

Production cross sections of charm-beauty mesons in proton-nucleus and nucleus-nucleus collisions at the LHC

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In this work, we calculate the production cross sections of the 1S and 1P states of the B_c meson for proton-nucleus and nucleus-nucleus colliding beam experiments at LHC and RHIC. We provide estimates for the Au nucleus at RHIC energies and for the Pb and Xe nuclei at LHC energies. Previous estimates of these cross sections have ignored quark antiquark annihilation diagrams and are confined to S states for Pb and Au nuclei. The cross sections of the P states are also equally important as these states lie below the BD threshold and cascade into B_c ground states with 100% probability. In addition to calculating the p_T , rapidity, and pseudorapidity distributions of the cross sections, we also determine the nuclear modification factors R_{pA} and R_{AA} for $A = \text{Pb, Xe, and Au}$. The results provide a baseline for the upcoming experimental studies of B_c mesons in pp, pA, and AA collisions in RUN III of LHC and could help develop experimental strategies for identification of hitherto undiscovered states of the B_c meson.

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I. INTRODUCTION

The charm-beauty meson (B_c) is a mixed bound state of heavy charm and bottom quarks. It was first discovered in 1998 by the CDF Collaboration at Tevatron (Fermilab, USA) through its semileptonic decay $B_c \rightarrow J/\psi l \nu_l$ [1]. CDF measured its mass as $6.40 \pm 0.39 \pm 0.13$ GeV and its lifetime as $0.46^{+0.18}_{-0.16} \pm 0.03$ ps. Later, it was produced by the D0 Collaboration [2] at Tevatron and LHCb experiment [3] at LHC (Large Hadron Collider) in CERN. Its current averaged mass and lifetime, as reported in PDG (Particle Data Group) [4], are 6.275 ± 0.8 GeV and 0.510 ± 0.009 ps respectively. Recently, the 2S state of the B_c meson was discovered by the ATLAS experiment in LHC by its strong decay $B_c(2S) \rightarrow J/\psi \pi$ [5]. Its measured mass was $6.842 \pm 4 \pm 5$ GeV. This discovery was later confirmed by the CMS [6] and LHCb [7] experiments. Nevertheless, further measurements of the lifetime and branching ratios of its decay modes are still required, although some decay events have been observed.

Being the only heavy quark meson carrying mixed quark flavors, it provides unique conditions to study the dynamics of the heavy quarks. Unlike other heavy quark mesons (charmonia and bottomonia), charm-beauty mesons, below the BD threshold (≈ 7.144 GeV), cannot disintegrate

through strong decays [8]. Consequently, they are more stable and relatively easy to study. There are at least two to three S states, two P states, one D state, and possibly one F state of B_c lying below the threshold of opening strong decays [8,9]. These excited states cascade through radiative and hadronic transitions to the B_c ground state (1^1S_0), which finally decays through the weak interaction. The decay chains of the excited B_c provide us with unique signatures for their identification and reconstruction in the experimental studies. The cleanest and most widely used decay channel to detect the B_c ground state is $B_c^\pm \rightarrow J/\psi \pi^\pm \rightarrow (\mu^+ \mu^-) \pi^\pm$, having a combined branching ratio of 0.013% and a detection efficiency of about 2% [8,10]. The $B_c(1^3S_1)$ decays into $B_c(1^1S_0)\gamma$ through the electromagnetic transition. However, the emitted soft photon of energy $E_\gamma \sim 60$ MeV escapes detection. This issue is not expected to be resolved at LHC RUN III, so direct detection of $B_c(1^3S_1)$ would remain a challenge; instead, it gives a feed-down contribution to the B_c ground state. The spin singlet (1^1P_1) and triplet ($1^3P_{J=0,1,2}$) states decay to $B_c(1^1S_0)\gamma$ and $B_c(1^3S_1)\gamma$, respectively. Since the physical states $1P_1$ and $1P_1'$ are mixed with the 1^1P_1 and 1^3P_1 states, both can decay into 1^1S_0 and 1^3S_1 states. Thus, four 1P states cascade to the B_c ground state through six decay chains. The energy of the emitted photon in P to S transition is expected to be ~ 400 MeV and can easily be resolved in LHC. However, the soft photon produced through subsequent decay of $B_c(1^3S_1)$ remains undetectable. So, if we reconstruct 1P states through the invariant mass of $B_c(1^1S_0)\gamma$, we expect six overlapping peaks in which four are displaced due to missing soft photon energy. Therefore,

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to accurately map the peaks to the corresponding six decay chains, we are required to estimate the corresponding number of events using the knowledge of the production cross sections of the 1P states. Recently, LHCb has observed 1P states as a broad structure peak using combined data of RUN I and II corresponding to integral luminosity of 9 fb^{-1} [11]. RUN III is expected to give additional data of 20-25 fb^{-1} for LHCb, and with slightly improved energy resolution, we expect that it would help in resolving peaks corresponding to the 1P states and providing accurate measurements of their production cross sections. Generally, RUN III's higher luminosity and improved detector performance across the board would significantly enhance the visibility of the 1P and other excited states below the BD threshold. For a comprehensive review on search strategies for the excited states of the B_c meson, we refer to Refs. [8,9]. It is, therefore, crucial to calculate the production cross sections of the excited states of the B_c meson to provide the estimates for the corresponding numbers of cascade events.

In this work, we calculate the production cross sections of the B_c states in pp (proton-proton), pA (proton-nucleus), and AA (nucleus-nucleus) collisions at the LHC and RHIC energies. The B_c production is particularly interesting in pA and AA collisions, where several other effects may significantly alter the estimates obtained from the hard production mechanism. The most widely anticipated effect of quark-gluon plasma (QGP), already very well studied for other heavy quark systems including charmonia [12–17] and bottomonia [18,19], is the suppression of heavy quarkonia. The color Debye screening during the QGP phase of the heavy-ion collisions can dissociate heavy quarkonia resulting in anomalous suppression in the observed production rates. This mechanism also predicts a pattern of sequential suppression in which the states of higher radii are affected before the smaller one. Remarkably, CMS Collaboration has recently measured this sequential suppression in radially excited states of Υ [20,21]. Owing to the unique nature of this effect, the observation could be regarded as robust evidence of QGP formation in LHC. Other than the effect of QGP, the observed yield of B_c depends on nuclear shadowing effect [22,23], energy loss of partons while passing through nuclear matter before involving in the hard process, dissociation of heavy-quark pairs $Q\bar{Q}$ while passing through nuclear matter, possible regeneration effect [24], and dissociation through inelastic interaction with light mesons in hadronic phase of heavy-ion collision [25]. Unlike pp collision, the production of B_c^+ can proceed through the combination of charm (c) and antibottom ($\bar{b}$) quarks produced in different nucleon-nucleon interactions of participation nucleons of colliding heavy-nuclei [24]. Moreover, this effect may also be boosted by the formation of QGP producing many unpaired charm and bottom quarks due to color Debye screening [24,26,27]. If B_c

production is significantly enhanced by the regeneration mechanism so that the total number of events is much larger than what we can possibly produce from pp collisions, then heavy-ion collision experiments can provide a new arena to complete the unfinished task of B_c spectroscopy in the coming days. As mentioned earlier, the observed B_c production may also be affected by its dissociation via inelastic interactions with comoving light mesons (π , ρ , etc.) in the hadronic phase. The exact amount of dissociation depends on the B_c hadronic cross sections that have been estimated in several studies [28,29]. A recent work of Ref. [25] indicates that suppression caused by this effect is small but not negligible.

A first step toward a thorough study of the B_c meson in heavy-ion collisions is to obtain estimates of its inclusive production cross sections. Theoretical studies of these production cross sections for hadronic colliders are very well established using fragmentation [30–33] and NRQCD approaches [34–38]; both using the QCD factorization theorem. However, the study of B_c production cross sections in relativistic heavy-ion collisions is still in the initial stages. Present estimates of B_c production cross sections in pA and AA collisions lack the inclusion of quark antiquark annihilation diagrams and calculations are confined to 1S states [39]. The knowledge of the cross sections of the 1P states is equally important because they lie below the BD threshold and cascade to the B_c ground state with 100% probability. In Ref. [39], the cross sections of 1S states are calculated at RHIC and LHC energies for Au and Pb targets, respectively. Since LHC has started collecting the data for p-Xe and Xe-Xe colliding beams as well, extending the theoretical estimates to Xe target is also important.

In this work, we reproduce and extend the work of Ref. [39]. We calculate the inclusive production cross section of both S and P states of B_c meson for pp, pA, and AA collisions at LHC and RHIC energies. At LHC energy, we calculate the cross sections for p-Pb, p-Xe, Pb-Pb, Xe-Xe collisions, and at RHIC energy we consider p-Au and Au-Au collisions. For pA and AA collisions, we use nuclear parton distribution functions, which include the effect of nuclear shadowing. To quantify the effect of nuclear shadowing in pA and AA collisions, we calculate the p_T and rapidity distributions of the nuclear modification factors of 1S and 1P states of B_c meson for pA and AA collisions. We anticipate that these results would provide a baseline for upcoming experimental studies of B_c in pp, pA, and AA collisions in RUN III of LHC.

The paper is organized as follows. In Sec. II, we cover the details of the methodology used to calculate the cross sections. In Sec. III, the values of the parameters used in computing the cross sections are discussed. In Sec. IV, we present the numerical results of cross section along with uncertainties, distributions of cross sections and nuclear modification factors. In Sec. V, we discuss the results and give concluding remarks.

II. METHODOLOGY

The most likely mechanism of producing a B_c^+ meson is via a hard process in which two pairs $b\bar{b}$ and $c\bar{c}$ are produced through interactions between the partons of the colliding hadrons. A B_c^+ meson emerges in the process when two collinear $\bar{b}$ and c quarks combine. By employing NRQCD factorization approach [40–42] along with the QCD factorization theorem as depicted schematically in Fig. 1, we can write the production cross section of a B_c^+ state as follows:

$$d\sigma_{(AB \rightarrow B_c^+ + X)} = N_A N_B \sum_{n,i,j} \int dx_1 dx_2 f_i^A(x_1, \mu_F) f_j^B(x_2, \mu_F) d\hat{\sigma}_{(ij \rightarrow c\bar{b}[n]X)} \langle \mathcal{O}_n^{B_c^+} \rangle, \quad (1)$$

where $d\hat{\sigma}_{(ij \rightarrow c\bar{b}[n]X)}$ is the perturbatively calculated partial cross section of producing $c\bar{b}$ pair in state with quantum numbers $n \equiv 2S+1 L_J^{(c)}$, where S , L , and J are spin, orbital and total angular momentum, respectively, and $c = 1, 8$ for color singlet and octet states, $\langle \mathcal{O}_n^{B_c^+} \rangle$ are long-distance-matrix elements (LDMEs) that describe the transition of perturbative $c\bar{b}[n]$ states to nonperturbative physical state of B_c^+ meson. In principle, the sum over n encompasses all possible perturbative states $c\bar{b}[n]$, requiring an infinite number of LDME's $\langle \mathcal{O}_n^{B_c^+} \rangle$ and corresponding short distance coefficients $d\hat{\sigma}_{(ij \rightarrow c\bar{b}[n]X)}$. However, velocity scaling rules [43] of NRQCD imply that only a finite number of contributions are required to get a result accurate up to a certain order in v and α_s , where v is the relative velocity of quark antiquark pair. For S physical states of B_c^+ only one $c\bar{b}[n]$ state contributes at the leading order in v in which n matches the quantum numbers of the physical state. Whereas, for P physical states two $c\bar{b}[n]$ states contribute at the leading order in v : one in which n matches the quantum number and the other is a color octet state $^1S_0^{(8)}$ or $^3S_1^{(8)}$ for $^1P_1^{(1)}$ and $^3P_J^{(1)}$ physical states respectively. The functions $f_i^A(x_1, \mu_F)$ and $f_j^B(x_2, \mu_F)$ are parton distribution functions (PDFs) of i and j partons in colliding particles A and B , where $A, B = p, Au, Pb, Xe$. For pp collisions

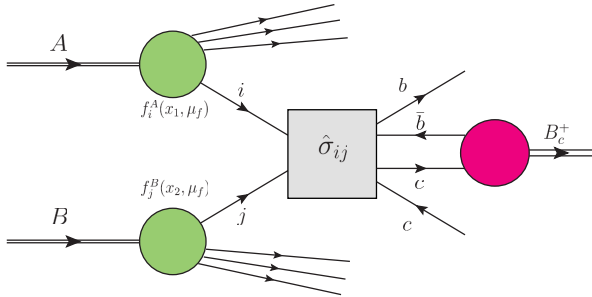


FIG. 1. Diagrammatic representation of production of B_c meson through partonic interaction $ij \rightarrow B_c X$ in a heavy-ion collision.

$N_A = N_B = 1$, for pA collisions $N_B = 1$ and N_A is the mass number of the nucleus A , and for AA collisions N_A and N_B are equal to mass numbers of A and B nuclei, respectively. It is noted that Eq. (1) gives minimum-bias (MB) value of the cross section. In case of pA and AA collisions we use nuclear PDFs incorporating the nuclear shadowing effect. We use a separate set of nCTEQ15 LO PDF [44] for Au, Pb, and Xe nuclei, respectively. For pp collisions, we use CTEQ6L1 PDF set [45]. The sum over i and j corresponds to the sum of all possible subprocesses in which $b\bar{b}$ and $c\bar{c}$ pairs are produced. However, at LO in α_s , only two subprocesses contribute.

$$g + g \rightarrow c\bar{b}[n] + \bar{c} + b \quad (2)$$

$$q + \bar{q} \rightarrow c\bar{b}[n] + \bar{c} + b \quad (3)$$

Corresponding to the gluon-gluon fusion process, we have 36 Feynman diagrams at leading order in α_s and 7 for the quark antiquark annihilation process. In this work, we have studied both subprocesses, though the dominant contribution comes from the gluon-gluon fusion process. At next-to-leading order (NLO), the Feynman diagrams enormously increase, making the computation extremely difficult. A study at NLO is under preparation by the authors.

III. INPUT PARAMETERS

At LHC, the collision energy for the proton-proton (pp) mode is $\sqrt{S_{pp}} = 13$ TeV, with each proton beam having an energy of 6.5 TeV. In the pA mode, the beam energy of the nucleus per nucleon is related to the proton energy by $E_N = \frac{Z}{N_A} E_p$. In case of AA mode, we use design values. The collision energies and corresponding beam energies at LHC and RHIC are summarized in Table I.

Most of the other input parameters are taken same as in Ref. [39]. We take heavy quark masses $m_c = 1.5$ GeV and $m_b = 4.9$ GeV. The mass of B_c is approximated by $m_c + m_b$. The renormalization and factorization scales are

TABLE I. Collision energies in cm frame and corresponding beam energies for different colliding modes. In case of pA mode, the energy of the nucleus per nucleon is fixed by $E_A = E_p Z/N_A$, whereas in case of AA mode, design value is used.

Colliding beams	Collision energy $\sqrt{S_{AB}}$ (TeV)	Beam energies $E_{A/B}$ (TeV)
pp	13	$E_p = 6.5$
pPb	8.16	$E_p = 6.5, E_{Pb} = 2.56$
PbPb	5.02	$E_{Pb} = 2.51$
pXe	8.3	$E_p = 6.5, E_{Xe} = 2.68$
XeXe	5.44	$E_{Xe} = 2.72$
pAu	0.2	$E_p = 0.150, E_{Au} = 0.07$
AuAu	0.2	$E_{Au} = 0.1$

TABLE II. Production cross sections of the 1S and 1P states of the B_c^+ meson at LHC energy $\sqrt{S} = 13$ TeV. The second and third columns contain our results for the cross sections via gluon fusion and $q\bar{q}$ annihilation, respectively. The fourth and fifth columns contain the corresponding values taken from Refs. [39,49], respectively.

State	$\sigma(pp \rightarrow B_c^+ X)$ nb (via gluon fusion)	$\sigma(pp \rightarrow B_c^+ X)$ nb (via $q\bar{q}$ annihilation)	$\sigma(pp \rightarrow B_c^+ X)$ nb [49] (via gluon fusion)	$\sigma(pp \rightarrow B_c^+ X)$ nb [39] (via gluon fusion)
1^1S_0	4.79×10^1	1.51×10^{-1}	3.56×10^1	4.24×10^1
1^3S_1	11.9×10^1	9.32×10^{-1}	8.85×10^1	10.5×10^1
1^1P_1	6.52×10^0	3.1×10^{-2}	4.92×10^0	...
1^3P_0	4.93×10^0	1.89×10^{-2}	3.23×10^0	...
1^3P_1	7.81×10^0	4.95×10^{-2}	5.27×10^0	...
1^3P_2	1.50×10^1	9.12×10^{-2}	1.18×10^1	...

taken same and set to $M_t = \sqrt{p_T^2 + M_{B_c}^2}$, where p_T is the transverse momentum of B_c . The strong coupling constant α_s is taken running. For isolated protons, we use CTEQ6L1 PDF set [45], whereas for Au, Pb, and Xe nuclei, we use nuclear PDF sets nCTEQ15LO [44]. To calculate the production cross sections of S and P states at the leading-order in v , we require the values of the following LDMEs:

$$\langle \mathcal{O}^{B_c^+} [1^1S_0^{(1)}] \rangle = \langle \mathcal{O}^{B_c^+} [3^1S_1^{(1)}] \rangle = \frac{|R(0)|^2}{4\pi}, \quad (4)$$

$$\begin{aligned} \langle \mathcal{O}^{B_c^+} [1^1P_1^{(1)}] \rangle &= \langle \mathcal{O}^{B_c^+} [3^1P_0^{(1)}] \rangle = \langle \mathcal{O}^{B_c^+} [3^1P_1^{(1)}] \rangle \\ &= \langle \mathcal{O}^{B_c^+} [3^1P_2^{(1)}] \rangle = \frac{3|R'(0)|^2}{4\pi}, \end{aligned} \quad (5)$$

where we have used heavy-quark spin symmetry to relate the matrix elements of spin-singlet and triplet states. Heavy quark spin symmetry is an approximate symmetry of NRQCD Lagrangian [42] which hold at leading order in v . The radial wave function and its derivative at origin can be obtained by applying nonrelativistic potential model. We also ignore small effects of hyperfine contact interaction producing spin-splitting and spin-orbit tensor interaction producing splitting in spin triplet P states. For 1S states, we take radial wave function at origin $|R(0)|^2 = 1.642 \text{ GeV}^3$ and for 1P states $|R'(0)|^2 = 0.201 \text{ GeV}^5$ [46–48]. Same values for 1S states are also applied in Ref. [39]. For color-octet matrix elements of S states, radial wave function at origin cannot be obtained from nonrelativistic potential model. However, NRQCD velocity scaling rules show that these matrix elements are one order higher in v^2 than the corresponding matrix elements of singlet states. In Ref. [49], this scaling property is used to relate LDMEs of S states as following

$$\langle \mathcal{O}^{B_c^+} [S^{(8)}] \rangle \approx \Delta_s(v)^2 \langle \mathcal{O}^{B_c^+} [S^{(1)}] \rangle, \quad (6)$$

where $\Delta_s(v)$ is of order v^2 and taken to be 0.1. Same values of LDME's of octet states are also used in Ref. [39].

IV. RESULTS

A. Cross sections

In Table II, we report our results of the production cross sections of the B_c meson for the 1S and 1P states in pp collision at LHC energy. To validate the accuracy of our calculations, we also provide a comparison with the results obtained in Ref. [49] for the 1S and 1P states and [39] for the 1S states. The apparent discrepancy between our results and that of Ref. [49] is mainly attributed to the choice of a different PDF set and, to a lesser extent, to slightly different values of LDME and c.m. energy, as indicated in Fig. 2, where we provide a detailed breakdown of all systematic variations. It is not possible to identify the exact reason for the quantitative difference with results of Ref. [39], as they do not specify the PDF set used and whether α_s is taken running or constant. We also separately provide the contribution to production cross sections from the gluon fusion and $q\bar{q}$ annihilation processes in the Table II. These results show that the contribution from $q\bar{q}$ annihilation process is less than 1% of the gluon fusion process for each state. In Table III, we report our results of production cross sections of the 1S and 1P states of the B_c meson in pA and AA collisions for Pb nucleus at LHC energies using nCTEQ15

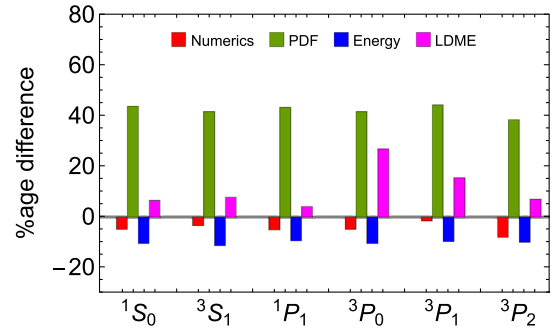


FIG. 2. Breakdown of all systematic differences between our results and those of Ref. [49], in which CTEQ6L PDF set is used, at $\sqrt{S} = 14$ TeV, and $|R(0)|^2 = 1.54 \text{ GeV}^3$. The difference due to numerical implementation is at most 5%.

TABLE III. Production cross sections of the 1S and 1P states of the B_c^+ meson in p-Pb and Pb-Pb collisions at LHC energies. In second and third columns, we provide our results using nCTEQ15 LO PDF sets. In fourth and fifth columns, the estimates of Ref. [39] are provided for the 1S states. The errors in our values are due to the uncertainty in the PDF set.

States	$\sigma(pPb \rightarrow B_c X)$ (μb)	$\sigma(PbPb \rightarrow B_c X)$ (μb)	$\sigma(pPb \rightarrow B_c X)$ (μb) [39]	$\sigma(PbPb \rightarrow B_c X)$ (μb) [39]
	(8.16 TeV)	(5.04 TeV)	(8.16 TeV)	(5.04 TeV)
1^1S_0	4.19 ± 0.25	232 ± 20	3.29	369
1^3S_1	10.5 ± 0.6	583 ± 49	8.26	921
1^1P_1	0.566 ± 0.030	31.4 ± 2.4	...	...
1^3P_0	0.426 ± 0.019	23.4 ± 1.5	...	...
1^3P_1	0.681 ± 0.030	37.6 ± 2.4	...	...
1^3P_2	1.32 ± 0.07	73.1 ± 5	...	...

TABLE IV. Production cross sections of the 1S and 1P states of the B_c^+ meson in p-Xe and Xe-Xe collisions at LHC energies using nCTEQ15 LO PDF. The errors in our values are due to the uncertainty in the PDF set.

States	$\sigma(pXe \rightarrow B_c X)$ (μb)	$\sigma(XeXe \rightarrow B_c X)$ (μb)
	(8.30 TeV)	(5.44 TeV)
1^1S_0	2.81 ± 0.12	104 ± 6
1^3S_1	7.01 ± 0.29	261 ± 15
1^1P_1	0.379 ± 0.014	14.1 ± 0.7
1^3P_0	0.285 ± 0.009	10.5 ± 0.5
1^3P_1	0.456 ± 0.014	16.9 ± 0.7
1^3P_2	0.882 ± 0.030	32.8 ± 1.6

LO PDF [44]. We also provide a comparison with the results obtained in Ref. [39] for 1S states. We use $m_c = 1.5$ GeV, $m_b = 4.9$ GeV, and $\mu_F = \sqrt{p_T^2 + M_{B_c}^2}$, and running α_s , the same as used in calculating the production cross section in the pp collision. The values of LDMEs estimated from the wave-function and its derivative at origin are also same. In Ref. [39], the authors used same PDF set and input parameters, however, they do not specify whether α_s is taken running or constant, so it not possible to identify the reason for apparent quantitative

difference. In Table IV, we report our results of production cross sections of S and P states of the B_c meson for Xe nucleus at LHC energy. At LHC energy, the contribution of $q\bar{q}$ annihilation process is negligible, so all values reported in Tables III and IV are for the gluon fusion process. In Table V, we report our results of production cross sections for Au nucleus at RHIC energy. A comparison with the results obtained in Ref. [39] for S states is also provided. At RHIC energy, it is expected that B_c production cross section may take a significant contribution from $q\bar{q}$ annihilation process. In to order highlight it, we separately provide the contributions to production cross sections from the gluon fusion and $q\bar{q}$ annihilation processes for both p-Au and Au-Au collisions. These results show that the contribution from $q\bar{q}$ annihilation process is about 10% of gluon fusion process for each state. All values of total cross sections reported in Tables III–V are obtained without any kinematical cuts on p_T and y (rapidity) of the B_c meson. These calculations utilize nCTEQ15 LO PDF sets, which include error sets. The error sets are used to estimate the errors in the cross sections arising from PDF uncertainties, as reported in these tables. Moreover, to study the impact of the choice of a particular PDF set (nCTEQ15), we employ a selection of alternative nuclear PDF sets for Pb and Xe nuclei at LHC energies. In Table VI, we compare the results of cross sections for p-Pb and Pb-Pb collisions obtained

TABLE V. Production cross sections of the 1S and 1P states of the B_c^+ meson in p-Au and Au-Au collisions at RHIC energies. In fourth and eighth columns, we provide our results using nCTEQ15 LO PDF sets. In fifth and ninth columns, the estimates of Ref. [39] are provided for 1S states. Contributions of the gluon fusion and $q\bar{q}$ annihilation processes to the cross sections in p-Au and Au-Au collisions at RHIC energy are also provided. The errors due to the uncertainty in the PDF set are provided only for the total values.

States	$\sigma(pAu \rightarrow B_c X)$ (nb)				$\sigma(AuAu \rightarrow B_c X)$ (μb)			
	(gg)	($q\bar{q}$)	Total	Ref. [39]	(gg)	($q\bar{q}$)	Total	Ref. [39]
1^1S_0	8.03	0.49	8.52 ± 0.50	8.19	1.11	0.06	1.17 ± 0.09	1.76
1^3S_1	18.86	3.59	22.5 ± 1.1	19.3	2.60	0.44	3.04 ± 0.22	4.15
1^1P_1	1.06	0.13	1.19 ± 0.06	...	0.146	0.017	0.163 ± 0.011	...
1^3P_0	1.03	0.08	1.11 ± 0.05	...	0.143	0.010	0.153 ± 0.008	...
1^3P_1	1.38	0.14	1.52 ± 0.08	...	0.191	0.018	0.209 ± 0.011	...
1^3P_2	2.39	0.33	2.72 ± 0.14	...	0.329	0.041	0.370 ± 0.022	...

TABLE VI. Comparison of the production cross sections of the 1S and 1P states for p-Pb and Pb-Pb collisions using different PDF sets.

States	$\sigma(pPb \rightarrow B_c X)$ (μb) at $\sqrt{S} = 8.16$ TeV				$\sigma(PbPb \rightarrow B_c X)$ (μb) at $\sqrt{S} = 5.04$ TeV			
	nCTEQ15	EPPS16	nNNPDF3.0	Ref.	nCTEQ15	EPPS16	nNNPDF3.0	Ref.
1^1S_0	4.19	4.41	4.14	3.29	232	254	225	369
1^3S_1	10.5	11.0	10.2	8.26	583	638	563	921
1^1P_1	0.566	0.571	0.569	...	31.4	33.2	30.4	...
1^3P_0	0.426	0.446	0.408	...	23.4	25.6	22.7	...
1^3P_1	0.681	0.705	0.676	...	37.6	40.4	36.3	...
1^3P_2	1.32	1.38	1.22	...	73.1	79.6	70.6	...

TABLE VII. Comparison of the production cross sections of 1S and 1P states for p-Xe and Xe-Xe collisions using different PDF sets.

States	$\sigma(pXe \rightarrow B_c X)$ (μb) at $\sqrt{S} = 8.16$ TeV		$\sigma(XeXe \rightarrow B_c X)$ (μb) at $\sqrt{S} = 5.44$ TeV	
	nCTEQ15	nNNPDF3.0	nCTEQ15	nNNPDF3.0
1^1S_0	2.81	2.84	104	107
1^3S_1	7.01	7.17	261	267
1^1P_1	0.379	0.383	14.1	14.4
1^3P_0	0.285	0.297	10.5	10.9
1^3P_1	0.456	0.471	16.9	17.4
1^3P_2	0.882	0.905	32.8	33.5

using nCTEQ15 LO PDF sets with those employing EPPS16 [50] and nNNPDF3.0 [51] PDF sets. Similarly, in Table VII, we compare the results of nCTEQ15 p-Xe and Xe-Xe collisions results with nNNPDF3.0 set only, due to nonavailability of EPPS16 PDF sets for Xe nucleus.

Leading-order results are usually very sensitive to the choice of factorization scale and the masses of heavy quarks including m_c and m_b . Given the mass of charm quark $m_c = 1.5 \pm 0.1$ GeV, we calculate the cross sections for three values of $m_c = 1.4, 1.5$, and 1.6 GeV, while taking $m_b = 4.9$ GeV. The resulting values of the cross sections for Pb, Xe, and Au nuclei are used to determine uncertainties due to charm quark mass. Similarly, since the

mass of bottom quark $m_b = 4.9 \pm 0.2$ GeV, we also calculate the cross sections for three values of $m_b = 4.7, 4.9$, and 5.1 GeV, taking $m_c = 1.5$ GeV. The resulting values are used to determine errors due the bottom quark mass. In Table VIII, we combine all these results and report the values of the cross sections with uncertainty due to heavy quark masses. First and second errors corresponds to $\Delta m_c = \pm 0.1$ GeV and $\Delta m_b = \pm 0.2$ GeV, respectively. It is noted that positive errors reported in the table corresponds to $\Delta m_c = -0.1$ GeV and $\Delta m_b = -0.2$ GeV as the cross sections increase with decrease in heavy quark masses. It is also found that a joint variation of charm and bottom quark masses has a cumulative effect, i.e., the total uncertainty is almost equal to the sum of uncertainties reported in the Table VIII due to independent variations in m_c and m_b .

To study the sensitivity of estimates of cross sections to the choice of factorization scale $\mu_F = \sqrt{p_T^2 + M_{B_c}^2}$, we vary it from $0.25\mu_F$ to $4\mu_F$. The results are given in Figs. 3 and 4. The plots show that for all collision modes and states of the B_c meson, the variation is about $\pm 25\%$ within the range $0.25\mu_F$ to $2\mu_F$. However, for pAu and AuAu modes, we observe relatively a large variation.

B. Kinematical distributions

In Figs. 5 and 6, we show the plots of p_T distributions of the 1S and 1P states of the B_c^+ meson in pA and AA collisions, respectively, for Pb, Xe, and Au nuclei.

TABLE VIII. Cross sections of the 1S and 1P states of the B_c^+ meson with uncertainty due to heavy-quark masses. First and second errors corresponds to $\Delta m_c = \pm 0.1$ GeV and $\Delta m_b = \pm 0.2$ GeV, respectively. The errors are calculated using nCTEQ15 LO PDF sets.

	p-Pb (μb)	Pb-Pb ($\times 10 \mu\text{b}$)	p-Xe (μb)	Xe-Xe ($\times 10 \mu\text{b}$)	p-Au (nb)	Au-Au (μb)
1^1S_0	$4.2^{+0.8+0.6}_{-0.9-0.7}$	23^{+4+3}_{-5-3}	$2.8^{+0.5+0.4}_{-0.6-0.4}$	$10.4^{+2.0+1.2}_{-2.3-1.6}$	$8.5^{+1.9+1.7}_{-2.5-2.2}$	$1.17^{+0.26+0.23}_{-0.35-0.30}$
1^3S_1	$10.5^{+1.2+0.5}_{-1.3-1.0}$	58^{+11+6}_{-16-8}	$7.0^{+1.7+0.9}_{-1.5-1.1}$	26^{+5+3}_{-7-4}	23^{+5+4}_{-8-5}	$3.0^{+0.7+0.6}_{-1.0-0.7}$
1^1P_1	$0.57^{+0.16+0.08}_{-0.23-0.09}$	$3.1^{+0.9+0.4}_{-1.2-0.5}$	$0.38^{+0.11+0.05}_{-0.15-0.05}$	$1.4^{+0.4+0.2}_{-0.6-0.2}$	$1.2^{+0.4+0.2}_{-0.6-0.3}$	$0.16^{+0.05+0.03}_{-0.08-0.04}$
1^3P_0	$0.43^{+0.10+0.06}_{-0.14-0.07}$	$2.3^{+0.6+0.3}_{-0.8-0.4}$	$0.29^{+0.07+0.04}_{-0.09-0.05}$	$1.05^{+0.26+0.15}_{-0.40-0.17}$	$1.11^{+0.29+0.18}_{-0.40-0.23}$	$0.15^{+0.04+0.02}_{-0.05-0.03}$
1^3P_1	$0.68^{+0.18+0.09}_{-0.26-0.11}$	$3.8^{+1.0+0.5}_{-1.4-0.6}$	$0.46^{+0.12+0.07}_{-0.17-0.07}$	$1.69^{+0.4+0.22}_{-0.7-0.27}$	$1.52^{+0.40+0.26}_{-0.60-0.32}$	$0.21^{+0.06+0.03}_{-0.09-0.05}$
1^3P_2	$1.32^{+0.40+0.17}_{-0.5-0.20}$	$7.3^{+2.0+0.9}_{-3.0-1.1}$	$0.88^{+0.25+0.11}_{-0.40-0.14}$	$3.3^{+0.9+0.4}_{-1.3-0.5}$	$2.7^{+0.8+0.5}_{-1.3-0.6}$	$0.37^{+0.11+0.07}_{-0.17-0.07}$

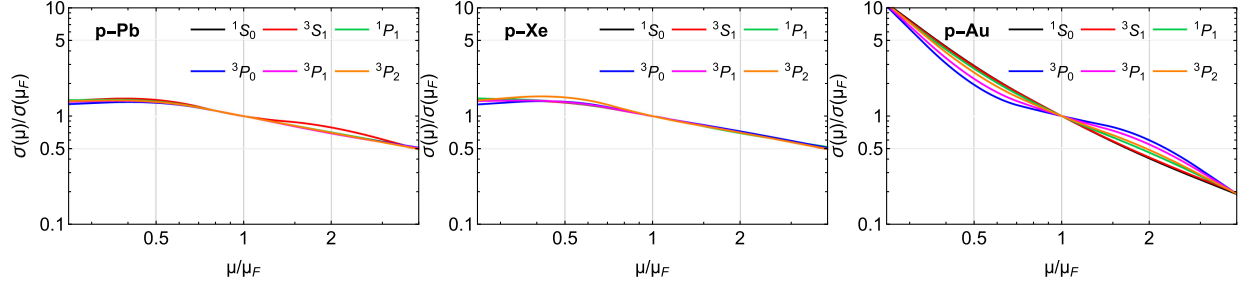


FIG. 3. Variation of the production cross sections of the 1S and 1P states of the B_c^+ meson for p-Pb (left), p-Xe (middle), and p-Au (right) collisions with factorization scale μ , varied from $0.25\mu_F$ to $4\mu_F$.

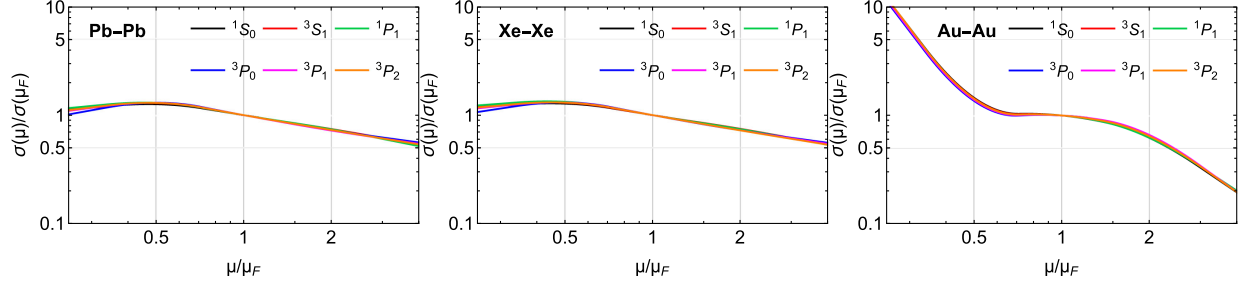


FIG. 4. Variation of the production cross sections of the 1S and 1P states of the B_c^+ meson for Pb-Pb (left), Xe-Xe (middle), and Au-Au (right) collisions with factorization scale μ , varied from $0.25\mu_F$ to $4\mu_F$.

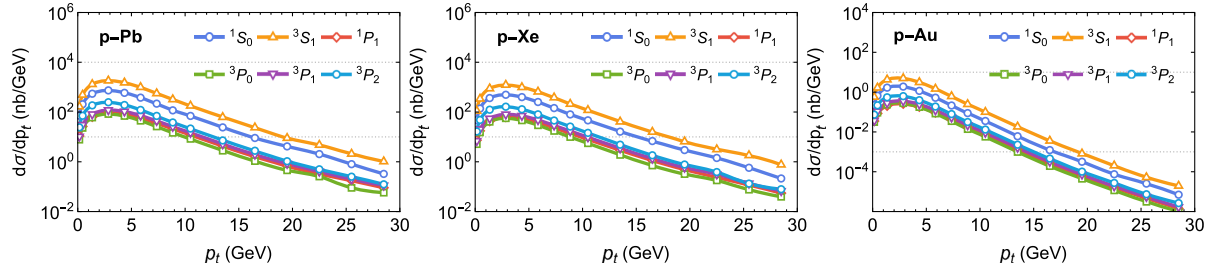


FIG. 5. p_T distributions of the 1S and 1P states of the B_c^+ meson for p-Pb (left), p-Xe (middle), and p-Au (right) collisions at $\sqrt{s_{pA}} = 8.16, 8.3, 0.2$ TeV, respectively.

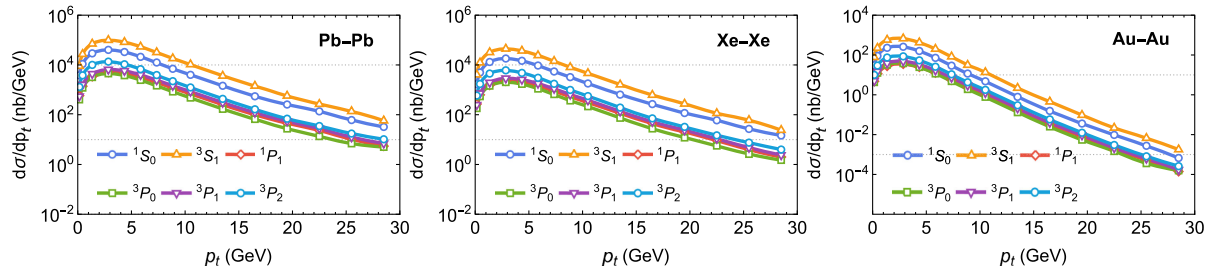


FIG. 6. p_T distributions of the 1S and 1P states of the B_c^+ meson for Pb-Pb (left), Xe-Xe (middle), and Au-Au (right) collisions at $\sqrt{s_{AA}} = 5.02, 5.44, 0.2$ TeV, respectively.

All distributions have a similar shape: increasing rapidly, exhibiting a maxima at about $p_T = 2.5$ GeV and then decreasing slowly. Beyond $p_T = 10$ GeV, the differential cross section is reduced by one order of magnitude and

beyond 20 GeV, it is reduced by two orders of magnitude. In Figs. 7 and 8, we show the plots of y (rapidity) distributions of the 1S and 1P states of the B_c^+ meson. The distributions of pA collisions are asymmetric due to the

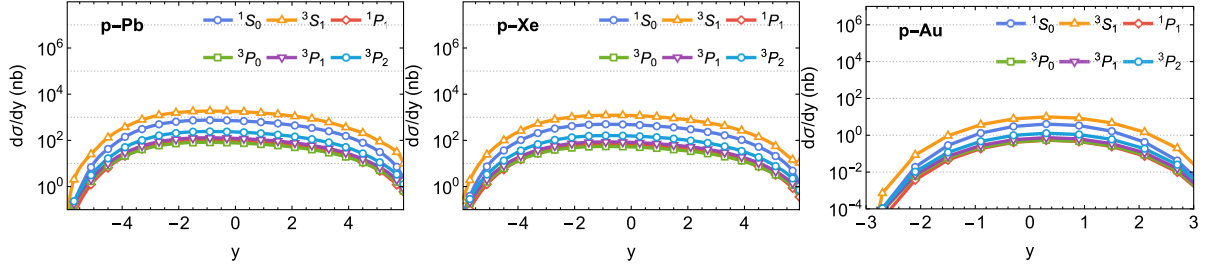


FIG. 7. y distributions of the 1S and 1P states of the B_c^+ meson for p-Pb (left), p-Xe (middle), and p-Au (right) collisions at $\sqrt{s_{pA}} = 8.16, 8.3, 0.2$ TeV, respectively.

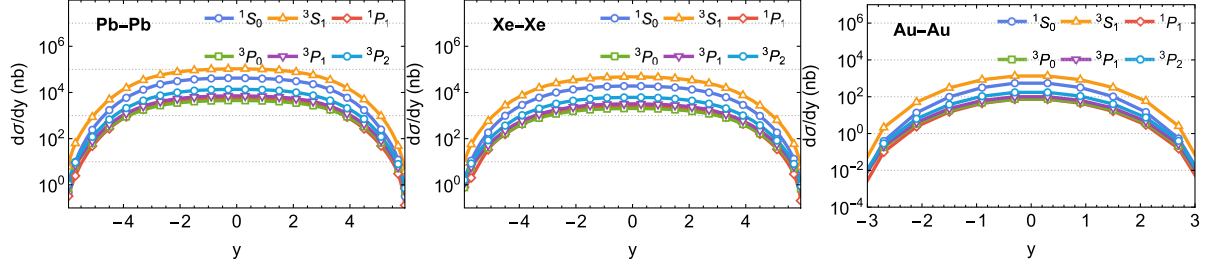


FIG. 8. y distributions of the 1S and 1P states of the B_c^+ meson for Pb-Pb (left), Xe-Xe (middle), and Au-Au (right) collisions at $\sqrt{s_{AA}} = 5.02, 5.44, \text{ and } 0.2$ TeV, respectively.

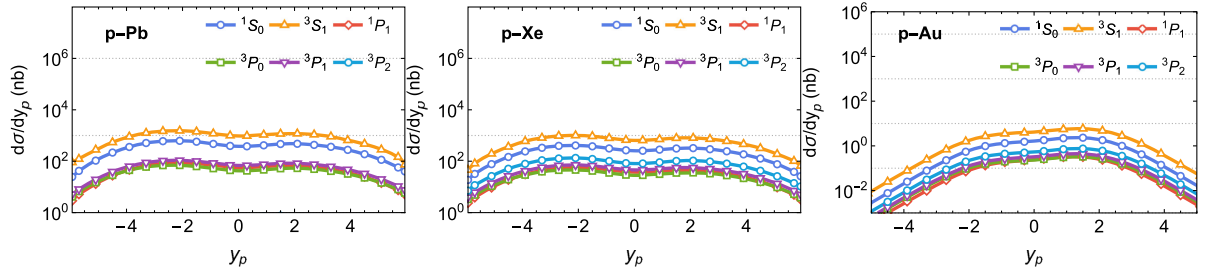


FIG. 9. y_p distributions of the 1S and 1P states of the B_c^+ meson for p-Pb (left), p-Xe (middle), and p-Au (right) collisions at $\sqrt{s_{pA}} = 8.16, 8.3, 0.2$ TeV, respectively.

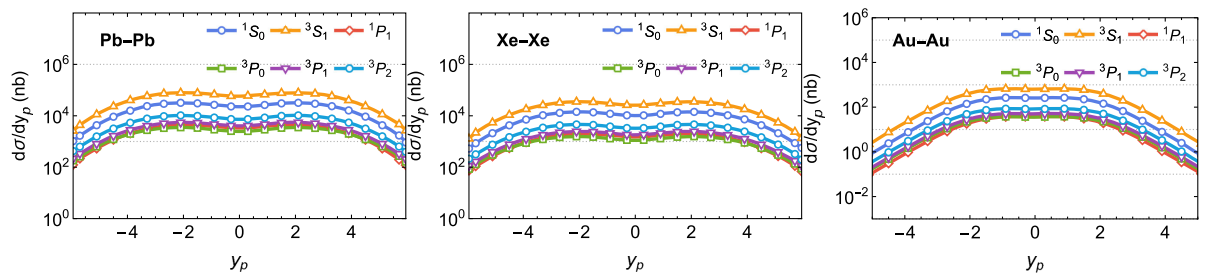


FIG. 10. y_p distributions of the 1S and 1P states of the B_c^+ meson for Pb-Pb (left), Xe-Xe (middle), and Au-Au (right) collisions at $\sqrt{s_{AA}} = 5.02, 5.44, \text{ and } 0.2$ TeV, respectively.

uneven energy of colliding particles. The asymmetry for p-Pb and p-Xe collisions is relatively mild as compared to p-Au collision. We also observe that the plateau in mid rapidity for pA and AA collisions at LHC energies is very

broad, extending over $-2 < y < 2$, whereas for pAu and Au-Au collisions at RHIC energy, the distributions are round-shaped. In Figs. 9 and 10, we show the plots of y_p (pseudorapidity) distributions of the 1S and 1P states of

the B_c^+ meson. The distributions of pA collisions are once again asymmetric due to the uneven energy of colliding particles, and plateau in case of collision at LHC energies is relatively broad.

C. Effect of kinematical cuts

The values of total cross sections reported in the Table VIII are obtained without any kinematical cuts on p_T and y (or y_p) of the B_c meson. A particle with a small value of p_T or large value of rapidity moves very close to beam axis and due to cylindrical geometry of a high energy particle detector, it is impossible to detect it. Therefore, we typically measure cross sections that are subjected to kinematical cuts on p_T and rapidity. Considering these limitations, we also study the effect of kinematical cuts on the production cross sections of $1S$ and $1P$ states of the B_c meson. To quantify the effect of the cuts in a more general way, we define following ratio:

$$R_{\text{kin}}(x_0) = \frac{(\sigma_{pA/AA})_{x > x_0}}{(\sigma_{pA/AA})_{\text{no cut}}}, \quad (7)$$

where $x = p_T, |y|, |y_p|$. In the denominator, we have total cross section without a kinematical cut, and in numerator, we have it with the kinematical cut $x > x_0$. It is also noted that for $|y|$ and $|y_p|$, the cut sets upper limit, so it is expressed by $x < x_0$. First, we chose 3S_1 state of B_c^+ as a

reference and determine how R_{kin} varies with x_0 in the case of pA and AA collisions, taking $A = \text{Pb, Xe, and Au}$. In Fig. 11, we show the plots of the variation in $R_{\text{kin}}(x_0)$ with a cut on p_T , $|y|$, and $|y_p|$ respectively. The left plot in the figure shows that the effect of the cut on p_T is nearly same for all collisions modes at LHC energies. Similarly, the effect is same for the collision modes (p-Au and Au-Au) at RHIC energies, but different from the collision modes at LHC energies. However, the middle and right plots given in the figure show that the impact of cuts on y and y_p is influenced not only by the collision energy but also by the collision mode. The middle plot of Fig. 11 for p-Au and Au-Au modes show that the values of cross sections saturate for cut on $|y| > 2$, whereas no saturation effect is observed for collision modes at LHC energies. Similarly, the right plot of the figure for p-Au and Au-Au modes show saturation effect for cut on $|y_p| > 3$, but no saturation effect for collision modes at LHC energies. In Fig. 12 (left), we show the variation of R_{kin} with value of cut on p_T for different states of the B_c meson. In this case, we refrain from distinguishing between collision modes because the profile of R_{kin} remains unaffected by this distinction, as indicated by the left plot of Fig. 11. Since the profile does depend on the energy scale, so we use red and black colors to distinguish LHC and RHIC results. The plot also shows that the effect of kinematical cut on p_T slightly varies with states of the B_c meson. In Fig. 12 (right), we show the variation of R_{kin} with the value of cut on $|y|$ for different

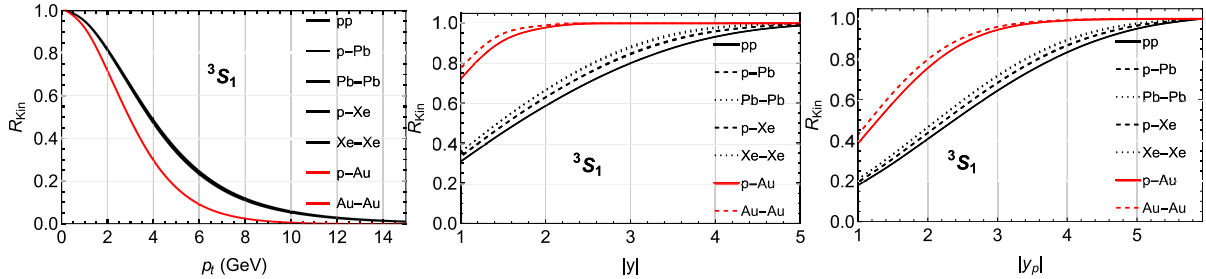


FIG. 11. Variation of R_{kin} with the values of cuts on p_T (left), $|y|$ (middle), and $|y_p|$ (right). Cuts in the case $|y|$ and $|y_p|$ set upper limit ($x < x_0$).

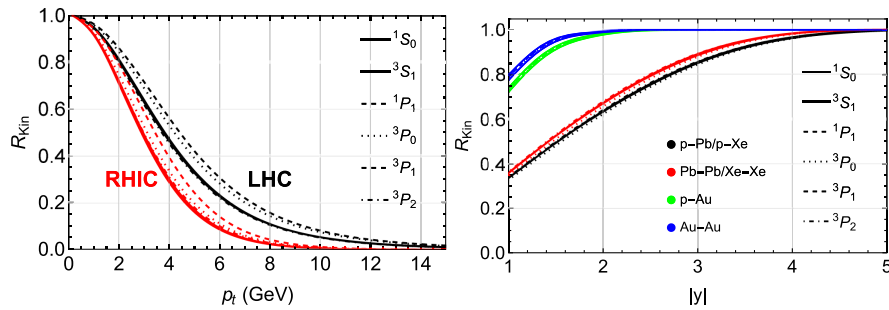


FIG. 12. Left: Variation of R_{kin} with the values of cuts on p_T cut for different states of the B_c meson. Collision mode at LHC and RHC energies have no impact on R_{kin} as implied by the plots of Fig. 11. Right: Variation of R_{kin} with $|y|$ cut for different states of the B_c meson. We use different color codes to separate collision modes and different line formats to separate states.

states of B_c meson. In this case, we do make a distinction between collision modes by using black (p-Pb, p-Xe), red (Pb-Pb, Xe-Xe), green (p-Au), and blue (Au-Au) colors. The plots show that the effect due to variation in the state of the meson is negligible.

D. Nuclear modification factors

Starting from the basic formula nuclear modification factor for case of minimum bias and expressed in terms of partial cross sections

$$R_{AB}^{(h)} = \frac{(d\sigma_{AB}^{(h)})^{(th)}}{N_A N_B (d\sigma_{pp}^{(h)})}, \quad (8)$$

we can define p_T and rapidity dependent nuclear modification factors as following

where for pA collision $N_B = 1$ and for AA collision $N_A = N_B$. We use these definitions to calculate p_T and rapidity distributions for pA and AA collisions for Pb and Xe nuclei at LHC energies and for Au at RHIC energy. In Fig. 13, we show the plots of p_T distributions of nuclear modification factor R_{pA} of S and P states of B_c^+ meson for p-Pb, p-Xe, and p-Au collisions respectively at the cm energies given in Table I. In each case, we are required to recalculate p_T distributions of the B_c^+ states in pp collision at $\sqrt{S} = 8.16, 8.30$, and 0.2 TeV for p-Pb, p-Xe, and p-Au

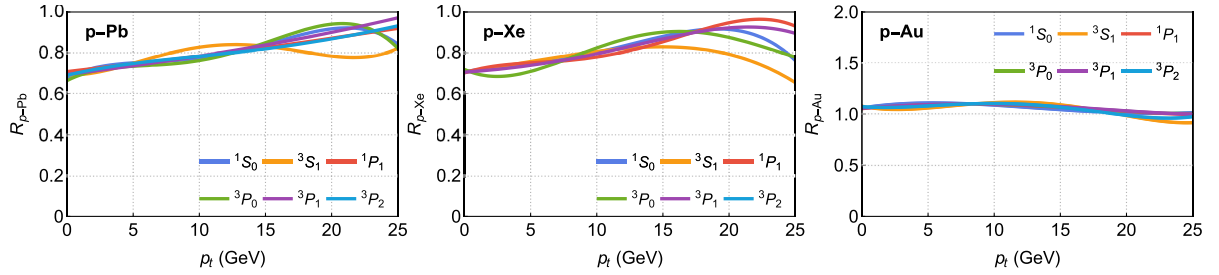


FIG. 13. p_T distributions of the nuclear modification factors R_{pA} of the 1S and 1P states of the B_c meson for p-Pb (left), p-Xe (middle), and p-Au (right) collisions.

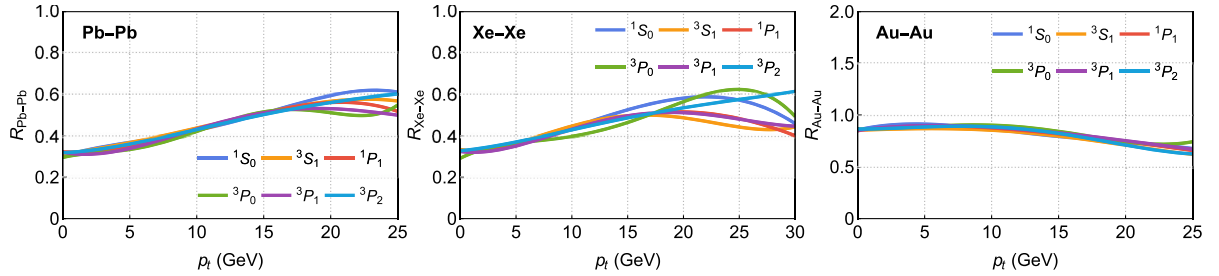


FIG. 14. p_T distributions of the nuclear modification factors R_{AA} of the 1S and 1P states of B_c meson for Pb-Pb (left), Xe-Xe (middle), and Au-Au (right) collisions.

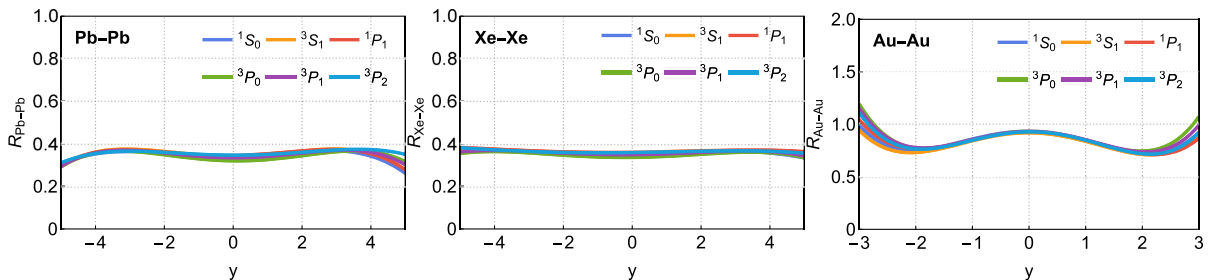


FIG. 15. y distributions of the nuclear modification factors R_{AA} of the 1S and 1P states of the B_c meson for Pb-Pb (left), Xe-Xe (middle), and Au-Au (right) collisions.

collisions respectively. Additionally, in calculating nuclear modification factor for p-Au collision, we also include the contribution of $q\bar{q}$ annihilation processes to B_c production cross section ($d\sigma_{pp}^{(h)}$) in pp collision appearing in the denominator as it is already done for corresponding cross section ($d\sigma_{pAu}^{(h)}$) in p-Au collision appearing in the numerator. In Fig. 14, we show the plots of p_T distributions of nuclear modification factor R_{AA} of S and P states of B_c^+ meson for Pb-Pb, Xe-Xe, and Au-Au collisions respectively at the cm of energies given in Table I. In each case, we are required to recalculate p_T distributions of the B_c^+ states in pp collision at $\sqrt{S} = 5.04, 5.44, \text{ and } 0.2 \text{ TeV}$ for Pb-Pb, Xe-Xe, and Au-Au collisions respectively. Again, in calculating nuclear modification factor for Au-Au collision, we include the contribution of $q\bar{q}$ annihilation processes. In Fig. 15, we show the plots of rapidity distributions of nuclear modification factors R_{AA} of S and P states for $A = \text{Pb, Xe, and Au}$ at the cm of energies given in Table I.

V. CONCLUSION

In this work, we have obtained several new results regarding the production of cross sections for various states of the B_c meson in heavy-ion collisions. Previous estimates of these cross sections were available for 1^1S_0 and 1^3S_1 states for the p-Pb, Pb-Pb collisions at LHC energies and for the p-Au and Au-Au collisions at RHIC energy. We have extended the calculations to include the spin singlet state 1^1P_1 and the spin triplet states $1^3P_0, 1^3P_1$, and 1^3P_2 . Additionally, we have included p-Xe and Xe-Xe collision modes at LHC energies, along with p-Pb, Pb-Pb, p-Au, and Au-Au modes. Apart from calculating p_T , rapidity, and pseudo rapidity distributions of cross sections, we have also determined the nuclear modification factors R_{pA} and R_{AA} for Pb, Xe, and Au nuclei. In this section, we schematically summarize these results.

- (i) Comparison with previous estimates: Currently, the estimates of cross sections for the B_c mesons are available at LO order and only for 1S and 1P states in pp collision. Recently, the cross sections for 1S states are provided for heavy-ion collisions, including p-Pb, Pb-Pb, p-Au, Au-Au modes. To validate the accuracy of our computations, we first reproduced these results. Comparison of our results with those given in Ref. [49] for the production cross sections of 1S and 1P states in pp collision shows a discrepancy of less than 5% after matching the PDF set and input parameters, as indicated in Fig. 2. For 1S states in p-Pb and Pb-Pb modes, the average difference between our results and that of Ref. [39] is about 30% which reduce to 20% for p-Au and Au-Au modes. It was not possible to identify the cause of this discrepancy because the authors do not provide any information about the choice of α_s .

Nevertheless, the difference is relatively small as compared to the uncertainties due to errors in the input parameters and PDF sets.

- (ii) New Results of the production cross sections in pA and AA collisions: Our results of the production cross sections for p-Pb, Pb-Pb, p-Xe, Xe-Xe, p-Au, and Au-Au collision modes are provided in Tables III, IV, and V. The results show that the production cross sections of $1^1P_1, 1^3P_0, 1^3P_1$, and 1^3P_2 states are almost 5%, 5%, 7%, and 13% of the cross section of 1^3S_1 state, respectively, irrespective of the collision mode and the collision energy. Whereas, the cross section 1^1S_0 state is almost 40% of 1^3S_1 state.
- (iii) p_T distributions of the cross sections: In Figs. 5 and 6, we show the plots of the p_T distributions of 1S and 1P states of the B_c^+ meson for pA and AA collisions. These distributions have similar shape: increasing rapidly, exhibiting a maxima at about $p_T = 2.5 \text{ GeV}$ and then decreasing slowly. Beyond $p_T = 10 \text{ GeV}$, the differential cross section is reduced by one order of magnitude and beyond $p_T = 20 \text{ GeV}$ it is reduced by two orders of magnitude.
- (iv) Rapidity (y) distributions of the cross sections: In Figs. 8 and 7, we show the plots of y (rapidity) distributions of the 1S and 1P states of the B_c^+ meson in pA and AA collisions, respectively. The distribution for pA collisions are asymmetric due to the uneven energy of colliding particles. The asymmetry for p-Pb and p-Xe collisions is relatively mild as compared to p-Au collisions. We also observe that the plateau in midrapidity for pA and AA collisions at LHC energies is very broad, extending over $-2 < y < 2$, whereas for collisions at RHIC energy, distribution are more round shaped.
- (v) Effect of kinematical cuts: To quantify the effect of kinematical cuts on production cross sections, we have introduced a ratio R_{kin} given in Eq. (7). We calculate it for different values of cuts on p_T or $|y|$. The resulting profile of the ratio provides a convenient method to estimate the cross sections for any given value of applied cut. In Fig. 12, we show the variation of R_{kin} with the cut on p_T and $|y|$, respectively, for different states of the B_c meson and for different collision modes. We use different color codes and line formats to distinguish collision modes and states, respectively. The plots in the Fig. 12 (left) show that the effect of kinematical cut on p_T varies slightly for different states of the B_c meson. It also depends on the collision energy but not on specific mode of collision at a given collision energy. Whereas the plots in the Fig. 12 (right) show that the effect of cut on rapidity does not depend on the states. Dependence on collision mode (p-A or A-A) is mild but significant on collision energy. For p-Au and

Au-Au modes, the plots show that the values of cross sections saturate for cuts on $|y| > 2$, however no saturation effect is observed for collision modes at LHC energies.

- (vi) Uncertainties due heavy quark masses: To study the effect of errors in masses of charm and bottom quarks, we calculate the cross sections for three values of m_c (1.4, 1.5, and 1.6 GeV) while taking $m_b = 4.9$ GeV. Similarly we calculate cross sections for three values of m_b (4.7, 4.9, and 5.1 GeV) while taking $m_c = 1.5$ GeV. In Table VIII, we combine all these results and report the values of cross sections with uncertainties due to heavy quark masses. In all cases, the uncertainty due to error in the b-quark mass is almost half that of the c-quark mass. The results show that the errors due m_c and m_b masses are about 25% and 13%, respectively, for p-Pb, Pb-Pb, p-Xe, and Xe-Xe modes. And for p-Au and Au-Au modes, the errors are about 30% and 20%, respectively.
- (vii) Nuclear modification factors: In Fig. 13, we show the plots of the p_T distributions of the nuclear modification factor R_{pA} of the S and P states of the B_c^+ meson for p-Pb, p-Xe, and p-Au collisions, respectively. The profiles of R_{pA} are similar for p-Pb and p-Xe modes. In both cases, R_{pA} exhibits almost linear increase with p_T , ranging from approximately 0.7 to 1 for $p_T = 0$ to 25 GeV. However, for p-Au mode at RHIC energy, $R_{pA} \approx 1$. In Fig. 14, we show the plots of p_T distributions of the nuclear modification factor R_{AA} of the 1S and 1P states of the B_c^+ meson for Pb-Pb, Xe-Xe, and Au-Au collisions respectively. The profiles of R_{AA} are similar for Pb-Pb and Xe-Xe modes. In both cases, R_{AA} exhibits almost linear variation with p_T , ranging from approximately 0.35 to 0.6, almost half of R_{pA} . However, for Au-Au mode, $R_{AA} \approx 0.9$ up to $p_T = 10$ GeV, and it gradually decreases to 0.7 at $p_T = 25$ GeV. In Fig. 15, we show the plots of the rapidity distributions of the nuclear modification factor R_{AA} for 1S and 1P states in Pb-Pb, Xe-Xe, and Au-Au collisions, respectively, at the relevant c.m. energies. The profiles of R_{AA} are similar for Pb-Pb

and Xe-Xe modes. In both cases, R_{AA} exhibits almost a constant value of 0.4. However, for Au-Au mode, it is almost 0.9. We do not present the plots of the rapidity distributions of the nuclear modification factor R_{pA} . These distributions are not useful, because the scaled rapidity distribution (the denominator of the R_{pA}) is calculated in the c.m. frame, while the distribution with nuclear PDF (the numerator of the R_{pA}) is not in the c.m. frame. Since rapidity is not boost invariant, the resulting profiles of R_{pA} do not truly quantify the modification in cross sections due to nuclear shadowing.

This study is focused on LO estimates of the production cross sections and nuclear modification factors of the 1S and 1P states of the B_c meson at LHC and RHIC energies. The results exhibit significant dependence on the masses of heavy-quarks and the factorization scale. We expect that NLO results would help addressing these issues. Nevertheless, our results provide a baseline for upcoming experimental studies of B_c mesons in pp, pA, and AA collisions in RUN III of LHC and could help in developing optimal experimental search strategies for identification of its new states. Moreover, with RUN III's higher luminosity, LHC would be able to measure production cross sections and distributions, providing more stringent constraints to test the validity of NRQCD approach for charm-beauty mesons.

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DATA AVAILABILITY

The data supporting this study's findings are available within the article.

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