Quarkonium and open charm production in the statistical hadronization model

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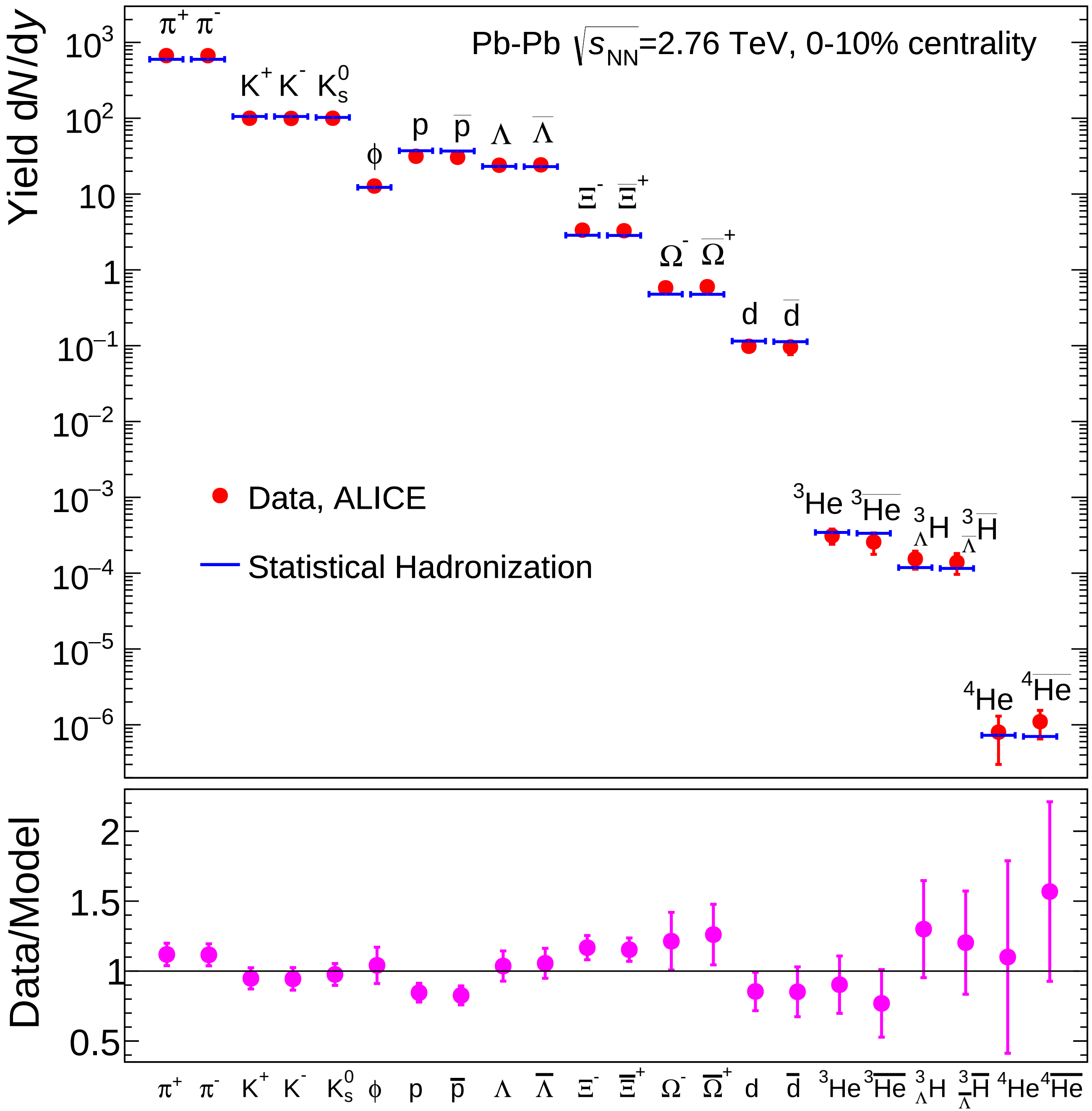
- Chemical freeze-out of light quark (u,d,s) hadrons
  ...and the connection to the QCD phase diagram
- Statistical hadronization of heavy quarks

AA, P. Braun-Munzinger, M. Köhler, K. Redlich, J. Stachel,
Nature 561 (2018) 321; PLB 797 (2019) 134836

Hadron yields and statistical hadronization



Matter and antimatter are produced in equal amounts in high-energy Pb-Pb collisions at the LHC

Best fit:

$T_{CF} = 156.5 \pm 1.5$ MeV

$\mu_B = 0.7 \pm 3.8$ MeV

$V_{\Delta y=1} = 5280 \pm 410$ fm^3

chemical freeze-out

ALICE, NPA 971 (2018) 1

AA et al, Nature 561 (2018) 321

Thermal fit of hadron abundances

A. Andronic

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

quantum numbber conservation ensured via chemical potentials:

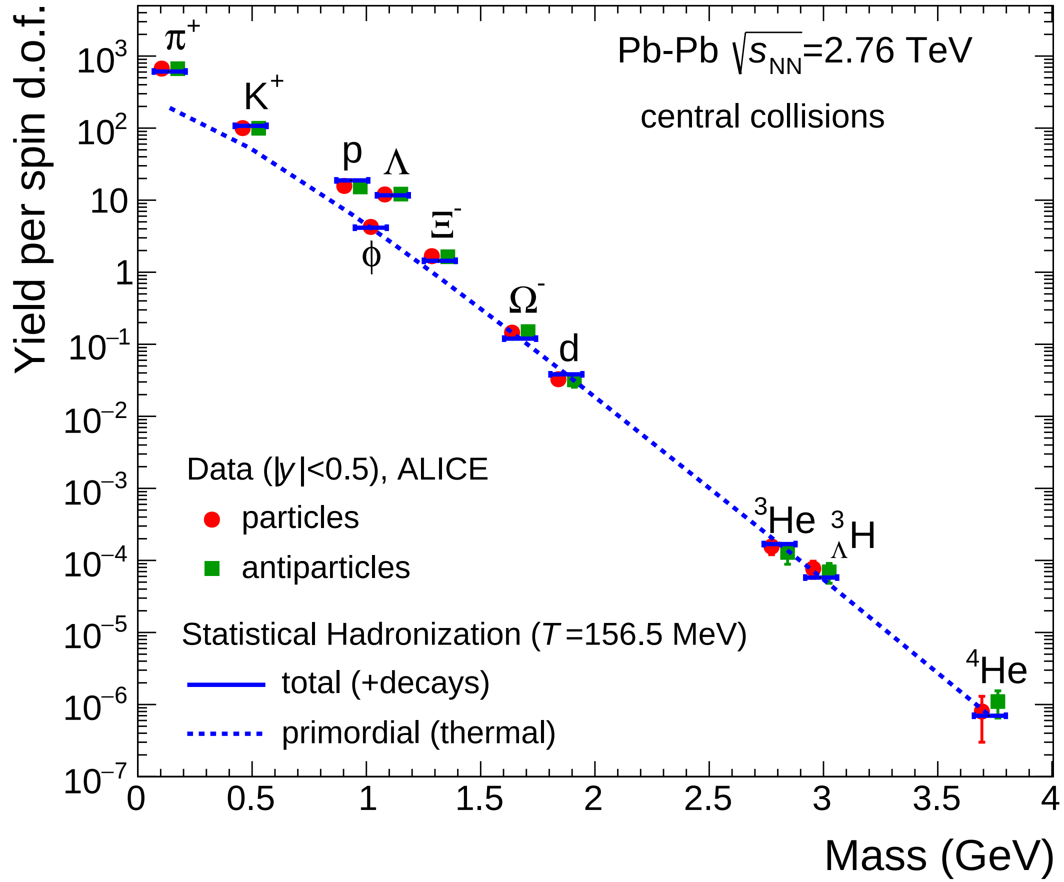
$$\mu_i = \mu_B B_i + \mu_{I_3} I_{3i} + \mu_S S_i + \mu_C C_i$$

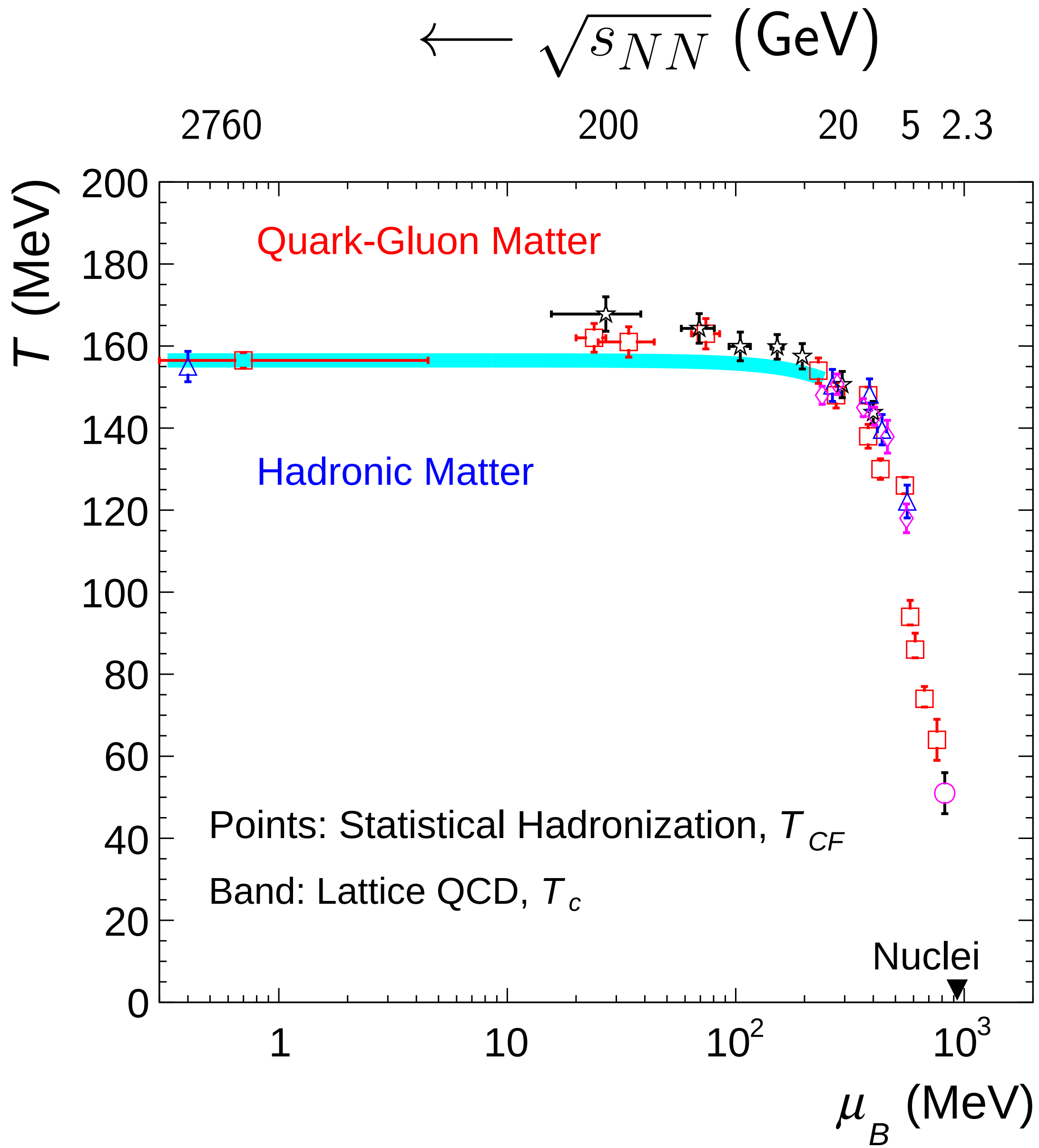
Latest PDG hadron mass spectrum (up to 3 GeV, 560 species)

Minimize: $\chi^2 = \sum_i \frac{(N_i^{exp} - N_i^{therm})^2}{\sigma_i^2}$

N_i: hadron yield $(\mathrm{d}N/\mathrm{d}y)$

$\Rightarrow (T,\, \mu_B,\, V)$





at LHC, remarkable "coincidence" with Lattice QCD results

μ_B is a measure of the net-baryon density, or matter-antimatter asymmetry

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

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

Nature 561 (2018) 321

Hot QCD, PLB 795 (2019) 15

Statistical hadronization of heavy quarks: assumptions

P.Braun-Munzinger, J.Stachel, PLB 490 (2000) 196

- 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)
  R_{AA} and $v_{2,3}$ of D and J/ψ data provided support for thermalization
- charmed hadrons are formed at chemical freeze-out together with all hadrons
  statistical laws, quantum no. conservation; stat. hadronization $\neq$ *coalescence*

  is freeze-out at(/the?) phase boundary?

  ...we believe yes ...based on data in the light-quark sector (support from LQCD)
- no J/ψ survival in QGP (full screening; Matsui, Satz)

  can J/ψ survive above T$_c$? ...yet to be settled (LQCD)

  A. Rothkopf, arXiv:1912.02253

for details, see NPA 789 (2007) 334

SHM for charm: method and inputs

- Thermal model calculation (grand canonical) T,μ_B: $\rightarrow n_X^{th}$

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

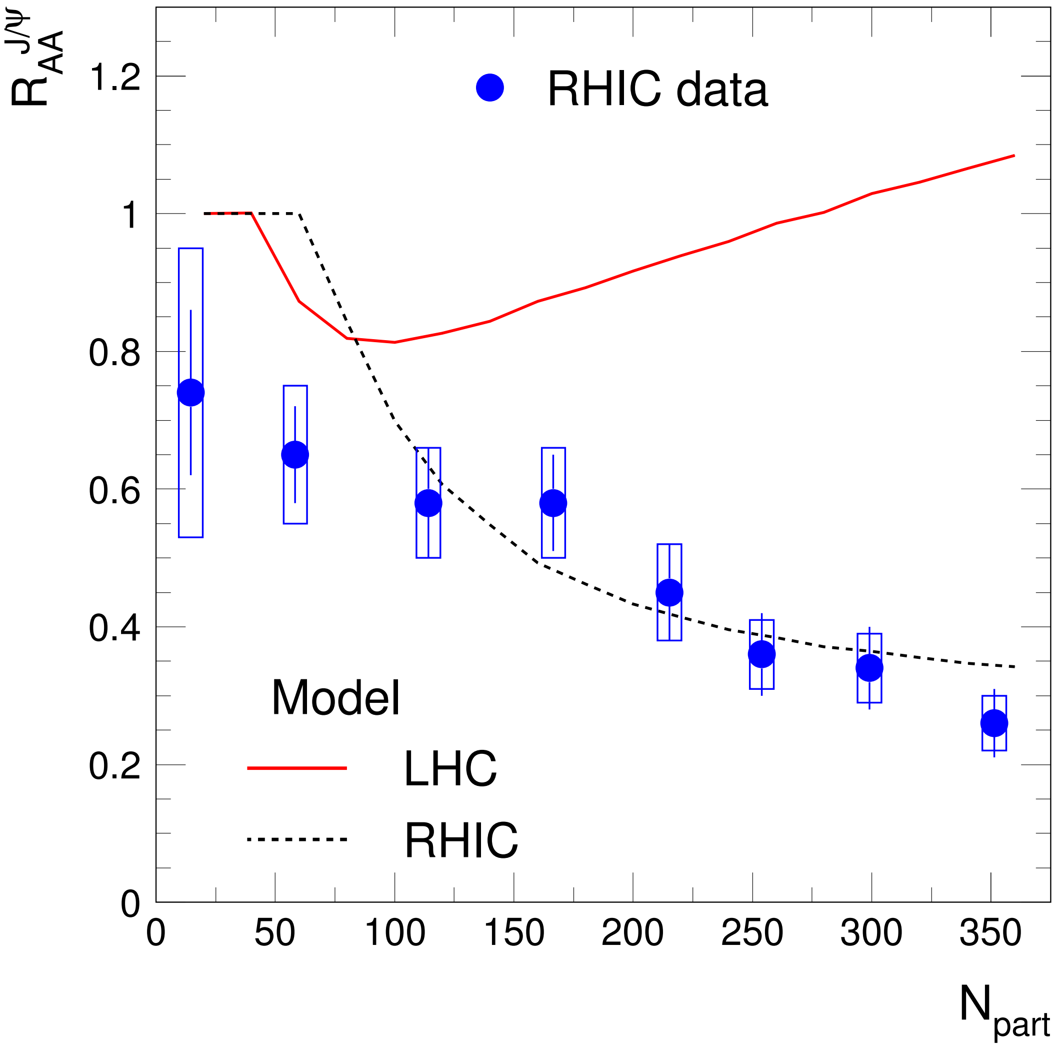
- $N_{c\bar{c}} << 1 \rightarrow$ Canonical (J.Cleymans, K.Redlich, E.Suhonen, Z. Phys. C51 (1991) 137):

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

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

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



$$R_{AA}^{J/\psi} = \frac{dN_{J/\psi}^{AuAu}/dy}{N_{coll} \cdot dN_{J/\psi}^{pp}/dy}$$

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

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

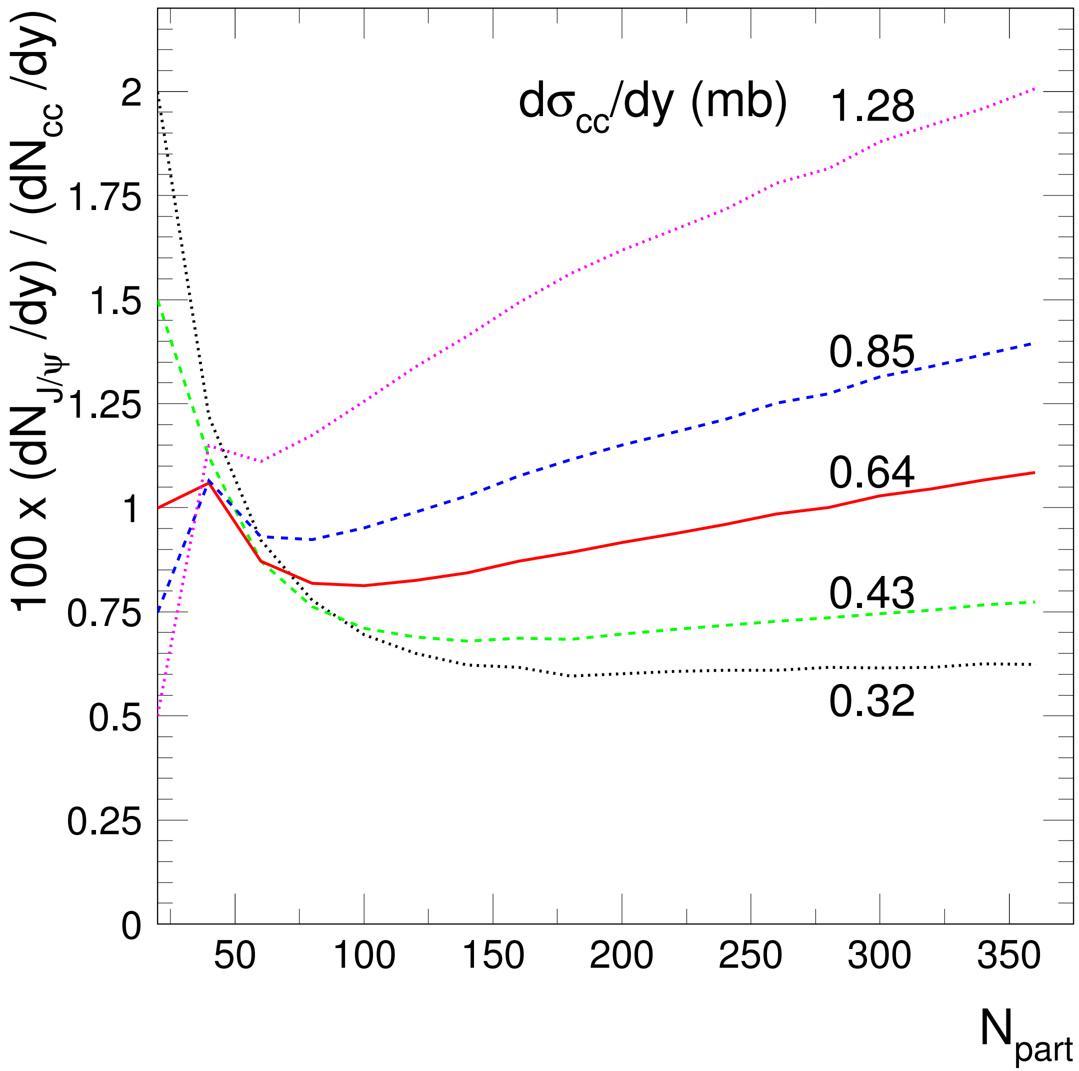
What is so different at LHC?

(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



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

(“proxy” for R_{AA})

- ”enhancement” at the LHC

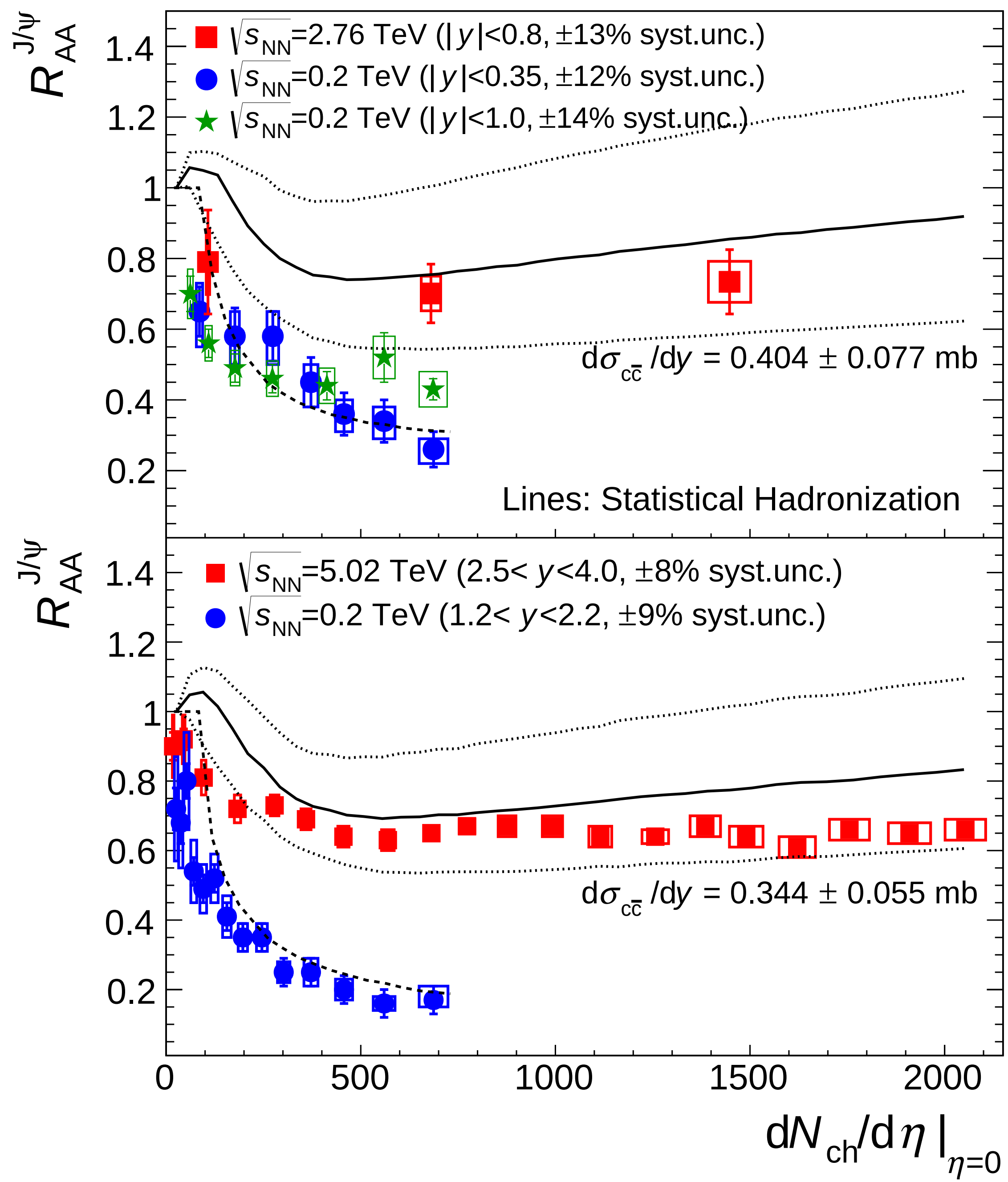
$N_{J/\psi} \sim (N^{dir}_{c\bar{c}})^2$

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



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

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

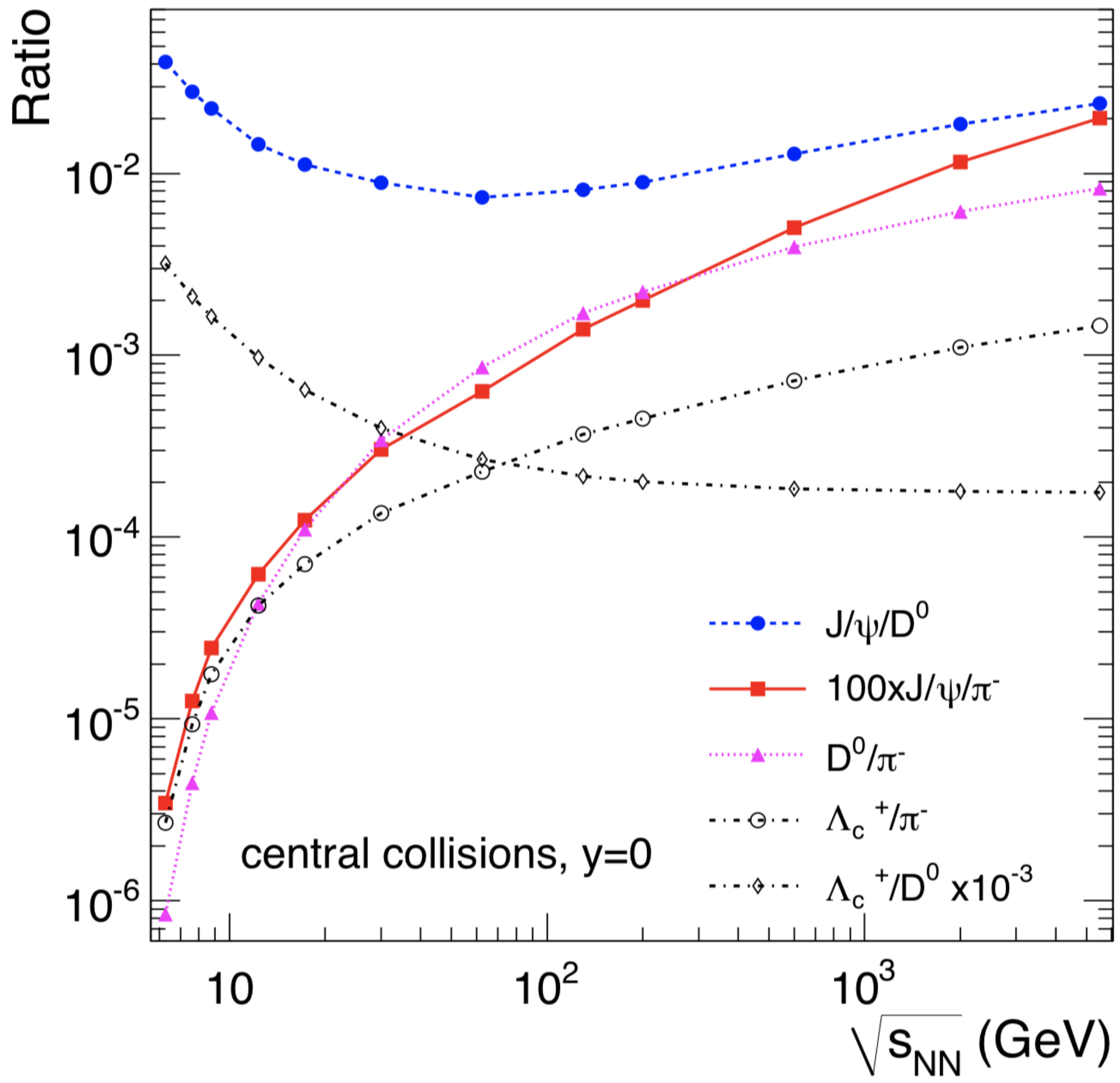
calculations are for T=156 MeV

$\sigma_{c\bar{c}}$: 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 $\mathrm{d}N_{ch}/\mathrm{d}\eta \simeq 2000$)

Charm chemistry in SHM



under the assumption of charm thermalization

a debatable assumption at lower energies

JPG 37 (2010) 094014

central coll.; $|y| < 0.5$

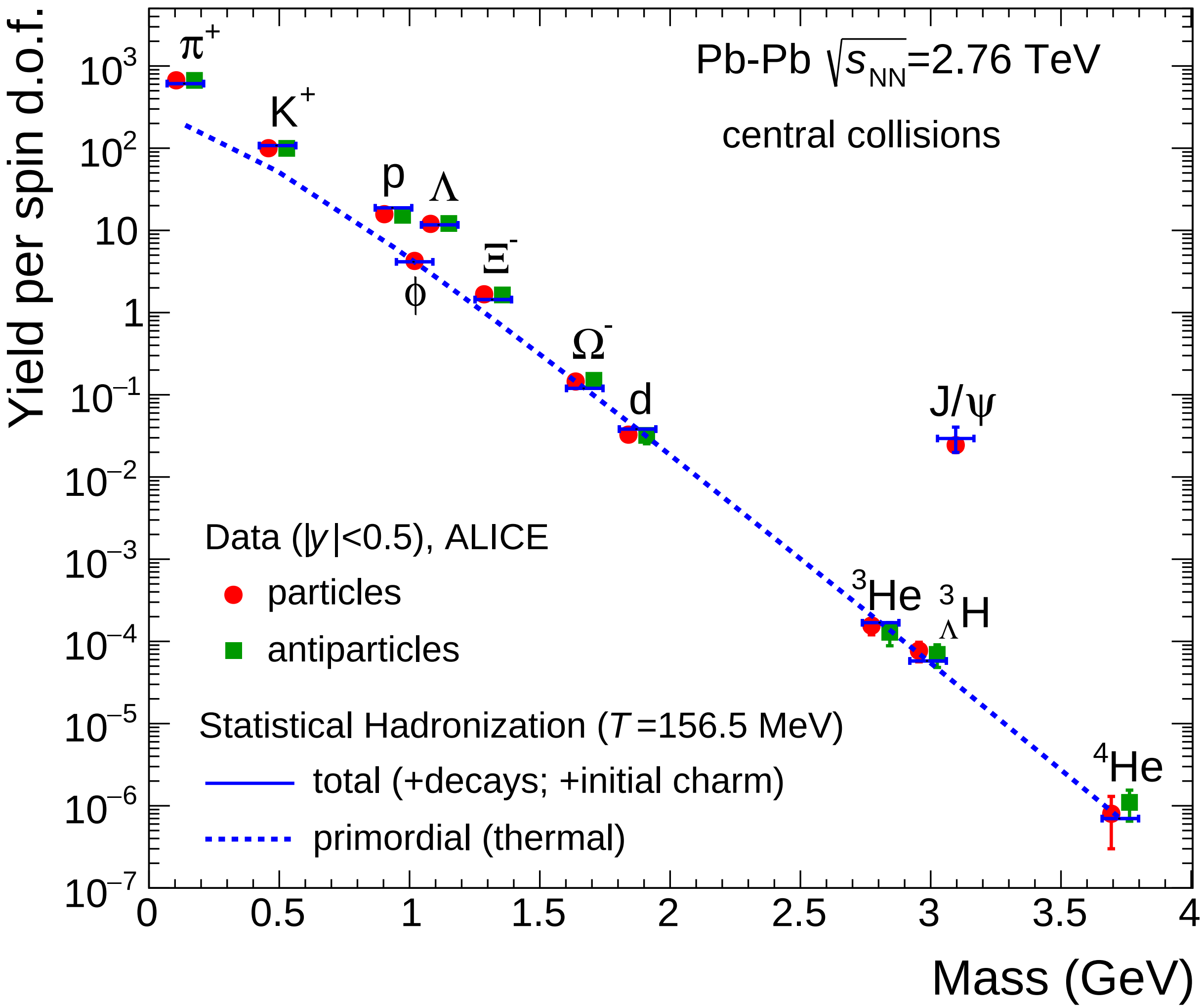
$T_{CF} = 156.5 \pm 1.5$ MeV

$\mu_B = 0.7 \pm 3.8$ MeV

$V_{\Delta y=1} = 5280 \pm 410$ fm^3

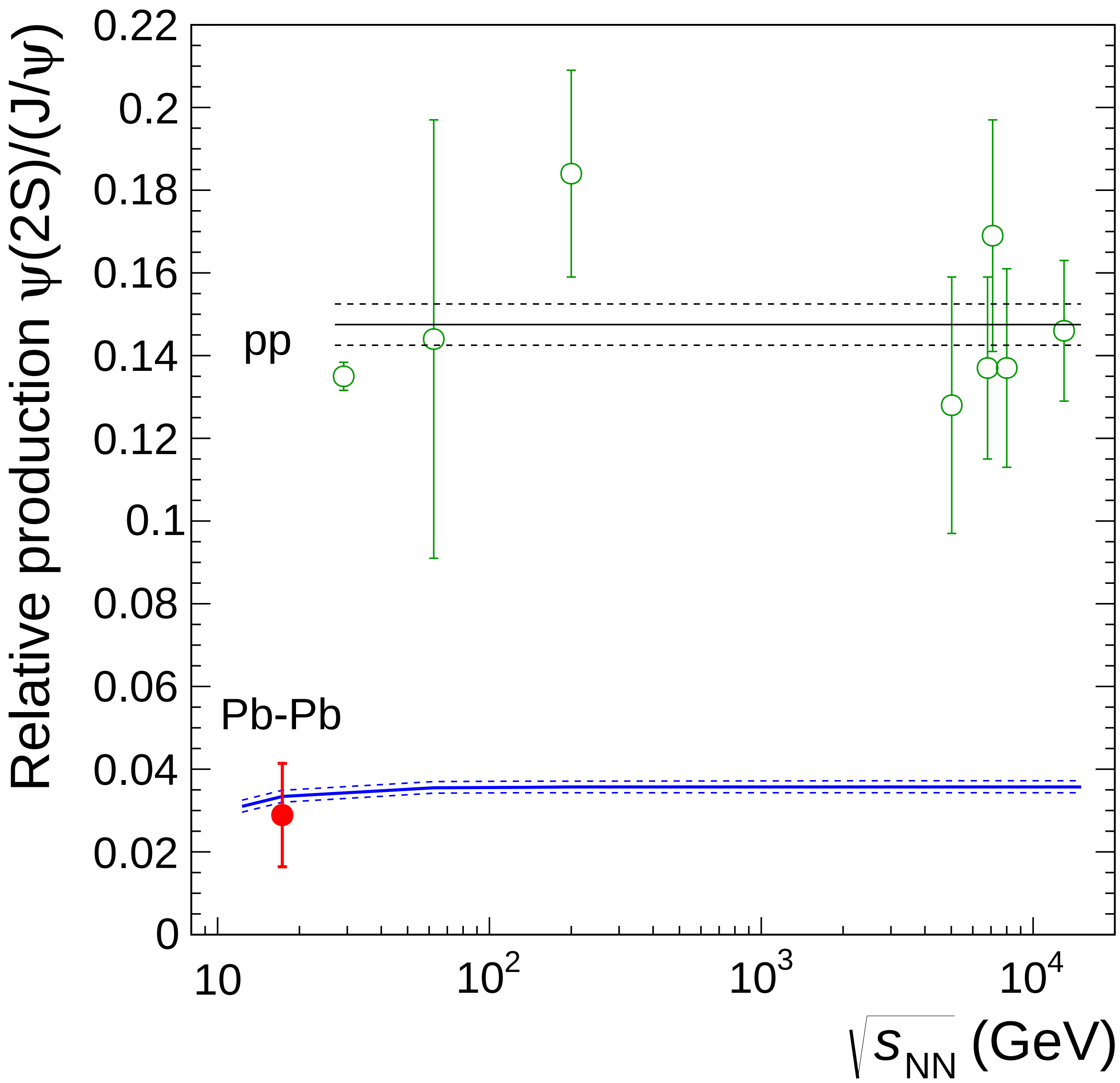
$N_{c\bar{c}} = 9.6$ ($I_1/I_0 = 0.974$)

$g_c = 30.1$



π, $K^{\pm}$, K^0 from charm included in the thermal fit

(0.7%, 2.9%, 3.1% for T=156.5 MeV)



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

PLB 678 (2009) 350

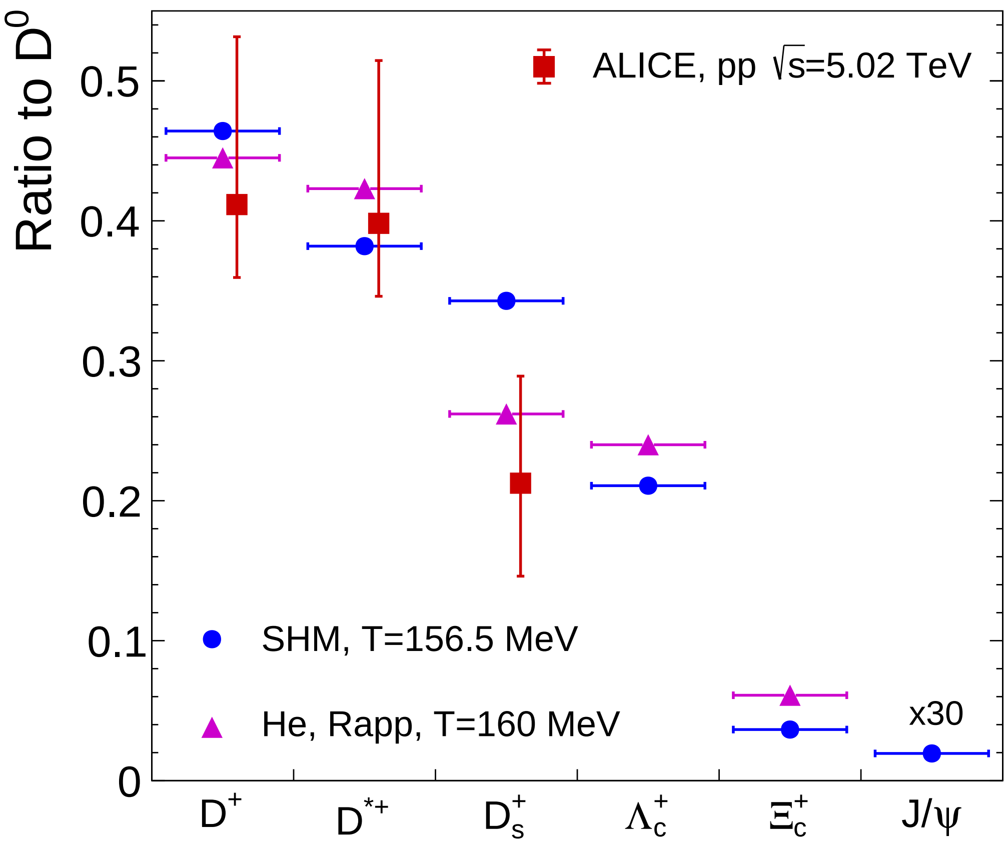
..litmus test: $\psi(2S)$

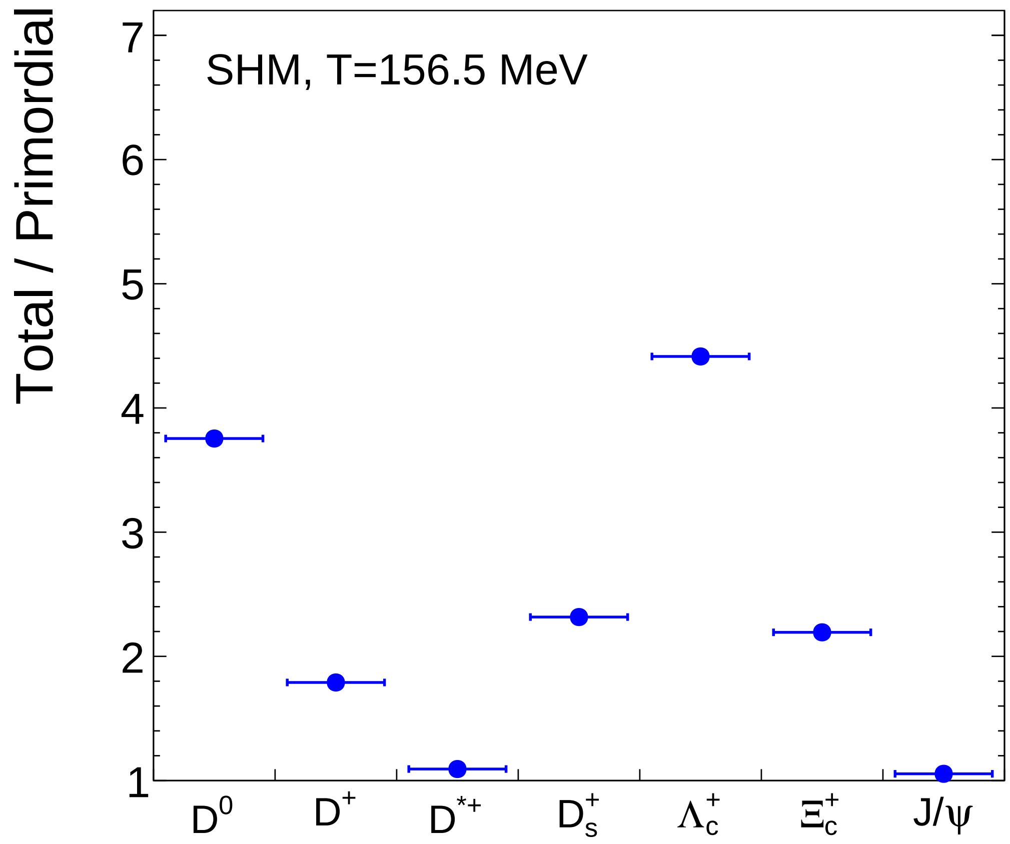
The measurement in Pb–Pb at LHC is a central goal for Run 3,4

see Yellow report WG5 HL-LHC

statistical description in Pb–Pb, Nature 561 (2018) 321

Charm chemistry in SHM at the LHC



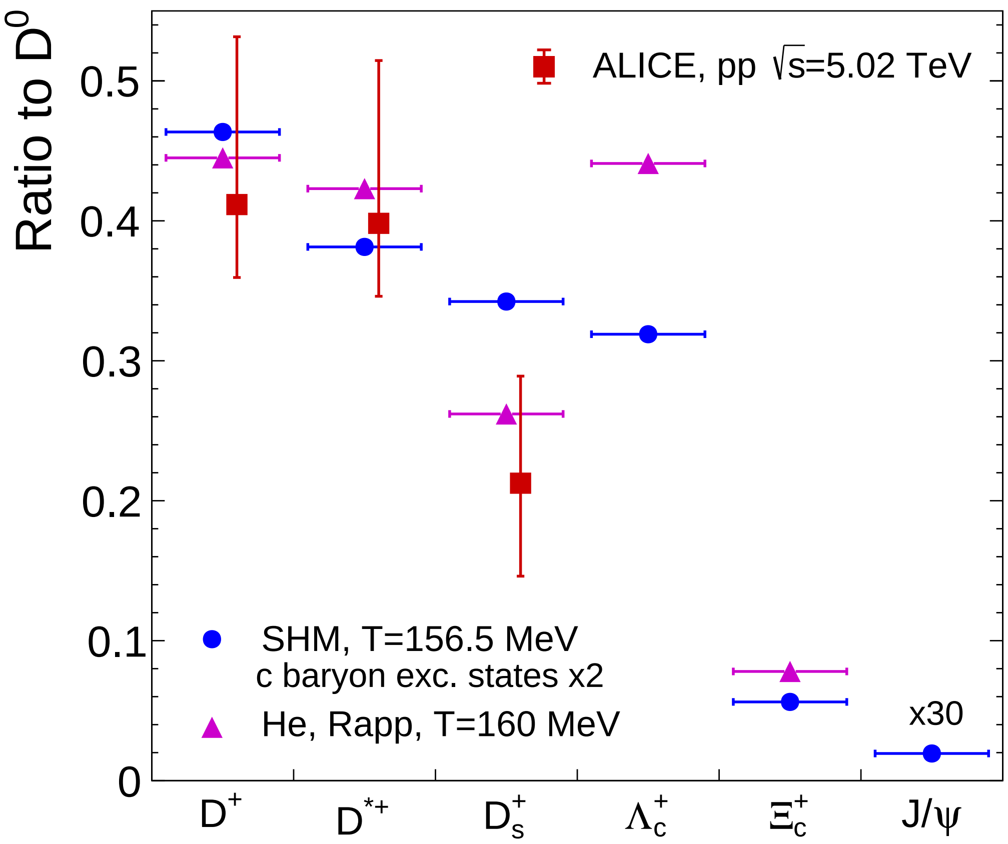


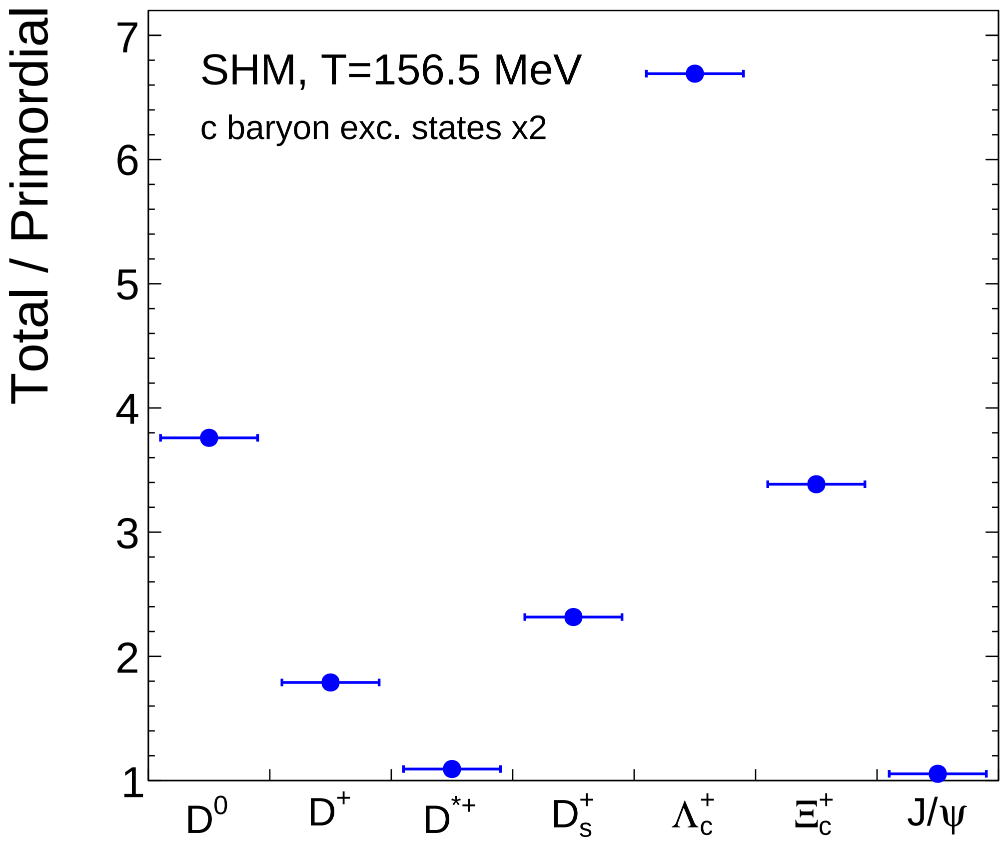
A large contribution from decays of high-mass resonances

Total number of states: 40 mesons, 68 baryons (particles and antiparticles)

...for comparison, strange: 38 mesons, 96 baryons

He, Rapp, PLB 795 (2019) 117, γ_s=0.6; ALICE data, EPJC 79 (2019)





If charm baryons excited states are doubled in our model

we observe a ∼1.5x increase of the Λ_c/D^0 ratio

well below the ratio by He, Rapp (Relativistic Quark Model; many more states)

$$\frac{\mathrm{d}N}{p_T\mathrm{d}p_T} \sim \int_0^R r\mathrm{d}r \left[m_T \cosh\rho K_1\left(\frac{m_T\cosh\rho}{T}\right) I_0\left(\frac{p_T\sinh\rho}{T}\right) - p_T\sinh\rho K_0\left(\frac{m_T\cosh\rho}{T}\right) I_1\left(\frac{p_T\sinh\rho}{T}\right)\right]$$

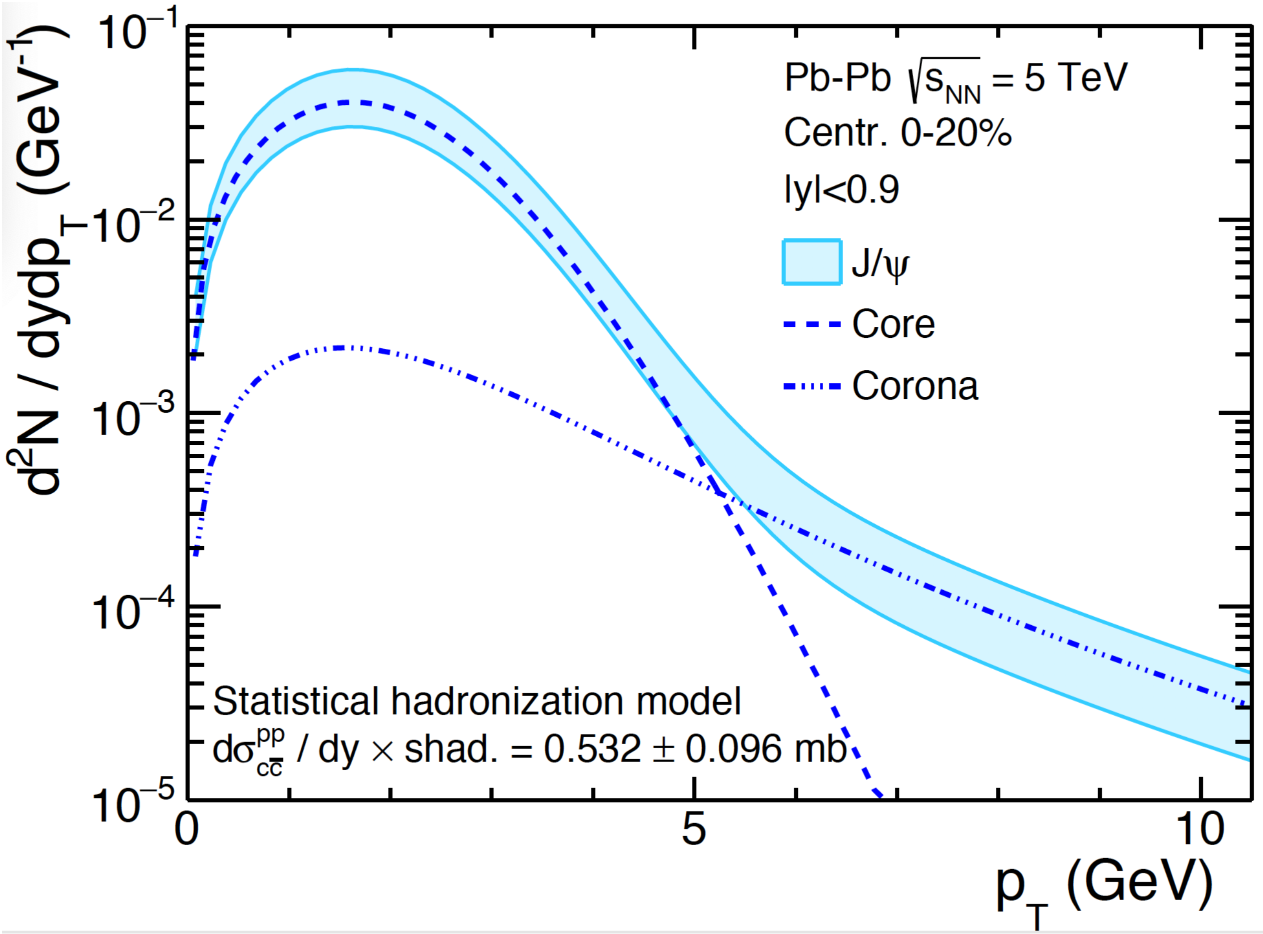
$\rho = \tanh^{-1}\beta$,

$\beta = \beta_T^s(r/R)^n$

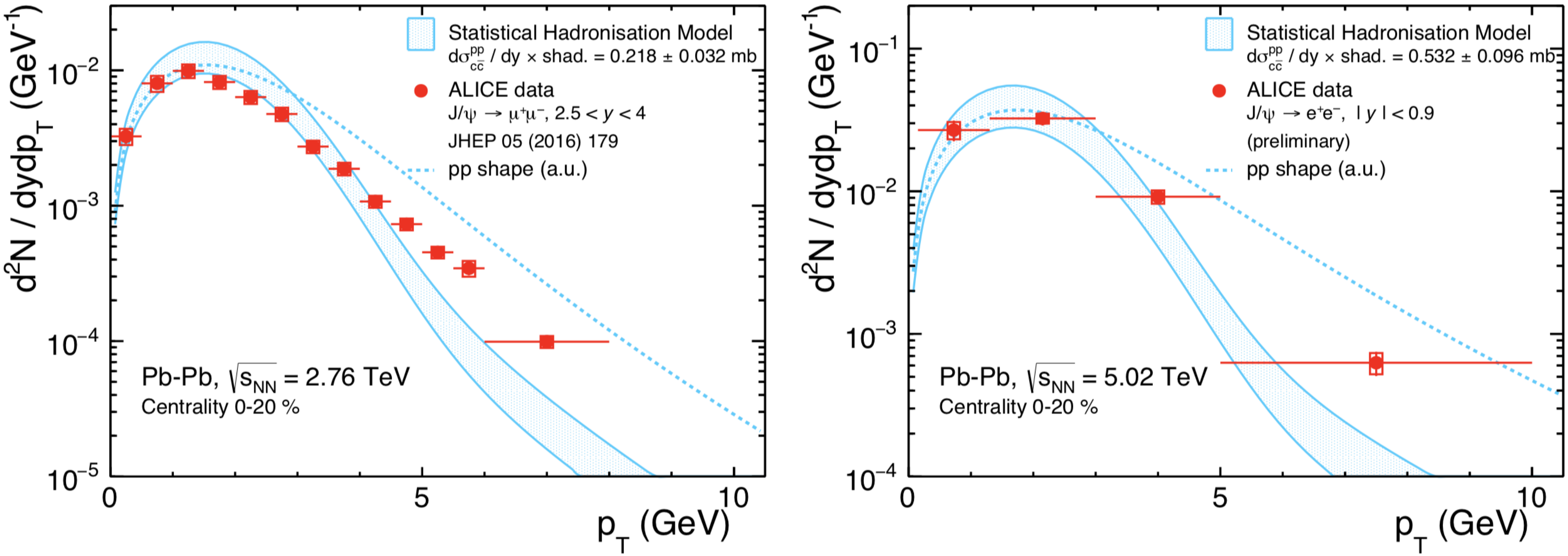
β_T^s at freeze-out (T_{CF})

hypersurface from hydro

MUSIC(3+1)D (IP-Glasma)



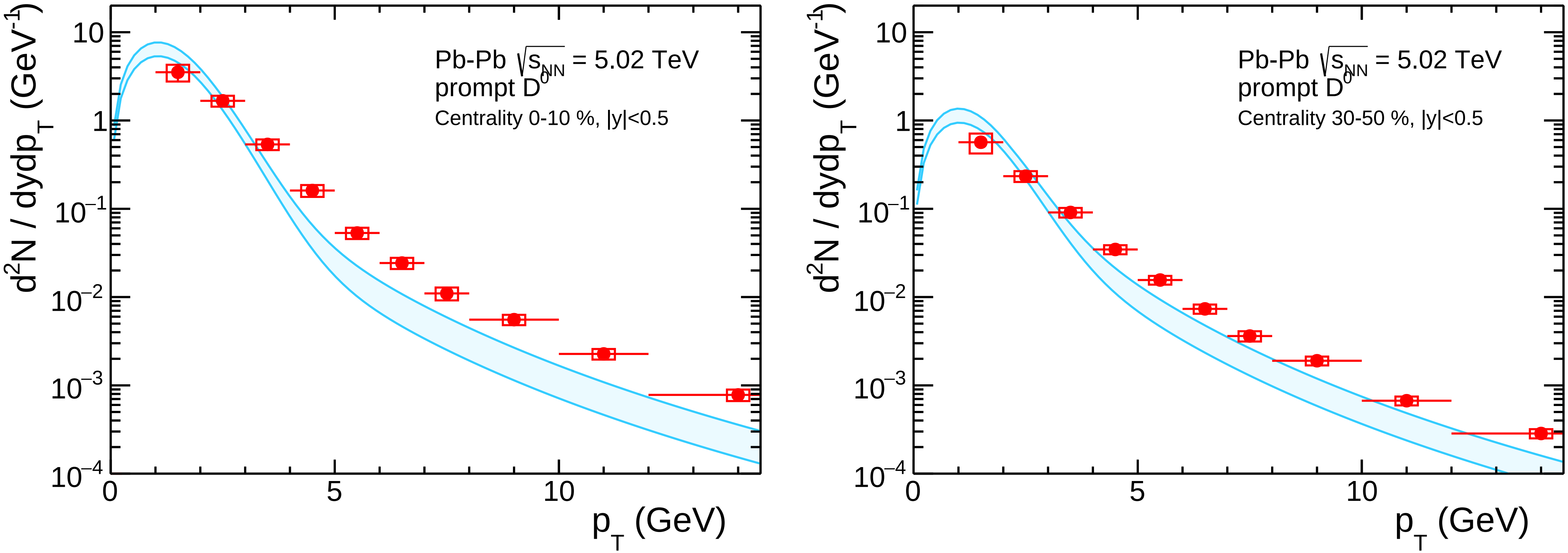
PLB 797 (2019) 134836



PLB 797 (2019) 134836

Very good agreement with the data for low p_T

Transverse momentum dependence in SHM: D mesons



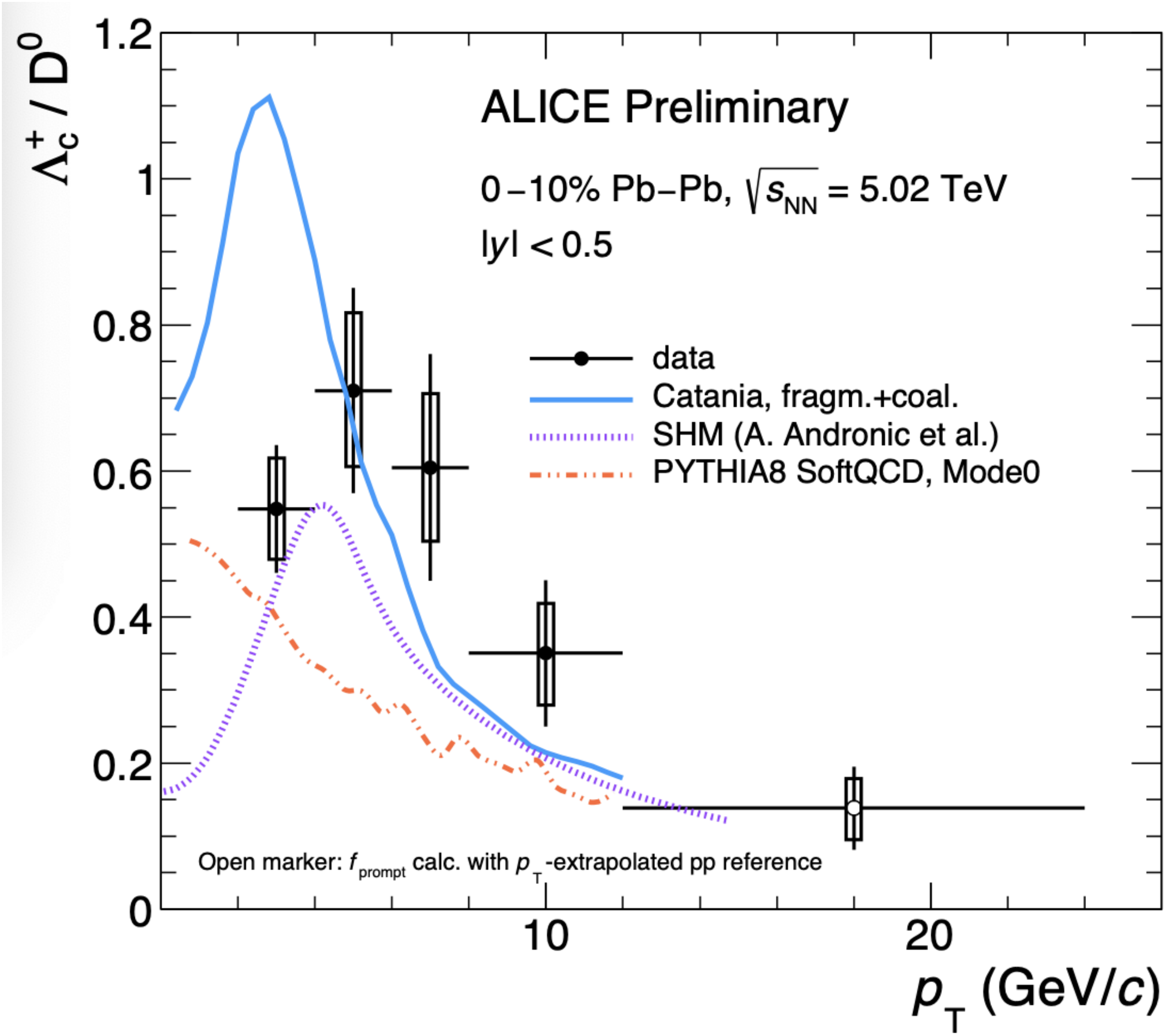
Data, ALICE JHEP 1810 (2018) 174

Very good agreement with the data for low p_T

A more rigorous treatment of feed-down contributions is under way

Mazeliauskas et al, EPJC 79 (2019) 284

Ratio Λ_c/D^0



Good agreement with the data for low p_T

Summary / Conclusions

In the statistical 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

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

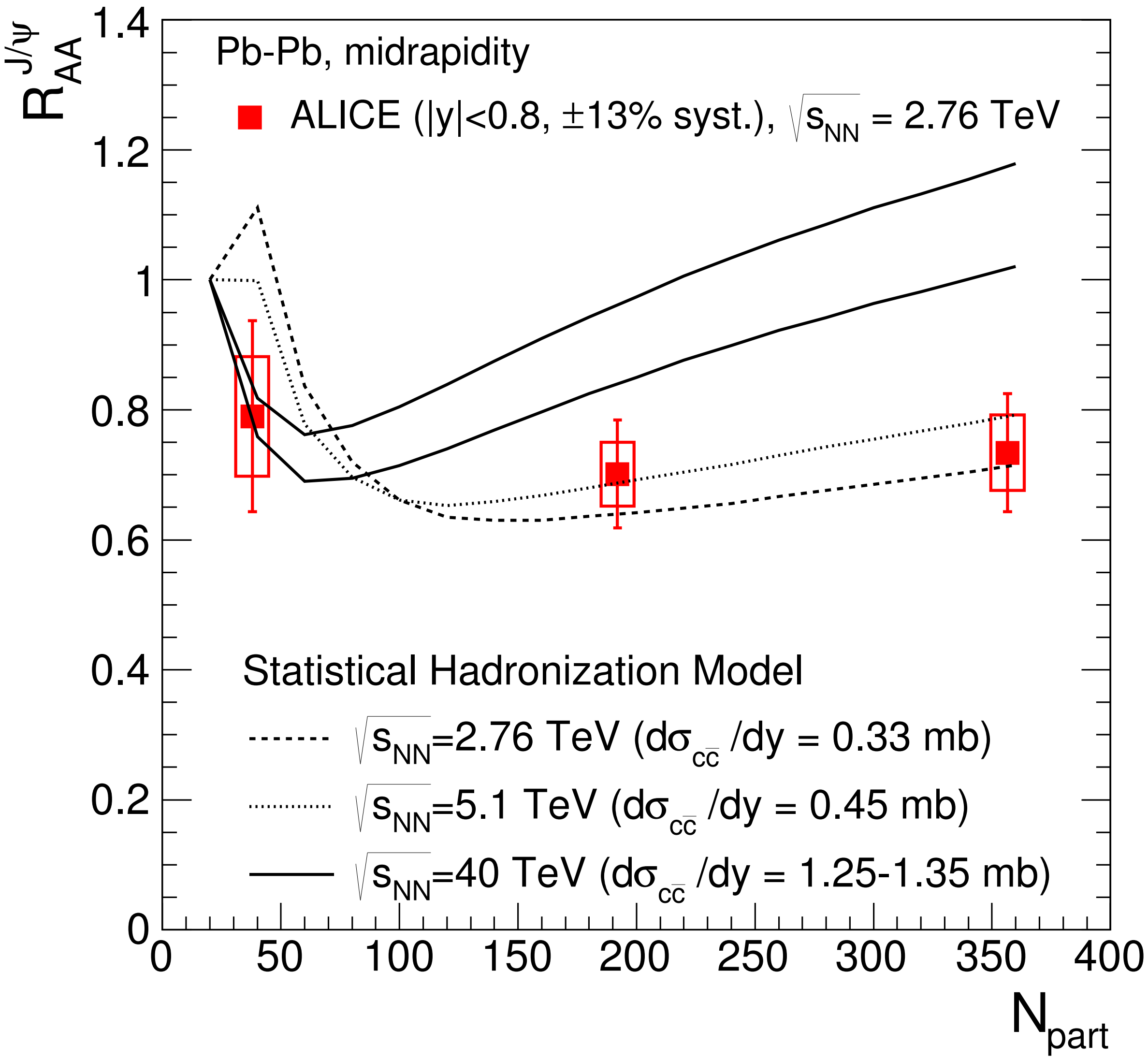
A precision ($\pm$10%) measurement of $\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y$ in Pb-Pb (Au-Au) collisions needed for a stringent test of SHM and other models (transport m. also successful)

within reach with the upgraded detectors at the LHC and RHIC

...and data on other charmonium (and open charm) states are crucial

Supplementary slides

Outlook for J/ψ (2014)



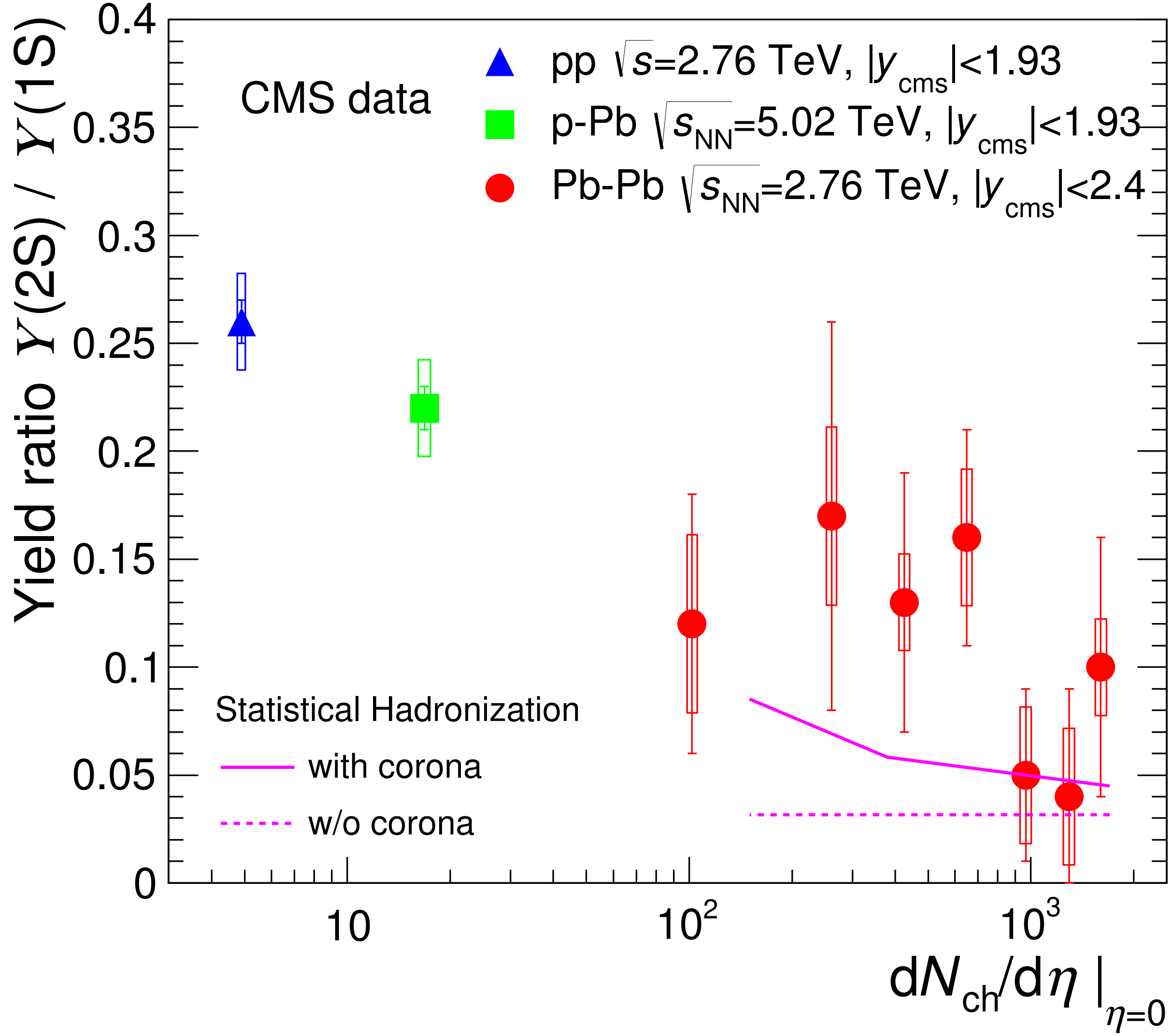
Predictions, Sep. 2014, FCC studies

modest increase for 5.1 TeV
(confirmed by data at 5.02 TeV)

...due to modest increase in $\sigma_{c\bar{c}}$

increasing trend vs. N_{part} at FCC

Yellow report



The data approach the thermal limit for central Pb-Pb coll.

fair description by model

also for R_{AA} of $\Upsilon(1S)$

CMS, PRL 109 (2012) 222301