Bottom quark hadronization in proton-proton collisions

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

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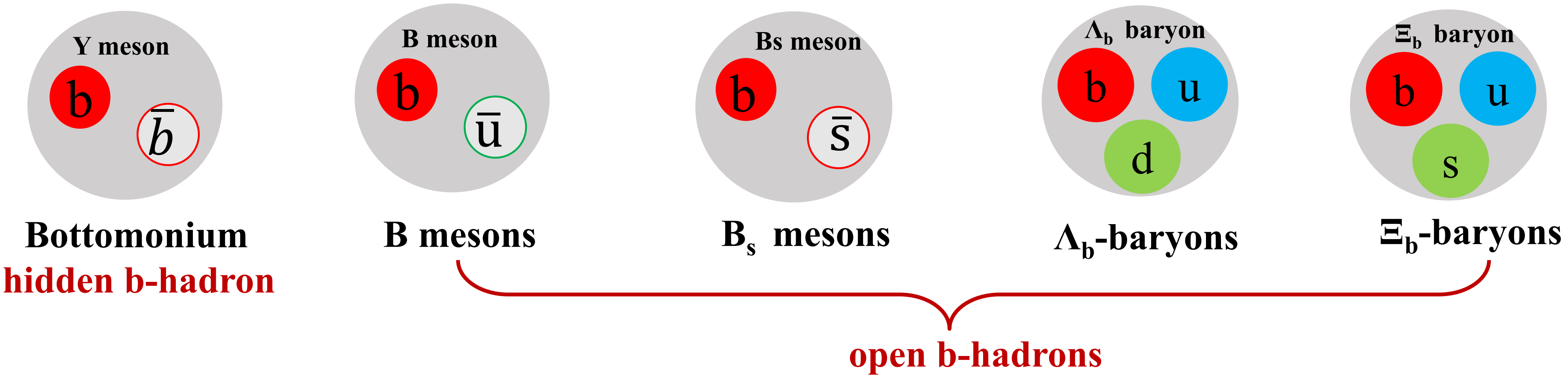
Heavy quarks & heavy hadrons

- Heavy quark m_c~1.5, m_b~4.5 GeV >>Λ_{QCD}

  ➔produced in early hard process $\tau \sim 1/2m_Q$

- Bottomonium vs open bottom hadrons



Heavy quark hadronization in pp collisions

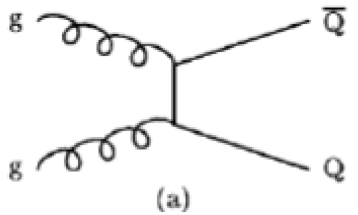
- Heavy hadron production cross section: factorization

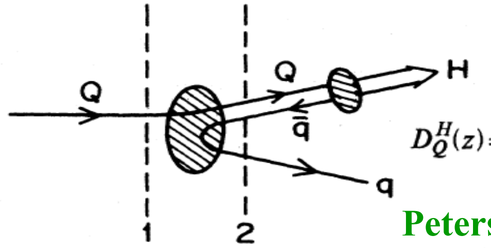
$$\frac{d\sigma^{H_c}}{dp_T^{H_c}}(p_T;\mu_F,\mu_R) = \boxed{\mathrm{PDF}(x_1,\mu_F)\cdot\mathrm{PDF}(x_2,\mu_F)} \otimes \boxed{\frac{d\sigma^c}{dp_T^c}(x_1,x_2,\mu_R,\mu_F)} \otimes \boxed{D_{c\to H_c}(z=p_{H_c}/p_c,\mu_F)}$$

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)

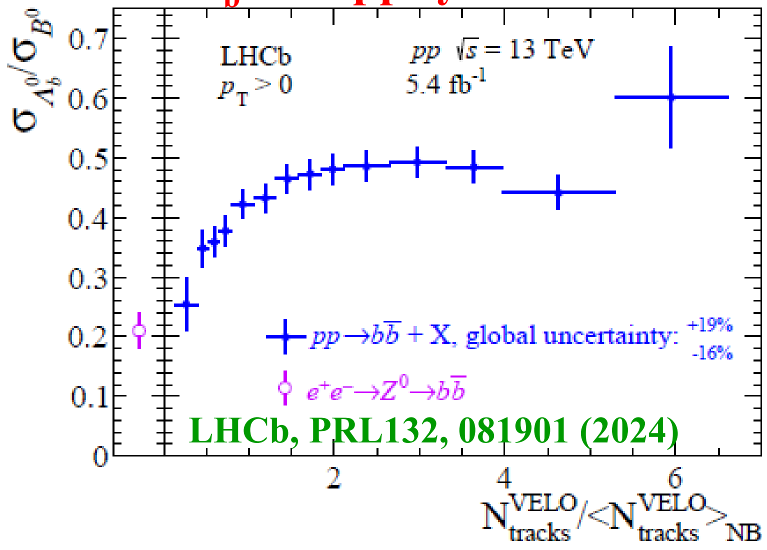
- Hadronization: heavy quark conservation $f_u + f_d + f_s + f_{baryon} = 1$

hadro-chemistry: universal? → non-universal!

Quantity		Z decays e^+e^-	Tevatron p-pbar
Mixing probability	$\overline{\chi}$	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)

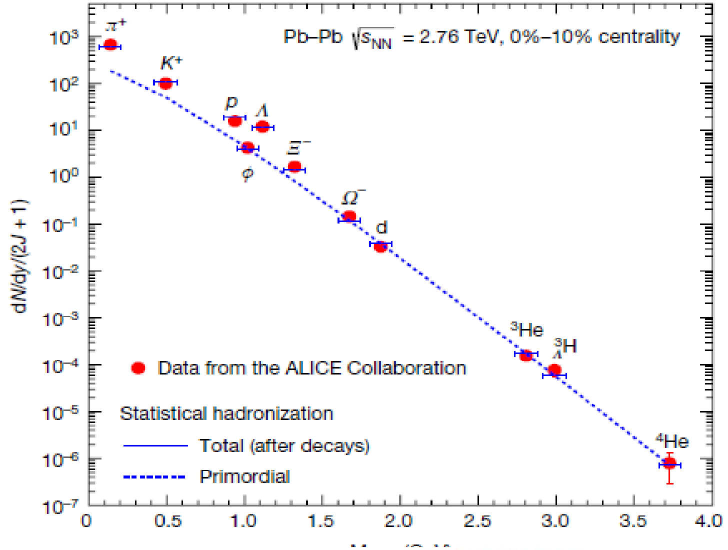
- QCD hadronic population from partons: born into equilibrium = maximum entropy state
  ➔Hadron yields governed by partition function of a free hadron resonance gas (HRG)

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

- Grand-canonical SHM for light hadrons in Pb-Pb

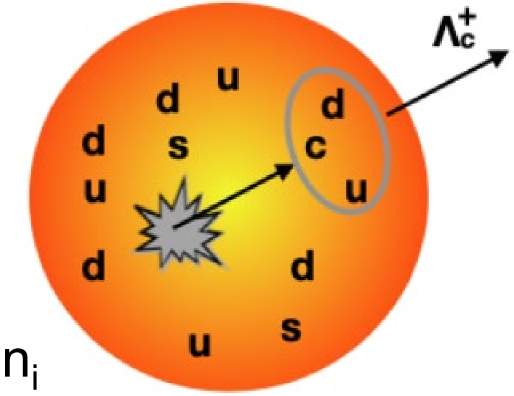
$$Z^{GC}(T, V, \mu_Q) = Tr[e^{-\beta(H - \sum_i \mu_{Q_i} Q_i)}]$$

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



- High-energy pp collisions = light-quark-rich environment
  ➔ stochastic/statistical coalescence of c/b with surrounding q

- SHM for heavy-hadrons in pp
  - Heavy hadrons 'thermal' production at 'universal' T_H~ 170 MeV
  - *Relative chemical equilibrium* ➔ primary yields $N_i \propto$ thermal densities n_i



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

$c\tau = 441.0$ μm

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

Mass $m = 5912.20 \pm 0.21$ MeV

Full width Γ < 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 Γ < 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, 30 Λ_b, 46 Σ_b, 75 Ξ_b, 42 Ω_b Ebert et al., PRD 84 (2011) 014025

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

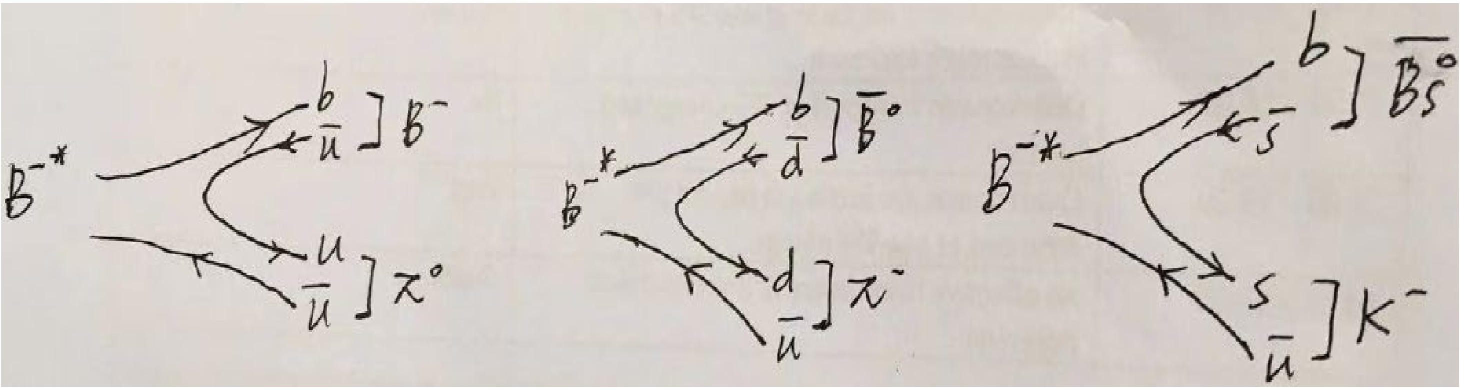
		$Q = c$		$Q = b$	
$I(J^P)$	Qd state	M	M^{exp} [1]	M	M^{exp} [1]
$0(\frac{1}{2}^+)$	1S	2286	2286.46(14)	5620	5620.2(1.6)
$0(\frac{1}{2}^+)$	2S	2769	2766.6(2.4)?	6089	
$0(\frac{1}{2}^+)$	3S	3130		6455	
$0(\frac{1}{2}^+)$	4S	3437		6756	
$0(\frac{1}{2}^+)$	5S	3715		7015	
$0(\frac{1}{2}^+)$	6S	3973		7256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

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

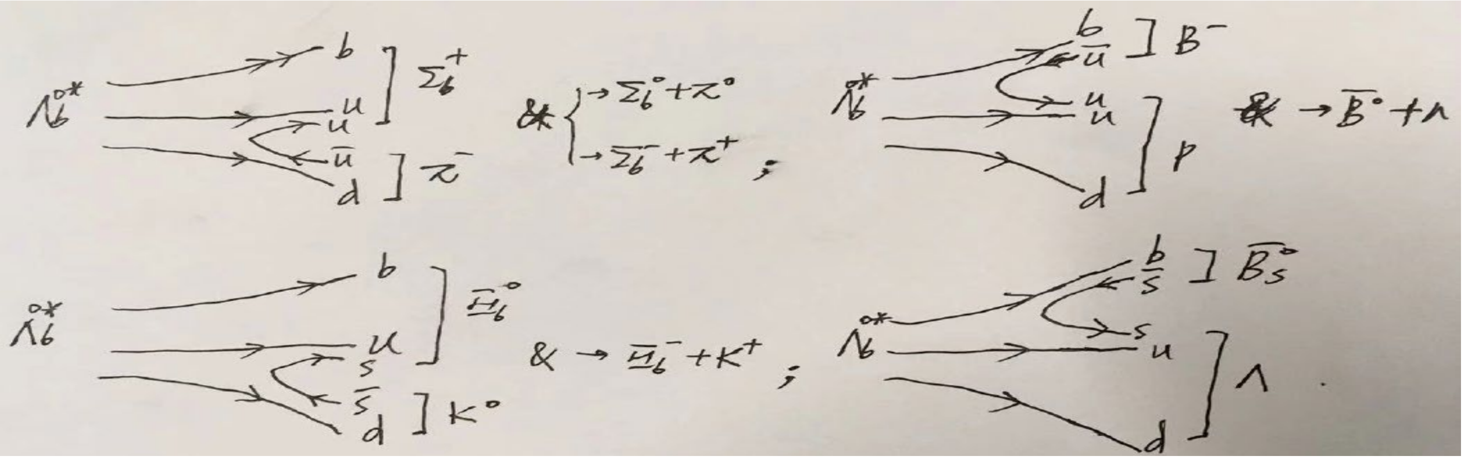
		$Q = c$		$Q = b$	
$I(J^P)$	Qd state	M	M^{exp} [1]	M	M^{exp} [1]
$1(\frac{1}{2}^+)$	1S	2443	2453.76(18)	5808	5807.8(2.7)
$1(\frac{1}{2}^+)$	2S	2901		6213	
$1(\frac{1}{2}^+)$	3S	3271		6575	
$1(\frac{1}{2}^+)$	4S	3581		6869	
$1(\frac{1}{2}^+)$	5S	3861		7124	
$1(\frac{3}{2}^+)$	1S	2519	2518.0(5)	5834	5829.0(3.4)
$1(\frac{3}{2}^+)$	2S	2936	$2939.3(^{1.4}_{1.5})$?	6226	
$1(\frac{3}{2}^+)$	3S	3293		6583	
$1(\frac{3}{2}^+)$	4S	3598		6876	
$1(\frac{3}{2}^+)$	5S	3873		7129	
$1(\frac{1}{2}^-)$	1P	2799	$2802(^{4}_{7})$	6101	
$1(\frac{1}{2}^-)$	2P	3172		6440	
$1(\frac{1}{2}^-)$	3P	3488		6756	
$1(\frac{1}{2}^-)$	4P	3770		7024	
$1(\frac{1}{2}^-)$	1P	2713		6095	
$1(\frac{1}{2}^-)$	2P	3125		6430	
$1(\frac{1}{2}^-)$	3P	3455		6742	
$1(\frac{1}{2}^-)$	4P	3743		7008	
$1(\frac{3}{2}^-)$	1P	2798	$2802(^{4}_{7})$	6096	
$1(\frac{3}{2}^-)$	2P	3172		6430	
$1(\frac{3}{2}^-)$	3P	3486		6742	
$1(\frac{3}{2}^-)$	4P	3768		7009	
$1(\frac{3}{2}^-)$	1P	2773	2766.6(2.4)?	6087	
$1(\frac{3}{2}^-)$	2P	3151		6423	
$1(\frac{3}{2}^-)$	3P	3469		6736	
$1(\frac{3}{2}^-)$	4P	3753		7003	
$1(\frac{5}{2}^-)$	1P	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^{-*}→B^-+π^0)=1/(1+1+1/3)=43%;
BR(B^{-*}→B^0_s+π^0)=1/3/(1+1+1/3)=14%;
BR(B_s^*→B^-+K)=1/(1+1+1/3)=43%



BR(Λ_b^{0*}→ Λ_b^0 +2π)=3/(3+2+2*1/3+1/3)=54%
BR(Λ_b^{0*}→ B^- + p) =1/(3+2+1/3+2*1/3)=16%
BR(Λ_b^{0*}→ Ξ_b + K) =2/3/(3+2+1/3+2*1/3)=11%
BR(Λ_b^{0*}→ B^0_s+ Λ) =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

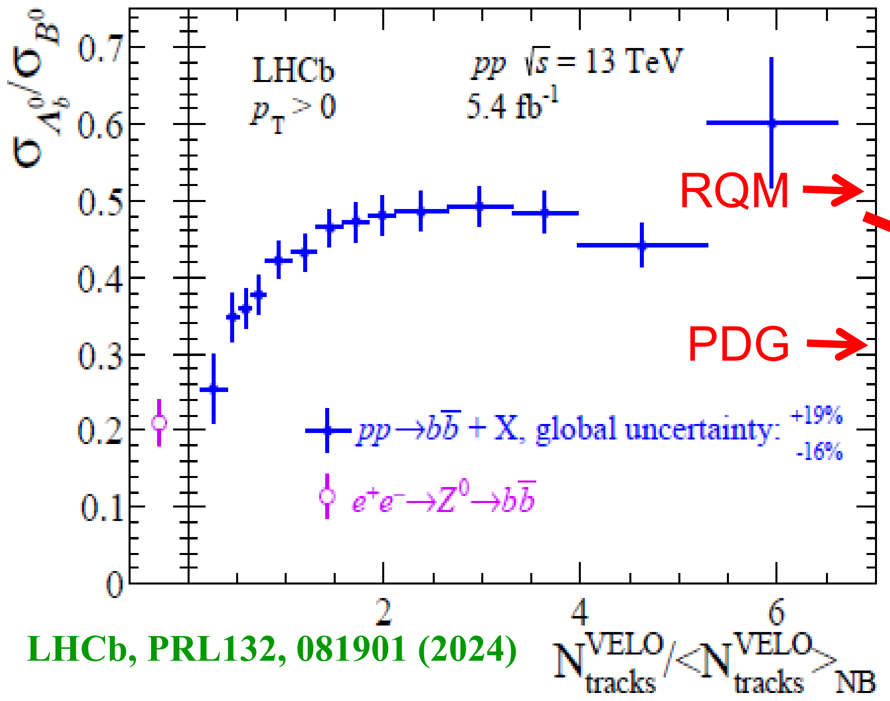
$$n_\alpha = n_\alpha^{\text{primary}} + \sum_i n_i^{\text{primary}} \cdot BR(i \to \alpha)$$

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!

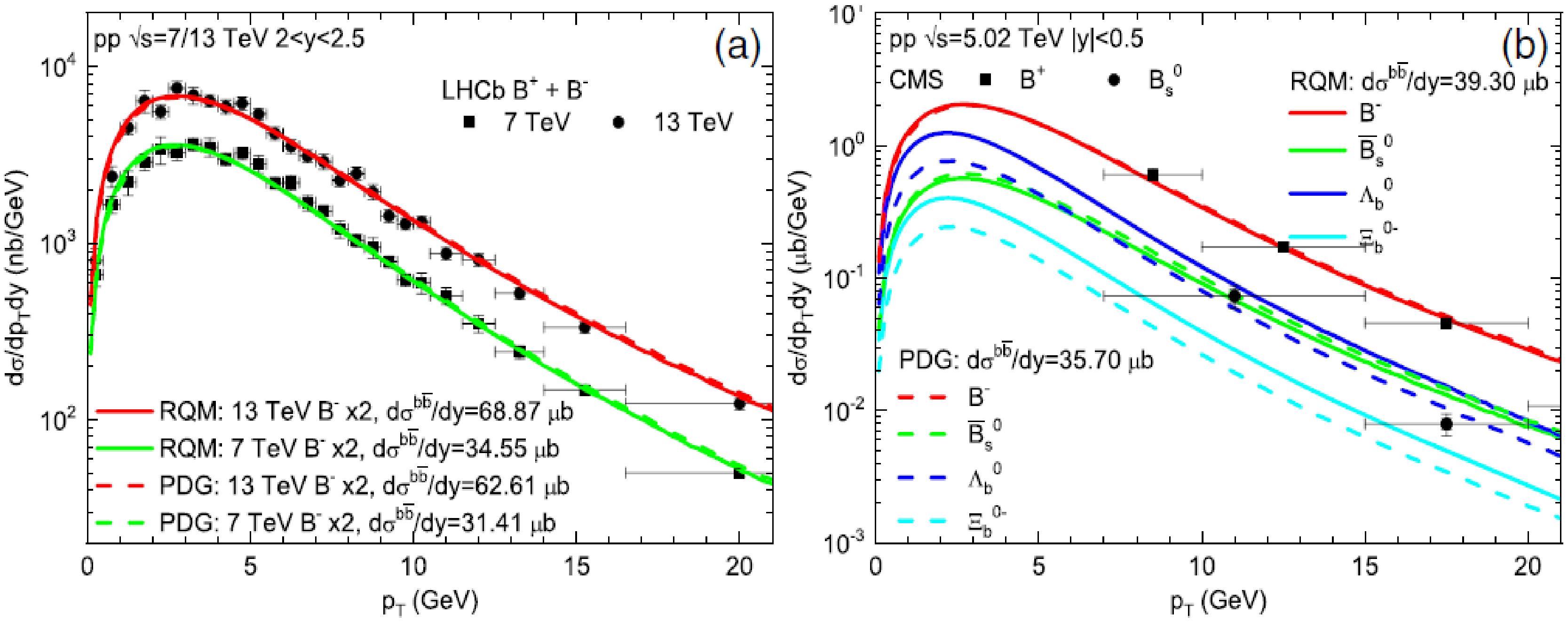
r_α	$\bar{B}^0/B^-$	$\bar{B}_s^0/B^-$	Λ_b^0/B^-	$\Xi_b^{0,-}/B^-$
PDG	0.9995	0.2904	0.3129	0.1000
RQM	0.9994	0.2699	0.5122	0.1623

Fragmentation & p_T-spectra

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

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

- weight ∝ primary density (relative chemical equilibrium)
- $\alpha_B=45$, $\alpha_{Bs}=25$, $\alpha_{baryon}=8$ to tune the slope of spectra



- 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)

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

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

correlation volume ~ system size

- Primary hadron yield: CE vs GCE

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

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

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 $\mathbf{B_s}$ **&** $\mathbf{\Lambda_b < B}$, canonical strangeness & baryon suppression
- CF of $\mathbf{\Omega_b < \Xi_b < \Lambda_b}$, increasing strangeness content despite common baryon

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
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$\Xi_b^{0-}/\bar{B}^0$	0.22494	0.37250	0.63648	0.77493	0.87776	0.94259	0.97217

As volume/system size increases,

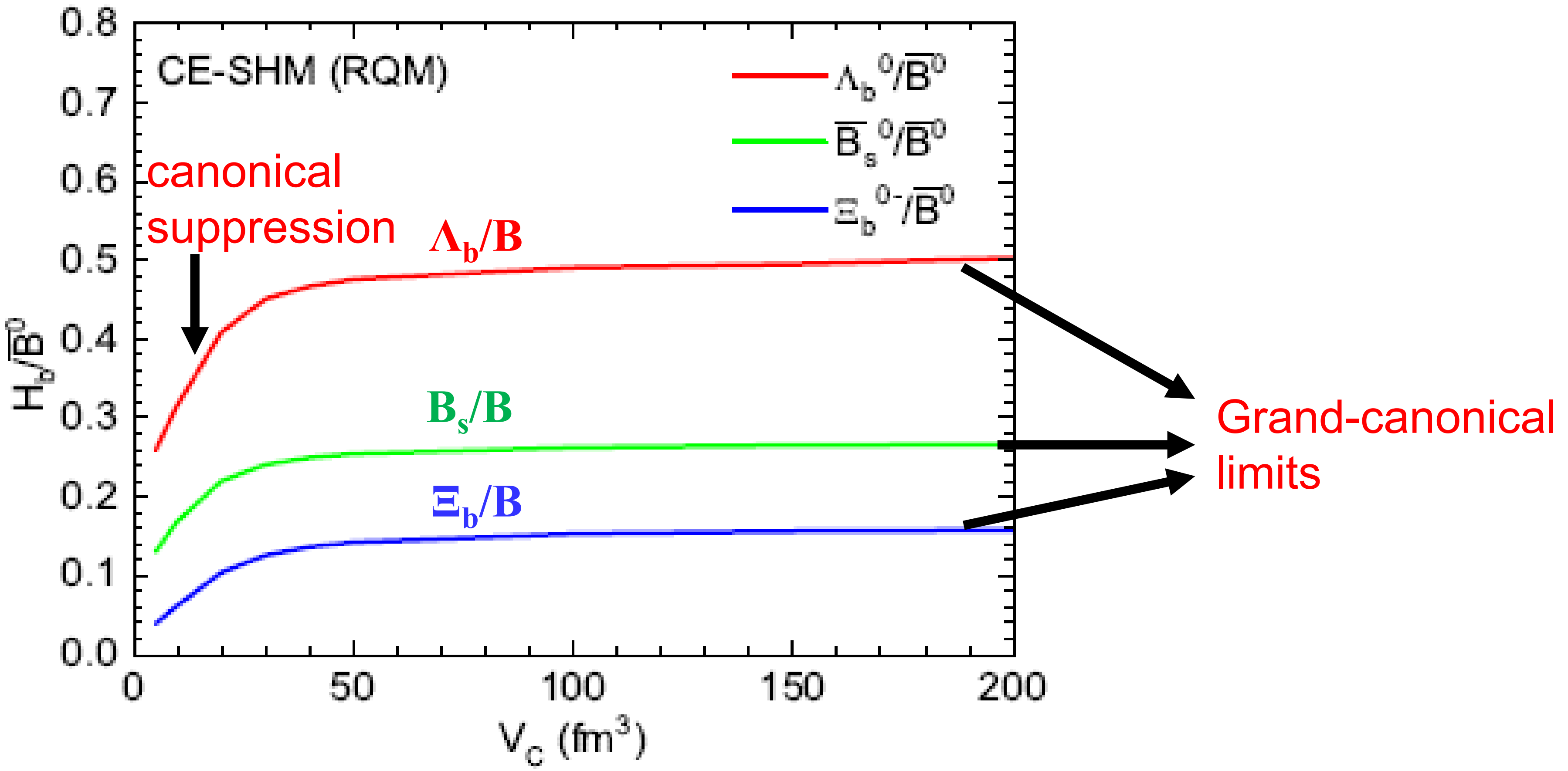
- canonical strangeness & baryon suppression attenuates
- same residual CF at large V: common canonical bottom number suppression

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



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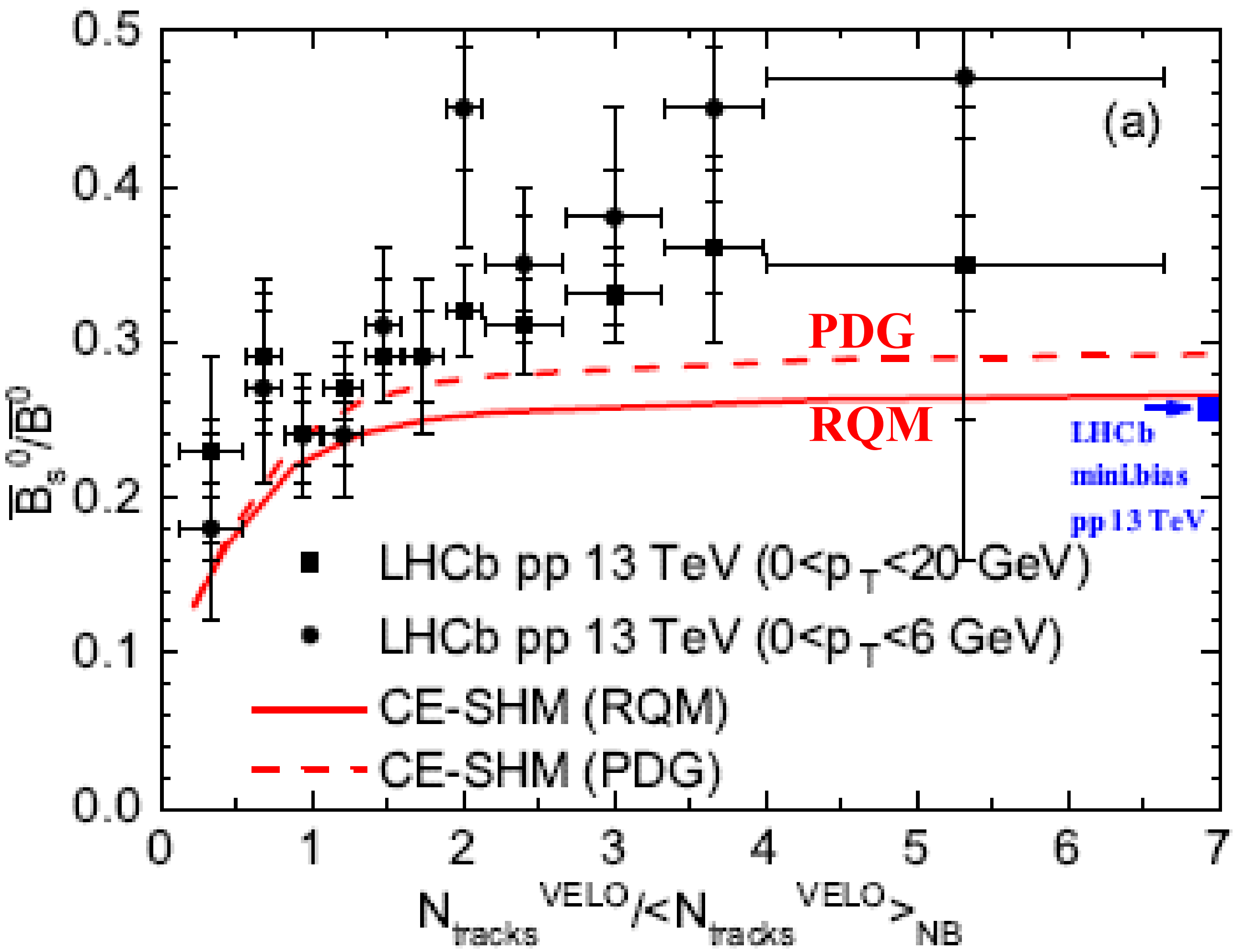
B^0_s/B vs $dN_{ch}/d\eta$



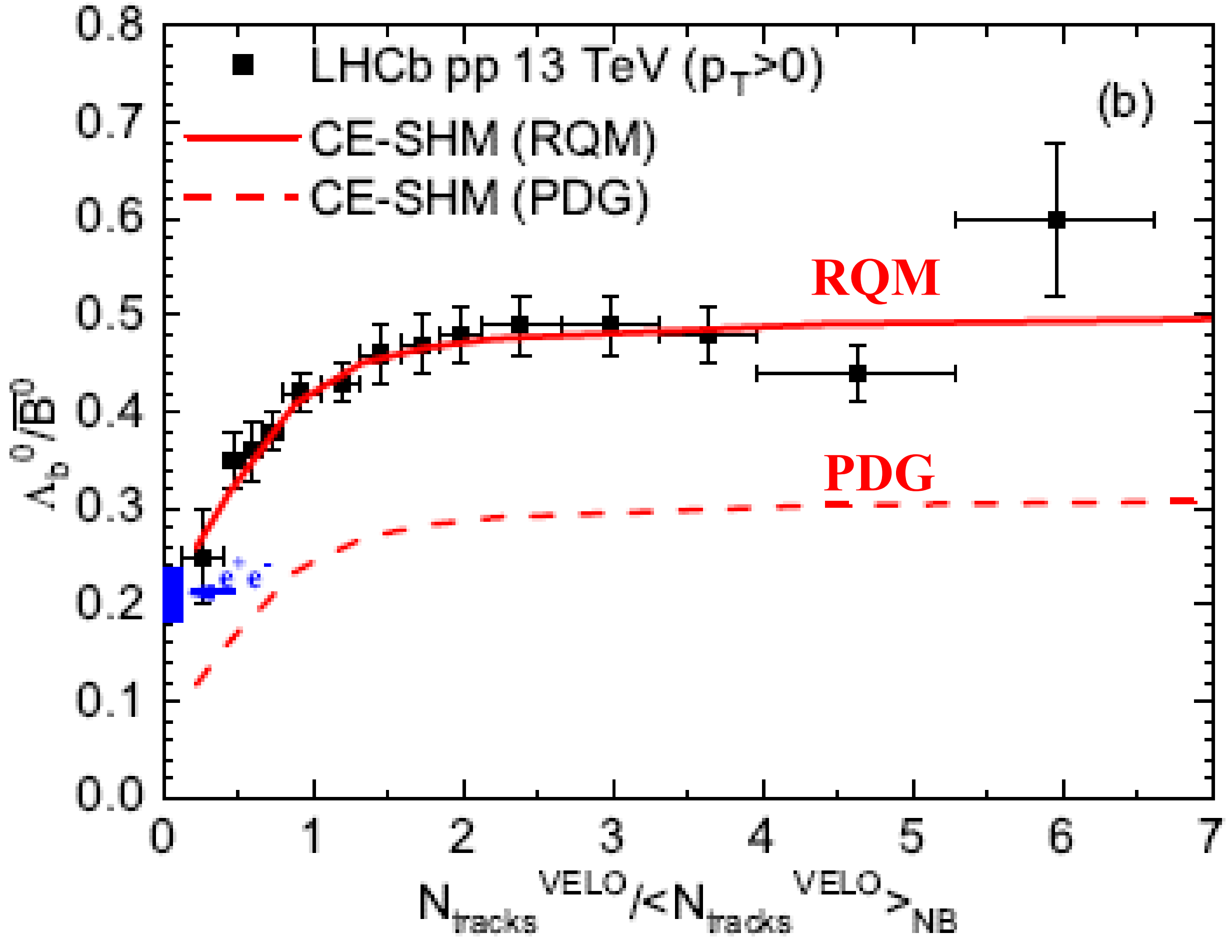
$$V_C/\langle V_C\rangle = N^{\rm VELO}_{\rm tracks}/\langle N^{\rm VELO}_{\rm tracks}\rangle_{\rm NB}$$

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

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$_{ch}$/dη



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

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

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

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

Summary: b-quark hadronization

- Bottom quark hadronization: non-universal, but environment dependent!

  ➔ Λ_b/B: GCE saturation limit (mini.bias pp & PbPb) VS vacuum fragmentation limit (e^+e^-)

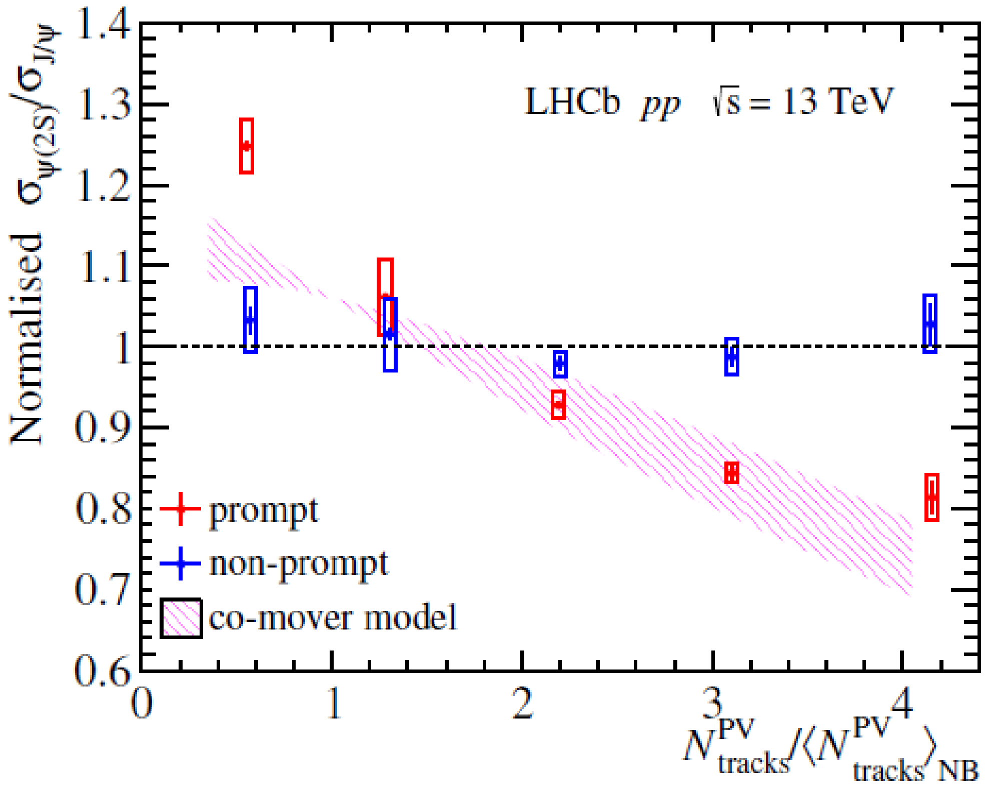
- Statistical hadronization of b-quarks: grand-canonical → canonical ensemble

  ➔ exact conservation of quantum charges leading to canonical suppression

- Role of many “missing” heavy-baryons highlighted

  ➔ awaiting measurement & confirmation

Back-up: $\psi(2S)/J/\psi$ vs $dN_{ch}/d\eta$ in pp collisions



LHCb collab.
JHEP05(2024)243