Quarkonium in the statistical model (in the LHC era)

A. Andronic – GSI Darmstadt

- The thermal model for the light quark (u,d,s) hadrons
- ...and the connection to the QCD phase diagram
- Charmonium in the statistical hadronization model
- Summary and outlook

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

Thermal fits of hadron abundances

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

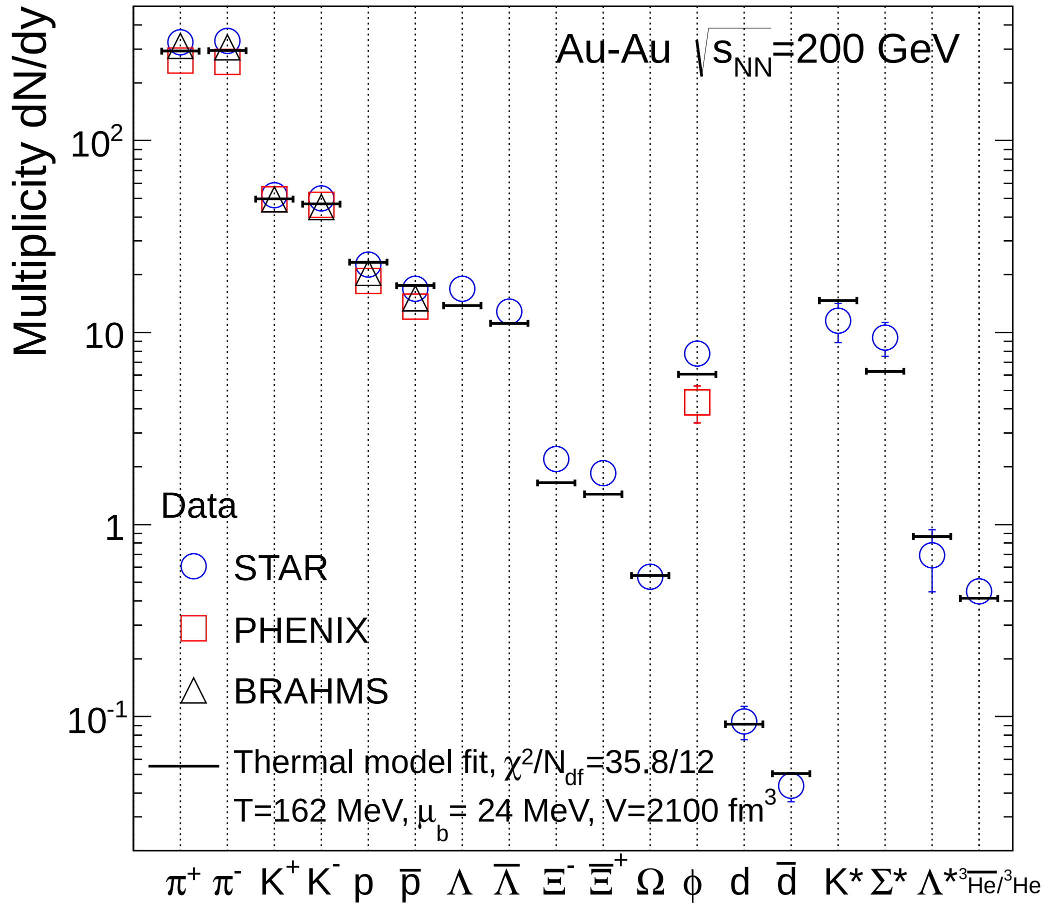
quantum no. conservation:

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

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

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

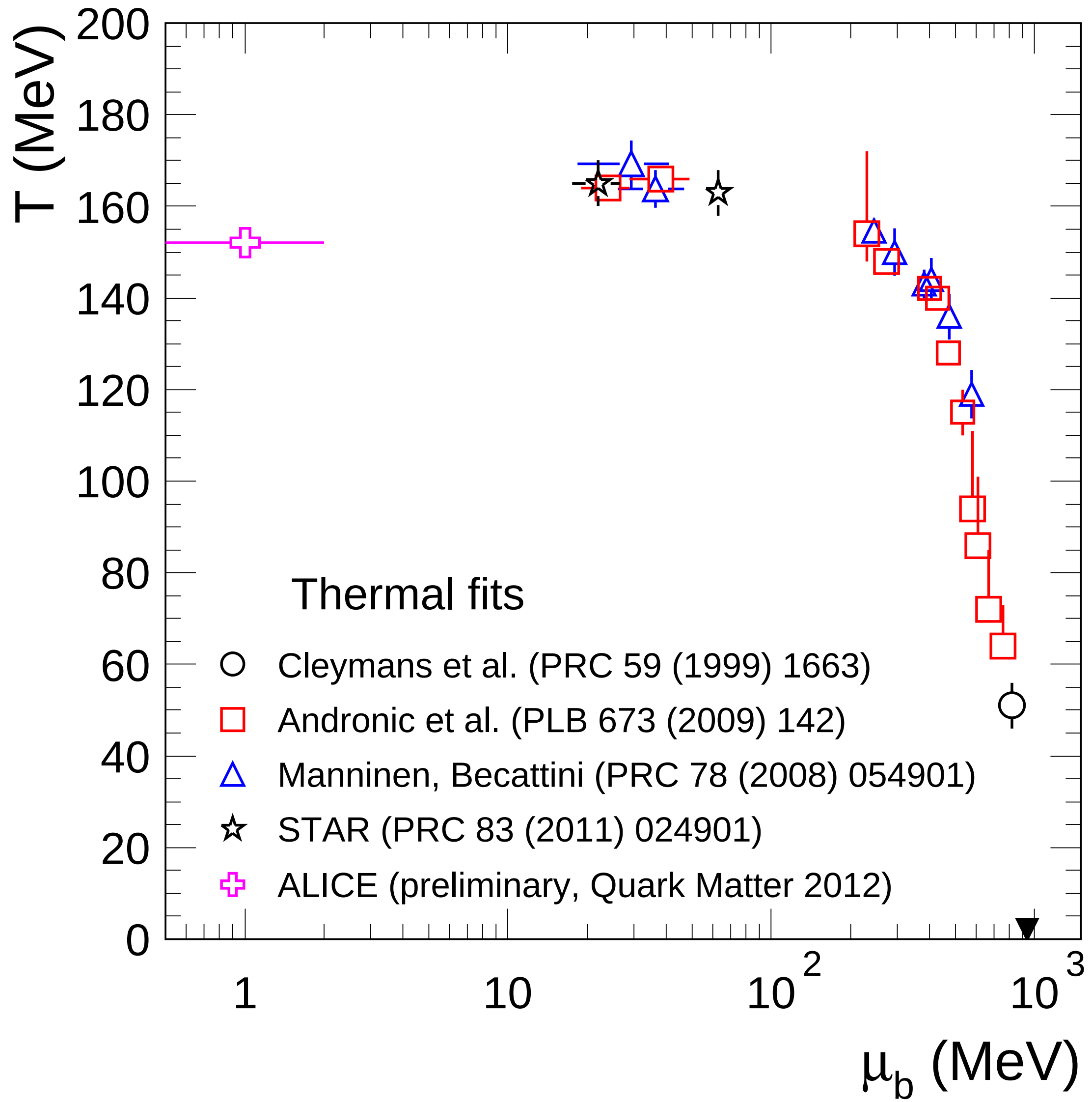
N_i: hadron yield $\Rightarrow (T,\ \mu_b,\ V)$



only STAR data: T=162 MeV, μ_b=24 MeV, V=2400 fm^3, χ^2/N_{df}=17.5/15

Hadron abundances consistent with a thermally equilibrated system

Connection to the phase diagram of QCD



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

if yes, how is thermalization achieved?

relevance for LQCD

$(\mu_s = \mu_{I_3} = 0)$

O. Kaczmarek et al., PRD 83, 014504 (2011)

does freeze-out curve follow the chiral phase transition or crossover line at $\mu_b \neq 0$?

P. Braun-Munzinger, J. Stachel, arXiv:1101.3167

Charmonium and the QGP

the original idea: Matsui & Satz, Phys. Lett. B 178 (1986) 178

"If high energy heavy-ion collisions lead to the formation of a hot quark-gluon-plasma, then color screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. ... It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon-plasma formation."

"Debye screening": no J/ψ if $\lambda_D < r_{J/\psi}$

Debye length in QGP: $\lambda_D \simeq 1/(g(T) \cdot T)$ ...so J/ψ is "thermometer" of QGP

Coulomb Debye screening: $\phi(r) = \frac{Q}{4\pi\varepsilon r}\exp(-\frac{r}{\lambda_D})$, $\lambda_D = \sqrt{\frac{k\varepsilon_0 k_B T}{e^2 \sum z^2 n_j^0}}$

Thermal picture ($n_{partons} = 5.2T^3$ for 3 flavors)

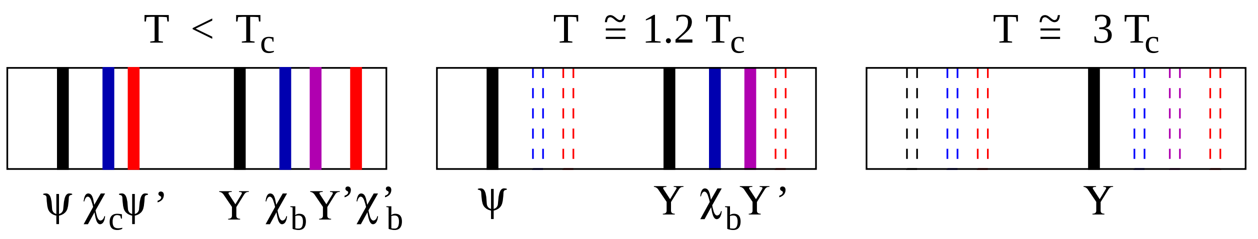
for T=500 MeV: $n_p \simeq$84/fm^3, mean separation $\bar{r}$=0.2 fm $< r_{J/\psi} \simeq$0.5 fm

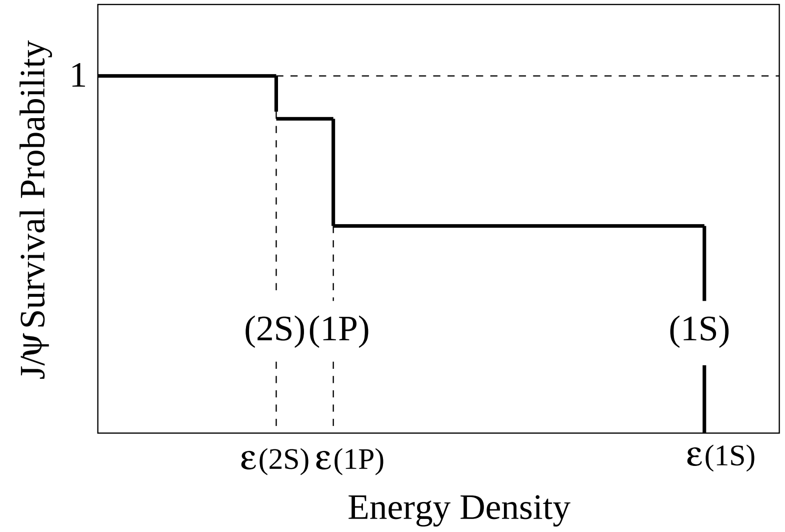
Dynamical picture: $J/\psi + g \rightarrow c + \bar{c}$ (J/ψ is bound by $\sim$600 MeV)

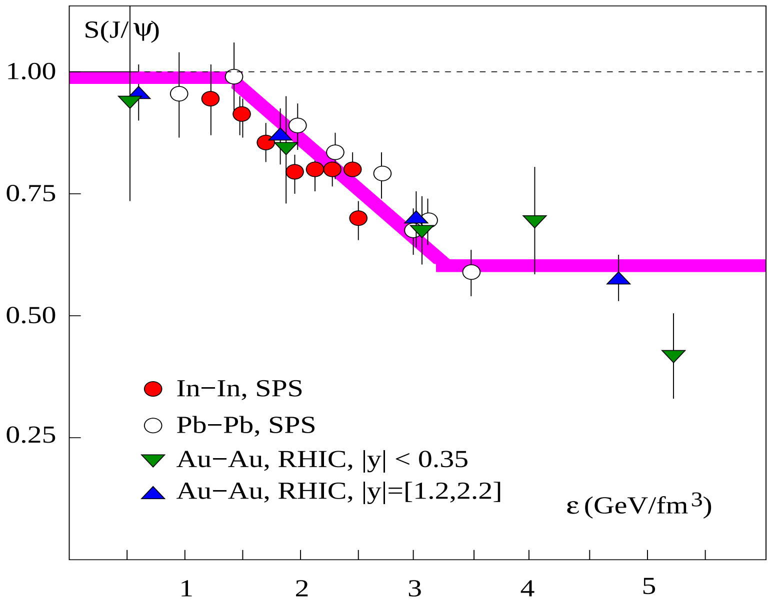
Sequential J/ψ suppression (2006, Matsui-Satz 20th anniv.)

H.Satz, hep-ph/0609197 ...more "thermometry"

LQCD results (still debated)







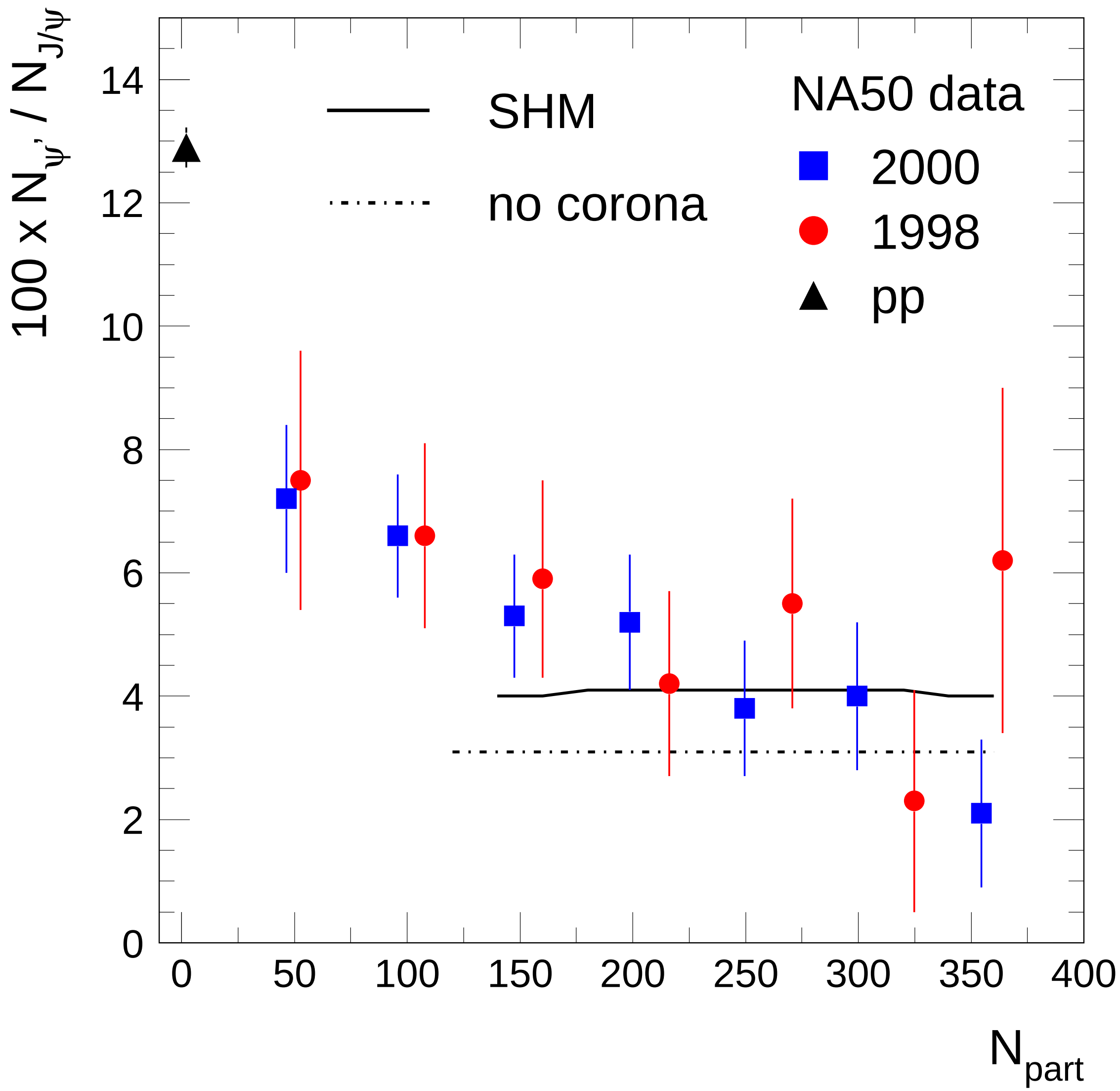
- NB: derived quantities:
  - $S(J/\psi)$: "anomalous" suppression
  - ε is not directly measurable (τ_0=1 fm/c)

- all suppression is from ψ',χ_c
  Karsch, Kharzeev, Satz, PLB 637 (2006) 75

  ! assumes 40% J/ψ from ψ' (10%), χ_c (30%)

ψ' at SPS and the thermal model

Nucl. Phys. A 789 (2007) 334



NA50 Data:
PbPb: EPJ G49 (2007) 559
pp: PLB 466 (1999) 408

$N_{\psi'}/N_{\psi} \neq 0$!

=0 in the screening model

(LQCD: ψ' melted at T_c)

$\Rightarrow$ ψ' prod. by stat. hadr.!

$$N_{J/\psi}/N_{\psi'} = \exp\left(-\frac{m_{\psi'}-m_{J/\psi}}{T}\right)$$

corona is important but alone cannot explain ψ' production

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)
- 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?

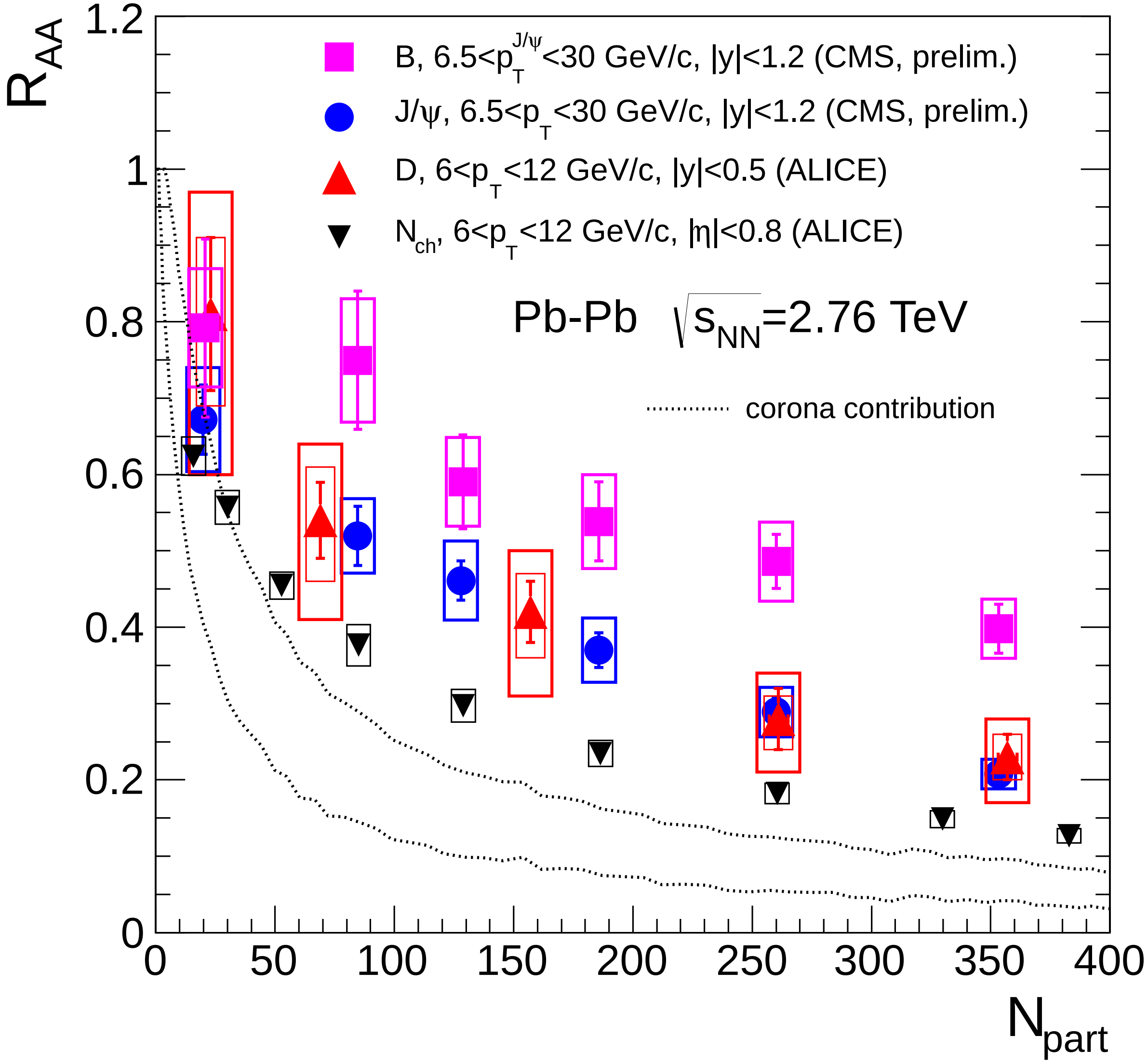
  ...we believe yes ...based on data in the light-quark sector (support from LQCD?)
- no J/ψ survival in QGP (full screening)

  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

Heavy quark thermlization



...from strong energy loss and flow

ordering vs. quark mass expected

established in data?
cum grano salis

similar values for $D(cu)$
and $J/\psi(c\bar{c})$ mesons

determined by c,$\bar{c}$ quarks
(fate in the medium)?

ALICE, JHEP 09 (2012) 112

CMS-PAS-HIN-12-014

Statistical hadronization of 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):

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

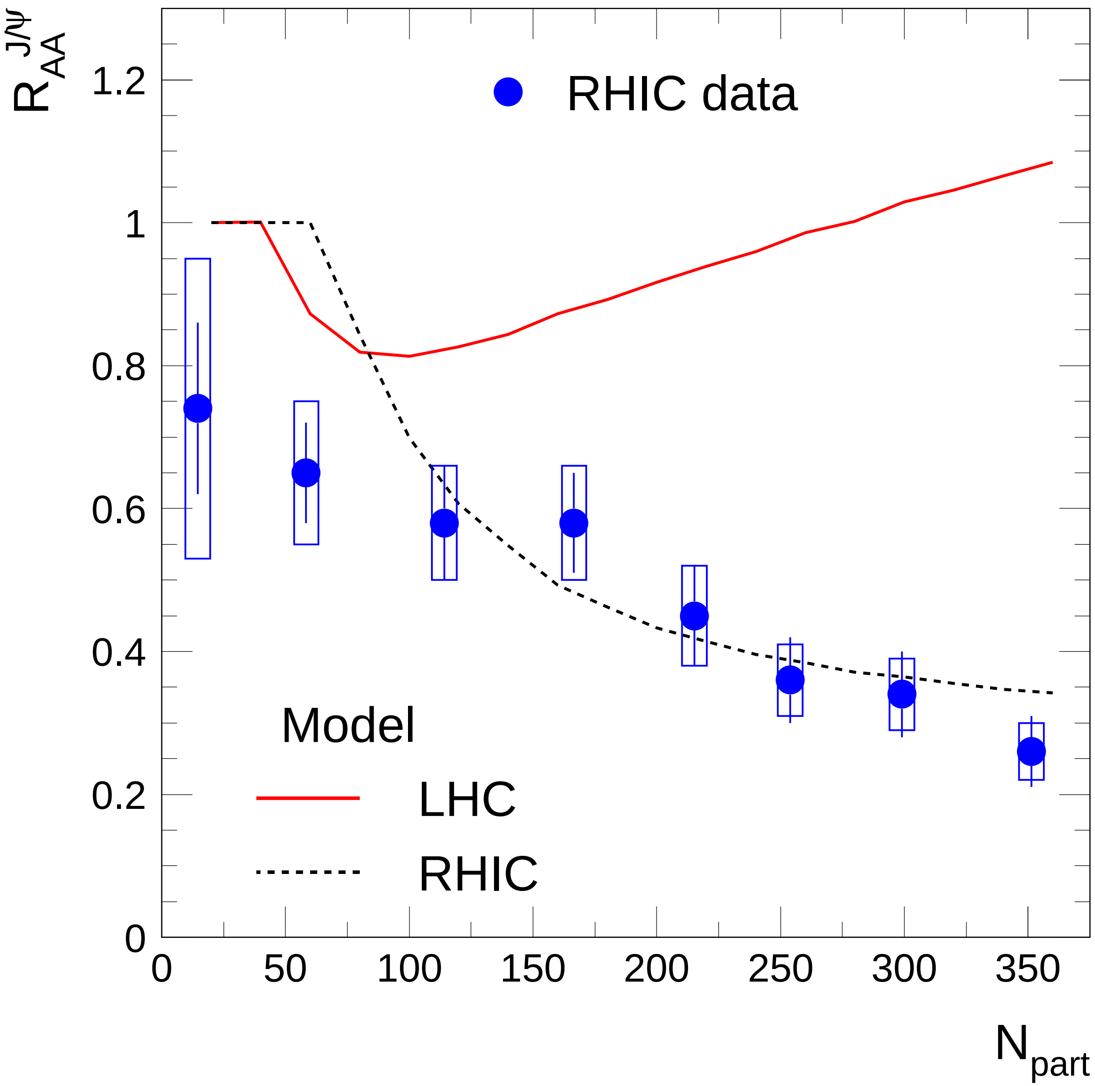
Outcome: $N_D = g_c V n_D^{th} I_1/I_0 \quad N_{J/\psi} = g_c^2 V n_{J/\psi}^{th}$

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

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

corona contribution considered

Charmonium in the statistical hadronization model



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

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

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

What is so different at LHC?

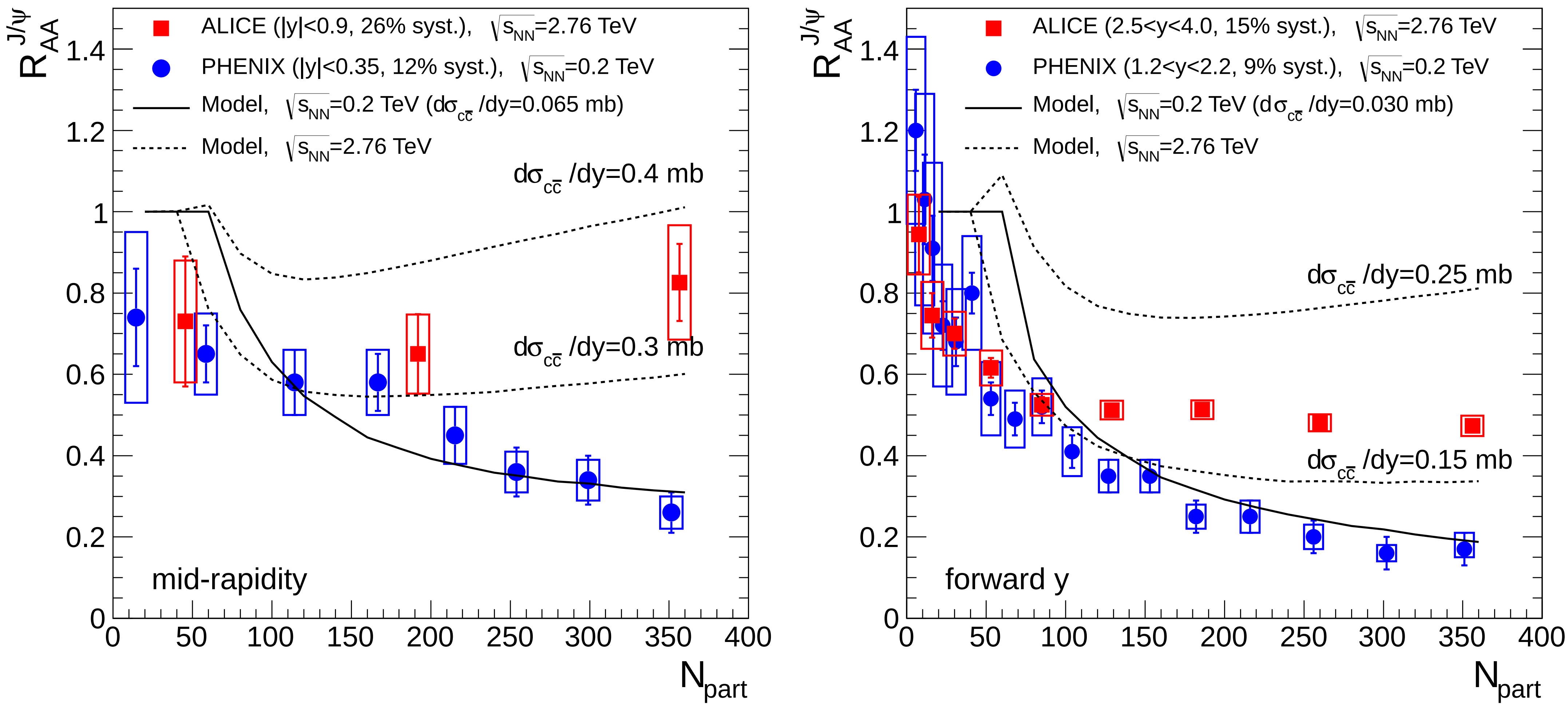
(compared to RHIC)

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

A.Andronic et al., PLB 652 (2007) 259

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

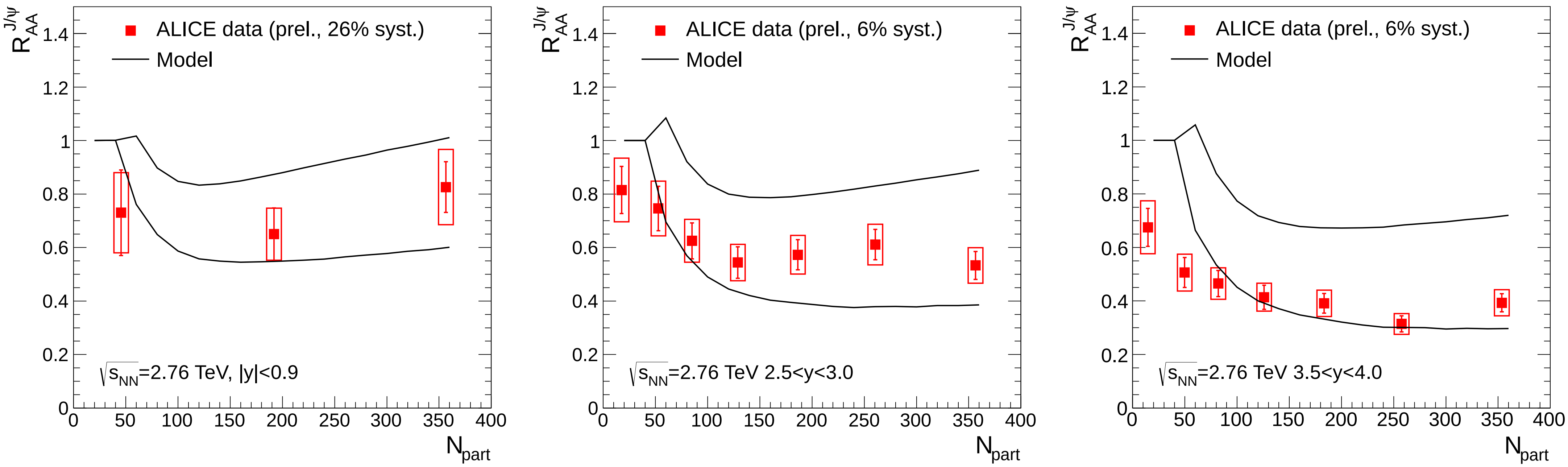
Charmonium in the statistical hadronization model at LHC



the generic prediction by the model is confirmed by data

establishes charmonium as an ultimate observable of the phase boundary

y dependence at the LHC



(correl. and uncorrel. syst. err. of the measurement added in quadrature)

the generic prediction by the model is confirmed by data

another generic prediction: more regeneration at low p_T

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.

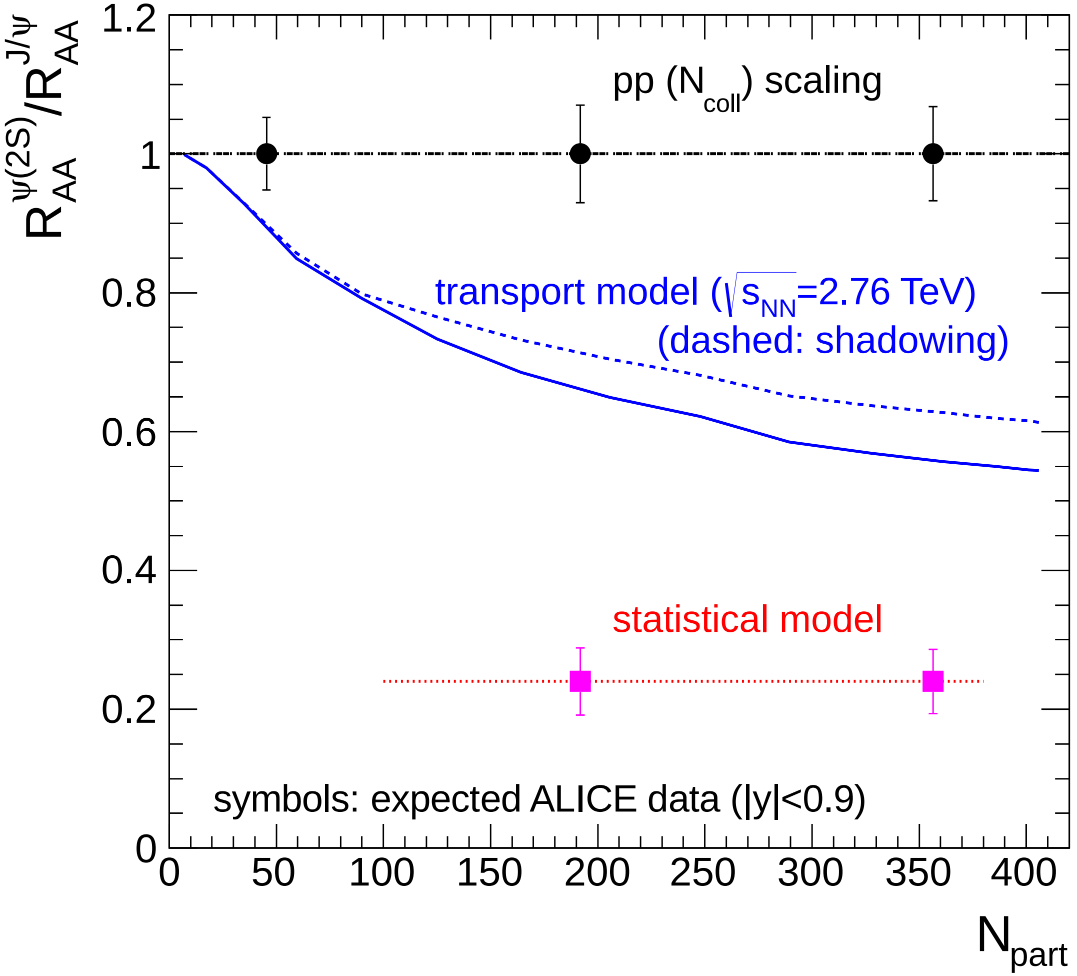
In the statistical model all charmonium states are generated exclusively at hadronization, while in the kinetic model only about half of the J/ψ yield (in central collisions) originates from deconfined charm and anti-charm quarks.

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)

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



$R < 1$ expected in both models, different magnitudes predicted

Transport:

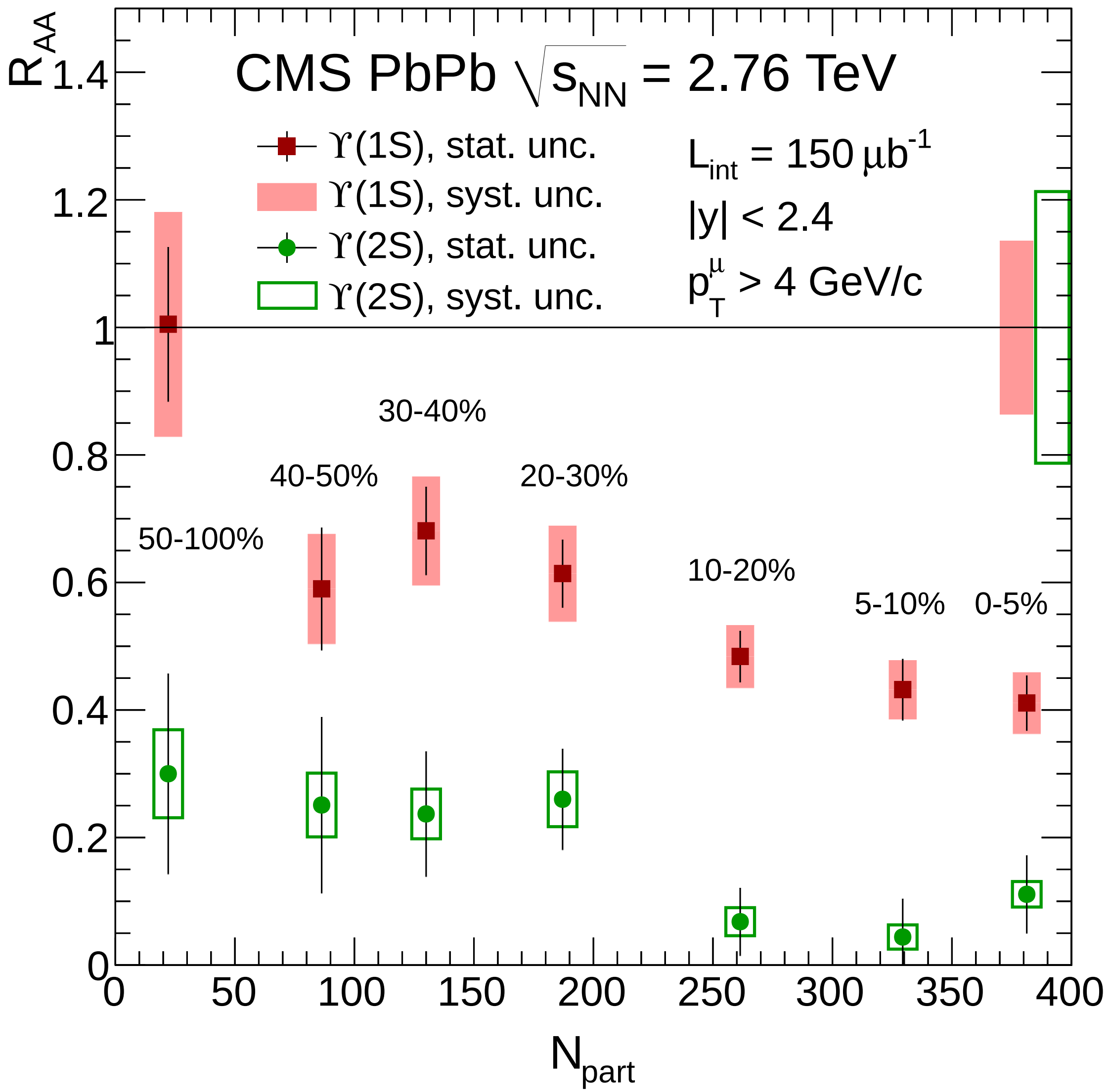
Zhao, Rapp, NPA 859 (211) 114 and priv. comm.

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

Bottonium at LHC

CMS, arXiv:1208.2826



"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

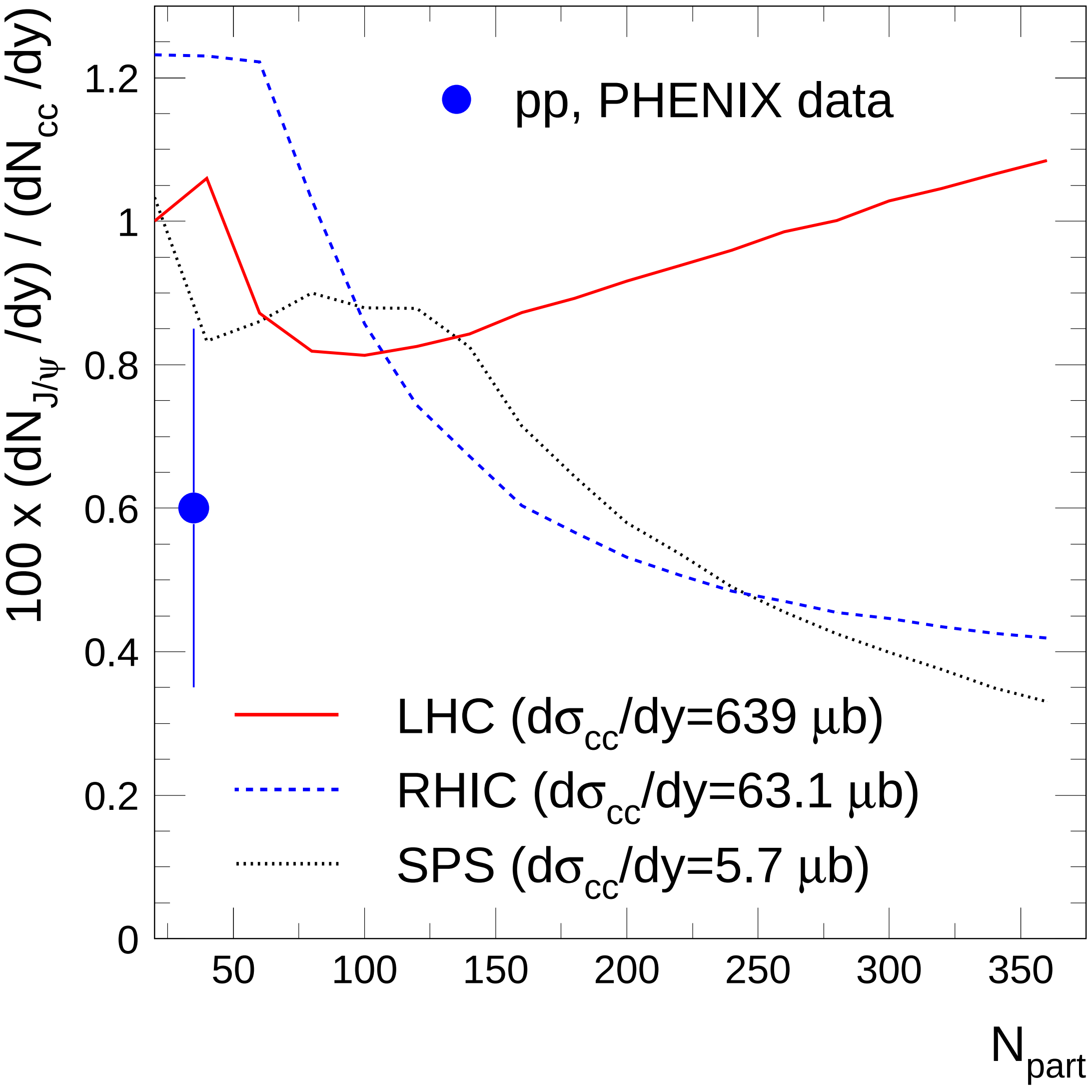
Data, pp:

$\Upsilon(2S)/\Upsilon(1S)$=0.56±0.13±0.02

$\Upsilon(3S)/\Upsilon(1S)$=0.41±0.11±0.04

J/ψ production relative to charm

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



- similar values at RHIC and SPS

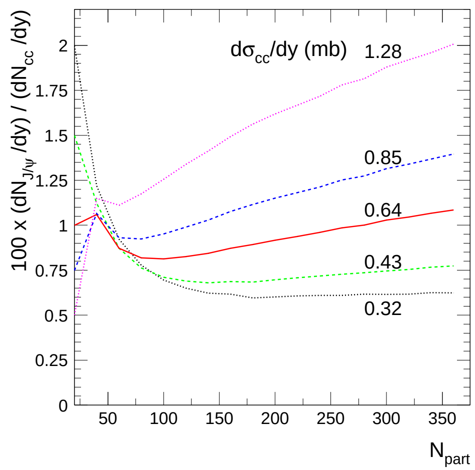
  ...with differences in fine details

  ...determined by canonical suppression of open charm

  same with Υ at RHIC and LNC?

- enhancement-like at LHC

  can. suppr. lifted, quadratic term dominant



Summary and outlook

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

crucial details are being checked right now (p_T, y dependence, elliptic flow)

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

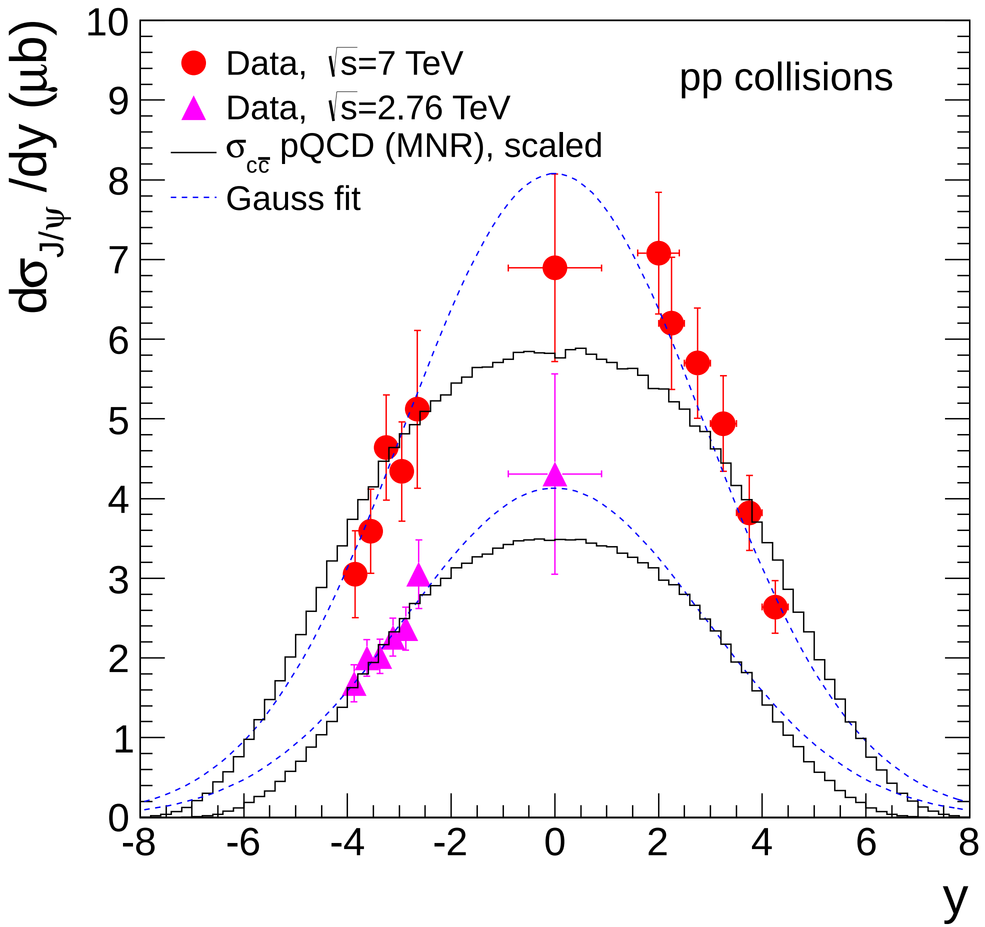
do bottom quarks also thermalize at LHC? (at RHIC?)

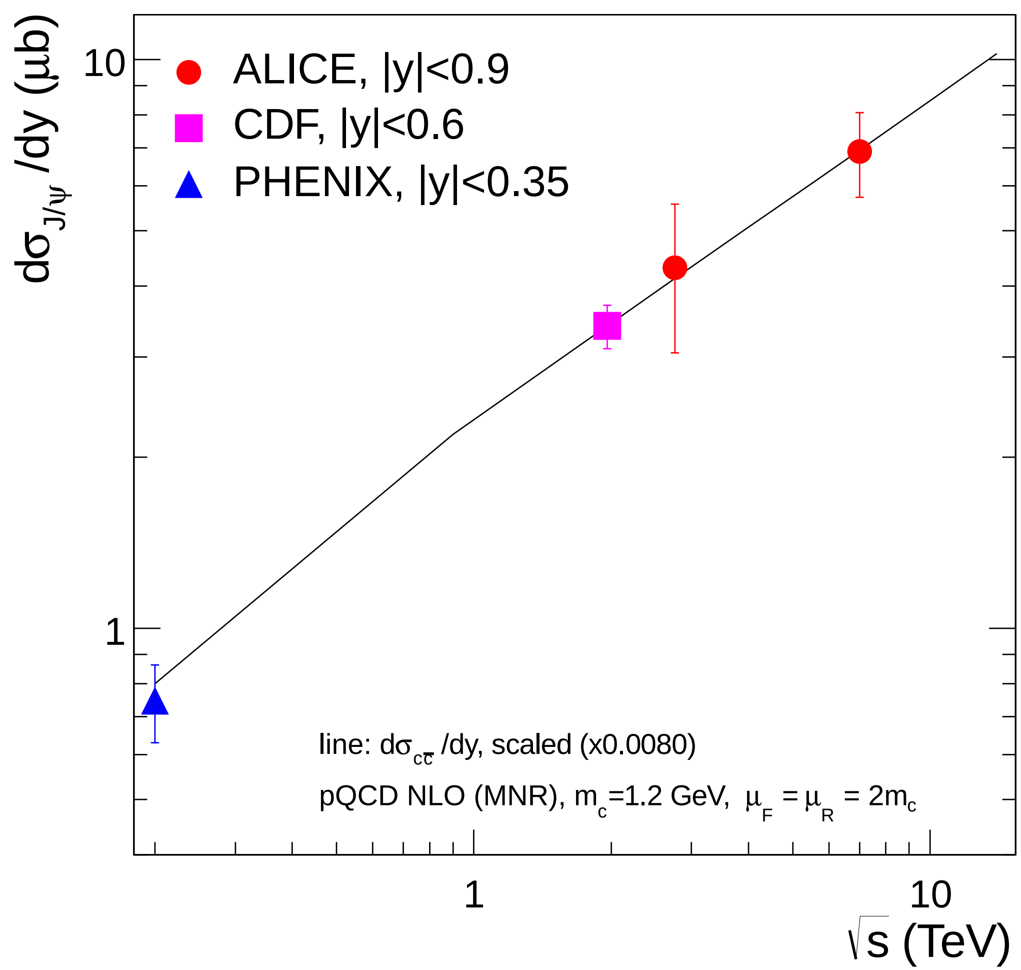
will Υ add more weight to the phase boundary?

while measurements in p–A and at (close to) top LHC energy are eagerly awaited

Backup slides

J/ψ cross sections in pp (corona)





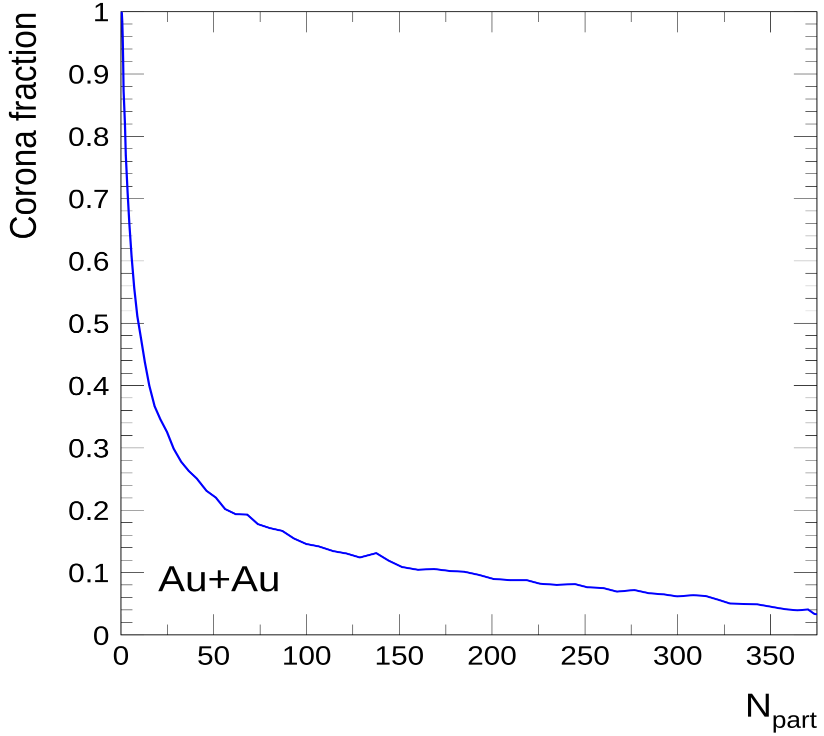
J/ψ: "core" and "corona"

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

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

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

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



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

Timescales for charm(onium) production

Karsch & Petronzio, PLB 193 (1987) 105, Blaizot & Ollitrault, PRD 39 (1989) 232

- QGP formation time, t_{QGP}
  - SPS (FAIR): $t_{QGP} \simeq 1$ fm/c $\sim t_{J/\psi}$
  - RHIC, LHC: $t_{QGP} \lesssim 0.1$ fm/c $\sim t_{c\bar{c}}$

survival of initially-produced J/ψ at SPS/FAIR energies? ($T_d \sim T_c$)

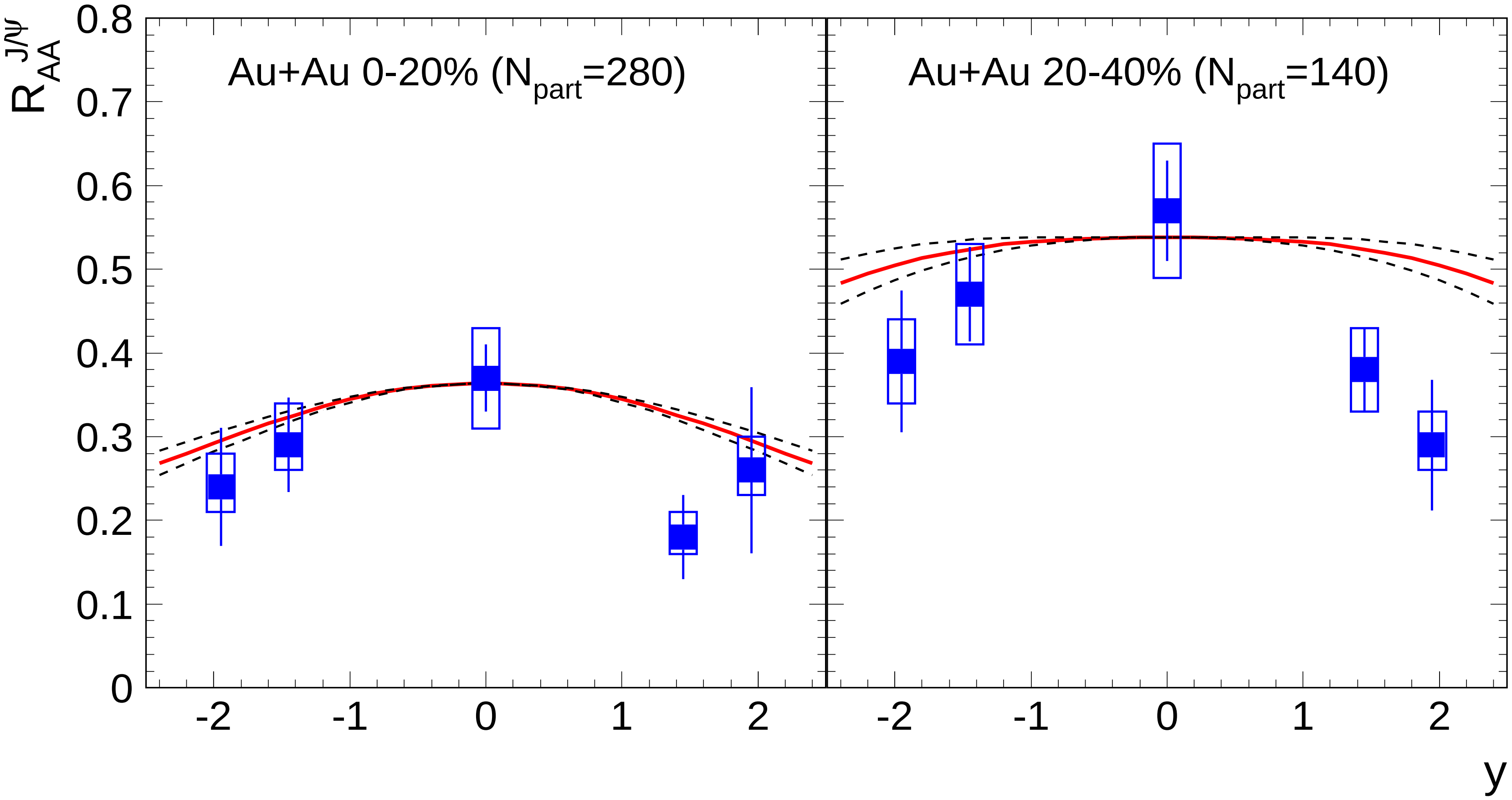
- collision time, $t_{coll} = 2R/\gamma_{cm}$
  - SPS (FAIR): $t_{coll} \gtrsim t_{J/\psi}$
  - RHIC: $t_{coll} < t_{J/\psi}$, LHC: $t_{coll} << t_{J/\psi}$

cold nuclear suppression (breakup by initial nucleons) important at SPS/FAIR energies but not at RHIC and LHC

shadowing is yet another (cold nuclear) effect - important at LHC (RHIC?)

NB: the only way to distinguish: measure $\sigma_{c\bar{c}}$ in pA and AA

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



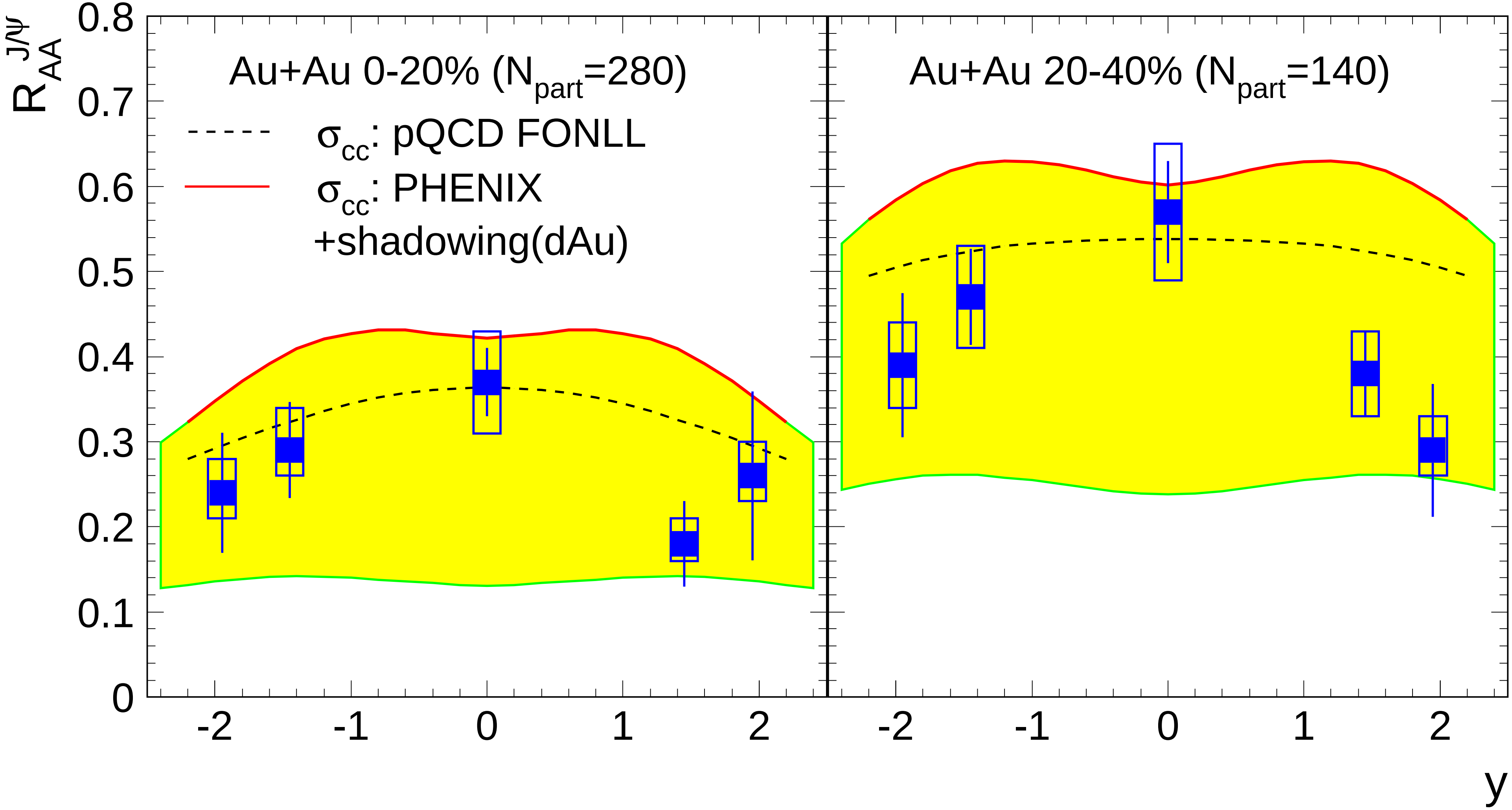
model reproduces data (PHENIX, nucl-ex/0611020) very well (pQCD $\sigma_{c\bar{c}}$)

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

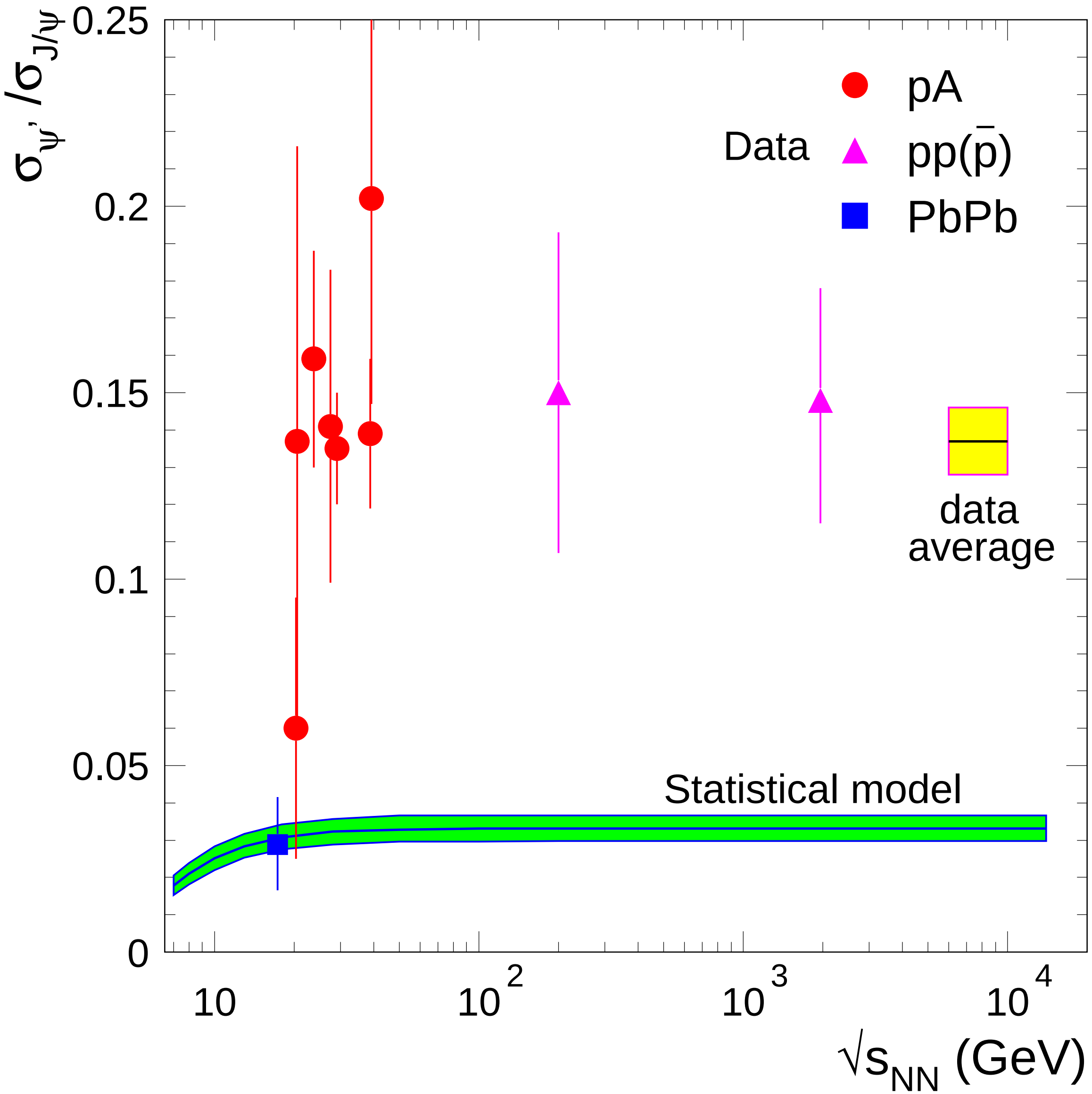
J/ψ at RHIC: effect of shadowing



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

J. Phys. G 35 (2008) 104155

The “null hypothesis”

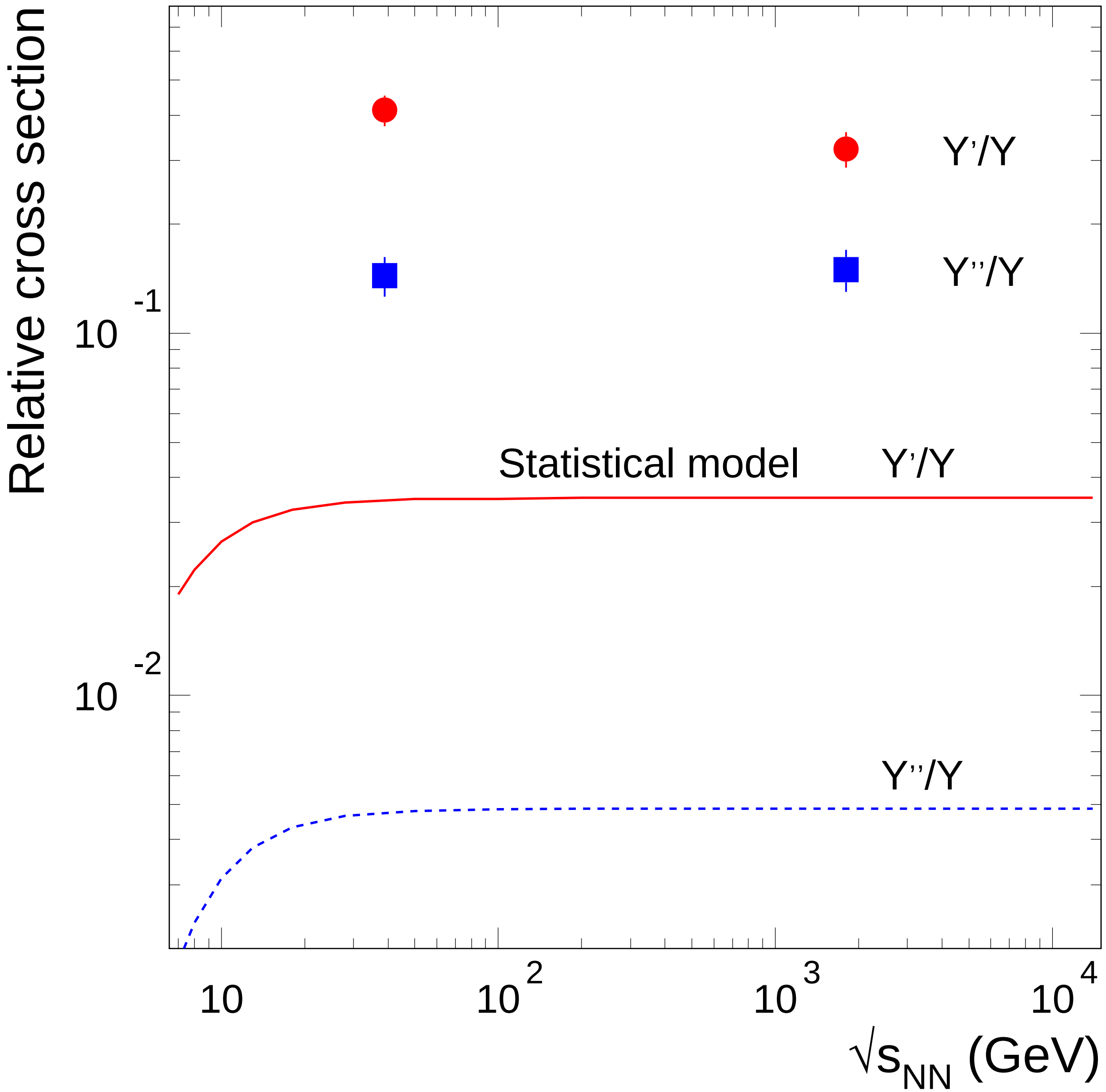


charmonium in pp(A) collisions

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

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

The "null hypothesis" for bottonium

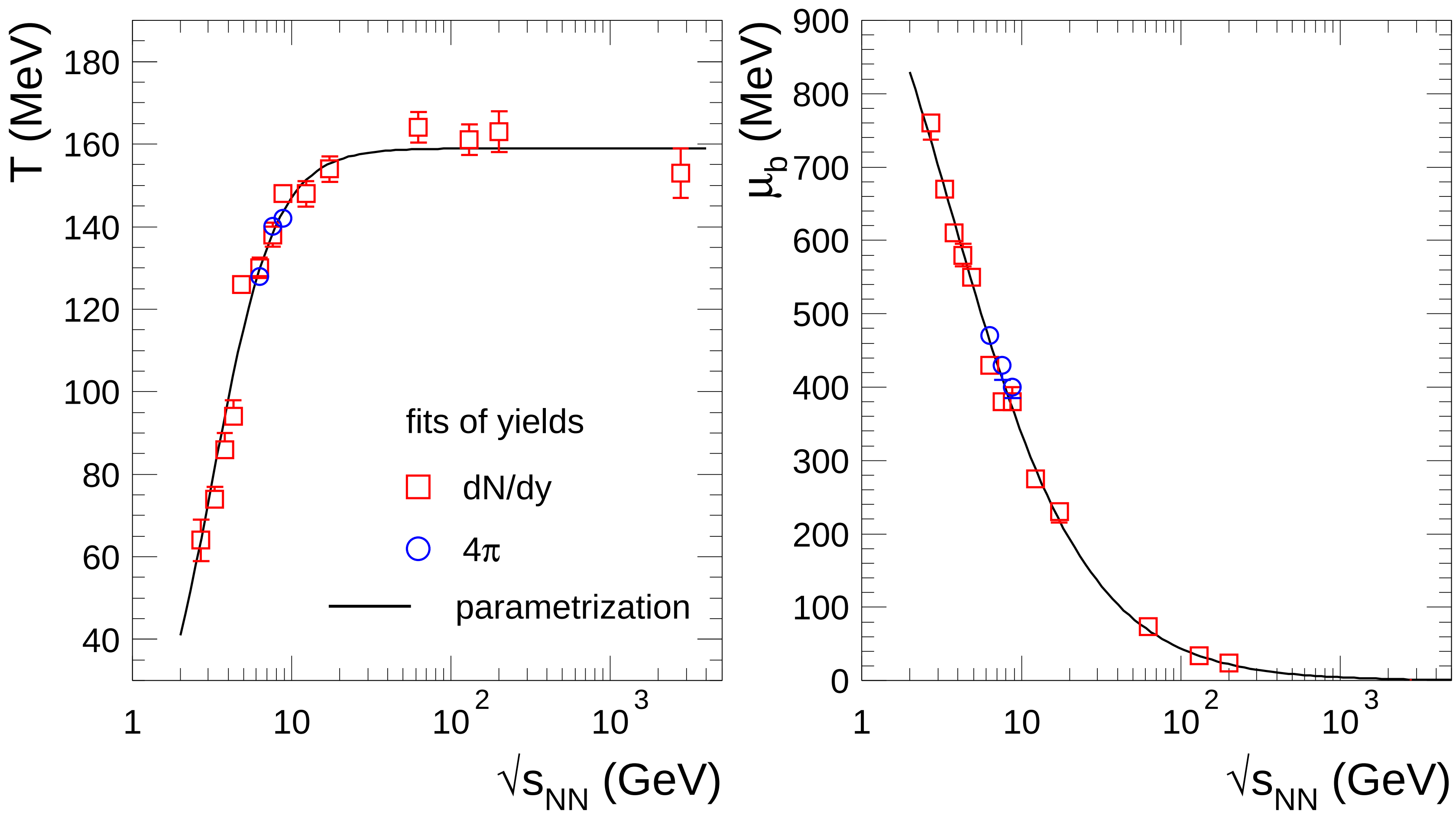


bottonium in pp(A) collisions

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

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

Energy dependence of T, μ_b (central collisions)

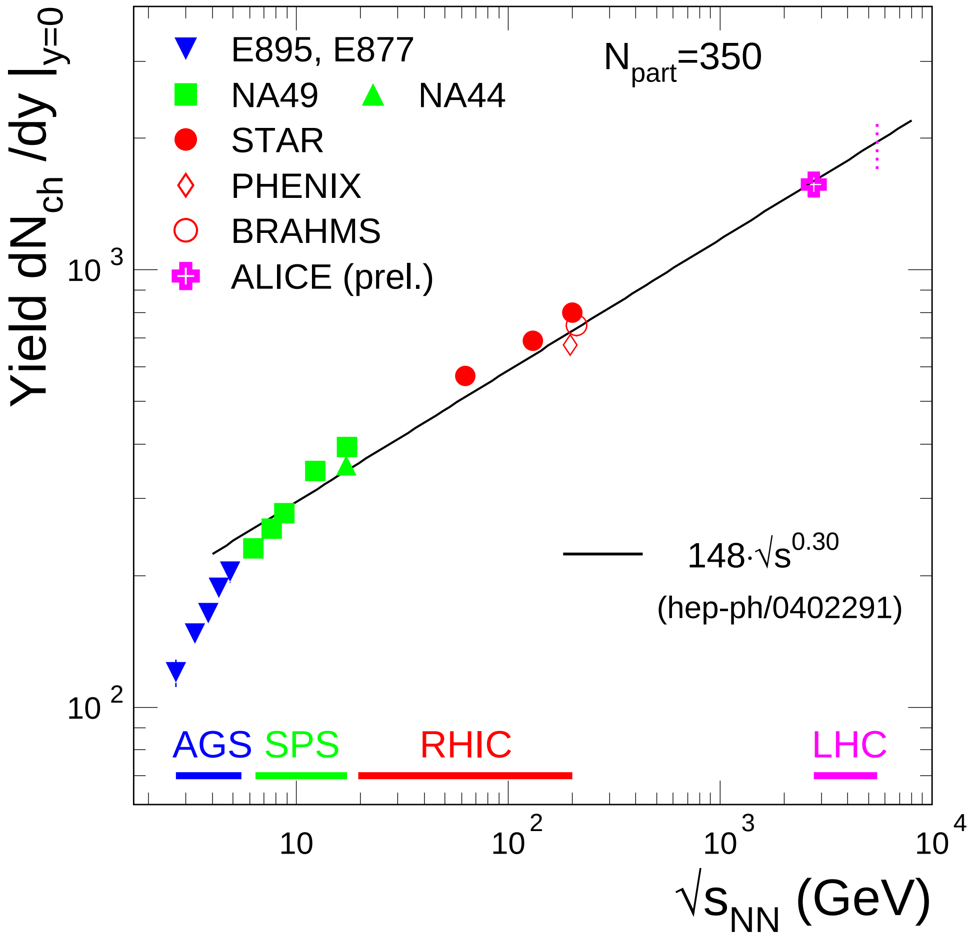


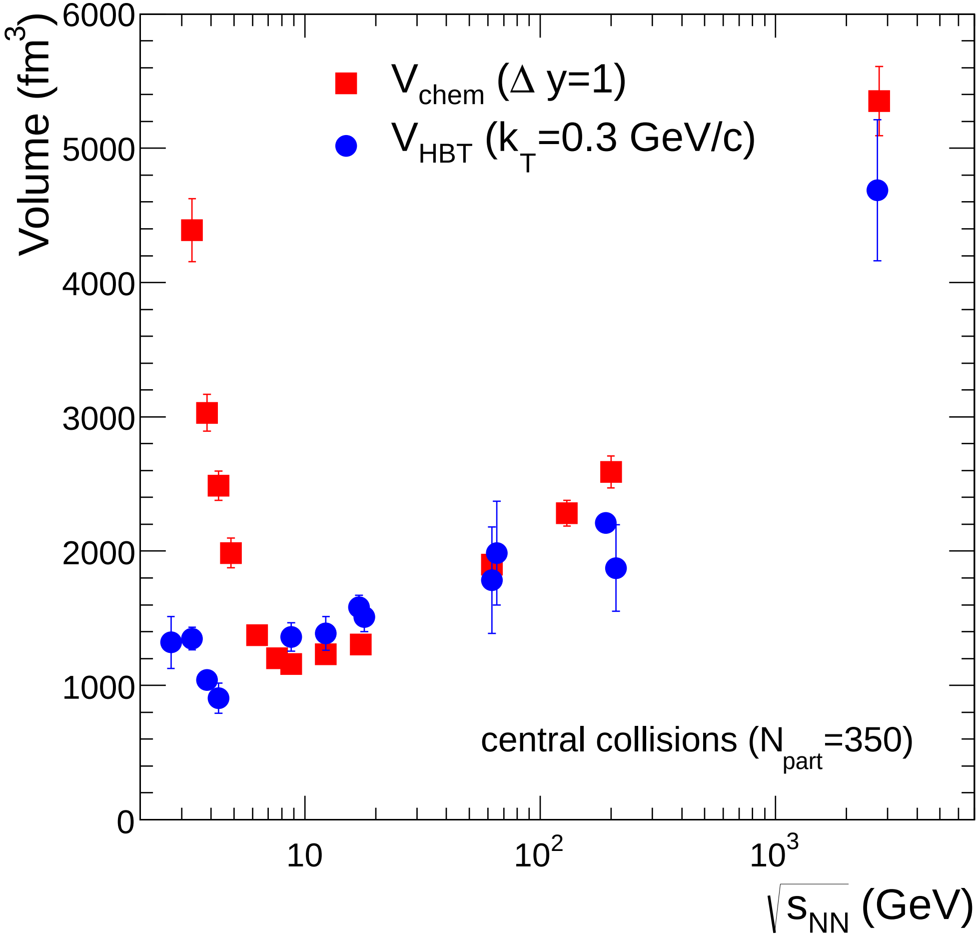
thermal fits exhibit a limiting temperature: $T_{lim} = 159 \pm 2.5$ MeV

$$T = T_{lim} \frac{1}{1+\exp(2.60-\ln(\sqrt{s_{NN}}(\mathrm{GeV}))/0.45)}, \qquad \mu_b[\mathrm{MeV}] = \frac{1303}{1+0.286\sqrt{s_{NN}}(\mathrm{GeV})}$$

PLB 673 (2009) 142

Volume in central collisions

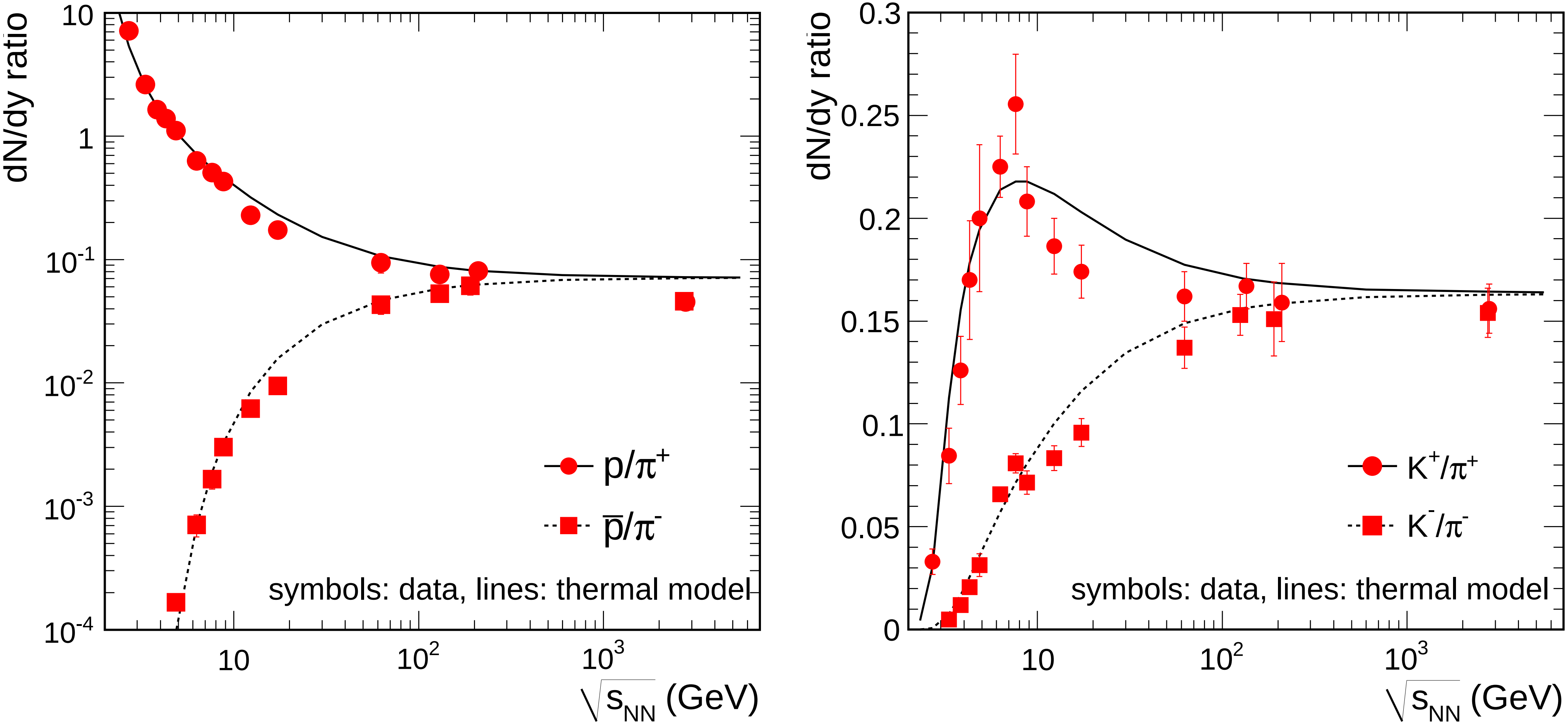




$$V_{chem}(\Delta y = 1) = \mathrm{d}N_{ch}/\mathrm{d}y|_{y=0}/n_{ch}^{therm}$$

$$V_{HBT} = (2\pi)^{3/2} R_{side}^2 R_{long}$$ ...data from ALICE, PLB 696, 328 (2011)

Overview of some hadron ratios



good agreement data-model

...but something special about protons (ALICE preliminary) at LHC?

p,$\bar{p}$ data of STAR ad-hoc "corrected" by -25% for feed-down