The statistical model in Pb-Pb collisions at the LHC

- Introductory remarks – is quark matter at LHC in equilibrium?
- Energy dependence of hadron production and statistical model
- Is there anything special at LHC energy?
- The case of heavy quarks and quarkonia

FIAS-Frankfurt

work based on collaboration with
A. Andronic, K. Redlich, and J. Stachel

QM2012 conference
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Peter Braun-Munzinger

Equilibration at the phase boundary

- Statistical model analysis of (u,d,s) hadron production: a test of equilibration of quark matter near the phase boundary

- No (strangeness) equilibration in hadronic phase

- Present understanding: multi-hadron collisions near phase boundary bring hadrons close to equilibrium – supported by success of statistical model analysis pbm, Stachel, Wetterich, Phys.Lett. B596 (2004) 61-69

- This implies little energy dependence above RHIC energy

- Analysis of hadron production → determination of T_c

Is this picture also supported by LHC data?

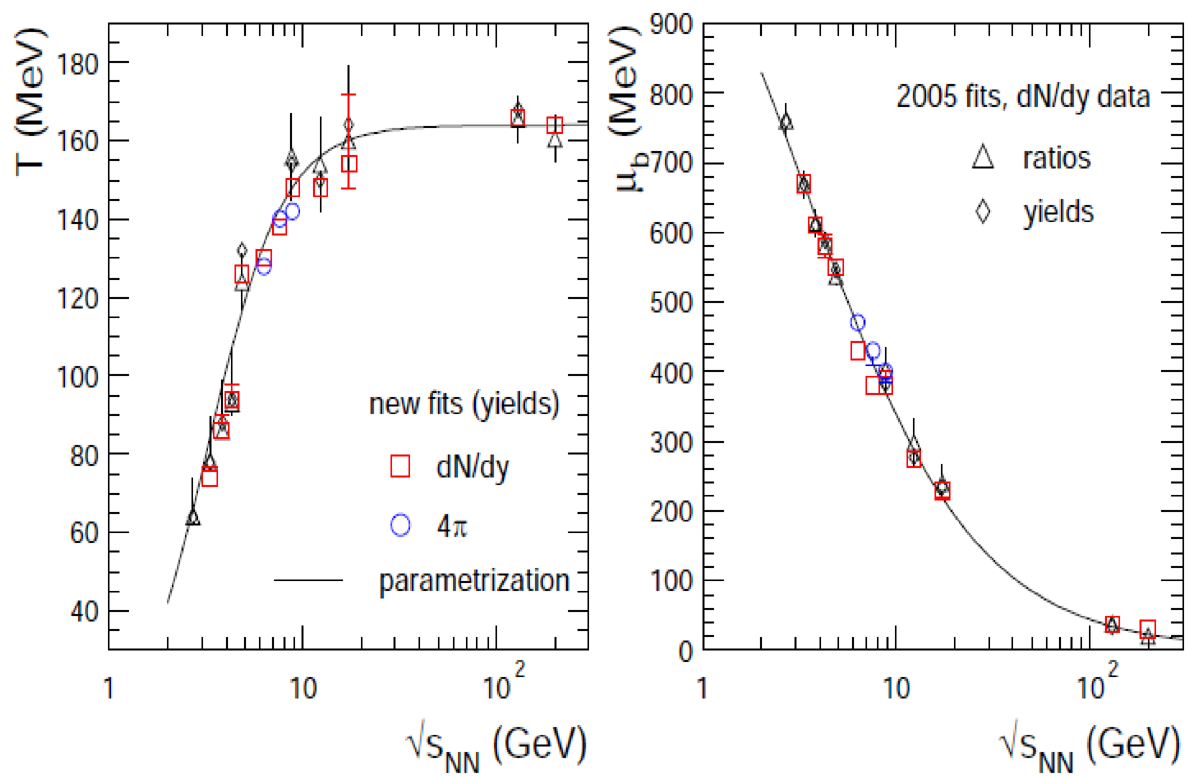
Parameterization of all freeze-out points before LHC data

note: establishment of limiting temperature

T_{lim} = 164 +/- 4 MeV

get T and μ_B for all energies

for LHC predictions we picked T = 164 MeV



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

Important note: corrections for weak decays

All ALICE data do not contain hadrons from weak decays of hyperons and strange mesons – correction done in hardware via ITS inner tracker

The RHIC data contain varying degrees of such weak decay hadrons. This was on average corrected for in previous analyses.

In light of high precision LHC data the corrections done at RHIC need to be revisited.

Re-evaluation of fits at RHIC energies – special emphasis on corrections for weak decays

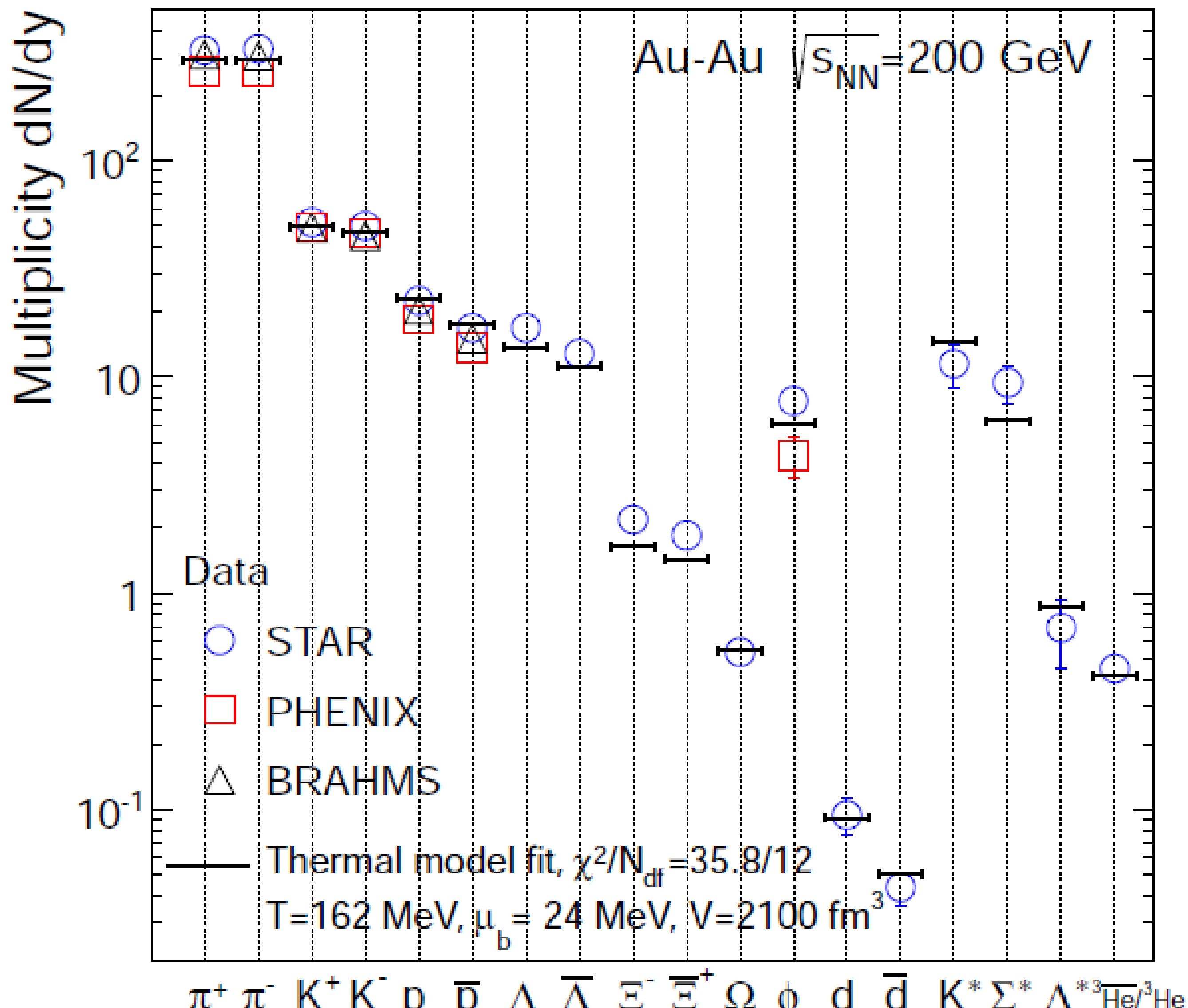
Note: corrections for protons and pions from weak decays of hyperons depend in detail on experimental conditions

RHIC hadron data all measured without application of Si vertex detectors

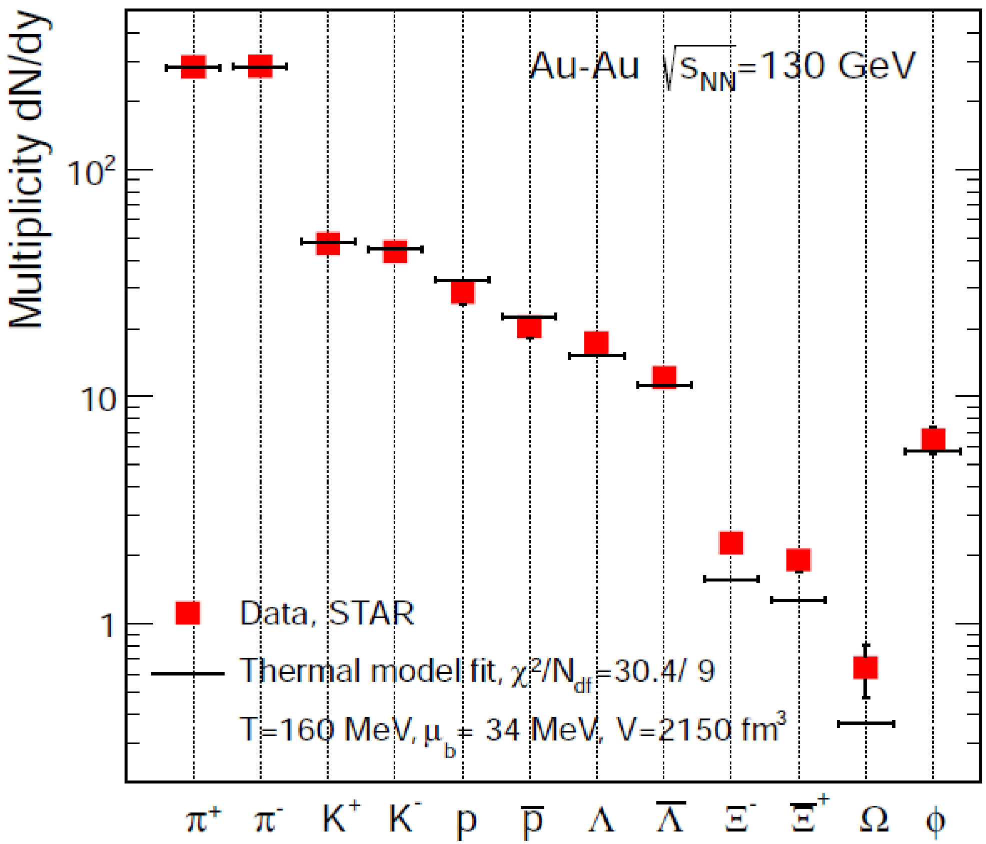
In the following, corrections were applied as specified by the different RHIC experiments

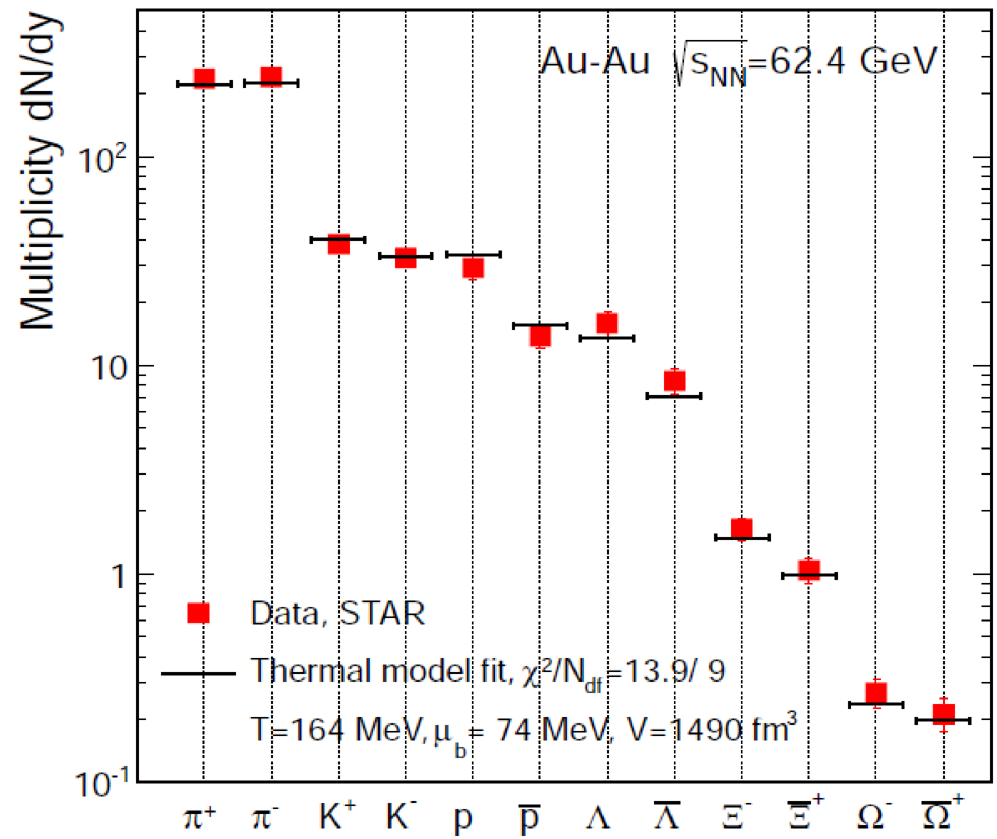
Au+Au central at 200 GeV, all experiments combined

T = 162 MeV



RHIC lower energies, STAR data alone



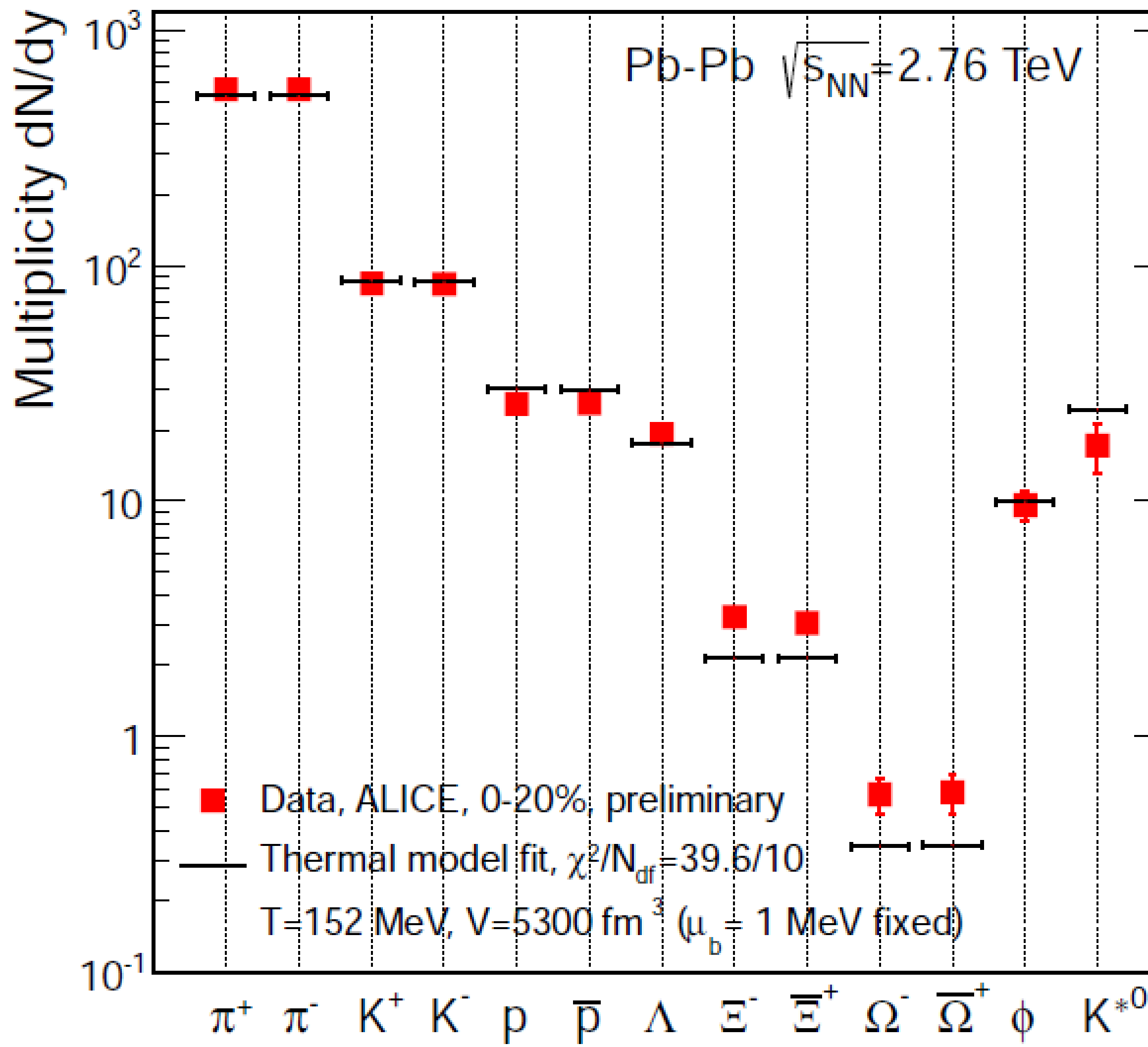


reasonable fits, T = 160 – 164 MeV

now new ALICE data at LHC energy
arXiv:1208.1974 [hep-ex]

rather poor fit,
low T = 152 MeV,
all hyperons
underestimated

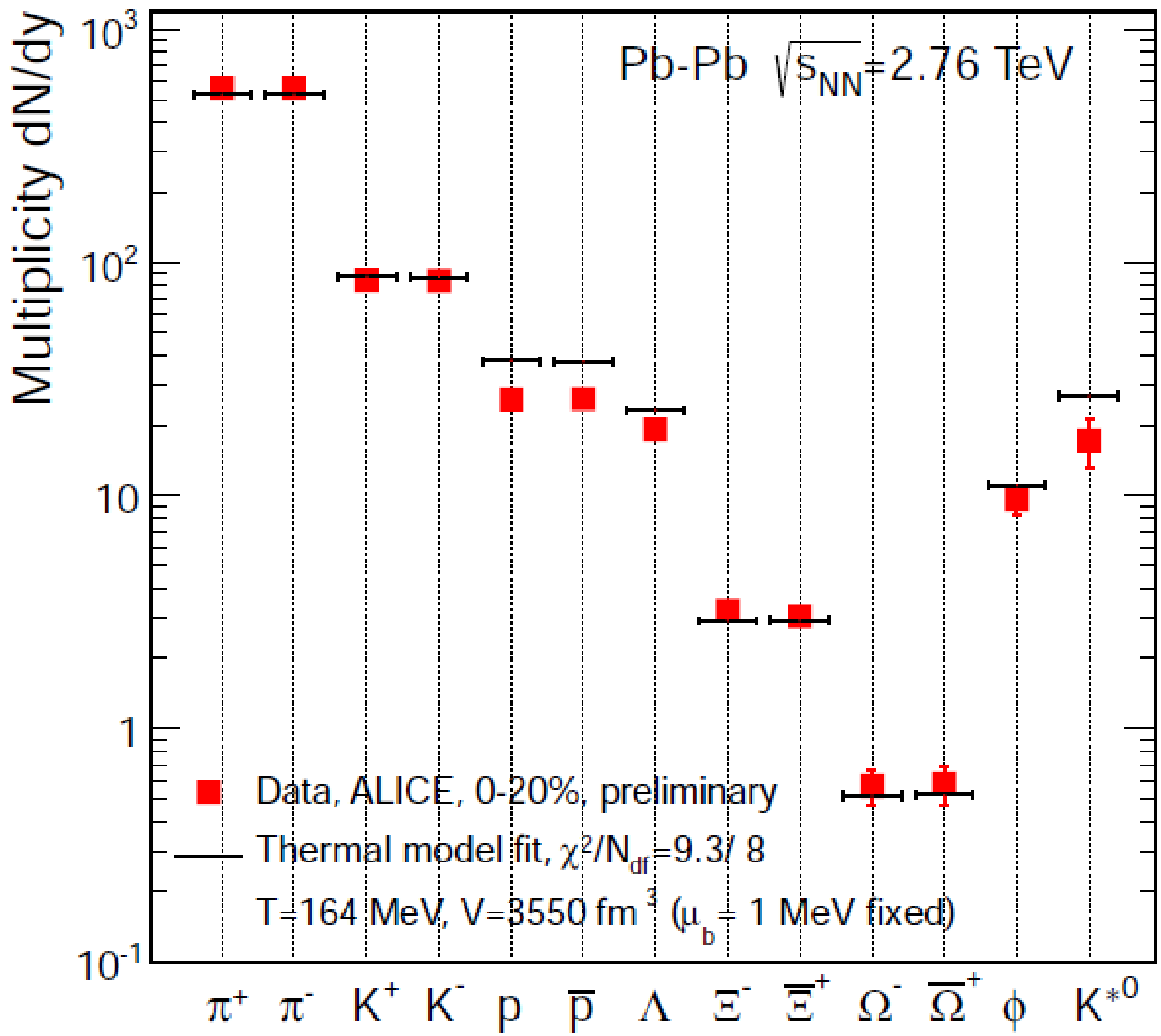
is there no equilibrium
near T_c?



fitting the data without protons and antiprotons

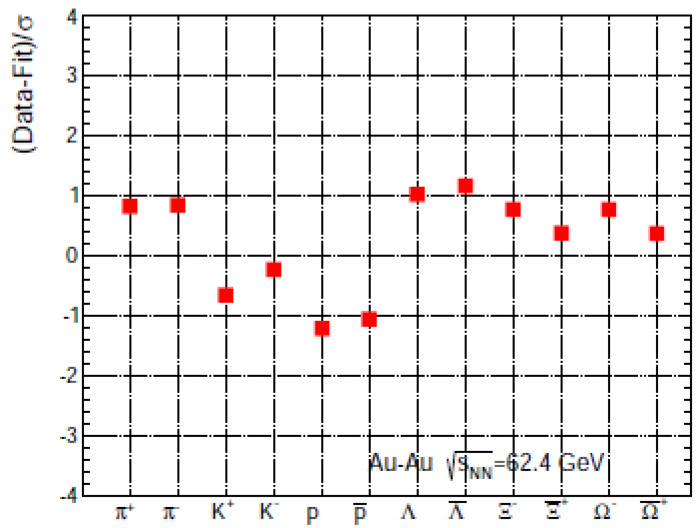
good fit, T = 164 MeV

is there a proton anomaly?

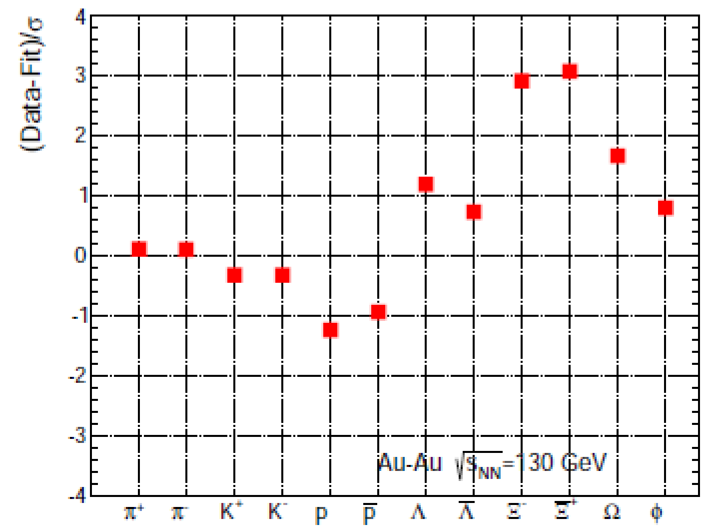


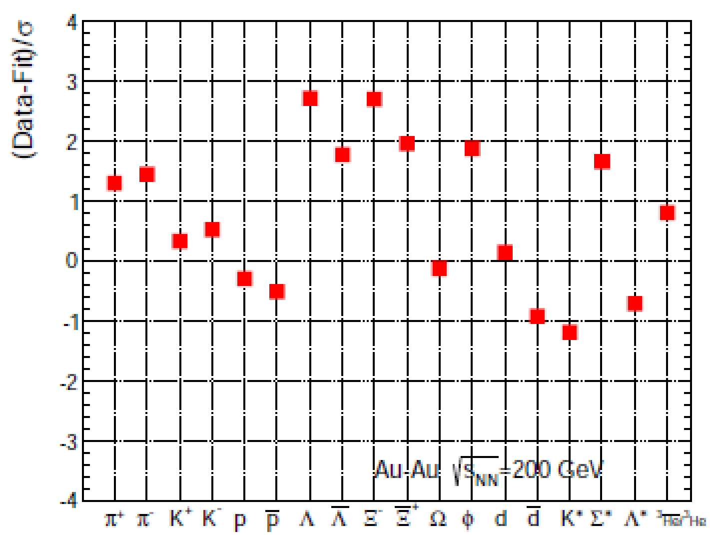
analyzing the deviations

Au-Au 62.4 GeV

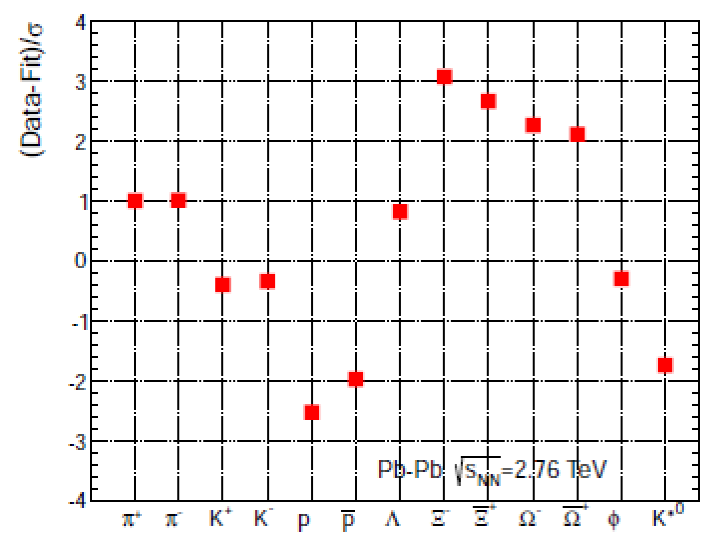


Au-Au 130 GeV





Au-Au 200 GeV



Pb-Pb 2.76 TeV
incl. protons

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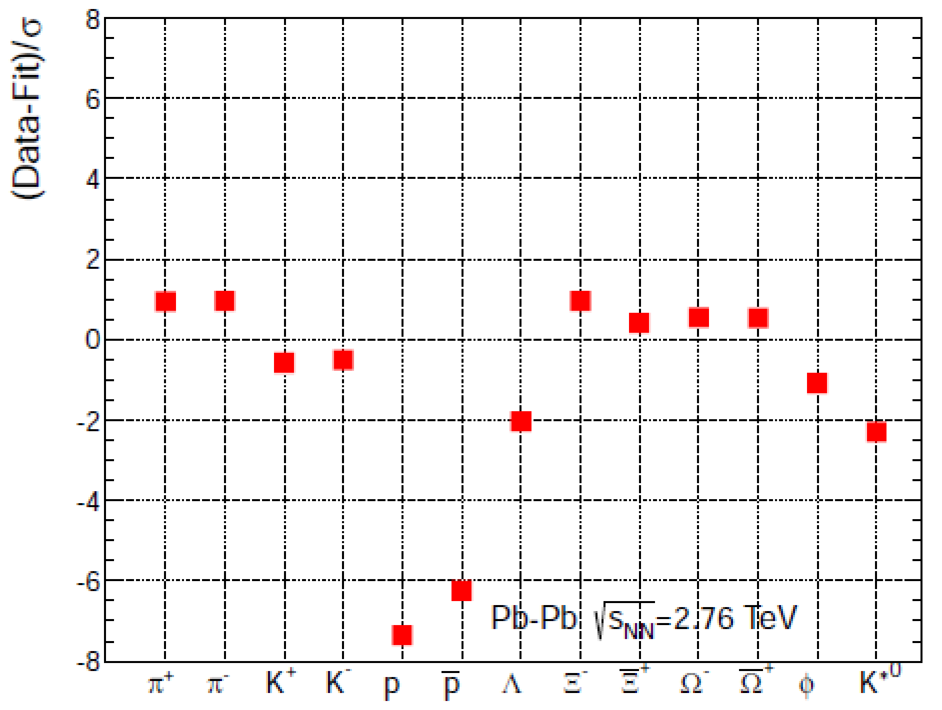
analyzing the deviations – LHC energy

Pb-Pb 2.76 TeV
fit without protons



protons are 6 sigma off, but note 6 % overall error, about a factor 2.5 smaller than all previous measurements

could it be weak decays from charm?

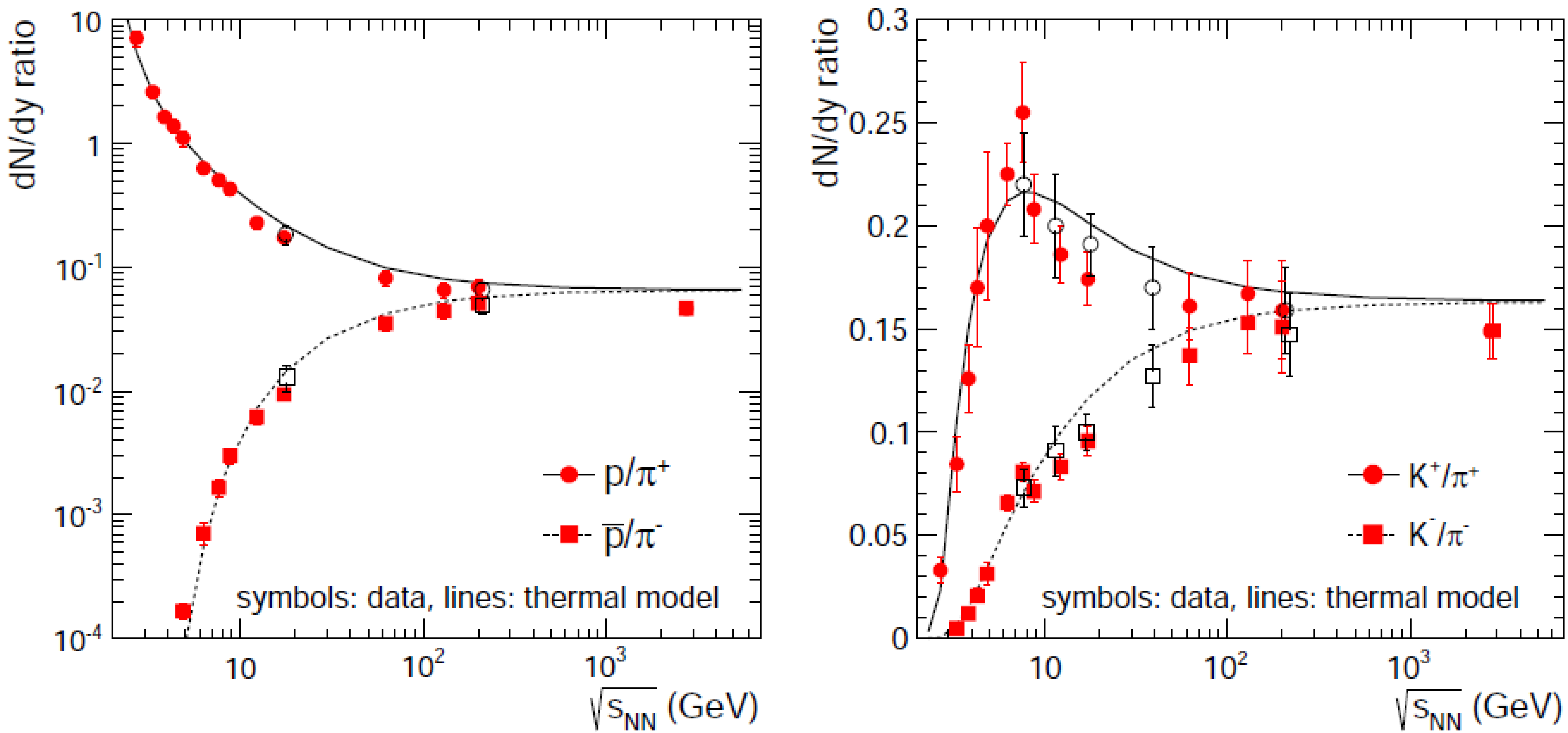
weak decays from charmed hadrons are included in the ALICE data sample

at LHC energy, cross sections for charm hadrons is increased by more than an order of magnitude compared to RHC

first results including charm and beauty hadrons indicate changes of less than 3%, mostly for kaons

not likely an explanation

overall systematics, including ALICE data, on proton/pion and kaon/pion ratios



Summary, light flavors (i)

- with more precision data, differences to thermal model 'predictions begin to appear, especially for protons and hyperons. Note that data precision at LHC is about 6% including systematic and statistical errors.

- at RHIC energies, differences of data for different experiments are of the order of the observed deviations, fits including weak decay corrections yield T close to 160 MeV and good chi2

- all thermal model fits at RHIC energies closely follow the systematics established previously

- fits to ALICE data are poor and yield anomalously low T (152 MeV)

- fits to ALICE data excluding protons are excellent and yield T ≈164 MeV

Summary, light flavors (ii)

- one scenario: flavor chemistry of QGP matter at LHC is established close to T_c as at RHIC but protons and anti-protons are anomalous

- maybe result of annihilation in hadronic phase close to T_c

- modelling annihilation in hadronic phase needs detailed balance (Rapp and Shuryak, Phys.Rev.Lett. 86 (2001) 2980-2983)

- what is the role of the 'quasi-mixed phase' and the asymmetry between protons and hyperons?

- what is the role of the 2x longer QGP lifetime at LHC energy compared to that at RHIC?

- simultaneous description of protons and all hyperons is required to settle the issue - **a challenge to theory**

On to hadrons with heavy quarks

specifically, charmonium

can charmonium production be understood in the framwork of the statistical hadronization model?

Charmonium (re)generation models

- statistical hadronization model

  original proposal: pbm, J. Stachel, Phys. Lett. B490 (2000) 196

  assumptions:

  - all charm quarks are produced in hard collisions, N_c const. in QGP
  - all charmonia are dissolved in QGP or not produced before QGP
  - charmonium production takes place at the phase boundary with statistical weights

    $\rightarrow$ yield ~ N_c^2 -- quarkonium enhancement at high energies

    -- no feeding from higher charmonia

- charm quark coalescence model

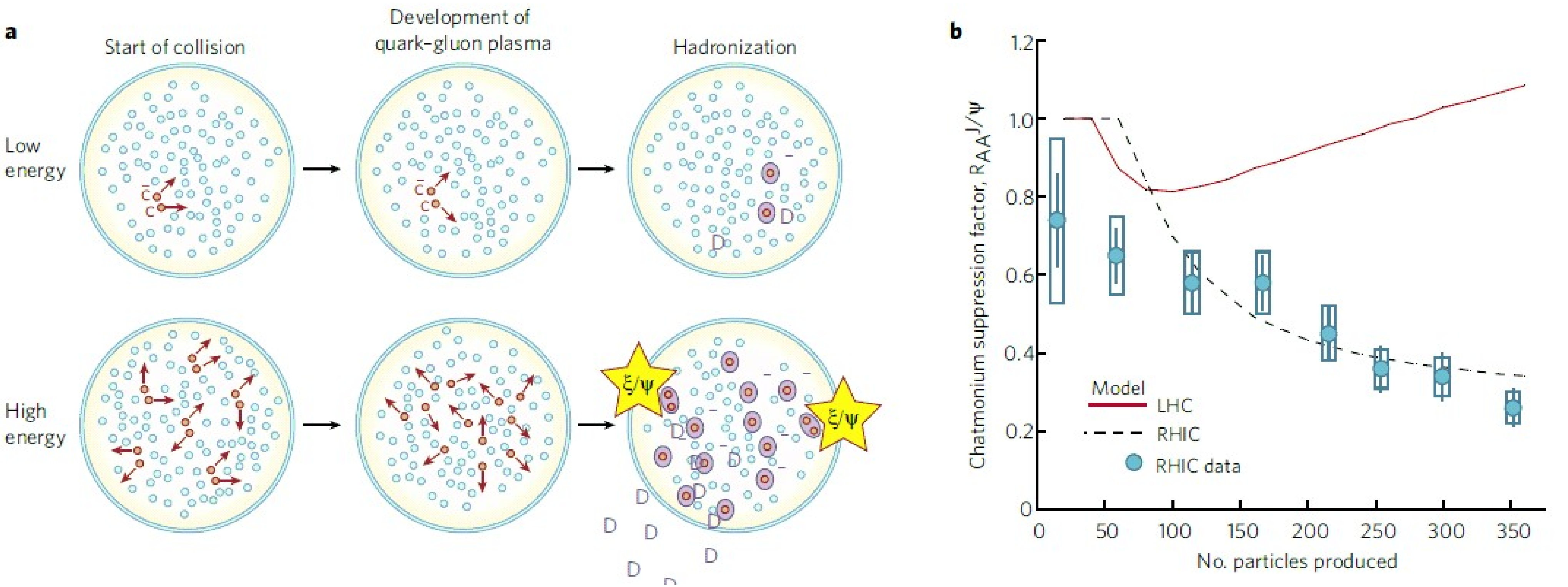
  original proposal: R.L. Thews, M. Schroedter, J. Rafelski, Phys. Rev. C63 (2001) 054905

  assumptions:

  - all charm quarks are produced in hard collisions
  - all charmonia are produced in the QGP via charm quark recombination

    $\rightarrow$ yield ~ N_c^2 -- quarkonium enhancement at high energies

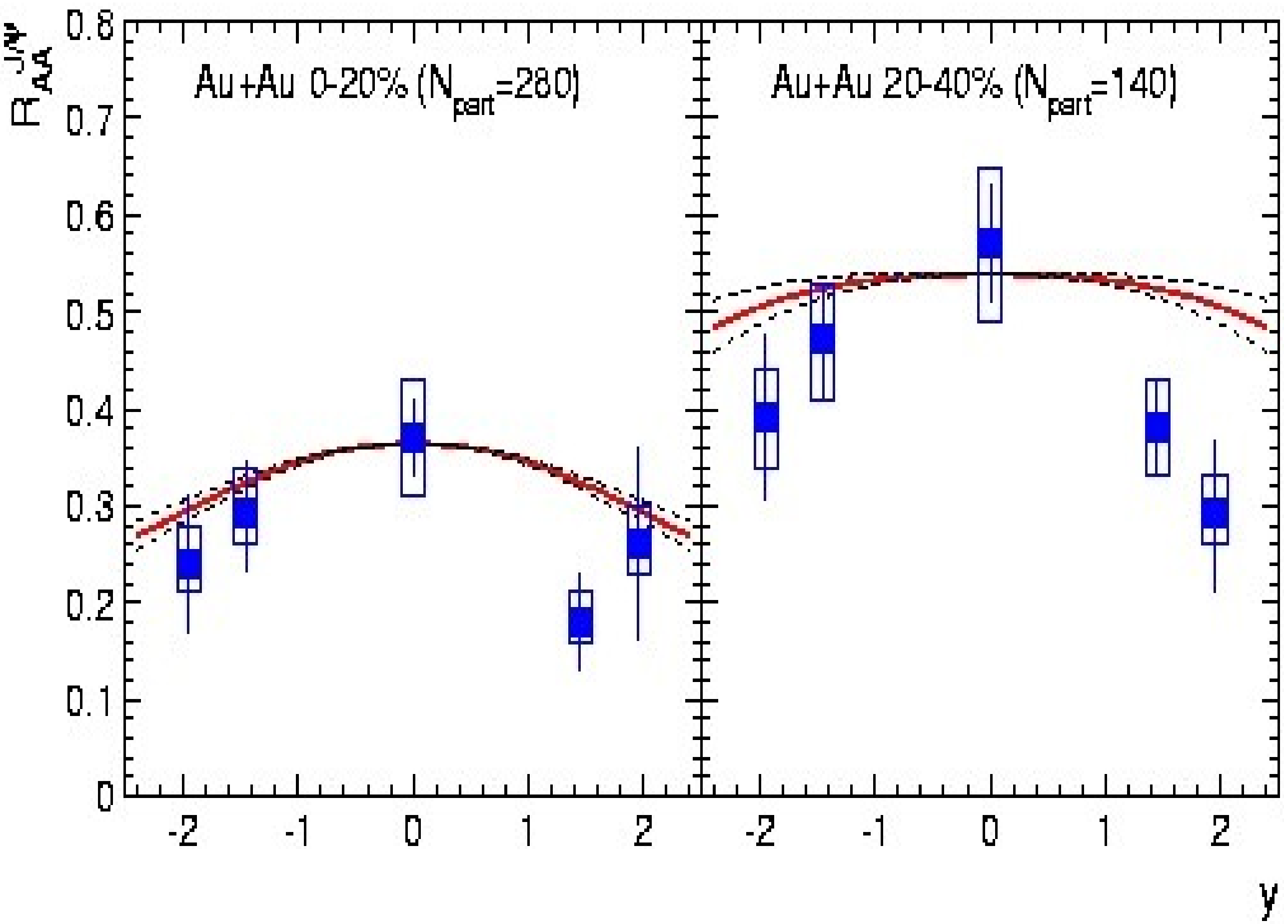
Quarkonium as a probe for deconfinement at the LHC



charmonium enhancement as fingerprint of deconfinement at LHC energy

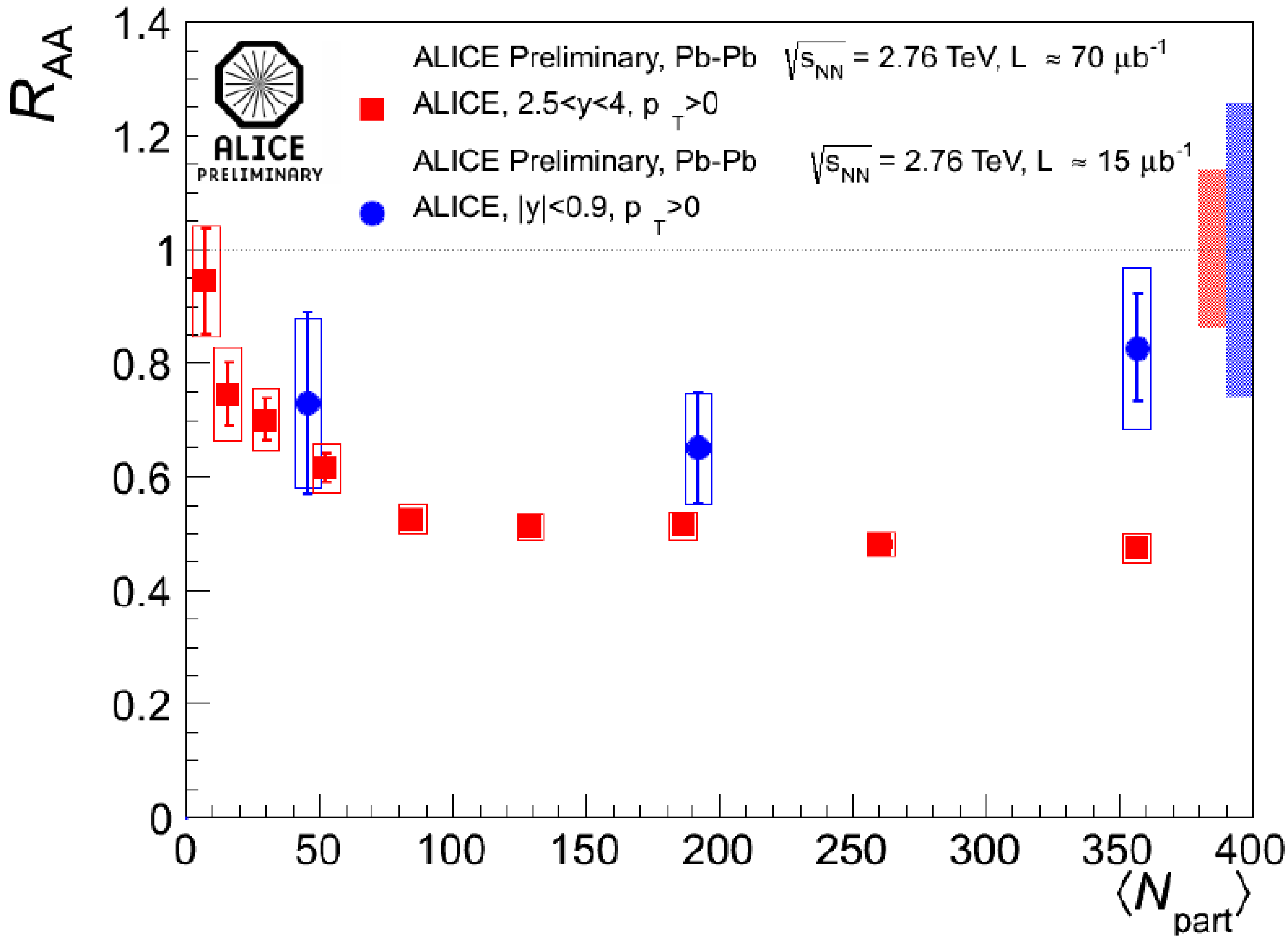
pbm, J. Stachel
Nature 448 (2007) 302-309

Comparison of model predictions to RHIC data: rapidity dependence



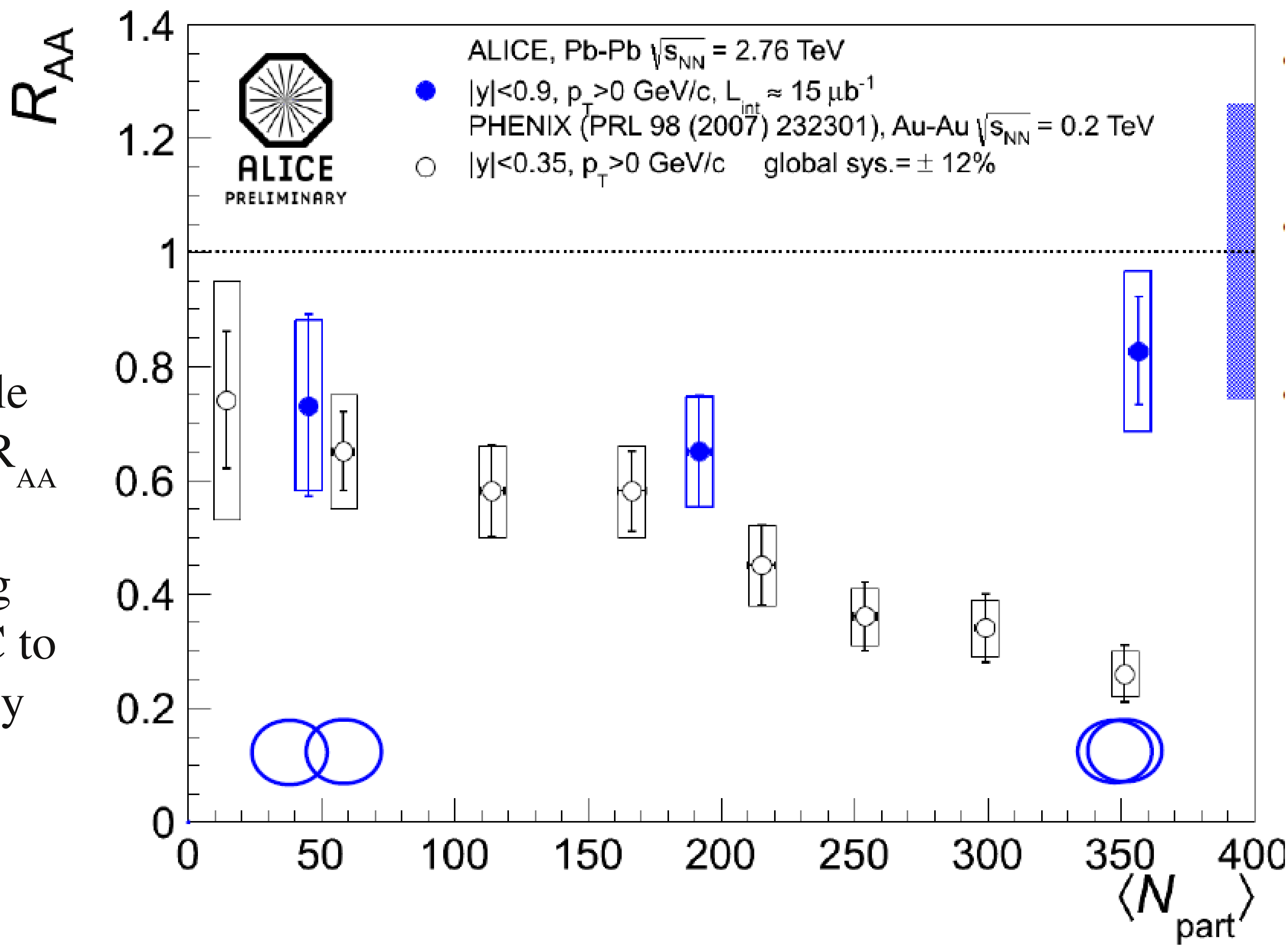
suppression is smallest at mid-rapidity (90 deg. emission)
a clear indication for regeneration at the phase boundary

newest ALICE data at central and forward rapidity

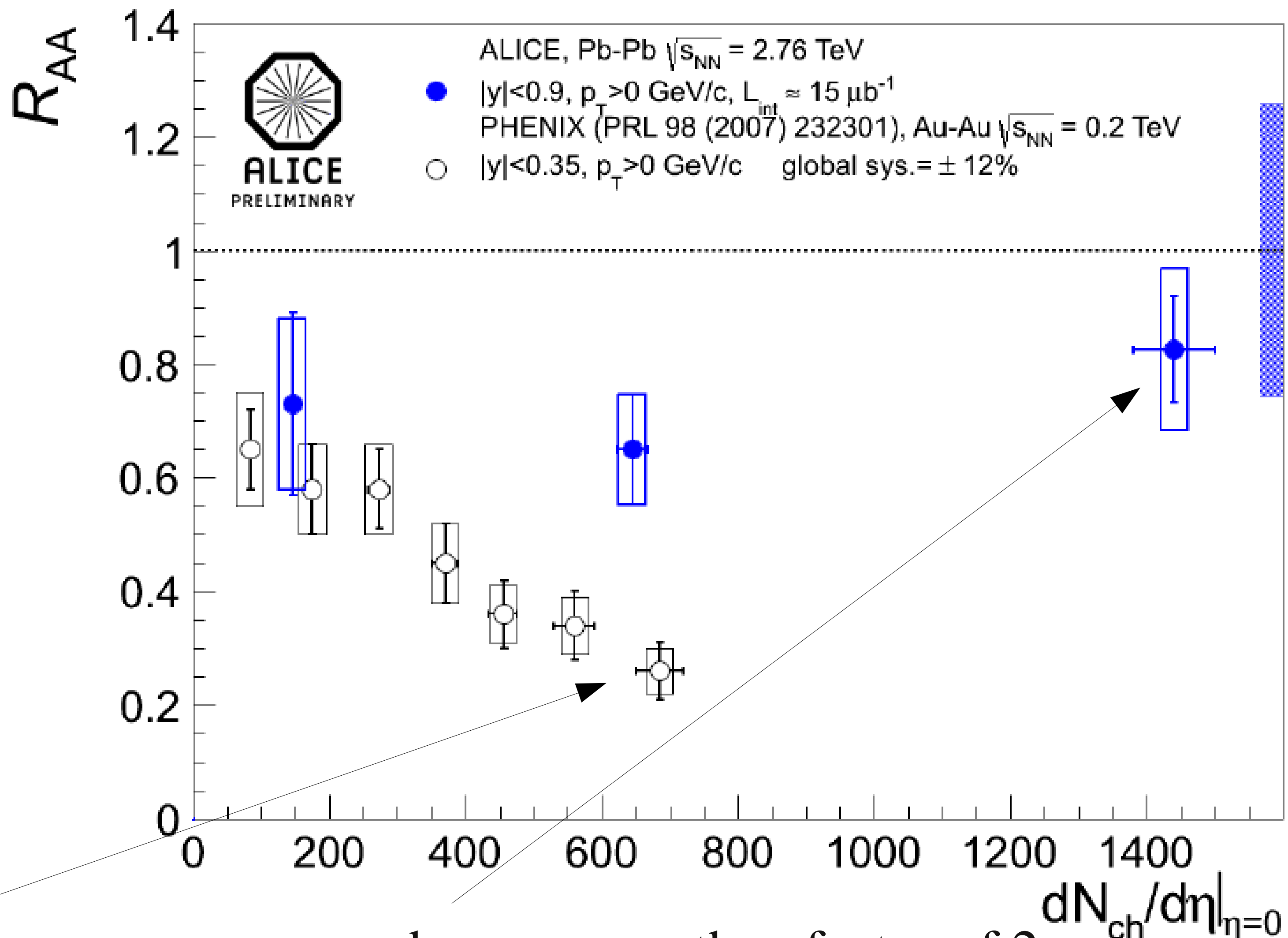


Comparison to PHENIX data

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

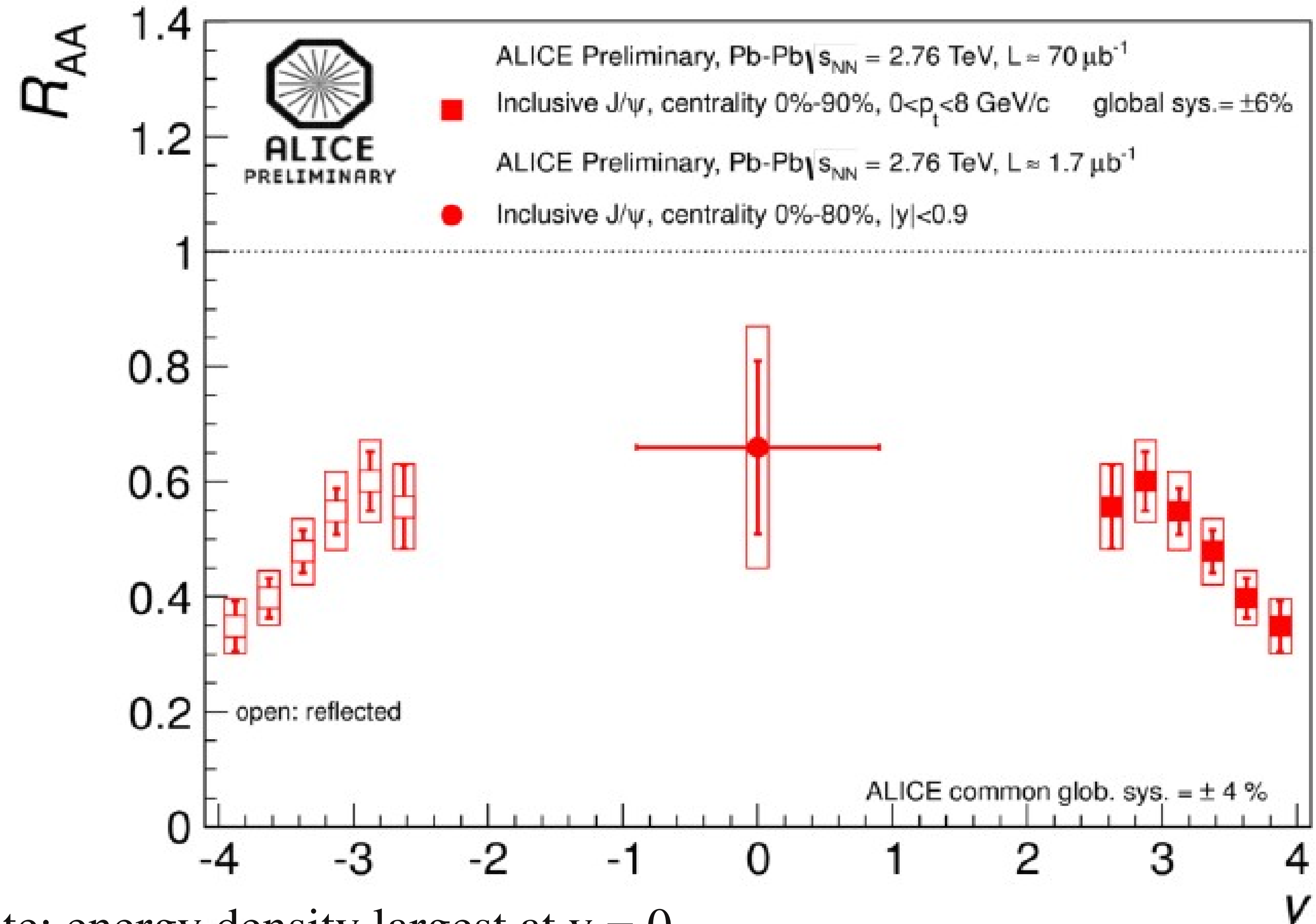


less suppression when increasing the energy density



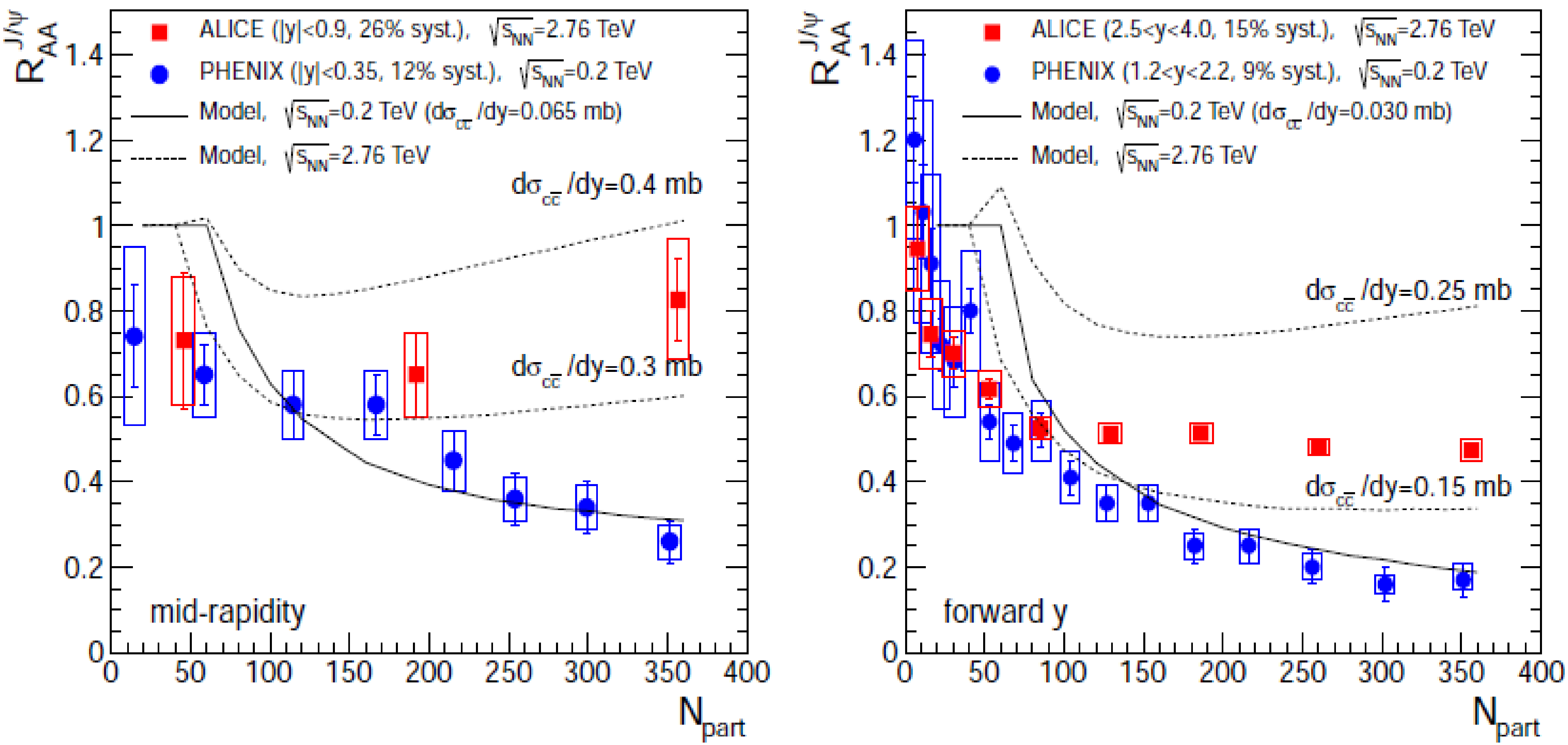
from here to here more than factor of 2 increase in energy density, but R_{AA} increases by more than a factor of 3

Rapidity dependence



note: energy density largest at y = 0

statistical hadronization model

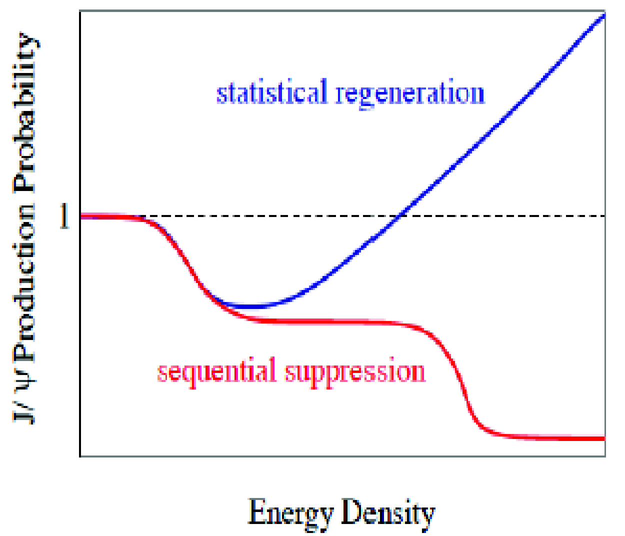


ALICE data and evolution from RHIC to LHC energy described quantitatively

Summary

- charmonium production – a fingerprint for deconfined quarks and gluons

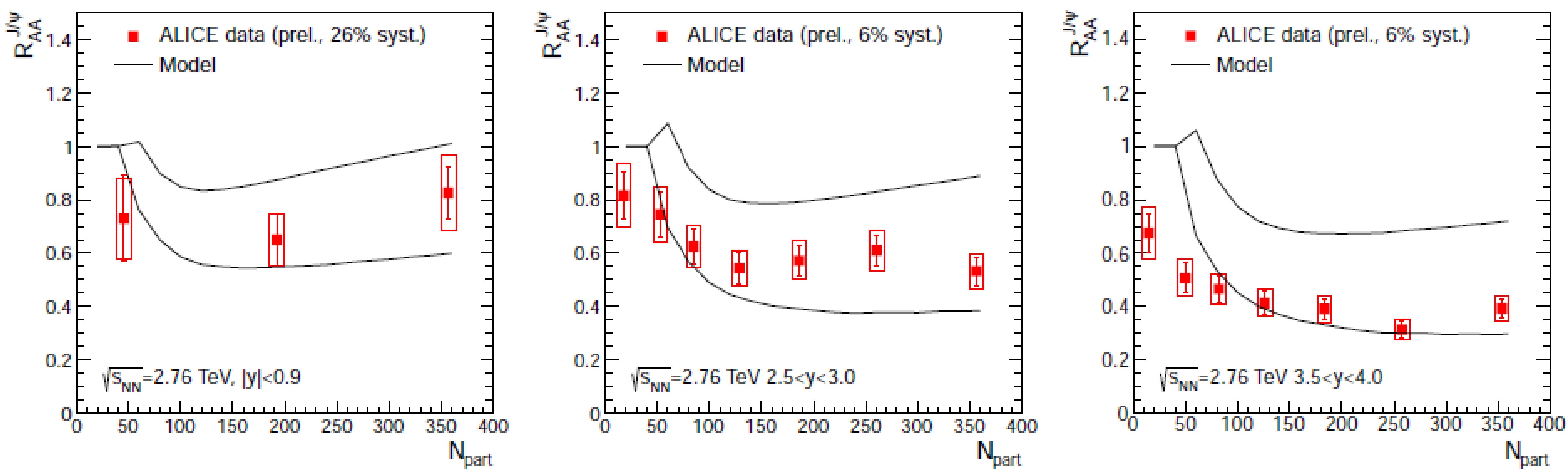
- evidence for energy loss and flow of charm quarks --> thermalization
- charmonium generation at the phase boundary – a new process
- first indications for this from psi'/(J/psi) SPS and J/psi RHIC data
- evolution from RHIC to LHC described quantitatively
- charmonium enhancement at LHC – deconfined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



cartoon Helmut Satz, 2009 SPS RHIC LHC

back-up

Rapidity dependence of J/psi in statistical hadronization model



Thermal model description of hadron yields

HELMHOLTZ GEMEINSCHAFT

Grand Canonical Ensemble

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

$$n_i = N/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 \, dp}{\exp((E_i - \mu_i)/T) \pm 1}$$

$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_i^3$$

for every conserved quantum number there is a chemical potential μ
but can use conservation laws to constrain:

- Baryon number: $V \sum_i n_i B_i = Z + N \quad \rightarrow V$
- Strangeness: $V \sum_i n_i S_i = 0 \quad \rightarrow \mu_S$
- Charge: $V \sum_i n_i I_i^3 = \frac{Z - N}{2} \quad \rightarrow \mu_{I_3}$

This leaves only μ_b and T as free parameter when 4π considered

for rapidity slice fix volume e.g. by dN_{ch}/dy

Fit at each energy provides values for T and μ_b and volume V when fitting yields

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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

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