# Charmonium and Open Charm from SIS300 to LHC Energy

- introductory remarks on charmonium and QGP
- discussion of time scales and open charm conservation equation
- the statistical hadronization model
- results for RHIC energy
- outlook for LHC energy
- results for SPS and lower energies

pbm, vi meeting on charmonia
GSI, May 9 2007

work performed in collaboration with
A. Andronic, Johanna Stachel, K. Redlich

# 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:

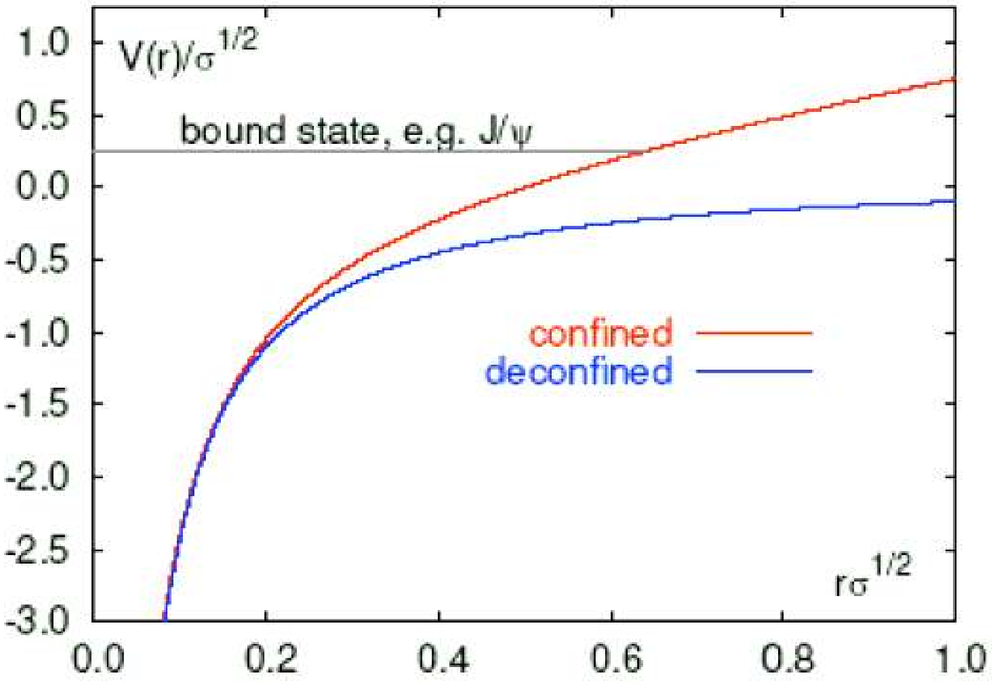
- **all** charmonia are produced before QGP formation
- suppression takes place in QGP
- some charmonia might survive beyond $T_c$

→ sequential suppression pattern due to feeding

# Debye screening

V(r,T large)   no bound state

V(r,T small)  bound state



σ = string tension = 1 GeV/fm

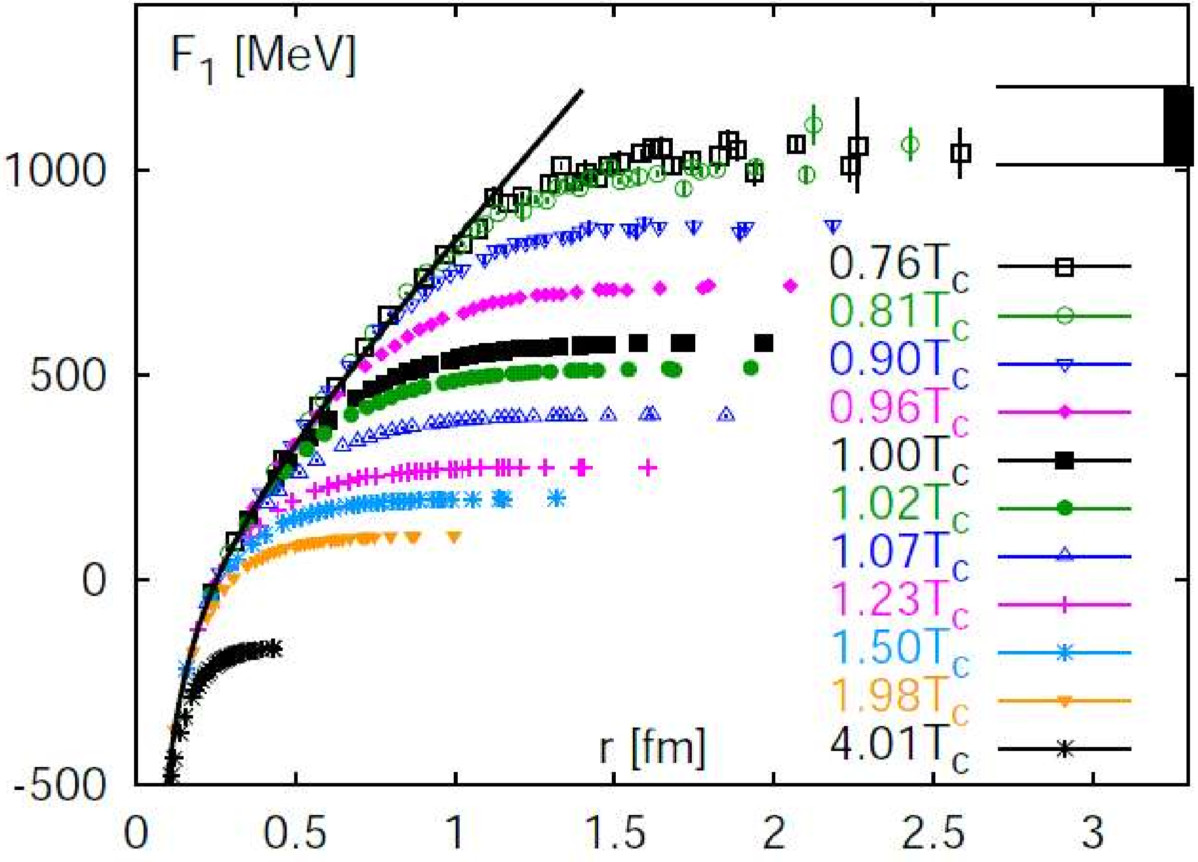
$= 0.2\ \mathrm{GeV}^2$

# 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

# In-medium modifications of charmed hadrons

decreasing plateau in the free energy may also imply a reduction in D meson masses:  the light constituent quark looses its mass near $T_c$

this may lead to a reduced in-medium charm quark mass

# Remarks on production of open charm and charmonia

- charm quark mass >> $\Lambda_{QCD}$ 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 $1/m_c$
  $m_c = 1.5$ GeV --> $t_c = 0.13$ 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

# Formation time of quarkonia

heavy quark velocity in charmonium rest frame:

$v = 0.55$ for $J/\psi$ 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 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

# 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

    → 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

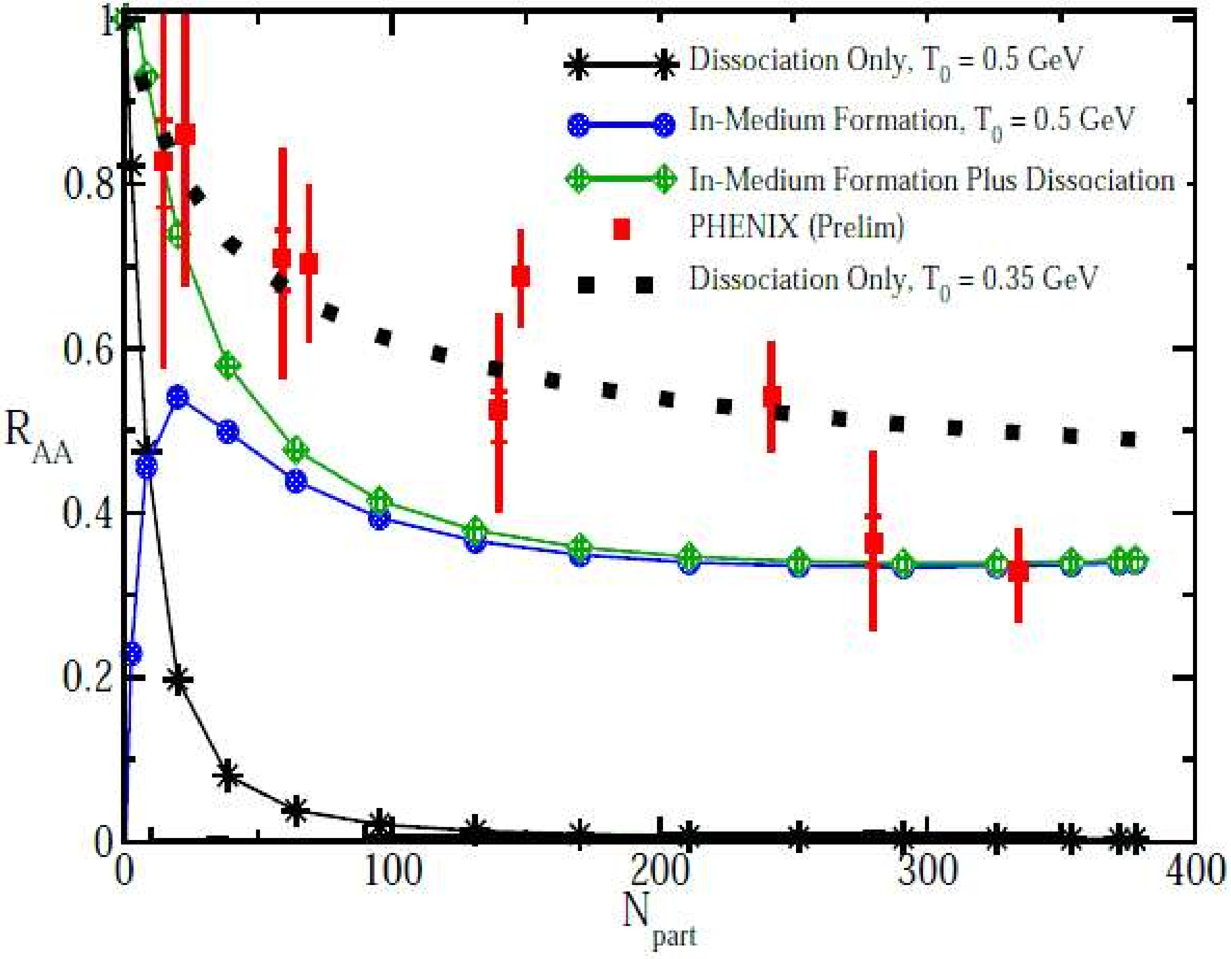
    → yield ~ $N_c^2$ -- quarkonium enhancement at high energies

# 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. A (in print)**
**A. Andronic, pbm, J. Stachel, K. Redlich,**
**nucl-th/0701079, Phys. Lett. B (in print)**
**pbm, nucl-th/0701093 J. Phys. G (in print)**

# 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

will concentrate on statistical hadronization model

# Method and inputs

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

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

$N_{c\bar{c}} << 1 \longrightarrow$ 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: $N_D = g_c V n_D^{th} I_1 / I_0$ $\quad N_{J/\psi} = g_c^2 V n_{J/\psi}^{th}$

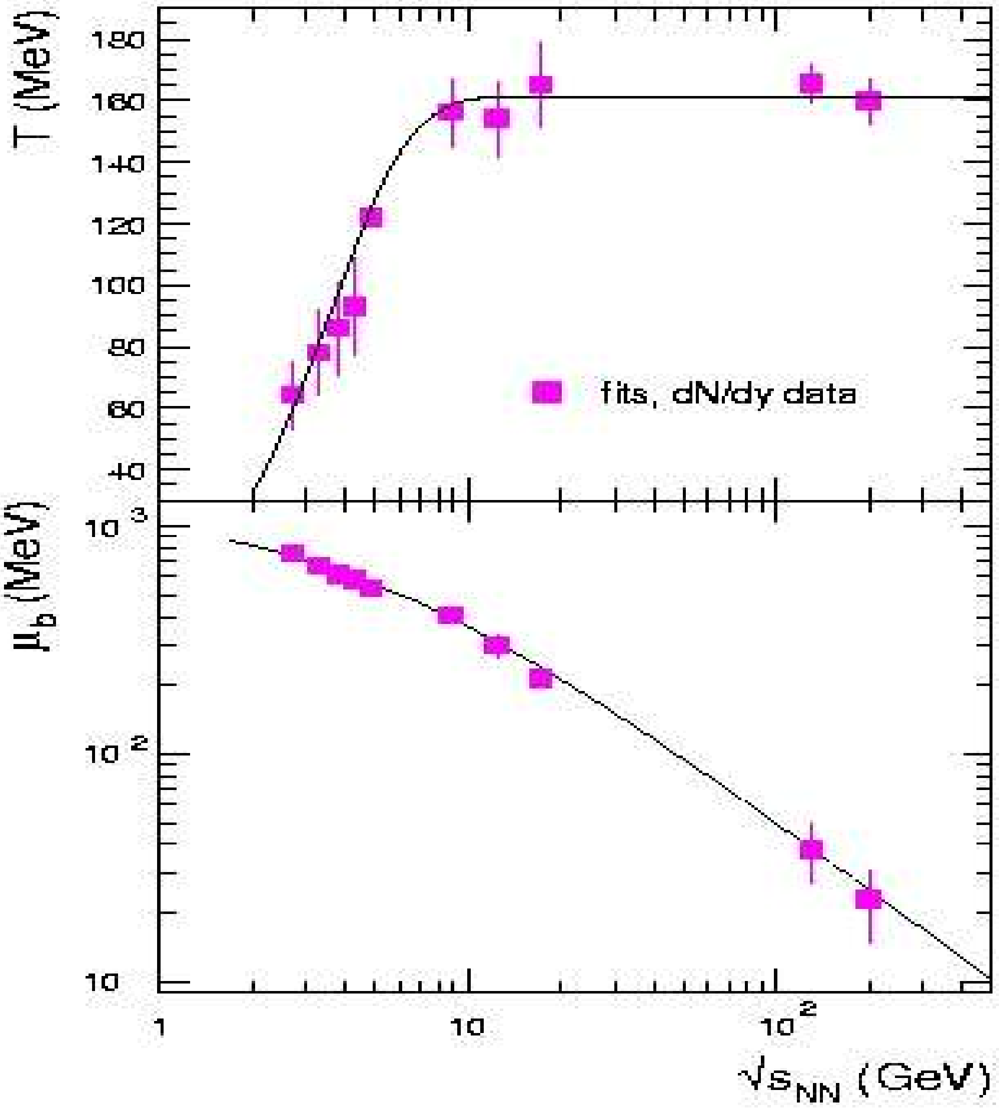
Inputs: $T$, $\mu_B$, $\quad V = N_{ch}^{exp} / n_{ch}^{th}$, $\quad N_{c\bar{c}}^{dir}$ (pQCD)

# Parameterization of all freeze-out points

note: establishment of limiting temperature

**$T_{lim}$ = 160 MeV**

**get T and $\mu_B$ for all energies**



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

# Ingredients for prediction of quarkonium and open charm cross sections

- open charm (open bottom) cross section in pp collisions

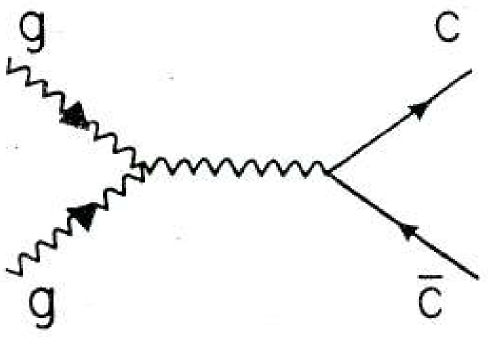
- quarkonium production cross section in pp collisions (for corona part)

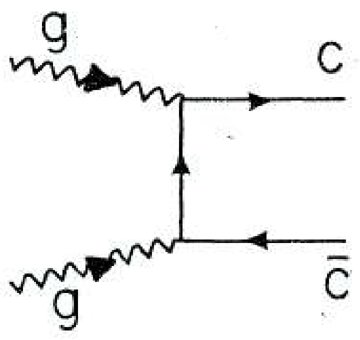
result: quarkonium and open charm cross sections as function of energy, centrality, rapidity, and transverse momentum

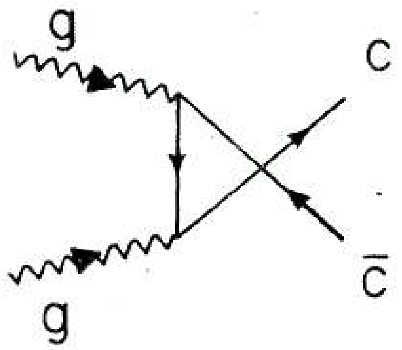
# Cross section for charm production

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

in leading order there are 3 important diagrams:







# differential cross section

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

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

with

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

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

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

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

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

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

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

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

# total cross section

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

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

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

this result plus NLO/NNLO/FONLL corrections are currently the basis of all open charm calculations (see, e.g., the calculations by Cacciari et al., discussed below.

# Definition of Modification of Charmonium in the Fireball

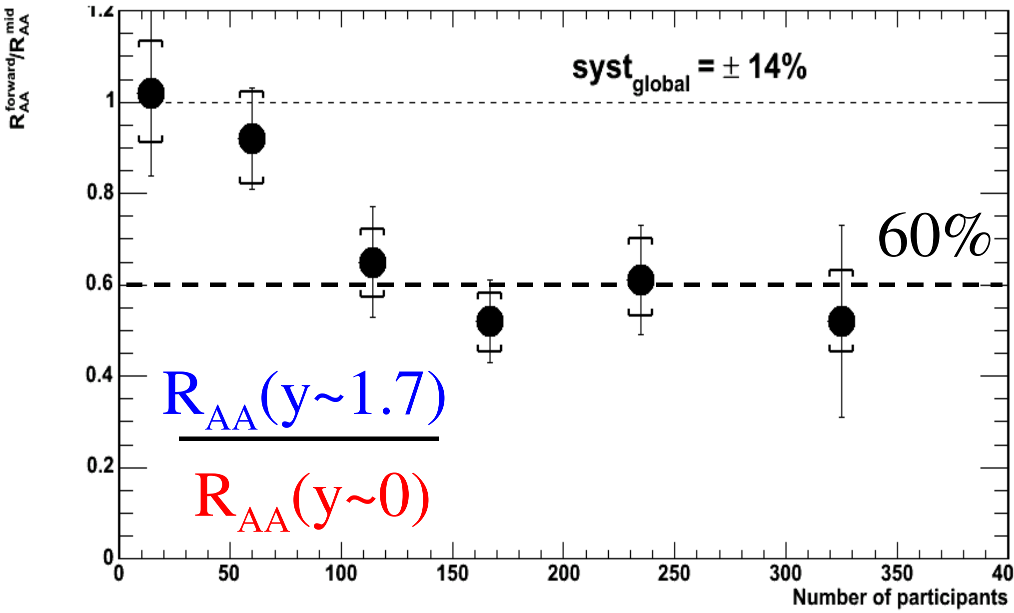
use $R_{AA}$ to define charmonium modification experimentally
no need to normalize to Drell-Yan process

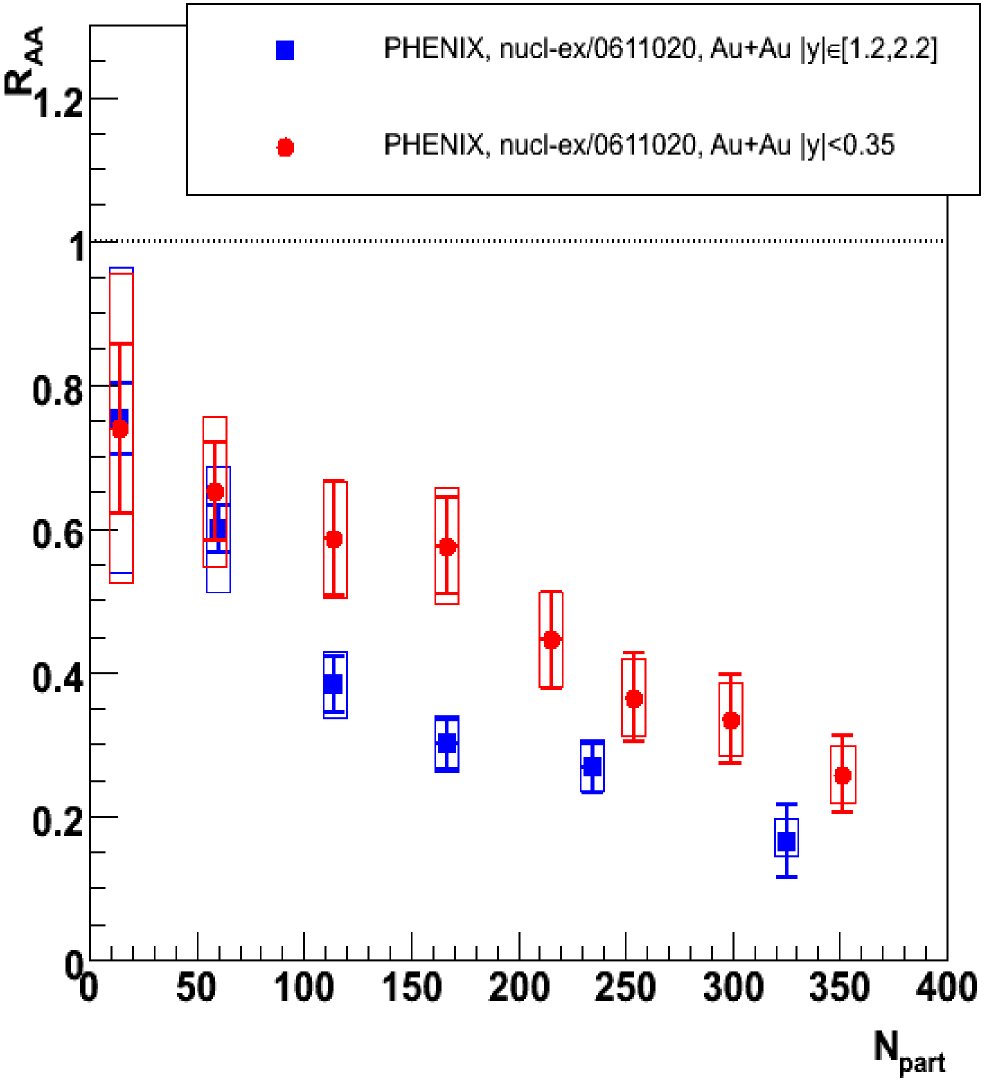
$$R_{AA}^{J/\psi} = \frac{\mathrm{d}N_{J/\psi}^{AuAu}/\mathrm{d}y}{N_{coll} \cdot \mathrm{d}N_{J/\psi}^{pp}/\mathrm{d}y}$$

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

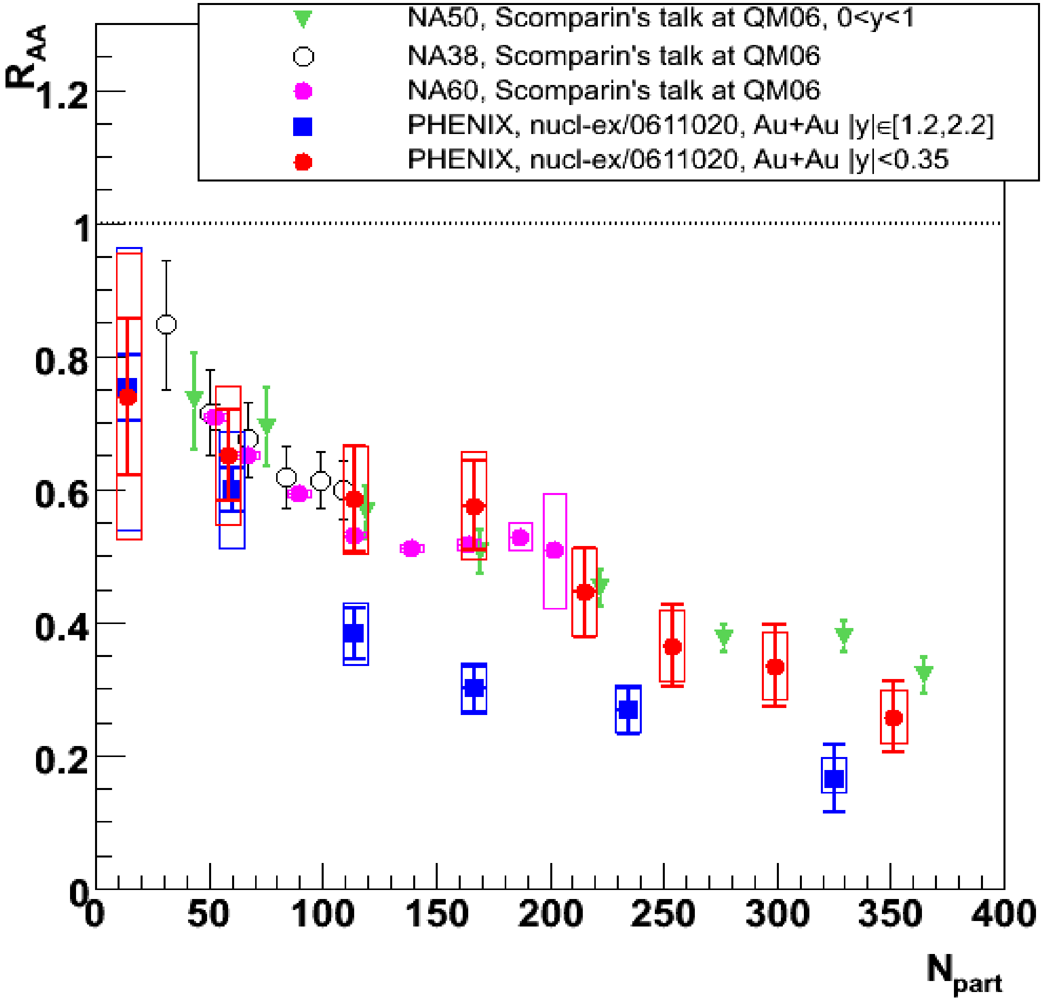
surprize:
suppression is weakest at
mid-rapidity





# Comparison of RHIC and SPS Results

surprize:
no energy dependence

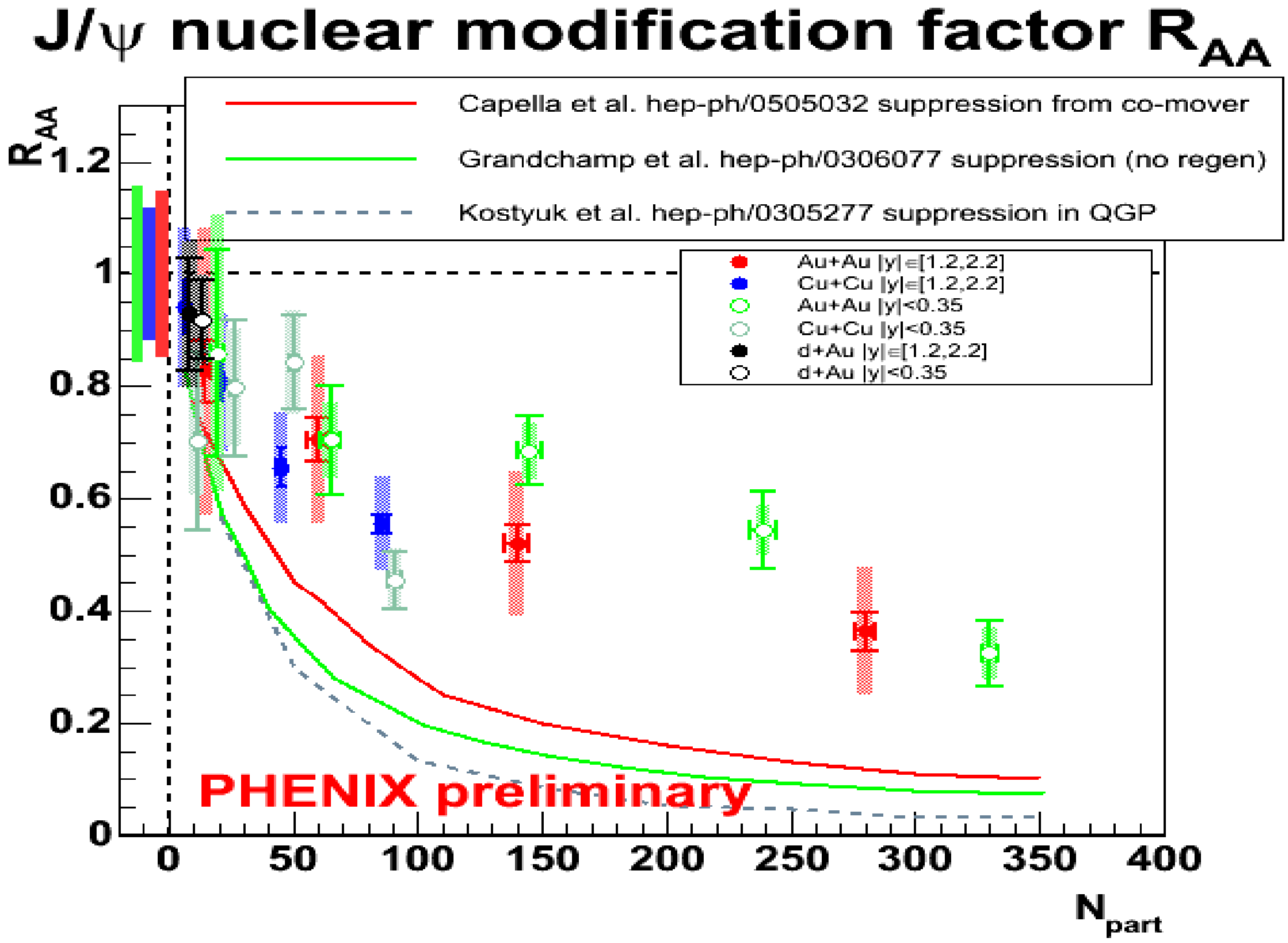


comparison produced by
R. Granier de Cassagnac

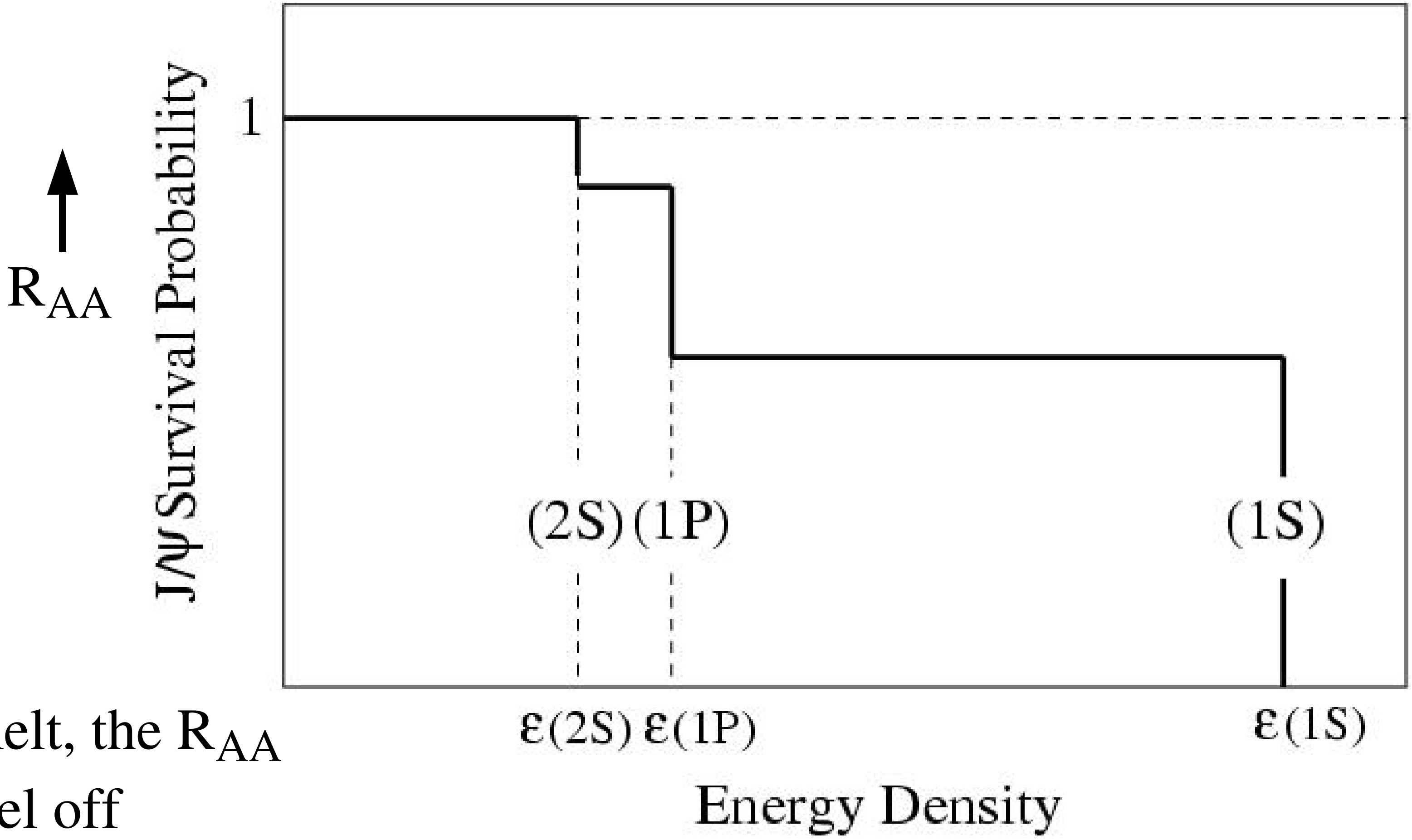
# Too much suppression at RHIC in Standard QGP Scenario

standard scenario: all charmonia melt near $T_c$

models tuned for SPS data fail at RHIC



# Sequential Melting – schematical picture



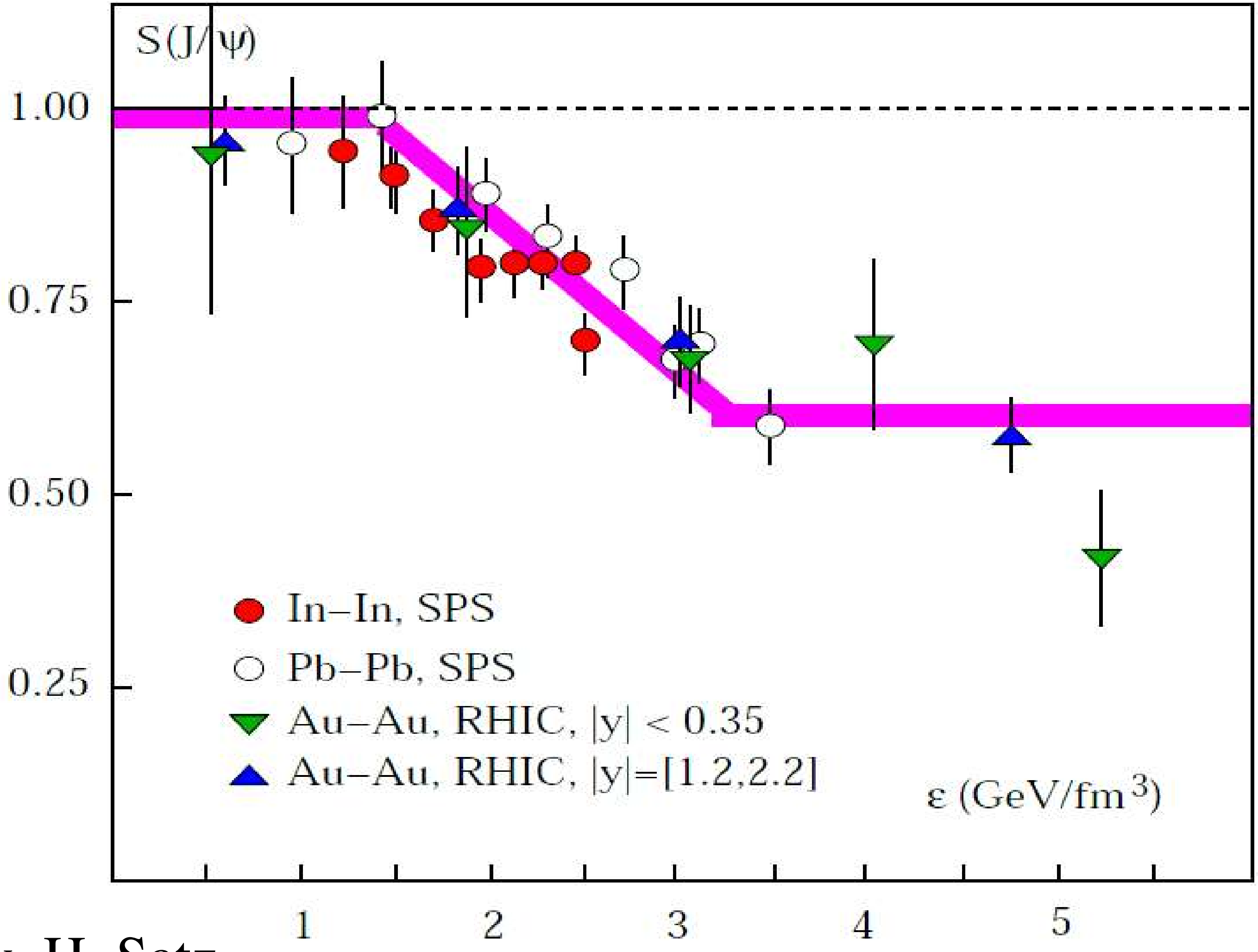
if J/ψ does not melt, the $R_{AA}$ factor should level off at around $R_{AA} > 0.6$ (loss of feeding from $\chi_c$ and ψ')

note: $\chi_c$ 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 $\chi_c$
and $\psi'$

but J/$\psi$ width is
large!
$\varepsilon_{crit}$ =
3.2 GeV/fm$^3$

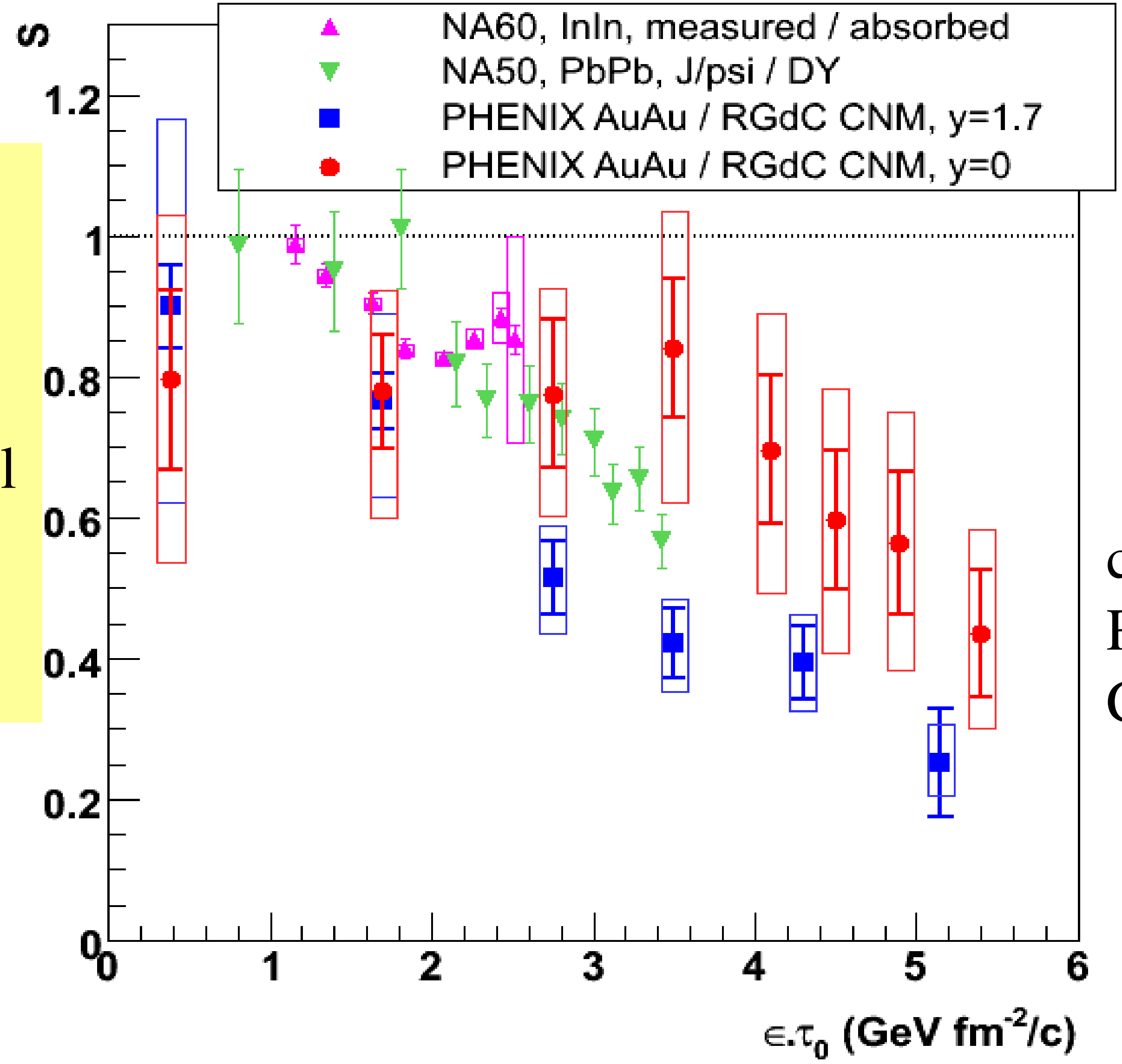


F. Karsch, D. Kharzeev, H. Satz,
Phys. Lett. B637 (2006) 75

preliminary RHIC data, no full error propagation

# No experimental evidence for sequential melting

new data at
various rapidities
rule out sequential
melting

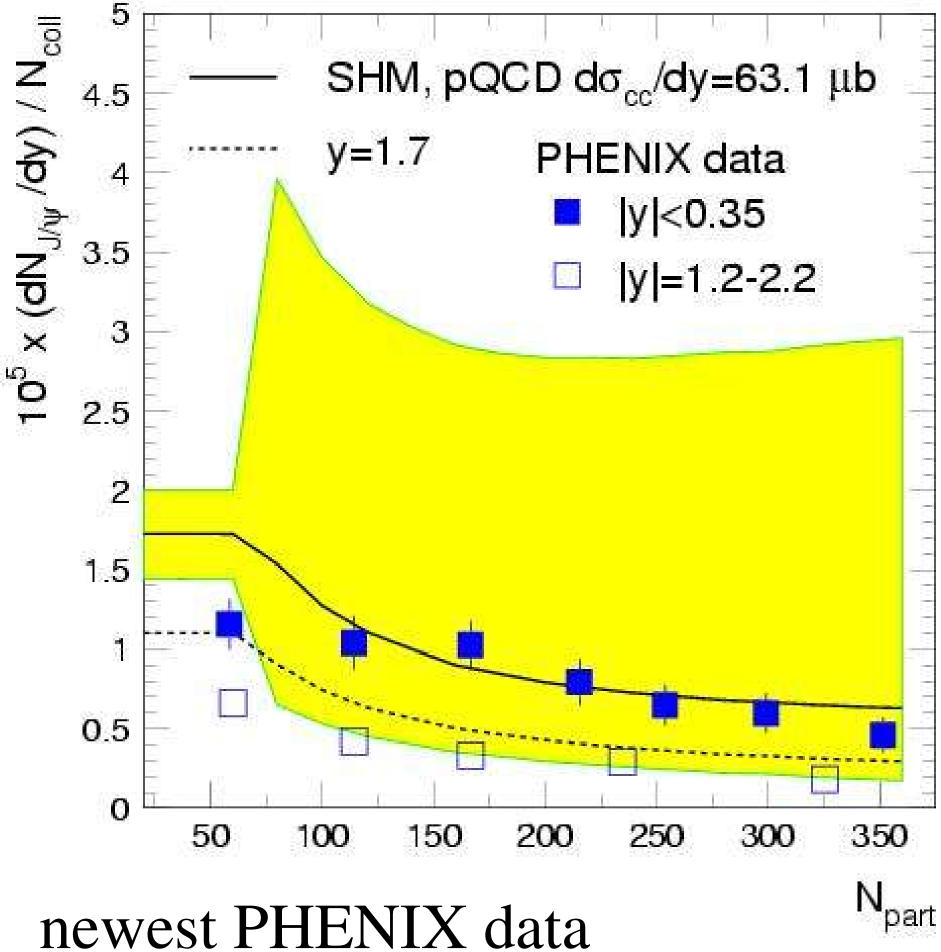


compilation by
R. Granier de
Cassagnac

# Comparison of model predictions to RHIC data: centrality dependence

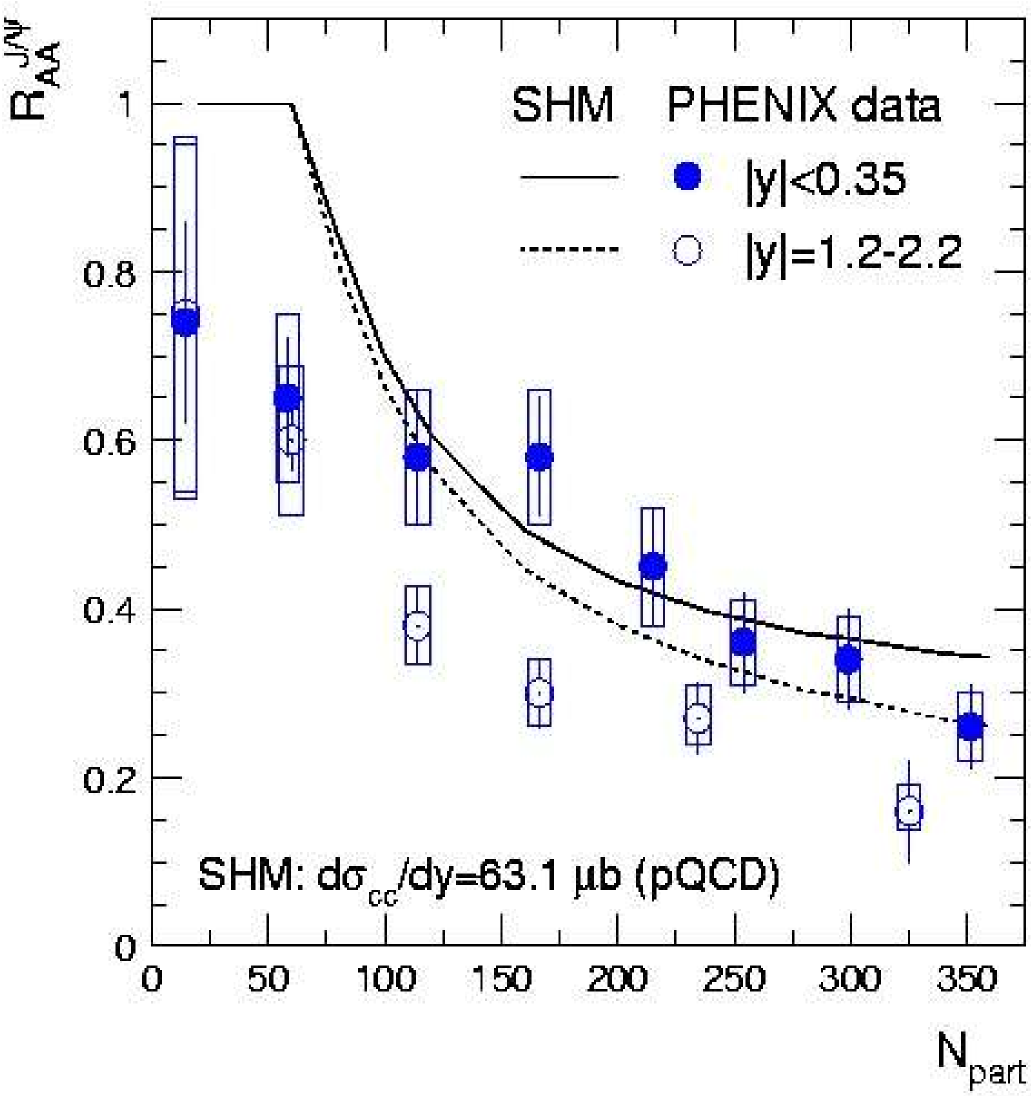
predictions for J/ψ production using NNLO pQCD results for open charm cross section by M. Cacciari, P. Nason, R. Vogt, Phys. Rev. Lett. 95 (2005) 122001, hep-ph/0502203

good agreement, no free parameters

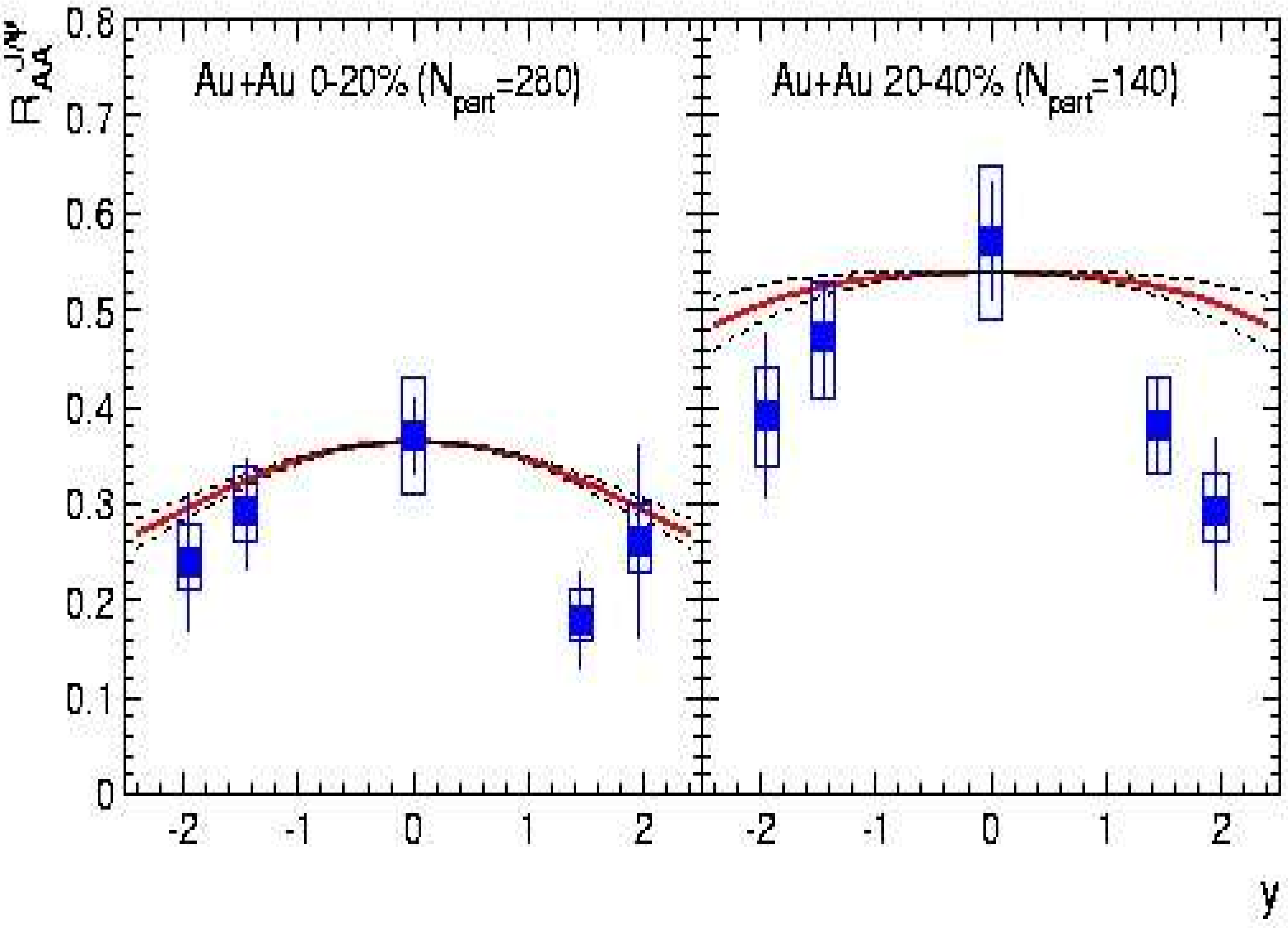


newest PHENIX data

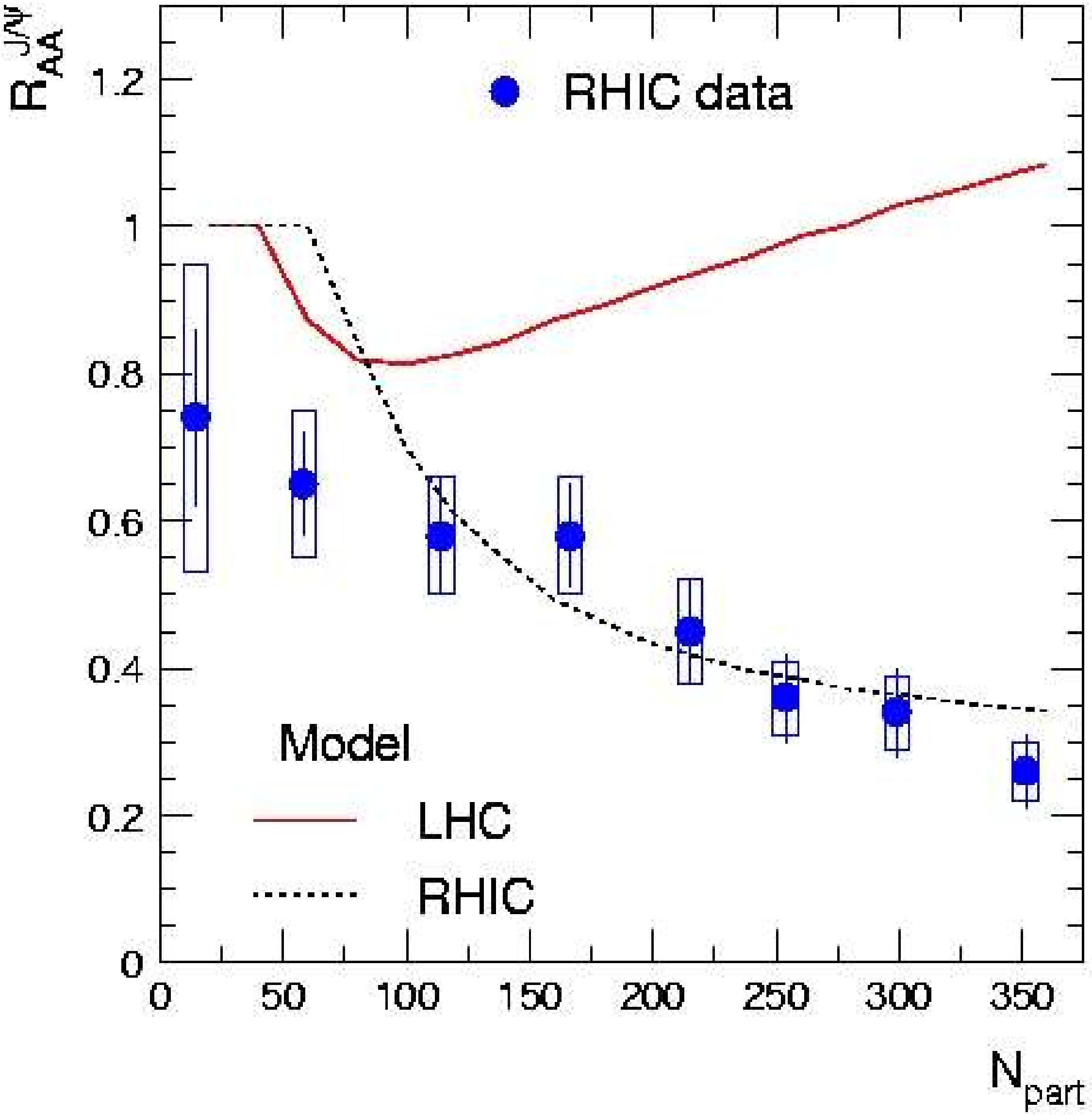
# Centrality dependence of nuclear modification factor



# Comparison of model predictions to RHIC data: rapidity dependence



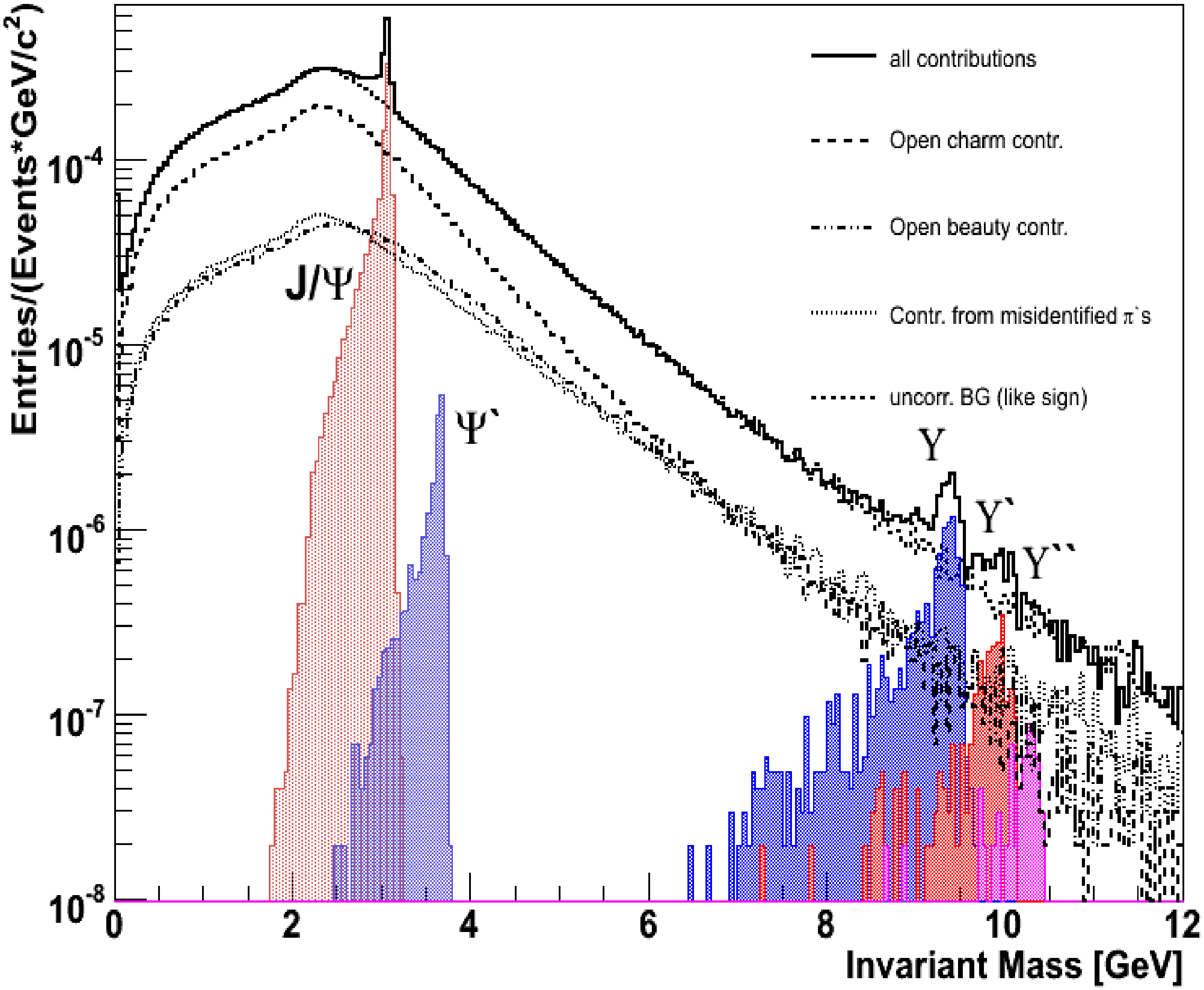
# Prediction for LHC energy: enhancement rather than suppression!



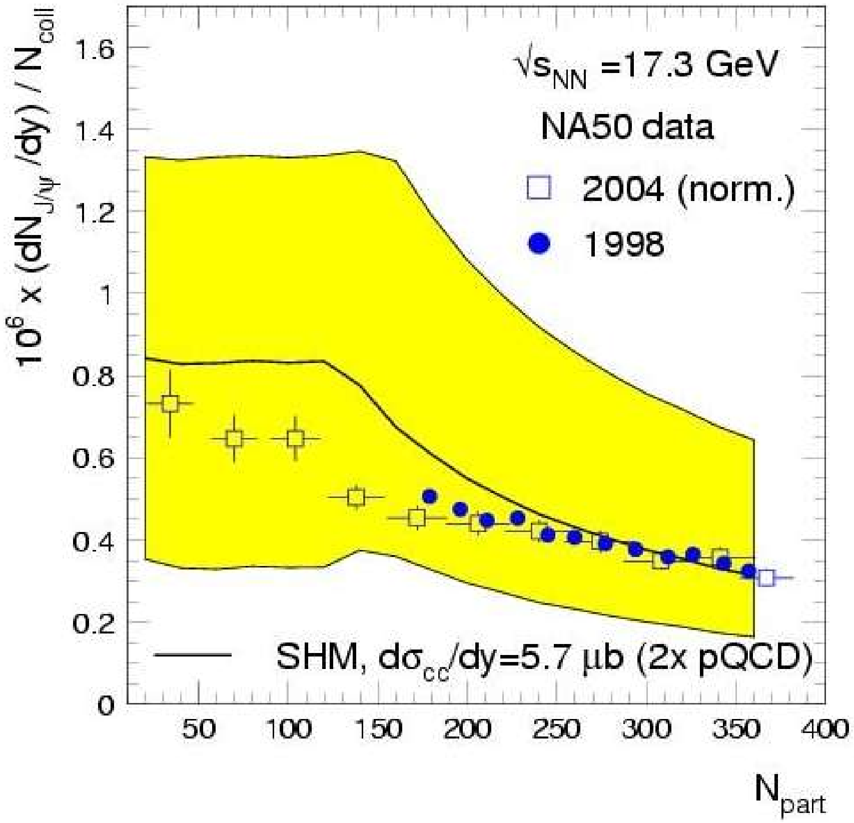
# ALICE@LHC

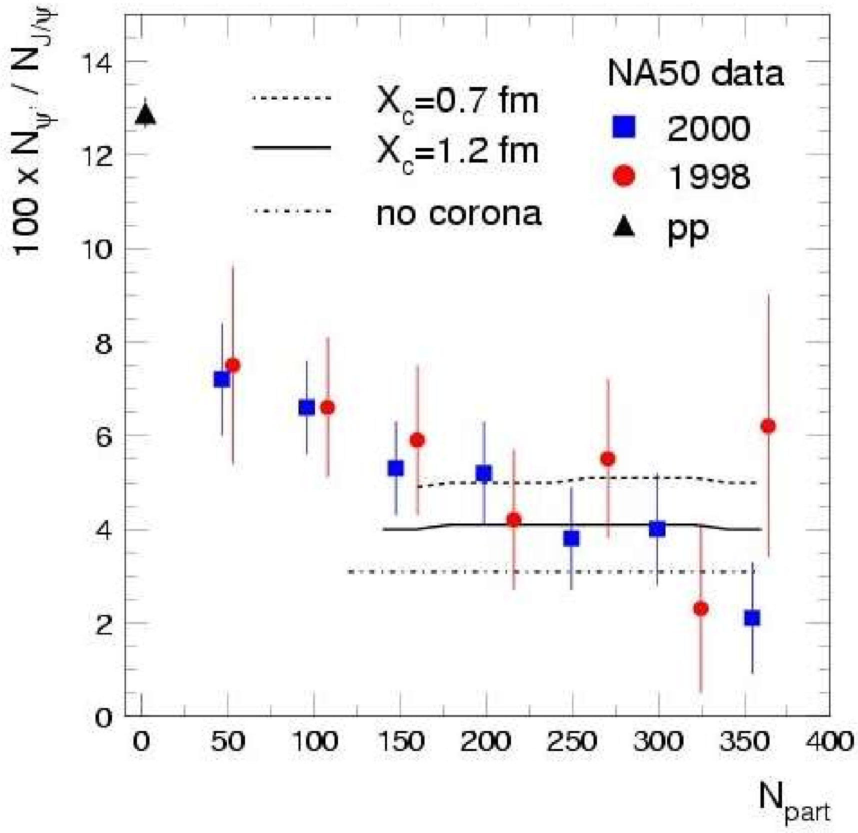
the ALICE TPC has been installed in the experiment,

# Simulation of dielectron mass spectrum
# 1 month Pb-Pb at ALICE



# back to SPS energy

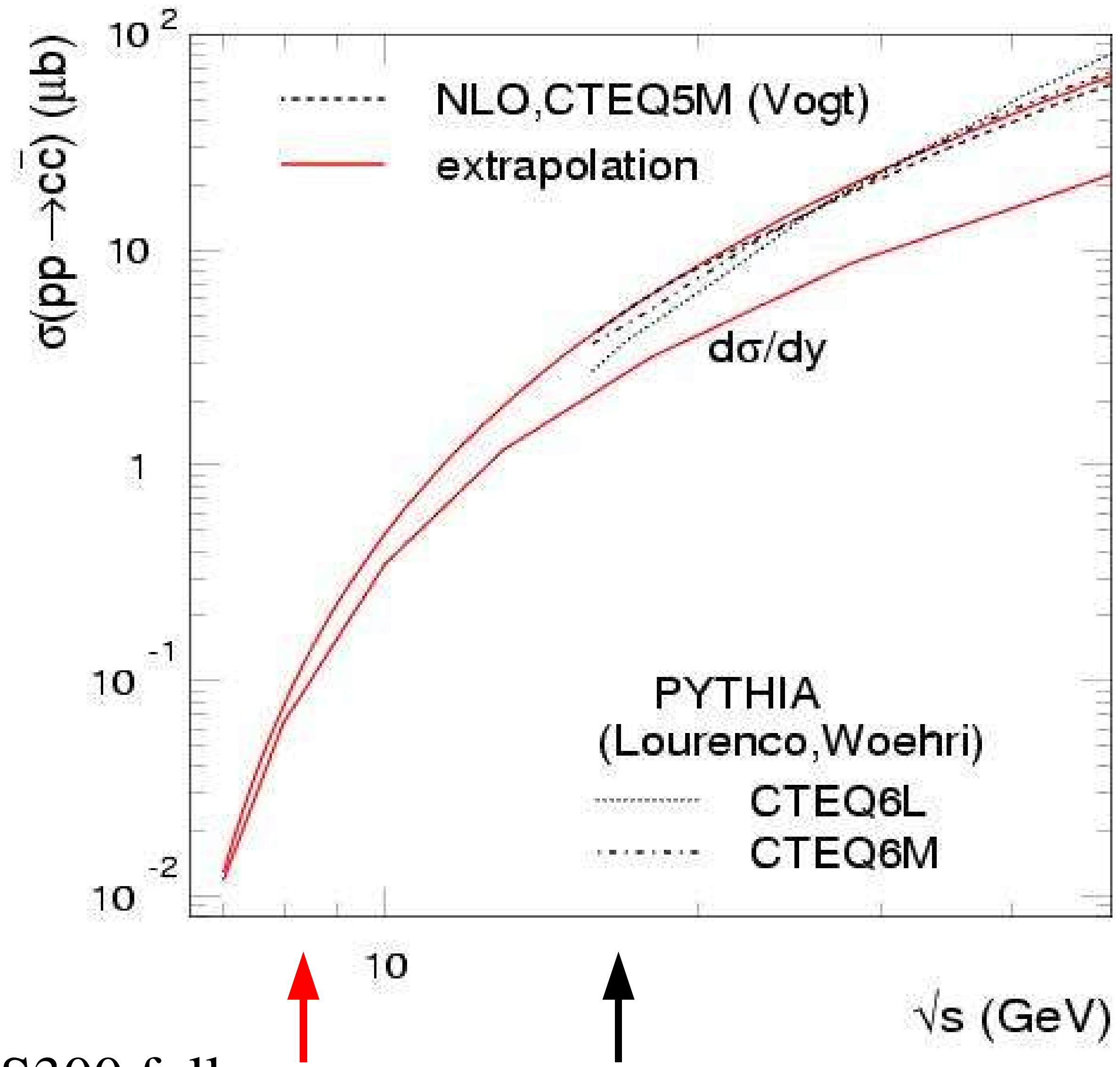




only moderately enhanced (2 x pQCD) cc_bar cross section needed

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

# Extrapolation of pQCD cross section to low energies



SIS300 full energy

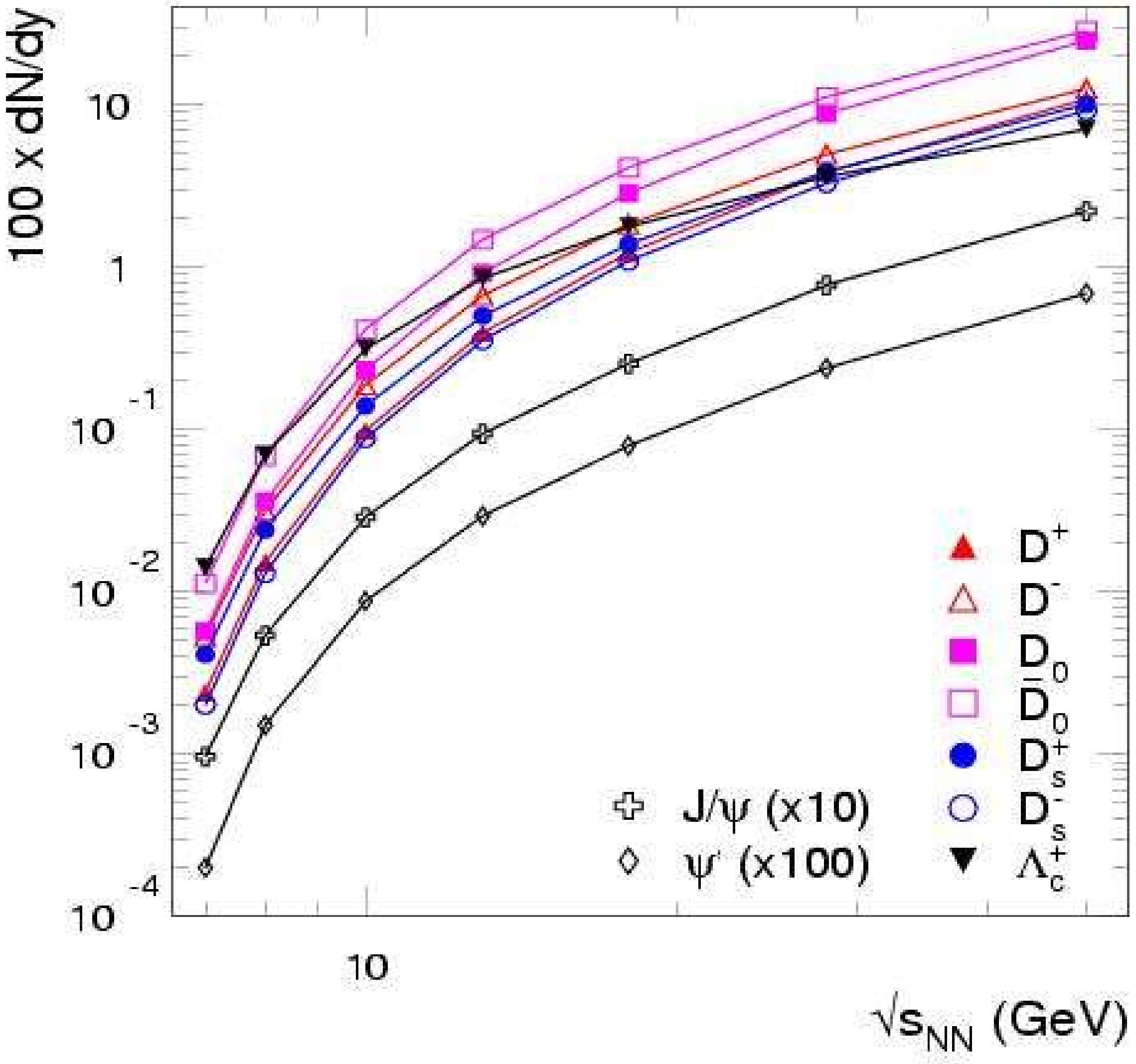
SPS full energy

charm threshold
in NN: 5.1 GeV

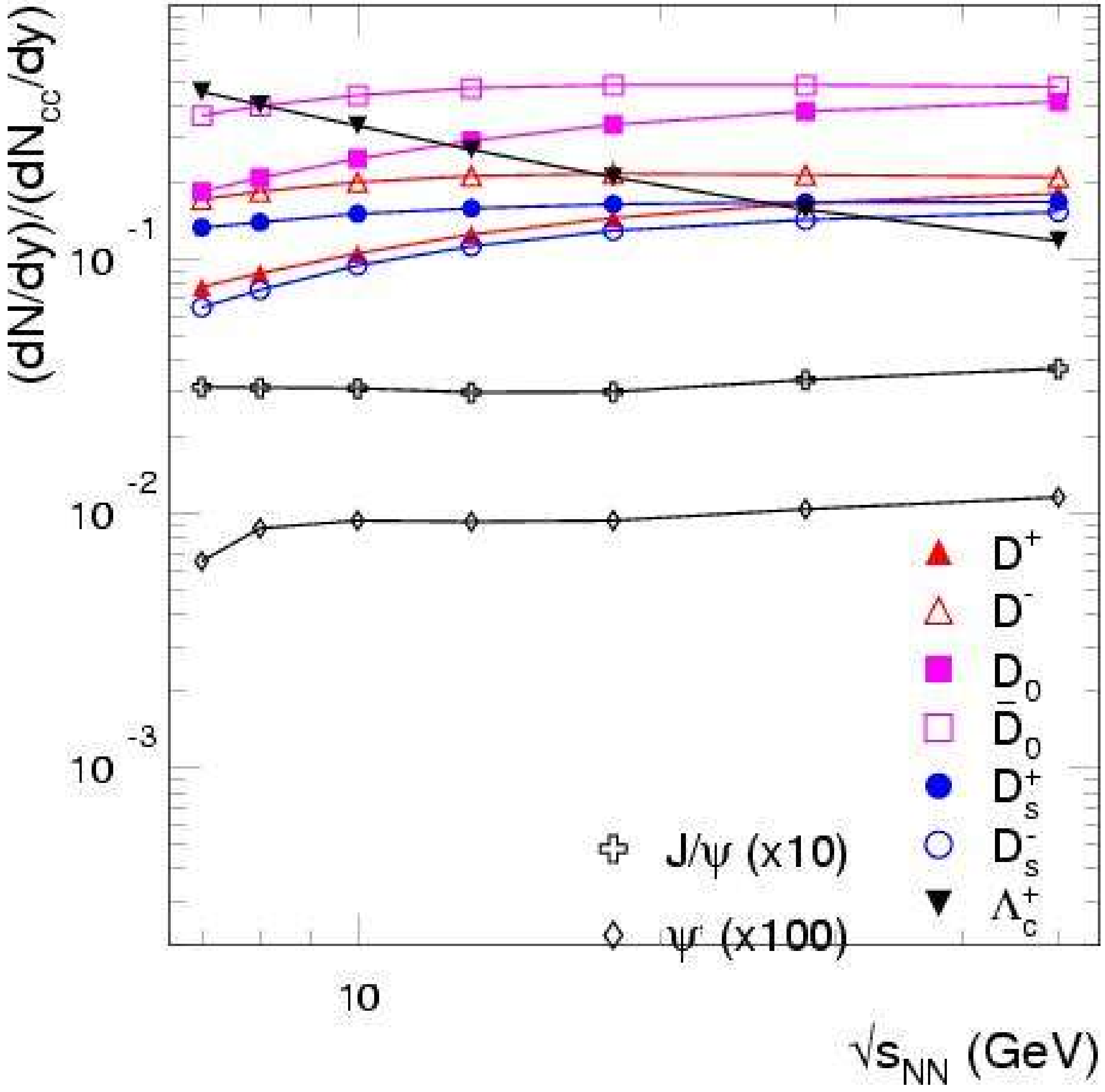
absolute threshold
in Pb-Pb
collisions:

$T_{lab}/A$ = 31 MeV

# Statistical hadronization predictions for open and hidden charm at low energies



Peter Braun-Munzinger


(dN/dy)/(dN$_{c\bar{c}}$/dy)
$10^{-1}$
$10^{-2}$
$10^{-3}$
10
$\sqrt{s_{NN}}$ (GeV)
$D^+$
$D^-$
$D_0$
$\bar{D}_0$
$D_s^+$
$D_s^-$
$\Lambda_c^+$
J/ψ (x10)
ψ' (x100)

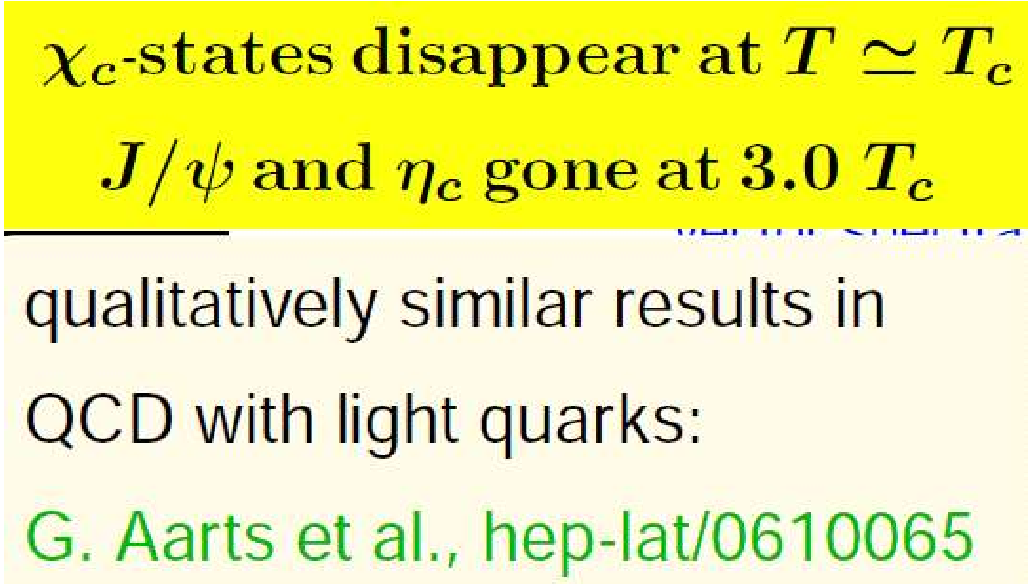
charmonium enhancement at LHC as a
unique fingerprint of deconfinement
in the hot and dense fireball

first results in about 2years from now

charmonium and open charm at low energies:
expect no strong medium modifications
in cross section near threshold to E/A = 40 GeV
unique pattern of charmed meson abundances from
statistical hadronization at the phase boundary

# backup slides

# Conclusion of F. Karsch at Beijing Heavy Flavor Meeting



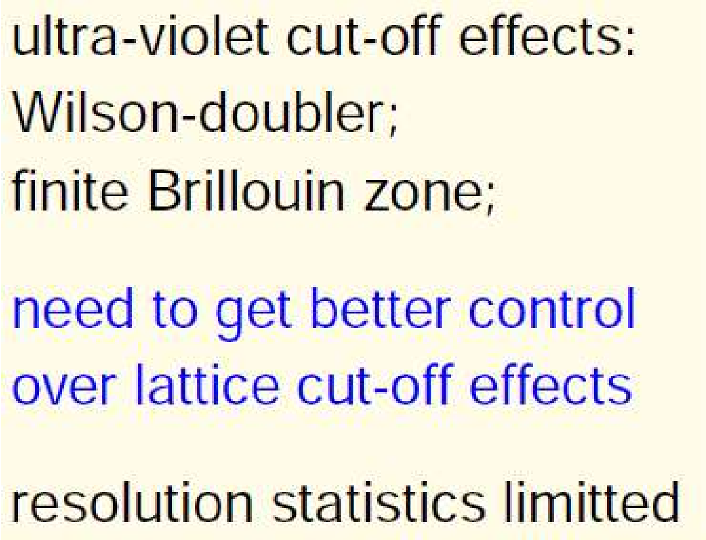
$\chi_c$-states disappear at $T \simeq T_c$

$J/\psi$ and $\eta_c$ 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

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

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

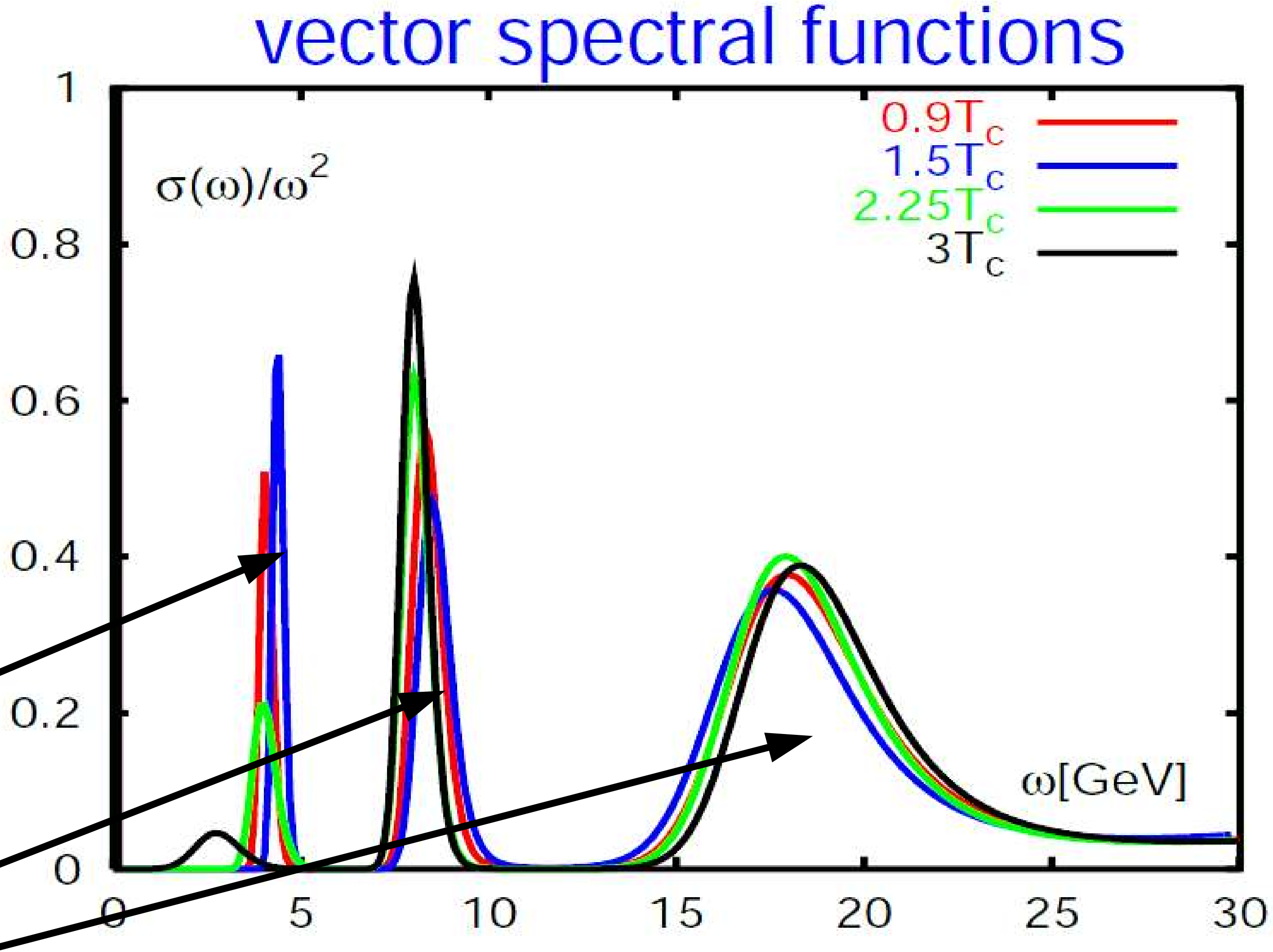
| state | $J/\psi$ | $\chi_c$ | $\psi'$ |
|---|---|---|---|
| $E_s^i$ [GeV] | 0.64 | 0.20 | 0.05 |
| $T_d/T_c$ | 1.1 | 0.74 | 0.1 - 0.2 |
| $T_d/T_c$ | $\sim 2.0$ | $\sim 1.1$ | $\sim 1.1$ |

using $F_1$

using U

# Spectral function analysis from Bielefeld group

bound state
disappears for
$T > 2.25\ T_c$

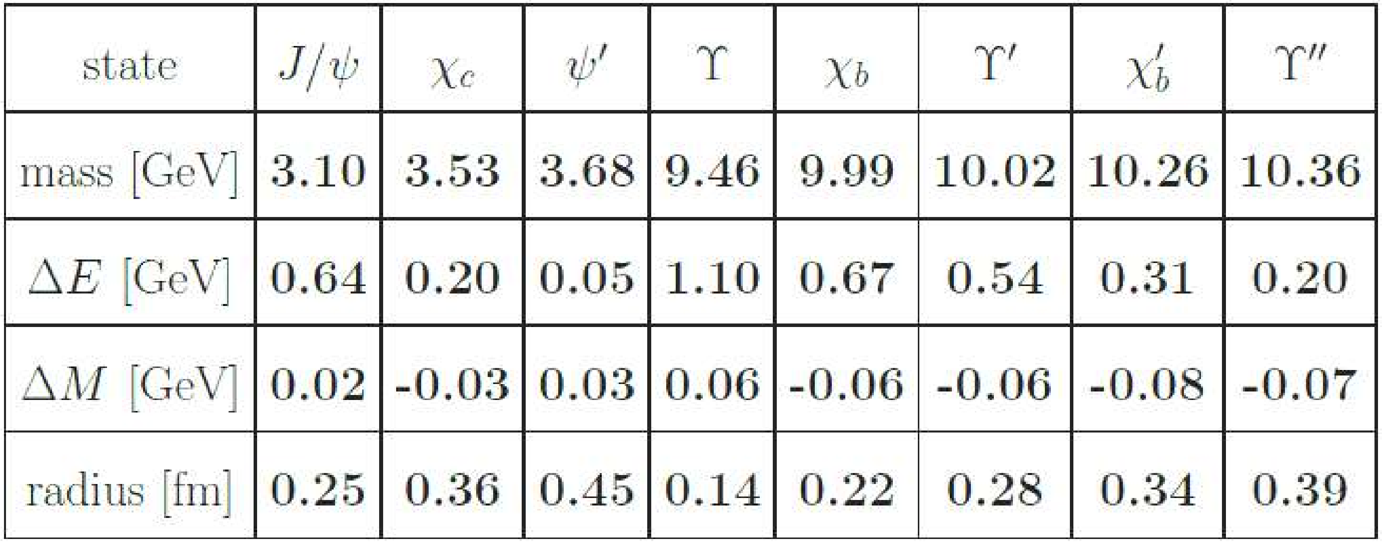


S. Datta et al., Phys. Rev. D69 (2004) 094507

J/ψ

lattice artefacts ?

# Quarkonium Properties and Debye Screening



| state | $J/\psi$ | $\chi_c$ | $\psi'$ | $\Upsilon$ | $\chi_b$ | $\Upsilon'$ | $\chi_b'$ | $\Upsilon''$ |
|---|---|---|---|---|---|---|---|---|
| mass [GeV] | 3.10 | 3.53 | 3.68 | 9.46 | 9.99 | 10.02 | 10.26 | 10.36 |
| $\Delta E$ [GeV] | 0.64 | 0.20 | 0.05 | 1.10 | 0.67 | 0.54 | 0.31 | 0.20 |
| $\Delta M$ [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 $r_{\mathrm{Debye}}(T)$ decreases with increasing T. If $r_{\mathrm{Debye}}(T) < r_{\mathrm{charmonium}}$ 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.

Quarkonia:
heavy quark bound states stable under strong decay

heavy: charm ($m_c \simeq 1.3$ GeV) or beauty ($m_b \simeq 4.7$ GeV)
stable: $M_{c\bar{c}} \leq 2M_D$ and $M_{b\bar{b}} \leq 2M_B$

heavy quarks ⇒ quarkonium spectroscopy via
non-relativistic potential theory

Schrödinger equation $\left\{2m_c - \frac{1}{m_c}\nabla^2 + V(r)\right\}\Phi_i(r) = M_i\Phi_i(r)$

confining ("Cornell") potential $V(r) = \sigma\ r - \frac{\alpha}{r}$

string tension $\sigma \simeq 0.2$ GeV$^2$, gauge coupling $\alpha \simeq \pi/12$

⇒ quarkonium masses $M_i$ and radii $r_i$