The charmonium story

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

Hot topics in hot matter
Weizmann Institute of Science
Oct. 17-18, 2012
pbm

TECHNISCHE UNIVERSITÄT DARMSTADT

FIAS Frankfurt Institute for Advanced Studies

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GSI

Actually: a birthday celebration for Itzhak

We go back a long way

Single nucleon transfer reactions induced by F-19 on Mg-24.
I. Tserruya (Weizmann Inst.), Jean Barrette, Peter Braun-Munzinger, C.K. Gelbke,
J. Kuzminski (Heidelberg, Max Planck Inst.). Jun 1976.
Published in Phys.Rev. C13 (1976) 2568-2570:

Transfer Reactions Induced by 16O on 29,30 Si, I. Tserruya, W. Bohne,
P. Braun-Munzinger, C.K. Gelbke, W. Grochulski, H.L. Harney and J.
Kuzminski, Nucl. Phys. A242 (1975)345

… and our most recent paper:

Elliptic flow of charged pions, protons and strange particles emitted in Pb+Au
collisions at top SPS energy.
CERES Collaboration (D. Adamova (Rez, Nucl. Phys. Inst.) et al.). May 2012.
e-Print: arXiv:1205.3692

In all: 36 joint papers happy birthday, Itzhak!!!!!

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

work reported here done in coll. with
Anton Andronic
Krzysztof Redlich
Johanna Stachel

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

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

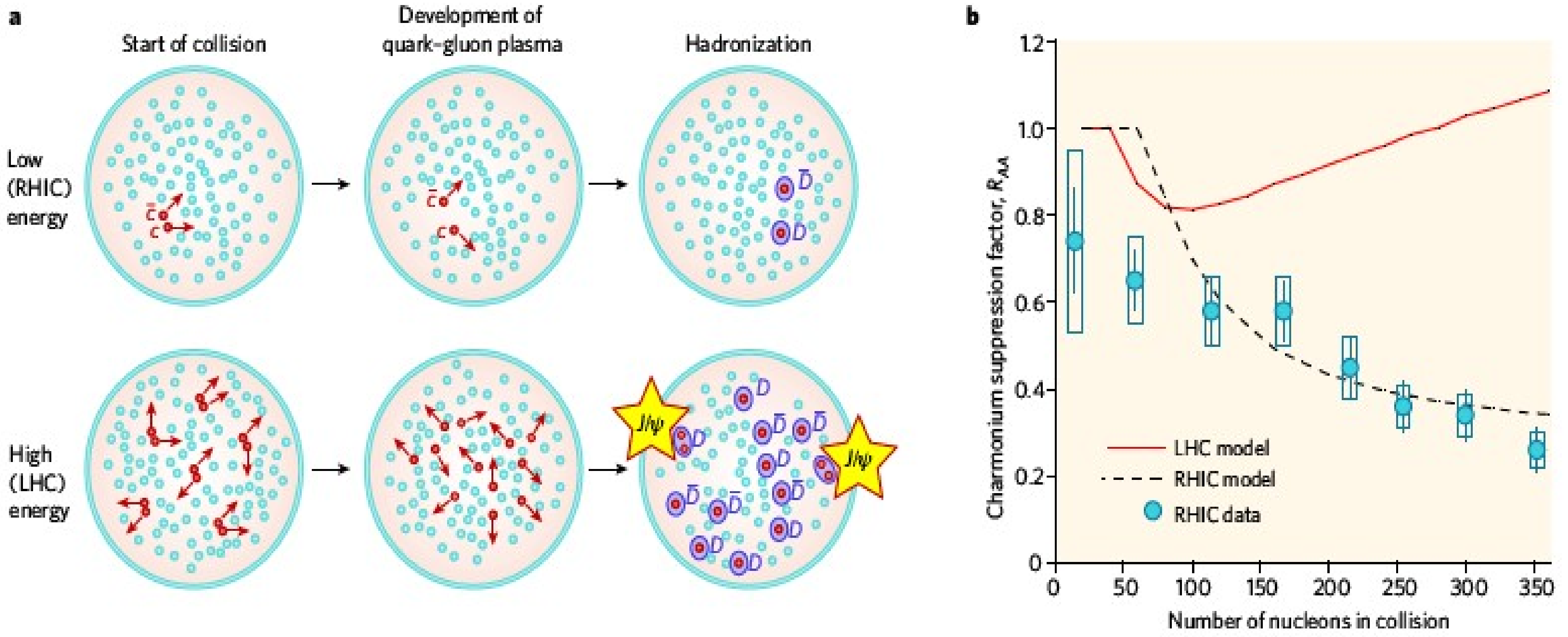
questions:
a) beam energy dependence of time scales
b) what happens with the (many) charm quarks at hadronization, i.e at the phase boundary?

at LHC energy, clean separation of time scales

collision time << QGP formation time < charmonium formation time

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, μ_B: $\rightarrow n_X^{th}$

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

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

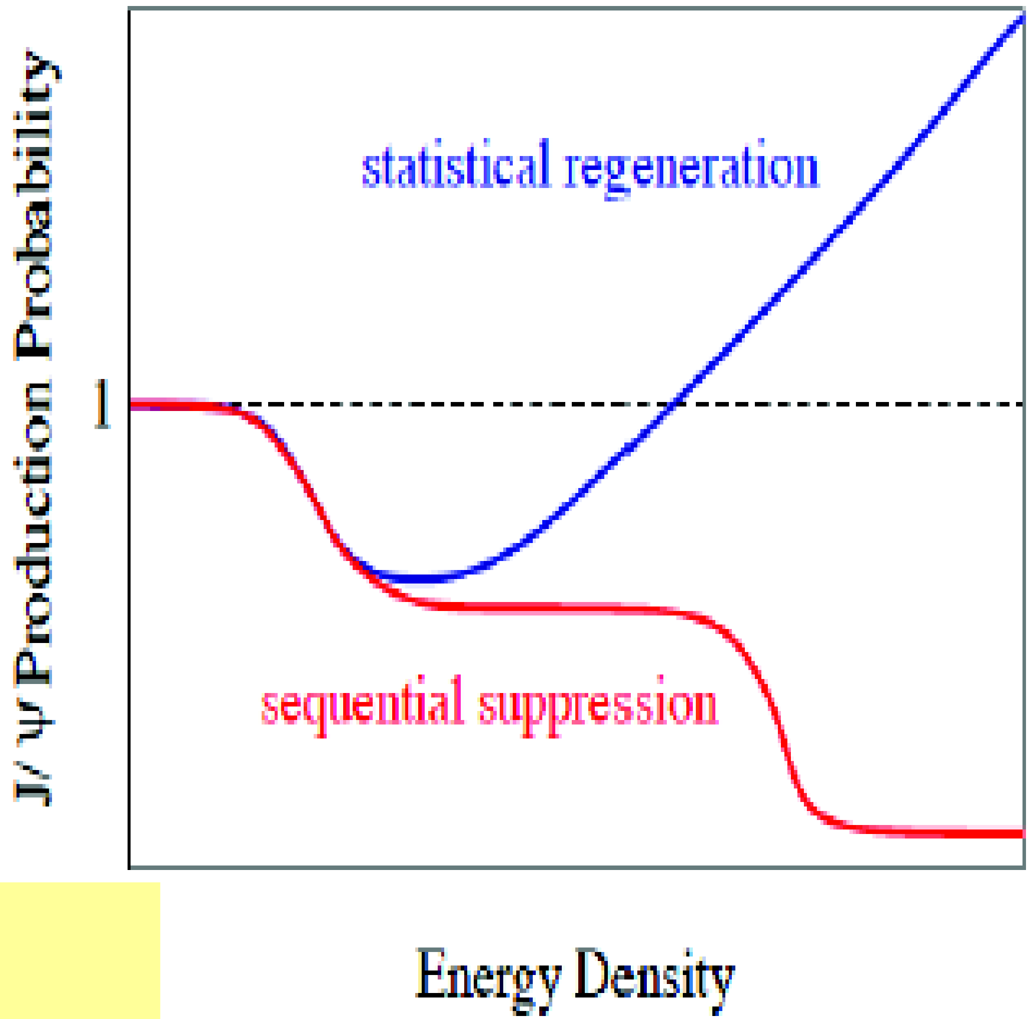
charm balance equation

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

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

decision on regeneration vs sequential suppression from LHC data



SPS RHIC LHC

Picture:
H. Satz 2009

Parameterization of all freeze-out points

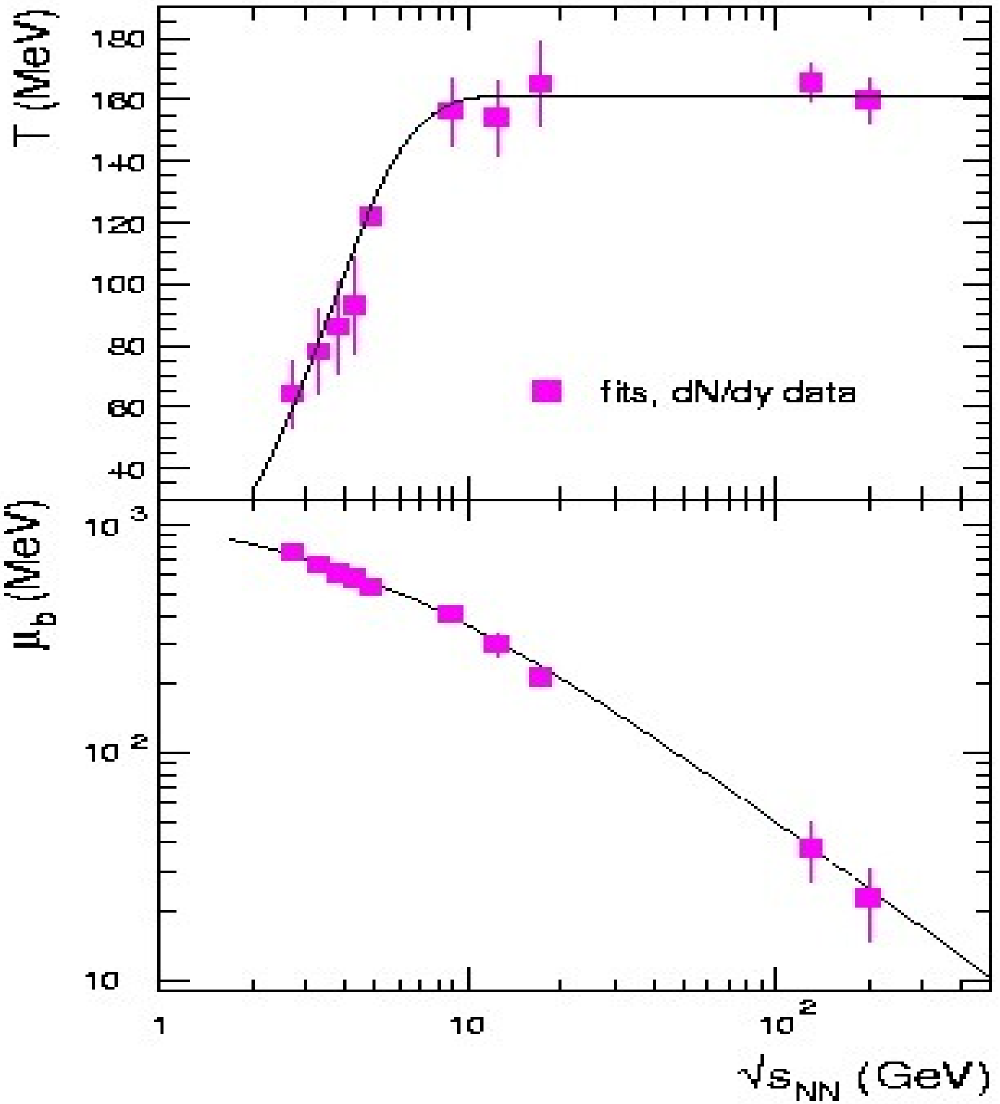
note: establishment of limiting temperature

T_{lim} = 160 MeV

get T and μ_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 to come soon

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

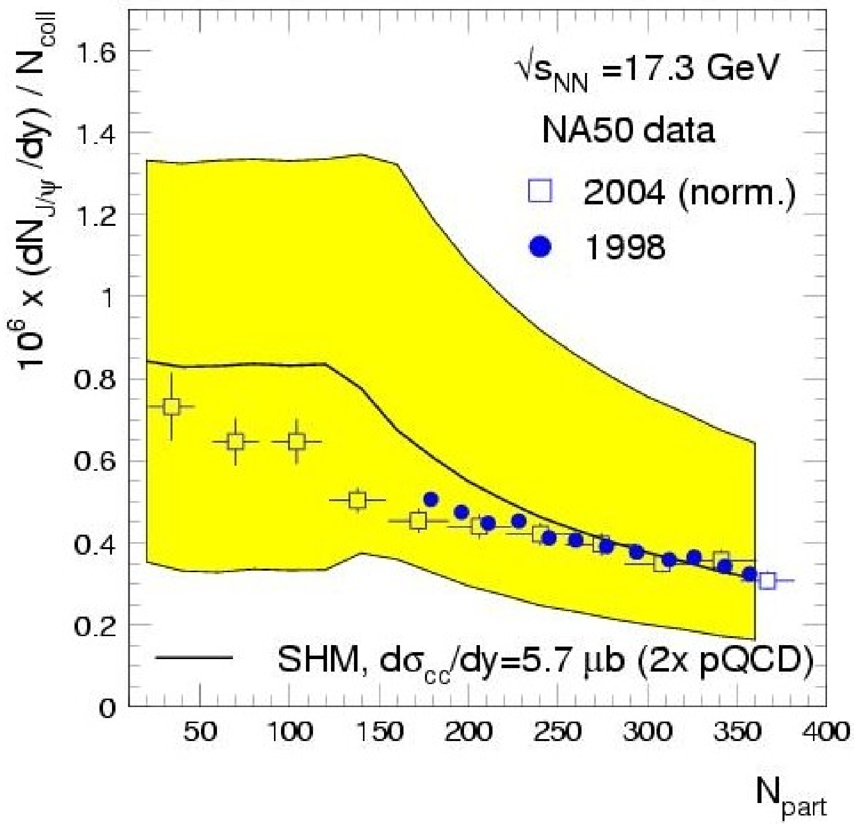
note: charmonium suppression or enhancement is quantified via the nuclear modification factor R_{AA}

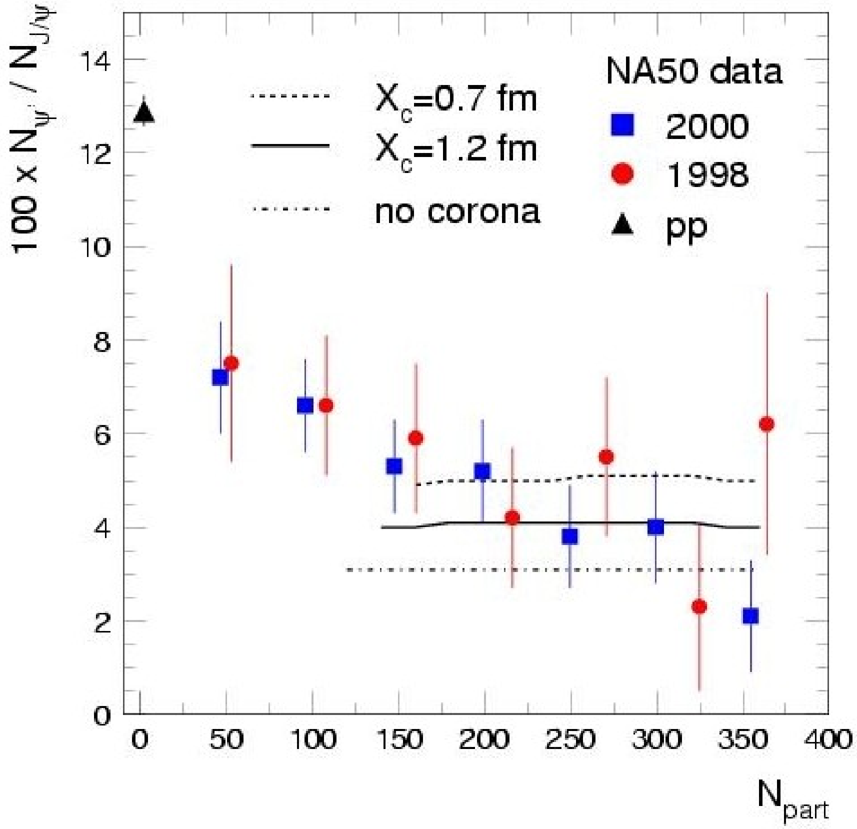
$$R^i_{\mathrm{AA}} = \frac{Y^i_{\mathrm{J}/\psi}(\Delta p_{\mathrm{t}}, \Delta y)}{\langle T^i_{\mathrm{AA}} \rangle \times \sigma^{\mathrm{PP}}_{\mathrm{J}/\psi}(\Delta p_{\mathrm{t}}, \Delta y)}$$

Here, T_{AA} is the nuclear thickness function

by construction, R_{AA} = medium/vacuum

results for SPS energy



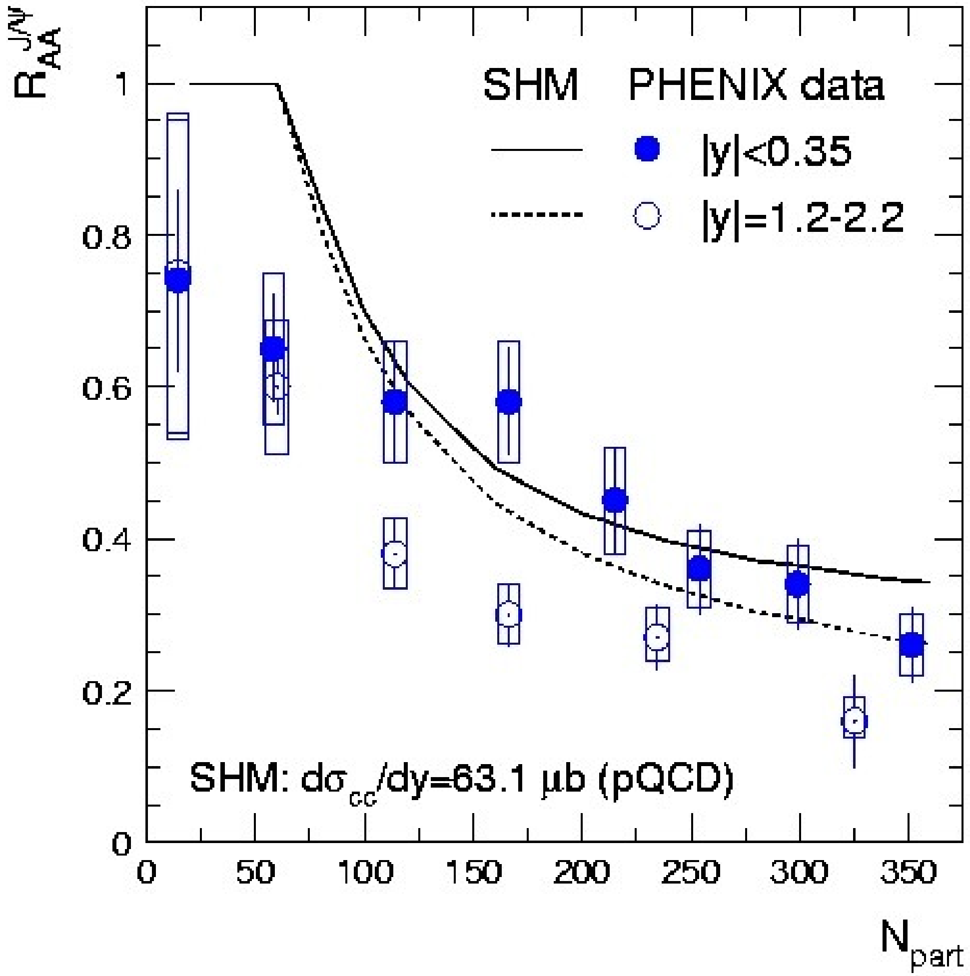


only moderately enhanced (2 x pQCD) cc_bar cross section needed

psi'/psi ratio is expected from a thermal scenario

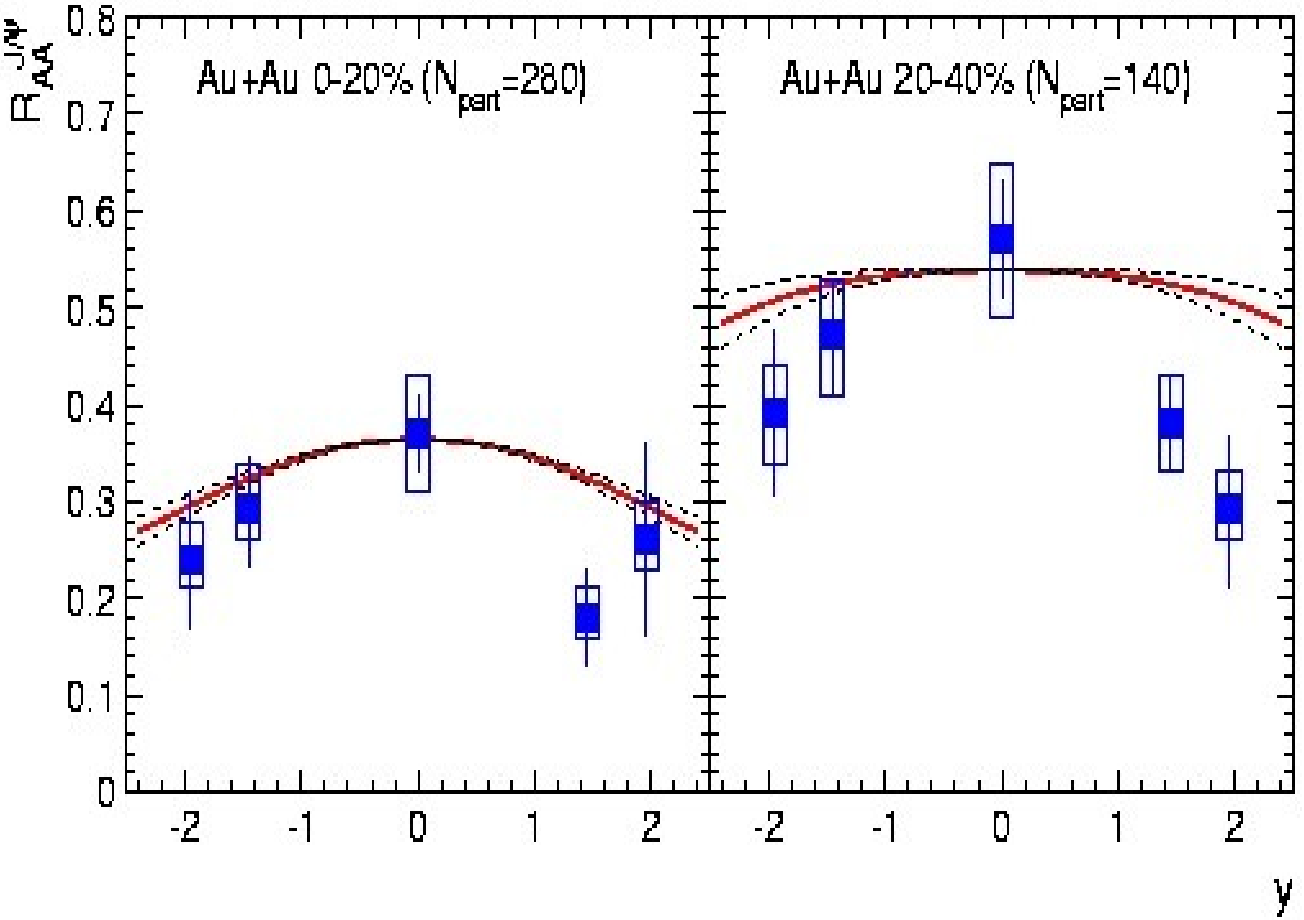
a brief look at RHIC data

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

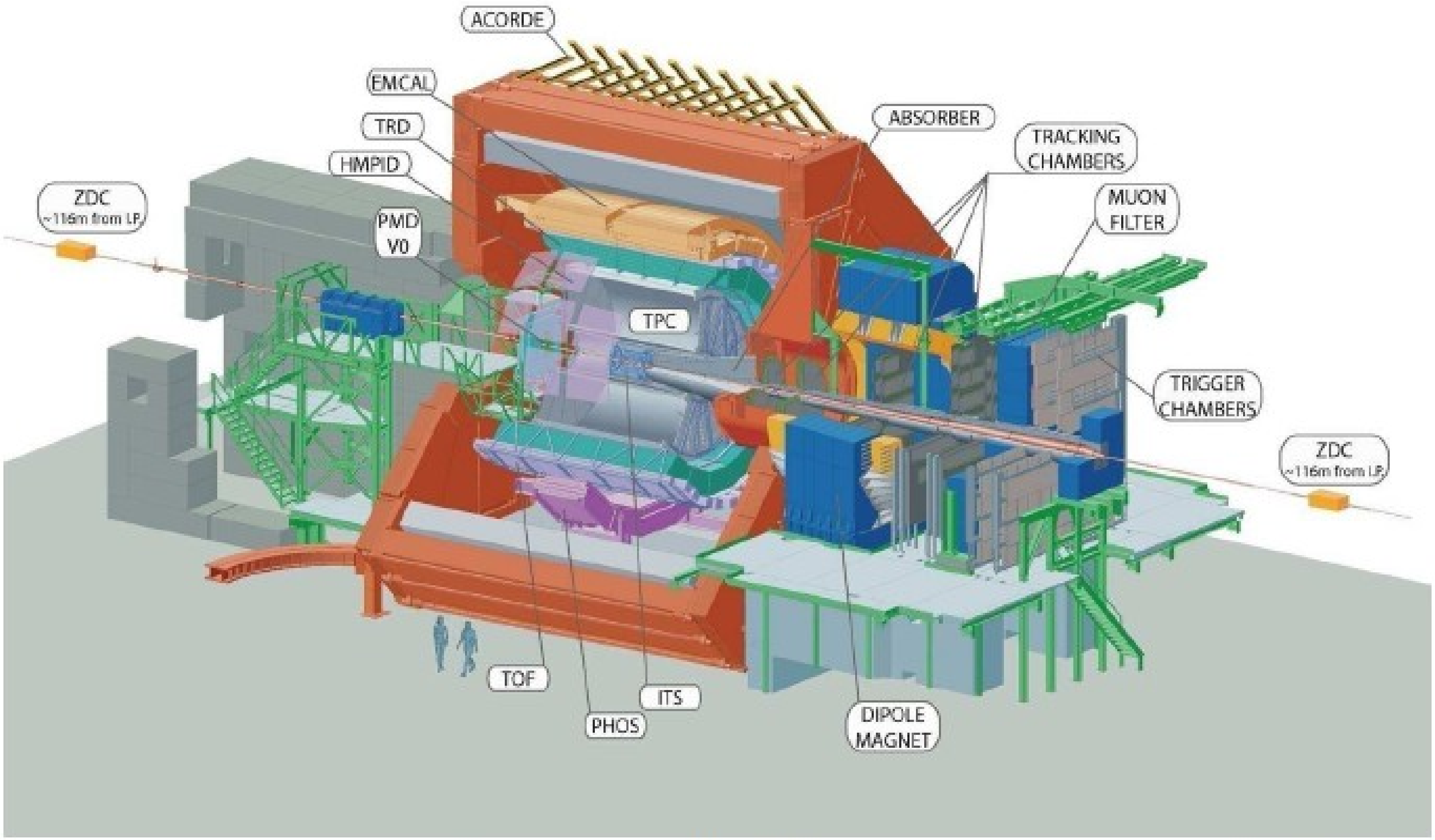
now to LHC data

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

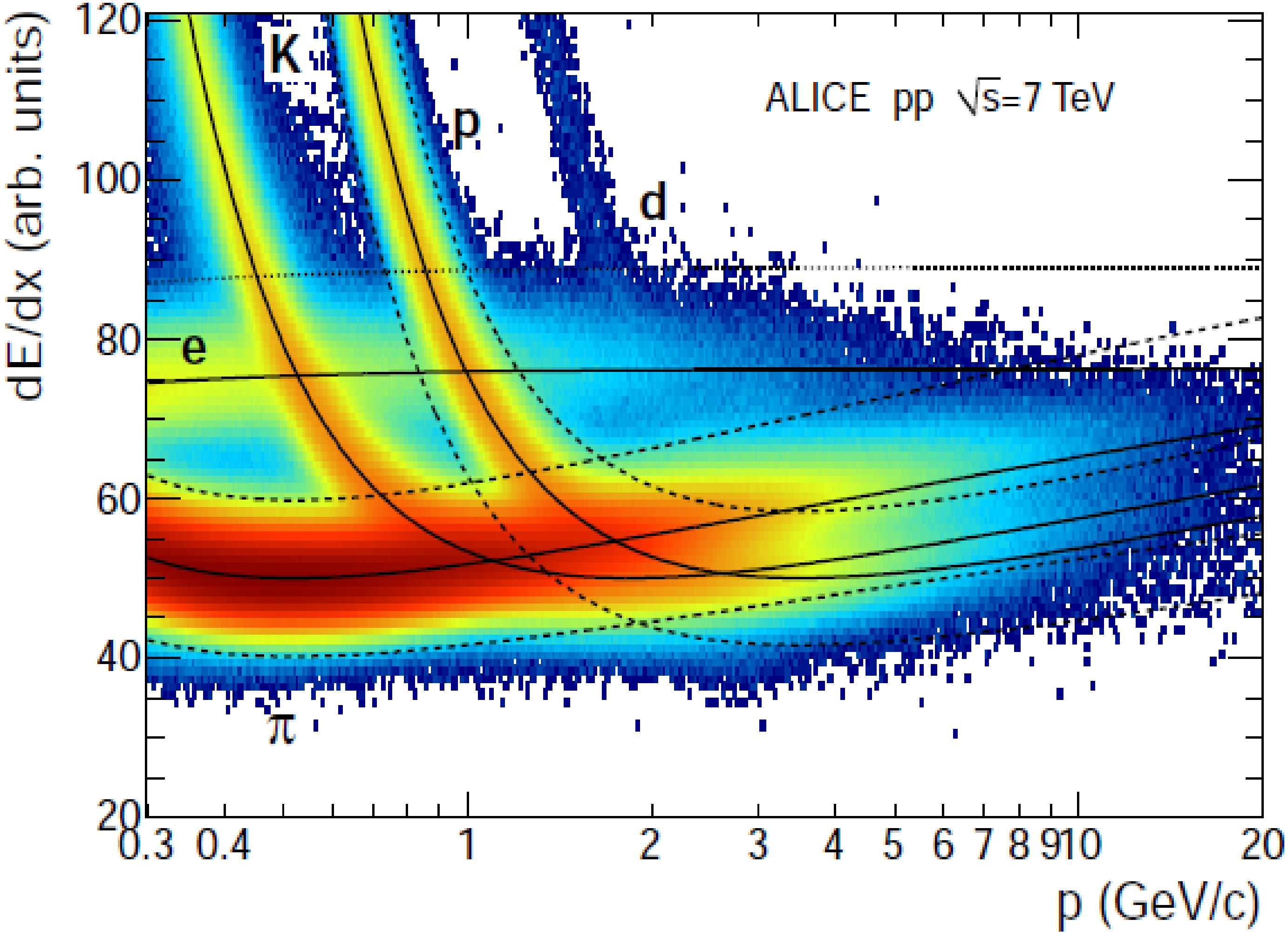
...we are on the way

Charm and charmonia measured in ALICE

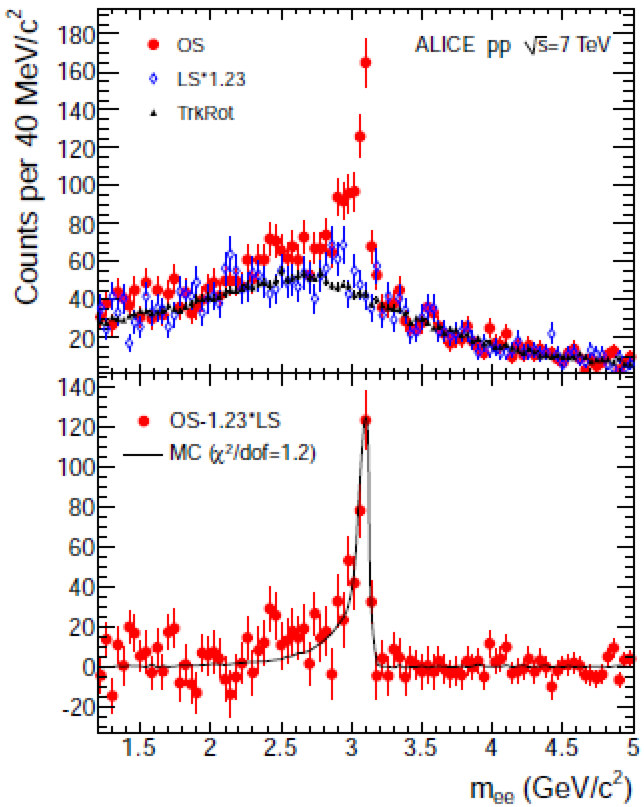


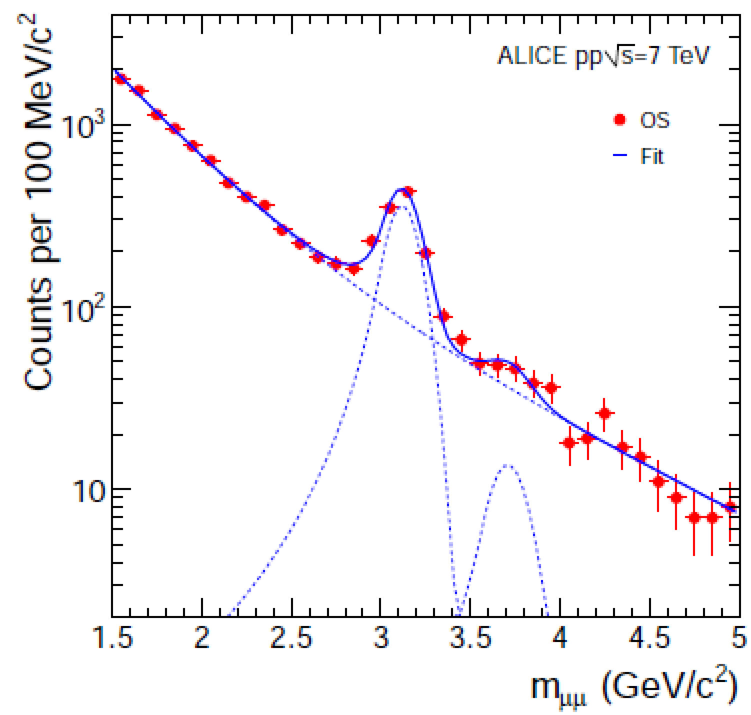
Measures charmonium at $|y| < 0.9$ (e^+e^-) and $-4 < y < -2.5$ ($\mu^+\mu^-$)

Electron identification with the Alice TPC



J/psi identification in pp collisions with ALICE





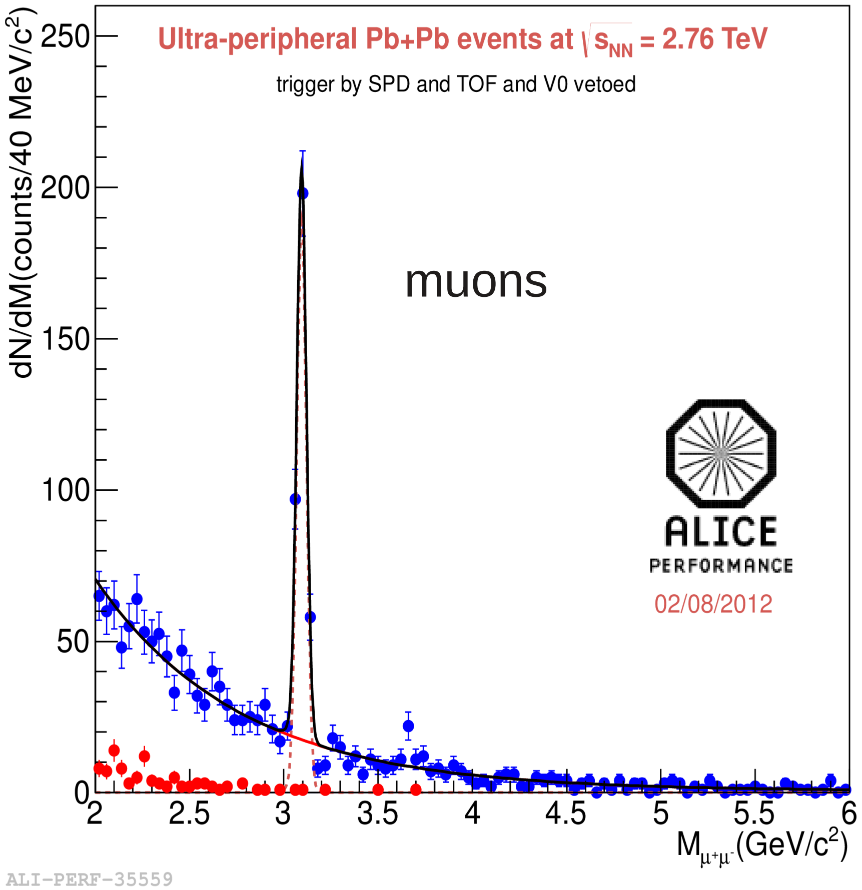
$N_{J/psi} = 957 \pm 56$ for L_{int}=7.9 nb^{-1}

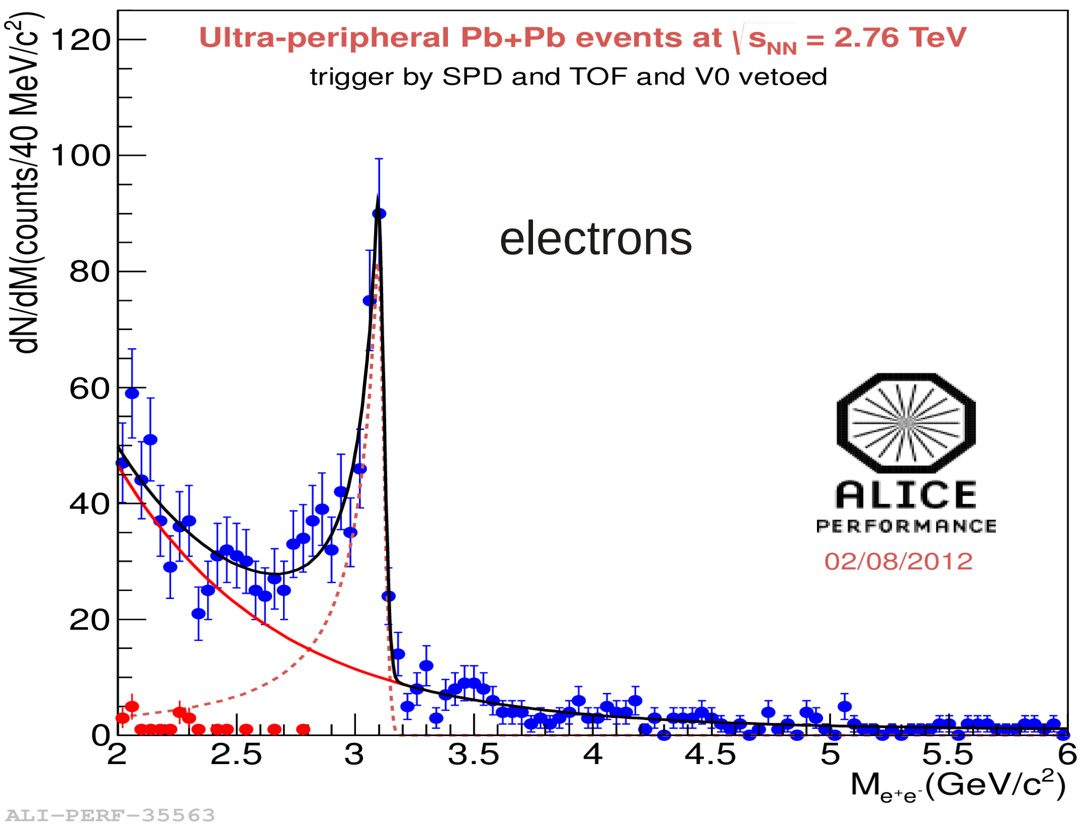
$N_{J/psi} = 352 \pm 32$ for L_{int}=5.6 nb^{-1}

Phys. Lett. B 704 (2011) 442

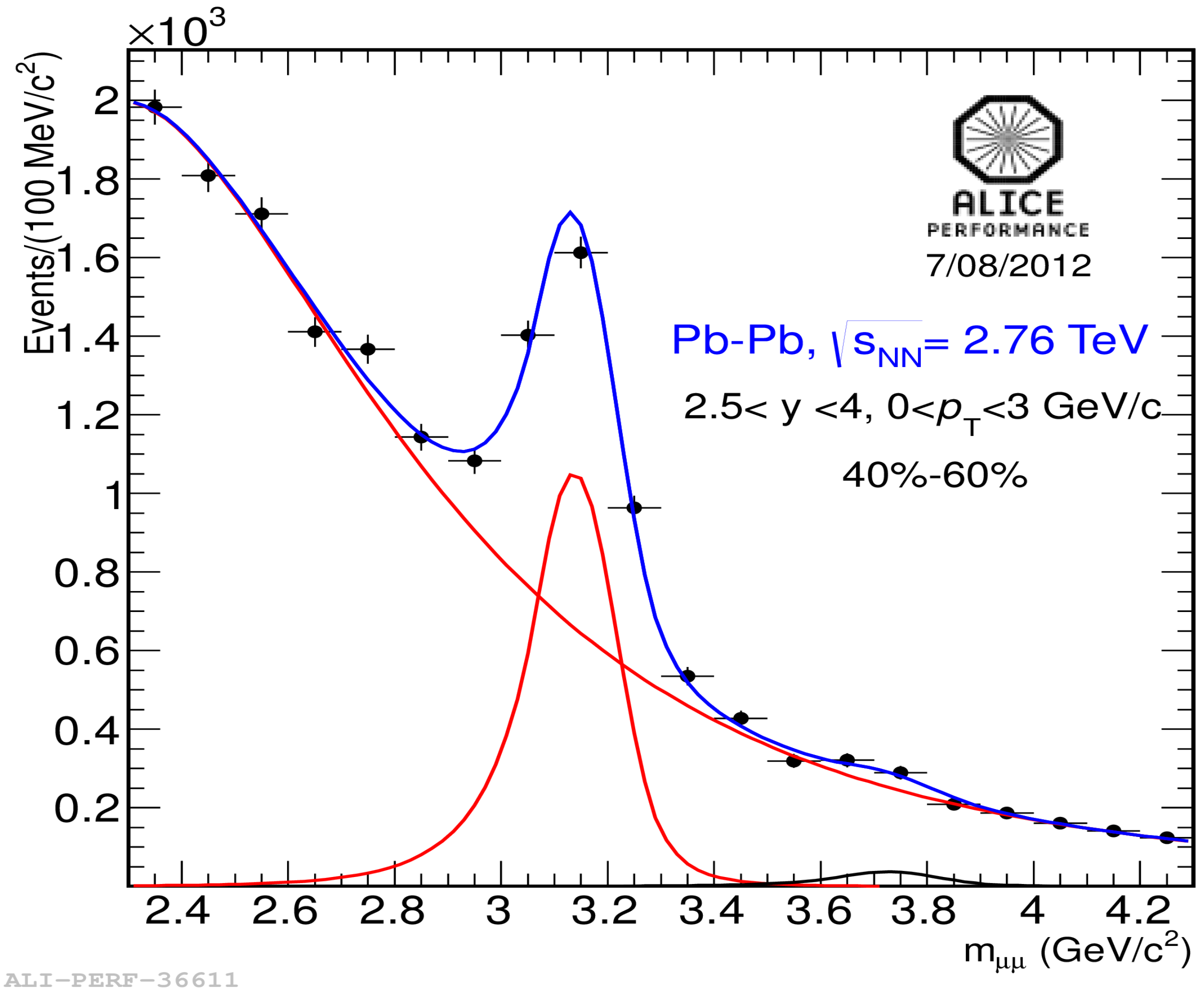
J/psi line shape in ultra-peripheral Pb—Pb collisions

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



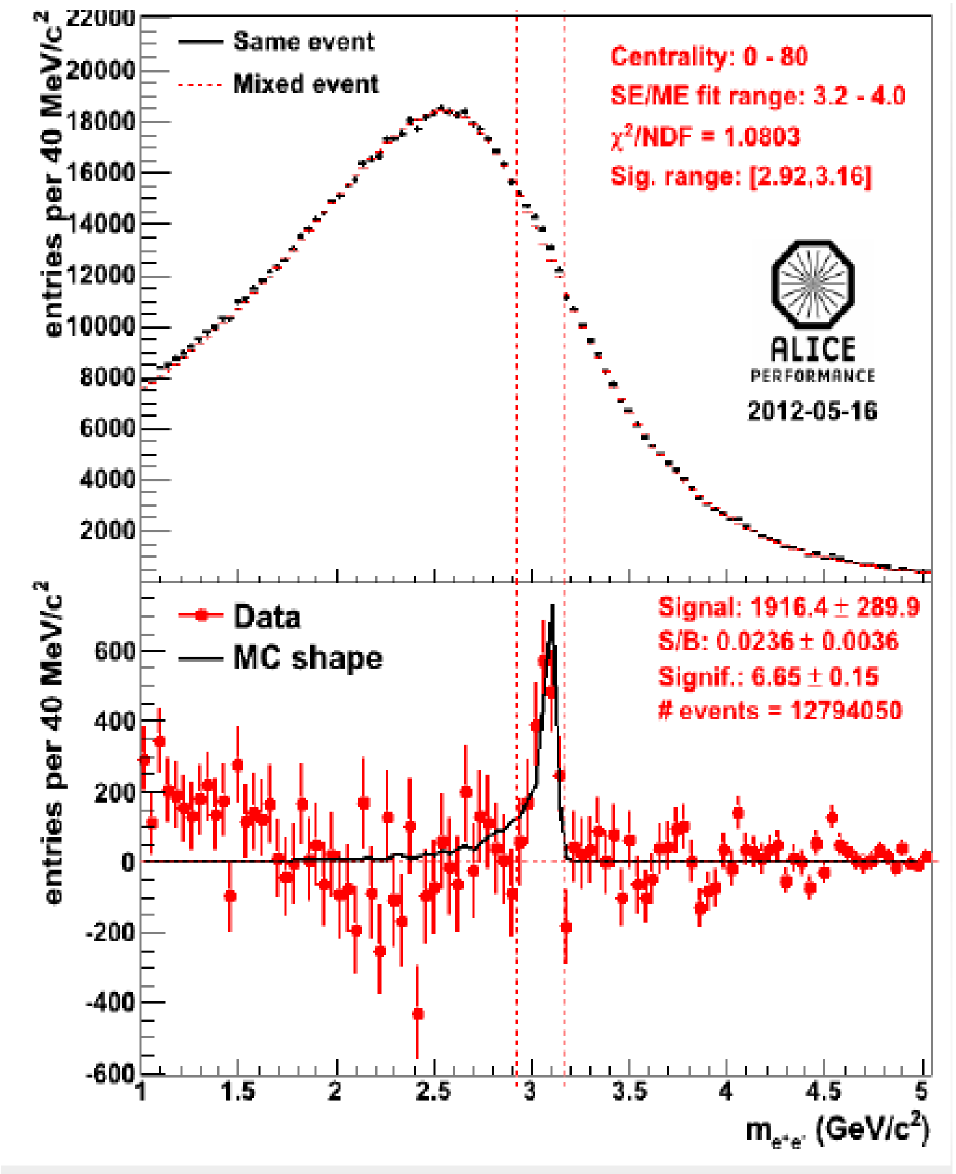


J/psi → mumu in PbPb collisions



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/ψ decay but e.g. D- or B-mesons) resonance well visible

in Pb—Pb collisions charm quarks are suppressed relative to pp collisions – see talk by Johanna Stachel

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

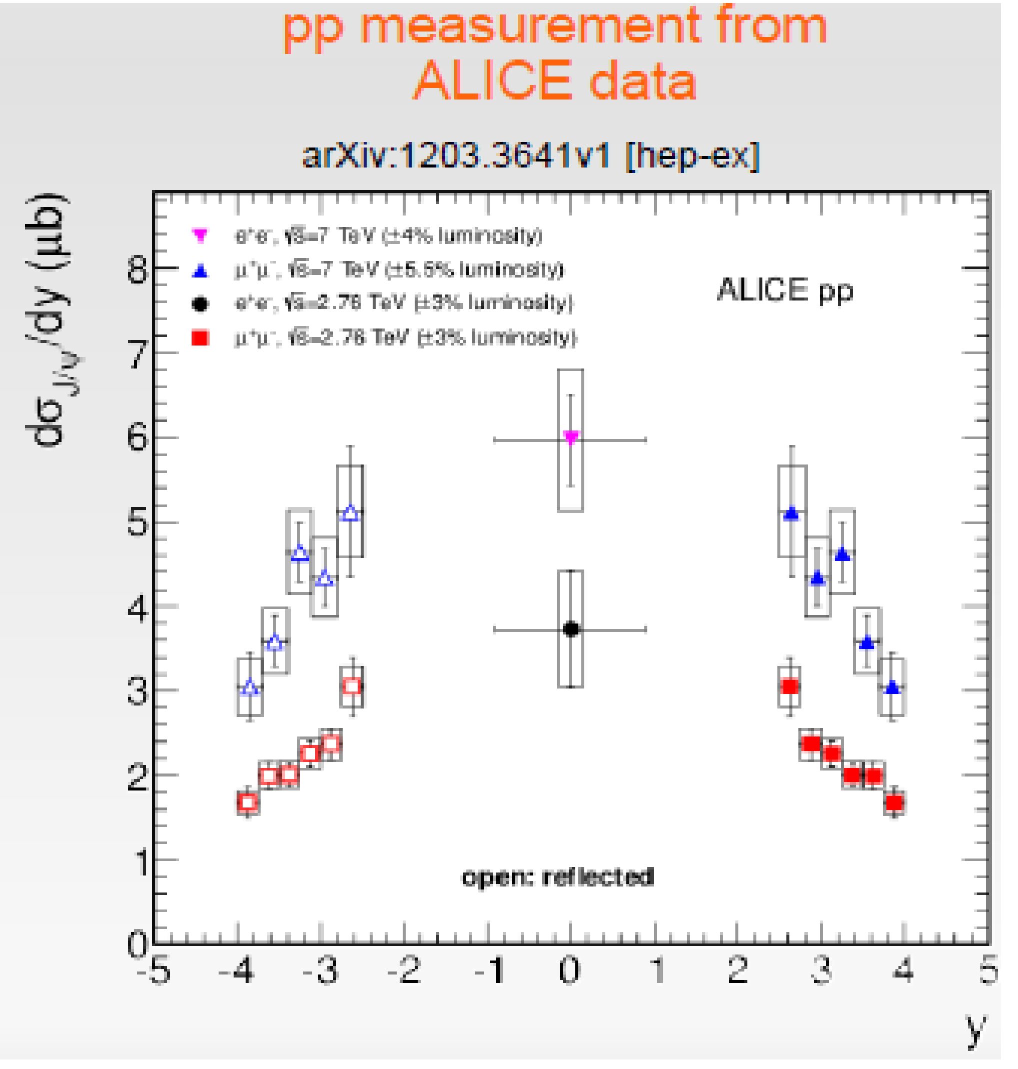
pp @ 2.76 TeV reference for the nuclear modification factor R_{AA} in Pb-Pb collisions

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

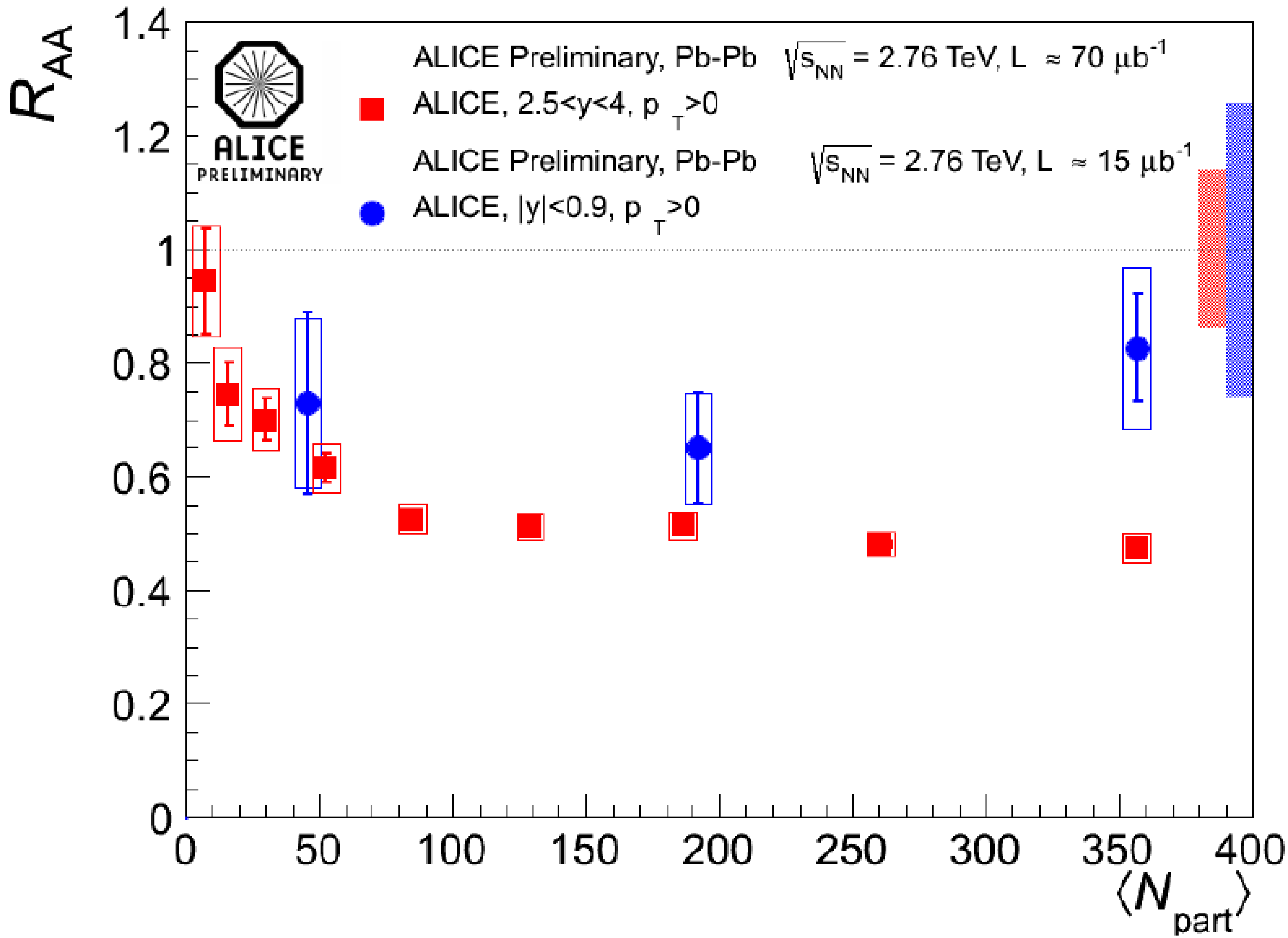
the pp reference is also the main source of systematic uncertainty in the R_{AA} computation:

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

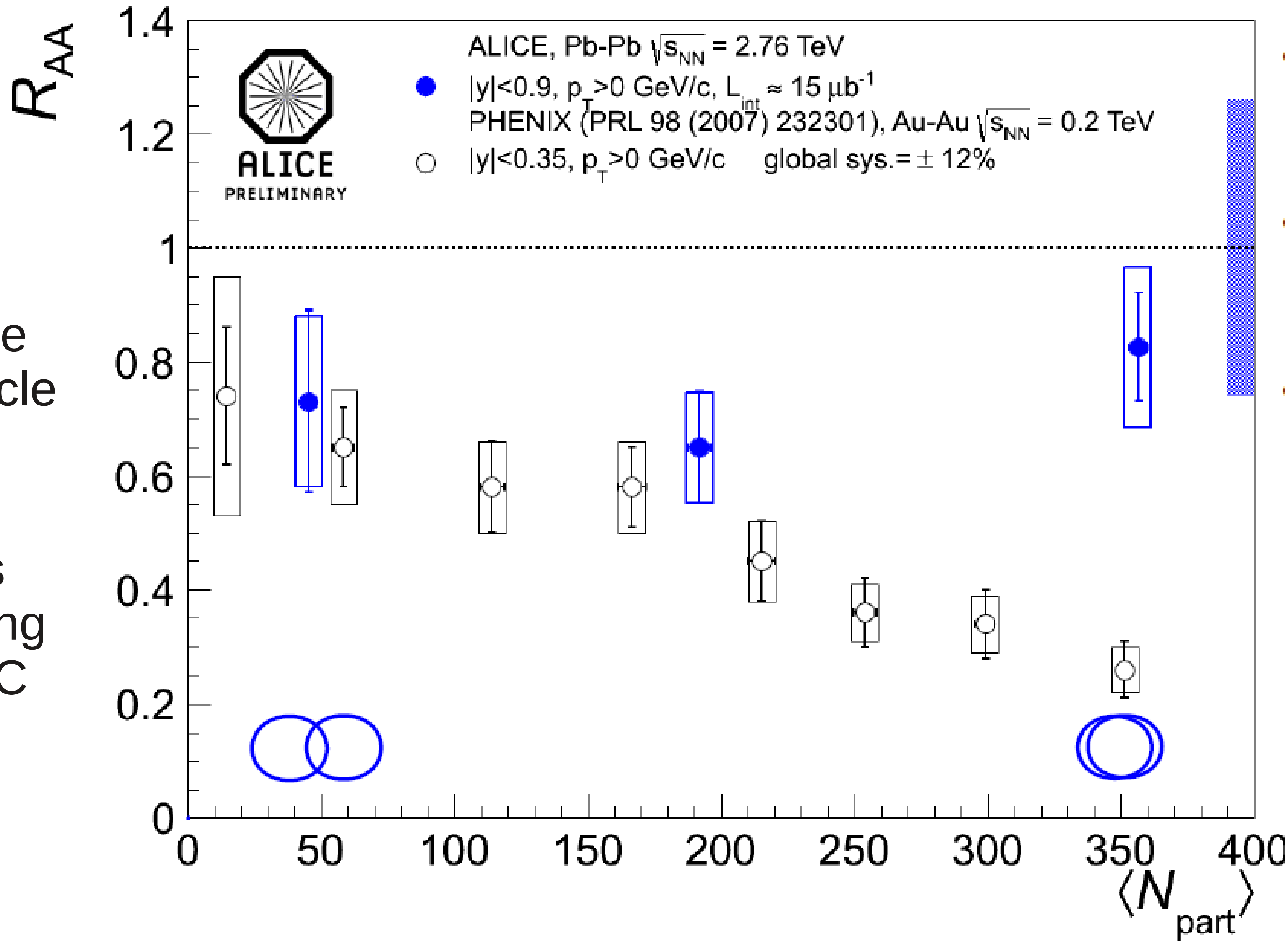
J/Ψ (|y|<0.9), total syst. uncertainty of 26%



newest ALICE data at central and forward rapidity

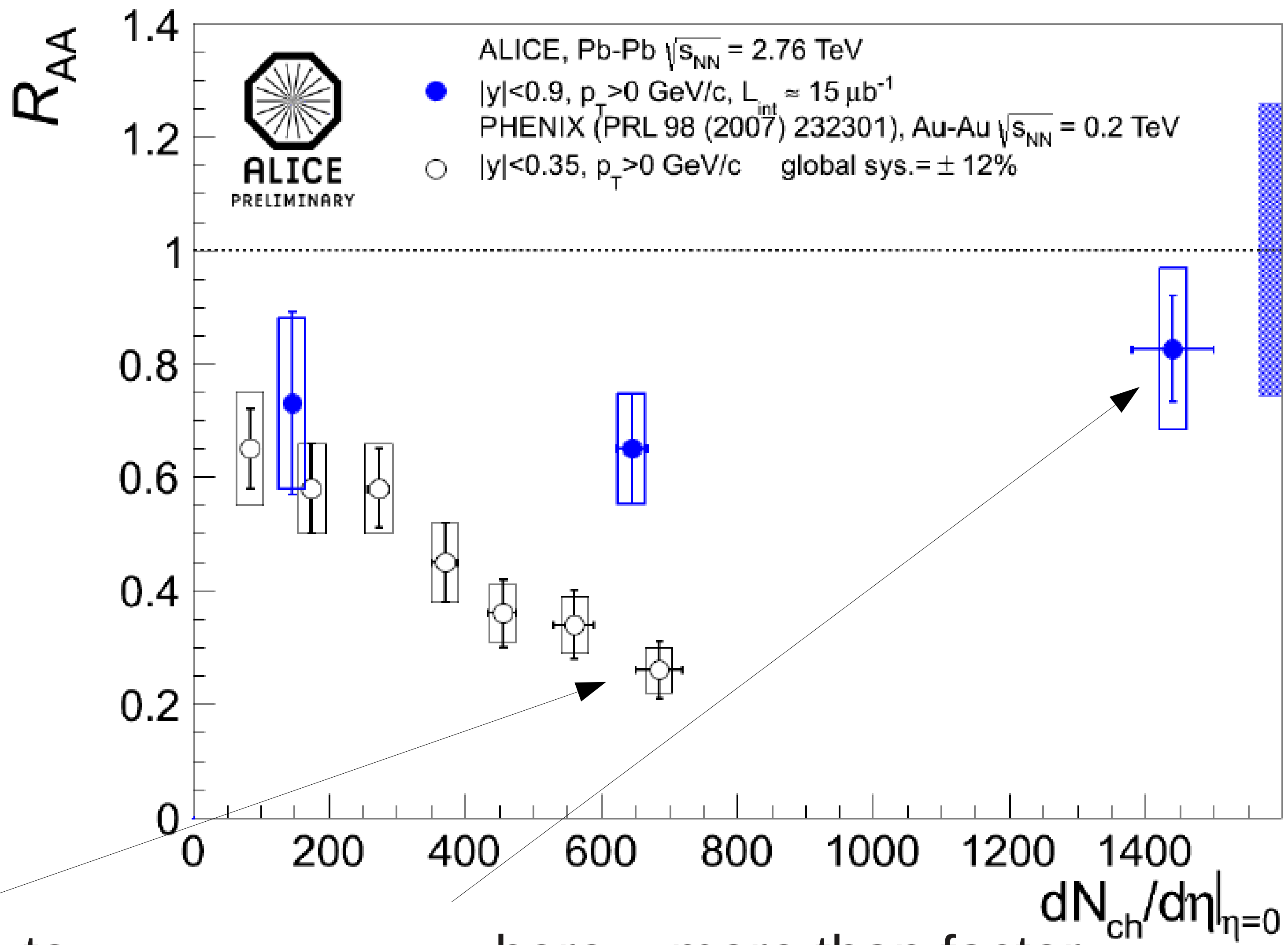


Comparison to PHENIX data



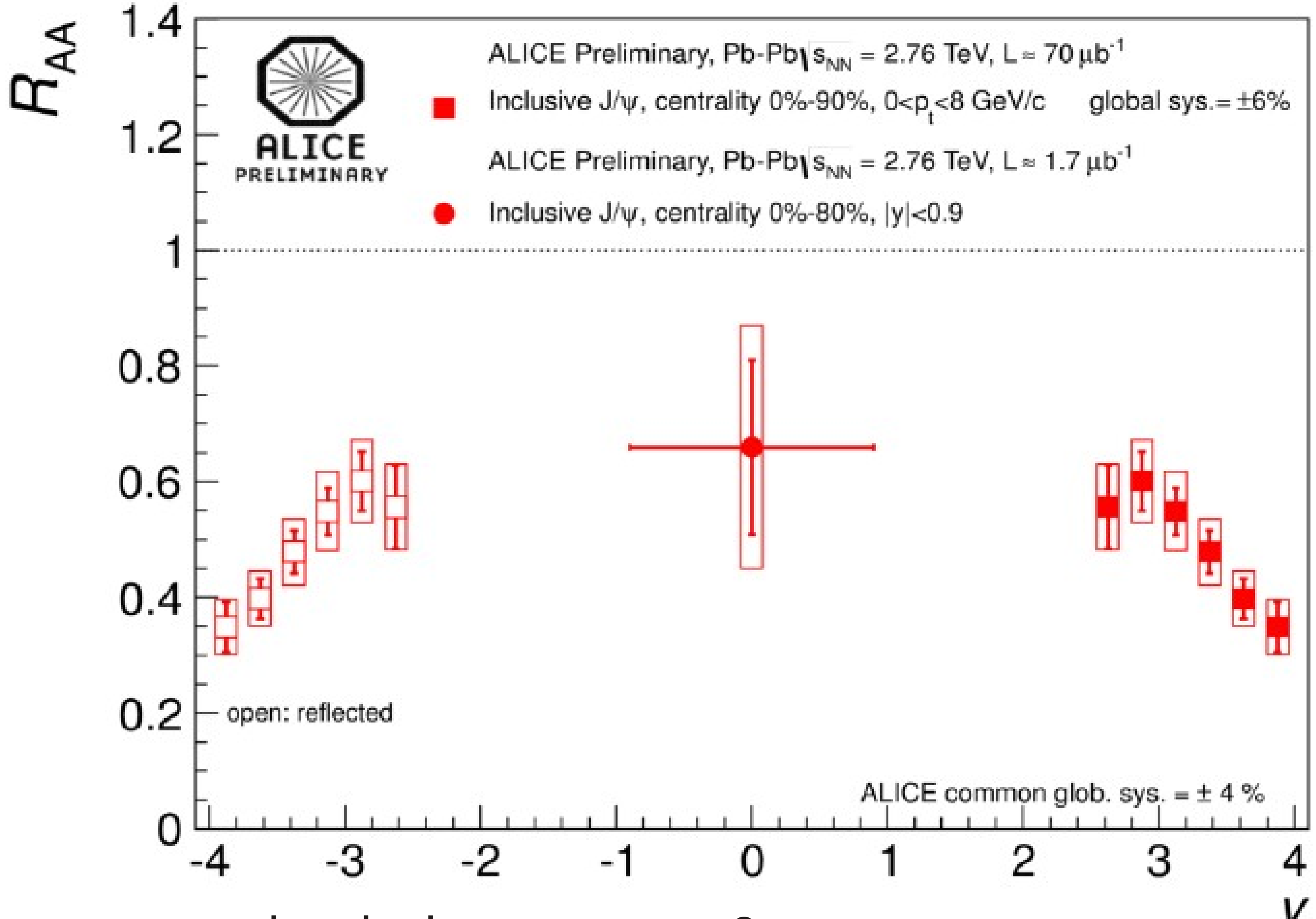
J/psi is the only particle for which R_{AA} increases when going from RHIC to LHC energy

less suppression when increasing the energy density



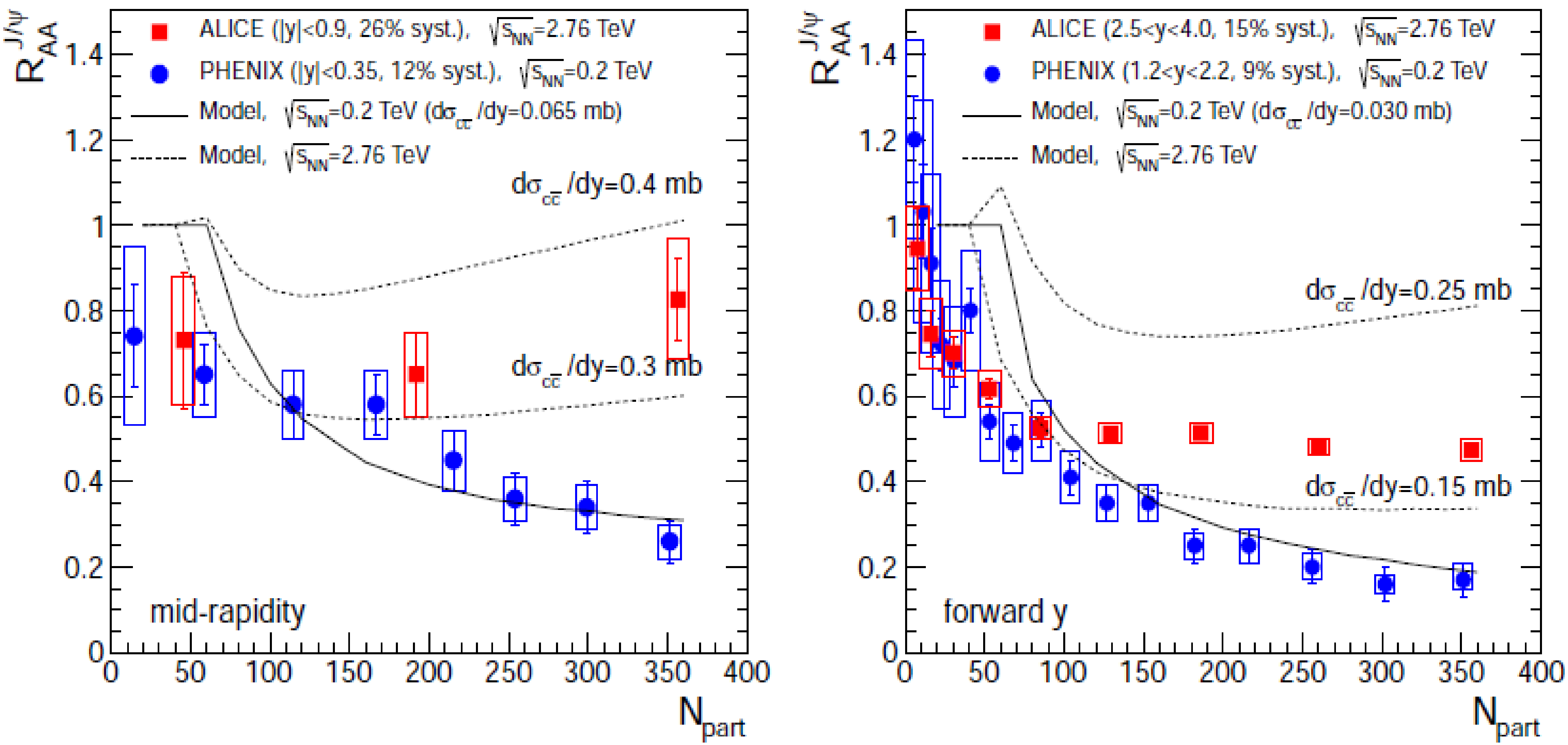
from here to here more than factor of 2 increase in energy density, but R_{AA} increases by more than a factor of 3

Rapidity dependence



note: energy density largest at y = 0

statistical hadronization model



ALICE data and evolution from RHIC to LHC energy described quantitatively

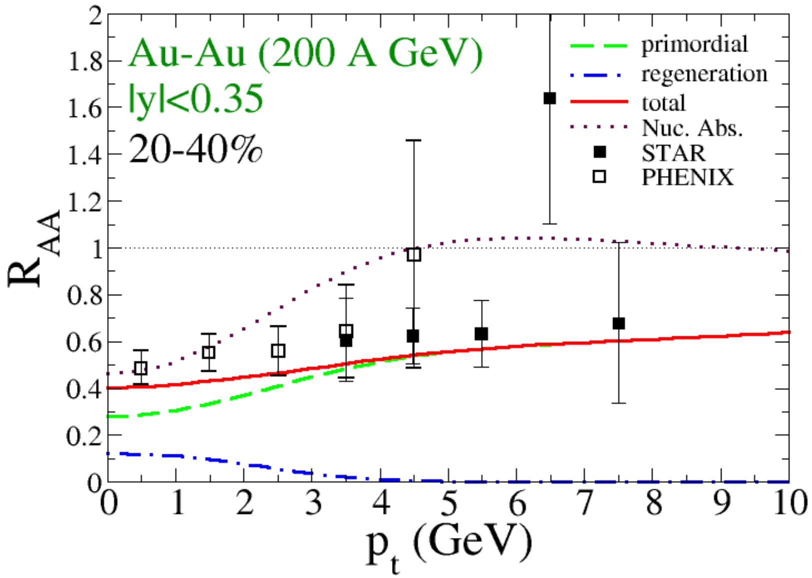
back to J/psi data – what about spectra and hydrodynamic flow of charm and charmonia?

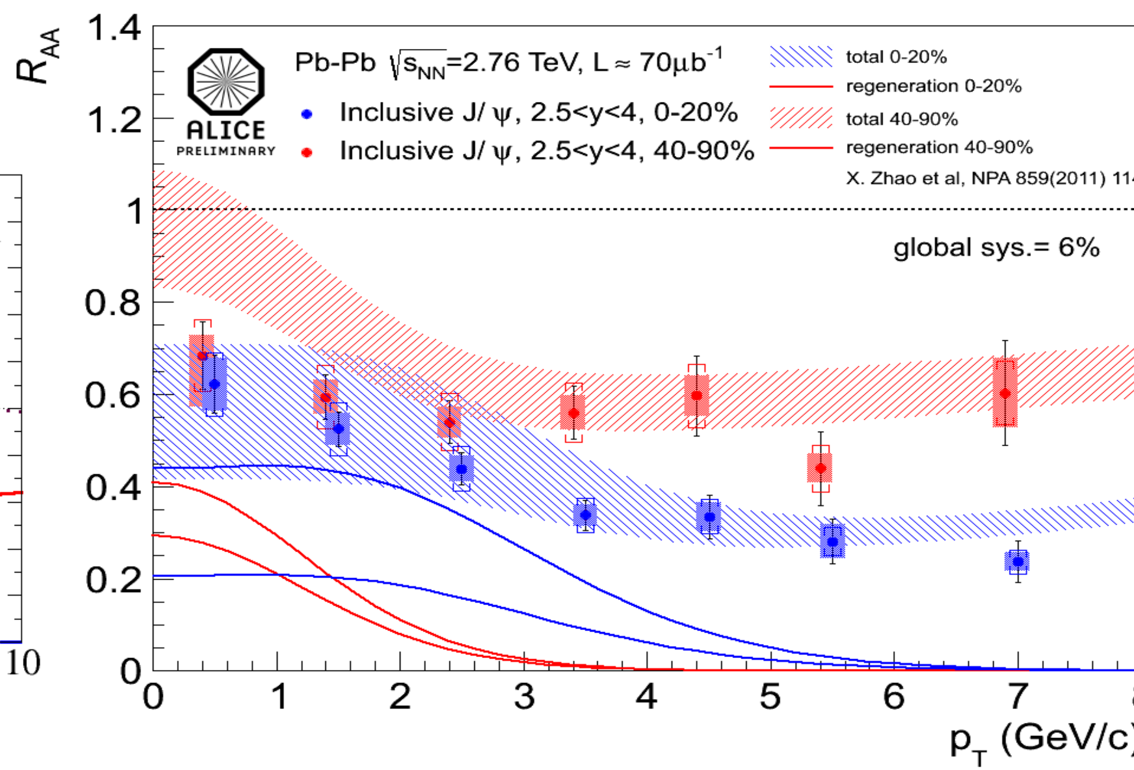
if charmonia are produced via statistical hadronization of charm quarks at the phase boundary, then:

- charm quarks should be in thermal equilibrium

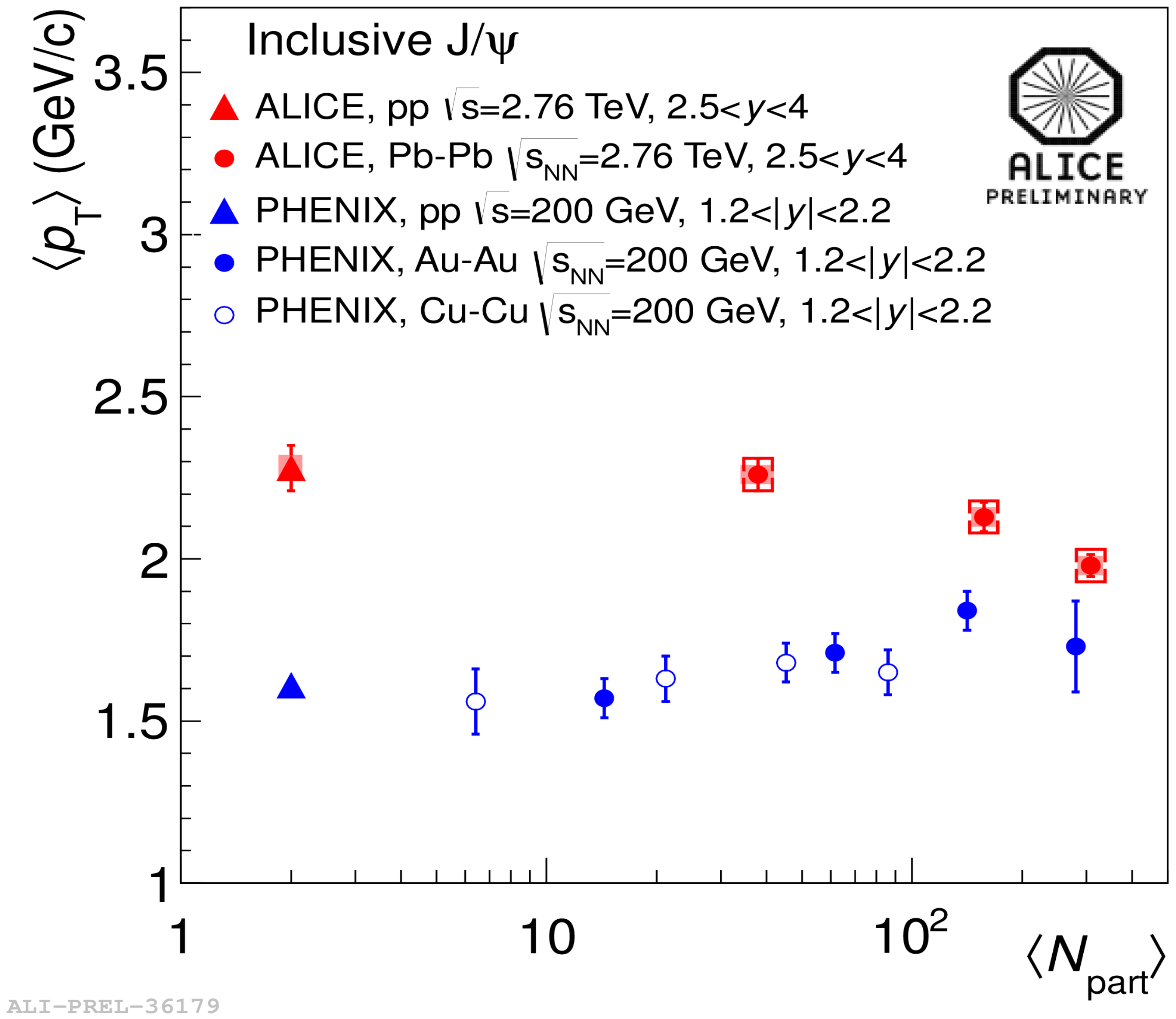
    - low pt enhancement
    - flow of charm quarks → Johanna's talk
    - flow of charmonia

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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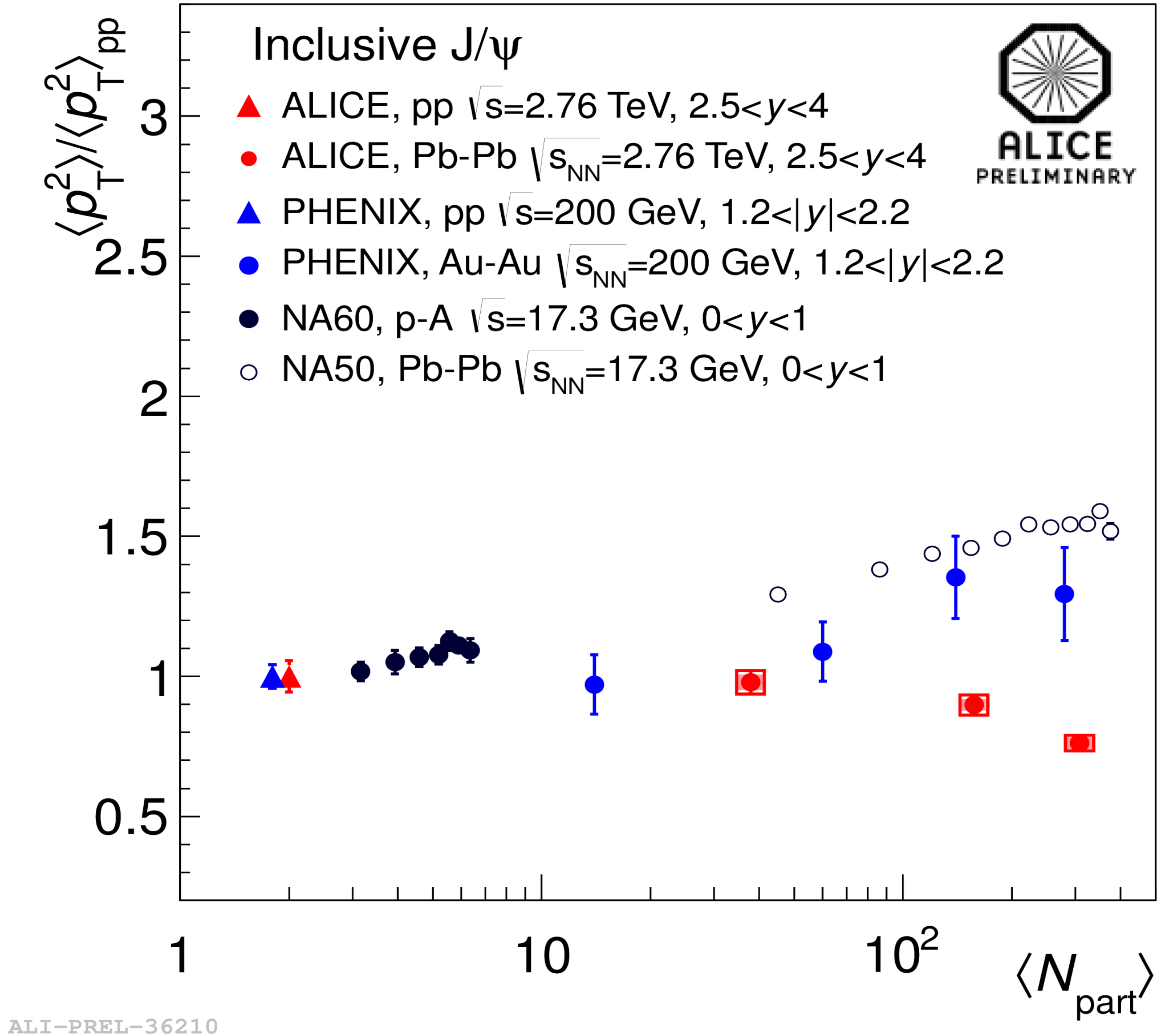
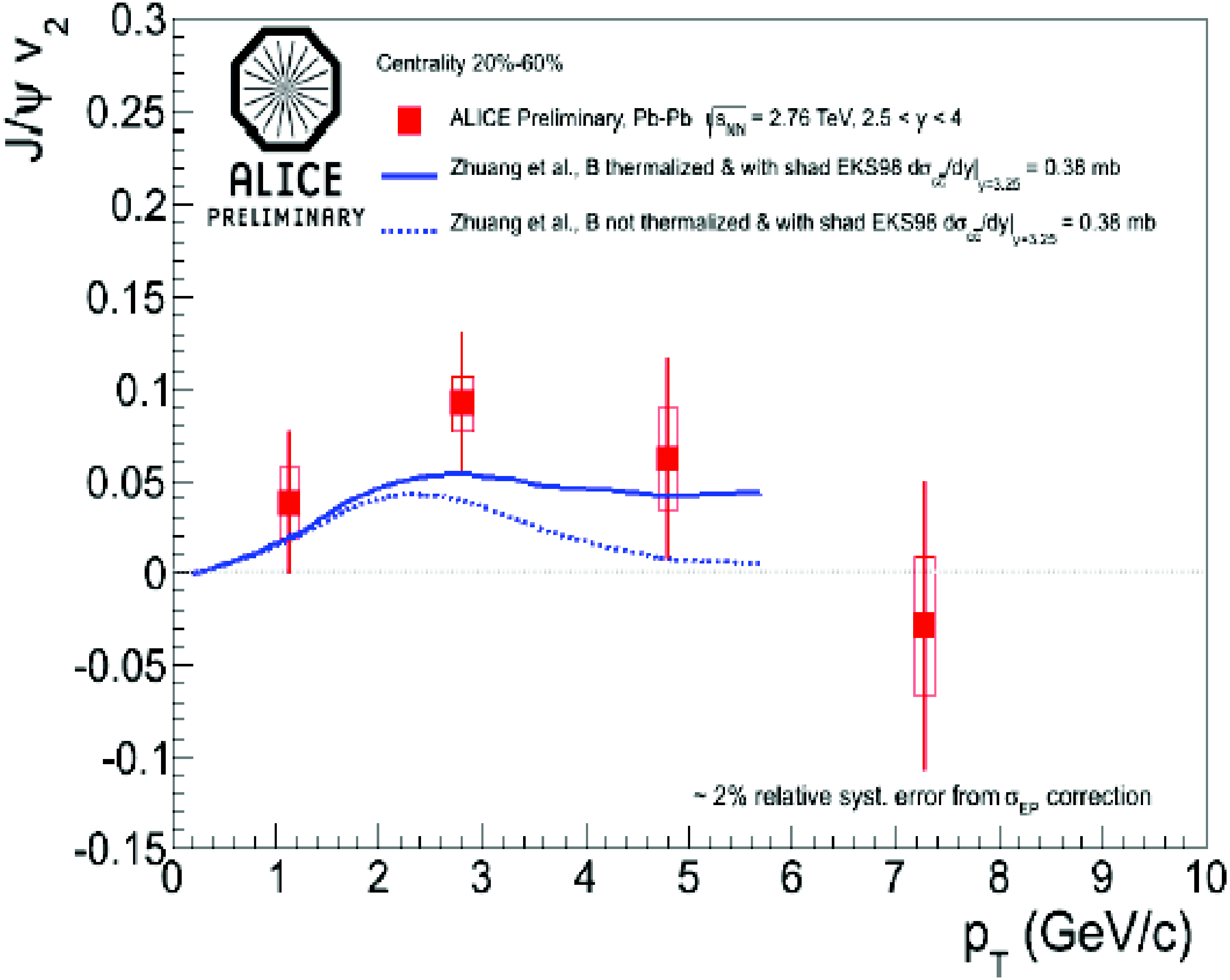


J/psi flow compared to models including (re-) generation



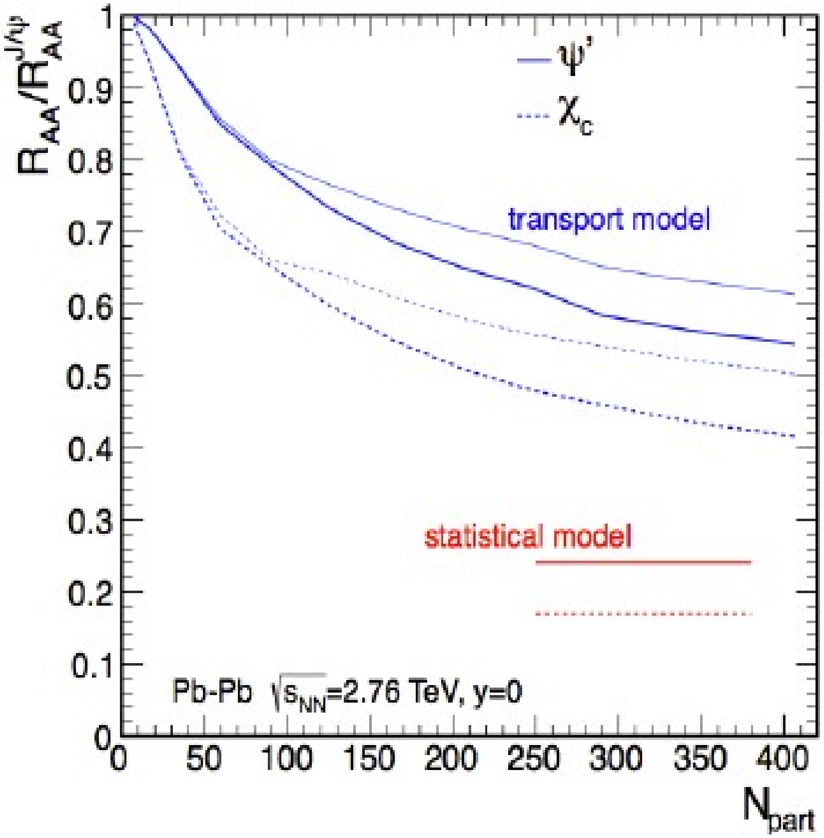
hydrodynamic flow of J/psi consistent with (re-)generation

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:

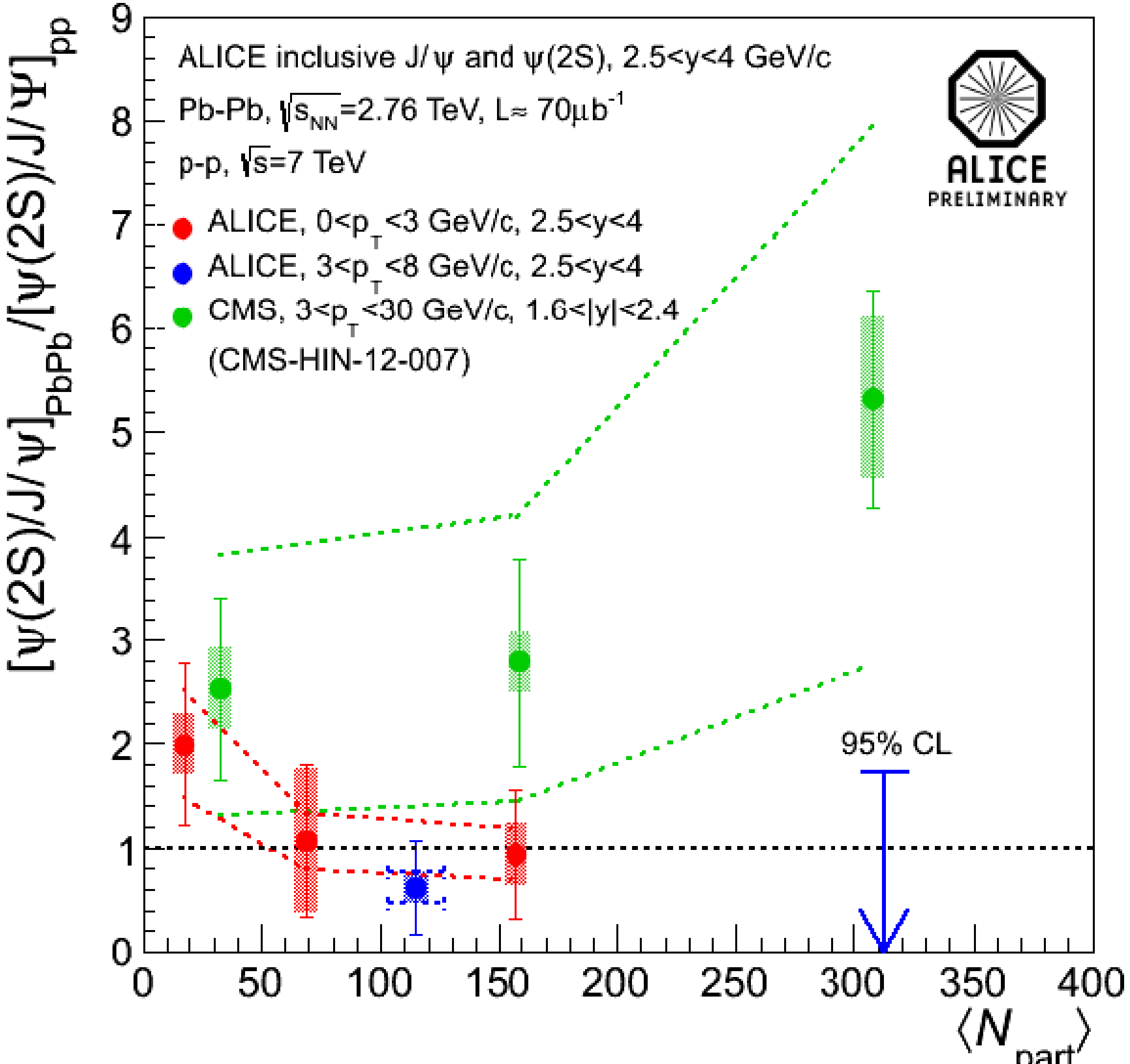
A. Andronic et al.,

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

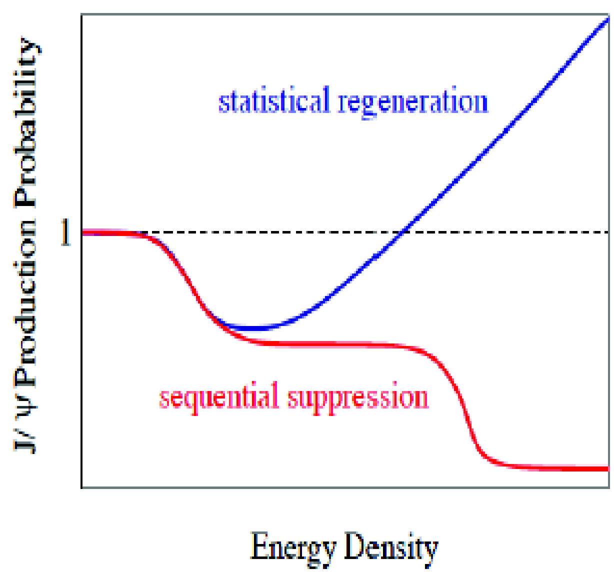


dramatic enhancement in CMS data not confirmed by ALICE measurements

Summary

- 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