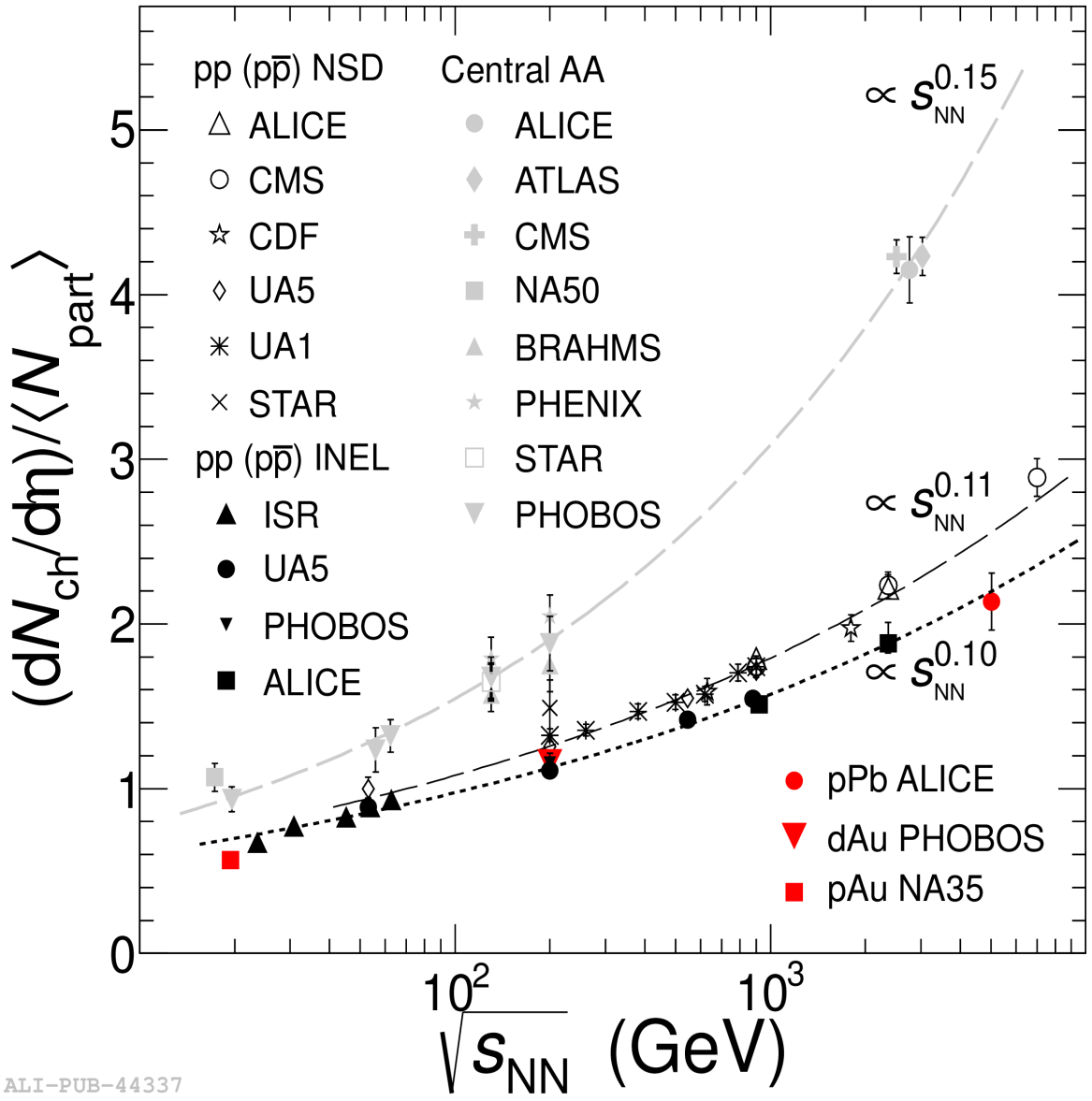
Heavy quark and quarkonium production from fixed target to collider energies

- Energy dependence of (u,d,s) hadron production and phase boundary
- The charmonium story – equilibration and statistical hadronization at the phase boundary
- RHIC and newest LHC – ALICE results
- Charmonia – probes for deconfinement and color screening at collider energies
- Issues at lower energies

FIAS-Frankfurt

EMMI workshop
Feb. 15, 2013

Charged particle multiplicity in pp, pPb and central PbPb collisions



increase with beam energy significantly steeper than in pp

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

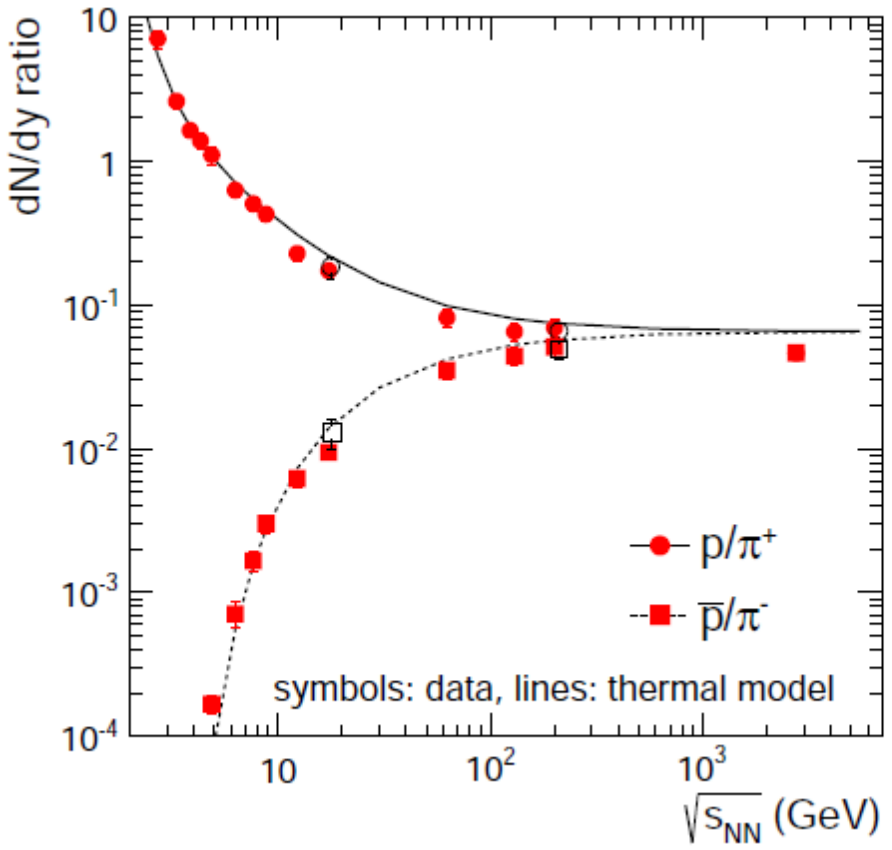
- Present understanding: multi-hadron collisions near phase boundary bring hadrons close to equilibrium – supported by success of statistical model analysis pbm, Stachel, Wetterich, Phys.Lett. B596 (2004) 61-69

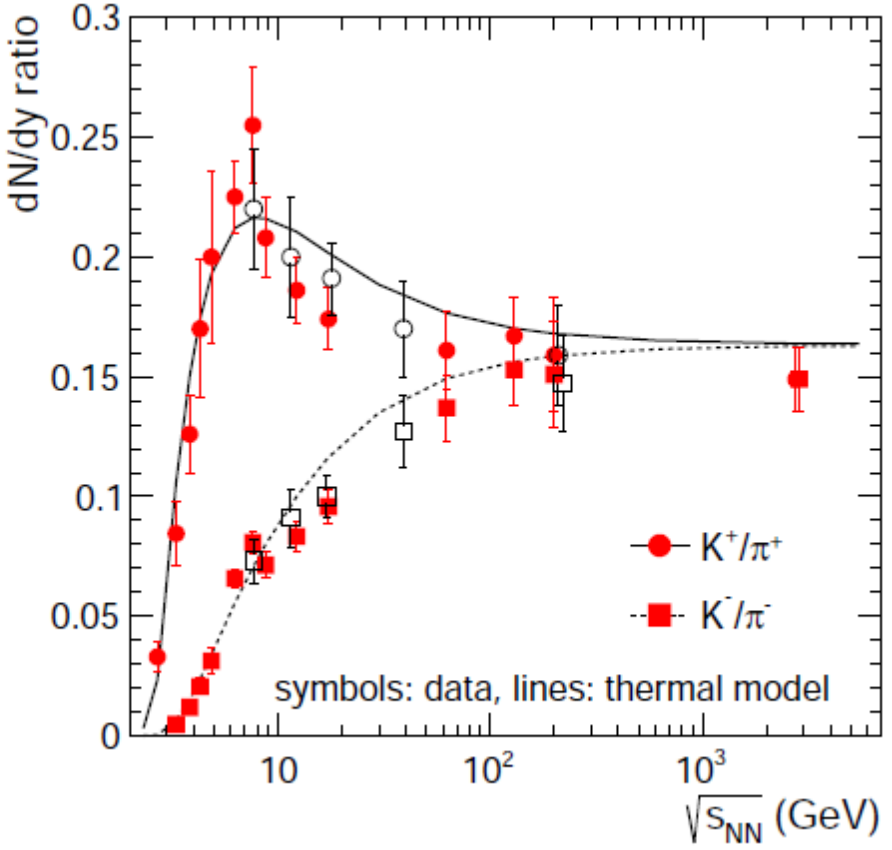
- This implies little energy dependence above RHIC energy

- Analysis of hadron production → determination of T_c

Is this picture also supported by LHC data?

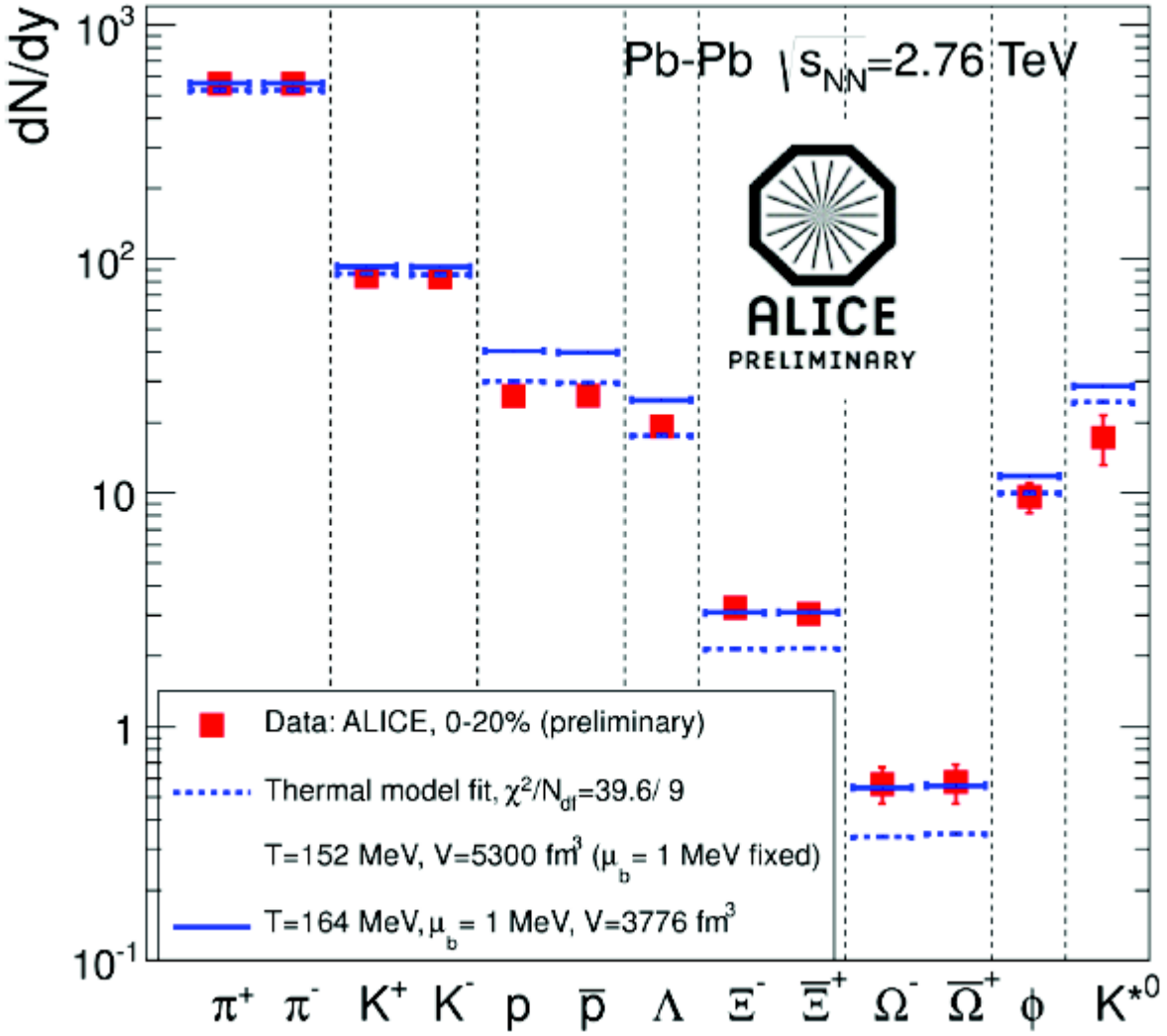
overall systematics, including ALICE data, on proton/pion and kaon/pion ratios





Identified particle yields at LHC energy

rather poor fit and lower temperature than expected

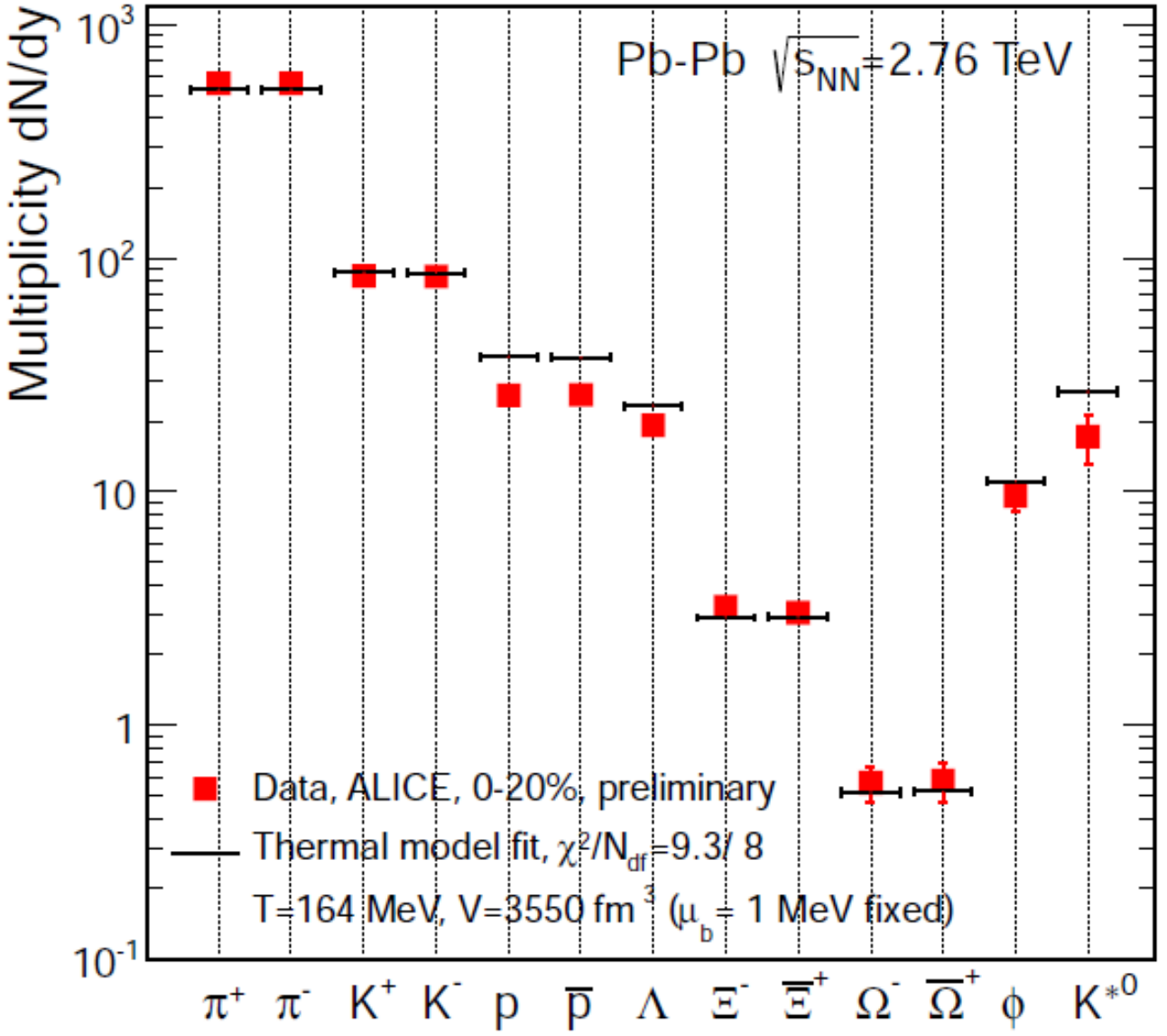


Thermal model analysis:
Andronic, pbm, Redlich, Stachel,
QM2012 arXiv:1210..7724

fitting the data without protons and antiprotons

good fit, T = 164 MeV

is there a proton anomaly?

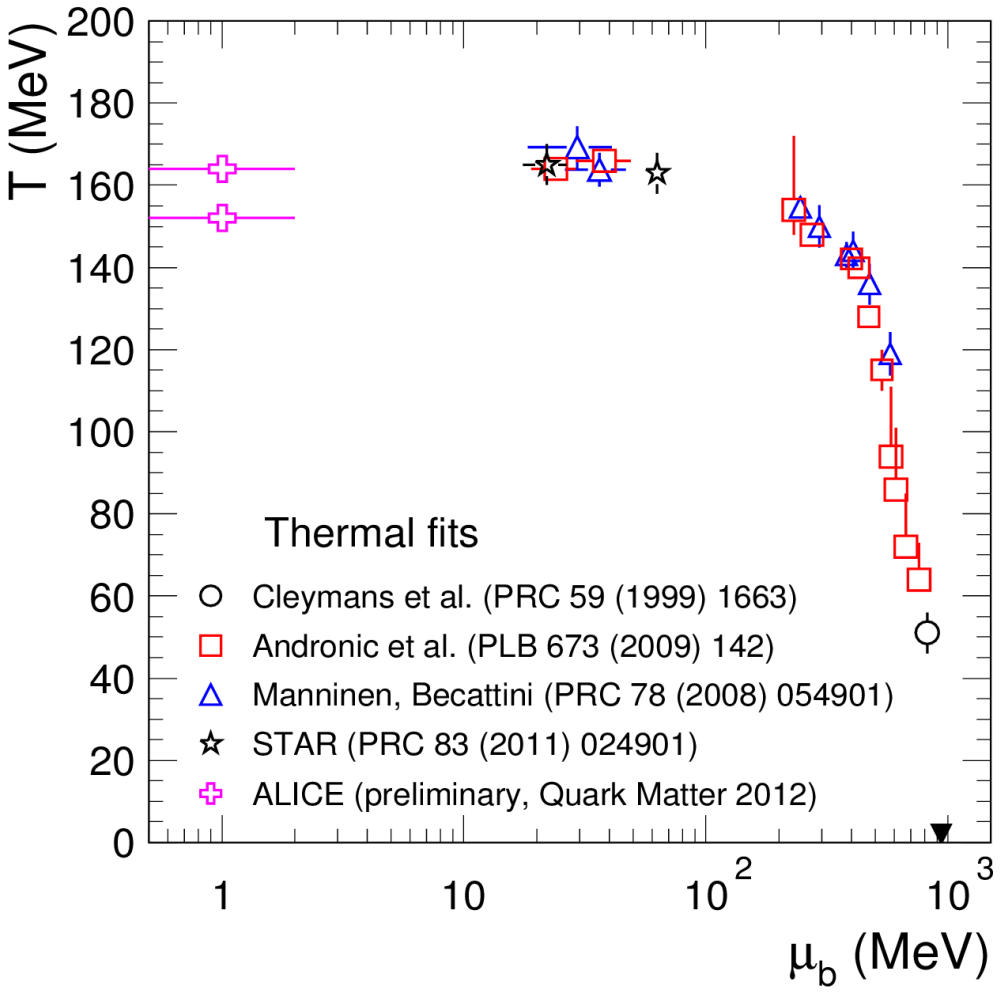


Parameterization of all freeze-out points inc. LHC data

note: establishment of limiting temperature

T_{lim} = 162 +/- 4 MeV

get T and μ_B for all energies



A. Andronic, pbm, J. Stachel, Nucl. Phys. A772 (2006) 167
Nucl-th/0511071
Andronic, pbm, Redlich, Stachel, arXiv:1210.7724

will charmed hadrons follow similar pattern?
since m_c >> T_c, expect only thermal, not chemical equilibration

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?
c) are charm quarks thermalized?

Only at LHC energy, clean separation of time scales

collision time << QGP formation time < charmonium formation time

J/psi production via statistical hadronization – production at the phase boundary from thermally equilibrated charm quarks

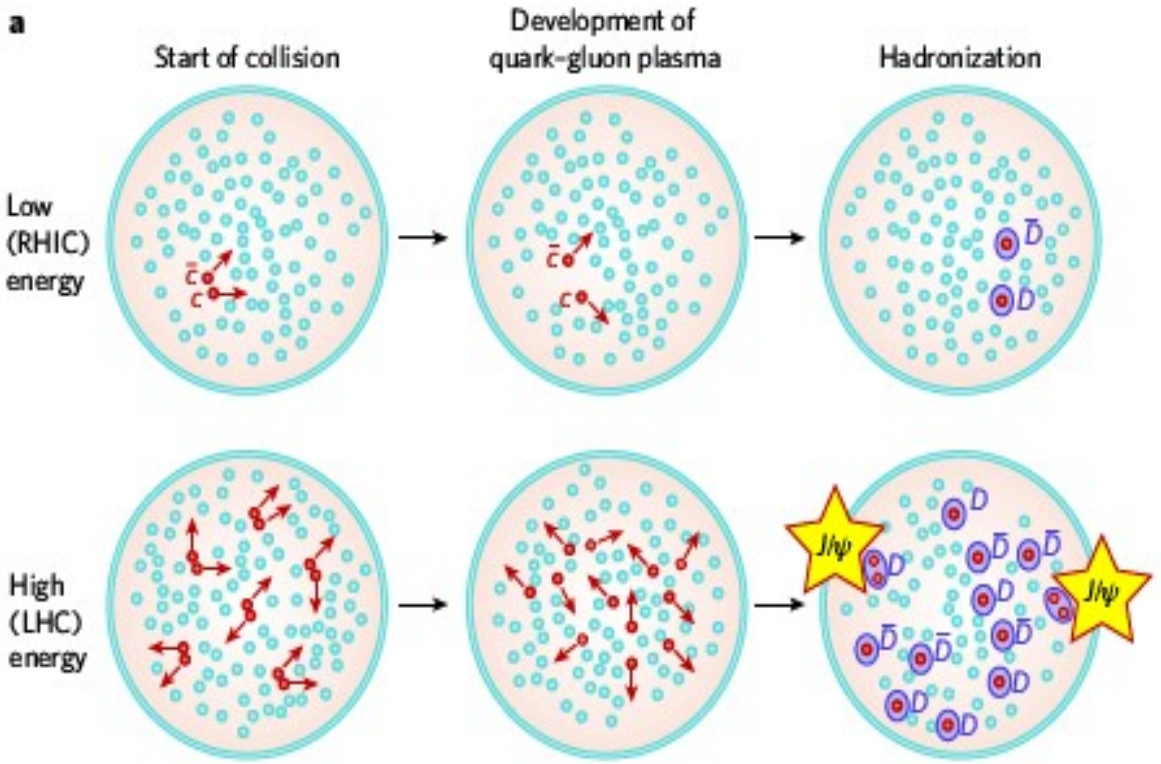
ingredients for prediction of quarkonium and open charm cross sections

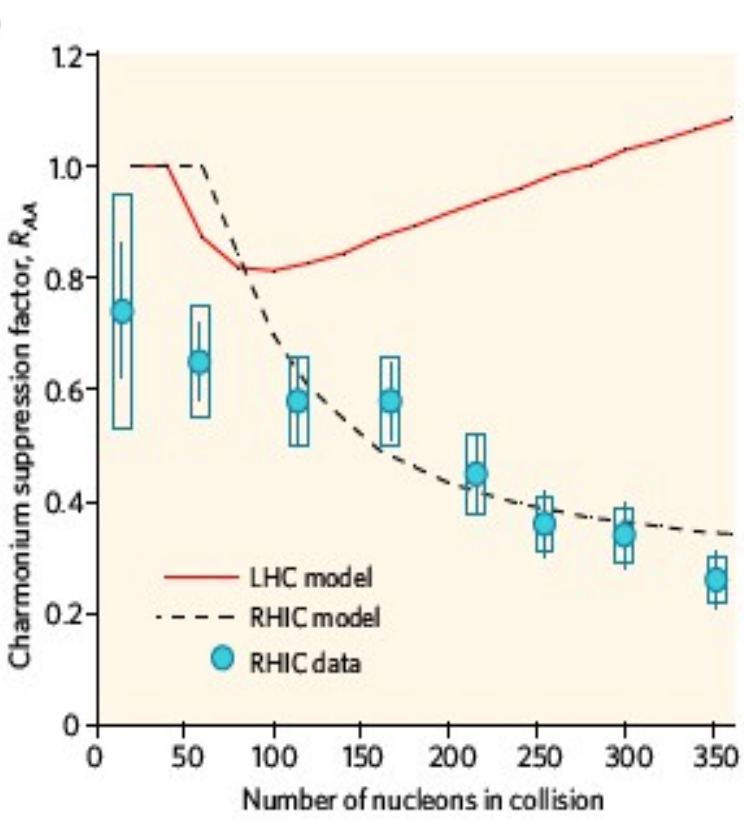
• energy dependence of temperature and baryo-chemical potential (from hadron production analysis)
• open charm (open bottom) cross section in pp or better AA collisions
• quarkonium production cross section in pp collisions (for corona part)

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

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.

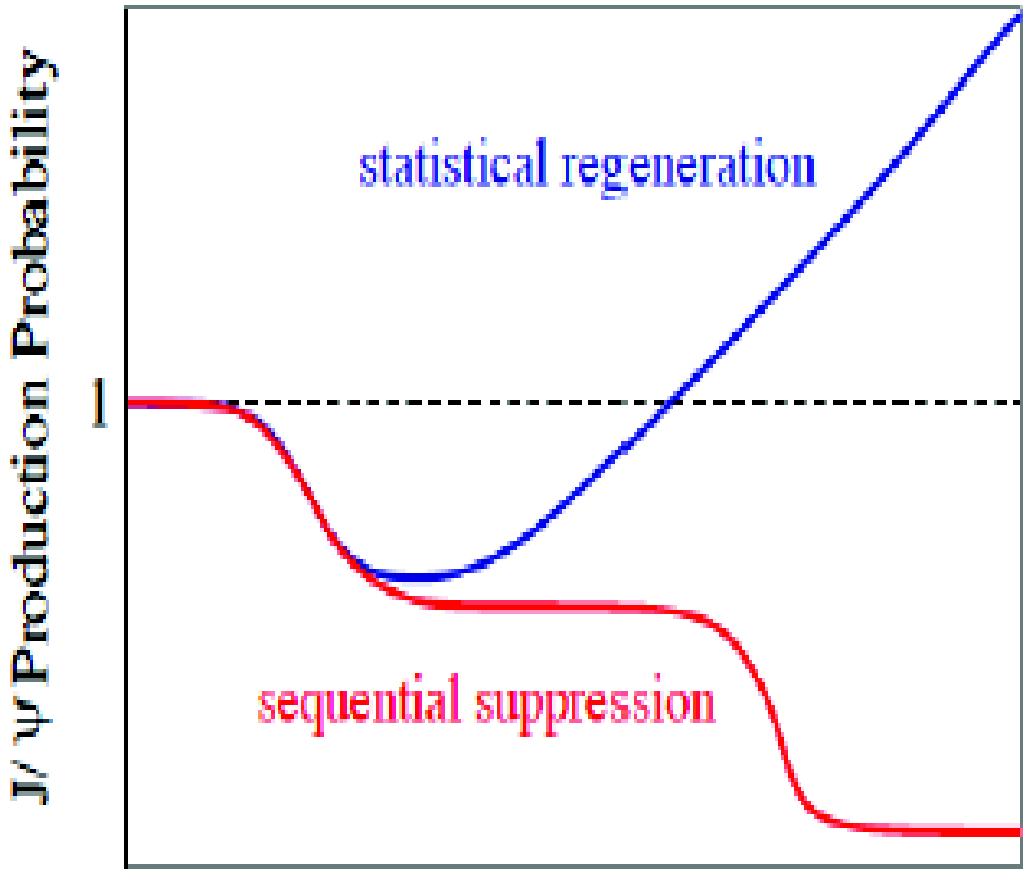




charmonium enhancement as fingerprint of color screening
and deconfinement at LHC energy

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

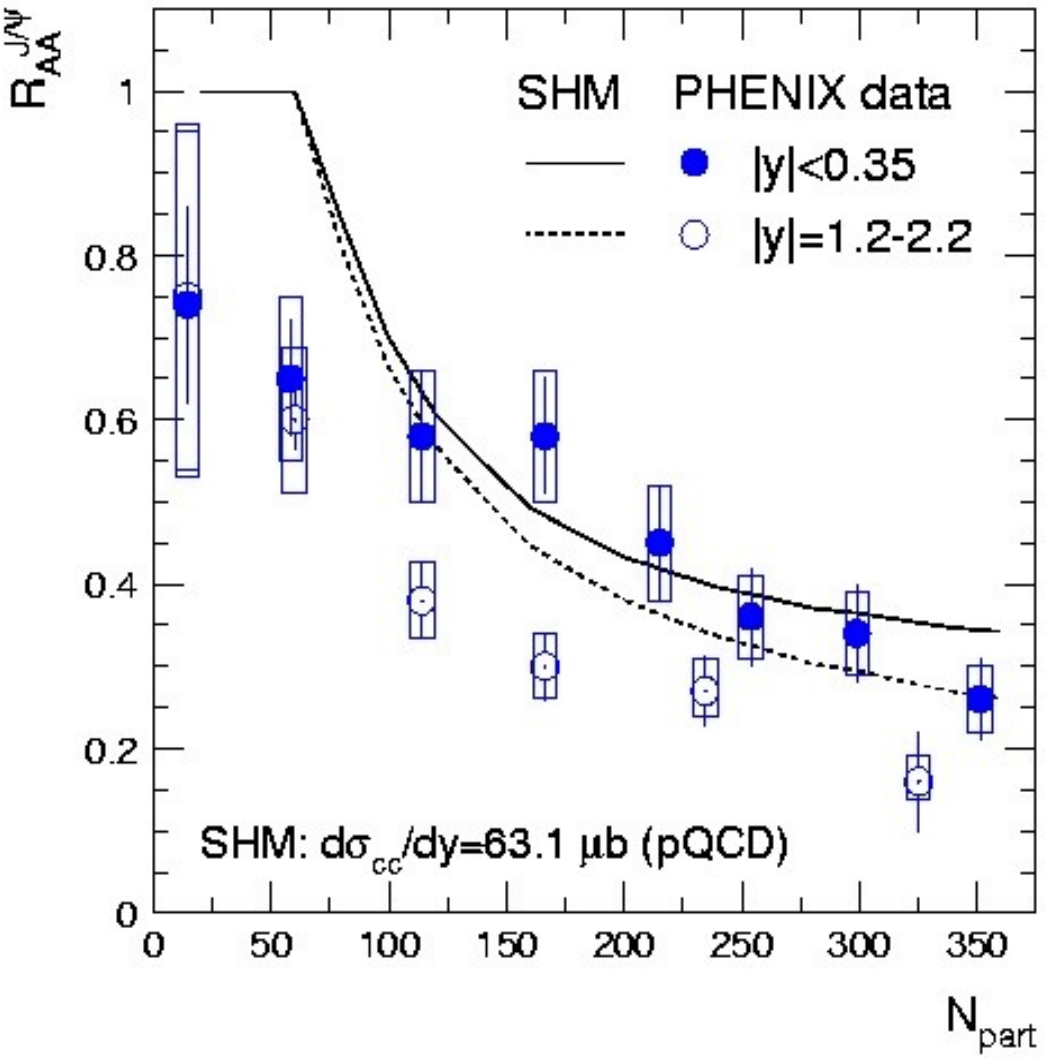
decision on regeneration vs sequential suppression from LHC data



Picture:
H. Satz 2009

Brief survey of RHIC results

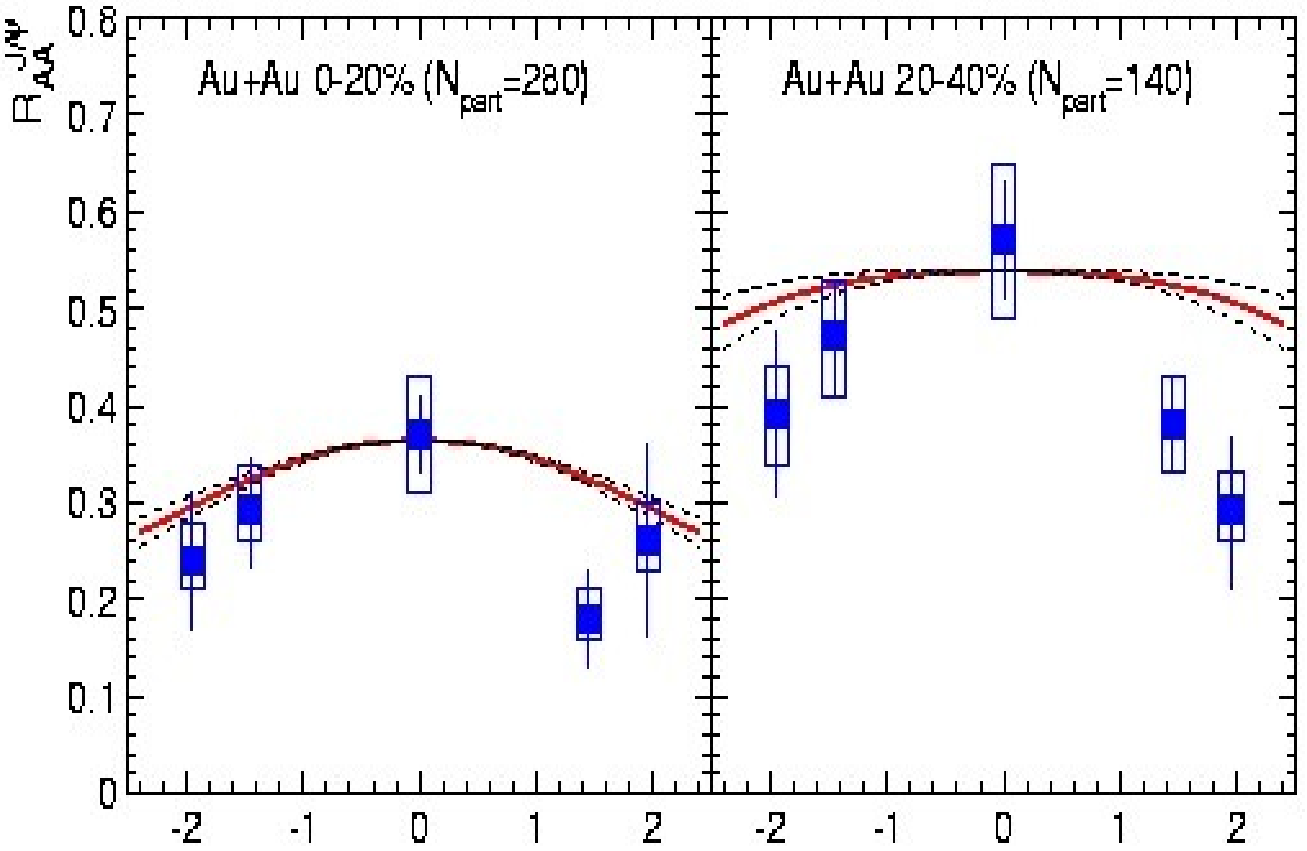
Centrality dependence of nuclear modification factor



data well described
by our regeneration model
without any new
parameters

calcs: Andronic, pbm,Redlich, Stachel
Phys. Lett. B562 (2007) 259l

Comparison of model predictions to RHIC data: rapidity dependence

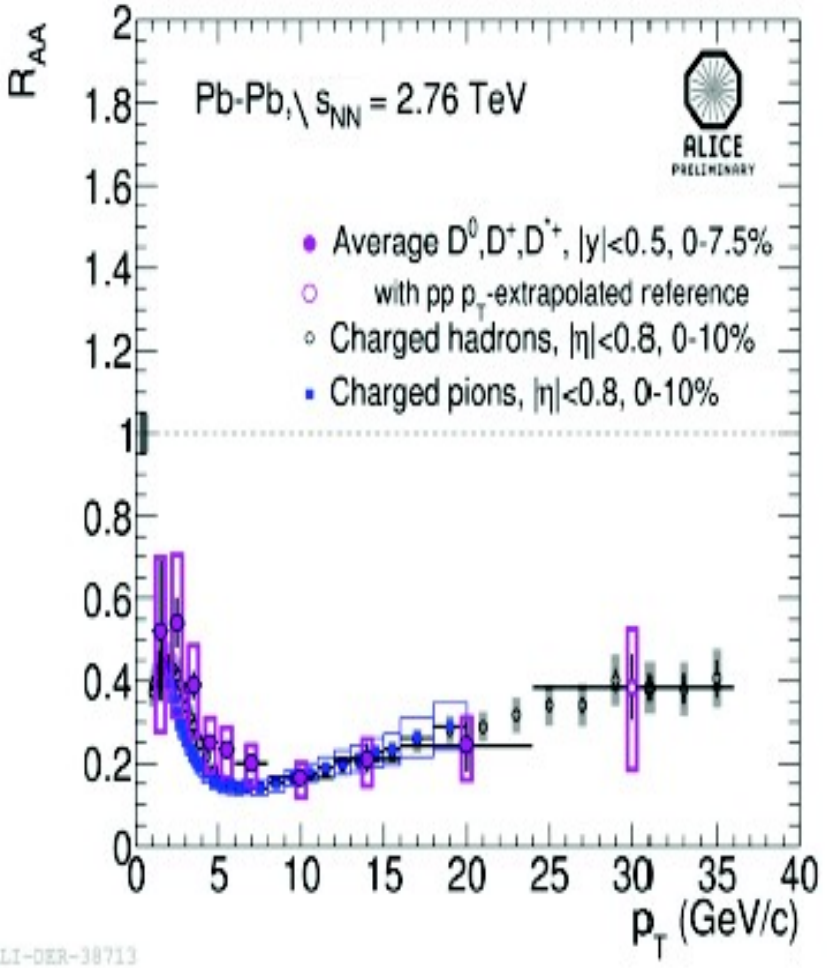


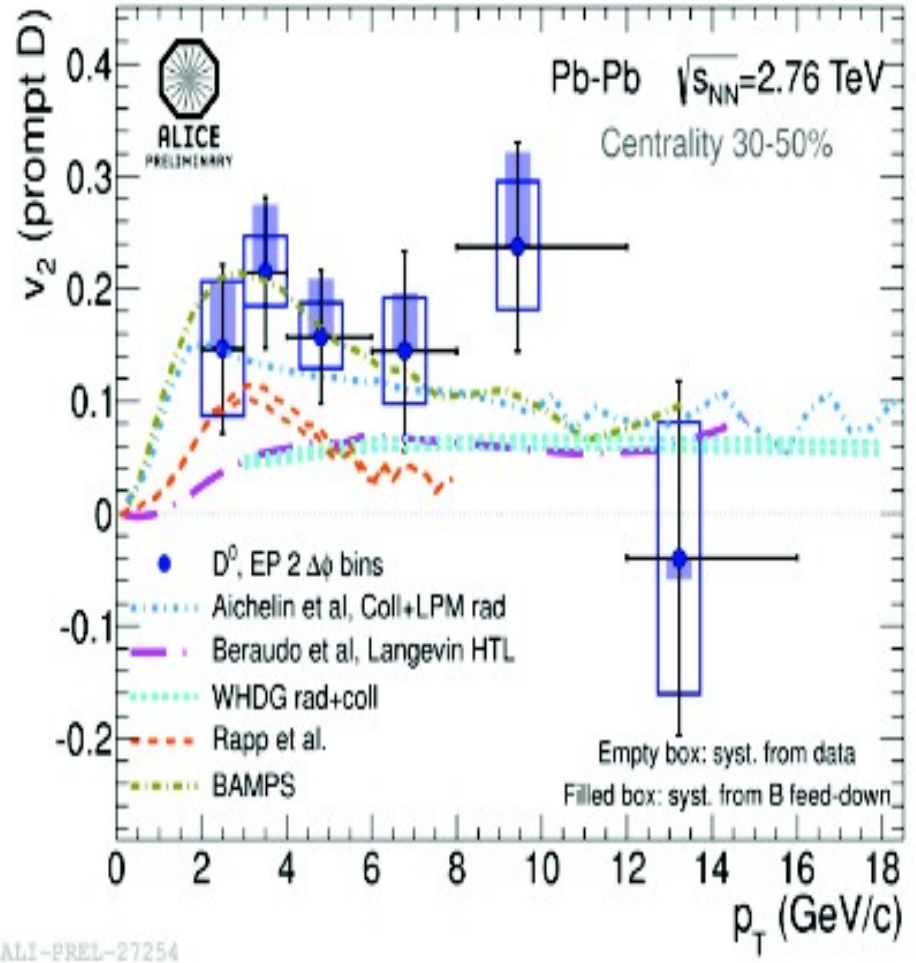
calcs: Andronic, pbm, Redlich, Stachel
Phys. Lett. B562 (2007) 259l

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

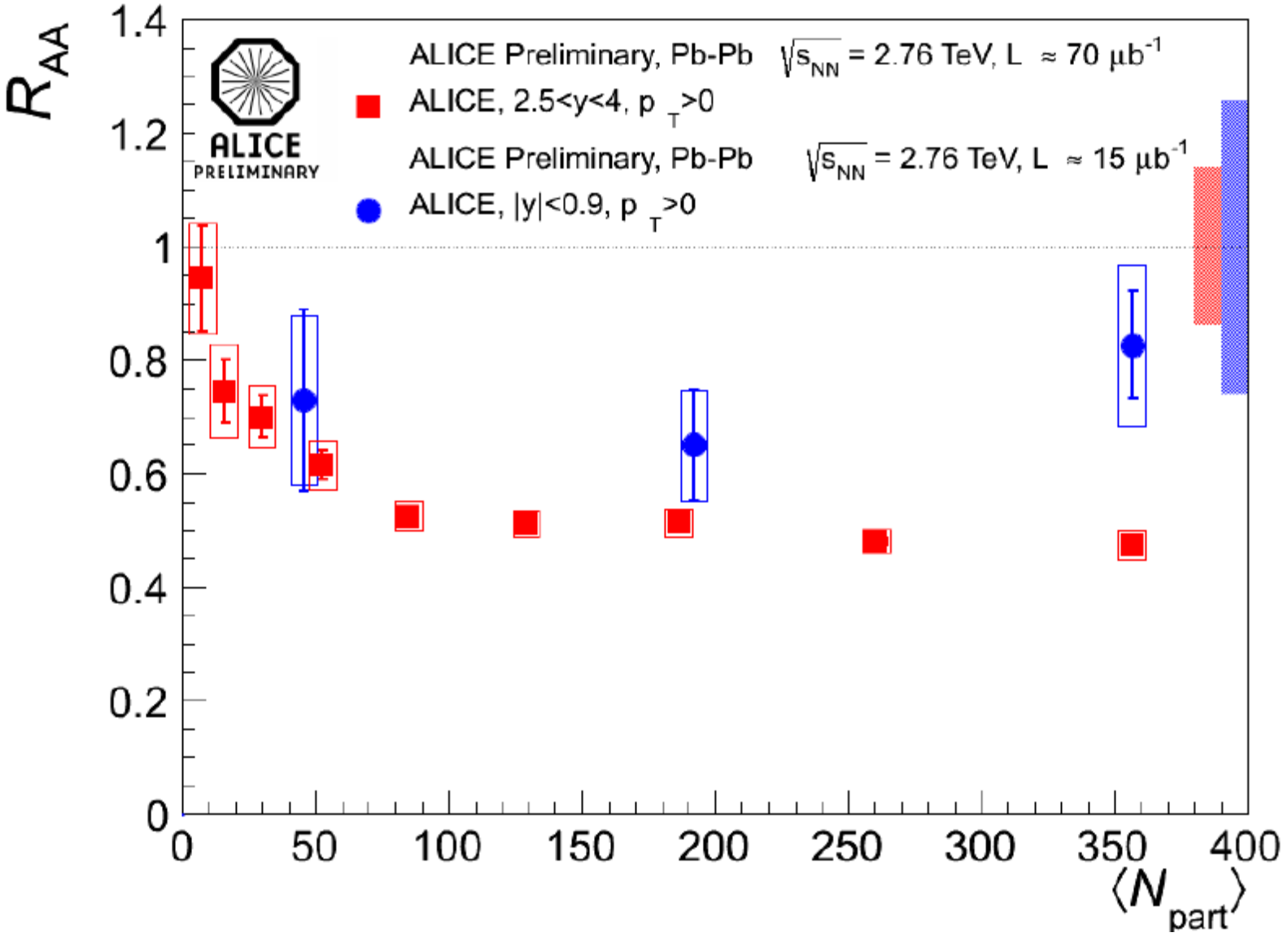
Status of LHC results

Thermalization of heavy quarks



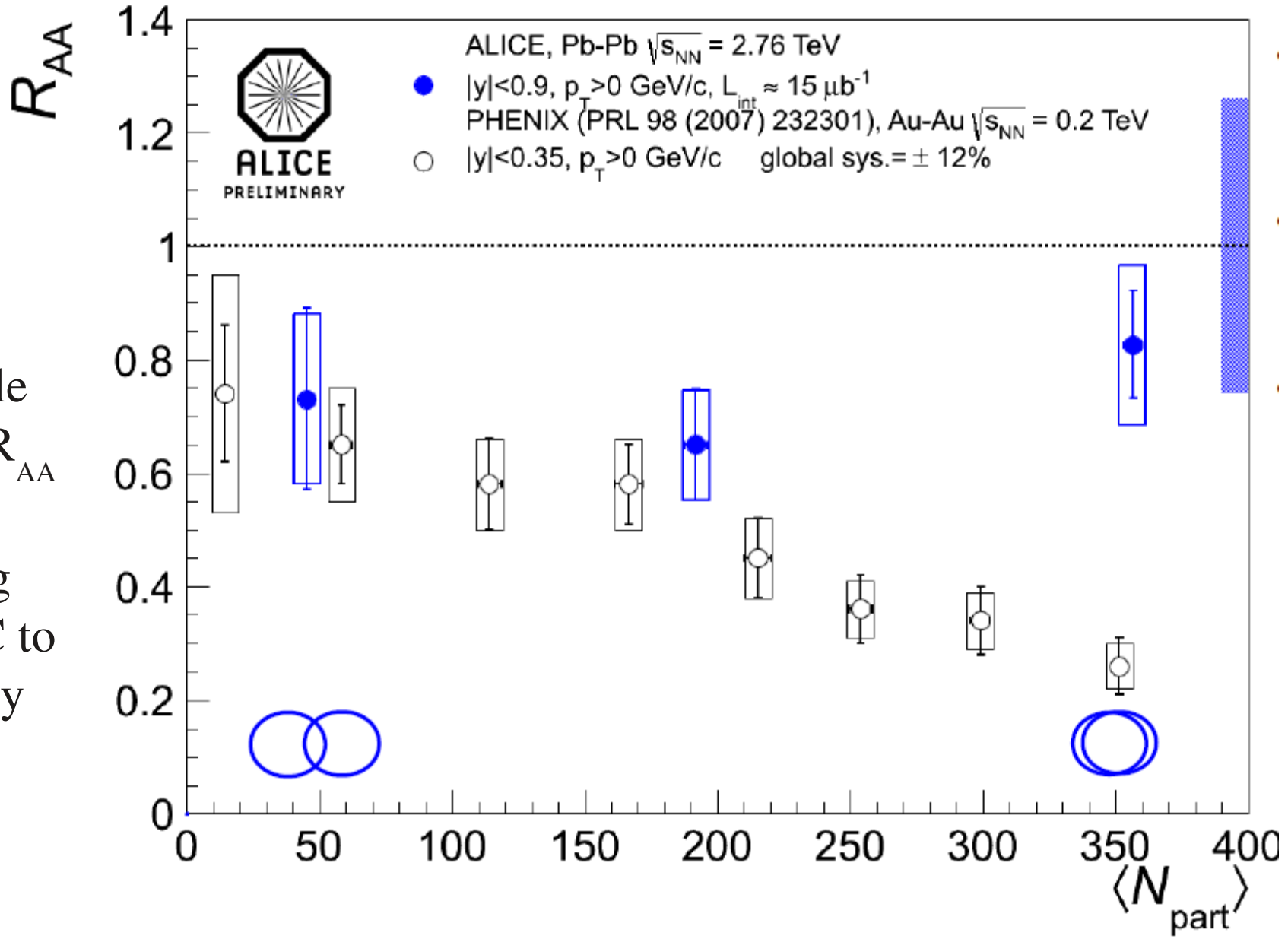


newest ALICE J/psi data at central and forward rapidity

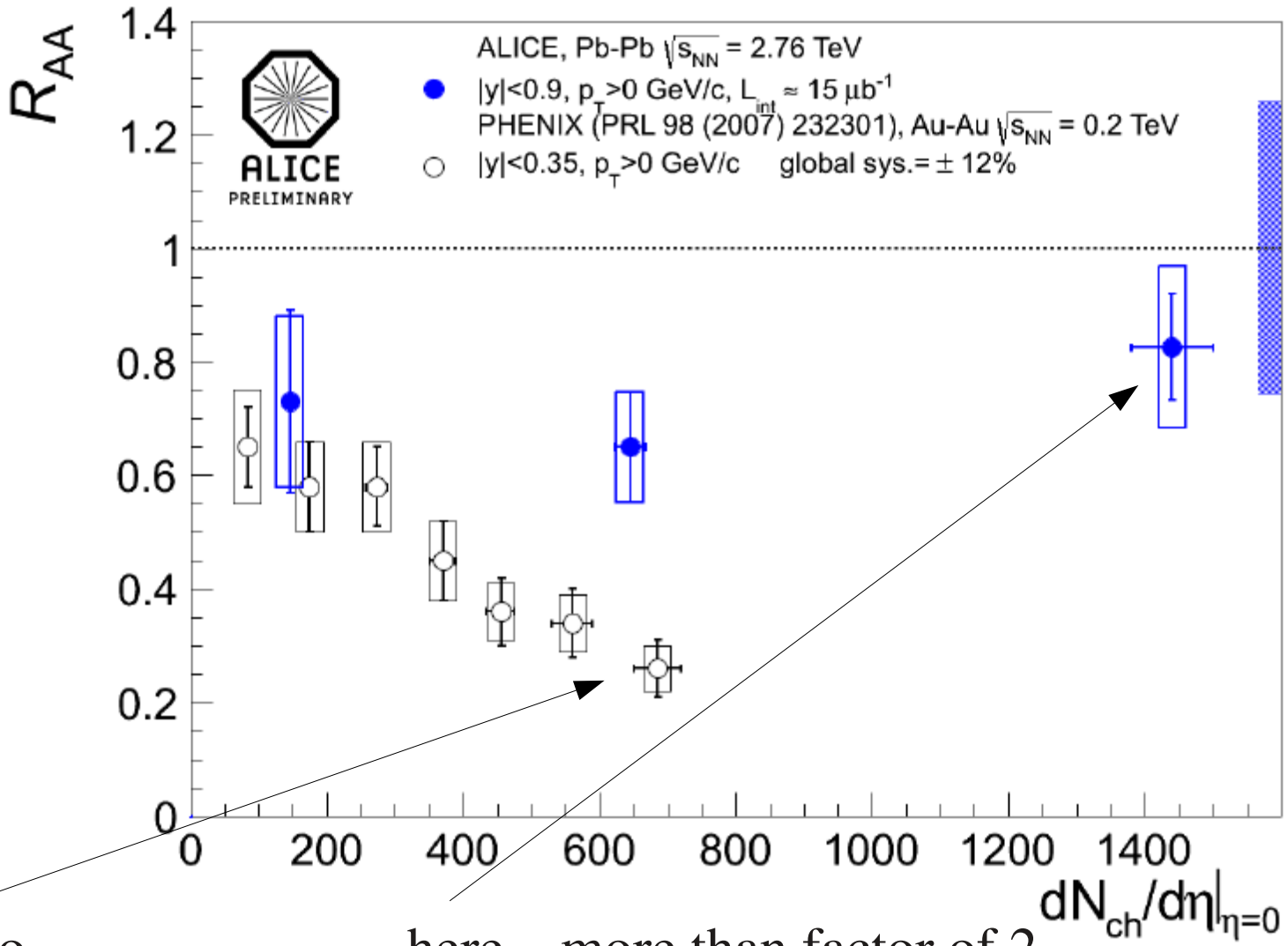


Comparison to PHENIX data

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

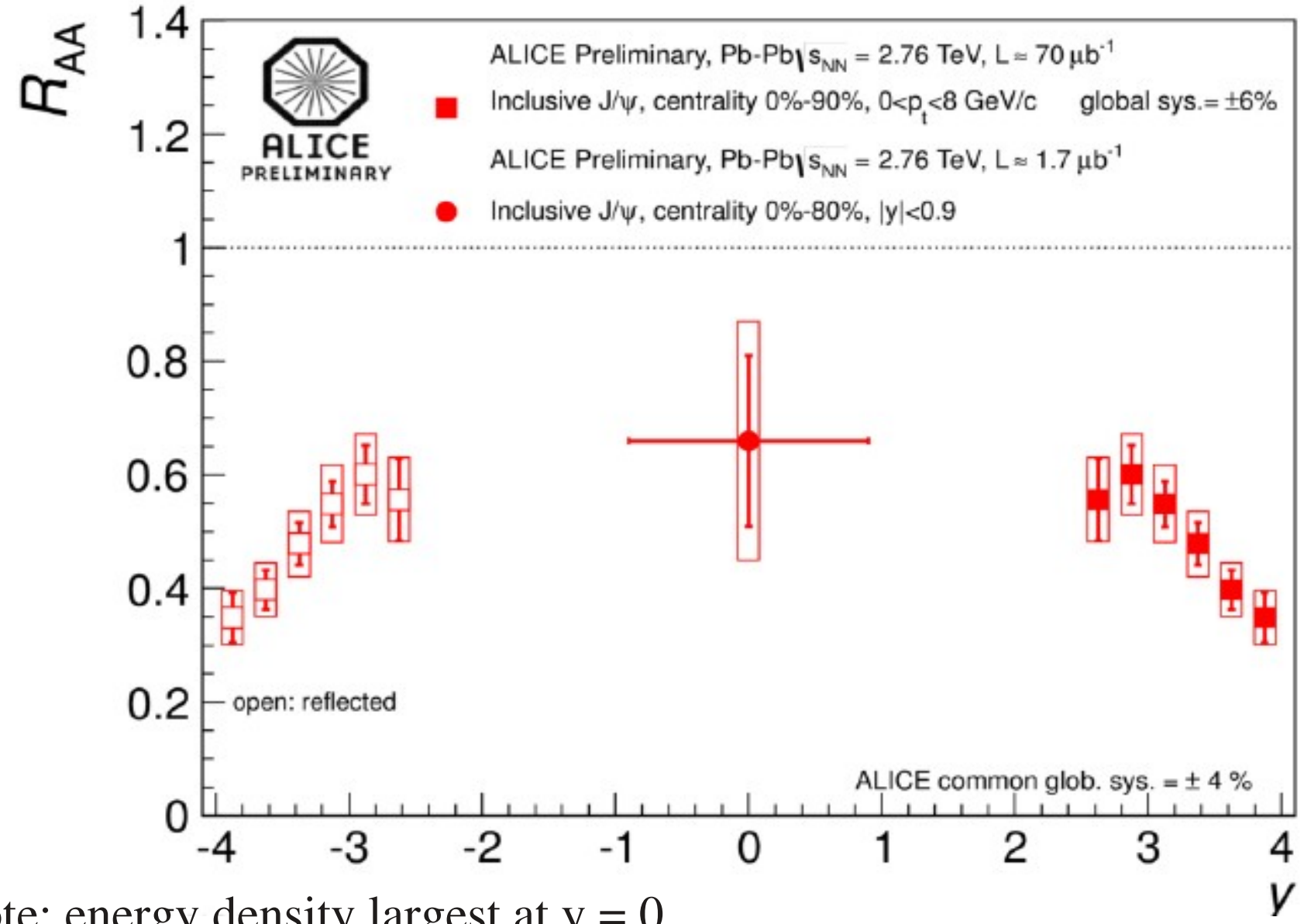


less suppression when increasing the energy density



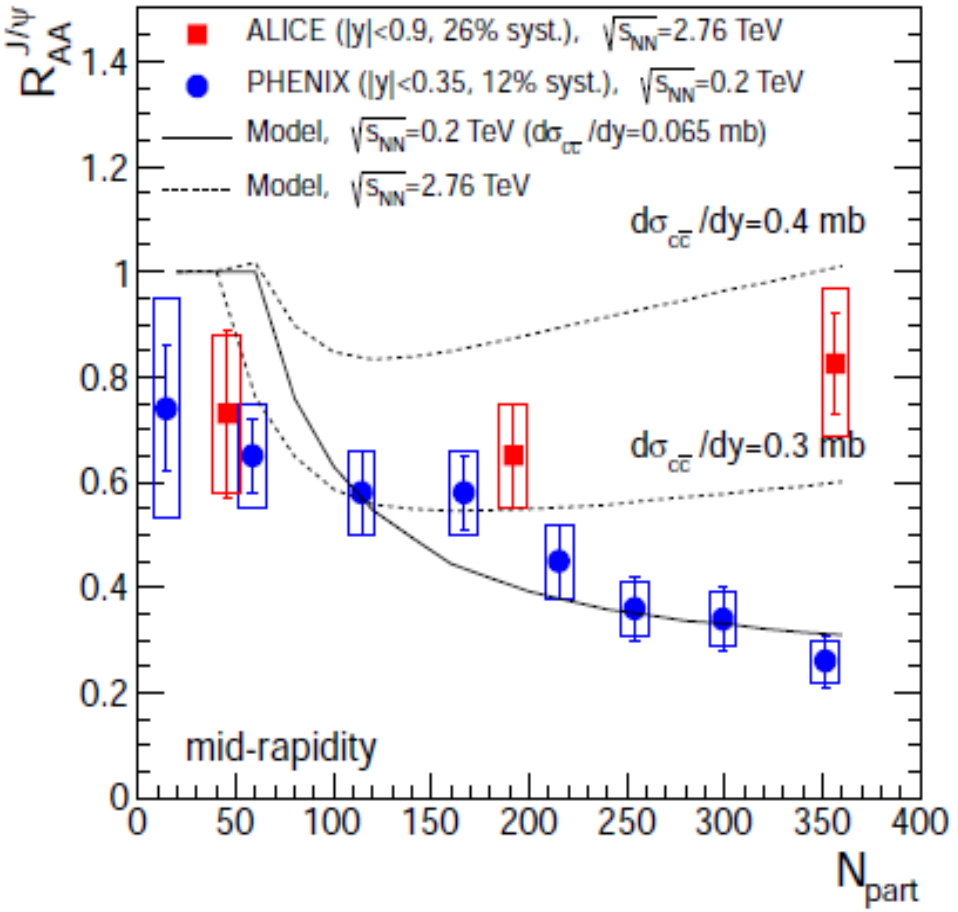
from here to here more than factor of 2 increase in energy density, but R_{AA} increases by more than a factor of 3

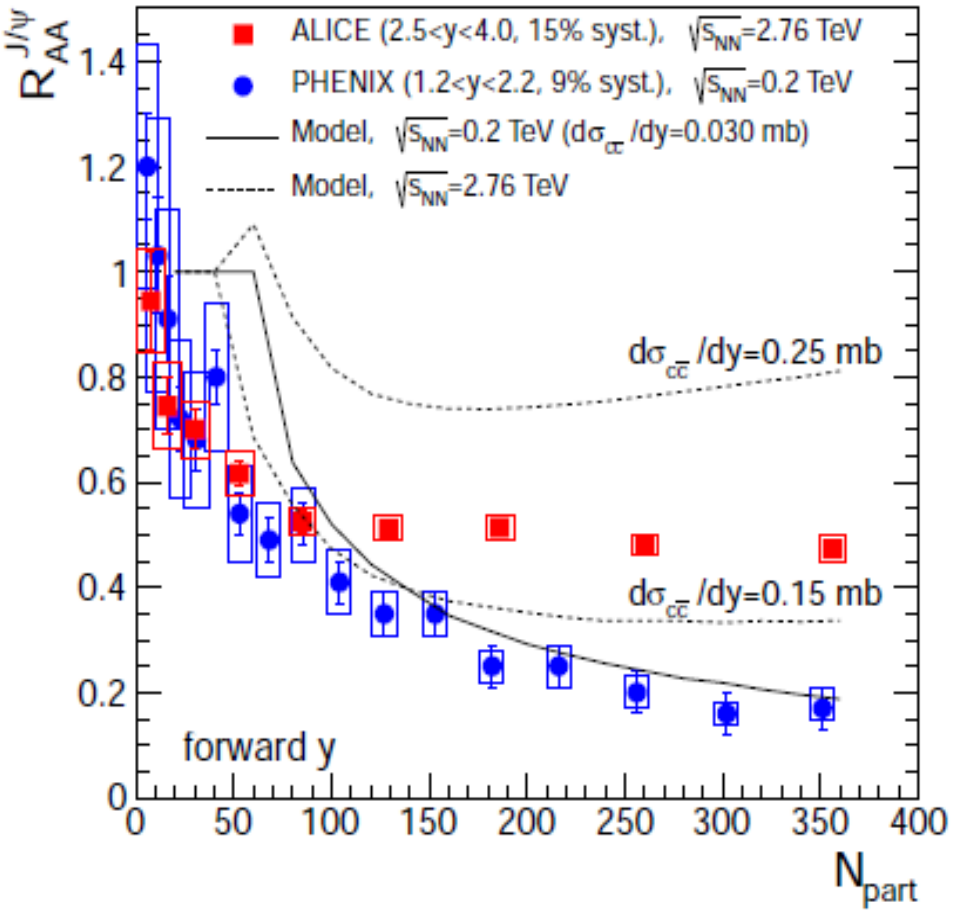
Rapidity dependence



note: energy density largest at y = 0

statistical hadronization model





ALICE data and evolution from RHIC to LHC energy described quantitatively

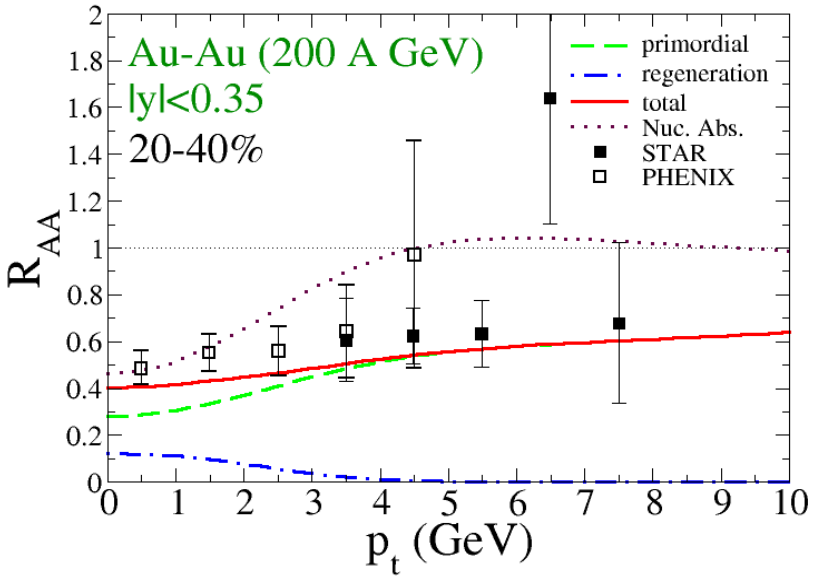
calcs: Andronic, pbm, Redlich, Stachel, arXiv:1210.7724

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:

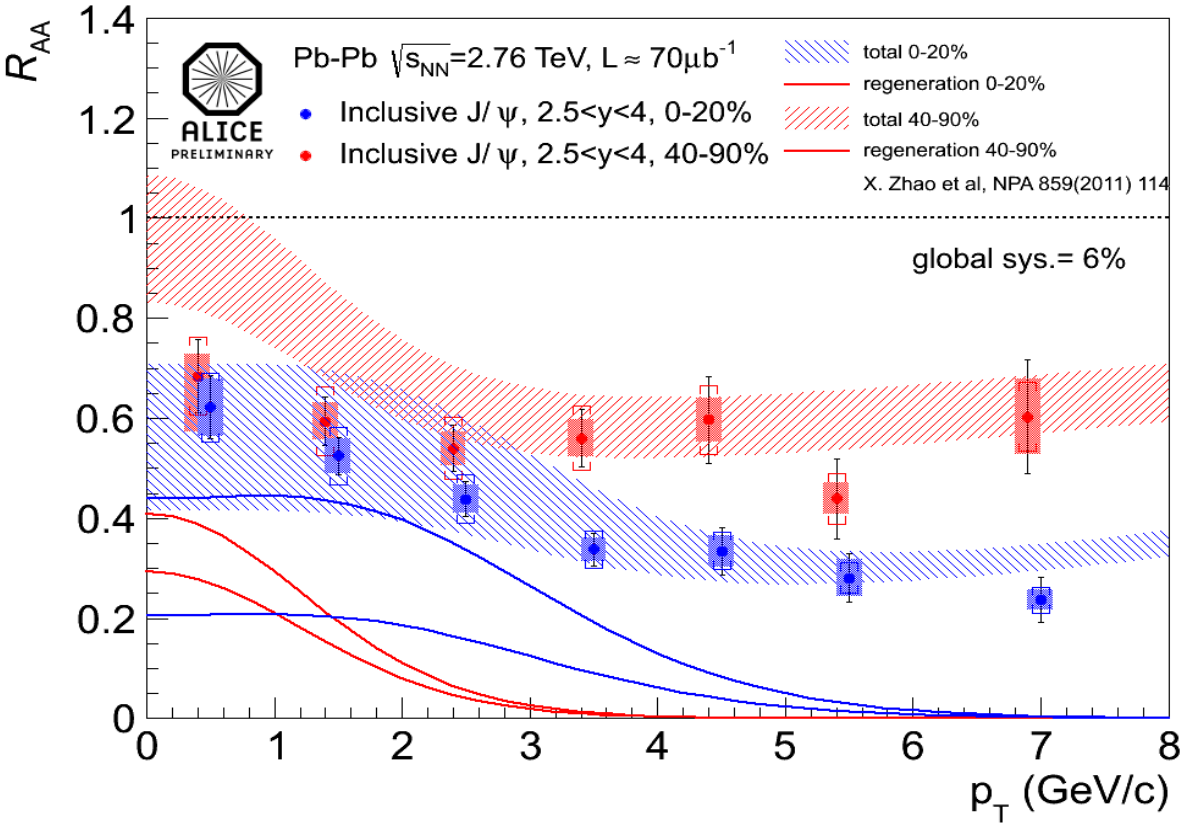
- charm quarks should be in thermal equilibrium
    - low pt enhancement
    - flow of charm quarks
    - flow of charmonia

Comparison of transverse momentum spectra at RHIC and LHC

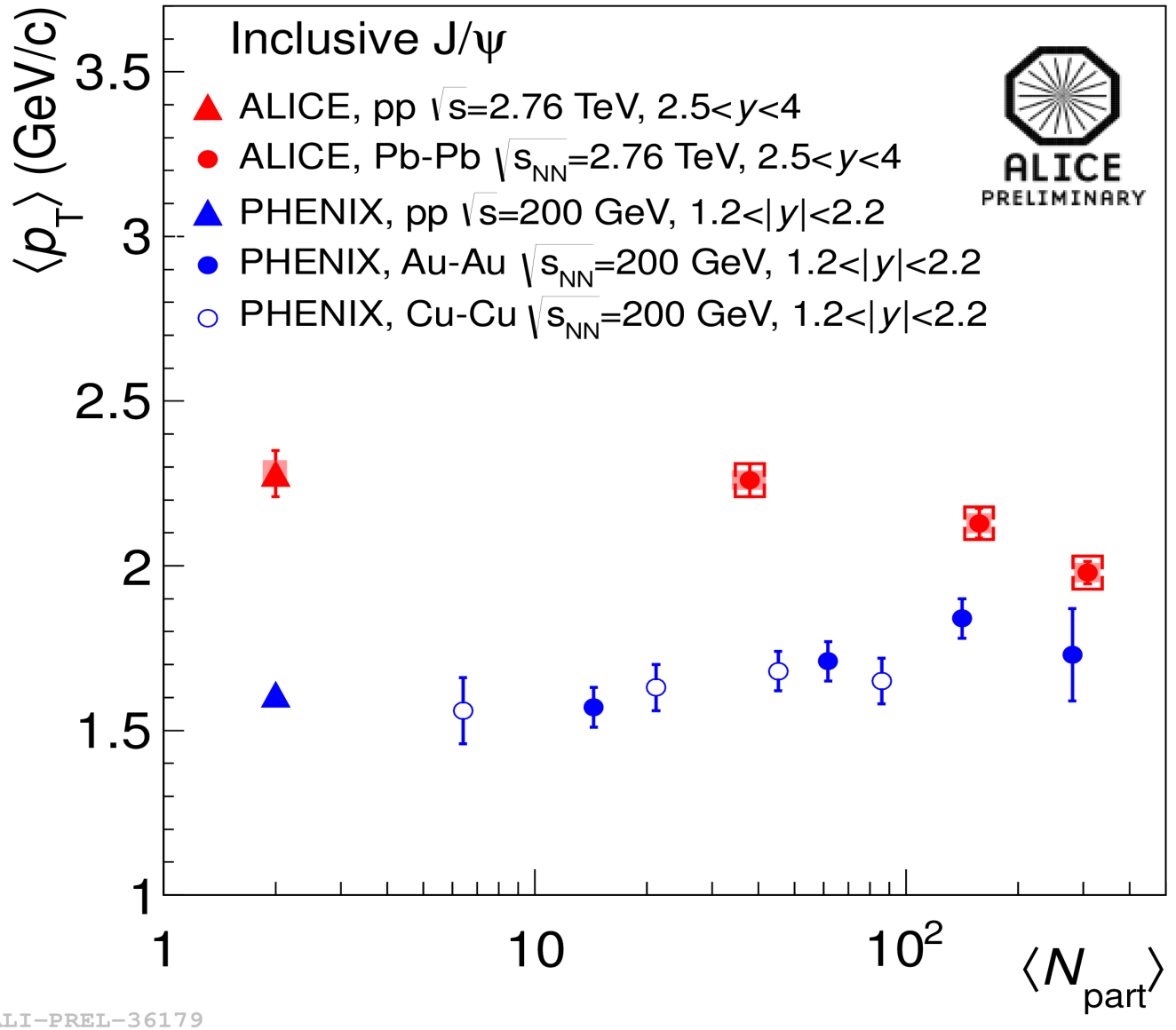


drastic difference!

low pt enhancement observed at ALICE

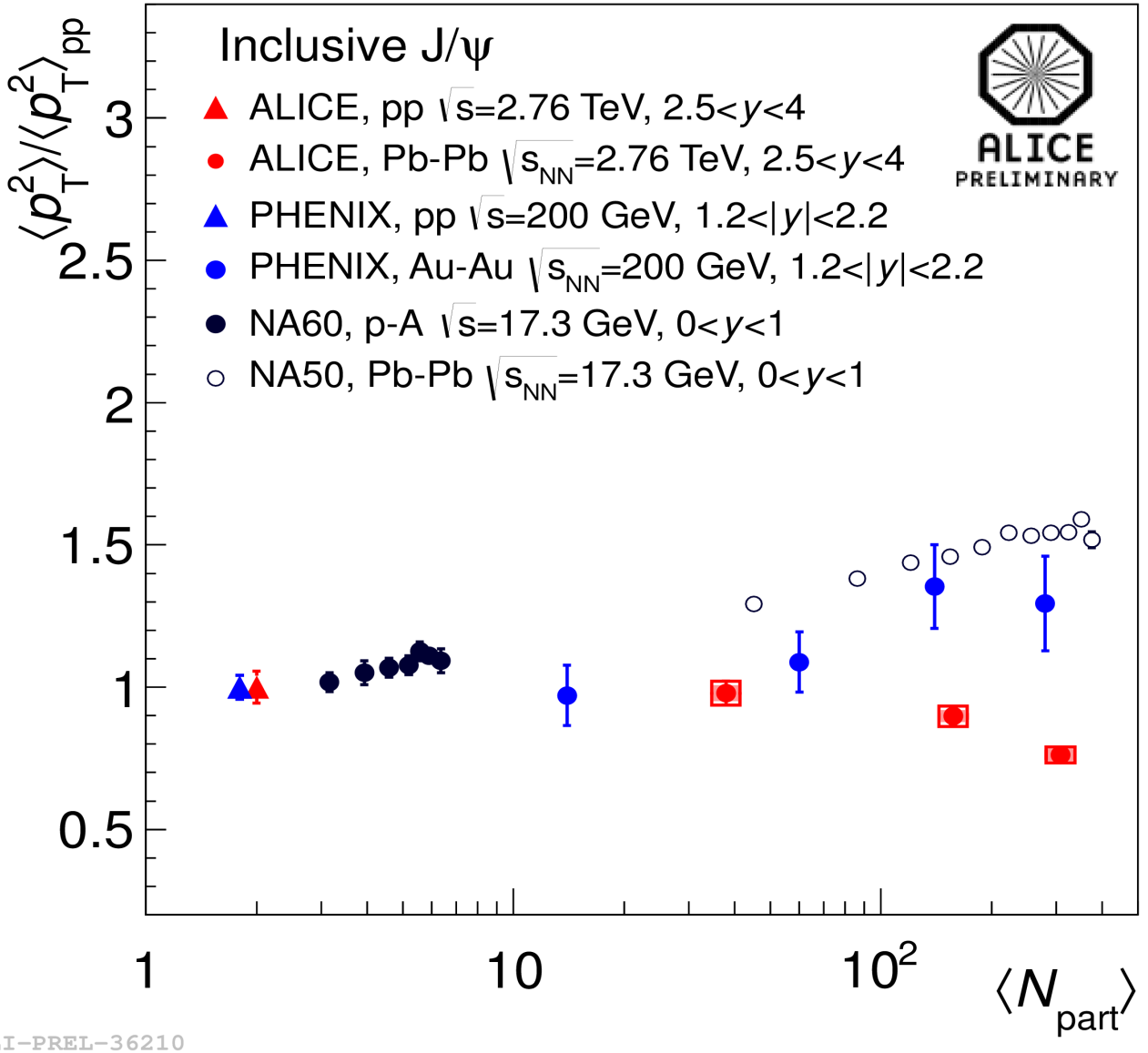


Evolution of J/psi transverse momentum spectra – evidence for thermalization and charm quark coalescence at the phase boundary



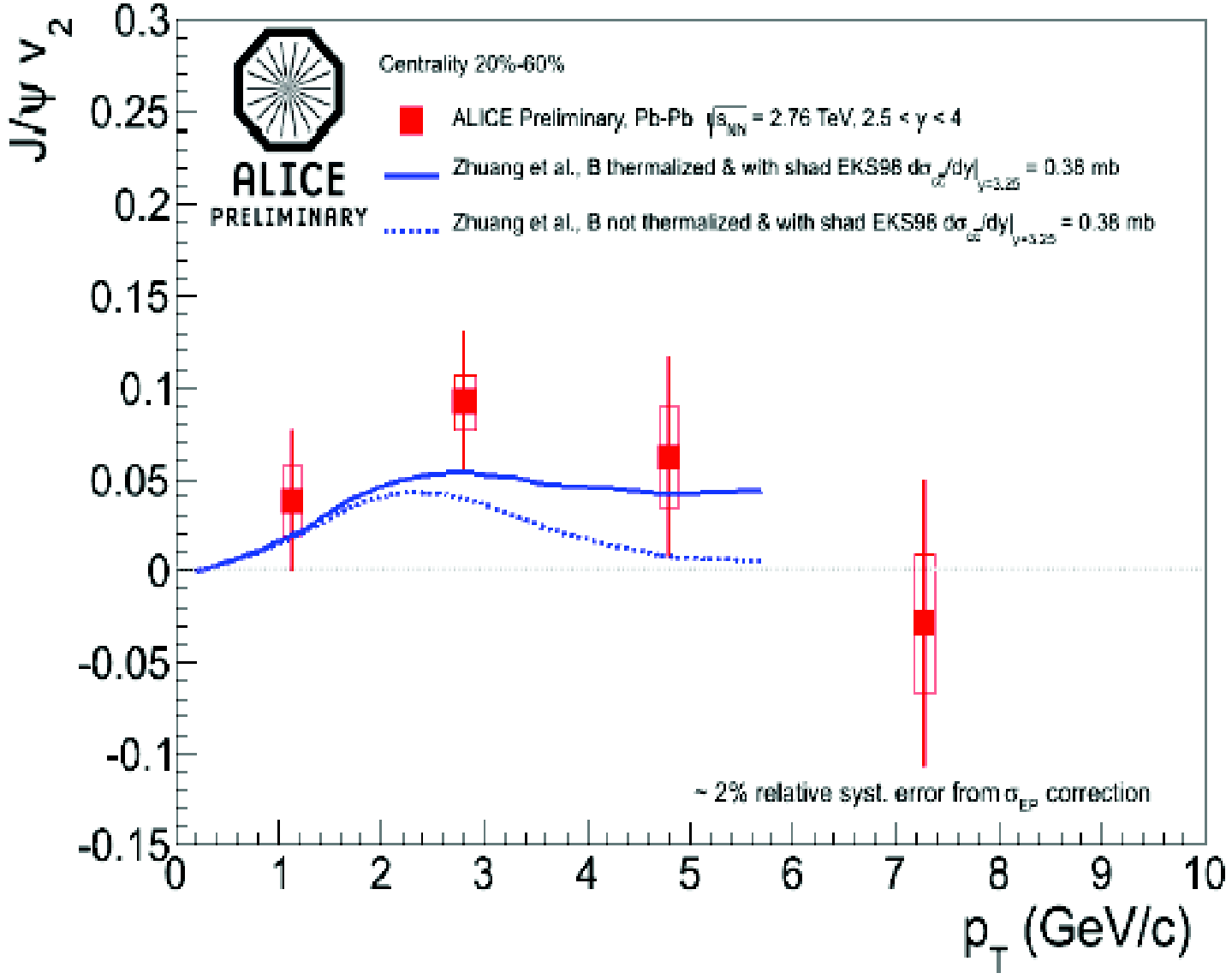
ALI-PREL-36179

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



ALI-PREL-36210

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

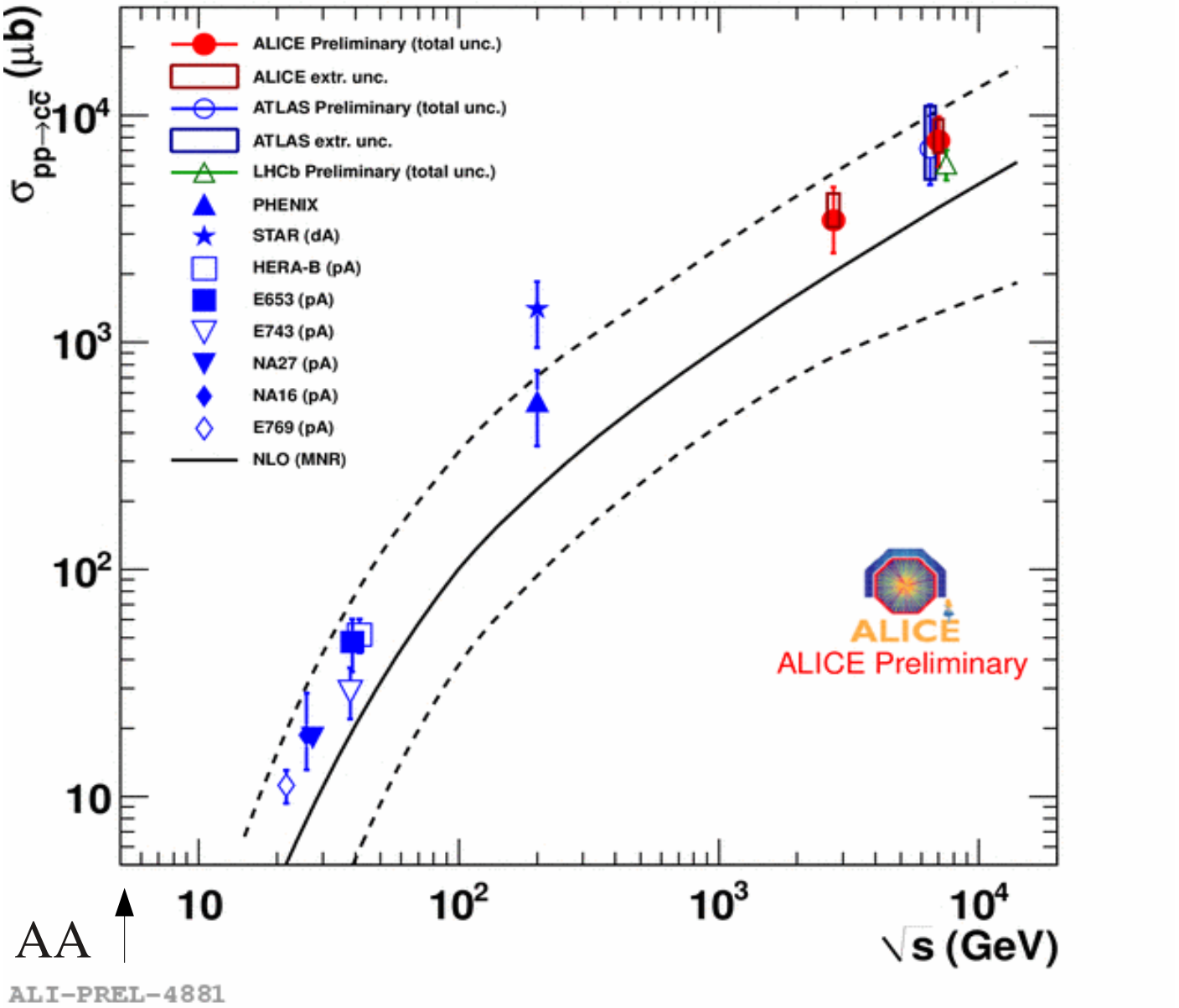
need to evaluate role of shadowing, to come soon from pPb data

What about open charm and charmonia at lower energies?

Remarks on production of open charm and charmonia

- charm quark mass >> Λ_{QCD} production described in QCD perturbation theory
- all calculations employ gluon fusion as starting point
- argument is energy independent until global energy conservation very close to threshold becomes important
- production of charm quark pairs takes place at timescale $1/2m_c$ $m_c = 1.3$ GeV --> $t_c = 0.08$ fm
- to build up wave function of mesons including those with open charm needs about t = 1fm **-->** charm production and charmed hadron formation are decoupled
- overall cross section is due to production of charm quark pairs
- time scale is much too short to dress the charm quarks essential to take current quarks for production

the total open charm cross section in pp collisions

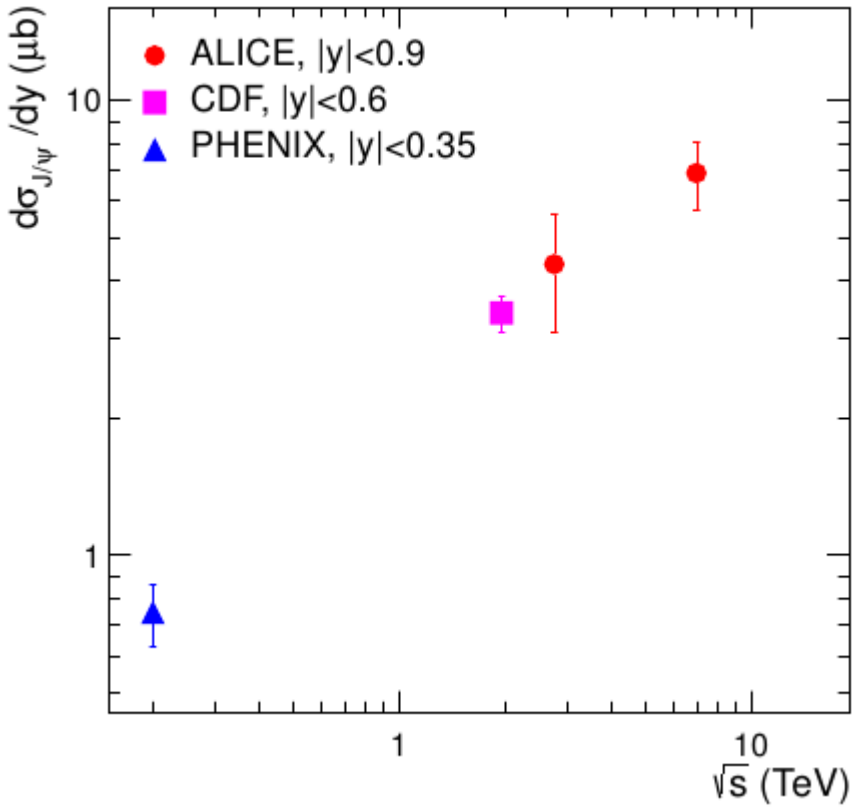


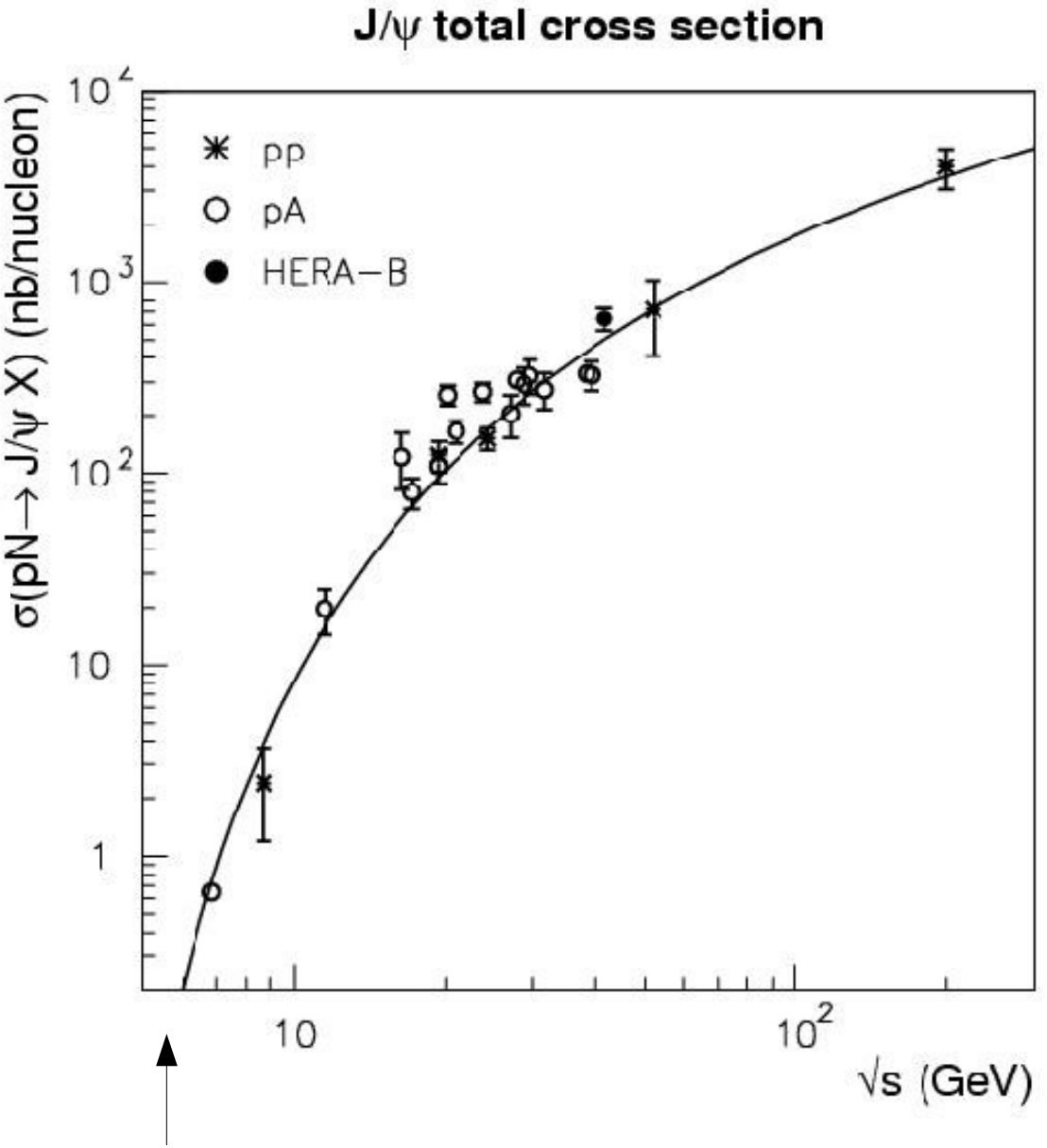
SIS100 AA

Energy dependence of charmonium production

well measured in pp and pA,

solid line is Hera-B fit





SIS100 AA

More timescales

formation and destruction of J/ψ (charmed hadrons)

- QGP formation time, t_{QGP}
  - FAIR, SPS: $t_{QGP} \simeq 1$ 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 FAIR/SPS energies? $(T_d \sim T_c)$

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

  cold nuclear suppression important at FAIR/SPS energies?

charm conservation equation and possible medium effects

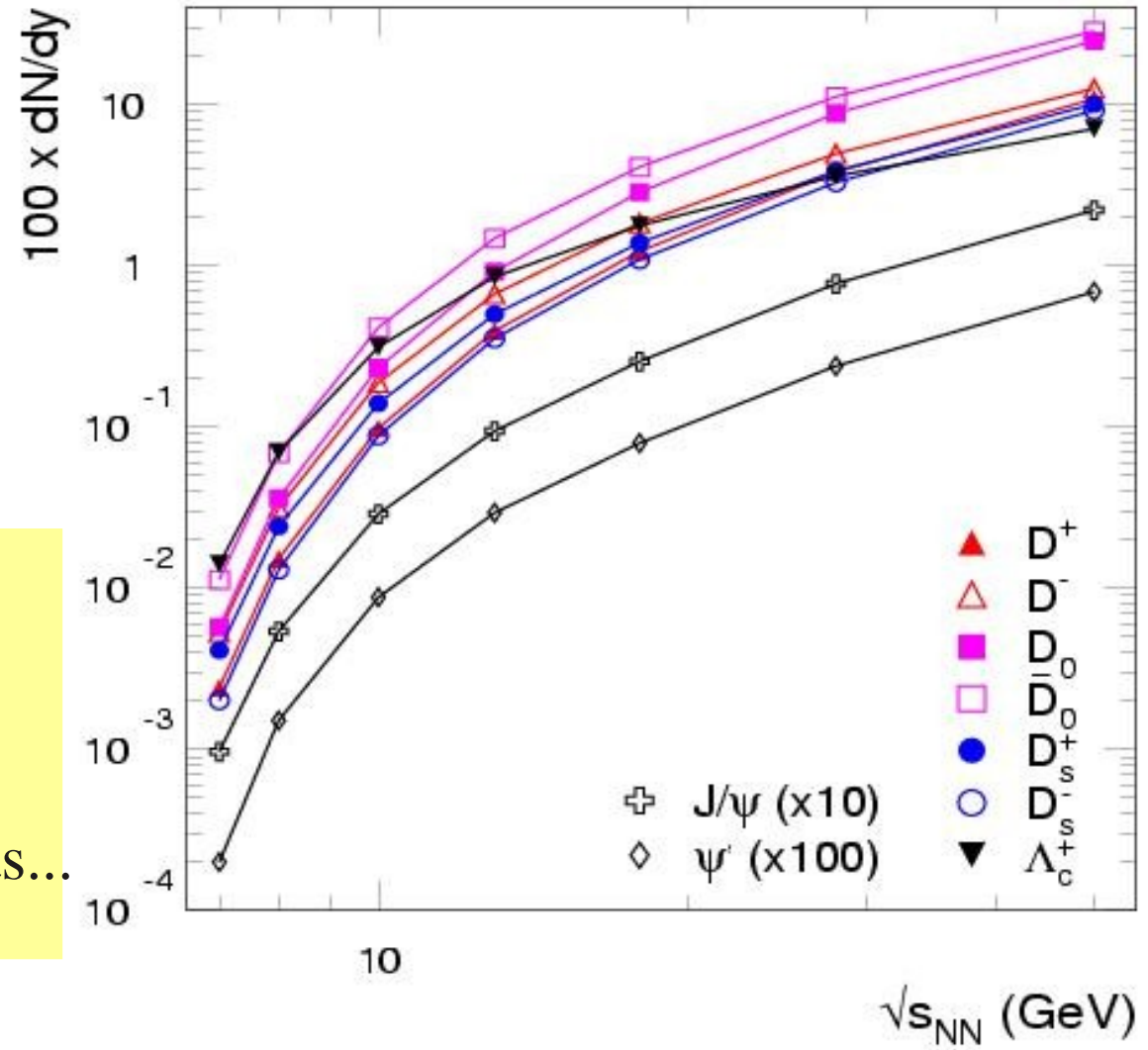
no medium effect

$$\sigma_{c\bar{c}} = 1/2\ \left[\sigma_{D^+} + \sigma_{D^-} + \sigma_{D^0} + \sigma_{\bar{D}^0} + \sigma_{\Lambda_c} + \sigma_{\bar{\Lambda}_c} \ldots\right]$$

medium effects on charmed hadrons affect redistribution of charm, but not overall cross section

it is not consistent with the charm conservation equation to reduce all charmed hadron masses in the medium for an enhanced cross section

Statistical hadronization predictions for open and hidden charm at low energies



only small medium
effects within SHM model
but
recent LHC results cast doubts...

A. Andronic, pbm, K. Redlich, J. Stachel
Phys. Lett. B659 (2008) 149

remarks on charm and charmonia at lower energies

thoughts much influenced by recent results from ALICE

- medium effects severely constrained by charm conservation
- charm quarks likely not thermalized – no access to color screening, see pt spectra at SPS and LHC energy
- collision time > J/psi formation time (opposite at LHC energy)
- cold nuclear suppression is a serious issue (absent at LHC energy)
- provocative statement: J/psi and open charm measurements very difficult at energies below SPS energy, no known connection to QGP

physics motivation is not obvious to me any more