Charmonium and Open Charm from SIS300 to SPS Energy

- introductory remarks on charmonium and QGP
- discussion of time scales and open charm conservation equation
- the statistical hadronization model
- medium modifications and charm production
- results for SPS and lower energies

pbm, VISIM Meeting
Bad Liebenzell, Sep. 2007

work performed in collaboration with
A. Andronic, Johanna Stachel, K. Redlich
arXiv:0708.1488 [nucl-th]

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

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Charmonium suppression

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

assumptions:

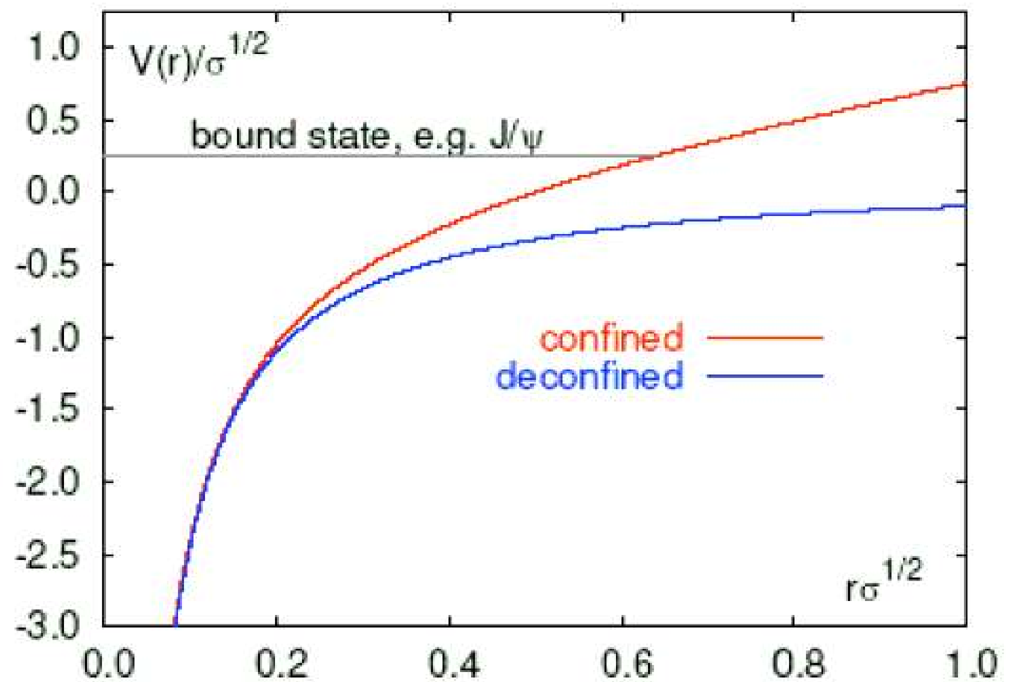
- **all** charmonia are produced before QGP formation
- suppression takes place in QGP
- some charmonia might survive beyond T_c

→ 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

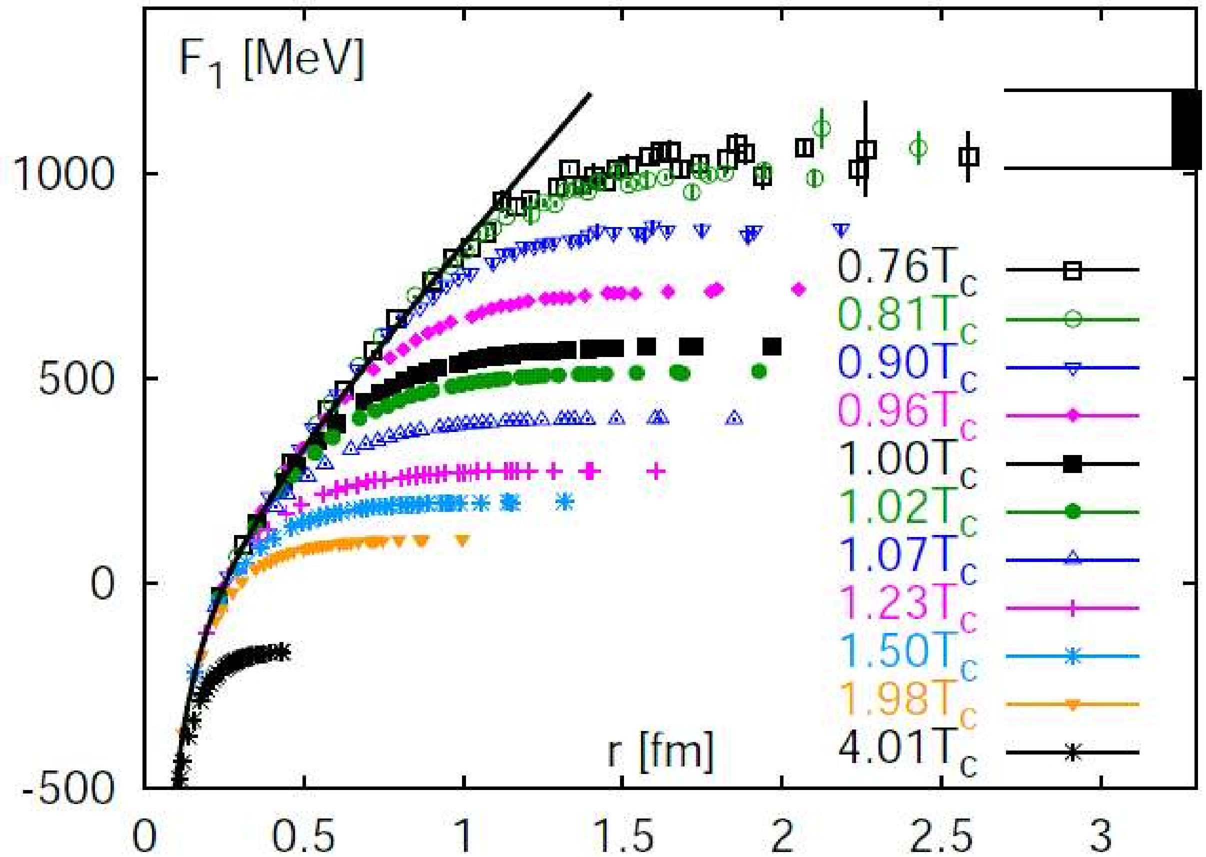
= 0.2 GeV^2

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 loses its mass near T_c

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

at low energy, also mass increases are possible

we will explore the consequences of such mass reductions

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

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

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

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

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?

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].

Are charmonia (and charmed hadrons) produced thermally?

ratios of charmed and beauty hadrons exhibit thermal features (Becattini 1997)
but: $(J/\psi)/\psi'$ ratio is far from thermal in e+e- and 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/ψ)/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.

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

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)

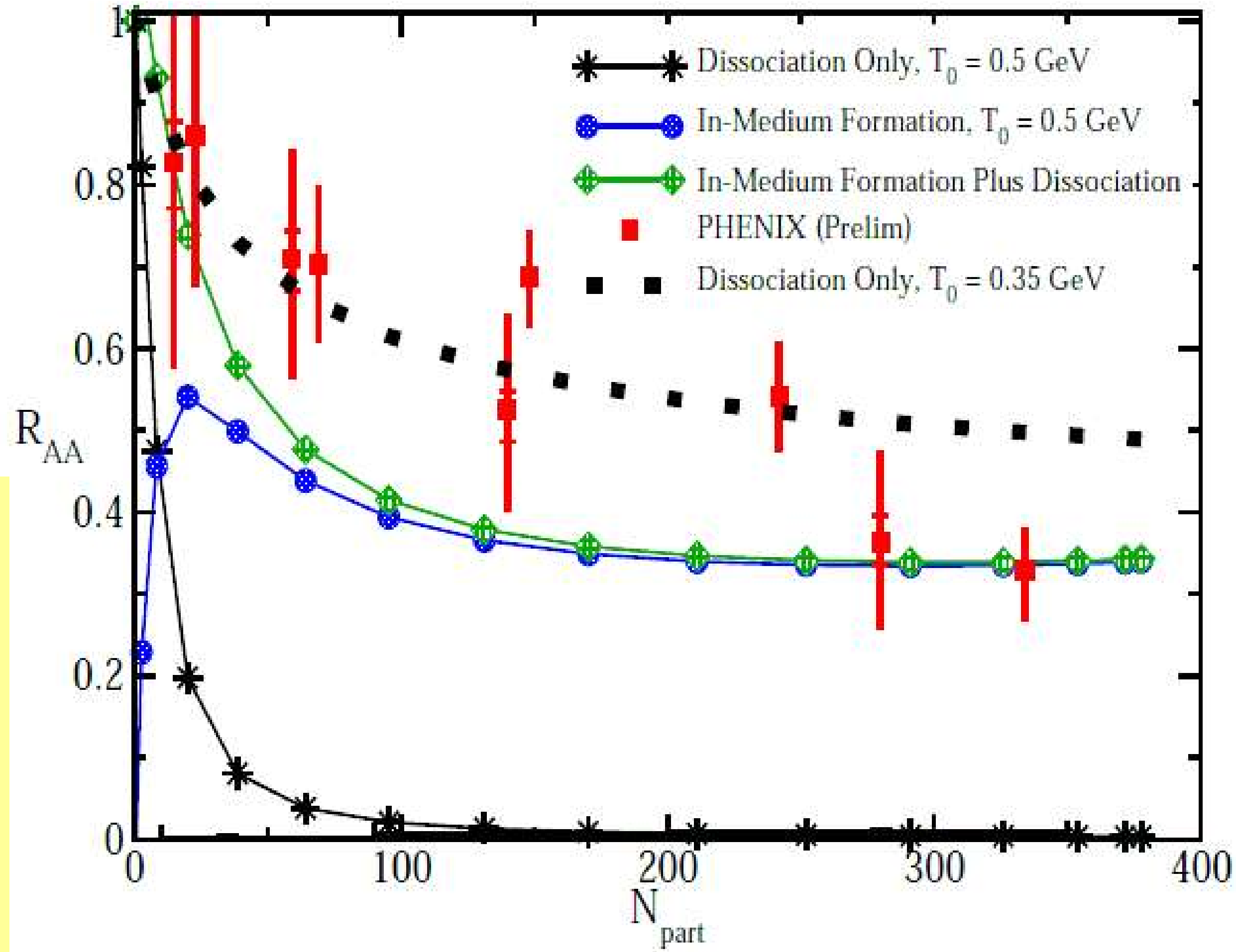
A. Andronic, pbm, J. Stachel, K. Redlich,

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, 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: $N_D = g_c V n_D^{th} I_1 / I_0 \quad N_{J/\psi} = g_c^2 V n_{J/\psi}^{th}$

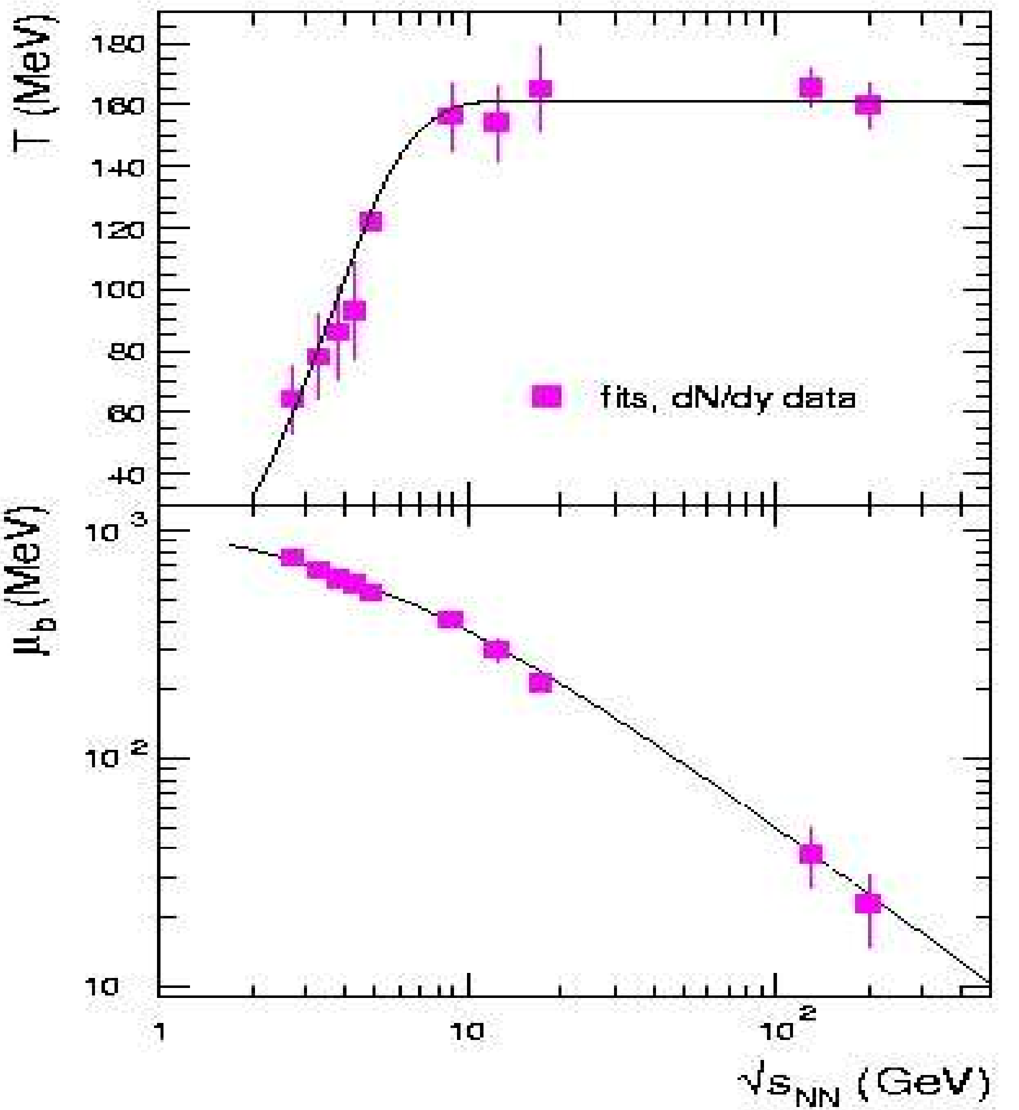
Inputs: T, μ_B, $\quad V = N_{ch}^{exp} / n_{ch}^{th}$, $\quad N_{c\bar{c}}^{dir}$ (pQCD)

Parameterization of all freeze-out points

note: establishment of limiting temperature

T_{lim} = 160 MeV

get T and μ_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

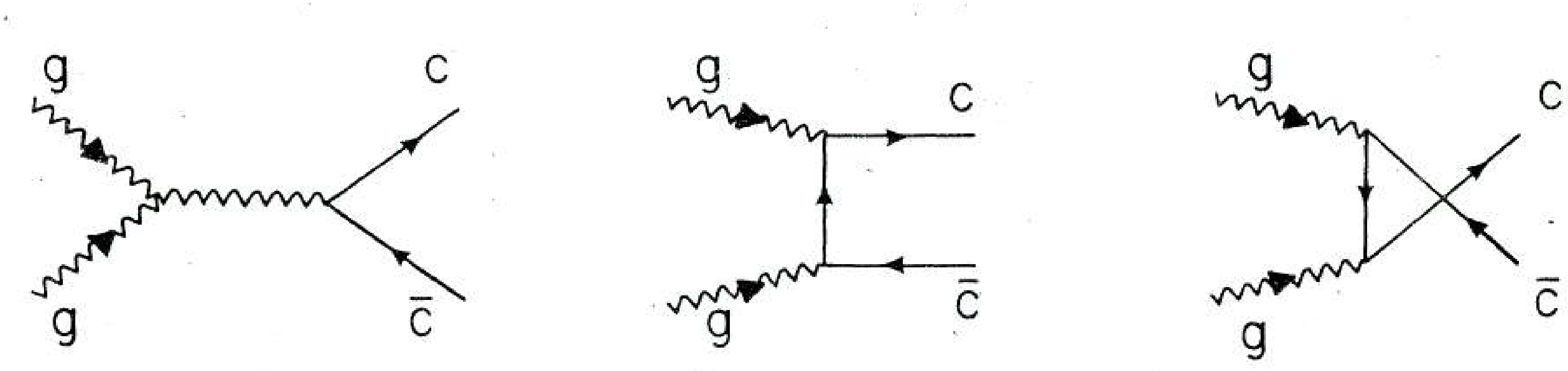
• quarkonium production cross section in pp collisions (for corona part)

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

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

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

with

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

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

$$M_{uu} = \frac{-2}{(u-m^2)^2}\left[4m^4 - (u-m^2)(t-m^2) + 2m^2(u-m^2)\right], \qquad \text{(A2)}$$

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

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

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

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

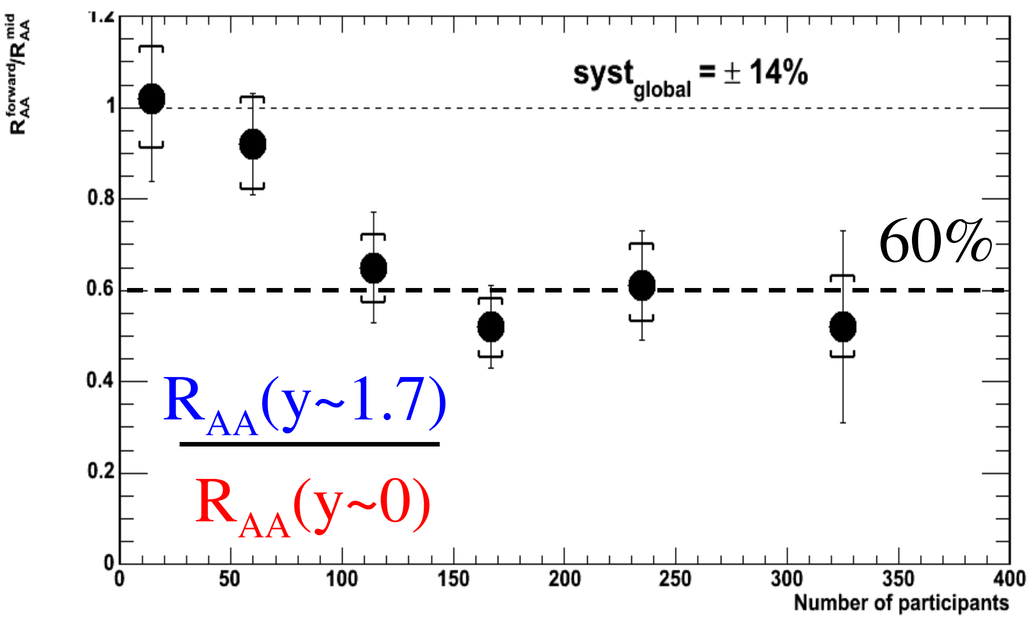
use R_{AA} to define charmonium modification experimentally
no need to normalize to Drell-Yan process

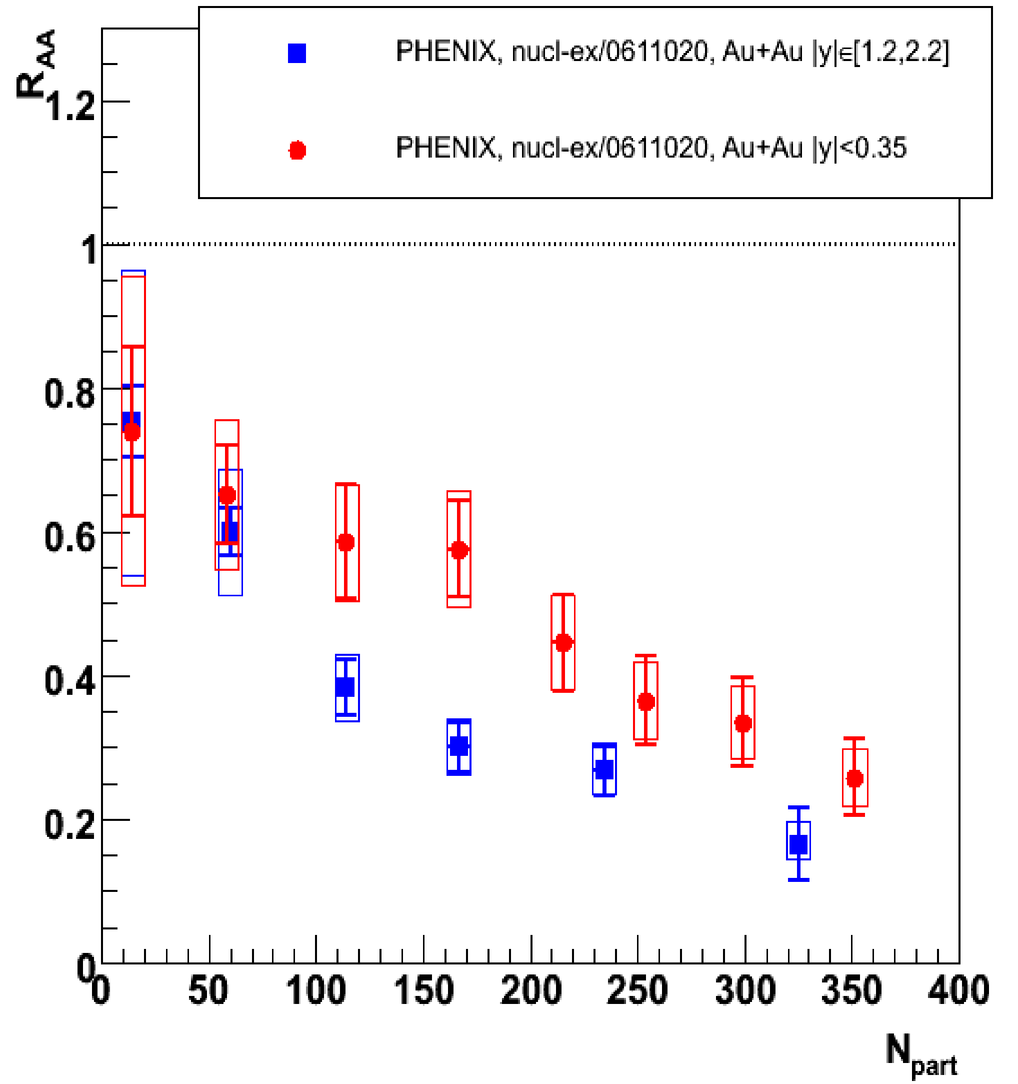
$$R_{AA}^{J/\psi} = \frac{\mathrm{d}N_{J/\psi}^{AuAu}/\mathrm{d}y}{N_{coll} \cdot \mathrm{d}N_{J/\psi}^{pp}/\mathrm{d}y}$$

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

charmonium suppression at RHIC

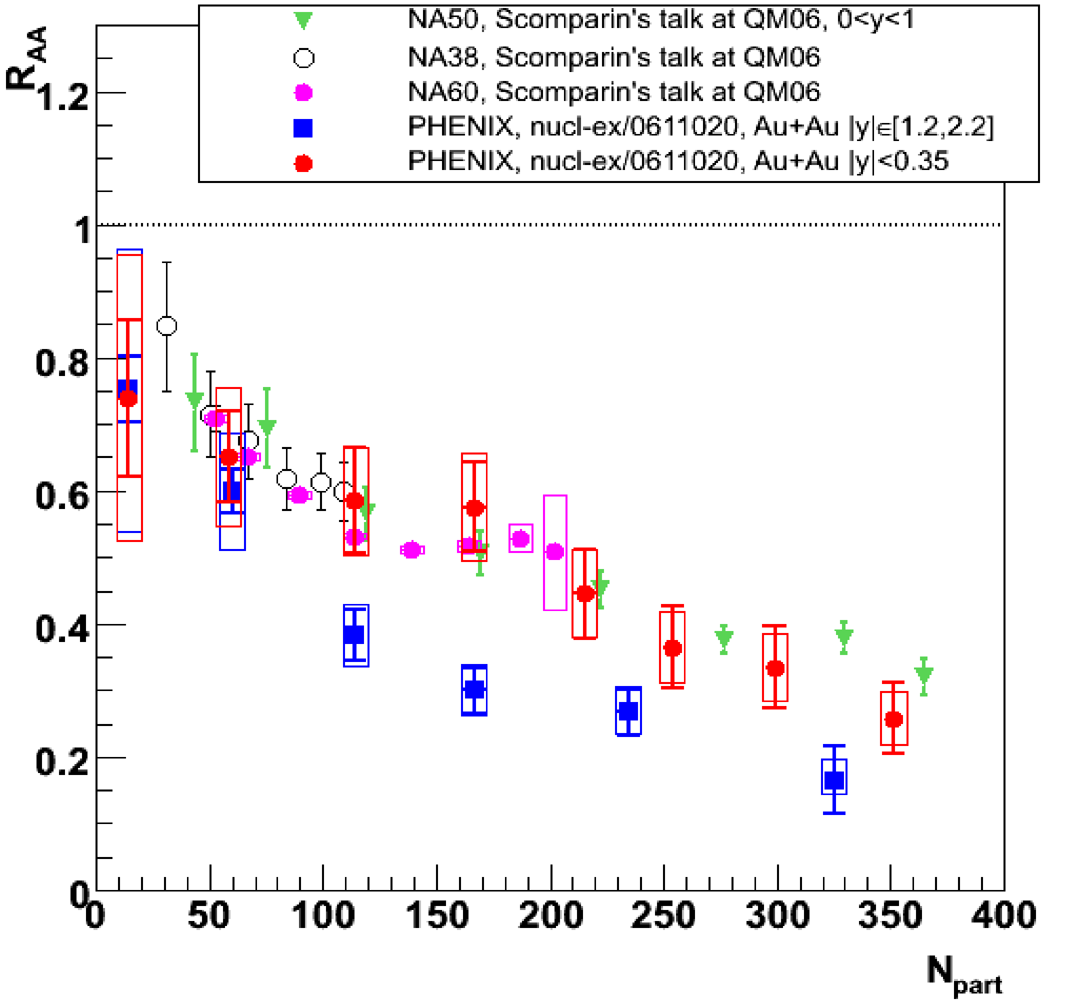
surprize:
suppression is weakest at
mid-rapidity





Comparison of RHIC and SPS Results

surprize:
no energy dependence

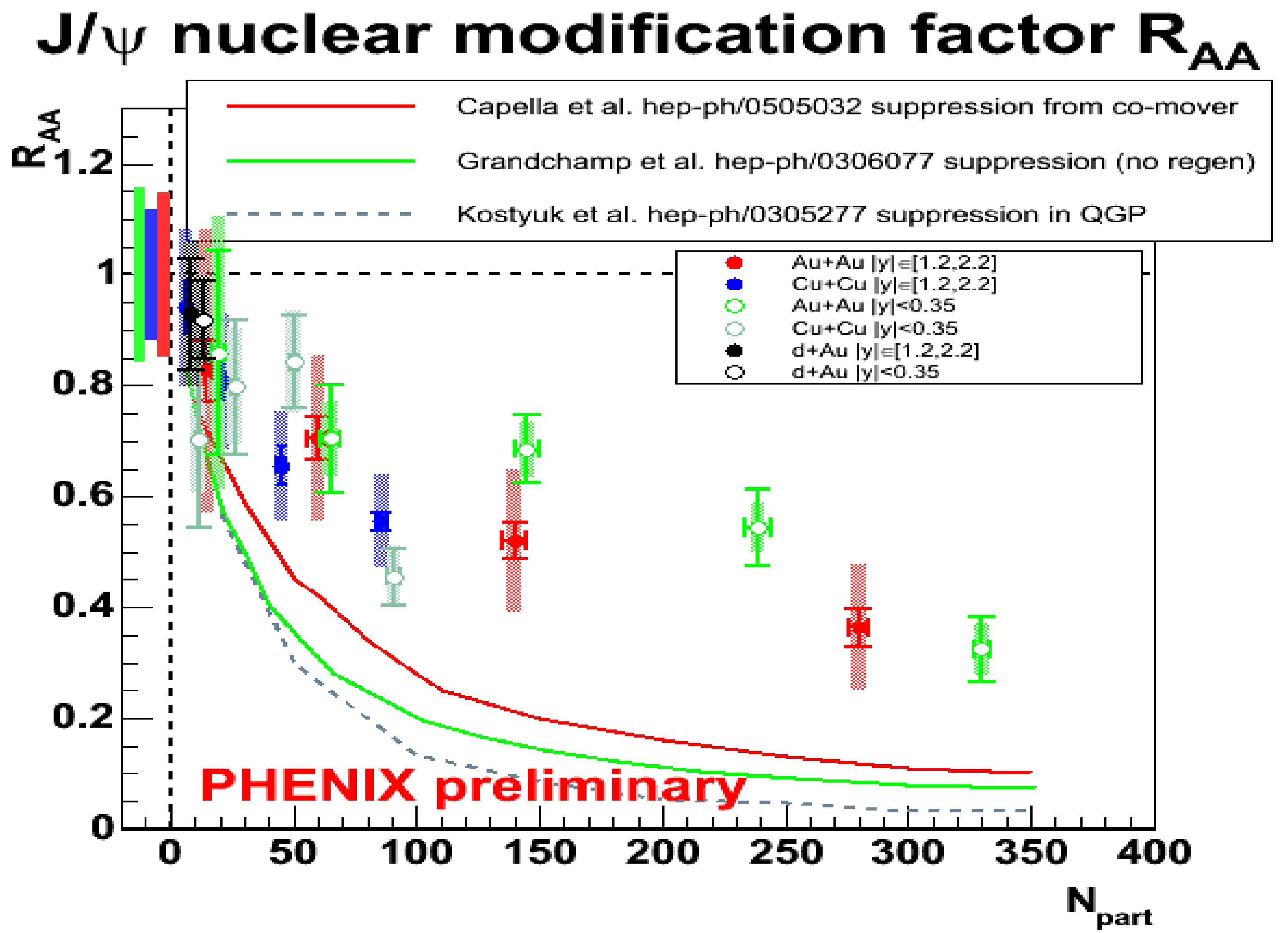


comparison produced by
R. Granier de Cassagnac

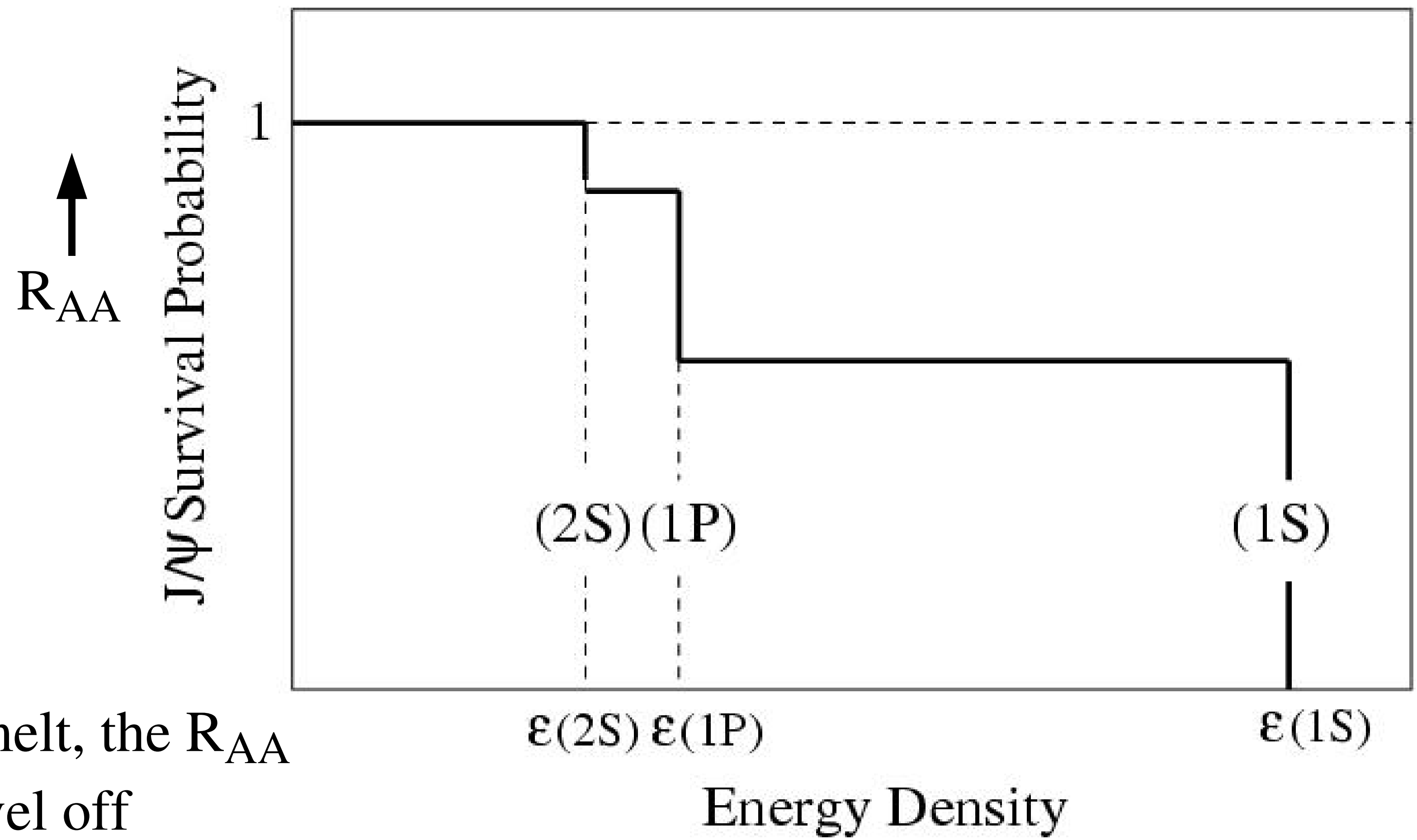
Too much suppression at RHIC in Standard QGP Scenario

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 χ_c and ψ')

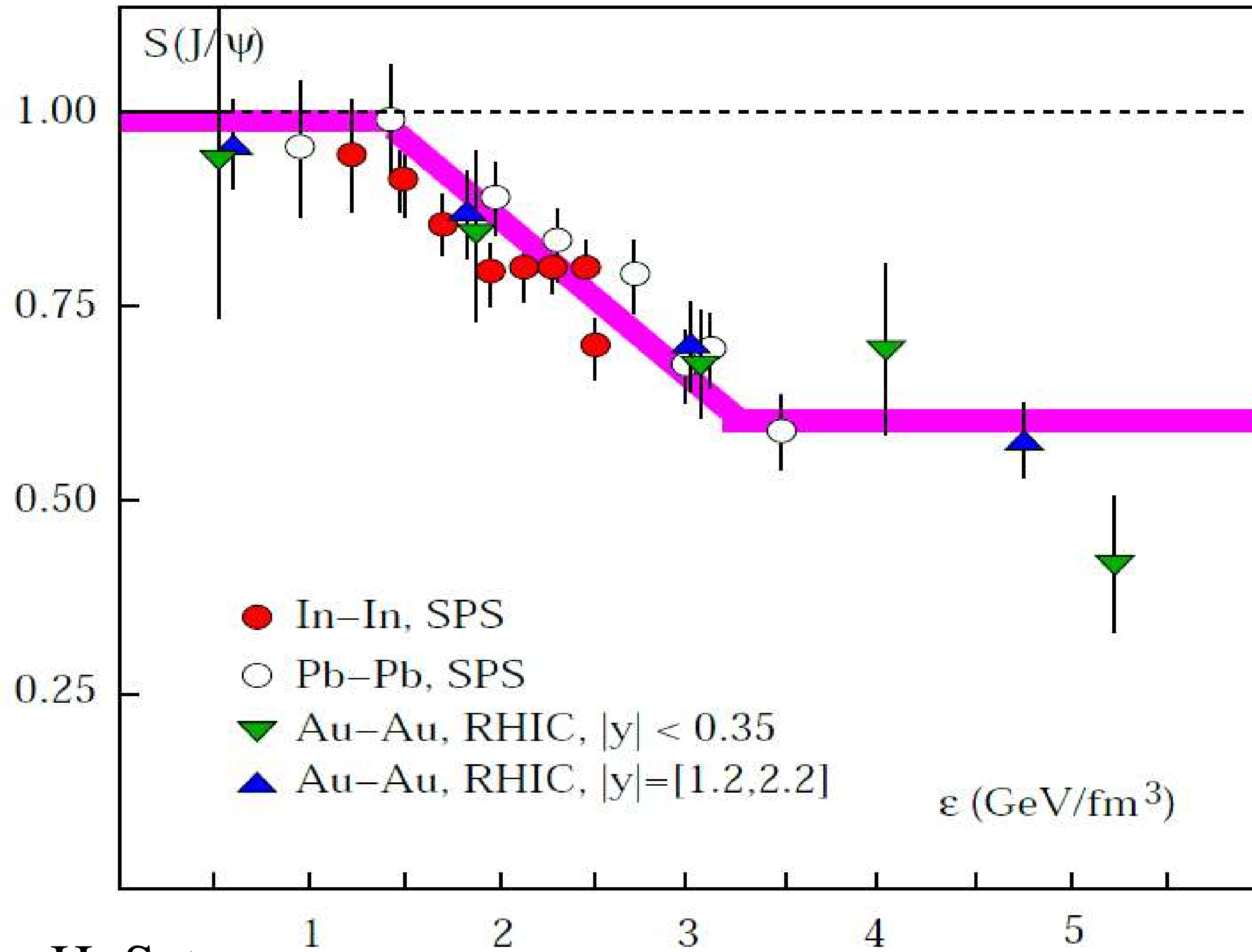
note: χ_c and ψ' not measured at RHIC
pA data at lower energies (HeraB) suggest:
$\chi_c/(J/\psi) < 0.35$

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

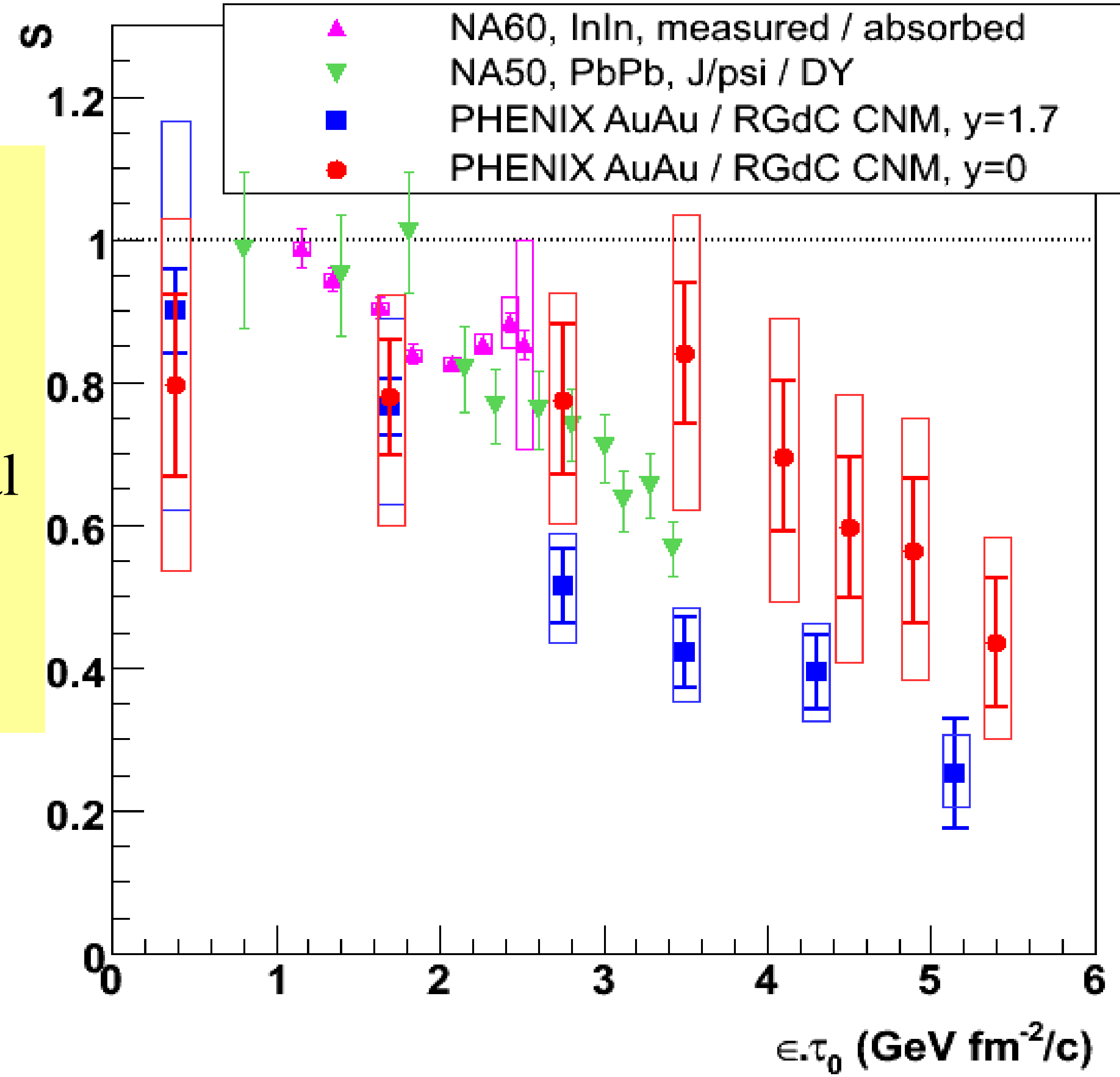


F. Karsch, D. Kharzeev, H. Satz, Phys. Lett. B637 (2006) 75

preliminary RHIC data, no full error propagation

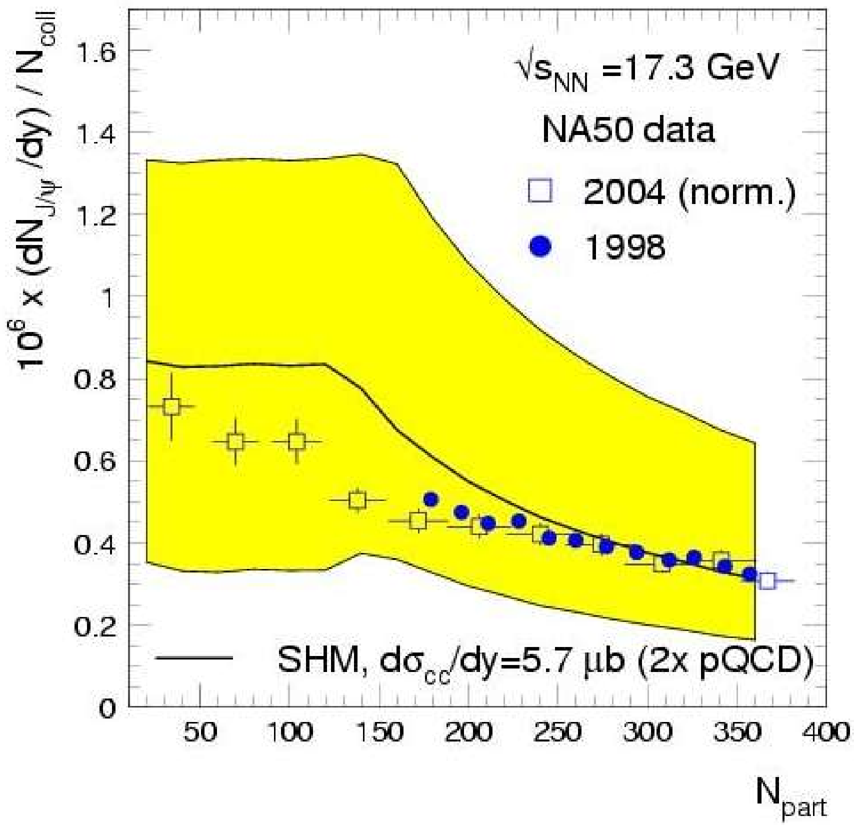
No experimental evidence for sequential melting

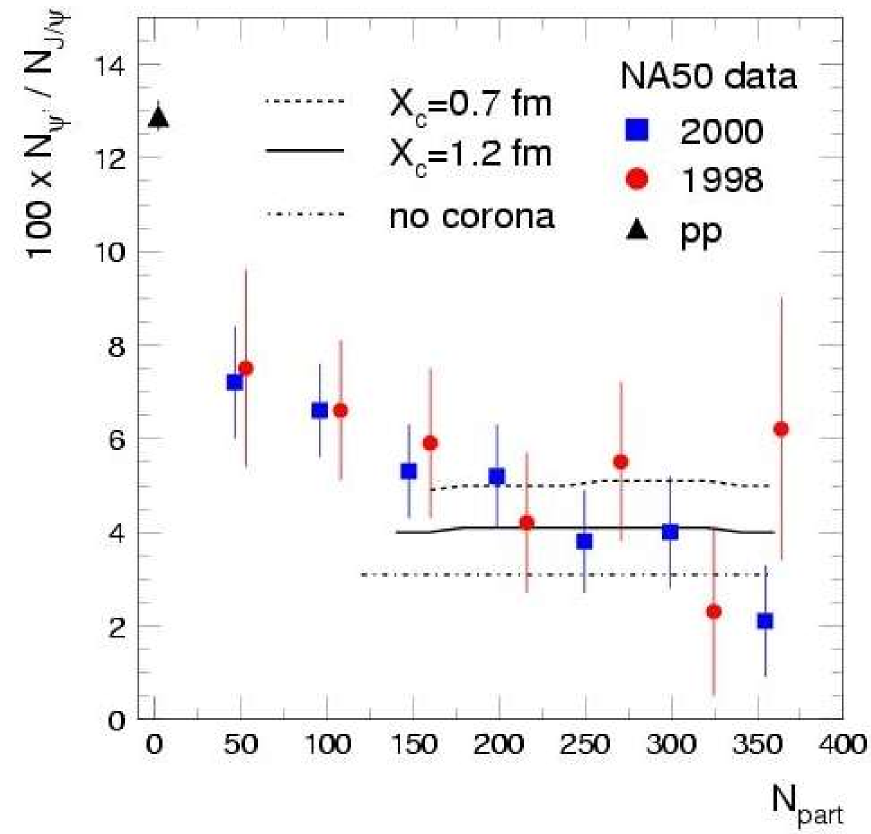
new data at various rapidities rule out sequential melting



compilation by R. Granier de Cassagnac

results for SPS energy

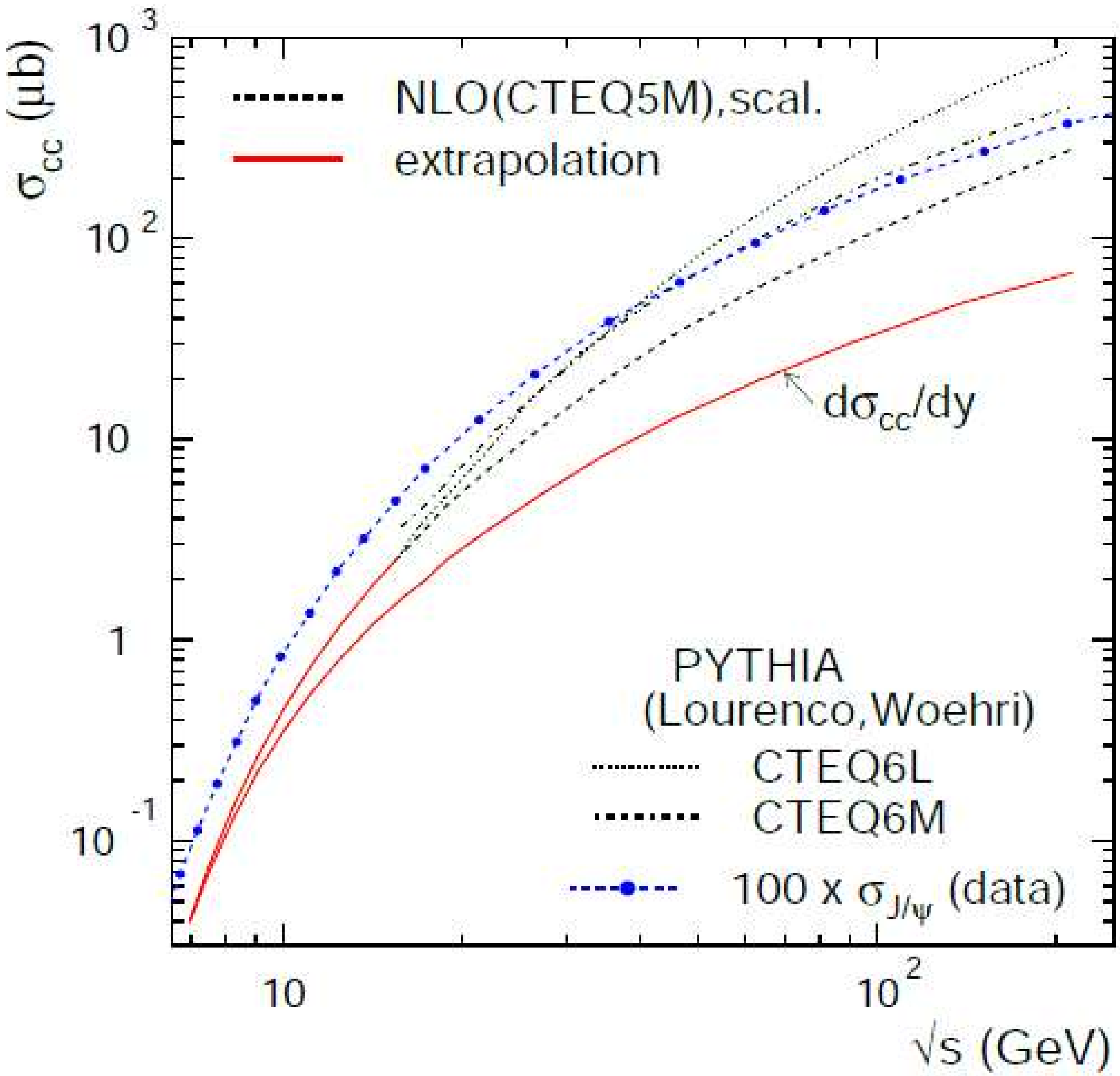




only moderately enhanced (2 x pQCD) cc_bar cross section needed

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

Extrapolation of pQCD cross section to low energies



SIS300 full energy

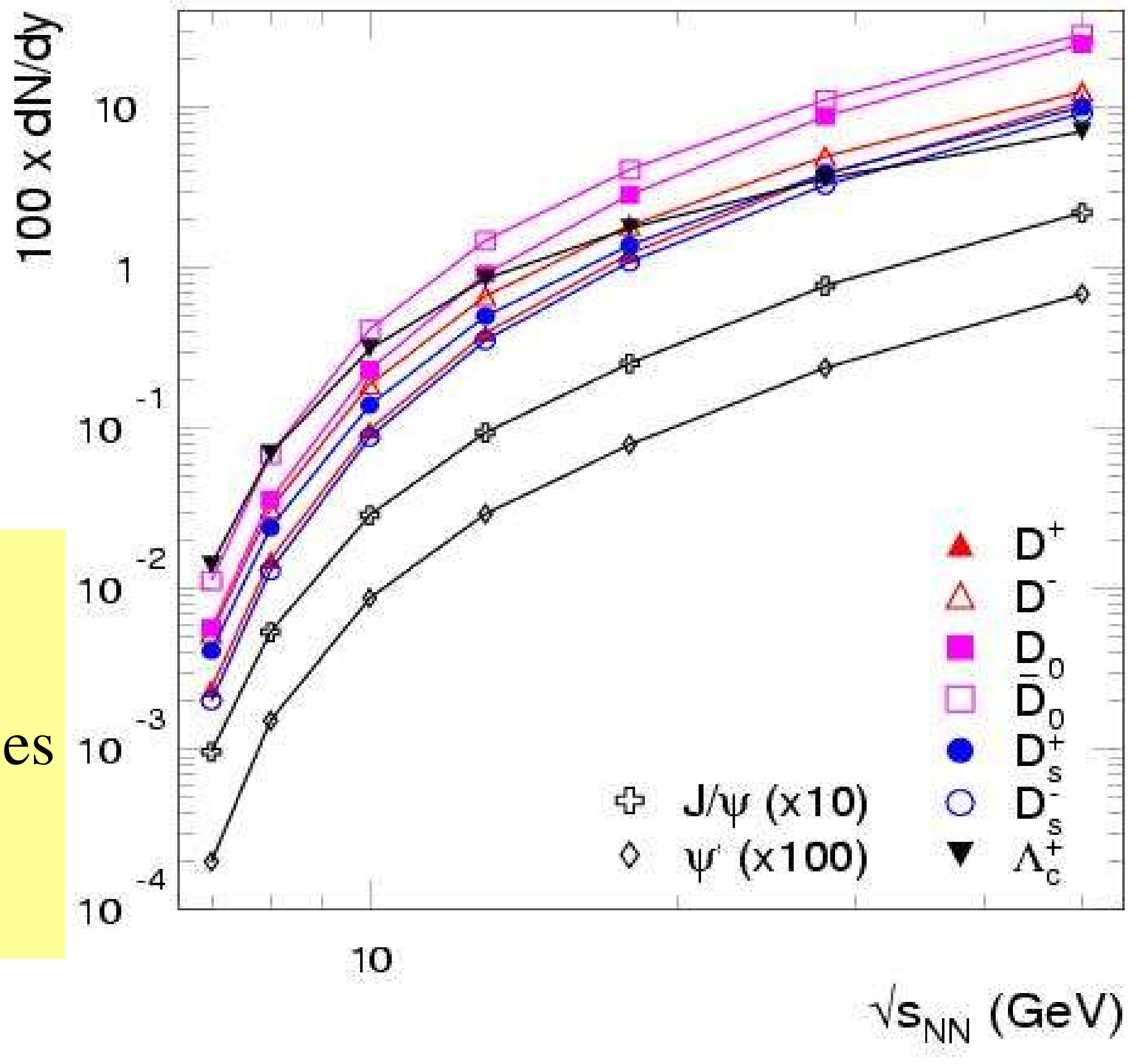
SPS full energy

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

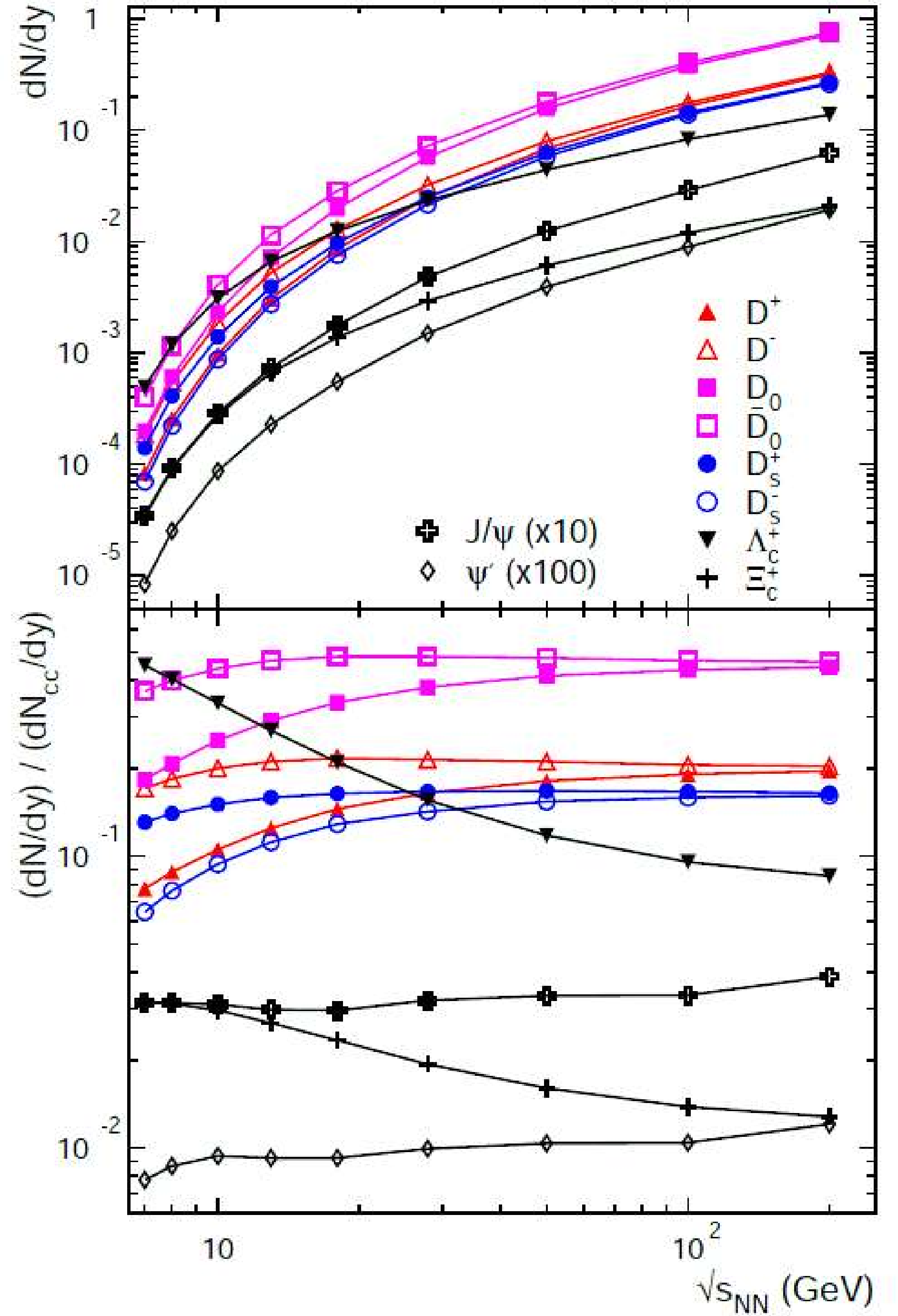


vacuum masses

Model predictions without any medium modifications

note in particular the role of charmed baryons

at SIS300 energies it is crucial to measure those



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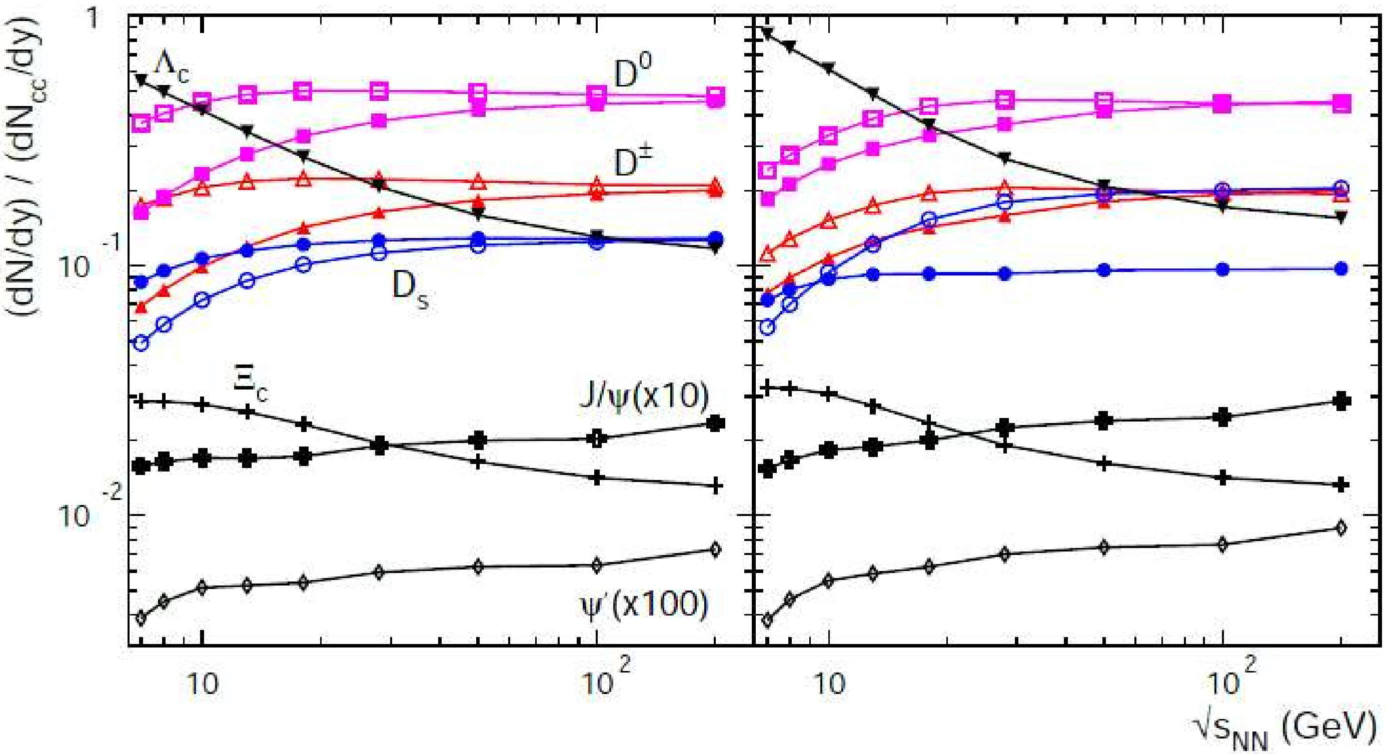
Scenarios of in-medium modified masses

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

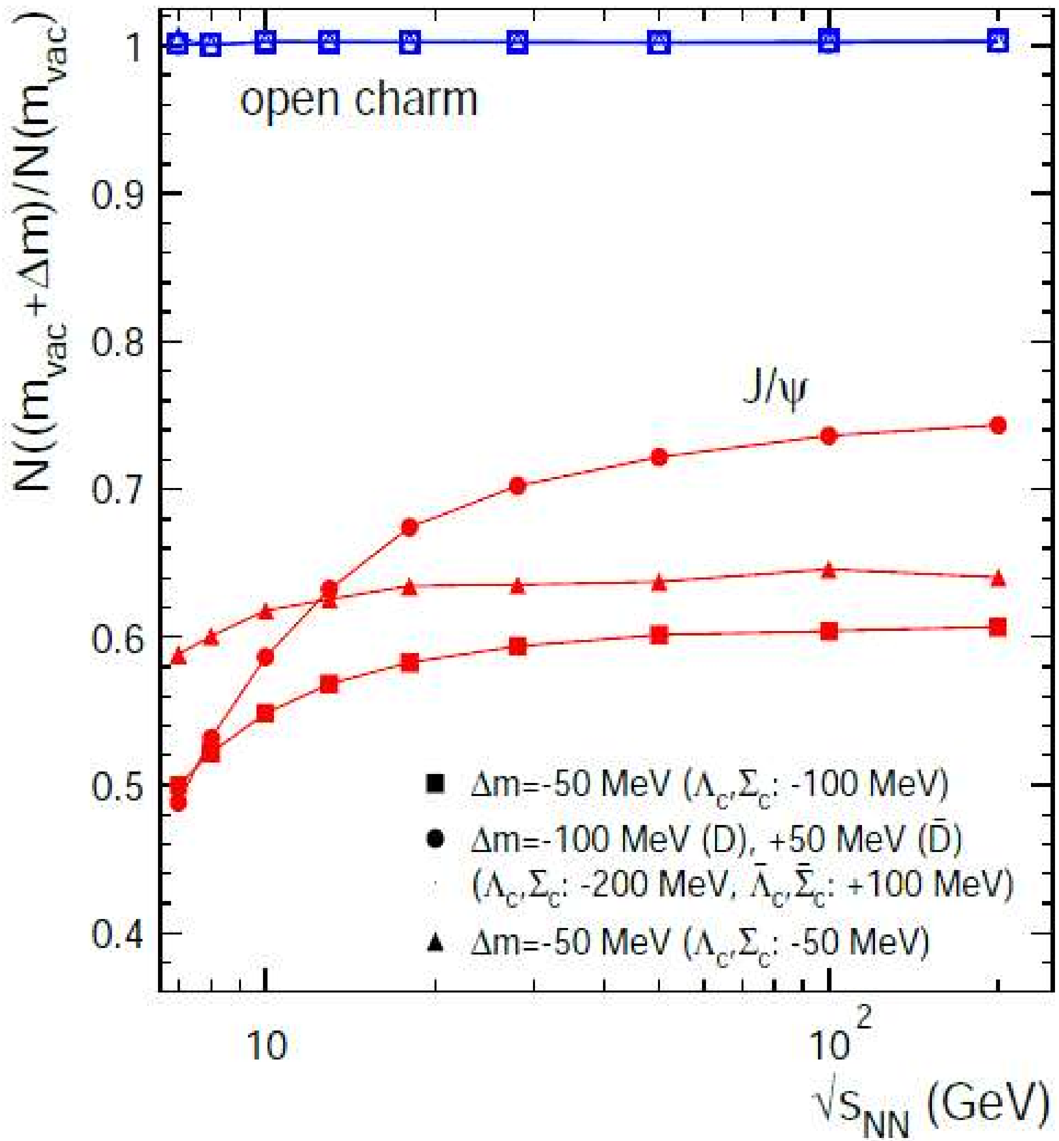
note: changes are subtle and show up ONLY when normalized to total charm cross section

Changes for charmonium assuming scenarios 1 – 3

charmonium masses unchanged

yield ot charmonium may change by up to factor of 2

difficult how to normalize



Summary

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

but:
effects are subtle, need normalization to total open
charm cross section
no strong reason to go very close to threshold

backup slides

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 limitted

Debye Screening

screened potential for heavy quark-antiquark pair

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

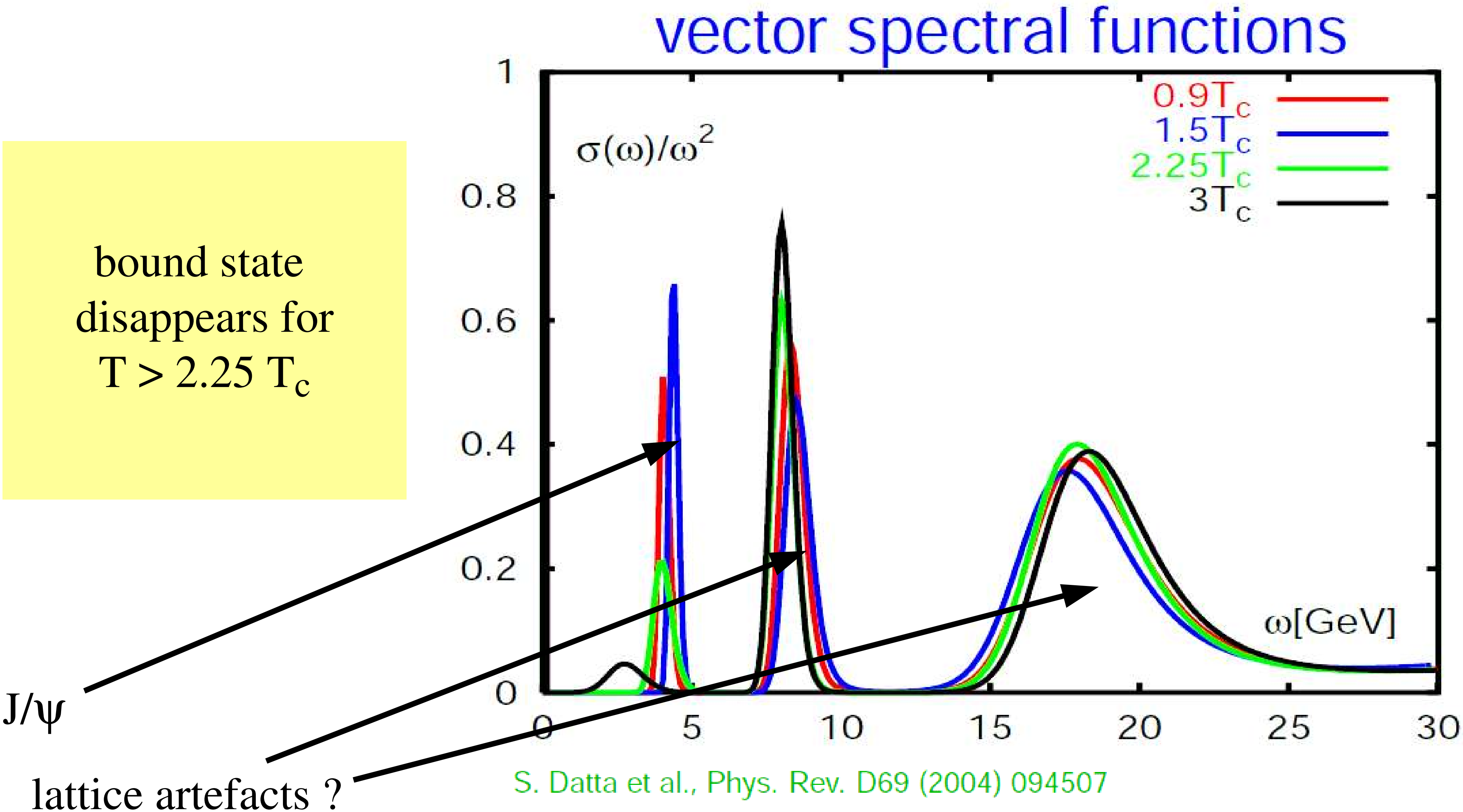
Debye radius $r_{Debye} = 1/\mu(T)$

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

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

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 $\rightarrow$ 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