# Lecture 3: the charmonium story

- some historical remarks
- the statistical hadronization model
- comparison to results from RHIC
- charmonium production at LHC energy

# Charmonium as a probe for the properties of the QGP

the original idea: (Matsui and Satz 1986) implant charmonia into the QGP and observe their modification, in terms of suppressed production in nucleus-nucleus collisions with or without plasma formation – sequential melting

new insight (pbm, Stachel 2000) QGP screens all charmonia, but charmonium production takes place at the phase boundary, enhanced production at colliders – signal for deconfined, thermalized charm quarks

recent reviews: L. Kluberg and H. Satz, arXiv:0901.3831

pbm and J. Stachel, arXiv:0901.2500

both published in Landoldt-Boernstein Review, R. Stock, editor, Springer 2010

Quarkonia:
heavy quark bound states stable under strong decay

heavy: charm ($m_c \simeq 1.3$ GeV) or beauty ($m_b \simeq 4.7$ GeV)
stable: $M_{c\bar{c}} \leq 2M_D$ and $M_{b\bar{b}} \leq 2M_B$

heavy quarks ⇒ quarkonium spectroscopy via
non-relativistic potential theory

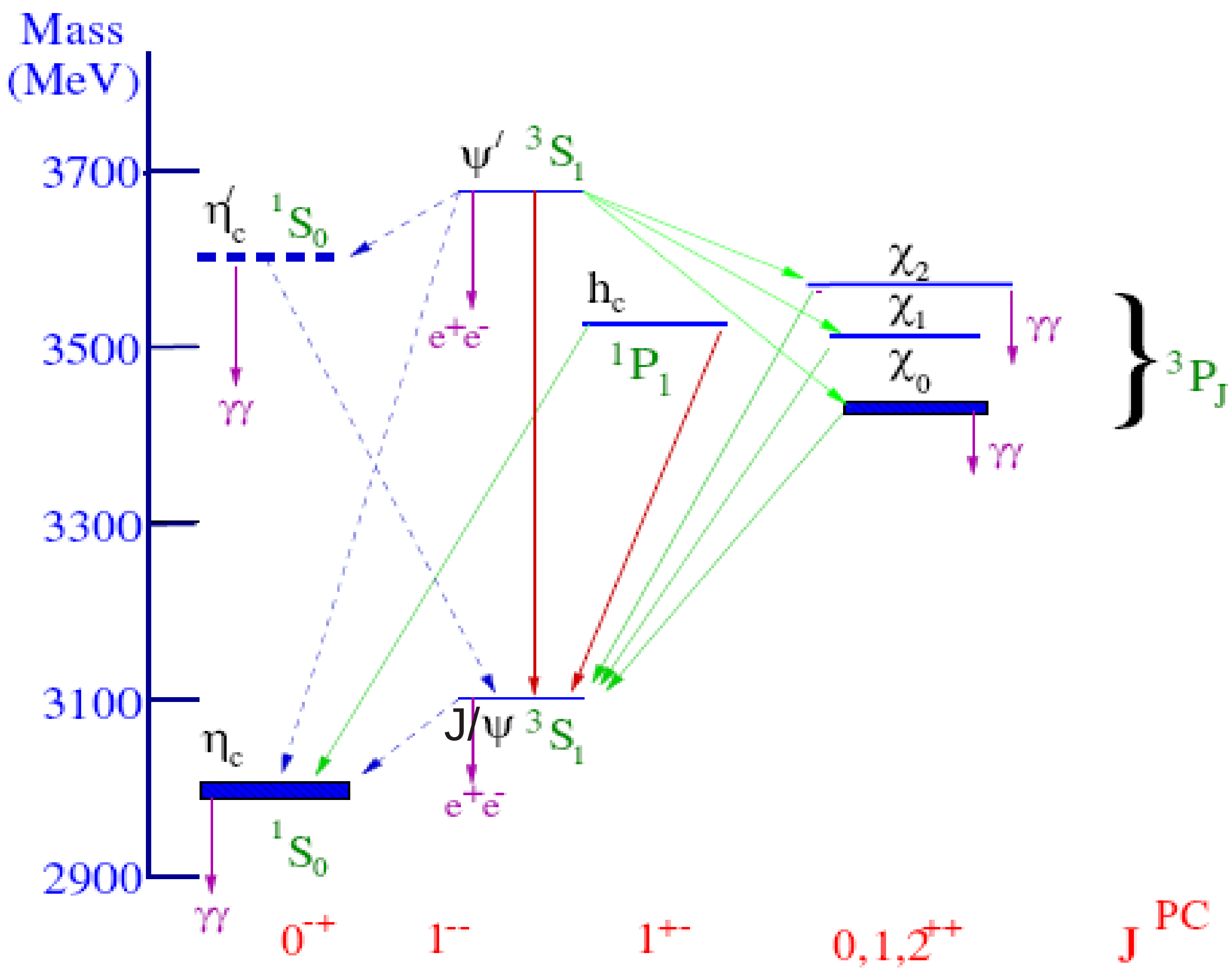
Schrödinger equation $\left\{2m_c - \frac{1}{m_c}\nabla^2 + V(r)\right\}\Phi_i(r) = M_i\Phi_i(r)$

confining ("Cornell") potential $V(r) = \sigma\, r - \frac{\alpha}{r}$

string tension $\sigma \simeq 0.2$ GeV$^2$, gauge coupling $\alpha \simeq \pi/12$

⇒ quarkonium masses $M_i$ and radii $r_i$

# charmonium, a bound state of charm and anti-charm quarks



# Quarkonium Properties and Debye Screening

| state | $J/\psi$ | $\chi_c$ | $\psi'$ | $\Upsilon$ | $\chi_b$ | $\Upsilon'$ | $\chi'_b$ | $\Upsilon''$ |
|---|---|---|---|---|---|---|---|---|
| mass [GeV] | 3.10 | 3.53 | 3.68 | 9.46 | 9.99 | 10.02 | 10.26 | 10.36 |
| $\Delta E$ [GeV] | 0.64 | 0.20 | 0.05 | 1.10 | 0.67 | 0.54 | 0.31 | 0.20 |
| $\Delta M$ [GeV] | 0.02 | -0.03 | 0.03 | 0.06 | -0.06 | -0.06 | -0.08 | -0.07 |
| radius [fm] | 0.25 | 0.36 | 0.45 | 0.14 | 0.22 | 0.28 | 0.34 | 0.39 |

table from H. Satz, J. Phys. G32 (2006) R25

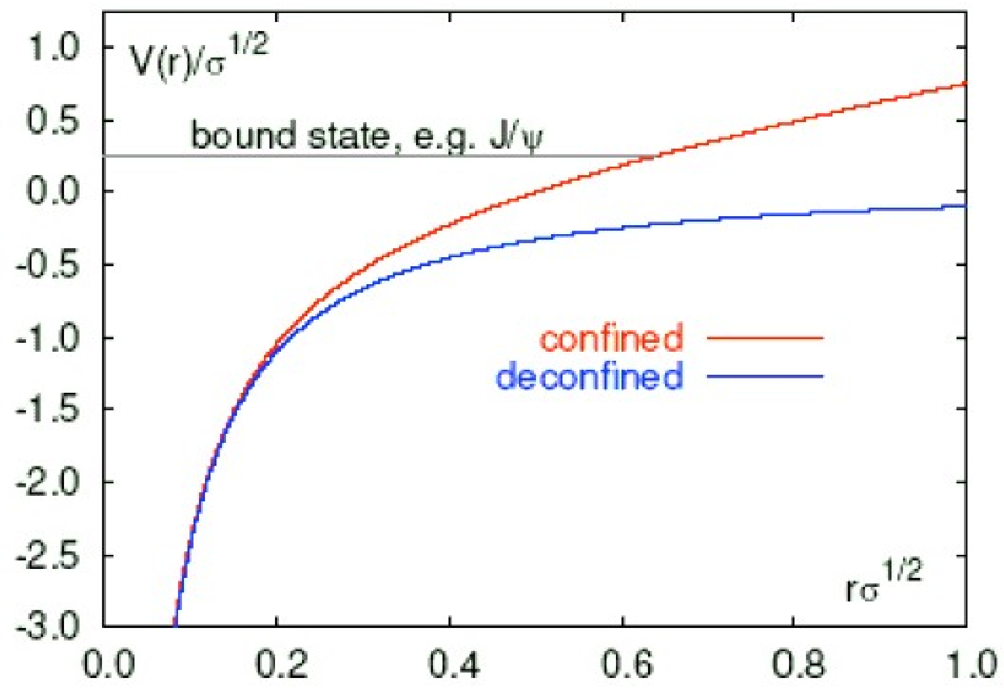
In the QGP, the screening radius $r_{Debye}(T)$ decreases with increasing T. If $r_{Debye}(T) < r_{charmonium}$ the system becomes unbound $\rightarrow$ suppression compared to charmonium production without QGP. The screening radius can be computed using potential models or solving QCD on the lattice.

# Debye screening

V(r,T large)   no bound state

V(r,T small)  bound state

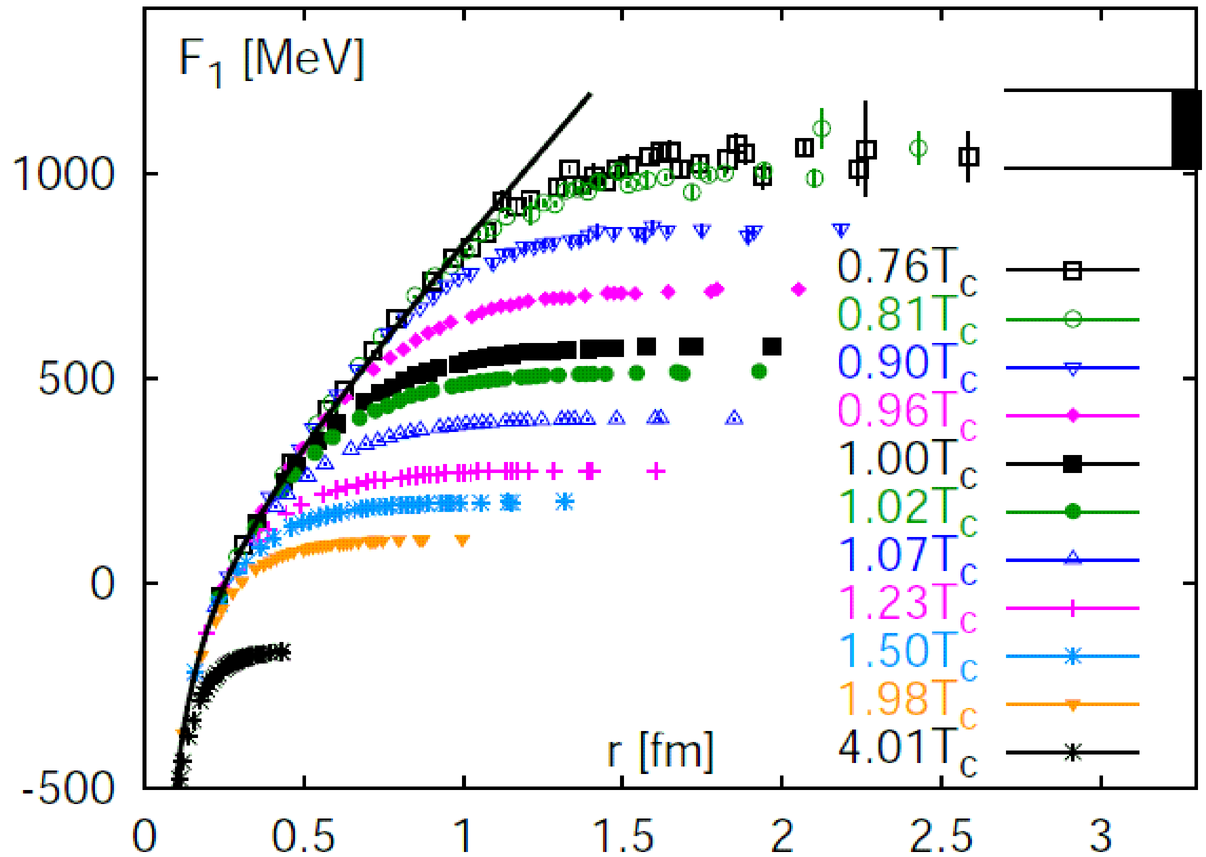
$\sigma$ = string tension = 1 GeV/fm
= 0.2 GeV$^2$



# Free energy of a heavy quark-antiquark pair

color singlet free energy
$F_1(T) = U(T) - T\,S(T)$

note: J/ψ is bound
by 640 MeV




J/ψ disappears for T > 1.6 $T_c$

O. Kaczmarek, F.Zantow, PRD 71(2005)114510

# Debye Screening

screened potential for heavy quark-antiquark pair

$$V_{q\bar{q}}(r,T) = \frac{\sigma}{\mu}\left(1 - \mathrm{e}^{-\mu(T)r}\right) - \frac{\alpha}{r}\mathrm{e}^{-\mu(T)r}$$

Debye radius $r_{Debye} = 1/\mu(T)$

$r_{Debye} \propto 1/n_g^{1/3} \propto 1/(g(T)\,T)$

| state | $J/\psi$ | $\chi_c$ | $\psi'$ | |
|---|---|---|---|---|
| $E_s^i$ [GeV] | 0.64 | 0.20 | 0.05 | |
| $T_d/T_c$ | 1.1 | 0.74 | 0.1 - 0.2 | using $F_1$ |
| $T_d/T_c$ | $\sim 2.0$ | $\sim 1.1$ | $\sim 1.1$ | using U |

# time scales

for the original Matsui/Satz picture to hold, the following time sequence is needed:

1) charmonium formation
2) quark-gluon plasma (QGP) formation
3) melting of charmonium in the QGP
4) decay of remaining charmonia and detection

questions:
a) beam energy dependence of time scales
b) what happens with the (many) charm quarks at hadronization, i.e at the phase boundary?

at LHC energy, clean separation of time scales

collision time << QGP formation time < charmonium formation time

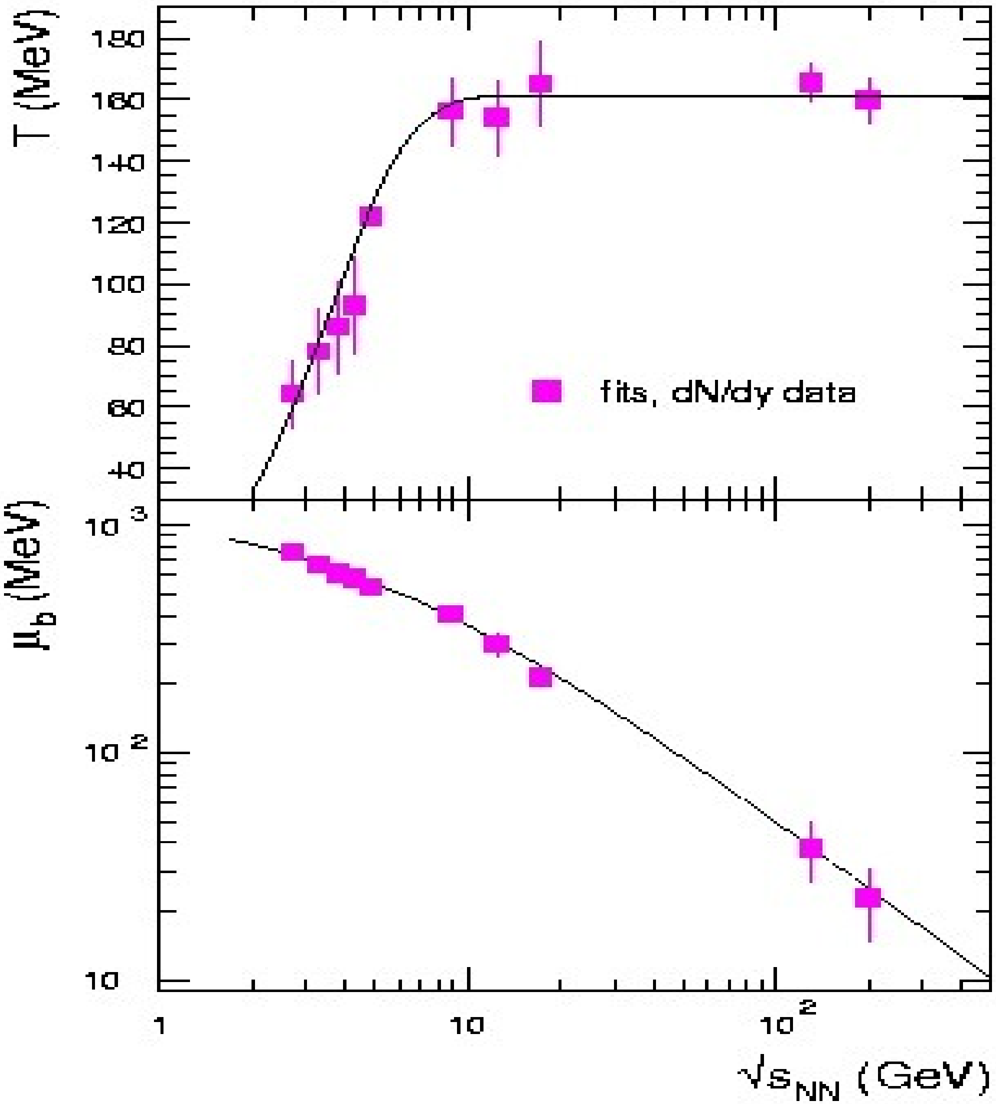
# all (u,d,s) hadrons are produced in a thermal state near the phase boundary

note: establishment of limiting temperature

**$T_{lim}$ = 160 MeV**

get T and $\mu_B$ for all energies

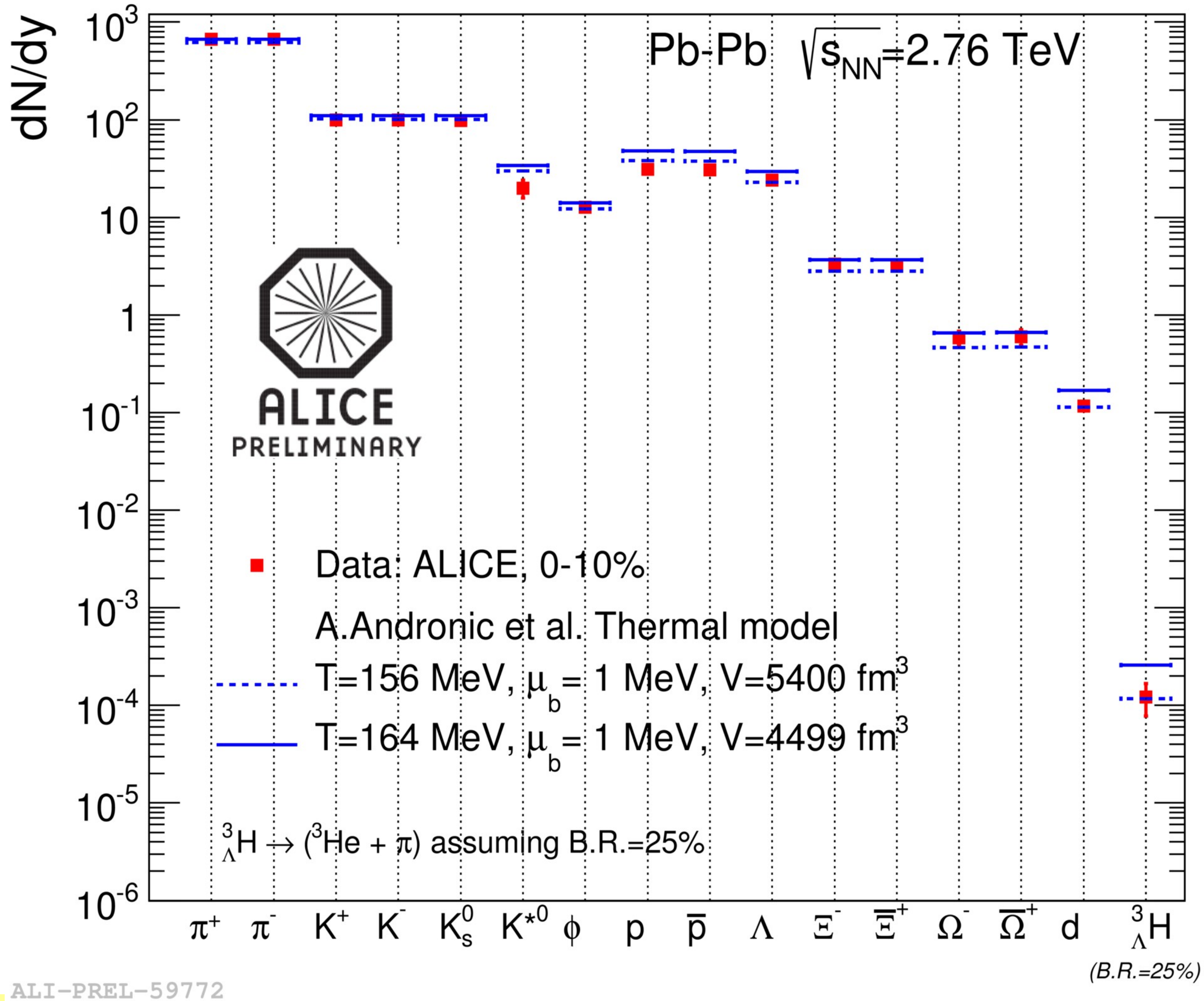
in this approach $T_{lim} = T_c$




A. Andronic, pbm, J. Stachel,
Nucl. Phys. A772 (2006) 167
nucl-th/0511071

freeze-out point at LHC energy see below

# new fit of Alice data including hypertriton




T = 156 MeV also works for hypertriton

good agreement over more than 6 orders of magnitude

# are charmonia (and charmed hadrons) produced thermally?

ratios of charmed and beauty hadrons exhibit thermal features (Becattini 1997)
but: psi'/psi ratio is far from thermal in pp collisions
see also Sorge&Shuryak, Phys. Rev. Lett. 79 (1997) 2775, where it is further noted that the psi'/psi ratio reaches a thermal value (T=170 MeV) in central PbPb collisions at SPS energy

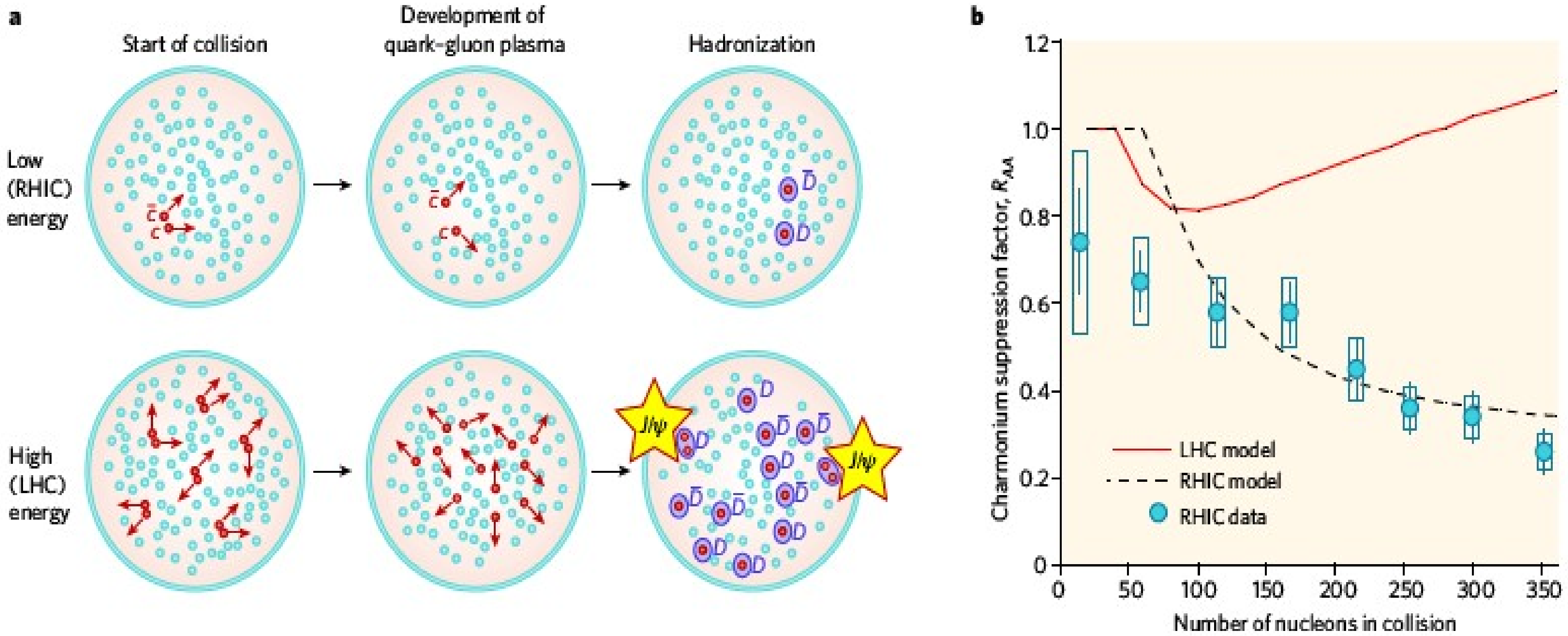
further analysis by Gorenstein and Gazdzicki, Phys. Rev. Lett. 83 (1999) 4003
result: (J/psi)/pi is approximately constant at SPS energy for PbPb

However, thermal production of charm quarks is appreciable
only at very high temperatures
(T > 800 MeV, pbm&Redlich, Eur. Phys. J. C16 (2000) 519).

solution: charm quarks produced in hard collisions, then statistical hadronization at the phase boundary.

# quarkonium as a probe for deconfinement at the LHC
# the statistical (re-)generation picture

P. Braun-Munzinger, J. Stachel, The Quest for the Quark-Gluon Plasma,
Nature **448** Issue 7151, (2007) 302-309.




charmonium enhancement as fingerprint of color screening and deconfinement at LHC energy

pbm, Stachel, Phys. Lett. B490 (2000) 196
Andronic, pbm, Redlich, Stachel, Phys. Lett. B652 (2007) 659

# Statistical hadronization in one page

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

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

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

charm balance equation

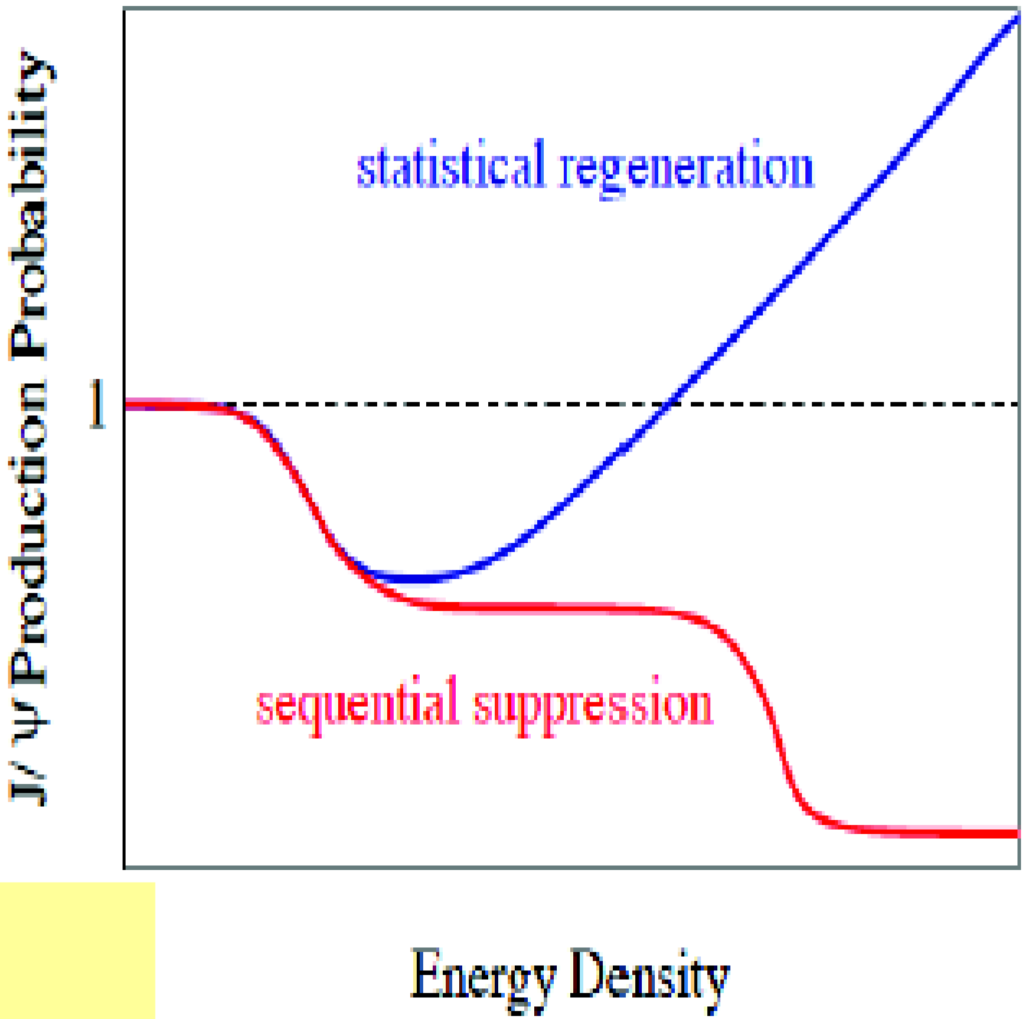
$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{th} \frac{I_1(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})} + g_c^2 N_{c\bar{c}}^{th} \quad \rightarrow g_c$$

---

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: $T$, $\mu_B$, $\quad V = N_{ch}^{exp} / n_{ch}^{th}$, $\quad N_{c\bar{c}}^{dir}$ (pQCD)

# decision on regeneration vs sequential suppression from LHC data




SPS RHIC LHC

Picture:
H. Satz 2009

# ingredients for prediction of quarkonium and open charm cross sections

• energy dependence of temperature and baryo-chemical potential (from hadron production analysis)
• open charm (open bottom) cross section in pp or better AA collisions
• quarkonium production cross section in pp collisions (for corona part)

result: quarkonium and open charm cross sections as function of
energy, centrality, rapidity, and transverse momentum

# now brief survey of SPS and RHIC results

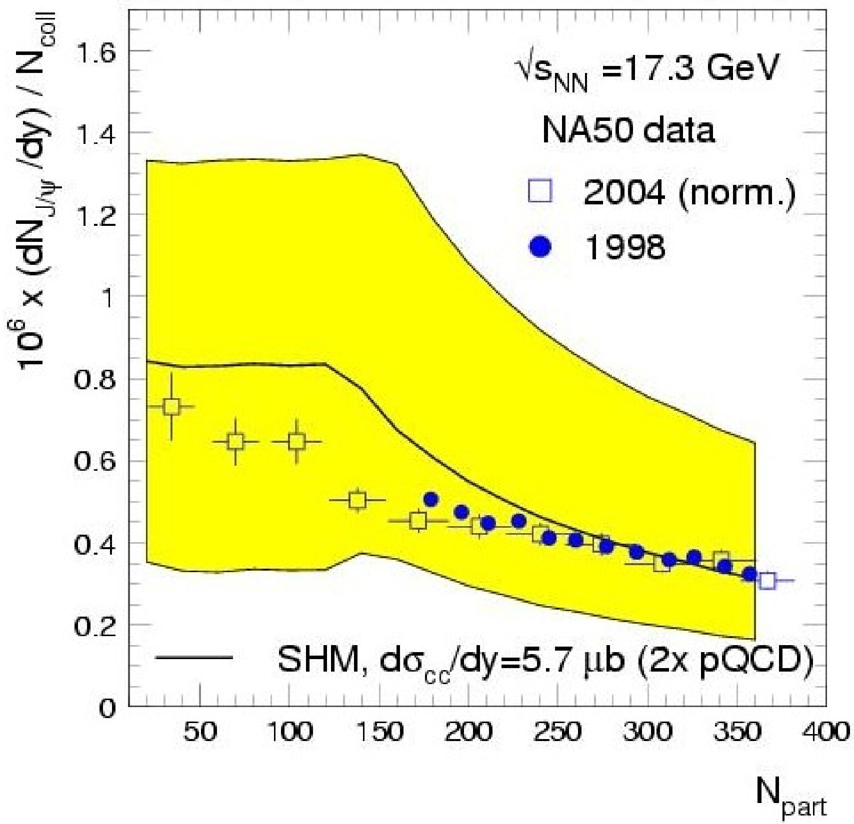
note: charmonium suppression or enhancement is quantified via the nuclear modification factor $R_{AA}$

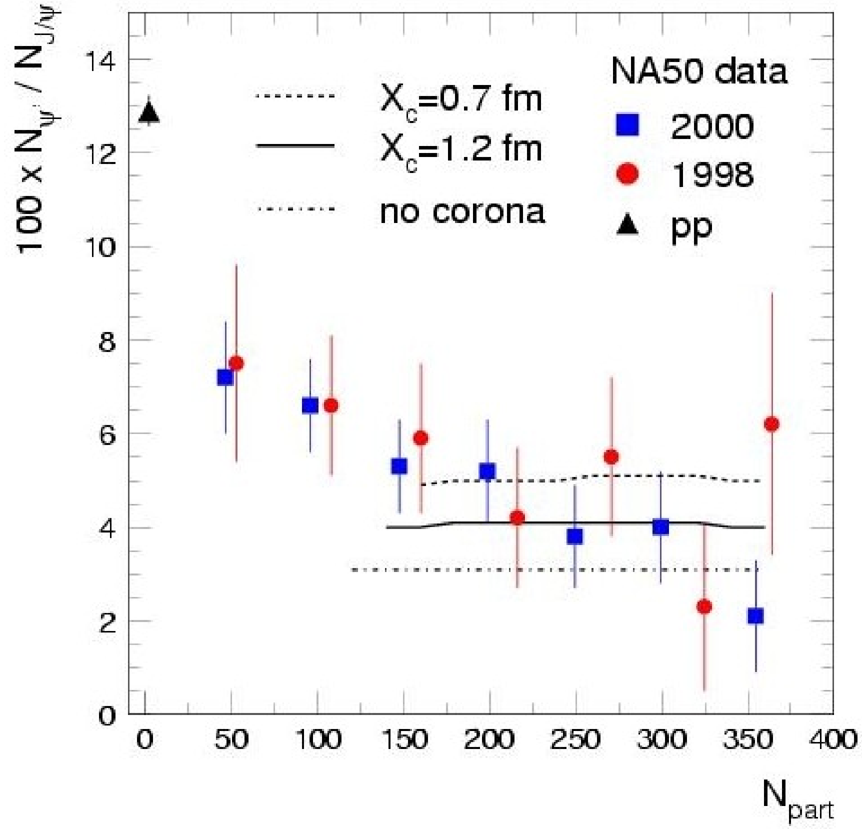
$$R^i_{\mathrm{AA}} = \frac{Y^i_{\mathrm{J}/\psi}(\Delta p_{\mathrm{t}}, \Delta y)}{\langle T^i_{\mathrm{AA}} \rangle \times \sigma^{\mathrm{PP}}_{\mathrm{J}/\psi}(\Delta p_{\mathrm{t}}, \Delta y)}$$

Here, $T_{AA}$ is the nuclear thickness function

by construction, $R_{AA}$ = medium/vacuum

# results for SPS energy



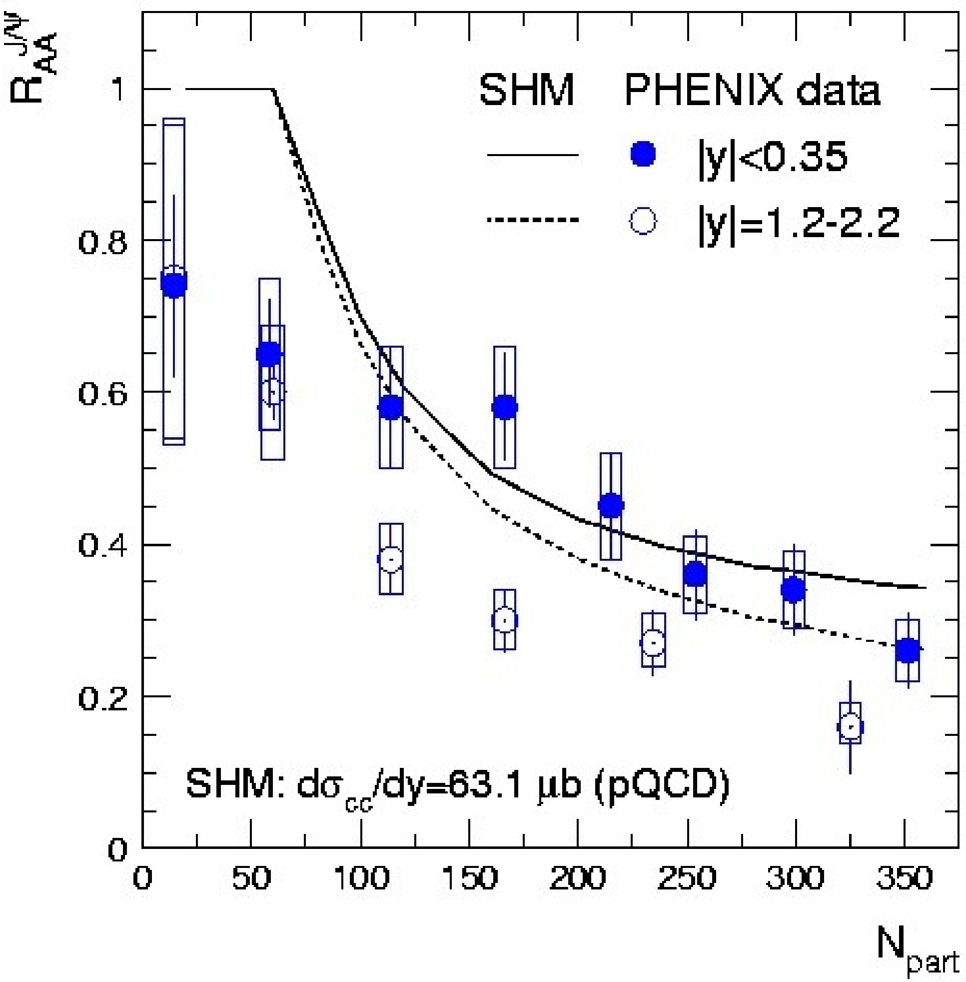




only moderately enhanced (2 x pQCD) cc_bar cross section needed

psi'/psi ratio is expected from a thermal scenario

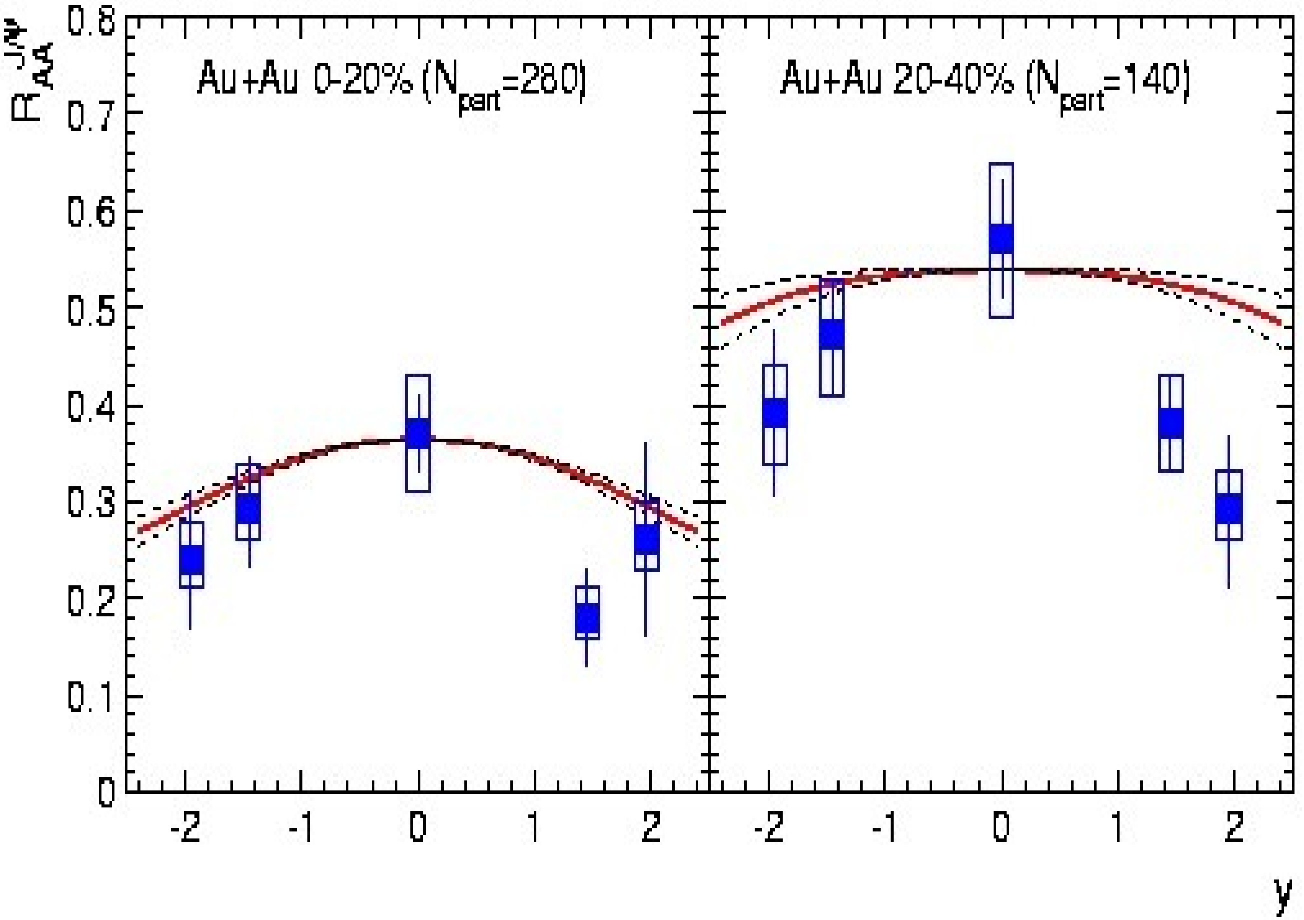
# a brief look at RHIC data

# Centrality dependence of nuclear modification factor




data well described
by our regeneration model
without any new
parameters

# Comparison of model predictions to RHIC data: rapidity dependence




suppression is smallest at mid-rapidity (90 deg. emission)
a clear indication for regeneration at the phase boundary

# summary of low energy (SPS, RHIC) results

first indications for (re-)generation picture

interpretation not unique

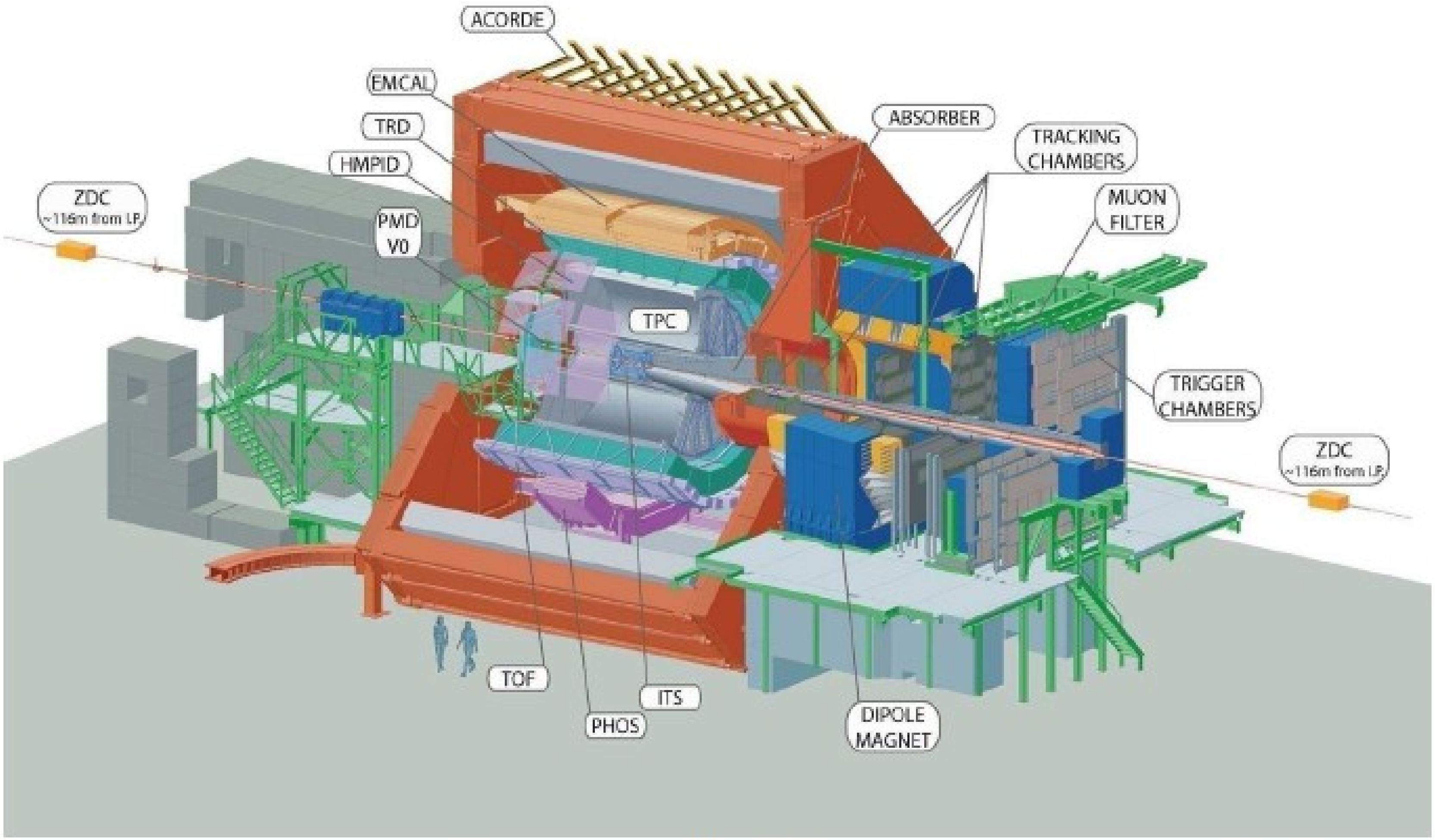
# now to LHC data

attempt full measurement of open charm and open beauty
in pp, pPb, PbPb as function of centrality, rapidity and transverse momentum

attempt full measurement including polarization of all quarkonia
in pp, pPb, PbPb as function of centrality, rapidity and transverse momentum

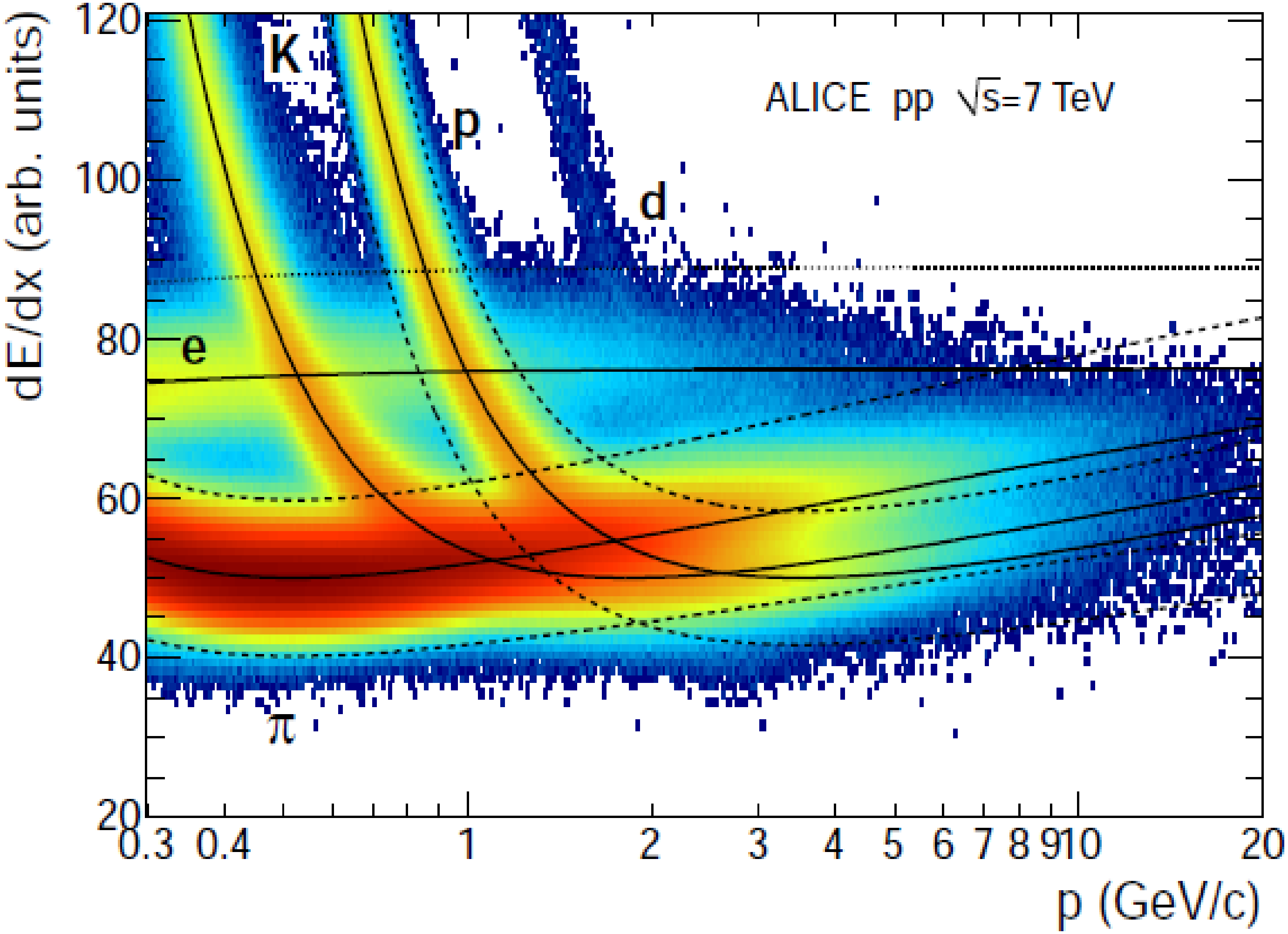
...we are on the way

# Charm and charmonia measured in ALICE

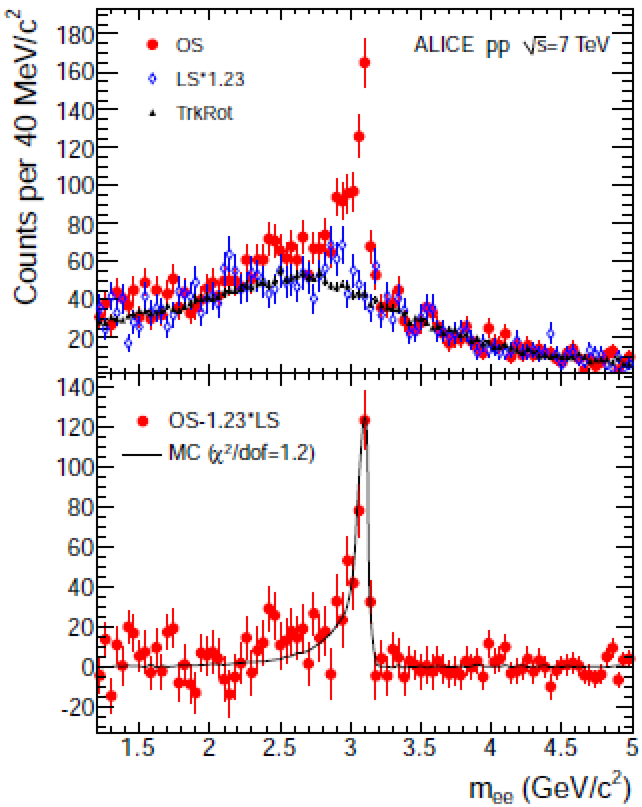


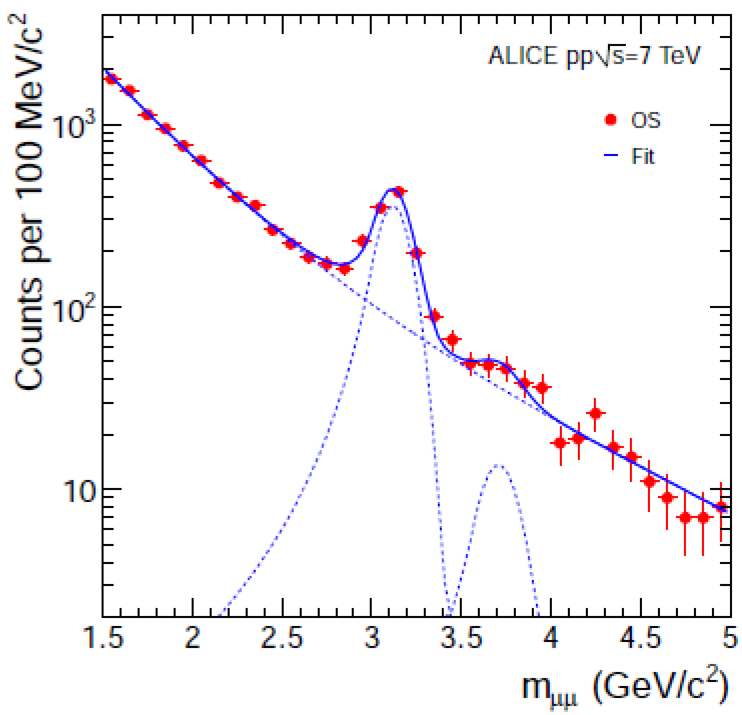

Measures charmonium at $|y| < 0.9$ ($e^+e^-$) and $-4 < y < -2.5$ ($\mu^+\mu^-$)

# Electron identification with the Alice TPC



# J/psi identification in pp collisions with ALICE



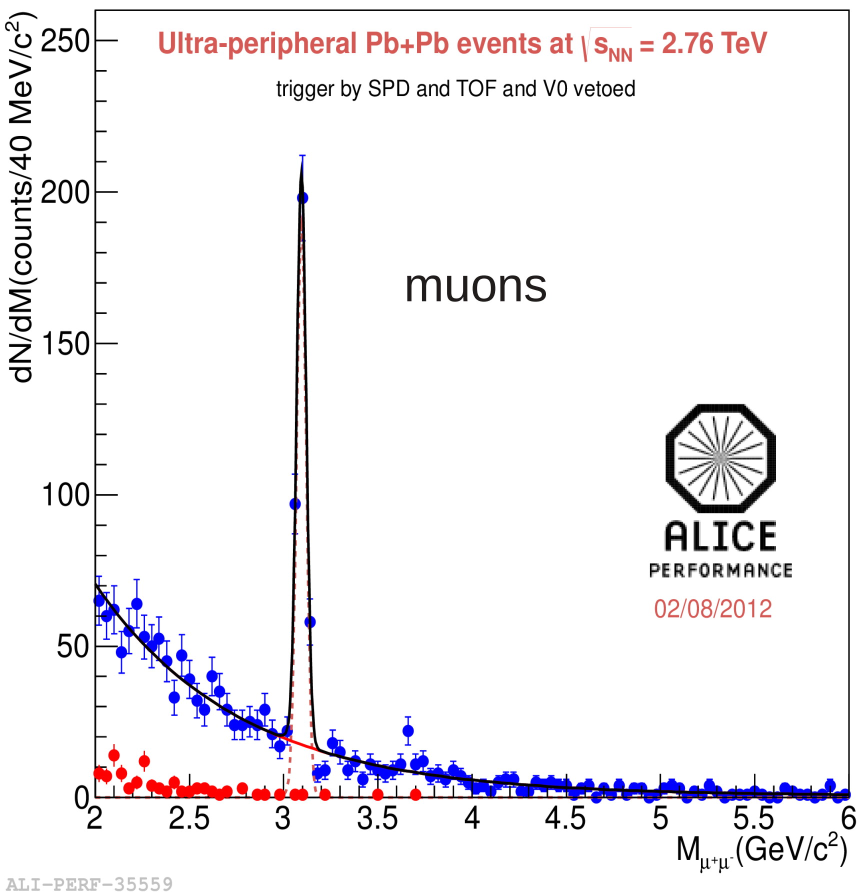

$N_{J/psi} = 957 \pm 56$ for $L_{int}$=7.9 $\text{nb}^{-1}$

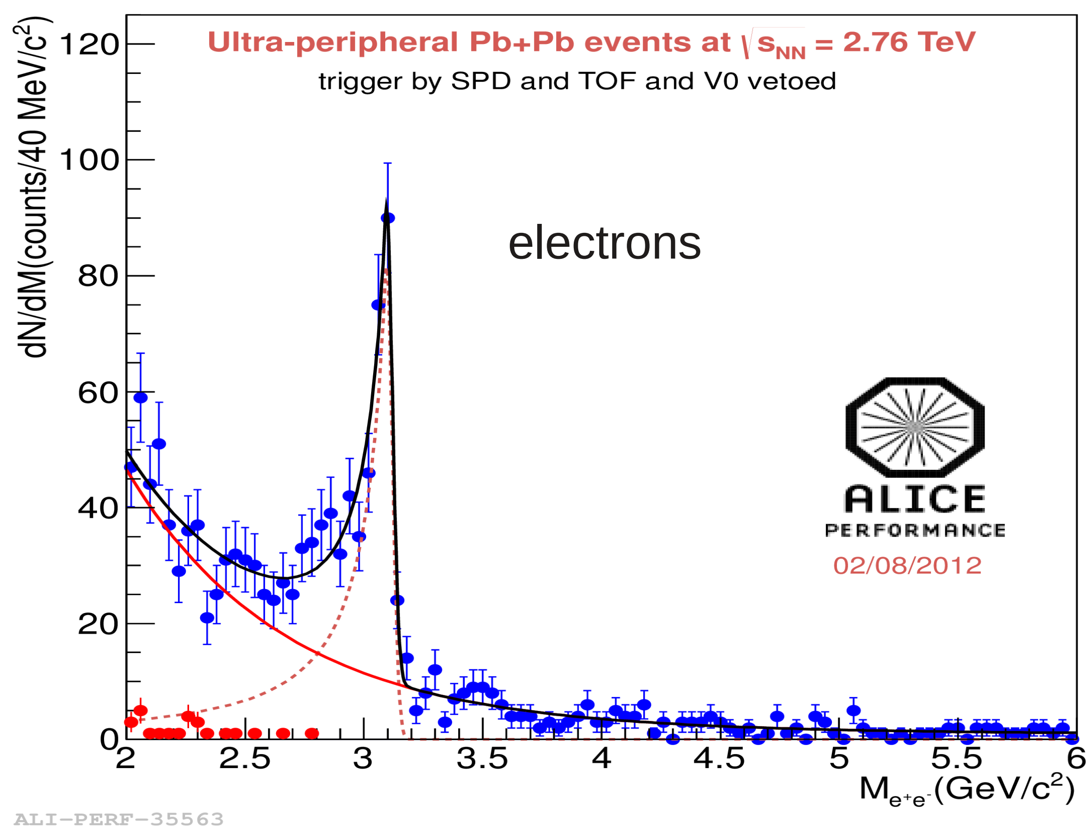
$N_{J/psi} = 352 \pm 32$ for $L_{int}$=5.6 $\text{nb}^{-1}$

Phys. Lett. B 704 (2011) 442

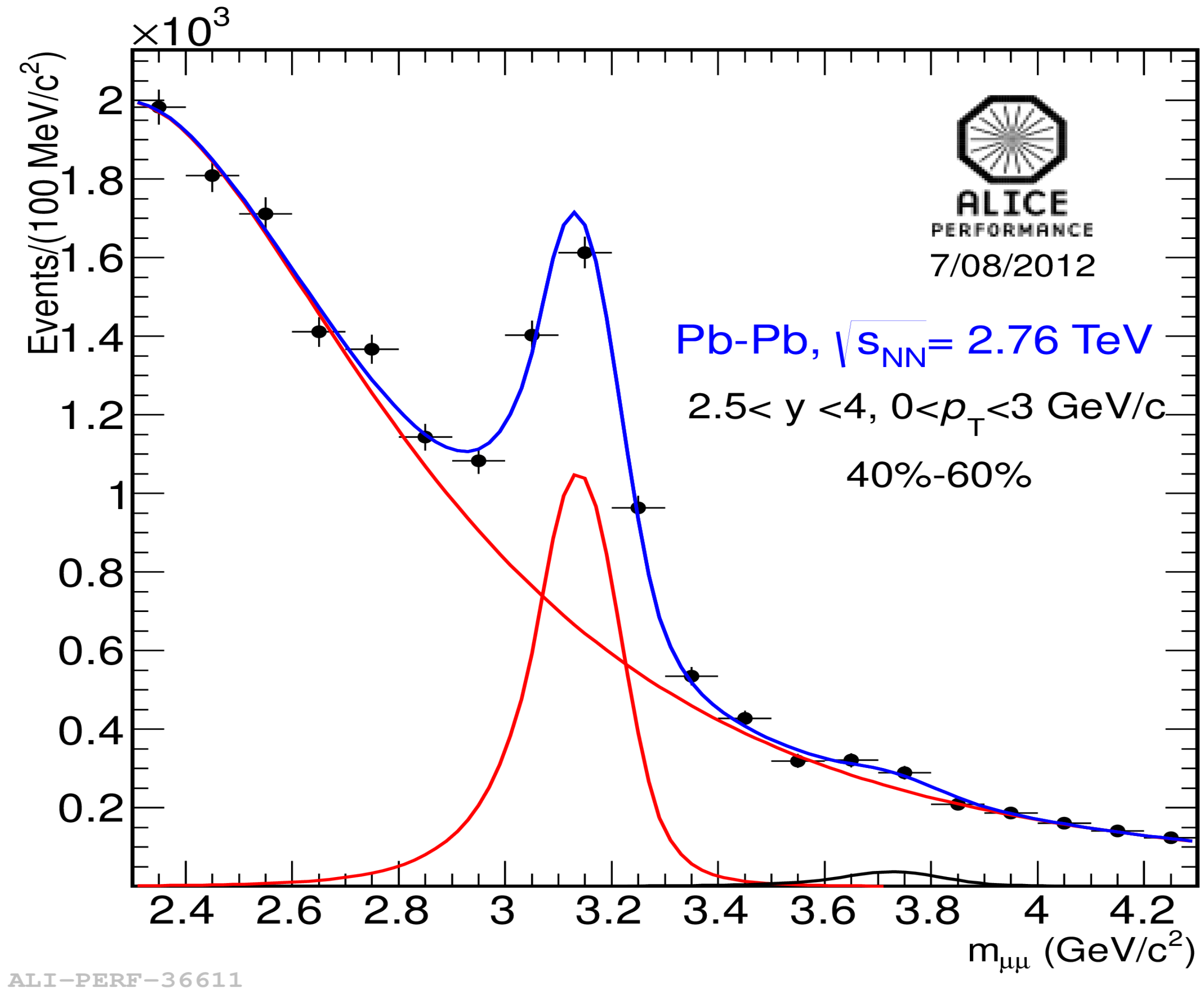
# J/psi line shape in ultra-peripheral Pb—Pb collisions

resolution: about 23 MeV for J/psi, precision determination of tail due to internal and external bremsstrahlung



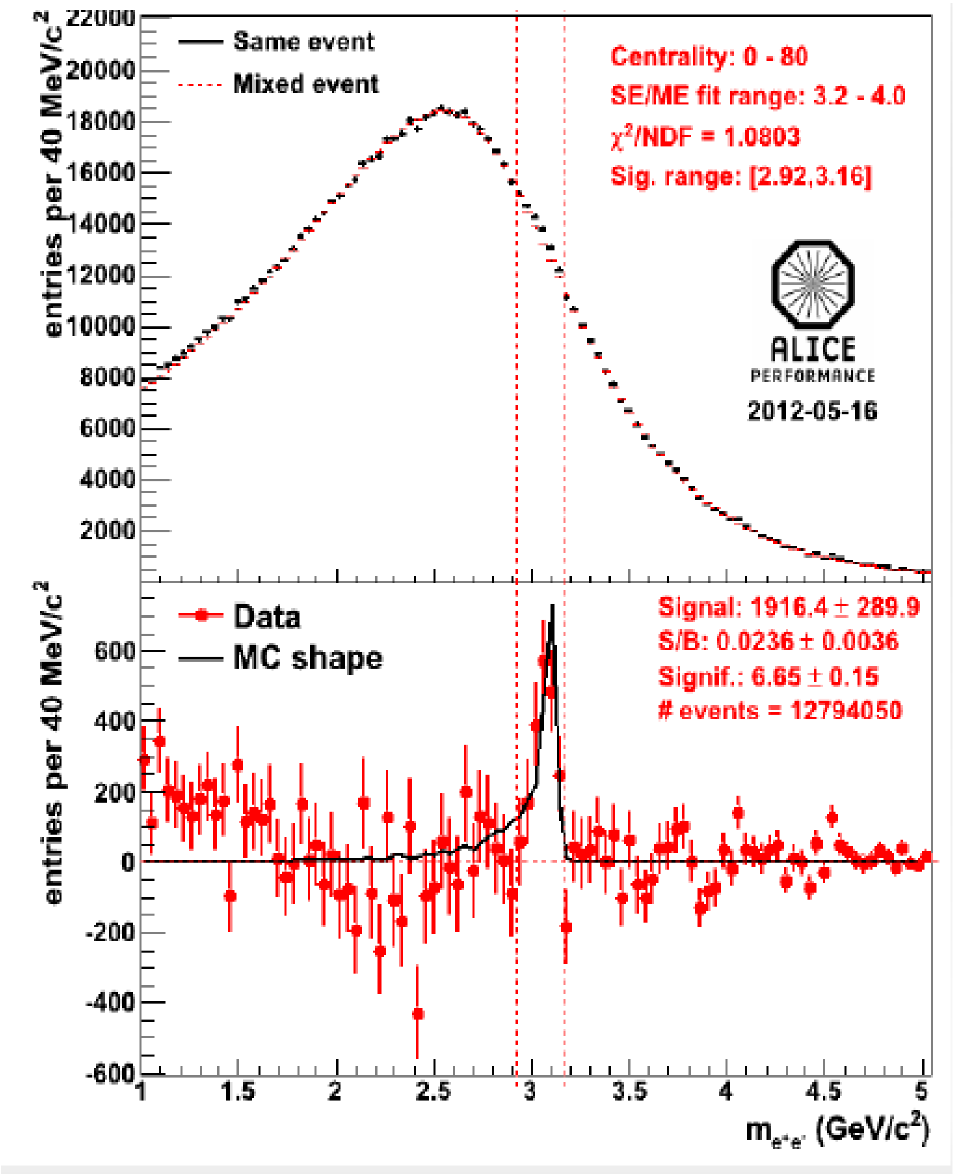



# J/psi → mumu in PbPb collisions




note: ALICE measurements include pt(J/psi) = 0

# J/psi in e+e- needs electron ID in both TPC and TRD




<u>most challenging:</u> PbPb collisions

in spite of significant combinatorial background

(true electrons, not from J/y decay but e.g. D- or B-mesons) resonance well visible

# in Pb—Pb collisions charm quarks are suppressed relative to pp collisions

in the pt range 3 < pt < 10 GeV there are much fewer charm quarks compared to expectations from pp collisions

**→ charm quarks in PbPb are at low pt!**

expect that charmonia are suppressed in the pt > 3GeV range

measurements at low pt are absolutely essential for the charmonium story

solution: normalization of J/psi to the open charm cross section in PbPb collisions

first step: (J/psi)/D ratio in PbPb collisions
to come soon from ALICE

# Normalization

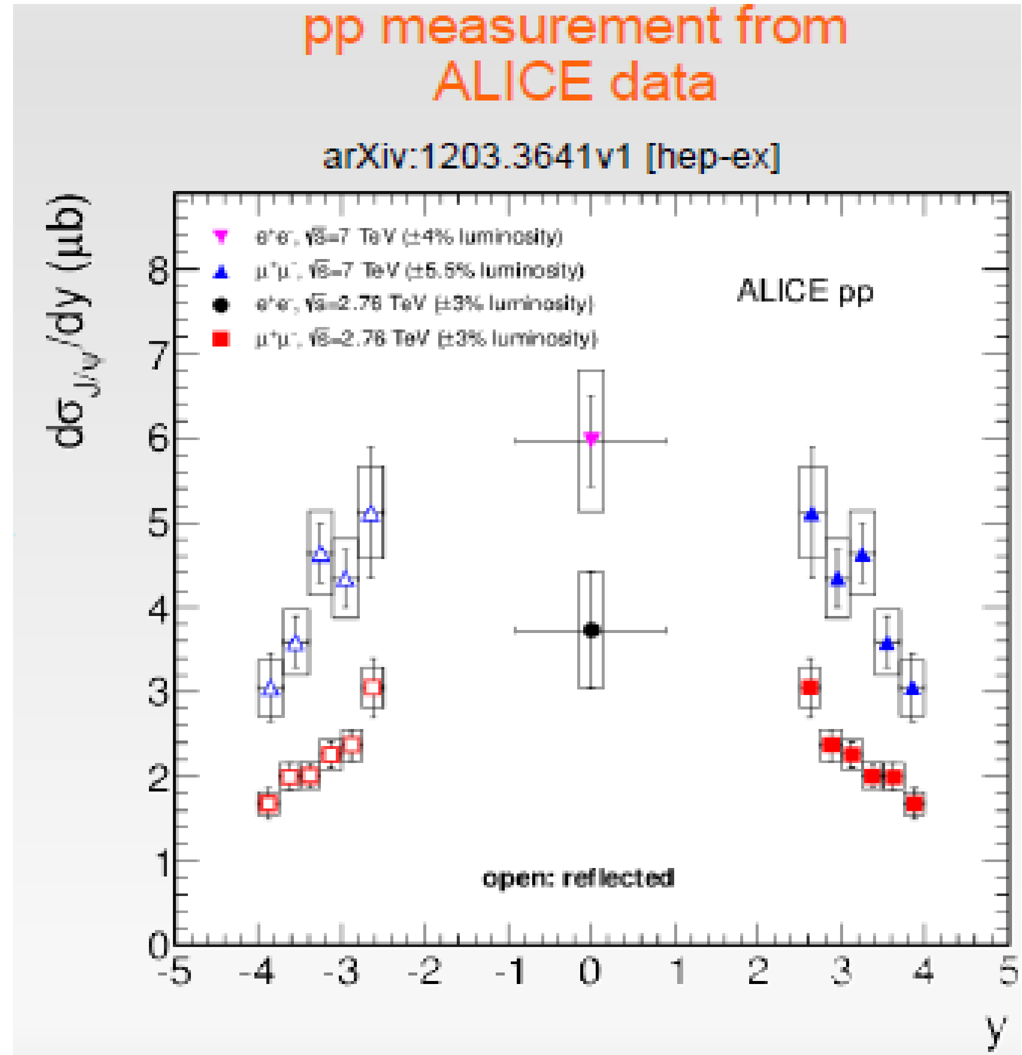
**pp @ 2.76 TeV reference for the nuclear modification factor $R_{AA}$ in Pb-Pb collisions**

$$R^i_{\mathrm{AA}} = \frac{Y^i_{\mathrm{J}/\psi}(\Delta p_{\mathrm{t}}, \Delta y)}{\langle T^i_{\mathrm{AA}} \rangle \times \sigma^{\mathrm{pp}}_{\mathrm{J}/\psi}(\Delta p_{\mathrm{t}}, \Delta y)}$$

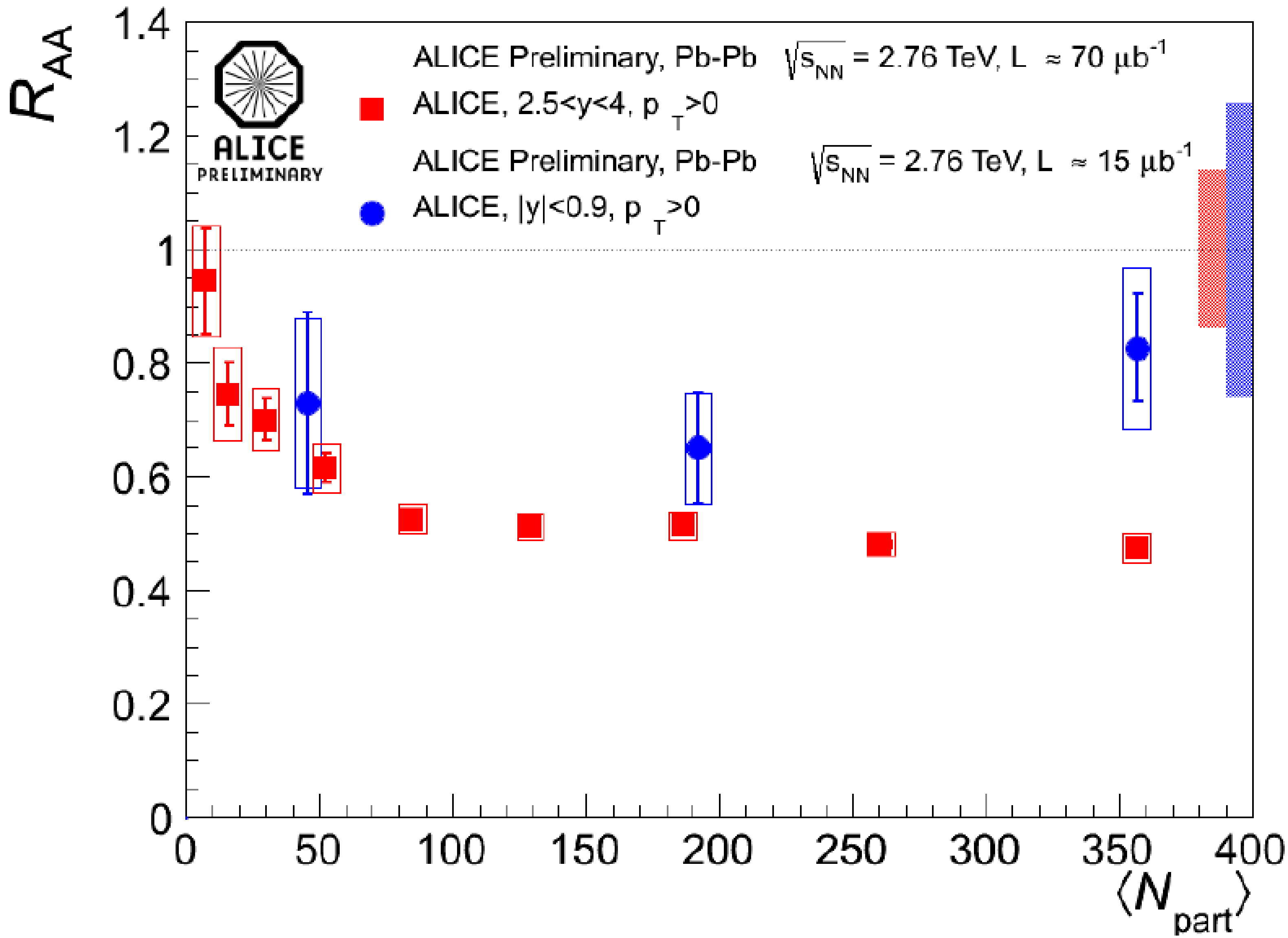
the pp reference is also the main source of systematic uncertainty in the $R_{AA}$ computation:

J/Ψ (2.5<y<4), total syst. uncertainty of 9%

J/Ψ (|y|<0.9), total syst. uncertainty of 26%

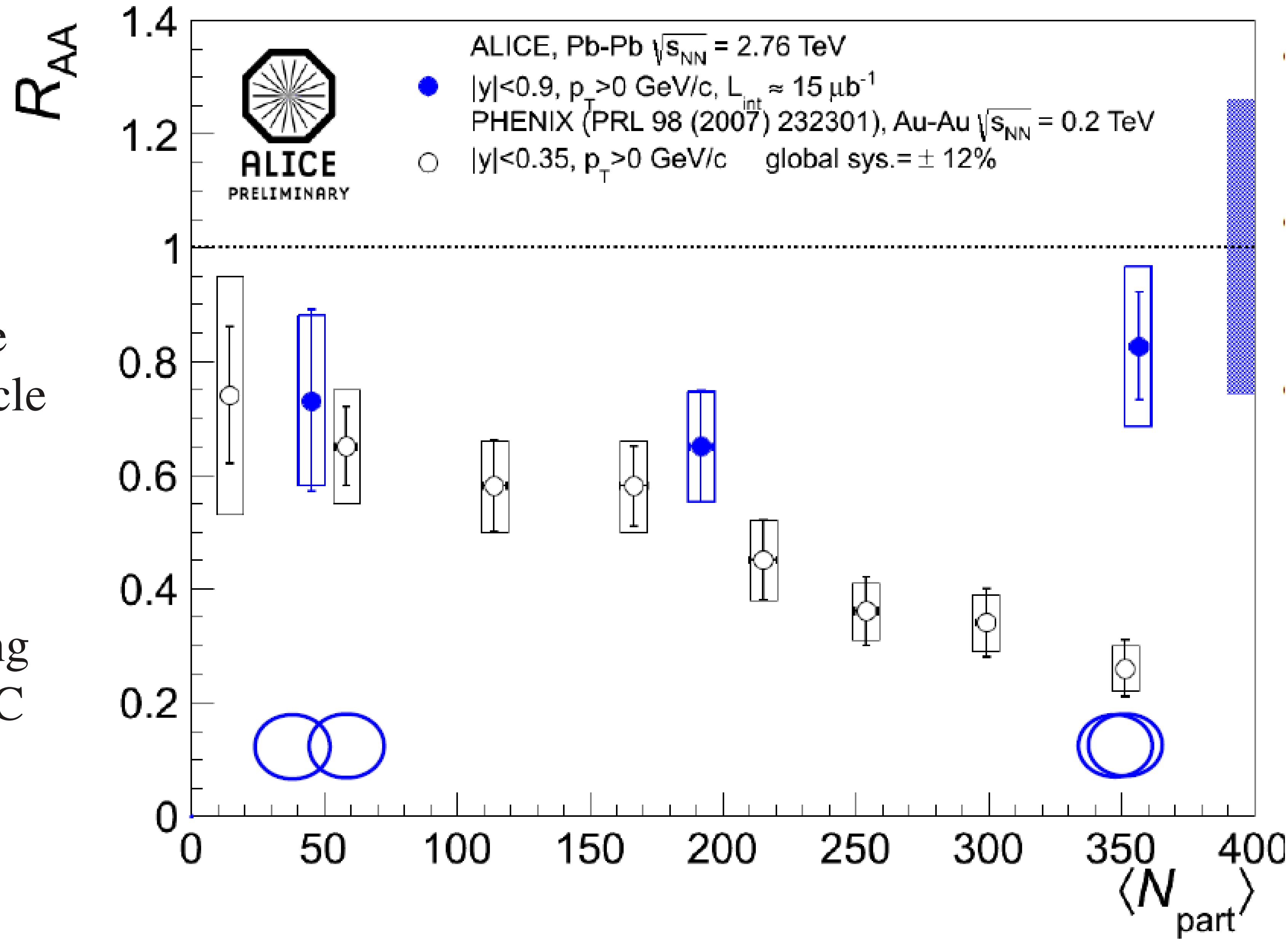


# newest ALICE data at central and forward rapidity

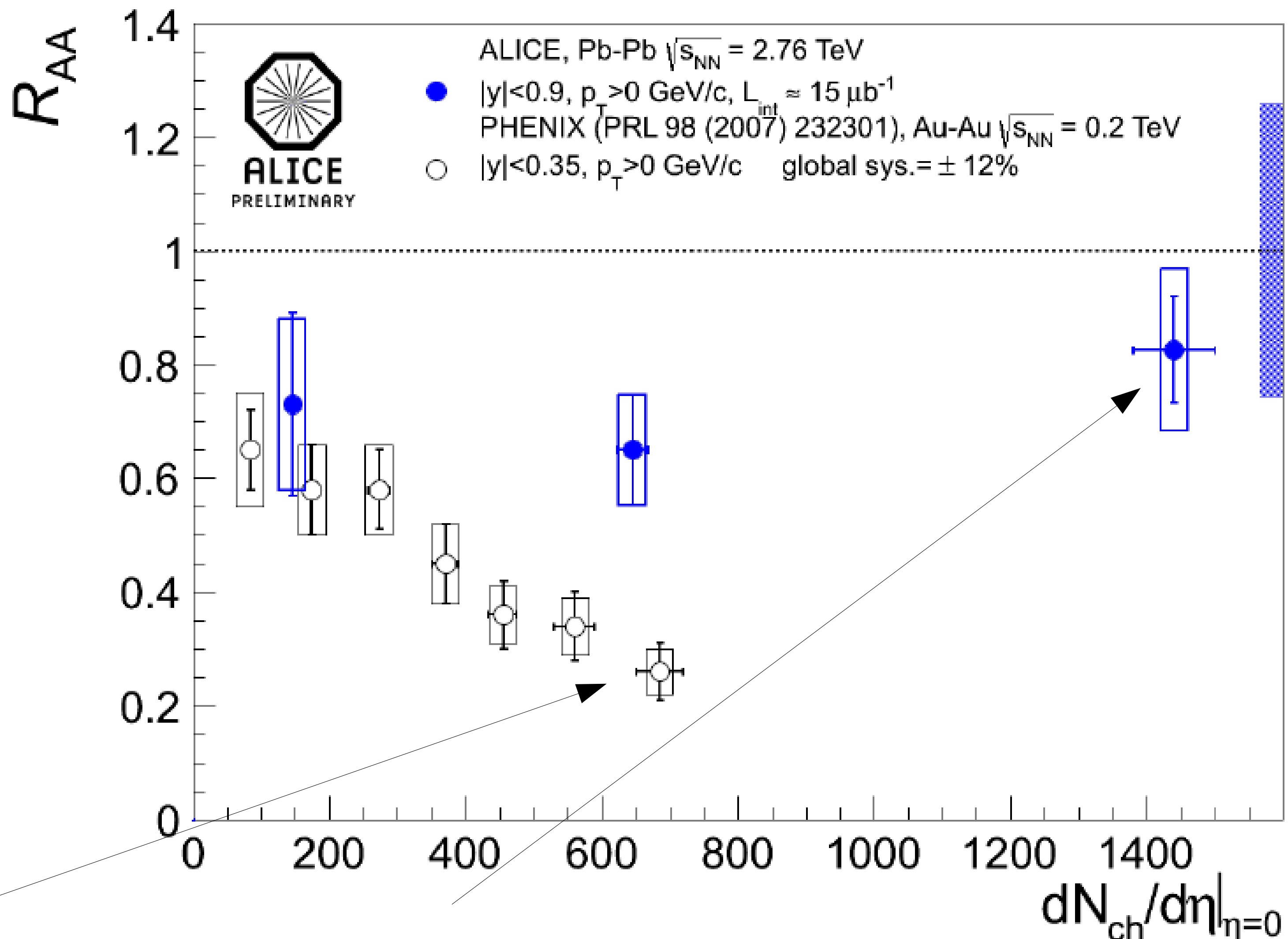


# Comparison to PHENIX data

J/psi is the only particle for which $R_{AA}$ increases when going from RHIC to LHC energy

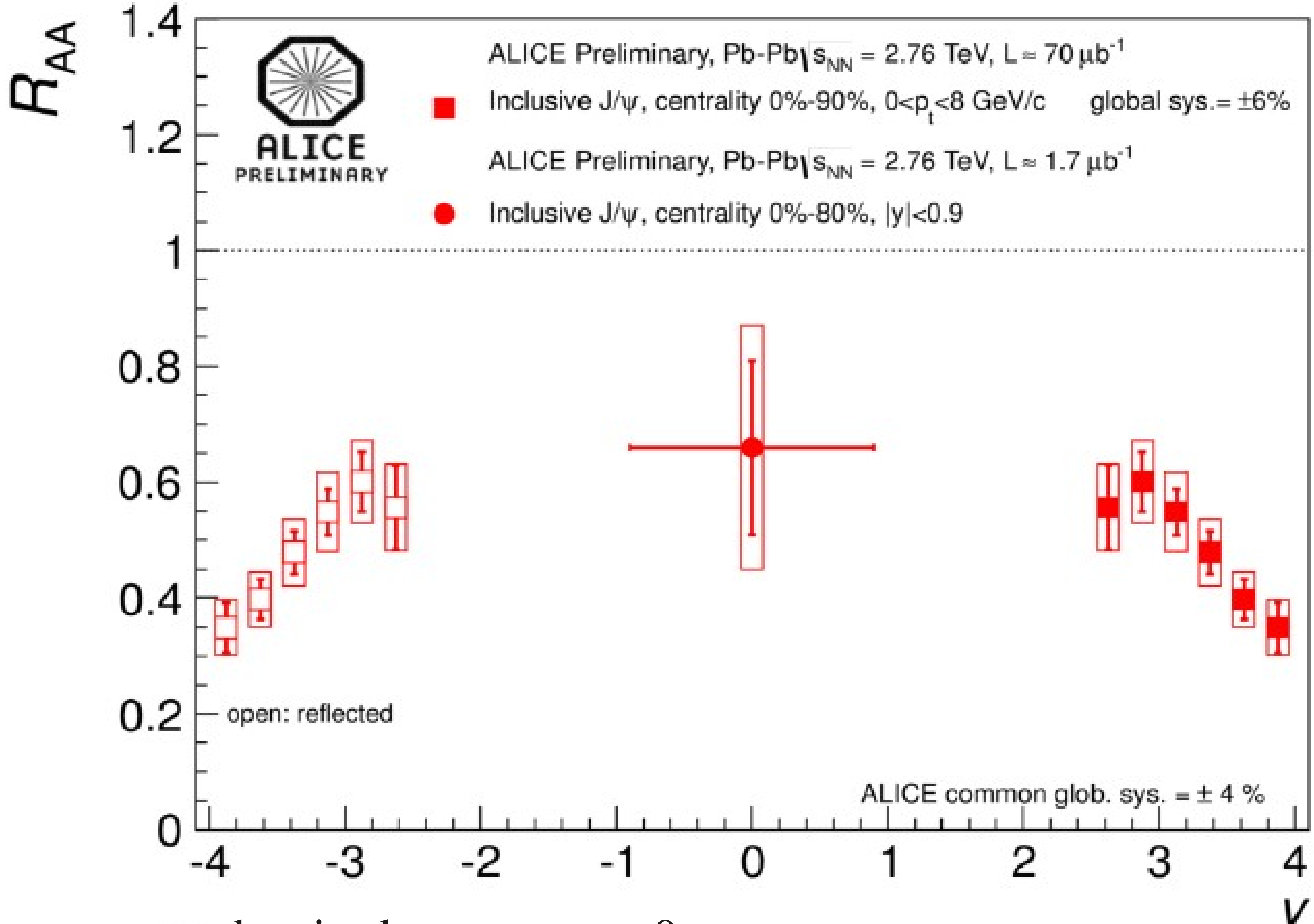


# less suppression when increasing the energy density



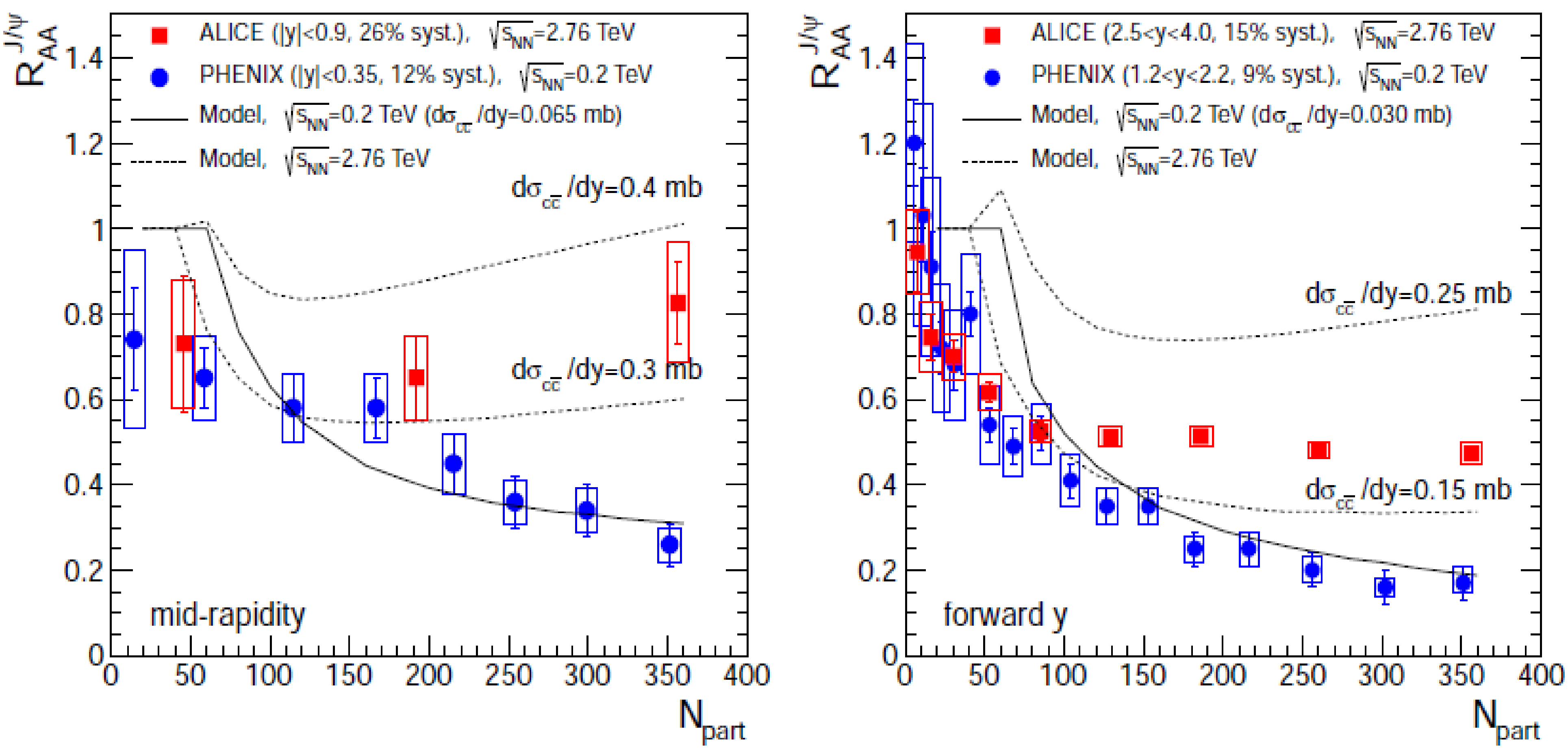

from here to here more than factor of 2 increase in energy density, but $R_{AA}$ increases by more than a factor of 3

# Rapidity dependence




note: energy density largest at $y = 0$

# statistical hadronization model



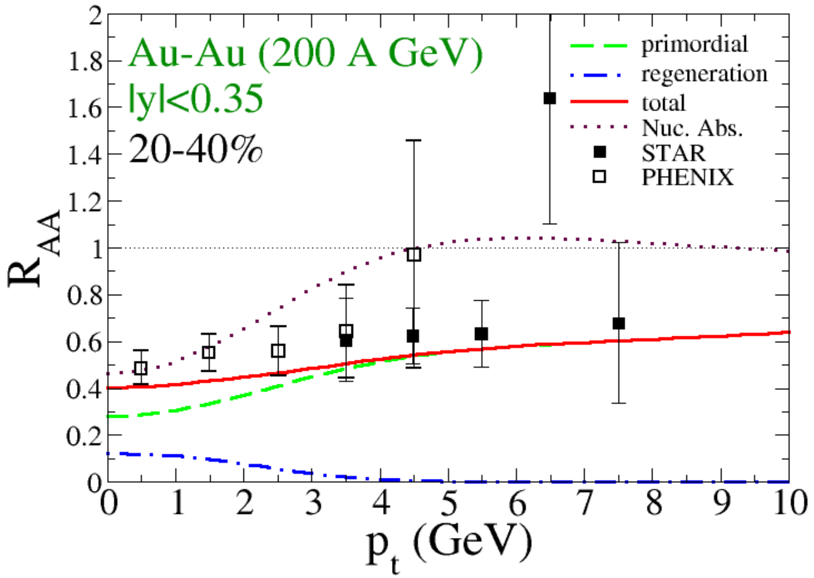

ALICE data and evolution from RHIC to LHC energy described quantitatively

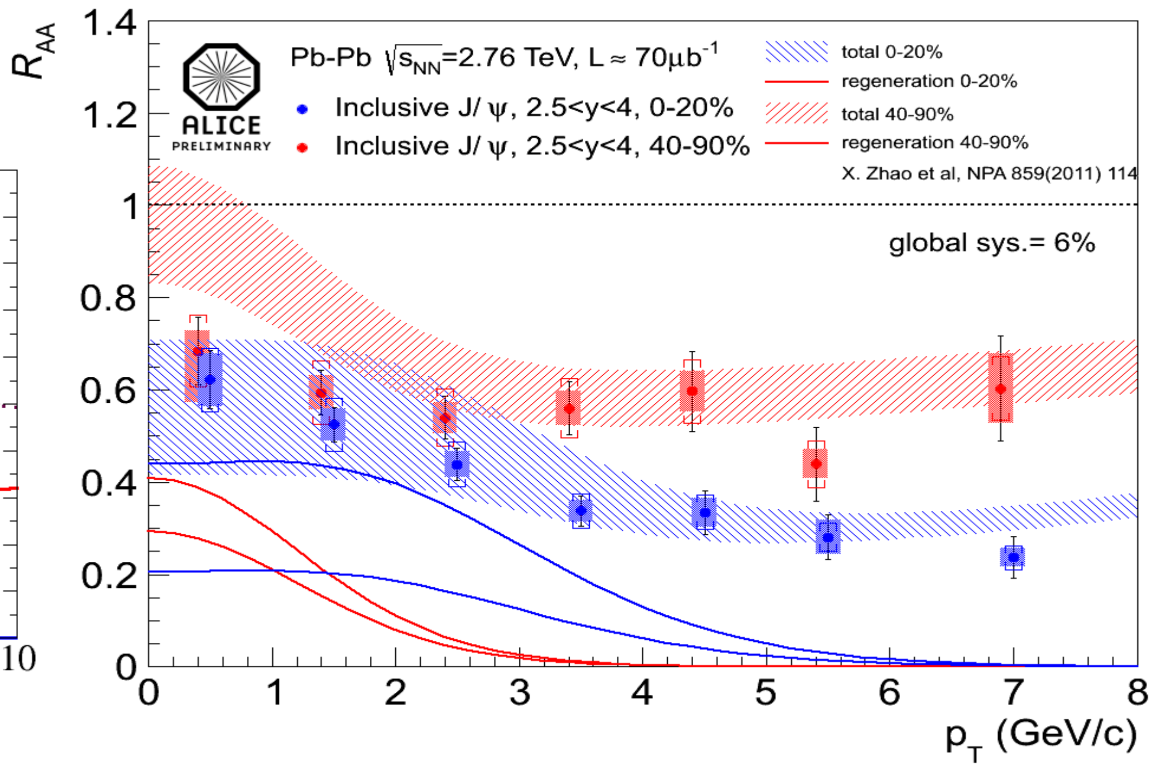
# back to J/psi data – what about spectra and hydrodynamic flow of charm and charmonia?

if charmonia are produced via statistical hadronization of charm quarks at the phase boundary, then:

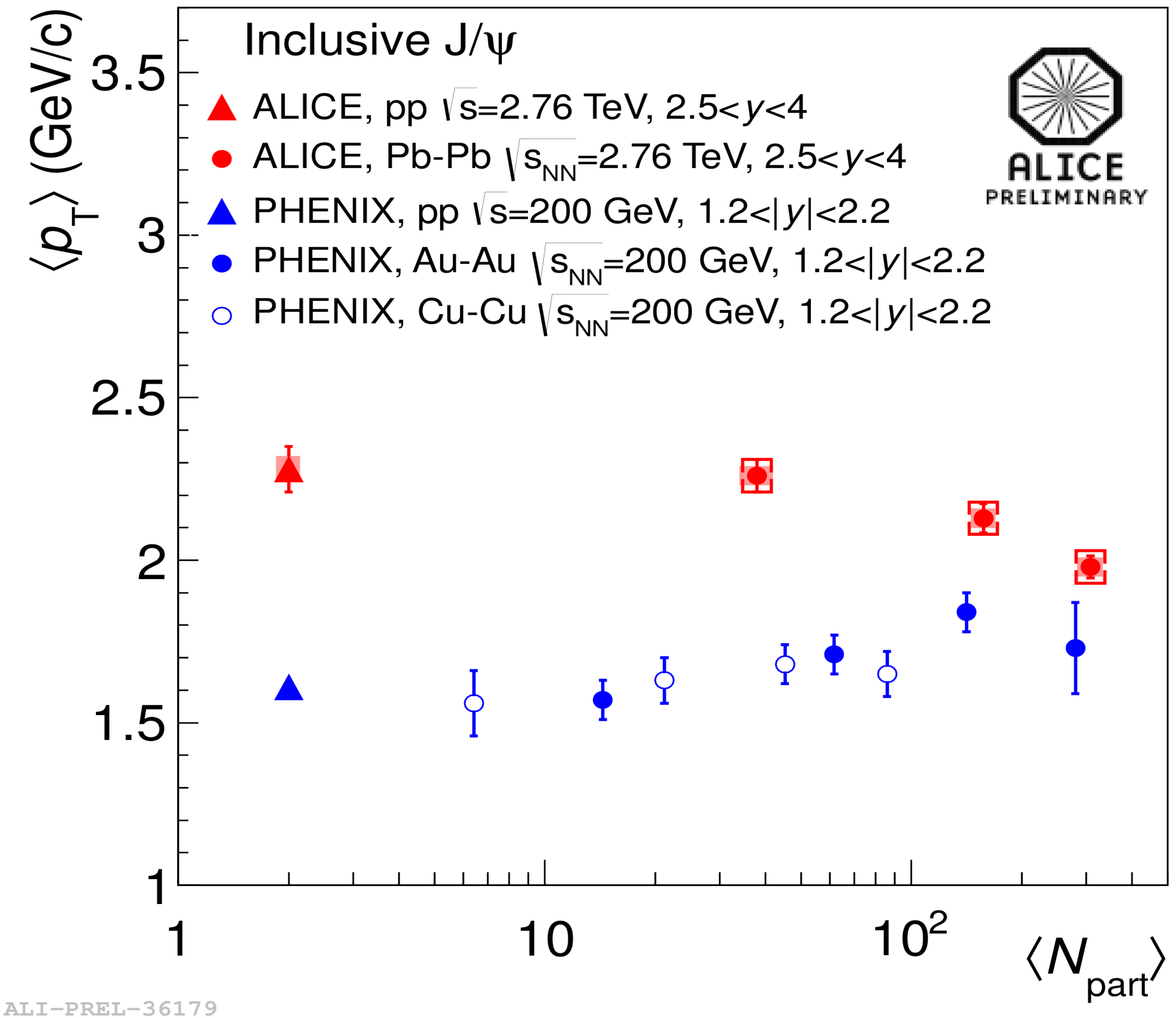
- charm quarks should be in thermal equilibrium
    - low pt enhancement
    - flow of charm quarks
    - flow of charmonia

# Comparison of transverse momentum spectra at RHIC and LHC



# Evolution of J/psi transverse momentum spectra – evidence for thermalization and charm quark coalescence at the phase boundary



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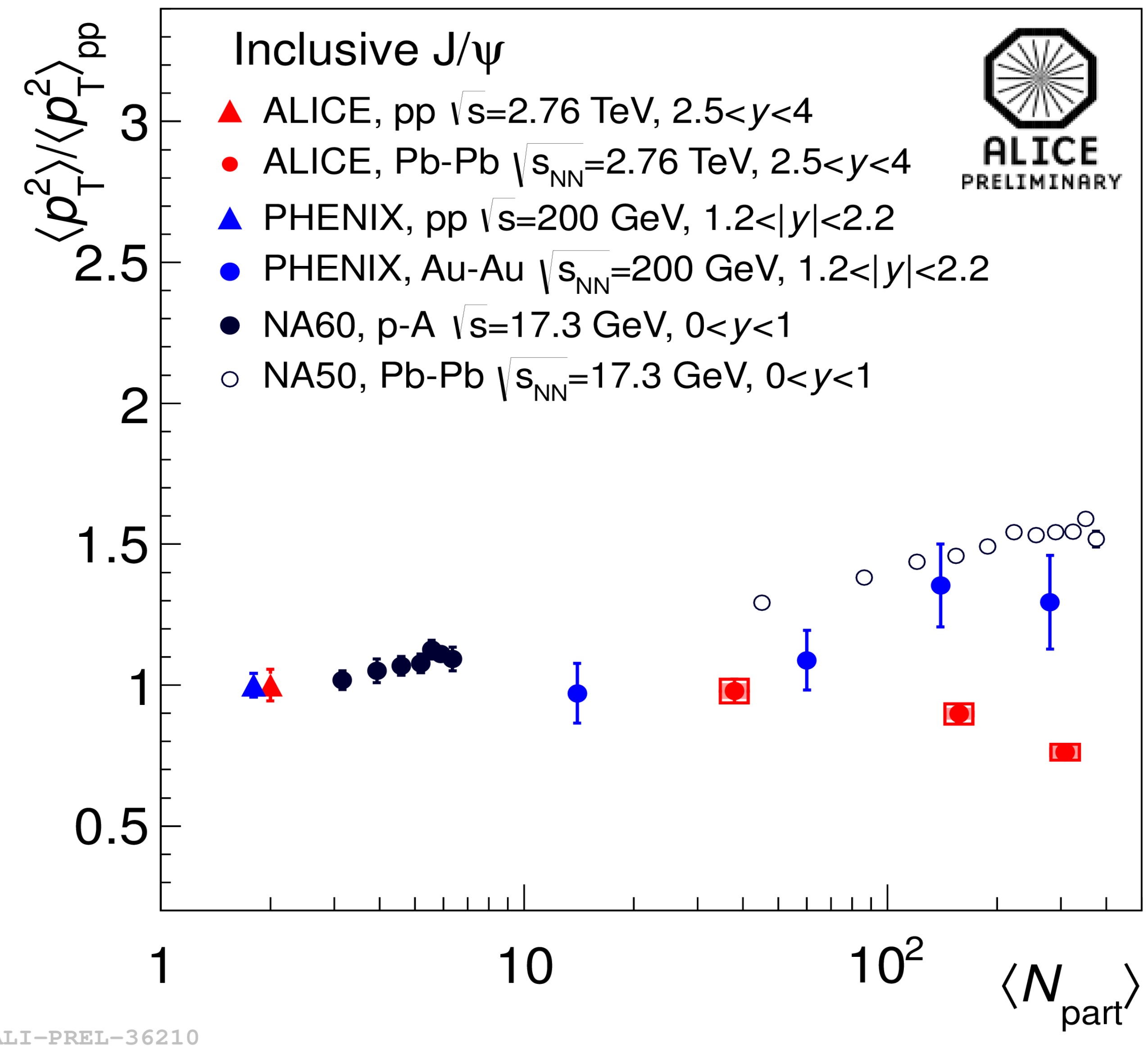
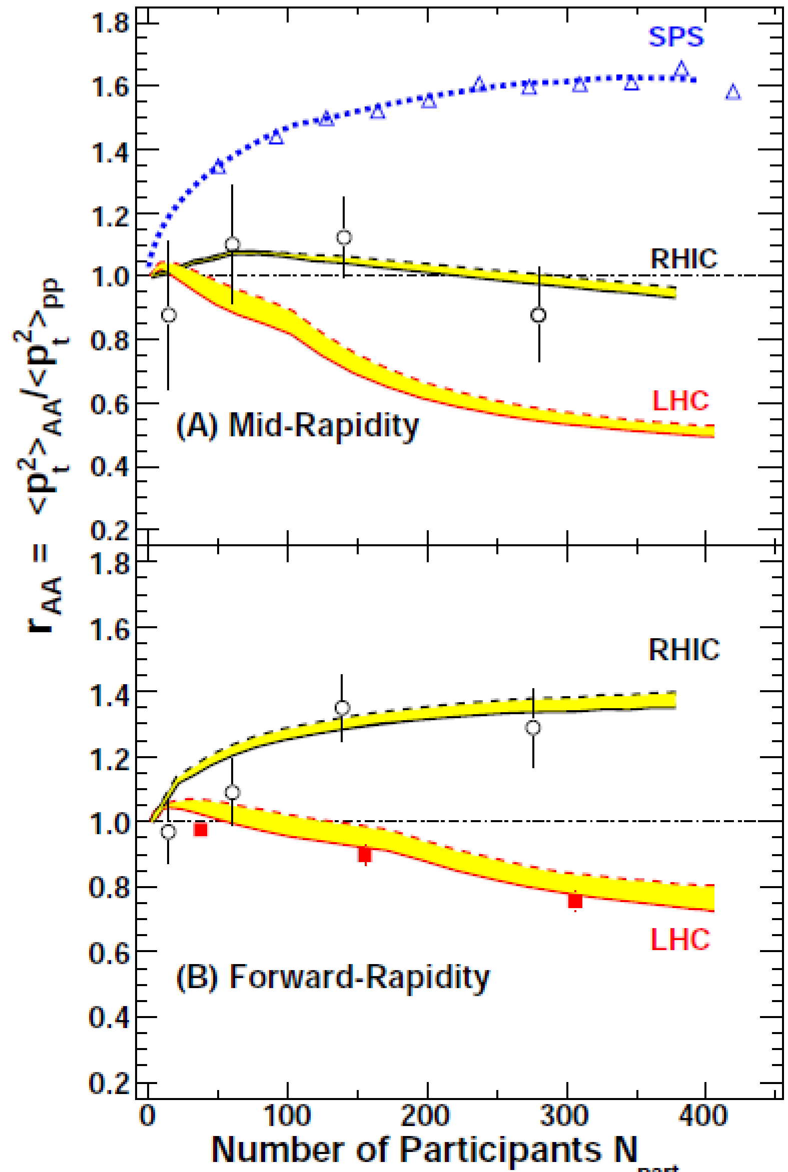


# analysis of transverse momentum spectra

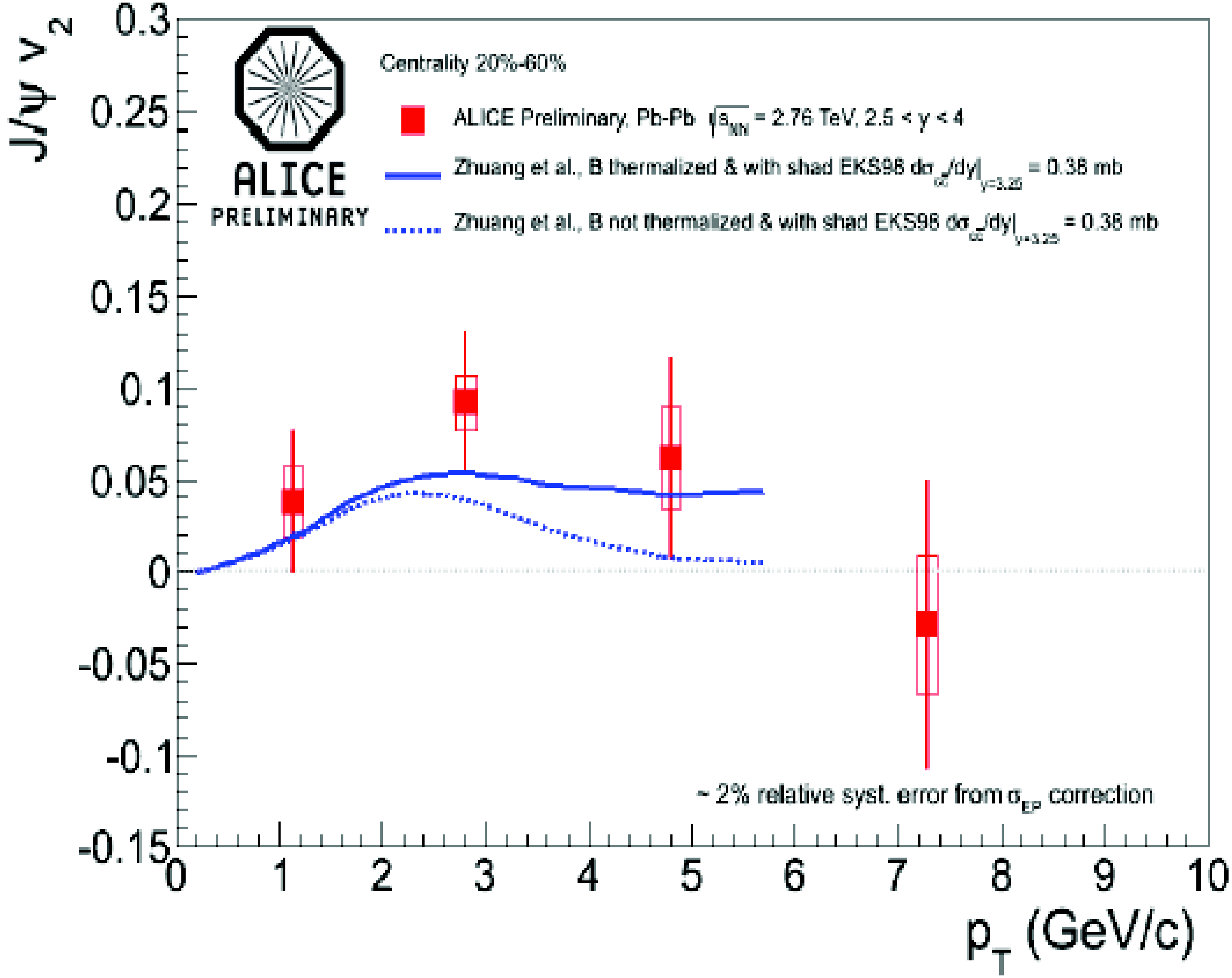
arXiv:1309.7520v1 [nucl-th] 29 Sep 2013

Zhou, Xu, Zhuang

at LHC energy, mostly (re-) generation of charmonium, p_t distribution exhibits features of strong energy loss and approach to thermalization for charm quarks



# J/psi flow compared to models including (re-) generation




hydrodynamic flow of J/psi consistent with (re-)generation

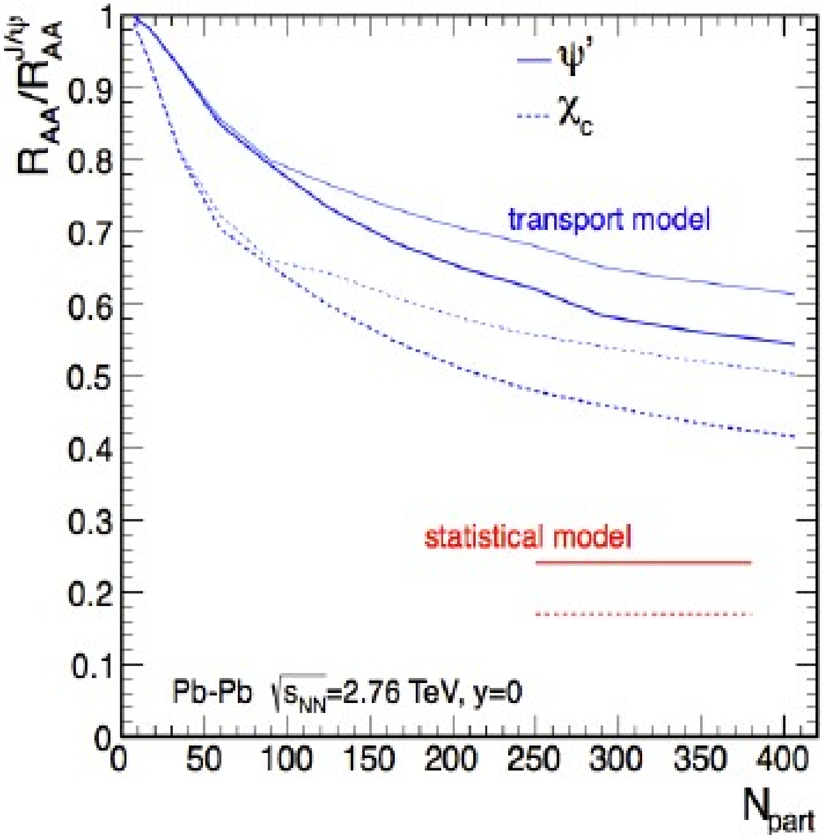
# Charmonium production at LHC energy: deconfinement,and color screening

- Charmonia formed at the phase boundary → full color screening at $T_c$

- Combination of uncorrelated charm quarks into J/psi → deconfinement

**statistical hadronization picture of charmonium production provides most direct way towards information on the degree of deconfinement reached as well as on color screening and the question of bound states in the QGP**

# Are there hadronic bound states in the QGP?



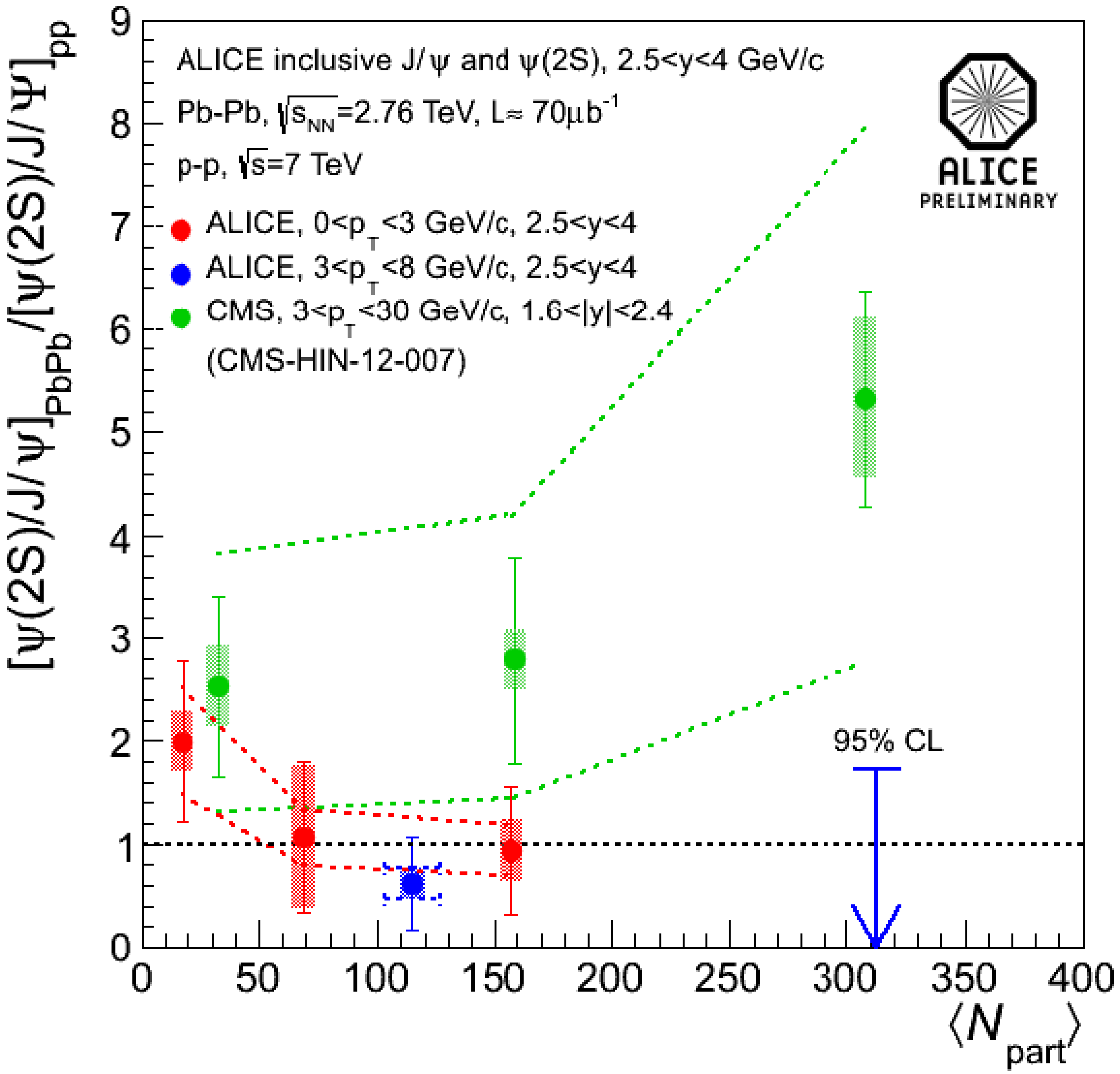

transport model:
X. Zhao, R. Rapp,
NPA 859 (2011) 114

statistical model:
A. Andronic et al.,
PLB 678 (2009) 350

**Possible resolution of a fundamental question:**
**can there be bound states of colorless hadrons in the QGP or are all hadrons formed at the phase boundary?**

measurement of psi'/psi and chi_c/psi ratio will settle the issue → ALICE upgrade

# First results on psi'/(J/psi) ratio

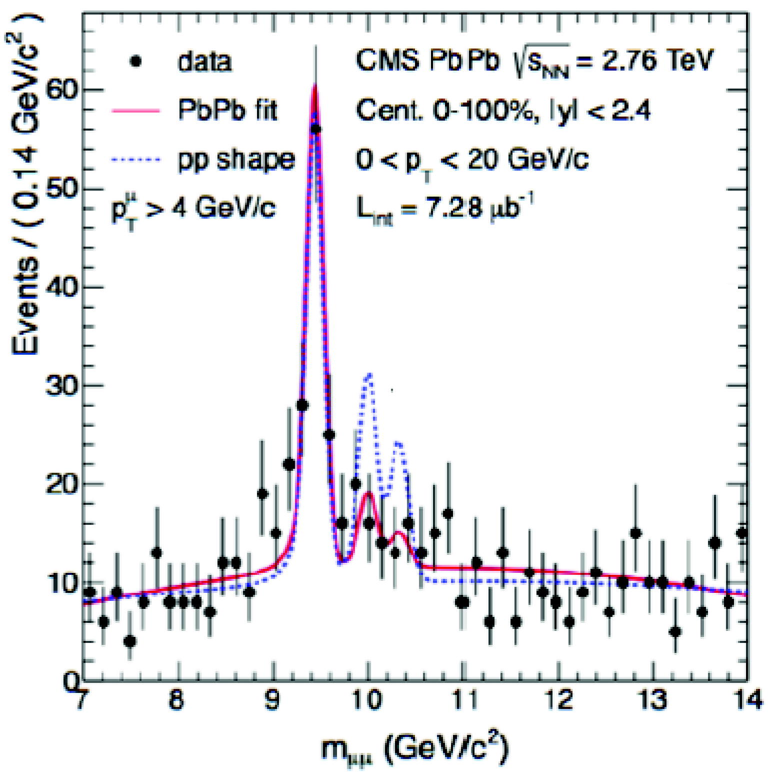



dramatic enhancement in CMS data not confirmed by ALICE measurements

# Sequential Upsilon suppression

2010 data

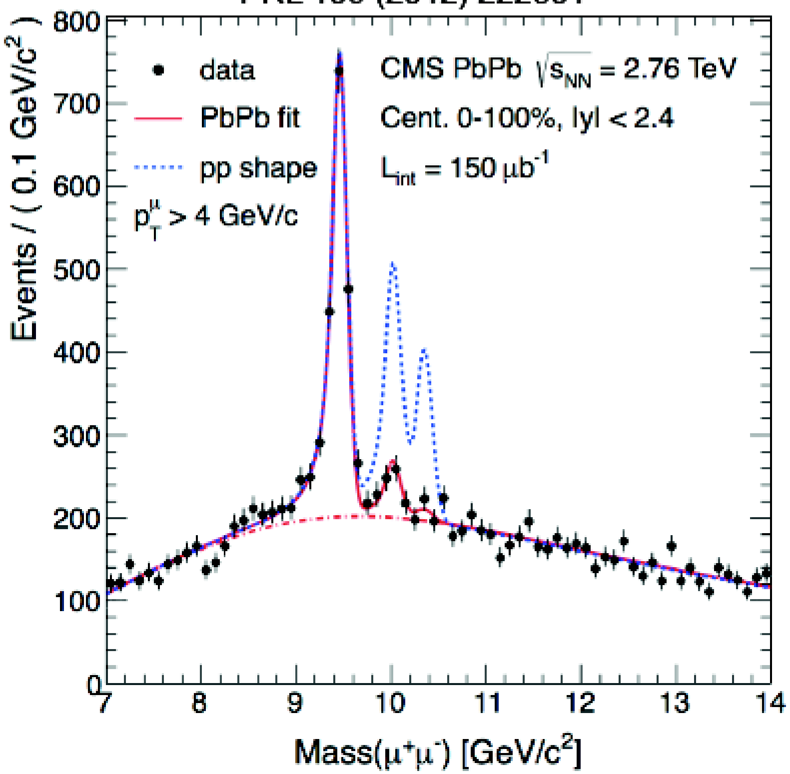
PRL 107 (2011) 052302




Indication of suppression of (Y(2S)+Y(3S)) relative to Y(1S)
→ 2.4σ significance

2011 data

PRL 109 (2012) 222301



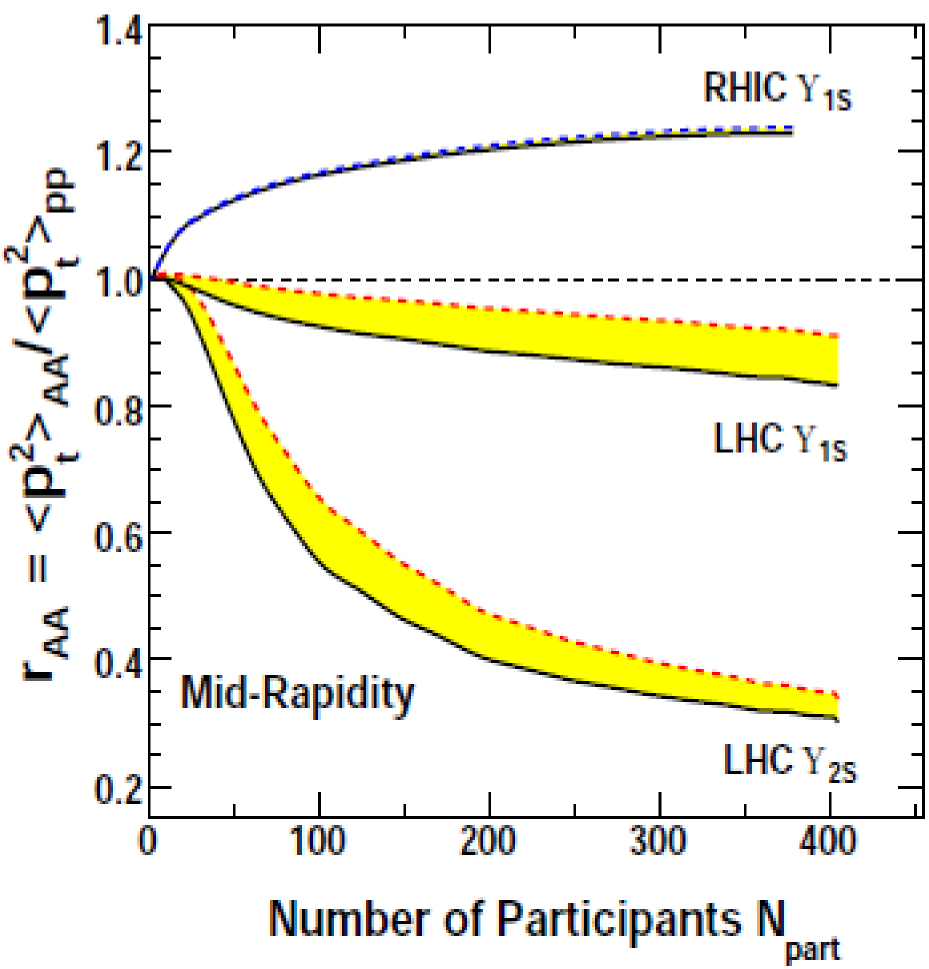

Observation of sequential suppression of Y family
→ Detailed studies

# transverse momentum distributions for Υ states

if picture of Debye screening and (re-)generation also applies to Υ states, expect similar p_t pattern as for charmonia

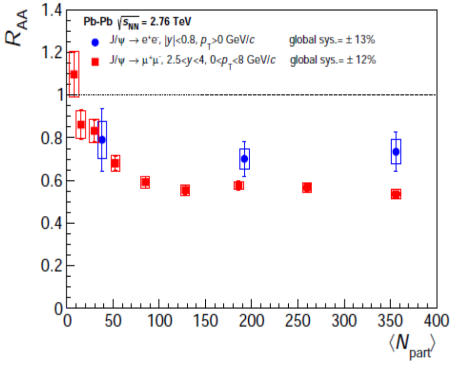
needs approach to thermalization for b quarks!

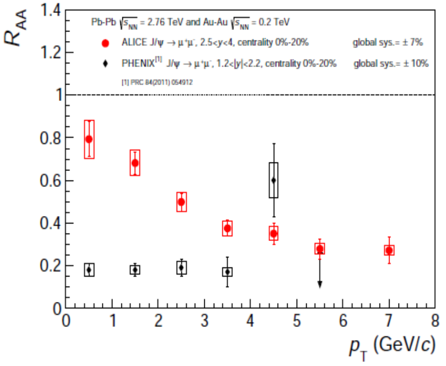
predictions by Zhou, Xu, Zhuang
arXiv:1309.7520 [nucl-th]



# summary 1 – quarkonium production

- spectacular difference between results from RHIC and LHC
- J/psi production is consistent with complete Debye screening and (re-)generation at the QCD phase boundary
- charm quarks are thermalized and deconfined
- Y production: also suppressed but unclear relation to color screening are b quarks and/or Y thermalized?

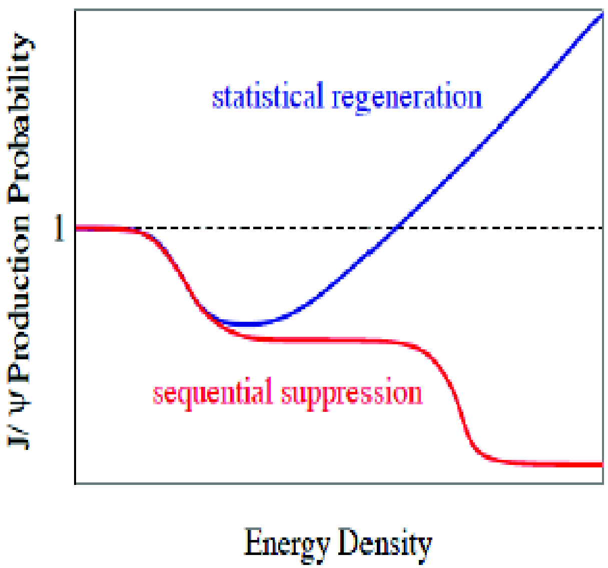


# summary 2

- charmonium production – a fingerprint for deconfined quarks and gluons

- evidence for energy loss and flow of charm quarks --> thermalization
- charmonium generation at the phase boundary – a new process
- first indications for this from psi'/(J/psi) SPS and J/psi RHIC data
- evolution from RHIC to LHC described quantitatively
- charmonium enhancement at LHC – J/psi color-screened at T_c, deconfined QGP




cartoon Helmut Satz, 2009 SPS RHIC LHC

# extra slides