Quarkonium as a probe of deconfinement

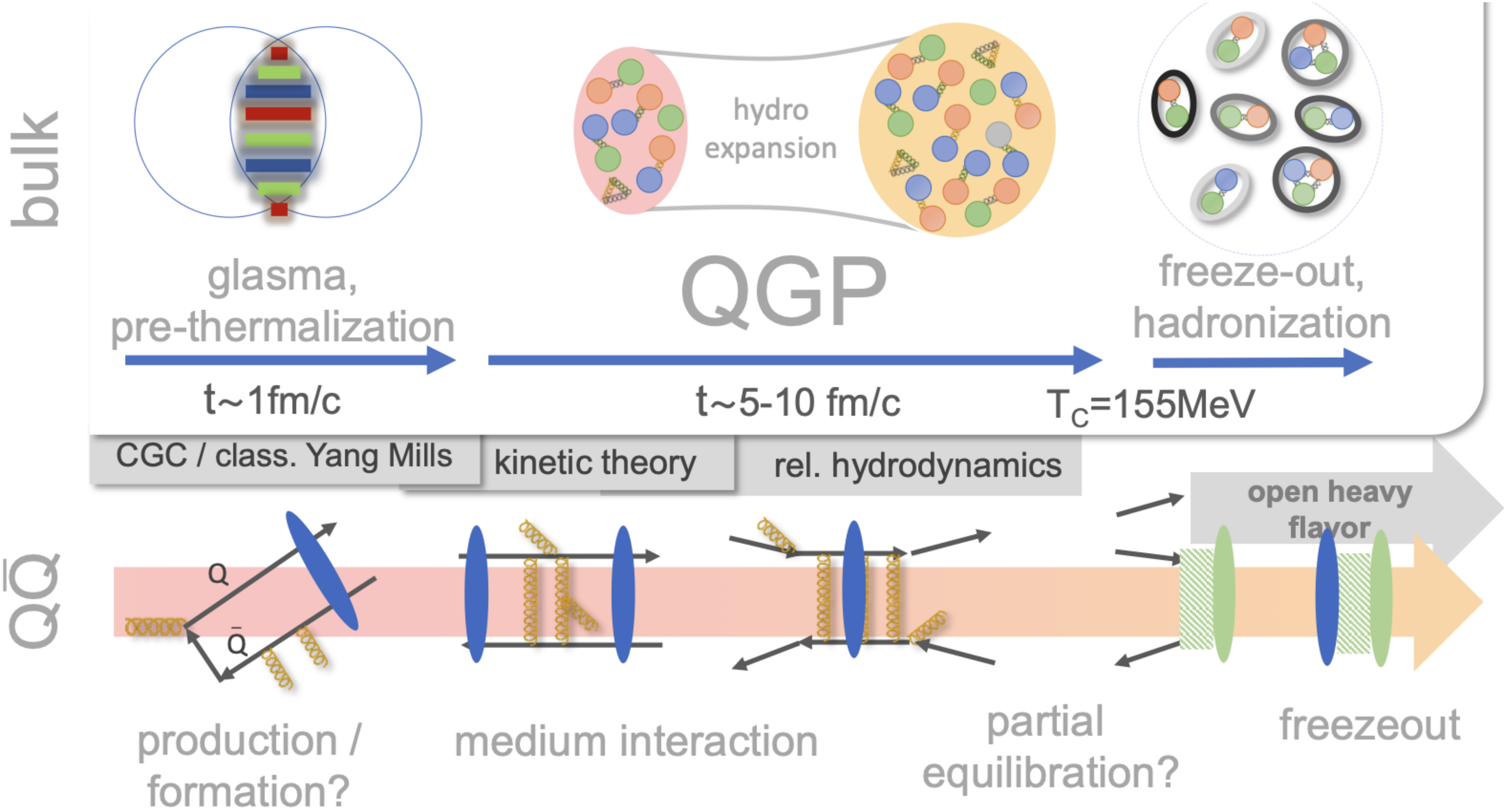
A. Andronic - University of Münster

Universität Münster

- Quarkonium as probe of deconfinement
- A brief overview of data
- Models in brief
- Quarkonium (and open HQ) in the statistical hadronization model

Andronic, Braun-Munzinger, Redlich, Stachel, Nature 561 (2018) 321

...+ Brunßen, Crkovská, Mazeliauskas, Vislavicius, Völkl, JHEP 07 (2021) 035; 2308.14821



A. Rothkopf, Phys. Rep. 858 (2020) 1

the original idea: Matsui & Satz, Phys.Lett. B 178 (1986) 178

"If high energy heavy-ion collisions lead to the formation of a hot quark-gluon-plasma, then color screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region."

Refinements: "sequential suppression":

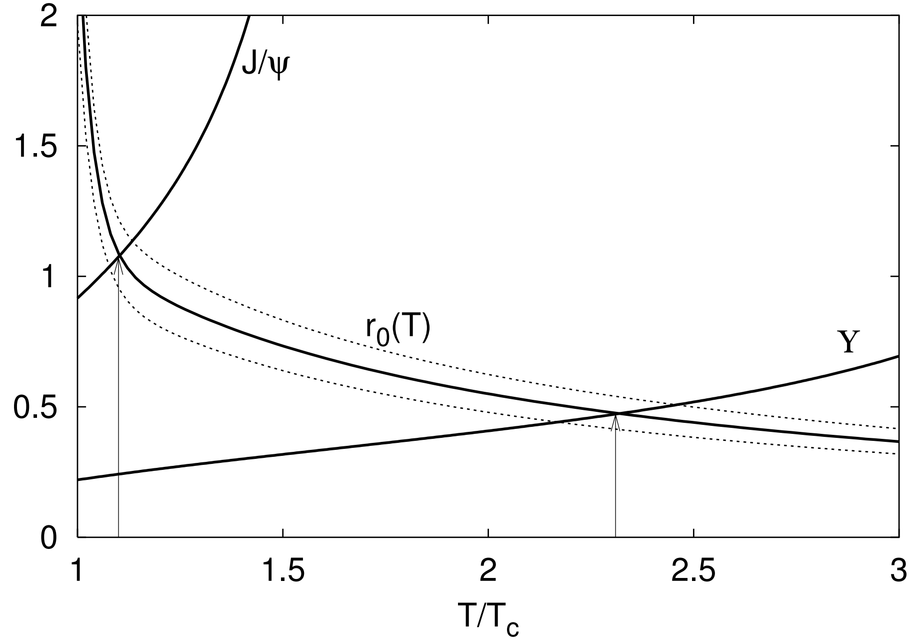
Digal et al., PRD 64 (2001) 75

no $\mathrm{q\bar{q}}$ bound state if

$r_{\mathrm{q\bar{q}}}(T) > r_0(T) \simeq \frac{1}{g(T)T}$

r_0 Debye length in QGP

$\Rightarrow$ $\mathrm{q\bar{q}}$ "thermometer" of QGP

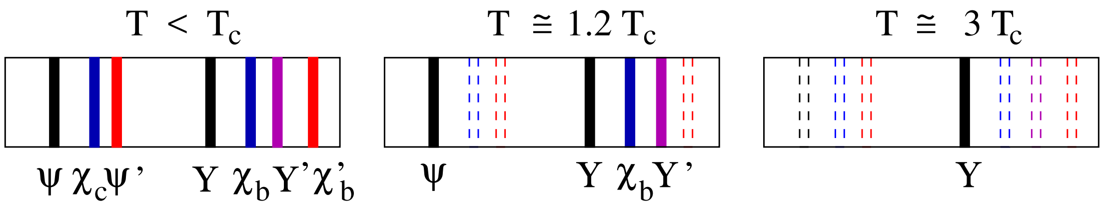


Thermal picture ($n_{partons} = 5.2T^3$ for 3 flavors)

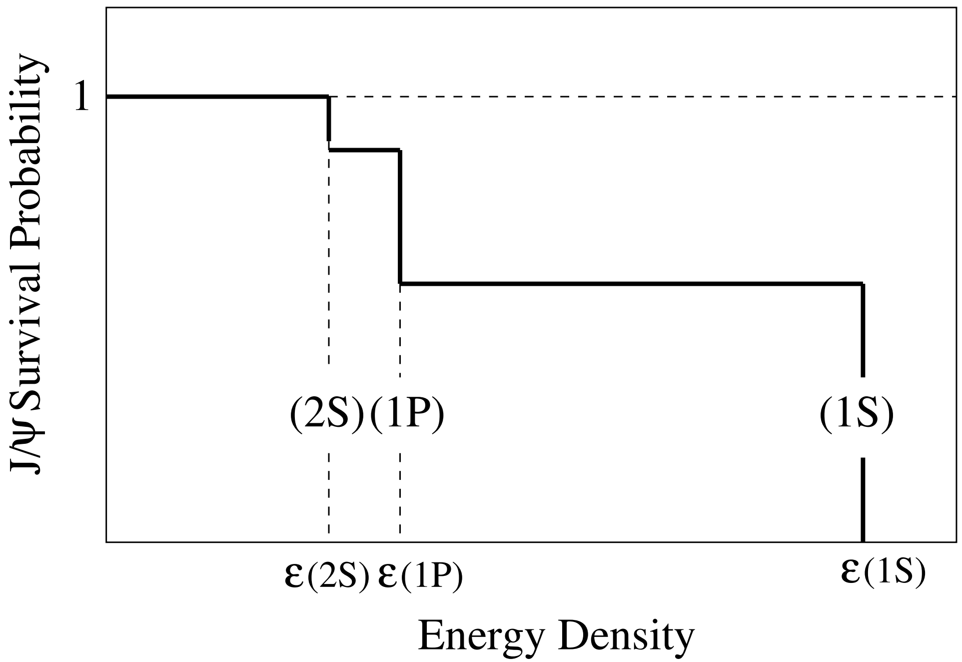
for T=500 MeV: $n_p \simeq$84/fm^3, mean separation $\bar{r}$=0.2 fm $< r_{J/\psi}$

Quarkonium and the QGP - “sequential suppression”

Digal et al., PRD 64 (2001) 75; H.Satz, arXiv:1310.1209



quantitative: lattice QCD



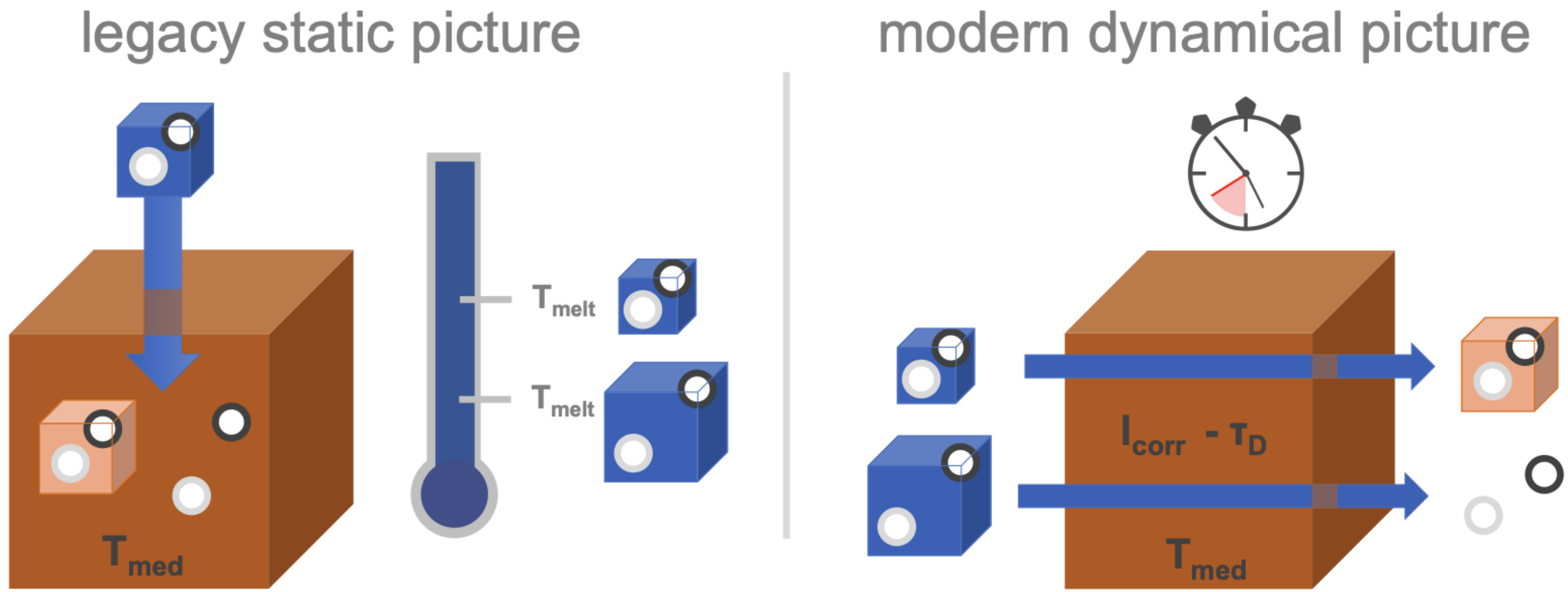
← assumed feed-down to J/ψ: 10% from $\psi(2S)$ and 30% from χ_c

Experimentally:

$$R_{AA}^{J/\psi} = \frac{\mathrm{d}N_{J/\psi}^{AA}/\mathrm{d}y}{N_{coll}\cdot\mathrm{d}N_{J/\psi}^{pp}/\mathrm{d}y}$$ vs. N_{part} or N_{ch}

quarkonium as thermometer

Quarkonium pictures

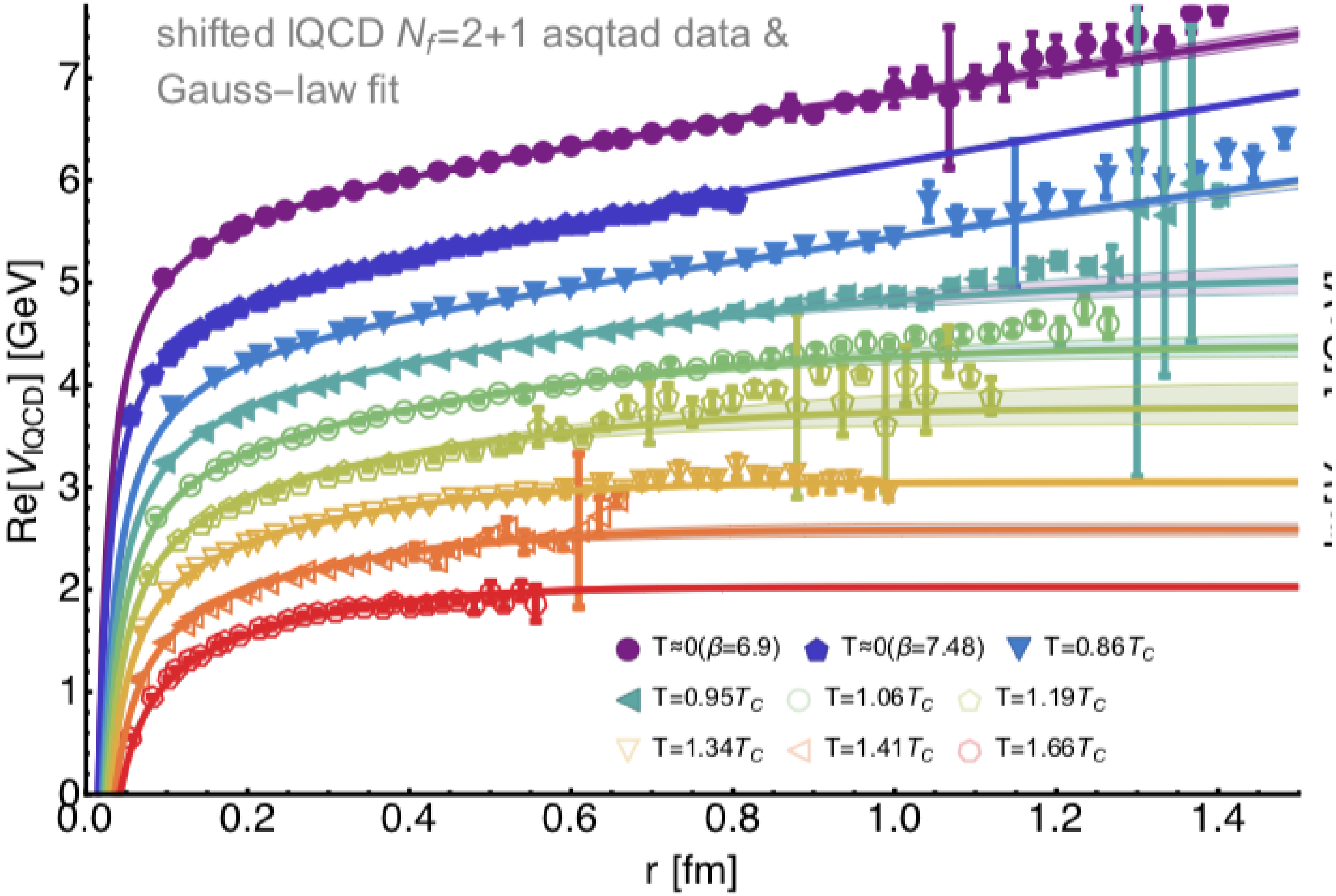


A. Rothkopf, Phys. Rep. 858 (2020) 1

for $T(\tau)$ we anyway have more basic (bulk) observables (collective flow)

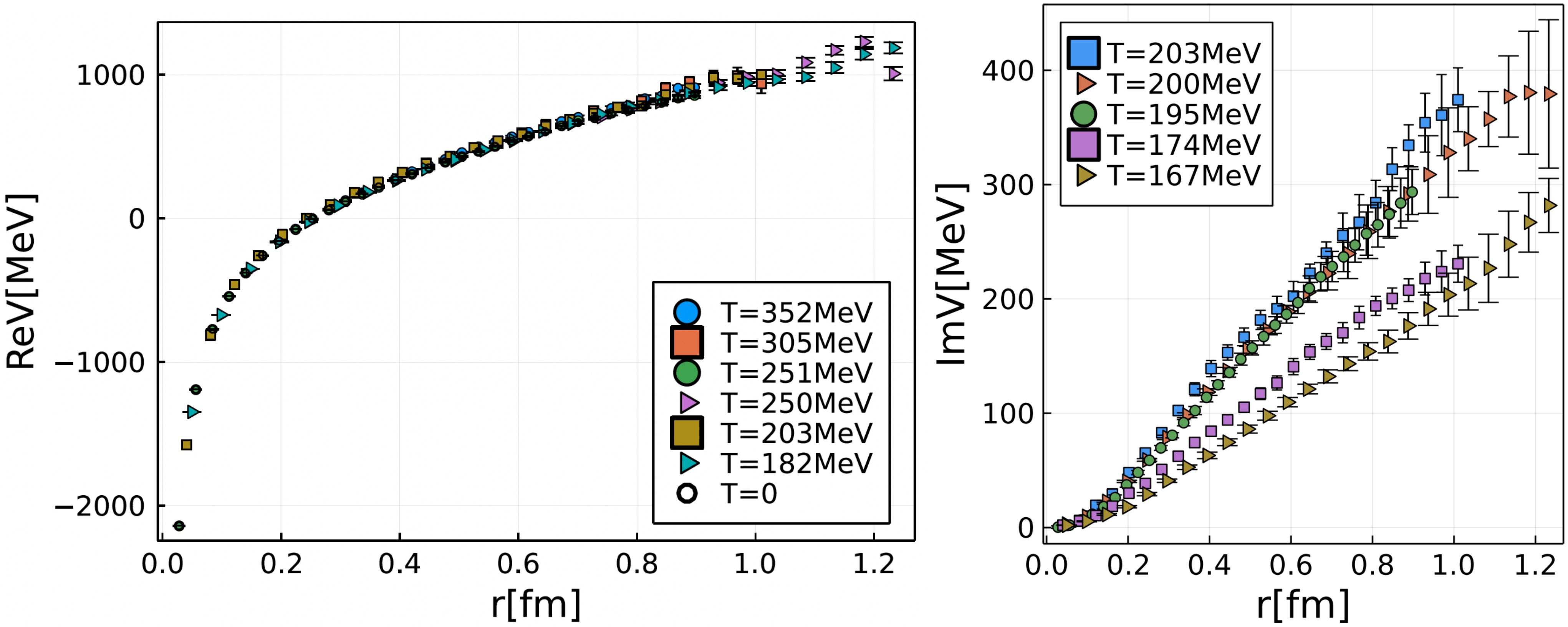
$$T \sim \Lambda_{QCD} \sim E^{vac}_{b,Q\overline{Q}} \; (m_Q \gg \Lambda_{QCD})$$

Heavy-quark potential - Lattice QCD



A. Rothkopf, Phys. Rep. 858 (2020) 1

$(T_C \simeq 174$ MeV)



HotQCD coll., arXiv:2308.16587

ReV: not screened! ImV: large, increases with distance

$\rightarrow$ "melting of quarkonium is not related to color screening" (P.Petreczky)

Charmonium data: SPS, RHIC, LHC

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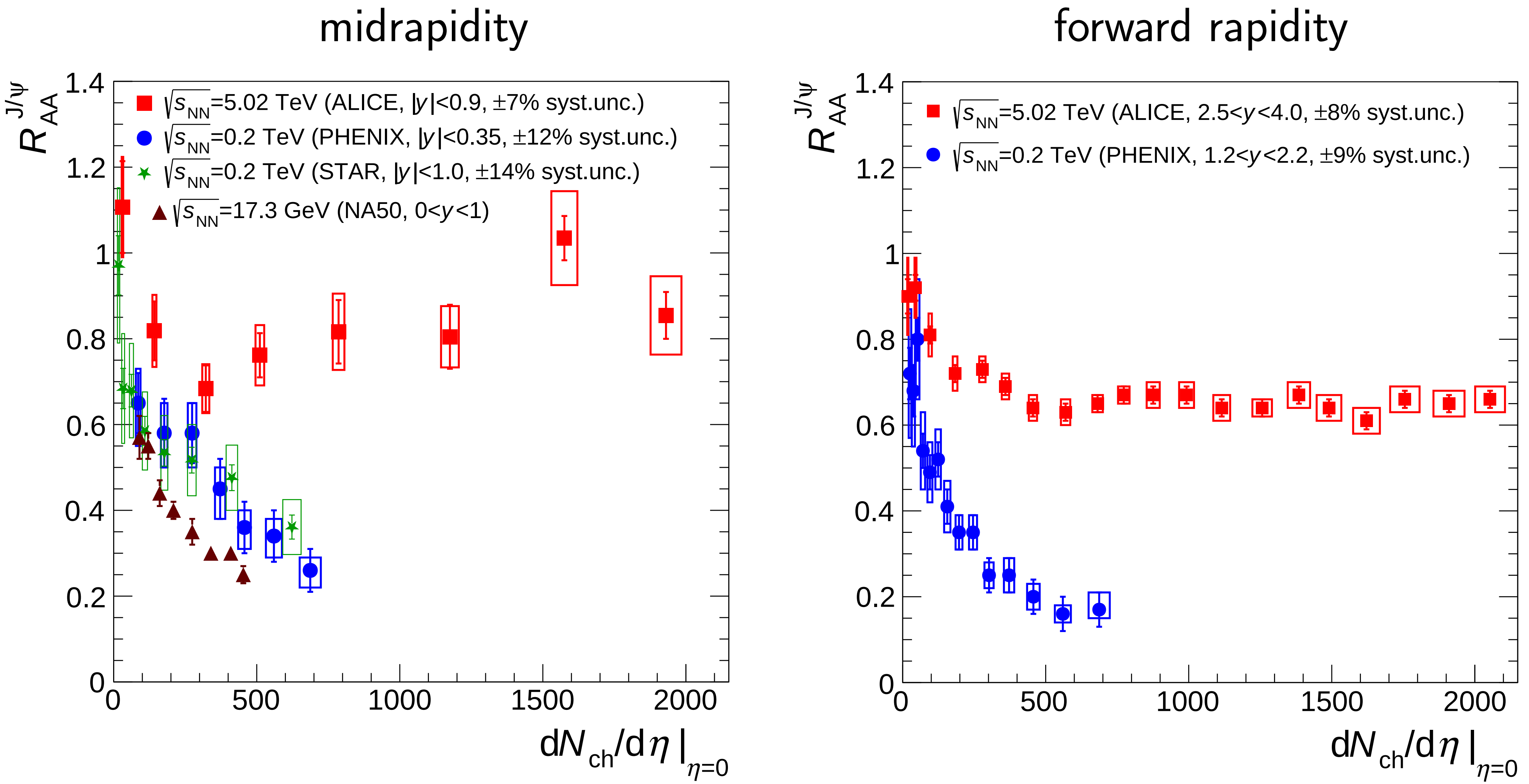
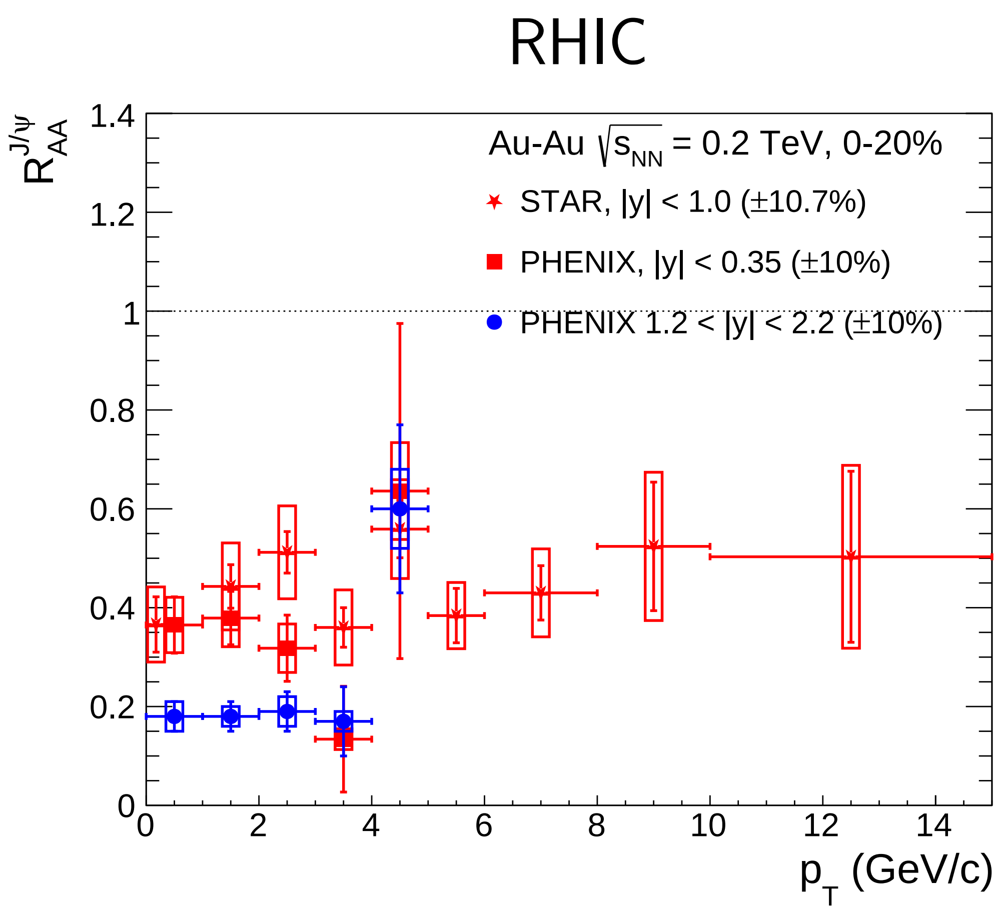
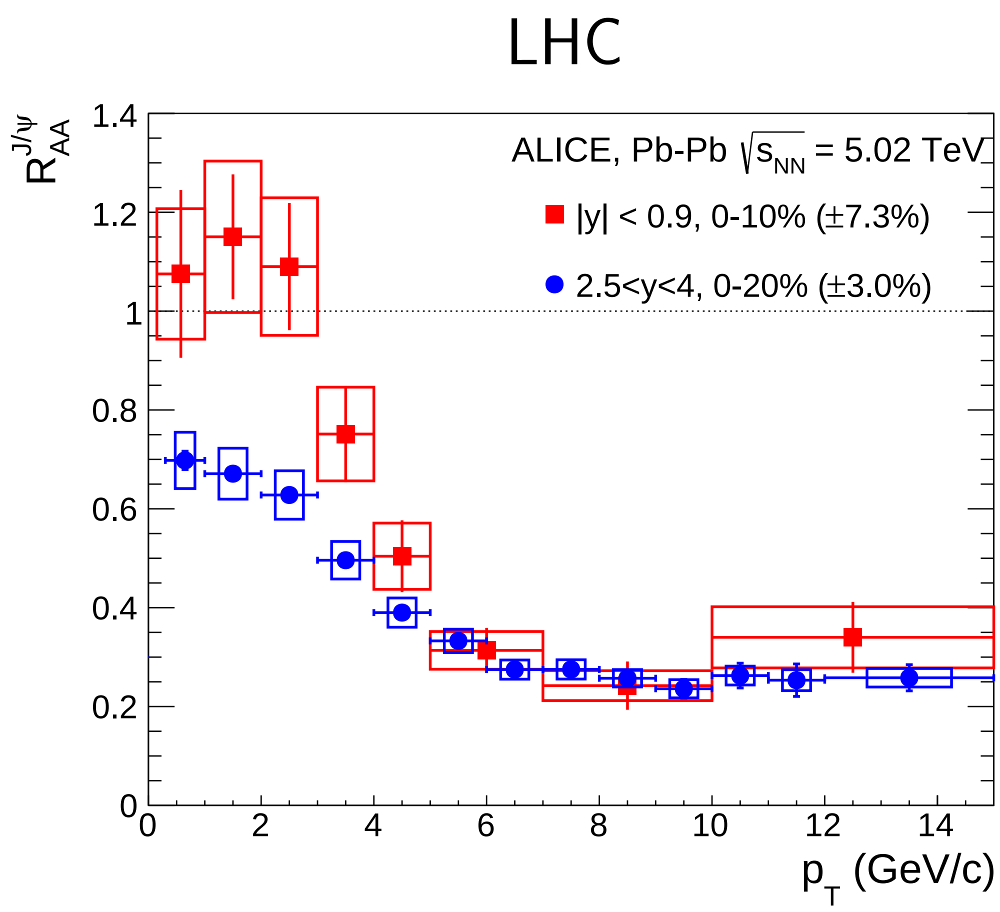


suppression at lower energies, but not obviously a sequential one

at the LHC another effect offsets the dissociation

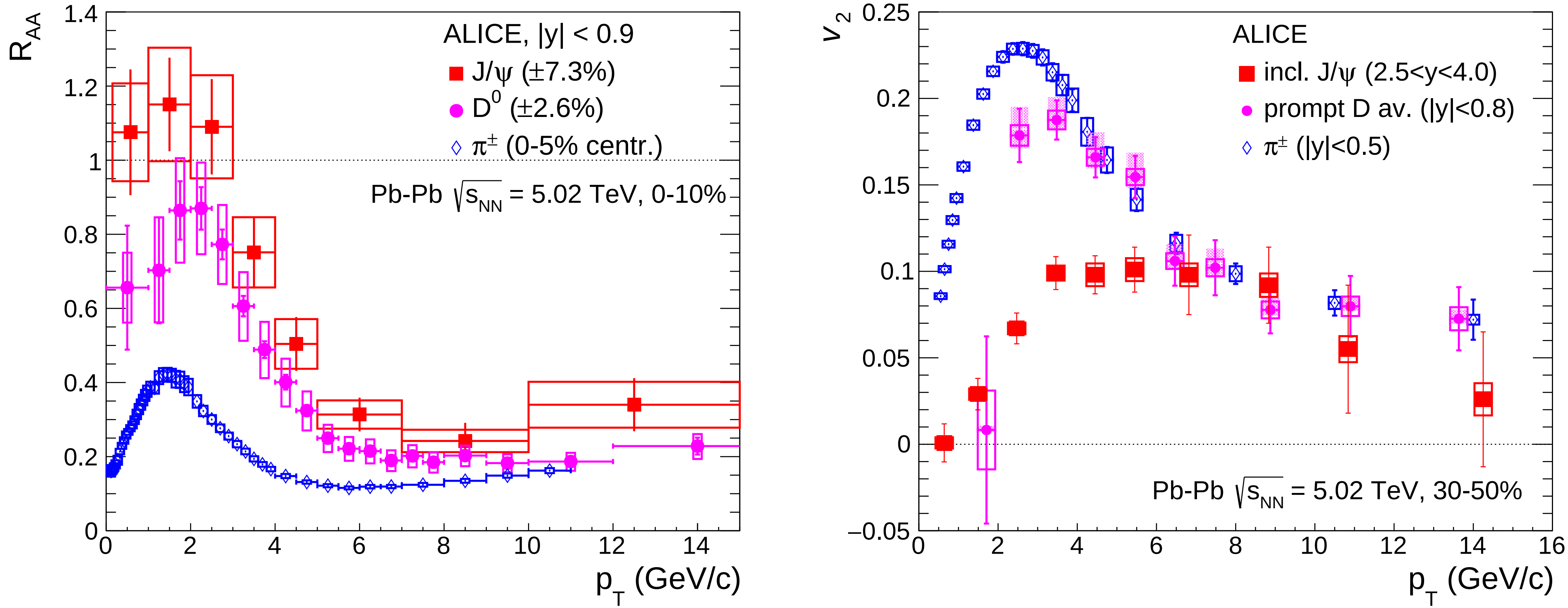
Charmonium data: RHIC and LHC





production at low p_{T} is enhanced at the LHC compared to RHIC

...stronger at midrapidity



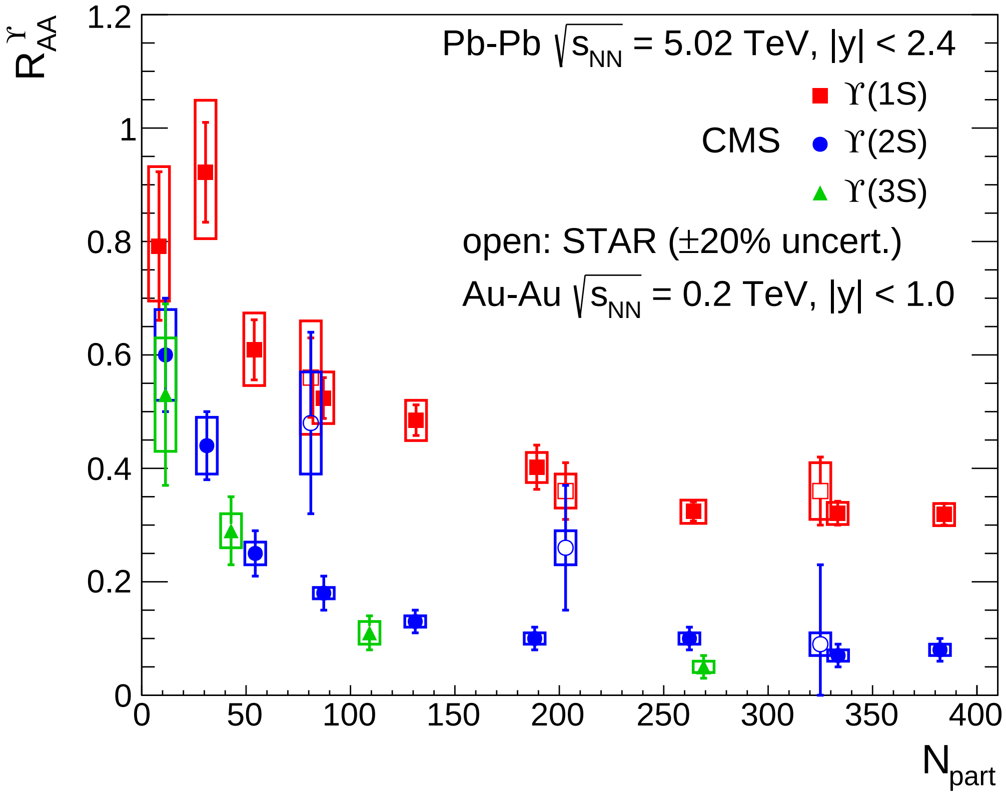
ALICE, arXiv:2303.13361, arXiv:2110.09420, arXiv:1802.09145

a very clear hierarchy at low/intermediate $p_{\rm T}$

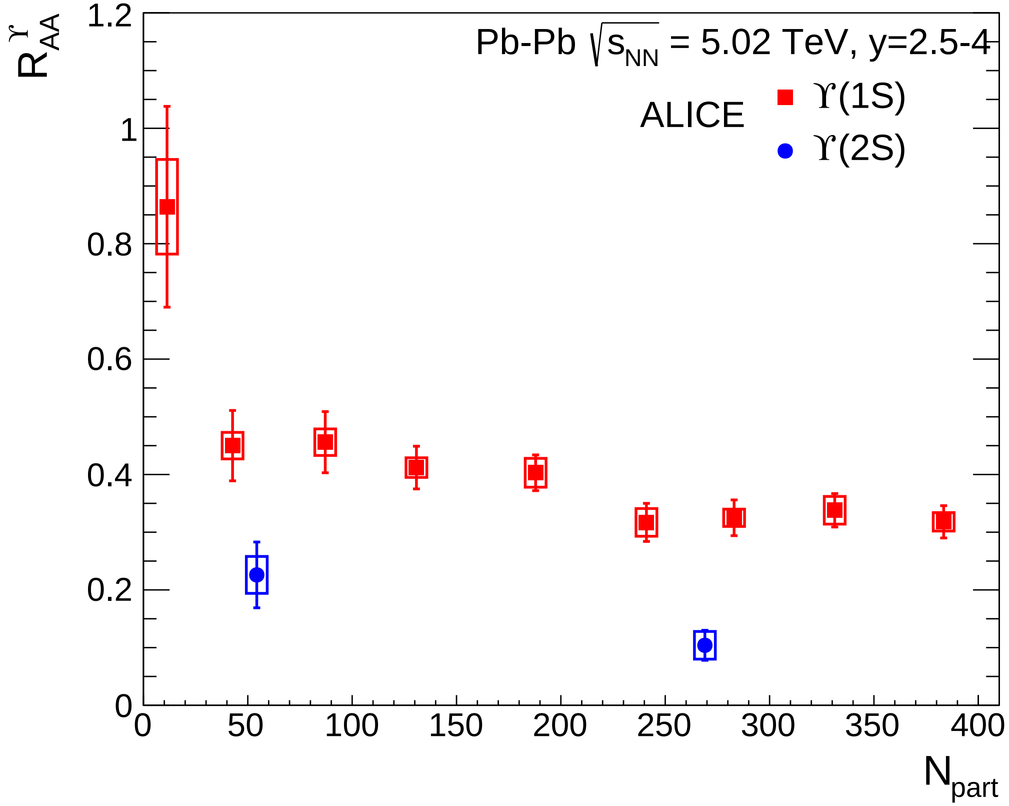
charm production is a pQCD process, pion production largely a thermal process

Bottomonium data: RHIC and LHC

midrapidity

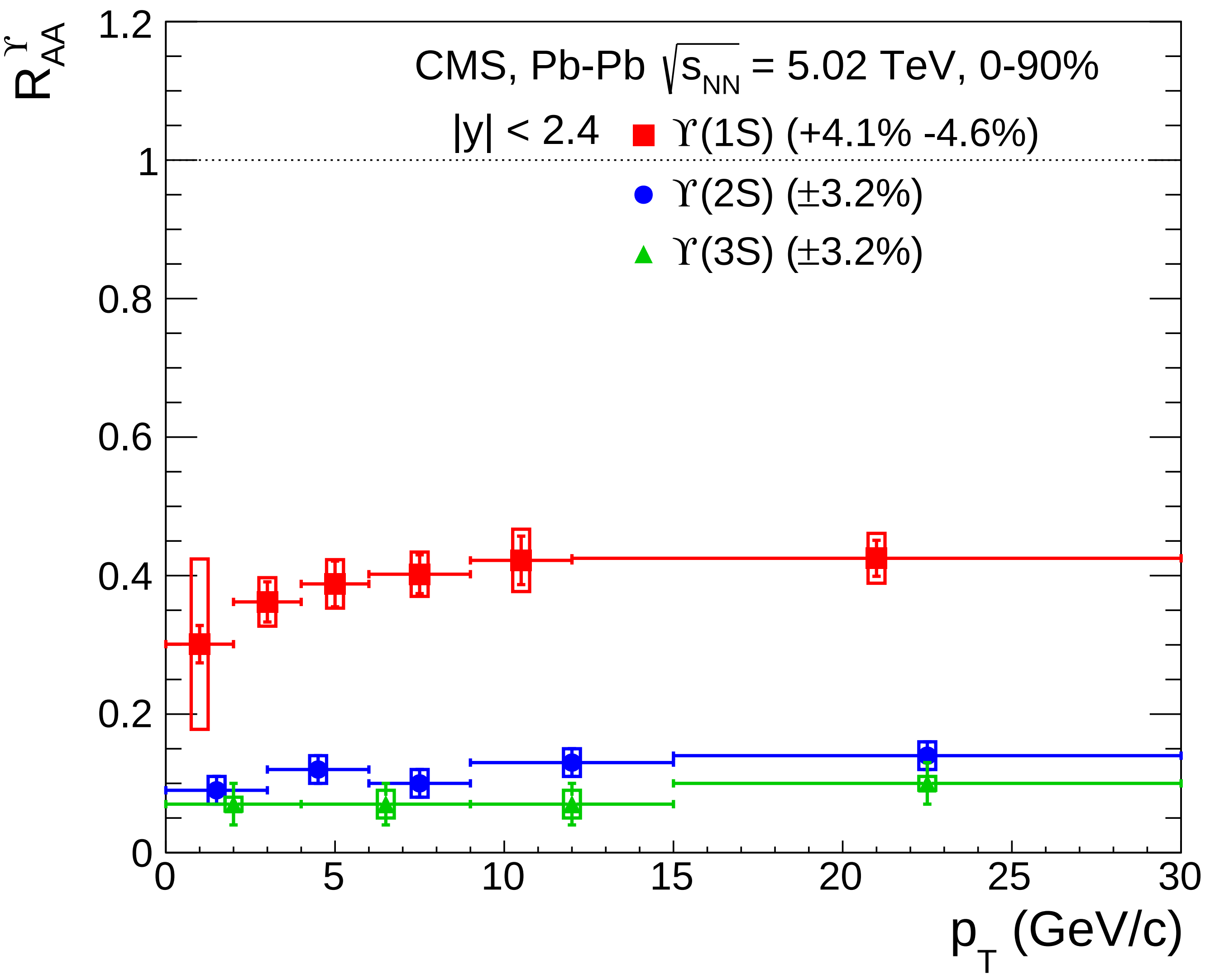


forward rapidity



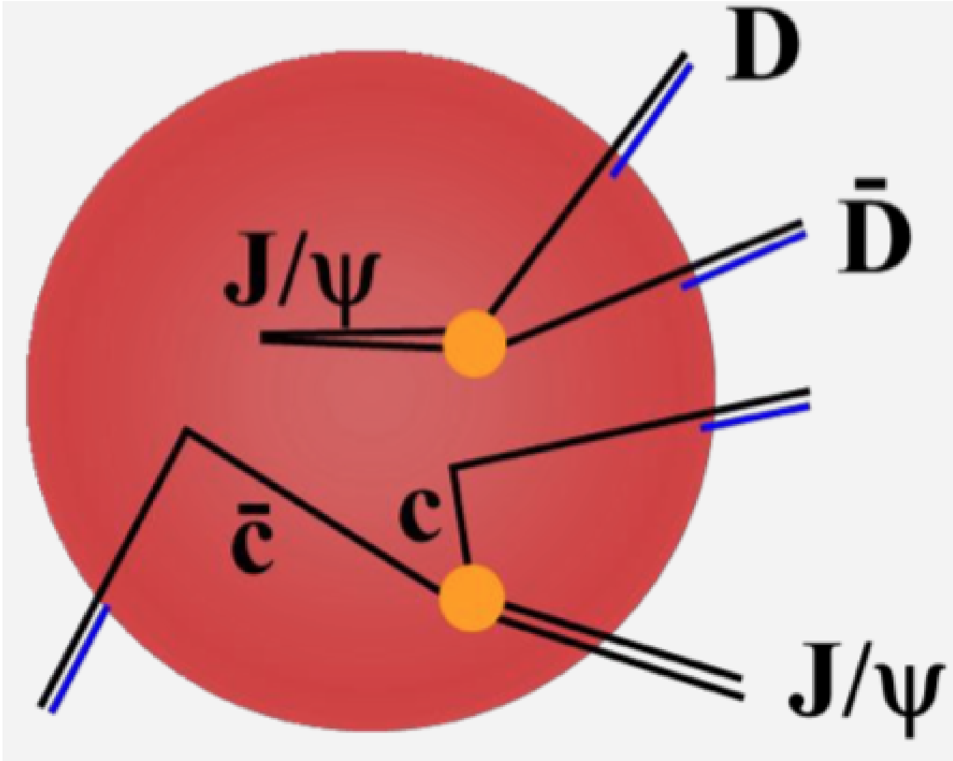
significant suppression, hierarchy between states (sequential?)

not significantly different at LHC and RHIC (except perhaps $\Upsilon(2S)$)



weak p_{T} dependence (dissociation expected to be stronger at low p_{T})

There is dissociation and there is (re)generation

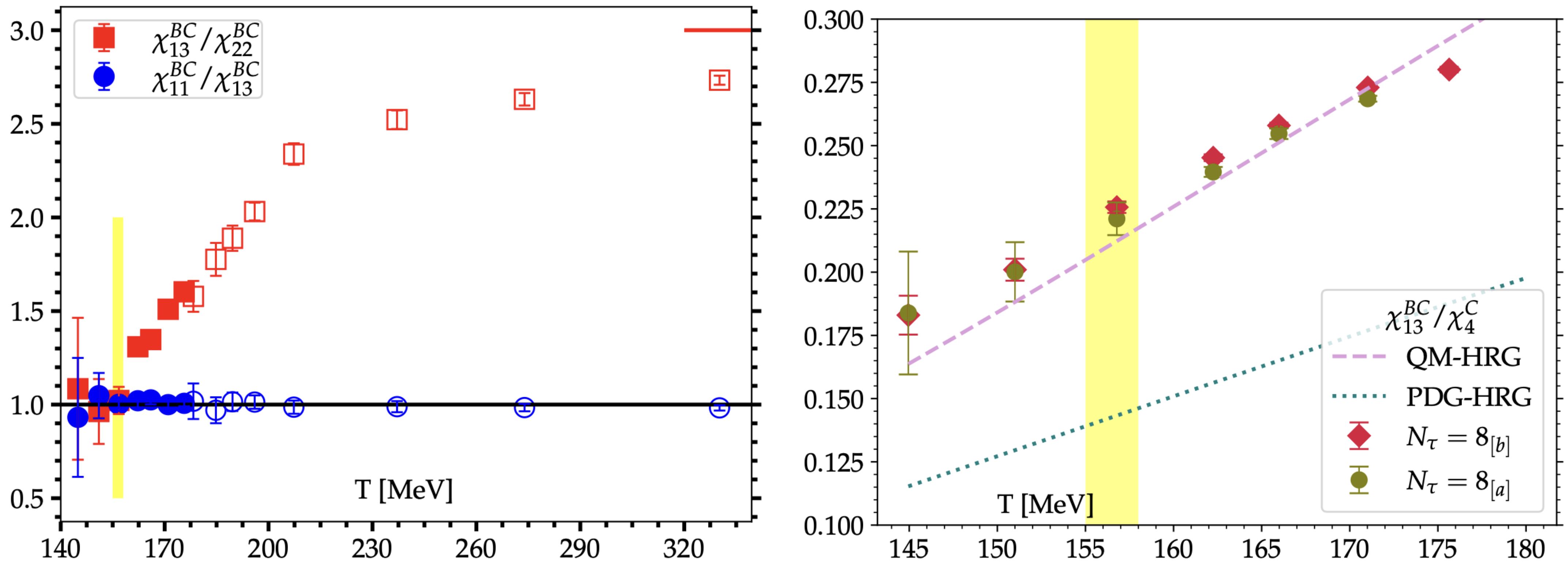


This picture is implemented in models in 2 basic ways:

1) statistical hadronization: full screening, generation at hadronization
($\mathrm{c},\bar{\mathrm{c}}$ produced in initial scattering and fully thermalized in QGP)

2) transport: continuous destruction and (re)generation, also from different $\mathrm{c},\bar{\mathrm{c}}$
(time evolution of T constrained by other measurements)

Charm in QGP - the lattice view



Bazavov et al., arXiv:2312.12857

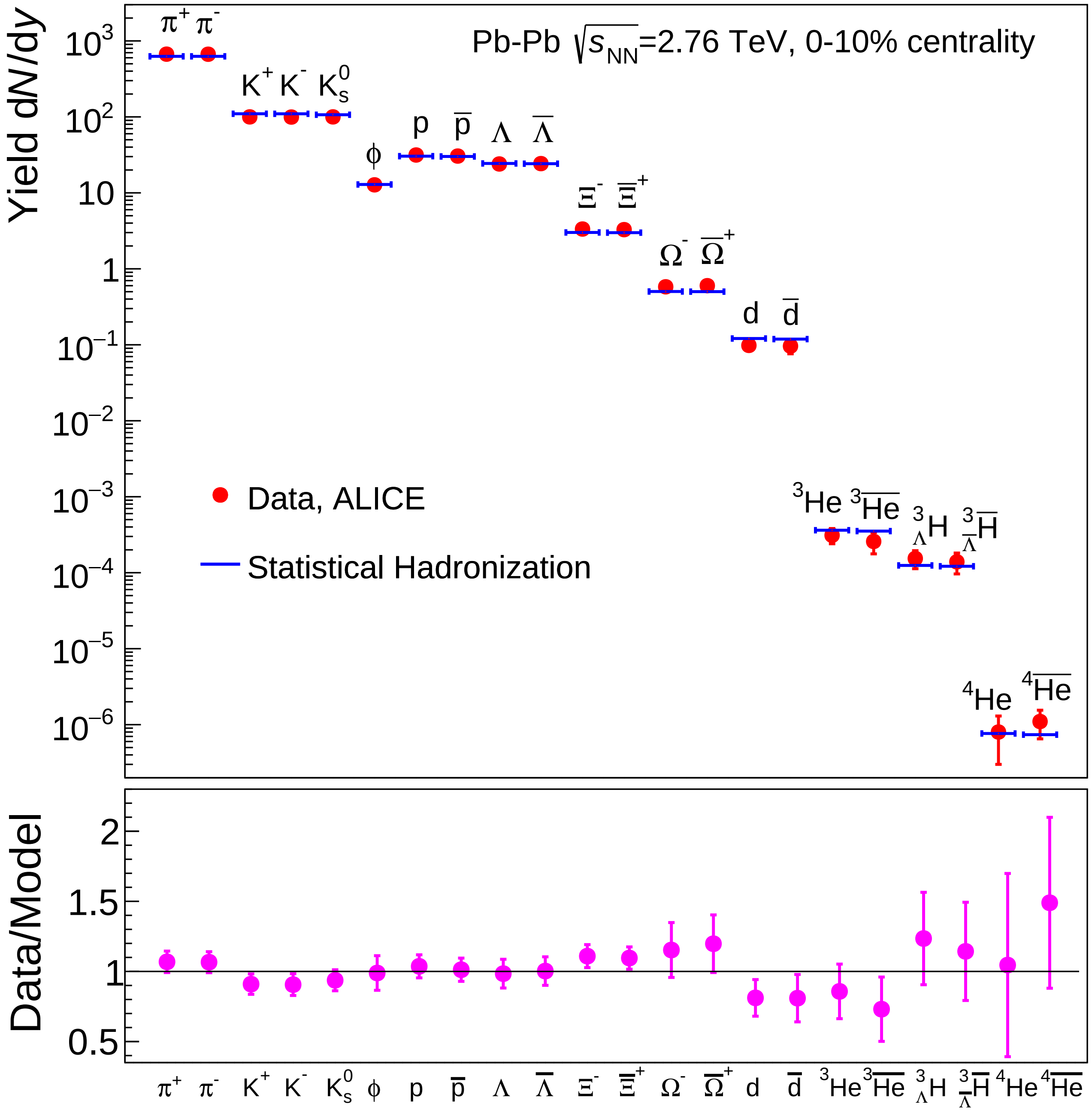
$\chi_{11}^{BC} = \chi_{1m}^{BC} = P_B^C$, m odd;

$\chi_{13}^{BC}/\chi_4^C \sim P_B^C/P^C$

Indication of charm-quark dofs at T_c, but “pure-quark” state at $\simeq$200 MeV

Clear need of an enhanced charm-baryon spectrum wrt PDG

Thermal fit – LHC, Pb–Pb, 0-10%



matter and antimatter produced in equal amounts

$T_{CF} = 156.6 \pm 1.7$ MeV
$\mu_B = 0.7 \pm 3.8$ MeV
$V_{\Delta y=1} = 4175 \pm 380$ fm^3

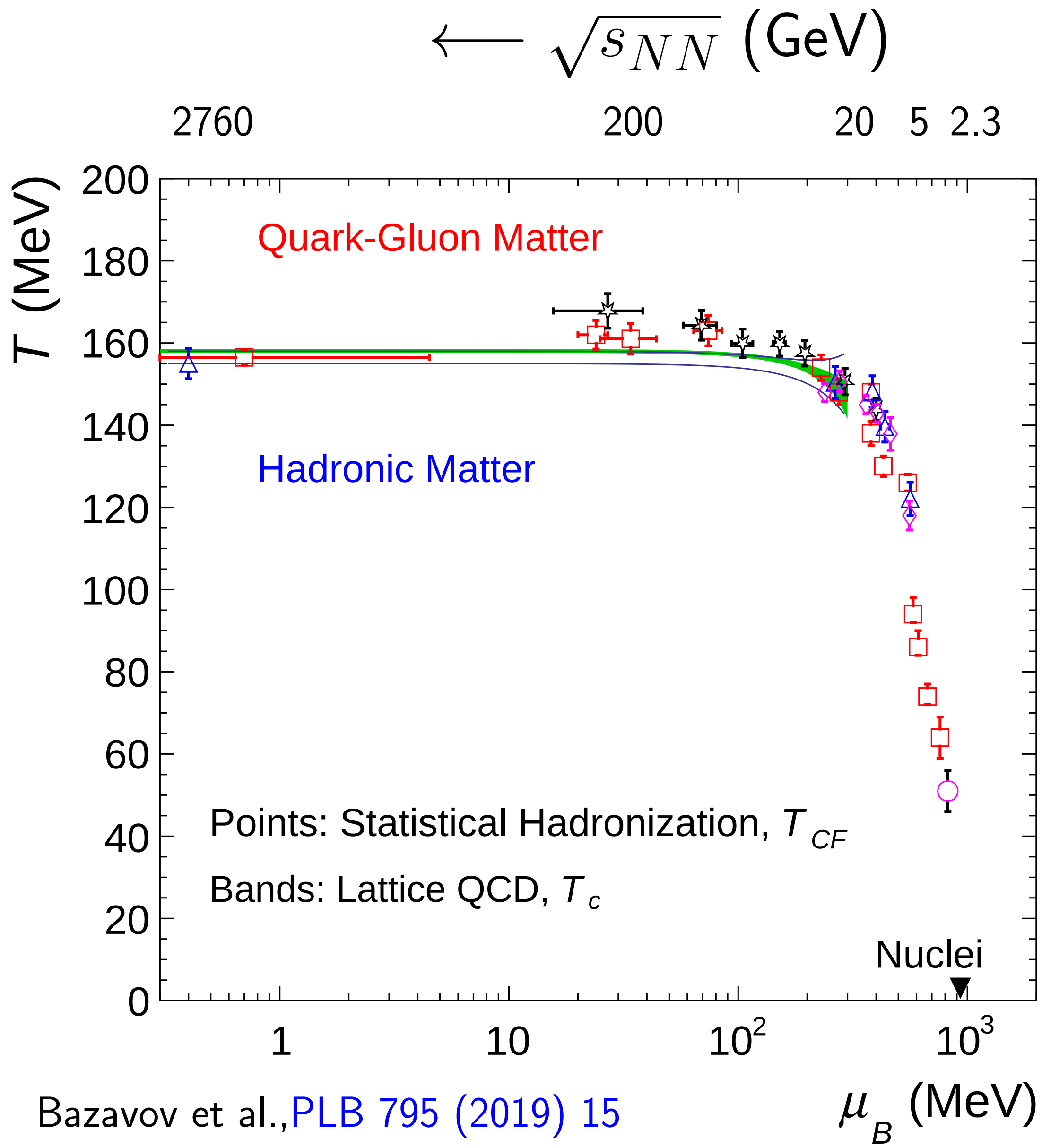
$\chi^2/N_{df} = 16.7/19$

S-matrix treatment $(\mathrm{p}, \bar{\mathrm{p}})$

remarkably, loosely-bound objects are also well described ($^3_\Lambda$H: 25% B.R.)

hadronization as bags of quarks and gluons?

hadron spectrum beyond PDG → same T_{CF} NPA 1010 (2021) 122176



Bazavov et al.,PLB 795 (2019) 15

Borsanyi et al., PRL 125 (2020) 052001

at LHC, remarkable "coincidence" with Lattice QCD results

at LHC ($\mu_B \simeq 0$): purely-produced (anti)matter ($m = E/c^2$), as in the Early Universe

$\mu_B > 0$: more matter, from "remnants" of the colliding nuclei

$\mu_B \gtrsim 400$ MeV: *the critical point awaiting discovery*

(RHIC BES / FAIR)

see refs. in Nature 561 (2018) 321

points: independent analyses of same data → "model/code uncert." are small

The statistical hadronization model

Braun-Munzinger, Stachel, PLB 490 (2000) 196; NPA 789 (2006) 334, PLB 652 (2007) 259

All charm quarks are produced in primary hard collisions ($t_{c\bar{c}} \sim 1/2m_c \simeq$ 0.1 fm/c)

...survive and thermalize **in QGP** (thermal, but not chemical equilibrium)

charmed hadrons are formed at chemical freeze-out together with all hadrons
"generation" ...no J/ψ survival in QGP (full screening)

(if supported by data) J/ψ looses status as "thermometer" of QGP
...and gains status as a powerful observable for the QCD phase boundary

Predicts p_T spectra too: hydrodynamics (MUSIC) (input for β_T in blast-wave formula)
JHEP 07 (2021) 035, arXiv:2308.14821

SHM for charm (SHMc)

pQCD production, "throw in": $N_{c\bar{c}} = 9.6 \rightarrow g_c = 30.1$ $(I_1/I_0 = 0.974)$

LHC, central collisions

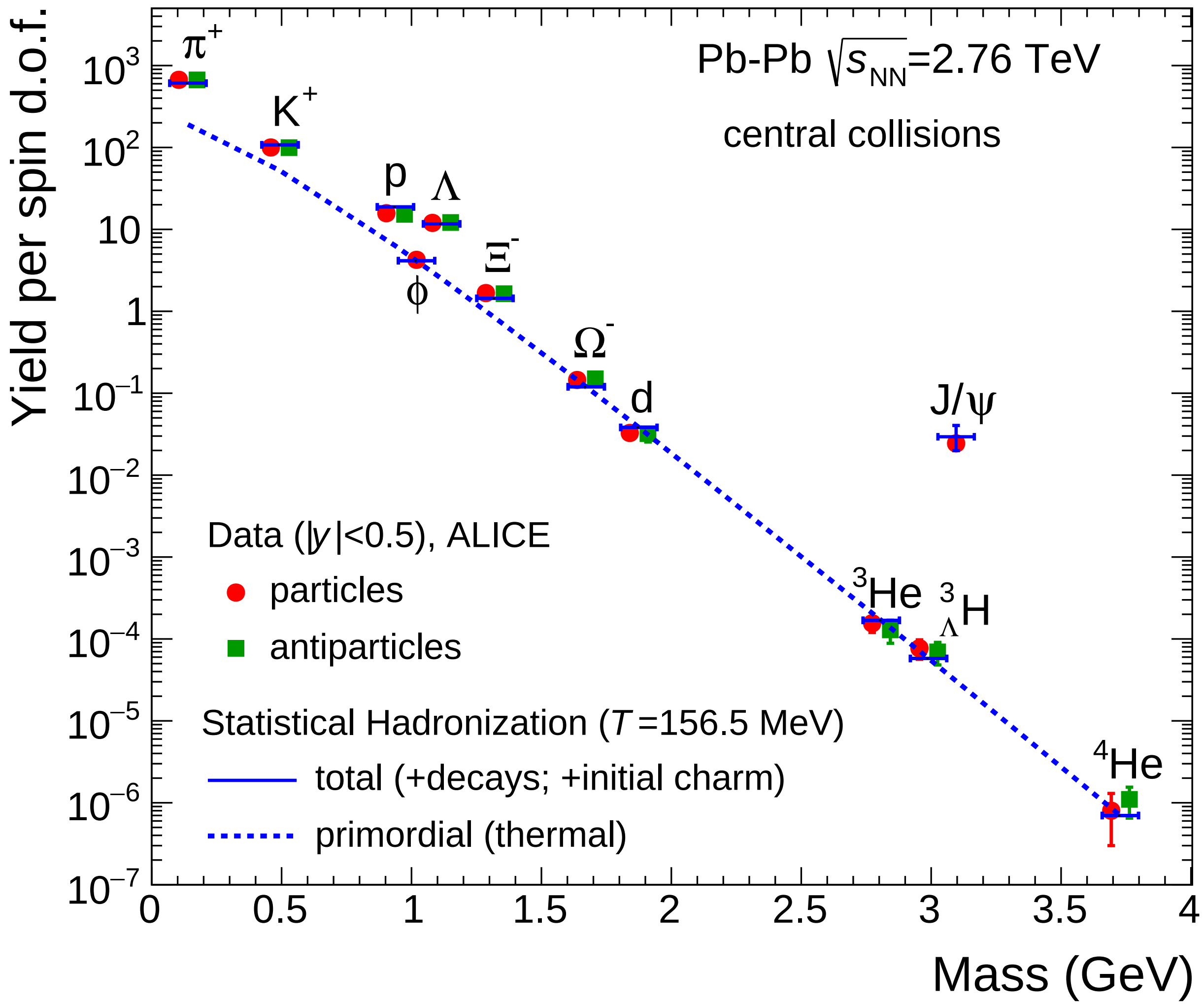
assume:

- full thermalization of $c, \bar{c}$ ("mobility" in V≃4000 fm^3)

- full color screening (Matsui-Satz)

Braun-Munzinger, Stachel, PLB 490 (2000) 196

Model predicts all charm chemistry ($\psi(2S)$, $X(3872)$)



π, $K^{\pm}$, K^0 from charm included in the thermal fit (0.7%, 2.9%, 3.1% for T=156.5 MeV)

PLB 797 (2019) 134836

SHMc: method and inputs

Braun-Munzinger, Stachel, PLB 490 (2000) 196, NPA 690 (2001) 119

- Thermal model calculation (grand canonical) T,μ_B: $\rightarrow n_X^{th}$
- $N_{c\bar{c}}^{dir} = \frac{1}{2} g_c V (\sum_i n_{D_i}^{th} + n_{\Lambda_i}^{th}) + g_c^2 V (\sum_i n_{\psi_i}^{th} + n_{\chi_i}^{th})$
- $N_{c\bar{c}} << 1 \rightarrow$ Canonical (Cleymans, Redlich, Suhonen, Z. Phys. C51 (1991) 137):

Gorenstein, Kostyuk, Stöcker, Greiner, PLB 509 (2001) 277

$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{th} \frac{I_1(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})} + g_c^2 N_{c\bar{c}}^{th} \quad \rightarrow g_c(N_{part}) \text{ (charm fugacity)}$$

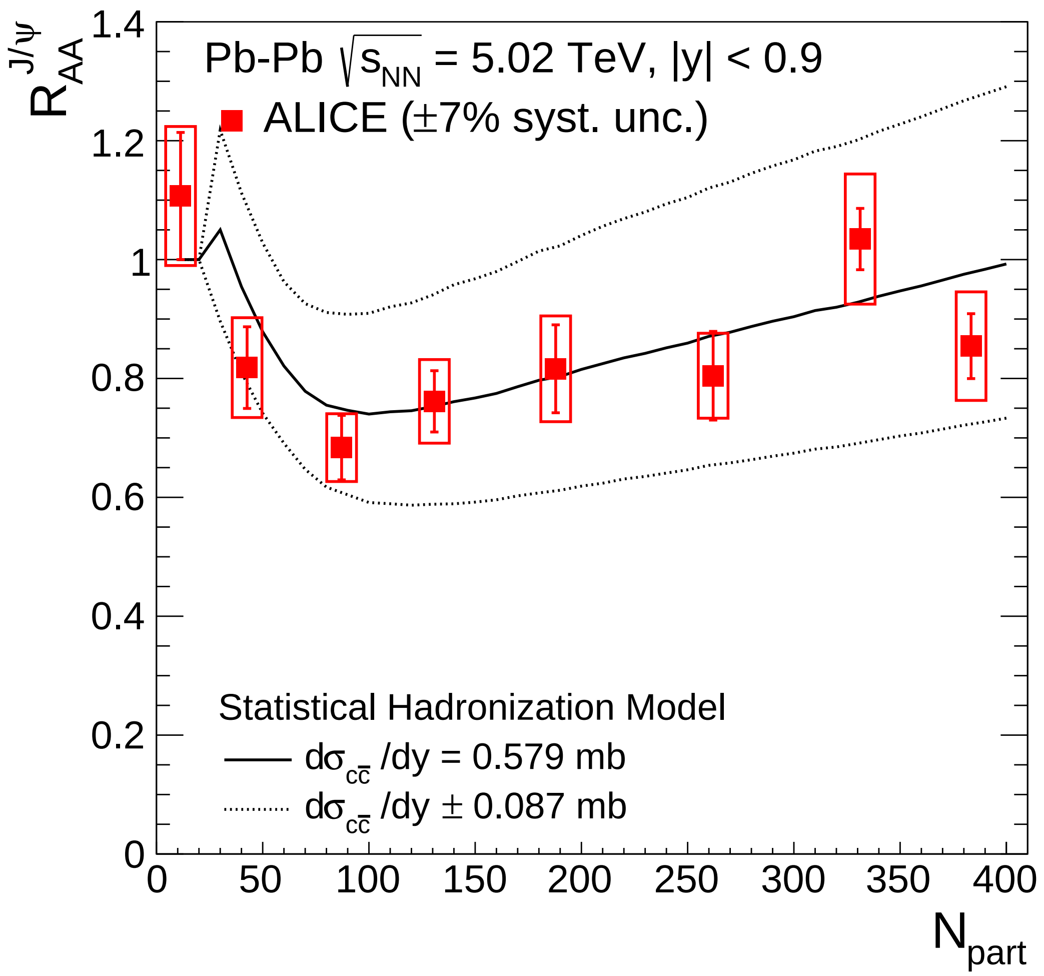
Outcome: $N_D = g_c V n_D^{th} I_1/I_0 + N_D^{\mathrm{corona}}$, $\quad N_{J/\psi} = g_c^2 V n_{J/\psi}^{th} + N_{J/\psi}^{\mathrm{corona}}$

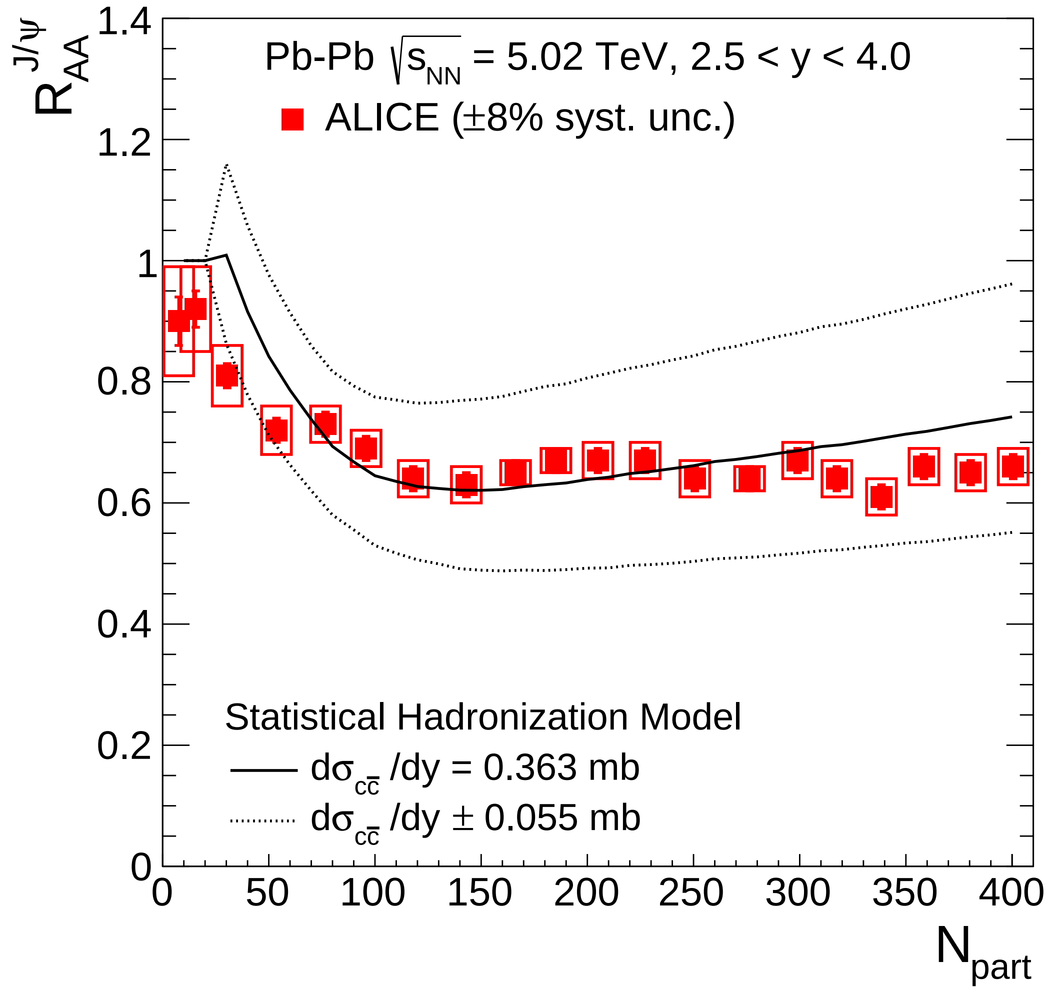
Inputs: T, μ_B, $\quad V_{\Delta y=1} (= (\mathrm{d}N_{ch}^{exp}/\mathrm{dy})/n_{ch}^{th})$, $\quad N_{c\bar{c}}^{dir}$ (exp. or pQCD)

Assumed minimal volume for QGP: V_{QGP}^{min}=200 fm^3

SHMc and charmonium data at the LHC

full thermalization of c quarks in QGP, hadronization at chemical freeze-out





$d\sigma_{c\bar{c}}/dy$ via normalization to D^0 in Pb–Pb 0-10%, ALICE, arXiv:2110.09420

$dN/dy =$ 6.82±1.03 ($|y| < 0.5$; FONLL for y=2.5-4; assuming hadronization fractions in data as in SHMc)

SHMc: the full charm zoo

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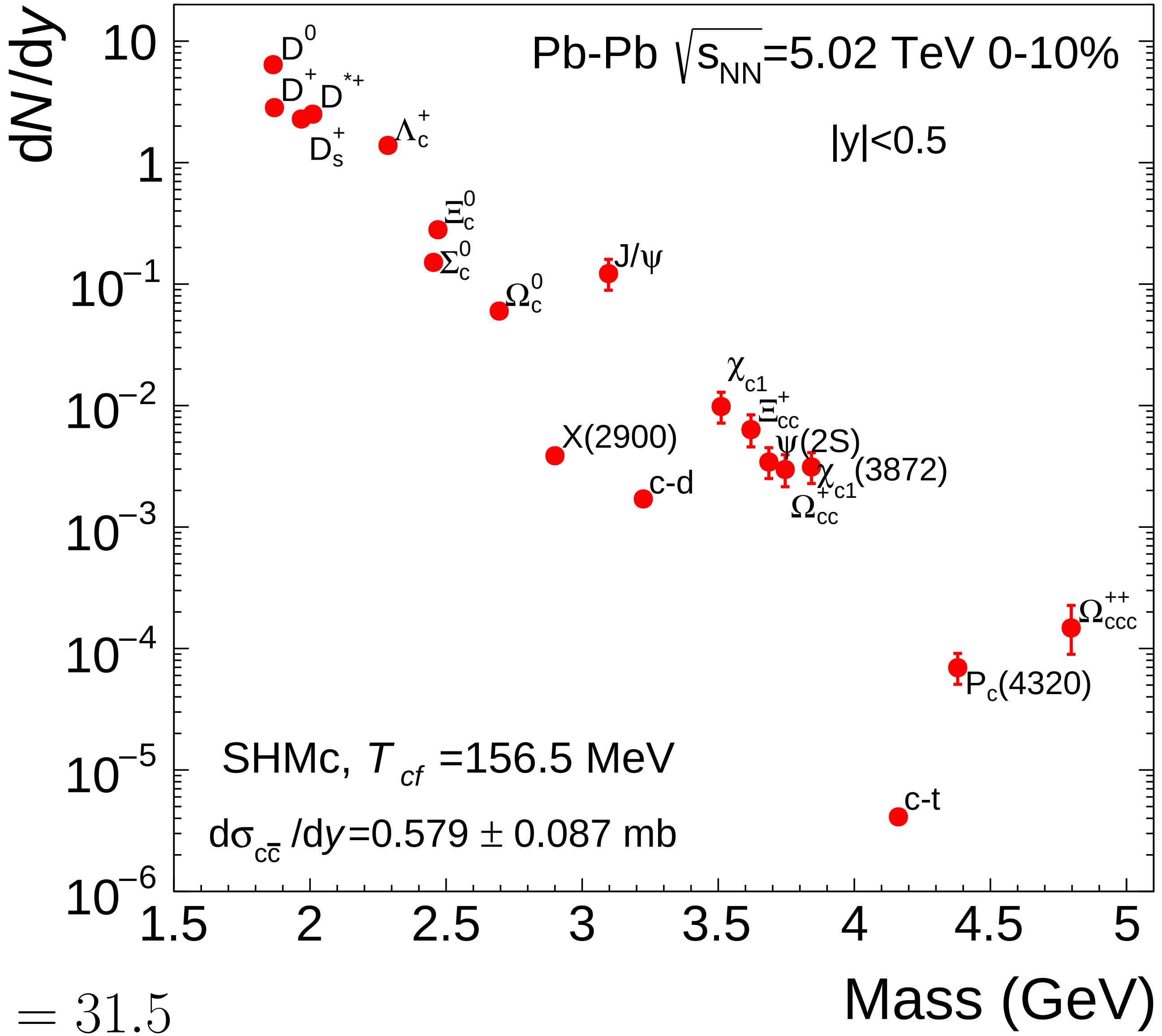


$T_{cc}^+ \simeq$ $0.9 \cdot \chi_{c1}(3872)$

$X(6900) \sim 10^{-8}$

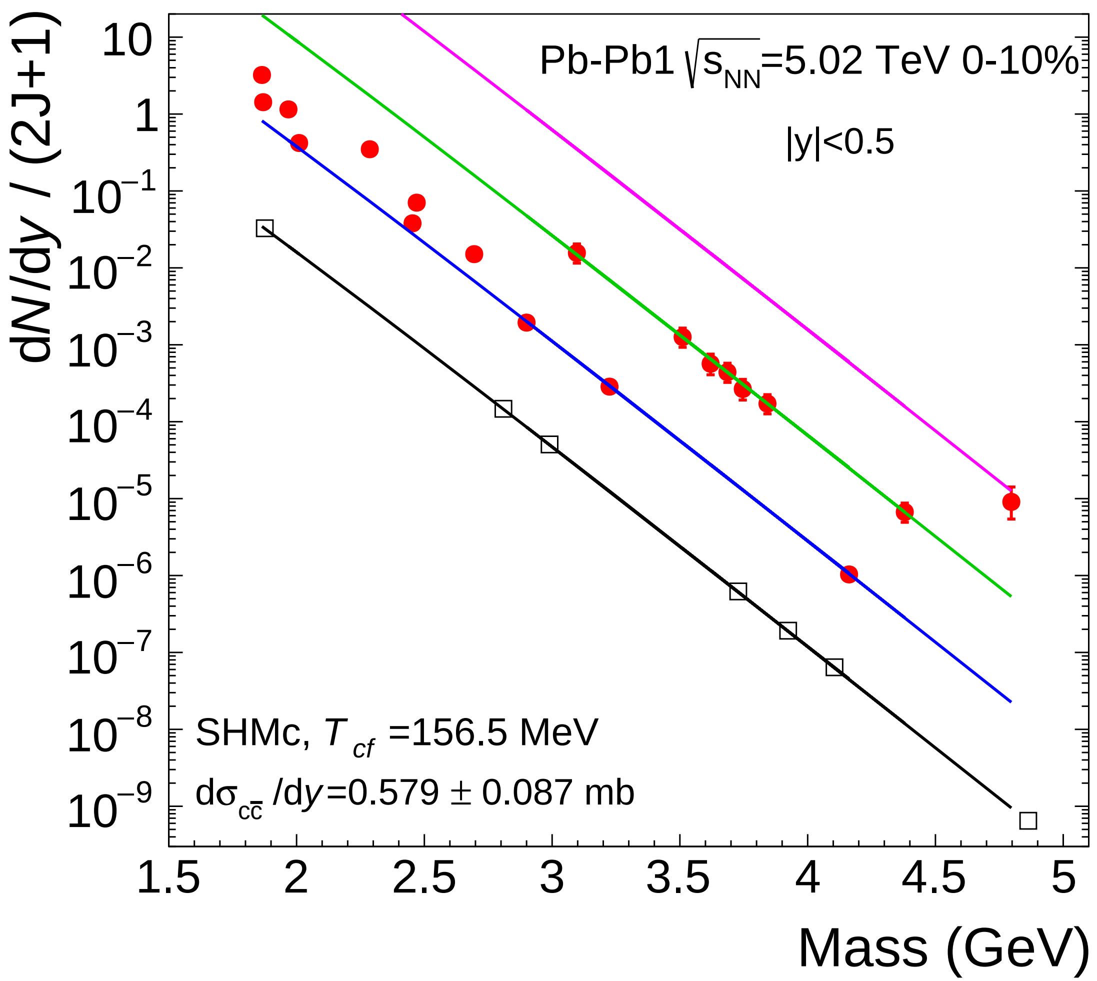
$\frac{dN_{c\bar{c}}}{dy} = 13.8$

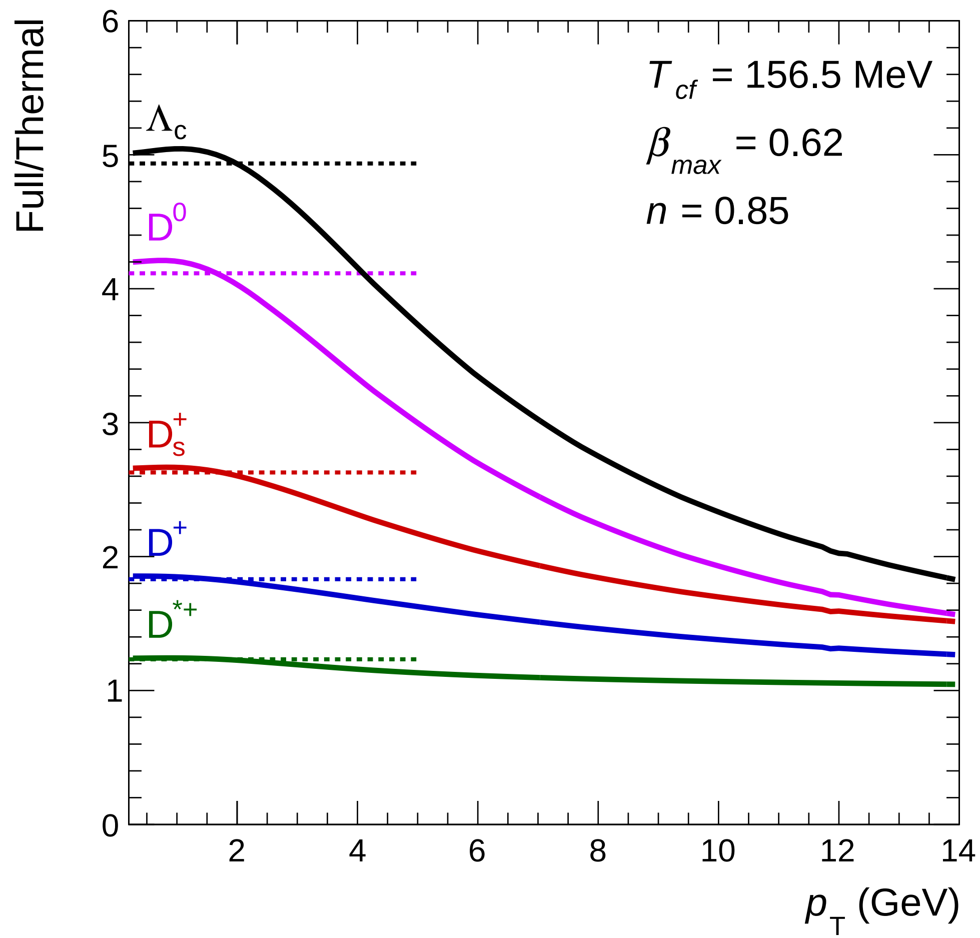
$\rightarrow g_c = 31.5$

The power of the model: predicting the full suite of charmed hadrons

Full charm predictions for the LHC

A. Andronic





Charm-hadron spectrum as in PDG: 55 c-mesons, 74 c-baryons (part.+antipart.)

...large, but may not be complete

JHEP 07 (2021) 035

Charm data and SHMc model

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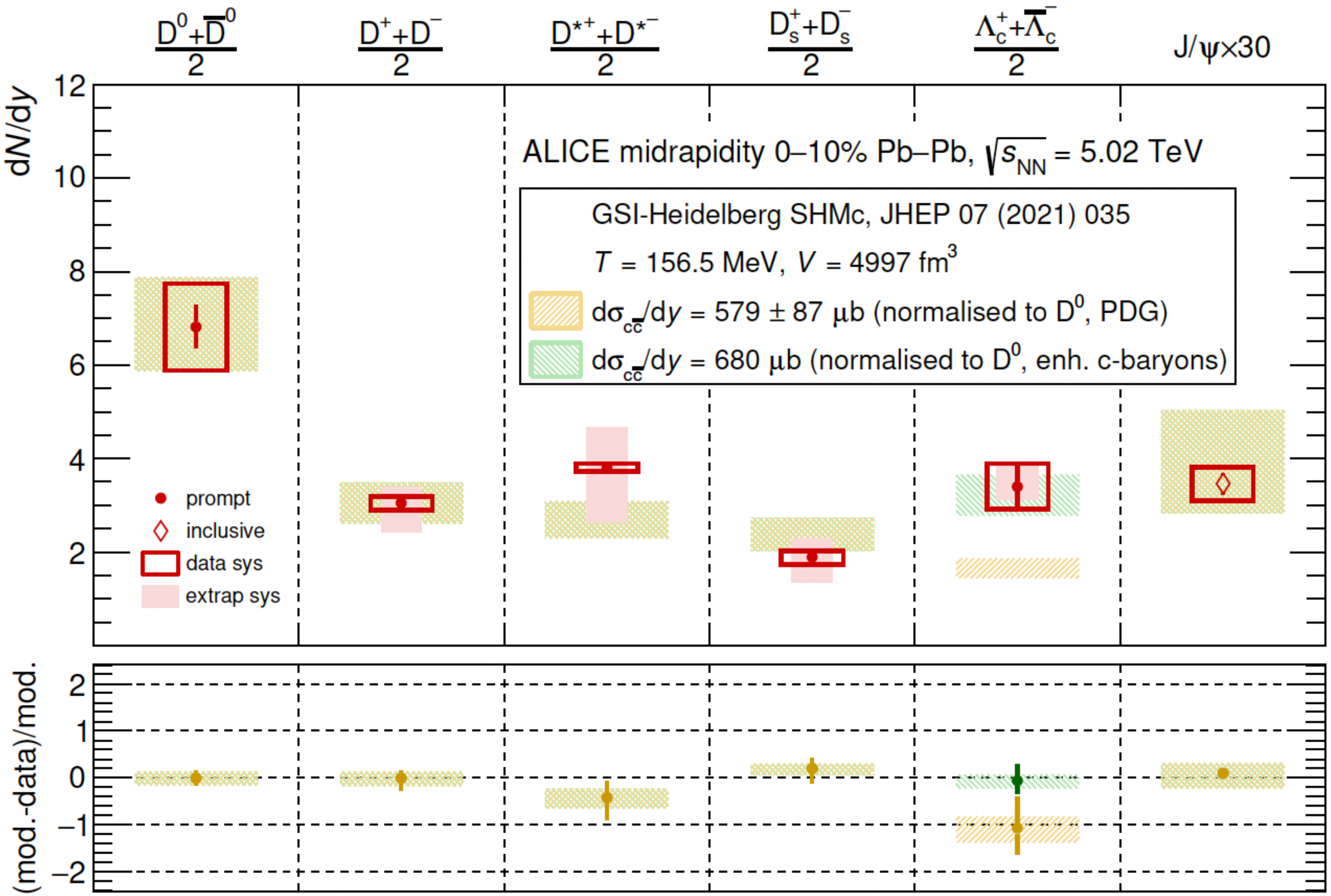


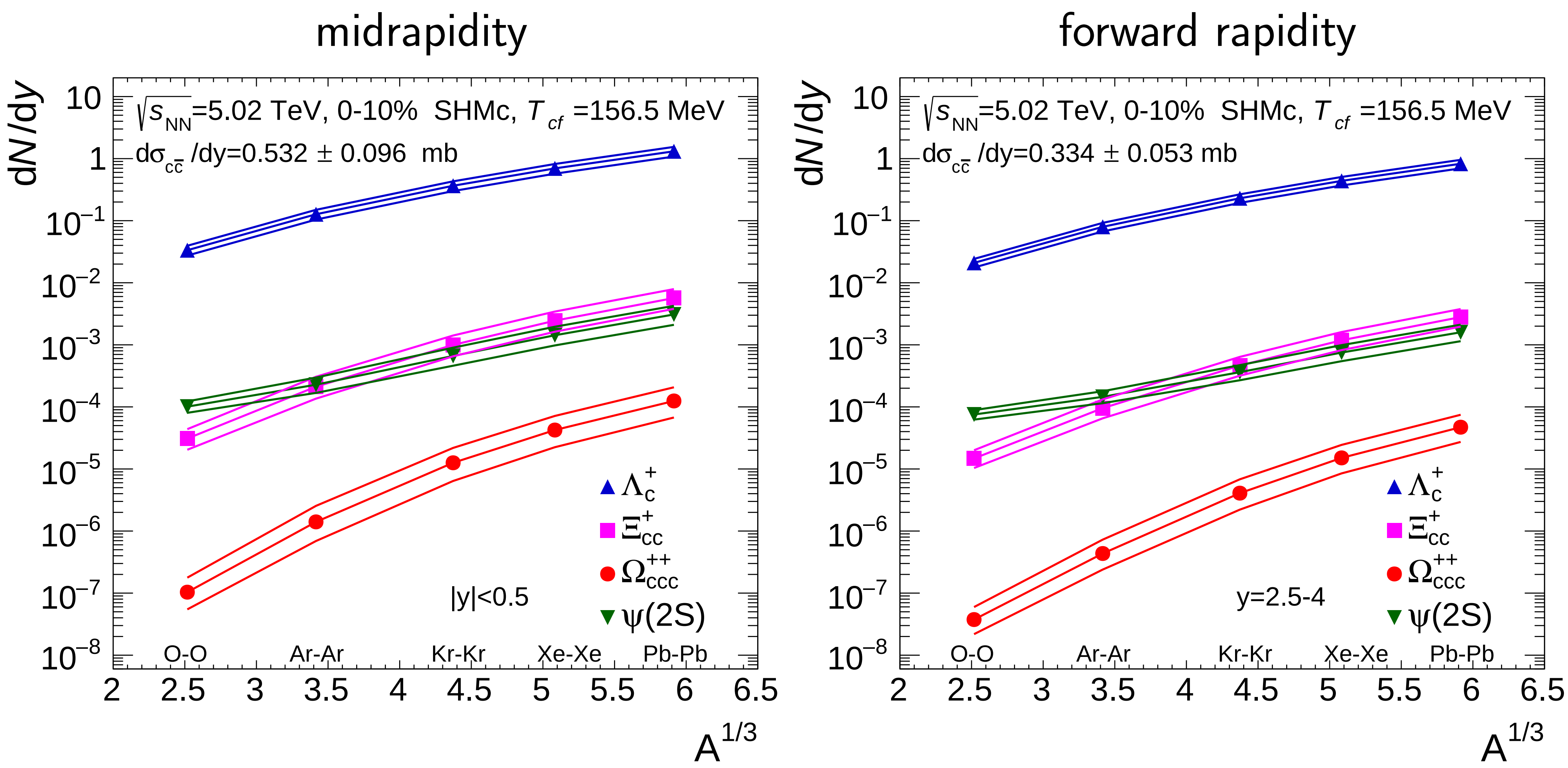
ALICE, arXiv:2212.04348

Enh. c-baryons: *tripled* the excited charm-baryon states, *and* $\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y$: +19%

RQM: He,Rapp, PLB 795 (2019) 117; LQCD, Bazavov et al., PLB 737 (2014) 210

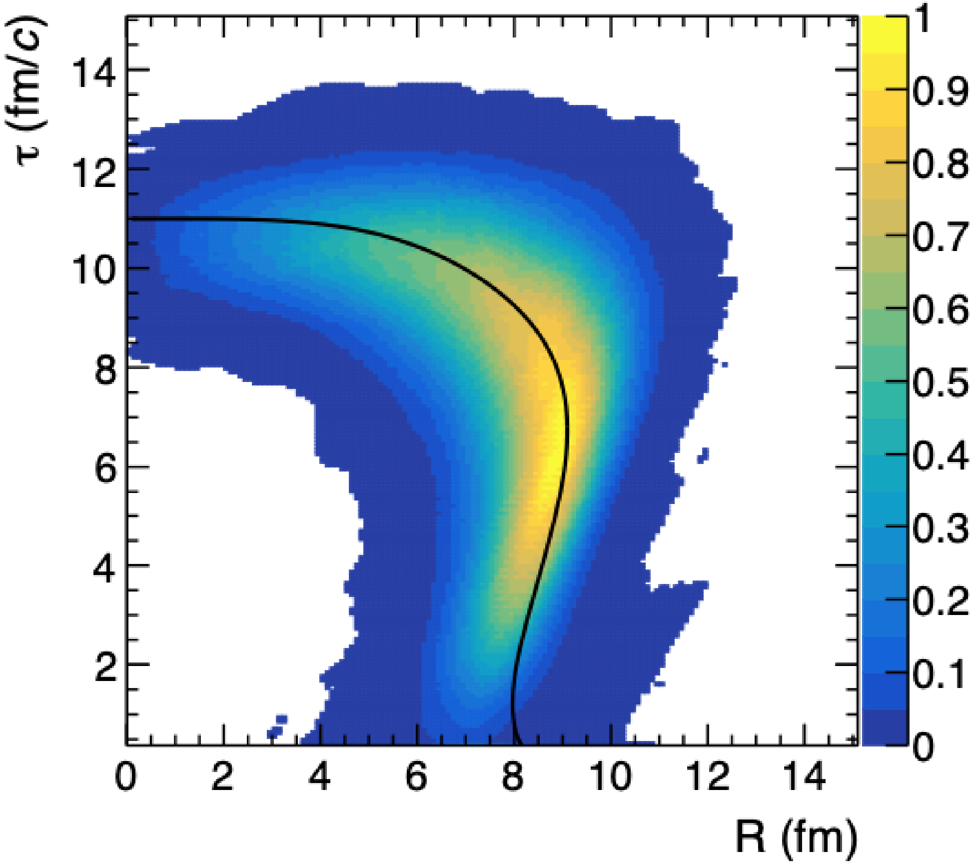
leaves the mesonic sector unaffected, for the commensurately larger $\sigma_{c\bar{c}}$

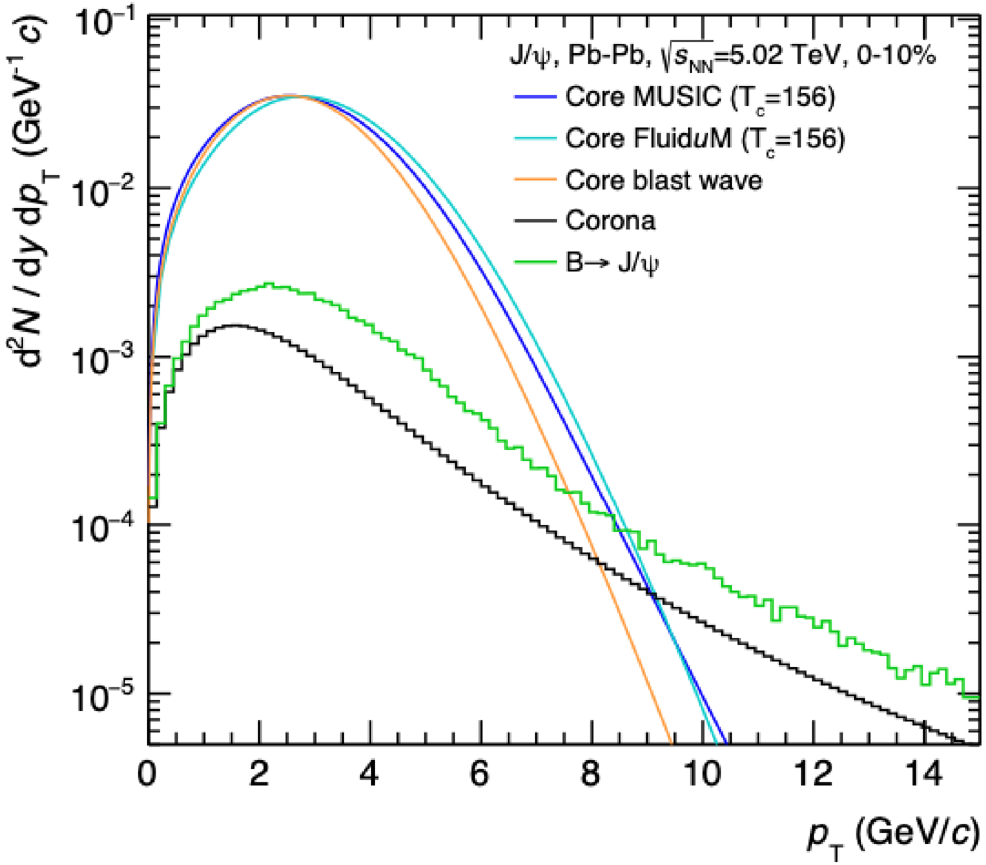
SHMc: system-size dependence (central, 0-10%)



JHEP 07 (2021) 035

SHMc - coupling to hydrodynamics



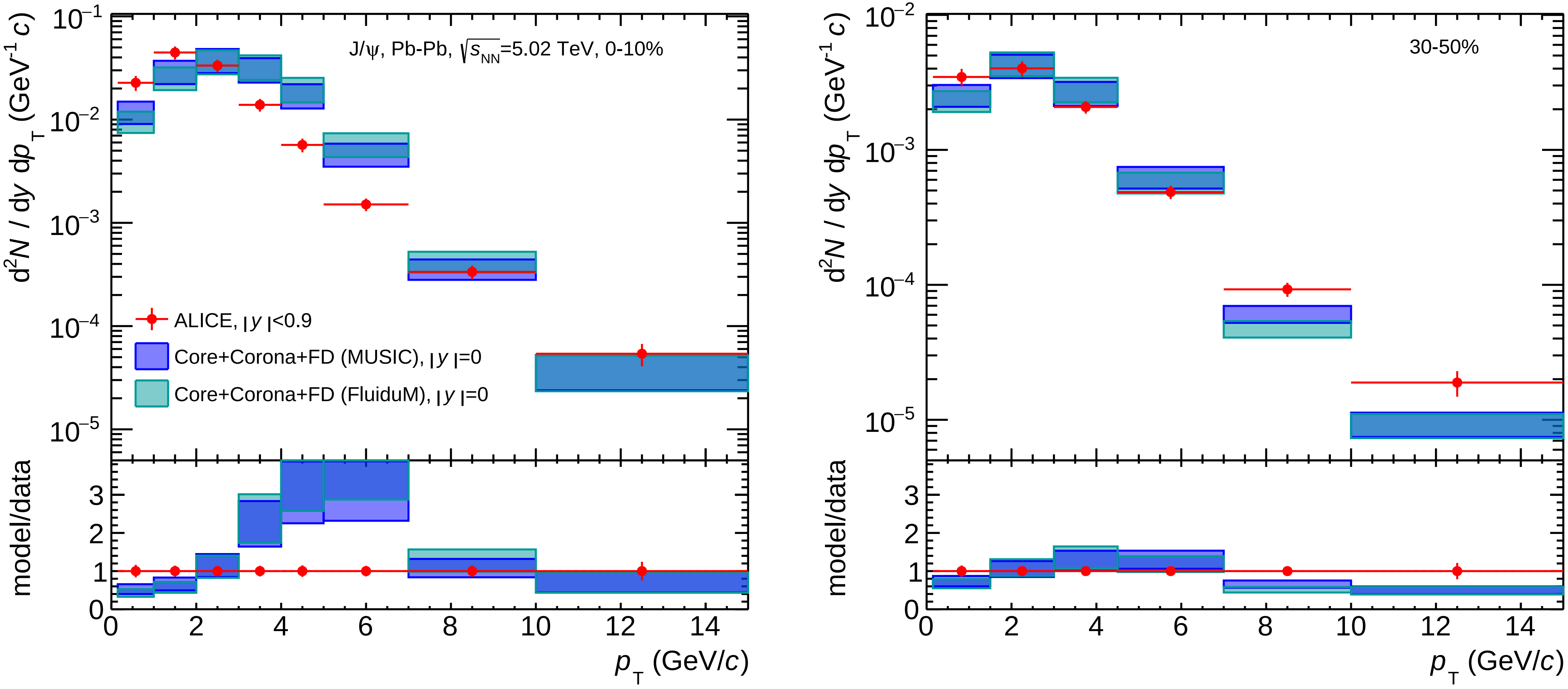


AA, ..., M. Völkl, arXiv:2308.14821

Distribution: MUSIC (IP-Glasma; τ_0=0.4 fm/c)

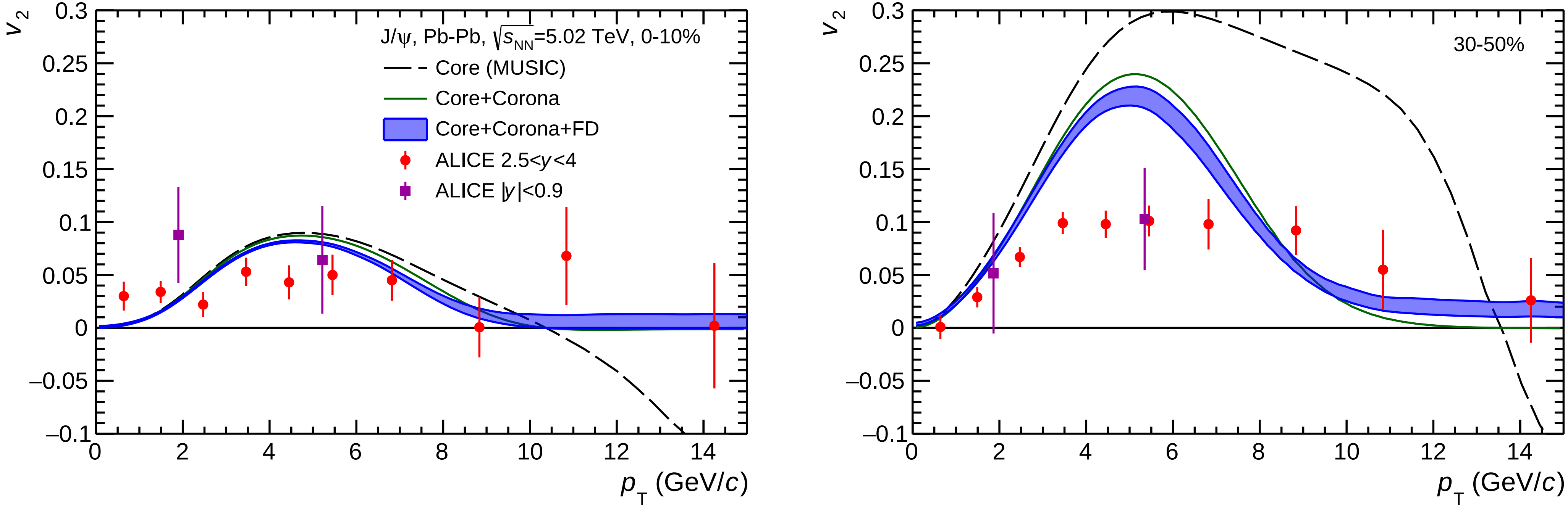
Line: Fluid$u$M (T$_\mathrm{R}$ENTO; τ_0=0.18 fm/c)

SHMc: p_T spectra



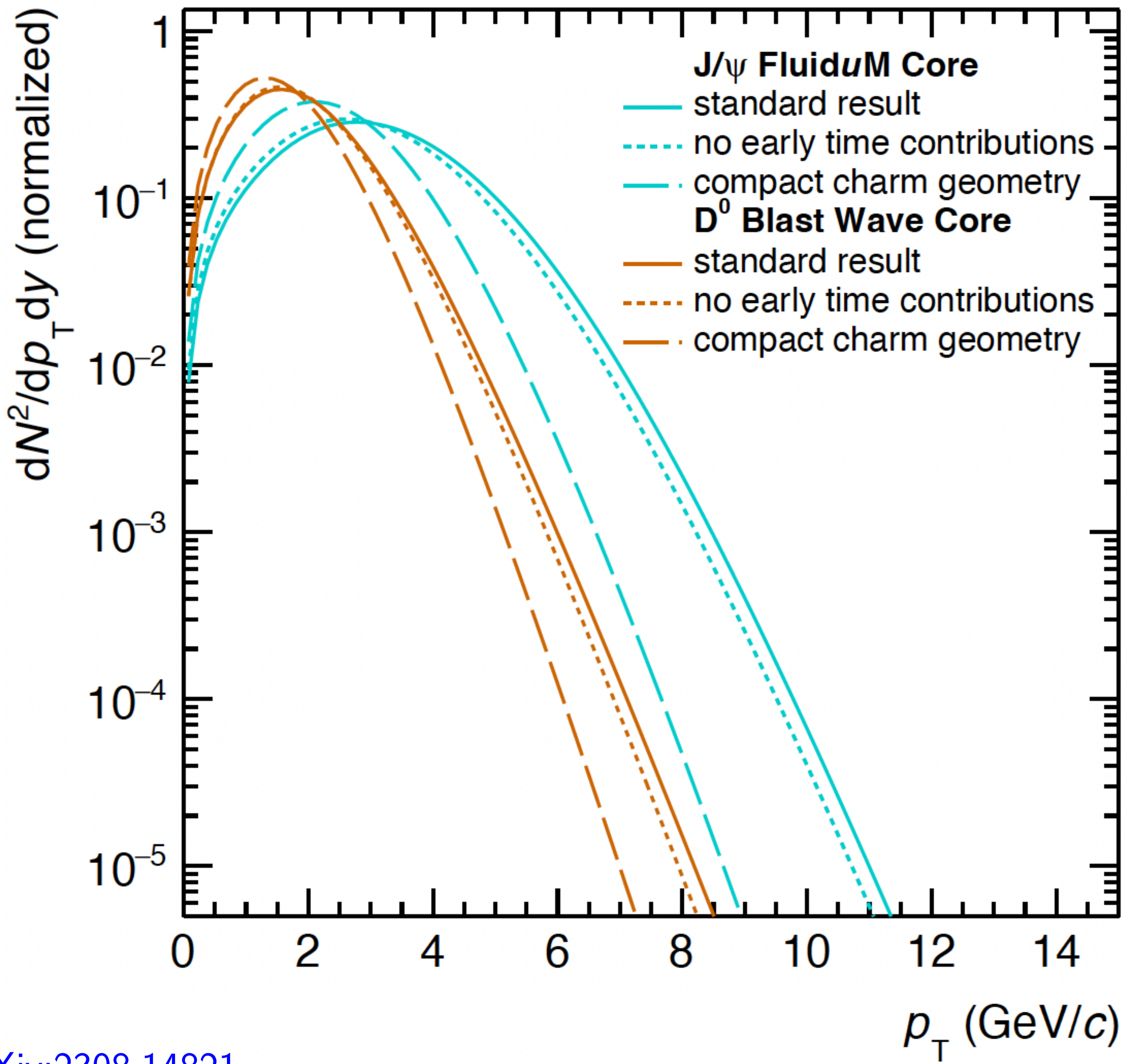
AA, ..., M. Völkl, arXiv:2308.14821

Too strong flow in 0-10% centrality



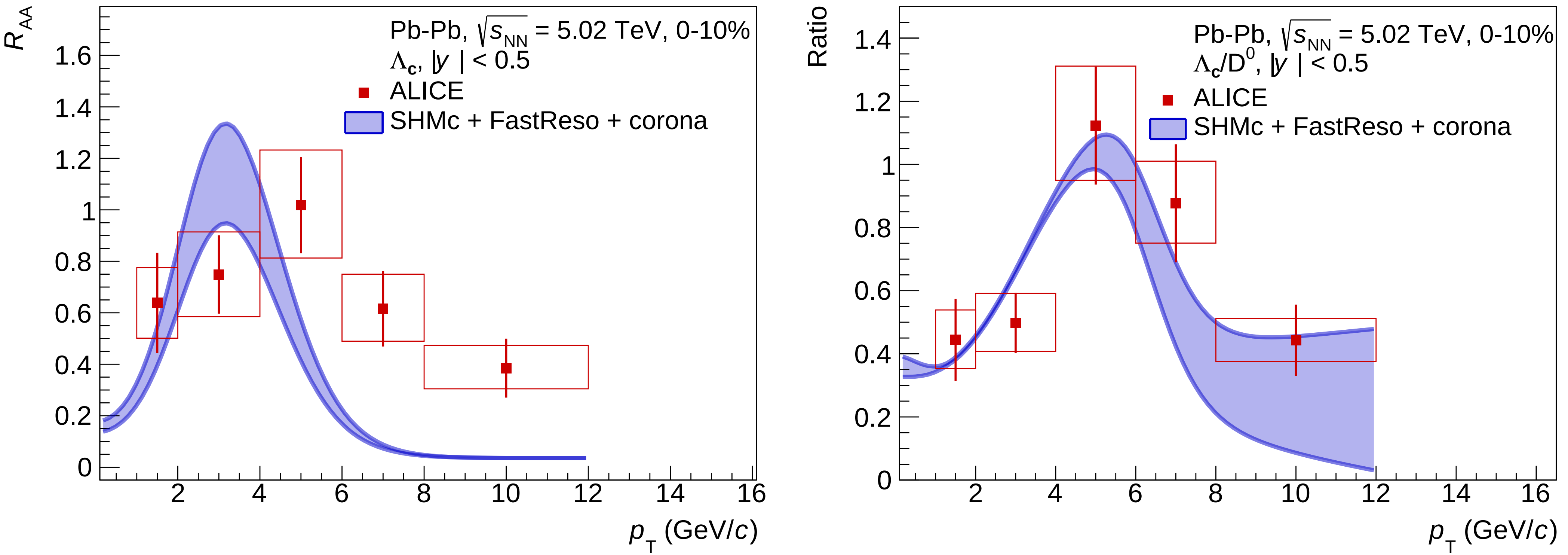
AA, ..., M. Völkl, arXiv:2308.14821

again, we predict too much flow (v_3 is also iverpredicted)



AA, ..., M. Völkl, arXiv:2308.14821

A spatially-mapped N_{coll} distribution needs to be implemented in addition.



AA, ..., M. Völkl, arXiv:2308.14821

Transport models

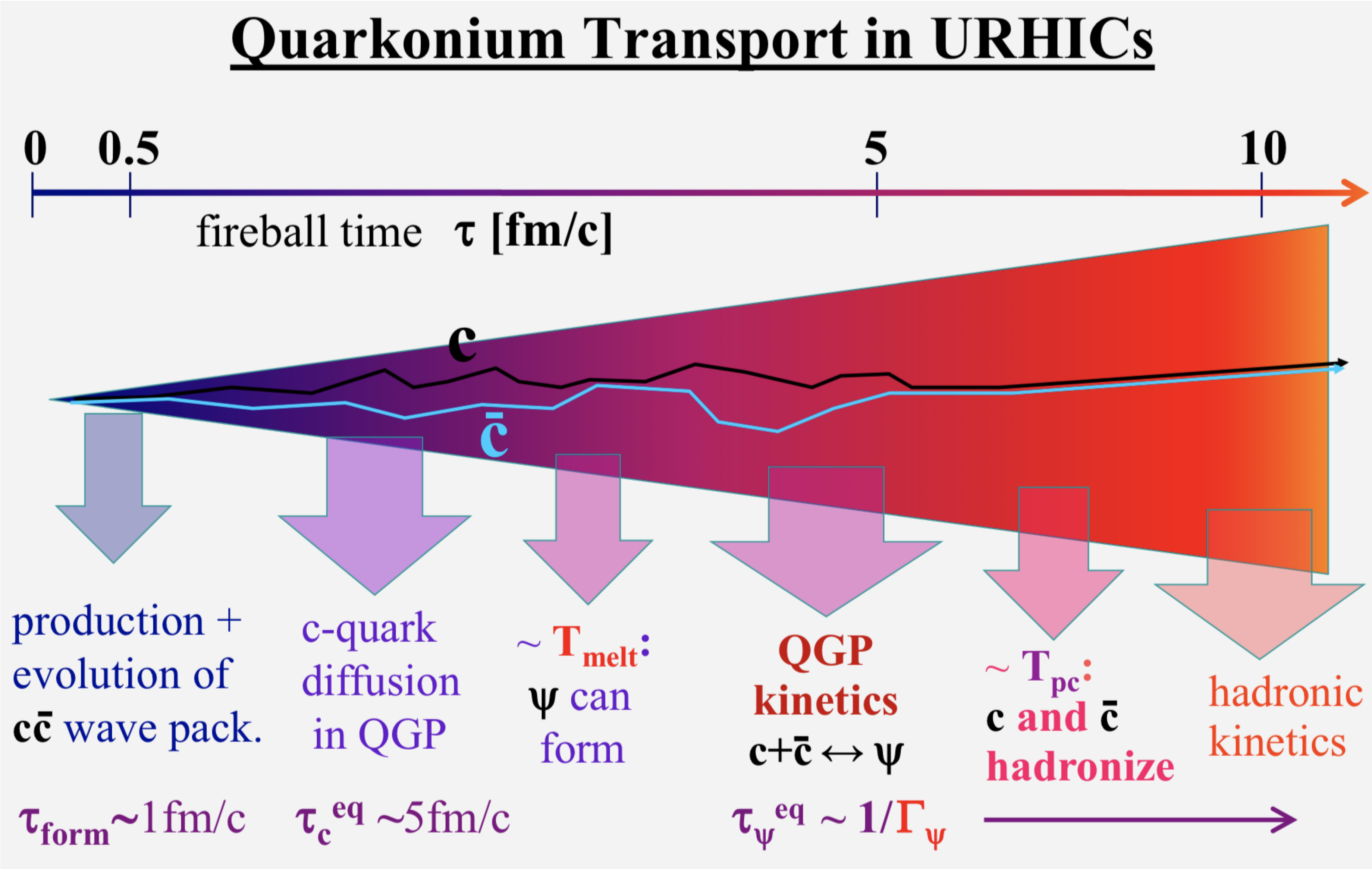
implement screening picture with space-time evolution of the fireball (hydro-like)
continuous destruction and "(re)generation" ("recombination")
Boltzmann equation (loss and gain terms)

Thews et al., PRC 63 (2001) 054905 ...

"TAMU", PLB 664 (2008) 253, NPA 859 (2011) 114, EPJA 48 (2012) 72

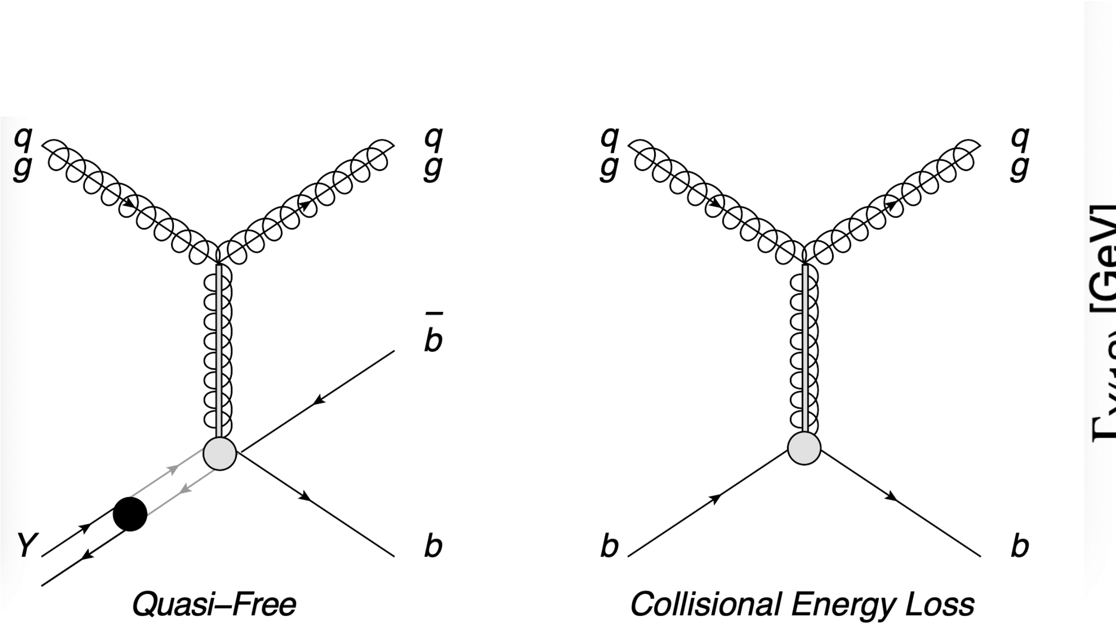
"Tsinghua", PLB 607 (2005) 107, PLB 678 (2009) 72, arXiv:1401.5845

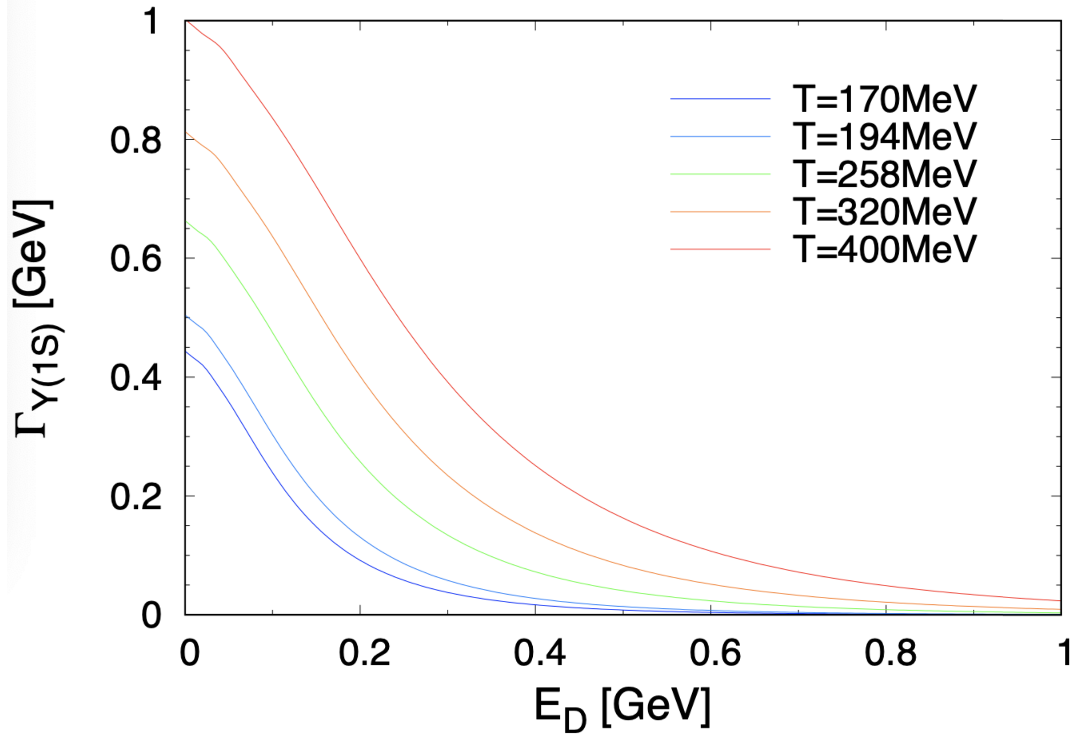
Predicts $R_{AA}, v_2(p_T)$ (TAMU describes D mesons too)



Rapp, Du, arXiv:1704.07923

$$\frac{\mathrm{d}N_\Upsilon}{\mathrm{d}\tau} = -\Gamma(T(\tau))\left[N_\Upsilon(\tau) - N_\Upsilon^{eq}(T(\tau))\right]$$





Du, Liu, Rapp, Phys. Lett. B 796 (2019) 20

Quasi-free = inelastic (dissociation) [imaginary part of HQ potential?]

K factor: enhancement over perturbative results ($K = 5$ in $\Gamma_{\Upsilon(1S)}$ above)

N^{eq}: SHM generation

- "Comovers" model (Santiago):

  (invented to describe suppression in the (final-state) hadronic medium at SPS

  $J/\psi + \pi \to D + \bar{D}$)

  at LHC: gluo-dissociation and a (re)generation component (dominant for J/ψ)

  (the Boltzmann equation of the transport model is also in the comoving system)

  E. Ferreiro at al., PLB 731 (2014) 57

- Hydrodynamic model (Kent State Univ.)

  hydro gives energy density vs. space-time

  suppression probability vs. ε gives R_{AA} (of Y)

  Strickland, Bazow, NPA 879 (2012) 25

...and one more: the quantum approach

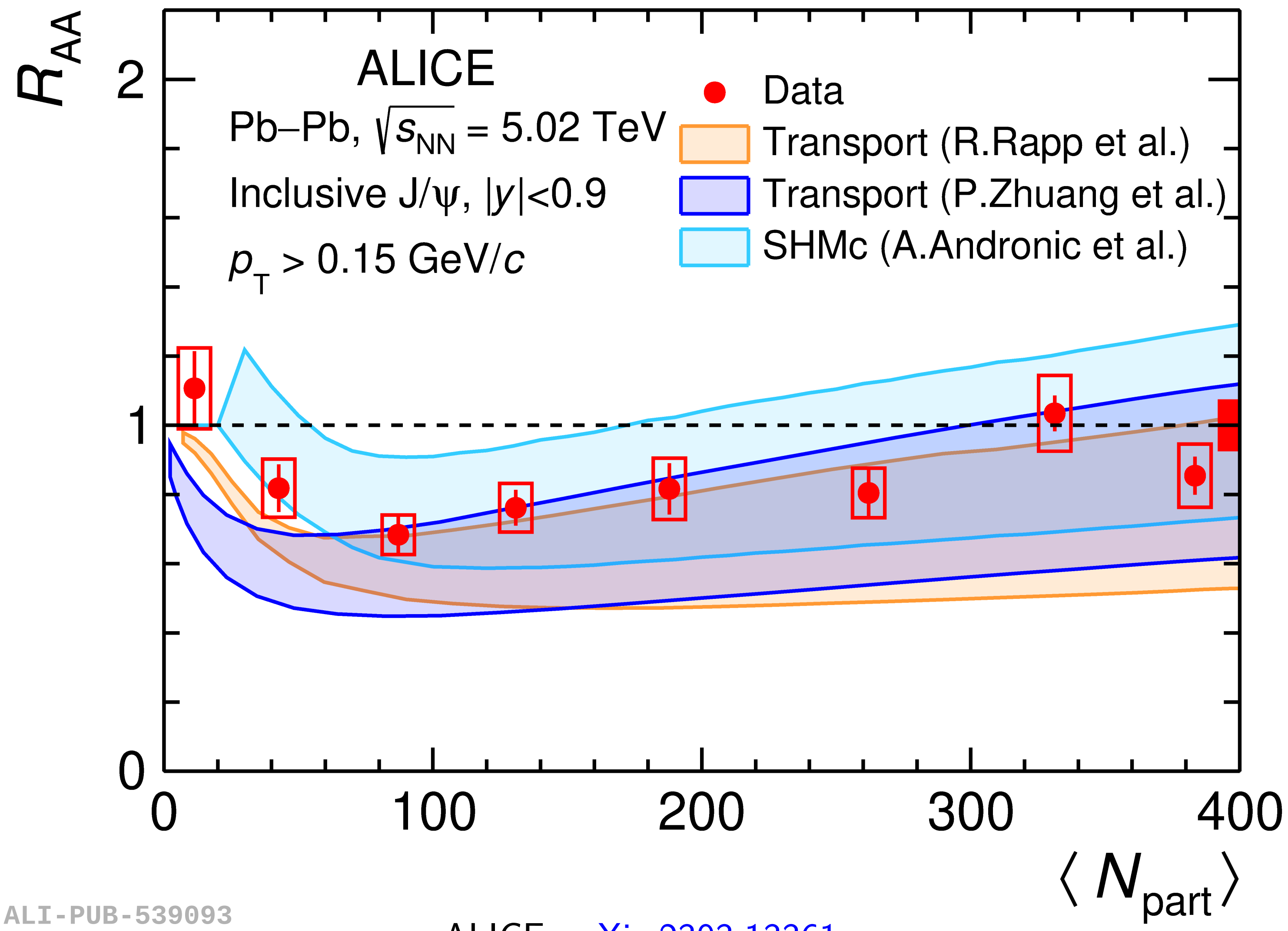
Open quantum systems description + Effective NRQCD theory

quantum evolution of the $\mathrm{b\bar{b}}$ pair in QGP (heat bath; hydrodynamics)

Lindblad equation (accuracy: at NLO in the binding energy over temperature)

Strickland, Thapa, PRD 108 (2023) 014031 and refs therein

SHMc vs. transport models

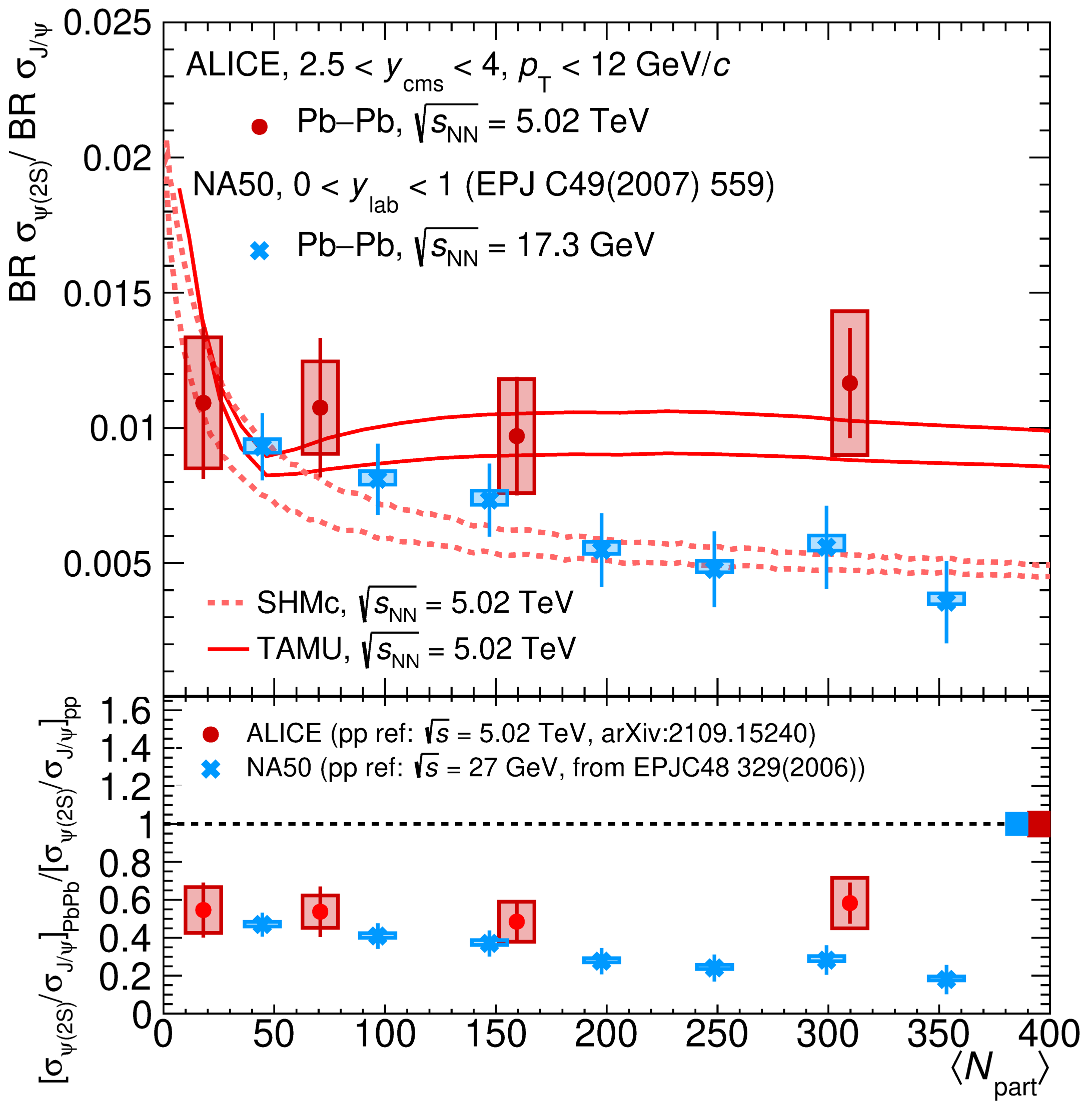


ALICE, arXiv:2303.13361

SHMc: $\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y$ via normalization to D^0 in Pb–Pb 0-10%, ALICE, arXiv:2110.09420

$\mathrm{d}N/\mathrm{d}y = 6.82\pm1.03$ ($|y| < 0.5$; FONLL for y=2.5-4; assuming hadronization fractions in data as in SHMc)

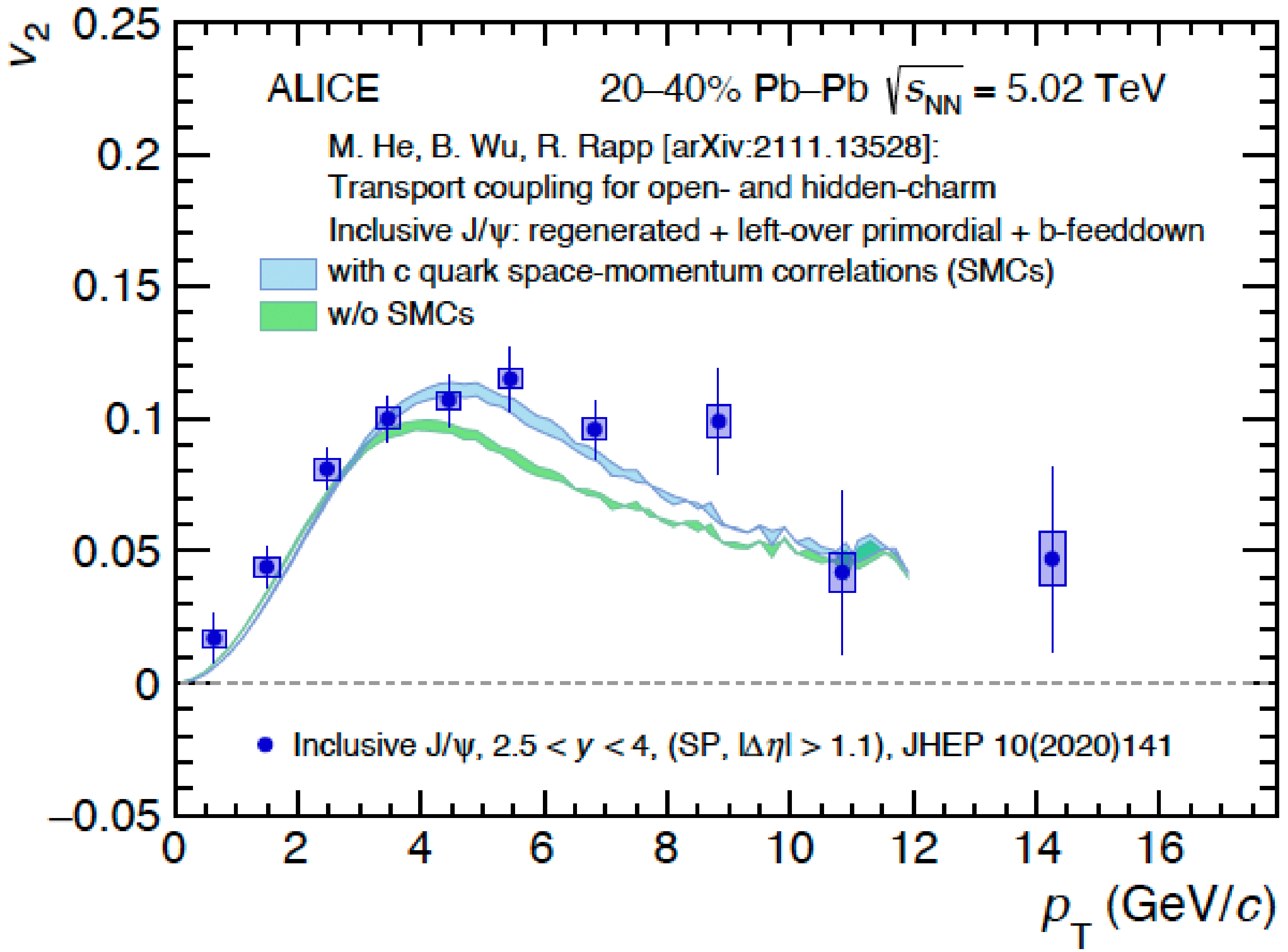
$\psi(2S)/J/\psi$ at the LHC (and SPS)



In SHMc uncertainty only due to nuclear-corona
($\sigma_{c\bar{c}}$ cancels out completely)

ALICE, arXiv:2210.08893

J/ψ elliptic flow: data and transport model



ALICE, arXiv:2212.04348

a very good description of data by the TAMU model PRL 128 (2022) 162301

Beauty quark thermalization?

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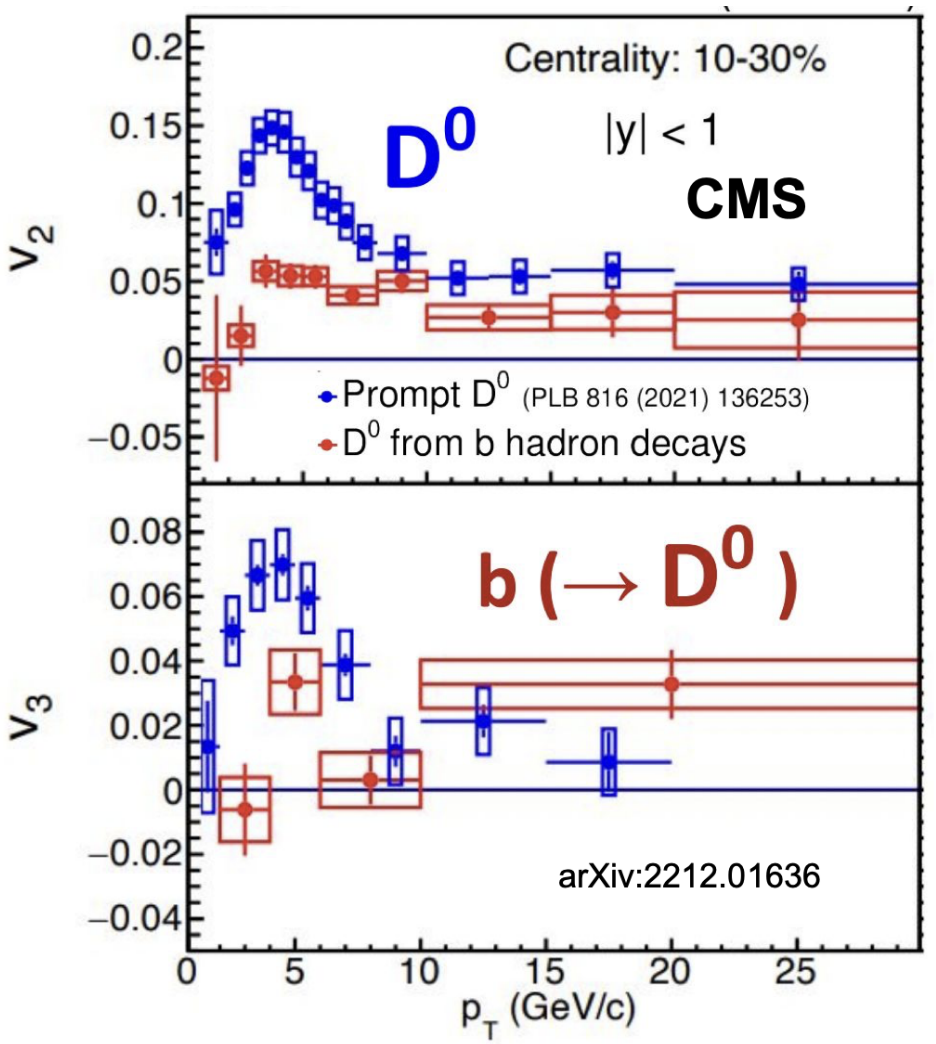
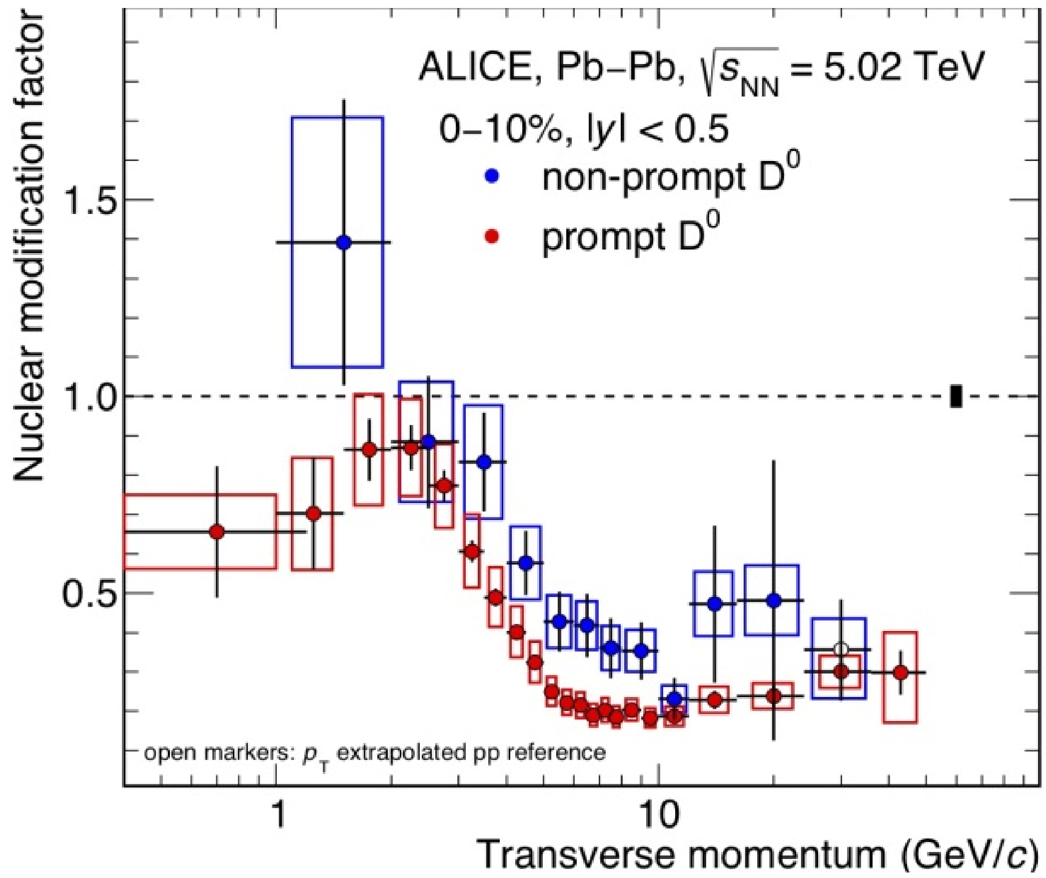




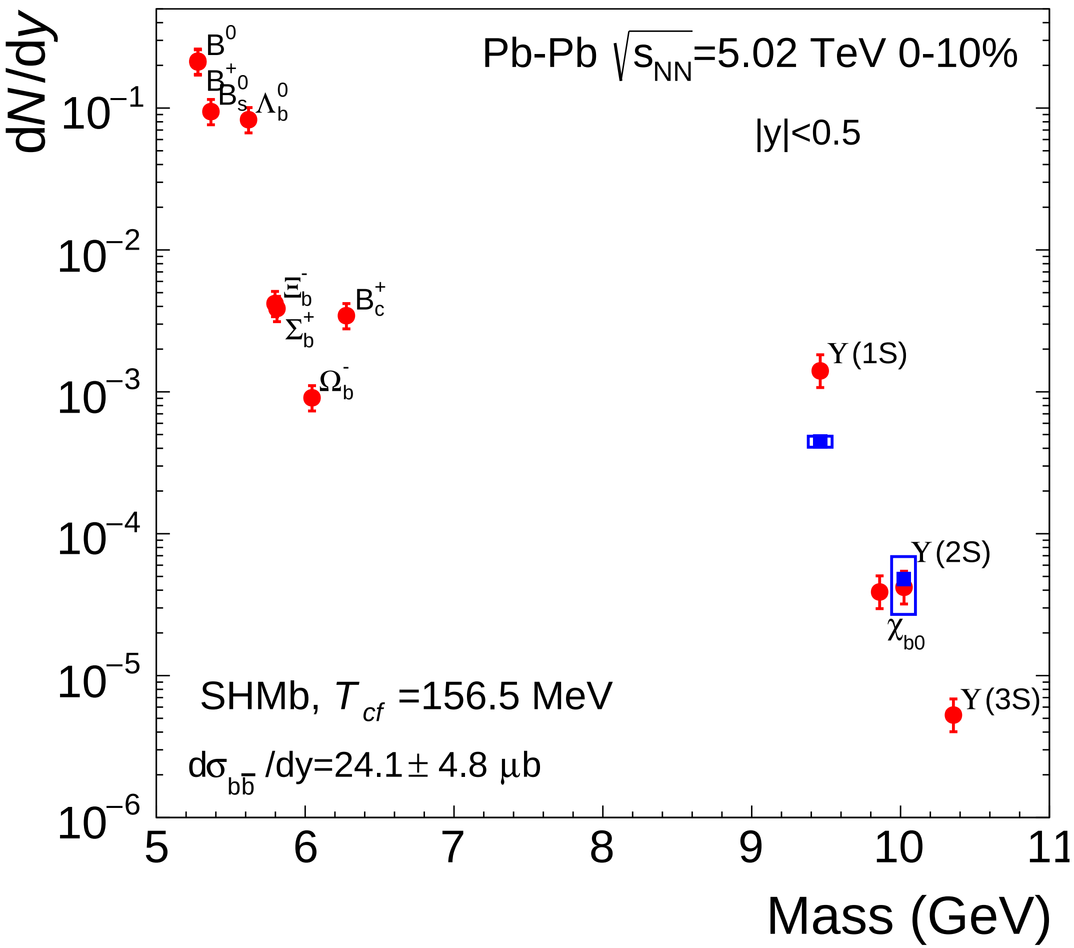
ALICE, arXiv:2202.00815, ATLAS

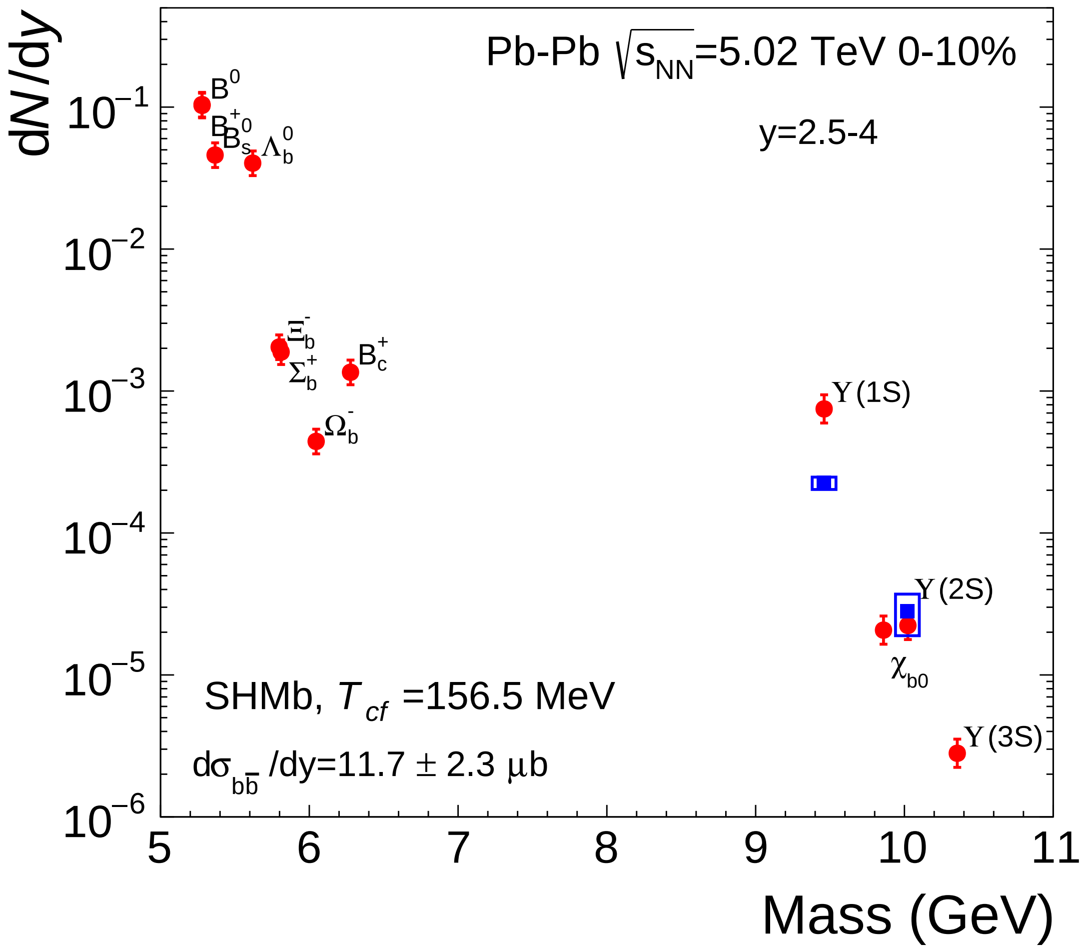
definitely strong flow but clearly less strong than for charm (CMS, QM'22, HIN-21-003)

...and a strong coupling with the medium (less energy loss than charm, $p_T \simeq 10$ GeV/c)

The limiting case: full beauty thermalization

A. Andronic





$$g_b = 1.05 \cdot 10^9 \quad (\frac{dN_{b\bar{b}}}{dy} = 0.57)$$

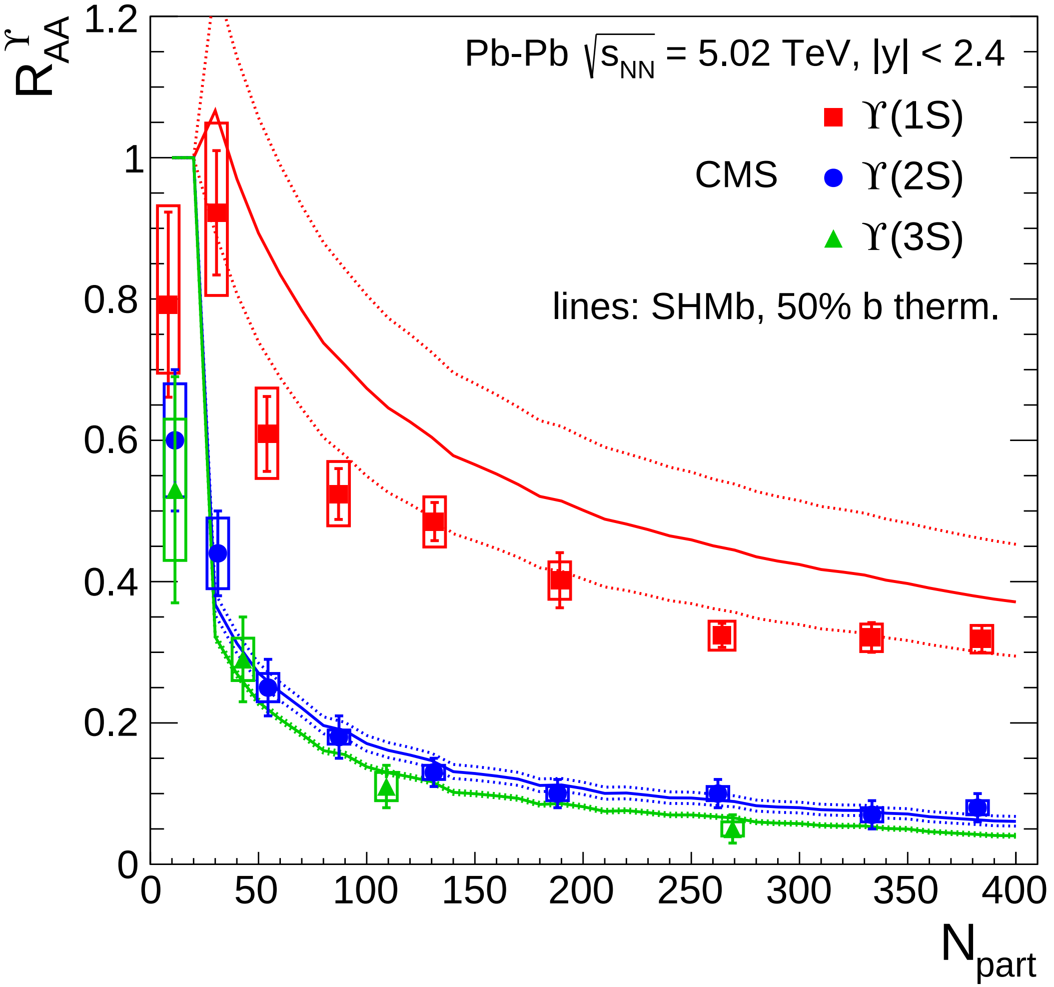
$$B_c : \ 3.44 \cdot 10^{-3}$$

$$g_b = 0.86 \cdot 10^9 \quad (\frac{dN_{b\bar{b}}}{dy} = 0.28)$$

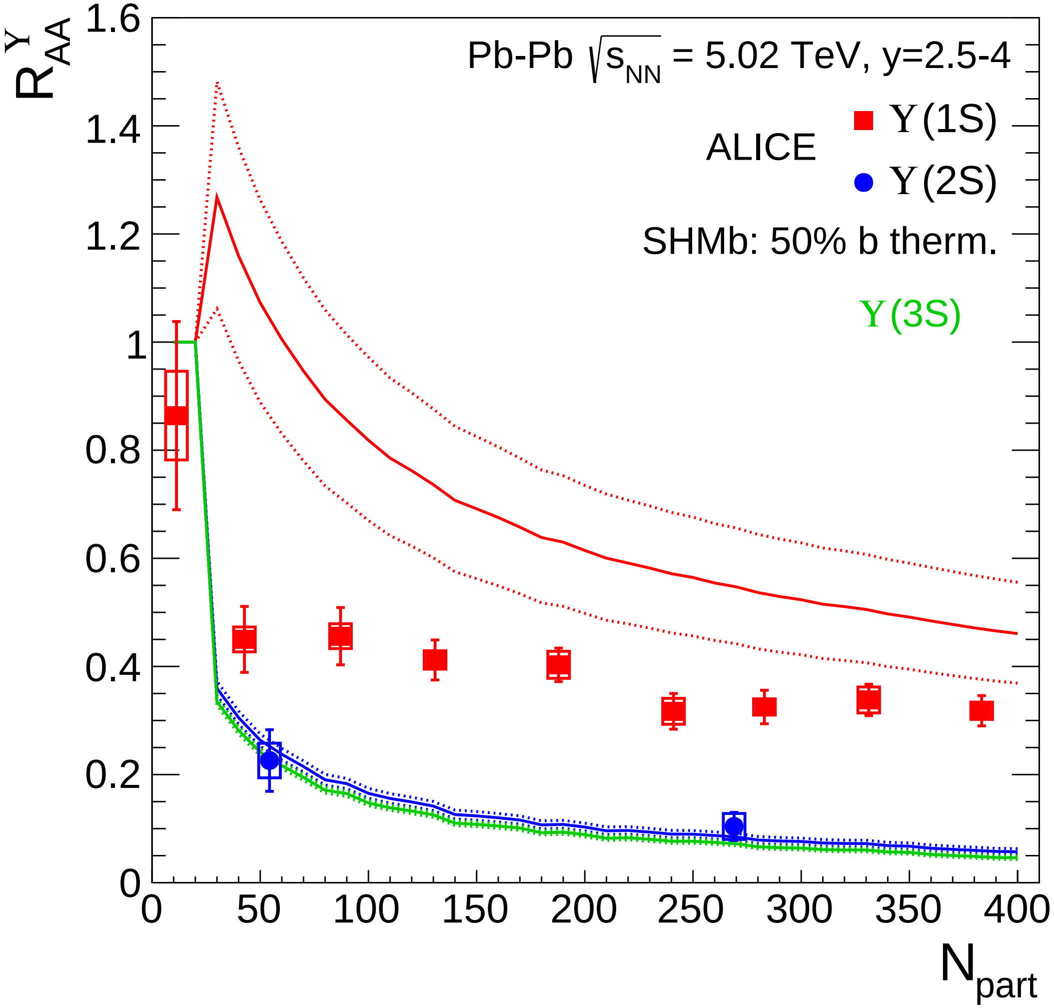
$$B_c : \ 1.36 \cdot 10^{-3}$$

Blue: Υ data (CMS, ALICE): calc. based on R_{AA} and pp (would be nice to include in publications dN/dy)

R_{AA}, 50% $\mathrm{b\bar{b}}$ thermalized



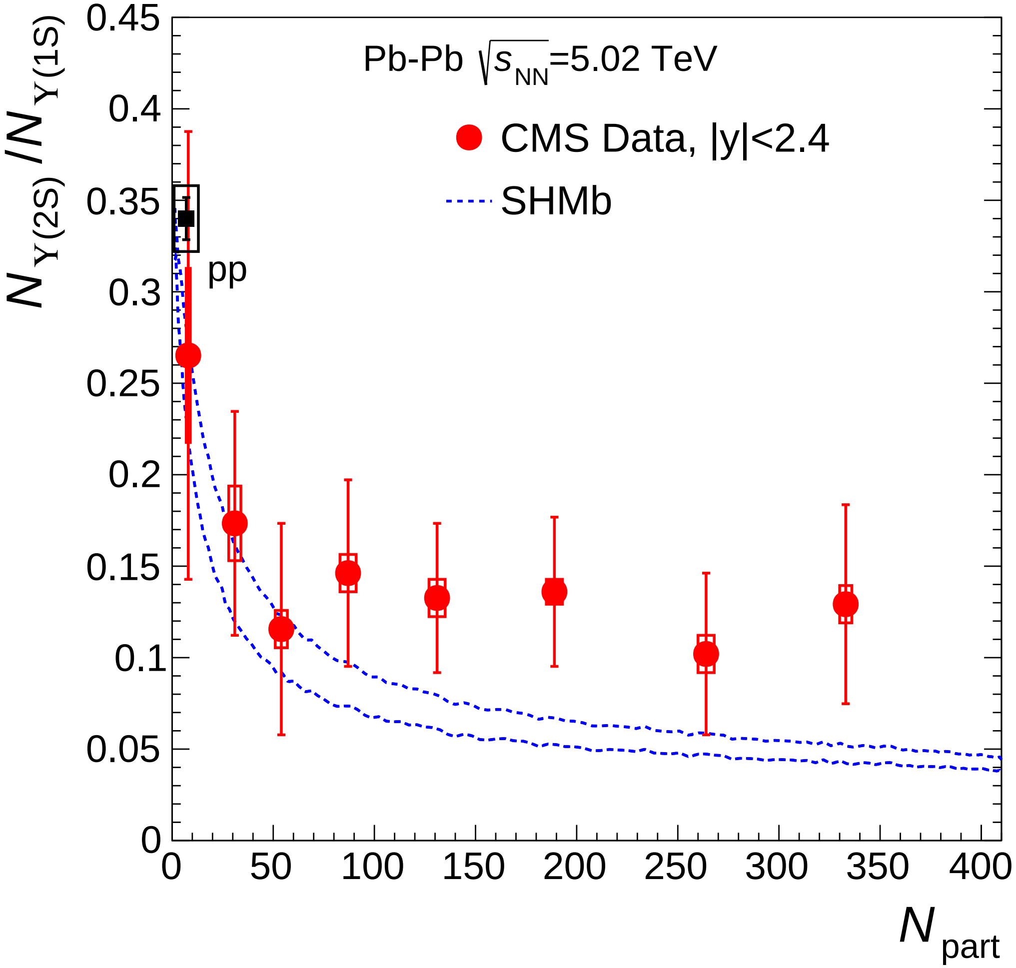
CMS, PRL 120 (2018) 142301

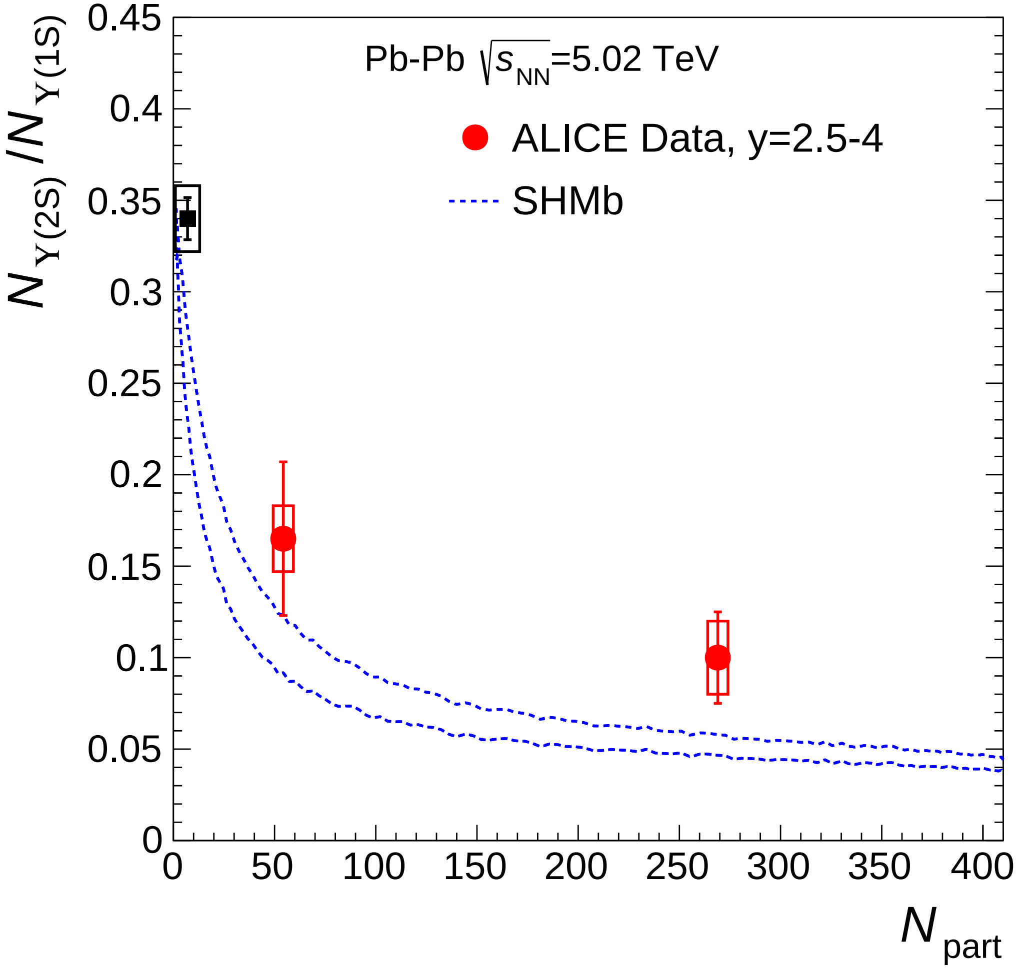


ALICE, PLB 822 (2021) 136579

What does non-thermalized beauty produce? (no room for it in SHMb)

$\Upsilon(2S)/\Upsilon(1S)$ ratio (100% b thermalization)





CMS, PRL 120 (2018) 142301

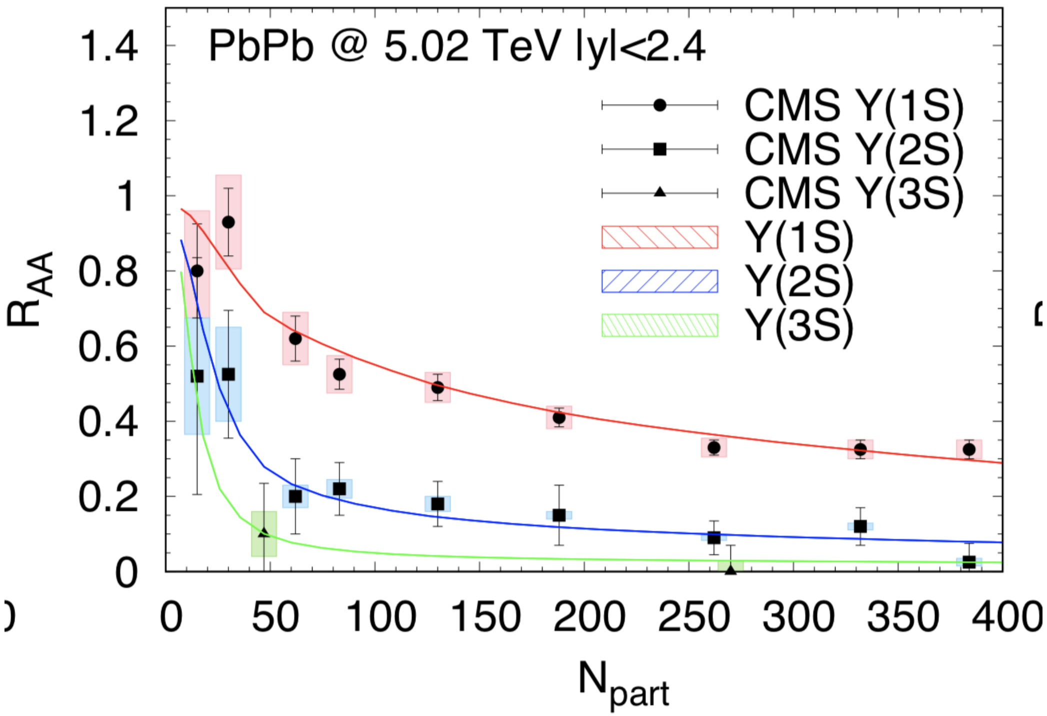
ALICE, PLB 822 (2021) 136579

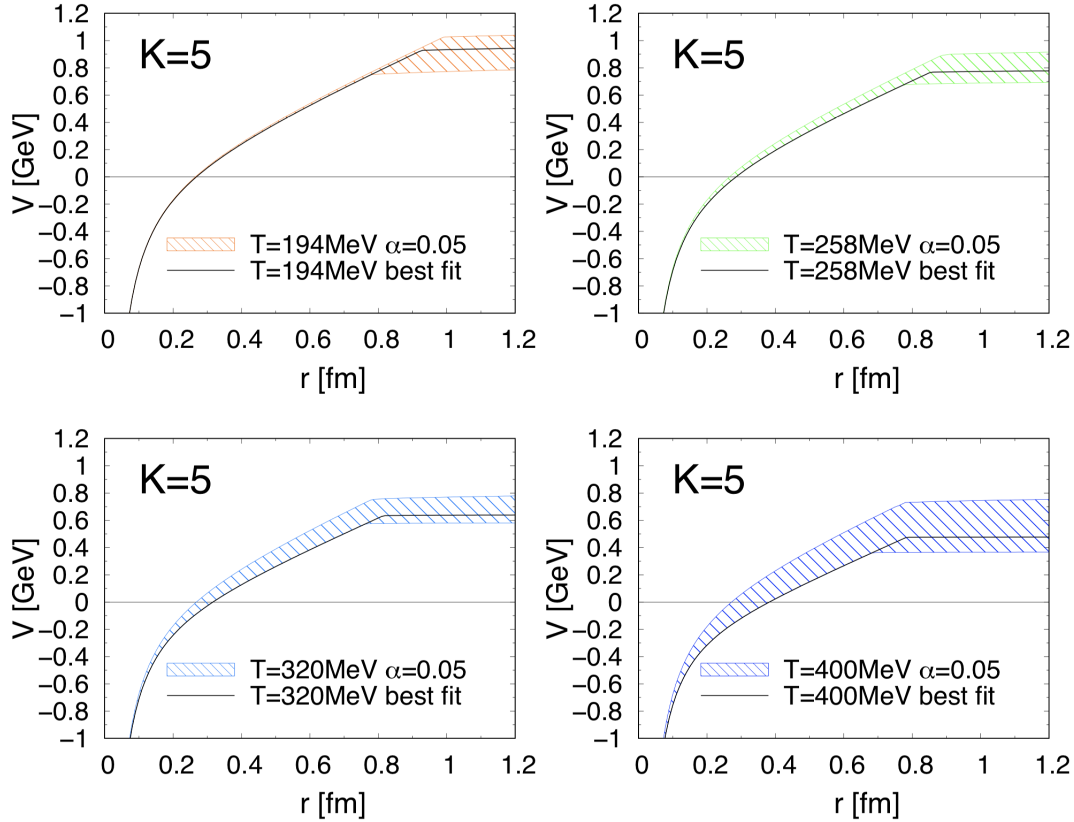
ALICE pp: $\Upsilon(2S)/\Upsilon(1S) = 0.5 \pm 0.1$, arXiv:2109.15240

SHMb uncert.: nuclear-corona (fraction)

Υ description in the transport model

...is very good; allows extraction of in-medium (Cornell) potential



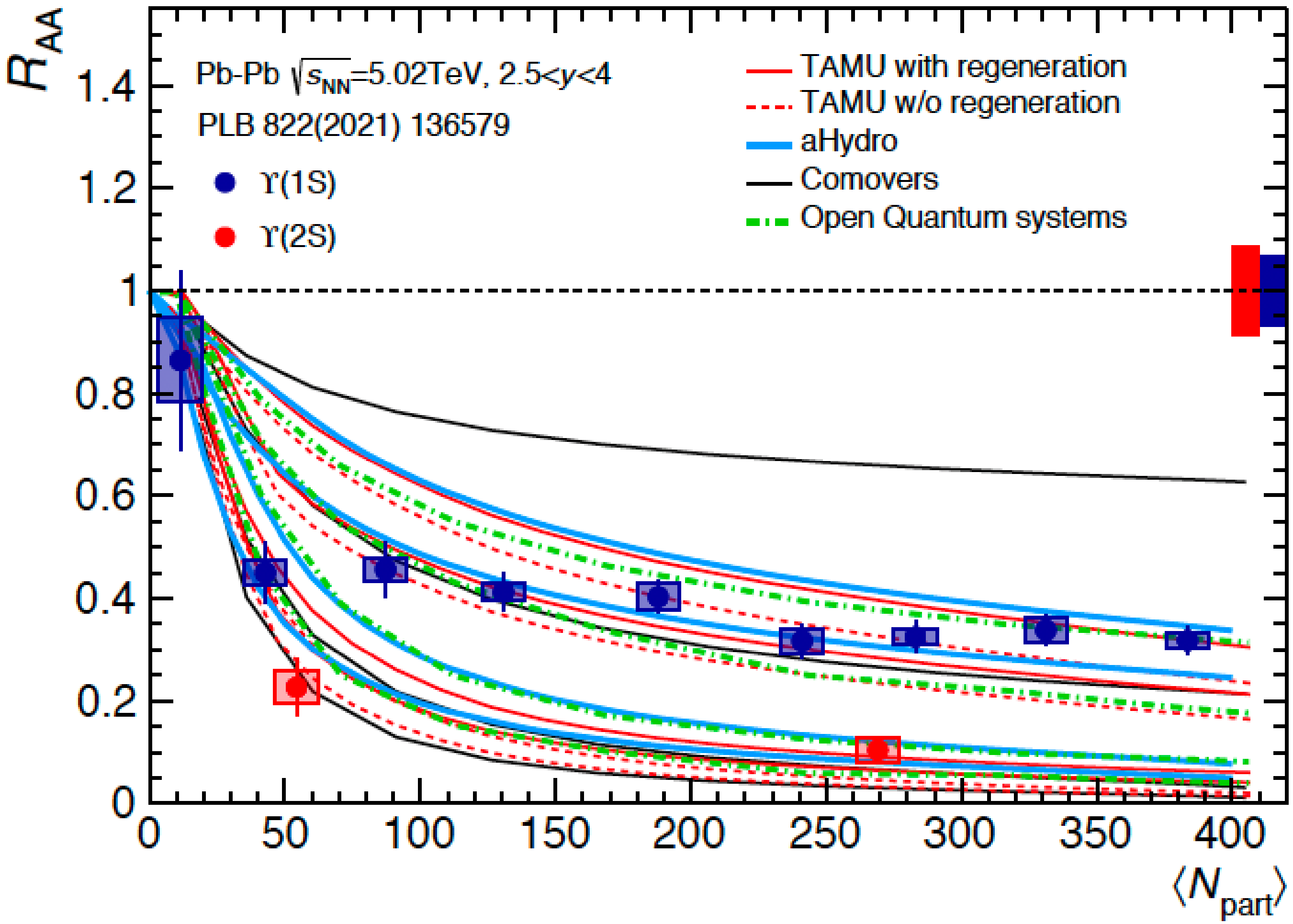


(re)generation important for $\Upsilon(2S)$

Transport Model (TAMU), Du, Liu, Rapp, PLB 796 (2019) 20

Substantial remnants of the long-range color confining force in QGP

Υ suppression data and models



ALICE, arXiv:2212.04348

All models (except perhaps Comovers ...large uncert.) reproduce the data well

TAMU: Regeneration important for $\Upsilon(2S)$

Summary / Conclusions: charm

- Charm quarks seem to thermalize very effectively (close to 100%) in QGP
- SHM: all charmonium *and open charm states* are generated exclusively at hadronization (chemical freeze-out) ...full color screening

  The model is very successful in reproducting the J/ψ and open charm data

  A handle for hadronization T with a mass scale well above T

- Transport models: continuous J/ψ destruction and (re)generation in QGP

  (only up to 2/3 of the J/ψ yield (LHC, central collisions) originates from deconfined c and $\bar{c}$ quarks)

  Discriminating the two pictures implies providing an answer to fundamental questions related to the fate of hadrons in a hot deconfined medium.

  A precision ($\pm$10%) measurement of $\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y$ in Pb-Pb (Au-Au) collisions needed for a stringent test

  (within reach with the upgraded detectors at the LHC and RHIC)

Summary / Conclusions: beauty

- Full beauty thermalization seems not realized in nature

  ...with 30-50% of beauty quarks fully thermalized SHM can explain the Υ data

  ...but this fraction is (significantly) dependent on the b-hadron spectrum

  What does non/partially-thermalized beauty produce?

  no Υ because strong coupling with the medium destroys the b-$\bar{b}$ correlation?

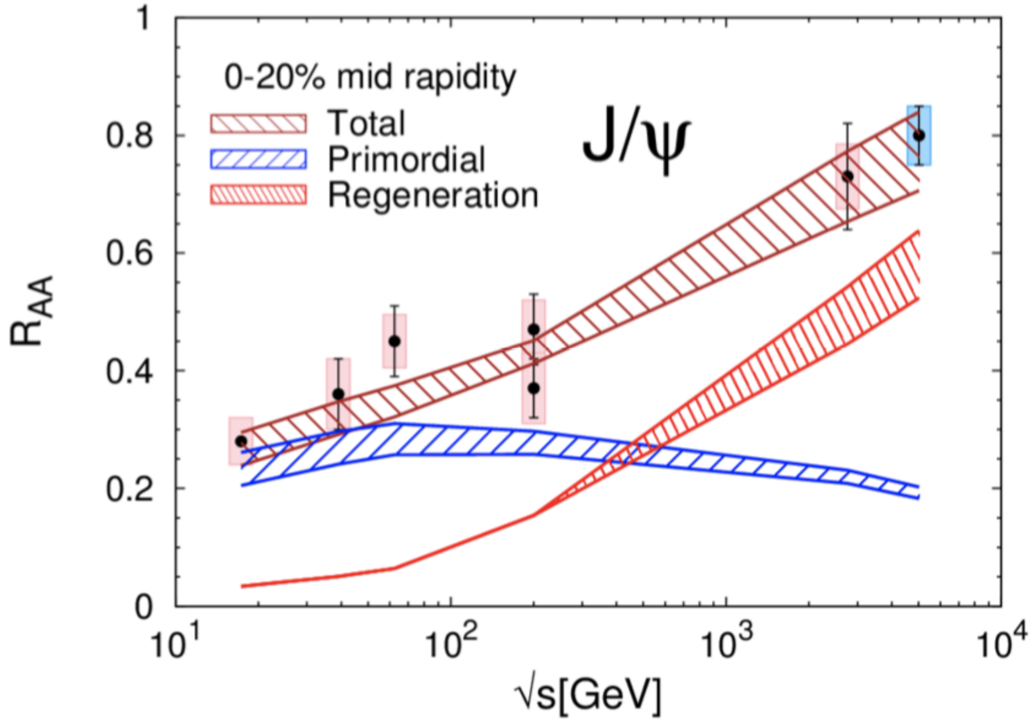
- Transport and Hydro models are successfully reproducing Υ suppression

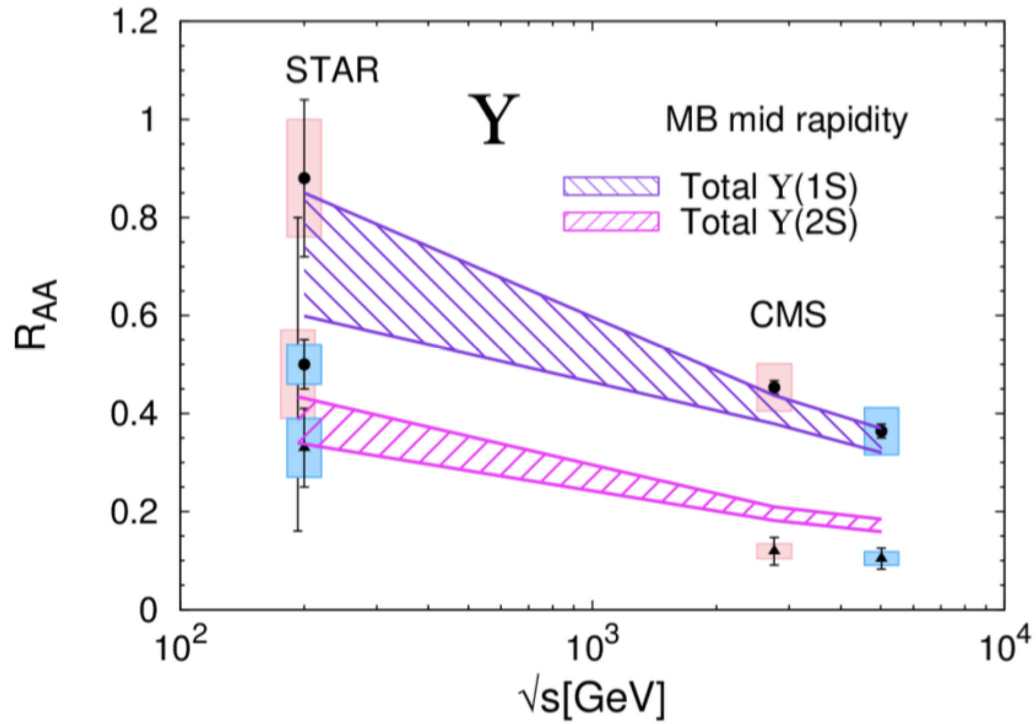
  Transport: regeneration important for $\Upsilon(2S)$ (at the LHC)

- Quantum approaches on strong rise

Additional material

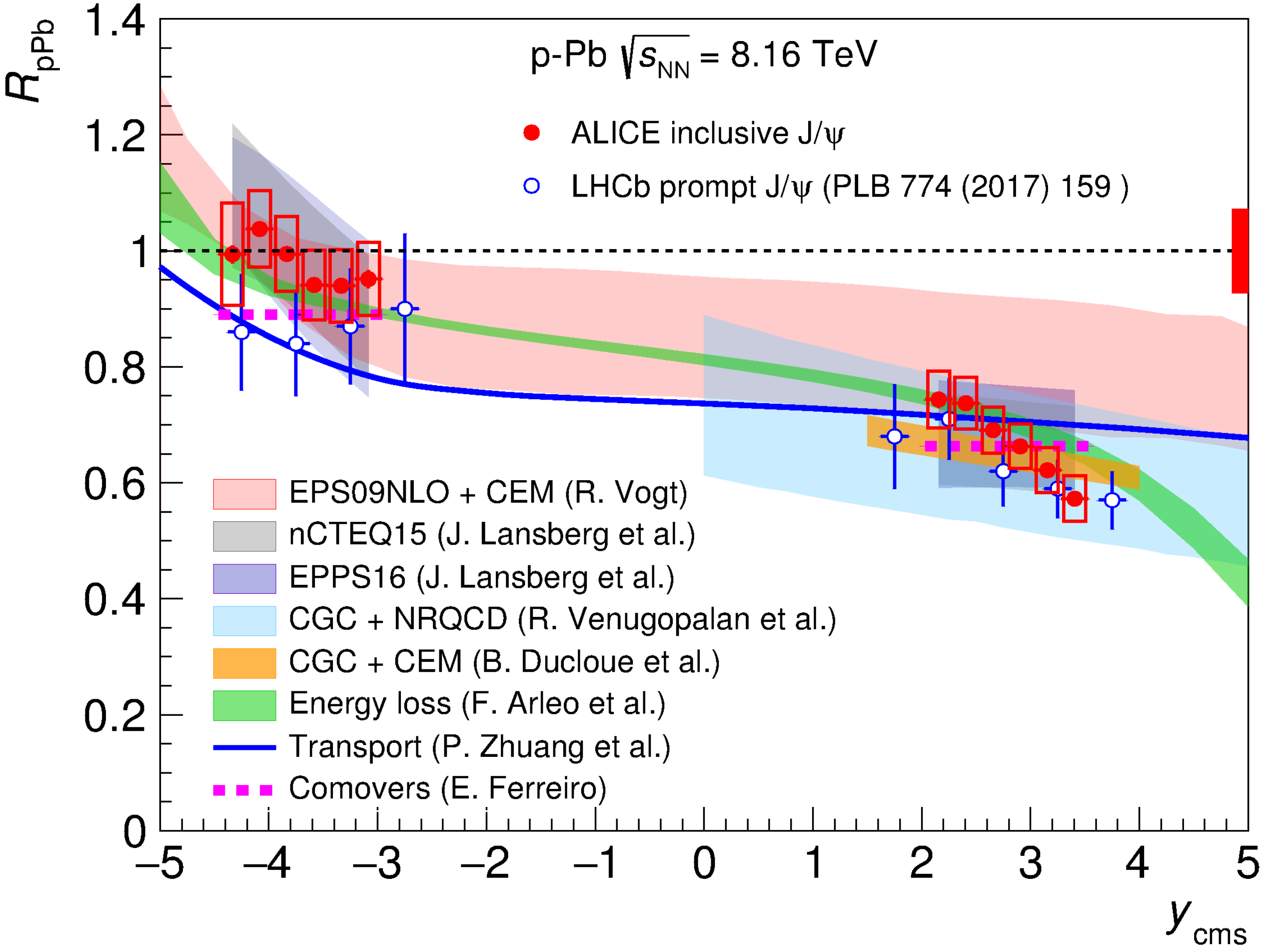
Fractions primordial, (re)generated - energy dependence





Rapp, Du, arXiv:1704.07923

J/ψ production in p–Pb collisions



$7 \cdot 10^{-3} \lesssim x \lesssim 3 \cdot 10^{-2}$ $10^{-5} \lesssim x \lesssim 5 \cdot 10^{-5}$

$$R_{\rm pPb} = \frac{{\rm d}N_{\rm pPb}/{\rm d}p_{\rm T}{\rm d}y}{\langle N_{\rm coll}^{\rm pPb}\rangle \cdot {\rm d}N_{\rm pp}/{\rm d}p_{\rm T}{\rm d}y}$$

$$\langle N_{\rm coll}^{\rm pPb}\rangle \simeq 7$$

Shadowing describes data (shadowing uncert. are large)

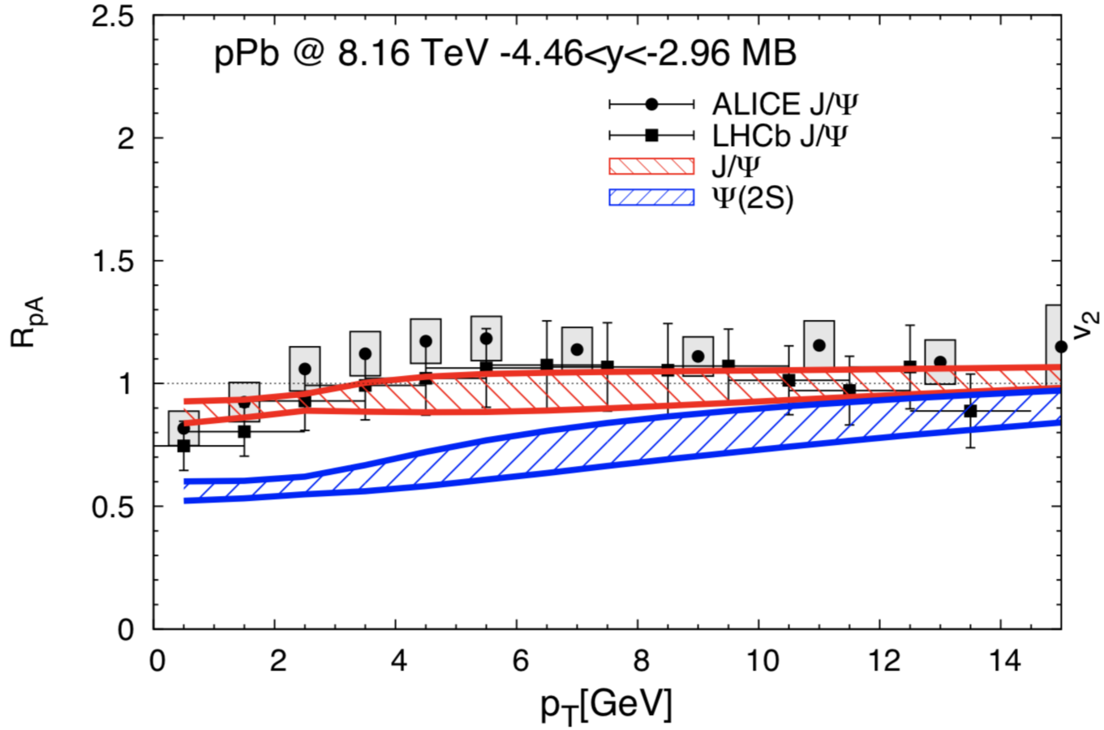
Color Glass Condensate also successful

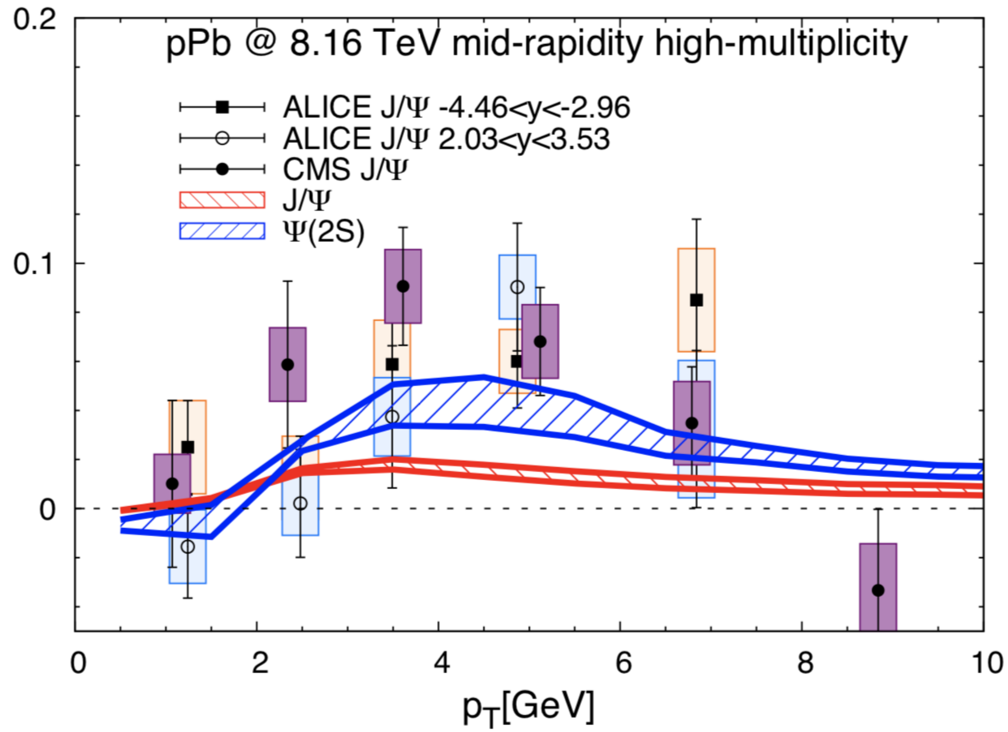
ALICE, JHEP 07 (2018) 160

LHCb, PLB 774 (2017) 159

Seen also with Run 1 data (5.02 TeV): ALICE, JHEP 02 (2014) 073, 06 (2015) 55

J/ψ production in p–Pb collisions

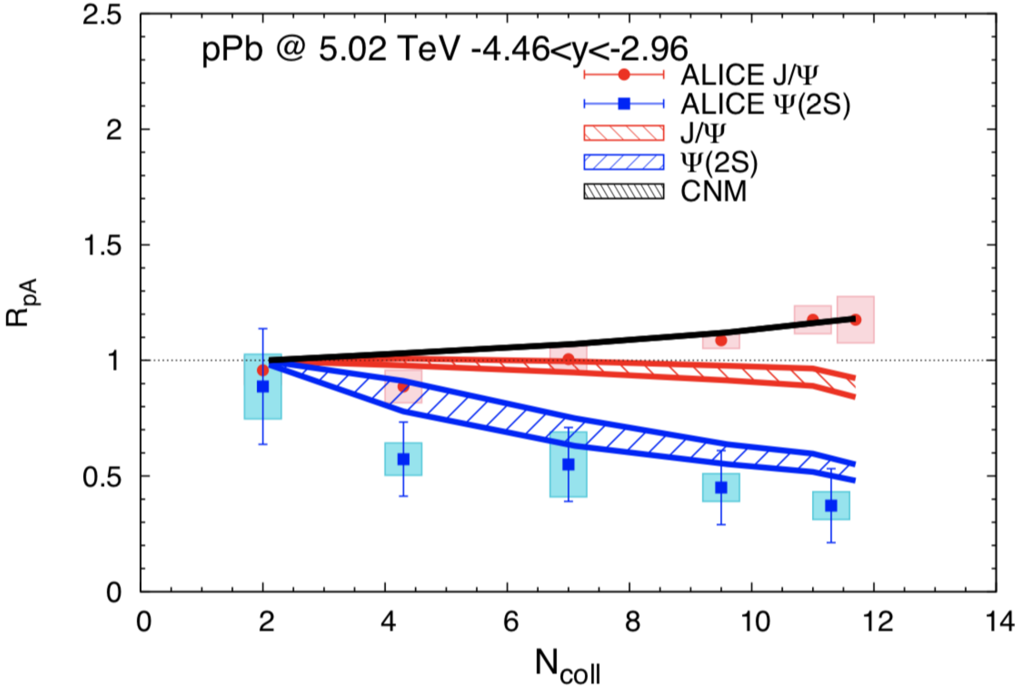


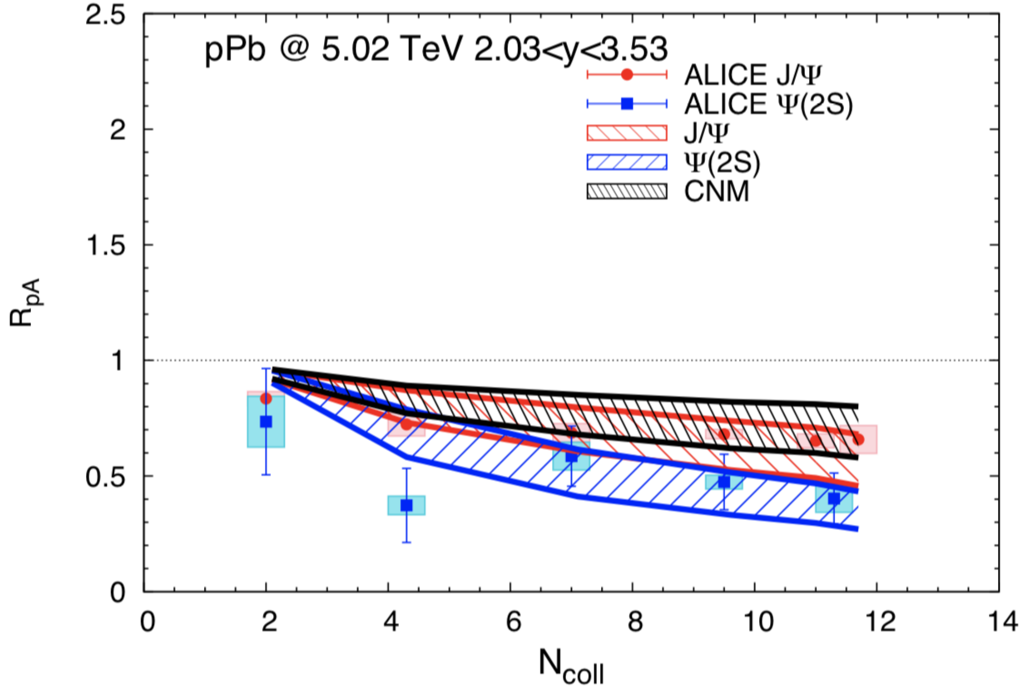


Bands: Transport Model, TAMU Du, Rapp, JHEP 1903 (2019) 015

Need experimentally (in reach for Run 3,4): better precision; also v_3; separate B component; v_2 of $\psi(2S)$?

J/ψ and $\psi(2S)$ production in p–Pb collisions





Du, Rapp, JHEP 1903 (2019) 015