Statistical production of B_c mesons in $\sqrt{s}$=5.02 TeV Pb-Pb collisions

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Abstract. The yield of B_c mesons produced in Pb-Pb collisions at $\sqrt{s}$=5.02 TeV can be greatly enhanced compared to that produced in pp collisions at the same energy due to the recombination of bottom (b) and charm (c) quarks in the environment of the quark-gluon plasma (QGP). Taking advantage of the high degree of thermalization of the abundant c quarks in the QGP, we calculate the integrated yields of B_c mesons using the statistical hadronization model by treating the B_c meson as a member of the open b-hadron family. The transverse momentum (p_T) spectrum is then computed by resonance recombination using transported c and b quark phase space distributions, supplemented by the component fragmented from b quarks. Both integrated and differential nuclear modification factors obtained show good agreement with pertinent data measured by the CMS experiment within theoretical uncertainties.

1 Introduction

The B_c mesons composed of a bottom (b) quark and an anticharm ($\bar{c}$) quark, or vice versa, are intermediate state between charmonium ($c\bar{c}$) and bottomonium ($b\bar{b}$) in terms of mass, size and binding energy [1], thus providing a unique avenue to study heavy quark dynamics. The production of B_c mesons in proton-proton (pp) collisions entails the simultaneous creation of a $c\bar{c}$ and a $b\bar{b}$ pair in a single collision event, rendering it much rarer than that of other b mesons containing a single b quark. However, in relativistic heavy-ion collisions where Quark-Gluon Plasma (QGP) is created, abundant heavy quarks are produced through primordial hard processes and then transported in QGP, leading to a new production mechanism for B_c mesons, *i.e.,* the recombination of b and c quarks from different primordial binary collisions which could significantly enhance the B_c yield. This novel production mechanism makes B_c a valuable probe to understanding the QGP properties. On the experimental side, measurement by CMS in $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV Pb-Pb collisions, although restricted to relatively large transverse momenta (p_T > 6 GeV), indeed gives a first hint that the B_c production in the presence of QGP is enhanced relative to that in pp collisions, as indicated by the nuclear modification factor (R_{AA}) well above unity in the lower p_T bin accessed in the measurement [2].

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2 Statistical hadronization model for B_c mesons in Pb-Pb collisions

We treat B_c as open b-hadrons and study its production in $\sqrt{s_{\rm NN}} = 5.02$ TeV Pb-Pb collisions in the canonical ensemble statistical hadronization model (CE-SHM) [3] that implements strict conservation of c and b numbers. The pertinent partition function reads

$$Z(C,B) \propto \int_0^{2\pi} \frac{d\phi_C d\phi_B}{(2\pi)^2} e^{i(C\phi_C+B\phi_B)} \exp[\sum_j \gamma_s^{N_{sj}} \gamma_c^{N_{cj}} \gamma_b^{N_{bj}} e^{-i(C_j\phi_C+B_j\phi_B)} z_j], \tag{1}$$

where the number of charm and bottom for a neutral system $C = B = 0$ which should be conserved; C_j and B_j are the charm and bottom number of the j-th particle; γ_s, γ_c and γ_b are fugacities for hadrons containing N_{sj}, N_{cj} and N_{bj} strange, c and b quarks plus antiquarks. In Eq. (1), z_j denotes the one-particle partition function

$$z_j = (2J_j + 1)\frac{VT_H}{2\pi^2} m_j^2 K_2(\frac{m_j}{T_H}), \tag{2}$$

which specifies the chemical equilibrium multiplicity of the j-th hadron of mass m_j and spin J_j in a fireball of volume V at hadronization temperature T_H, with K_2 the modified Bessel function of the second kind. The primary multiplicity of a heavy hadron in the CE-SHM is then given by

$$\langle N_j \rangle = \gamma_s^{N_{sj}} \gamma_c^{N_{cj}} \gamma_b^{N_{bj}} z_j \frac{Z(C-C_j, B-B_j)}{Z(C,B)}, \tag{3}$$

where $Z(C-C_j, B-B_j)/Z(C,B)$ characterizes the canonical suppression relative to the grand-canonical statistical yield as a result of the conservation of C and B. Then the fugacities γ_c and γ_b are self-consistently determined by the balance equation

$$\frac{dN_{c/b}}{dy} = \sum_{j\in oc^+/ob^+} \langle N_j \rangle + \sum_{j\in hc/hb} \langle N_j \rangle + \sum_{j\in B_c^+} \langle N_j \rangle, \tag{4}$$

where the summation runs over the primary multiplicities $\langle N_j \rangle$ of positive charged open c/b hadrons (oc^+ and ob^+), charmonia (hc) and bottomonia (hb) and B_c mesons.

Once the primary multiplicities are obtained, the total production yields of ground state open b hadrons and B_c^- mesons are obtained from the sum of the direct one and the feeddown contributions from excited states

$$\langle N_\alpha^{\rm tot} \rangle = \langle N_\alpha \rangle + \sum_j \langle N_j \rangle \cdot \mathcal{B}(j \to \alpha), \tag{5}$$

where the branching fractions $\mathcal{B}$ for the strong decays of excited open b hadrons have been estimated from a $^3P_0$ model [4] and that for the strong or radiative decays of excited B_c mesons to the ground state B_c^- are all taken to be 100% [1]. We take T_H=170 MeV and the fireball volume is obtained by scaling the one $V_{\Delta y=1} = 4997$ fm^3 determined from SHM for light hadrons in the most central 0-10% centrality [5] to other centralities using the measured charged-particle multiplicities by ALICE [6].

3 B_c's p_T spectra and nuclear modification factors

We first construct the p_T-differential cross section of ground state B_c^- meson in pp collisions as a reference to nuclear modification. Assuming that the production faction of B_c^-

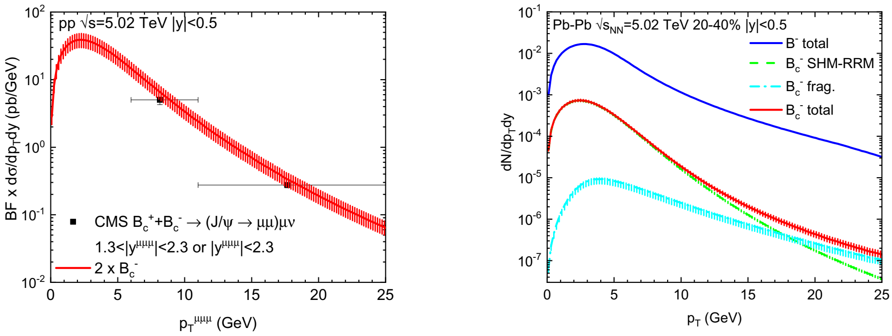

Figure 1. Left panel: The computed $B_c^- + B_c^+$ differential cross section multiplied by branching fractions (BF) as a function of $p_T^{\mu\mu\mu}$ in comparison with CMS data [2]. Right panel: The p_T differential yield for the recombination (green) and fragmentation (cyan) components of B_c^-, alongside those for the total B_c^- (red) and B^- (quoted from [4], blue) in the 20-40% centrality of $\sqrt{s_{\rm NN}}$ = 5.02 TeV Pb-Pb collisions.

relative to the sum of B^- and $\bar{B}^0$ measured by LHCb in forward rapidity at $\sqrt{s}$=7 TeV and 13 TeV pp collisions [7] remains unchanged in mid-rapidity at 5.02 TeV, we evaluate the B_c's $d\sigma/dp_T dy$ by multiplying the measured faction B_c^-/B^- with B^-'s $d\sigma/dp_T dy$ determined in [4]. To compare with CMS data, we multiply the B_c^-'s $d\sigma/dp_T dy$ constructed above with $\mathcal{B}(B_c^- \to J/\psi\mu^-\bar{\nu}) = 1.95\% \pm 0.46\%$ [7] and $\mathcal{B}(J/\psi \to \mu\mu) = 5.96\%$ [8], then take into account the average p_T shift by $p_T^{\mu\mu\mu} = 0.85 \cdot p_T^{B_c}$ [2]. The result is plotted in the left panel of Fig. 1, with the band arising from the uncertainty of $\mathcal{B}(B_c^- \to J/\psi\mu^-\bar{\nu})$.

In Pb-Pb collisions B_c mesons at low momentum is mostly generated from the quark recombination. The differential yield for the B_c^-'s recombination component is obtained by normalizing the B_c's p_T spectrum calculated from the resonance recombination model (RRM) of c and b quarks to its SHM production yield calculated in Sec. 2 corrected for the b-quark recombination probability which is ∼ 92% for the 20-40% centrality [4]. The momentum distribution given by RRM reads

$$f_{B_c}(\vec{x},\vec{p}) = C_{B_c}\frac{E_{B_c}(\vec{p})}{m_{B_c}\Gamma_{B_c}}\int\frac{d^3\vec{p}_1 d^3\vec{p}_2}{(2\pi)^3} f_b(\vec{x},\vec{p}_1) f_{\bar{c}}(\vec{x},\vec{p}_2)\sigma_{B_c}(s)v_{\rm rel}(\vec{p}_1,\vec{p}_2)\delta^3(\vec{p}-\vec{p}_1-\vec{p}_2) \quad (6)$$

where f_b and $f_{\bar{c}}$ are the phase space distributions of b and $\bar{c}$ quarks on the hadronization hypersurface (constructed from Langevin simulations down to T_H = 170 MeV); $v_{\rm rel}$ is their relative velocity. The resonance cross section $\sigma_{B_c}(s)$ is taken to be of the Breit-Wigner form and the factor C_{B_c} ensures normalization to the statistical production yield. The recombination p_T spectrum thus computed for B_c mesons is then supplemented with the fragmentation component simulated using transported b quarks and the b-hadron chemistry in pp collisions. The total p_T differential yields of different dynamical components for B_c^- are presented in the right panel of Fig. 1 in comparison with the total yields for B^-.

Same as in pp collisions the obtained absolute p_T spectrum is multiplied by pertinent branching factions and shifted by $p_T^{\mu\mu\mu} = 0.85 \cdot p_T^{B_c}$ [2] for comparing with the CMS data. We then compute the B_c^-'s nuclear modification factor ($R_{\rm AA}$) which is defined as $R_{\rm AA}(p_T) = \frac{dN^{\rm PbPb}/dp_T dy}{\langle T_{\rm AA}\rangle d\sigma^{pp}/dp_T dy}$ with $\langle T_{AA}\rangle$ the thickness function. As presented in Fig. 2(a), the $R_{\rm AA}$ for B_c^- reaches the value of ∼ 5-6 at p_T < 5 GeV, evidencing the great enhancement due to the recombination at low p_T. The width of the band for B_c^-'s $R_{\rm AA}$ at low p_T indicates uncertainties due to shadowing of c's participating in recombination as well as the spread of the pp reference spectrum, but is dominated by the latter.

Finally we calculate B_c's integrated R_{AA} in the full p_T range and in the $7 < p_T < 13$ GeV interval (corresponding to $6 < p_T^{\mu\mu\mu} < 11$ GeV in the CMS data [2]) as a function of participant numbers. As shown in Fig. 2(b), the integrated R_{AA} in the full p_T range reaches ~ 5 in central and semicentral collisions but gradually drops off toward peripheral collisions. The integrated R_{AA} in the intermediate p_T bin corresponding to the experimental selection shows good agreement with the CMS data [2].

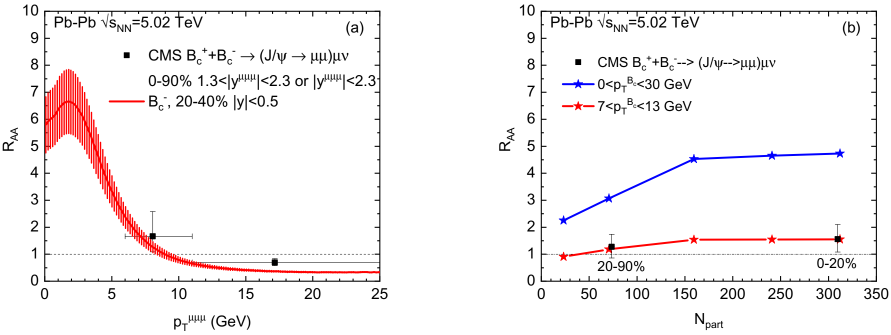

Figure 2. (a) The B_c^-'s nuclear modification factor as a function of three-muon's transverse momentum $p_T^{\mu\mu\mu}$, compared to CMS data [2]. (b) The B_c^-'s integrated nuclear modification factor in the full p_T range vs. in the $7 < p_T < 13$ GeV interval. The latter corresponds to $6 < p_T^{\mu\mu\mu} < 11$ GeV in CMS data [2].

4 Summary

The integrated production of B_c mesons has been computed in the canonical ensemble statistical hadronization model by placing B_c as a member of the open b hadrons implementing strict conservation of charm and bottom number. The p_T differential distribution of B_c^- mesons was constructed by normalizing the shape of p_T spectrum computed from resonance recombination to the SHM yield. The resulting p_T dependent nuclear modification factors for B_c^- mesons reach up to ~5-6 at low p_T. Our study provides strong support for the formation of B_c mesons through statistical recombination of abundant and highly thermalized c and b quarks in the deconfined QGP created in Pb-Pb collisions at the LHC energy.

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