Production & Hadronization of Heavy-Flavor Hadrons

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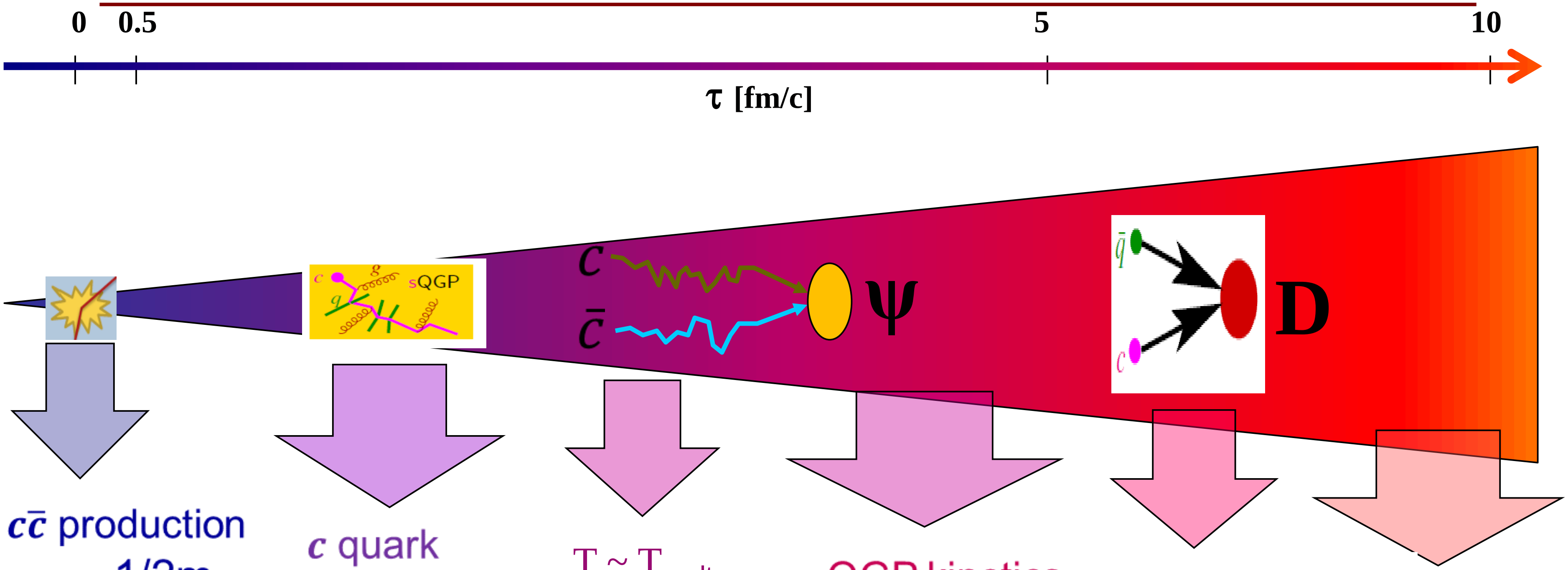
Heavy flavor transport as probes of QGP



$c\bar{c}$ 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 ~ T$_{melt}$
onset of
quarkonium
regeneration

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

T ~ T$_c$
hadronization:
c+q → D
c+q+q → Λ_c

hadronic
diffusion

Outline & disclaimer

Part I: charm-hadron production in pp

- Λ_c/D^0 : data vs model
- Σ_c/D^0 & Ξ_c/D^0

Part II: charm-hadron production in AA

- diffusion coefficient & hadronization
- D-meson R_{AA} & v_2: extracting $\mathcal{D}_s(2\pi T)$
- Λ_c/D^0: in-medium hadrochemistry

Part III: quarkonium production in AA

- HQ potential: remnants of confining force
- J/ψ v_2 puzzle
- open quantum approach to Υ states

***Disclaimer**: selection of topics, no high p_T HF jets*

Part I: Charm-hadron production in pp

- pQCD factorization & fragmentation
- Λ_c/D^0 enhancement vs hadronization models
- Σ_c & Ξ_c production

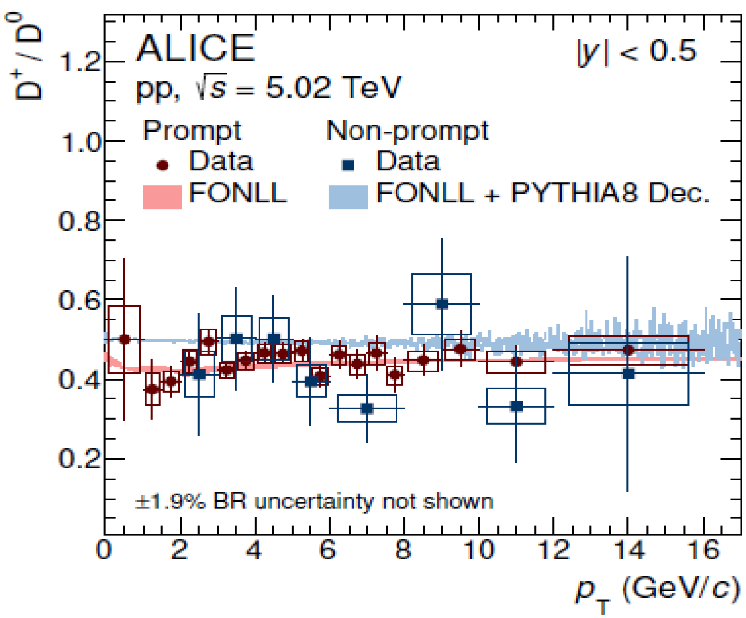
pQCD factorization & fragmentation

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

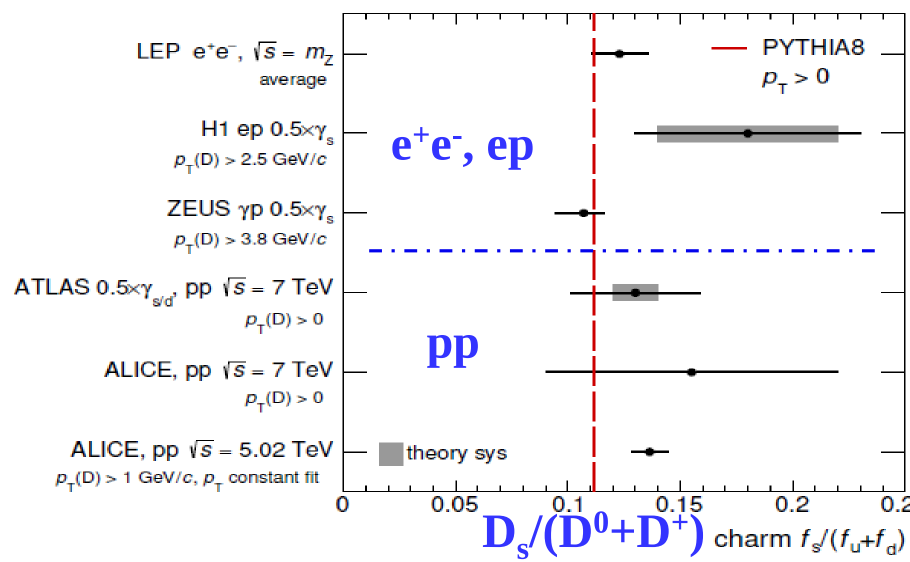
Parton distribution functions (PDFs)	Hard scattering cross section (pQCD)	Fragmentation function (hadronization)

→ **from e^+e^-, universal?**

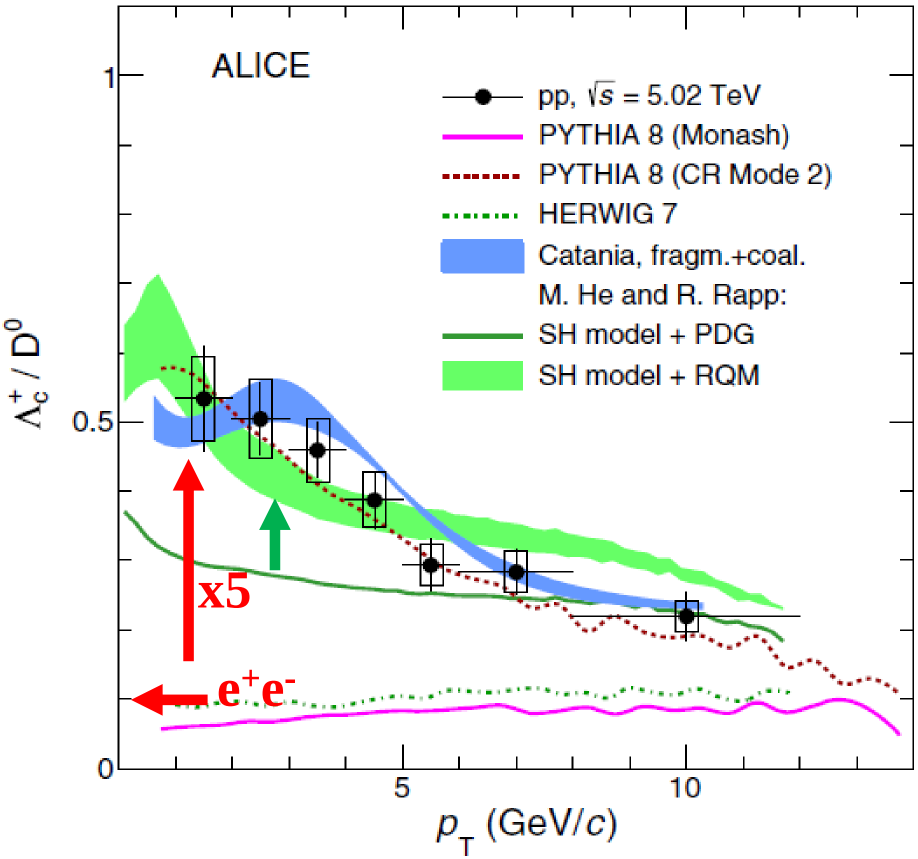
❖ phenomenological FF: assumed universal & constrained by e^+e^-



charm-meson ratios in pp reproduced

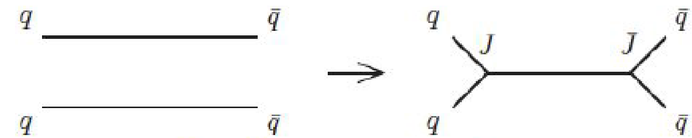


Λ_c^+/D^0 @ 5 TeV pp collisions



ALICE, PRL 127, 202301(2021)
ALICE, PRC 104, 054905(2021)

- ❖ PYTHIA8: Color-reconnection with junctions frag. into baryons



Bierlich et al. ’15

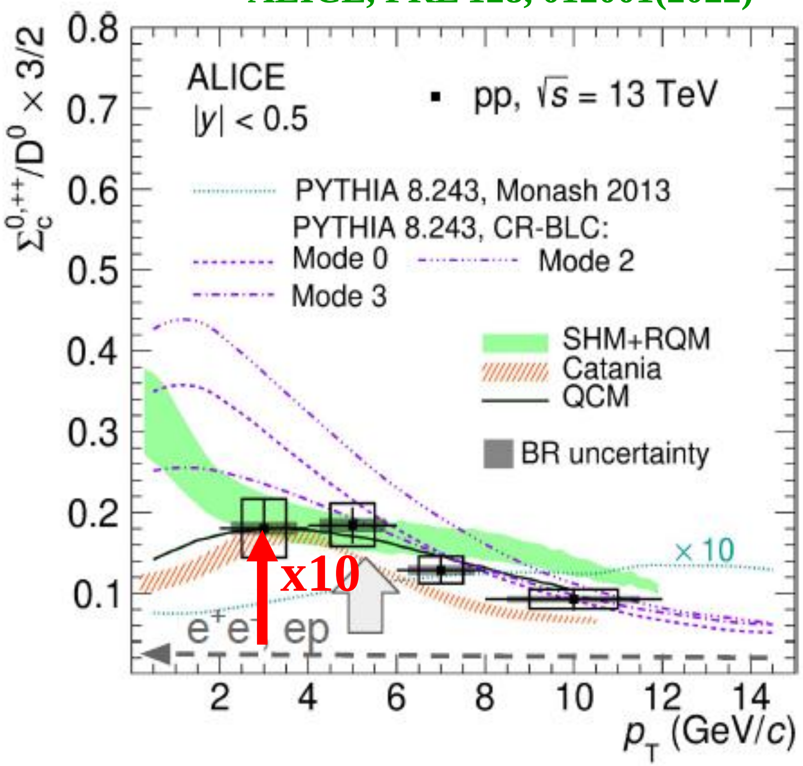
- ❖ Catania: c-q(-q) coalescence in a small QGP fireball Minissale et al. ’21

- ❖ Statistical hadronization in q-rich environment (unlike e^+e^-)
  - augmented by “missing” charm-baryons assuming *relative* chemical equilibrium

MH & Rapp ’19

Σ_c/D^0 & Ξ_c/D^0

ALICE, PRL 128, 012001(2022)



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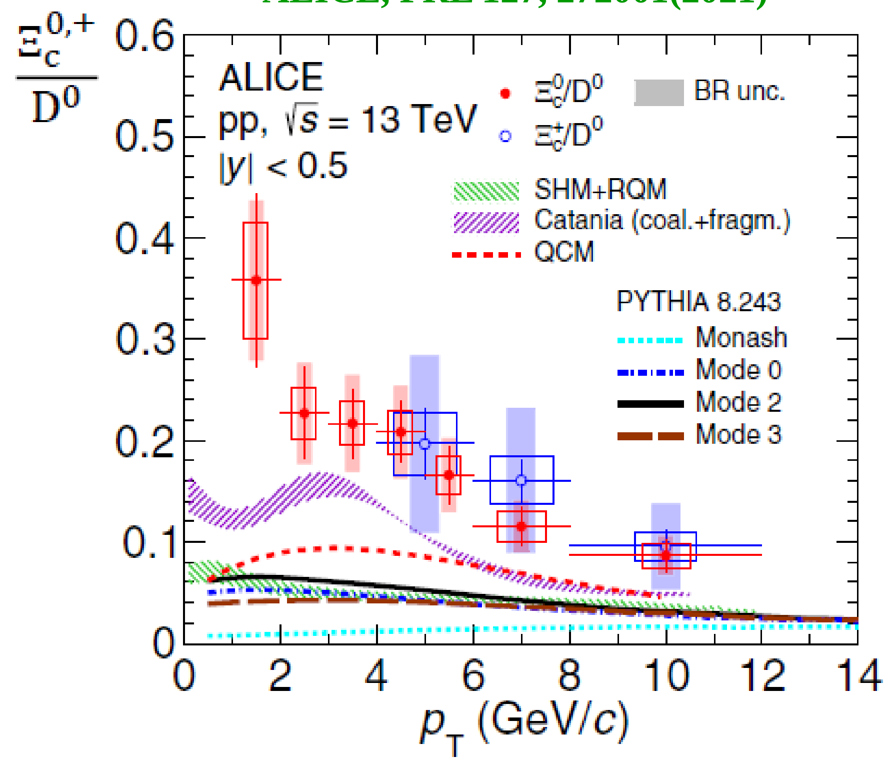
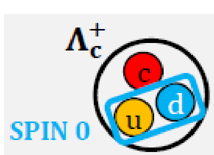
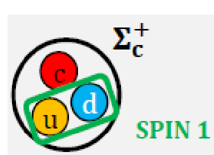


- ❖ Σ_c/D^0 x10 enhanced despite more massive spin-1 diquark



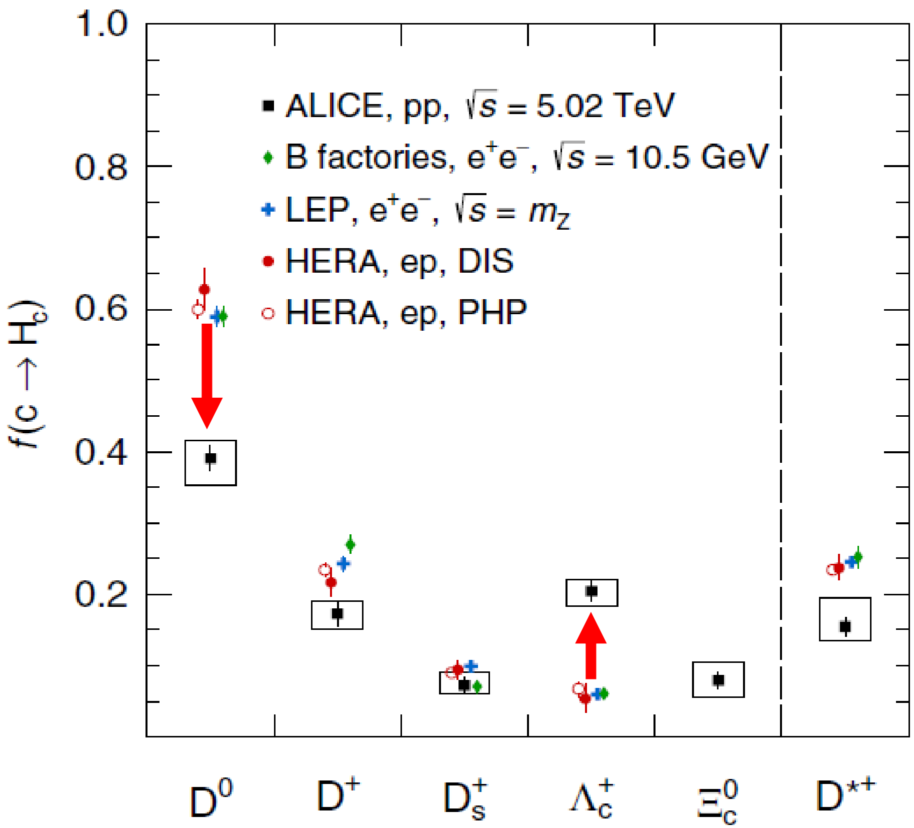


- ❖ Ξ_c/D^0 ratio underestimated by all models

Take-aways from Part I

❖ charm quark fragmentation is non-universal from e^+e^- to pp

ALICE, PRD 105, L011103 (2022)



- $c \rightarrow \Lambda_c$ much enhanced vs $c \rightarrow D^0$ reduced

- full charm-hadrons measured $d\sigma^{c\bar{c}}/dy \sim 1.16\ \mu b$ at mid-y

➔ significant impact on charmonia production

Part II: Charm-hadron production in AA

- Microscopic interactions & diffusion coefficient
- Hadronization: Coalescence, Resonance Reco., SHMc
- D-meson R_{AA} & v_2: Diffusion coefficient
- Charm hadro-chemistry: Λ_c/D^0

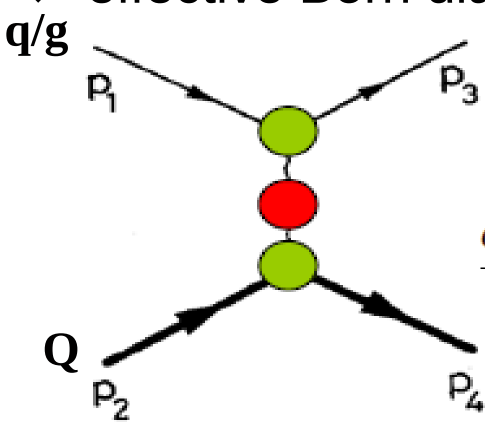
Transport coefficient: pQCD vs T-matrix

❖ HQ Brownian diffusion via Fokker-Planck

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

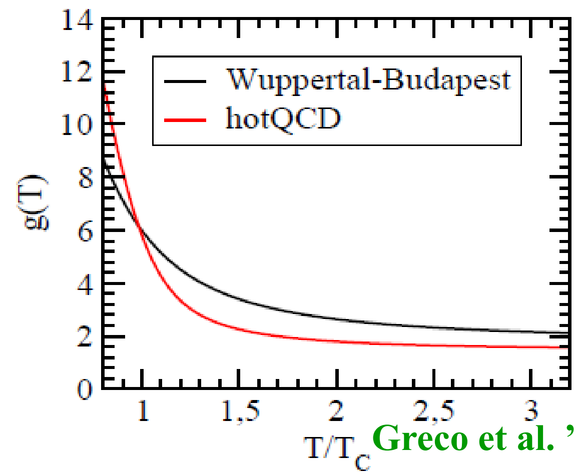
$\gamma = A \sim \int |T_{Qj}|^2 (1-\cos\theta) f^j$

❖ effective Born diagram w/ large α_s



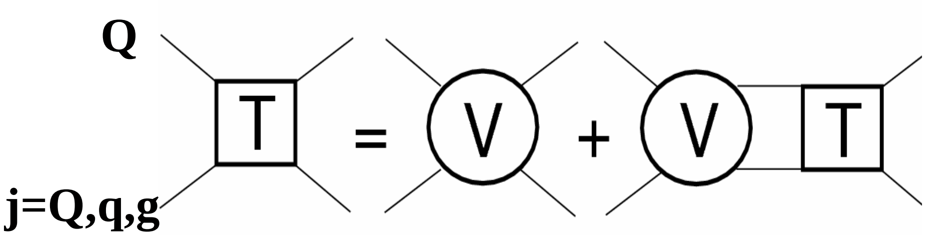
Moore & Teney '05
Nantes, Catania, LBT, PHSD …

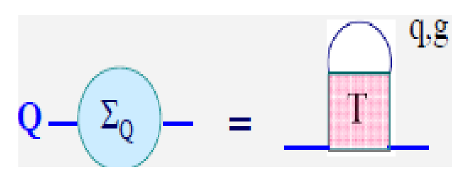
$$\frac{\alpha}{t} \rightarrow \frac{\alpha}{t-\mu^2} \rightarrow \frac{\alpha eff}{t-\kappa m_D^2(T)}$$



Greco et al. '11

❖ T-matrix: coupled two- and one-body integral equations

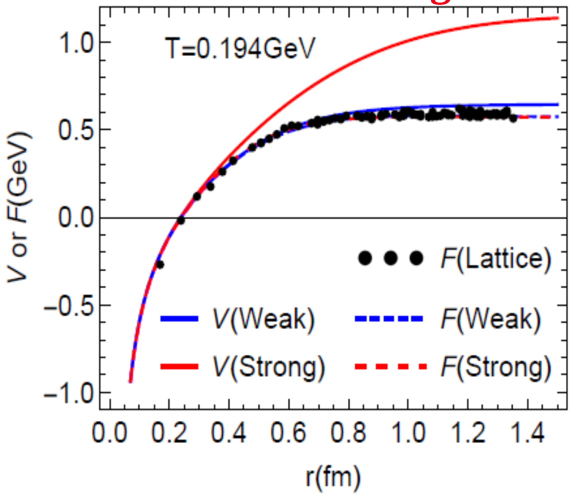




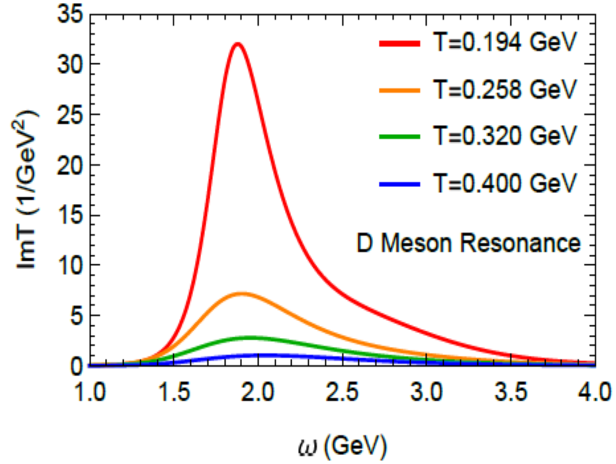
TAMU '05-'19

T-matrix approach: Spectral + Transport Properties

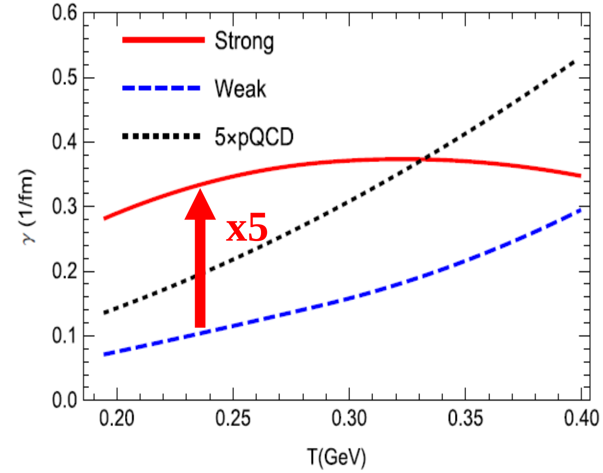
Remnant confining force



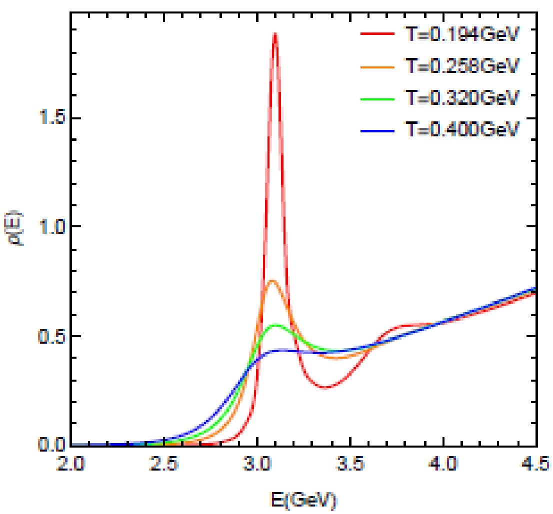
Resonances form near T_c

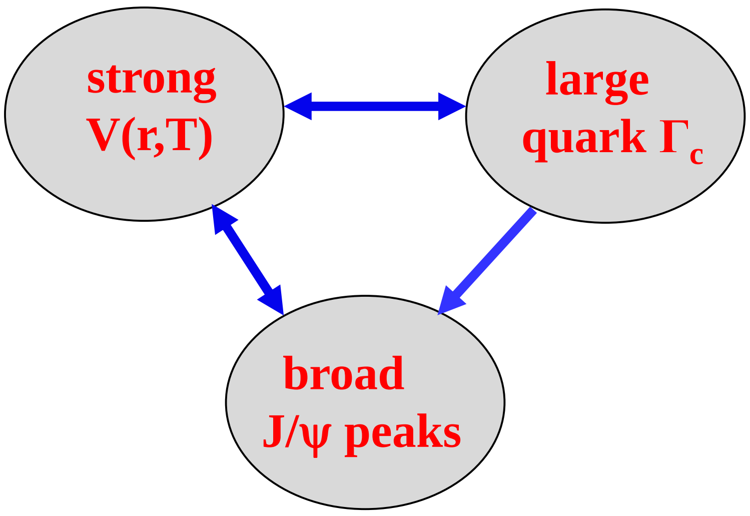


Accelerates thermalization

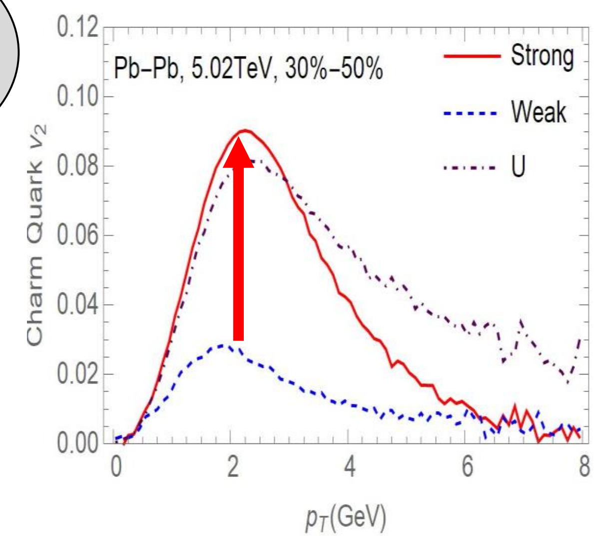


J/ψ survives in QGP





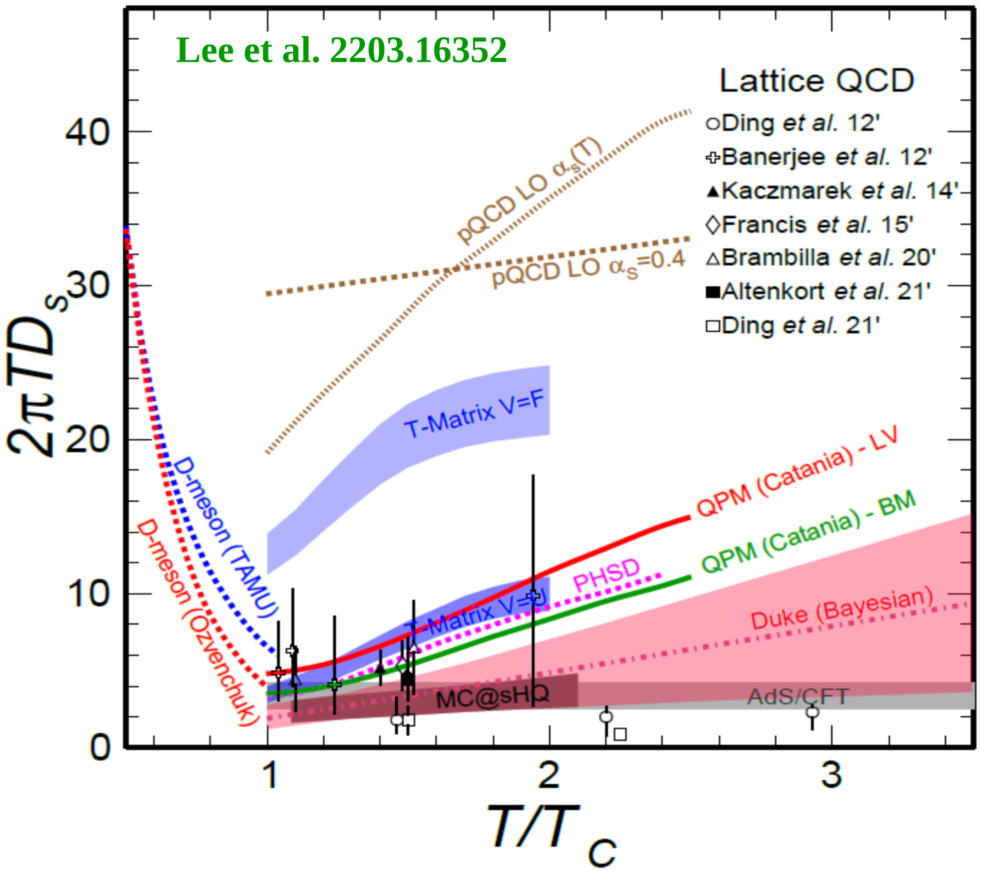
Coupling strength ↔ HQ v_2



S.Y.F Liu et al ’18, ’19

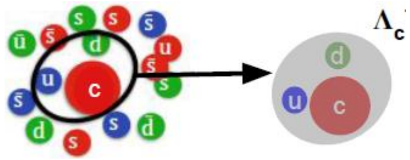
Transport coefficient: $\mathcal{D}_s(2\pi T)$

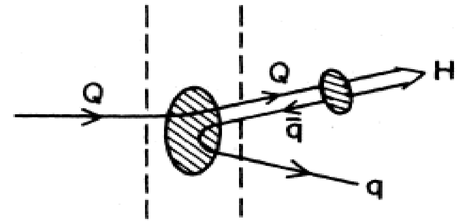
- HQ spatial diffusion coefficient: $\mathcal{D}_s = T/m_Q A(p=0) = T/m_Q \gamma$



- models & lattice $\mathcal{D}_s(2\pi T)$~2-4 near T_c, x10 smaller than pQCD
- maximum coupling strength near T_c, remnant of confining force?

HQ hadronization in QGP

Coalescence: 

vs. Fragmentation 

❖ Instantaneous coalescence models (ICM)

$$f_h(\boldsymbol{p}'_h) = \int \Big[\prod_i d\boldsymbol{p}_i f_i(\boldsymbol{p}_i)\Big] W(\{\boldsymbol{p}_i\})\delta(\boldsymbol{p}'_h - \sum_i \boldsymbol{p}_i)$$

Fries et al., Greco et al., Voloshin ’03

- static Wigner distribution w/ hadron radius
- equilibrium limit challenging at low p_T
- improvement: c-q(-q) form excited cluster + decay

Greco et al. ’04, Oh et al.’09, Plumari et al.’18, Cao et al. ’16, ’20, Katz ’20, Li+Liao ’20

Beraudo et al. ’15, ’22 Cao et al.’20

❖ Statistical hadronization with charm (SHMc) **Andronic et al. ’21**

- *thermalized* c-quarks hadronize at T_c

$$\frac{\mathrm{d}N(h^i_{oc,\alpha})}{\mathrm{d}y} = g_c^\alpha\, V\, n_i^{\mathrm{th}} \frac{I_\alpha(N_c^{\mathrm{tot}})}{I_0(N_c^{\mathrm{tot}})}$$ $\propto g_c^\alpha \leftarrow d\sigma^{c\bar{c}}/dy$

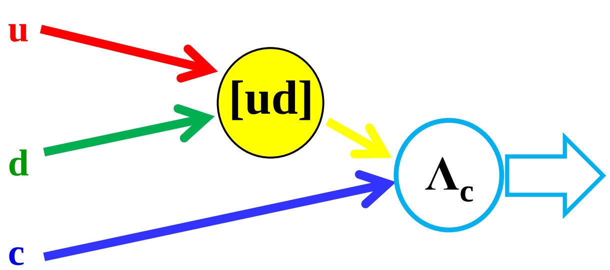
- p_T-spectrum by hydrodynamic blast wave at T_c

HQ hadronization II

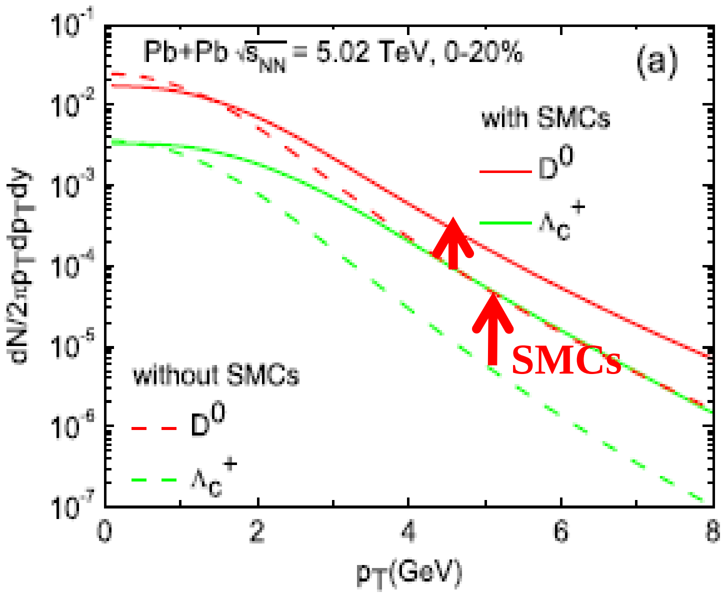
❖ Resonance recombination model (RRM) **Ravagli et al.'07, MH et al.'12**

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

- $\sigma_M(s)$ resonant cross section: energy conservation & equilibrium limit
- 3-body RRM & space-momentum correlations (SMCs)

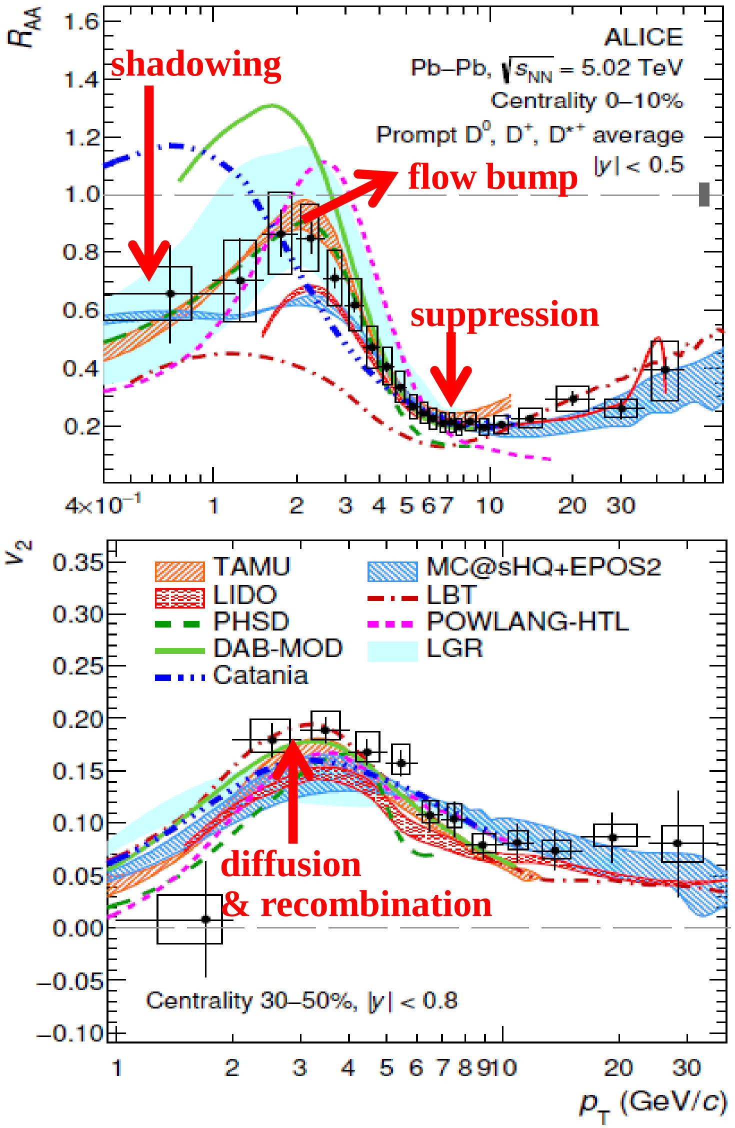


MH & Rapp '20



harder p_T-spectra for Λ_c

D-meson R_{AA} & v_2: extracting $\mathcal{D}_s(2\pi T)$

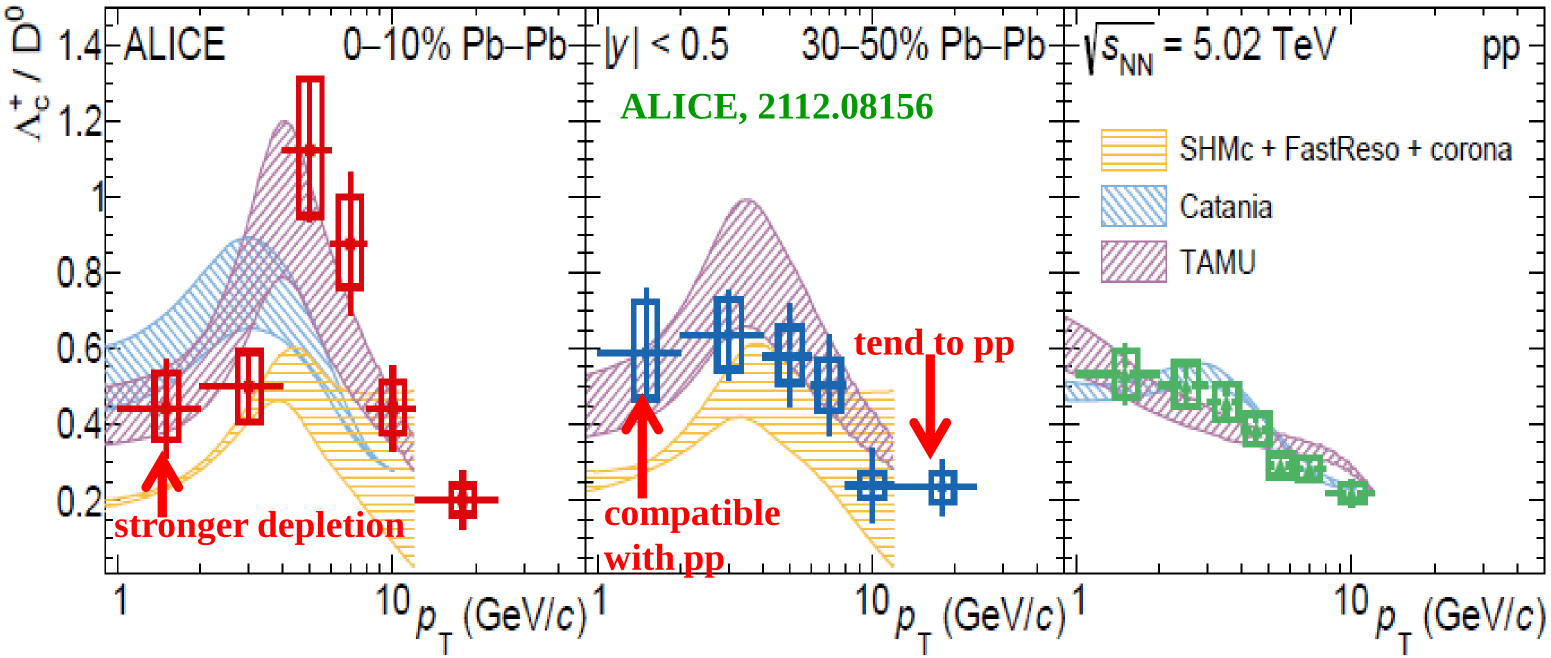


ALICE, JHEP01(2022)174; PLB 813(2021)136054

Model	χ^2/ndf R_{AA}	χ^2/ndf v_2
Catania [6, 7]	143.8/30	14.0/8
DAB-MOD [9]	234.1/30	9.8/6
LBT [10, 11]	411.8/30	15.8/12
LIDO [13]	46.4/26	62.0/11
LGR [12]	9.2/30	15.5/11
MC@sHQ+EPOS2 [8]	56.6/30	5.7/12
PHSD [5]	294.7/30	19.6/11
POWLANG-HTL [3, 4]	468.6/30	13.5/8
TAMU [2]	30.2/30	8.15/9

- models with χ^2/ndf < 5 (2) for R_{AA} (v_2) ➔ $\mathcal{D}_s(2\pi T)$=1.5-4.5 near T_c
- caveat: also affected by hadronization, hydro, hadronic phase

Charm hadro-chemistry: Λ_c/D^0

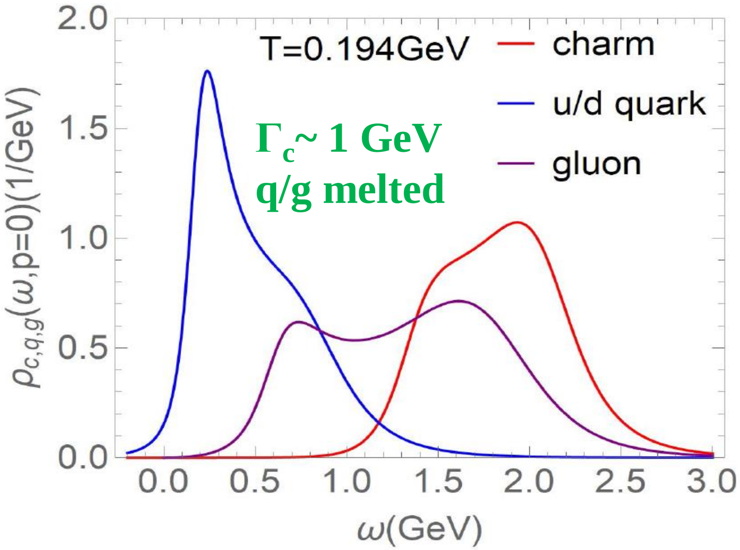


- Catania: instantaneous coalescence + fragmentation **Plumari et al. '18**
- SHMc: hydrodynamic blast wave spectrum on PDG-only baryons + corona pp **Andronic et al. '21**
- TAMU: RQM charm-baryons + RRM w/ SMCs
  integrated ratio compatible with pp **MH & Rapp '20**

Take-aways from Part II

❖ Heavy-quark diffusion

- $\mathcal{D}_s(2\pi T)$=1.5-4.5 near T_c ➔ scattering rate Γ_{coll} ~3/$\mathcal{D}_s$ ~1 GeV > $M_{q,g}$
  ➔ thermal partons melt, Brownian markers survive
- strong coupling via remnants of confining force



❖ Heavy-quark hadronization

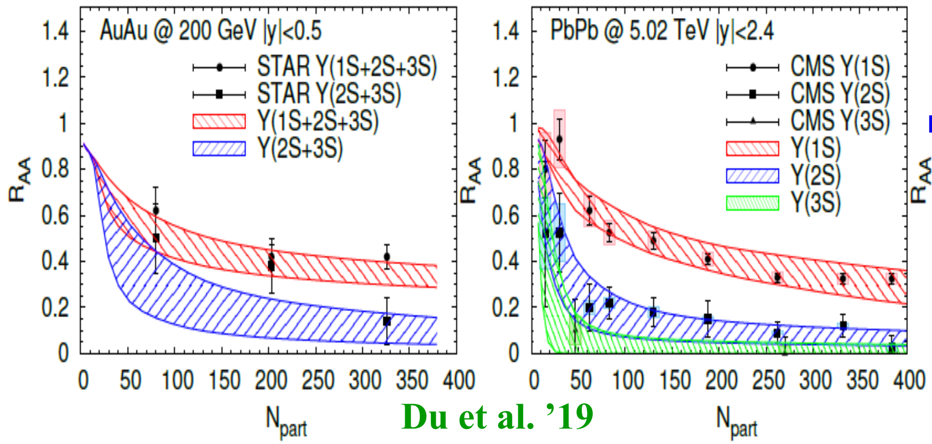
- recombination → p_T-dependent charm hadro-chemistry
- p_T-integrated Λ_c/D^0 compatible with pp → kinematic redistribution in p_T in AA

Part III: Heavy quarkonium production in AA

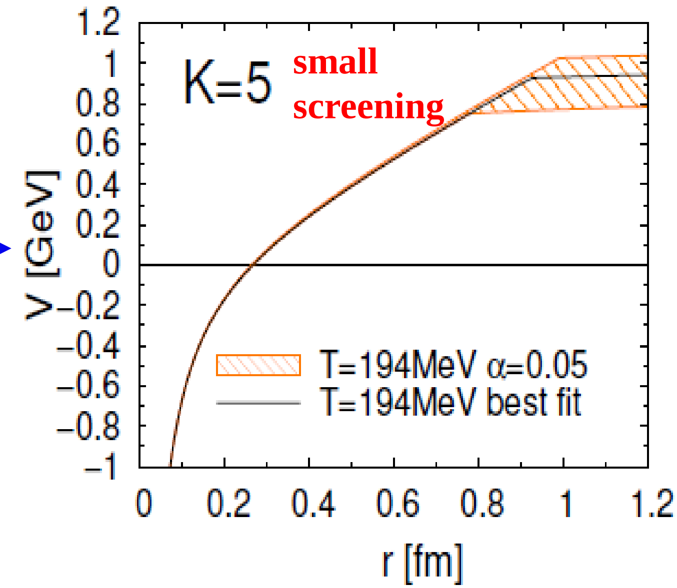
- Strong HQ potential
- Semi-classical approach: suppression vs regeneration
- J/ψ v_2 puzzle
- Open quantum system approach to Y states

Extraction of HQ potential

- statistical transport analysis of Y data with trial input potential



Du et al. '19

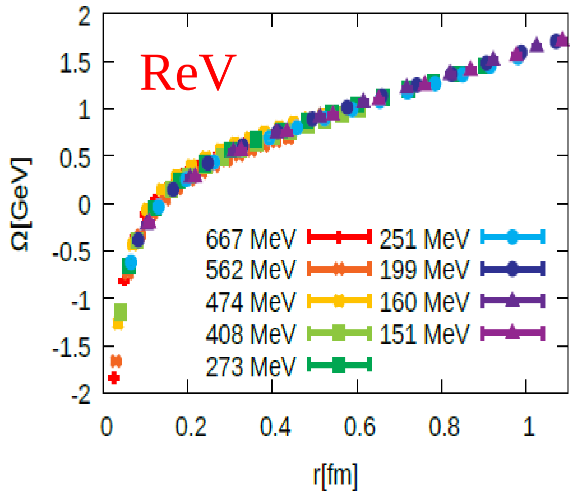


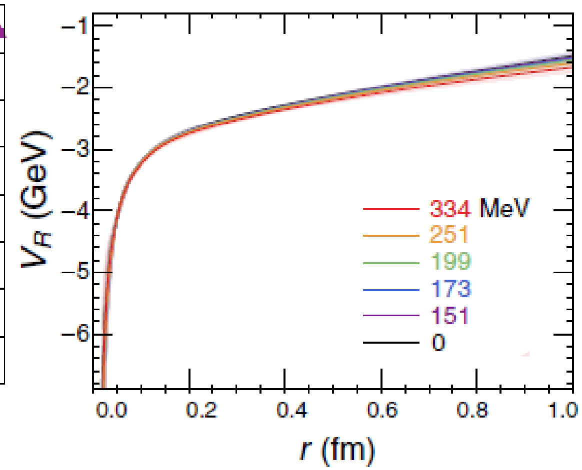
- lattice QCD extraction of static potential

Bala et al., 2110.11659

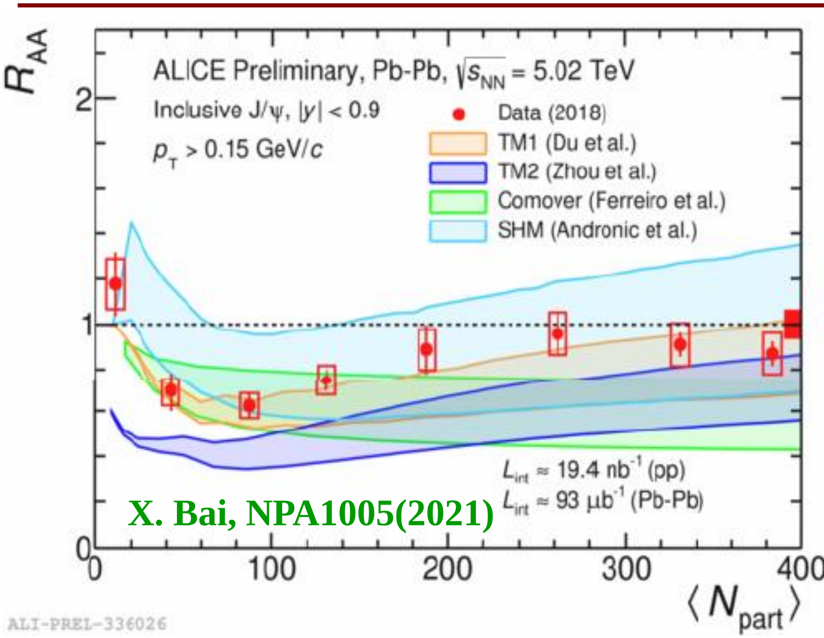
- neural network approach

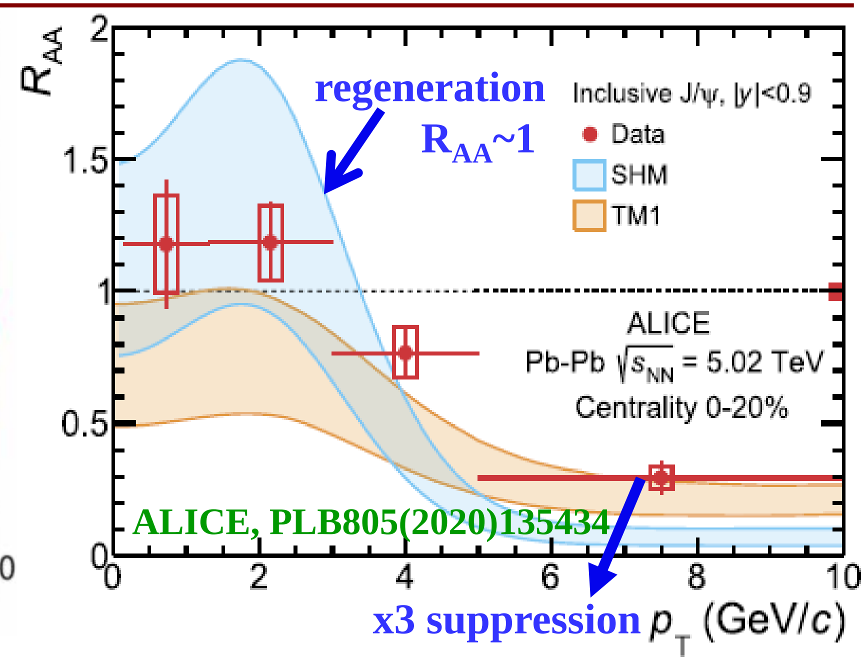
Shi et al. '22





J/ψ: suppression vs regeneration





- semi-classical transport **Du et al. '15, Zhou et al. '14, Ferreiro et al. '14**

$$\frac{dN_\Psi(\tau(T))}{d\tau} = -\Gamma_\Psi(T)[N_\Psi(\tau(T)) - N_\Psi^{eq}(T)]$$

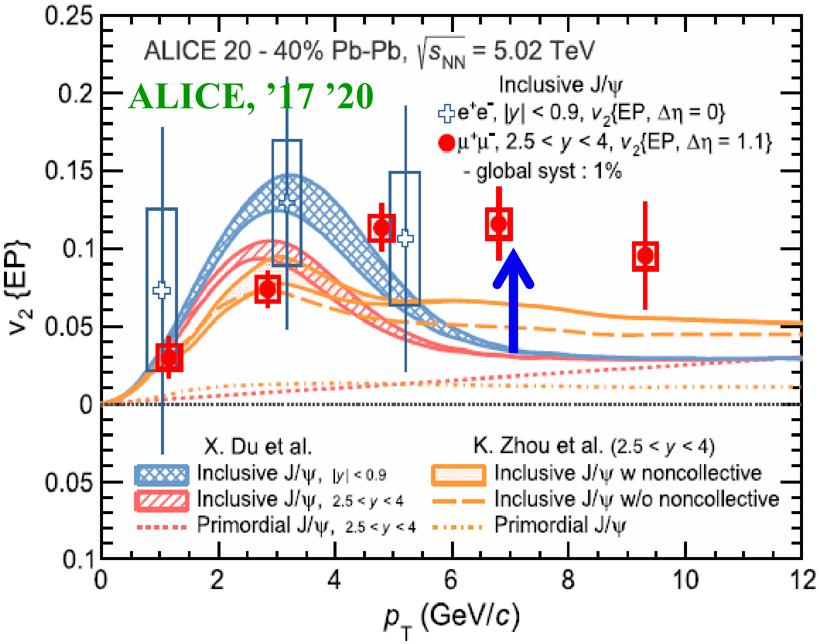
reaction rate Γ_ψ

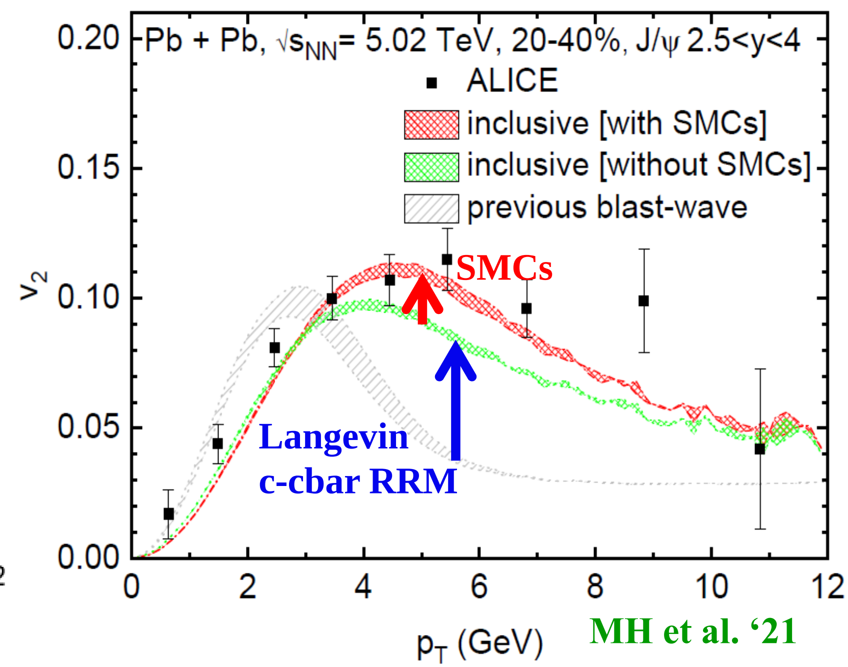
regeneration toward equilibrium

- SHMc: hydrodynamic blastwave spectrum + pp corona **Andronic et al. '19**

$$\frac{dN(h_{hc}^j)}{dy} = g_c^2\, V\, n_j^{th} \;\propto g_c^2 \leftarrow d\sigma^{ccbar}/dy$$

J/ψ "v_2 puzzle"





- regeneration via RRM

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

transported c & $\bar{c}$ quark spectra
constrained by D-meson observables

- off-equilibrium $c/\bar{c}$ spectra + space-momentum correlations (SMCs)
  ➔ regeneration up to p_T~8 GeV ➔ v_2 enhanced

Open quantum system approach to Υ states

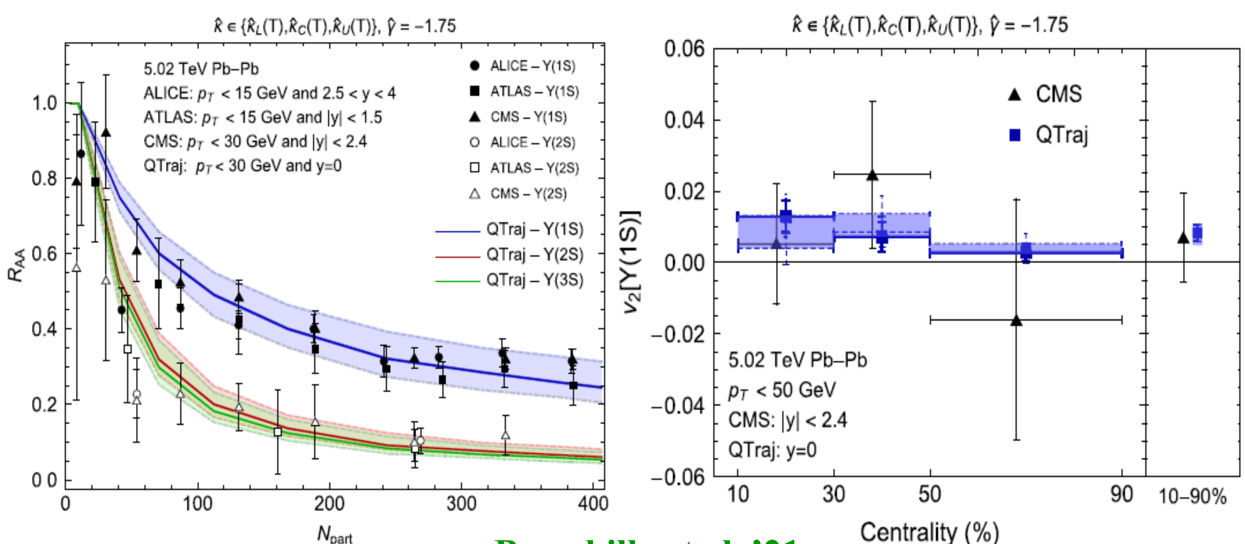
❖ OQS + pNRQCD ➔ Lindblad equation

Brambilla et al. '17-21, Yao et al., '21, Blaizot '18
Akamatsu '21, Rothkopf '20, Gossiaux et al. '21

$$\frac{d\rho(t)}{dt} = -i[H,\rho(t)] + \sum_n \left(C_n \rho(t) C_n^\dagger - \frac{1}{2}\{C_n^\dagger C_n, \rho(t)\} \right)$$

$M \gtrsim 1/a_0 \gg \pi T \sim m_D \gg E.$

- quantum transition between different states included, lacking in semi-classical
- regeneration currently limited to diagonal $b\bar{b}$
- Coulomb potential + transport coefficient κ encoded in C_n



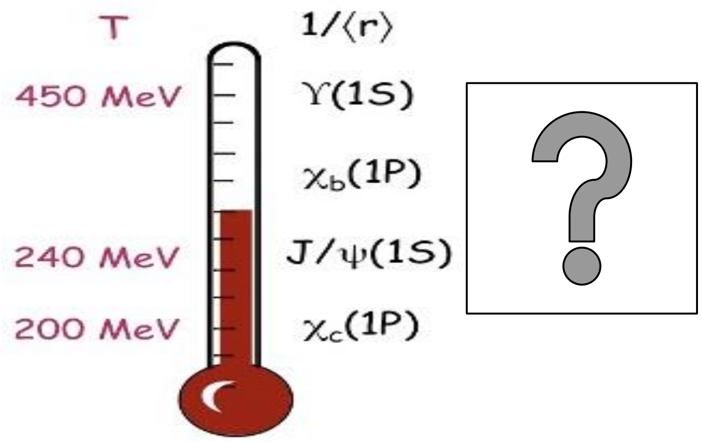
Brambilla et al. '21

- Υ(1S) in-medium width $\Gamma_{\Upsilon(1S)} = 3a_0^2\kappa \sim$ 50 MeV at T~250 MeV
- values & results comparable to semi-classical approach
  Strickland et al. '15

Take-aways from Part III

- strong HQ potential with little screening close to T_c
  quarkonia melt through large reaction rates (↔ small HQ $\mathcal{D}_s$)

  - probe of in-medium force via in-medium “spectroscopy”, not “thermometer”



- Quantitative connections open- ↔ hidden-charm transport

  - transported c/cbar distributions & $d\sigma^{c\bar{c}}/dy$

Summary & outlook

- HFs: excellent probes of sQGP structure, transport properties, in-medium force & hadronization

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

  } ⟺ strong V(r,T)

  ➔ connection between open- & hidden-HF, e.g. via J/ψ regeneration

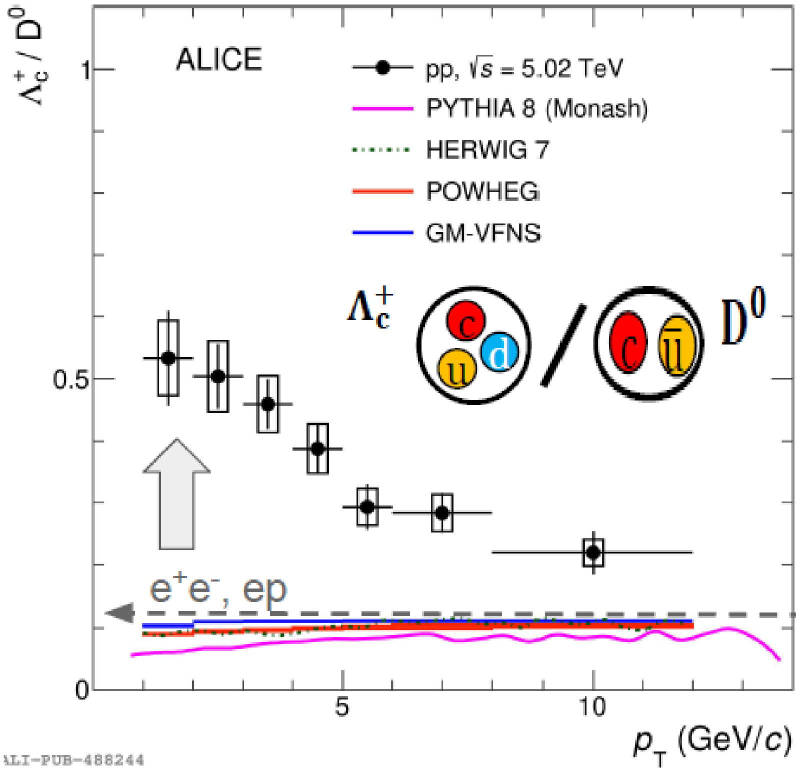
- outlook

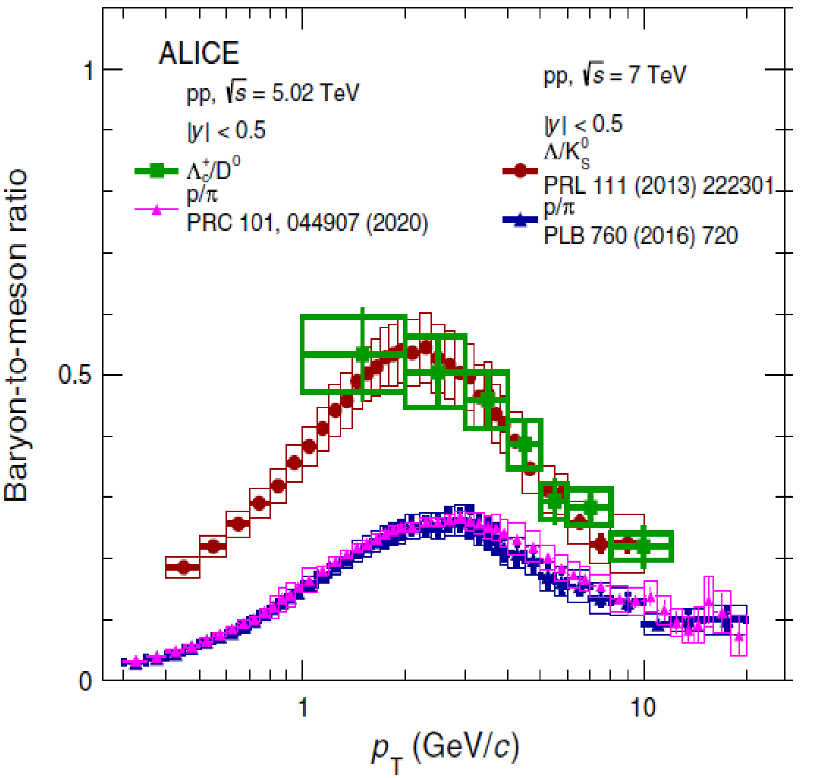
  - Ξ_c production in pp
  - p-dependence of $\mathcal{D}_s$:
    nonperturabtive diffusion → perturbative radiative e-loss?
  - more …

Back-up

The following are back-up pages

Λ_c^+/D^0 enhancement surprise

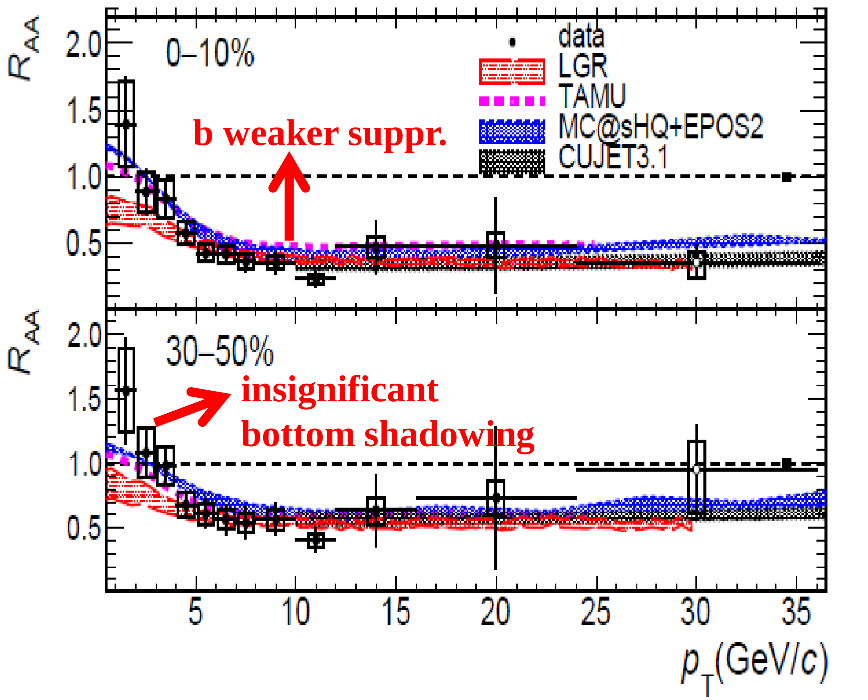




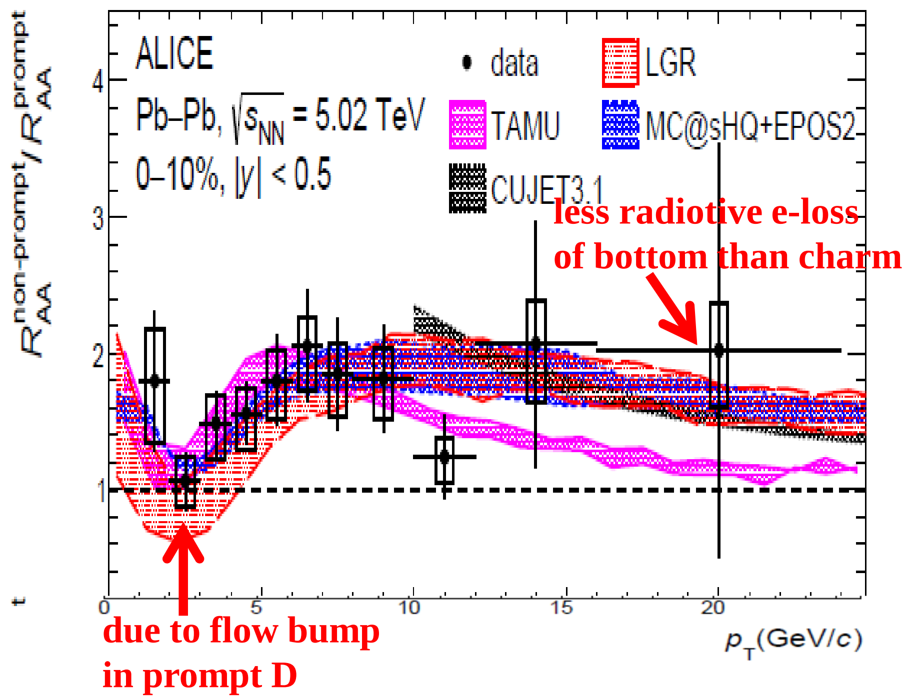
- ❖ a factor ~5 enhancement w.r.t. e^+e^- at low p_T, much underestimated by FFs tuned to e^+e^-
- ❖ decreasing toward high p_T, trend similar to Λ/K and p/pi

Flavor dependence: charm vs bottom

nonprompt D (← B) R_{AA} , ALICE:2202.00815



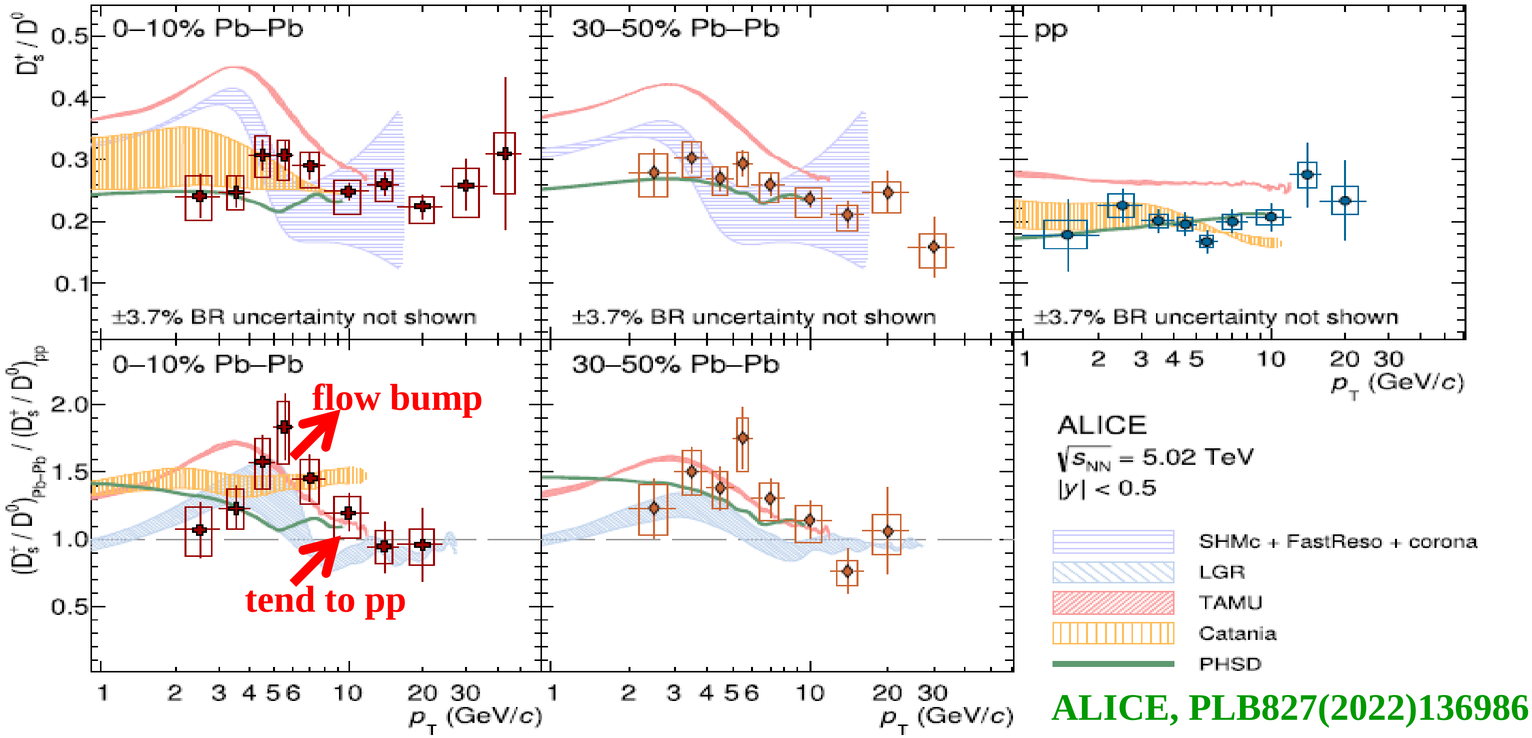
nonprompt-to-prompt D-meson R_{AA} ratio



❖ x3 mass: b-quark longer thermalization time at low p_T than charm
less flow added to b from recombination with u/d/s

❖ high p_T>15 GeV: b-quark less radiative e-loss← stronger "dead cone"

Charm hadro-chemistry: D_s/D^0



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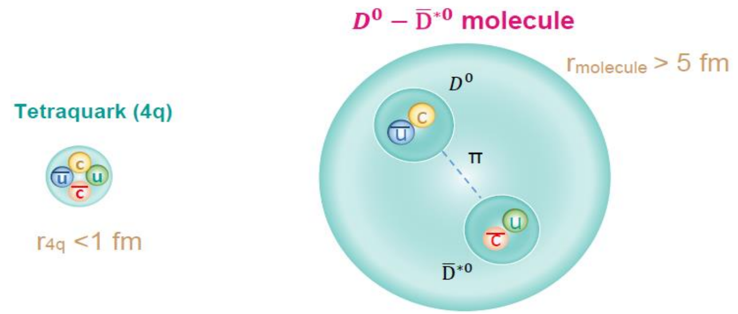
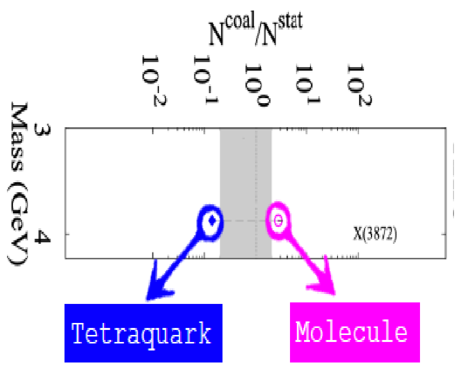
- low p_T: enhancement due to charm recombination in a strangeness-equilibrated QGP reproduced by Cantania & PHSD; overestimated by TAMU in both pp and PbPb
- high p_T: tending to pp value as fragmentation takes over
- flow bump due to recombination with flowing s-quark heavier than u/d, predicted by TAMU (RRM w/ SMCs) & SHMc (hydro blastwave spectrum)

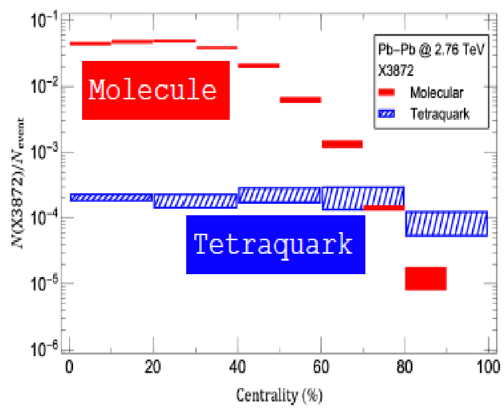
X(3872) production in HIC

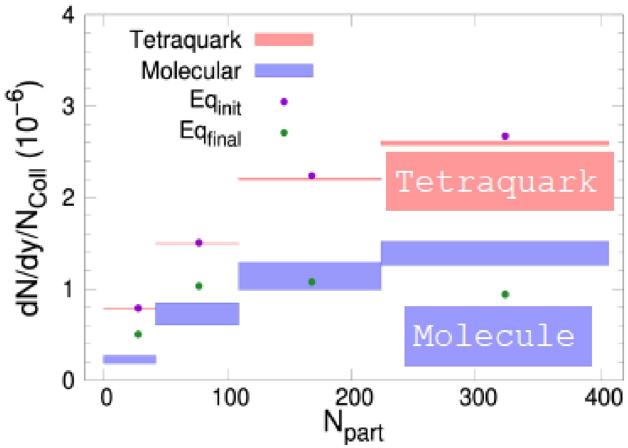
❖ inner structure: compact tetraquark vs loosely bound molecule



coalescence model	coalescence within AMPT	transport model
Cho et al. '11	zhang et al. '21	Wu et al. '21







- $N_{molecule} > N_{tetraquark}$ by x10 or 100, yet no account of hadron phase reactions πX <-->DD*
  ➔to be better constrained
- $N_{tetraquark} > N_{molecule}$ by x2, molecule regenerated in late hadronic phase, tetraquark chem. freezeout at T_c

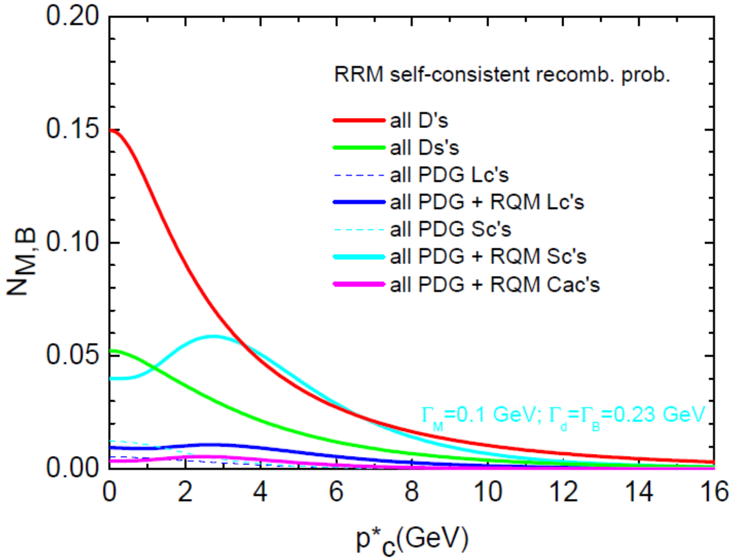
Charm quark recombination probability

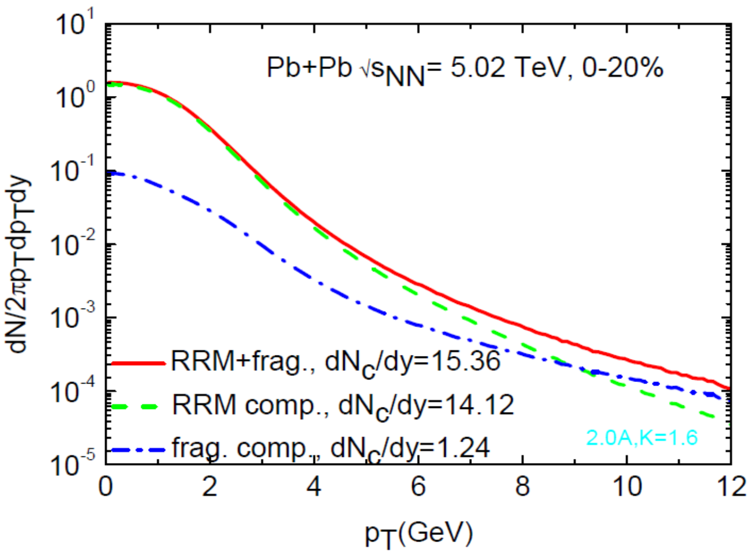
- No. of mesons/baryons formed from a single c-quark of rest frame p_c*

$$N_M(p_c^*) = \int \frac{d^3\vec{p}_1^*}{(2\pi)^3} g_q e^{-E(\vec{p}_1^*)/T_{pc}} \frac{E_M(\vec{p}^*)}{m_M \Gamma_M} \sigma(s) v_{\rm rel},$$

$$N_B(p_c^*) = \int \frac{d^3p_1 d^3p_2}{(2\pi)^6} g_1 e^{-E(\vec{p}_1)/T_c} g_2 e^{-E(\vec{p}_2)/T_c} \frac{E_d(\vec{p}_{12})}{m_d\Gamma_d} \sigma(s_{12}) v_{\rm rel}^{12}(\vec{p}_1,\vec{p}_2) \frac{E_B(\vec{p})}{m_B\Gamma_B} \sigma(s_{d3}) v_{rel}^{d3}(\vec{p}_{12},\vec{p}_{30}),$$

- Renormalizing $N_M(p_c^*)$ and $N_B(p_c^*)$ by a common factor ~4 for all charmed mesons/baryons such that $\sum_M P_{{\rm coal},M}(p_c^*=0) + \sum_B P_{{\rm coal},B}(p_c^*=0) = 1$





➔ charm conservation consistently built in, in an (e-by-e) way without spoiling the relative chemical equilibrium realized by RRM

Space-momentum correlations: light-q

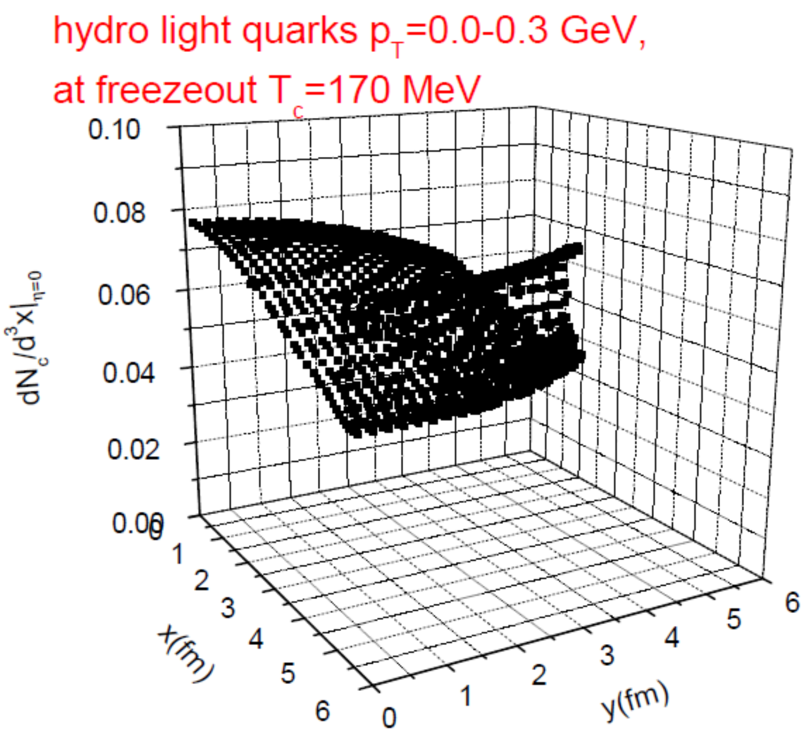
- hydro: a manifestation of SMCs

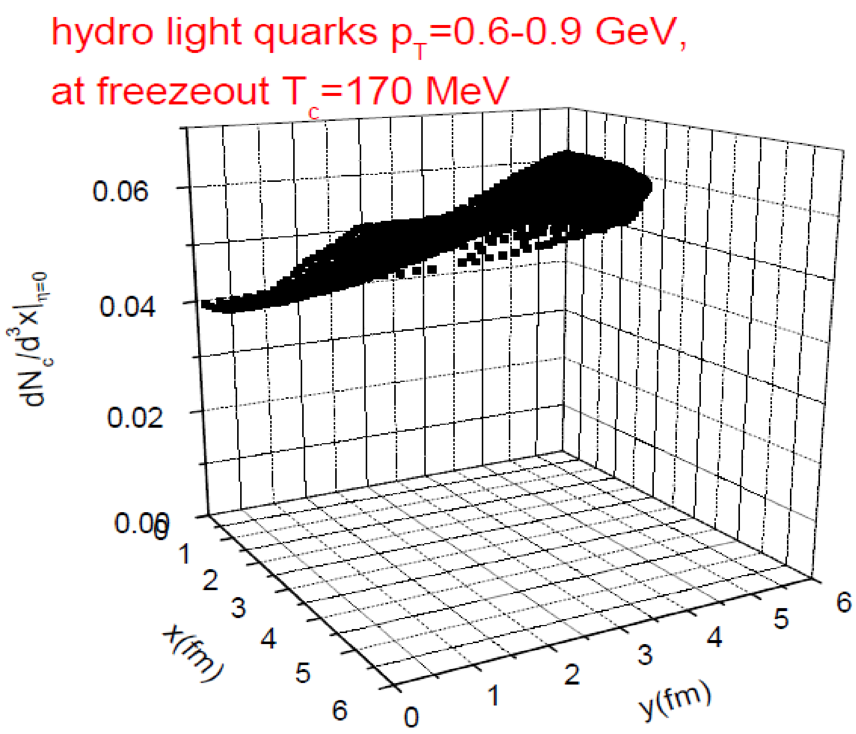
$$f_q^{eq}(\vec{x},\vec{p}) = g_q e^{-p\cdot u(x)/T(x)} = g_q e^{-\gamma_T(x)[m_T\cosh(y-\eta)-\vec{p}_T\cdot\vec{v}_T(x)]/T(x)}$$

longitudinal boost invariance: y- η

transverse SMCs pT▪vT

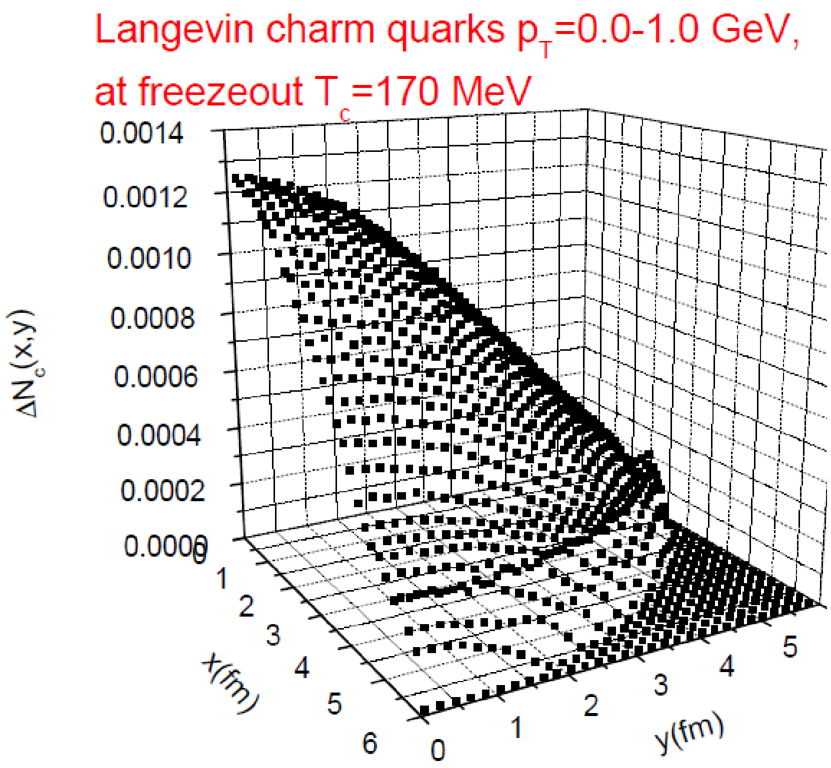
- hydro-q: low (high) p_T more concentrated in center (boundary)

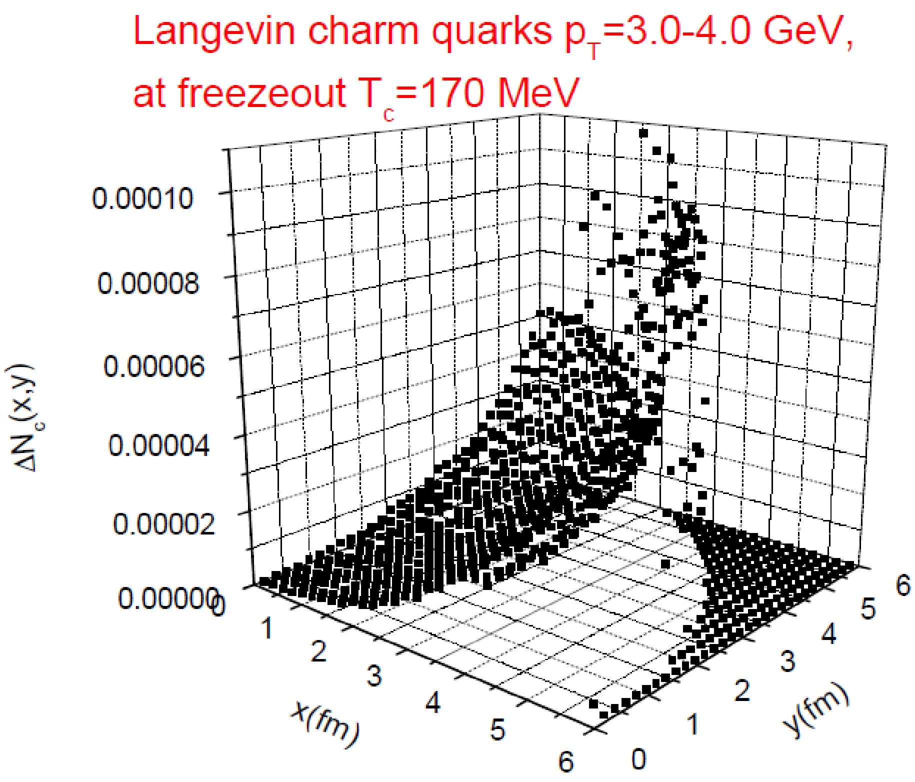




SMCs: Langevin charm quarks

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





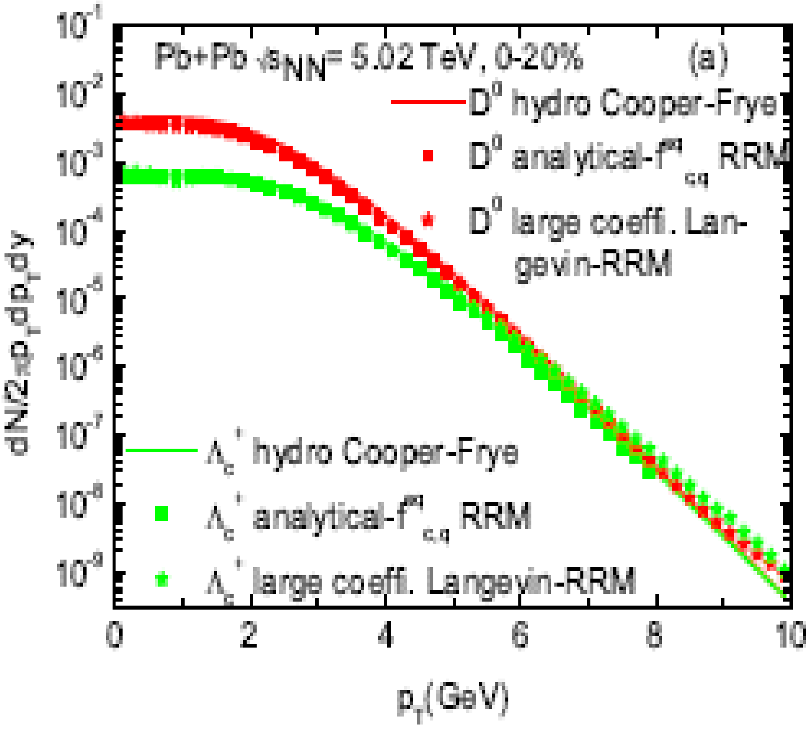
- SMCs usually neglected in ICMs: uniformly distributed independent of p_T

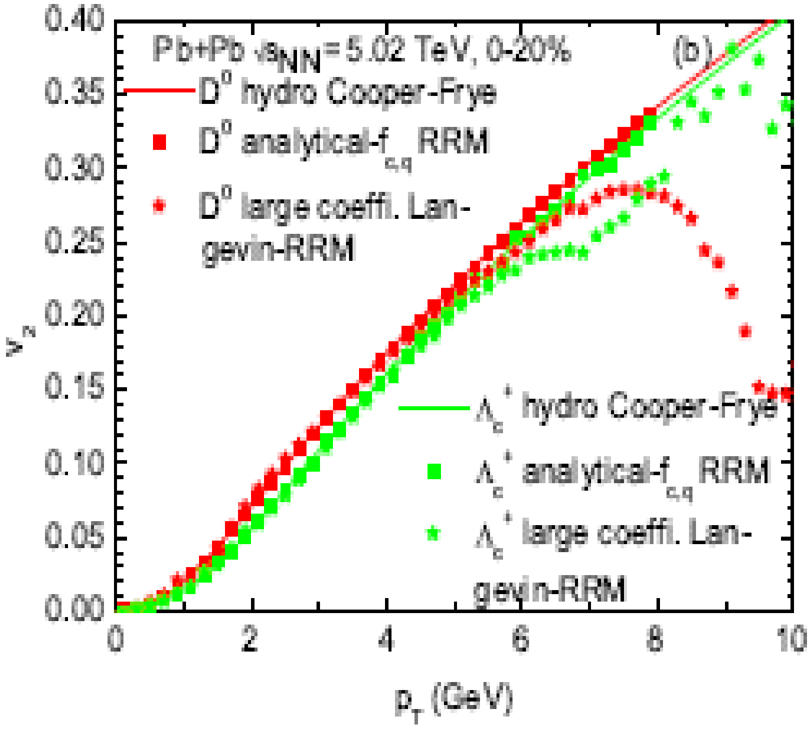
$$f_{c,q}(\vec{x},\vec{p}) = (2\pi)^3 \frac{dN_{c,q}}{d^3\vec{x}d^3\vec{p}} = \frac{(2\pi)^3}{VE(\vec{p})} \frac{dN_{c,q}}{p_T dp_T d\phi_q dy}$$

RRM equilibrium mapping

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

  ➔ kinetic & chemical equil. mapping

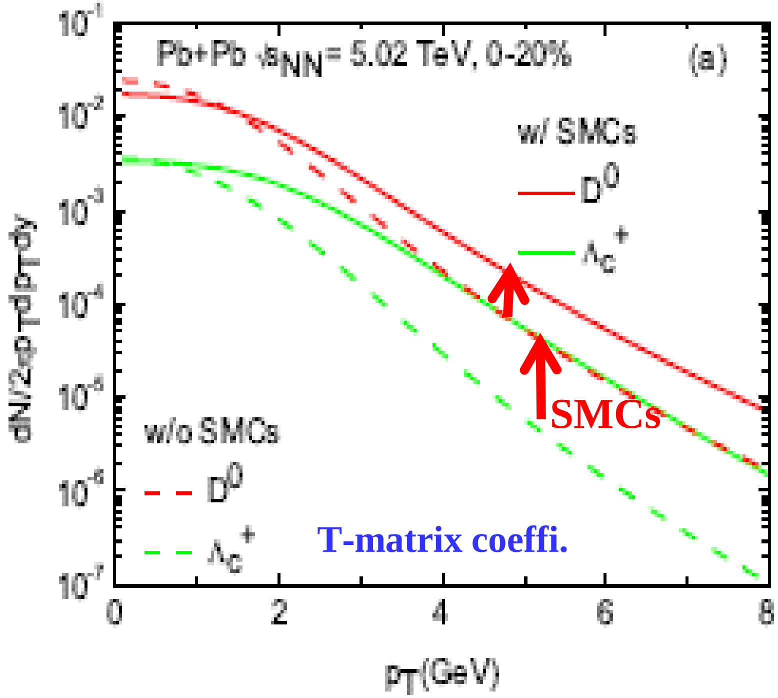


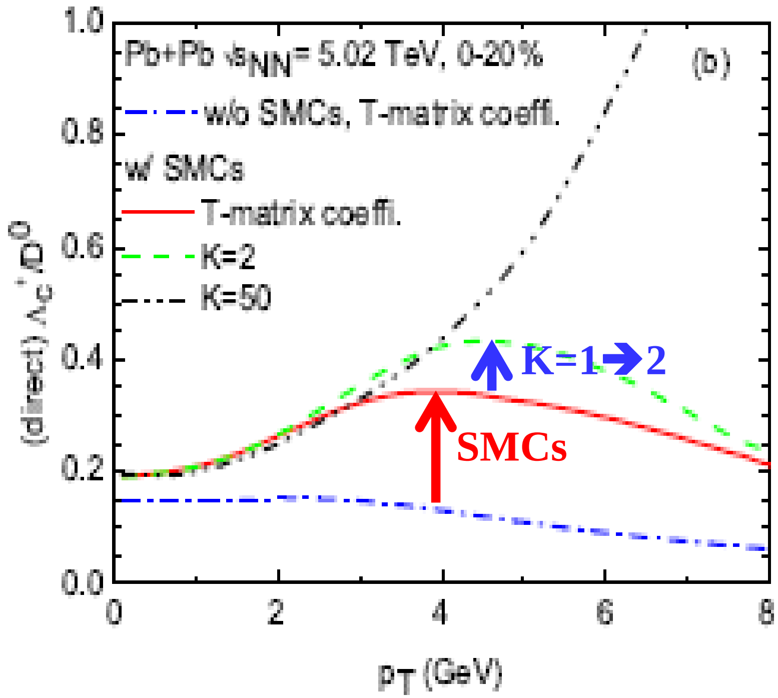


➔ Observables come out as RRM predictions with realistic T-matrix coeffi.

Direct D^0 & Λ_c^+ production via RRM

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

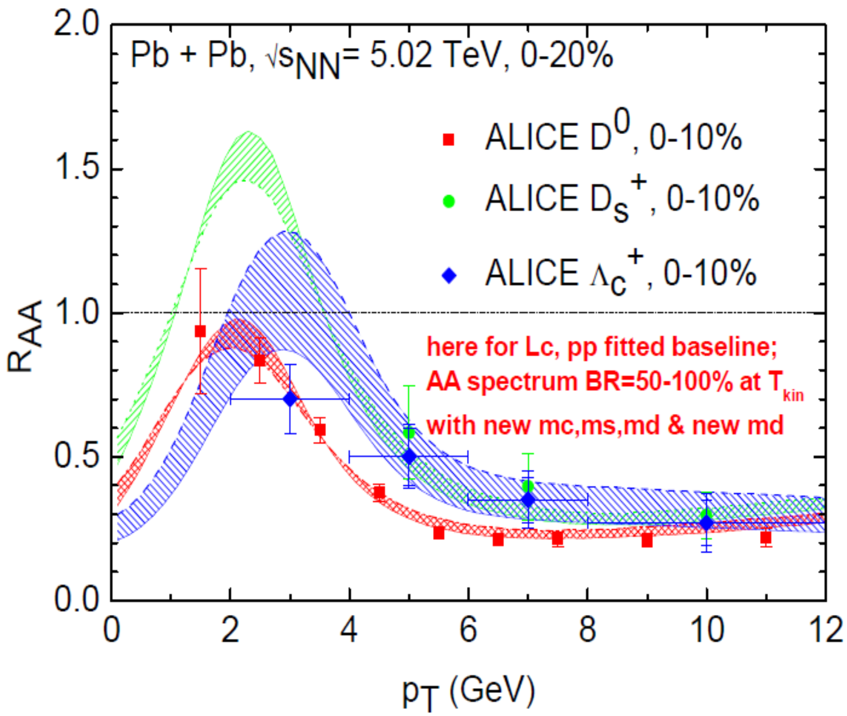


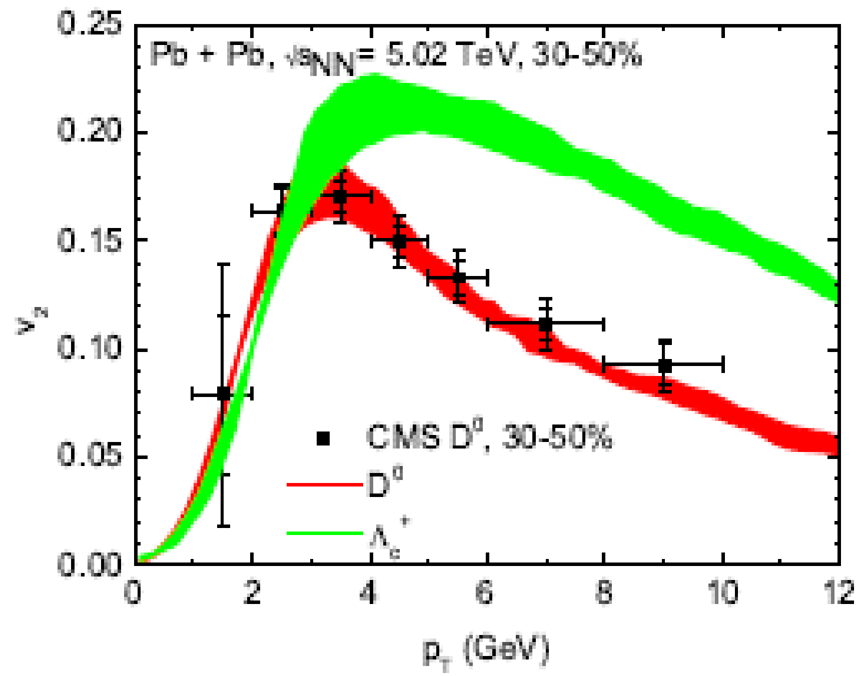


- Fast-moving c-quarks [p_T~ 3-4 GeV] moving to outer part of fireball find higher-density of harder [p_T~ 0.6-0.9 GeV] light quarks for recombination
- An effect entering squared for the recombination production of Λ_c^+ ➔ larger enhancement for Λ_c^+ ➔ Λ_c^+/D^0 ratio enhanced!

D^0, D_s^+ & Λ_c^+ suppression & elliptic flow

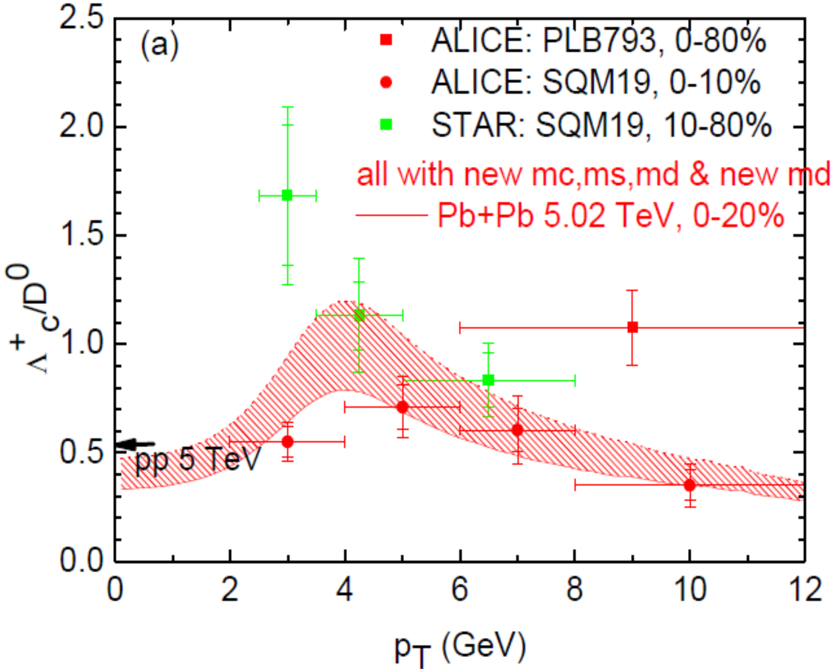
- Final D^0, D_s^+ & Λ_c^+, including feeddowns from all RQM baryons

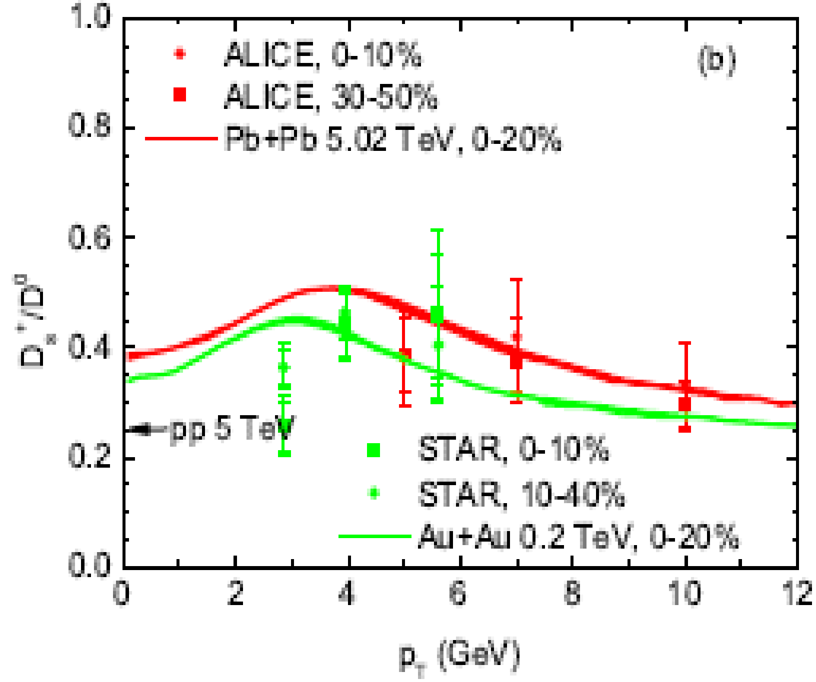




- T-matrix coefficient*K-factor(=1.6), to compensate for radiative e-loss; uncertainty: BR=50-100% to Λ_c^+ for Λ_C's & Σ_C's above DN (2805 MeV)
- Hadronic phase diffusion also included: seamlessly connected to hadronization (RRM+frag), increasing D-meson v_2 by ~15%

Charm-hadron ratios: Λ_c^+/D^0 & D_s^+/D^0



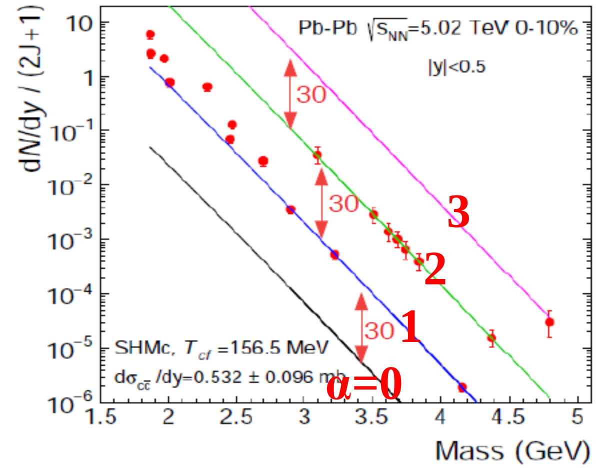


- Λ_c^+/D^0 : low p_T approaching RRM equil. limit = SHM pp; intermediate p_T enhancement from RRM with SMCs; high p_T fragmentation tending to pp value

- D_s^+/D^0 enhancement: recombination of charm in a strangeness-equilibrated QGP

Hadronization: SHMc Andronic, PBM et al. 2104.12754

- SHMc: open-charm statistical hadronization at T_c $\frac{dN(h^i_{oc,\alpha})}{dy} = g_c^\alpha V n_i^{th} \frac{I_\alpha(N_c^{tot})}{I_0(N_c^{tot})}$
  - multicharm baryons α=1,2,3 emerging pattern
  - yields enhanced by $g_c^\alpha \sim 30^\alpha$ than pure thermal →strong signal of deconfinement



- SHMc yields + blast wave→p_T spectra