

Bottom-hadron production in high-energy pp and heavy-ion collisions

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Abstract. The hadro-chemistry of bottom quarks produced in hadronic collisions encodes valuable information on the mechanism of color-neutralization in these reactions. We first compute the chemistry of bottom-hadrons in high-energy pp collisions employing statistical hadronization with a largely augmented set of states beyond the currently measured spectrum. This enables a comprehensive prediction of fragmentation fractions of weakly decaying bottom hadrons for the first time and a satisfactory explanation of the existing measurements in pp collisions at the LHC. Utilizing the bottom hadro-chemistry thus obtained as the baseline, we then perform transport simulations of bottom quarks in the hot QCD matter created in PbPb collisions at the LHC energy and calculate the pertinent bottom-hadron observables. The transverse momentum (p_T) dependent modifications of the bottom baryon-to-meson ratio (Λ_b^0/B^-) relative to their pp counterparts are highlighted as a result of bottom quark diffusion and hadronization in the Quark-Gluon Plasma (QGP). We finally summarize the heavy quark (charm vs bottom) diffusion coefficients as extracted from transport simulations and compare them to result from recent full lattice QCD computations.

1 Introduction

The production of bottom (b) quarks is believed to be well separated from the subsequent hadronization, as facilitated by its large mass. While the former can be reliably computed using perturbative QCD techniques, the hadronization as an intrinsically nonperturbative process relies on phenomenological modelling. The fragmentation fractions of b quarks into weakly decaying b -hadrons (including strong and electromagnetic feeddown contributions from excited states), f_u , f_d , f_s and f_{baryon} , characterizing the probabilities of a b quark hadronizing into a B^- , B^0 and \bar{B}_s^0 meson and a b baryon, respectively, thus provide a critical test of the hadronization mechanisms. These fractions have been measured in $p\bar{p}$ collisions at the Tevatron and found to be different from the values measured in e^+e^- collisions [1], in that the f_{baryon} is significantly larger in hadronic collisions, implying that the b quark hadronization is non-universal across different collision systems. The corresponding fractions in the charm sector have been measured by ALICE collaboration in pp collisions at the LHC energies and similar enhancement of the baryon fraction relative to the e^+e^- case was identified [2], confirming that the heavy quark hadronization may depend on the collision environment.

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2 Bottom hadro-chemistry in pp collisions

Assuming *relative* chemical equilibrium between different b -hadron production yields, we have evaluated the comprehensive set of fragmentation fractions of all weakly decaying b hadrons in a generalized statistical hadronization model (SHM) [3]. The thermal density of a given b hadron of mass m_i and spin-degeneracy d_i and containing N_s^i strange or anti-strange quarks is computed at the hadronization temperature $T_H \sim 170$ MeV in the grand-canonical statistical ensemble

$$n_i^{\text{primary}} = \frac{d_i}{2\pi^2} \gamma_s^{N_s^i} m_i^2 T_H K_2\left(\frac{m_i}{T_H}\right), \quad (1)$$

with $\gamma_s \sim 0.6$ being the strangeness suppression factor in elementary collisions. With the branching ratios (BR's) estimated from the 3P_0 quark model [3] for the excited b hadrons decaying into the ground state particles, the total densities of the weakly decaying b hadrons are obtained via

$$n_\alpha = n_\alpha^{\text{primary}} + \sum_i n_i^{\text{primary}} \cdot Br(i \rightarrow \alpha). \quad (2)$$

Assuming that fragmentation weights of b quarks into a given b -hadron is governed by its thermal density, Eq. (2) can be converted into the fragmentation fractions of the ground state b hadrons, under the constraint of $f_u + f_d + f_s + f_{\Lambda_b^0} + f_{\Xi_b^{0,-}} + f_{\Omega_b^-} = 1$. Fig. 1 summarizes the results for the fragmentation fractions of ground state b hadrons from the statistical hadronization model with two scenarios for the input of b -hadron mass spectrum: the current particle data group (PDG) listings [4] and the relativistic quark model (RQM) predictions [5, 6]. The fragmentation fractions as measured in hadronic (pp and $p\bar{p}$) collisions are well reproduced by the SHM-RQM calculation, which features a significant enhancement of the baryonic fractions as a result of the feeddowns of the many yet unobserved excited states.

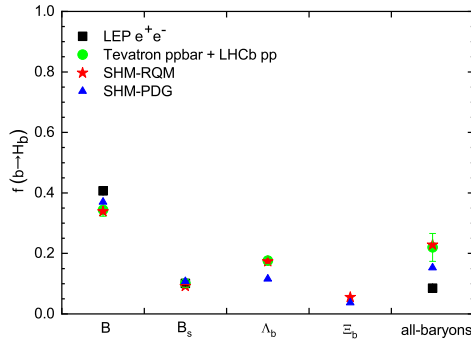


Figure 1. Fragmentation fractions of ground state b hadrons calculated from statistical hadronization model [3], in comparison with experimental measurements in e^+e^- and $p\bar{p}$ or pp collisions [1].

By further combining the transverse momentum (p_T) distributions of b quarks from perturbative QCD (FONLL) calculations [7, 8] with thermal weights, we've conducted a fragmentation simulation which, complemented with the decay simulation, allows us to make predictions for the p_T dependent ground-state baryon-to-meson ratio, Λ_b^0/B^- . As shown by the red curves in the left panel of Fig. 2, the substantial gap between the LHCb data [9]

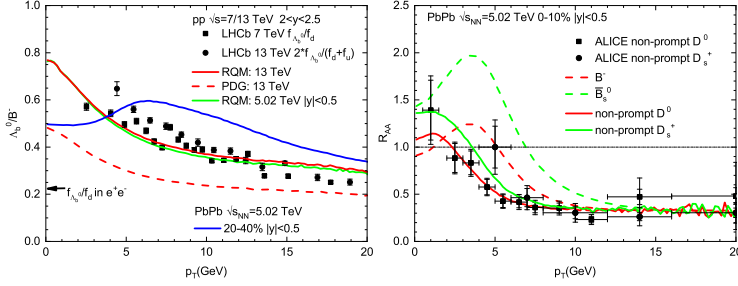


Figure 2. Left: Λ_b^0/B^- computed from SHM [3] in comparison with LHCb measurements in pp collisions [9], and the same ratio computed from transport approach [3] in 20-40% $\sqrt{s_{NN}}=5.02$ TeV PbPb collisions. Right: the nuclear modification factors [3] for non-prompt D^0 and D_s^+ (0-10% PbPb collisions) in comparison with ALICE data [10, 11].

and the SHM-PDG result is largely overcome by the feeddown of the large set of “missing” baryons included in the SHM-RQM calculations.

3 Bottom baryon-to-meson ratios in Pb-Pb collisions

The hadro-chemistry computed above in pp collisions serves as a controlled reference for studying its modifications in heavy-ion collisions. To this end, we employ a strongly coupled transport approach previously developed for the charm sector [12] and calculate the hadro-chemistry and nuclear modification factors of b hadrons in $\sqrt{s_{NN}}=5.02$ TeV PbPb collisions. This transport model features nonperturbative interactions of heavy flavor with the medium, in terms of heavy quark diffusion in the QGP [13], resonance recombination as the dominant hadronization mechanism at low to intermediate p_T [3], and heavy-hadron diffusion in the hadronic phase [14], therefore conceptually fully consistent with the notion of strongly-coupled QGP.

We found that when amplifying the b -quark thermal relaxation rate as computed from T -matrix approach [13] by a $K = 1.6$ factor, which is to mimic the missing contributions from radiative energy loss, the nuclear modification factors R_{AA} of both nonprompt D and D_s mesons, which are the weak decay product of b hadrons including b baryons, can be well reproduced, as shown in the right panel of Fig. 2. Furthermore, the full set of R_{AA} ’s of ground-state b hadrons develops an expected hierarchy of flow effects and suppression as driven by their different quark content [3]. Accordingly, the Λ_b^0/B^- ratio exhibits a significant enhancement at intermediate- p_T (blue curve in the left panel of Fig. 2) relative to the pp baseline due to a stronger flow effect on generally heavier baryons, which is fully captured by the resonance recombination incorporating space-momentum correlations [3]. Notable is the peak of Λ_b^0/B^- at a higher $p_T \sim 6$ GeV and extending to significantly larger $p_T \sim 15$ GeV than the corresponding ratio in the charm sector [12] because of the larger b -quark mass.

In Fig. 3, the charm and bottom quark spatial diffusion coefficients in unit of thermal wave length as used in [12] and [3], respectively, representing decent description of both charm and bottom hadro-chemistry, collective flow and suppression observables, are summarized. The extracted charm and bottom quark diffusion coefficients are almost identical and come to a small value of $D_s(2\pi T) \sim 2-4$ at temperatures $(1-1.5T_c)$ near the phase boundary, implying a strong coupling of heavy quarks with the medium. It is remarkable to find that the

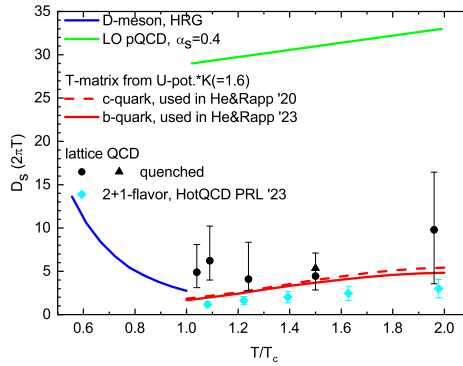


Figure 3. Charm [12] and bottom [3] quark spatial diffusion coefficient in unit of thermal wave length as extracted from the nonperturbative transport model calculations of charm- and bottom-hadron observables in comparison with experimental data in PbPb collisions. The recent full lattice QCD result [15] is also plotted for comparison. The D -meson diffusion coefficient (blue line) is taken from [14].

heavy quark diffusion coefficient extracted from nonperturbative transport model calculations is very comparable to recent full lattice QCD result [15].

4 Conclusions

The bottom hadrochemistry in pp collisions has been addressed in the generalized statistical hadronization model, corroborating that a vast spectrum of additional b -baryon excited states awaits discovery. Using this as a baseline, the b -hadron collective flow pattern in PbPb collisions has been computed in a nonperturbative transport model and a small heavy quark diffusion coefficient has been extracted.

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