Nonuniversality of heavy quark hadronization in elementary high-energy collisions

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It has been traditionally hypothesized that the heavy quark (charm c and bottom b) fragmentation is universal across different collision systems, based on the notion that hadronization as a soft process should occur at the characteristic nonperturbative quantum chromodynamics (QCD) scale, Λ_{QCD}. However, this universality hypothesis has recently been challenged by the observation that the c- and b-baryon production relative to their meson counterparts in minimum bias proton-proton (pp) collisions at the CERN Large Hadron Collider (LHC) energies is significantly enhanced as compared to the electron-positron (e^+e^-) collisions. The conception of nonuniversality is unambiguously reinforced by the latest measurement of the charged-particle multiplicity dependence of the b-baryon–to–meson yield ratio, Λ_b/B, by the LHCb experiment in $\sqrt{s} = 13$ TeV pp collisions at the LHC, evolving continuously from the saturation value in minimum bias pp collisions toward the small value in e^+e^- collisions as the system size gradually reduces. We address the multiplicity dependence of b-baryon production in the canonical statistical hadronization model with input b-hadron spectrum augmented with many hitherto unobserved states from quark model predictions. We demonstrate that the decreasing trend of the Λ_b/B toward low multiplicities can be quantitatively understood from the canonical suppression on the yield of Λ_b, as caused by the requirement of strict conservation of baryon number in sufficiently small systems. We have therefore proposed a plausible scenario for understanding the origin of the nonuniversality of heavy quark fragmentation in elementary collisions.

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I. INTRODUCTION

Owing to their large masses, the production of heavy quarks (charm c and bottom b) is arguably separated from their hadronization, as implied in the quantum chromodynamics (QCD) factorization theorem describing the production cross sections of heavy hadrons at collider energies [1]. While the heavy quark partonic cross section can be computed as perturbative series in powers of the coupling constant, the hadronization, usually termed fragmentation in elementary collisions, is an intrinsically soft process and thus relies on phenomenological modeling [2]. Fragmentation fractions of heavy quarks into weakly decaying heavy hadrons (including feed-down contributions from excited states via strong or electromagnetic decays) and ratios between their production yields provide critical probes of the pertinent hadronization mechanisms. Traditionally these fractions (and thus ratios) are thought to be universal across different colliding systems and energies [3].

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However, recent measurements of the charm baryon-to-meson production ratios (Λ_c/D, Σ_c/D, and Ξ_c/D) by ALICE experiment in minimum bias pp collisions at the CERN Large Hadron Collider (LHC) energies have revealed a significant enhancement at low transverse momentum (p_T) relative to the corresponding values in e^+e^- collisions [4–7], therefore challenging the universality hypothesis. A significantly larger b baryon-to-meson yield ratio (Λ_b/B) at low p_T compared to e^+e^- collisions has also been observed by the LHCb experiment [8,9] in pp collisions and earlier in $p\bar{p}$ collisions at the Tevatron [10]. To account for the enhancement of these ratios in hadronic collisions, a statistical hadronization model (SHM) was put forward by assuming *relative* chemical equilibrium between the production yields of different heavy hadron species and augmenting the c- or b-baryon mass spectrum with many hitherto unobserved but theoretically predicted excited states [11,12]; the observed enhancement of the Λ_c and Λ_b production was attributed to the feed-down from these "missing" states. The measured Λ_c/D in pp collisions was also explained by PYTHIA8 calculations that include new color-reconnection "junctions" fragmenting into baryons [13] and by a coalescence model in the presence of a deconfined partonic droplet [14].

The charged-particle-multiplicity dependent measurements provide a natural means to quantify the evolution of these ratios from e^+e^- to minimum bias pp collisions, and thus characterize how the fragmentation of heavy quarks depends on the density of partons involved. This has been undertaken by the ALICE experiment in pp collisions at $\sqrt{s} = 13$ GeV, where Λ_c^+/D^0 was measured as a function of charged-particle pseudorapidity density $\langle dN_{\rm ch}/d\eta\rangle$ at midrapidity and shown to exhibit a significant increase from the lowest to highest multiplicity intervals for $1 < p_T < 12$ GeV [15]. The same endeavor has been recently also pursued by the LHCb experiment in the b sector in $\sqrt{s} = 13$ GeV pp collisions at forward rapidity; both B_s^0/B^0 [16] and Λ_b^0/B^0 [9] were measured and demonstrated to increase with multiplicity when limited to relatively low p_T. In particular, the high-quality data of p_T-integrated Λ_b^0/B^0 converges to the value measured in e^+e^- collisions at the lowest multiplicity and increases by a factor of ≈ 2 toward the saturation value at high multiplicities [9], providing an ideal chance of looking into the evolution of heavy quark fragmentation versus the density of the hadronic environment. In this regard, effects of the partonic environment on heavy quark hadronization have long been proposed in elementary hadronic collisions [17,18].

To account for the system size dependence of the Λ_c^+/D^0, it was noted that strict conservation of quantum charges, e.g., baryon number, is important when the multiplicity becomes sufficiently low; therefore, one should turn to the version of canonical ensemble of SHM [19]. Indeed, the *strict* baryon number conservation would require the simultaneous production of an antibaryon when creating a baryon, which is very expensive in term of energy, given that the lightest baryon (proton) already has a large mass ≈ 1 GeV (compared to the typical hadronization temperature $T_H \sim 160$–170 MeV). Consequently, the production of the heavy baryons suffers from a canonical suppression, resulting in a decreasing baryon-to-meson ratio toward low multiplicities.

In the present work, we generalize the canonical treatment of the statistical hadronization to the b sector, utilizing the augmented b-hadron spectrum that proved indispensable for the statistical interpretation of the enhancement of Λ_b/B in minimum bias pp collisions relative to the e^+e^- case [12]. We compute the chemical factors and thermal densities of b hadrons from the canonical partition function and demonstrate the system size dependence of the production of B_s mesons and Λ_b and Ξ_b baryons relative to that of B mesons, for both the integrated and p_T differential yields. We show that, with the b-hadron input spectrum augmented with many more excited states (in particular excited baryons) beyond the current measured listings, LHCb data of the multiplicity dependence of Λ_b/B can be quantitatively understood from the canonical suppression on Λ_b production as caused by the *strict* conservation of baryon number toward small multiplicities, thereby unveiling a plausible origin of the non-universality of heavy quark hadronization in elementary collisions that is currently under hot debates [20–22].

II. CANONICAL PARTITION FUNCTION AND INPUT BOTTOM-HADRON SPECTRUM

When applied to large systems where the fluctuations of quantum charges are relatively small, SHM is formulated in a grand-canonical ensemble (GCE) of an ideal hadron resonance gas [23]. The Abelian quantum charges, such as electric charge Q, baryon number N, strangeness S, charm number C, and bottom number B are thus conserved *on average* and regulated by the corresponding chemical potentials $\vec{\mu} = (\mu_Q, \mu_N, \mu_S, \mu_C, \mu_B)$. The primary mean yield for the jth hadron produced from GCE-SHM is given by

$$\langle N_j\rangle^{GCE} = \gamma_s^{N_{sj}}\gamma_c^{N_{cj}}\gamma_b^{N_{bj}} z_j e^{\vec{\mu}\cdot\vec{q}_j/T_H}, \tag{1}$$

where $\vec{q}_j = (Q_j, N_j, S_j, C_j, B_j)$ denote the quantum charges for the hadron and z_j is the one-particle partition function

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

which specifies the chemical equilibrium multiplicity of the jth hadron of mass m_j and spin J_j in a fireball of volume V under the Boltzmann approximation at hadronization temperature T_H, with K_2 being the modified Bessel function of the second order. In Eq. (1), γ_s, γ_c, and γ_b denote fugacities that account for the deviation from chemical equilibrium for hadrons containing N_{sj}, N_{cj}, and N_{bj} strange, charm, and bottom quarks or antiquarks, respectively.

In contrast, for sufficiently small systems where relative fluctuations of quantum charges become significant, one has to turn to the canonical ensemble (CE) SHM, in order to *strictly* conserve the quantum charges [24–26], which have been employed to study the light- and heavy-hadron production in elementary collisions [19,26–31]. For a system having conserved quantum charges $\vec{Q} = (Q, N, S, C, B)$ with associated phase angles $\vec{\phi} = (\phi_Q, \phi_N, \phi_S, \phi_C, \phi_B)$, the CE-SHM partition function reads

$$Z(\vec{Q}) = \int_0^{2\pi} \frac{d^5\phi}{(2\pi)^5} e^{i\vec{Q}\cdot\vec{\phi}} \exp\left[\sum_j \gamma_s^{N_{sj}}\gamma_c^{N_{cj}}\gamma_b^{N_{bj}} e^{-i\vec{q}_j\cdot\vec{\phi}} z_j\right], \tag{3}$$

where the volume in z_j should now be understood as the correlation volume V_C that characterizes the range of the *strict* conservation of quantum charges. In Eq. (3), the summation $\sum_j$ should be taken over *all* hadrons up to the most massive b mesons and baryons, for the present aim of investigating the statistical hadronization of b quarks. More specifically, all light hadrons in the Particle Data Group (PDG) listings [32] are included. For c hadrons, in particular c baryons, excited states from relativistic quark model (RQM) predictions [33,34] beyond the current PDG listings are included, which have proved essential for interpreting the observed enhancement of Λ_c/D in minimum bias pp collisions in the GCE-SHM [11]. All charmonium states listed in PDG are also included. For b-hadron spectrum serving as the direct input for the present study, we compare two sets of b hadrons in the same spirit as in the GCE-SHM study for minimum bias collisions [12]: (a) PDG-only states [32] and (b) RQM states [33,34] that additionally include 18 B's, 16 B_s's, 27 Λ_b's, 45 Σ_b's, 71 Ξ_b's, and 41 Ω_b's, up to meson (baryon) masses of 6.5 (7.0) GeV.

The primary mean yield of the jth hadron produced from the CE-SHM then reads [19,35]

$$\langle N_j\rangle^{CE} = \gamma_s^{N_{sj}}\gamma_c^{N_{cj}}\gamma_b^{N_{bj}} z_j \frac{Z(\vec{Q} - \vec{q}_j)}{Z(\vec{Q})}. \tag{4}$$

TABLE I. Chemical factors (CF) of the direct ground-state b hadrons at $T_H = 170\,\mathrm{MeV}$, $\gamma_s = 0.6$, $\gamma_c = 15$, and $\gamma_b = 10^9$ for varying correlation volumes, with b-hadron input spectrum taken from the RQM scenario. The ratios of the CF's of B_s^0, Λ_b^0, and Ξ_b^{0-} to $\bar{B}^0$ are also summarized in the last three rows.

CF	$V_C = 5\ \mathrm{fm}^3$	10	20	30	50	100	200
$\bar{B}^0$	0.0097194	0.023927	0.058660	0.094845	0.16493	0.32591	0.56988
B^-	0.0078259	0.021863	0.056893	0.093168	0.16331	0.32438	0.56858
$\bar{B}_s^0$	0.0039920	0.013624	0.045935	0.082725	0.15364	0.31546	0.56101
Λ_b^0	0.0049325	0.014844	0.047305	0.084415	0.15574	0.31768	0.56300
Ξ_b^{0-}	0.0021863	0.0089128	0.037336	0.073498	0.14477	0.30720	0.55402
Ω_b^-	0.0004649	0.0030092	0.019475	0.047296	0.11221	0.27231	0.52265
$\bar{B}_s^0/\bar{B}^0$	0.41072	0.56939	0.78307	0.87221	0.93155	0.96793	0.98443
$\Lambda_b^0/\bar{B}^0$	0.50749	0.62039	0.80643	0.89003	0.94427	0.97474	0.98793
$\Xi_b^{0-}/\bar{B}^0$	0.22494	0.37250	0.63648	0.77493	0.87776	0.94259	0.97217

The *chemical factor* $Z(\vec{Q} - \vec{q}_j)/Z(\vec{Q})$ in favor of the chemical potential term in Eq. (1) arises from the requirement of *exact* conservation of quantum charges. As will be shown in the following, for a completely neutral system (i.e., $\vec{Q} = 0$ and thus $\vec{\mu} = 0$), this factor for charged hadrons with $\vec{q}_j \neq 0$ is always less than unity but only tends to unity at asymptotically large volumes, therefore characterizing the *canonical suppression* of the production of charged hadrons at small system size.

III. SYSTEM SIZE DEPENDENCE OF *b*-HADRON YIELDS

The measurements of charged particle multiplicity dependence of B_s/B [16] and Λ_b/B [9] by the LHCb experiment in $\sqrt{s} = 13\,\mathrm{TeV}$ *pp* collisions were performed at forward rapidity ($2 < y < 4.5$), where particle and antiparticle production is not totally symmetric. However, the measured asymmetry between Λ_b^0 and $\bar{\Lambda}_b^0$ is at the level of ≈1–2 % in $\sqrt{s} = 7\,\mathrm{TeV}$ *pp* collisions at $2 < y < 4.5$, and becomes even smaller in $\sqrt{s} = 8\,\mathrm{TeV}$ collisions [36]. Therefore, as a good approximation, we focus on a completely neutral system with vanishing quantum charges [$\vec{Q} = (Q, N, S, C, B) = (0, 0, 0, 0, 0)$] in the following CE-SHM studies, with RQM being the default scenario for b-hadron spectrum input. Furthermore, although quantum-charge-momentum correlations have been integrated out in the full phase space in CE-SHM [Eq. (4)], we expect the longitudinal boost invariance [37] to work well for the rapidity range covered by the LHCb experiment and thus the particle yield ratios likely to be constant across different rapidity slices (as supported by the observation of the flat behavior of charged-particle multiplicity [38] as well as Λ_b/B [39] across a wide rapidity window in minimum bias *pp* collisions at the LHC energies), rendering the comparison of CE-SHM predictions with LHCb data feasible. For very forward rapidity, $\eta \geqslant 4$–5 [38], where boost invariance breaks down, the rapidity dependence of these particle yield ratios should be boiled down to their system size ($dN_{ch}/d\eta$) dependence discussed in Sec. III C.

A. Chemical factors of direct *b* hadrons

To evaluate the canonical partition function, hadrons to be summed over in the exponential of Eq. (3) are divided into three categories [19]: the completely neutral mesons with $\vec{q}_j = (Q_j, N_j, S_j, C_j, B_j) = (0, 0, 0, 0, 0)$, e.g., π^0, ρ^0, ϕ, and J/ψ; the charged mesons, including positively charged mesons with at least one of $Q_j = +1, S_j = +1, C_j = +1, B_j = +1$ but $N_j = 0$, e.g., $\pi^+, K^+, D^+, D_s^+, B^+, B_s^0$ and their antimesons; the baryons with $N_j = +1$ and antibaryons with $N_j = -1$. More details of the method can be found in Ref. [19]. While the GCE-SHM analysis of light-hadron yields in heavy-ion collisions [23] indicates a hadronization temperature very comparable to the pseudocritical chiral transition temperature (≈155 MeV) as determined by lattice QCD, a higher hadronization temperature (≈ 170 MeV) appears to be more appropriate in elementary reactions, in particular for heavy hadrons [28,29]. Therefore in the present work, we take the hadronization temperature to be $T_H = 170\,\mathrm{MeV}$. To proceed, the strangeness under-saturation parameter (fugacity) is fixed to be the typical value $\gamma_s = 0.6$ in elementary collisions [11,12], which has been shown to be insensitive to the system size for charged particle multiplicity $dN_{ch}/d\eta \leqslant 50$ [30]. For the c and b fugacity, γ_c and γ_b, respectively, that measure their initial hard production in excess of the chemical equilibrium limit, we take the typical value of $\gamma_c \approx 15$ [19] and $\gamma_b \approx 10^9$ determined in the canonical SHM study of c- and b-hadron production in semicentral heavy-ion collisions at the LHC energy [40,41]. We have checked that our final result of the b baryon relative to b-meson production is rather robust against a significant variation of γ_b within four orders of magnitude around the default value used here, since anyway the rather massive b hadrons only account for a tiny contribution to the canonical partition function [through summation in the exponential of Eq. (3)].

In Table I, chemical factors (CF) of the direct ground state b hadrons are displayed for varying correlation volumes (V_C). At small V_C, $\bar{B}_s^0$, and Λ_b^0 exhibit significantly smaller CF's than $\bar{B}^0$ and B^- (we focus on mesons and baryons both containing a b quark, instead of the antiquark $\bar{b}$), owing to their additional canonical suppression brought about by the *exact* strangeness and baryon number conservation, respectively. Despite all being b baryons, the CF's of Ξ_b^{0-} and Ω_b^- are further progressively smaller compared to those of Λ_b^0, as a result of their increasing strangeness content leading to stronger canonical strangeness suppression. As the correlation volume increases, the canonical suppression effects induced by the *exact* strangeness and baryon-number conservation

TABLE II. Total (i.e., with feed-downs) thermal densities of ground-state b hadrons at $T_H = 170$ MeV, $\gamma_s = 0.6$, $\gamma_c = 15$, and $\gamma_b = 10^9$ for varying correlation volumes, with b-hadron input spectrum taken from the RQM scenario. The ratios of the thermal densities of B_s^0, Λ_b^0, and Ξ_b^{0-} to $\bar{B}^0$ are also summarized in the last three rows. The last column denotes the values in the grand canonical limit.

$n_\alpha (\times 10^{-5}\ \mathrm{fm}^{-3})$	$V_C = 5\ \mathrm{fm}^3$	10	20	30	50	100	200	GCE
$\bar{B}^0$	1.1220	2.7920	6.9508	11.313	19.759	39.148	68.534	120.41
B^-	0.96934	2.6261	6.8105	11.181	19.635	39.038	68.452	120.45
$\bar{B}_s^0$	0.14641	0.47267	1.5299	2.7242	5.0273	10.285	18.263	32.513
Λ_b^0	0.29886	0.90201	2.8845	5.1551	9.5210	19.435	34.453	61.702
Ξ_b^{0-}	0.043883	0.17479	0.72393	1.4247	2.8132	5.9882	10.818	19.548
Ω_b^-	0.00028060	0.0018164	0.011755	0.028549	0.067730	0.16437	0.31548	0.63204
$\bar{B}_s^0/\bar{B}^0$	0.13049	0.16929	0.22010	0.24080	0.25443	0.26273	0.26648	0.27002
$\Lambda_b^0/\bar{B}^0$	0.26635	0.32307	0.41499	0.45568	0.48186	0.49644	0.50271	0.51243
$\Xi_b^{0-}/\bar{B}^0$	0.039110	0.062602	0.10415	0.12594	0.14238	0.15296	0.15785	0.16235

attenuate, and hence at asymptotically large volume, the CF's of all b hadrons end up with almost the same residual value $\approx$0.56 that arises solely from their *common* canonical bottom-number suppression. This is also seen from the gradual increase of the *relative* canonical suppression (i.e., the ratios of CF's listed in the last three rows of Table I) $\bar{B}_s^0/\bar{B}^0$, $\Lambda_b^0/\bar{B}^0$, and $\Xi_b^{0-}/\bar{B}^0$ toward unity from small to large volumes. Incidentally for the charm sector, the residual canonical charm suppression common for all charm hadrons was shown to be important even for light ion collisions [40].

B. Total thermal densities of ground-state b hadrons

With the primary mean yields of b hadrons computed from Eq. (4), the total thermal densities of ground state b hadrons are obtained from the sum of the direct one and the feed-down contributions from excited states

$$n_\alpha = \frac{\langle N_\alpha\rangle^{CE}}{V_C} + \sum_j \frac{\langle N_j\rangle^{CE}}{V_C}\cdot \mathrm{BR}(j\to\alpha), \qquad (5)$$

where the branching ratios (BR) for excited b hadrons decaying to the ground states were given from a $^3P_0$ quark model estimate [12]. These densities are shown in Table II for varying correlations volumes, together with the GCE-SHM results. An immediate observation is that as the volume increases, the thermal density for each b-hadron also grows. While these thermal densities at the largest volume ($V_C = 200\,\mathrm{fm}^3$) computed here are still far from the GCE-SHM values, the corresponding ratios between them are already almost the same as the grand-canonical limiting values, simply because the effects of canonical strangeness and baryon-number suppression already become vanishing and the residual canonical bottom-number suppression is *common* for all b hadrons. As the most important finding of the present work, the thermal density ratios $\bar{B}_s^0/\bar{B}^0$, $\Lambda_b^0/\bar{B}^0$, and $\Xi_b^{0-}/\bar{B}^0$, as summarized in the last three rows of Table II and also plotted in Fig. 1, demonstrate a marked system-size dependence, amounting to a factor of 2–4 reduction from the saturation value in the grand-canonical limit to the smallest volume and serving as a direct signal of the canonical suppression effects due to *strict* conservation of strangeness and baryon number.

C. Confronting LHCb data

In order to compare the system size dependence of the $\bar{B}_s^0/\bar{B}^0$, $\Lambda_b^0/\bar{B}^0$ as uncovered from the present GC-SHM study with the LHCb measurements [9,16], where the system size was quantified by the total number of charged tracks, we follow a previous canonical thermal study of the light hadrons that suggests a linear dependence between the correlation volume and the measured charged particle multiplicity [30]. We find that assuming a mean correlation volume $\langle V_C\rangle = 22.6\,\mathrm{fm}^3$ corresponding to the mean number of tracks $\langle N_{\mathrm{tracks}}^{\mathrm{VELO}}\rangle_{\mathrm{NB}}$, one could establish a simple relation $V_C/\langle V_C\rangle = N_{\mathrm{tracks}}^{\mathrm{VELO}}/\langle N_{\mathrm{tracks}}^{\mathrm{VELO}}\rangle_{\mathrm{NB}}$ that translates the predicted volume dependence of $\Lambda_b^0/\bar{B}^0$ into a best fit of the LHCb data, as shown in Fig. 2(b) together with $\bar{B}_s^0/\bar{B}^0$ [Fig. 2(a)], where we also compare the RQM versus PDG scenario as the b-hadron spectrum input. While the current LHCb data of the system size dependence of $\bar{B}_s^0/\bar{B}^0$ do not allow for a discrimination between the PDG and RQM scenario [however the minimum bias datum indicated by the filled box at the right vertical axis in panel (a) prefers the RQM scenario], data of $\Lambda_b^0/\bar{B}^0$ show an unambiguous preference for the RQM scenario. While

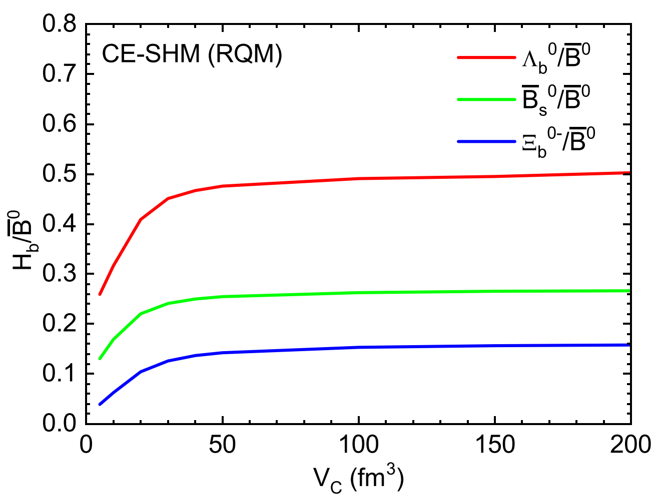

FIG. 1. The correlation volume dependence of the ratios of the thermal densities of $\bar{B}_s^0$, Λ_b^0, and Ξ_b^{0-} to that of $\bar{B}^0$ from CE-SHM with b-hadron input spectrum taken from the RQM scenario.

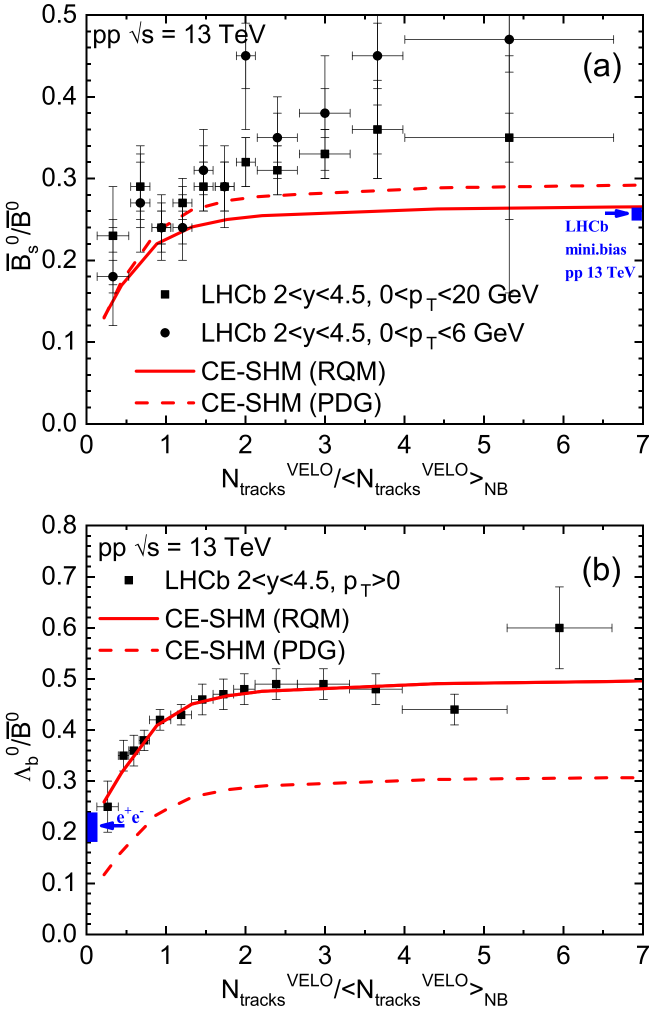

FIG. 2. The system size dependence of the yield ratios of (a) $\bar{B}_s^0/\bar{B}^0$ and (b) $\Lambda_b^0/\bar{B}^0$ as predicted from CE-SHM with b-hadron input spectrum taken from the RQM (solid lines) versus PDG (dashed lines) scenario, in comparison with LHCb data [9,16]. The filled box at the right vertical axis of the upper panel indicate a separate measurement of $\bar{B}_s^0/\bar{B}^0 = 0.2539 \pm 0.0079$ in minimum bias pp collisions at the same $\sqrt{s} = 13$ TeV by the LHCb experiment [42], and the filled box at the left vertical axis of the lower panel indicates the $\Lambda_b^0/\bar{B}^0$ measured in e^+e^- collisions [9,10].

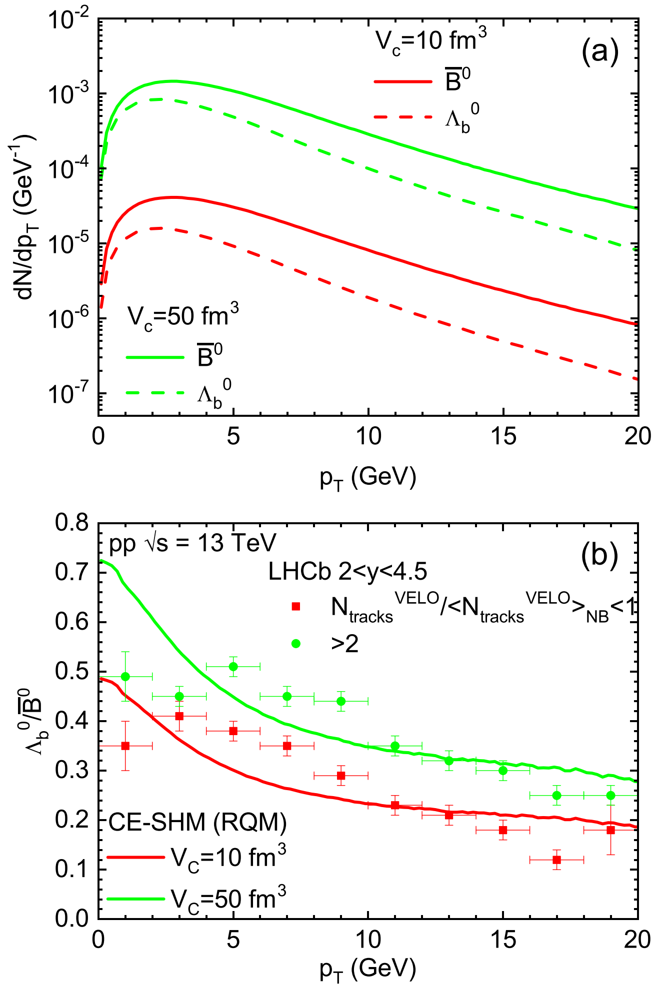

FIG. 3. (a) The p_T differential yields of Λ_b^0 and $\bar{B}^0$ at two correlation volumes. (b) The corresponding p_T differential $\Lambda_b^0/\bar{B}^0$'s in comparison with LHCb data in two multiplicity intervals [9], respectively.

the uncertainty in the linear relation assumed between correlation volume and the number of charged tracks persists, the description of the decreasing behavior of the $\Lambda_b^0/\bar{B}^0$ data from the saturation value in minimum bias collisions toward the e^+e^- value at the smallest system size, as emerging from our CE-SHM computations within the RQM scenario, should be qualitatively robust. This provides another strong evidence for the existence of many not-yet-observed excited states of b hadrons (particularly baryons) [12], and suggests a plausible mechanism for the nonuniversality of heavy quark fragmentation in elementary collisions, namely the canonical suppression of baryon production at sufficiently small system size as caused by the requirement of *exact* baryon-number conservation.

IV. FRAGMENTATION SIMULATION: p_T DIFFERENTIAL RATIOS

It has long been suggested that the p_T spectra of primarily produced light hadrons in elementary collisions follow the Boltzmann distribution, which was regarded as a major indication in favor of the statistical hadron production [43]. It has indeed been shown that the p_T spectra of stable light hadrons in the low p_T ($\leqslant$1–2 GeV) regime can be well described by assuming a thermal-like shape (at the same hadronization temperature as for calculating the thermal yields, but boosted by an average transverse four-velocity of the prehadronic clusters whose phase space are to be populated in the purely statistical fashion) for all primary hadrons, which are then subject to decays into stable light hadrons [44,45]. However, the p_T of heavy hadrons is largely inherited from the parent heavy quarks that are produced in perturbative primordial hard processes and thus possess power-law p_T shape. Therefore, while the integrated production yields of various heavy-hadron species obey *relative* chemical equilibrium as dictated by the CE-SHM, their p_T spectra are not likely to be of thermal shape. A full understanding of this inconsistence may require building pertinent dynamics into the formulation of SHM, which is beyond the scope of the present work.

To compute the p_T differential spectrum and ratios of ground-state b hadrons, we build the computed statistical densities into a b quark fragmentation simulation [12]. We sample the perturbative b quark p_t spectrum computed from FONLL [46,47] in $\sqrt{s} = 13$ TeV collisions and perform the fragmentation simulation with the fragmentation function [48]

$$D_{b\to H_b}(z) \propto z^{\alpha}(1-z)\,, \tag{6}$$

where $z = p_T/p_t$ is the fraction of the b hadron's (H_b) transverse momentum, p_T, over the b-quark one, p_t. The fragmentation weight of H_b is assumed to be proportional to its primary thermal density, $\langle N_{H_b}\rangle^{CE}/V_C$ [Eq. (4)], in the spirit of *relative* chemical equilibrium. Each H_b produced from fragmentation is then decayed into the ground-state particles with a constant matrix element (i.e., decay kinematics solely determined by phase space) and BR's used in Eq. (5) [12]. The parameter α in Eq. (6) is tuned to fit the slope of the p_T spectrum of ground-state b hadrons. For simplicity, we take $\alpha = 45, 25, 8$ for all B mesons, all B_s mesons and all b baryons, respectively, following Ref. [12] for minimum bias collisions. The obtained p_T differential spectra of $\bar{B}^0$ and Λ_b^0, normalized to their SHM yields in Table II, are shown in Fig. 3(a) for two correlation volumes. The corresponding p_T differential ratios of $\Lambda_b^0/\bar{B}^0$, as displayed in Fig. 3(b), are compared to the LHCb data in the low and high multiplicity intervals, respectively. The separation of $\Lambda_b^0/\bar{B}^0$ between these two intervals and its trend of p_T dependence can be qualitatively described.

V. SUMMARY

We have addressed the system size dependence of the production of b baryons relative to that of mesons in high-energy pp collisions. By introducing many hitherto unobserved but theoretically predicted b hadrons (in particular excited baryons) into the canonical ensemble SHM, we have demonstrated that the charged-particle-multiplicity dependence of Λ_b/B measured by the LHCb experiment can be quantitatively described, attributed to the canonical suppression on Λ_b production toward low multiplicities as a result of *exact* conservation of baryon number as required by the canonical treatment of SHM. The Λ_b/B as explored bridges continuously the gap between the saturation value in minimum bias pp collisions and the small value in e^+e^- collisions, reinforcing the conception that the heavy quark hadronization depends on the hadronic environment involved in the collision systems. We have therefore proposed a possible origin of the nonuniversality of heavy quark hadronization in terms of canonical baryon suppression at sufficiently small system size in the presence of many "missing" baryons awaiting discovery.

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