Quarkonium and the phase boundary of QCD

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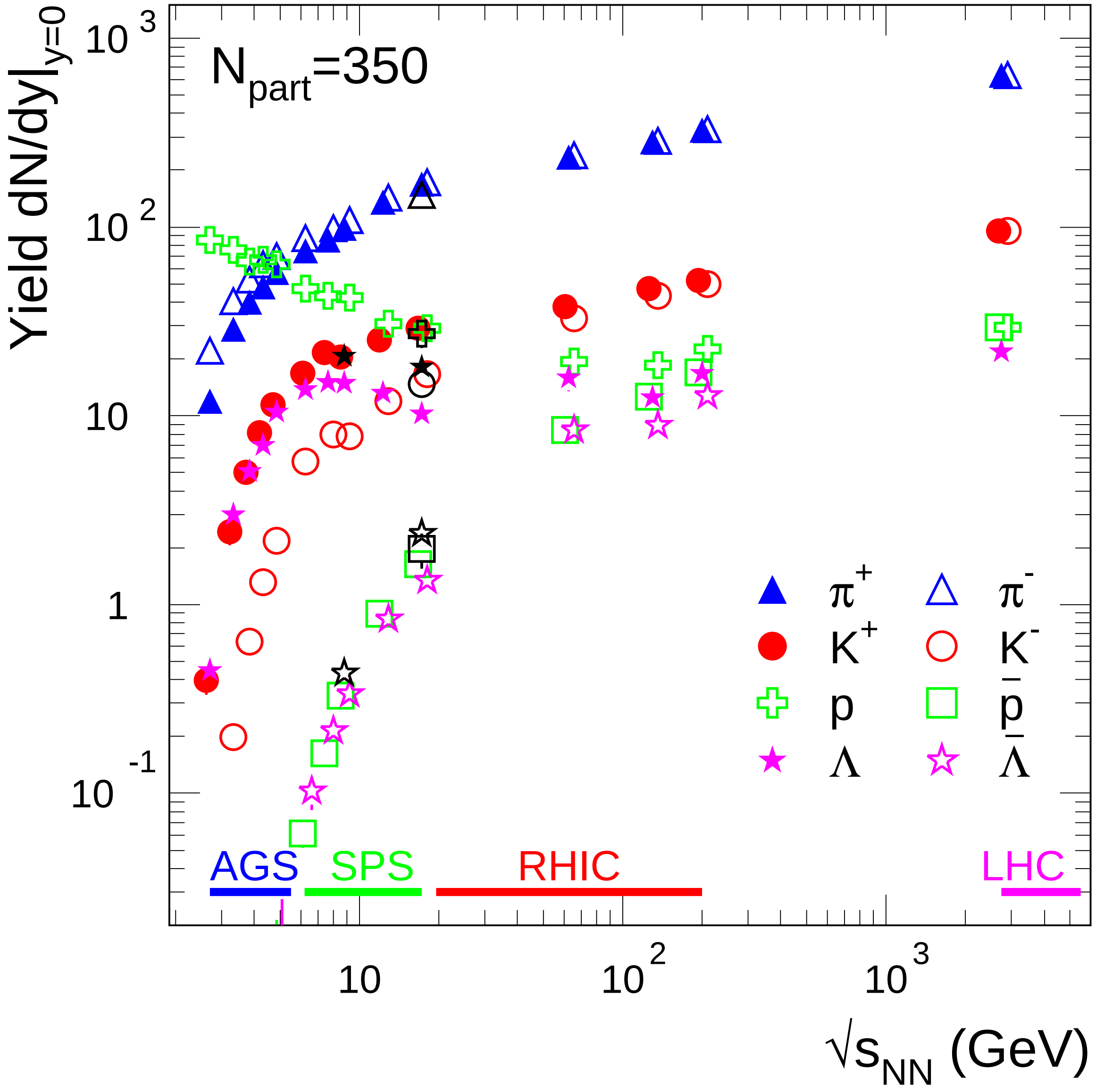
- Chemical freeze-out of light quark (u,d,s) hadrons
- ...and the connection to the QCD phase diagram
- Charmonium and the phase boundary
- Bottomonium - outlook to FHC

AA, P. Braun-Munzinger, K. Redlich, J. Stachel, JPG 38 (2011) 124081 [arXiv:1106.6321]
arXiv:1210.7724 (and refs. therein)

Chemical freeze-out: hadron yields (central collisions)

lots of particles, mostly newly created ($m = E/c^2$)



- a great variety of species:

  $\pi^{\pm}$ $(u\bar{d},\ d\bar{u})$, m=140 MeV
  $K^{\pm}$ $(u\bar{s},\ \bar{u}s)$, m=494 MeV
  p (uud), m=938 MeV
  Λ (uds), m=1116 MeV
  also: $\Xi(dss)$, $\Omega(sss)$...

- mass hierarchy in production (at low en.: u, d quarks remnants from the incoming nuclei)

- chemistry explained by thermal model

  with 3 parameters: T, μ_b, V

The statistical (thermal) model

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grand canonical partition function for specie i ($\hbar = c = 1$):

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

$g_i = (2J_i + 1)$ 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: $V_{cons} \sum_i n_i I_{3i} = I_3^{tot}$, with $V_{cons} = N_B^{tot} / \sum_i n_i B_i$
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 fits of hadron abundances

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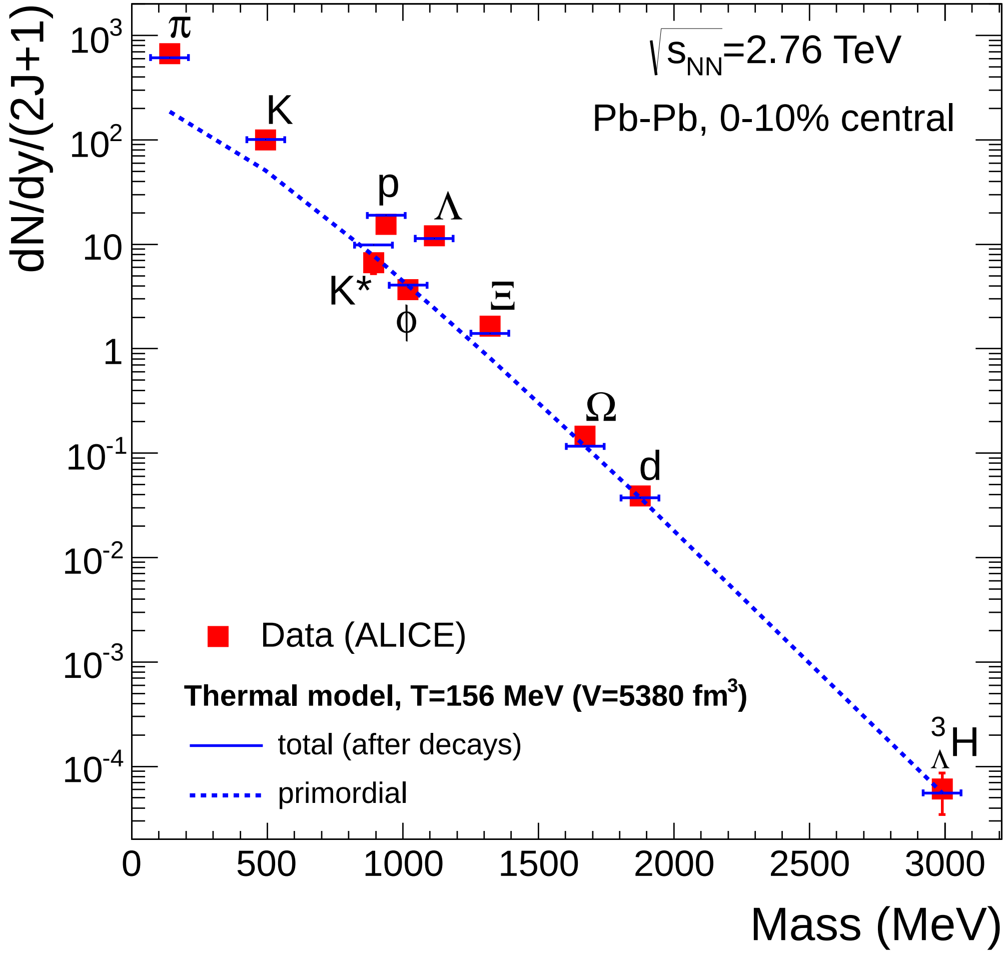
$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i-\mu_i)/T]\pm 1}$$

quantum no. conservation:

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

Latest PDG hadron mass spectrum
(up to 3 GeV, 485 species)



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

N_i: hadron yield $\Rightarrow (T, \mu_b, V)$

Hadron abundances consistent with a thermally equilibrated system

Energy dependence of T, μ_b (central collisions)

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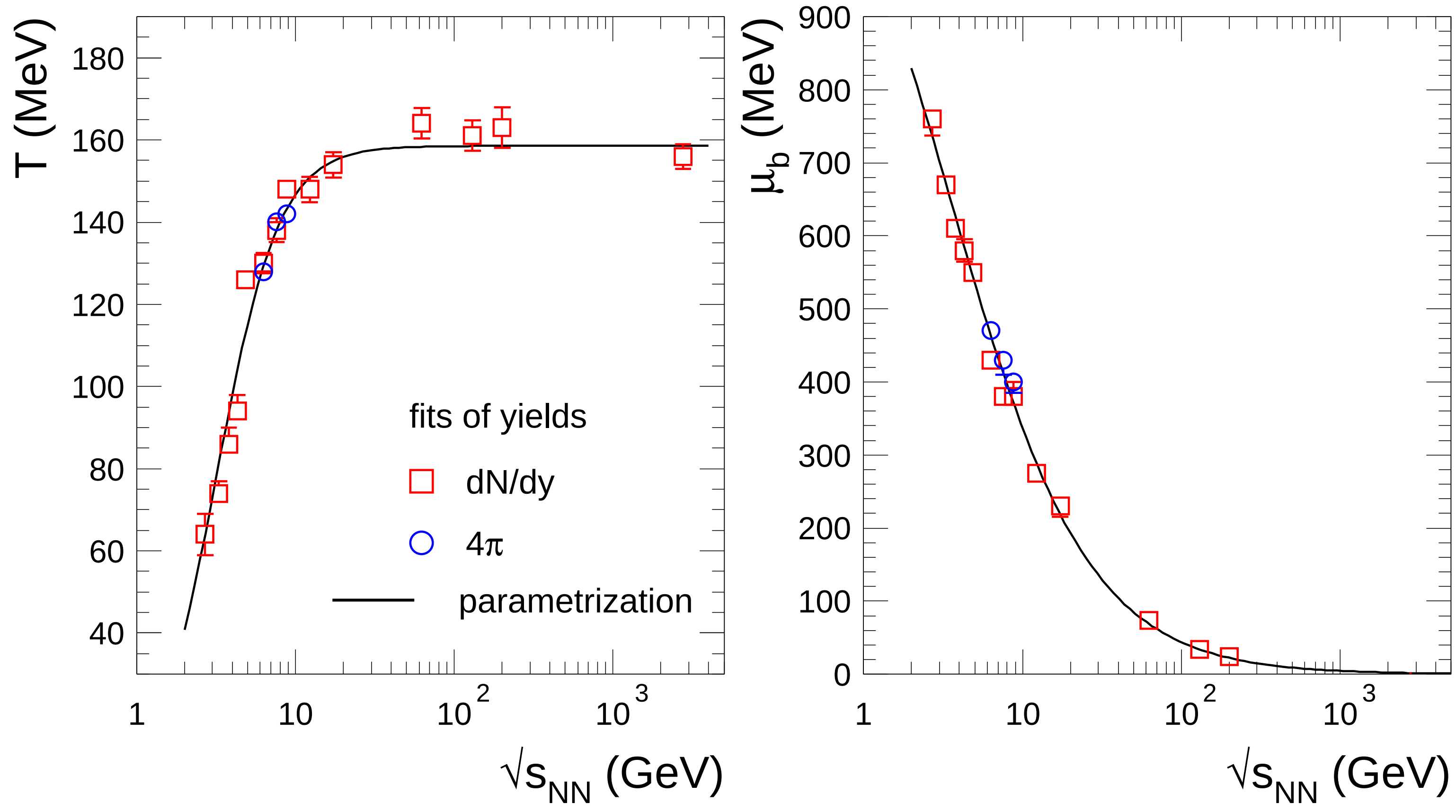

thermal fits exhibit a limiting temperature: $T_{lim} = 159 \pm 2$ MeV

$$T = T_{lim}\frac{1}{1+\exp(2.60-\ln(\sqrt{s_{NN}}(\mathrm{GeV}))/0.45)}, \qquad \mu_b[\mathrm{MeV}] = \frac{1307.5}{1+0.288\sqrt{s_{NN}}(\mathrm{GeV})}$$

PLB 673 (2009) 142

Volume in central collisions

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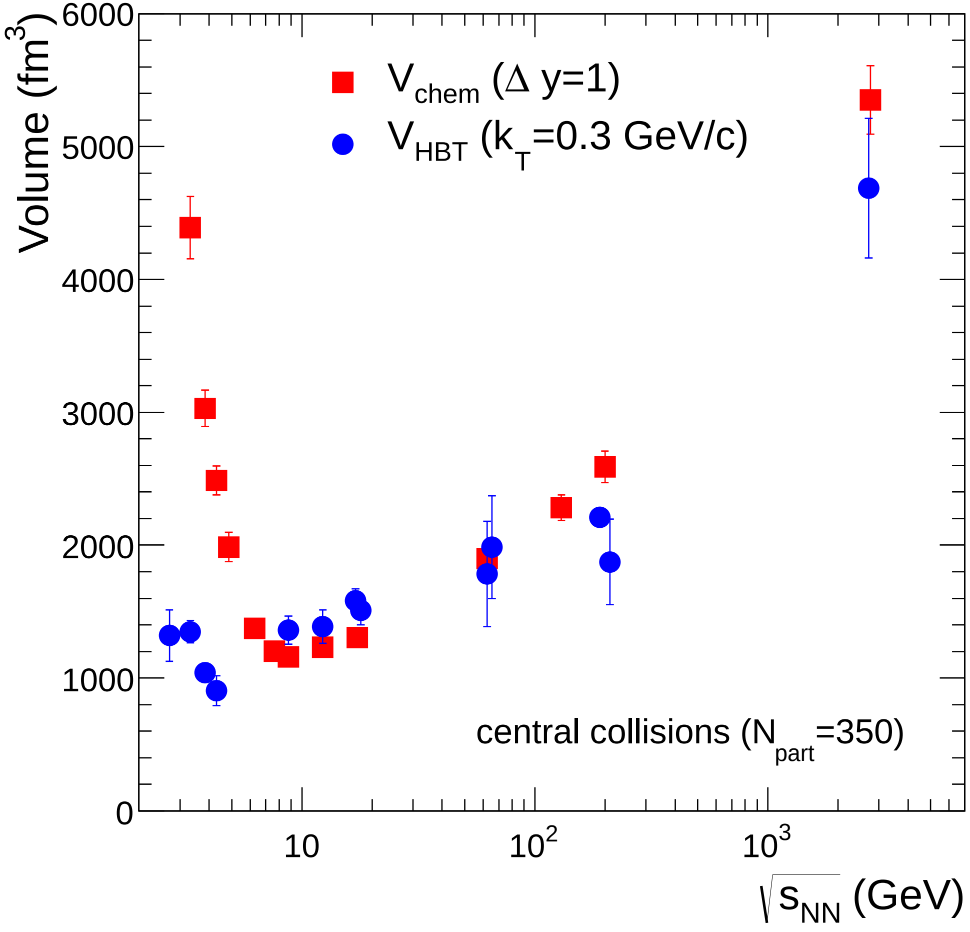
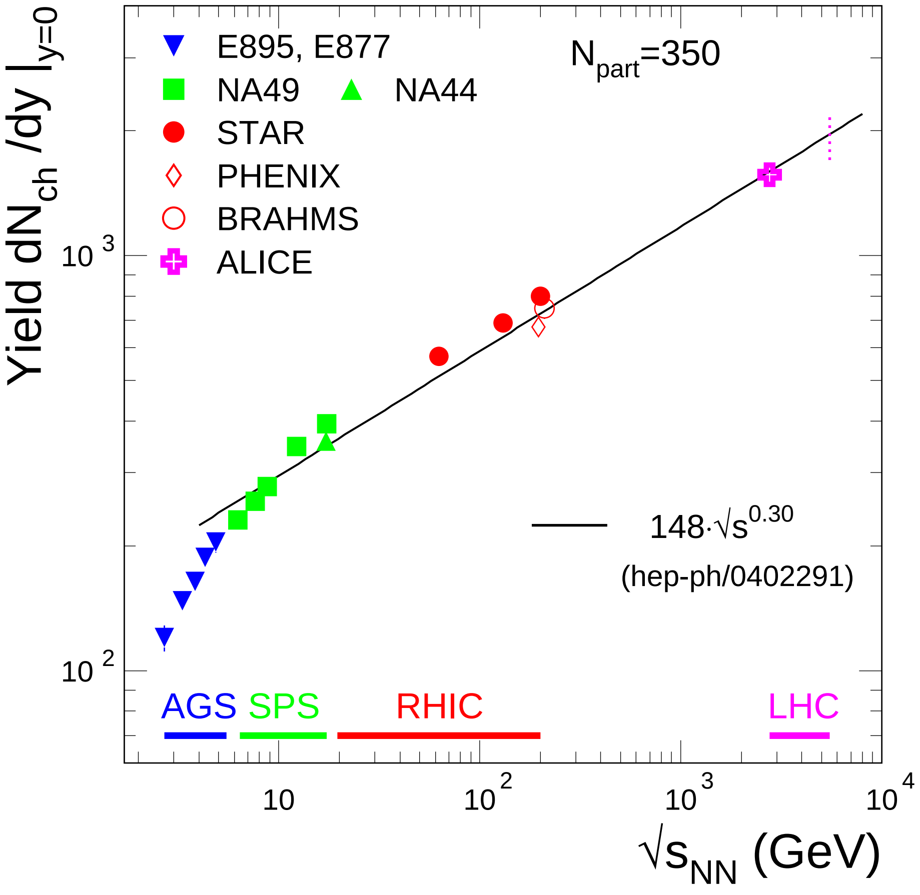


$$V_{chem}(\Delta y = 1) = \mathrm{d}N_{ch}/\mathrm{d}y|_{y=0}/n_{ch}^{therm}$$



$$V_{HBT} = (2\pi)^{3/2} R_{side}^2 R_{long}$$

HBT data: ALICE, PLB 696, 328 (2011)

40 TeV: $V = 12000$ fm^3 (2.2x $V_{2.76}$)

Connection to the phase diagram of QCD

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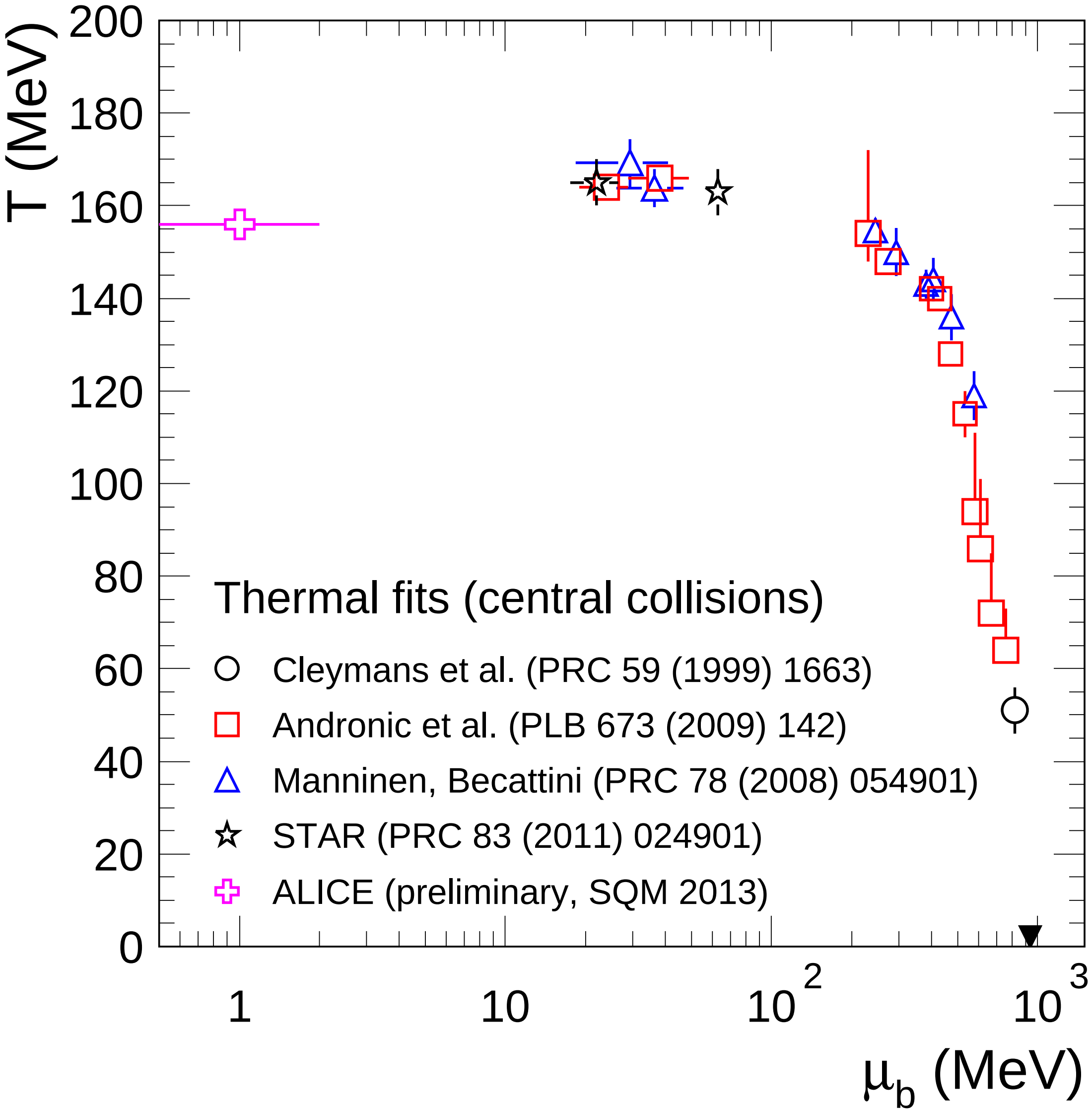

(as $T \rightarrow T_{lim}$) is chemical freeze-out a determination of the phase boundary?

...for entire μ_b range?

PBM, Stachel, Wetterich, PLB 596 (2004) 61
McLerran, Pisarski, NPA 796 (2007) 83
AA et al., NPA 837 (2010) 65
Floerchinger, Wetterich, NPA 890 (2012) 11

Statistical hadronization of heavy quarks: assumptions

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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)
- 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)

  can J/ψ survive above T$_c$? ...not settled yet (LQCD)

  Asakawa, Hatsuda, PRL 92 (2004) 012001; Mocsy, Petreczky, PRL 99 (2007) 211602

if all this supported by data, J/ψ looses status as "thermometer" of QGP
...and gains status as a powerful observable for the phase boundary

Statistical hadronization of charm: method and inputs

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

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

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

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

Outcome: $N_D=g_cVn_D^{th}I_1/I_0 \quad N_{J/\psi}=g_c^2Vn_{J/\psi}^{th}$

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

Minimal volume for QGP: V_{QGP}^{min}=400 fm^3

Charmonium in the statistical hadronization model

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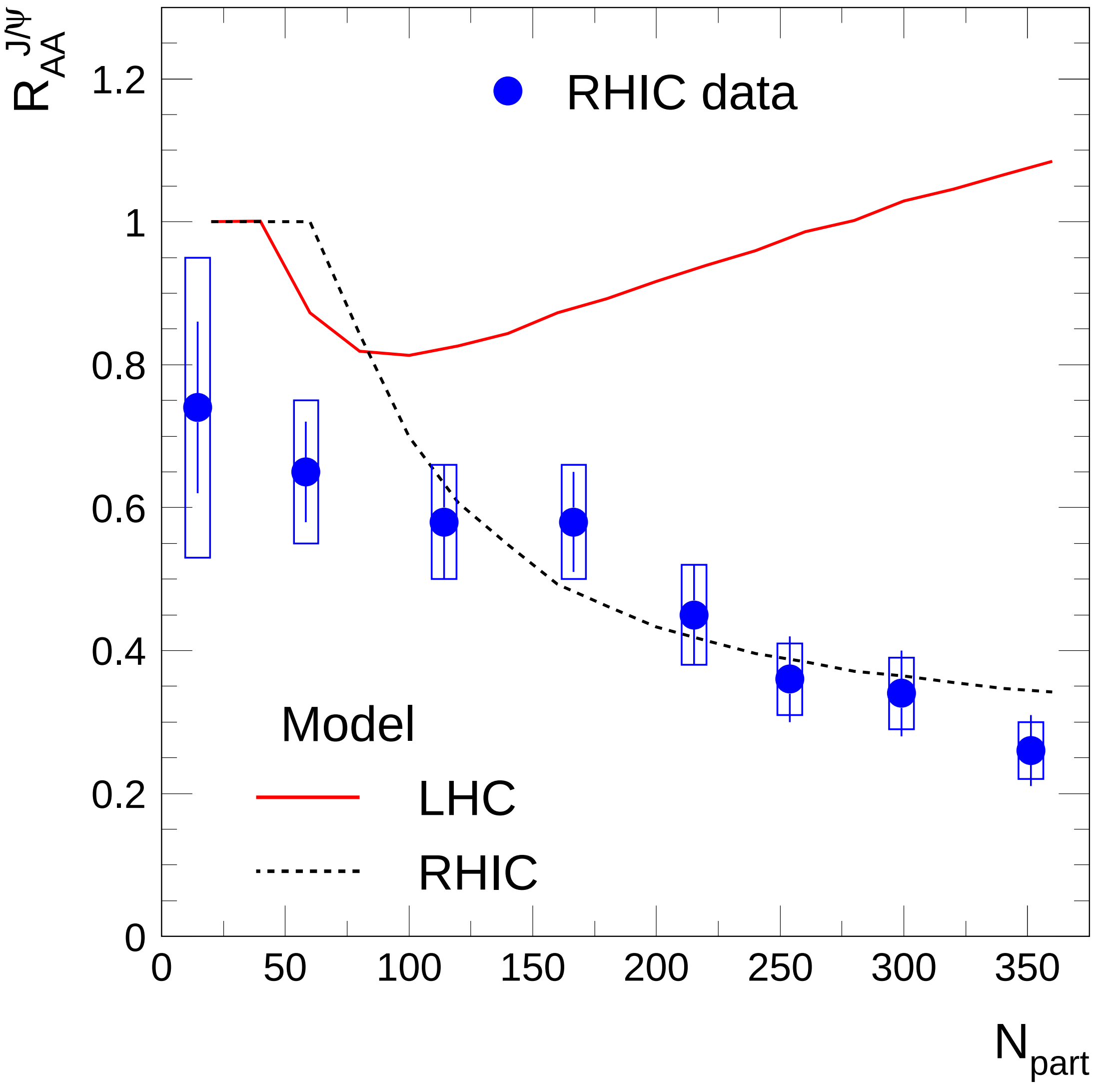

$$R_{AA}^{J/\psi} = \frac{\mathrm{d}N_{J/\psi}^{AA}/\mathrm{d}y}{N_{coll} \cdot \mathrm{d}N_{J/\psi}^{pp}/\mathrm{d}y}$$

- "suppression" at RHIC
- "enhancement" at the 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: 2.2-3x

AA et al., PLB 652 (2007) 259

this was for full LHC energy ... but is a generic prediction of the model

Charmonium in the statistical hadronization model at LHC

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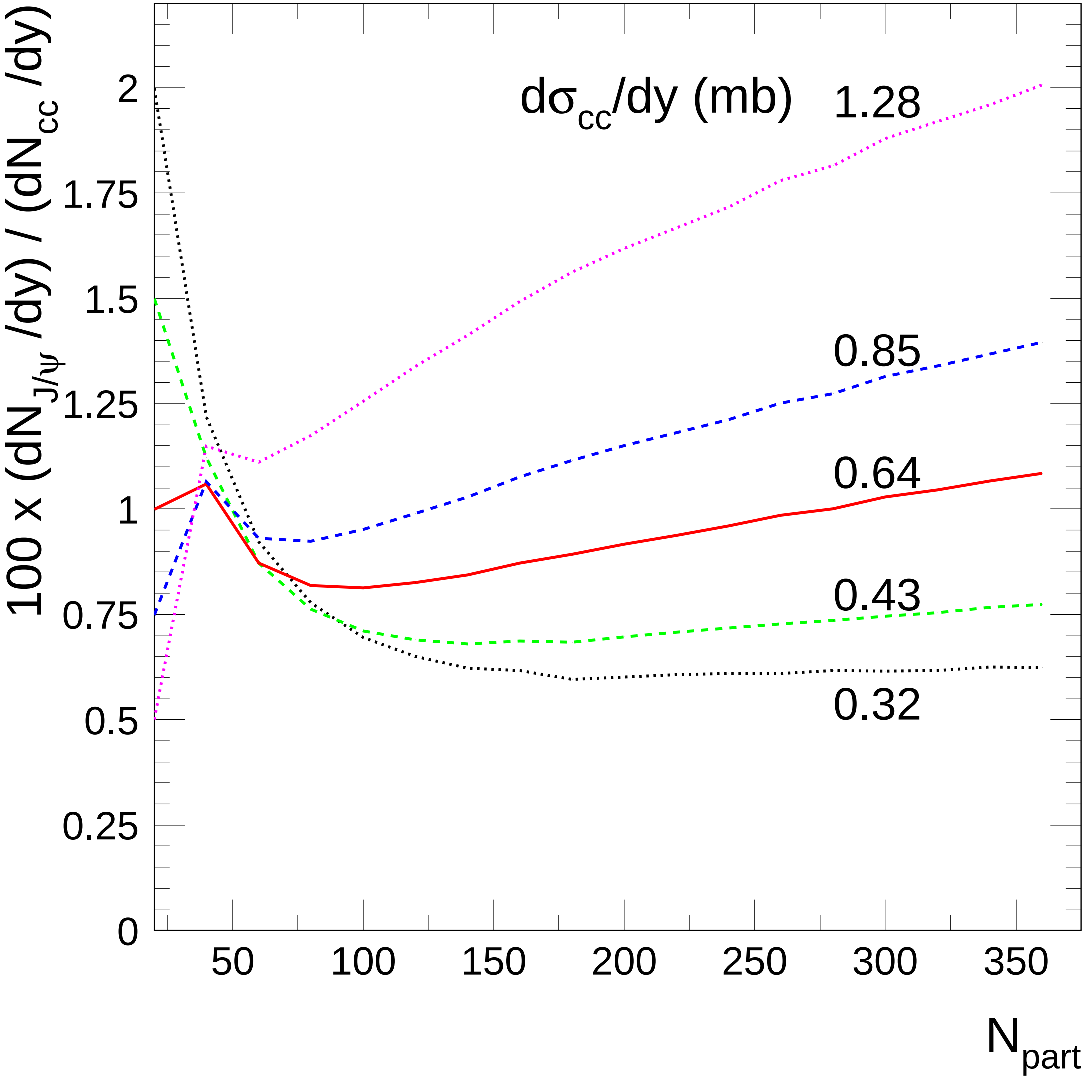

$$\frac{\mathrm{d}N^{AA}_{J/\psi}/\mathrm{d}y}{\mathrm{d}N^{AA}_{c\bar{c}}/\mathrm{d}y}$$

(“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 FHC

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

this was for full LHC energy ... but is a generic prediction of the model

Charmonium in the statistical hadronization model at LHC

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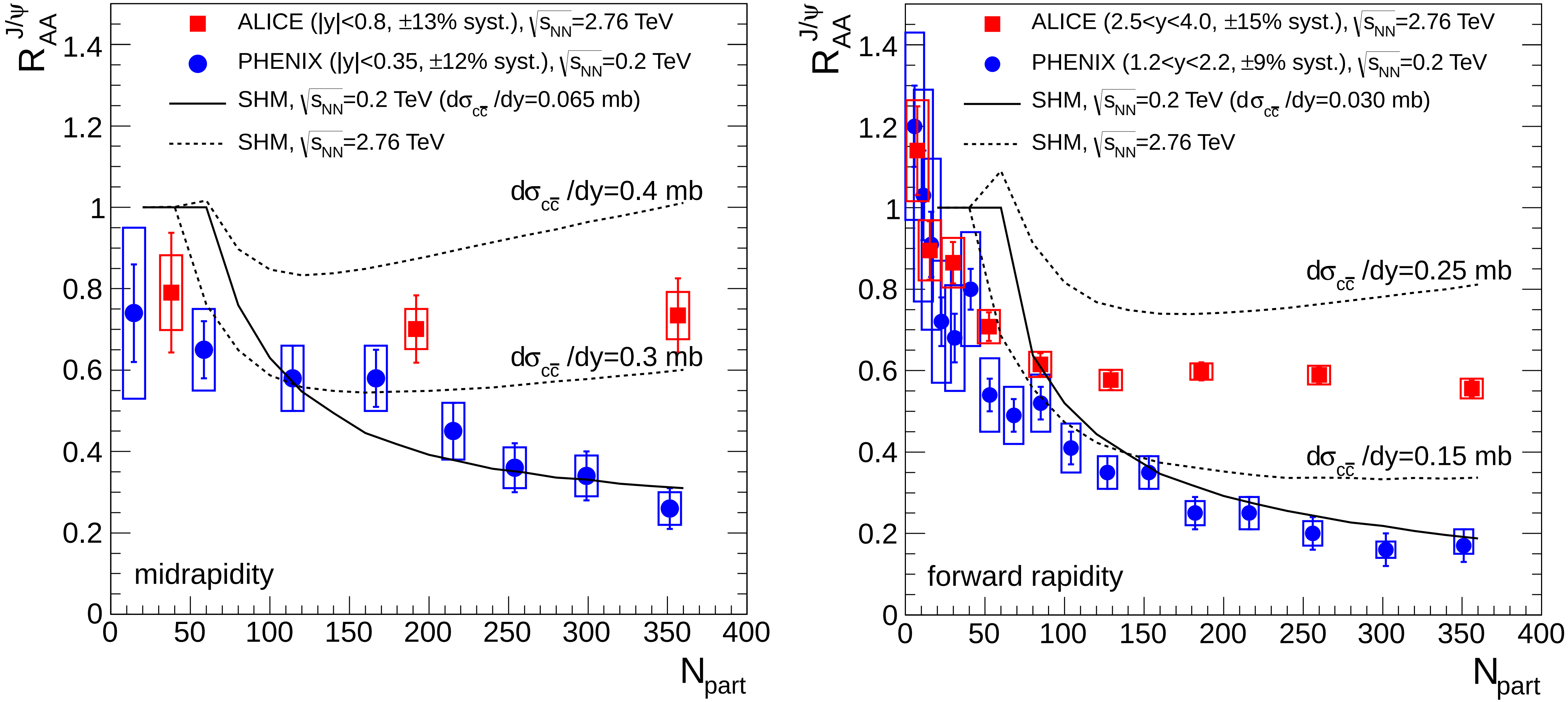

the generic prediction by the model is confirmed by data ALICE, arXiv:1311.0214

establishes charmonium as an ultimate observable of the phase boundary

More model comparisons

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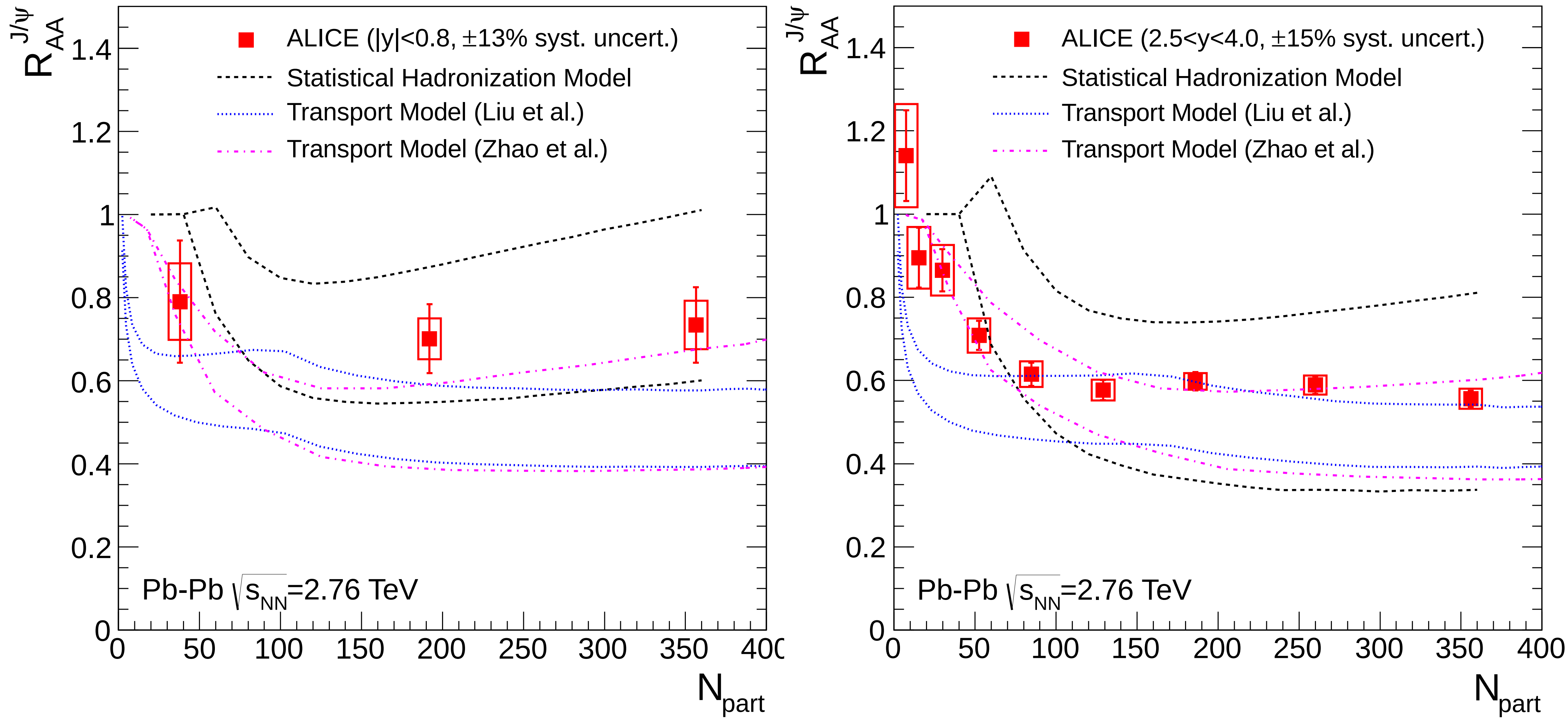


Both the transport and the statistical hadronization models reproduce the data

...with a component of production in deconfined matter ($\simeq$50%) or, respectively, at hadronization

We stand at a crossroad

Two models describe the data well, with two rather different physics.

While in the statistical model the hadronization is a process in which all quark flavors take part concurrently, in the kinetic model J/ψ survives as a hadron in the hot medium dominated by deconfined gluons and light quarks.

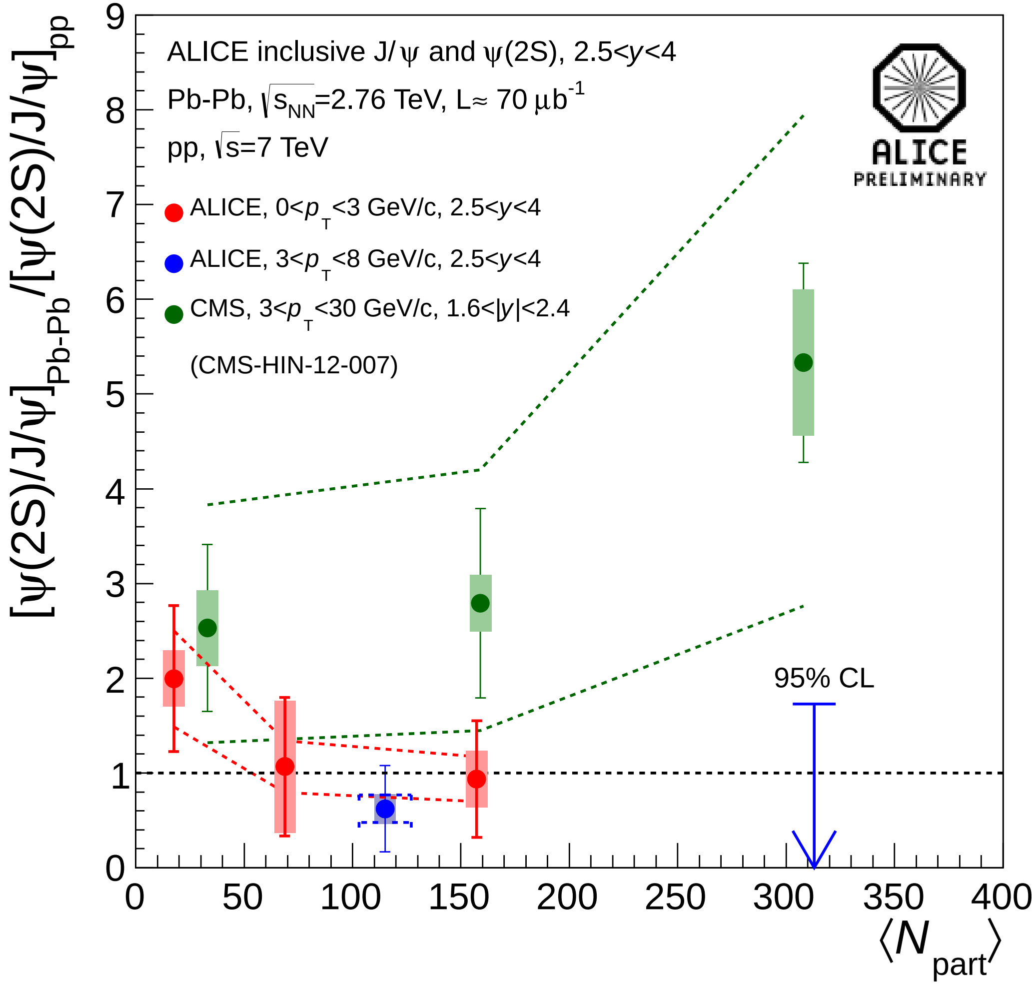
In the statistical model all charmonium states are generated exclusively at hadronization, while in the kinetic model only about half of the J/ψ yield (in central collisions) originates from deconfined charm and anti-charm quarks.

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

A precision measurement of $\sigma_{c\bar{c}}$ in Pb-Pb collisions, within reach with the proposed ALICE upgrade, will place an important constraint to models.

...and data on other charmonium states is crucial (ALICE Upgrade project)

$\psi(2S)$ production at the LHC



R. Arnaldi, arXiv:1211.2578

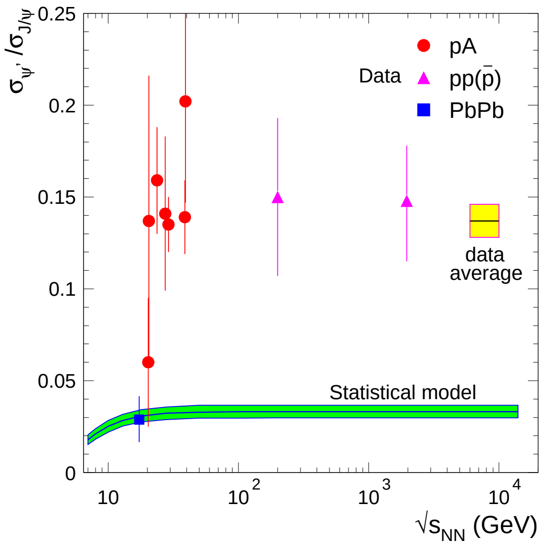
$$R = \frac{N^{\psi(2S)}_{\mathrm{Pb-Pb}}/N^{J/\psi}_{\mathrm{Pb-Pb}}}{N^{\psi(2S)}_{\mathrm{pp}}/N^{J/\psi}_{\mathrm{pp}}} = \frac{R^{\psi(2S)}_{\mathrm{AA}}}{R^{J/\psi}_{\mathrm{AA}}}$$

N - production yields

discrepancy ALICE / CMS ?

not conclusive as uncertainties are large

at SPS (NA50): $R \simeq 0.24$



The weight of the $\psi(2S)$ measurement

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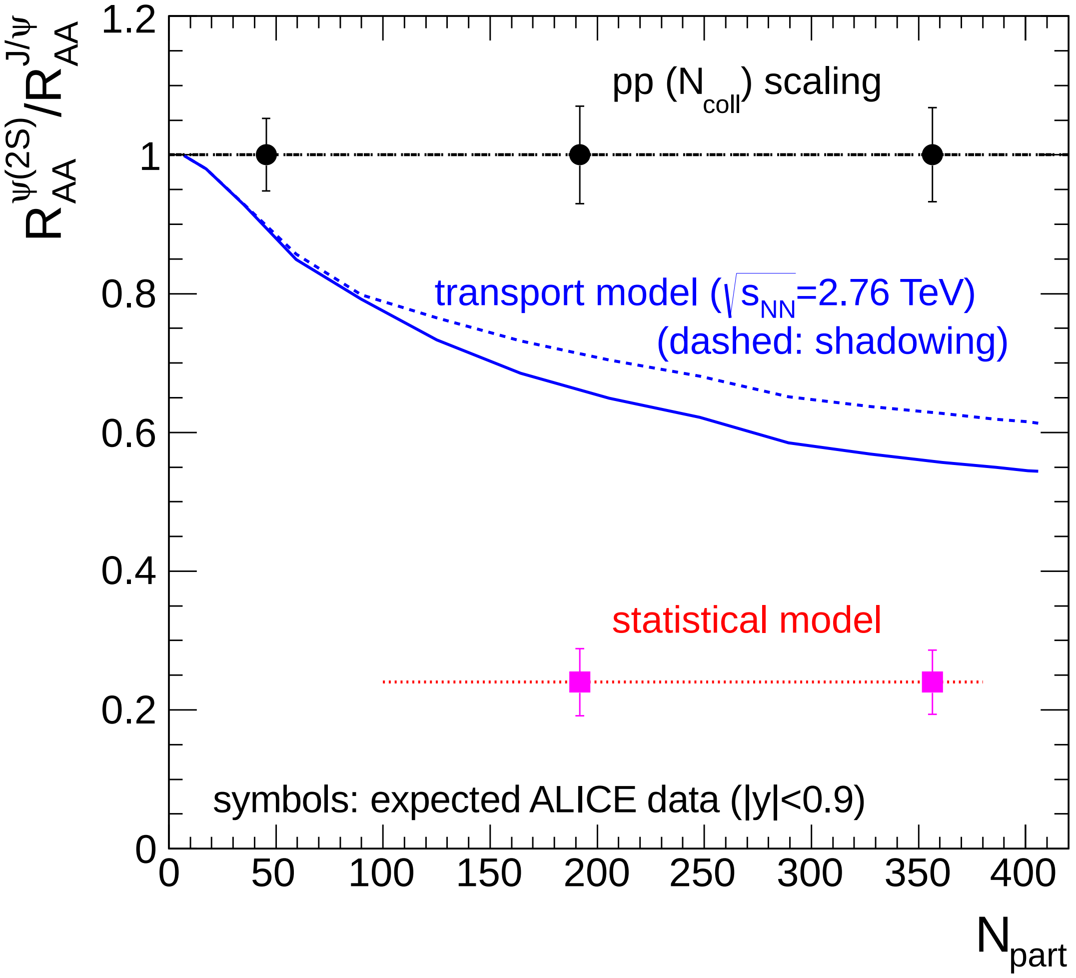
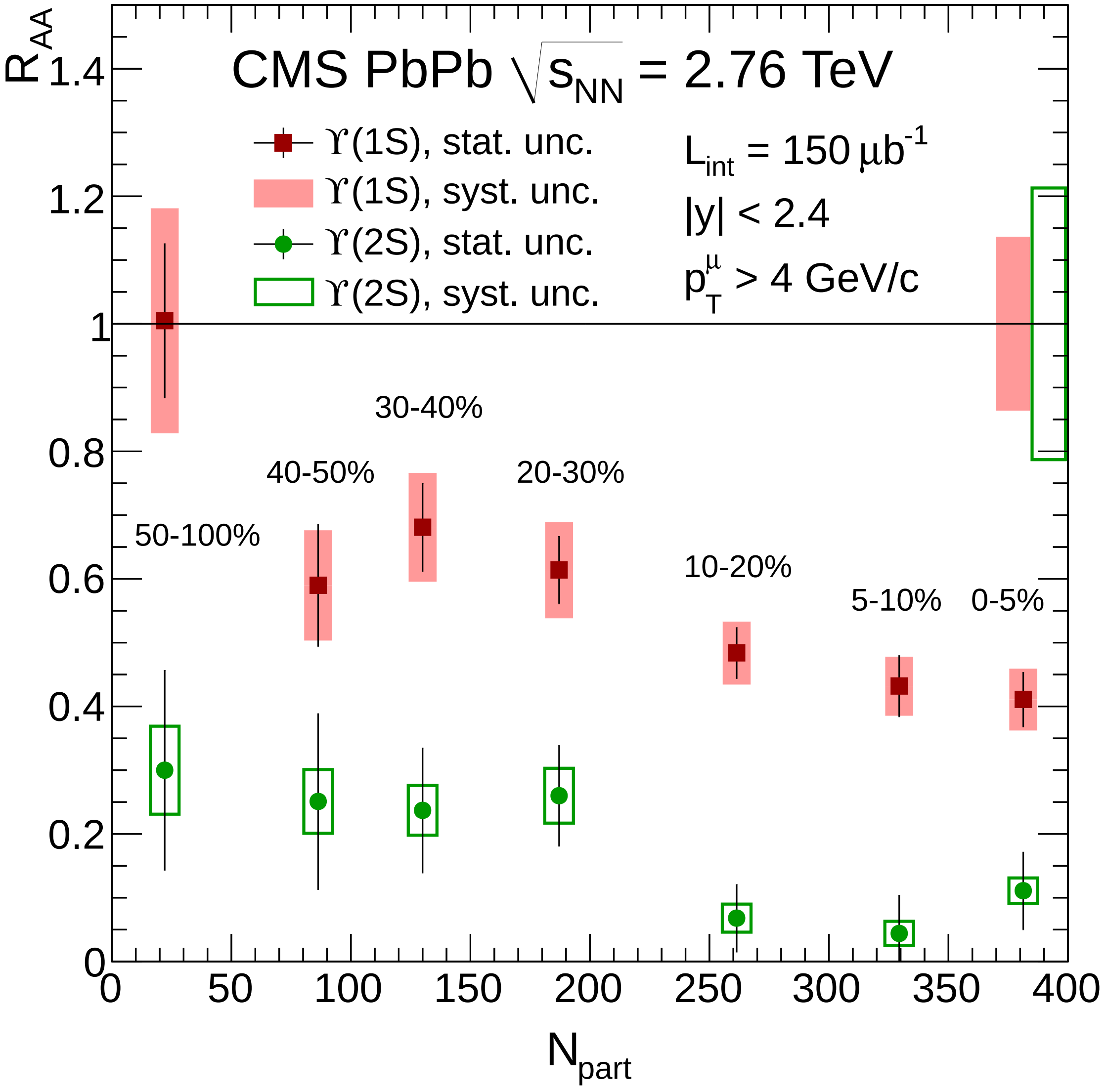
$R < 1$ expected in both models, different magnitudes predicted (p_{T}-integrated)

Transport model:
Zhao, Rapp, NPA 859 (2011) 114
and priv. comm.



Central Barrel: measurement possible only with upgrade (10 nb^{-1})
Muon Spectrometer: a first glimpse with baseline data (1 nb^{-1}), a real measurement only with upgrade

Bottomonium at the LHC



CMS, PRL 109 (2012) 222301

“sequential suppression”
(less-bound states melt)

ratio of excited states to $\Upsilon(1S)$:

Data, Pb–Pb:
$\Upsilon(2S)/\Upsilon(1S)$=0.12±0.03±0.02
$\Upsilon(3S)/\Upsilon(1S)$=0.02±0.02±0.02

thermal model:
$\Upsilon(2S)/\Upsilon(1S)$=0.033
$\Upsilon(3S)/\Upsilon(1S)$=0.005

Data, pp:
$\Upsilon(2S)/\Upsilon(1S)$=0.56±0.13±0.02
$\Upsilon(3S)/\Upsilon(1S)$=0.41±0.11±0.04

Bottomonium at the LHC in SHM

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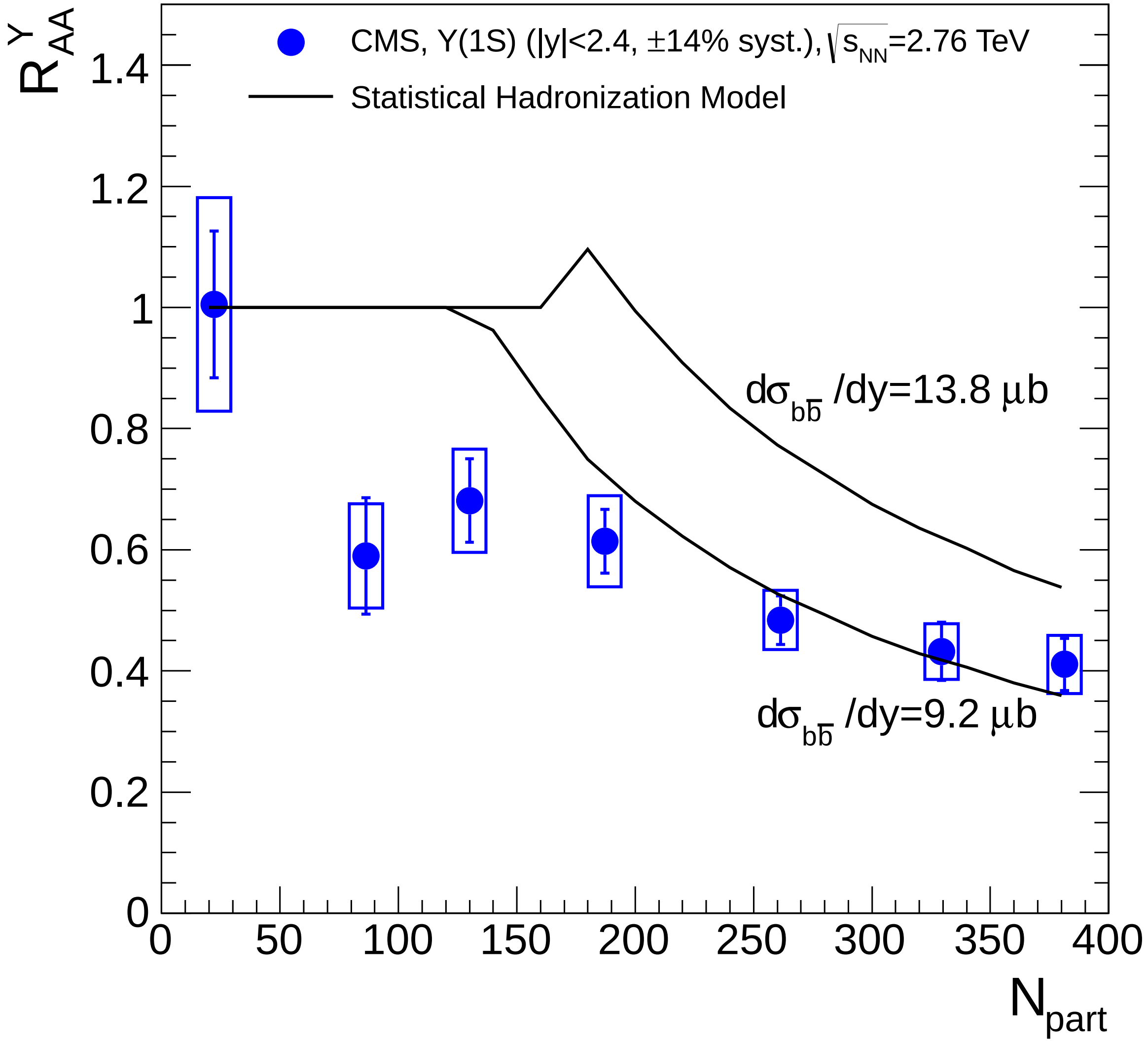

$$\frac{d\sigma_{b\bar{b}}}{dy} = 13.8\ \mu b \text{ (MNR x0.8 shad.)}$$

fair description by model

Data: CMS, PRL 109 (2012) 222301

Bottomonium at the FHC in SHM

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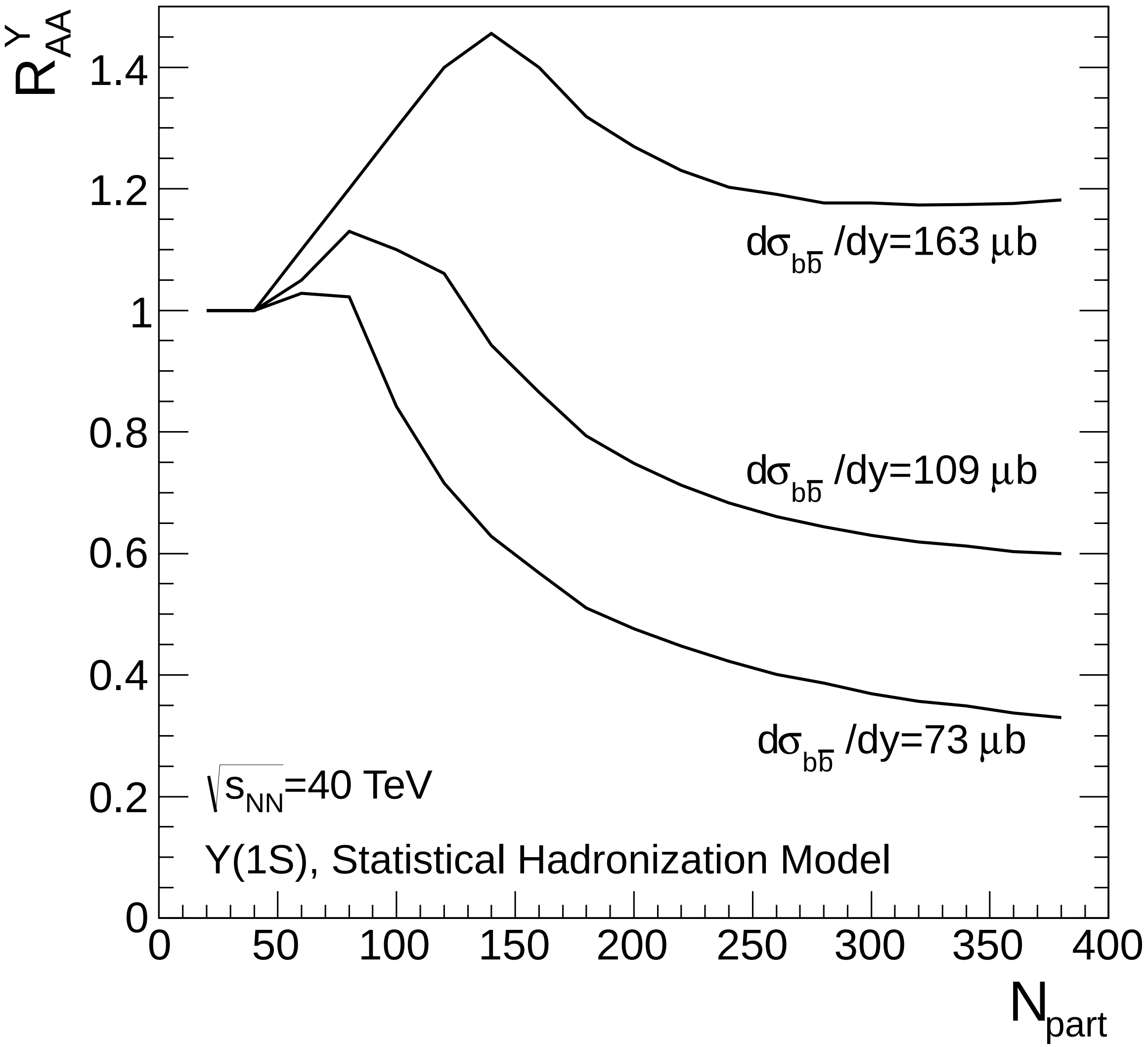

$\frac{\mathrm{d}\sigma_{b\bar{b}}}{\mathrm{d}y} = 109\ \mu$b (MNR x0.7 shad.)

$V = 12000$ fm^3

$Y(1S)$ in pp: 7 TeV data scaled by MNR factor of $\sigma_{b\bar{b}}$

Summary and outlook

abundance of hadrons with light quarks consistent with chemical equilibration

the story of J/ψ as a (rare) probe for QGP is long and rather intricate

went from "thermometer" to probe of the phase boundary (story continues)

(I think:) everybody agrees that we see (re)combination of charm quarks at LHC

...(in QGP and/or) at the phase boundary ...maybe similar at RHIC (SPS?)

model results dependent on $\sigma_{c\bar{c}}$, to be constrained by measurements

interesting "disappearance" pattern in the bottom (Υ) sector observed

do bottom quarks also thermalize at LHC? (at RHIC?)

will Υ add more weight to the phase boundary?

will this be clarified (only) at the FHC? :)

Backup slides

J/ψ production relative to charm

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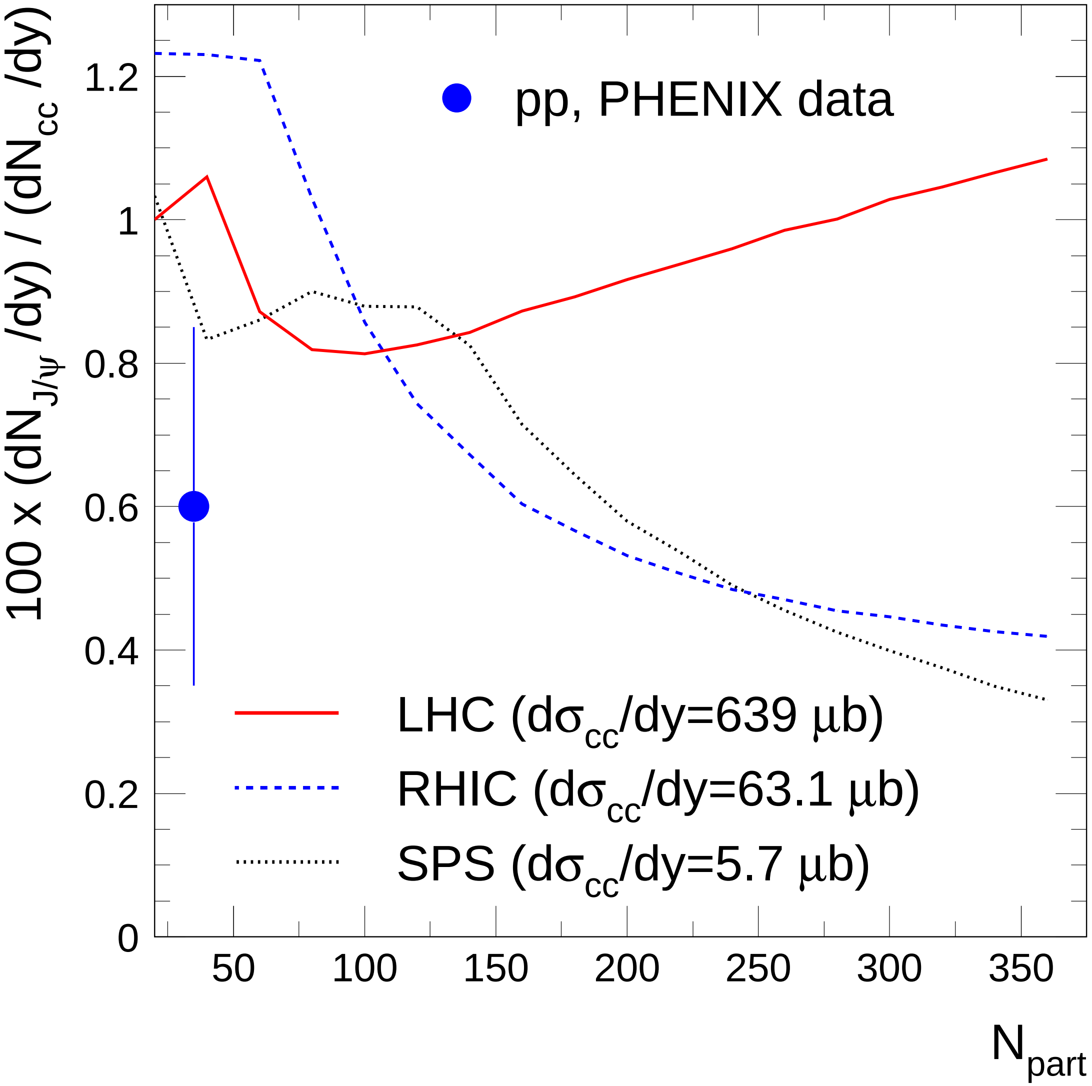
...the most "solid" observable ...with similar features as R_{AA}



- similar values at RHIC and SPS

  ...with differences in fine details

  ...determined by canonical suppression of open charm

  same with Υ at RHIC and LHC?

- enhancement-like at LHC

  can. suppr. lifted, quadratic term dominant

J/ψ cross sections in pp (corona)

x2

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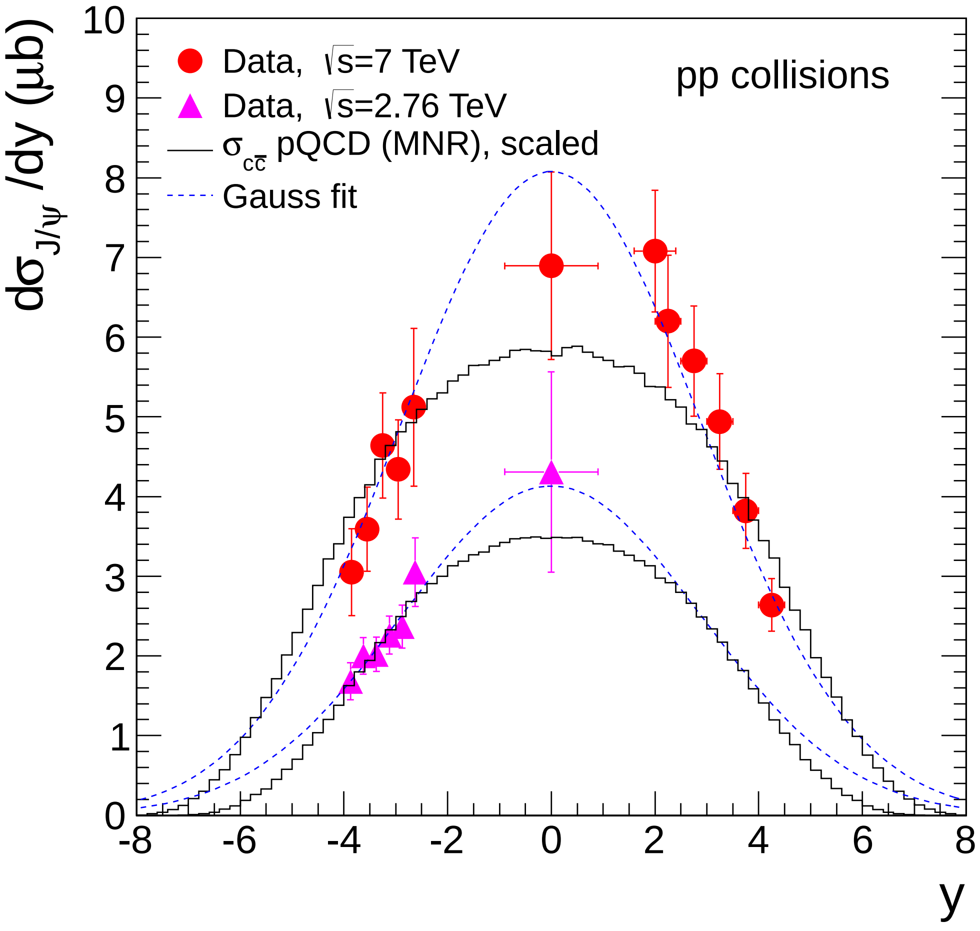

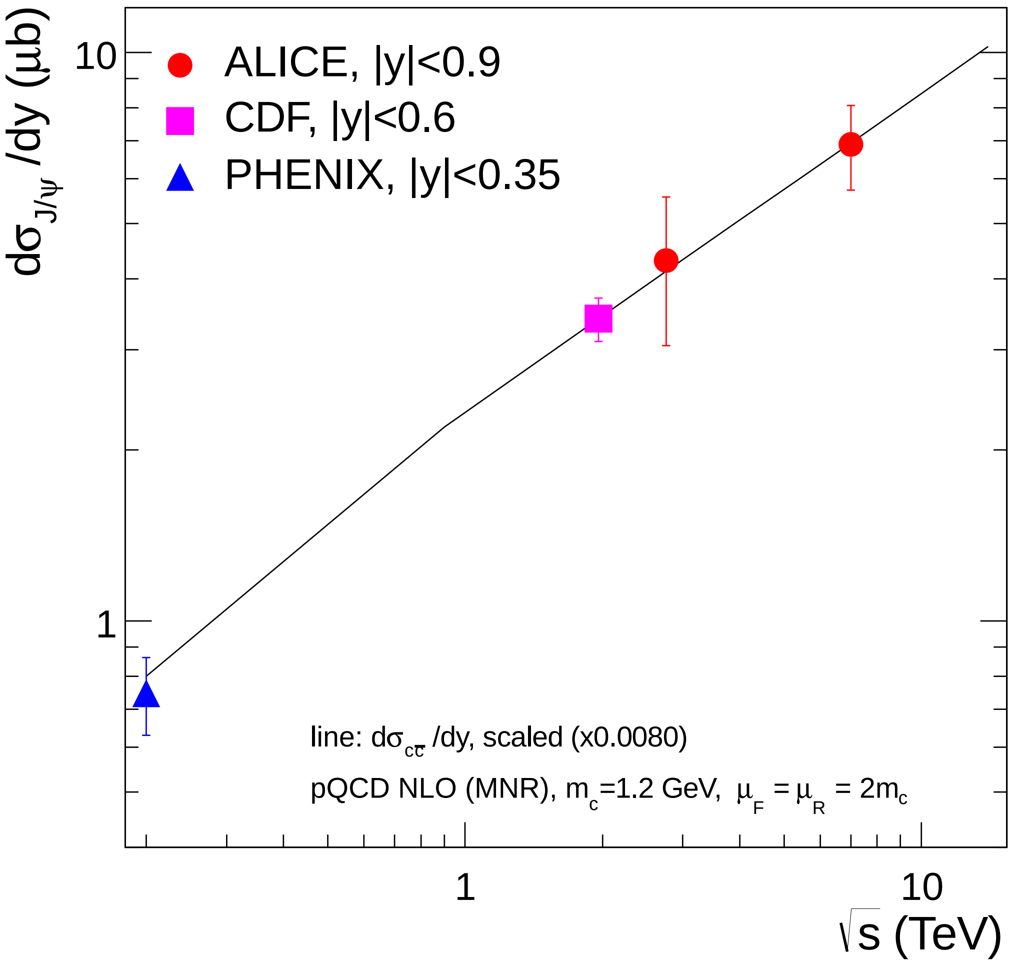

J/ψ: "core" and "corona"

x3

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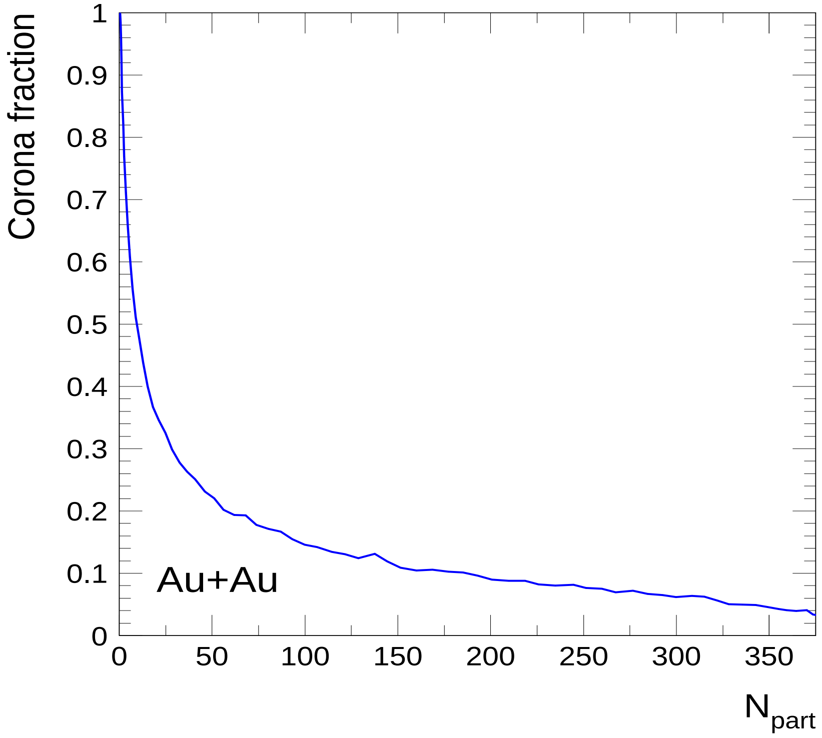
realistic nuclei: "core" (QGP, apply stat. hadr.) and "corona" (NN coll.)

$$N_{J/\psi}^{core} = g_c^2 n_{J/\psi}^{th} V^{core}$$

$$g_c \sim N_{c\bar{c}}^{dir} = N_{coll}^{core} \sigma_{c\bar{c}}^{pp} / \sigma_{inel}^{pp}$$

$$N_{J/\psi}^{corona} = N_{coll}^{corona} \sigma_{J/\psi}^{pp} / \sigma_{inel}^{pp}$$



$$\Rightarrow N_{J/\psi} = N_{J/\psi}^{core} + N_{J/\psi}^{corona}$$

J/ψ at RHIC: rapidity dependence, R_{AA}

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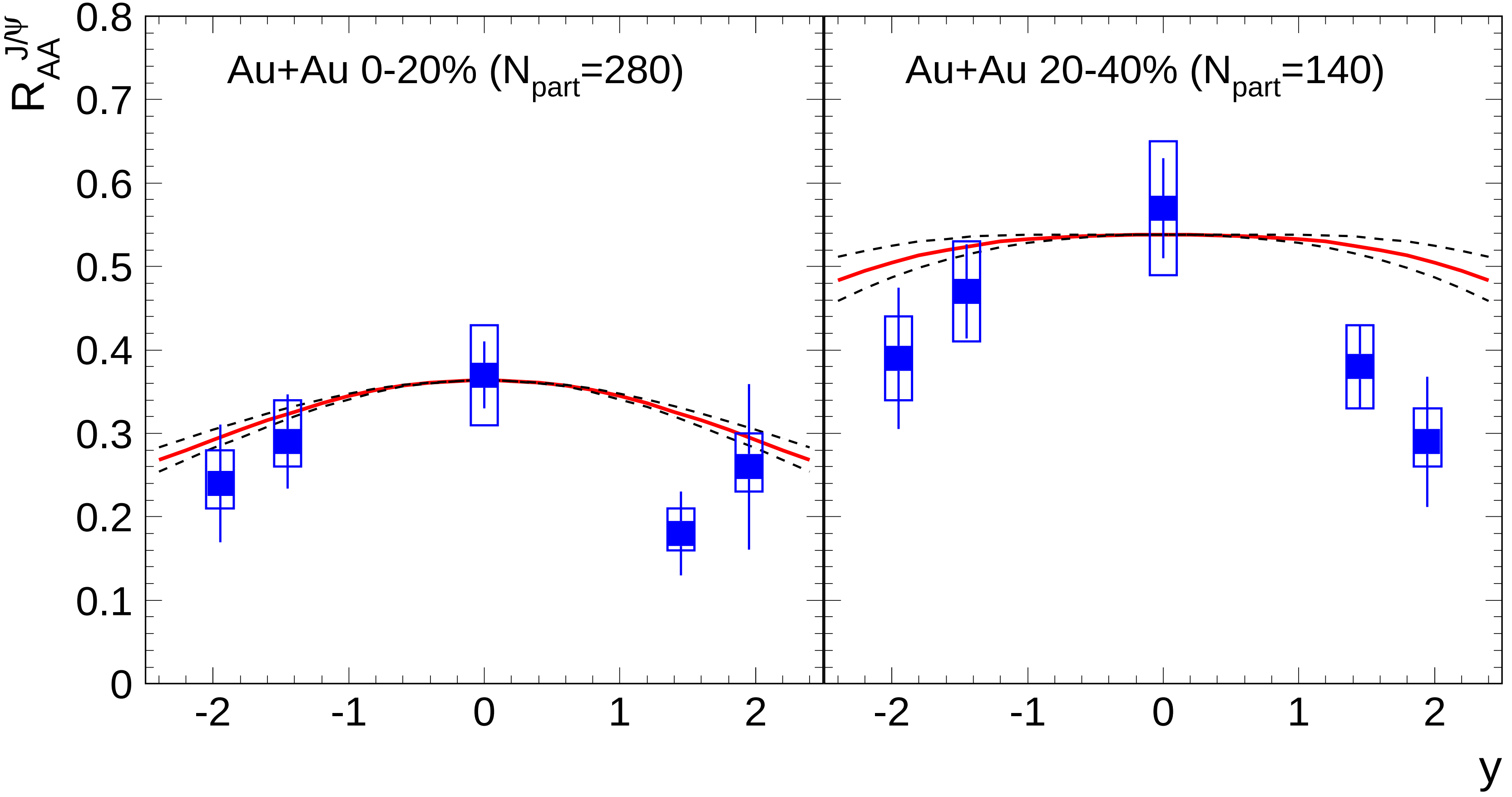

model reproduces data (PHENIX, nucl-ex/0611020) very well (pQCD $\sigma_{c\bar{c}}$)

direct indication of J/ψ generation at hadronization (enhanced at y=0)

(constant R_{AA} expected within Debye screening model)

Phys. Lett. B 652 (2007) 259

J/ψ at RHIC: effect of shadowing

$\boxed{x5}$

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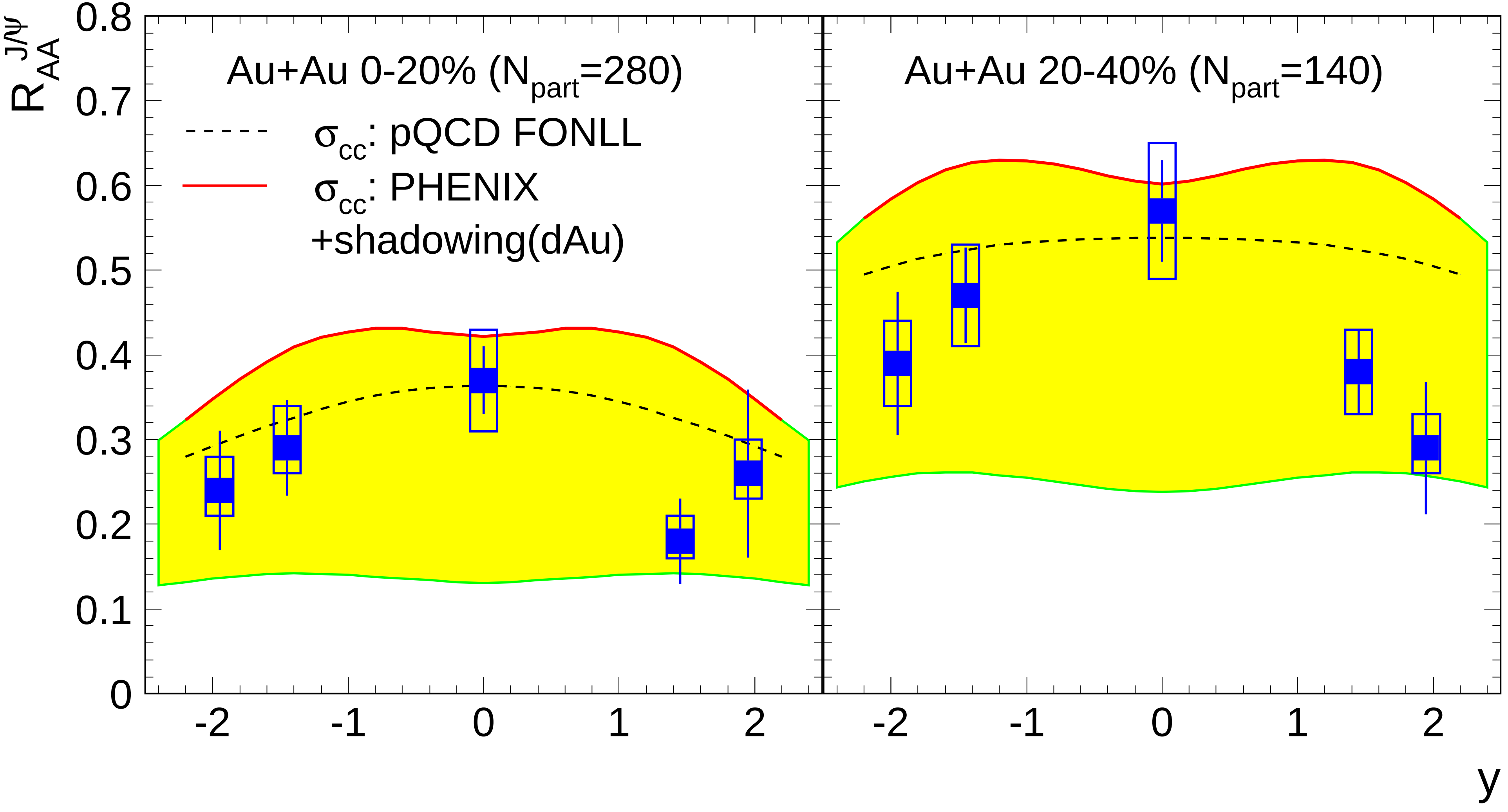
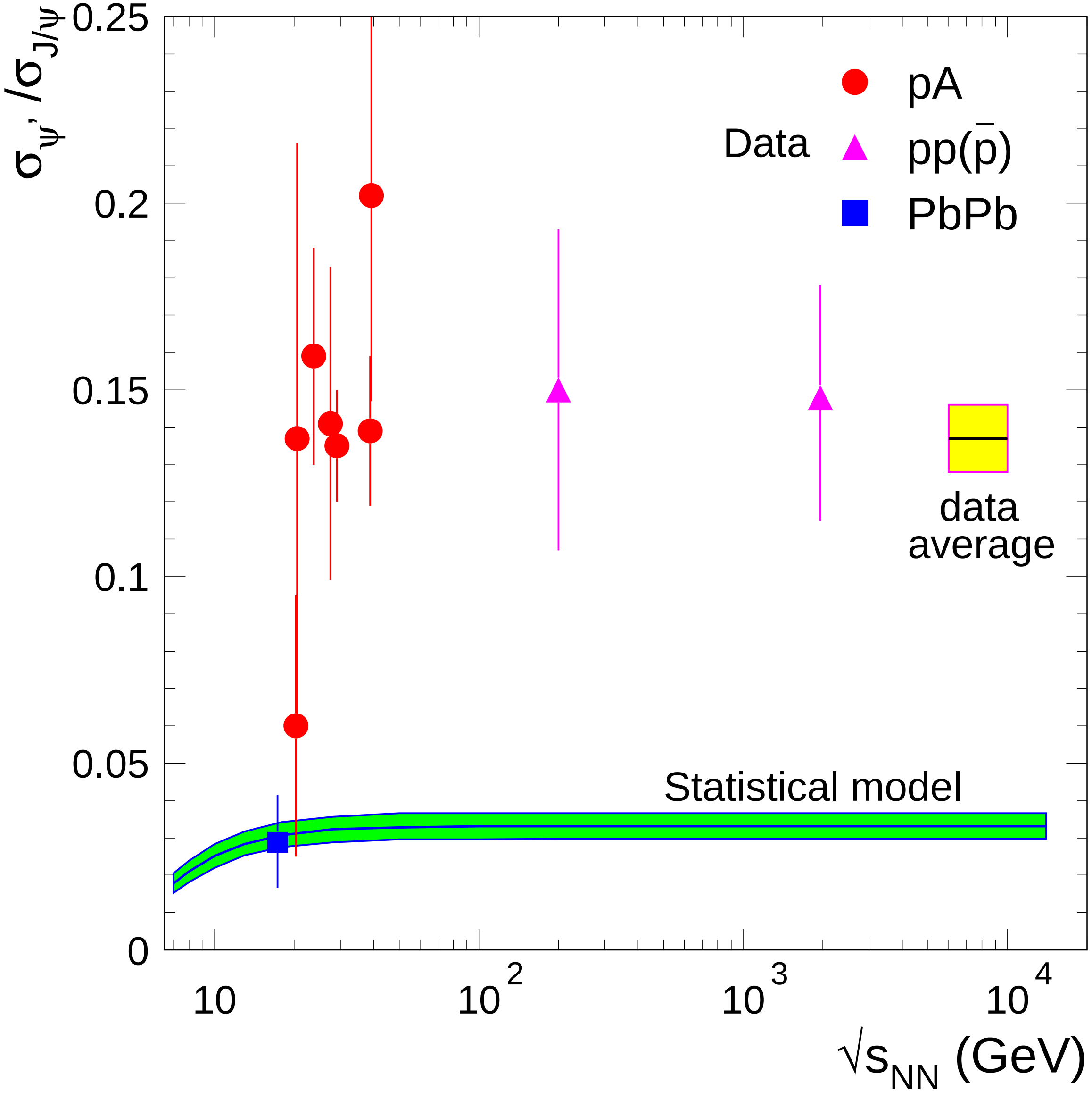


model describes data with PHENIX $\sigma_{c\bar{c}}$ (lower error plotted)

J. Phys. G 35 (2008) 104155

The "null hypothesis"



charmonium in pp(A) collisions

...is far from thermalized (model is for AA)

...while a thermal value is reached in central PbPb (NA50, SPS)

The "null hypothesis" for bottomonium

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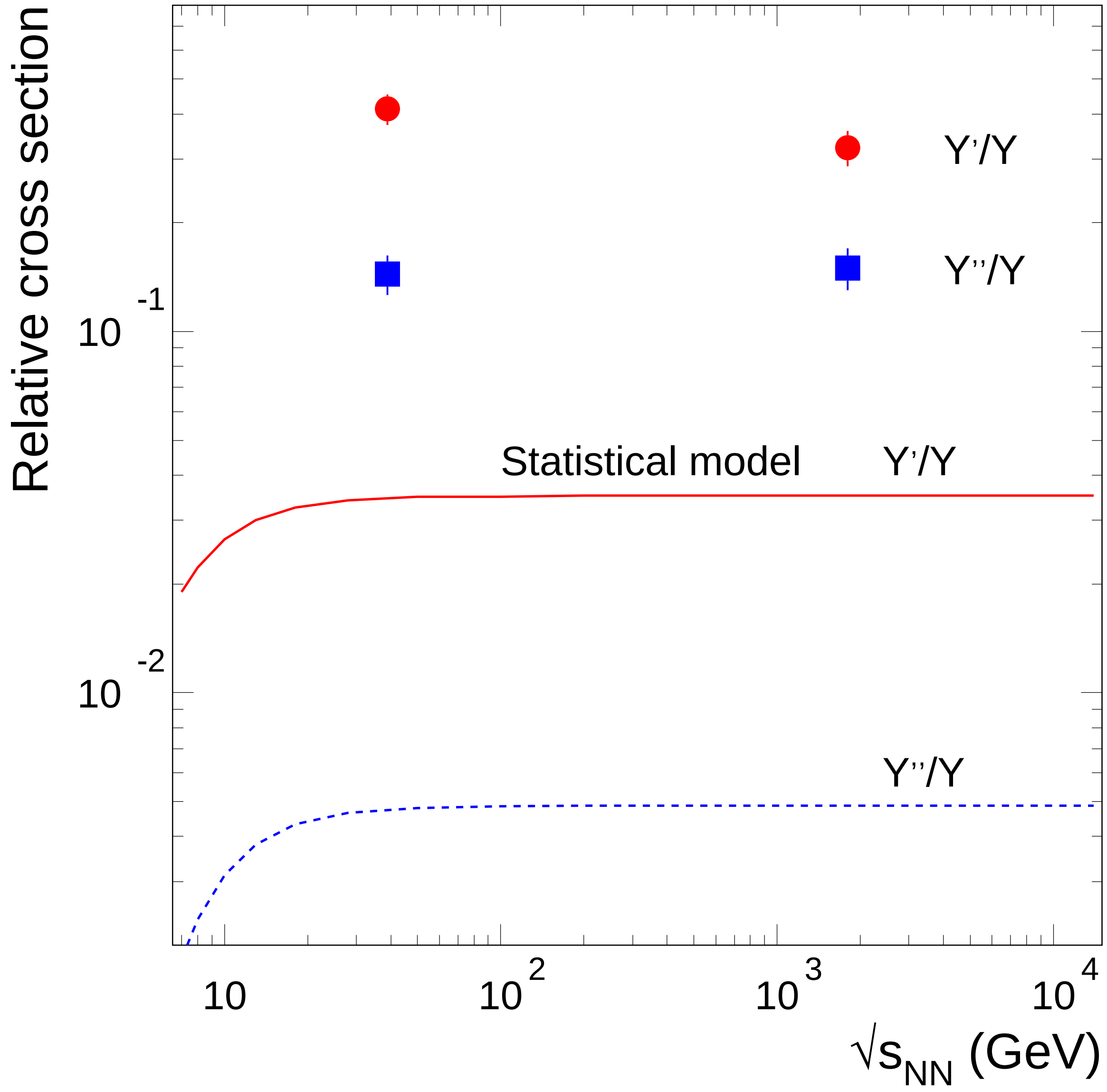

bottonium in pp(A) collisions

...is far from thermalized (model is for AA)

...will we find a thermal value at LHC?