charmonium production, statistical hadronization, and LHC data

- some historical remarks
- the statistical hadronization model
- comparison to results from RHIC
- the first LHC data

pbm, Berkeley school
LBNL, May 14, 2012

TECHNISCHE UNIVERSITÄT DARMSTADT

FIAS Frankfurt Institute for Advanced Studies

EMMI

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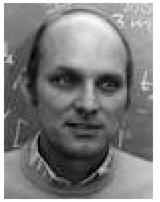
GSI

Charmonium as a probe for the properties of the QGP



the Matsui/Satz paper has created an industry

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

new insight (pbm, Stachel 2000) QGP screens all charmonia, but charmonium production takes place at the phase boundary, enhanced production at colliders – signal for deconfined, thermalized charm quarks

work reported here done in coll. with Anton Andronic Krzysztof Redlich Johanna Stachel

recent reviews: L. Kluberg and H. Satz, arXiv:0901.3831

pbm and J. Stachel, arXiv:0901.2500

both published in Landoldt-Boernstein Review, R. Stock, editor, Springer 2010

Are charmonia (and charmed hadrons) produced thermally?

ratios of charmed and beauty hadrons exhibit thermal features (Becattini 1997)

but: $(J/\psi)/\psi'$ ratio is far from thermal in e+e- and pp collisions

see also Sorge&Shuryak, Phys. Rev. Lett. 79 (1997) 2775, where it is further noted that the $(J/\psi)/\psi'$ ratio reaches a thermal value (T=170 MeV) in central PbPb collisions at SPS energy

further analysis by Gorenstein and Gazdzicki, Phys. Rev. Lett. 83 (1999) 4003

result: $(J/\psi)/\pi$ is approximately constant at SPS energy for PbPb

However, thermal production of charm quarks is appreciable only at very high temperatures (LHC) (T > 800 MeV, pbm&Redlich, Eur. Phys. J. C16 (2000) 519).

solution: charm quarks produced in hard collisions, then statistical hadronization at the phase boundary.

time scales

for the original Matsui/Satz picture to hold, the following time sequence is needed:

1) charmonium formation
2) quark-gluon plasma (QGP) formation
3) melting of charmonium in the QGP
4) decay of remaining charmonia and detection

questions:

a) beam energy dependence of time scales
b) what happens with the (many) charm quarks at hadronization, i.e at the phase boundary?

More timescales

formation and destruction of J/ψ (charmed hadrons)

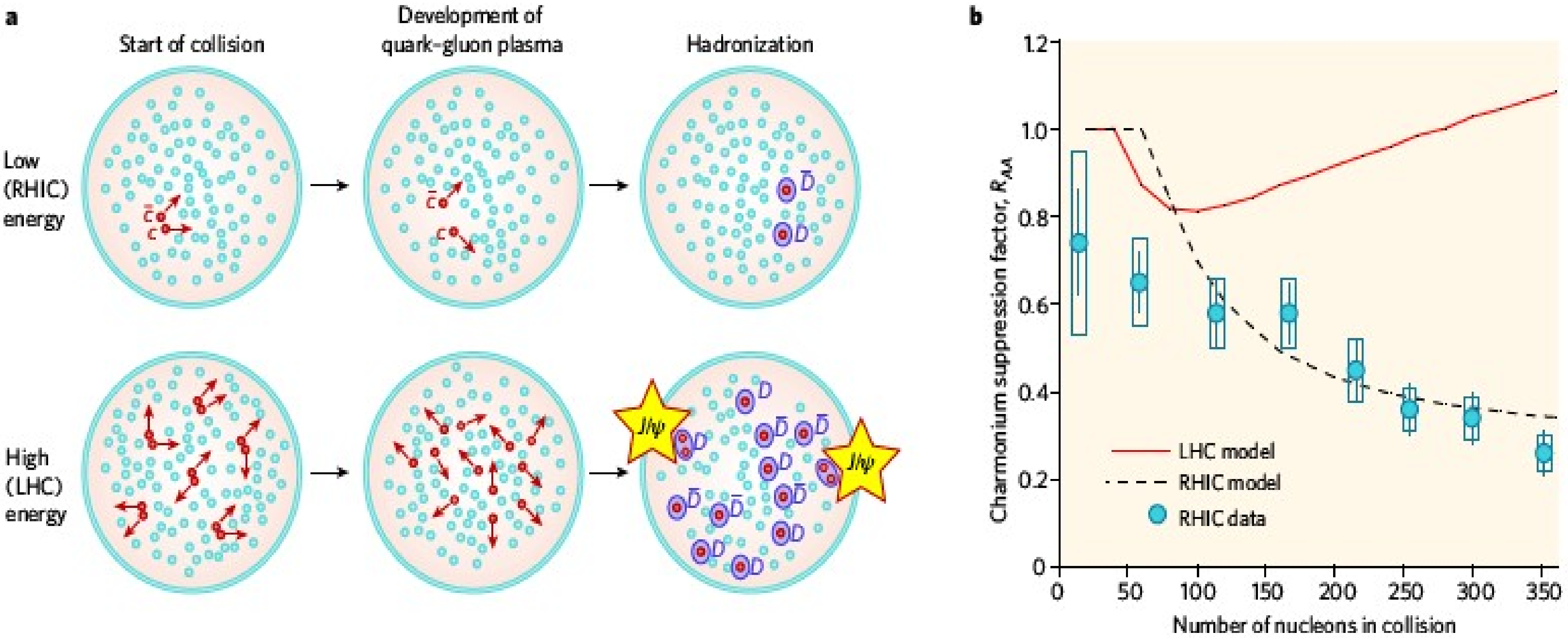
- QGP formation time, t_{QGP}
  - FAIR, SPS: $t_{QGP} \simeq 1$ fm/c $\sim t_{J/\psi}$
  - RHIC, LHC: $t_{QGP} \lesssim 0.1$ fm/c $\sim t_{c\bar{c}}$

survival of initially-produced J/ψ at FAIR/SPS energies? $(T_d \sim T_c)$

- collision time, $t_{coll} = 2R/\gamma_{cm}$
  - FAIR, SPS: $t_{coll} \gtrsim t_{J/\psi}$
  - RHIC: $t_{coll} < t_{J/\psi}$, LHC: $t_{coll} << t_{J/\psi}$

cold nuclear suppression important at FAIR/SPS energies?

quarkonium as a probe for deconfinement at the LHC
the statistical (re-)generation picture



charmonium enhancement as fingerprint of deconfinement at LHC energy

pbm, Stachel, Phys. Lett B490 (2000) 196
Andronic, pbm, Redlich, Stachel, Phys. Lett. B652 (2007) 659

Statistical hadronization in one page

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

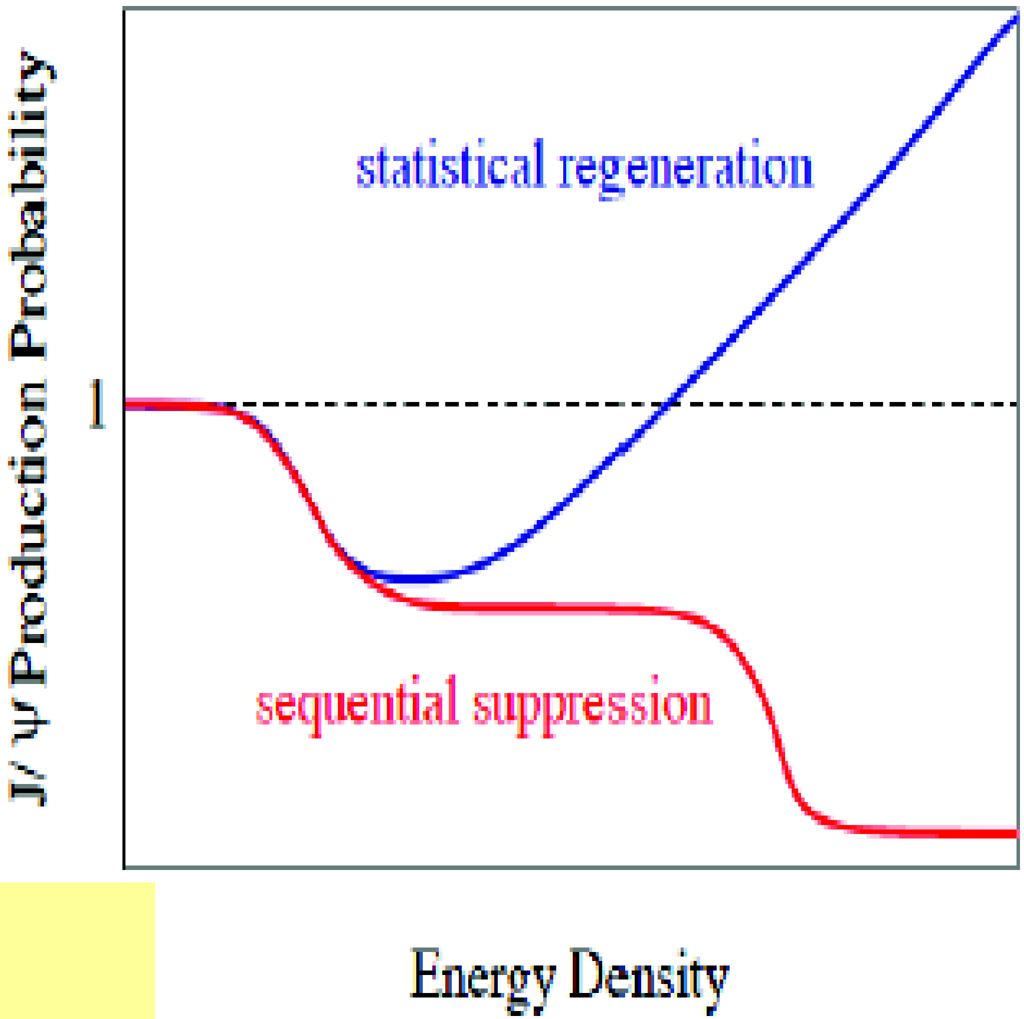
charm balance equation

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

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)

Decision on regeneration vs sequential suppression from LHC data



SPS RHIC LHC

Picture:
H. Satz 2009

Parameterization of all freeze-out points

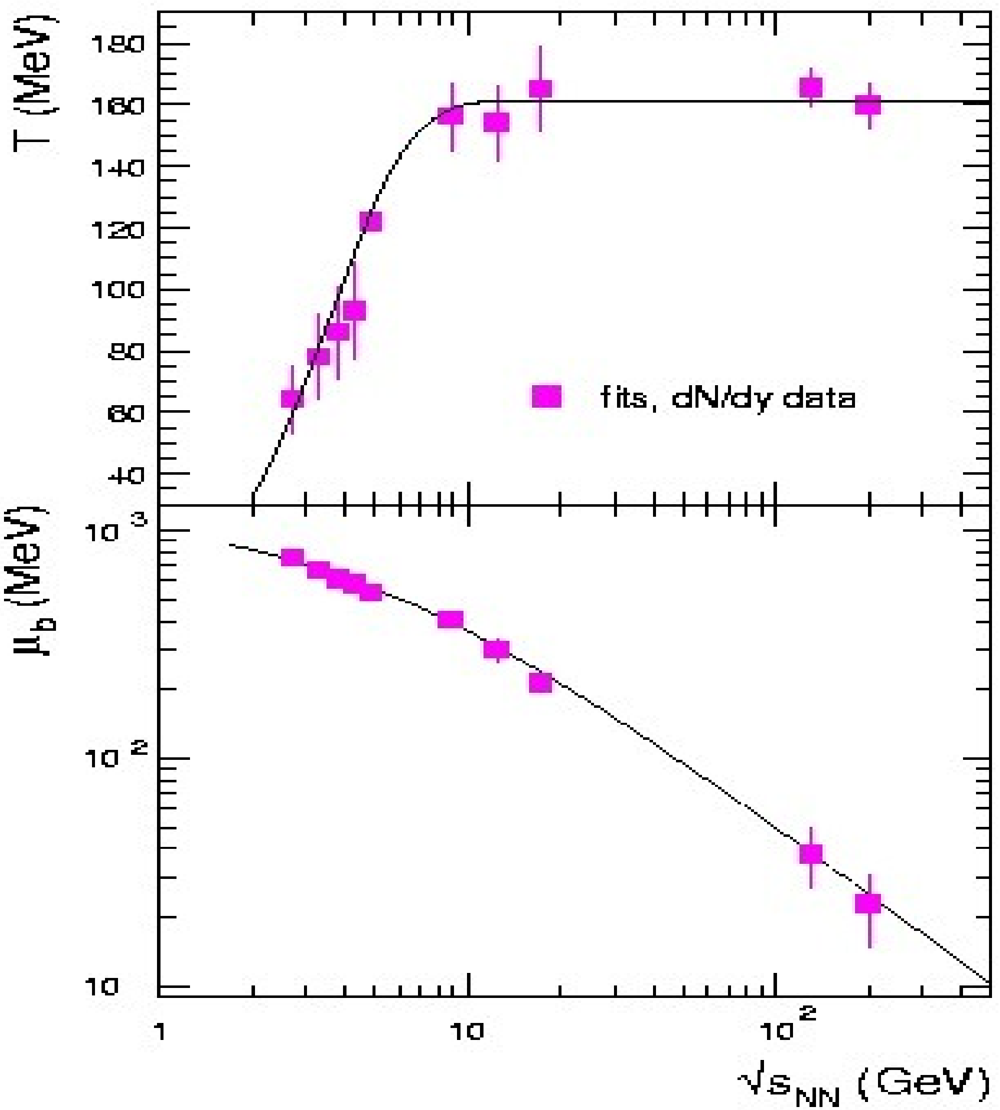
note: establishment of limiting temperature

T_{lim} = 160 MeV

get T and μ_B for all energies

in this approach $T_{lim} = T_c$

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



freeze-out point at LHC energy to come soon

Ingredients for prediction of quarkonium and open charm cross sections

• energy dependence of temperature and baryo-chemical potential (from hadron production analysis)
• open charm (open bottom) cross section in pp or better AA 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

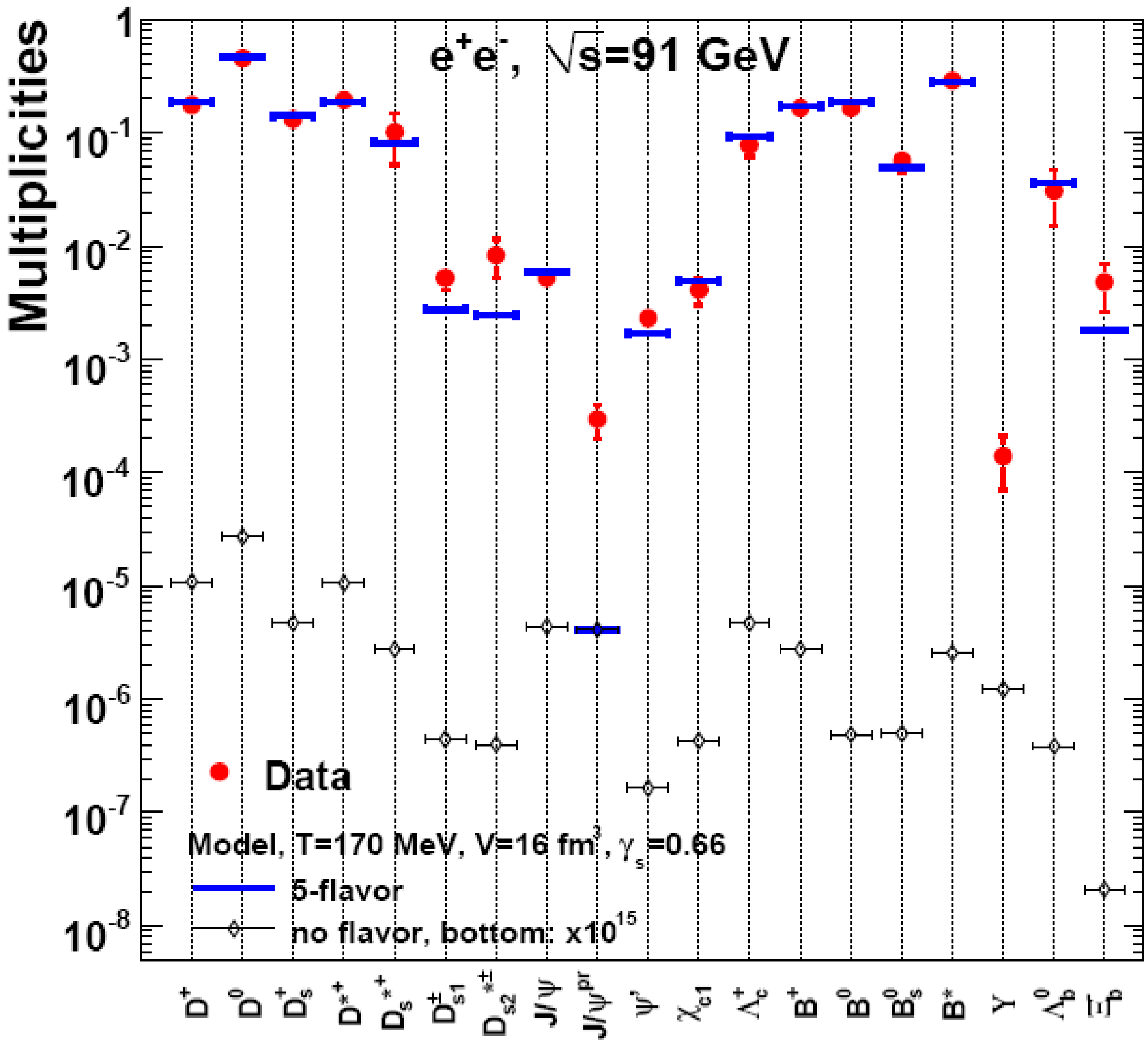
Hadronization of charm quarks – a special case?

If charmonium survives beyond T_c in the quark-gluon plasma, this implies in return that charm quarks hadronize at T > T_c.

The concept of a phase boundary between hadronic matter and quark-gluon plasma implies conversion of partons into hadrons within the (cross over?) transition.

A flavor-dependent phase boundary calls the whole concept of the deconfinement phase transition into question.

Heavy quark and quarkonium production in e+e- collisions

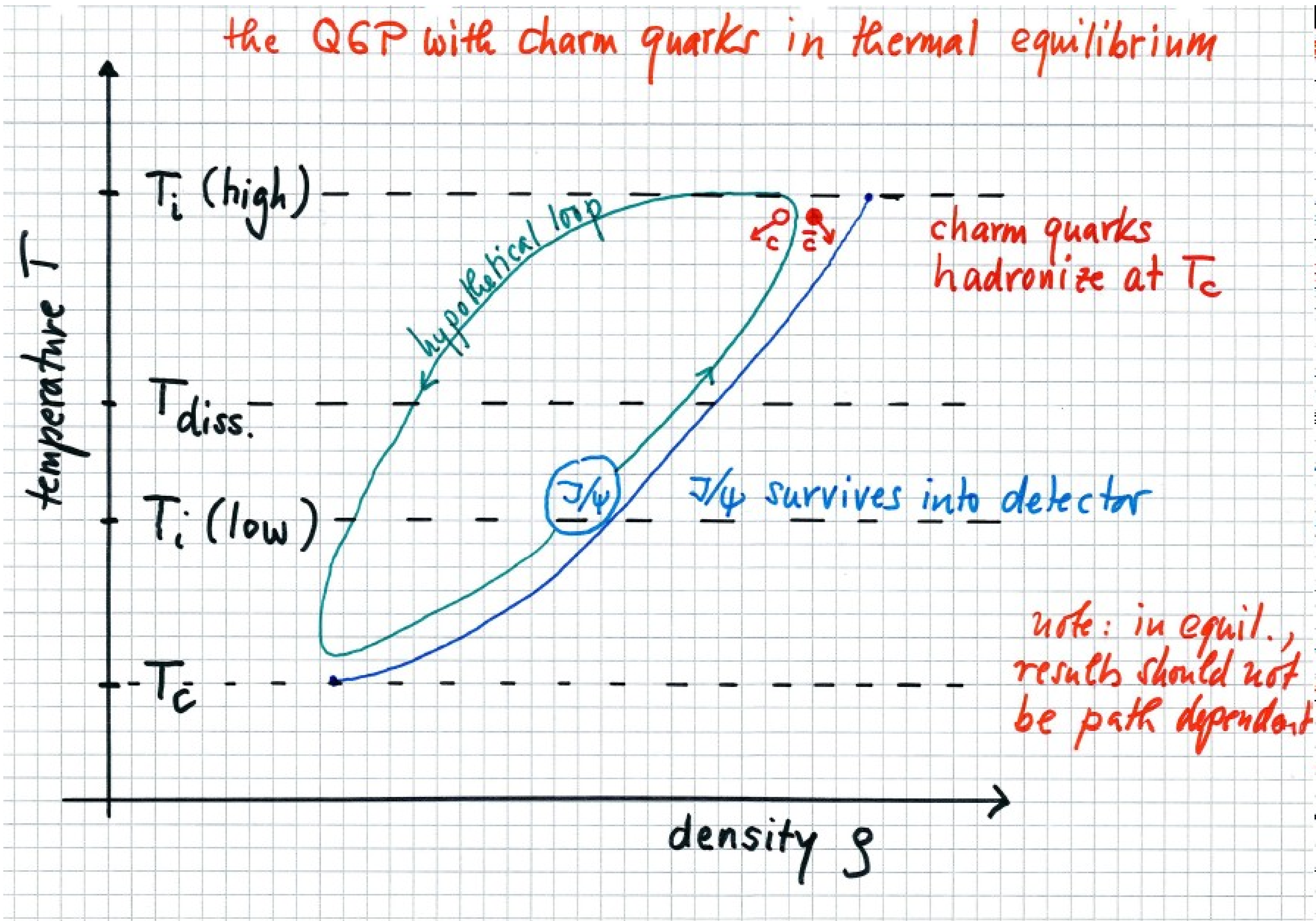


Comparison of stat. model calcs. with data

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

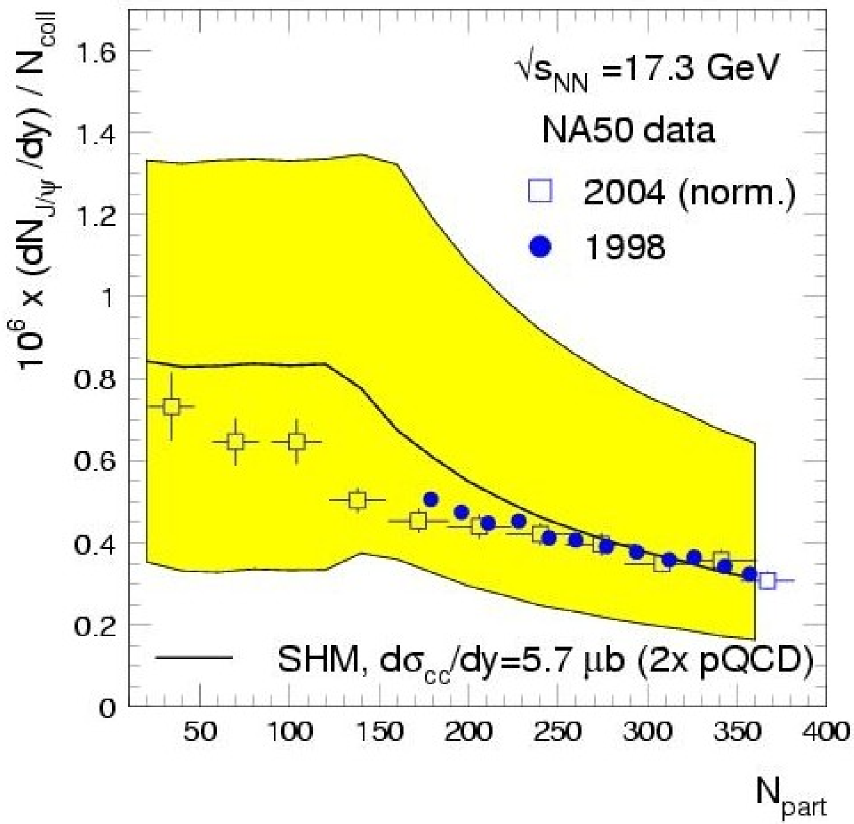


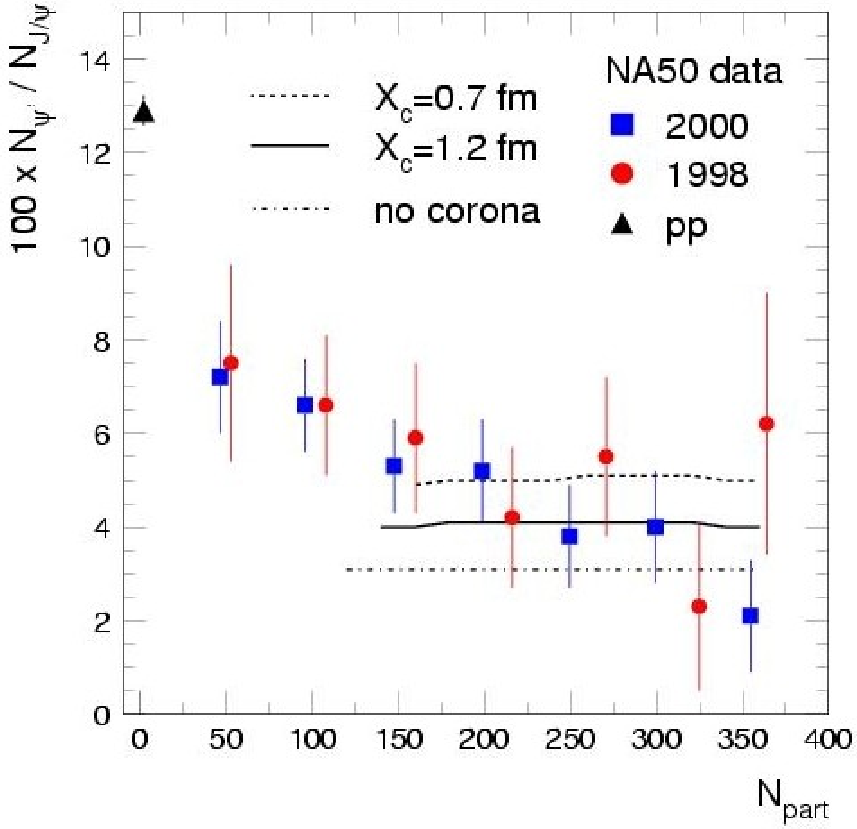
if charmed hadrons in PbPb follow statistical hadronization at the phase boundary

→ no J/psi bound state in QGP (complete color screening)

Now brief survey of SPS and RHIC results

results for SPS energy





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

psi'/psi ratio is expected from a thermal scenario

a note on excited quarkonia and statistical hadronization

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

$$R = \exp(-(M1-M0)/T)$$

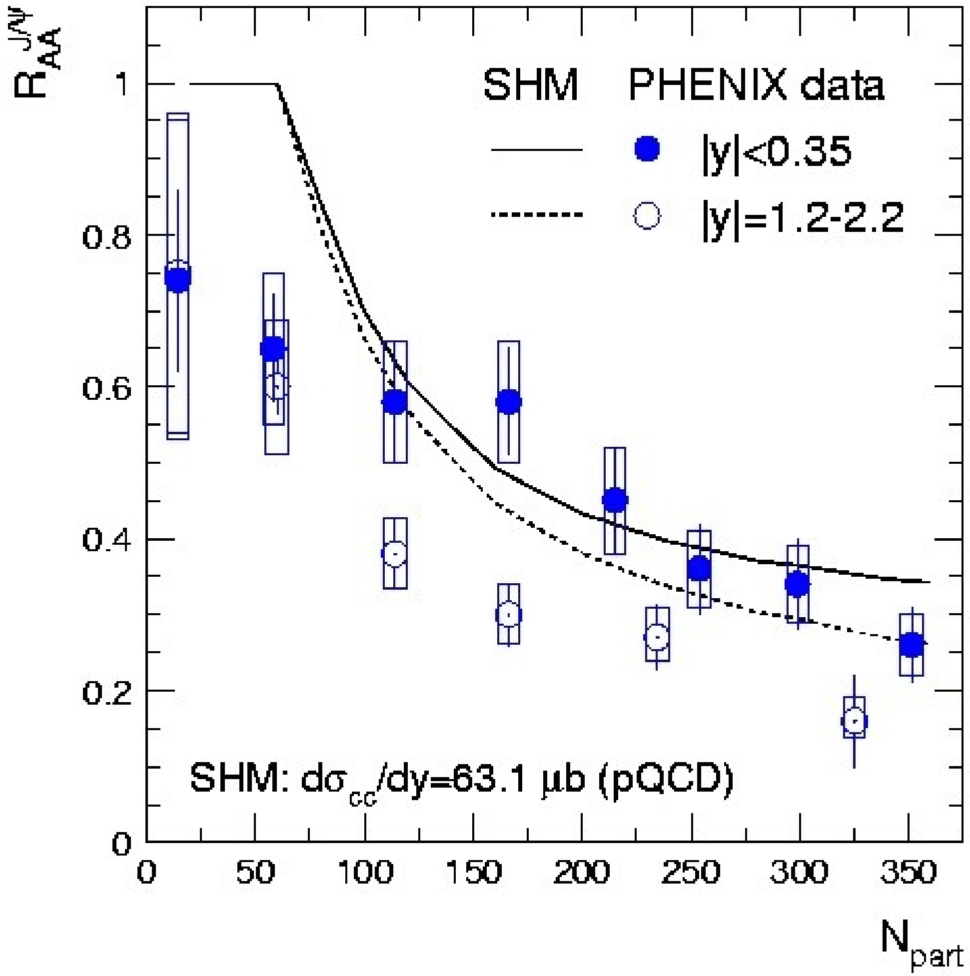
T = 164 MeV is the critical (or hadronization) temperature

for psi'/(J/psi) this yields: $R_{psi'} = 0.023$ (plus small correction from feeding)

for Y'/Y this yields: $R_{Y'} = 0.032$ $R_{Y''} = 0.004$

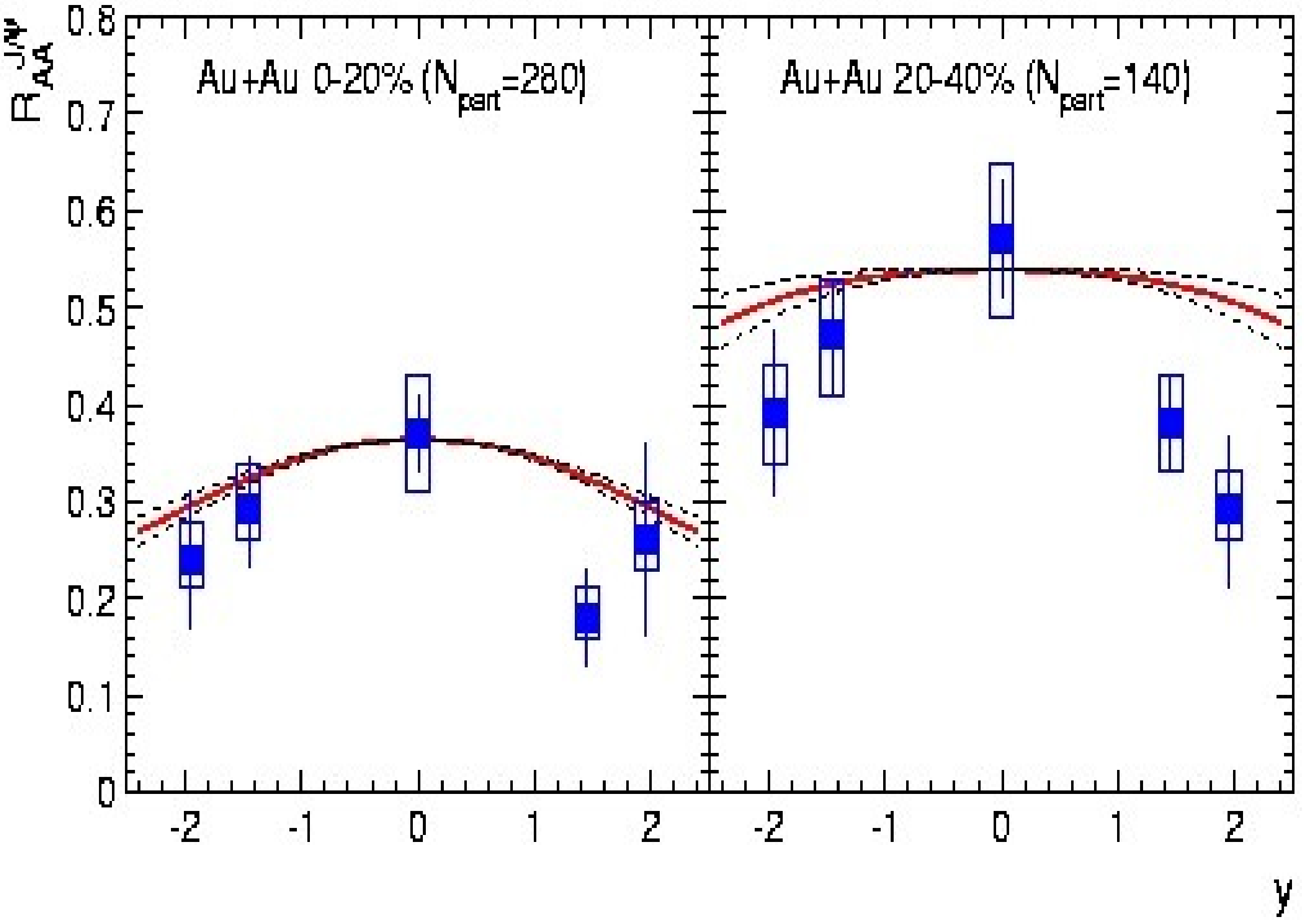
a brief look at RHIC data

Centrality dependence of nuclear modification factor



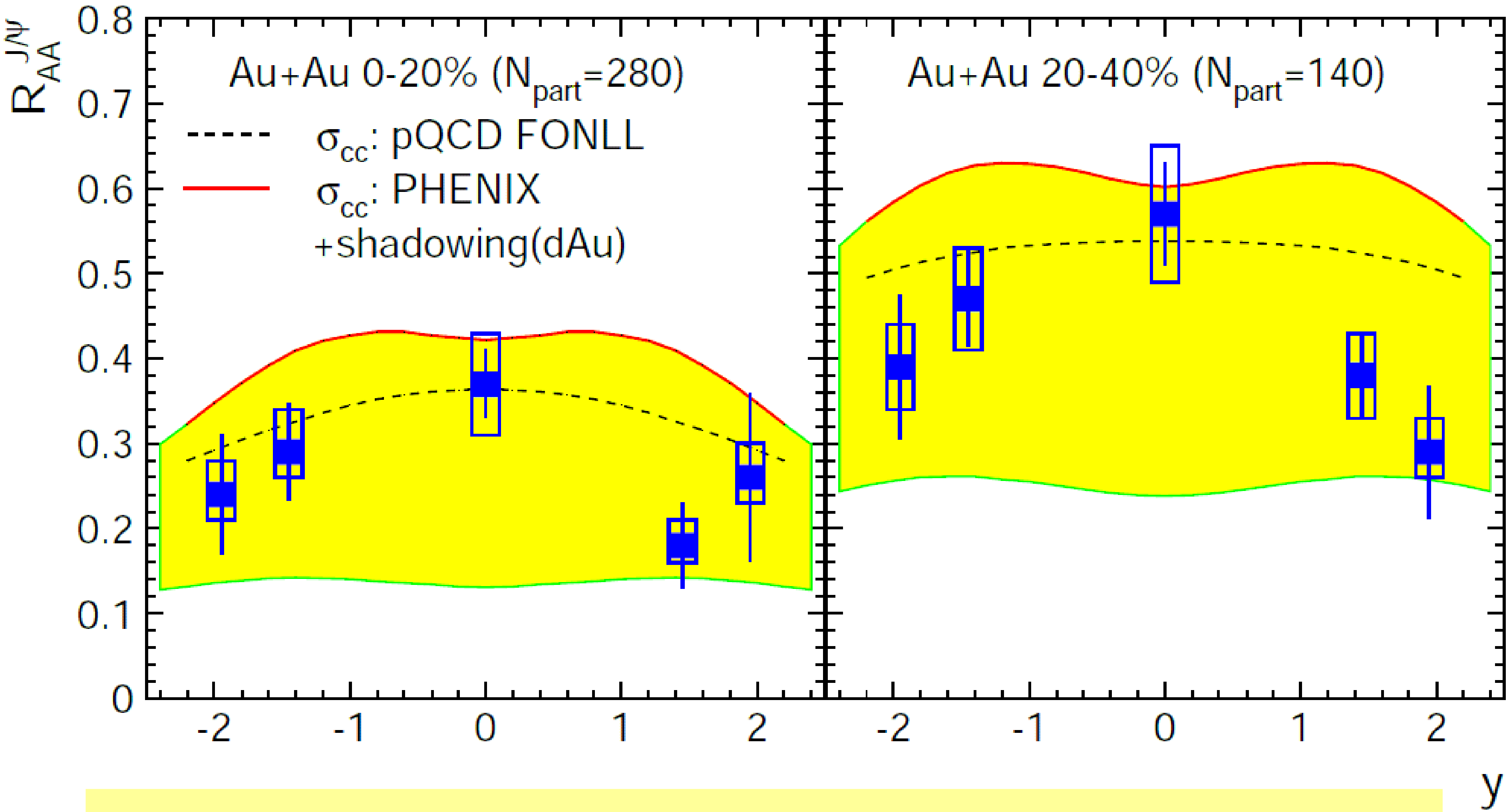
data well described
by our regeneration model
without any new
parameters

Comparison of model predictions to RHIC data: rapidity dependence



suppression is smallest at mid-rapidity (90 deg. emission)
a clear indication for regeneration at the phase boundary

Calculations including shadowing



assume PHENIX pA data reflect shadowing

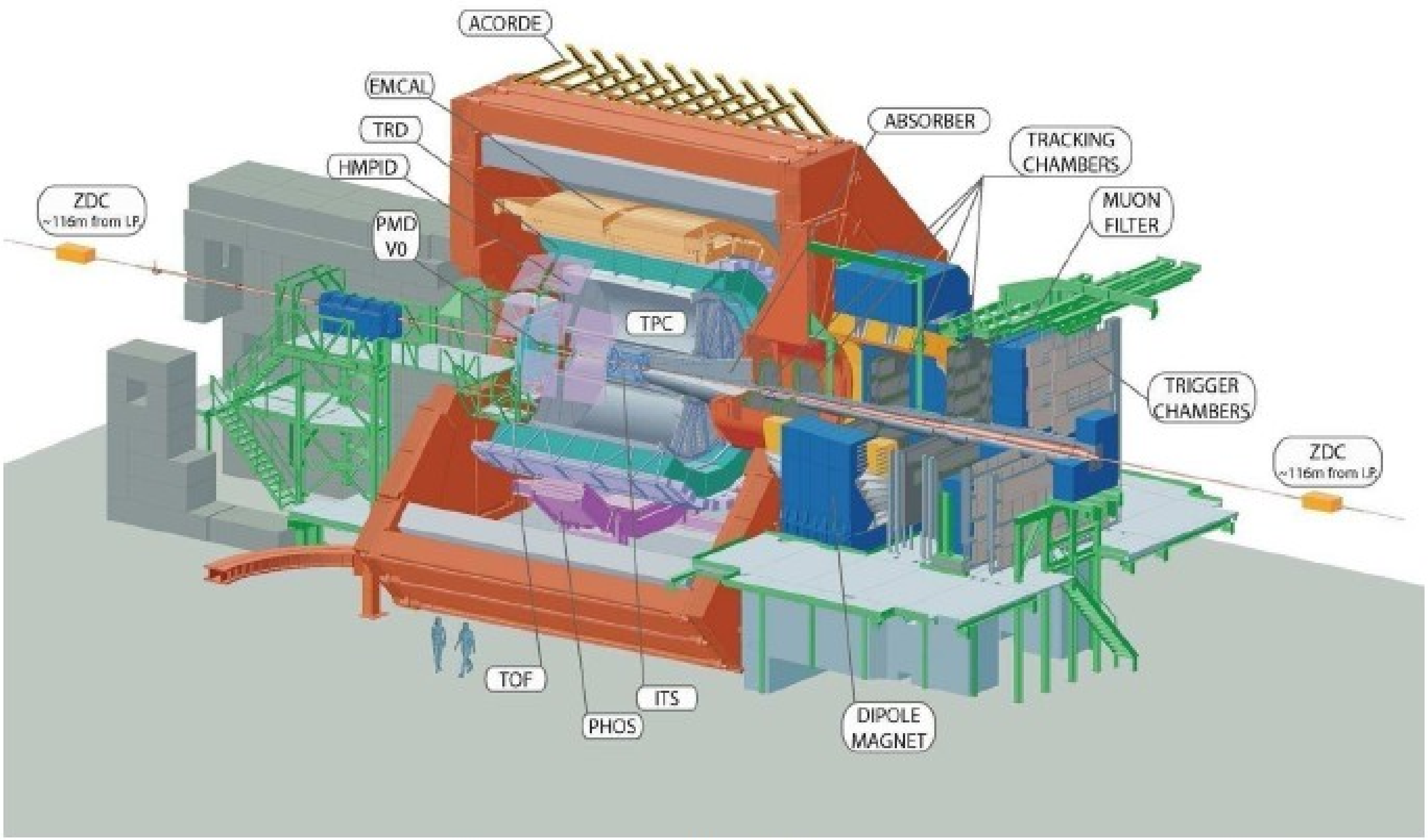
now to LHC data

attempt full measurement of open charm and open beauty
in pp, pPb, PbPb as function of centrality, rapidity and transverse momentum

attempt full measurement including polarization of all quarkonia
in pp, pPb, PbPb as function of centrality, rapidity and transverse momentum

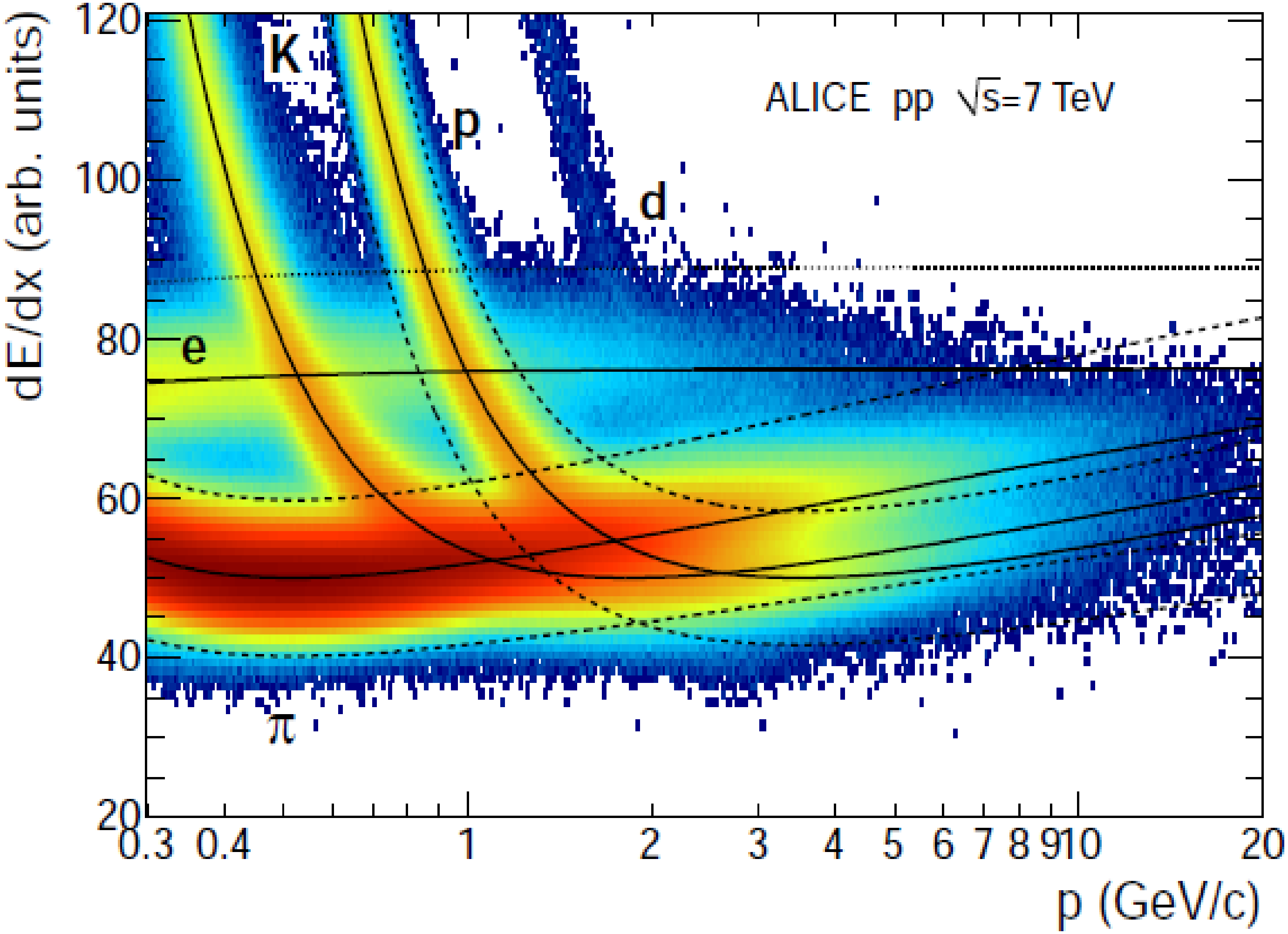
...we are on the way

Charm and charmonia measured in ALICE

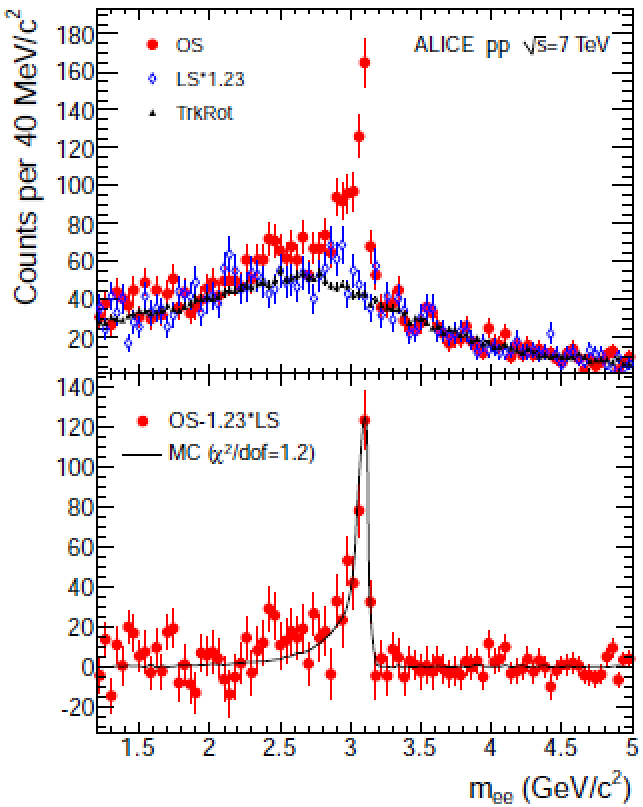


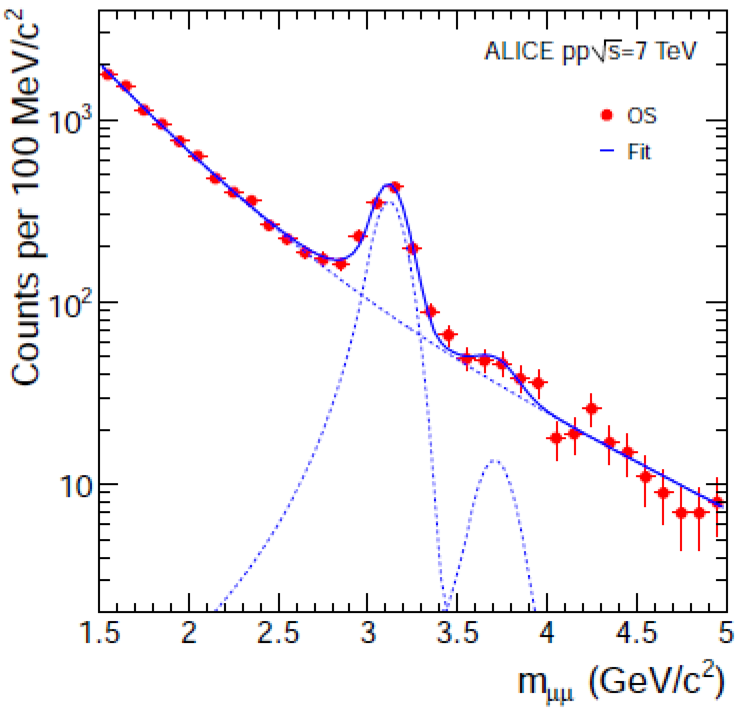
Measures charmonium at $|y| < 0.9$ (e^+e^-) and $-4 < y < -2.5$ ($\mu^+\mu^-$)

Electron identification with the Alice TPC



J/psi identification in pp collisions with ALICE



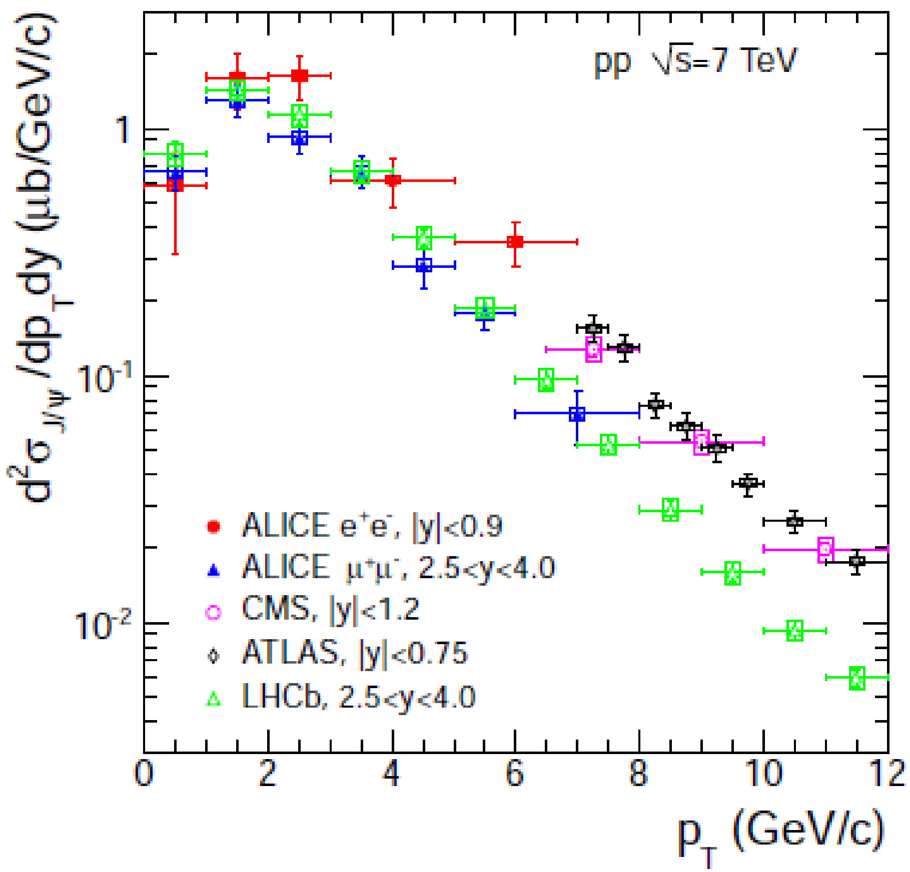


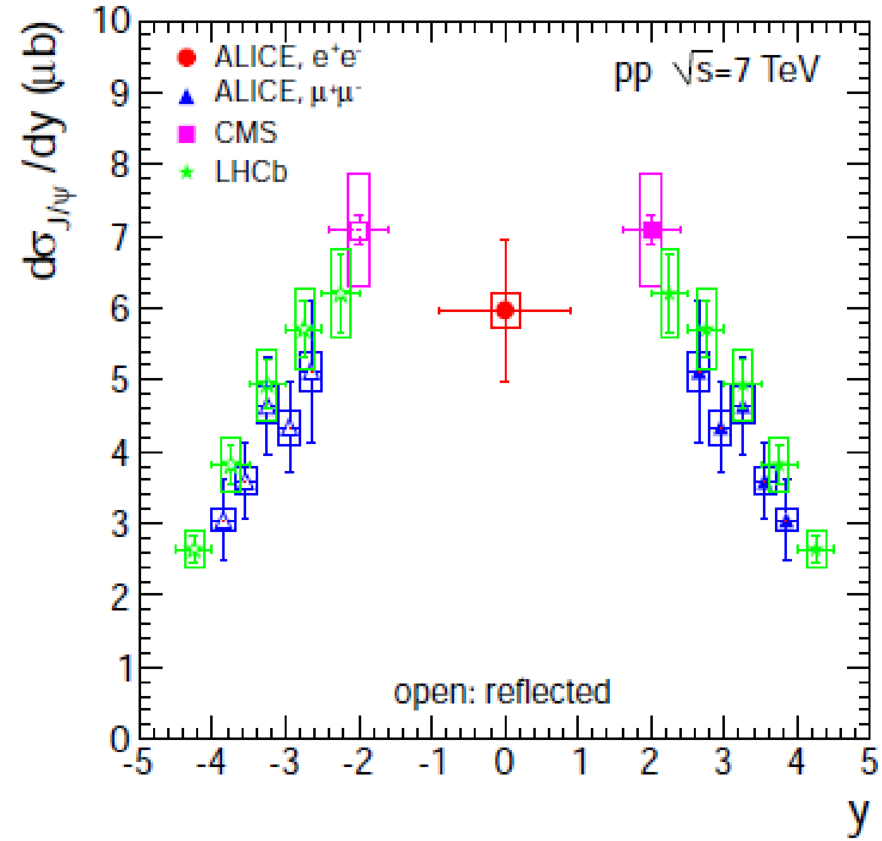
$N_{J/psi} = 957 \pm 56$ for L_{int}=7.9 nb^{-1}

$N_{J/psi} = 352 \pm 32$ for L_{int}=5.6 nb^{-1}

Phys. Lett. B 704 (2011) 442

J/psi in pp collisions



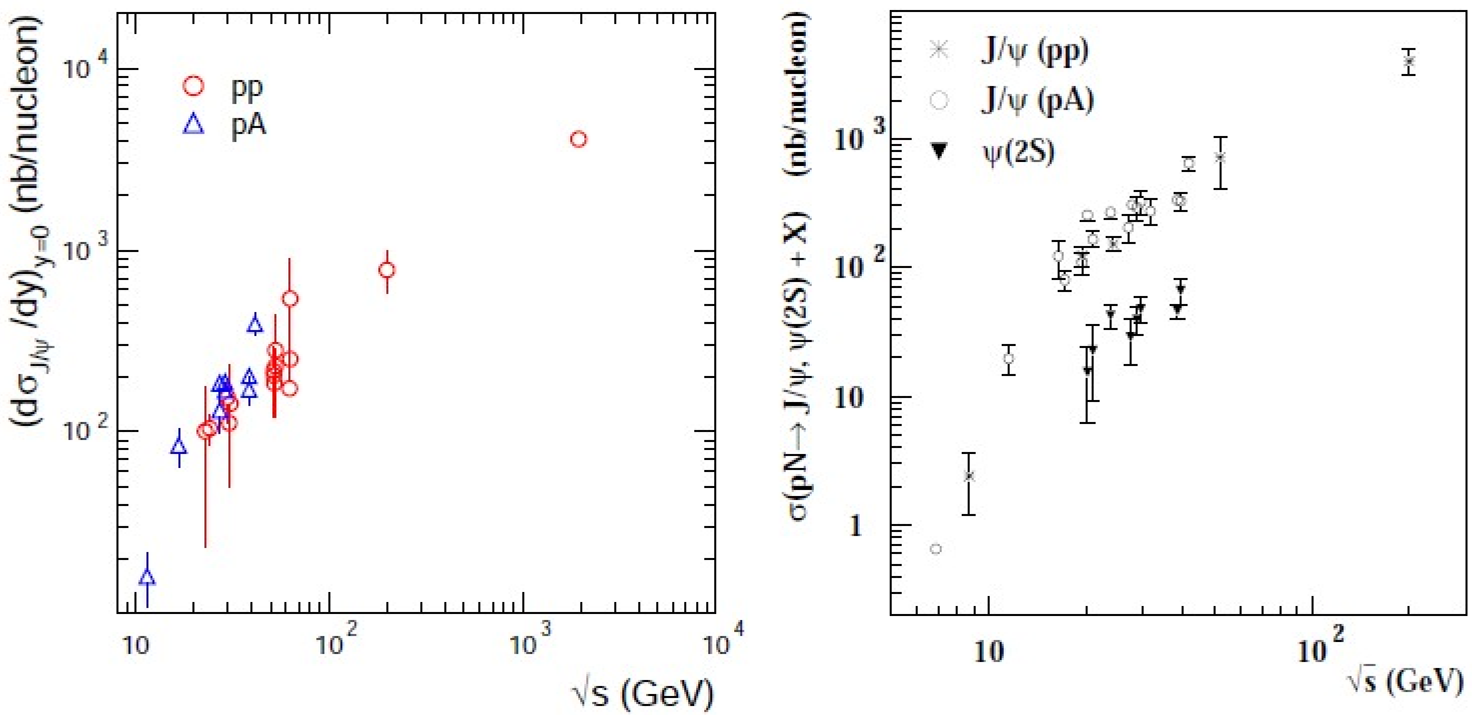


ALICE measures down to p_T=0, with broad y coverage

good agreement between the 4 LHC experiments PLB 704 (2011) 442

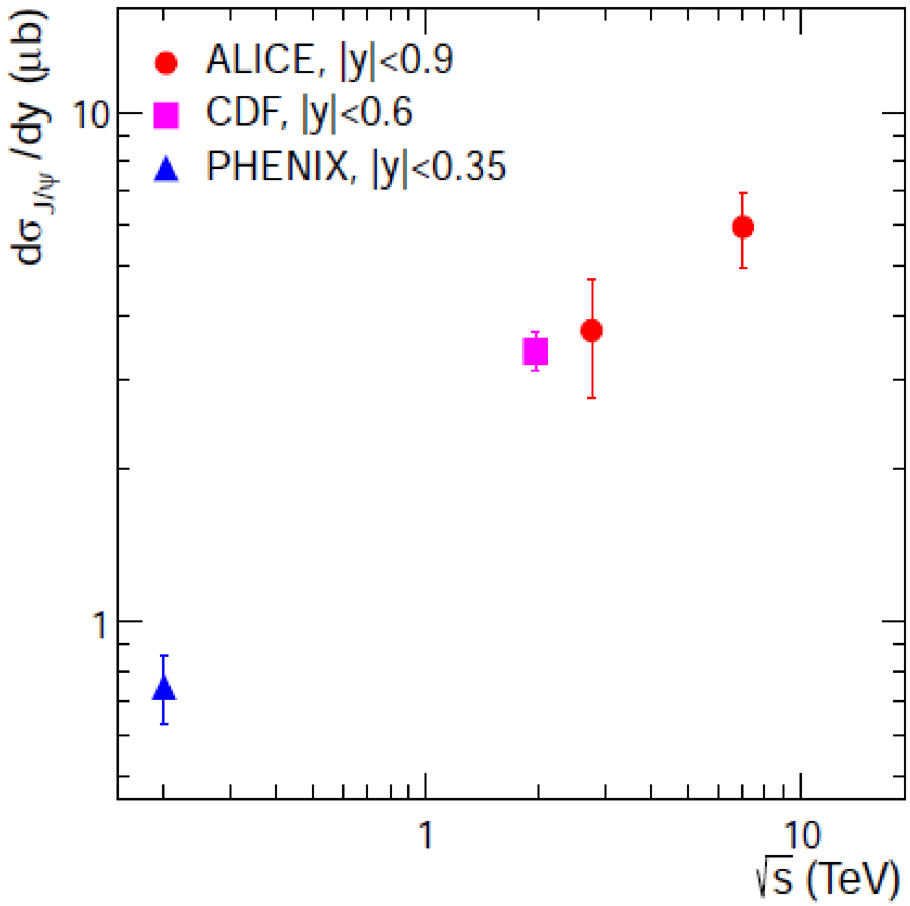
Energy dependence of J/psi production in pp and pA collisions – lower energies

F. Maltoni et al., Phys. Lett. B638 (2006) 202



$$\sigma_{pA} = \sigma_{pp} A^{\alpha},\ \alpha \simeq 0.92 \text{ for } J/\psi,\ \alpha \simeq 0.85 \text{ for } \psi'$$

Energy dependence of J/psi production in pp collisions – collider energies

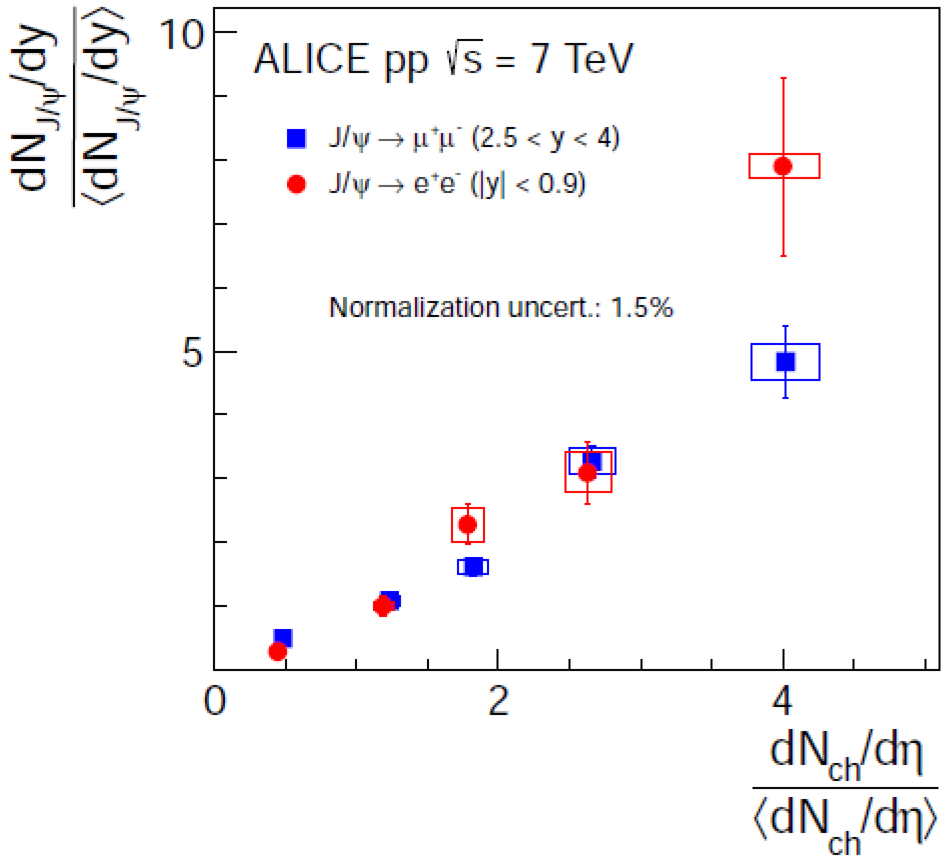


arXiv:1203.3641

...and more: polarization results (PRL 108 (2012) 082001), $B \rightarrow J/\psi$

A big surprize – multiplicity dependence

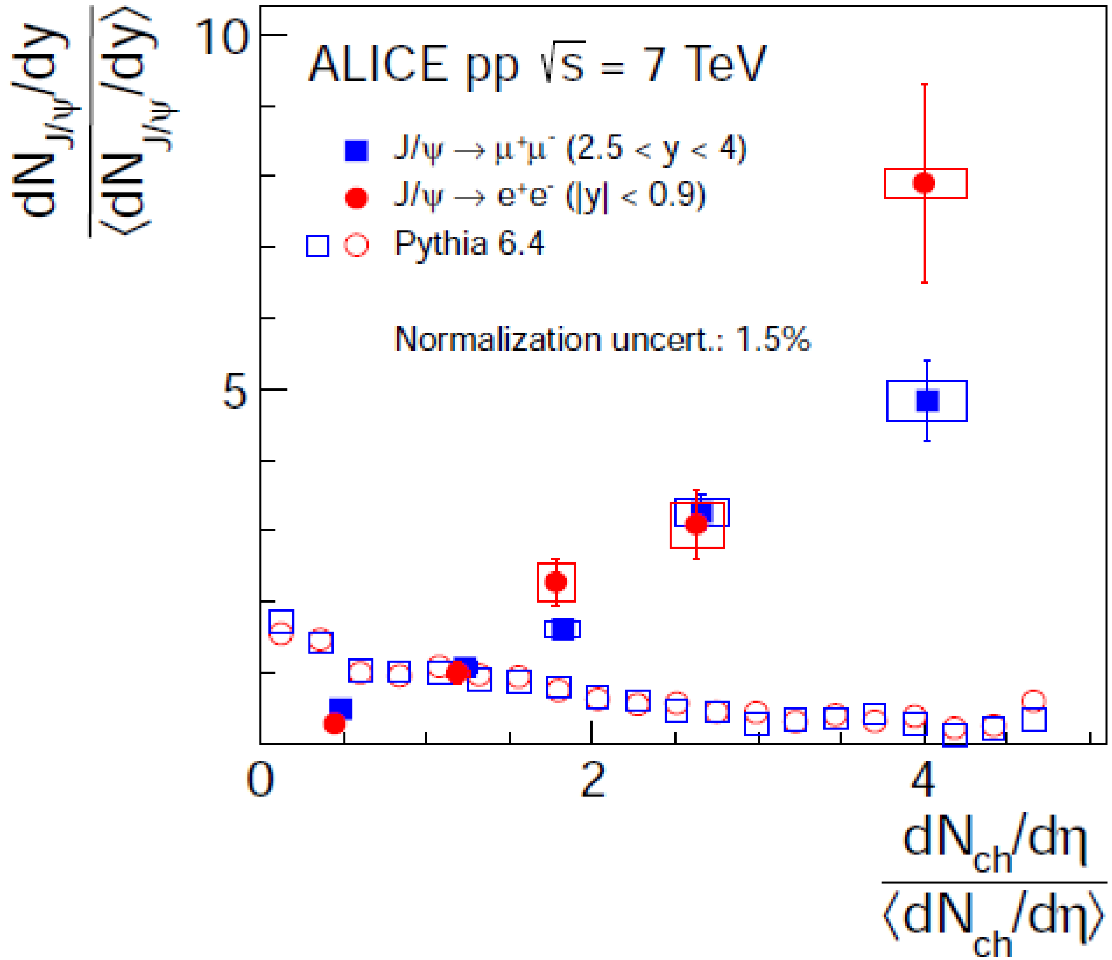
ALICE, arXiv:1202.2816



Non-linear behavior??? Is this a signature of multi-parton interactions?

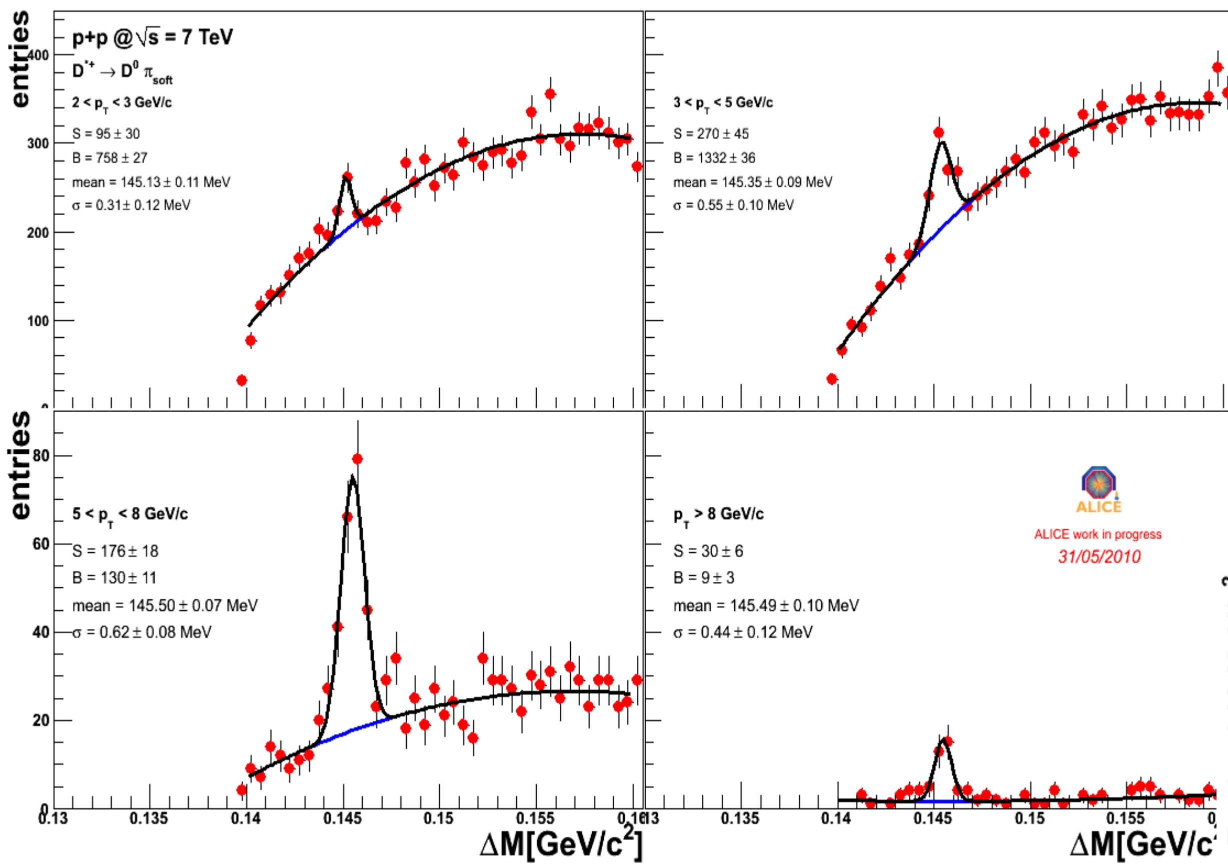
Observations not in agreement with implementation of multi-parton collisions in Pythia 6.4

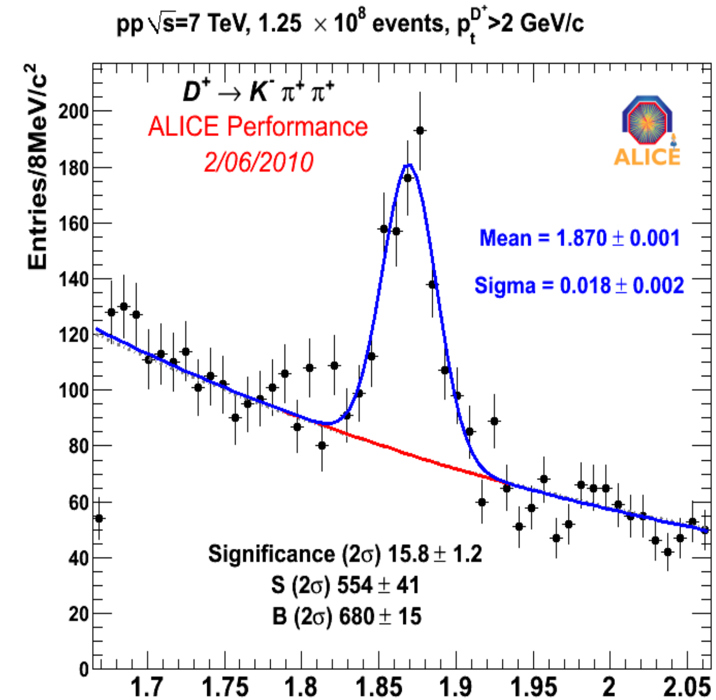
ALICE, arXiv:1202.2816

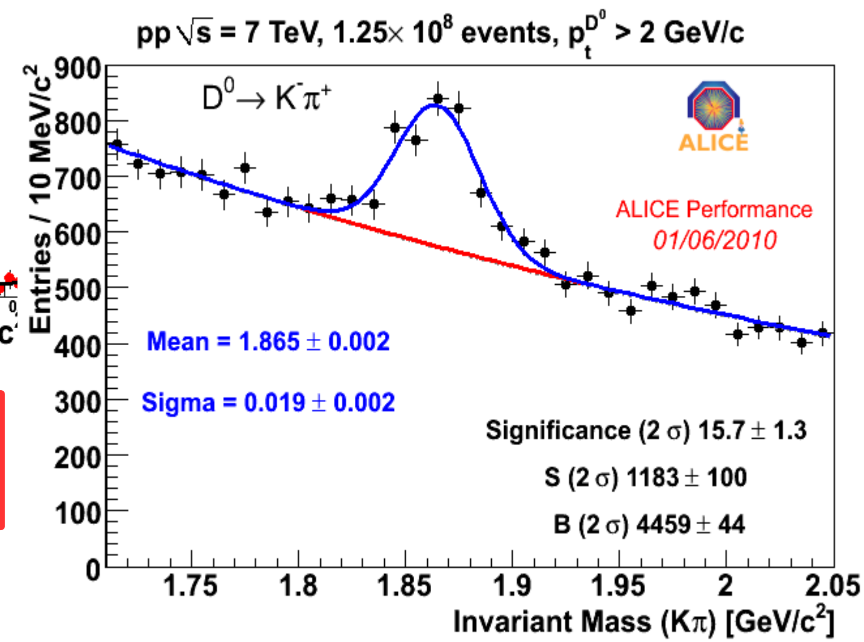


D^0, D^+ and D^{0*} in 7 TeV pp data

1.25 10^8 events

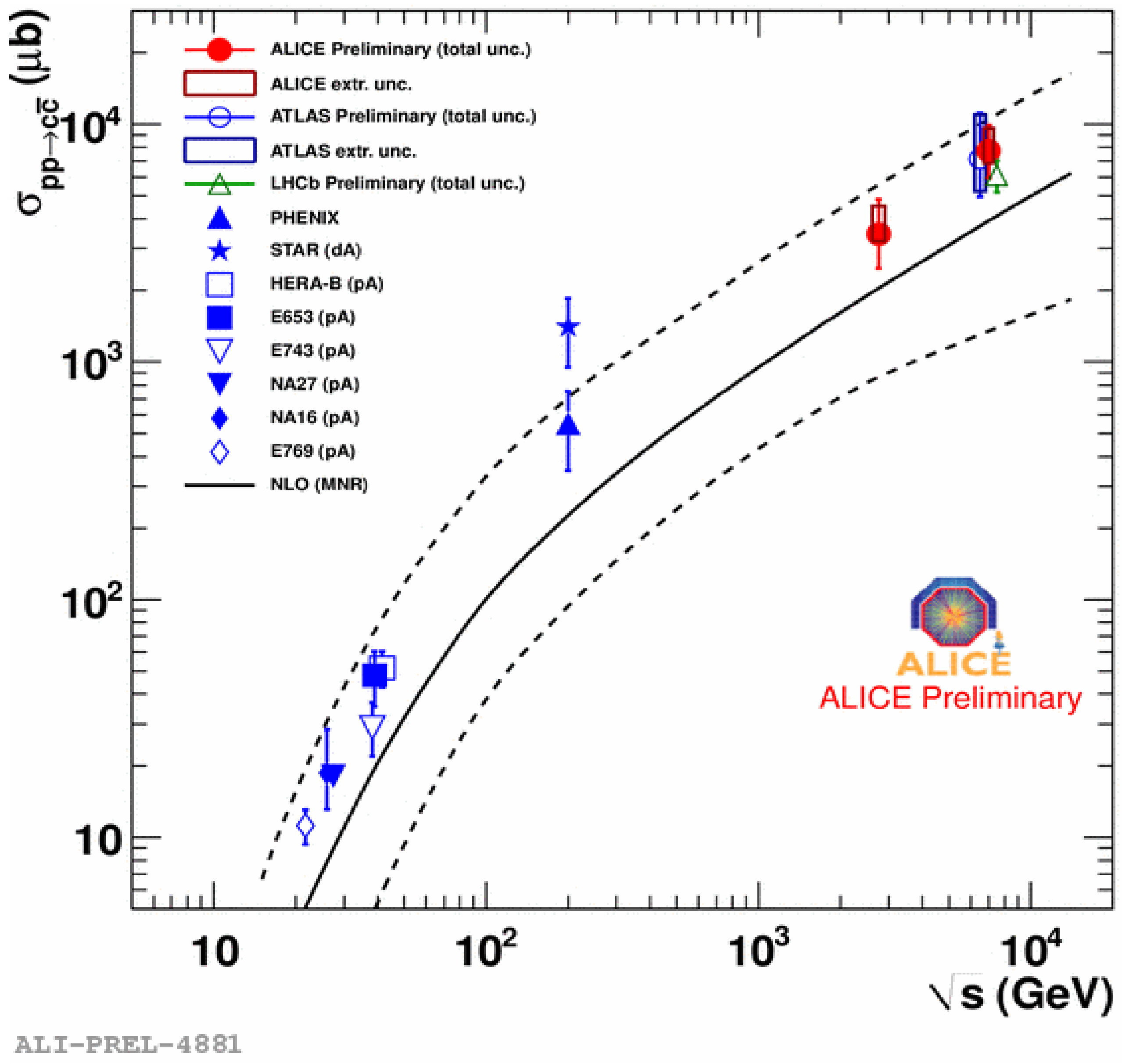




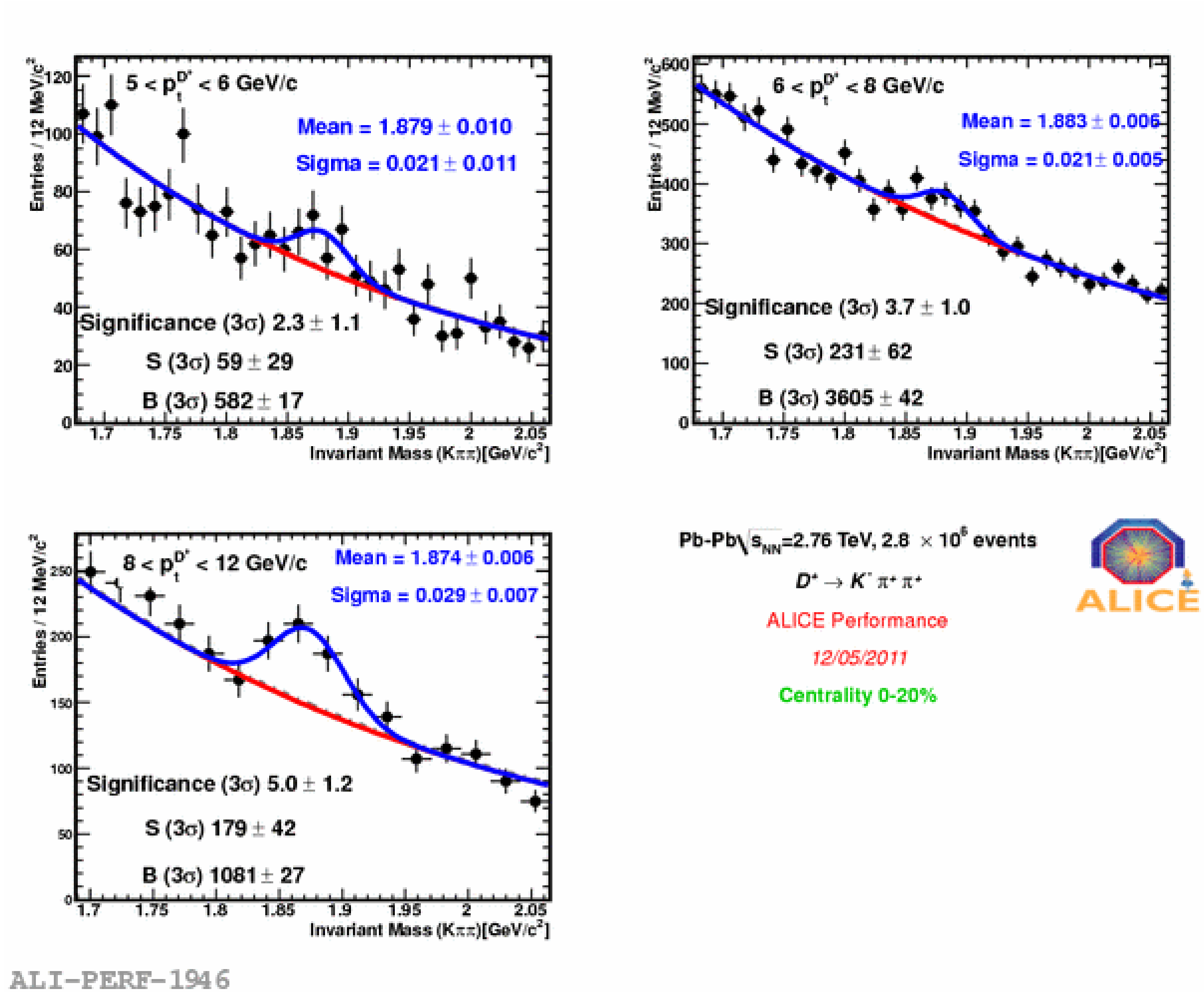


for 10^9 events, expect to measure open charm for p_t = 0.5 – 15 GeV/c

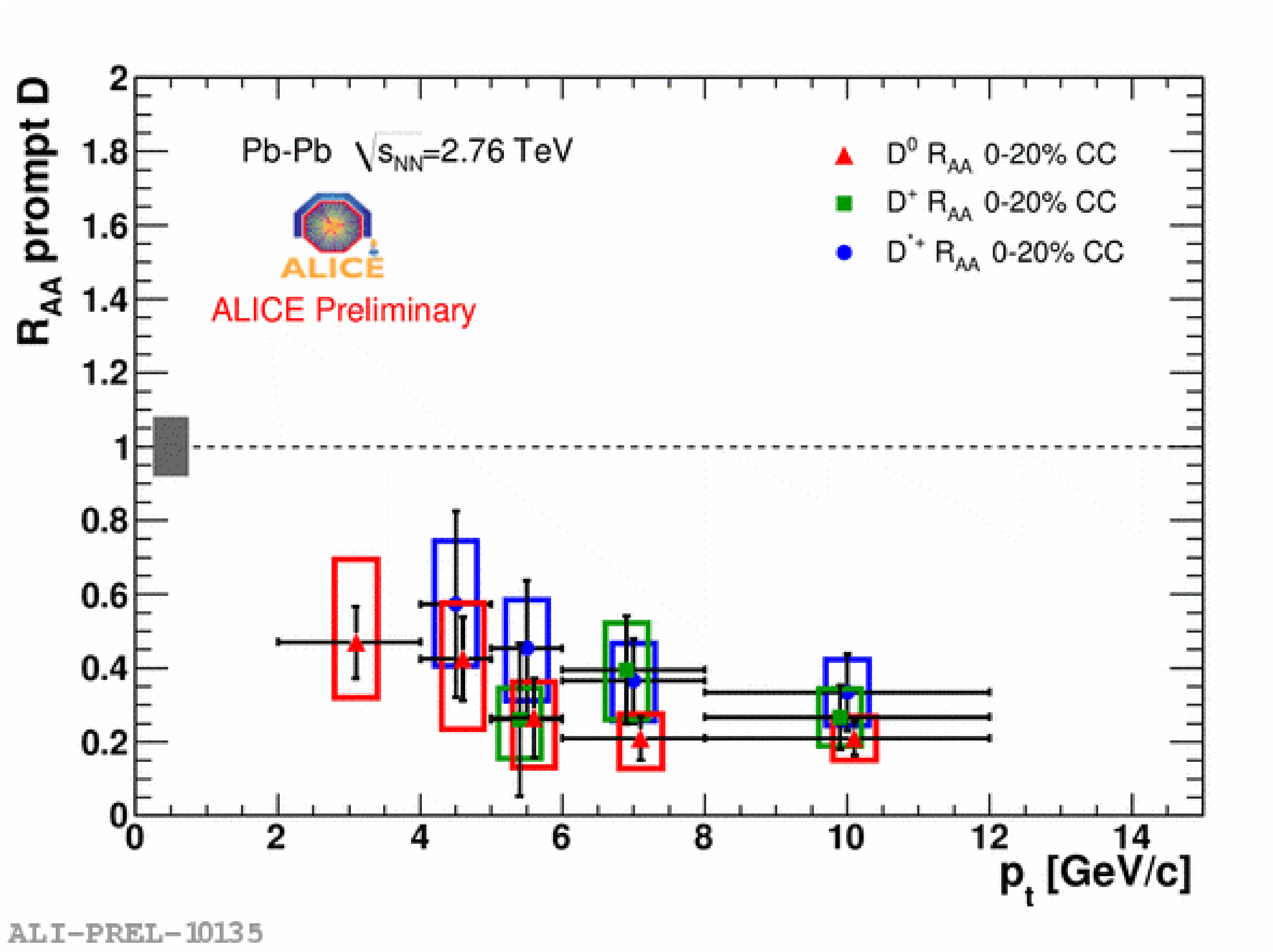
a first try at the total ccbar cross section in pp collisions



D meson signals in Pb—Pb collisions

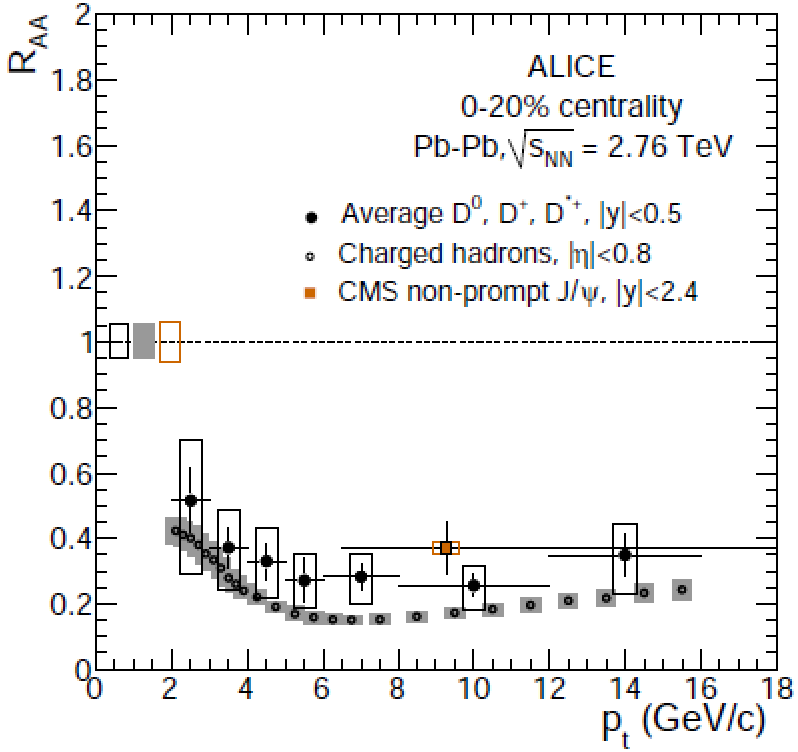


D mesons in PbPb collisions at LHC



Suppression of charm at LHC energy

$$R_{AA} = \frac{\mathrm{d}N^{AA}/\mathrm{d}p_t}{N_{coll} \cdot \mathrm{d}N^{pp}/\mathrm{d}p_t}$$



ALICE, arXiv:1203.2160

Energy loss of charm quarks close to that for light quark → thermalization

charm quarks are suppressed relative to pp collisions

in the pt range 3 < pt < 10 GeV there are much fewer charm quarks compared to expectations from pp collisions

→ **charm quarks in PbPb are at low pt!**

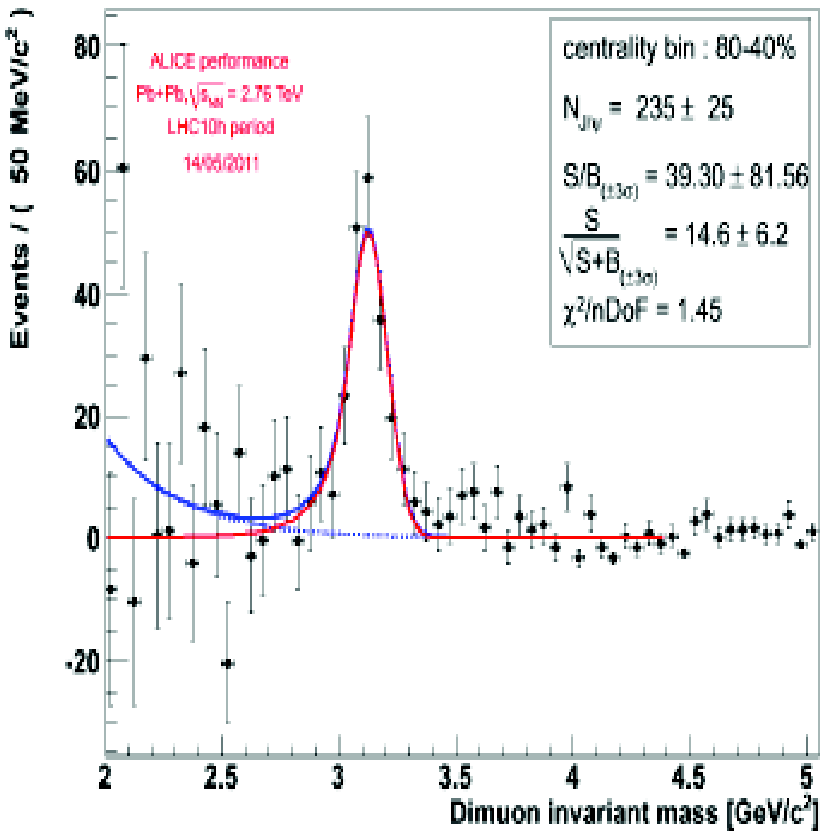
expect that charmonia are suppressed in the pt > 3GeV range

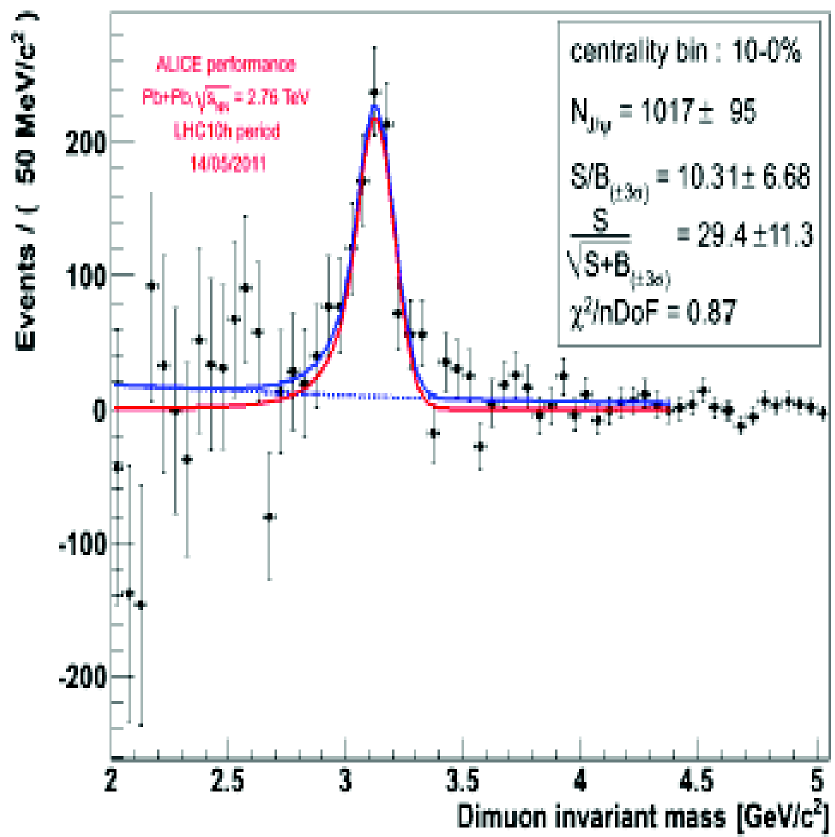
measurements at low pt are absolutely essential for the charmonium story

solution: normalization of J/psi to the open charm cross section in PbPb collisions

first step: (J/psi)/D ratio in PbPb collisions
to come soon from ALICE

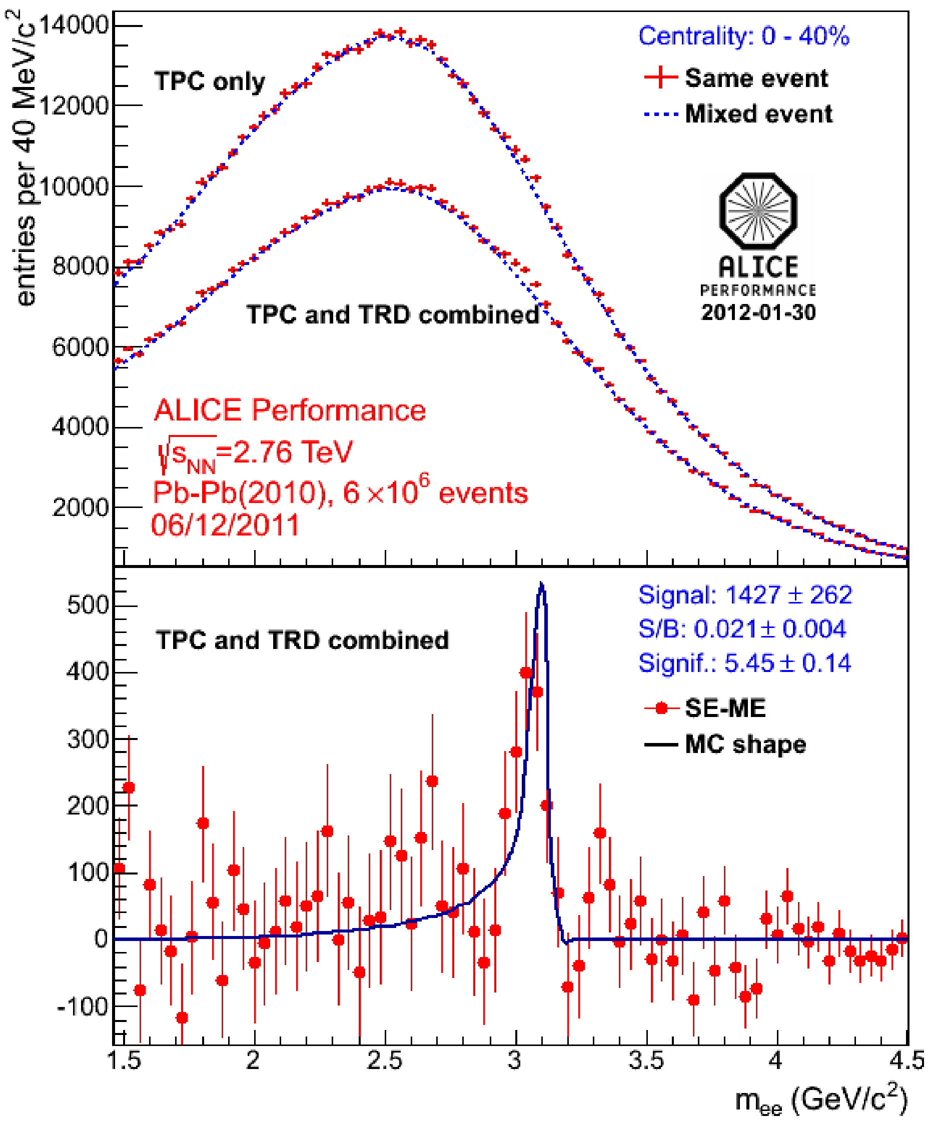
J/psi → mumu in PbPb collisions





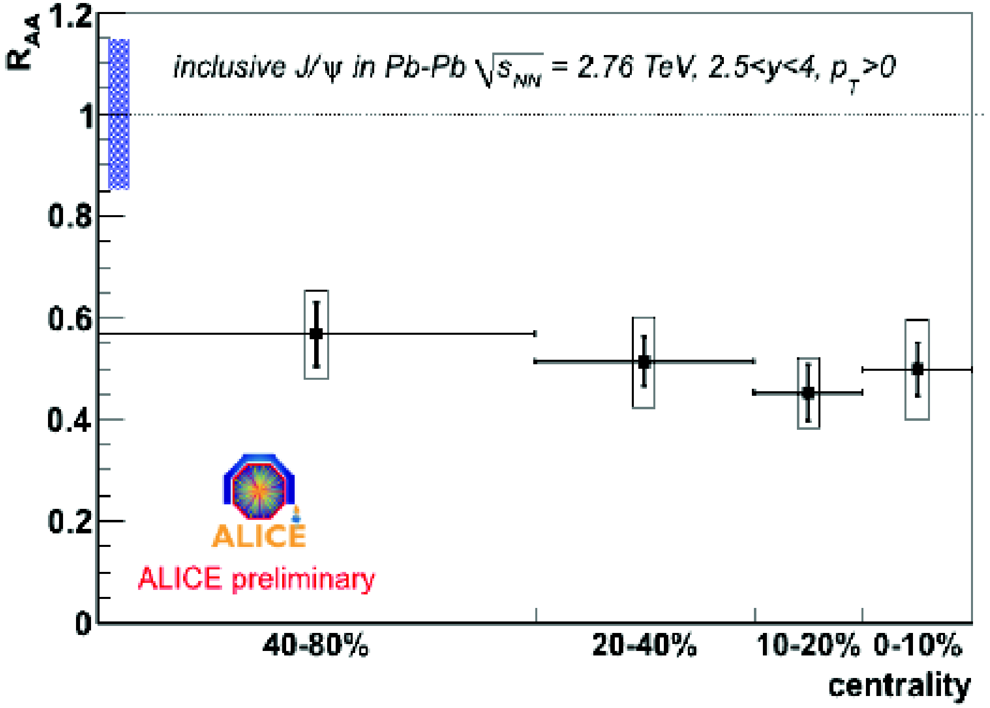
note: ALICE measurements include pt(J/psi) = 0

J/psi in e+e- needs electron ID in both TPC and TRD



<u>most challenging:</u> PbPb collisions
in spite of significant combinatorial background
(true electrons, not from J/ψ decay but e.g. D- or B-mesons) resonance well visible

first J/psi results at LHC energy from ALICE

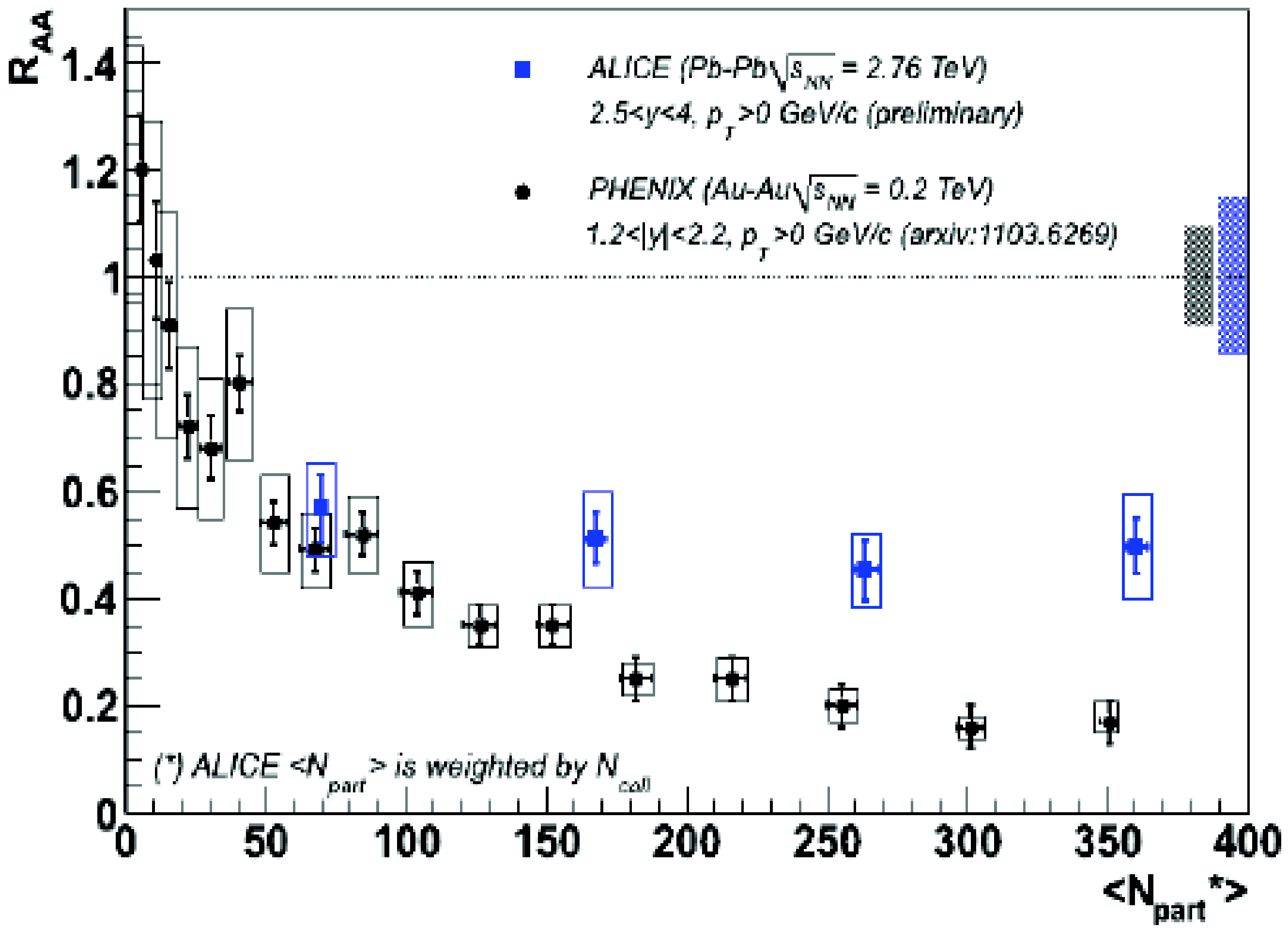


- Error bars:
Statistical uncertainties
- Empty boxes:
Centrality-dependent systematic uncertainties
- Blue box:
Overall systematic uncertainties

- Contamination from B feed-down: 10.7% from p-p measurement (arxiv: 1103.0423)

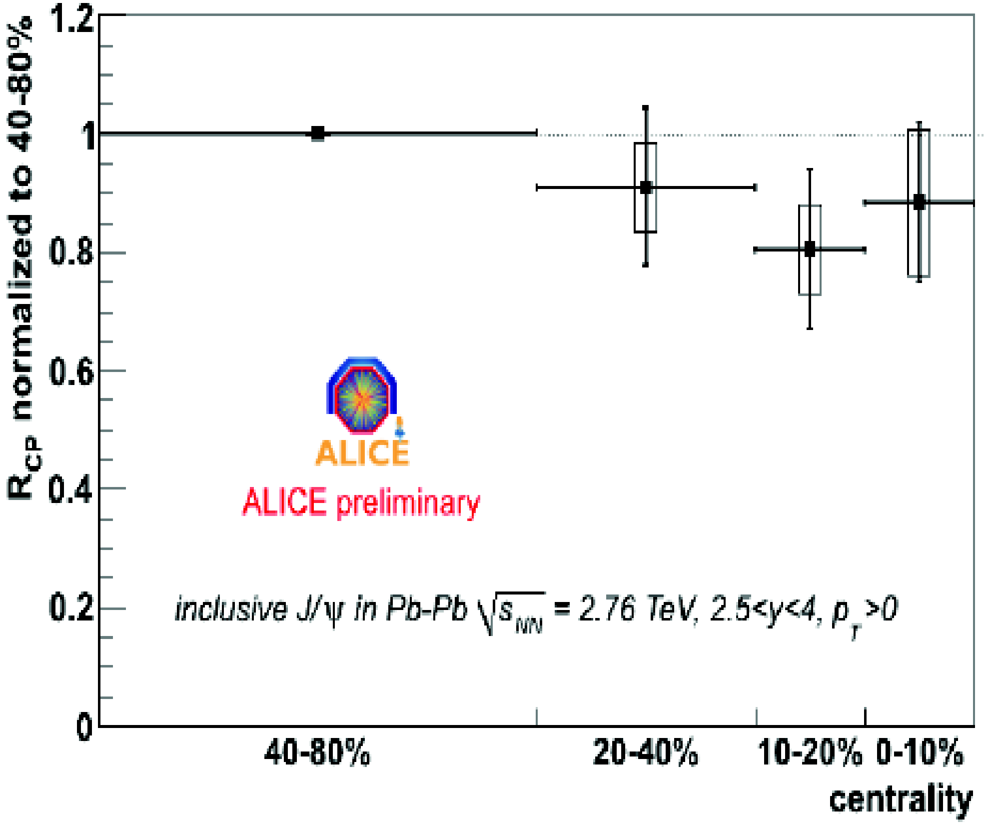
→ Assuming it scales with N_{coll}: ~12% reduction of the R_{AA} in 0-10% can be expected

comparison with results from PHENIX at RHIC



R_AA increases as function of energy!

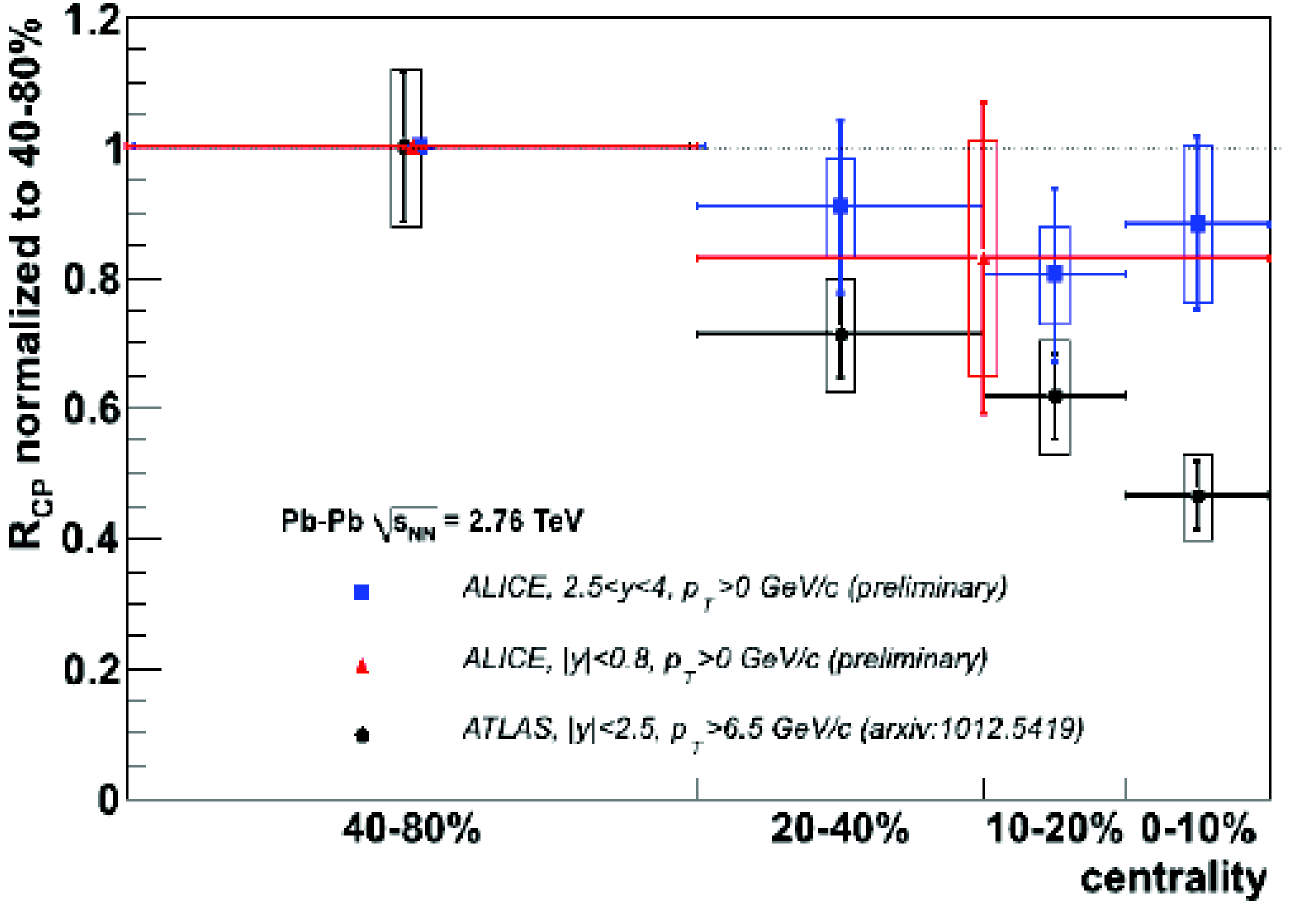
centrality dependence via R_CP



- Error bars:
  Statistical uncertainties

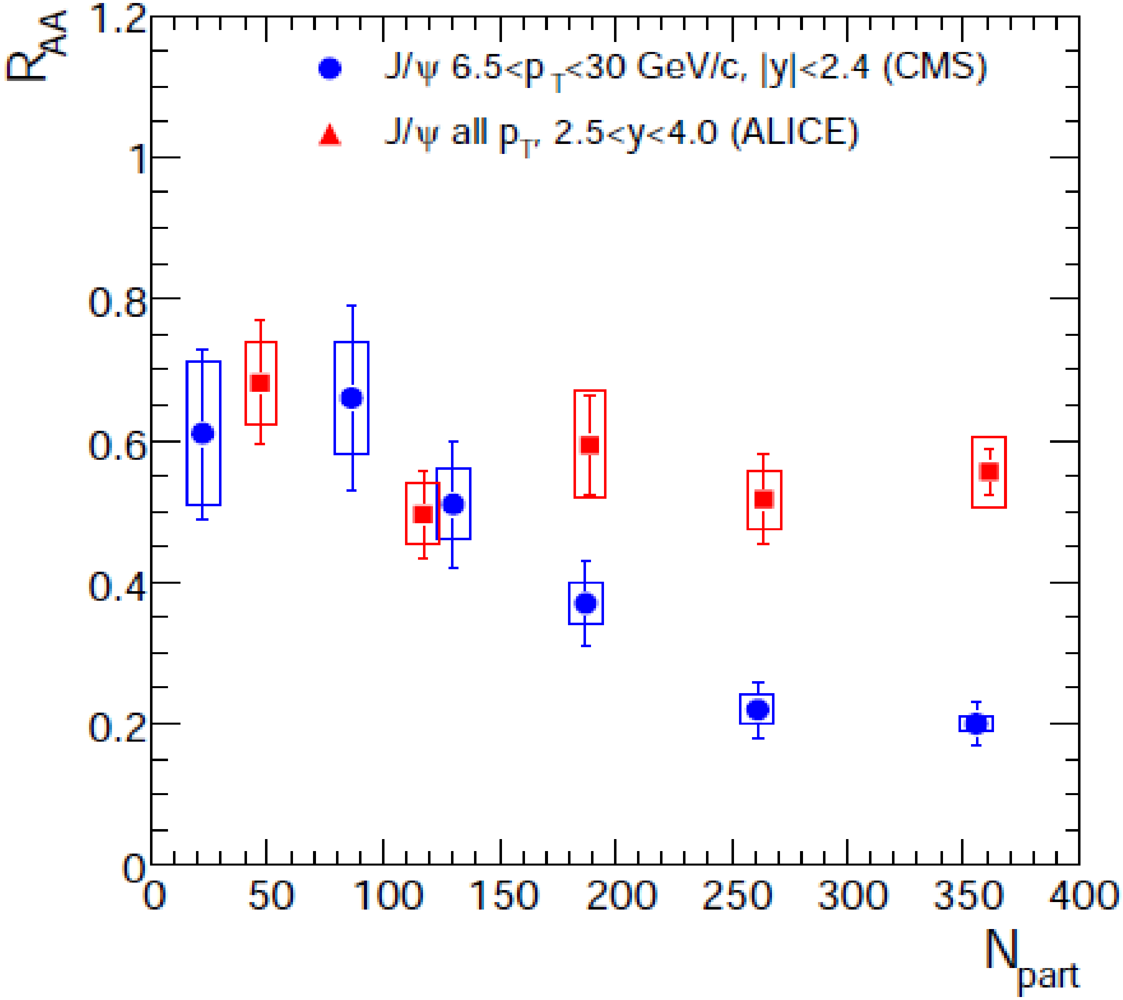
- Empty boxes:
  Centrality-dependent systematic uncertainties

inclusion of first J/psi data at midrapidity



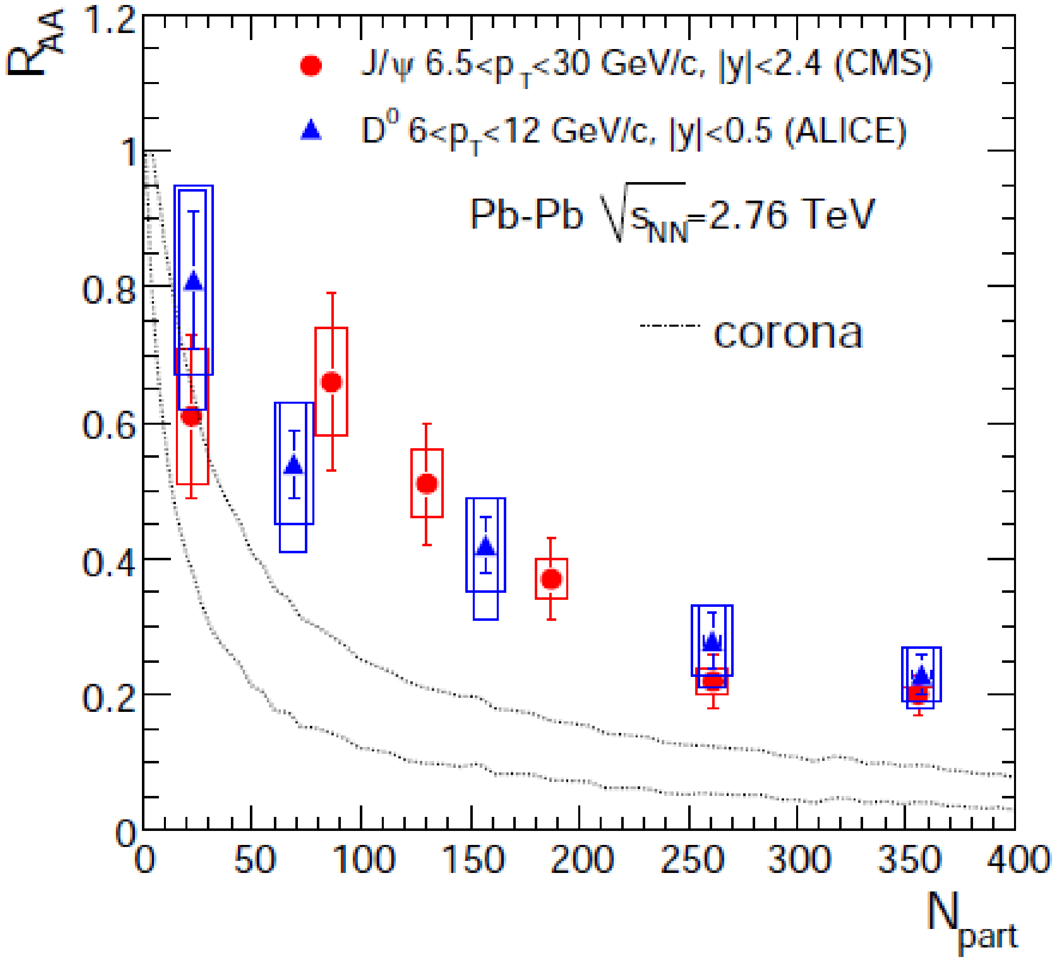
J/psi suppression increases with increasing pt

Transverse momentum dependence



ALICE, arXiv:1202.1383
CMS, arXiv:1201.5069

Comparison open and hidden charm at high transverse momentum

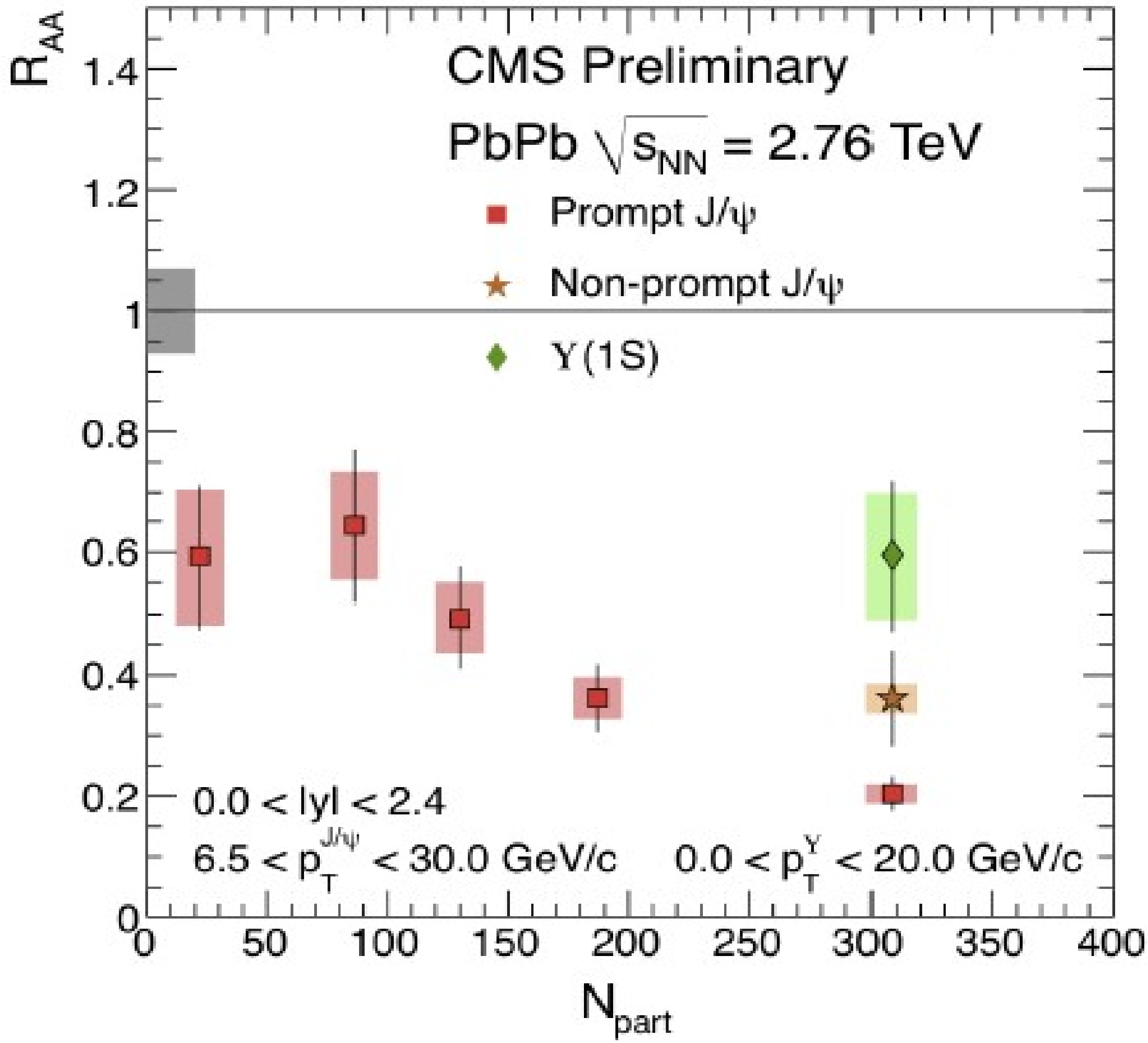


CMS, arXiv:1201.5069

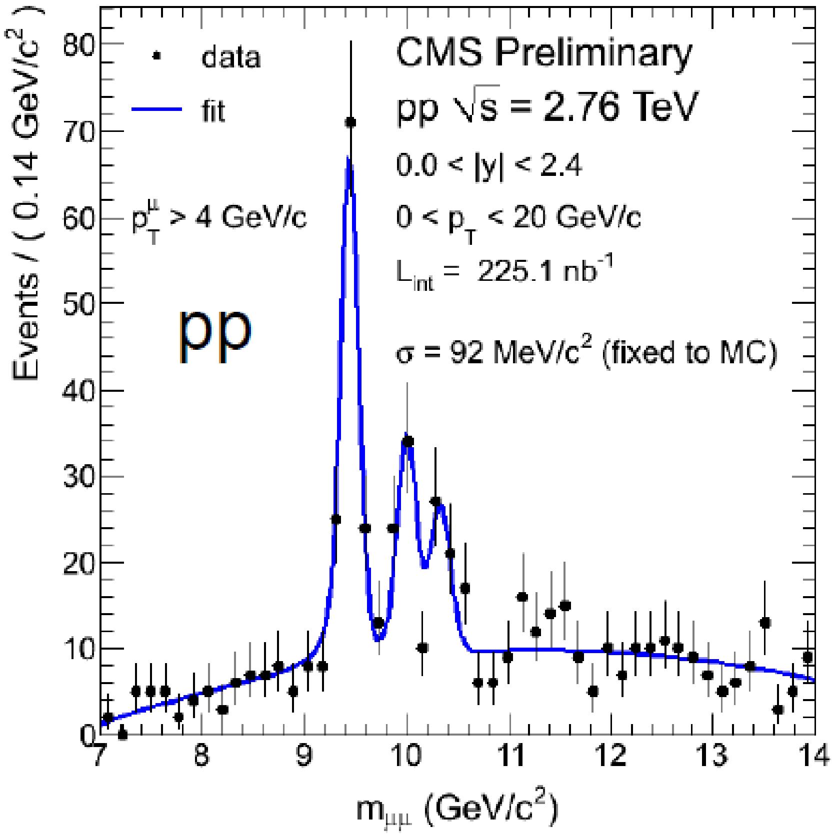
ALICE, arXiv:1203.2160

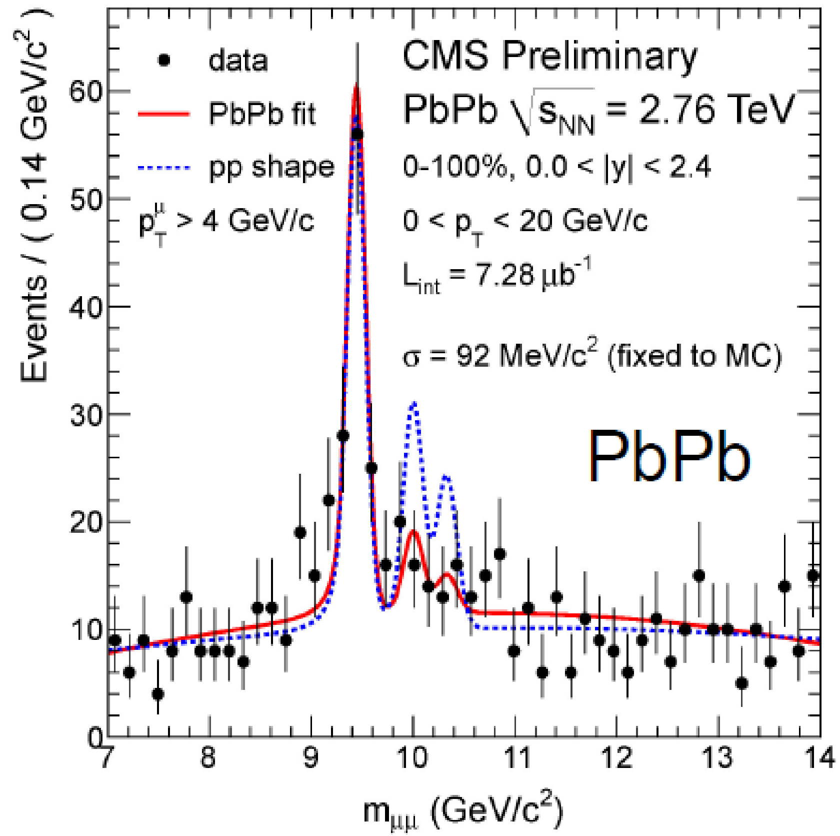
Suppression close to maximum possible

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



excited states of Υ are significantly suppressed in PbPb collisions (CMS PRL 107 (2011) 052302)





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

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

result qualitatively consistent with predictions of statistical hadronization model

a note on excited quarkonia and statistical hadronization

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

$$R = \exp(-(M1-M0)/T)$$

T = 164 MeV   is the critical (or hadronization) temperature

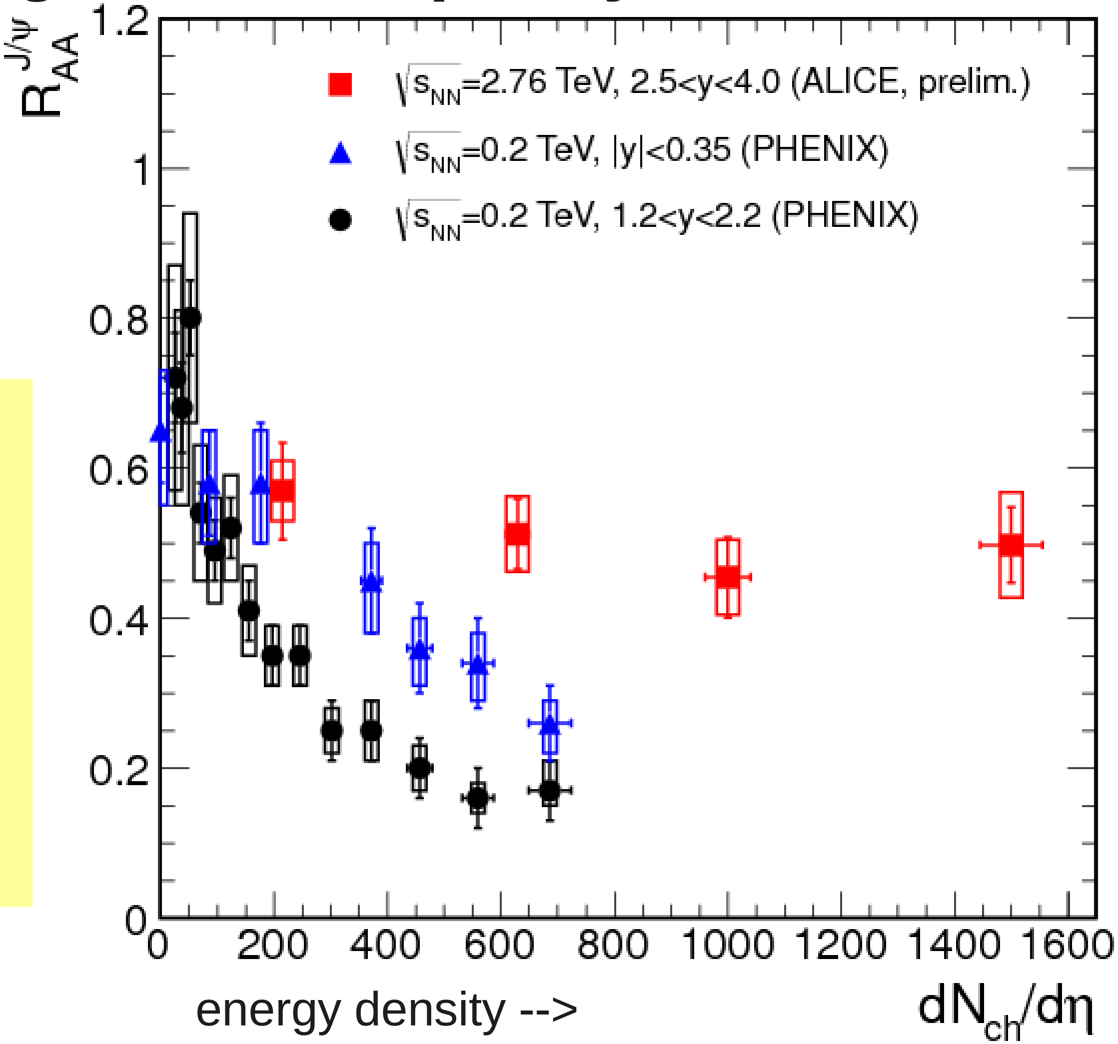
for psi'/(J/psi) this yields: $R_{psi'} = 0.023$ (plus small correction from feeding)

for Y'/Y this yields: $R_{Y'} = 0.032$ $R_{Y''} = 0.004$

this is consistent with the current CMS data

back to J/psi data

scaling with multiplicity

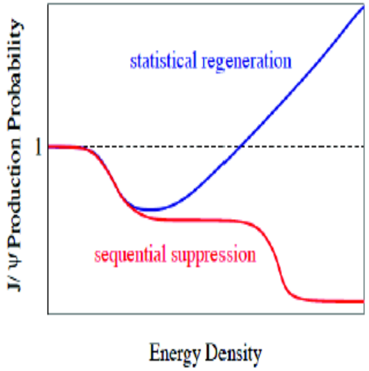


energy density -->

scaling is not observed!

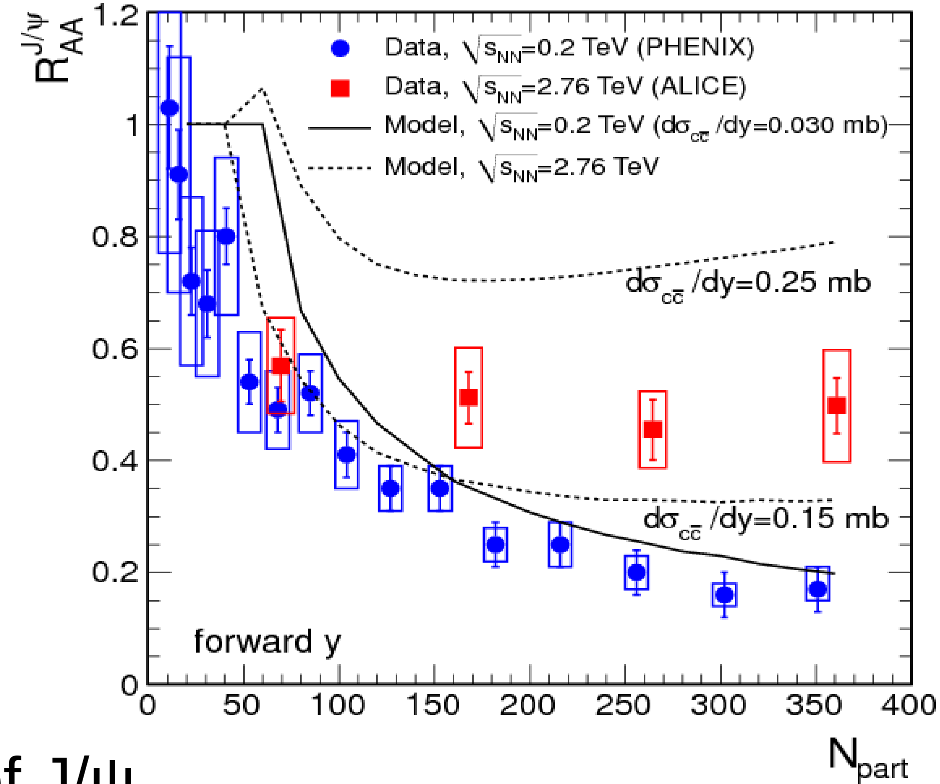
melting scenario is not in agreement with data

N_{ch} is proportional to energy density
→ enhancement with increasing energy density!



J/ψ story – generation at the phase boundary

total ccbar cross section from 7 TeV pp and scaled to 2.76 TeV using data

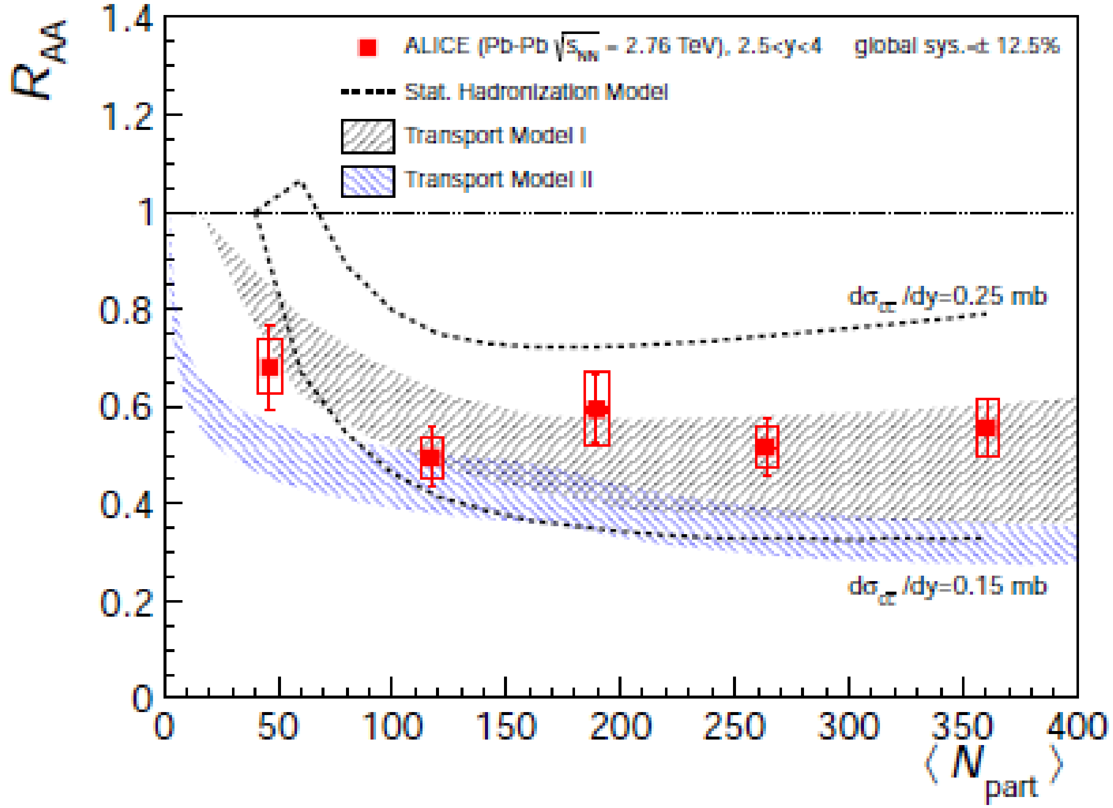


In AA collisions: indication of J/ψ regeneration

- 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)

trends in data as predicted with statistical hadronization scenario

Various model predictions including (re-)generation and ALICE data

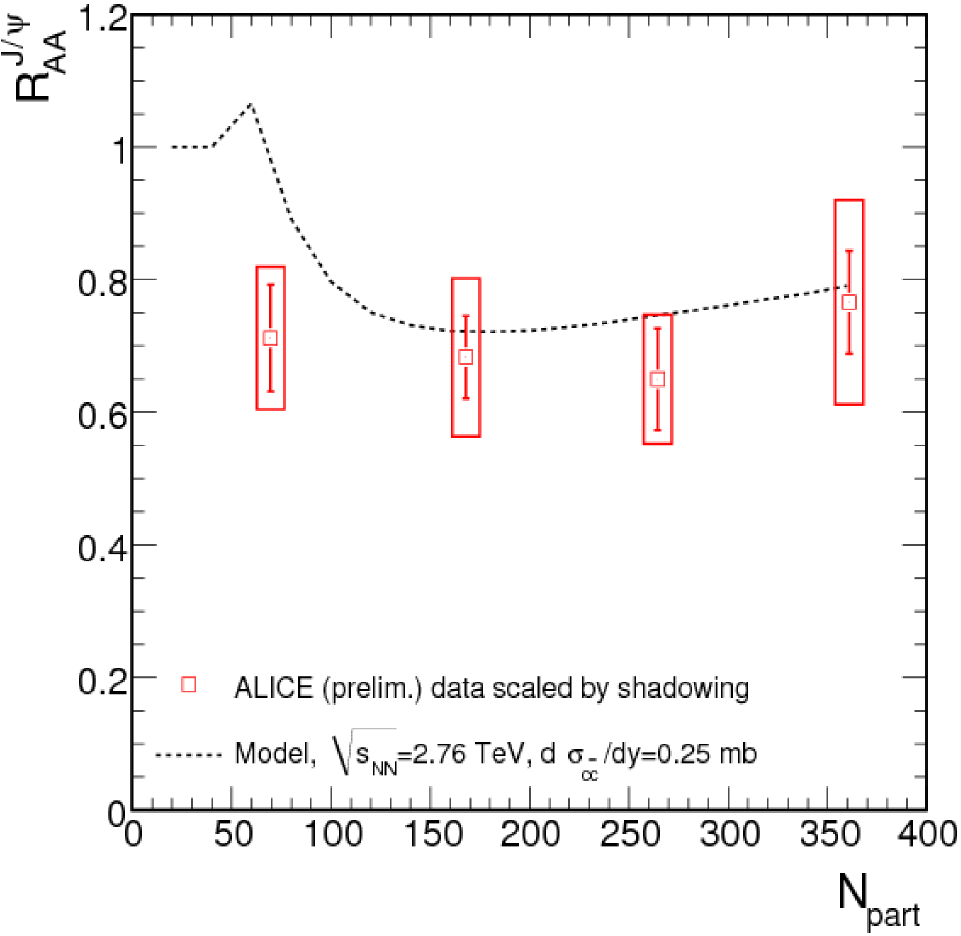


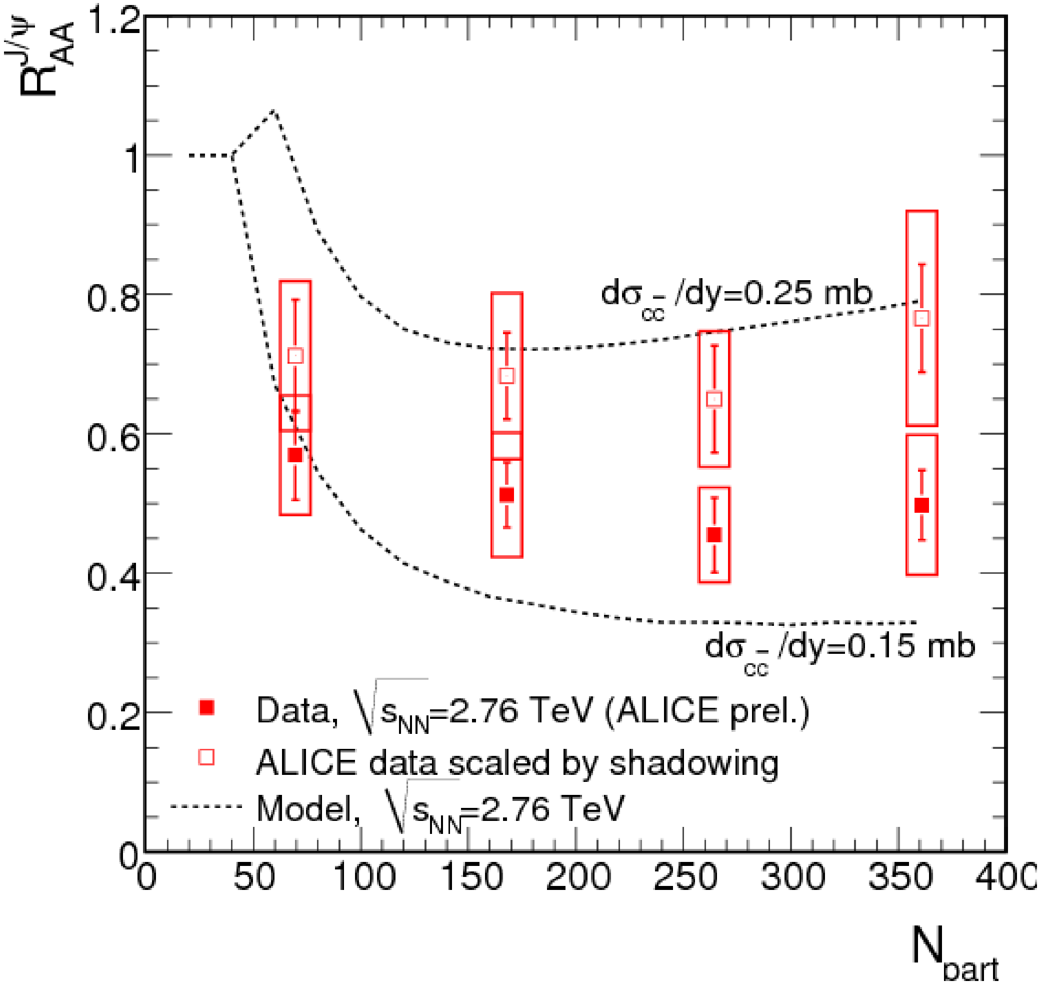
I: Zhao, Rapp, Nucl. Phys. A 859 (2011) 114 (2/3 from regener., central coll.)

II: Liu, Qu, Xu, Zhuang, Phys. Lett. B 678 (2009) 7 (regeneration dominates)

Stat. hadr. (thermal): Andronic et al., arXiv:1106.6321 (pure generation)

if we knew shadowing...





First results from pPb run in late Fall 2012

summary

- quarkonium production in PbPb collisions at LHC has to be seen in light of c and b quark suppression
- centrality and beam energy dependence of J/psi production is inconsistent with the scenario of (sequential) melting of charmonia in the QGP
- trends in J/psi and Y data are consistent with predictions from statistical hadronization model – generation of quarkonia at the phase boundary from deconfined heavy quarks
- quantitative understanding needs understanding of shadowing

  - need open charm cross section in PbPb collisions
  - need open charm and J/psi production in pPb collisions

  2011 PbPb data are currently analyzed (10x more stat.)
  next experimental campaign with pPb should bring exciting and hopefully decisive results

Comparison with EPS09 shadowing calcs