Hadron Production in Ultra-relativistic Nuclear Collisions and the QCD Phase Boundary

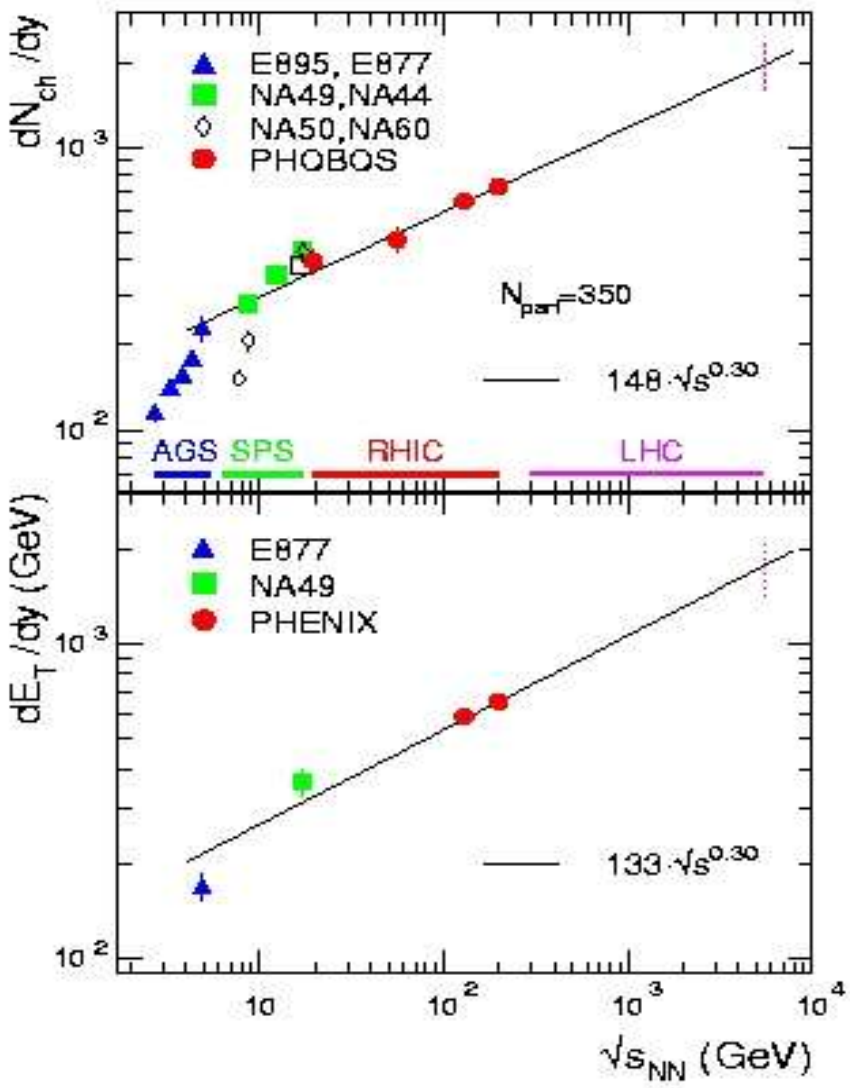
- hadron production and the thermal model
- thermal parameters and the QCD phase boundary
- introductory remarks on open charm, charmonium and QGP
- discussion of time scales and open charm conservation equation
- the statistical hadronization model
- results for RHIC energy
- outlook for LHC energy
- results for SPS and lower energies

pbm, 2nd Berkeley School on
Collective Dynamics, May 21 - 25, 2007

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

dedicated to Gerry Brown

Energy dependence of global observables



Mid-rapidity data for central Au-Au collisions.

Energy density from Bjorken estimate:

$\varepsilon = dE_T/dy \; 1/(\pi R^2) 1/\tau$

$\pi R^2 = 150 \text{ fm}^2$

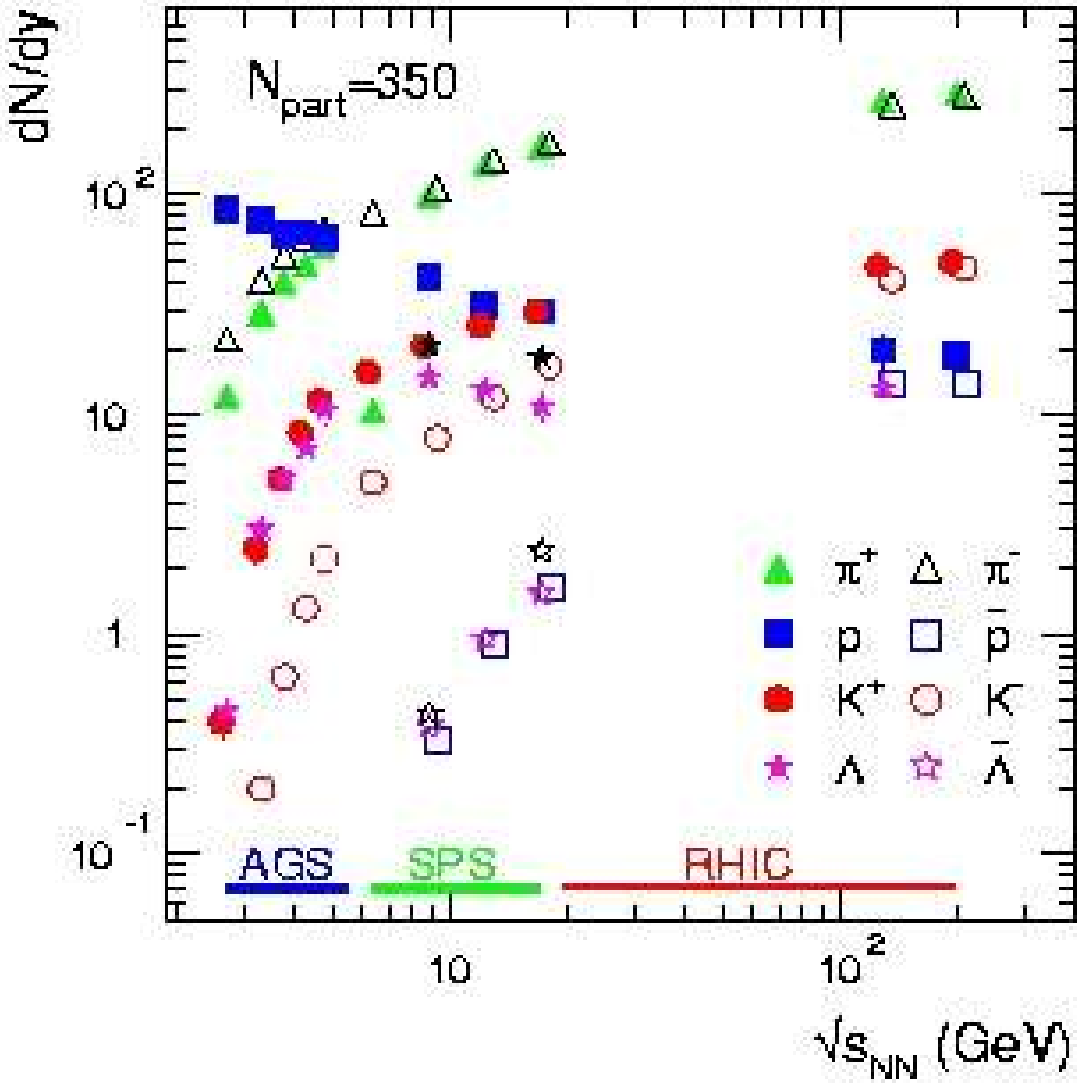
$= 1, \quad 0.3, \quad 0.1 \text{ fm}$

SPS RHIC LHC

$\varepsilon = 2.5, \quad 14, \quad (120) \text{ GeV/fm}^3$

$\varepsilon >> \varepsilon_c$ for all energies

... a wealth of data



Hadron yields signal chemical equilibrium

- From AGS energy on, all hadron yields in central PbPb collisions reflect grand-canonical equilibration
- Strangeness suppression observed in elementary collisions is lifted

For a recent review see:

pbm, Stachel, Redlich, QGP3, R. Hwa, editor, Singapore 2004, nucl-th/0304013

Thermal model description of hadron yields

Grand Canonical Ensemble

$$\ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 dp \ln(1 \pm \exp(-(E_i - \mu_i)/T))$$

$$n_i = N/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2\,\mathrm{d}p}{\exp((E_i - \mu_i)/T) \pm 1}$$

$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_i^3$$

for every conserved quantum number there is a chemical potential μ
but can use conservation laws to constrain:

- Baryon number: $V \sum_i n_i B_i = Z + N \quad \rightarrow V$
- Strangeness: $V \sum_i n_i S_i = 0 \quad \rightarrow \mu_S$
- Charge: $V \sum_i n_i I_i^3 = \frac{Z - N}{2} \quad \rightarrow \mu_{I_3}$

This leaves only μ_b and T as free parameter when 4π considered
for rapidity slice fix volume e.g. by dN_{ch}/dy

Fit at each energy provides values for T and μ_b

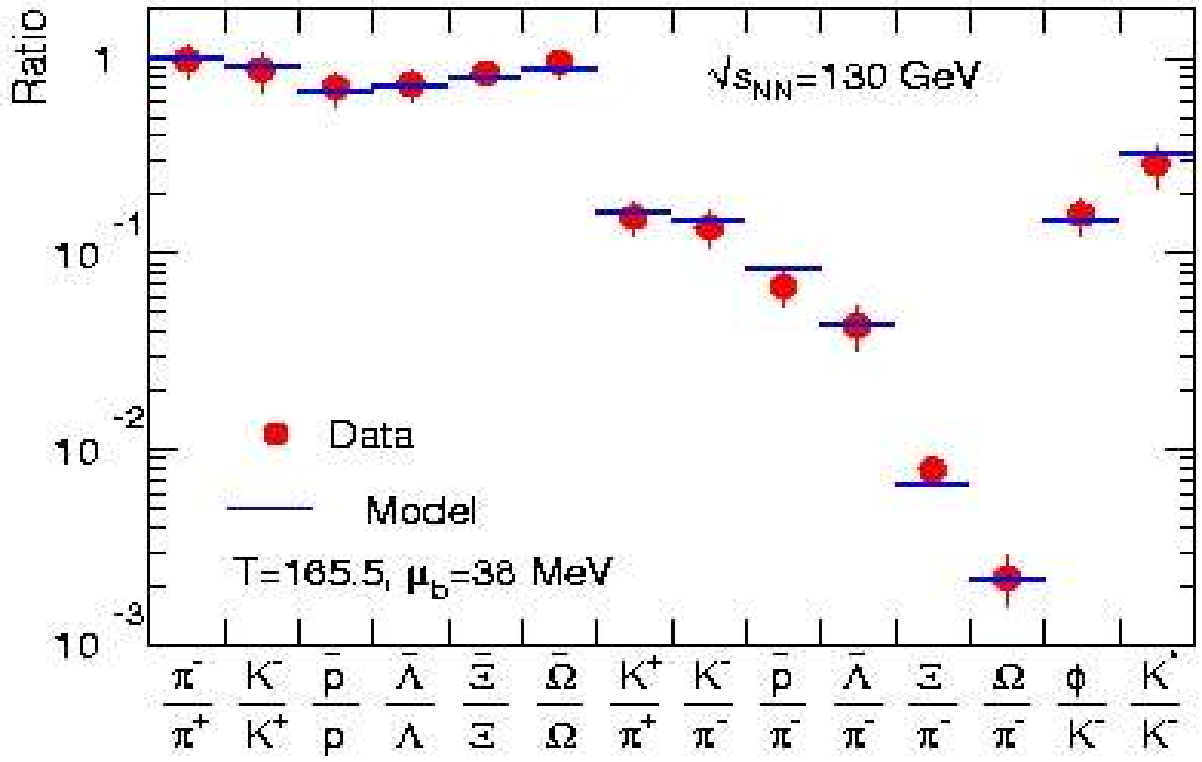
GSI
TECHNISCHE UNIVERSITÄT DARMSTADT

Hadro-chemistry at RHIC -- weakly decaying particles

All data in excellent agreement with thermal model predictions

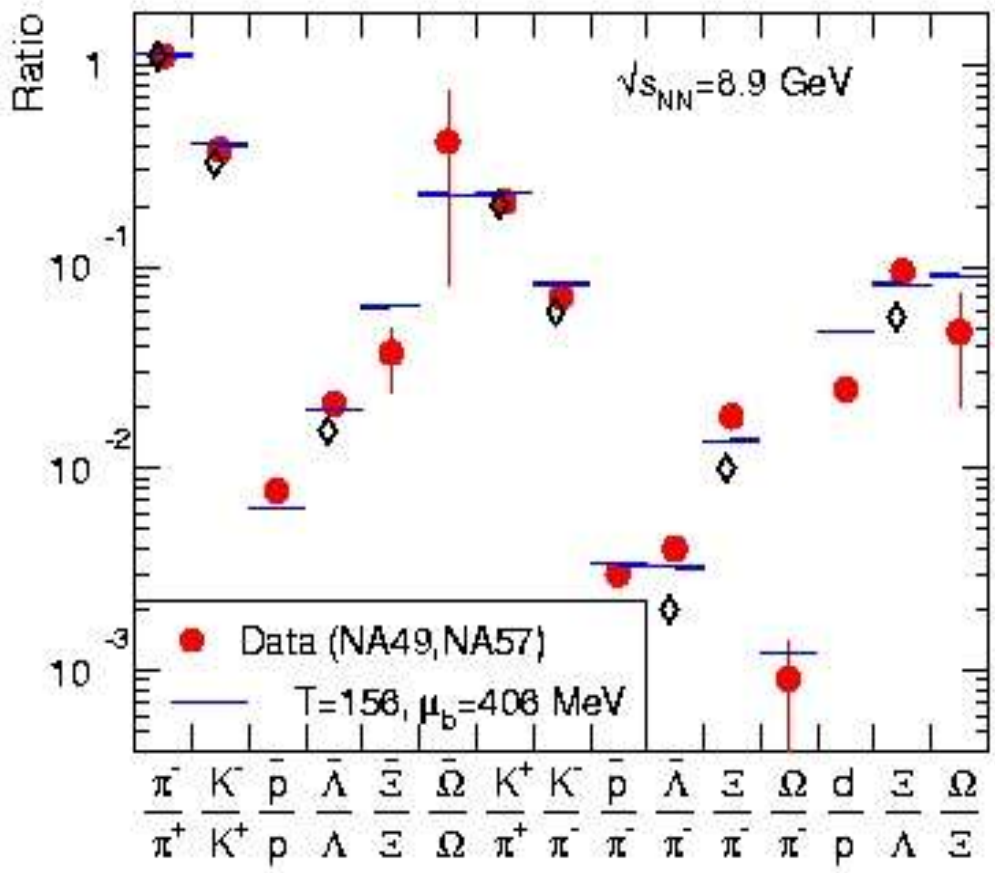
chemical freeze-out at: T = 165 ± 8 MeV

fit uses vacuum masses
most recent analysis: A. Andronic, pbm, J. Stachel, nucl-th/0511071 Nucl. Phys. A772 (2006) 167



pbm, d. magestro, j. stachel, k. redlich, Phys. Lett. B518 (2001) 41; see also Xu et al., Nucl. Phys. A698(2002) 306; Becattini, J. Phys. G28 (2002) 1553; Broniowski et al., nucl-th/0212052.

Hadro-chemistry at SPS



Data at 40 GeV/u Pb+Pb central collisions

T = 156 MeV,

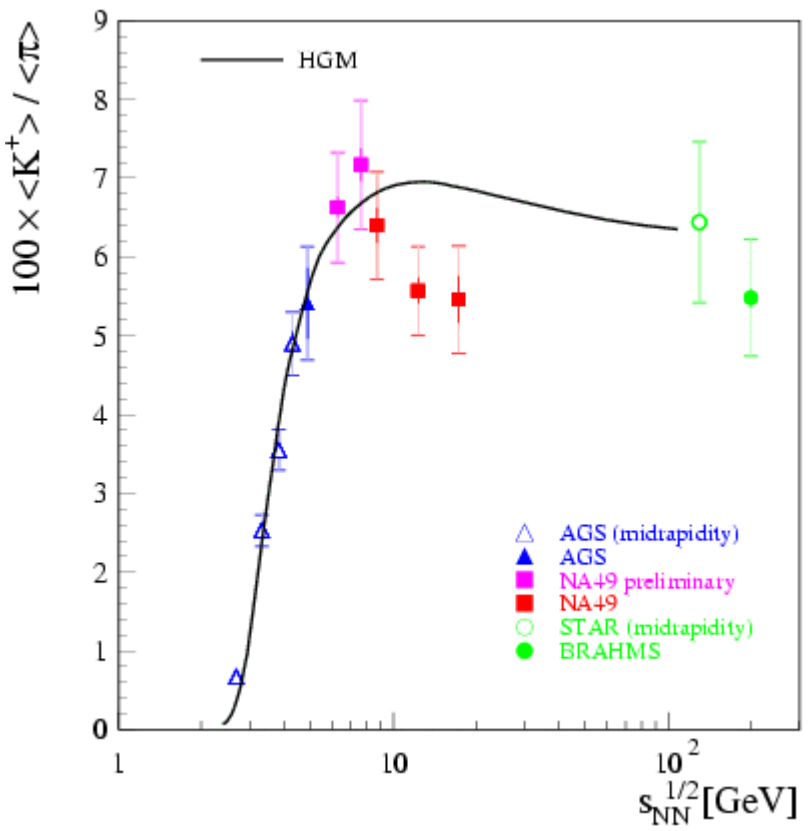
μ_b= 406 MeV

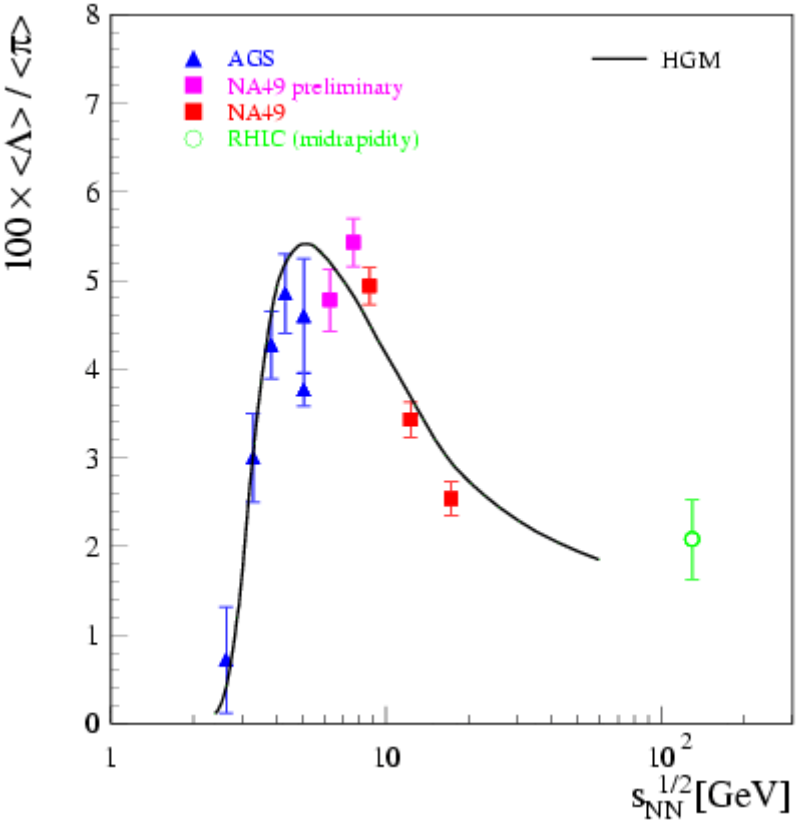
analysis from Andronic, pbm, Stachel,

nucl-th/0511071

Nucl. Phys. A772 (2006) 167

Open Issue: the NA49 „horn“ in K/π

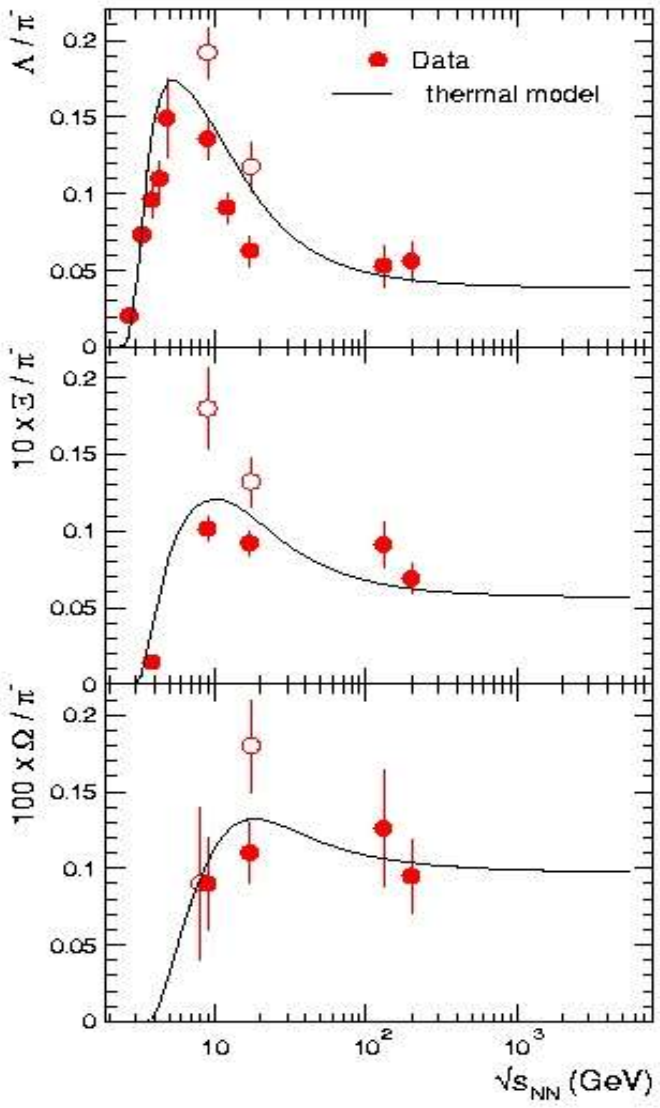


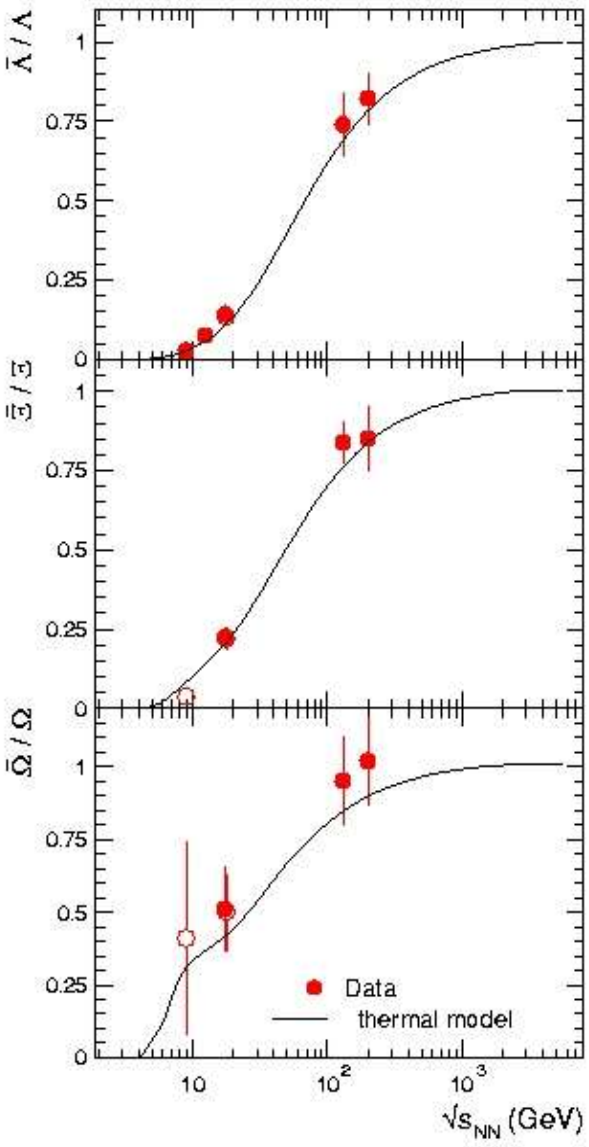


The structure near √s = 8 GeV is not reproduced but note: natural „ smearing“ is ≈ 3 GeV near √s = 8 GeV

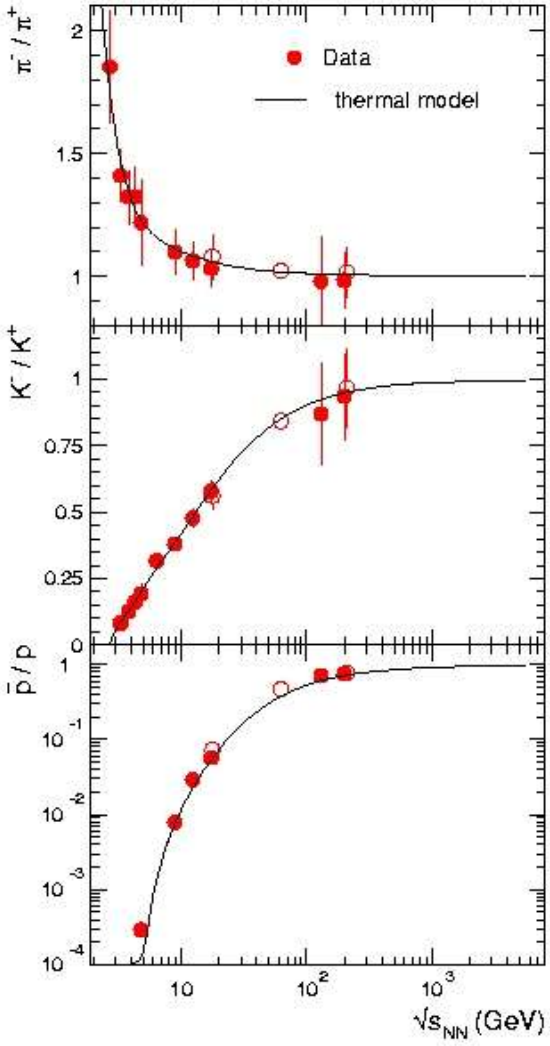
Strangeness undersaturated at 80 and 160 A GeV, saturated at all other energies?

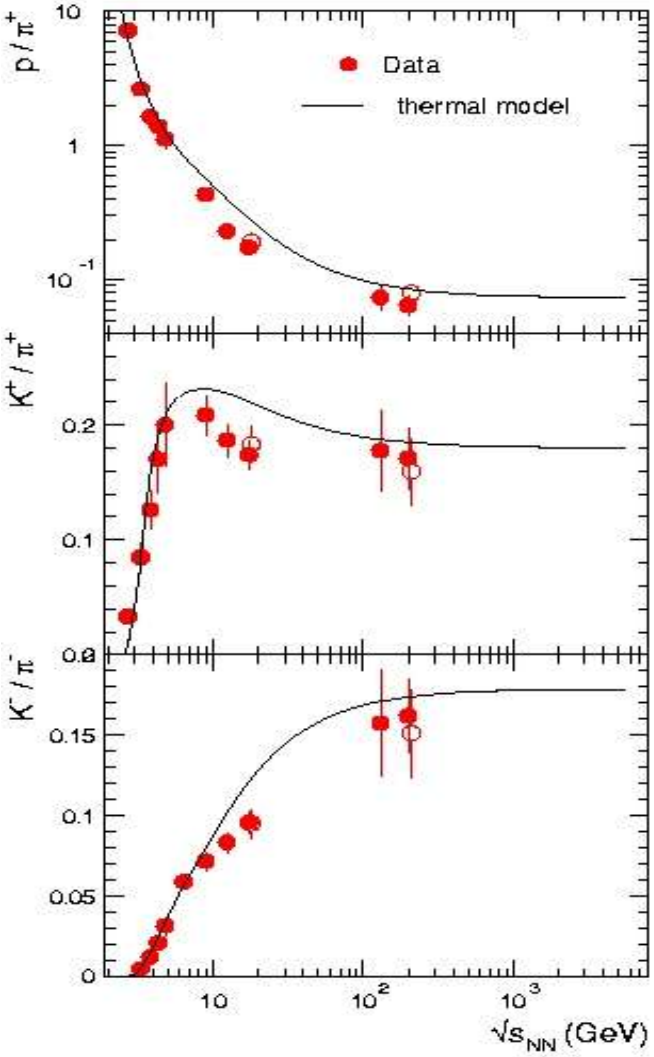
excitation functions and thermal model predictions





excitation functions and thermal model predictions



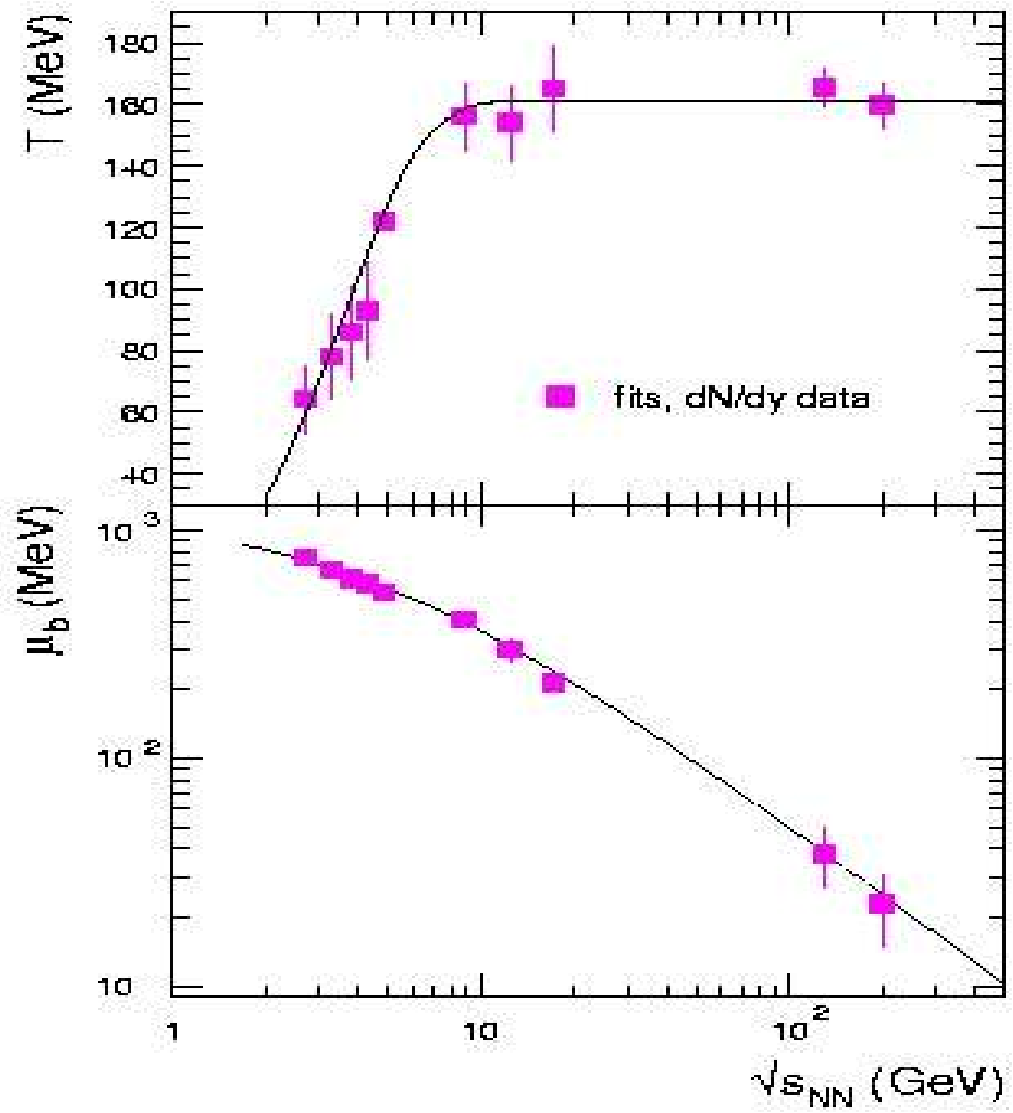


Parameterization of all freeze-out points

note: establishment of limiting temperature

T_{lim} = 160 MeV

get T and μ_B for all energies

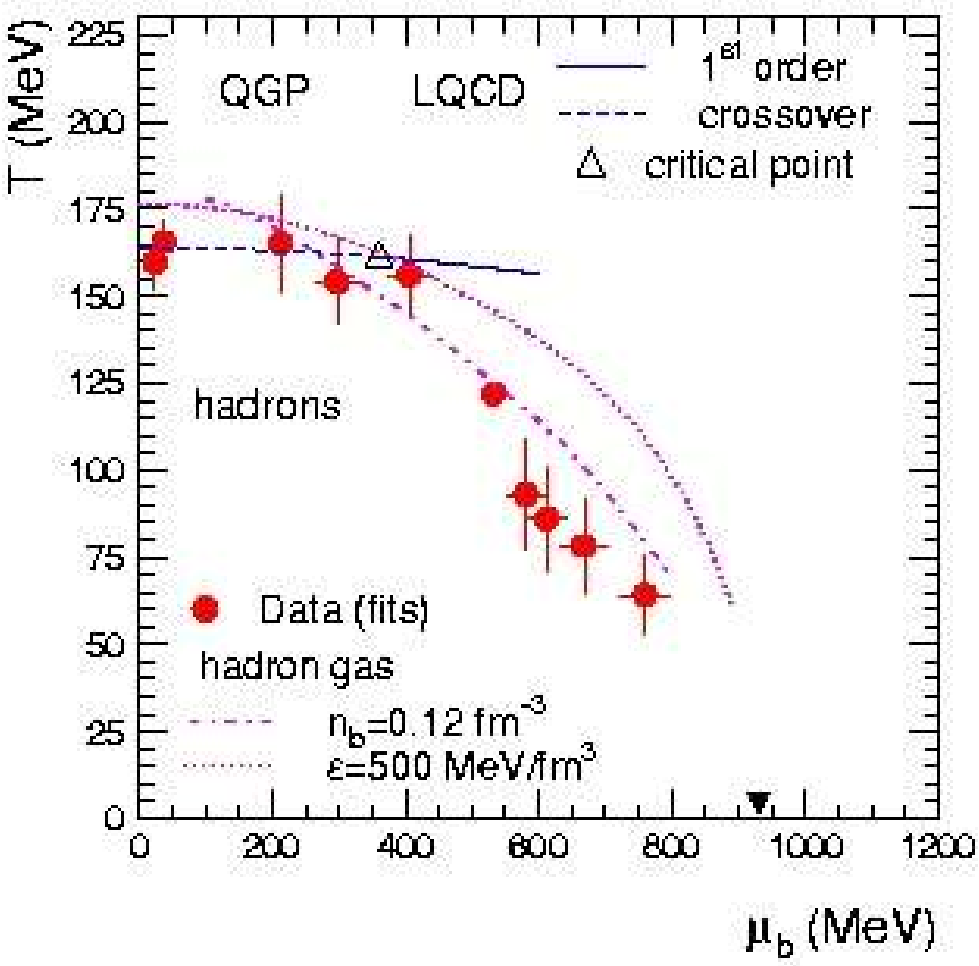


A. Andronic, pbm, J. Stachel, Nucl. Phys. A772 (2006) 167
nucl-th/0511071

The QCD phase diagram and chemical freeze-out (I)

Main result: chemical freeze-out points seem to delineate the QCD phase boundary at small μ (< 400 MeV)

can this be used to determine the critical temperature of the QCD phase transition?



How is chemical equilibration achieved?
Our Scenario

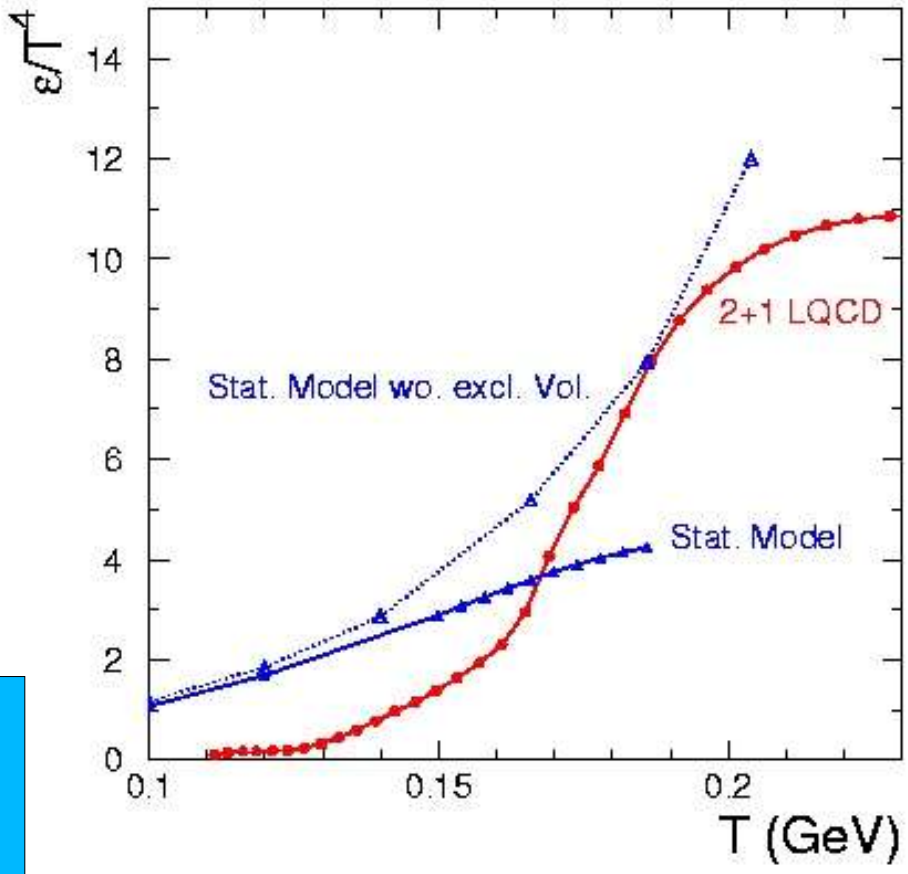
- Strangeness saturation takes place in the QGP phase.
- Phase transition is crossed from above.
- Near T_c new dynamics associated with collective excitations will take place and trigger the transition.
- Propagation and scattering of these collective excitations (Goldstone bosons) is expressed in the form of multi-hadron scattering. Near T_c multi-hadron processes will therefore be dominant. Chemical equilibrium is reached via these multi-hadron scattering events.

Chemical Equilibration must take place in the Hadronic Phase

- Hadron yields determined by Boltzmann factors with 'free' vacuum masses.
- Particle distribution in QGP phase has no 'memory' of vacuum hadron masses .
- Relative yields are not determined by the strange quark mass but by individual strange hadron masses (at fixed T and m).
- But: the number of strange quarks is determined in the QGP phase! Equilibrium then implies redistribution of strange quarks.

Chemical freeze-out takes place at T_c!

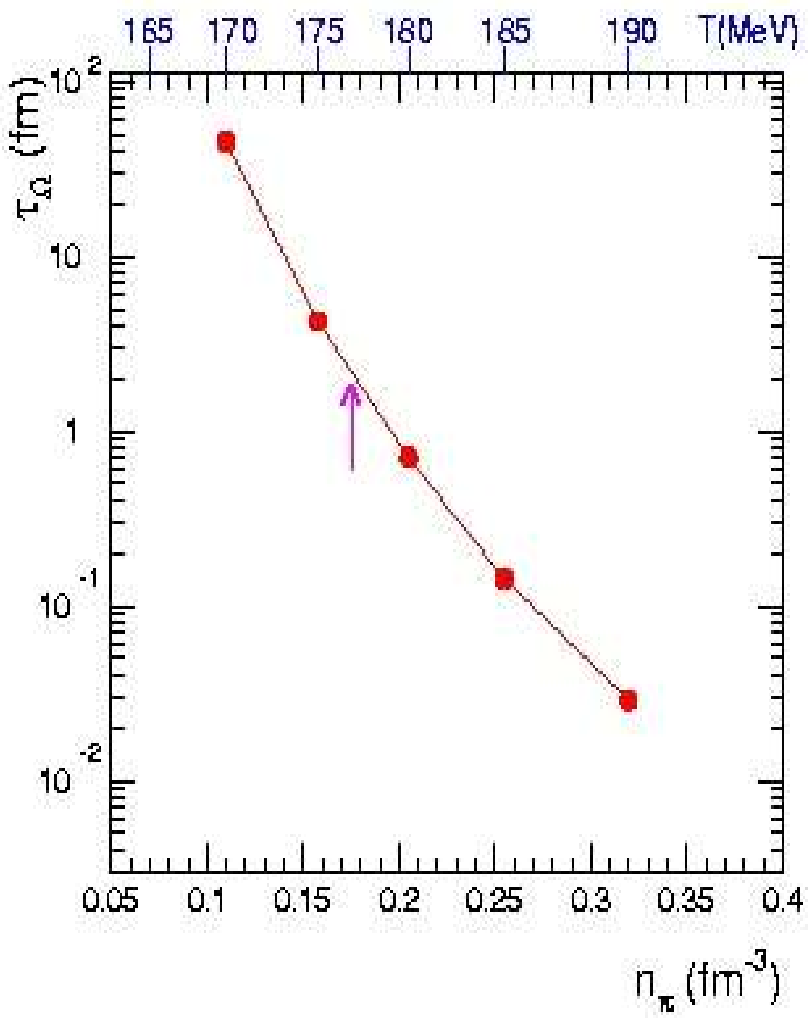
- Two-body collisions are not sufficient to bring multi-strange baryons into equilibrium.
- The density of particles varies rapidly with T near the phase transition.
- Multi-particle collisions are strongly enhanced at high density and lead to chem. equilibrium very near to T_c.



Lattice QCD calcs.
By F. Karsch et al.

pbm, J. Stachel, C. Wetterich
Phys. Lett. B596 (2004) 61
nucl-th/0311005

Density dependence of characteristic time for strange baryon production



- Near phase transition particle density varies rapidly with T.
- For small μ_b, reactions such as $KKK\pi\pi \rightarrow \Omega N_{bar}$ bring multi-strange baryons close to equilibrium.
- Equilibration time $\tau \propto T^{-60}$!
- All particles freeze out within a very narrow temperature window.

pbm, J. Stachel, C. Wetterich
Phys. Lett. B596 (2004) 61
nucl-th/0311005

Chemical freeze-out determines T_c for small

phase transition brings multi-strange (and all other hadrons) into equilibrium

chemical freeze-out temperature closely coincides with critical temperature

determination of a fundamental QCD parameter from experiments on hadron production in ultra-relativistic nuclear collisions

T_c = 160 (+12 -16) MeV

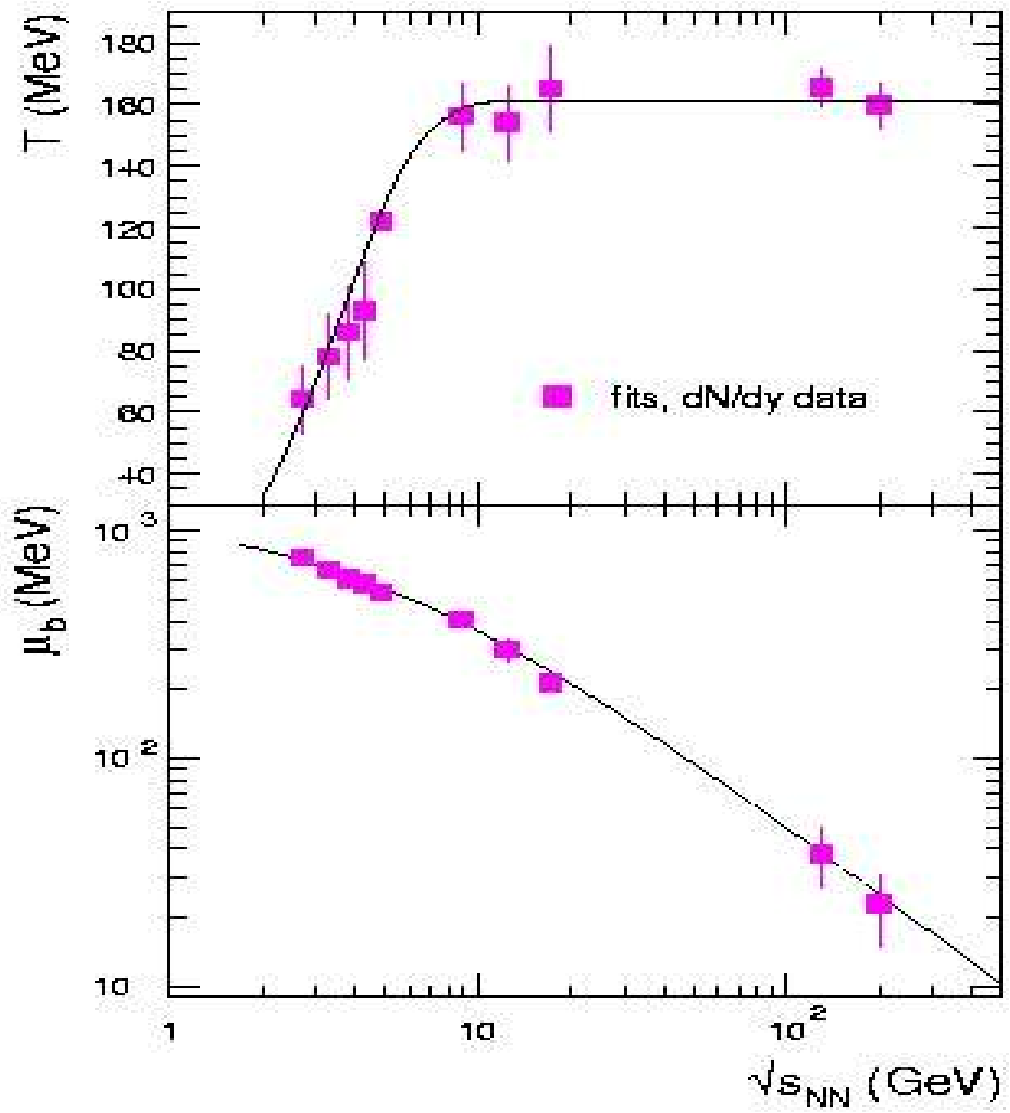
2 sigma discrepancy with latest lattice resuts of Bielefeld/Columbia/BNL group, but in agreement with Fodor et al., see also T. Hatsuda, hep-ph/0702293

The limiting temperature is T_c

T_{lim} = 160 MeV

T_c = 160 (+12 -16) MeV

estimated systematic errors



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

Charmonia and open charm as a probe for the properties of the QGP

- production of hadrons with heavy quarks: also thermal?

- charm quark mass >> T_c
- charm quark mass >> Λ_{QCD}

special role of charm and bottom

production of charm quarks early, in hard collisions
no thermal production
production of open and hidden charm hadrons late
separation of time scales brings in new physics

Charmonium suppression

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

assumptions:

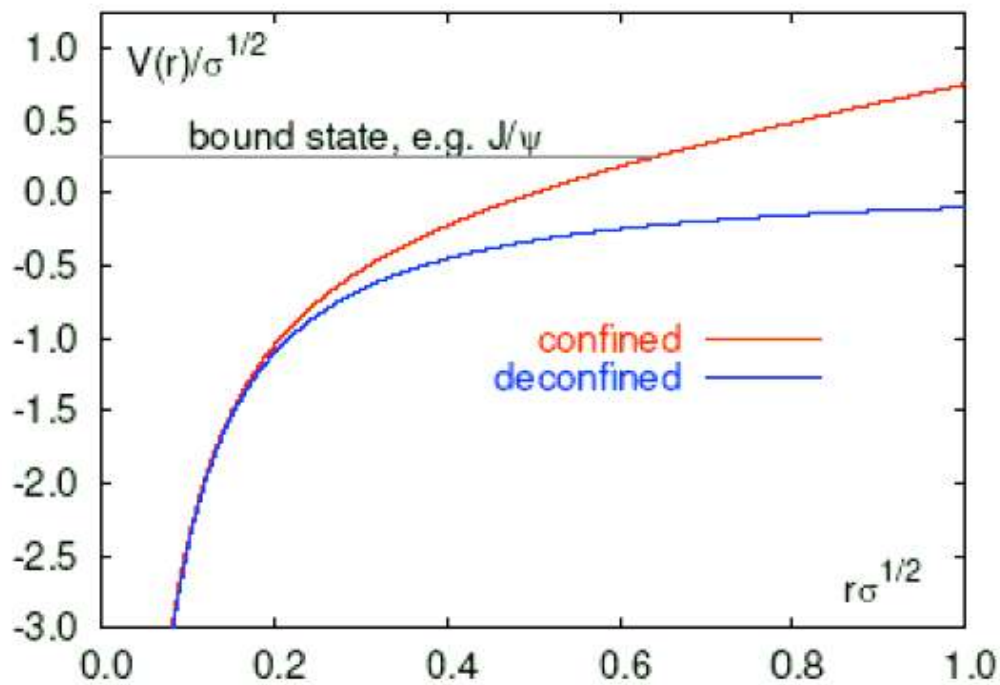
- **all** charmonia are produced before QGP formation
- suppression takes place in QGP
- some charmonia might survive beyond T_c

$\rightarrow$ sequential suppression pattern due to feeding

Debye screening

V(r,T large) no bound state

V(r,T small) bound state

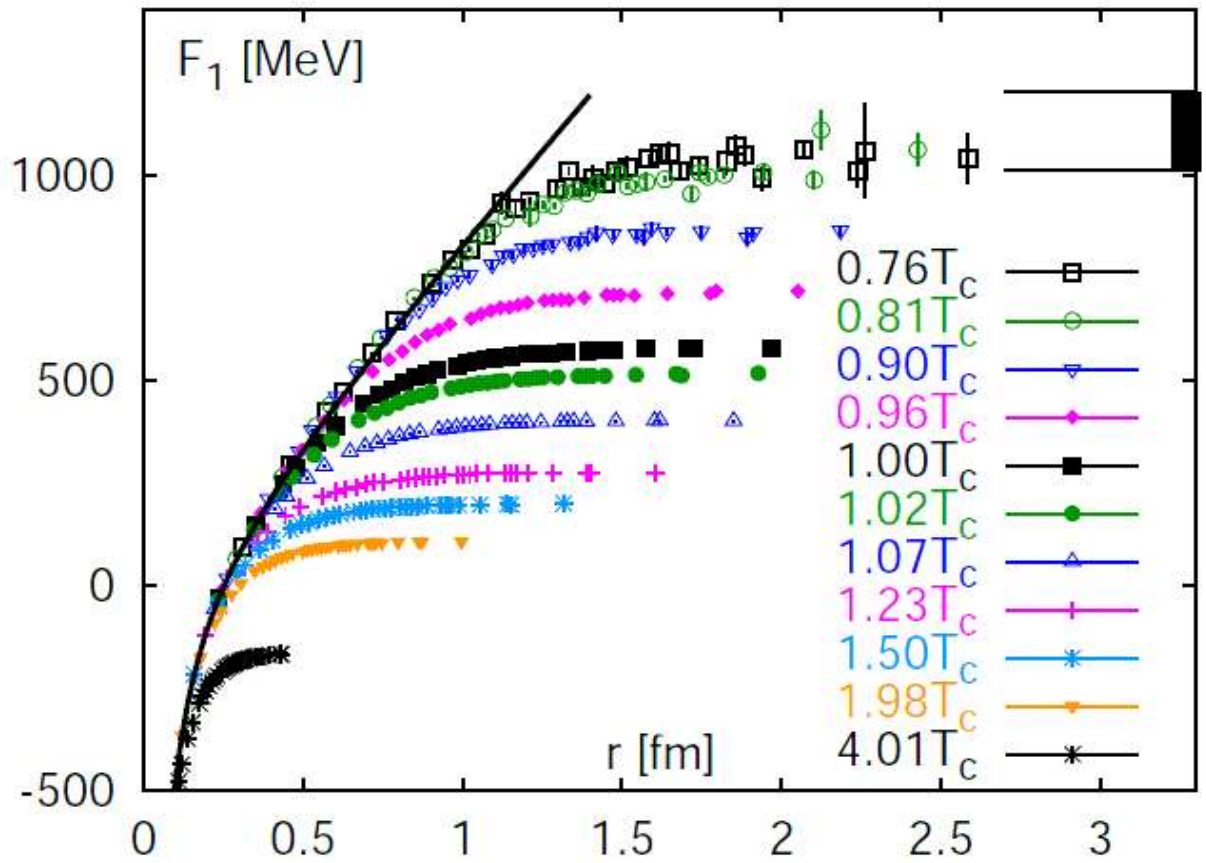


σ = string tension = 1 GeV/fm
= 0.2 GeV^2

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

but see: A. Mocsy, P. Petreczky,
hep-ph/0705.2559

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 >> 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 $1/m_c$
  $m_c = 1.5$ 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/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

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

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

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

    $\rightarrow$ 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

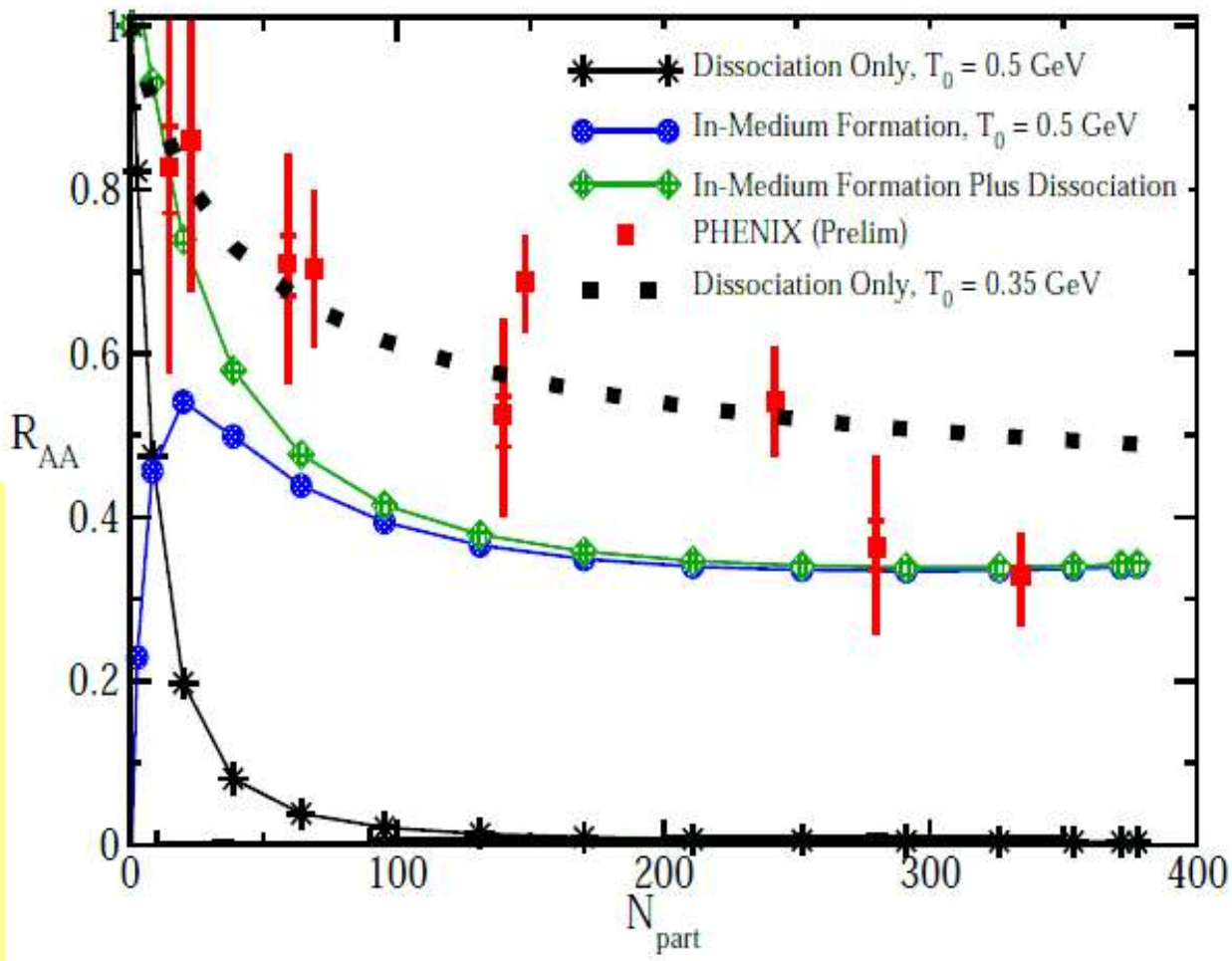
    $\rightarrow$ yield ~ N_c^2 -- quarkonium enhancement at high energies

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: $\rightarrow n_X^{th}$

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

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

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

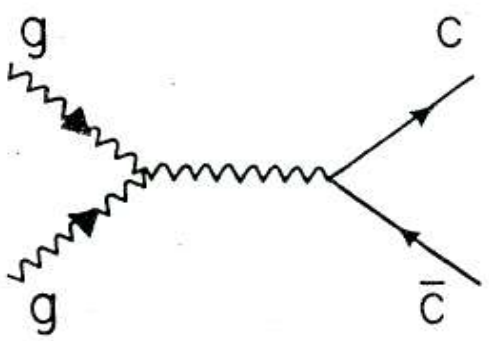
- quarkonium production cross section in pp collisions (for corona part)

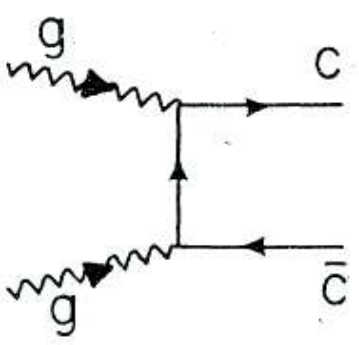
result: quarkonium and open charm cross sections as function of
energy, centrality, rapidity, and transverse momentum

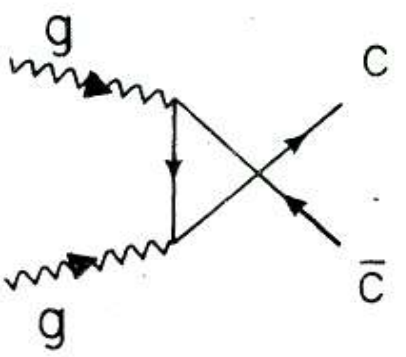
Cross section for charm production

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

$$\frac{d\sigma^{gg\to c\bar{c}}}{dt} = \frac{\pi\alpha_s^2}{64s^2}\left(12M_{ss} + \tfrac{16}{3}M_{tt} + \tfrac{16}{3}M_{uu} + 6M_{st} + 6M_{su} - \tfrac{2}{3}M_{tu}\right), \qquad \text{(A1)}$$

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

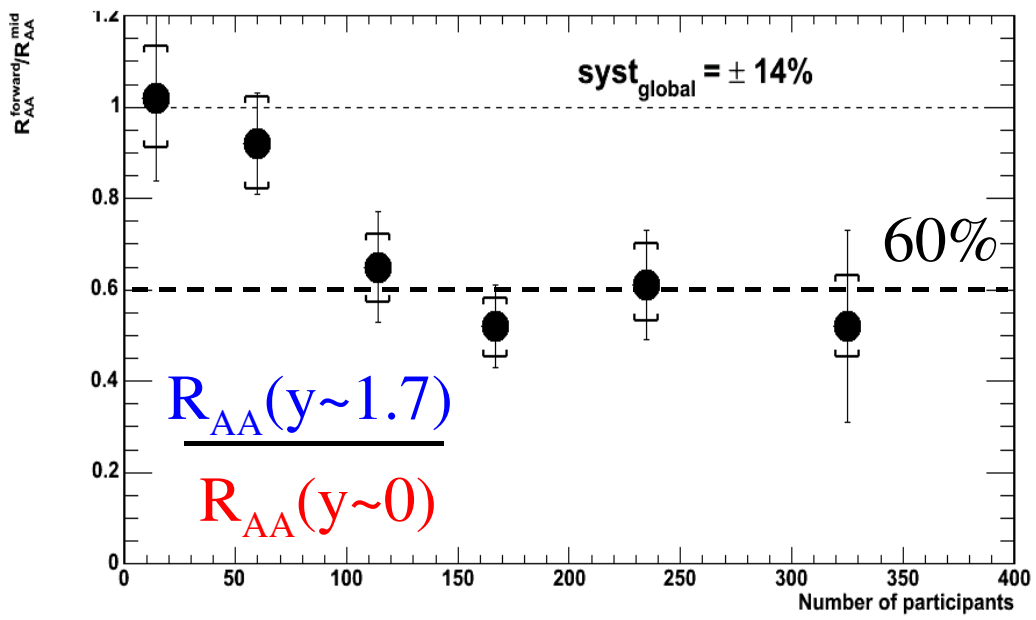
use R_{AA} to define charmonium modification experimentally
no need to normalize to Drell-Yan process

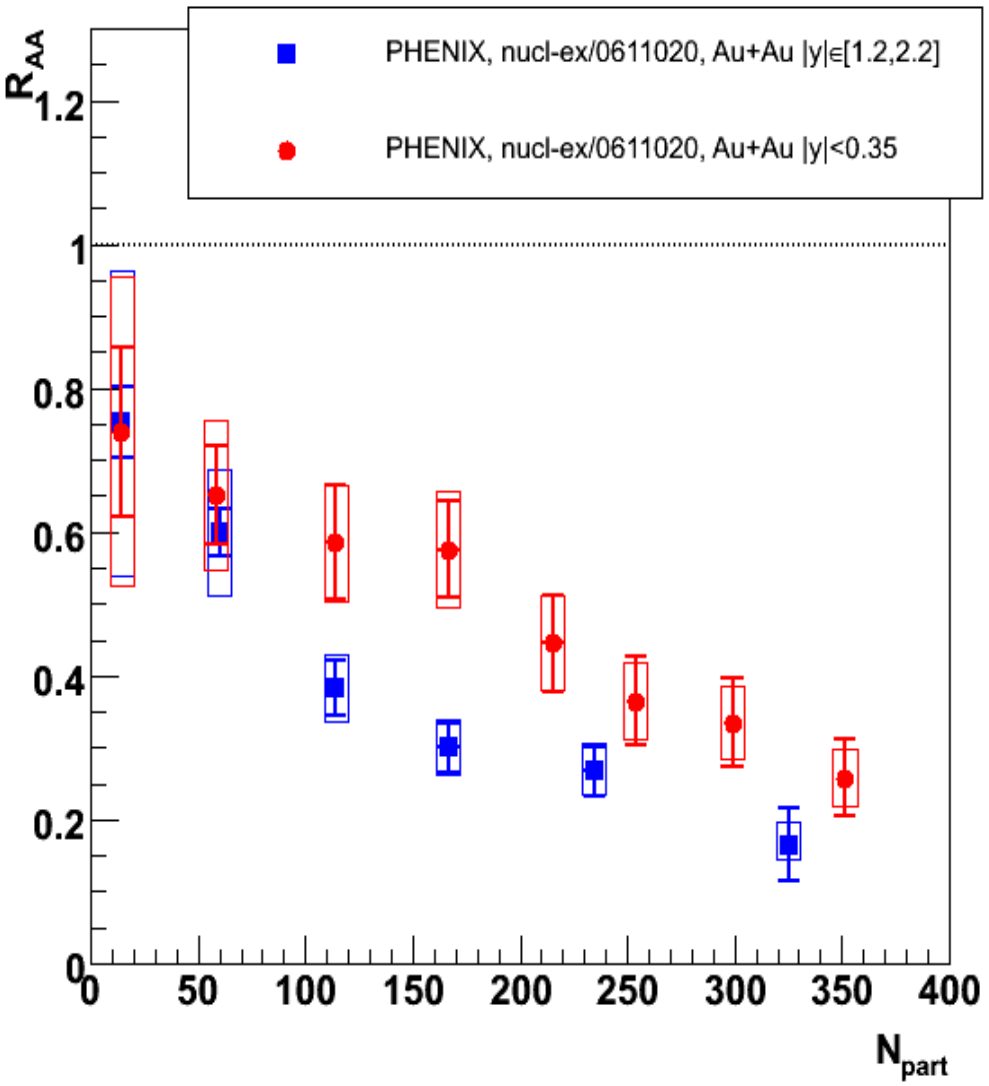
$$R_{AA}^{J/\psi} = \frac{\mathrm{d}N_{J/\psi}^{AuAu}/\mathrm{d}y}{N_{coll} \cdot \mathrm{d}N_{J/\psi}^{pp}/\mathrm{d}y}$$

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

charmonium suppression at RHIC

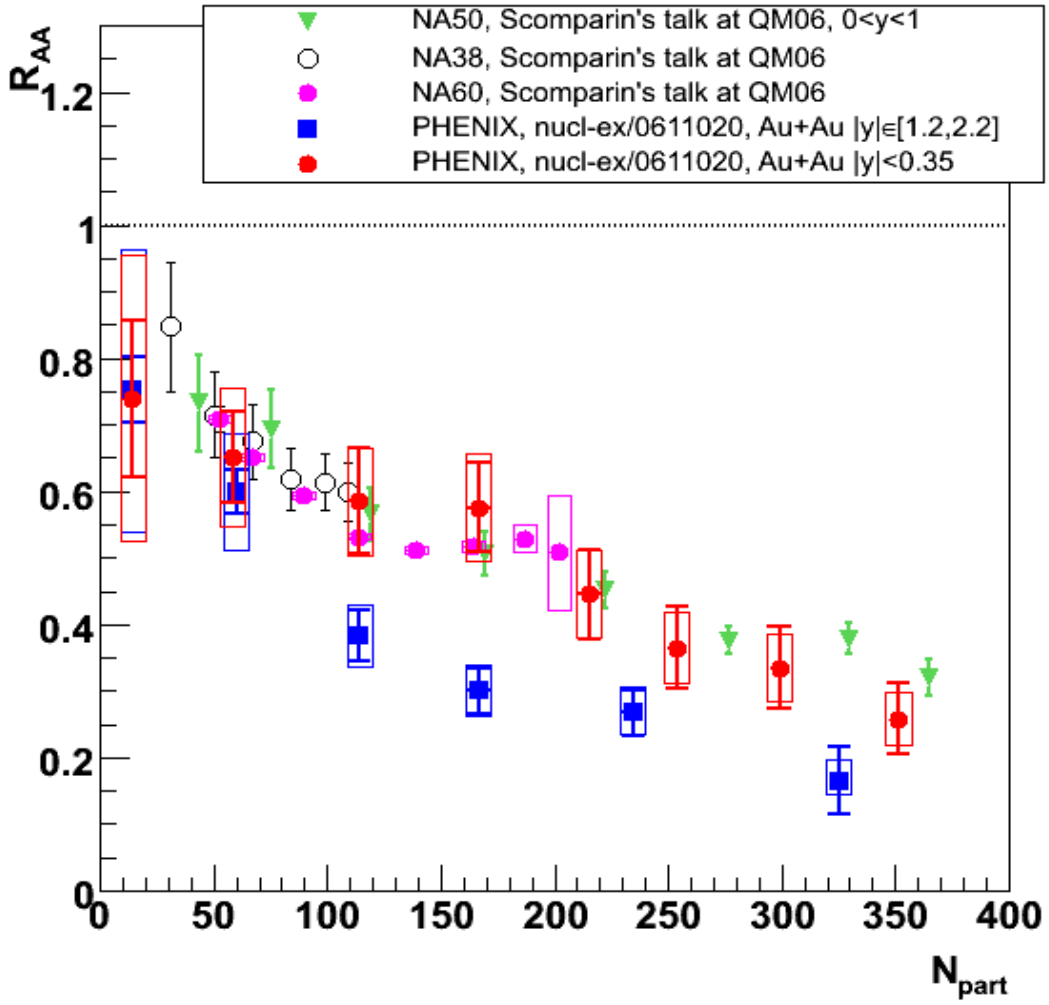
surprize:
suppression is weakest at mid-rapidity





Comparison of RHIC and SPS Results

surprize:
no energy dependence

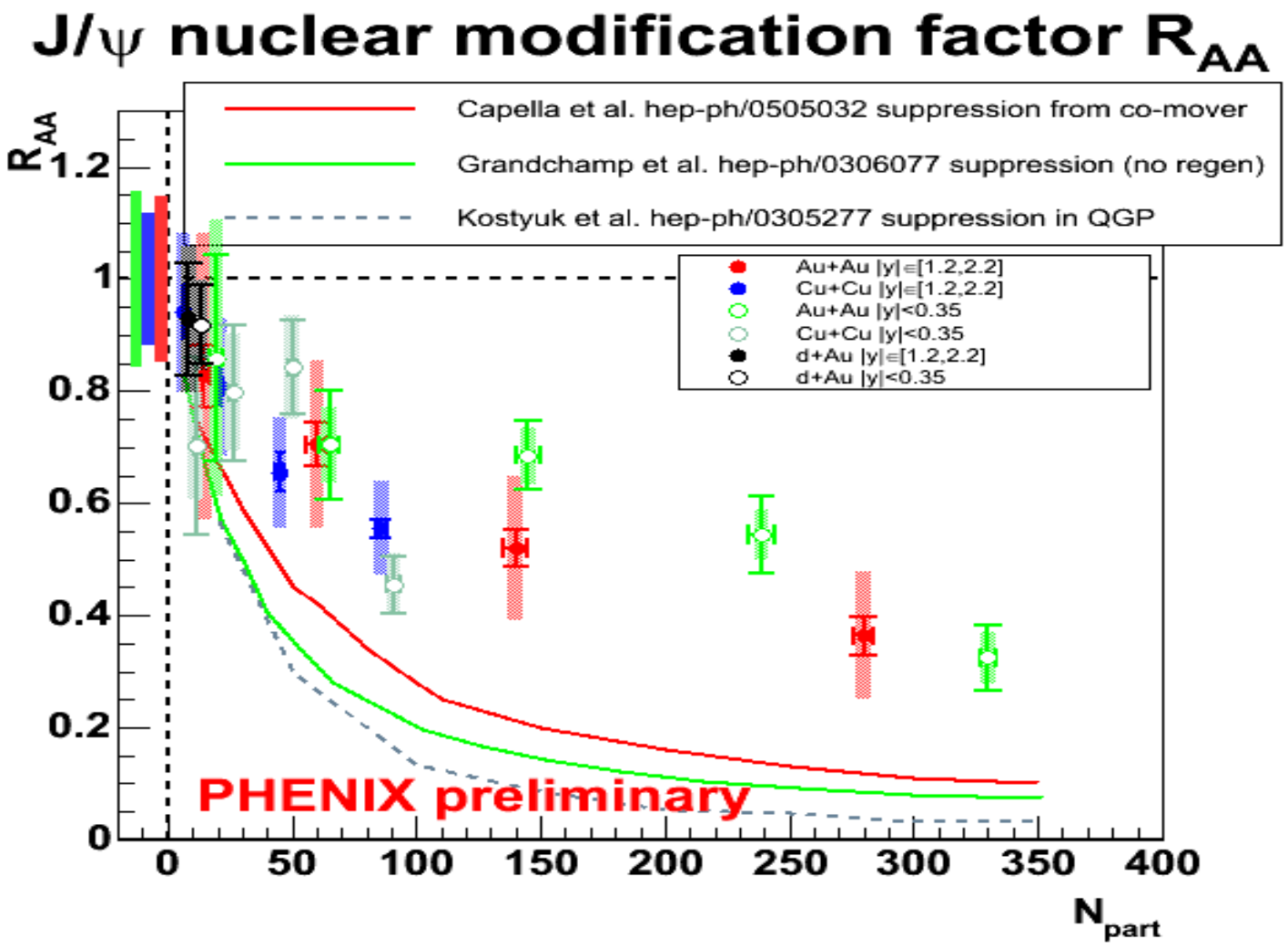


comparison produced by
R. Granier de Cassagnac

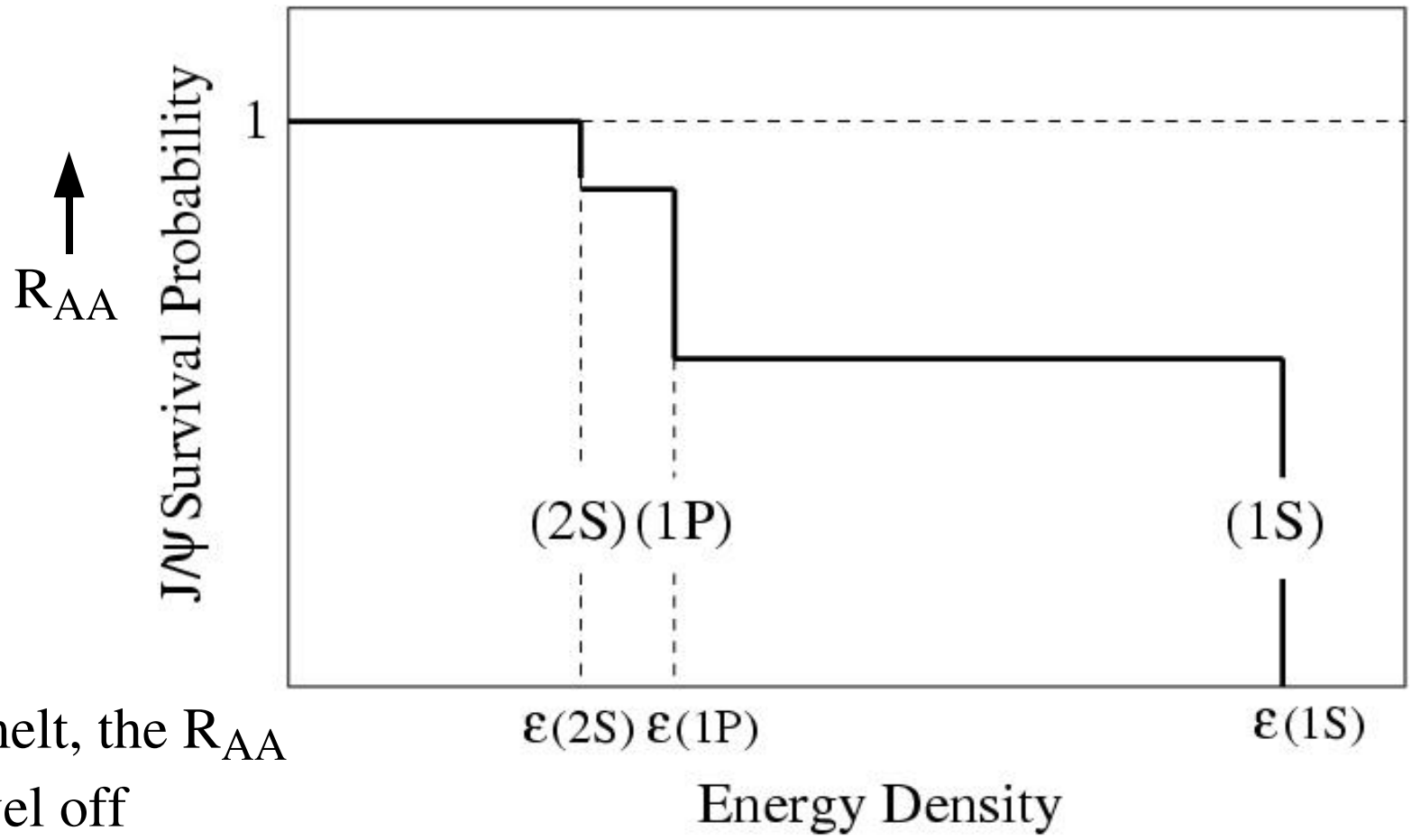
Too much suppression at RHIC in Standard QGP Scenario

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 χ_c and ψ')

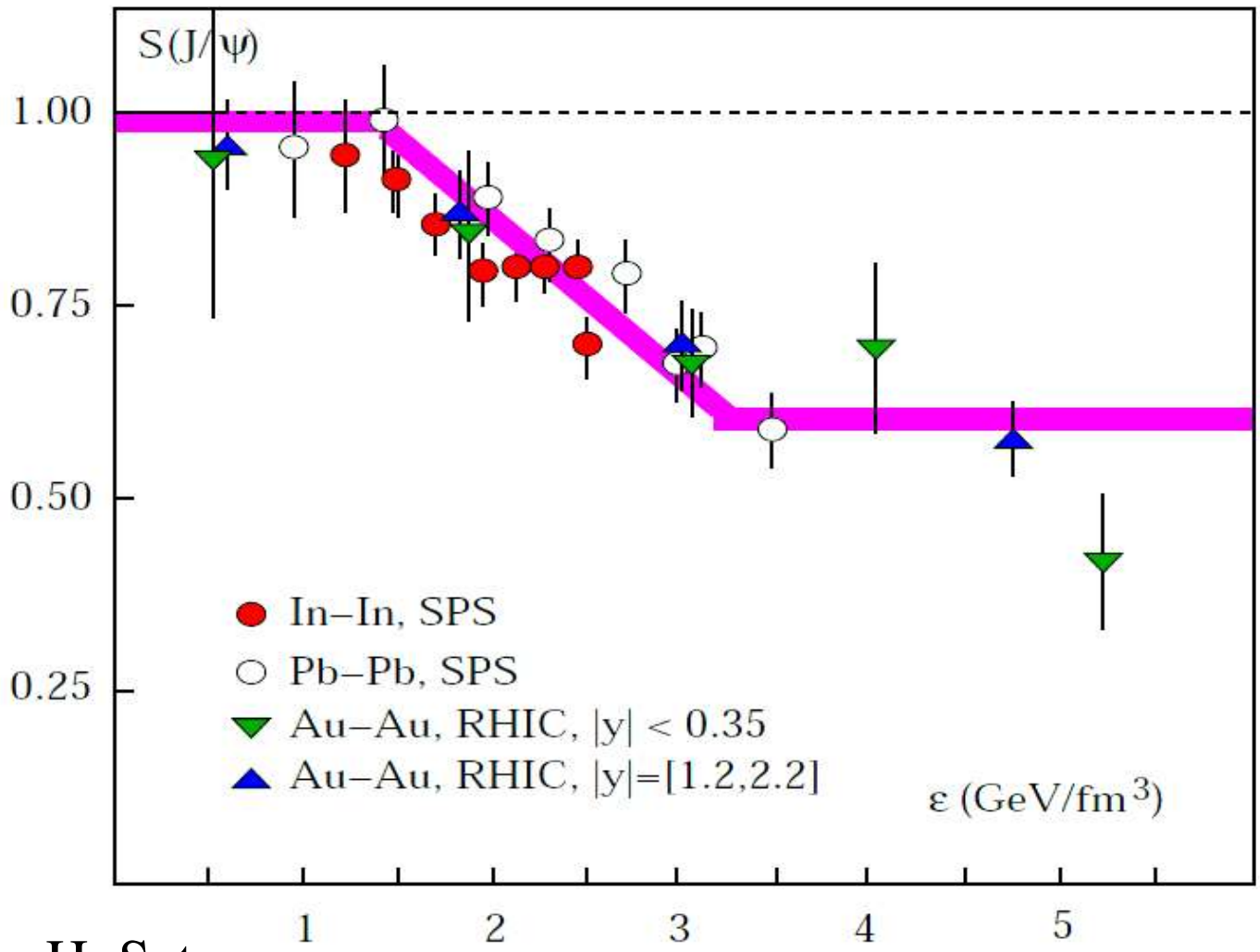
note: χ_c and ψ' not measured at RHIC
pA data at lower energies (HeraB) suggest:
$\chi_c/(J/\psi) < 0.35$

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

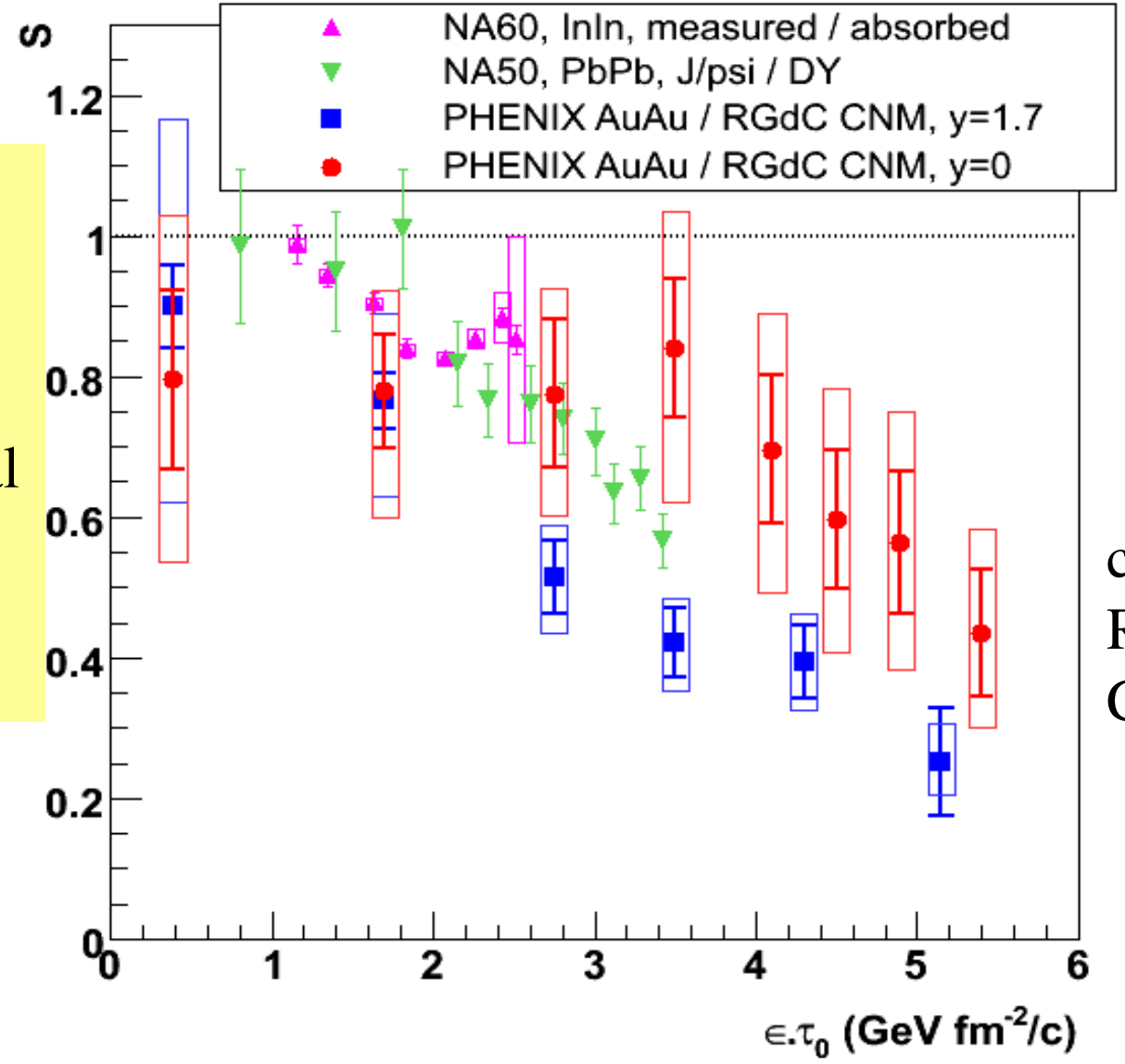


F. Karsch, D. Kharzeev, H. Satz, Phys. Lett. B637 (2006) 75

preliminary RHIC data, no full error propagation

No experimental evidence for sequential melting

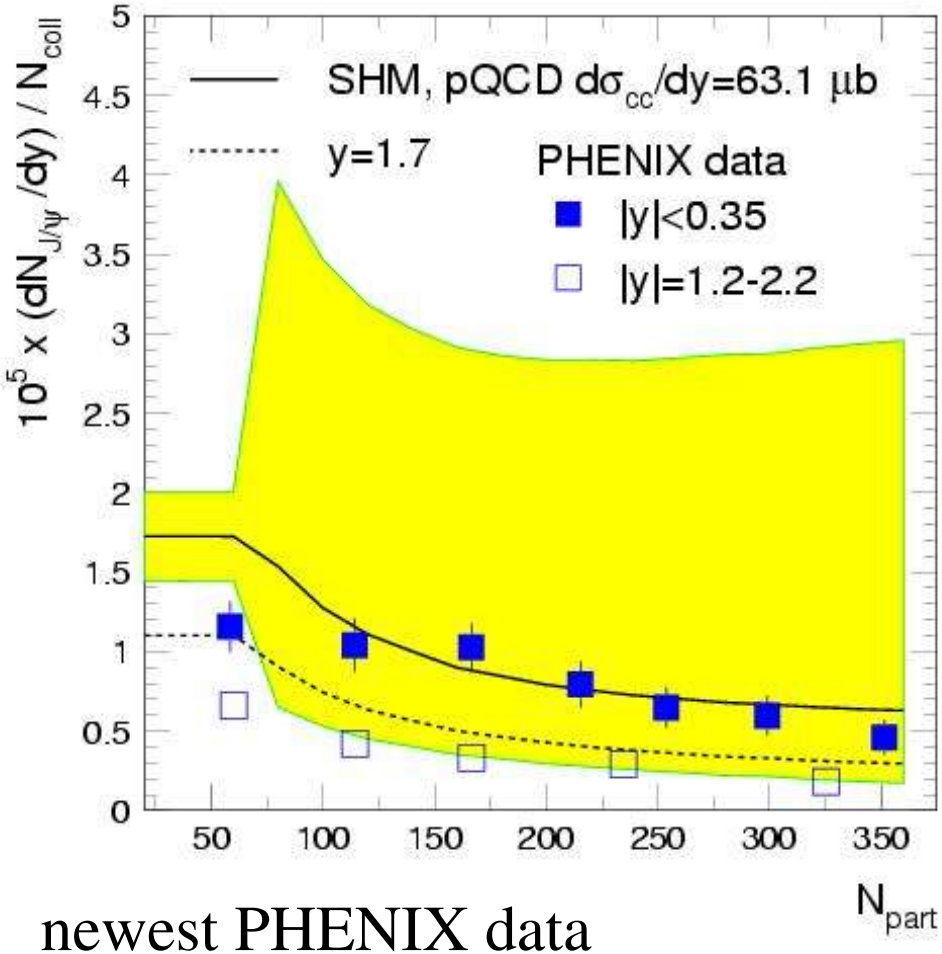
new data at various rapidities rule out sequential melting



compilation by R. Granier de Cassagnac

Comparison of model predictions to RHIC data: centrality dependence

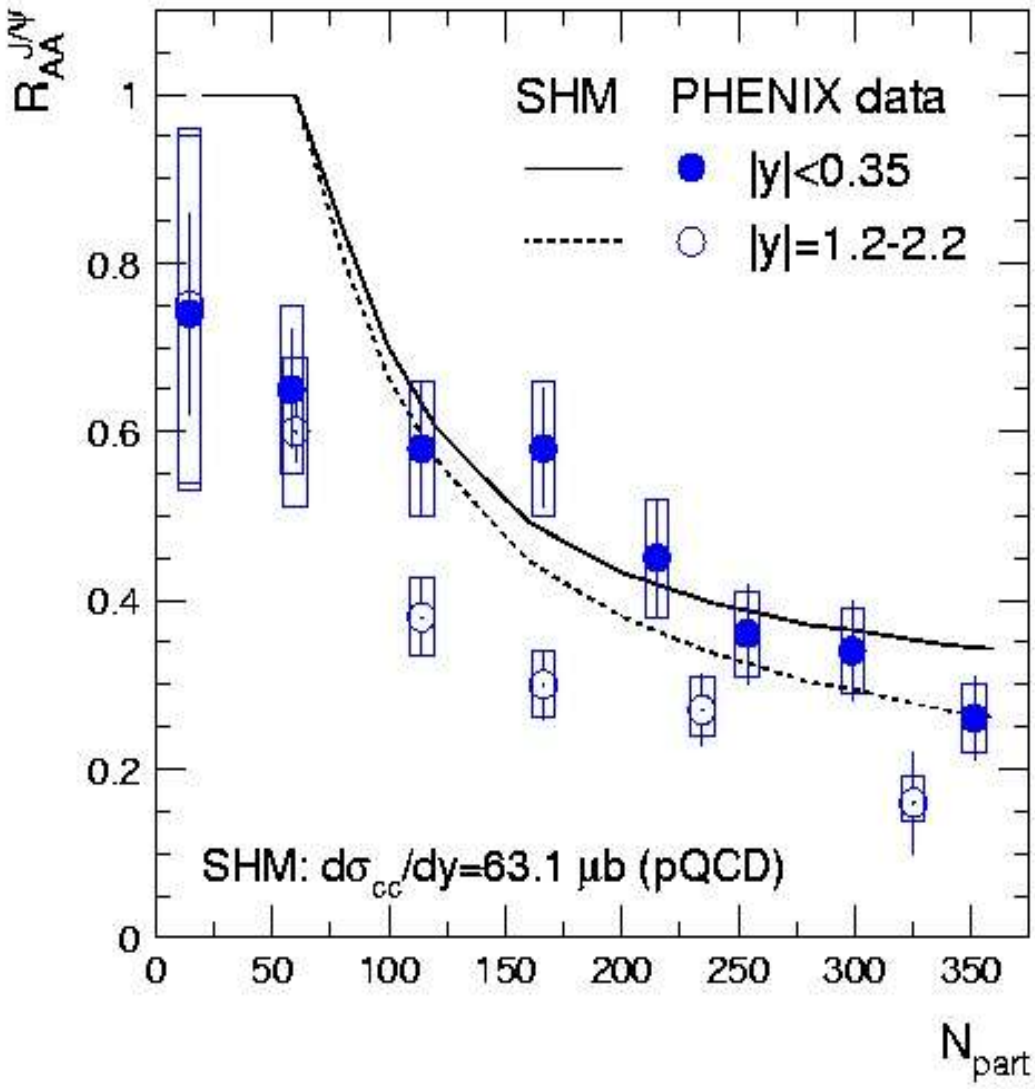
predictions for J/ψ production using NNLO pQCD results for open charm cross section by M. Cacciari, P. Nason, R. Vogt, Phys. Rev. Lett. 95 (2005) 122001, hep-ph/0502203



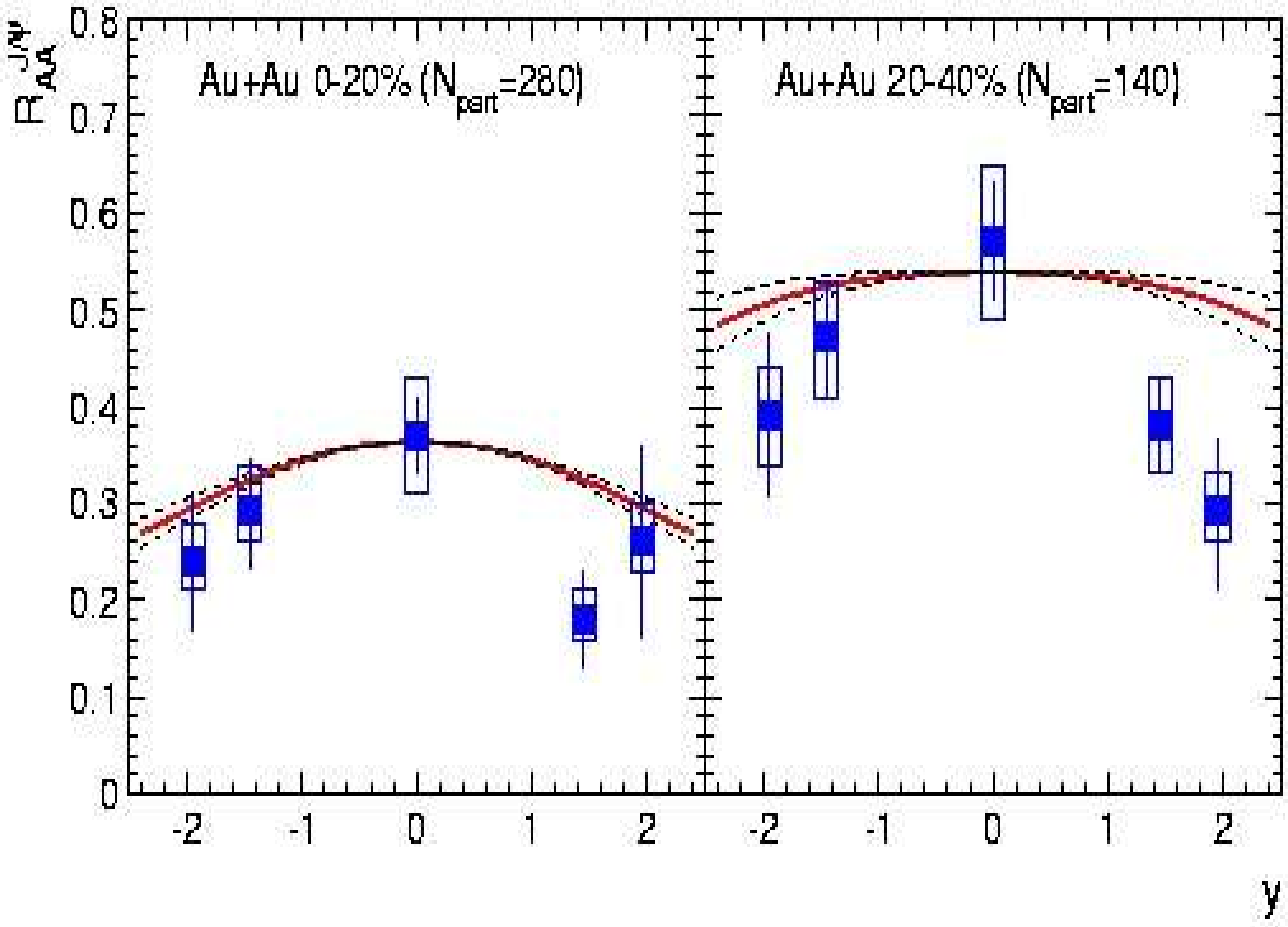
newest PHENIX data

good agreement, no free parameters

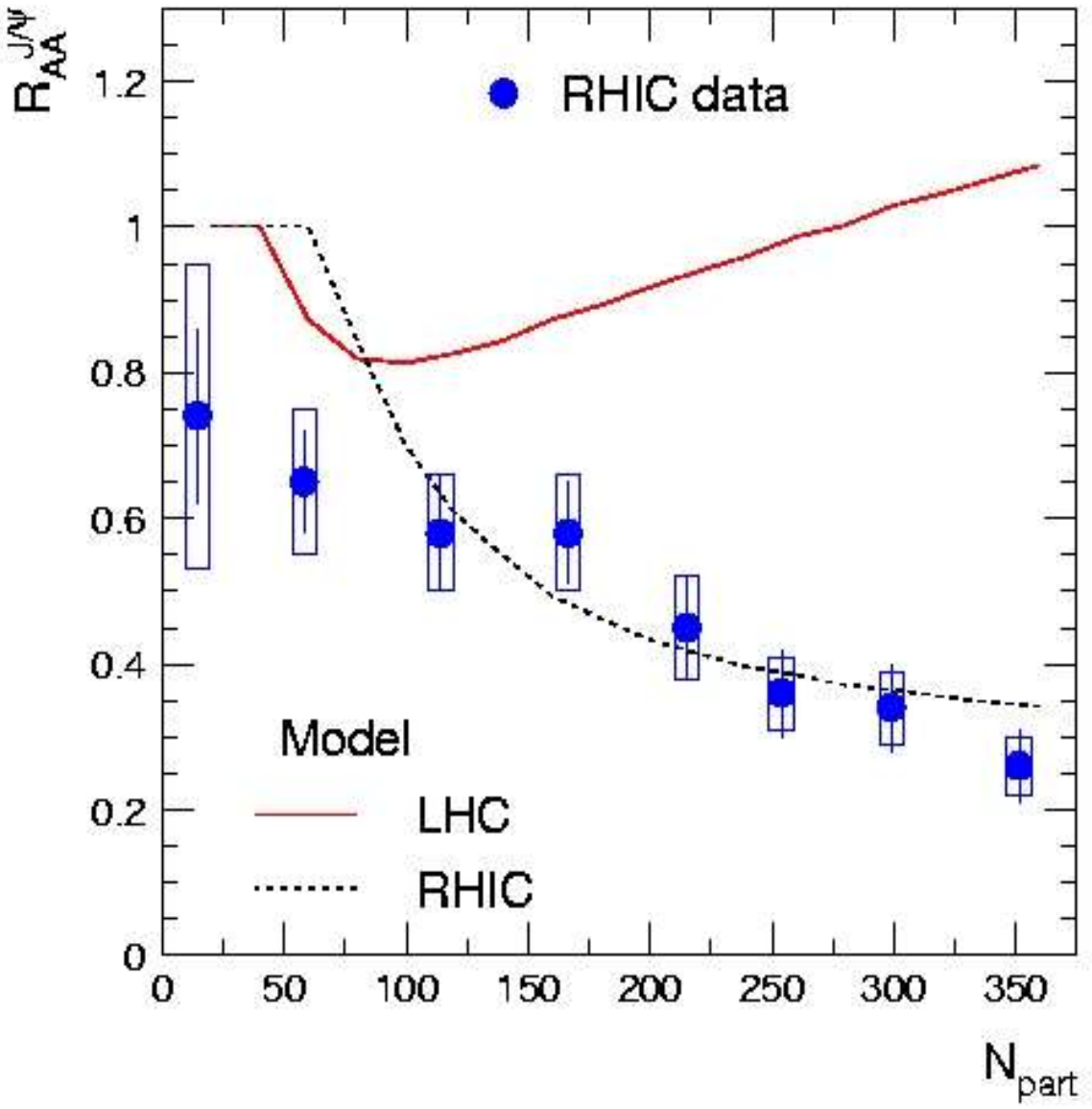
Centrality dependence of nuclear modification factor



Comparison of model predictions to RHIC data: rapidity dependence



Prediction for LHC energy: enhancement rather than suppression!

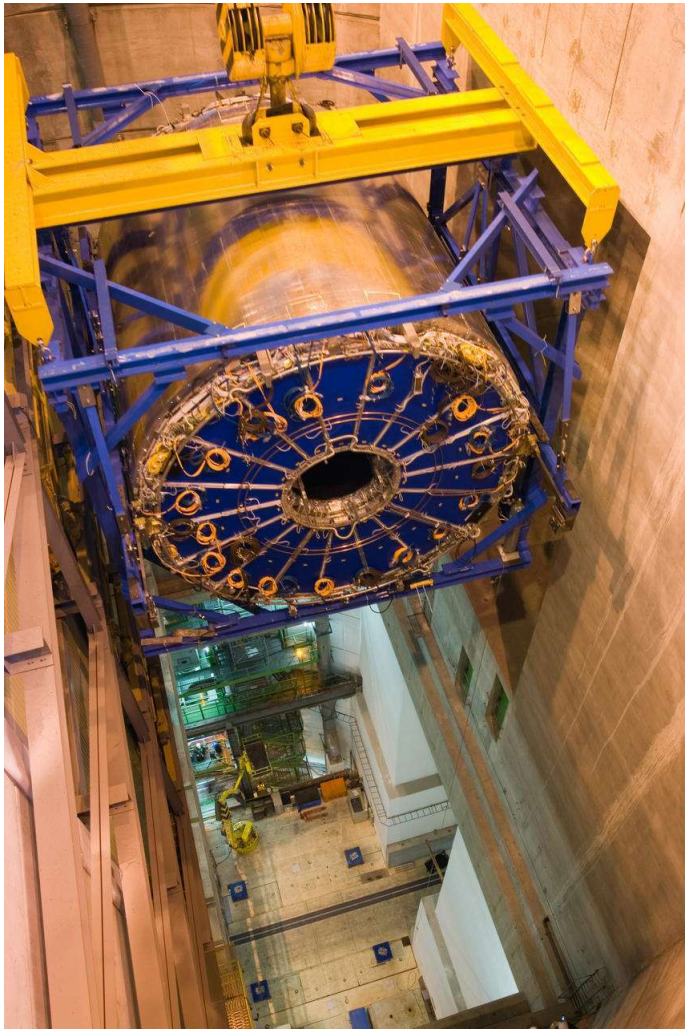


ALICE@LHC

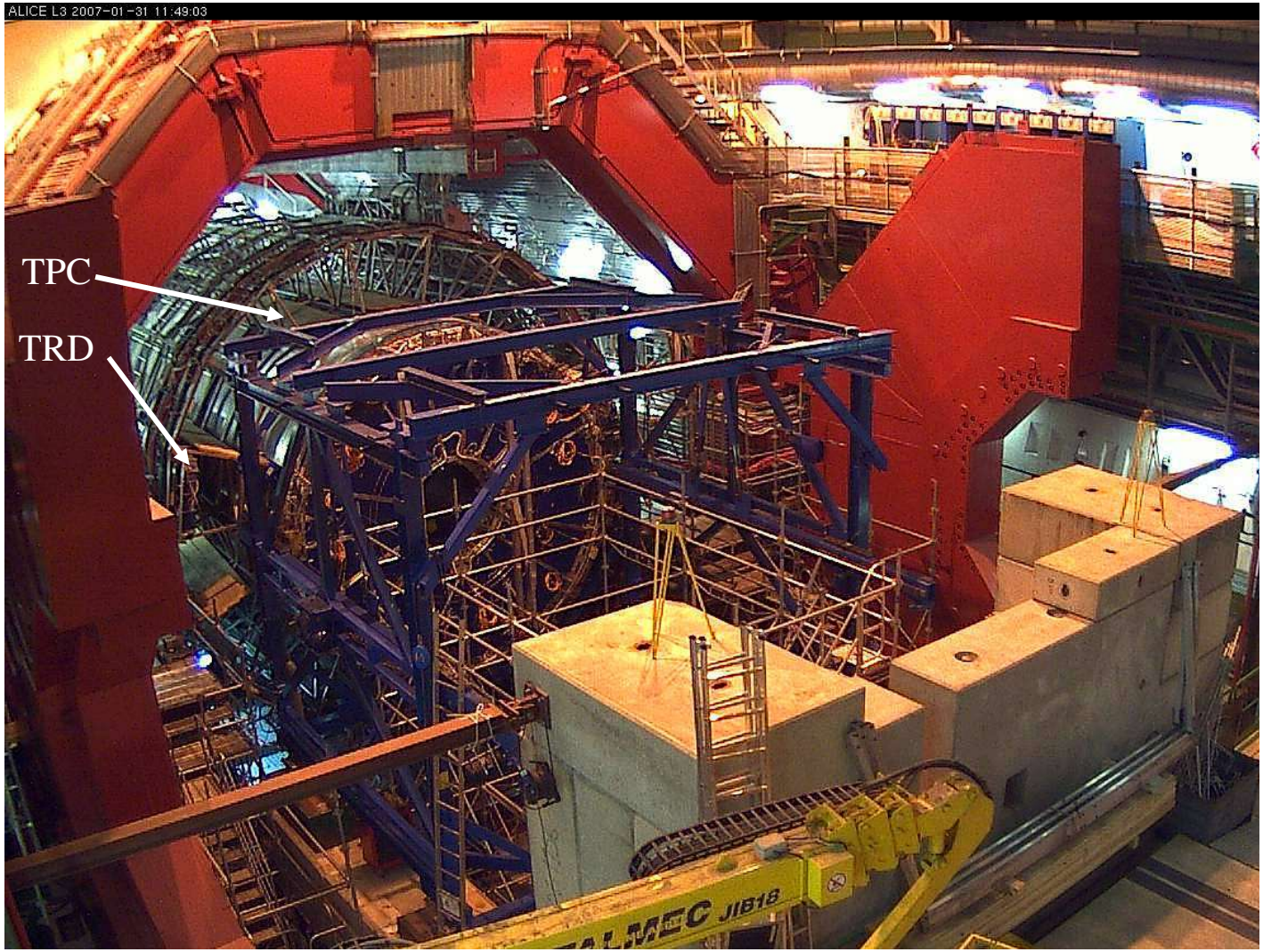
the ALICE TPC has been installed in the experiment,

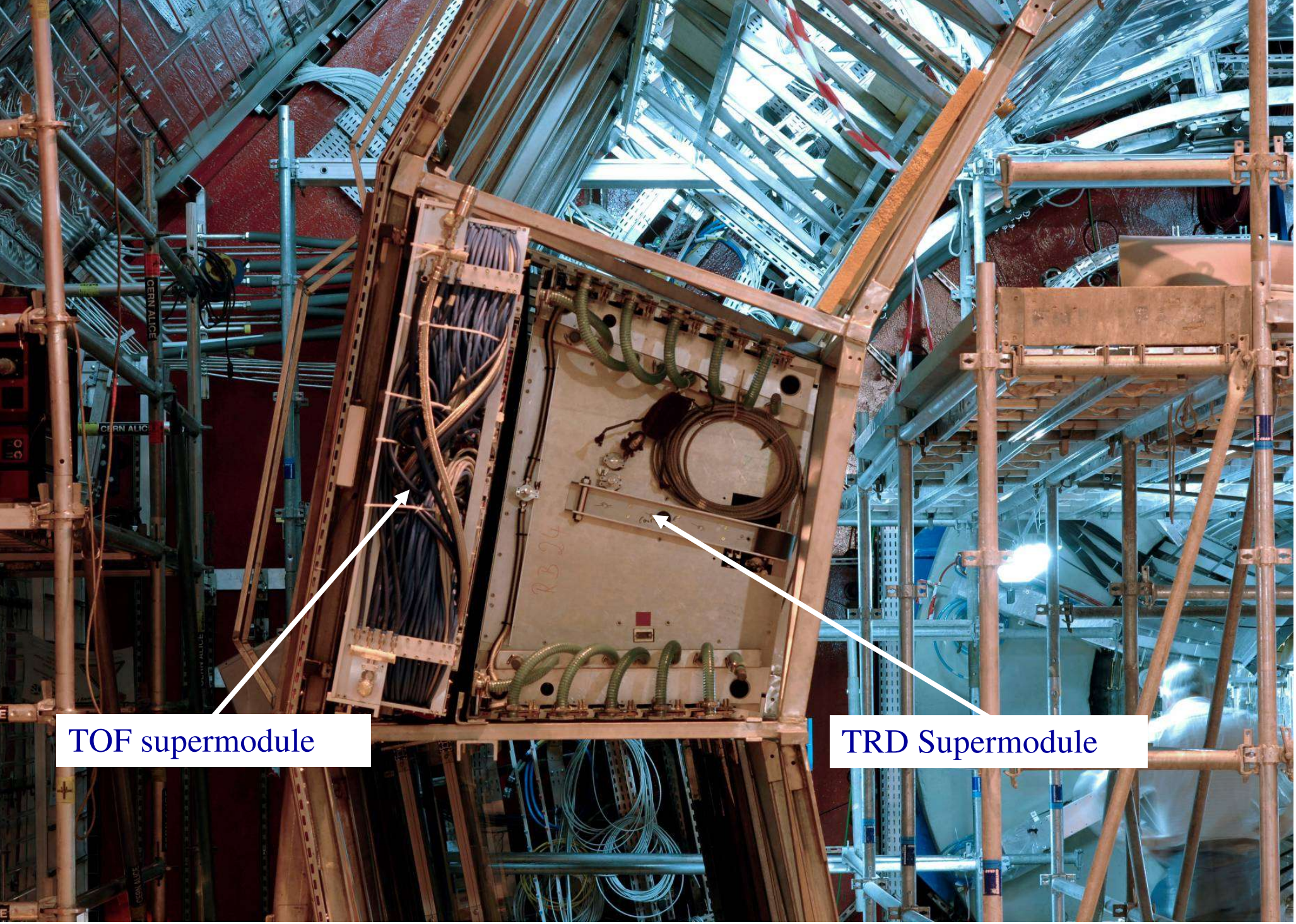
TPC::Transport

transport of TPC on from assembly hall to underground location

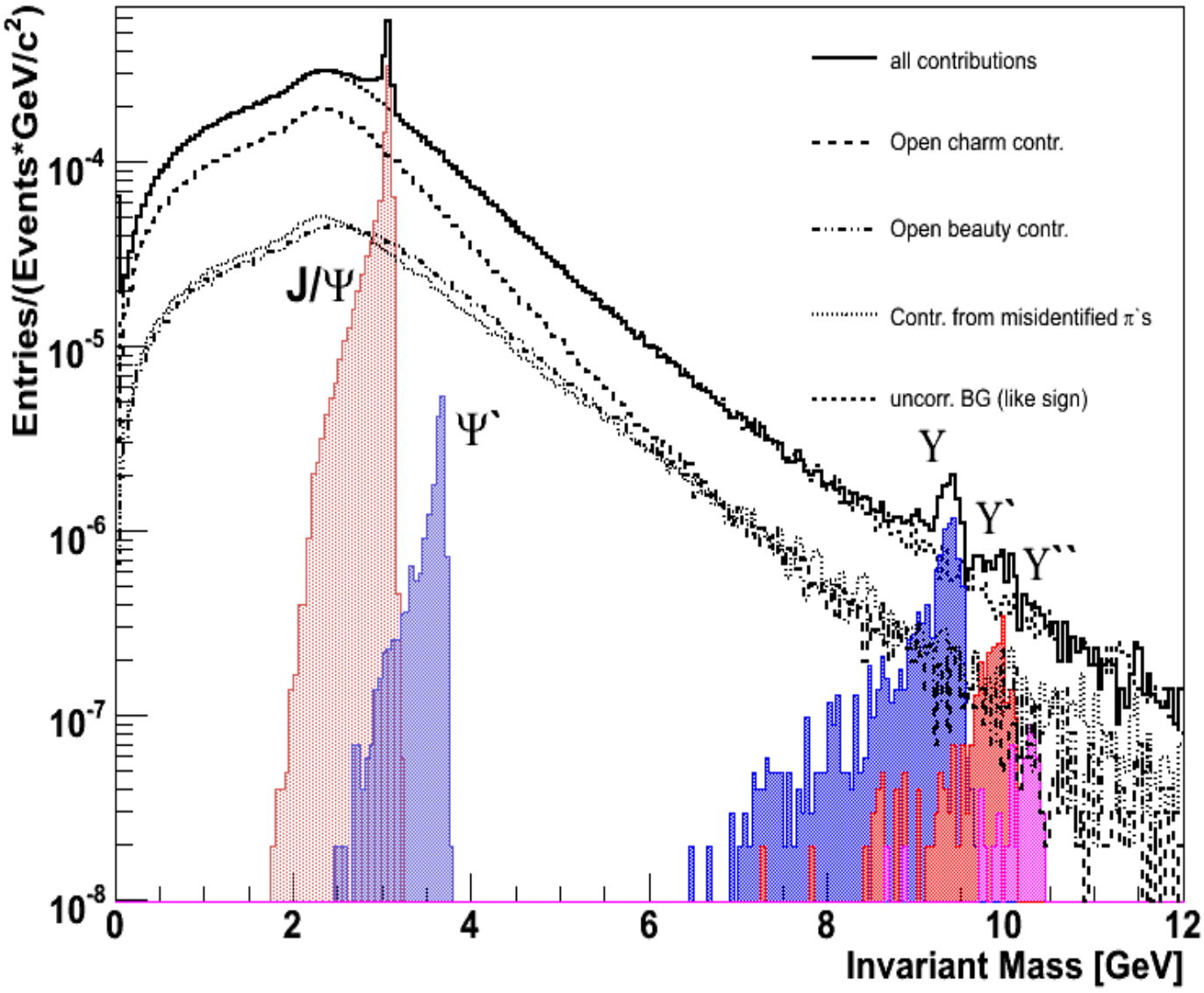


TPC::Parking Position

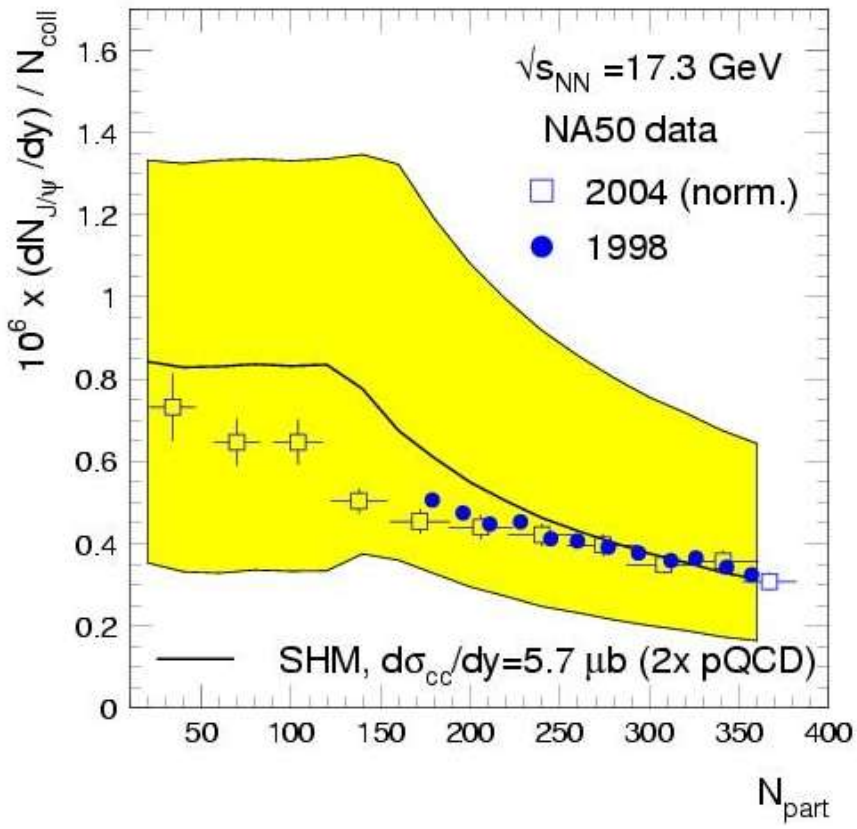


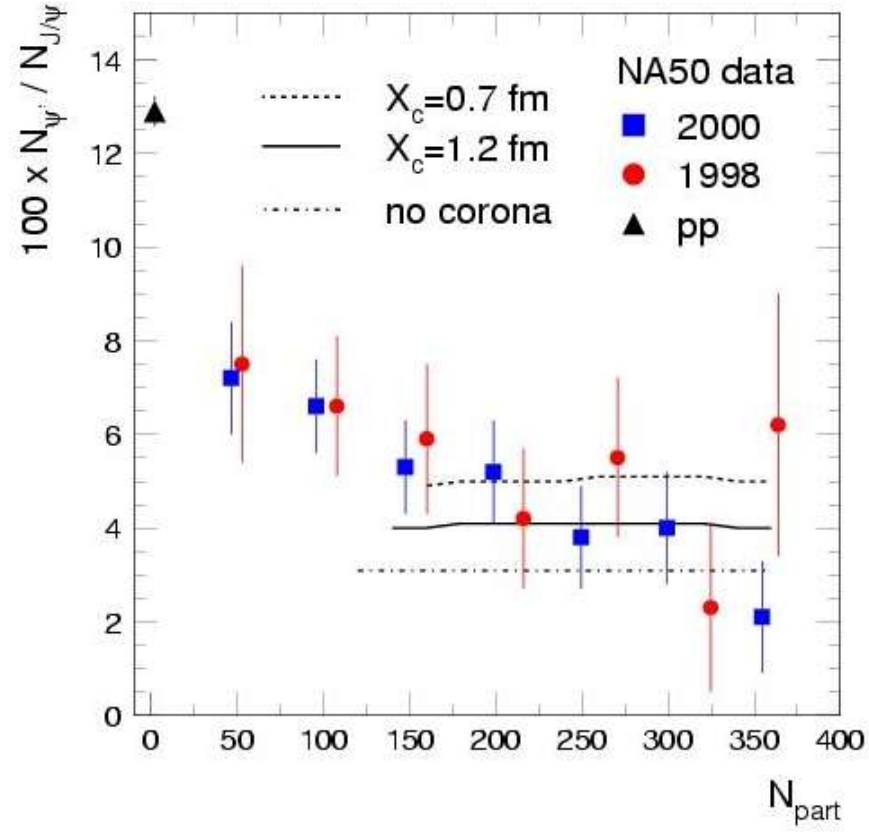

TOF supermodule
TRD Supermodule

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



back to SPS energy

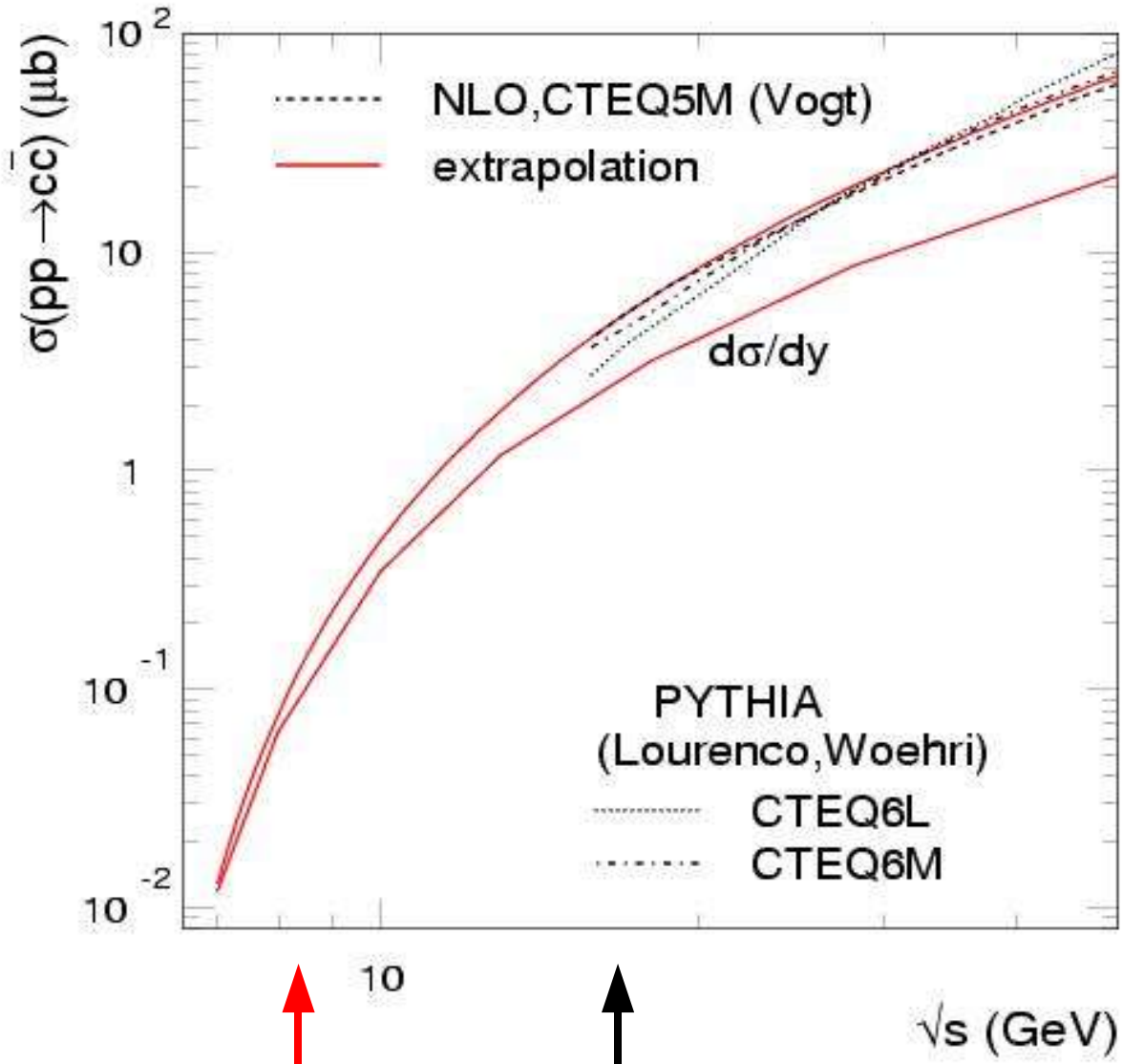




only moderately enhanced (2 x pQCD) cc_bar cross section needed

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

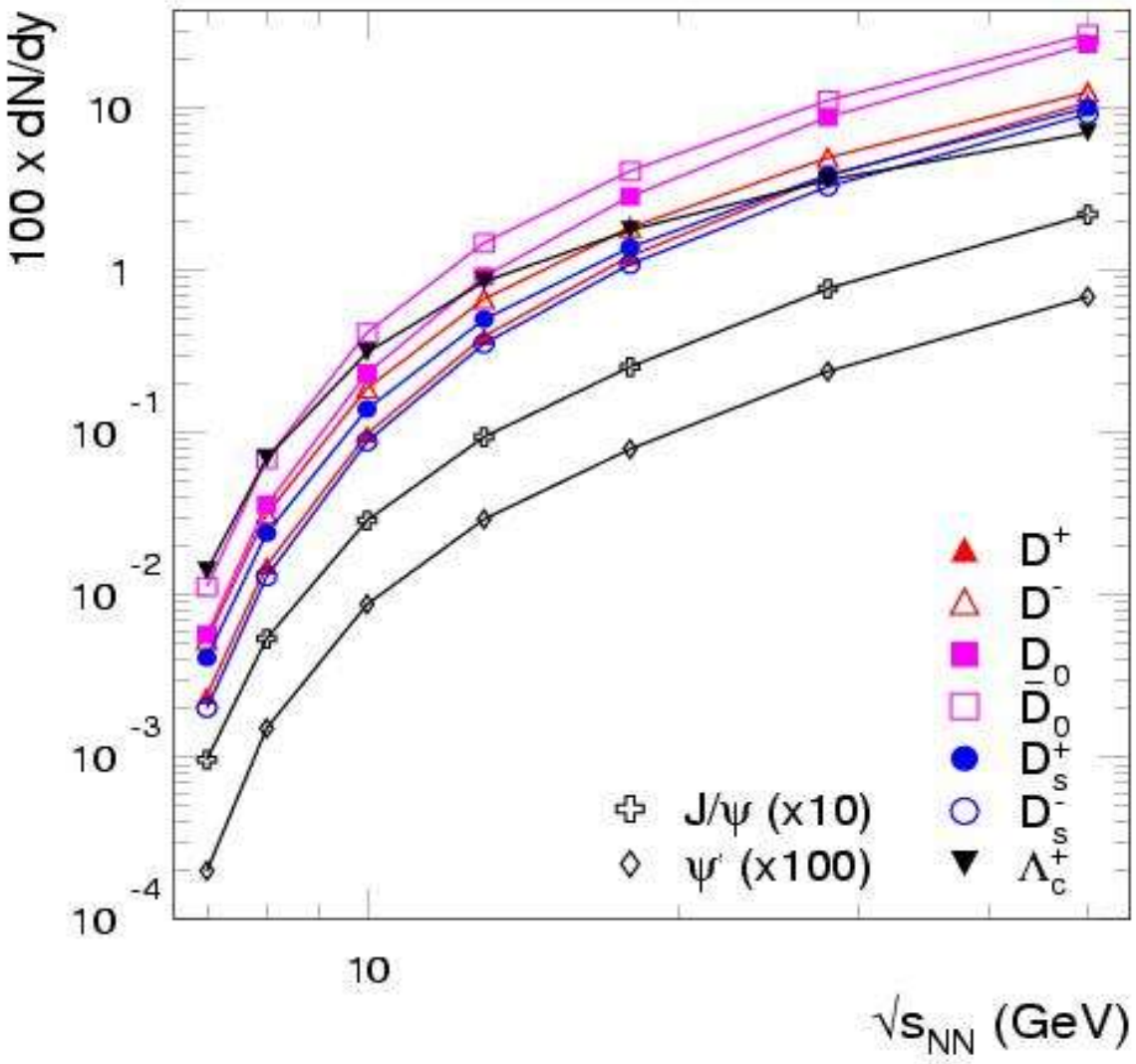
SPS full energy

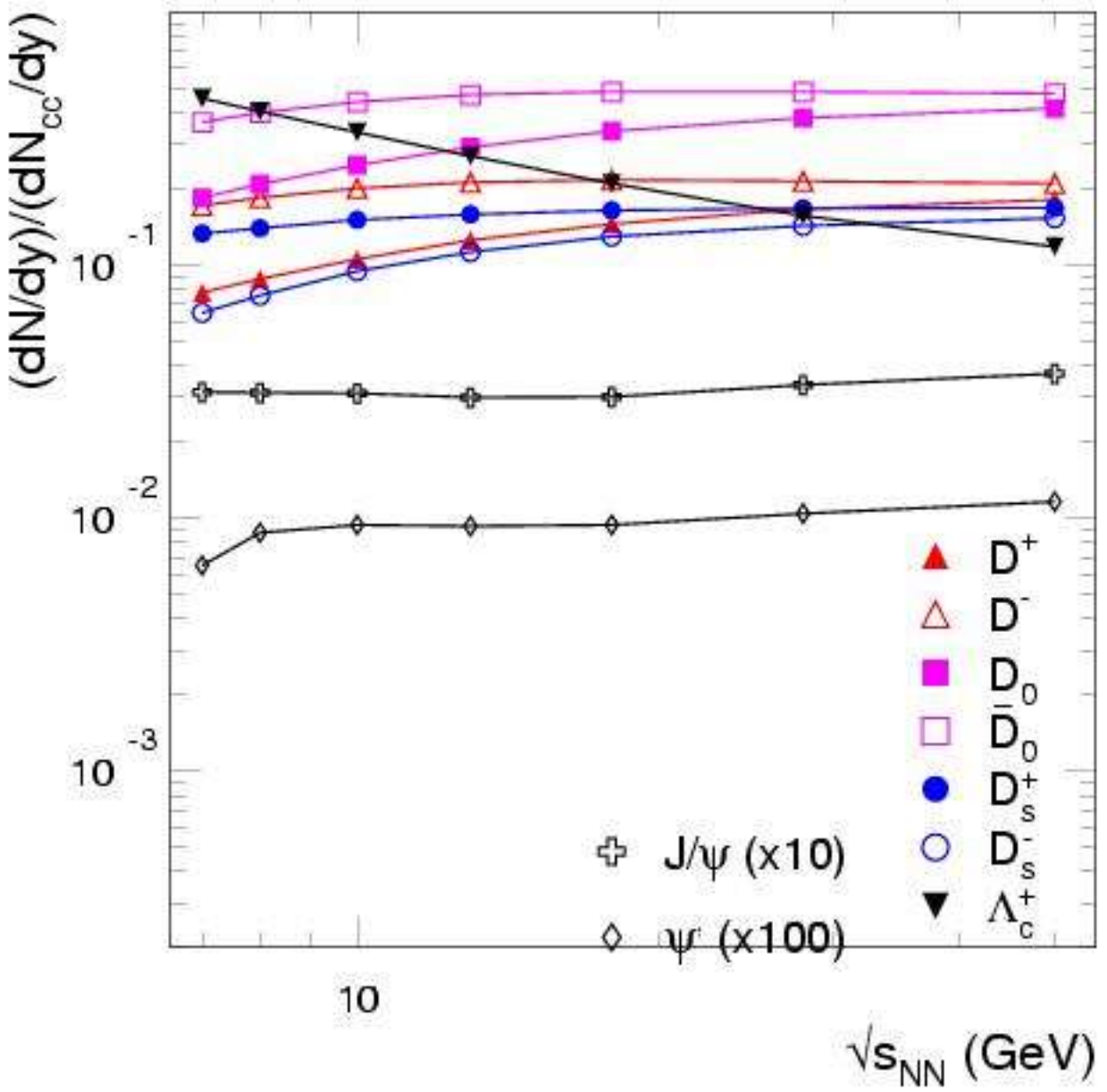
charm threshold in NN: 5.1 GeV

absolute threshold in Pb-Pb collisions:

$T_{lab}/A = 31$ MeV

Statistical hadronization predictions for open and hidden charm at low energies




(dN/dy)/(dN_cc/dy)
10^-1
10^-2
10^-3
10
√s_NN (GeV)
D+
D-
D0
D̄0
Ds+
Ds-
Λc+
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

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

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

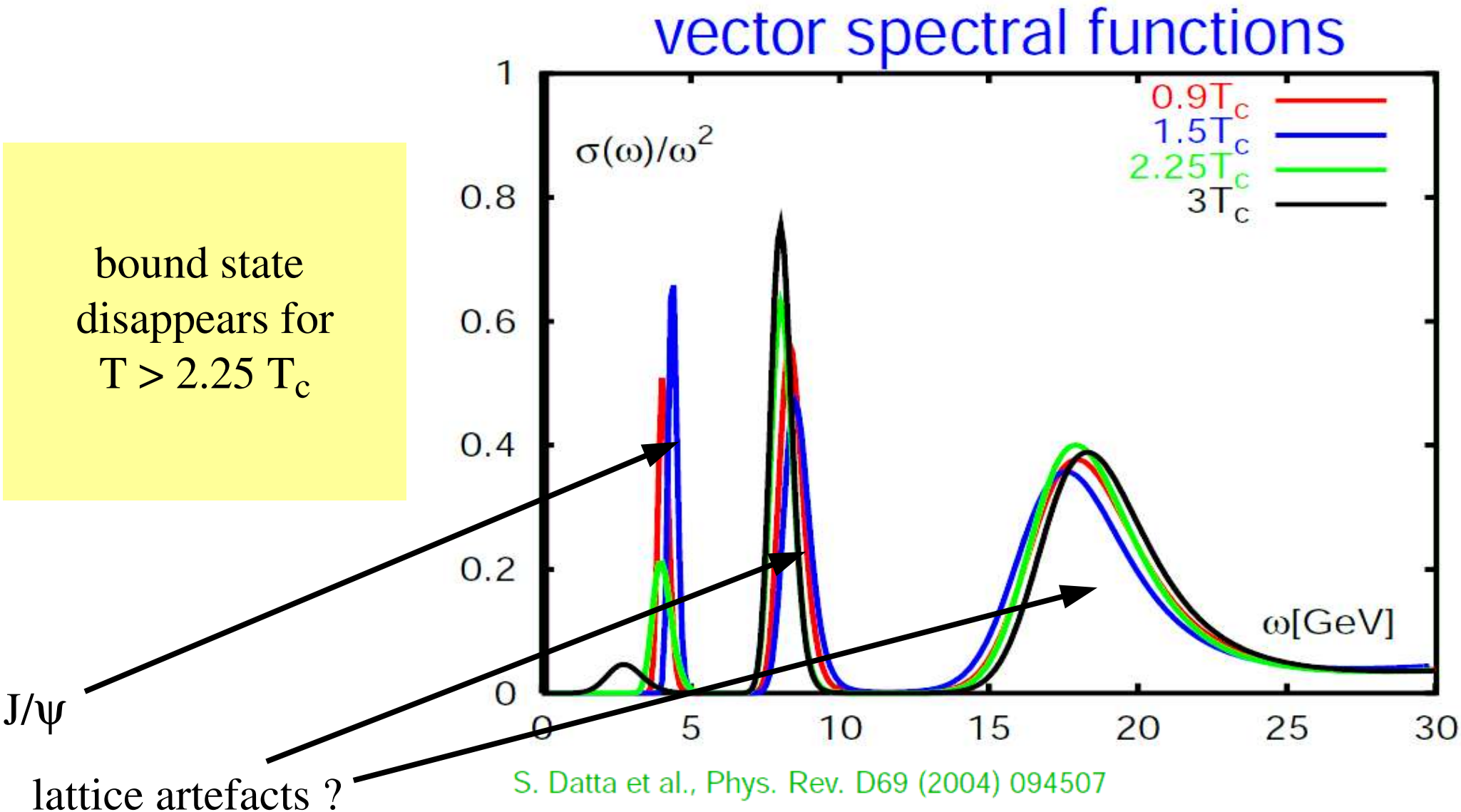
state	J/ψ	χ_c	ψ'
E_s^i [GeV]	0.64	0.20	0.05
T_d/T_c	1.1	0.74	0.1 - 0.2
T_d/T_c	~ 2.0	~ 1.1	~ 1.1

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

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 $\Rightarrow$ 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 $\alpha \simeq \pi/12$

$\Rightarrow$ quarkonium masses M_i and radii r_i