

Quarkonium in the Statistical Hadronization Model

A. Andronic - University of Münster



- Quarkonium as probe of deconfinement
- A brief look at the data
- Quarkonium (incl. exotica; charm) in the SHM

Andronic, Braun-Munzinger, Redlich, Stachel, [Nature 561 \(2018\) 321](#)

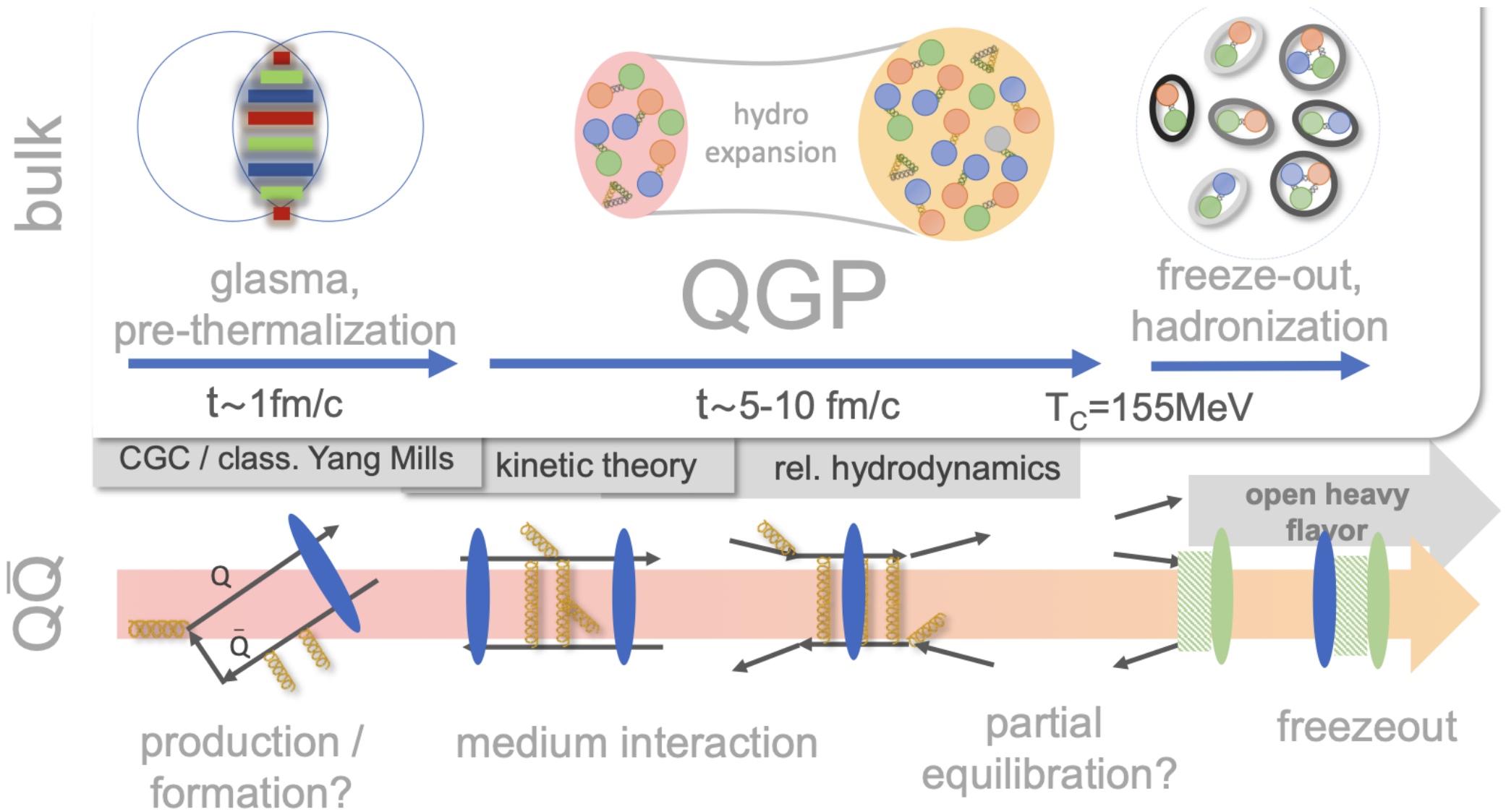
...+ Köhler, Mazeliauskas, Vislavicius, [JHEP 07 \(2021\) 035](#)

...+ Brunßen, Crkovská, Mazeliauskas, Vislavicius, Völkl, [JHEP 10 \(2024\) 229](#)

The Quark-Gluon Plasma

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Charmonium and deconfined matter

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":

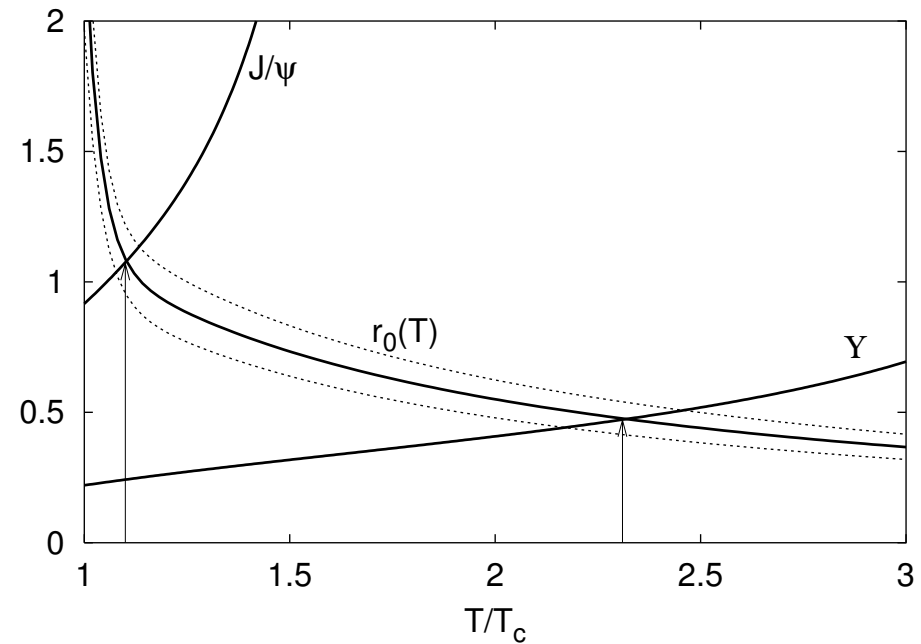
Digal et al., [PRD 64 \(2001\) 75](#)

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

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

r_0 Debye length in QGP

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



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

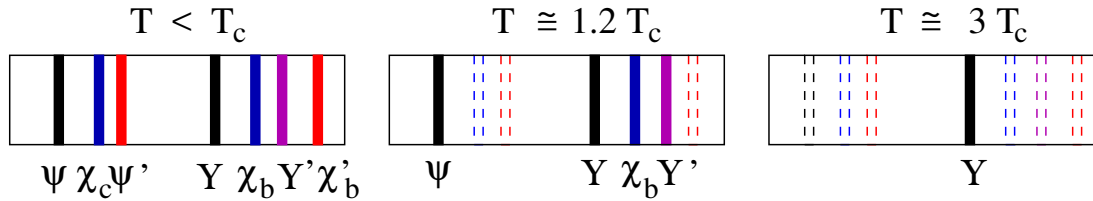
for $T=500$ MeV: $n_p \simeq 84/\text{fm}^3$, mean separation $\bar{r}=0.2$ fm $< r_{J/\psi}$

Quarkonium and the QGP - “sequential suppression”

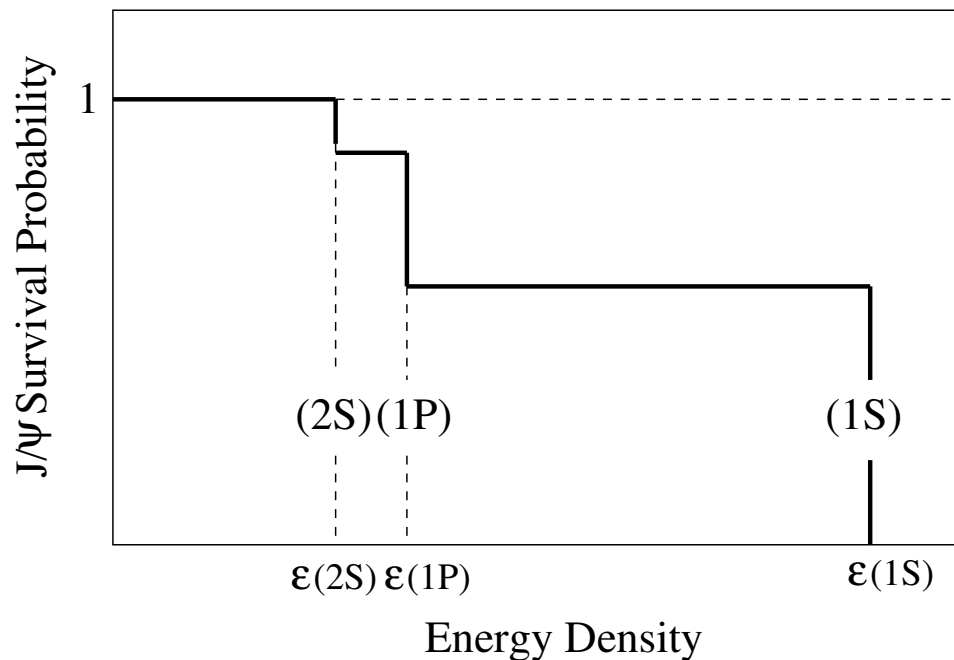
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Digal et al., [PRD 64 \(2001\) 75](#); H.Satz, [arXiv:1310.1209](#)



quantitative: lattice QCD



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

Experimentally:

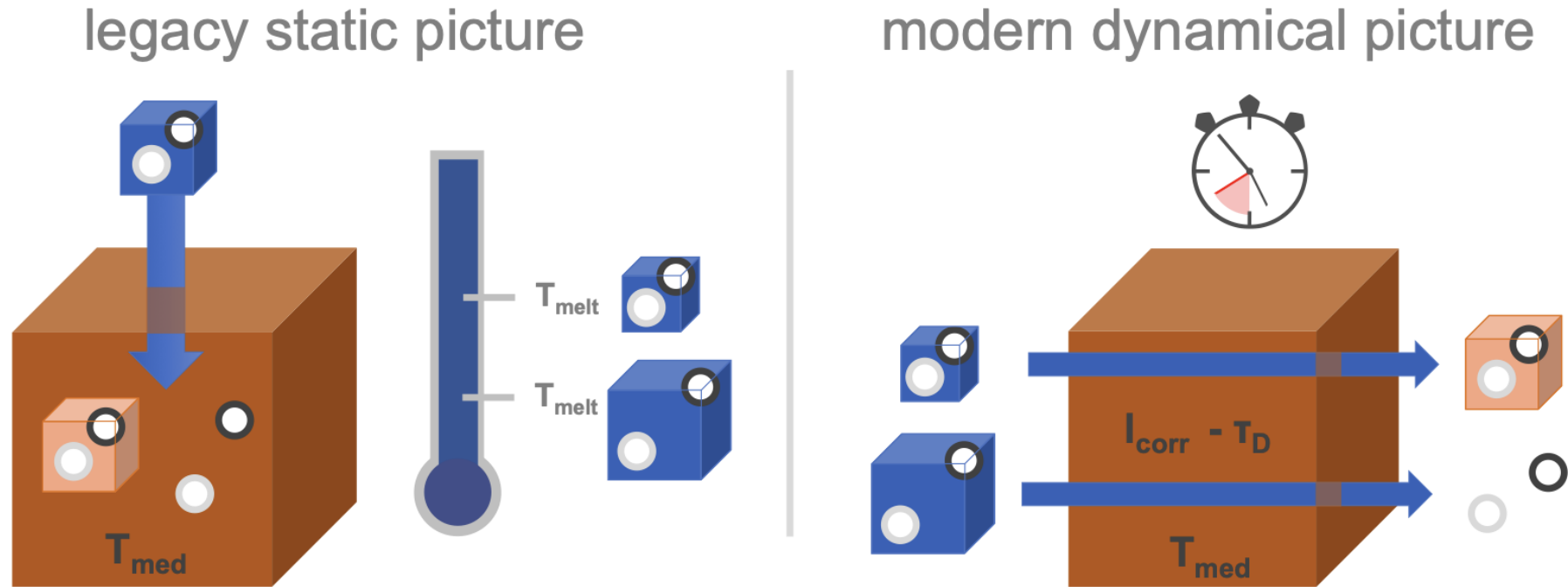
$$R_{AA}^{J/\psi} = \frac{dN_{J/\psi}^{AA}/dy}{N_{coll} \cdot dN_{J/\psi}^{pp}/dy} \quad \text{vs. } N_{part} \quad \text{or } N_{ch}$$

quarkonium as thermometer

Quarkonium pictures

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A. Rothkopf, [Phys. Rep. 858 \(2020\) 1](#)

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

$$T \sim \Lambda_{QCD} \sim E_{b, Q\bar{Q}}^{\text{vac}} \quad (m_Q \gg \Lambda_{QCD})$$

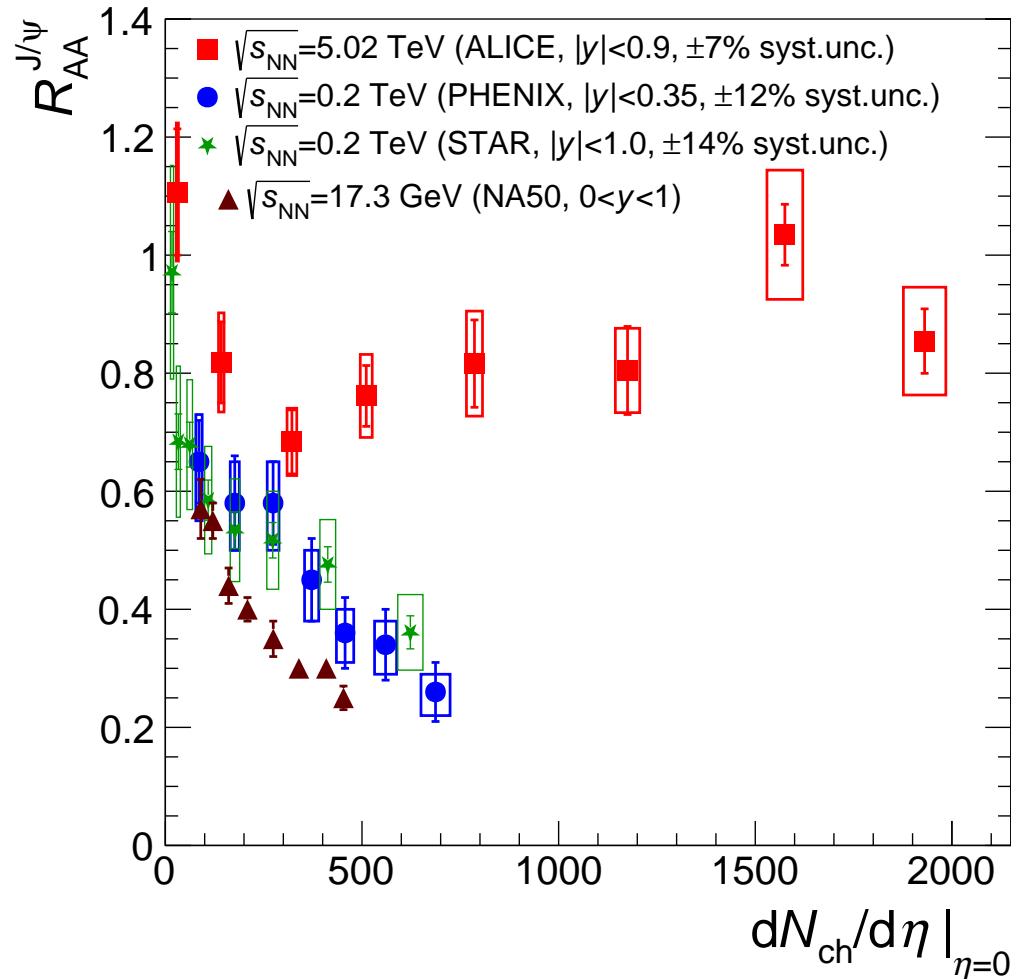
Reviews: theory (EMMI RRTF), [EPJA 60 \(2024\) 88](#); data (mostly), [ARNPS 75 \(2025\) 351](#)

Charmonium data: SPS, RHIC, LHC

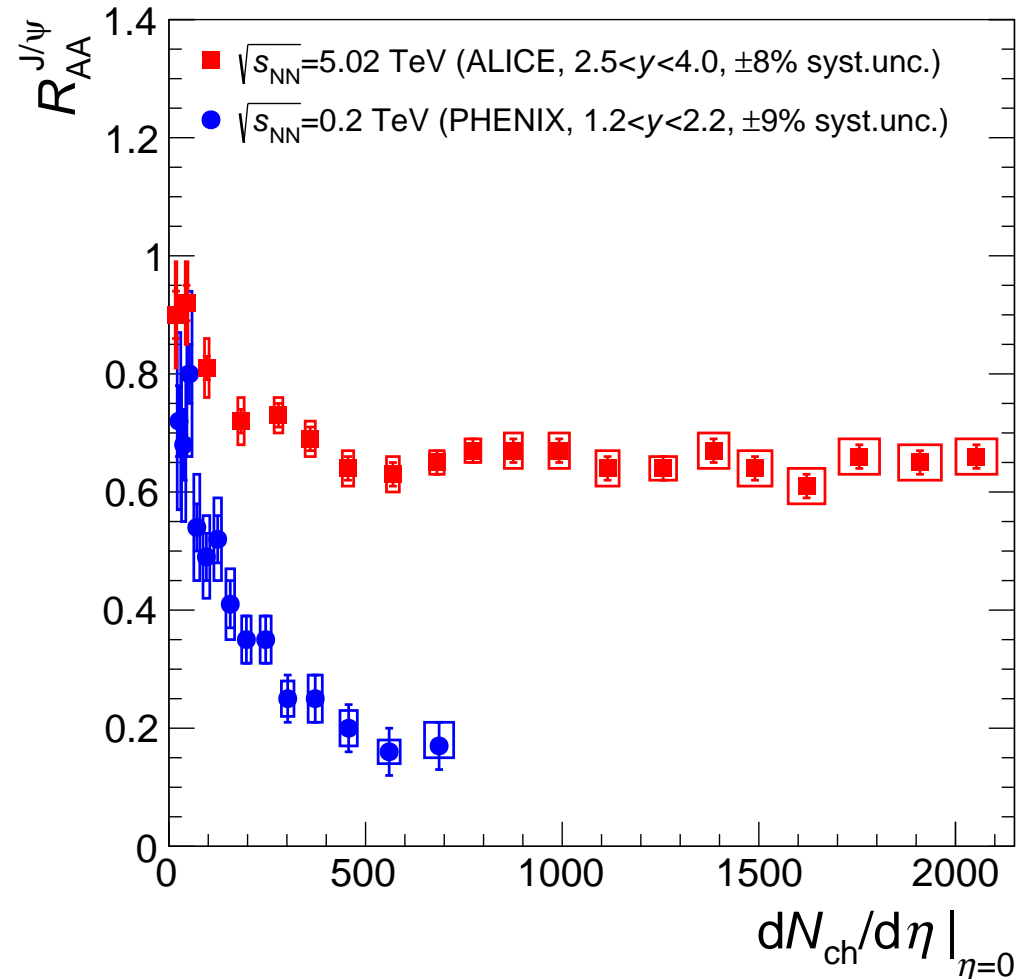
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midrapidity



forward rapidity

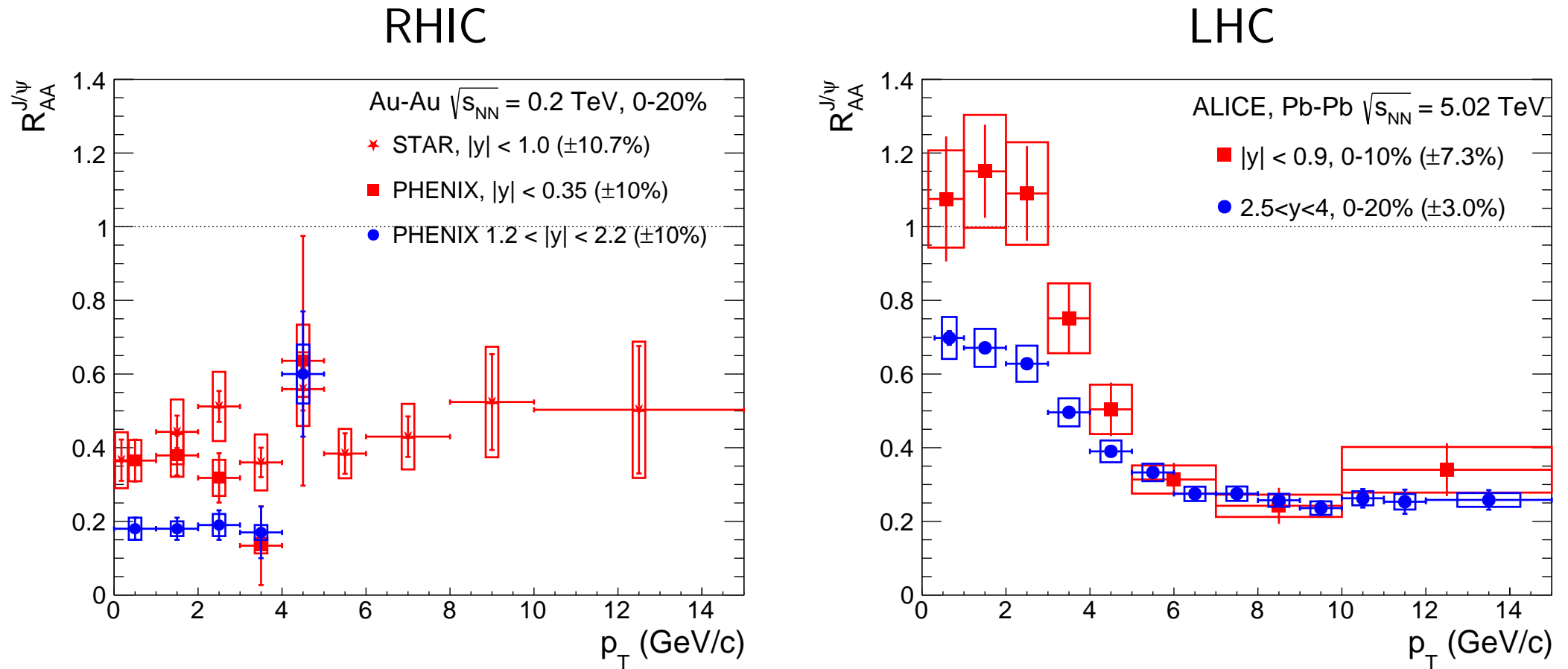


suppression at lower energies, but not obviously a sequential one
at the LHC another effect offsets the dissociation

Charmonium data: RHIC and LHC

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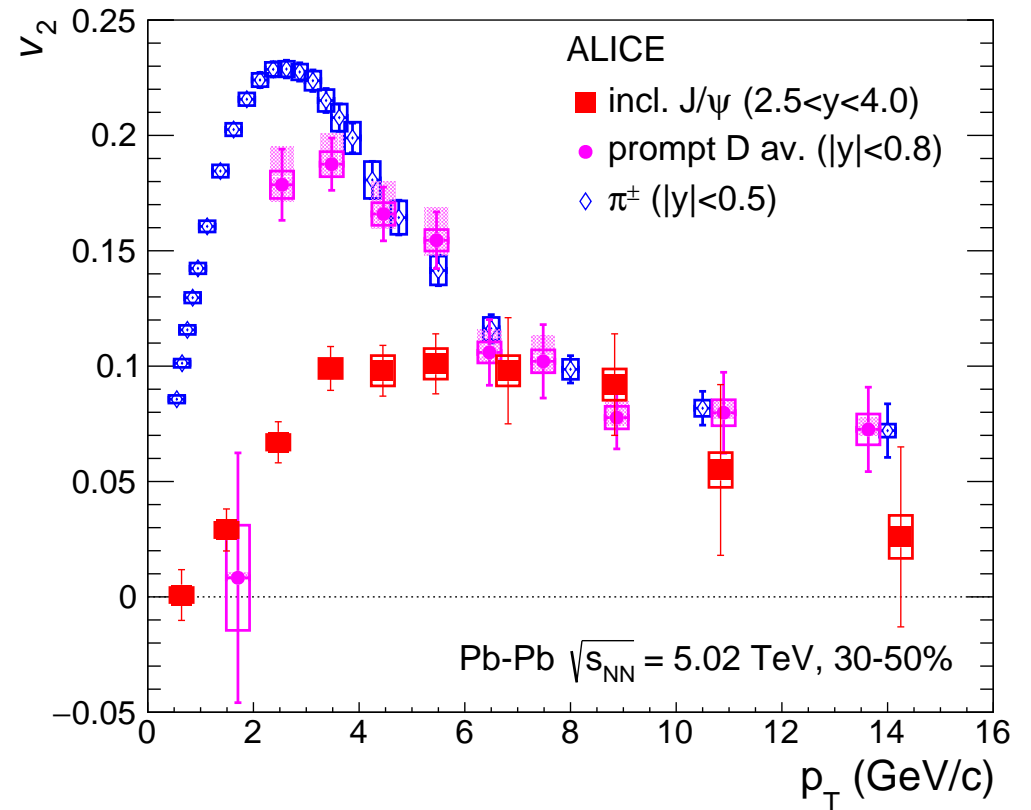
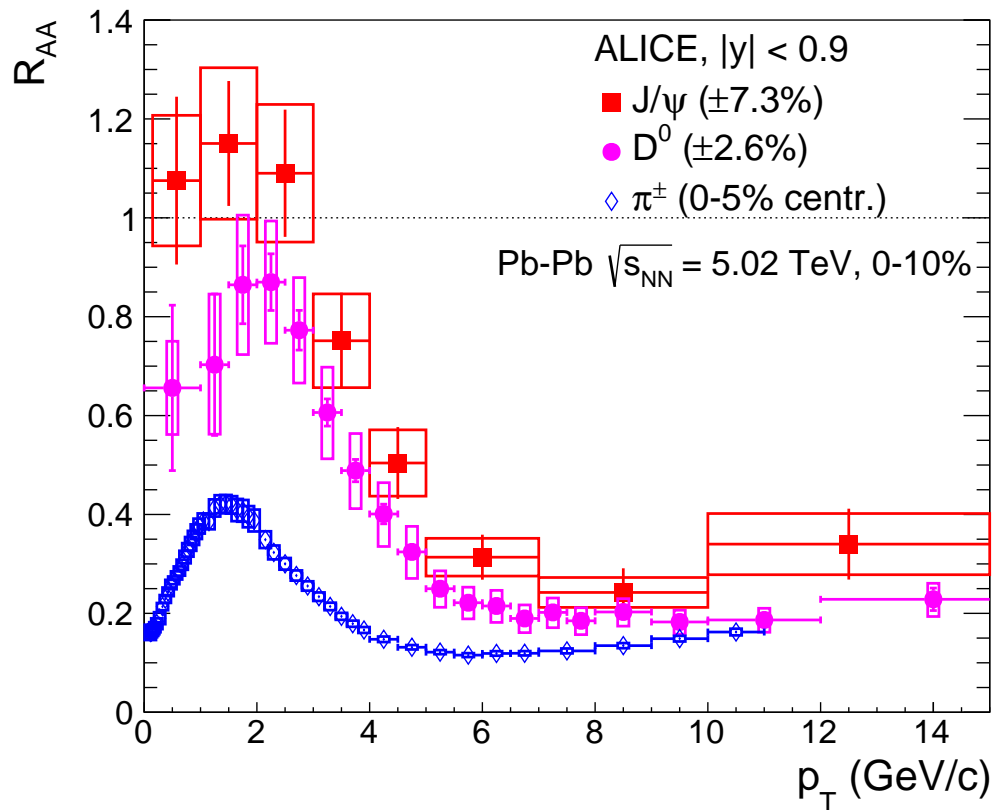


production at low p_T is enhanced at the LHC compared to RHIC
...stronger at midrapidity

Charmonium data at the LHC: in perspective

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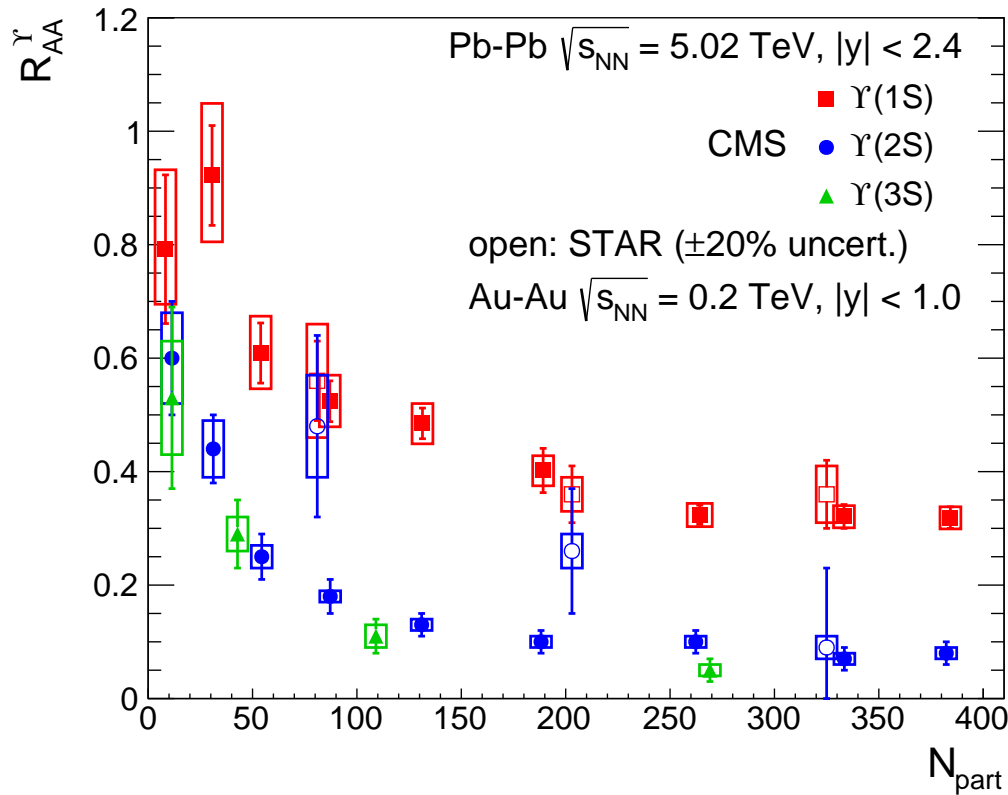
ALICE, [arXiv:2303.13361](https://arxiv.org/abs/2303.13361), [arXiv:2110.09420](https://arxiv.org/abs/2110.09420), [arXiv:1802.09145](https://arxiv.org/abs/1802.09145)

a very clear hierarchy at low/intermediate p_T

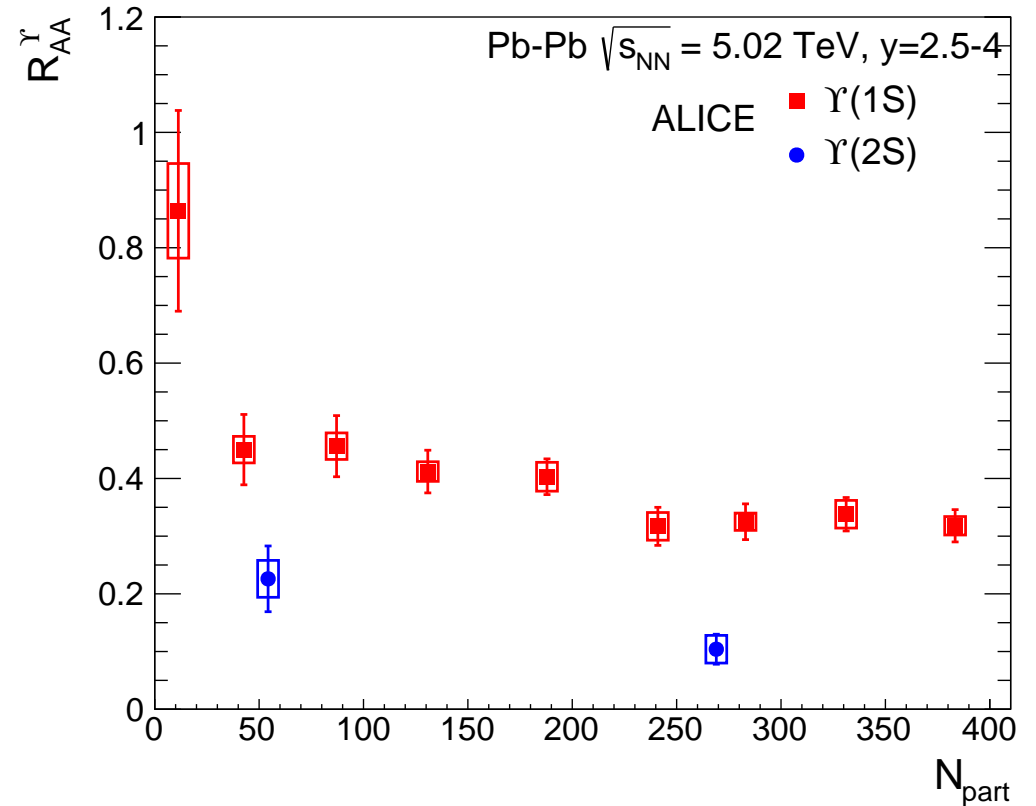
charm production is a pQCD process, pion production largely a thermal process

Bottomonium data: RHIC and LHC

midrapidity



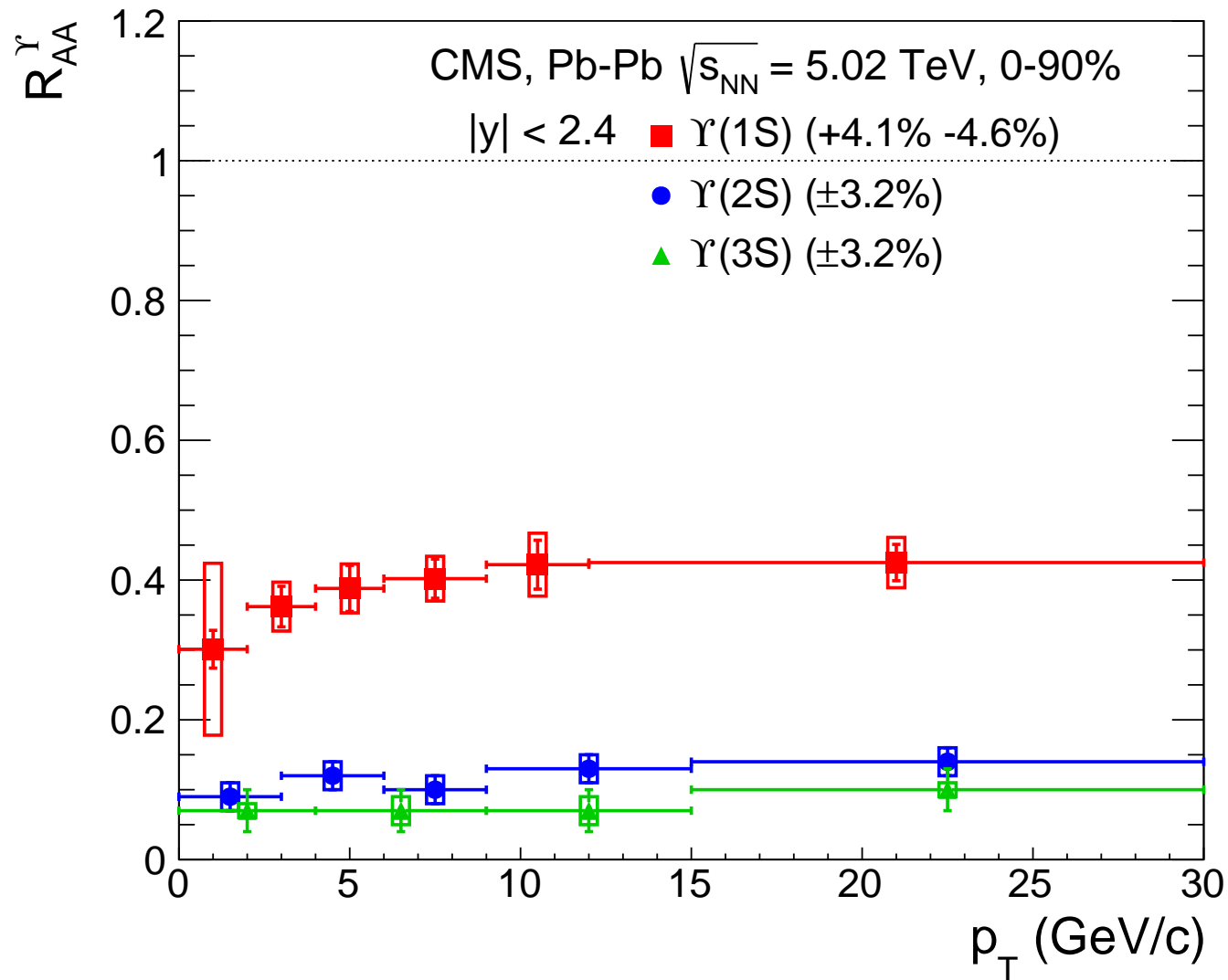
forward rapidity



significant suppression, hierarchy between states (sequential?)

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

Bottomonium data at the LHC

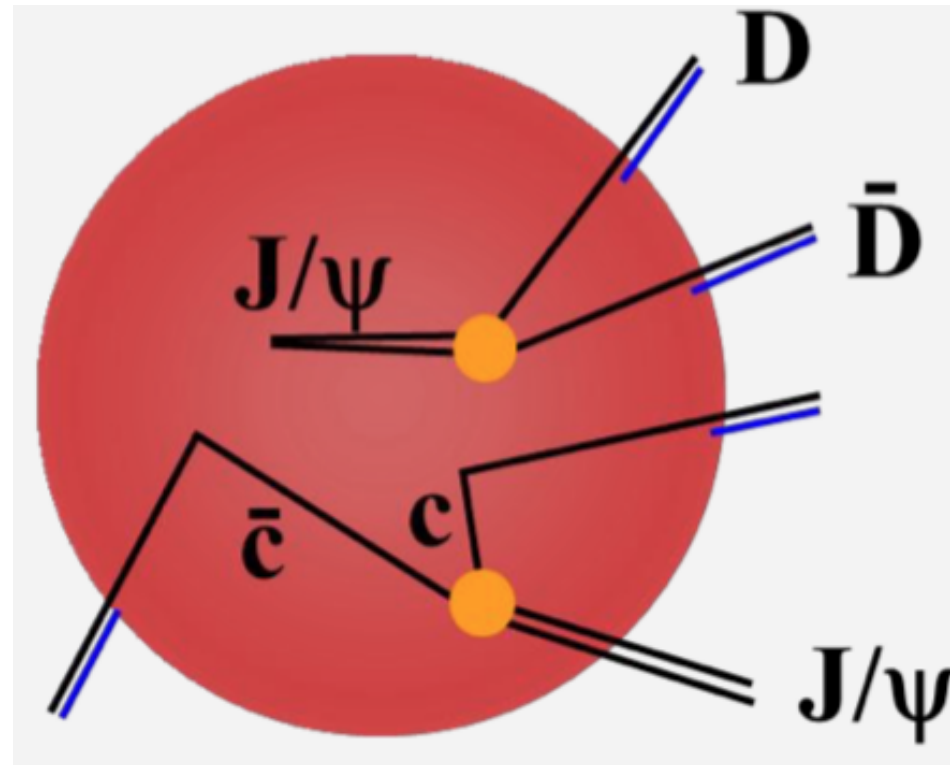


weak p_T dependence (dissociation expected to be stronger at low p_T)

There is dissociation and there is (re)generation

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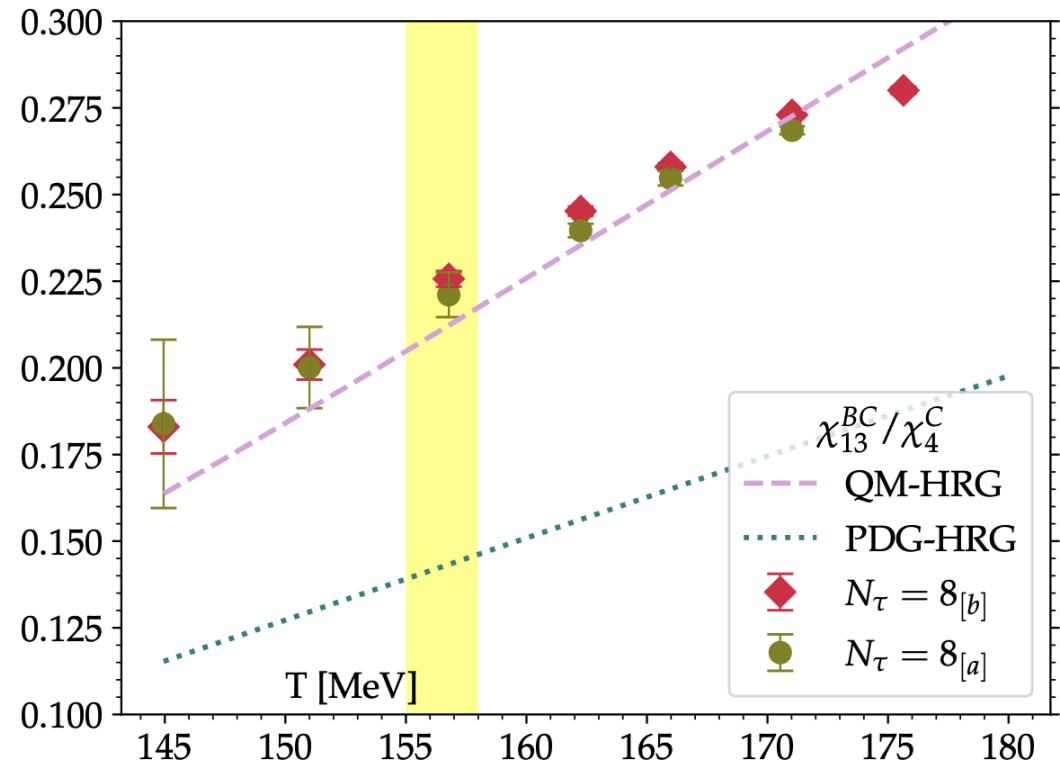
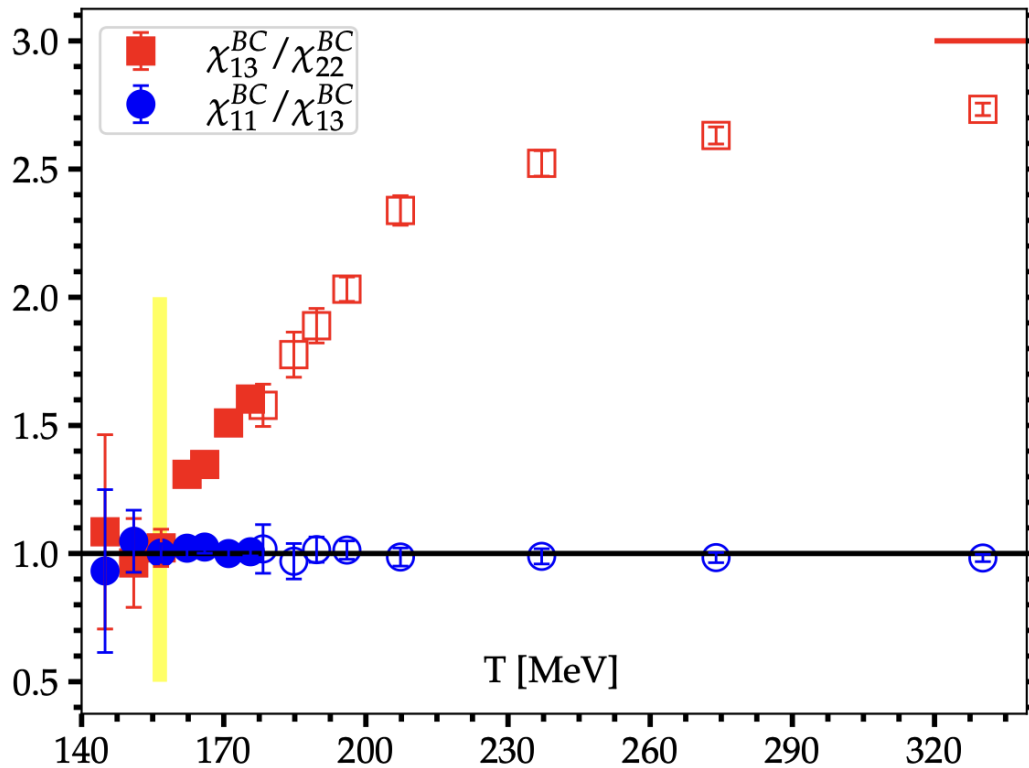
This picture is implemented in models in 2 basic ways:

- 1) statistical hadronization: full screening, generation at hadronization (c, \bar{c} produced in initial scattering and fully thermalized in QGP)
- 2) transport: continuous destruction and (re)generation, also from different c, \bar{c} (time evolution of T constrained by other measurements)

Charm in QGP - the lattice view

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Bazavov et al., [PLB 850 \(2024\) 138520](#)

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

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

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

The statistical hadronization model

grand canonical partition function for specie (hadron) i :

$$\ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 dp \ln[1 \pm \exp(-(E_i - \mu_i)/T)]$$

$g_i = (2J_i + 1)$ spin degeneracy factor; T temperature;

$E_i = \sqrt{p^2 + m_i^2}$ total energy; (+) for fermions (-) for bosons

$\mu_i = \mu_B B_i + \mu_{I_3} I_{3i} + \mu_S S_i + \mu_C C_i$ chemical potentials

μ ensure conservation (on average) of quantum numbers, fixed by “initial conditions”

i) isospin: $\sum_i n_i I_{3i} / \sum_i n_i B_i = I_3^{tot} / N_B^{tot}$, $N_B^{tot} \sim \mu_B$

I_3^{tot} , N_B^{tot} isospin and baryon number of the system (=0 at high energies)

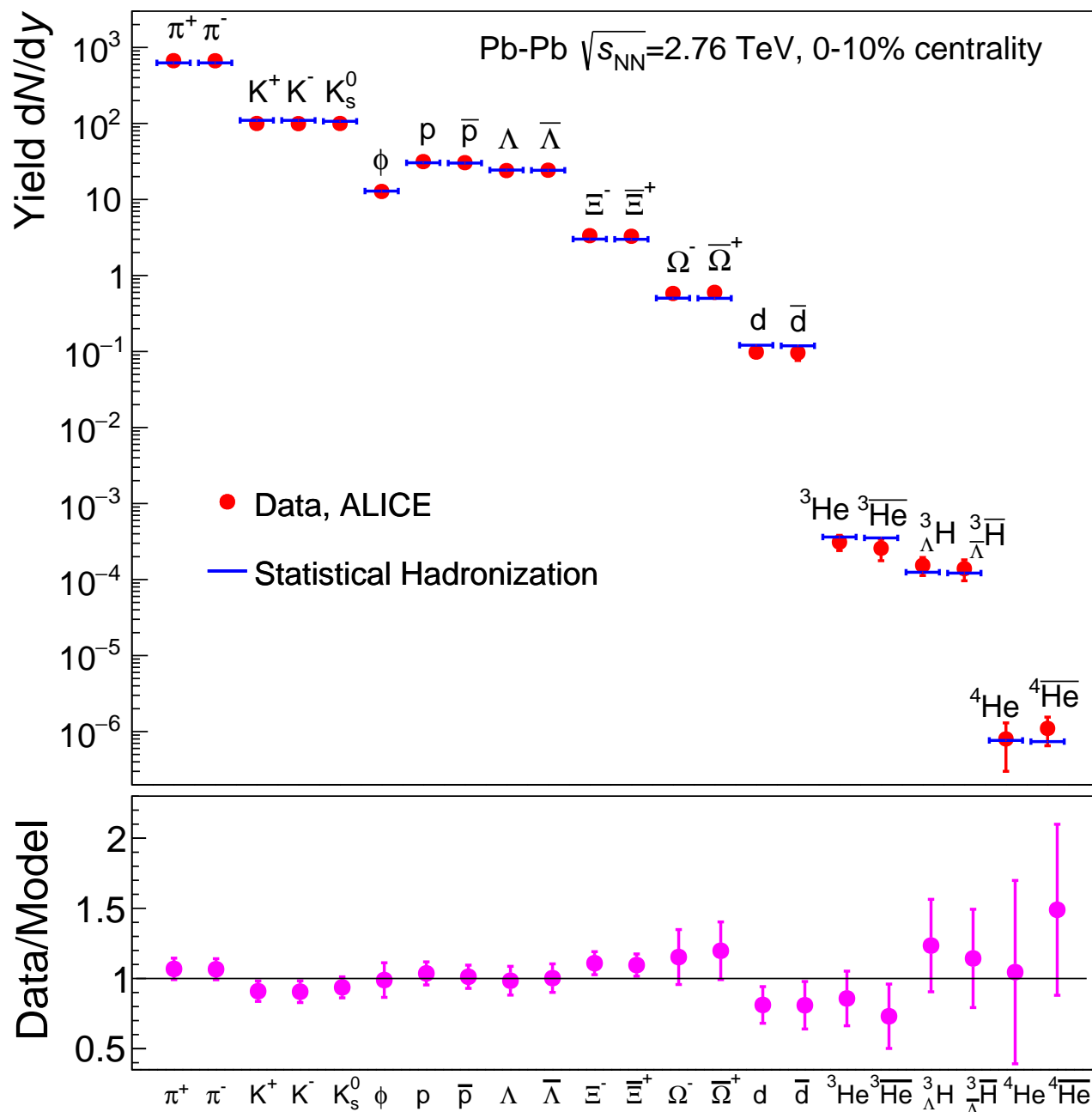
ii) strangeness: $\sum_i n_i S_i = 0$

iii) charm: $\sum_i n_i C_i = 0$. $\Rightarrow (T, \mu_B, V)$ fit parameters

Thermal fit – LHC, Pb–Pb, 0-10%

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matter and antimatter produced in equal amounts

$$T_{CF} = 156.6 \pm 1.7 \text{ MeV}$$

$$\mu_B = 0.7 \pm 3.8 \text{ MeV}$$

$$V_{\Delta y=1} = 4175 \pm 380 \text{ fm}^3$$

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

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

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

hadronization as bags of quarks and gluons?

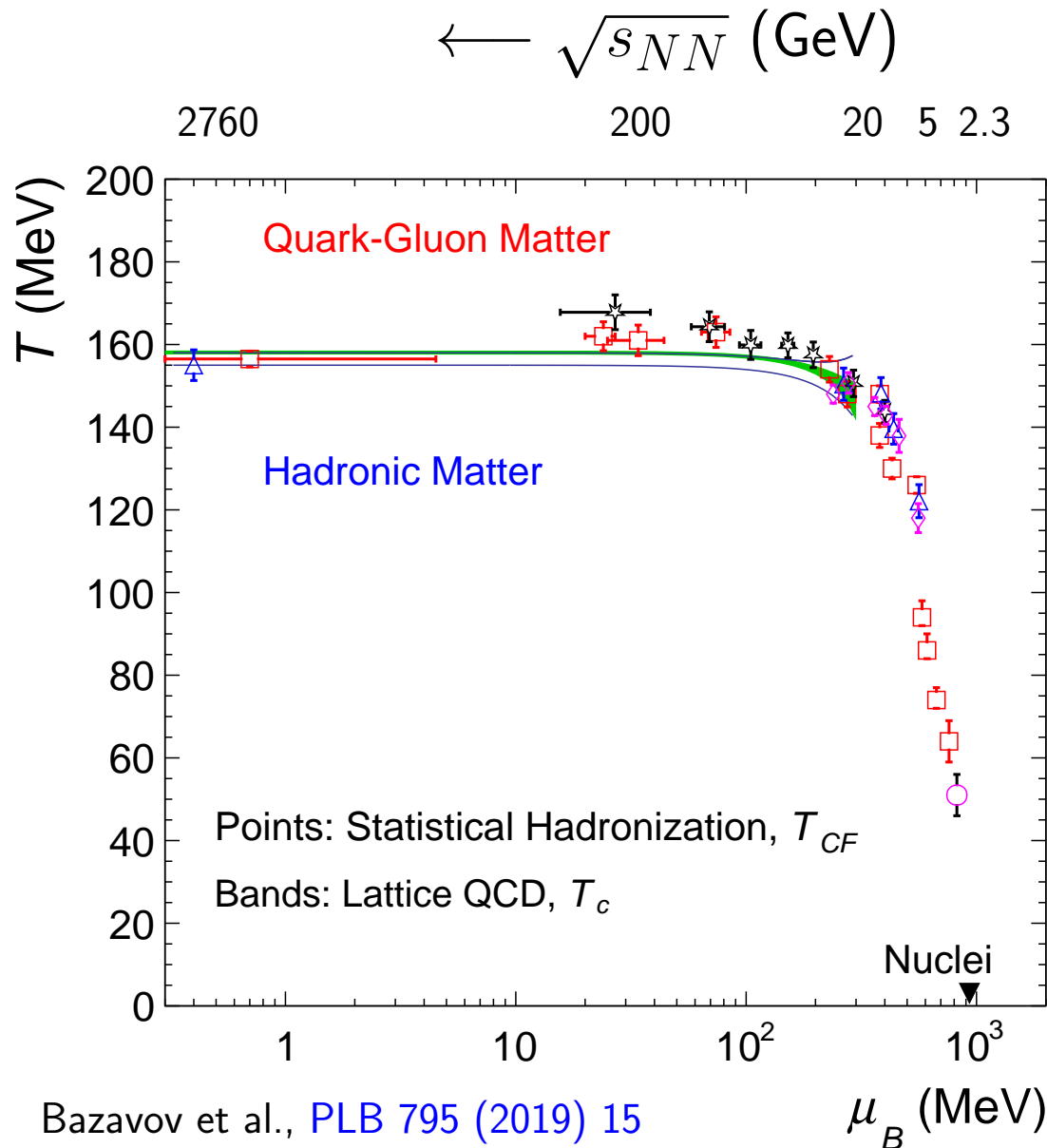
hadron spectrum beyond PDG \rightarrow

same T_{CF} [NPA 1010 \(2021\) 122176](#)

The phase diagram of QCD

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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)

Bazavov et al., [PLB 795 \(2019\) 15](#)

Borsanyi et al., [PRL 125 \(2020\) 052001](#)

see refs. in [Nature 561 \(2018\) 321](#)

points: independent analyses of same data \rightarrow “model/code uncert.” are small

The statistical hadronization model for charm

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

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

...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 loses 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, JHEP 10 (2024) 229

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:

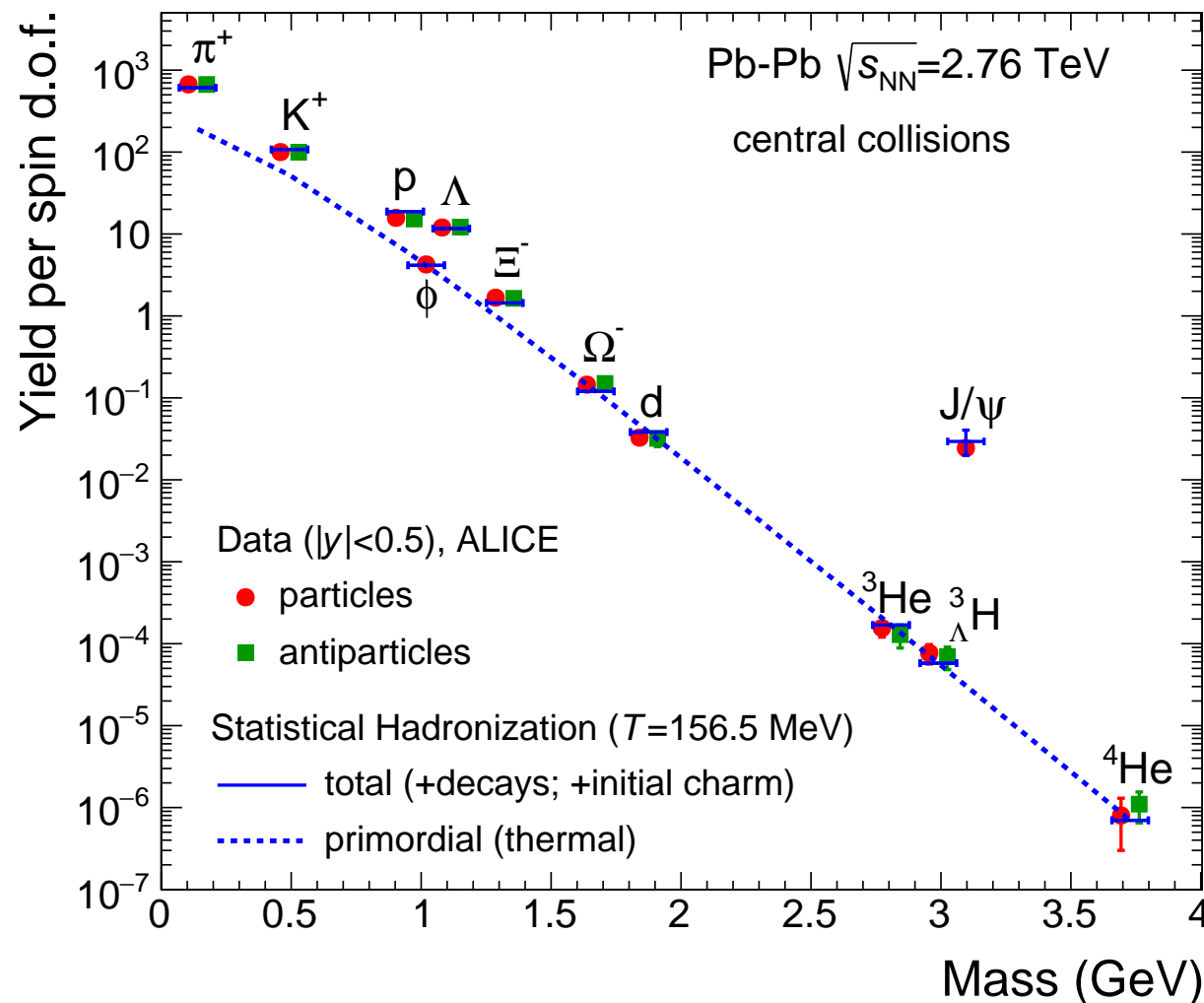
- full thermalization of c, \bar{c}
("mobility" in $V \simeq 4000 \text{ fm}^3$)

- 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 $T=156.5 \text{ MeV}$)



SHMc: method and inputs

Braun-Munzinger, Stachel, [PLB 490 \(2000\) 196](#), [NPA 690 \(2001\) 119](#)

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

Gorenstein, Kostyuk, Stöcker, Greiner, [PLB 509 \(2001\) 277](#)

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

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

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

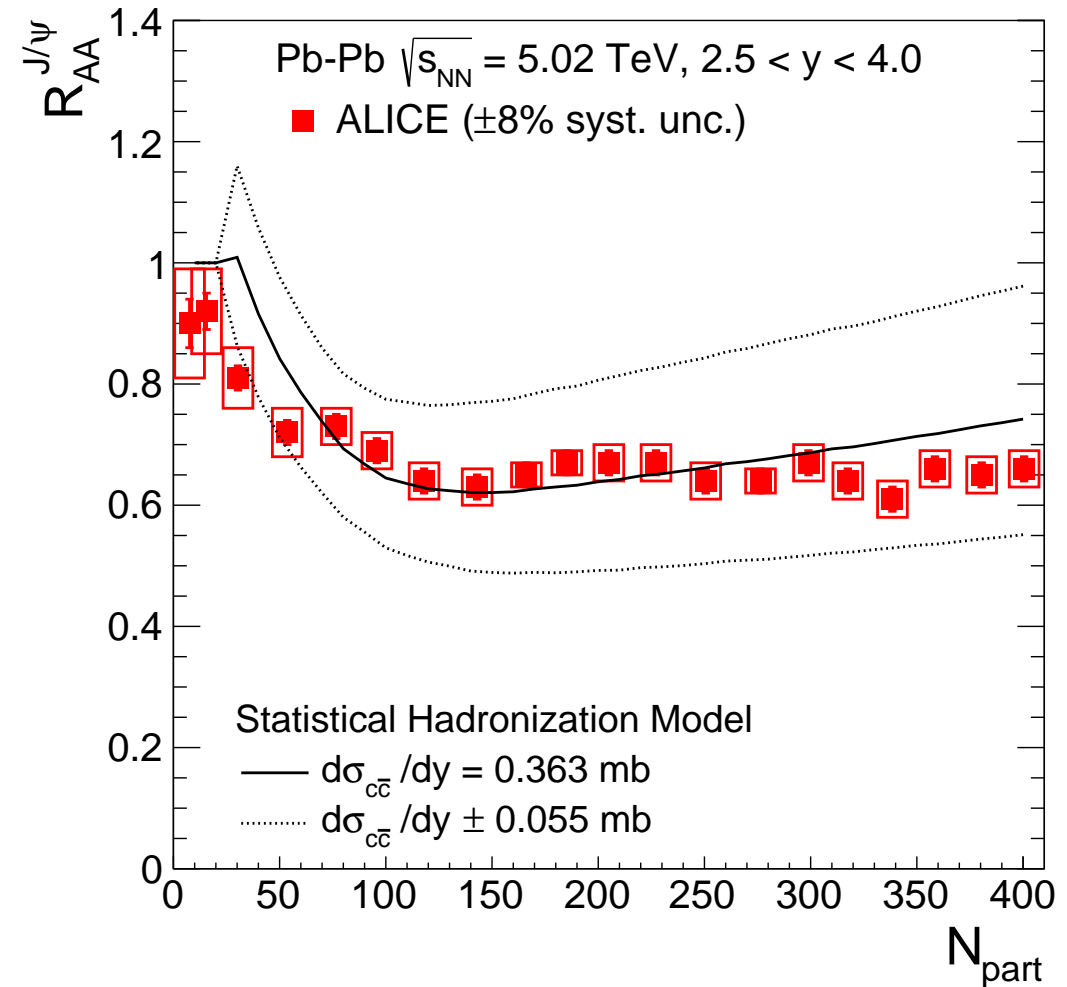
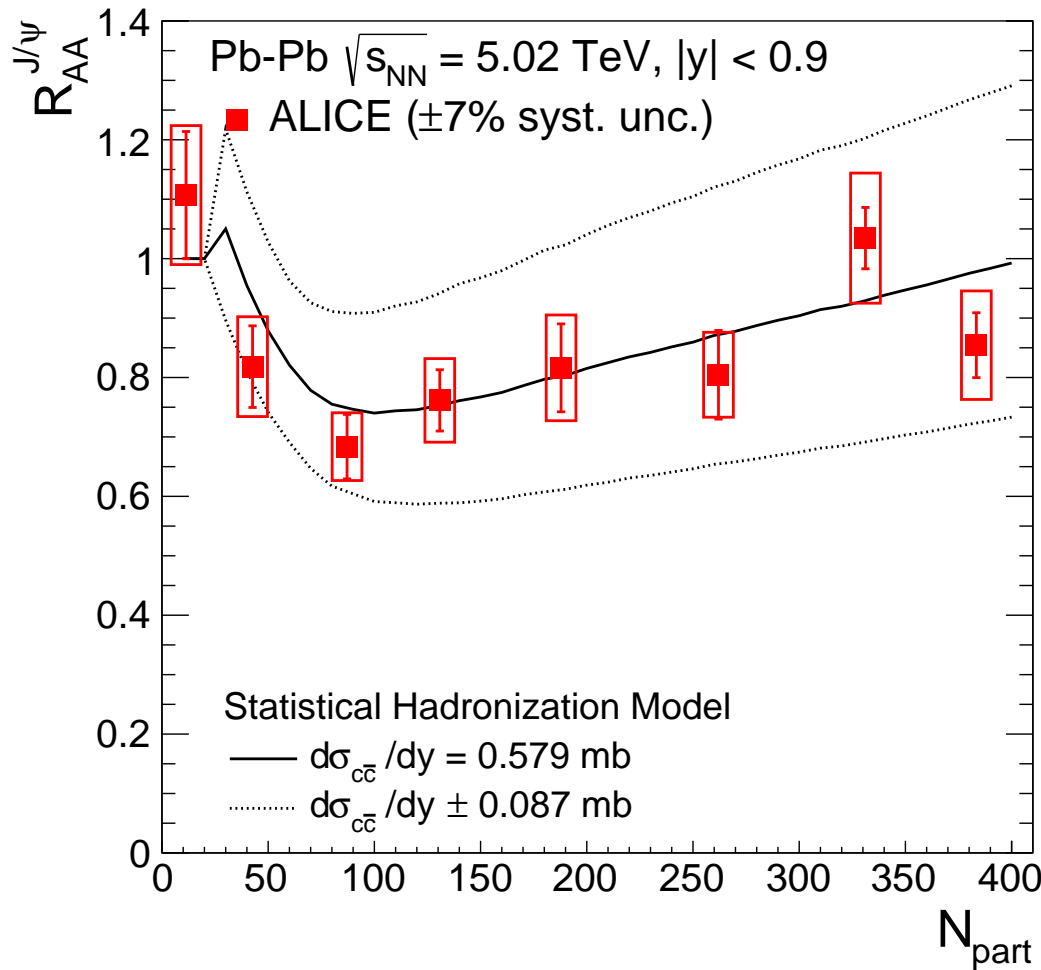
Assumed minimal volume for QGP: $V_{QGP}^{min} = 200 \text{ fm}^3$

SHMc and charmonium data at the LHC

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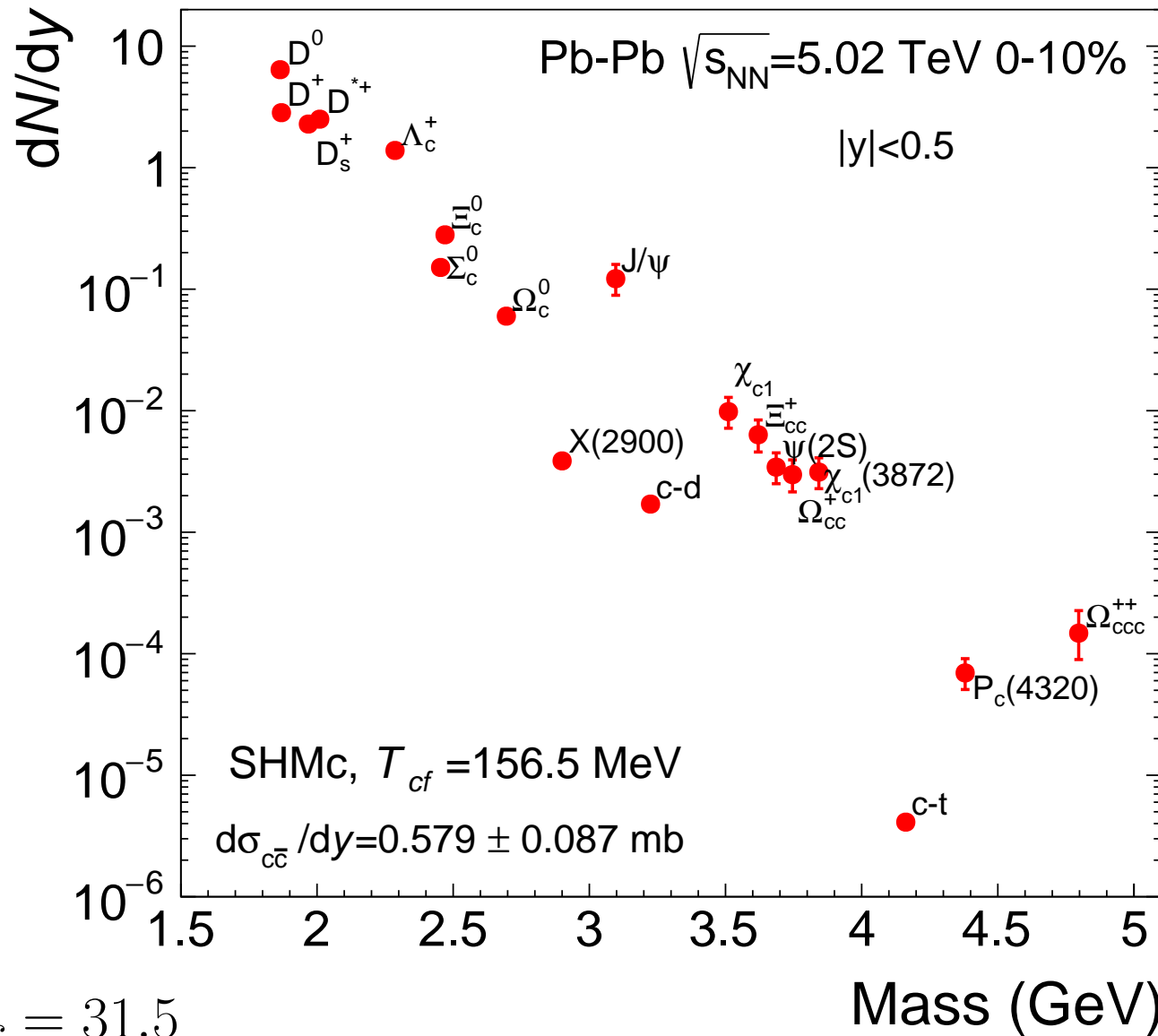
full thermalization of c quarks in QGP, hadronization at chemical freeze-out



$d\sigma_{c\bar{c}}/dy$ via normalization to D^0 in Pb-Pb 0-10%, ALICE, [arXiv:2110.09420](https://arxiv.org/abs/2110.09420)

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

SHMc: the full charm zoo



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

$$\rightarrow g_c = 31.5$$

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

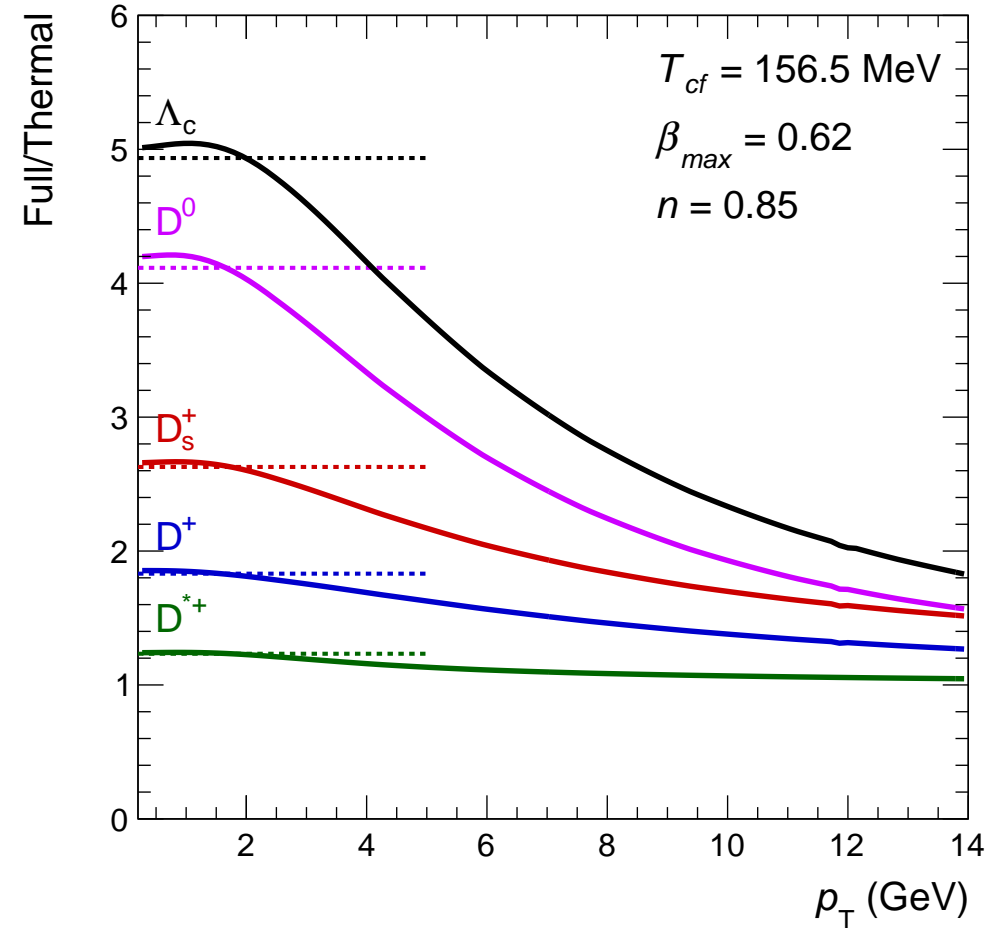
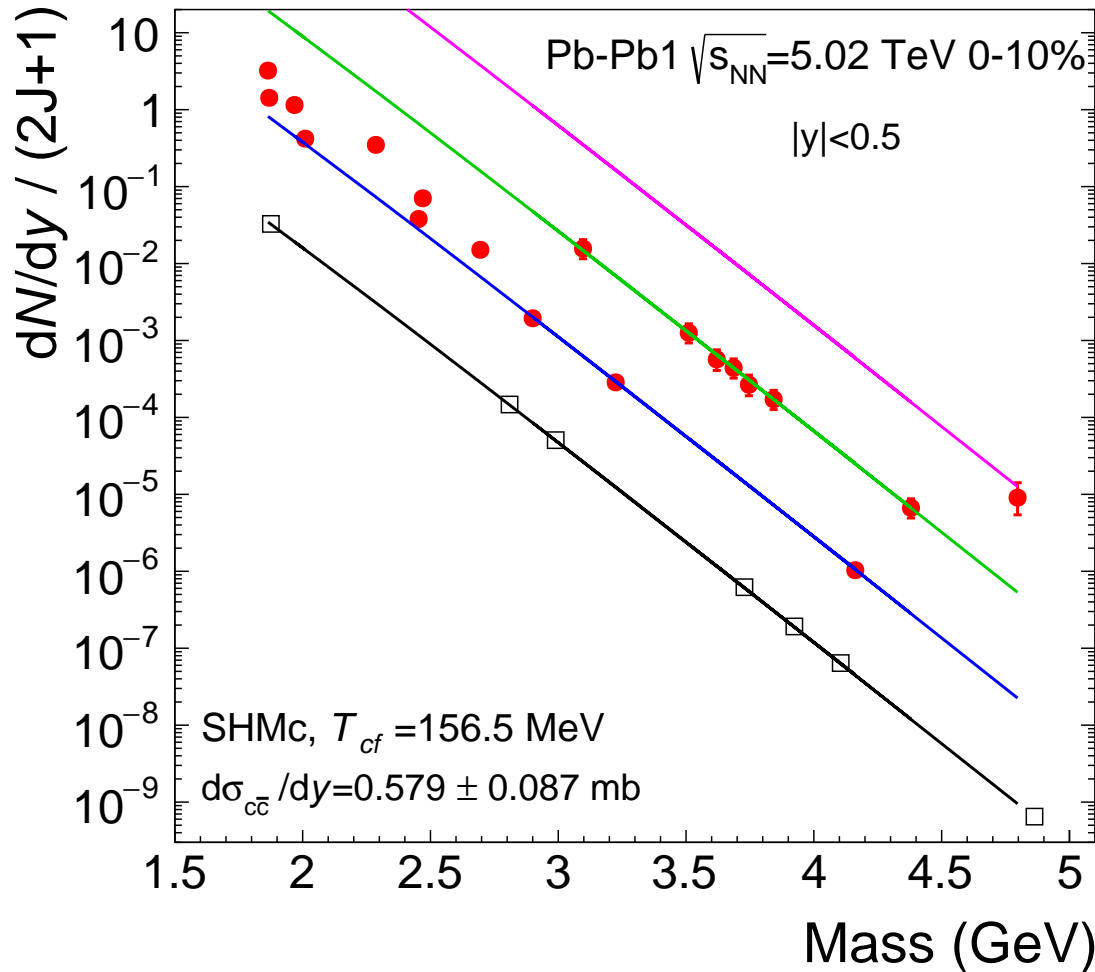
$$X(6900) \sim 10^{-8}$$

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

Full charm predictions for the LHC

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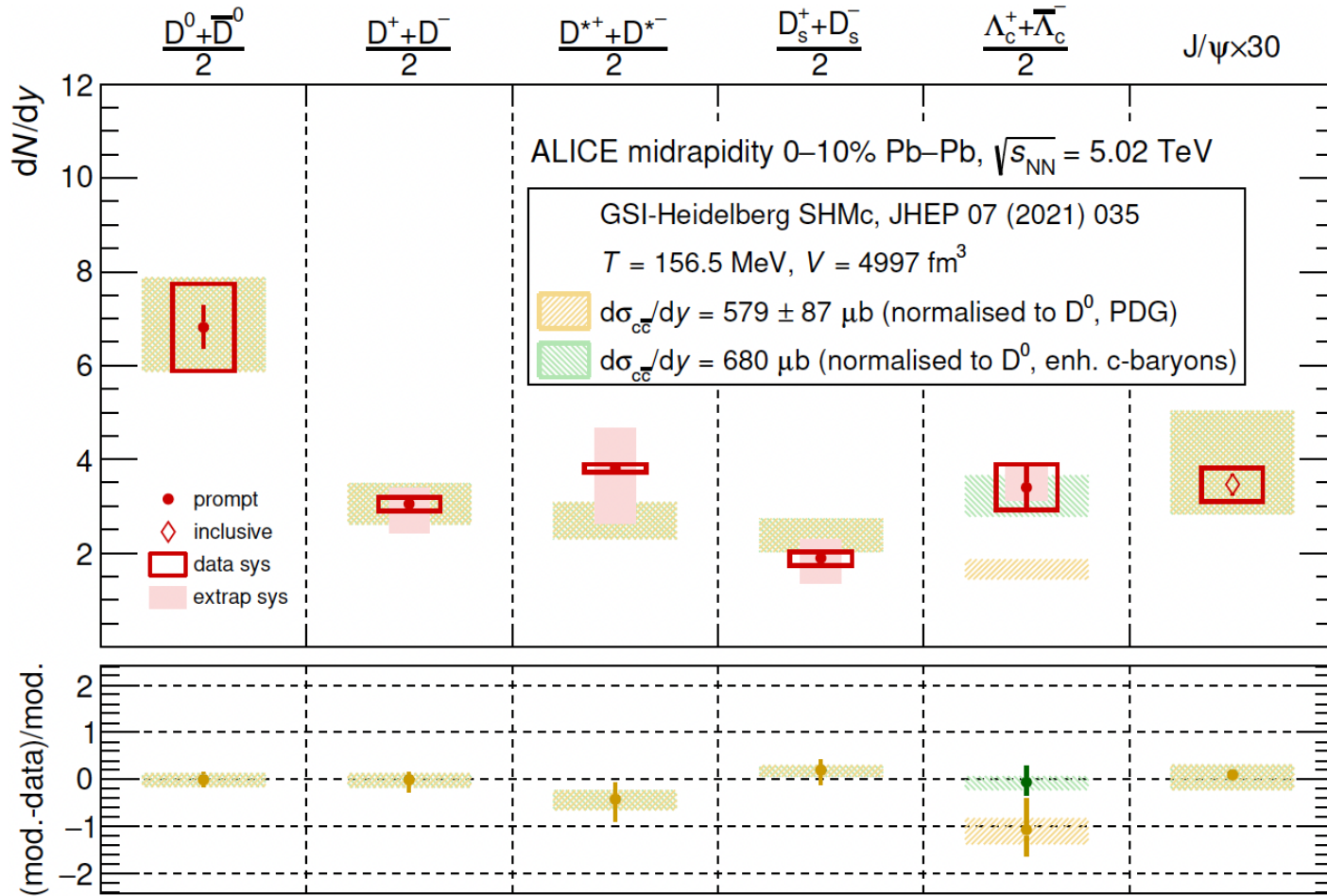
Charm-hadron spectrum as in PDG: 55 c-mesons, 74 c-baryons (part.+antipart.)

...large, but may not be complete

Charm data and SHMc model

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ALICE, [arXiv:2212.04348](https://arxiv.org/abs/2212.04348)

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

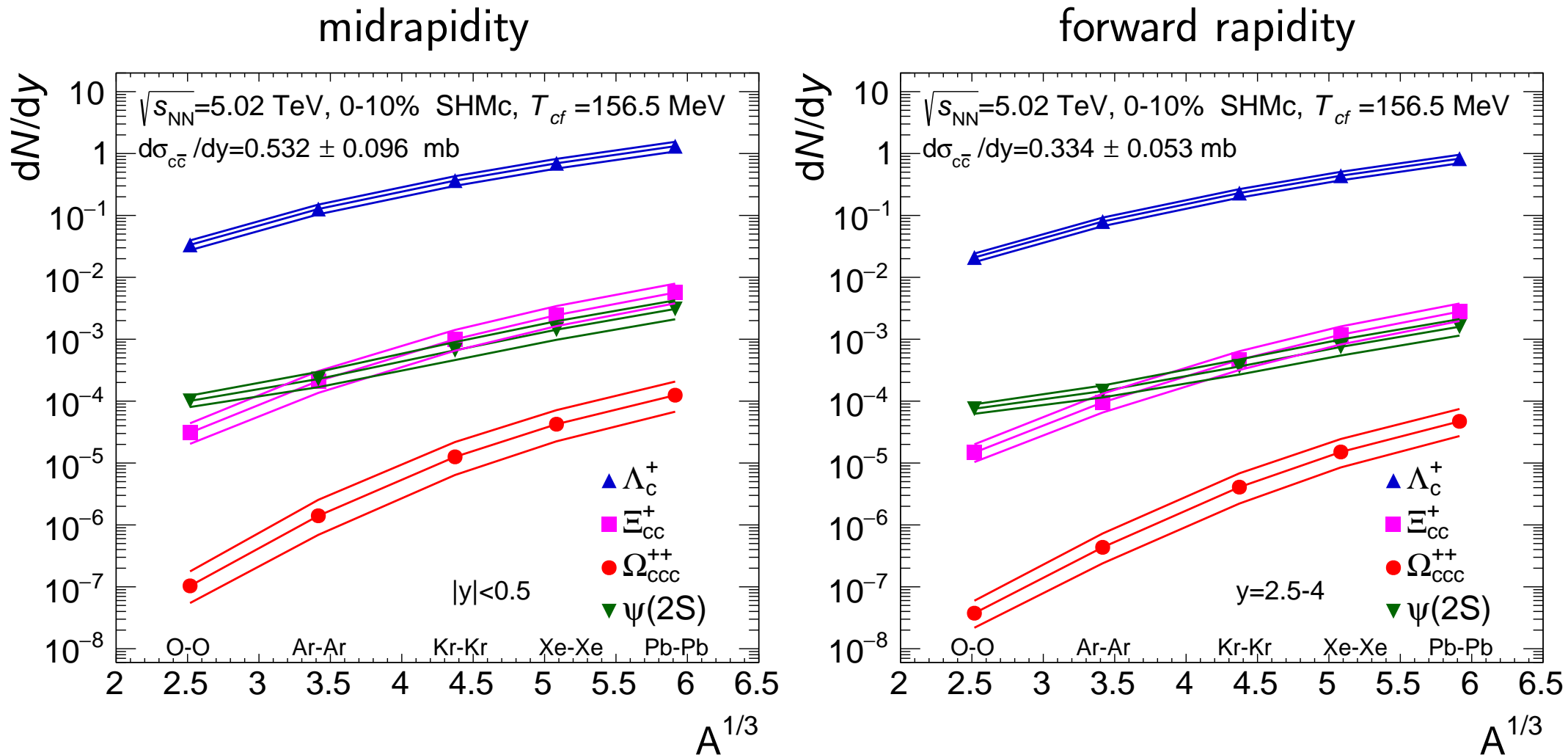
RQM: He,Rapp, [PLB 795 \(2019\) 117](https://arxiv.org/abs/1905.07603); LQCD, Bazavov et al., [PLB 850 \(2024\) 138520](https://arxiv.org/abs/2308.13852)

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

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

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JHEP 07 (2021) 035

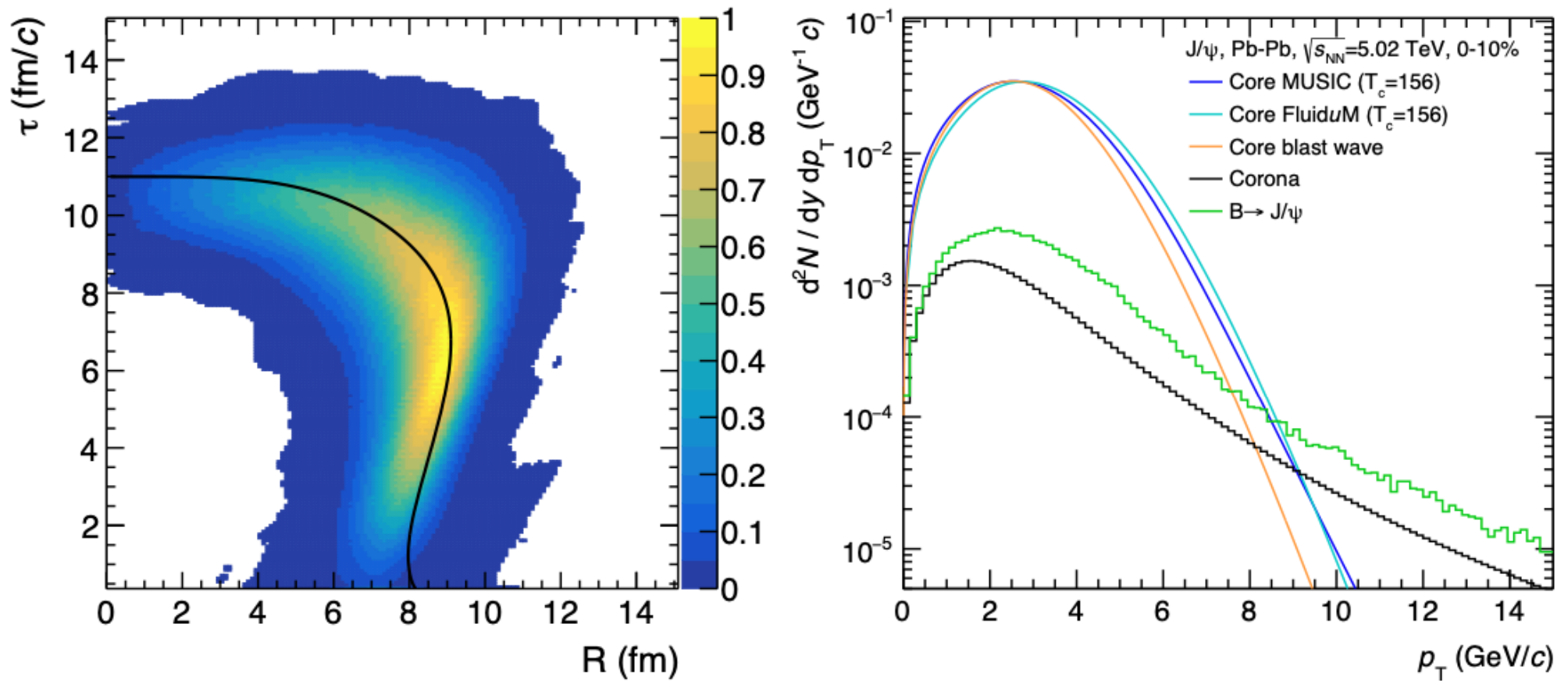
Canonical suppression of open charm plays a major role for the system-size dep.

$X(3872)$ yields: about half those of $\psi(2S)$

SHMc - coupling to hydrodynamics

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AA, ..., M. Vökl, [JHEP 10 \(2024\) 229](#)

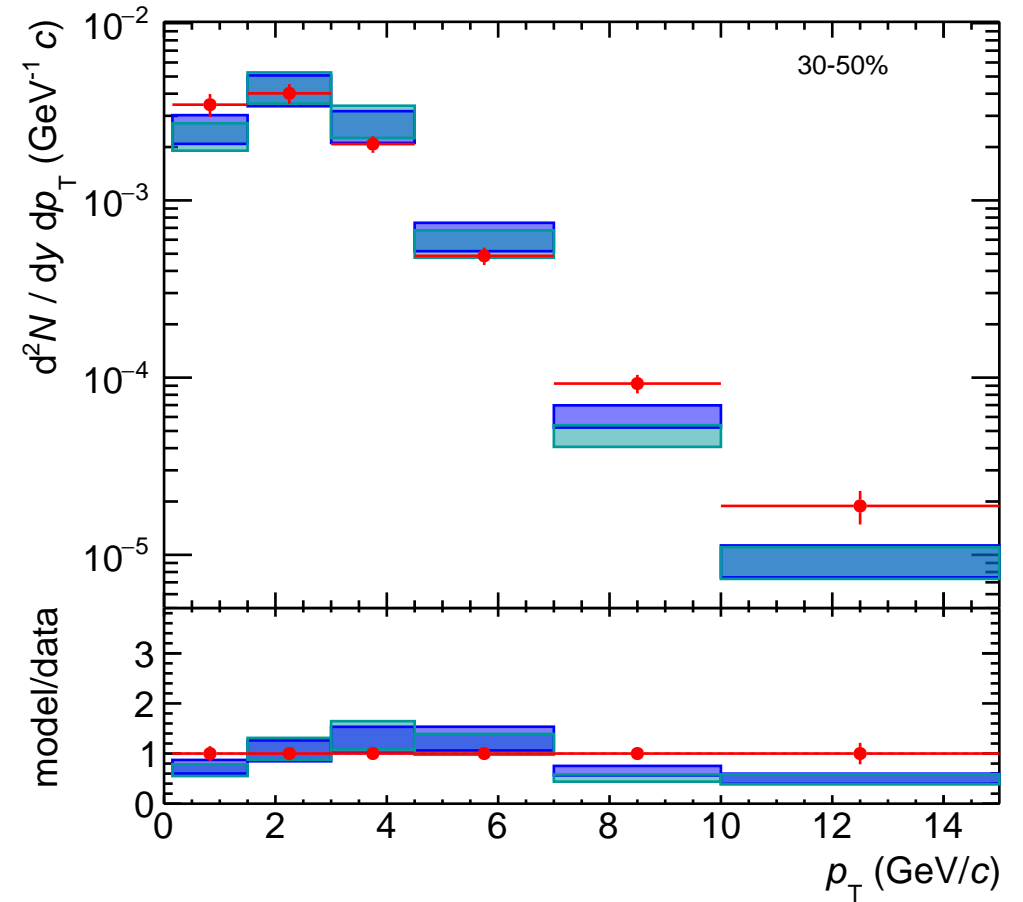
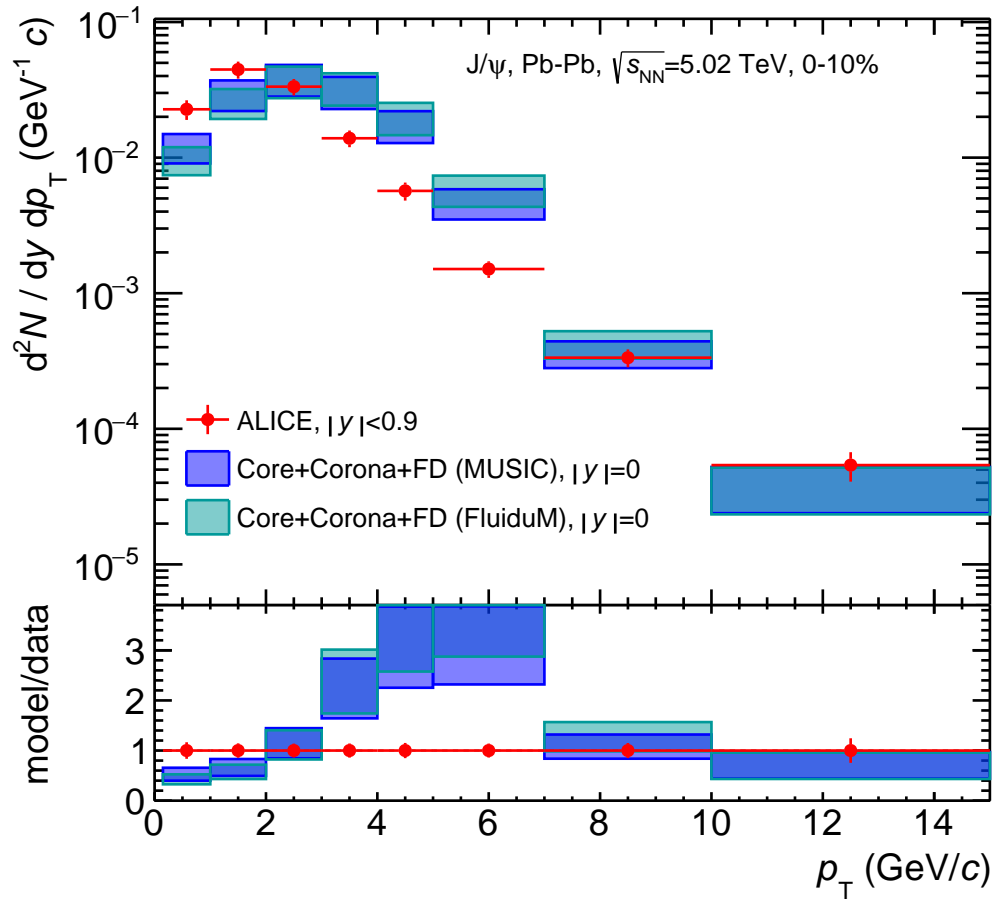
Distribution: MUSIC (IP-Glasma; $\tau_0=0.4$ fm/c)

Line: FluiduM (T_{R} ENTO; $\tau_0=0.18$ fm/c)

SHMc: p_T spectra

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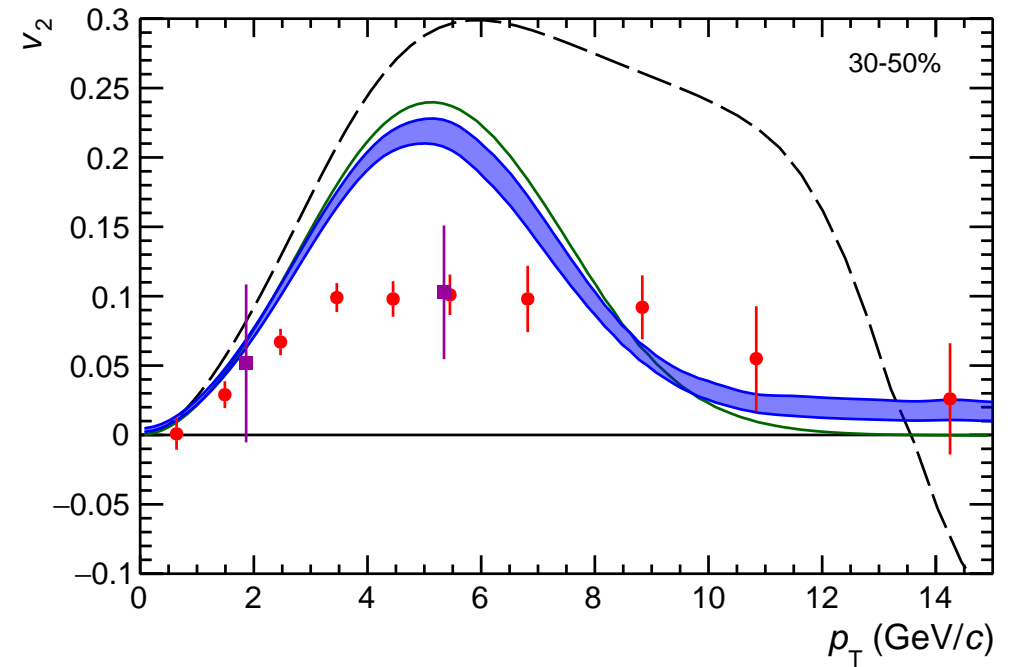
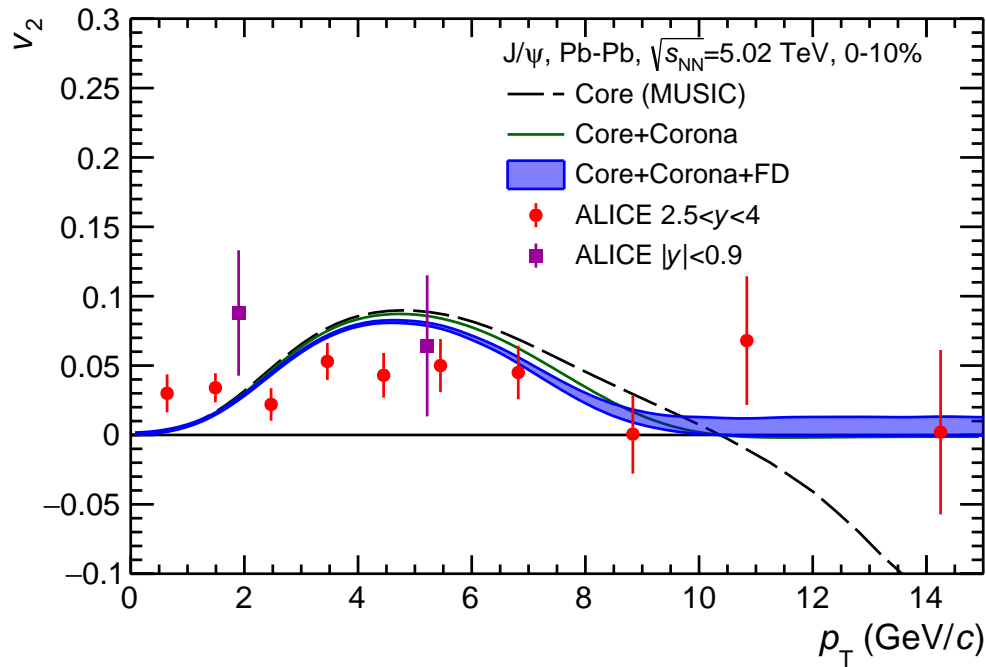
AA, ..., M. Vökl, [JHEP 10 \(2024\) 229](#)

Too strong flow in 0-10% centrality

SHMc: v_2 distributions

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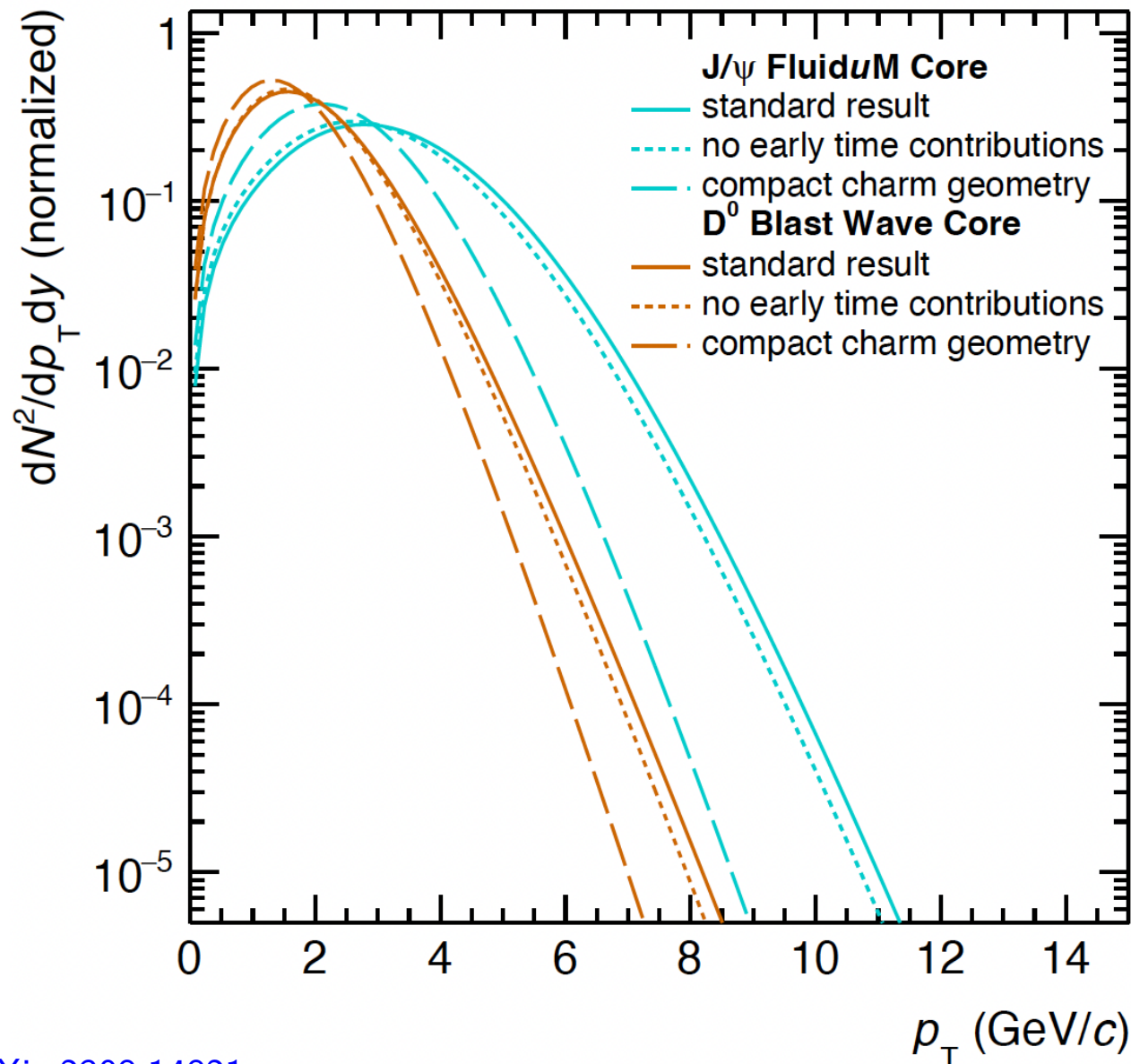
AA, ..., M. Vökl, [arXiv:2308.14821](https://arxiv.org/abs/2308.14821)

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

SHMc - coupling to hydrodynamics, refinements

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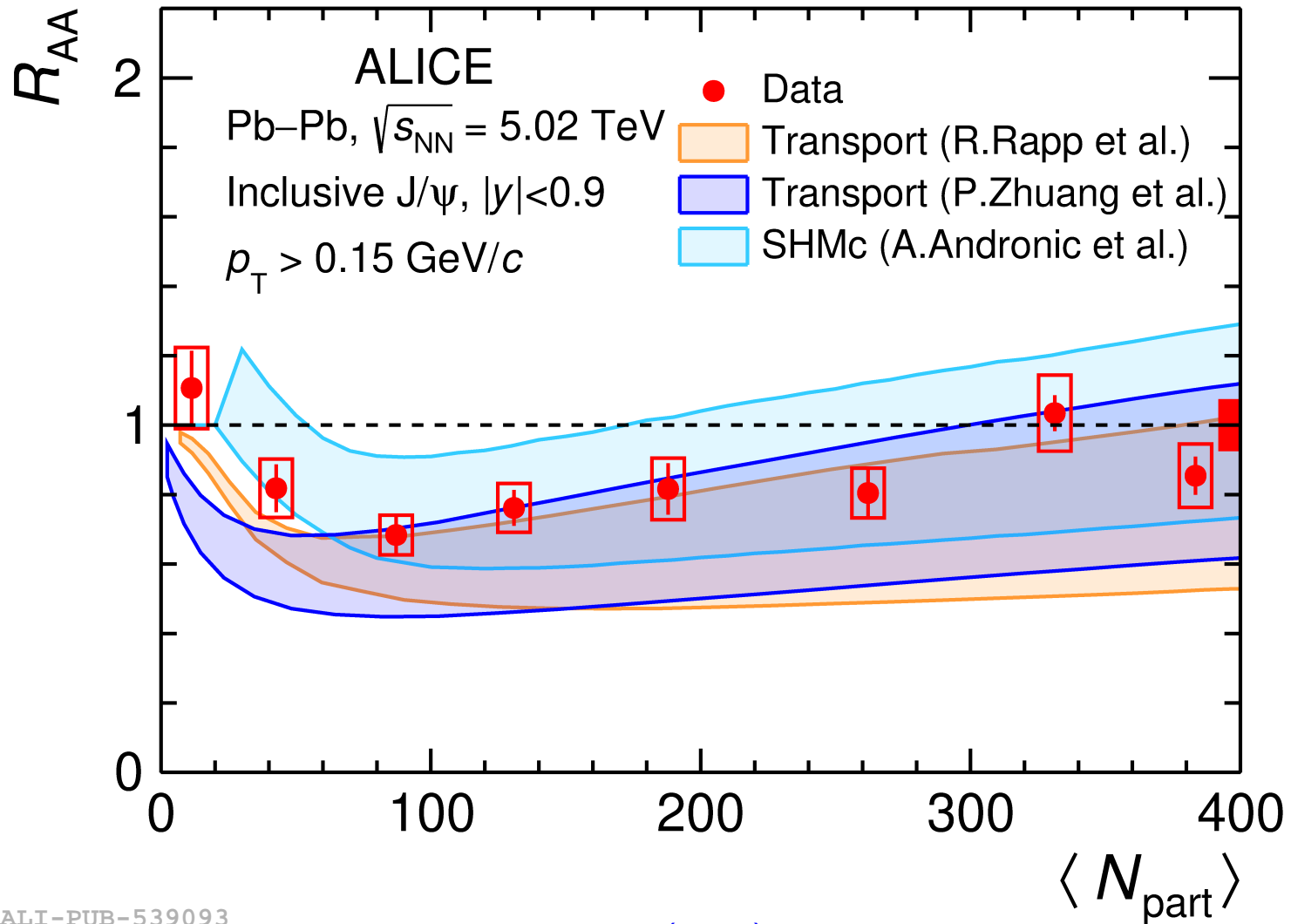
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AA, ..., M. Völkl, [arXiv:2308.14821](https://arxiv.org/abs/2308.14821)

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

SHMc vs. transport models



ALI-PUB-539093

ALICE, PLB 849 (2024) 138451

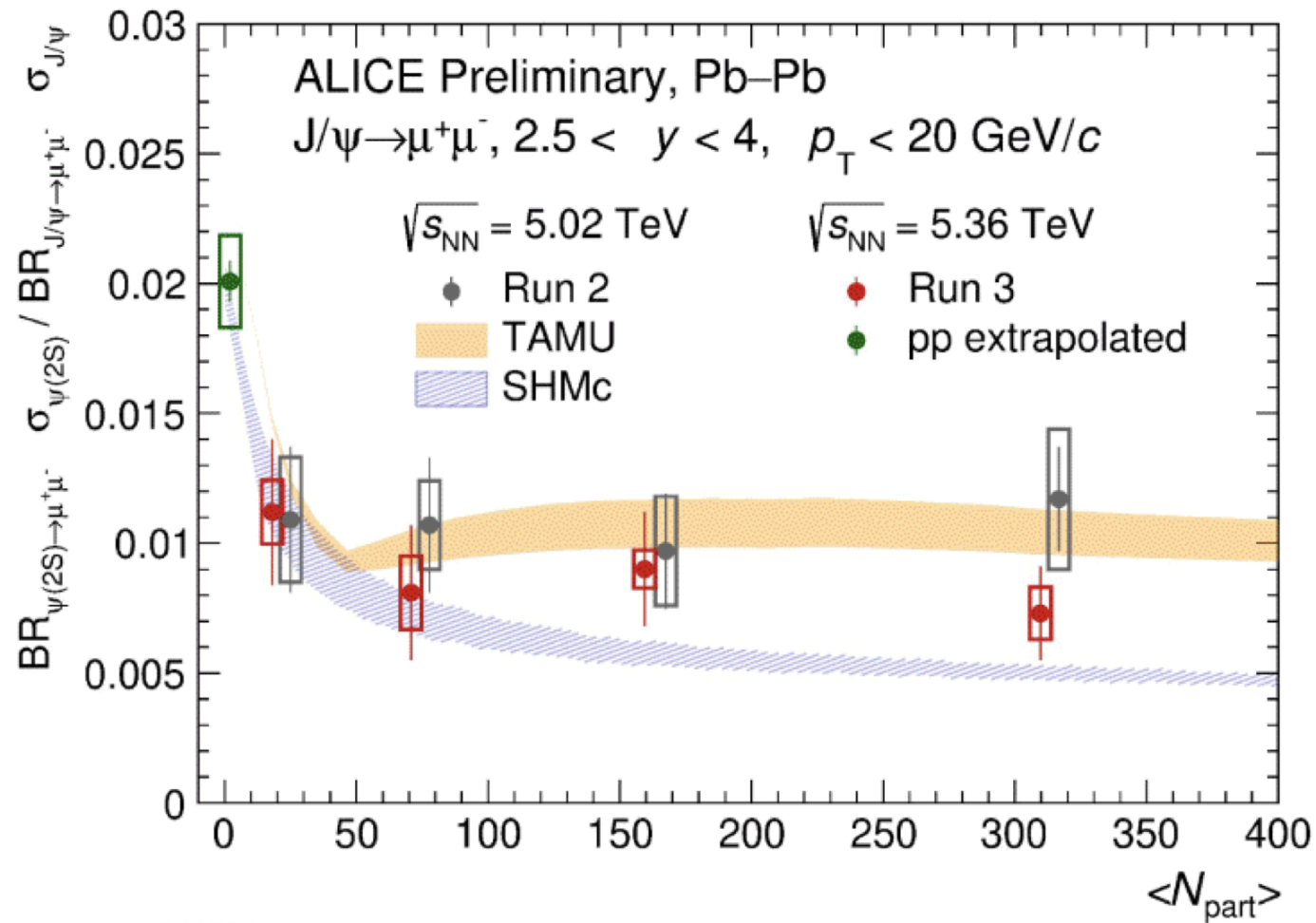
SHMc: $d\sigma_{c\bar{c}}/dy$ via normalization to D^0 in Pb–Pb 0-10%, ALICE, [arXiv:2110.09420](https://arxiv.org/abs/2110.09420)

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

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

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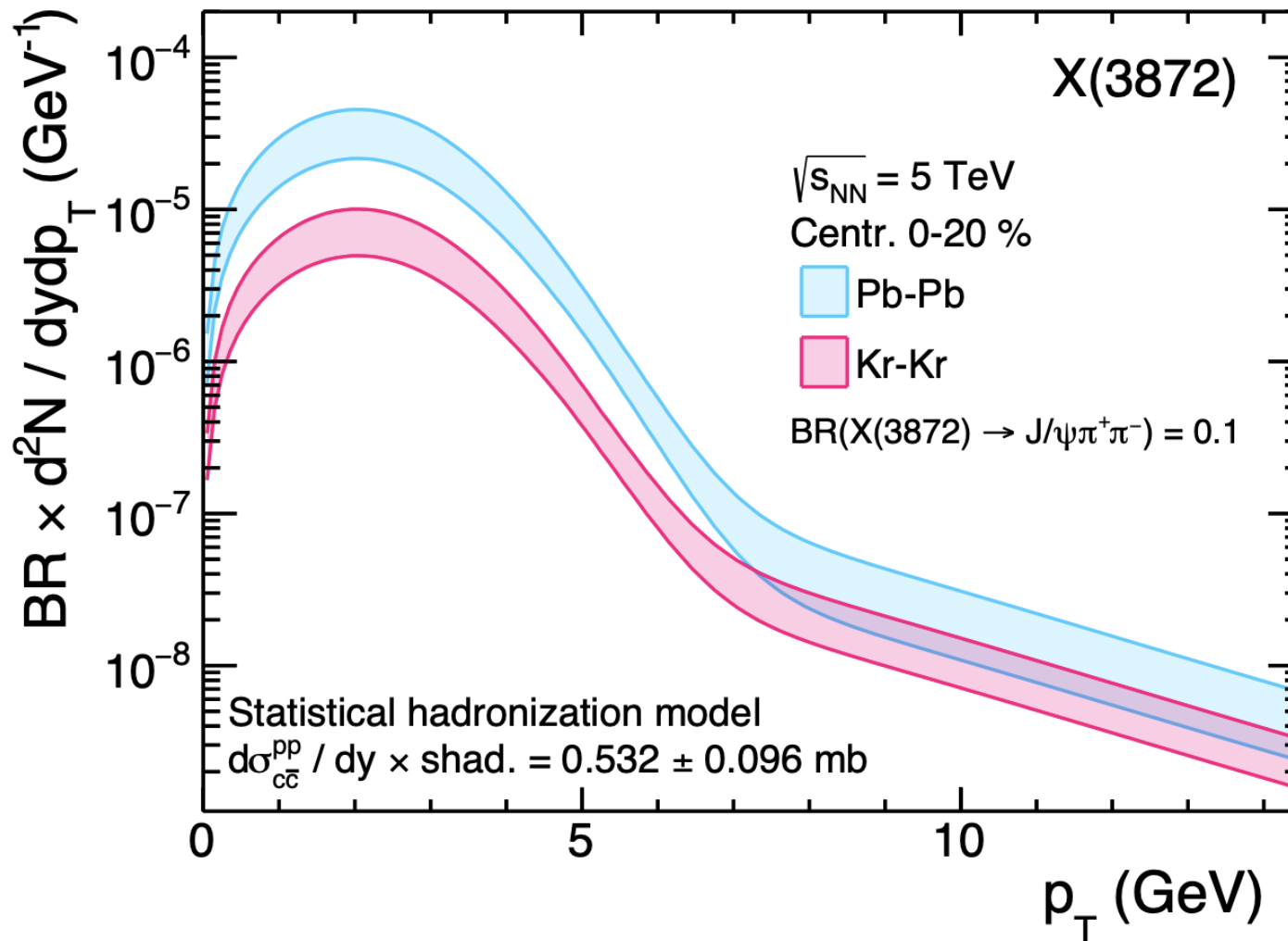
ALICE, S.Garetti, Poster QM'25; Run 2: [PRL 132 \(2024\) 042301](#)

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

$X(3872)$ predictions

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PLB 797 (2019) 134836

To test SHMc (hadronization as normal charmonia) low- p_T data are essential
A “wave-function penalty” is expected in case $X(3872)$ is not a compact state

Summary / Conclusions:

- 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 reproducing the J/ψ and open charm data
A handle for hadronization T with a mass scale well above T
- The power of the model: predicts full suite of hadrons, incl. exotic ones
- Is charm hadronization taking place 100% at the QCD phase boundary

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

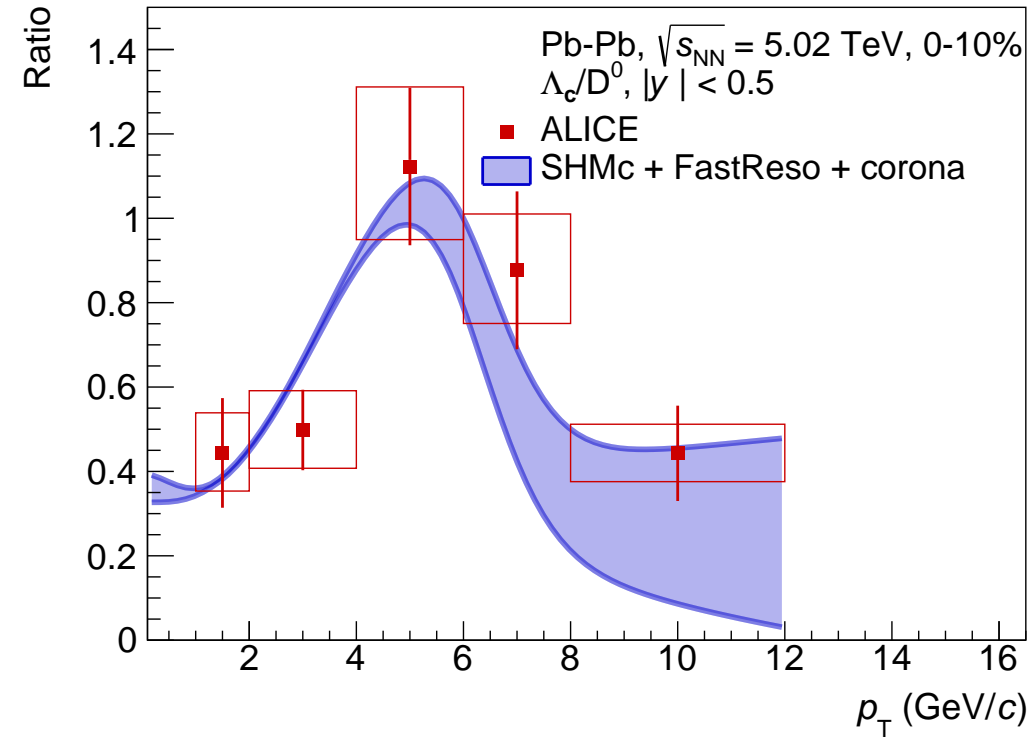
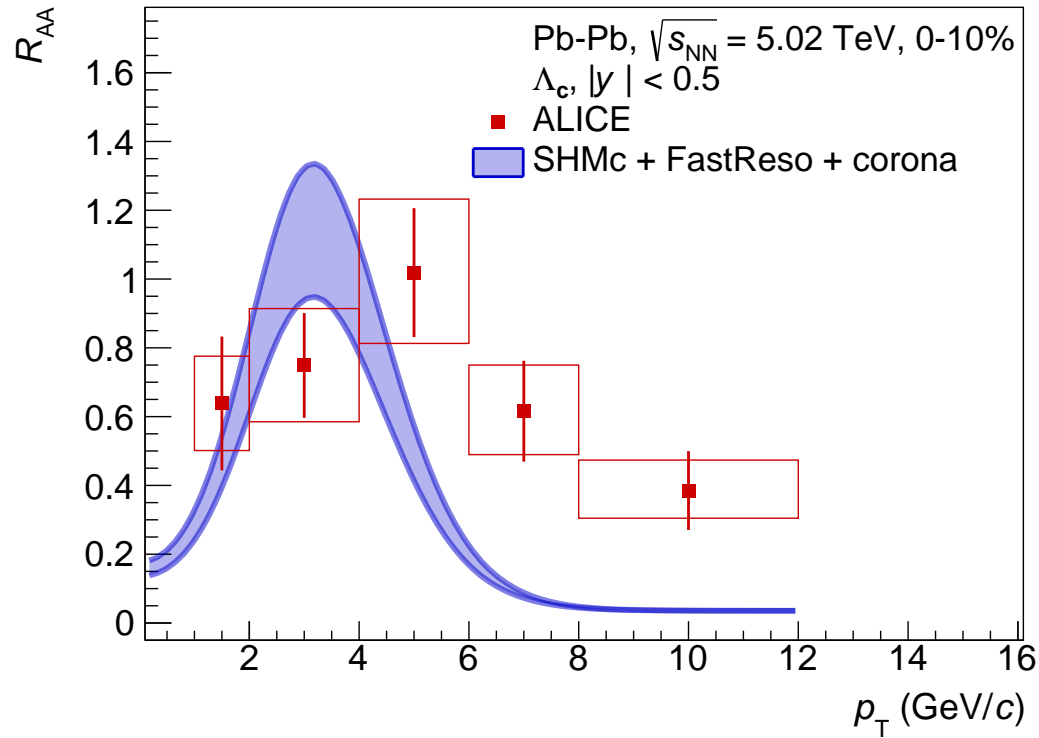
Discriminating the two pictures implies providing an answer to fundamental questions related to the fate of (exotic) hadrons in a hot deconfined medium.

A precision ($\pm 10\%$) measurement of $d\sigma_{c\bar{c}}/dy$ in Pb-Pb collisions needed for a stringent test (within reach with the upgraded detectors at LHC and RHIC)

Additional slides

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SHMc: p_T , open charm

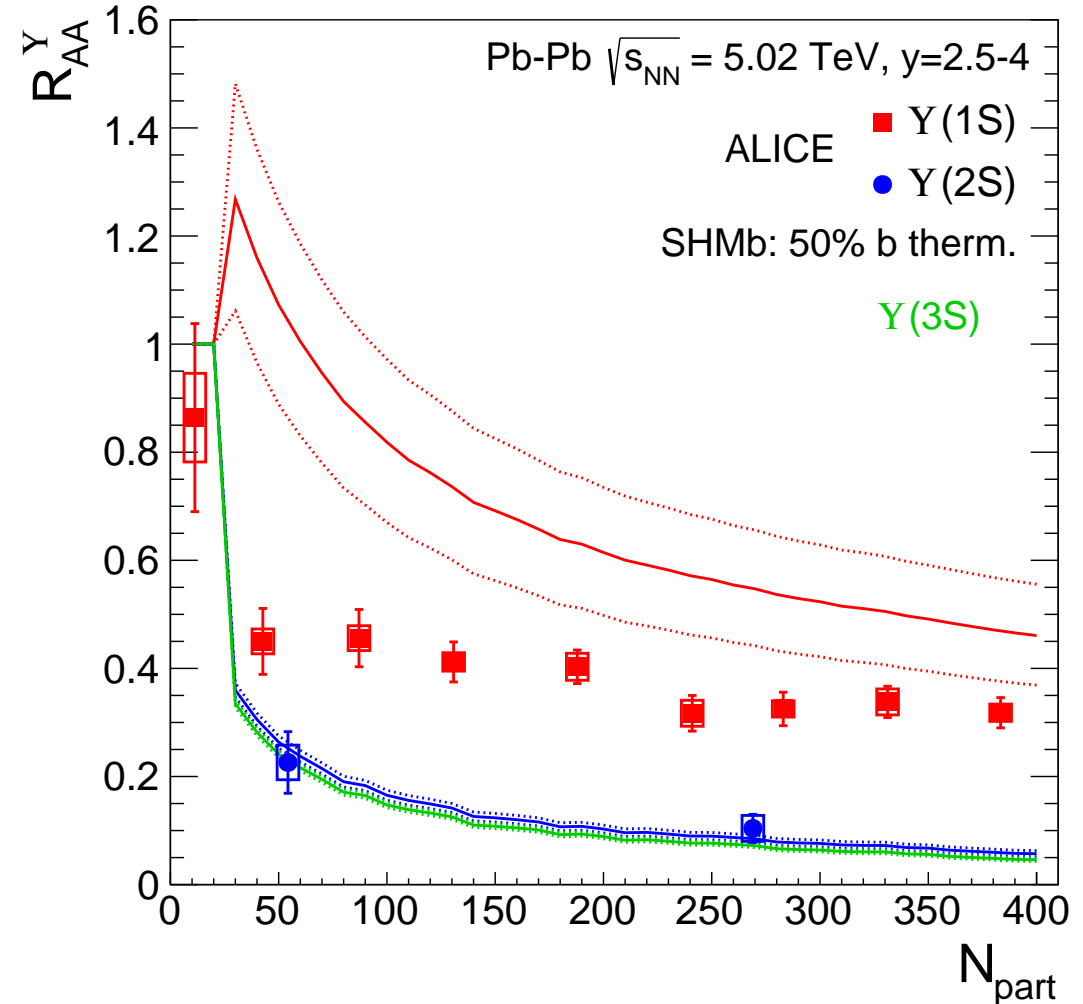
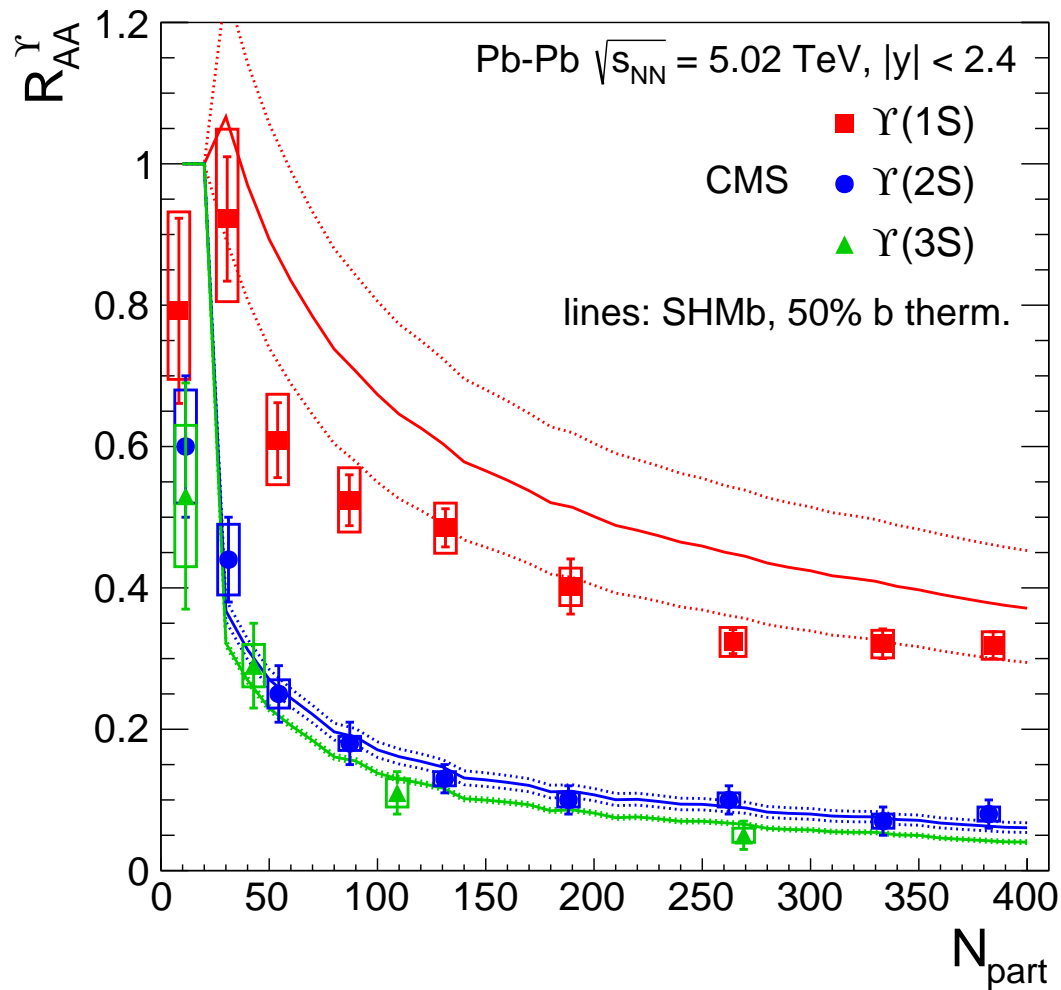


AA, ..., M. Vökl, [arXiv:2308.14821](https://arxiv.org/abs/2308.14821)

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

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CMS, PRL 120 (2018) 142301

ALICE, PLB 822 (2021) 136579

*What does non-thermalized beauty produce? (no room for it in SHM**b**)*