The statistical hadronization model for heavy quarks

A. Andronic - University of Münster

WWU 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

HFwiNC 2020

A. Andronic

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"

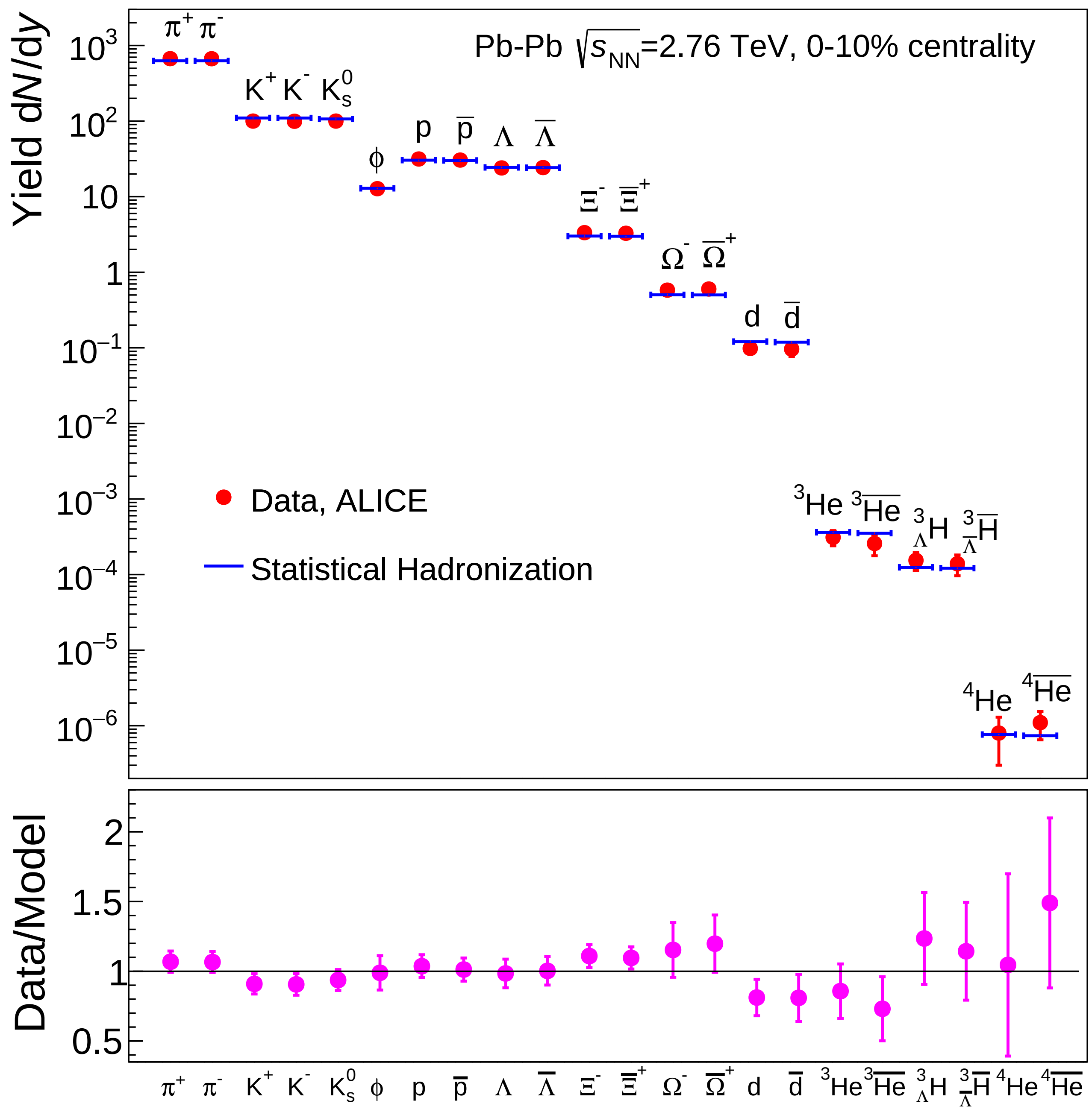
i) isospin: $\sum_i n_i I_{3i} / \sum_i n_i B_i = I_3^{tot} / N_B^{tot}, \quad N_B^{tot} \sim \mu_B$

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

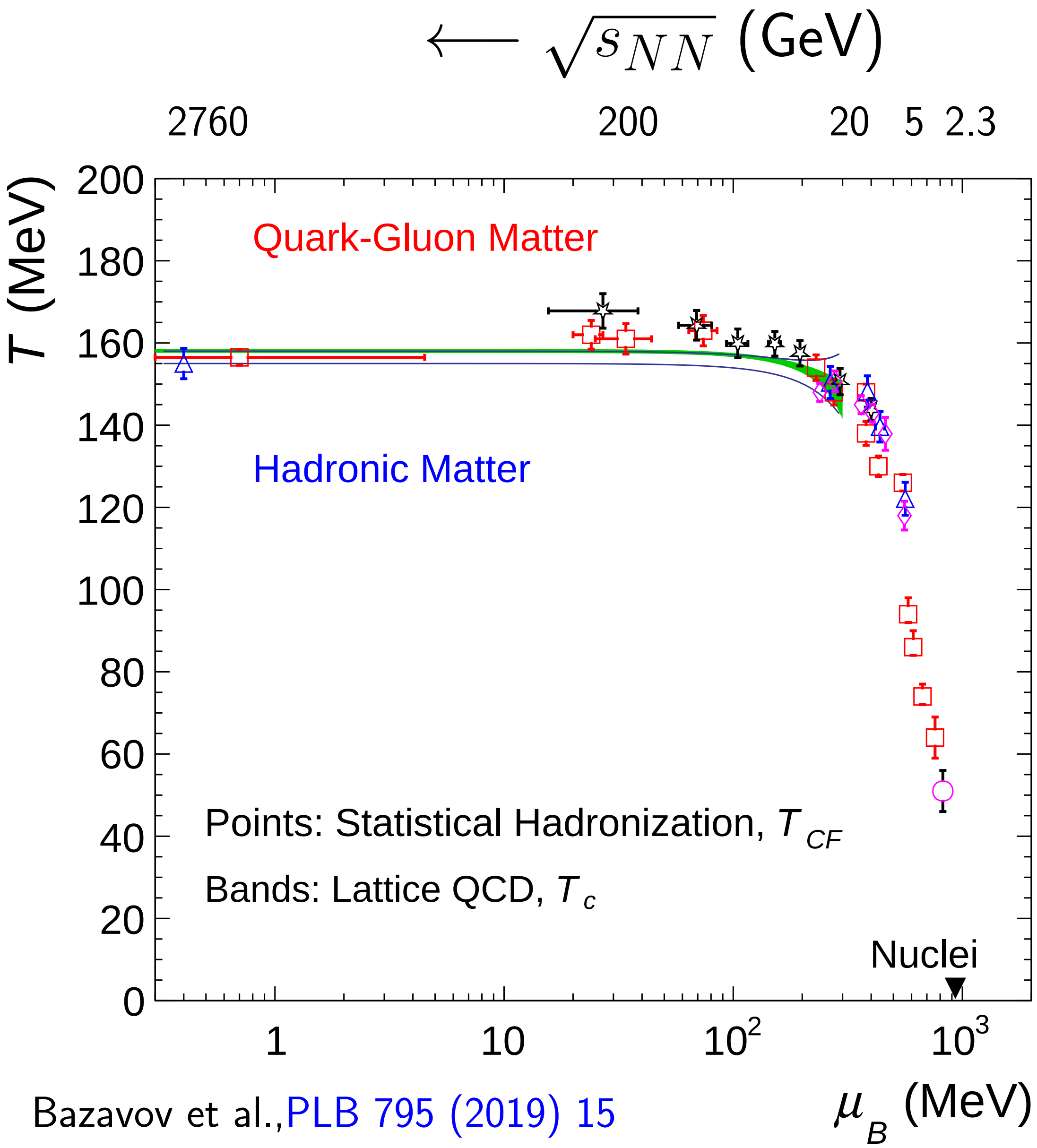
$T_{CF} = 156.6 \pm 1.7$ MeV
$\mu_B = 0.7 \pm 3.8$ MeV
$V_{\Delta y=1} = 4175 \pm 380$ fm^3

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

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?



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

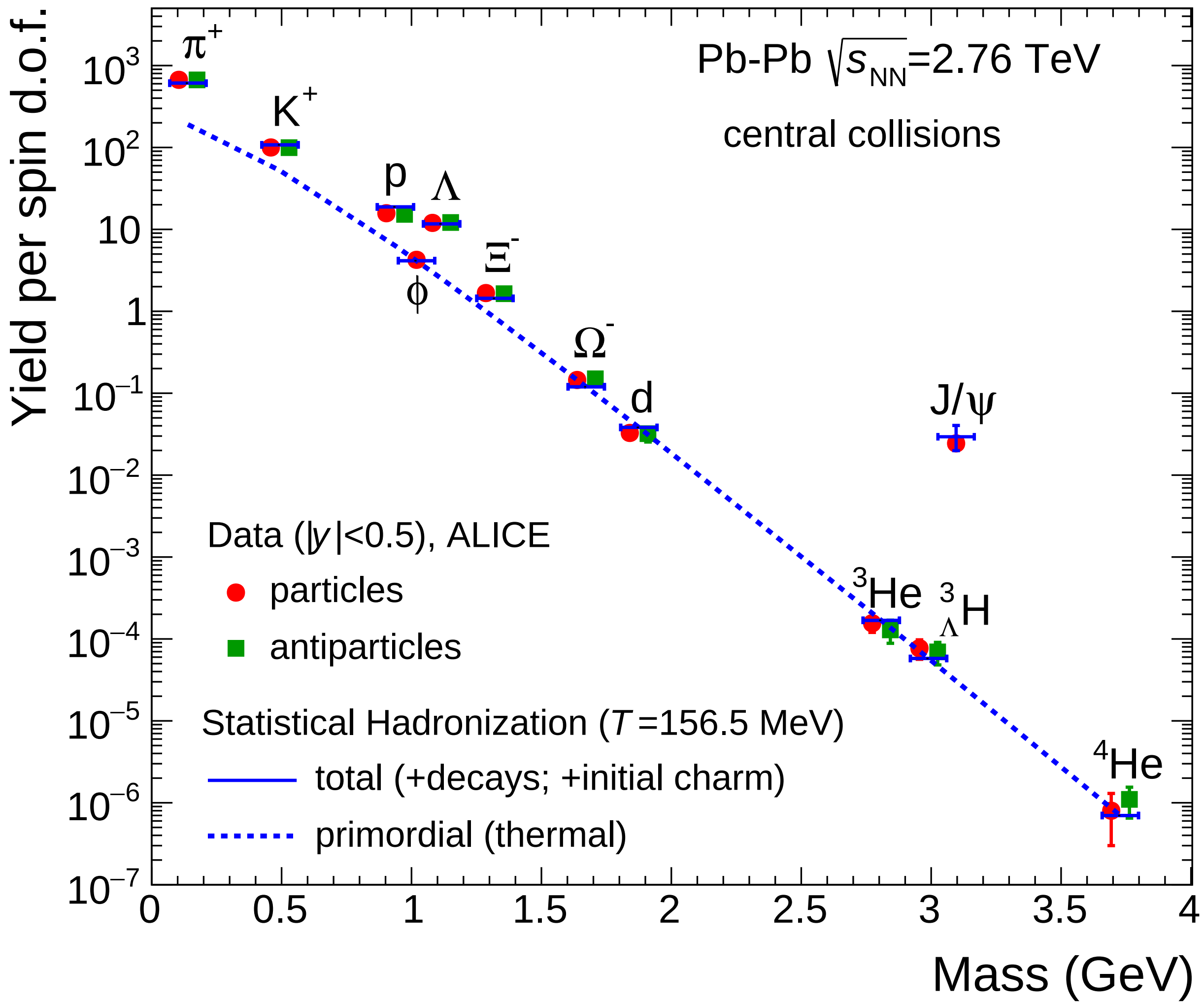
LHC, central collisions

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

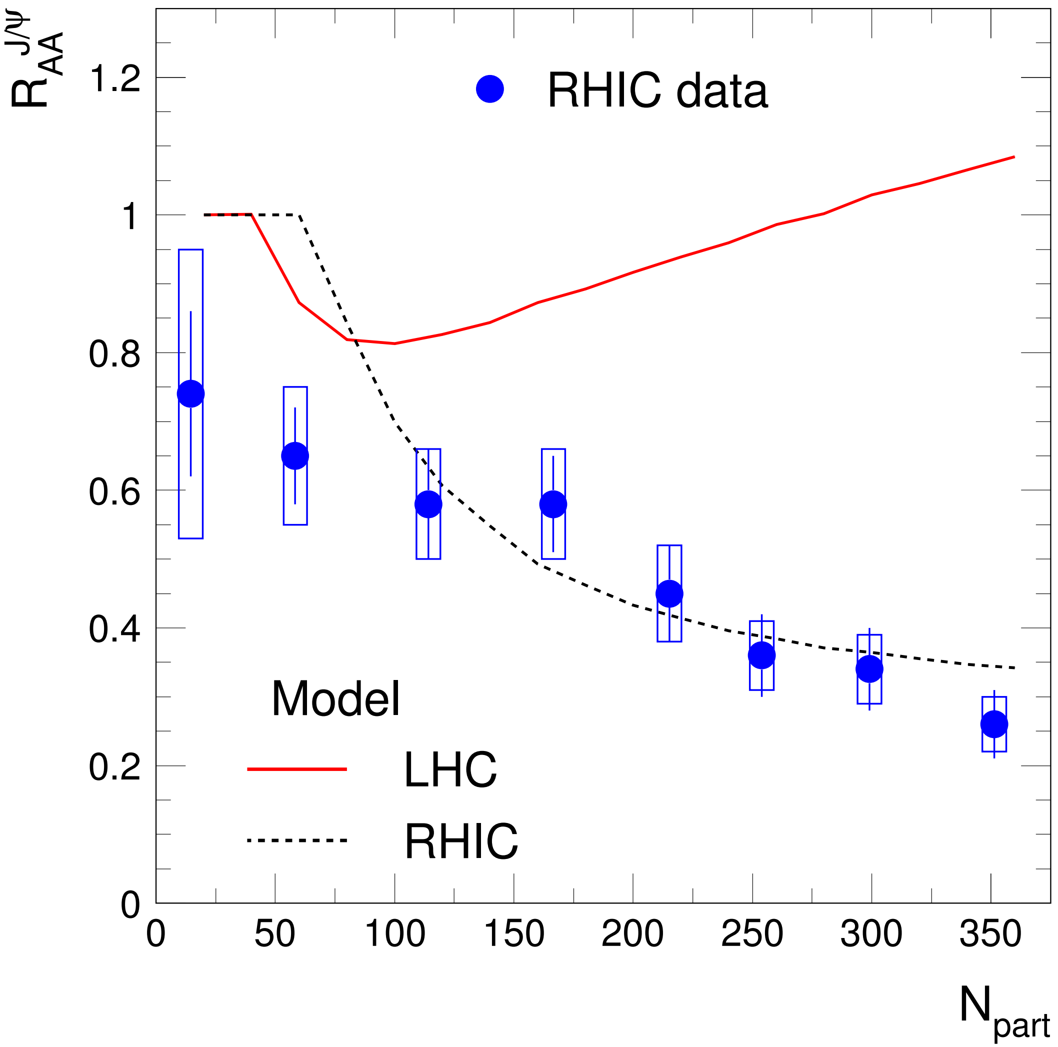
$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{th} \frac{I_1(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})} + g_c^2 N_{c\bar{c}}^{th} \quad \rightarrow g_c(N_{part}) \text{ (charm fugacity)}$$

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

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

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

High hopes for charmonium at the LHC



$$R_{AA}^{J/\psi} = \frac{\mathrm{d}N_{J/\psi}^{AuAu}/\mathrm{d}y}{N_{coll} \cdot \mathrm{d}N_{J/\psi}^{pp}/\mathrm{d}y}$$

- "suppression" at RHIC
- "enhancement" at LHC

$N_{J/\psi} \sim (N_{c\bar{c}}^{dir})^2$

What is so different at LHC?

(compared to RHIC)

$\sigma_{c\bar{c}}$: ∼10x, Volume: 2.5x

PLB 652 (2007) 259

this is a generic prediction of SHM ...was confirmed by LHC data

RHIC warrants another look ($\sigma_{c\bar{c}}$ lowish, at that time)

High hopes for charmonium at the LHC

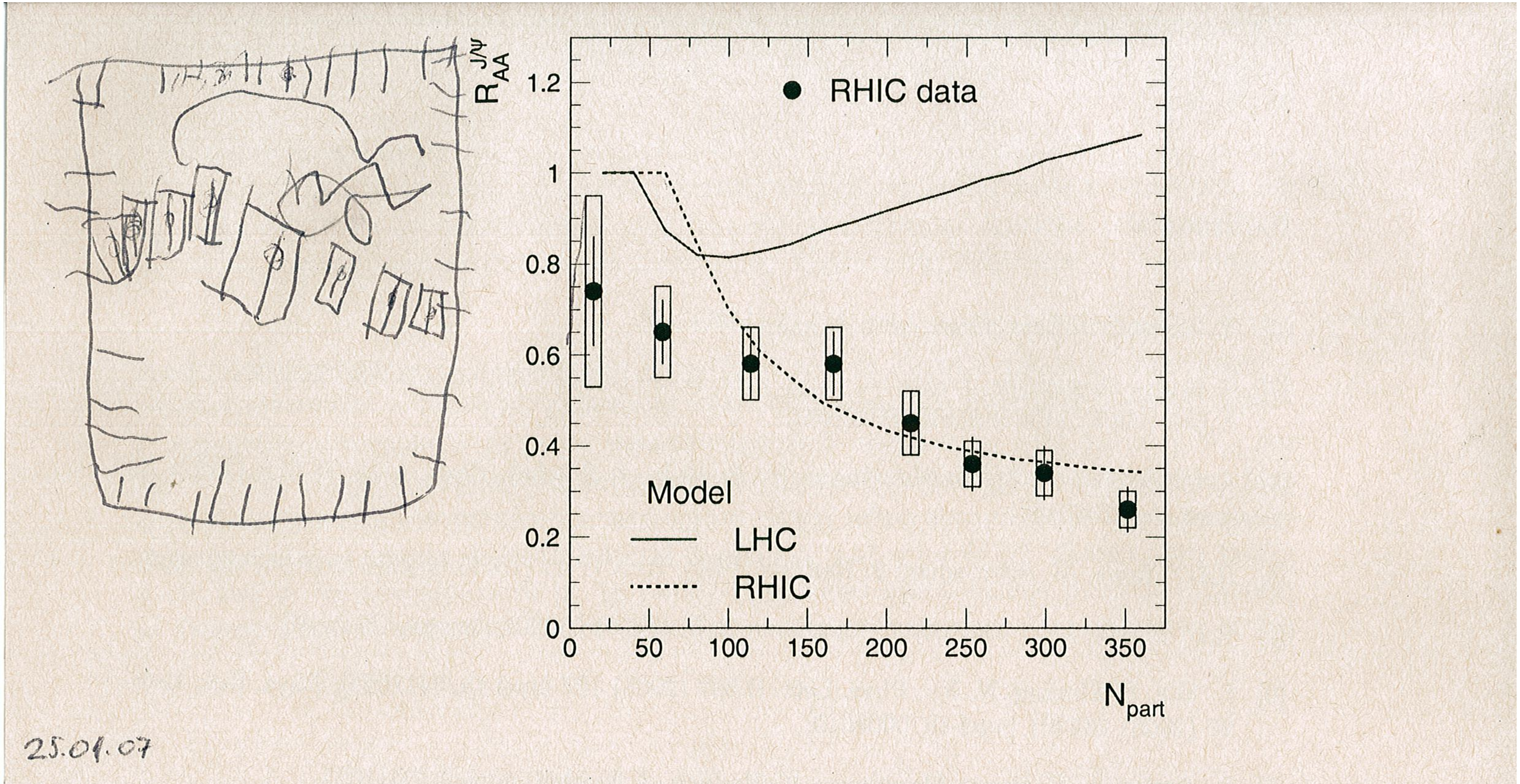
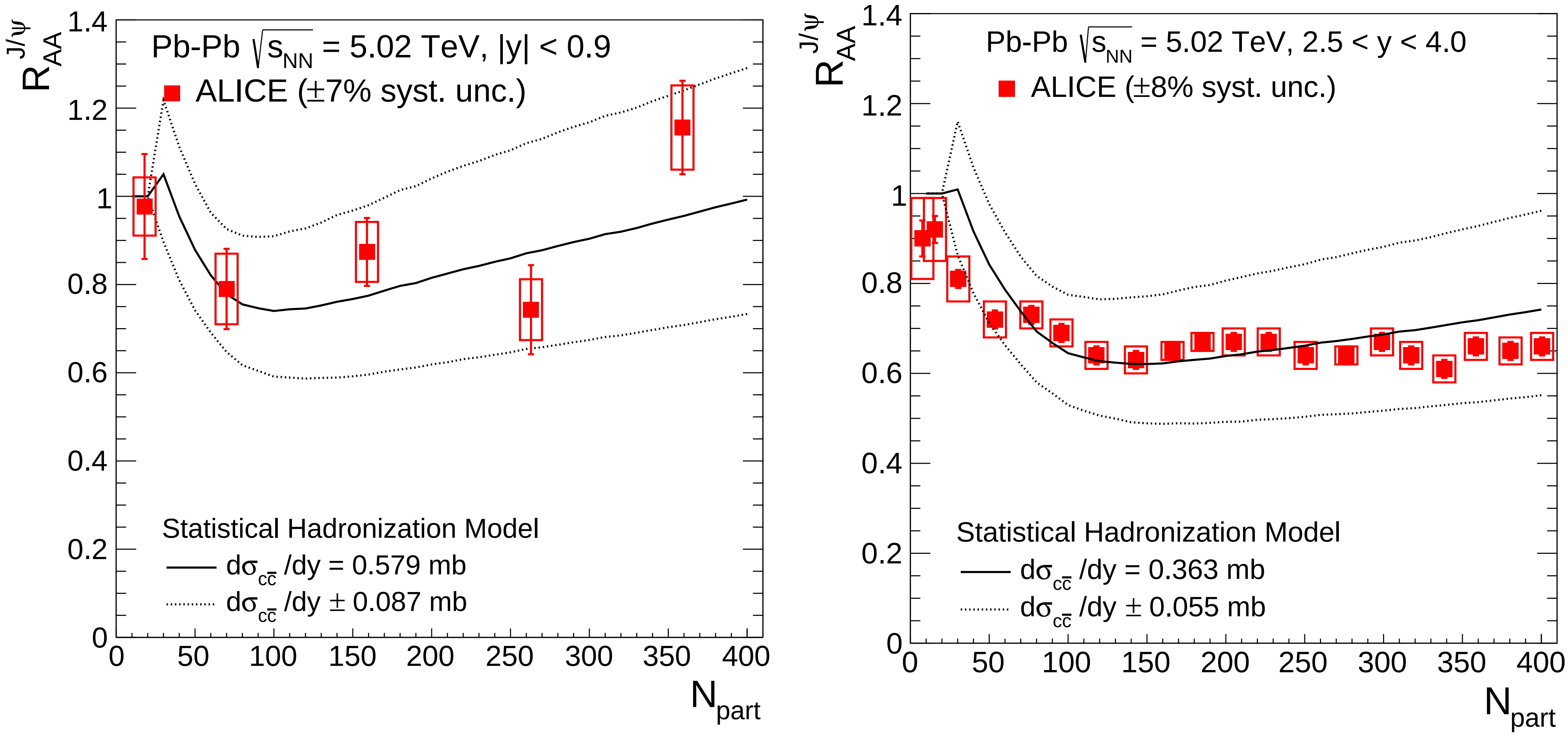


Fig. 2. Centrality dependence of the relative J/ψ yield $R_{AA}^{J/\psi}$.

...was impressing a 3-years old girl ...who described better data than model

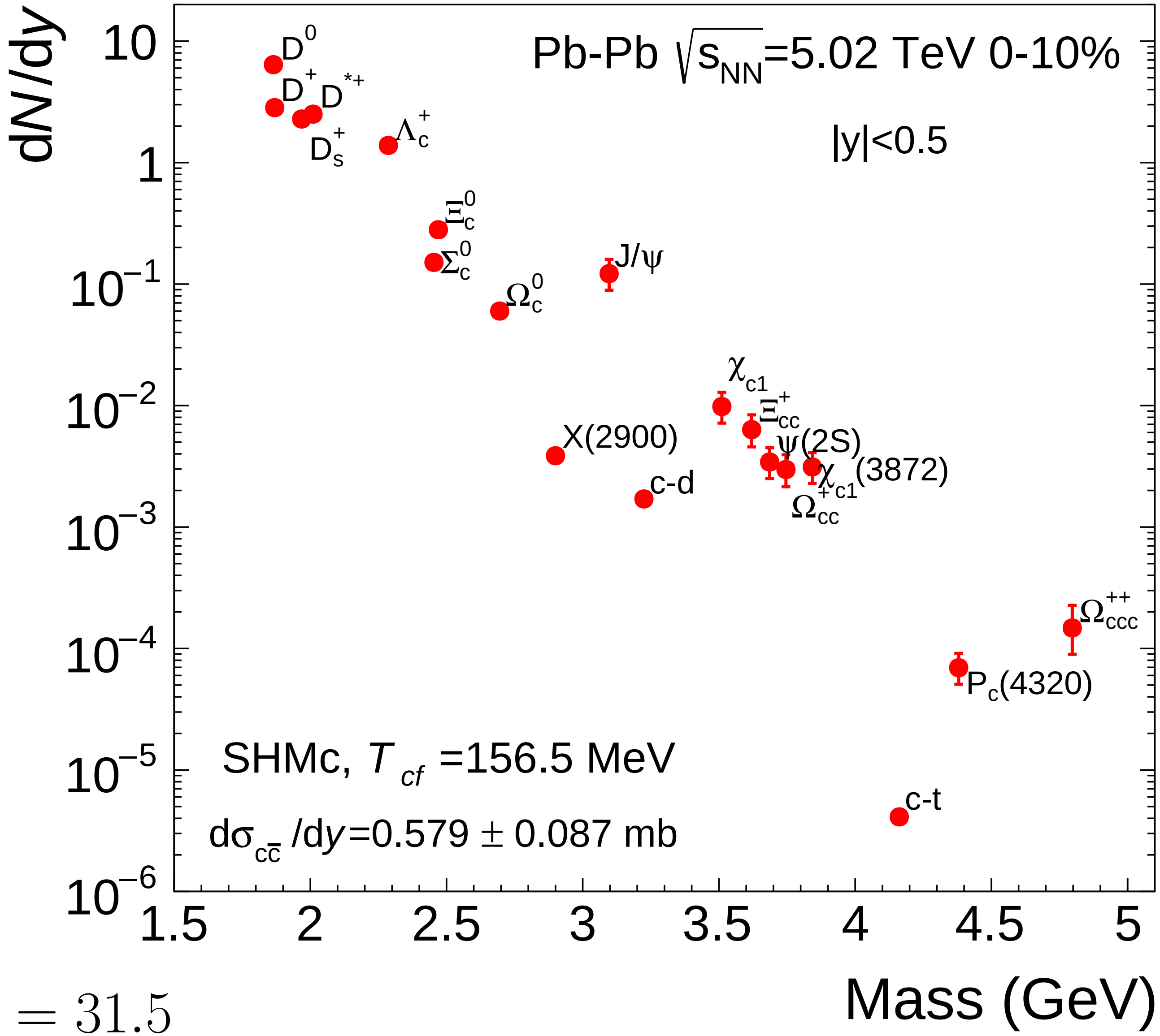
SHMc and charmonium data at the LHC

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)

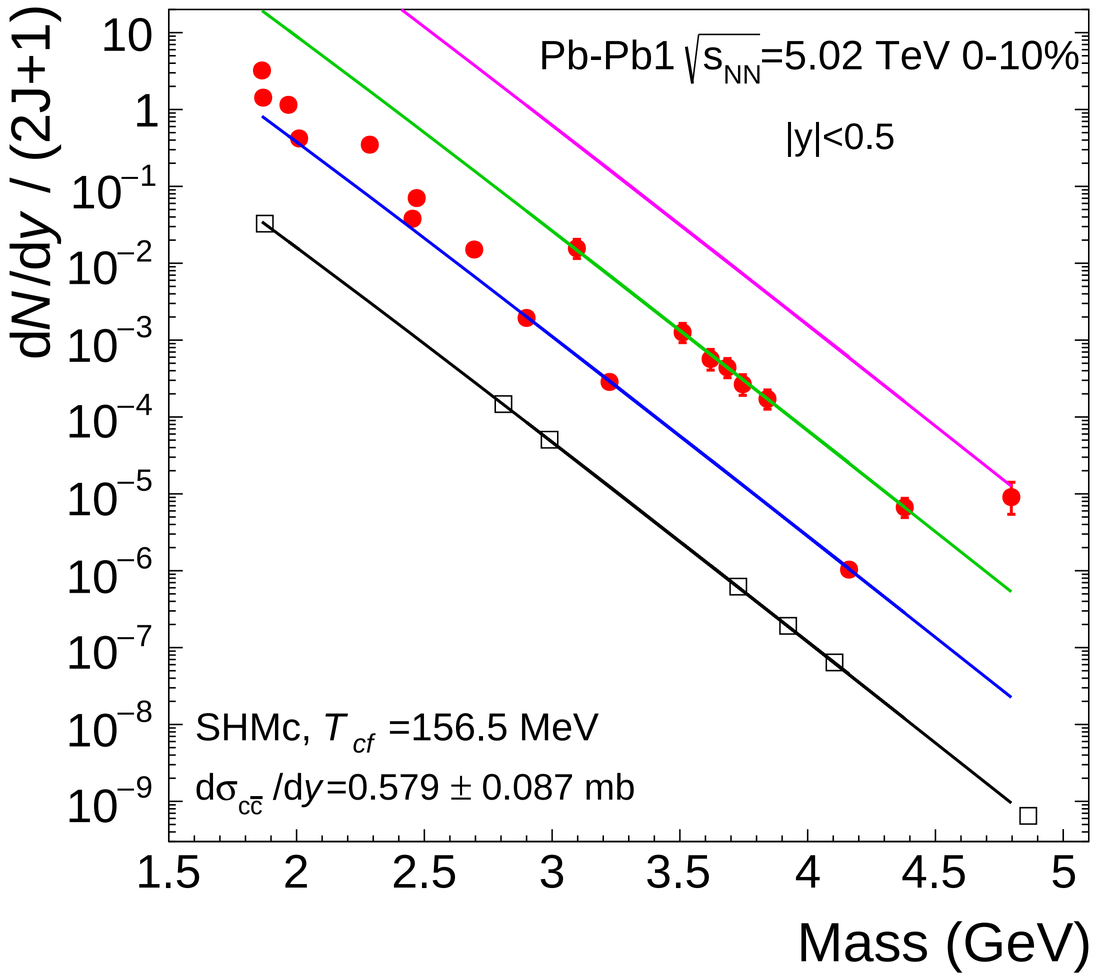


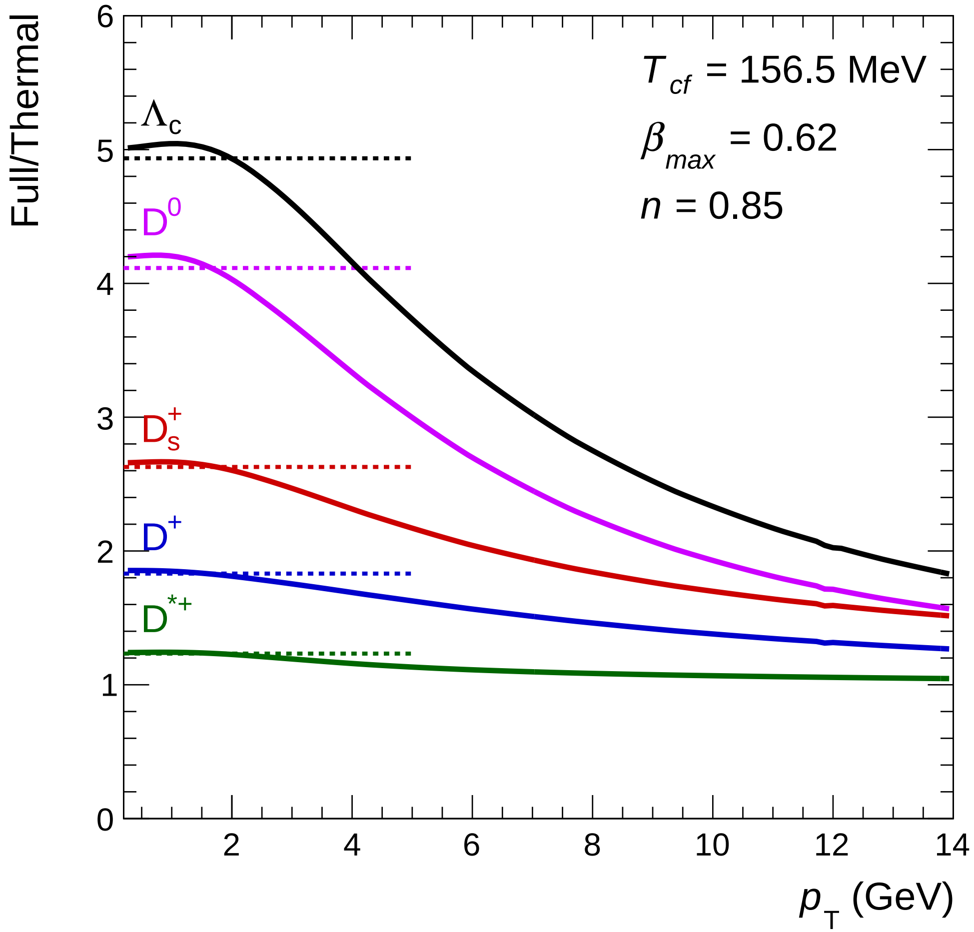
$T_{cc}^+ \simeq$
$0.9 \cdot \chi_{c1}(3872)$

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

$\frac{dN_{c\bar{c}}}{dy} = 13.8$
$\rightarrow g_c = 31.5$

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



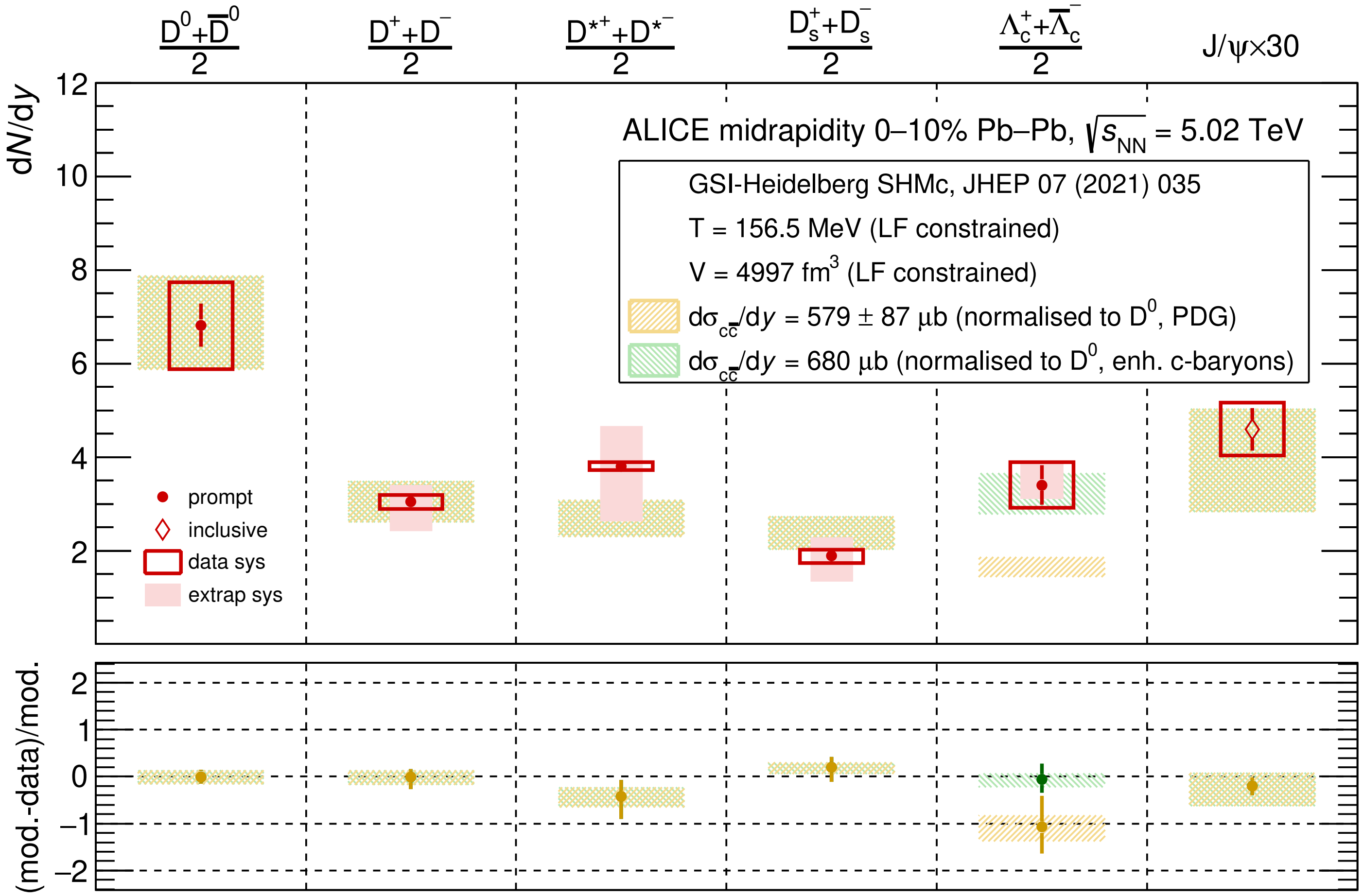


Charm-hadron spectrum as in PDG: 55 c-mesons, 74 c-baryons (part.+antipart.)

...large, but may not be complete

...ad-hoc: *tripled* the excited charm-baryon states, enhanced $\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y$ by 19%

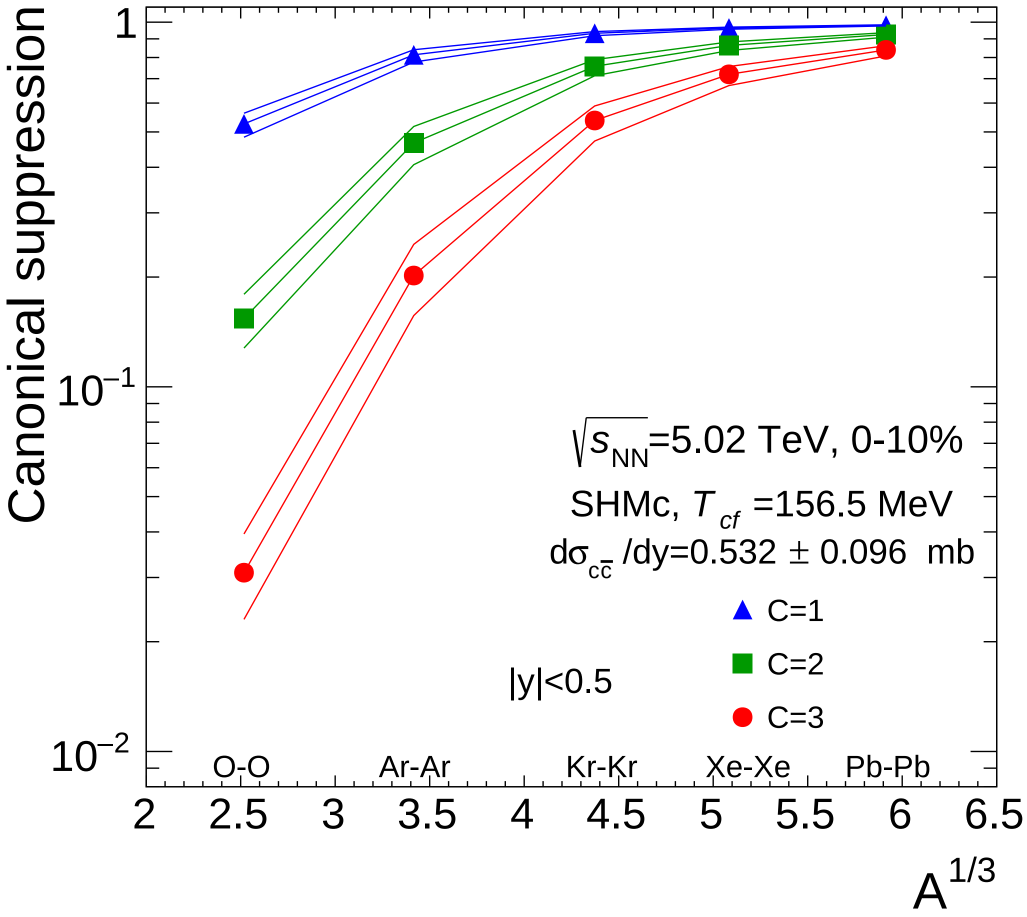
RQM: He,Rapp, PLB 795 (2019) 117; LQCD, Bazavov et al., PLB 737 (2014) 210

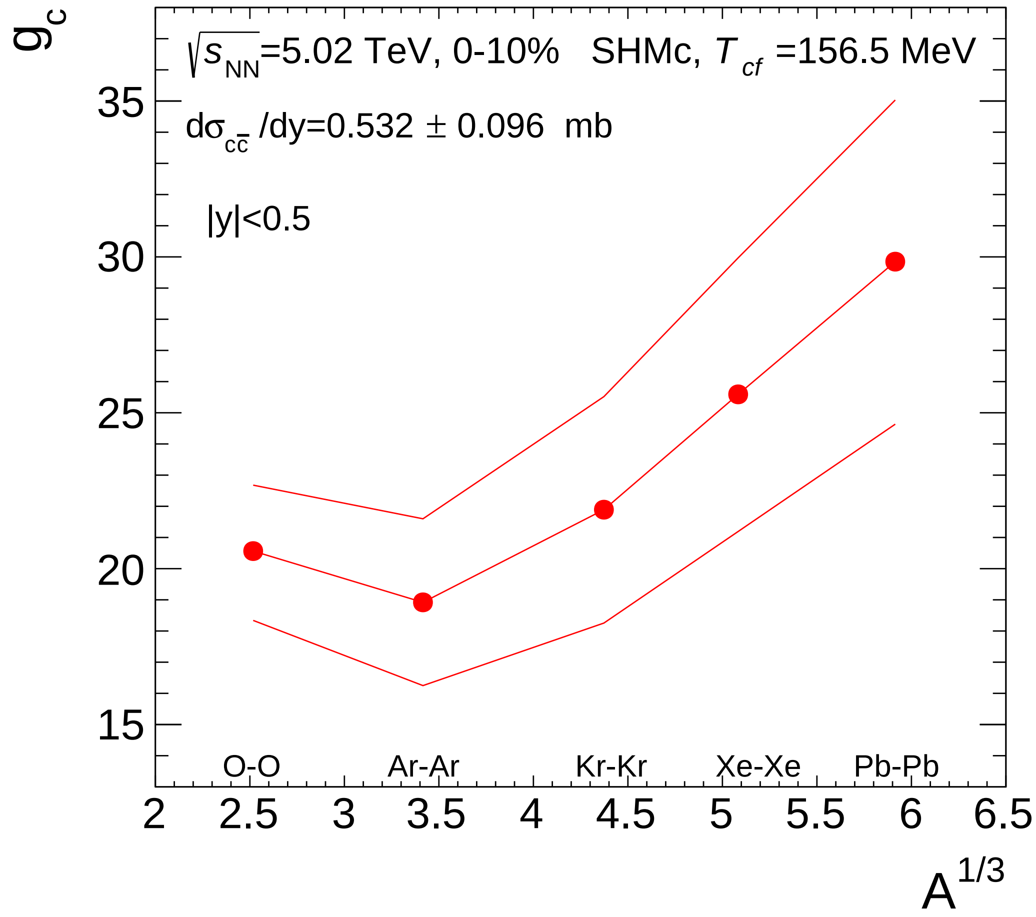


ALICE (QM'22 talk, L. Vermunt)

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

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

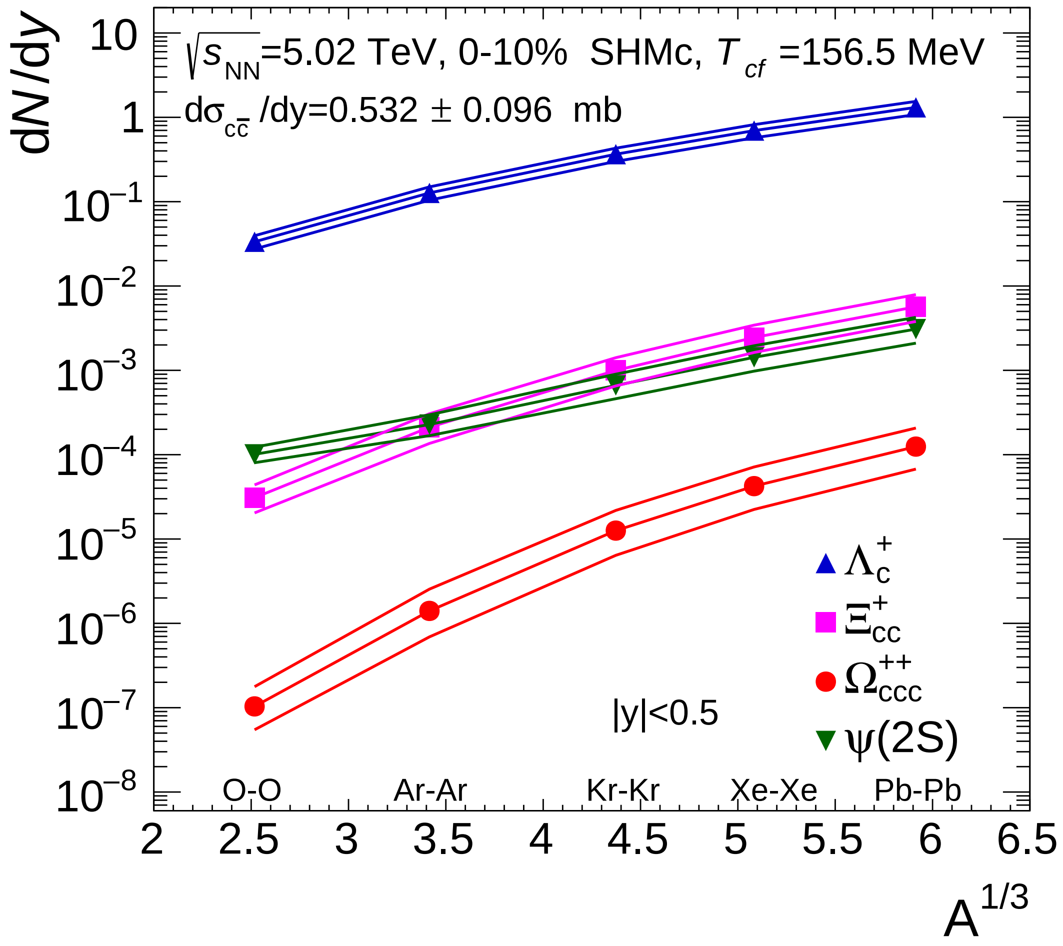


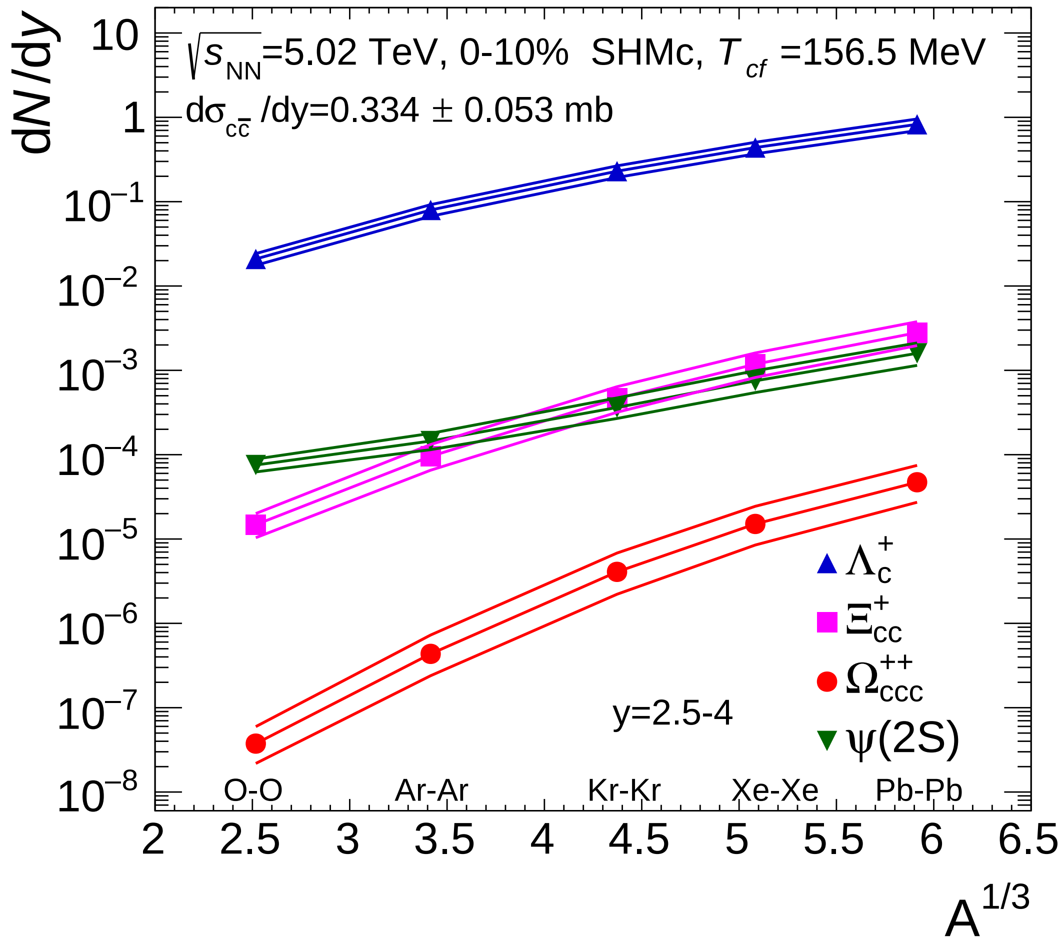


Strong canonical suppression for light systems (for multi-charm hadrons)

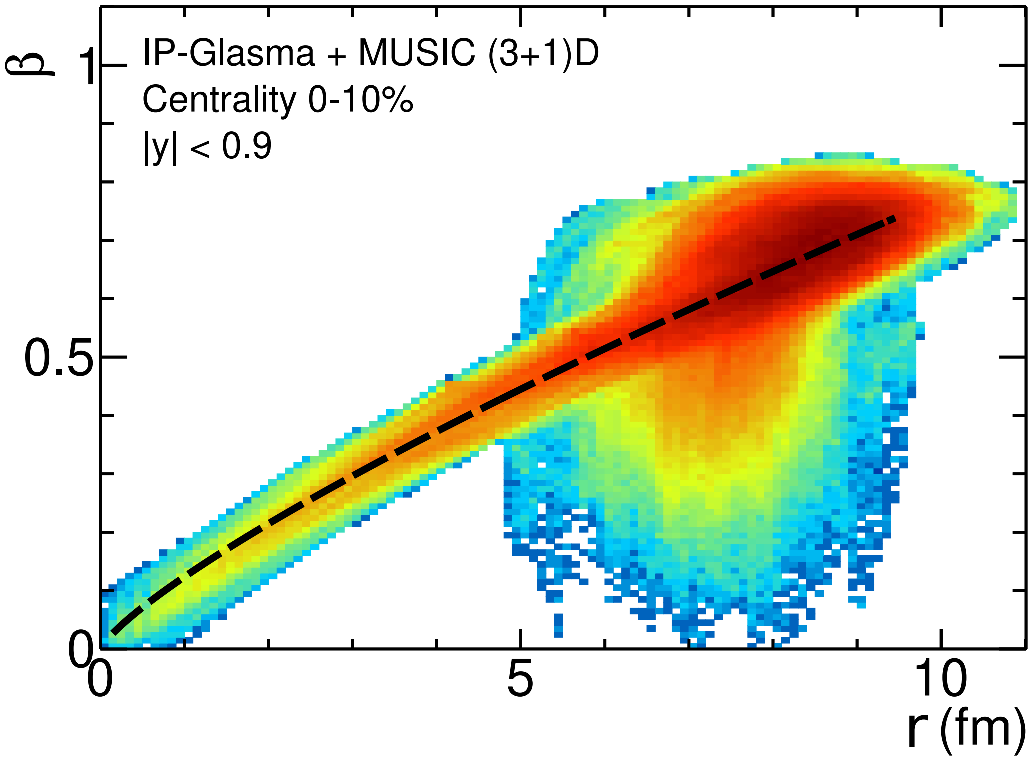
SHMc: system dependence (central, 0-10%)

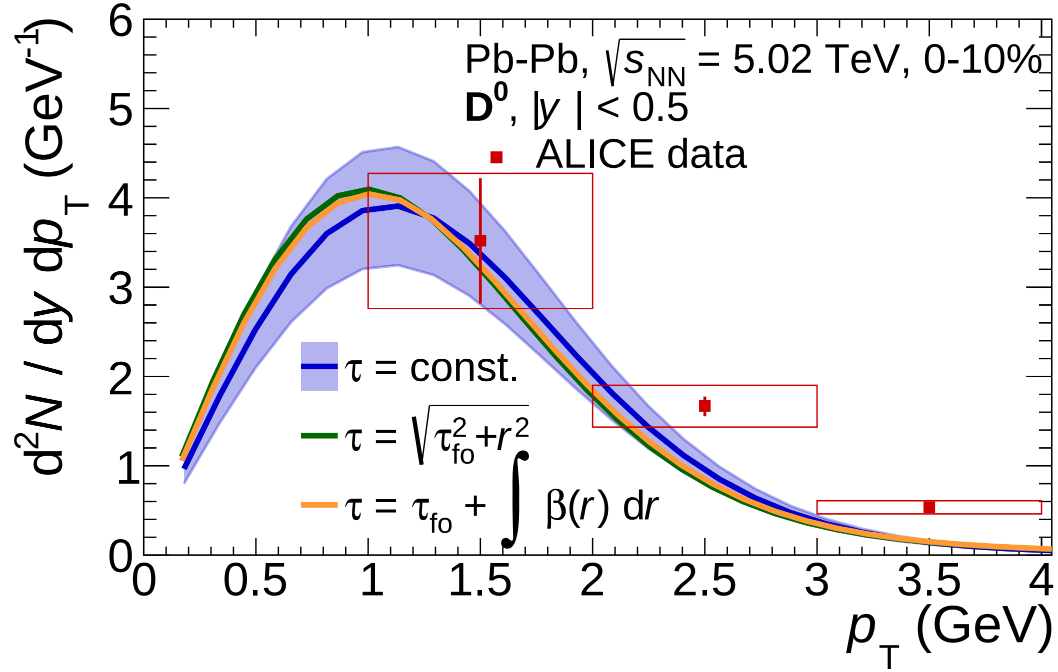
A. Andronic





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

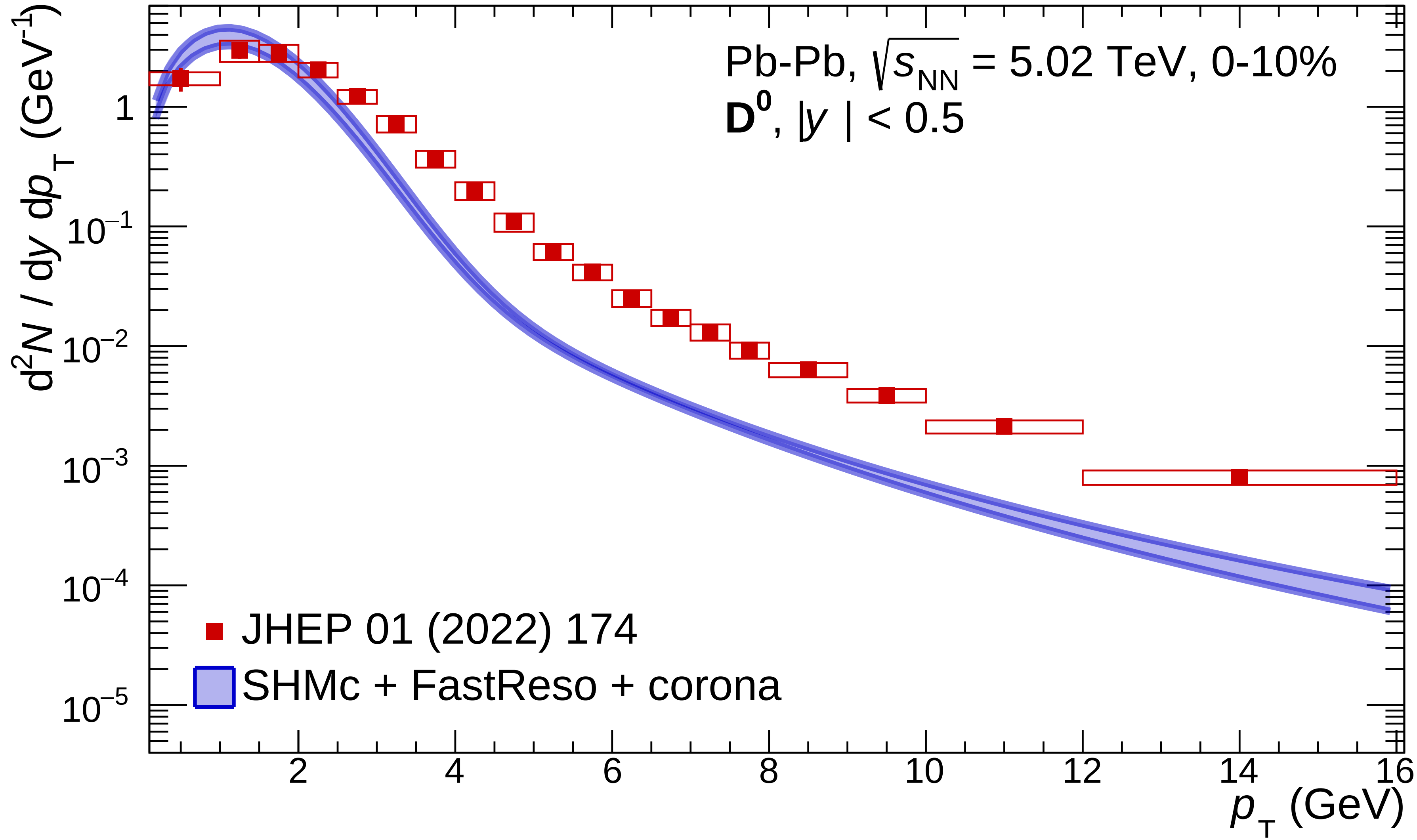




$$\frac{\mathrm{d}^2N}{2\pi p_\mathrm{T}dp_\mathrm{T}dy} = \frac{2J+1}{(2\pi)^3}\int \mathrm{d}\sigma_\mu p^\mu f(p) = \frac{2J+1}{(2\pi)^3}\int_0^{r_\mathrm{m}} \mathrm{d}r\ \tau(r)r\left[K_1^{\mathrm{eq}} - \frac{\partial\tau}{\partial r}K_2^{\mathrm{eq}}\right]$$

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

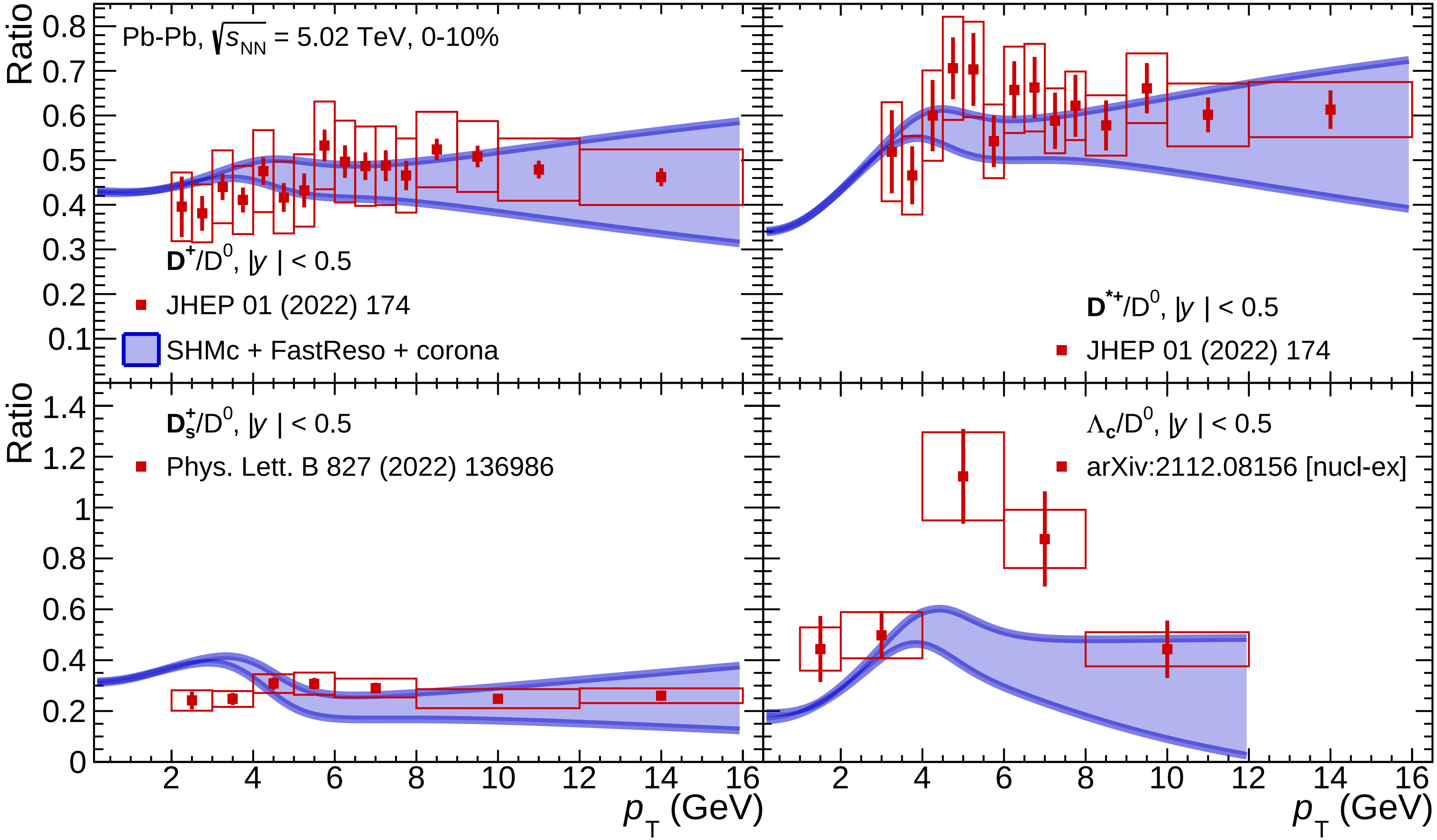
SHMc: p_T dependence



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

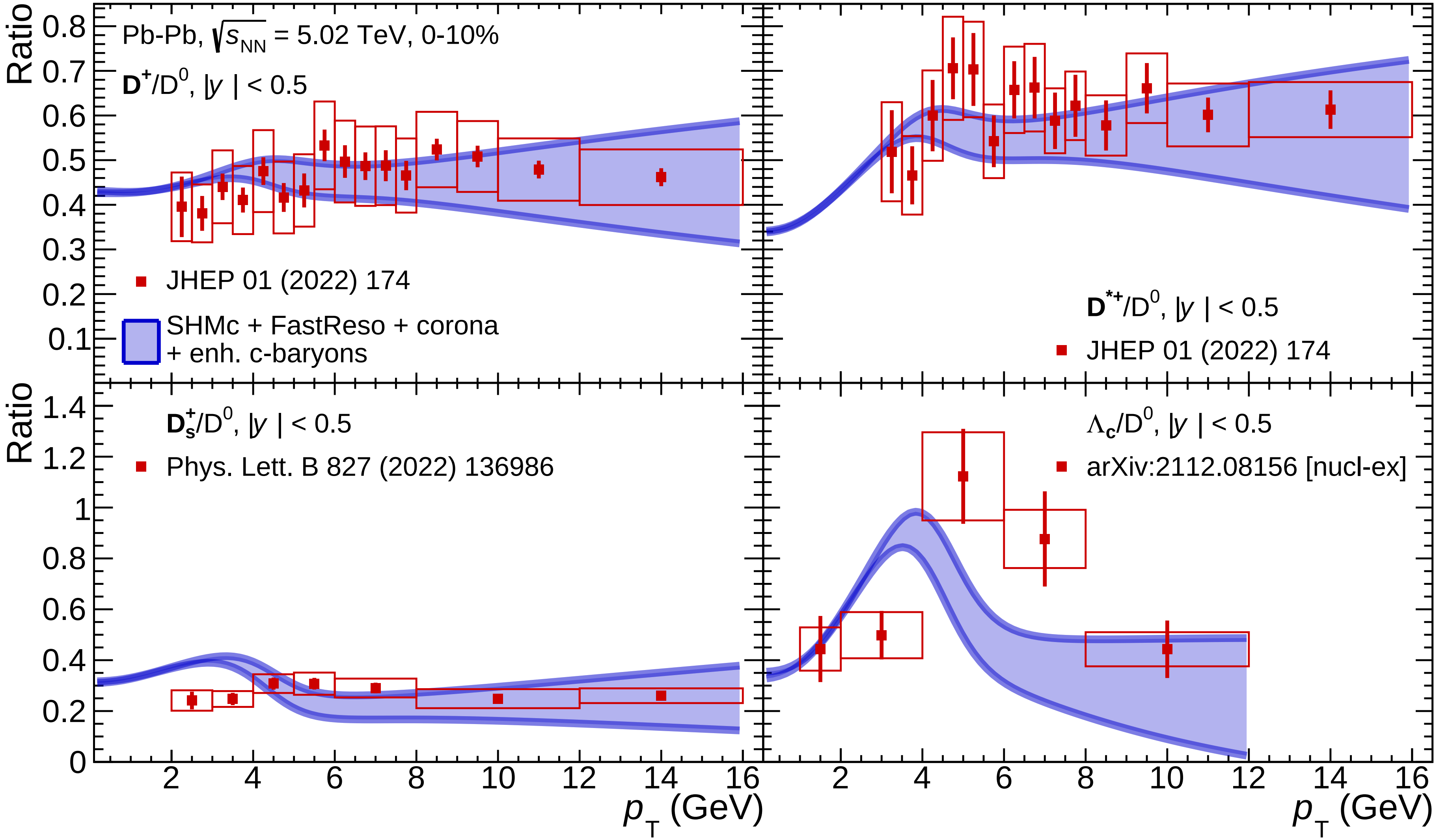
ALICE, JHEP 01 (2022) 174

Ratios to D^0

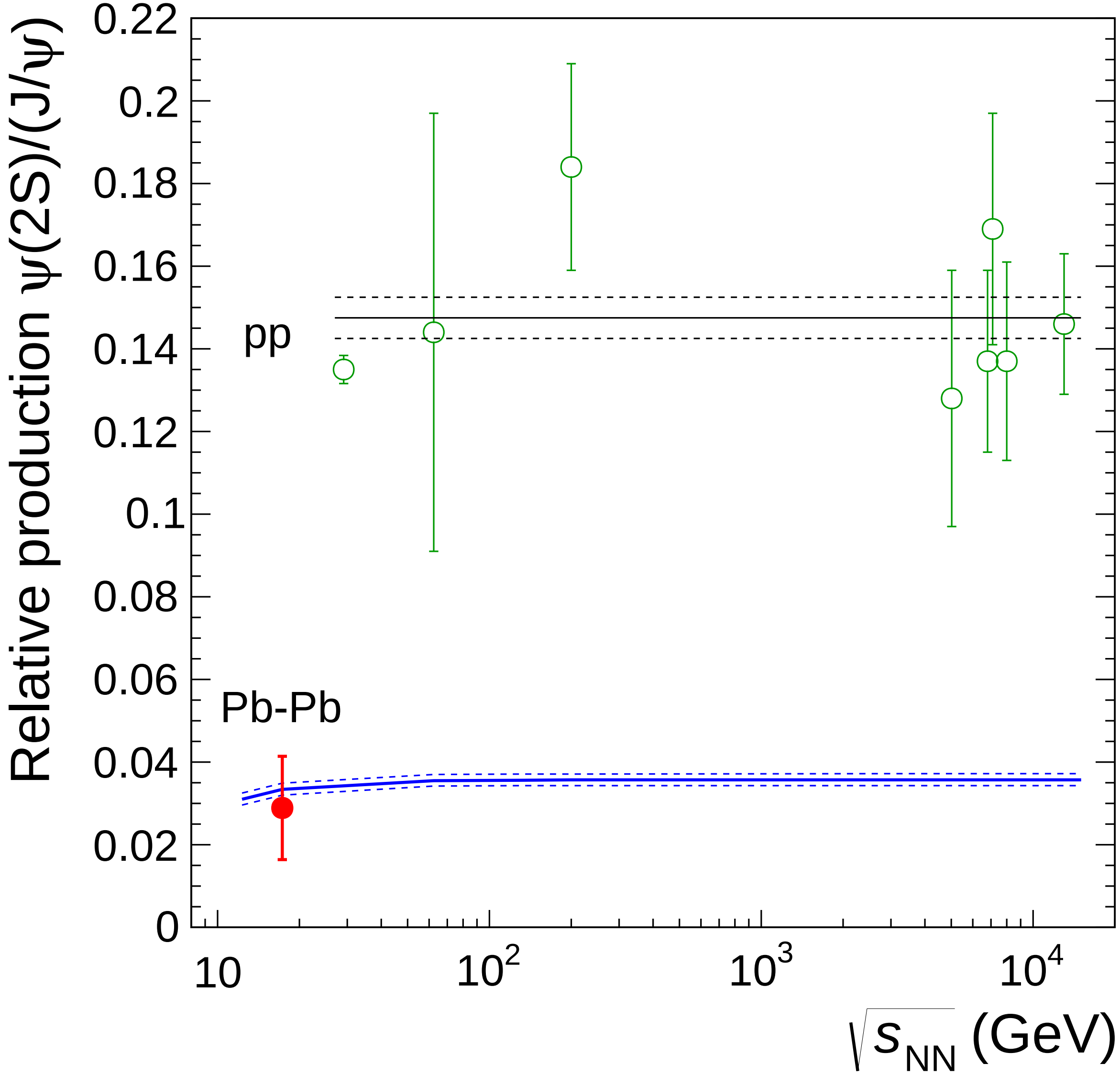


Charm-hadron spectrum: PDG

Ratios to D^0



Charm-hadron spectrum: enhanced c-baryons (tripled excited states)



...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

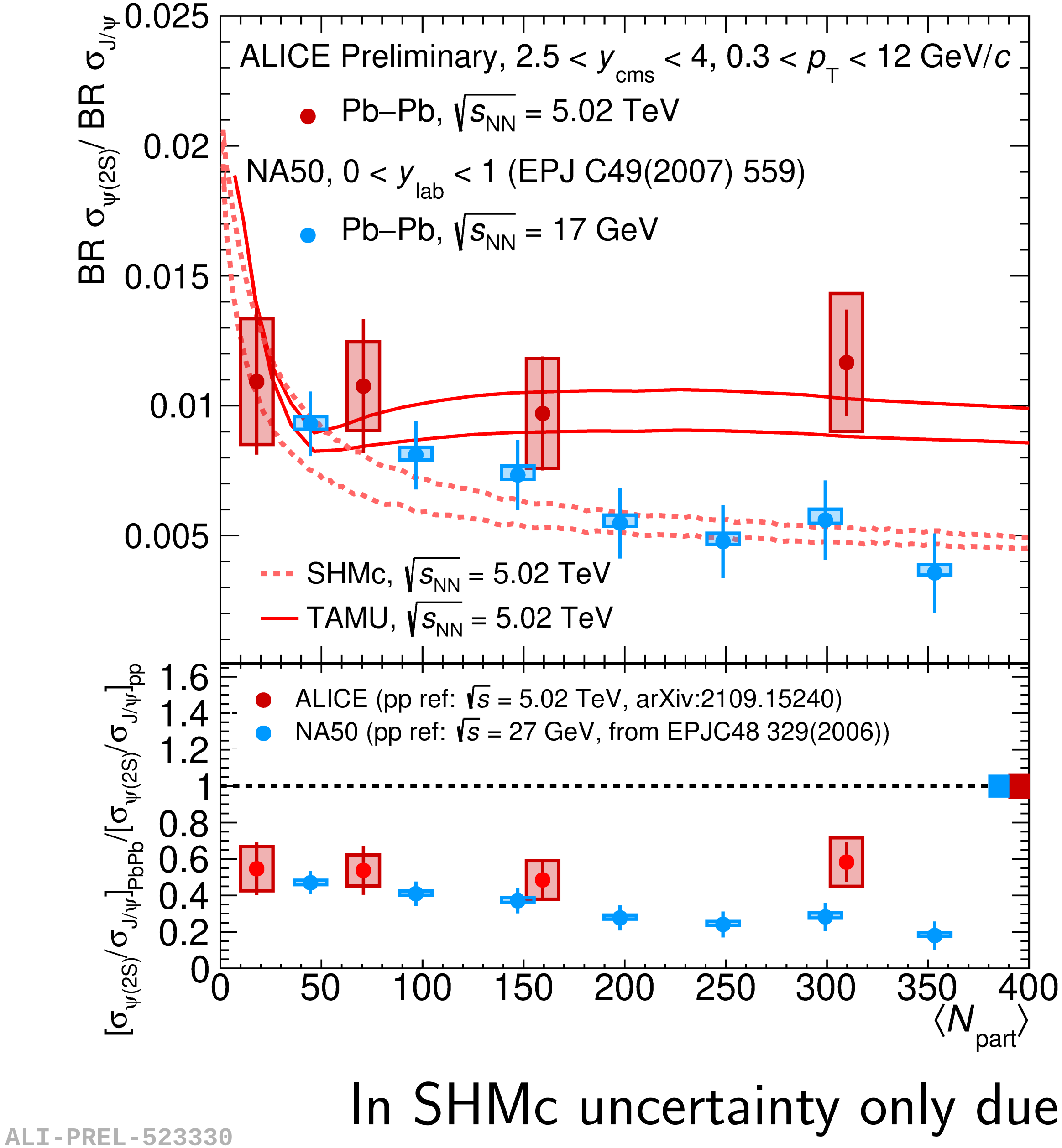
Braun-Munzinger, Stachel, PLB 490 (2000) 196

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)

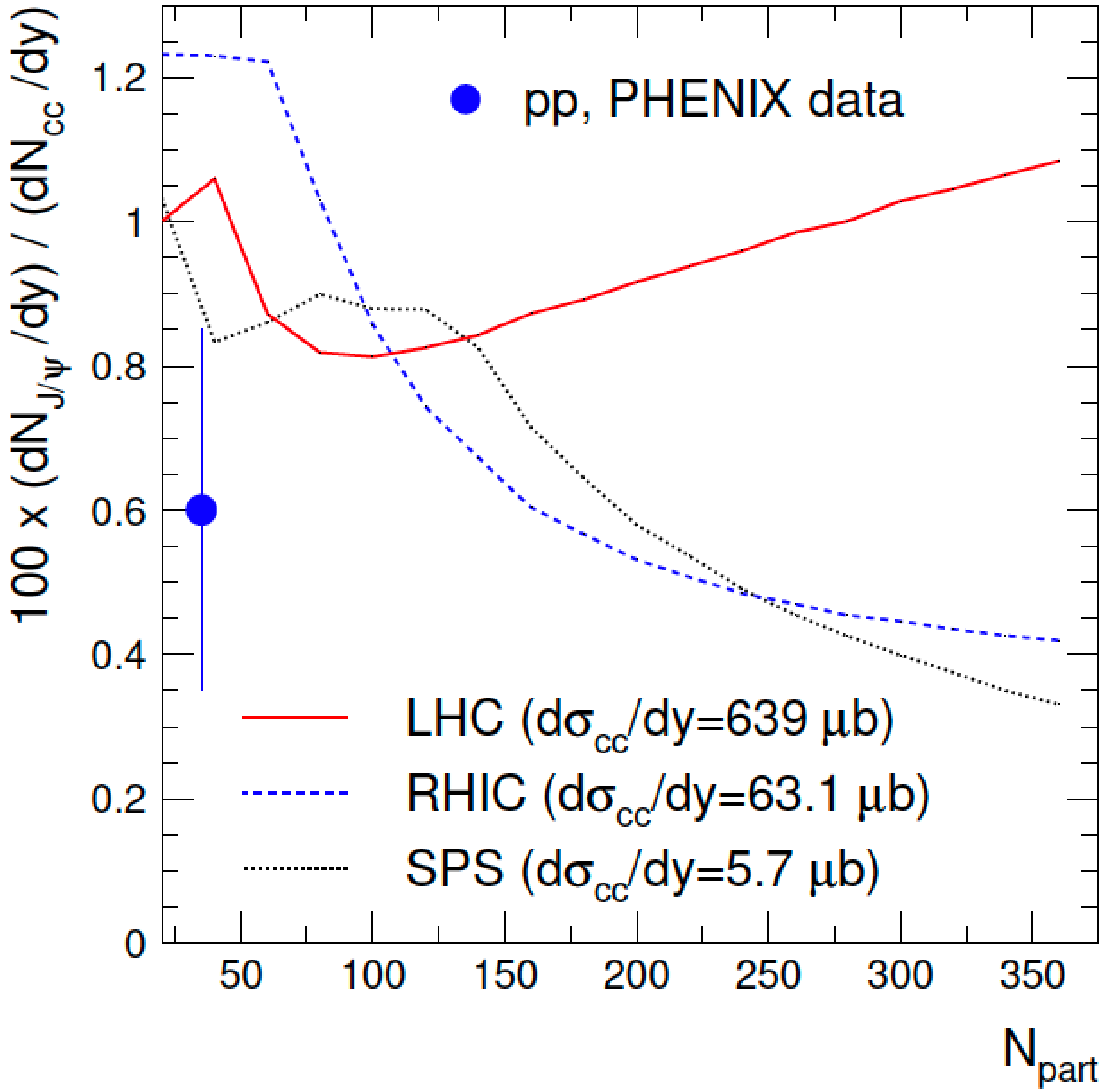
$\psi(2S)/J/\psi$ at the LHC



In SHMc uncertainty only due to nuclear-corona

($\sigma_{c\bar{c}}$ cancels out completely)

...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

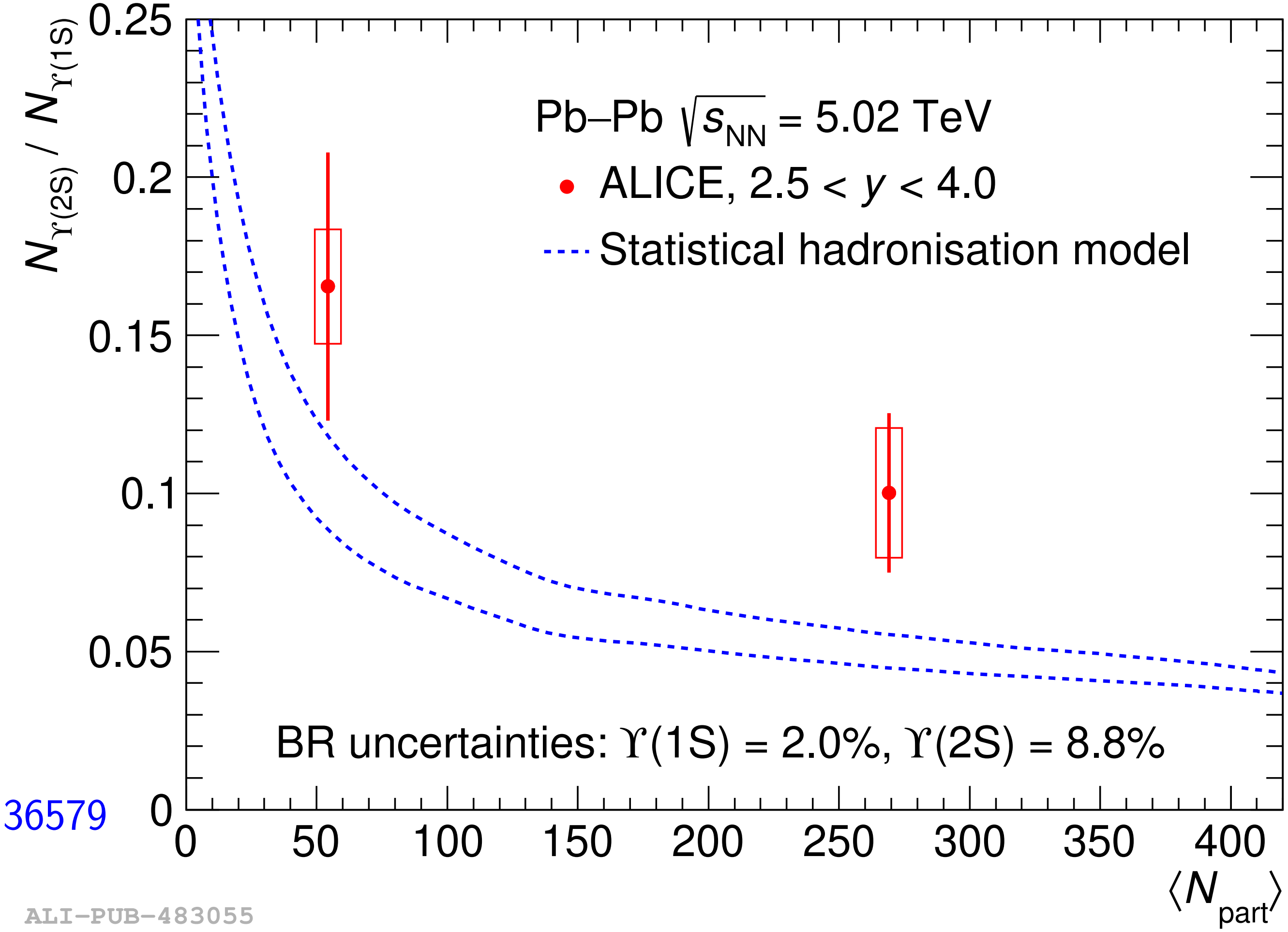
  ssame features in RHIC BES data (talk, K.Smith)

- enhancement-like at LHC

  can. suppr. lifted, quadratic term dominant

Beauty is expected (R_{AA}, v_2 data) to be less thermalized compared to charm

The beauty-hadron spectrum is less well known (PDG: 48 b-mes, 46 b-bar total)

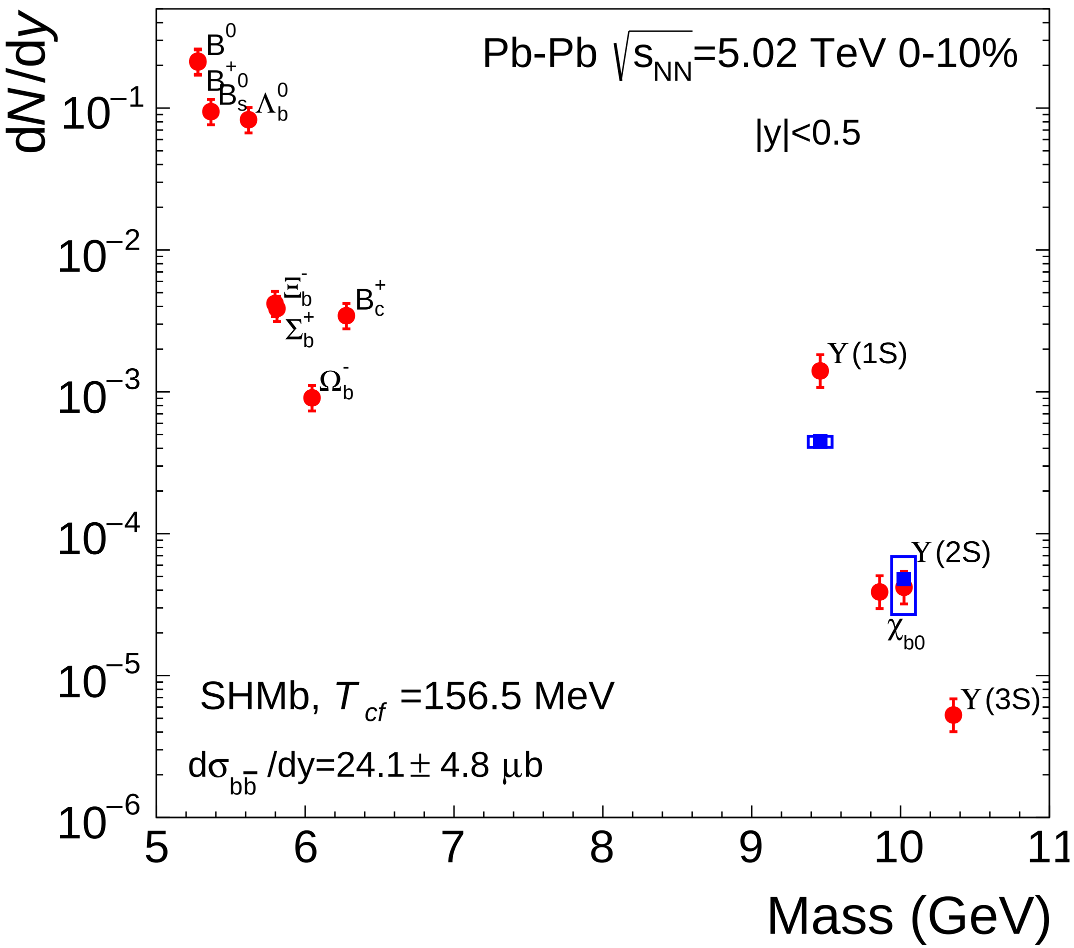


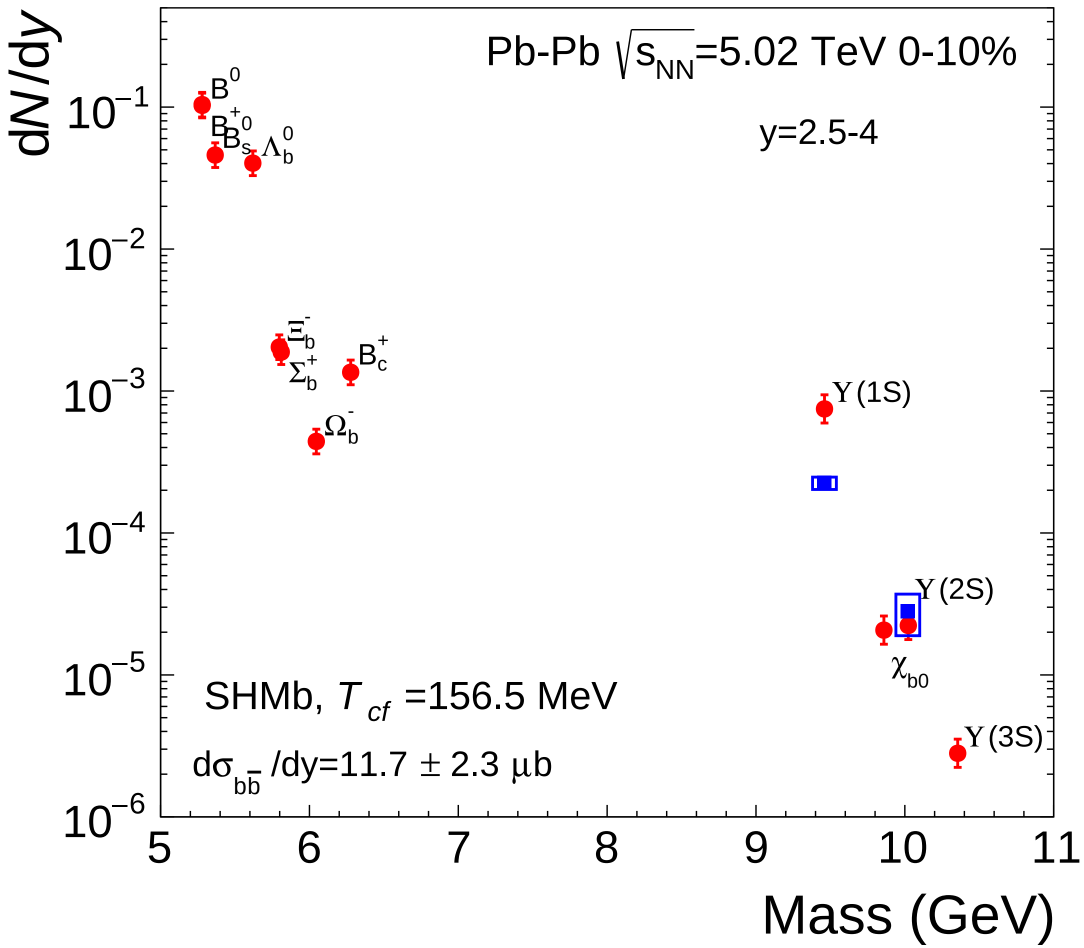
ALICE,

PLB 822 (2021) 136579

Color screening may not destroy all Υ mesons in QGP

Uncertainty band determined by nuclear-corona





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

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

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

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

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% $\mathrm{b\bar{b}}$ thermalized

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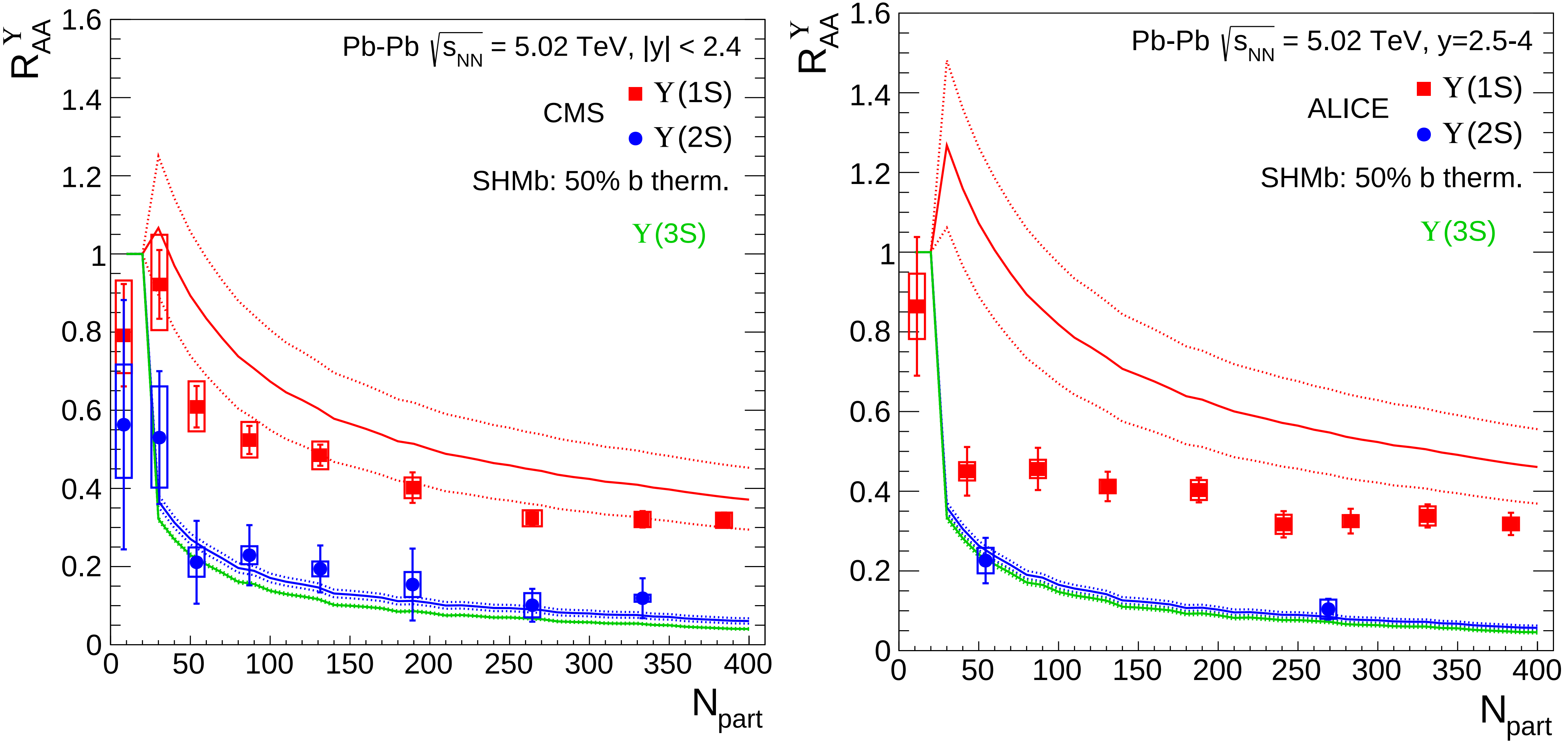
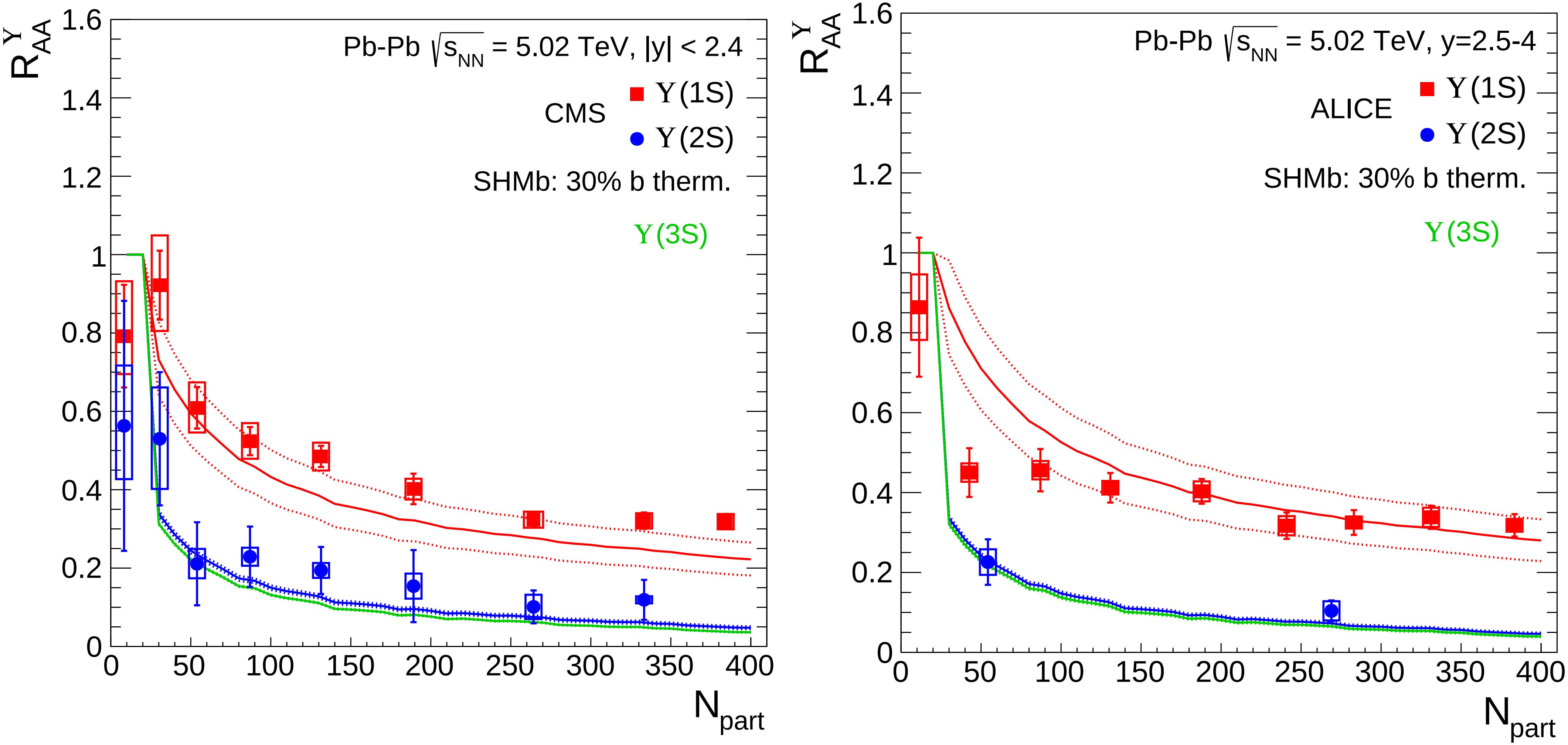


CMS, PRL 120 (2018) 142301

ALICE, PLB 822 (2021) 136579

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

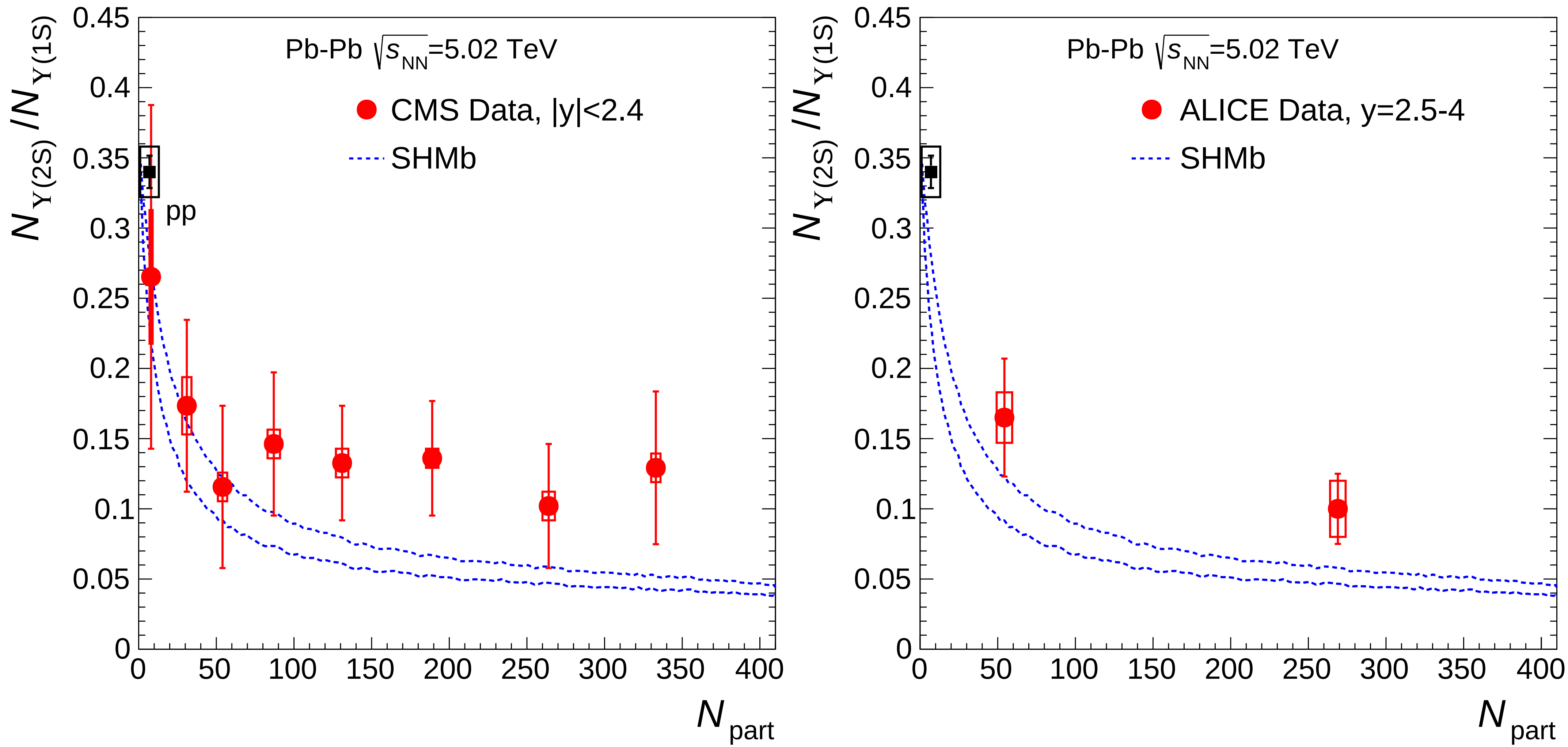


CMS, PRL 120 (2018) 142301

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)



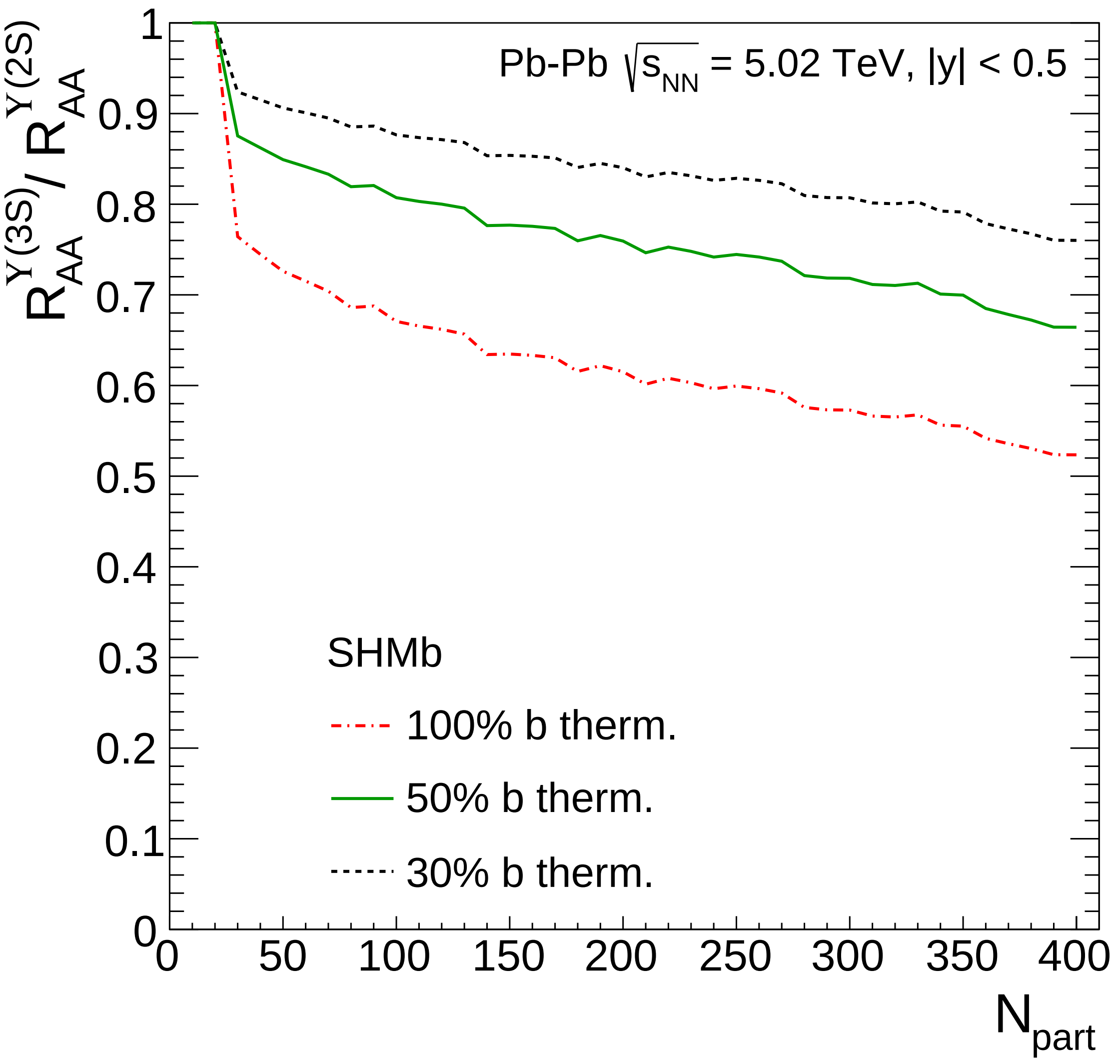
CMS, PRL 120 (2018) 142301

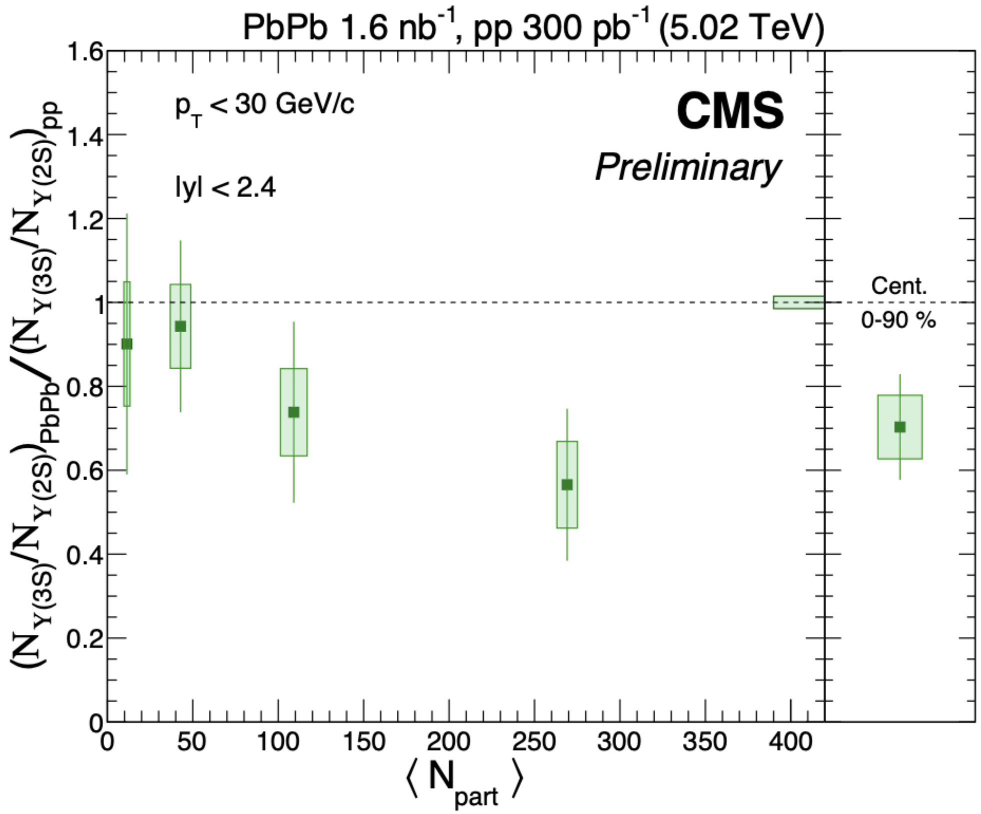
ALICE, PLB 822 (2021) 136579

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

SHMb uncert.: nuclear-corona (fraction)

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

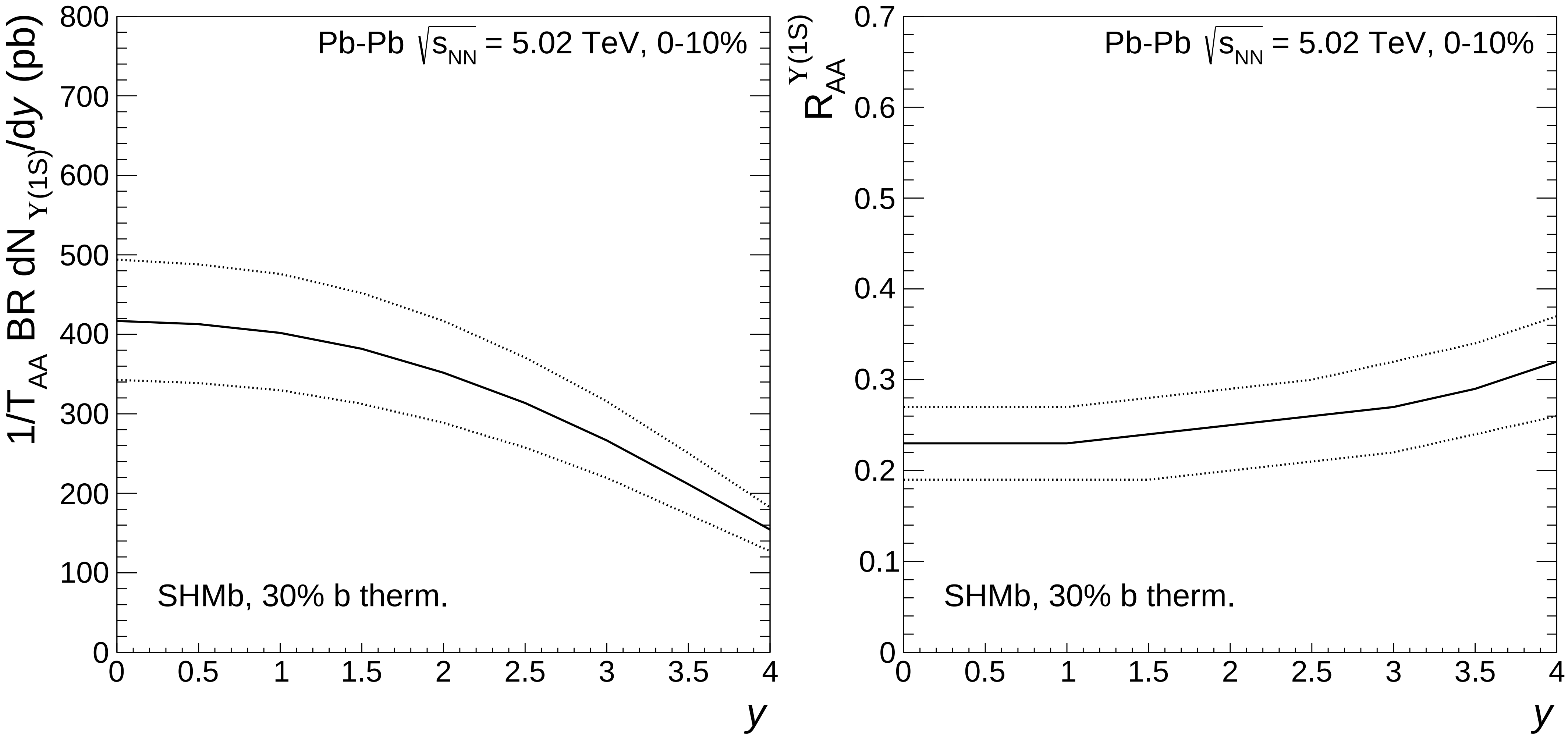




CMS, QM'22, HIN-21-007

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

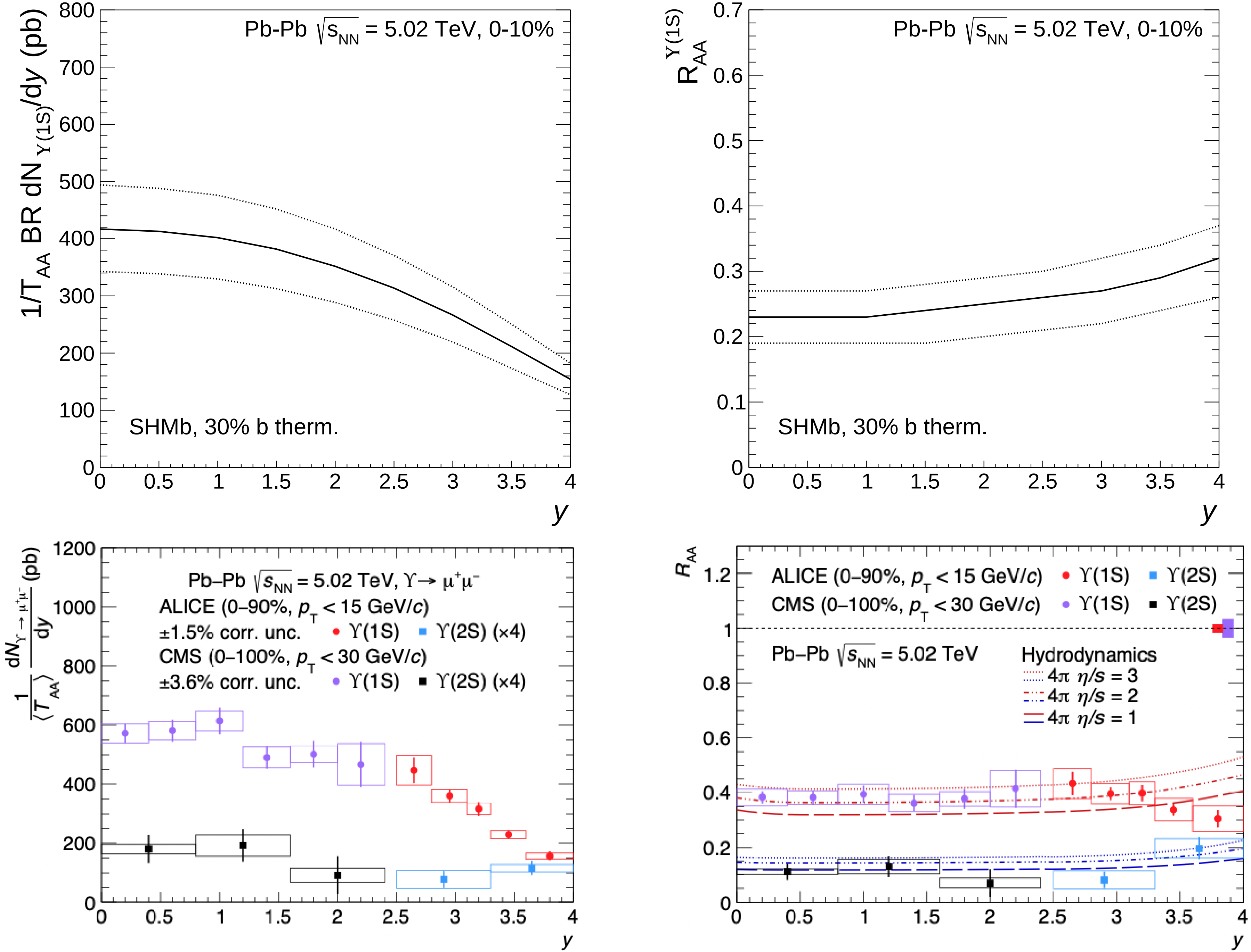
Rapidity dependence $\Upsilon(1S)$, 30% $b\bar{b}$ thermalized



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

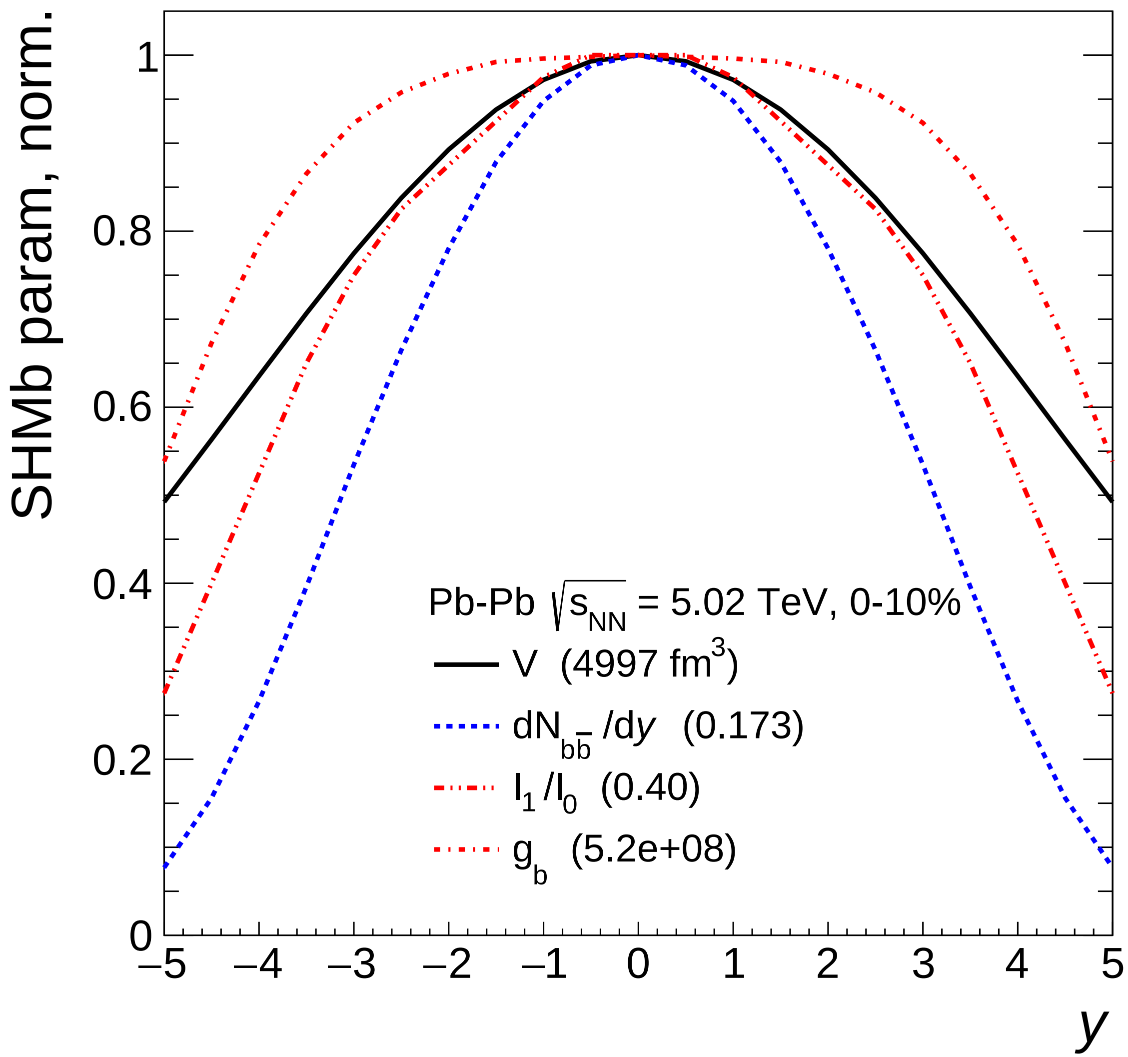
CMS, PRL 120 (2018) 142301; ALICE, PLB 822 (2021) 136579

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



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

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



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

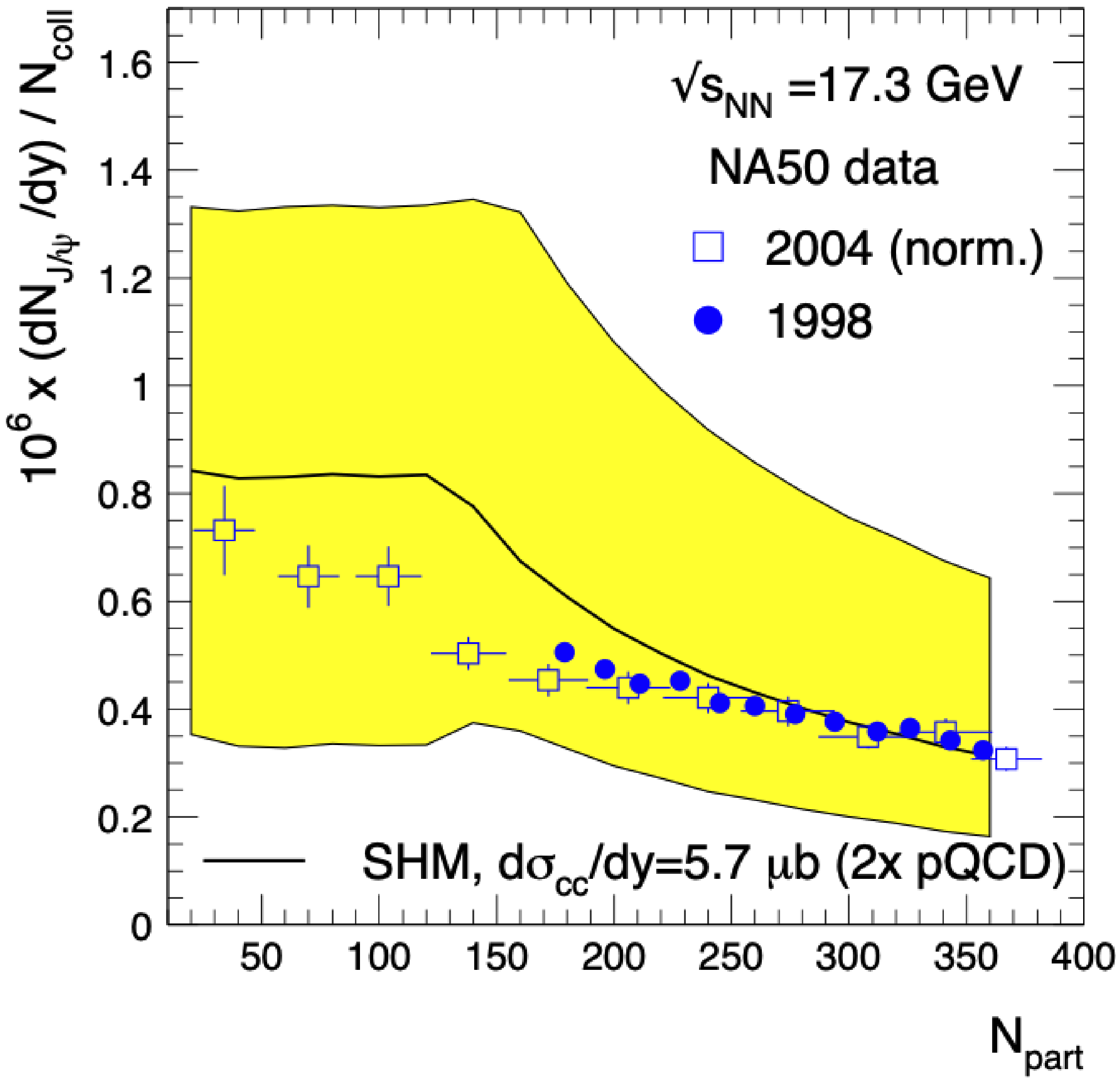
- What does non/partially-thermalized beauty produce?
  no Υ because strong coupling with the medium destroys the b-$\bar{b}$ correlation?
  ...related: is there non-screened bottomonium at all? (...or maybe just $\Upsilon(1S)$?)

- 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:)

Extra slides

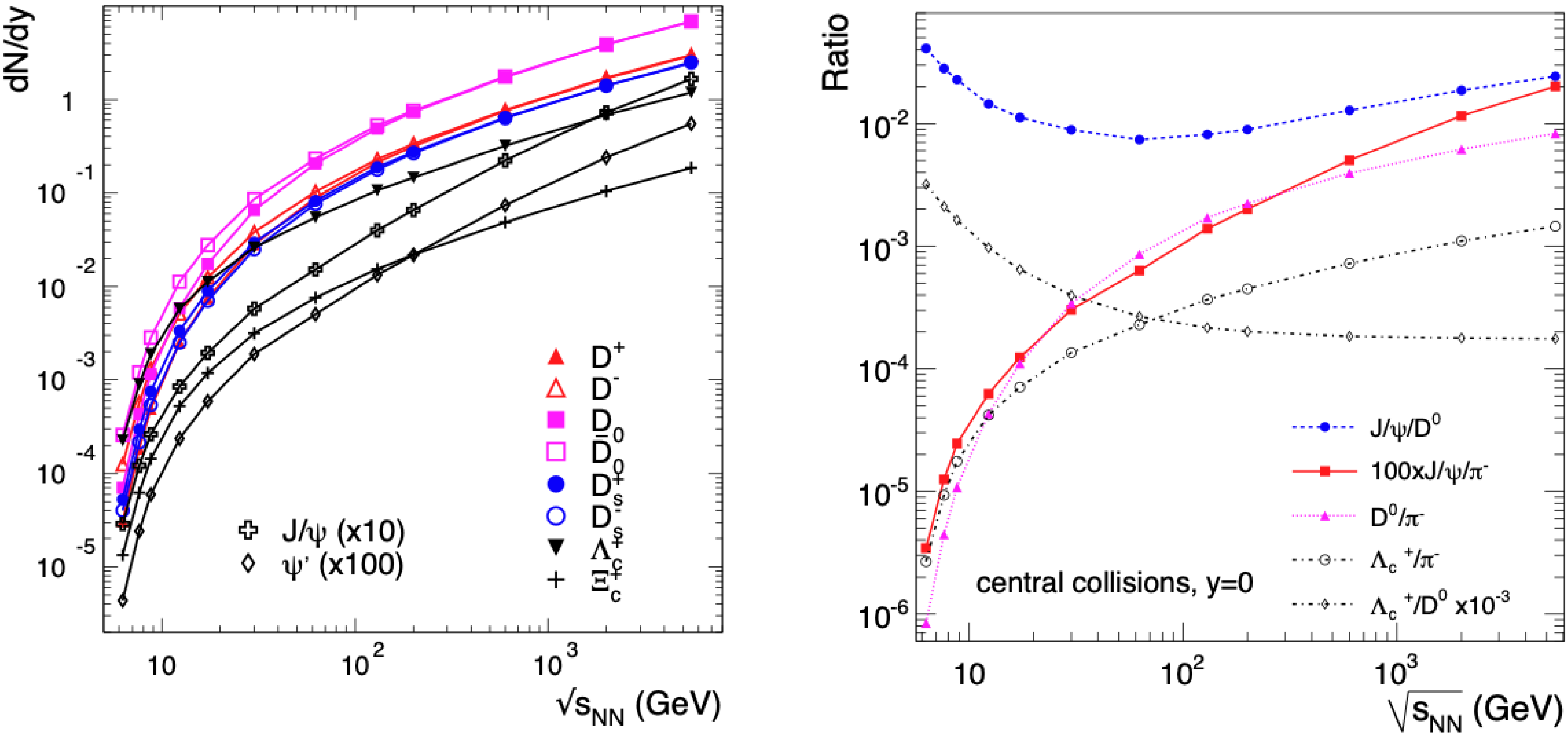


NPA 789 (2007) 334

Trend determined by canonical suppression of open charm

Model uncertainties large ($\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y$)

...constraining the model needs a good measurement of $\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y$

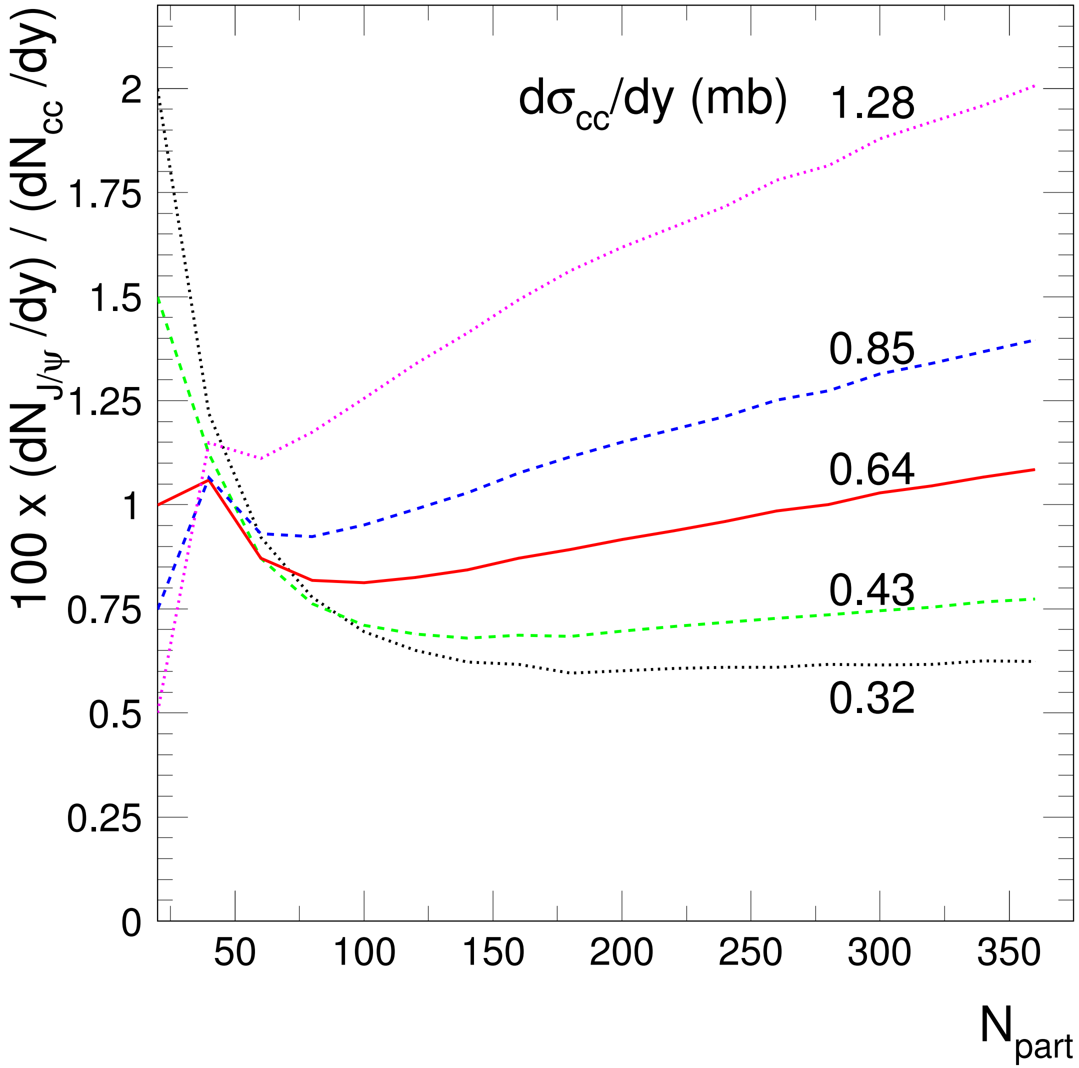


AA, Braun-Munzinger, Redlich, Stachel, JPG 37 (2010) 094014

NB: uncertainties from $\sigma_{c\bar{c}}$ are large

There are non-monotonic ratios ($J/\psi/D$), determined by canonical suppression

SHM and charmonium production at the LHC



$$\frac{\mathrm{d}N^{AA}_{J/\psi}/\mathrm{d}y}{\mathrm{d}N^{AA}_{c\bar{c}}/\mathrm{d}y}$$

("proxy" for R_{AA})

- "enhancement" at the LHC

  $N_{J/\psi} \sim (N^{dir}_{c\bar{c}})^2$

  canonical suppression (mostly) lifted, quadratic term dominant

  it can be more dramatic at FCC

AA et al., in N. Armesto et al., "Last Call...", JPG 35 (2008) 054001

this was for $\sqrt{s_{NN}} = 5.5$ TeV ... but is a generic prediction of the model

- LHCb $p_T < 8\,GeV/c$, $2.0 < y < 4.5$

pp 5 TeV, JHEP 06 (2017) 147

$\sigma(c\bar{c}) = 1193 \pm 3(stat) \pm 67(syst) \pm 58(frag)\,\mu\text{b}, \quad \rightarrow \frac{\mathrm{d}\sigma_{c\bar{c}}}{\mathrm{d}y} = 0.477 \pm 0.036$ mb

pp 7 TeV, NPB 871 (2013) 1

$\sigma(c\bar{c}) = 1419 \pm 12(stat) \pm 116(syst) \pm 65(frag)\,\mu$b

$$\Lambda_c/D^0 = 0.140 \pm 0.045$$

- ALICE, $|y| < 0.5$, $p_T > 0\,GeV/c$

pp 5 TeV, arXiv:2105.06335, arXiv:2102.13601 :

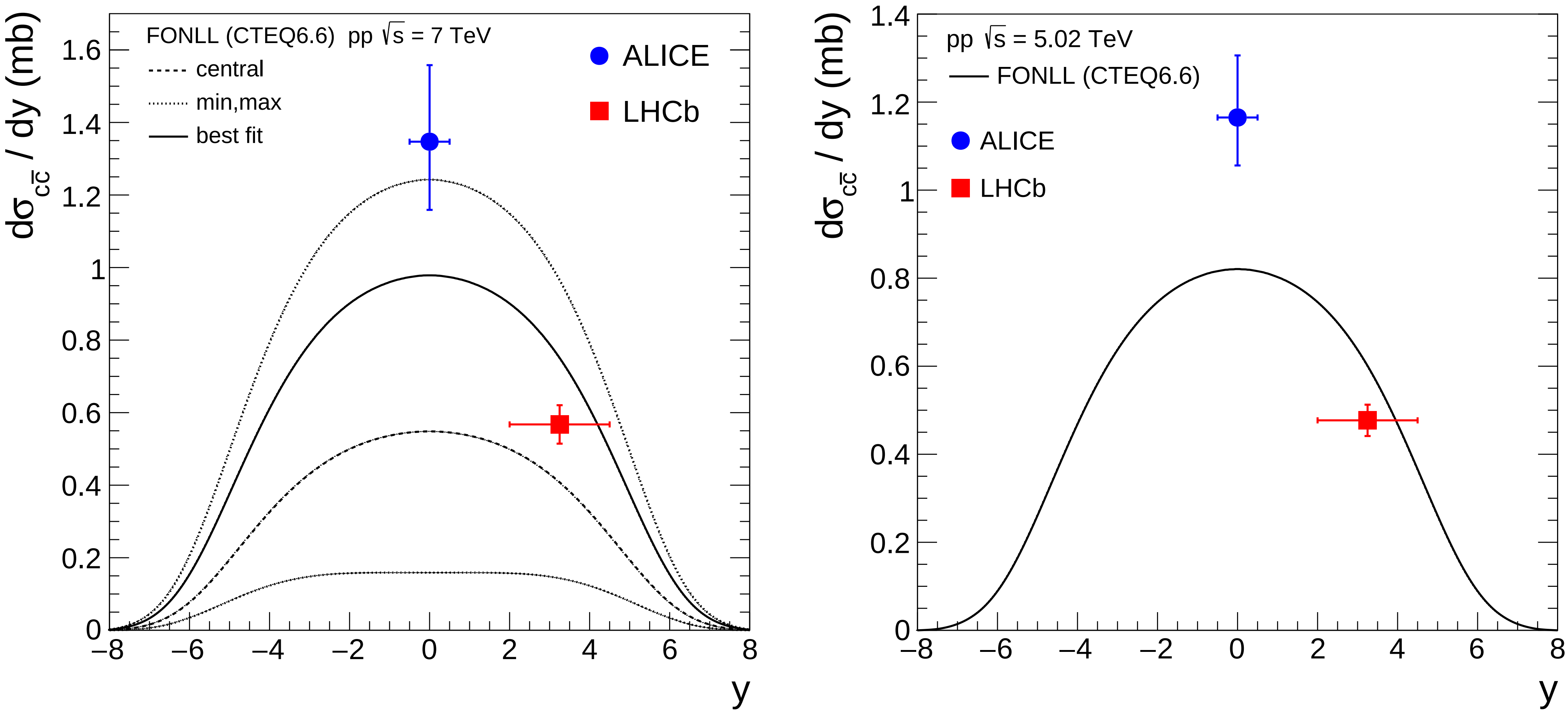
$\frac{\mathrm{d}\sigma_{c\bar{c}}}{\mathrm{d}y} = 1.165 \pm 0.044(stat) \pm 0.065(syst)^{+.098}_{-.038}(extr) \pm 0.043(BR) \pm 0.042(RS) \pm 0.024(lumi)$ mb

$$\Lambda_c/D^0 = 0.51 \pm 0.06$$

pp 7 TeV, JHEP 04 (2018) 108

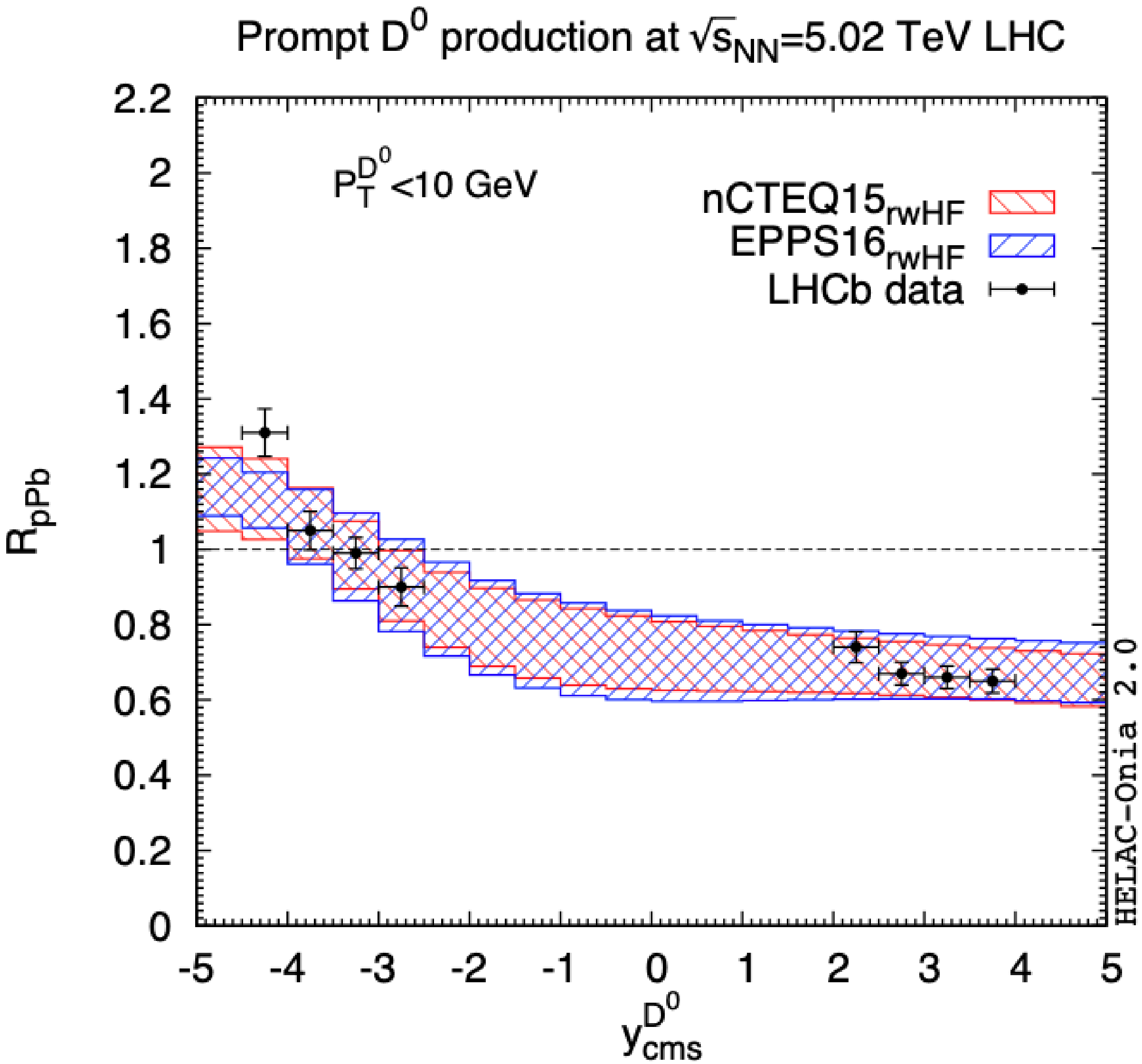
$\frac{\mathrm{d}\sigma_{c\bar{c}}}{\mathrm{d}y} = 1.347 \pm 0.097(stat) \pm 0.104(syst)^{+.142}_{-.105}(FF) \pm 0.011(BR) \pm .044(RS) \pm 0.047(lumi)$ mb

...p_T-integrated ($p_T > 0$); FONLL web interface



R_{pPb} and shadowing

A. Andronic



weighted nPDFs (90% CL):

Kusina et al, PRD 104 (2021) 014010

Data: LHCb, JHEP 10 (2017) 090

ALICE: 0.960 ± 0.086, JHEP 12 (2019) 092

y=0:

$R_{pPb} = 0.73 \pm 0.067\,(1\,\sigma)$

$\Rightarrow S_{PbPb} = 0.53 \pm 0.097$

in SHMc (earlier value):

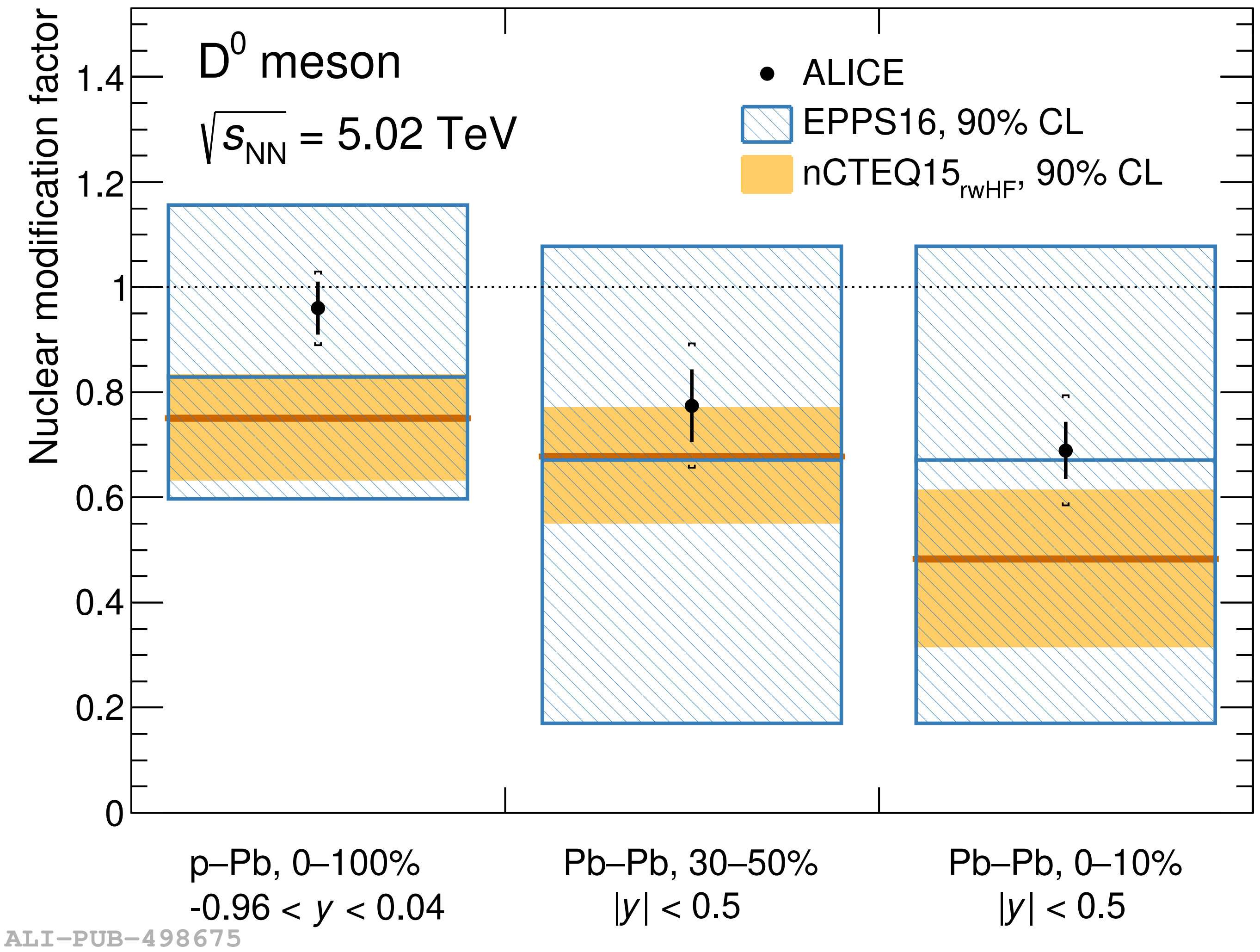
$S_{PbPb} = 0.65 \pm 0.12$

assumed shadowing in Pb–Pb

$S_{PbPb} = R_{pPb}(-y) \cdot R_{pPb}(y)$

$\Rightarrow \frac{\mathrm{d}\sigma_{c\bar{c}}}{\mathrm{d}y} = 0.532 \pm 0.096$ mb for y=0 (Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV, SHMc)

0.334 ± 0.053 for y=2.5-4



0-10%

Data (stat+sys):

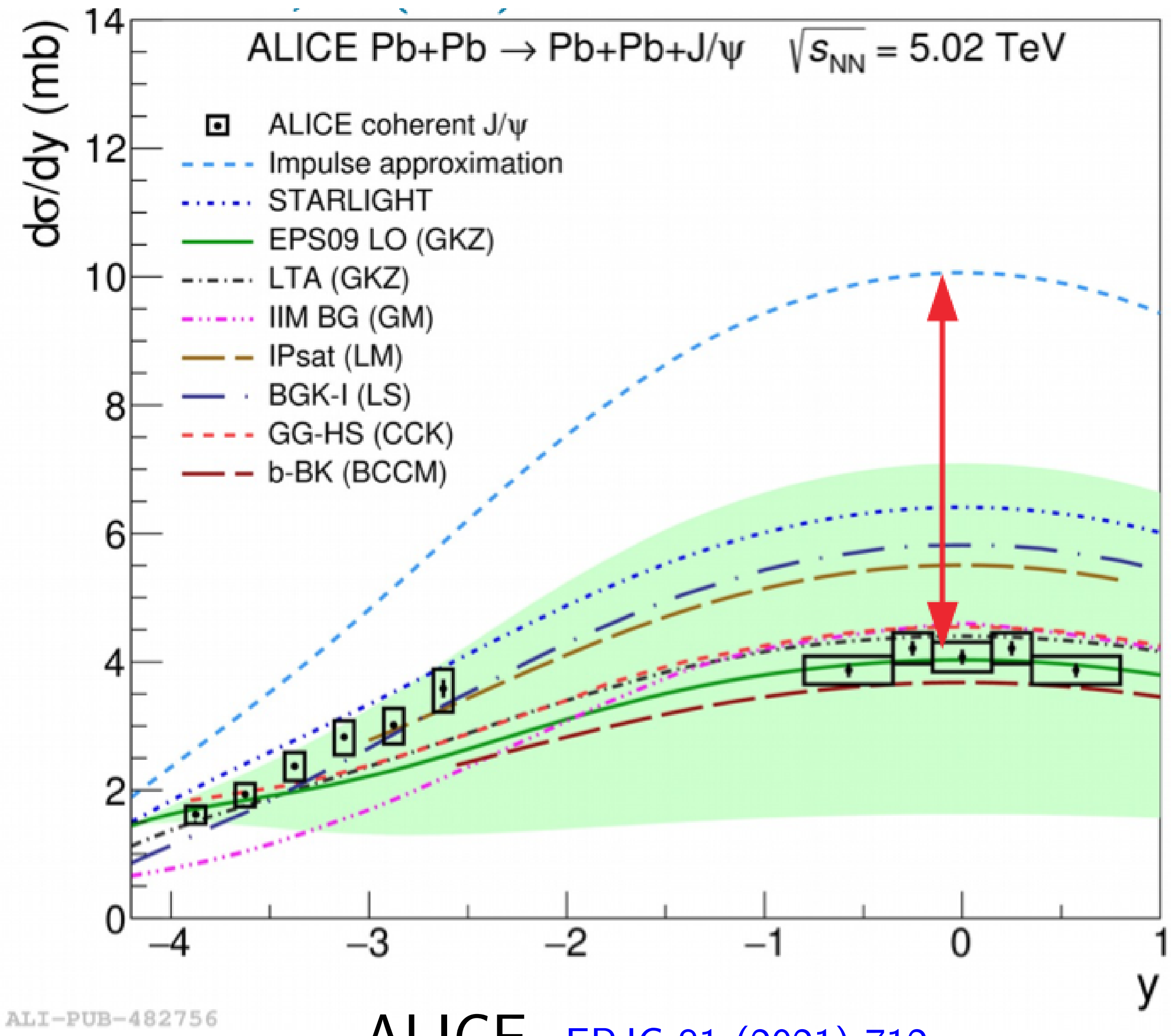
$$S_{PbPb} = 0.69 \pm 0.11$$

nCTEQ15$_{\mathrm{rwHF}}$ (1 σ):

$$S_{PbPb} = 0.47 \pm 0.09$$

(centrality-dependent)

ALICE, arXiv:2110.09420



ALICE, EPJC 81 (2021) 712

J/ψ photoproduction

$$S_{PbPb} = \frac{\mathrm{d}\sigma/\mathrm{dy}(data)}{\mathrm{d}\sigma/\mathrm{dy}(Imp.approx.)}$$

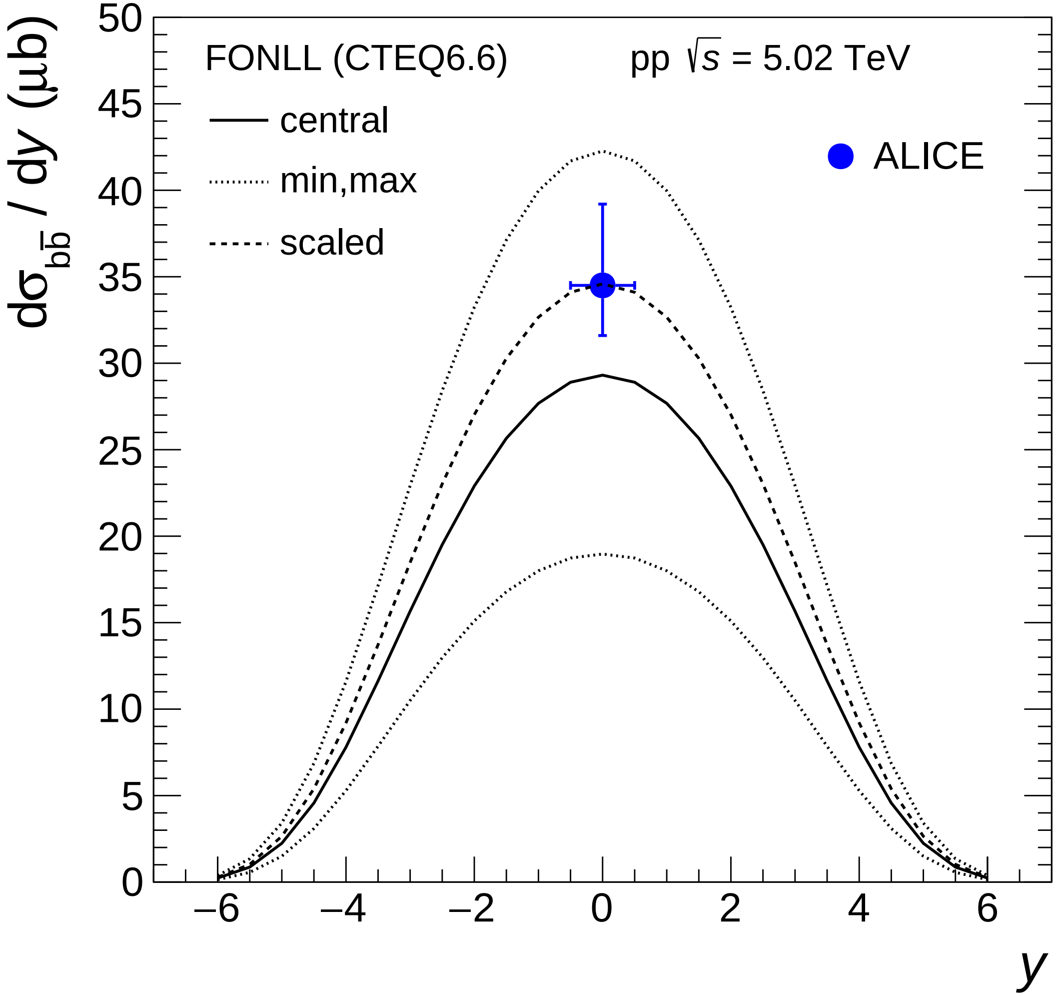
$$S_{PbPb} = 0.42 \pm 0.04$$

$$(x_{Bj} \simeq (0.3 - 1.4) \cdot 10^{-4})$$

Impulse approximation: STARLIGHT, no nuclear effects except coherence

Caveat: there are sophistications, see Eskola et al. 2203.11613

ALICE, JHEP 05 (2021) 220: $\frac{\mathrm{d}\sigma_{\mathrm{b\bar{b}}}}{\mathrm{d}y} = 34.5 \pm 2.4(stat)^{+4.7}_{-2.9}(tot.syst)\mu\mathrm{b}$



FONLL, Caccciari et al., JHEP 1210 (2012)

scaling for y=2.5–4

Shadowing: 0.7, independent on y

$y = 0: \frac{\mathrm{d}N_{\mathrm{b\bar{b}}}}{\mathrm{d}y} = 0.57$

$\pm$20% total uncertainty

All produced anew ...no Υ state survives in QGP (extreme for $\Upsilon(1S)$?)

Core(SHMb)-corona with pp data input CMS, PLB 790 (2019) 270, ALICE, arXiv:2109.15240