Statistical Hadronization, Quarkonia, and the Quark-Gluon Plasma

- discussion of time scales
- remarks on 'cold nuclear matter effects'
- the statistical hadronization model
- results for SPS and RHIC energies
- outlook: what do we expect at LHC energy

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

EMMi workshop and XXVI Max Born symposium
Wroclaw, July 2009

Peter Braun-Munzinger

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

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

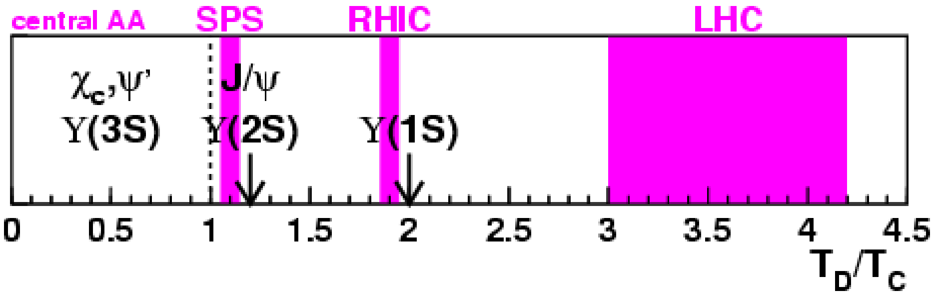
pbm and J. Stachel, arXiv:0901.2500

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

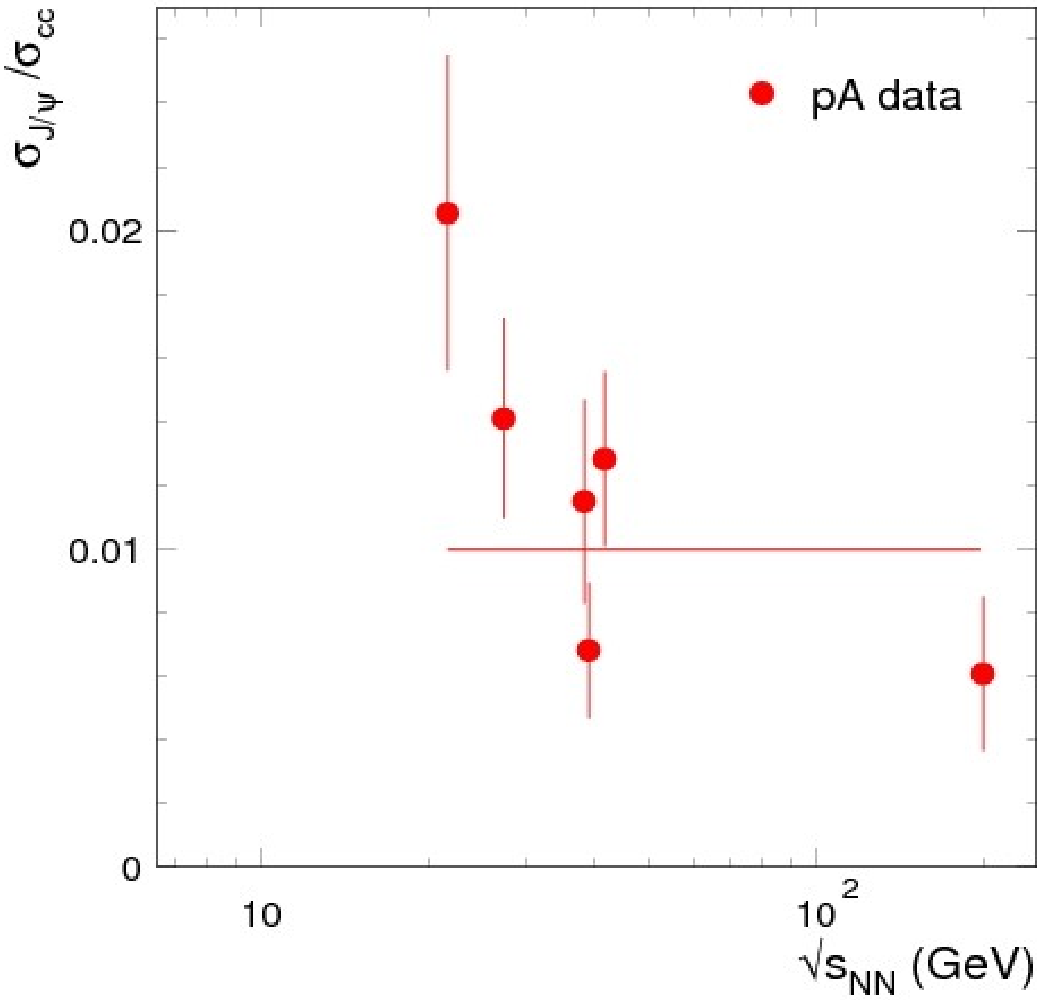


expect all charmonia to be destroyed
by QGP
but: regeneration at the phase boundary!

J/psi/cc_bar cross section

about 1 % of cc_bar pairs end up in J/psi

variation reflects uncertainty in open charm cross section?



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

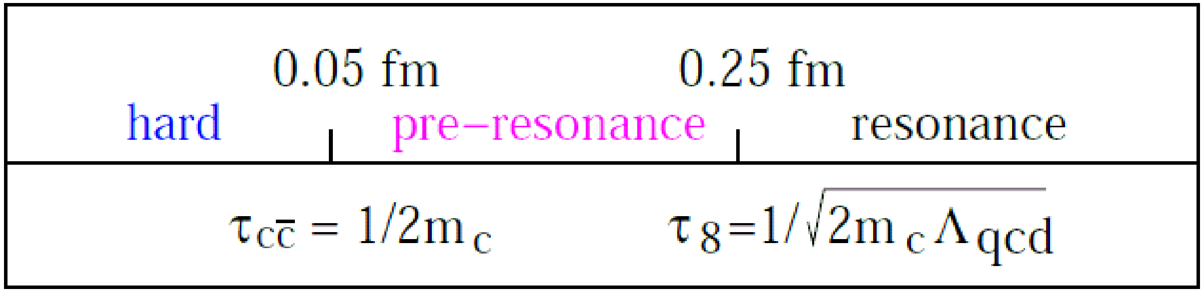
minimum formation time: $t = \text{radius}/v = 0.45$ fm

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

More timescales

formation and destruction of J/ψ (charmed hadrons)

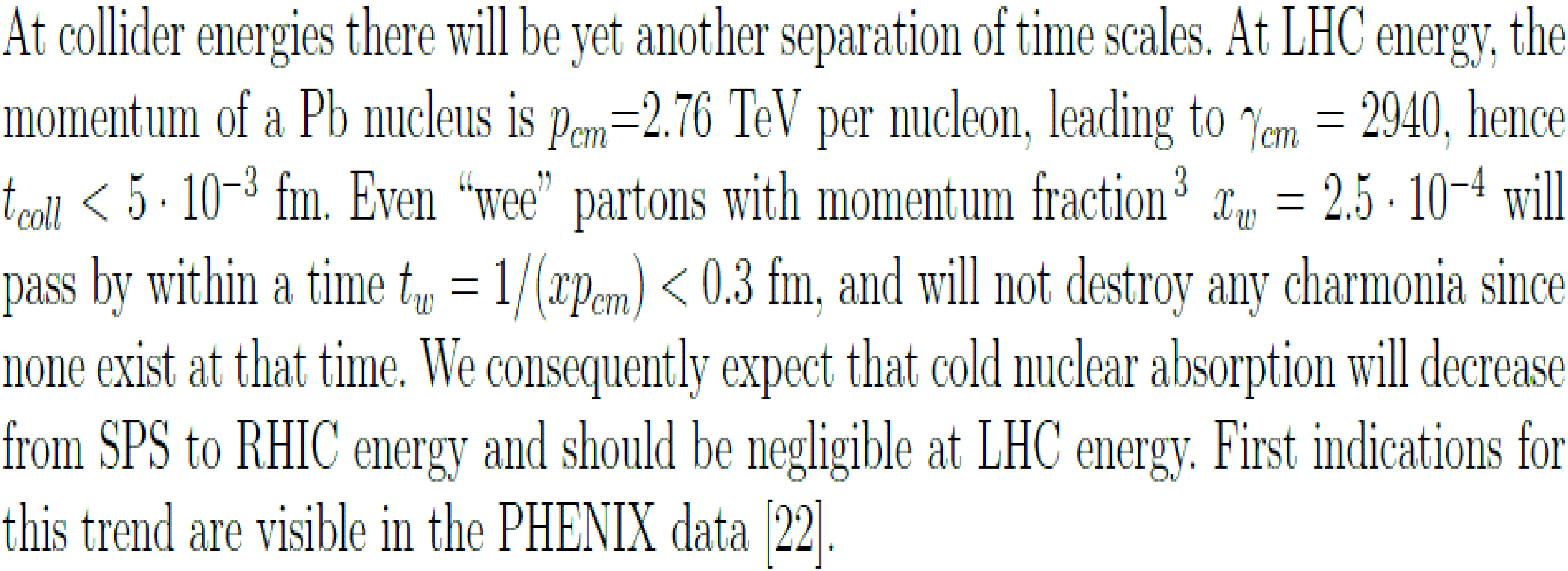
- QGP formation time, t_{QGP}
  - FAIR, SPS: $t_{QGP} \simeq 1$ fm/c $\sim t_{J/\psi}$
  - RHIC, LHC: $t_{QGP} \lesssim 0.1$ fm/c $\sim t_{c\bar{c}}$

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?

full separation of time scales at LHC energy



At collider energies there will be yet another separation of time scales. At LHC energy, the momentum of a Pb nucleus is p_{cm}=2.76 TeV per nucleon, leading to $\gamma_{cm} = 2940$, hence $t_{coll} < 5 \cdot 10^{-3}$ fm. Even "wee" partons with momentum fraction[3] $x_w = 2.5 \cdot 10^{-4}$ will pass by within a time $t_w = 1/(xp_{cm}) < 0.3$ fm, and will not destroy any charmonia since none exist at that time. We consequently expect that cold nuclear absorption will decrease from SPS to RHIC energy and should be negligible at LHC energy. First indications for this trend are visible in the PHENIX data [22].

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
energy loss effects

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

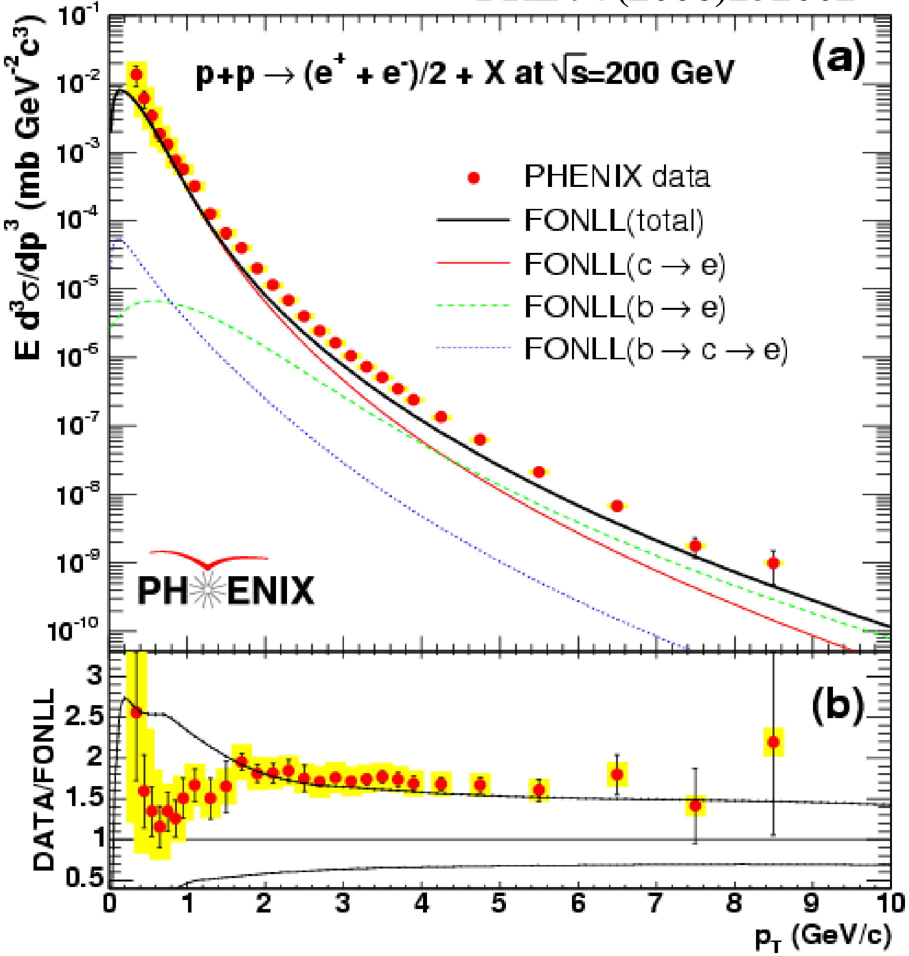
need to normalize charmonium production to open charm cross section in AA collisions

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

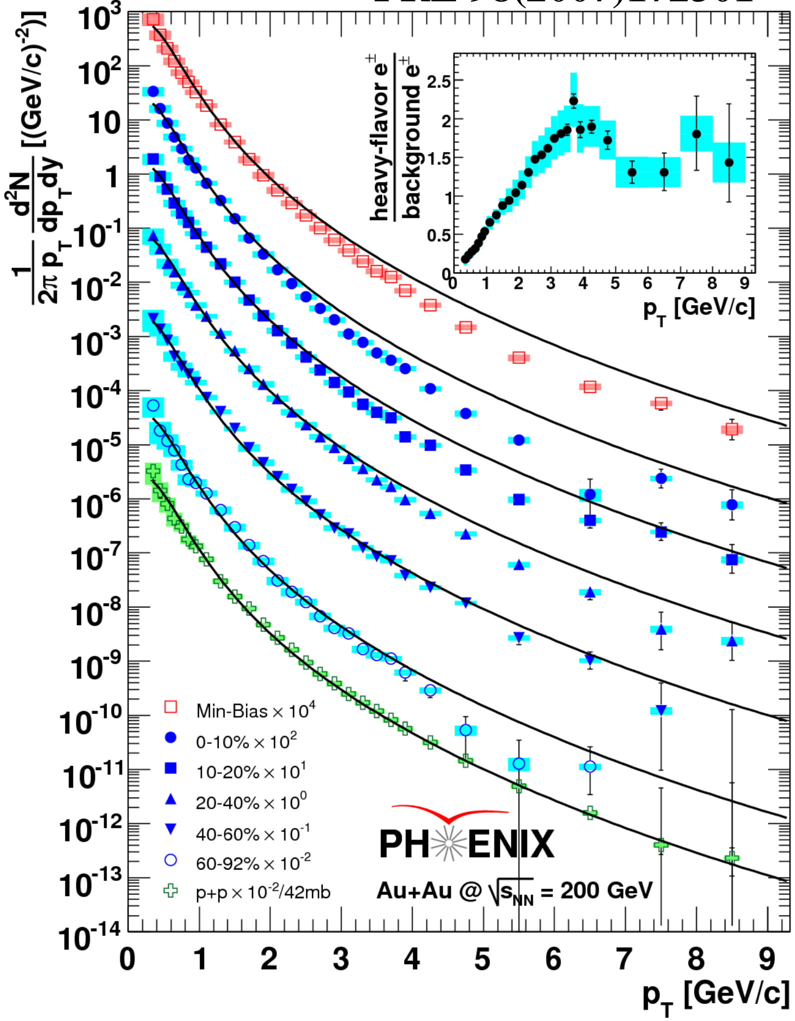
is there any evidence for saturation or shadowing from RHIC data?? $\sigma_{ccbar}(AA) = N_{coll}\,\sigma_{ccbar}(pp)$??

PHENIX data on charm cross section

PRL 97(2006)252002

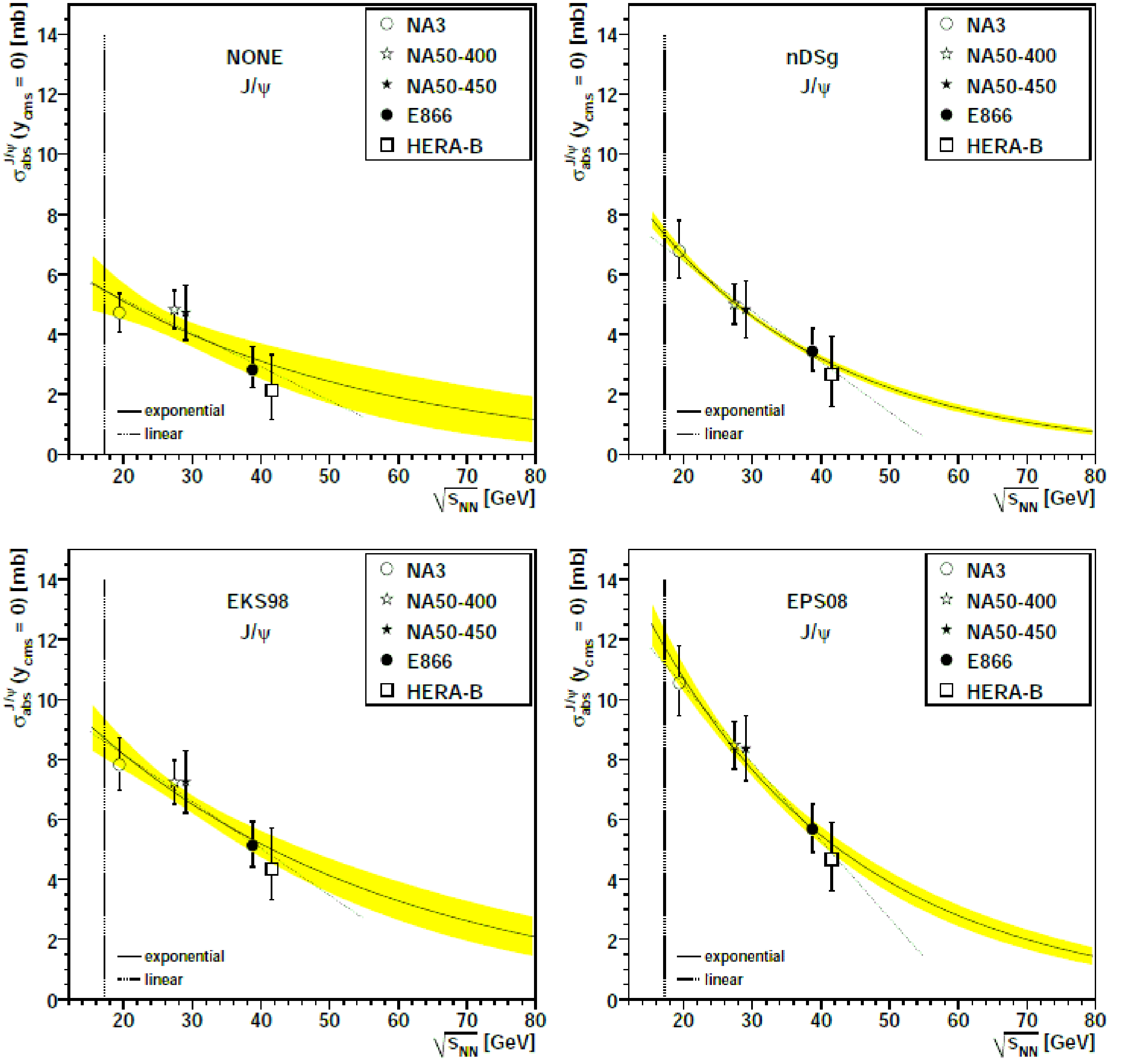


PRL 98(2007)172301



PHENIX open charm cross section is close to pQCD prediction
STAR value is about a factor of 2 larger ... not understood
need vertex detectors!   But no evidence for shadowing so far.

Energy dependence of J/psi absorption cross section



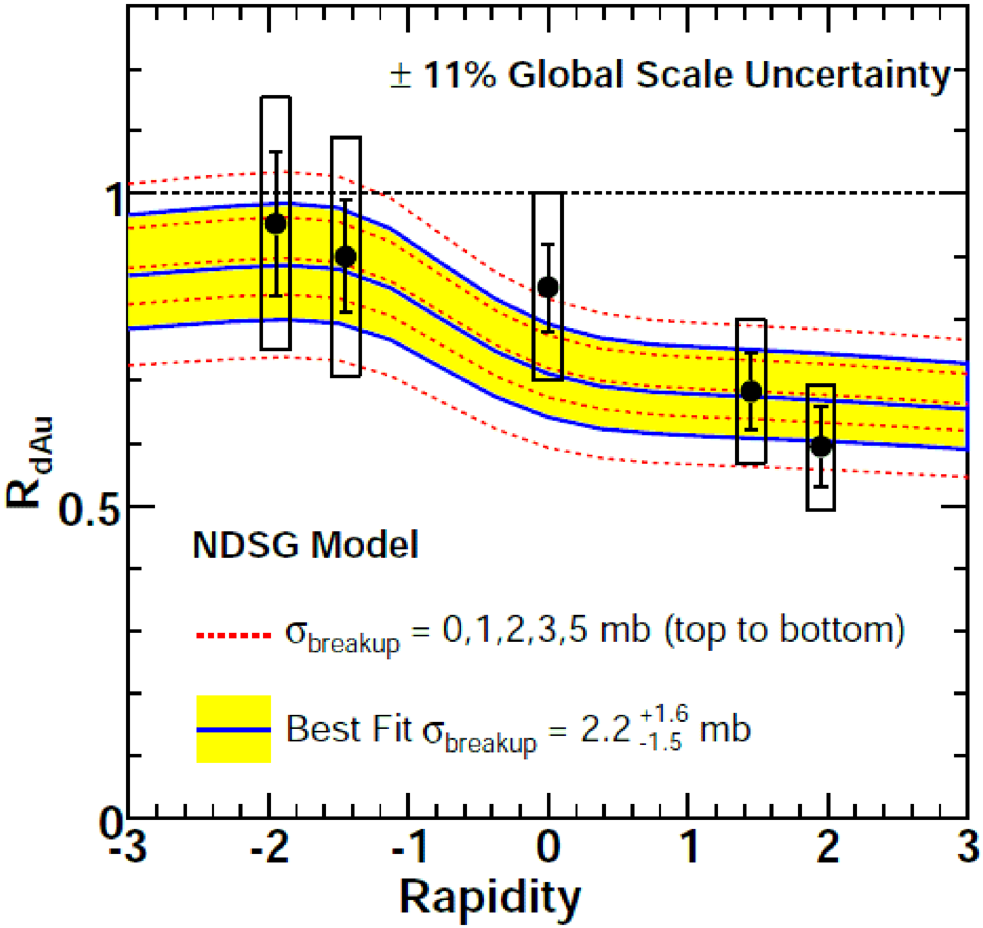
C. Lourenco, R. Vogt, H. Woehri
JHEP 0902 (2009) 014
arXiv:0901.3054 [hep-ph]

sig_abs = 5.8 – 11.5 mb
depending on shadowing

Cold nuclear matter effects at RHIC

see: R. Granier de Cassagnac
SQM2008
arXiv:0901.1647 [hep-ph]

large systematic uncertainty
(about 2 mb)

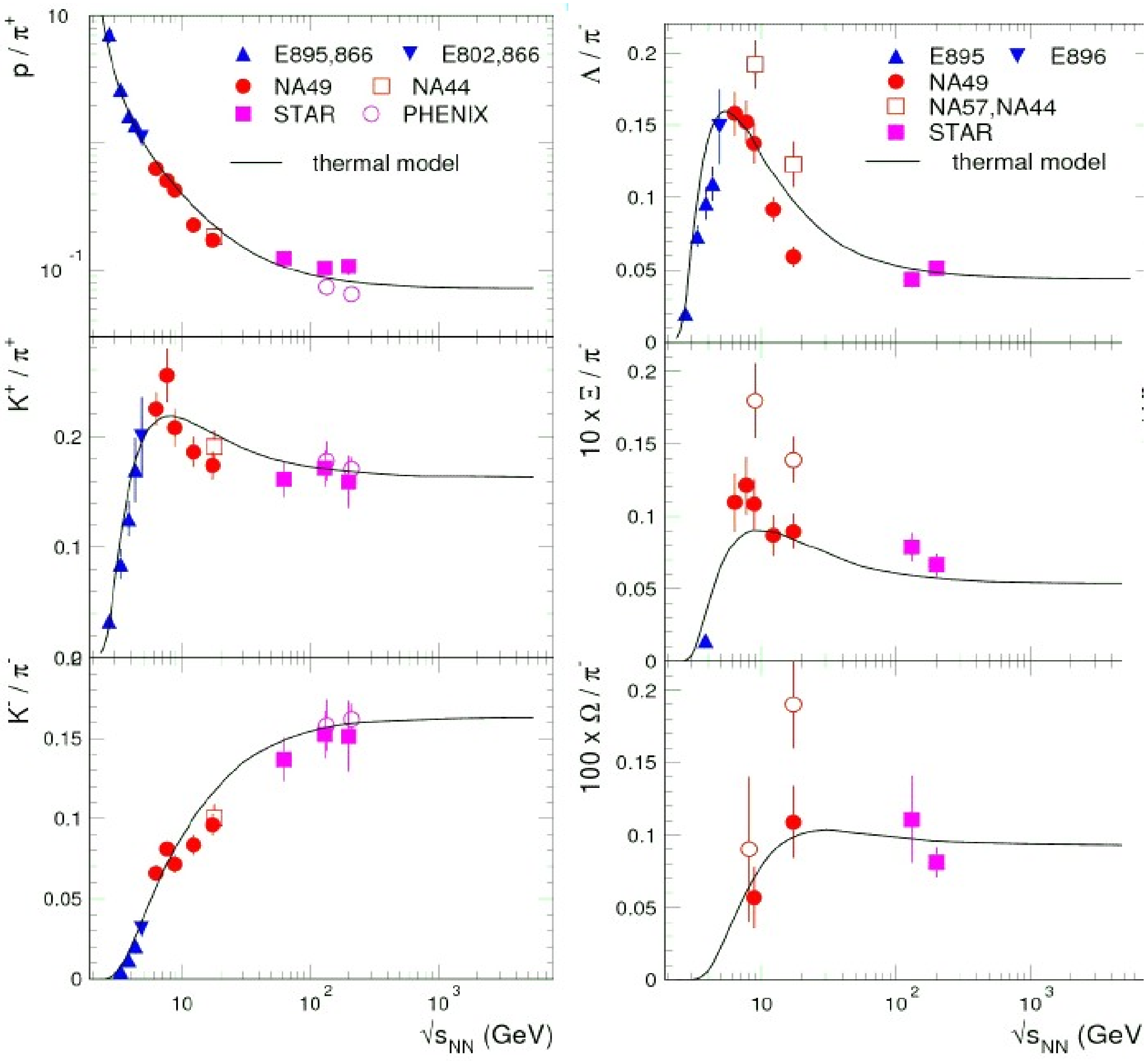


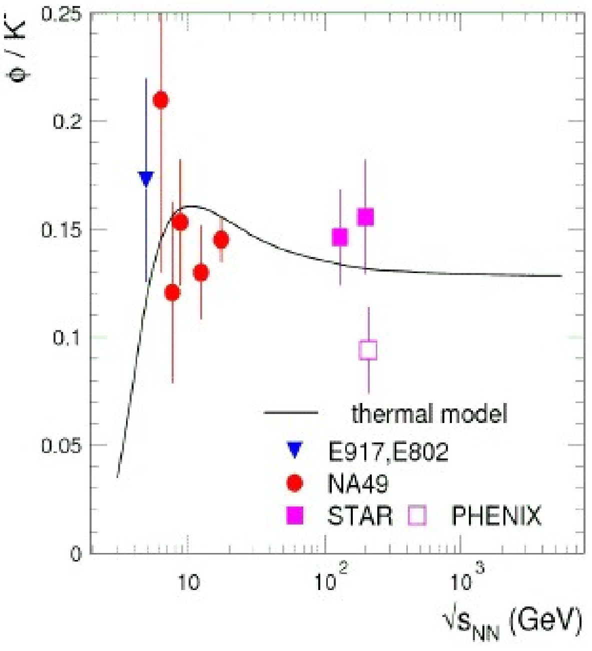
A brief aside: production of light-flavored hadrons (u,d,s)

- no separation of scales
- strong evidence for thermal production at the QCD phase boundary

Synopsis of most recent thermal model results for (u,d,s) hadrons

A. Andronic, pbm, J. Stachel,
Phys. Lett. B673 (2009) 142
arXiv:0812.1186 [nucl-th]



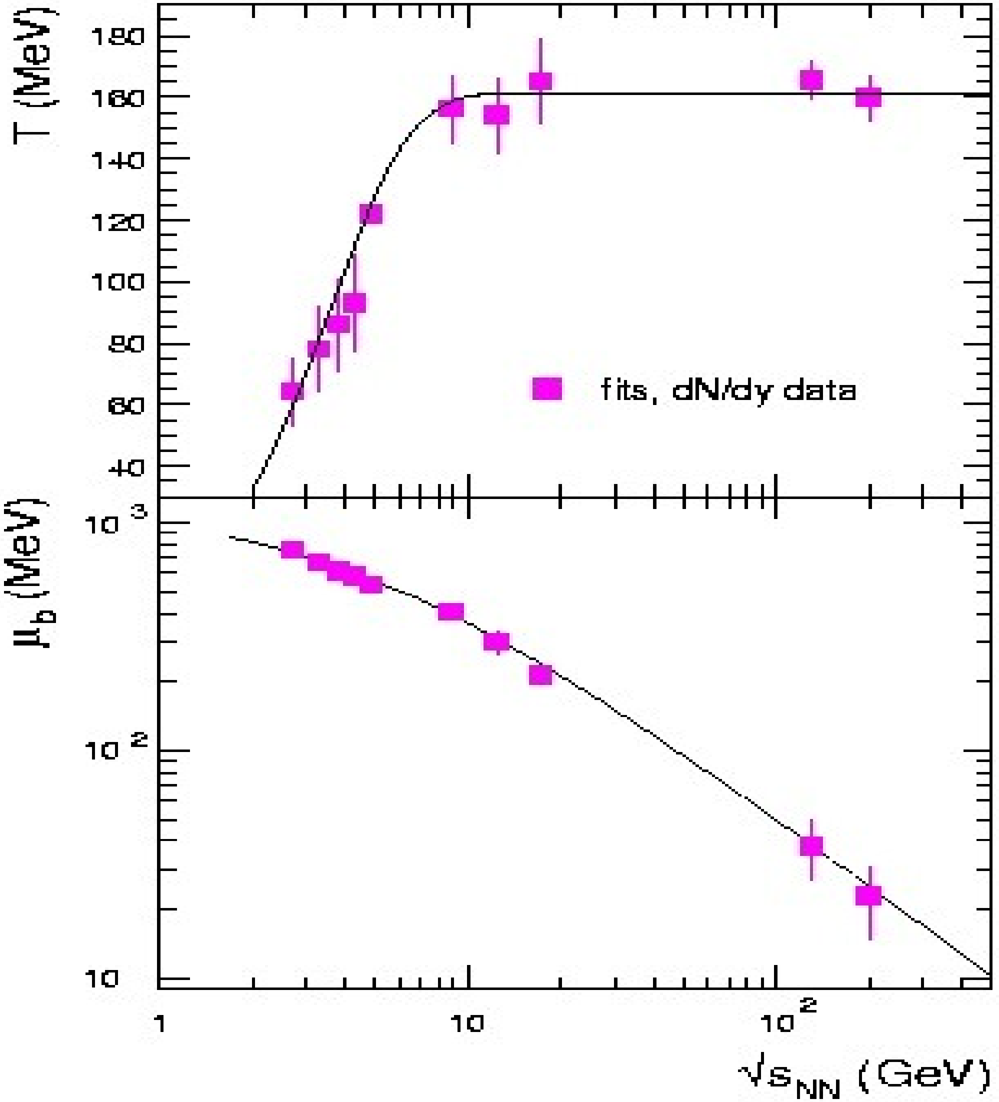


Parameterization of all freeze-out points

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

Are charmonia (and charmed hadrons) produced thermally?

ratios of charmed and beauty hadrons exhibit thermal features (Becattini 1997)
but: (J/ψ)/ψ' 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/ψ)/ψ' ratio reaches a thermal value (T=170 MeV) in central PbPb collisions at SPS energy

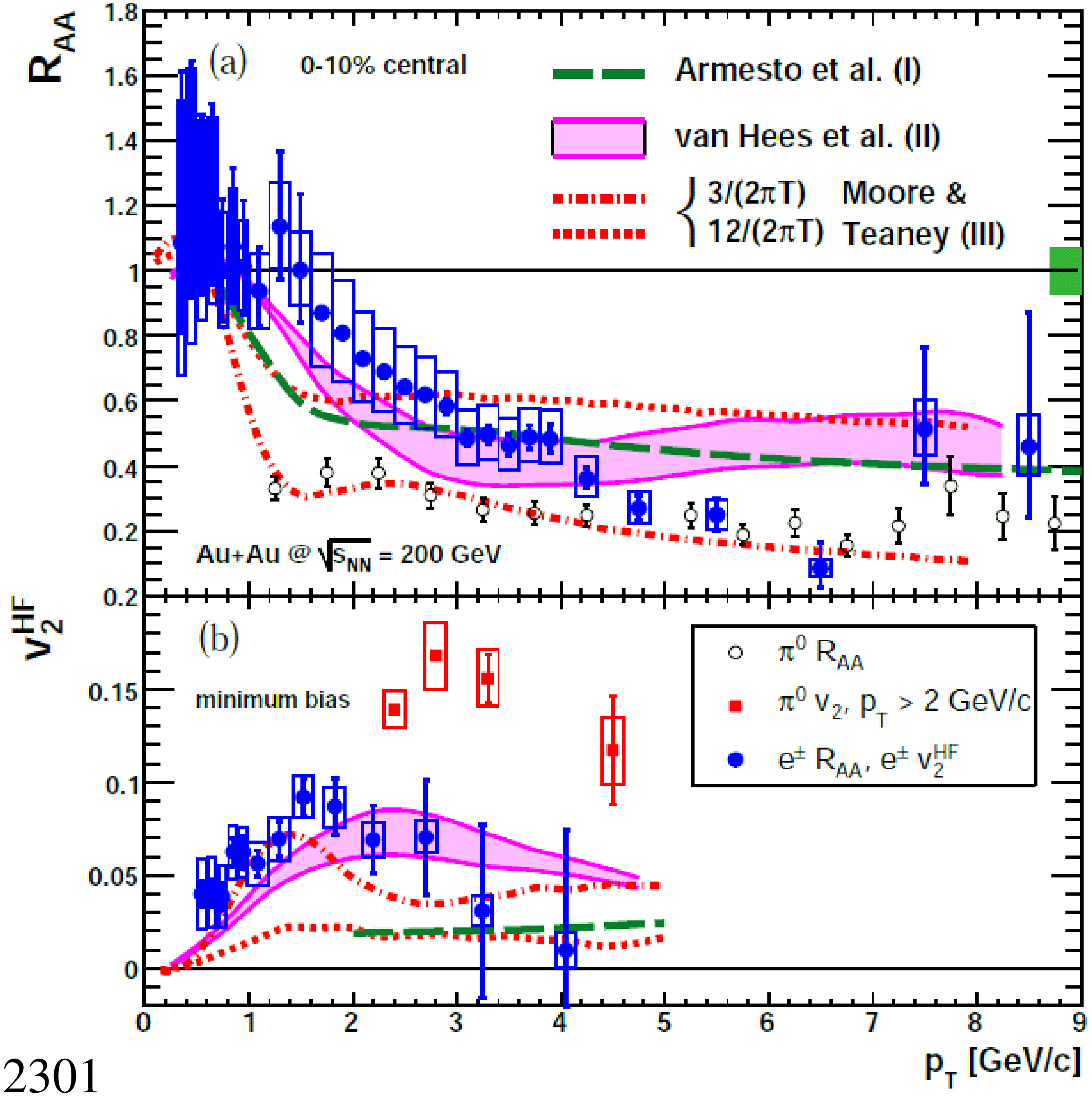
further analysis by Gorenstein and Gazdzicki, Phys. Rev. Lett. 83 (1999) 4003
result: (J/ψ)/π is approximately constant at SPS energy for PbPb

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.

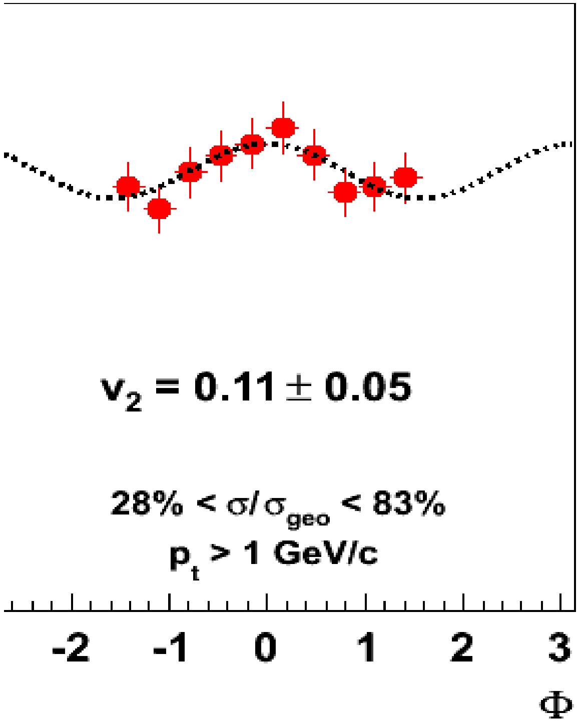
Energy loss and flow of heavy quarks

charm quark flow and large energy loss imply approach to thermal but not chemical equilibrium



PHENIX coll., PRL 98 (2007) 172301
nucl-ex/0611018

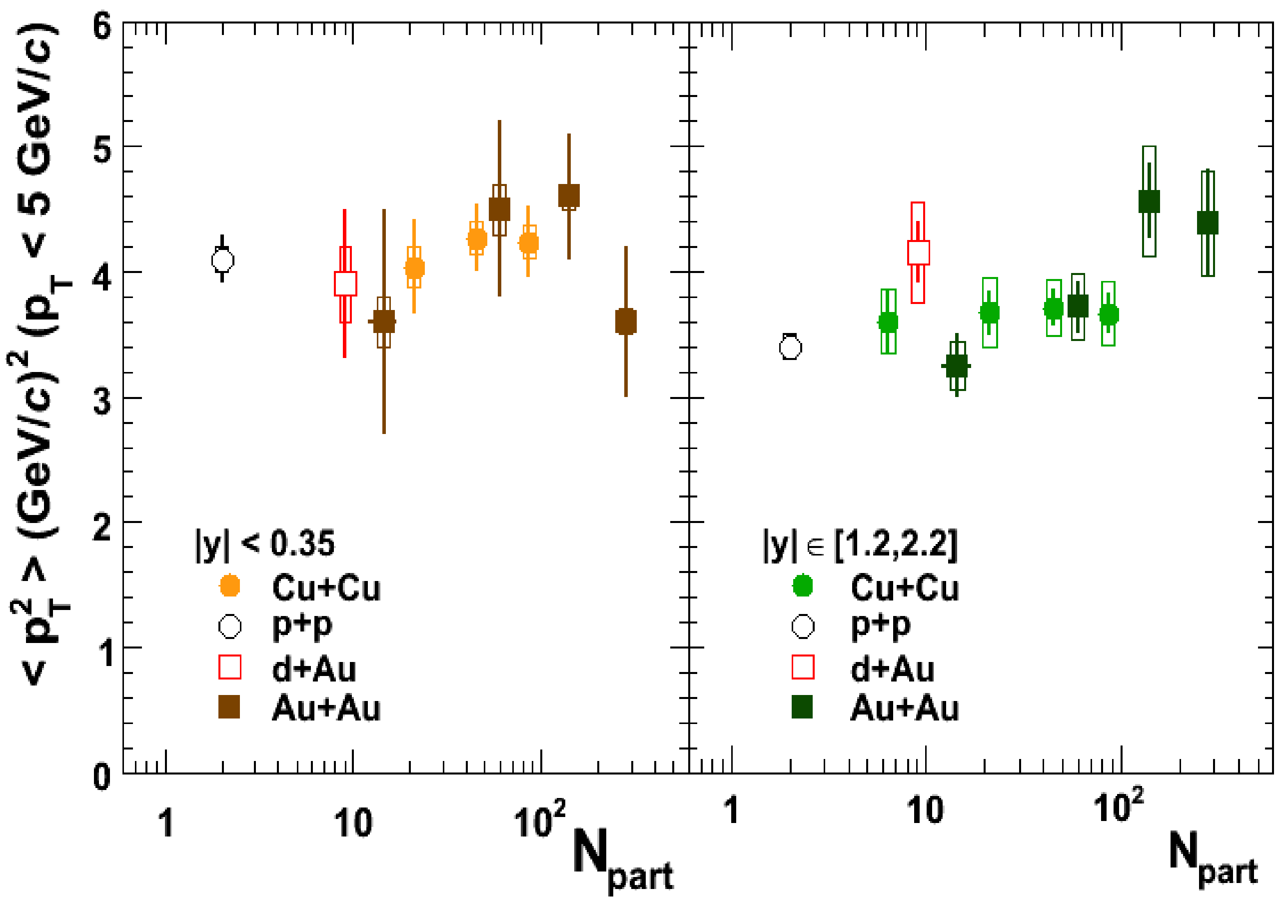
Elliptic flow of J/psi!!



In+In, SPS energy, NA60 collaboration

thermalization of charm quarks

Transverse Momentum Distributions



no strong broadening observed as expected for initial state scattering

this is different from the situation at the SPS

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

  → 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

  → yield ~ N_c^2 -- quarkonium enhancement at high energies

Method and inputs

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

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

$N_{c\bar{c}} << 1 \rightarrow$ **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)

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

important pre-requisite: all ratios among charmonia must be thermal

Recent publications:

Anton Andronic, pbm, Krzysztof Redlich, Johanna Stachel

J.Phys.G35:104155,2008.
e-Print: arXiv:0805.4781 [nucl-th]

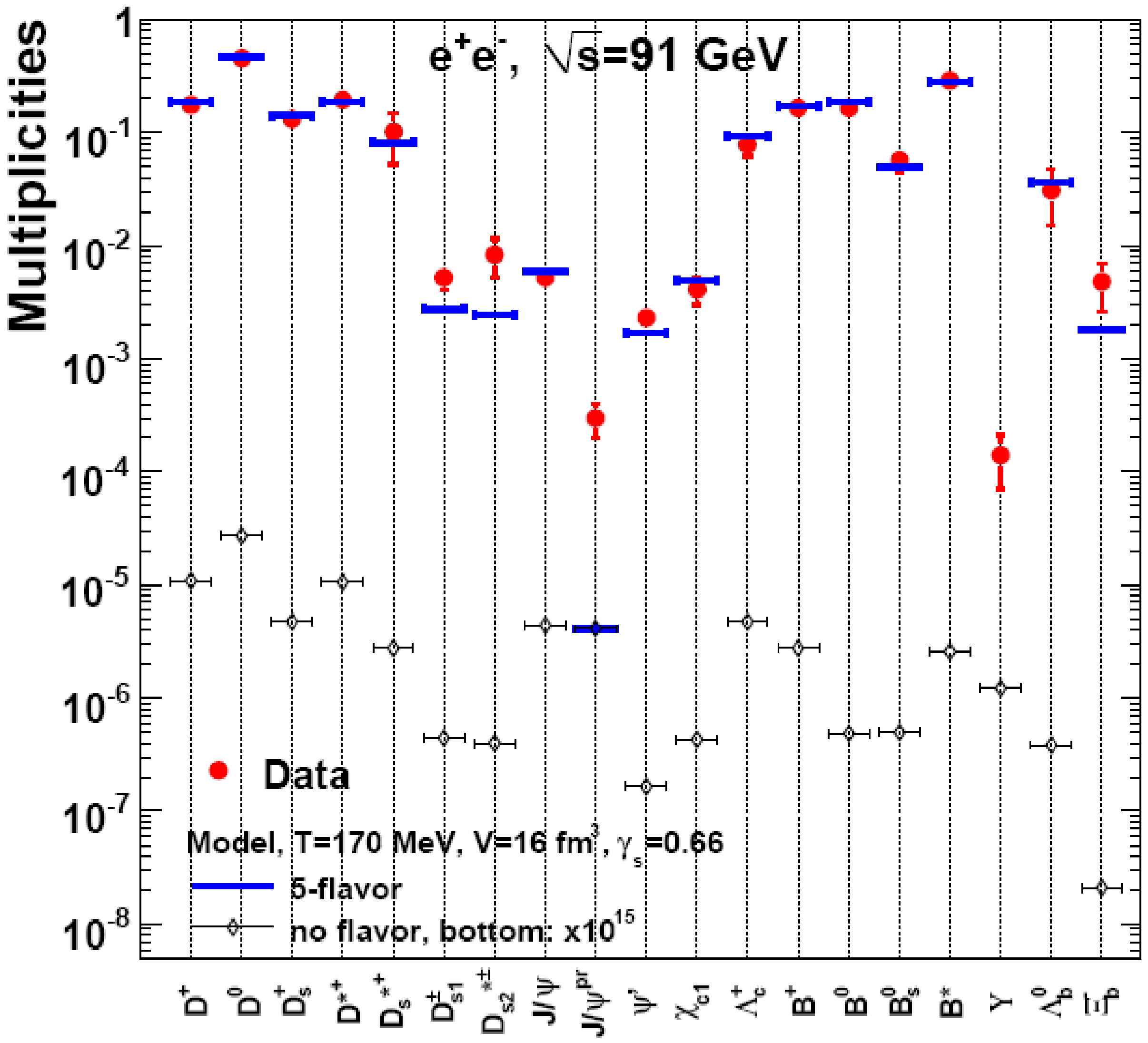
PoS CPOD07:044,2007.
e-Print: arXiv:0710.1851 [nucl-th]

Phys.Lett.B652:259-261,2007.
e-Print: nucl-th/0701079

Nucl.Phys.A789:334-356,2007.
e-Print: nucl-th/0611023

Phys. Lett. B in print, arXiv:0903.1610 [hep-ph]

Heavy quark and quarkonium production in e+e- collisions

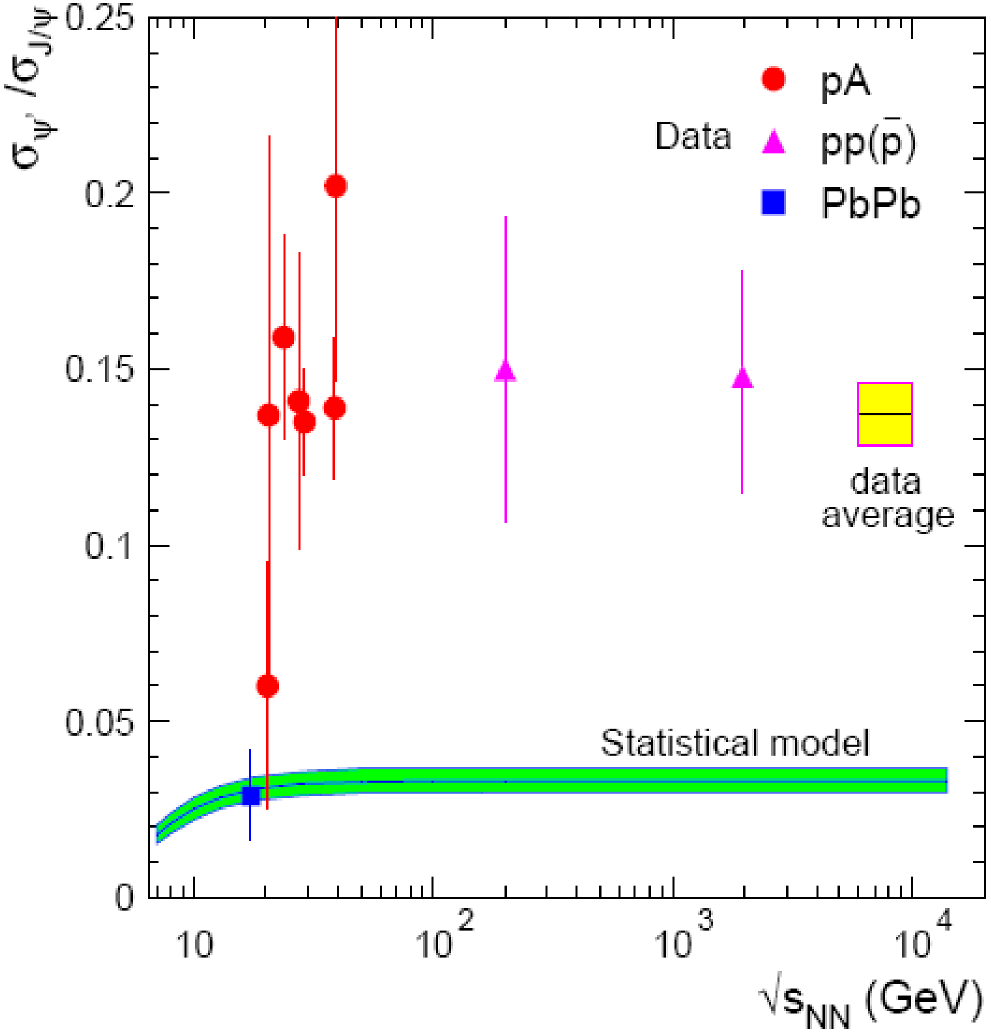


Comparison of stat.
model calcs.
with data

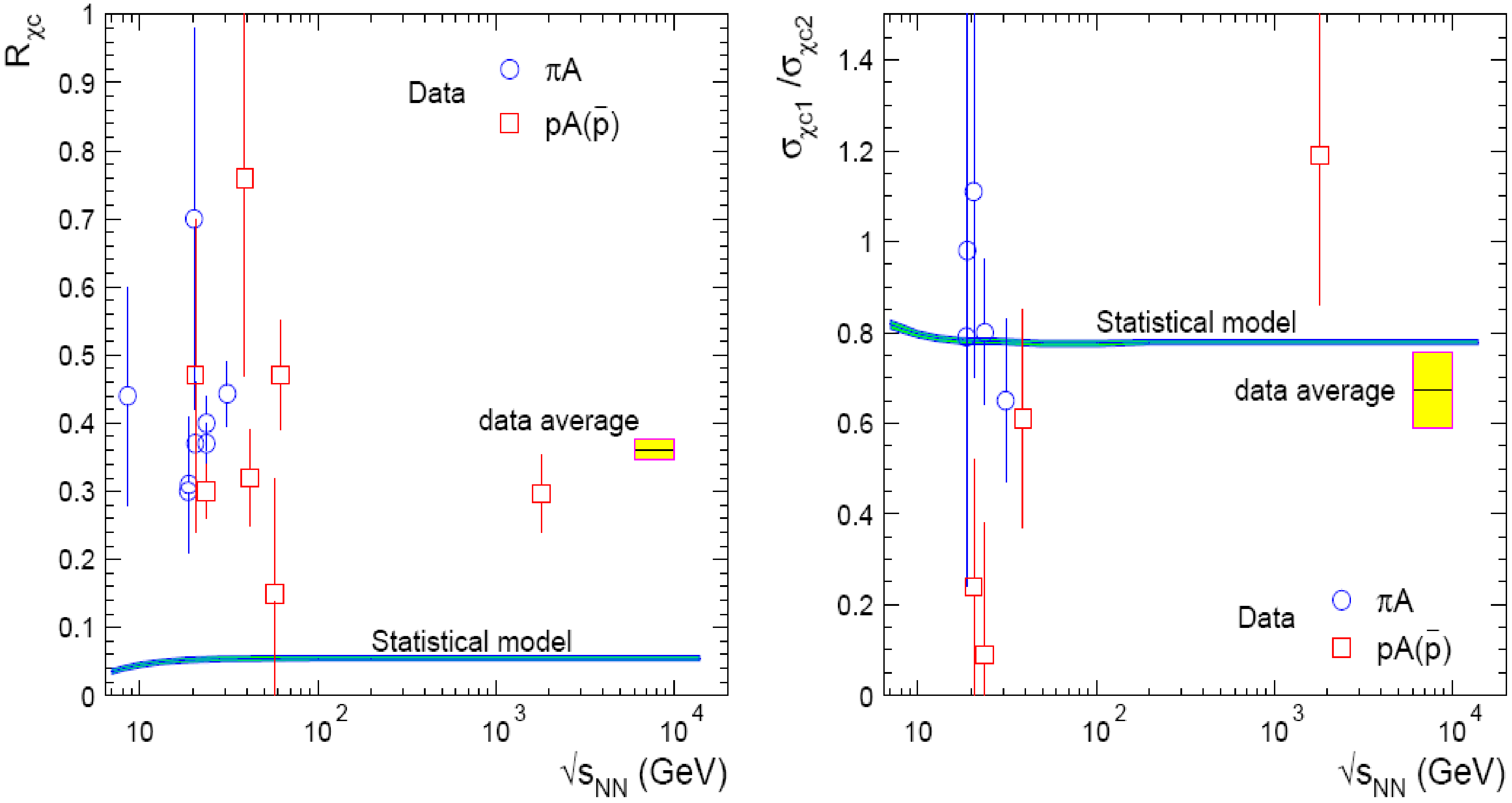
Phys. Lett. B in print,
arXiv:0903.1610 [hep-ph]

charmonium ratios not thermal

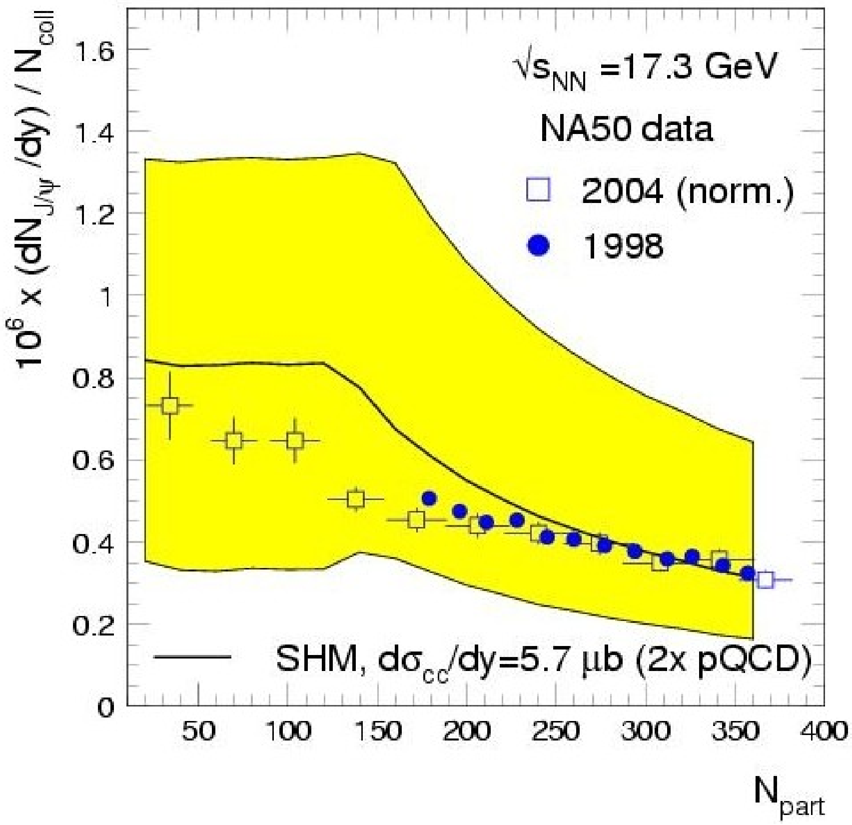
The psi'/psi ratio in elementary and AA collisions

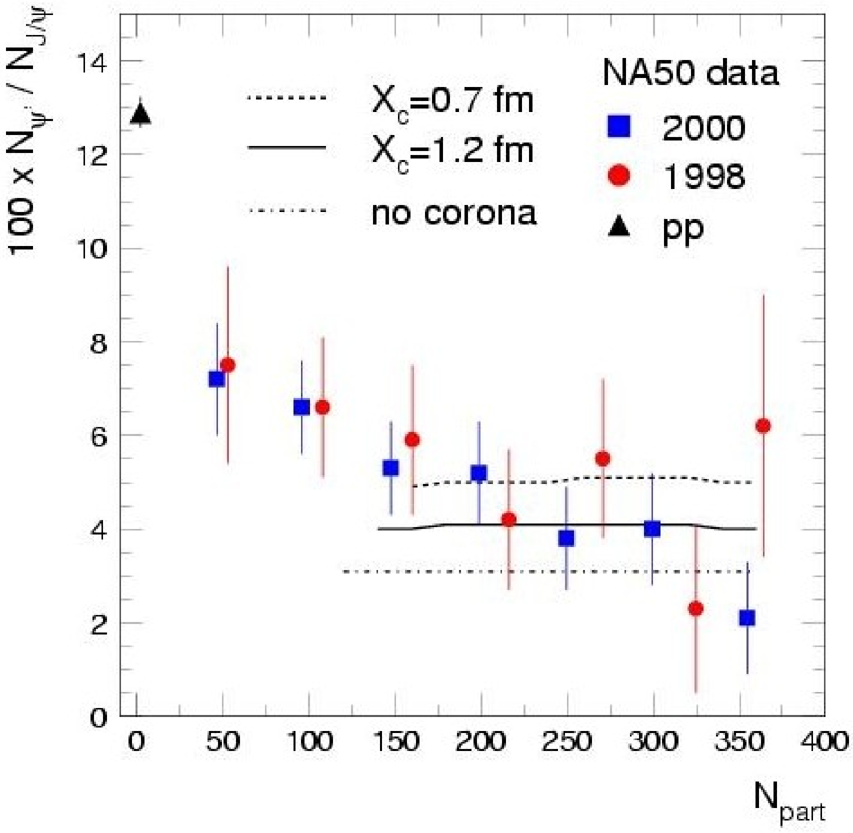


Ratios involving chi_c



results for SPS energy

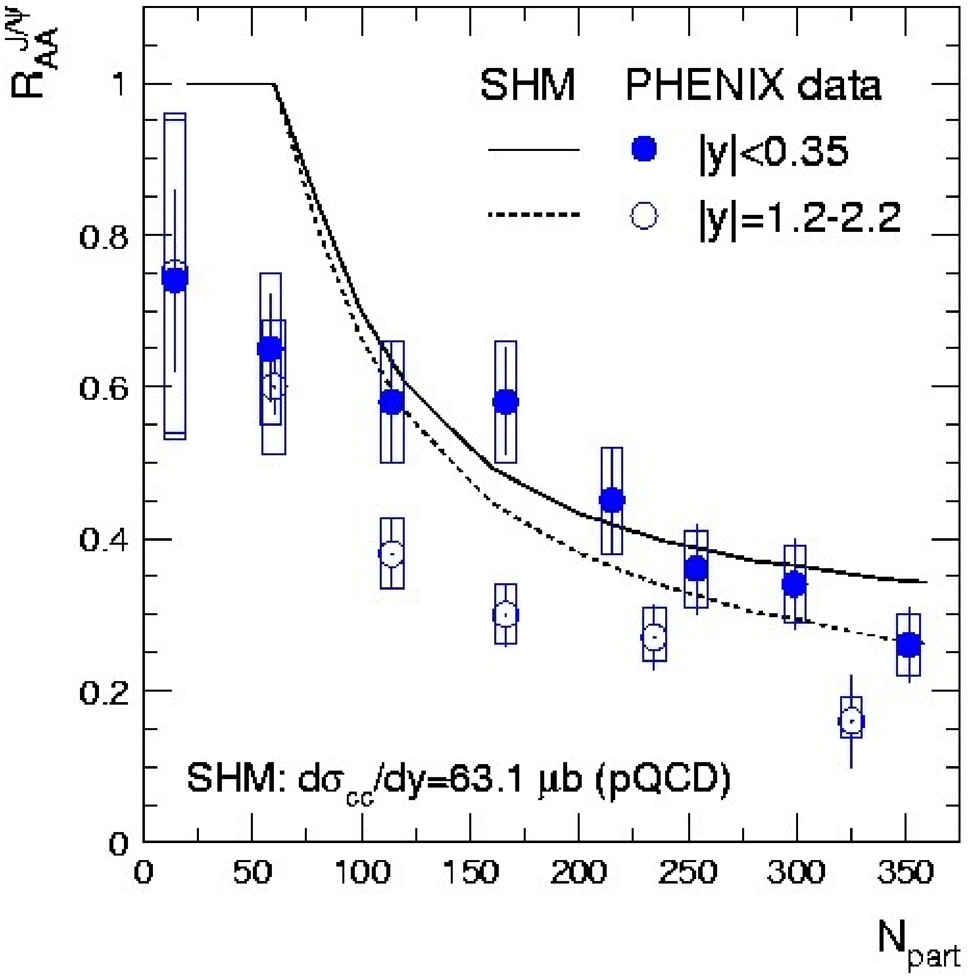




only moderately enhanced (2 x pQCD) cc_bar cross section needed

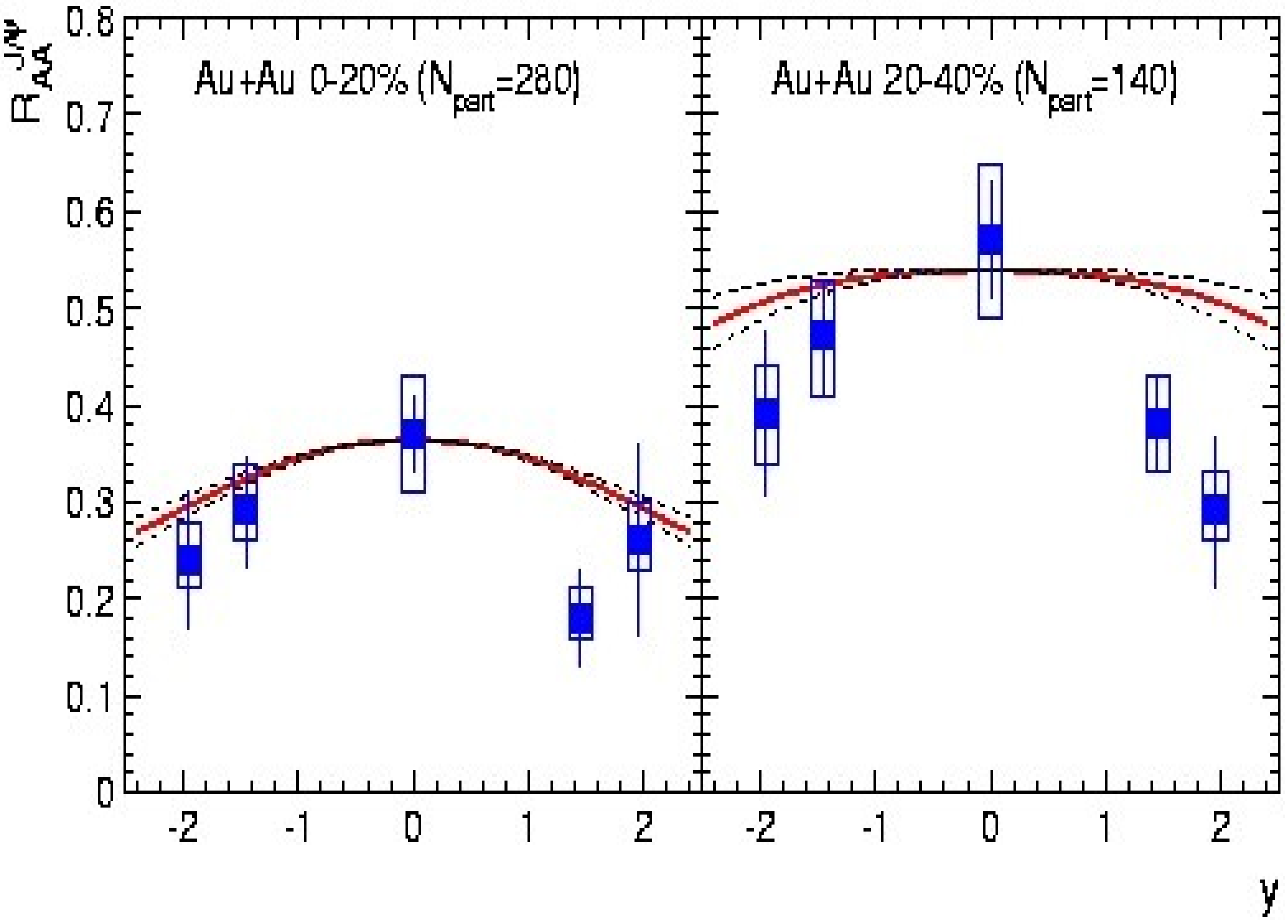
extrapolation to pp for ψ'/ψ ratio still problematic in the model, although intuitively clear

Centrality dependence of nuclear modification factor



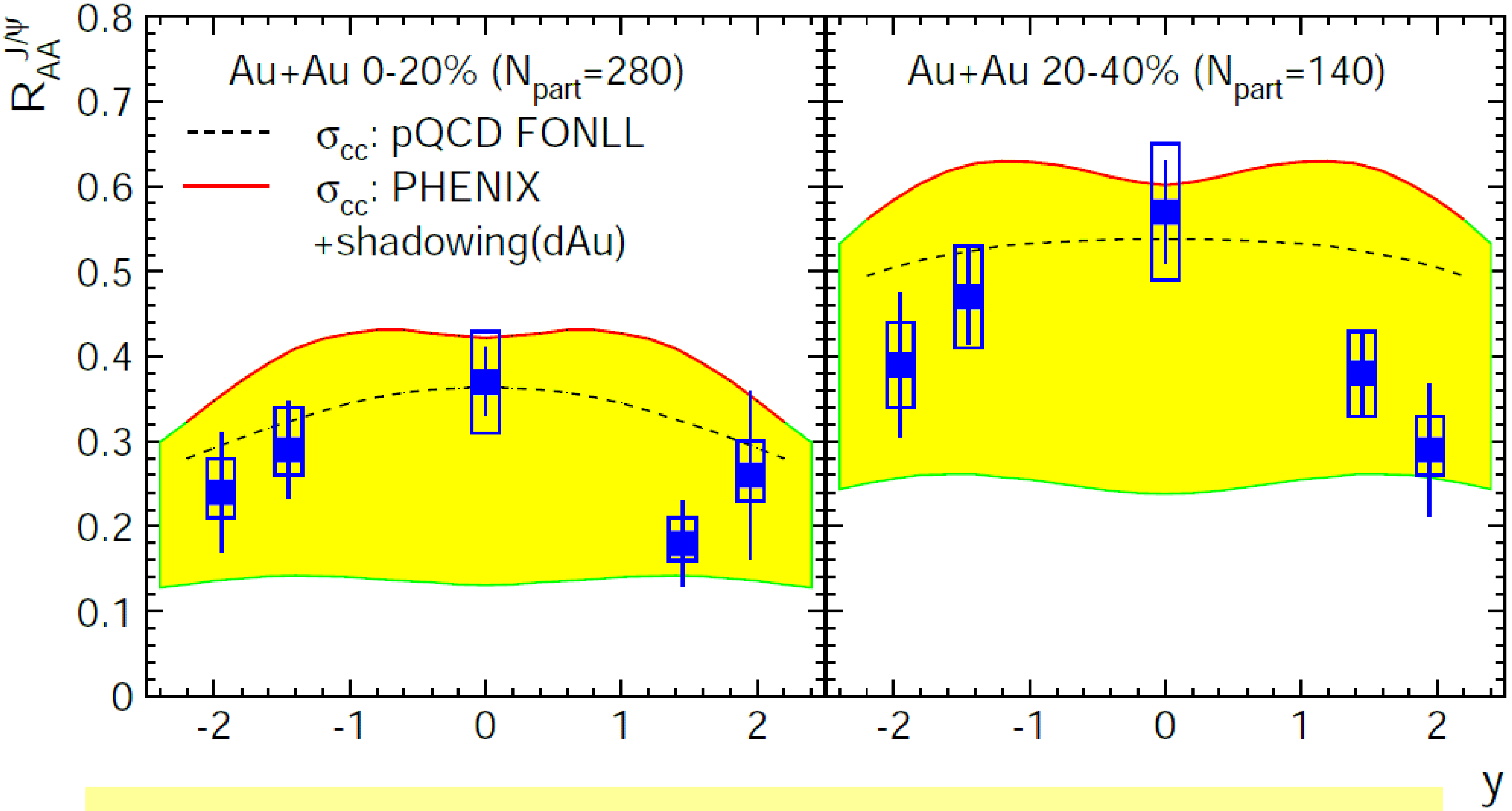
data well described
by our regeneration model
without any new
parameters

Comparison of model predictions to RHIC data: rapidity dependence



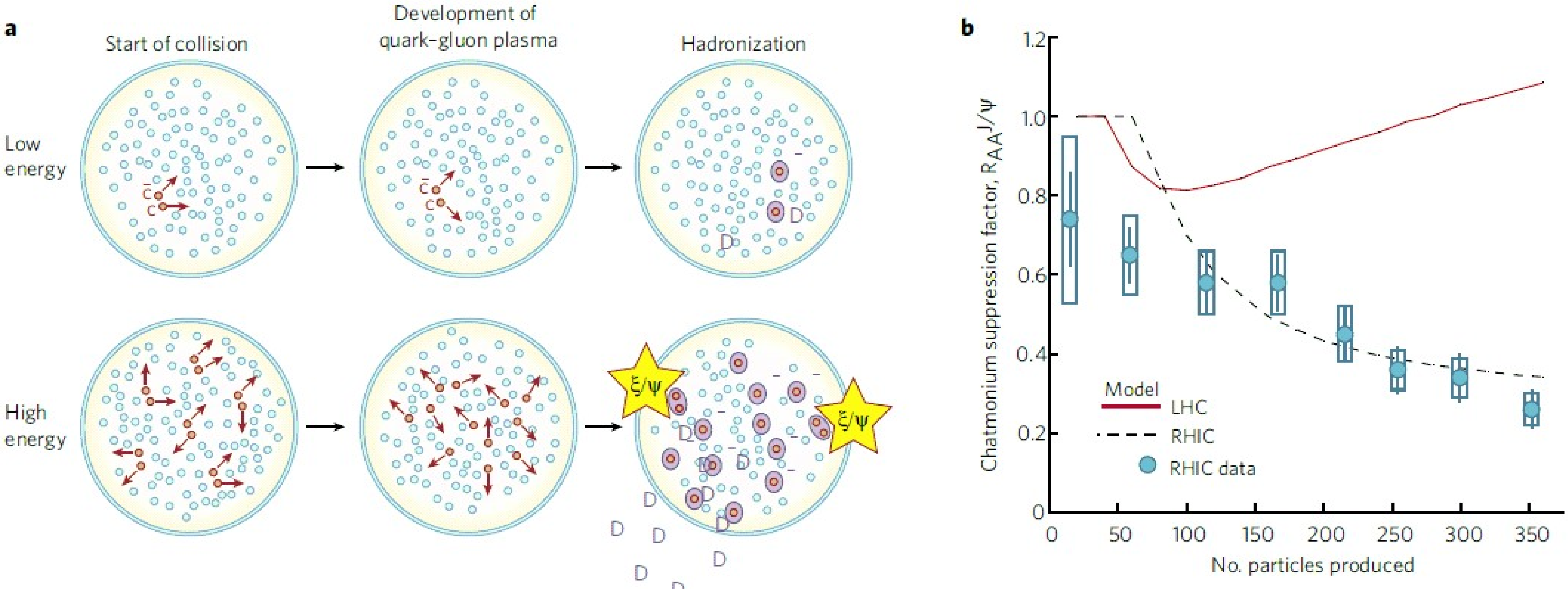
suppression is smallest at mid-rapidity (90 deg. emission)
a clear indication for regeneration at the phase boundary

Calculations including shadowing



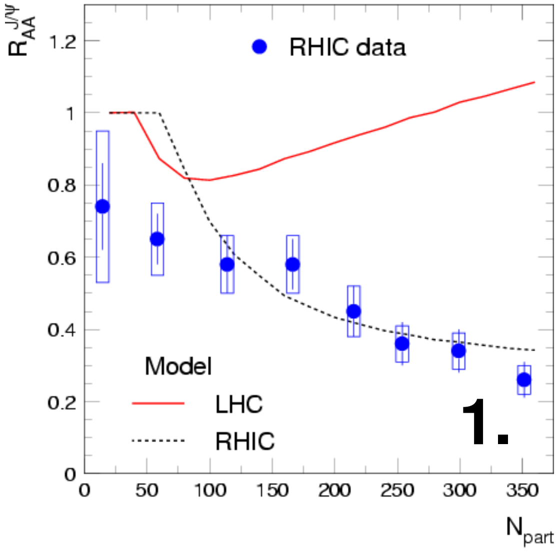
assume PHENIX pA data reflect shadowing
consistent with most recent PHENIX analysis
by Frawley et al.

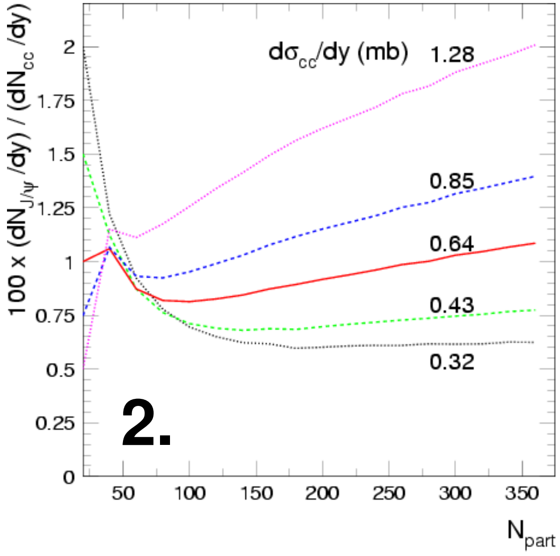
Quarkonium as a probe for deconfinement at the LHC

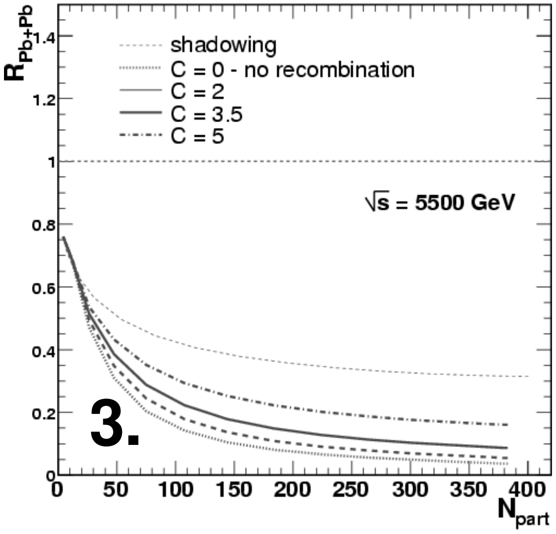


charmonium enhancement as fingerprint of deconfinement at LHC energy

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







1 and 2: stat. hadronization

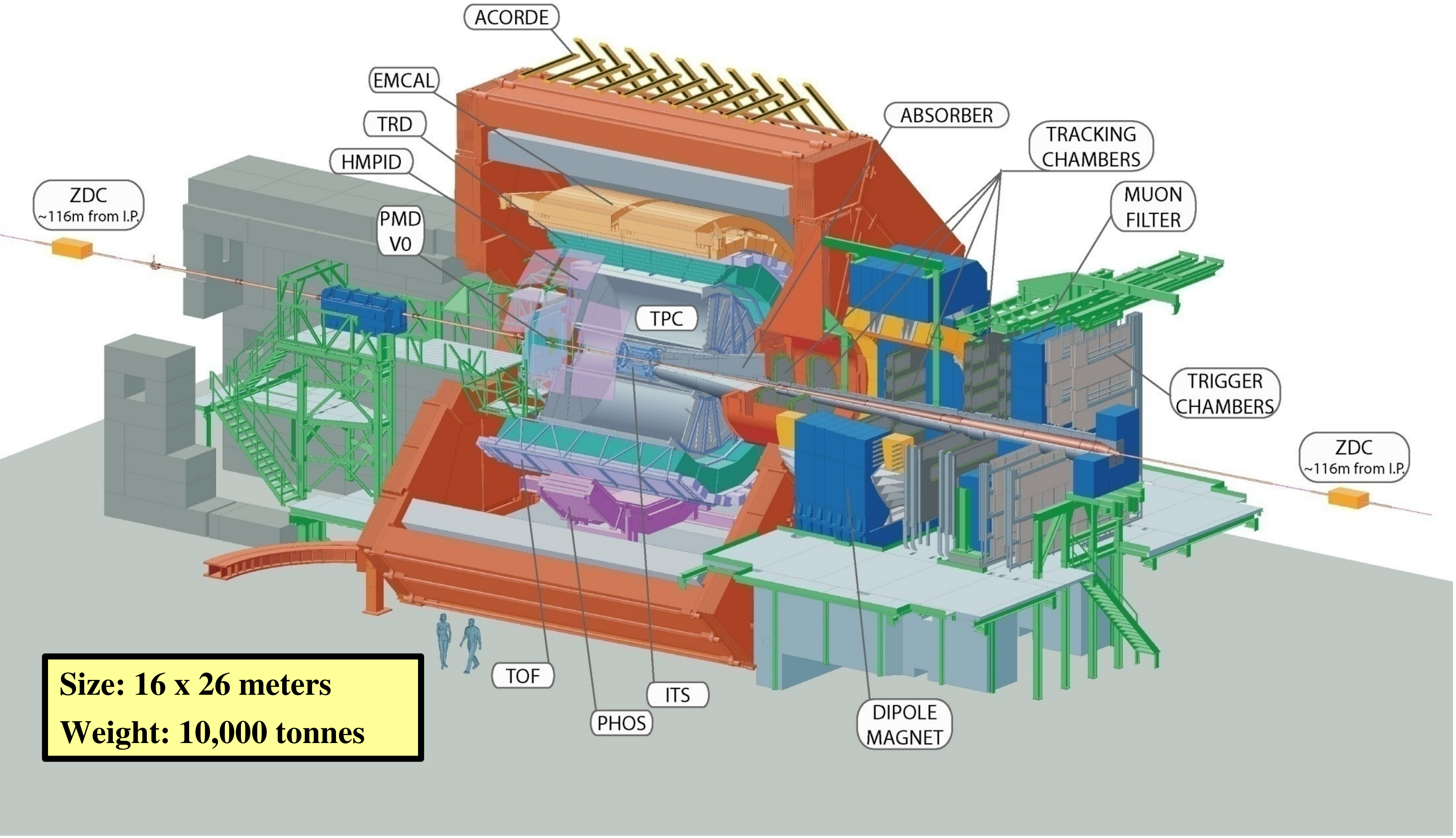
3: shadowing and regeneration in the hadronic phase only

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

Summary

- charmonium production – still a fingerprint for deconfined quarks and gluons but disentangling 'cold nuclear matter' and ' shadowing' effects is not trivial
- charm production is a hard process --> charm conservation eq. medium effects on charmed hadrons strongly suppressed
- data situation for open charm production is not impressive – need vertex detectors
- evidence for energy loss and flow of charm quarks --> thermalization
- charmonium generation at the phase boundary – a new process
- first indications for this from RHIC data
- charmonium enhancement at LHC – deconfined QGP

ALICE: A Large Ion Collider Experiment at CERN-LHC

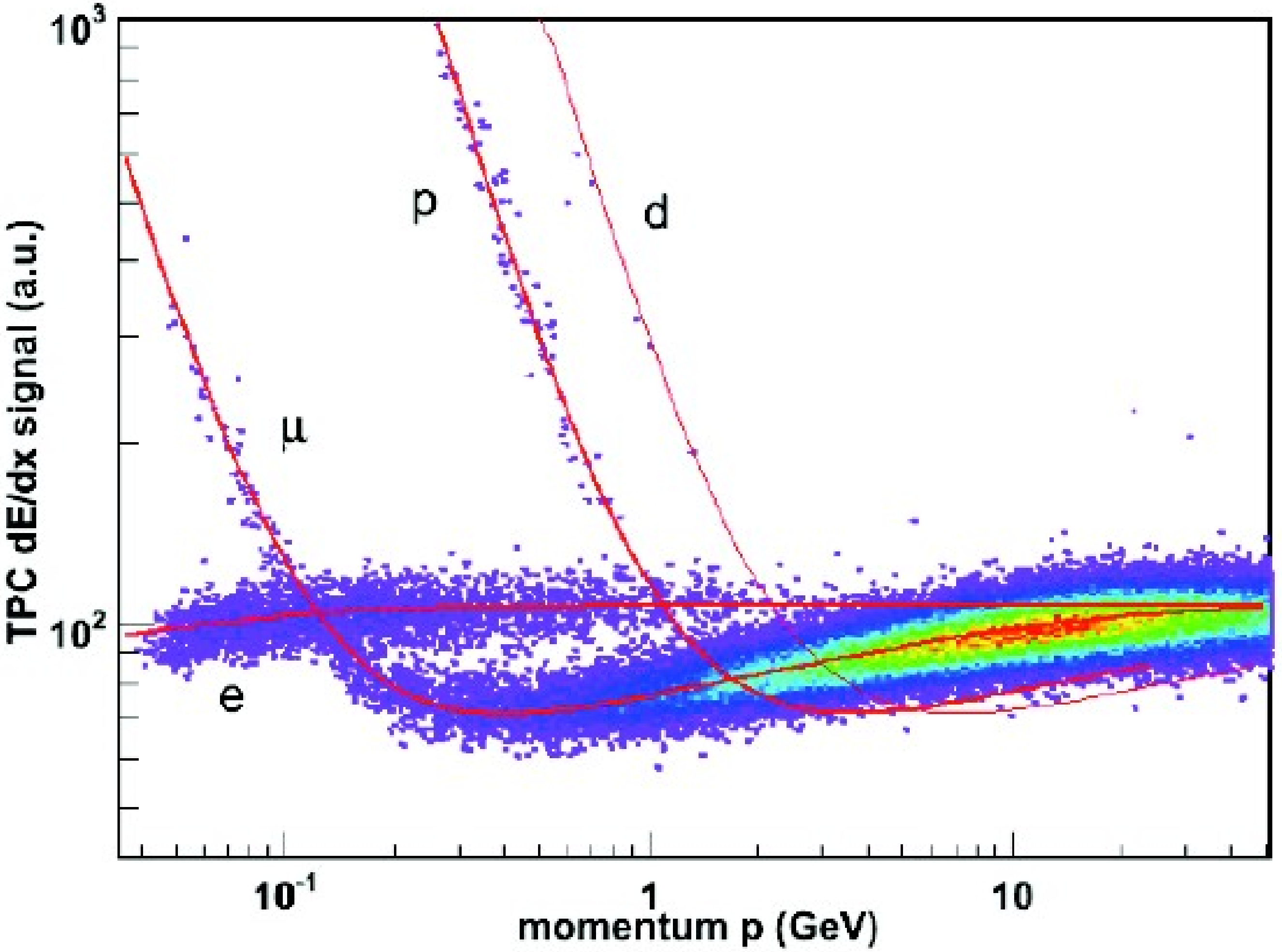


Size: 16 x 26 meters

Weight: 10,000 tonnes

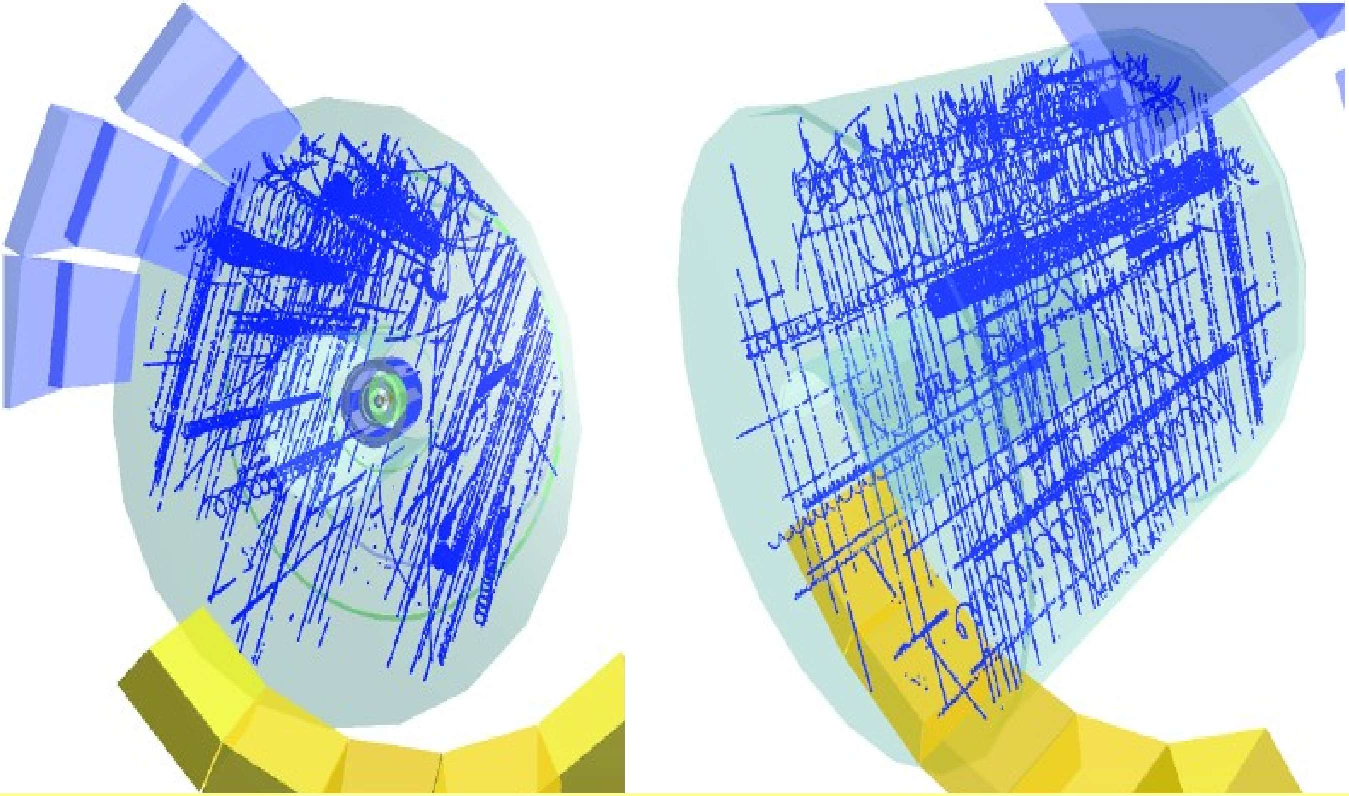
Calibration of ALICE TPC

dE/dx spectra of cosmics



Exotic events in the ALICE TPC

- multi-muon events / muon bundles

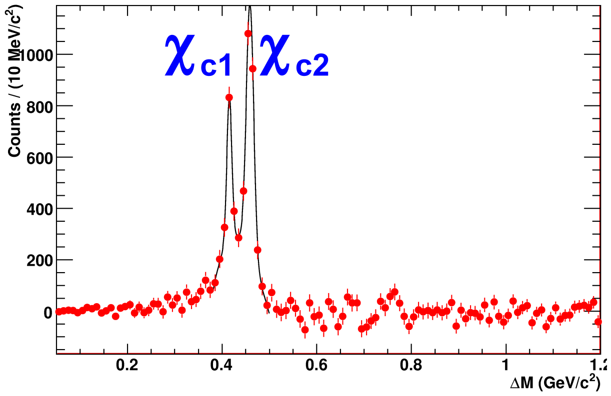


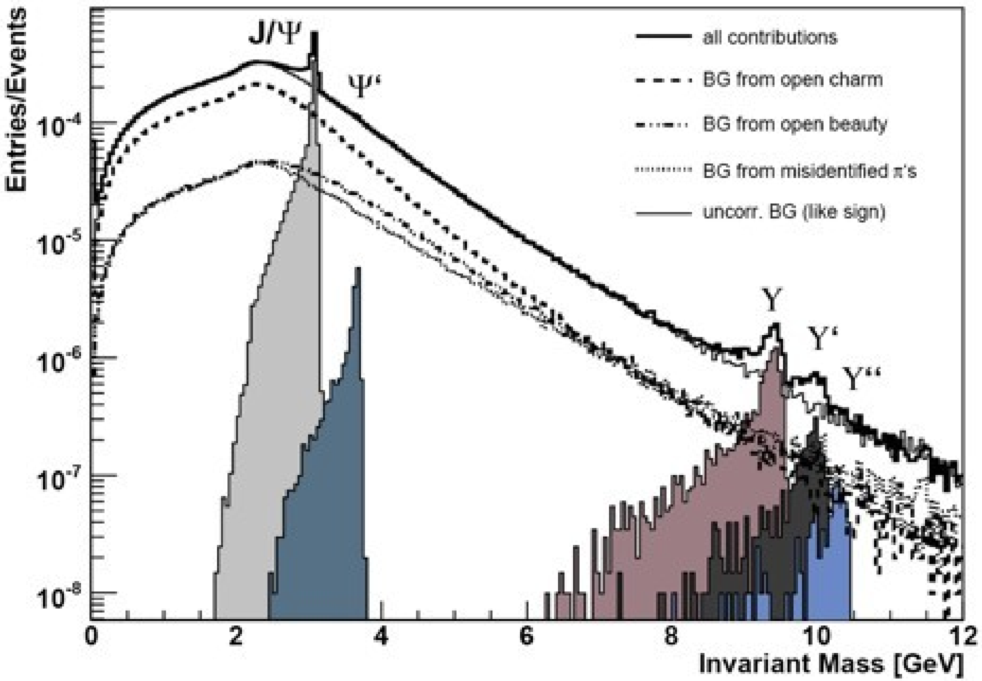
More than 60 parallel muons with p > 30 GeV
Entering the Tera-scale

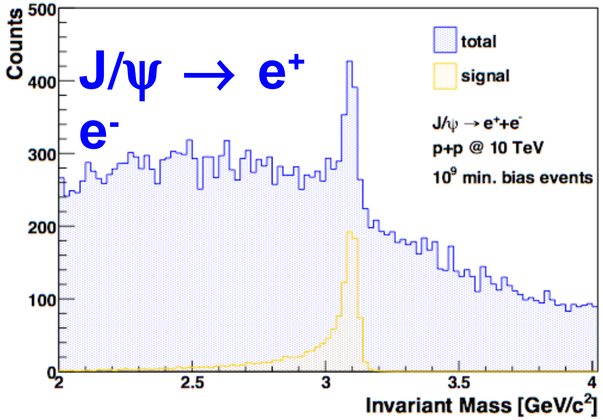
Charmonia via Di-Electron Measurement in ALICE

- electron ID with TPC and TRD
- expect 1000 ϒ mesons per Pb+Pb year with good mass resolution and S/B

Simulation: pp coll.







Simulation: $2{\cdot}10^8$ central PbPb collisions

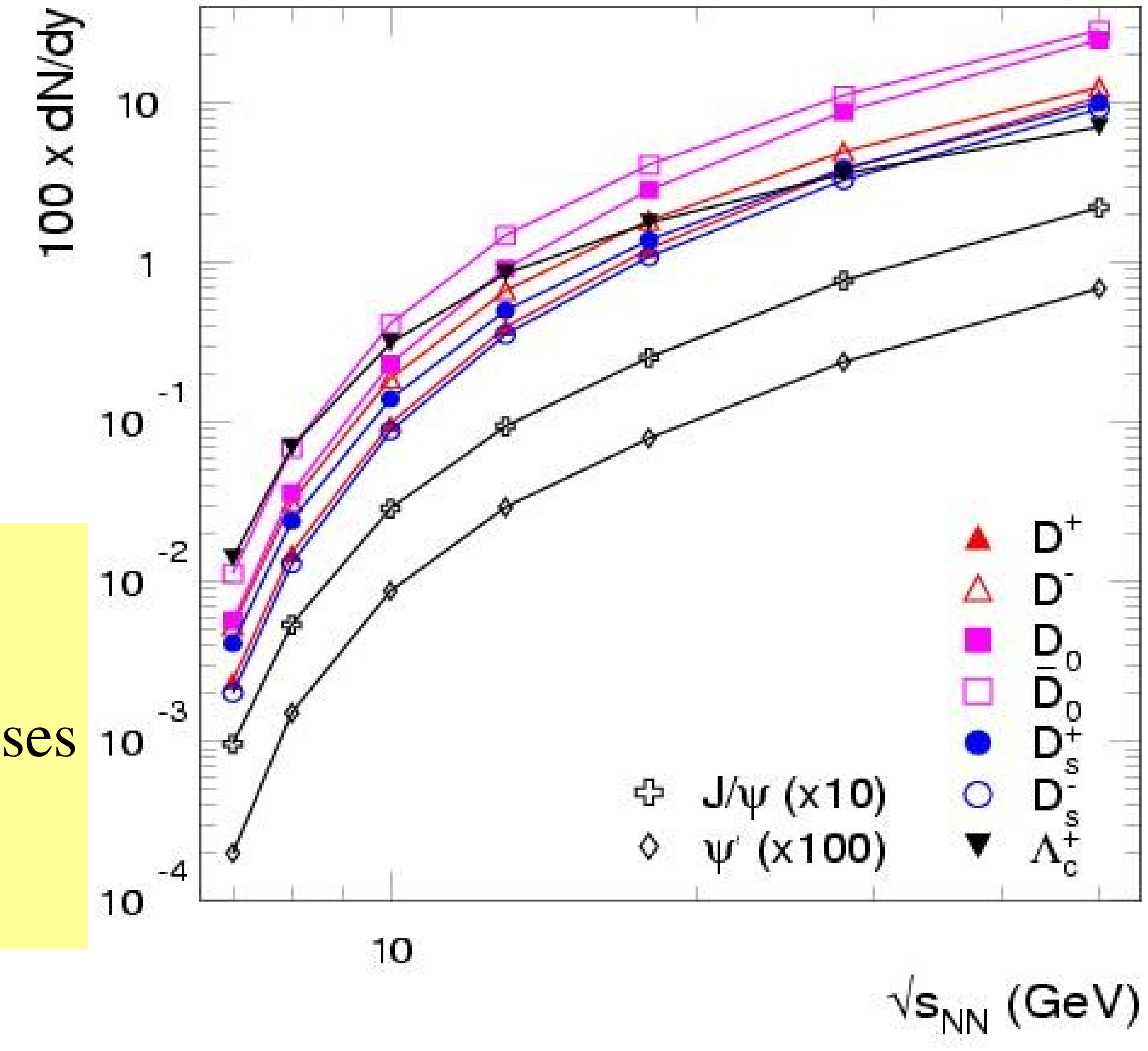
Next meeting: data from LHC

Many more papers on late generation

L. Grandchamp, R. Rapp, Phys. Lett. B523 (2001) 60
R. Rapp et al., PRL 92, 212301 (2004)
and refs. there
R. Thews et al, Eur. Phys. J C43, 97 (2005)
and refs. there
M. I. Gorenstein et al., Phys. Lett. B509 (2001)277, ib. 524 (2002) 265
A.P. Kostyuk et al., Phys. Lett. B531 (2002) 195, Phys. Rev. C68 (2003) 041902
Yan, Zhuang, Xu, nucl-th/0608010
Bratkovskaya et al., PRC 69, 054903 (2004)
A. Andronic et al, Phys. Lett. B571 (2003) 36
A. Andronic et al, nucl-th/0611023, Nucl. Phys. A789 (2007) 334
A. Andronic, pbm, J. Stachel, K. Redlich,
nucl-th/0701079, Phys. Lett. B562 (2007) 259
pbm, nucl-th/0701093 J. Phys. G34 (2007) S471
A. Andronic et al, Phys. Lett. B659 (2008) 149

Statistical hadronization predictions for open and hidden charm at low energies

vacuum masses



Annihilation of charm quarks in the QGP

- first note that production of charm quarks in the QGP is strongly Boltzmann suppressed

--- consider only annihilation

- likely annihilation channels:

$$c + \bar{c} \rightarrow g + g$$

or

$$c + \bar{c} \rightarrow q + \bar{q},$$

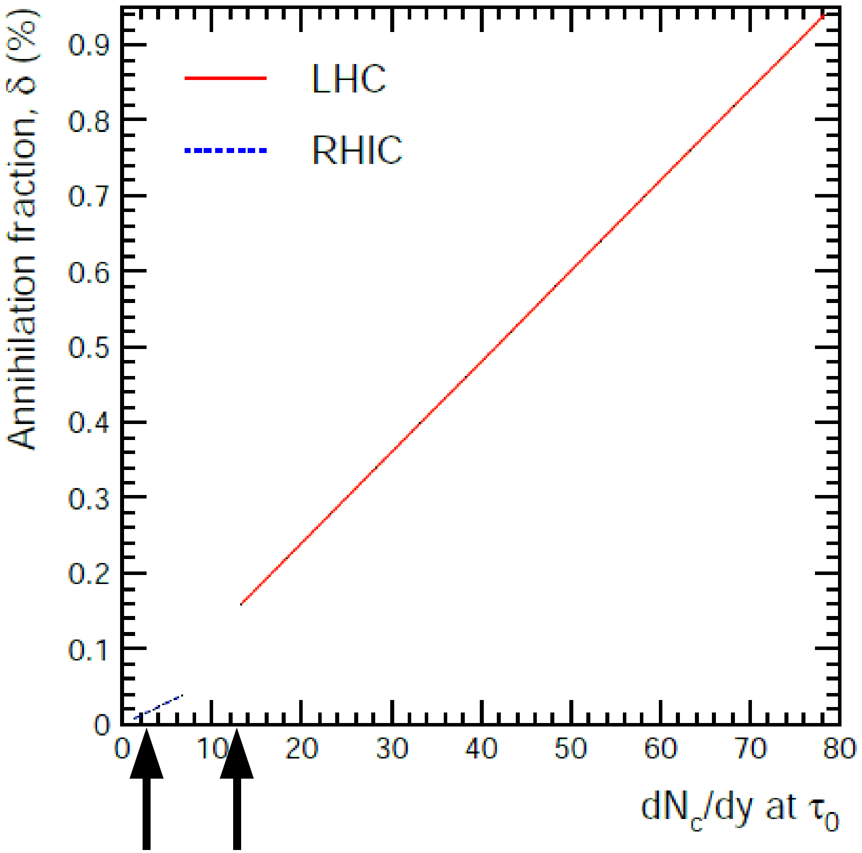
- total annihilation rate:

$$\frac{dr_{c\bar{c}}}{d\tau} = n_c n_{\bar{c}} \langle \sigma_{c\bar{c} \rightarrow gg} v_r \rangle$$

< > implies thermal average

annihilation fraction

annihilation fraction is less than 0.2 %, even at LHC energy and with $\alpha_s = 1$



RHIC LHC
pQCD value

summary of annihilation calculation

- charm quark number does not change during plasma evolution
  → quadratic term in J/ψ production is unavoidable
- J/ψ formation in plasma is very small (<< 0.2 % of cc_bar)
  → question of whether or not bound states of J/ψ exist is immaterial for final production yield
- since charmonia formation time (≈ 1 fm in rest frame, Blaizot and Ollitrault, Phys. Lett. 217B (1989) 386) is less (at LHC) or comparable (at RHIC) to the initial time of plasma formation, all charmonia must be produced at the phase transition, i.e at hadronization

For details see Nucl. Phys. A789 article

Saturation model for J/psi production

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

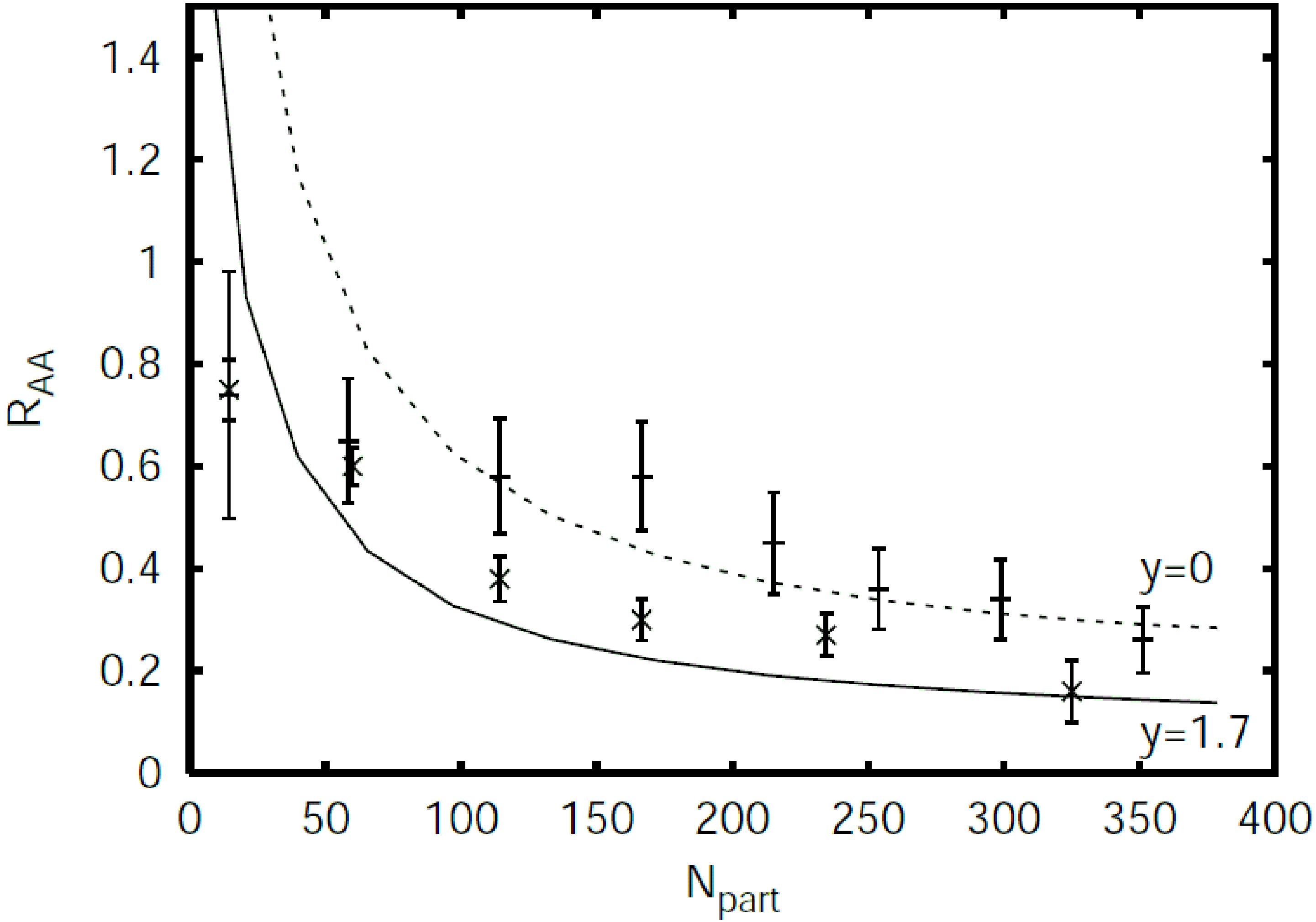
this leads to increasing suppression of the charm and J/psi cross section away from mid-rapidity as the size of the colliding nuclei increases

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

Saturation model for J/psi production

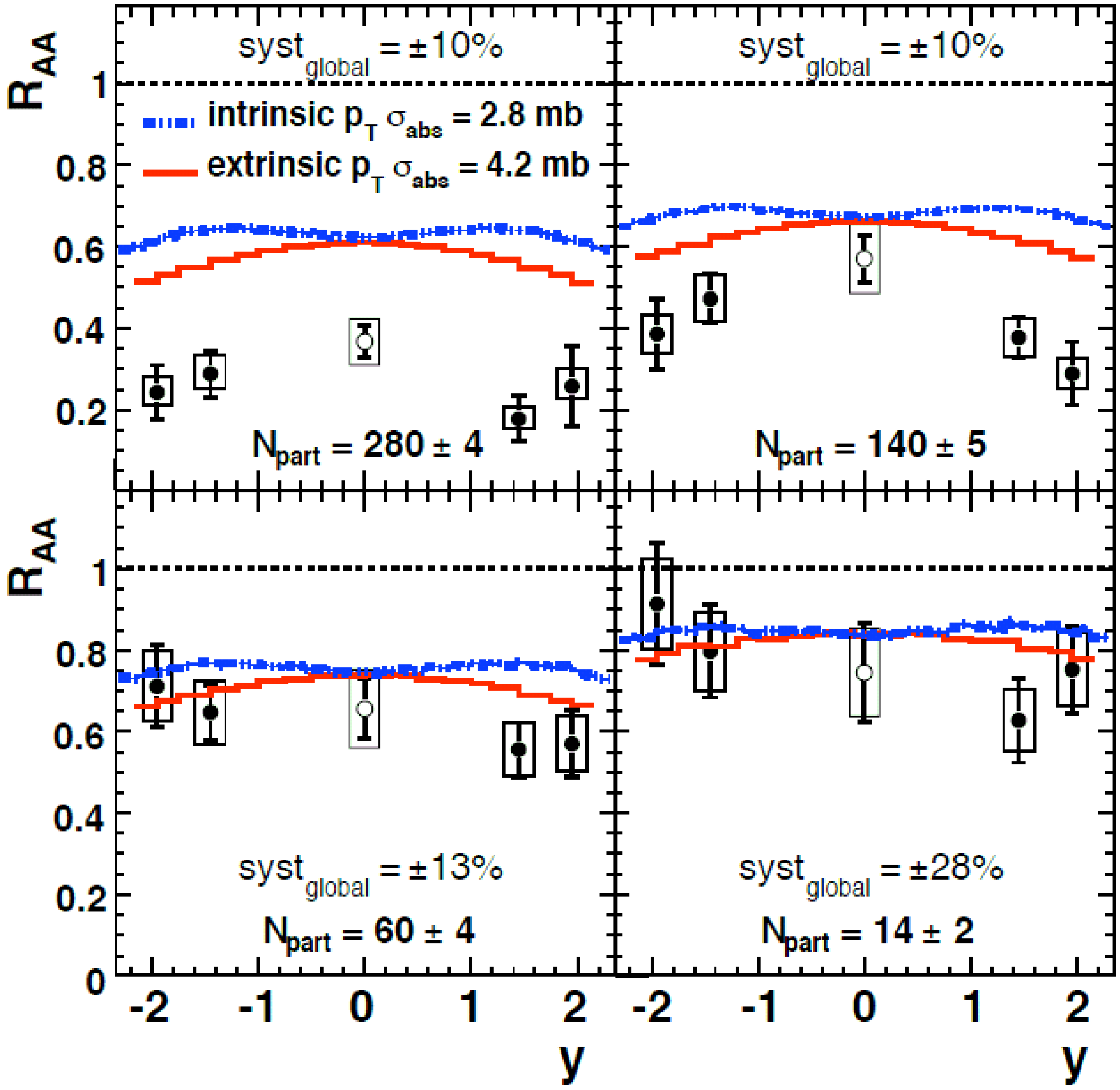


gets rapidity ordering right but N_{part} dependence too strong?

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

sQGP and Charmonium Suppression

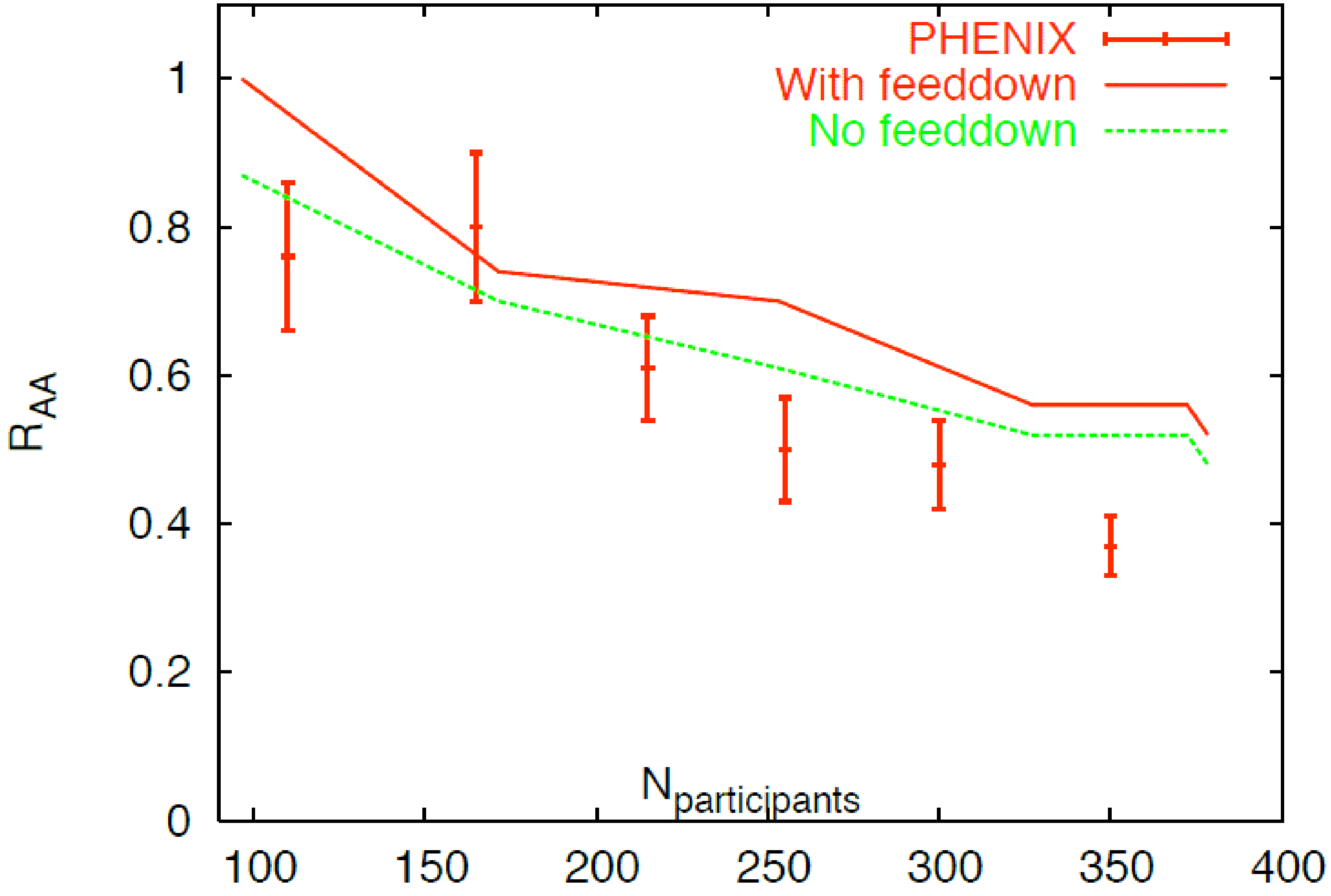
argument: spatial diffusion of charm quarks is slow in ideal fluid

⇒ 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]

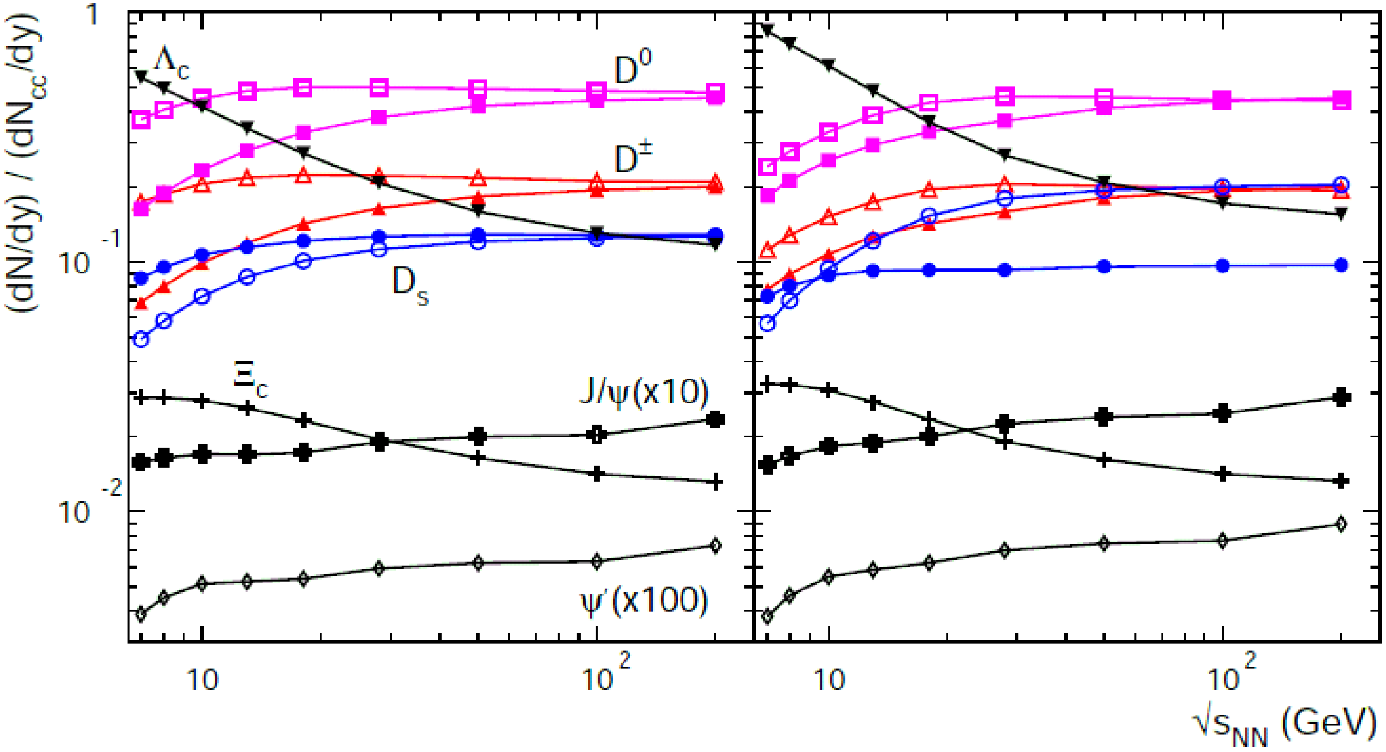
Scenarios of in-medium modified masses

modification of the constituent quark masses of light (u and d) quarks
(no change of J/ψ mass, $\Delta m_{\Lambda_c}/2$ for Ξ_c)

case	Δm_D	$\Delta m_{\Lambda_c,\Xi_c}$
i)	-50 MeV ($D, \bar{D}$)	-100 MeV ($\Lambda_c, \bar{\Lambda}_c$)
ii) (FAIR)	-100 MeV (D), +50 MeV ($\bar{D}$)	-200 MeV (Λ_c), +100 MeV ($\bar{\Lambda}_c$)
iii)	-50 MeV ($D, \bar{D}$)	-50 MeV ($\Lambda_c, \bar{\Lambda}_c$)

Tsushima et al.,PRC 59 (1999) 2824 [nucl-th/9810016].
Sibirtsev et al., EPJA 6 (1999) 351 [nucl-th/9904016]; PLB 484 (2000) 23 [nucl-th/9904015].
Hayashigaki, PLB 487 (2000) 96 [nucl-th/0001051].
Cassing et al., NPA 691 (2001) 753 [nucl-th/0010071].
Friman et al., PLB 548 (2002) 153 [nucl-th/0207006].
Grandchamp et al., PRL 92 (2004) 212301 [hep-ph/0306077].
Tolos et al, PLB 635 (2006) 85 [nucl-th/0509054].
Lutz, Korpa, PLB 633 (2006) 43 [nucl-th/0510006].

Results including medium modifications



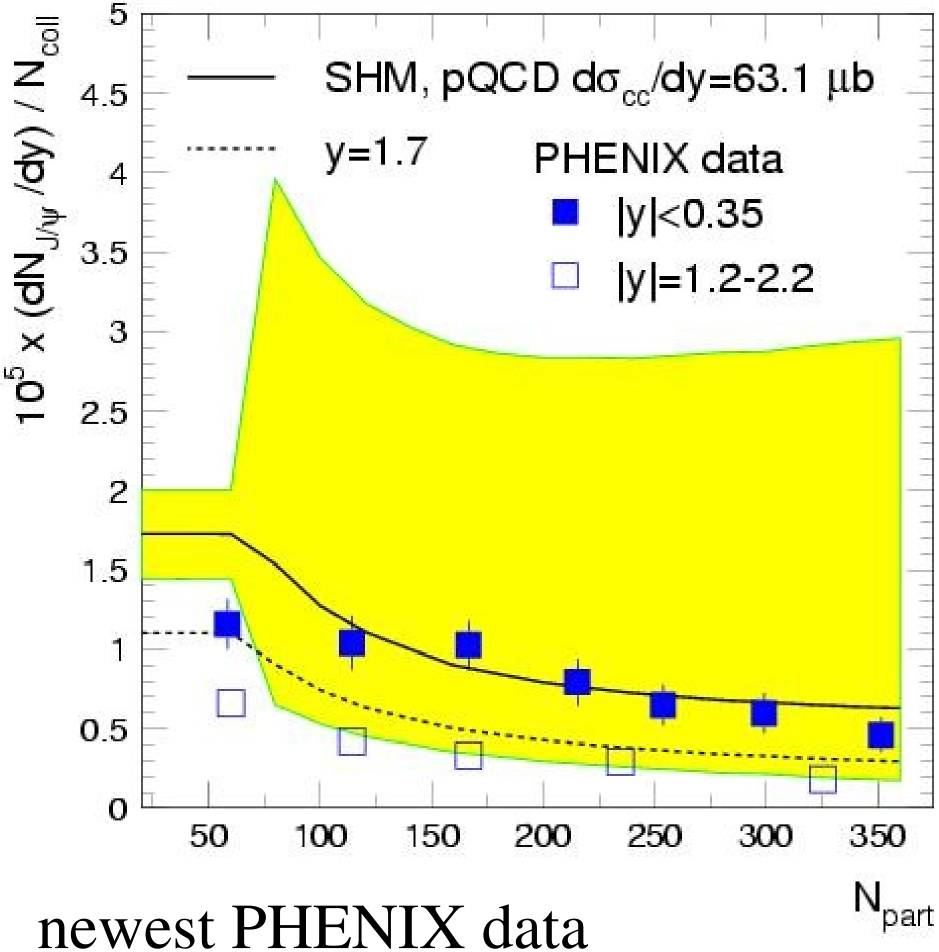
scenario 1 scenario 2

note: changes are subtle and show up ONLY
when normalized to total charm cross section

Comparison of model predictions to RHIC data: centrality dependence

predictions for J/ψ production using NNLO pQCD results for open charm cross section by M. Cacciari, P. Nason, R. Vogt, Phys. Rev. Lett. 95 (2005) 122001, hep-ph/0502203

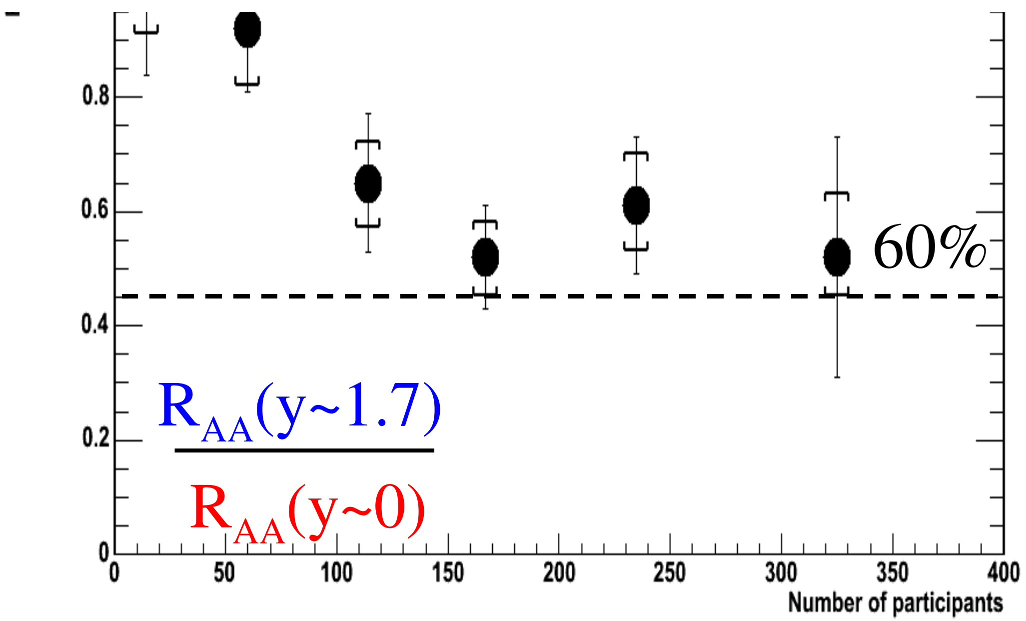
good agreement, no free parameters

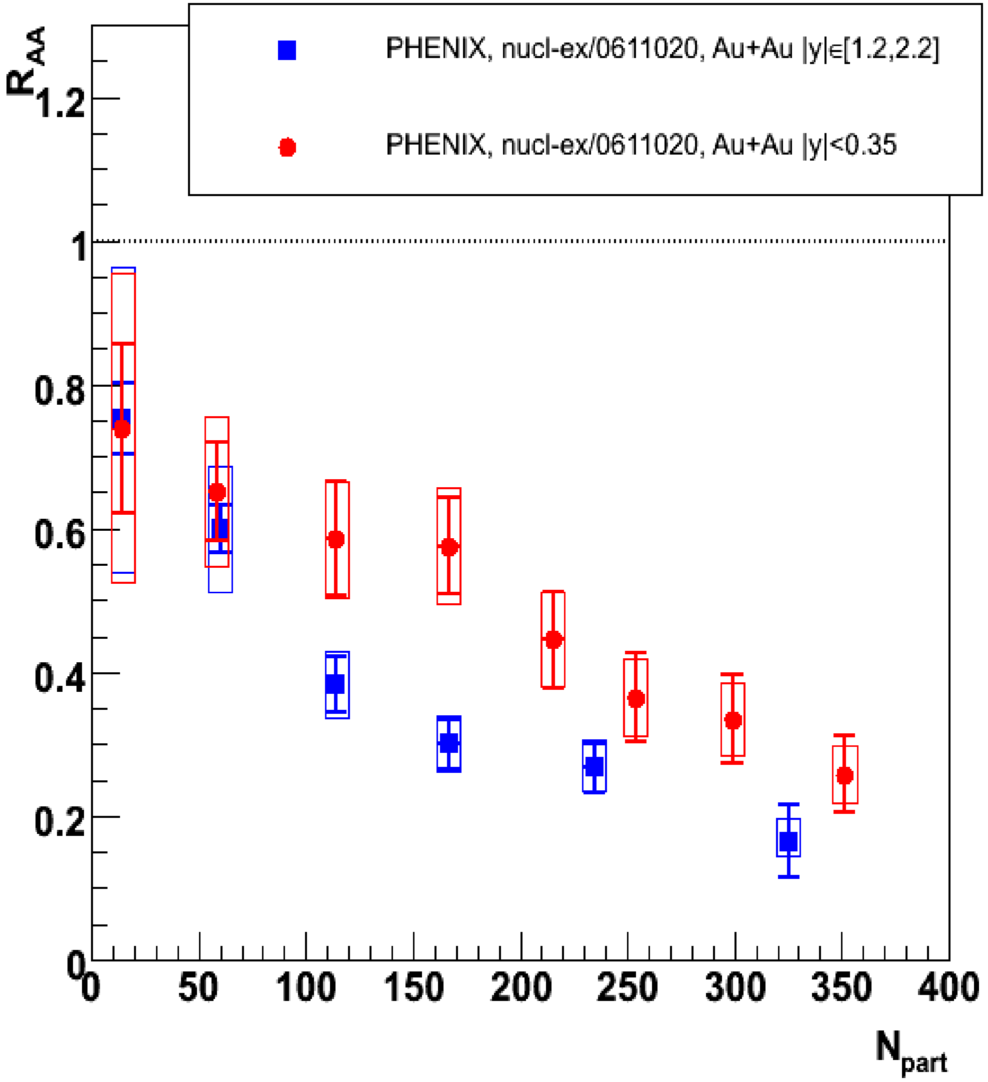


newest PHENIX data

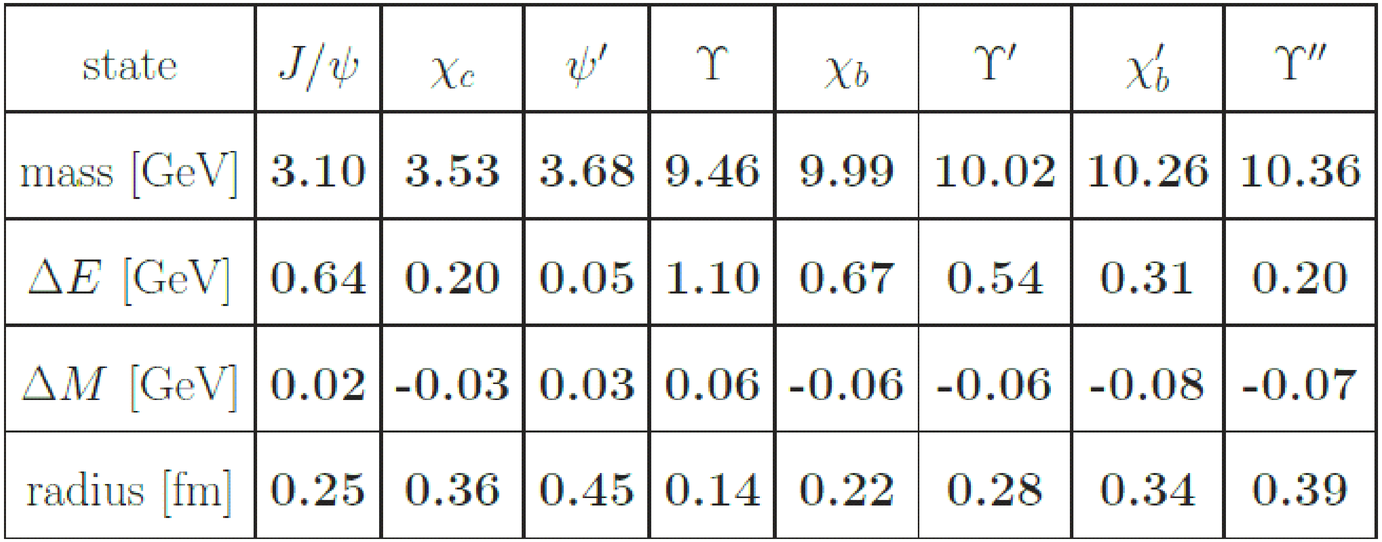
charmonium suppression at RHIC

surprize:
suppression is weakest at mid-rapidity





Quarkonium Properties and Debye Screening



state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [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 → suppression compared to charmonium production without QGP. The screening radius can be computed using potential models or solving QCD on the lattice.

$r_{Debye}(T) \sim 1/[g(T)T]$

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 $\lambda = 1/(n\ \sigma)$
$\sigma = J/\psi$ – 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

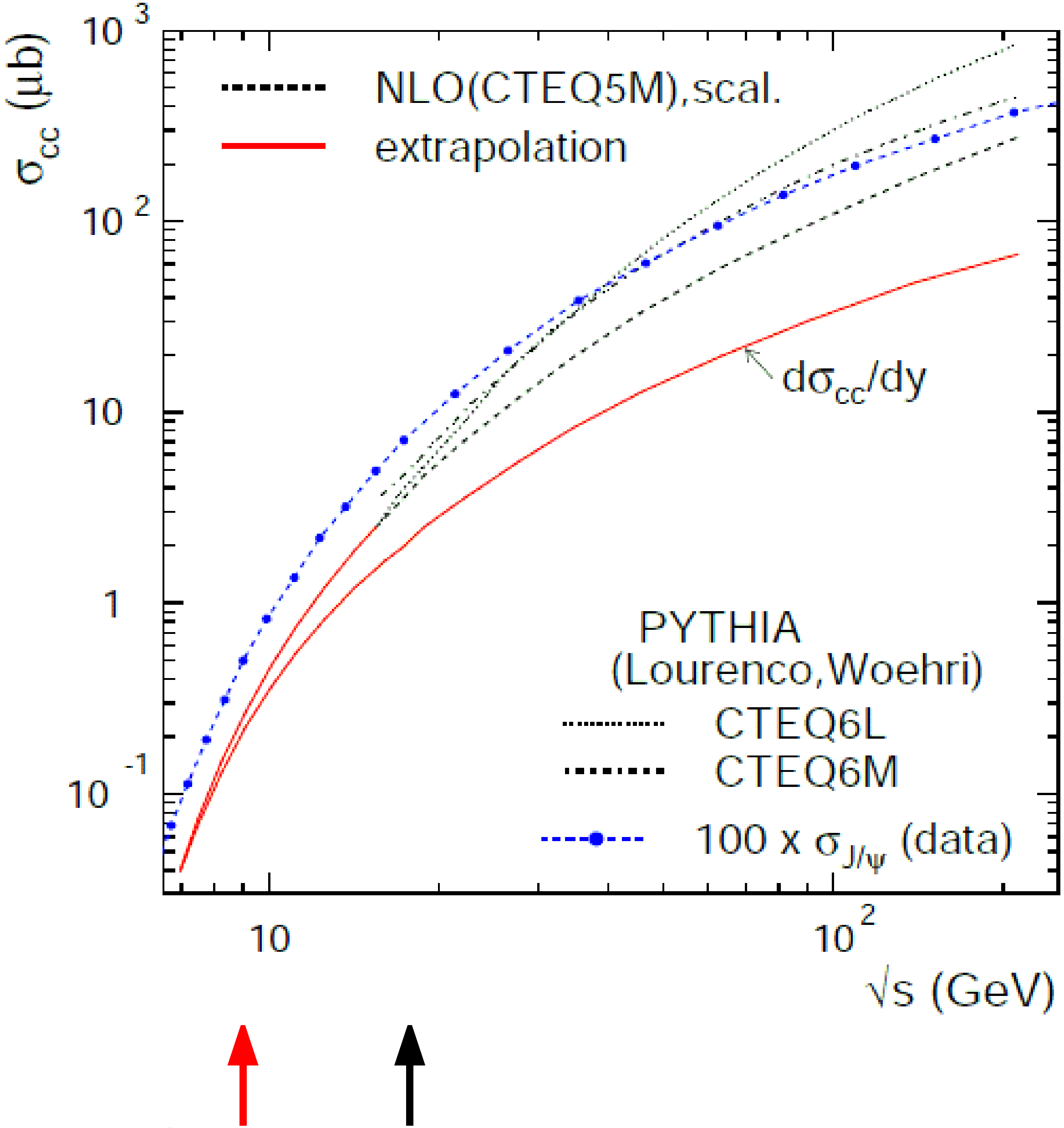
$p(\text{decay inside}) = 1-\exp(-\Gamma\, \tau_{QGP})$

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

An attempt to look at near threshold production

- charm cross section unknown
- but: $N_{ccbar} << 1$: only diagonal terms in recombination
- independent of energy, charm production still a hard process

Extrapolation of pQCD cross section to low energies



SIS300 full energy

SPS full energy

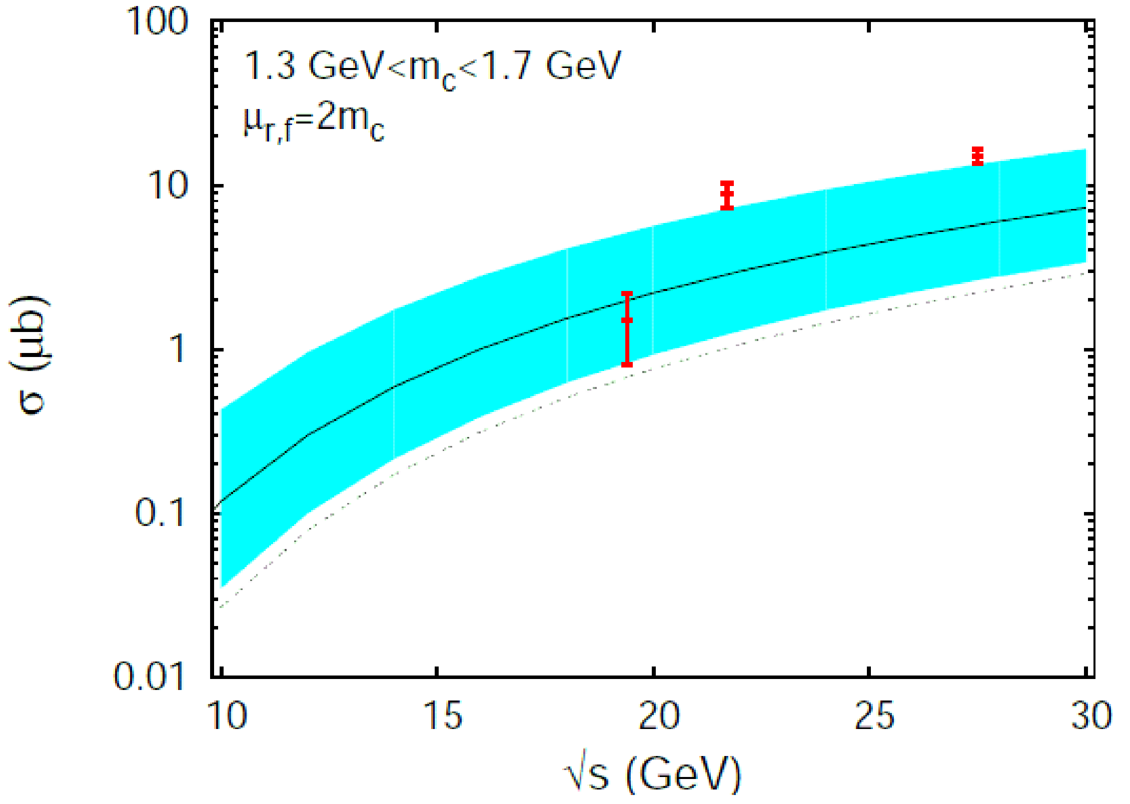
charm threshold
in NN: 5.1 GeV

absolute threshold
in Pb-Pb
collisions:

$T_{lab}/A = 31$ MeV

most recent NLO calculation of open charm production

Braaten and Artoisenet, arXiv:0903.2573 [hep-ph]

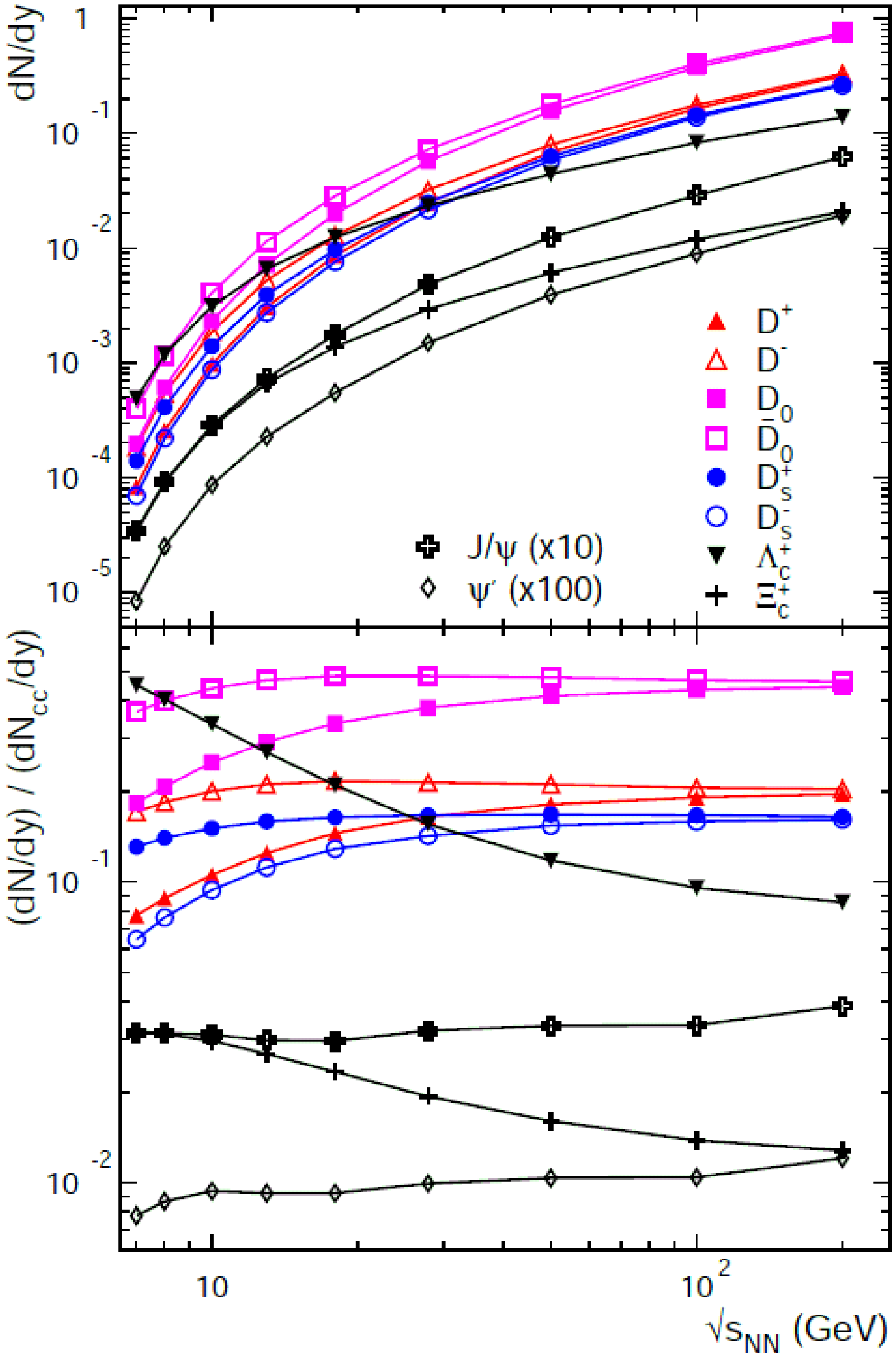


S. Barlag *et al.* [ACCMOR Collaboration], Z. Phys. C **39**, 451 (1988).
M. Aguilar-Benitez *et al.* [LEBC-EHS Collaboration], Z. Phys. C **40**, 321 (1988).
G. A. Alves *et al.* [E769 Collaboration], Phys. Rev. Lett. **77**, 2388 (1996) [Erratum-ibid. **81**, 1537 (1998)].

Model predictions without any medium modifications

note in particular the role of charmed baryons

at SIS300 energies it is crucial to measure those

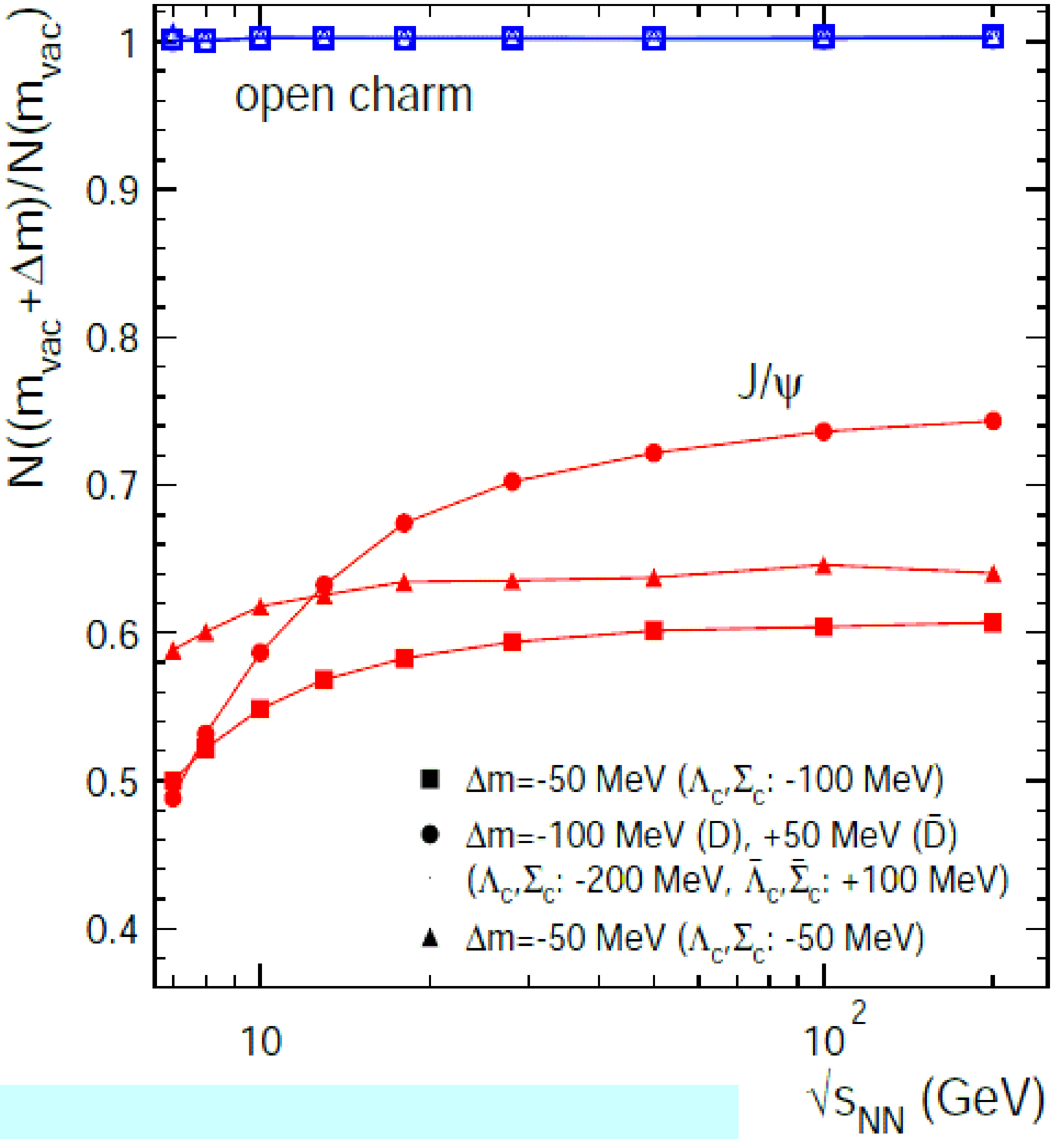


Changes for charmonium assuming scenarios 1 – 3

charmonium masses unchanged

yield of charmonium may change by up to factor of 2

difficult how to normalize



can STAR and PHENIX address this at sqrt{s_NN} = 10 – 20 GeV?