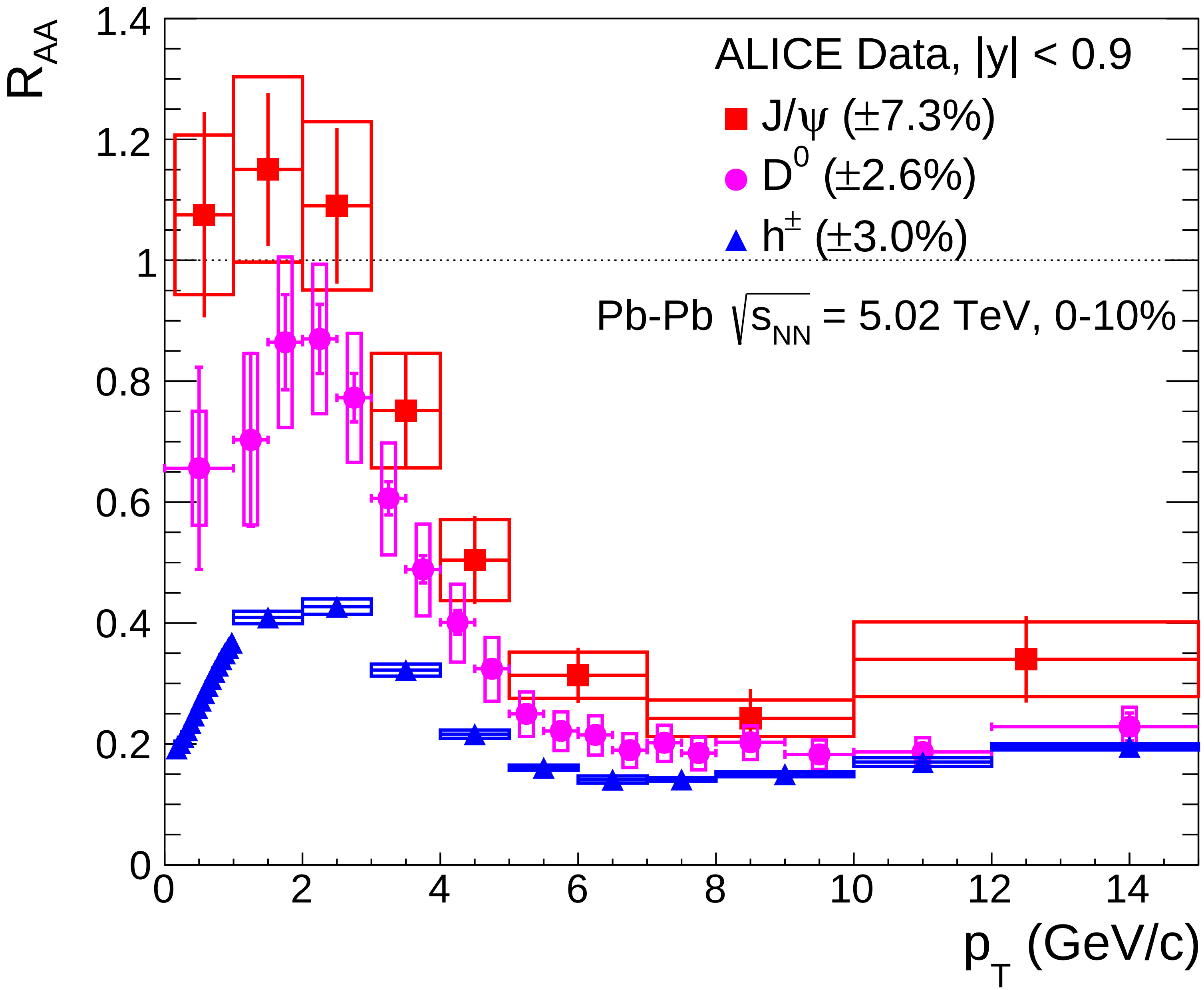
The post-mortem QGP analysis:
the statistical hadronization model for heavy quarks

A. Andronic - University of Münster

- The statistical model and the thermal fits
- The charm quarks
- The beauty quarks

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

...+ Köhler, Mazeliauskas, Vislavicius, JHEP 07 (2021) 035



ALICE, arXiv:2303.13361, etc.

grand canonical partition function for specie (hadron) i :

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

$g_i = (2J_i + 1)$ 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

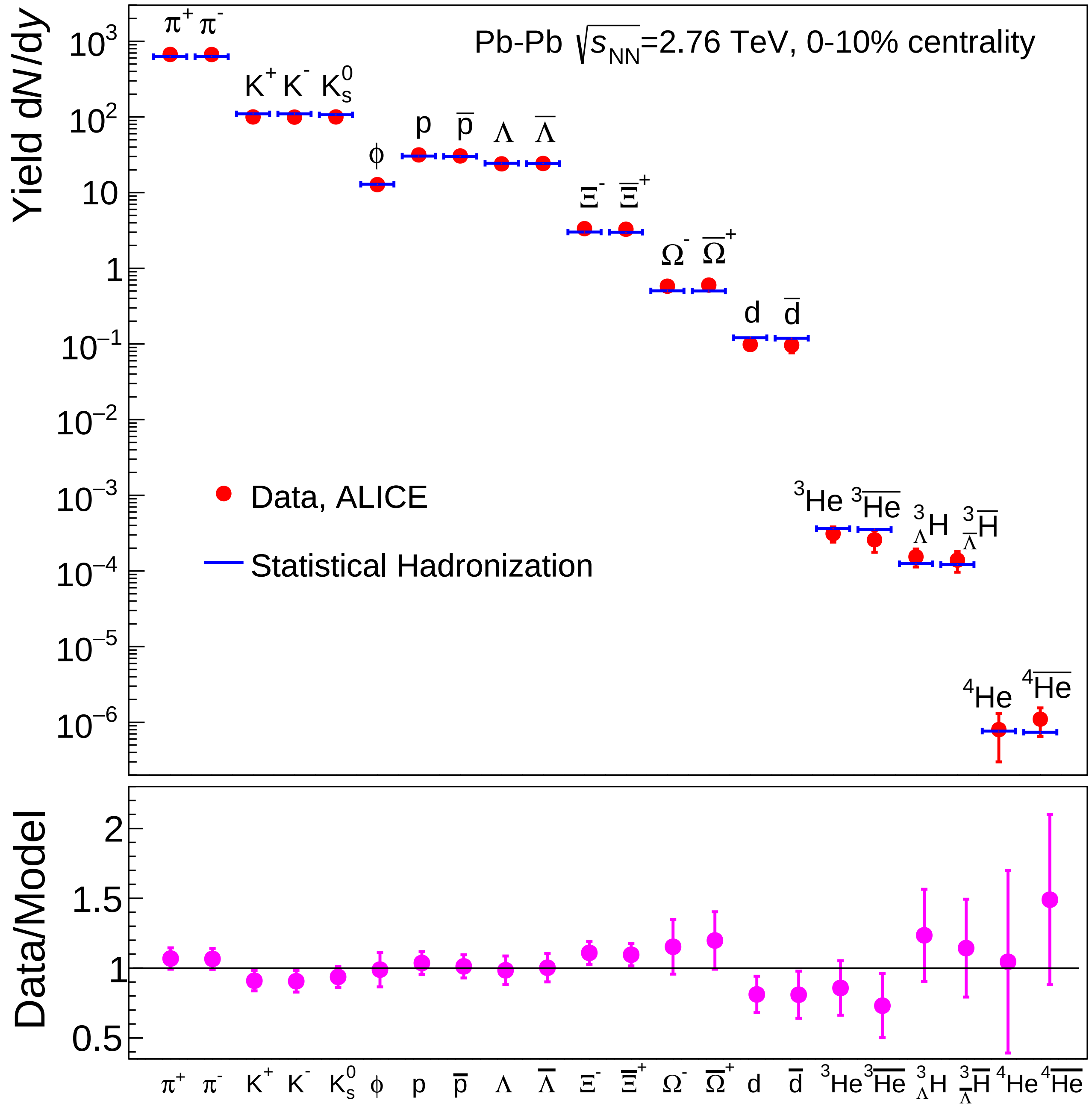
μ ensure conservation (on average) of quantum numbers, fixed by "initial conditions"

i) isospin: $\sum_i n_i I_{3i} / \sum_i n_i B_i = I_3^{tot} / N_B^{tot}$, $\quad N_B^{tot} \sim \mu_B$
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: $\sum_i n_i C_i = 0$.

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

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

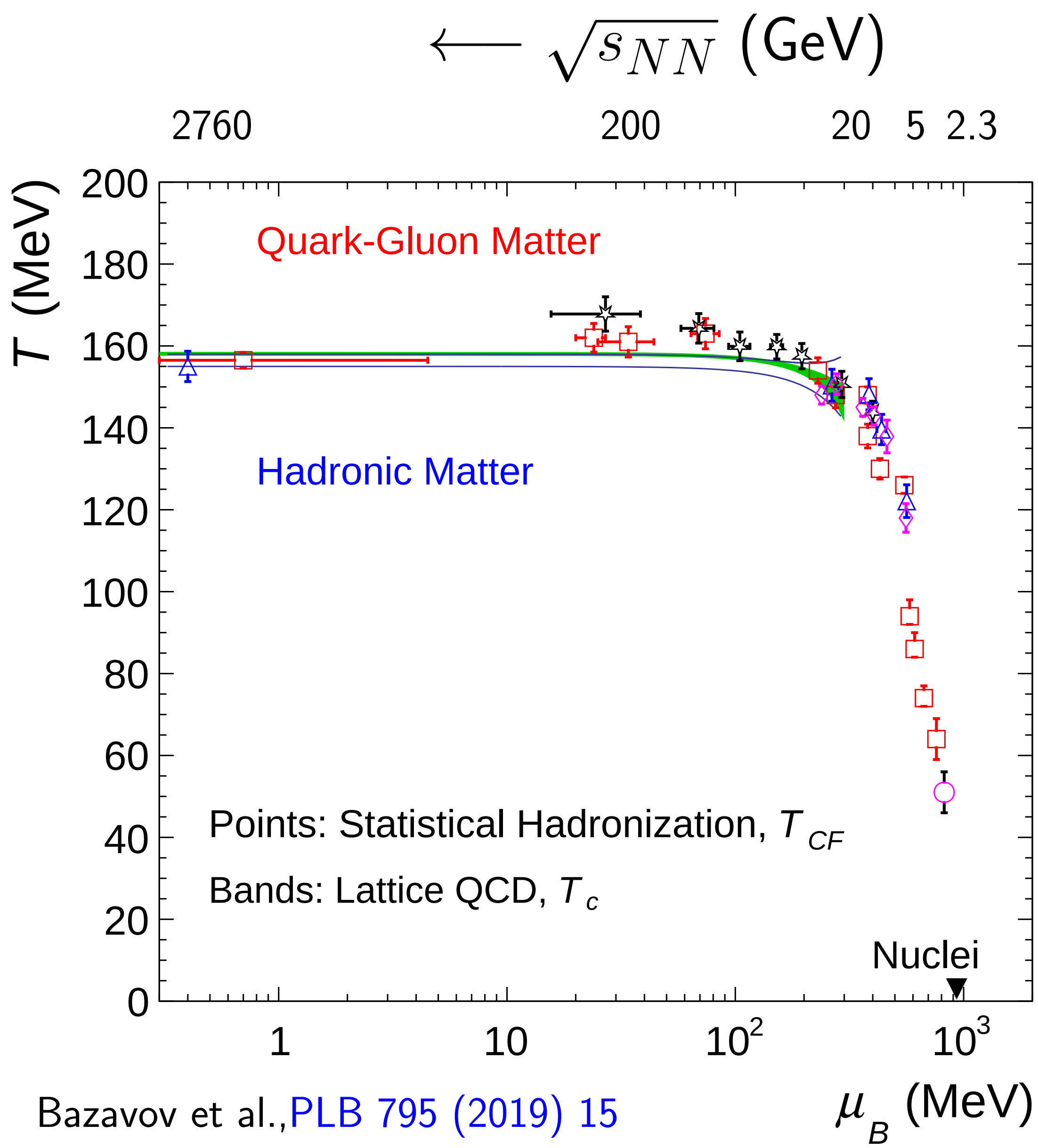
S-matrix treatment

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

hadronization as bags of quarks and gluons?

The phase diagram of QCD

A. Andronic



Bazavov et al., PLB 795 (2019) 15

Borsanyi et al., PLB 370 (2014) 99

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

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

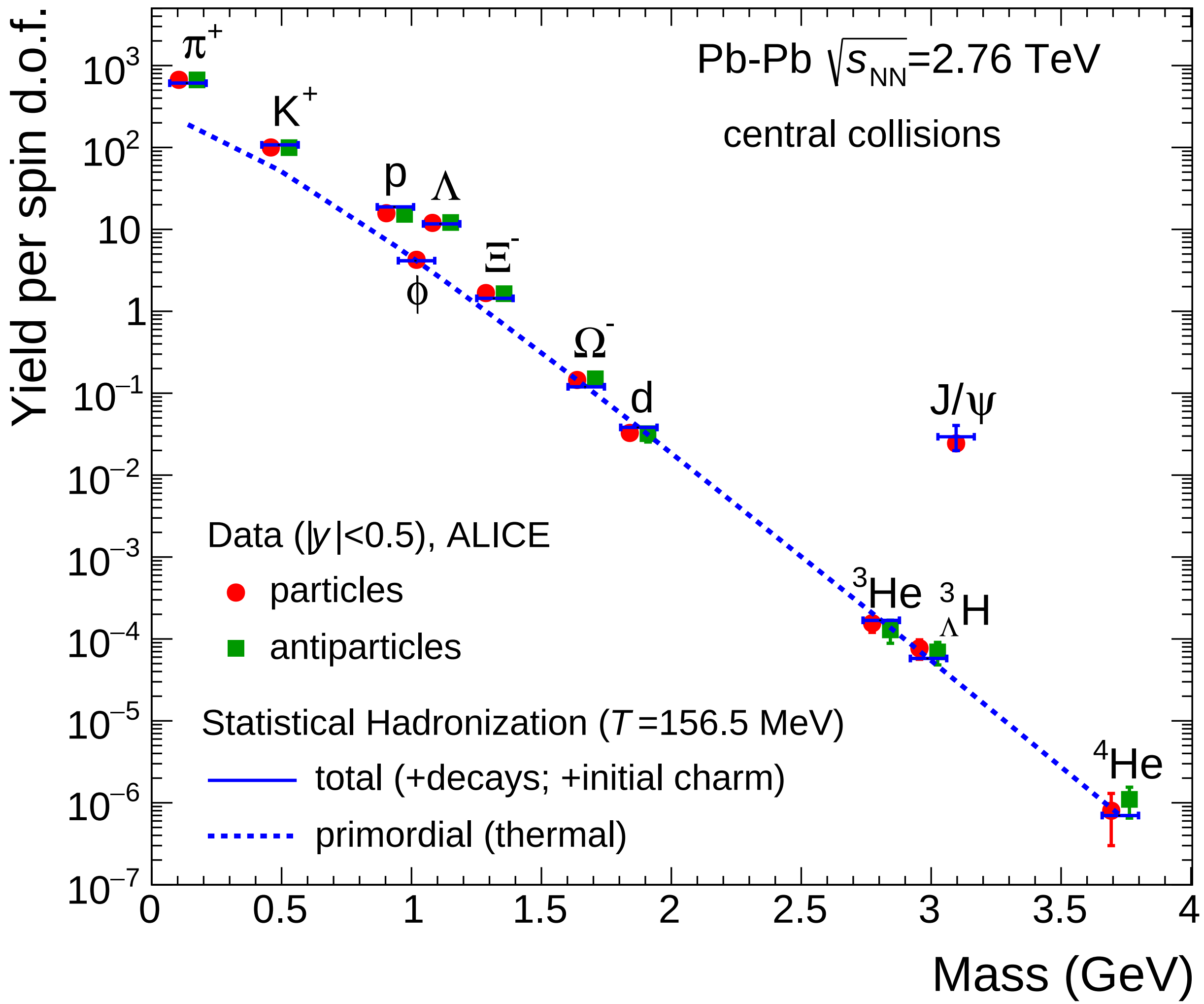
assume:

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

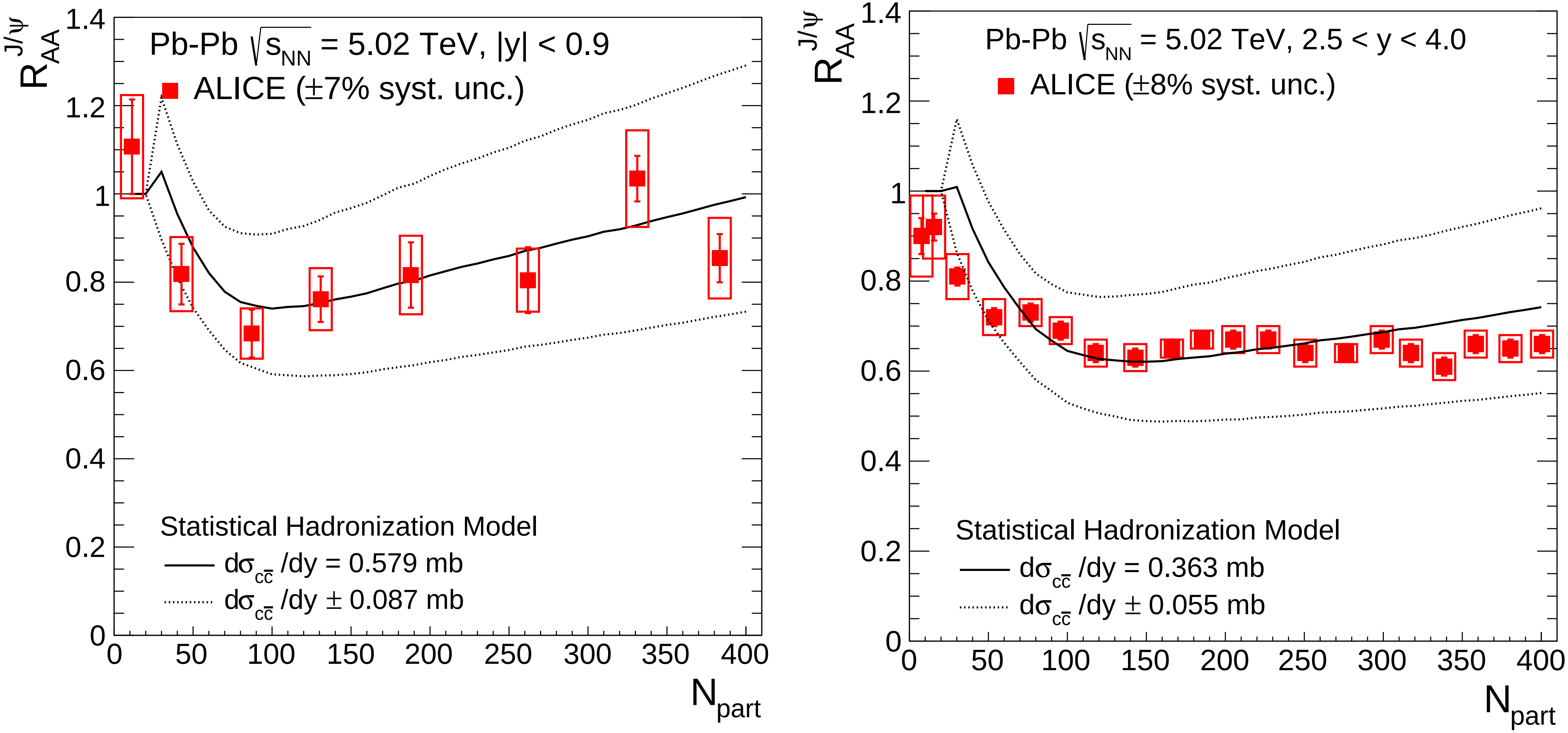
Inputs: T, μ_B, $V_{\Delta y=1} (= ({\rm d}N_{ch}^{exp}/{\rm d}y)/n_{ch}^{th})$, $N_{c\bar{c}}^{dir}$ (exp. or pQCD)

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

SHMc and charmonium data at the LHC

A. Andronic

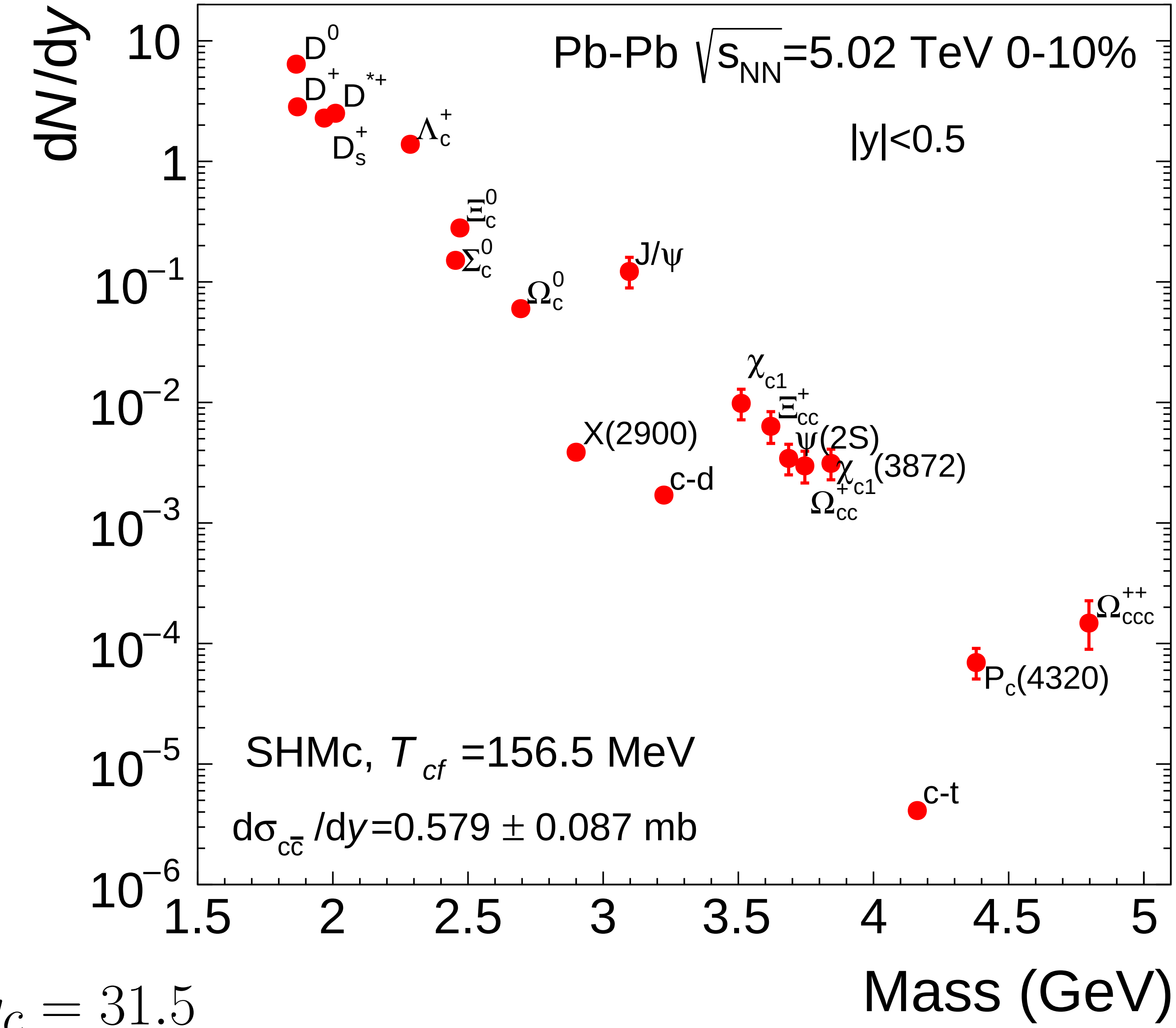
full thermalization of c quarks in QGP, hadronization at chemical freeze-out



$d\sigma_{c\bar{c}}/dy$ 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



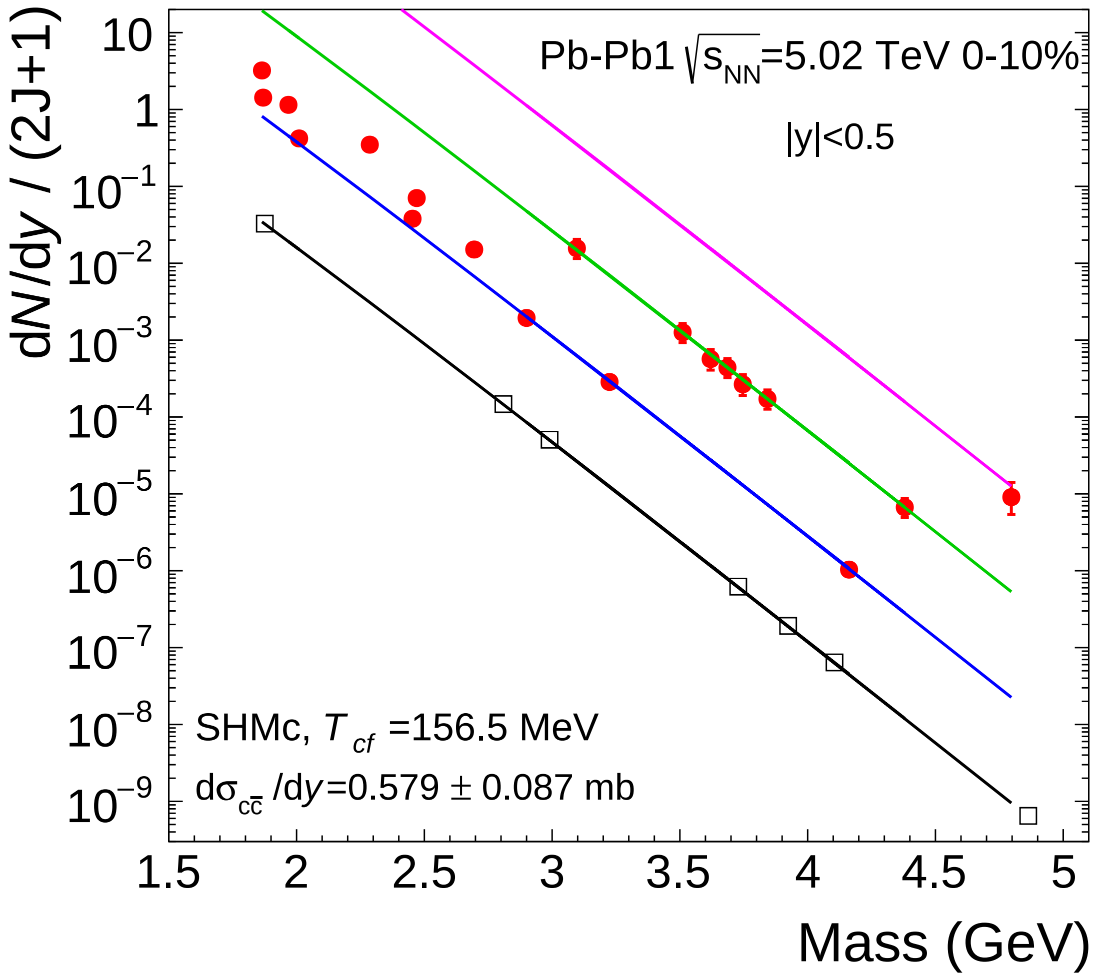
$T_{cc}^{+} \simeq 0.9 \cdot \chi_{c1}(3872)$

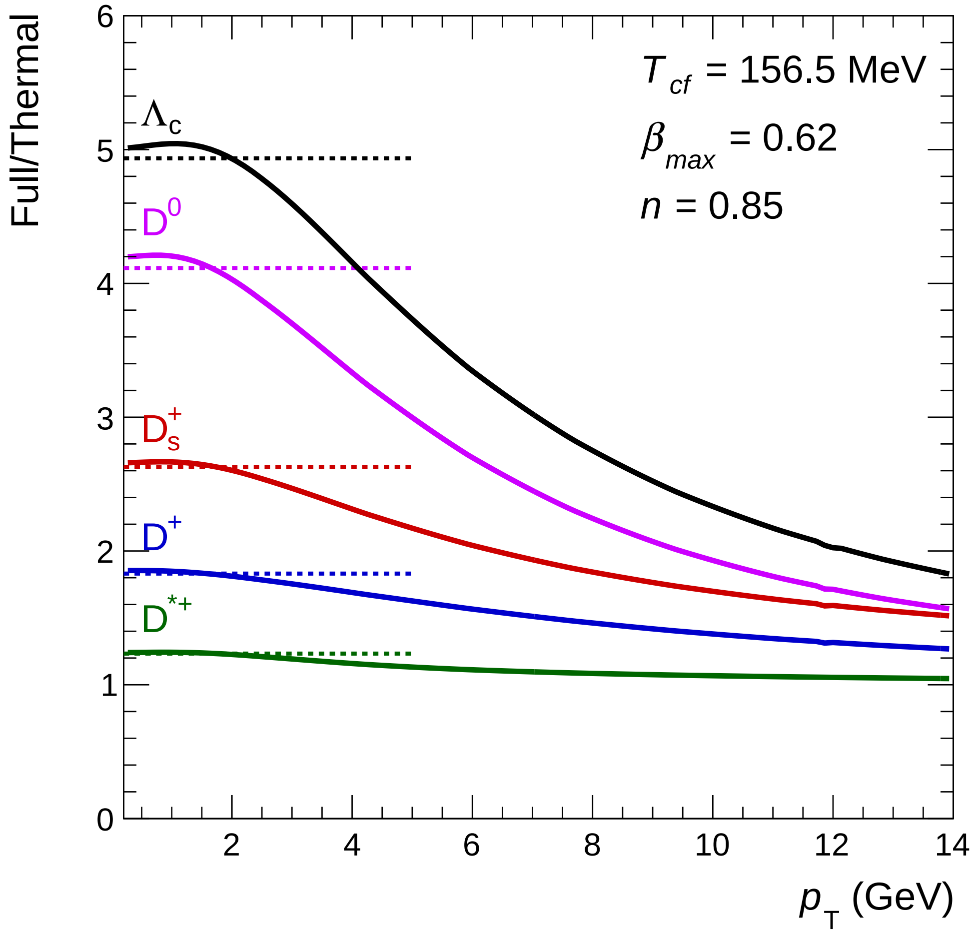
$X(6900) \sim 10^{-8}$

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

$\rightarrow g_c = 31.5$

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

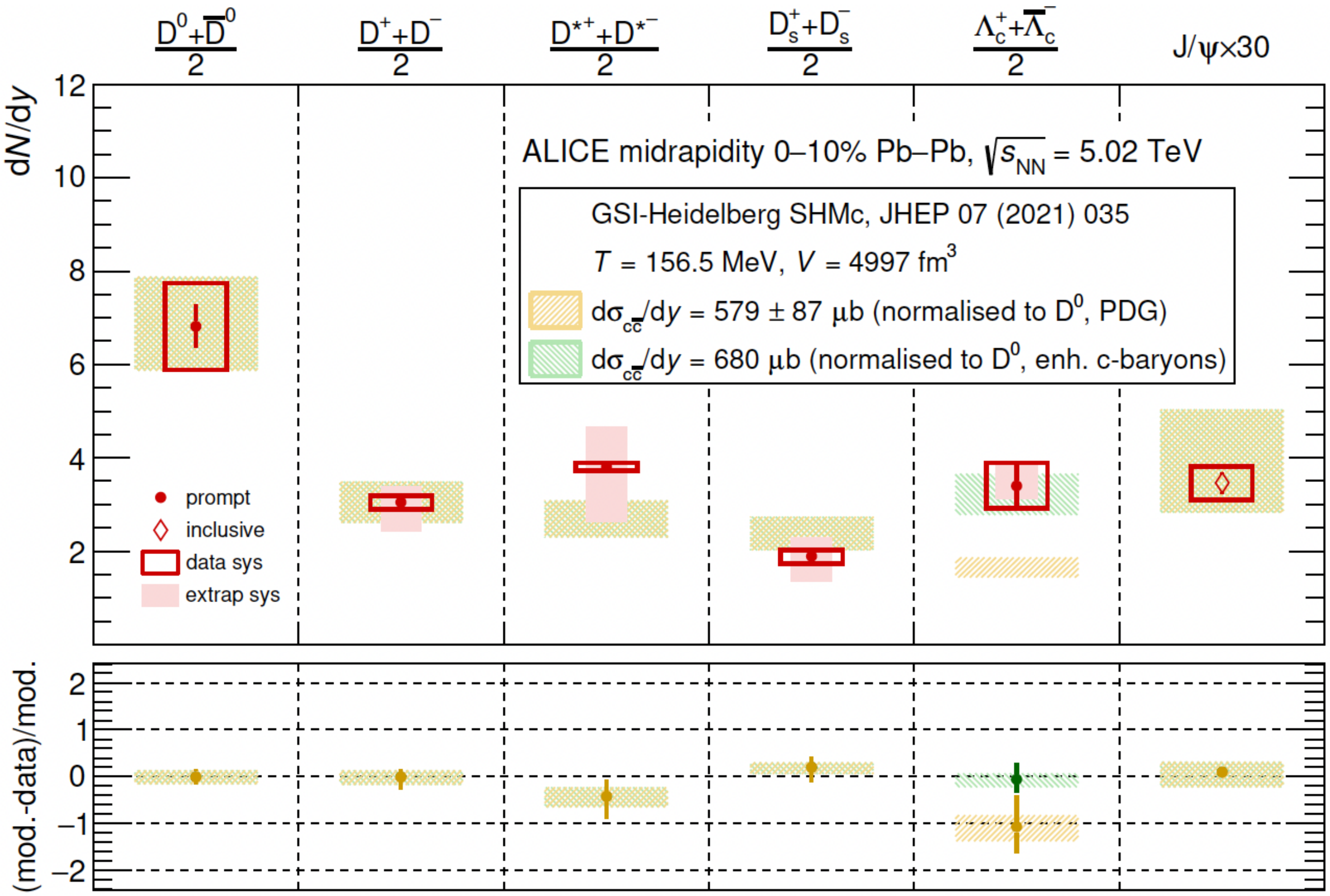




Charm-hadron spectrum as in PDG: 55 c-mesons, 74 c-baryons (part.+antipart.)

...large, but may not be complete

Charm data and SHMc model



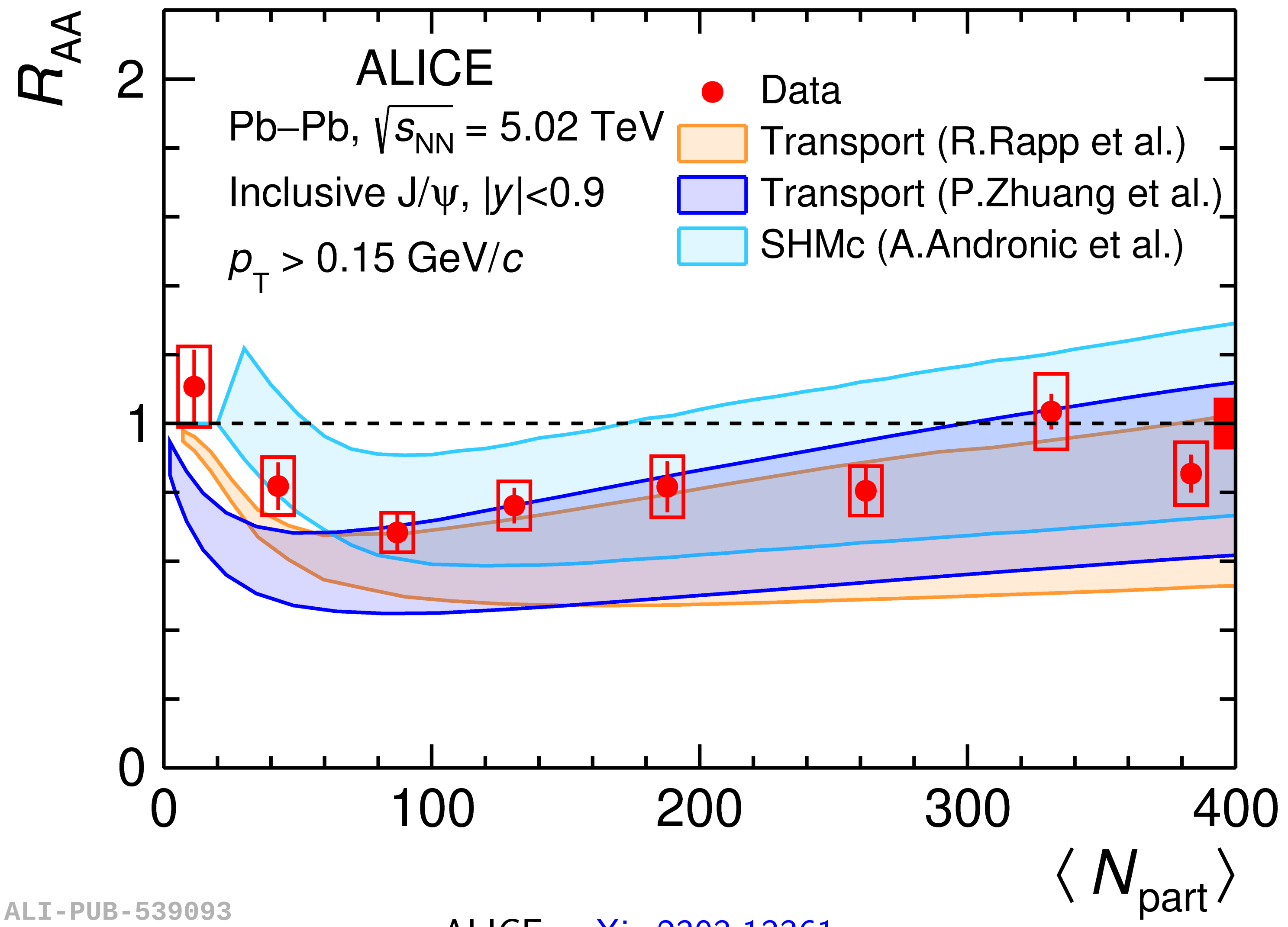
ALICE, arXiv:2212.04348

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

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

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

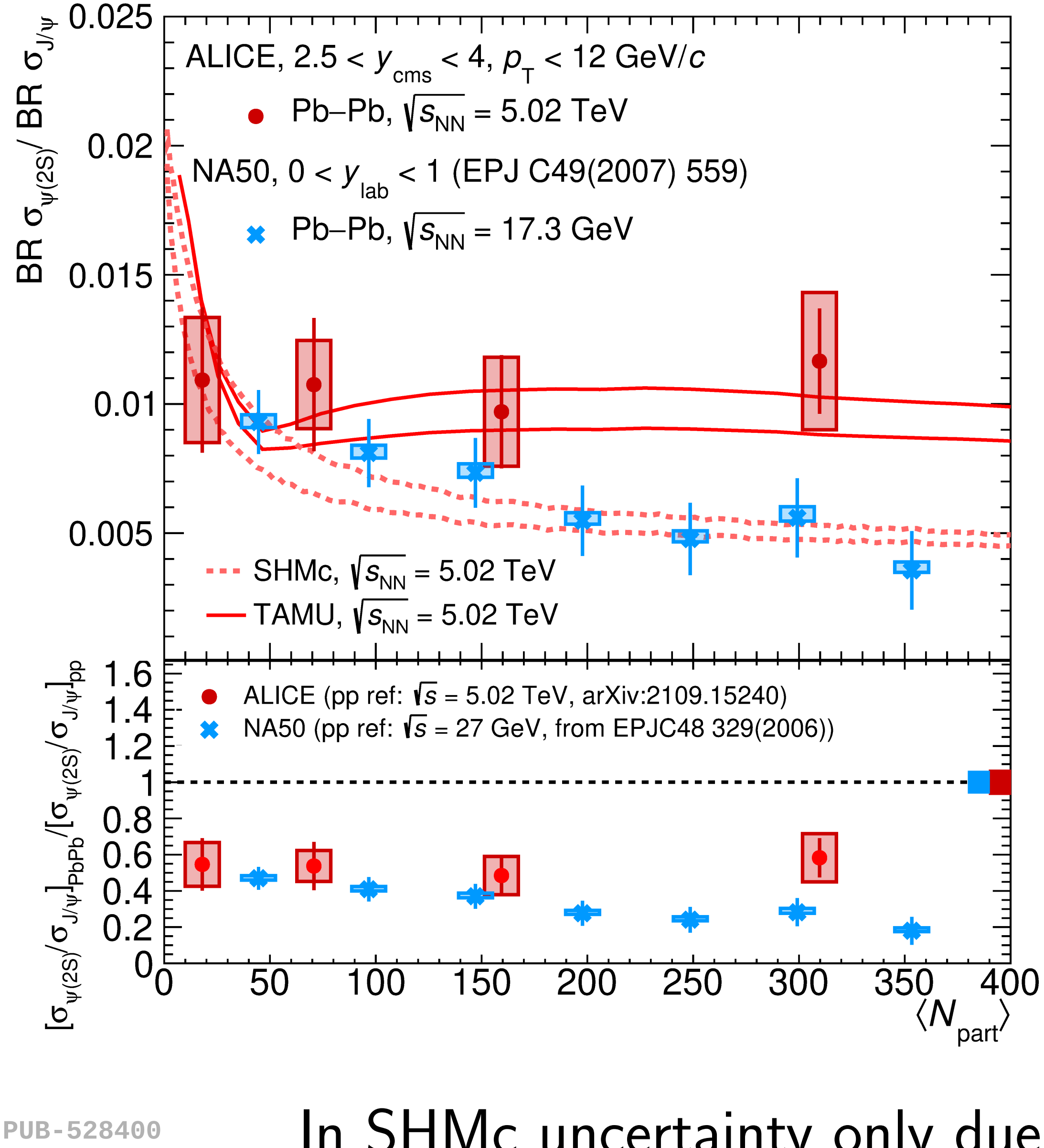
SHMc vs. transport models



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

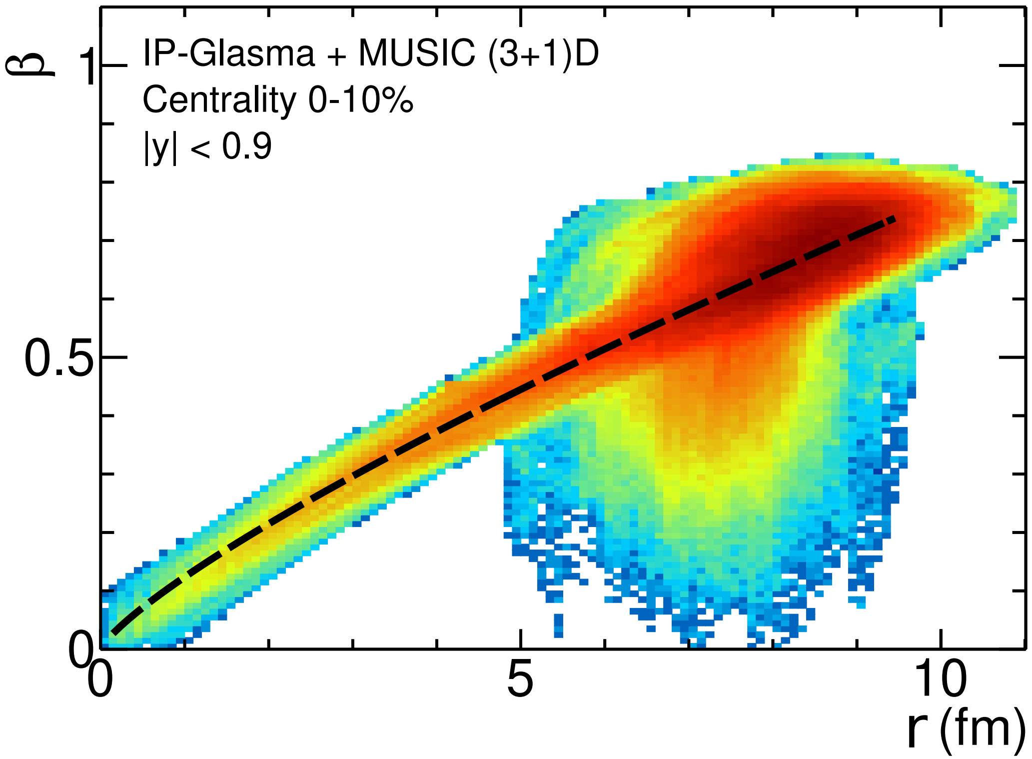
$\mathrm{d}N/\mathrm{d}y$ = 6.82±1.03 ($|y| < 0.5$; FONLL for y=2.5-4; assuming hadronization fractions in data as in SHMc)

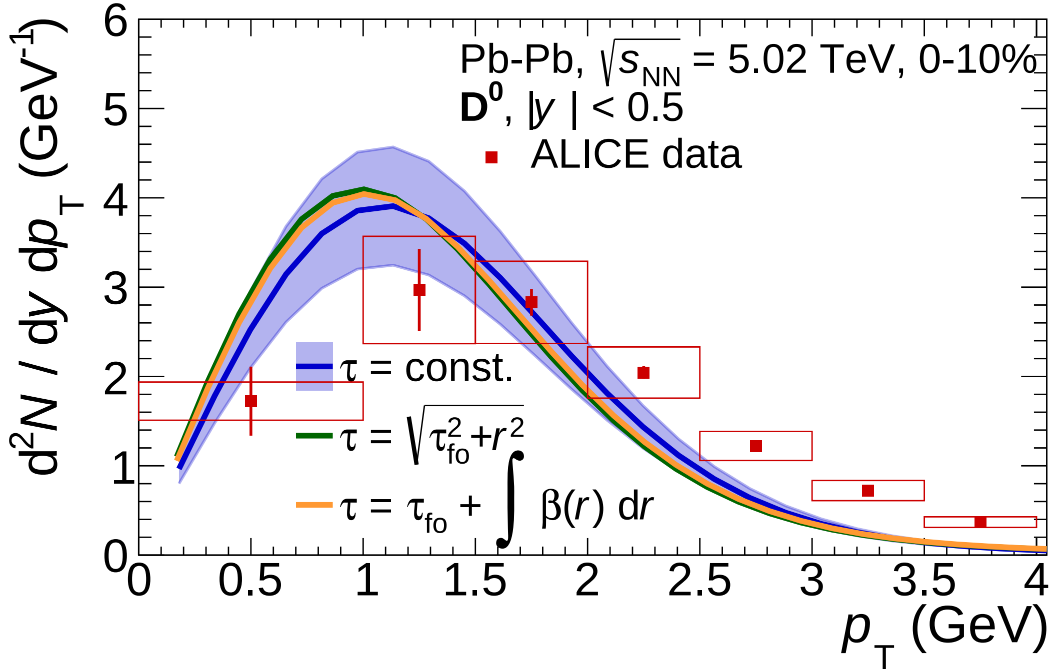


In SHMc uncertainty only due to nuclear-corona ($\sigma_{c\bar{c}}$ cancels out completely)

ALICE, arXiv:2210.08893

full hydrodynamic flow (MUSIC(3+1)D, IP-Glasma; parametrized via blast-wave

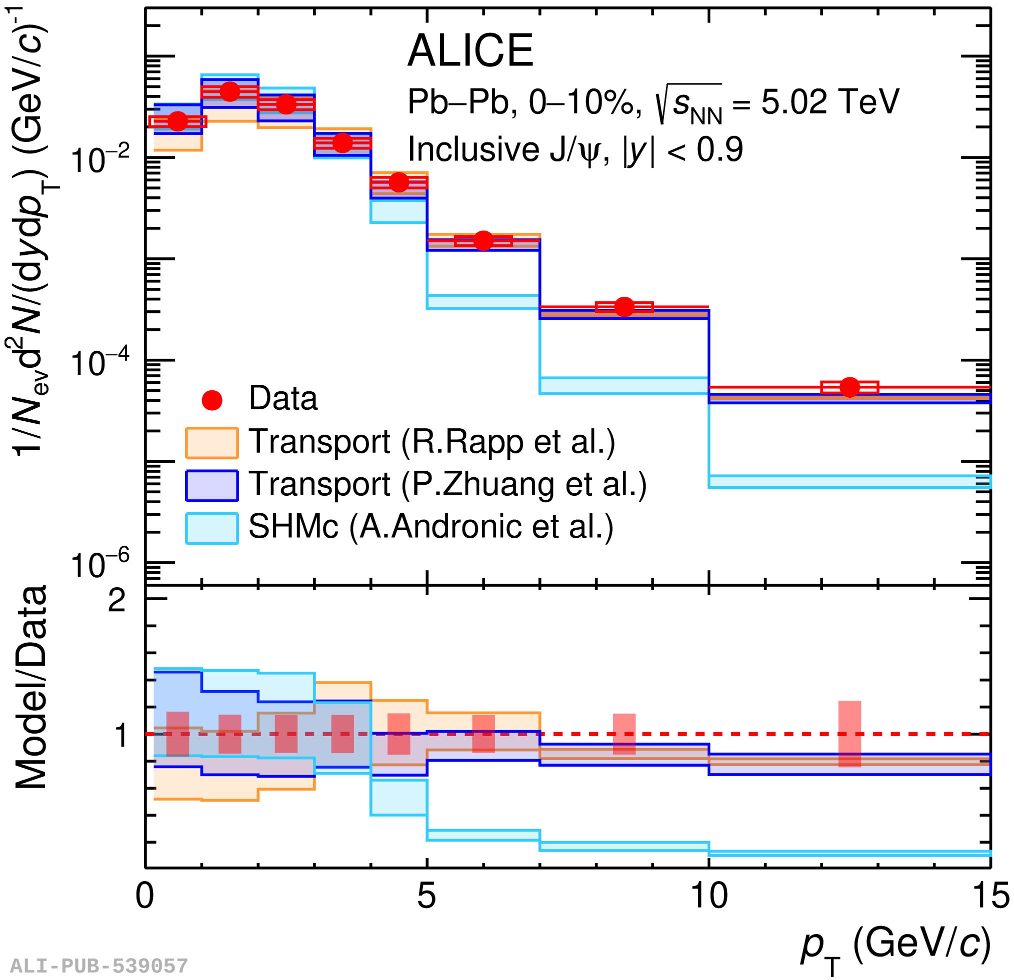


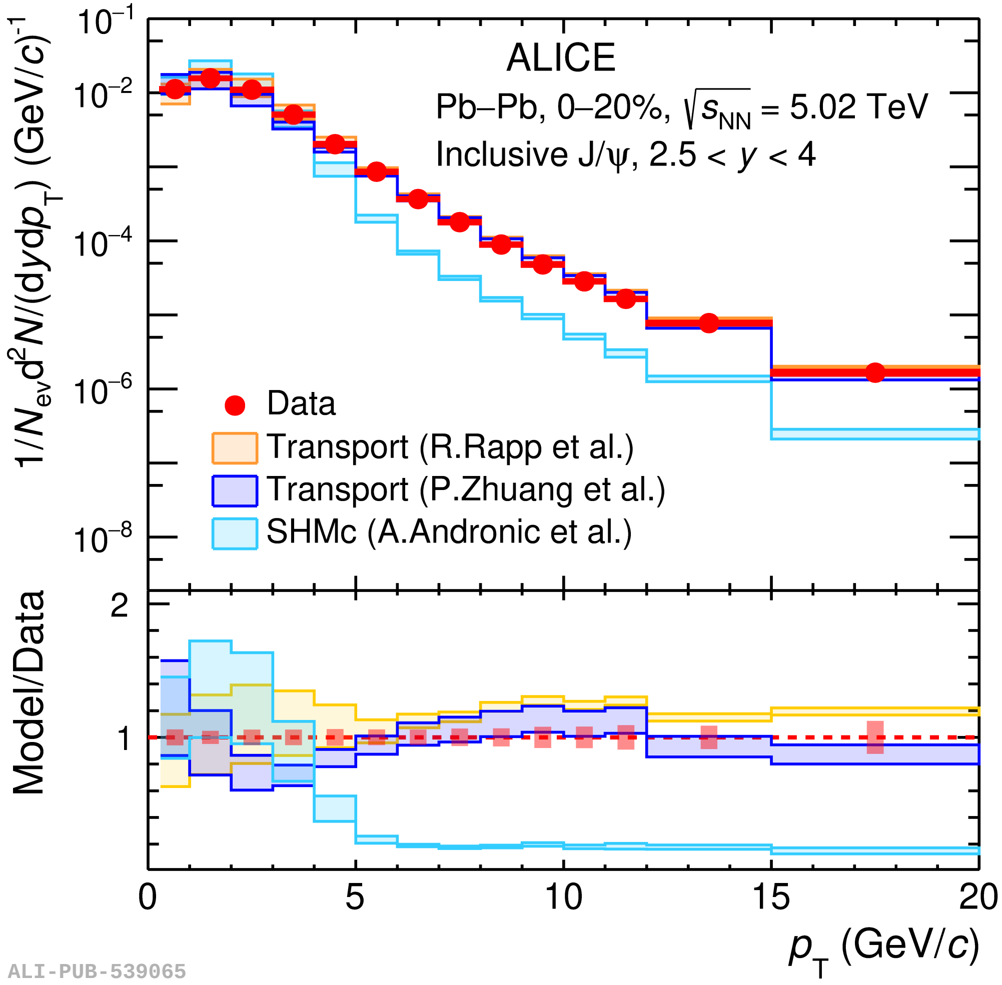


$$\frac{d^2N}{2\pi p_T dp_T dy} = \frac{2J+1}{(2\pi)^3} \int d\sigma_\mu p^\mu f(p) = \frac{2J+1}{(2\pi)^3} \int_0^{r_m} dr\ \tau(r) r \left[K_1^{eq} - \frac{\partial \tau}{\partial r} K_2^{eq} \right]$$

$$K_1^{eq}(p_T, u^r) = 4\pi m_T I_0 \left(\frac{p_T u^r}{T} \right) K_1 \left(\frac{m_T u^\tau}{T} \right), \quad K_2^{eq}(p_T, u^r) = 4\pi p_T I_1 \left(\frac{p_T u^r}{T} \right) K_0 \left(\frac{m_T u^\tau}{T} \right)$$

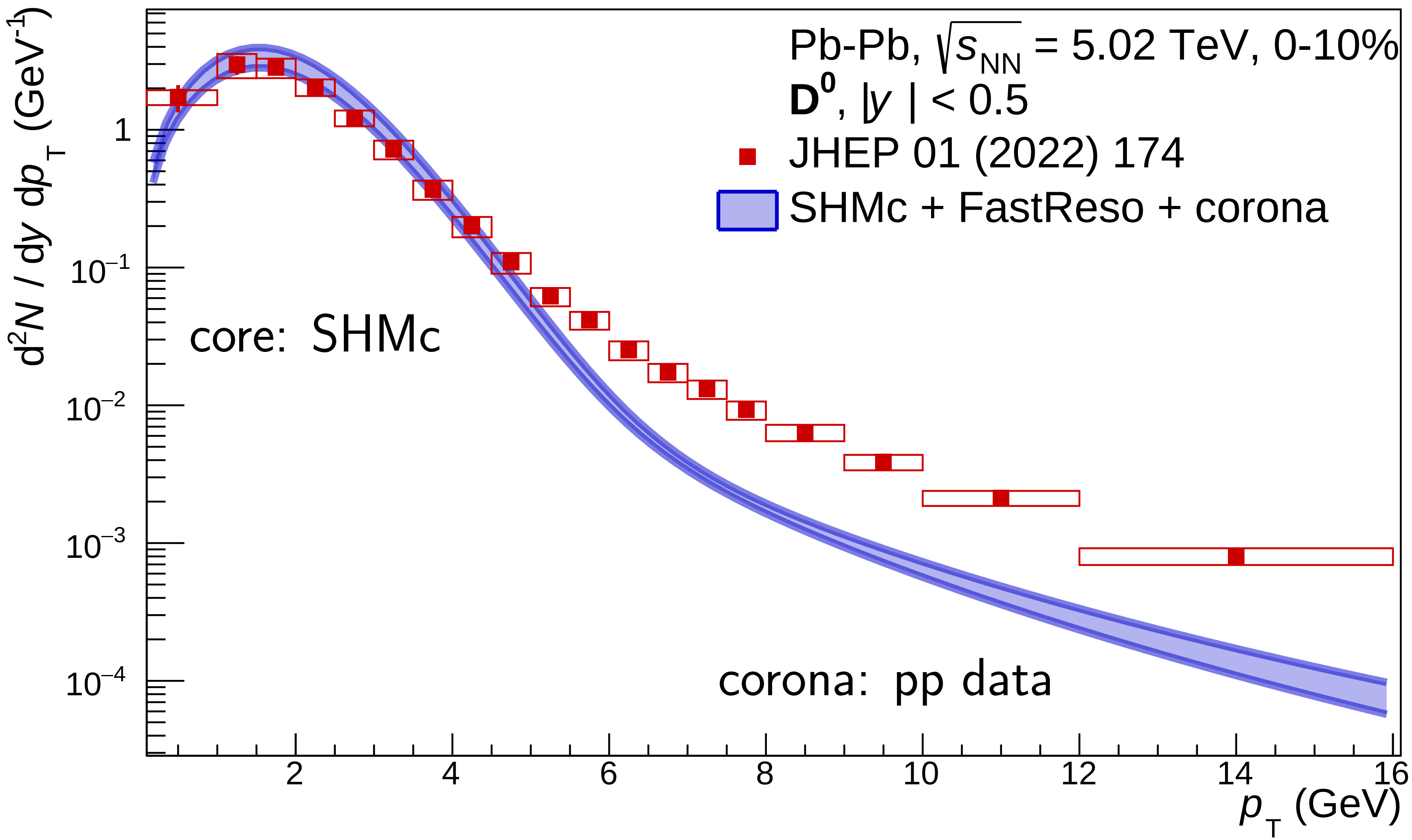
SHMc and charmonium data at the LHC





ALICE, arXiv:2303.13361

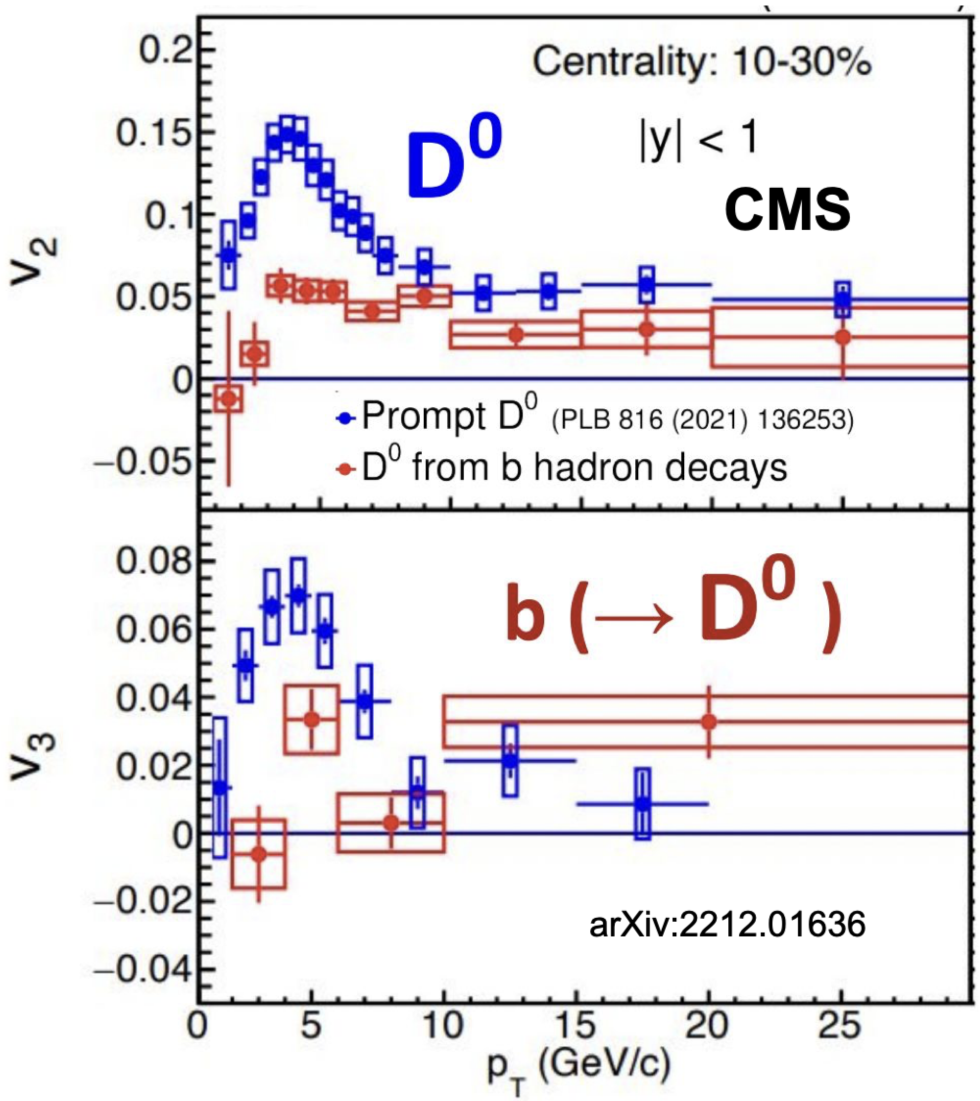
SHMc: p_T dependence

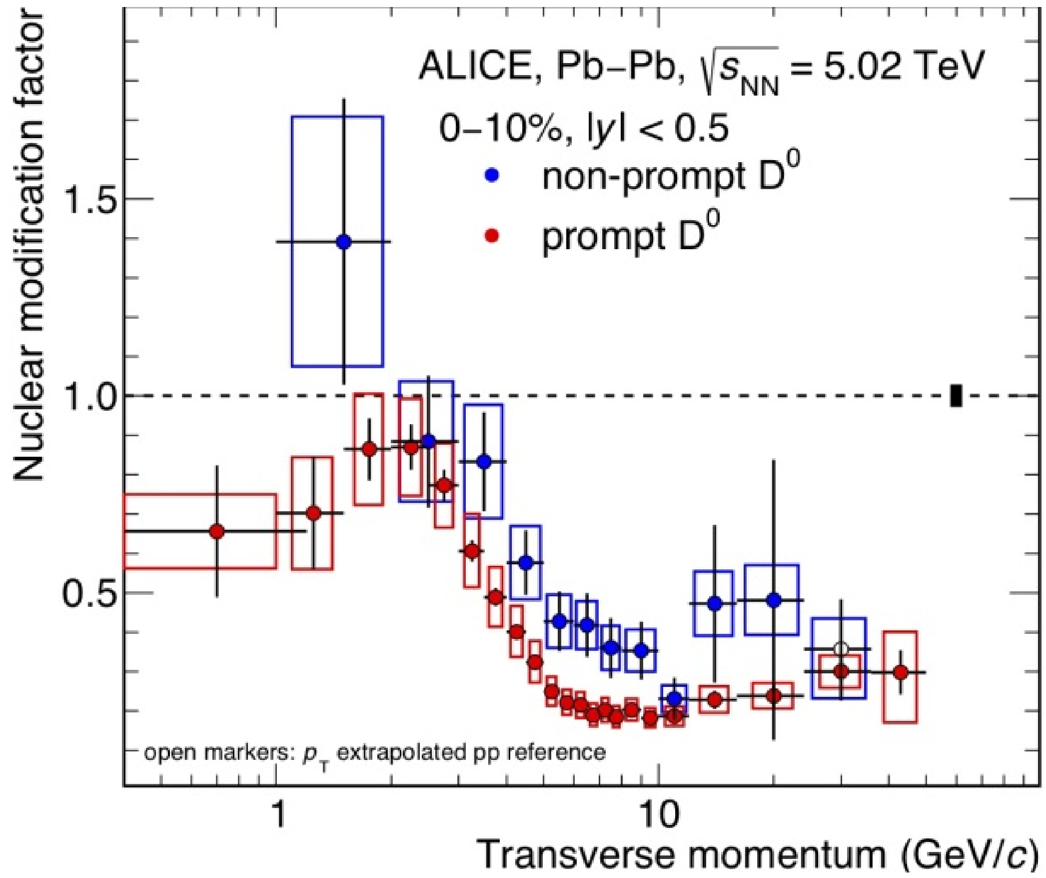


SHMc: low p_T; high p_T: only nuclear-corona contribution (incl. uncert.)

ALICE, JHEP 01 (2022) 174

SHMc: on-going updates



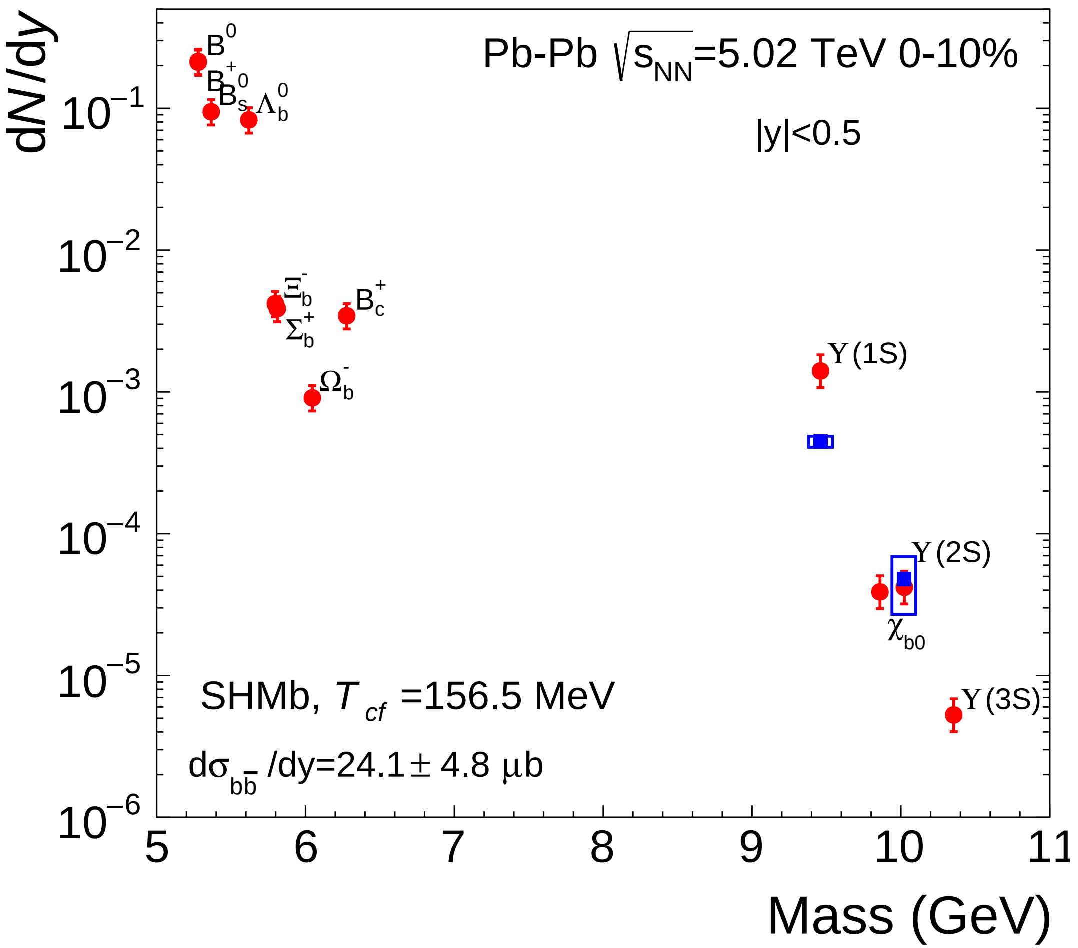


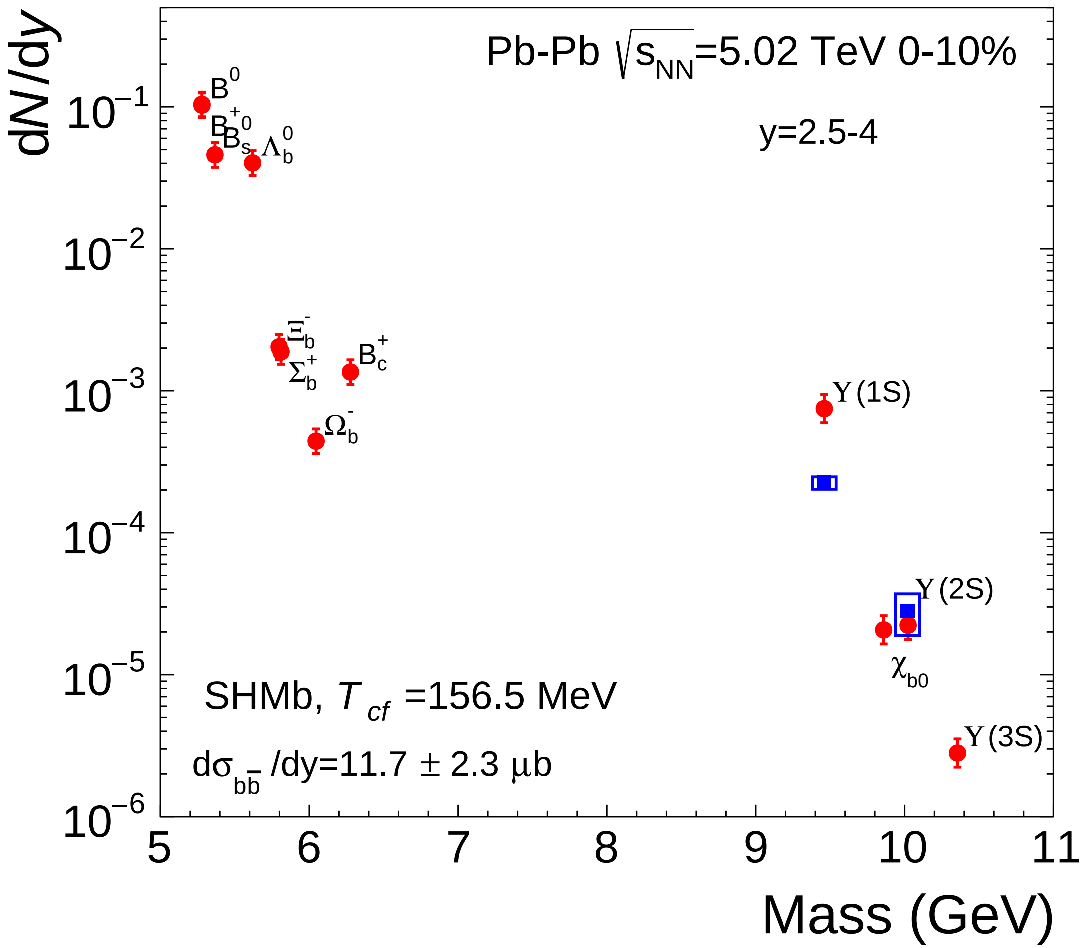
ALICE, arXiv:2202.00815, ATLAS

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



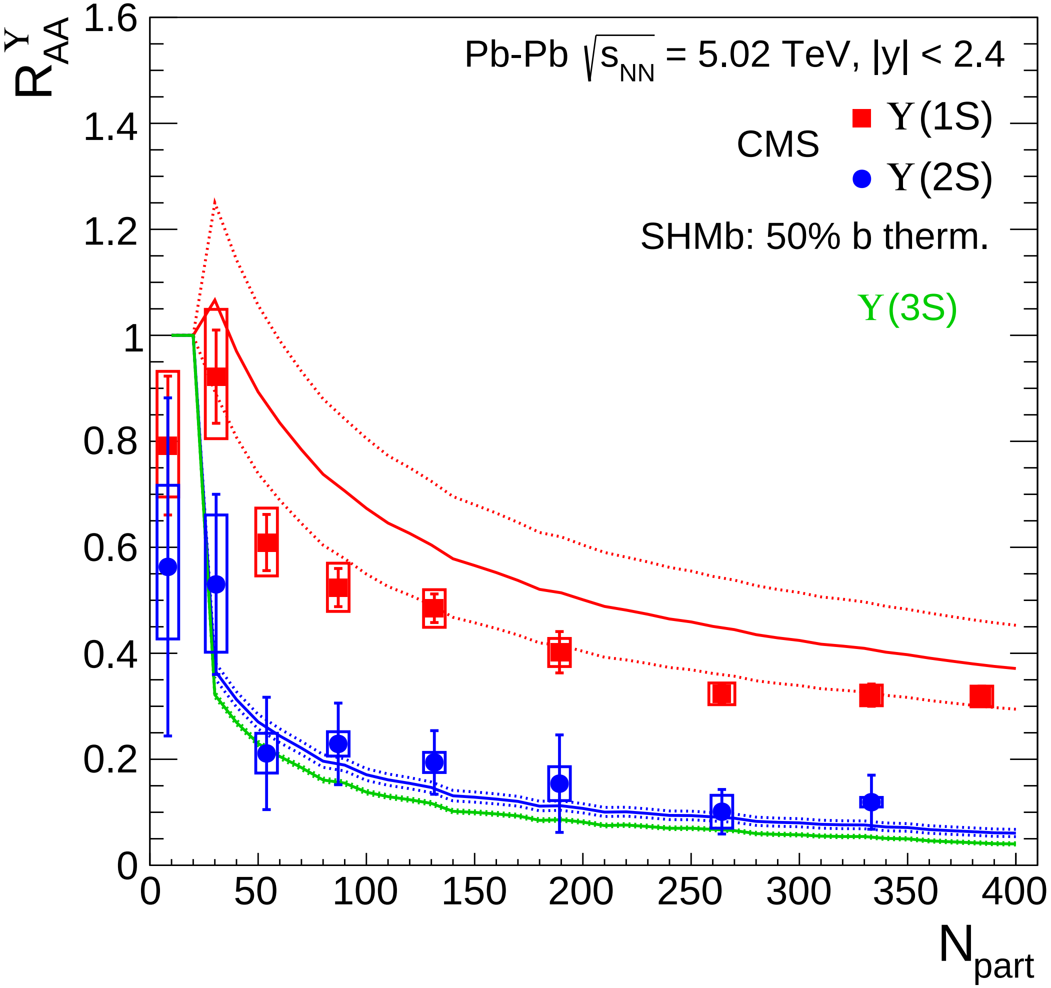


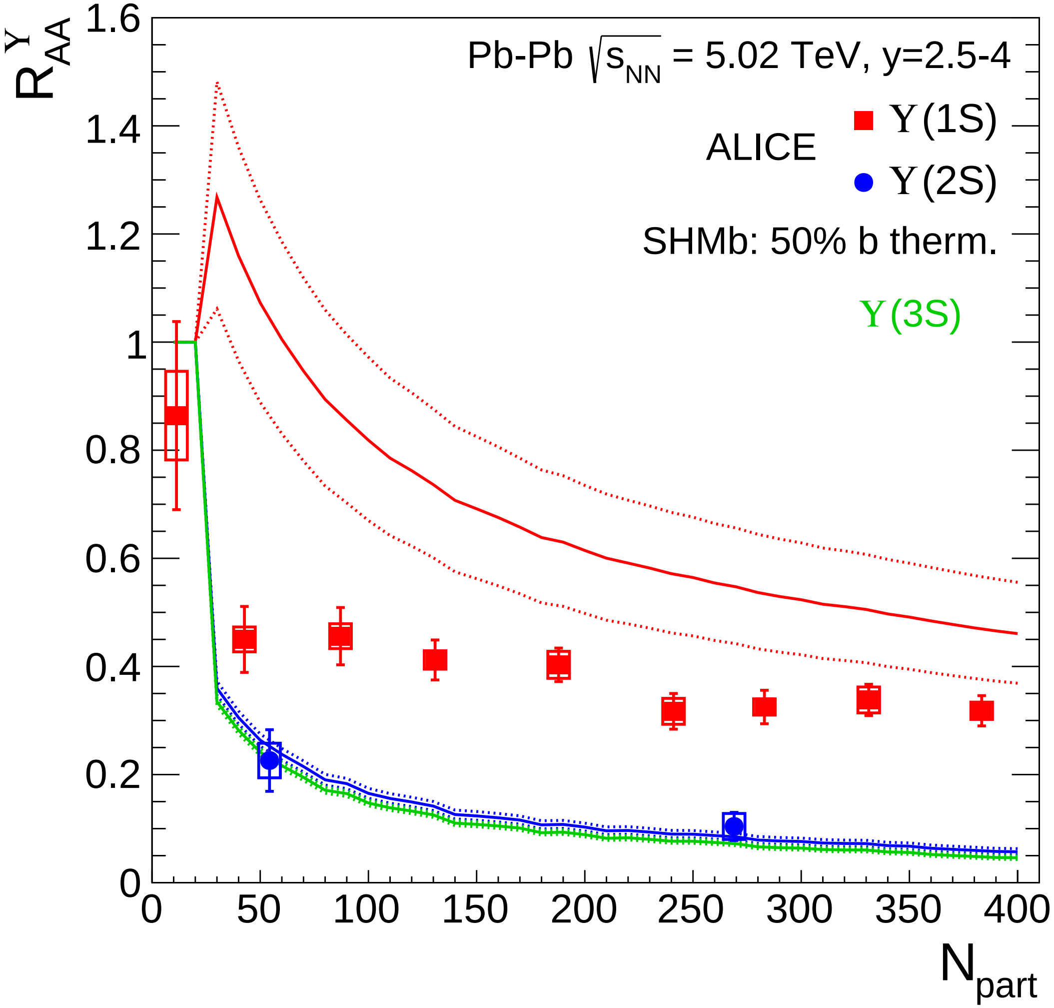
$$g_b = 1.05 \cdot 10^9 \quad \left(\frac{\mathrm{d}N_{b\bar{b}}}{\mathrm{d}y} = 0.57\right) \qquad g_b = 0.86 \cdot 10^9 \quad \left(\frac{\mathrm{d}N_{b\bar{b}}}{\mathrm{d}y} = 0.28\right)$$

$$B_c: \ 3.44 \cdot 10^{-3} \qquad B_c: \ 1.36 \cdot 10^{-3}$$

Blue: Υ data (CMS, ALICE): calc. based on R_{AA} and pp (would be nice to include in publications $\mathrm{d}N/\mathrm{d}y$)

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

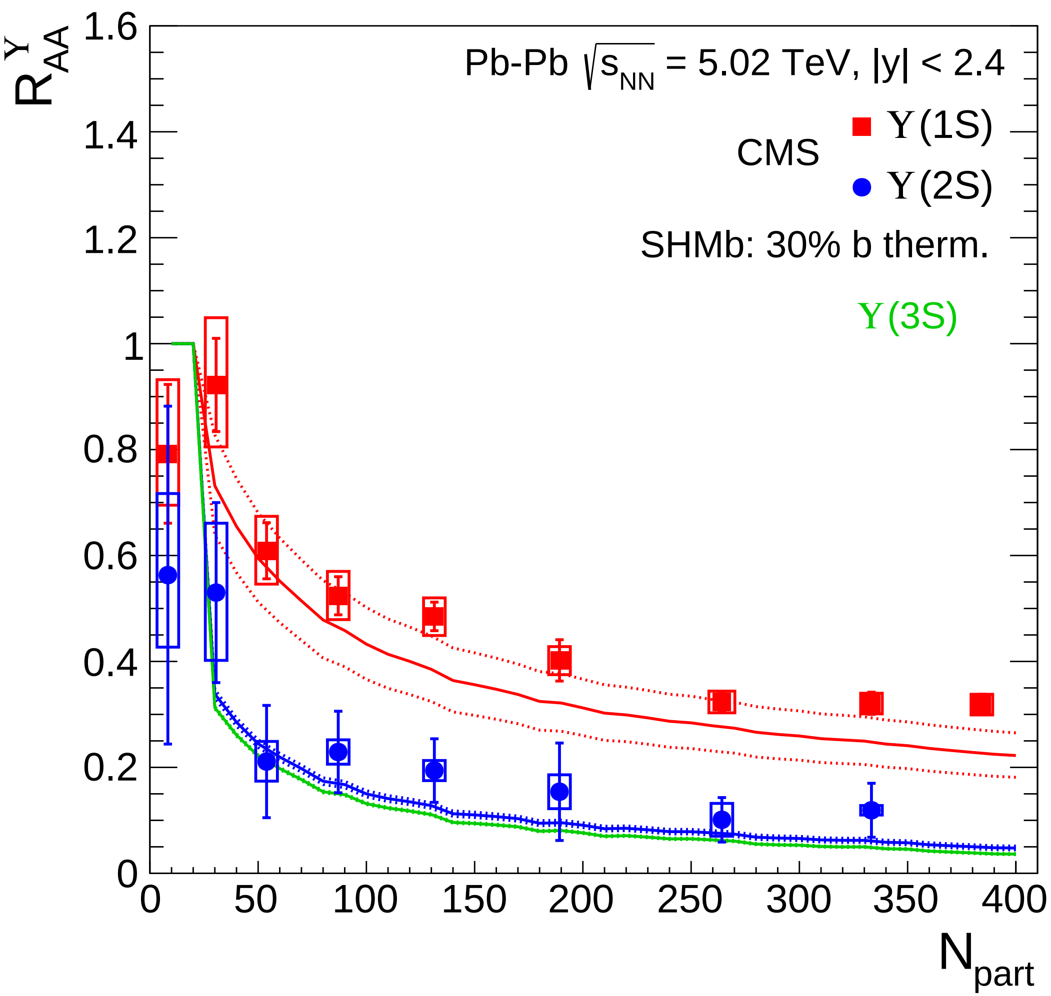




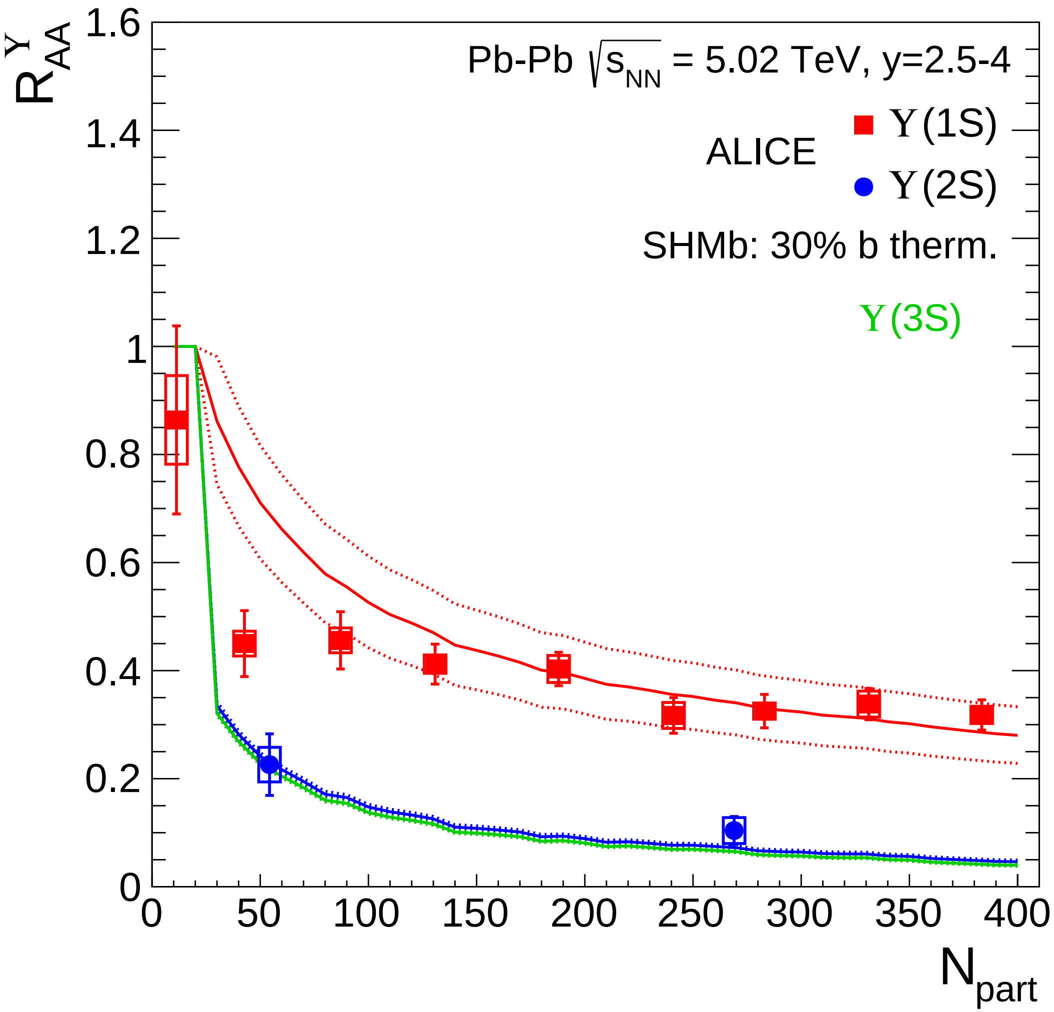
CMS, PRL 120 (2018) 142301

ALICE, PLB 822 (2021) 136579

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

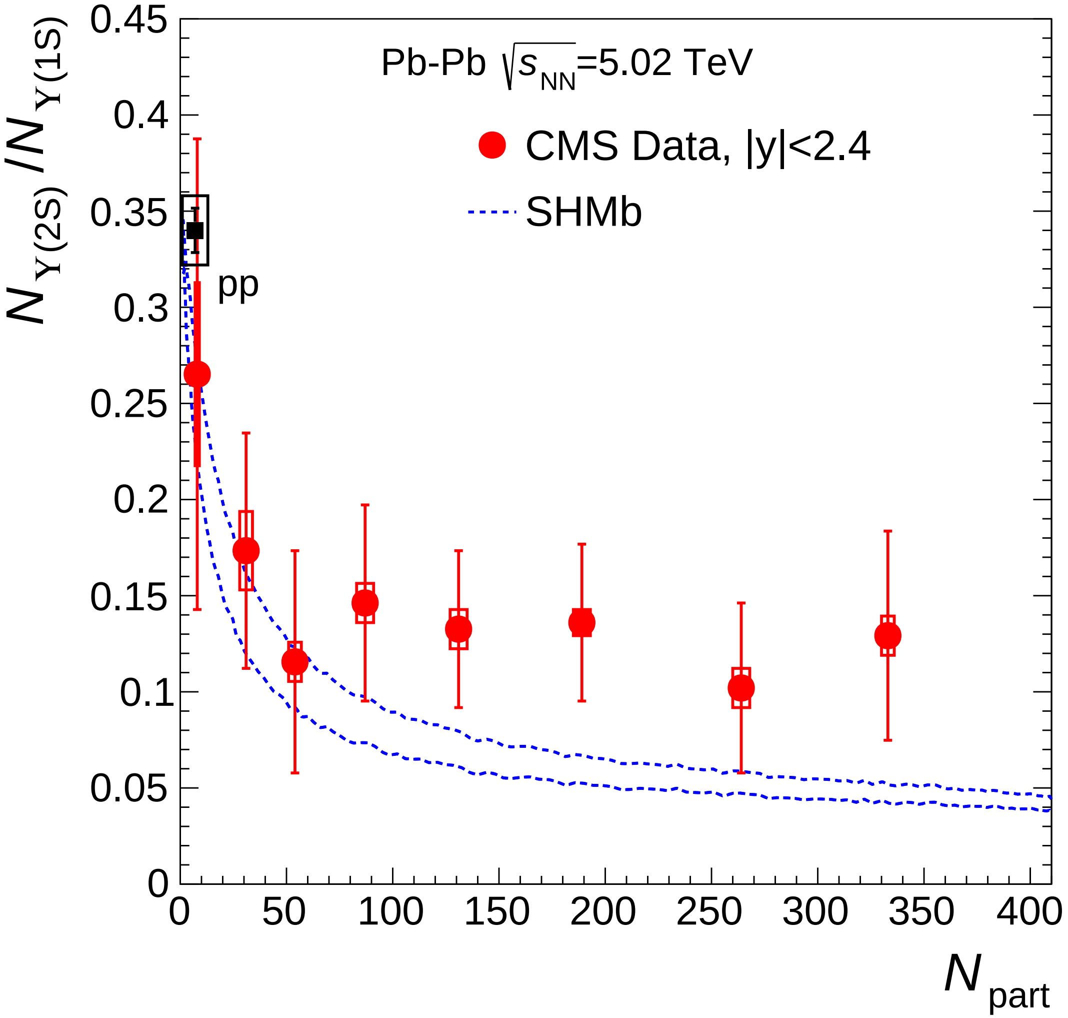


CMS, PRL 120 (2018) 142301

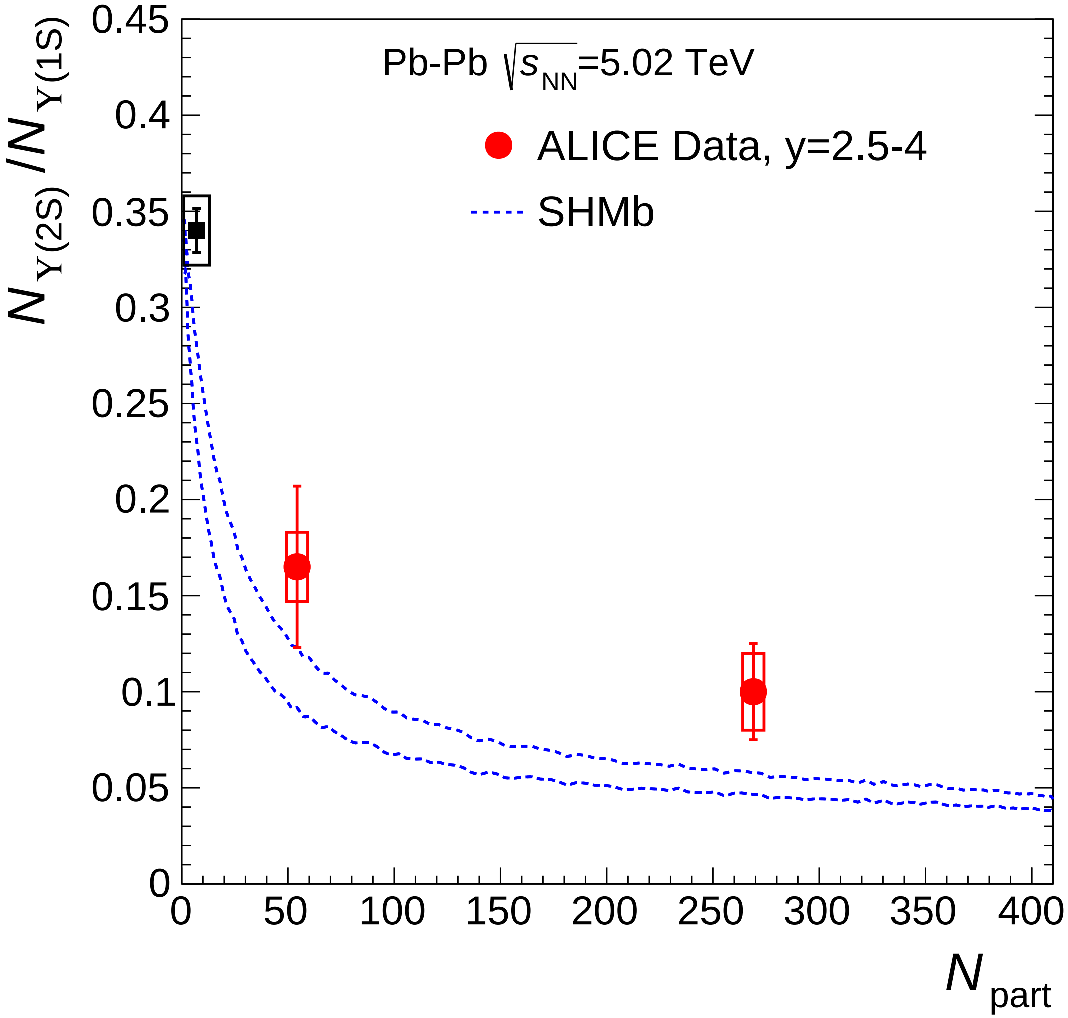


ALICE, PLB 822 (2021) 136579

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



CMS, PRL 120 (2018) 142301

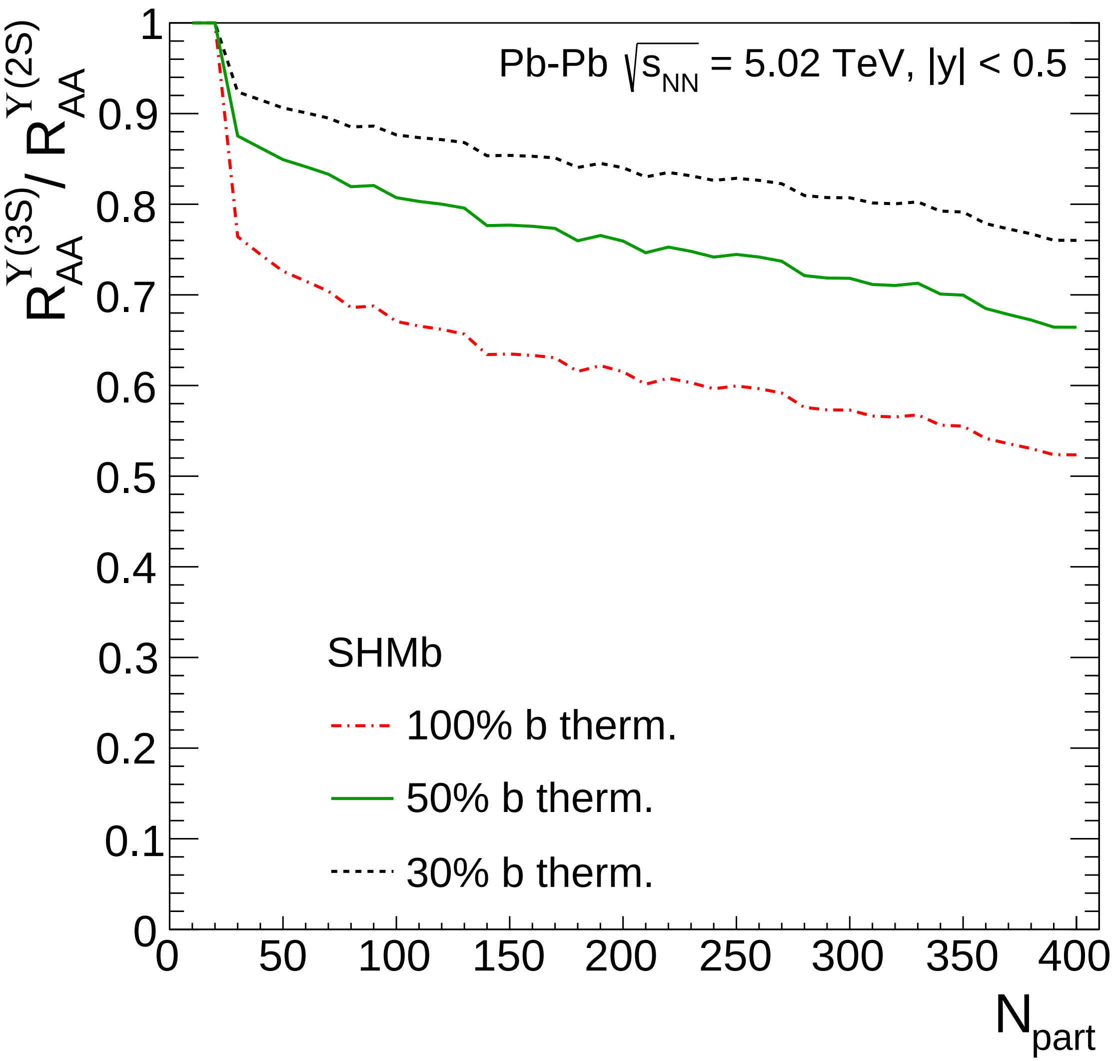


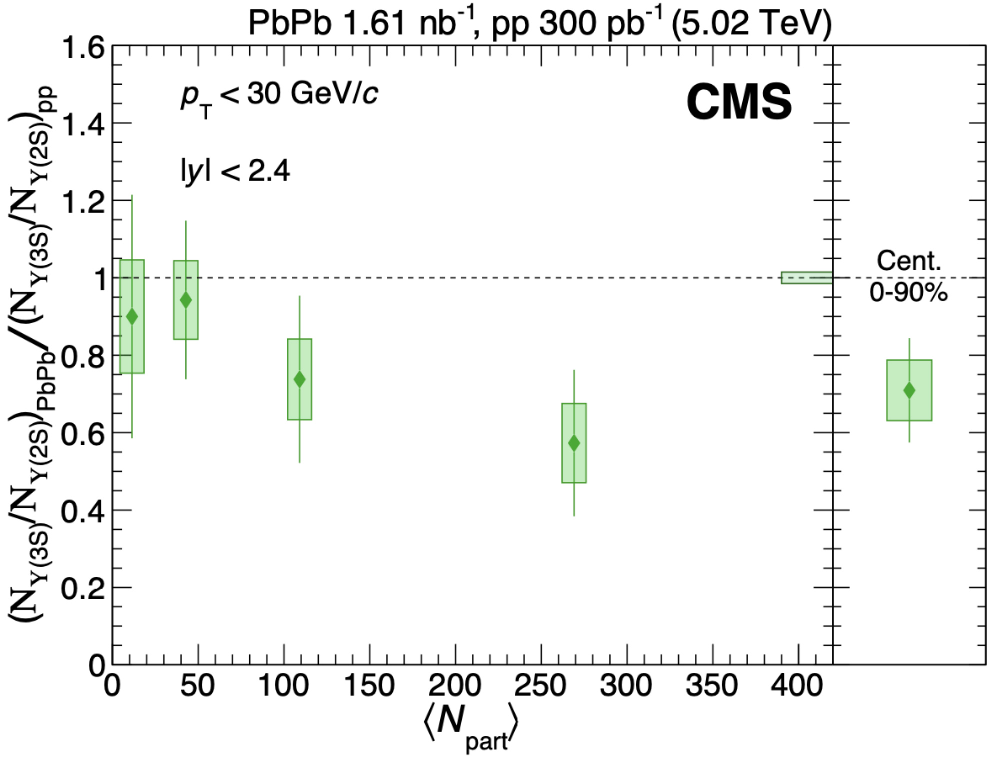
ALICE, PLB 822 (2021) 136579

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

SHMb uncert.: nuclear-corona (fraction)

$\Upsilon(3S)/\Upsilon(2S)$ R_{AA} ratio





CMS, arXiv:2303.17026

The $\Upsilon(3S)/\Upsilon(2S)$ R_{AA} ratio is quite sensitive to the degree of b thermalization

Summary / Conclusions: charm

In the (our) statistical hadronization model:

- The hadronization is a rapid process in which all quark flavors take part concurrently
- 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

  "The competition":

  the kinetic model, 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 we 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?
  ...related: is there non-screened bottomonium at all? (...or maybe just $\Upsilon(1S)$?)

- Another difficulty: $R_{AA}^{Y(1S)}(p_T)$ is flat (we would predict a bump), v_2 is small

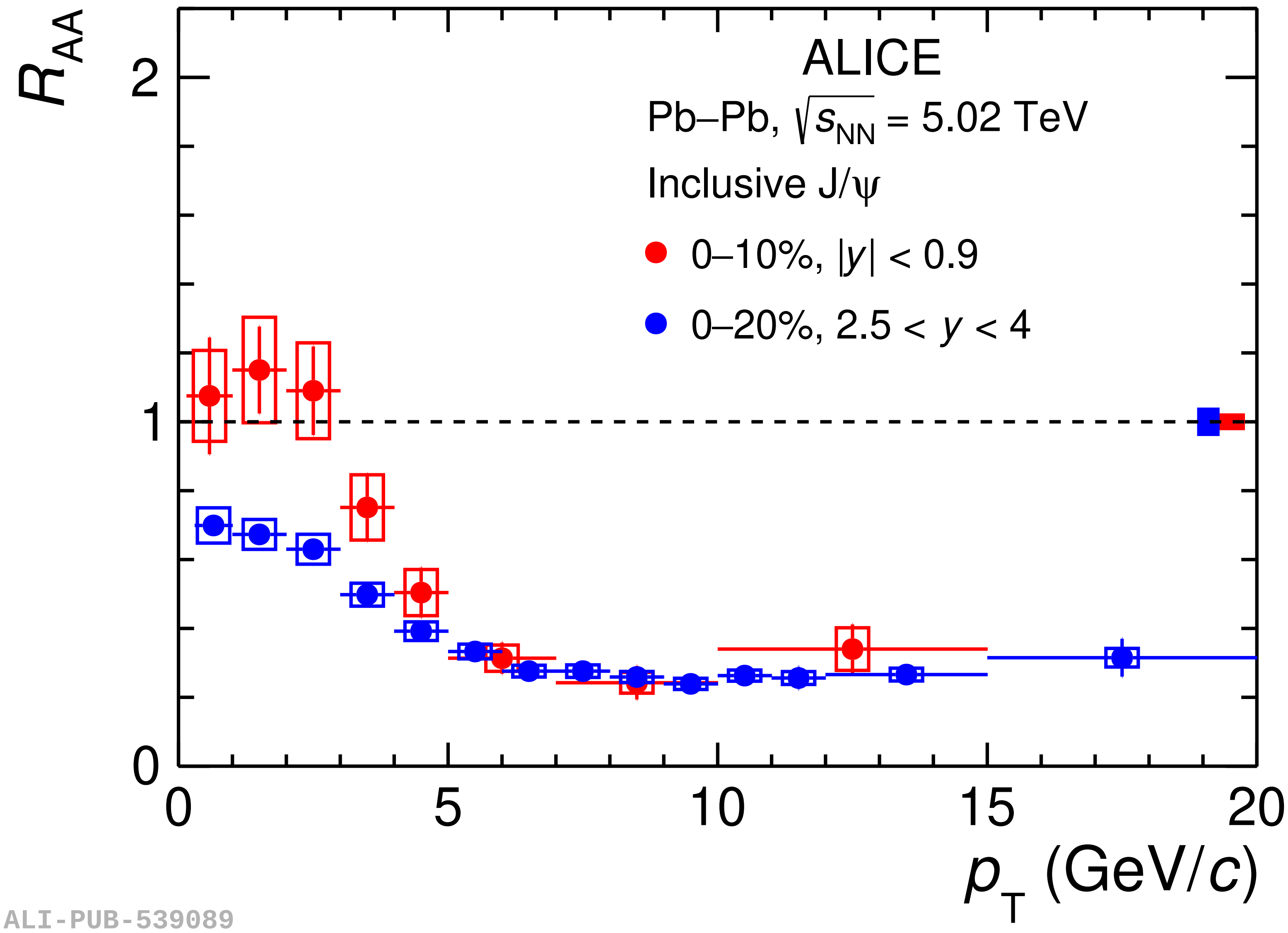
similar to Reygers et al., PRC 101 (2020) 064905

forthcoming LHC data will (hopefully) clarify these questions (...in a while)

inspite (because:) of its simplicity SHM provides for all more sophisticated models a meaningful (powerful) limit to check (worth even if not fully realized in nature:)

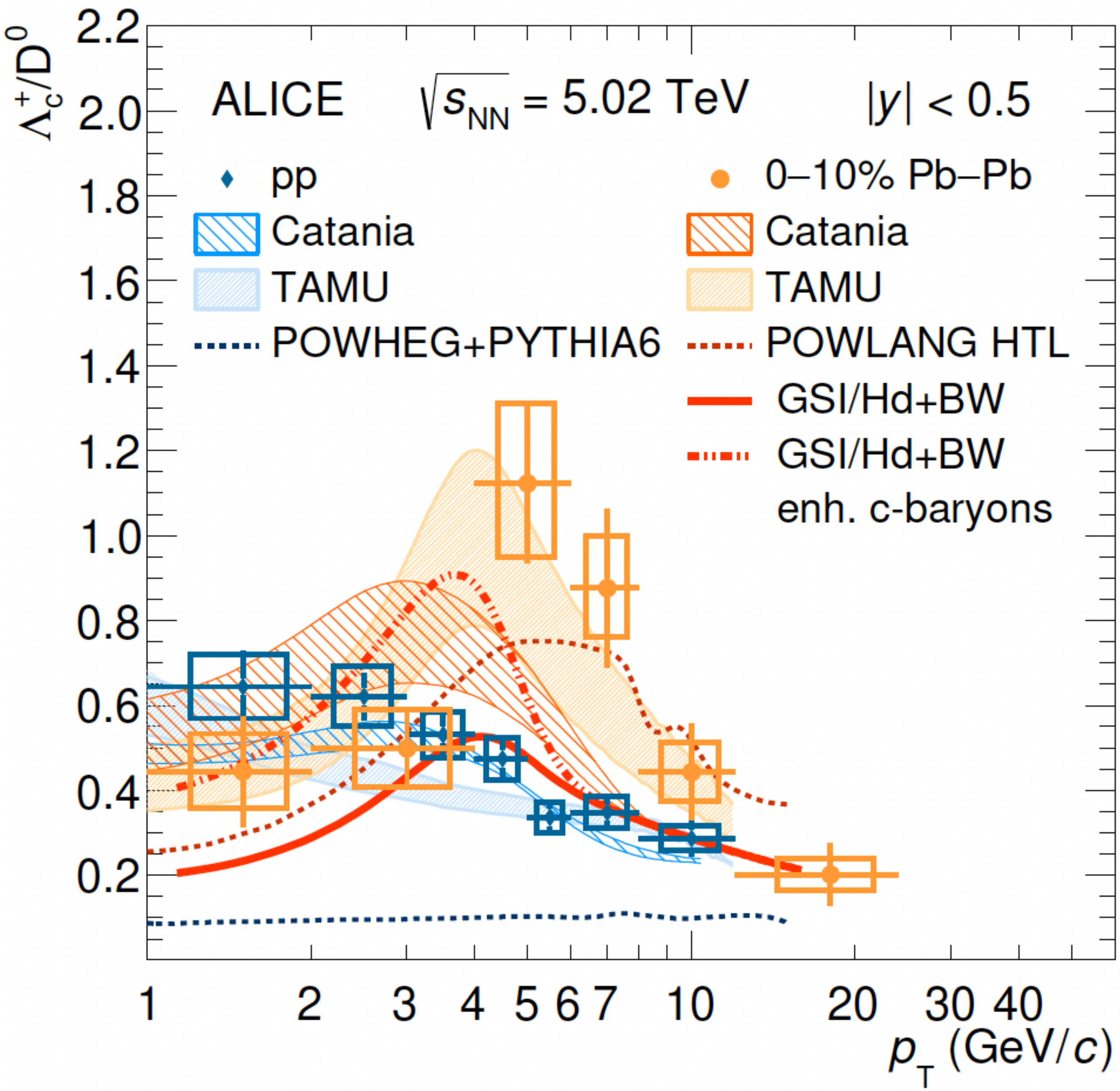
Additional material

Charmonium data at the LHC



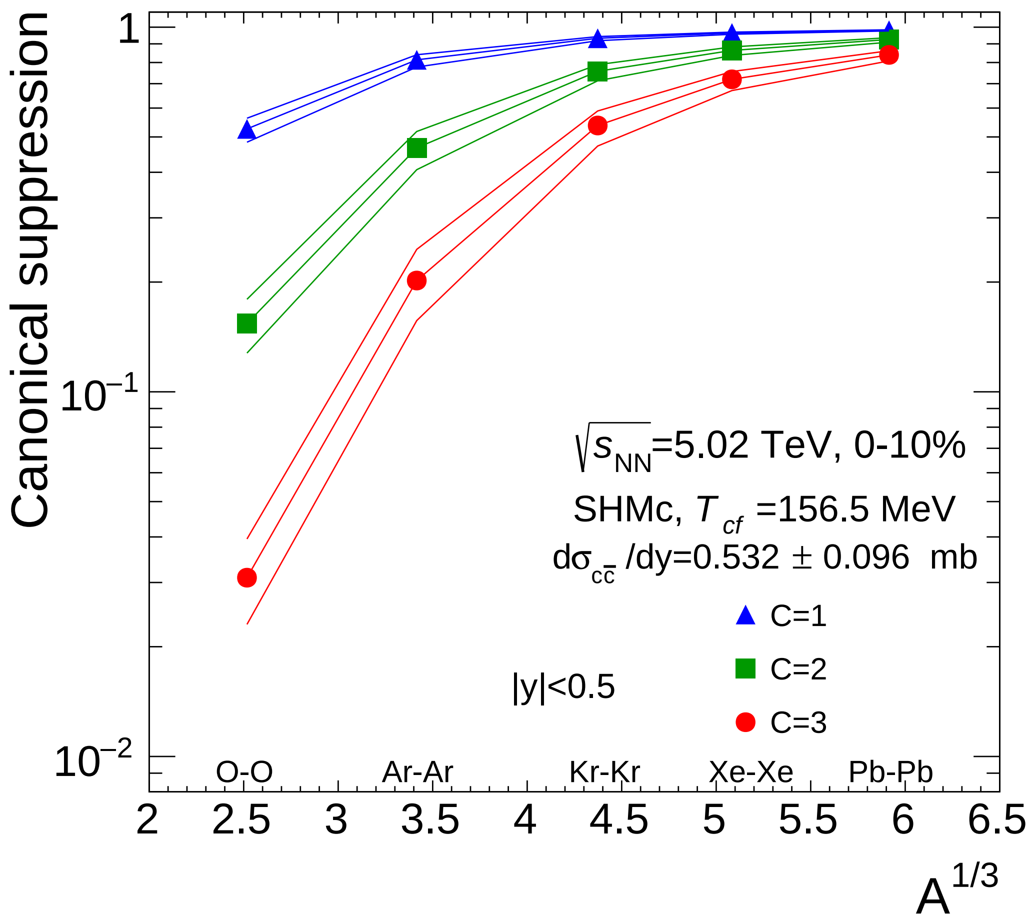
ALICE, arXiv:2303.13361

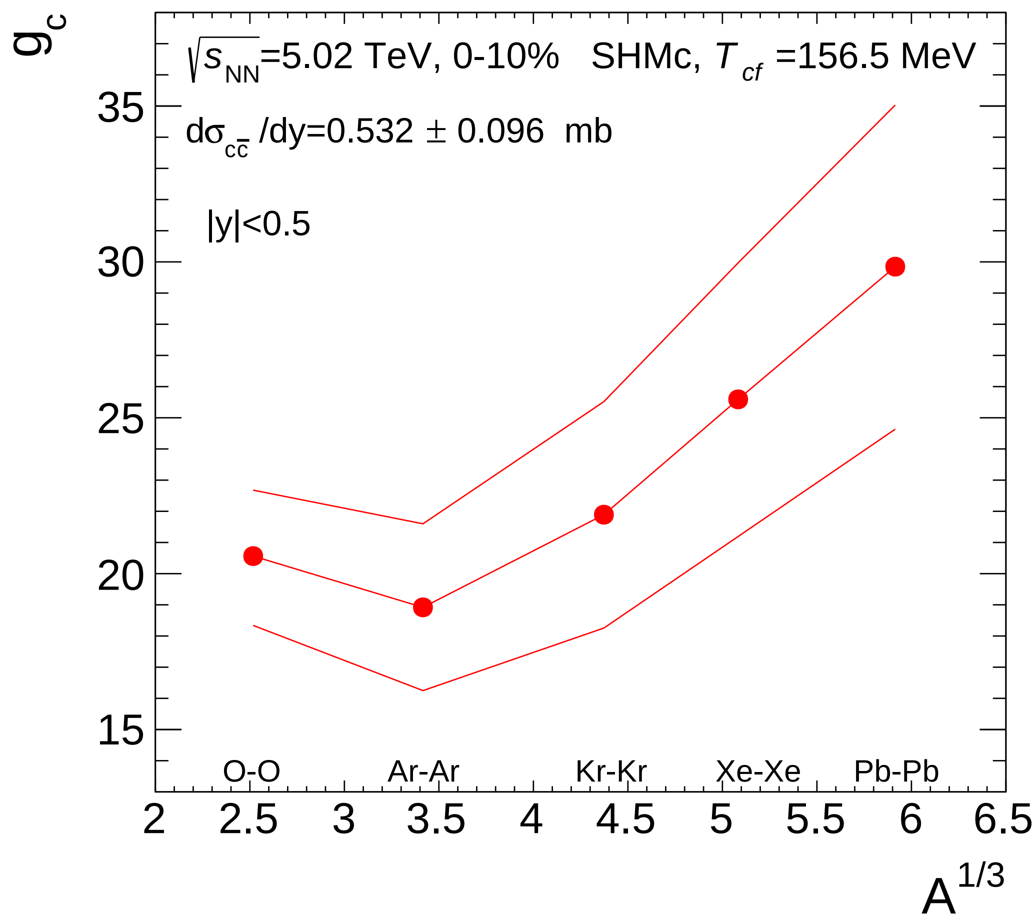
Open charm data vs. models at the LHC



ALICE, arXiv:2212.04384

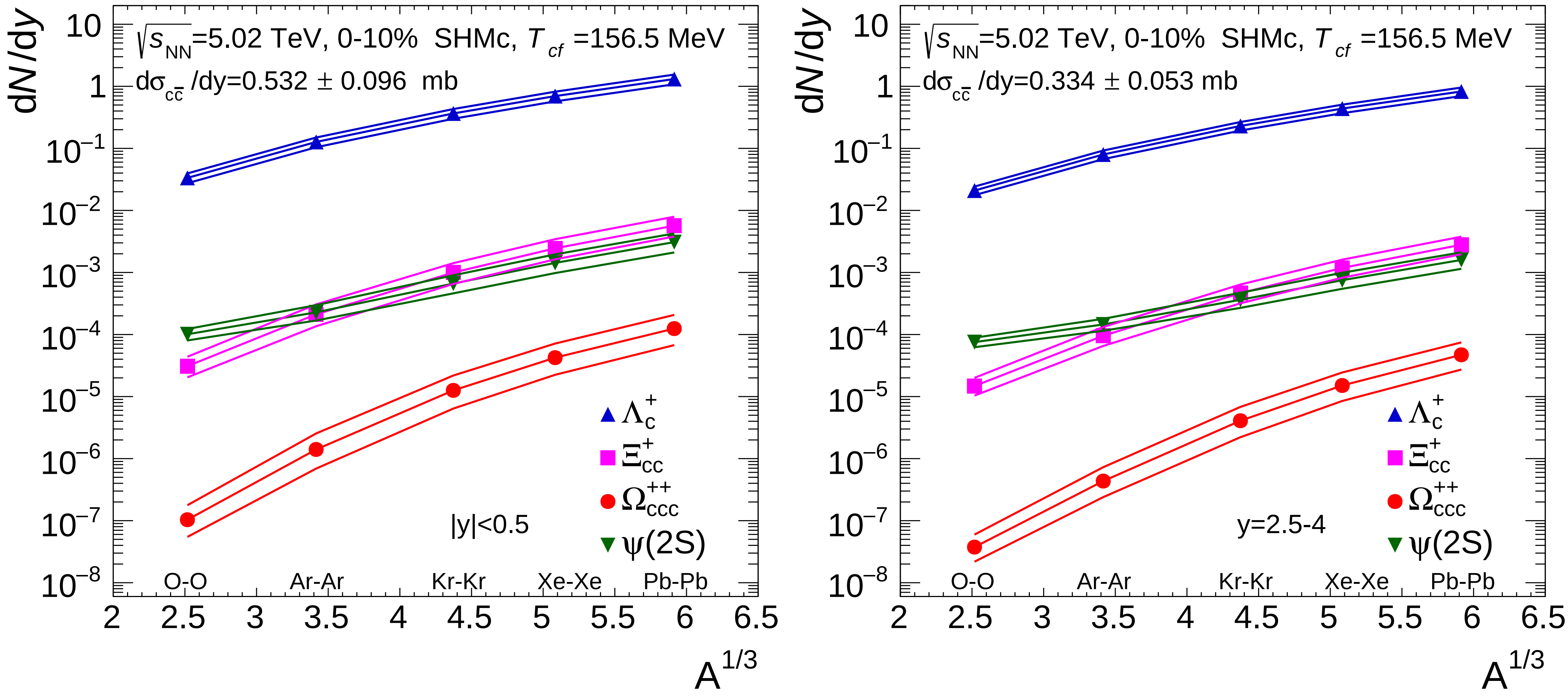
SHMc: system-size dependence (central, 0-10%)



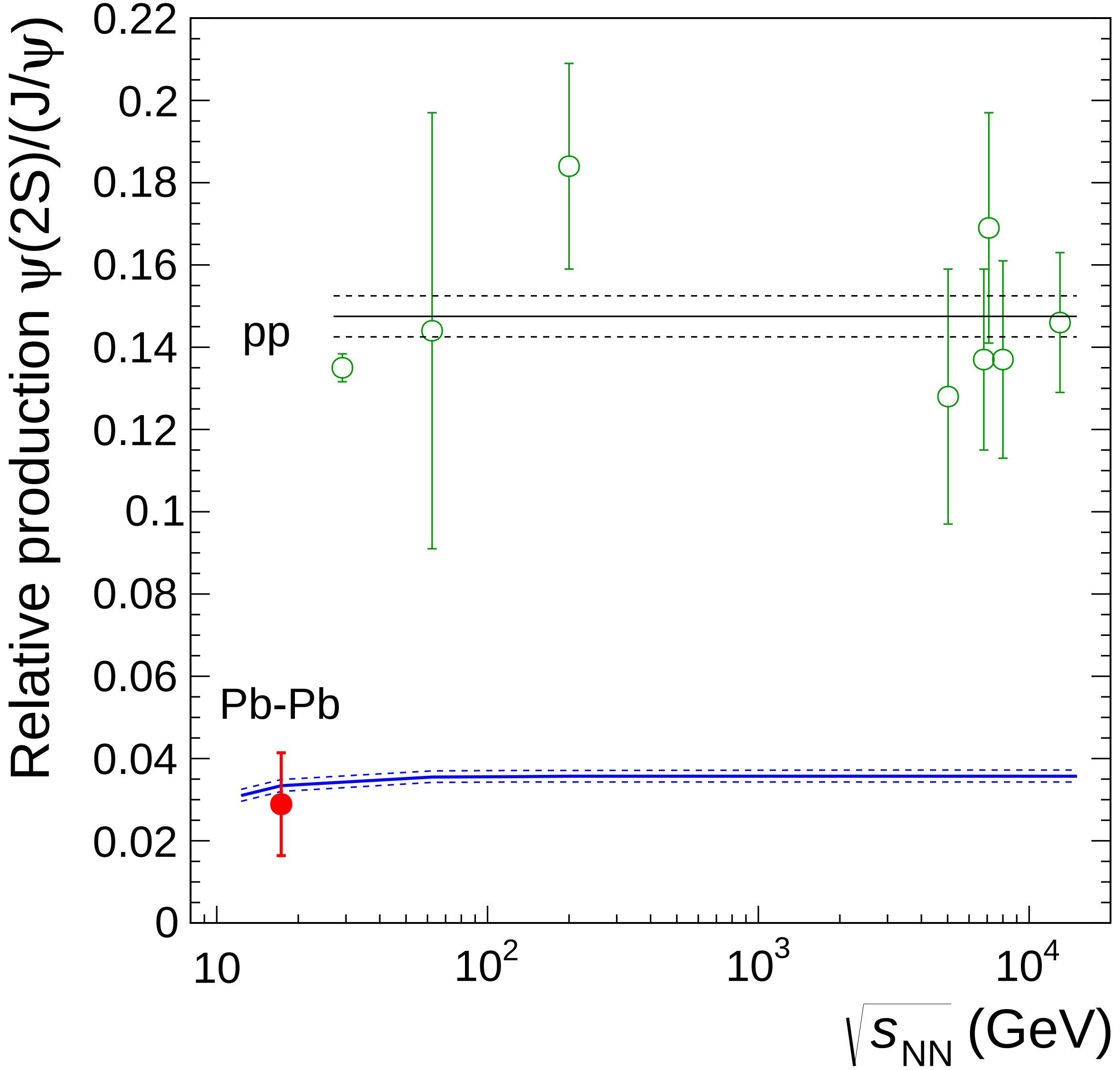


Strong canonical suppression for light systems (for multi-charm hadrons)

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



IF charm thermalizes (fully) also at lower energies



...SHMc is easy to be extended to lower energies

AA, Braun-Munzinger, Redlich, Stachel, PLB 659 (2008) 149

..litmus test: $\psi(2S)$ $(+v_2,\, R_{AA})$

SHMc works (was proposed) at SPS

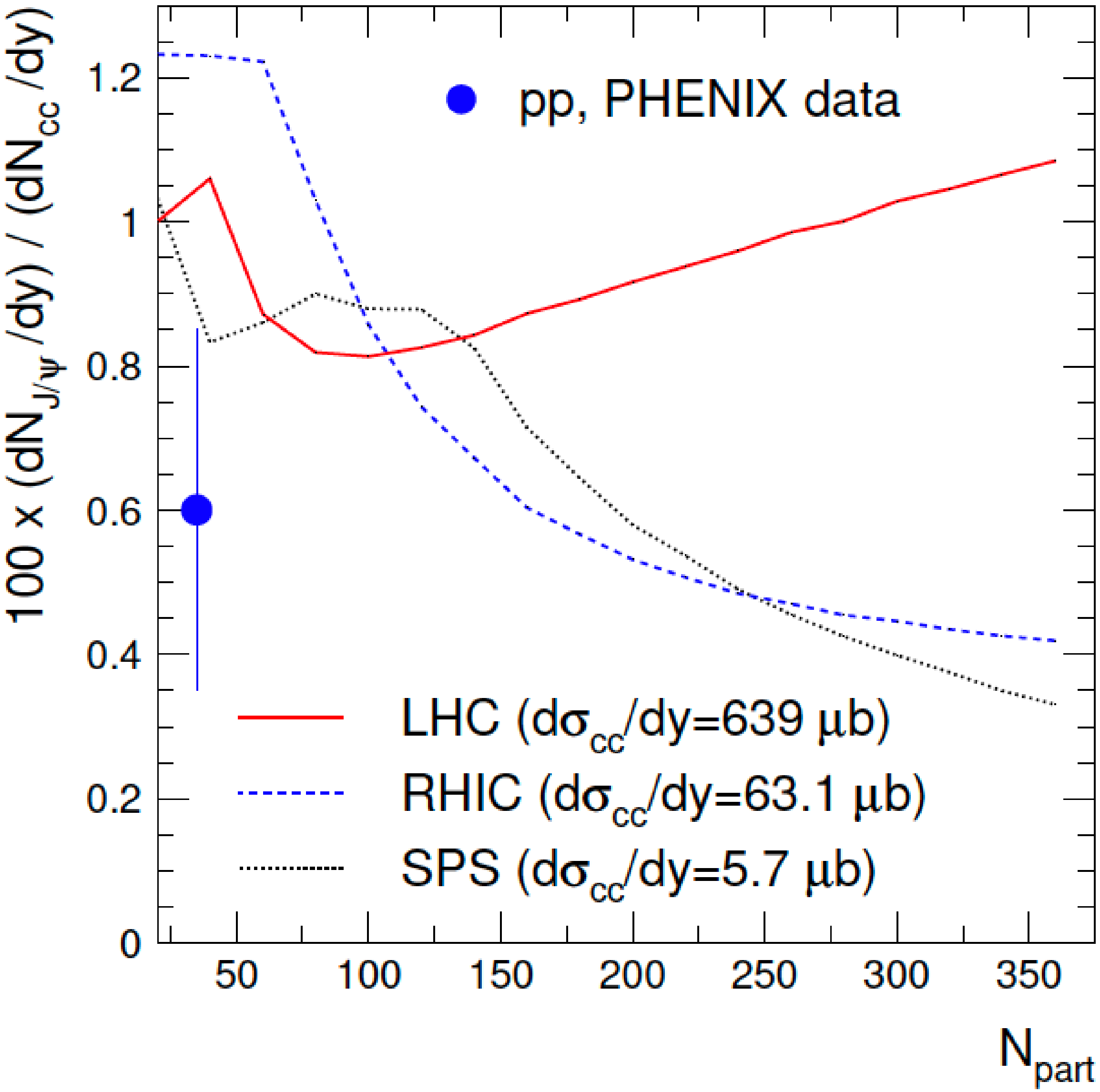
Braun-Munzinger, Stachel, PLB 490 (2000) 196

for D, stat. hadronization is a simpler act, may be at work in pp and in e^+e^-

PLB 678 (2009) 350

The measurement in Pb–Pb at LHC is a central goal for Run 3,4 (YR, WG5 HL-LHC)

...an observable with similar features as R_{AA}



NPA 789 (2007) 334

(see also: Satz, Adv.HEP 2013 (2013) 242918)

- similar values at RHIC and SPS

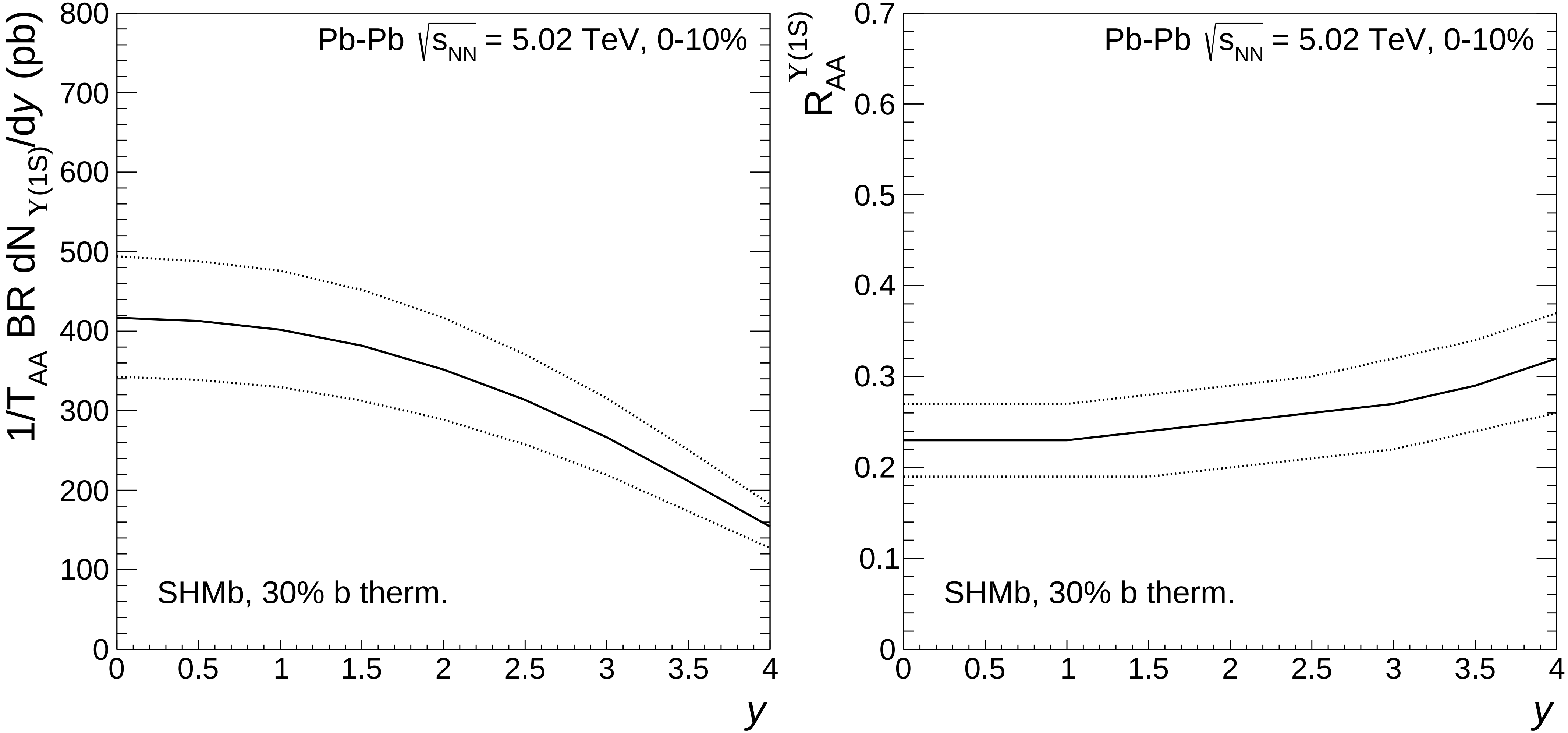
  ...with differences in fine details

  ...determined by canonical suppression of open charm

  same features in RHIC BES data

- enhancement-like at LHC

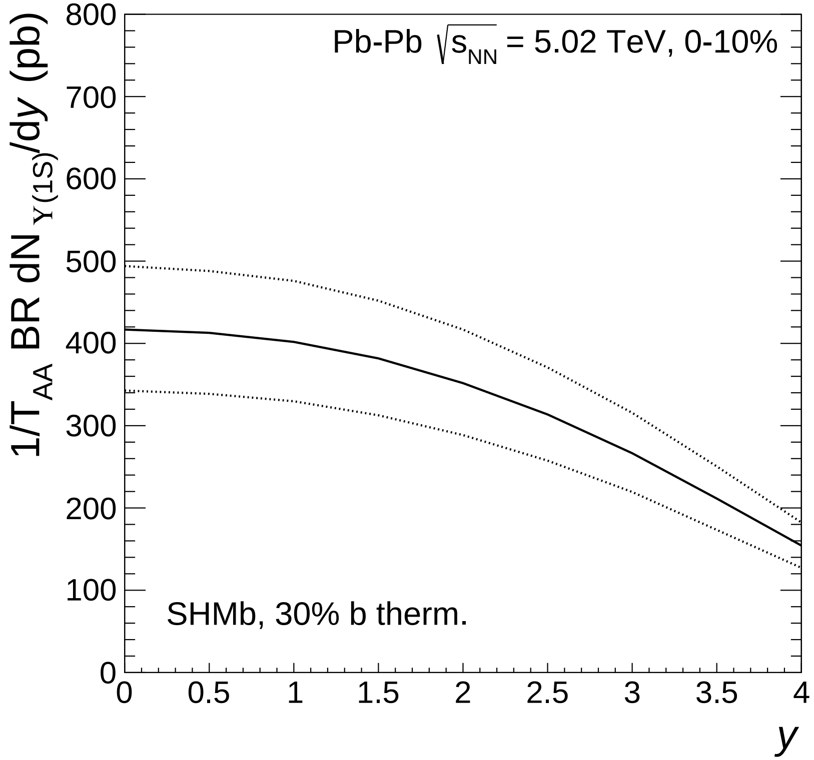
  can. suppr. lifted, quadratic term dominant

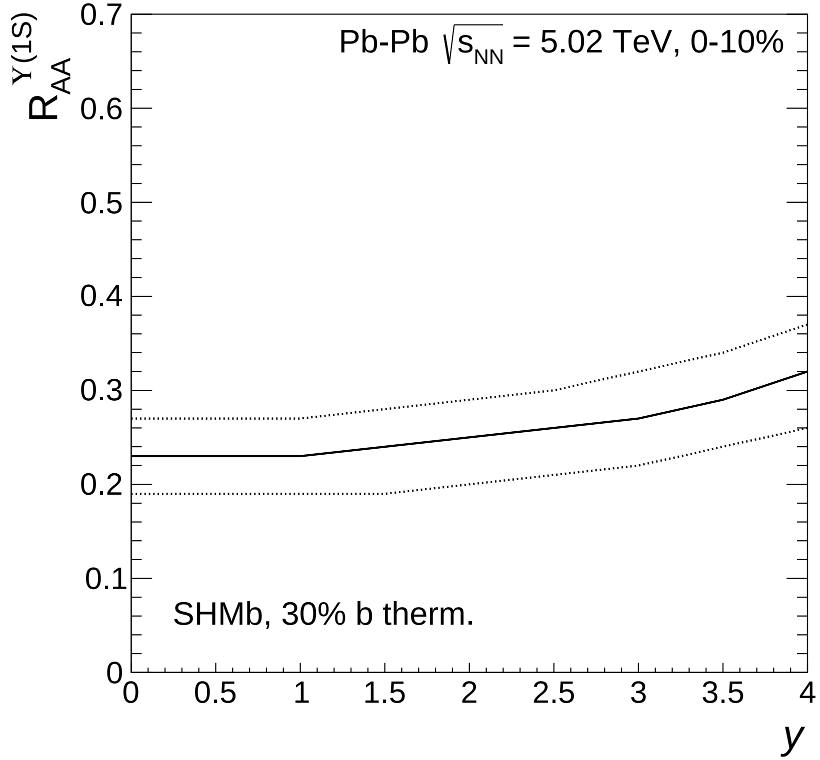


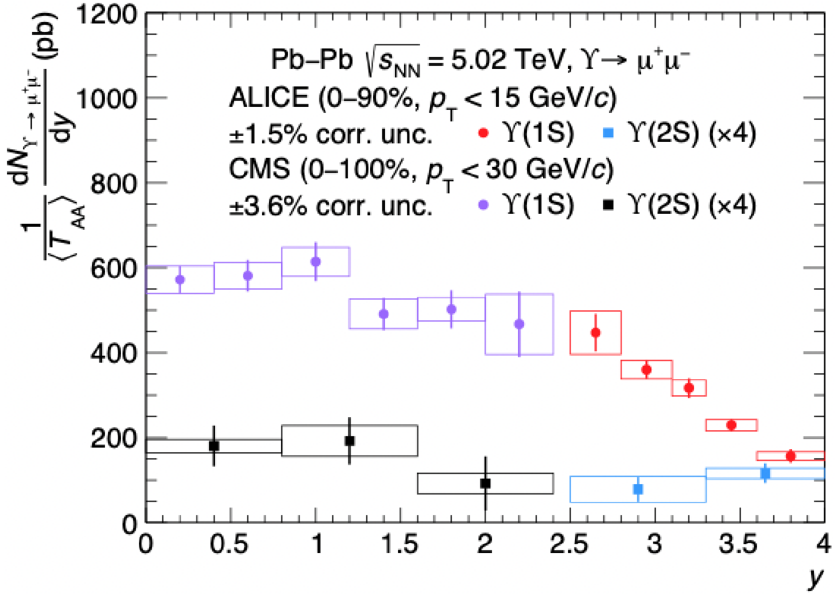
Data available only centrality-integrated ...is 0-10% (or 0-20%) doable?

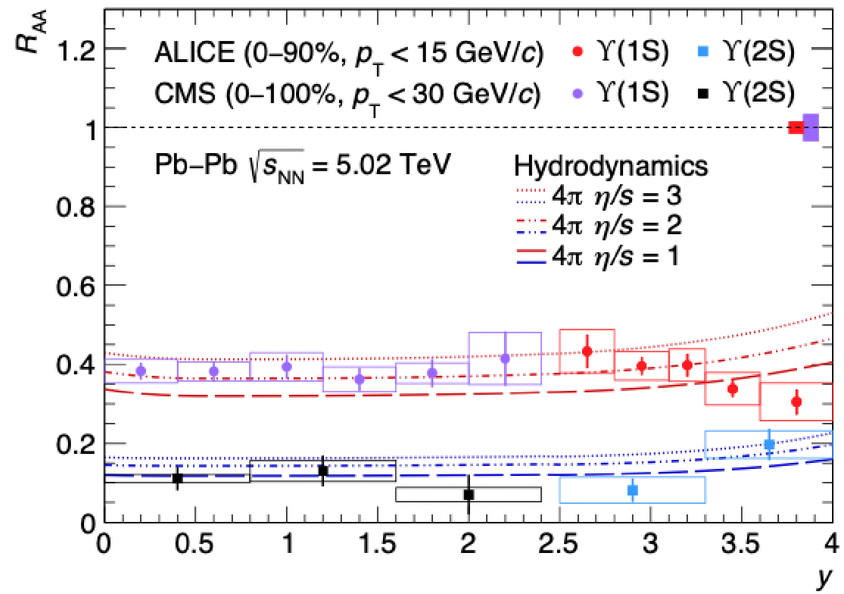
CMS, PRL 120 (2018) 142301; ALICE, PLB 822 (2021) 136579

Rapidity dependence $\Upsilon(1S)$, 30% $b\bar{b}$ thermalized









ALICE, PLB 822 (2021) 136579, CMS, PRL 120 (2018) 142301

SHMb parameters

NB: none is a free parameter, except the 30% b thermalization fraction