

# Charmonium production via statistical hadronization

the statistical hadronization model  
phase boundary between QGP and hadronic matter  
statistical hadronization of charm  
and experimental data on charmonia

based on work done in collaboration with  
A. Andronic, P. Braun-Munzinger and K. Redlich

Johanna Stachel, Physikalisches Institut, U. Heidelberg  
QWG 2011 - 8<sup>th</sup> Int. Workshop on Heavy Quarkonium - GSI Oct. 6, 2011

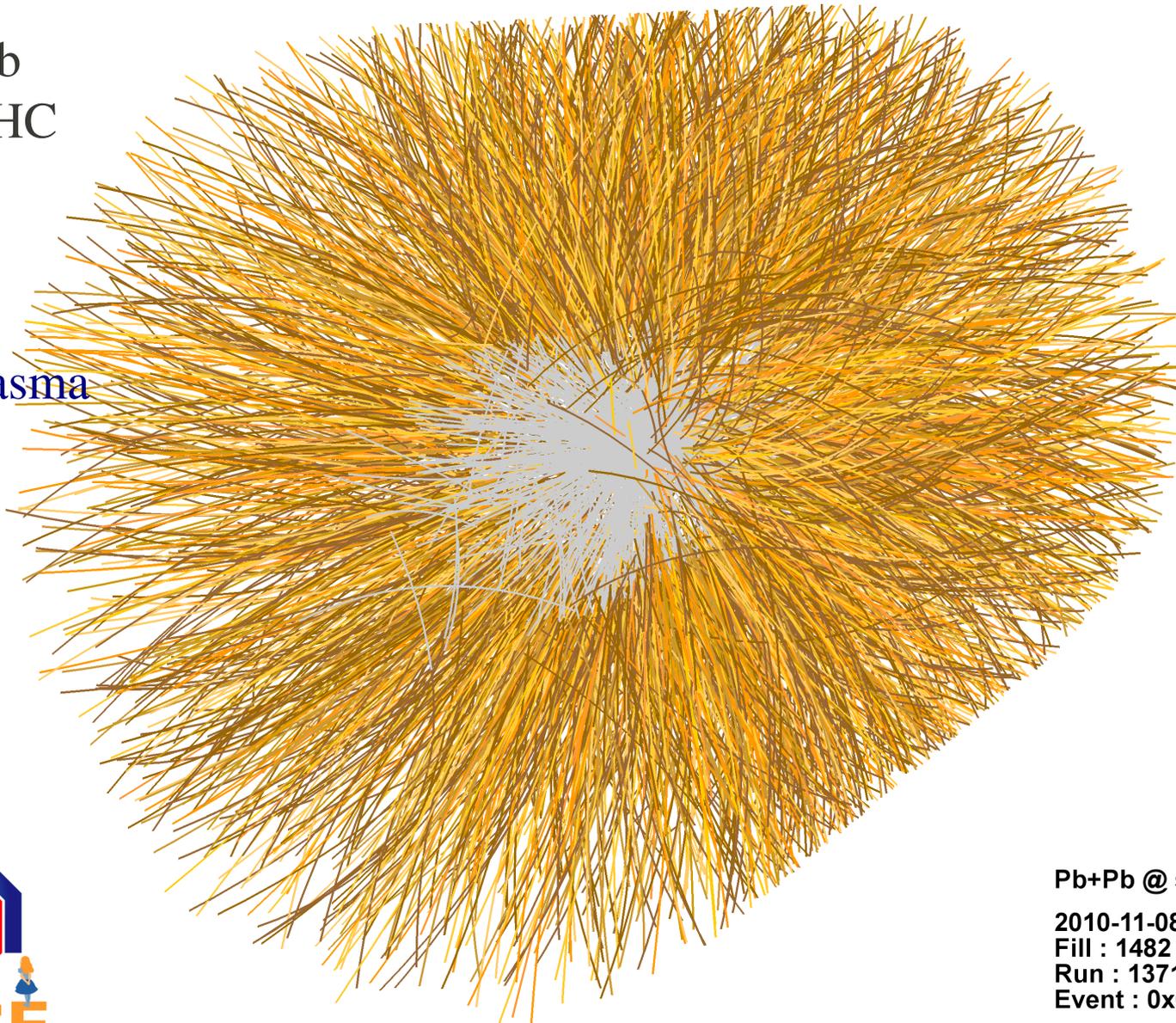


the starting point: in high energy nuclear collisions the hot fireball hadronizes into thousands of mesons and baryons

e.g. in central PbPb collisions at the LHC  
 $dN_{ch}/dy = 1600$

hadronization of a Quark-Gluon Plasma of tens of thousands of quarks and gluons

can we treat this statistically?



Pb+Pb @ sqrt(s) = 2.76 ATeV  
2010-11-08 11:30:46  
Fill : 1482  
Run : 137124  
Event : 0x00000000D3BBE693

# analysis of yields of produced hadronic species in statistical model – grand canonical

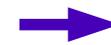
partition function:  $\ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 dp \ln(1 \pm \exp(-(E_i - \mu_i)/T))$

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

for every conserved quantum number there is a chemical potential:

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

but can use conservation laws to constrain  $V, \mu_S, \mu_{I_3}$



**Fit at each energy  
provides values for  
T and  $\mu_b$**

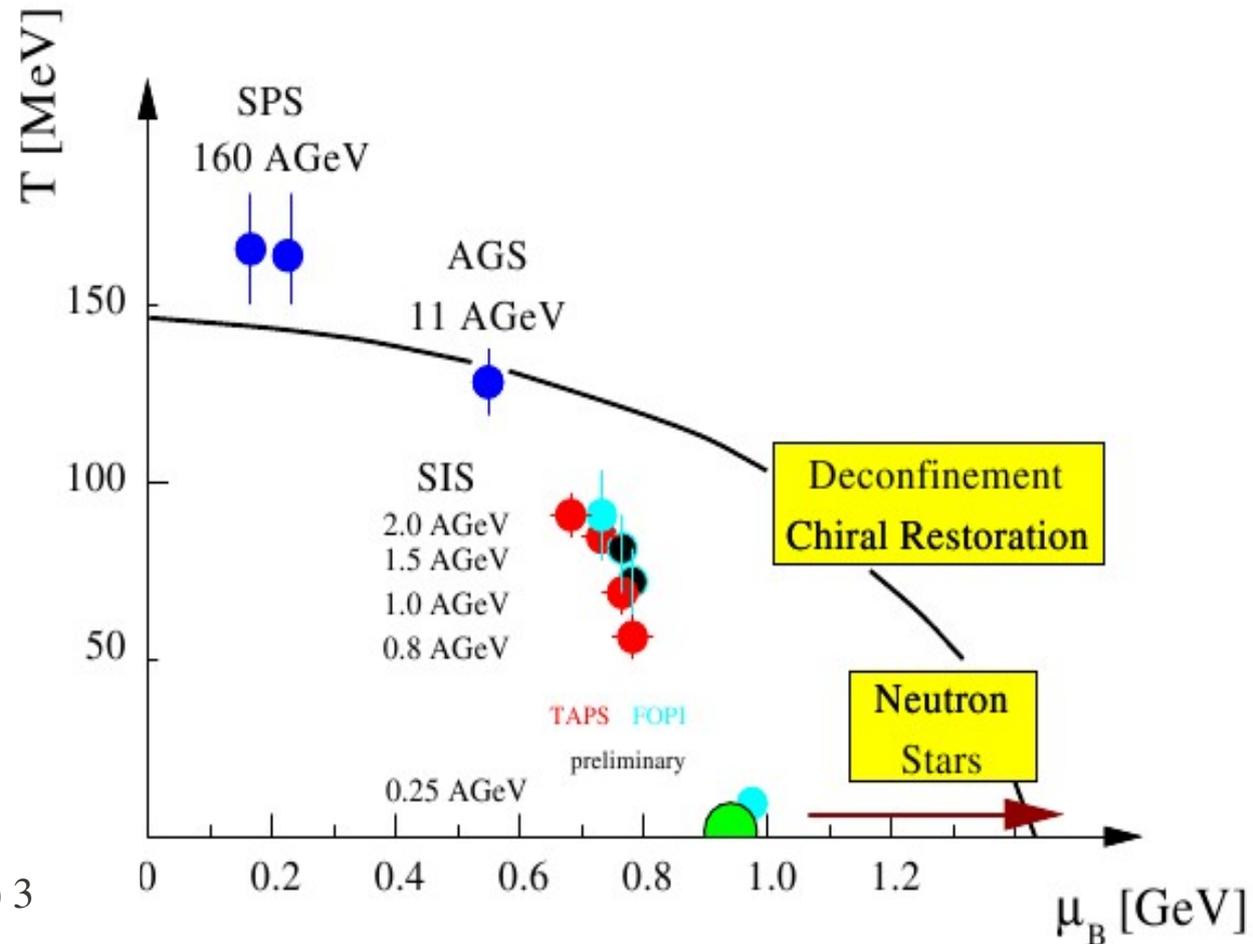
for a review see: Braun-Munzinger, Redlich, Stachel, QGP3,  
R. Hwa ed. (Singapore 2004) 491-599; nucl-th/0304013

attempts go way back: Shuryak for pp at ISR  
J. Cleymans Quarkmatter 1990 - at that time not very successful

### first successful description of data for SiPb collisions at AGS

P.Braun-Munzinger, J. Stachel, J.P. Wessels, N. Xu, Phys. Lett. B344 (1994) 43

leading eventually to the first phase diagram with experimental points

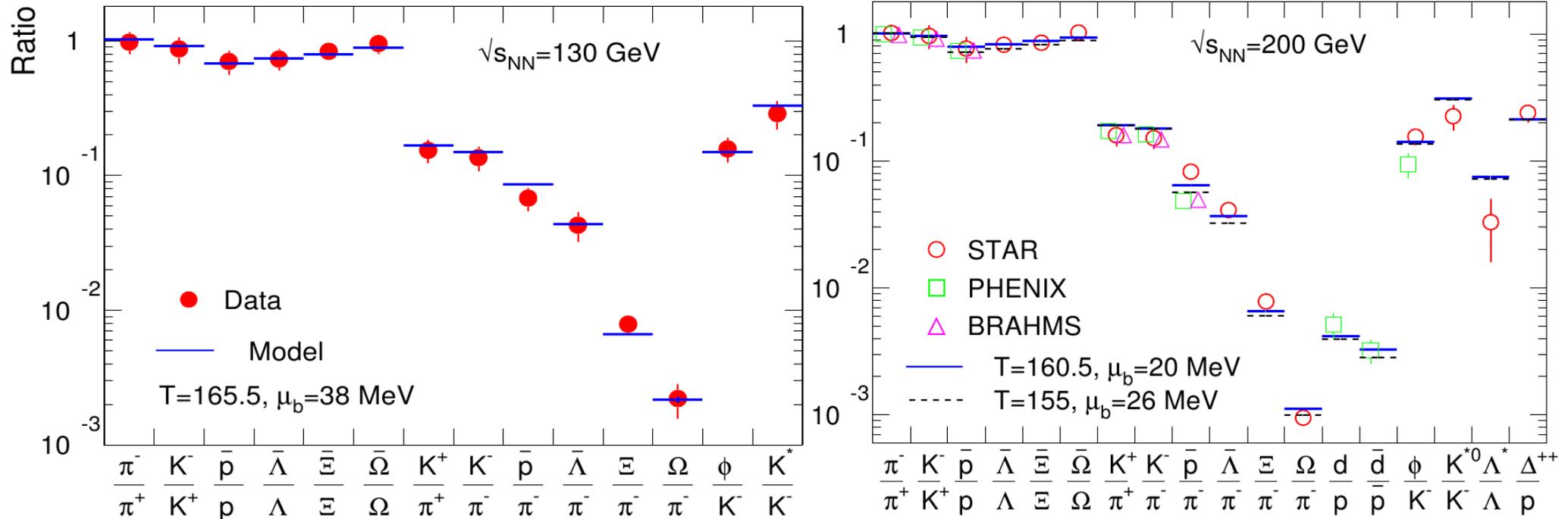


P.Braun-Munzinger and J. Stachel,  
nucl-th/9803015, Nucl. Phys. A638 (1998) 3

# for RHIC hadron yields are reproduced really well compared to statistical model (GC)

130 GeV data in excellent agreement with thermal model **predictions**

prel. 200 GeV data fully in line still some experimental discrepancies



chemical freeze-out at:  $T = 165 \pm 5$  MeV

P. Braun-Munzinger, D. Magestro, K. Redlich, J. Stachel, Phys. Lett. B518 (2001) 41

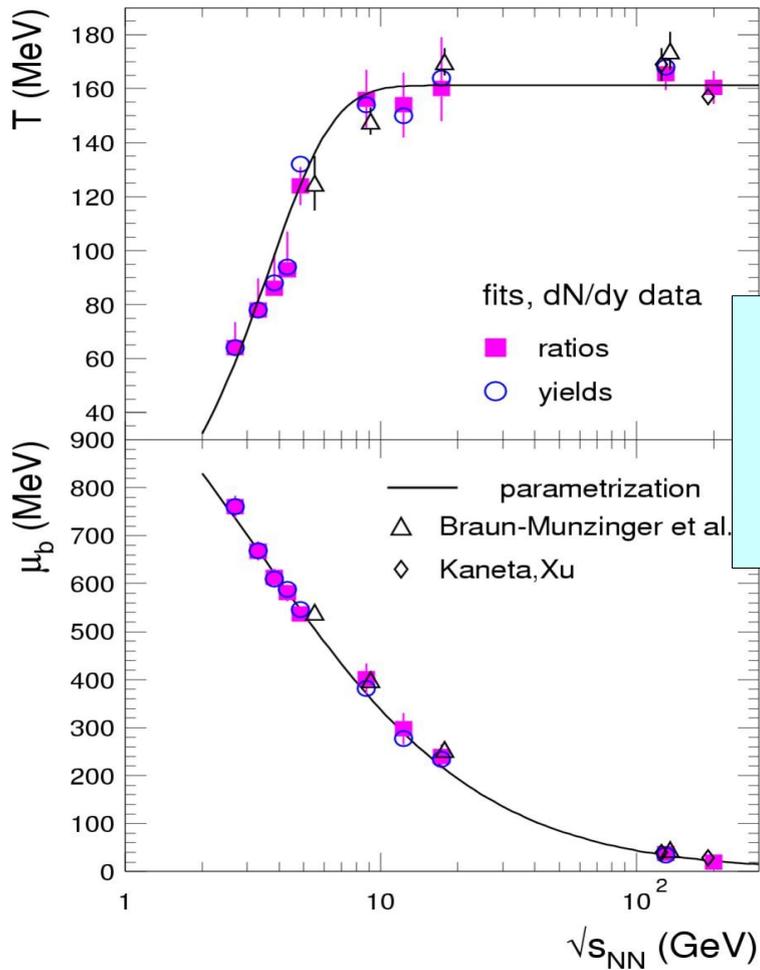
A. Andronic, P. Braun-Munzinger, J. Stachel, Nucl. Phys. A772 (2006) 167

confirmed by Xu and Kaneta and by F. Becattini

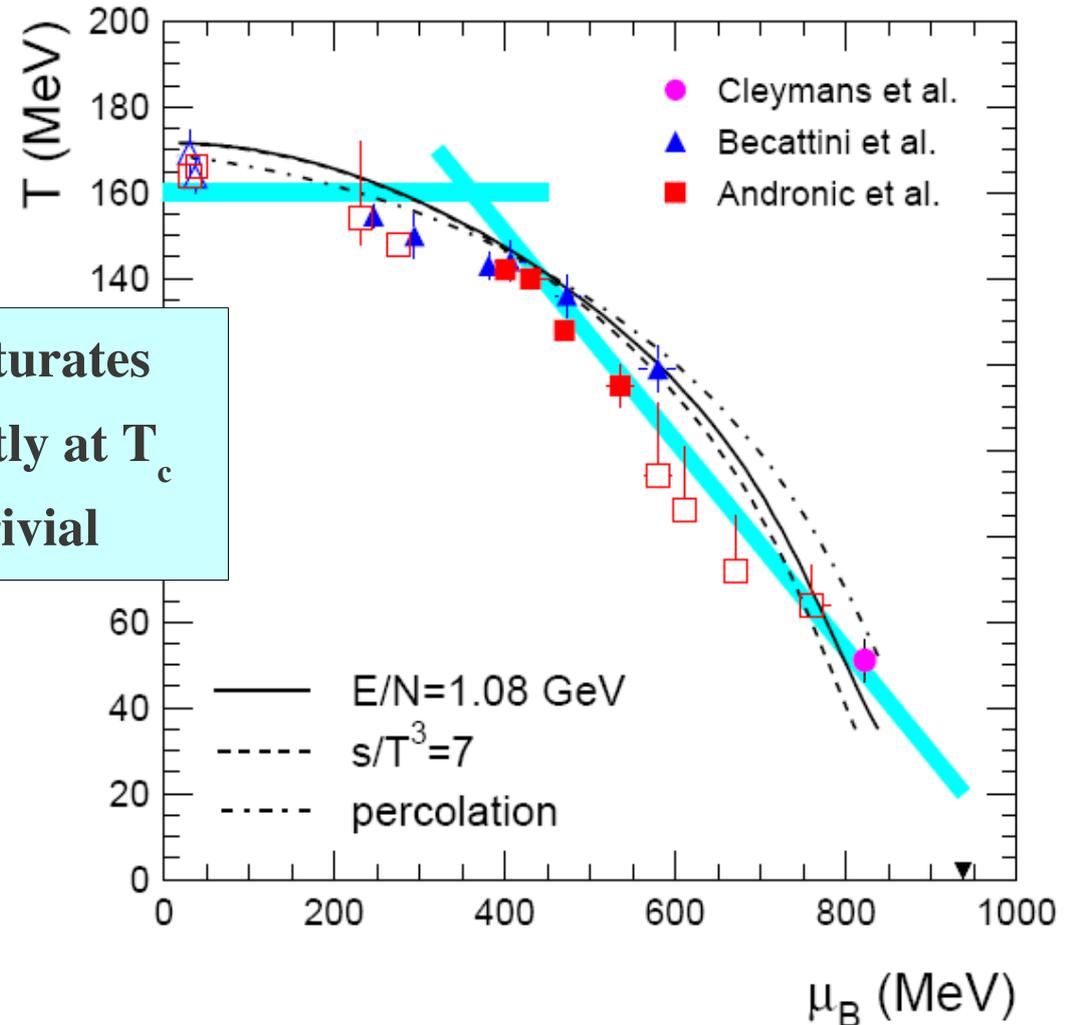
# Experimental Knowledge of the QCD Phase Diagram

- agreement between groups doing finite temperature lattice gauge theory:  $T_c(\mu=0) = 160 - 170$  MeV

Bazavov & Petreczky, arXiv:1005.1131 [hep-lat] S. Borsanyi et al., arXiv:1005.3508 [hep-lat]



$T_{chem}$  saturates  
apparently at  $T_c$   
not trivial



- data points 'chemical' freeze-out of hadrons

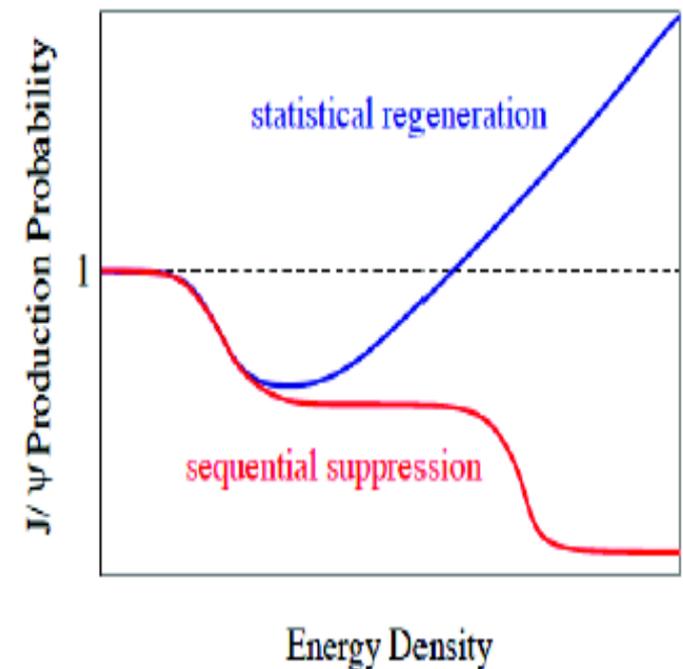
A. Andronic, P. Braun-Munzinger, J. S., Nucl. Phys. A772 (2006) 167

# Charmonia as probe of deconfinement

the original idea (Matsui and Satz 1986): implant charmonia into the QGP and observe their modification (Debye screening of QCD), in terms of suppressed production in nucleus-nucleus collisions with or without plasma formation – **sequential melting**

new insight (Braun-Munzinger, J.S. 2000): QGP screens all charmonia, but charmonium production takes place at the phase boundary, large charm cross section would lead to enhanced production at colliders – **signal for deconfinement**

recent reviews: L. Kluberg and H. Satz, arXiv:0901.3831  
P. Braun-Munzinger and J. S., arXiv:0901.2500  
both published in Landoldt-Boernstein Review,  
R. Stock, editor, Springer 2010



# Quarkonia Production through Statistical Hadronization

- Assume: all charm quarks are produced in initial hard scattering number not changed in QGP
- Hadronization at  $T_c$  following grand canonical statistical model used for hadrons with light valence quarks (fugacity to fix number of charm quarks, canonical correction factors at low beam energies)

P. Braun-Munzinger, J. Stachel, Phys. Lett. B490 (2000) 196 and Nucl. Phys. A690 (2001) 119  
A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Nucl. Phys. A715 (2003) 529c and  
Phys. Lett. B571 (2003) 36 and nucl-th/0611023 and nucl-th/0701079

M. Gorenstein et al., Phys. Lett. B509 (2001)277, ib. 524 (2002) 265; A. Kostyuk et al., Phys. Lett. B531 (2001) 225 and Phys. Rev. C68 (2003) 041902; E. Bratkovskaya et al., PRC 69, 054903 (2004)

R. Rapp and L. Grandchamp, Phys. Lett. B523 (2001) 60 and PRL 92, 212301 (2004)

## extension of statistical model to include charmed hadrons

- assume: all charm quarks are produced in initial hard scattering; number not changed in QGP
- hadronization at  $T_c$  following grand canonical statistical model used for hadrons with light valence quarks

number of charm quarks fixed by a charm-balance equation containing fugacity  $g_c$

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

and for  $N_{c,\bar{c}} \ll 1 \rightarrow$  canonical: 
$$N_{c\bar{c}}^{dir} = \frac{1}{2}g_c N_{oc}^{therm} \frac{I_1(g_c N_{oc}^{therm})}{I_0(g_c N_{oc}^{therm})}$$

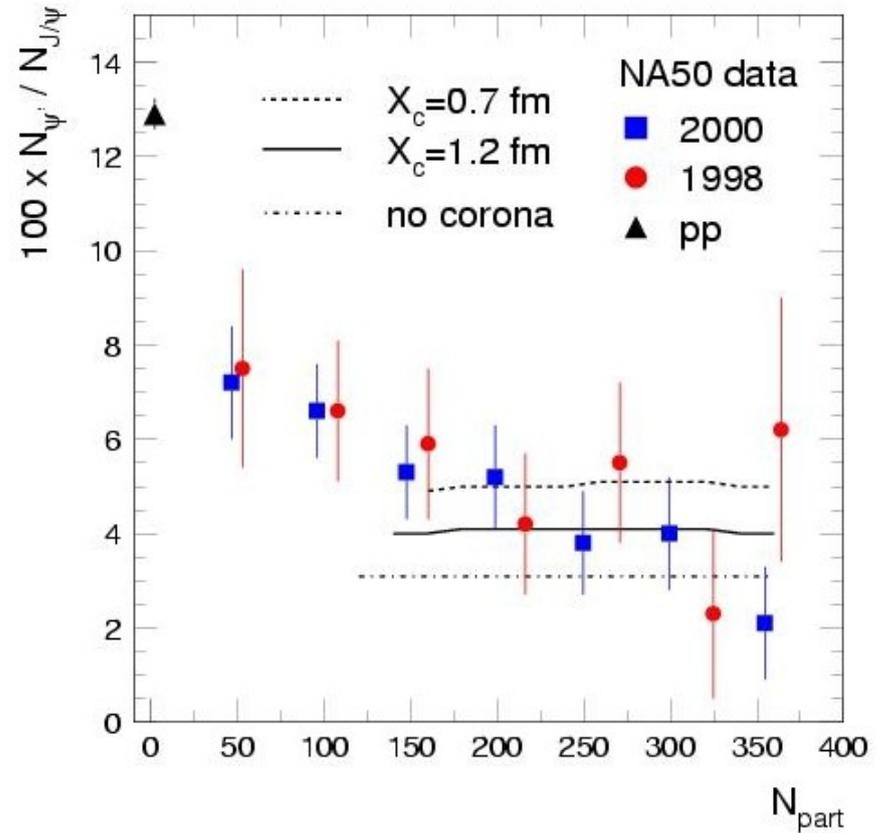
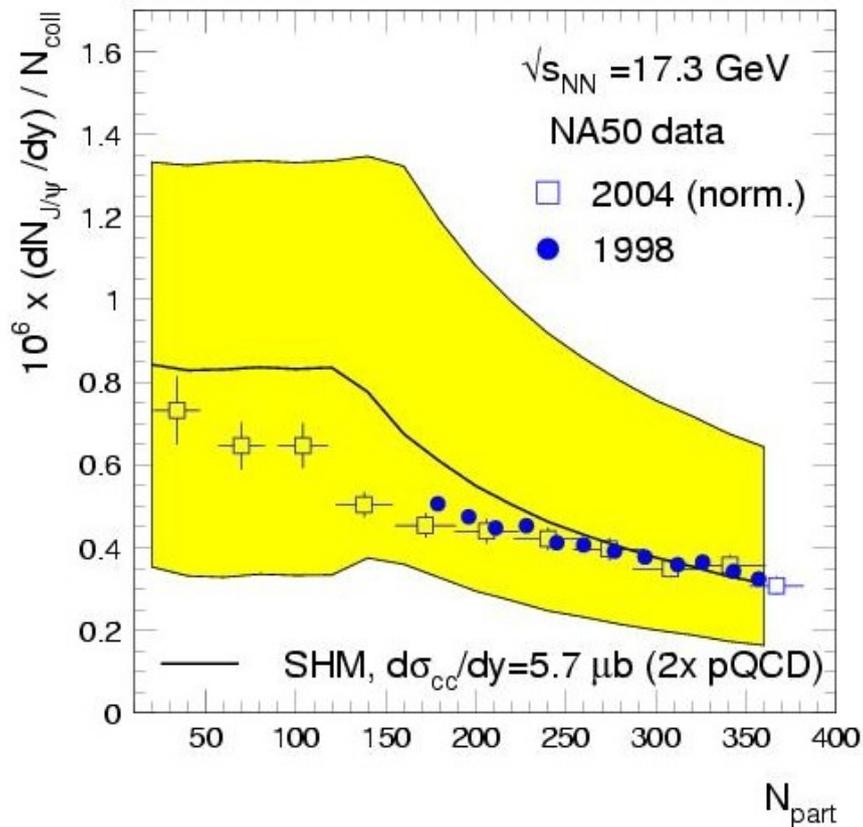
obtain: 
$$N_D = N_D^{therm} \cdot g_c \cdot \frac{I_1}{I_0} \quad \text{and} \quad N_{J/\psi} = N_{J/\psi}^{therm} \cdot g_c^2 \quad \text{and same for all other charmed hadrons}$$

additional input parameters:  $V, N_{c\bar{c}}^{direct}$

Volume fixed by  $dN_{ch}/d\eta$

$N_{c\bar{c}}^{direct}$  from pQCD as long as precision data are lacking

# results for SPS energy



only moderately enhanced (2 x pQCD)  $c\bar{c}$  cross section needed  
 $\psi'/\psi$  ratio is expected from a thermal scenario

# excited quarkonia and statistical hadronization

in the statistical hadronization model, the ratio  $R$  of excited/ground state is simply determined by a Boltzmann factor:

$$R = \left(\frac{m_1}{m_0}\right)^{3/2} \exp(-(m_1 - m_0)/T)$$

here  $T = 170 \text{ MeV}$  is the critical (or hadronization) temperature

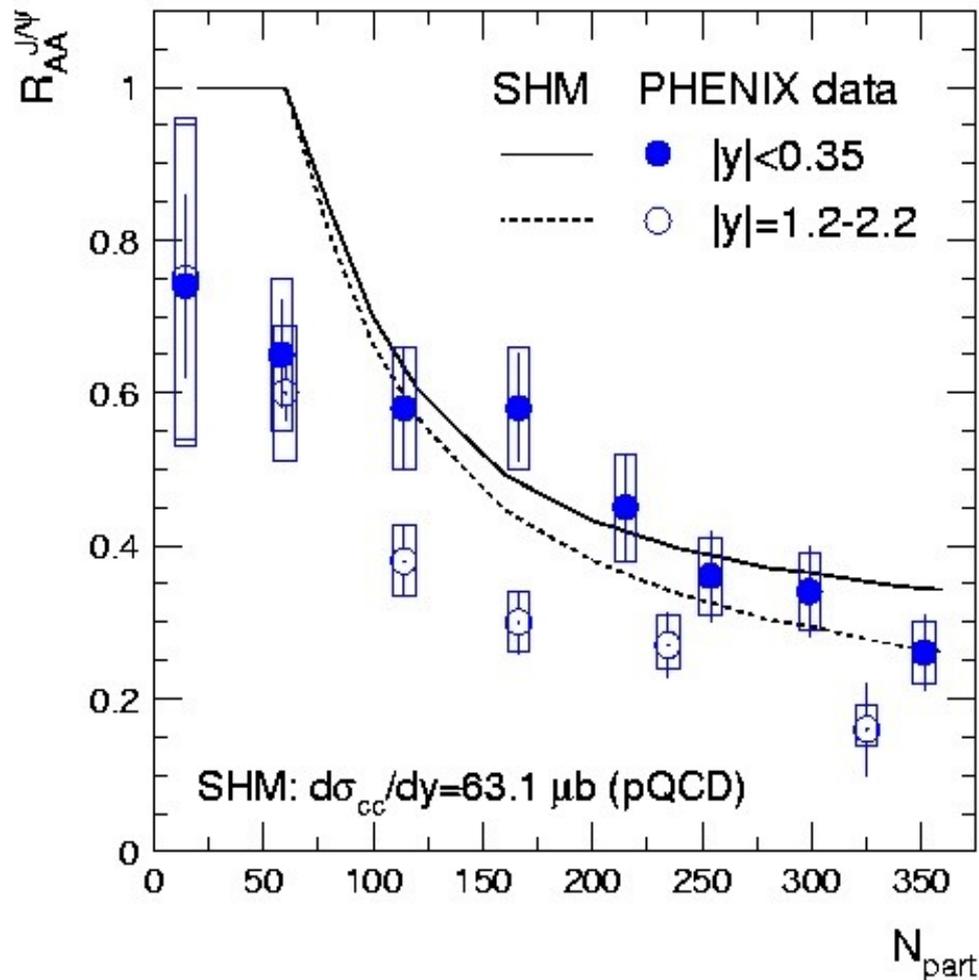
for  $\psi'/(J/\psi)$  this yields:  $R_{\psi'} = 0.04$

for  $\chi_c/(J/\psi)$  :  $R_{\chi_c} = 0.12$

for  $Y'/Y$  :  $R_{Y'} = 0.04$   $R_{Y''} = 0.006$

# Model prediction and RHIC data: Centrality dependence

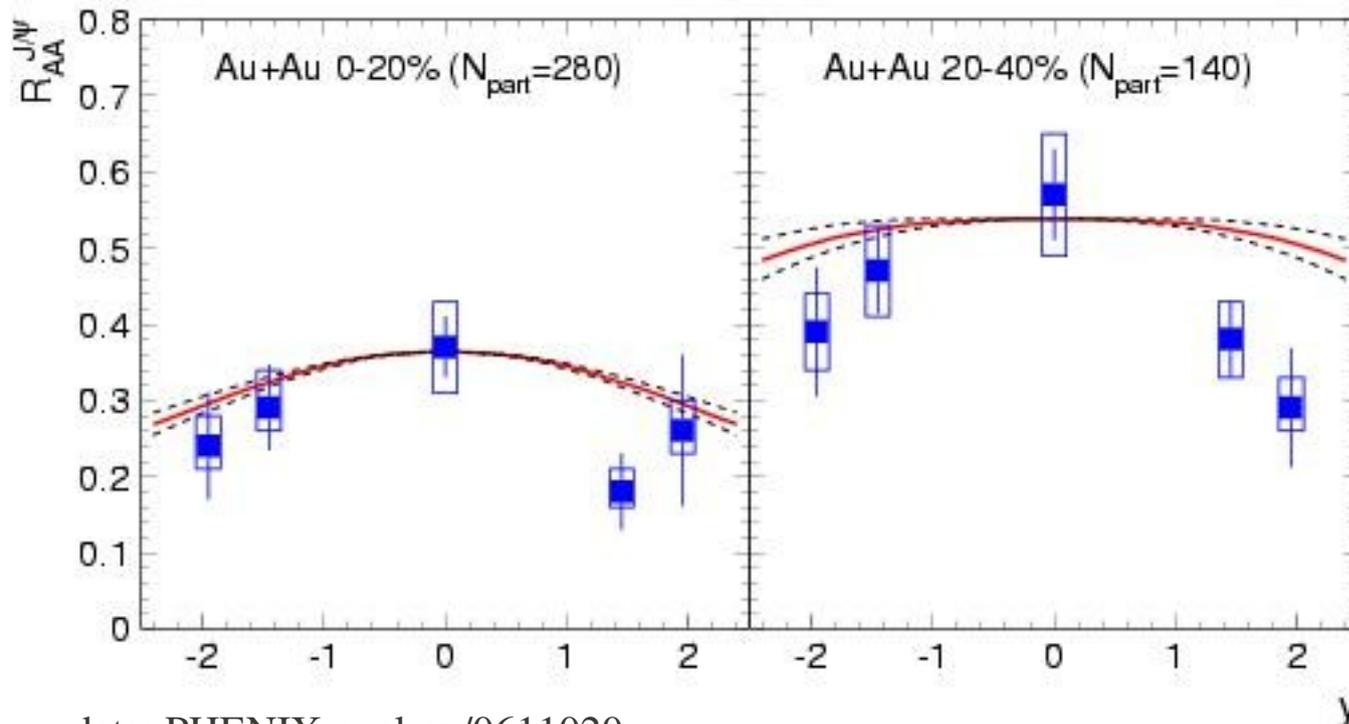
$R_{AA}$ :  $J/\psi$  yield in AuAu /  $J/\psi$  yield in pp times  $N_{coll}$



data well described  
by statistical model  
without any new  
parameters

# Model prediction and RHIC data: rapidity dependence

$R_{AA}^{J/\psi}$ : J/ $\psi$  yield in AuAu / J/ $\psi$  yield in pp times  $N_{coll}$



data: PHENIX nucl-ex/0611020

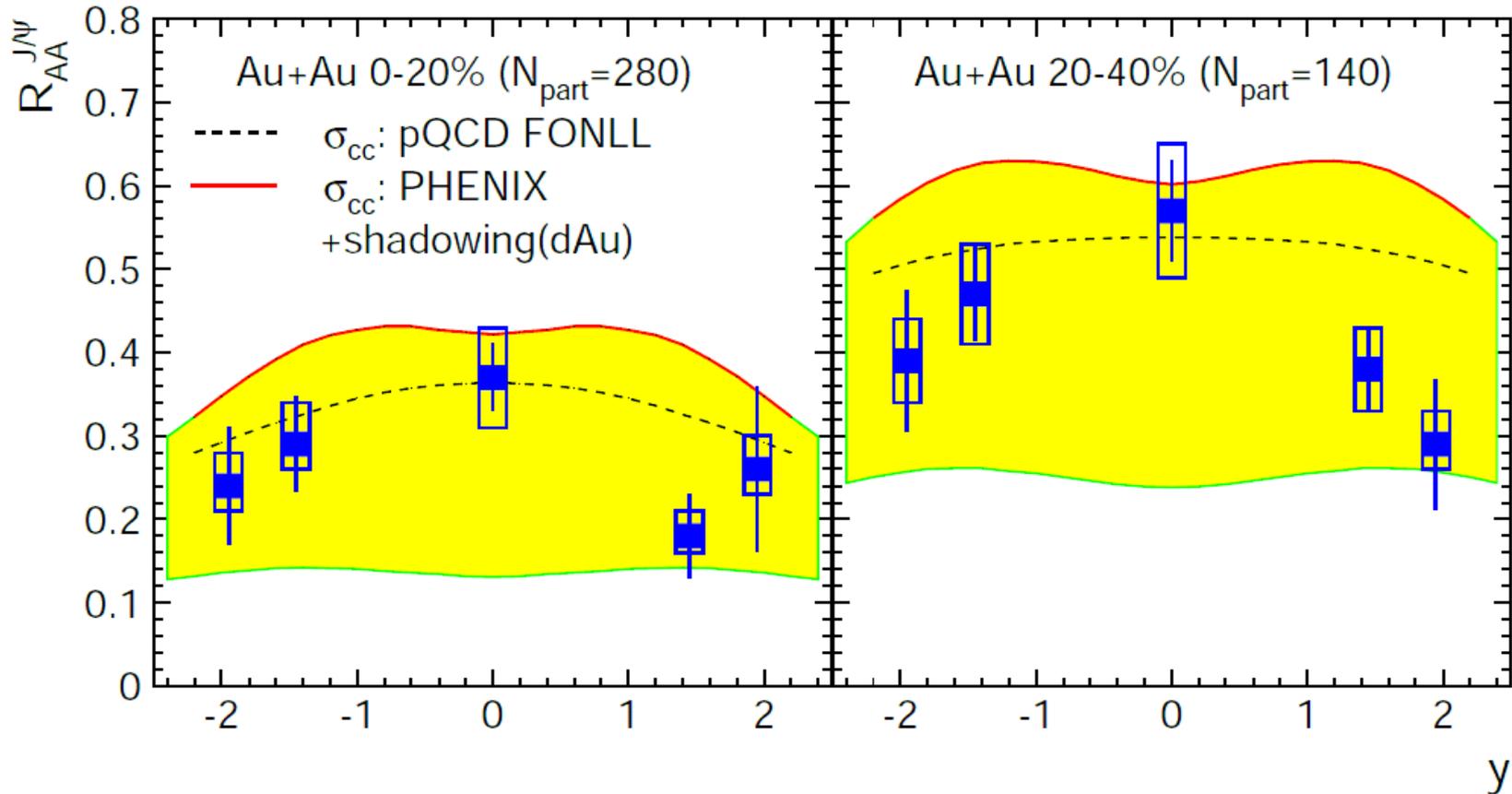
additional 14% syst error beyond shown

model: A. Andronic, P. Braun-Munzinger, K. Redlich,  
J. Stachel Phys. Lett. B652 (2007) 259

good agreement, no free parameters

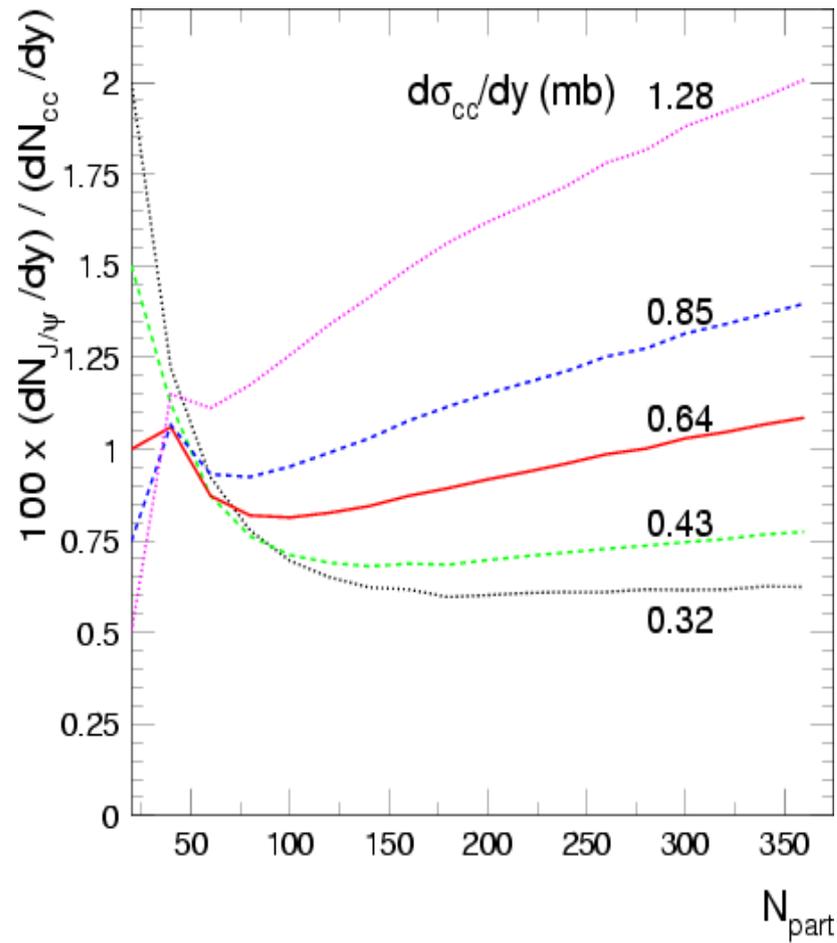
remark: y-dep **opposite** in 'normal Debye screening' picture; suppression strongest at midrapidity (largest density of color charges)

# Shadowing leads to slight modification in shape



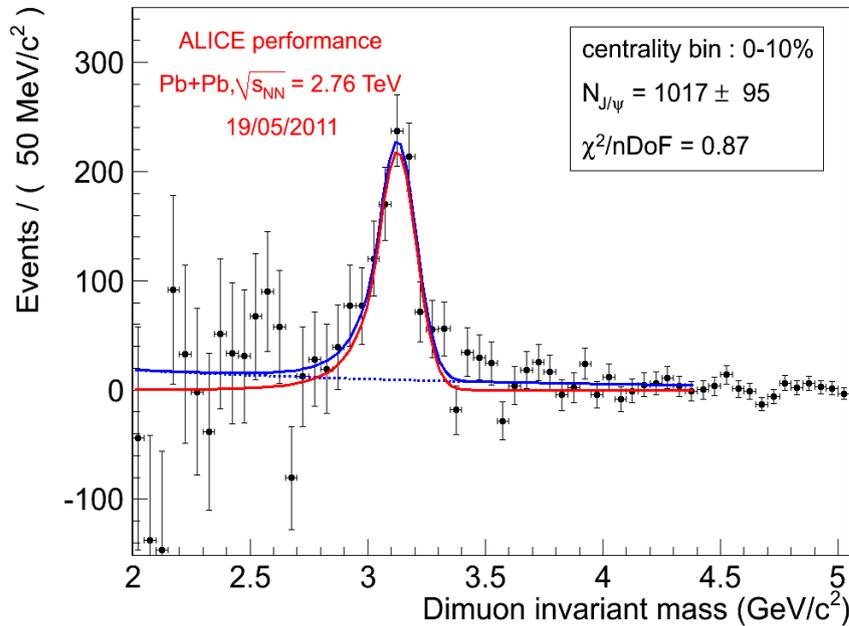
assume PHENIX pA data reflect shadowing  
need accurate charm cross section for AuAu!

# Predictions for LHC energies

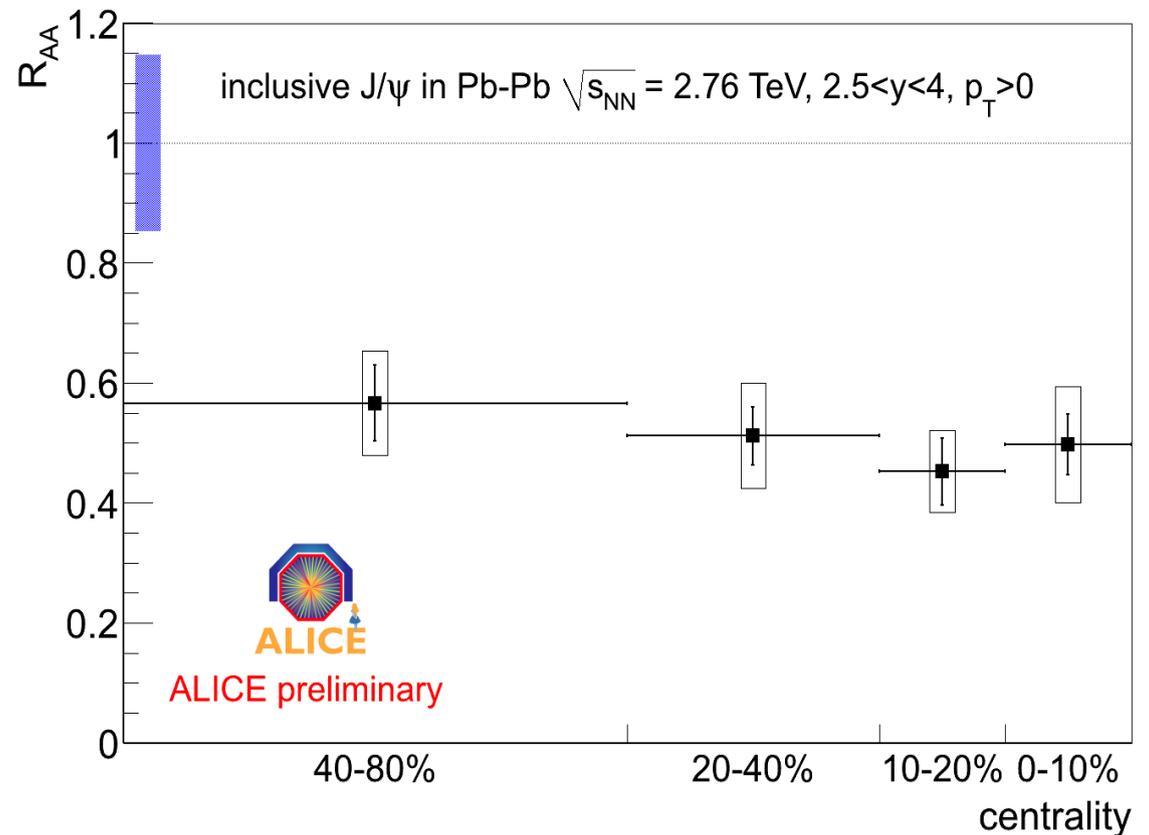


A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel Phys. Lett. B652 (2007) 259

# First J/psi results in PbPb collisions relative to pp

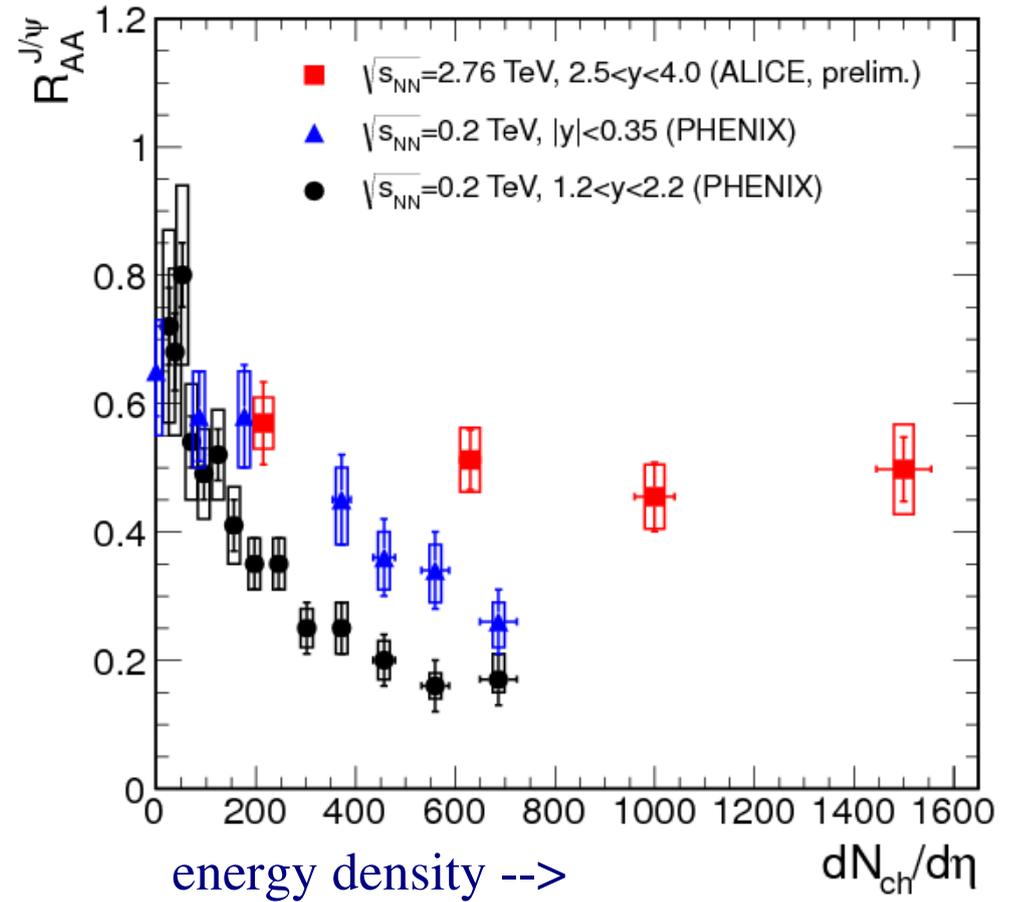
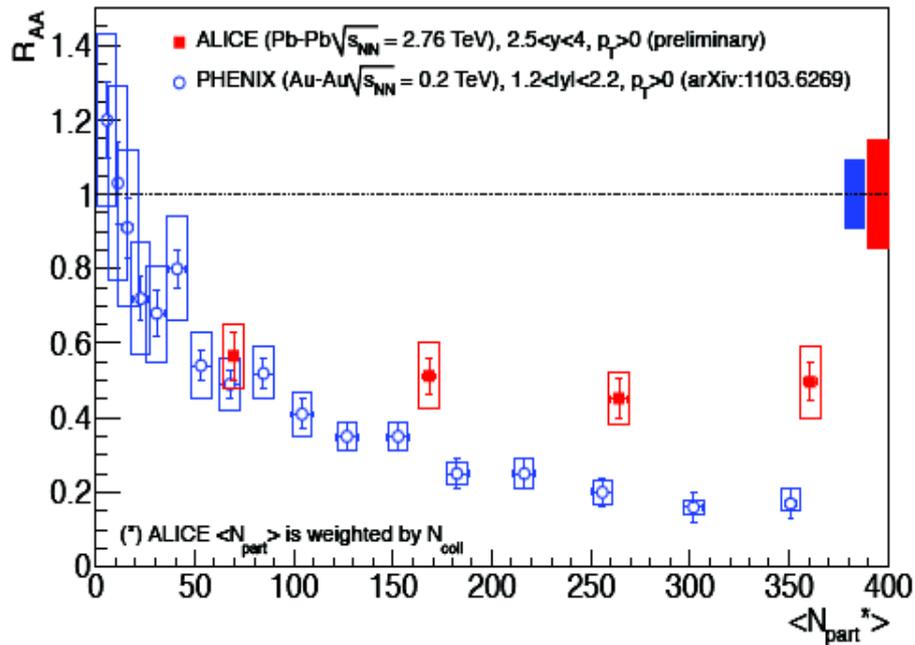


note: ALICE measurements  
include  $p_T(J/\psi) = 0$



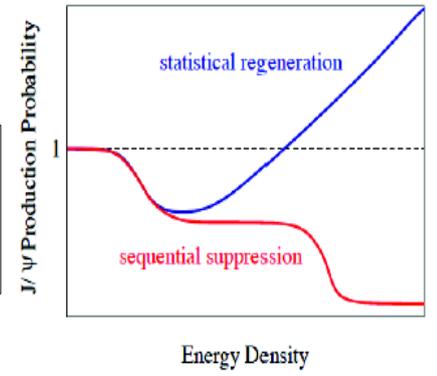
contribution from B feed-down:  
10.7% from pp measurement (LHCb)  
scaling with  $N_{coll}$ : reduction of  $R_{AA}$   
for 0-10% central by 12%

# J/psi in PbPb collisions: LHC relative to RHIC

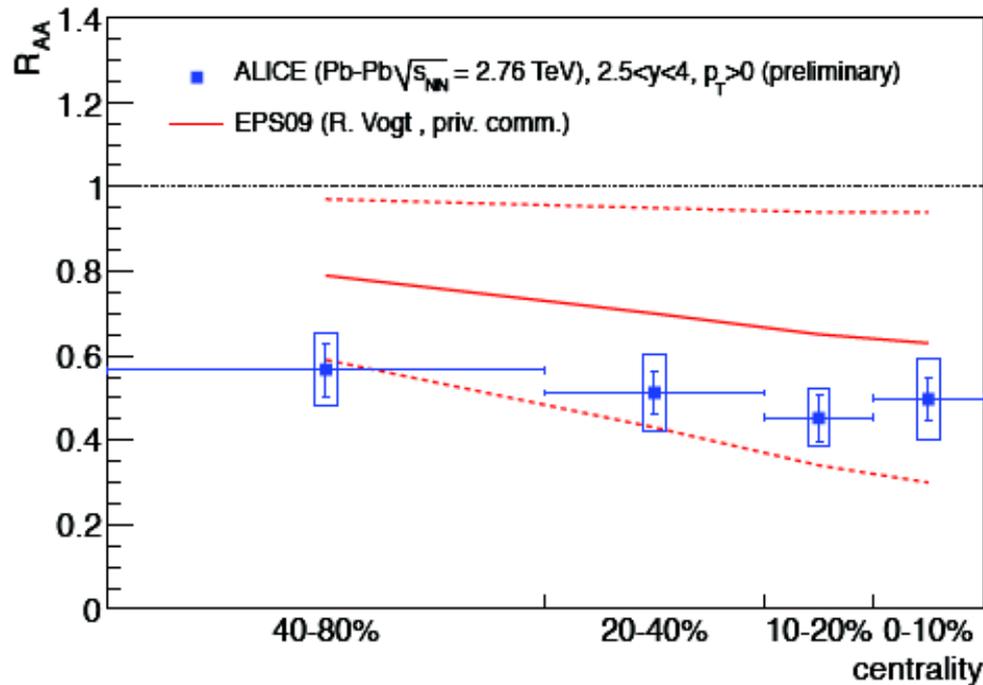


$R_{AA}$  increases as function of energy!

melting scenario not observed  
rather: enhancement with increasing energy density!



# J/psi in PbPb collisions relative to pp

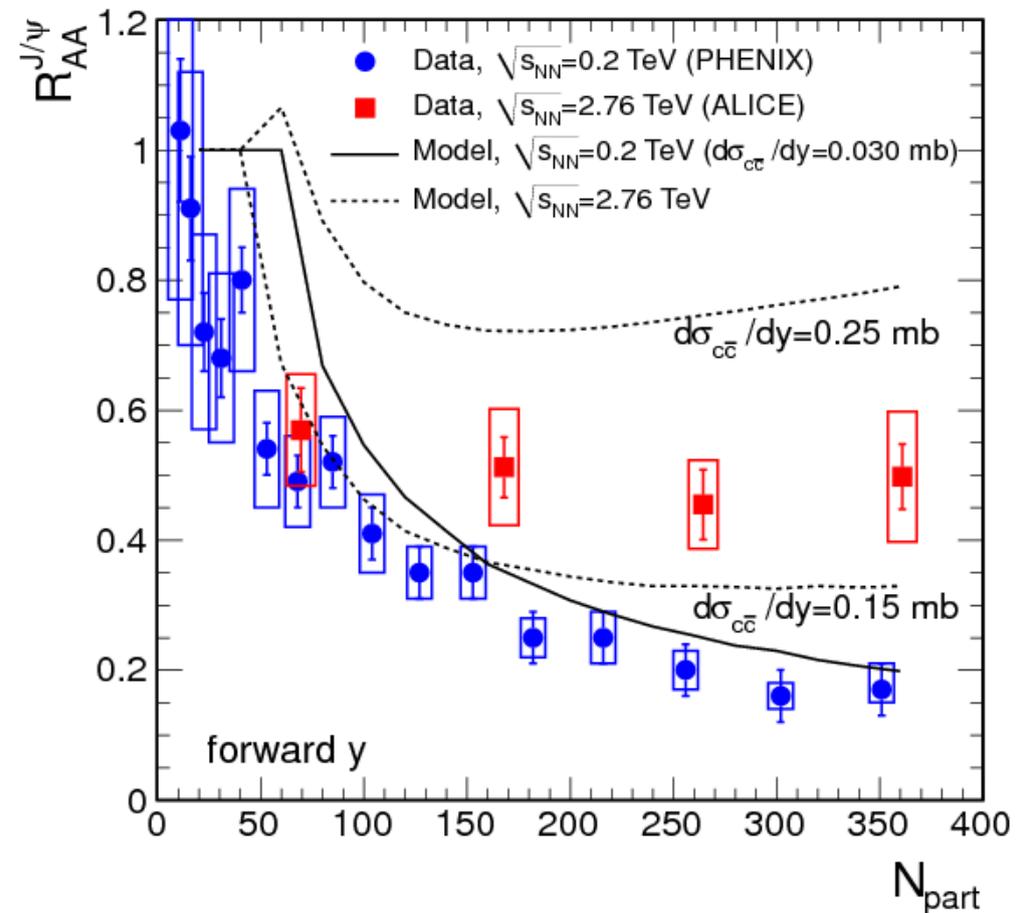


- before quantitative interpretation need to know: shadowing - presumably important at LHC prediction see red lines above next need to measure this via open charm in PbPb

# J/ $\psi$ story: first ALICE data support generation at the phase boundary



trends in data as predicted with statistical hadronization scenario



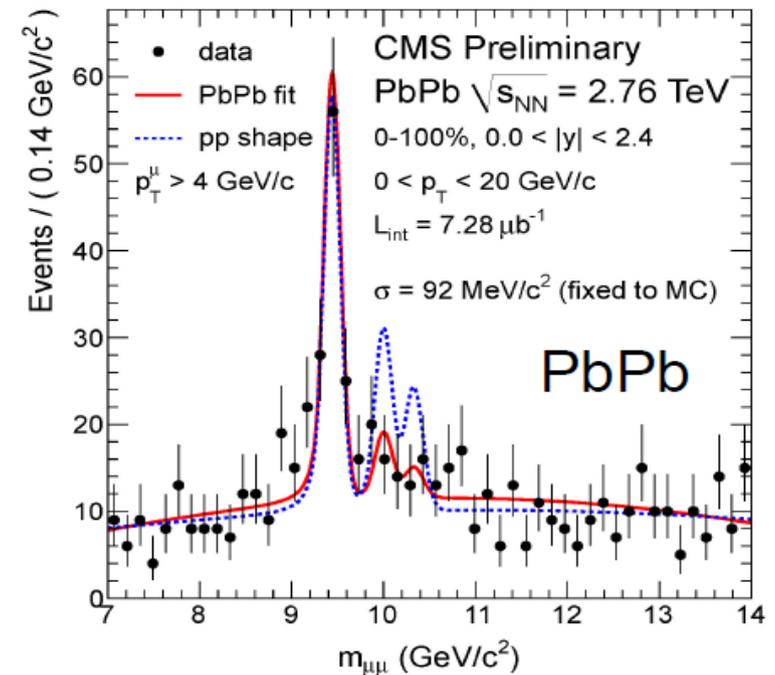
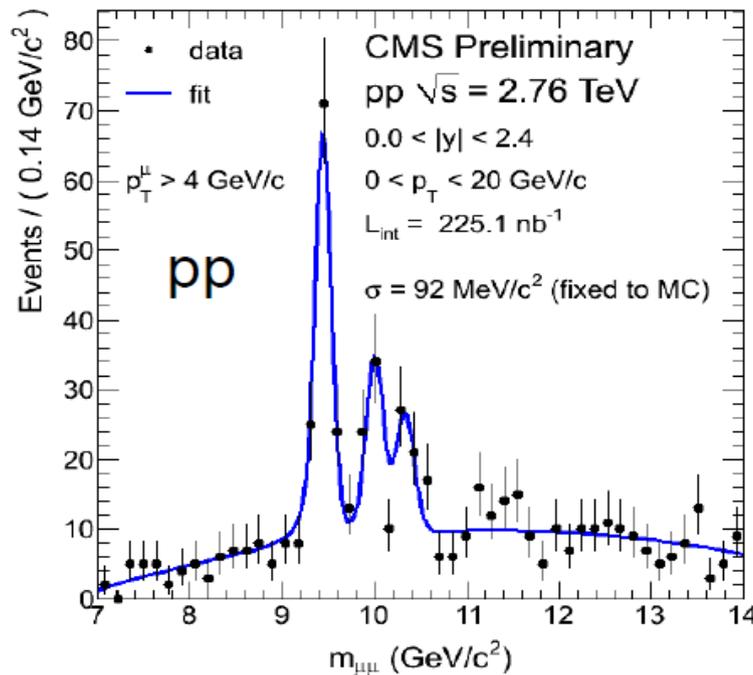
total  $c\bar{c}$  cross section from 7 TeV pp and scaled to 2.76 TeV using data

In AA collisions: indication of J/ $\psi$  regeneration

- Larger  $R_{AA}$  (at forward rapidity) at LHC compared to RHIC, a generic prediction of the statistical model (lines)
- The charm cross section needs experimental constraints (shadowing important at LHC)



# Suppression of higher Upsilon states in CMS



raw ratios:  $\Upsilon(2S+3S)/\Upsilon(1S)|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$

$\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$

from CMS cross section measurements:

$$(Y(2S) + Y(3S))/Y(1S)|_{PbPb} = 0.14^{+0.08}_{-0.07}$$

vs thermal model at  $T=170$  MeV: 0.046

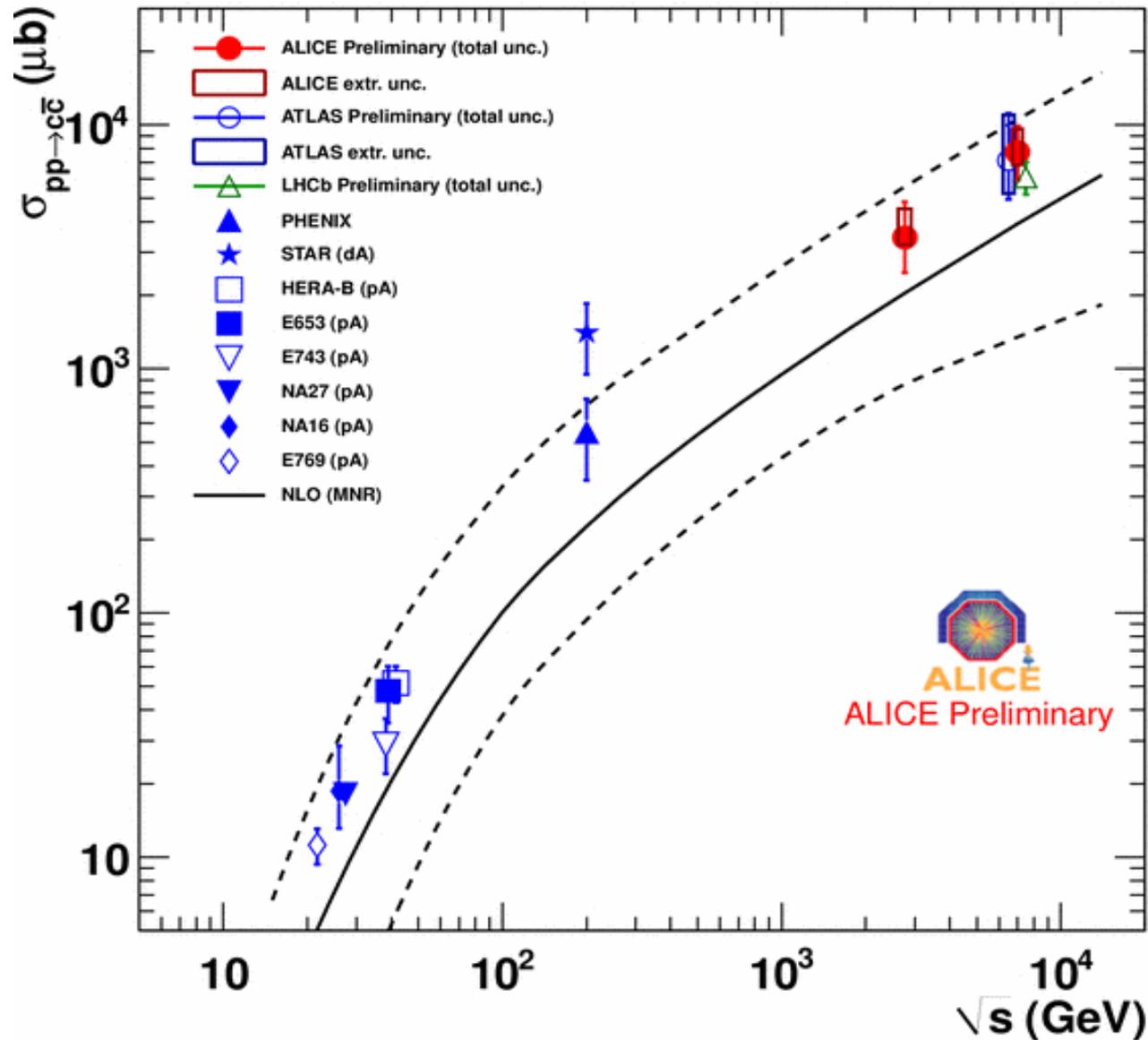
ok within the current uncertainties

# Summary

- data on quarkonia in central nuclear collisions at RHIC and LHC in line with predictions from statistical hadronization model and inconsistent with only sequential melting of quarkonia
- generation of the quarkonia from deconfined heavy quarks at the phase boundary
- quantitative understanding needs
  - measurement of shadowing, i.e. open charm in PbPb collisions
  - rapidity dependence
  - precision data on J/psi and upsilon excited states

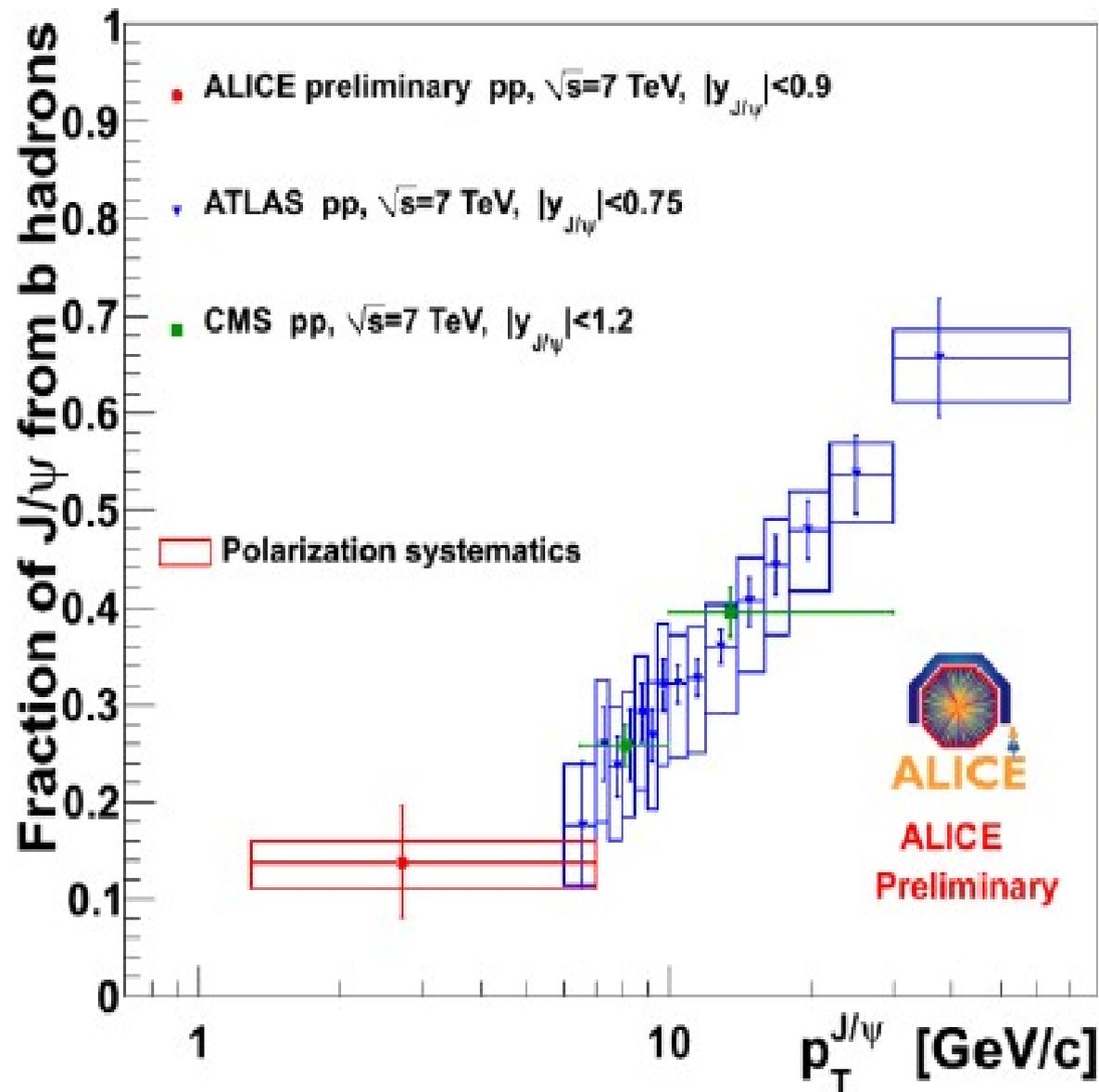
backup

# a first try at the total $c\bar{c}$ cross section in pp collisions at LHC energy

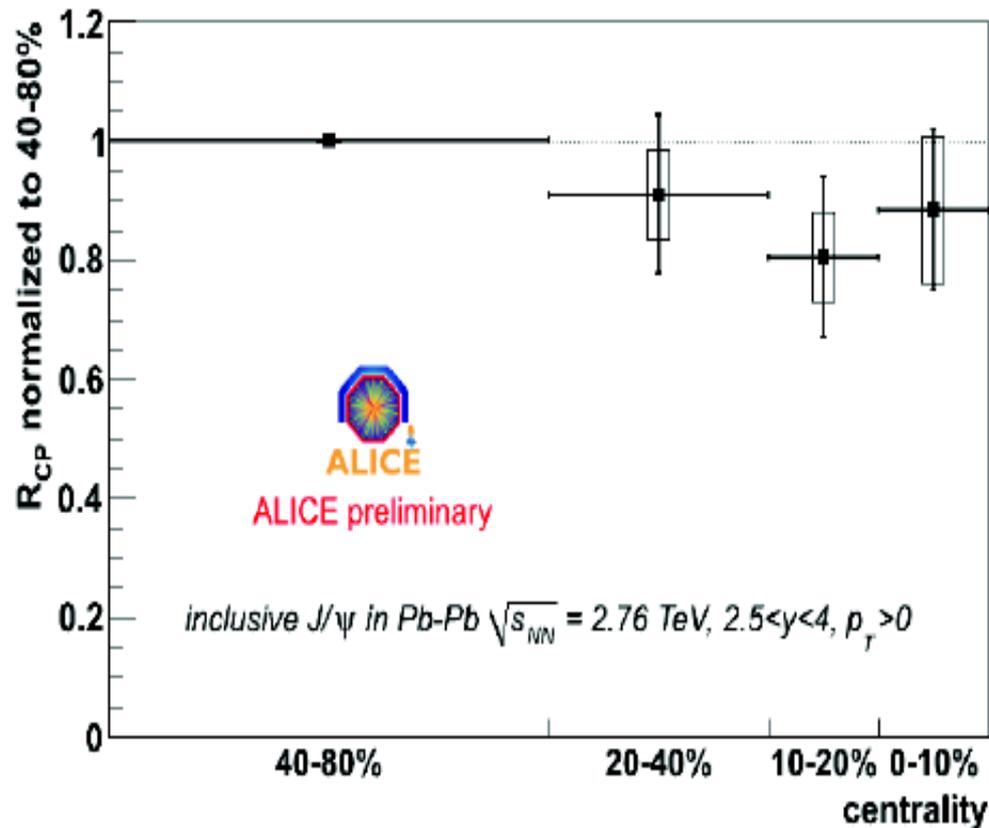


ALI-PREL-4881

# feeding from B mesons: first measurement at very low $p_T$

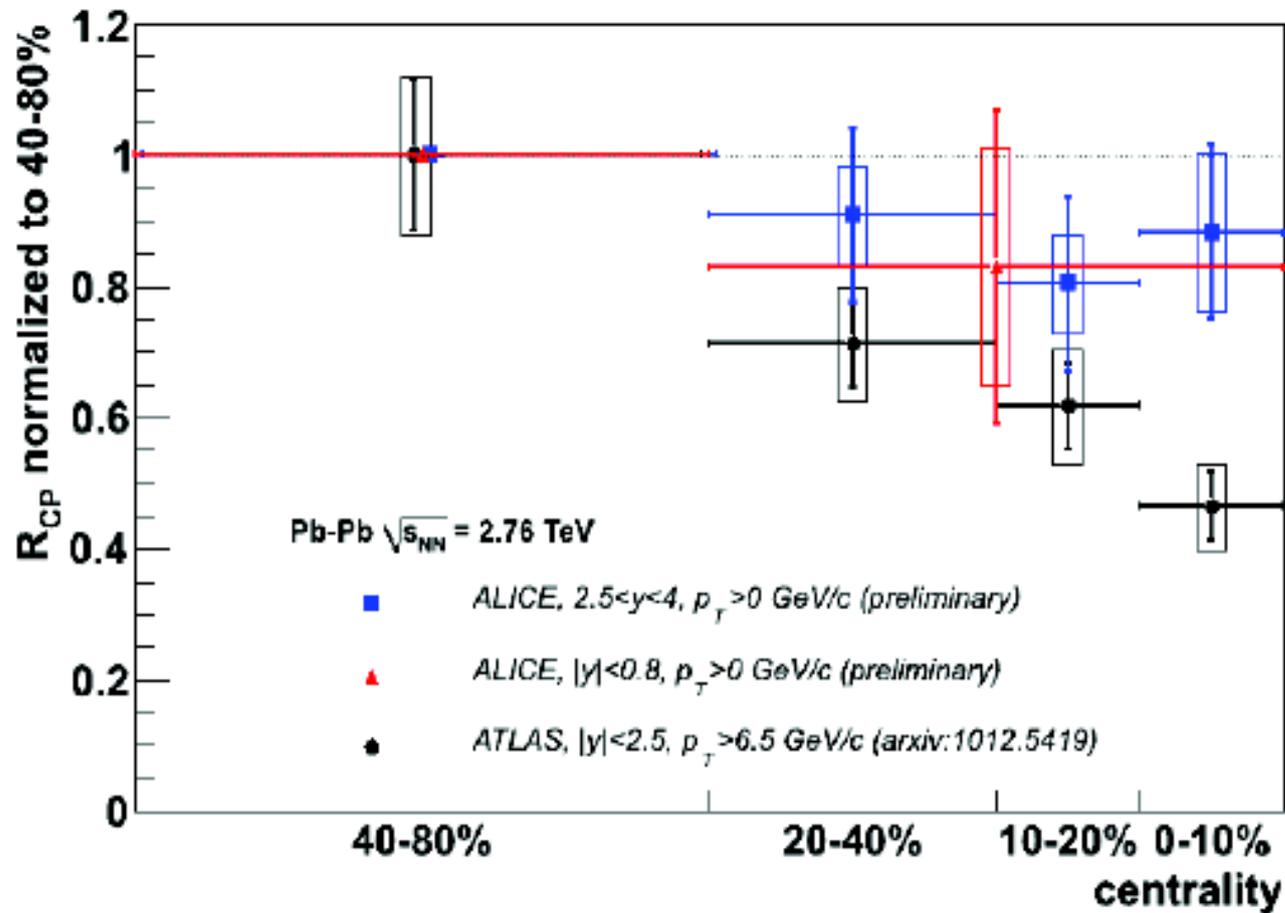


# centrality dependence via $R_{CP}$



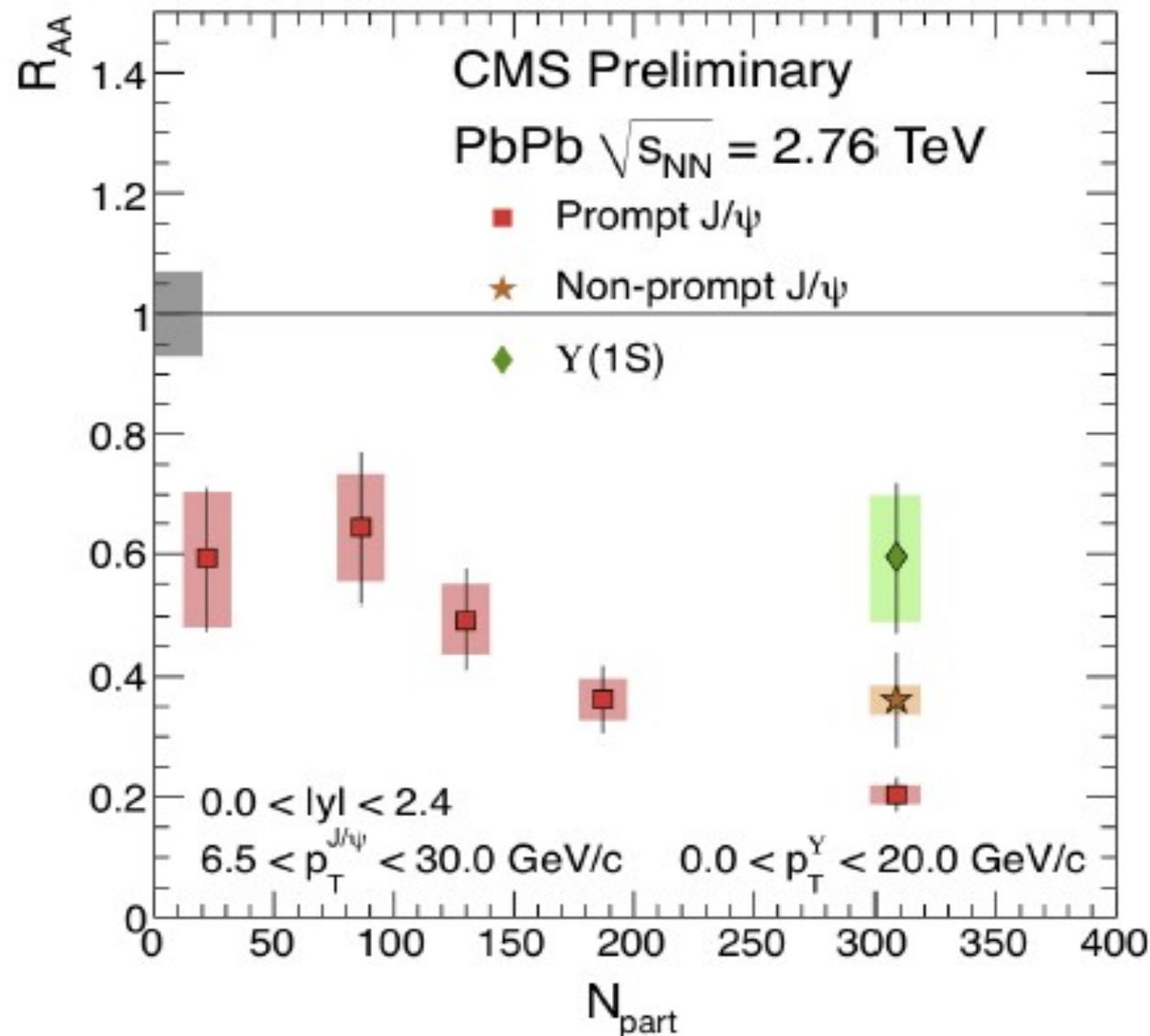
- Error bars:  
Statistical uncertainties
- Empty boxes:  
Centrality-dependent  
systematic uncertainties

# inclusion of first J/psi data at midrapidity

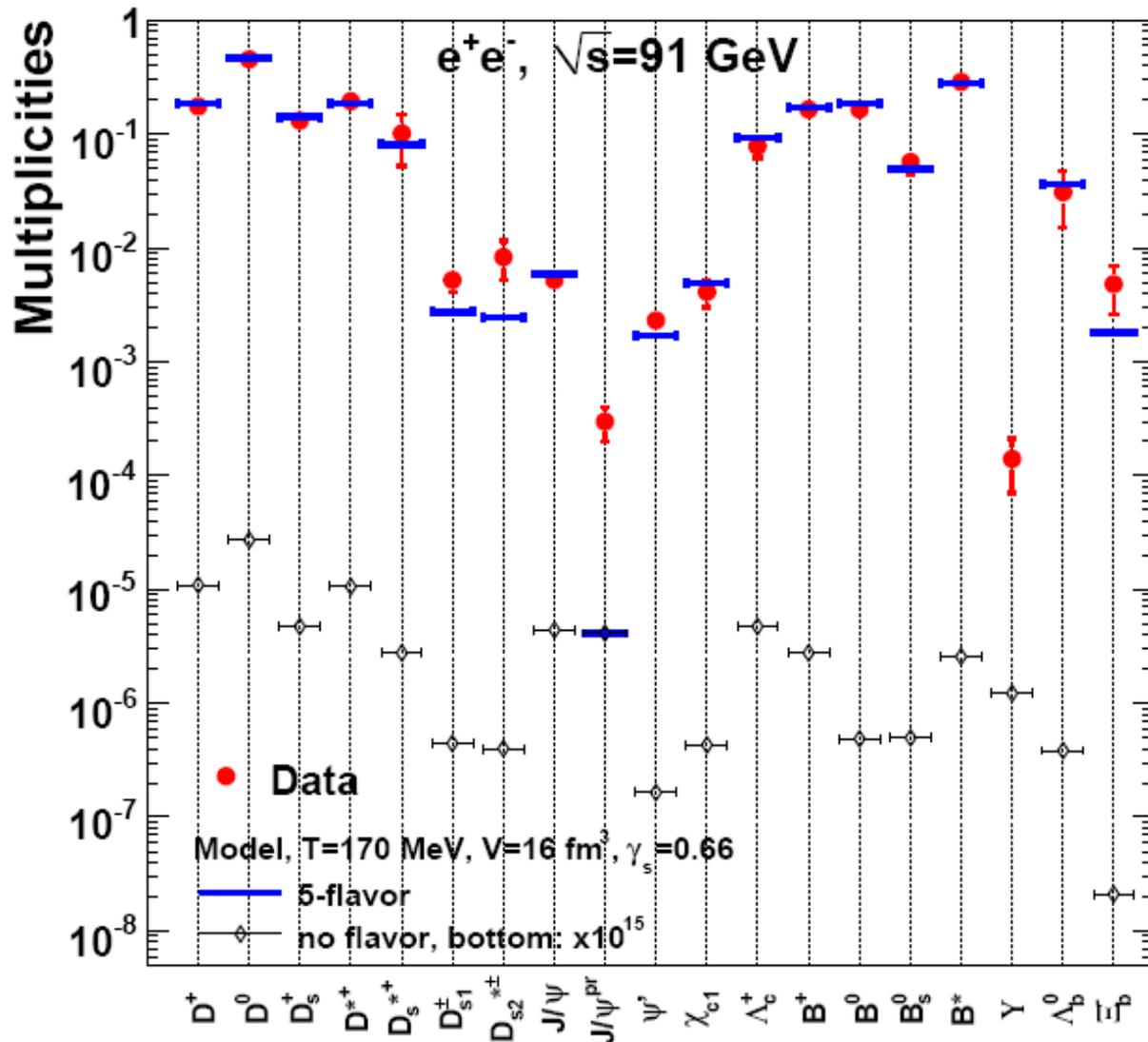


J/psi suppression increases with increasing  $p_T$

# Y and J/psi suppression – at high pt a consequence of heavy quark thermalization and energy loss



# Heavy quark and quarkonium production in $e^+e^-$ collisions



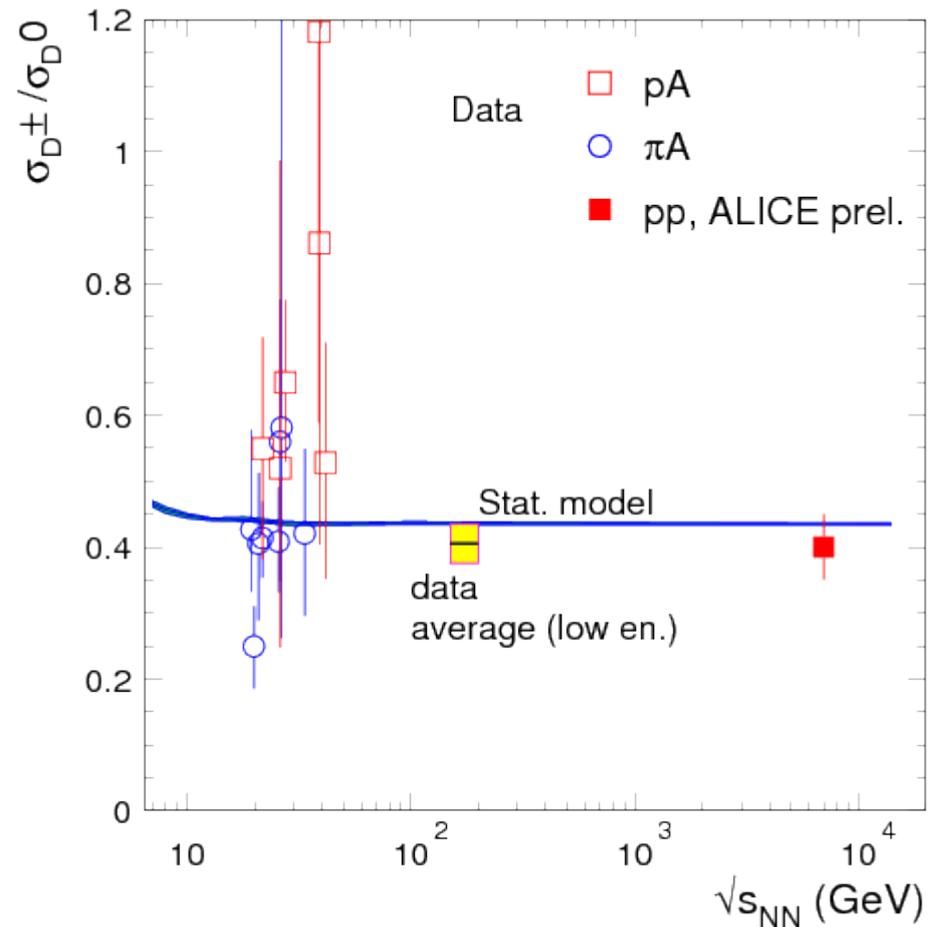
Comparison of stat.  
model calcs.  
with data

Phys. Lett. B678 (2009) 350,  
arXiv:0903.1610 [hep-ph]

charmonium cannot be  
described  
at all in this approach

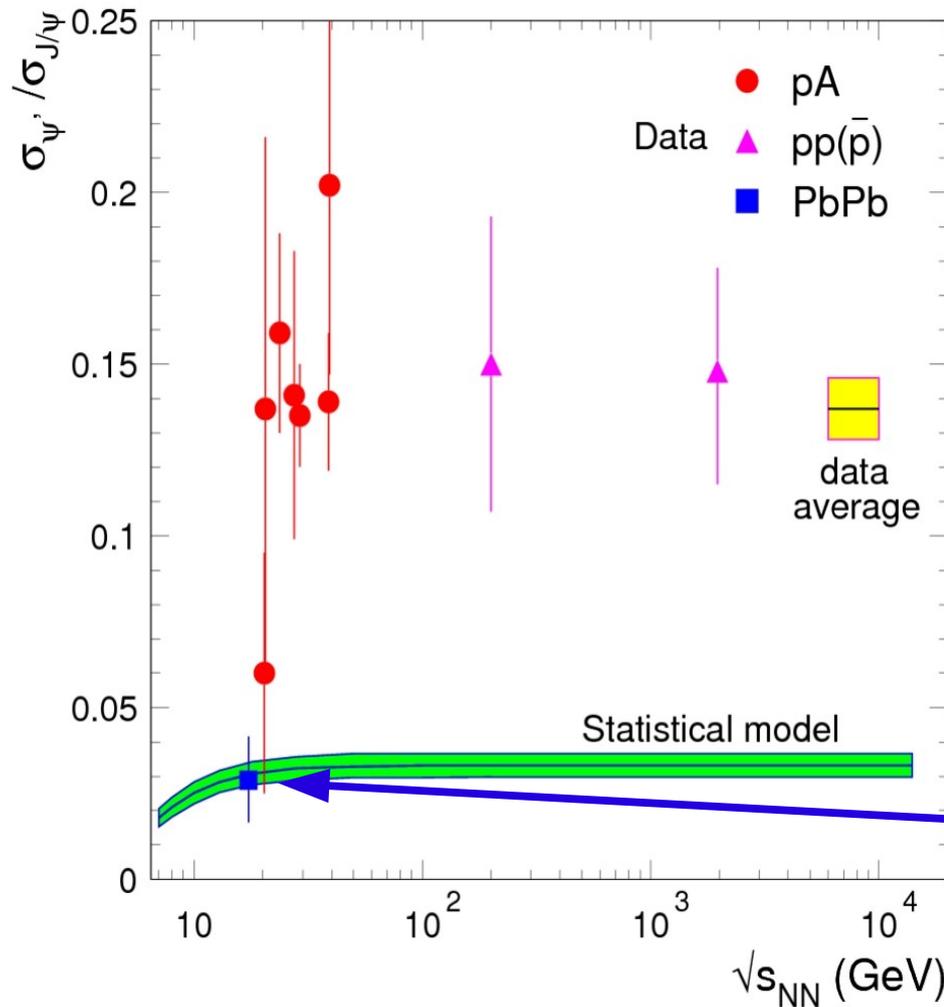
But: all charm quarks  
hadronize  
at 170 MeV

# D meson ratios and statistical hadronization



also in pp collisions c quarks hadronize at about  $T = 165$  MeV  
what about PbPb collisions? To come soon!

# Statistical Hadronization Model Predictions are Different from Data for Elementary Collisions



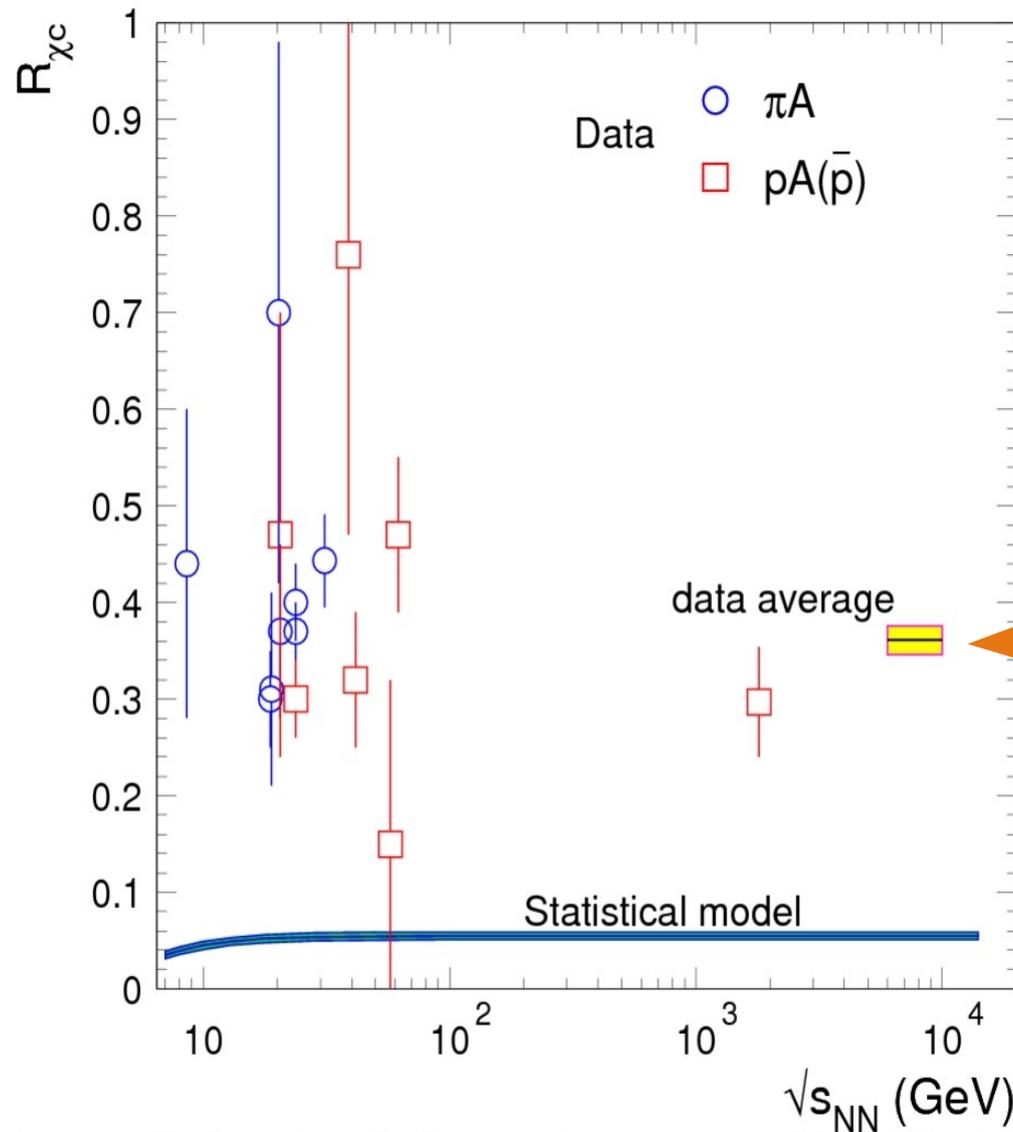
← pp and pA data factor 3 above statistical hadronization value

only result for AA at SPS energy; very close agreement

data at higher energies will be crucial test

A. Andronic, F. Beutler, P. Braun-Munzinger, K. Redlich, J. Stachel arXiv:0904.1368 [hep-ph], PLB in print

# Situation even more dramatic for P-states



$$R_{\chi_c} = \frac{\sum_{J=1}^2 \sigma(\chi_{cJ}) Br(\chi_{cJ} \rightarrow J/\psi \gamma)}{\sigma(J/\psi)}$$

$\rightarrow$  pA and  $\pi A$  data on average factor 7 above statistical model prediction

A. Andronic, F. Beutler, P. Braun-Munzinger, K. Redlich,  
J. Stachel arXiv:0904.1368 [hep-ph], PLB in print