in  $d$ Au collisions at  $\sqrt{s_{NN}} = 200$  GeV [15], consistent with measurements in  $pp$  collisions at the same energy within the large statistical uncertainty. The identified  $\chi_{c1}$  and  $\chi_{c2}$  yields measured by the LHCb Collaboration in  $p$ Pb collisions at  $\sqrt{s_{NN}} = 8.16$  TeV are consistent [16], although with large uncertainties given the difficulty in resolving the mass peaks.

This Letter reports, for the first time at the LHC, the fraction  $F_{\chi_c \rightarrow J/\psi}$  of  $\chi_c \rightarrow (J/\psi \rightarrow \mu^+\mu^-)\gamma$  decays in prompt  $J/\psi \rightarrow \mu^+\mu^-$  yields. The measurement is made in eight  $p_{T,J/\psi}$  ranges over  $1 < p_{T,J/\psi} < 20$  GeV/ $c$  in  $p$ Pb collisions at  $\sqrt{s_{NN}} = 8.16$  TeV at forward ( $1.5 < y^* < 4.0$ ) and backward ( $-5.0 < y^* < -2.5$ ) rapidities, where  $y^*$  is the  $J/\psi$  rapidity in the nucleon-nucleon center-of-mass system. Prompt  $J/\psi$  mesons are produced directly when  $c\bar{c}$  pairs form a bound state (direct production) or via decays of higher-mass charmonium states (feed-down contribution). The measured  $\chi_c$  yield is the sum of the  $\chi_{c1}$  and  $\chi_{c2}$  yields, which minimizes the uncertainties related to the separation of these states. The fraction  $F_{\chi_c \rightarrow J/\psi}$  is obtained by

$$F_{\chi_c \rightarrow J/\psi} \equiv \frac{\sigma_{\chi_c \rightarrow J/\psi\gamma}}{\sigma_{J/\psi}} = \frac{N_{\chi_c \rightarrow J/\psi\gamma}}{N_{J/\psi} \epsilon_{\chi_c/J/\psi}}, \quad (1)$$

where  $N_{\chi_c \rightarrow J/\psi\gamma}$  and  $N_{J/\psi}$  are the prompt  $\chi_c \rightarrow J/\psi\gamma$  and  $J/\psi$  yields, and  $\epsilon_{\chi_c/J/\psi}$  is the fraction of  $\chi_c \rightarrow J/\psi\gamma$  decays which are detected in the LHCb acceptance relative to the decays where only the  $J/\psi$  is detected. The contribution from  $B$  hadron decays is negligible after the selection of prompt  $J/\psi$  decays.

The LHCb detector is a single-arm forward spectrometer described in Refs. [17,18]. The silicon-strip vertex detector (VELO) surrounding the interaction region allows the determination of the position of the collision point, the primary vertex (PV). Charged particle tracks are determined by the combination of hits in the VELO, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes (OT) placed downstream of the magnet. Muons are identified by a system composed of alternating layers of iron and multi-wire proportional chambers behind electromagnetic and hadronic calorimeters. Photons are identified by the calorimeter system [19] consisting of a scintillating pad detector (SPD), a preshower system (PS), an electromagnetic (ECAL) calorimeter, and a hadronic (HCAL) calorimeter. The SPD and PS are designed to discriminate between signals from photons and electrons, while the ECAL and HCAL provide the energy measurement and

identification of photons and neutral hadrons. The relative energy resolution of the ECAL is  $8\%/\sqrt{E} + 0.9\%$ , where  $E$  is in GeV.

This analysis is based on data acquired during the 2016 LHC heavy-ion run, where the LHCb experiment recorded proton and  $^{208}\text{Pb}$  ion collisions at a center-of-mass energy per nucleon pair of  $\sqrt{s_{NN}} = 8.16$  TeV. The forward (positive) rapidity sample is collected in collisions where the proton follows the direction from the VELO to the muon detectors, namely,  $p$ Pb collisions, corresponding to an integrated luminosity of  $13.6 \pm 0.3$  nb $^{-1}$ . The backward (negative) rapidity sample is obtained with a reverse beam direction,  $\text{Pb}p$  collisions, with  $20.8 \pm 0.5$  nb $^{-1}$  integrated luminosity.

The on-line event selection used in this analysis is performed by a trigger system consisting of a hardware stage that selects events containing at least one muon candidate, and two software trigger stages in which events with two tracks identified as muons with  $p_T > 500$  MeV/ $c$  are selected. The muon pair is required to have an invariant mass within 150 MeV/ $c^2$  of the known  $J/\psi$  mass [13]. In the off-line selection, muons are identified by a neural network algorithm [18,20]. The muon also must satisfy the momentum requirements  $p_T > 600$  MeV/ $c$ ,  $p > 8$  GeV/ $c$ , and be in the LHCb pseudorapidity range  $2 < \eta < 5$ . The  $J/\psi$  candidate is selected by requiring the muon pair invariant mass to be within 80 MeV/ $c^2$  of its known mass and its transverse momentum  $p_{T,J/\psi}$  must be larger than 1 GeV/ $c$ . The  $J/\psi$  candidate must be consistent with originating from the collision point.

Photons are identified as isolated clusters in the ECAL. The cluster must not belong to a charged particle or a  $\pi^0$  decay with 80% confidence level as determined by neural network algorithms. The photon must be in the ECAL acceptance  $2 < \eta < 4.5$  and have transverse momentum  $p_{T,\gamma} > 400$  MeV/ $c$ .

The detector performance for the  $J/\psi$  and  $\chi_c$  signals are studied using simulated samples generated by PYTHIA [21] and embedded with events generated by EPOS [22], which accounts for the underlying event activity of  $p$ Pb collisions. Decays of short-lived particles are performed with the EvtGen decay package [23]. Radiative QED corrections to the decays containing charged particles in the final state are applied with the PHOTOS package [24]. The generated  $\chi_{c1}$  and  $\chi_{c2}$  decays are required to have both muons from the  $J/\psi$  decay in the LHCb acceptance. The response of the LHCb detector is modelled using GEANT4 [25]. Weights are assigned to the simulated events such that the VELO cluster multiplicity matches that of the data. The LHCb detection efficiency correction  $\epsilon_{\chi_c/J/\psi}$  is obtained from the simulated  $\chi_c$  sample using Eq. (1), where  $F_{\chi_c \rightarrow J/\psi} = 1$  by definition.

The selected sample is overwhelmingly composed of combinatorial background (CBG). The remaining components are correlated background, also called physics background, and the signal  $\chi_c$  decays. This analysis uses the invariant mass difference  $\Delta M = M_{\mu^+\mu^-\gamma} - M_{\mu^+\mu^-}$  for

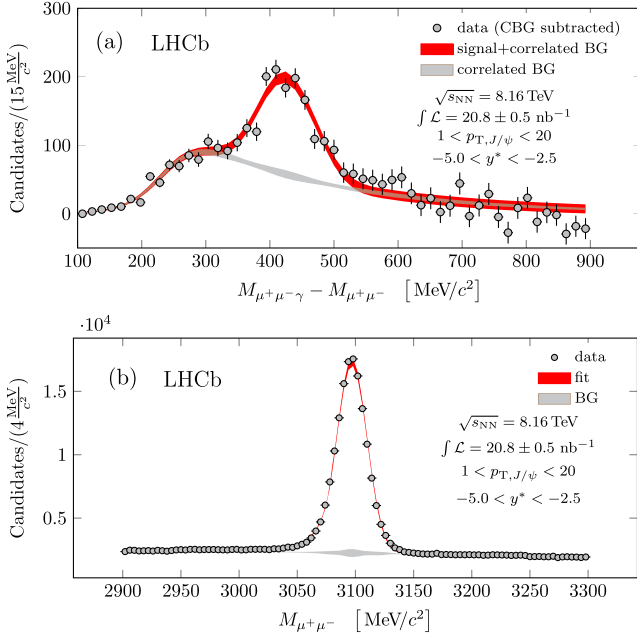


FIG. 1. (a) Difference in the invariant mass of the  $\mu^+\mu^-\gamma$  and  $\mu^+\mu^-$  combinations in the  $\chi_c$  region. Here the fitted combinatorial background component has been subtracted from both the data points and the fitted curve. The gray band represents the correlated physics background component and the red band is the sum of the signal and correlated physics background components. The widths of the bands represent 68% C.L. (b) Invariant mass distribution of  $\mu^+\mu^-$  pairs in the  $J/\psi$  mass region along with the fitted function.

fitting, minimizing the impact of the muon pair mass resolution. The shape of the combinatorial background distribution,  $Y_{\text{CBG}}(\Delta M)$ , is determined by mixing  $J/\psi$  decays and photons from different events. The two events must have similar track multiplicities and collision vertex positions. The overall combinatorial background yield  $N_{\text{CBG}}$  is determined by normalizing the CBG shape  $Y_{\text{CBG}}$  to have the same integral as the default sample in the mass region  $700 < \Delta M < 900 \text{ MeV}/c^2$ , where the signal and the correlated background are expected to be negligible. Figure 1(a) shows the  $\Delta M$  distribution after the combinatorial background subtraction.

The correlated background is composed of radiative  $J/\psi$  decays ( $J/\psi \rightarrow \mu^+\mu^-\gamma$ ) and partially reconstructed  $\psi(2S) \rightarrow J/\psi\pi^0\pi^0 \rightarrow \mu^+\mu^-\gamma$  decays which are studied using simulated samples. The partially reconstructed  $\psi(2S)$  contribution is 8 (30) times smaller than the  $J/\psi$  radiative decay at high (low)  $p_{T,J/\psi}$  when considering its measured yield relative to  $J/\psi$  decays [12] and the branching ratio  $\mathcal{B}[\psi(2S) \rightarrow J/\psi\pi^0\pi^0]$  [13]. The  $\Delta M$  distribution accounting for the total correlated background is described by

$$Y_{\text{corr}}(\Delta M) = \frac{A_{\text{corr}} e^{B \cdot \Delta M}}{1 + e^{\frac{\Delta M - \Delta M_0}{\sigma_{\Delta M_b}}}}, \quad (2)$$

with  $p_{T,\gamma}$ -dependent parameters  $B$ ,  $\Delta M_0$ , and  $\sigma_{\Delta M_b}$  initially determined from the simulation and  $A_{\text{corr}}$  is its normalization. The two  $\chi_c$  states are described by the sum of two Gaussian functions,  $G$ , with a common resolution term as

$$Y_{\chi_c}(\Delta M) = f_{\chi_{c1}} G(\Delta M; \Delta M_{\chi_{c1}}, \sigma_{\Delta M}) + (1 - f_{\chi_{c1}}) \times G(\Delta M; \Delta M_{\chi_{c1}} + \Delta M_{1,2}, \sigma_{\Delta M}), \quad (3)$$

where  $0.4 < f_{\chi_{c1}} < 0.6$  is the contribution of the  $\chi_{c1}$  decay to the total  $\chi_c$  yield as obtained in Ref. [16],  $\Delta M_{\chi_{c1}} = M_{\chi_{c1}} - M_{J/\psi}$  is the free parameter accounting for the mass difference of the  $\chi_{c1}$  state as measured by the detector,  $\Delta M_{1,2} = 45.5 \text{ MeV}/c^2$  is the known mass difference between the  $\chi_{c1}$  and  $\chi_{c2}$  states [13]. The total shape of the  $\Delta M$  distribution accounting for the  $\chi_c$  signal and background is given by

$$Y_{\mu^+\mu^-\gamma}(\Delta M) = N_{\text{CBG}} Y_{\text{CBG}}(\Delta M) + N_{\text{corr}} Y_{\text{corr}}(\Delta M) + N_{\chi_c \rightarrow J/\psi\gamma} Y_{\chi_c}(\Delta M), \quad (4)$$

where  $N_{\text{corr}}$  is the yield of the correlated background. The signal yields are obtained with a maximum-likelihood fit to Eq. (4) to the  $\Delta M$  distributions, including combinatorial background, with the initial parameters determined from simulation. The total  $\chi_c$  yields, integrated over  $p_{T,J/\psi}$ , are  $(11.8 \pm 0.6) \times 10^3$  and  $(15.2 \pm 0.8) \times 10^3$  in the forward and backward rapidity samples, respectively. The  $\chi_c$  yields are independently obtained in eight  $p_{T,J/\psi}$  ranges and are stable with Gaussian variation of the initial parameters determined from simulation. Figure 1(a) shows the  $\Delta M$  distribution, integrated over  $p_{T,J/\psi}$ , with the fit results overlaid. The fit for each  $p_{T,J/\psi}$  range is shown in Ref. [26].

The  $J/\psi$  yield is determined in eight  $p_{T,J/\psi}$  ranges using a maximum-likelihood fit to the  $\mu\mu$  invariant mass distribution. The fitting function is defined by the sum of a Crystal Ball function,  $\text{CB}_{\text{pdf}}$ , [27] for signal and an exponential function for background

$$Y_{\mu^+\mu^-}(M) = A e^{bM} + N_{J/\psi} \text{CB}_{\text{pdf}}(M; M_{J/\psi}, \sigma_M, \alpha, n) \quad (5)$$

to the  $\mu^+\mu^-$  invariant mass distribution using the log-likelihood method. The parameters  $A$  and  $b$  define the scale and slope of the exponential components. The parameters  $\alpha$  and  $n$  are determined from a  $p_{T,J/\psi}$ -integrated fit and fixed for the fits in different  $p_{T,J/\psi}$  ranges. The parameter  $M_{J/\psi}$  is fixed to the known value of the  $J/\psi$  mass [13]. The  $p_{T,J/\psi}$ -integrated  $\mu^+\mu^-$  distribution and the results of the fit are shown in Fig. 1(b). The distributions for each  $p_{T,J/\psi}$  range is shown in Ref. [26].

Variation of the initial parameters when fitting the  $\Delta M$  distribution and the fixed mass resolution parameter  $\Delta\sigma_M$  cause the largest systematic uncertainties on the  $\chi_c$  yields, mostly for the lowest  $p_{T,J/\psi}$  interval. These variations

account for potential multiple local minima in the log-likelihood function used in the fits. Any deviation from the Gaussian shape assumption for the  $\chi_c$  peaks is tested by comparing the yields obtained by fitting Eq. (4) and from the integral over  $300 < \Delta M < 600$  MeV/ $c^2$  after subtracting the fitted background contributions  $Y_{\text{CBG}} + Y_{\text{cont}}$ . The difference between the yield obtained from the fit and the integral is assigned as a systematic uncertainty on the yield. The statistical uncertainties associated to the mixed  $J/\psi$  and  $\gamma$  event samples are negligible. However, variations on the mass range used to normalize the mixed event distribution  $Y_{\text{CBG}}$  contribute to the uncertainty in the  $\chi_c$  yields. The only significant uncertainty in the  $J/\psi$  yield determination comes from the difference between the result obtained from the mass peak fitting and the integral over the  $J/\psi$  peak region after subtracting the background component.

The photon detection efficiency is the main contribution to the factor  $\varepsilon_{\chi_c/J/\psi}$ . A validation of the photon detection efficiency  $\varepsilon_\gamma$  is performed by studying partially reconstructed  $\eta$  decays in data and simulation. Clear peaks are observed in the  $\pi^+\pi^-\gamma$  invariant mass distribution (well separated from the fully reconstructed  $\eta \rightarrow \pi^+\pi^-\gamma$  peak) and the  $\pi^+\pi^-$  mass distribution coming from  $\eta \rightarrow \pi^+\pi^-(\pi^0 \rightarrow \gamma\gamma)$  and  $\eta \rightarrow \pi^+\pi^-(\pi^0 \rightarrow \not{\gamma}\not{\gamma})$  decays, where  $\not{\gamma}$  is a missing photon. The detection efficiency in  $\eta$  decays is measured in data and simulation by

$$\varepsilon_\gamma(p_{T,\gamma}) = \frac{N_{\eta \rightarrow \pi^+\pi^-(\pi^0 \rightarrow \gamma\gamma)}(p_{T,\gamma})}{\mathcal{M}_{\gamma(\pi\pi)} N_{\eta \rightarrow \pi^+\pi^-(\pi^0 \rightarrow \not{\gamma}\not{\gamma})}(p_{T,\pi^+\pi^-})}, \quad (6)$$

where  $\mathcal{M}_{\gamma(\pi\pi)}$  is a matrix, obtained from simulation, that unfolds the  $p_{T,\gamma}$  distribution from  $\eta \rightarrow \pi^+\pi^-(\pi^0 \rightarrow \not{\gamma}\not{\gamma})$  decays as a function of  $p_{T,\pi^+\pi^-}$ . The efficiencies measured in data and simulation are consistent within 3% in the photon  $p_T$  range  $400 < p_{T,\gamma} < 5000$  MeV/ $c$ . Initial-state effects in the nucleus on the input kinematics are accounted for in simulation by weighting events according to the nuclear parton density function EPPS21 [28].

All the measurements assume  $\chi_c$  production with zero polarization. The effects of a potential  $\chi_c$  polarization on the detector efficiency are studied by weighting the simulated events according to different polarization scenarios as reported in Ref. [29]. The measured  $J/\psi$  polarization by LHCb [30] and the observation that either  $\chi_{c1}$  or  $\chi_{c2}$  states is strongly polarized by the CMS Collaboration [31] poses constraints to the scenarios adopted when weighting simulated events. The standard deviation of the  $F_{\chi_c \rightarrow J/\psi}$  values after polarization weighting is taken as the systematic uncertainty.

Any potential  $B$ -meson decay contamination of the prompt  $J/\psi$  yield is checked by tightening the collision point and  $\chi_c$  vertex association requirement, and the results are consistent with the default selection within the

TABLE I. Systematic uncertainty sources and maximum individual contributions.

Source	$1.5 < y^* < 4.0$	$-5.0 < y^* < -2.5$
Fit parameter initial values	<0.050	<0.058
Shape of $\chi_c$	<0.056	<0.110
Shape of $J/\psi$	<0.002	<0.002
Mixed event normalization	<0.03	<0.010
Kinematic input in simulation	<0.012	<0.018
Photon efficiency	<0.030	<0.030
Polarization of $\chi_c$	<0.031	<0.050

statistical uncertainties. Table I summarizes the maximum systematic uncertainty contributions. The largest uncertainties are found at the lowest  $p_{T,J/\psi}$  range. The total systematic uncertainty corresponds to the standard deviation of the  $F_{\chi_c \rightarrow J/\psi}$  results obtained from the different systematic uncertainty sources.

The  $p_{T,J/\psi}$ -dependent values of  $F_{\chi_c \rightarrow J/\psi}$  are shown in Fig. 2. The numerical results are shown in Ref. [26]. The points are located at the mean  $p_{T,J/\psi}$  of each bin determined by a fit to the prompt  $J/\psi$  differential cross-section reported by the LHCb Collaboration in Ref. [32]. The new results are compared with those obtained in  $pp$  collisions at  $\sqrt{s} = 7$  TeV [29]. The  $F_{\chi_c \rightarrow J/\psi}$  results obtained in  $p\text{Pb}$  and in  $pp$  collisions have an overall consistency. The fraction is slightly larger in the backward rapidity region for  $p_{T,J/\psi} < 3$  GeV/ $c$ . The result is also consistent with results obtained by the HERA-B experiment in  $p\text{C}$  and  $p\text{W}$  collisions at  $\sqrt{s_{\text{NN}}} = 41.6$  GeV [14]. The HERA-B result covers a rapidity range  $-5.2 < y^* < -2.2$  and  $p_{T,J/\psi} < 2$  GeV/ $c$ . A measurement of  $F_{\chi_c \rightarrow J/\psi}$  was performed by the PHENIX Collaboration in  $d\text{Au}$  collisions at  $\sqrt{s_{\text{NN}}} = 200$  GeV [15], covering the midrapidity range (Center-of-mass and laboratory rapidities are the same in

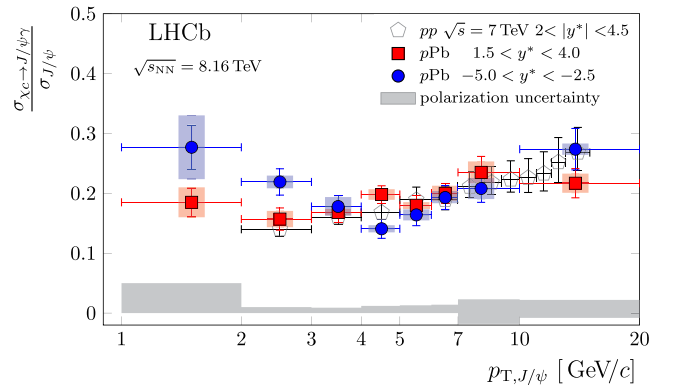


FIG. 2. Fraction of  $\chi_c$  decays in the prompt  $J/\psi$  yield in  $p\text{Pb}$  and  $pp$  collisions [29] as a function of  $p_{T,J/\psi}$ . The error bars show the statistical uncertainties. Boxes represent systematic uncertainties and the gray band represents the maximum uncertainties from  $\chi_c$  and  $J/\psi$  polarization effects.

TABLE II.  $F_{\chi_c \rightarrow J/\psi}$  results for wide  $p_{T,J/\psi}$  bins. The two uncertainties are statistical and systematic, respectively.

$\{p_T/[GeV/c]\}$	$\{\langle p_T \rangle/[GeV/c]\}$	$1.5 < y^* < 4.0$	$-5.0 < y^* < -2.5$
1–3	1.9	$0.164 \pm 0.016 \pm 0.015$	$0.253 \pm 0.019 \pm 0.022$
2–20	3.9	$0.179 \pm 0.008 \pm 0.006$	$0.210 \pm 0.013 \pm 0.007$
3–20	5.0	$0.187 \pm 0.008 \pm 0.006$	$0.170 \pm 0.013 \pm 0.008$
1–20	3.2	$0.174 \pm 0.009 \pm 0.010$	$0.222 \pm 0.013 \pm 0.010$

TABLE III. Description of the double ratio measurements shown in Fig. 3.

Ratio	Reference	$y^*$	$\sqrt{s_{NN}}$	$p_T$
$[\psi(2S)/(J/\psi)]$	[12]	$[-5.0, -2.5]$	8.16 TeV	$< 14$ GeV/c
$[\chi_c/(J/\psi)]$	This Letter	$[-5.0, -2.5]$	8.16 TeV	$2 < p_{T,J/\psi} < 20$ GeV/c
$[(J/\psi)/D^0]$	[8]	$[-4.0, -2.5]$	5 TeV	$< 10$ GeV/c
$\{[\Upsilon(3S), \Upsilon(2S)]/\Upsilon(1S)\}$	[35]	$[-4.5, -2.5]$	8.16 TeV	$< 25$ GeV/c
$[\Upsilon(1S)/(B \rightarrow J/\psi)]$	[35]	$[-4.5, -2.5]$	8.16 TeV	$< 25$ GeV/c

the PHENIX measurement.)  $|y^*| < 0.5$  and integrated over  $p_{T,J/\psi}$ , and is consistent with the  $p_{T,J/\psi} < 2$  GeV/c result presented here, though the PHENIX measurement has large statistical uncertainties. The comparison with HERA-B and PHENIX is shown in Ref. [26].

The difference between the backward and forward rapidity results at low  $p_{T,J/\psi}$  is further investigated by redoing the measurements using wide  $p_{T,J/\psi}$  bins to reduce statistical and systematic uncertainties. Table II indicates that the fraction  $F_{\chi_c \rightarrow J/\psi}$  at  $p_{T,J/\psi} < 3$  GeV/c is  $2.4\sigma$  larger at backward than at forward rapidity. This apparent increase can be attributed to the suppression of  $\psi(2S)$  and other feed-down sources to the prompt  $J/\psi$  yield  $\sigma_{J/\psi}$  in Eq. (1). The fraction of  $\psi(2S)$  contribution to the prompt  $J/\psi$  yield is  $(\sigma_{\psi(2S)}/\sigma_{J/\psi})\mathcal{B}(\psi(2S) \rightarrow J/\psi + X) = 0.080 \pm 0.011$  according to the cross section measured by the LHCb Collaboration in  $pp$  collisions at  $\sqrt{s} = 7$  TeV [33,34] and the branching ratio from Ref. [13]. The  $\sigma_{\psi(2S)}/\sigma_{J/\psi}$  ratio is reduced between  $pPb$  collisions at backward rapidity when compared to  $pp$  results [9–12], consistent with  $F_{\chi_c \rightarrow J/\psi}$  being larger at backward rapidity.

The  $F_{\chi_c \rightarrow J/\psi}$  result in  $pPb$  collisions suggests that neither  $J/\psi$  mesons, produced directly in the collisions, nor  $\chi_c$  states are dissociated in the medium formed in  $pPb$  collisions, consistent with the similar nuclear modification factor measurement of  $J/\psi$  and  $D^0$  yields in  $pPb$  collisions [8]. The nondissociation of the  $\chi_c$  states leads to a constraint on the free energy (or temperature) of the system to be no larger than 180 MeV in  $pPb$  collisions, based on the smallest binding energy among the  $\chi_c$  states. This maximum temperature is close to the estimated freeze-out temperature in  $pPb$  collisions, which ranges between 155–160 MeV [4–6]. The result presented here is integrated over collision centrality. Future studies selecting central events could be more sensitive to a short-lived hot medium in  $pPb$  collisions.

The most common method to quantify quarkonium dissociation in medium is the use of the quarkonium state yield ratios  $r$  relative to their corresponding ground state  $J/\psi$  for  $c\bar{c}$  and  $\Upsilon(1S)$  for  $b\bar{b}$  or to an open heavy flavor meson ( $D^0$  and  $B^+$  for  $c\bar{c}$  and  $b\bar{b}$ , respectively). The double ratio  $\mathcal{R} = r_{pPb}/r_{pp}$  compares the  $r$  values between  $pp$  and  $pPb$  collisions. It is obtained for  $\chi_c$  states from the  $2 < p_{T,J/\psi} < 20$  GeV/c integrated result presented in Table II and a weighted average of the  $pp$  results presented in Ref. [29]. The double ratio  $\mathcal{R}(\chi_c)$  is  $1.10 \pm 0.12$  at forward rapidity and  $1.29 \pm 0.17$  at backward rapidity. Figure 3 shows the binding-energy dependence of  $\mathcal{R}$  for all quarkonium states measured by the LHCb experiment in  $pPb$  collisions at backward rapidity, where  $pPb$  collisions achieve the highest particle multiplicities. The only dissociated ( $\mathcal{R} < 1$ ) quarkonium state with binding energy above the freeze-out temperature is the  $\Upsilon(3S)$ . With a similar binding energy and size as the  $\chi_c$  states, according to nonrelativistic potential theory [3], the  $\Upsilon(3S)$  resonance

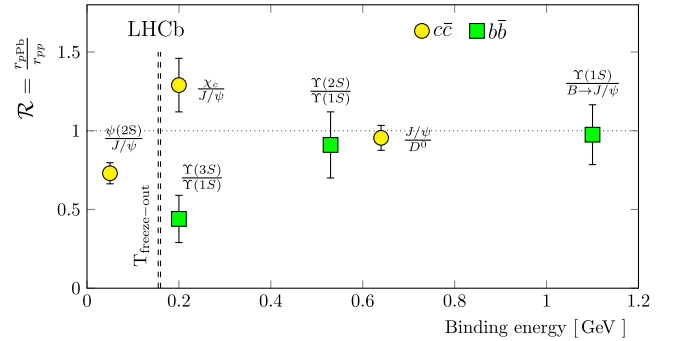


FIG. 3. Double ratio of the quarkonium state yield relative to its ground state or open heavy quark meson in  $pPb$  to  $pp$  collisions vs the binding energy of the given quarkonium state. The estimated freeze-out temperature in  $pPb$  collisions [4–6] is indicated. The details of the measurement for each data point in the figure are given in Table III.

is 2.9 times heavier and may travel the medium slower than the  $\chi_c$  states favoring its dissociation by its interaction with comoving particles [7].

In summary, this Letter presents the first LHC measurement of the fraction of  $\chi_c$  decays in the prompt  $J/\psi$  yield in heavy ion collisions. The ratio measured in  $p$ Pb collisions is consistent with no dissociation of  $\chi_c$  states, indicating that the average free energy available in these collisions is not able to inhibit the formation of quarkonium states with binding energy equal or larger than 180 MeV. Such an energy is only 20–25 MeV larger than the expected freeze-out temperature estimated in these systems.

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