Charmonium Production at the QCD Phase Boundary – from SPS to LHC

HELMHOLTZ GEMEINSCHAFT

- introduction and historical perspective
- hadronic bound states in the QGP?
- time scales and the 'cold nuclear matter' baseline
- the statistical hadronization model
- results for SPS and RHIC energies
- a digression towards threshold
- pp results at LHC energy
- first PbPb results at LHC energy

EMMI

FIAS-Frankfurt

work based on collaboration with
A. Andronic, K. Redlich, and J. Stachel

Lectures, Zakopane June 2011

Peter Braun-Munzinger

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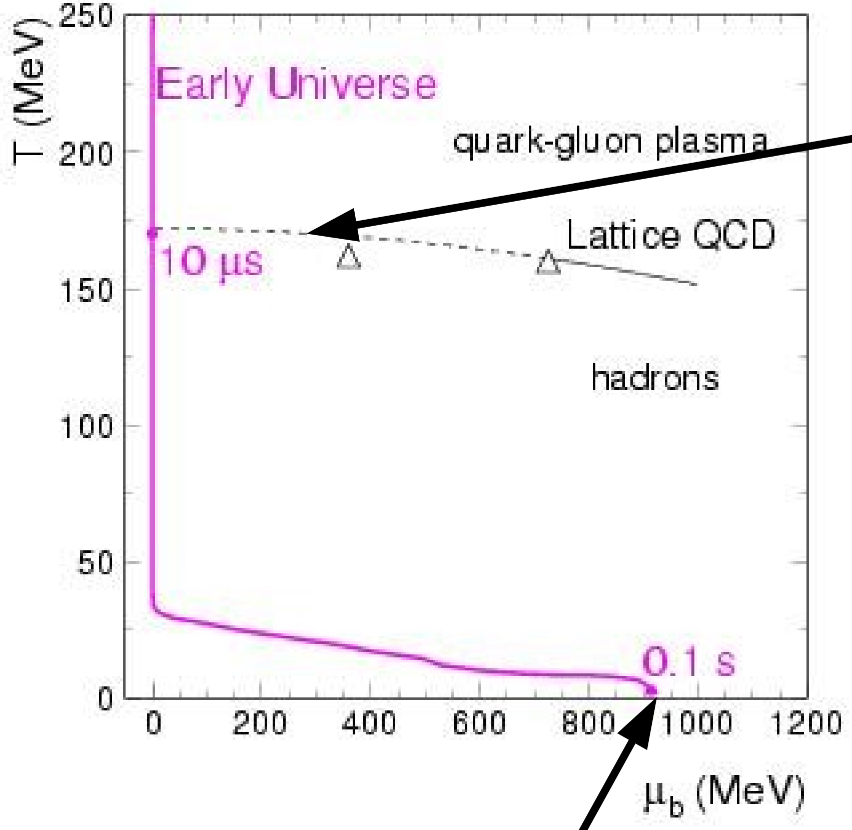
Evolution of the Early Universe



QCD Phase Boundary

Homogeneous Universe in Equilibrium, this matter can only be investigated in nuclear collisions

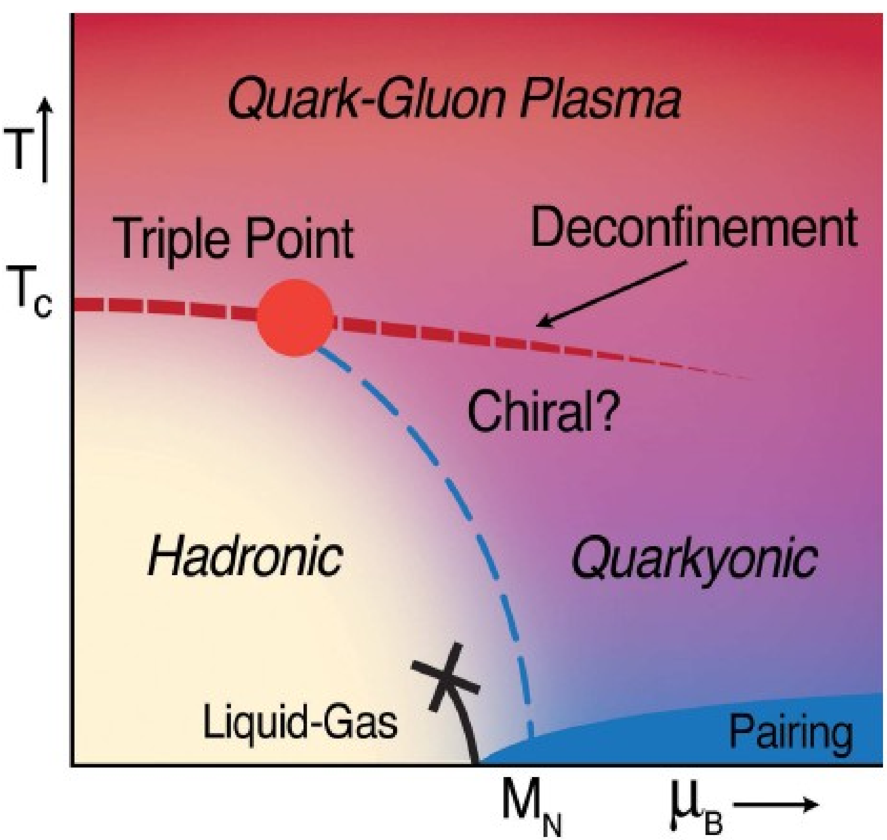
- Charge neutrality
- Net lepton number = net baryon number
- Constant entropy/baryon

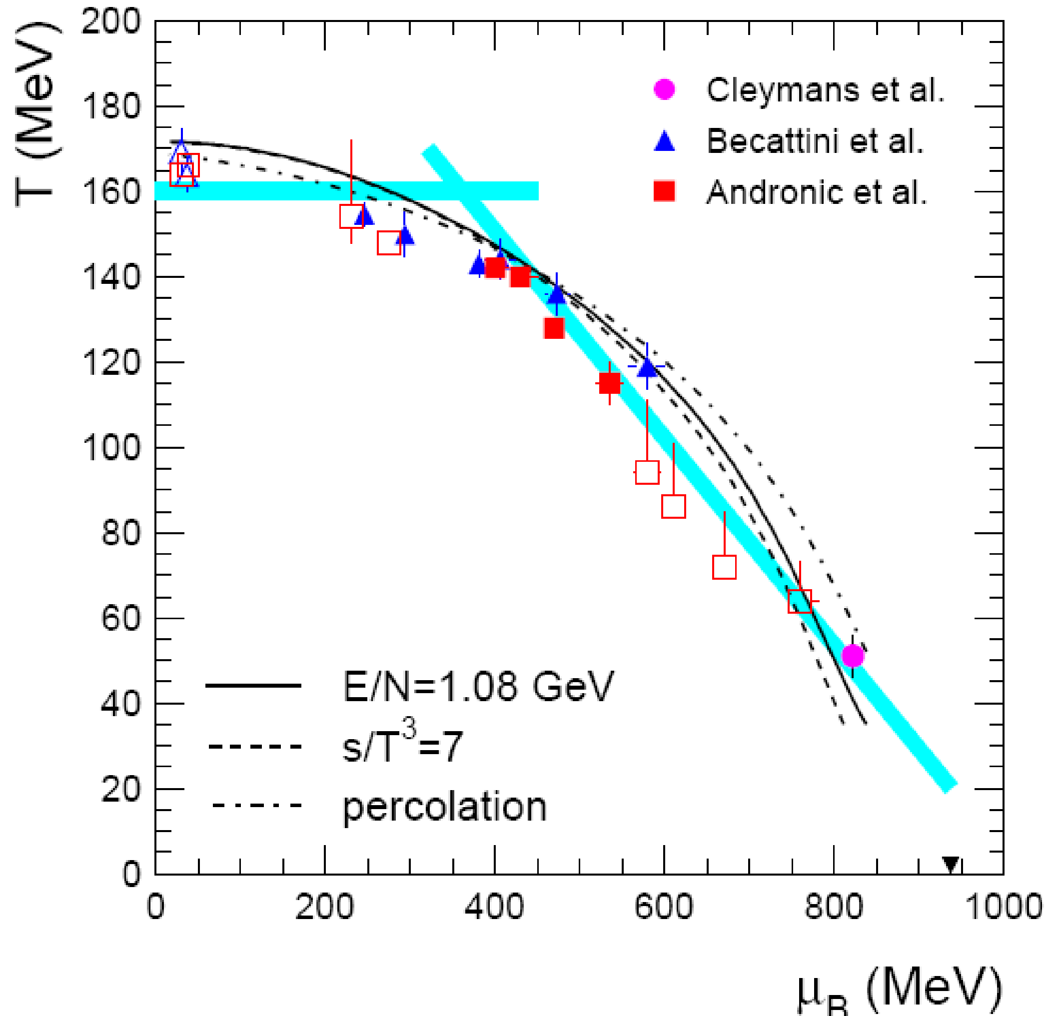
neutrinos decouple and light nuclei begin to be formed

the QCD phase diagram

Andronic et al.,, arXiv:0911.4806
Nucl. Phys. A837 (2010) 65

data points:
'chemical' freeze-out of hadrons

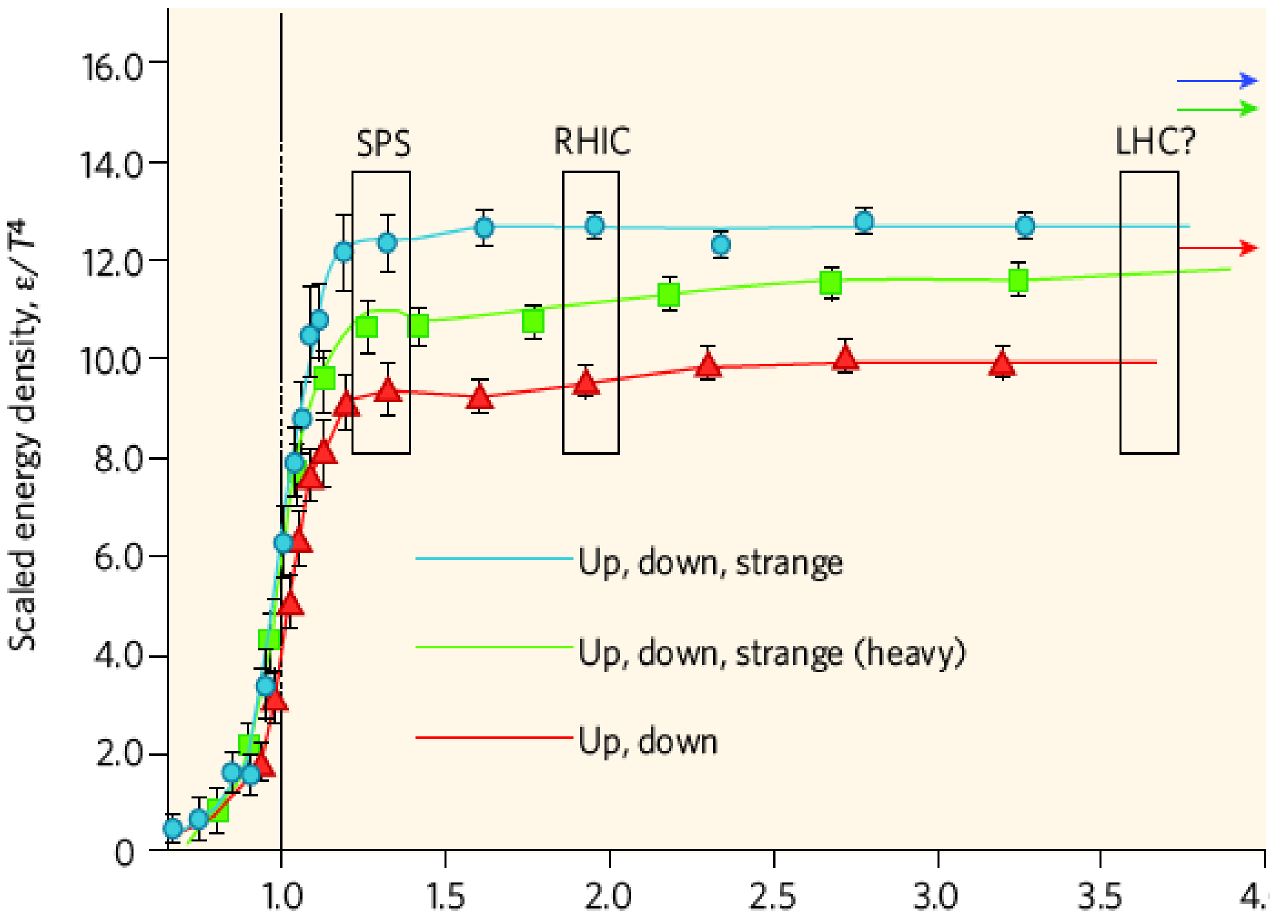




all lattice groups now agree: T_c(mu=0) is close to 170 MeV
Bazavov & Petreczky, arXiv:1005.1131 [hep-lat]
S. Borsanyi et al., arXiv:1005.3508 [hep-lat]

review: pbm, wambach
RMP 81 (2009) 1031

the QCD phase transition from lattice QCD



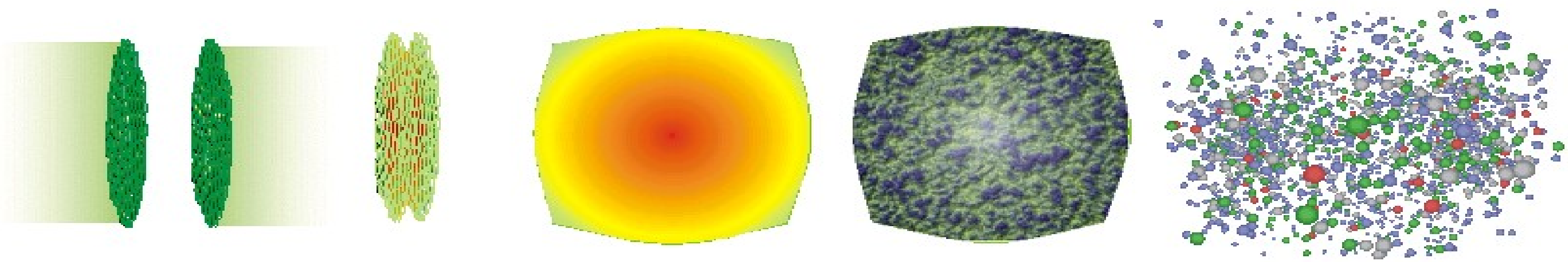
temperature T/T_c

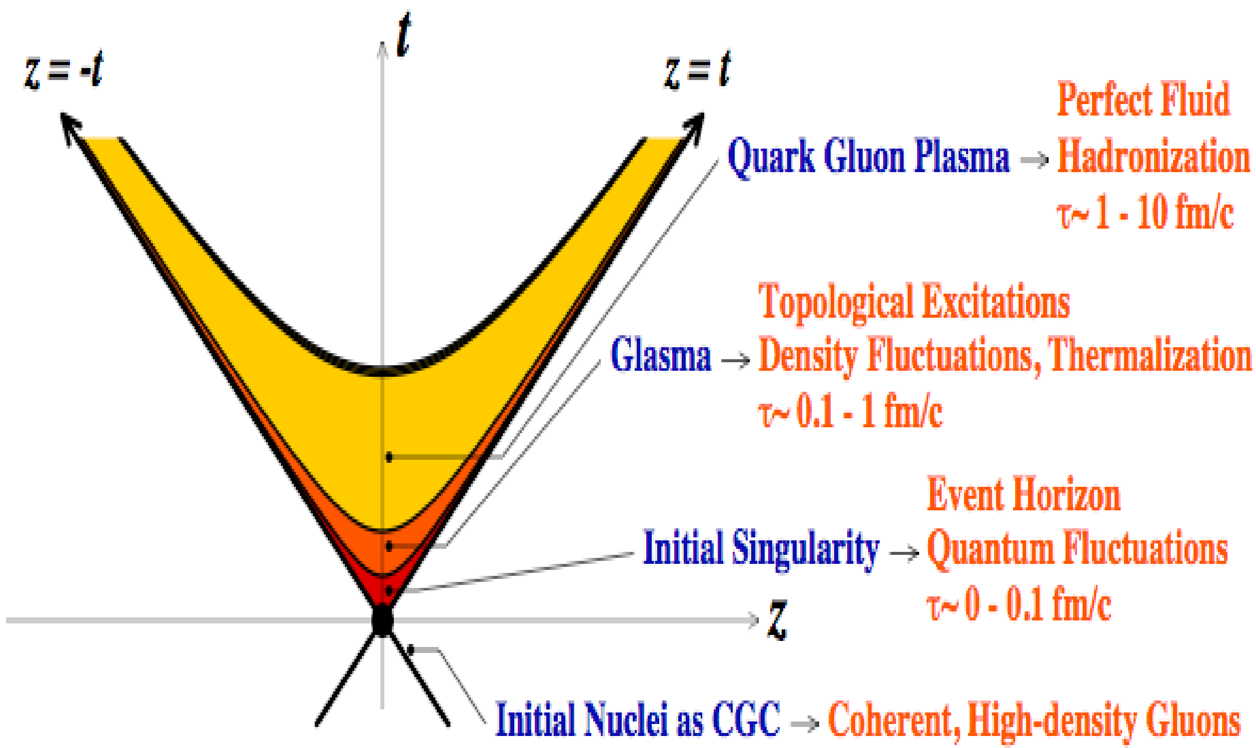
all lattice groups now agree: T_c(mu=0) is close to 170 MeV

Bazavov & Petreczky, arXiv:1005.1131 [hep-lat]

S. Borsanyi et al., arXiv:1005.3508 [hep-lat

The Space-Time Evolution of a Relativistic Nuclear Collision at LHC Energy





one possible view
(courtesy
Larry McLerran)

Charmonium as a probe for the properties of the QGP

the main idea: implant charmonia into the QGP and observe their modification, in terms of suppressed (or enhanced) production in nucleus-nucleus collisions with or without plasma formation

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

time scales

for this picture to hold, the following time sequence is needed:

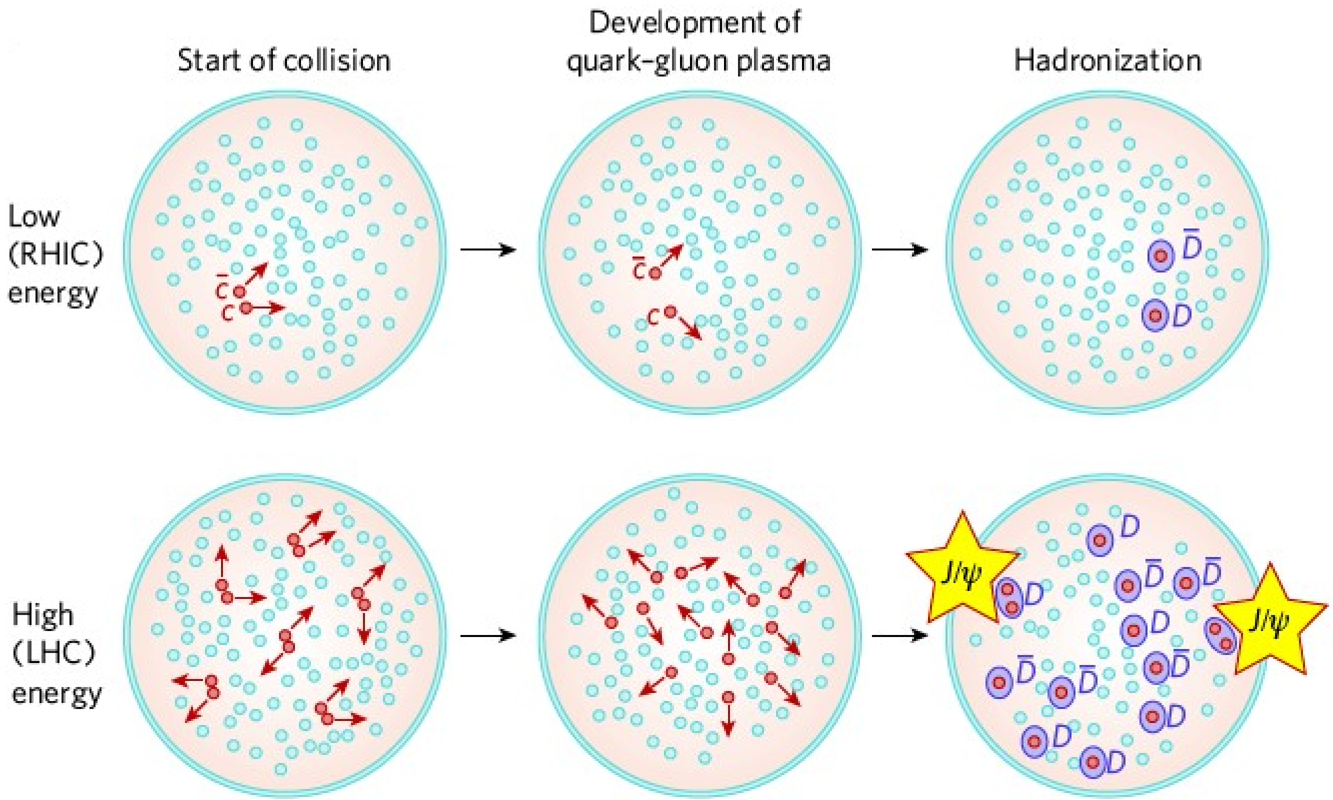
1) charmonium formation
2) quark-gluon plasma (QGP) formation
3) melting of charmonium in the QGP
4) decay of remaining charmonia and detection

questions:

a) beam energy dependence of time scales

b) what happens with the (many) charm quarks at hadronization, i.e at the phase boundary?

energy dependence of charmonium production



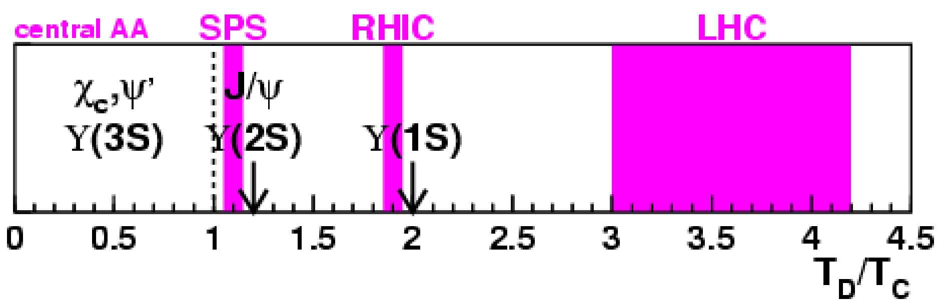
Survival of Quarkonia in the QGP

new development:
J/ψ does not survive above T_c

predicted quarkonium dissociation temperatures

in the QGP

A. Mocsy & P. Petreczky, Phys. Rev. Lett. 99 (2007) 211602



expect all charmonia to be destroyed
by QGP
but: regeneration at the phase boundary!

Hadronization of charm quarks – a special case?

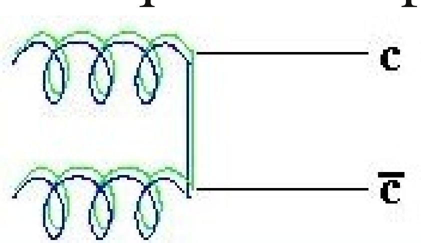
If charmonium survives beyond T_c in the quark-gluon plasma, this implies in return that charm quarks hadronize at T > T_c.

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

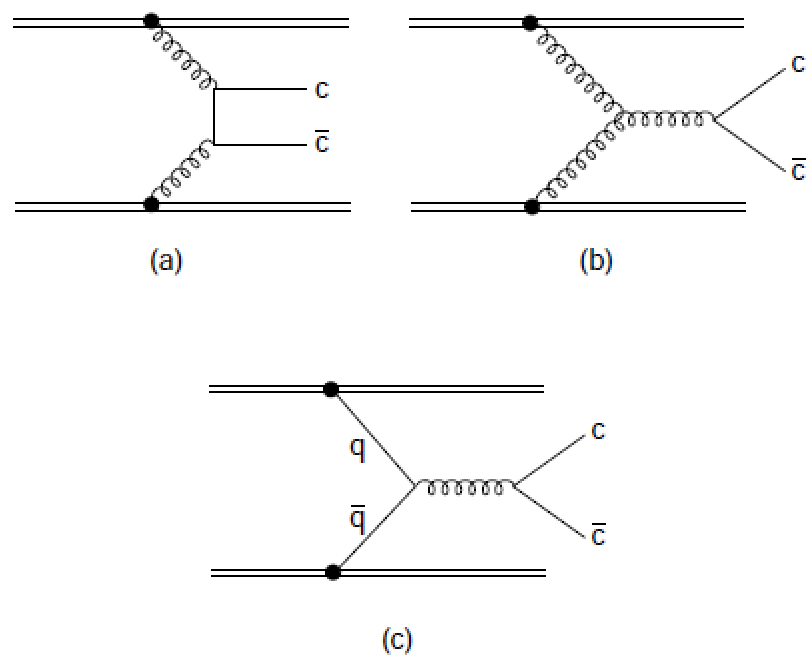
A flavor-dependent phase boundary calls the whole concept of the deconfinement phase transition into question.

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 $1/2m_c$
  $m_c = 1.3$ GeV --> $t_c = 0.08$ 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 for production



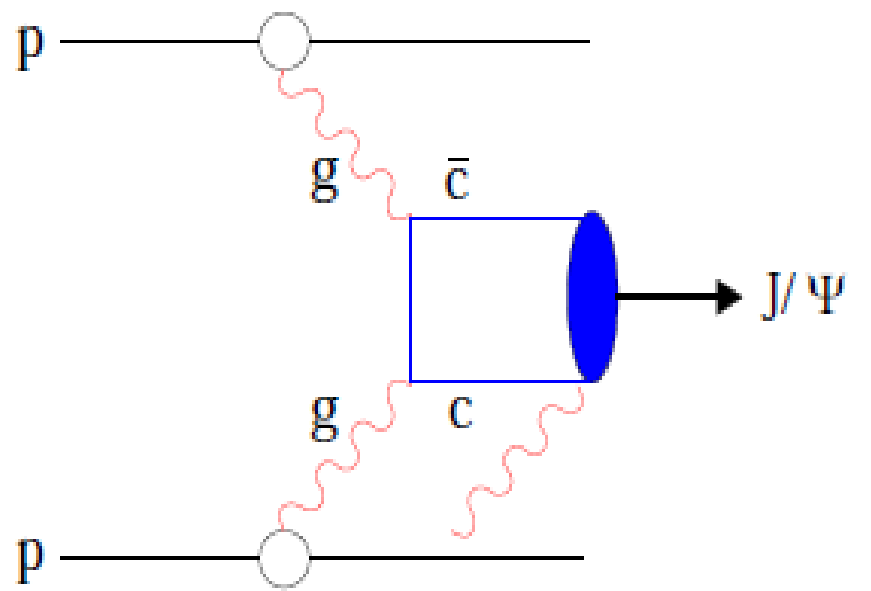
open charm production in hadronic collisons



lowest order diagrams: gluon fusion (a,b) and annihilation (c)

charmonium production in hadronic collisions

color neutralization as additional step

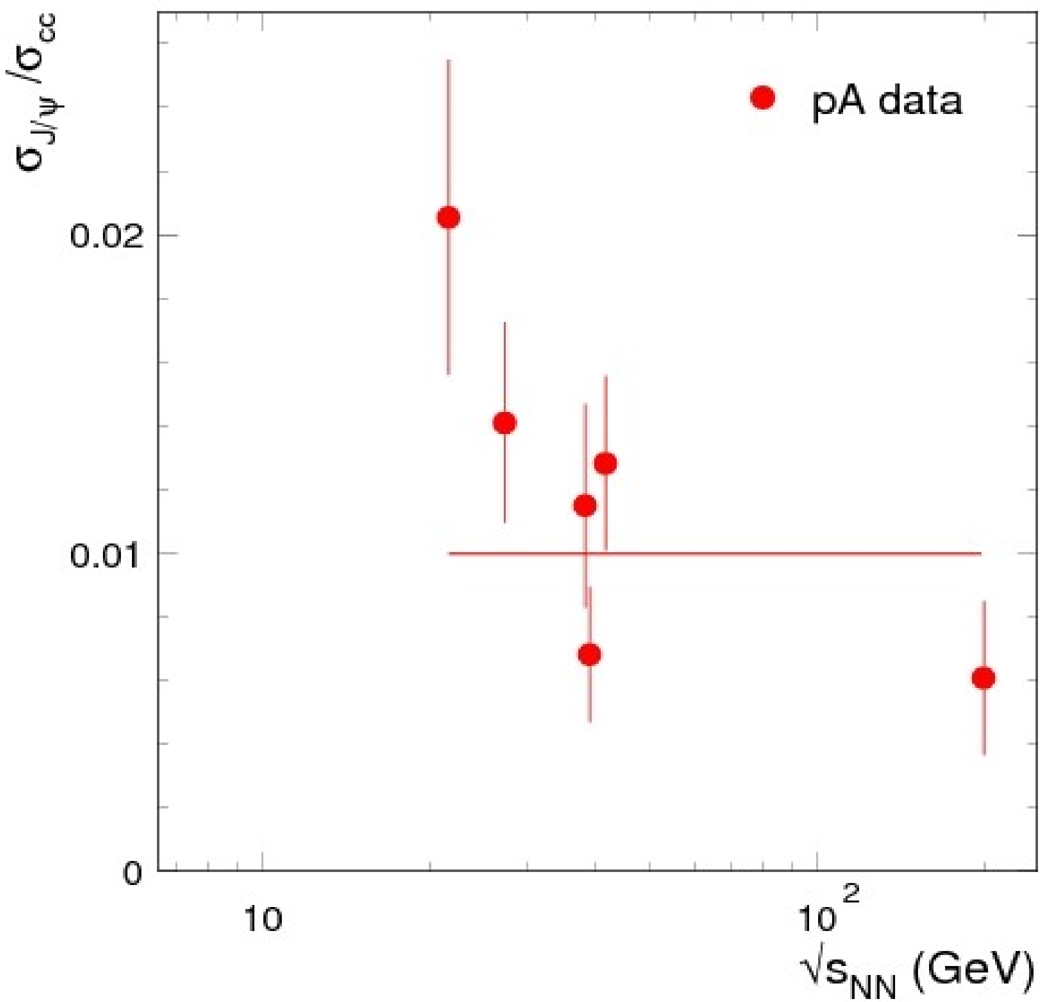


J/psi/cc_bar cross section

about 1 % of cc_bar pairs end up in J/psi

variation reflects uncertainty in open charm cross section?

→ at hadronization 99% of initial charm quarks are still there



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?

full separation of time scales at LHC energy

At collider energies there will be yet another separation of time scales. At LHC energy, the momentum of a Pb nucleus is p_{cm}=2.76 TeV per nucleon, leading to $\gamma_{cm} = 2940$, hence $t_{coll} < 5 \cdot 10^{-3}$ fm. Even "wee" partons with momentum fraction[3] $x_w = 2.5 \cdot 10^{-4}$ will pass by within a time $t_w = 1/(xp_{cm}) < 0.3$ fm, and will not destroy any charmonia since none exist at that time. We consequently expect that cold nuclear absorption will decrease from SPS to RHIC energy and should be negligible at LHC energy. First indications for this trend are visible in the PHENIX data [22].

Role of cold nuclear matter effects

what is it:

destruction of charmonia by colliding nuclei before QGP formation

- may be important at SPS and lower energies
- charmonium formation time long compared to QGP formation time,

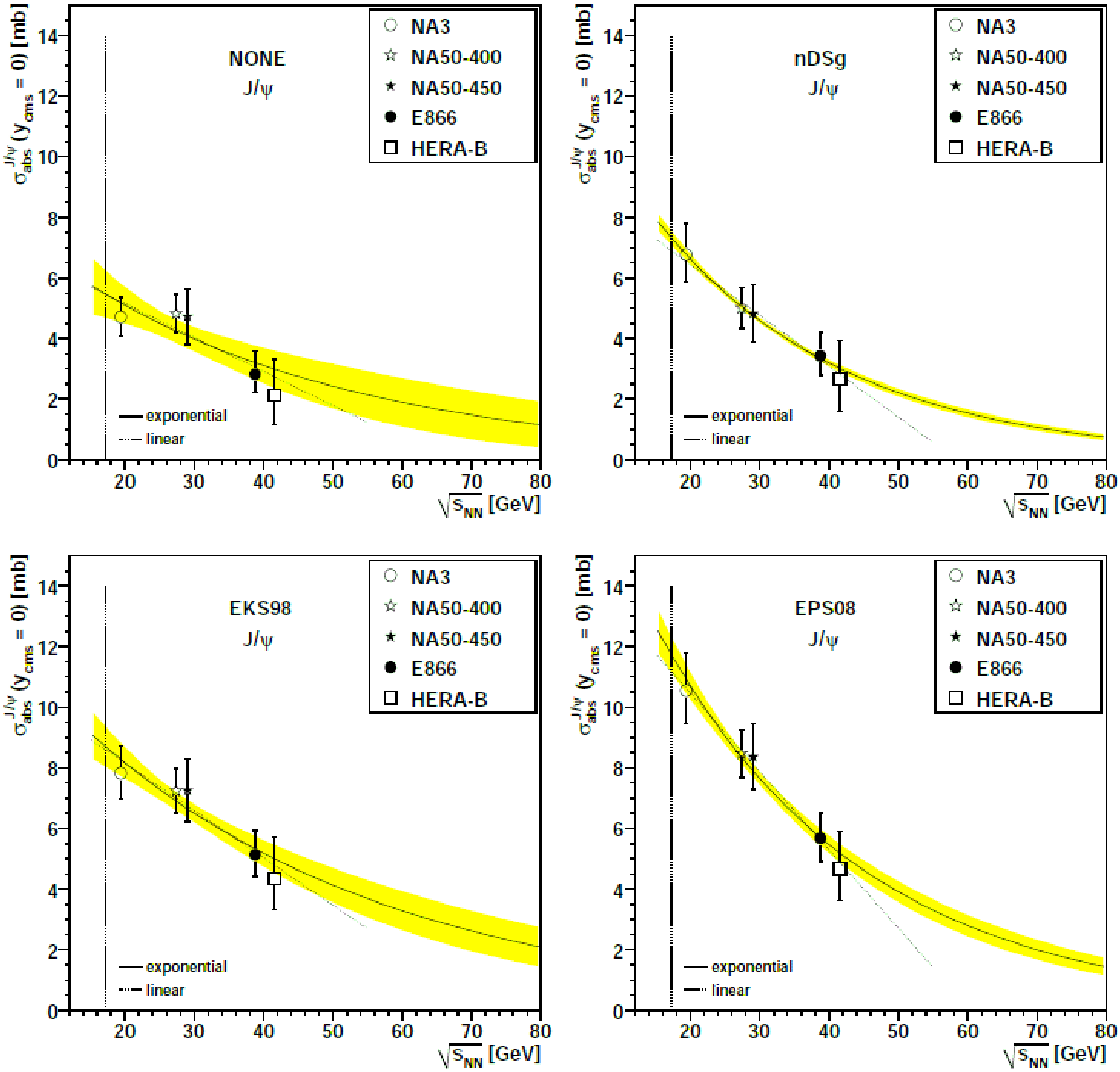
especially at LHC --> **no cold nuclear matter effects at LHC**

what it is not:

rapidity dependent reduction of charm and charmonium production due to shadowing or saturation
energy loss effects

A. Andronic et al., Nucl. Phys. A709 (2007) 334
standard view of CNM effects, see R. Vogt, arXiv:1003.3497

Energy dependence of J/psi absorption cross section



C. Lourenco, R. Vogt, H. Woehri
JHEP 0902 (2009) 014
arXiv:0901.3054 [hep-ph]

sig_abs = 5.8 – 11.5 mb depending on shadowing

Role of non-QGP effects

investigation of 'anomalous' charmonium production in AA collisions

need to normalize charmonium production to open charm cross section in AA collisions for given centrality

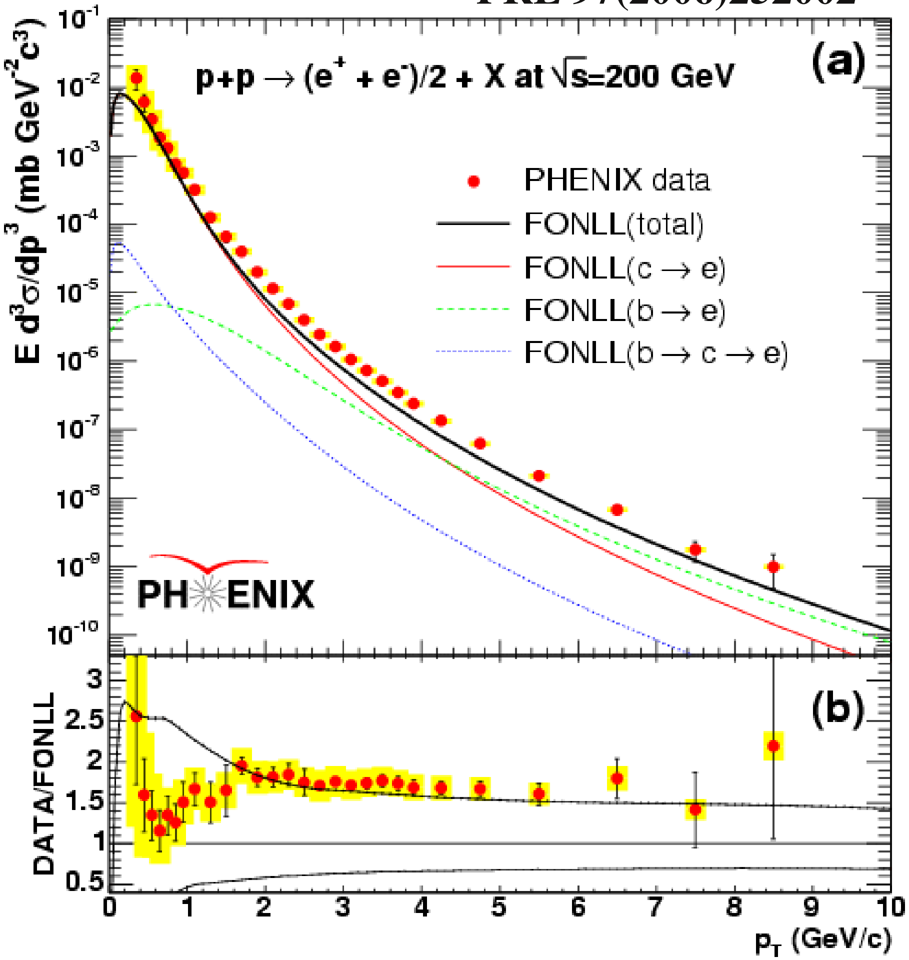
pp and pA collisions are useful to study possible shadowing or saturation effects, not for charmonium suppression or enhancement in the QGP

actually, the pA or dA baseline is questionable at LHC because of thermal production of charm quarks (K. Redlich and pbm, Eur. J. Phys. C16 (2000) 334)

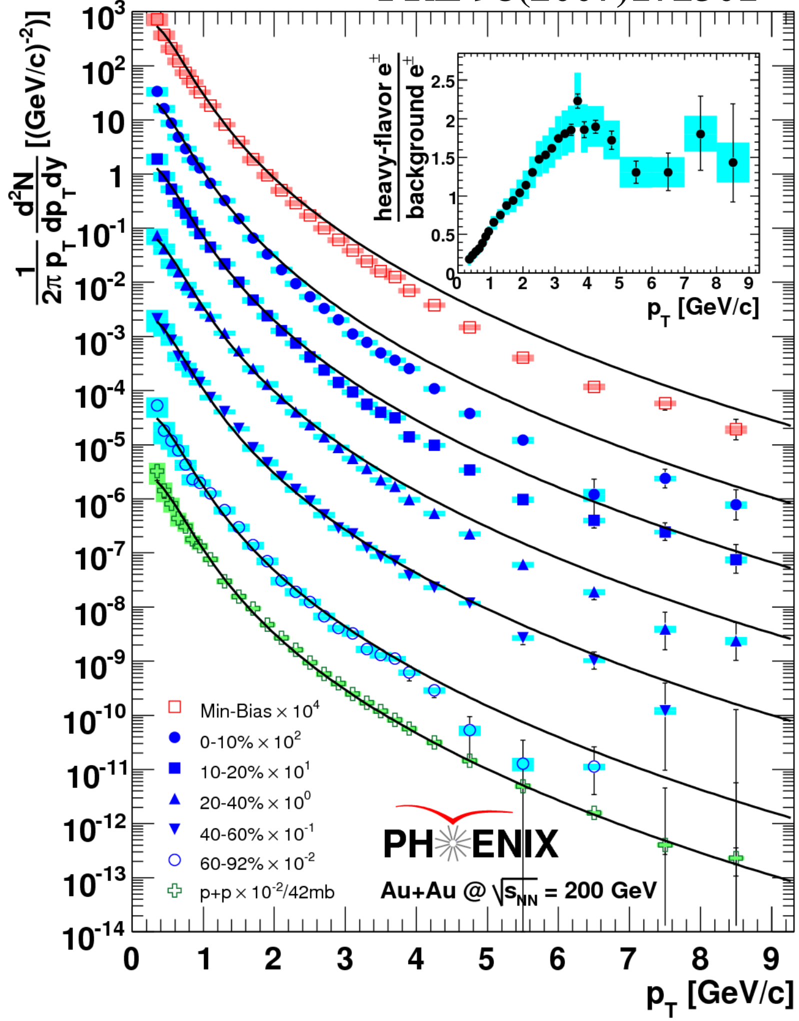
is there any evidence for saturation or shadowing from RHIC data?? $\text{sigma}_{ccbar}(AA) = N_{coll}\ \text{sigma}_{ccbar}(pp)$??

PHENIX data on charm cross section

PRL 97(2006)252002



PRL 98(2007)172301



PHENIX open charm cross section is close to pQCD prediction
STAR value was about a factor of 2 larger ... now resolved (material)
need vertex detectors! But no evidence for shadowing so far.
This is an area for LHC!!! See later.

A brief digression: the fireball emits hadrons from an equilibrium state

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

how do we get information on the phase boundary?

For a recent review see:

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

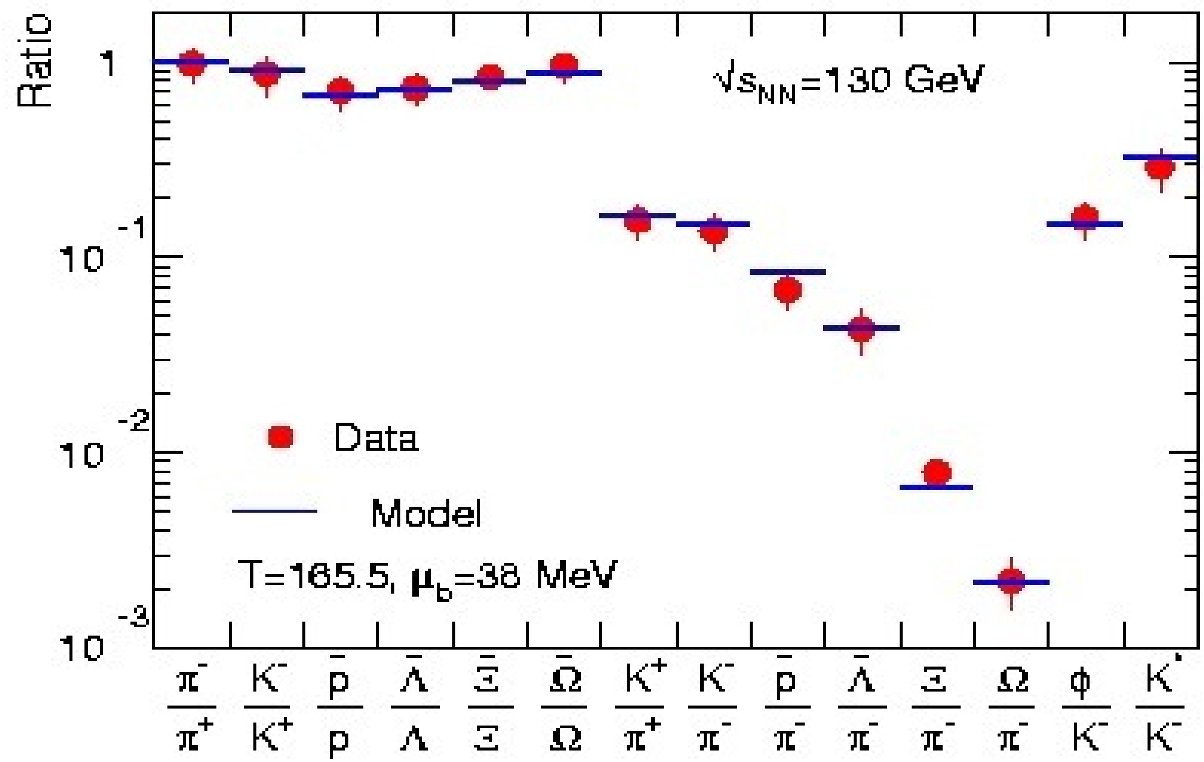
Hadro-chemistry at RHIC -- weakly decaying particles

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

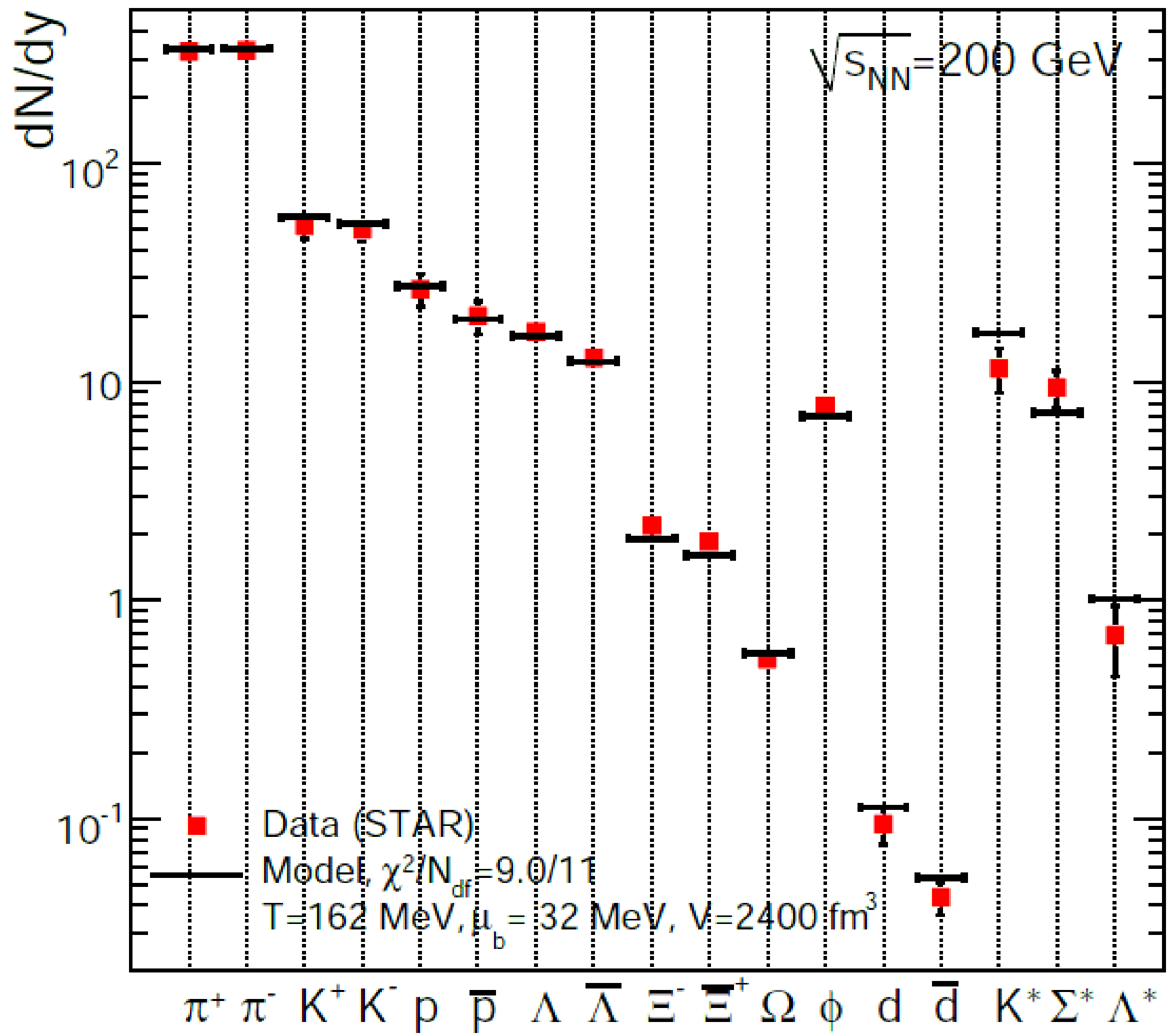


pbm, d. magestro, j. stachel, k. redlich, Phys. Lett. B518 (2001) 41; see also Xu et al., Nucl. Phys. A698(2002) 306; Becattini, J. Phys. G28 (2002) 1553; Broniowski et al., nucl-th/0212052.

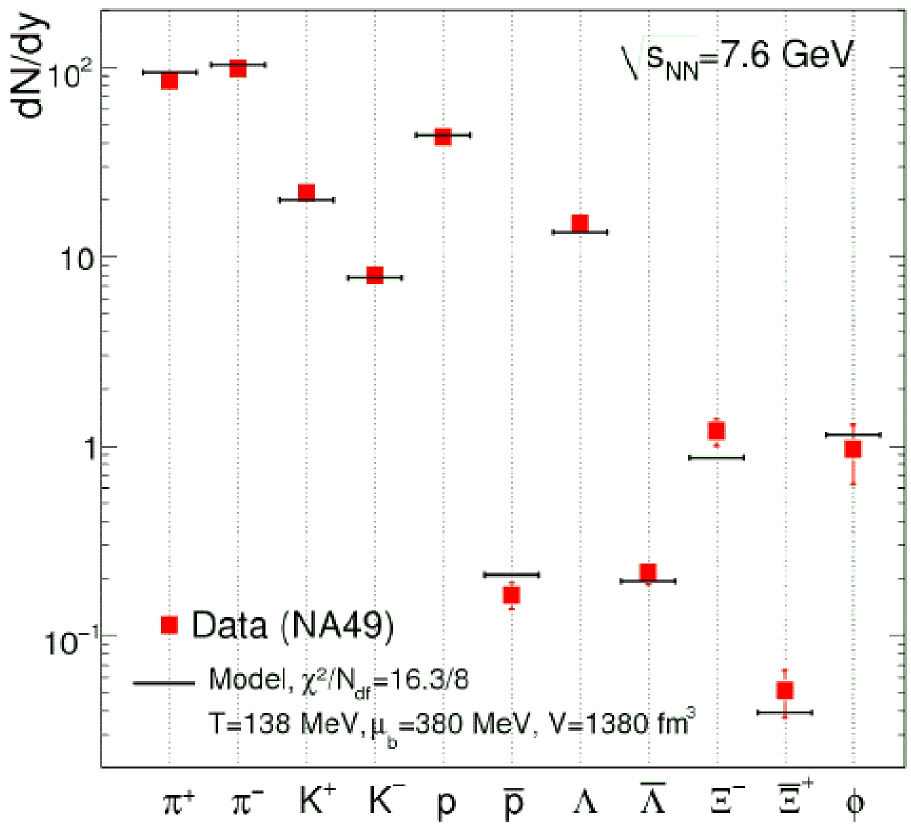
Fit to STAR data alone

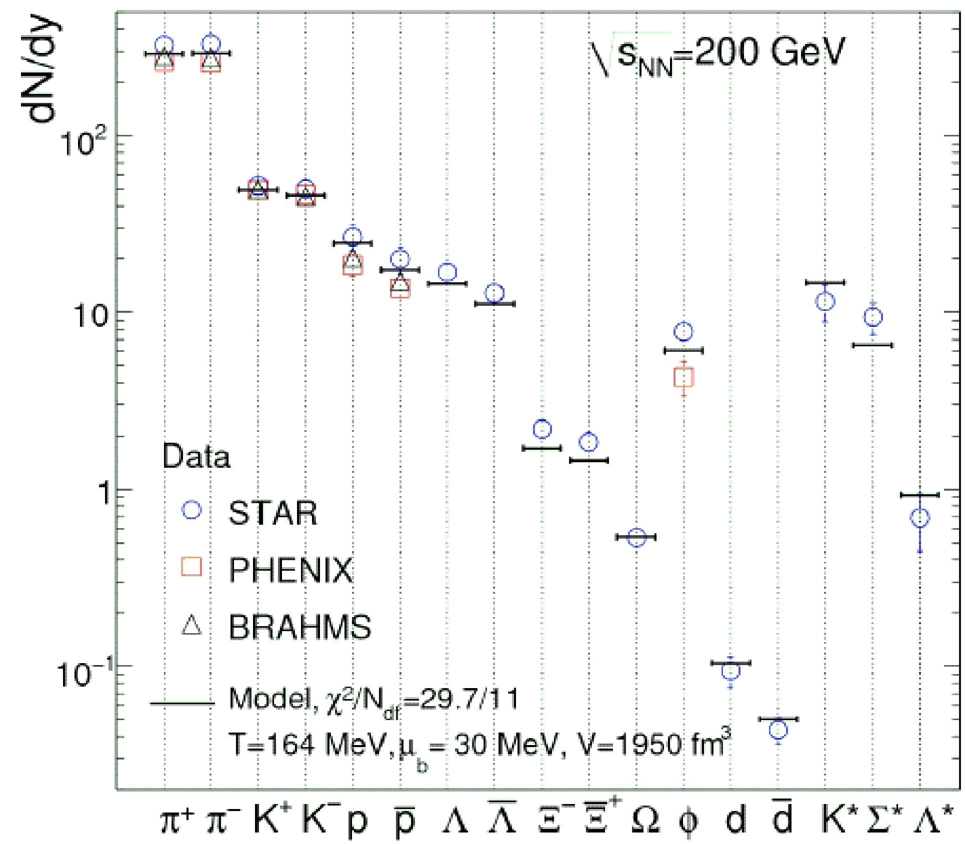
very good fit, even including strongly decaying resonances

no evidence for special role of wide states



… but, in general, fits are not perfect





for example, PHENIX protons are significantly below the model results

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

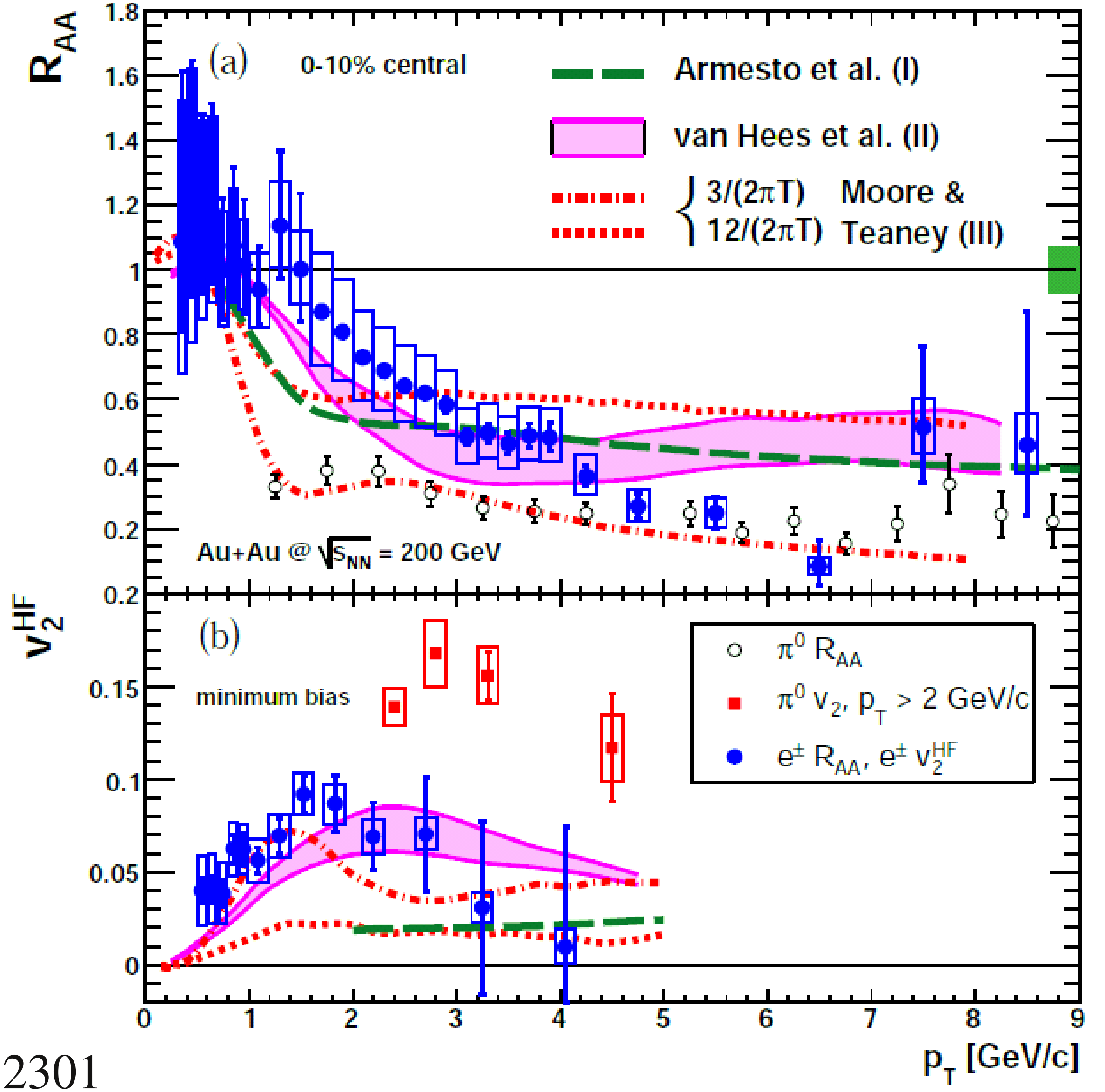
However, thermal production of charm quarks is appreciable only at very high temperatures (LHC)
(T > 800 MeV, pbm&Redlich, Eur. Phys. J. C16 (2000) 519).

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

Energy loss and flow of heavy quarks

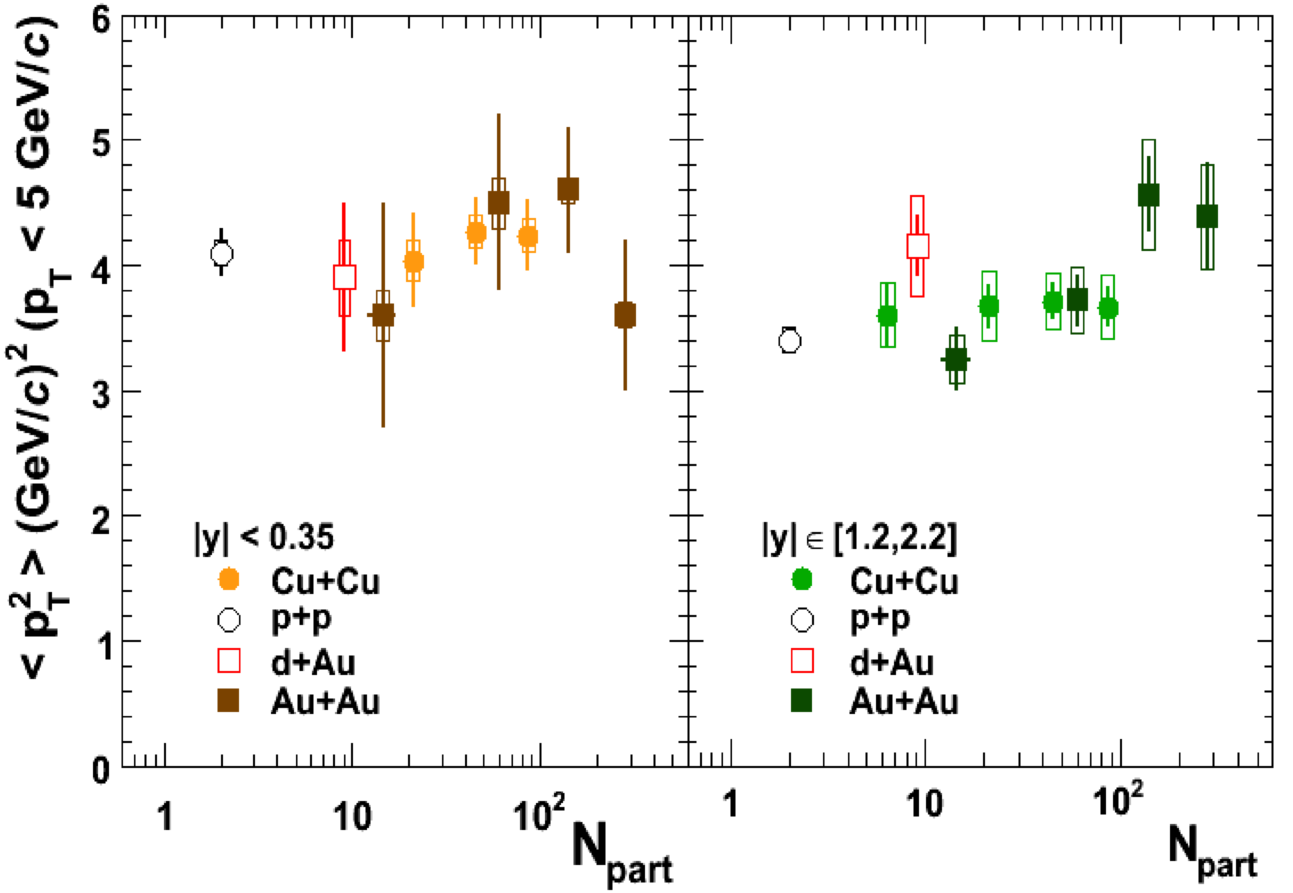
charm quark flow and large energy loss imply approach to thermal but not chemical equilibrium

new ALICE results for HF electrons and D mesons discussed below



PHENIX coll., PRL 98 (2007) 172301
nucl-ex/0611018

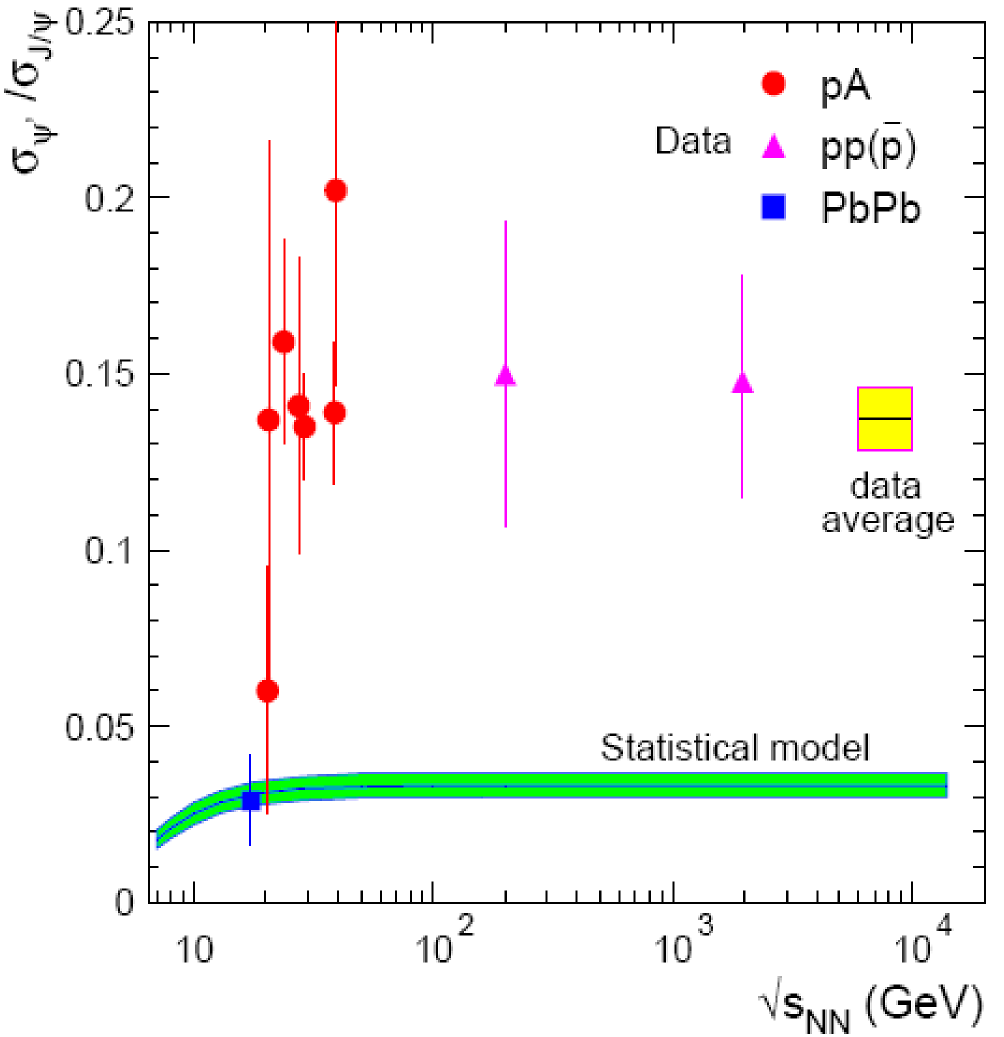
Transverse Momentum Distributions



no strong broadening observed as expected for initial state scattering

this is different from the situation at the SPS

The psi'/psi ratio in elementary and AA collisions



Summary of this part

- charmonium production very different in elementary and AA collisions
- charm quark production mainly non-thermal
- at collider energies, charmonia are formed late, QGP is earlier
- no serious evidence for hadrons formed or surviving in the QGP

→ charmonia are formed at the phase boundary like all other hadrons

→ statistical hadronization model

Charmonium (re)generation 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

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)

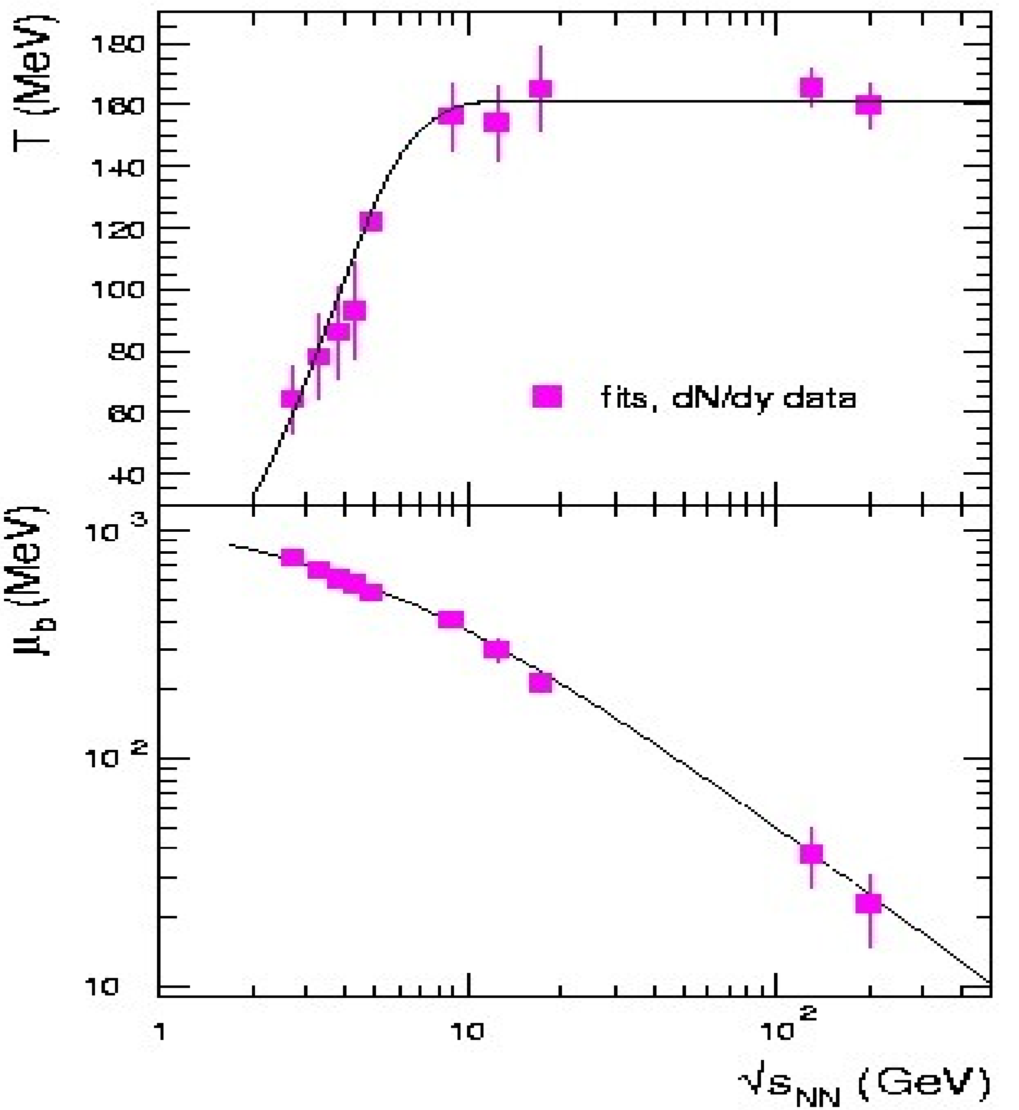
Parameterization of all freeze-out points

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



Ingredients for prediction of quarkonium and open charm cross sections

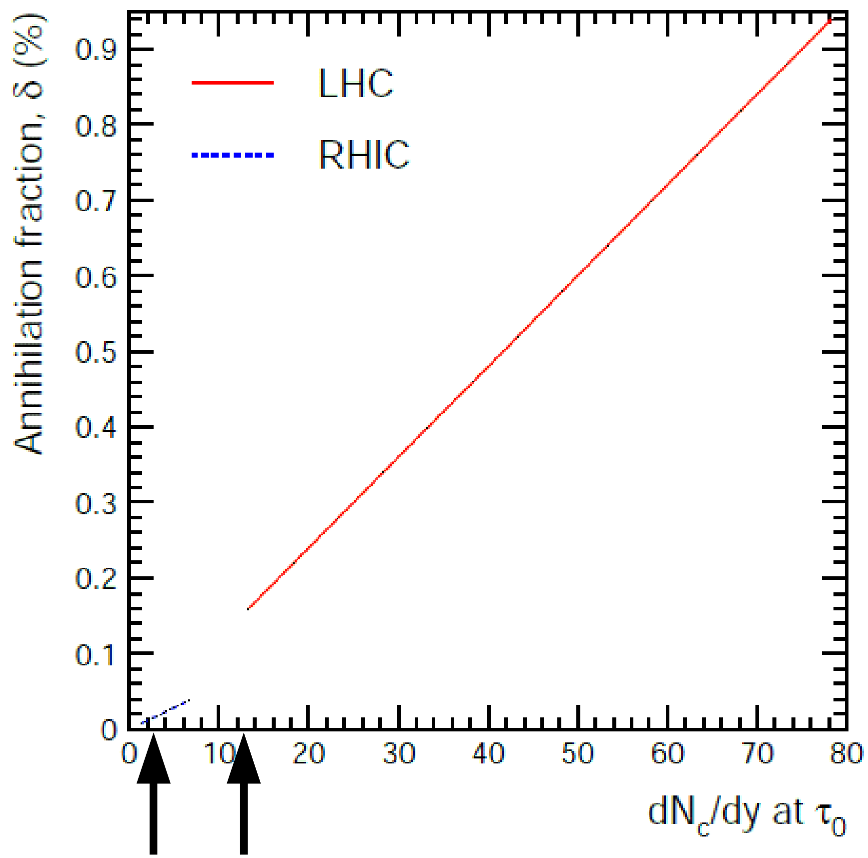
- energy dependence of temperature and baryo-chemical potential (from hadron production analysis)
- open charm (open bottom) cross section in pp and AA collisions
- quarkonium production cross section in pp collisions (for corona part)

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

important pre-requisite: all ratios among charmonia must be thermal

annihilation fraction

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



RHIC LHC
pQCD value

Recent publications:

Anton Andronic,F. Beutler, pbm, Krzysztof Redlich, Johanna Stachel

J.Phys.G35:104155,2008.
e-Print: arXiv:0805.4781 [nucl-th]

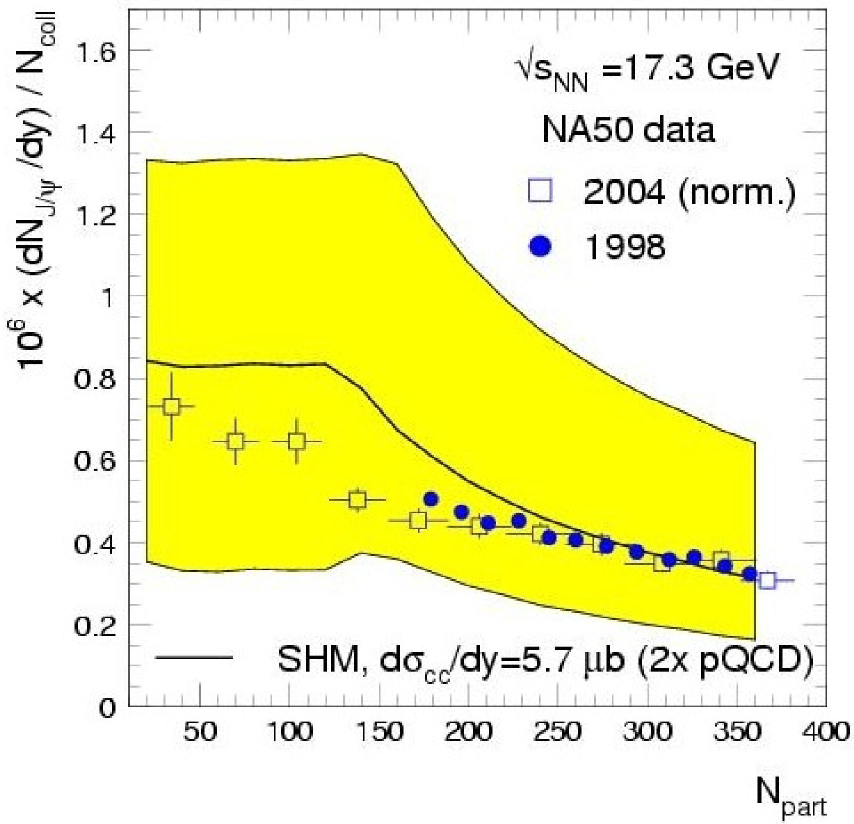
PoS CPOD07:044,2007.
e-Print: arXiv:0710.1851 [nucl-th]

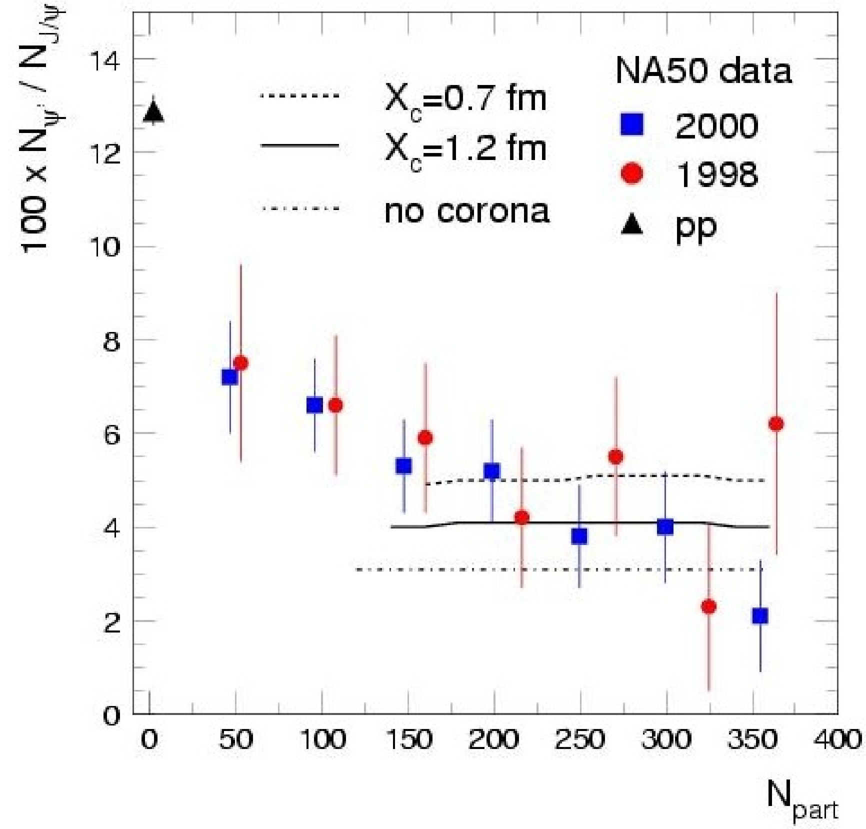
Phys.Lett.B652:259-261,2007.
e-Print: nucl-th/0701079

Nucl.Phys.A789:334-356,2007.
e-Print: nucl-th/0611023

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

results for SPS energy

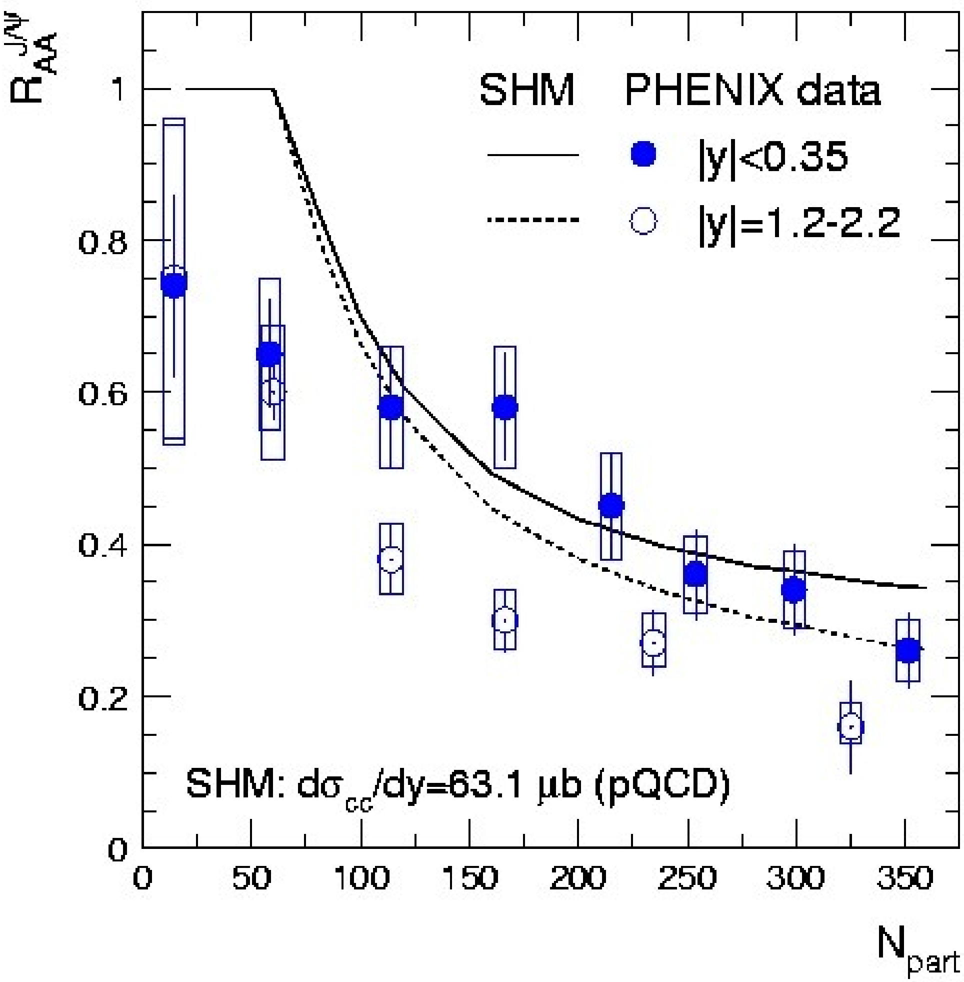




only moderately enhanced (2 x pQCD) cc_bar cross section needed

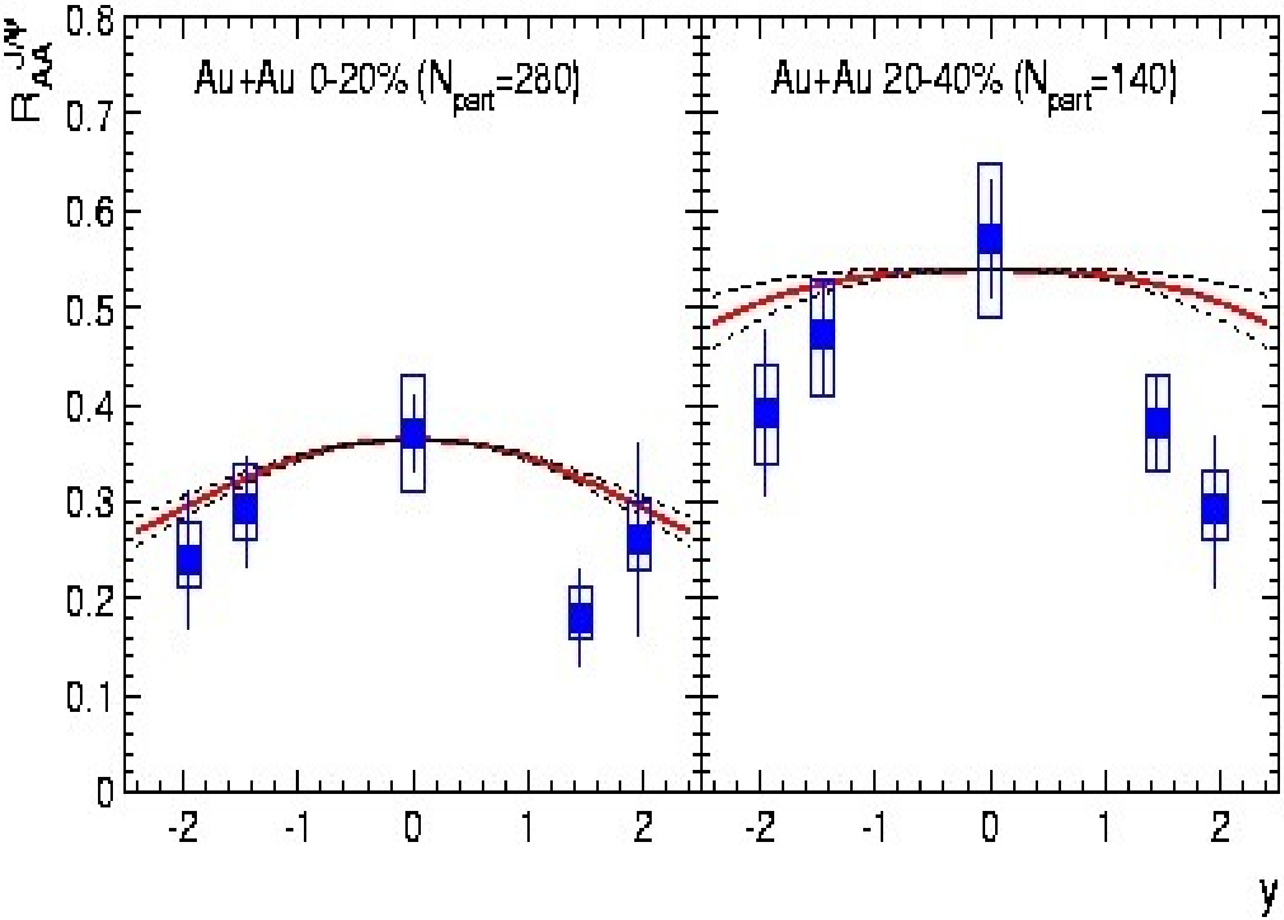
extrapolation to pp for ψ'/ψ ratio still problematic in the model, although intuitively clear

RHIC result: nuclear modification factor



data exhibit strong centrality dependence and suppression, well described
by our regeneration model without any new parameters

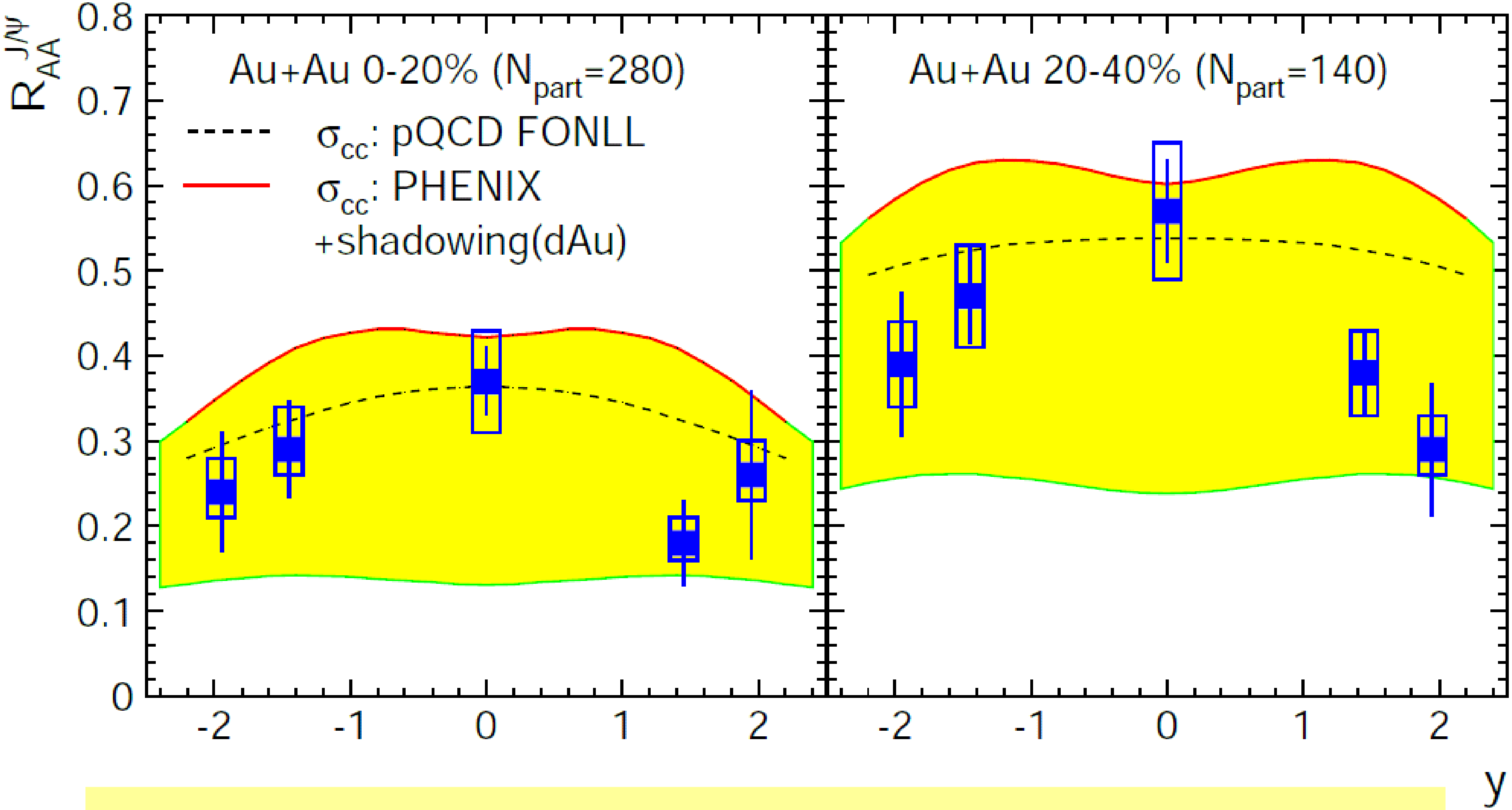
Comparison of model predictions to RHIC data: rapidity dependence



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

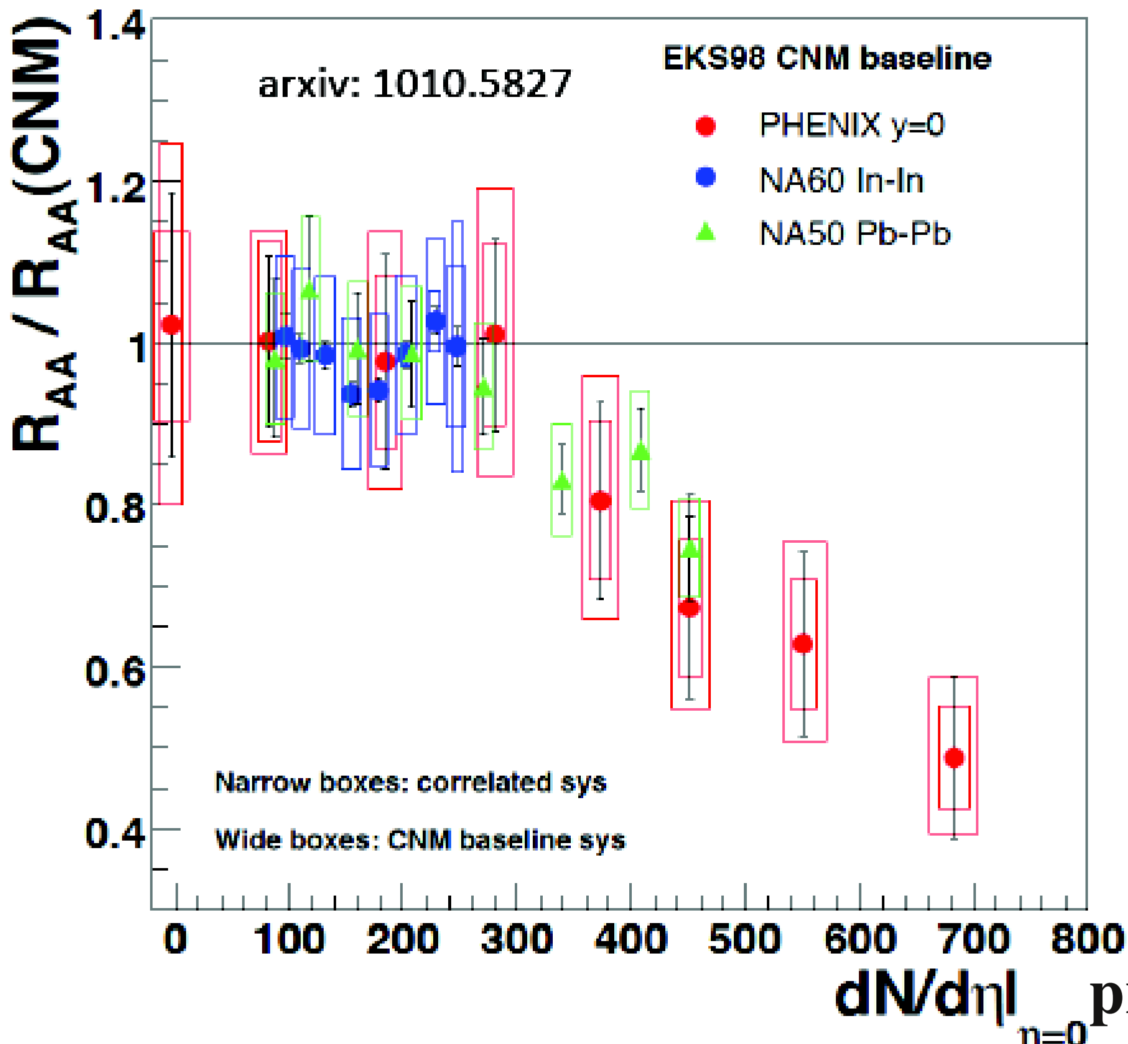
Calculations including shadowing

andronic, pbm, redlich, stachel
J. Phys. G37 (2010) 094014, arXiv:1002.4441 [nucl-th]



assume PHENIX pA data reflect shadowing
consistent with most recent PHENIX analysis
by Frawley et al.

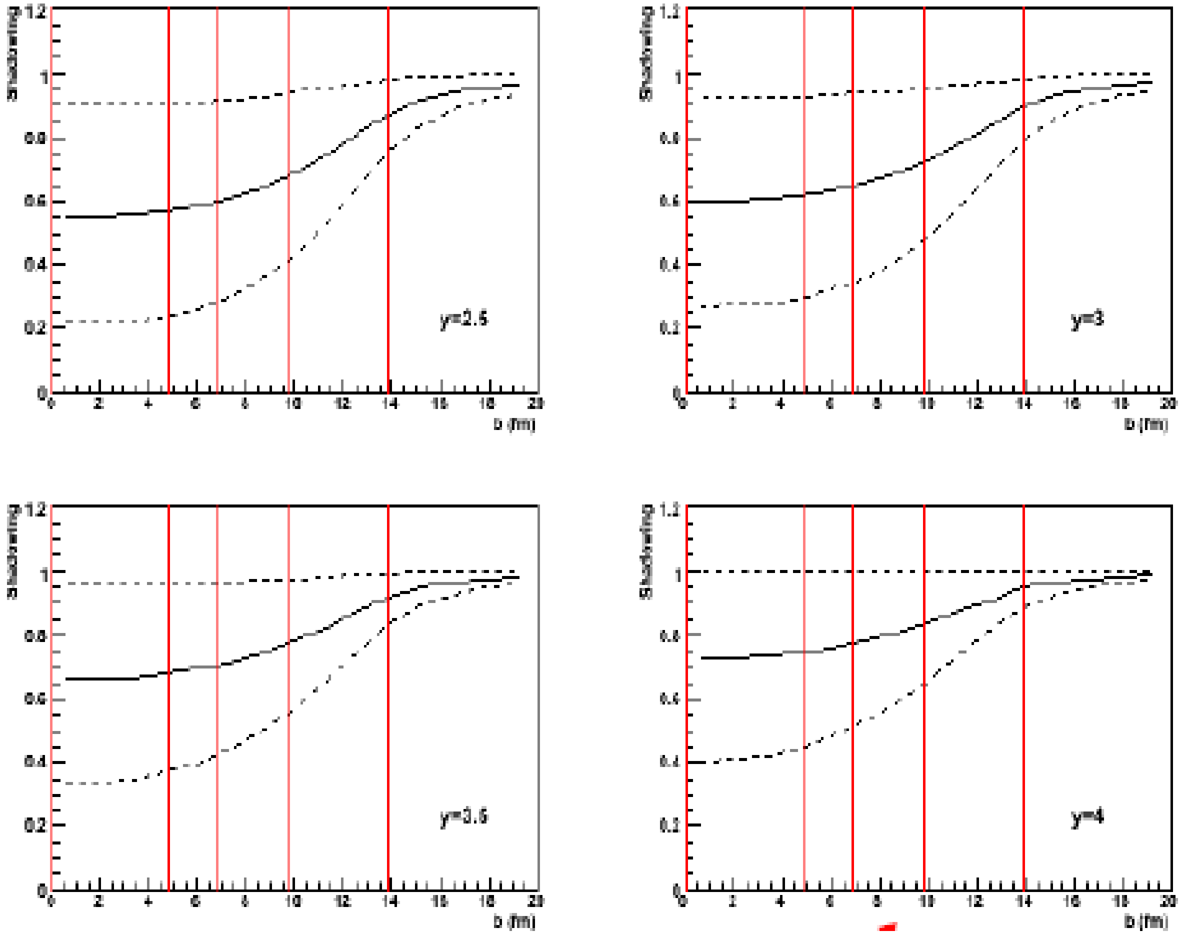
summary of all pre-LHC data on J/psi production in AA collisions



prop. to energy density

Is there scaling with energy density? Note that dN/deta = 1600 at LHC energy (y=0)

EKS09 shadowing for J/psi production at LHC



At LHC energy, shadowing reduces R_AA significantly, but the exact amount needs to be determined, need open charm cross section in PbPb. Note also the centrality dependence!

An attempt to look at near threshold production

- charm cross section unknown
- but: $N_{ccbar} << 1$: only diagonal terms in recombination
- independent of energy, charm production
  still a hard process

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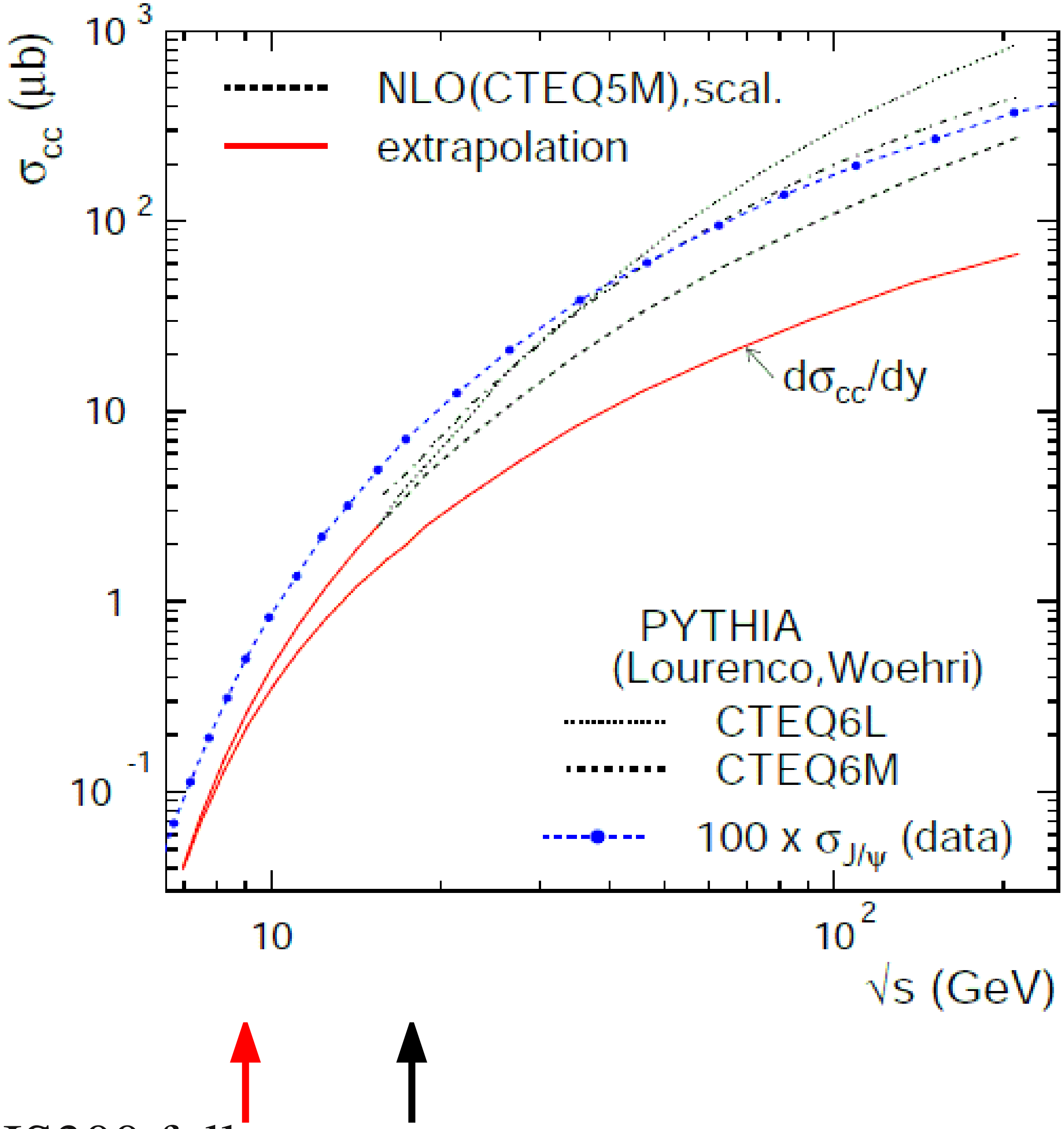
Extrapolation of pQCD cross section to low energies



charm threshold in NN: 5.1 GeV

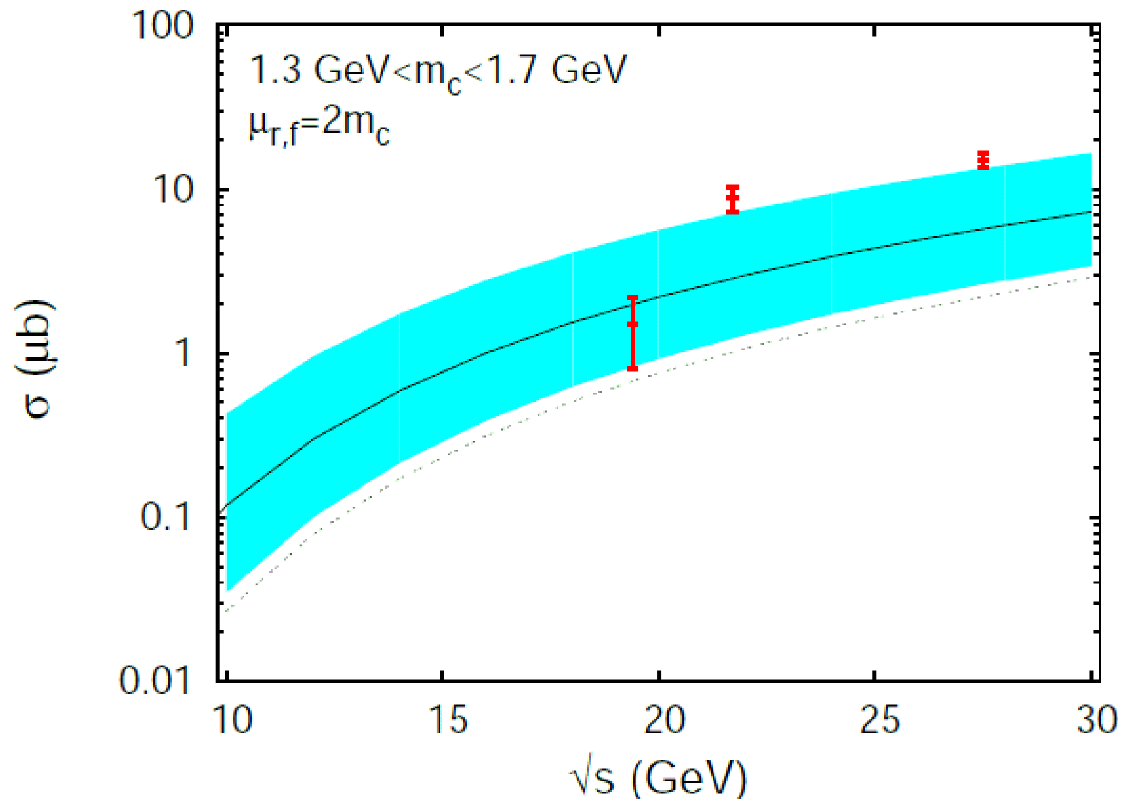
absolute threshold in Pb-Pb collisions:

T_{lab}/A = 31 MeV

SIS300 full energy SPS full energy

most recent NLO calculation of open charm production

Braaten and Artoisenet, arXiv:0903.2573 [hep-ph]

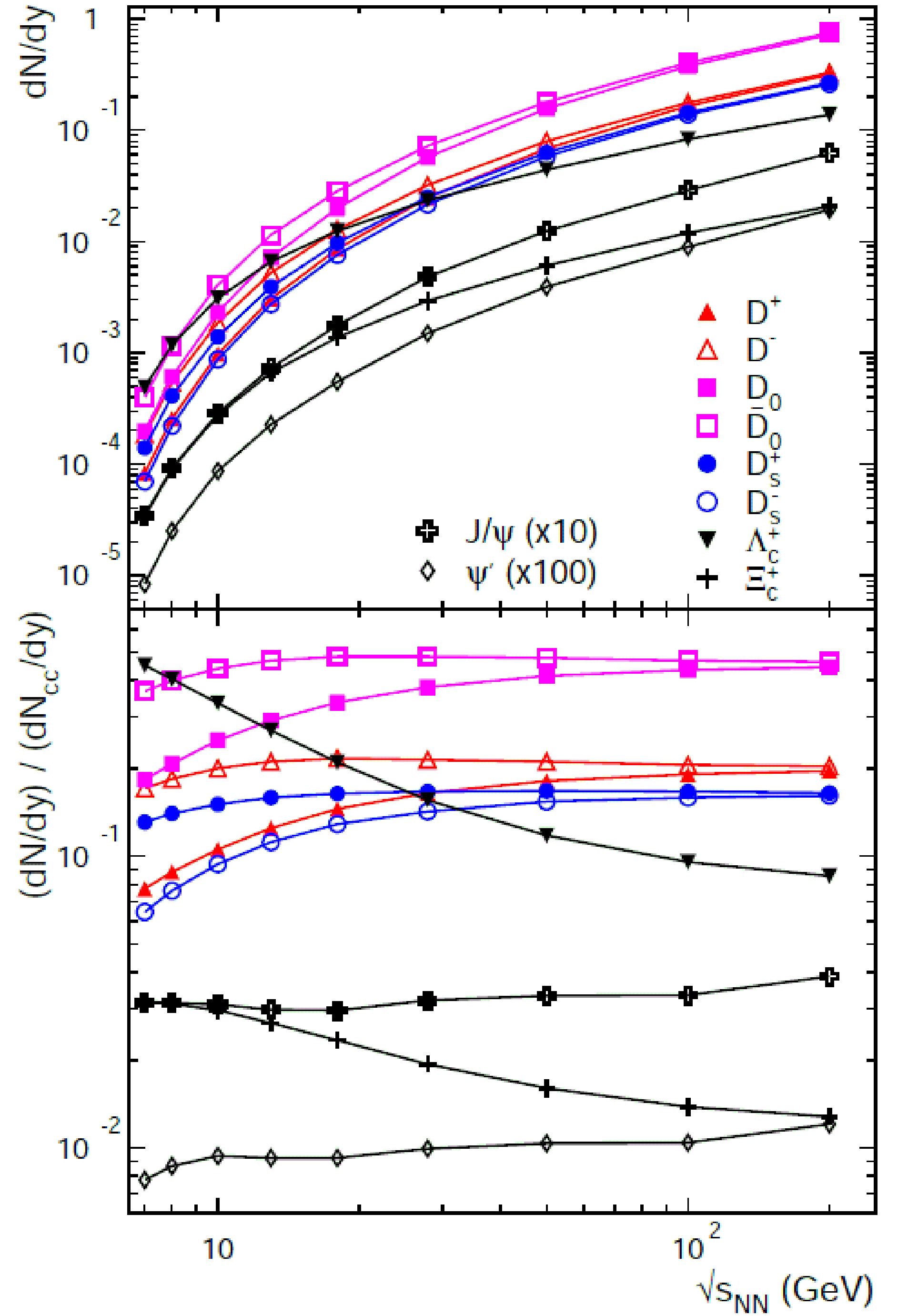


S. Barlag *et al.* [ACCMOR Collaboration], Z. Phys. C **39**, 451 (1988).
M. Aguilar-Benitez *et al.* [LEBC-EHS Collaboration], Z. Phys. C **40**, 321 (1988).
G. A. Alves *et al.* [E769 Collaboration], Phys. Rev. Lett. **77**, 2388 (1996) [Erratum-ibid. **81**, 1537 (1998)].

Model predictions without any medium modifications

note in particular the role of charmed baryons

at SIS300 energies it is crucial to measure those



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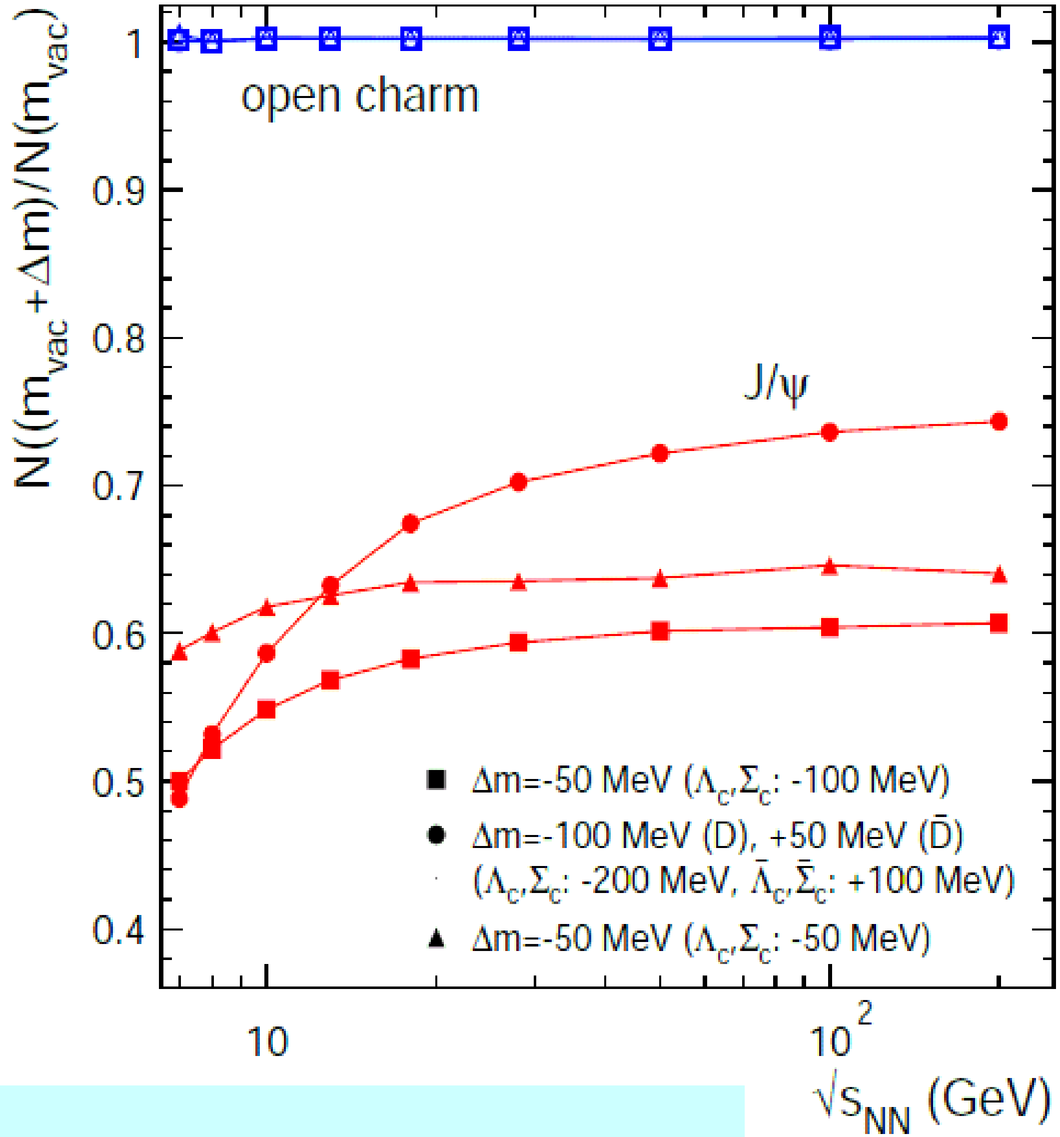
Changes for charmonium assuming scenarios 1 – 3

charmonium masses unchanged

yield of charmonium may change by up to factor of 2

difficult how to normalize

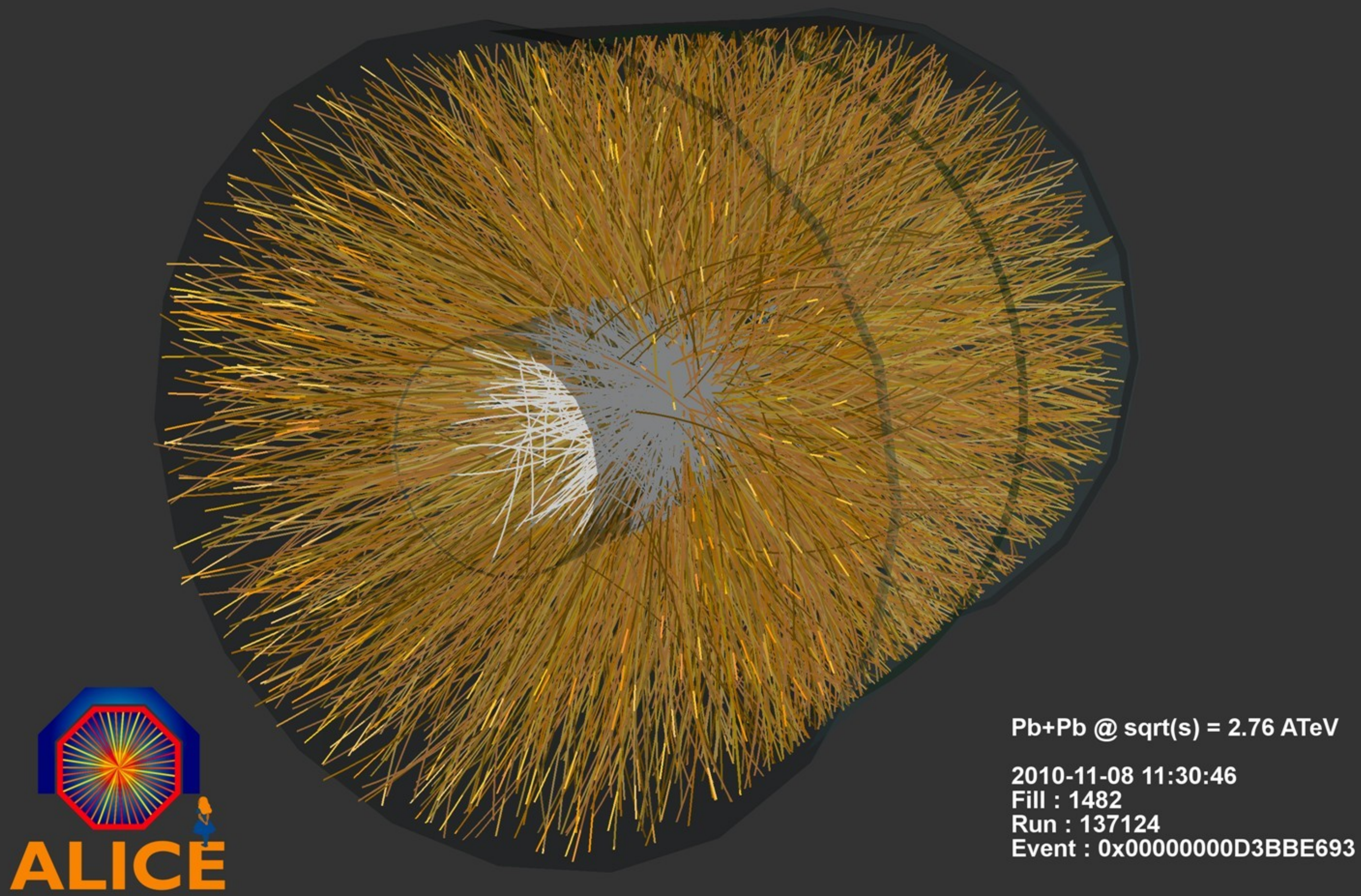


can STAR and PHENIX address this at sqrt{s_NN} = 10 – 20 GeV?

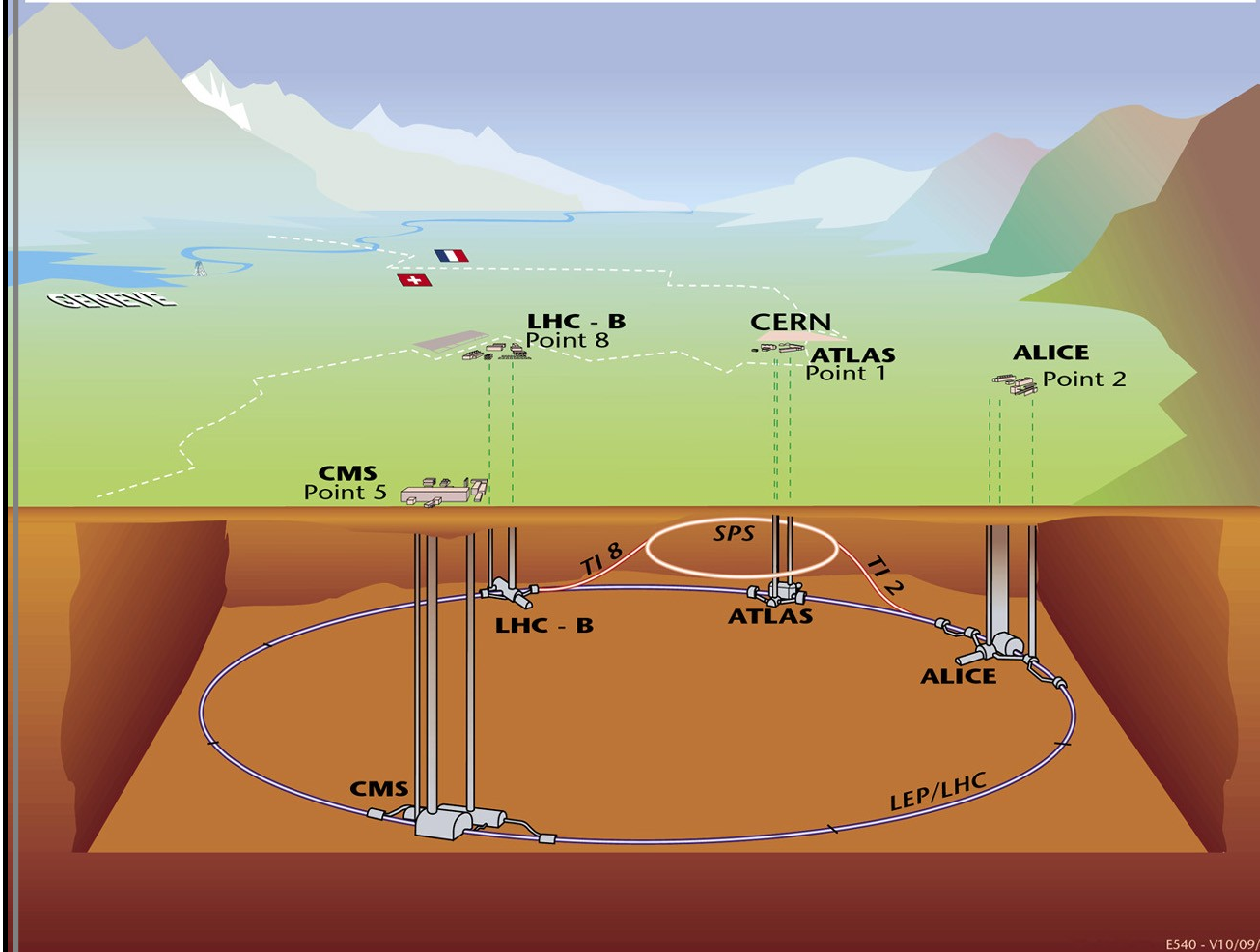
First results at LHC energy

1. open charm production in pp at 7 TeV
2. J/psi production in pp at 7 TeV
3. performance results from PbPb
4. first PbPb physics results

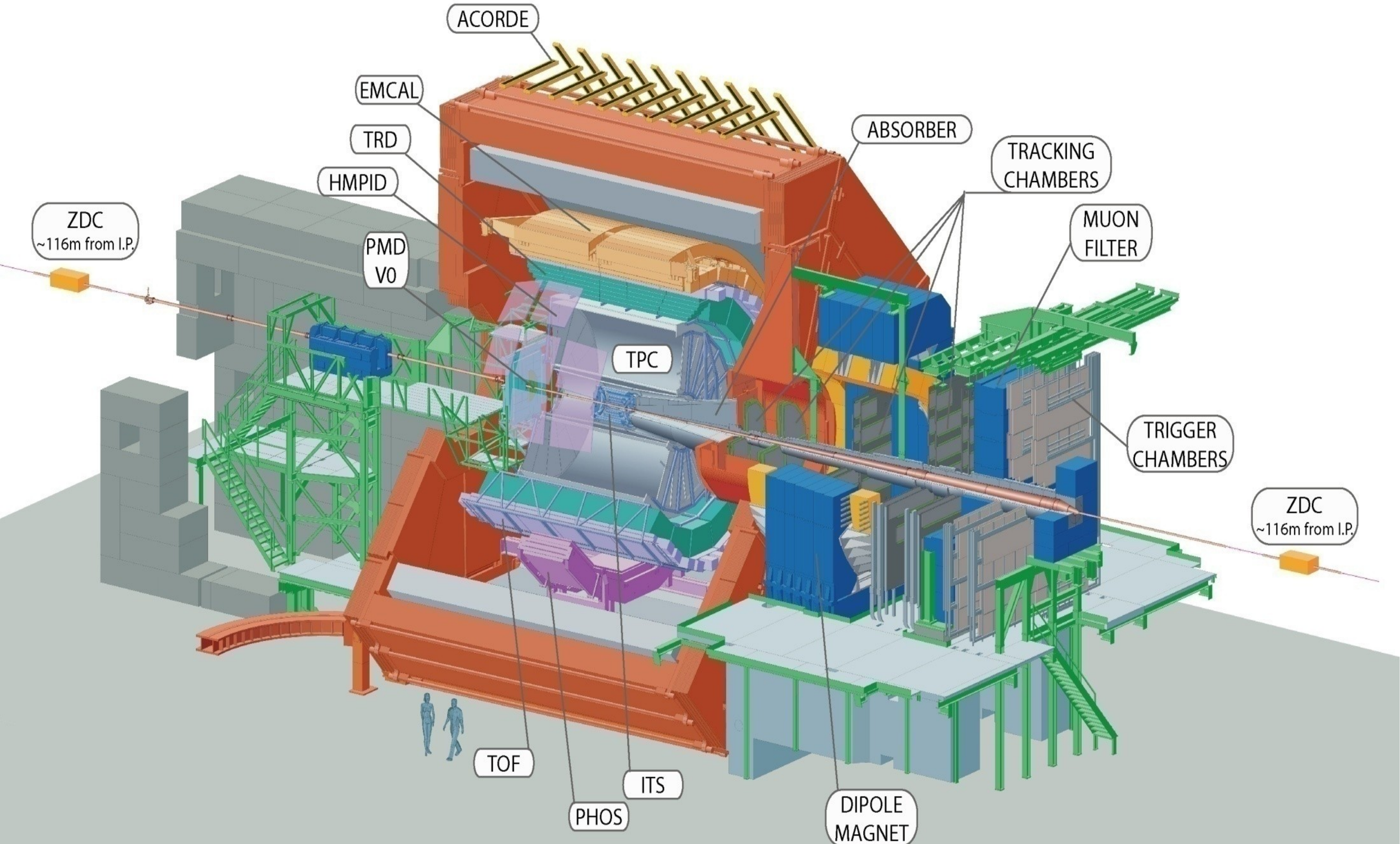
A challenging environment!



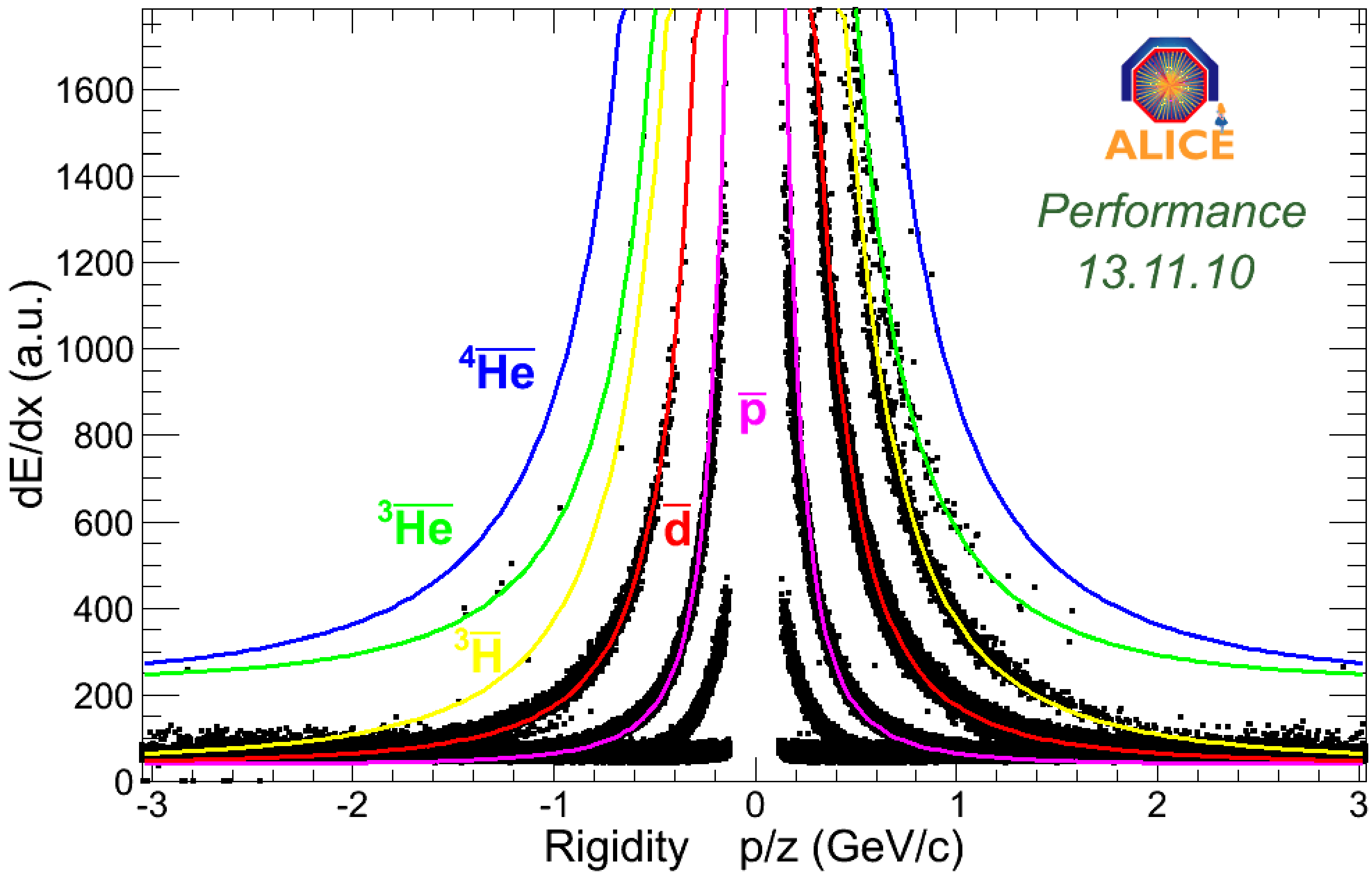
Overall view of the LHC experiments.



ALICE schematic setup

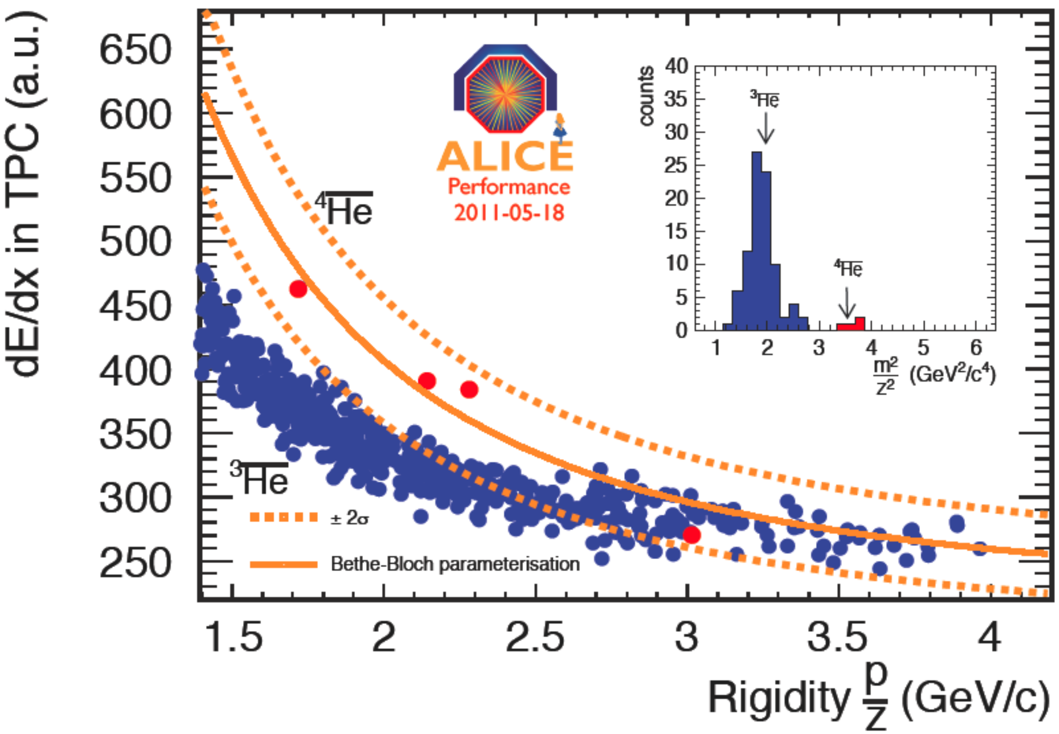


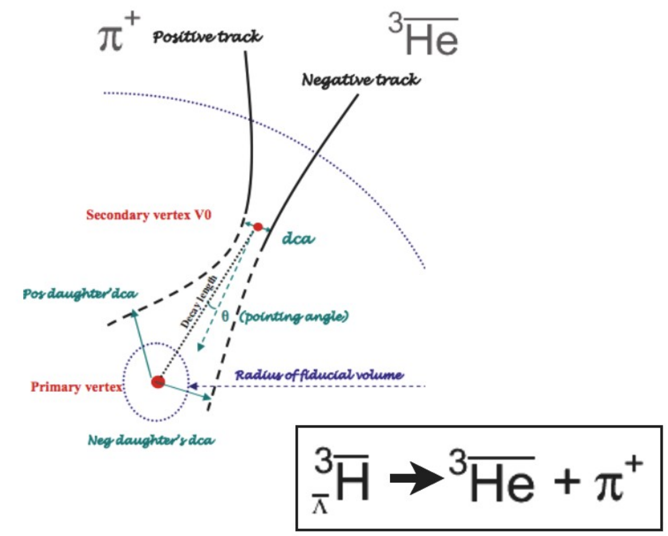
a closer look at performance: TPC dE/dx

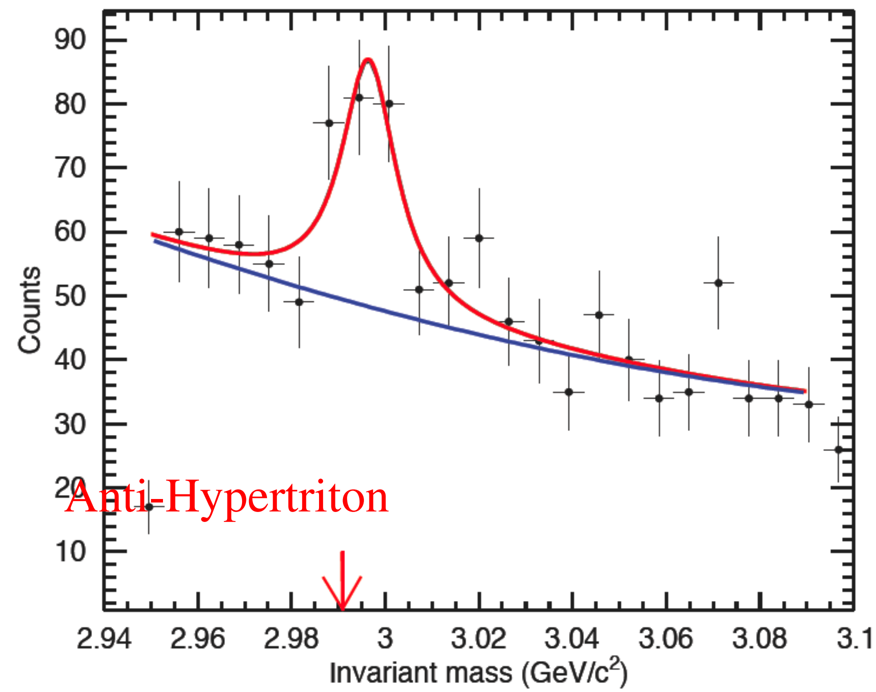


note: copious anti-nucleus production

Anti-Matter PID







first charm measurements in ALICE pp

D mesons, charmed baryons, charmonia, J/psi from B decays

provide input to solve longstanding problem to understand the mechanism of open charm and charmonium production in pp collisions

provide baseline for PbPb measurements

OPEN CHARM

- Heavy flavor electron inclusive spectrum
- $D^0 \rightarrow K\pi$
- $D^\pm \rightarrow K\pi\pi$
- $D^* \rightarrow D^0\pi$
- $\Lambda_c \rightarrow pK\pi$, $K^0_S p$, $\Lambda\pi$

  baryon/meson ratio

OPEN BEAUTY

- $B \rightarrow J/\psi\ X$
- Heavy flavor electron inclusive spectrum

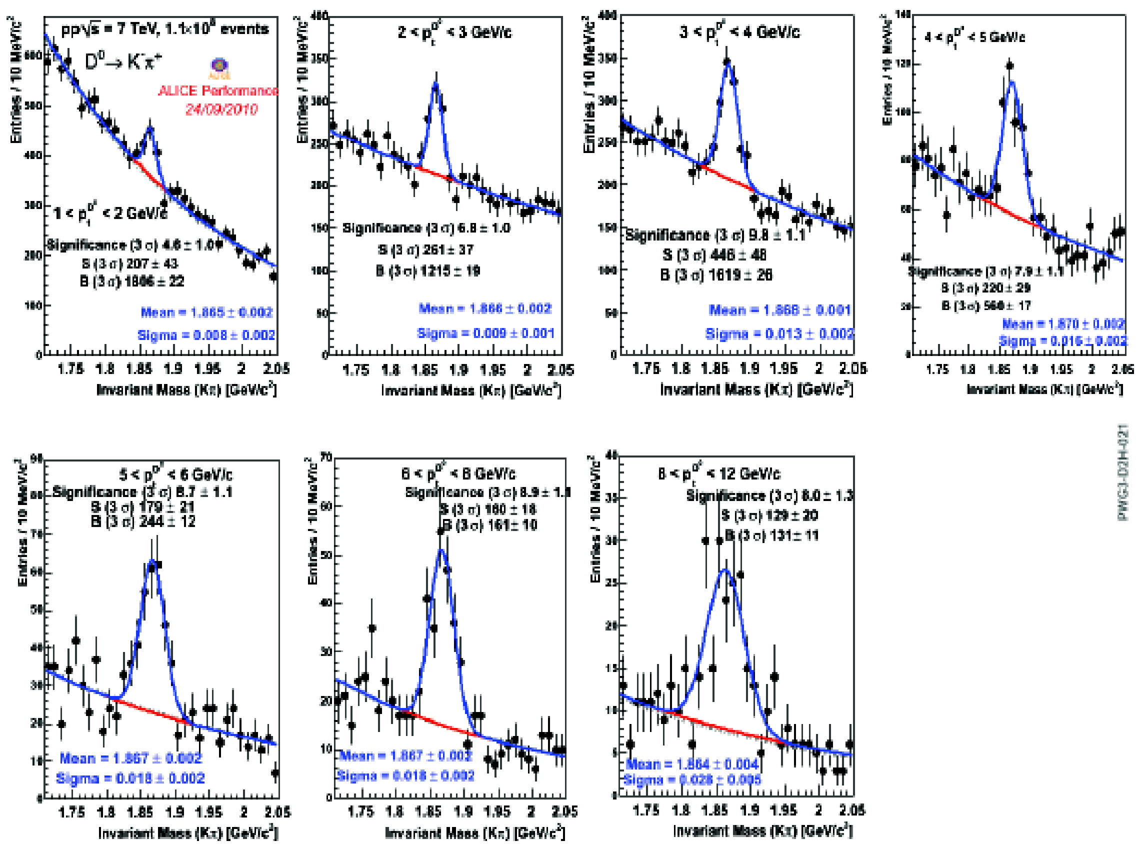
QUARKONIA

- J/ψ, ψ'
- Υ

open charm production and the pp baseline

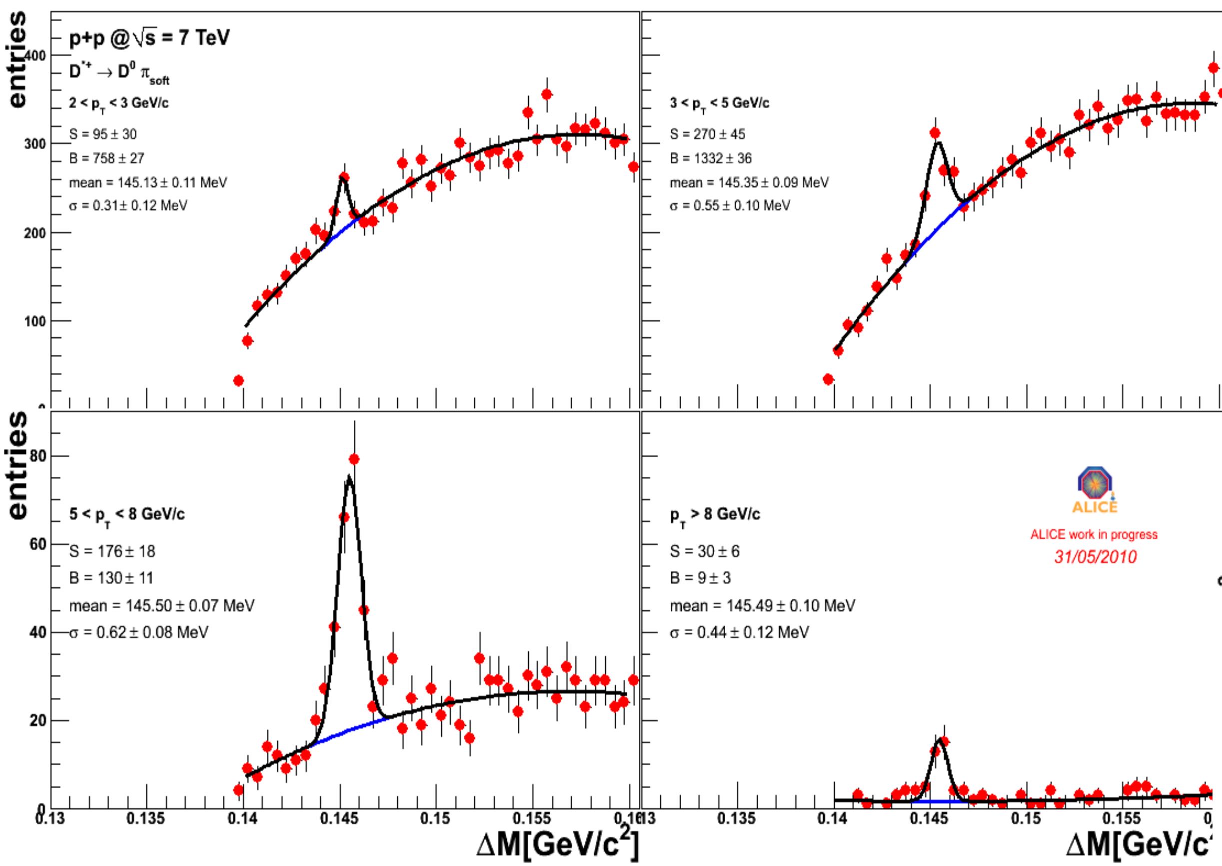
pp → D_0 + X 7 TeV, ALICE

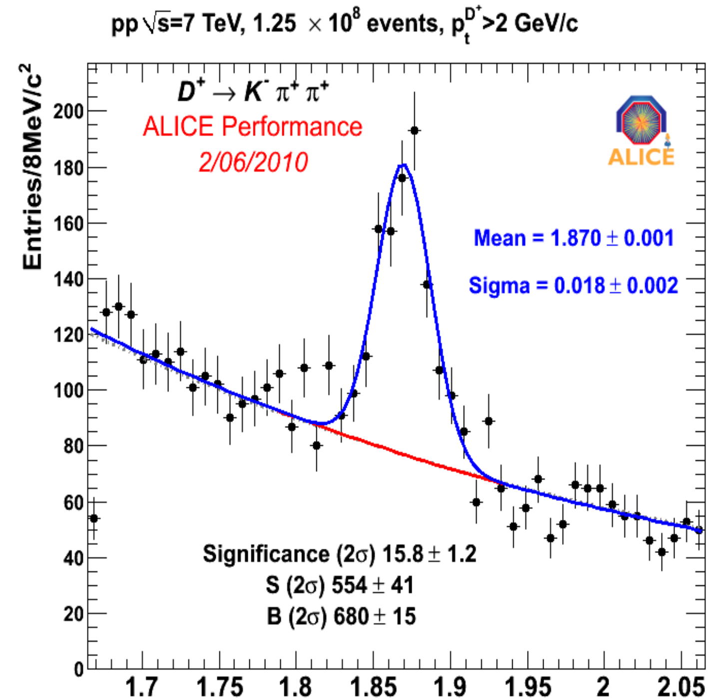
10^8 events; 1-12 GeV in 7 bins

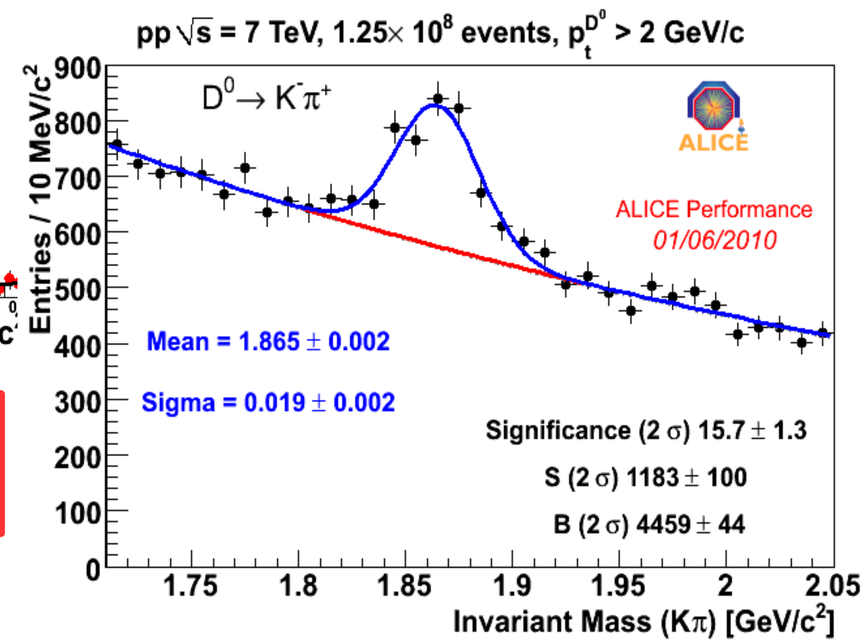


D^0, D^+ and D^{0*} in 7 TeV pp data

$1.25\ 10^8$ events

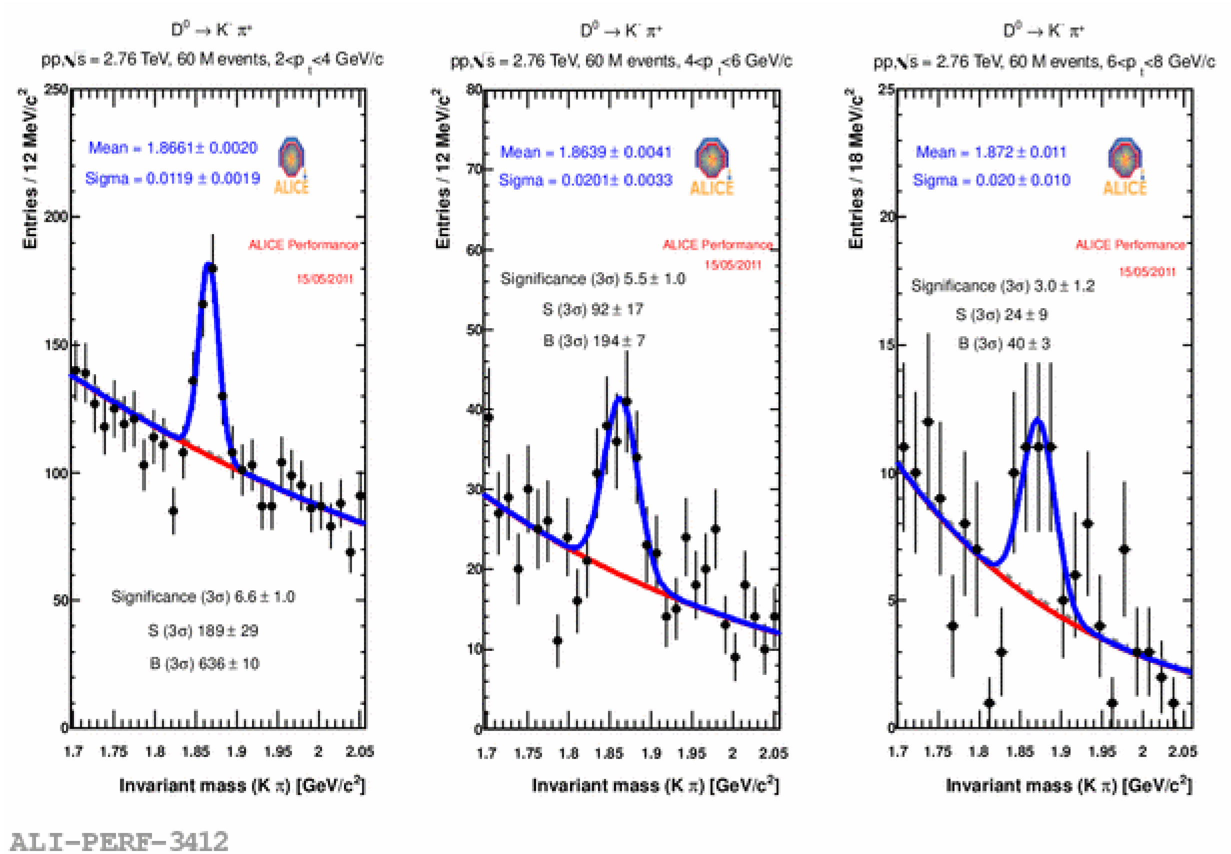




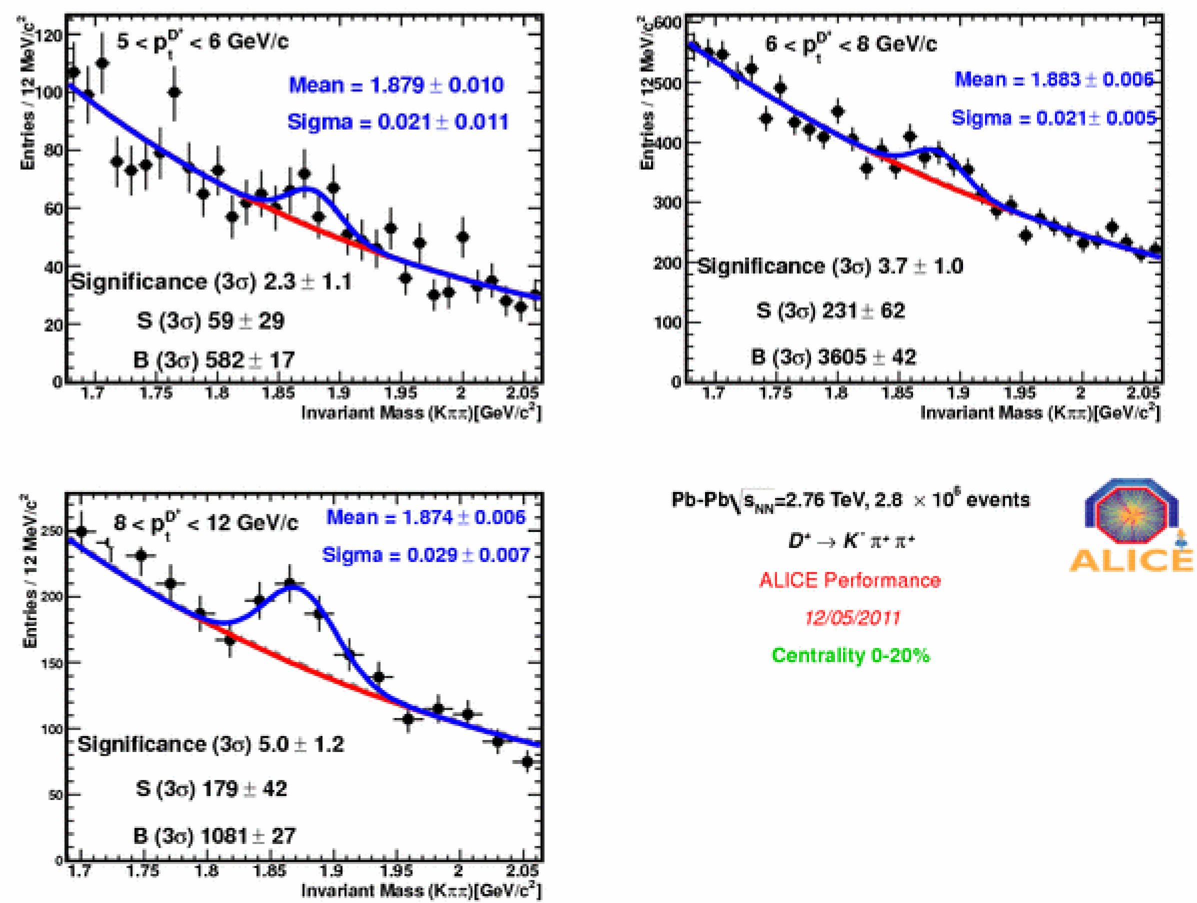


for 10^9 events, expect to measure open charm for $p_t = 0.5 – 15$ GeV/c

D meson production at roots = 2.76 TeV – reference energy

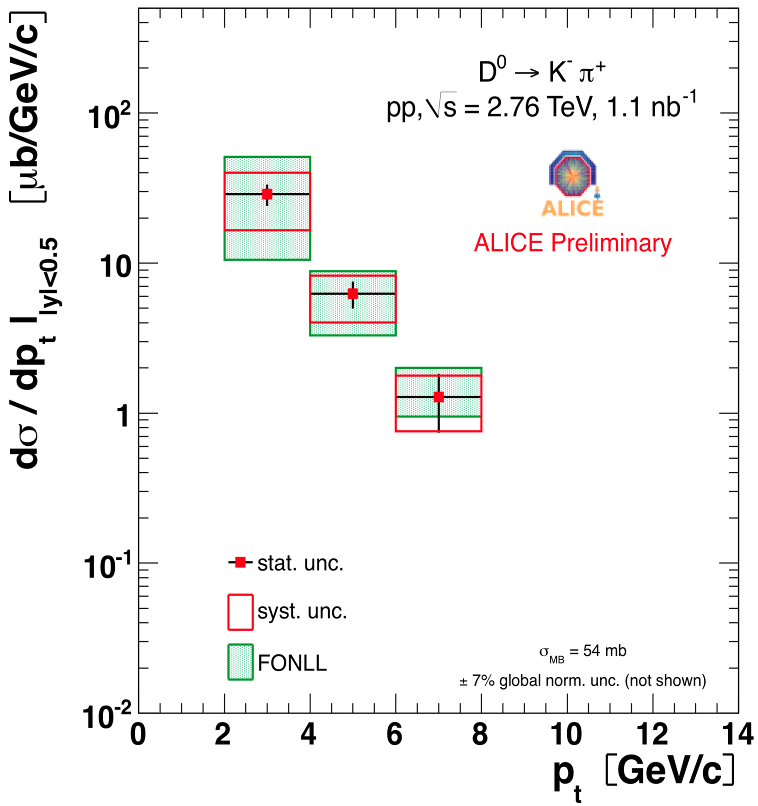


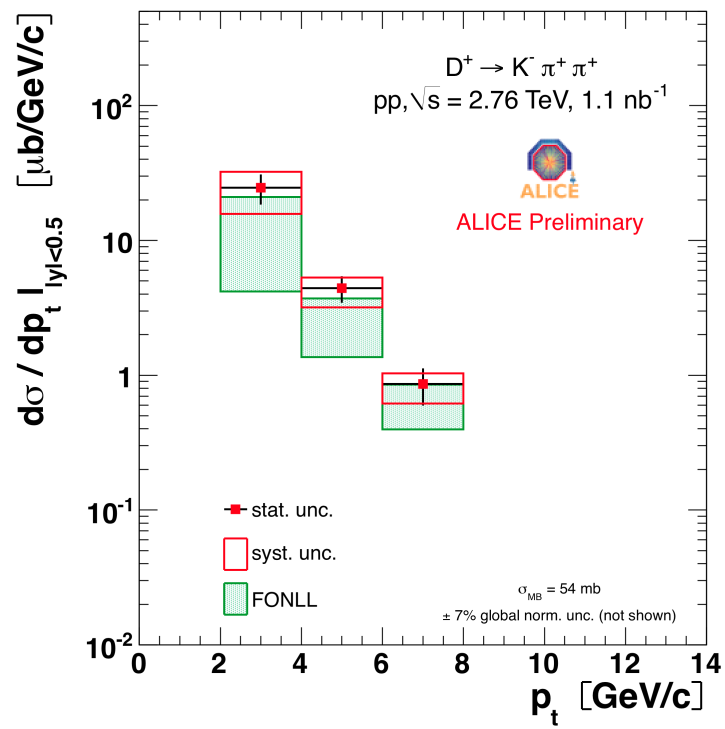
D meson signals in Pb—Pb collisions



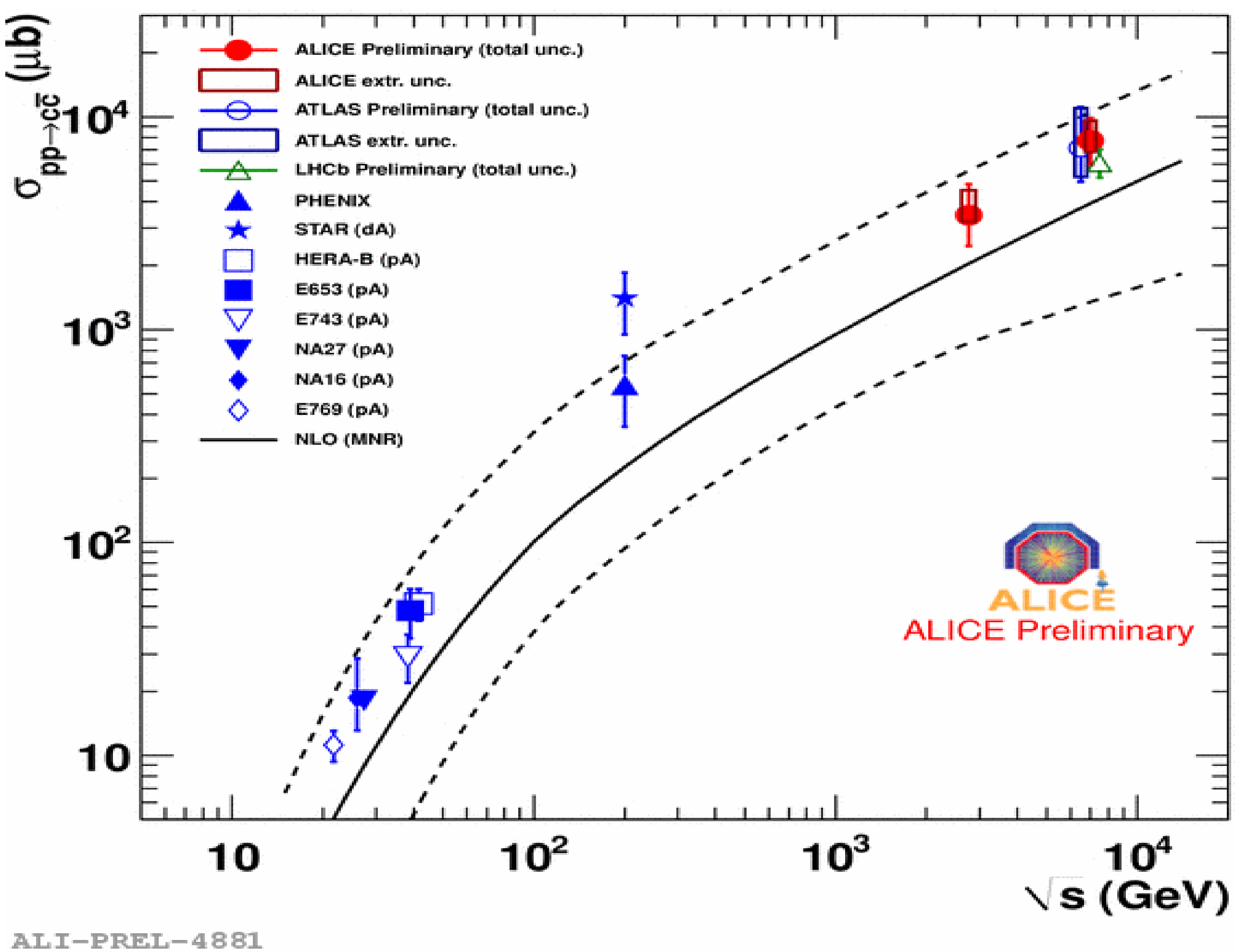
ALI-PERF-1946

Some results on D mesons

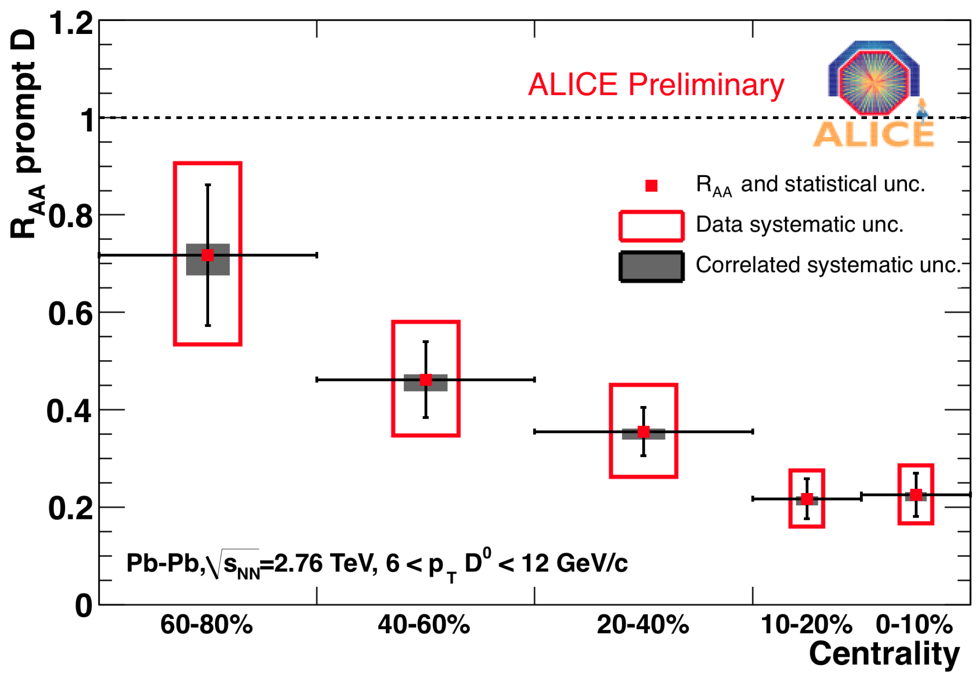


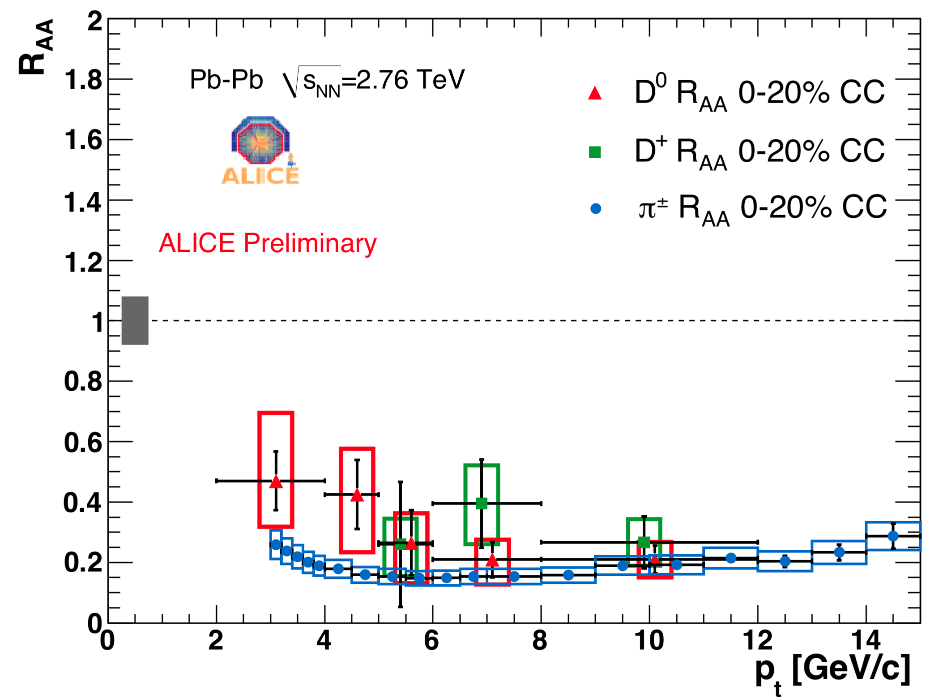


a first try at the total ccbar cross section in pp collisions



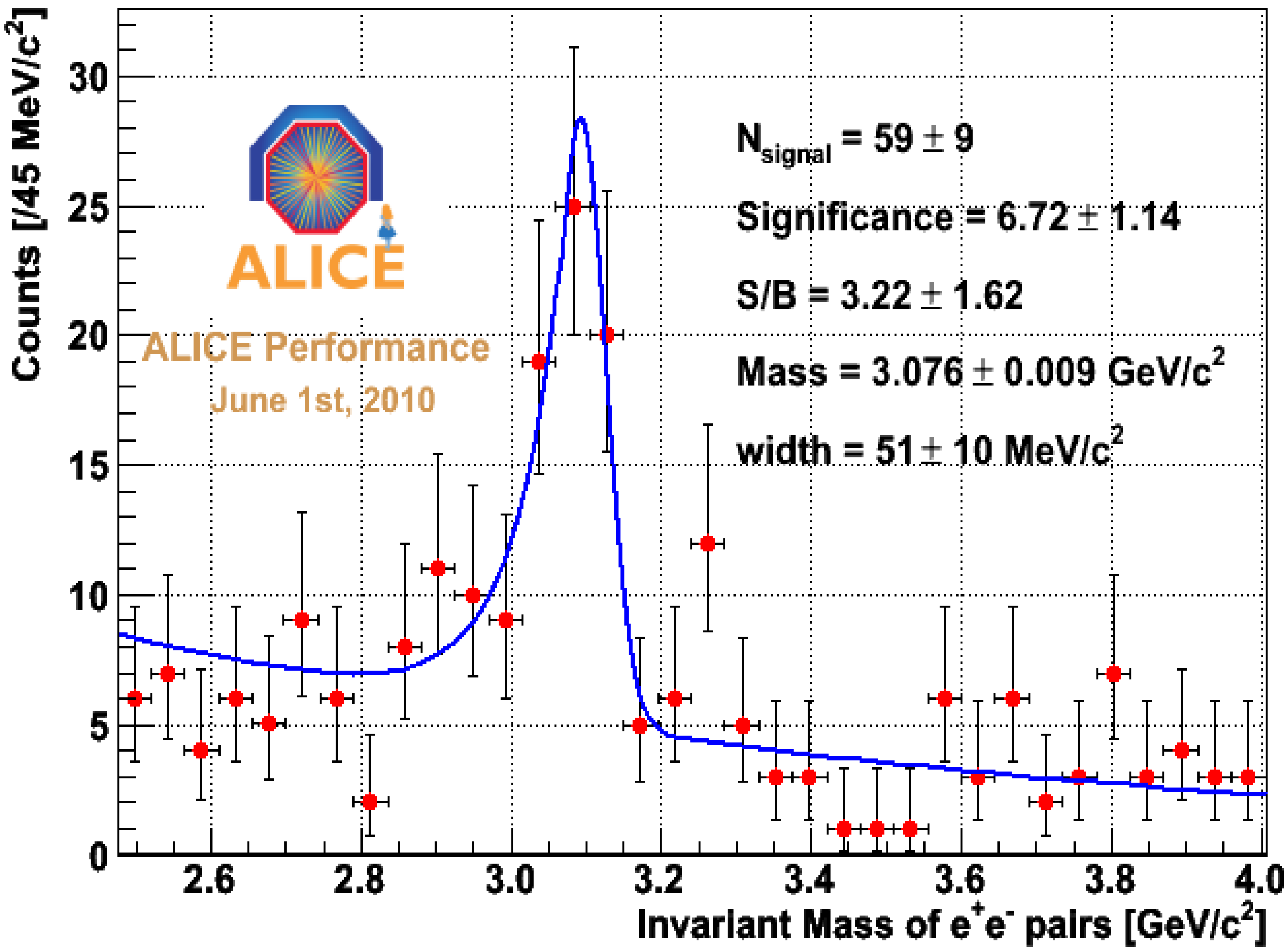
R_AA for D mesons

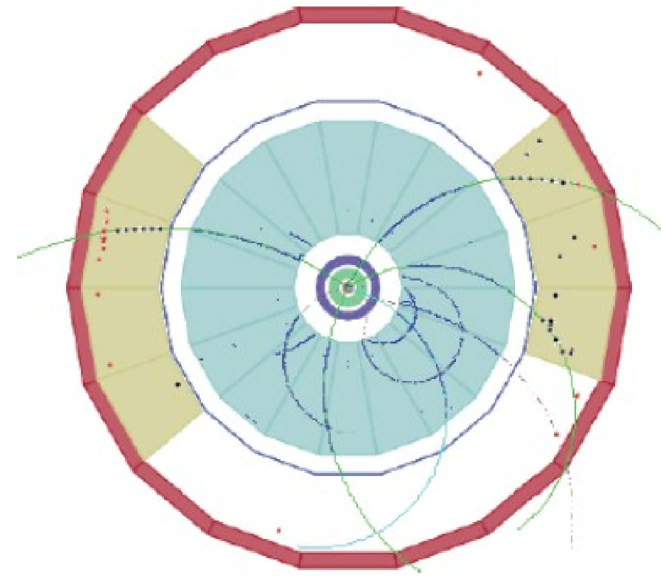




charm quark energy loss, shadowing,... need to measure at low transverse momentum!

first J/psi in ALICE central barrel from 110 million pp collisions at 7 TeV

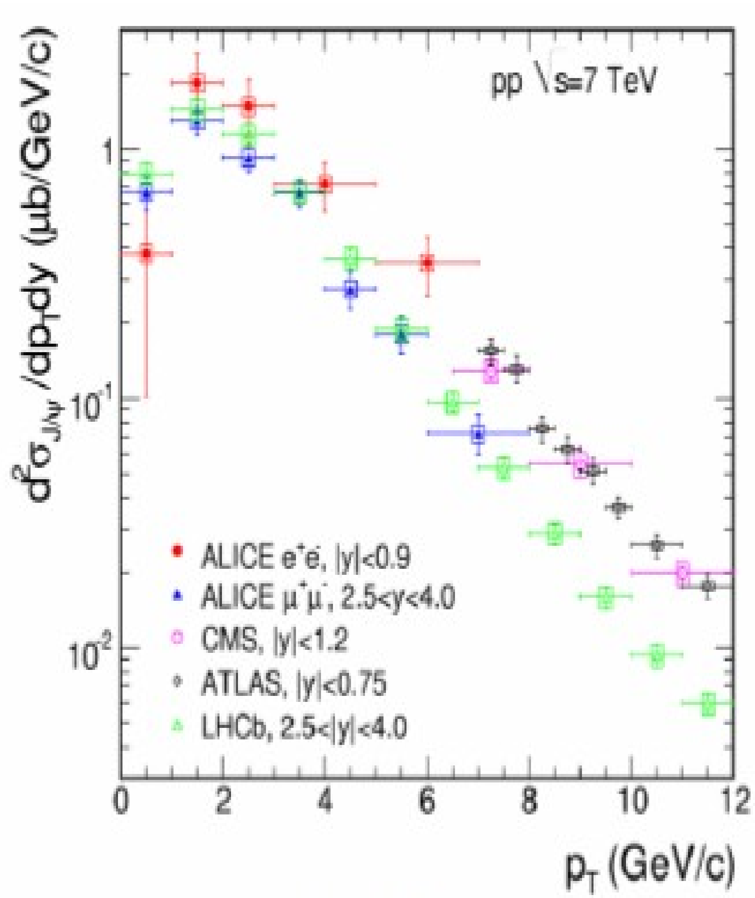


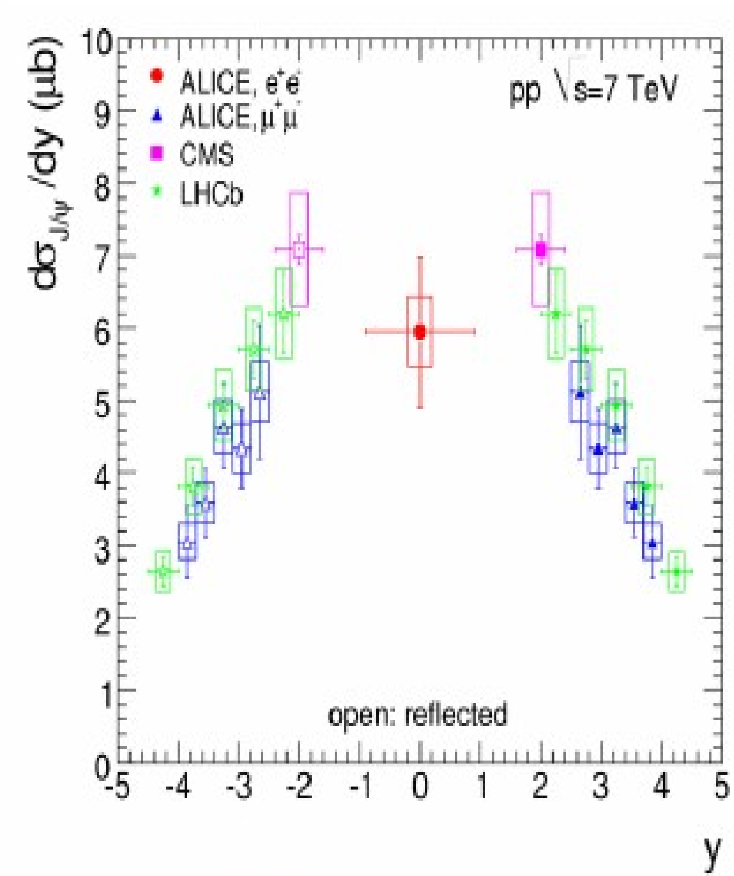


expect about 300 J/ψ mesons by end 2010 --> p_t and y distributions and production cross section

J/psi in pp collisions

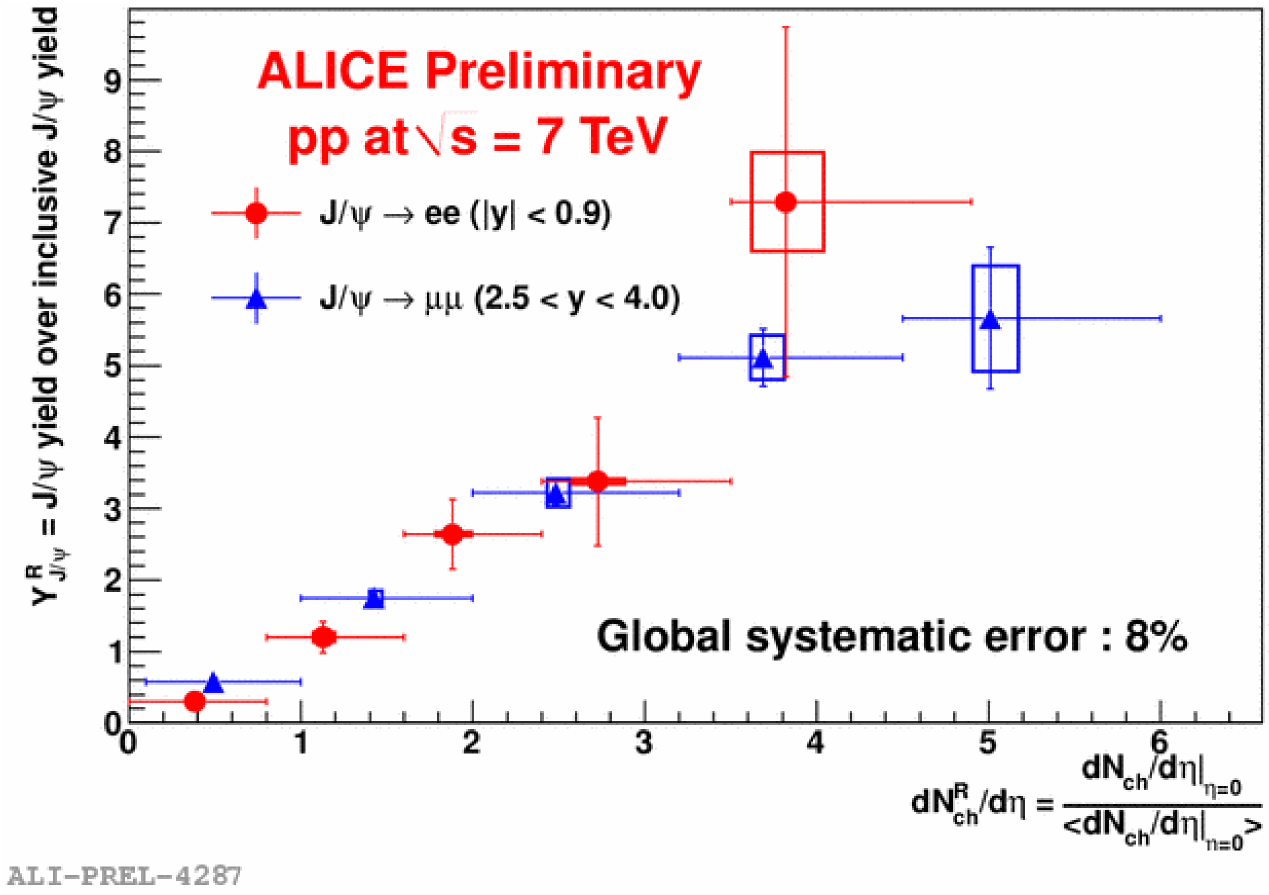
ALICE Coll., arXiv:1105.0380



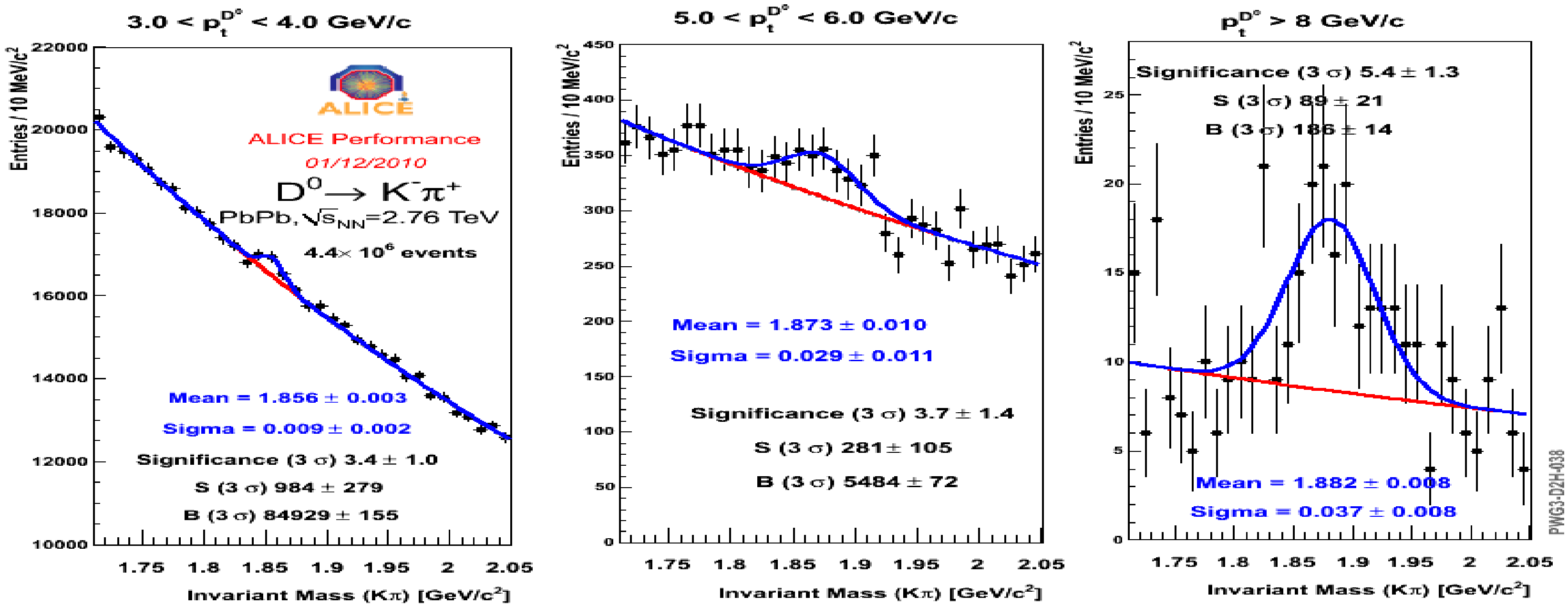


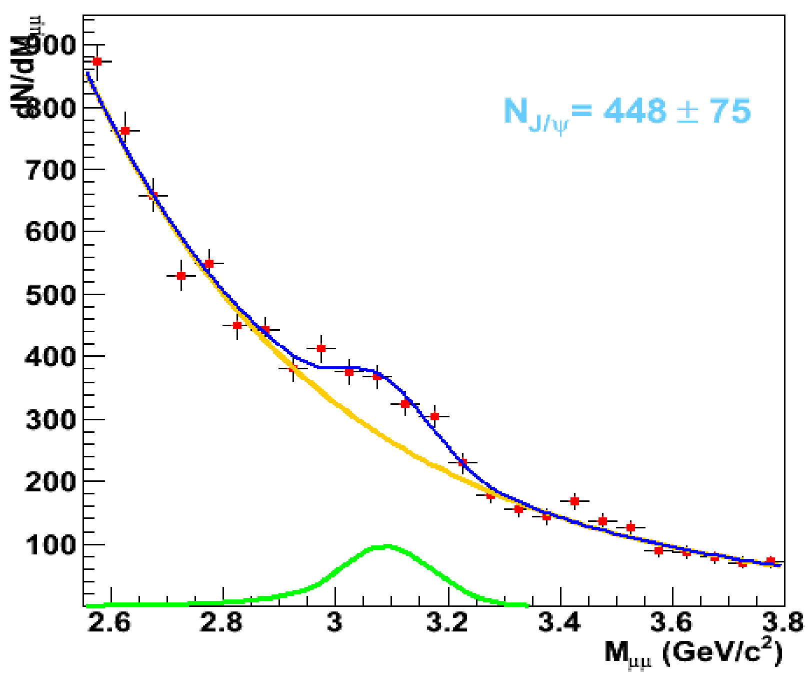
(ATLAS Coll, arXiv:1104.3038, CMS Coll, arXiv:1011.4193, LHCb Coll, arXiv:1103.0423)

a very peculiar multiplicity dependence

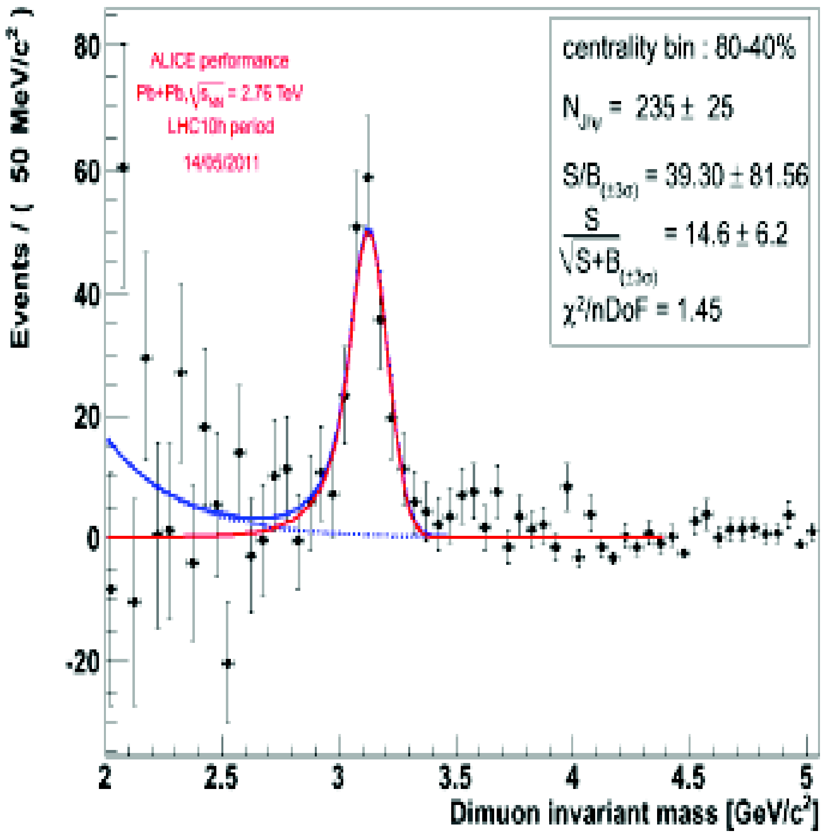


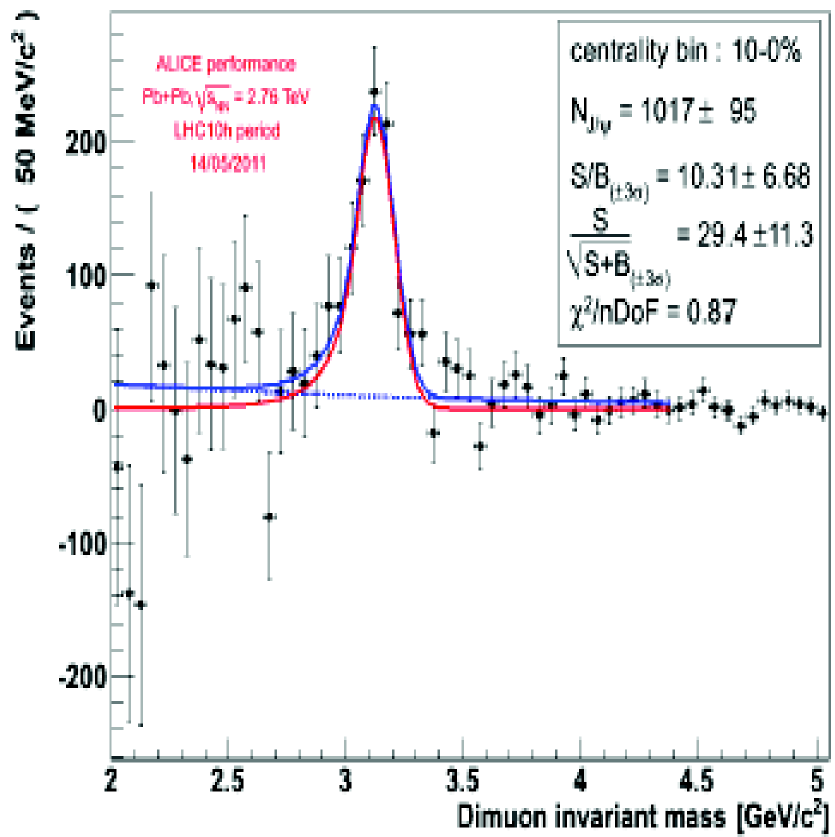
and 1st min bias results in PbPb at 2.76 TeV



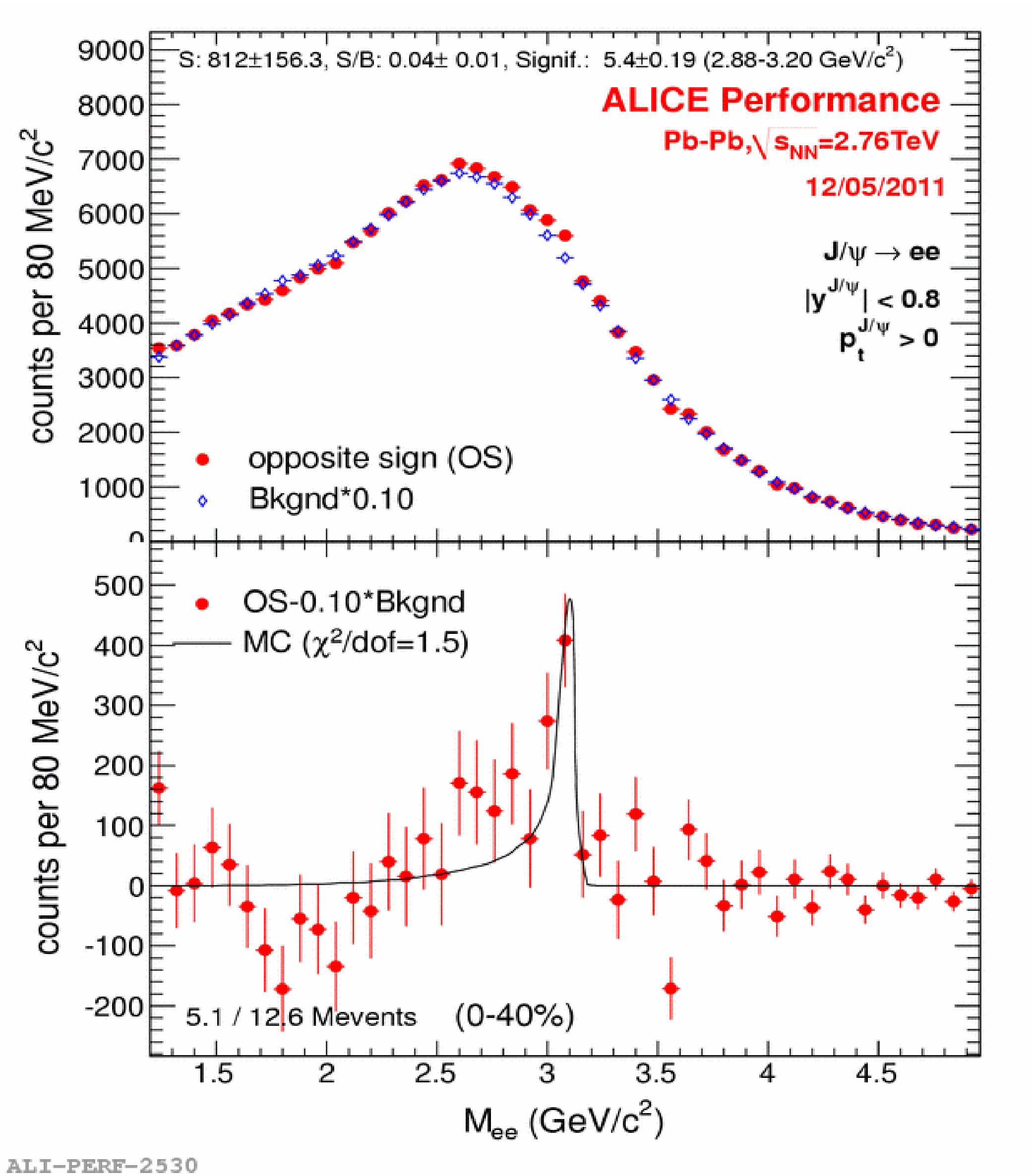


J/psi → mumu in PbPb collisions





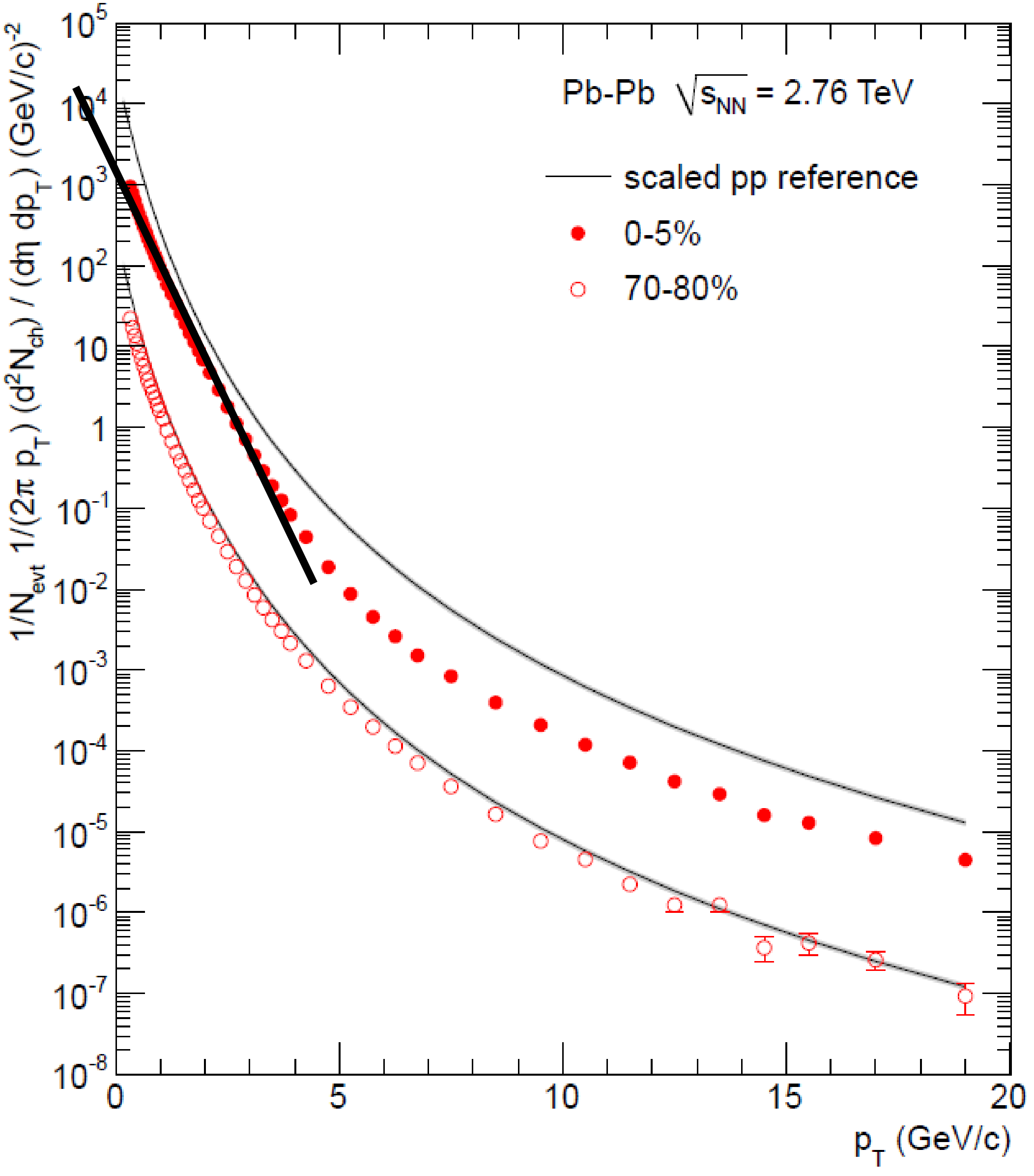
J/psi also seen in e+e- channel



evidence for strong thermalization in PbPb at LHC energy

for central collisions, spectrum is nearly exponential up to 5 GeV

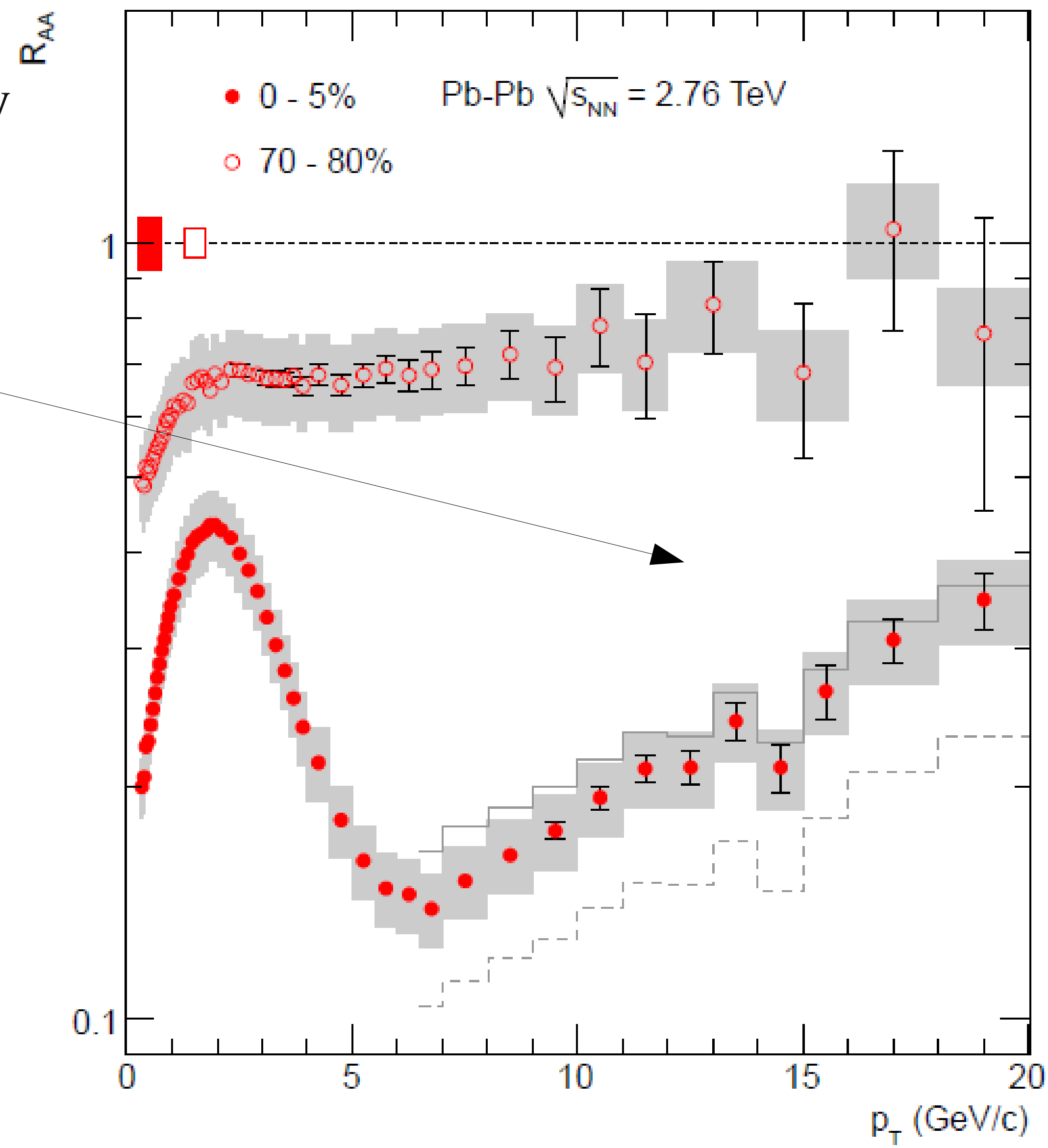
ALICE coll., arXiv:1012.1004 [nucl-ex]



Shadowing at LHC in Pb – Pb collisions ?

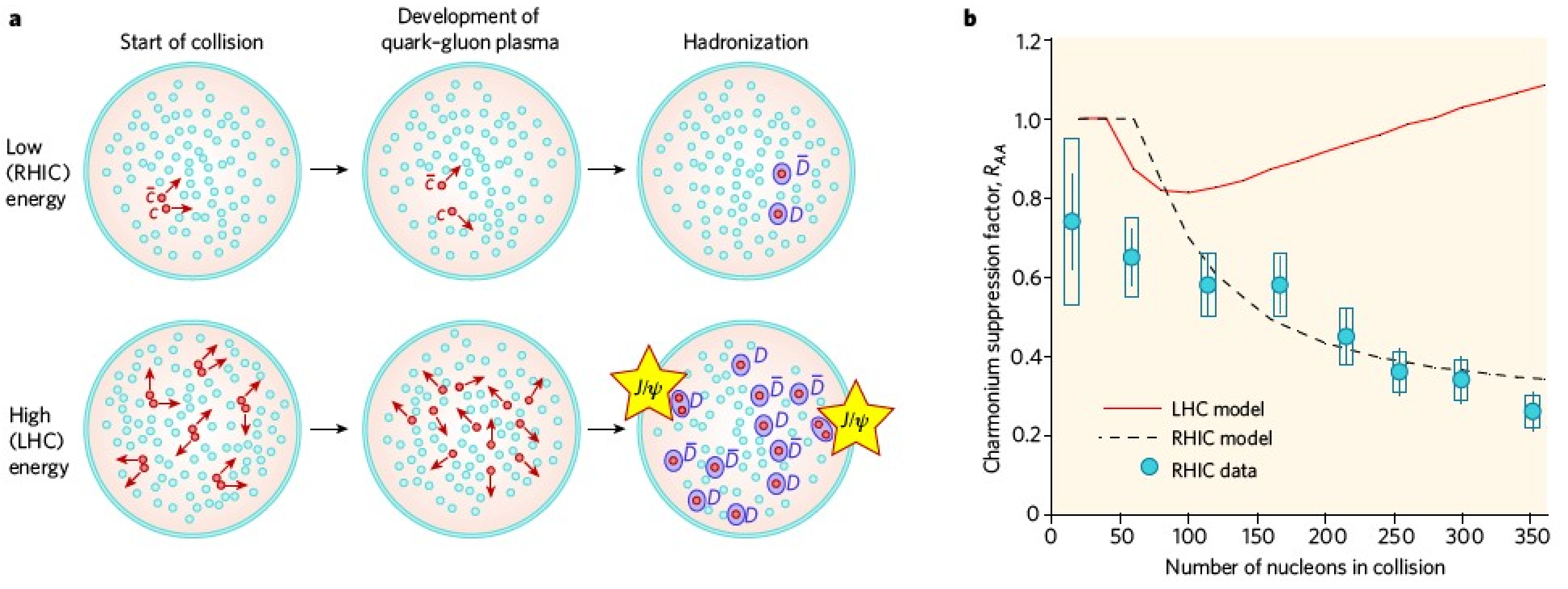
shadowing needs to be considered carefully, ALICE data on centrality dependence of multiplicity and on pt dependence of RAA may provide info on shadowing in the light quark sector

need to measure centrality dependence of open charm cross section in Pb – Pb collisions as baseline for charmonium measurements



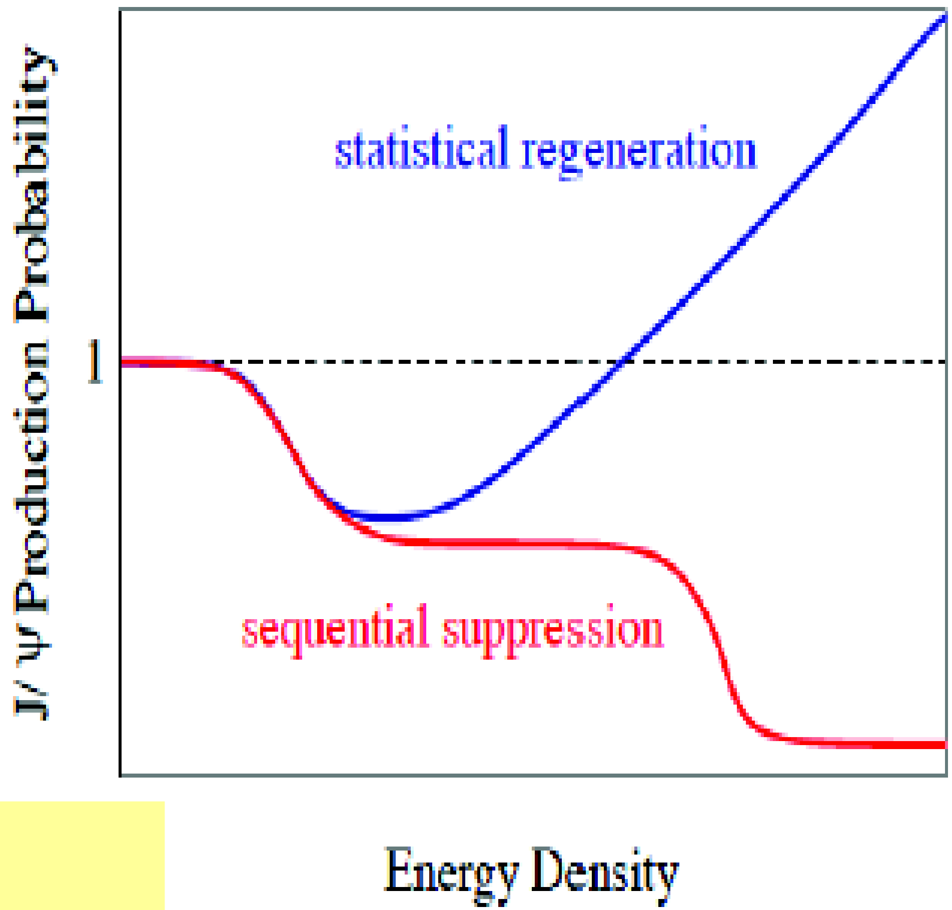
ALICE coll., arXiv:1012.1004 [nucl-ex]

Quarkonium as a probe for deconfinement at the LHC



charmonium enhancement as fingerprint of deconfinement at LHC energy

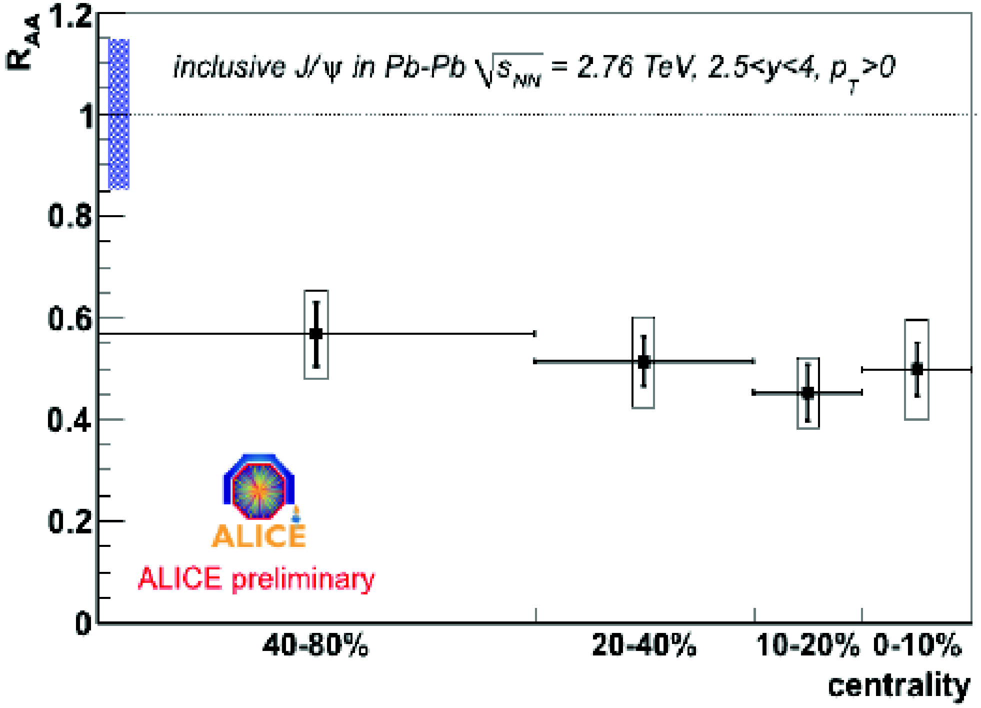
Decision on regeneration vs sequential suppression from LHC data



SPS RHIC LHC

Picture:
H. Satz 2009

first J/psi results at LHC energy from ALICE

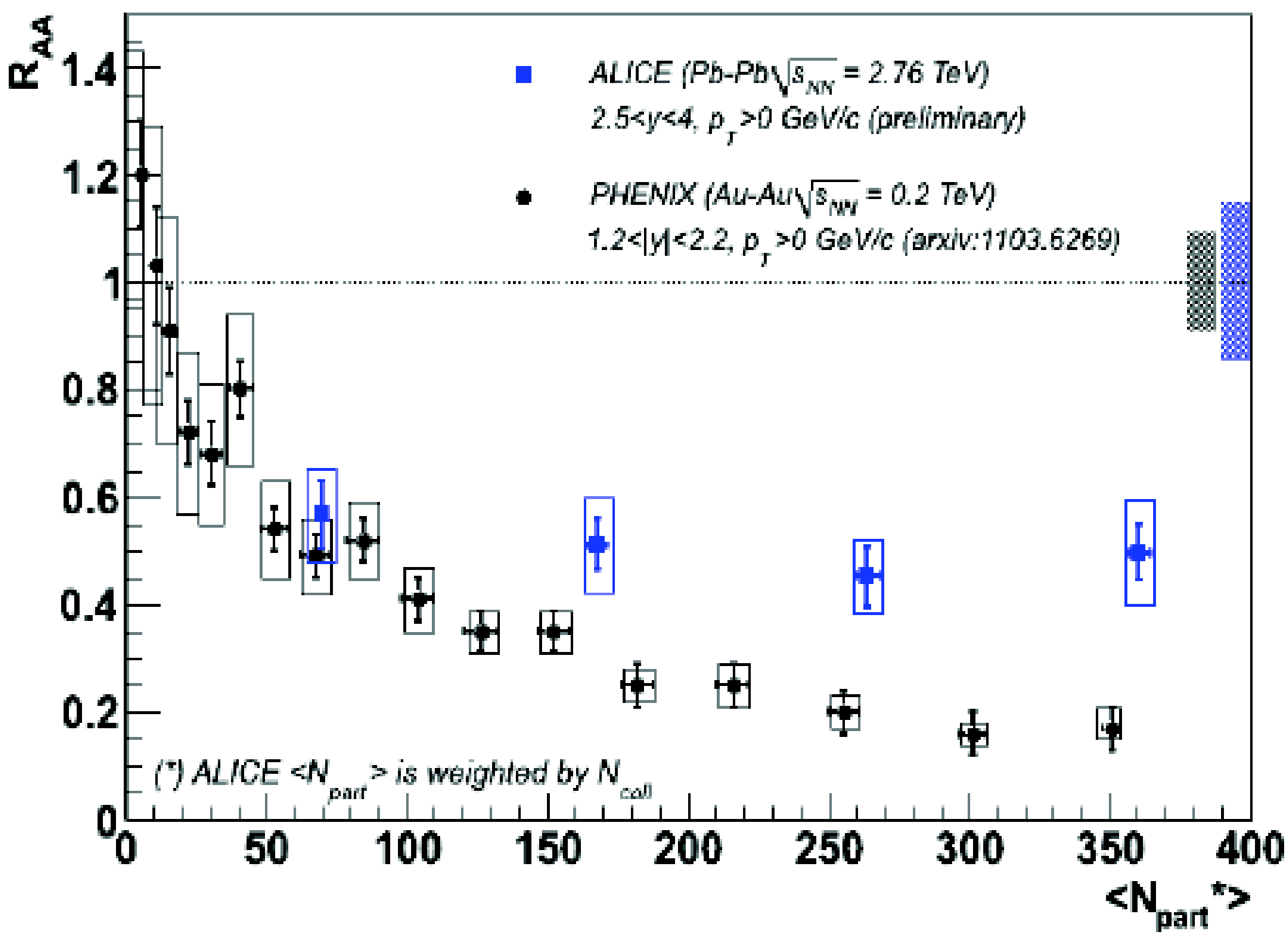


- Error bars: Statistical uncertainties
- Empty boxes: Centrality-dependent systematic uncertainties
- Blue box: Overall systematic uncertainties

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

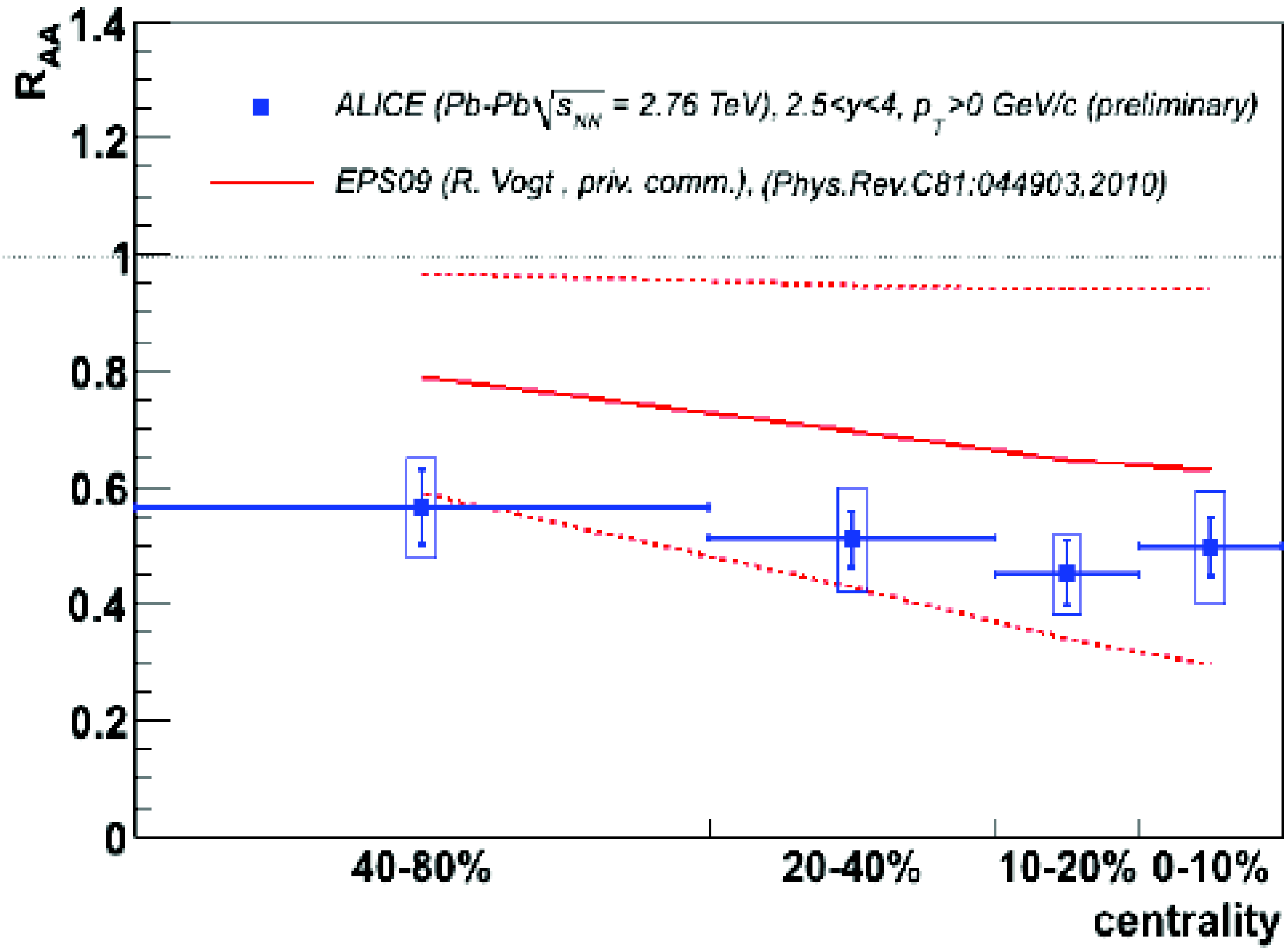
→ Assuming it scales with N_{coll}: ~12% reduction of the R_{AA} in 0-10% can be expected

comparison with results from PHENIX at RHIC

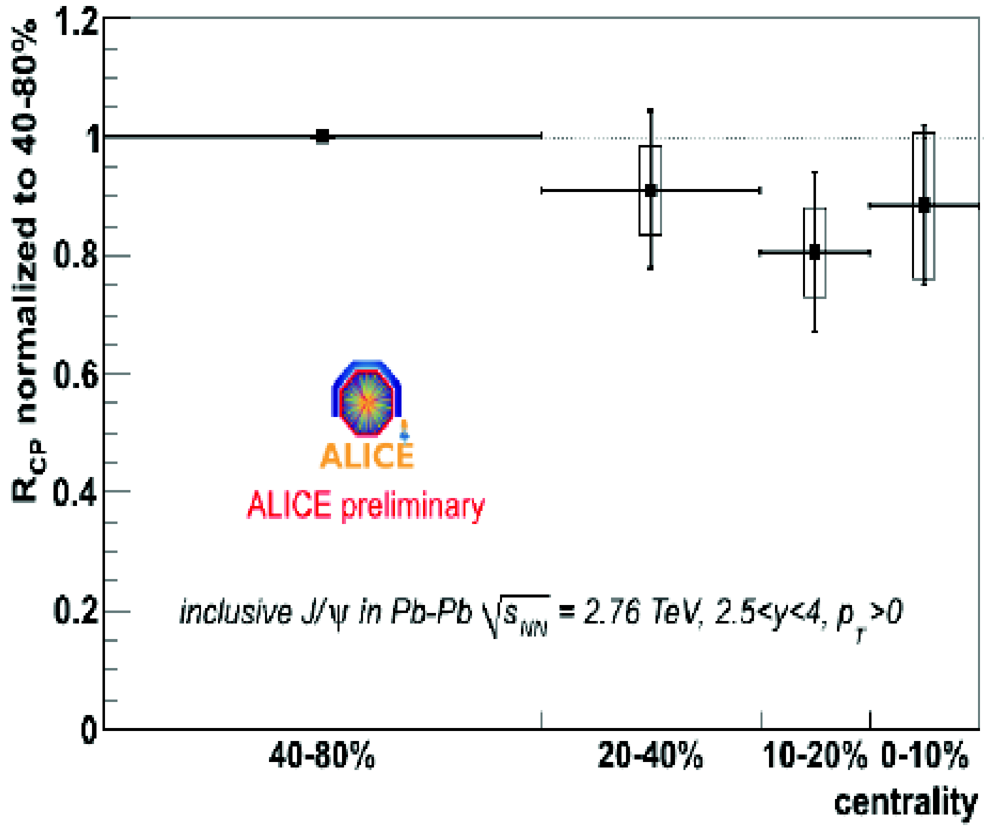


R_AA increases as function of energy!

Comparison with EPS09 shadowing calcs



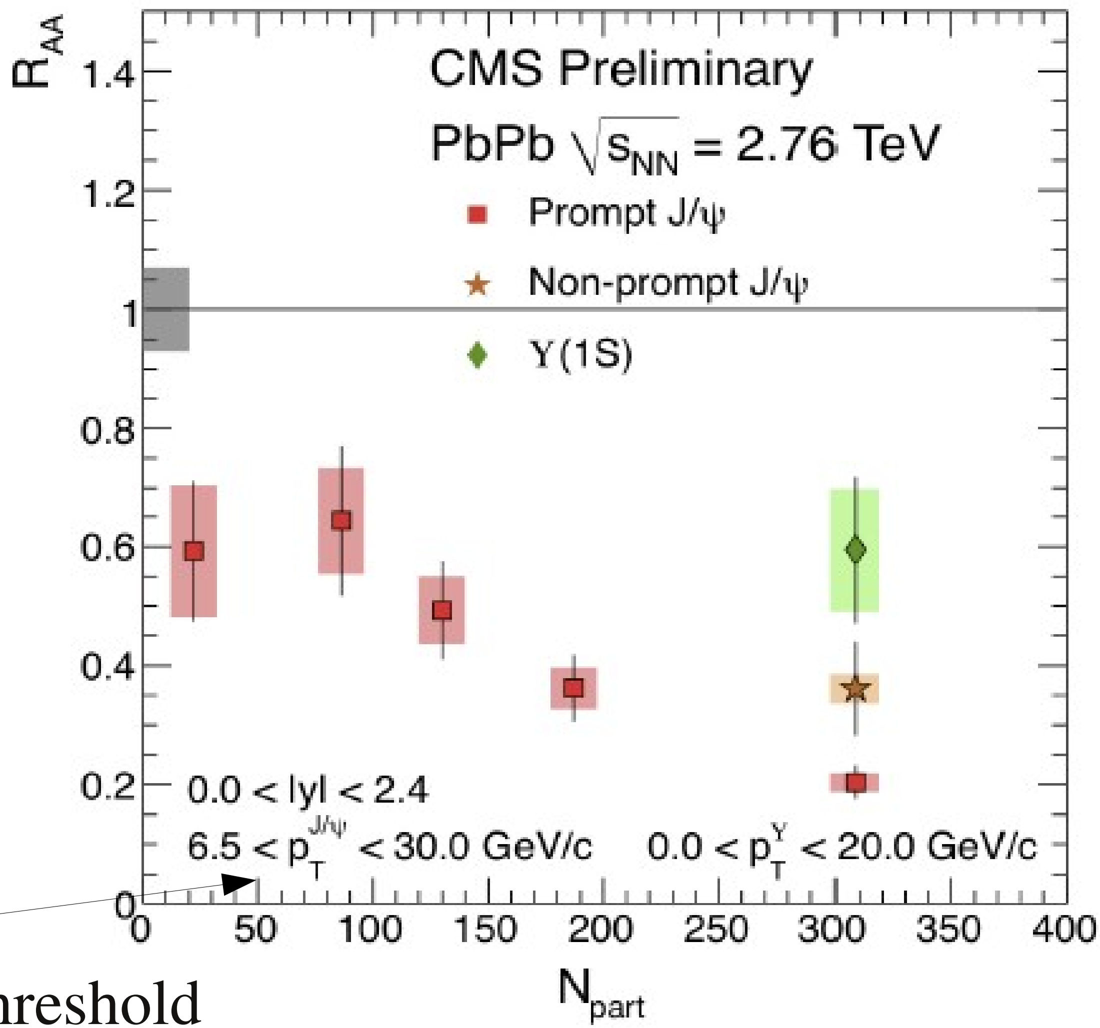
centrality dependence via R_CP



- Error bars:
Statistical uncertainties

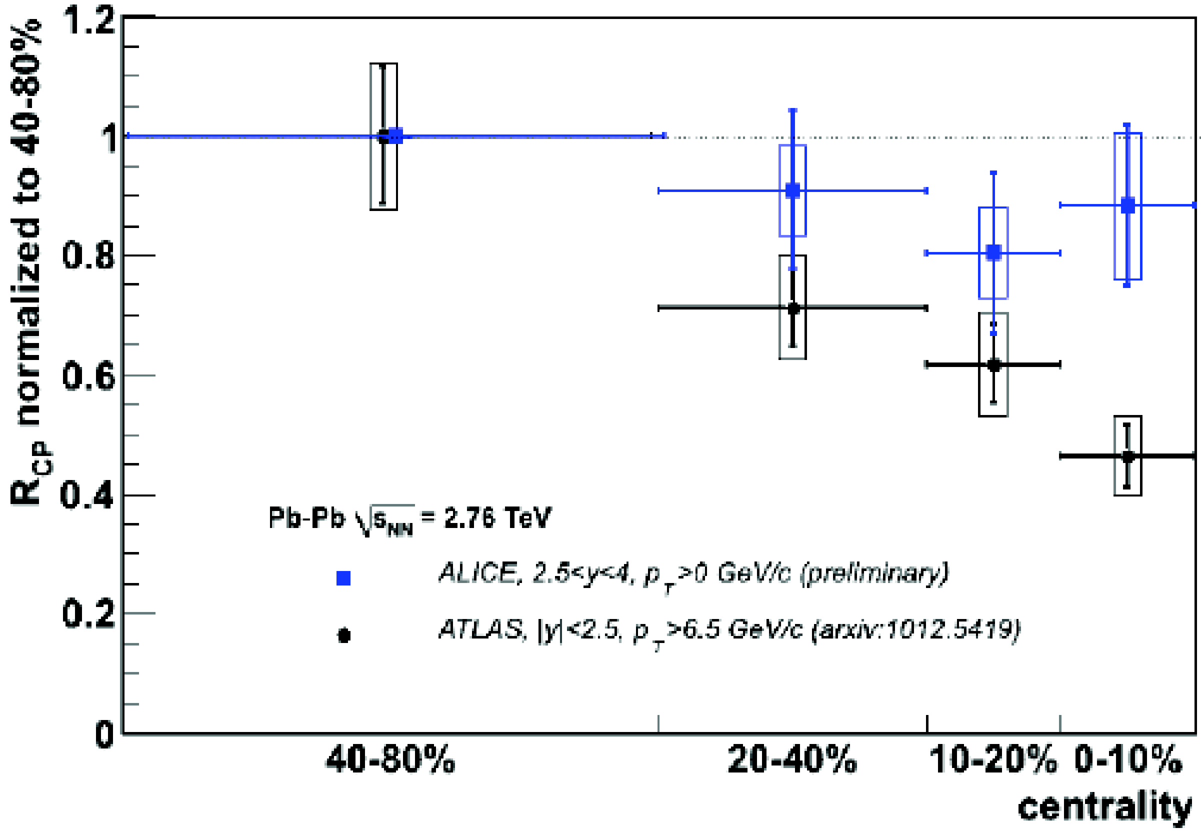
- Empty boxes:
Centrality-dependent systematic uncertainties

First data from CMS

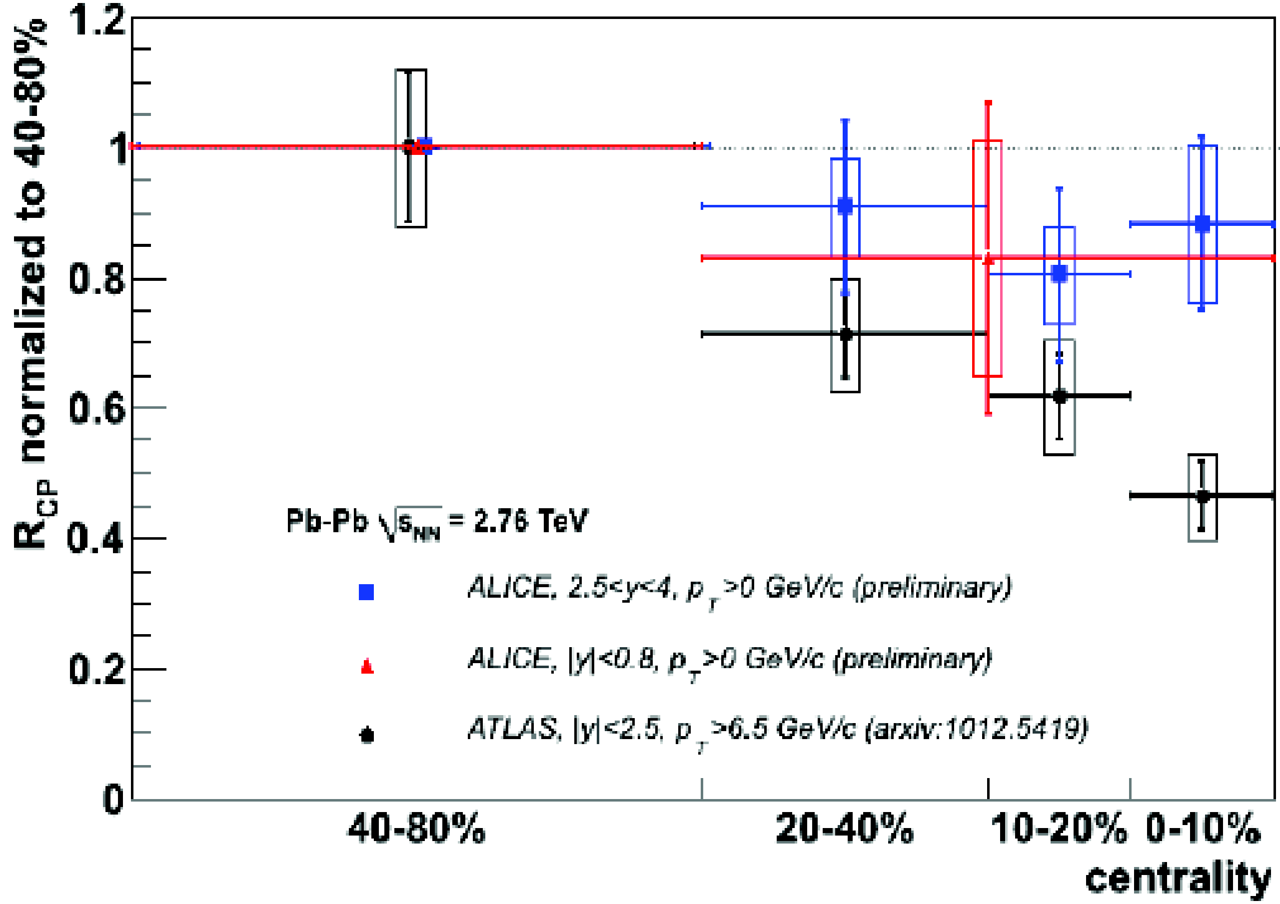


note the p_t threshold

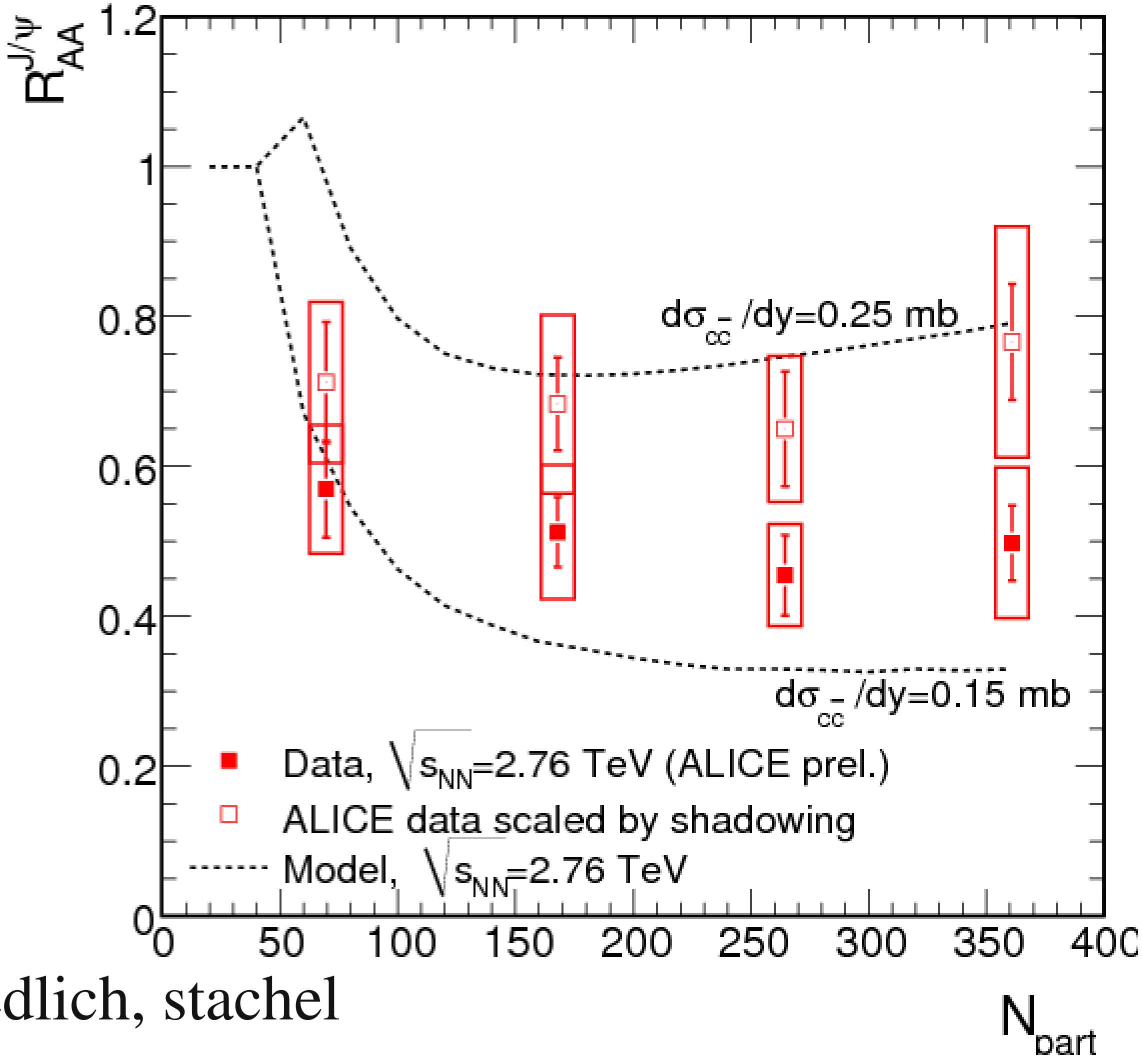
comparison with ATLAS data at high p_t



inclusion of first data at midrapidity



ALICE LHC data are consistent with (re)generation picture



andronic, pbm, redlich, stachel

Summary

- charmonium production – a fingerprint for deconfined quarks and gluons

- evidence for energy loss and flow of charm quarks --> thermalization
- normalization to open charm in AA collisions – pA or dA normalization not easily applicable at LHC
- charmonium generation at the phase boundary – a new process
- first indications for this from RHIC data
- no evidence for new physics near threshold
- charmonium enhancement at LHC – deconfined QGP still work to do but clear indications from J/psi