Charmonium Production and the Quark-Gluon Plasma

- introductory remarks on charmonium and QGP
- discussion of time scales and open charm conservation equation
- remarks on 'cold nuclear matter effects
- charm and charmonium production in e+e- and pp collisions
- the statistical hadronization model
- results for SPS and collider energies

pbm, Extreme Matter Institute ***EMMI***, GSI
also at TU Darmstadt and FIAS, Frankfurt

The **E**xtre**M**e **M**atter **I**nstitute ***EMMI***

- topical research institute housed at GSI
  18.75 Meuro for 5 years
- programs on and research in interdisciplinary aspects of the physics of extreme matter
- expert groups initially representing the 4 major research areas
  1. QGP   2. Dense Plasmas 3. Neutron Matter
  4. Atomic Physics/Cold Gases
- focus on experimental and theoretical issues
- topical workshops and special lecture series

vision: bringing together the best minds from these communities

Charmonium as a probe for the properties of the QGP

the main idea: implant charmonia into the QGP and observe their modification, in terms of suppressed (or enhanced) production in nucleus-nucleus collisions with or without plasma formation

Charmonium suppression

original proposal: H. Satz and T. Matsui, Phys. Lett. B178 (1986) 416

assumptions:

- **all** charmonia are produced before QGP formation
- suppression takes place in QGP
- some charmonia might survive beyond T_c

$\rightarrow$ sequential suppression pattern due to feeding

actually, in 1978, Edward Shuryak investigated gluonic destruction of charmonium,

$$gJ/\psi \rightarrow \bar{c}c$$

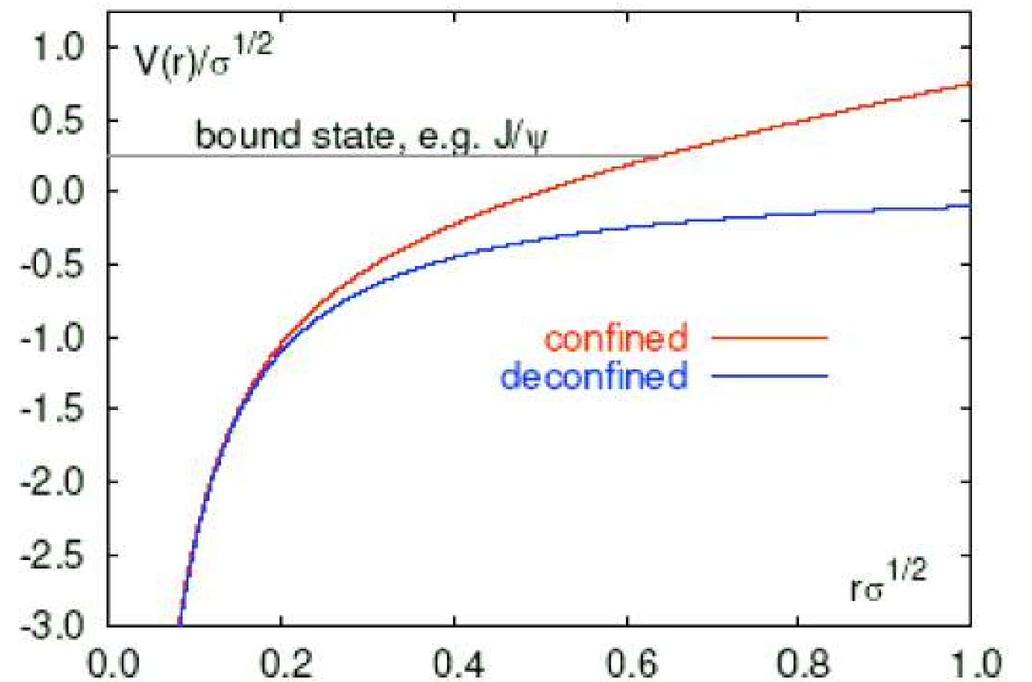
and concluded that it would not survive the gluon-rich plasma

E. V. Shuryak, Phys. Lett. B **78**, 150 (1978) [Sov. J. Nucl. Phys. **28**, 408.1978 YAFIA,28,796 (1978 YAFIA,28,796-808.1978)].

Debye screening

V(r,T large)   no bound state

V(r,T small) bound state



σ = string tension = 1 GeV/fm

= 0.2 GeV^2

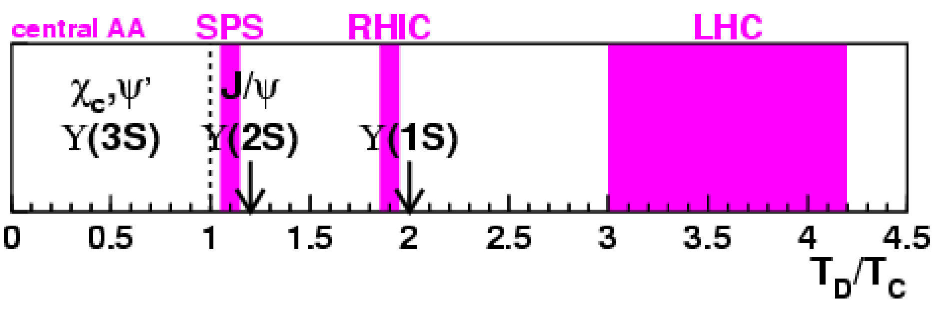
Survival of Quarkonia in the QGP

new development:
J/ψ does not survive above T_c

predicted quarkonium dissociation temperatures

in the QGP

A. Mocsy & P. Petreczky, Phys. Rev. Lett. 99 (2007) 211602



expect all charmonia to be destroyed
by QGP
but: regeneration at the phase boundary!

Collision broadening in QGP

collisions of charmonia with quarks and gluons in the QGP broaden the width of these states

estimate: density of partons in QGP $n = 4.25\ T^3$

3 massless flavors

mean free path of J/ψ $\lambda = 1/(n\ \sigma)$

σ = J/ψ parton cross section take 2 mb as reference

(factor 2 smaller than NA50 absorption cross section)

velocity of J/ψ in the QGP $v = \sqrt{(3\ T/m)} \approx v_{rel}$

in-medium width $\Gamma = v_{rel}/\lambda$

final result:

$T = 200$ MeV $\Gamma = 80$ MeV

$T = 300$ MeV $\Gamma = 320$ MeV

$T = 500$ MeV $\Gamma = 1940$ MeV

Collision broadening in QGP

for T > 200 MeV charmonia, if they exist there, will decay inside the QGP and will not be reconstructed by experiments

p(decay inside) = $1\text{-}\exp(-\Gamma\, \tau_{QGP})$

$\tau_{QGP} = 5$ fm $\Gamma = 100$ eV --> p = 0.92

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

Formation time of quarkonia

heavy quark velocity in charmonium rest frame:

v = 0.55 for J/ψ   see, e.g. G.T. Bodwin et al., hep-ph/0611002

minimum formation time: t = radius/v = 0.45 fm

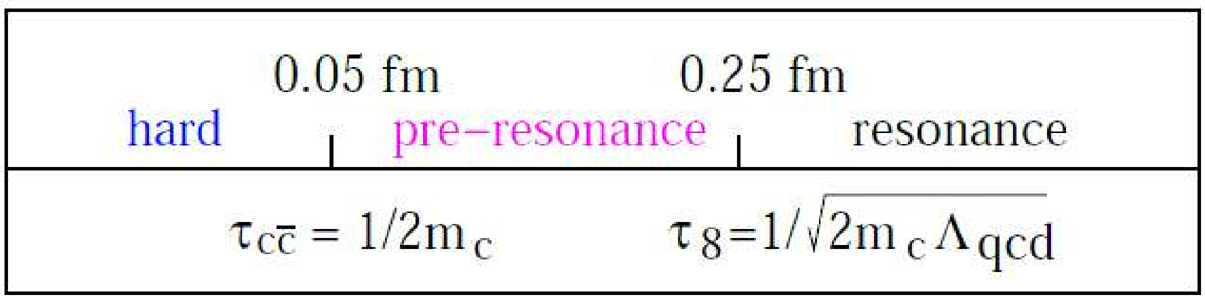
see also: Huefner, Ivanov, Kopeliovich, and Tarasov, Phys. Rev. D62 (2000) 094022; J.P. Blaizot and J.Y. Ollitrault, Phys. Rev. D39 (1989) 232

formation time of order 1 fm

formation time is not short compared to plasma formation time especially at high energy

Time scales continued

at LHC energies, even the color octet state is not formed before the QGP



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

formation time of open charm hadrons not well understood

presumably similar to charmonia

separation of time scales for initial hard process and late hadronization/hadron formation is called „factorization“

rigorously proven for deep inelastic scattering

charm conservation equation

no medium effect

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

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

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?

GSI
TECHNISCHE UNIVERSITÄT DARMSTADT

Role of cold nuclear matter effects

what is it:

destruction of charmonia by colliding nuclei before QGP formation

- may be important at SPS and lower energies
- charmonium formation time long compared to QGP formation time, especially at LHC --> **no cold nuclear matter effects at LHC**

what it is not:

rapidity dependent reduction of charm and charmonium production due to shadowing or saturation

need to normalize charmonium production to open charm cross section in AA collisions

Role of cold nuclear matter effects

investigation of 'anomalous' charmonium production in AA collisions

need to normalize charmonium production to open charm cross section in AA collisions

pp and pA collisions are needed to study possible shadowing or saturation effects, not for charmonium suppression or enhancement in the QGP

is there any evidence for saturation or shadowing from RHIC data?? $\sigma_{ccbar}(AA) = N_{coll}\,\sigma_{ccbar}(pp)$??

Hadron Production in elementary collisions``

as first noticed by F. Becattini in 1996

F. Becattini, Z. Phys. C **69** (1996) 485

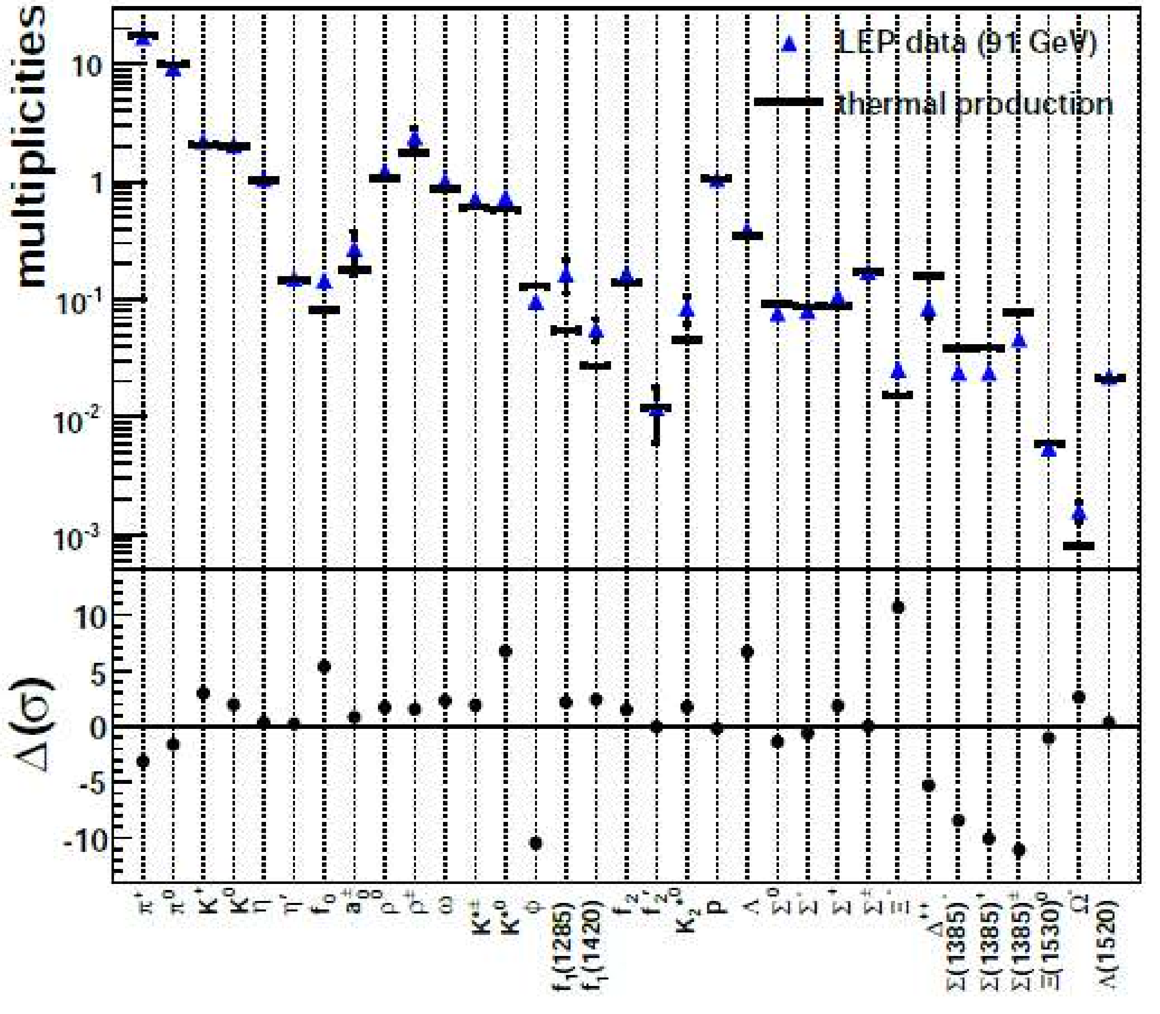
thermal features observed for overall production pattern but:

thermal fit is possible only
with several external, non-statistical parameters
($gamma_S$, production probability of c and b quarks, ...)

also: fit quality is rather poor

Thermal fit to e+e- data at 91 GeV

T=168 MeV, V=18 fm^3 and γ_s=0.66



$\chi^2/\mathrm{dof}=696/30$

poor fit quality

A. Andronic, F. Beutler, P. Braun-Munzinger, K. Redlich, J. Stachel, arXiv:0804.4132

Charm and Beauty Hadrons in e+e- Collisions

open charm and open beauty hadrons well reproduced in thermal approach: heavy quark hadronization follows statistical phase space.

however, hidden beauty and charm formation is highly suppressed (by $\exp(-m_{hq}/T)$)

similar expectations for production of charmonia in pp collisions at high energy:

production ratios not thermal!

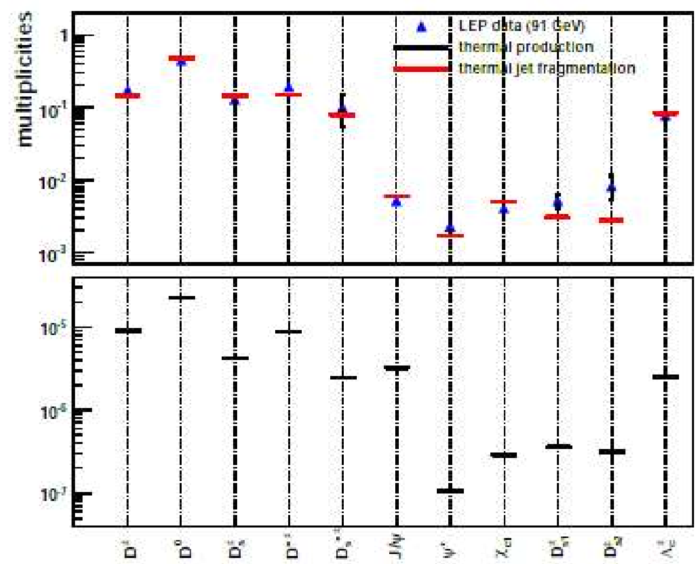
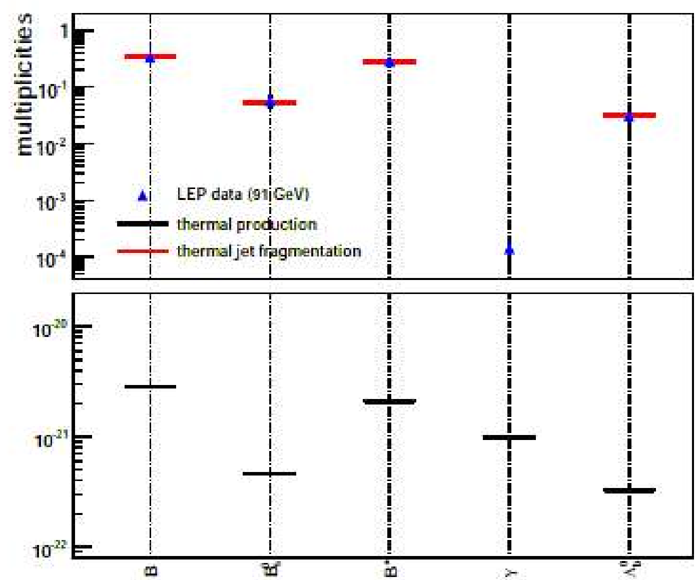
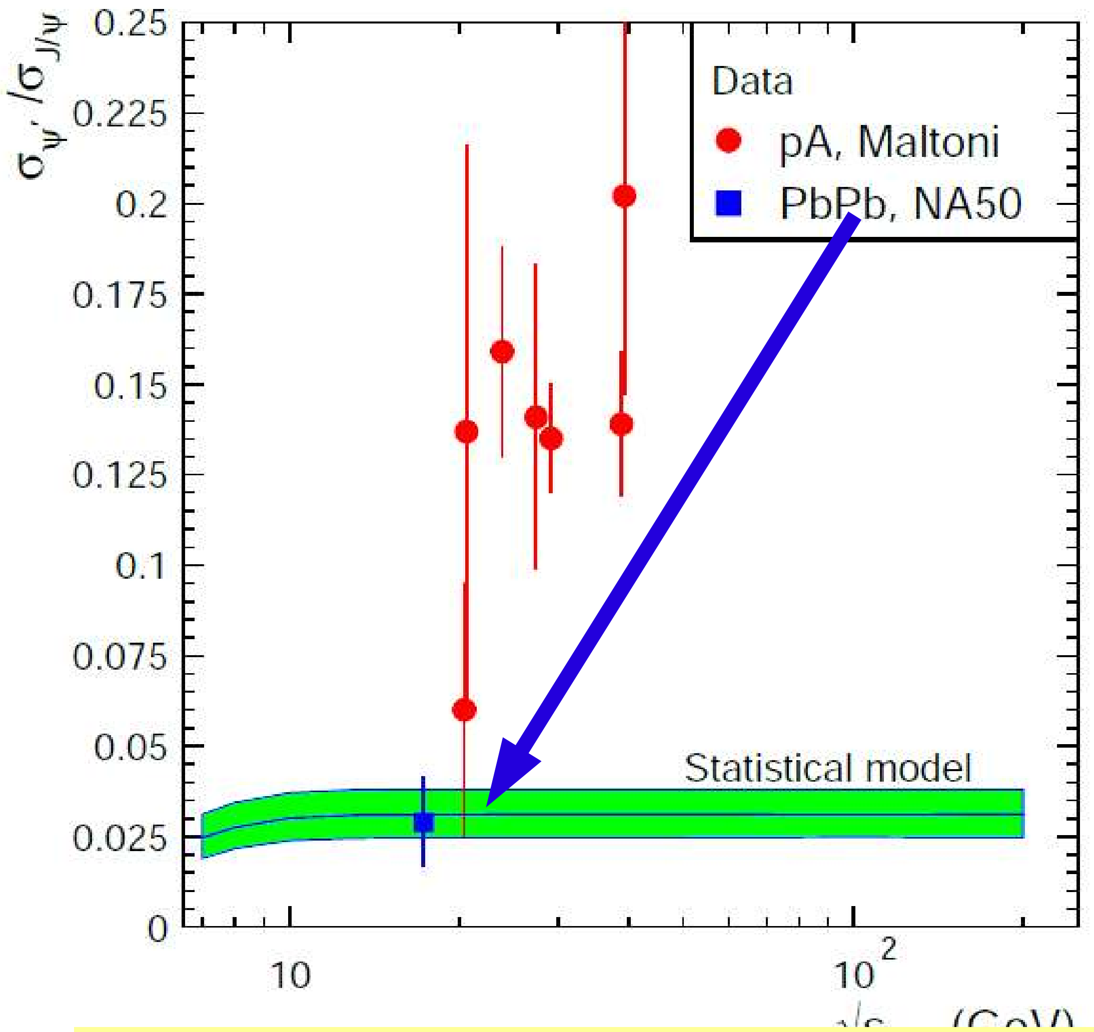
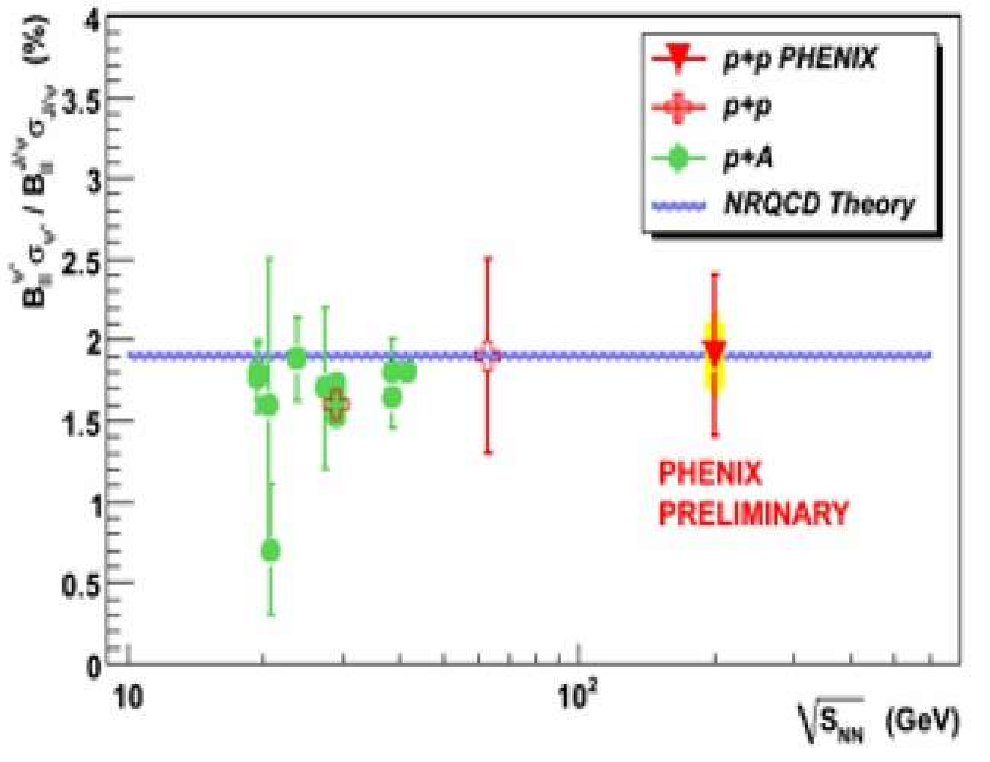


Figure 2.



Summary of ψ'/(J/ψ) measurements





all pp and pA results (including new PHENIX value) agree
central PbPb value is anomalous (thermal)

From e+e- and pp to AA collisions

production of charmed and beauty hadrons exhibits thermal features (Becattini 1997)
but: $(J/\psi)/\psi'$ 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 $(J/\psi)/\psi'$ ratio reaches a thermal value (T=170 MeV) in central PbPb collisions at SPS energy

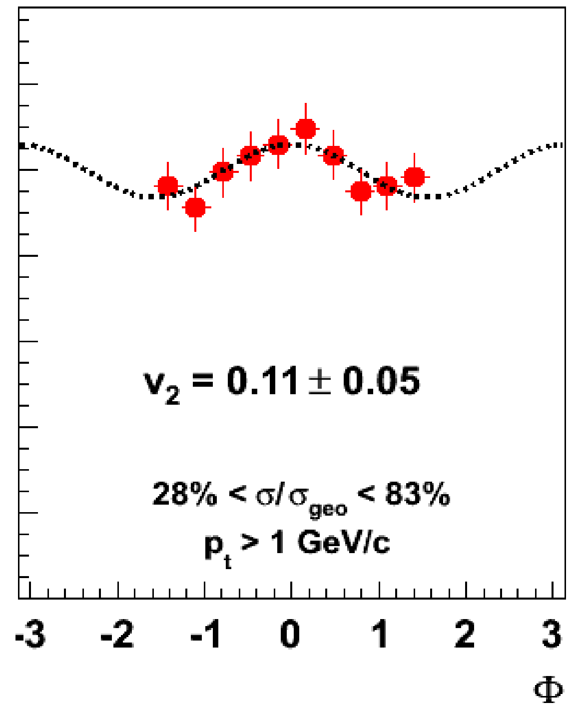
further analysis by Gorenstein and Gazdzicki, Phys. Rev. Lett. 83 (1999) 4003
result: $(J/\psi)/\pi$ is approximately constant at SPS energy for PbPb

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.

TECHNISCHE UNIVERSITÄT DARMSTADT

Thermal behavior of charmonia in AA collisions: Elliptic flow of J/psi!!



In+In, SPS energy, NA60 collaboration

see also RHIC results on flow and energy loss of charm quarks

Charmonium regeneration 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

Method and inputs

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

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

$N_{c\bar{c}} << 1 \longrightarrow$ 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, $V = N_{ch}^{exp} / n_{ch}^{th}$, $N_{c\bar{c}}^{dir}$ (pQCD)

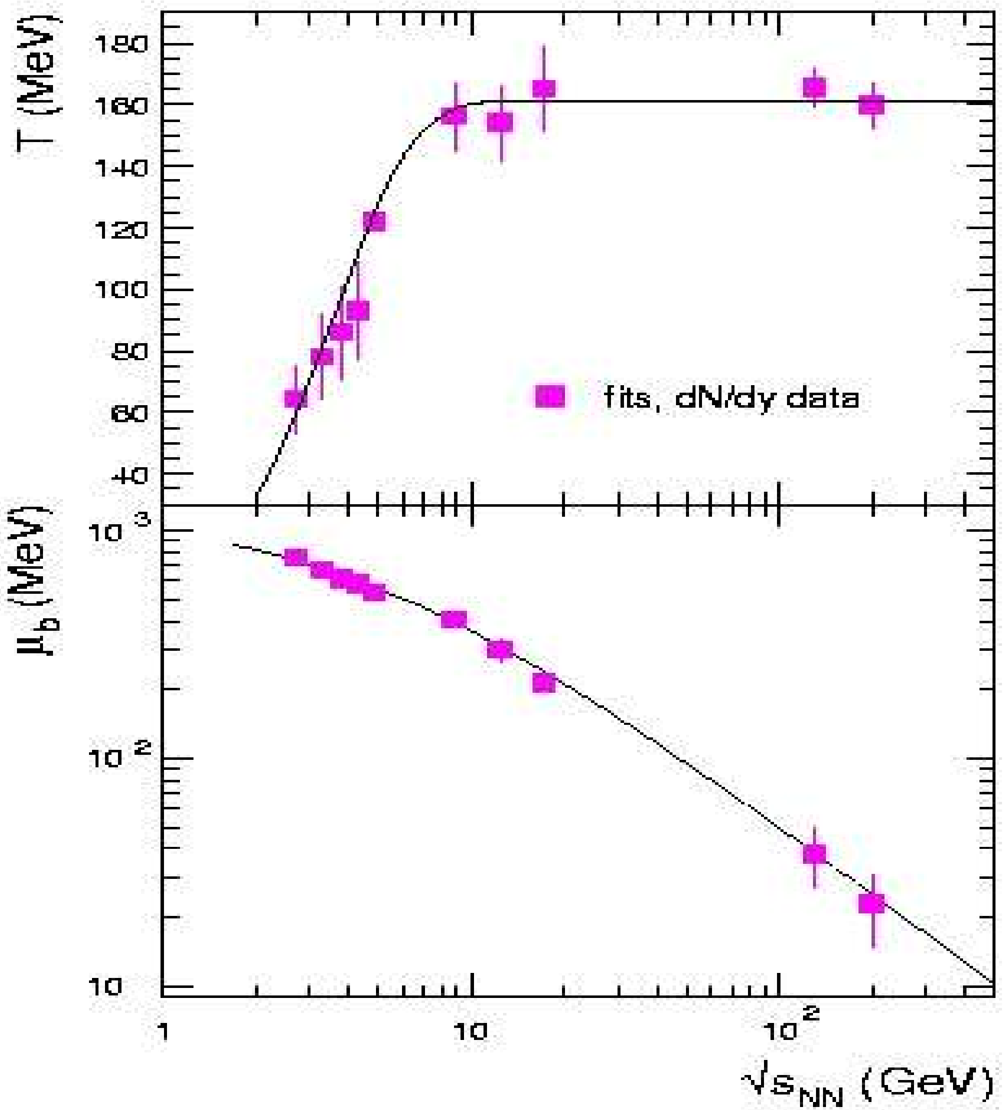
GSI TECHNISCHE UNIVERSITÄT DARMSTADT

Parameterization of all freeze-out points

note: establishment of limiting temperature

T_{lim} = 160 MeV

get T and μ_B for all energies



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

GSI
TECHNISCHE UNIVERSITÄT DARMSTADT

Ingredients for prediction of quarkonium and open charm cross sections

- 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

Review of results from SPS and RHIC

new aspects:

- absolute normalization of yields
- rapidity dependence
- comparison to results from pp collisions

Definition of Modification of Charmonium in the Fireball

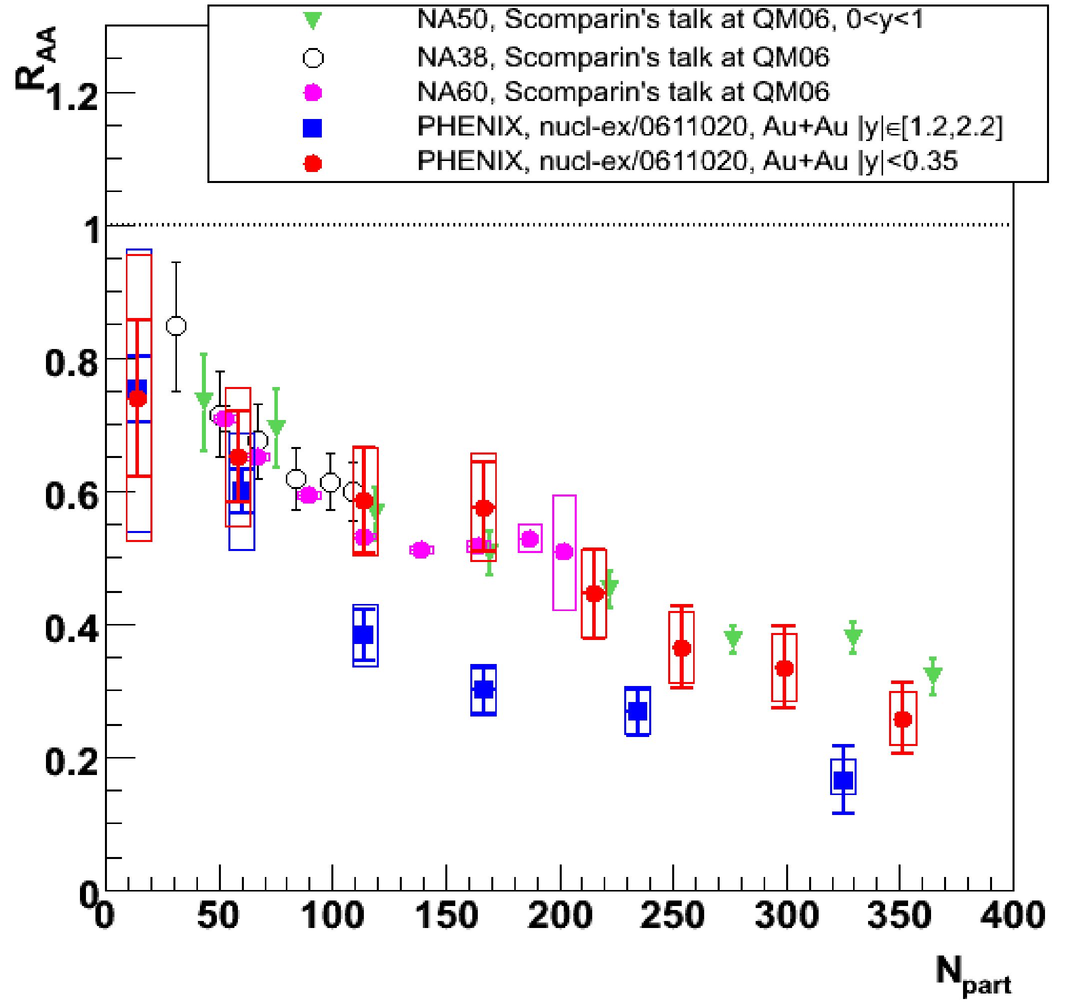
use R_{AA} to define charmonium modification experimentally
no need to normalize to Drell-Yan process

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

if $\sigma_{\text{Drell-Yan}} \propto N_{coll}$, R_{AA} is equivalent to NA50 definition, except for 'cold nuclear matter' effects

Comparison of RHIC and SPS Results

surprize:
no energy dependence
but unexpected
rapidity dependence

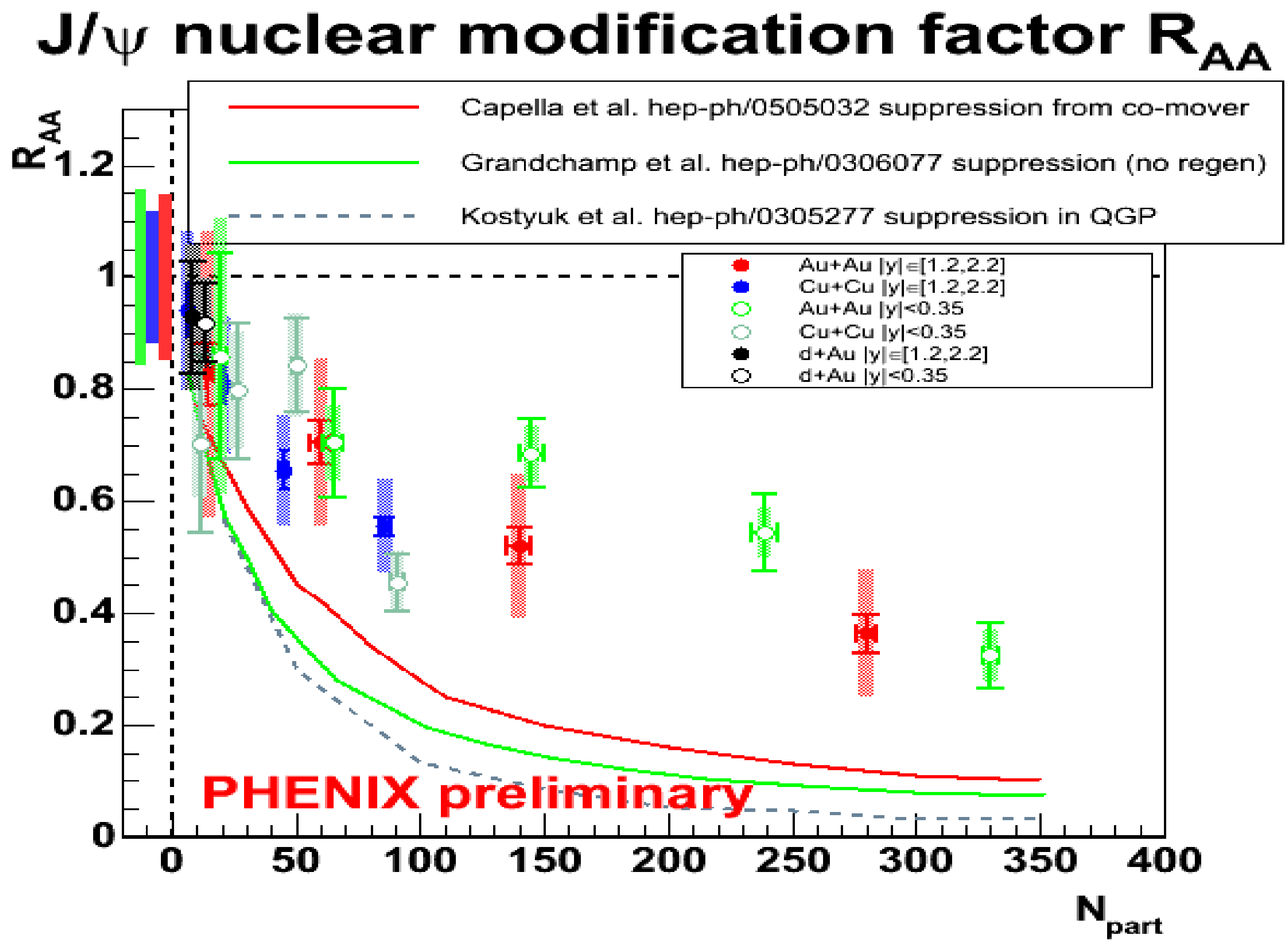


comparison produced by
R. Granier de Cassagnac

Too much suppression at RHIC in Standard QGP Scenario

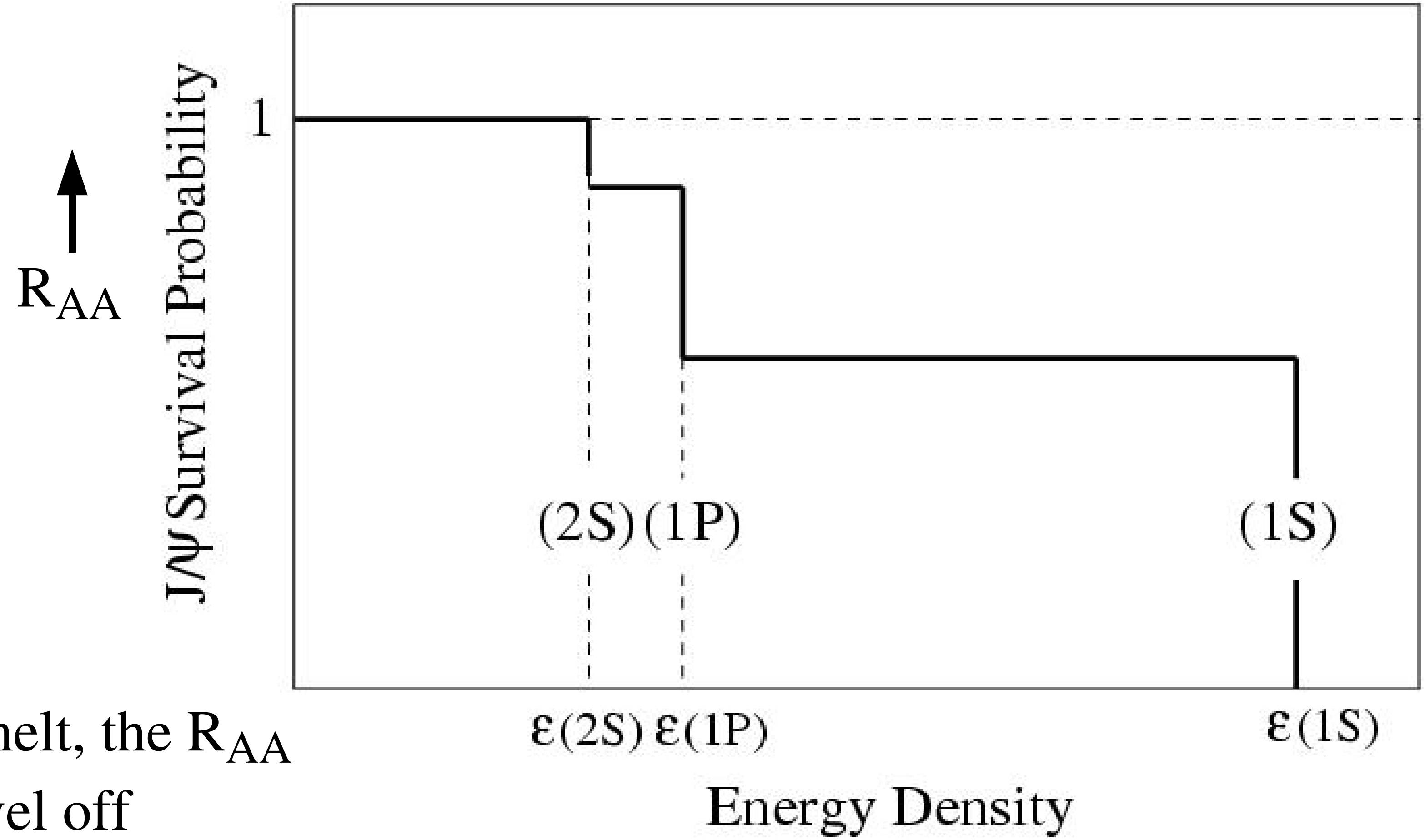
standard scenario: all charmonia melt near T_c

models tuned for SPS data fail at RHIC



TECHNISCHE UNIVERSITÄT DARMSTADT

Sequential Melting – schematical picture

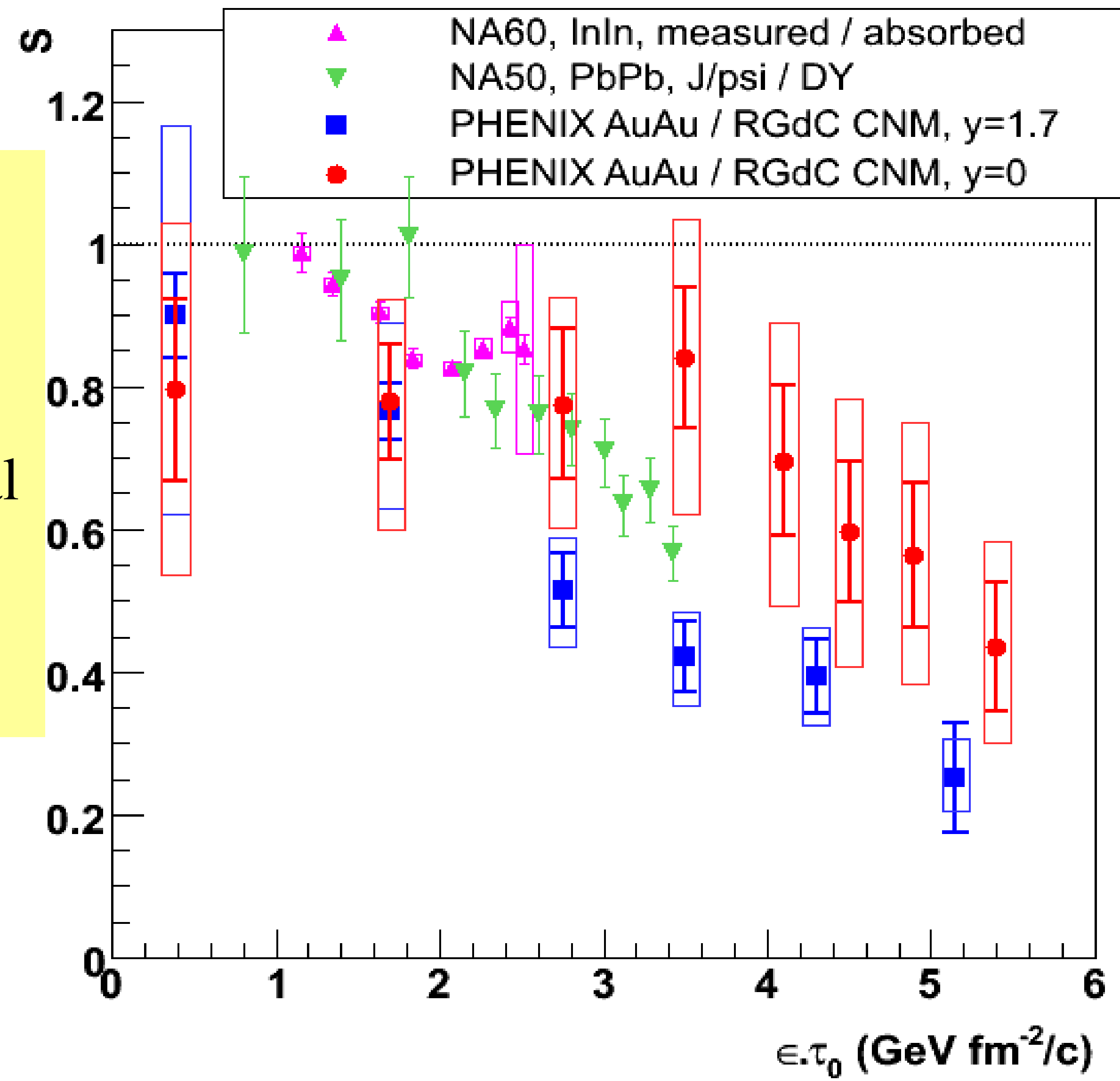


if J/ψ does not melt, the R_{AA} factor should level off at around $R_{AA} > 0.6$ (loss of feeding from χ_c and ψ')

note: χ_c and ψ' not measured at RHIC
pA data at lower energies (HeraB) suggest:
$\chi_c/(J/\psi) < 0.35$

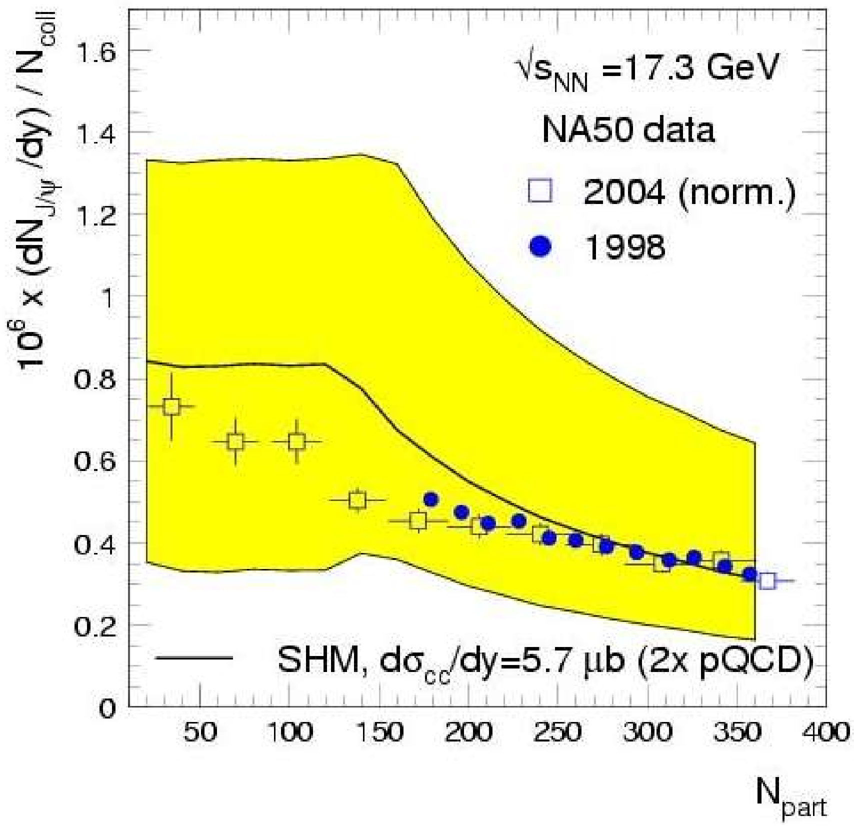
No experimental evidence for sequential melting

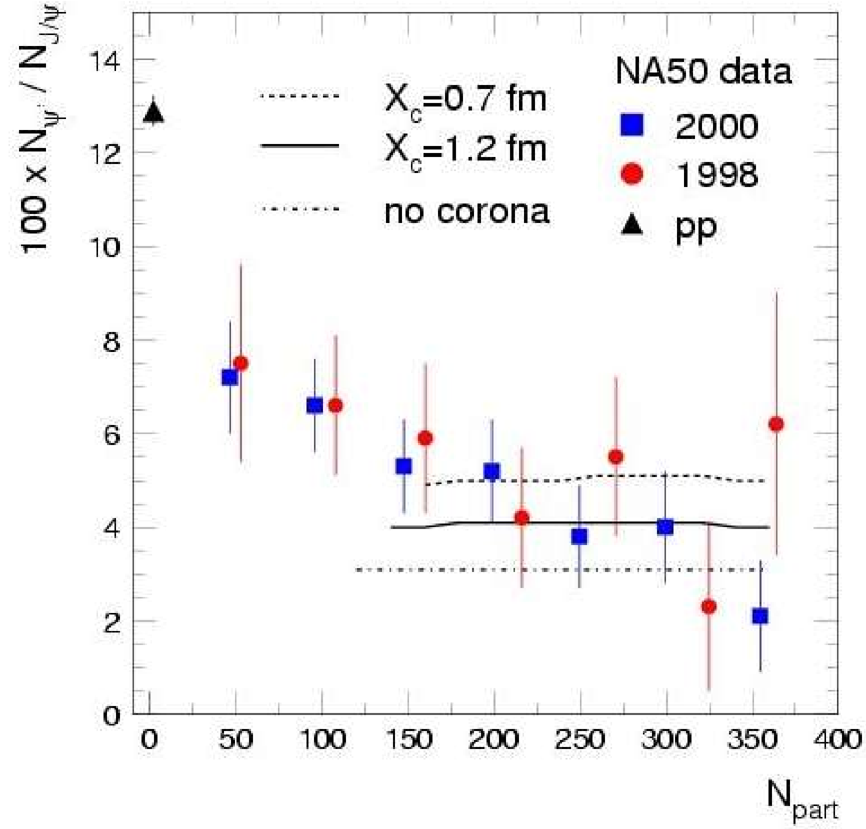
new data at various rapidities rule out sequential melting



compilation by R. Granier de Cassagnac

results for SPS energy

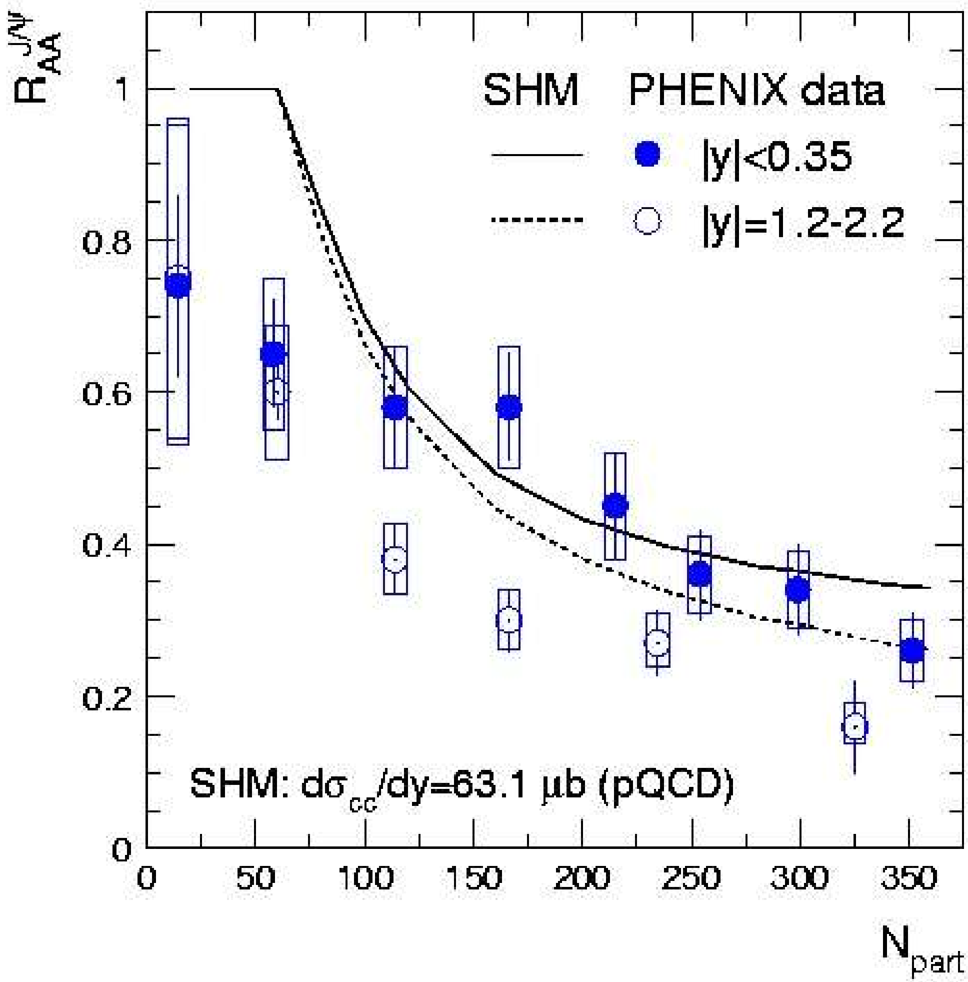




only moderately enhanced (2 x pQCD) cc_bar cross section needed

extrapolation to pp for ψ'/ψ ratio still problematic in the model, although intuitively clear

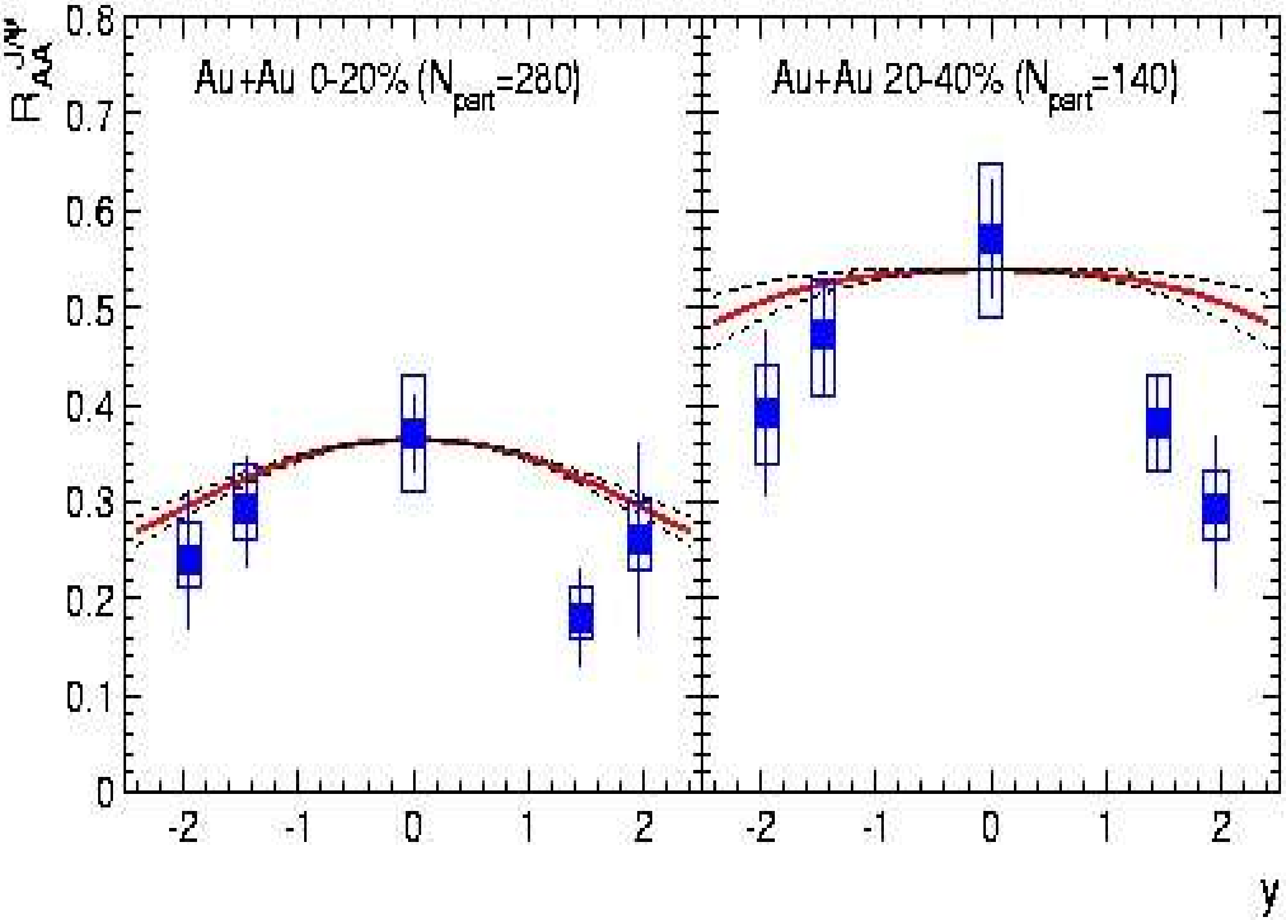
Centrality dependence of nuclear modification factor



data well described
by our regeneration model
without any new
parameters

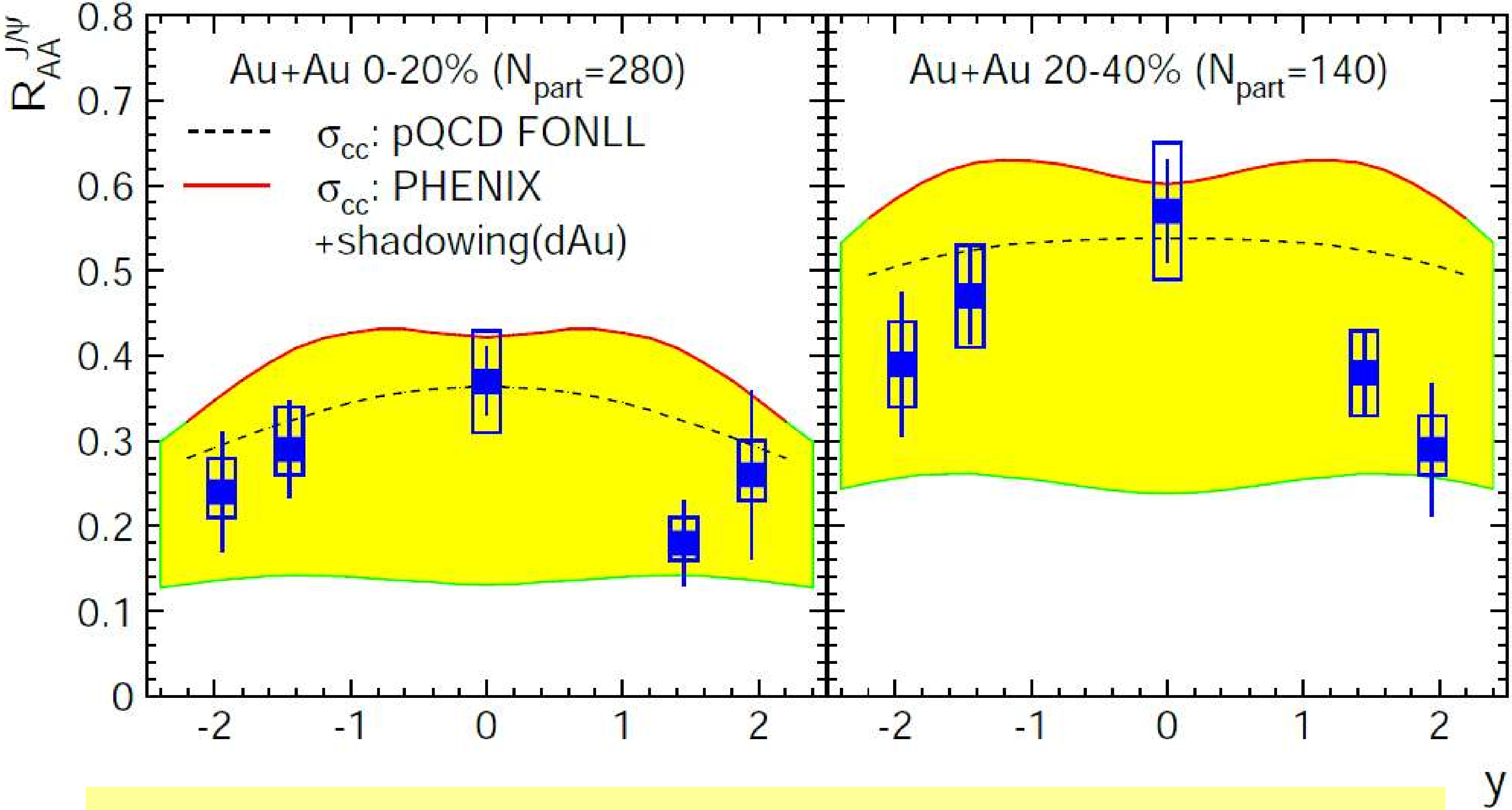
GSI TECHNISCHE UNIVERSITÄT DARMSTADT

Comparison of model predictions to RHIC data: rapidity dependence



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

Calculations including shadowing



assume PHENIX pA data reflect shadowing

Saturation model for J/psi production

basis: strong gluon saturation in the wave function of the colliding nuclei

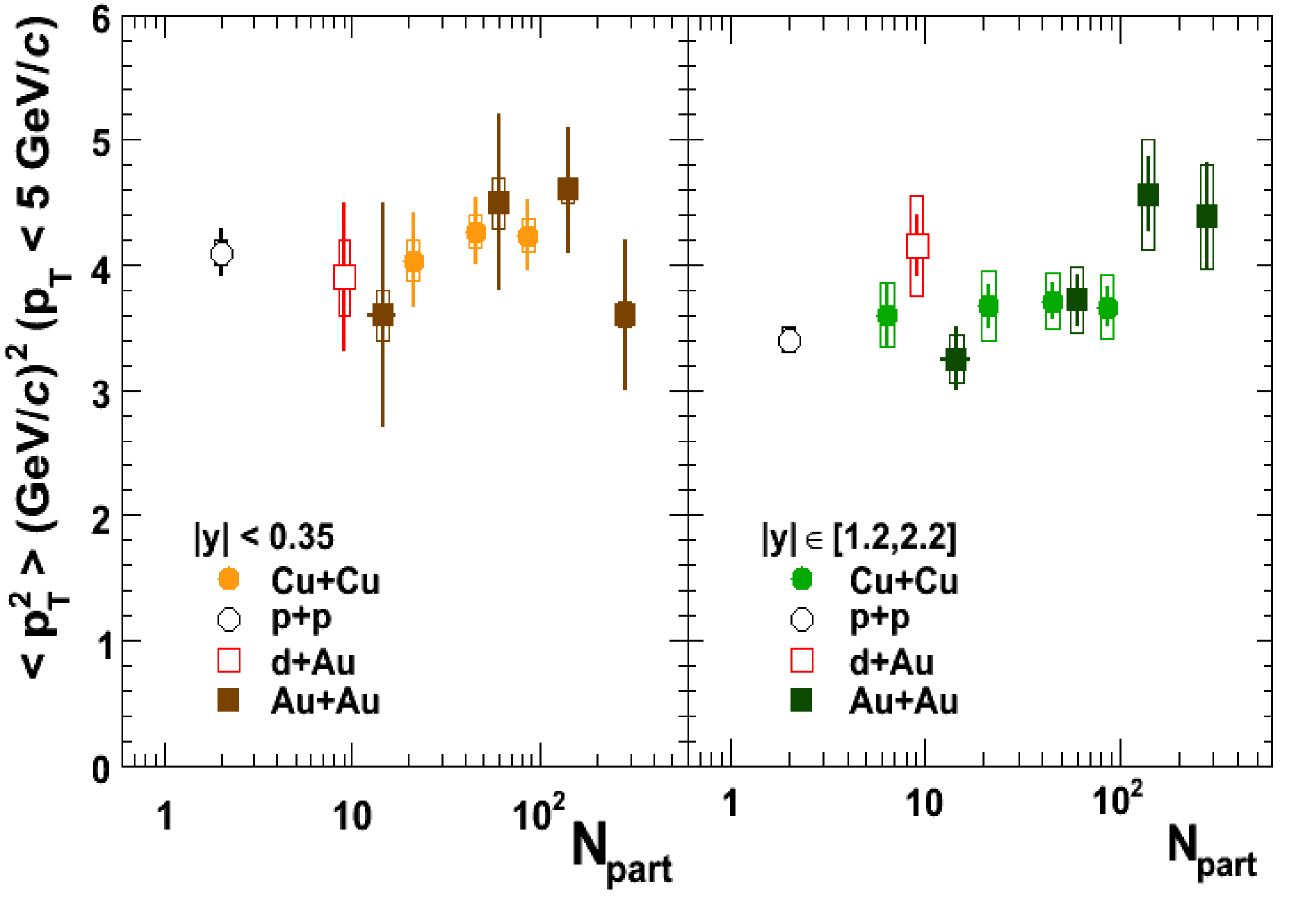
this leads to increasing suppression of the charm and J/psi cross section away from mid-rapidity as the size of the colliding nuclei increases

assumes incoherent superposition of color fields of the colliding nuclei -- ultra-high energy limit

would provide stronger overall suppression at LHC energy

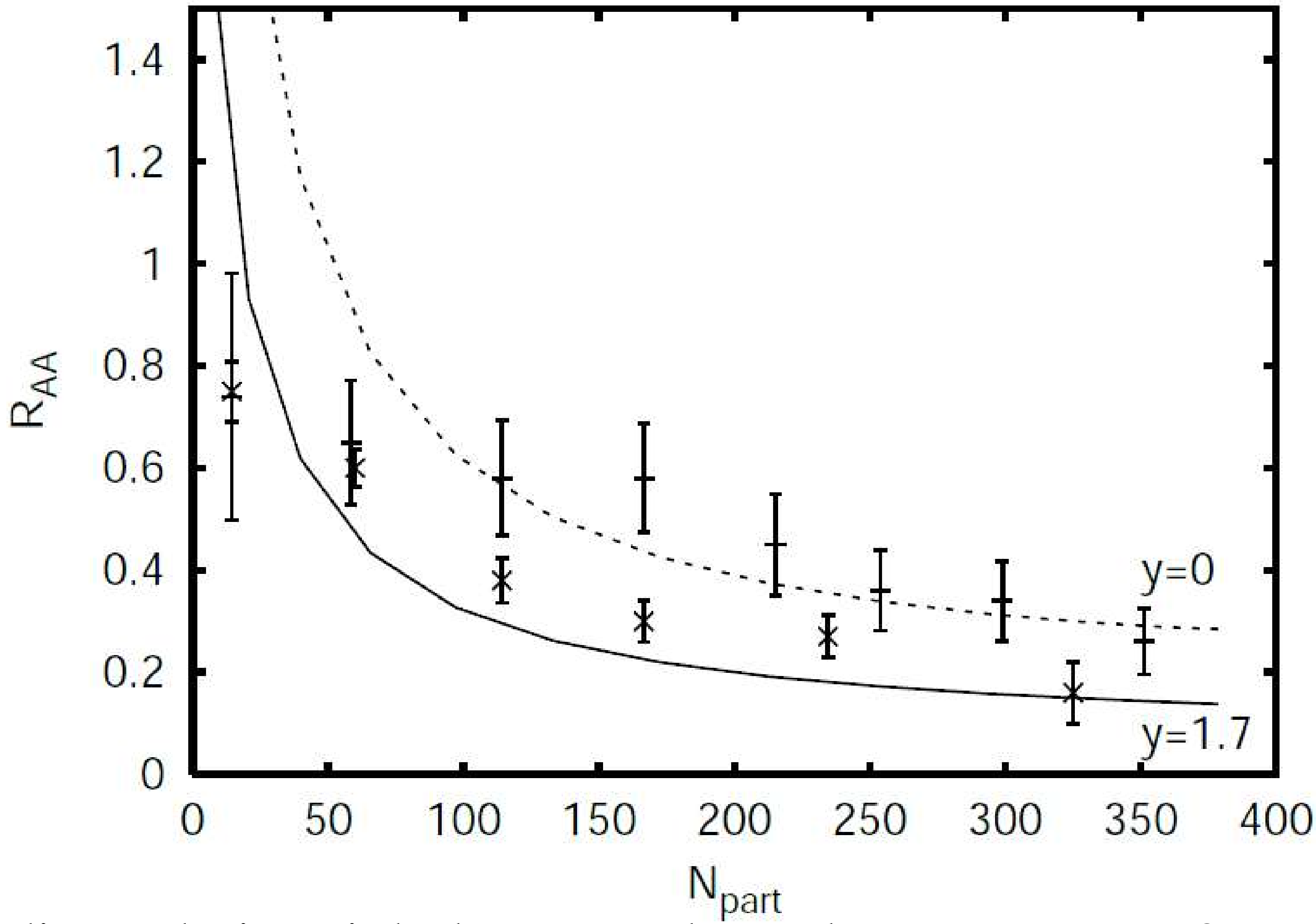
Kharzeev, Levin, Nardi, Tuchin, arXiv:0809.2933

Transverse Momentum Distributions



no strong broadening observed as expected for initial state scattering

Saturation model for J/psi production

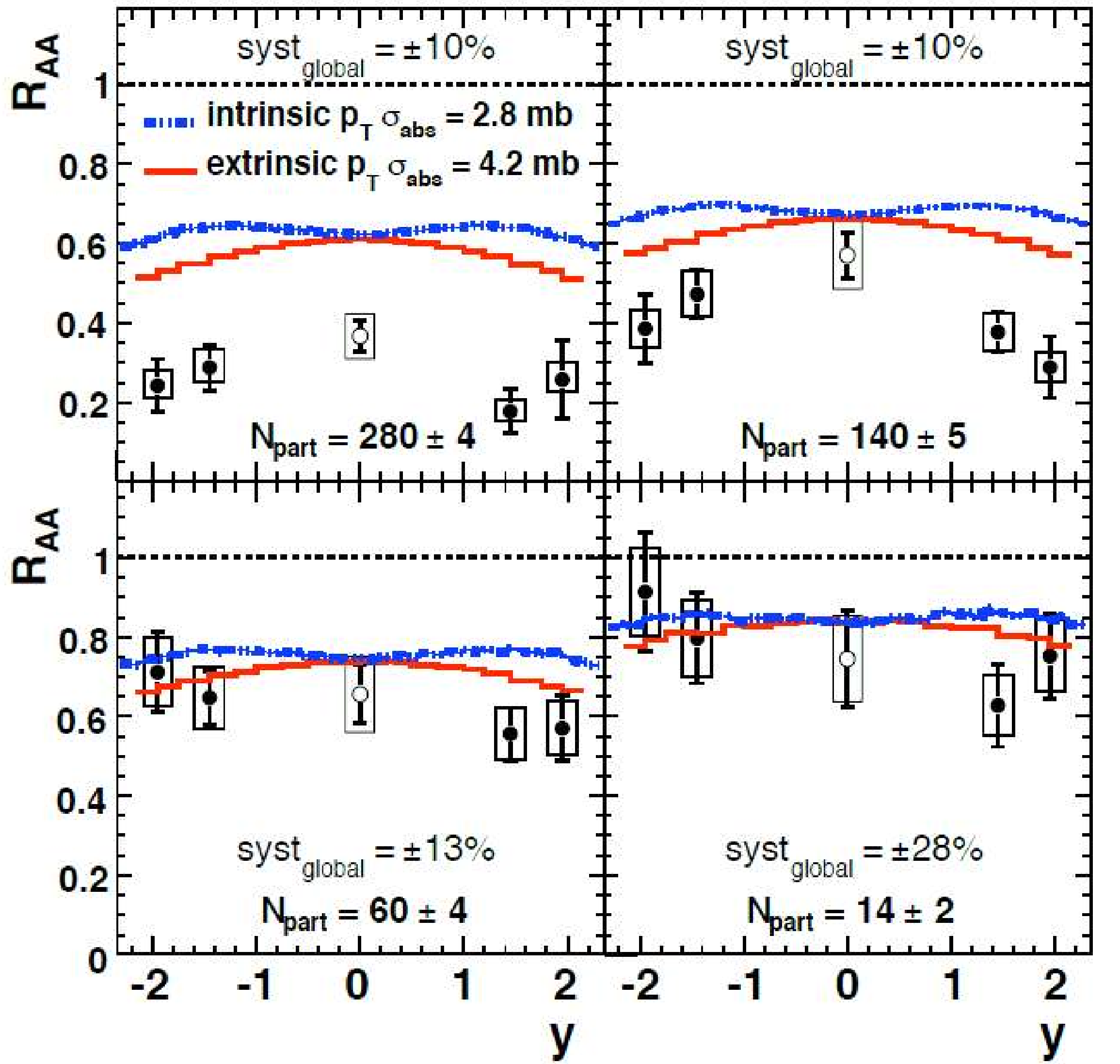


gets rapidity ordering right but N_{part} dependence too strong?

LHC data will be decisive

Kharzeev, Levin, Nardi, Tuchin, arXiv:0809.2933

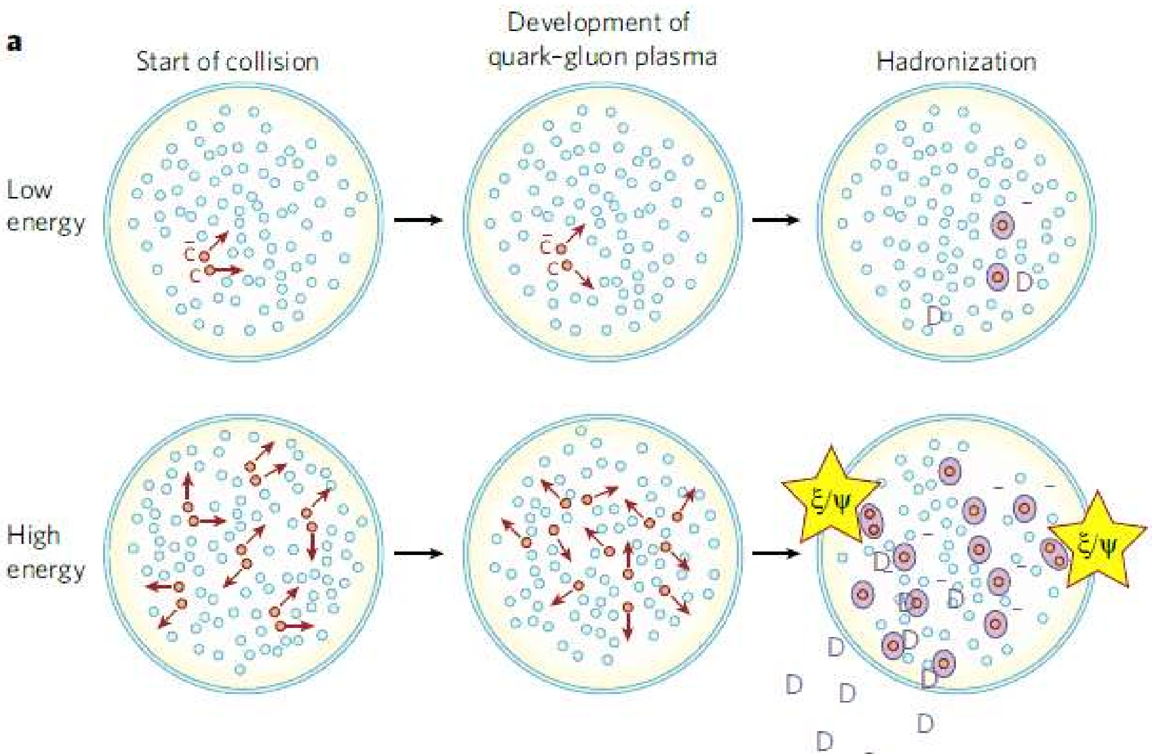
Cold nuclear matter effects on J/ψ production: intrinsic and extrinsic transverse momentum effects

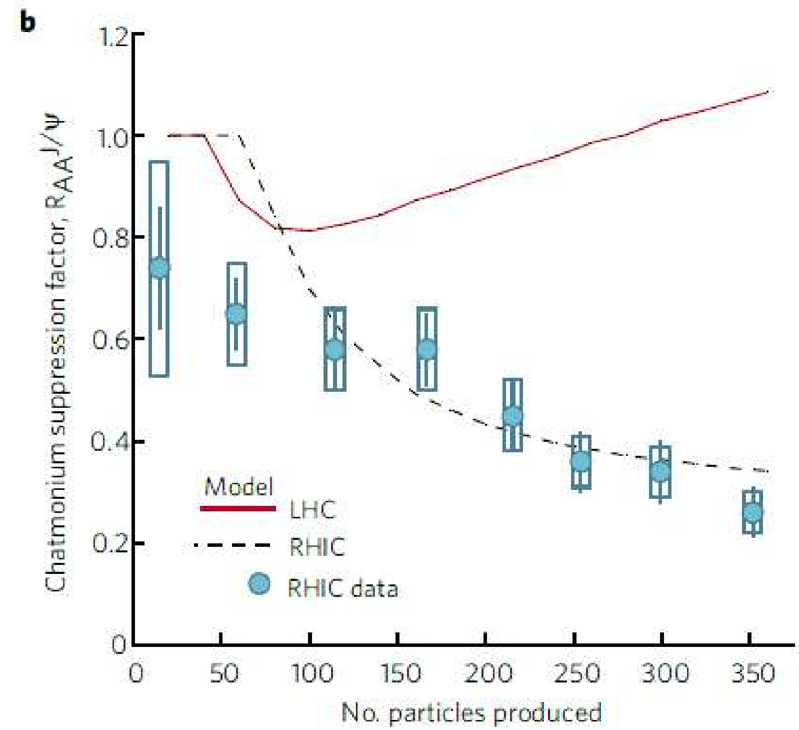


considering the process
g + g --> J/psi + g
„extrinsic“, leads to a maximum, due to gluon shadowing, in R_{AA} at y=0
but:
central collisions poorly described

Ferreiro, Fleuret, Lansberg, Rakotozafindrabe, arXiv:0809.4684

Quarkonium as a probe for deconfinement at the LHC

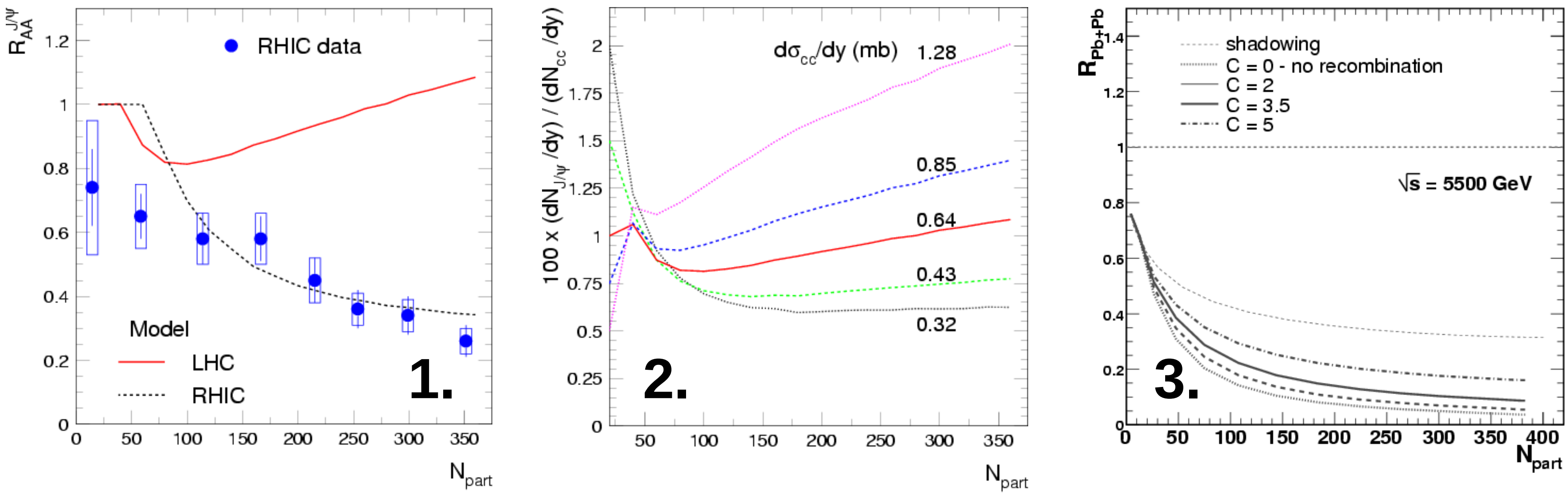




charmonium enhancement as fingerprint of deconfinement at LHC energy

TECHNISCHE UNIVERSITÄT DARMSTADT

Prediction for LHC energy: enhancement depends on charm cross section!



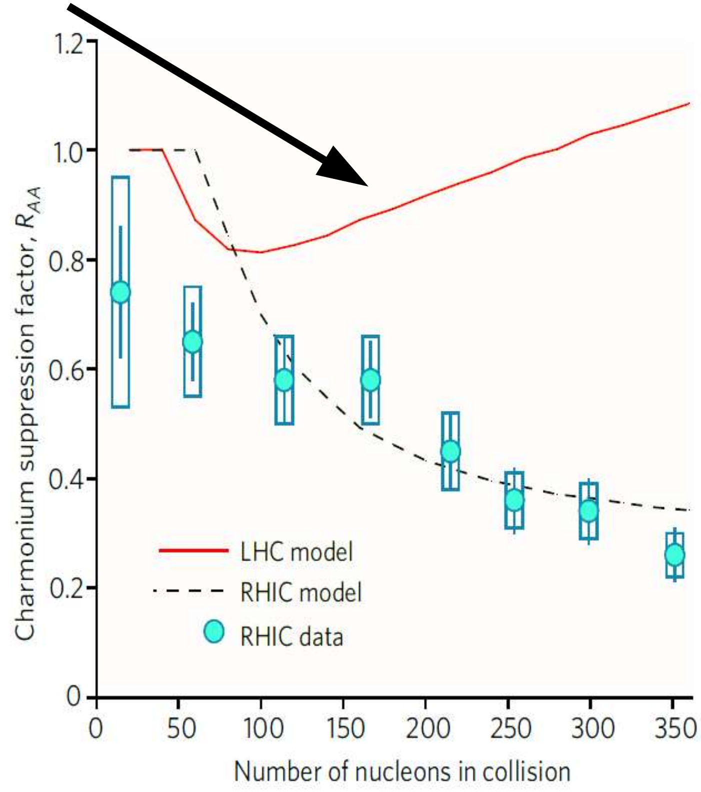
1 and 2: stat. hadronization

3: shadowing and regeneration in the hadronic phase only

A. Capella et al., arXiv:0712.4331 [hep-ph]

Summary

- charmonium production – still a fingerprint for deconfined quarks and gluons
- charm production is a hard process --> charm conservation eq. medium effects on charmed hadrons strongly suppressed
- charmonium generation at the phase boundary – a new process
- first indications for this from RHIC data
- charmonium enhancement at LHC – deconfined QGP



only at LHC energy will time scale for J/psi formation be well separated from from collision and QGP formation time

additional slides

sQGP and Charmonium Suppression

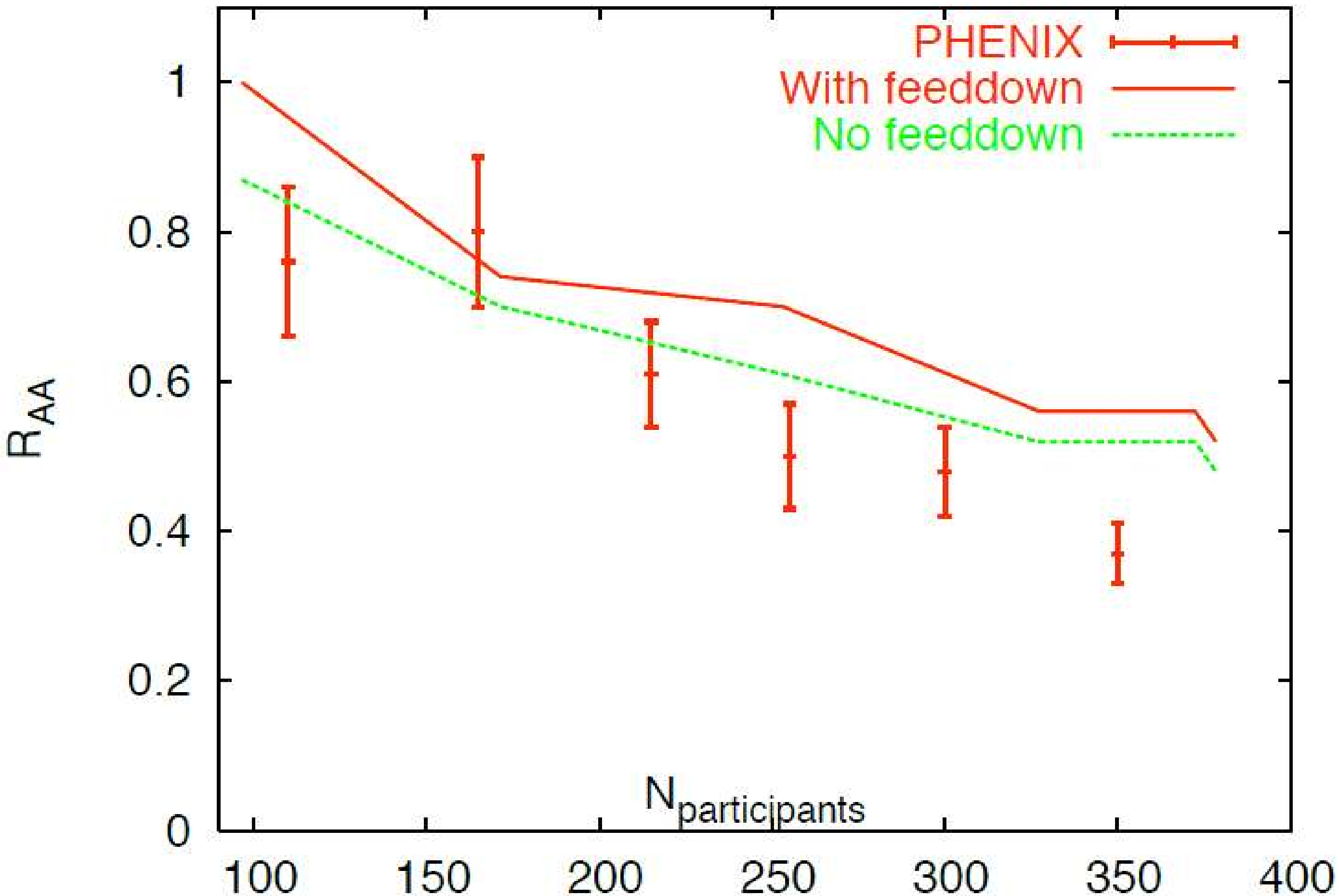
argument: spatial diffusion of charm quarks is slow in ideal fluid

$\Rightarrow$ recombination at the phase transition strongly favors 'diagonal' pairs

expect little suppression in this scenario

C. Young and E. Shuryak, arXiv:0803.2866 [nucl-th]

sQGP and Charmonium Suppression



C. Young and E. Shuryak, arXiv:0803.2866 [nucl-th]