Quarkonium in the statistical hadronization model
or better
Quarkonium and the phase boundary of QCD

A. Andronic – GSI Darmstadt

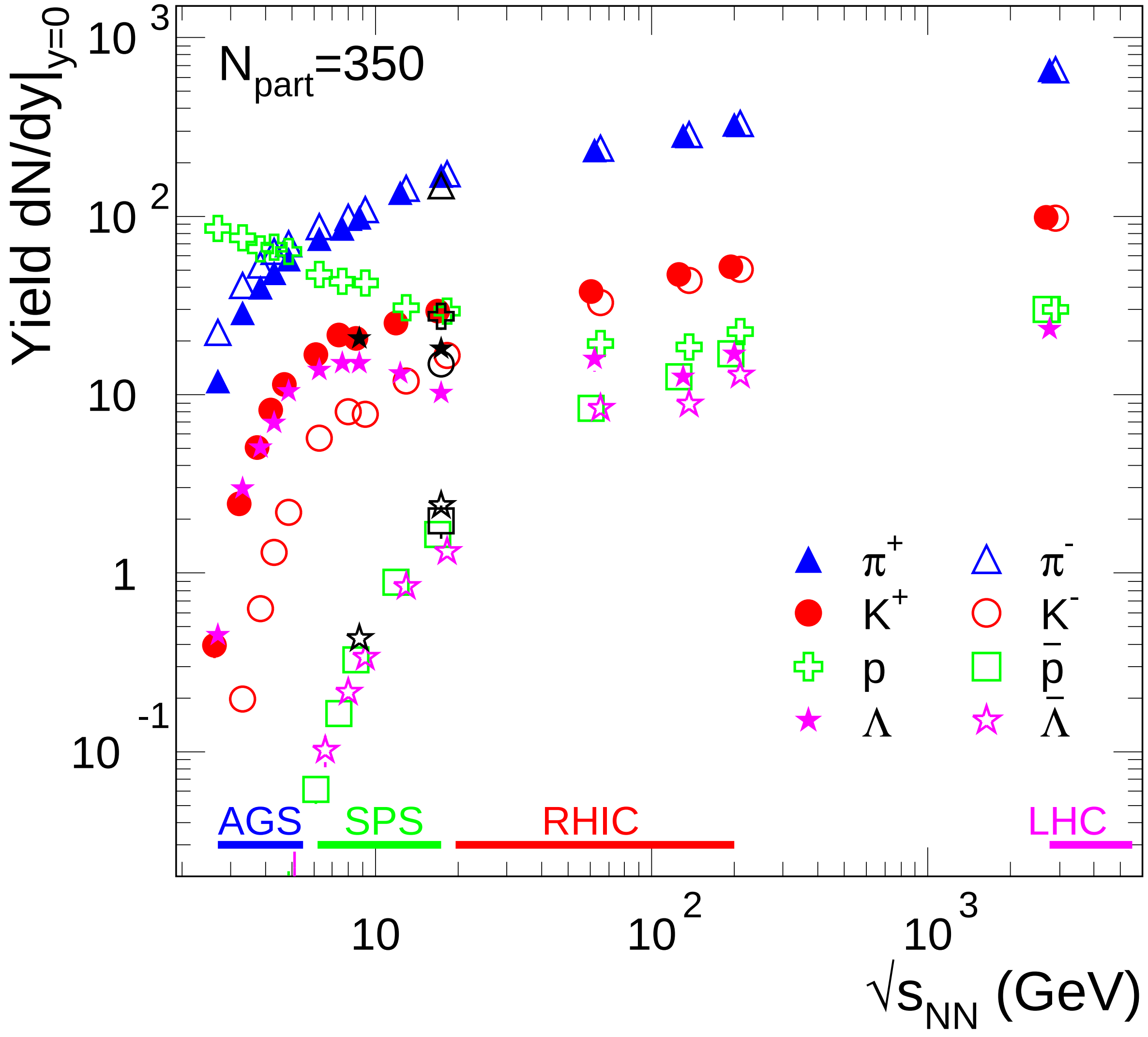
- Chemical freeze-out of light quark (u,d,s) hadrons
- ...and the connection to the QCD phase diagram
- Charmonium
- Bottomonium
- Outlook to full energy LHC and FCC

AA, P. Braun-Munzinger, K. Redlich, J. Stachel, JPG 38 (2011) 124081 [arXiv:1106.6321]
arXiv:1210.7724, 1409.5778 (and refs. therein)

Chemical freeze-out: hadron yields (central collisions)

A.Andronic@GSI.de

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

A.Andronic@GSI.de

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

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

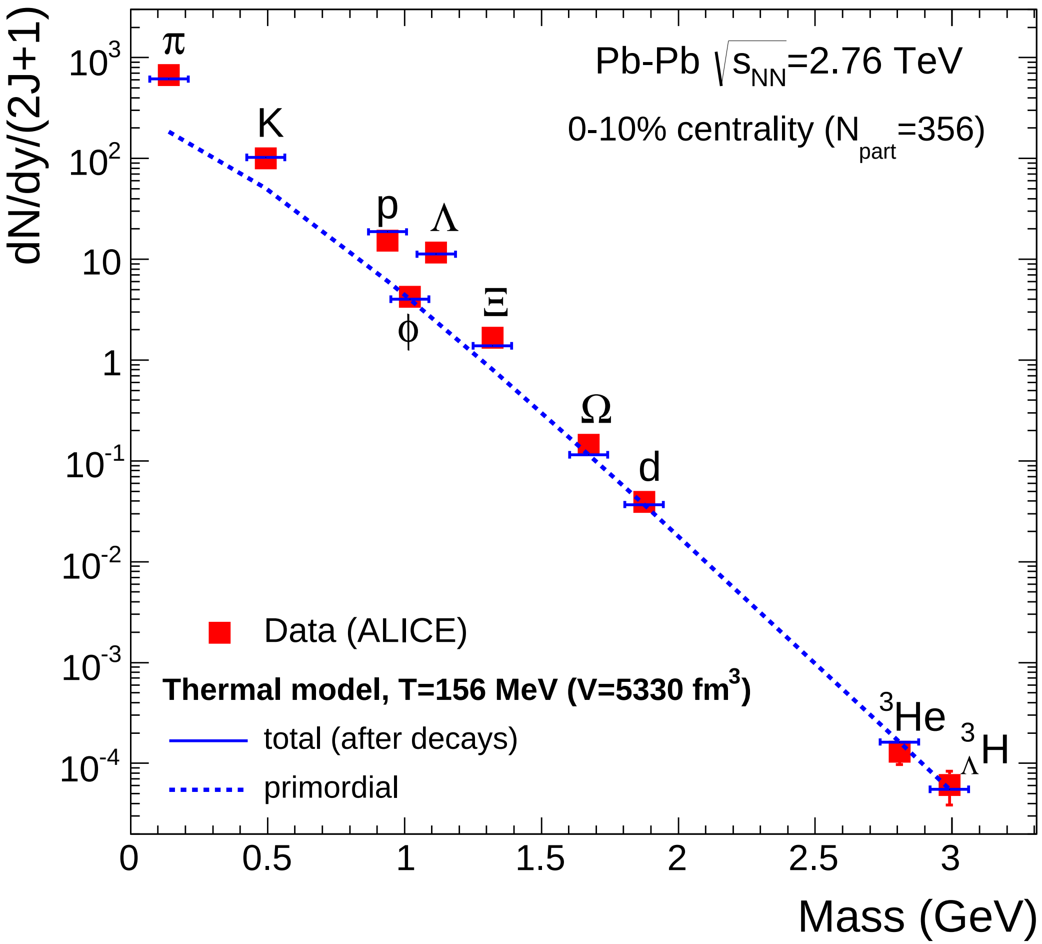
quantum no. conservation:

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

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

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

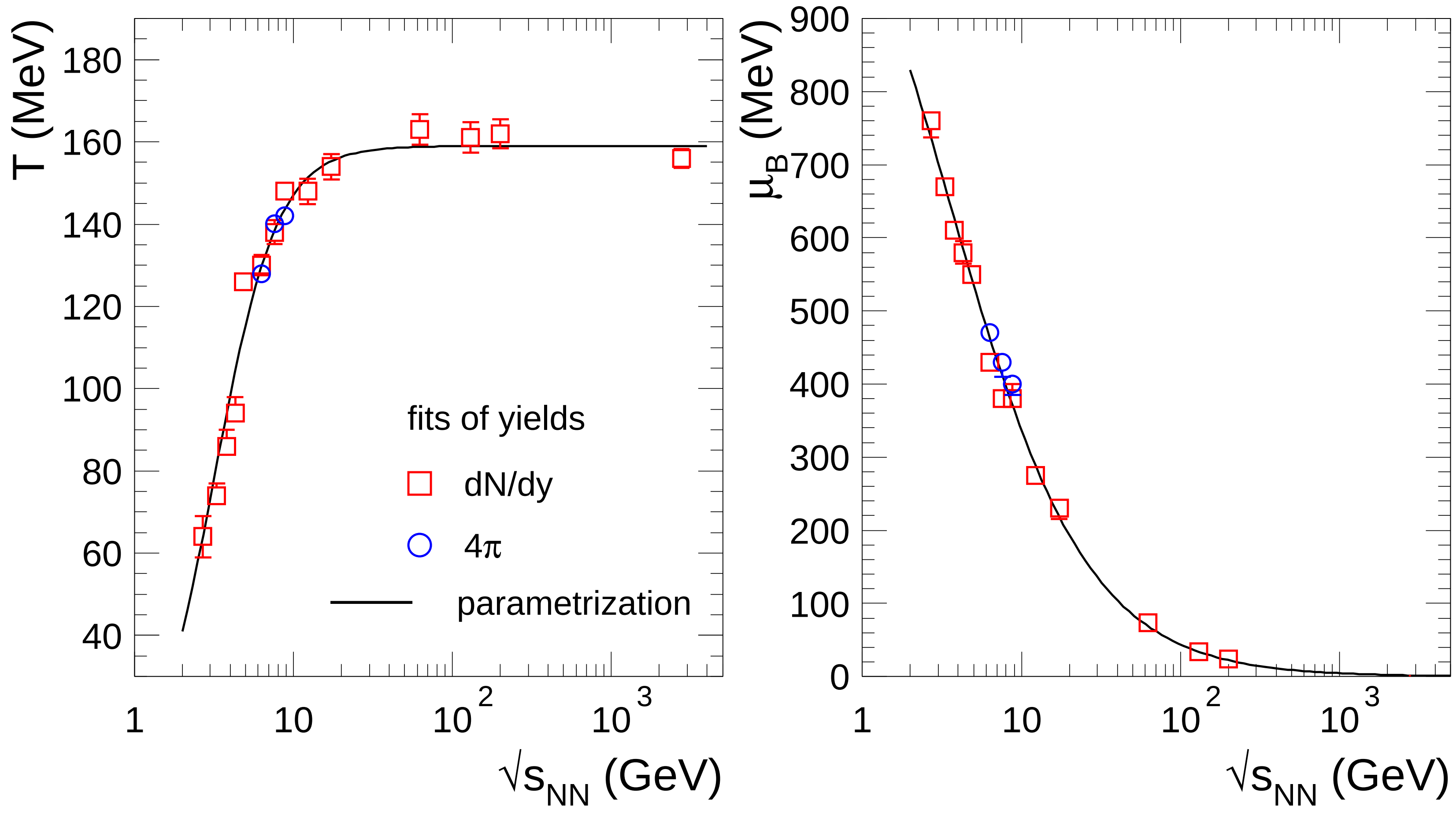
N_i: hadron yield ⇒ (T, μ_B, V)



Hadron abundances consistent with a thermally equilibrated system

Energy dependence of T, μ_B (central collisions)

A.Andronic@GSI.de



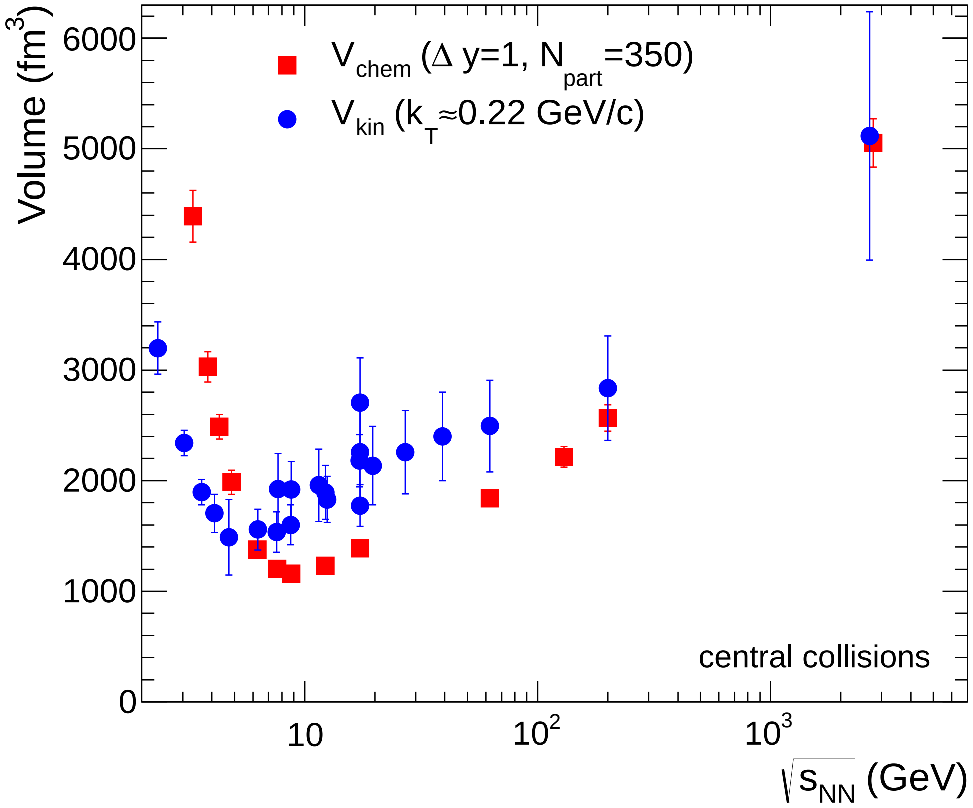
thermal fits exhibit a limiting temperature: $T_{lim} = 159 \pm 2$ MeV

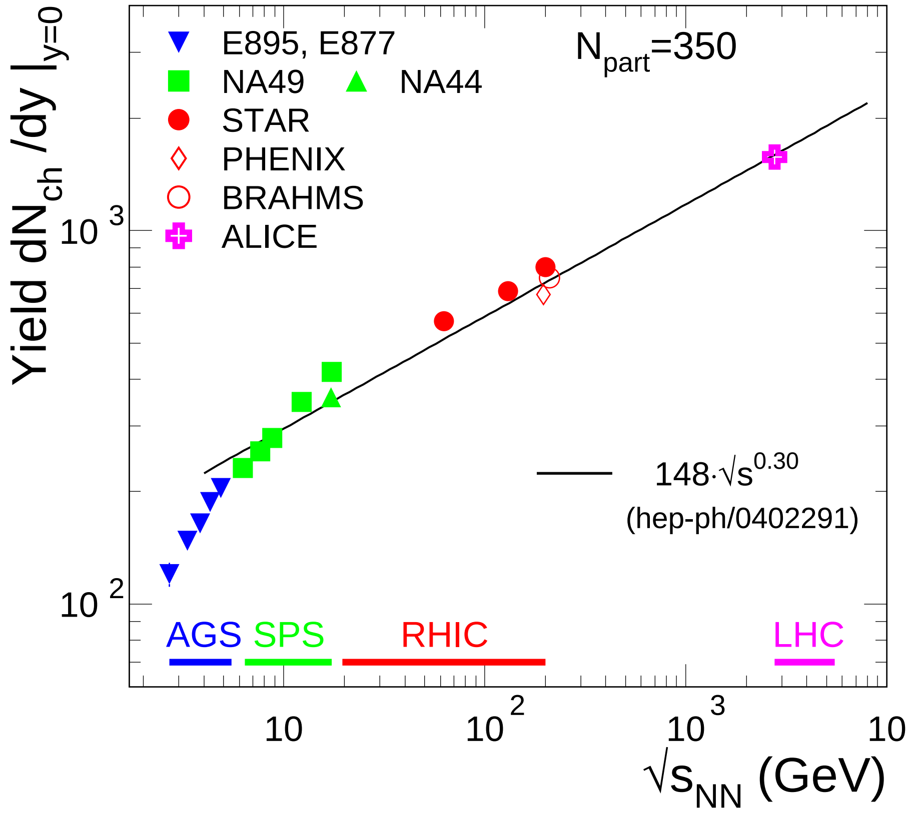
$$T = T_{lim} \frac{1}{1+\exp(2.60-\ln(\sqrt{s_{NN}(\mathrm{GeV})})/0.45)}, \qquad \mu_B[\mathrm{MeV}] = \frac{1307.5}{1+0.288\sqrt{s_{NN}}(\mathrm{GeV})}$$

PLB 673 (2009) 142 ...with updates

Volume in central collisions

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





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

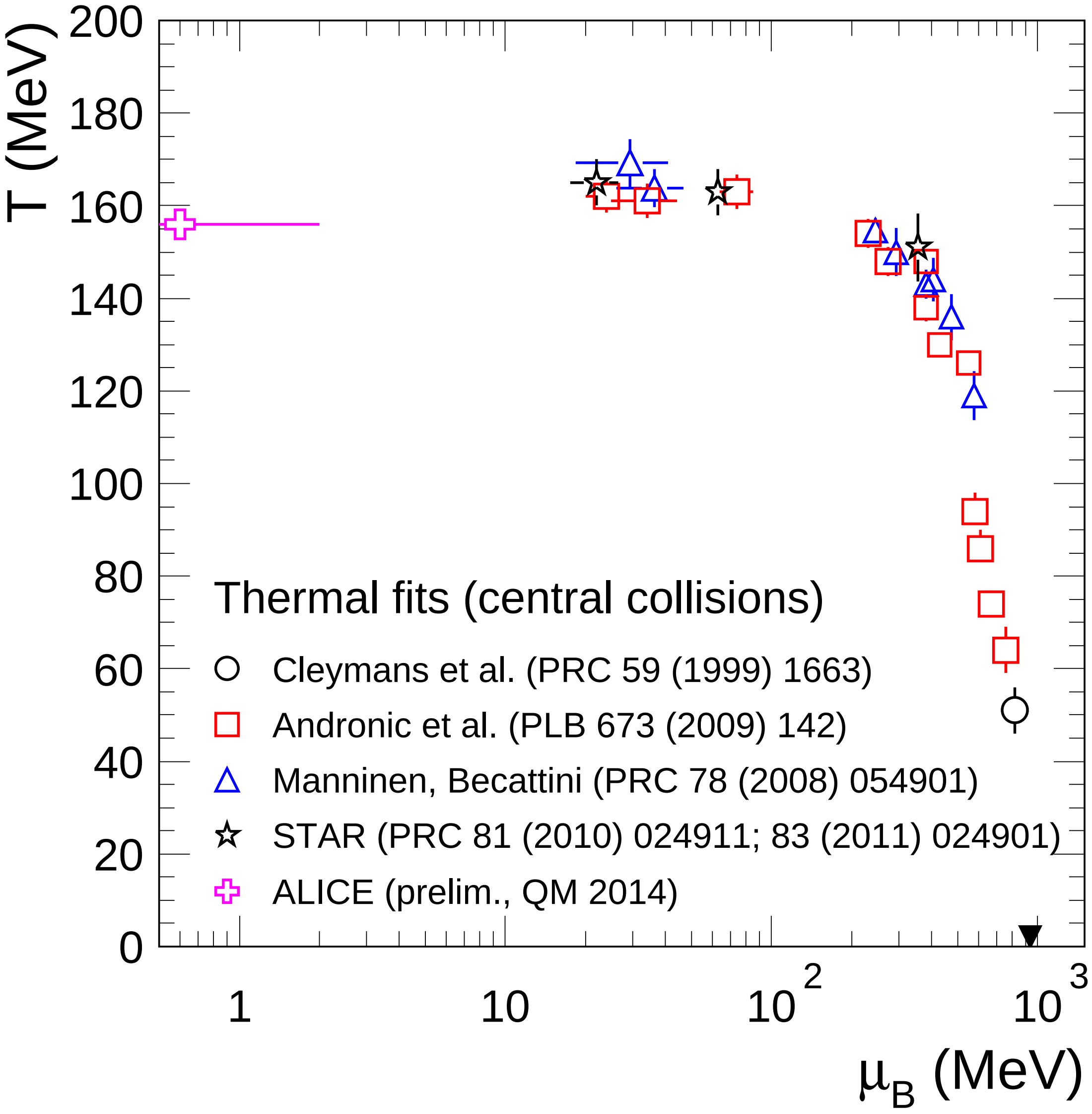
HBT data: ALICE, PLB 696, 328 (2011)

5.1 TeV: $V = 6400$ fm^3

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

Connection to the phase diagram of QCD

A.Andronic@GSI.de



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

Lattice QCD, $\mu_B = 0$:
crossover T=145-165 MeV

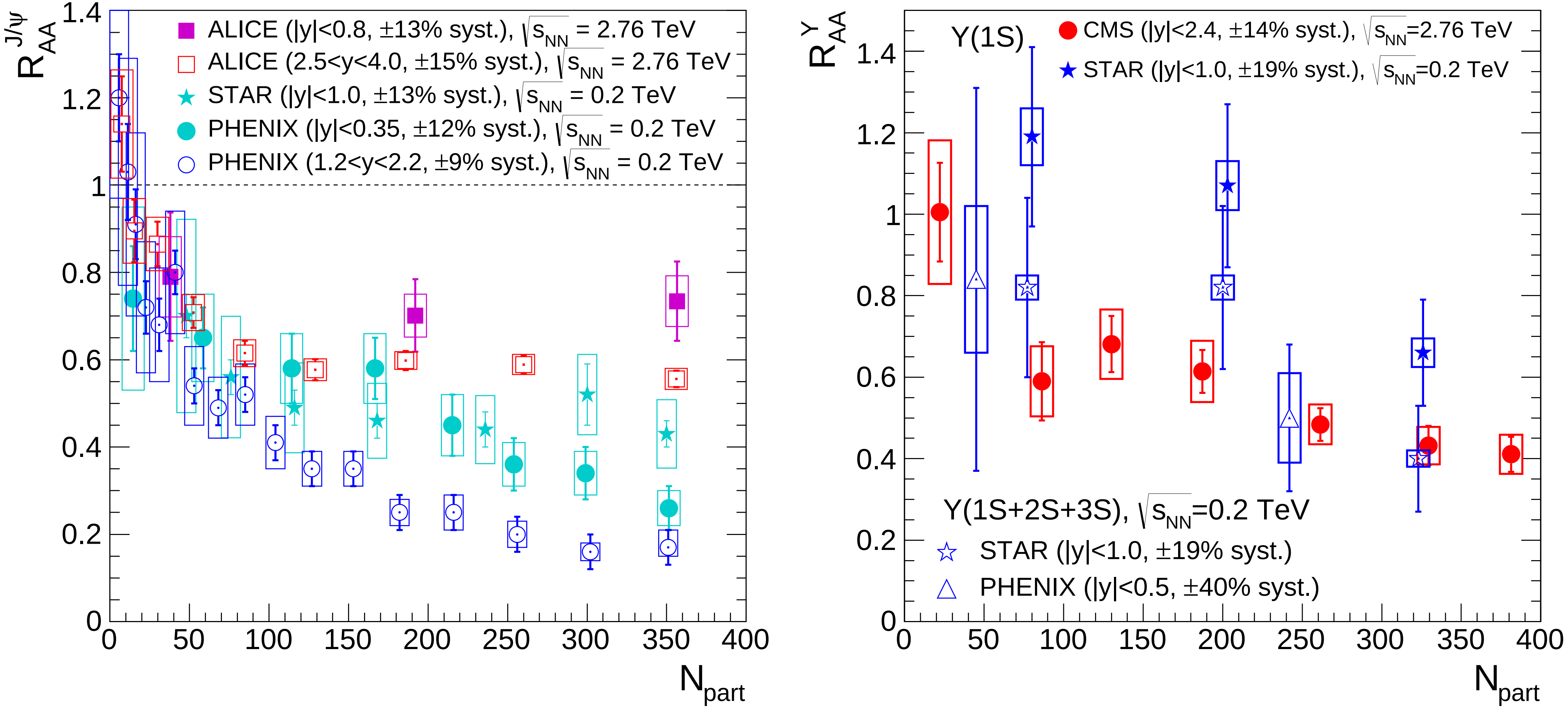
BW, JHEP 1009 (2010) 073

HotQCD arXiv:1407.6387

...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

We turn now to quarkonium



arXiv:1409.5778

Statistical hadronization of heavy quarks: assumptions

A.Andronic@GSI.de

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$_c$? ...yet to be settled (LQCD)

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

Statistical hadronization of heavy quarks: assumptions

A.Andronic@GSI.de

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$_c$? ...yet to be settled (LQCD)

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

if all this is 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

A.Andronic@GSI.de

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

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

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

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

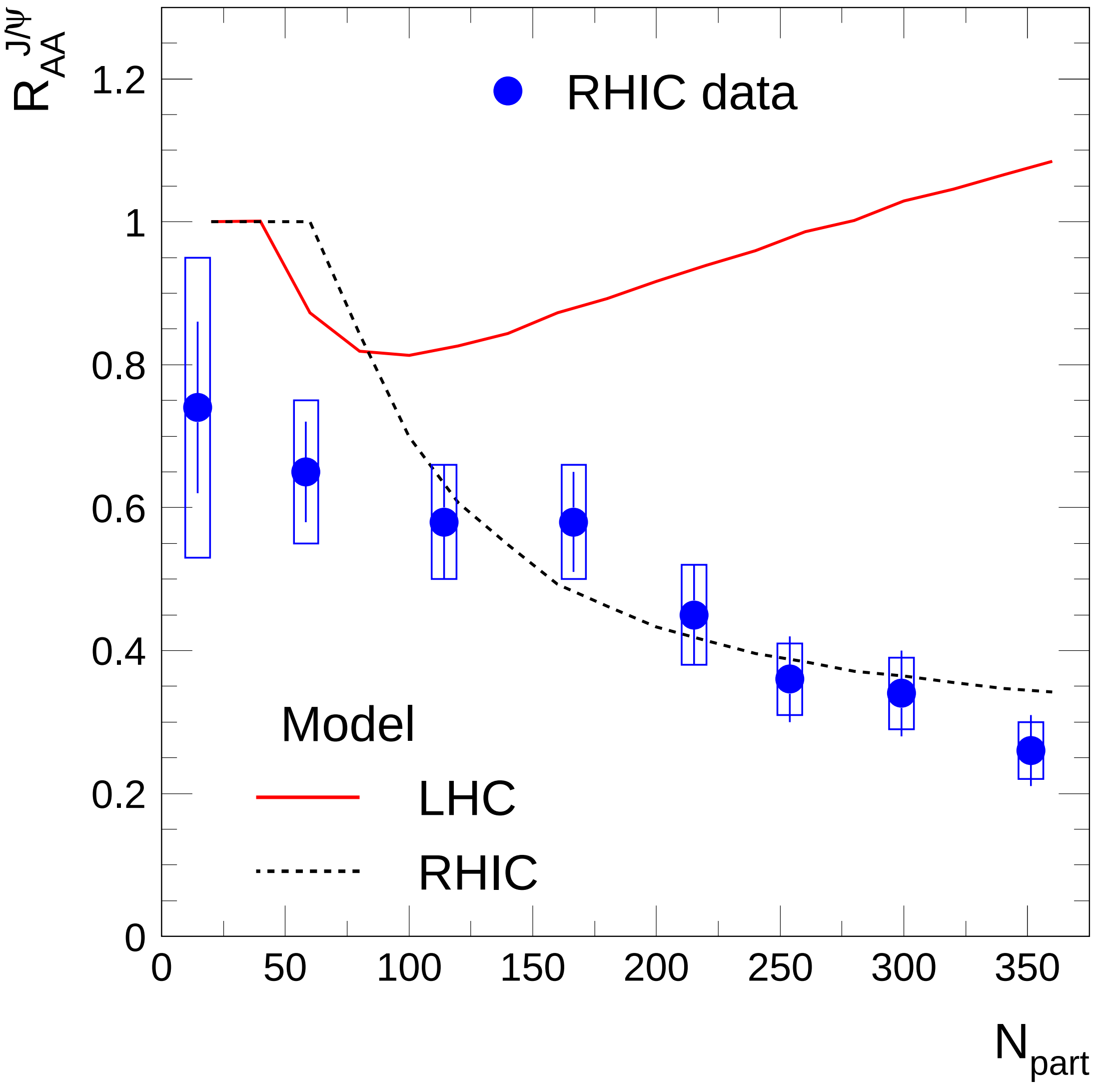
Outcome: $N_D = g_c V n_D^{th} I_1/I_0 \quad N_{J/\psi} = g_c^2 V n_{J/\psi}^{th}$

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

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

Charmonium in the statistical hadronization model

A.Andronic@GSI.de



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

- "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)

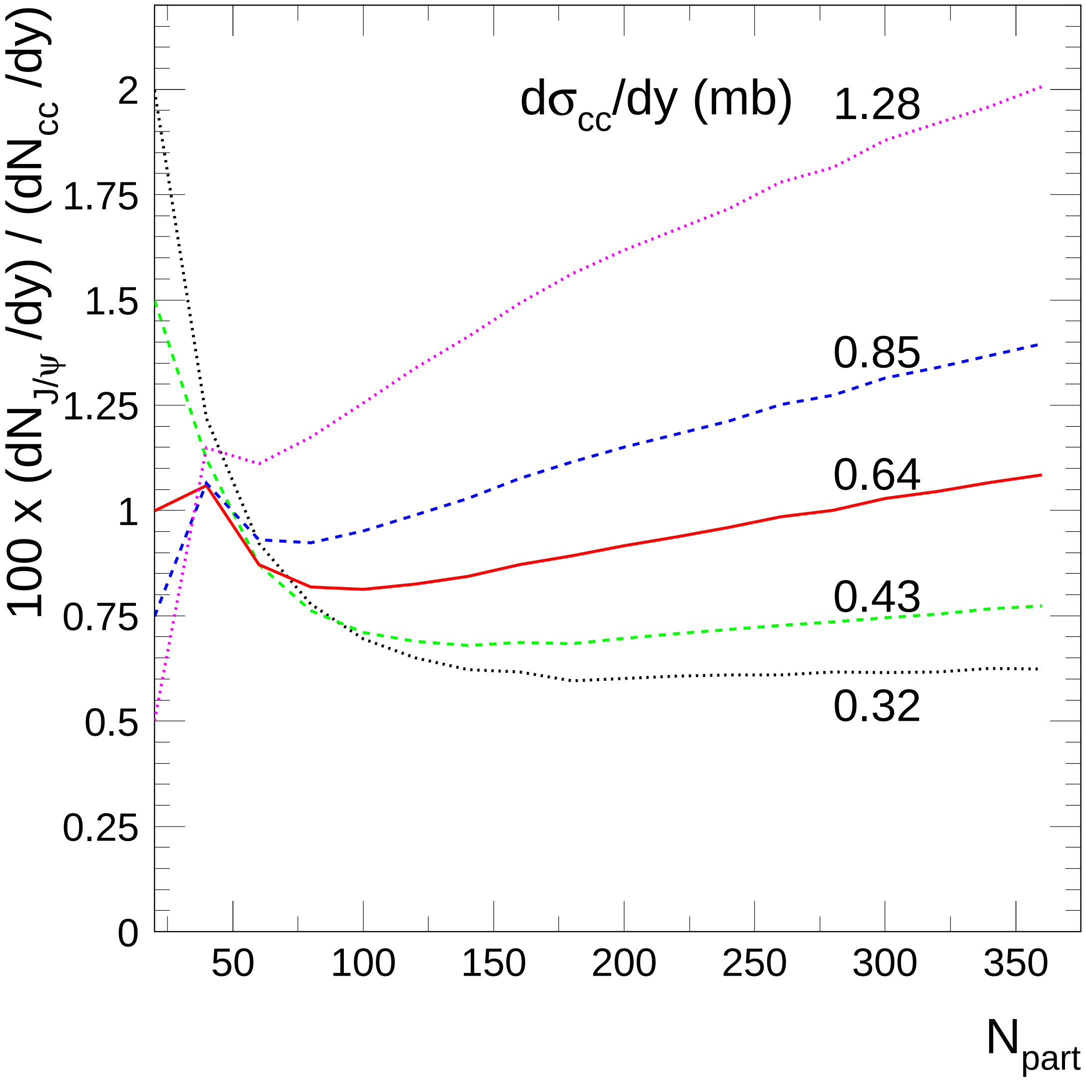
$\sigma_{c\bar{c}}$: ∼10x, Volume: 2.2-3x

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

A.Andronic@GSI.de



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

(“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

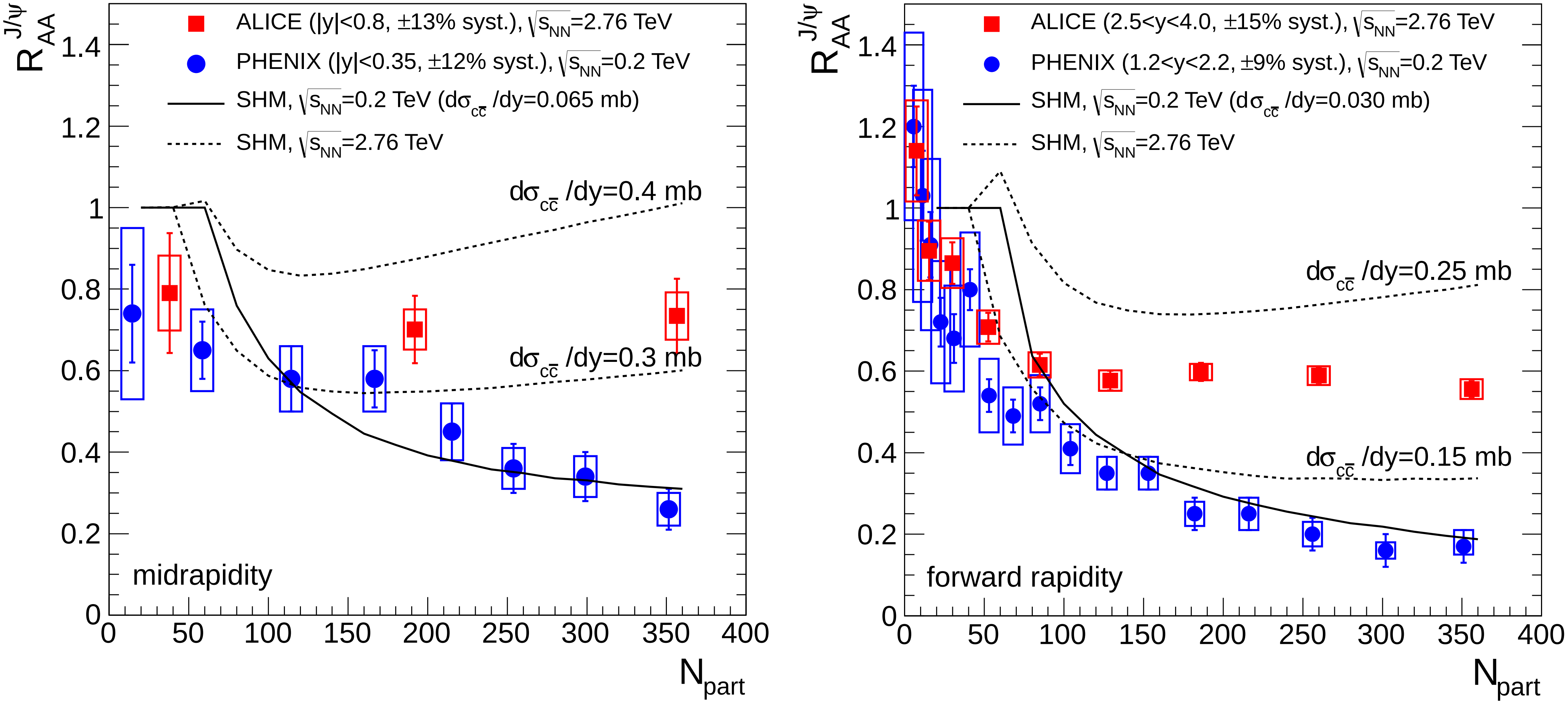
  it can be more dramatic at FHC

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

A.Andronic@GSI.de

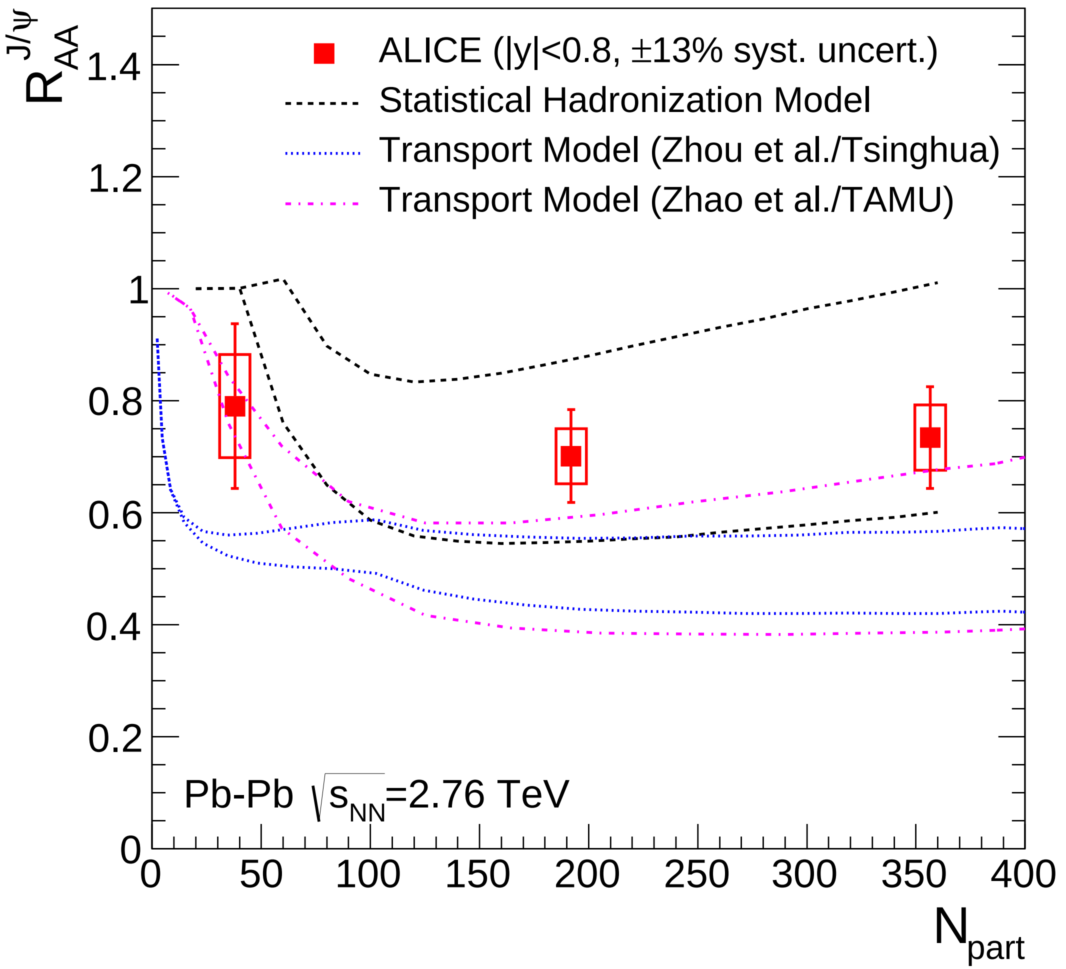


the generic prediction by the model is confirmed by data ALICE, PLB 734 (2014) 314

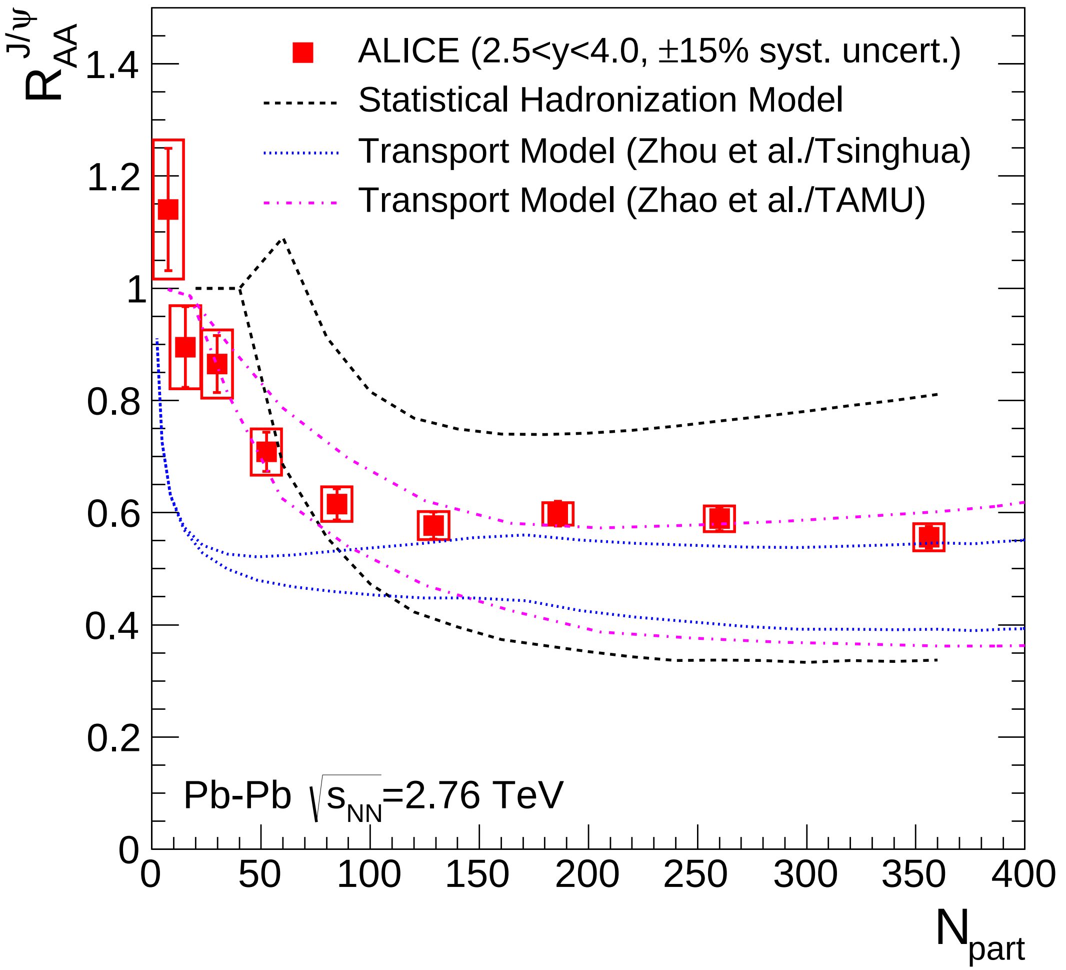
establishes charmonium as an ultimate observable of the phase boundary

More model comparisons (LHC)

midrapidity



forward rapidity



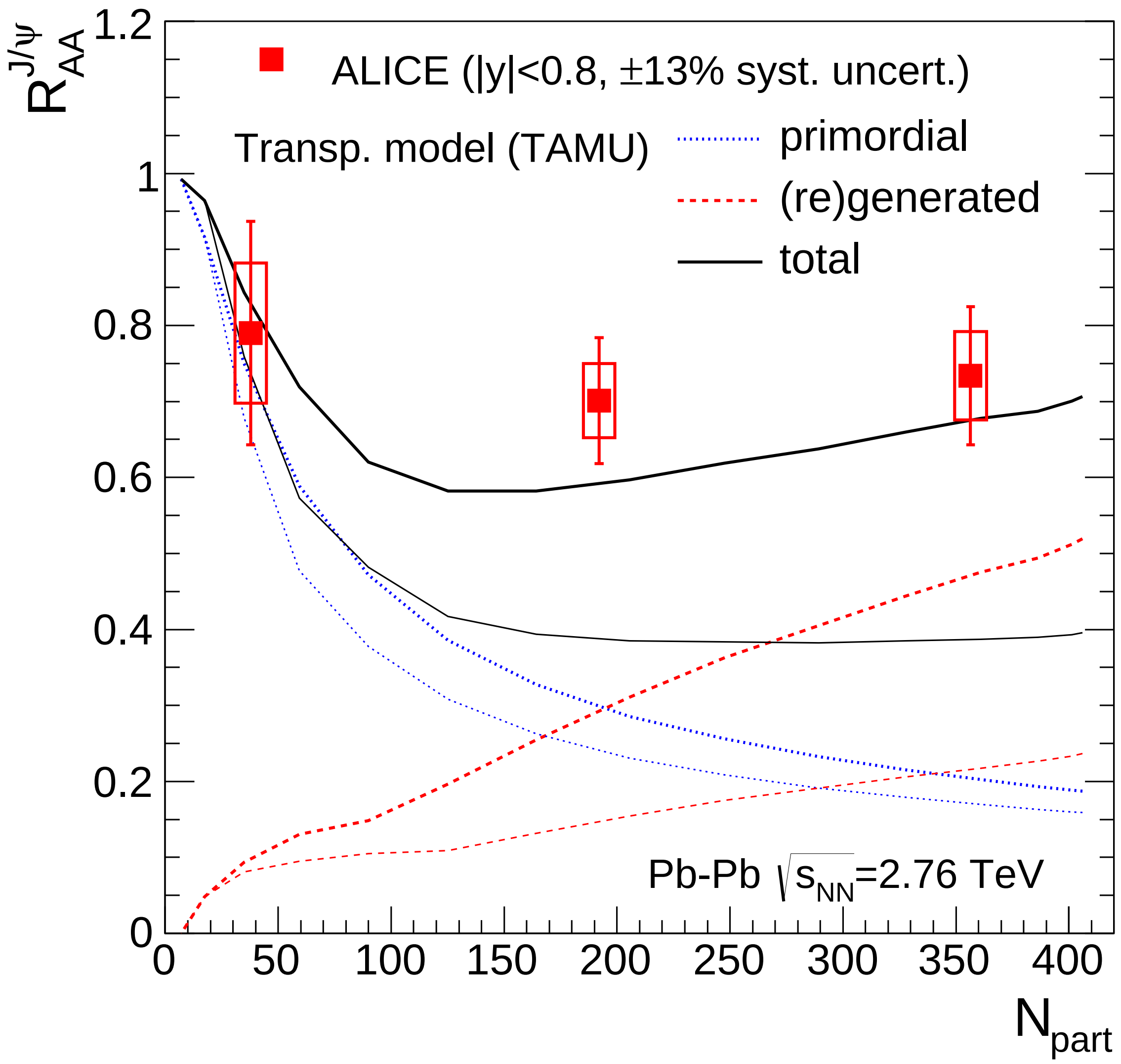
Both model categories reproduce the data ...$\mathrm{d}\sigma_{c\bar{c}}/\mathrm{d}y$ values rather different:

midrapidity: Stat. Hadr.: 0.3-0.4 mb (will go up with incl. of more open charm states)

Transport: 0.5-0.75 mb (TAMU), 0.65-0.8 mb (Tsinghua)

Fractions primordial, (re)generated

A.Andronic@GSI.de



TAMU transport model:

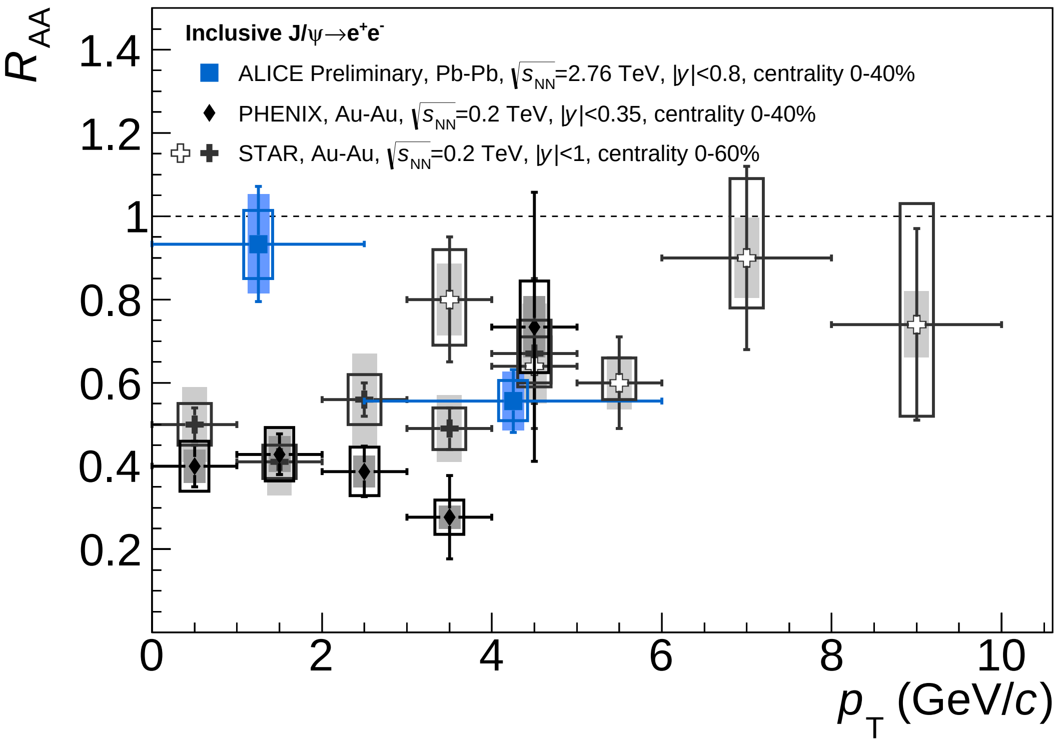
Zhao et al., NPA 859 (2011) 114 and priv. comm.

similar fractions in the Tsinghua model

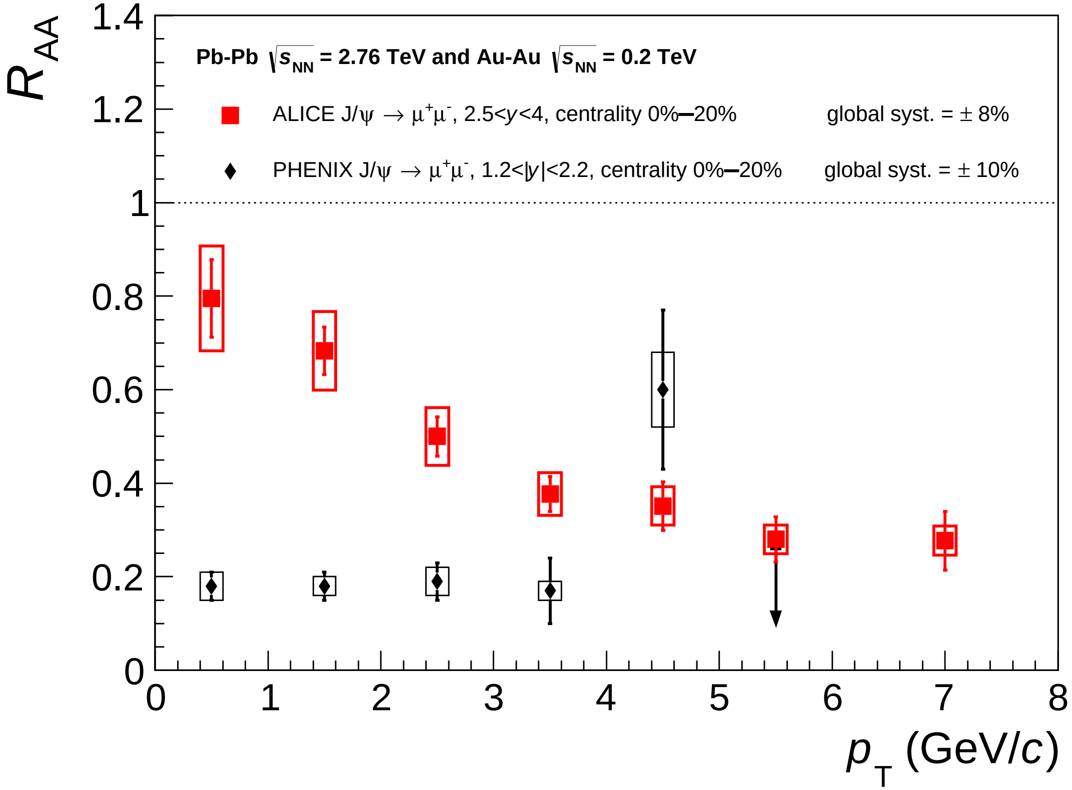
NB: not only regeneration but
also generation

J/ψ vs. p_T - data

midrapidity



forward rapidity



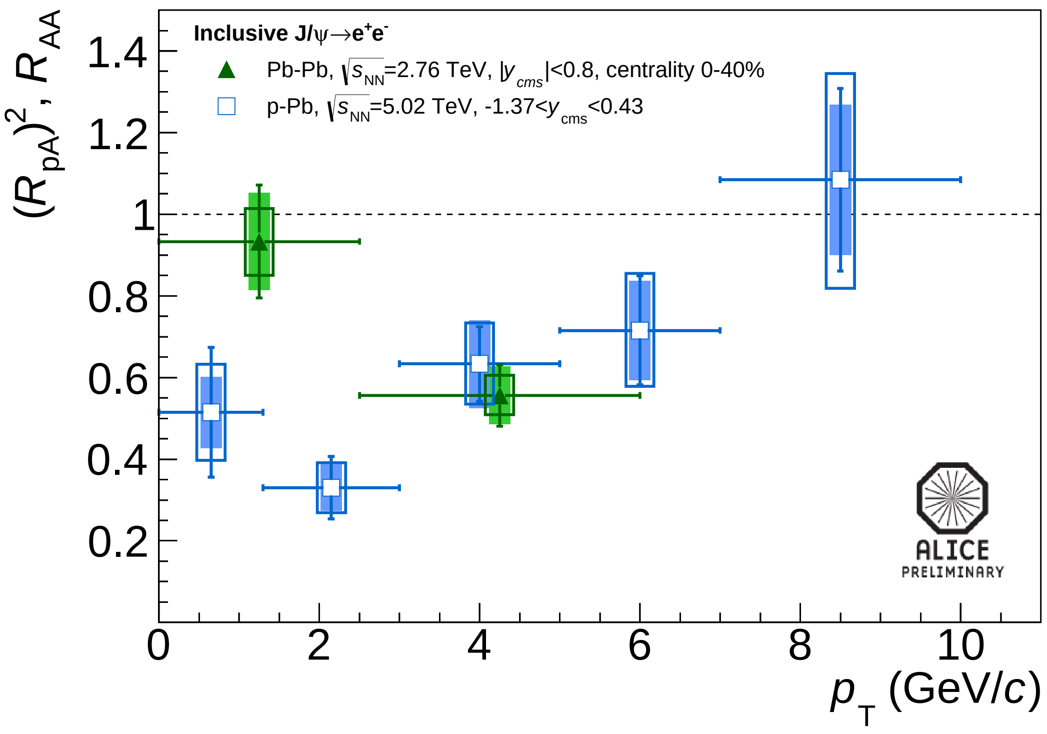
further support of (dominance of) a new production mechanism: “(re)generation” (re)generation in QGP or generation at chemical freeze-out (hadronization)

ALICE, PLB 734 (2014) 314 (& prelim., QM’14)

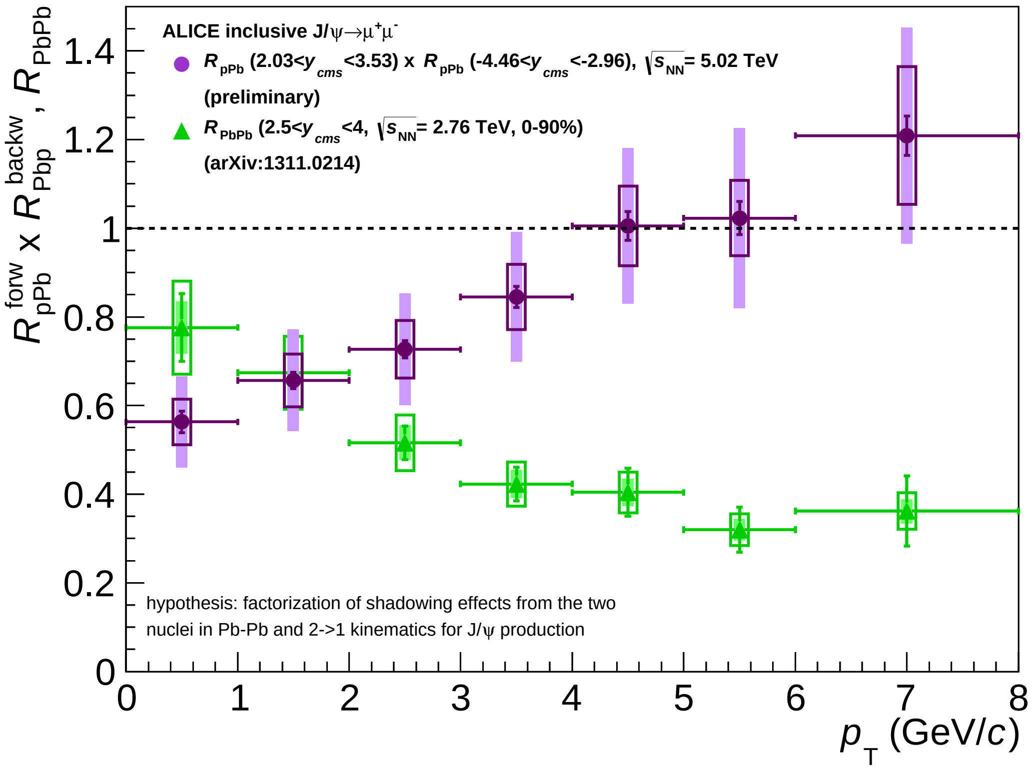
J/ψ Pb–Pb in context (p–Pb)

ALICE (Book, talk QM'14; C. Hadjidakis, arXiv:1405.1177)

midrapidity



forward rapidity



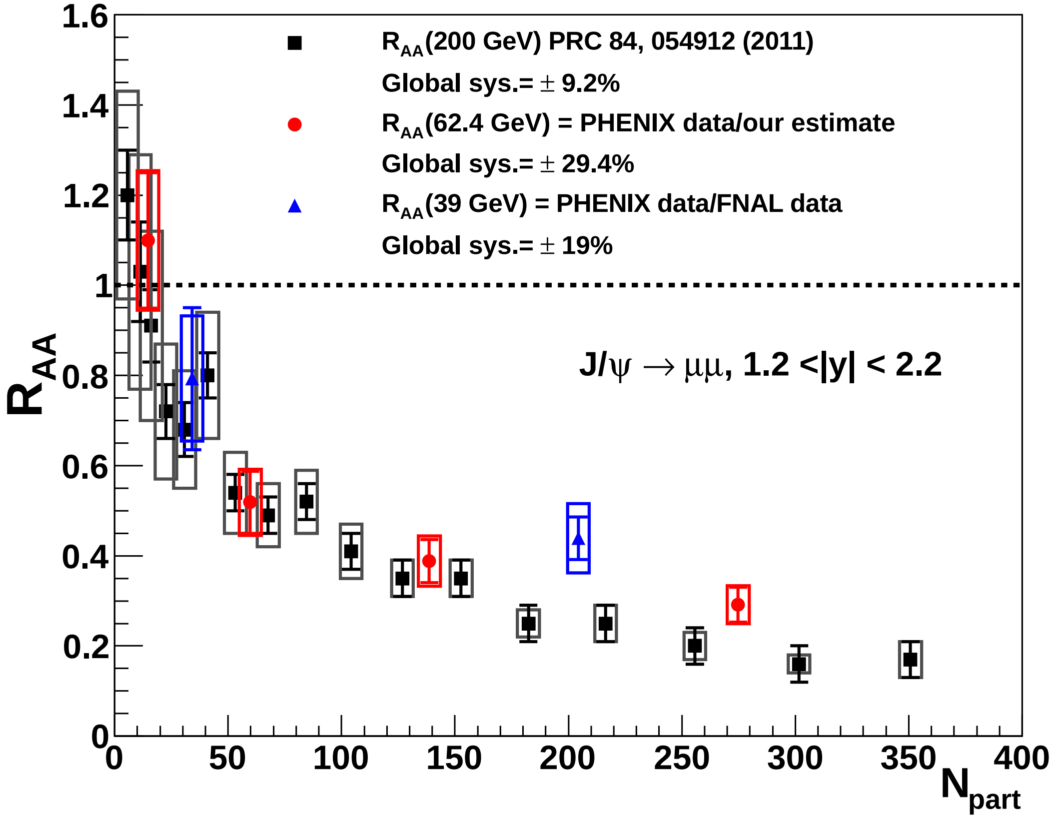
distinct differences between Pb–Pb and p–Pb, further support that low-p_T J/ψ are from (re)generation (while high-p_T is result of charm energy loss)

tantalizing implication for Pb–Pb: $R_{AA} > 1$ (at low p_{T}) *if-more-charm*

...cannot turn off shadowing, but means we may see this at the top LHC energy

J/ψ at RHIC, lower energies

A.Andronic@GSI.de

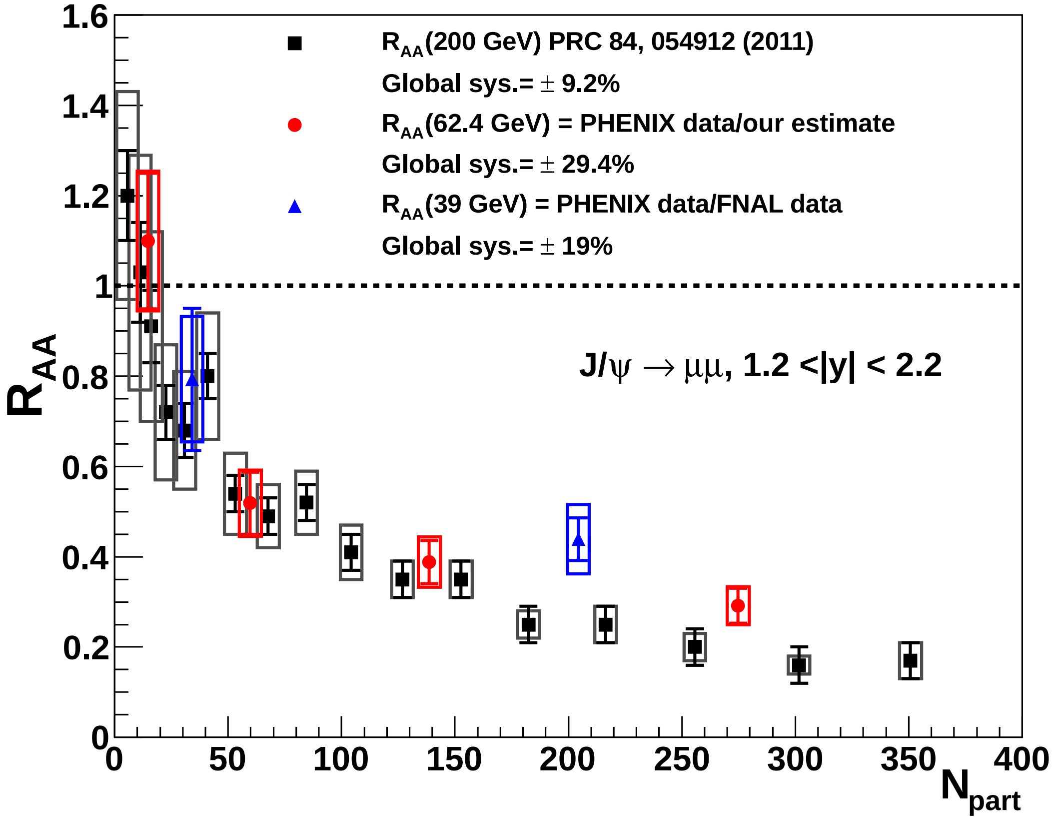


PHENIX, PRC 86 (2012) 064901

...not much “action”

J/ψ at RHIC, lower energies

A.Andronic@GSI.de

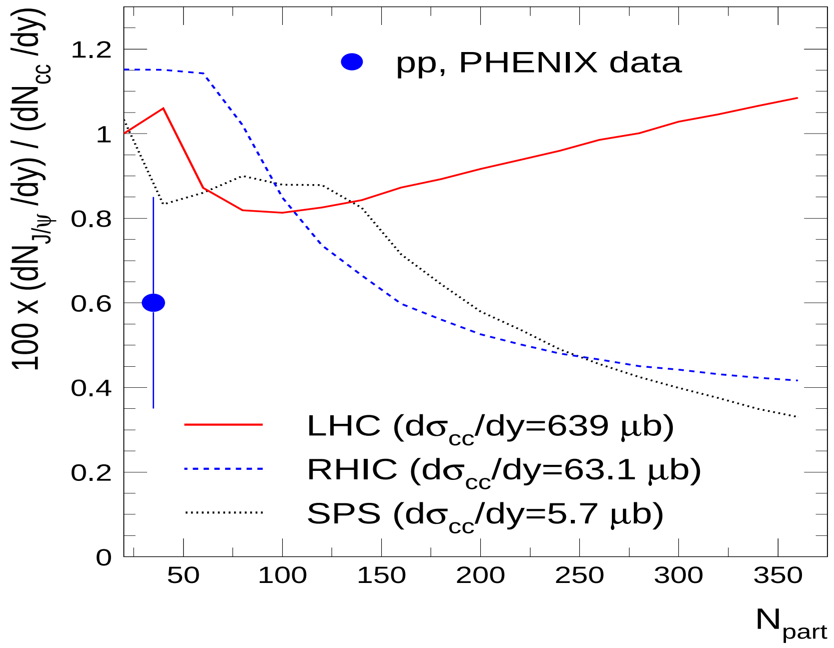


PHENIX, PRC 86 (2012) 064901

...not much “action”

seen already with the SPS data

...and “seen” in the stat. hadr. model



AA et al., NPA 789 (2007) 334

...and in transport models (TAMU)

(after a fruitful journey) we stand at a crossroad...

...with two models describing the LHC (and RHIC) data well, with two rather different physics.

[one, simpler and well-constrained, the other with more capabilities ...but with more parameters]

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

In the statistical model all charmonium states are generated exclusively at hadronization, while in the kinetic model 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.

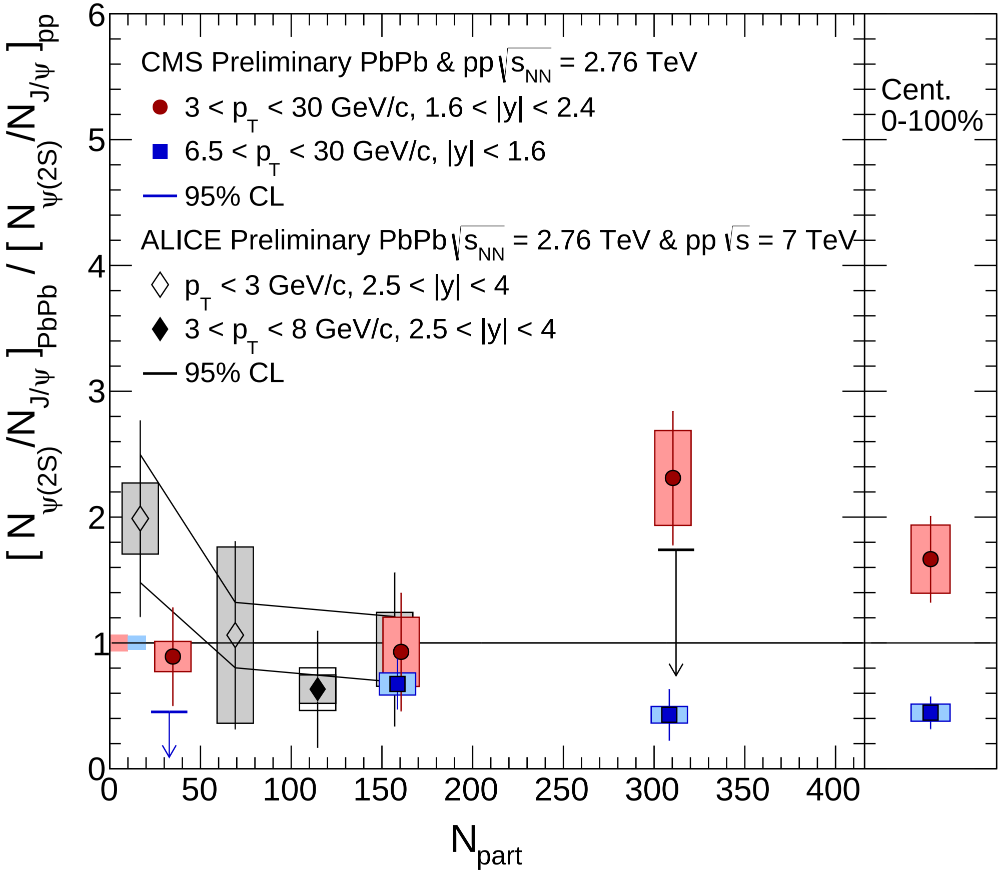
A precision ($\pm$10%) measurement of $\sigma_{c\bar{c}}$ in Pb-Pb (Au-Au) collisions needed

within reach (?) with the upgraded detectors at the LHC and RHIC

...and data on other charmonium states is crucial

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

A.Andronic@GSI.de



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

N - production yields

(light) “discrepancy” ALICE / CMS ?

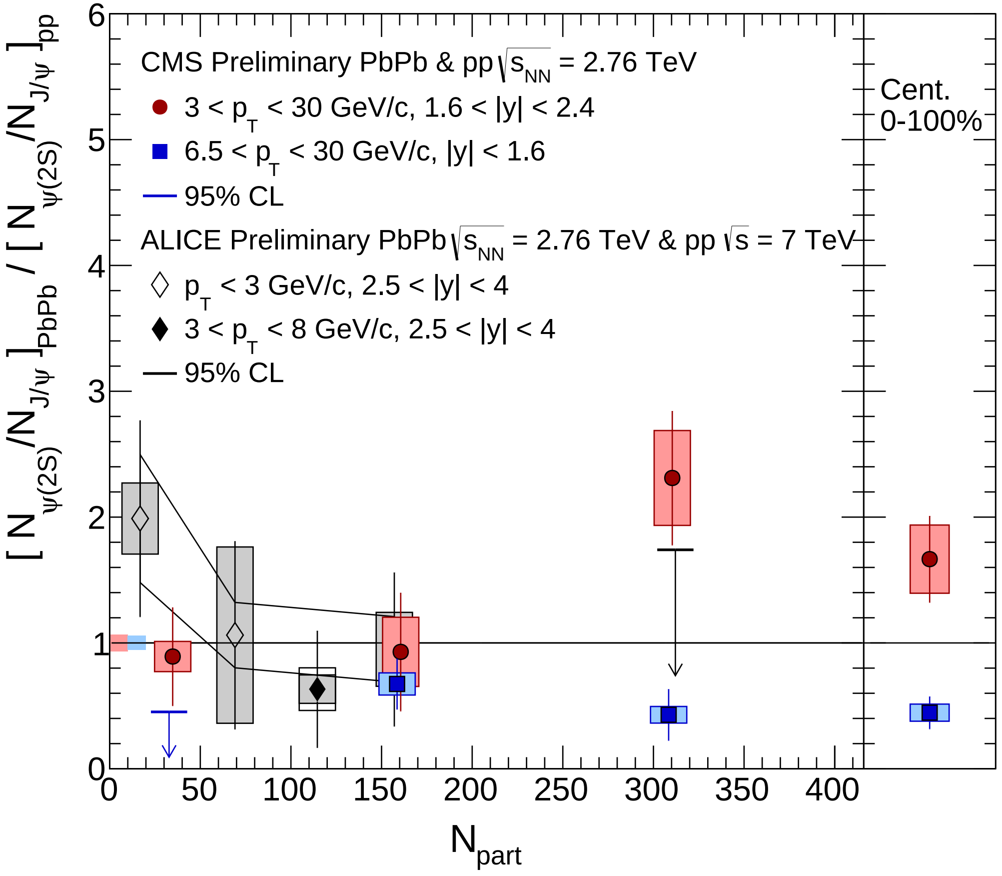
mind diff. p_T, y ranges

CMS (Moon, talk QM’14)

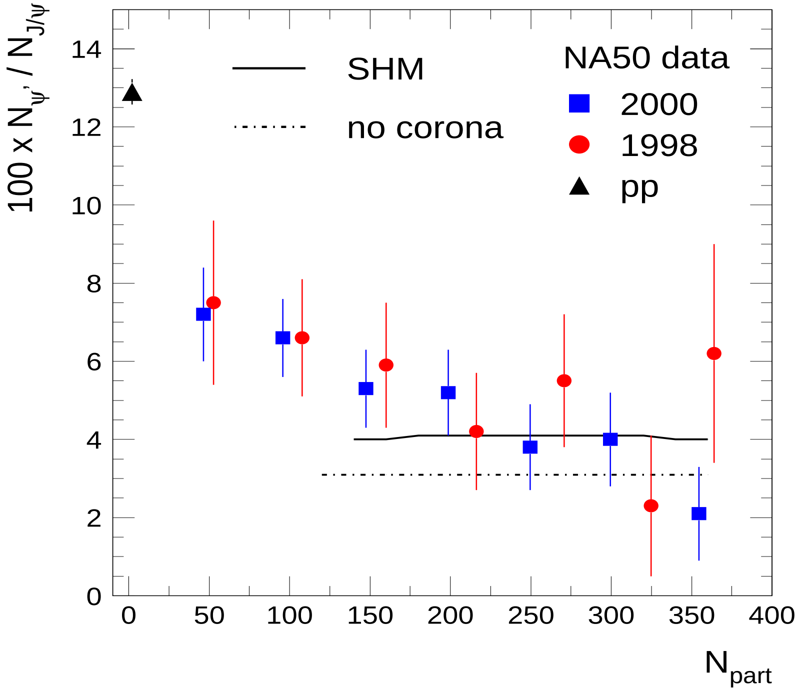
$\psi(2S)$ production at the LHC

A.Andronic@GSI.de

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



AA et al., NPA 789 (2007) 334



at SPS: $R \simeq$0.24 (p_T-integrated)

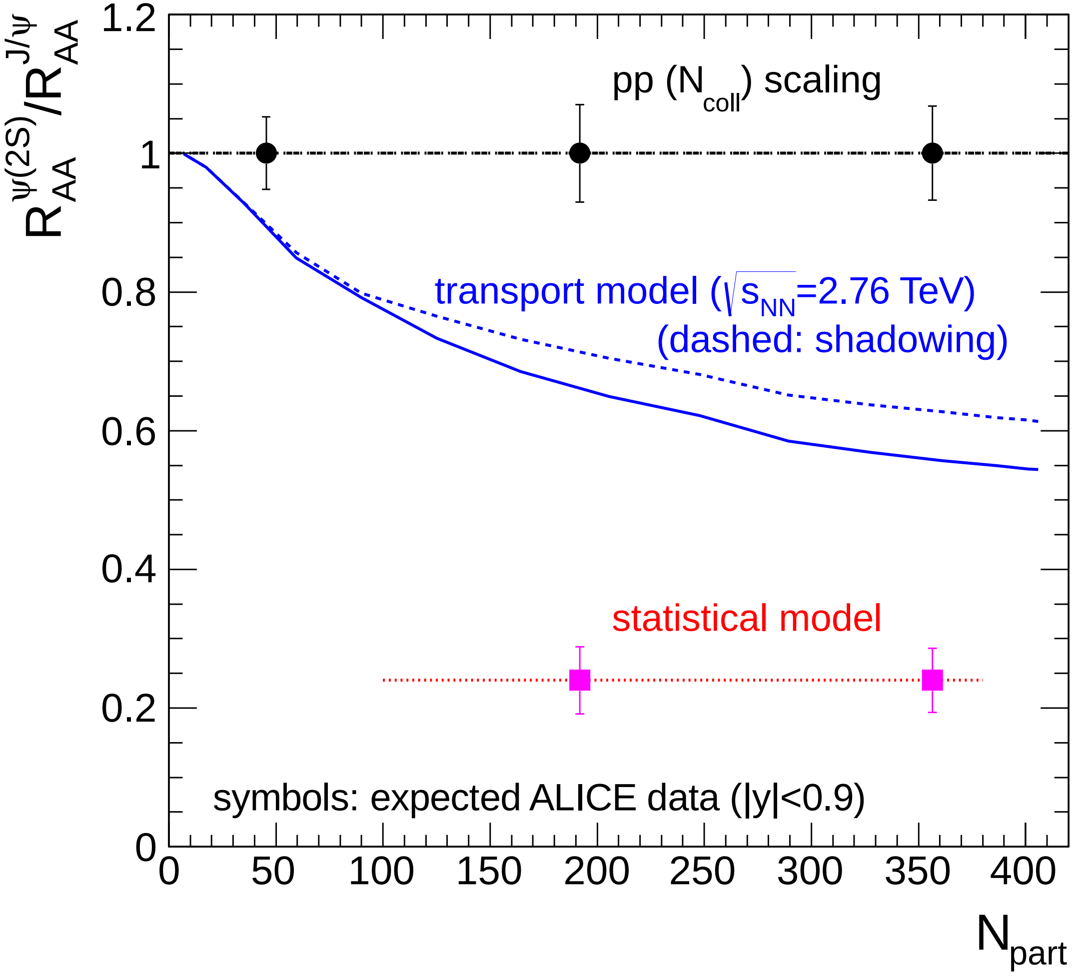
...evidence against sequential dissociation?

CMS (Moon, talk QM'14)

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

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

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

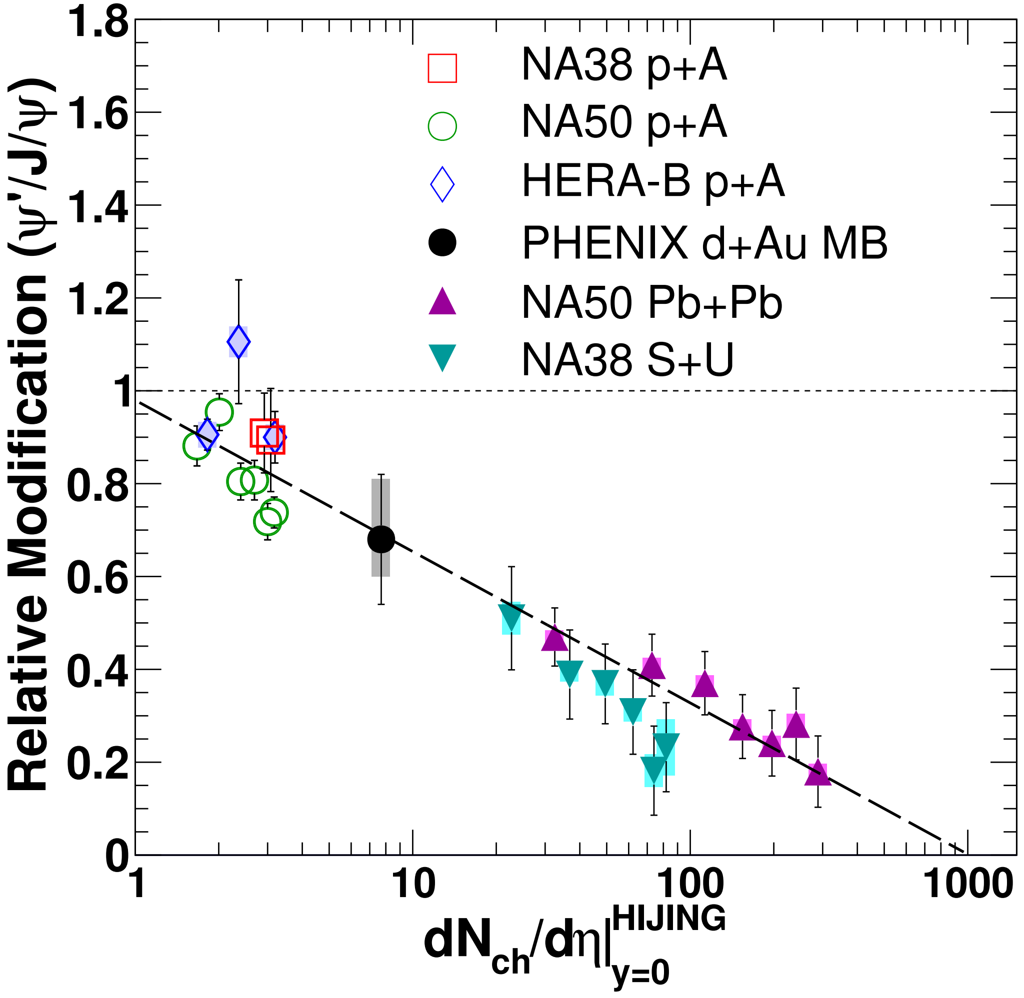


Central Barrel: measurement possible only with upgrade (10 nb^{-1})
Muon Spectrometer: a first glimpse with baseline data (1 nb^{-1}), a real measurement only with upgrade

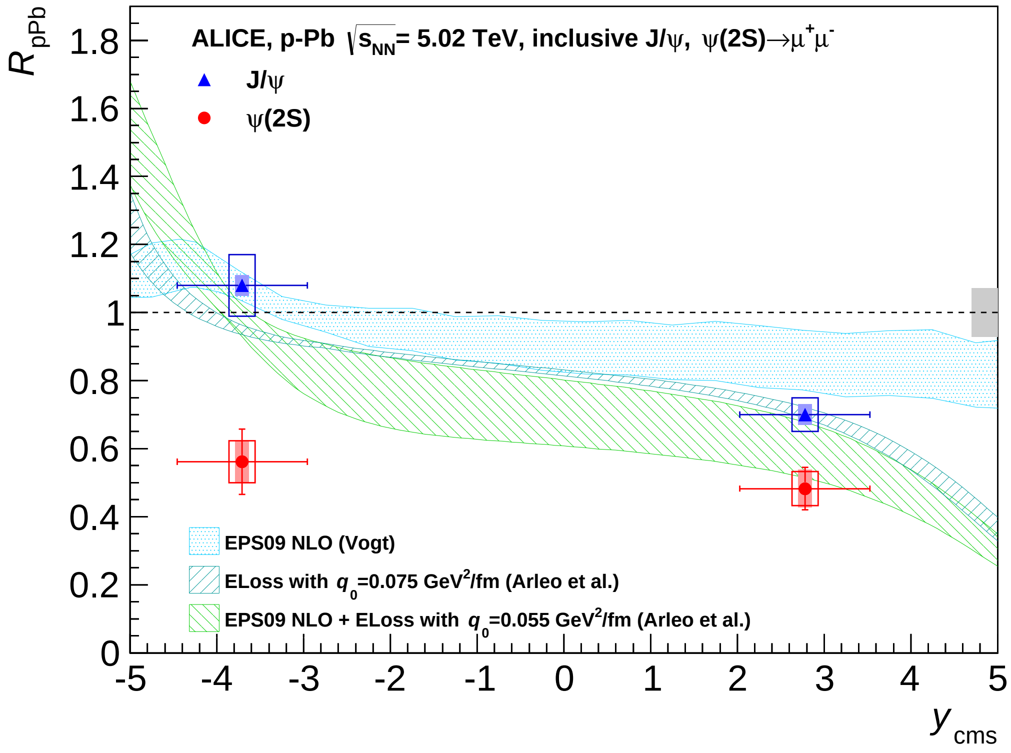
ALICE, JPG 41 (2014) 087001

Charmonium ratios in p(d)-A collisions

PHENIX, PRL 111 (2013) 202301



ALICE, arXiv:1405.3796



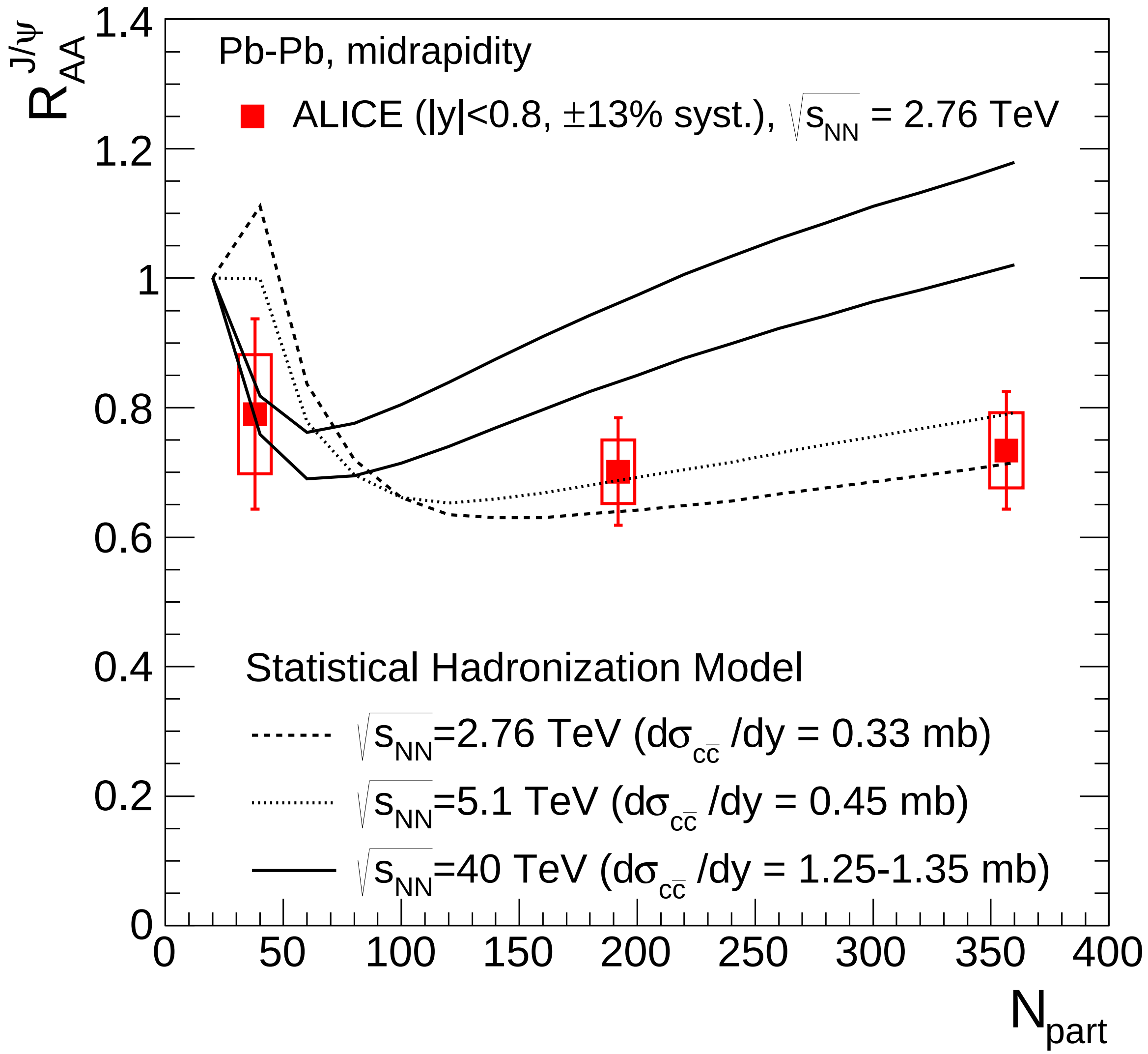
abs. cross sect. depends on time spent in the nucleus

(McGlinchey et al., PRC 87 (2013) 054910)

at the LHC, the strong $\psi(2S)$ suppression in Pb-side remains puzzling

indication for final-state effects?

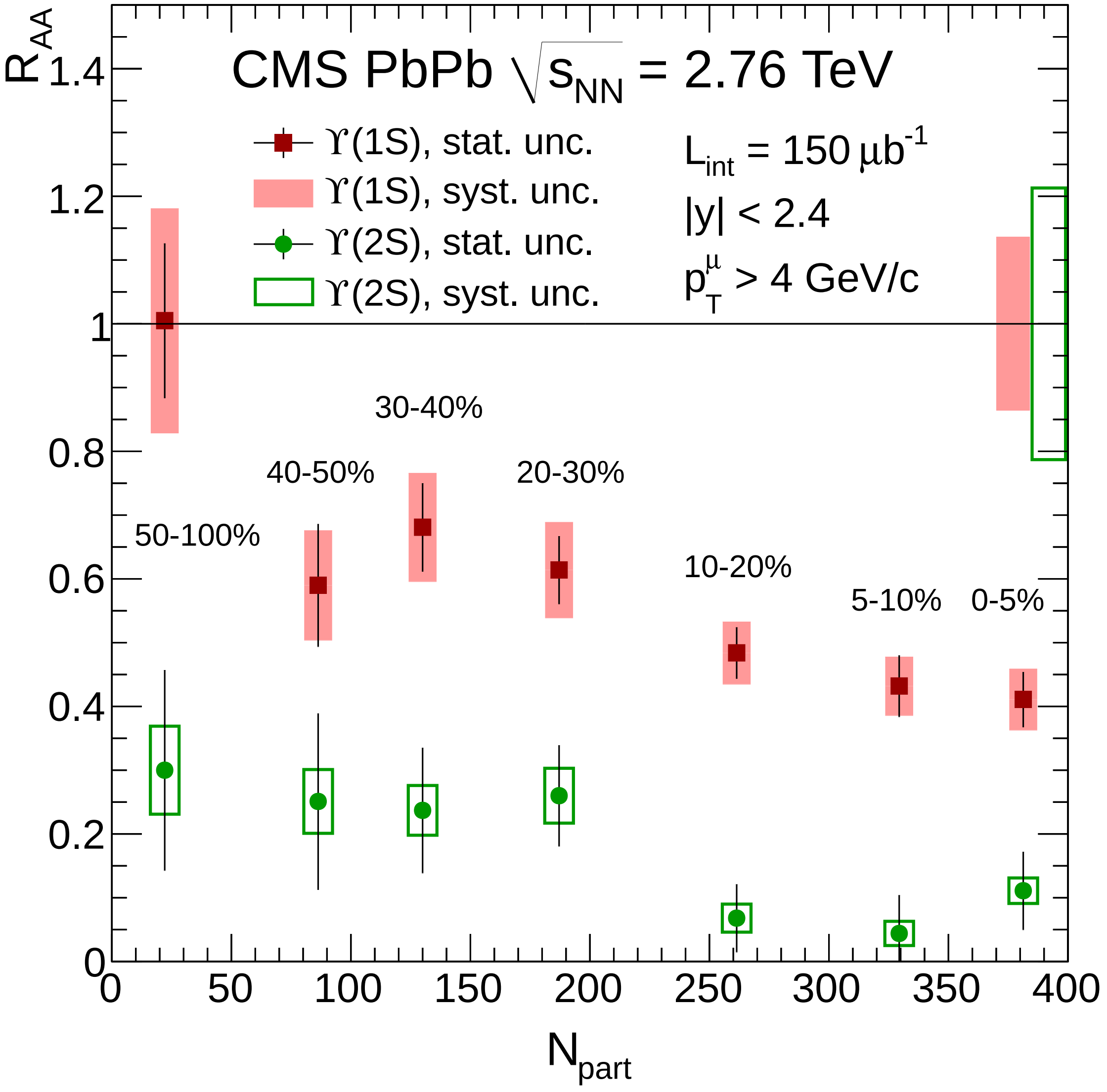
Outlook for J/ψ



modest increase for 5.1 TeV
...due to modest increase in $\sigma c\bar{c}$
(slightly larger at forward y)

increasing trend vs. N_{part} at FCC

Bottomonium at the LHC



CMS, PRL 109 (2012) 222301

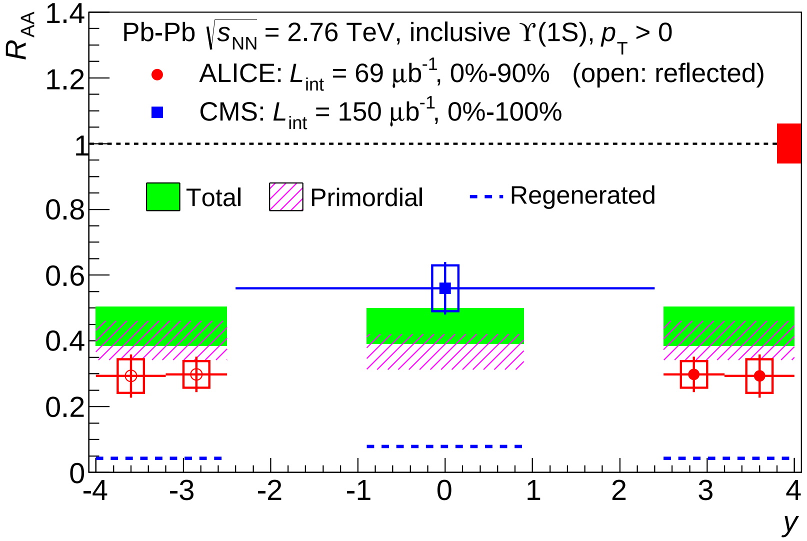
interpreted as effect of (almost:) full dissoc. of $\Upsilon(2S)$, $\Upsilon(3S)$, χ_b

Transport models:

Emerick et al./TAMU, EPJA 48 (2012) 72

Zhuang, arXiv:1408.3900

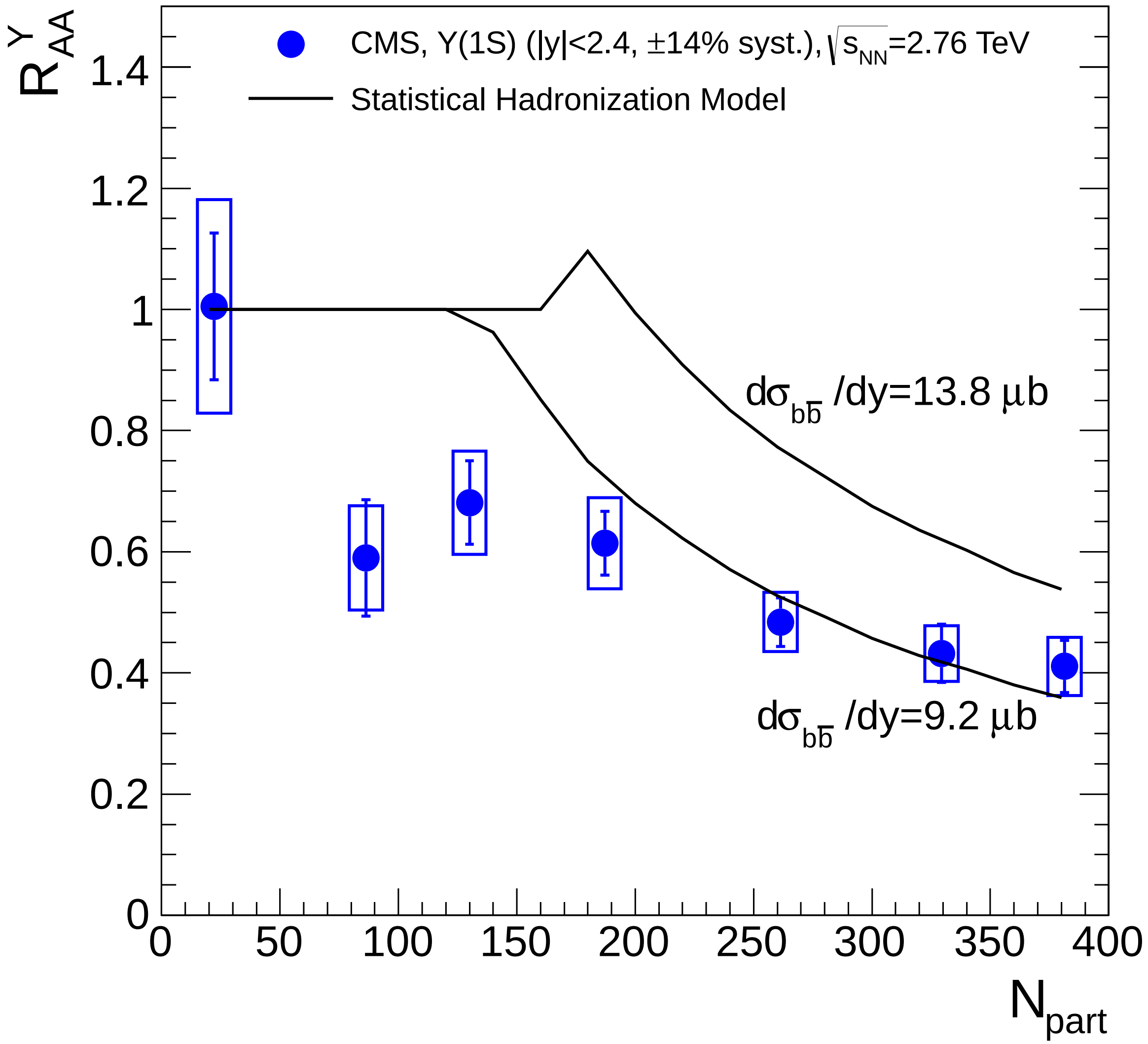
(re)gen. component small ($\lesssim$10%)



ALICE, arXiv:1405.4493

Bottomonium at the LHC in SHM

A.Andronic@GSI.de



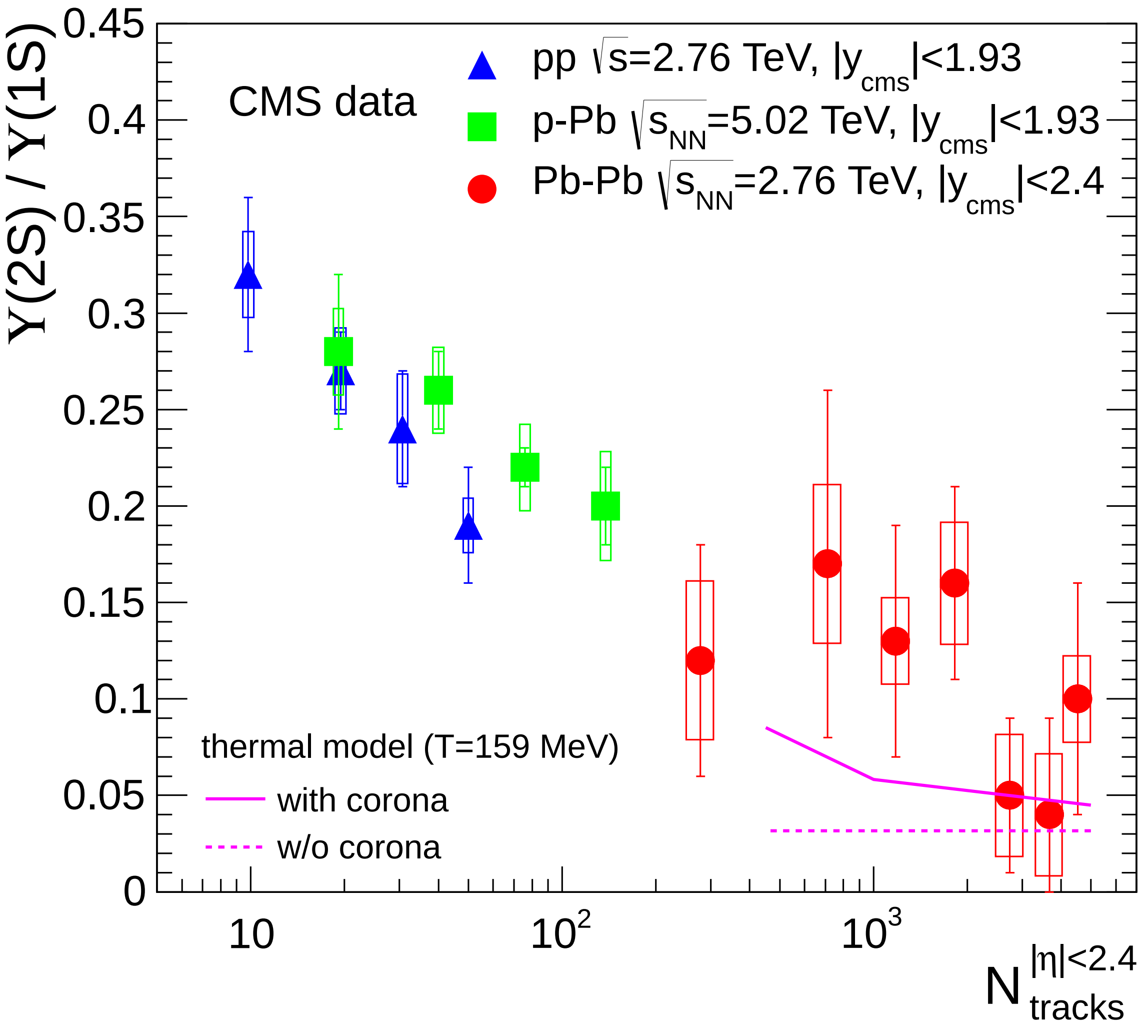
$$\frac{d\sigma_{b\bar{b}}}{dy} = 13.8\ \mu\text{b (MNR x0.8 shad.)}$$

fair description by model

CMS, PRL 109 (2012) 222301

Bottomonium ratios

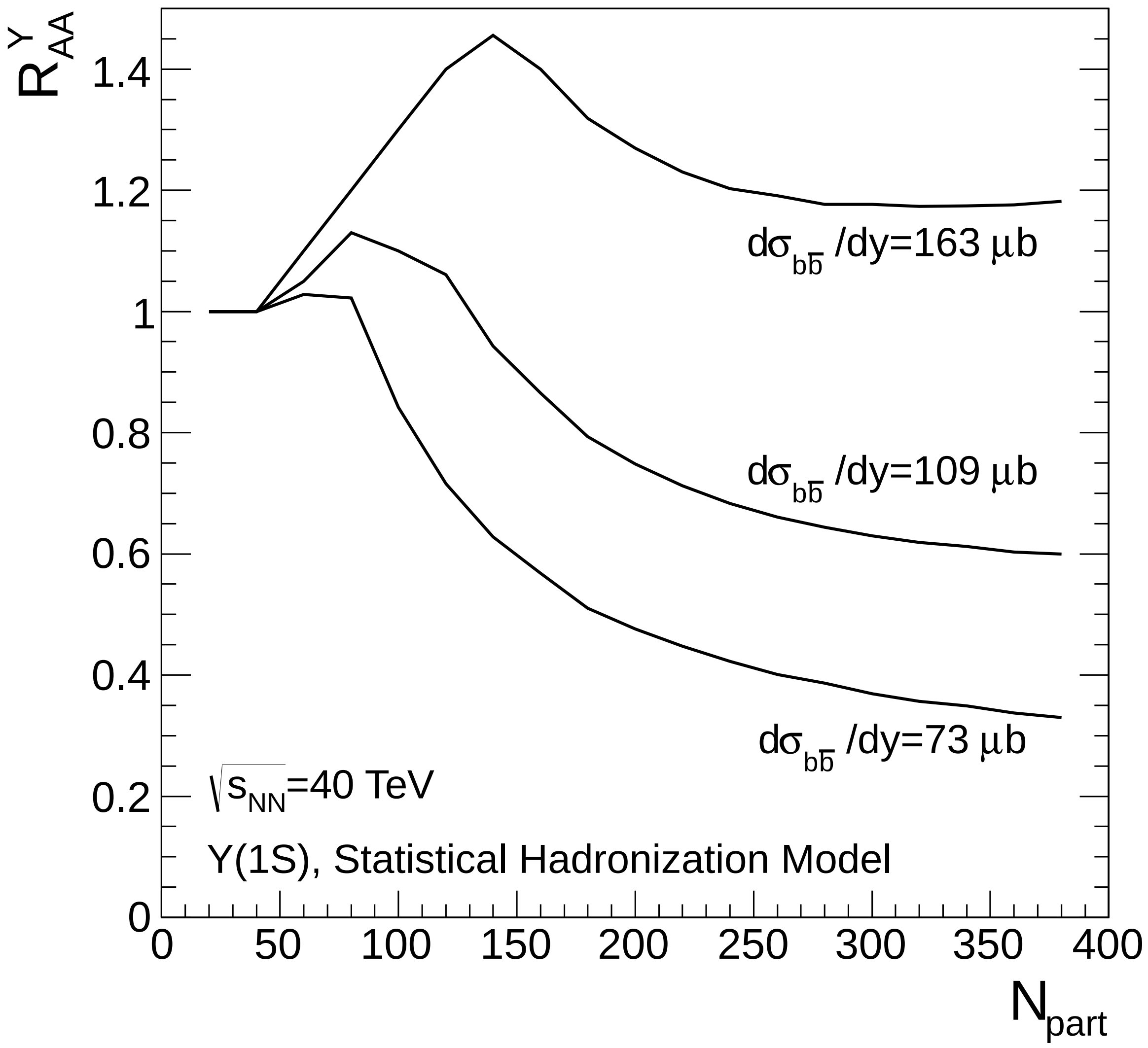
A.Andronic@GSI.de



statistical model describes central Pb–Pb data

CMS, JHEP 1404 (2014) 103

Bottomonium at the FCC in SHM



$\frac{d\sigma_{b\bar{b}}}{dy} = 109\ \mu$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

the story of quarkonium as a “golden probe” for QGP is rather intricate

(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 better constrained by measurements

interesting (sequential?) “disappearance” pattern in the bottom (Υ) sector

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

will Υ add more weight to the phase boundary?

a wealth of data (and puzzling too) in d-Au (RHIC) and p-Pb (LHC) awaits better understanding

while measurements at the LHC at 5.1 TeV are eagerly awaited

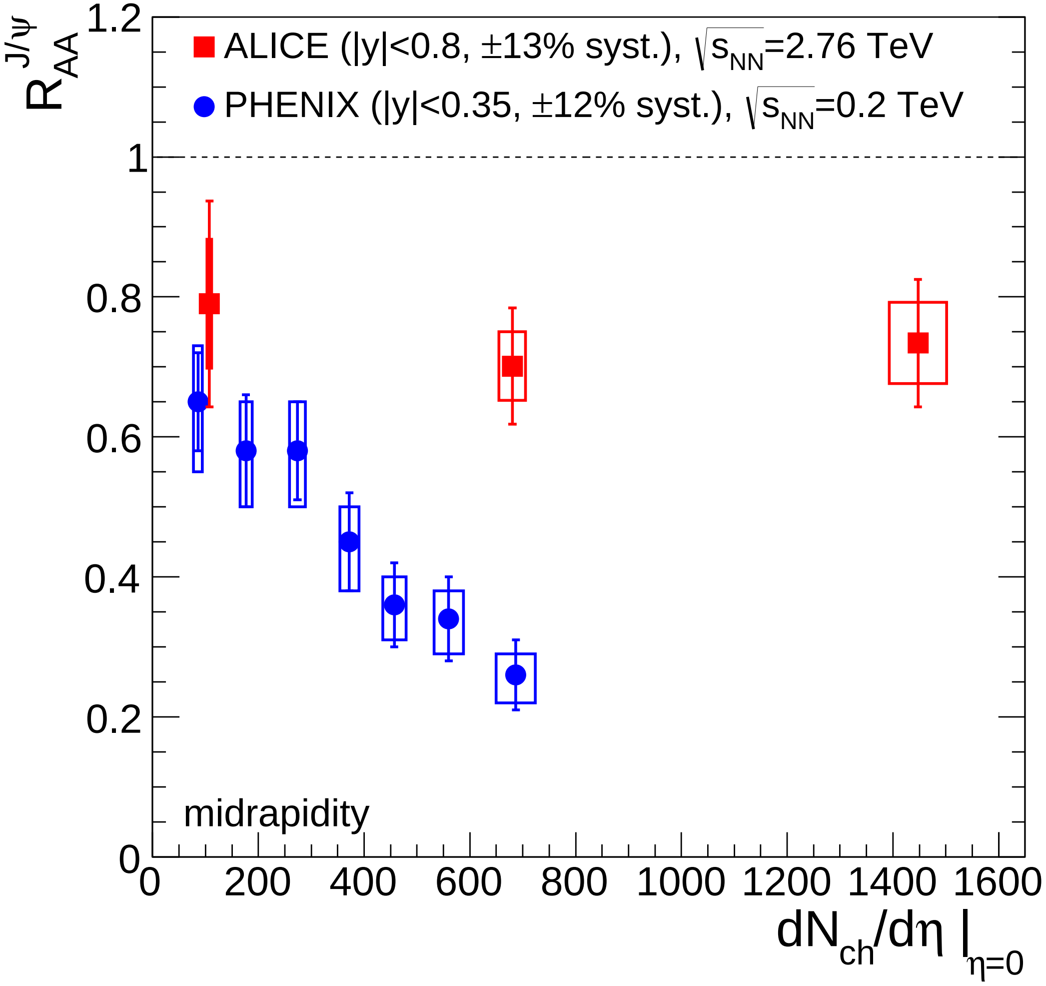
...strong bet: $R_{AA}^{J/\psi}$ will increase

Backup slides

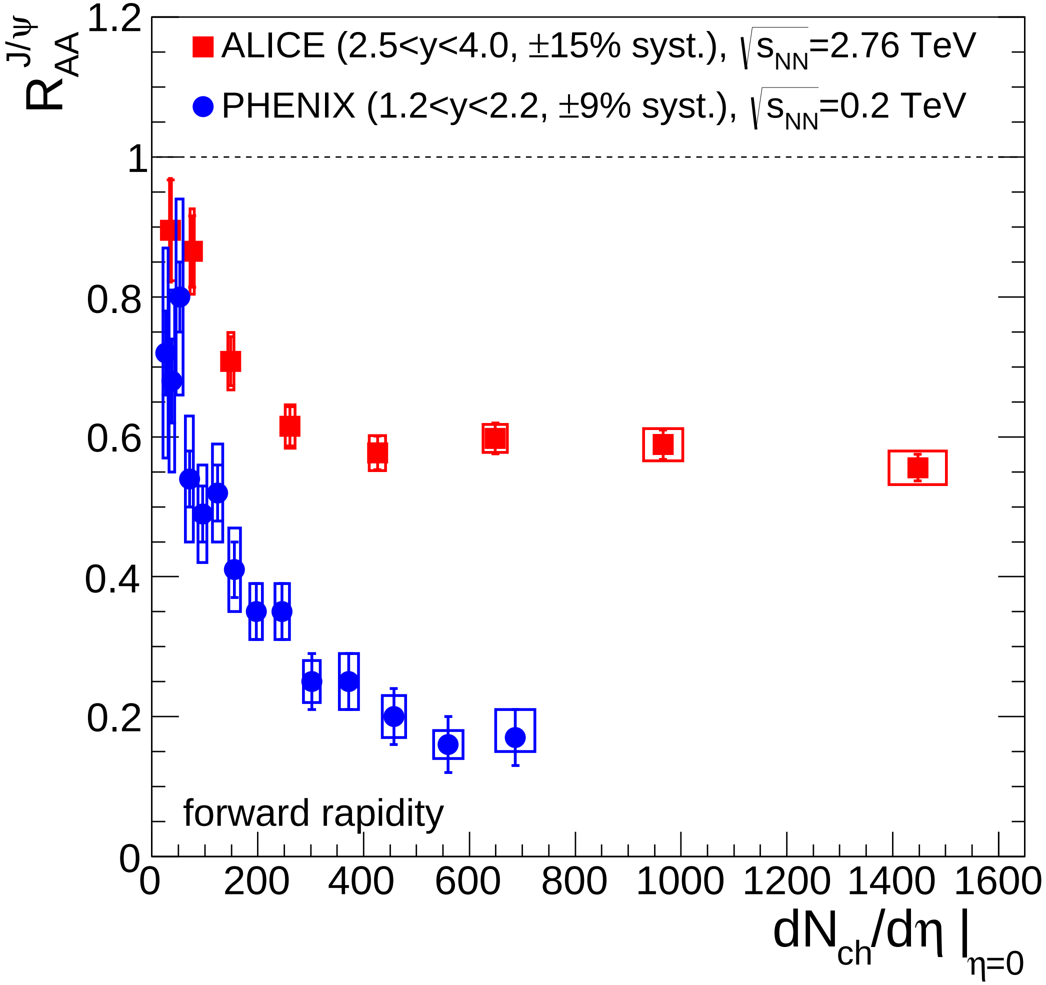
Charmonium data at RHIC and the LHC

x1

midrapidity



forward rapidity



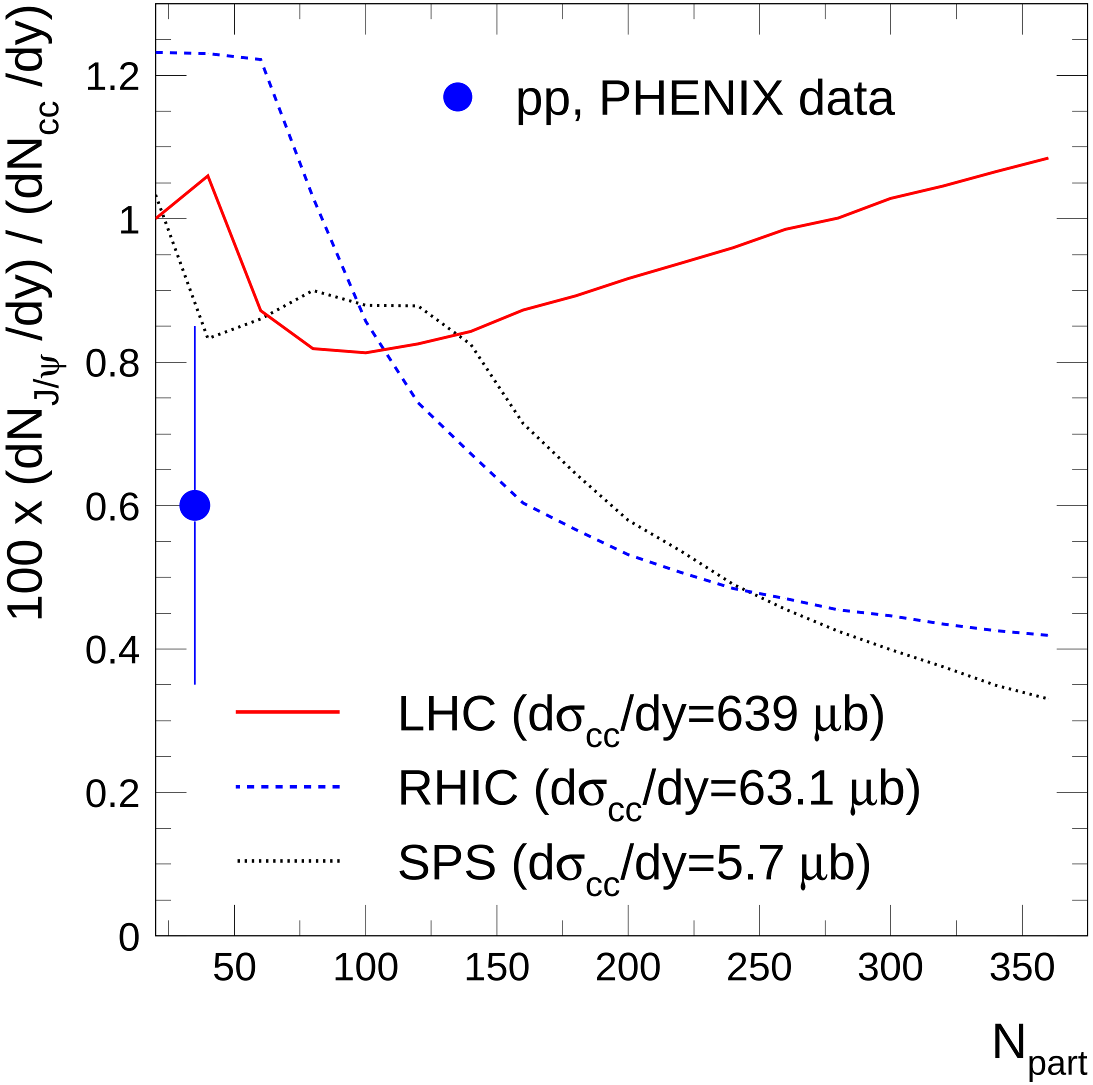
$$\mathrm{d}N_{ch}/\mathrm{d}\eta \sim \varepsilon$$

J/ψ production relative to charm

x2

A.Andronic@GSI.de

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



AA, PBM, JS, NPA 789 (2007) 334

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 with Υ at RHIC and LHC?

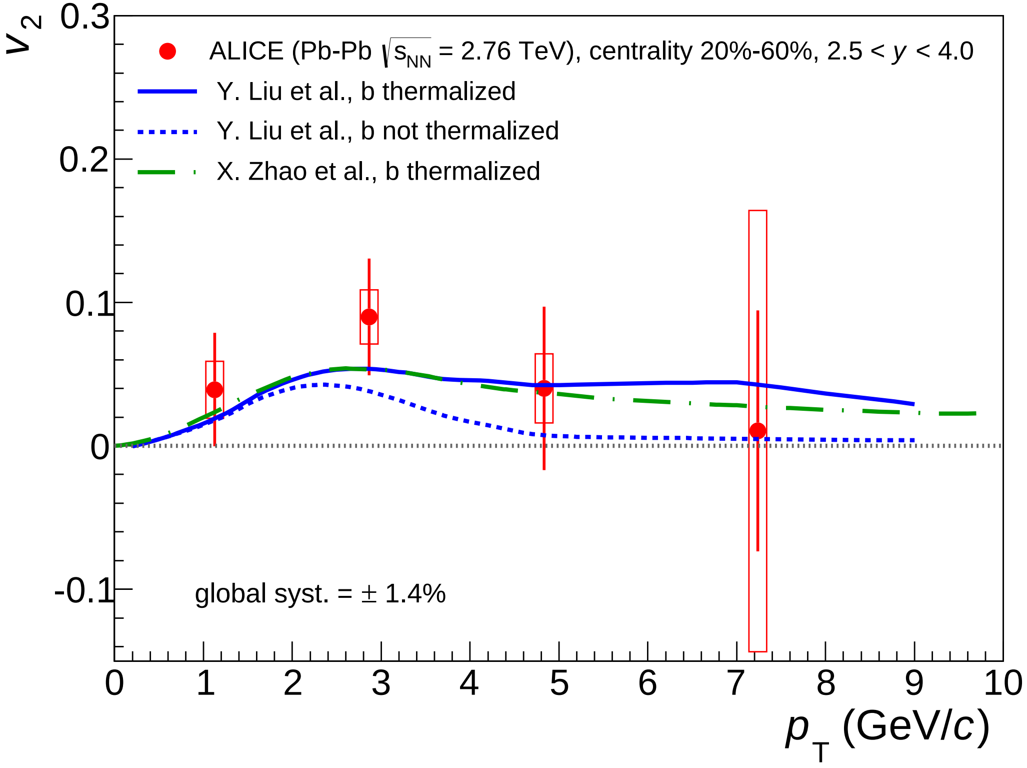
- enhancement-like at LHC

  can. suppr. lifted, quadratic term dominant

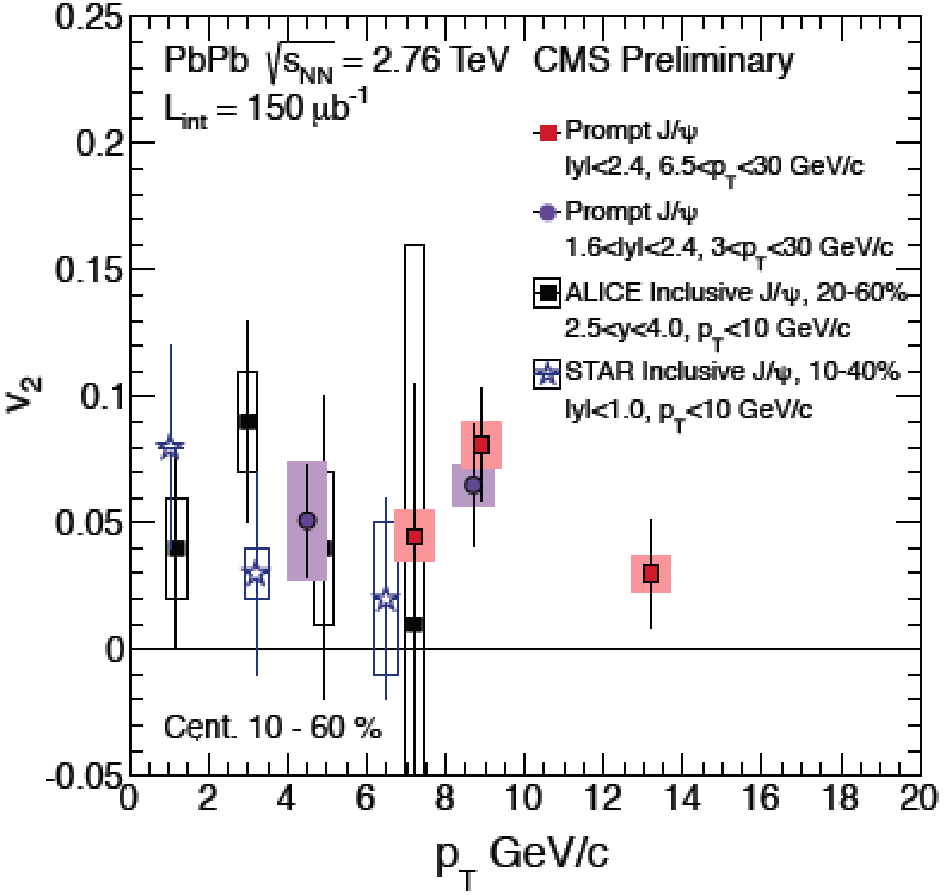
J/ψ flow

x3

ALICE, PRL 111 (2013) 162301



CMS (Moon, QM'14)



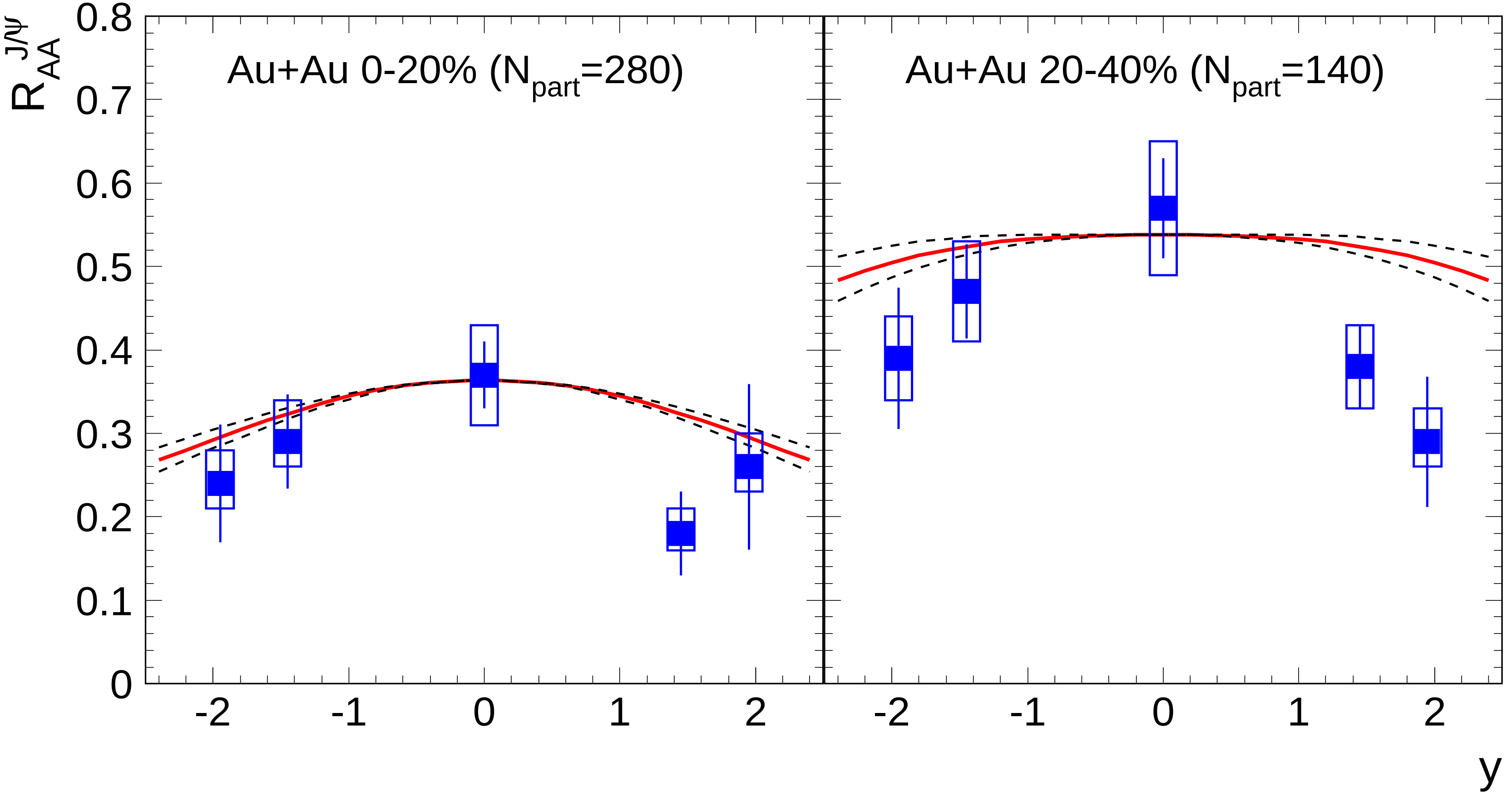
further support of production in QGP or at chemical freeze-out at the LHC

(requiring thermalization of $c, \bar{c}$ and generically leading to flow)

Recall: non-zero v_2 was measured at SPS ("leakage effect")
...the RHIC case (STAR, $v_2 \sim 0$) remains open ...upcoming data will settle it

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

A.Andronic@GSI.de



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)

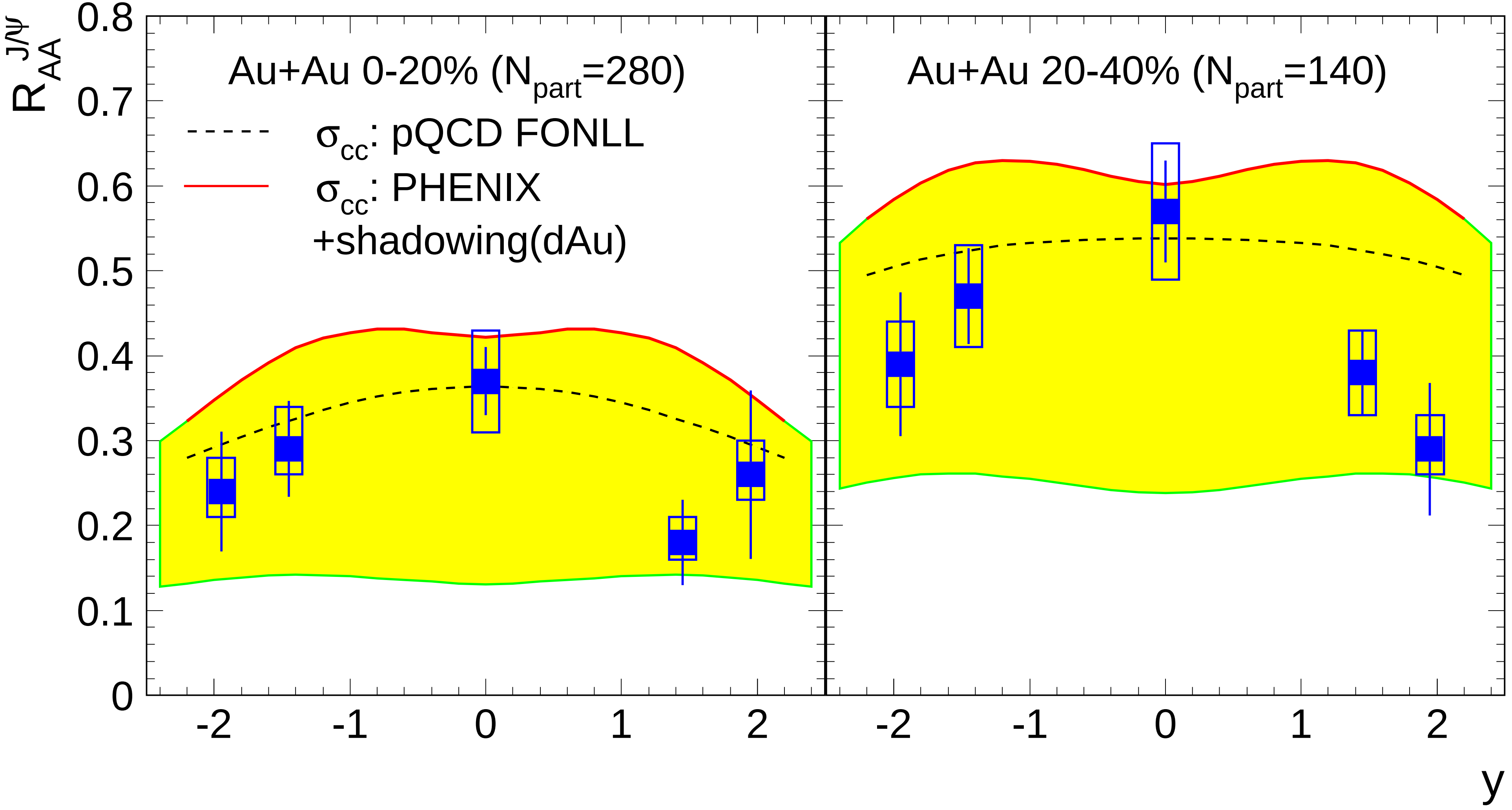
(constant R_{AA} expected within Debye screening model)

PLB 652 (2007) 259

J/ψ at RHIC: effect of shadowing

x5

A.Andronic@GSI.de

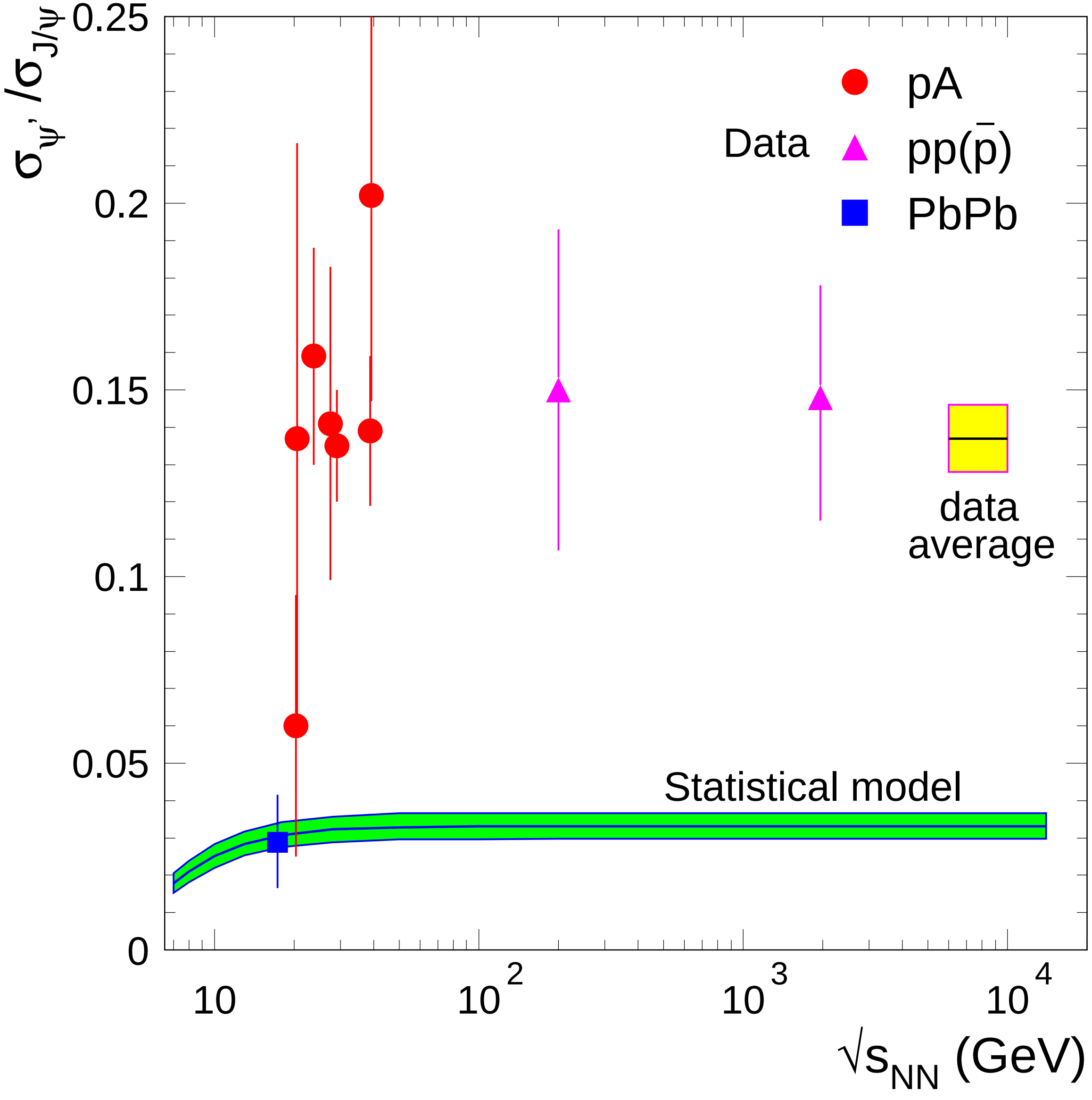


model describes data with PHENIX $\sigma_{c\bar{c}}$ (lower error plotted)

JPG 35 (2008) 104155

The “null hypothesis”

A.Andronic@GSI.de



charmonium in pp(A) collisions

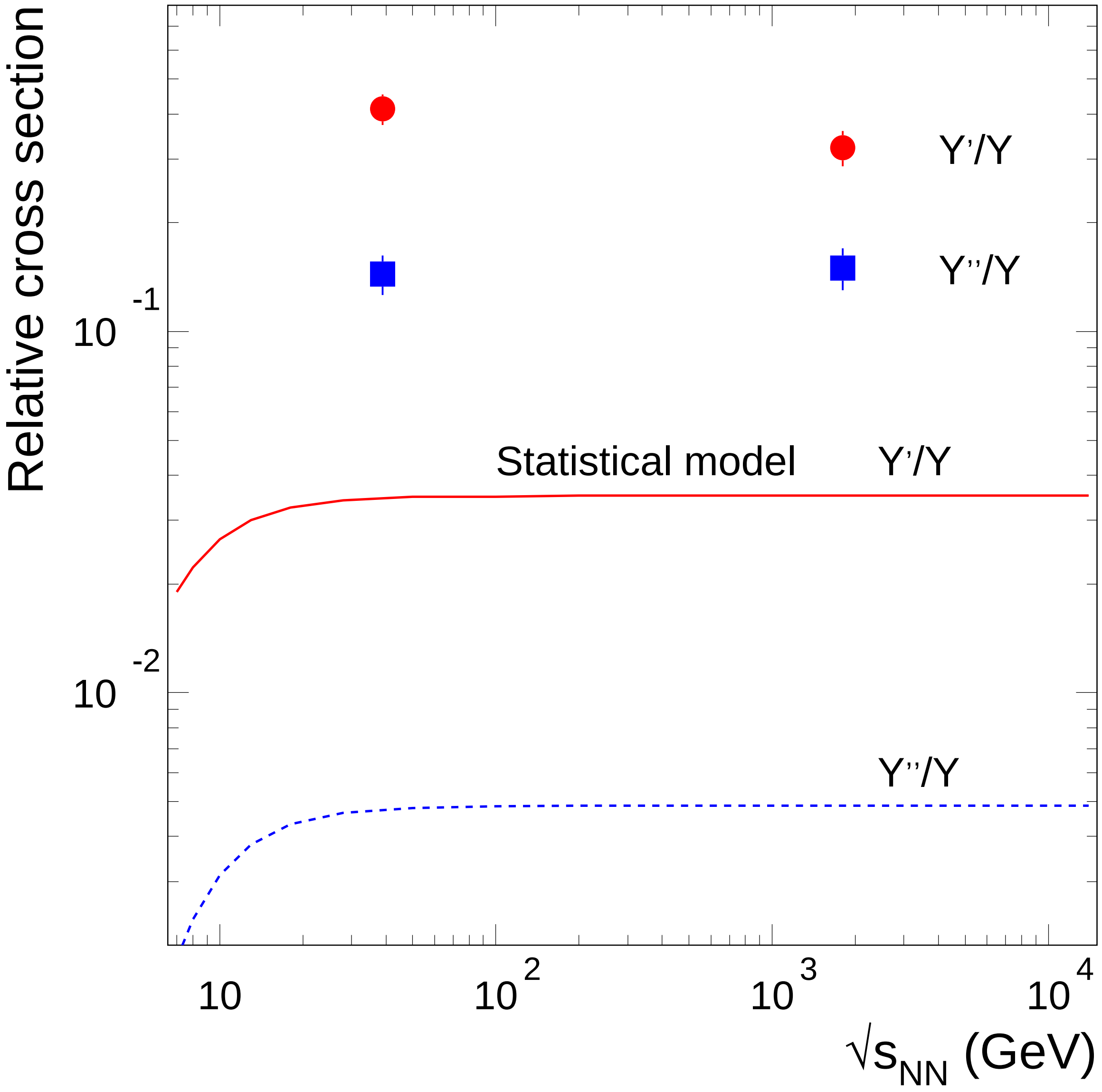
...is far from thermalized (model is for AA)

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

PLB 678 (2009) 350

The "null hypothesis" for bottomonium

A.Andronic@GSI.de



bottonium in pp(A) collisions

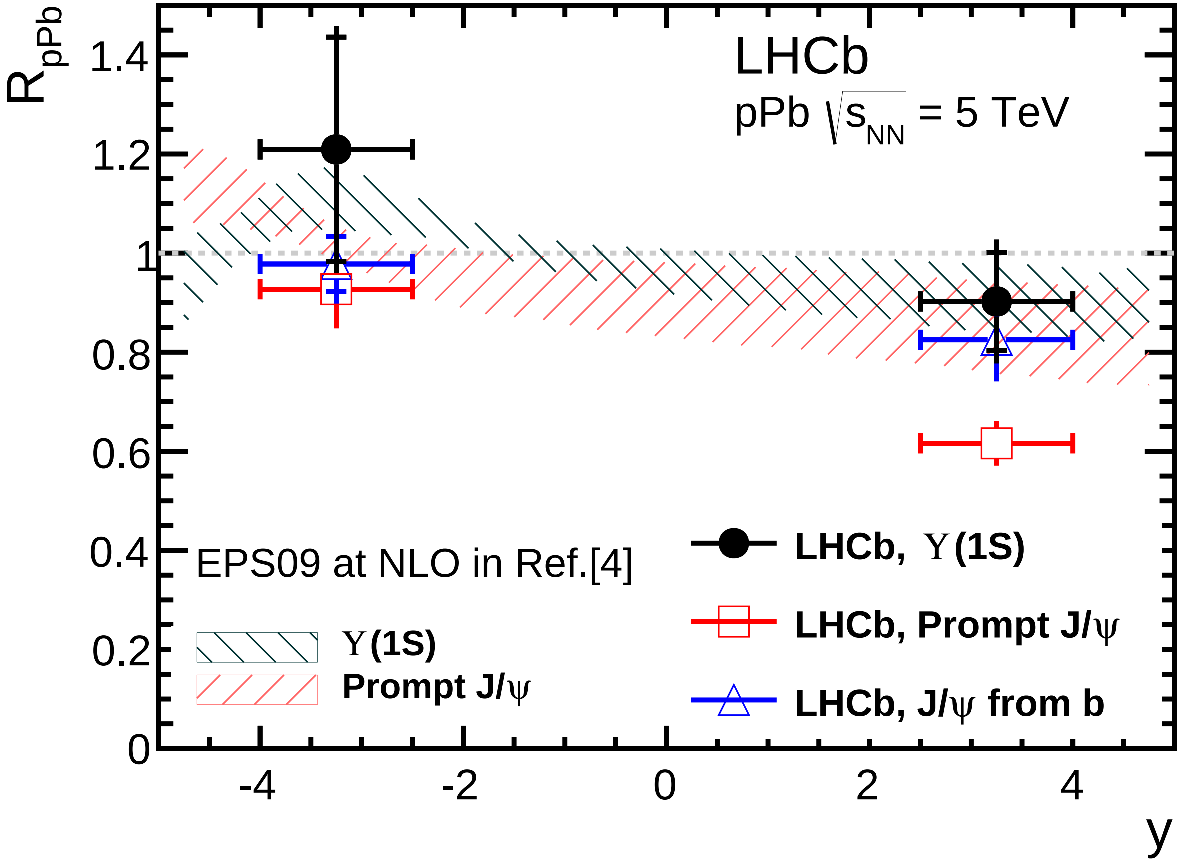
...is far from thermalized
(model is for AA)

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

PLB 678 (2009) 350

Bottomonium in p–Pb collisions

A.Andronic@GSI.de



LHCb, JHEP 1407 (2014) 094