Heavy quark probes of the QCD matter: a theoretical perspective

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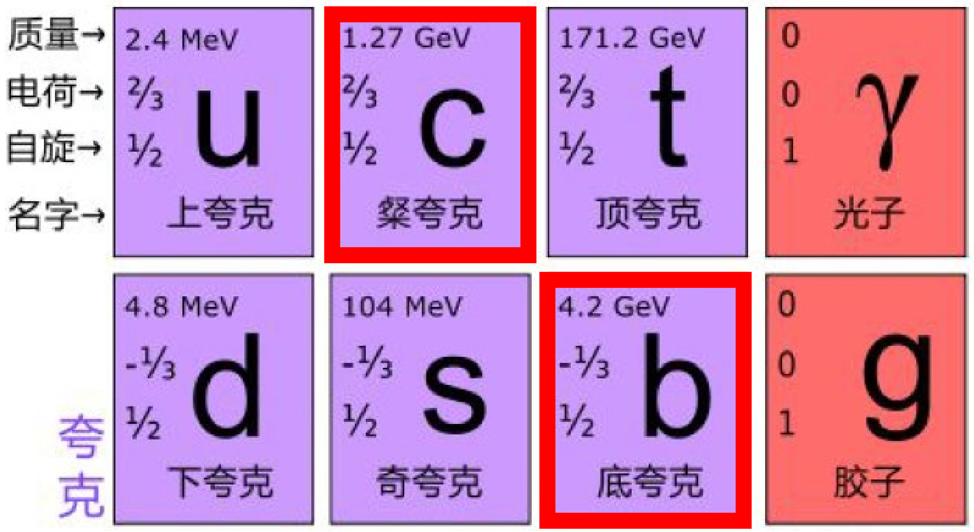
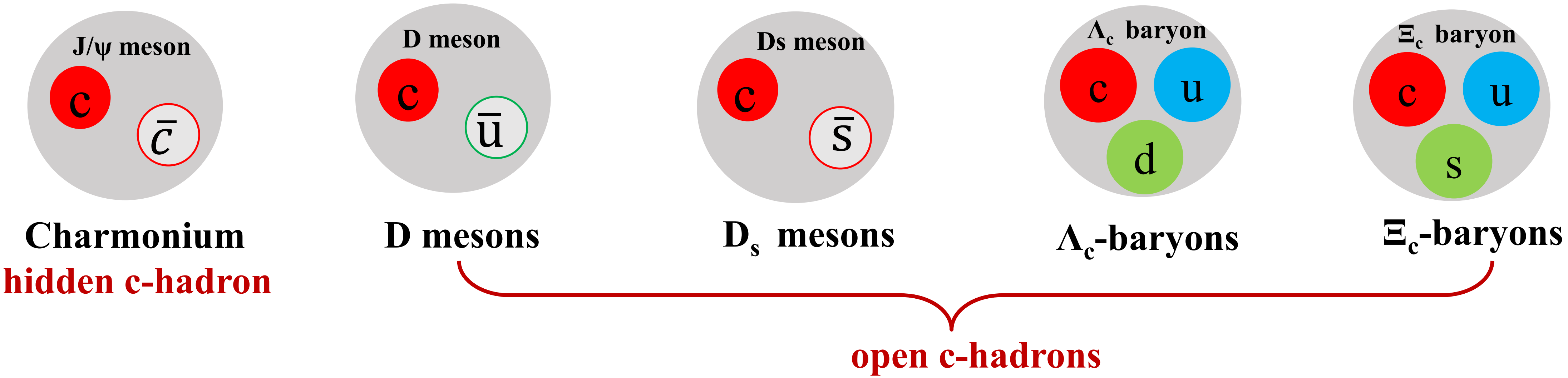
Heavy quarks & heavy hadrons

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

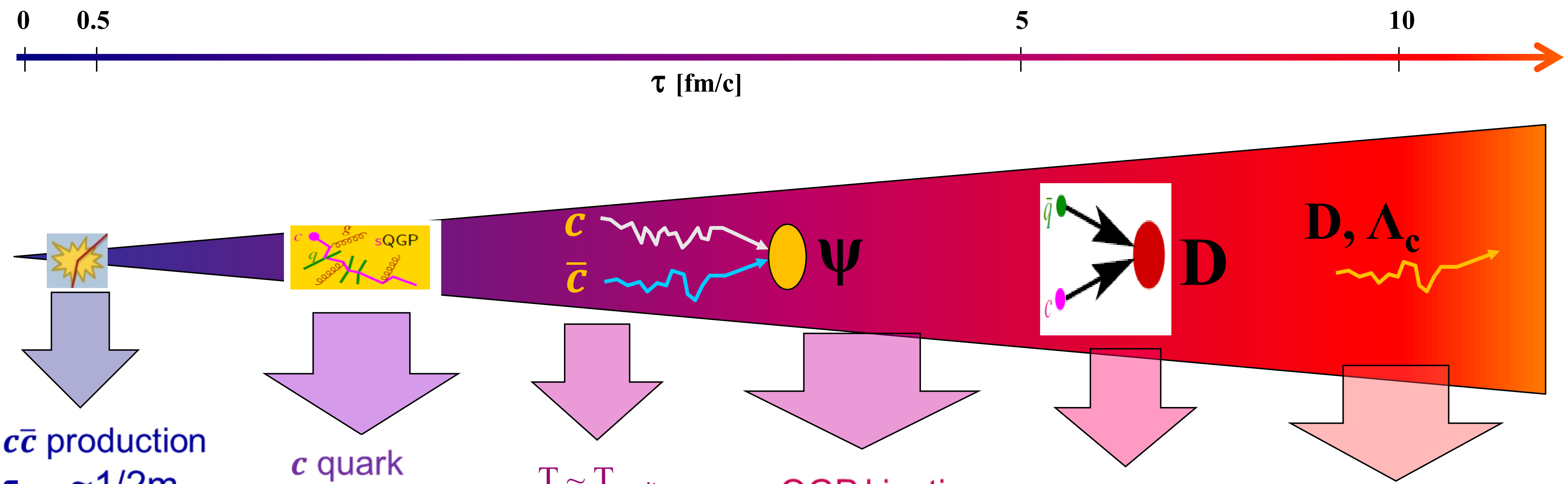
  ➔produced in early hard process $\tau \sim 1/2m_Q$



- Hadronization ➔ charmonium vs open charm hadrons



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

Outline of the presentation

Part I: Open heavy-hadron production in pp

- Heavy flavor hadro-chemistry: non-universal
- Statistical hadronization: grand-canonical → canonical

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

- Interaction of HF with medium: T-matrix approach
- Diffusion & hadronization
- Collective flow & p_T-dependent modifications of hadro-chemistry

Part III: Heavy quarkonium transport in Pb-Pb

- Semi-classical transport of heavy quarkonia in QGP
- LO vs NLO reaction rate
- J/ψ & ψ(2S) collective flow

Disclaimer: selection of topics constrained by my knowledge
focused on low & intermediate p_T, no high p_T HF jets

Outline of Part I

Part I: Open heavy-hadron production 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

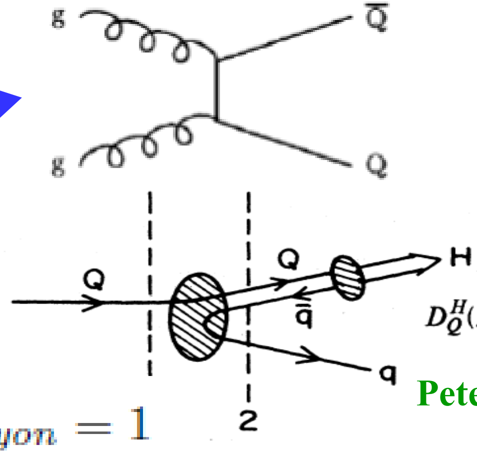
- Heavy hadron production cross section: factorization

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

Parton distribution functions (PDFs)

Hard scattering cross section (pQCD)

Fragmentation function (hadronization)



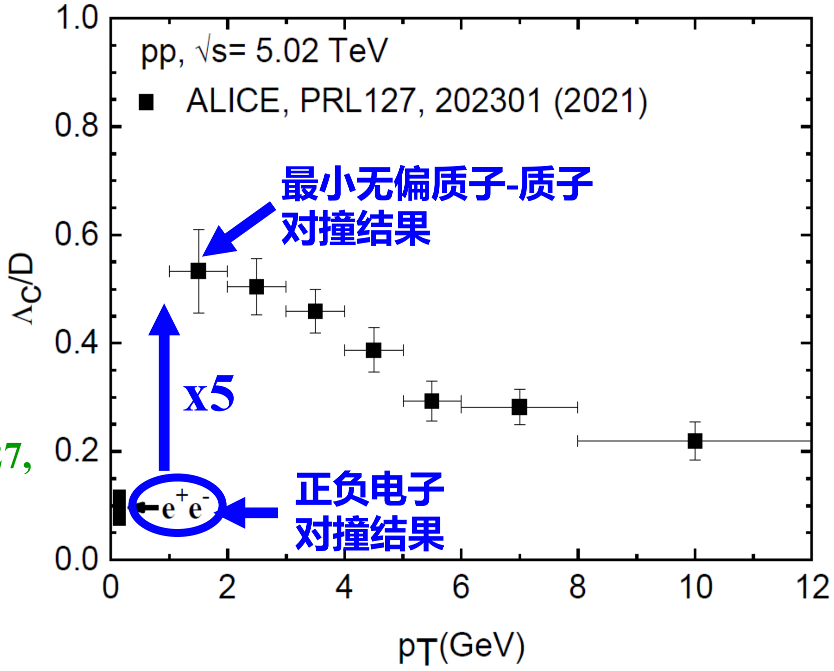
$$D_Q^H(z) = \frac{N}{z[1-(1/z)-\epsilon_Q/(1-z)]^2}$$

Peterson, PRD27, 105 (1983)

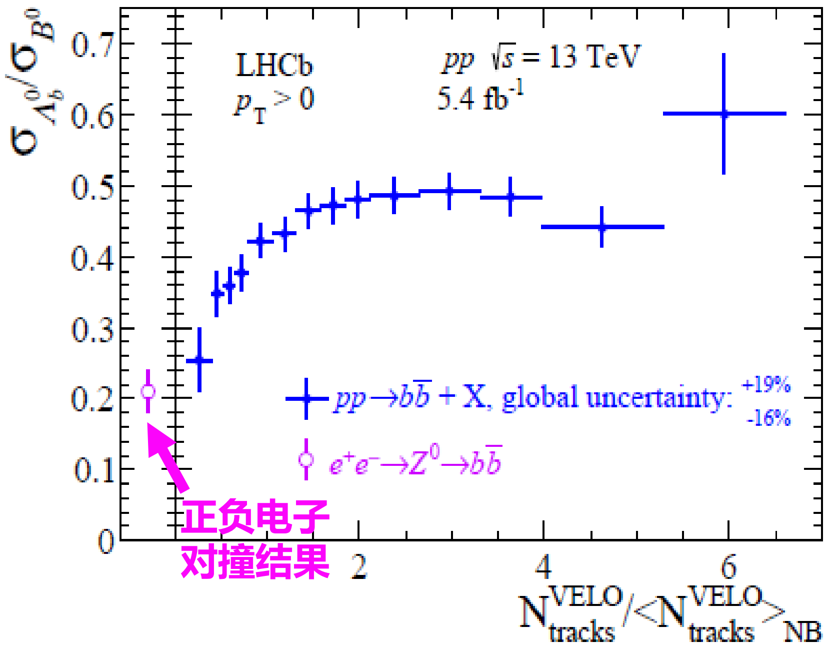
- Hadronization: heavy quark conservation $f_u + f_d + f_s + f_{baryon} = 1$

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

ALICE, PRL127, 202301 (2021)



Λ_b/B vs 质子-质子对撞系统大小扫描

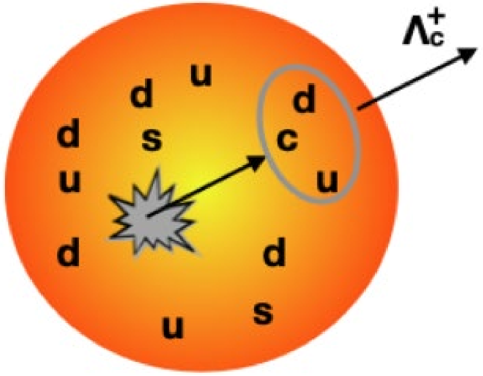


LHCb, PRL132, 081901 (2024)

Statistical Hadronization Model (SHM)

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

  ➔ stochastic/statistical coalescence of c/b with surrounding q



- Statistical hadronization model for heavy-hadrons

  { Hadronic population born into equilibrium = maximum entropy ➔ 'thermal' production
  Khazeev & Satz, EPJC 52,187 (2007)

  Relative chemical equilibrium ➔ primary production yields $N_i \propto$ thermal densities n_i

- Grand-canonical ensemble for mini.bias pp

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

{ γ_s=0.6 – strangeness suppression factor

T_H=170 MeV – 'universal' hadronization temperature

Heavy-hadron mass spectra as input of SHM

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

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

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).

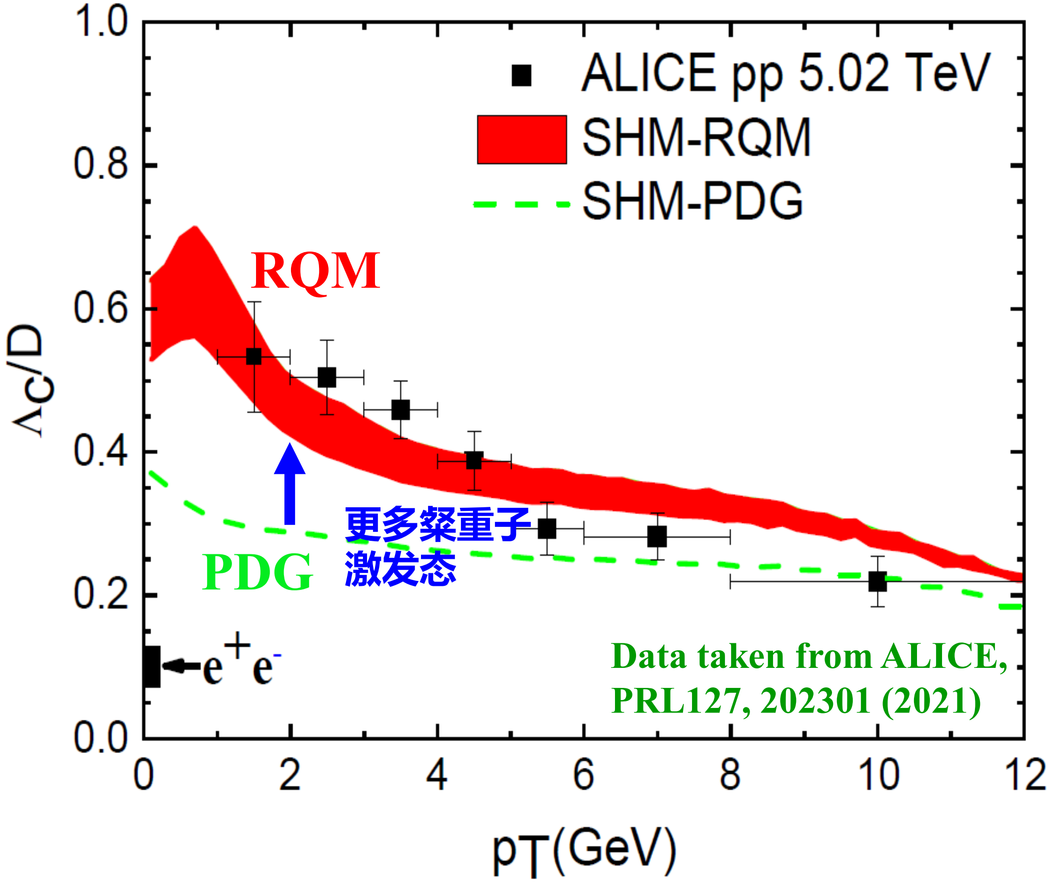
		$Q = c$		$Q = b$	
$I(J^P)$	Qd state	M	$M^{\exp}$ [1]	M	$M^{\exp}$ [1]
$0(\frac{1}{2}^+)$	1S	2286	2286.46(14)	5620	5620.2(1.6)
$0(\frac{1}{2}^+)$	2S	2769	2766.6(2.4)?	6089	
$0(\frac{1}{2}^+)$	3S	3130		6455	
$0(\frac{1}{2}^+)$	4S	3437		6756	
$0(\frac{1}{2}^+)$	5S	3715		7015	
$0(\frac{1}{2}^+)$	6S	3973		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	

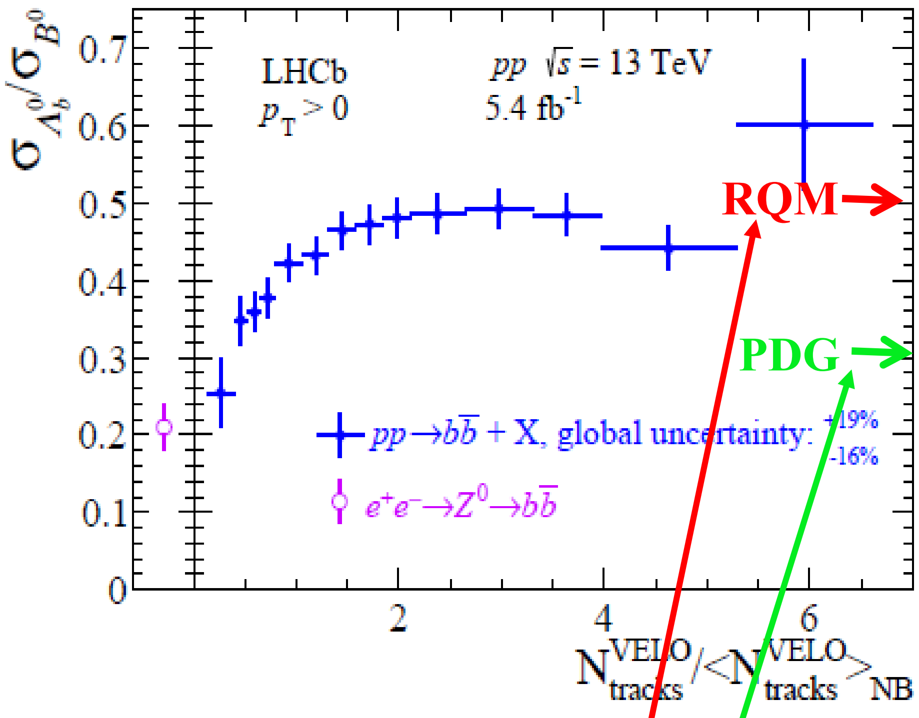
Heavy baryon-to-meson ratio: mini.bias pp

Λ_c/D vs p_T



MH & Rapp, PLB 795, 117 (2019)
Chen & MH, PLB 815, 136144 (2021)

Λ_b/B vs system-size



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

MH & Rapp, PRL 131, 012301 (2023)

Canonical ensemble (CE) SHM

- Canonical ensemble partition function: strict conservation of quantum charges

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

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

correlation volume ~ system size

- Primary hadron yield: CE vs GCE

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

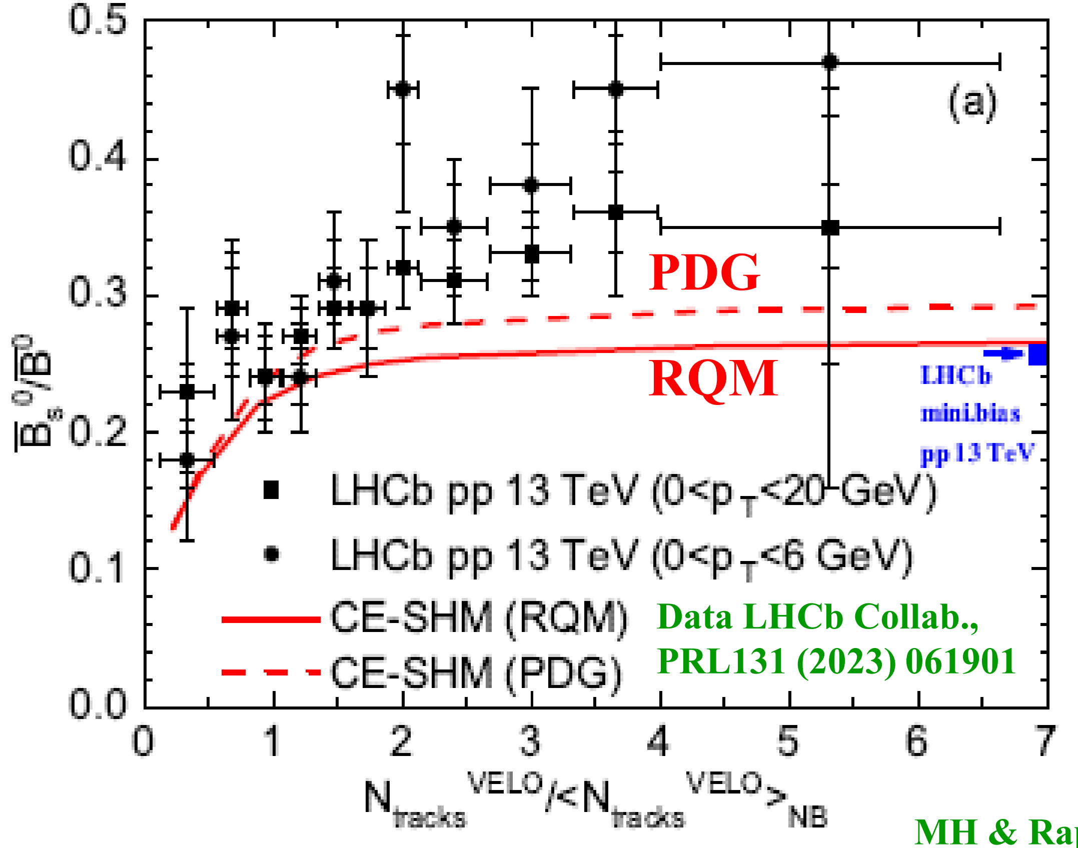
$$= \langle N_j \rangle^{GCE} \frac{Z(\vec{Q} - \vec{q}_j)}{Z(\vec{Q})}.$$

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

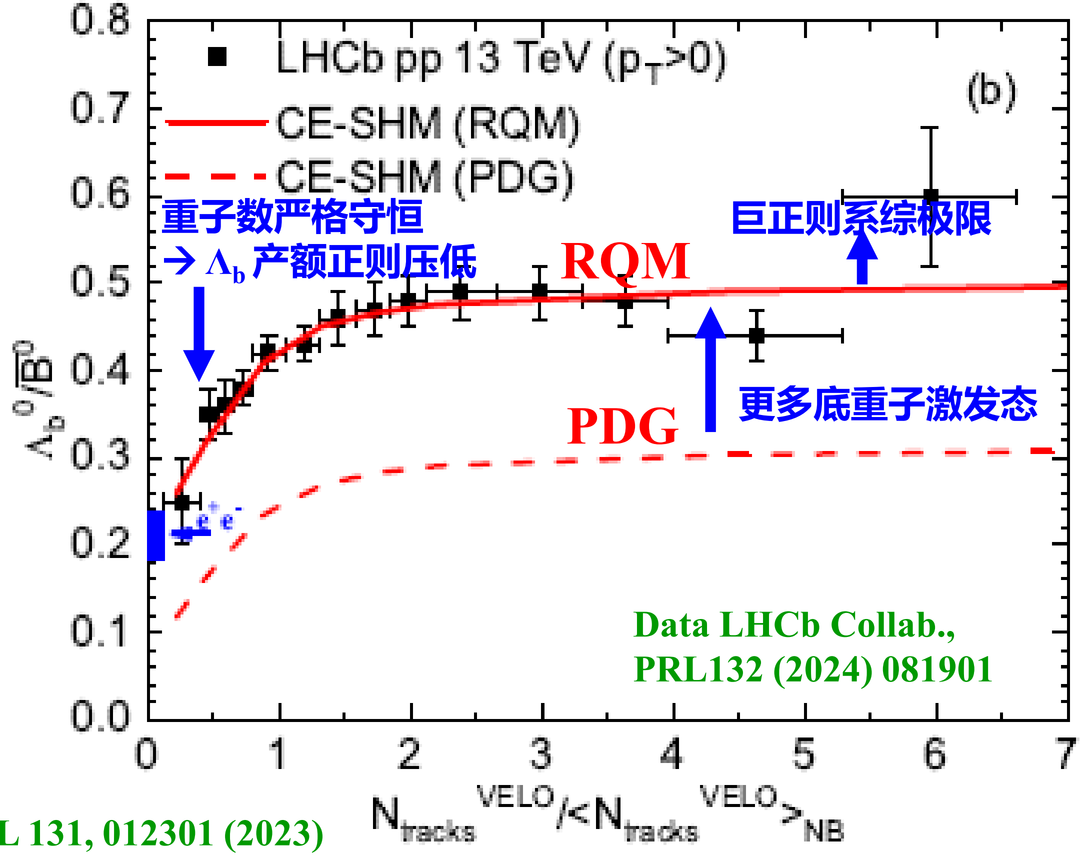
- E.g. exact baryon-number conservation requires: simultaneous creation of a pair of baryon and antibaryon ➔ energy-expensive $\exp(-2m_N/T_H)$
 ➔ canonical suppression for baryon production

Ground-state b-hadron production ratios

B_s/B vs system-size



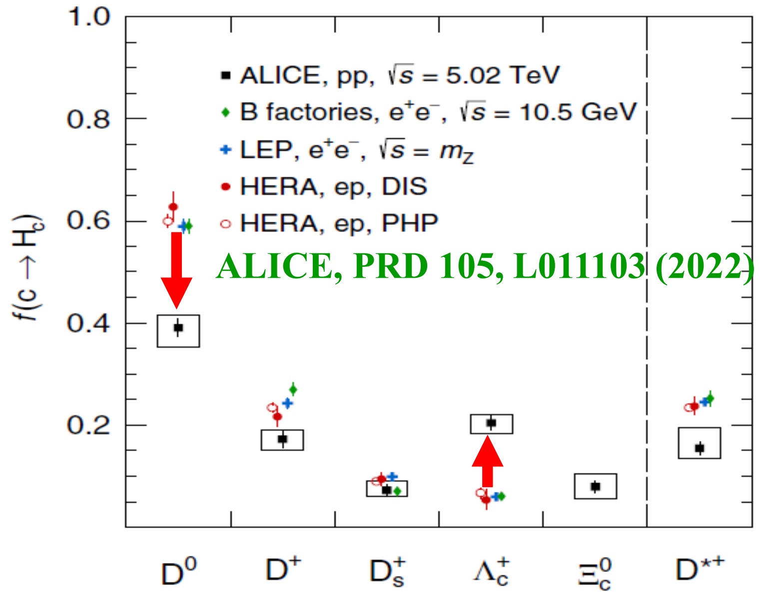
Λ_b/B vs system-size

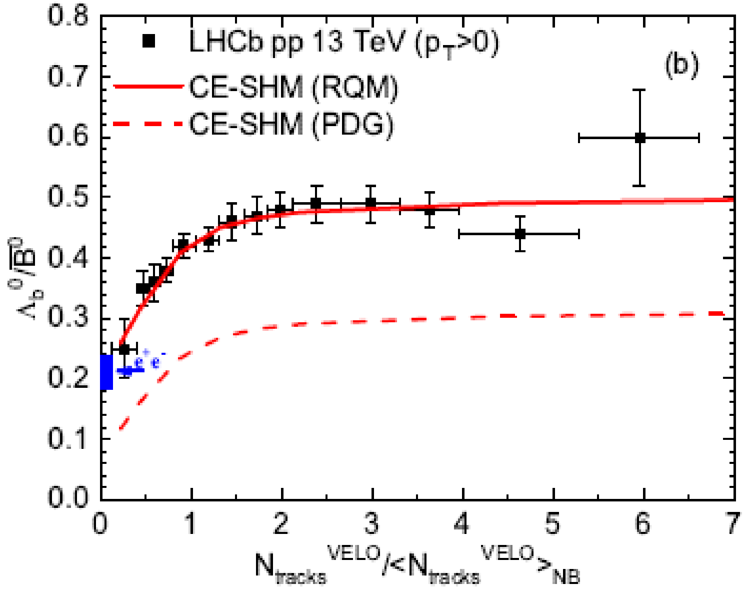


MH & Rapp, PRL 131, 012301 (2023)
Dai & MH, PRC 110, 034905 (2024)

- Λ_b^0/B GCE saturation limit → e^+e^- vacuum fragmentation limit
- RQM strongly favored by data

Take-aways from Part I





- Heavy flavor hadro-chemistry: non-universal
  - c/b → $\Lambda_{c/b}$ enhanced & c/b→D/B reduced in pp vs e^+e^-
- Grand-canonical → canonical statistical hadronization
  - exact conservation of quantum charges ➔ canonical suppr.
  - large volume saturation limit → vacuum fragmentation e^+e^- limit
- "Missing" heavy-baryon excited states highlighted ➔ awaiting measurement & confirmation

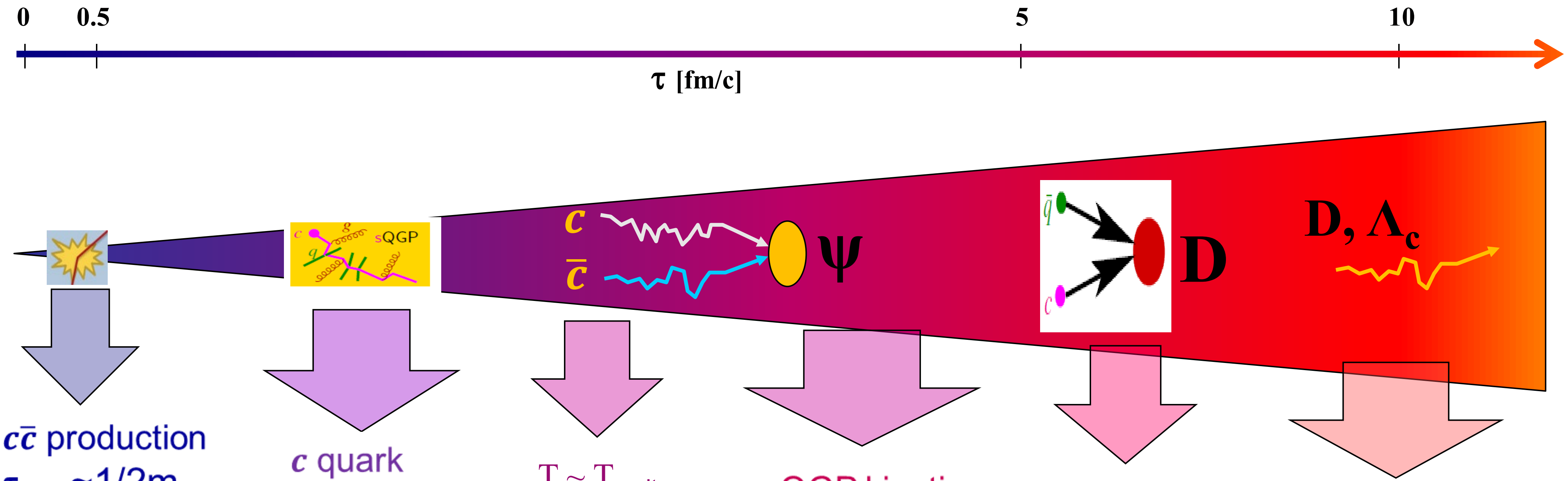
Outline of Part II

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



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$c + \bar{c} \leftrightarrow \psi$
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hadronization:
$c+q \rightarrow D$
$c+q+q \rightarrow \Lambda_c$

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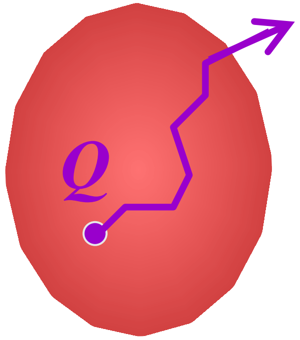
- m_Q>>T ➔ number conserved through diffusion/hadronization: tagged & traceable probes
- $\tau_Q^{eq} \geq \tau_{QGP}$ ➔ carrying a memory of interaction history: quantitative gauge of coupling strength

HQ interaction & diffusion in QGP

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



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

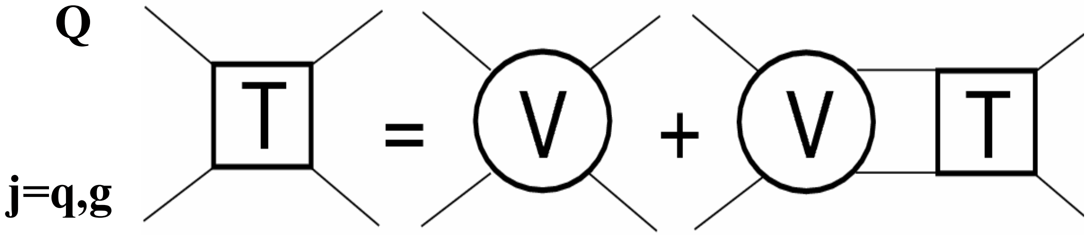
$$\frac{\partial}{\partial t} f_Q(t,p) = \gamma \frac{\partial}{\partial p_i}[p_i f_Q(t,p)] + D_p \Delta_{\vec{p}} f_Q(t,p)$$

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

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

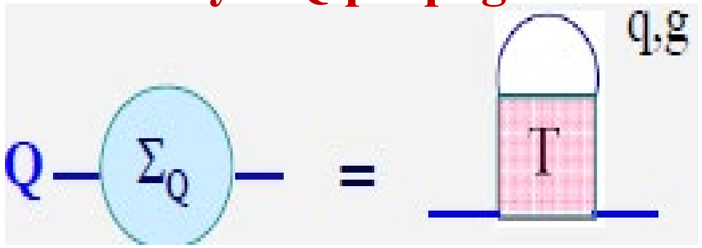
- Q-q/g soft scatterings: T-matrix resummation of lattice-constrained in-medium HQ potential

2-body scattering amplitude



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

1-body HQ propagator



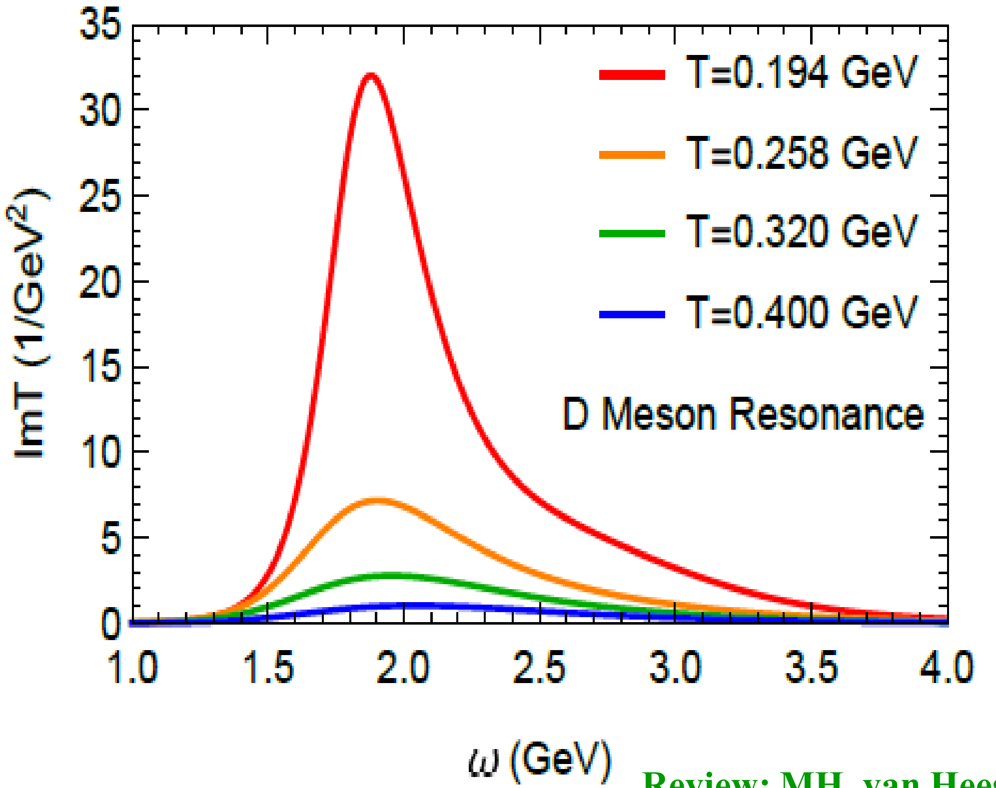
$D = 1/[\omega - \omega_k - \Sigma(\omega,k)]$

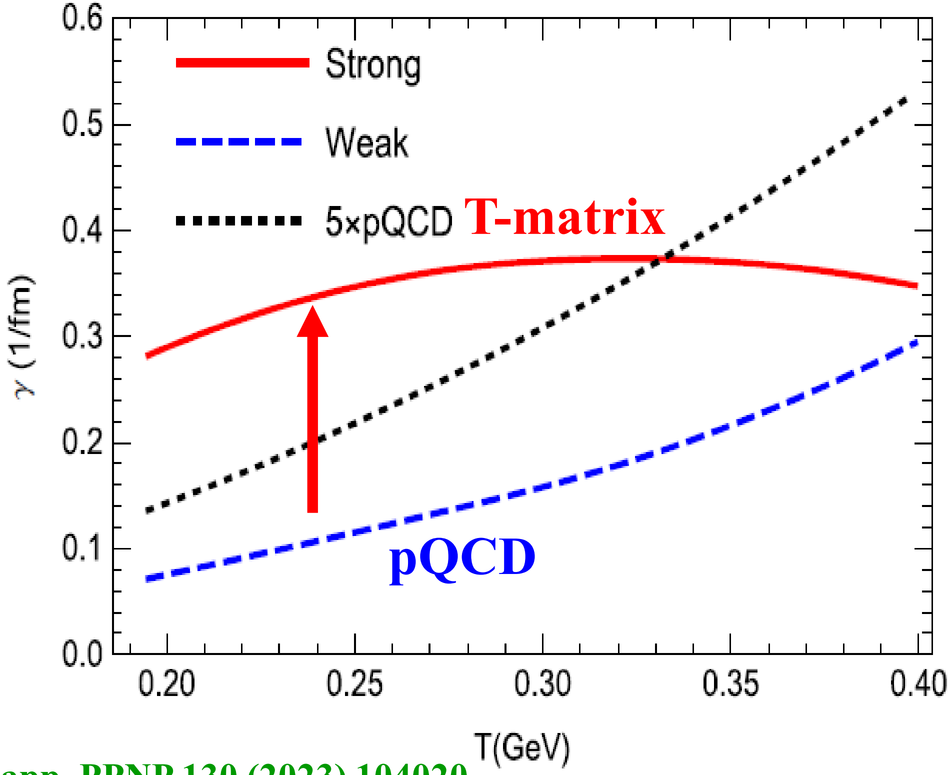
Review: MH, van Hees & Rapp, PPNP 130 (2023) 104020

Charm quark thermal relaxation rate in QGP

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

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





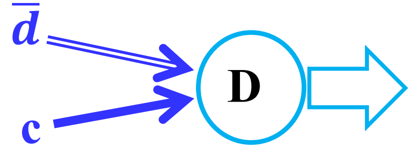
Review: MH, van Hees & Rapp, PPNP 130 (2023) 104020

- 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

HQ hadronization: resonance recombination

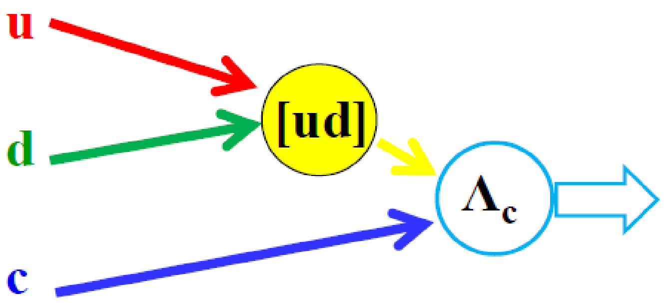
- 2→1 Resonance Recombination Model (RRM) via Boltzmann equation

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



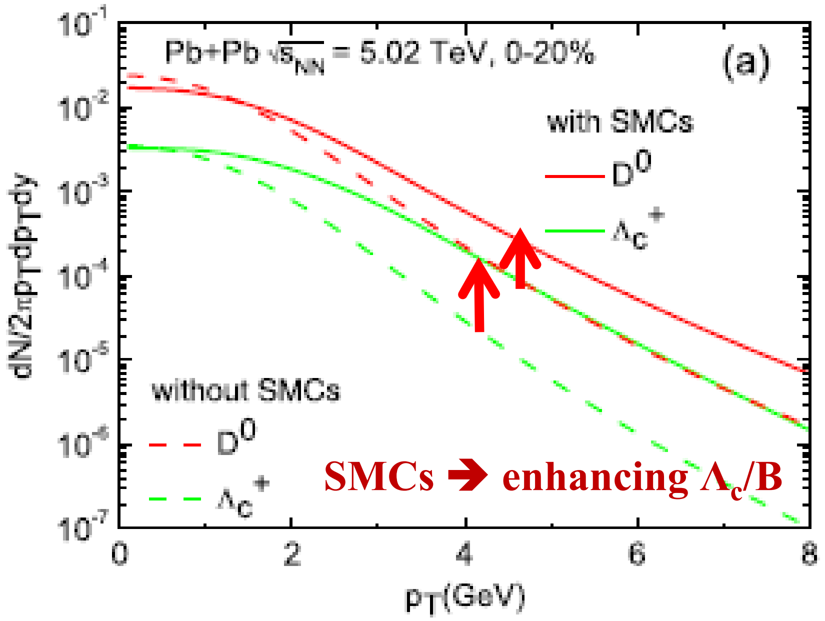
- Resonant cross section $\sigma_M(s)$ ← T-matrix resonance amplitude
- Encoding energy conservation & correct equilibrium limit

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



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

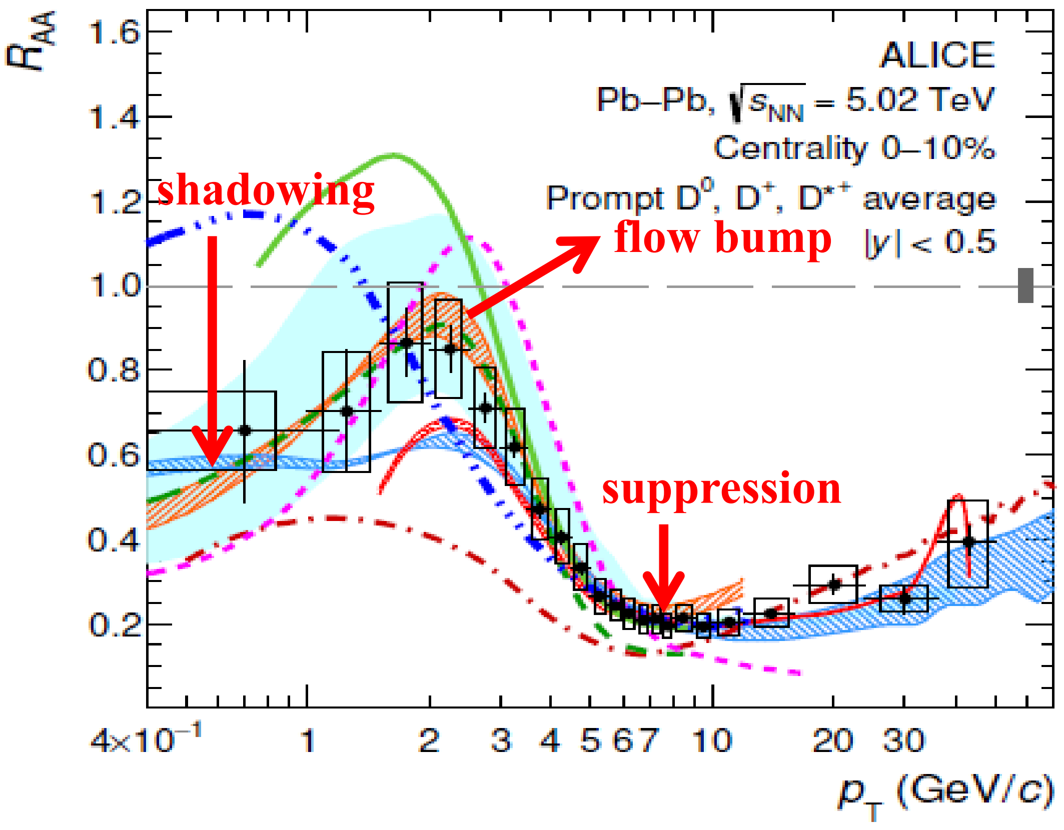
Space-Momentum Correlations



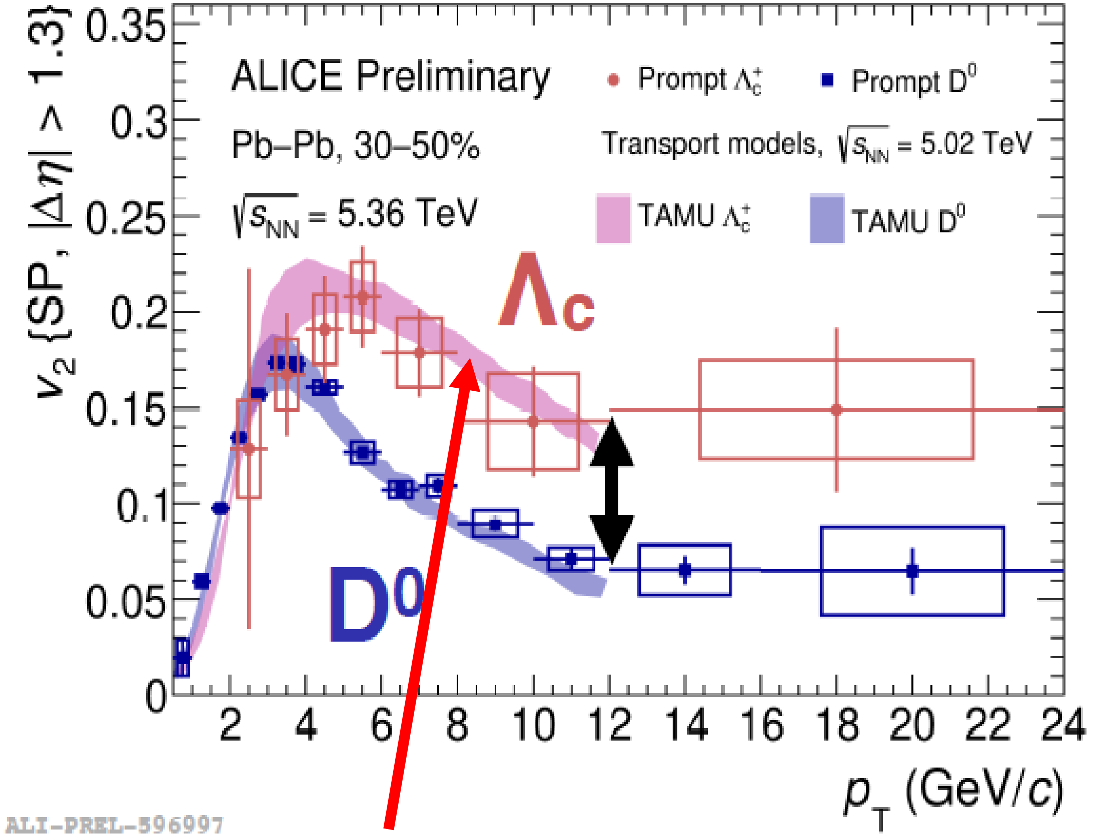
MH & Rapp PRL 124, 042301 (2020); Lu & MH, PRC 106, 064903 (2022)

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

ALICE, JHEP 01 (2022) 174



ALICE highlights @ Quark Matter 2025

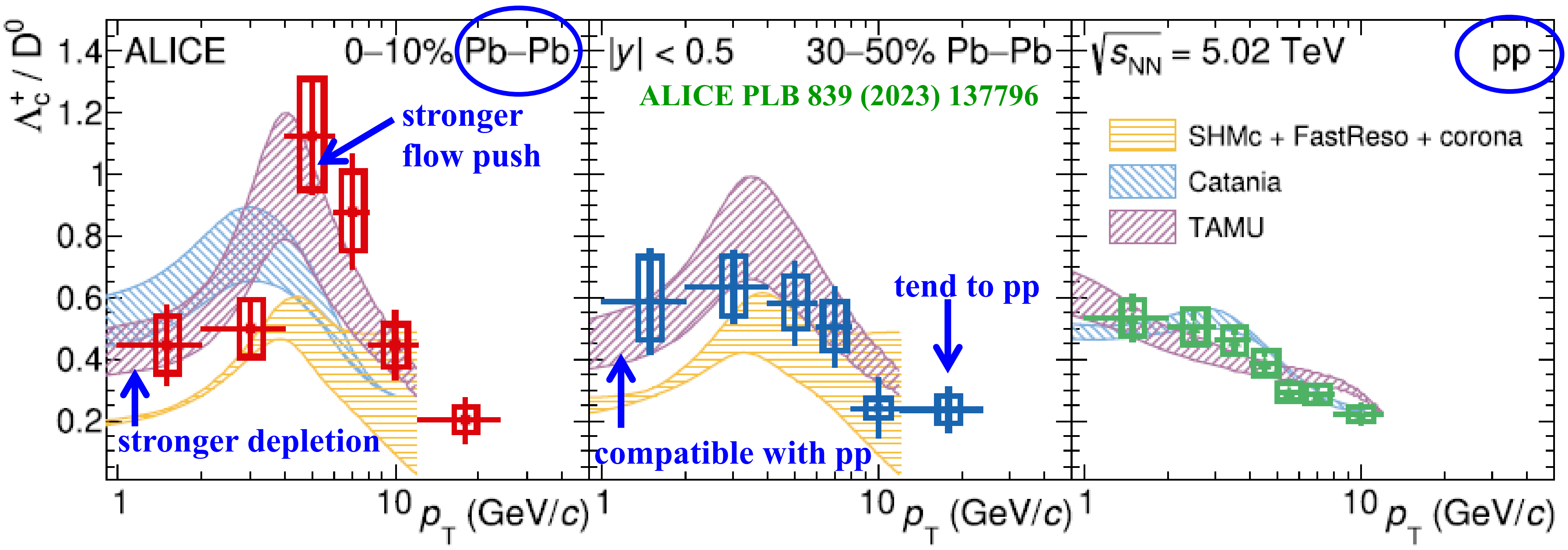


- Brown curve taken from our model calculation in **PRL 124, 042301 (2020)**
- Simultaneous description of D's R_{AA} & v_2

- In particular, Λ_c's v_2 curve taken from our predictions in **PRL 124, 042301 (2020)**
- v_2 at low p_T: gauge of coupling strength

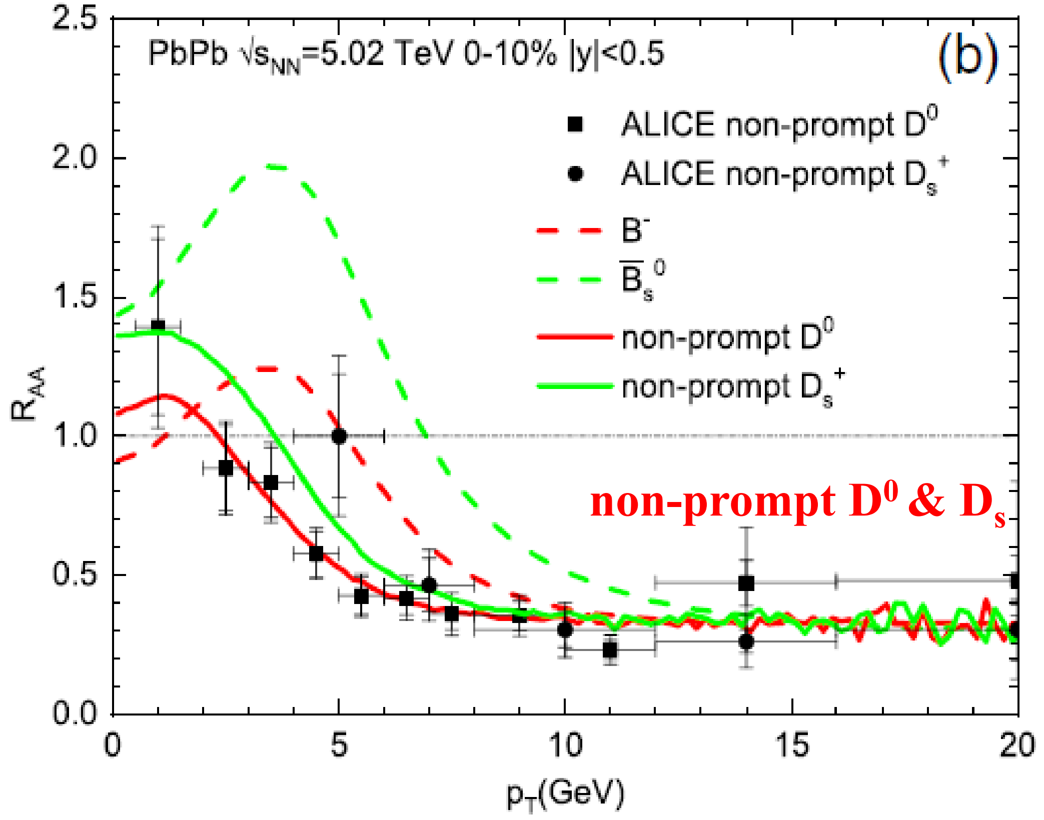
Charm hadro-chemistry Λ_c/D: pp→Pb-Pb

purple curves taken from our model predictions in **PRL 124, 042301 (2020) & PLB 795, 117 (2019)**

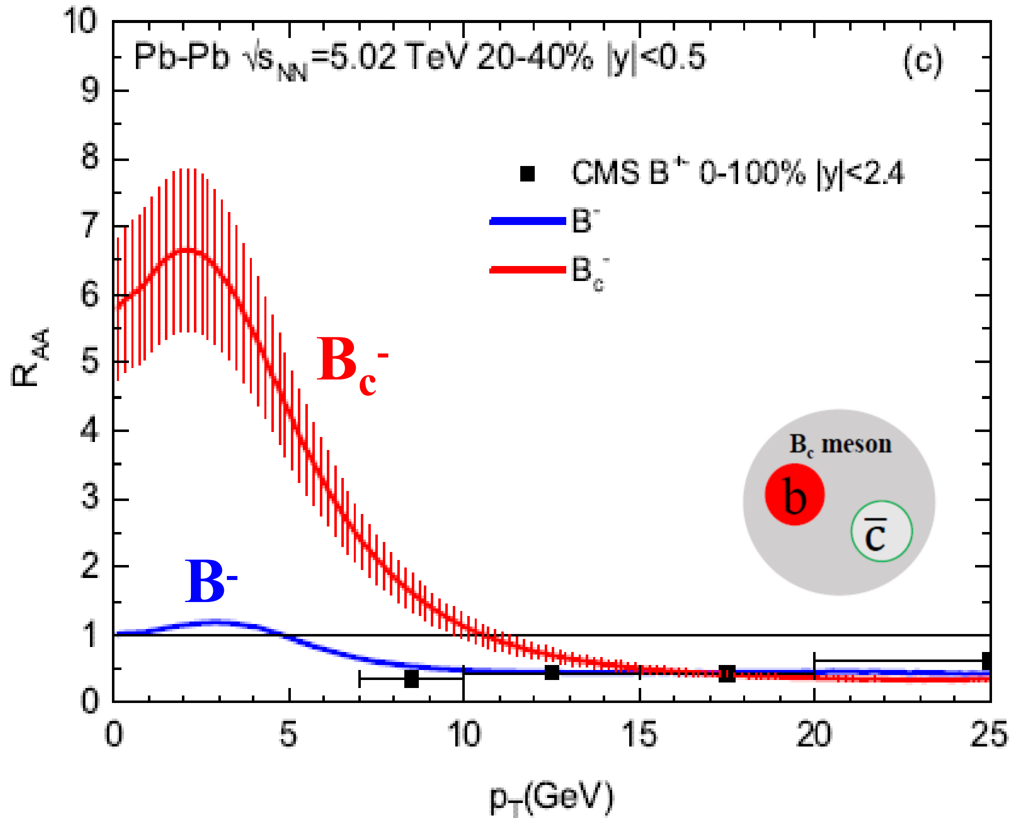


- Same RQM charm-hadron spectra (in particular baryons) in Pb-Pb & pp
- RRM satisfying correct relative chemical equilibrium limit ➔ same integrated Λ_c/D as in pp
- RRM with SMCs capaturing full flow effects ➔ enhancement of Λ_c/D at intermediate p_T

Bottom-hadron nuclear modification factors



MH & Rapp, PRL 131, 012301 (2023)



Zhao & MH, PLB 861, 139283 (2025)

- 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

Take-aways from Part II

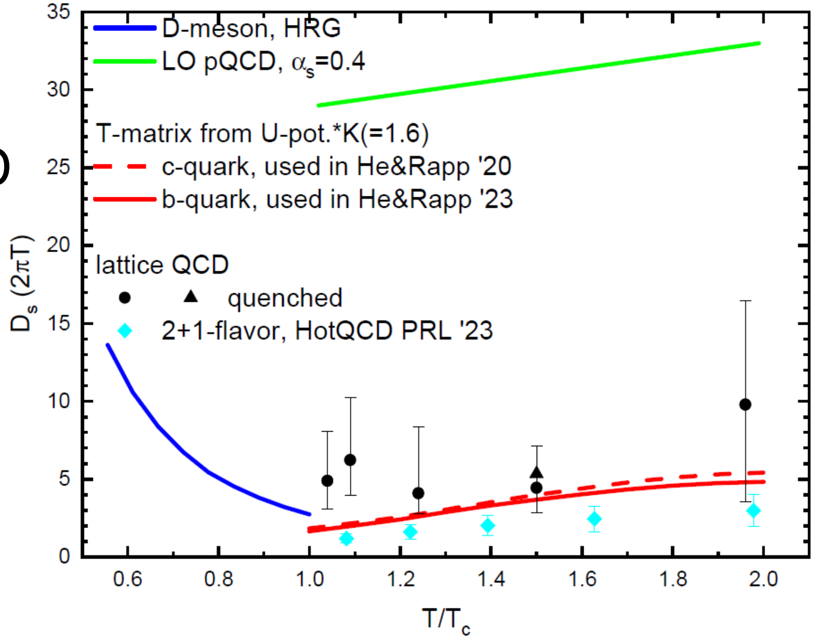
- Heavy quark diffusion

  - spatial diffusion coefficient: $\mathcal{D}_s = T/m_Q\gamma$ ➔ $\langle x^2 \rangle \sim \mathcal{D}_s t$
    model & lattice $\mathcal{D}_s(2\pi T) \sim 1\text{-}3$ near T_c, x10 smaller than pQCD

  - collisional width $\Gamma_{coll} \sim 3/\mathcal{D}_s \sim 1$ GeV $> M_{q,g}$ ➔ thermal partons melted, while HQs as Brownian markers survive

  - maximum coupling strength near T_c ➔ strongly coupled QGP liquid

c/b transport coefficient



- Heavy-quark hadronization

  - recombination on top of diffusion → characteristic flow features (c vs b, meson vs baryon)

  - recombination → p_T-dependent modifications of hadro-chemistry, but only kinematic redistribution in p_T with integrated Λ_c/D unchanged

Outline of Part III

Part III: Heavy quarkonium transport in Pb-Pb

- Semi-classical transport of heavy quarkonia in QGP
- Reaction rate: LO vs NLO
- J/ψ & ψ(2S) collective flow

Semi-classical transport of charmonium in QGP

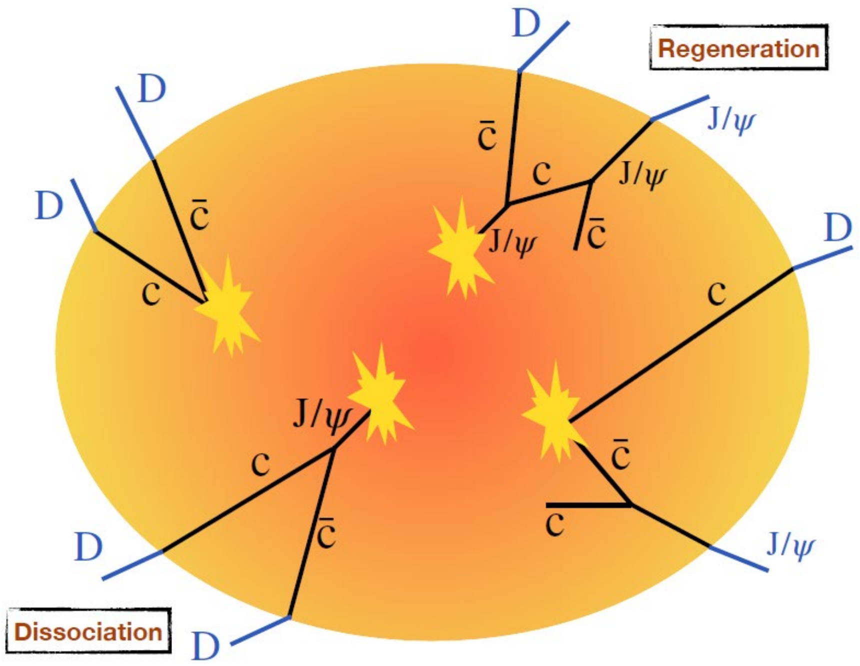
- Boltzmann ➔ rate equation for charmonium yields

$$\frac{dN_\psi}{dt} = -\Gamma_\psi \left(N_\psi - N_\psi^{eq}\right)$$

dissociation/ reaction rate Γ_ψ

regeneration toward equilibrium

Review: MH, van Hees & Rapp, PPNP 130 (2023) 104020

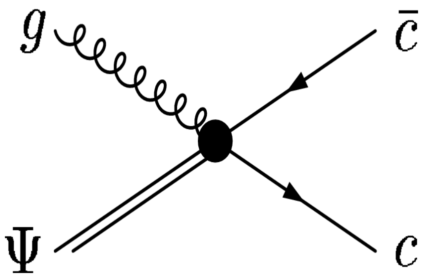


- Transport coefficients

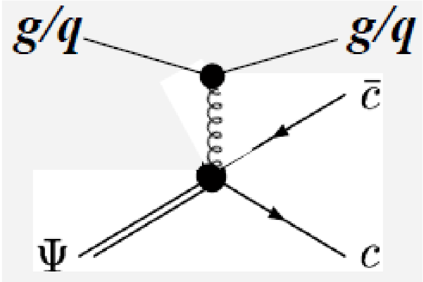
  - equilibrium limit $N_\psi^{eq}(T) = \gamma_c^2 n_\psi(T) V_{FB}$, with $\gamma_c \propto \sigma_{ccbar}$

  - dissociation/reaction rate $\Gamma_\psi\ [E_B(T)]$:

LO: gluo-dissociation g+ψ → c+cbar

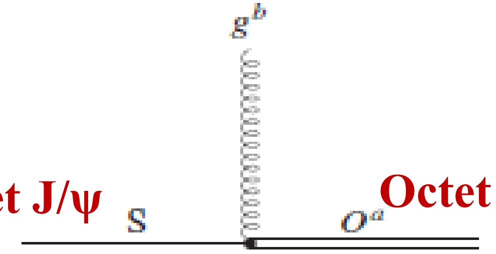


NLO: parton-inelastic g/q+ψ → g/q+c+cbar



Charmonium dissociation rate in QGP

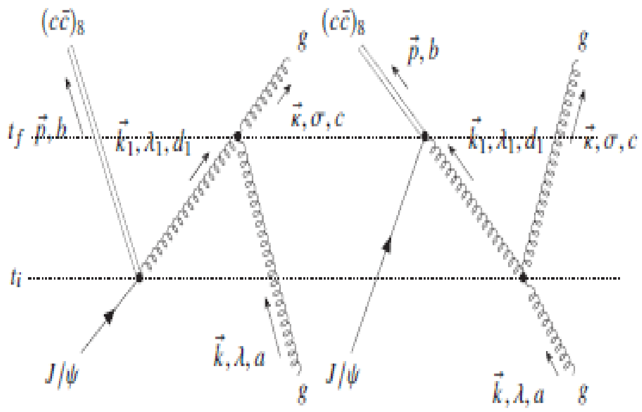
- Heavy quarkonium-gluon coupling: pNRQCD color-electric dipole



$$\langle O,a|V_{SO}|S\rangle = \langle O,a|\frac{1}{2}g_s\vec{r}\left(\frac{\lambda^b}{2}-\frac{\bar{\lambda}^b}{2}\right)\cdot\vec{E}^b|S\rangle$$

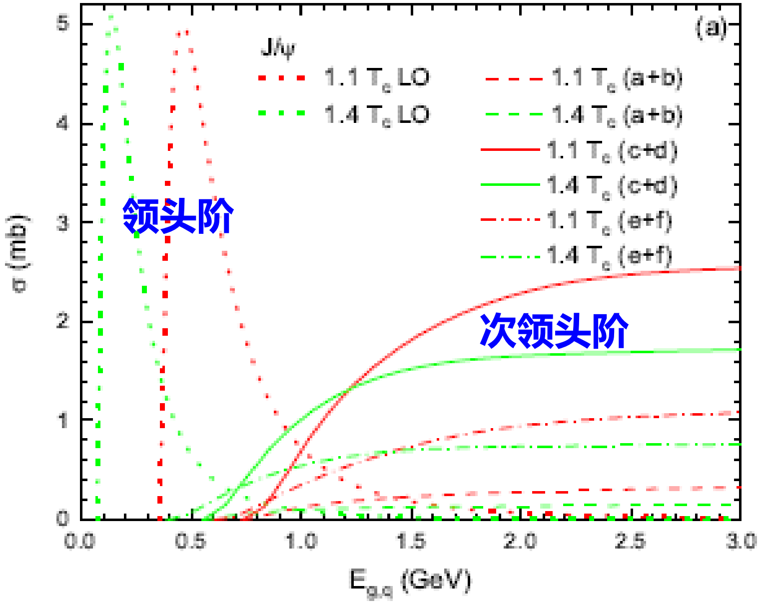
- Second-order quantum-mechanical perturbation

Feynman diagrams

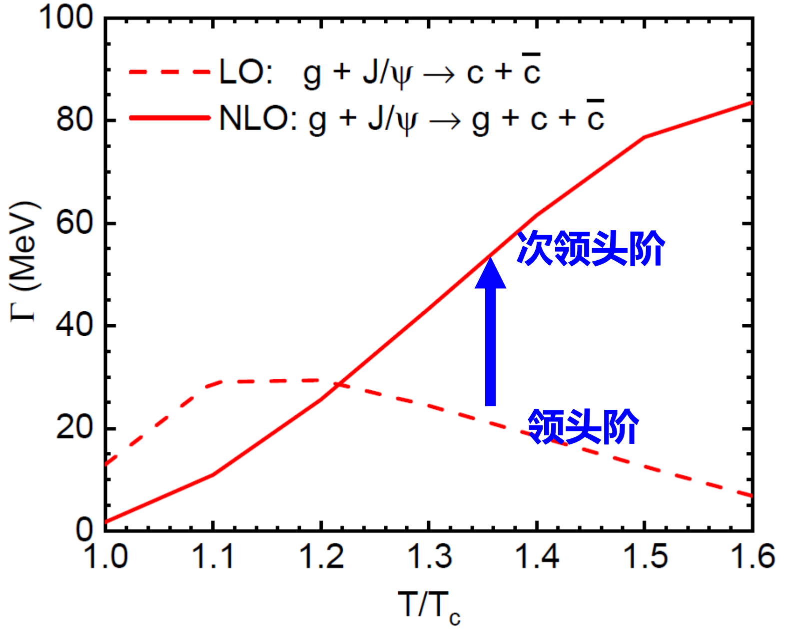


$$T_{fi} = \sum_m \frac{\langle f|V|m\rangle\langle m|V|i\rangle}{E_i - E_m + i\epsilon}$$

Cross sections



Dissociation rates



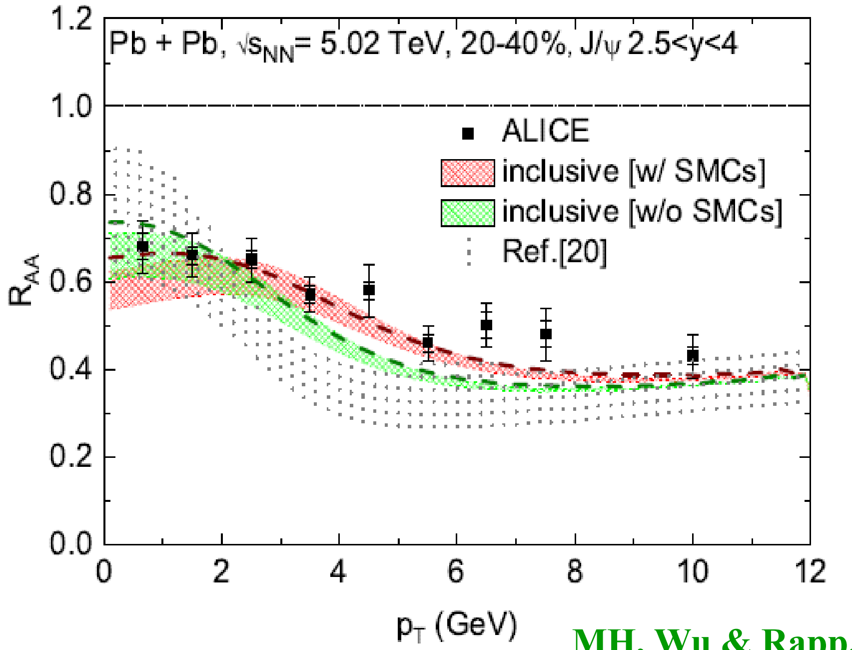
Chen & MH, PLB 786 (2018) 260–267; Zhao & MH, PRD 110, 074040 (2024)

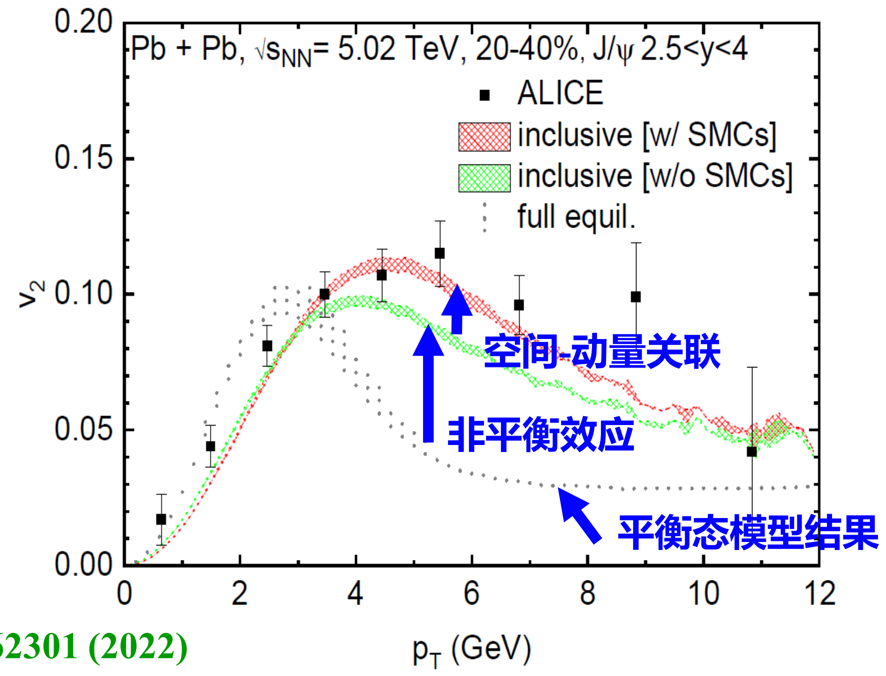
Resolving the 'J/ψ v_2 puzzle'

- RRM for J/ψ p_T-shape: normalized to $N^{regeneration}$

$$f_\Psi(\vec{x},\vec{p}) = C_\Psi \frac{E_\Psi(\vec{p})}{m_\Psi \Gamma_\Psi} \int \frac{d^3\vec{p}_1 d^3\vec{p}_2}{(2\pi)^3} f_c(\vec{x},\vec{p}_1) f_{\bar{c}}(\vec{x},\vec{p}_2) \times \sigma_\Psi(s) v_{\rm rel}(\vec{p}_1,\vec{p}_2) \delta^3(\vec{p}-\vec{p}_1-\vec{p}_2)$$

Off-equilibrium Langevin c/cbar distributions constrained by D-meson observables





MH, Wu & Rapp, PRL 128, 162301 (2022)

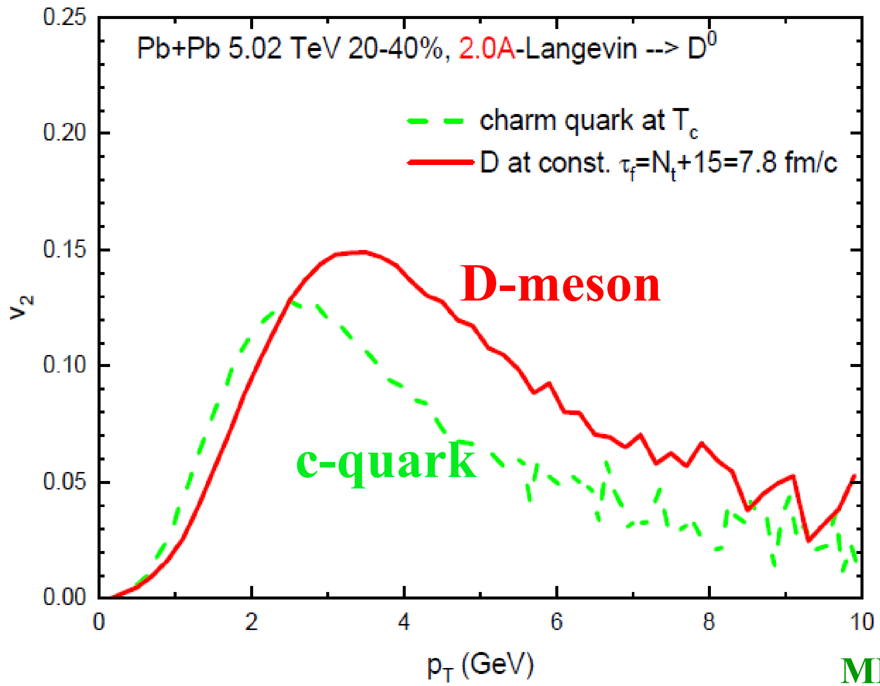
- Intermediate p_T: harder off-equi. c/cbar spectra + SMCs ➔ p_T reach of regeneration much extended

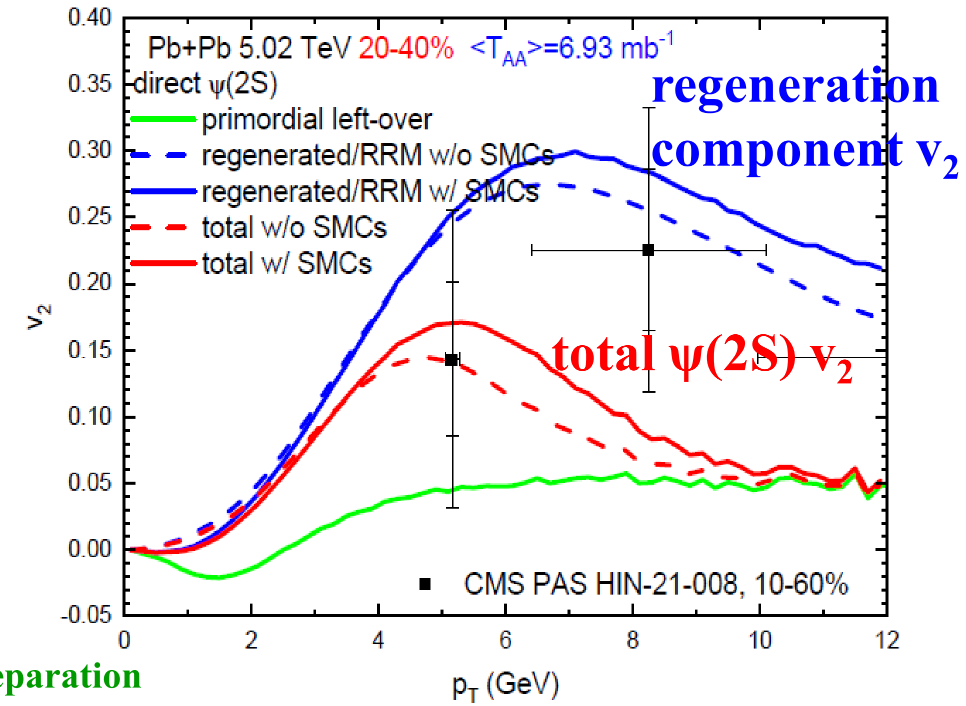
- High p_T: hydro simulation of suppression of primordial ψ ➔ path-length dependent v_2~0.05

Sequential regeneration: v_2 of ψ(2S)

- Binding energy J/ψ > ψ(2S) → dissociation temperature T_d J/ψ > ψ(2S)
  ➔ regeneration of ψ(2S) at $T_d \sim T_c$ in hadronic phase, significantly later than J/ψ

$$f_{\psi'}(\vec{x},\vec{p}) = C_{\psi'}\frac{\gamma_{p,\psi'}}{\Gamma_{\psi'}}\int\frac{d^3\vec{p}_1 d^3\vec{p}_2}{(2\pi)^3} f_D(\vec{x},\vec{p}_1) f_{\bar{D}}(\vec{x},\vec{p}_2)\sigma_{\psi'}(s)v_{\rm rel}(\vec{p}_1,\vec{p}_2)\delta^3(\vec{p}-\vec{p}_1-\vec{p}_2)$$





MH, in preparation

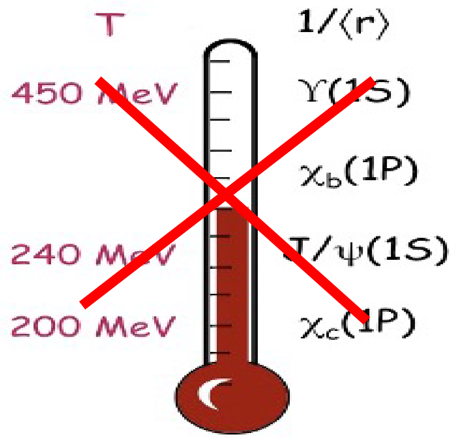
- Regeneration c + cbar → J/ψ but D + Dbar → ψ(2S)
- ψ(2S) v_2 ~17% vs. J/ψ ~ 11%, a strong indication of sequential regene. if confirmed

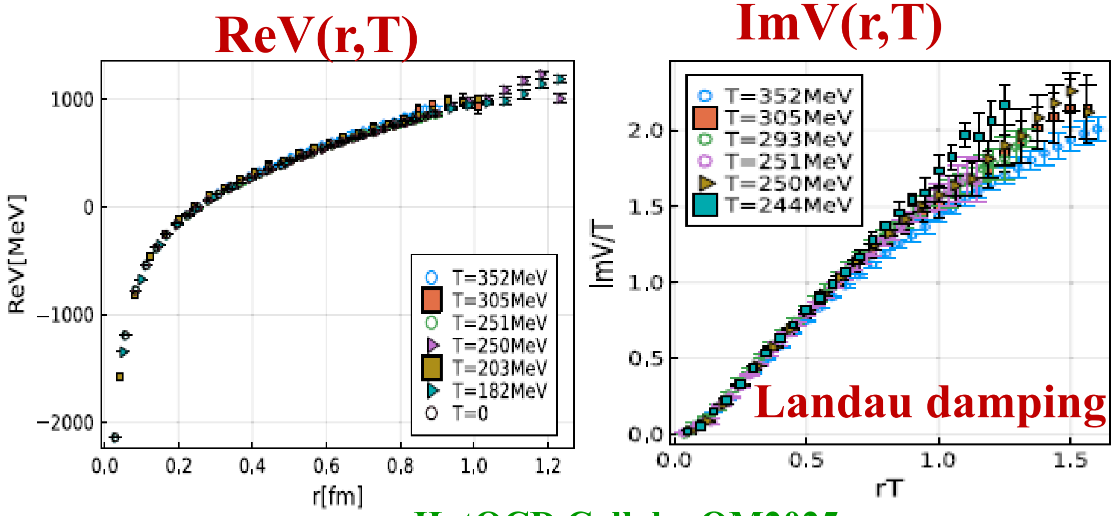
Take-aways from Part III

- Heavy quarkonia melt through large reaction rates (↔ small HQ $\mathcal{D}_s$) , rather than static screening of color force

  - lattice QCD: strong HQ potential ReV with little screening near T_c, but large ImV ~ Γ_{diss}

  - probe of in-medium force via in-medium "spectroscopy", not "thermometer" via static screening





HotQCD Collab., QM2025

- Quantitative connections between open- ↔ hidden-charm transport

  - transported c/cbar distributions & $d\sigma^{cc}/dy$ via regeneration

Summary & outlook

- HFs: excellent probes of sQGP transport properties, hadronization mechanisms, in-medium force & and inner structure/working

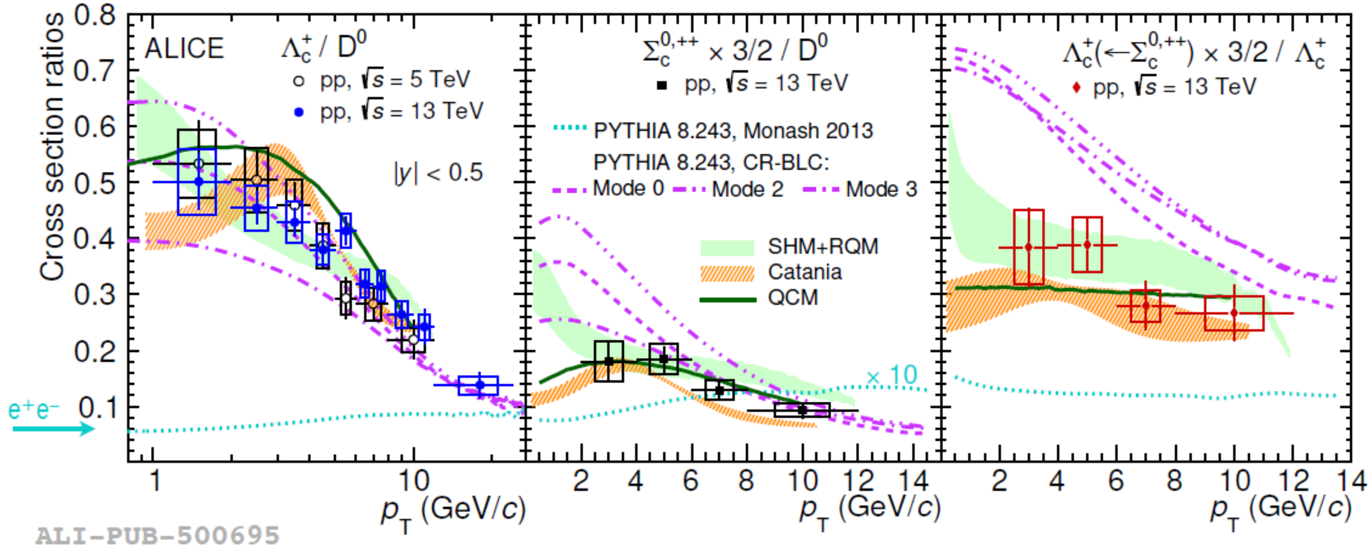
  - a small open HF diffusion coefficient $\mathcal{D}_s$
  - recombination/color neutralization important
  - quarkonia melting by large reaction rates
  - close connection between open- & hidden-HF

  ⟷ strongly coupled QGP likely supported by significant remnant confining force well above T_c

- Outlook: LHC Run 3/4, sPHENIX, SHINE/NA61, ALICE3 …

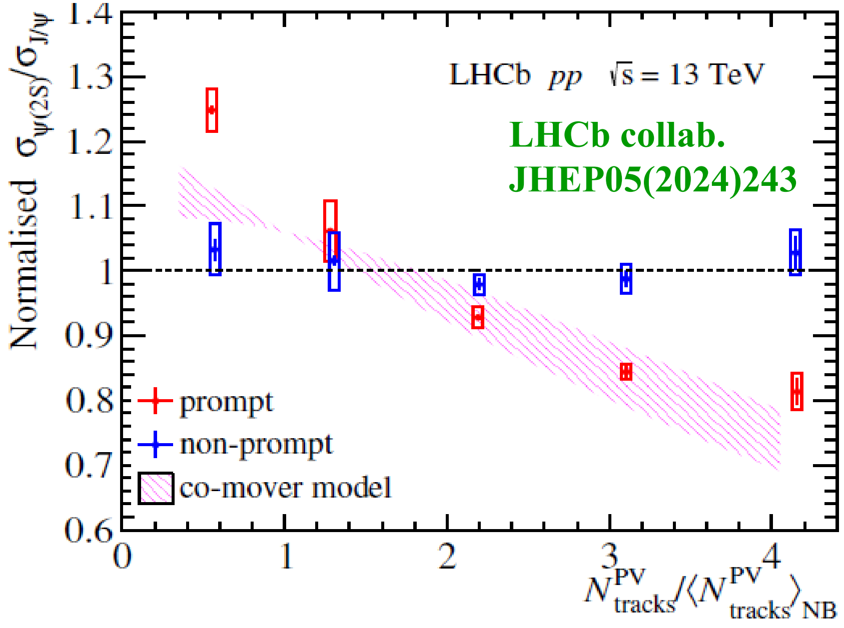
  - pp: Ξ_c production puzzle, rapidity dependence of Λ_c/D?
  - p-dependence of $\mathcal{D}_s$: nonperturabtive diffusion → perturbative radiative e-loss
  - quantum effects in open & hidden HF transport

Back-up: Σ_c/D & ψ(2S)/J/ψ in pp collisions



- Ground and excited charm baryons enhanced compared to e+e− collisions

ALICE, PRL 128 (2022) 012001



Ground-state b-hadron densities/ratios

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

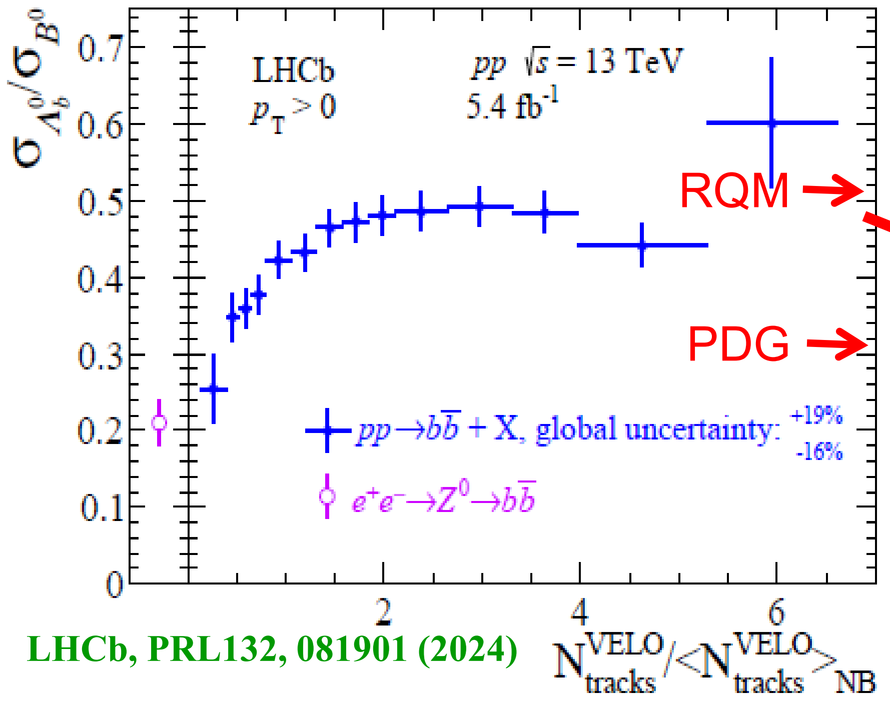
$$n_\alpha = n_\alpha^{\rm primary} + \sum_i n_i^{\rm primary} \cdot BR(i \to \alpha)$$

n_α $(\cdot 10^{-12}\ {\rm fm}^{-3})$	B^-	$\bar{B}^0$	$\bar{B}^0_s$	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^-	$\bar{B}^0$	$\bar{B}^0_s$	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!

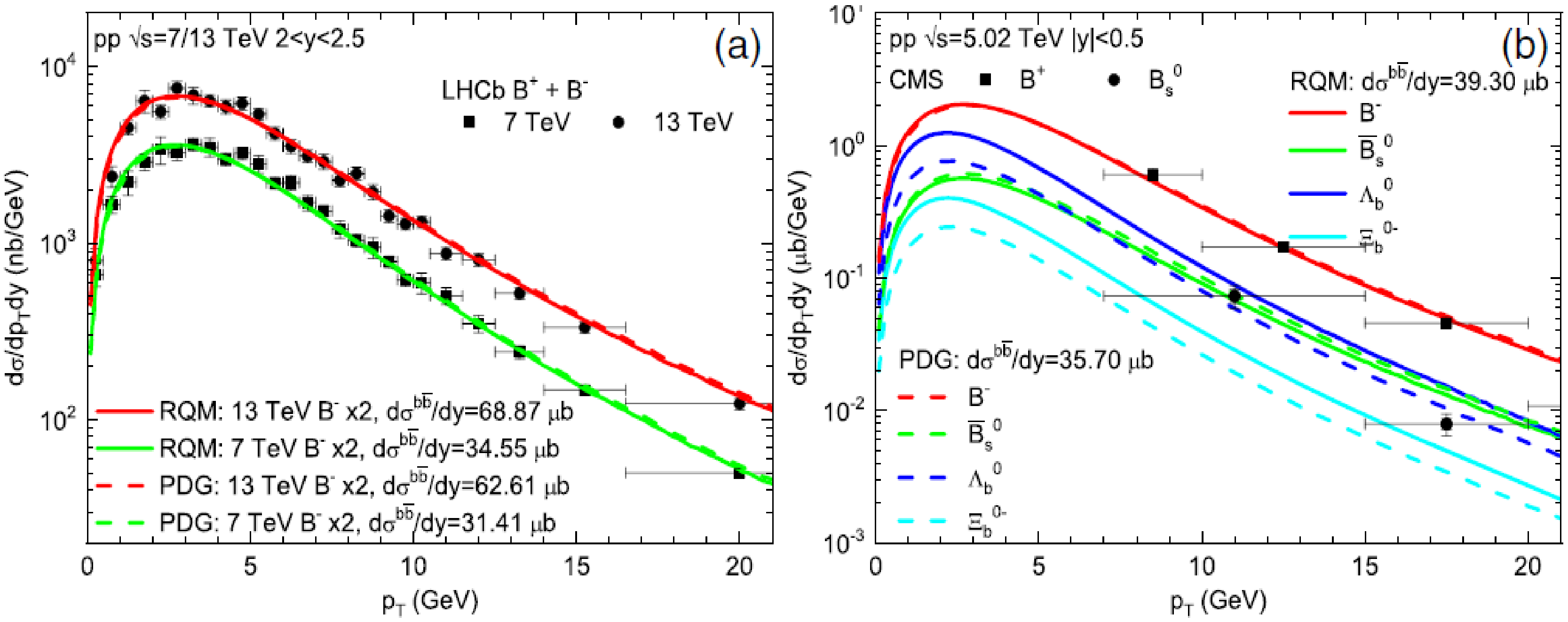
r_α	$\bar{B}^0/B^-$	$\bar{B}^0_s/B^-$	Λ_b^0/B^-	$\Xi_b^{0,-}/B^-$
PDG	0.9995	0.2904	0.3129	0.1000
RQM	0.9994	0.2699	0.5122	0.1623

Fragmentation & p_T-spectra

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

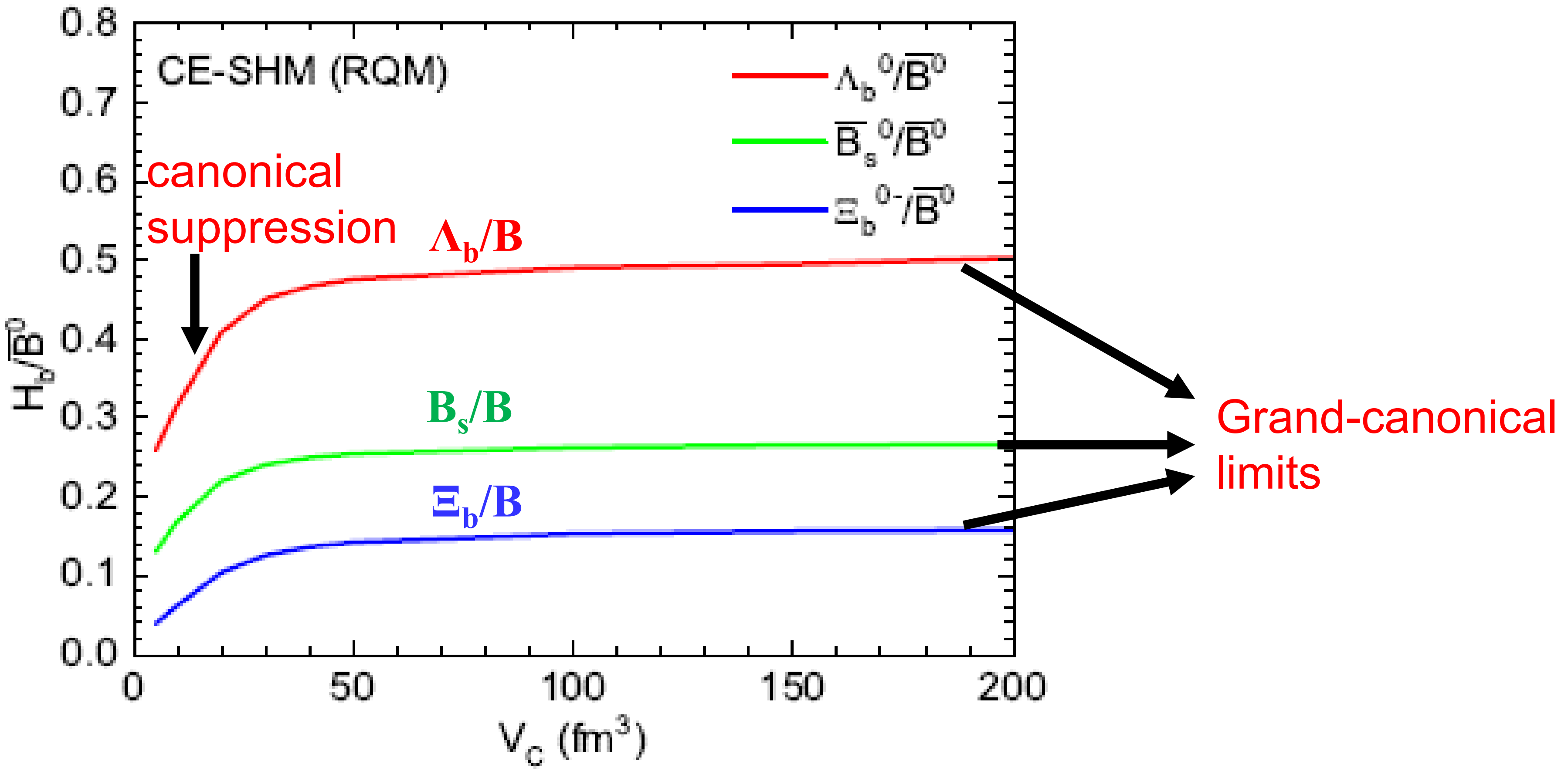
$$D_{b\to H_b}(z) \propto z^{\alpha}(1-z),$$

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



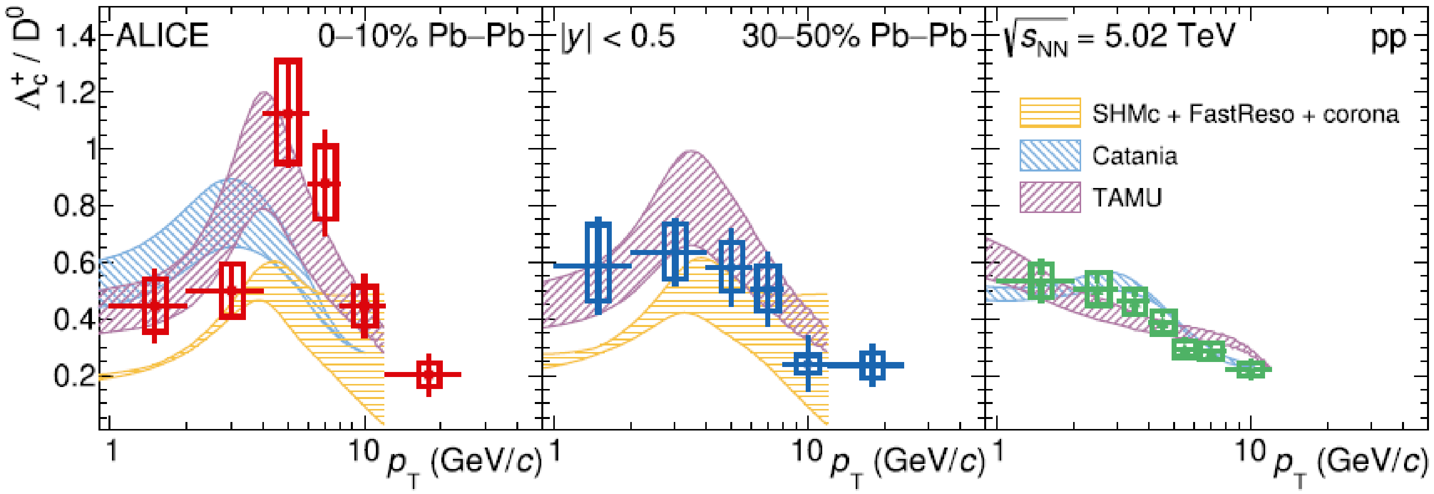
- Fitting meson spectra ➔ predicting baryon & total $d\sigma^{bbbar}/dy$= 39.3 μb for 5.02 TeV mid-y based on SHM chemistry ➔ baseline for b-hadron production in Pb-Pb collisions

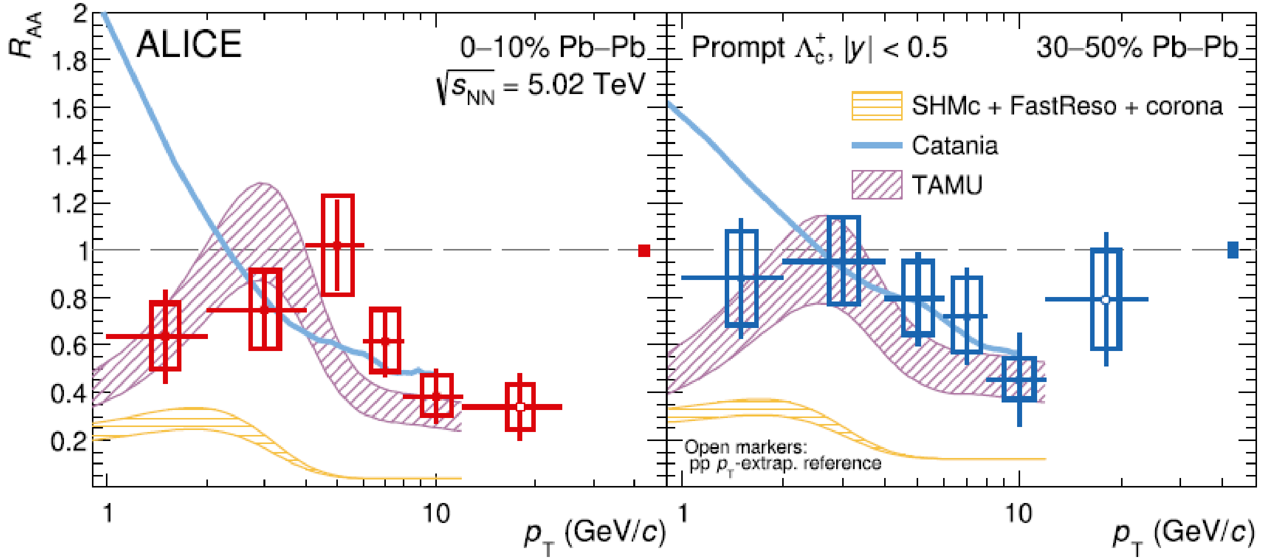
Ground-state b-hadron ratios vs Volume



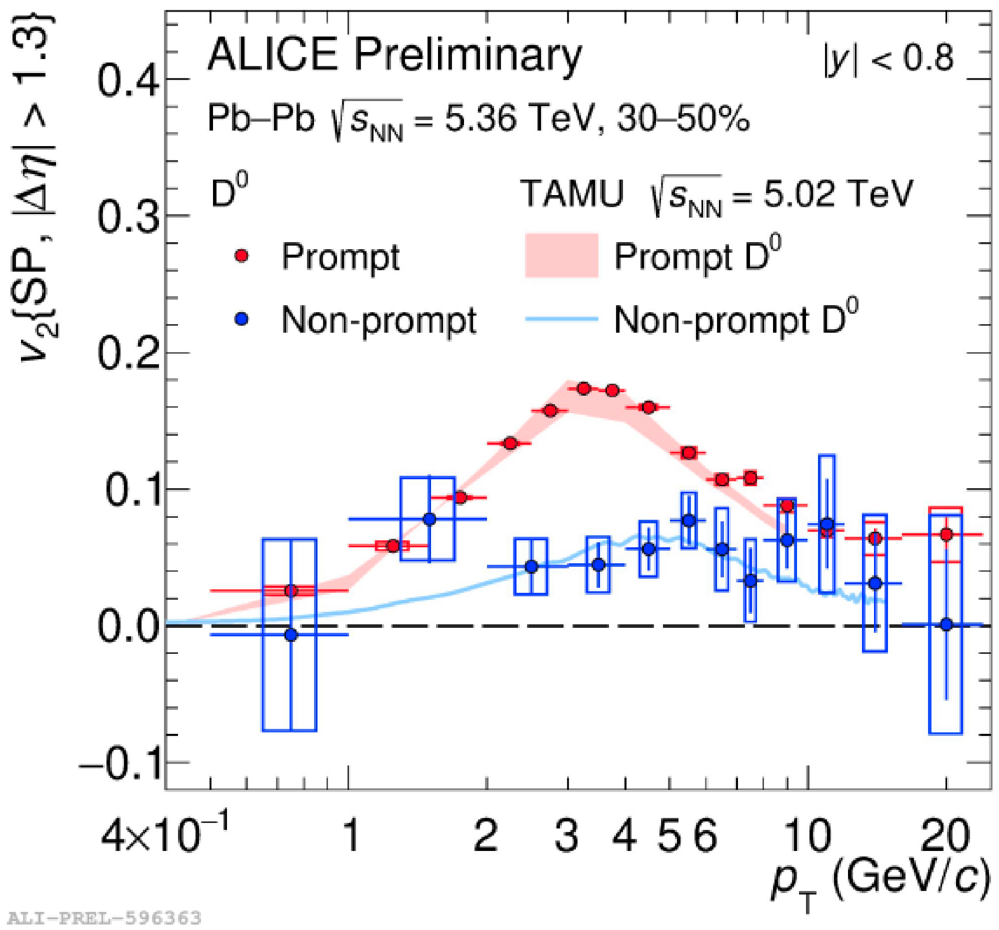
- As volume/system size reduces, B_s/B, Λ_b/B suppressed by a factor 2; Ξ_b/B suppression stronger, two-fold role of baryon + strangeness
- All ratios tend to the corresponding GCE-SHM values at large system size

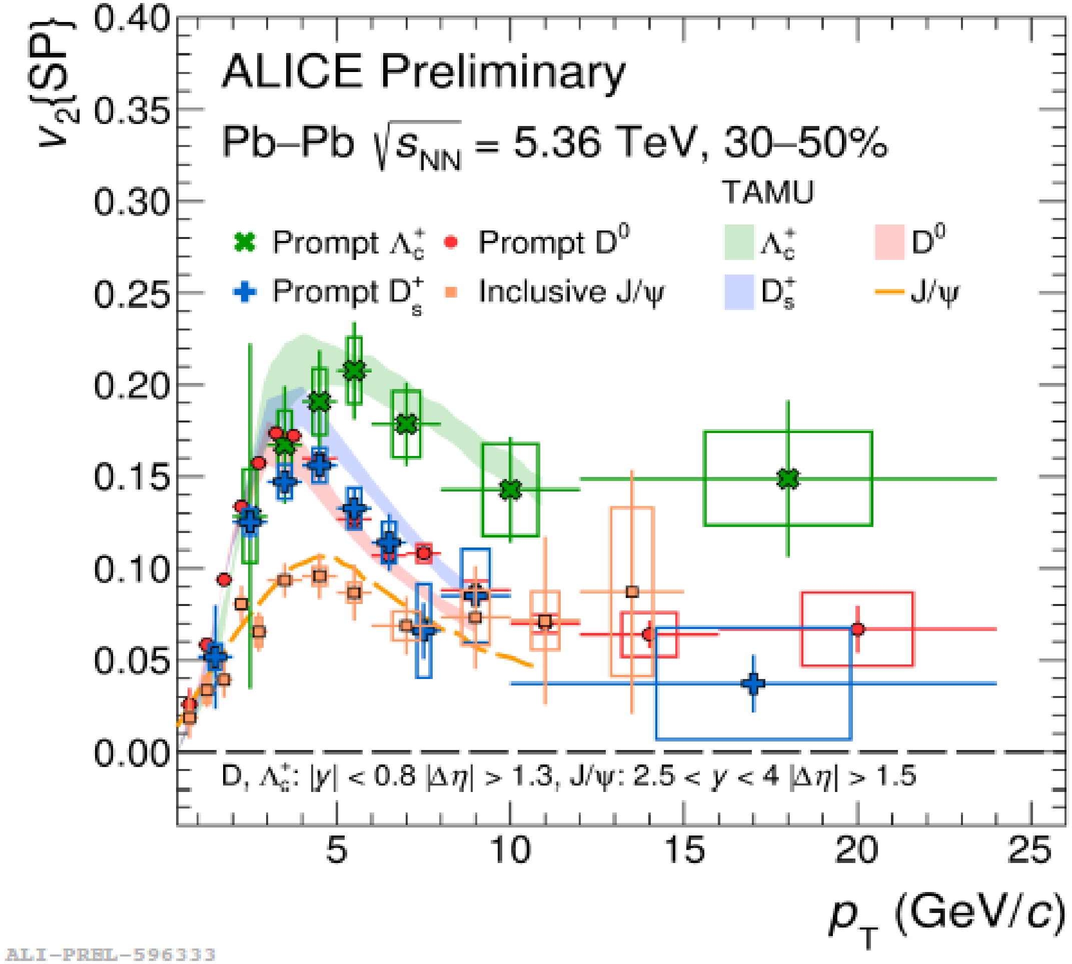
Λ_c/D & Λ_c R_{AA} , ALICE PLB 839 (2023) 137796





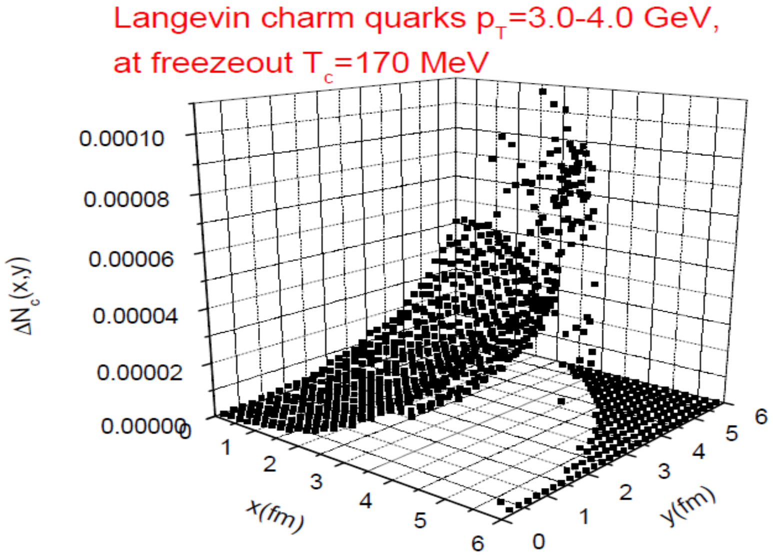
HF elliptic flows, ALICE highlights @ QM2025

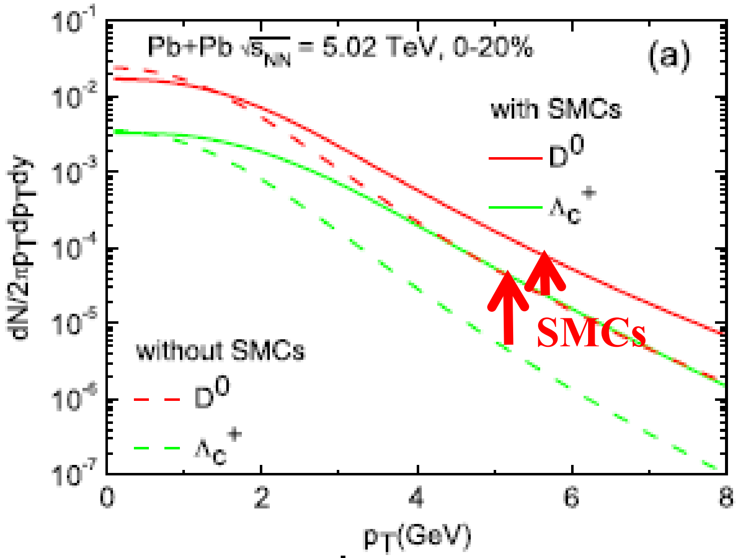




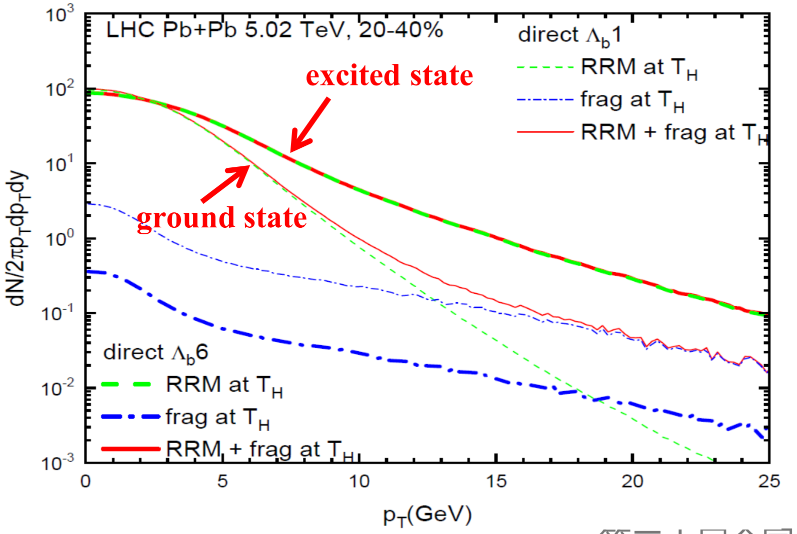
Recombination: space-momentum correlations

- Inhomogeneous distribution: SMCs ➔ recombination beyond momentum space



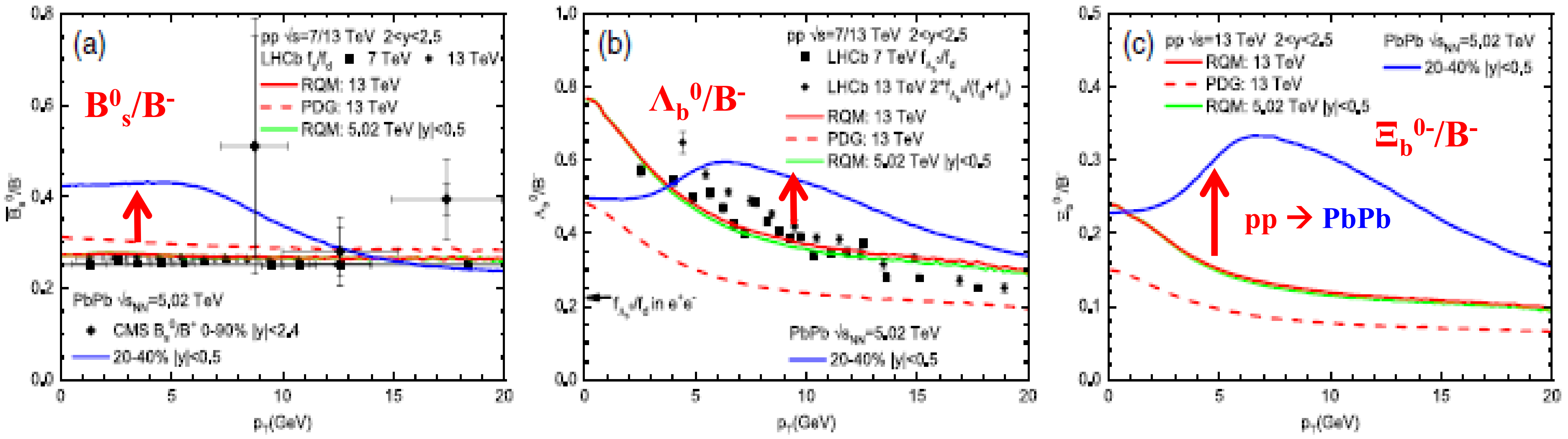


- Left-over b-quarks: fragmentation in the same manner as in pp



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

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

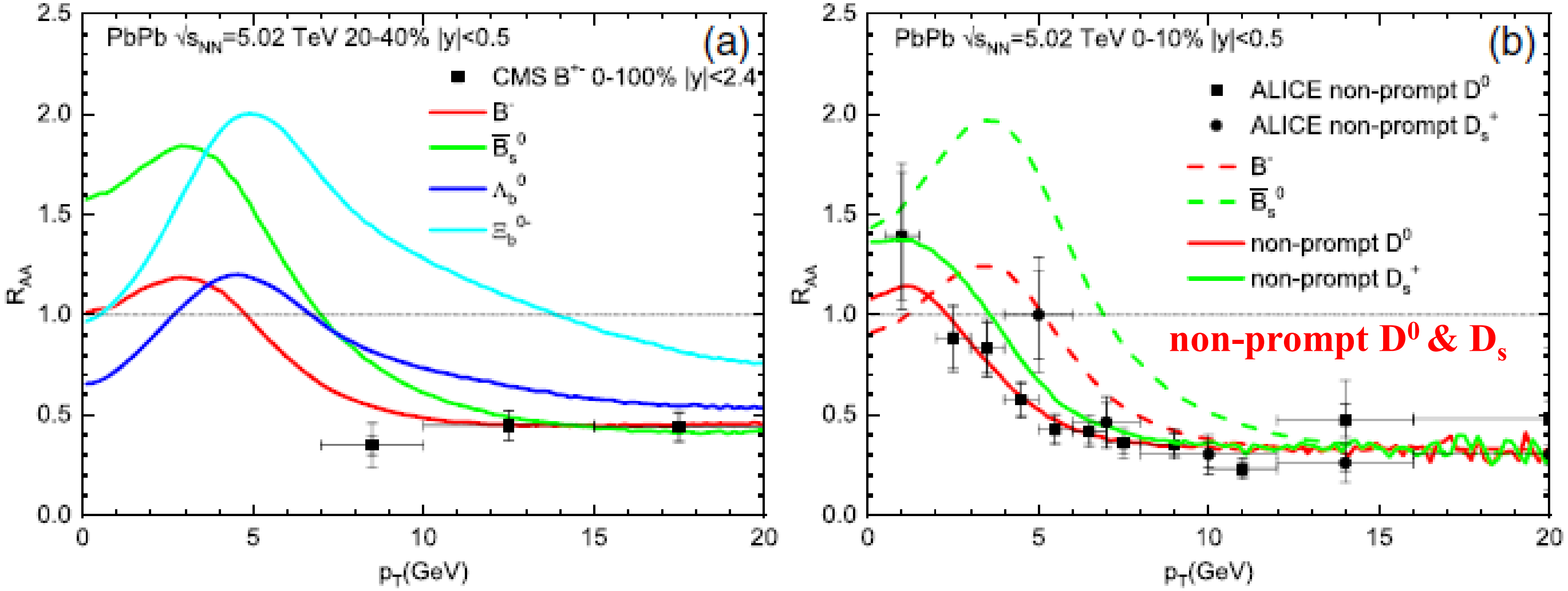
b-hadron nuclear modification factors

- 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%

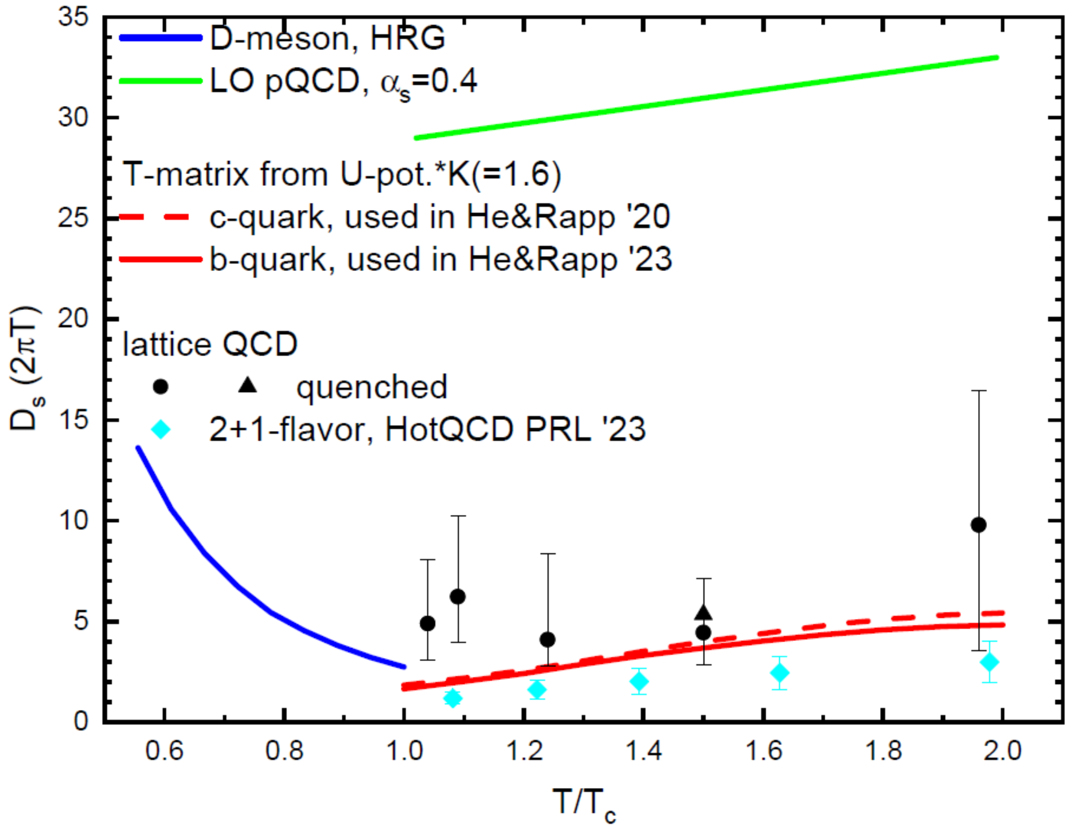
→ pp reference from SHM



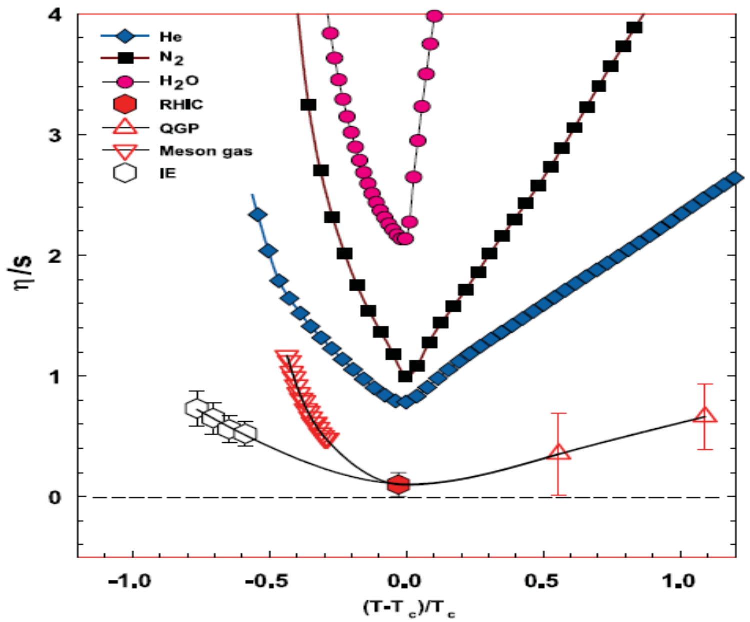
- B_s: b-quark coupled to equilibrated strangeness via recombination
  Λ_b: 3-body baryon recombination, RRM with SMCs
  Ξ_b: combining two-fold role of being baryon + containing a s-quark
- Non-prompt D^0 & Ds: weak decays of all b-hadrons via PYTHIA8

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