

Quark Matter 2023

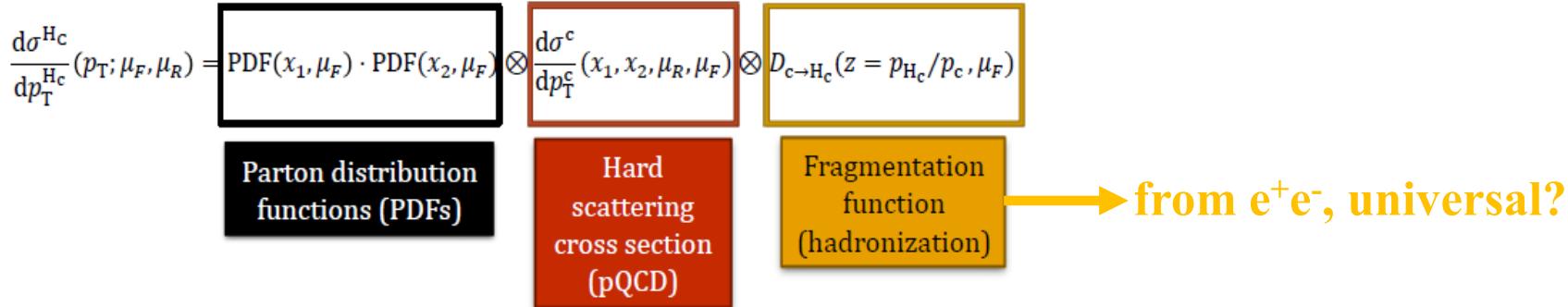
# **Bottom hadro-chemistry in pp & PbPb collisions**

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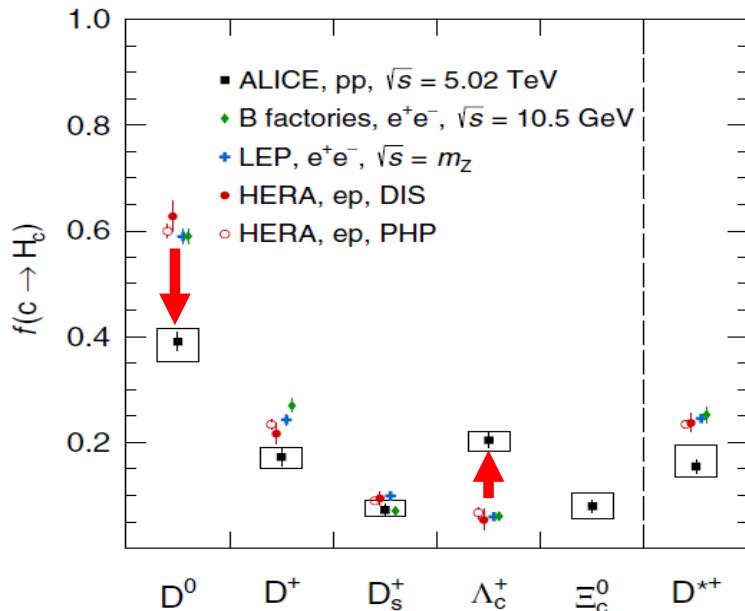
# Introduction: heavy quark fragmentation

- $\text{HQ } m_Q \gg \Lambda_{\text{QCD}} \rightarrow$  production separated from hadronization in hadronic collisions

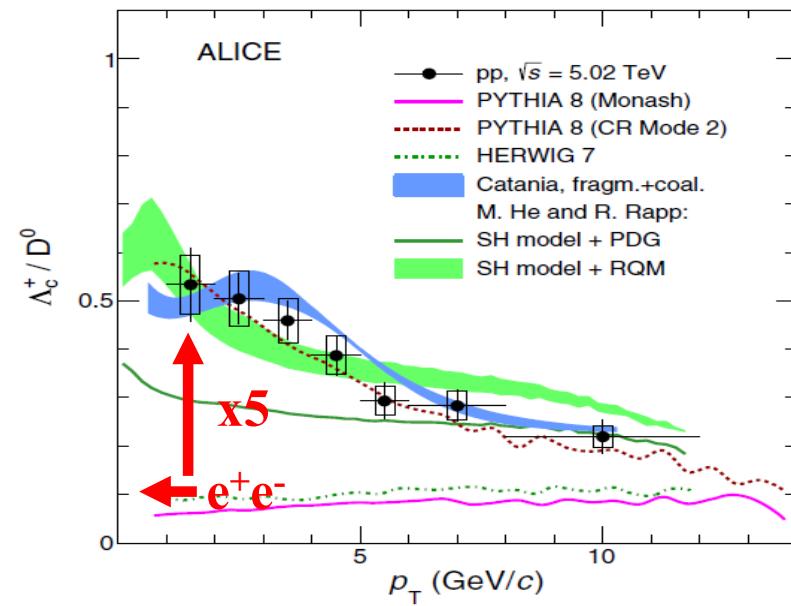


- Charm FF non-universal  $e^+e^- \rightarrow pp: c \rightarrow \Lambda_c$  enhanced vs  $c \rightarrow D^0$  reduced

ALICE, PRD105(2022)L011103



ALICE, PRL127(2021)202301; PRC104(2021)054905



# What about bottom?

**Table 6** Time-integrated mixing probability  $\bar{\chi}$  (defined in Eq. (32)), and production fractions of the different  $b$ -hadron species in an unbiased sample of weakly decaying  $b$  hadrons, obtained from both direct and mixing measurements. The correlation coefficients  $\rho$  between the fractions are also given

Quantity	Z decays	Tevatron	ATLAS [51]	LHCb [49]
Mixing probability	$\bar{\chi}$	$0.1259 \pm 0.0042$	$0.147 \pm 0.011$	
$B^+$ or $B^0$ fraction	$f_u = f_d$	$0.407 \pm 0.007$	$0.344 \pm 0.021$	Heavy Flavor Averaging Group, Eur. Phys. J., C81, 226 (2021)
$B_s^0$ fraction	$f_s$	$0.101 \pm 0.008$	$0.115 \pm 0.013$	
$b$ -baryon fraction	$f_{baryon}$	$0.085 \pm 0.011$	$0.198 \pm 0.046$	

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

- weakly-decaying  $b$ -hadron fractions: LEP( $e^+e^-$ ) vs Tevatron( $p-p\bar{p}$ ) different!
- What's different between  $e^+e^-$  vs  $pp/p-p\bar{p}$ ?
  - $e^+e^-$ : a single string formed with limited phase space → not conducive to baryons
  - $pp$ : a multi-parton interacting / quark-rich environment →  $b-q-q$  coalescence
  - statistical coalescence hadronization & **relative chemical equilibrium** (according to statistical weights) achieved between different bottom-hadron species

# Part (I)

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## **Bottom hadro-chemistry in pp/pp-bar collisions: augmented statistical hadronization**

# Augmented SHM for bottom

- grand-canonical ensemble for mini.bias pp → thermal density for primary b-hadrons

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

$\gamma_s = 0.6$  -- strangeness suppression factor  
 $T_H = 160/170$  MeV -- hadronization temperature

- PDG:** 5 B, 4 B<sub>s</sub>,  
5 Λ<sub>b</sub>, 2 Σ<sub>b</sub>, 4 Ξ<sub>b</sub>, 1 Ω<sub>b</sub>

**Λ<sub>b</sub>**

$J^P = 0(\frac{1}{2}^+)$

$J^P$  not yet measured;  $0(\frac{1}{2}^+)$  is the quark model prediction.  
 Mass  $m = 5619.60 \pm 0.17$  MeV  
 $m_{A_b^0} - m_{B^0} = 339.2 \pm 1.4$  MeV  
 $m_{A_b^0} - m_{B^+} = 339.72 \pm 0.28$  MeV  
 Mean life  $\tau = (1.471 \pm 0.009) \times 10^{-12}$  s  
 $c\tau = 441.0 \mu\text{m}$

**Λ<sub>b</sub>(5912)<sup>0</sup>**

$J^P = \frac{1}{2}^-$

Mass  $m = 5912.20 \pm 0.21$  MeV  
 Full width  $\Gamma < 0.66$  MeV, CL = 90%

**Λ<sub>b</sub>(5920)<sup>0</sup>**

$J^P = \frac{3}{2}^-$

Mass  $m = 5919.92 \pm 0.19$  MeV (S = 1.1)  
 Full width  $\Gamma < 0.63$  MeV, CL = 90%

**Λ<sub>b</sub>(6146)<sup>0</sup>**

$J^P = \frac{3}{2}^+$

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

**Λ<sub>b</sub>(6152)<sup>0</sup>**

$J^P = \frac{5}{2}^+$

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<sub>s</sub>, Ebert et al., PRD 84 (2011) 014025  
30 Λ<sub>b</sub>, 46 Σ<sub>b</sub>, 75 Ξ<sub>b</sub>, 42 Ω<sub>b</sub>

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

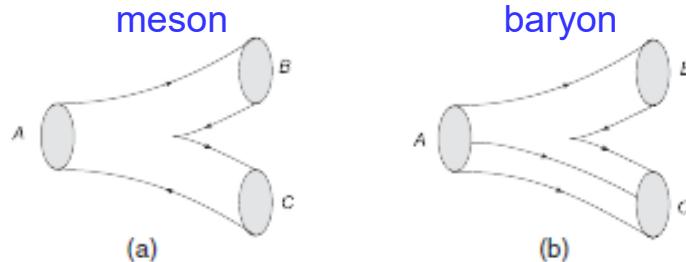
$J(J^P)$	$Qd$ state	$M$	$Q = c$ $M^{\text{exp}}$ [1]	$M$	$Q = b$ $M^{\text{exp}}$ [1]
$0(\frac{1}{2}^+)$	1S	2286	2286.46(14)	5620	5620.2(1.6)
$0(\frac{3}{2}^+)$	2S	2769	2766.6(2.4)?	6089	
$0(\frac{5}{2}^+)$	3S	3130		6455	
$0(\frac{7}{2}^+)$	4S	3437		6756	
$0(\frac{9}{2}^+)$	5S	3715		7015	
$0(\frac{11}{2}^+)$	6S	3973		7256	
$0(\frac{1}{2}^-)$	1P	2598	2595.4(6)	5930	
$0(\frac{3}{2}^-)$	2P	2983	2939.3(1.4)?	6326	
$0(\frac{5}{2}^-)$	3P	3303		6645	
$0(\frac{7}{2}^-)$	4P	3588		6917	
$0(\frac{9}{2}^-)$	5P	3852		7157	
$0(\frac{11}{2}^-)$	1P	2627	2628.1(6)	5942	
$0(\frac{1}{2}^-)$	2P	3005		6333	
$0(\frac{3}{2}^-)$	3P	3322		6651	
$0(\frac{5}{2}^-)$	4P	3606		6922	
$0(\frac{7}{2}^-)$	5P	3869		7171	
$0(\frac{1}{2}^+)$	1D	2874		6190	
$0(\frac{3}{2}^+)$	2D	3189		6526	
$0(\frac{5}{2}^+)$	3D	3480		6811	
$0(\frac{7}{2}^+)$	4D	3747		7060	
$0(\frac{9}{2}^+)$	1D	2880	2881.53(35)	6196	
$0(\frac{11}{2}^+)$	2D	3209		6531	
$0(\frac{1}{2}^+)$	3D	3500		6814	

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

$J(J^P)$	$Qd$ state	$M$	$Q = c$ $M^{\text{exp}}$ [1]	$M$	$Q = b$ $M^{\text{exp}}$ [1]
$1(\frac{1}{2}^+)$	1S	2443	2453.76(18)	5808	5807.8(2.7)
$1(\frac{3}{2}^+)$	2S	2901		6213	
$1(\frac{5}{2}^+)$	3S	3271		6575	
$1(\frac{7}{2}^+)$	4S	3581		6869	
$1(\frac{9}{2}^+)$	5S	3861		7124	
$1(\frac{1}{2}^+)$	1S	2519	2518.0(5)	5834	5834(0.3.4)
$1(\frac{3}{2}^+)$	2S	2936	2939.3(1.5)?	6226	
$1(\frac{5}{2}^+)$	3S	3293		6583	
$1(\frac{7}{2}^+)$	4S	3598		6876	
$1(\frac{9}{2}^+)$	5S	3873		7129	
$1(\frac{1}{2}^-)$	1P	2799	2802(4)?	6101	
$1(\frac{3}{2}^-)$	2P	3172		6440	
$1(\frac{5}{2}^-)$	3P	3488		6756	
$1(\frac{7}{2}^-)$	4P	3770		7024	
$1(\frac{9}{2}^-)$	1P	2713		6095	
$1(\frac{1}{2}^-)$	2P	3125		6430	
$1(\frac{3}{2}^-)$	3P	3455		6742	
$1(\frac{5}{2}^-)$	4P	3743		7008	
$1(\frac{7}{2}^-)$	1P	2798	2802(4)?	6096	
$1(\frac{9}{2}^-)$	2P	3172		6430	
$1(\frac{1}{2}^+)$	2P	3125		6742	
$1(\frac{3}{2}^+)$	3P	3455		7008	
$1(\frac{5}{2}^+)$	4P	3743		6096	
$1(\frac{7}{2}^+)$	1P	2798	2802(4)?	6096	
$1(\frac{9}{2}^+)$	2P	3172		6430	
$1(\frac{1}{2}^-)$	3P	3486		6742	
$1(\frac{3}{2}^-)$	4P	3768		7009	
$1(\frac{5}{2}^-)$	1P	2773	2766.6(2.4)?	6087	
$1(\frac{7}{2}^-)$	2P	3151		6423	
$1(\frac{9}{2}^-)$	3P	3469		6736	
$1(\frac{1}{2}^+)$	4P	3753		7003	
$1(\frac{3}{2}^+)$	1P	2789		6084	

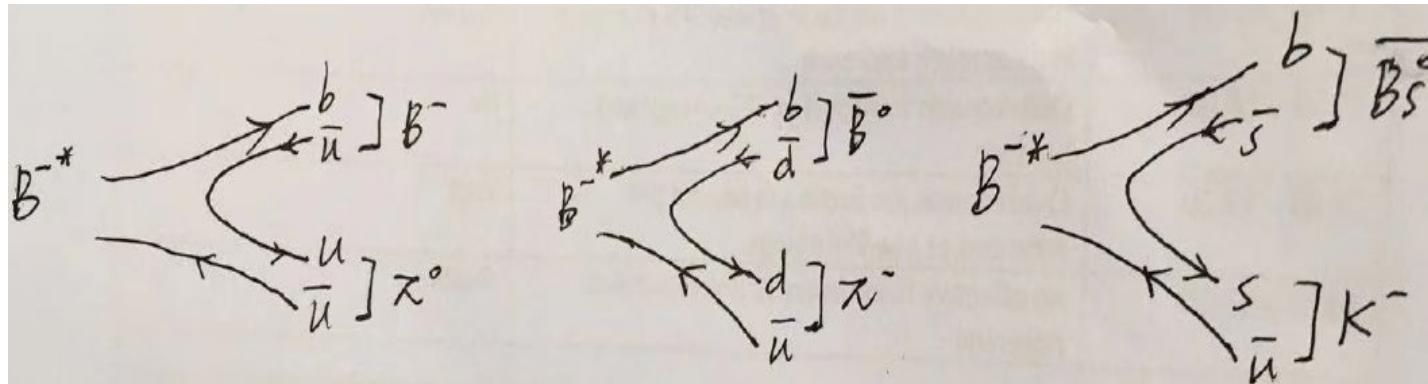
# Strong decay systematics of excited states

- $^3P_0$  model:  $A \rightarrow B + C$  via creating a q-qbar pair of  $J^{PC}=0^{++}$



$$\Gamma_{A \rightarrow BC} = \Phi_{A \rightarrow BC}(q_0) \sum_{\ell} |\langle BC q_0 \ell J | T^\dagger | A \rangle|^2.$$

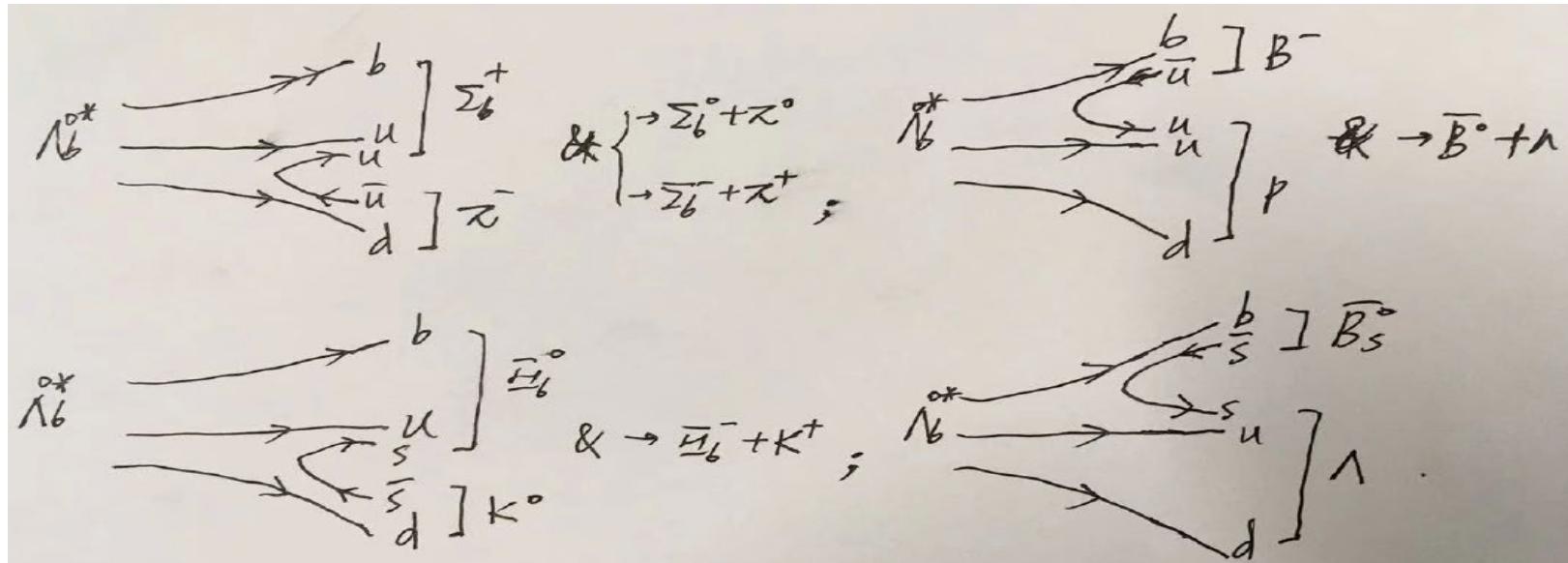
- Branching Ratio  $\propto$  # of possible diagrams once a decay channel opens up (mesons)



- probability of producing a q-qbar pair  $\propto \exp(-2m/T_H)$   
→  $\exp(-2m_q/T_H) : \exp(-2m_s/T_H) = 1 : 1/3$  [ $m_q \sim 8$ ,  $m_s \sim 100$  MeV]  
→ diagrams involving s-sbar counted as 1/3
- E.g.  $\text{BR}(B^{-*} \rightarrow B^- + \pi^0) = \text{BR}(B^{-*} \rightarrow B^0 \bar{b} + \pi^-) = 1/(1+1+1/3) = 43\%;$   
 $\text{BR}(B^{-*} \rightarrow B_s^0 \bar{b} + \pi^0) = 1/3/(1+1+1/3) = 14\%;$     $\text{BR}(B_s^{-*} \rightarrow B^- + K) = 1/(1+1+1/3) = 43\%$

# Strong decay systematics: BR's estimation

- Branching Ratio  $\propto$  # of possible diagrams once a decay channel opens up (**baryons**)



- E.g.  $\text{BR}(\Lambda_b^{0*} \rightarrow \Sigma_b + \pi^- \rightarrow \Lambda_b^0 + 2\pi) = 3/(3+2+2*1/3+1/3) = 54\%$   
 $\text{BR}(\Lambda_b^{0*} \rightarrow B^- + p) = 1/(3+2+1/3+2*1/3) = 16\%$   
 $\text{BR}(\Lambda_b^{0*} \rightarrow \Xi_b^0 + K^-) = 2/3/(3+2+1/3+2*1/3) = 11\%$   
 $\text{BR}(\Lambda_b^{0*} \rightarrow B_s^0 \bar{u} + \Lambda) = 1/3/(3+2+1/3+2*1/3) = 6\%$
- done for all RQM excited mesons/baryons ( $\Sigma_b^{*}, \Xi_b^{*}, \Omega_b^{*}$ )  
numbers **comparable to (limited) results in PDG** & computed in  ${}^3P_0$  with full wave functions

X. Liu et al. '07, Ferretti et al., '18, Z. Wang et al., '23

# Ground-state b-hadron densities

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- total density of weakly-decaying b-hadrons @  $T_H=170 / 160$  MeV

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

$n_\alpha \cdot 10^{-12} \text{ fm}^{-3}$	$B^-$	$\bar{B}^0$	$\bar{B}_s^0$	$\Lambda_b^0$	$\Xi_b^{0,-}$	$\Omega_b^-$
PDG(170)	1.0094	1.0089	0.29308	0.31591	0.10097	0.002341
PDG(160)	0.12655	0.12649	0.036622	0.034241	0.010520	0.00023076
RQM(170)	1.2045	1.2041	0.32513	0.61702	0.19548	0.0063204
RQM(160)	0.14567	0.14561	0.039664	0.061914	0.018819	0.00061087

- fragmentation fractions & ratios

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

$f_\alpha$	$B^-$	$\bar{B}^0$	$\bar{B}_s^0$	$\Lambda_b^0$	$\Xi_b^{0,-}$
PDG(170)	0.3697	0.3695	0.1073	0.1157	0.03698
PDG(160)	0.3782	0.3780	0.1094	0.1023	0.03144
RQM(170)	0.3391	0.3389	0.09152	0.1737	0.05503
RQM(160)	0.3533	0.3532	0.09620	0.1502	0.04565

$r_\alpha$	$\bar{B}^0/B^-$	$\bar{B}_s^0/B^-$	$\Lambda_b^0/B^-$	$\Xi_b^{0,-}/B^-$
PDG(170)	0.9995	0.2904	0.3129	0.1000
PDG(160)	0.9995	0.2894	0.2706	0.08313
RQM(170)	0.9994	0.2699	0.5122	0.1623
RQM(160)	0.9996	0.2723	0.4250	0.1292

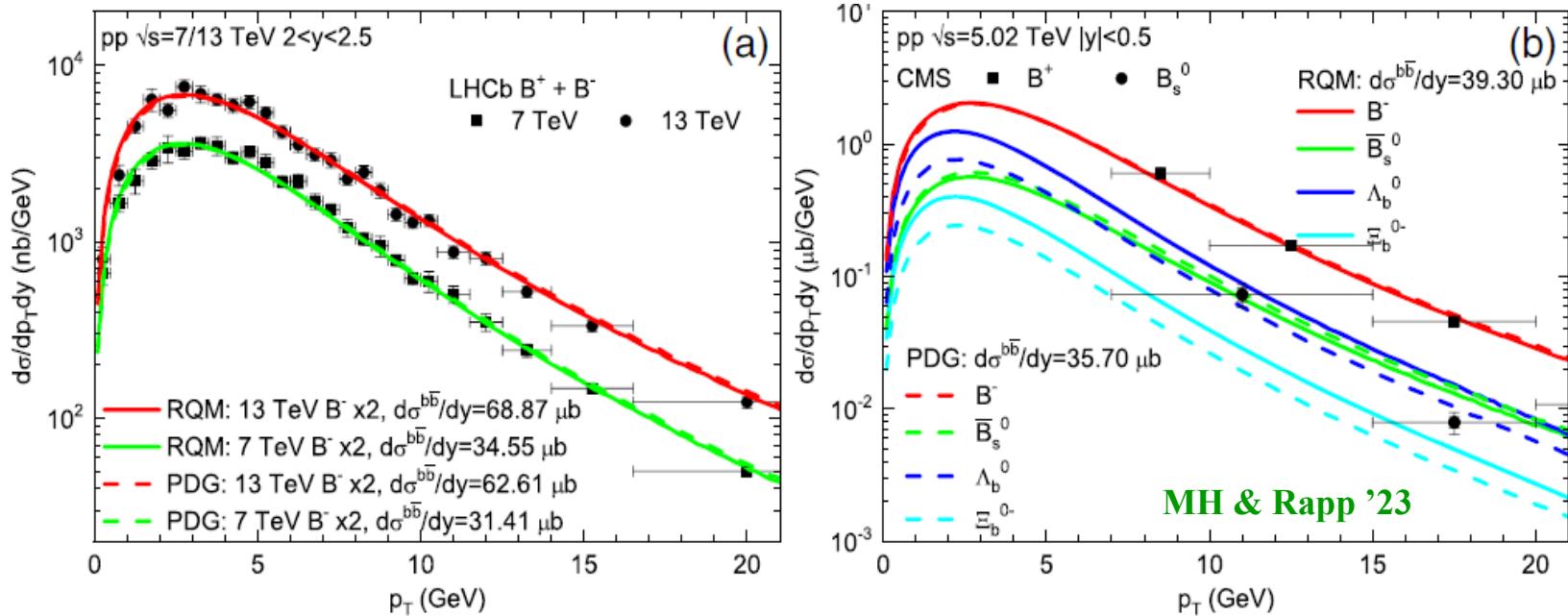
- PDG → RQM:  $\Lambda_b^0$  &  $\Xi_b^{0,-}$  enhanced by ~50%
- good agreement with Tevatron p-pbar data  
 $f_u=f_d=0.340$ ,  $f_s=0.101$ ,  $f_{\text{baryon}}=0.220$
- PDG → RQM:  $B_s^0 \bar{B}_s^0 / B^- \bar{B}^0$  reduced by ~7%
- baryonic ratios enhanced by ~ 60%  
 $\Lambda_b^0/B^- \sim 0.51$  vs : LHCb 13TeV pp data  
of  $f_{\Lambda_b}/(f_u+f_d) = 0.259 \pm 0.018$

# Fragmentation & $p_T$ -spectra

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

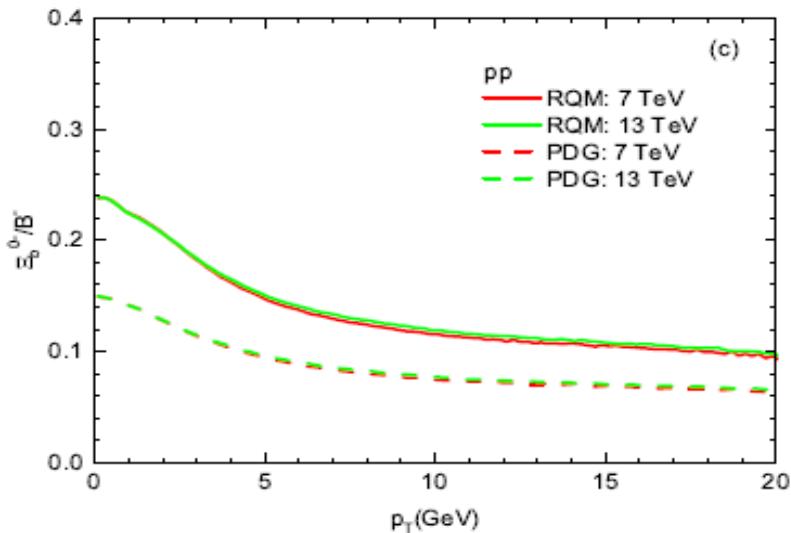
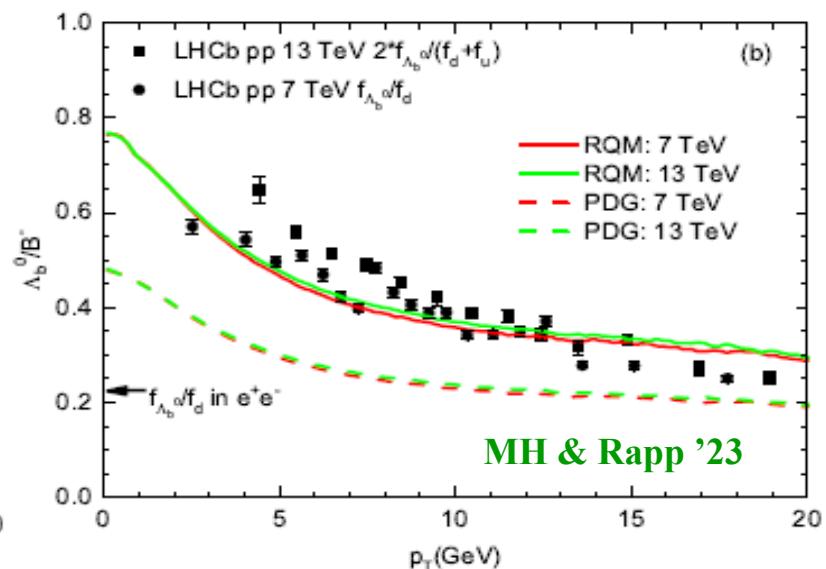
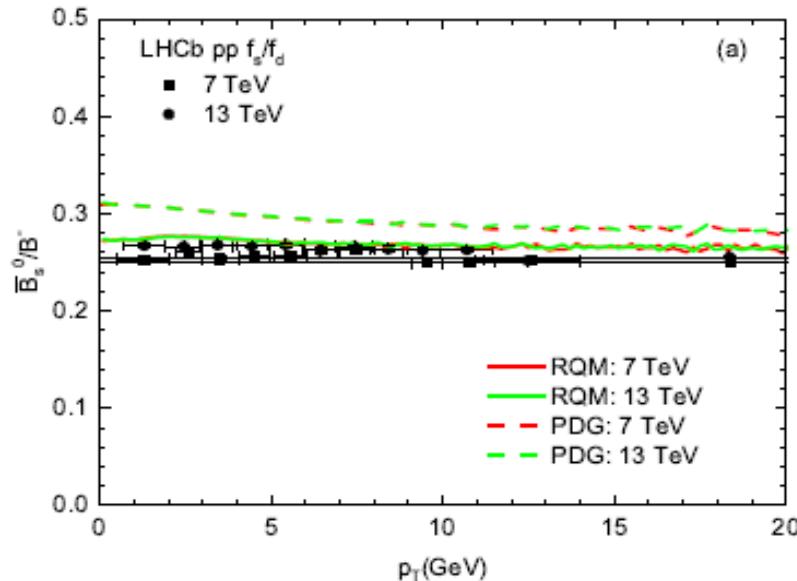
$$D_{b \rightarrow H_b}(z) \propto z^\alpha(1-z), \quad \left. \begin{array}{l} \text{weight } \propto \text{primary density} \\ (\text{relative chem. equilibrium}) \end{array} \right\}$$

$\alpha_B = 45, \alpha_{Bs} = 25, \alpha_{\text{baryon}} = 8$  to tune the slope of spectra



- PDG vs RQM equally well for mesons, but ~10% smaller  $\sigma$ : reduction of b-content in baryon
- $d\sigma^{b\bar{b}\bar{b}\bar{b}}/dy = 34.55 \mu\text{b}$  for 7 TeV  $2 < y < 2.5$ ;  $39.3 \mu\text{b}$  for 5.02 TeV mid-y → **baseline for AA**

# Hadro-chemistry: $p_T$ -dependent ratios



- $B_s^0/\bar{B}^-$ : almost flat, reduced by  $\sim 10\%$  by RQM additional states
- $\Lambda_b^0/\bar{B}^-$ : PDG far off, gap overcome by feeddown of “missing” baryons from RQM, much larger than  $e^+e^-$  value
- $\Xi_b^0/\bar{B}^-$ : similar enhancement from RQM

## Part (II)

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Hadro-chemistry computed above in pp collisions = a controlled reference for studying modifications in AA collisions →

**Bottom hadro-chemistry in  
PbPb collisions:**

**diffusion + recombination in QGP**

# HQ diffusion in QGP

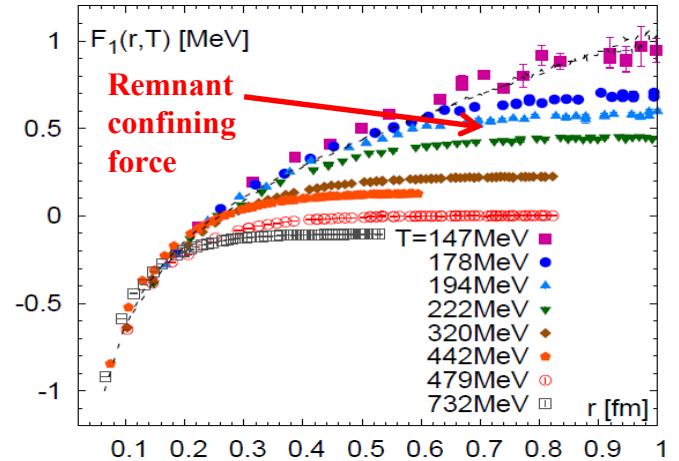
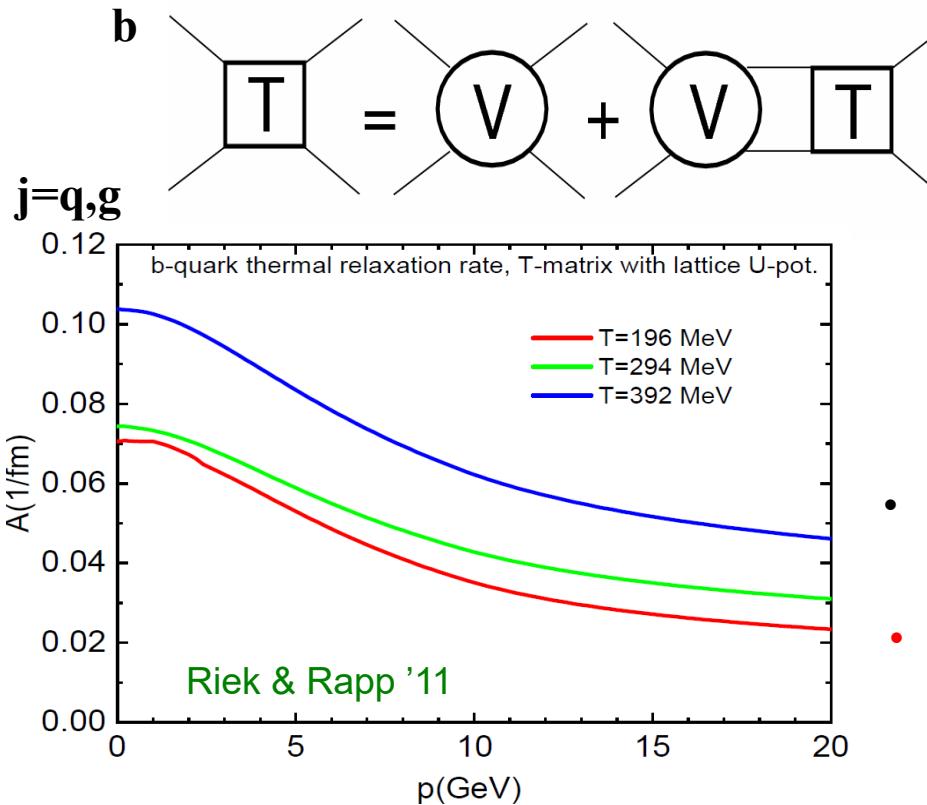
- Brownian motion by Langevin equations: b accuracy improved wrt c

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

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

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

- T-matrix resummation of lattice-constrained HQ potential MH, van Hees & Rapp, PPNP '23



- p-dependence: long-range remanant confining force at low p → pQCD high p
- X K-factor=1.6 for better phenomenology, also mimicking spin-dependent force /radiative contributions Tang & Rapp '23

# Hadronization: resonance recombination

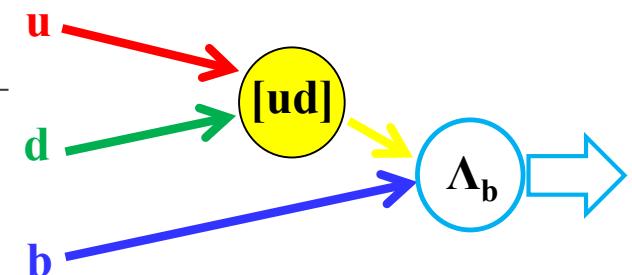
- Resonance recombination model (RRM) **Ravagli et al.'07, MH et al.'12**

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

- derived from Boltzmann eq., E-conserved & equilibrium limit encoded
- $\sigma_M(s)$  resonant cross section <--> T-matrix resonant interaction in QGP
- 3-body RRM: diquark correlations in heavy-baryons **MH & Rapp '20**

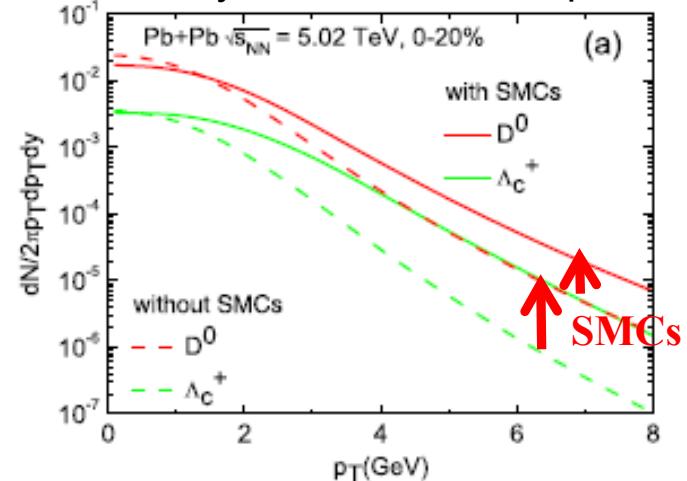
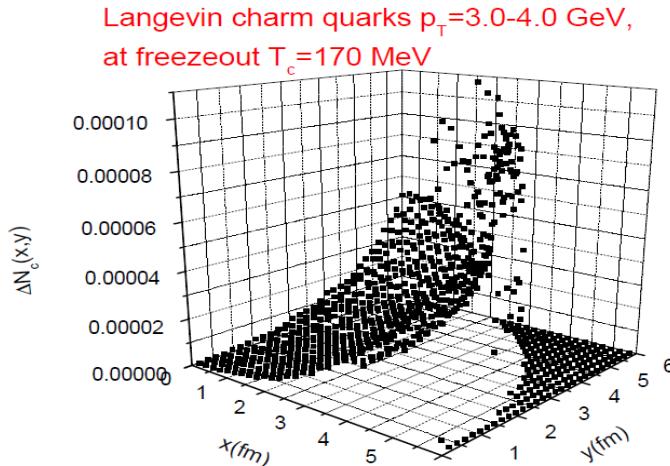
diquark type	mass (MeV)	wave func.	charm-baryon
Scalar [u,d]	710	$\bar{3}_{\text{color}} \bar{3}_{\text{flavor}} 0_{\text{spin}}^+$	$\Lambda_c$ : c[ud]
Axialvector {u,d}	909	$\bar{3}_{\text{color}} 6_{\text{flavor}} 1_{\text{spin}}^+$	$\Sigma_c$ : c{ud}

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

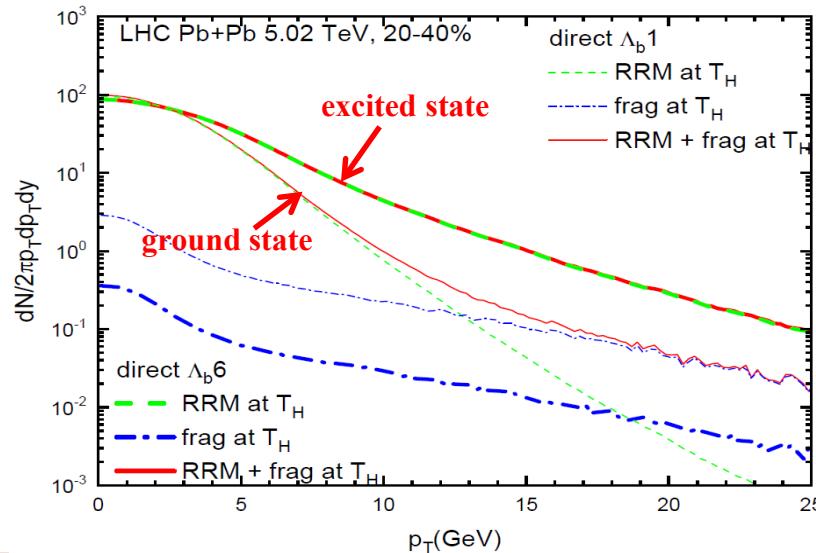


# RRM: space-momentum correlations

- Inhomogeneous distribution: SMCs → recombination beyond momentum space



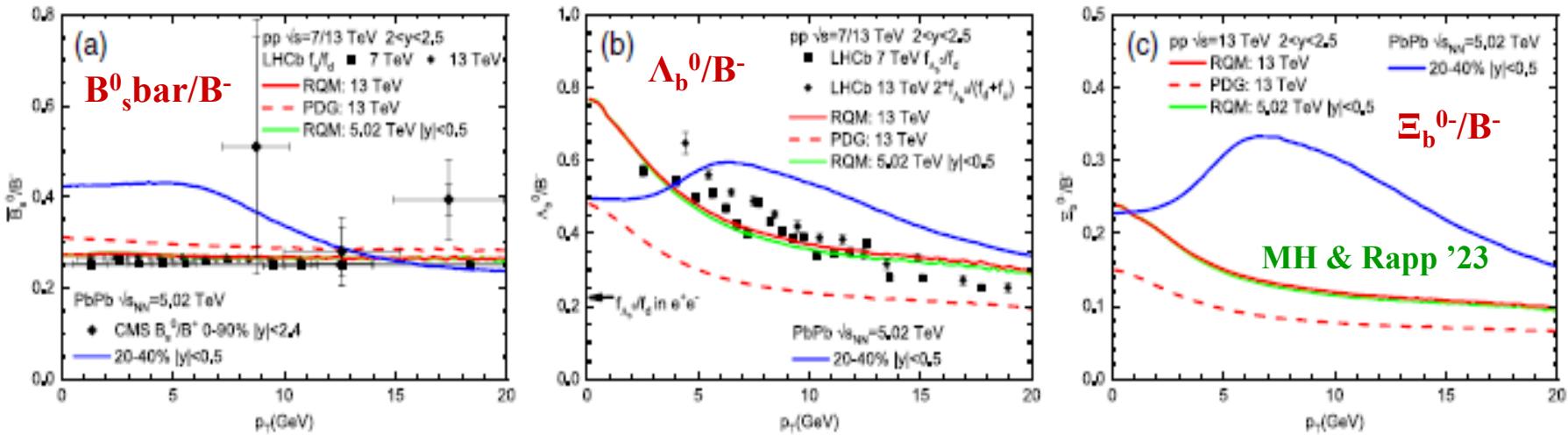
- Left-over b-quarks: fragmentation in the same manner as in pp



- Excited state more massive: recombination spectrum harder than ground state (SMCs/flow)
- RRM vs frag. crossing at  $p_T \sim 14 \text{ GeV}$  for  $\Lambda_b 1$  vs  $\Lambda_b 6$  at  $p_T > 25 \text{ GeV}$
- both much higher than charm counterparts

# Modifications of hadro-chemistry

- Further complemented with hadronic phase diffusion



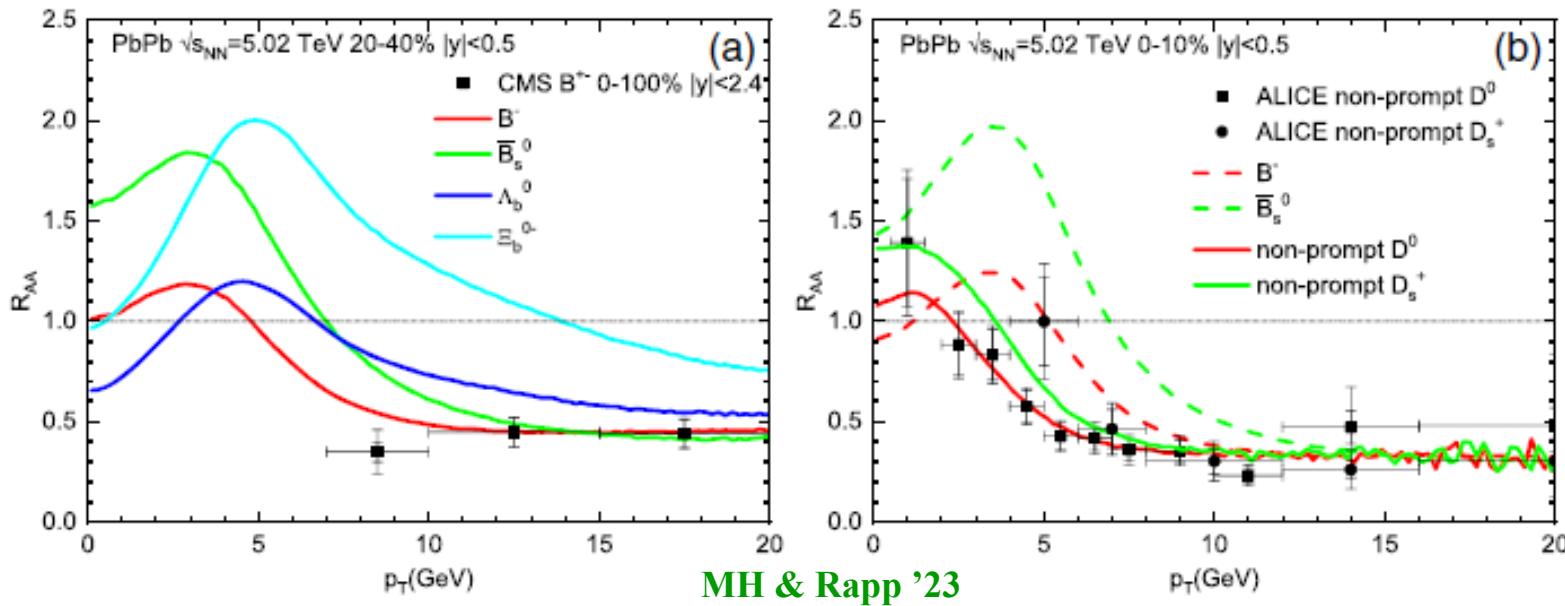
- $pp \rightarrow PbPb$ 
  - $B_s/B$  – enhancement at low  $p_T$ : b coupled to equilibrated strangeness via recombination
  - $\Lambda_b/B$  – flow-bump at intermediate  $p_T \sim 5-15$  GeV [significantly higher than c-sector]: stronger flow push on baryons, captured by 3-body RRM with SMCs
  - $\Xi_b/B$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

# b-hadron nuclear modification factors

- $R_{AA}$  for ground state b-hadrons: hierarchy of flow effects and suppression driven by their quark content

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

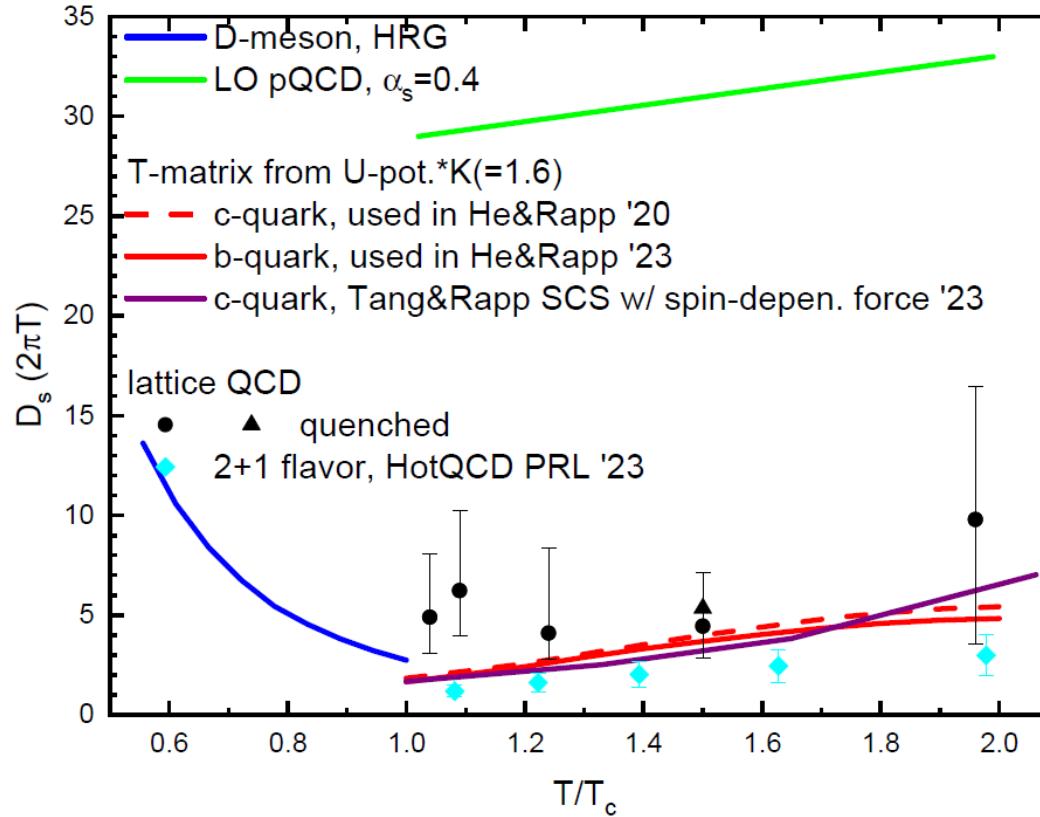
→  $dN^{\text{bbbar}}/dy \sim 0.9$  for 0-10%  
 → reference from pp-SHM



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

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

- HQ spatial diffusion coefficient:  $\mathcal{D}_s = T/m_Q A(p=0) = T/m_Q \gamma$



- models & lattice  $\mathcal{D}_s(2\pi T) \sim 1-3$  near  $T_c$ ,  $\times 10$  smaller than pQCD scattering rate  $\Gamma_{\text{coll}} \sim 3/\mathcal{D}_s \sim 1 \text{ GeV} > M_{q,g}$  → thermal partons melt, Brownian markers survive
- maximum coupling strength near  $T_c$ , significant remnant of confining force?!  
→ insignificant (little) screening of HQ potential **HotQCD: 2308.16587**

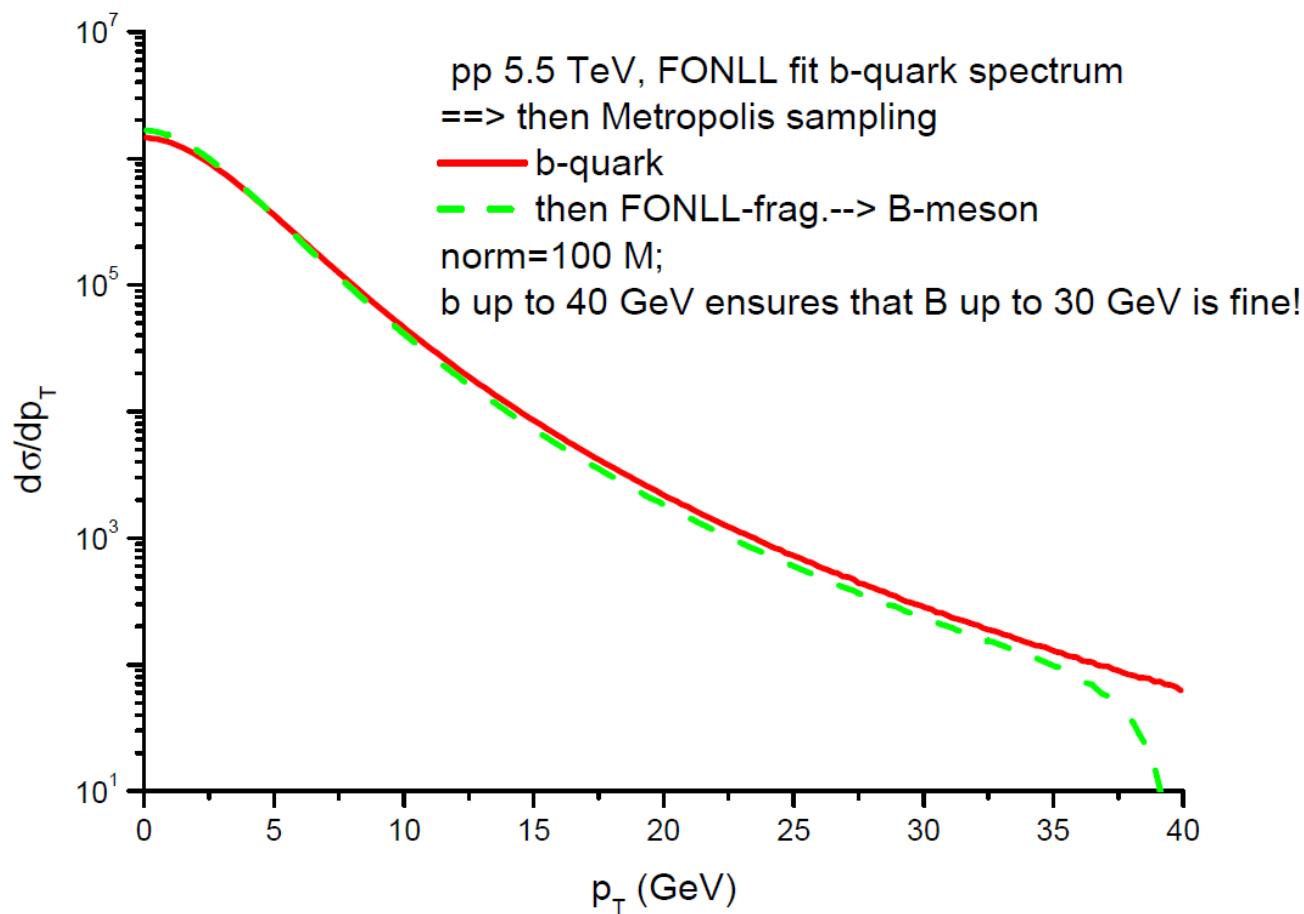
# Back-up: Summary

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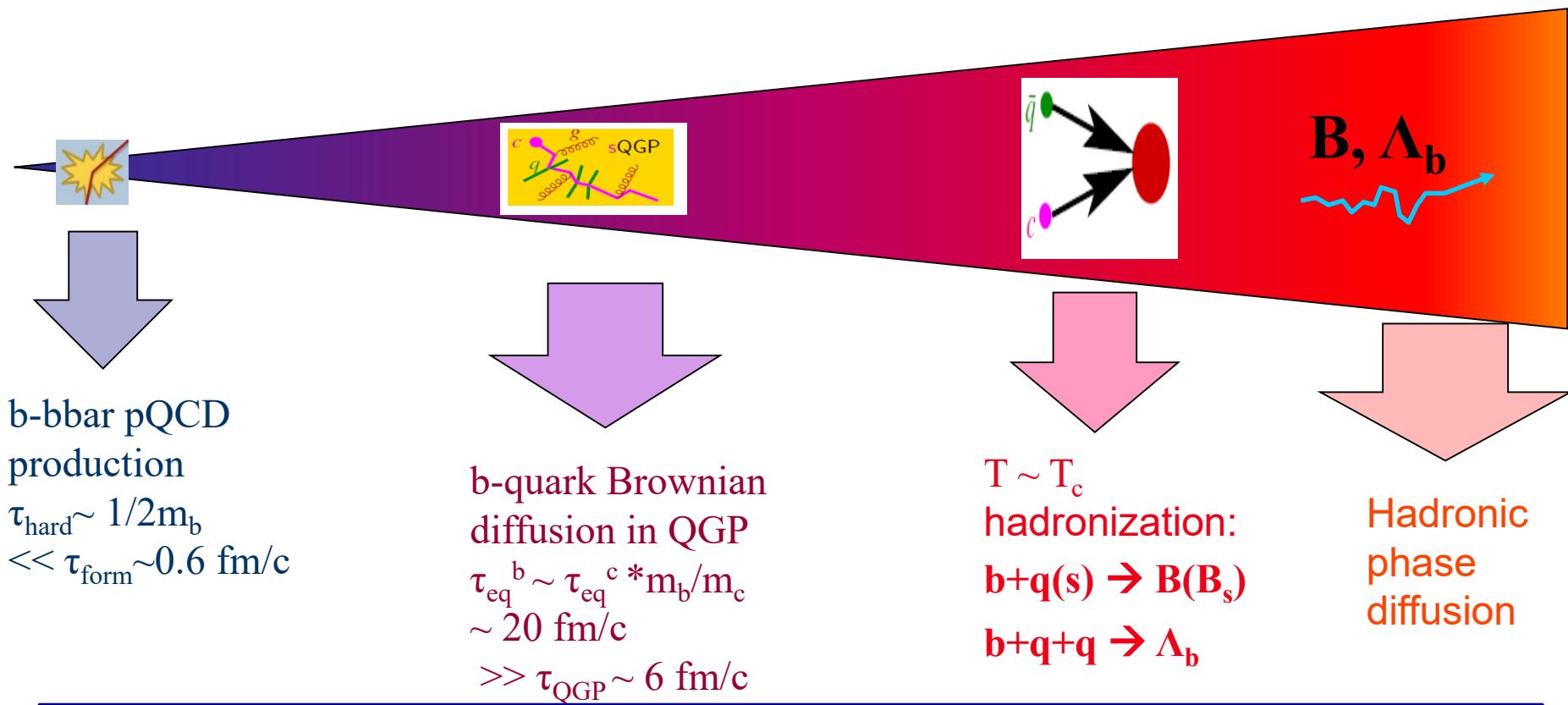
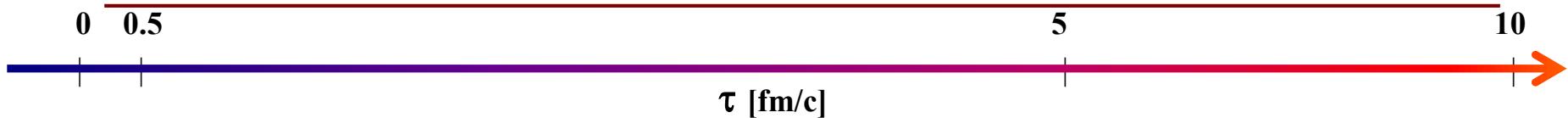
- High-energy pp collisions: *relative* chemical equilibrium assumed
  - “missing” bottom-baryons (in particular) essential
  - fragmentation fractions &  $p_T$ -dependent ratios decently predicted
  - b-bbar cross section determined
  - ➔ a controlled baseline for bottom probes of PbPb
- heavy ion collisions: same b-hadron spectrum used
  - baseline hadro-chemistry deployed into strongly coupled HF transport model
  - modifications of  $p_T$ -dependent b-hadro-chemistry quantified
  - collective behavior of b-hadron  $R_{AA}$  from diffusion + recombination identified
  - ➔ role of b-quark as probes of QGP identified

# Back-up: fragmentation $b \rightarrow B$

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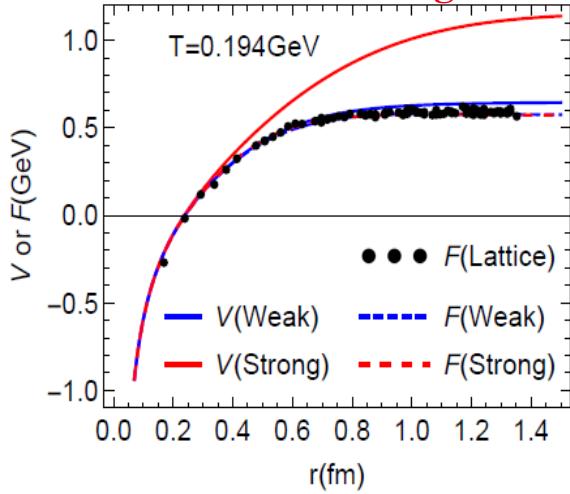
# b-quark transport as probes of QGP



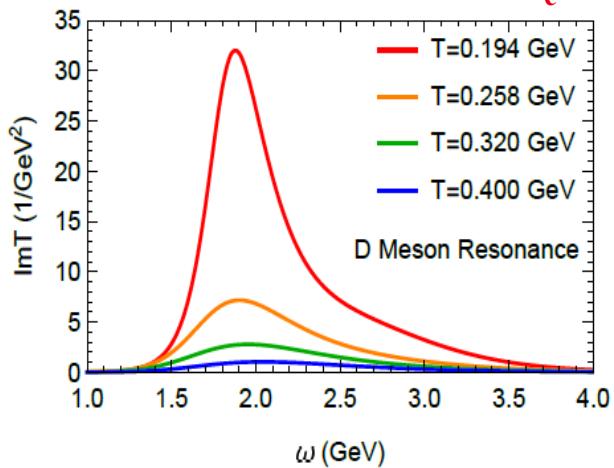
- $m_c \gg \Lambda_{\text{QCD}}$  → controlled baseline calculable via pQCD
- $\tau_{\text{hard}} \sim 1/2m_b$  → color test charge experiencing full evolution of medium

# Landscape of T-matrix HQ & quarkonium interactions

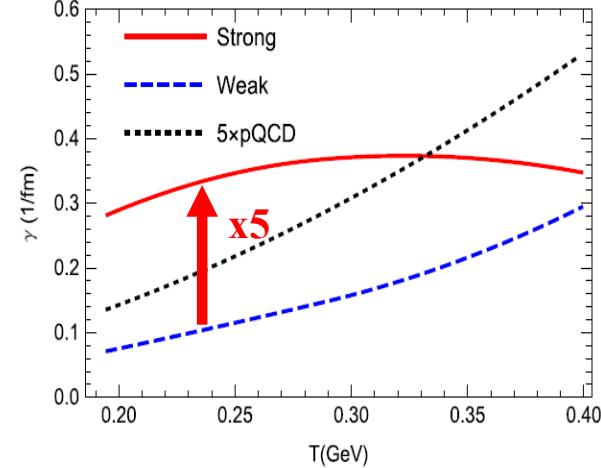
## Remnant confining force



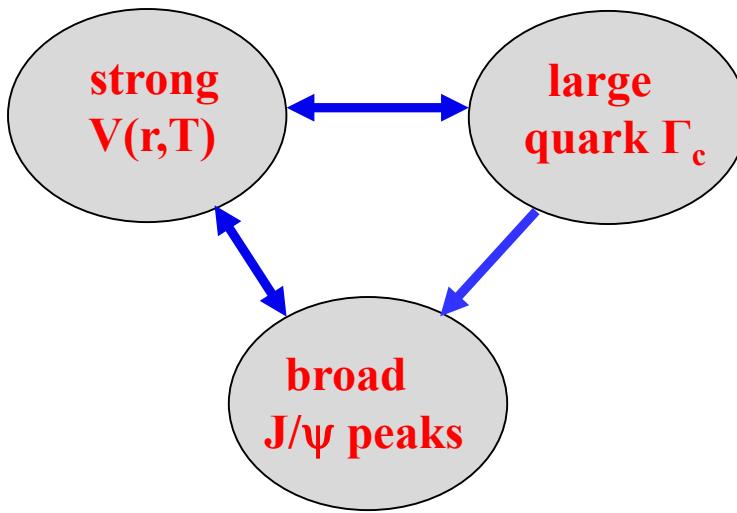
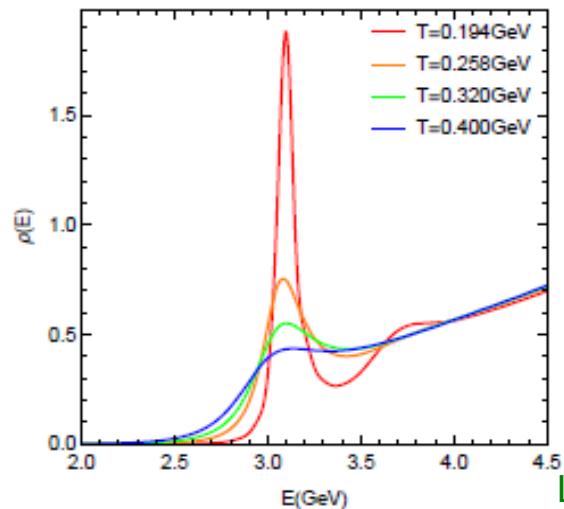
## Resonances form near $T_c$



## Accelerates thermalization

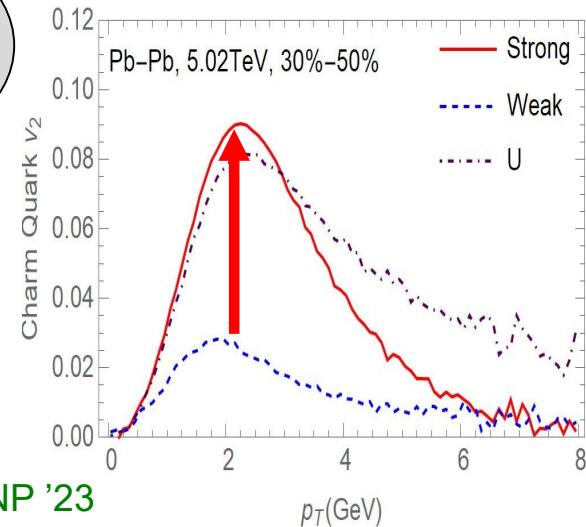


## $J/\psi$ survives in QGP



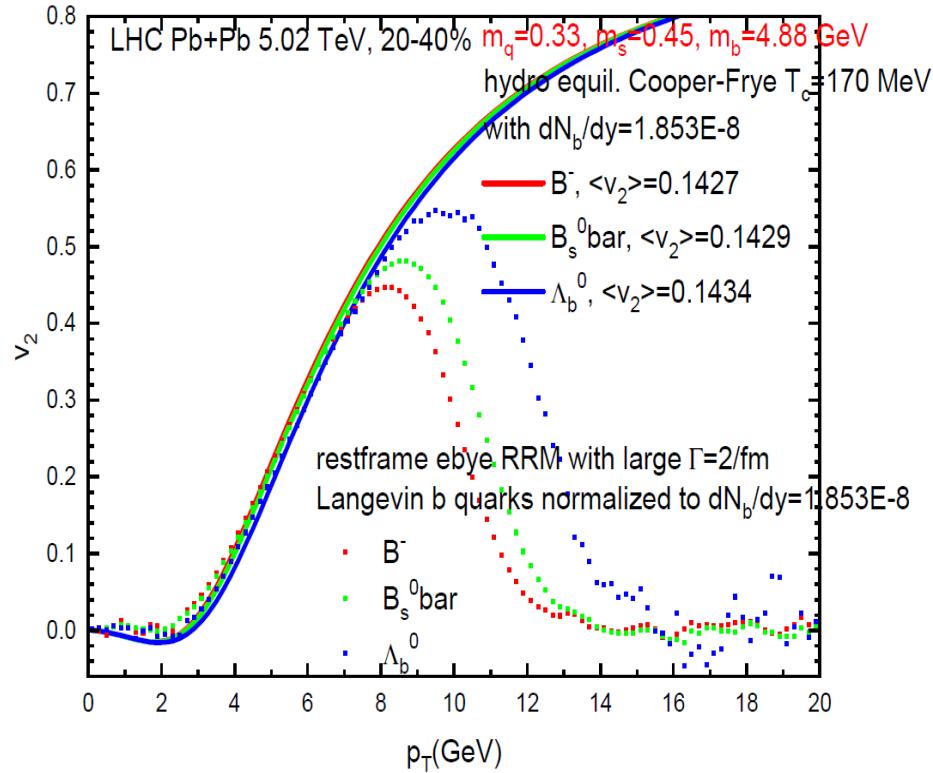
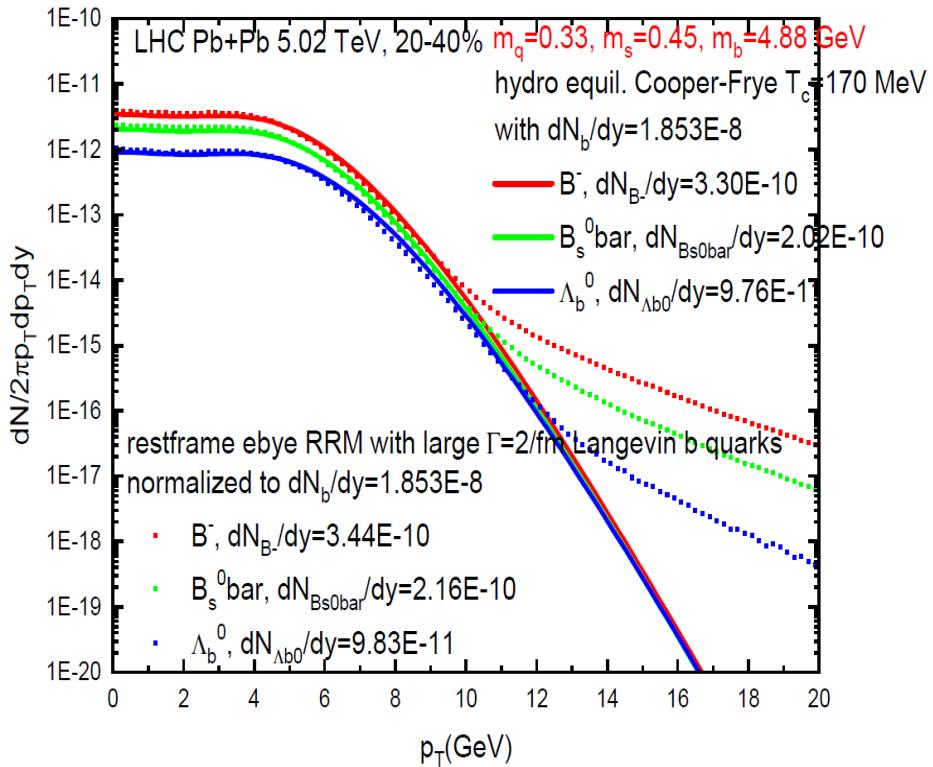
Liu & Rapp, '18; MH, van Hees & Rapp, PPNP '23

## Coupling strength $\leftrightarrow$ HQ $v_2$



# Back-up: Langevin+RRM equil. limit check

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# RRM with SMCs: coal. vs frag.

