

Quarkonia Production

suppression vs enhancement

- quarkonia suppression
 - ingredients and assumptions
 - quarkonia in the QGP
 - confrontation with data
- quarkonia enhancement
 - ingredients and assumptions
 - annihilation of charm quarks in the plasma
 - confrontation with data
 - predictions for LHC
- outlook

QM2006 Shanghai

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
- some charmonia might survive beyond T_c

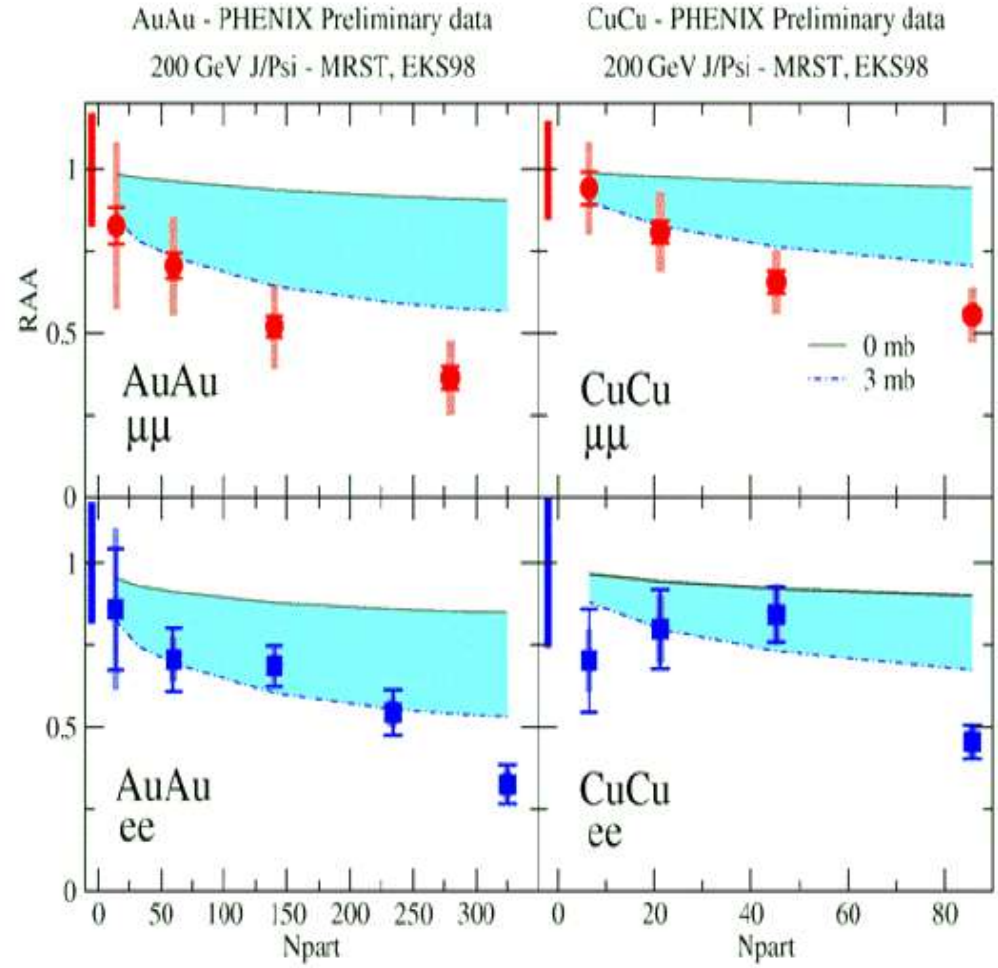
sequential suppression pattern due to feeding

charmonium suppression at RHIC

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

suppression models
describing SPS data fail

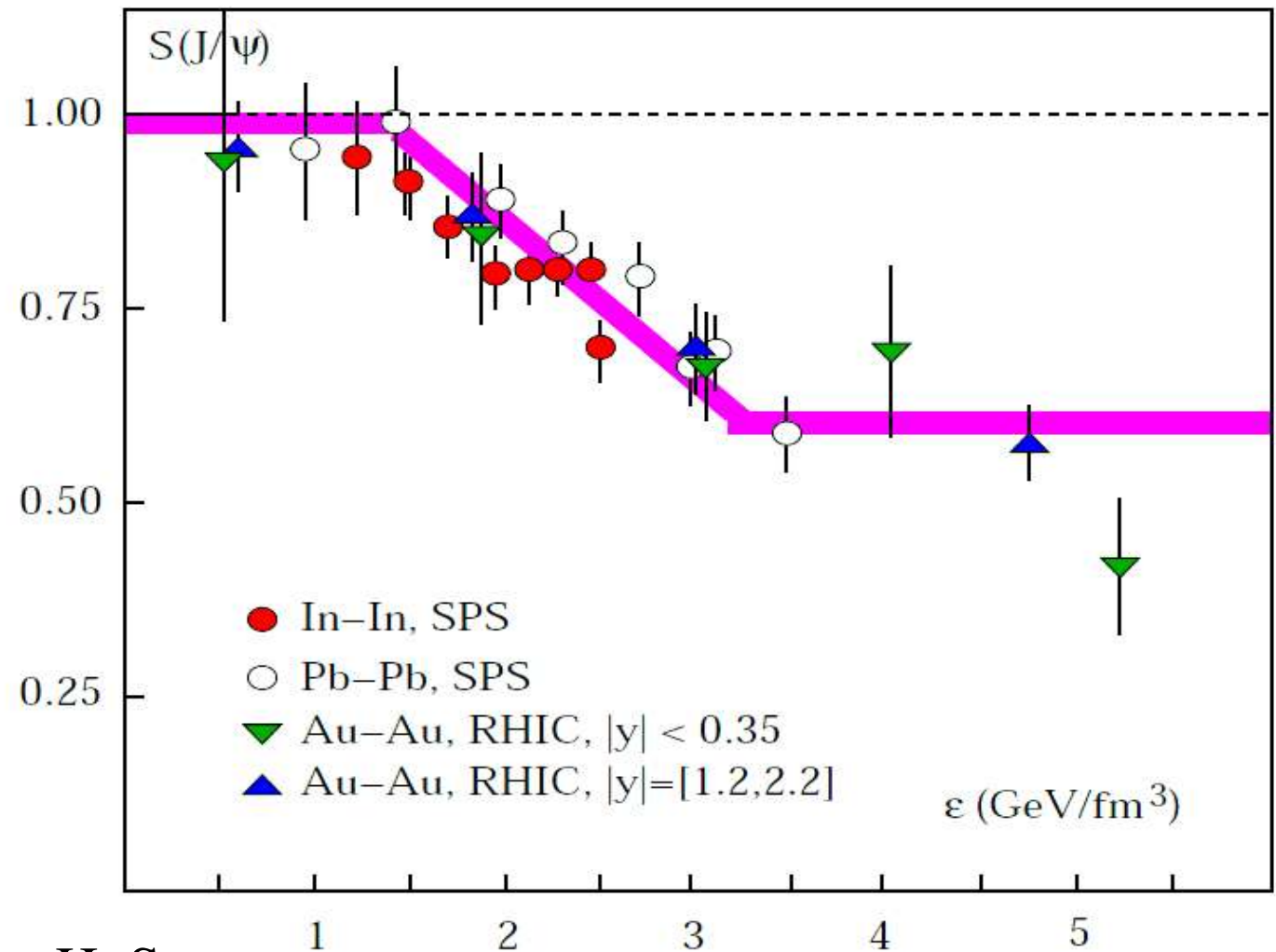
possible way out:
 J/ψ may survive
in plasma until near
 $2 T_c$



Suppression pattern --- SPS and RHIC data

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

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 $\lambda = 1/(n \sigma)$

$\sigma = J/\psi$ parton cross section take 2 mb as reference
(factor 2 smaller than NA50 absorption cross section)

velocity of J/ψ in the QGP $v = \sqrt{(3 T/m)} \approx v_{\text{rel}}$

in-medium width $\Gamma = v_{\text{rel}}/\lambda$

final result: $T = 200 \text{ MeV}$ $\Gamma = 80 \text{ MeV}$

$T = 300 \text{ MeV}$ $\Gamma = 320 \text{ MeV}$

$T = 500 \text{ MeV}$ $\Gamma = 1940 \text{ MeV}$

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) = $\exp(-\Gamma \tau_{\text{QGP}})$

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 $\sim N_c^2$ -- 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

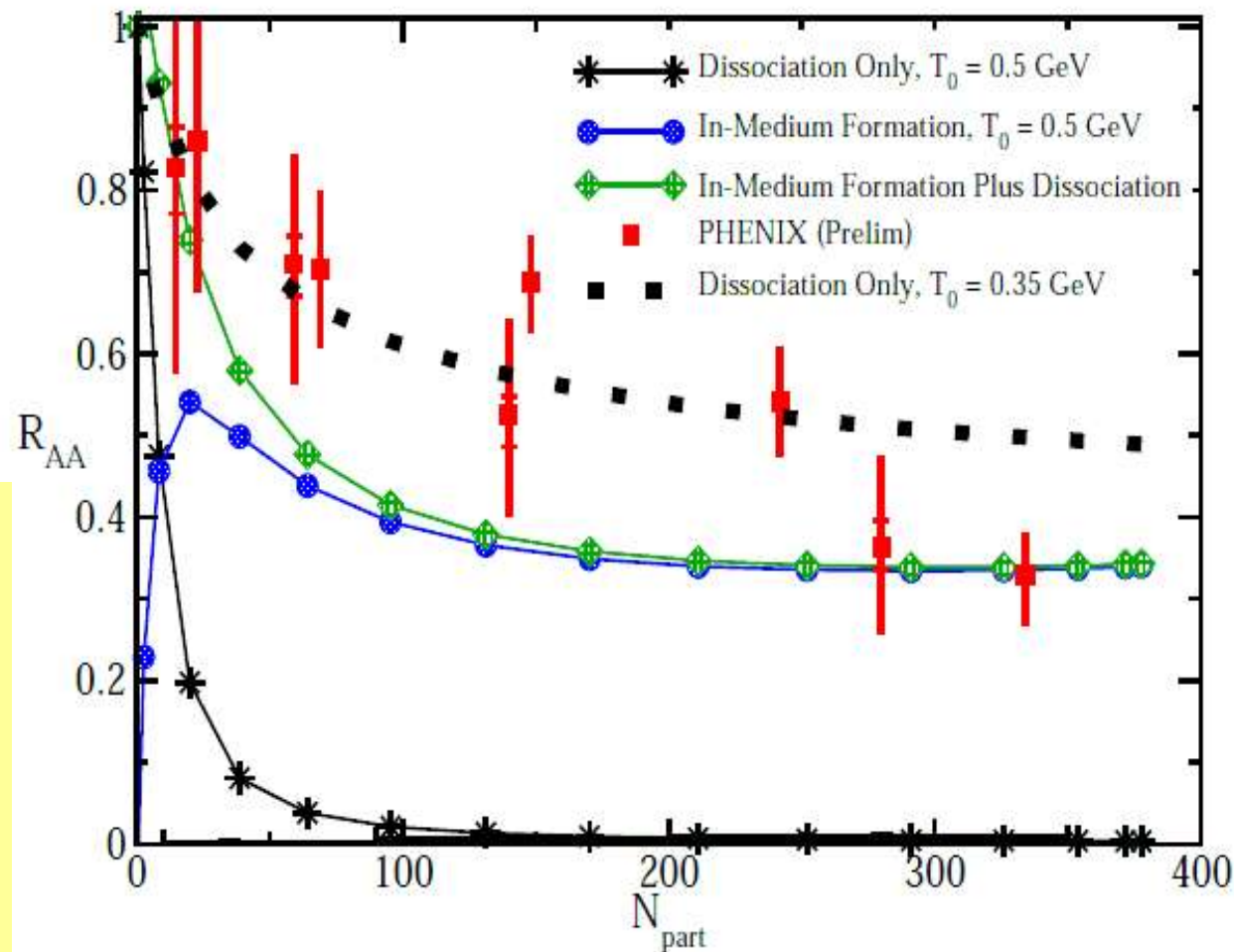
assumptions:

- all charm quarks are produced in hard collisions
- all charmonia are produced in the QGP via charm quark recombination
 - yield $\sim N_c^2$ -- quarkonium enhancement at high energies

Results from quark coalescence

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

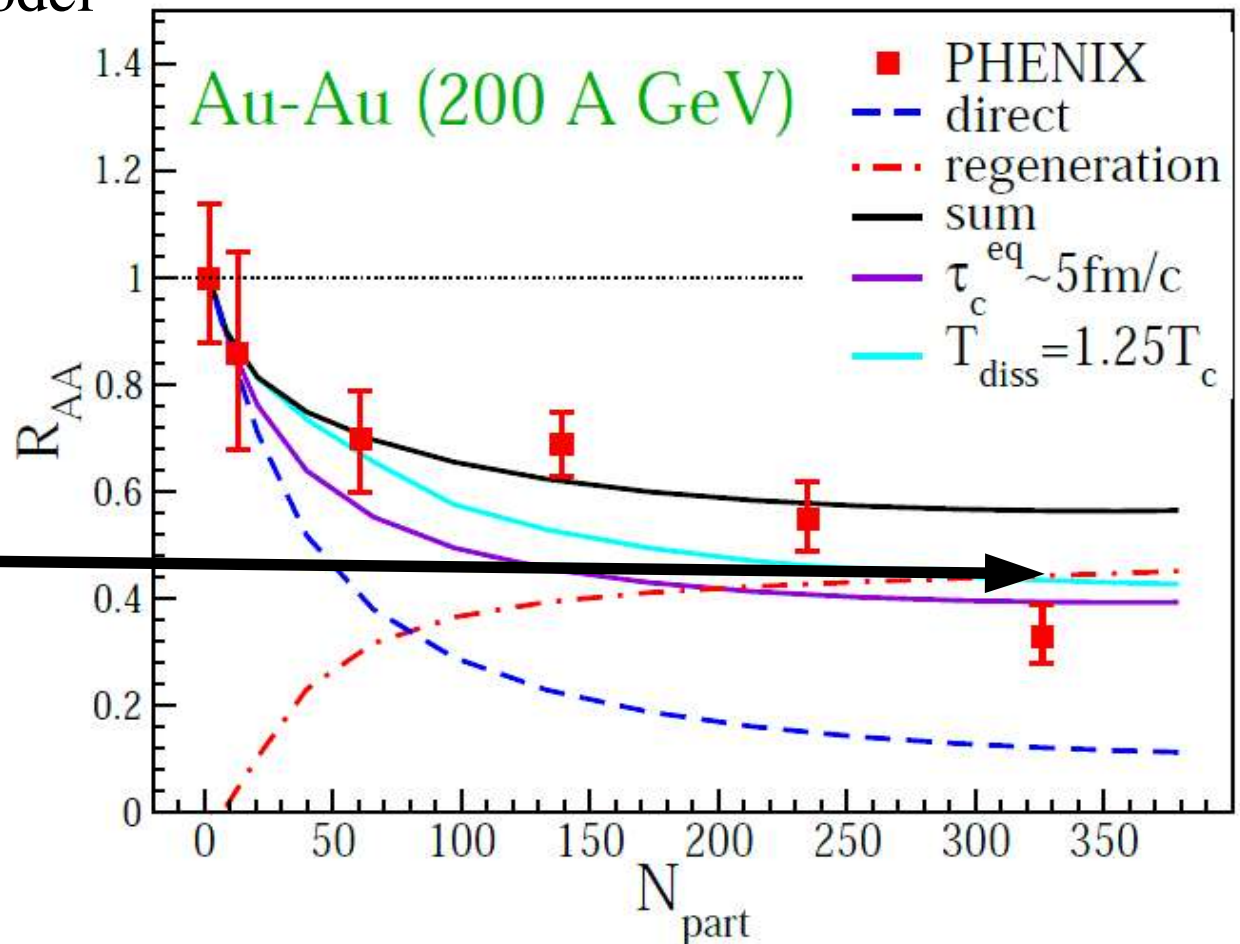
data described for a
specific set of QGP
parameters and
charmonium production
cross section



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



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) $T, \mu_B: \rightarrow n_X^{th}$

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

$N_{c\bar{c}} \ll 1 \rightarrow$ **Canonical:** J.Cleymans, K.Redlich, E.Suhonen, Z. Phys. C51 (1991) 137

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

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

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

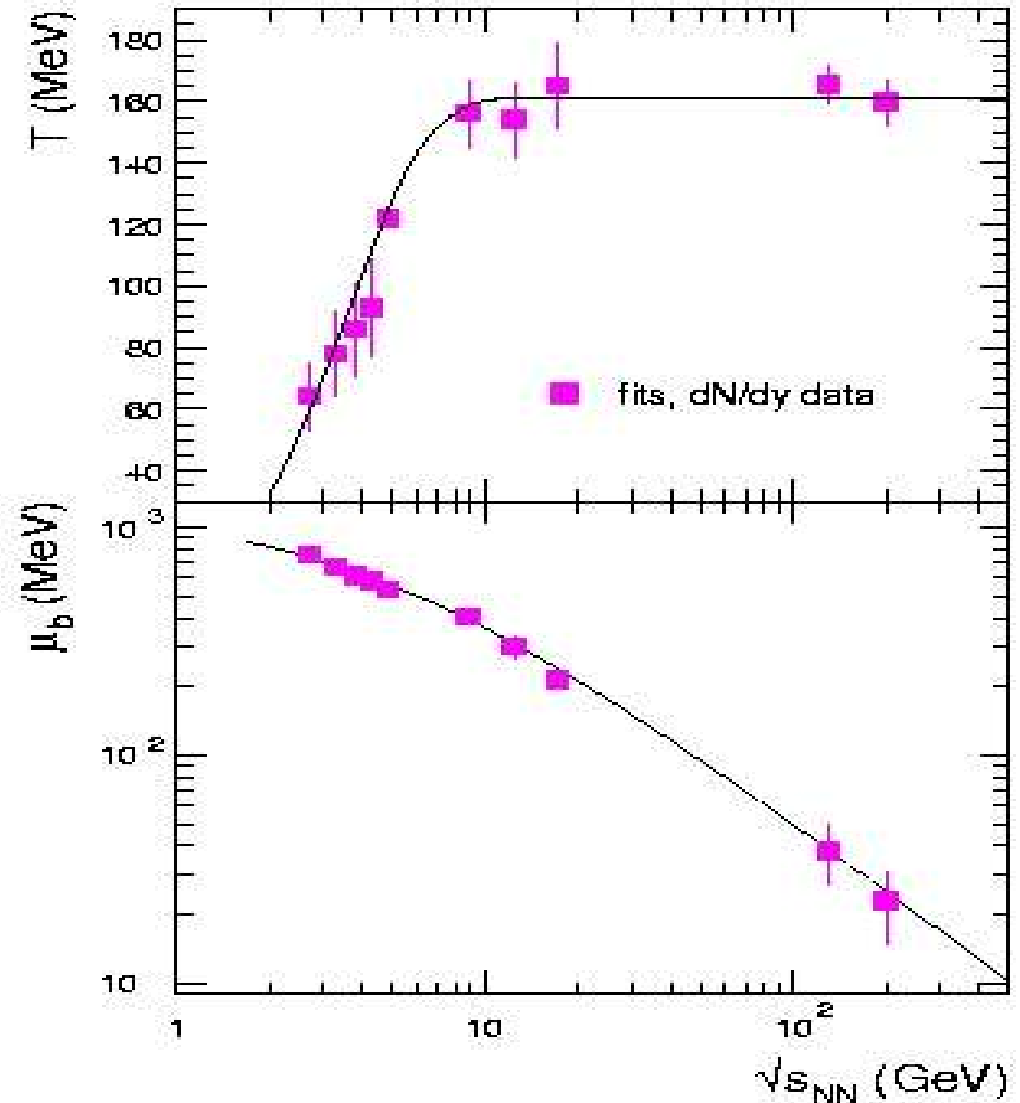
Parameterization of all freeze-out points

note: establishment of
limiting temperature

$$T_{\text{lim}} = 160 \text{ MeV}$$

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:

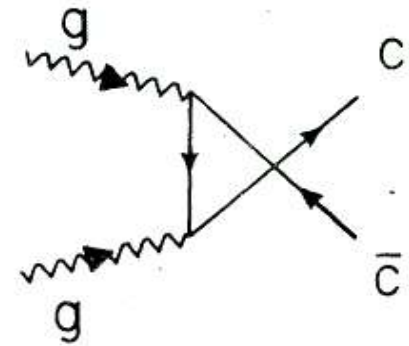
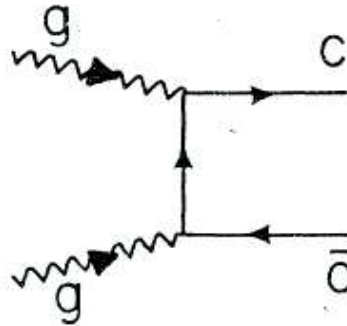
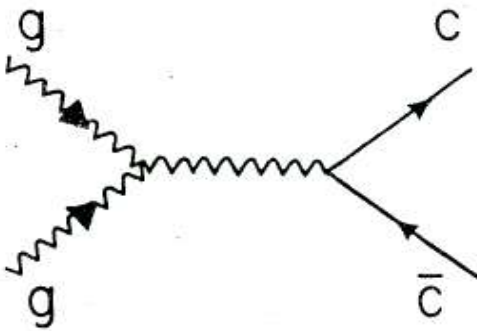
$\langle \rangle$ implies thermal average

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

Cross section for $c\bar{c}$ annihilation

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

first compute inverse process:



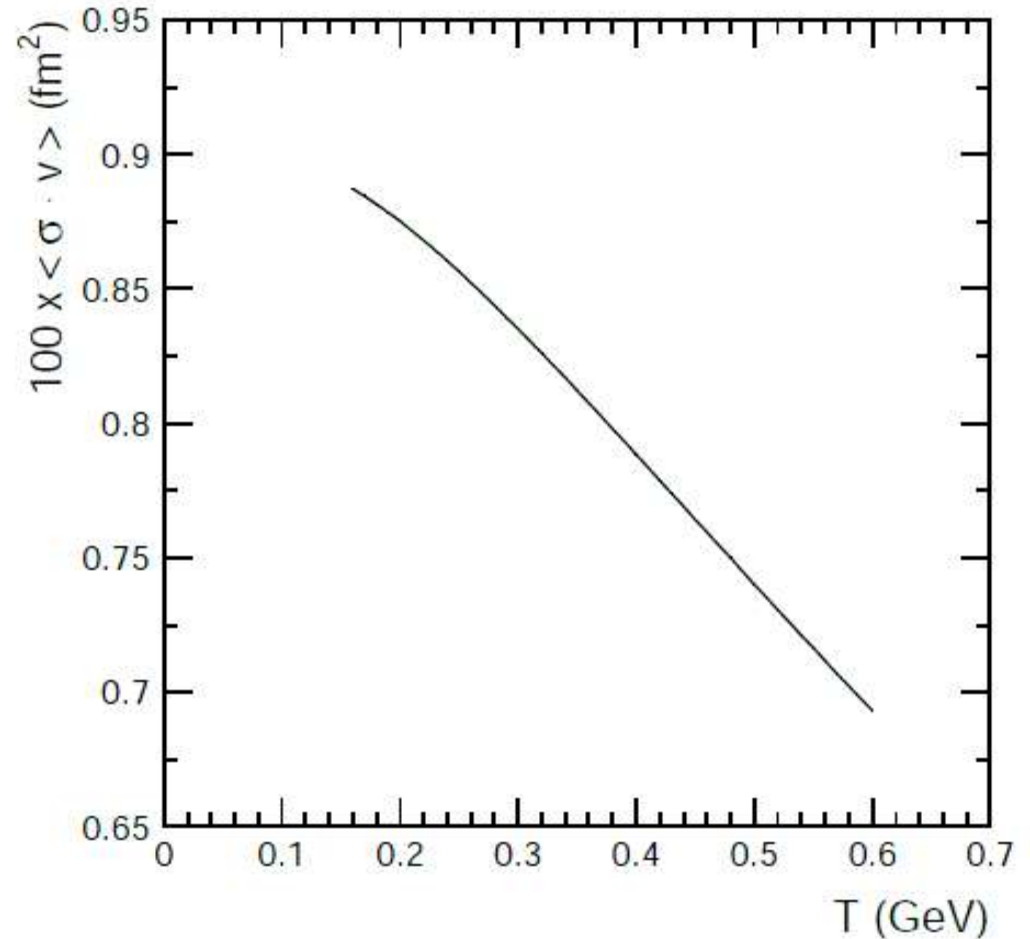
then use detailed balance
(time reversal)

numerical results

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

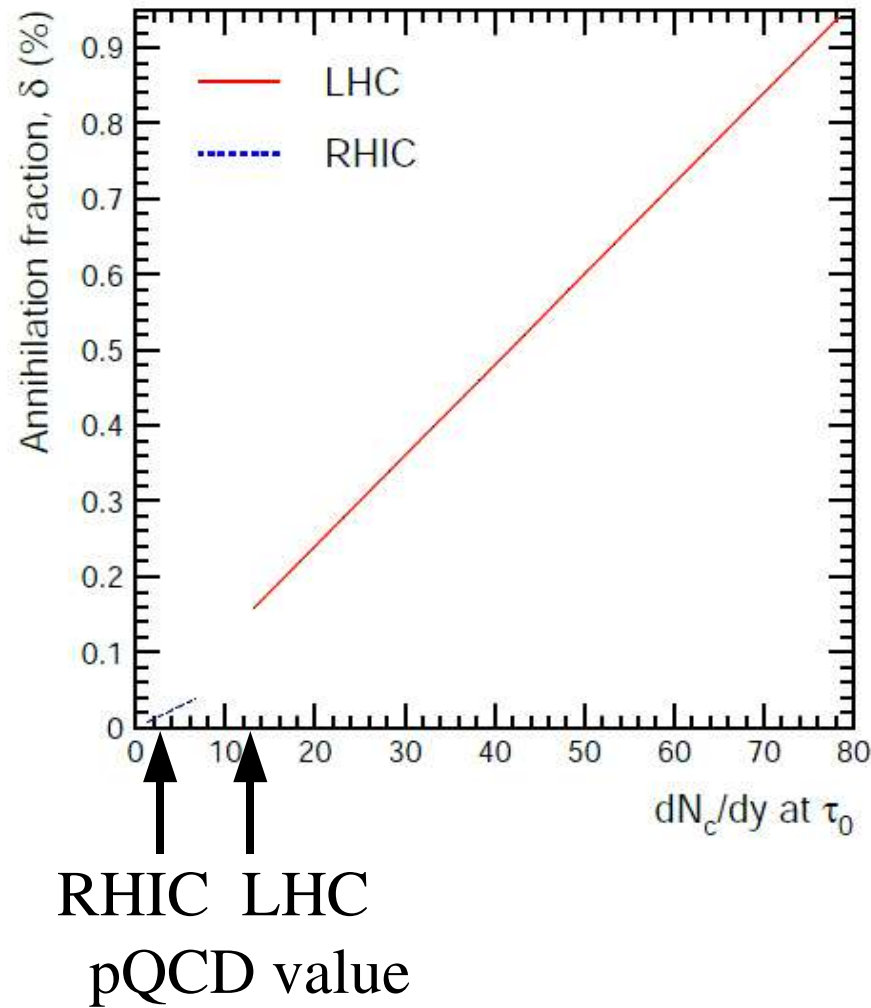
thermal average evaluated in Boltzmann approximation following Lin & Ko, PRC 62 (2000) 034903

cross section is of order 0.1 mb



annihilation fraction

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

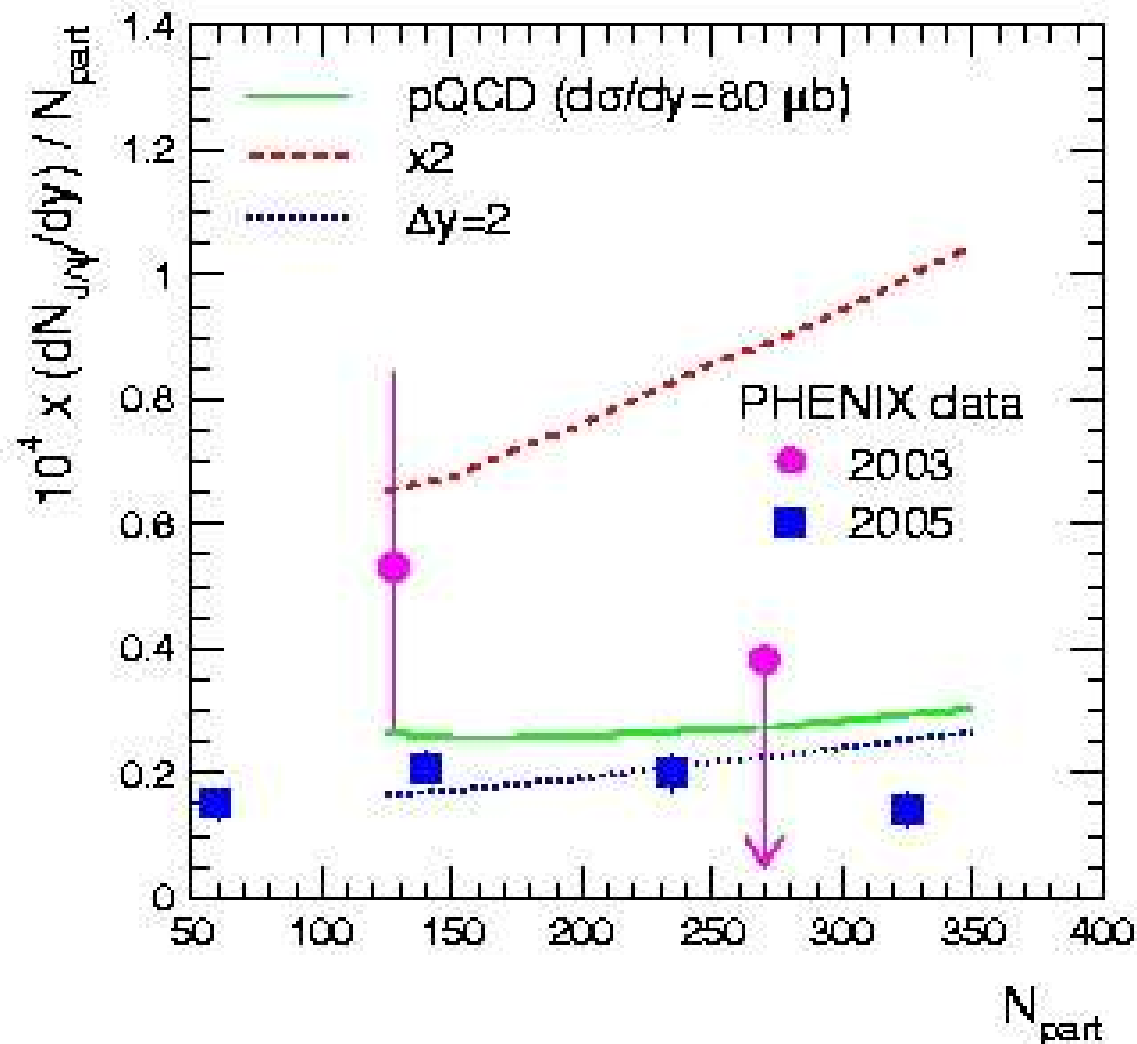


summary of annihilation calculation

- 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 ($\ll 0.2\%$ of $c\bar{c}$)
→ 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

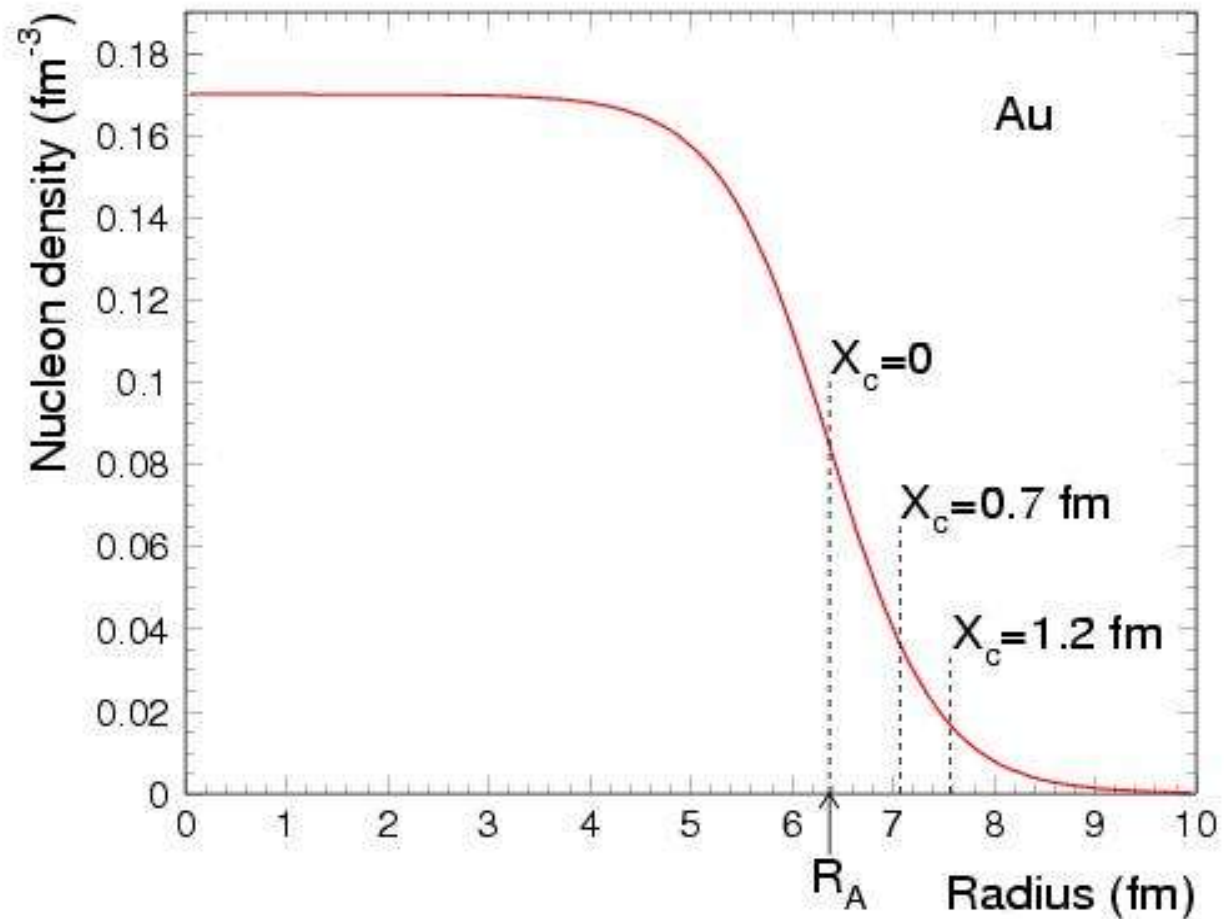


New results: take into account the corona effect

see also: Klaus Werner,
hep-ph/0603064

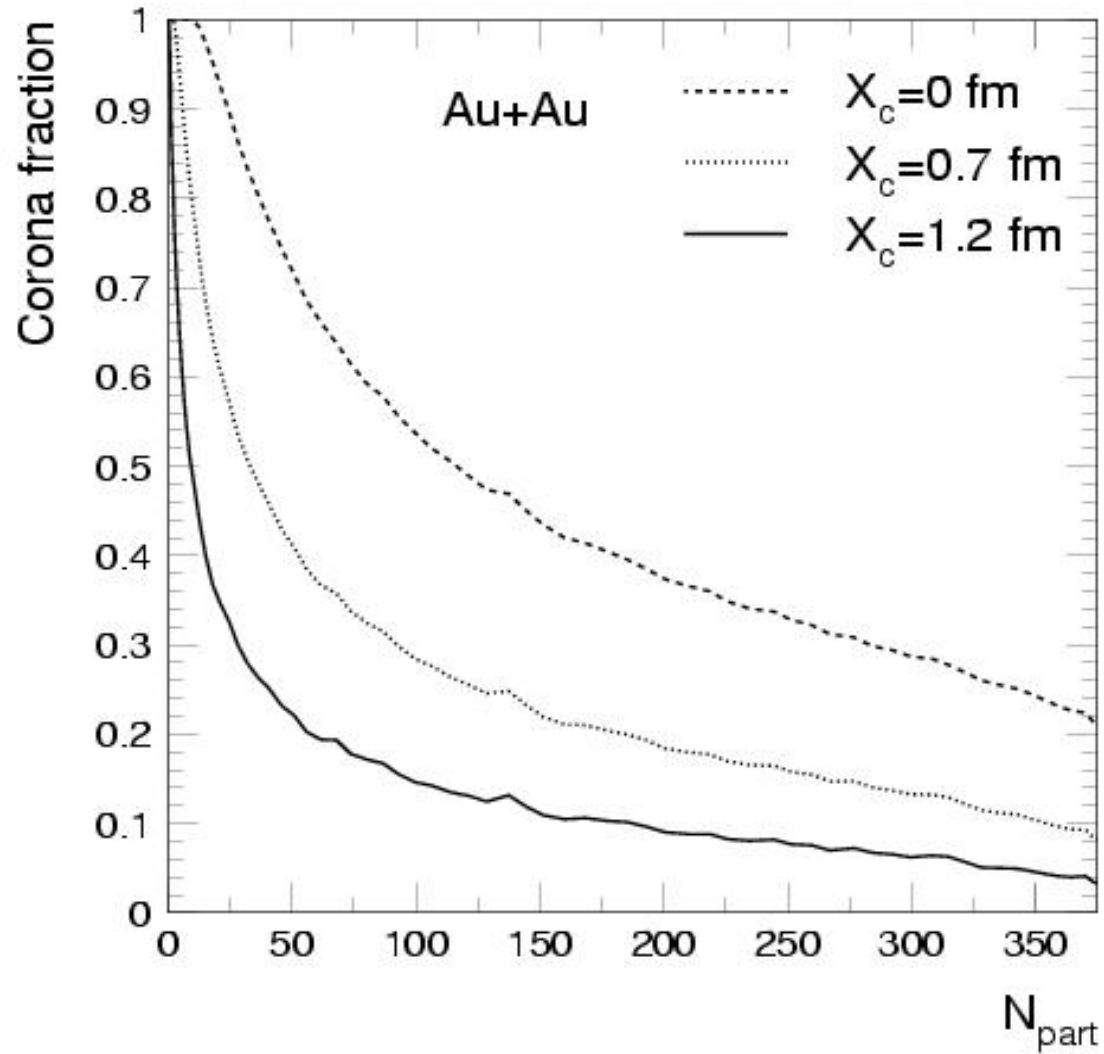
$$N_{\text{part}}(b) = N_{\text{core}}(b) + N_{\text{corona}}(b)$$

$$X_c = 1.2 \text{ fm} \quad \text{chosen}$$



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

Effect of corona



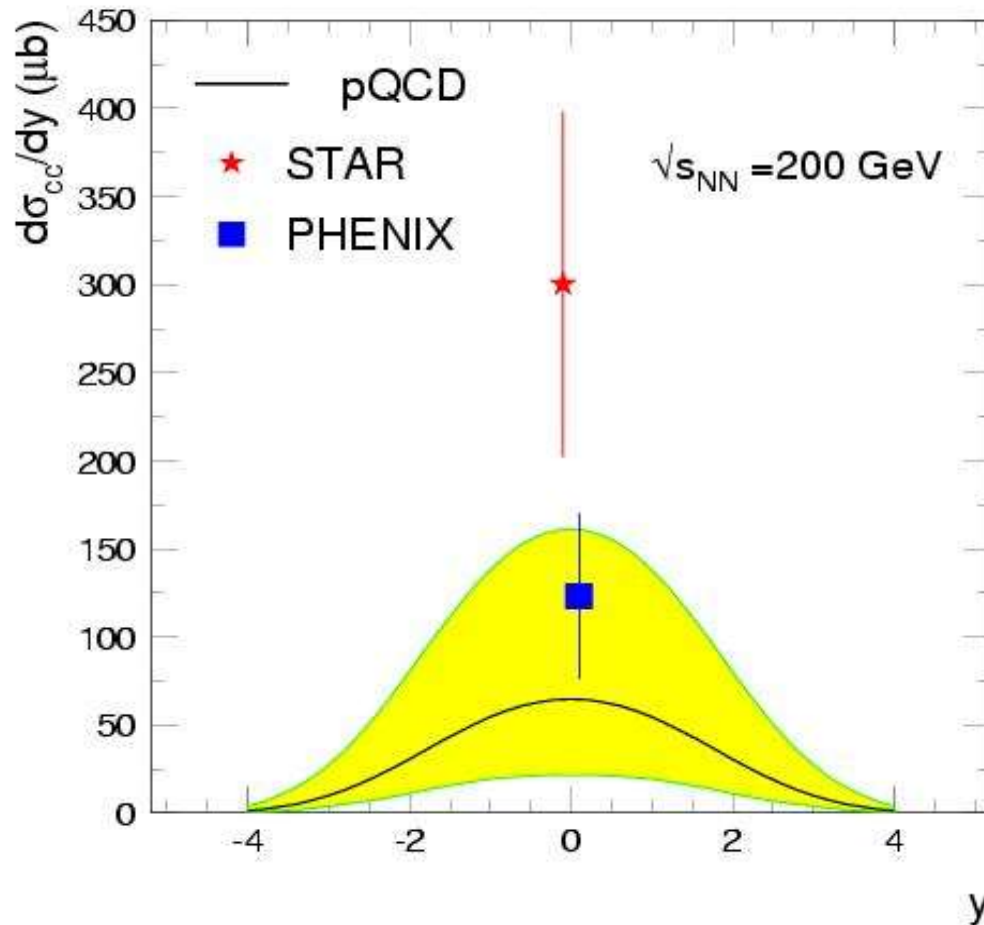
Ingredients for prediction of quarkonia cross section

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

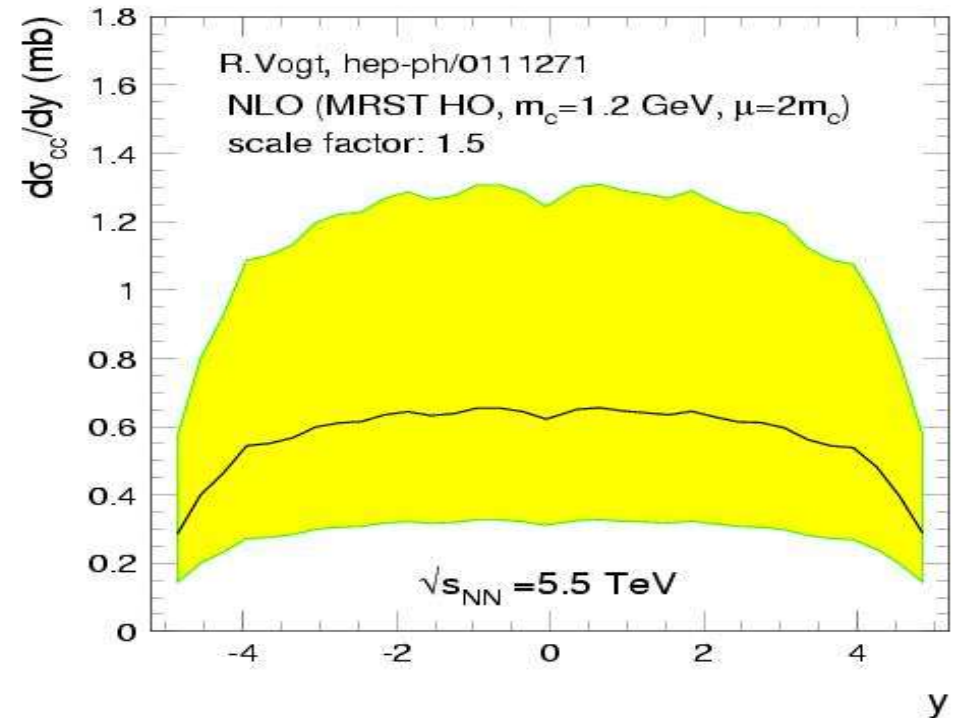
result: quarkonia cross sections as function of energy, centrality, rapidity, and transverse momentum

open charm data and comparison with pQCD

RHIC



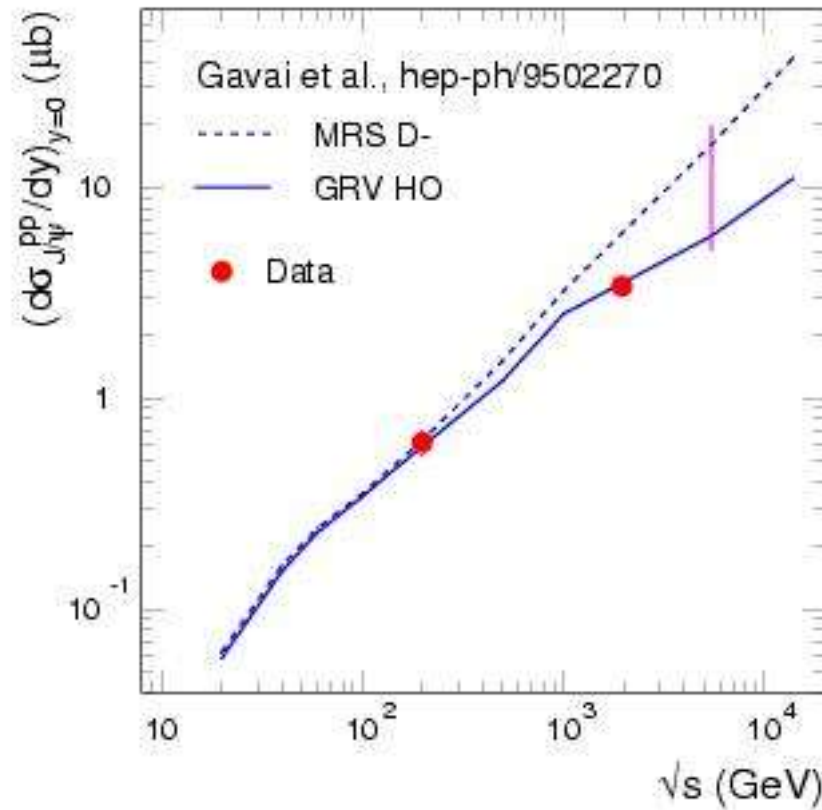
LHC



measured values somewhat (Phenix) larger than pQCD predictions

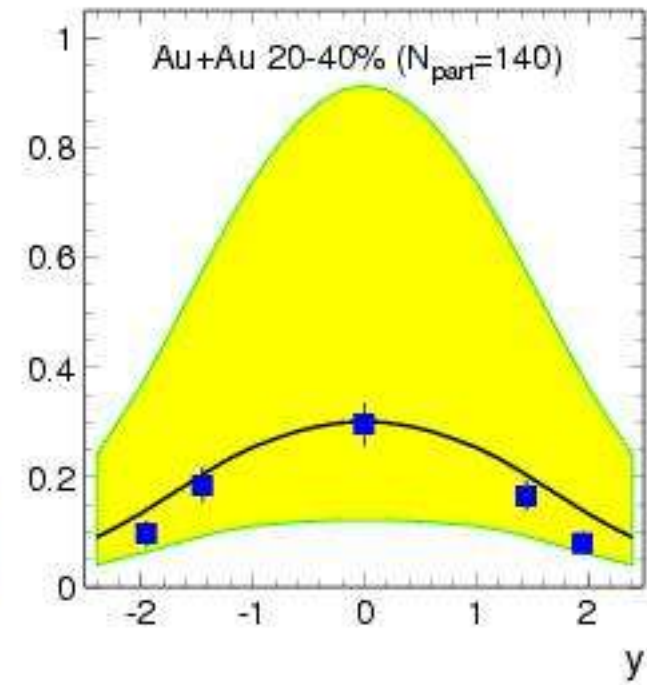
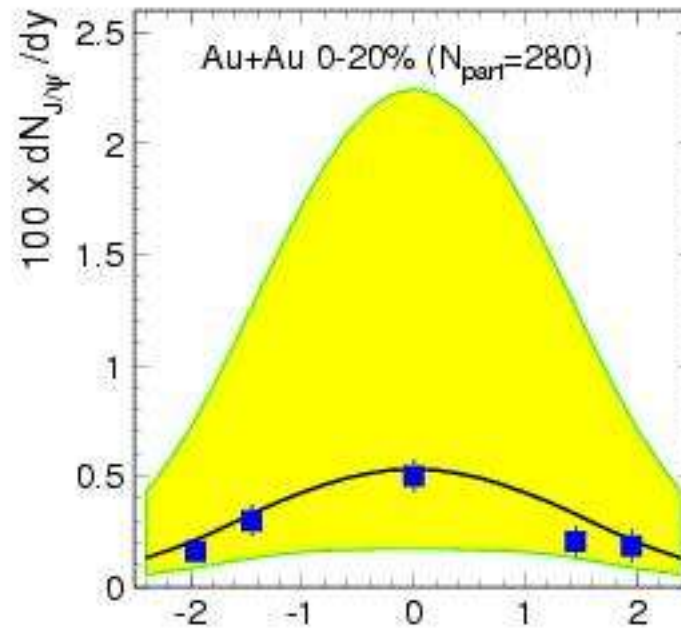
J/ψ cross section in pp collisions

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 section
by:
M. Cacciari, P. Nason, R.
Vogt,
Phys. Rev. Lett. 95 (2005)
122001, hep-ph/0502203



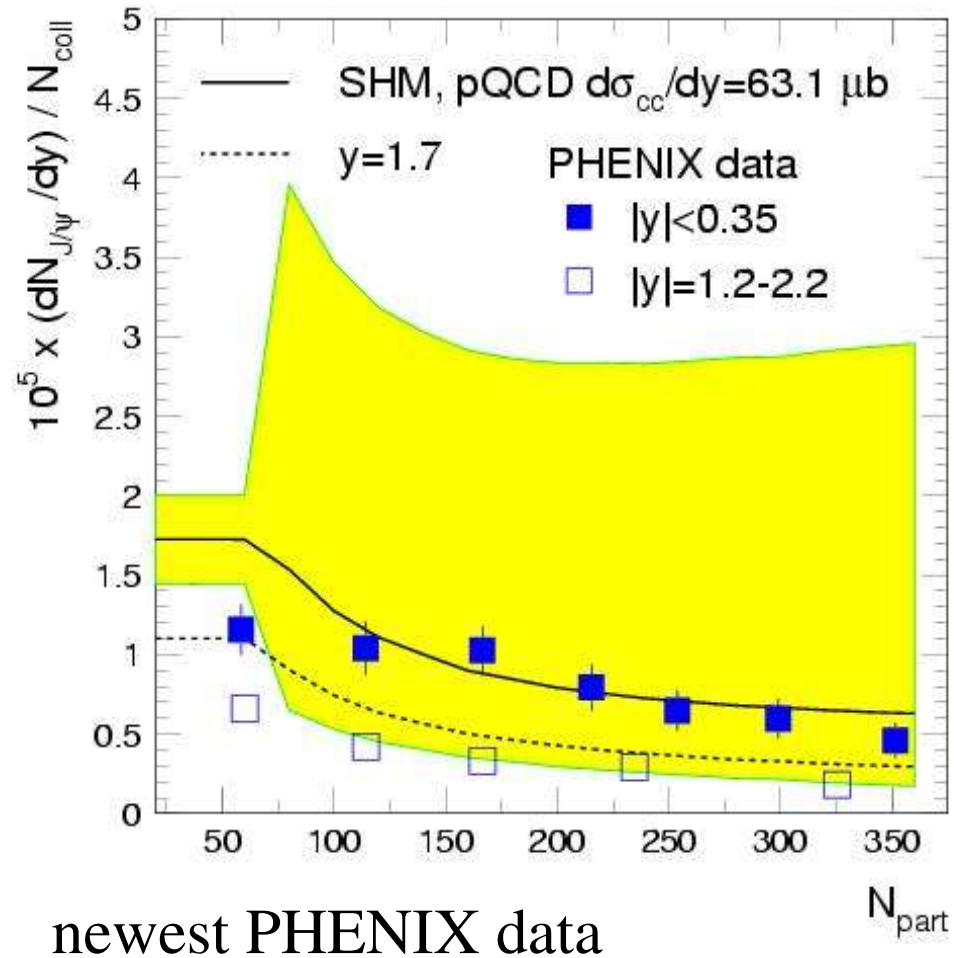
newest PHENIX data

rapidity dependence is
very well reproduced
by statistical
hadronization model

Comparison of model predictions to RHIC data: centrality dependence

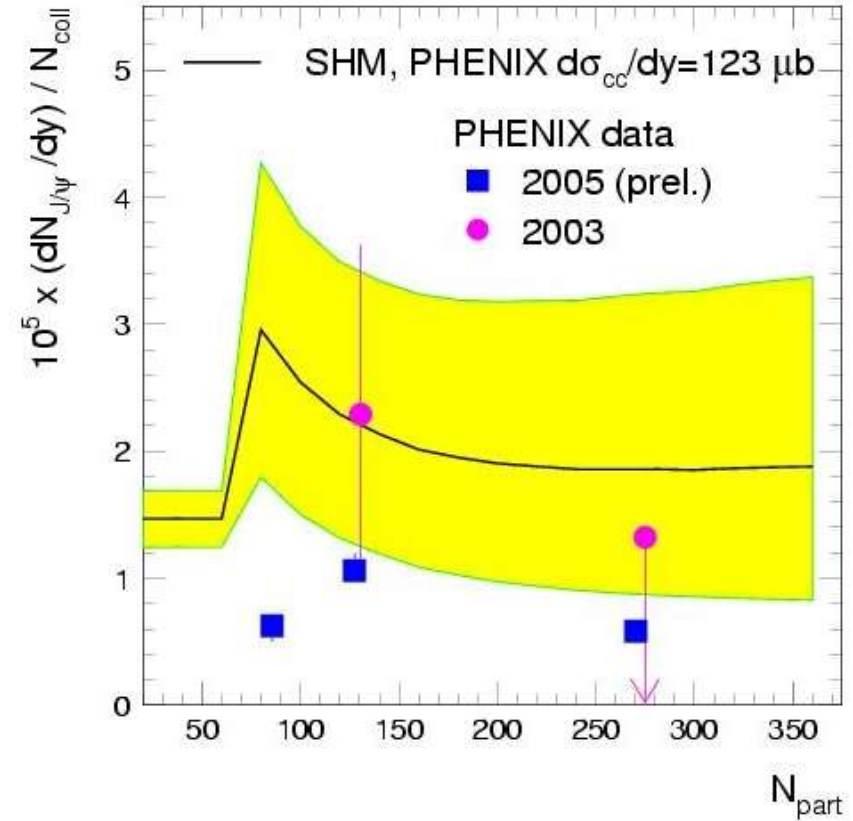
predictions for J/ψ production
using NNLO pQCD results for
open charm cross section by
M. Cacciari, P. Nason, R. Vogt,
Phys. Rev. Lett. 95 (2005)
122001, hep-ph/0502203

good agreement, no free
parameters



Comparison of model predictions to RHIC data: centrality dependence

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

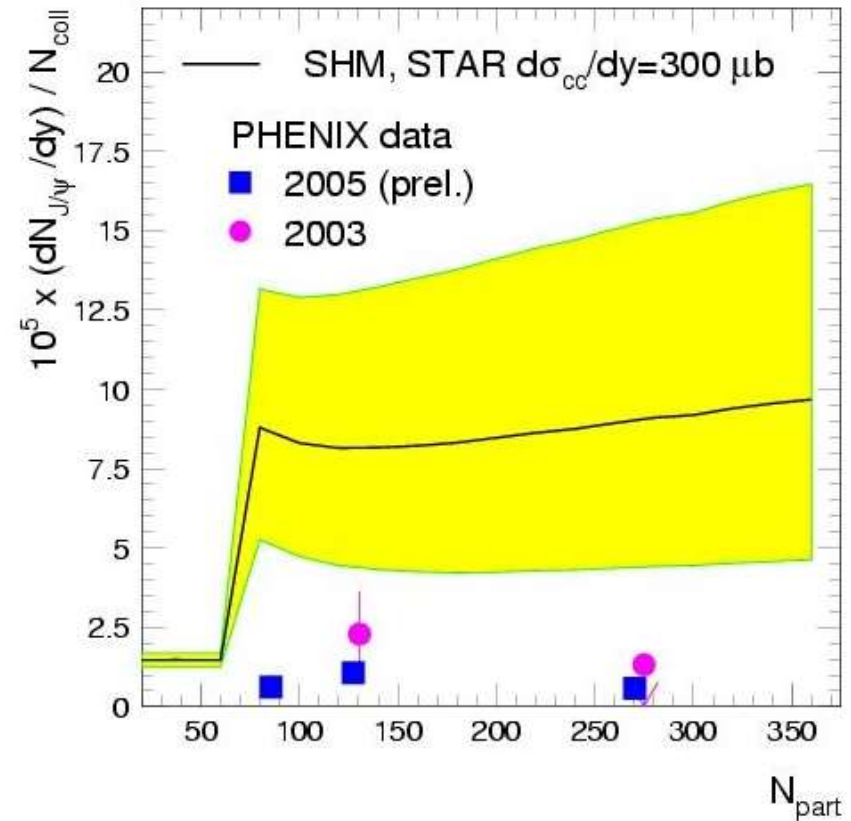


Comparison of model predictions to RHIC data: centrality dependence

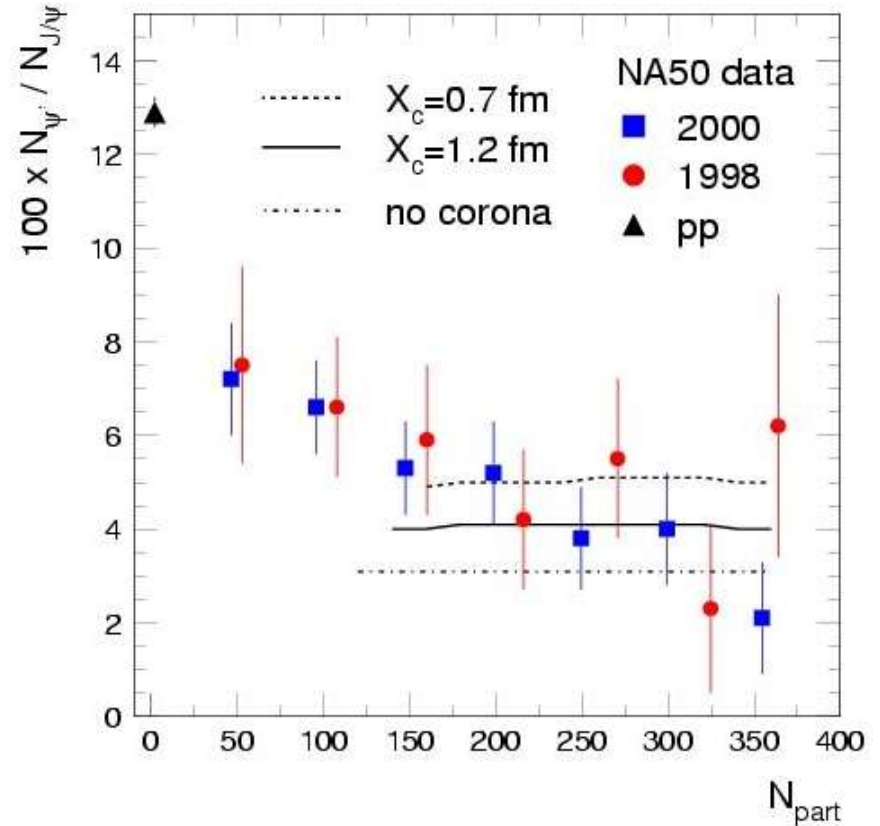
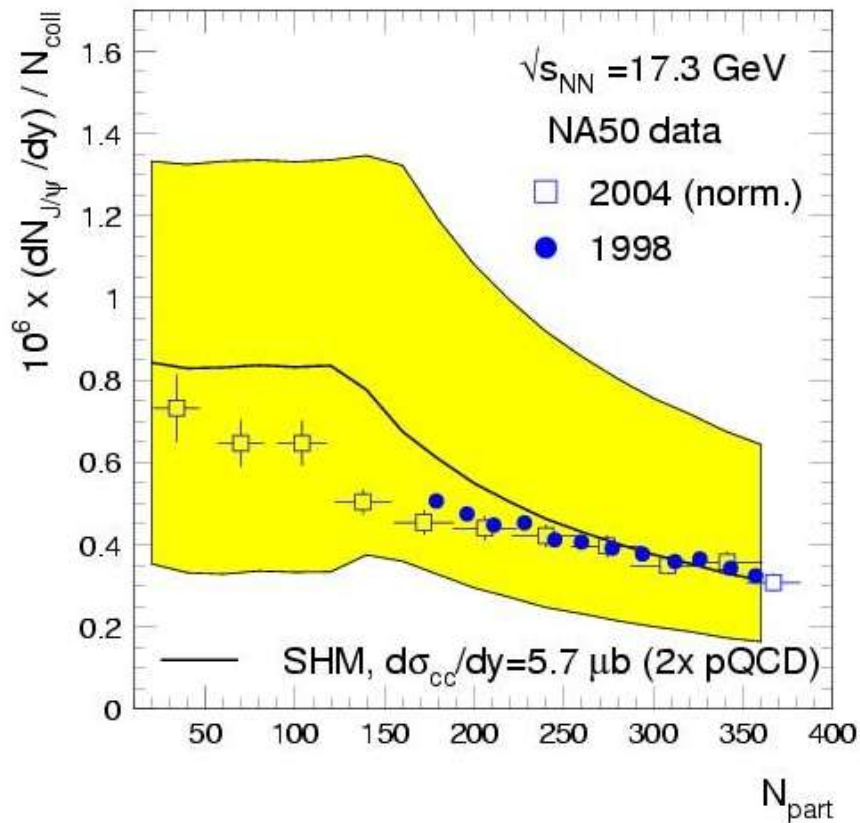
predictions for J/ψ production
using STAR exp. results for
the open charm cross section

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

$$J/\psi/cc_bar = 0.2 \%$$



back to SPS energy



only moderately enhanced (2 x pQCD) $c\bar{c}$ cross section needed

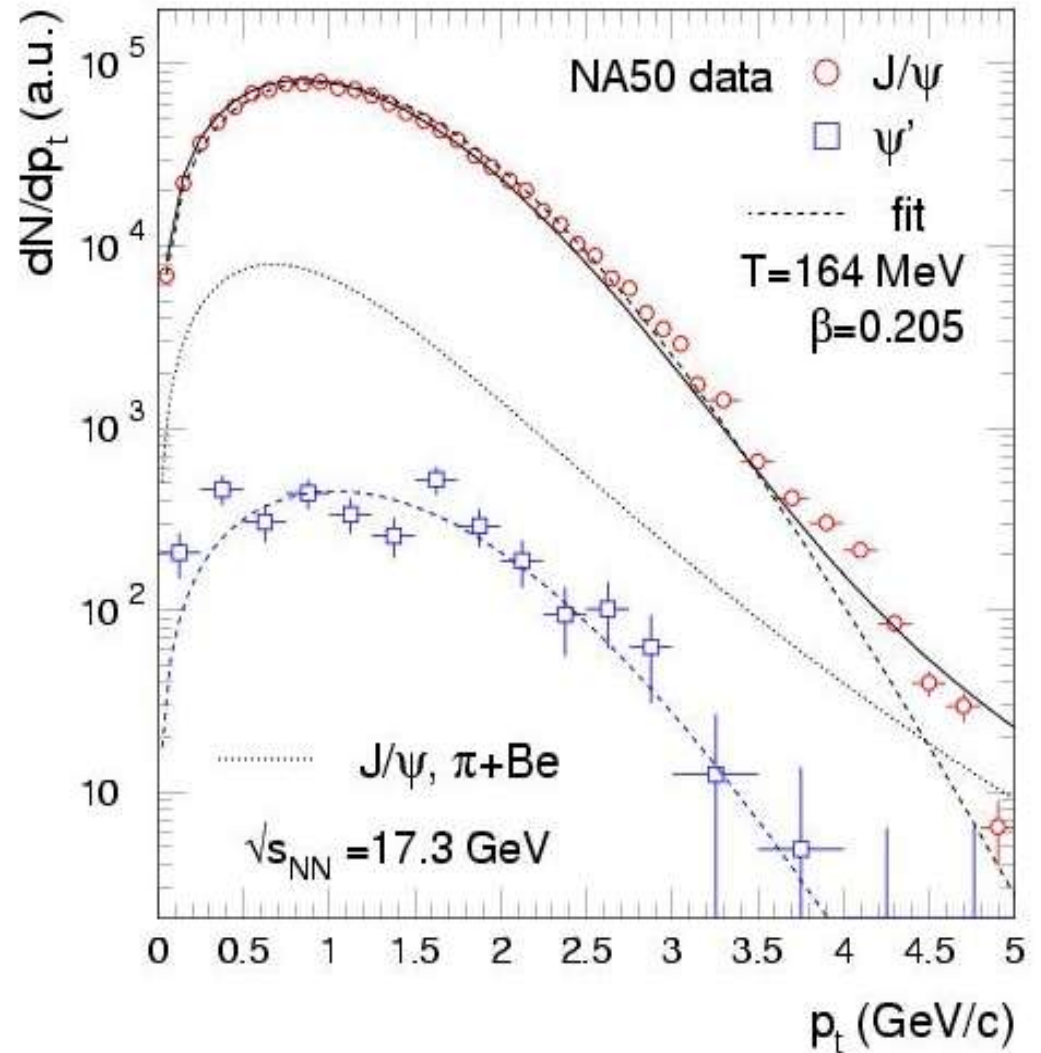
extrapolation to pp for ψ'/ψ ratio still problematic in the model,
 although intuitively clear

Transverse momentum distributions

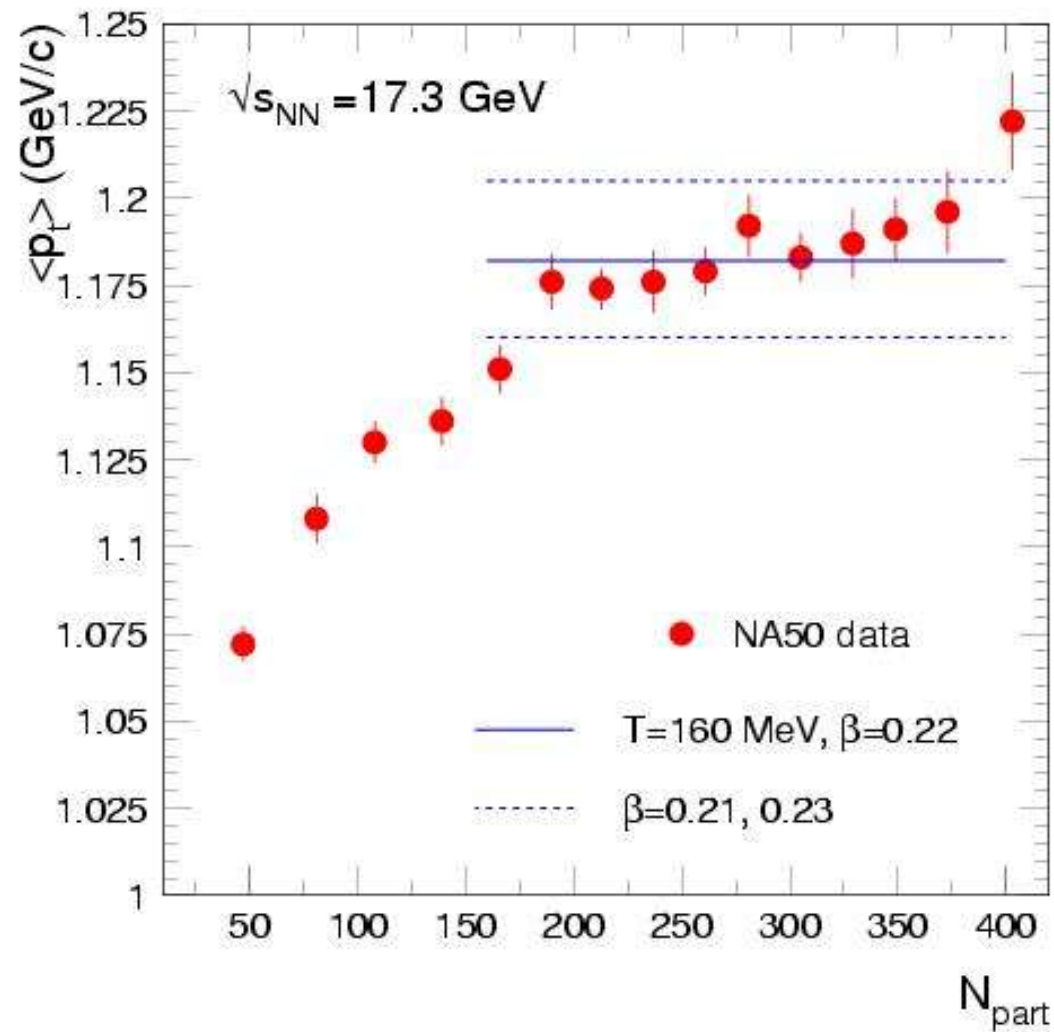
NA50 data

$$\frac{dN}{dp_t} \sim p_t \cdot m_t \cdot I_0\left(\frac{p_t \sinh y_t}{T}\right) \cdot K_1\left(\frac{p_t \cosh y_t}{T}\right)$$

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



Centrality dependence of $\langle p_T \rangle$ from NA50



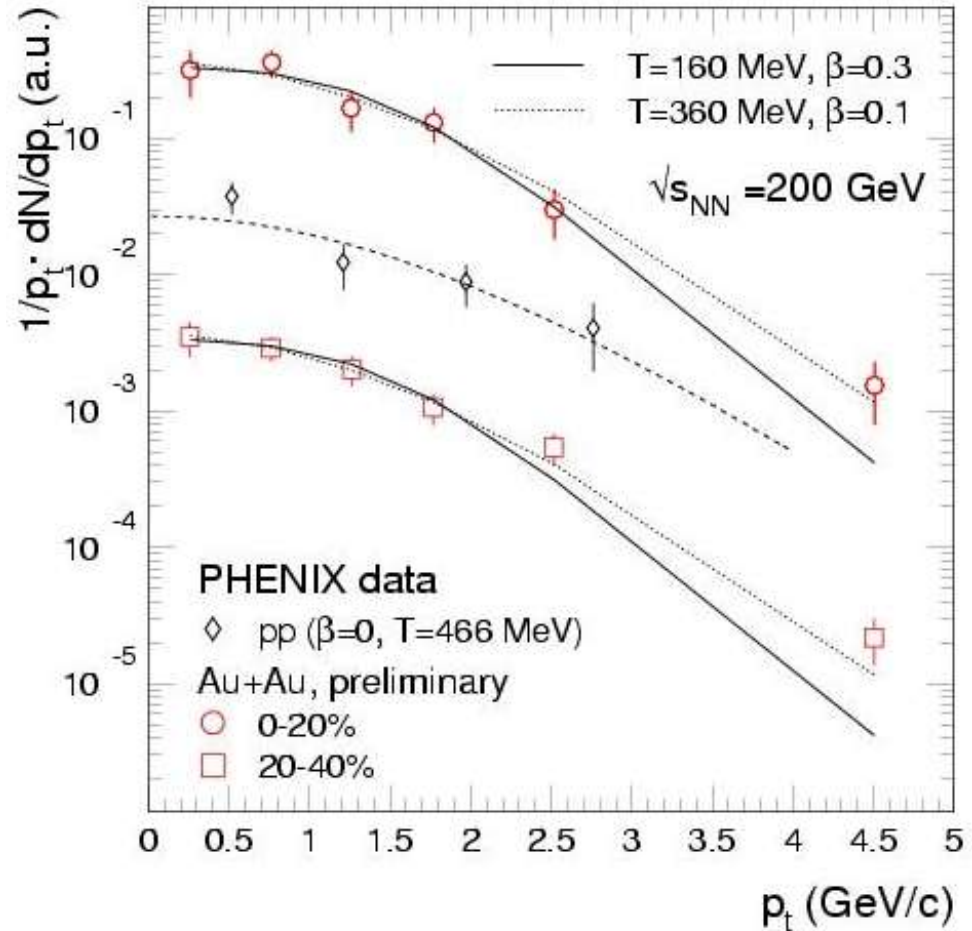
Transverse momentum distributions

PHENIX data

not yet very conclusive

$$\frac{dN}{dp_t} \sim p_t \cdot m_t \cdot I_0\left(\frac{p_t \sinh y_t}{T}\right) \cdot K_1\left(\frac{p_t \cosh y_t}{T}\right)$$

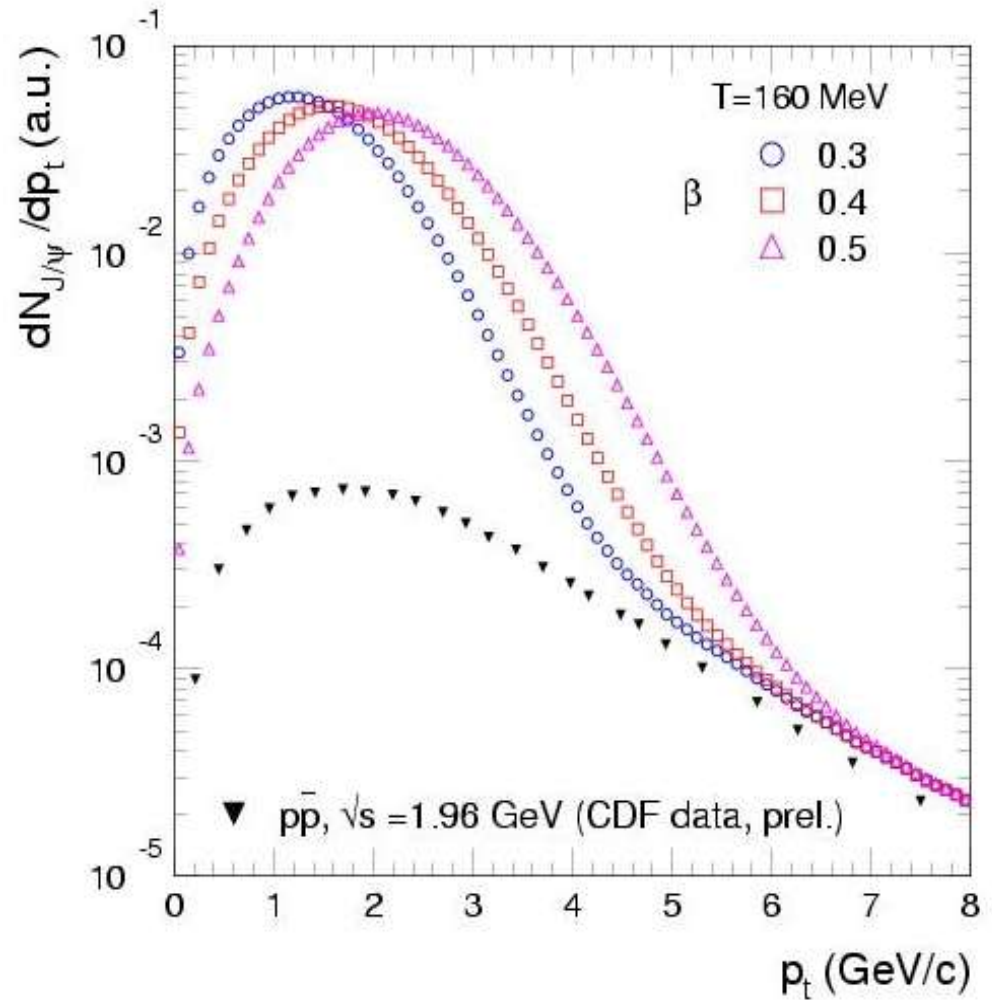
$$y_t = \tanh^{-1}(\beta)$$



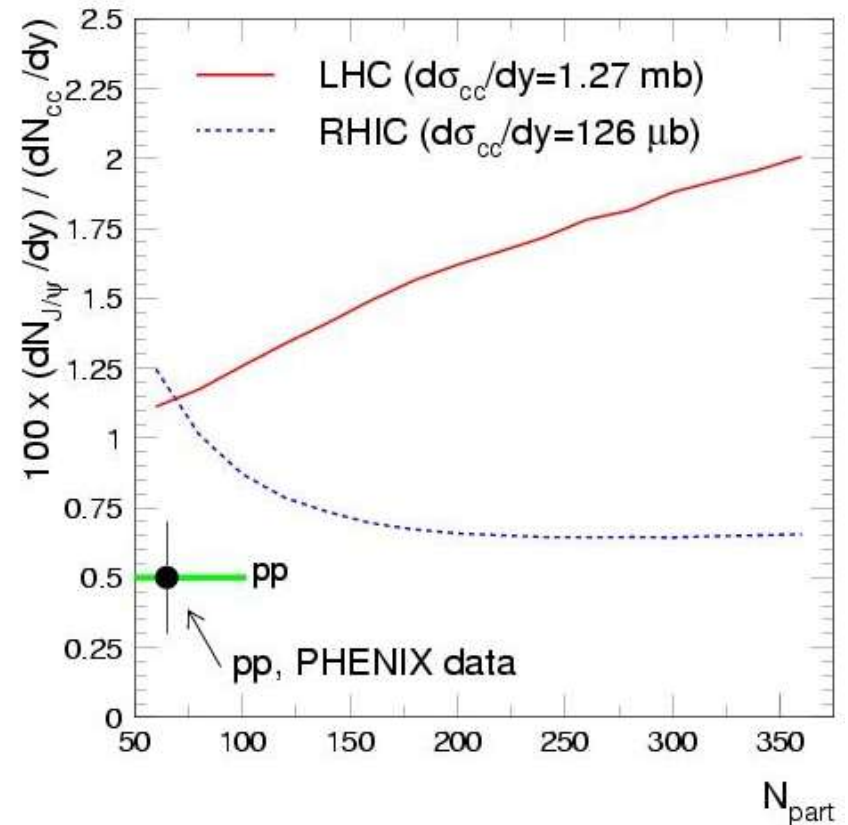
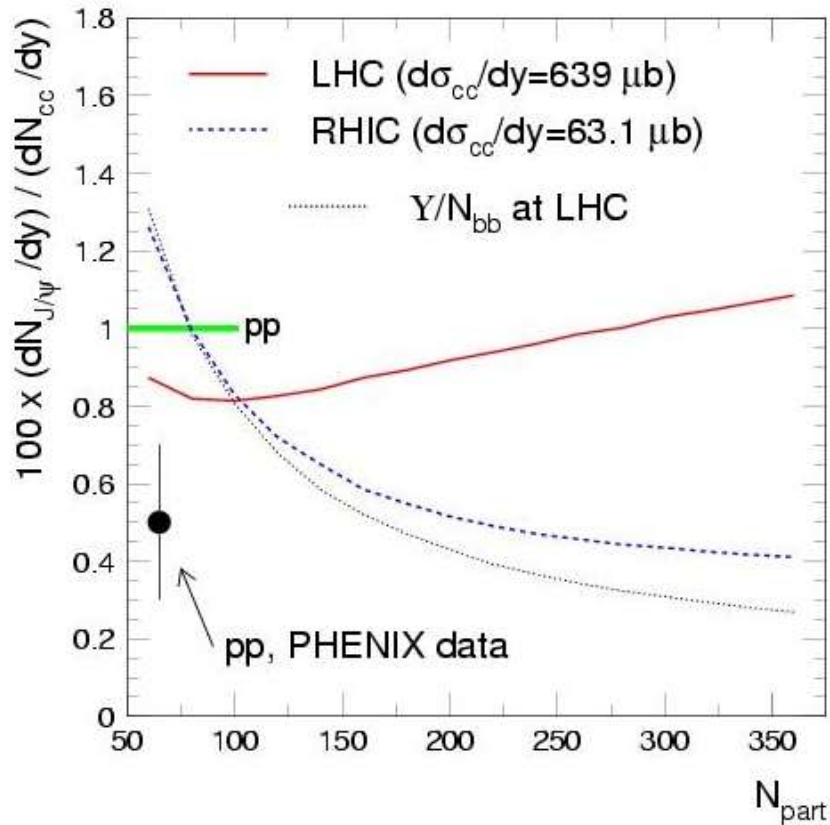
Flow of quarkonia?

pt spectra with flow are very different for charmonia from those measured in $p\bar{p}$ at Fermilab

should be easy to discriminate at LHC



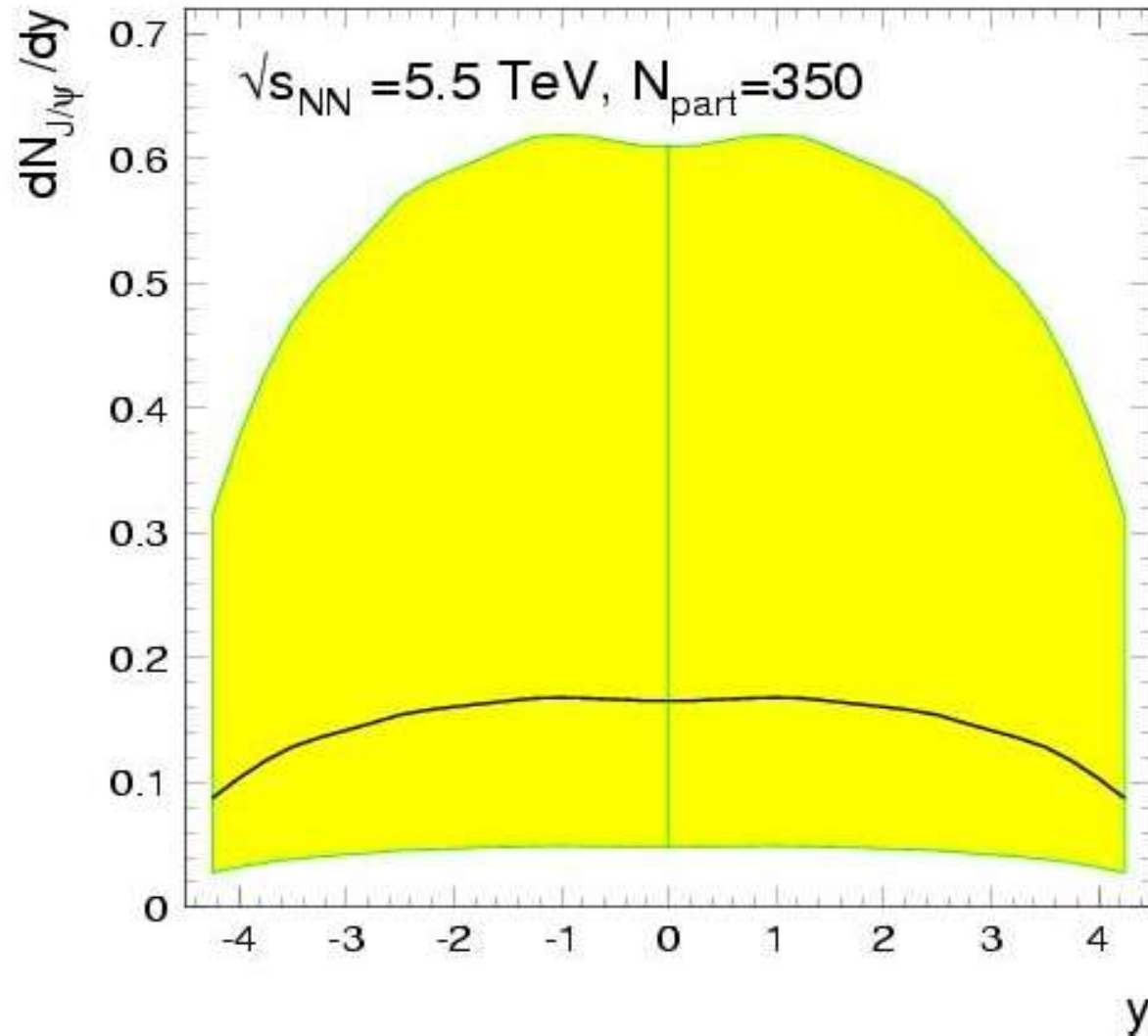
Extrapolation to LHC energy



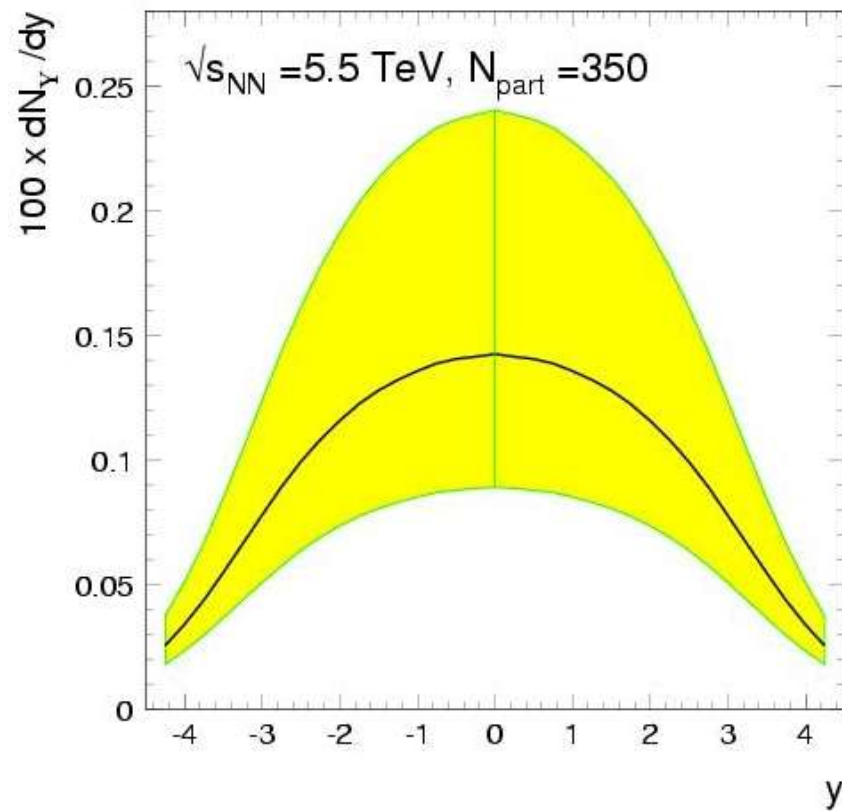
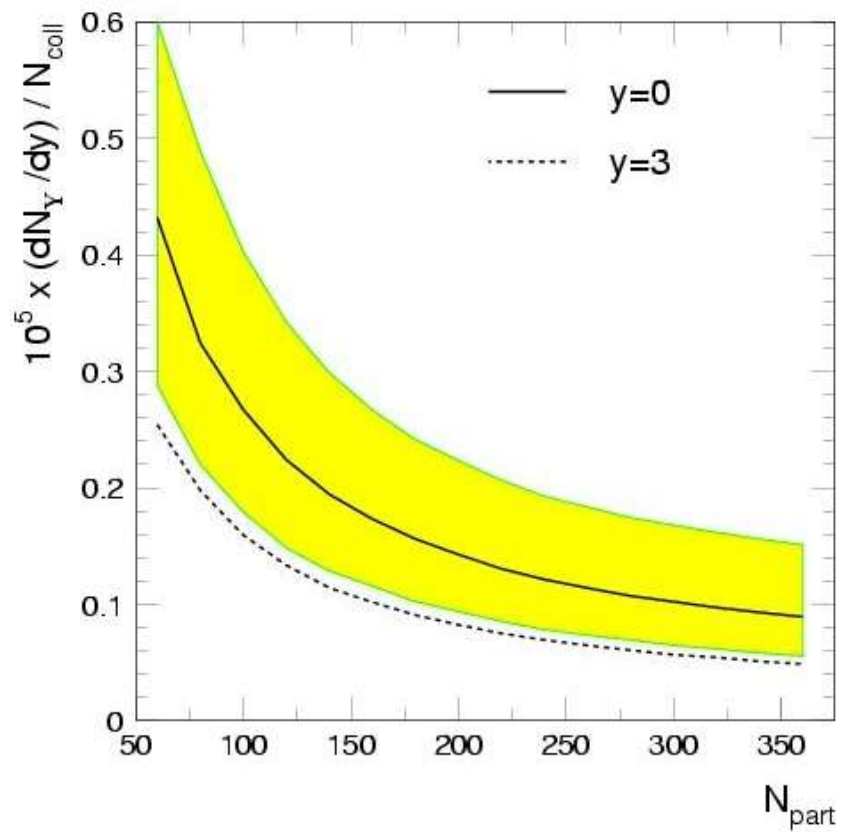
centrality dependence and enhancement beyond pp value
will be fingerprint of stat. coalescence at LHC

a direct signal for deconfinement

Predictions for charmonium at LHC



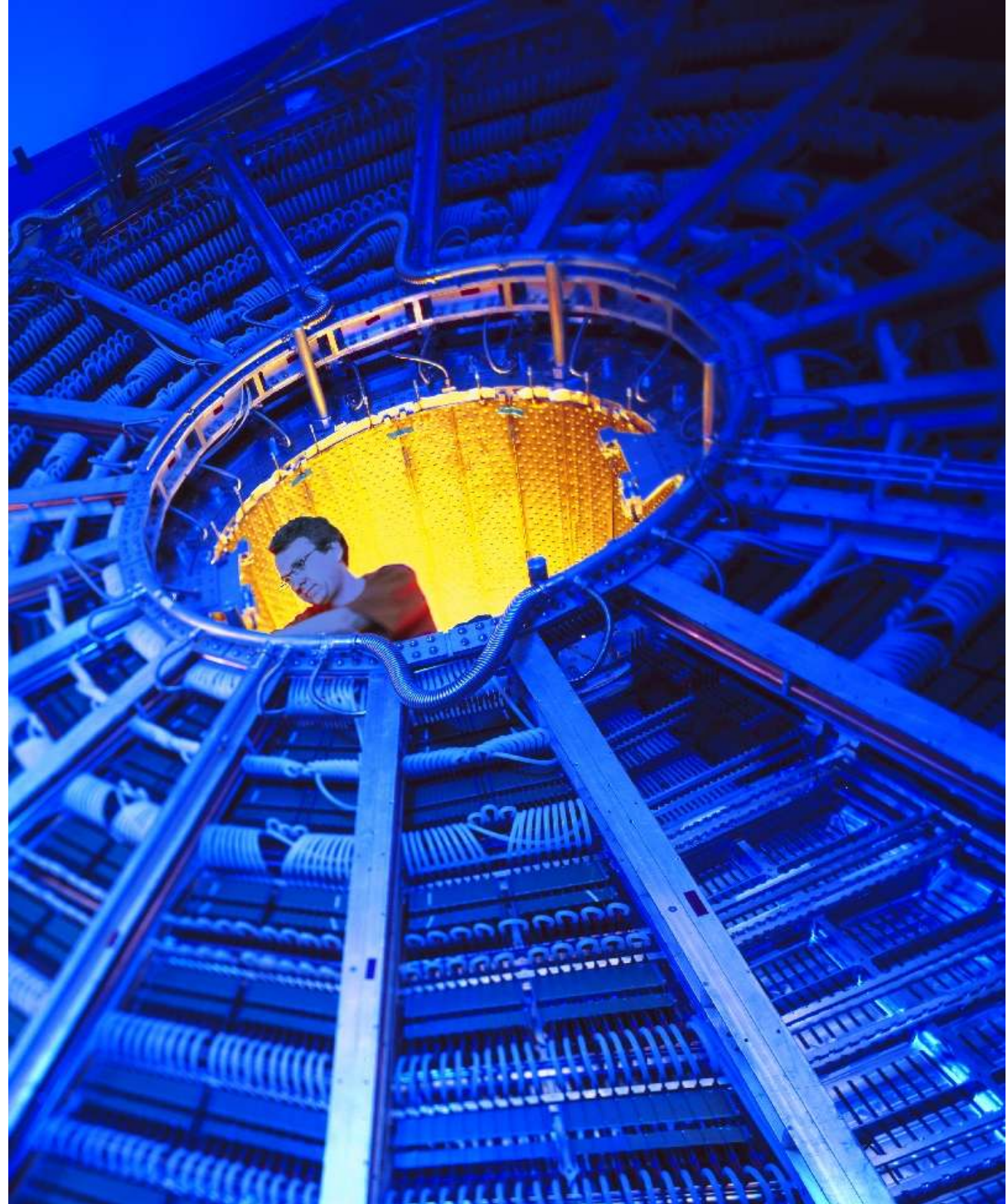
Beauty at LHC



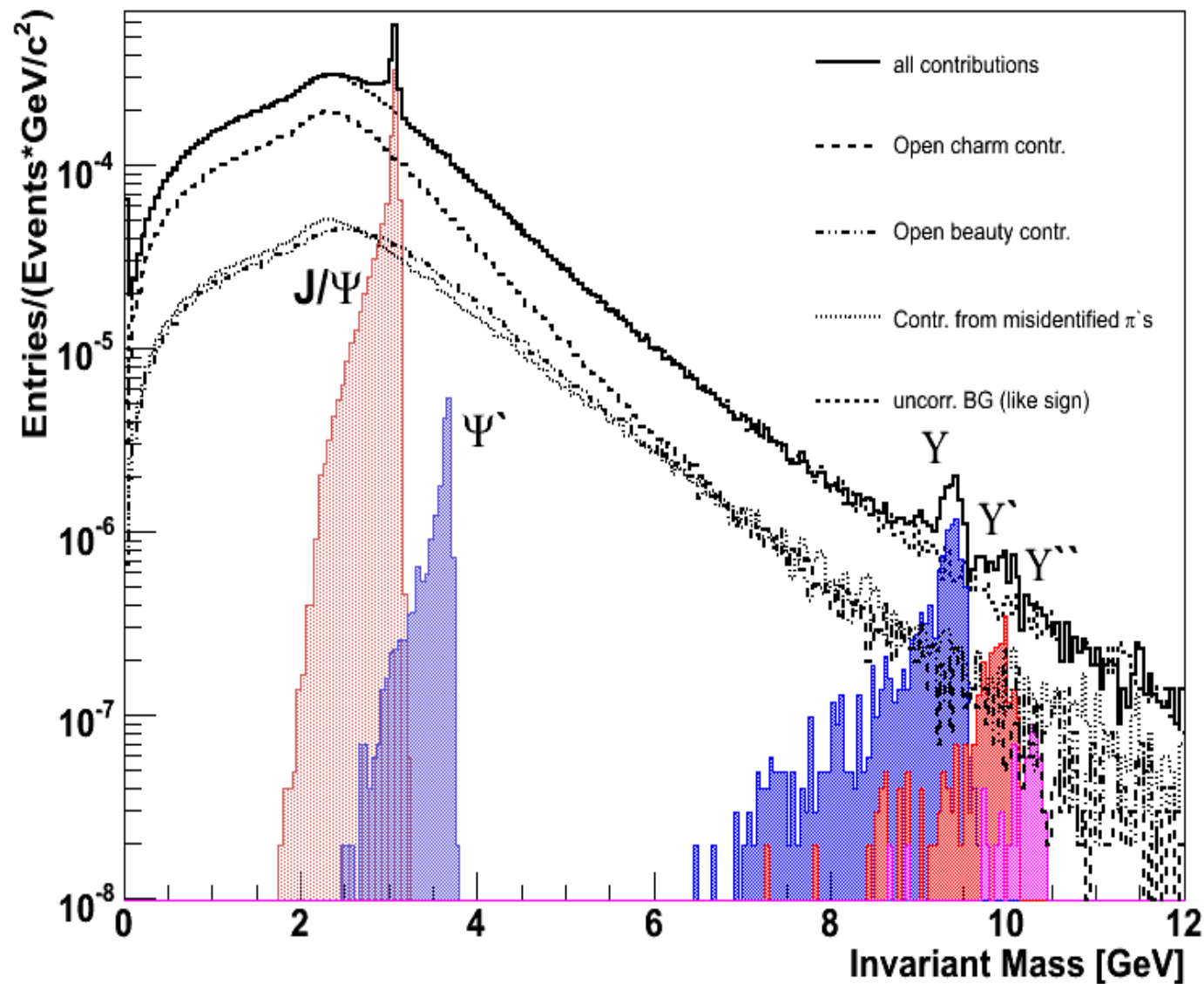
ALICE@LHC

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

presentation by Luciano Musa on Wednesday



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



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

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:

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

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

differential cross section

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

with

$$M_{ss} = \frac{4}{s^2} (t - m^2)(u - m^2),$$
$$M_{tt} = \frac{-2}{(t - m^2)^2} \left[4m^4 - (t - m^2)(u - m^2) \right. \\ \left. + 2m^2(t - m^2) \right],$$
$$M_{uu} = \frac{-2}{(u - m^2)^2} \left[4m^4 - (u - m^2)(t - m^2) \right. \\ \left. + 2m^2(u - m^2) \right], \quad (\text{A2})$$
$$M_{st} = \frac{4}{s(t - m^2)} \left[m^4 - t(s + t) \right],$$
$$M_{su} = \frac{4}{s(u - m^2)} \left[m^4 - u(s + u) \right],$$
$$M_{tu} = \frac{-4m^2}{(t - m^2)(u - m^2)} \left[4m^2 + (t - m^2) + (u - m^2) \right],$$

total cross section

$$\sigma^{gg \rightarrow c\bar{c}} = \frac{\pi \alpha_s^2}{64s} \left[12 \left(\frac{2}{3} + \frac{1}{3} \gamma \right) (1 - \gamma)^{1/2} + \frac{16}{3} \left((4 + 2\gamma) \ln \frac{1 + (1 - \gamma)^{1/2}}{1 - (1 - \gamma)^{1/2}} - 4(1 + \gamma)(1 - \gamma)^{1/2} \right) \right. \\ \left. + 6 \left(2\gamma \ln \frac{1 + (1 - \gamma)^{1/2}}{1 - (1 - \gamma)^{1/2}} - 4(1 + \gamma)(1 - \gamma)^{1/2} \right) - \frac{2}{3} 2\gamma(1 - \gamma) \ln \frac{1 + (1 - \gamma)^{1/2}}{1 - (1 - \gamma)^{1/2}} \right]$$

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

using detailed balance yields final result:

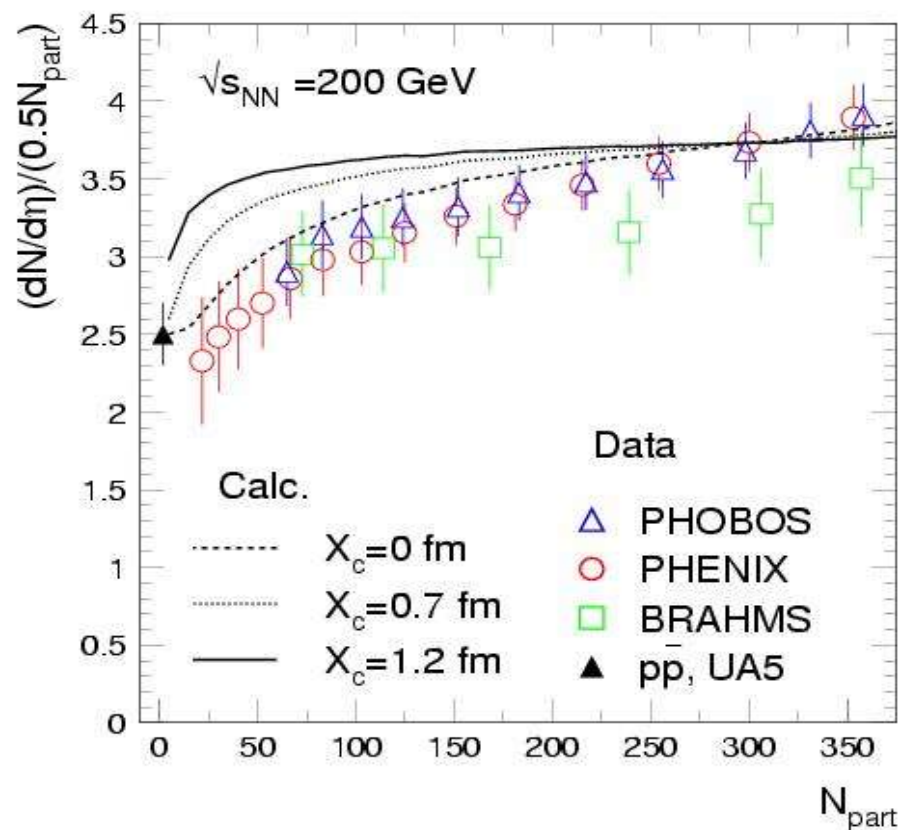
$$\sigma_{c\bar{c} \rightarrow gg}(s) = \sigma_{gg \rightarrow c\bar{c}} \cdot \frac{9}{4} \frac{s^2}{\sqrt{(s^2 - 4m_c^2)s} \sqrt{((s - 2m_c^2)^2 - 4m_c^4)}}$$

note: giving gluons a thermal mass $\sim gT$ 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

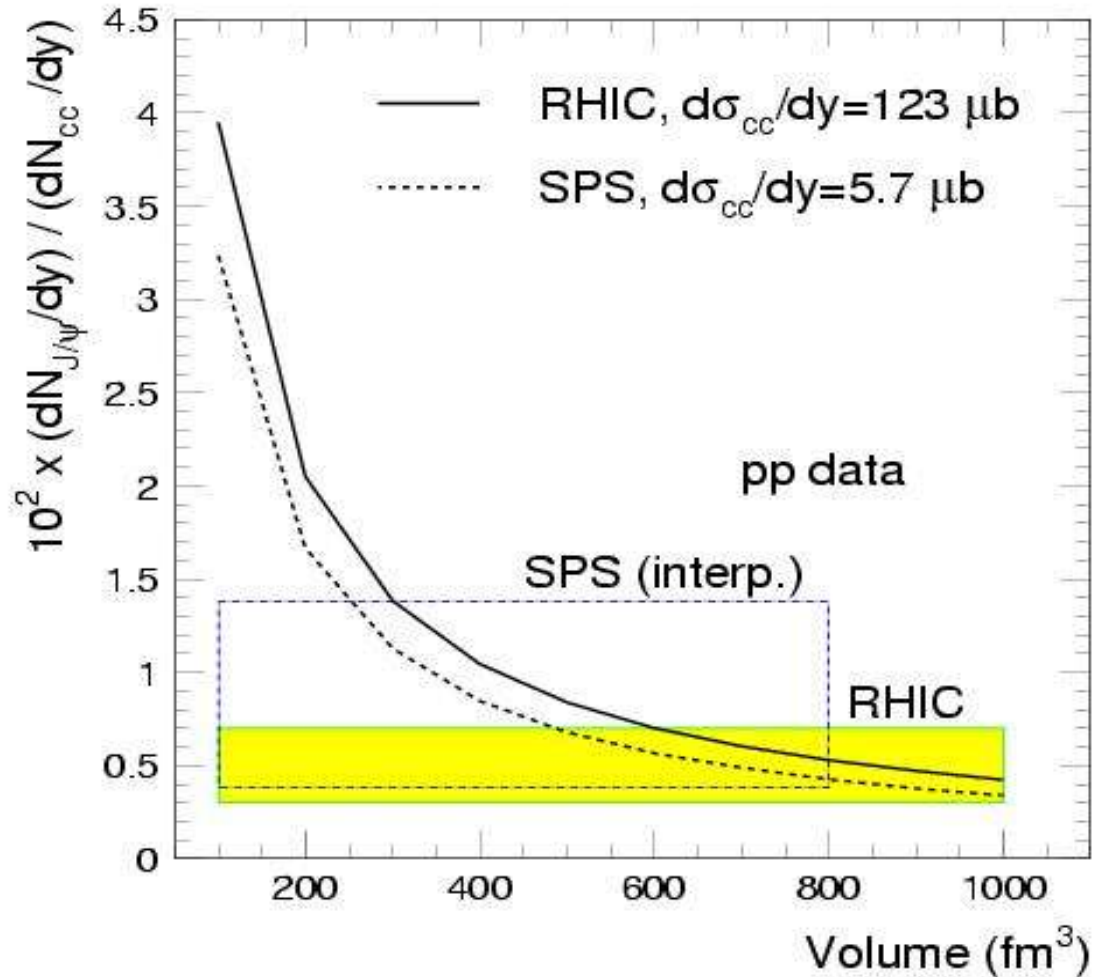
only small X_c values compatible with measured $dN_{ch}/d\eta$



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 1st approximation



Charm at LHC: Statistical hadronization vs. NLO

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

we have also
yields for multiply
charmed hadrons

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