Hadronization of Heavy Flavor in pp & Pb-Pb collisions

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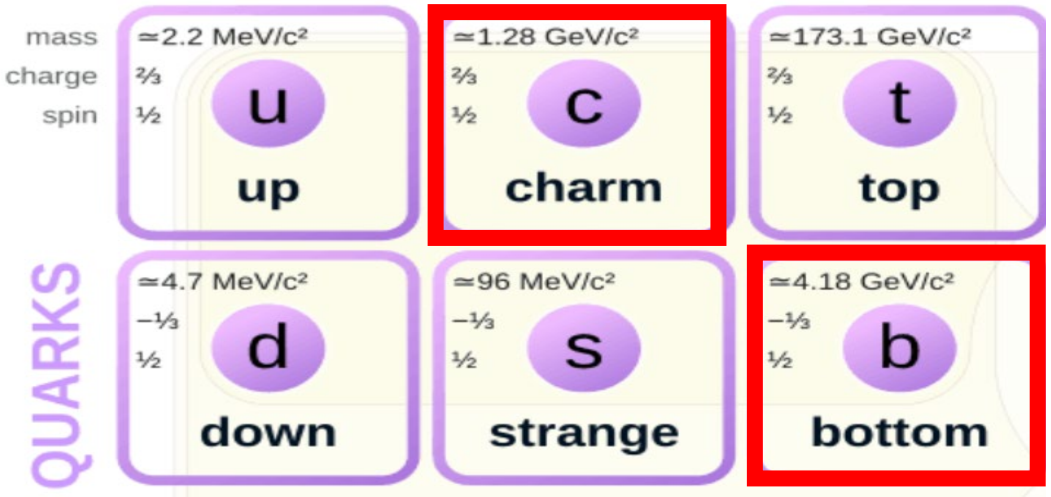
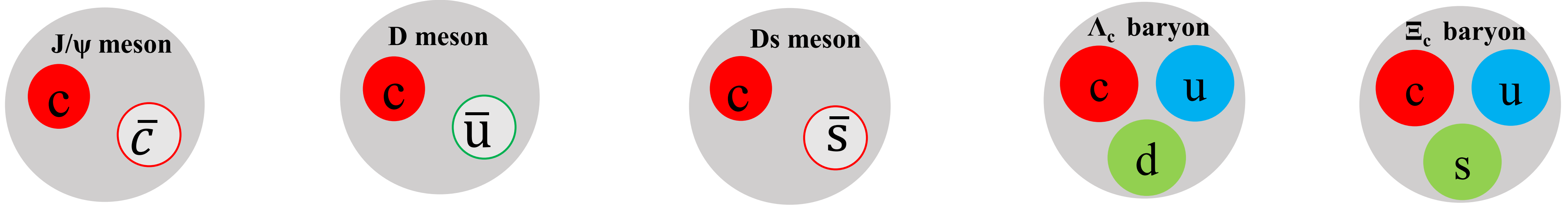
Heavy quarks & heavy hadrons

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

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



- Hadronization ➔ well separated from production



Charmonium **D mesons** **D_s mesons** **Λ_c-baryons** **Ξ_c-baryons**

hidden charm

open charm-hadrons

Outline of Part I

Part I: Heavy quark hadronization in pp

- Heavy flavor hadro-chemistry: non-universal
- Statistical hadronization: grand-canonical → canonical
- Providing baseline heavy-hadron p_T-spectra for Pb-Pb

Heavy quark hadronization in pp collisions

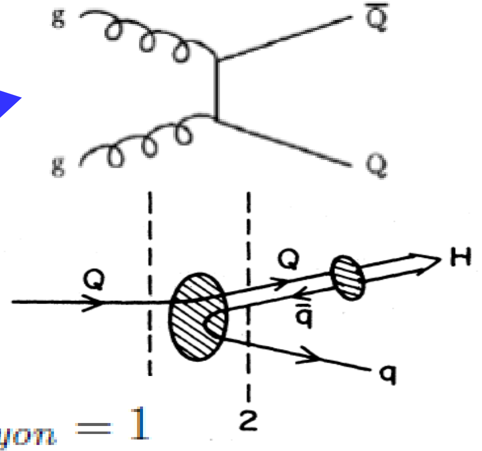
- Heavy hadron production cross section: factorization

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

Parton distribution functions (PDFs)

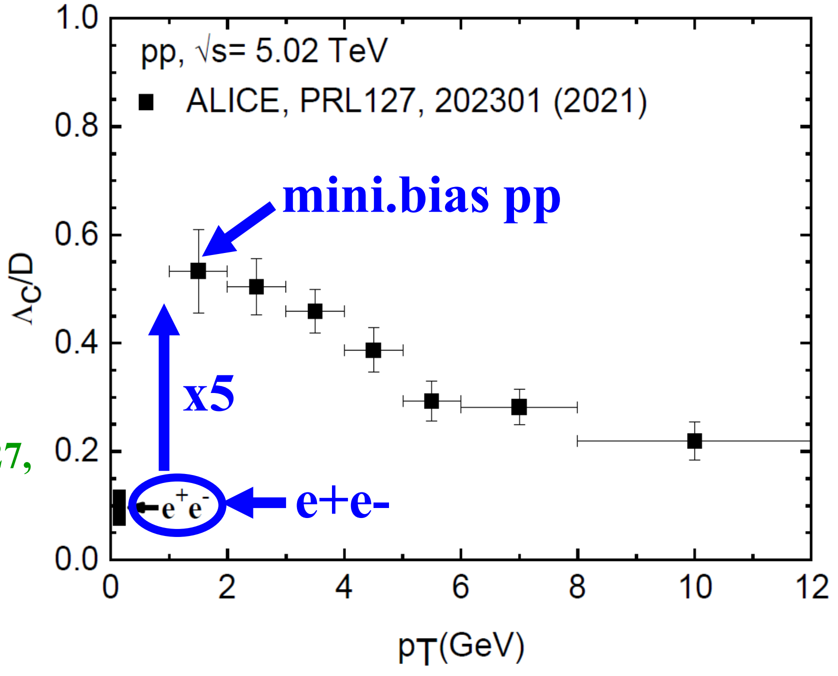
Hard scattering cross section (pQCD)

Fragmentation function (hadronization)



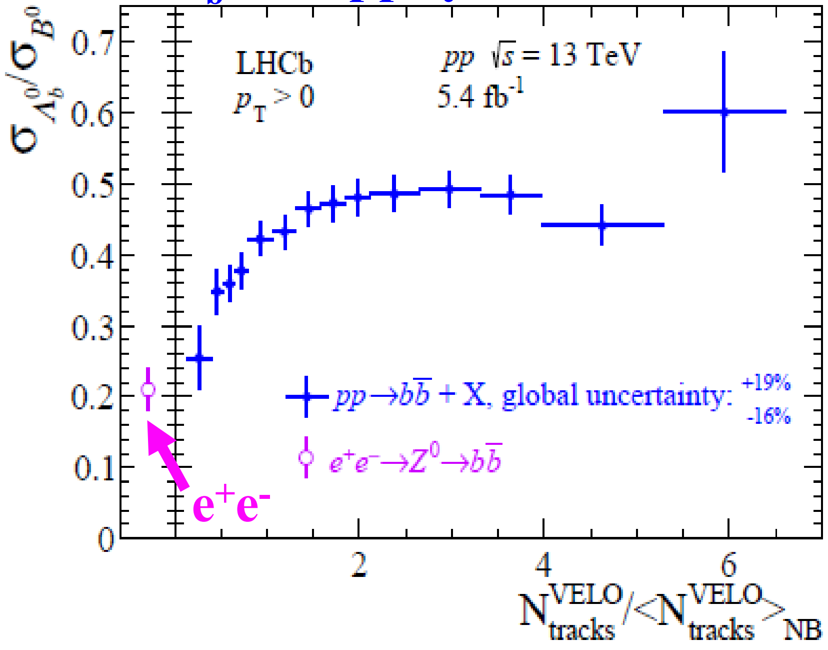
- Hadronization: heavy quark conservation $f_u + f_d + f_s + f_{baryon} = 1$

  - hadro-chemistry: universal? → non-universal!



ALICE, PRL127, 202301 (2021)

Λ_b/B vs pp system size scan



LHCb, PRL132, 081901 (2024)

Difference e^+e^- vs pp ➔ statistical hadronization

- e^+e^- = heavy Q-Qbar produced as two back-to-back jets

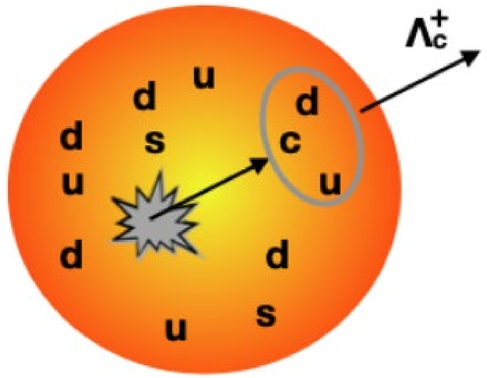
  ➔ heavy quark vacuum fragmentation: costly to excite a diquark-antidiquark pair

  ➔ not conducive to Λ_c baryon production

- High-energy pp collisions = light-quark-rich environment

  ➔ Coalescence of c/b with surrounding q

  ➔ Enhancing heavy-baryon production: $n_{\Lambda c} \propto n_q^2$ vs $n_D \propto n_q$



- Stochastic/statistical coalescence = Statistical Hadronization Model (SHM)

  { *Relative* chemical equilibrium between different heavy-hadron species

  { Heavy-hadron primary production yields $N_i \propto$ thermal densities n_i

Mini. bias pp: Grand-canonical SHM

- Grand-canonical thermal density for primary heavy-hadrons

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

γ_s=0.6 – strangeness suppression factor

T_H=170 MeV – ‘universal’ hadronization temperature

- Heavy-hadron mass spectrum: ‘missing’ c/b-baryons

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

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

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 $\Gamma < 0.66$ 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

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).

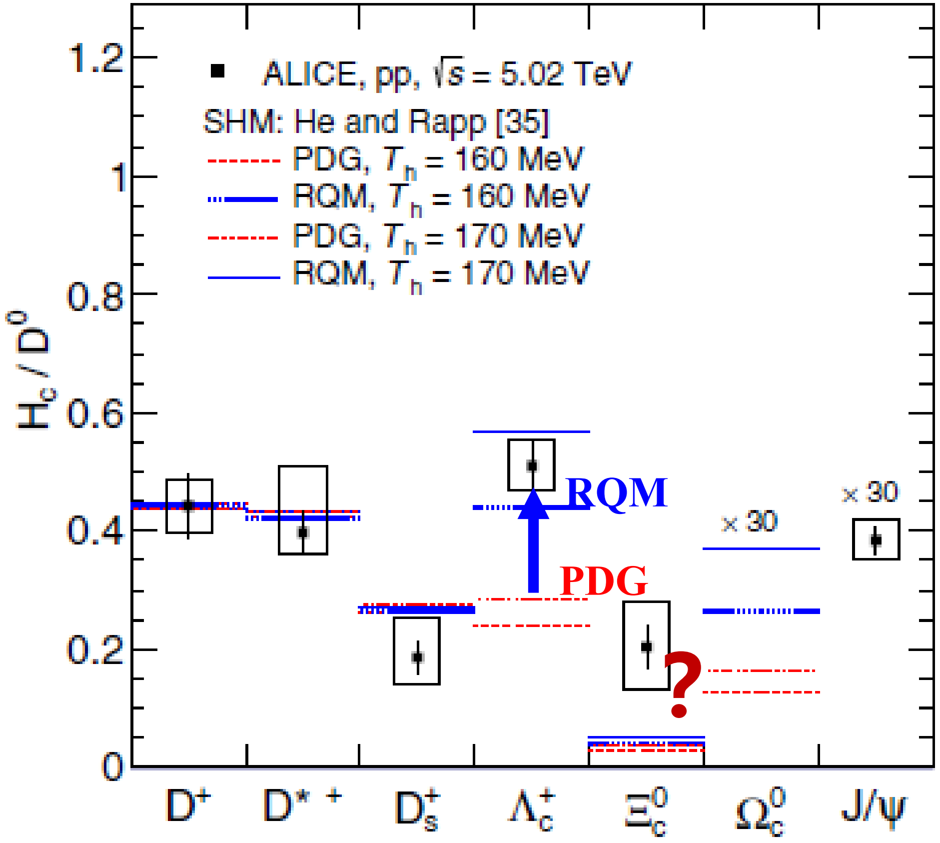
		$Q = c$		$Q = b$	
$I(J^P)$	Qd state	M	M^{exp} [1]	M	M^{exp} [1]
$1(\frac{1}{2}^+)$	1S	2443	2453.76(18)	5808	5807.8(2.7)
$1(\frac{1}{2}^+)$	2S	2901		6213	
$1(\frac{1}{2}^+)$	3S	3271		6575	
$1(\frac{1}{2}^+)$	4S	3581		6869	
$1(\frac{1}{2}^+)$	5S	3861		7124	
$1(\frac{3}{2}^+)$	1S	2519	2518.0(5)	5834	5829.0(3.4)
$1(\frac{3}{2}^+)$	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	

Ground-state c/b-hadron ratios

- Ground-state heavy-hadron total density = primary + feed-downs

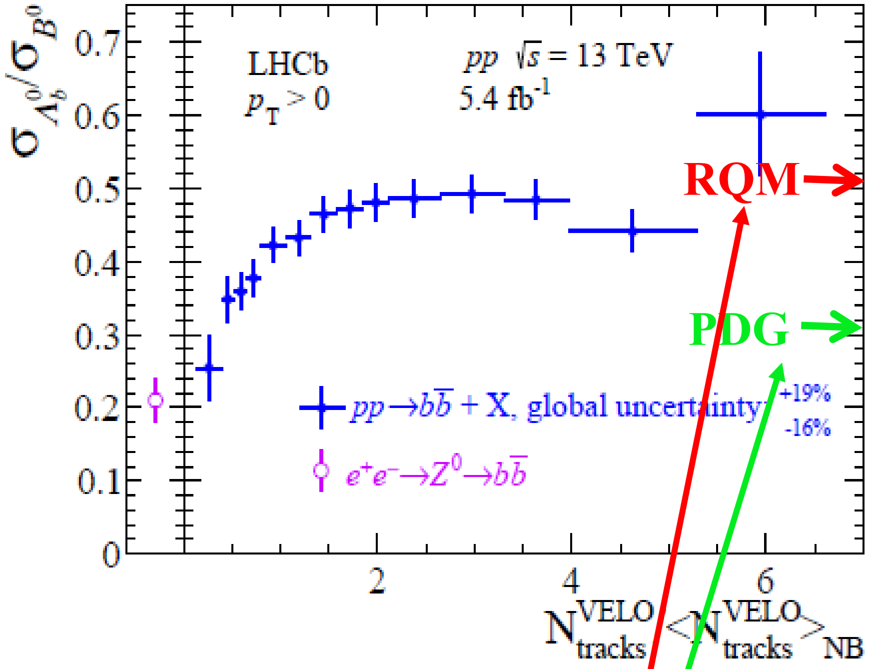
$$n_\alpha = n_\alpha^{\rm primary} + \sum_i n_i^{\rm primary} \cdot BR(i \to \alpha)$$

H_c/D^0 mini.bias pp



ALICE, PRD 105 (2022) L011103; MH & Rapp '19

Λ_b/B vs system-size



MH & Rapp '23

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

p_T-dependence: fragmentation + decay simulation

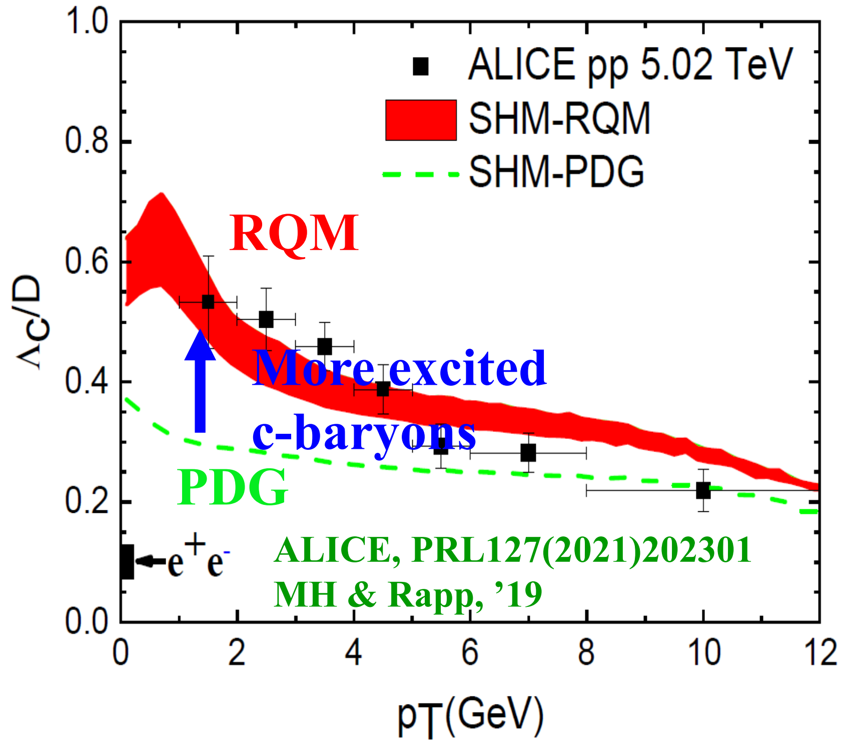
- FONLL c/b-quark p_t-spectrum + fragmentation into all primary states + decay simulations

➔ ground-state b-hadrons p_T-spectra: $z = p_T/p_t$

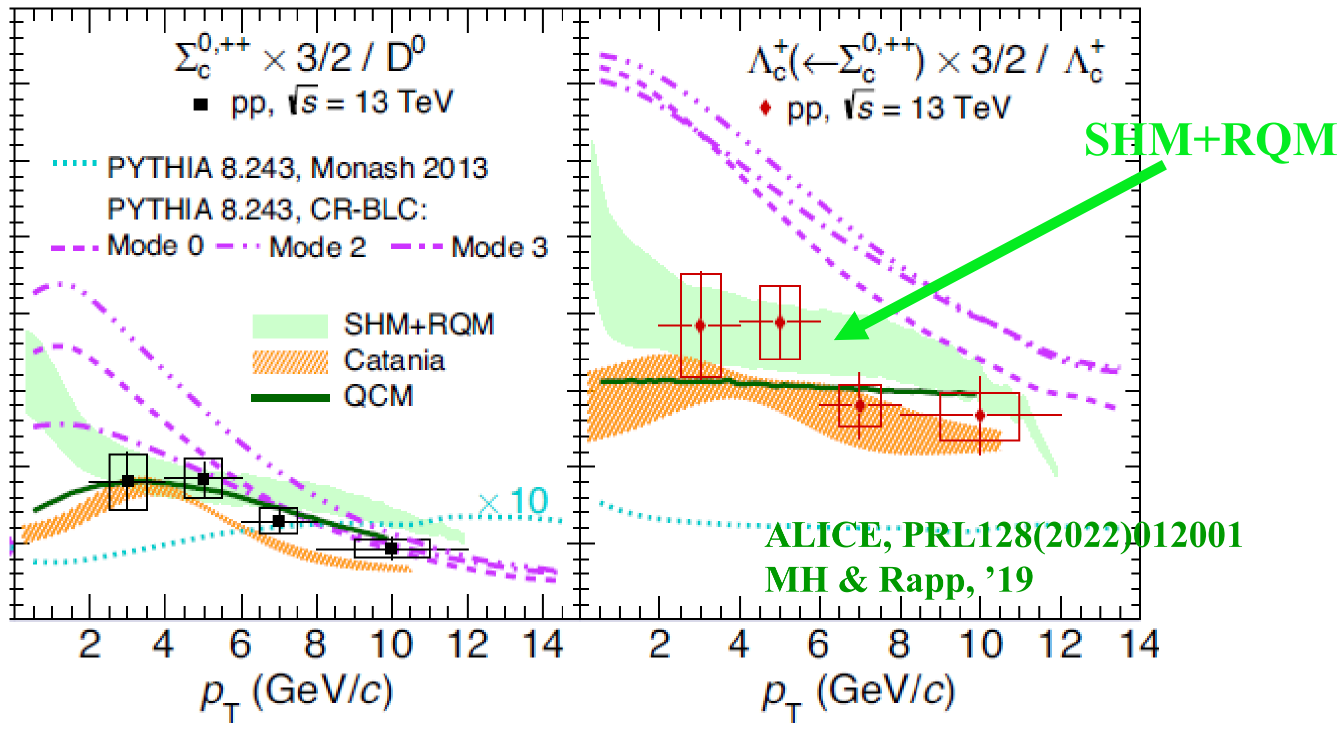
$$D_{b\to H_b}(z) \propto z^{\alpha}(1-z),$$

- weight ∝ primary density (relative chemical equilibrium)
- α tuned to fit the slope of known spectra

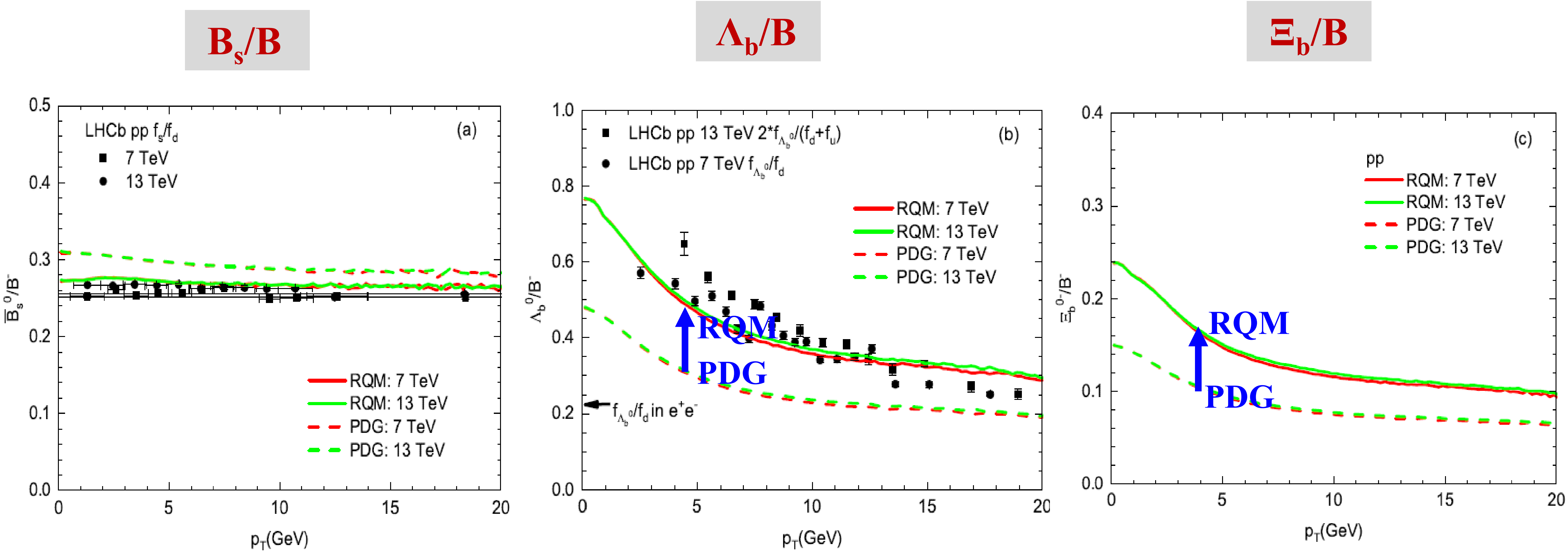
Λ_c/D^0 vs p_T



$\Sigma_c(2455)/D^0$ vs p_T



p_T-dependence: b-hadron ratios in mini. bias pp

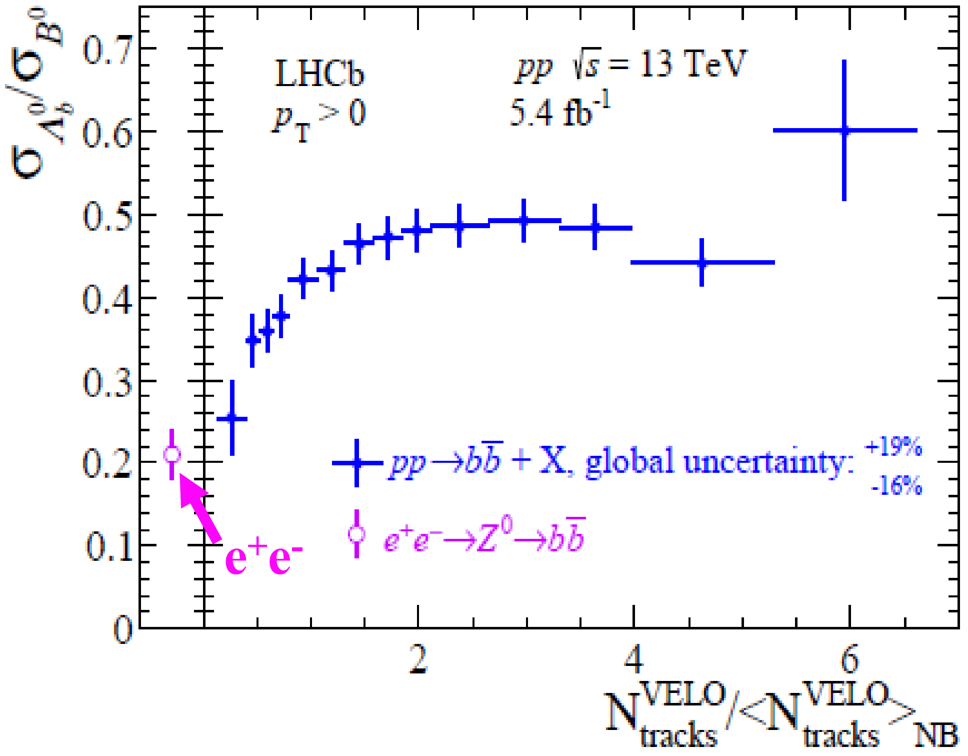


- PDG → RQM: feeddown of more "missing" excited baryons ➔ enhancing the ground-state Λ_b & Ξ_b to B ratio

MH & Rapp, '23

But still why Λ_b/B falls with system size?

Λ_b/B vs pp system size scan



LHCb, PRL132, 081901 (2024)

- Coalescence viewpoint: $n_{\Lambda b} \propto n_q^2$ vs $n_B \propto n_q$ ➔ Λ_b/B $\propto n_q^2/n_q = n_q$ falling toward smaller system
- Statistical hadronization viewpoint: switch to canonical ensemble for smaller system

Canonical ensemble (CE) SHM

- Canonical ensemble partition function: strict conservation of quantum charges

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

$$\vec{Q} = (Q, N, S, C, B)$$

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

correlation volume ~ system size

- Primary hadron yield: CE vs GCE

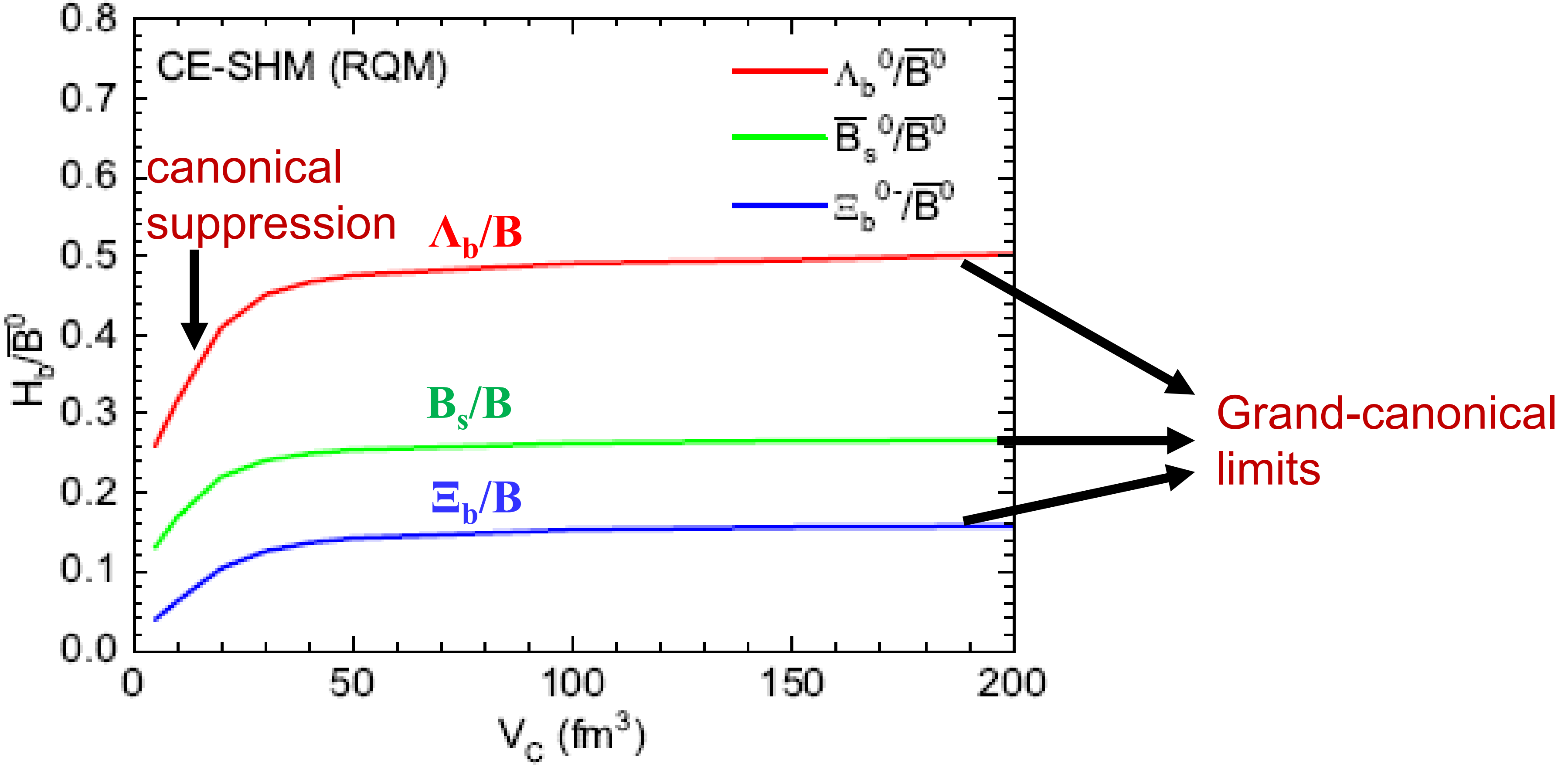
$$\langle N_j\rangle^{CE} = \gamma_s^{N_{sj}} \gamma_c^{N_{cj}} \gamma_b^{N_{bj}} z_j \frac{Z(\vec{Q}-\vec{q}_j)}{Z(\vec{Q})}$$

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

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

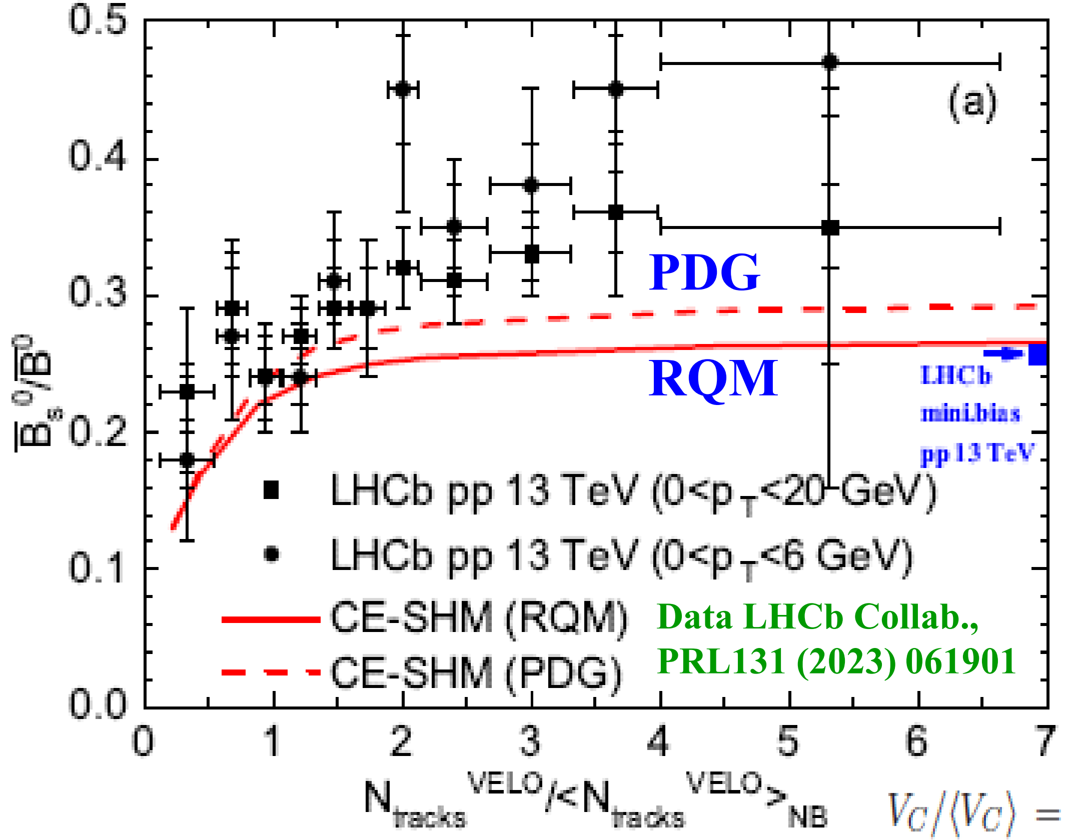
Ground-state b-hadron ratios vs Volume



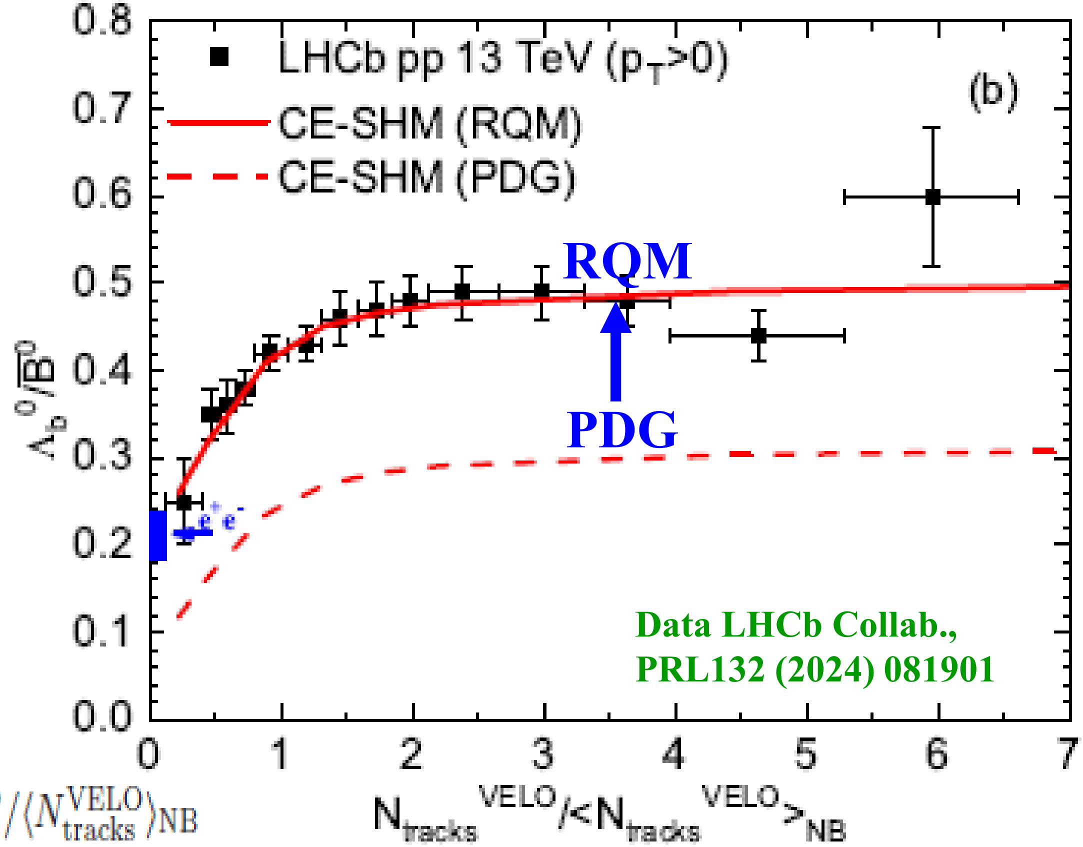
- As volume/system size reduces, canonical suppression due to strangeness/baryon number conservation ➔ B_s/B, Λ_b/B, Ξ_b/B suppressed by a factor 2 or more
- All ratios tend to the corresponding GCE-SHM values at large system size

Ground-state b-hadron production ratios

B_s/B vs system-size



Λ_b/B vs system-size



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

$\langle V_C\rangle = 22.6\ {\rm fm}^3$ Dai & MH, '24

- Λ_b^0/B GCE saturation limit → e^+e^- vacuum fragmentation limit

- RQM strongly favored by data

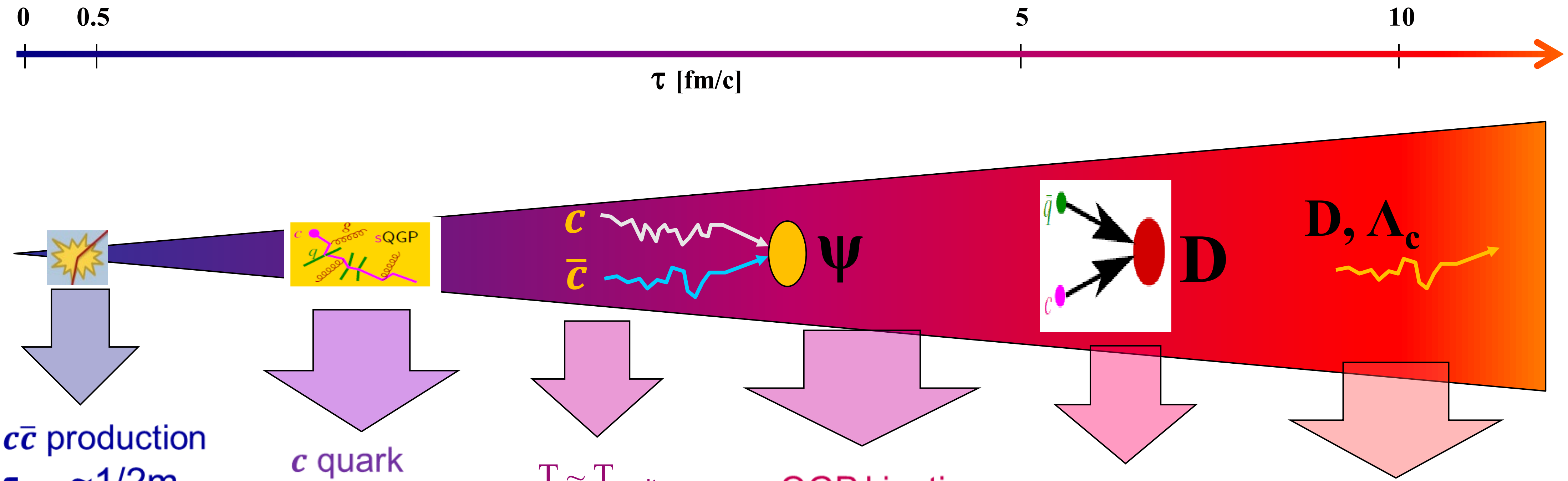
Outline of Part II

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

Part II: Open heavy-flavor transport in Pb-Pb

- Interaction of HF with medium: T-matrix approach
- Heavy quark diffusion & hadronization in QGP
- Collective flow & p_T-dependent modifications of hadro-chemistry

Heavy flavor transport as probes of QGP



$c\bar{c}$ production
τ_{hard}~1/2m_c,
buildup of ψ
wave packet
τ_ψ ~1 fm/c

c quark
Brownian
diffusion
in QGP
τ_c^{eq} ~5 fm/c

$T \sim T_{melt}$
onset of
quarkonium
regeneration

QGP kinetics
$c + \bar{c} \leftrightarrow \psi$
$\tau_\psi^{eq} \sim 1/\Gamma_\psi$

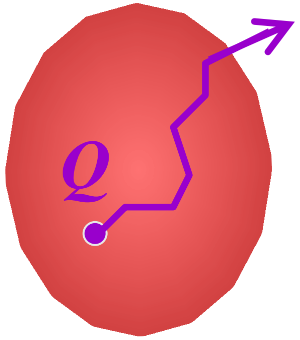
$T \sim T_c$
hadronization:
c+q → D
c+q+q → Λ_c

hadronic
phase
diffusion

- m_Q>>T ➔ number conserved through diffusion/hadronization: tagged & traceable probes
- $\tau_Q^{eq} \geq \tau_{QGP}$ ➔ carrying a memory of interaction history: quantitative gauge of coupling strength

HQ interaction & diffusion in QGP

- Heavy quark Brownian motion: Fokker-Planck/Langevin equation



$$\frac{\partial}{\partial t} f_Q(t,p) = \gamma \frac{\partial}{\partial p_i}[p_i f_Q(t,p)] + D_p \Delta_{\vec{p}} f_Q(t,p)$$

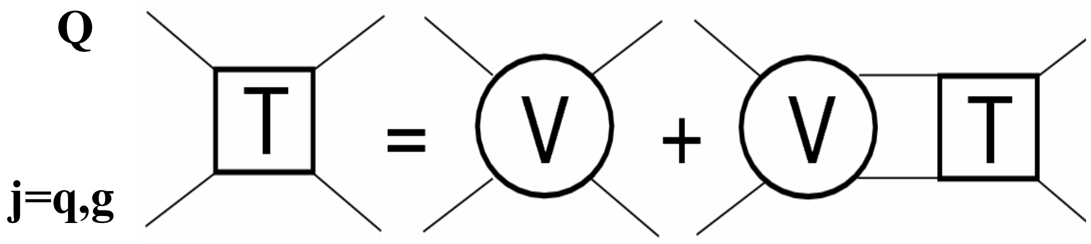
$q_0 \sim q^2/2m_Q << q \sim T << m_Q$

thermal relaxation rate
$\gamma \sim \int |T_{Qj}|^2 (1\text{-}\cos\theta) f^j$

momentum diffusion coeffi.
Einstein relation $D_p = \gamma m_Q T$

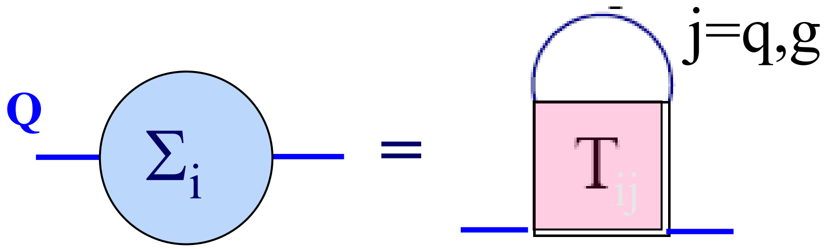
- Q-q/g soft scatterings: T-matrix resummation of in-medium HQ potential

2-body scattering amplitude



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

1-body HQ propagator



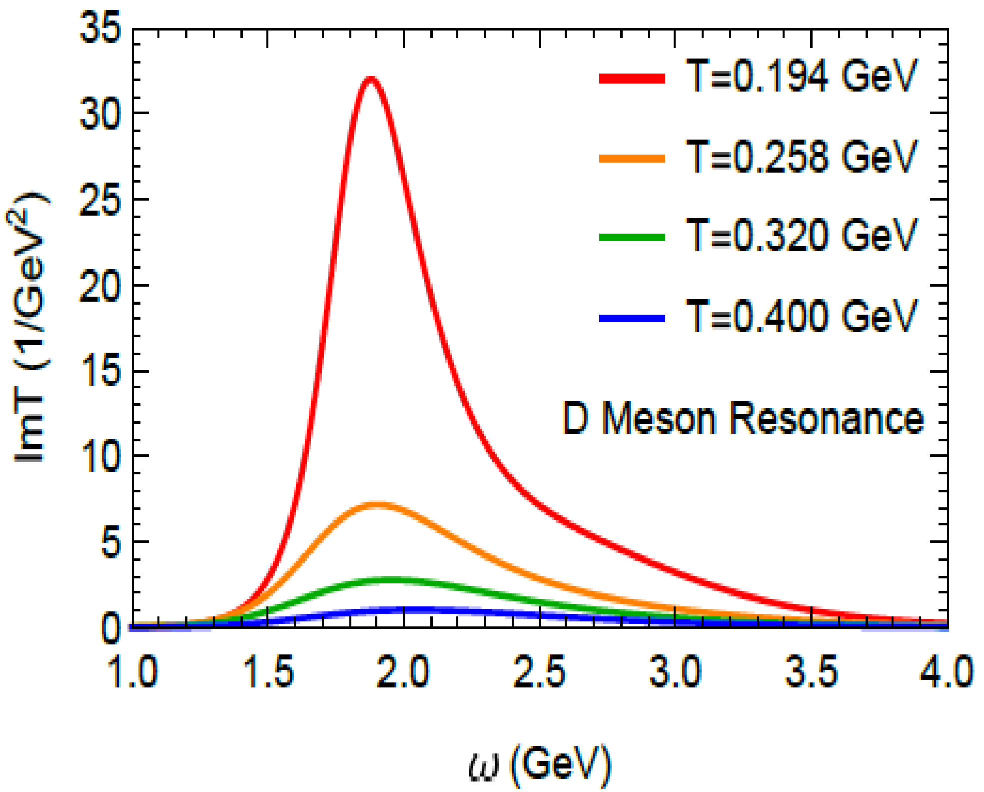
$$D = 1 / [\omega - \omega_k - \Sigma(\omega,k)]$$

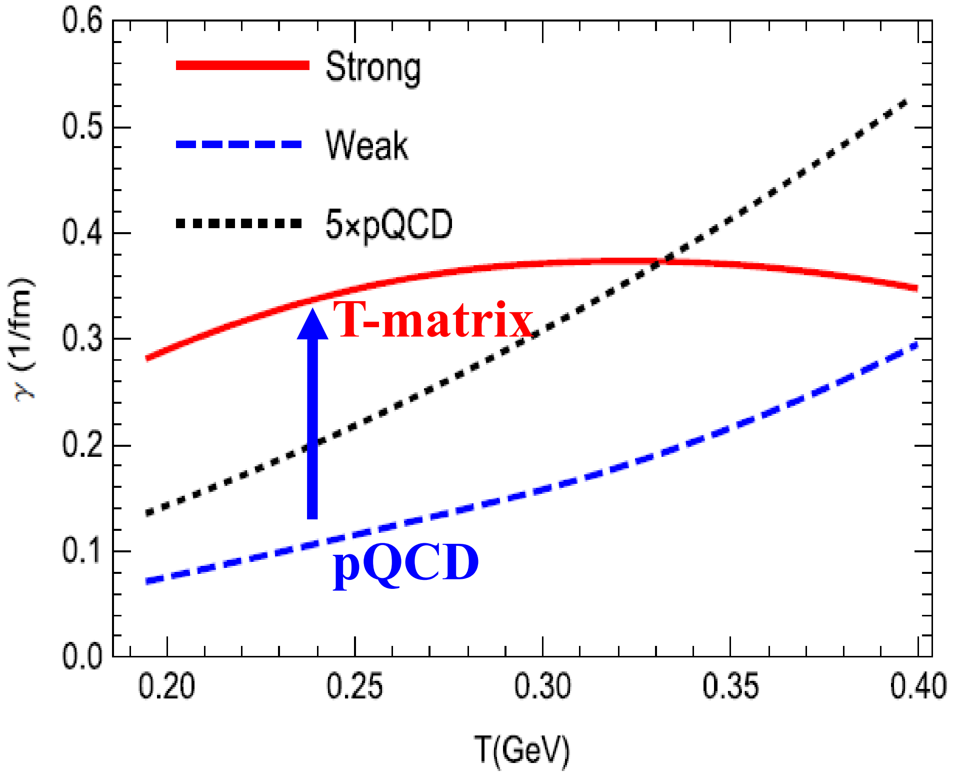
Riek & Rapp '10; Liu, MH & Rapp '19; Review: MH, van Hees & Rapp '23

Charm quark thermal relaxation rate in QGP

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

T-matrix w/ U-potential → Resonance formation near T_c → Accelerating charm thermalization

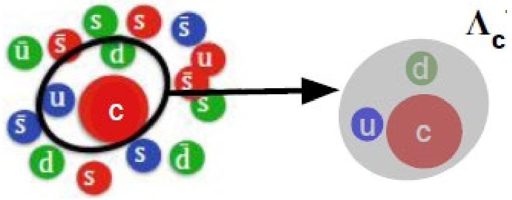


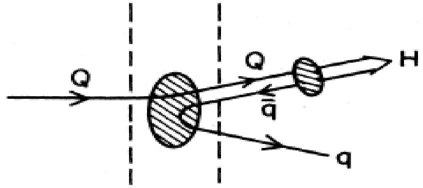


Riek & Rapp '10; Liu, MH & Rapp '19; Review: MH, van Hees & Rapp '23

- Non-perturbative enhancement at low p & T; approaching pQCD at high p & T
- x K-factor=1.6 for mimicking spin-dependent force/radiative contributions → Tang & Rapp '23

Hadronization: resonance recombination

Recombination: 

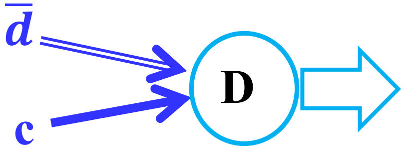
vs. Fragmentation: 

- 2→1 Resonance Recombination via Boltzmann equilibrium limit

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

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

- energy-conservation via finite width Γ_M ← T-matrix $c\bar{q}$ resonance

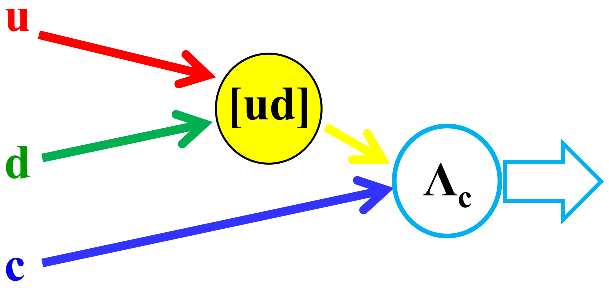


Ravagli & Rapp '07; MH, Fries & Rapp '12

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

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

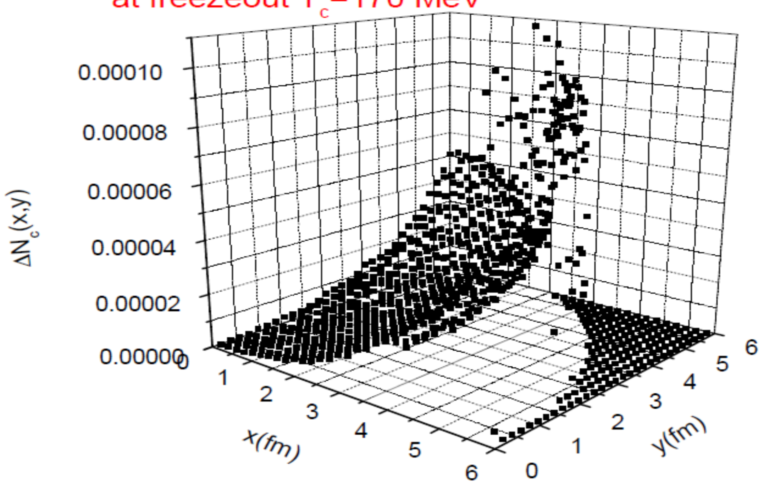
$$f_B(\vec{x},\vec{p}) = \frac{E_B(\vec{p})}{\Gamma_B m_B}\int \frac{d^3p_1 d^3p_2 d^3p_3}{(2\pi)^6}\frac{E_d(\vec{p}_{12})}{\Gamma_d m_d} f_1(\vec{x},\vec{p}_1) f_2(\vec{x},\vec{p}_2) f_3(\vec{x},\vec{p}_3)$$
$$\times\, \underline{\sigma_{12}(s_{12})}\, v^{12}_{\rm rel}(\vec{p}_1,\vec{p}_2)\, \underline{\sigma_B(s_{d3})}\,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

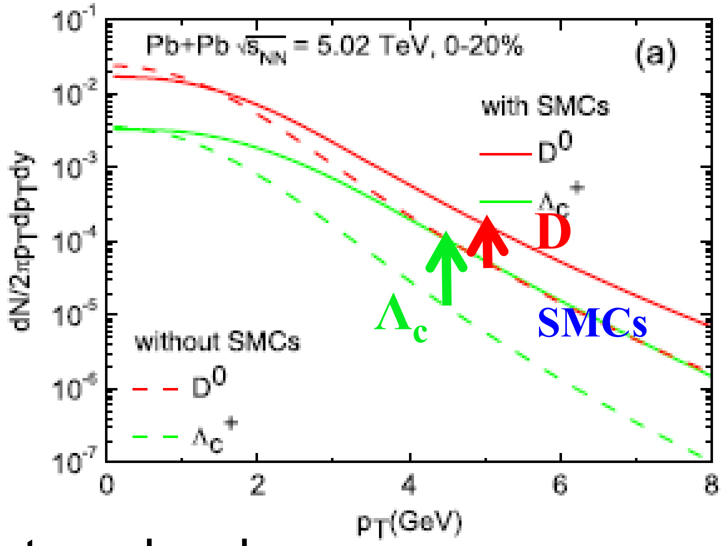


MH & Rapp '20

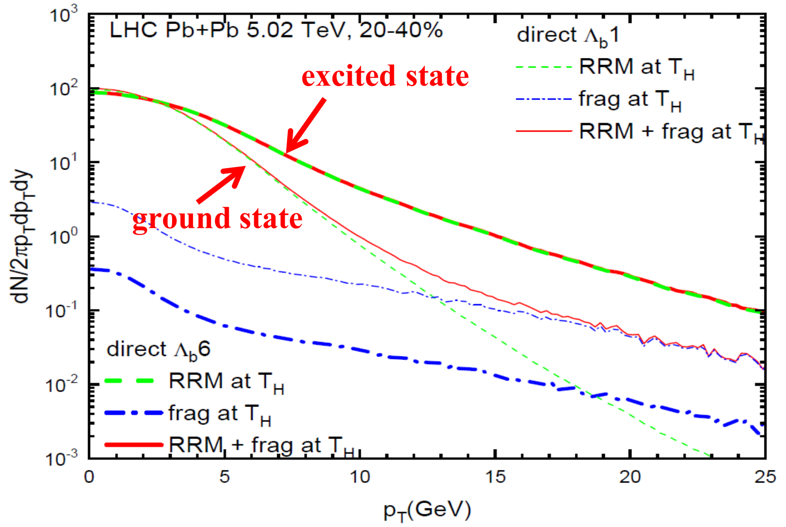
Recombination: space-momentum correlations

- Inhomogeneous distribution: SMCs ➔ enhancing Λ_c/D at intermediate p_T





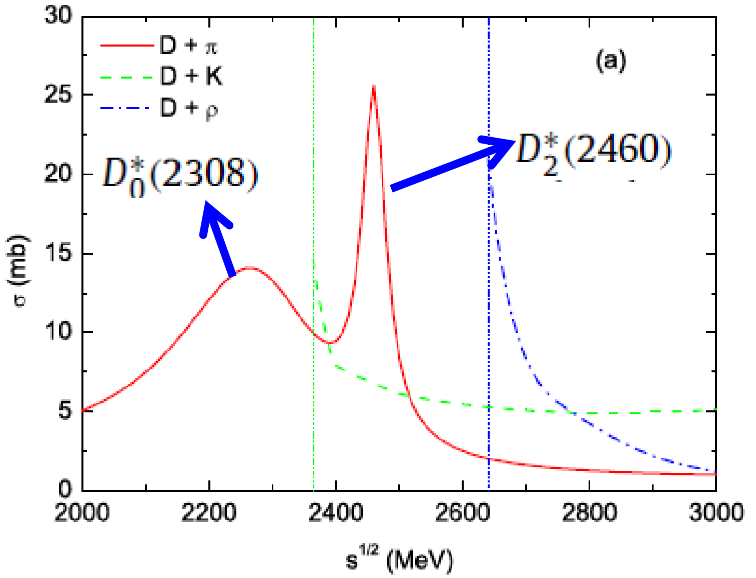
- Capturing full flow ➔ Heavier particle's p_T-spectrum harder

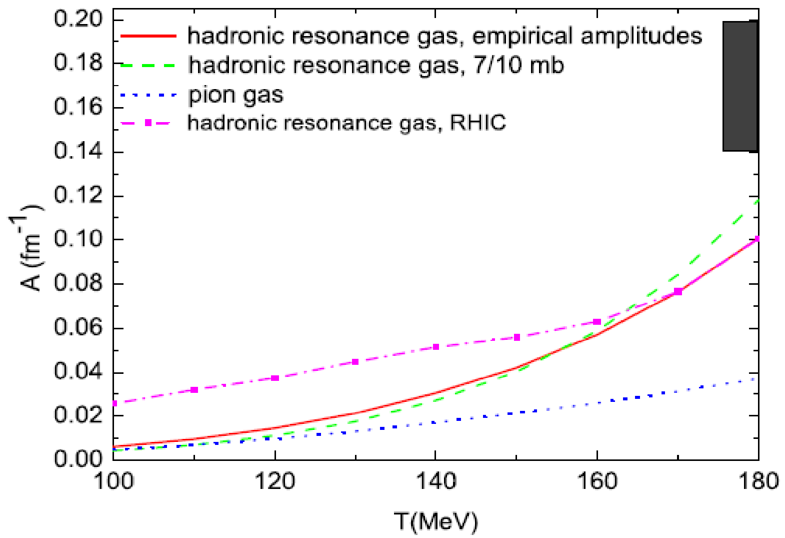


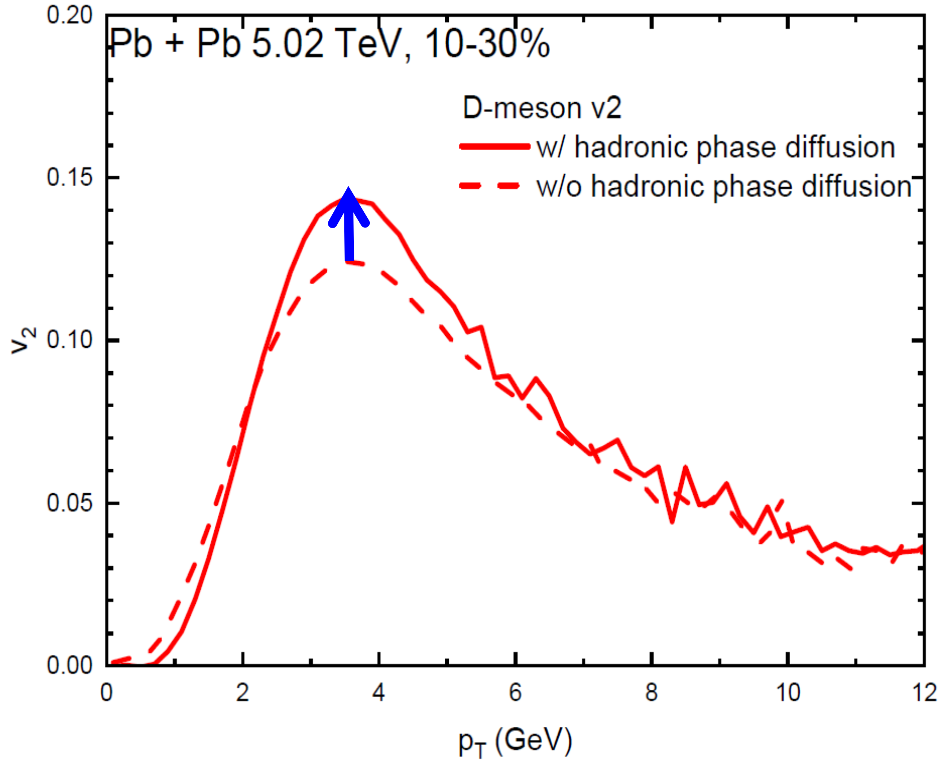
- Excited state more massive: recombination spectrum harder than ground state (SMCs/flow)
- SMCs extends recombination to higher p_T → increasing total v_2

Hadronic phase diffusion

- D + light mesons/baryons: mostly empirical resonant scattering amplitudes MH, Fries & Rapp ’11



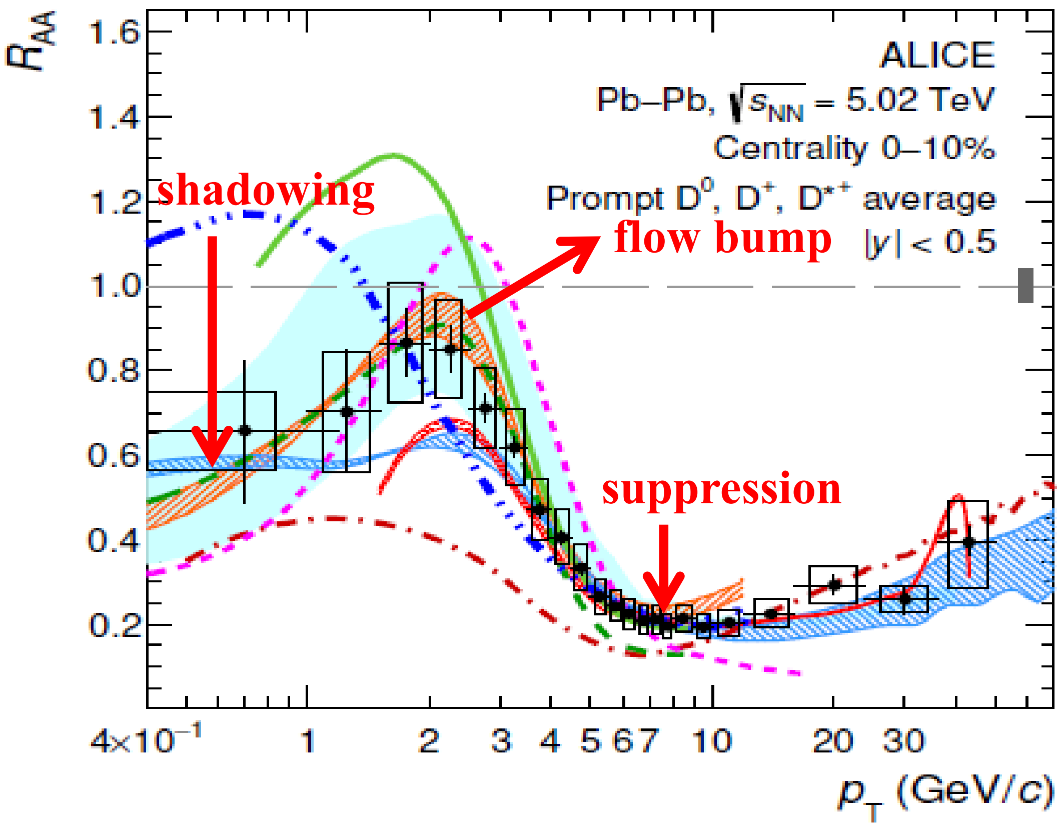




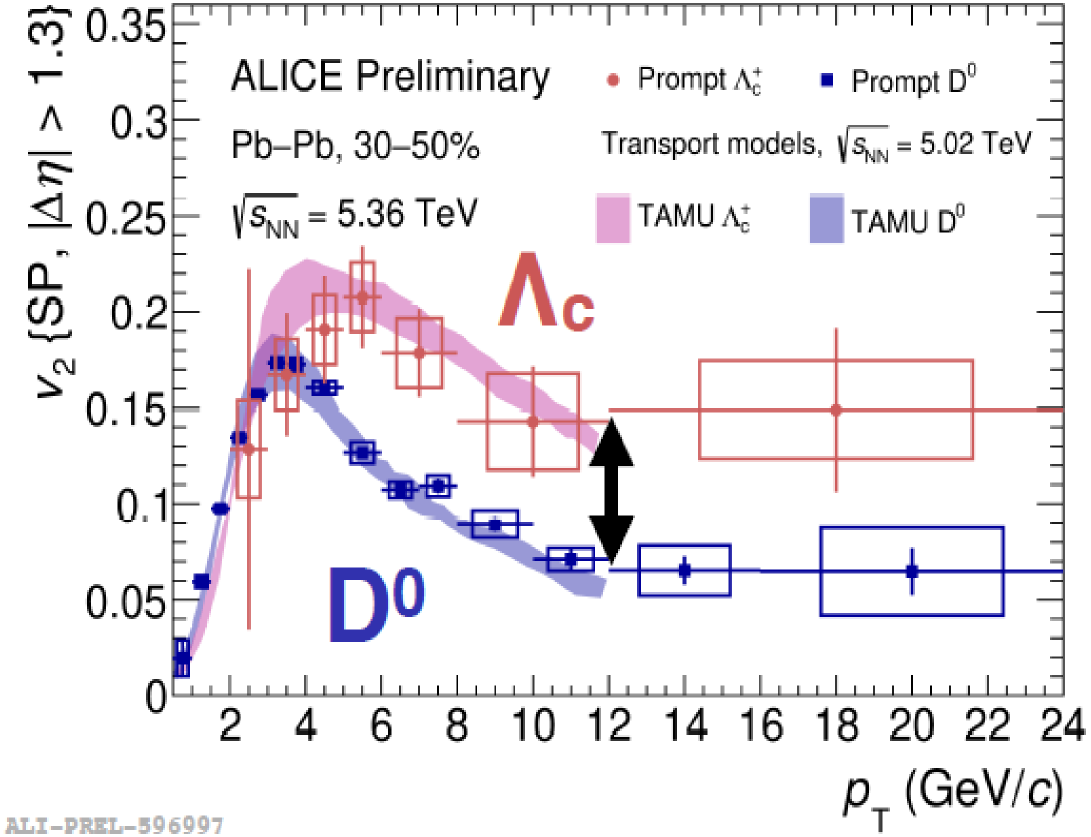
- $A_D(p=0)$ ~ 0.1 fm/c near T_c → to be updated
- D-meson v_2 increased by ~15% at intermediate p_T~ 3-4 GeV

D-meson & Λ_c-baryon's flow @ 5 TeV Pb-Pb

ALICE, JHEP 01 (2022) 174



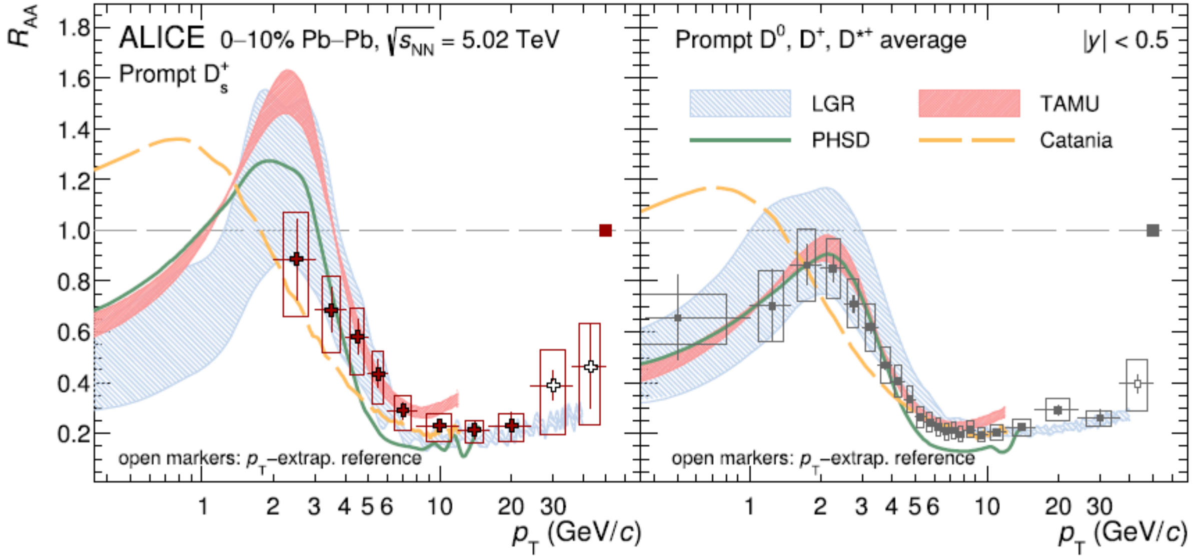
ALICE highlights @ Quark Matter 2025



- Brown curve taken from our model calculation in MH & Rapp '20
- Simultaneous description of D's R_{AA} & v_2

- Λ_c's v_2 significantly larger than D^0, predictions from RRM in MH & Rapp '20
- v_2 at low p_T: gauge of coupling strength

D_s enhancement over D^0

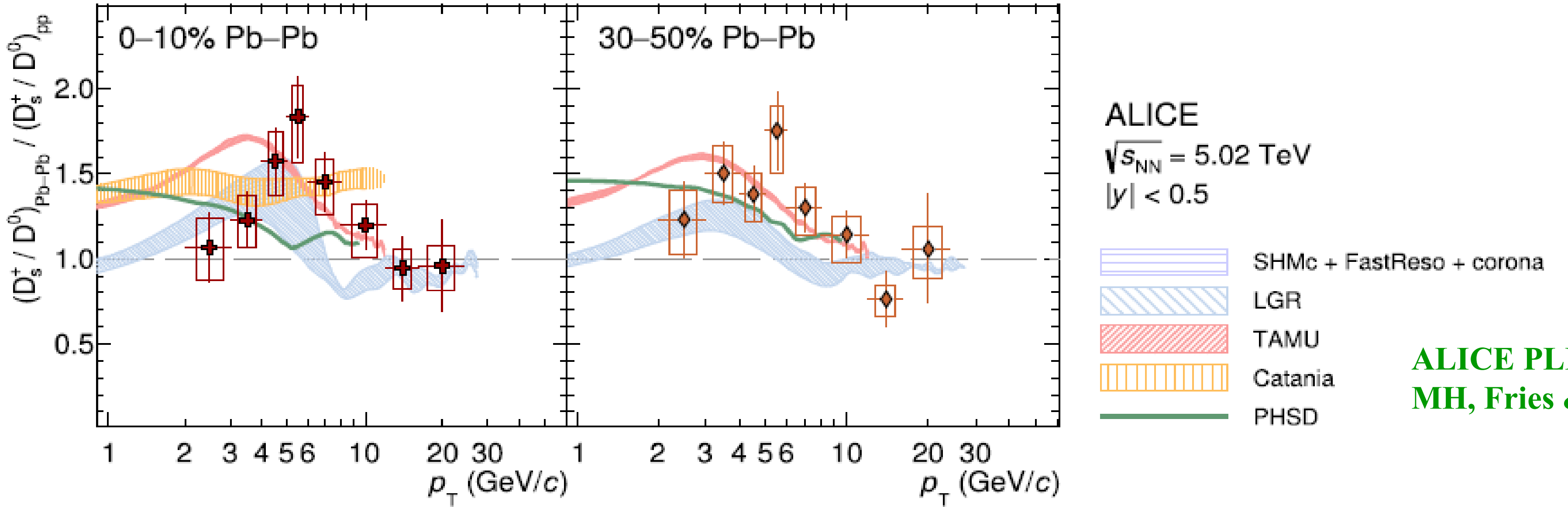


- In pp, strangeness is under-saturated γ_s=0.6 in Pb-Pb, strangeness equilibrated γ_s=1

- Equilibrated strangeness coupled to c-quark via recombination ➔

  $R_{AA}[D_s] > R_{AA}[D^0]$ at low p_T

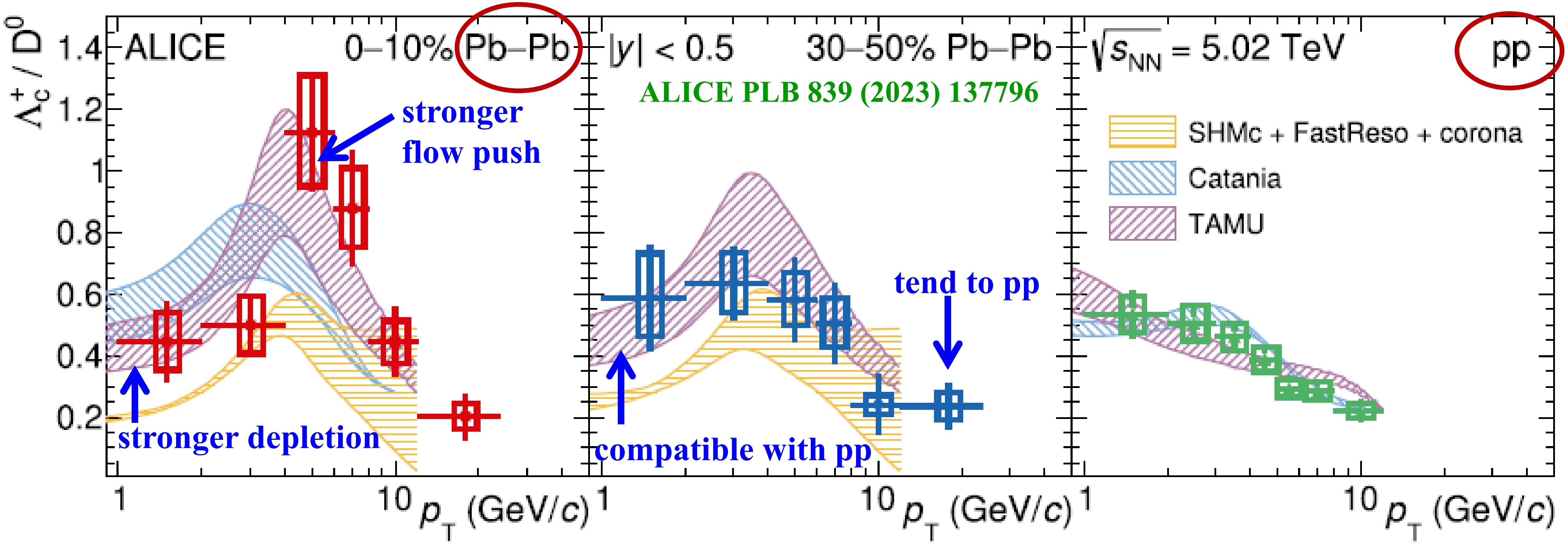
  D_s/D^0 enhanced in PbPb vs pp



ALICE PLB 827 (2022) 136986
MH, Fries & Rapp '13; MH & Rapp '20

Charm hadro-chemistry Λ_c/D: pp→Pb-Pb

purple curves taken from our model predictions in **MH & Rapp '20 & MH & Rapp '19**

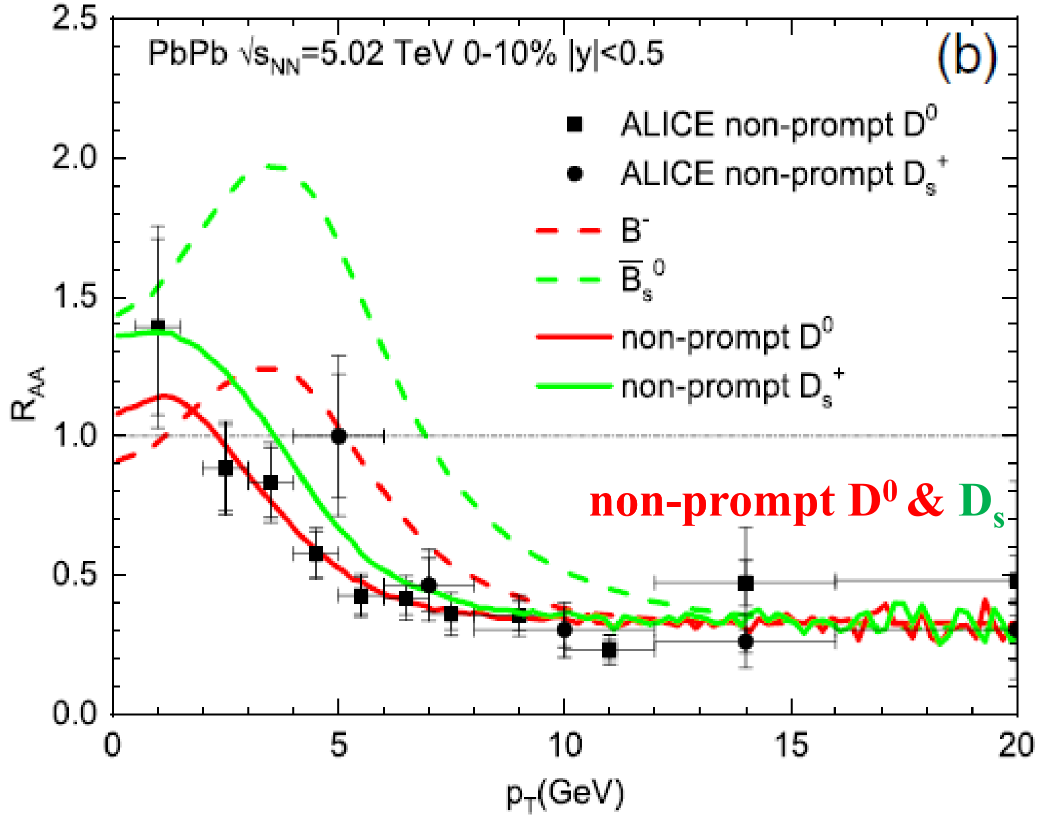


- Same RQM charm-hadron spectra (in particular baryons) in Pb-Pb & pp

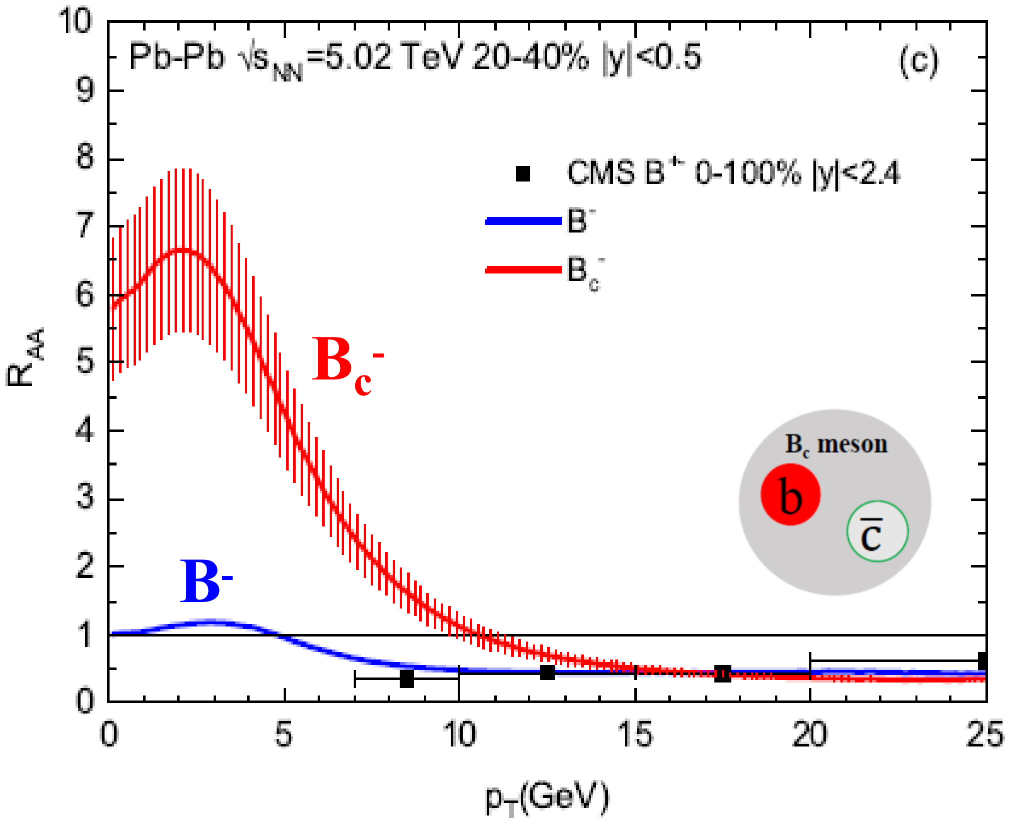
- RRM with SMCs capturing full flow effects ➔ enhancing Λ_c/D at intermediate p_T

- RRM satisfying correct relative chemical equilibrium limit ➔ same integrated Λ_c/D as in pp

Bottom-hadron nuclear modification factors



MH & Rapp '23

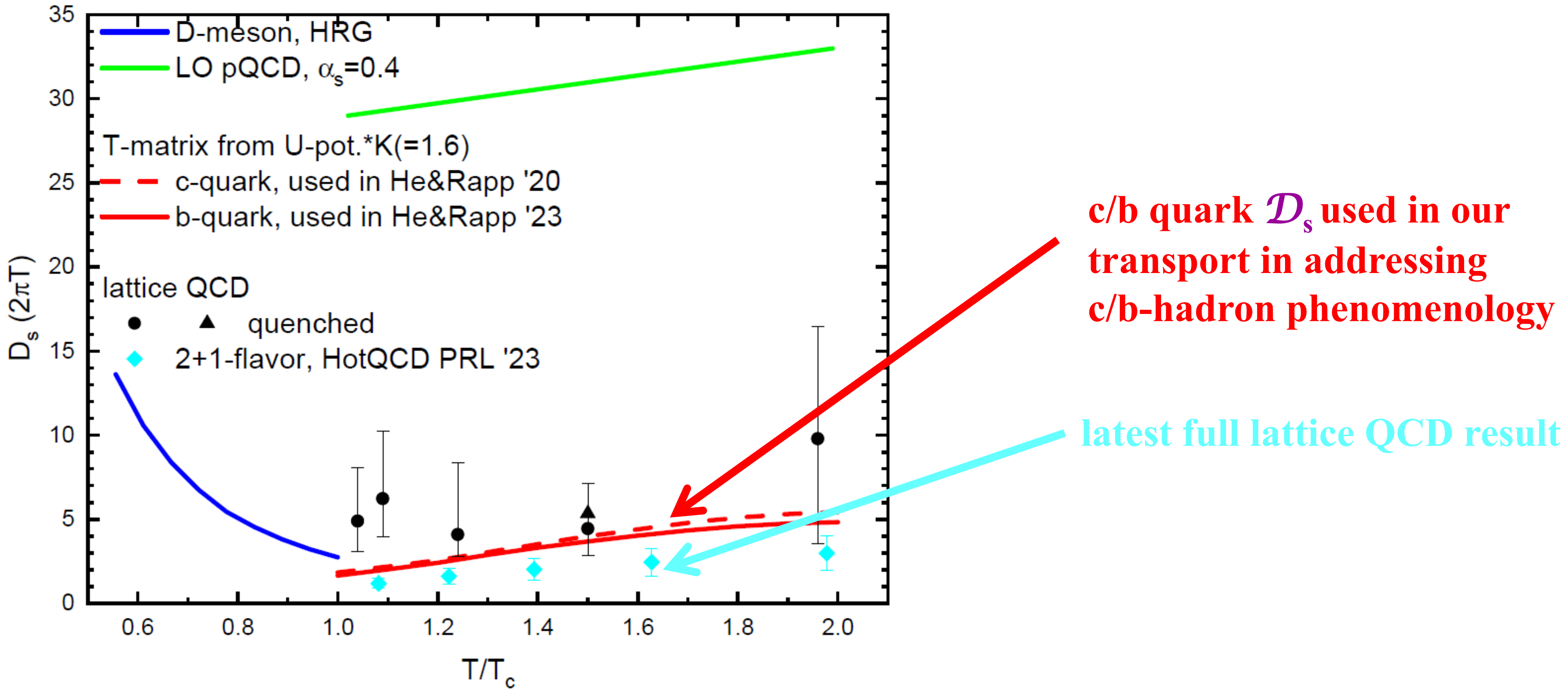


Zhao & MH, '25

- Enhanced strangeness coupled to b-quark via RRM ➔ larger R_{AA} for non-prompt D_s
- Statistical recombination of b-quark with plenty of near-thermalized c-quarks ➔ x5-6 enhancement of B_c at low p_T

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

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



- 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
- Minimum $\mathcal{D}_s(2\pi T)$ near T_c ➔ maximum coupling strength of strongly coupled QGP

Summary: hadronization & sQGP

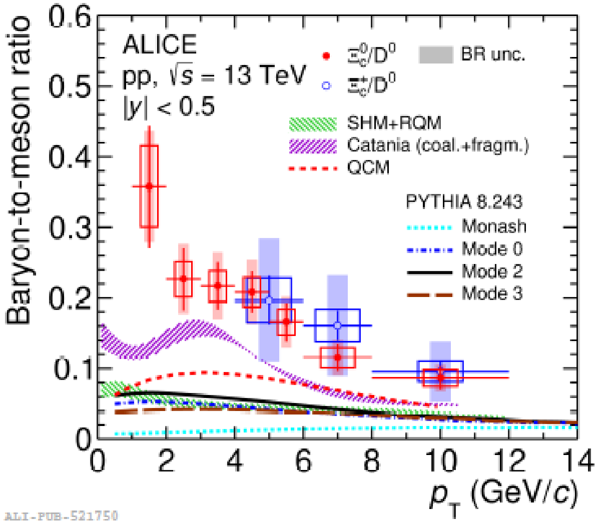
- Heavy flavor hadro-chemistry: non-universal but environment-dependent
  - Large enough system: mini.bias pp → PbPb, grand-canonical ensemble SHM saturation
  - e^+e^-: vacuum fragmentation limit; In between, canonical suppression important for Λ_c/D
  - "Missing" baryons essential via SHM

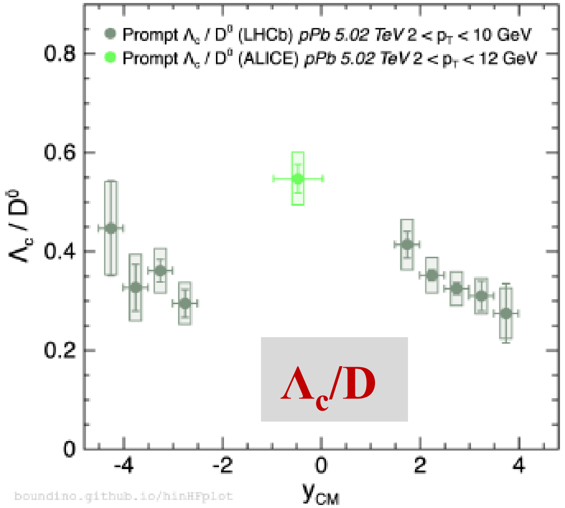
- HQ probing the inner working of sQGP
  - Small $\mathcal{D}_s$ close to quantum limit ➔ large collisional rate: sQGP = quantum liquid
  - Likely supported by residual confining force (small screening of HQ potential) **Liu & Rapp, '15** **HotQCD Colla. '24**
  - Same force responsible for color-neutralization = hadronization ~ recombination
  - Recombination ➔ flow pattern + p_T-dependent modifications of hadro-chemistry (but only kinematic redistribution in p_T with integrated Λ_c/D unchanged)

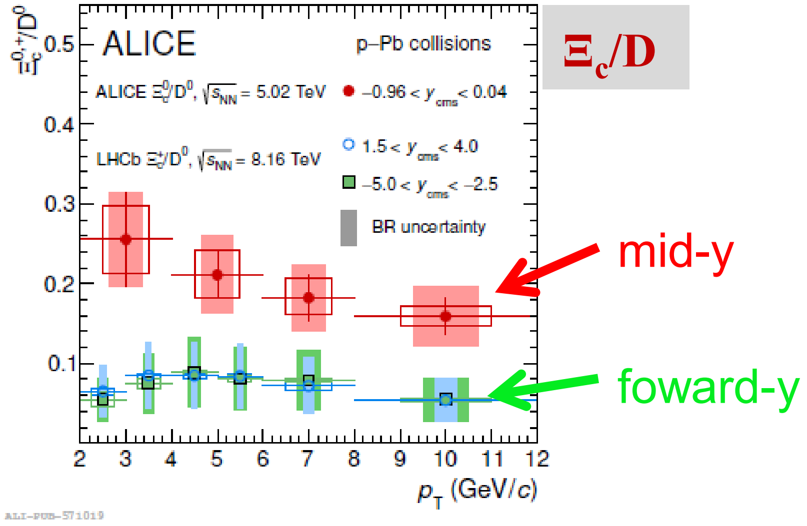
Outlook

- Open problems: Ξ_c/D & y-dependence of Λ_c/D in pp/pA

Ξ_c/D







- Outlook for charm at finite μ_B

  - Adapting our transport model:
    - c-quark interaction in μ_B-QGP ➔ $A(p,T,\mu_B)$
    - D-meson interaction in μ_B-HRG ➔ hadronic phase more important
    - finite μ_B EoS & hydro

  - Recombination in a quark excessive QGP still pivotal
    - $D^-/D^+ > 1$ ➔ p-dependence via recombination
    - Λ_c/D^0 [cud/c-ubar] may be more pronounced wrt LHC

Back-up

The following are back-up slides

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 $\Omega_b < \Xi_b < \Lambda_b$, increasing strangeness content despite common baryon

Canonical suppression: chemical factors

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As volume/system size increases,

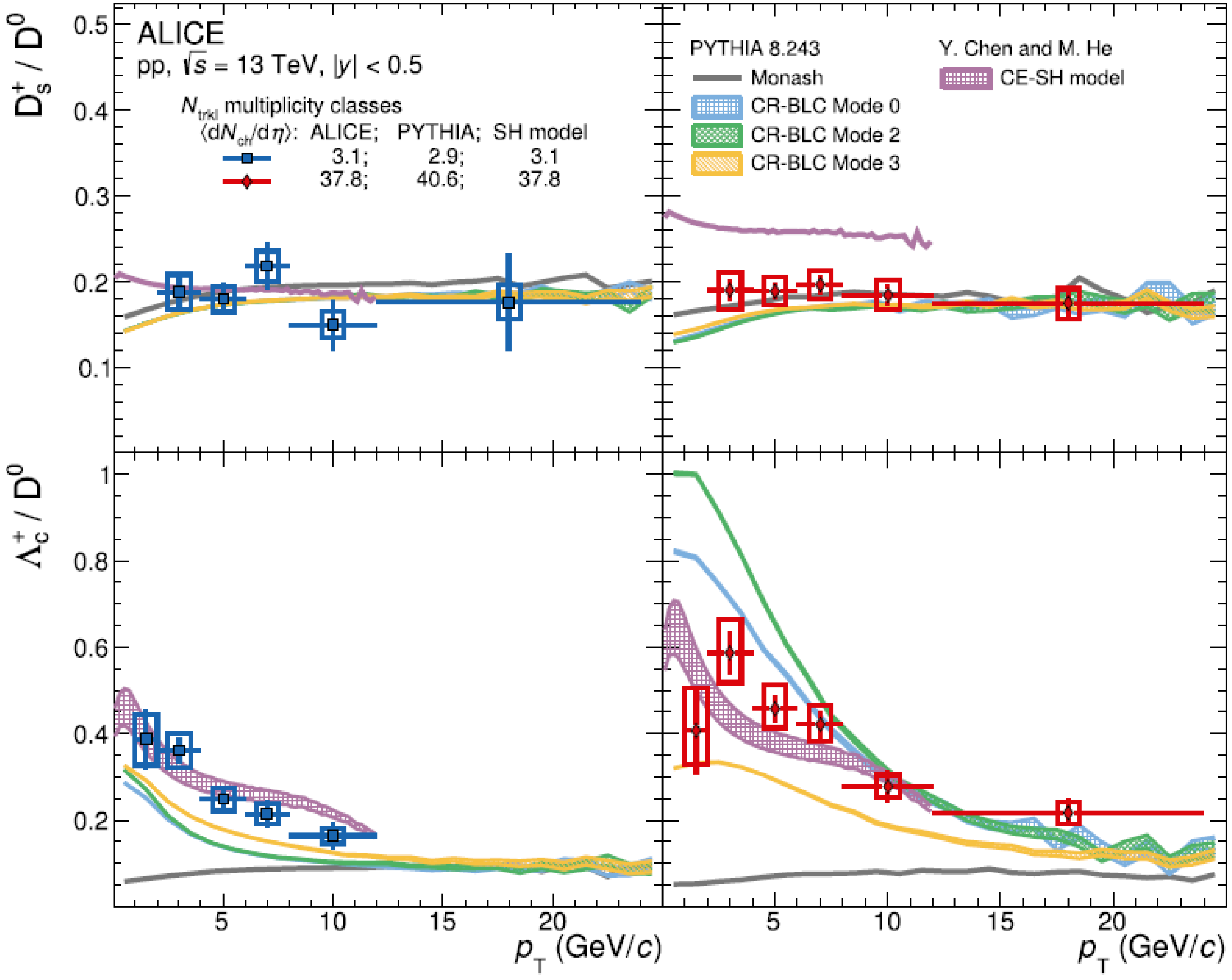
- canonical strangeness & baryon suppression attenuates
- same residual CF at large V: common canonical bottom number suppression

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

Ds/D & Lc/D vs $dN_{ch}/deta$

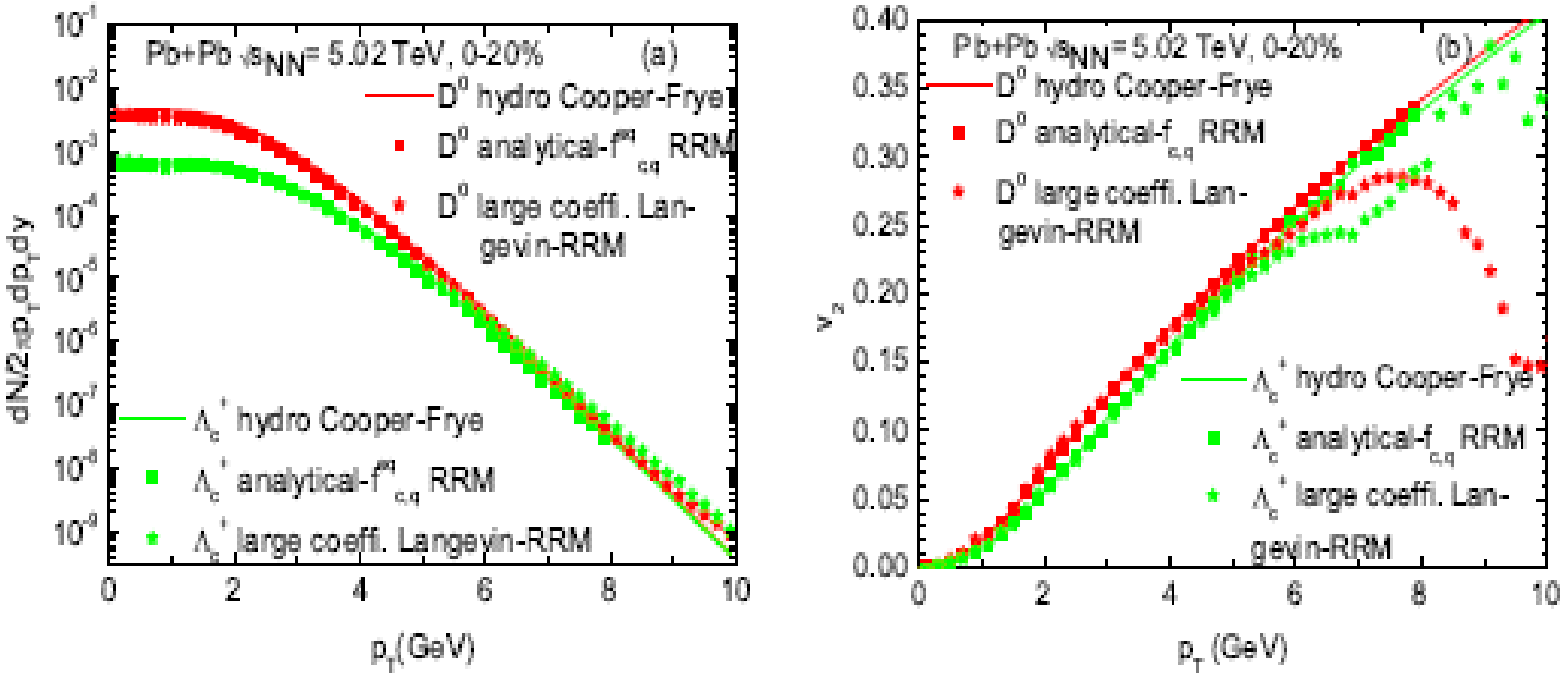


ALICE, PLB829(2022)137065
Chen & MH, '21

RRM equilibrium mapping: check out

- Event-by-event Langevin-RRM simulation with very large trans. coeffi. & with SMCs properly incorporated

  ➔ kinetic & chemical equil. mapping



➔ Observables come out as RRM predictions with realistic T-matrix coeffi.

SMCs in hydro light quark distribution

- hydro: a manifestation of SMCs

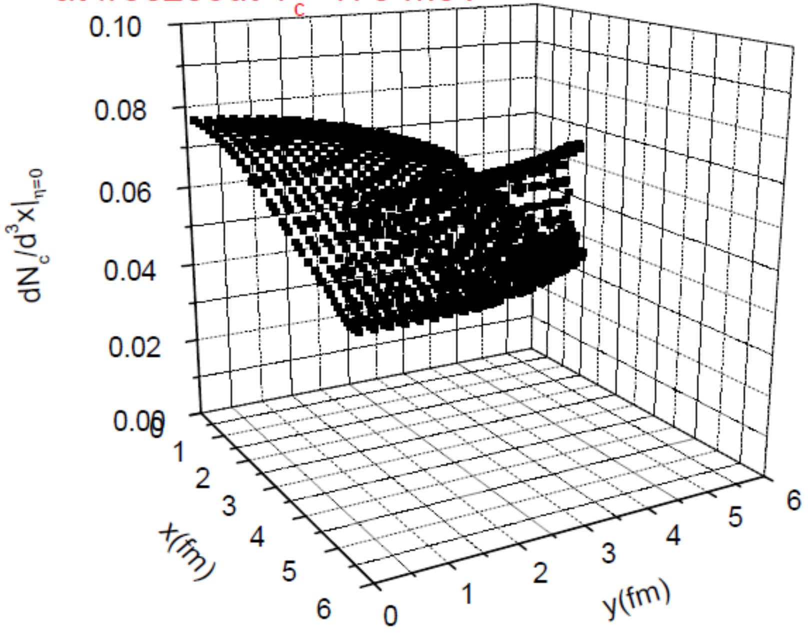
$$f_q^{eq}(\vec{x},\vec{p}) = g_q e^{-p\cdot u(x)/T(x)} = g_q e^{-\gamma_T(x)[m_T\cosh(y-\eta)-\vec{p}_T\cdot\vec{v}_T(x)]/T(x)}$$

longitudinal boost invariance: y- η

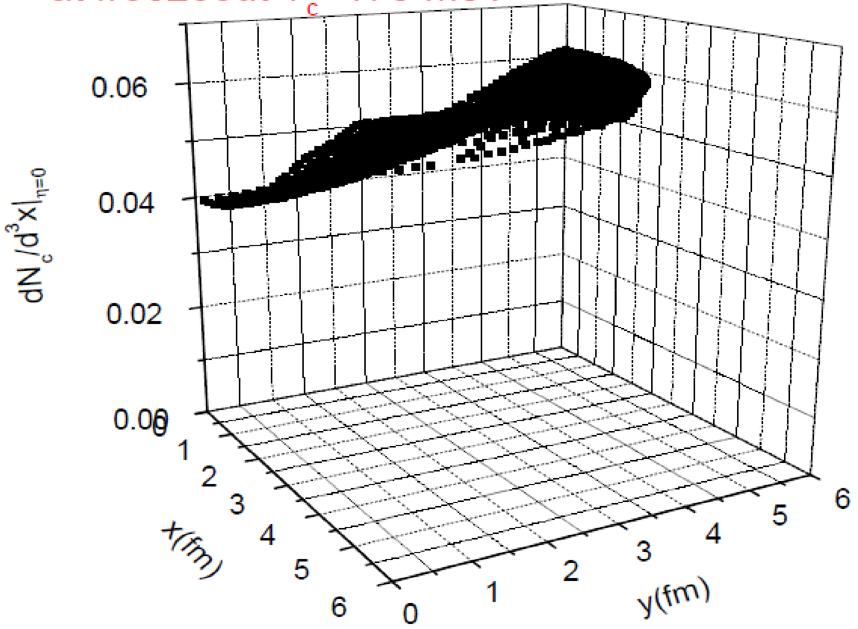
transverse SMCs pT▪vT

- hydro-q: low (high) p_T more concentrated in center (boundary)

hydro light quarks p_T=0.0-0.3 GeV, at freezeout T_c=170 MeV

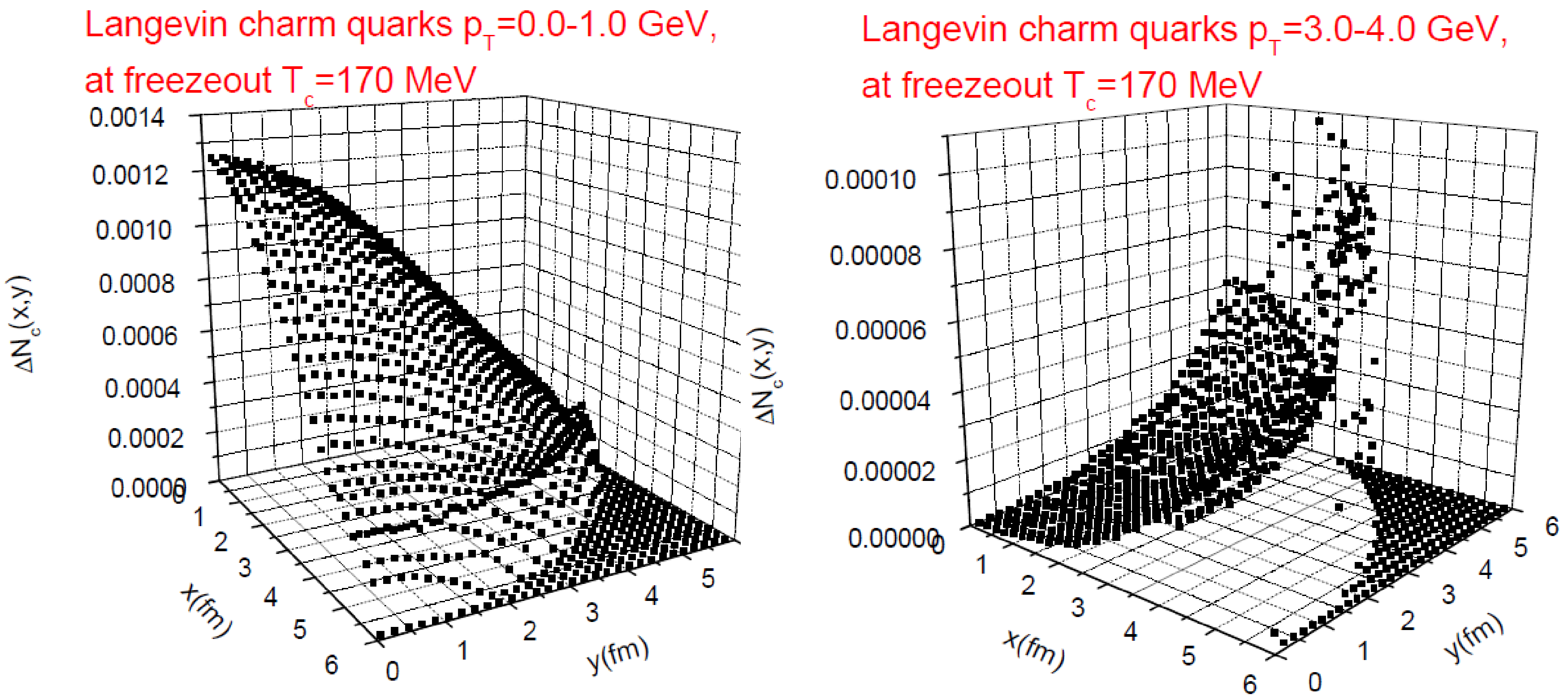


hydro light quarks p_T=0.6-0.9 GeV, at freezeout T_c=170 MeV



SMCs in Langevin-charm quark distribution

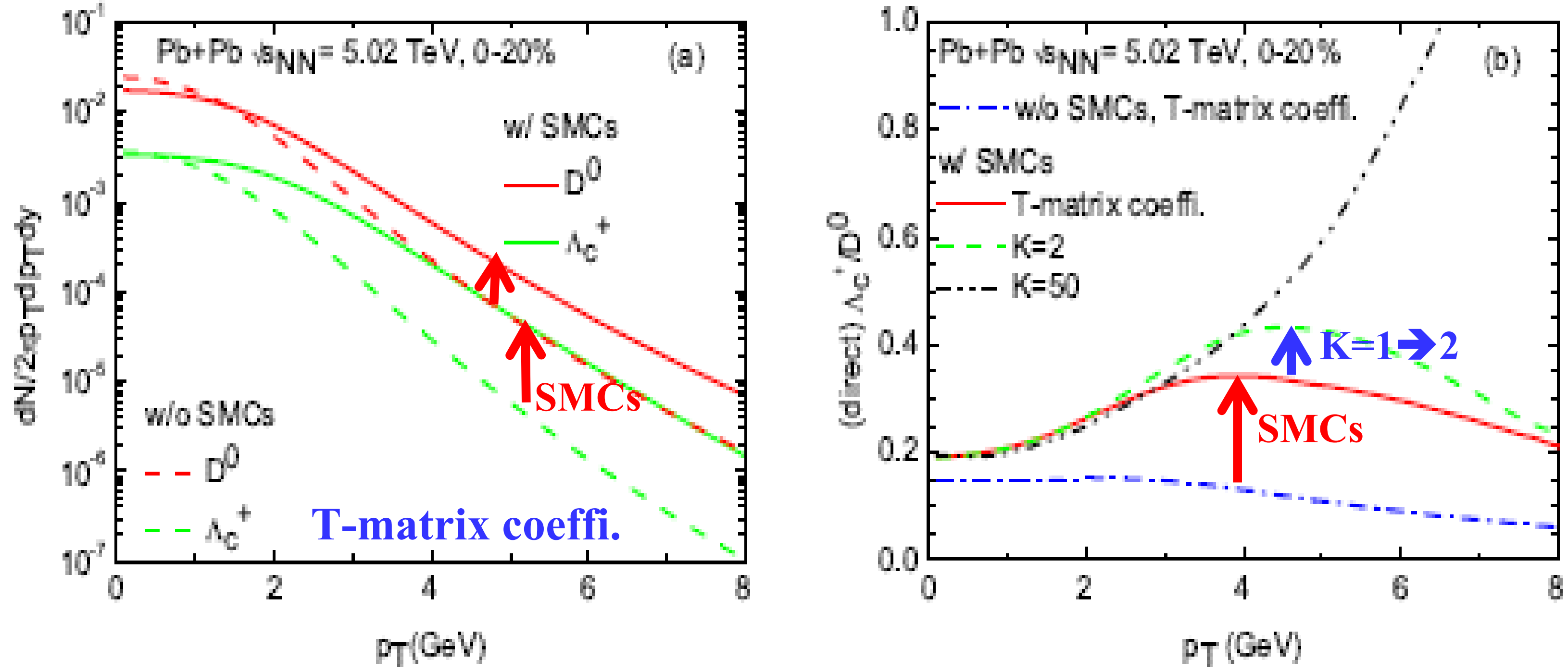
➢ Langevin-c: low (high) p_T more populated in central (outer)



$$f_{c,q}(\vec{x},\vec{p}) = (2\pi)^3 \frac{dN_{c,q}}{d^3\vec{x}d^3\vec{p}} = \frac{(2\pi)^3}{V E(\vec{p})} \frac{dN_{c,q}}{p_T dp_T d\phi_q dy}$$

SMCs: enhancing Λ_c/D^0

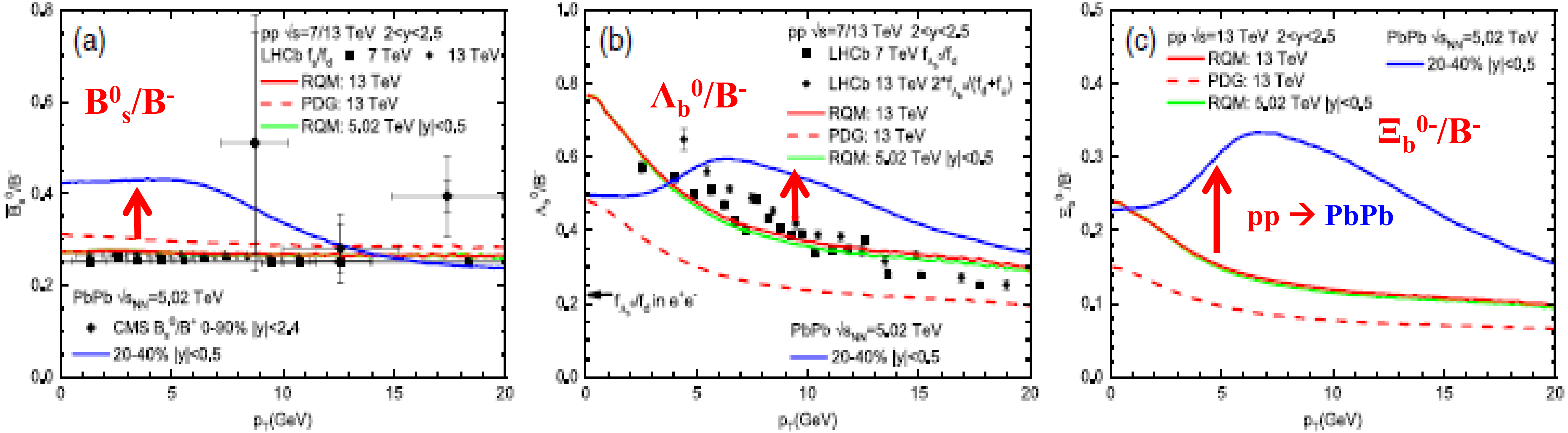
➢ Including SMCs makes spectra harder & enhances the Λ_c^+/D^0



- Fast-moving c-quarks [p_T~ 3-4 GeV] moving to outer part of fireball find higher-density of harder [p_T~ 0.6-0.9 GeV] light quarks for recombination

- An effect entering squared for the recombination production of Λ_c^+
  ➔ larger enhancement for Λ_c^+ ➔ Λ_c^+/D^0 ratio enhanced!

Modifications of bottom 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