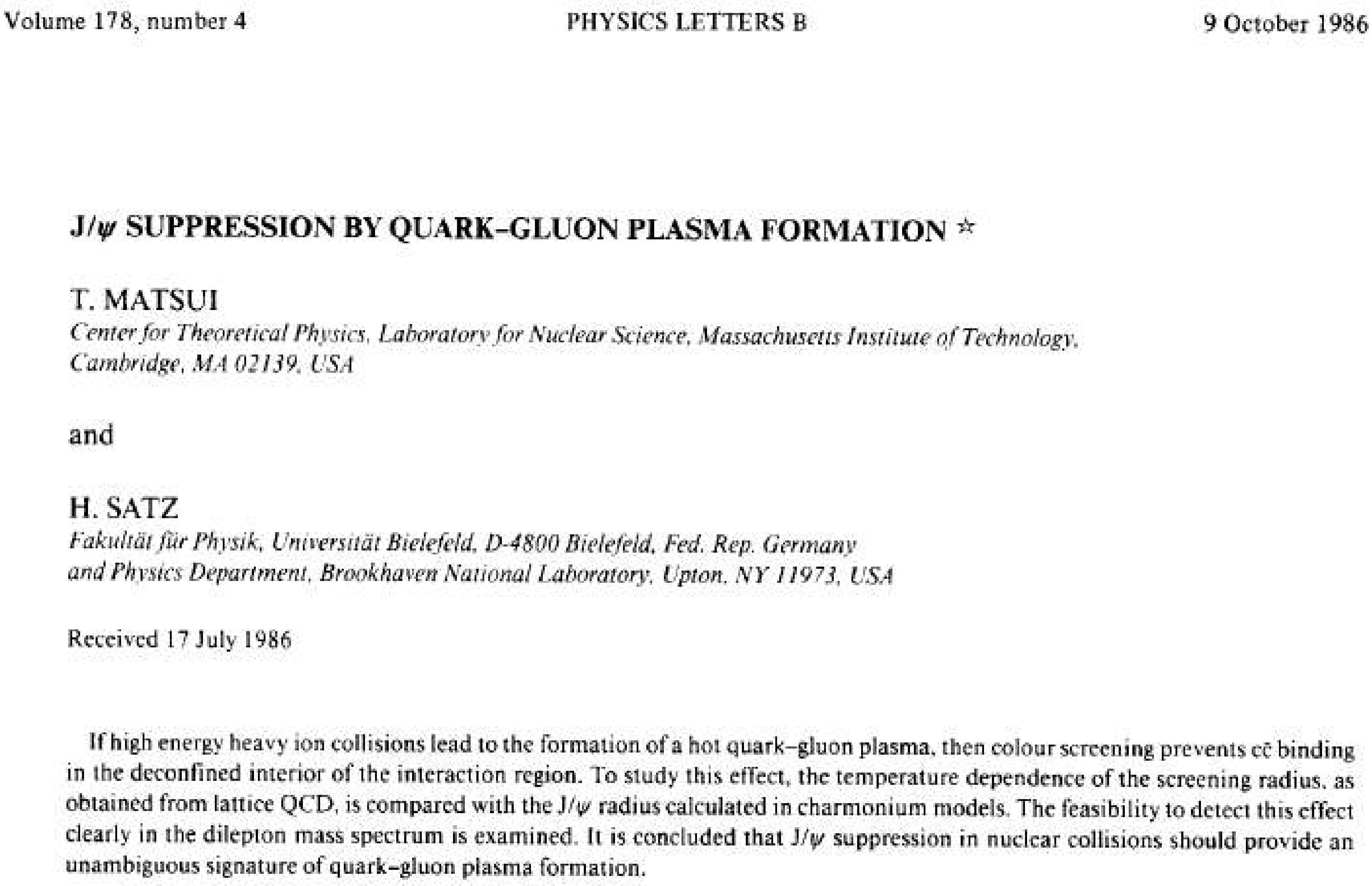
Quarkonium Production in Nuclear Collisions from FAIR to LHC

- Introduction
- quarkonium suppression
  - ingredients and assumptions
  - quarkonia in the QGP
  - confrontation with data

- quarkonium enhancement
  - ingredients and assumptions
  - annihilation of charm quarks in the plasma
  - confrontation with data
  - predictions for LHC
  - charmonium at FAIR
- outlook

Valparaiso, Chile, Dec. 2006



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J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

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Received 17 July 1986

If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

... It is concluded that J/ψ suppression in nuclear collisions should provide an **unambiguous** signature of quark-gluon plasma formation.

Charmonium suppression

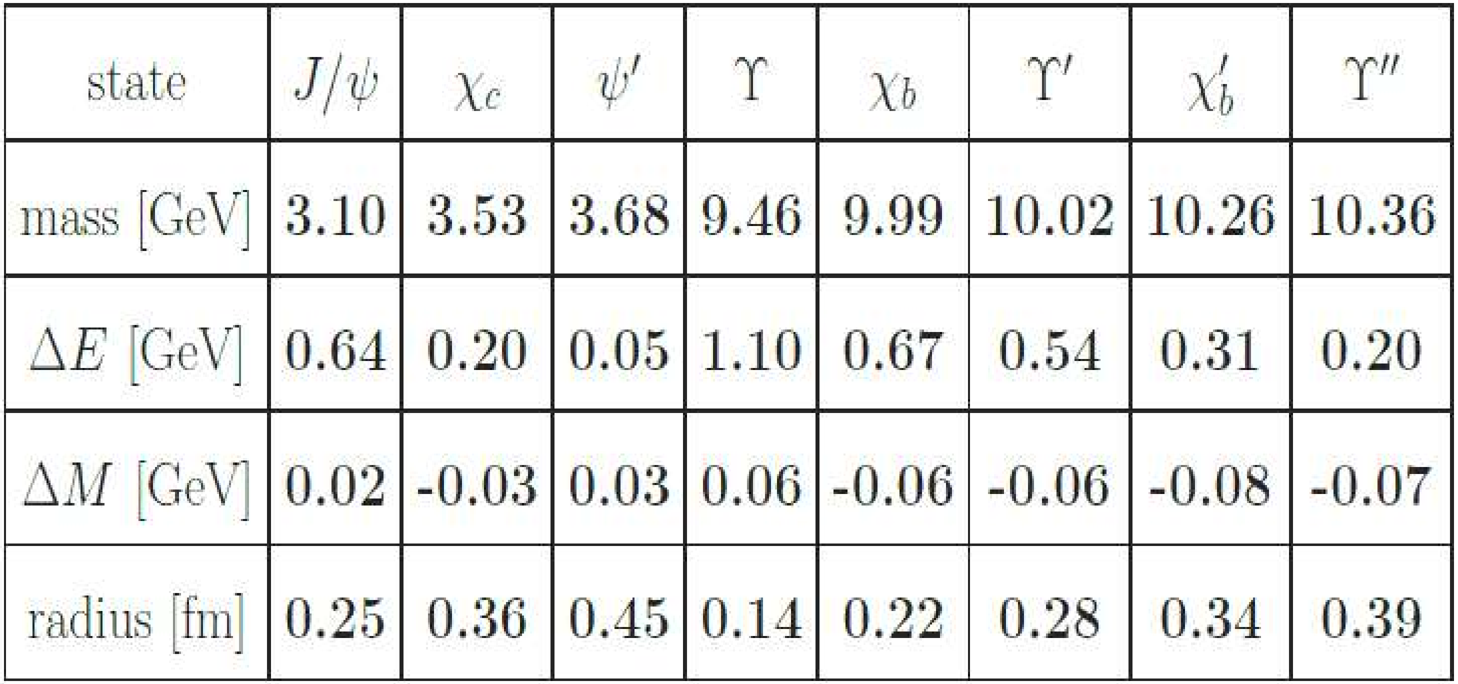
original proposal: H. Satz and T. Matsui, Phys. Lett. B178 (1986) 416

assumptions:

- charmonia are produced before QGP formation
- suppression takes place in QGP (Debye screening at high temperature)
- some charmonia might survive beyond T_c

→ sequential suppression pattern due to feeding

Properties of quarkonia



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

from: H. Satz, hep-ph/0609197

all properties well understood in potential models

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

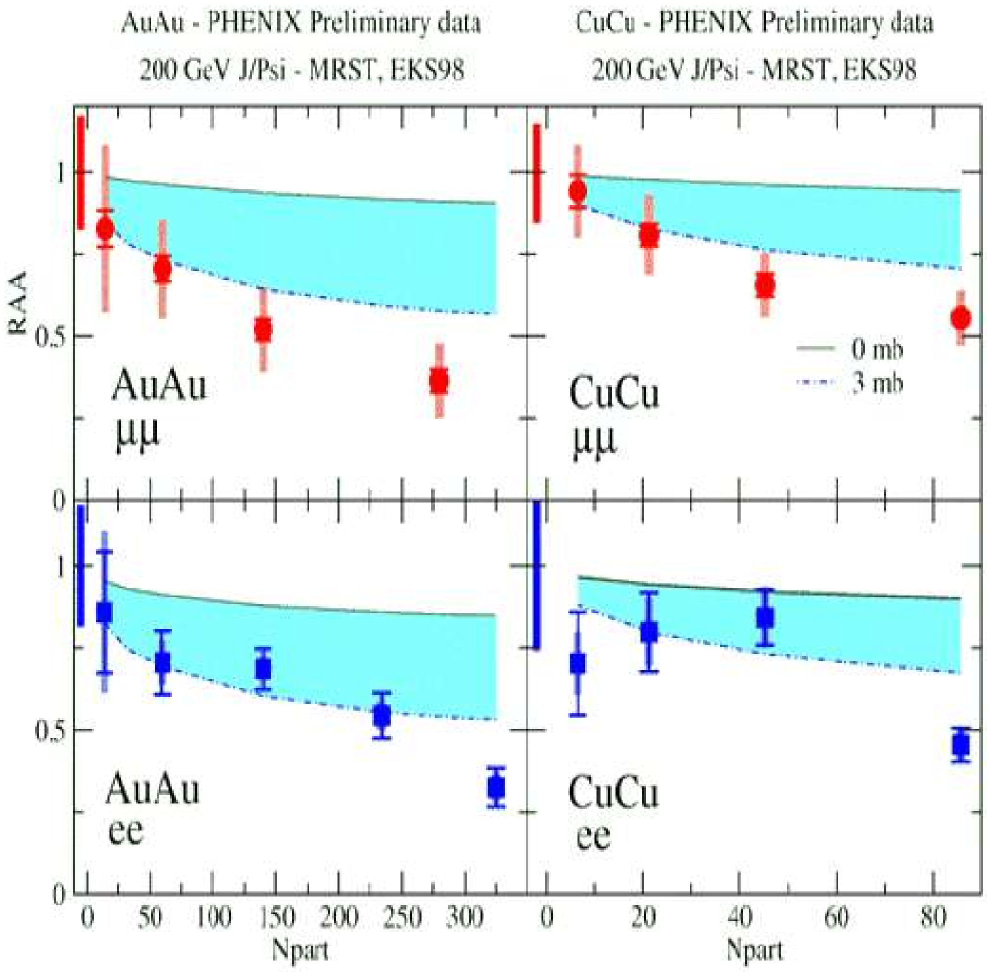
formation time is not short compared to plasma formation time
especially at high energy

charmonium suppression at RHIC -first data

surprize:
data nearly compatible
with normal nuclear
suppression
(blue shaded area)

suppression models
describing SPS data fail

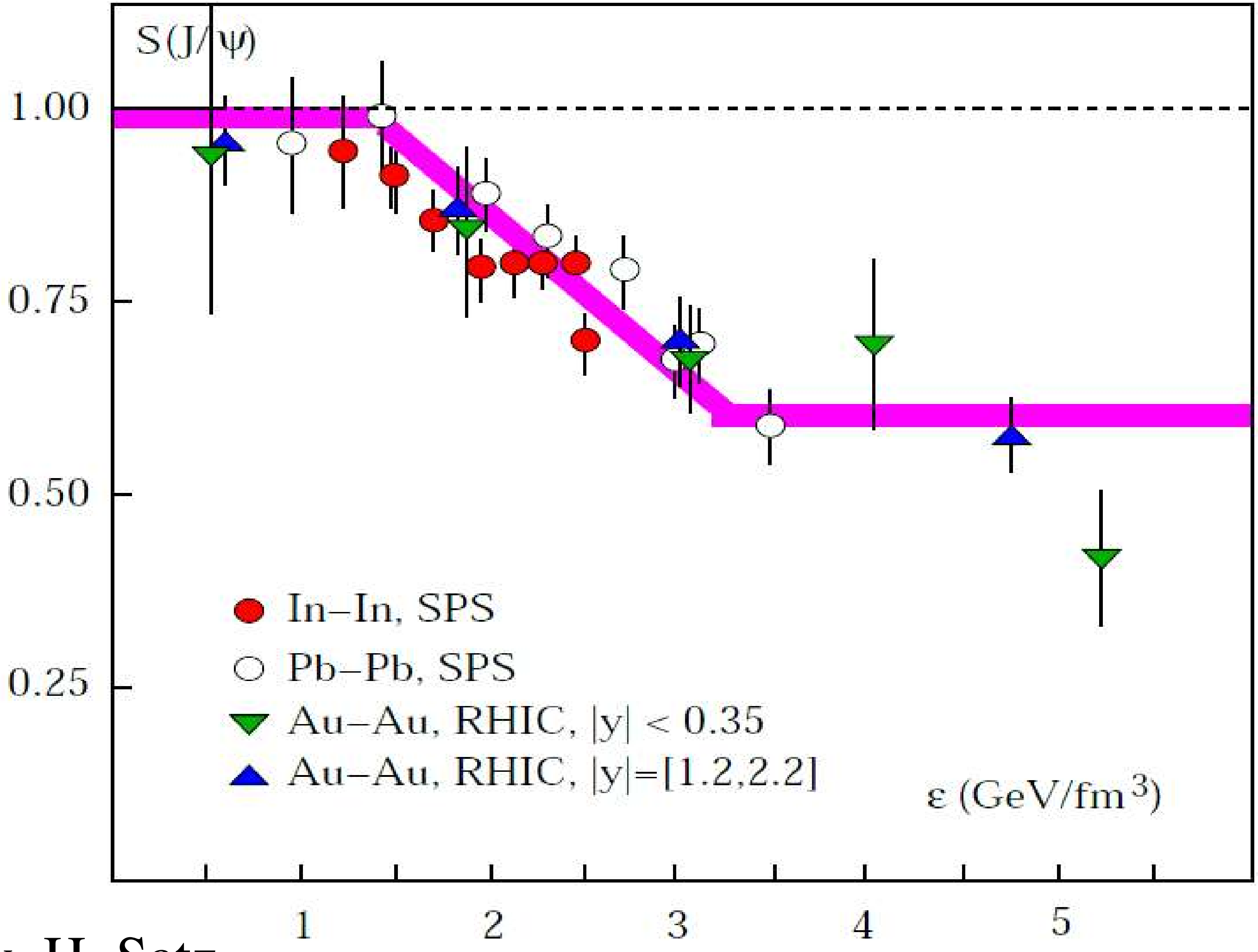
possible way out:
J/ψ may survive
in plasma until near
2 T_c



Suppression pattern --- SPS and RHIC data prior to QM2006

assumption:
suppression is
only due to χ_c
and ψ'

but J/ψ width is
large!

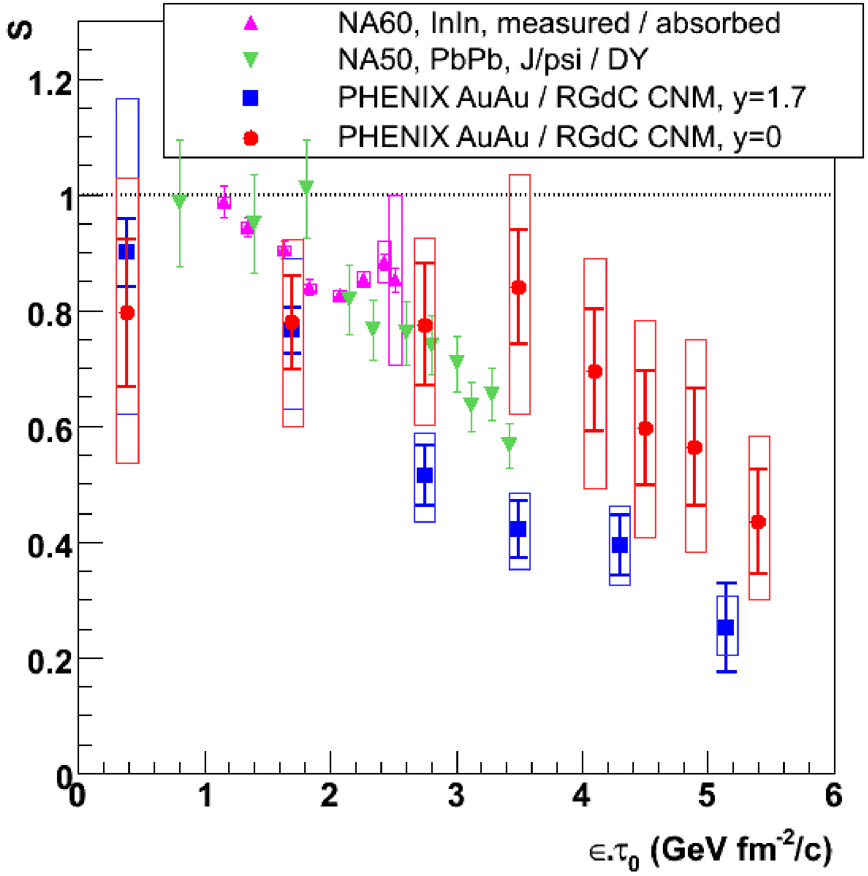


F. Karsch, D. Kharzeev, H. Satz,
Phys. Lett. B637 (2006) 75

Suppression pattern --- SPS and RHIC data including newest PHENIX data

no universal pattern visible any more
suppression too large and with the wrong rapidity dependence to fit into „sequential melting“ pattern

new PHENIX data:
A. Adare et al., nucl-ex/0611020



plot taken from R. Granier de Cassagnac

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 Y: smaller cross section compensated by higher temperatures

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

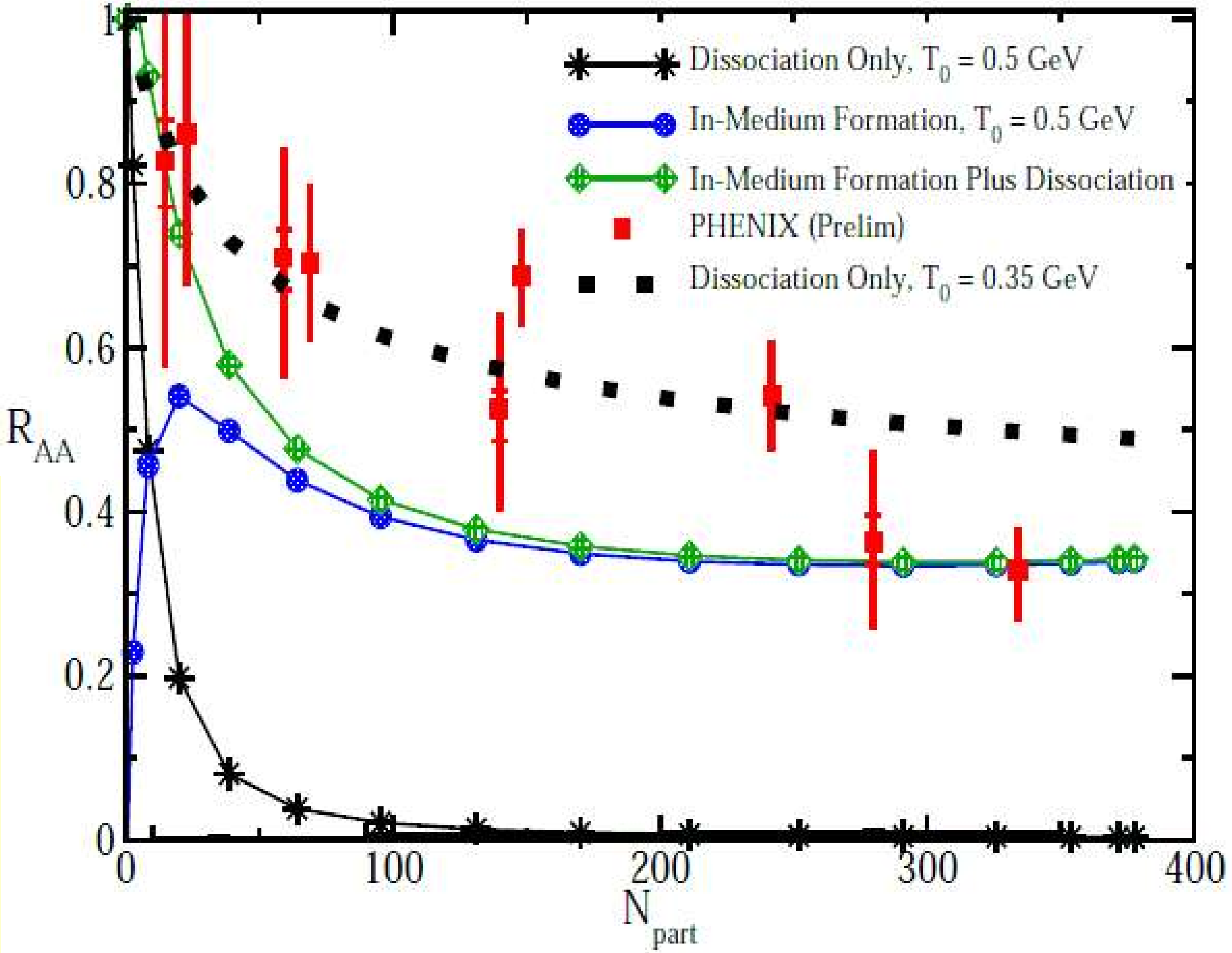
  original proposal: R.L. Thews, M. Schroedter, J. Rafelski, Phys. Rev. C63 (2001) 054905

  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

Results from quark coalescence

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

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

Method and inputs

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

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

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

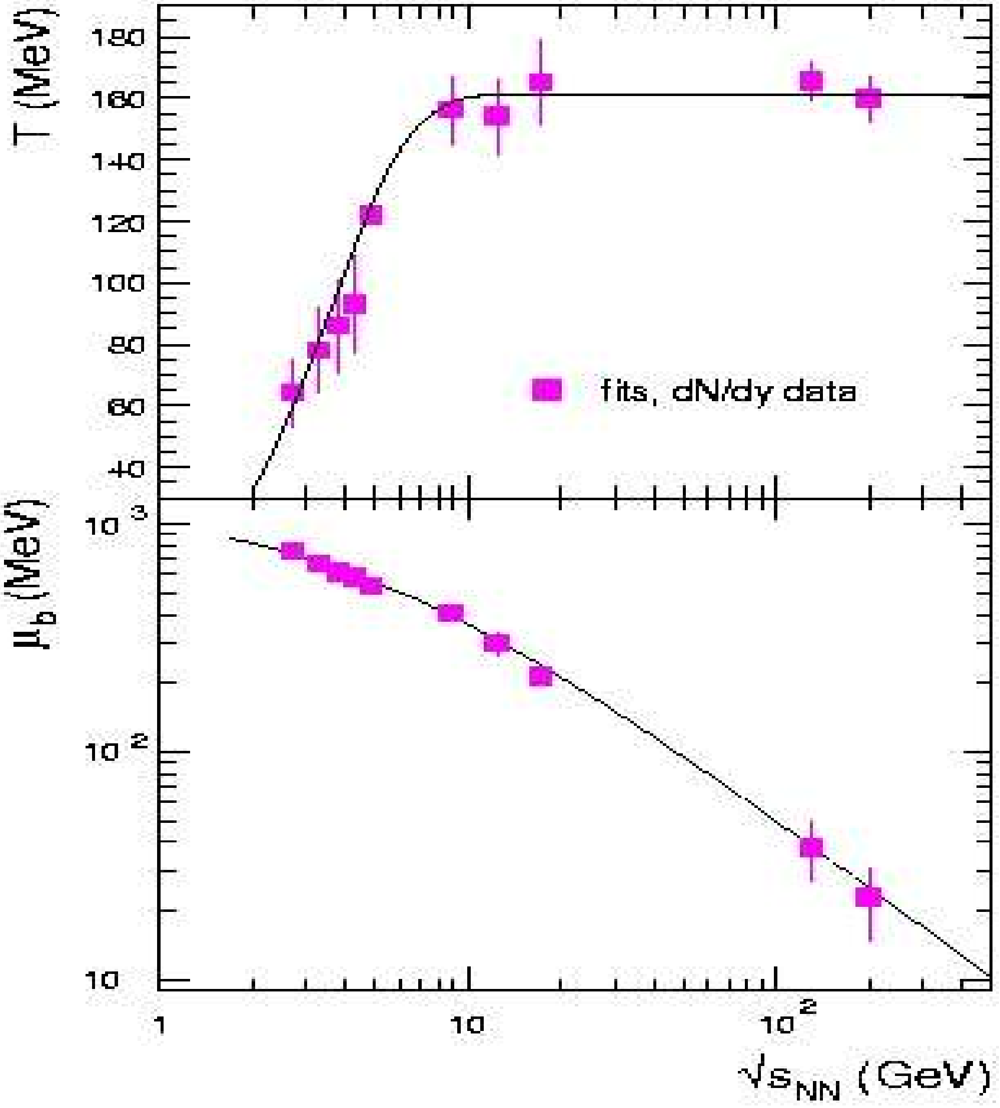
Inputs: T, μ_B, $V = N_{ch}^{exp} / n_{ch}^{th}$, $N_{c\bar{c}}^{dir}$ (pQCD)

Parameterization of all freeze-out points

note: establishment of limiting temperature

T_{lim} = 160 MeV = T_c

get T and μ_B for all energies



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

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:

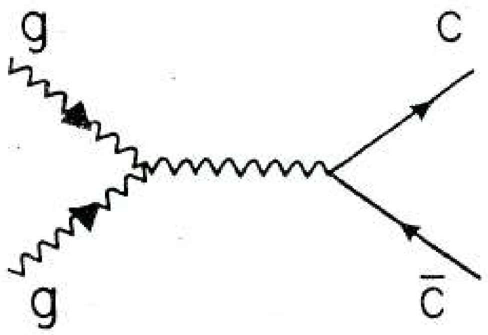
$$\frac{dr_{c\bar{c}}}{d\tau} = n_c n_{\bar{c}} \langle \sigma_{c\bar{c} \rightarrow gg} v_r \rangle$$

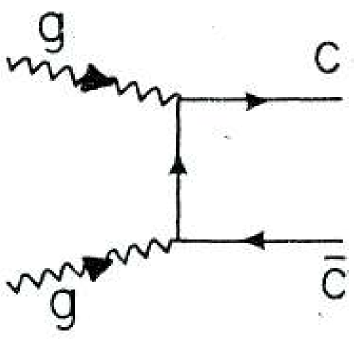
< > implies thermal average

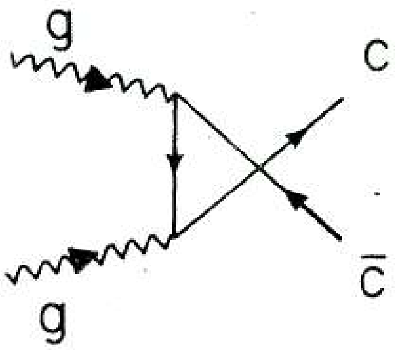
Cross section for ccbar annihilation

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

first compute inverse process:







then use detailed balance
(time reversal)

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

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

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:

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

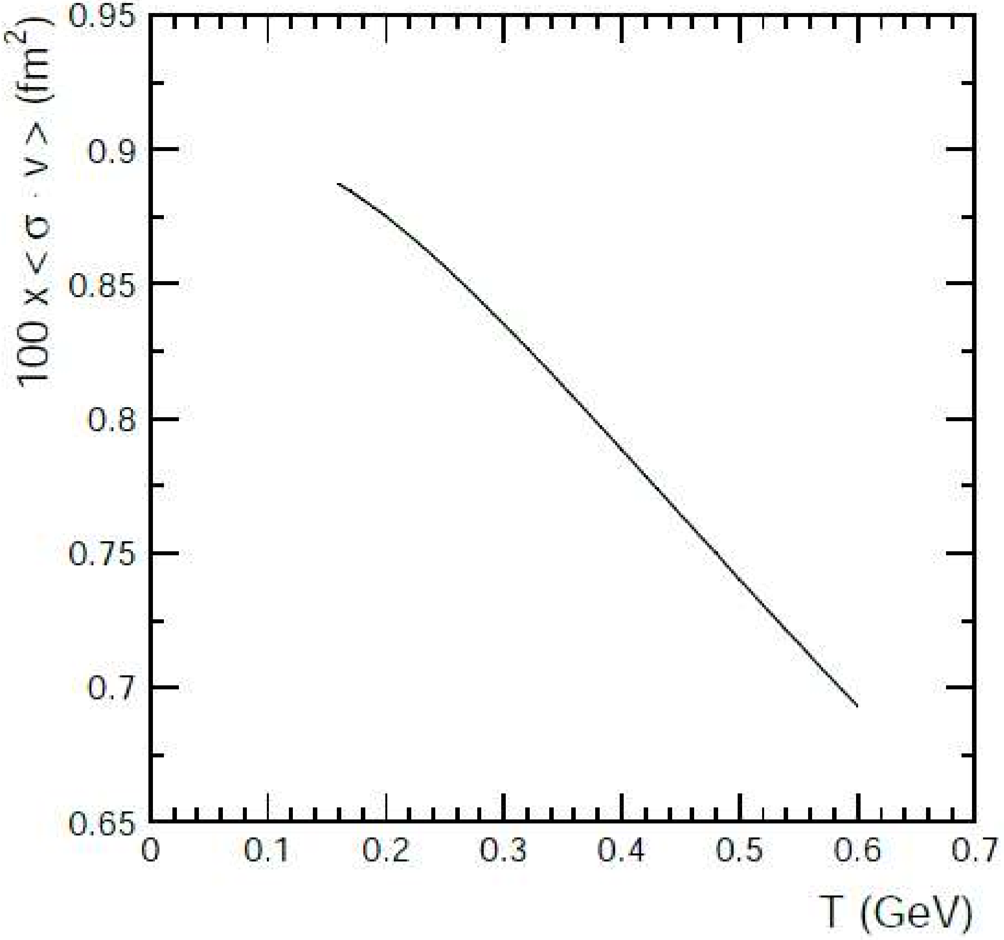
with $N_f = 2.2$ and $\tau_0 = 1$ fm, get 2 scenarios:

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

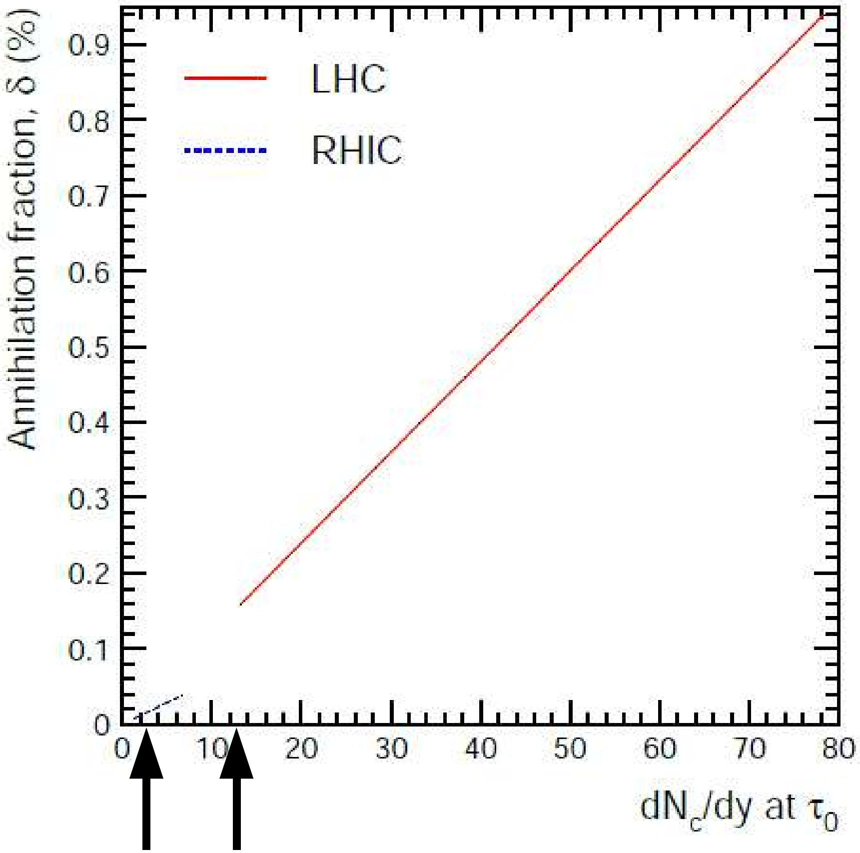


thermal average evaluated in Boltzmann approximation following Lin & Ko, PRC 62 (2000) 034903

cross section is of order 0.1 mb

annihilation fraction

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



RHIC LHC

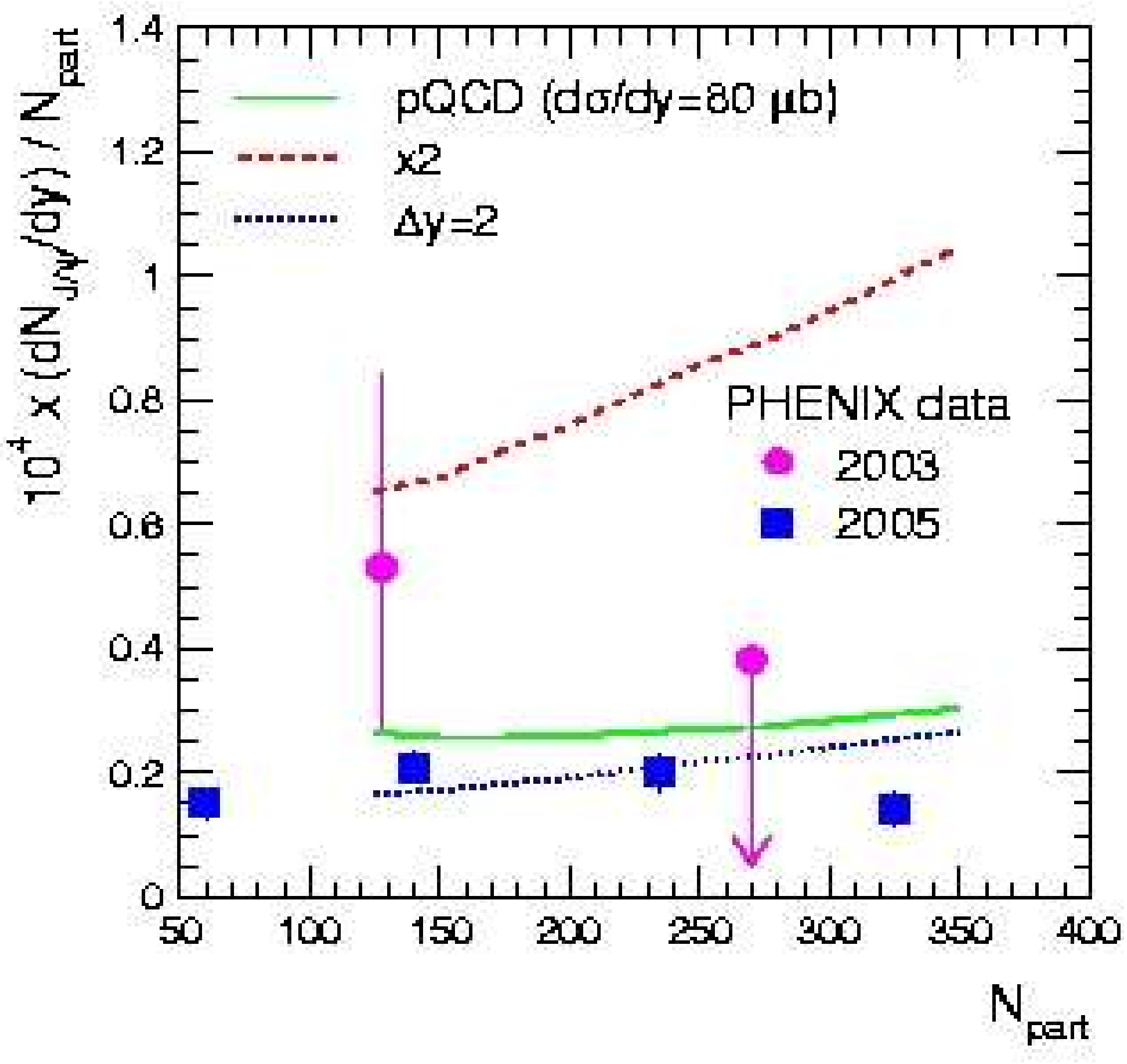
pQCD value

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 must be produced at the phase transition, i.e at hadronization

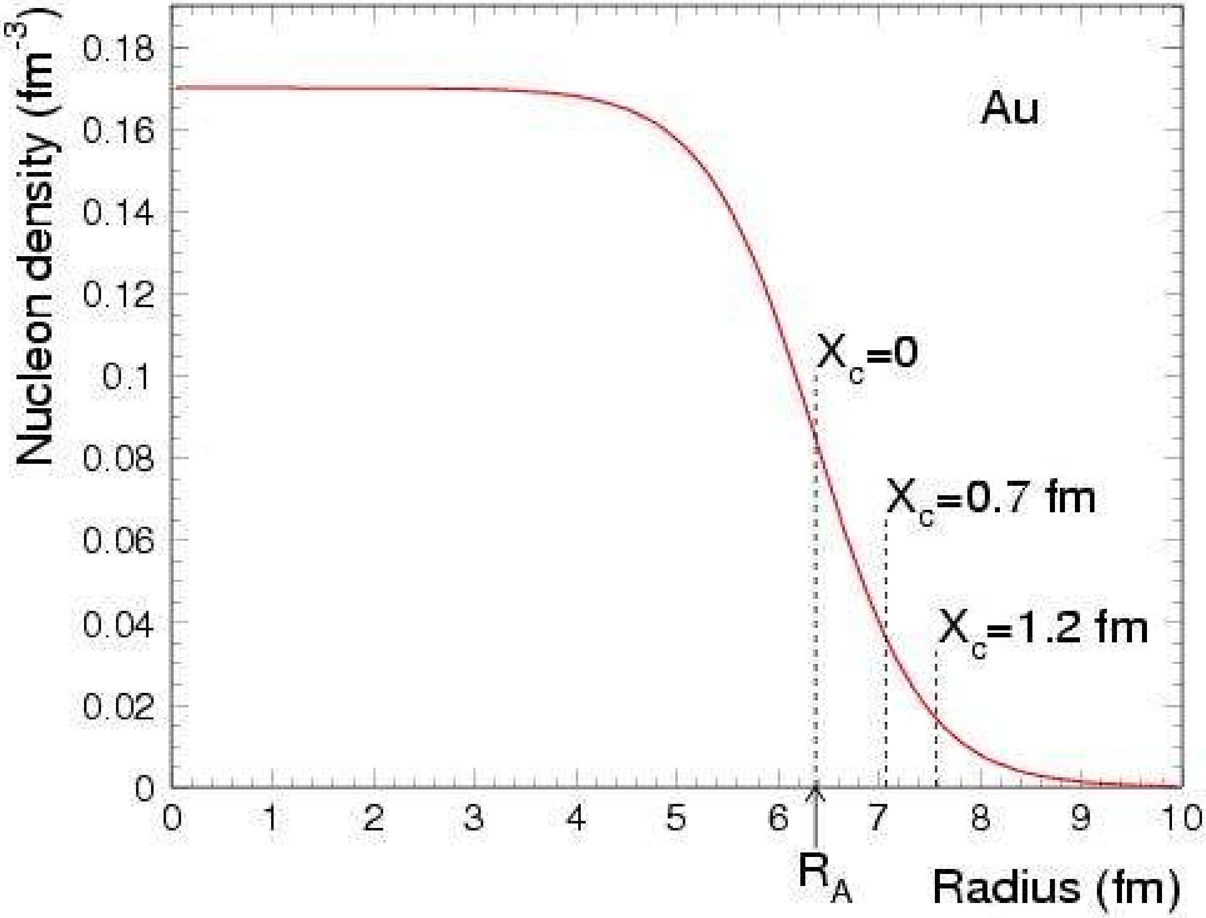
early model predictions for RHIC results

predictions for J/ψ production by Andronic, pbm, Redlich, Stachel, Phys. Lett. B571 (2003) 36
using NNLO pQCD results for open charm cross section



New results: take into account the corona effect

see also: Klaus Werner, hep-ph/0603064

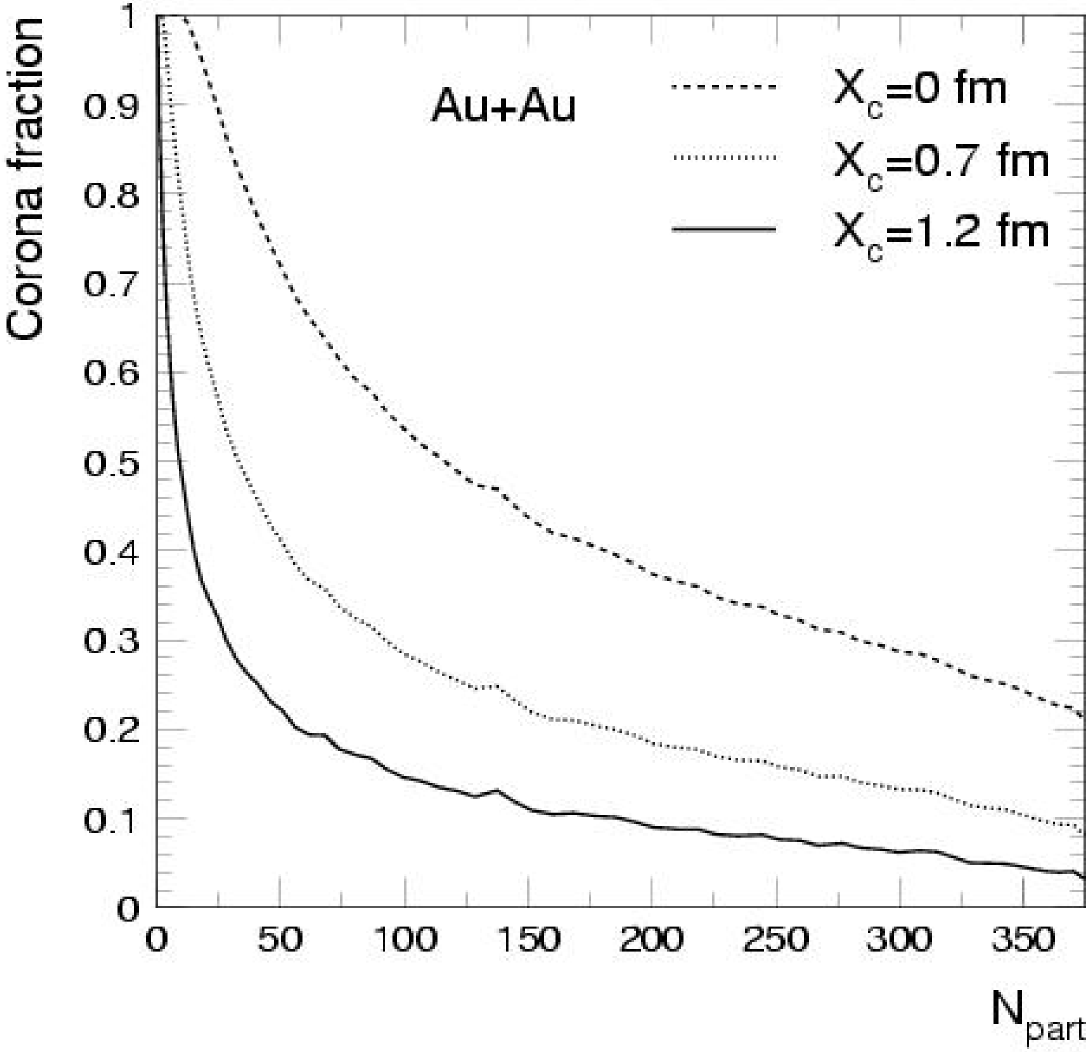


$N_{part}(b) = N_{core}(b) + N_{corona}(b)$

$X_c = 1.2$ fm chosen

$dN_{ch}/d\eta/N_{part}(b) = dN_{ch}/d\eta/N_{core}(b) + dN_{ch}^{pp}/d\eta/N_{corona}(b)$

Effect of corona



Ingredients for prediction of quarkonia cross section

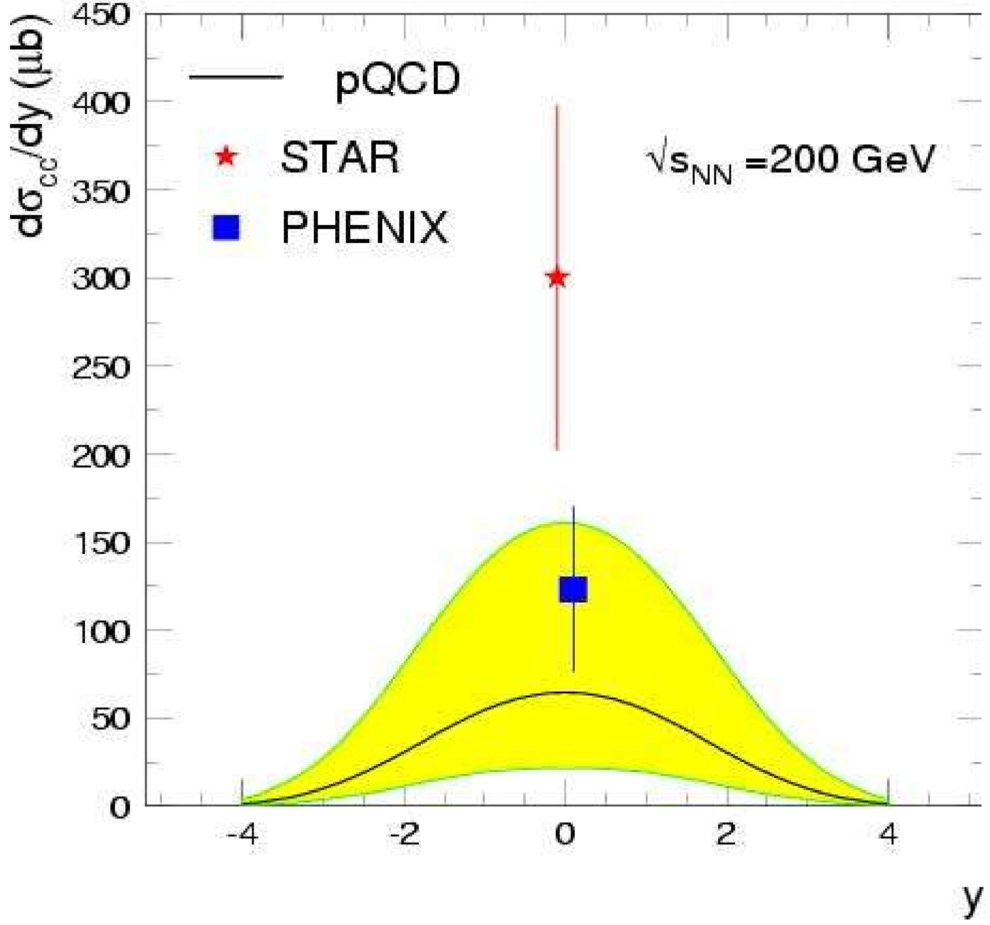
- open charm (open bottom) cross section

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

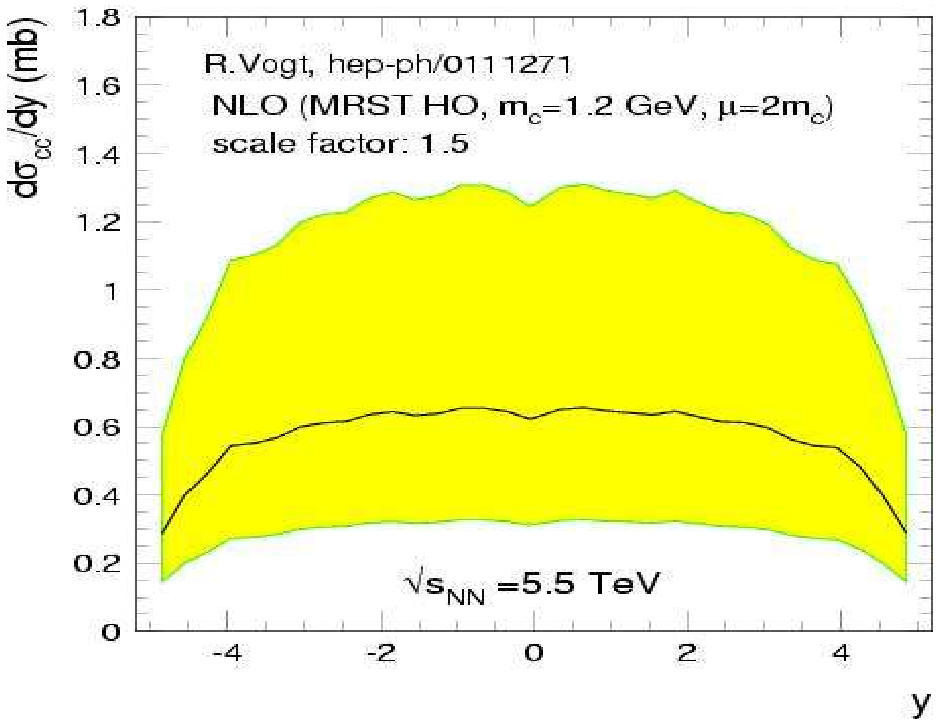
result: quarkonia cross sections as function of energy, centrality, rapidity, and transverse momentum

open charm data and comparison with pQCD

RHIC



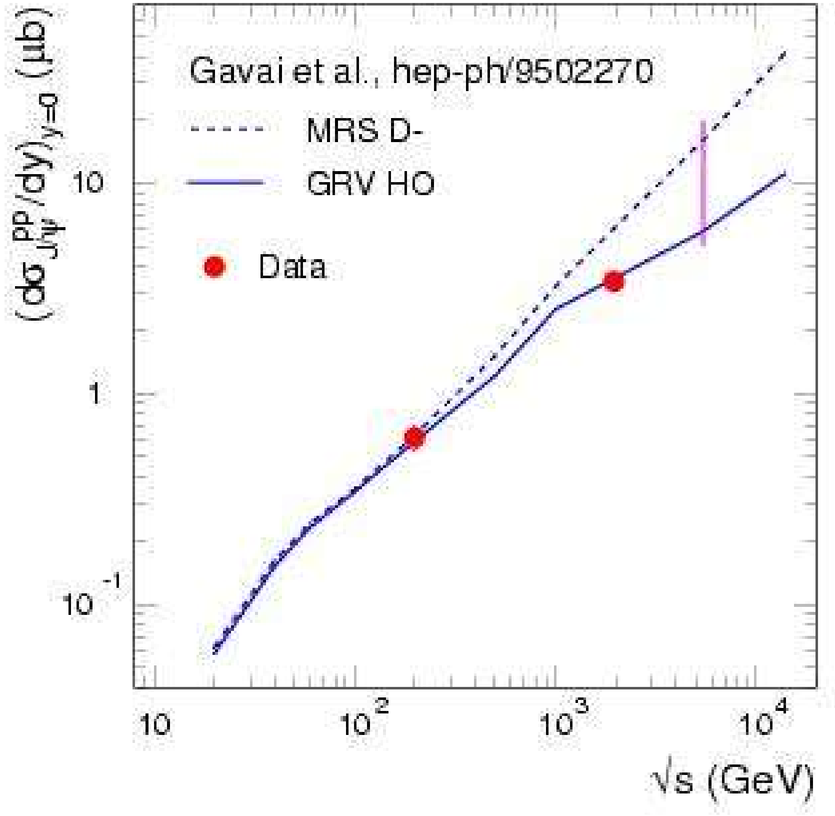
LHC



measured values somewhat (Phenix) larger than pQCD predictions

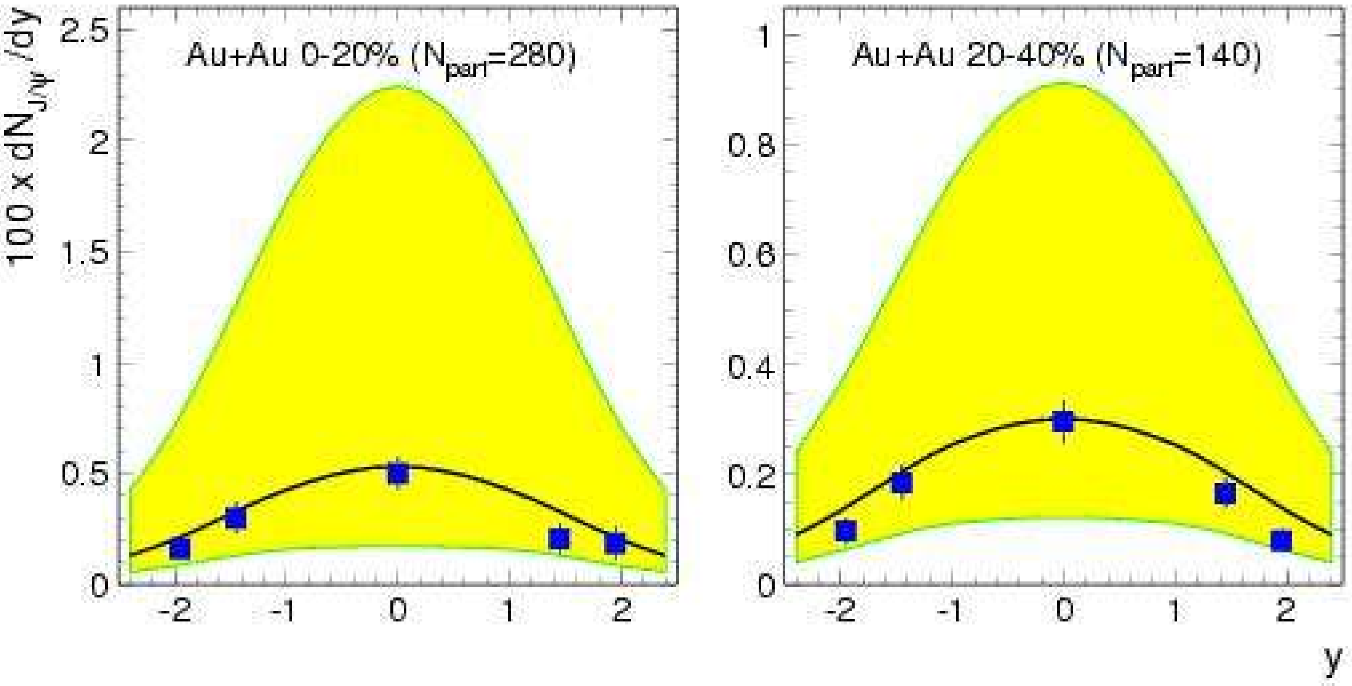
J/ψ cross section in pp collisions

GRV HO is used in the following



Comparison of model predictions to RHIC data: rapidity dependence

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



rapidity dependence is very well reproduced by statistical hadronization model

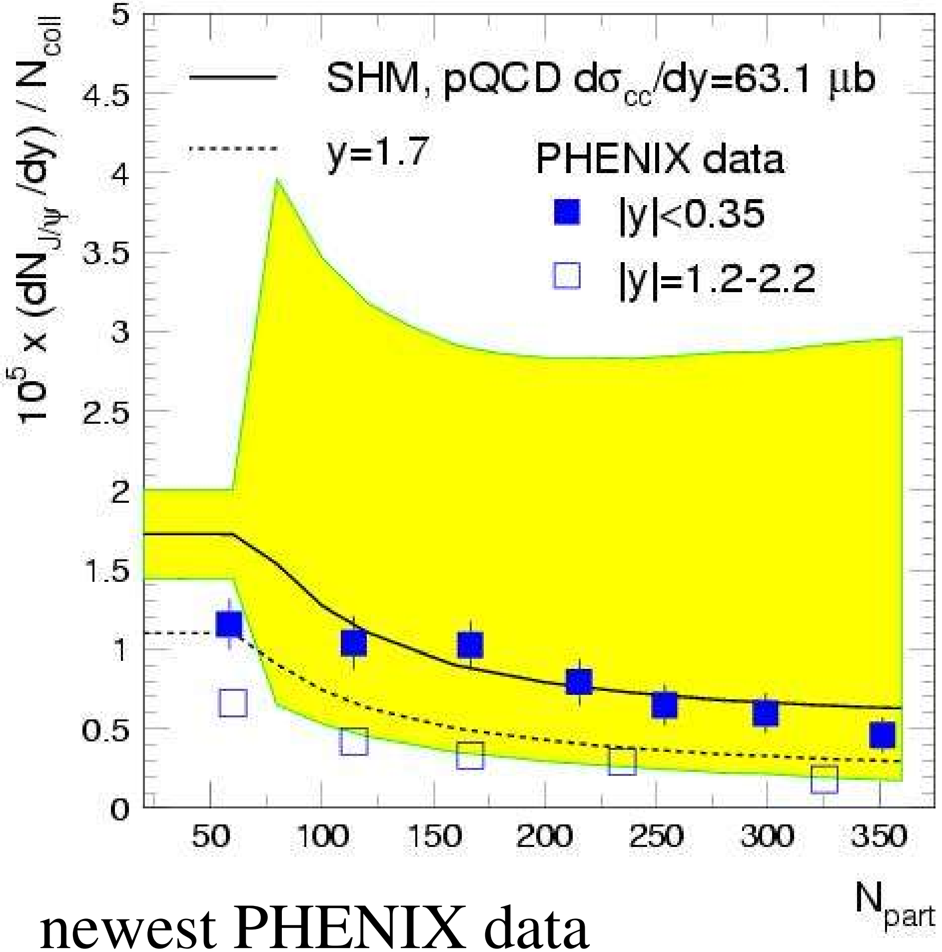
newest PHENIX data: nucl-ex/0611020

note: J/ψ production increase with increasing energy density!

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

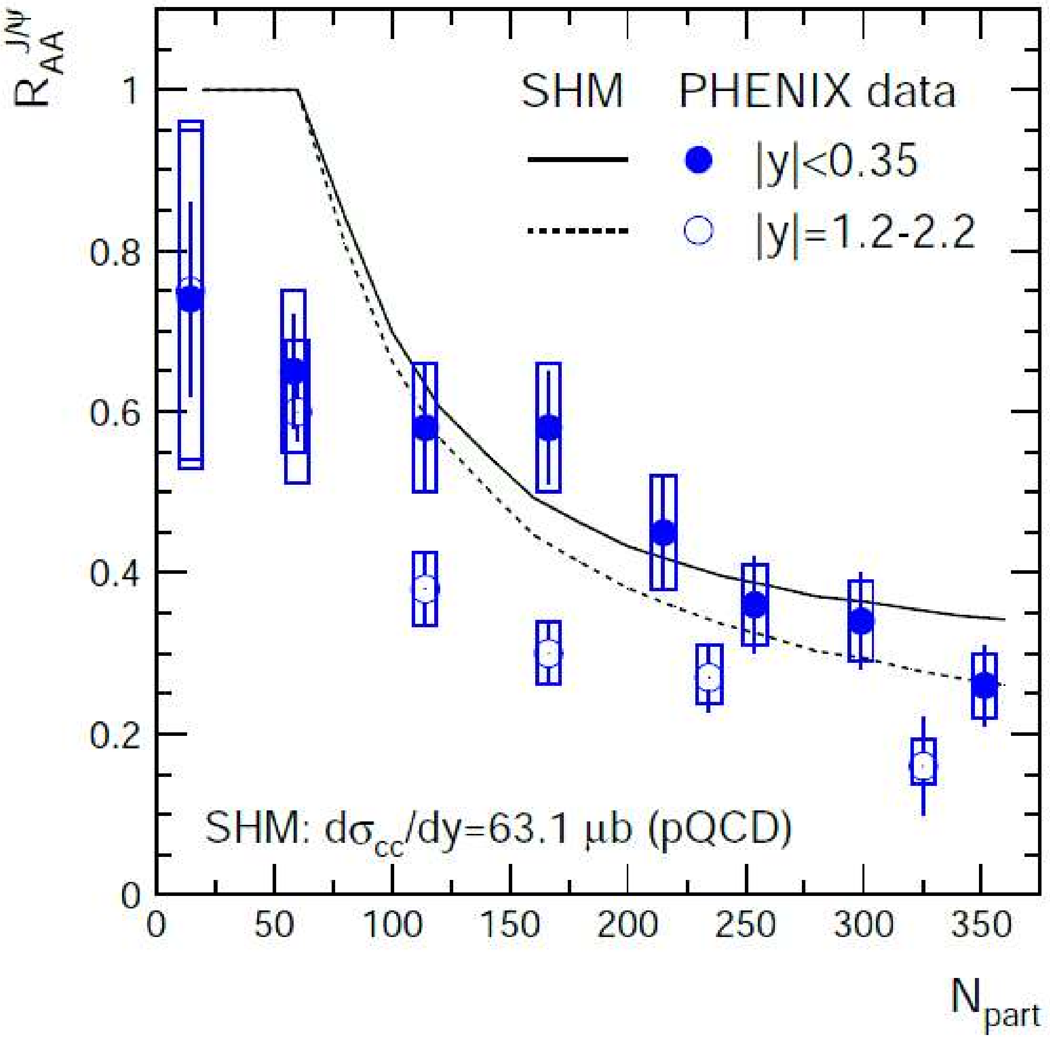


newest PHENIX data

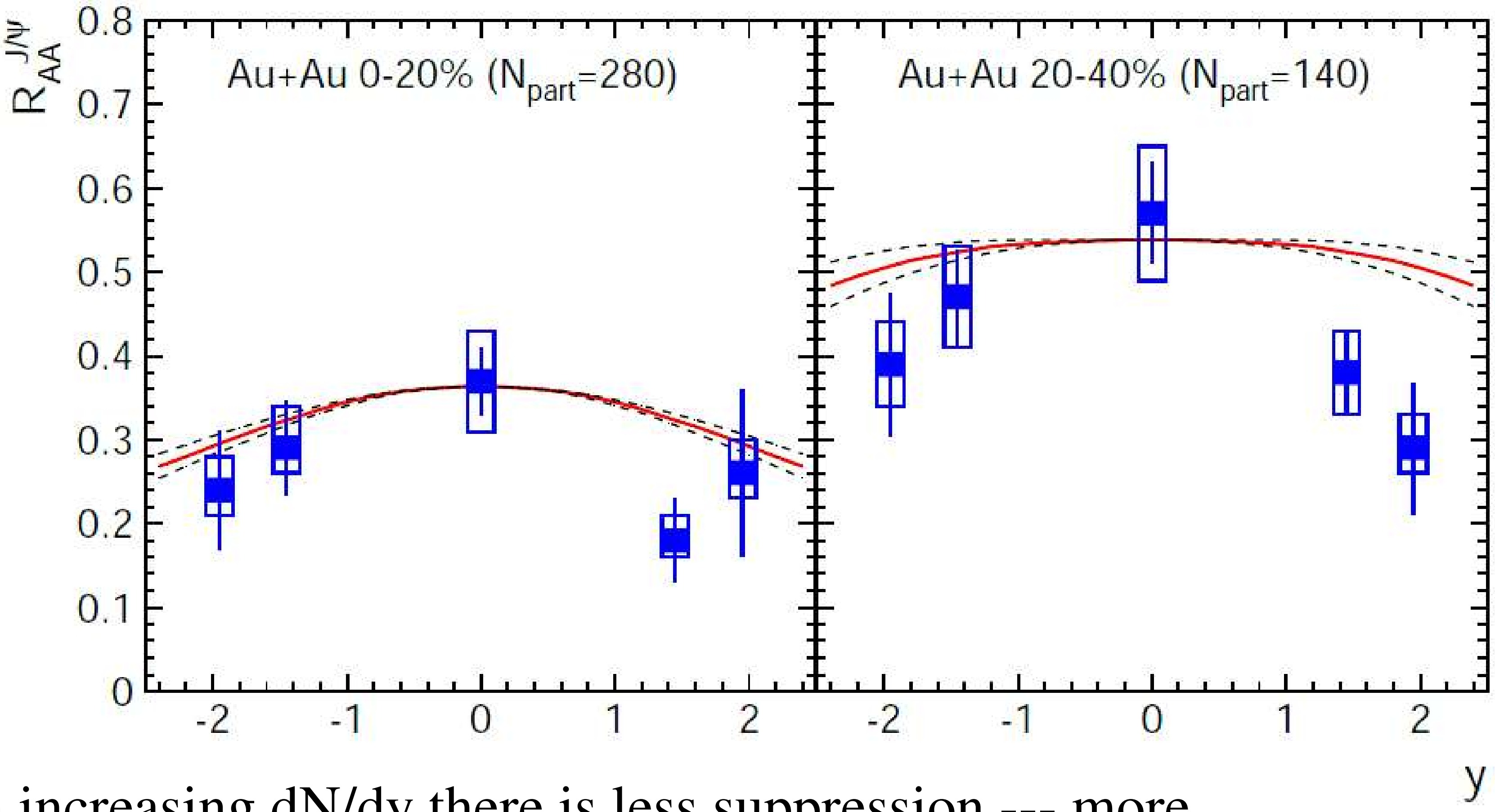
Centrality dependence of R_{AA}

note: suppression is smallest at mid-rapidity opposite to standard suppression models

SHM prediction describes observed trend – evidence for regeneration at the phase boundary



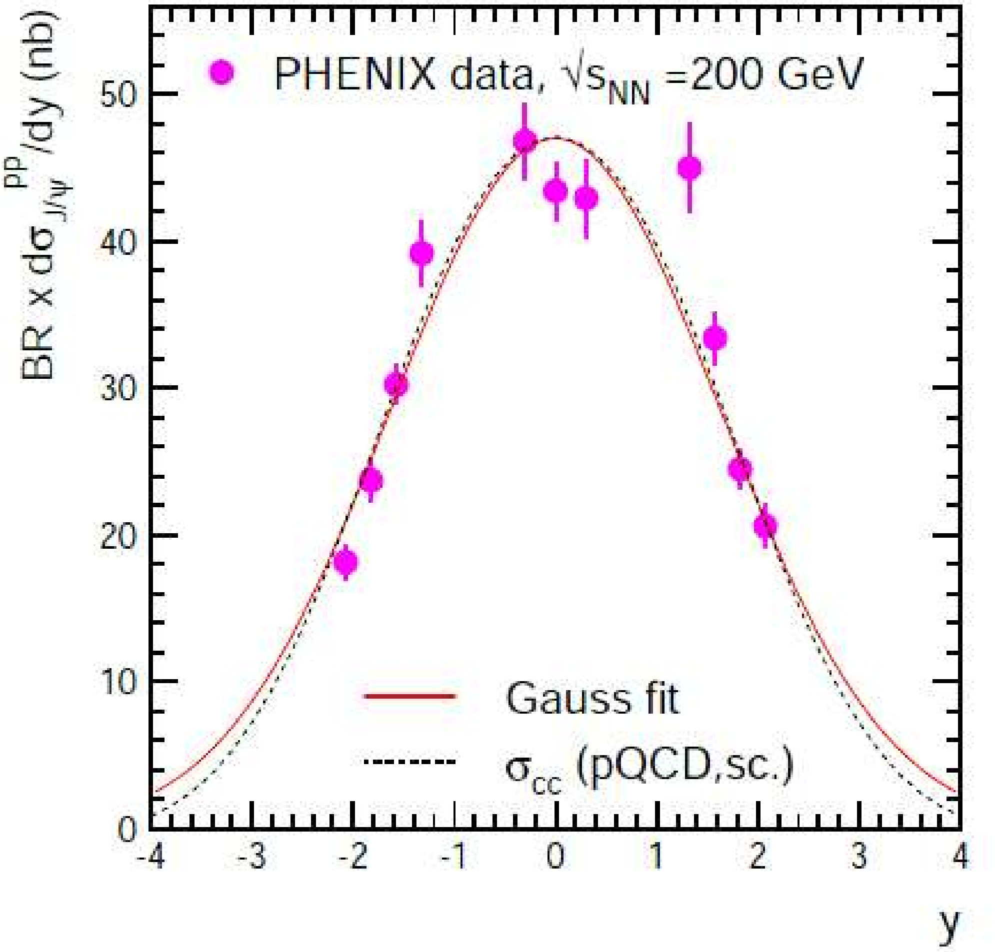
Rapidity dependence of R_{AA}



with increasing dN/dy there is less suppression --- more enhancement. Detailed shape depends on width in rapidity of charm and charged particle distribution

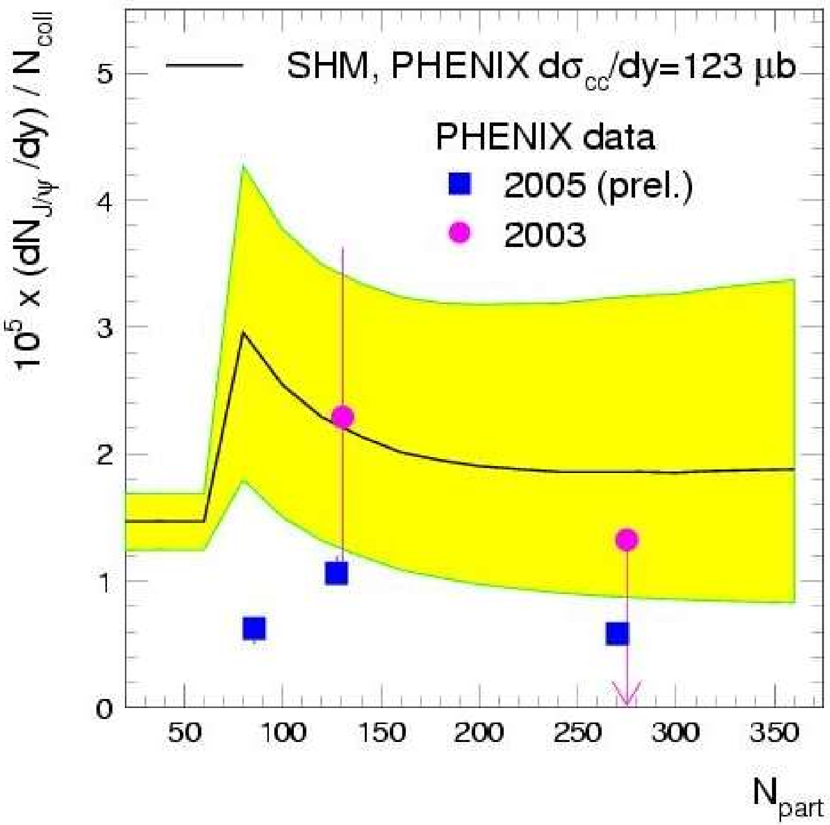
Rapidity distribution of J/ψ mesons in pp collisions

shape close to pQCD open charm rapidity distribution but details not yet well determined



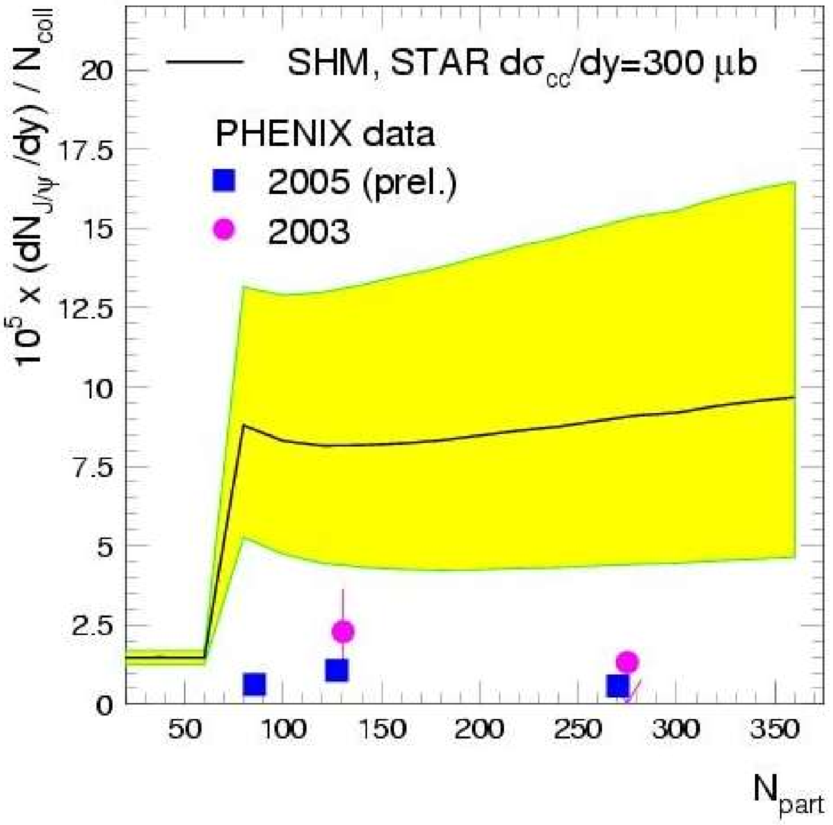
Comparison of model predictions to RHIC data: centrality dependence

predictions for J/ψ production using PHENIX exp. results for the open charm cross section



Comparison of model predictions to RHIC data: centrality dependence

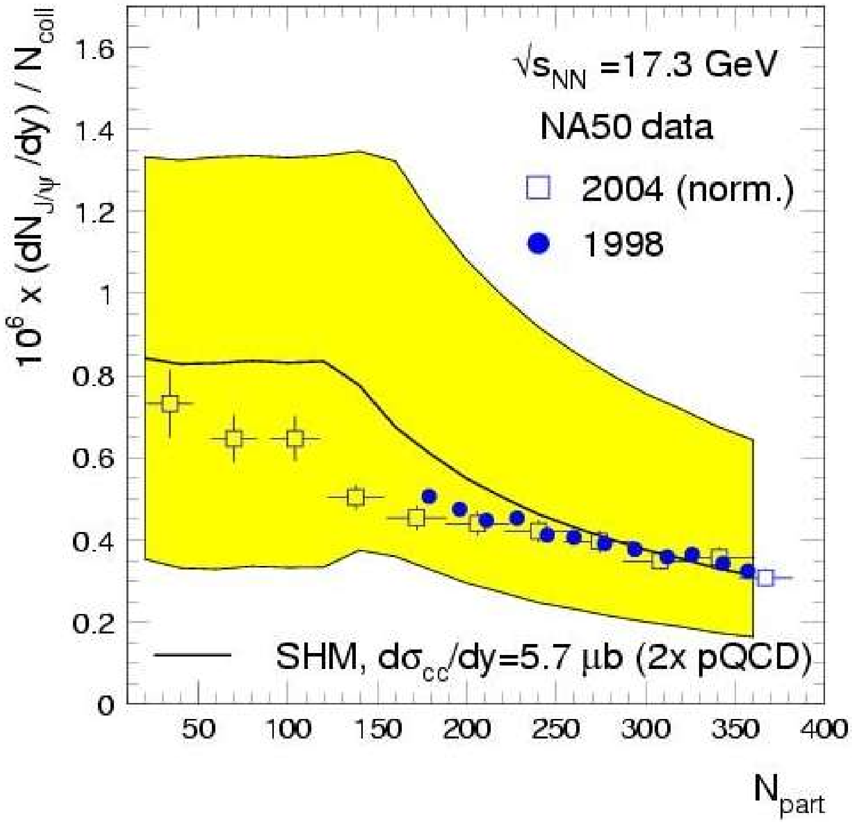
predictions for J/ψ production using STAR exp. results for the open charm cross section

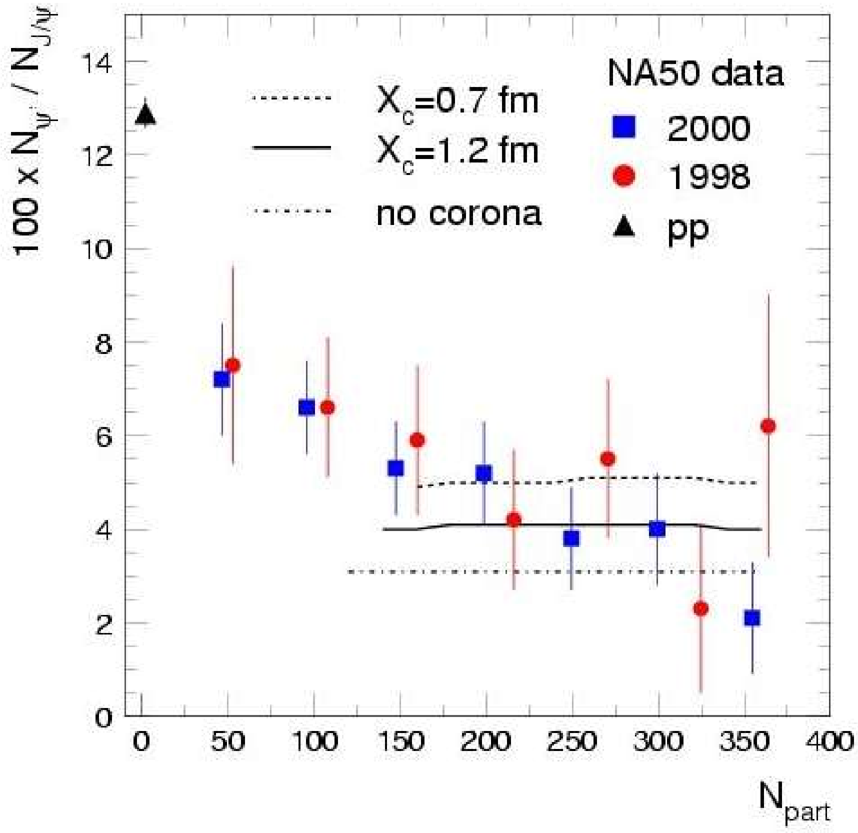


STAR open charm data are not compatible with charmonia data, also:

J/ψ/cc_bar = 0.2 %

back to SPS energy





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

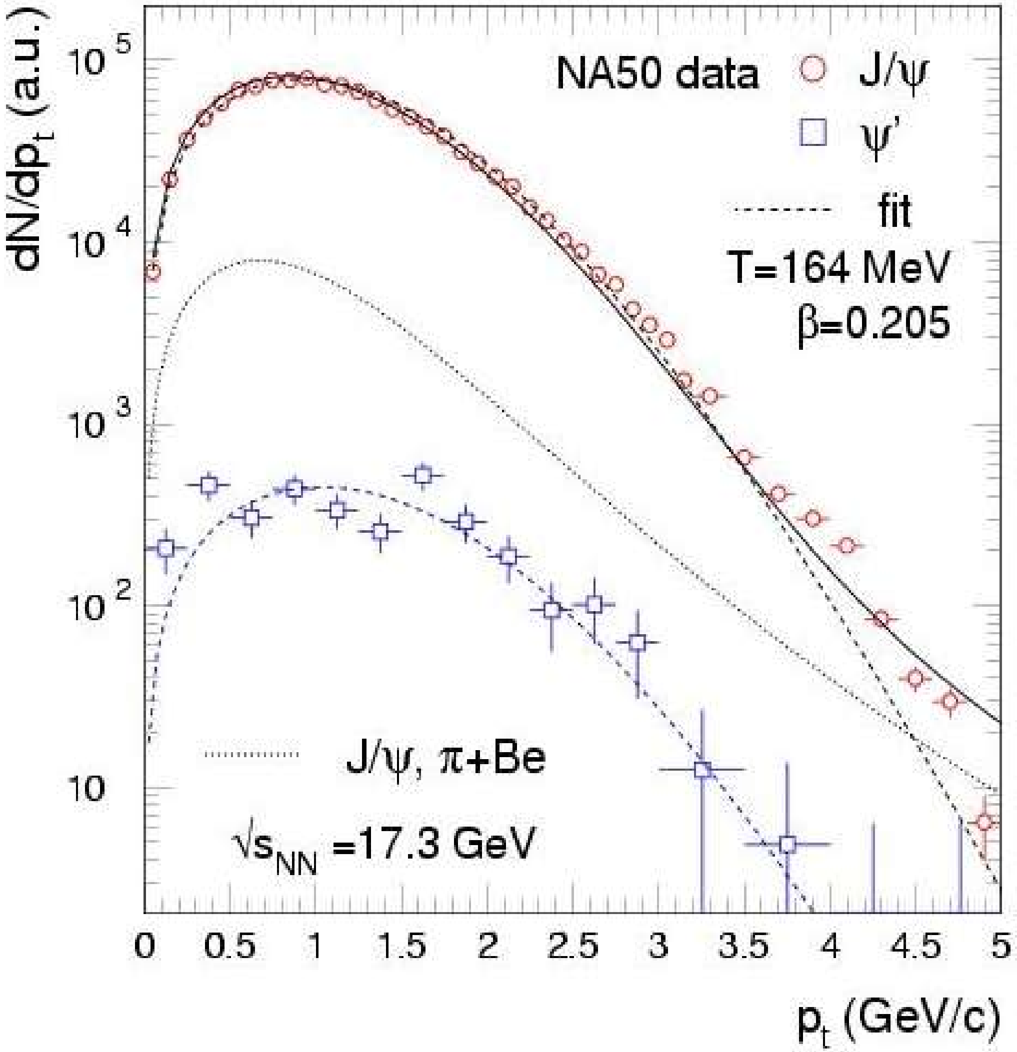
extrapolation to pp for ψ'/ψ ratio still problematic in the model, although intuitively clear

Transverse momentum distributions

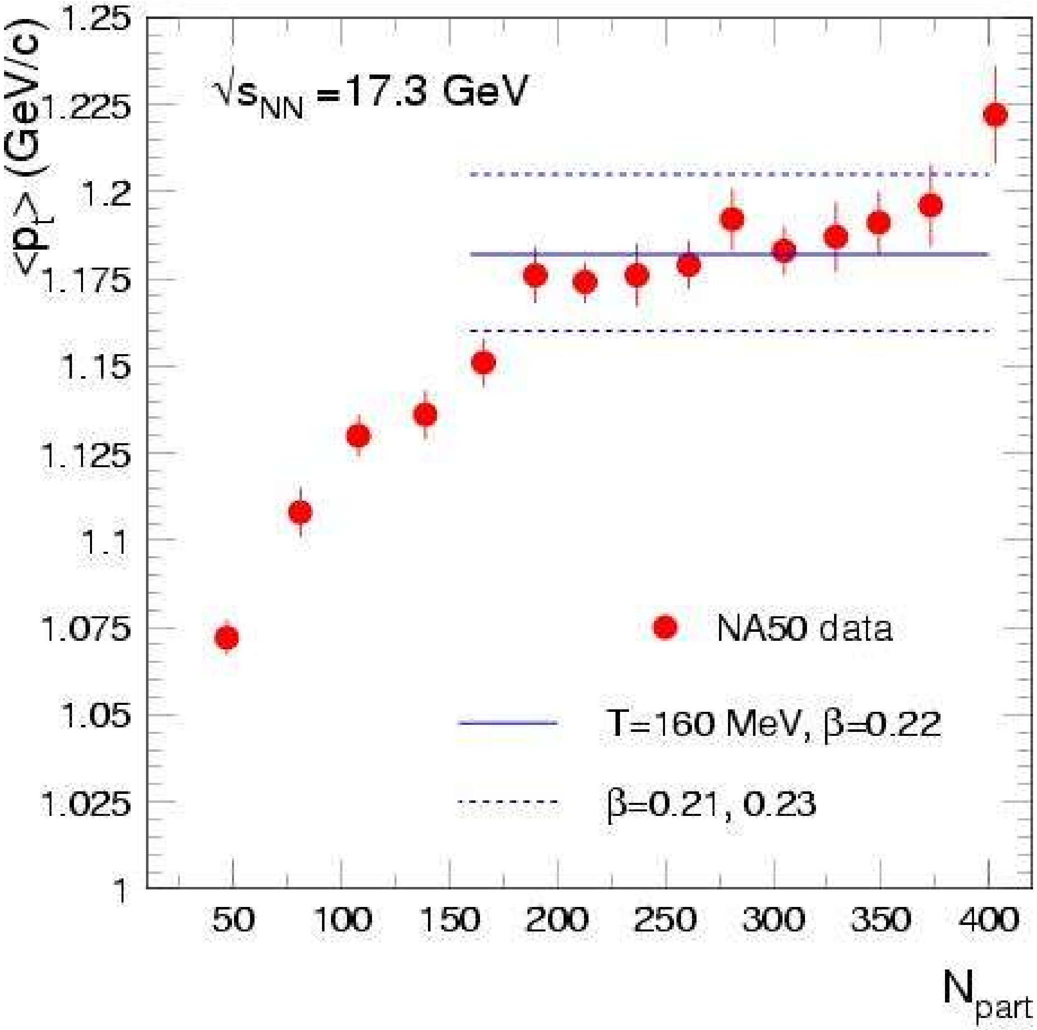
NA50 data

$$\frac{\mathrm{d}N}{\mathrm{d}p_t} \sim p_t \cdot m_t \cdot I_0\left(\frac{p_t \sinh y_t}{T}\right) \cdot K_1\left(\frac{p_t \cosh y_t}{T}\right)$$

$$y_t = \tanh^{-1}(\beta)$$



Centrality dependence of <pt> from NA50



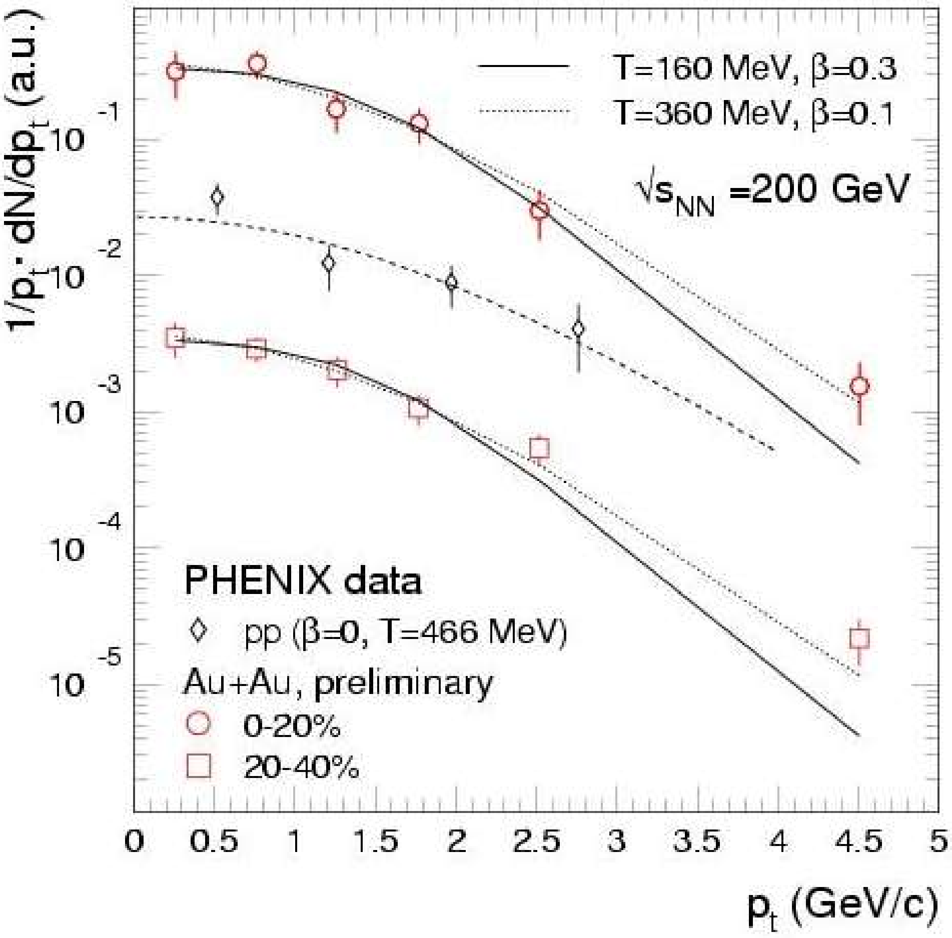
Transverse momentum distributions

PHENIX data

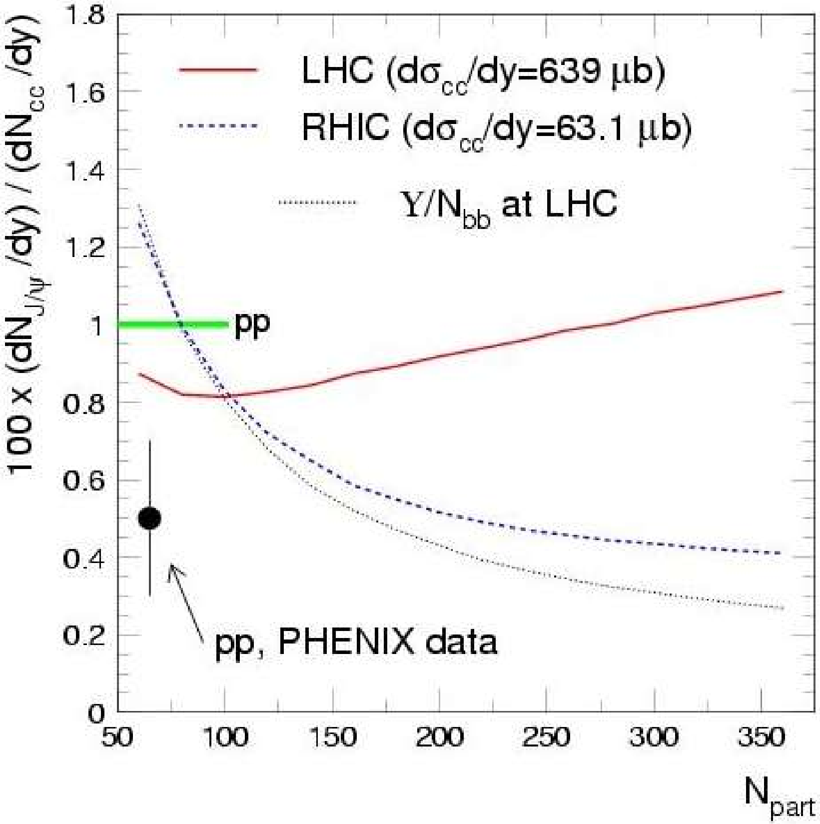
not yet very conclusive

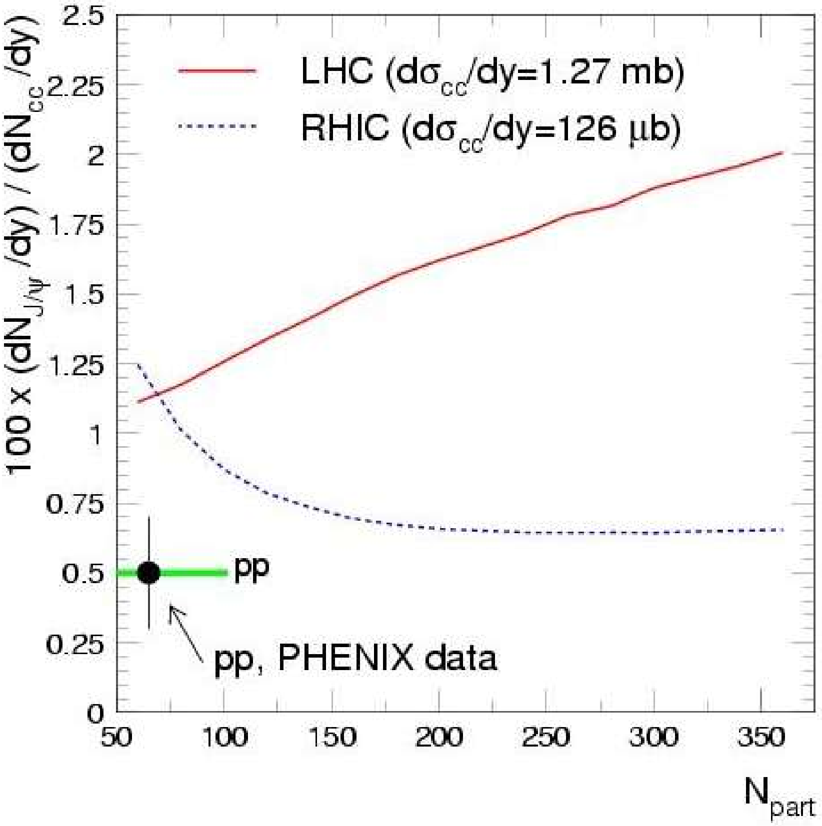
$$\frac{\mathrm{d}N}{\mathrm{d}p_t} \sim p_t \cdot m_t \cdot I_0\left(\frac{p_t \sinh y_t}{T}\right) \cdot K_1\left(\frac{p_t \cosh y_t}{T}\right)$$

$$y_t = \tanh^{-1}(\beta)$$



Extrapolation to LHC energy





centrality dependence and enhancement beyond pp value will be fingerprint of stat. coalescence at LHC

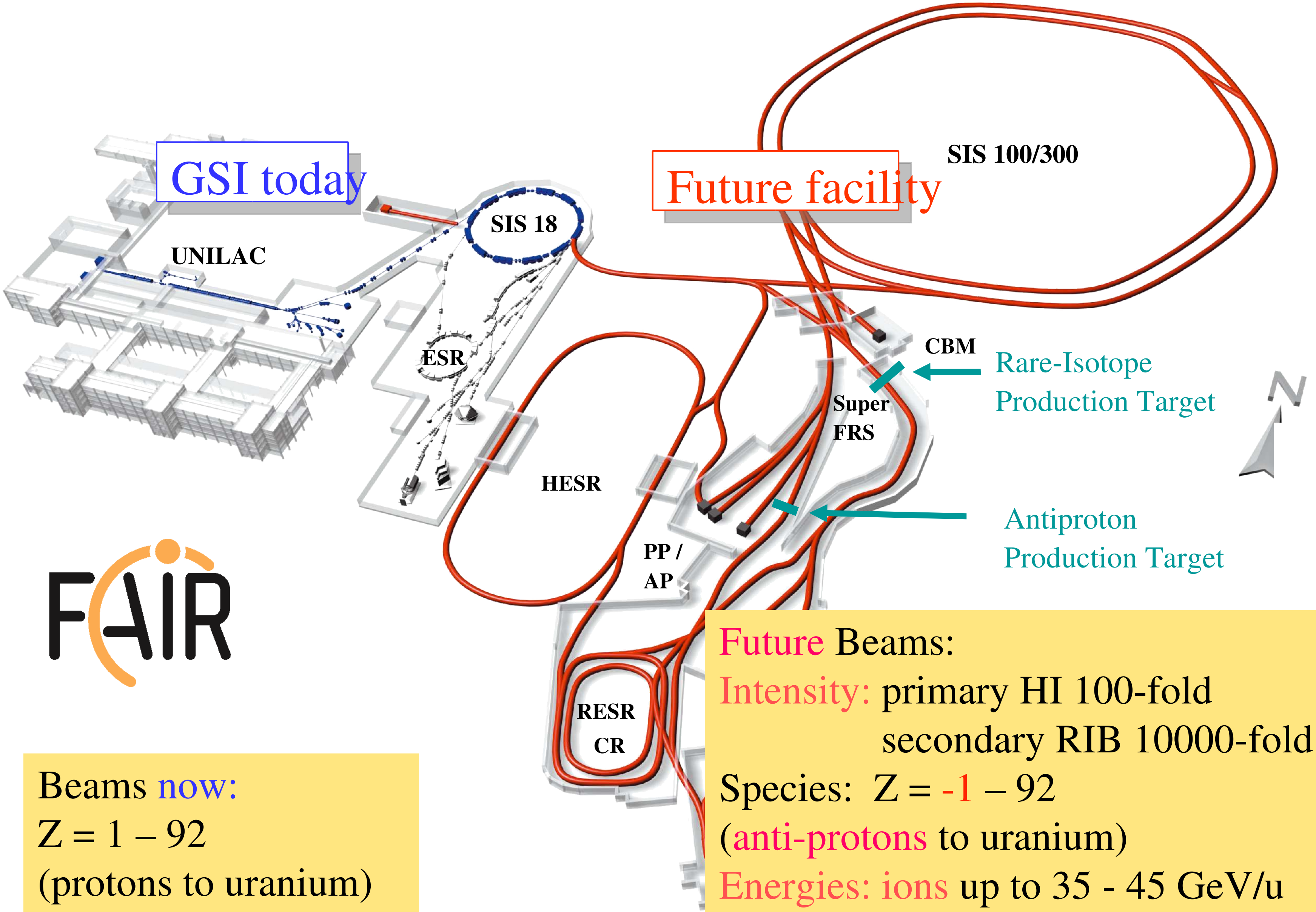
a direct signal for deconfinement

ALICE@LHC

the ALICE TPC is ready to be installed in the experiment,

see presentation by Johanna Stachel for more on ALICE@LHC

The International FAIR Project
at GSI



GSI today

Future facility

Rare-Isotope Production Target

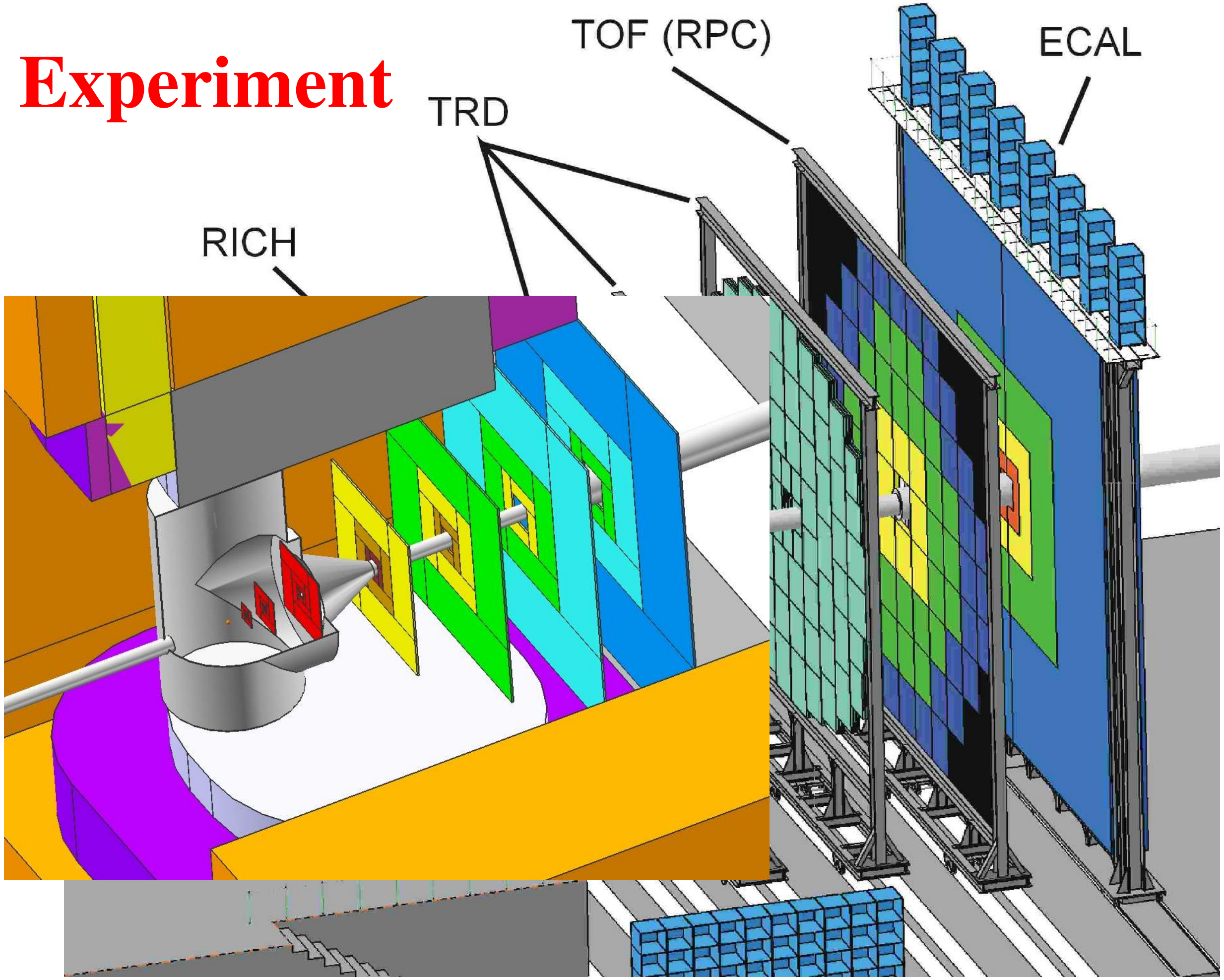
Antiproton Production Target

FAIR

Beams now:
Z = 1 – 92
(protons to uranium)
up to 2 GeV/nucleon
Some beam cooling

Future Beams:
Intensity: primary HI 100-fold
secondary RIB 10000-fold
Species: Z = -1 – 92
(anti-protons to uranium)
Energies: ions up to 35 - 45 GeV/u
antiprotons 0 -15 GeV/c
Precision: full beam cooling

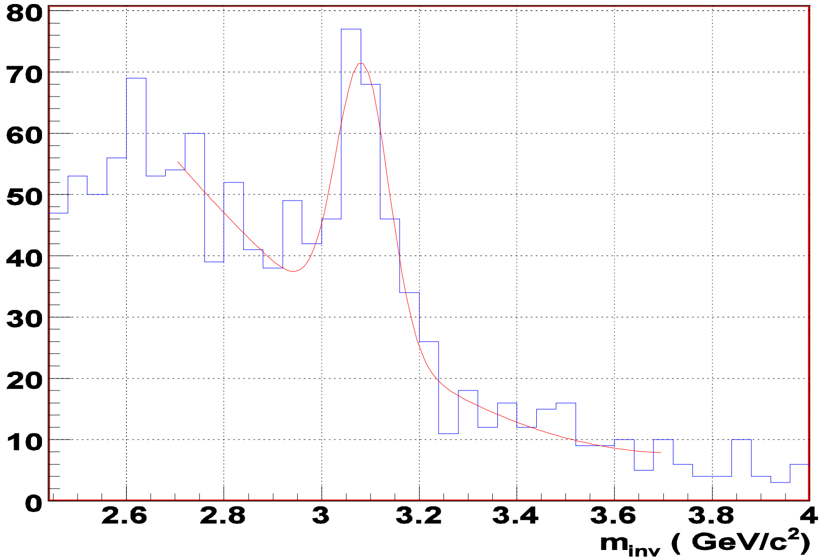
The CBM Experiment



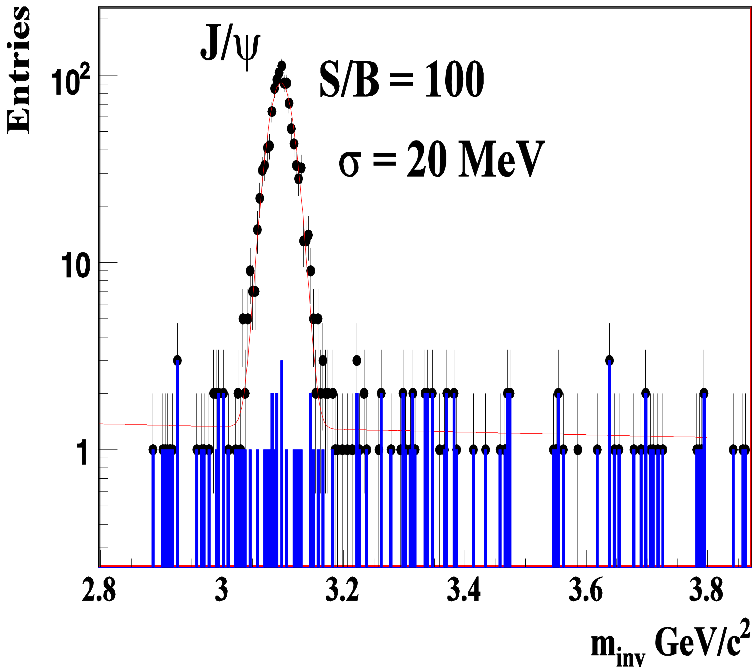
- Radiation hard Silicon (pixel/strip) Tracking System in a magnetic dipole field
- Electron detectors: RICH & TRD & ECAL: pion suppression better 10^4
- Hadron identification: TOF-RPC
- Measurement of photons, π, η, and muons: electromagn. calorimeter (ECAL)
- High speed data acquisition and trigger system

CBM charmonium feasibility

J/Ψ→e^+e^-



J/Ψ→$\mu^+\mu^-$



Au + Au, central collisions, 25 GeV/nucleon beam energy

Charmonia at low energies

- can be measured down to 20 GeV/nucleon beam energy
- separate energy density from co-mover effects at low energy
- is all production still at the phase boundary?

Summary and Outlook

charmonium formation during QGP phase very unlikely even if bound states exist

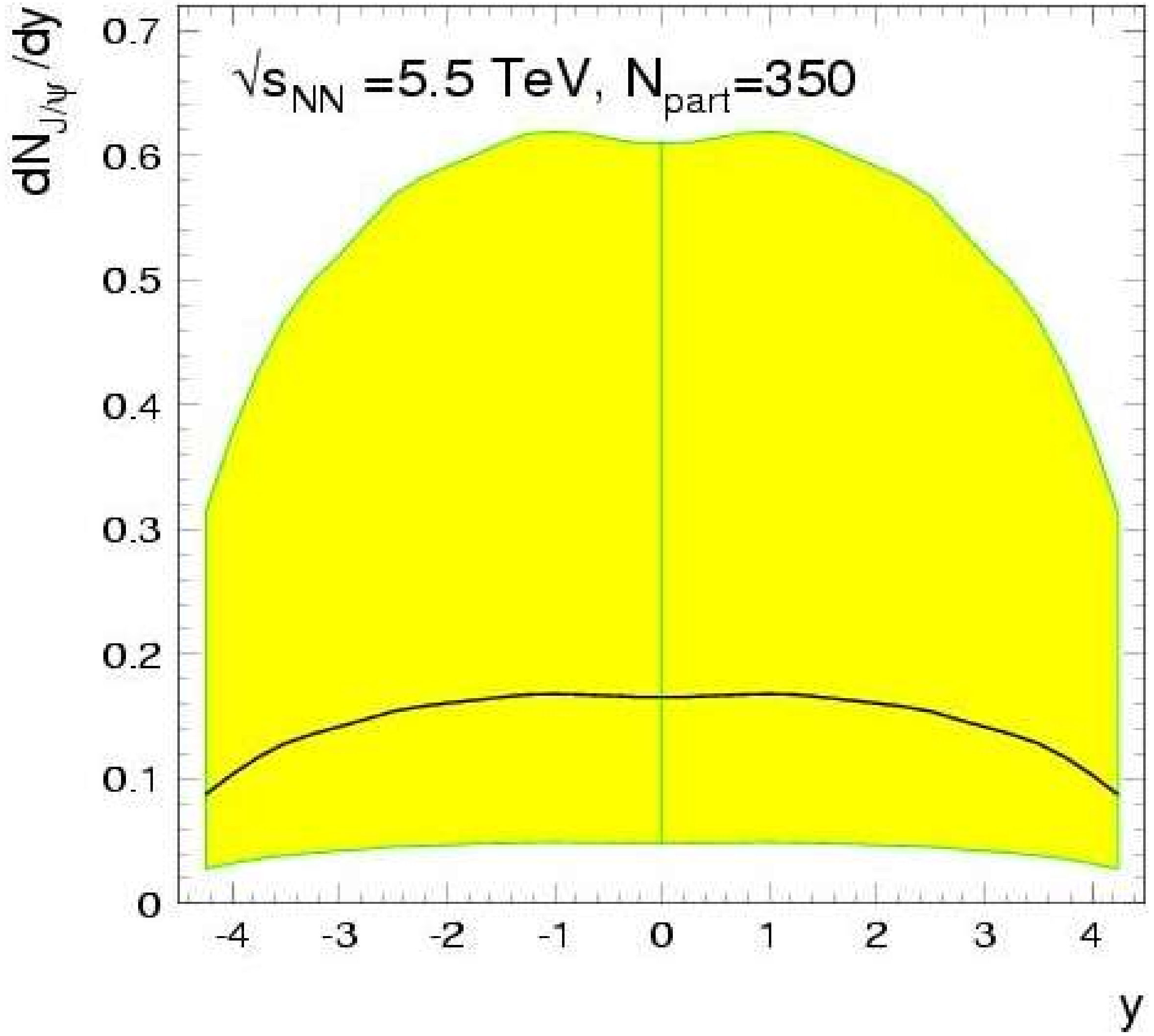
collision broadening substantial

strong indications for statistical hadronization of charm quarks at RHIC

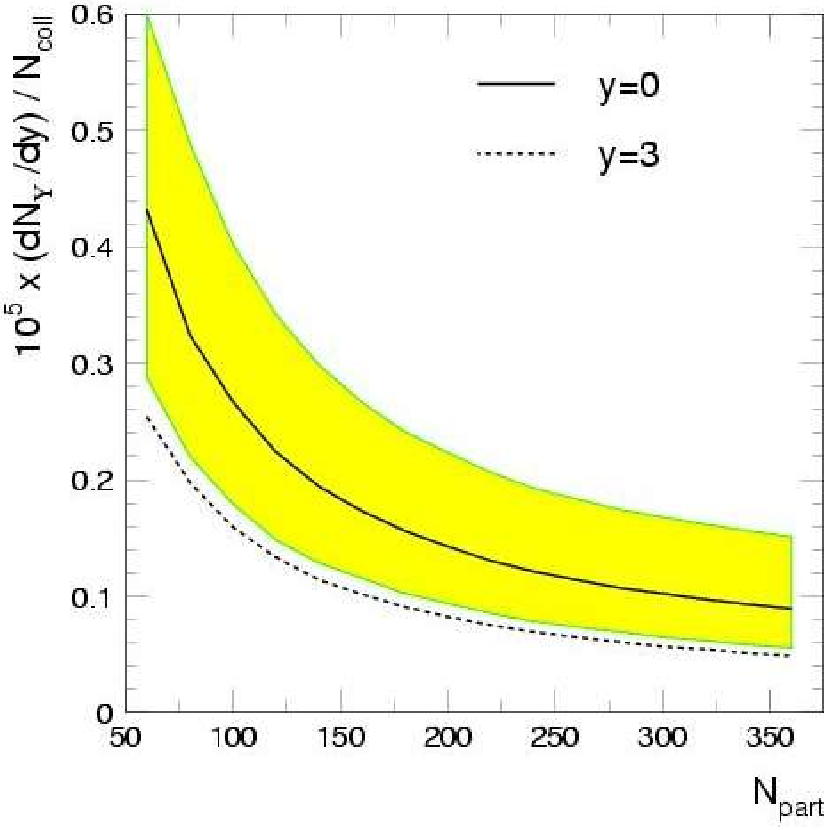
quarkonia studies at LHC look exciting indeed, fingerprint for deconfinement

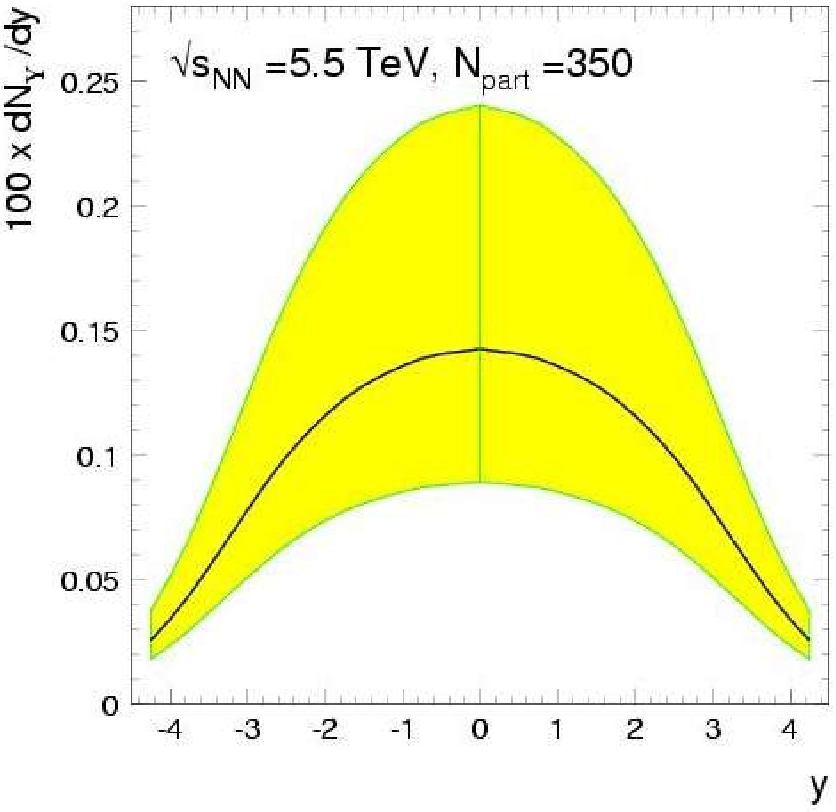
Extra slides

Predictions for charmonium at LHC



Beauty at LHC

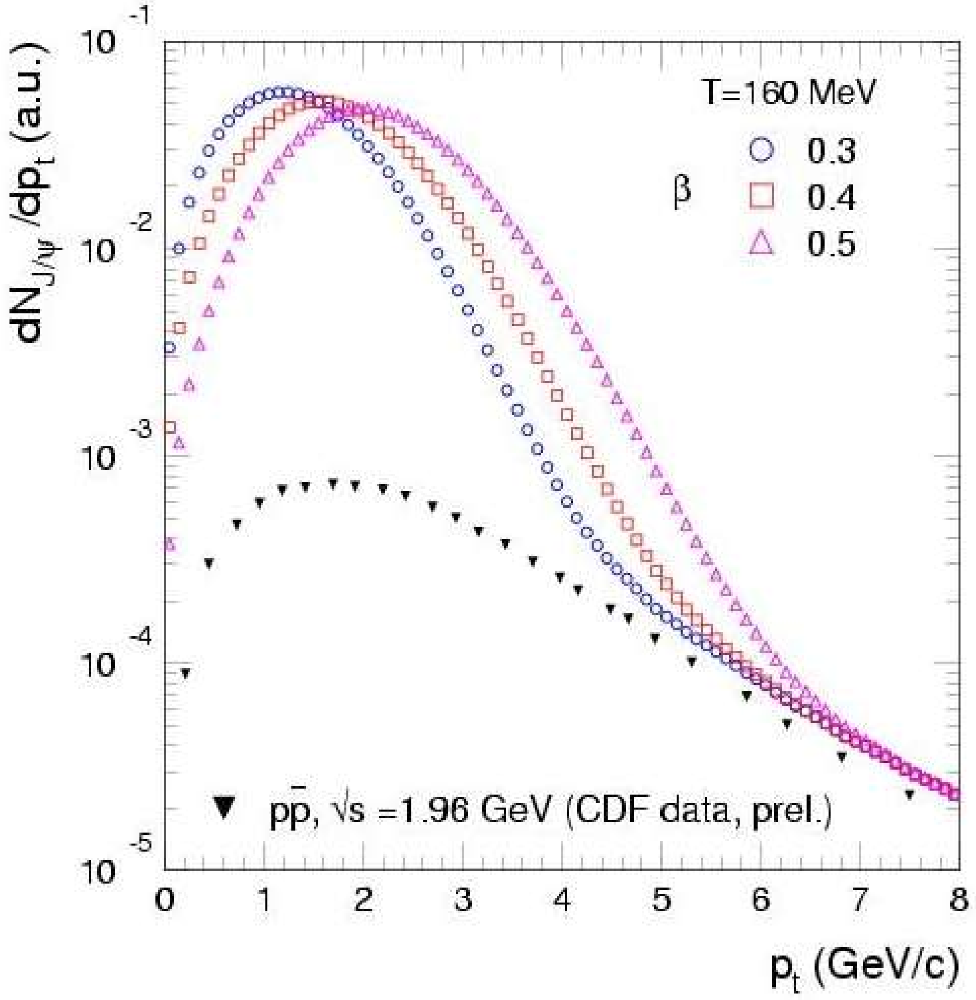




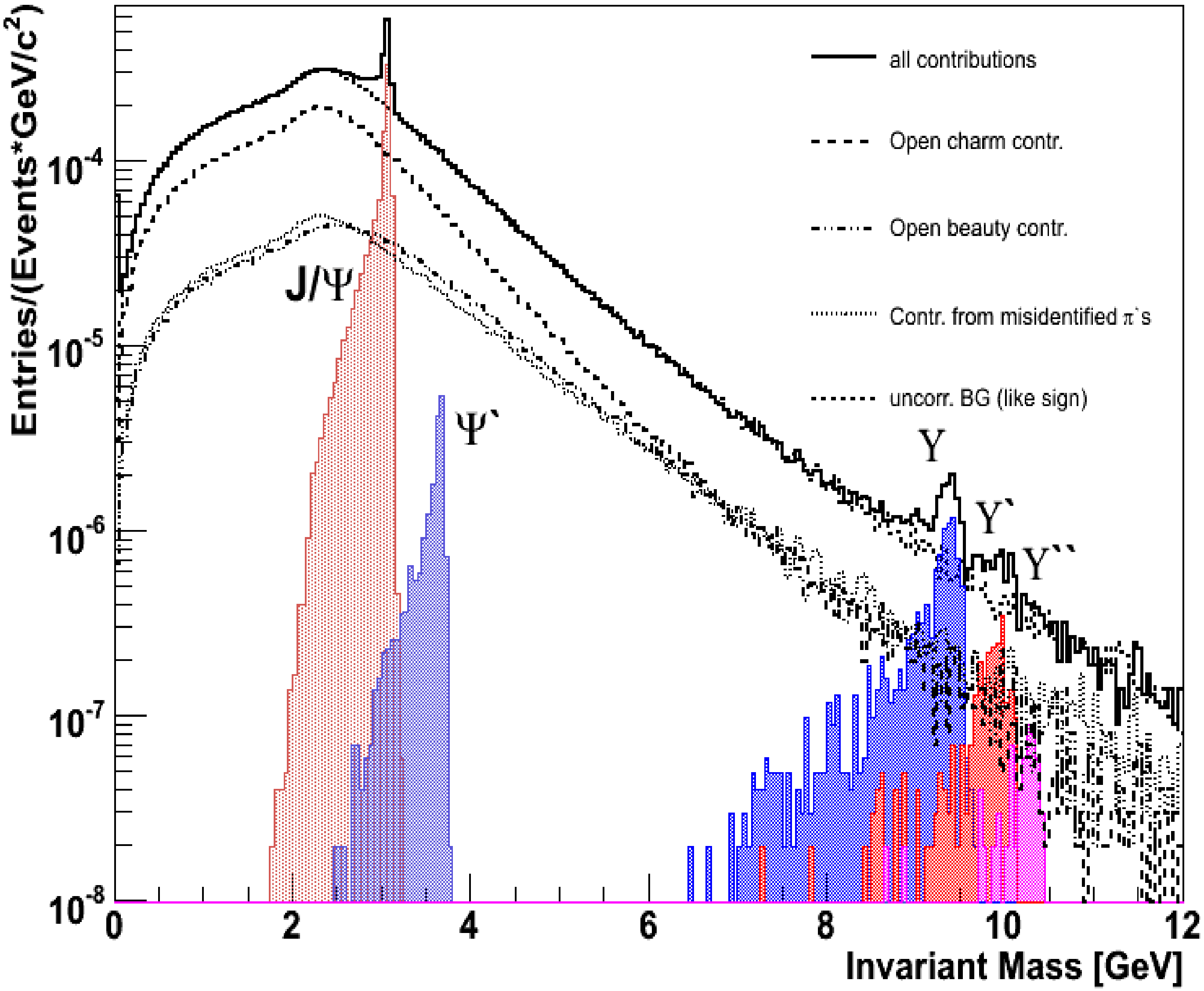
Flow of quarkonia?

pt spectra with flow are very different for charmonia from those measured in pp_bar at Fermilab

should be easy to discriminate at LHC



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



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

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

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

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

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

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

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

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

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

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

using detailed balance yields final result:

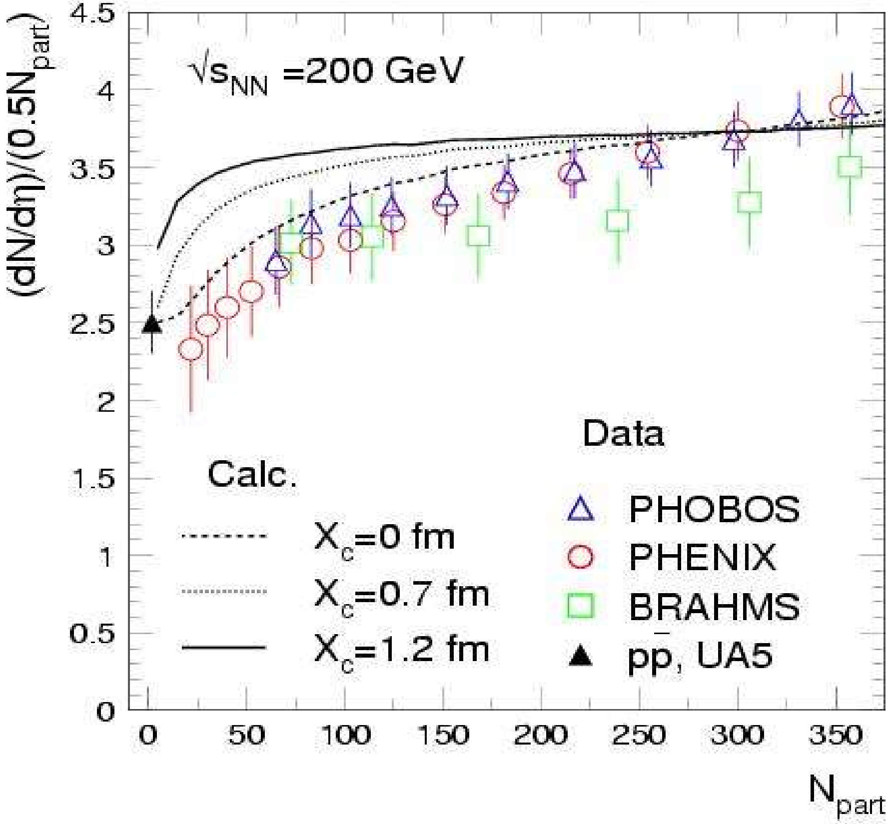
$$\sigma_{c\bar{c}\to gg}(s) = \sigma_{gg\to c\bar{c}} \cdot \frac{9}{4}\frac{s^2}{\sqrt{(s^2-4m_c^2 s)}\sqrt{((s-2m_c^2)^2-4m_c^4)}}$$

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

Corona continued

all collisions in the corona region are assumed to take on the value measured in pp collisions

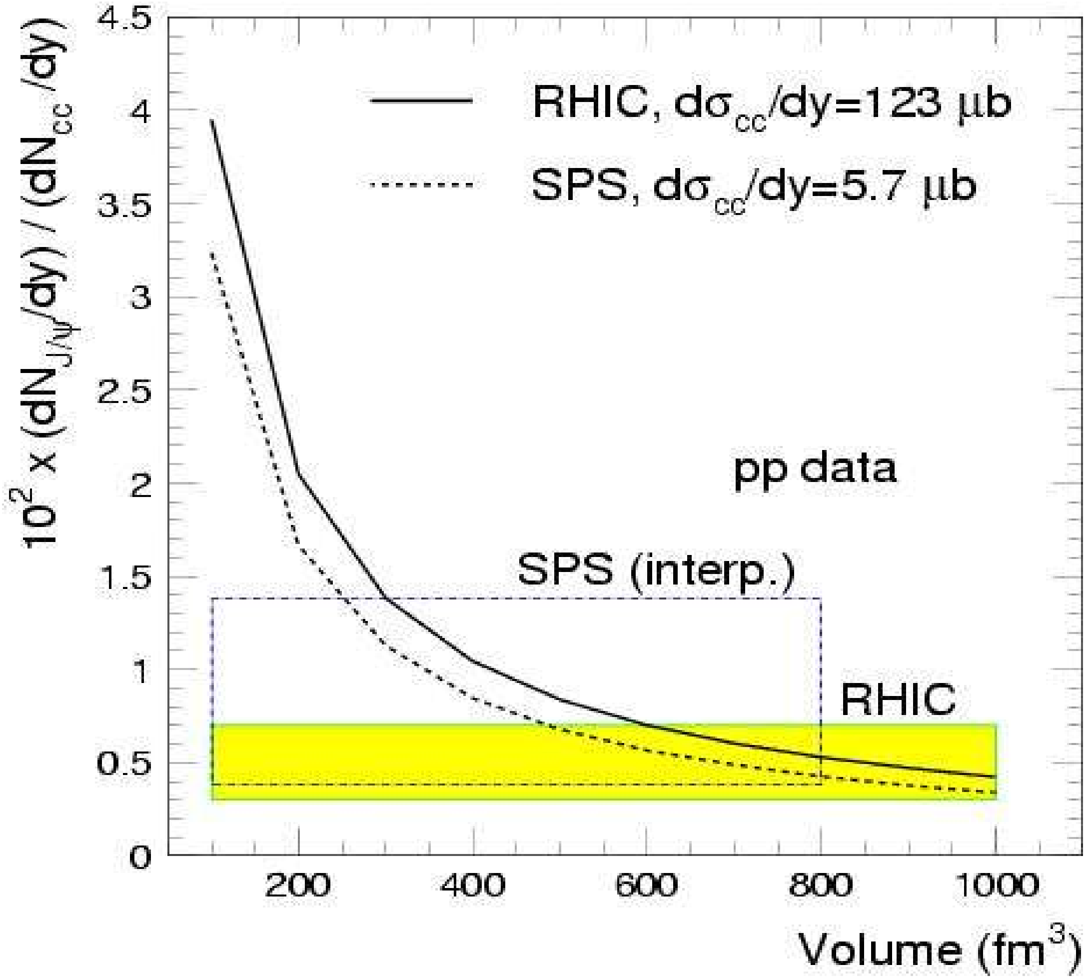
only small Xc values compatible with measured $dN_{ch}/d\eta$



The model and pp data

charm quarks do not thermalize in pp, so the „core only“model strongly overpredicts pp data

detailed approach to corona (pp) value needs complex dynamics, core-corona approach only 1^{st} approximation



Charm at LHC: Statistical hadronization vs. NLO

we have also yields for multiply charmed hadrons

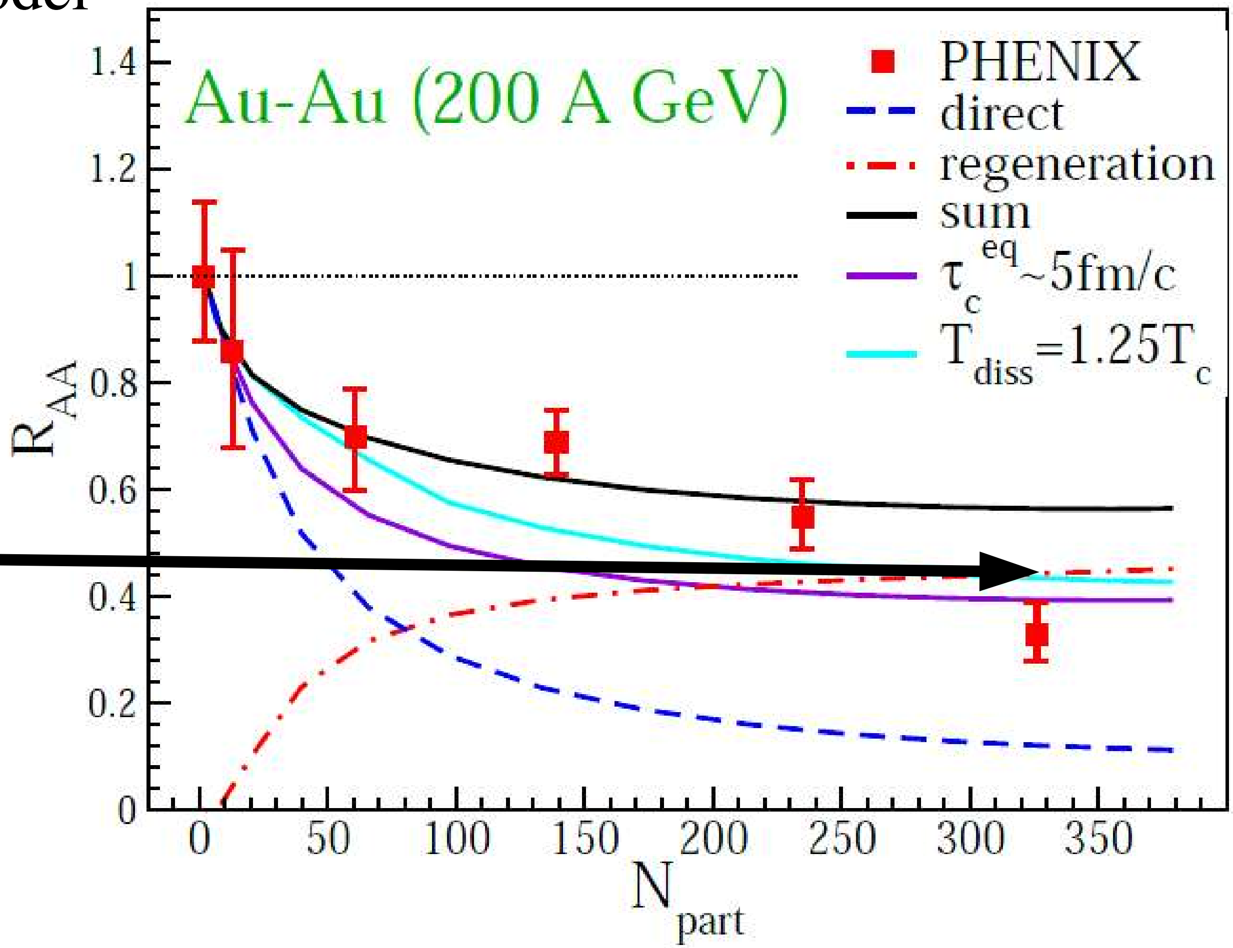
Yields (dN/dy) in central collisions (N_{part}=350)

Particle	Stat. hadr.	NLO
D^+	3.56	3.10
D^-	3.53	2.92
D^0	7.80	10.08
$\bar{D}^0$	7.82	9.97
D_s^+	2.96	1.90
D_s^-	2.95	1.78
Λ_c	1.16	1.72
$\bar{\Lambda}_c$	1.15	1.24

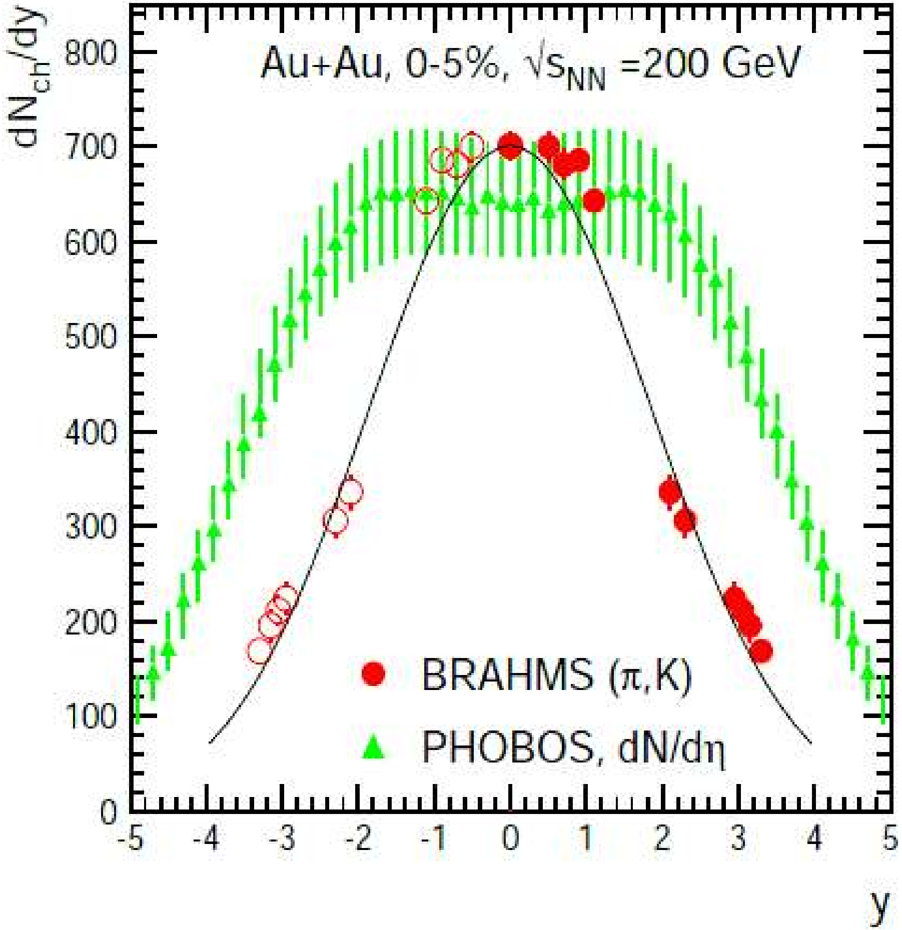
NLO (rescaled for $dN^{dir}_{c\bar{c}}/dy$=16.8): N. Carrer, ALICE PPR, *http://alice.web.cern.ch/ALICE/ppr/*

Charmonium regeneration a la Rapp

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



regeneration becomes dominant for central collisions


Au+Au, 0-5%, √s_NN =200 GeV
dN_ch/dy
800
700
600
500
400
300
200
100
0
-5
-4
-3
-2
-1
0
1
2
3
4
5
y
BRAHMS (π,K)
PHOBOS, dN/dη