Quarkonium Production
review of models

- remarks about the experimental situation
- quarkonium suppression in the QGP
  - ingredients and assumptions
  - quarkonia in the QGP
  - confrontation with data
- comover suppression
- cold nuclear matter effects

- models with quarkonium enhancement
  - ingredients and assumptions
  - annihilation of charm quarks in the plasma
  - comparison of kinetic model predictions with data
- outlook

ALICE physics week, Muenster, Feb. 15, 2007

Definition of Modification of Charmonium in the Fireball

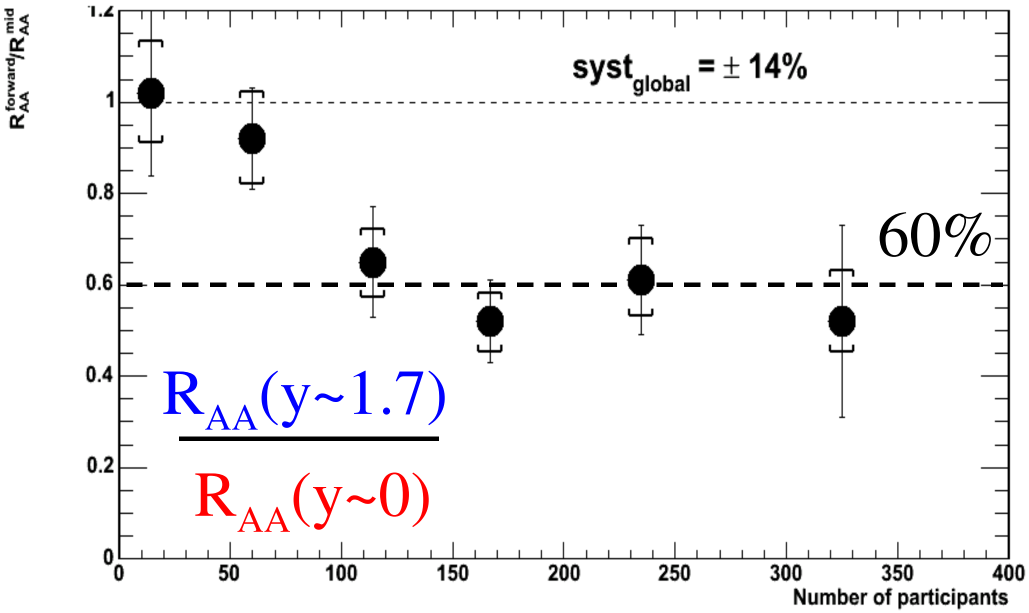
use R_{AA} to define charmonium modification experimentally
no need to normalize to Drell-Yan process

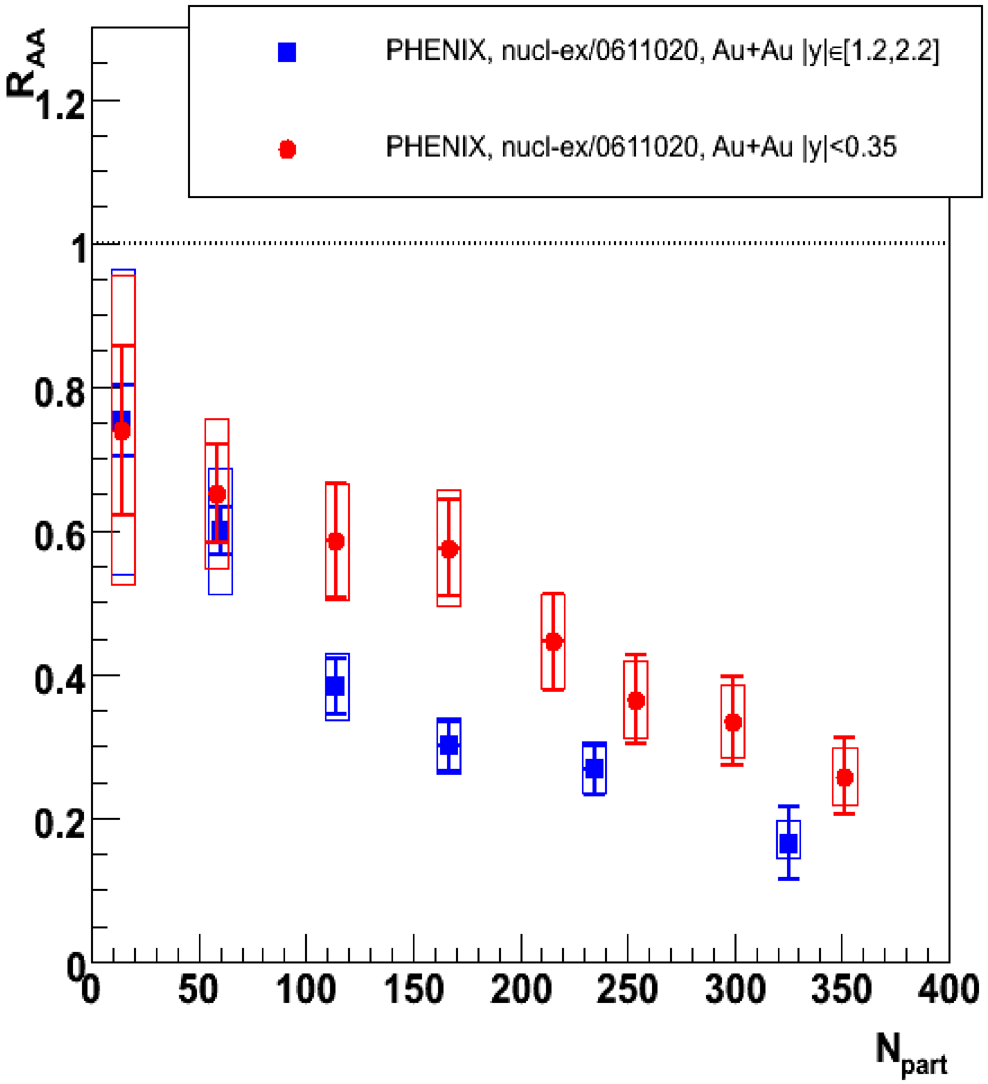
$$R_{AA}^{J/\psi} = \frac{\mathrm{d}N_{J/\psi}^{AuAu}/\mathrm{d}y}{N_{coll} \cdot \mathrm{d}N_{J/\psi}^{pp}/\mathrm{d}y}$$

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

charmonium suppression at RHIC

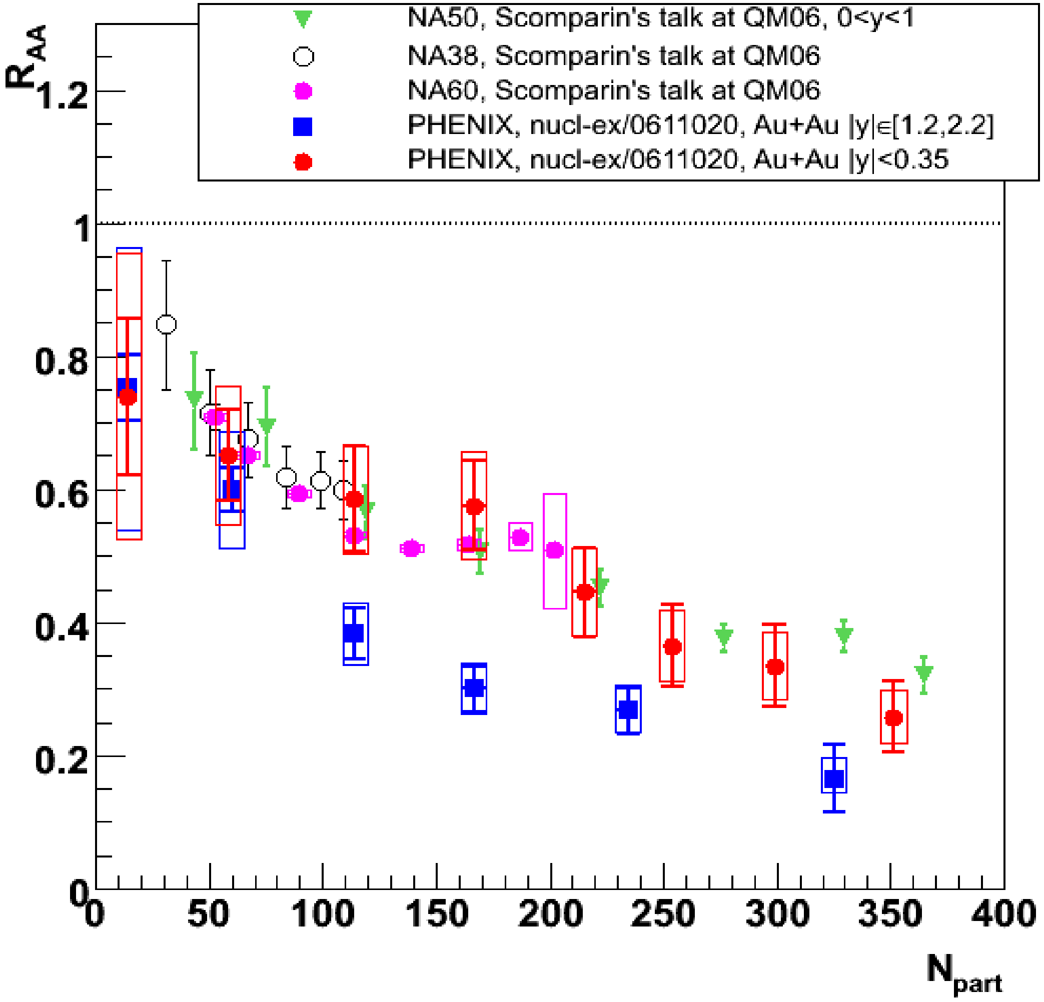
surprize:
suppression is weakest at
mid-rapidity





Comparison of RHIC and SPS Results

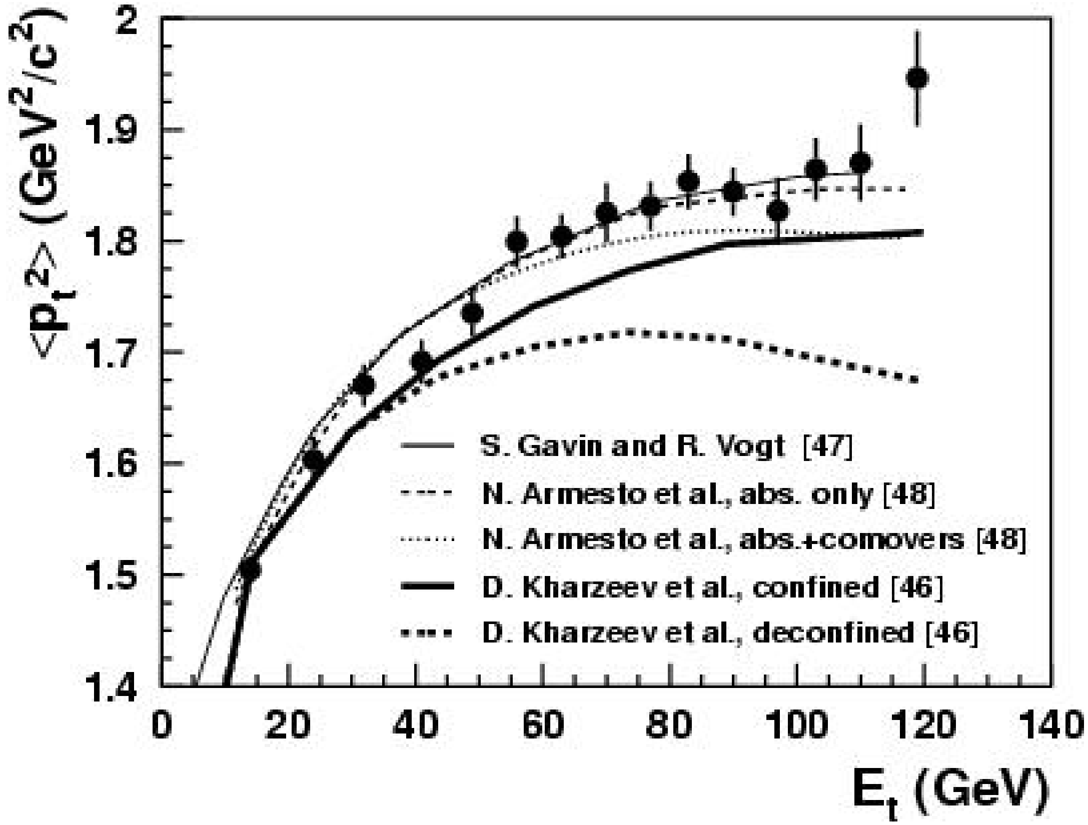
surprize:
no energy dependence



comparison produced by
R. Granier de Cassagnac

Centrality dependence of p_t spectra at SPS energy

looks like initial state multiple scattering

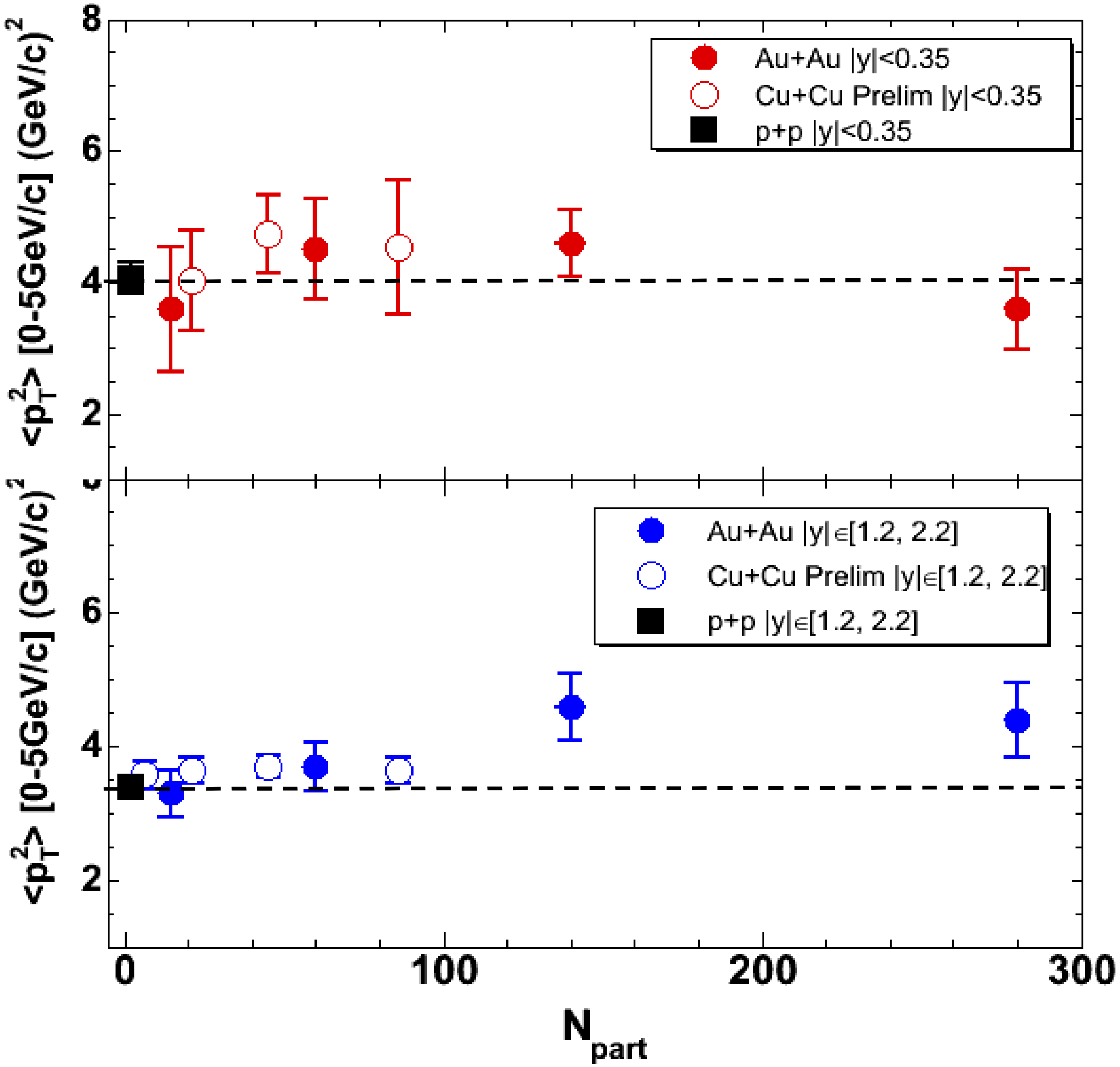


Pb Pb collisions, NA50

Centrality dependence of p_t spectra at RHIC energy

no strong evidence from PHENIX data for initial state scattering

different from SPS data



Charmonium suppression

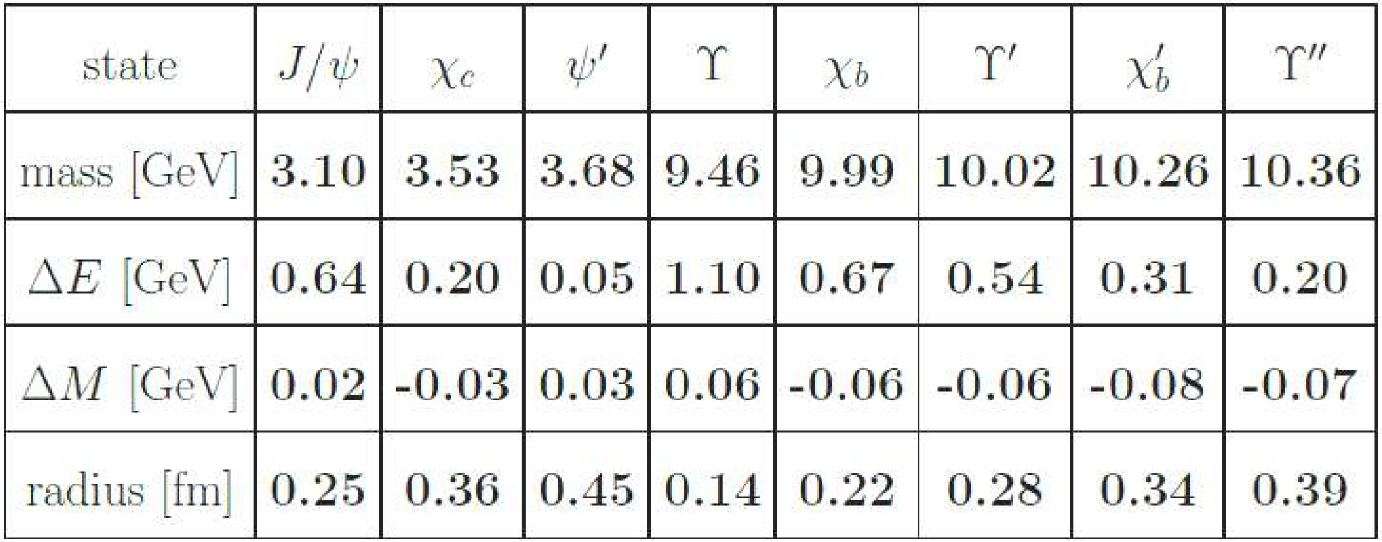
original proposal: H. Satz and T. Matsui, Phys. Lett. B178 (1986) 416

assumptions:

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

→ sequential suppression pattern due to feeding

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

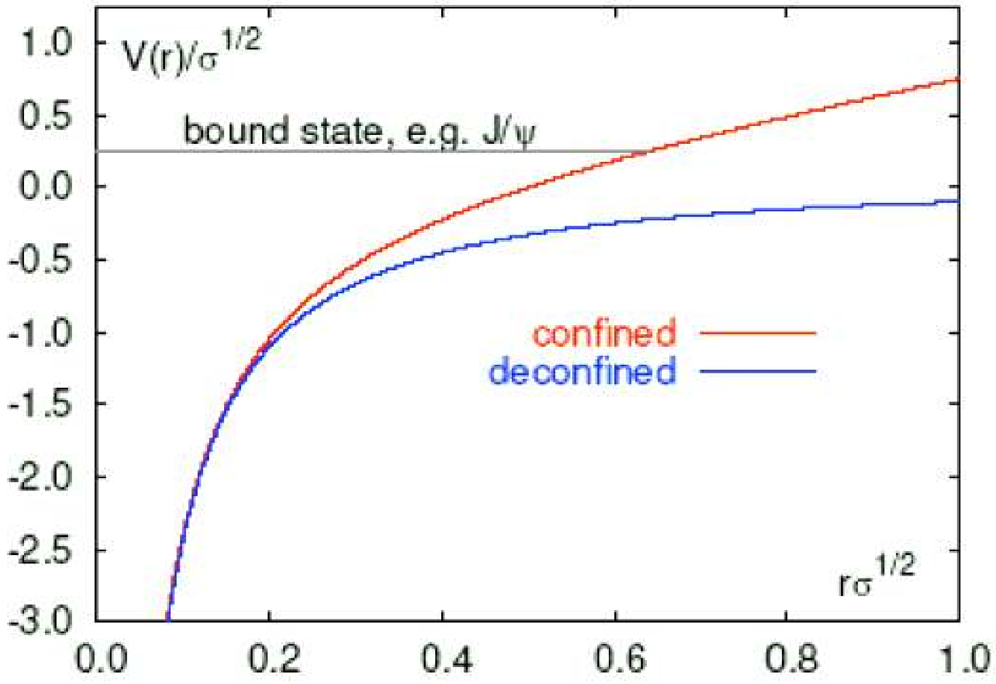
In the QGP, the screening radius $r_{Debye}(T)$ decreases with increasing T. If $r_{Debye}(T) < r_{charmonium}$ the system becomes unbound → suppression compared to charmonium production without QGP. The screening radius can be computed using potential models or solving QCD on the lattice.

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

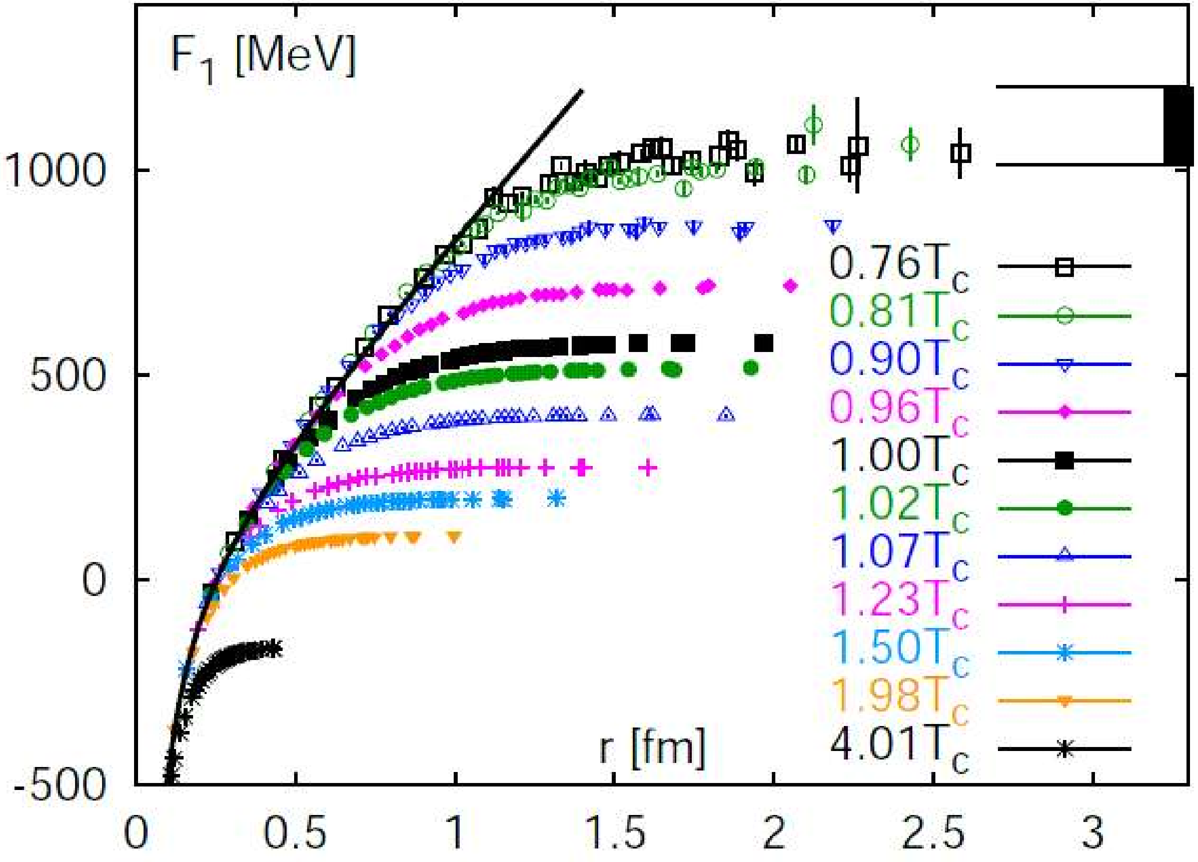


Free energy of a heavy quark-antiquark pair

color singlet free energy
$F_1(T) = U(T) - T\,S(T)$

note: J/ψ is bound
by 640 MeV

J/ψ disappears for T
> 1.6 T_c



O. Kaczmarek, F.Zantow, PRD 71(2005)114510

Debye Screening

screened potential for heavy quark-antiquark pair

$$V_{q\bar{q}}(r,T) = \frac{\sigma}{\mu}\left(1 - \mathrm{e}^{-\mu(T)r}\right) - \frac{\alpha}{r}\mathrm{e}^{-\mu(T)r}$$

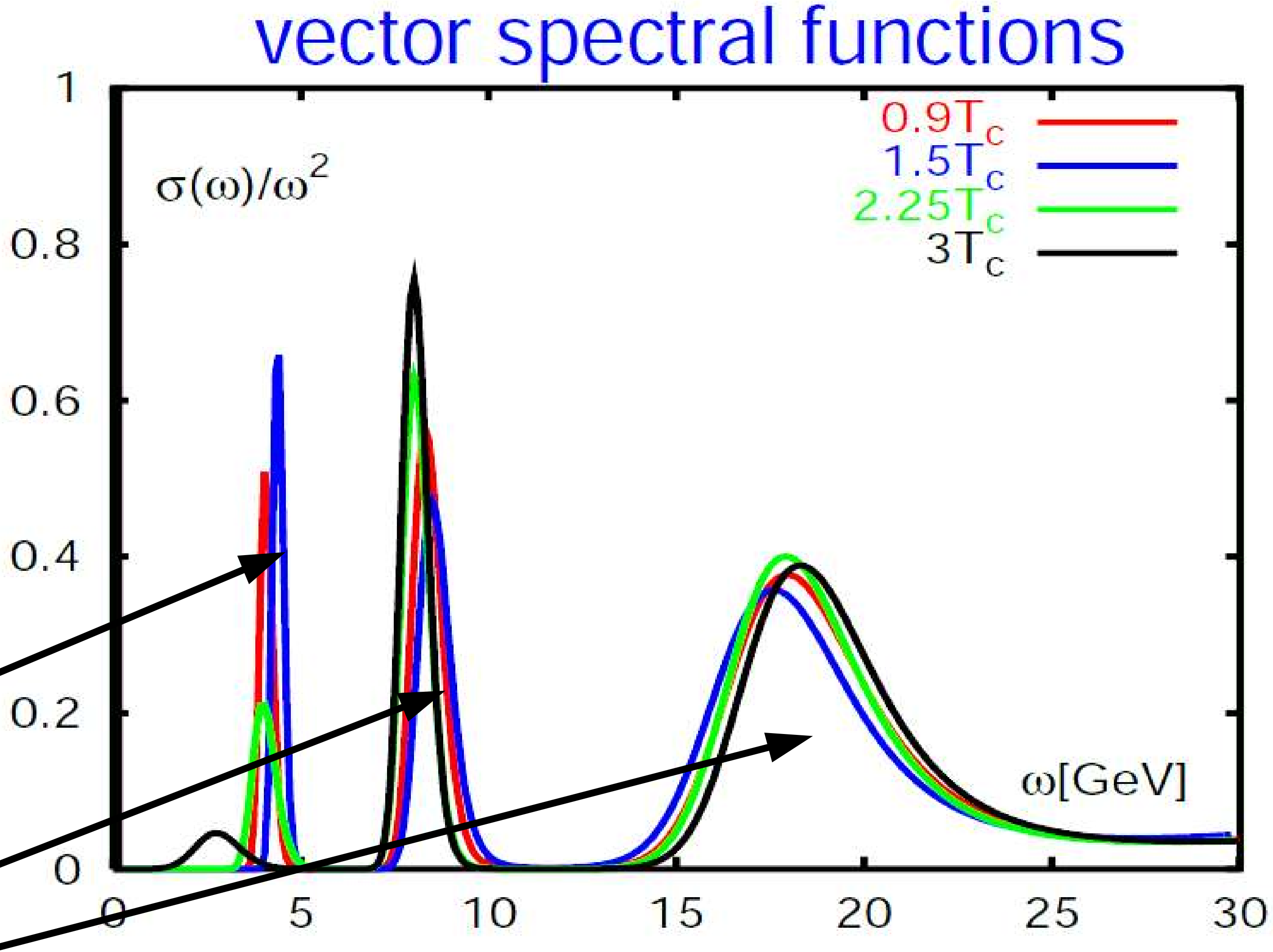
Debye radius $r_{\mathrm{Debye}} = 1/\mu(T)$

$$r_{\mathrm{Debye}} \propto 1/n_g^{1/3} \propto 1/(g(T)\,T)$$

state	J/ψ	χ_c	ψ'	
E_s^i [GeV]	0.64	0.20	0.05	
T_d/T_c	1.1	0.74	0.1 - 0.2	using F_1
T_d/T_c	~ 2.0	~ 1.1	~ 1.1	using U

Spectral function analysis from Bielefeld group

bound state disappears for $T > 2.25\ T_c$



S. Datta et al., Phys. Rev. D69 (2004) 094507

J/ψ

lattice artefacts ?

Conclusion of F. Karsch at Beijing Heavy Flavor Meeting

χ_c-states disappear at $T \simeq T_c$

J/ψ and η_c gone at 3.0 T_c

qualitatively similar results in QCD with light quarks:

G. Aarts et al., hep-lat/0610065

but:

ultra-violet cut-off effects:
Wilson-doubler;
finite Brillouin zone;

need to get better control over lattice cut-off effects

resolution statistics limited

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 > 250 MeV charmonia, if they exist there, will decay inside the QGP and will not be reconstructed by experiments

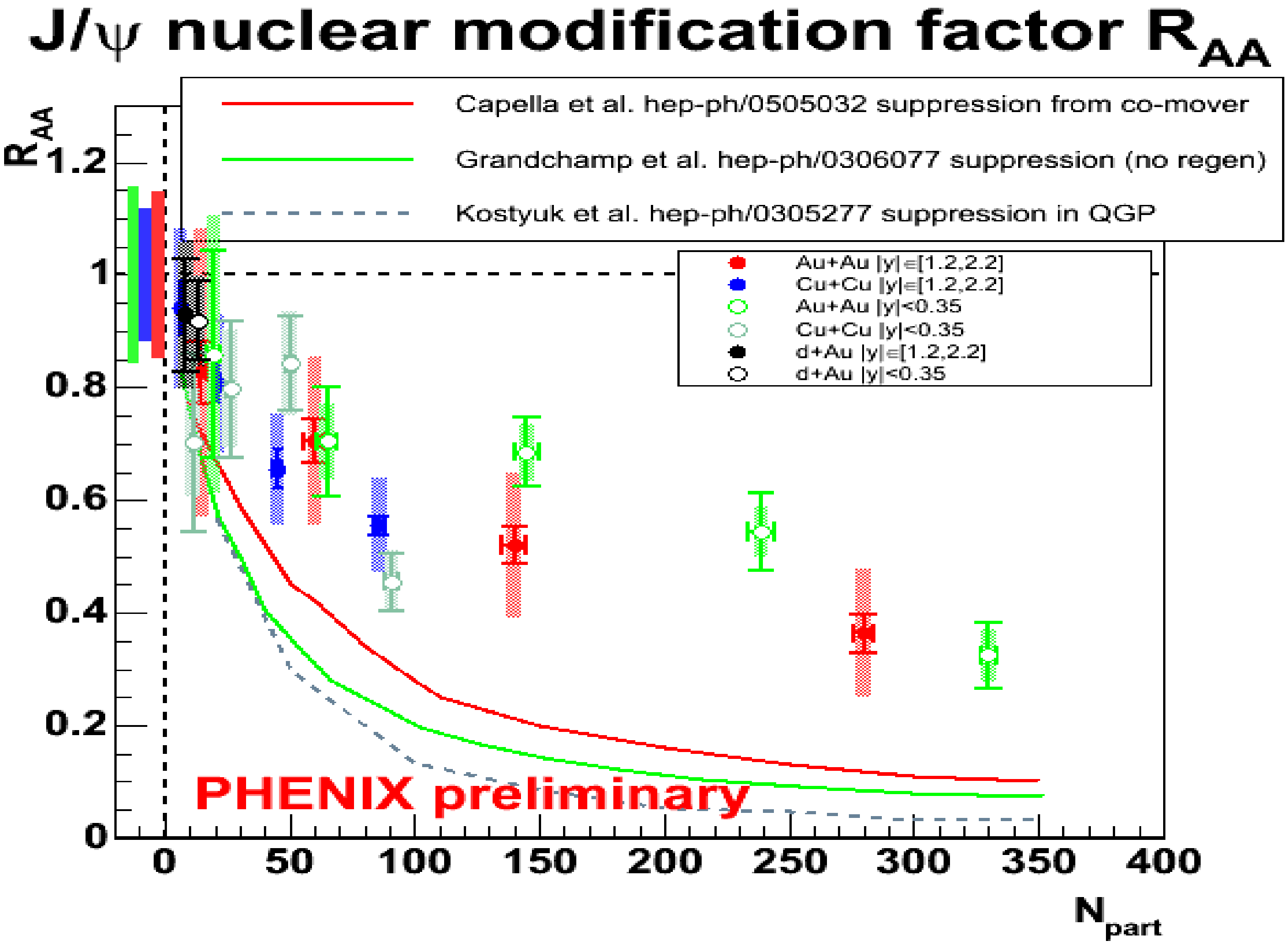
prob.(decay inside) = $\exp(-\Gamma\, \tau_{QGP})$
plasma suppression factor 0.5 for RHIC – not seen!

similar numbers for Υ: smaller cross section compensated by higher temperatures

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



Can sequential melting explain the data?

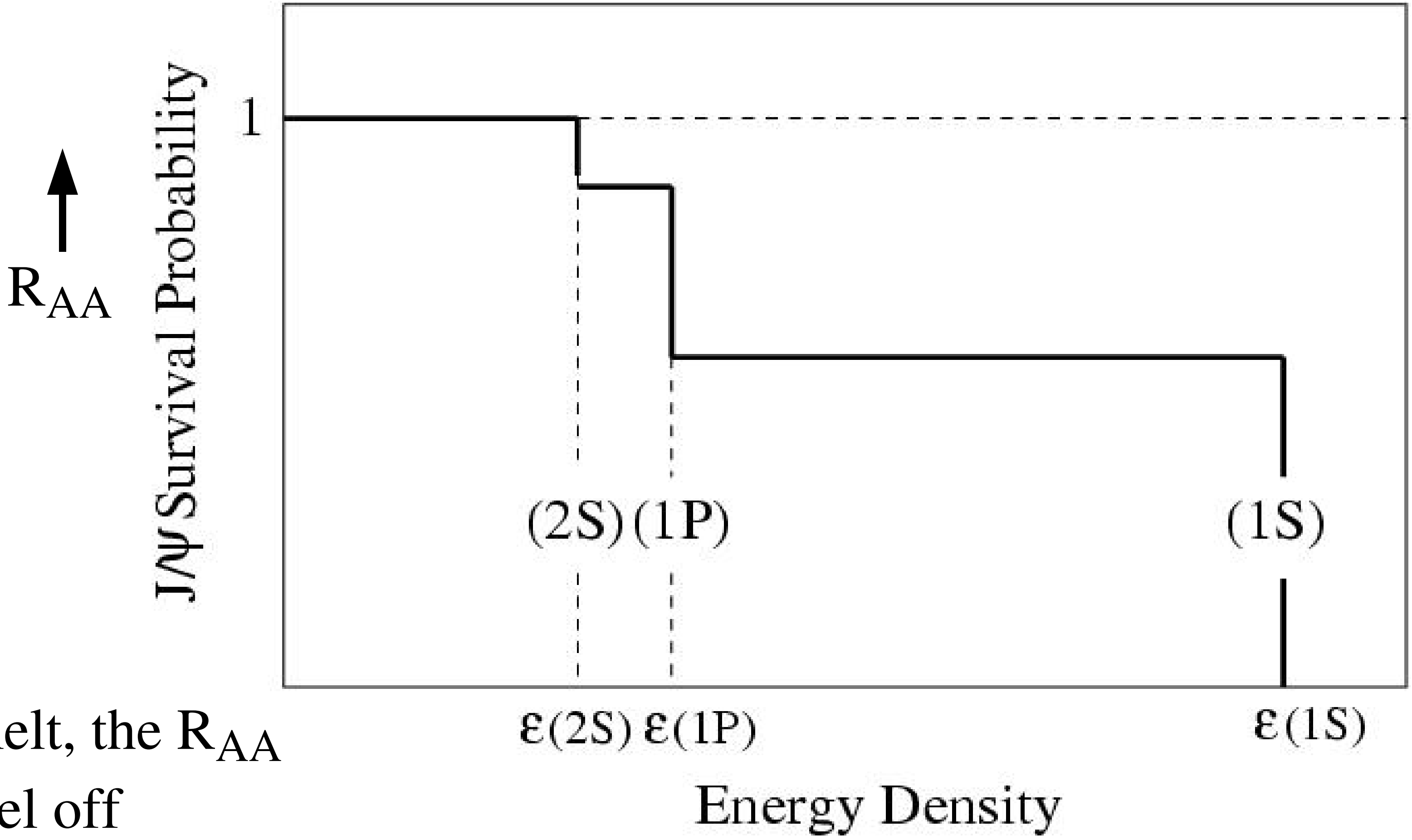
J/ψ should melt at $T > 2\,T_c$,

$\varepsilon > 16$ GeV/fm3

χ_c and ψ' should melt at T_c

$\varepsilon = 1\ \mathrm{GeV/fm^3}$

Sequential Melting – schematical picture



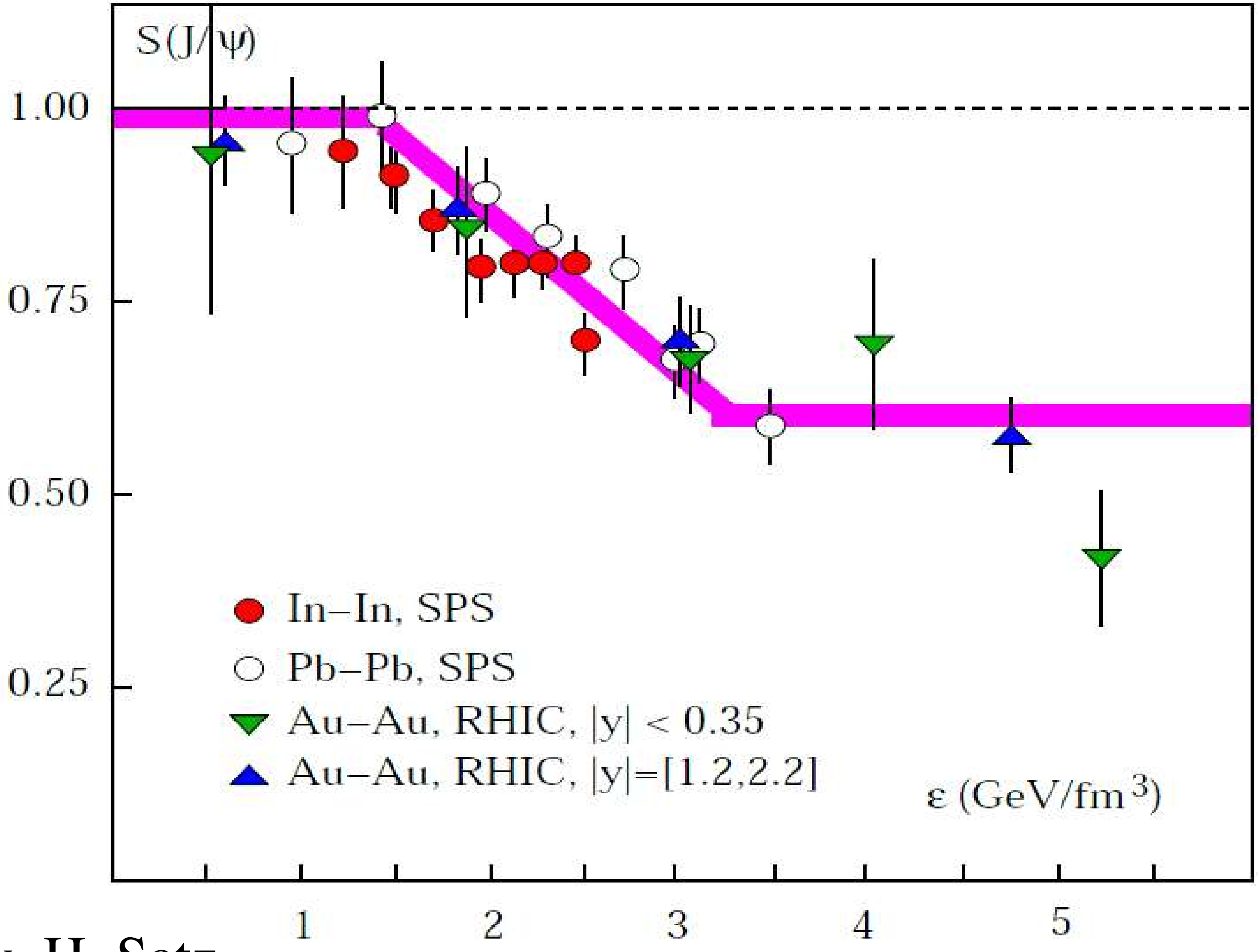
if J/ψ does not melt, the R_{AA} factor should level off at around $R_{AA} > 0.6$ (loss of feeding from χ_c and ψ')

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

Suppression pattern --- SPS and old RHIC data

assumption:
suppression is
only due to χ_c
and ψ'

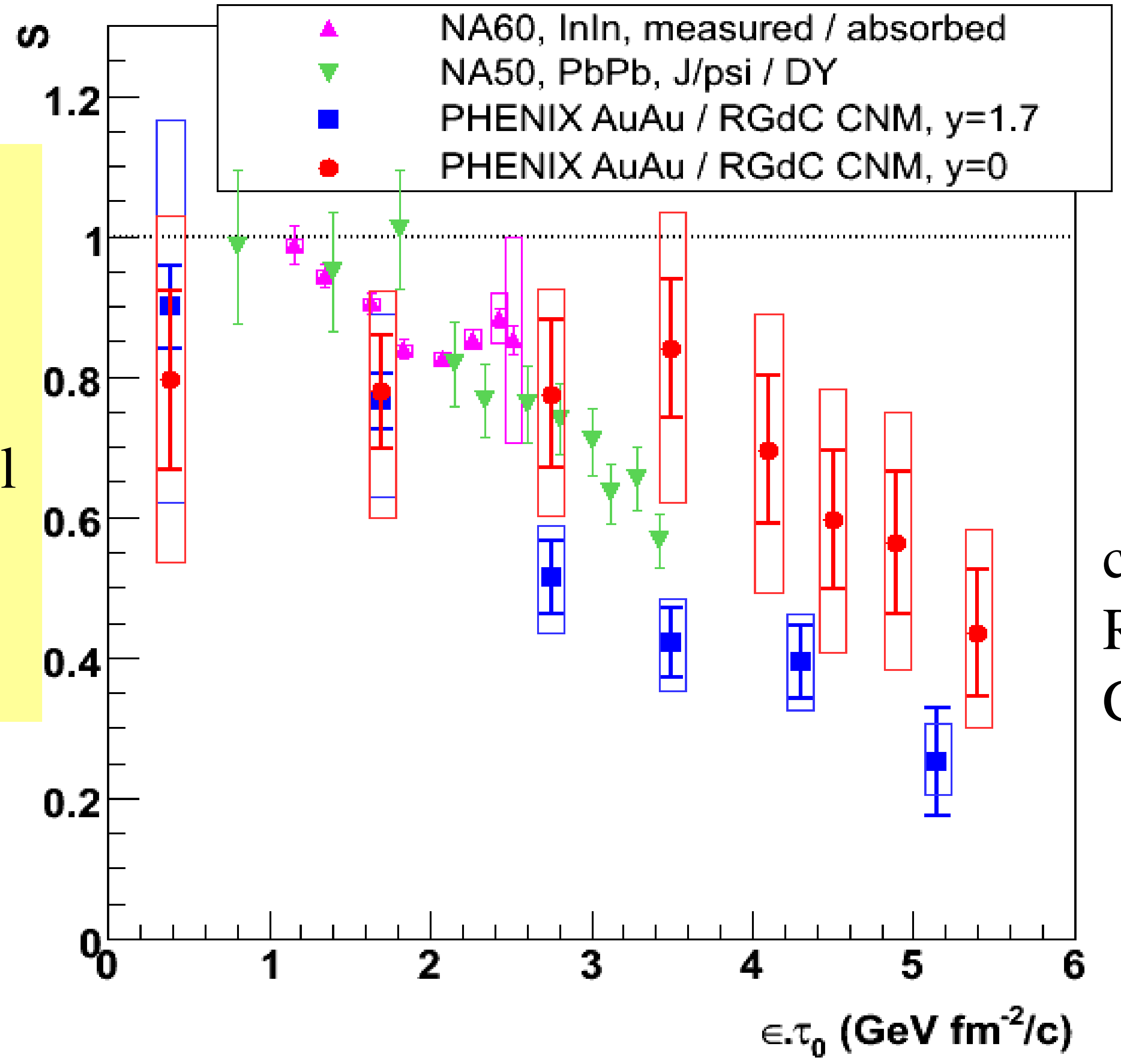
but J/ψ width is
large!
ε_{crit} =
3.2 GeV/fm^3



F. Karsch, D. Kharzeev, H. Satz,
Phys. Lett. B637 (2006) 75

preliminary RHIC data, no full error propagation

No experimental evidence for sequential melting



new data at various rapidities rule out sequential melting

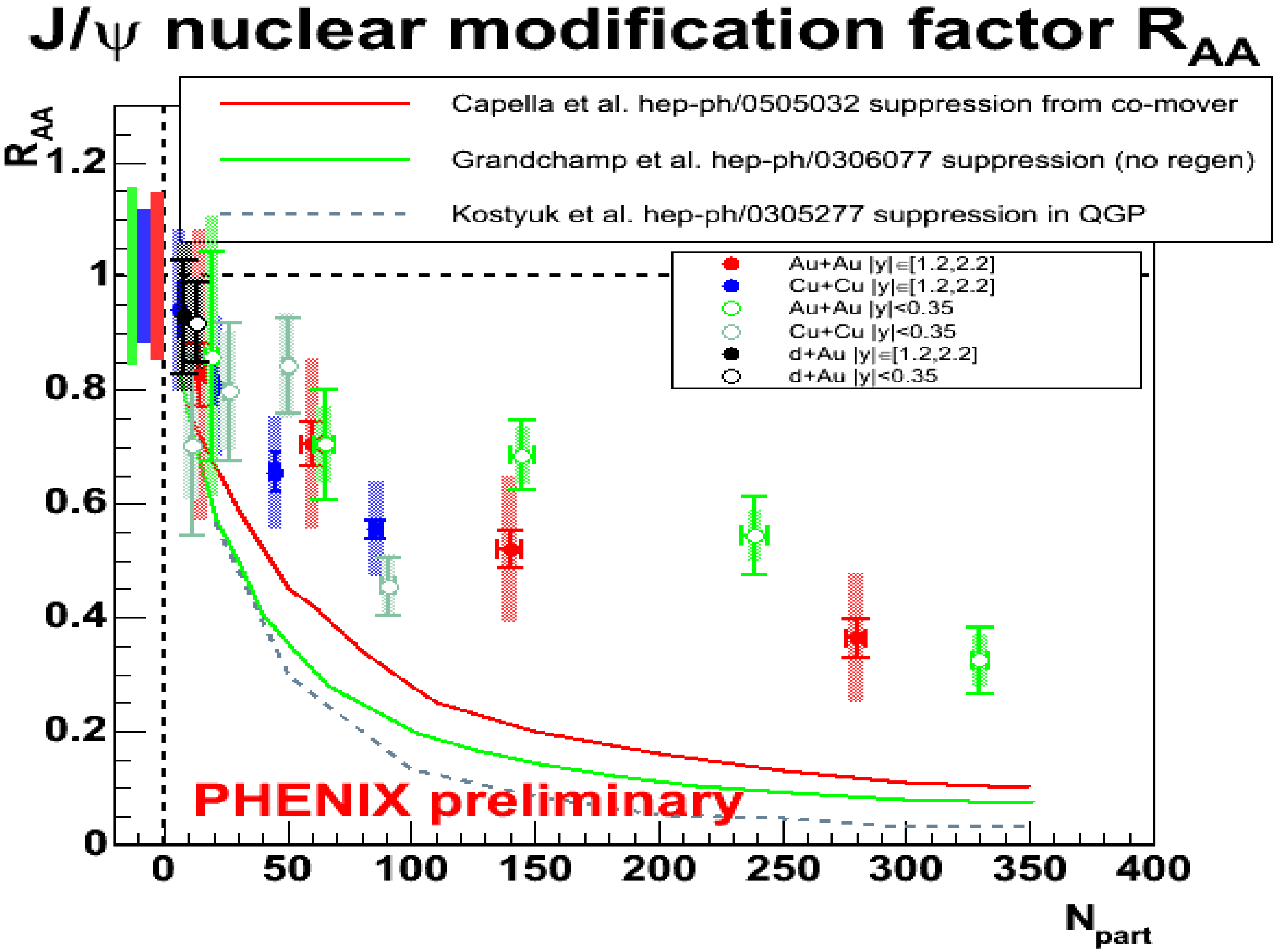
compilation by R. Granier de Cassagnac

Destruction of charmonia by comoving hadrons

interaction of pions or ρ mesons with charmonium leads to break-up in the hadronic phase of the fireball

- charmonium break-up cross sections unknown, typically assumed to be in the several mb range
- density of comovers must exceed 1/fm^3 to make a significant effect

Too much suppression at RHIC due to Co-Movers



Remark on the rapidity dependence of R_{AA}

- since the energy density (in the Bjorken model) scales like dN/dy, the suppression factor in the original Matsui-Satz picture should have a minimum at y=0 or at best be flat in rapidity.

- in the comover picture, the suppression factor should also have a minimum at y=0.

inconsistent with PHENIX data

unfortunately there are no data on rapidity dependence of J/ψ production at the SPS

What about „Cold Nuclear Matter Effects“

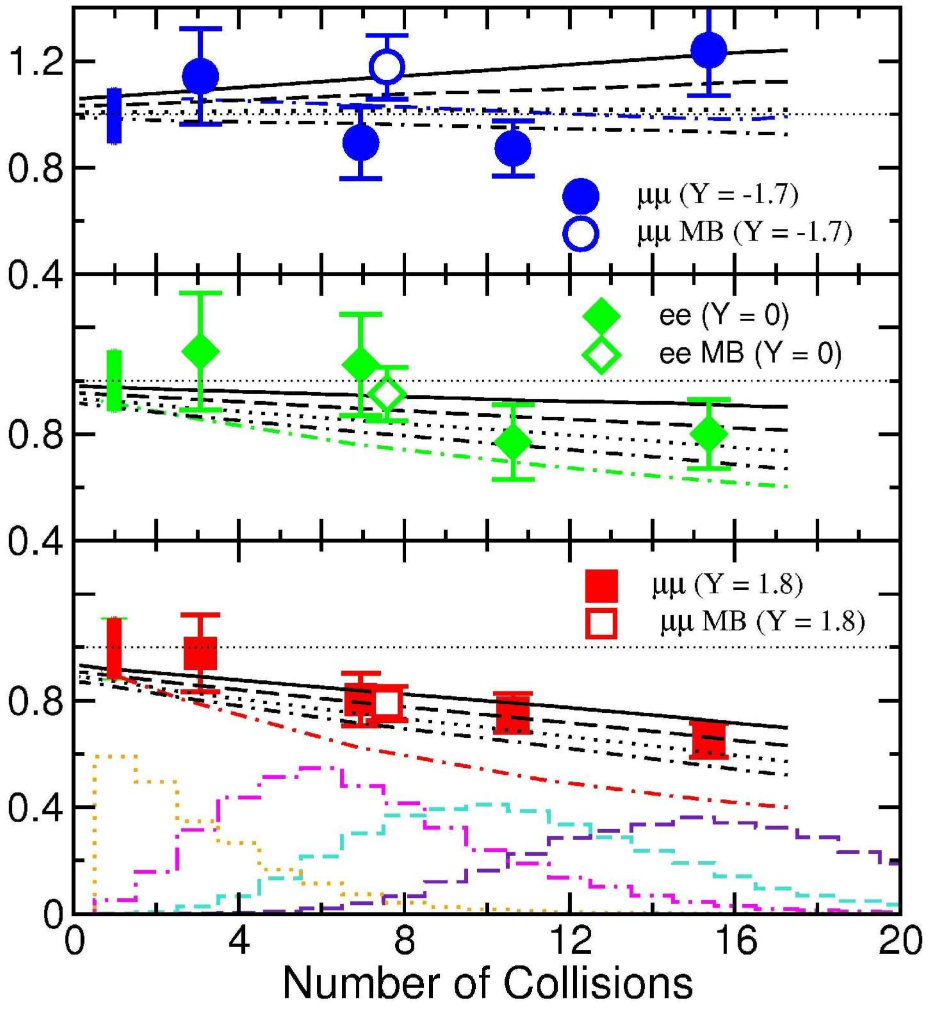
assumption: charmonia are formed very rapidly and are subsequently destroyed by the two contracted nuclear pancakes passing over them

note: time scale of charmonium production is comparable to passing-by time at SPS, but much longer at RHIC and especially LHC

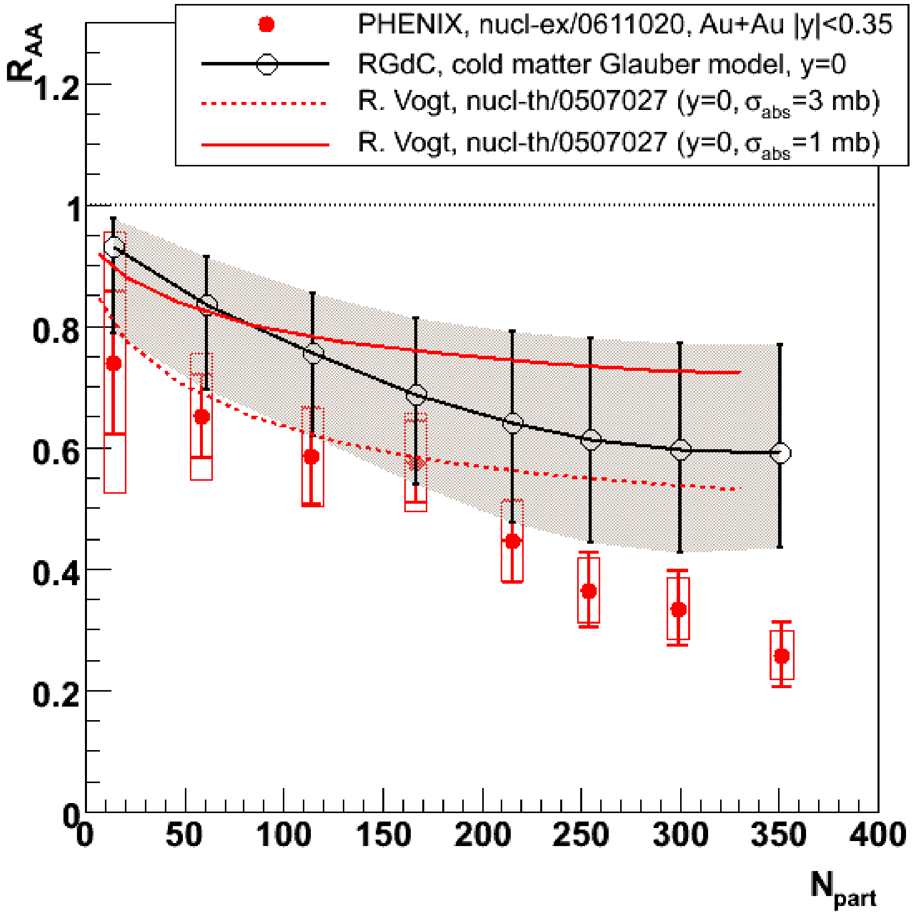
expect small CNM effects at RHIC
none at LHC

CNM effects are small at RHIC

curves: EKS shadowing and nucl. absorption, $\sigma_{abs} = 0 – 3$ mb



d Au collisions



Au Au collisions

Models with late generation of charmonium

- 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, no production 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 or kinetic recombination 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

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
A. Andronic, pbm, J. Stachel, K. Redlich,
nucl-th/0701079
pbm, nucl-th/0701093

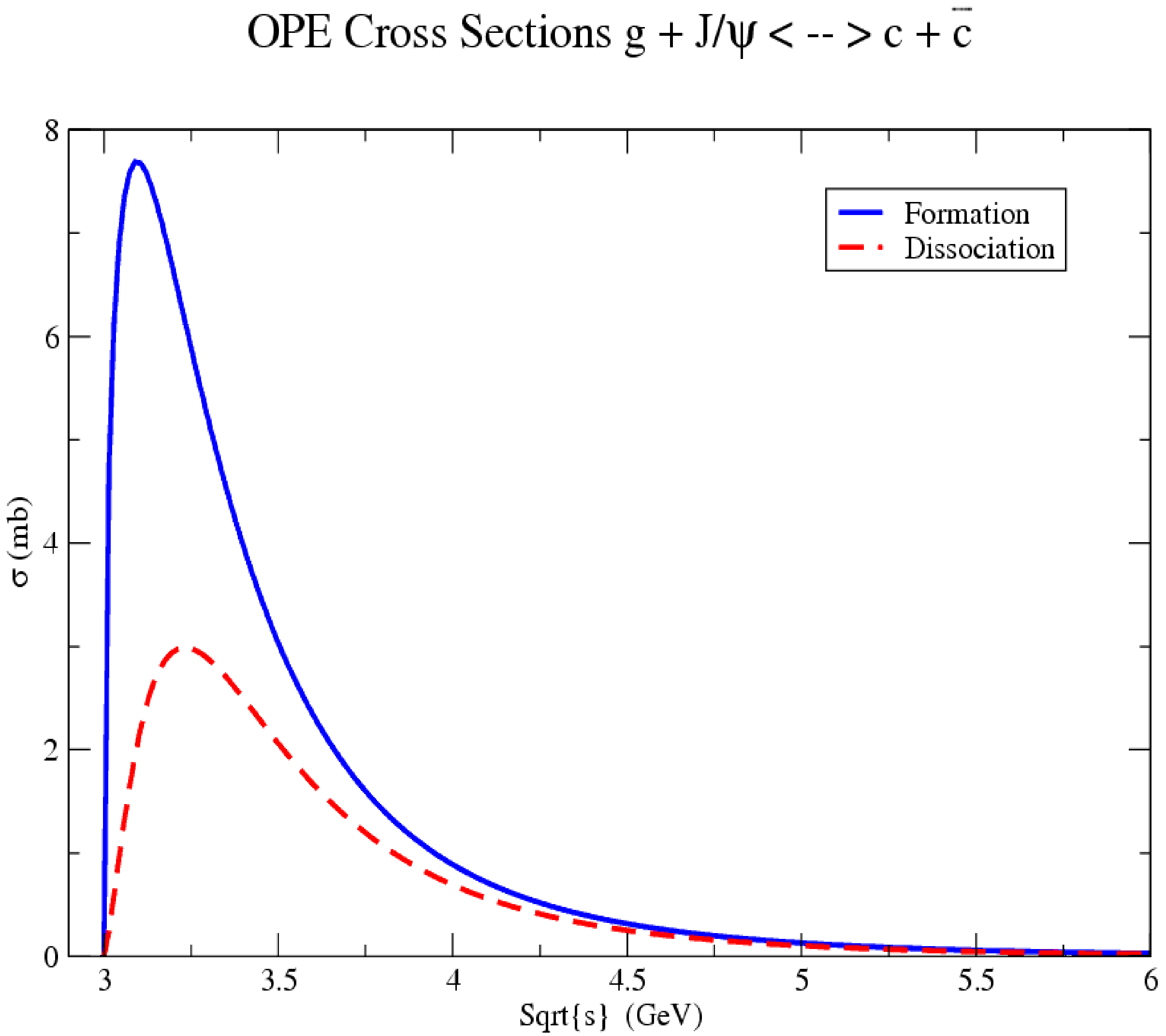
Kinetic model of R.L. Thews

balance between formation and destruction of charmonium in the QGP

needs rate equation and cross sections

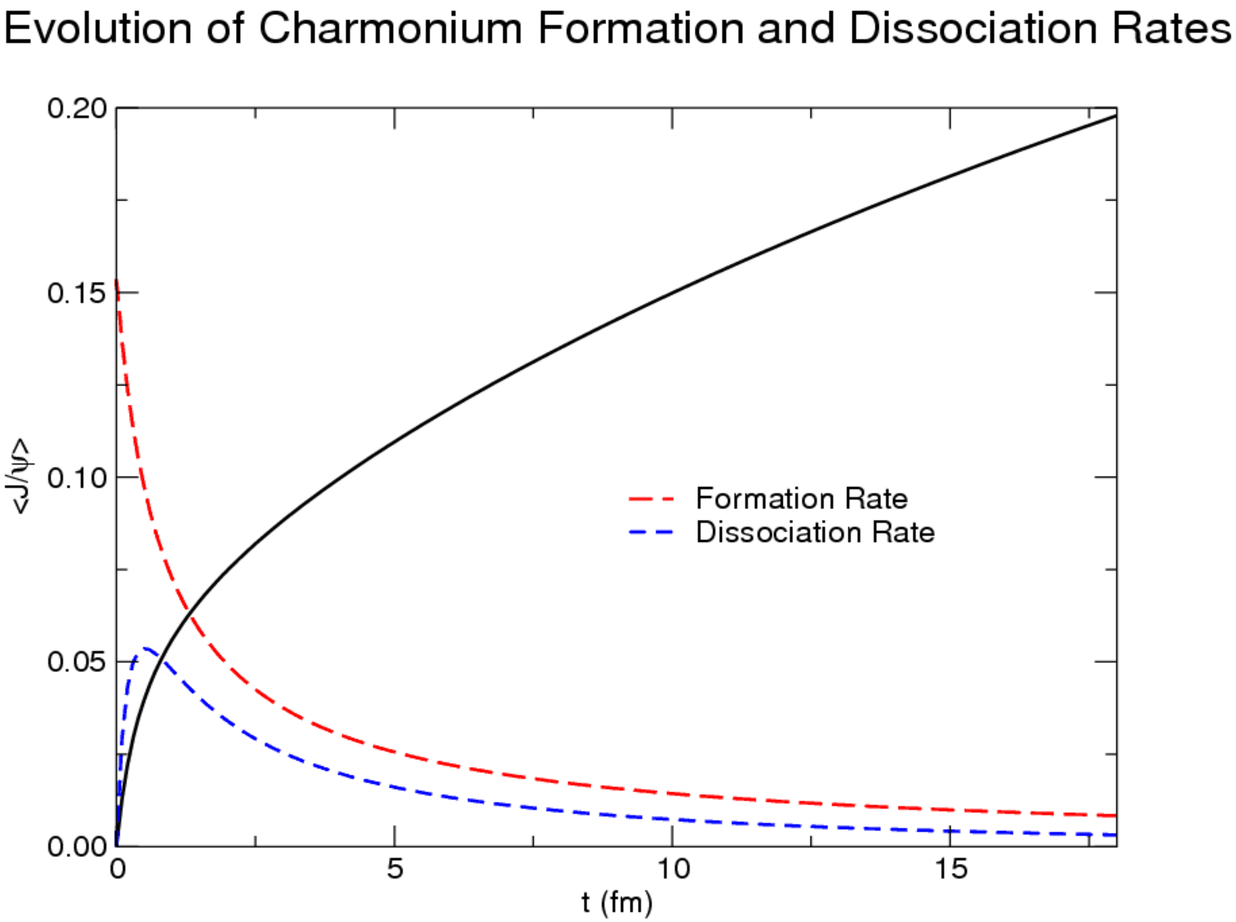
$$\frac{dN_{J/y}}{dt} = \langle vs_F \rangle \rho_c N_c - \langle vs_D \rangle \rho_g N_{J/y}$$

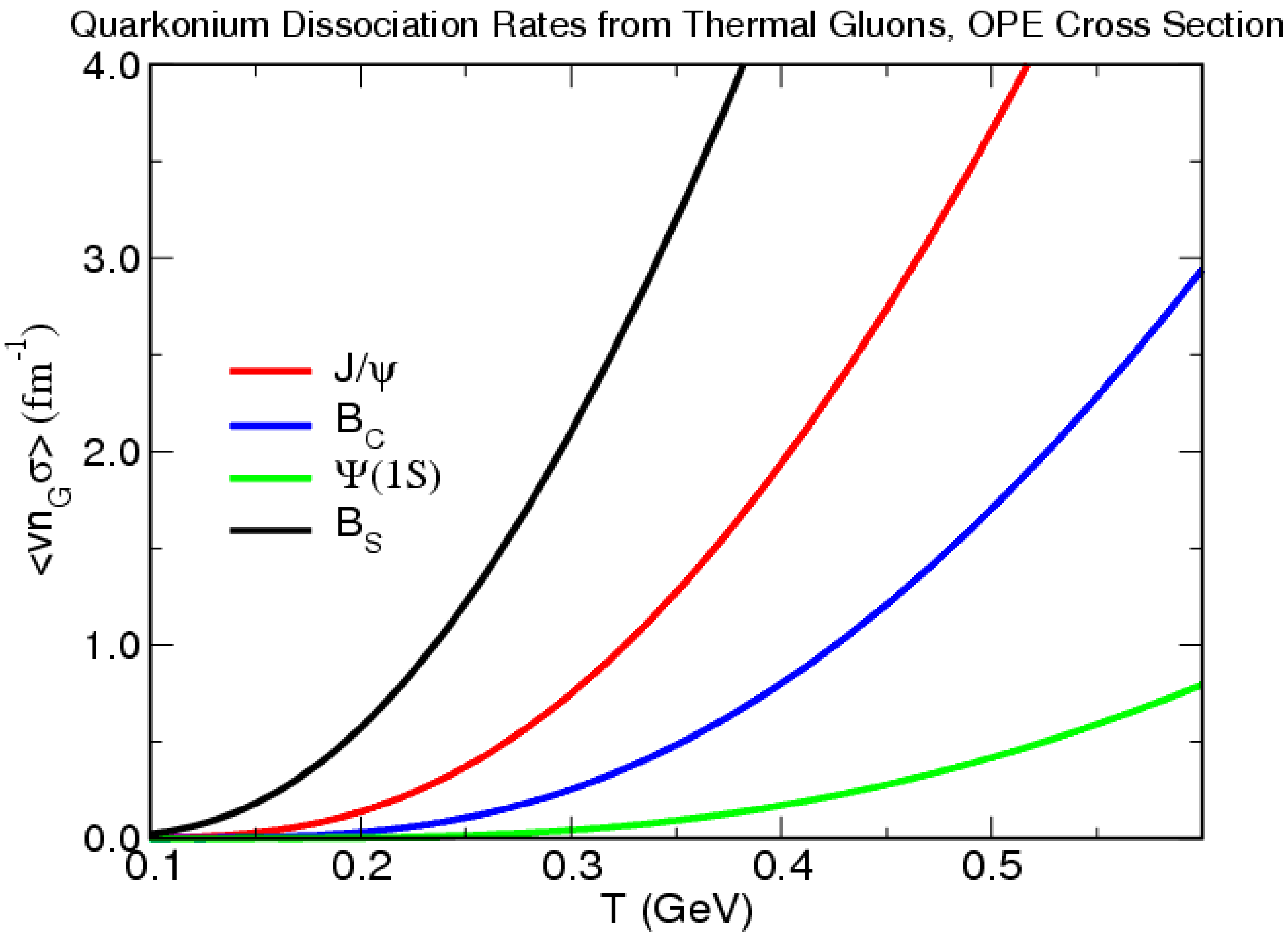
but: MANY THEORETICAL INPUT PARAMETERS



cross section is very large compared to total annihilation cross section, see below

Temporal evolution in the Thews picture

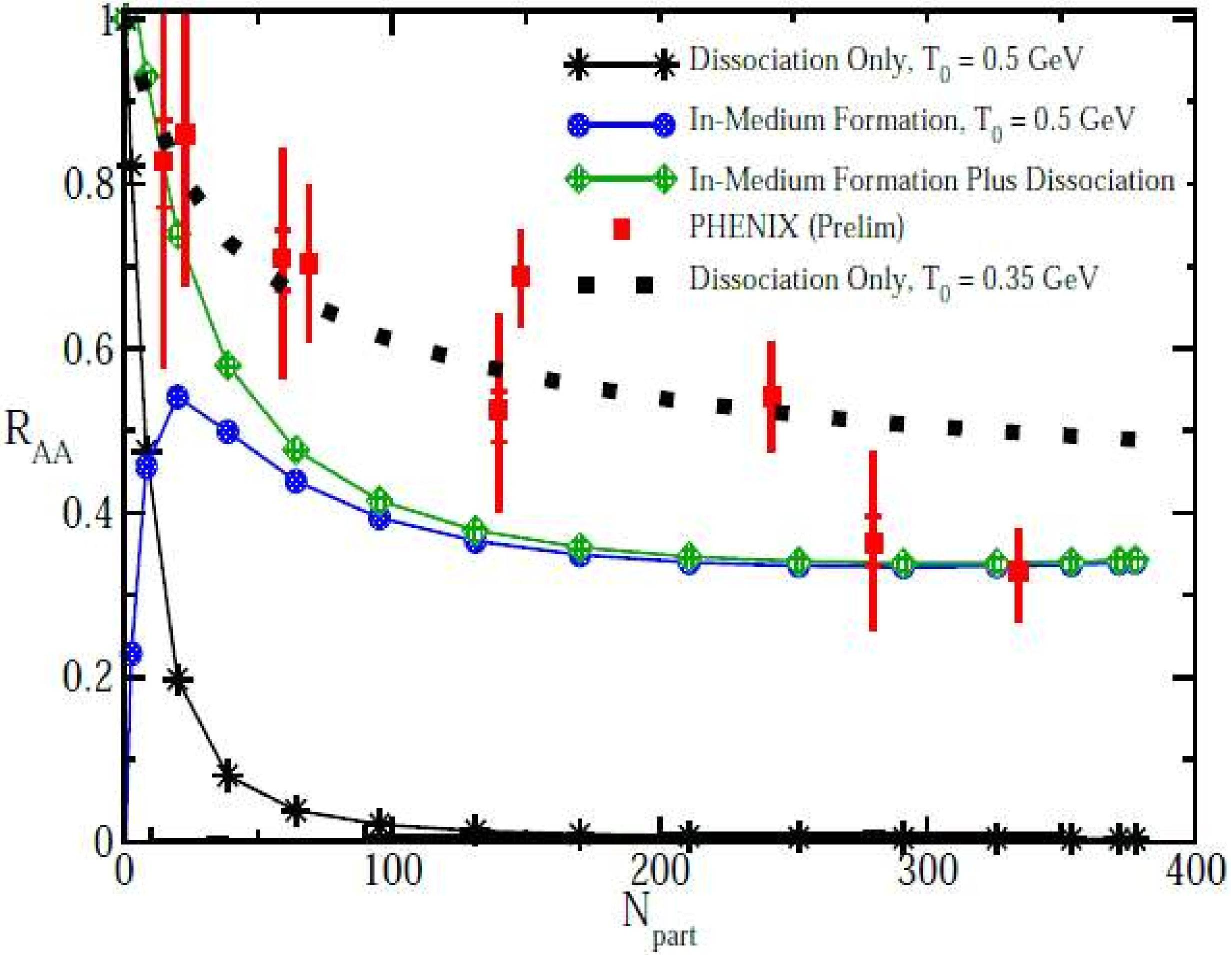




Thews, Beijing workshop,
Nov. 2006

Results from kinetic model

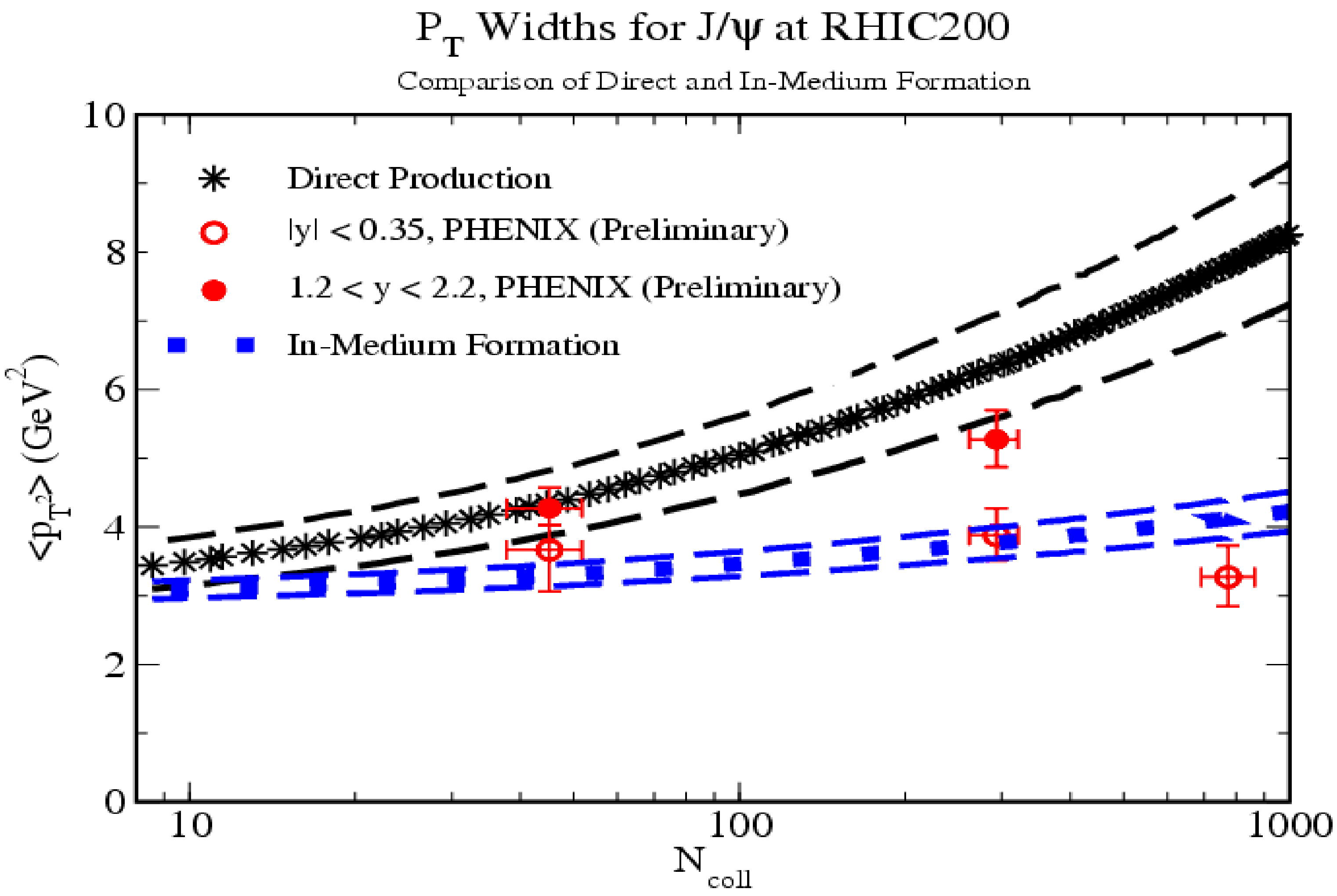
R.L Thews,
nucl-th/0609121
J. Phys. G30 (2004) S369



data described for a specific set of QGP parameters and charmonium production cross section

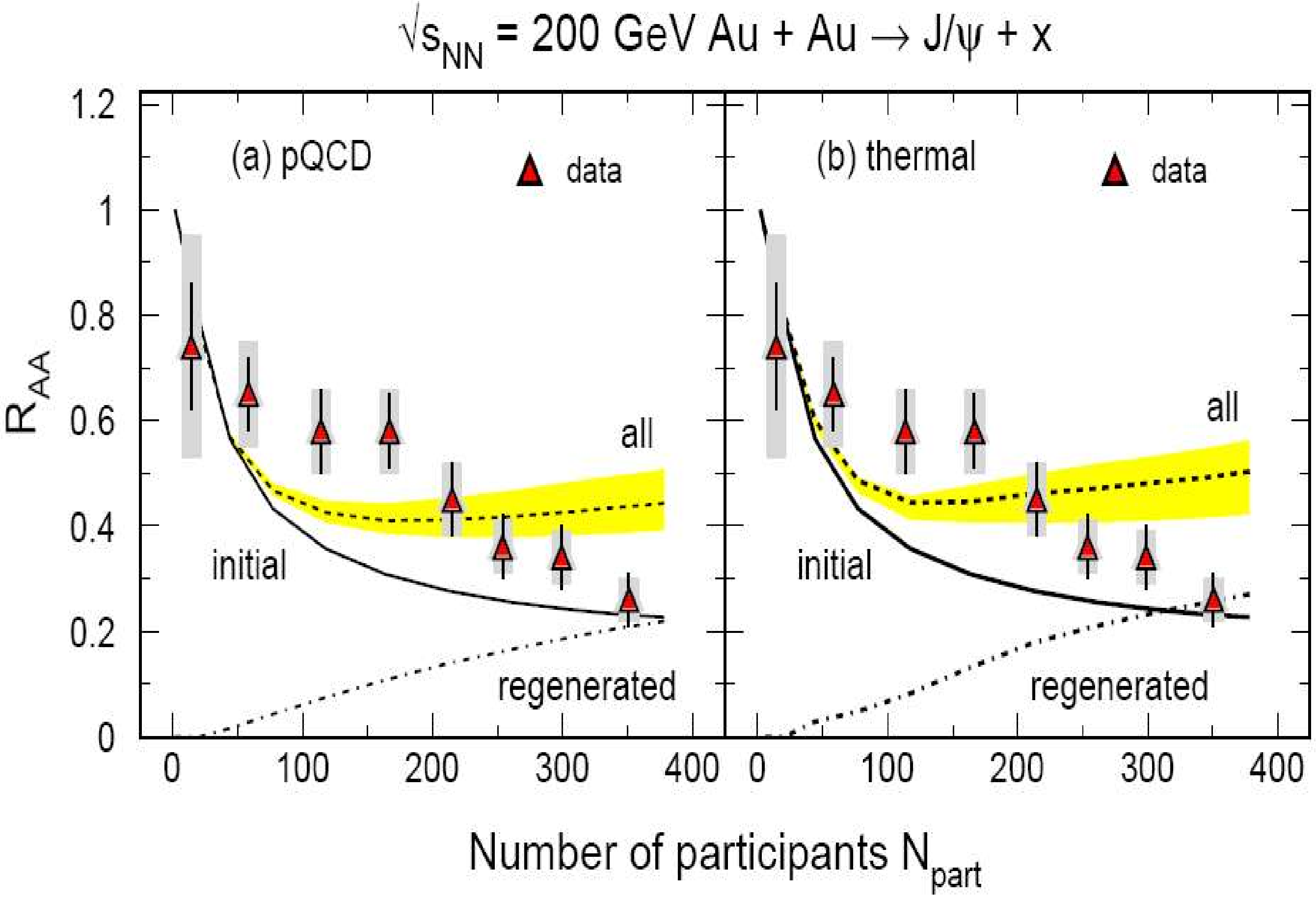
hard to make a quantitative prediction

Transverse momentum distributions and kinetic recombination model



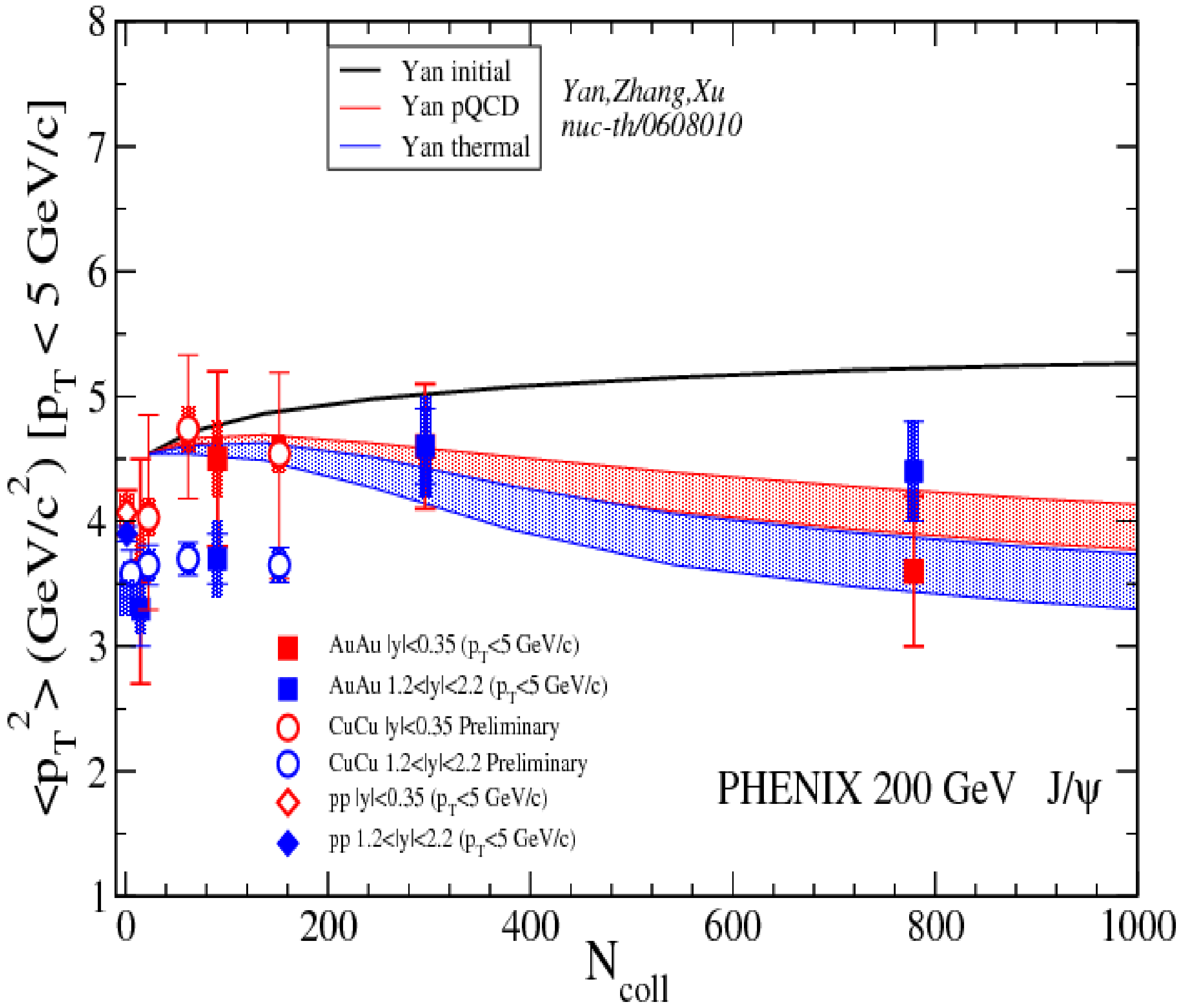
data not yet conclusive, Thews, Beijing, Nov. 2006

Charmonium transport in the QGP



P. Zhuang, L. Yan, X. Zhu, N. Xu, nucl-th/0608010, and Phys. Lett. B607 (2005) 107, approach similar to Thews

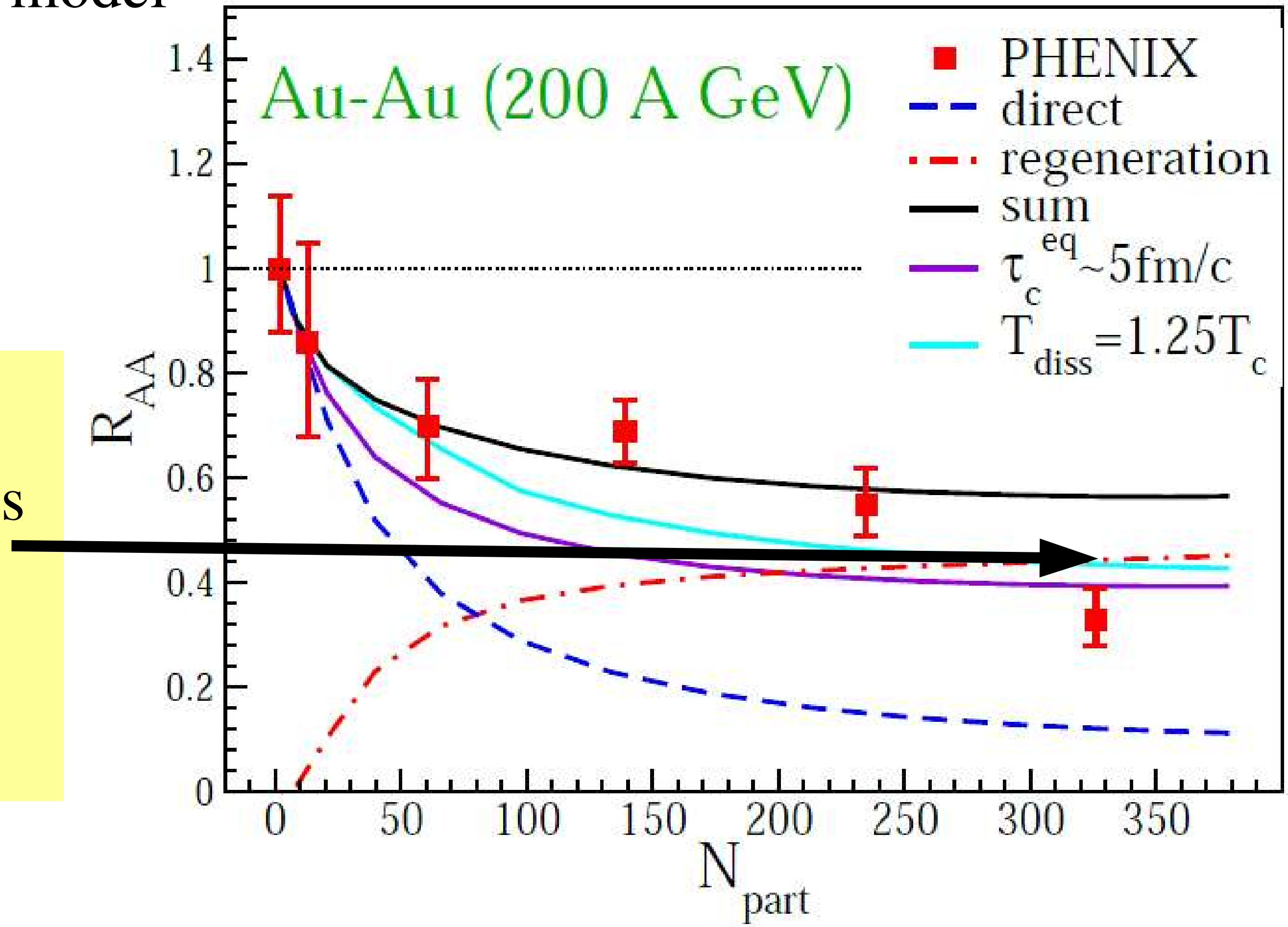
Transverse momentum distributions in the transport model



Charmonium regeneration a la Rapp

R. Rapp, D. Cabrera,
H. van Hees,
nucl-th/0608033, based on
statistical hadronization model

Rapp et al. use for charmonium generation the original prescription of pbm, stachel, Phys. Lett. B490 (2000) 196



(re)generation becomes dominant for central collisions

the following results are based on:

Statistical hadronization of heavy quarks in ultra-relativistic nucleus-nucleus collisions

A. Andronic, pbm, K. Redlich, J. Stachel

nucl-th/0611023

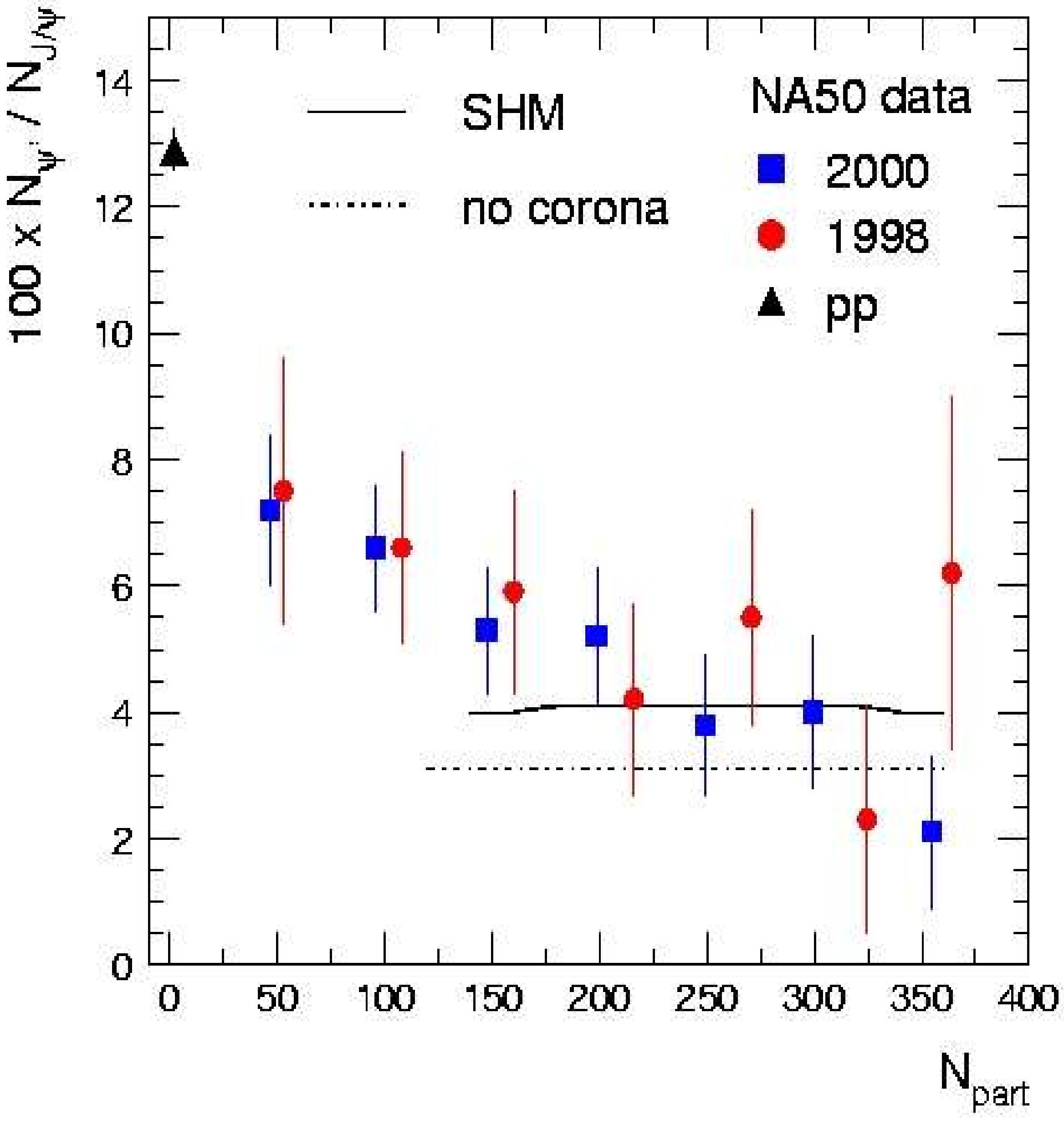
all charm quarks are produced in initial hard collisions

all charmonia and all hadrons with open and hidden charm are produced at the phase boundary

no quarkonium production before or in the plasma

$\chi_c/(J/\psi) = \exp(-\Delta M/T_c) < 10\ \%$ no feeding of higher charmonia   at all beam energies

ψ'/ψ ratio at SPS in agreement with statistical hadronization model



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

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

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)

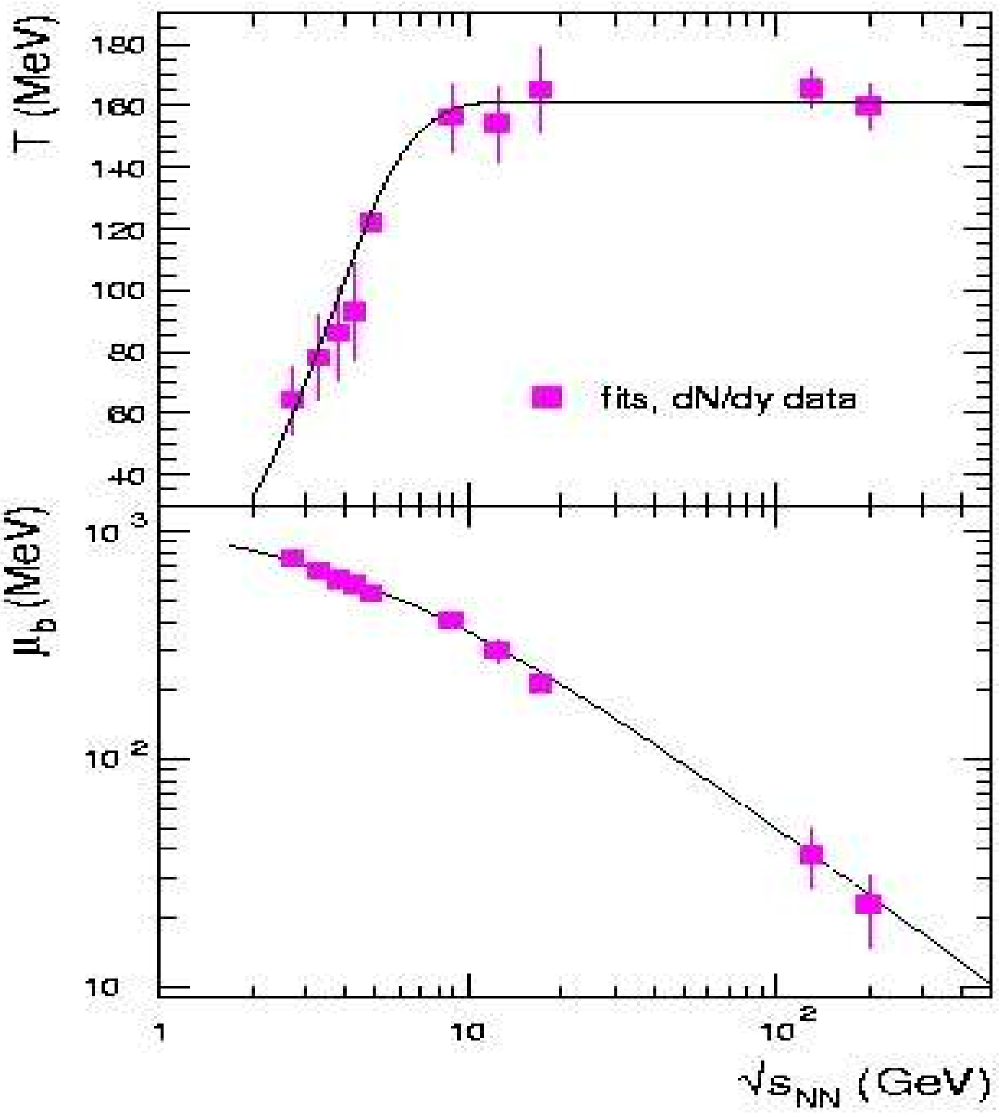
Parameterization of all freeze-out points

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



Ingredients for prediction of quarkonium cross section

- open charm (open bottom) cross section
- quarkonium production cross section in pp collisions (for corona part)

result: quarkonia cross sections as function of energy, centrality, rapidity, and transverse momentum

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

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

annihilation into 3 or more gluons is strongly suppressed see nucl-th/0701093

- total annihilation rate:

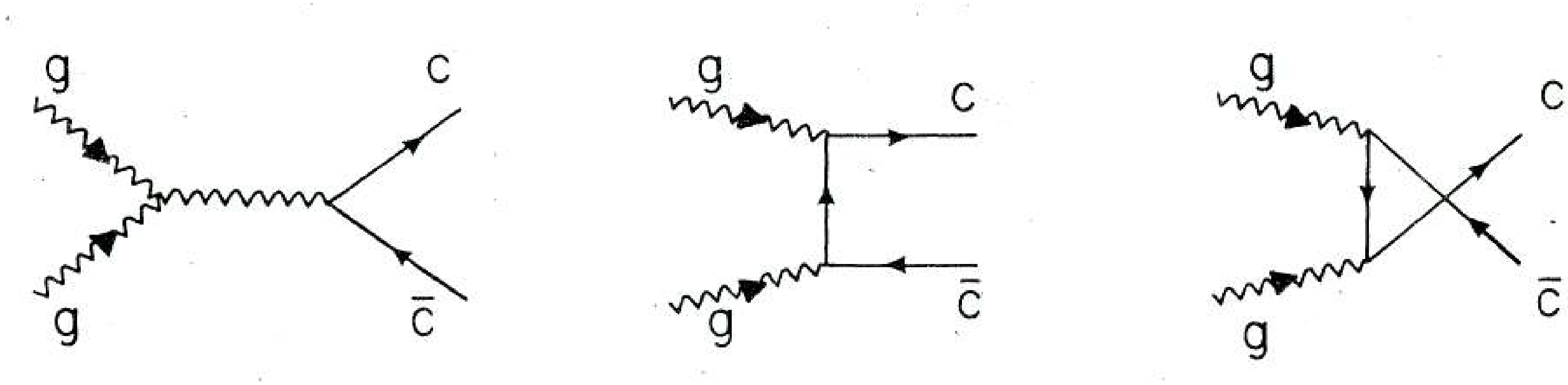
$$\frac{dr_{c\bar{c}}}{d\tau} = n_c n_{\bar{c}} \langle \sigma_{c\bar{c} \rightarrow gg} v_r \rangle$$

< > implies thermal average

Cross section for ccbar annihilation

based on M. Glueck, J. F. Owens, E. Reya,
Phys. Rev. D17 (1978) 2324

first compute inverse process:



then use detailed balance
(time reversal)

total cross section

$$\sigma^{gg\to c\bar{c}}=\frac{\pi\alpha_s^2}{64s}\Big[12(\tfrac{2}{3}+\tfrac{1}{3}\gamma)(1-\gamma)^{1/2}+\tfrac{16}{3}\Big((4+2\gamma)\ln\frac{1+(1-\gamma)^{1/2}}{1-(1-\gamma)^{1/2}}-4(1+\gamma)(1-\gamma)^{1/2}\Big)$$

$$+6\Big(2\gamma\ln\frac{1+(1-\gamma)^{1/2}}{1-(1-\gamma)^{1/2}}-4(1+\gamma)(1-\gamma)^{1/2}\Big)-\tfrac{2}{3}2\gamma(1-\gamma)\ln\frac{1+(1-\gamma)^{1/2}}{1-(1-\gamma)^{1/2}}\Big]$$

with $\gamma\equiv 4m^2/s\leqslant 1$.

using detailed balance yields final result:

$$\sigma_{c\bar{c}\to gg}(s)=\sigma_{gg\to c\bar{c}}\cdot\frac{9}{4}\frac{s^2}{\sqrt{(s^2-4m_c^2s)}\sqrt{((s-2m_c^2)^2-4m_c^4)}}$$

note: giving gluons a thermal mass ~gT in the plasma will reduce the cross section.

differential cross section

$$\frac{d\sigma^{gg\to c\bar{c}}}{dt}=\frac{\pi\alpha_s^2}{64s^2}\left(12M_{ss}+\tfrac{16}{3}M_{tt}+\tfrac{16}{3}M_{uu}\right.$$

$$\left.+\,6M_{st}+6M_{su}-\tfrac{2}{3}M_{tu}\right)\,, \qquad \text{(A1)}$$

with

$$M_{ss}=\frac{4}{s^2}(t-m^2)(u-m^2)\,,$$

$$M_{tt}=\frac{-2}{(t-M^2)^2}\left[4m^4-(t-m^2)(u-m^2)\right.$$

$$\left.+\,2m^2(t-m^2)\right]\,,$$

$$M_{uu}=\frac{-2}{(u-m^2)^2}\left[4m^4-(u-m^2)(t-m^2)\right.$$

$$\left.+\,2m^2(u-m^2)\right]\,, \qquad \text{(A2)}$$

$$M_{st}=\frac{4}{s(t-m^2)}\left[m^4-t(s+t)\right]\,,$$

$$M_{su}=\frac{4}{s(u-m^2)}\left[m^4-u(s+u)\right]\,,$$

$$M_{tu}=\frac{-4m^2}{(t-m^2)(u-m^2)}\left[4m^2+(t-m^2)+(u-m^2)\right]\,,$$

further evaluation needs expansion dynamics -- Bjorken hydro

$$\frac{\pi^2}{45}(32+21N_f)T^3\tau = 3.8\frac{dN/dy}{A_\perp}$$

volume:

$$V(\Delta y = 1, \tau) = A_\perp \tau$$

total annihilation yield:

$$N_{c\bar{c}}^{anni} \leq (\frac{dN_c/dy(\tau_0)}{dy})^2 \frac{1}{A_\perp} \int_{\tau_0}^{\tau_c} \frac{d\tau}{\tau} \langle \sigma_{c\bar{c}\to gg} v_r \rangle$$

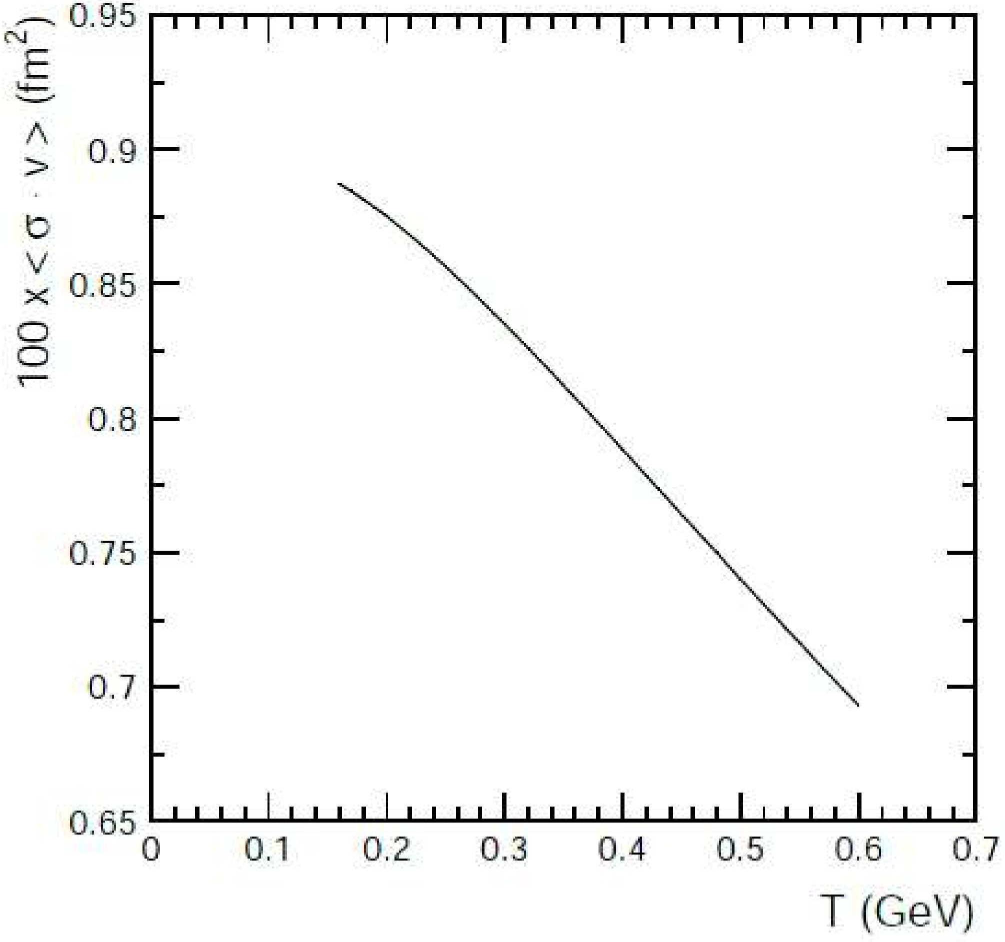
with $N_f = 2.2$ and $\tau_0 = 1$ fm, get 2 scenarios:

RHIC: $T_0 = 225$ MeV, $\tau_c = 2.3$ fm
LHC: $T_0 = 325$ MeV, $\tau_c = 8.3$ fm

note: annihilation yield depends
only logarithmically
on expansion scenario

numerical results

temperature dependence of thermal average for $\alpha_s = 1$, to get upper limit



thermal average evaluated in Boltzmann approximation following Lin & Ko, PRC 62 (2000) 034903

cross section is of order 0.1 mb

evolution of charm quark density:

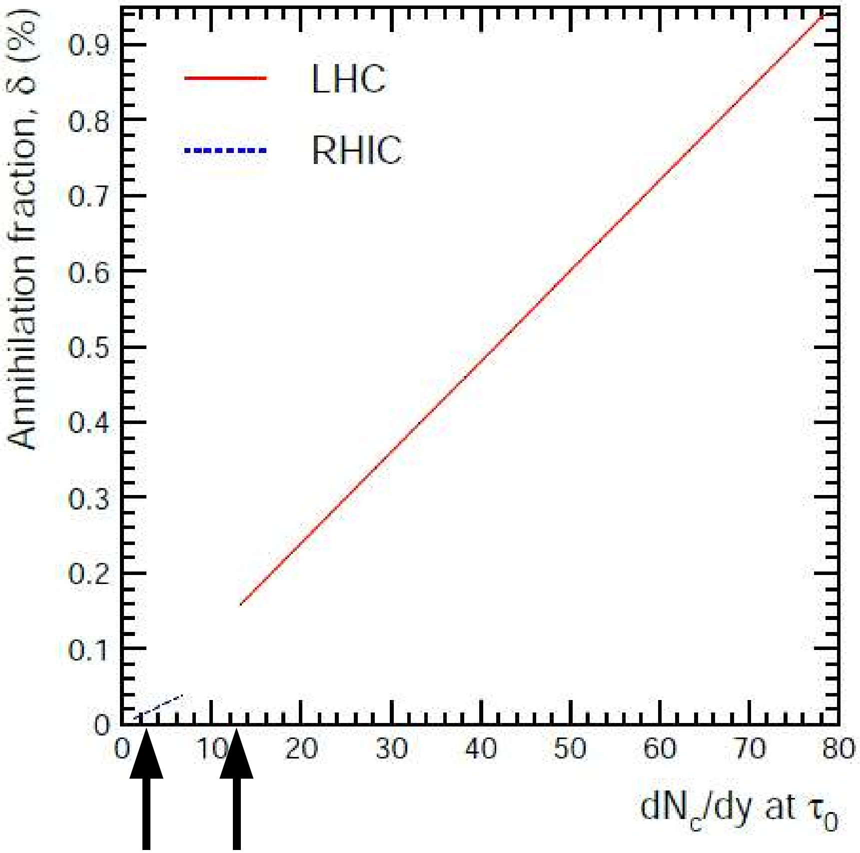
$$n_c = \frac{dN_c/dy(\tau)}{V(\Delta y = 1, \tau)} \leq \frac{dN_c/dy(\tau_0)}{V(\Delta y = 1, \tau)}$$

total annihilation yield

$$N_{c\bar{c}}^{anni} = \int_{\tau_0}^{\tau_c} \frac{dr_{c\bar{c}}}{d\tau} V(\Delta y = 1, \tau) d\tau$$

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 comparable to the initial time of plasma formation, all charmonia should be produced at the phase transition, i.e at hadronization

Results and discussion for SPS, RHIC, and LHC,

see talk by Johanna Stachel