Bottom quark hadronization in proton-proton collisions & in QGP

Based on MH & R. Rapp, PRL131, 012301 (2023)
Y. Dai & MH, PRC110, 034905 (2024)

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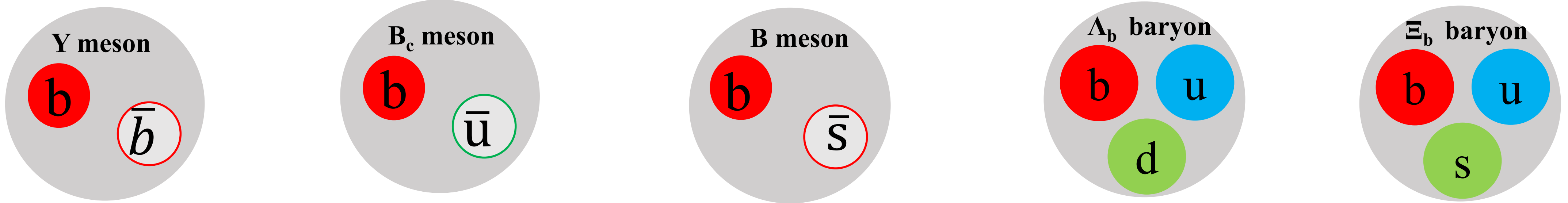
Heavy quarks & heavy hadrons

- Heavy quark $m_Q >> \Lambda_{QCD}$
  $m_c \sim 1.5$ GeV, $m_b \sim 4.5$ GeV

- Bottomonium vs open bottom hadrons



Bottomonium **B mesons** **B_s mesons** **Λ_b-baryons** **Ξ_b-baryons**

hidden b-hadron

open b-hadrons

Heavy quark hadronization in pp collisions

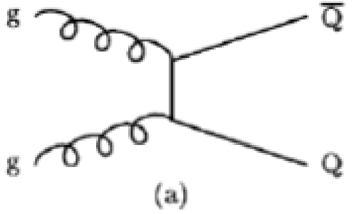
- Heavy quark $m_Q >> \Lambda_{QCD}$ ➔ production separated from hadronization: factorization

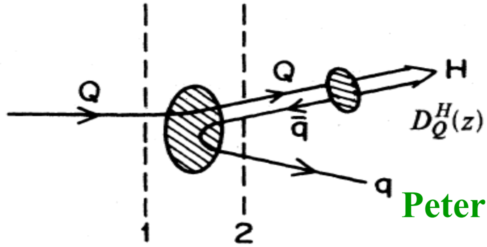
$$\frac{d\sigma^{H_c}}{dp_T^{H_c}}(p_T;\mu_F,\mu_R) = \boxed{\mathrm{PDF}(x_1,\mu_F)\cdot \mathrm{PDF}(x_2,\mu_F)} \otimes \boxed{\frac{d\sigma^c}{dp_T^c}(x_1,x_2,\mu_R,\mu_F)} \otimes \boxed{D_{c\to H_c}(z=p_{H_c}/p_c,\mu_F)}$$

Parton distribution functions (PDFs)

Hard scattering cross section (pQCD)

Fragmentation function (hadronization)



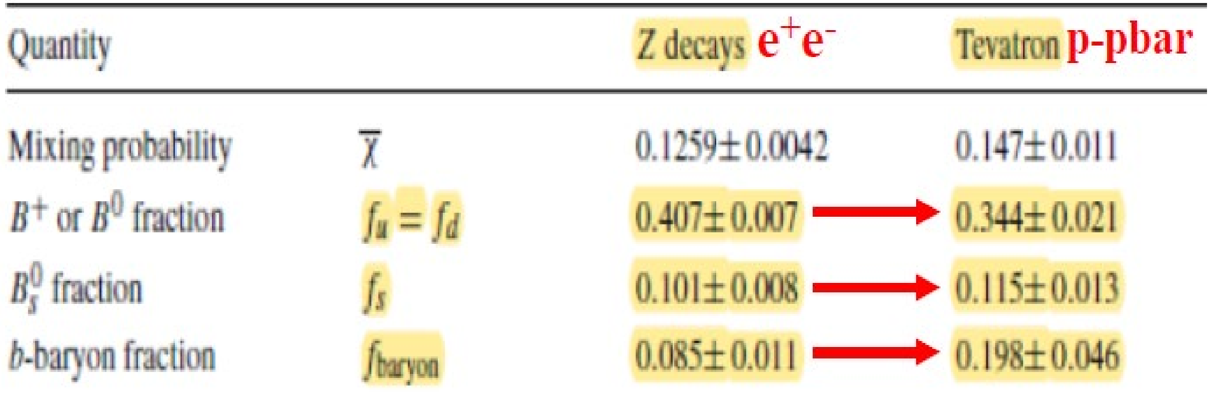


$$D_Q^H(z) = \frac{N}{z[1-(1/z)-\epsilon_Q/(1-z)]^2}$$

Peterson, PRD27, 105 (1983)

- b-quark hadronization: hadro-chemistry non-universal!

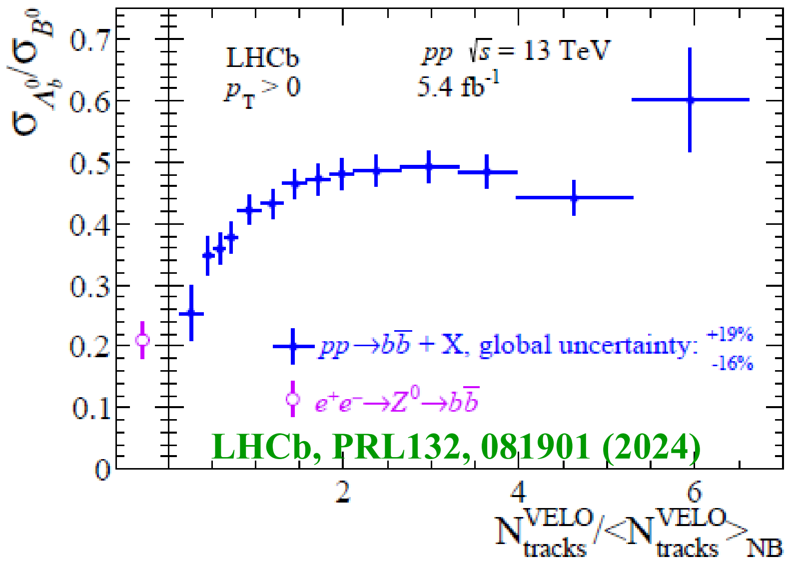
$$f_u + f_d + f_s + f_{baryon} = 1$$



Quantity		Z decays e$^+$e$^-$	Tevatron p-pbar
Mixing probability	$\bar{\chi}$	0.1259±0.0042	0.147±0.011
B^+ or B^0 fraction	$f_u = f_d$	0.407±0.007	0.344±0.021
B_s^0 fraction	f_s	0.101±0.008	0.115±0.013
b-baryon fraction	f_{baryon}	0.085±0.011	0.198±0.046

HFAG, EPJC81, 226 (2021)

Λ_b/B vs pp system size



LHCb, PRL132, 081901 (2024)

Part (I)

Bottom hadro-chemistry in minimum bias pp collisions

Grand-canonical Ensemble Statistical Hadronization Model

Statistical Hadronization Model (SHM)

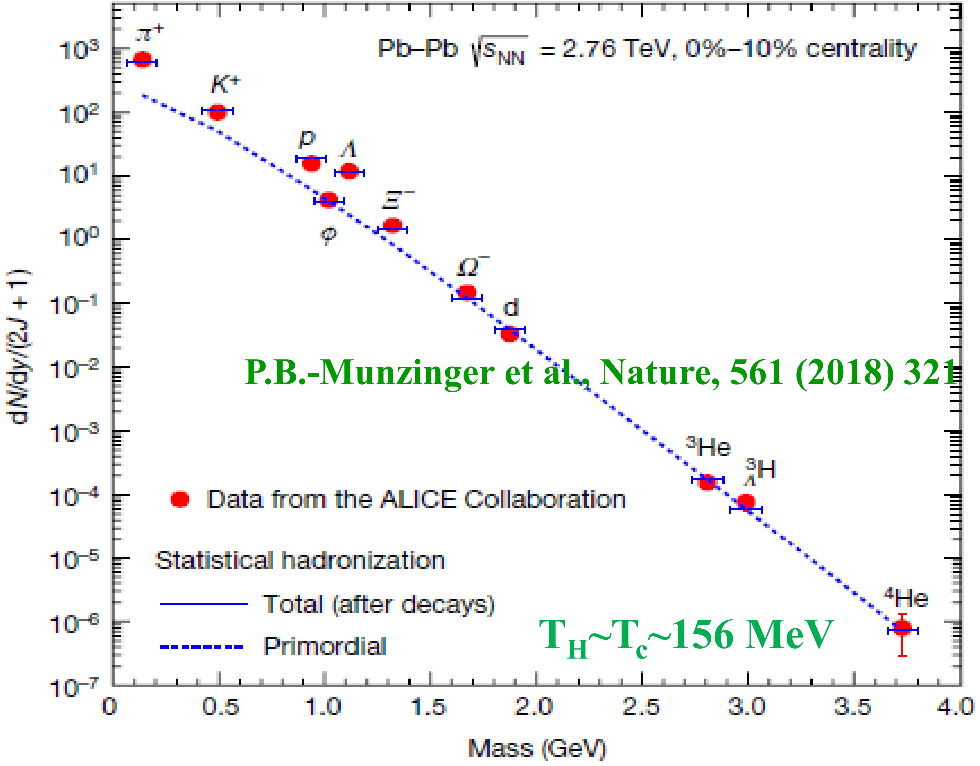
- QCD hadronic population from partons: born into equilibrium = maximum entropy state
- Hadron yields governed by partition function of a free hadron resonance gas (HRG)
- Grand-canonical ensemble SHM for light hadrons in PbPb

$$Z^{GC}(T,V,\mu_Q) = Tr[e^{-\beta(H-\sum_i \mu_{Q_i} Q_i)}]$$

$$logZ^{GC}(T,V,\mu_Q) = \sum_i logZ_i(T,V,\mu_{Q_i})$$

- hadron yield

$$< N_i >= \frac{g_i VT}{2\pi^2}\sum_n^{\infty} \frac{(\pm1)^{n+1}}{n}\lambda_i^n m_i^2 K_2(\frac{nm_i}{T})$$



P.B.-Munzinger et al., Nature, 561 (2018) 321

$T_H \sim T_c \sim 156$ MeV

SHM for Bottom-hadrons in pp

- QCD hadronic population from partons: born into equilibrium = maximum entropy state

Khazeev & Satz, EPJC 52,187 (2007)

- Statistical Hadronization Model (SHM) for bottom-hadron production in pp

➔ bottom quarks produced in early hard processes, bottom-hadron yields not in absolute equilibrium (unlike light hadrons)

➔ *relative* chemical equilibrium achieved between different bottom-hadron species
primary production yields $N_i \propto$ statistical thermal densities

- Mass spectrum of bottom-hadrons: PDG incomplete? ➔ to be augmented by RQM

Grand-canonical SHM for b-hadrons

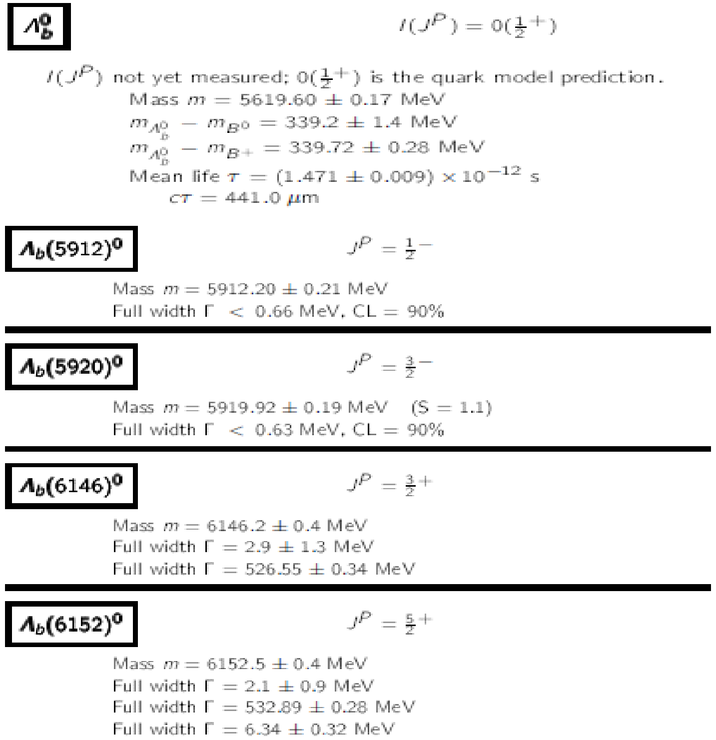
- Grand-canonical ensemble ➔ thermal density for primary b-hadrons

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

γ_s=0.6 -- strangeness suppression factor

T_H=170 MeV -- hadronization temperature

- PDG: 5 B, 4 B_s, 5 Λ_b, 2 Σ_b, 4 Ξ_b, 1 Ω_b



Λ_b^0 $I(J^P) = 0(\frac{1}{2}^+)$

$I(J^P)$ not yet measured; $0(\frac{1}{2}^+)$ is the quark model prediction.

Mass $m = 5619.60 \pm 0.17$ MeV

$m_{\Lambda_b^0} - m_{B^0} = 339.2 \pm 1.4$ MeV

$m_{\Lambda_b^0} - m_{B^+} = 339.72 \pm 0.28$ MeV

Mean life $\tau = (1.471 \pm 0.009) \times 10^{-12}$ s

$c\tau = 441.0\ \mu$m

$\Lambda_b(5912)^0$ $J^P = \frac{1}{2}^-$

Mass $m = 5912.20 \pm 0.21$ MeV

Full width $\Gamma < 0.66$ MeV, CL = 90%

$\Lambda_b(5920)^0$ $J^P = \frac{3}{2}^-$

Mass $m = 5919.92 \pm 0.19$ MeV (S = 1.1)

Full width $\Gamma < 0.63$ MeV, CL = 90%

$\Lambda_b(6146)^0$ $J^P = \frac{3}{2}^+$

Mass $m = 6146.2 \pm 0.4$ MeV

Full width $\Gamma = 2.9 \pm 1.3$ MeV

Full width $\Gamma = 526.55 \pm 0.34$ MeV

$\Lambda_b(6152)^0$ $J^P = \frac{5}{2}^+$

Mass $m = 6152.5 \pm 0.4$ MeV

Full width $\Gamma = 2.1 \pm 0.9$ MeV

Full width $\Gamma = 532.89 \pm 0.28$ MeV

Full width $\Gamma = 6.34 \pm 0.32$ MeV

- RQM: 25 B, 20 B_s, Ebert et al., PRD 84 (2011) 014025 30 Λ_b, 46 Σ_b, 75 Ξ_b, 42 Ω_b

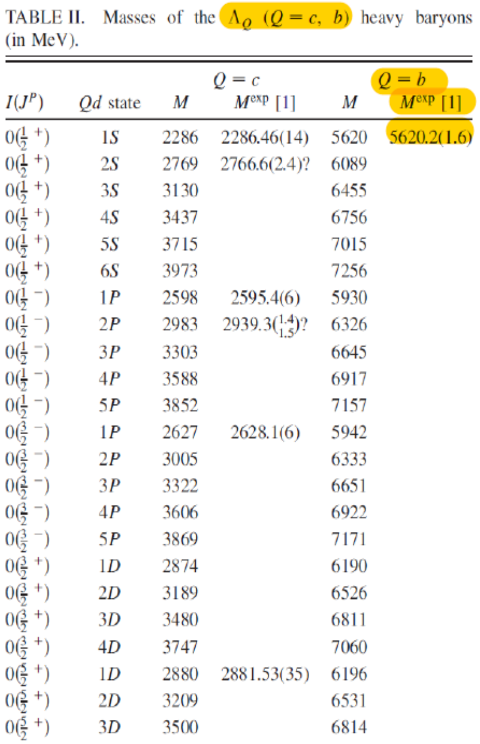


TABLE II. Masses of the Λ_Q $(Q = c,\ b)$ heavy baryons (in MeV).

		$Q = c$		$Q = b$	
$I(J^P)$	Qd state	M	M^{exp} [1]	M	M^{exp} [1]
$0(\frac{1}{2}^+)$	1*S*	2286	2286.46(14)	5620	5620.2(1.6)
$0(\frac{1}{2}^+)$	2*S*	2769	2766.6(2.4)?	6089	
$0(\frac{1}{2}^+)$	3*S*	3130		6455	
$0(\frac{1}{2}^+)$	4*S*	3437		6756	
$0(\frac{1}{2}^+)$	5*S*	3715		7015	
$0(\frac{1}{2}^+)$	6*S*	3973		7256	
$0(\frac{1}{2}^-)$	1*P*	2598	2595.4(6)	5930	
$0(\frac{1}{2}^-)$	2*P*	2983	$2939.3(^{1.4}_{1.5})$?	6326	
$0(\frac{1}{2}^-)$	3*P*	3303		6645	
$0(\frac{1}{2}^-)$	4*P*	3588		6917	
$0(\frac{1}{2}^-)$	5*P*	3852		7157	
$0(\frac{3}{2}^-)$	1*P*	2627	2628.1(6)	5942	
$0(\frac{3}{2}^-)$	2*P*	3005		6333	
$0(\frac{3}{2}^-)$	3*P*	3322		6651	
$0(\frac{3}{2}^-)$	4*P*	3606		6922	
$0(\frac{3}{2}^-)$	5*P*	3869		7171	
$0(\frac{3}{2}^+)$	1*D*	2874		6190	
$0(\frac{3}{2}^+)$	2*D*	3189		6526	
$0(\frac{3}{2}^+)$	3*D*	3480		6811	
$0(\frac{3}{2}^+)$	4*D*	3747		7060	
$0(\frac{5}{2}^+)$	1*D*	2880	2881.53(35)	6196	
$0(\frac{5}{2}^+)$	2*D*	3209		6531	
$0(\frac{5}{2}^+)$	3*D*	3500		6814	

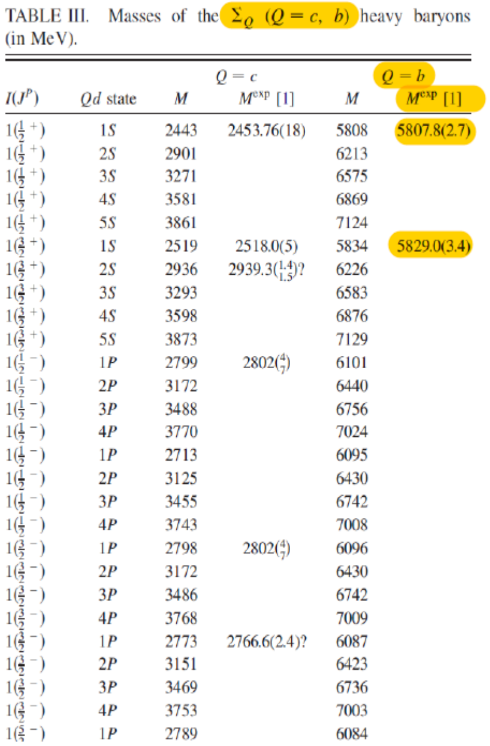
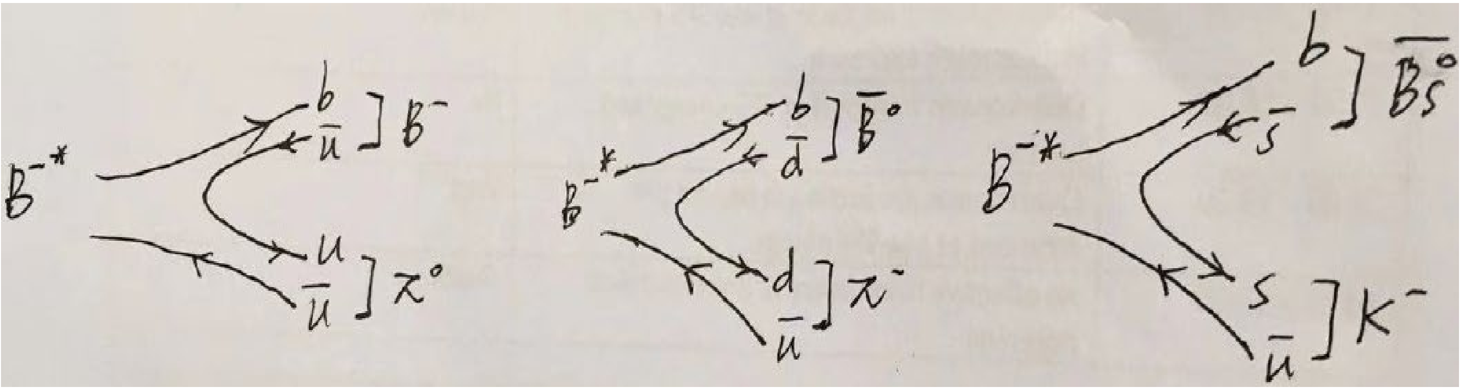


TABLE III. Masses of the Σ_Q $(Q = c,\ b)$ heavy baryons (in MeV).

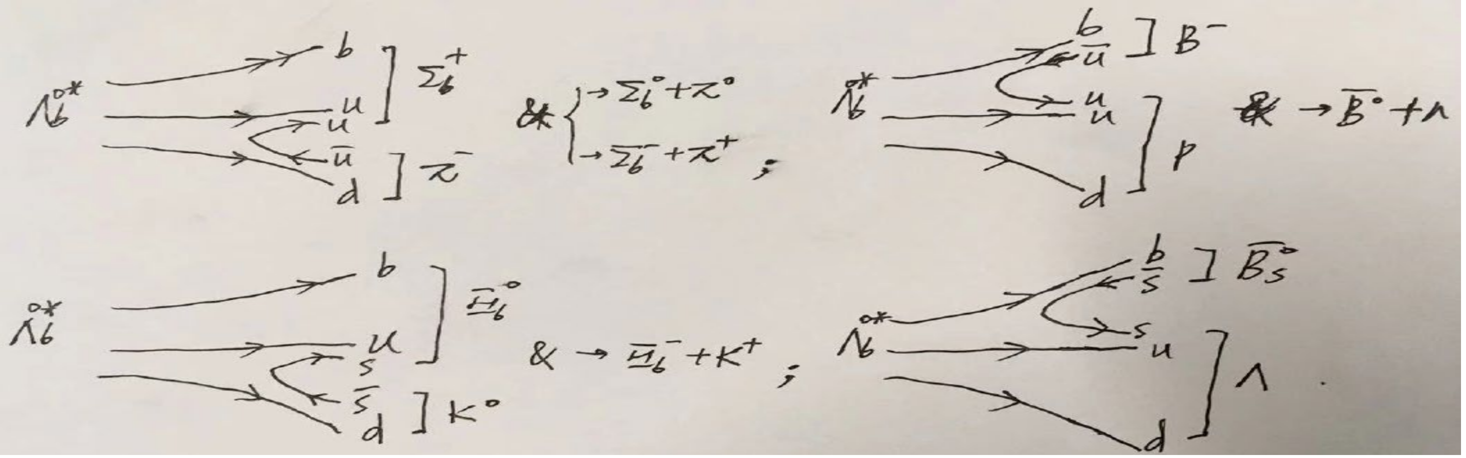
		$Q = c$		$Q = b$	
$I(J^P)$	Qd state	M	M^{exp} [1]	M	M^{exp} [1]
$1(\frac{1}{2}^+)$	1*S*	2443	2453.76(18)	5808	5807.8(2.7)
$1(\frac{1}{2}^+)$	2*S*	2901		6213	
$1(\frac{1}{2}^+)$	3*S*	3271		6575	
$1(\frac{1}{2}^+)$	4*S*	3581		6869	
$1(\frac{1}{2}^+)$	5*S*	3861		7124	
$1(\frac{3}{2}^+)$	1*S*	2519	2518.0(5)	5834	5829.0(3.4)
$1(\frac{3}{2}^+)$	2*S*	2936	$2939.3(^{1.4}_{1.5})$?	6226	
$1(\frac{3}{2}^+)$	3*S*	3293		6583	
$1(\frac{3}{2}^+)$	4*S*	3598		6876	
$1(\frac{3}{2}^+)$	5*S*	3873		7129	
$1(\frac{1}{2}^-)$	1*P*	2799	$2802(^{4}_{7})$	6101	
$1(\frac{1}{2}^-)$	2*P*	3172		6440	
$1(\frac{1}{2}^-)$	3*P*	3488		6756	
$1(\frac{1}{2}^-)$	4*P*	3770		7024	
$1(\frac{1}{2}^-)$	1*P*	2713		6095	
$1(\frac{1}{2}^-)$	2*P*	3125		6430	
$1(\frac{1}{2}^-)$	3*P*	3455		6742	
$1(\frac{1}{2}^-)$	4*P*	3743		7008	
$1(\frac{3}{2}^-)$	1*P*	2798	$2802(^{4}_{7})$	6096	
$1(\frac{3}{2}^-)$	2*P*	3172		6430	
$1(\frac{3}{2}^-)$	3*P*	3486		6742	
$1(\frac{3}{2}^-)$	4*P*	3768		7009	
$1(\frac{3}{2}^-)$	1*P*	2773	2766.6(2.4)?	6087	
$1(\frac{3}{2}^-)$	2*P*	3151		6423	
$1(\frac{3}{2}^-)$	3*P*	3469		6736	
$1(\frac{3}{2}^-)$	4*P*	3753		7003	
$1(\frac{5}{2}^-)$	1*P*	2789		6084	

Strong decay of excited states: Branching ratios

- $^3P_0$ model: A → B + C via creating a q-qbar pair of $J^{PC}=0^{++}$
  → Branching Ratio ∝ # of possible diagrams once a decay channel opens up



$BR(B^{-*} \to B^- + \pi^0) = 1/(1+1+1/3) = 43\%$;
$BR(B^{-*} \to B^0_s + \pi^0) = 1/3/(1+1+1/3) = 14\%$;
$BR(B_s^* \to B^- + K) = 1/(1+1+1/3) = 43\%$

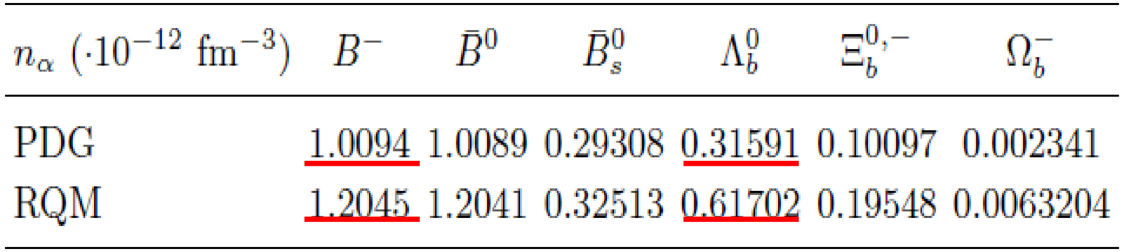


$BR(\Lambda_b^{0*} \to \Lambda_b^0 + 2\pi) = 3/(3+2+2*1/3+1/3) = 54\%$
$BR(\Lambda_b^{0*} \to B^- + p) = 1/(3+2+1/3+2*1/3) = 16\%$
$BR(\Lambda_b^{0*} \to \Xi_b + K) = 2/3/(3+2+1/3+2*1/3) = 11\%$
$BR(\Lambda_b^{0*} \to B^0_s + \Lambda) = 1/3/(3+2+1/3+2*1/3) = 6\%$

Ground-state b-hadron densities/ratios

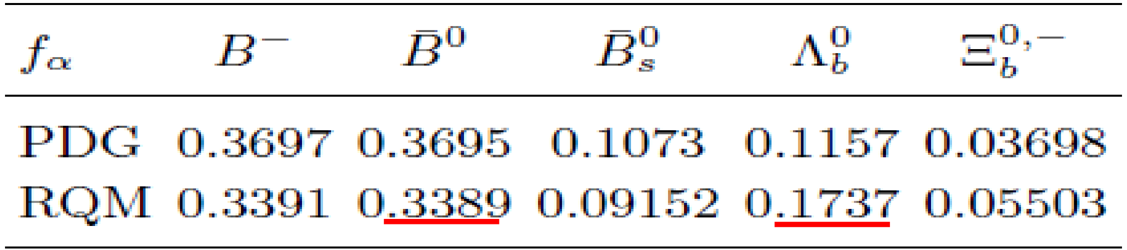
- total density & production fractions of ground state b-hadrons @ T_H=170 MeV

$$n_\alpha = n_\alpha^{\text{primary}} + \sum_i n_i^{\text{primary}} \cdot BR(i \to \alpha)$$



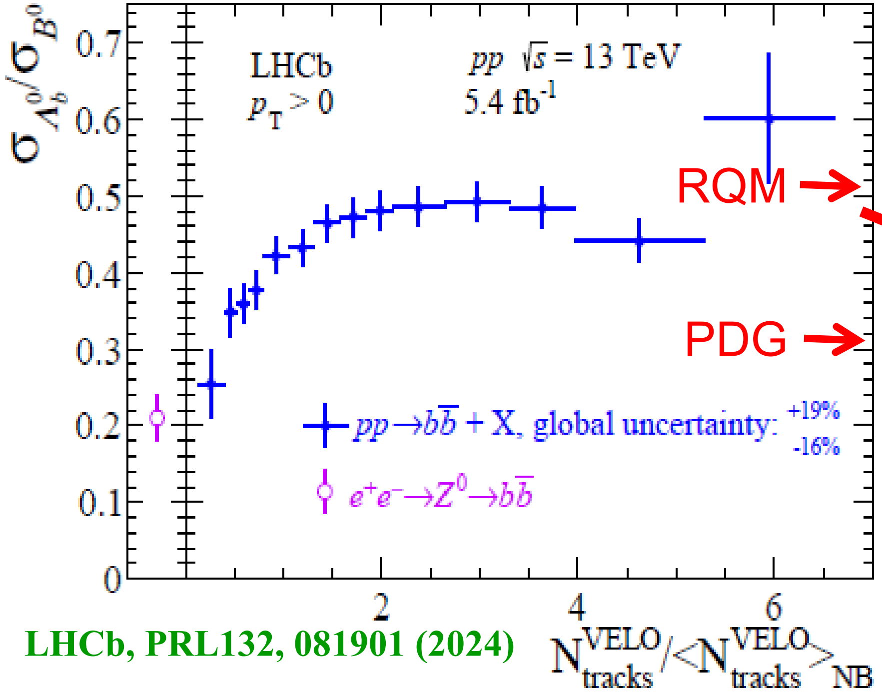
n_α $(\cdot 10^{-12}\ \text{fm}^{-3})$	B^-	$\bar{B}^0$	$\bar{B}_s^0$	Λ_b^0	$\Xi_b^{0,-}$	Ω_b^-
PDG	1.0094	1.0089	0.29308	0.31591	0.10097	0.002341
RQM	1.2045	1.2041	0.32513	0.61702	0.19548	0.0063204

$$f_u + f_d + f_s + f_{\Lambda_b^0} + f_{\Xi_b^{0,-}} + f_{\Omega_b^-} = 1$$



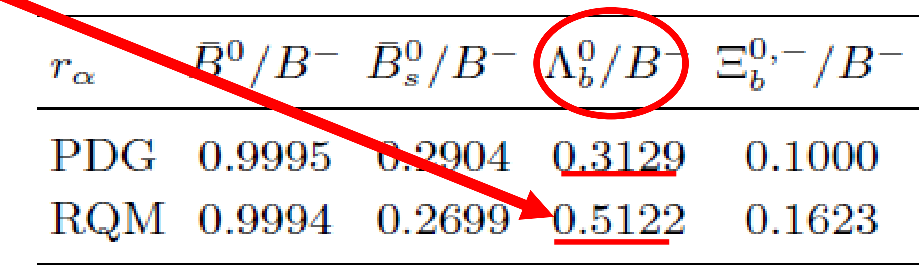
f_α	B^-	$\bar{B}^0$	$\bar{B}_s^0$	Λ_b^0	$\Xi_b^{0,-}$
PDG	0.3697	0.3695	0.1073	0.1157	0.03698
RQM	0.3391	0.3389	0.09152	0.1737	0.05503

→ Agree with Tevatron p-pbar



LHCb, PRL132, 081901 (2024)

- production ratios at large $dN_{ch}/d\eta$: RQM favored!

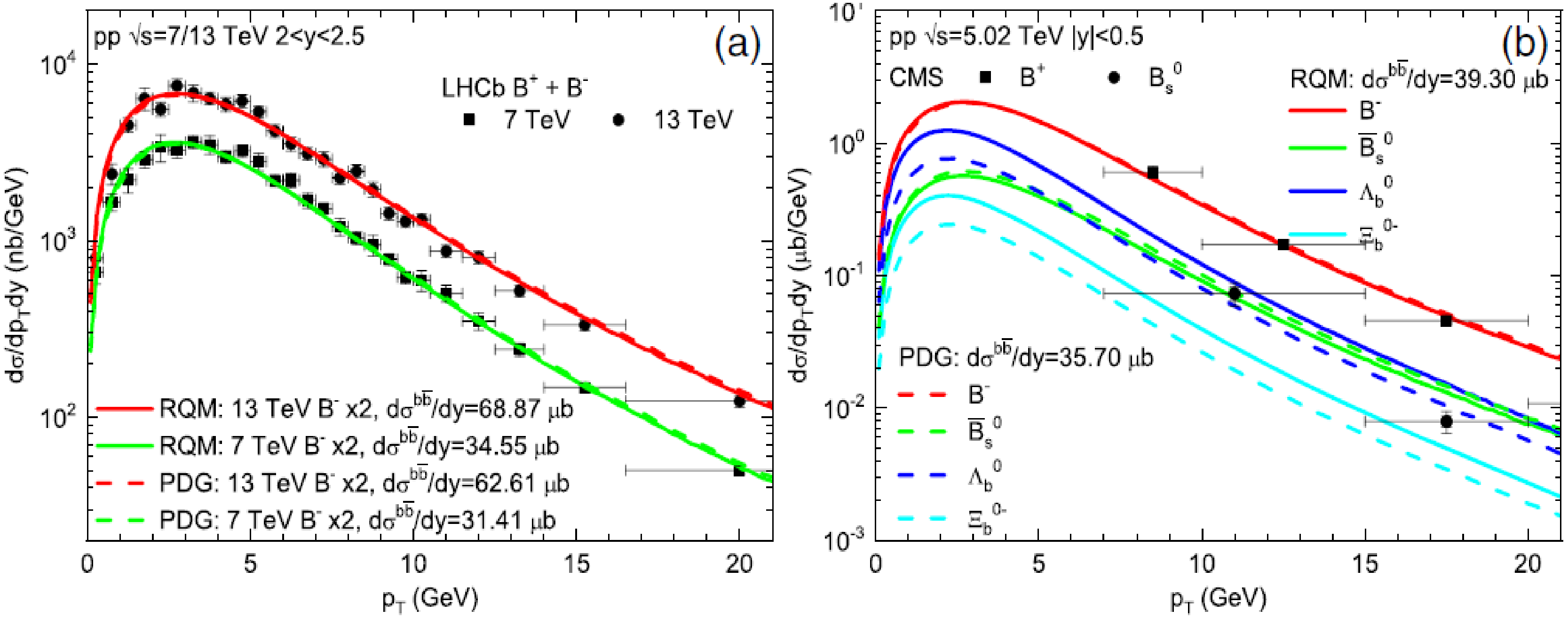


r_α	$\bar{B}^0/B^-$	$\bar{B}_s^0/B^-$	Λ_b^0/B^-	$\Xi_b^{0,-}/B^-$
PDG	0.9995	0.2904	0.3129	0.1000
RQM	0.9994	0.2699	0.5122	0.1623

Fragmentation & p_T-spectra

- FONLL b-quark p_t-spectrum + fragmentation into all primary states + decay simulations
  ➔ ground-state b-hadrons p_T-spectra: $z= p_T/p_t$

$$D_{b\to H_b}(z) \propto z^{\alpha}(1-z), \quad \begin{cases} \text{weight} \propto \text{primary density (relative chemical equilibrium)} \\ \alpha_B=45,\ \alpha_{Bs}=25,\ \alpha_{baryon}=8 \text{ to tune the slope of spectra} \end{cases}$$



- Fitting meson spectra ➔ predicting baryon & total $d\sigma^{bbbar}/dy$= 39.3 µb for 5.02 TeV mid-y based on SHM chemistry ➔ baseline for b-hadron production in Pb-Pb collisions

Part (II)

System size ($dN_{ch}/d\eta$) dependence of bottom hadro-chemistry in pp collisions

Canonical Ensemble Statistical Hadronization Model

Canonical ensemble (CE) SHM

- Canonical ensemble partition function: strict conservation of quantum charges (electric charge, baryon-number, strangeness, charm-, bottom-number)

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

$$z_j = (2J_j+1)\frac{\boxed{V} T_H}{2\pi^2} m_j^2 K_2(\frac{m_j}{T_H})$$

correlation volume ~ system size

- Primary hadron yield: CE vs GCE

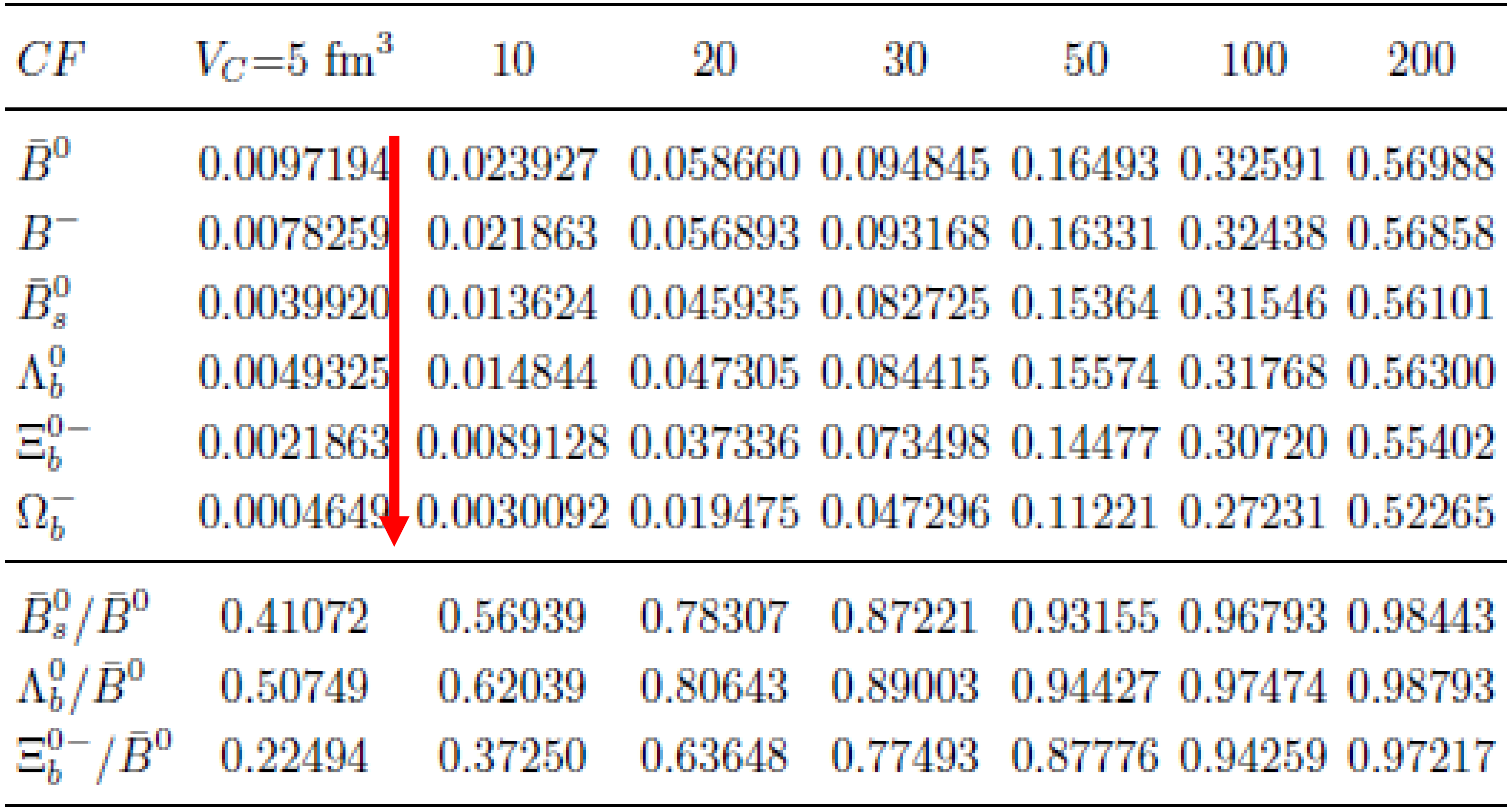
$$\langle N_j\rangle^{CE} = \gamma_s^{N_{sj}} \gamma_c^{N_{cj}} \gamma_b^{N_{bj}} z_j \frac{Z(\vec{Q}-\vec{q}_j)}{Z(\vec{Q})}$$

$$= \langle N_j\rangle^{GCE} \boxed{\frac{Z(\vec{Q}-\vec{q}_j)}{Z(\vec{Q})}}.$$

chemical factor <1: canonical suppression for charged hadron with $\vec{q}_j \neq 0$

- E.g. exact baryon-number conservation requires: simultaneous creation of a pair of baryon and antibaryon ➔ energy-expensive $\exp(-2m_N/T_H)$ ➔ canonical suppression for baryon production

Canonical suppression: chemical factors

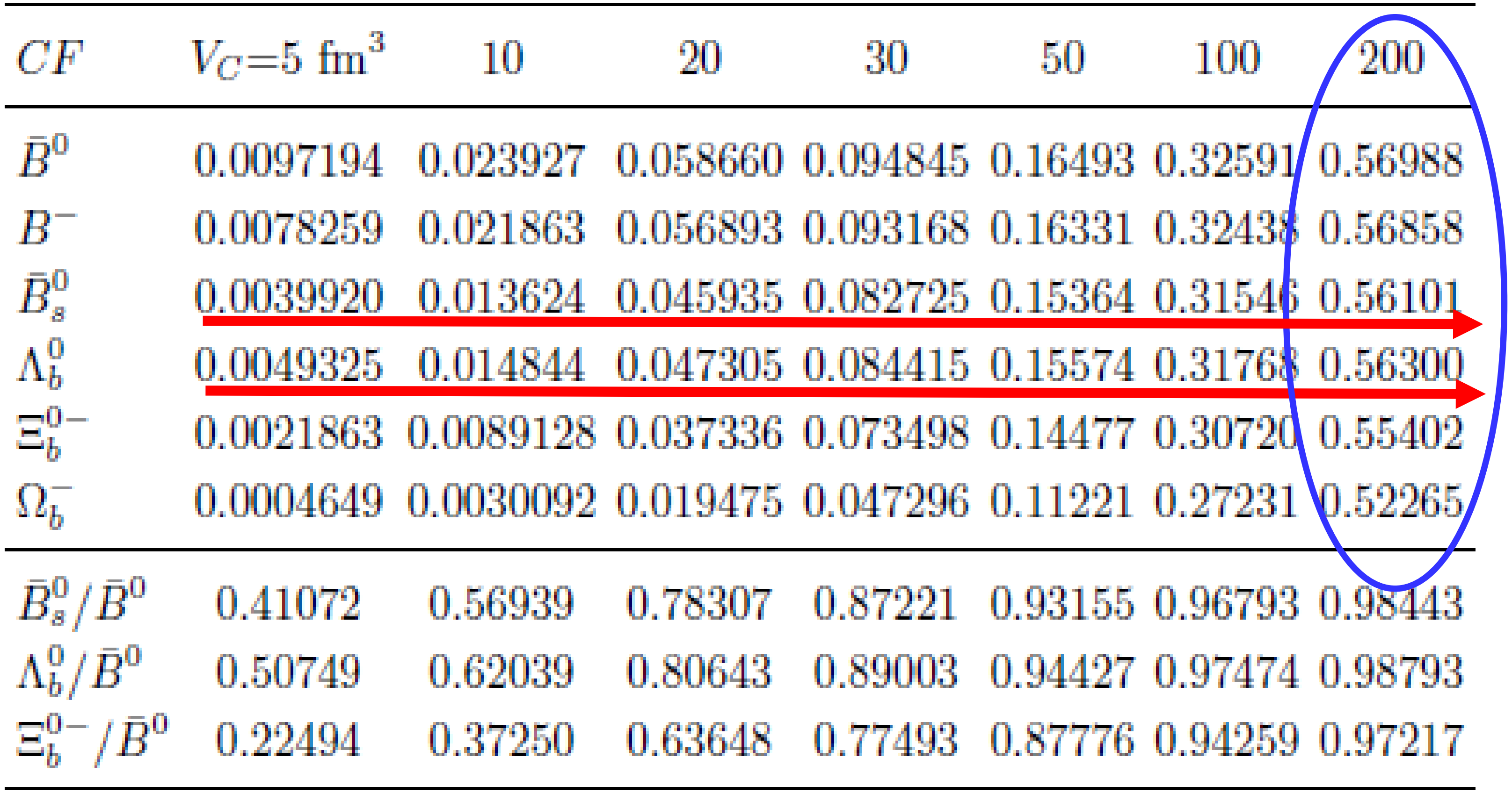


CF	V_C=5 fm^3	10	20	30	50	100	200
$\bar{B}^0$	0.0097194	0.023927	0.058660	0.094845	0.16493	0.32591	0.56988
B^-	0.0078259	0.021863	0.056893	0.093168	0.16331	0.32438	0.56858
$\bar{B}_s^0$	0.0039920	0.013624	0.045935	0.082725	0.15364	0.31546	0.56101
Λ_b^0	0.0049325	0.014844	0.047305	0.084415	0.15574	0.31768	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

At a small volume/system size,

- CF of **B_s & Λ_b < B**, canonical strangeness & baryon suppression
- CF of **Ω_b < Ξ_b < Λ_b**, increasing strangeness content despite common baryon

Canonical suppression: chemical factors



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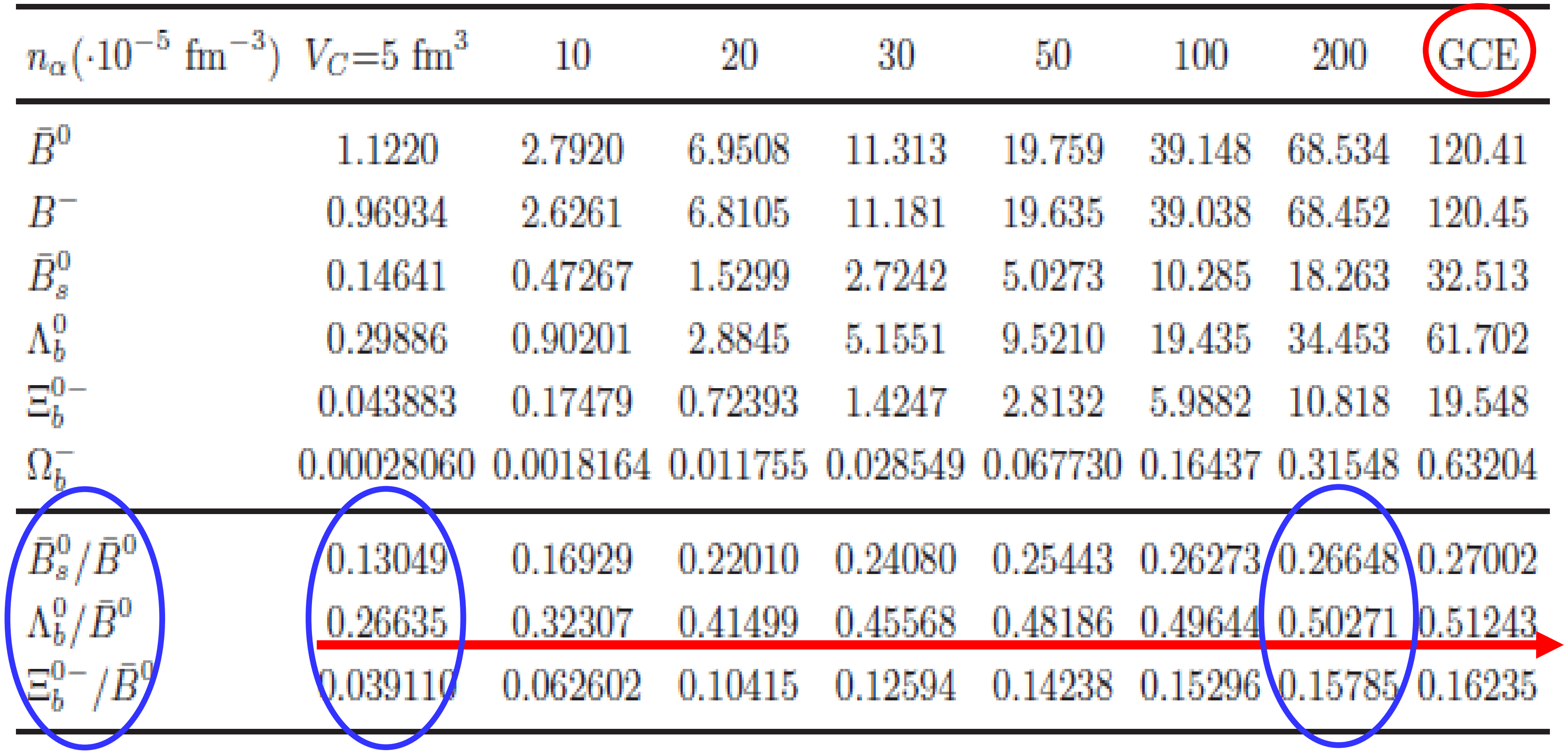
As volume/system size increases,

- canonical strangeness & baryon suppression attenuates
- same residual CF at large V: common canonical bottom number suppression

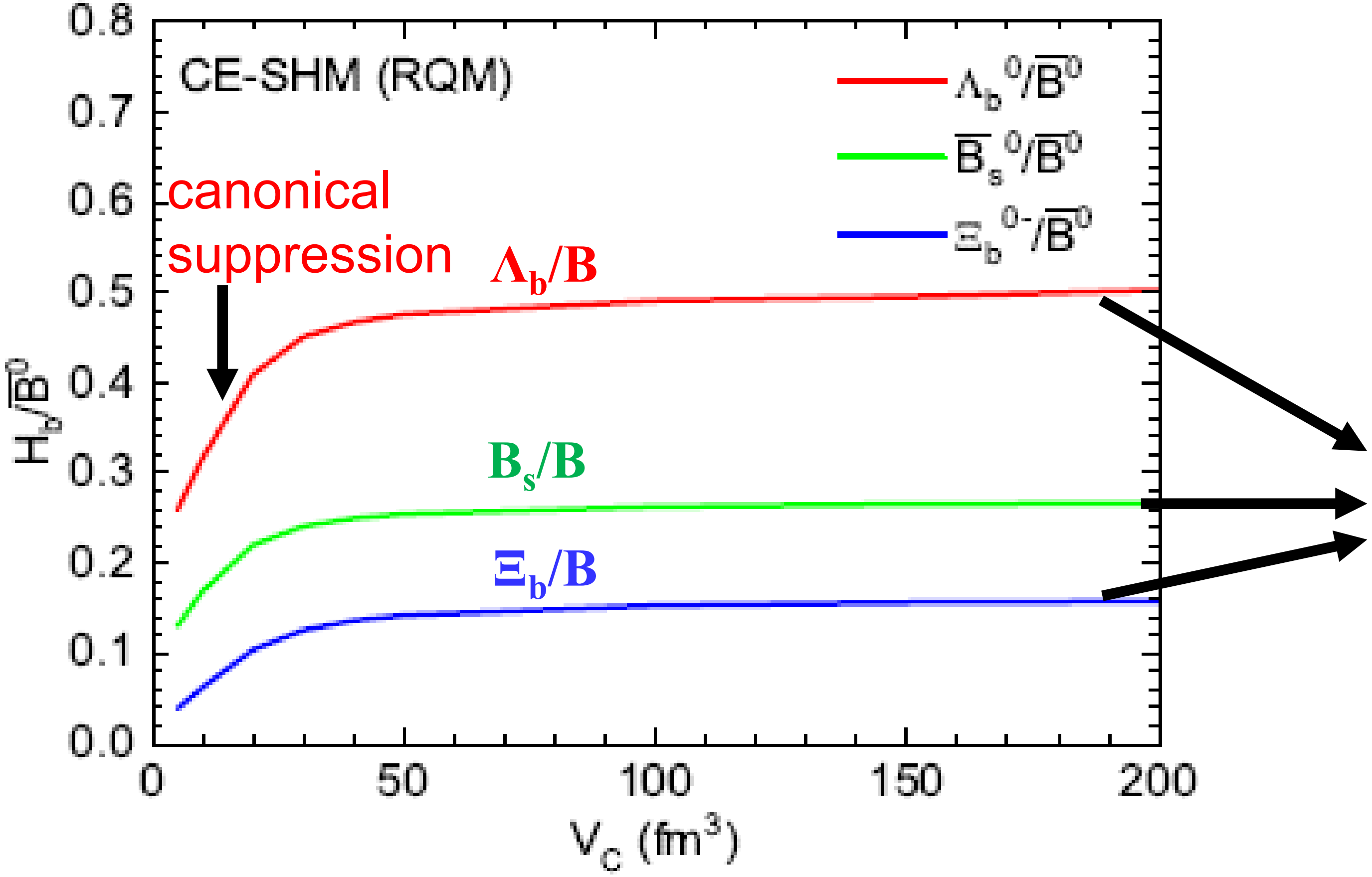
Ground-state b-hadron densities with feeddowns



$n_\alpha(\cdot 10^{-5}\ \mathrm{fm}^{-3})$	V_C=5 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

- As volume/system size reduces, **B_s/B, Λ_b/B** suppressed by a factor 2; **Ξ_b/B** suppression stronger, two-fold role of baryon + strangeness
- All ratios tend to the corresponding GCE-SHM values at large system size

Ground-state b-hadron ratios vs Volume



canonical suppression

Λ_b/B

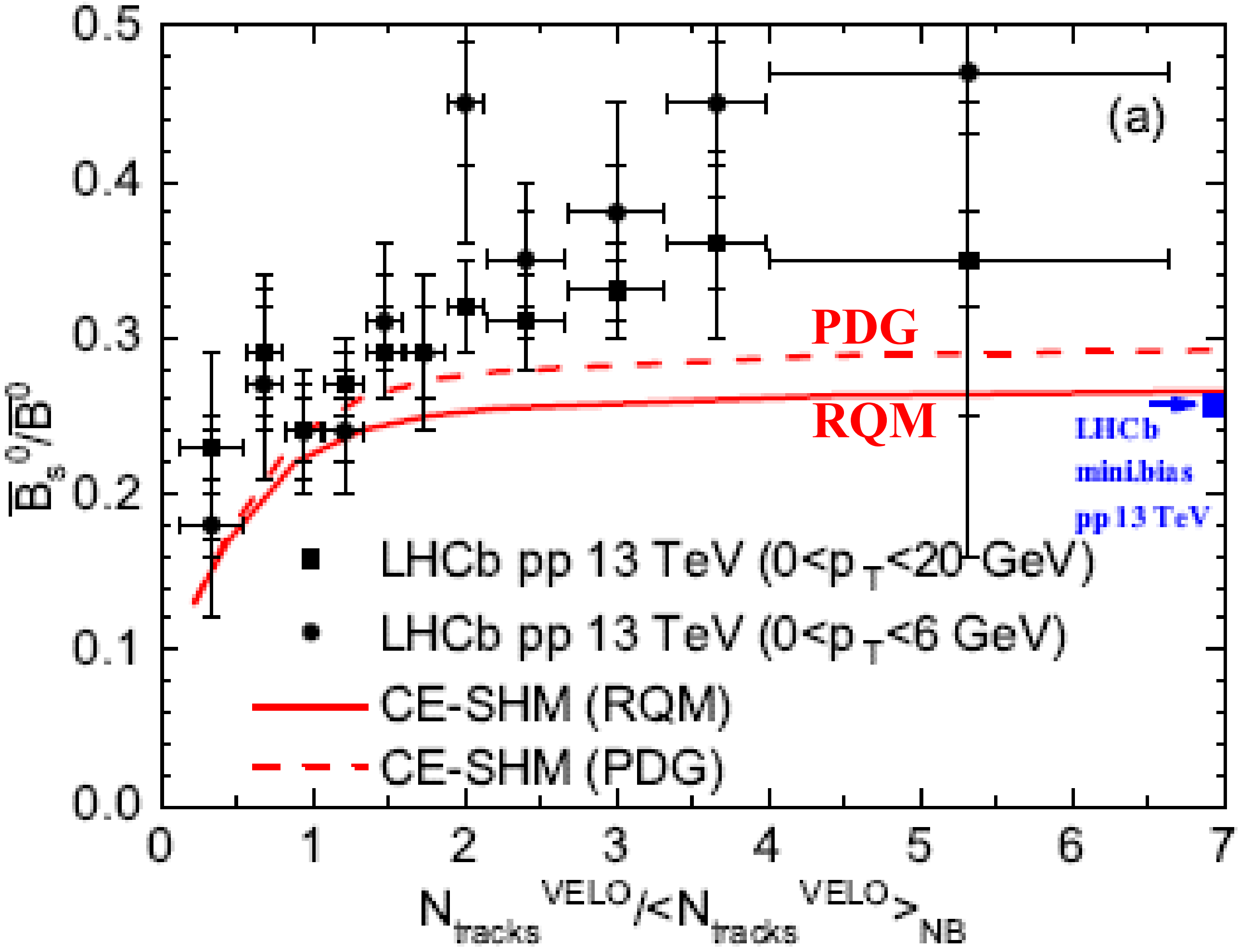
B_s/B

Ξ_b/B

Grand-canonical limits

- As volume/system size reduces, B_s/B, Λ_b/B suppressed by a factor 2; Ξ_b/B suppression stronger, two-fold role of baryon + strangeness
- All ratios tend to the corresponding GCE-SHM values at large system size

B^0_s/B vs $dN_{ch}/d\eta$



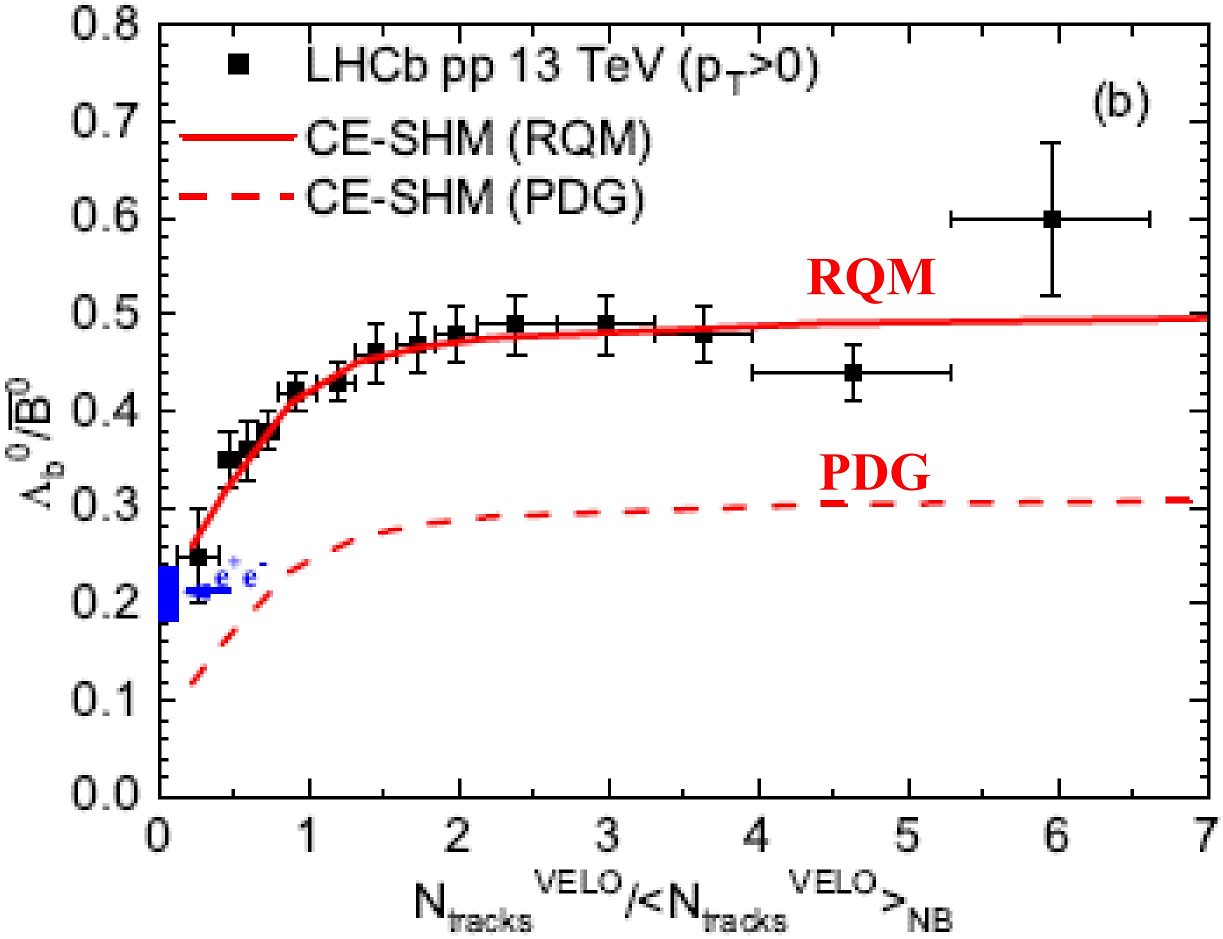
$$V_C/\langle V_C\rangle = N_{\rm tracks}^{\rm VELO}/\langle N_{\rm tracks}^{\rm VELO}\rangle_{\rm NB}$$

$$\langle V_C\rangle = 22.6\ {\rm fm}^3$$

Data taken from LHCb Collab., PRL131 (2023) 061901

- **B^0_s/B vs $dN_{ch}/d\eta$** increasing from small multiplicity to saturation at large size
- RQM a bit smaller than PDG

Λ_b^0/B vs $dN_{ch}/d\eta$



$$V_C/\langle V_C\rangle = N_{\rm tracks}^{\rm VELO}/\langle N_{\rm tracks}^{\rm VELO}\rangle_{\rm NB}$$

$$\langle V_C\rangle = 22.6\ {\rm fm}^3$$

Data taken from LHCb Collab., PRL132 (2024) 081901

- **Λ_b^0/B vs $dN_{ch}/d\eta$** increasing from e^+e^- value with small multiplicity to saturation/GCE limit at large size
- RQM strongly favored by data

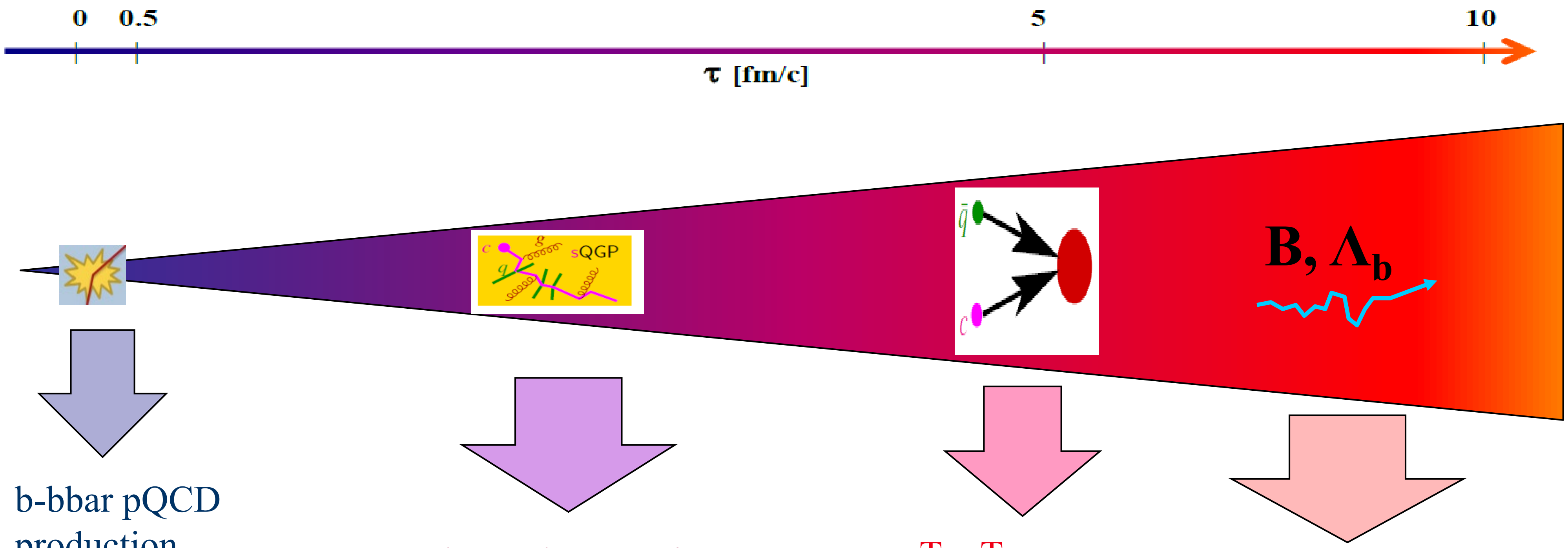
Part (III)

Hadro-chemistry computed above in minimum bias pp collisions
= a controlled reference for studying modifications in heavy-ion collisions ➔

Bottom hadro-chemistry in Pb-Pb collisions:

b-quark diffusion + recombination in QGP

b-quark diffusion & hadronization in QGP



b-bbar pQCD production
$\tau_{hard} \sim 1/2m_b$
$<< \tau_{form} \sim 0.6$ fm/c

b-quark Brownian diffusion in QGP
$\tau_{eq}^{b} \sim \tau_{eq}^{c} * m_b/m_c$
~ 20 fm/c
$>> \tau_{QGP} \sim 6$ fm/c

$T \sim T_c$
hadronization:
b+q(s) → B(B_s)
b+q+q → Λ_b

Hadronic phase diffusion

- $m_b >> \Lambda_{QCD}$, T ➔ controlled baseline via pQCD & number conservation
- $\tau_{hard} \sim 1/2m_b$ ➔ color test charge experiencing full evolution of medium

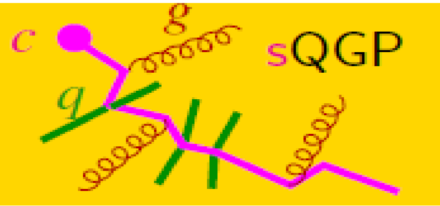
HQ interaction & diffusion in QGP

- Heavy quark Brownian motion simulated by Langevin equations

Langevin + hydro simulation down to T_c=170 MeV
fluid rest frame updates → boost to lab frame

$$dx_j = \frac{p_j}{E}dt,$$

$$dp_j = -\Gamma(p)p_j dt + \sqrt{2dt\, D(|\vec{p}+\xi d\vec{p}|)}\rho_j.$$

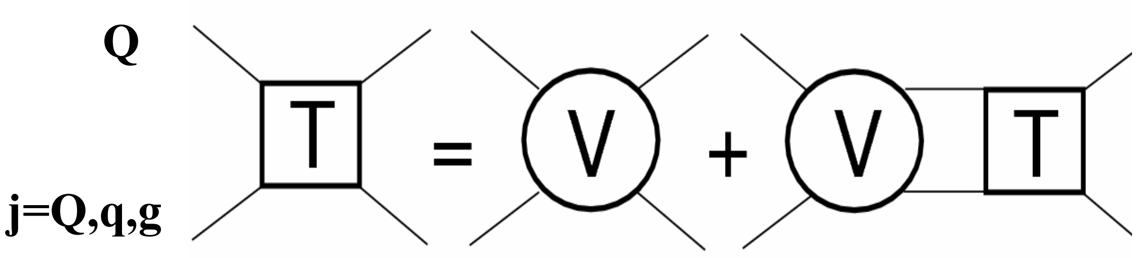


- **momentum transfer**

$$q^2 = q_0^2 - \vec{q}^{\,2} \approx -\vec{q}^{\,2}$$

$$q_0 \sim \vec{q}^{\,2}/2m_Q << |\vec{q}\,|$$

- Q-q/g soft scatterings: T-matrix resummation of lattice-constrained HQ potential



$$T_{Qj} = V_{Qj} + \int V_{Qj} D_Q D_j T_{Qj}$$

scattering amplitude

$$D = 1/[\omega - \omega_k - \Sigma(\omega,k)]$$

quark propagator

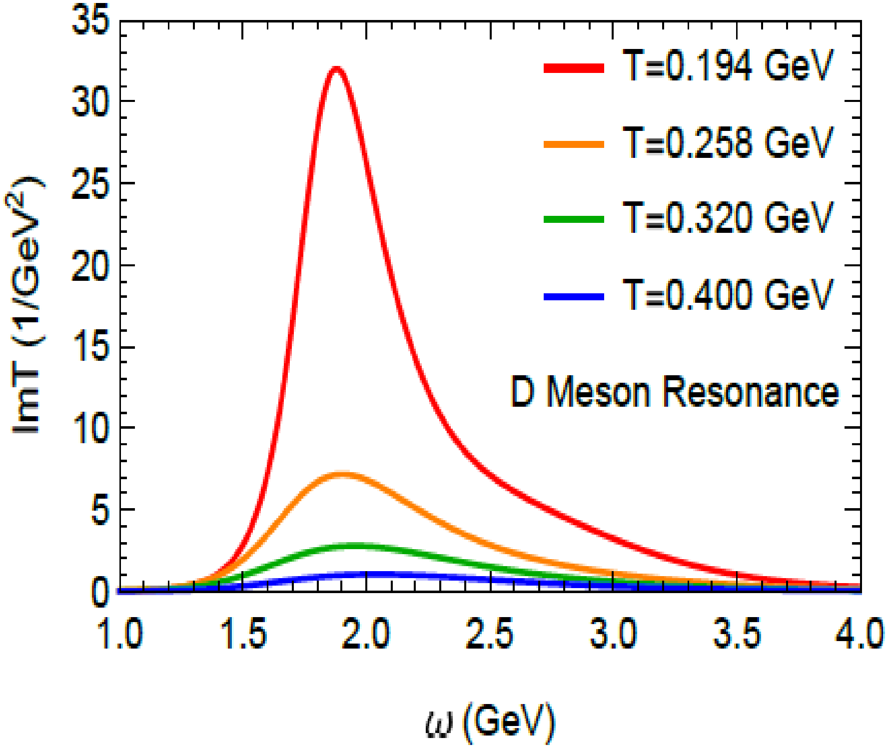
Review: MH, van Hees & Rapp, PPNP '23

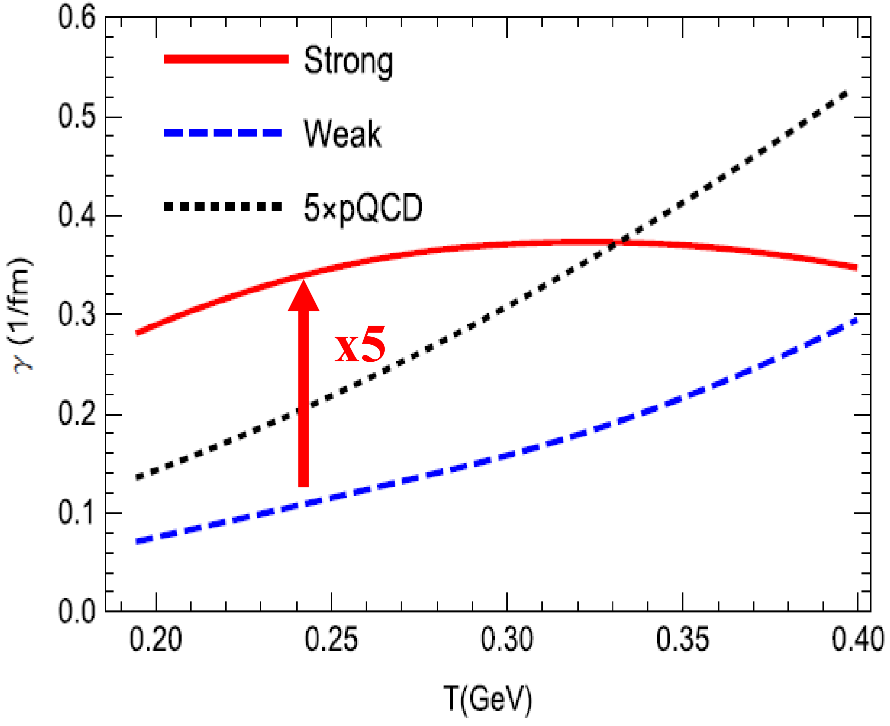
HQ thermal relaxation rate in QGP

- T-matrix resummation of lattice-constrained HQ potential ➔ relaxation rate

$$\gamma = A \sim \int |T_{Qj}|^2 (1-\cos\theta) f^j$$

HQ potential U = F + TS → **Resonance formation near T_c** → **Accelerating thermalization**

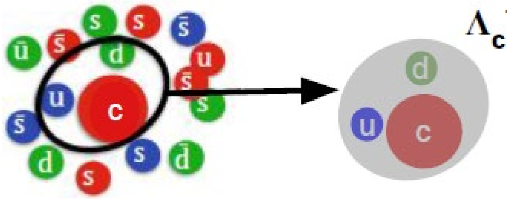




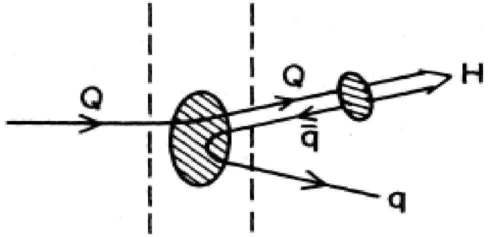
- Non-perturbative enhancement at low p & T; pQCD at high p & T
- x K-factor=1.6 for better phenomenology, also mimicking spin-dependent force/radiative contributions

Hadronization: resonance recombination

Recombination:



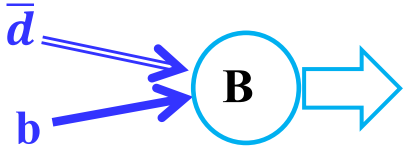
vs. Fragmentation:



- 2→1 Resonance Recombination via Boltzmann equilibrium limit ➔ energy conservation

$$p^{\mu}\partial_{\mu} f_M(t,\vec{x},\vec{p}) = -m\Gamma f_M(t,\vec{x},\vec{p}) + p^0\beta(\vec{x},\vec{p})$$

$$f_M(\vec{x},\vec{p}) = \frac{\gamma_M(p)}{\Gamma_M}\int\frac{d^3\vec{p}_1 d^3\vec{p}_2}{(2\pi)^3} f_q(\vec{x},\vec{p}_1) f_{\bar{q}}(\vec{x},\vec{p}_2)\, \sigma_M(s) v_{\rm rel}(\vec{p}_1,\vec{p}_2)\delta^3(\vec{p}-\vec{p}_1-\vec{p}_2)$$



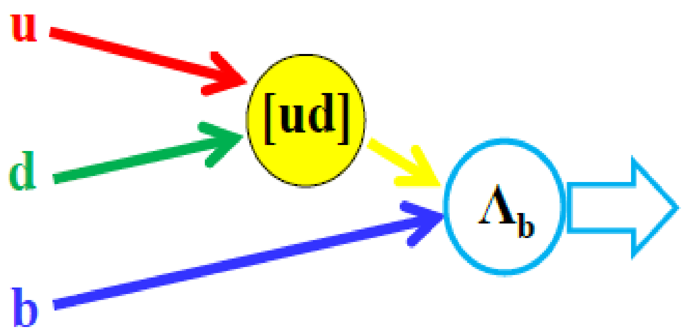
Breit-Wigner

$$\sigma(s) = g_{\sigma}\frac{4\pi}{k^2}\frac{(\Gamma m)^2}{(s-m^2)+(\Gamma m)^2}$$

- 3→1 RRM: diquark correlations in heavy-baryons

diquark type	mass (MeV)	wave func.	charm-baryon
Scalar [u,d]	710	$\bar{3}_{\rm color}\bar{3}_{\rm flavor}0^+_{\rm spin}$	Λ_c: c[ud]
Axialvector {u,d}	909	$\bar{3}_{\rm color}6_{\rm flavor}1^+_{\rm spin}$	Σ_c: c{ud}

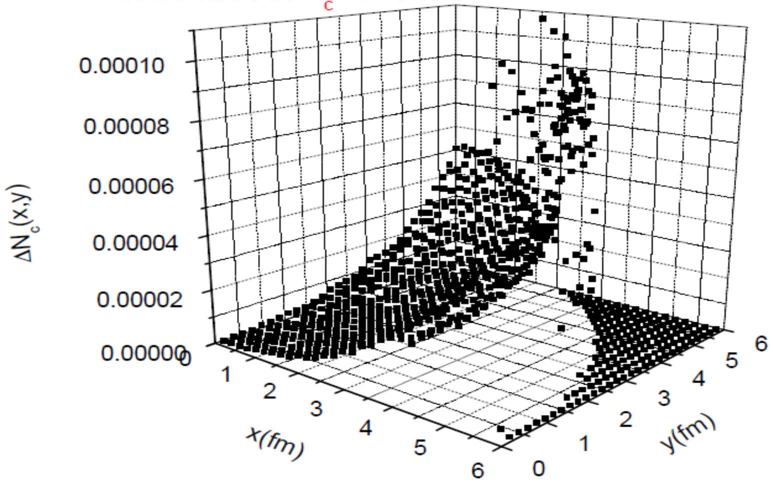
$$f_B(\vec{x},\vec{p}) = \frac{E_B(\vec{p})}{\Gamma_B m_B}\int\frac{d^3p_1 d^3p_2 d^3p_3}{(2\pi)^6}\frac{E_d(\vec{p}_{12})}{\Gamma_d m_d} f_1(\vec{x},\vec{p}_1) f_2(\vec{x},\vec{p}_2) f_3(\vec{x},\vec{p}_3)$$
$$\times\, \sigma_{12}(s_{12}) v^{12}_{\rm rel}(\vec{p}_1,\vec{p}_2)\sigma_B(s_{d3}) v^{d3}_{\rm rel}(\vec{p}_{12},\vec{p}_3)|_{\vec{p}_{12}=\vec{p}_1+\vec{p}_2}\delta^3(\vec{p}-\vec{p}_1-\vec{p}_2-\vec{p}_3)$$



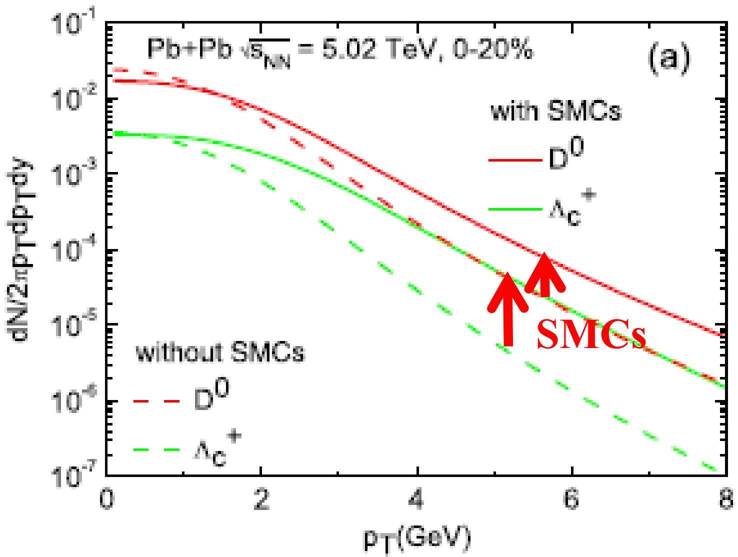
Ravagli et al.'07, MH et al.'12, '20

Recombination: space-momentum correlations

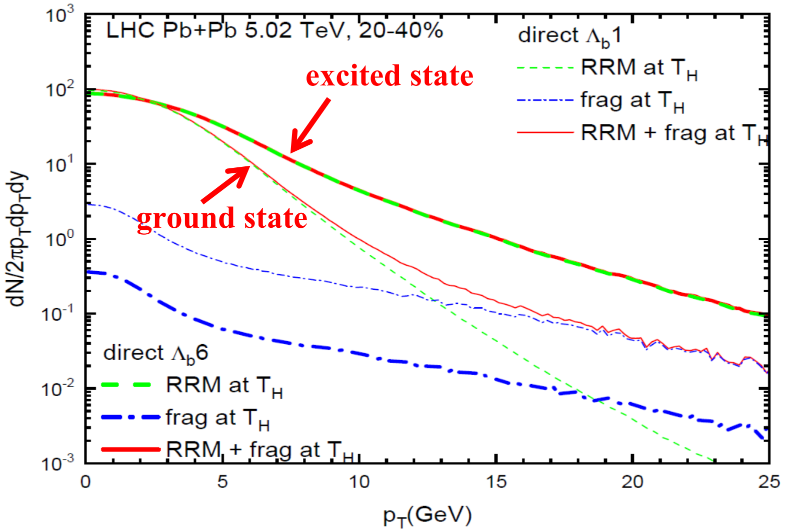
- Inhomogeneous distribution: SMCs ➔ recombination beyond momentum space



Langevin charm quarks p_T=3.0-4.0 GeV,
at freezeout T_c=170 MeV

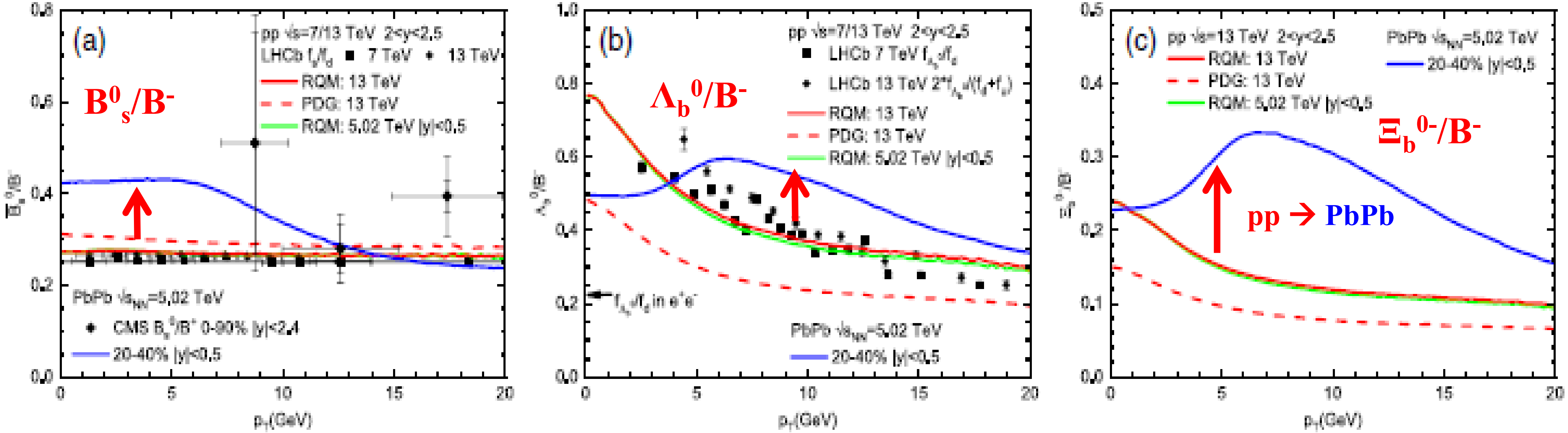


- Left-over b-quarks: fragmentation in the same manner as in pp



- Excited state more massive: recombination spectrum harder than ground state (SMCs/flow)
- RRM vs frag. crossing at p_T~14 GeV for Λ_b1 vs Λ_b6 at p_T>25 GeV

Modifications of hadro-chemistry



- pp → PbPb
  - ❑ B_s/B – enhancement at low p_T: b coupled to equilibrated strangeness via recombination
  - ❑ Λ_b/B – flow-bump at intermediate p_T~5-15 GeV [significantly higher than c-sector]: stronger flow push on baryons, captured by 3-body RRM with SMCs
  - ❑ Ξ_b/B – enhancement more pronounced: combining two-fold role of containing a s-quark & being a 3-body baryon

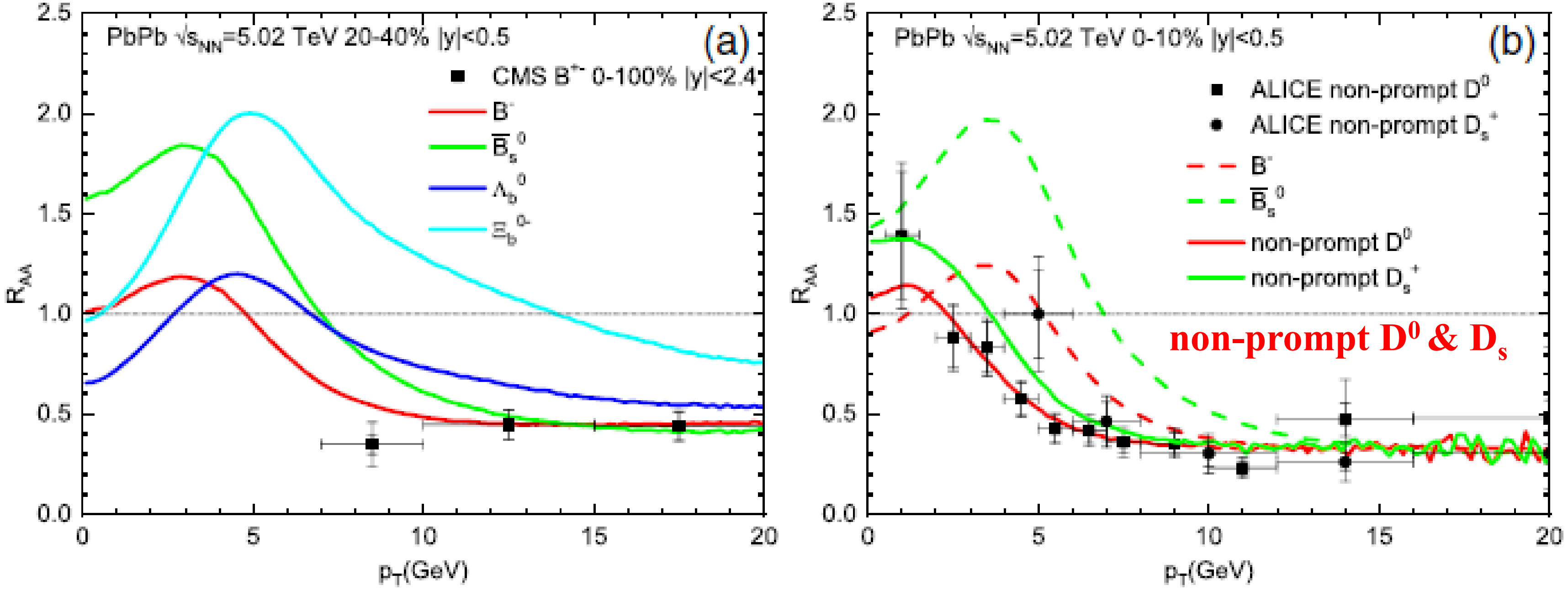
b-hadron nuclear modification factors

- R_{AA} : hierarchy of flow effects and suppression driven by their quark content

$$R_{AA}(p_T) = \frac{dN^{AA}/dp_T dy}{< T_{AA} > d\sigma^{pp}/dp_T dy}$$

dN^{bbbar}/dy~0.9 for 0-10%

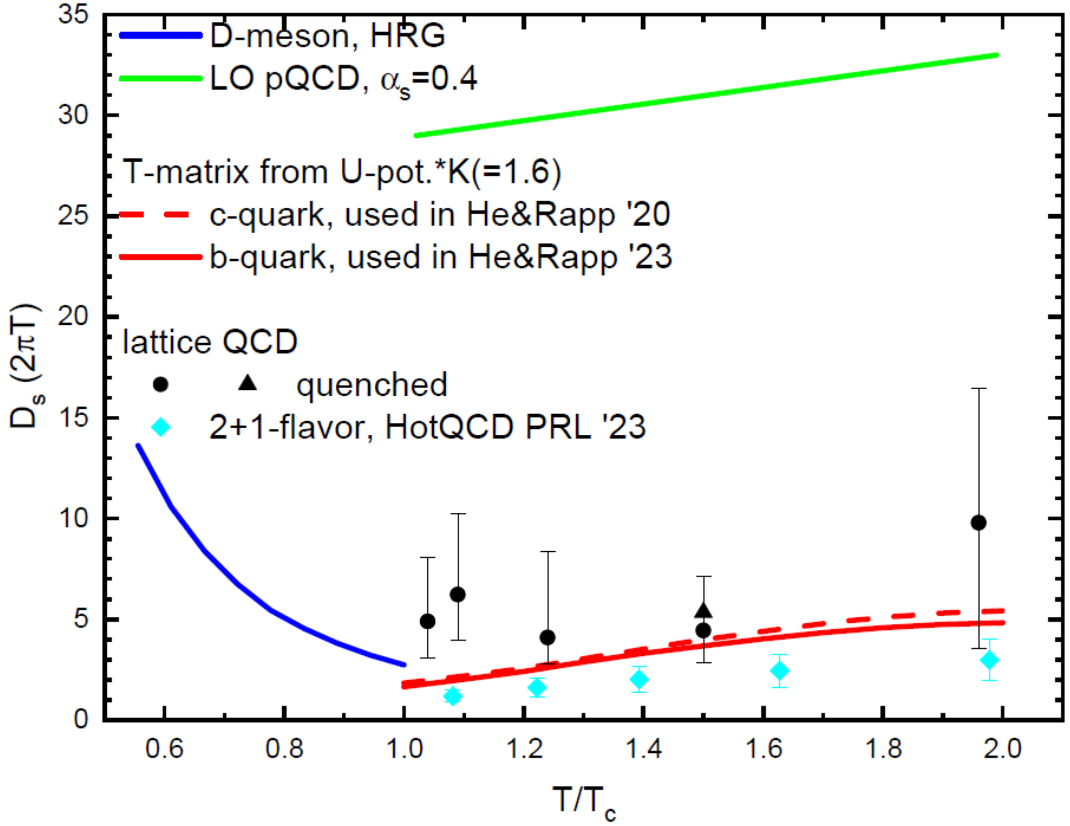
pp reference from SHM



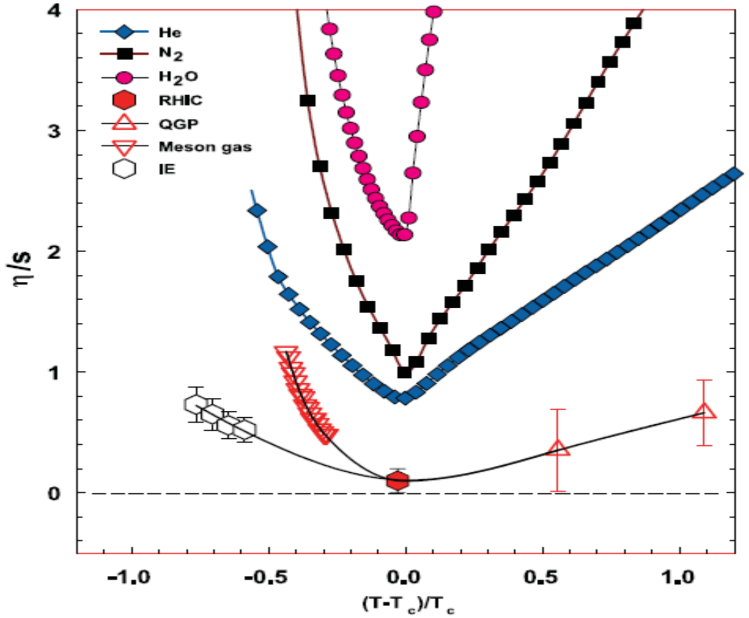
- B_s: b-quark coupled to equilibrated strangeness via recombination
  Λ_b: 3-body baryon recombination, RRM with SMCs
  Ξ_b: combining two-fold role of being baryon + containing a s-quark
- Non-prompt D^0 & Ds: weak decays of all b-hadrons via PYTHIA8

Summary: transport coefficient $\mathcal{D}_s(2\pi T)$

- HQ spatial diffusion coefficient: $\mathcal{D}_s = T/m_Q A(p=0) = T/m_Q\gamma$ ➔ $\langle x^2\rangle \sim \mathcal{D}_s t$



$D_s(2\pi T) = (\eta/s)4\pi * (1\text{-}2.5)$



- models & lattice $\mathcal{D}_s(2\pi T)\sim 1\text{-}3$ near T_c, x10 smaller than pQCD ➔ collisional rate $\Gamma_{coll} \sim 3/\mathcal{D}_s \sim 1$ GeV > $M_{q,g}$ ➔ thermal partons melted, Brownian markers/HQs survive

- maximum coupling strength near T_c ➔ small D_s & η/s ➔ strongly coupled QGP

Summary: b-quark hadronization

- Statistical hadronization of b-quarks in high-energy pp collisions:
  grand-canonical → canonical ensemble

  ➔ bottom hadro-chemistry well described in mini.bias & system-size scan – non-universal!

- role of many "missing" heavy-baryons highlighted

  ➔ awaiting discovery!

- b-quark diffusion + hadronization in QGP created in heavy-ion collisions

  ➔ probe of hadro-chemistry modifications & QGP transport properties