The statistical hadronization model for heavy quarks

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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

The statistical (thermal) model

grand canonical partition function for specie (hadron) i :

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

$g_i = (2J_i + 1)$ 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%

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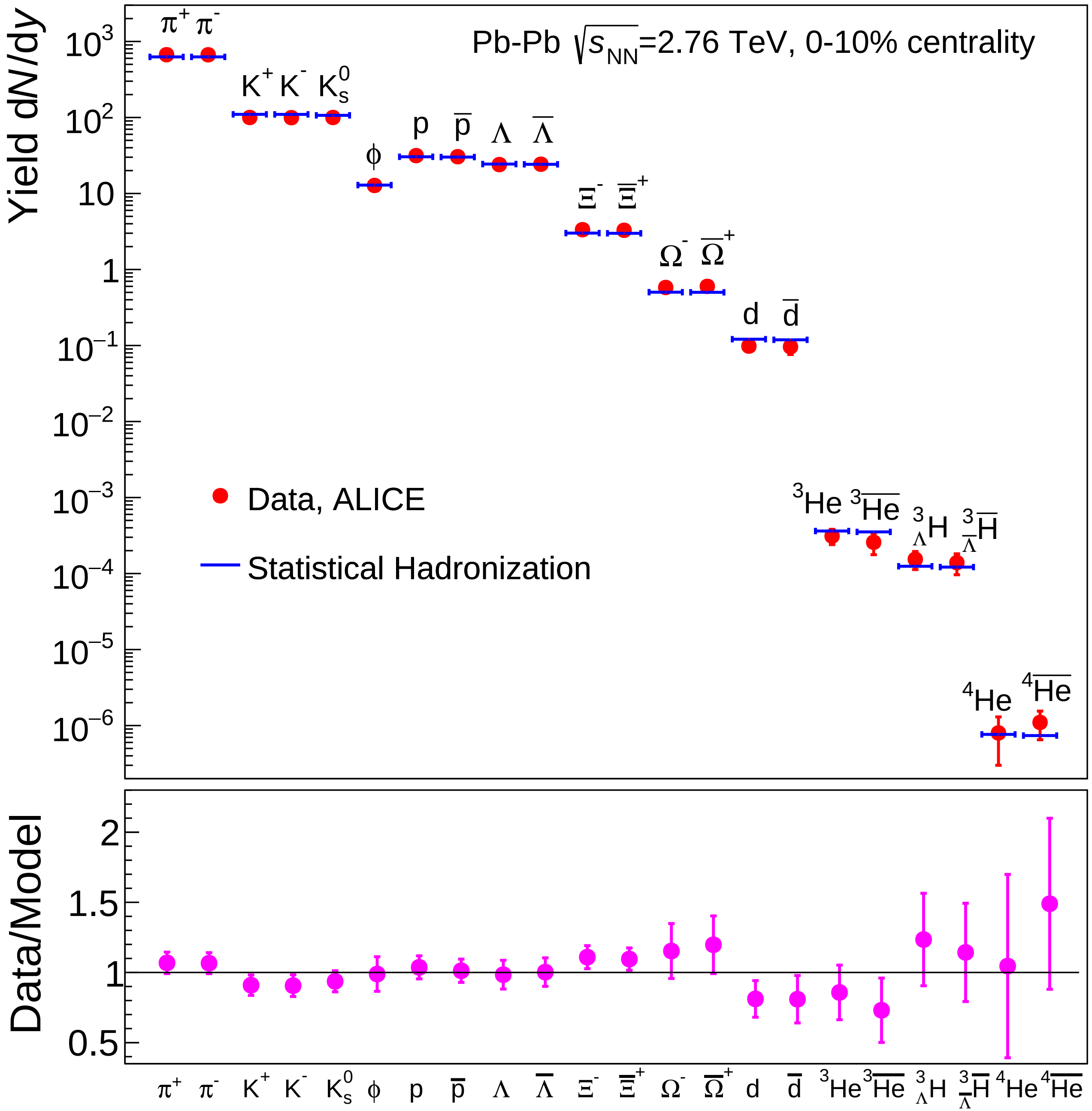


matter and antimatter produced in equal amounts

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

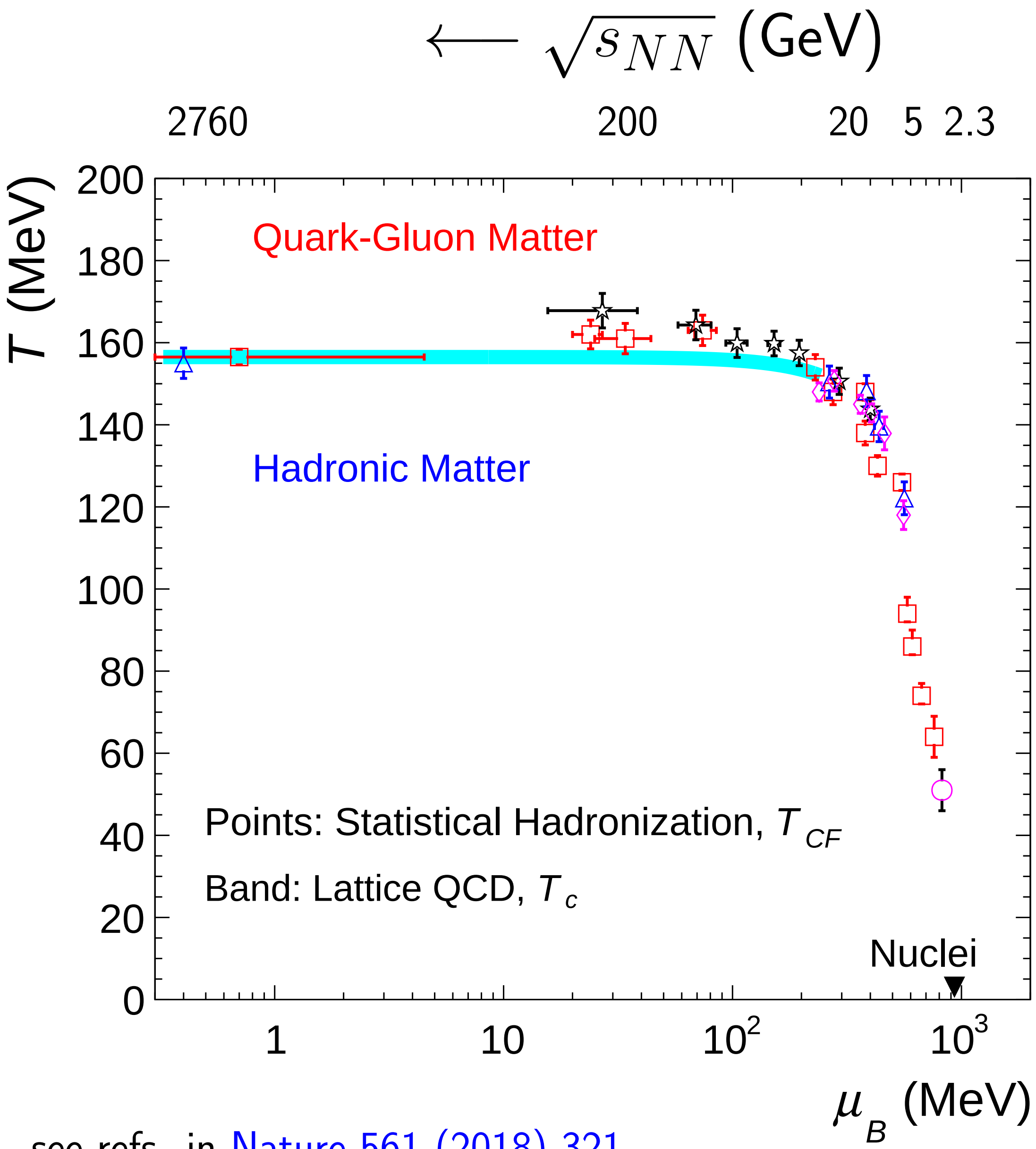
$\chi^2/N_{df} = 16.7/19$

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



see refs. in Nature 561 (2018) 321

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)

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

SHM for charm (SHMc)

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

LHC, central collisions

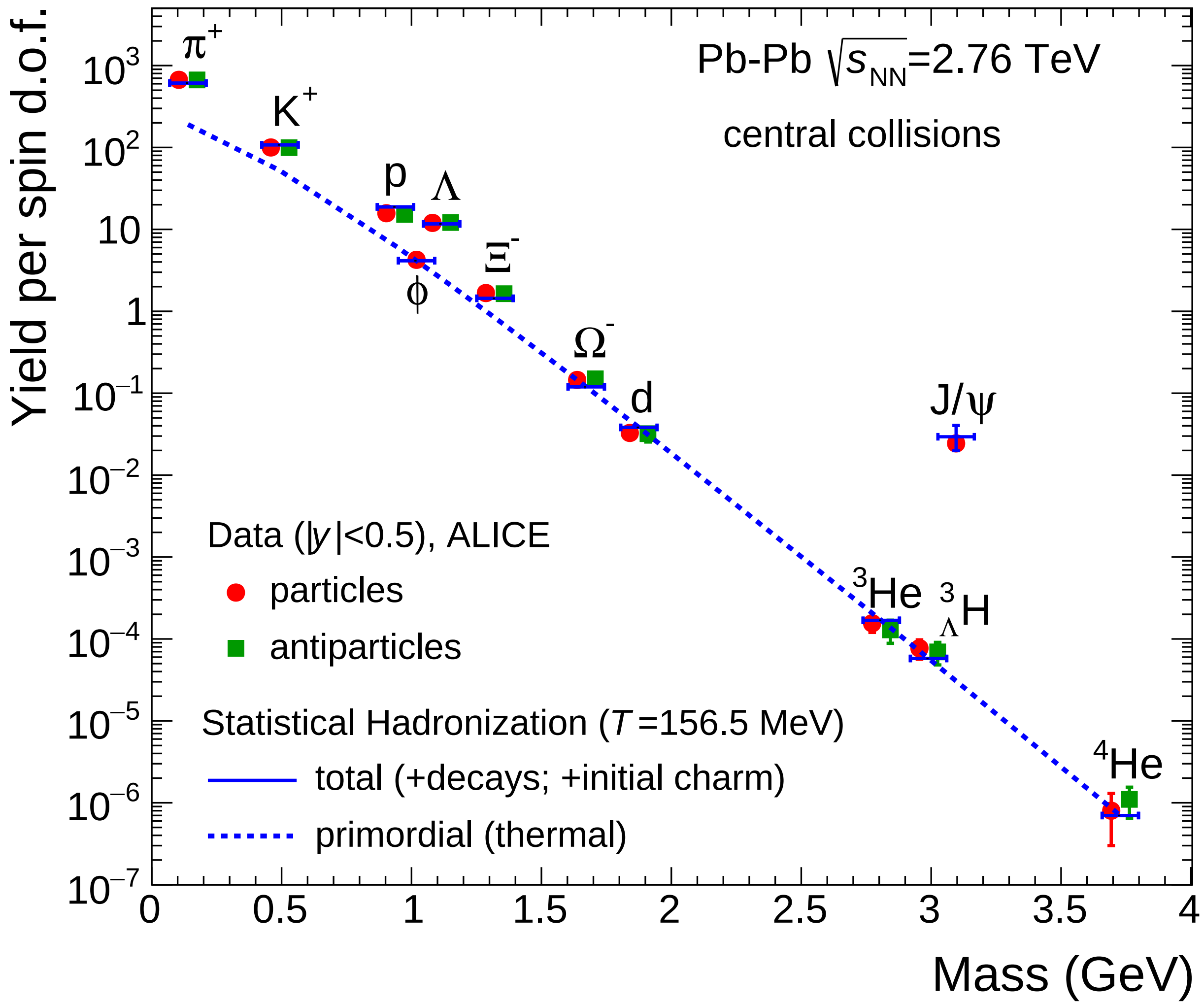
assume:

- full thermalization of $c, \bar{c}$ ("mobility" in V$\simeq$4000 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: $\rightarrow n_X^{th}$

- $N_{c\bar{c}}^{dir} = \frac{1}{2} g_c V (\sum_i n_{D_i}^{th} + n_{\Lambda_i}^{th}) + g_c^2 V (\sum_i n_{\psi_i}^{th} + n_{\chi i}^{th})$

- $N_{c\bar{c}} << 1 \rightarrow$<u>Canonical</u> (Cleymans, Redlich, Suhonen, Z. Phys. C51 (1991) 137):

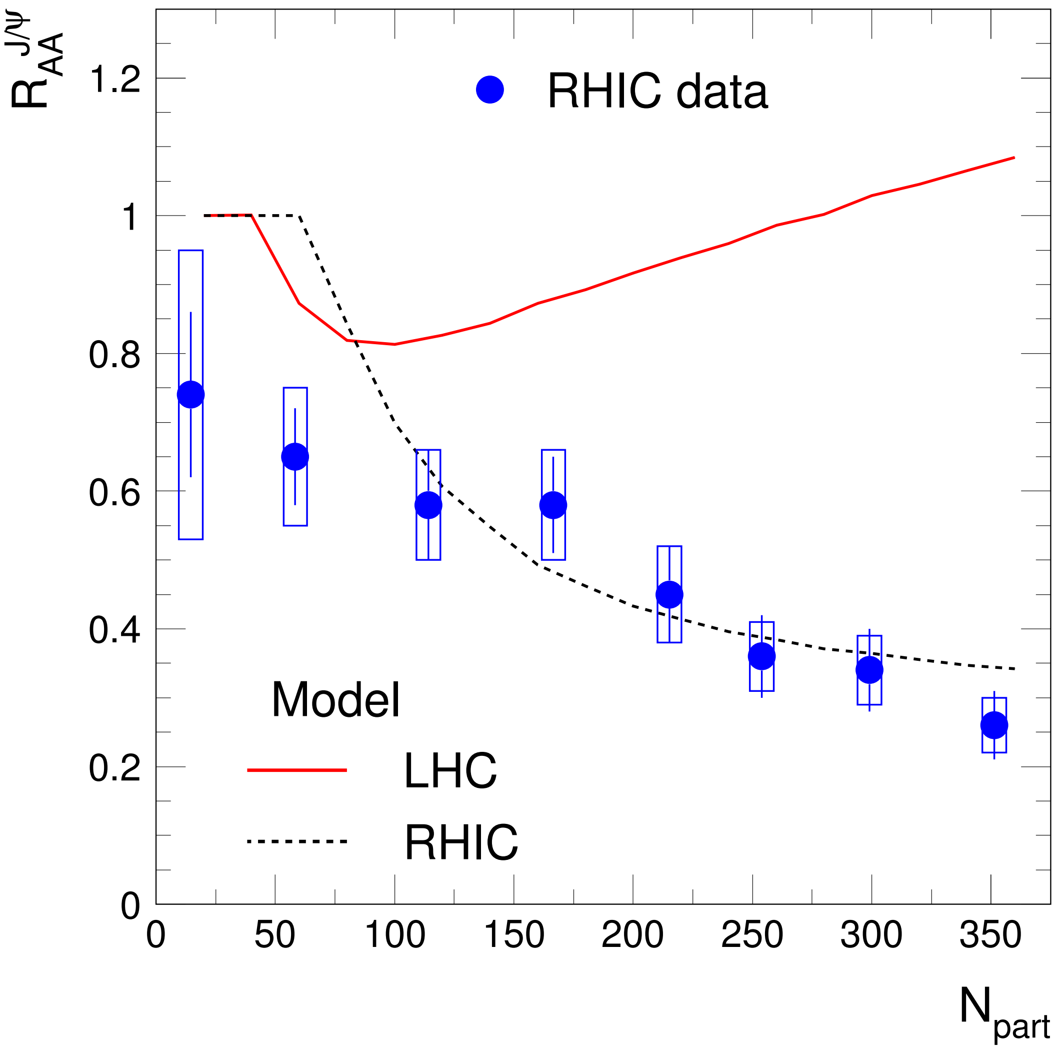
Gorenstein, Kostyuk, Stöcker, Greiner, PLB 509 (2001) 277

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

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

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



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

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

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

What is so different at LHC?

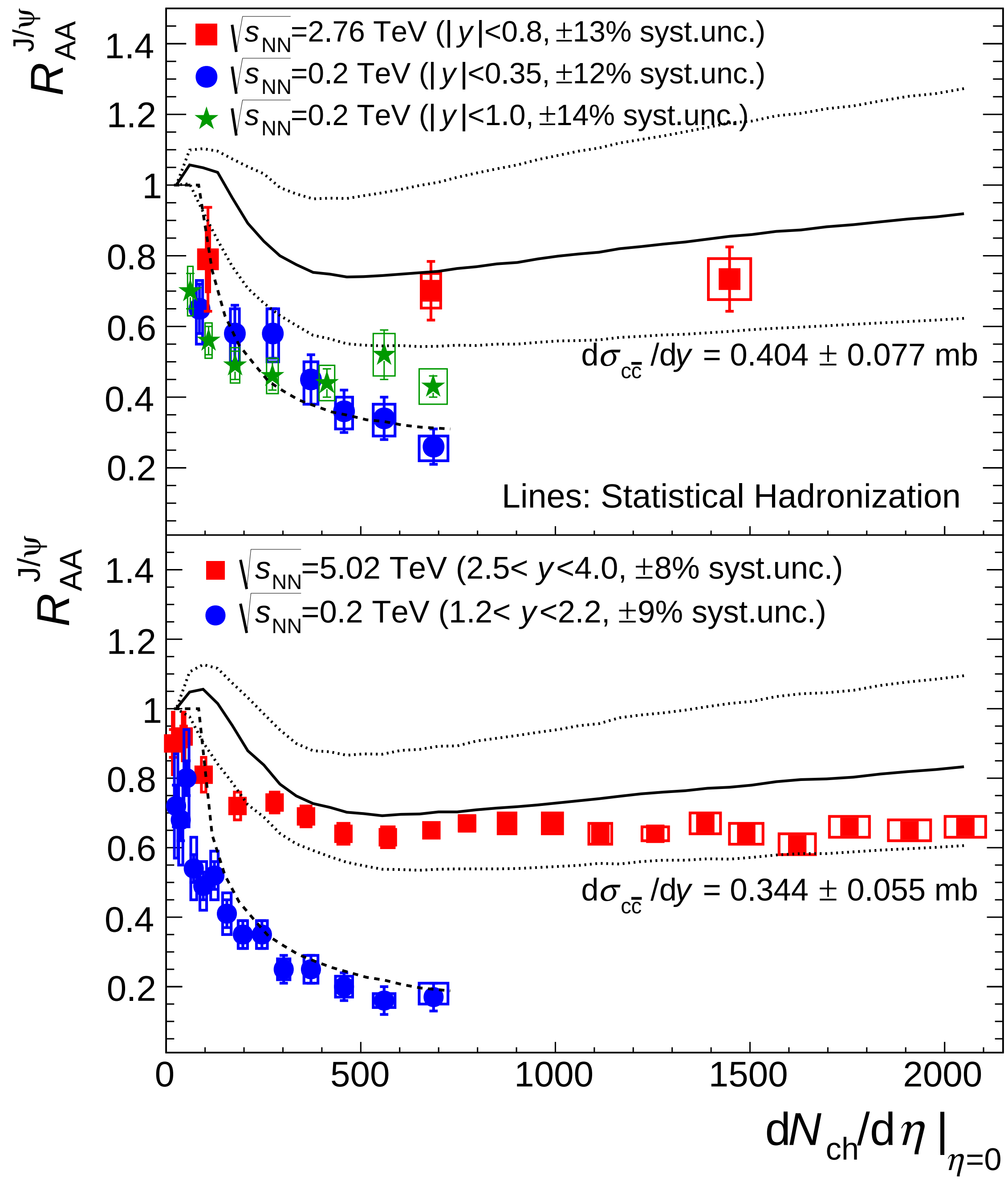
(compared to RHIC)

$\sigma_{c\bar{c}}$: ~10x, Volume: 2-3x

PLB 652 (2007) 259

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

Charmonium data at RHIC and the LHC



- "suppression" at RHIC (PHENIX)
- dramatically different at the LHC

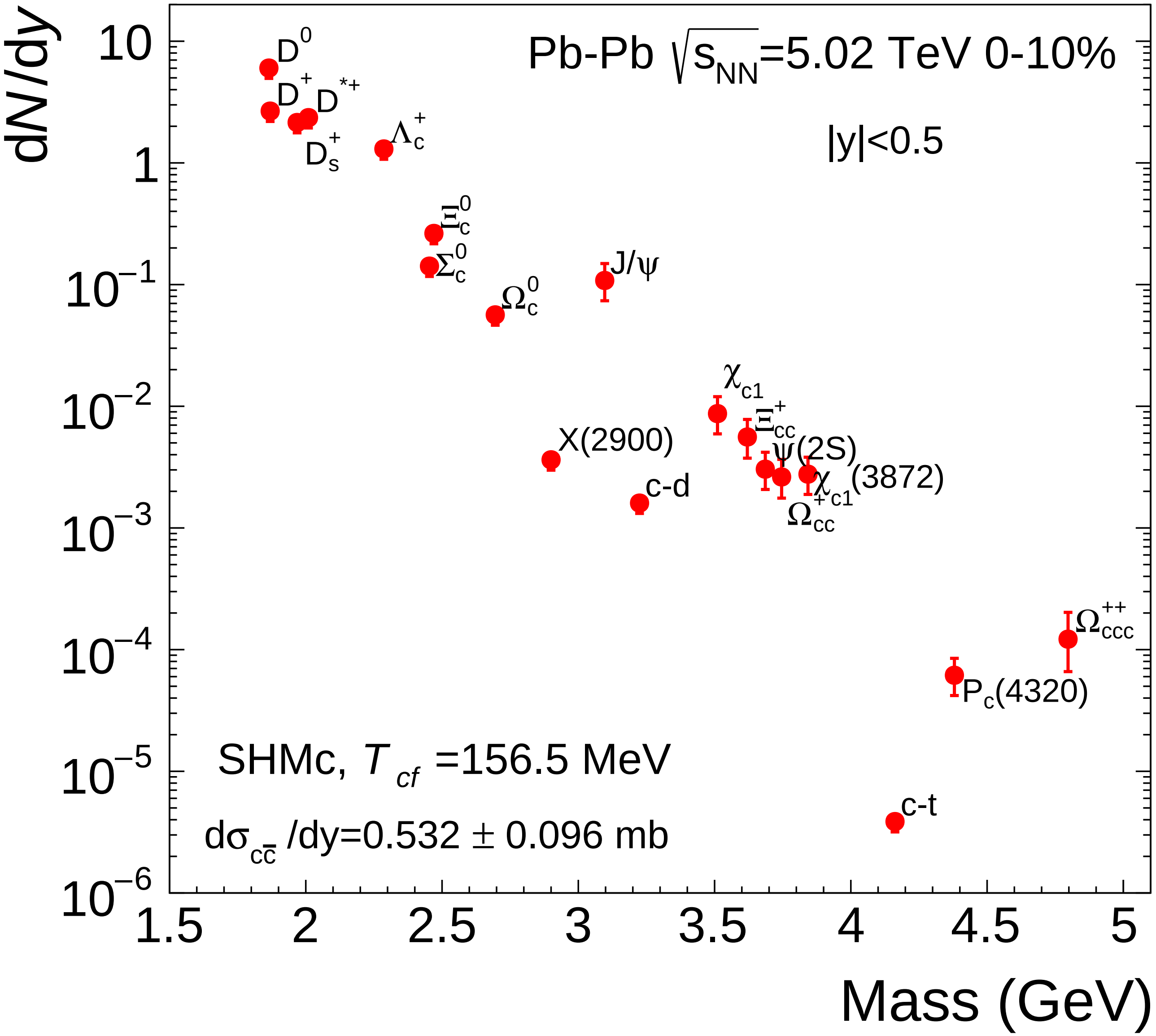
J/ψ is another observable (charm) for the phase boundary

calculations are for T=156 MeV

$\sigma_{c\bar{c}}$: current knowledge at LHC (data in pp, p–Pb; ALICE, LHCb)

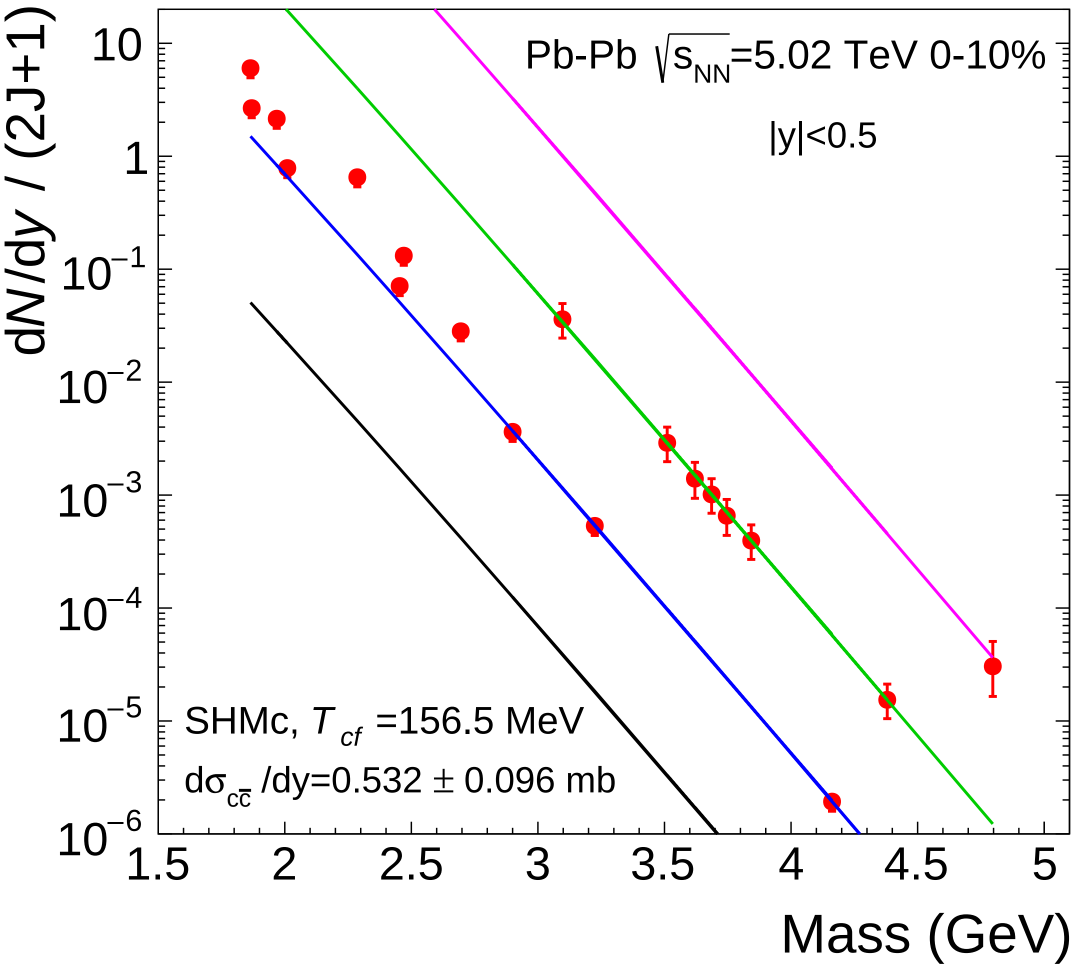
$\mathrm{d}N_{ch}/\mathrm{d}\eta \sim \varepsilon$

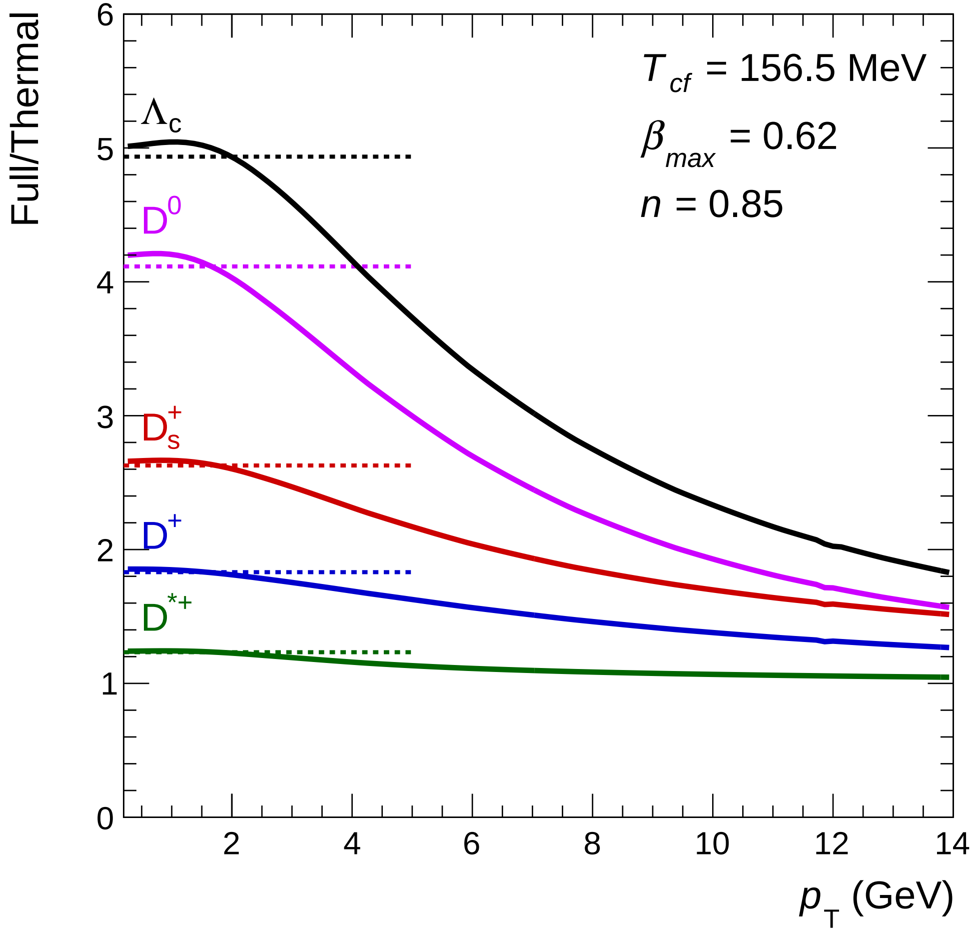
(>20 GeV/fm^3, for $\mathrm{d}N_{ch}/\mathrm{d}\eta \simeq 2000$)



We do have predictions for different collision systems and y ranges (+30-50%)

Full charm predictions for the LHC





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

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

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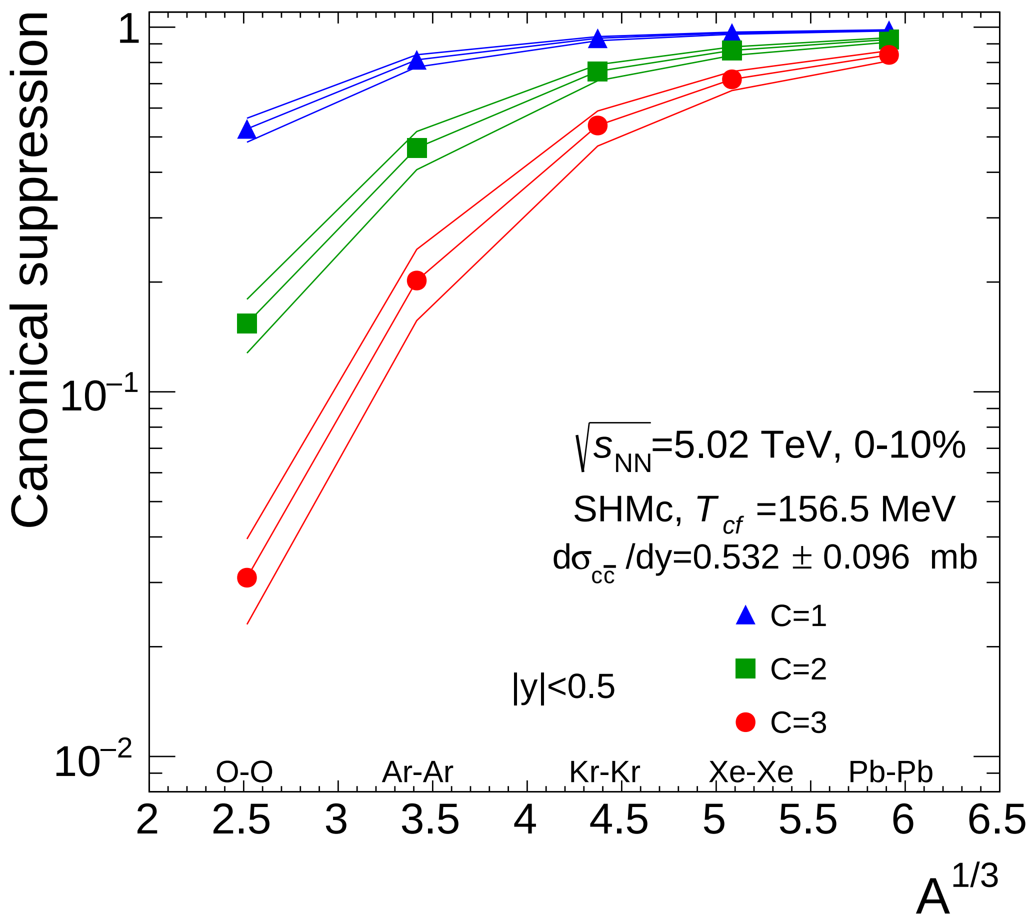
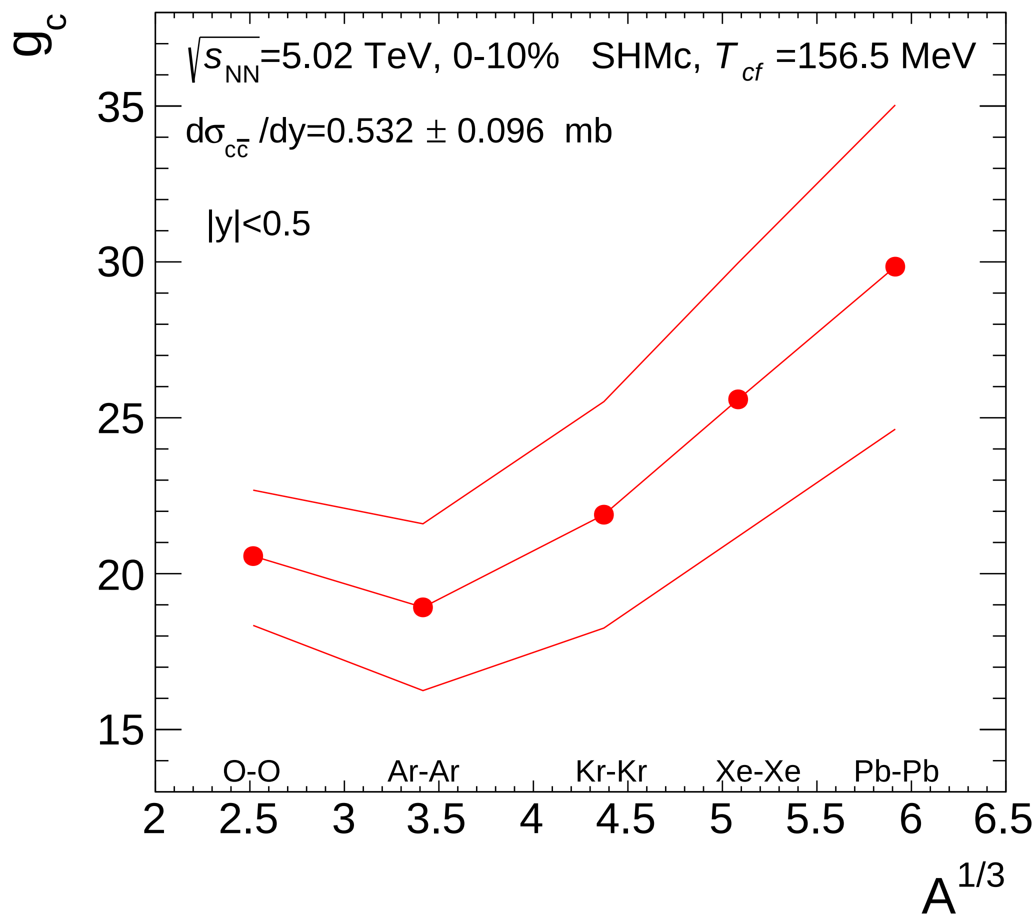
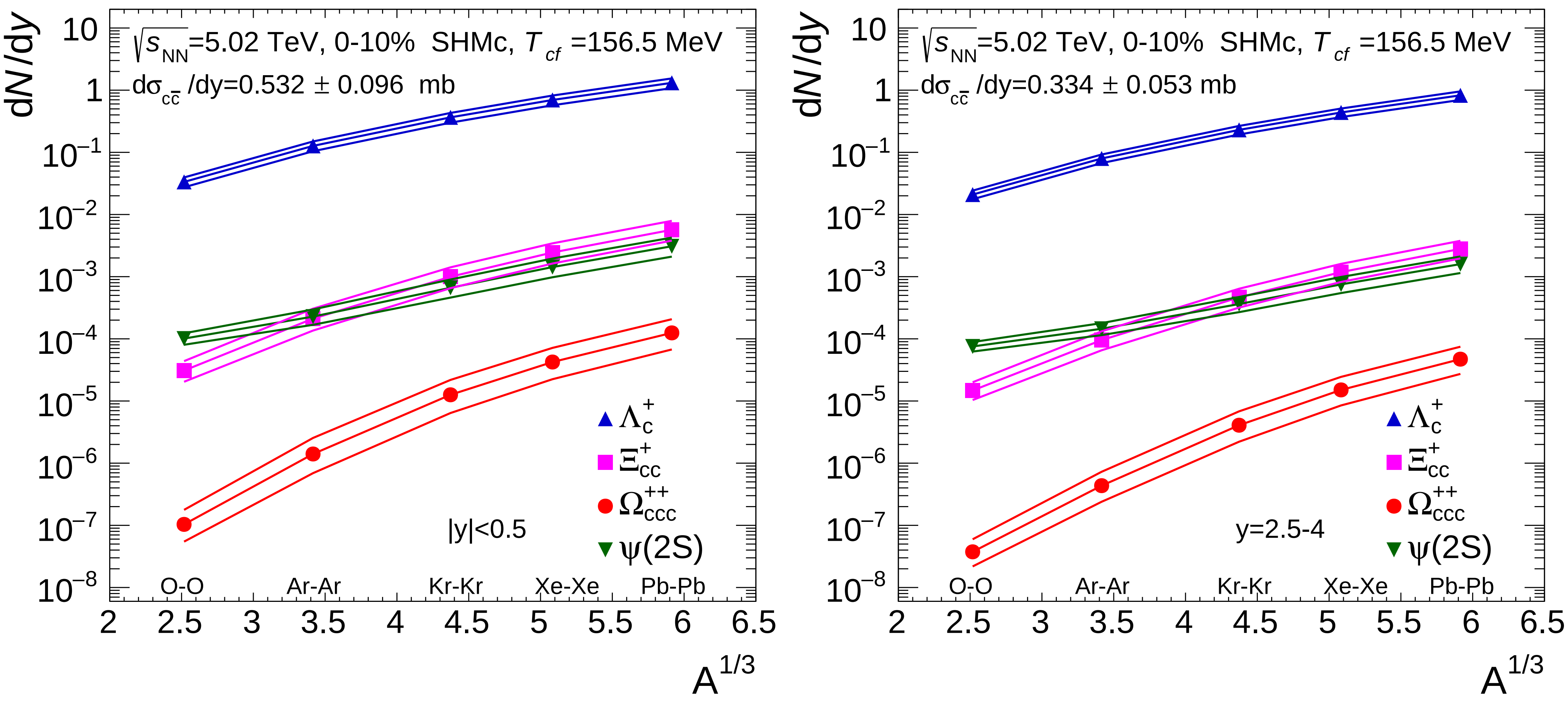


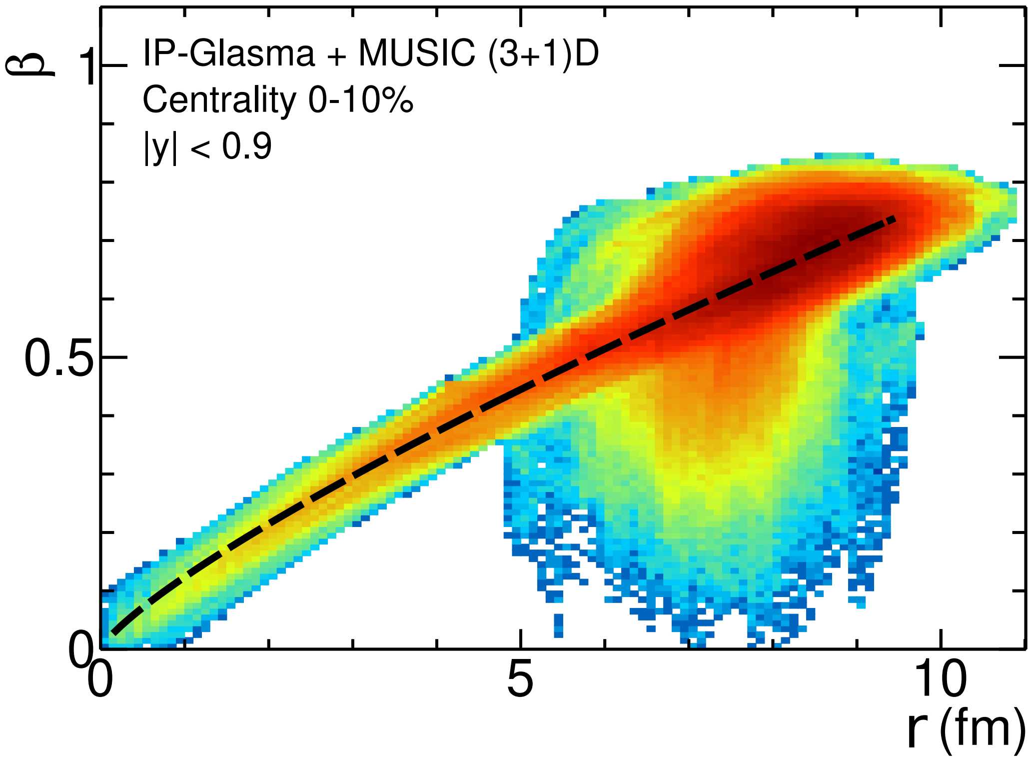


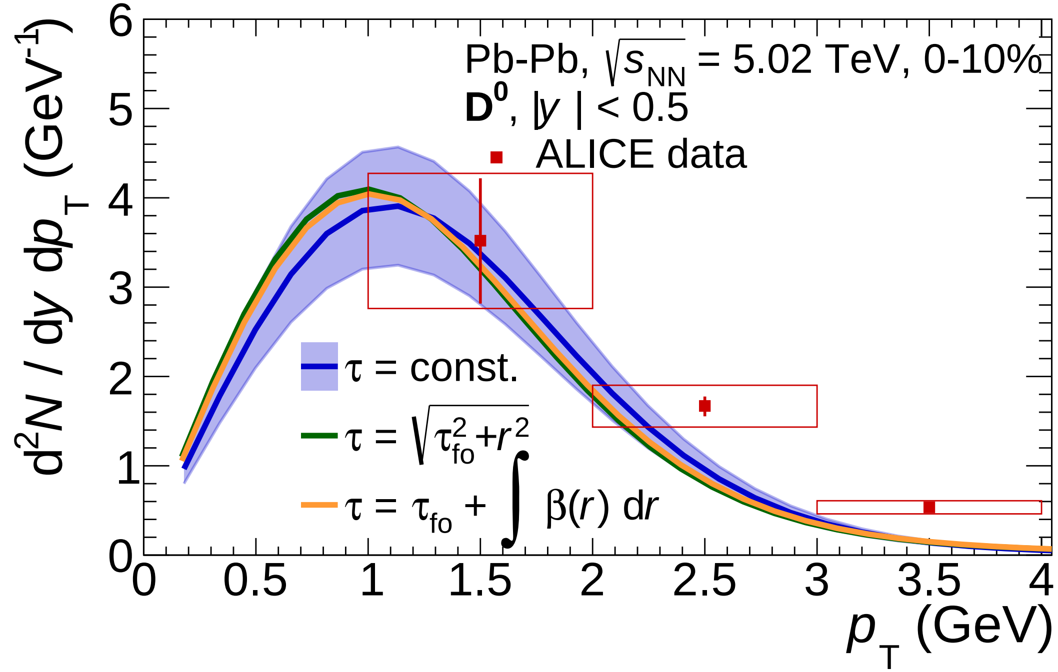
Strong canonical suppression for light systems (for multi-charm hadrons)

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



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

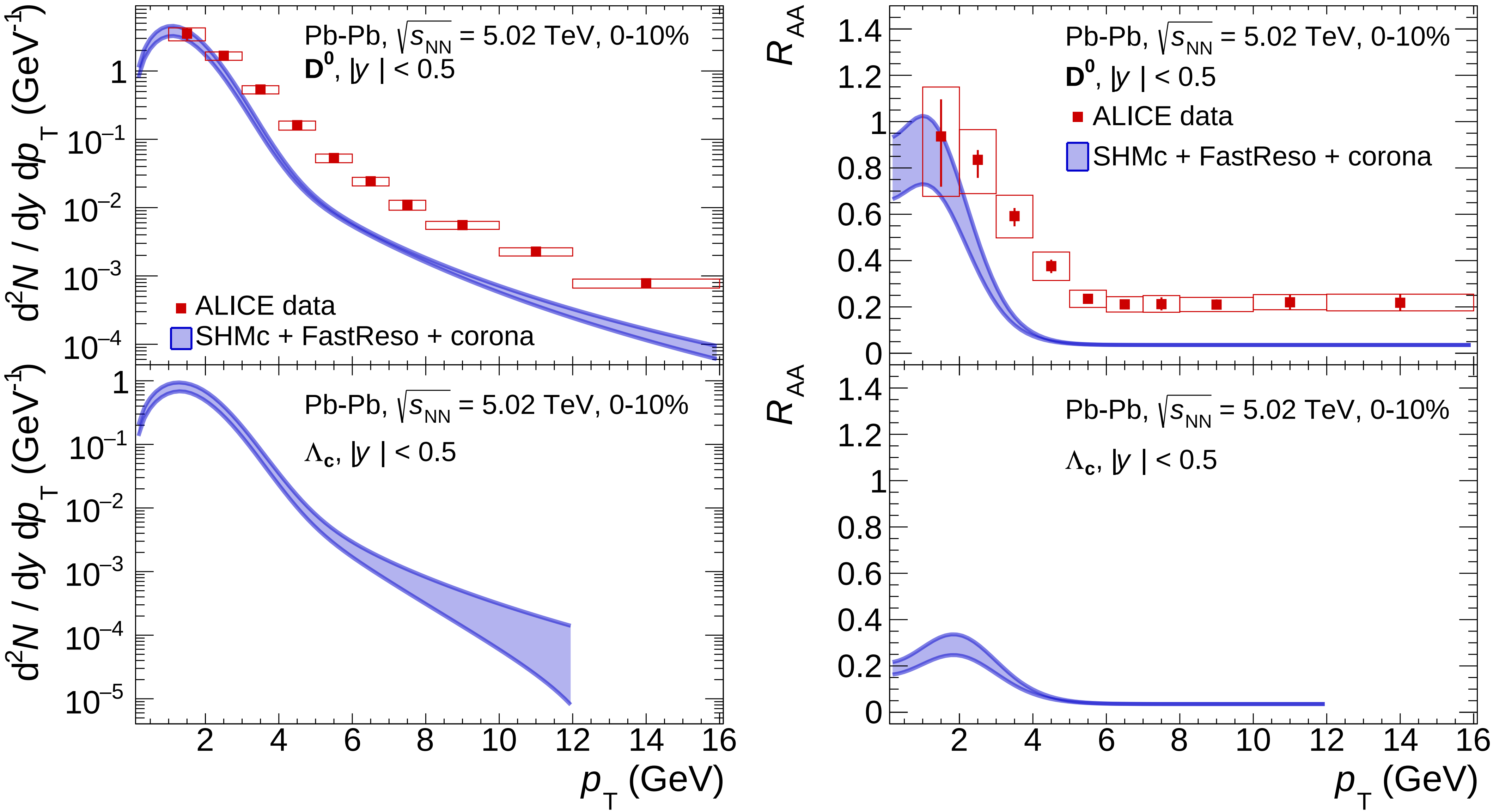




$$\frac{\mathrm{d}^2 N}{2\pi p_\mathrm{T} dp_\mathrm{T} dy} = \frac{2J+1}{(2\pi)^3}\int \mathrm{d}\sigma_\mu p^\mu f(p) = \frac{2J+1}{(2\pi)^3}\int_0^{r_\mathrm{m}} \mathrm{d}r\ \tau(r) r \left[K_1^{\mathrm{eq}} - \frac{\partial \tau}{\partial r} K_2^{\mathrm{eq}}\right]$$

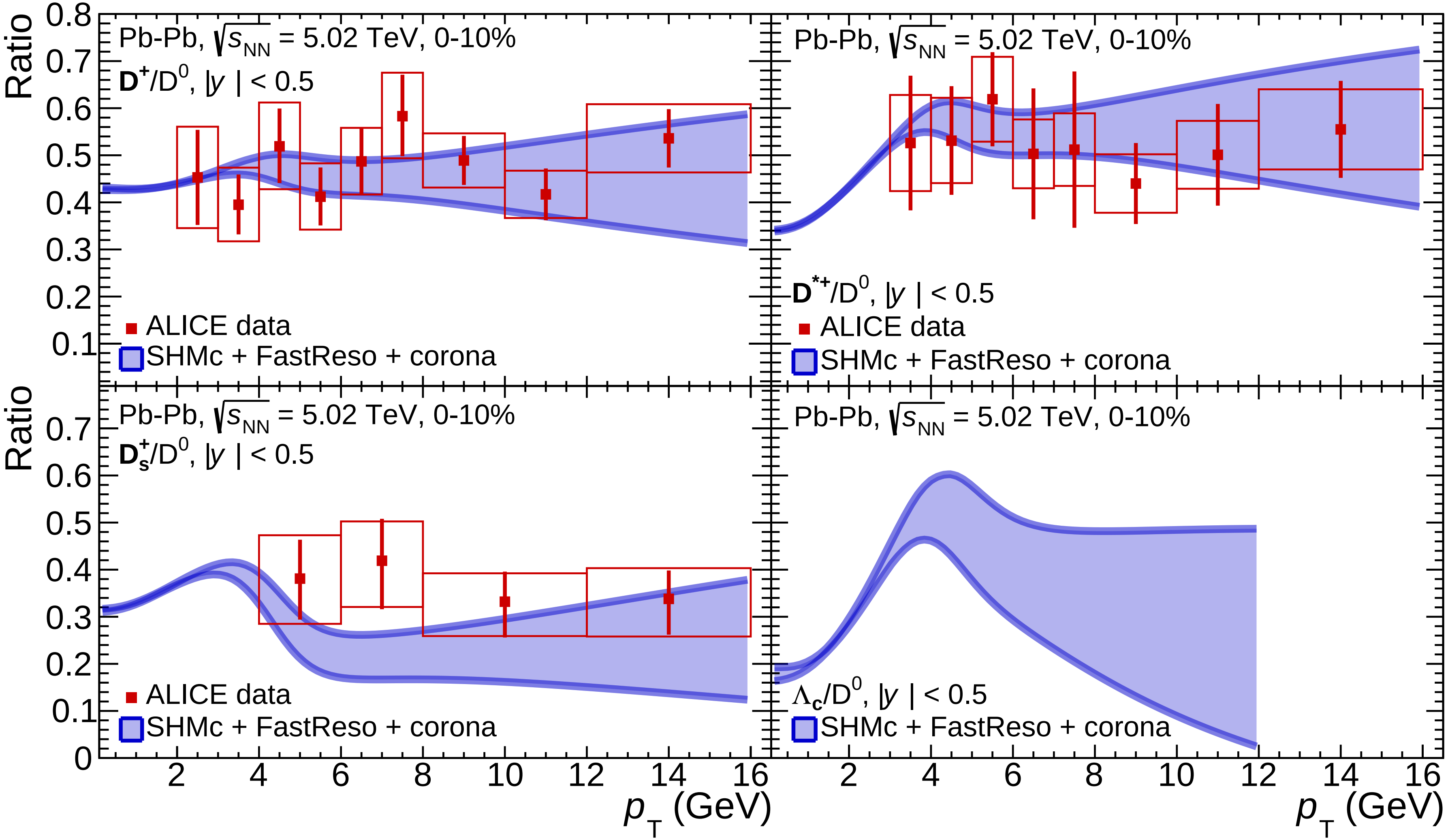
$$K_1^{\mathrm{eq}}(p_\mathrm{T}, u^r) = 4\pi m_\mathrm{T} I_0\left(\frac{p_\mathrm{T} u^r}{T}\right) K_1\left(\frac{m_\mathrm{T} u^\tau}{T}\right),\ \ K_2^{\mathrm{eq}}(p_\mathrm{T}, u^r) = 4\pi p_\mathrm{T} I_1\left(\frac{p_\mathrm{T} u^r}{T}\right) K_0\left(\frac{m_\mathrm{T} u^\tau}{T}\right)$$

SHMc: p_T dependence

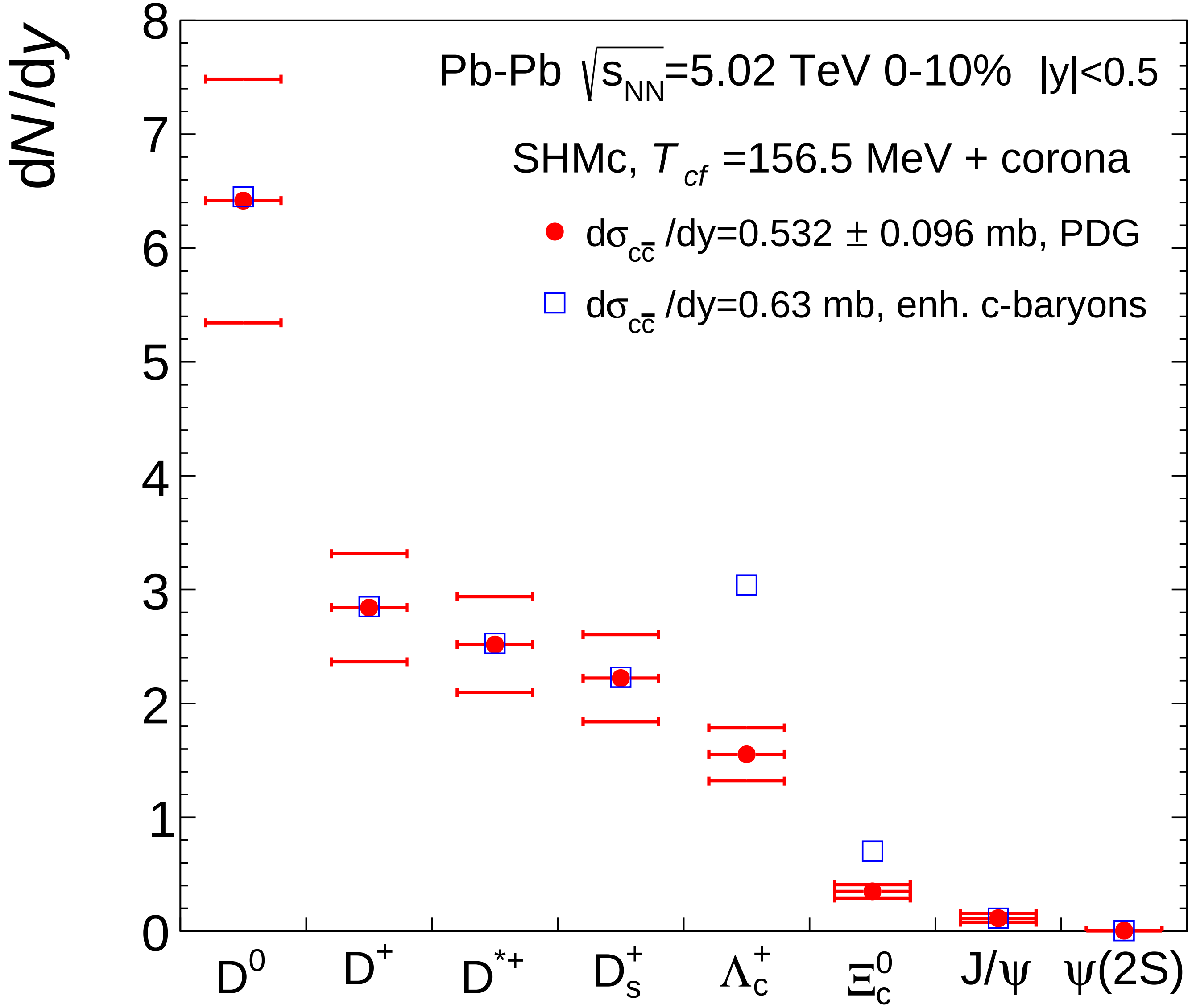


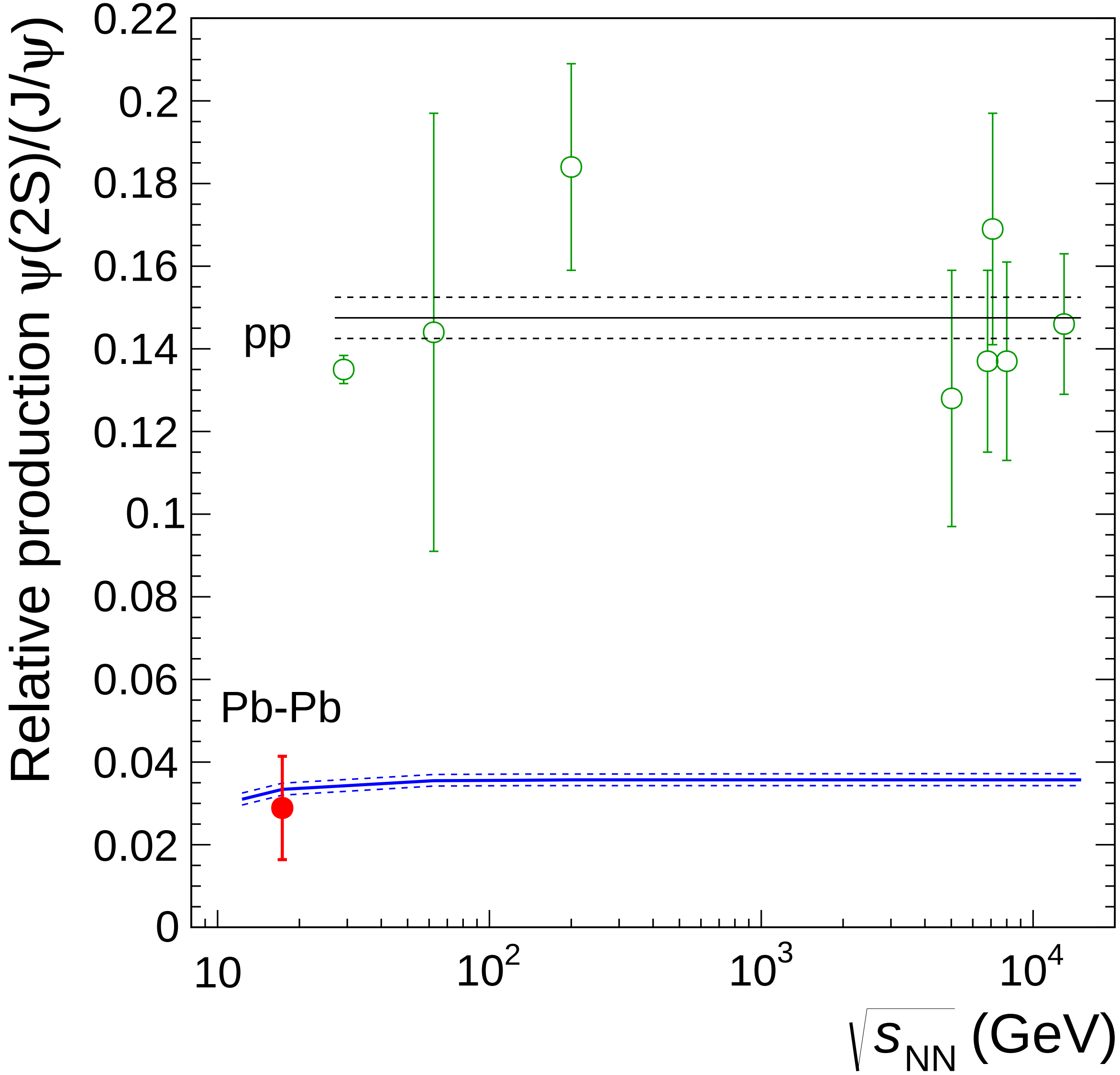
Nuclear-corona contribution added whenever pp measurements available

Ratios to D^0


Ratio
Pb-Pb, √sNN = 5.02 TeV, 0-10%
D+/D0, |y| < 0.5
ALICE data
SHMc + FastReso + corona
Pb-Pb, √sNN = 5.02 TeV, 0-10%
D*+/D0, |y| < 0.5
ALICE data
SHMc + FastReso + corona
Ratio
Pb-Pb, √sNN = 5.02 TeV, 0-10%
Ds+/D0, |y| < 0.5
ALICE data
SHMc + FastReso + corona
Pb-Pb, √sNN = 5.02 TeV, 0-10%
Λc/D0, |y| < 0.5
SHMc + FastReso + corona
pT (GeV)
pT (GeV)

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





...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

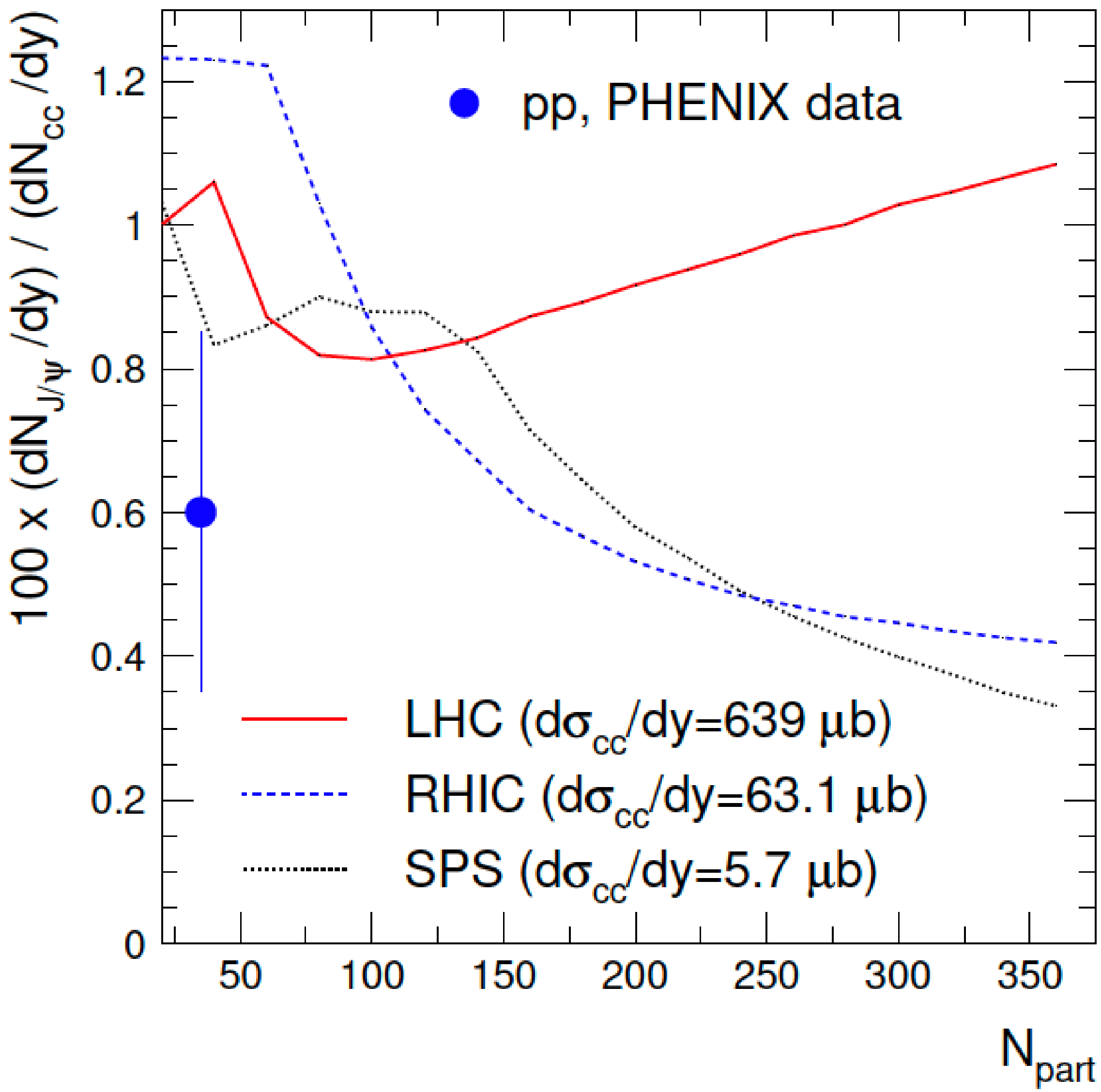
Braun-Munzinger, Stachel, PLB 490 (2000) 196

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

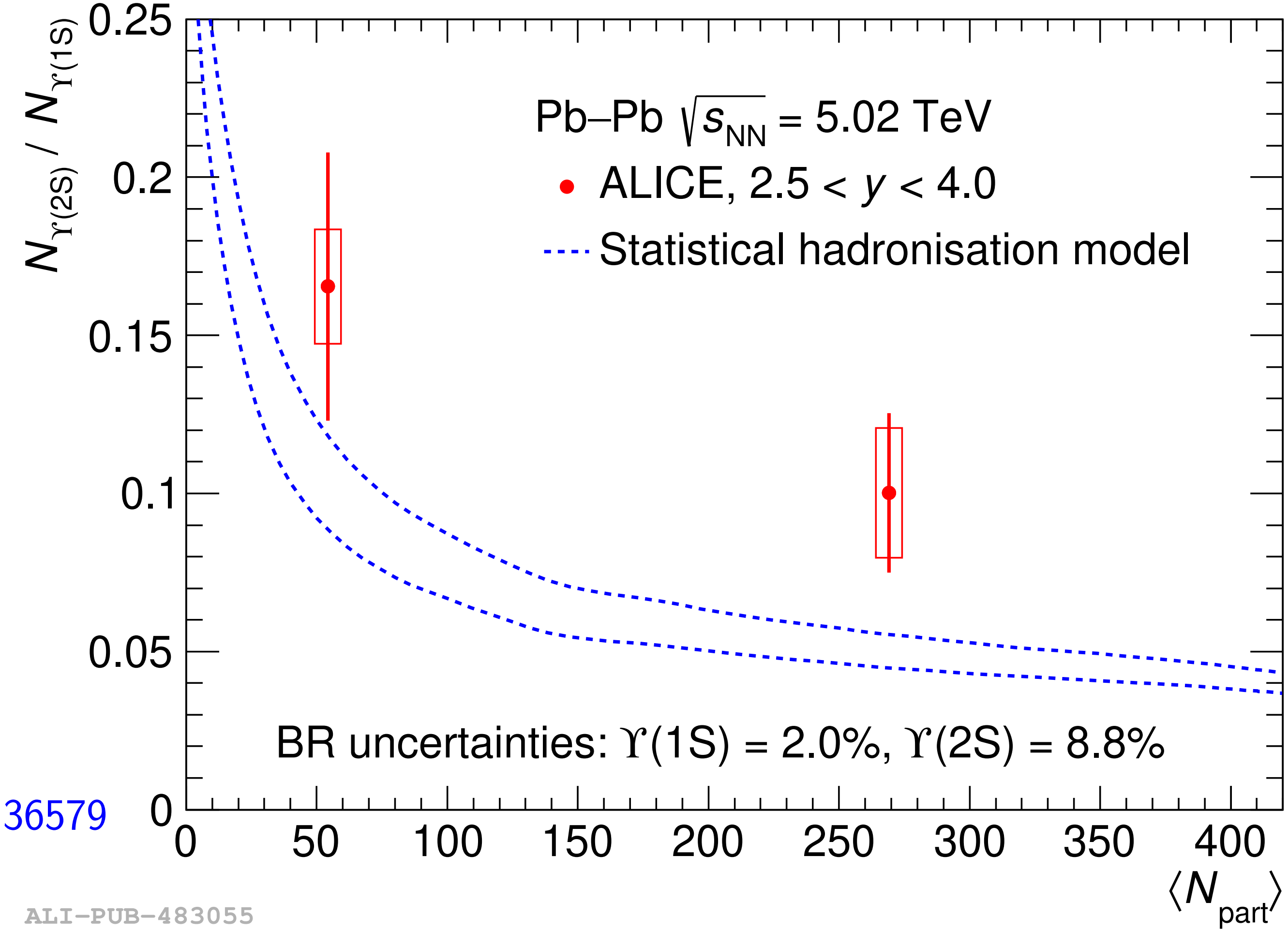
  ...determined by canonical suppression of open charm

- enhancement-like at LHC

  can. suppr. lifted, quadratic term dominant

Beauty is expected (data: scarce) to be less thermalized compared to charm

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

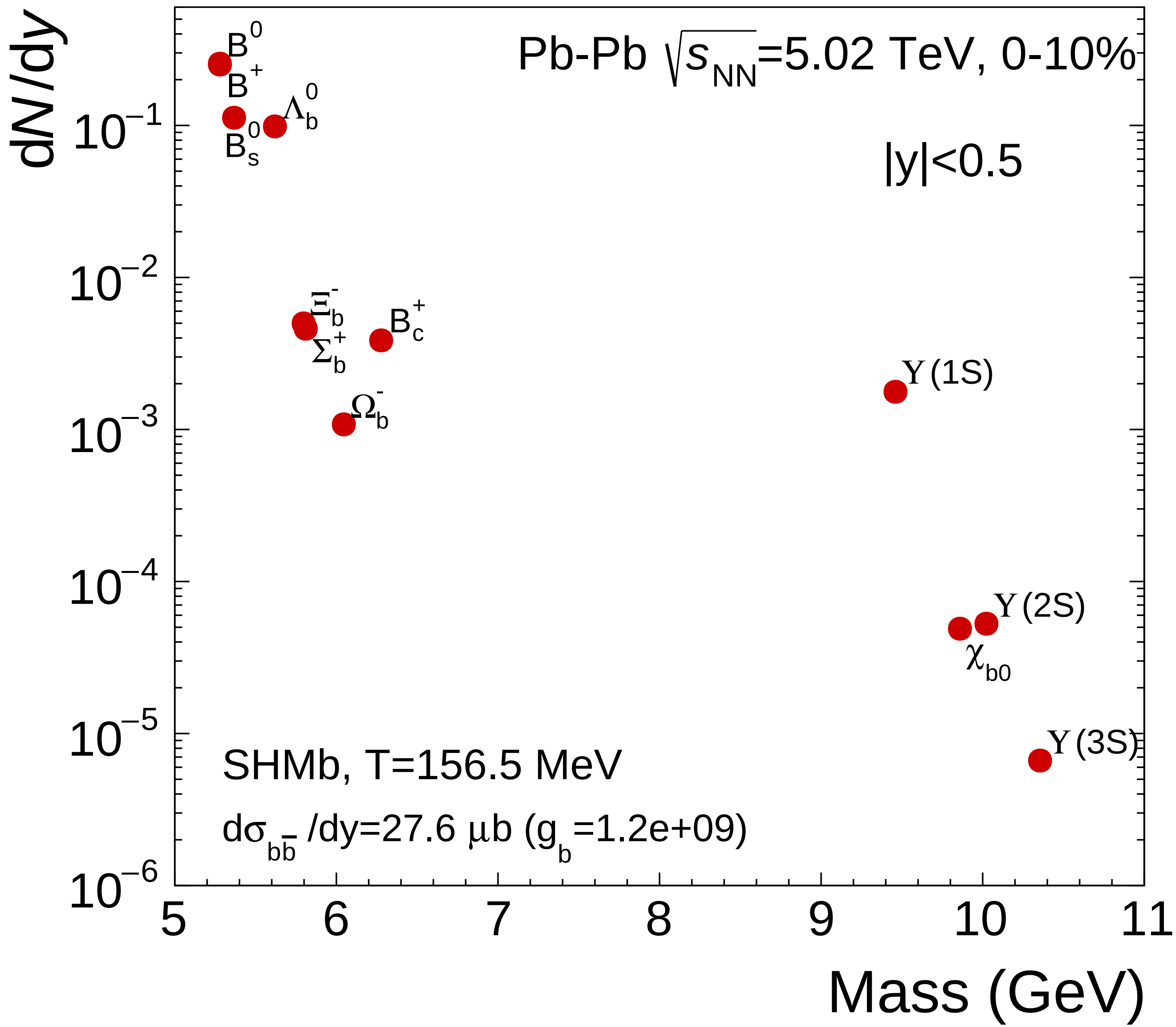


ALICE, PLB 822 (2021) 136579

Color screening may not destroy all ϒ mesons in QGP

Uncertainty band determined by nuclear-corona

The limiting case: full beauty thermalization



Summary / Conclusions

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

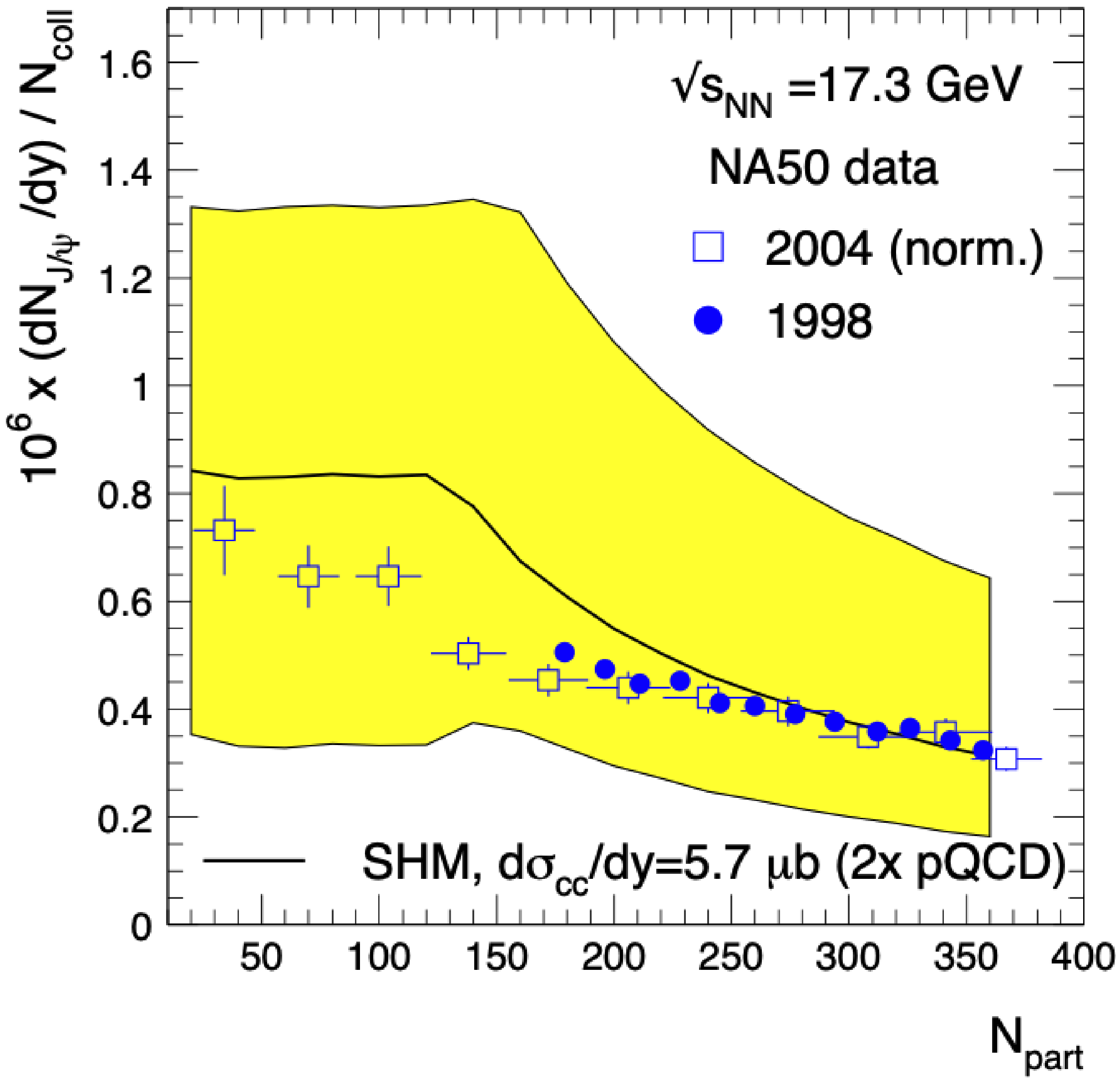
In the (our)statistical hadronization model:

- The hadronization is a rapid process in which all quark flavors take part concurrently
- Beauty may be only partially ($\sim$50%?) thermalized
- Υ states may not be fully destroyed by color screening in QGP

$\rightarrow$ consequently, our predictions in the beauty sector are upper limits

Extra slides

J/ψ production at SPS and SHMc



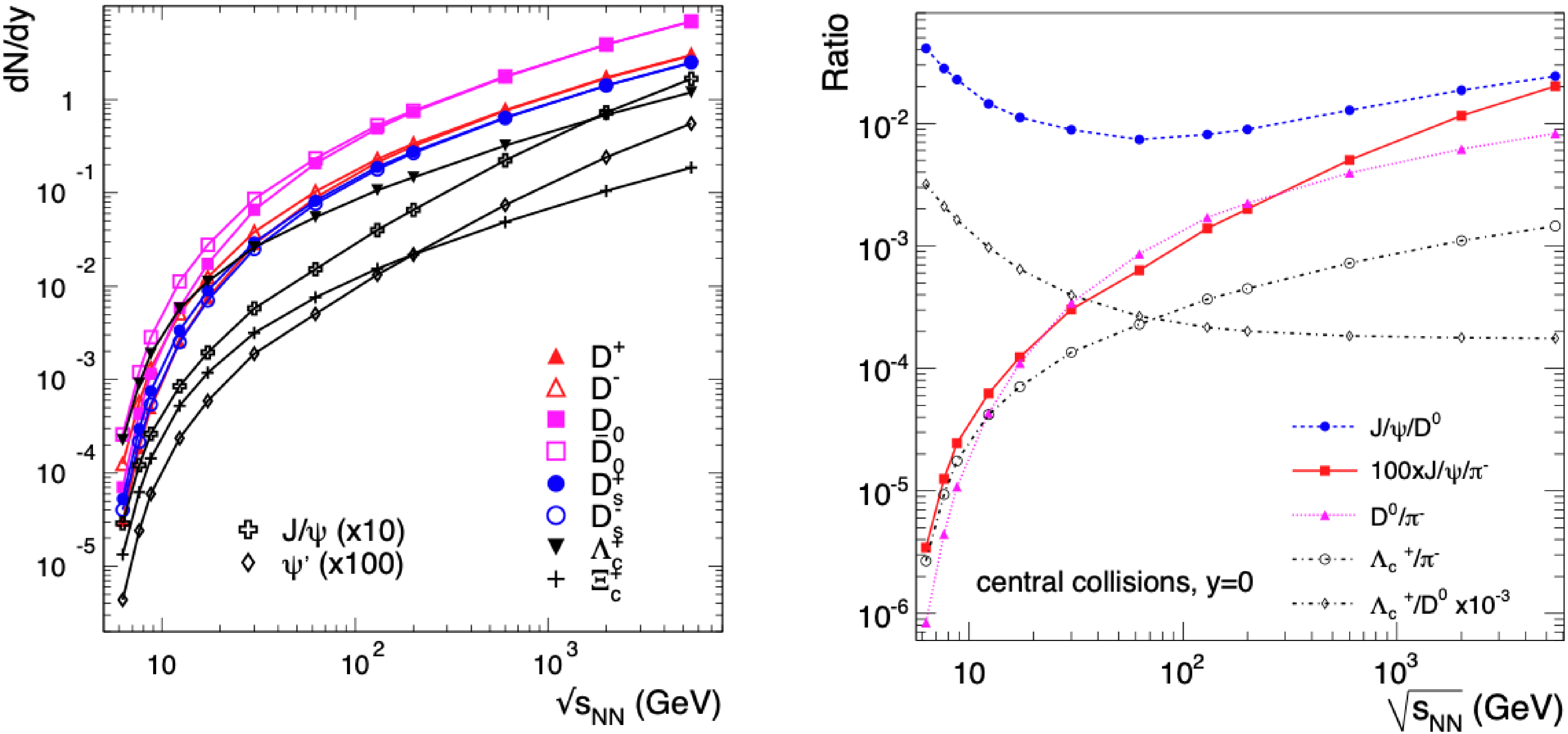
NPA 789 (2007) 334

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 $\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y$

Charm chemistry at lower energies

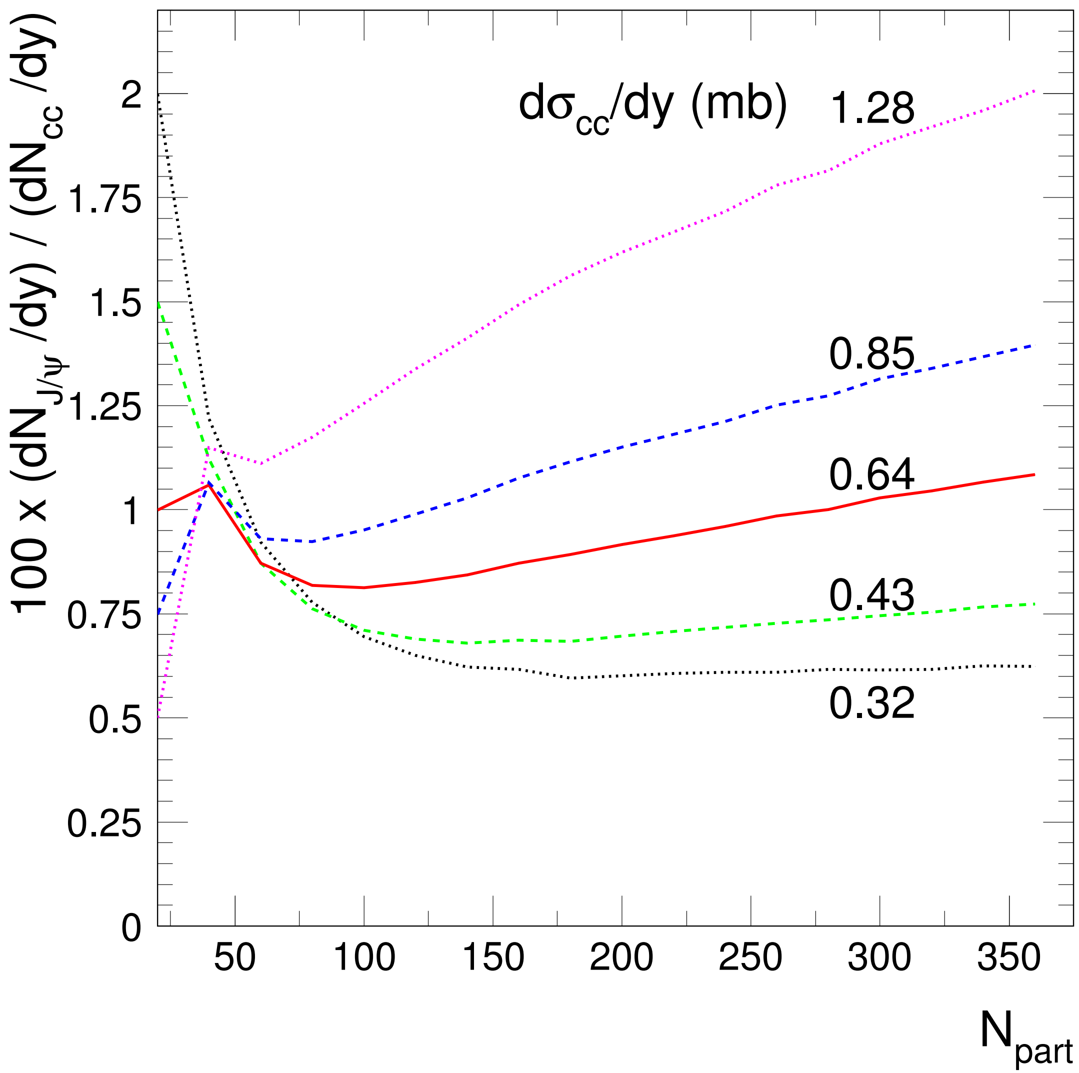


AA, Braun-Munzinger, Redlich, Stachel, JPG 37 (2010) 094014

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

There are non-monotonic ratios (J/ψ/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

The charm production cross section at the LHC

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

  pp 5 TeV, JHEP 06 (2017) 147

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

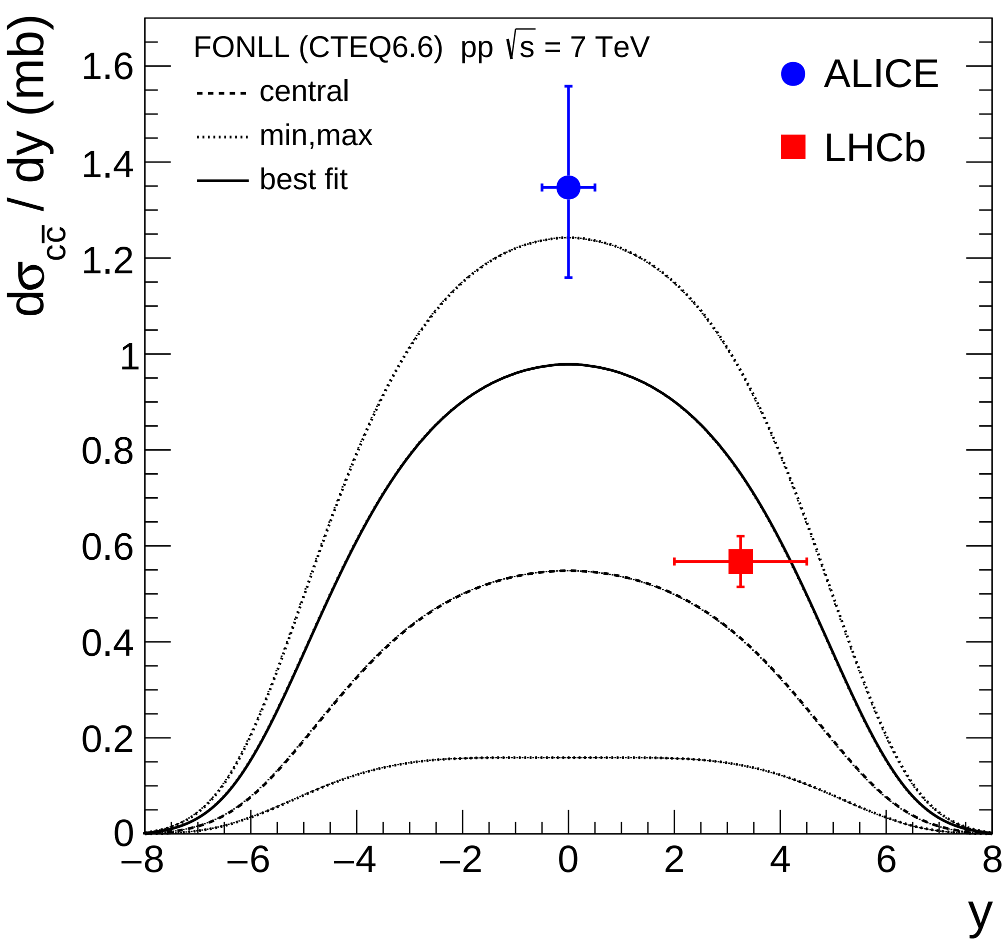
  $\frac{\mathrm{d}\sigma_{c\bar{c}}}{\mathrm{d}y} = 1.165 \pm 0.044(stat) \pm 0.065(syst)^{+.098}_{-.038}(extr) \pm 0.043(BR) \pm 0.042(RS) \pm 0.024(lumi)$ mb

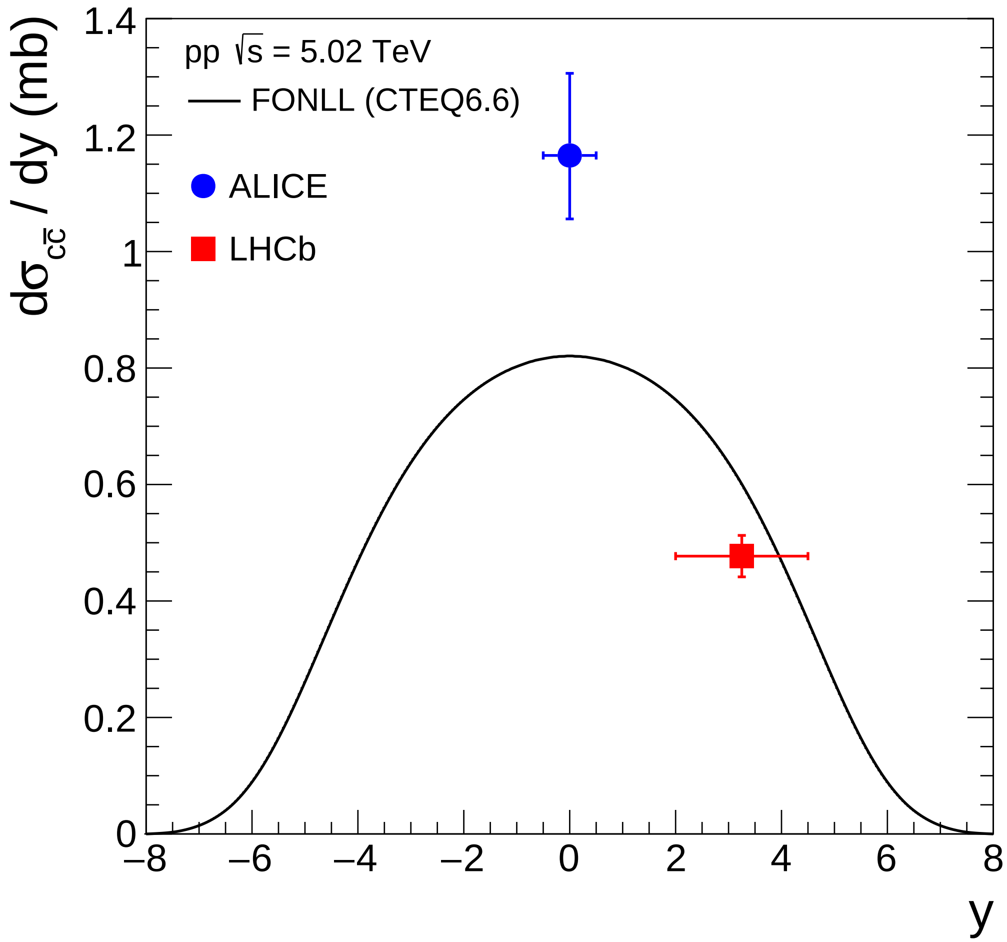
$$\Lambda_c/D^0 = 0.51 \pm 0.06$$

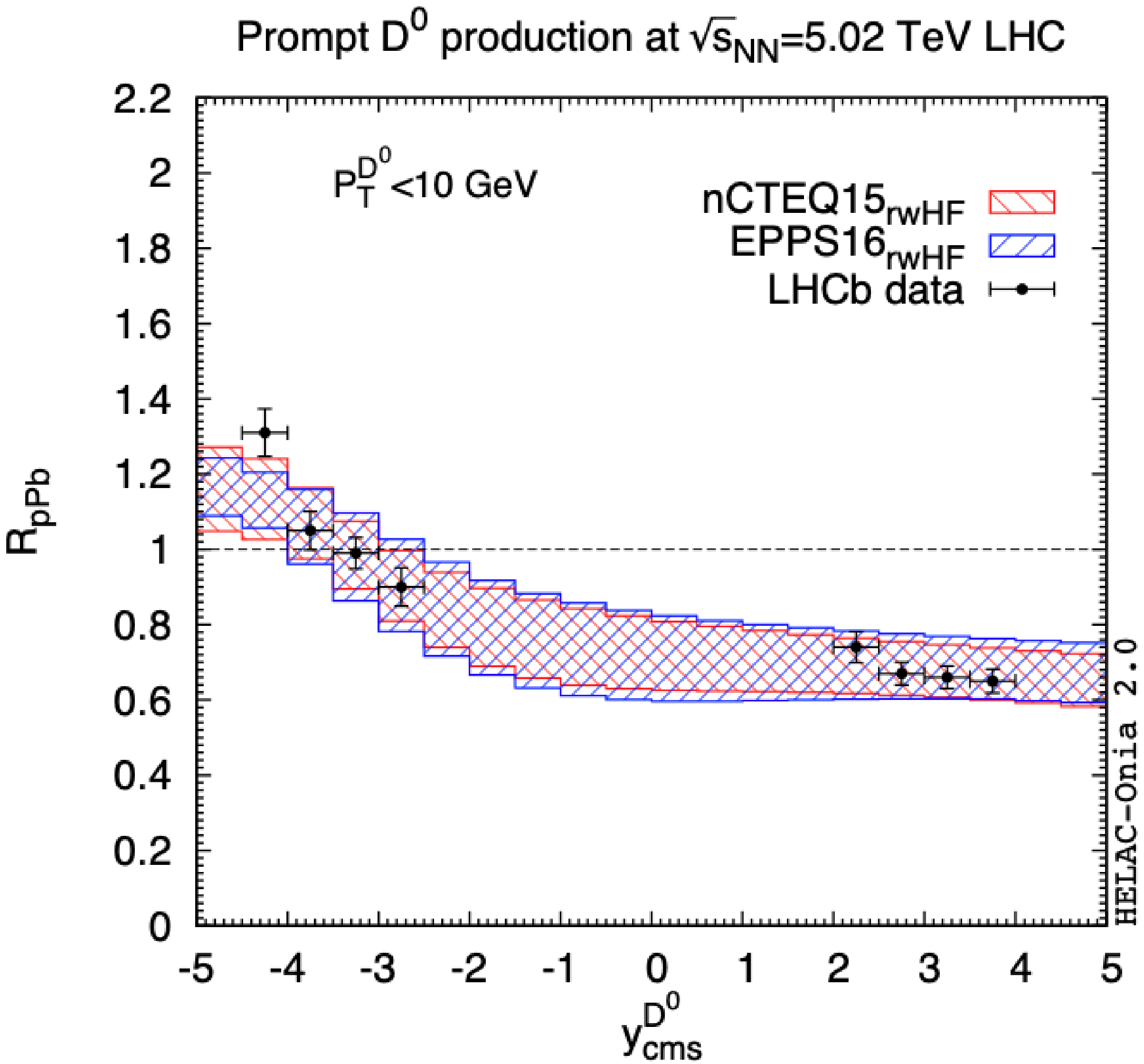
  pp 7 TeV, JHEP 04 (2018) 108

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

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







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):

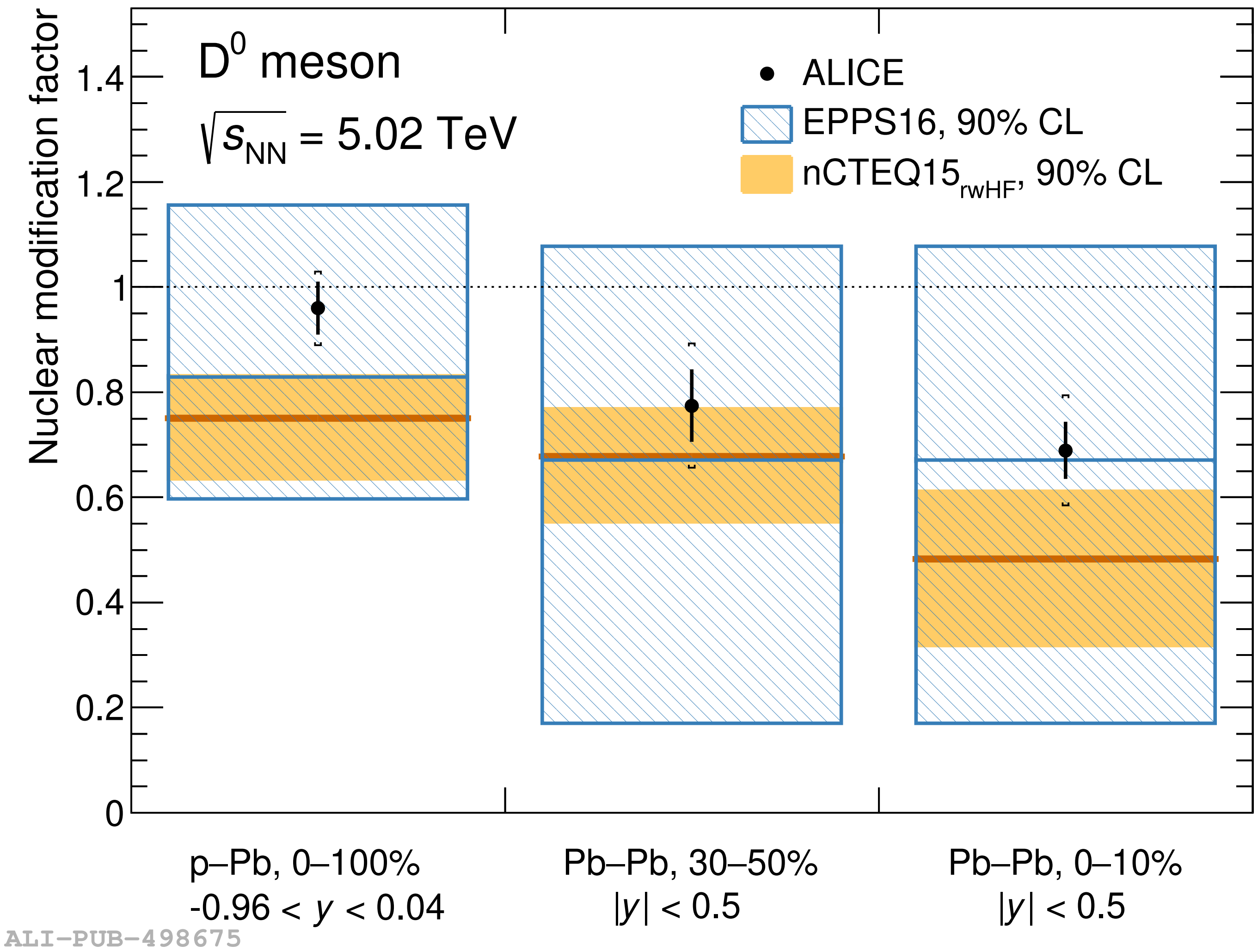
$S_{PbPb} = 0.65 \pm 0.12$

assumed shadowing in Pb–Pb

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

$\Rightarrow \frac{d\sigma_{c\bar{c}}}{dy} = 0.532 \pm 0.096$ 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):

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

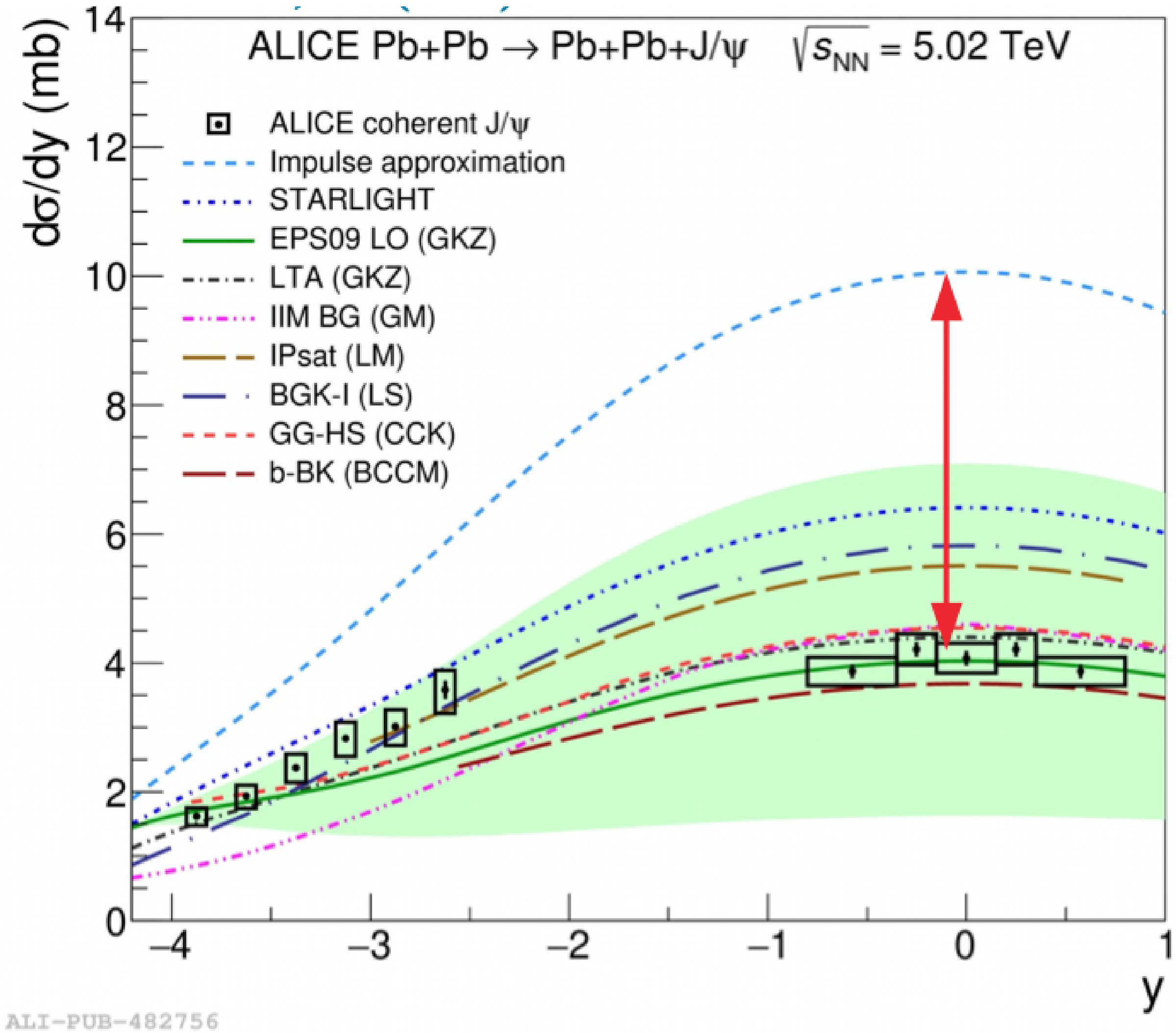
nCTEQ15$_{\rm rwHF}$ (1 σ):

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

(centrality-dependent)

ALICE, arXiv:2110.09420

Another argument for large shadowing in Pb-Pb



J/ψ photoproduction

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

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

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

ALICE, EPJC 81 (2021) 712

Impulse approximation: STARLIGHT, no nuclear effects except coherence