Lecture2a: open heavy flavor in the QGP

Open heavy flavor production and the QGP

1. m_q >> Lambda_QCD charm quark production is independent of the medium formed in the collision (see above)

2. propagation of heavy quarks in the medium can be used to diagnose it

energy loss – thermalization – hydrodynamic flow

interaction with the hot/dense QCD medium

- energy loss
  - dependence on medium density and volume
  - color charge dependent (Casimir factor) → $\Delta E_{gluon} > \Delta E_{quark}$
  - parton mass dependent (dead cone effect: Dokshitzer & Kharzeev, PLB 519(2001)199) → $\Delta E_{u,d,s} > \Delta E_{c} > \Delta E_{b}$
- thermalization
  - dependence on transport properties of the medium

Formation time of quarkonia

heavy quark velocity in charmonium rest frame:

v = 0.55 for J/ψ see, e.g. G.T. Bodwin et al., hep-ph/0611002

minimum formation time: t = radius/v = 0.45 fm

see also: Huefner, Ivanov, Kopeliovich, and Tarasov, Phys. Rev. D62 (2000) 094022; J.P. Blaizot and J.Y. Ollitrault, Phys. Rev. D39 (1989) 232
formation time of order 1 fm

formation time is not short compared to plasma formation time especially at high energy formation time of open charm hadrons not well understood

presumably similar to charmonia

separation of time scales for initial hard process and late hadronization/hadron formation is called „factorization“

rigorously proven for deep inelastic scattering

charm conservation equation

no medium effect

$$\sigma_{c\bar{c}} = 1/2\ [\sigma_{D^+} + \sigma_{D^-} + \sigma_{D^0} + \sigma_{\bar{D}^0} + \sigma_{\Lambda_c} + \sigma_{\bar{\Lambda}_c} \ldots]$$

medium effects on charmed hadrons affect redistribution of charm, but not overall cross section

it is not consistent with the charm conservation equation to reduce all charmed hadron masses in the medium for an enhanced cross section

gluon radiation by a quark traversing a medium

from Dokshitzer & Kharzeev, Phys.Lett. B519 (2001) 199-206
we get for the probability of radiation of a gluon with energy ω by a quark with mass M and energy E

$$dP = \frac{\alpha_s\, C_F}{\pi}\,\frac{d\omega}{\omega}\,\frac{k_\perp^2\, dk_\perp^2}{(k_\perp^2 + \omega^2\theta_0^2)^2}, \qquad \theta_0 \equiv \frac{M}{E}$$

$$k_\perp^2 \simeq \sqrt{\hat{q}\,\omega} \qquad \hat{q} \equiv \rho \int \frac{d\sigma}{dq^2}\, q^2\, dq^2 \qquad C_F = \frac{N_c^2-1}{2N_c}$$

here the density of scatterers in the medium is encoded in q^

'dead cone' effect for charm quarks

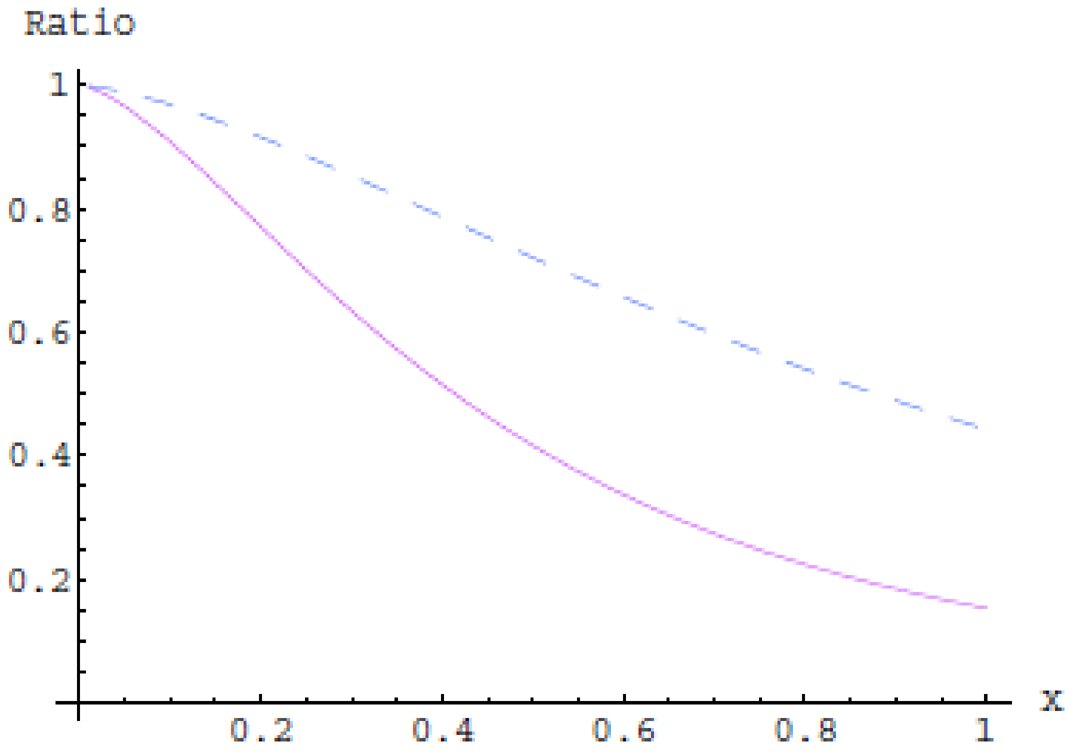


Figure 1: Ratio of gluon emission spectra off charm and light quarks for quark momenta $p_\perp = 10\,\mathrm{GeV}$ (solid line) and $p_\perp = 100\,\mathrm{GeV}$ (dashed); $x = \omega/p_\perp$.

now open charm and open beauty in AA collisions

how to quantify the effect of the medium?

R_{AA}=yield(AA)/(N_{coll} yield(pp))

R_AA = medium/vacuum

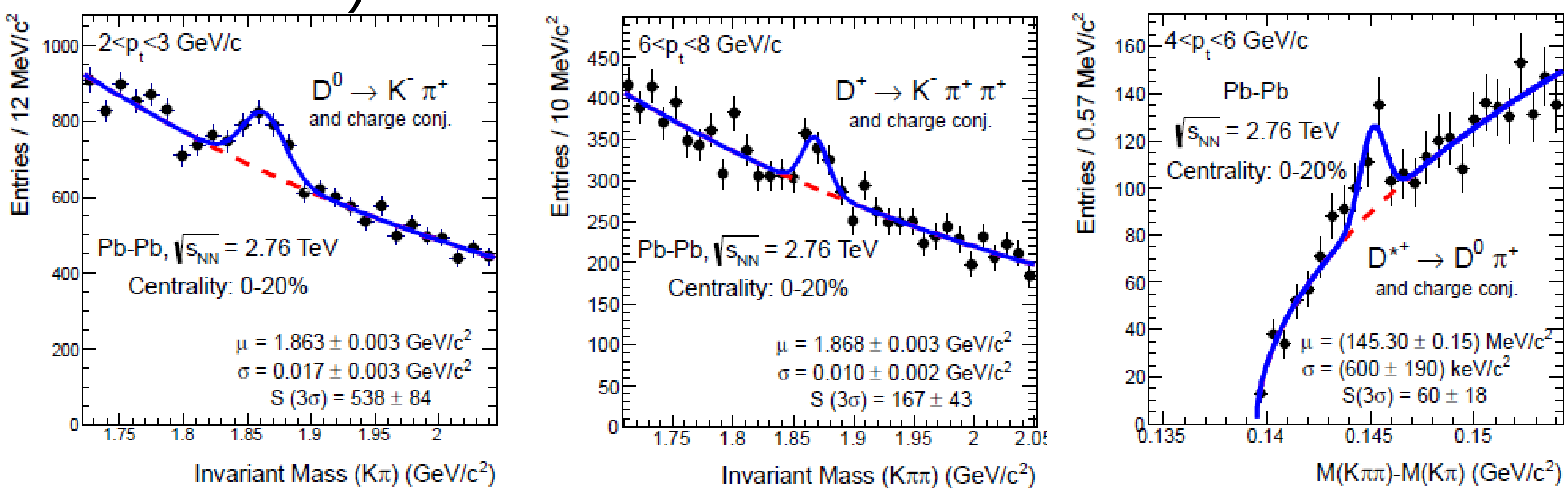
R_AA = 1 if no dense medium is formed

or

if one looks at electro-weak probes

D meson signals in Pb Pb collisions

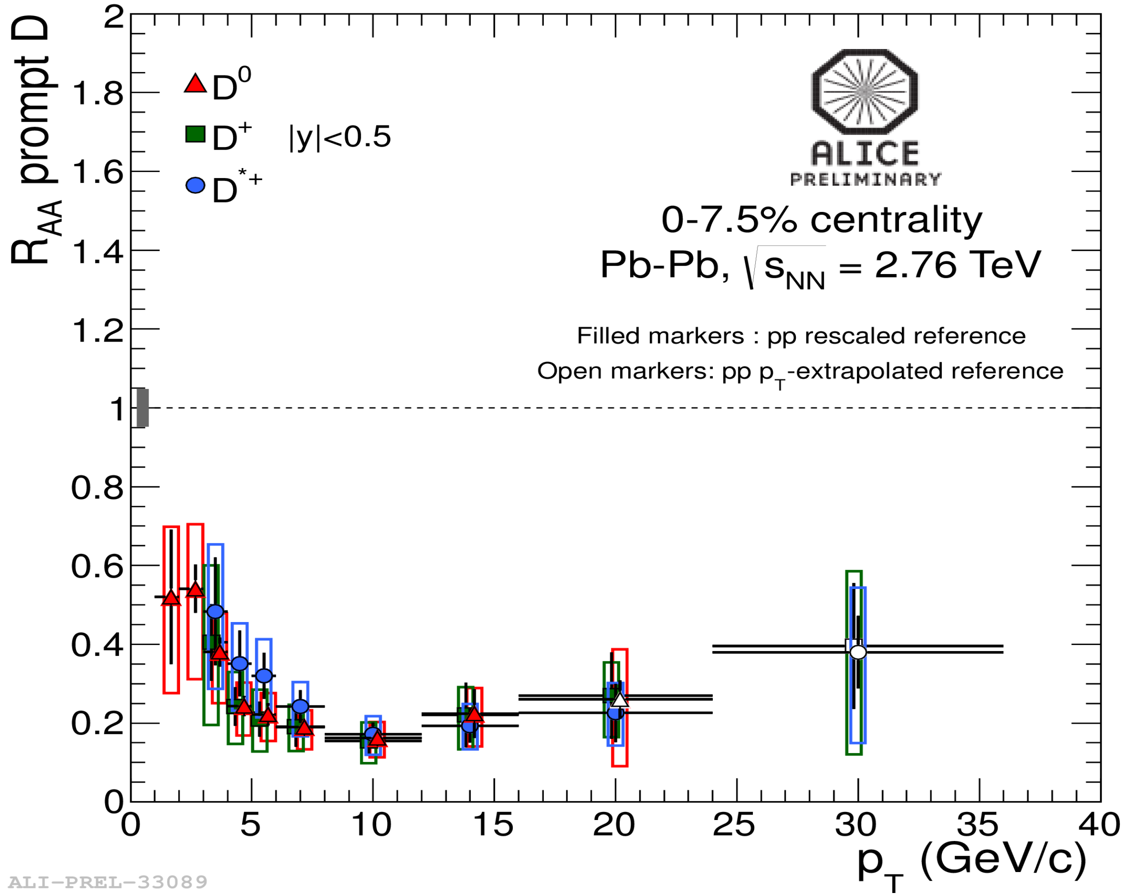
measurement:
reconstruction of hadronic decays of D-mesons (ALICE)
semi-leptonic decays into electrons (ATLAS, ALICE)
“ into muons (ATLAS, ALICE)



data: ALICE
arXiv:1203.2160

suppression of charm at LHC energy

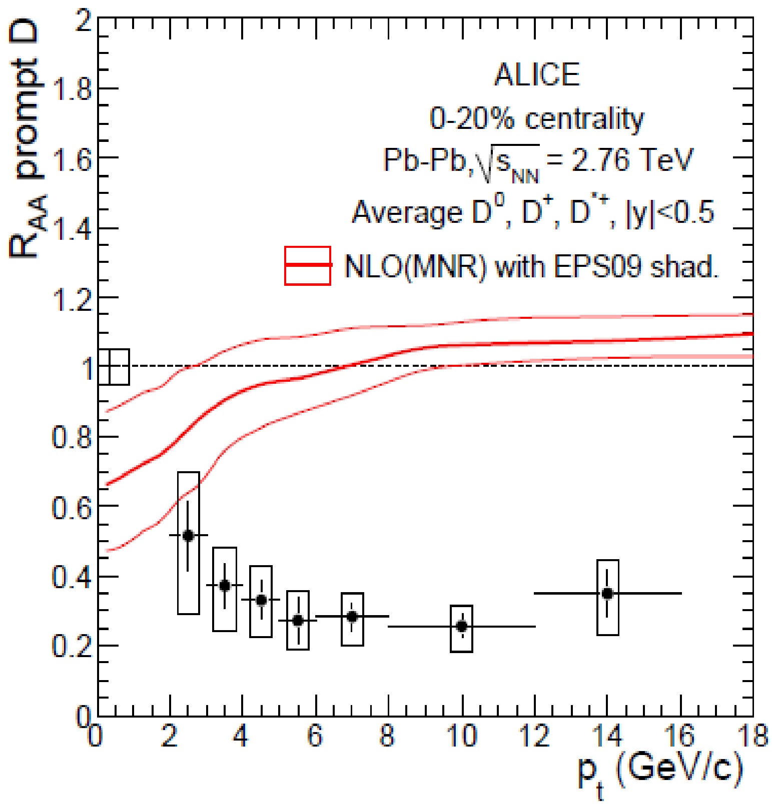
pp reference at 2.76 TeV: measured 7 TeV spectrum scaled with FONLL
cross checked with 2.76 TeV measurement (large uncertainty due to limited luminosity)

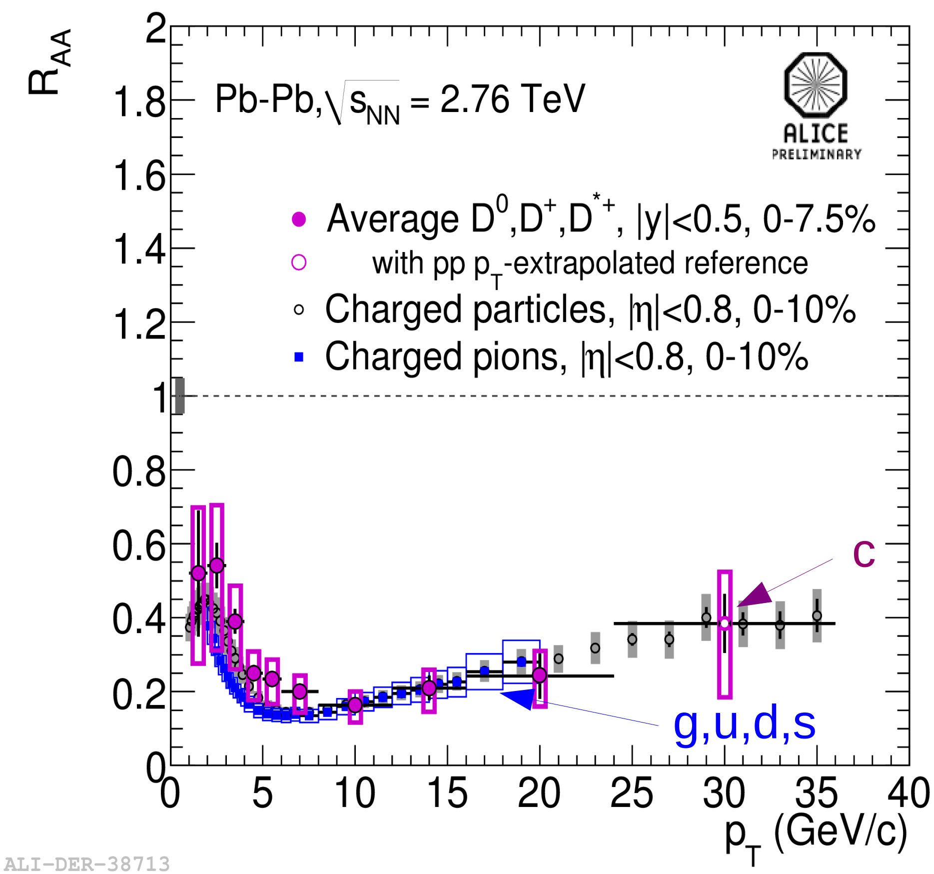


energy loss for all species of D-mesons within errors equal - not trivial
energy loss of central collisions very significant - suppr. factor 5 for 5-15 GeV/c

suppression of charm at LHC energ

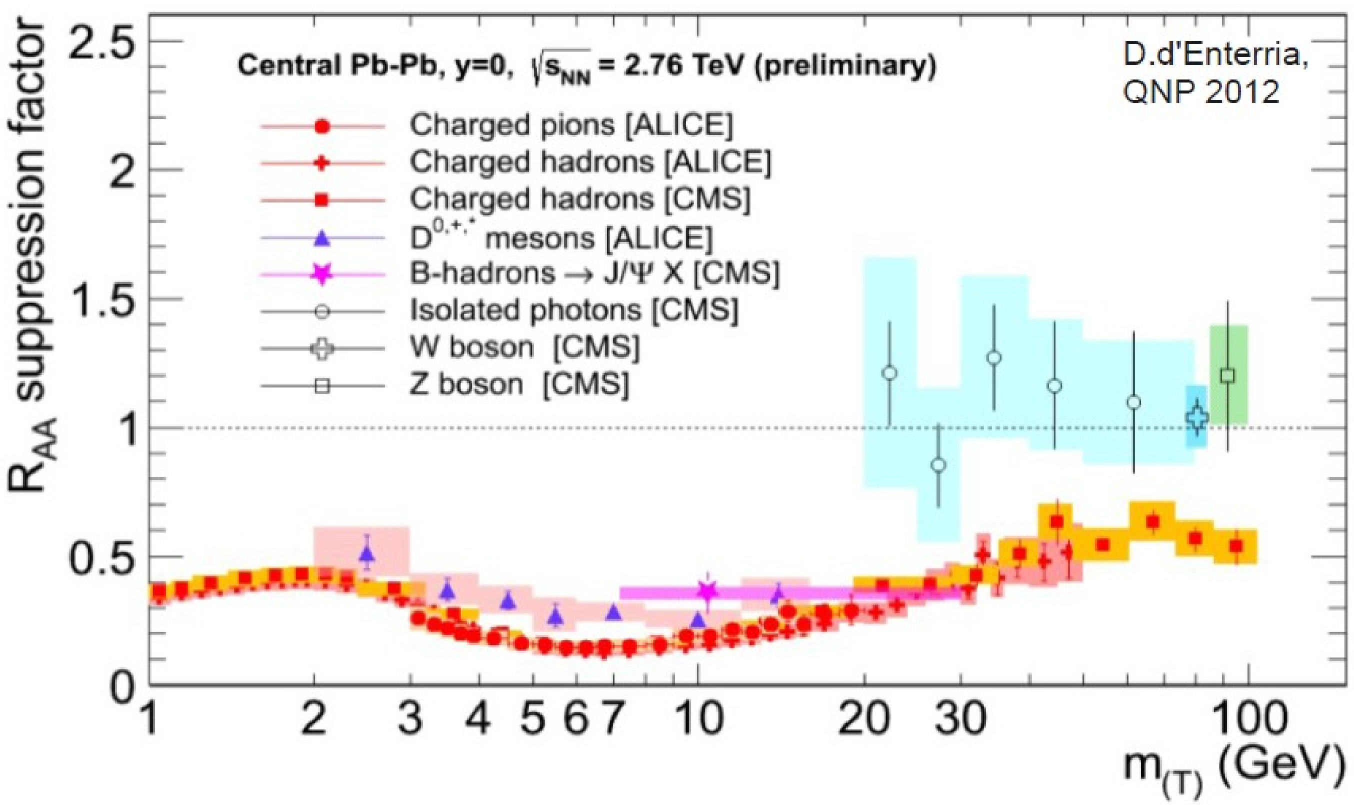
comparison to EPS09 shadowing:
suppression not an initial state effect
will be measured directly in pPb collisions





energy loss of charm quarks only slightly less than that for light quark → thermalization

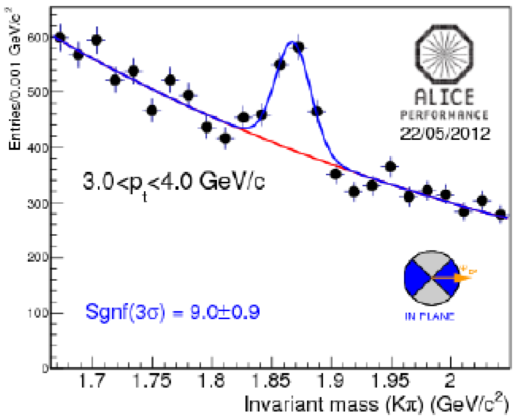
Suppression only for Strongly Interacting Hard Probes

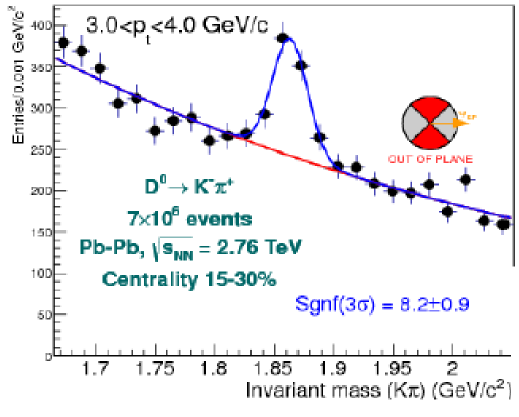


photons, Z and W scale with number of binary collisions in PbPb – not affected by medium

→ demonstrates that charged particle suppression is medium effect: energy loss in QGP

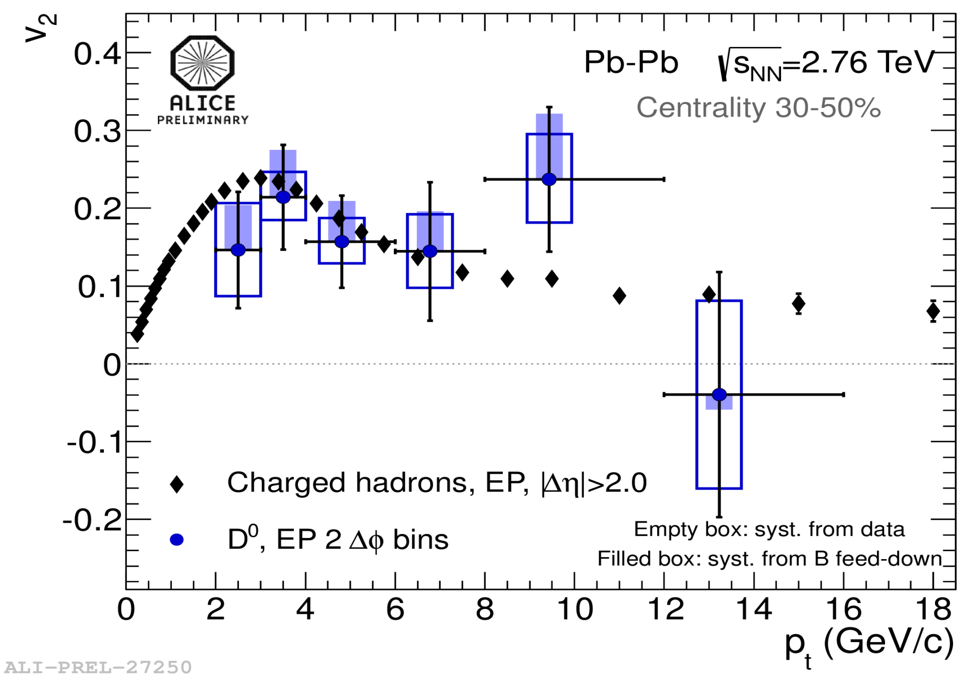
charm Quarks also Exhibit Elliptic Flow





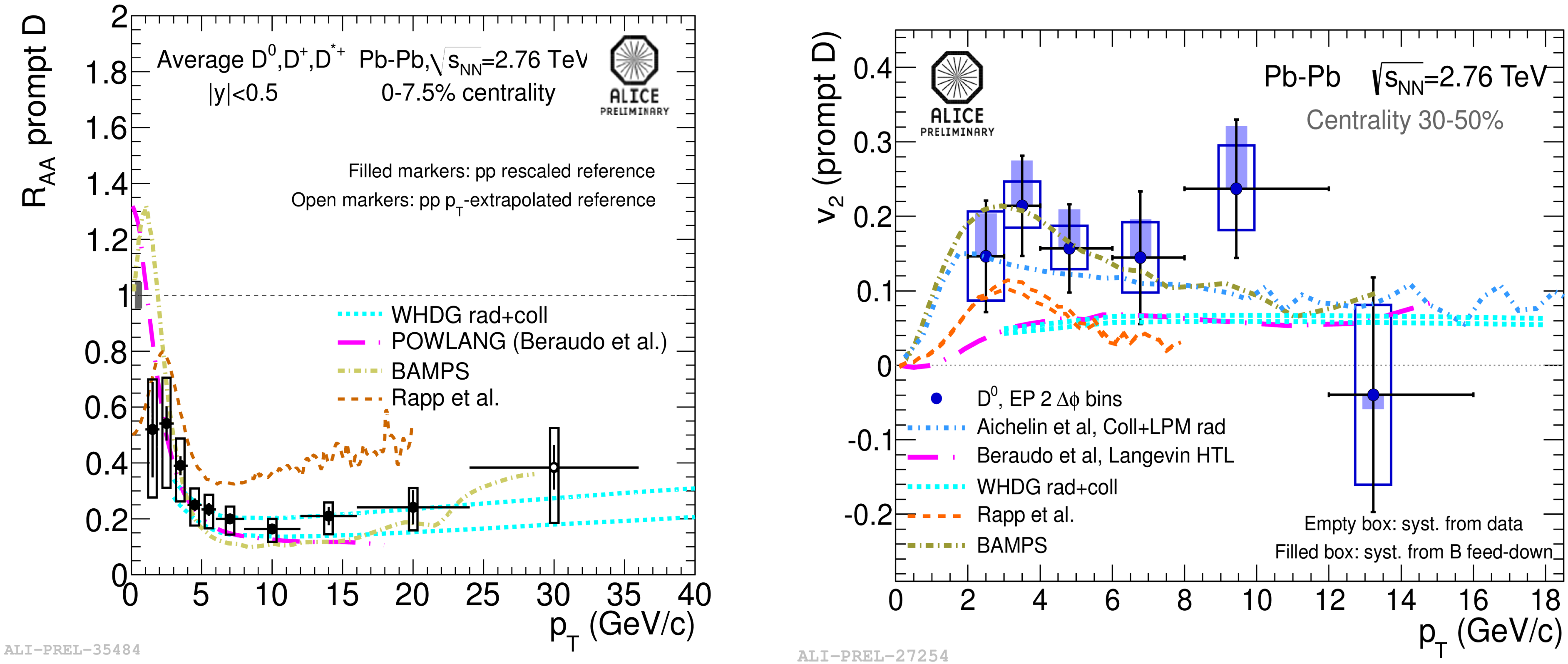
$$v_2 = \frac{\pi}{4}\frac{N_{IN}-N_{OUT}}{N_{IN}+N_{OUT}}$$

2 centrality classes
event plane from TPC
corrected for B-feed down (FONLL)



non-zero elliptic flow for 3 σ effect for D^0 2-6 GeV/c
within errors charmed hadron v_2 equal to that of all charged hadrons

model description of energy loss and flow of D-mesons

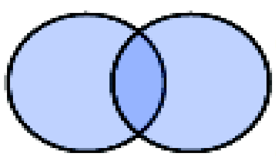


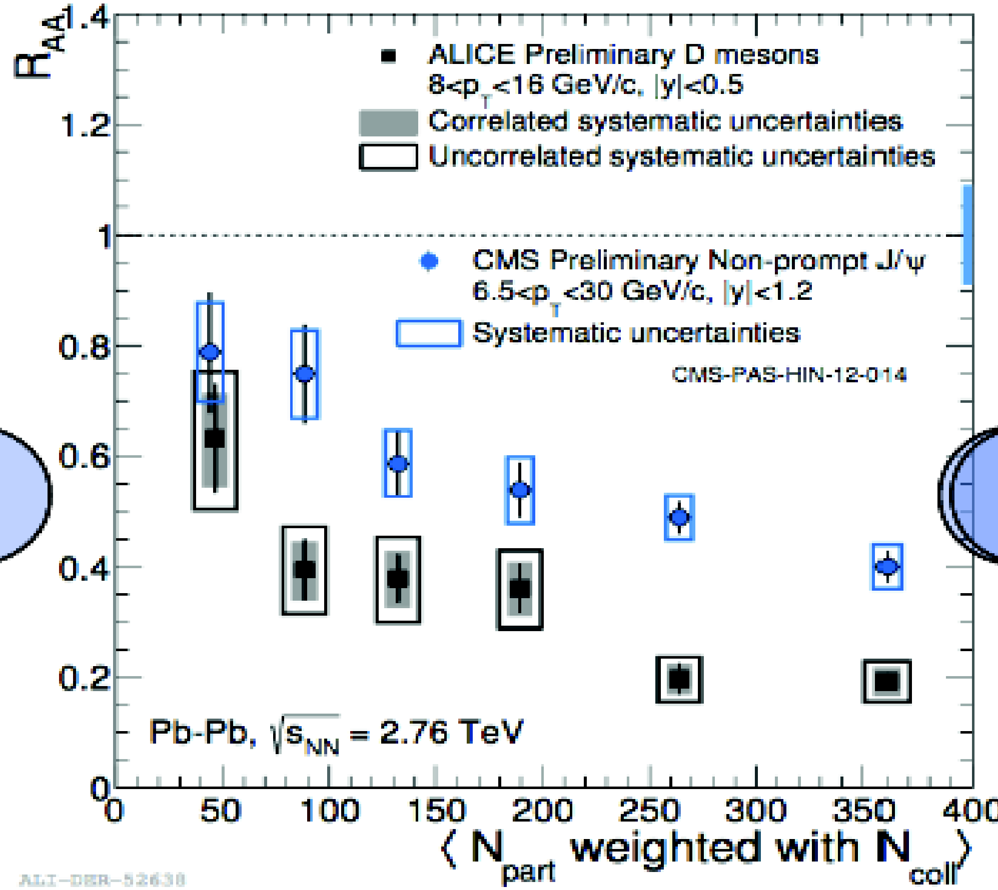
both are determined by transport properties of the medium (QGP) simultaneous description still a challenge for some models

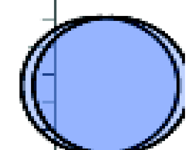
comparison of suppression for b-quarks and c-quarks

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA} / dp_T}{dN_{pp} / dp_T}$$

is this the dead-cone
effect? need
quantitative analysis







2b) the quarkonium story

- some historical remarks
- the statistical hadronization model
- comparison to results from RHIC
- charmonium production at LHC energy
- the color screening length in the QGP
- remarks on bottomonium

Charmonium as a probe for the properties of the QGP

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

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

Quarkonia:

heavy quark bound states stable under strong decay

heavy: charm ($m_c \simeq 1.3$ GeV) or beauty ($m_b \simeq 4.7$ GeV)

stable: $M_{c\bar{c}} \leq 2M_D$ and $M_{b\bar{b}} \leq 2M_B$

heavy quarks $\Rightarrow$ quarkonium spectroscopy via
non-relativistic potential theory

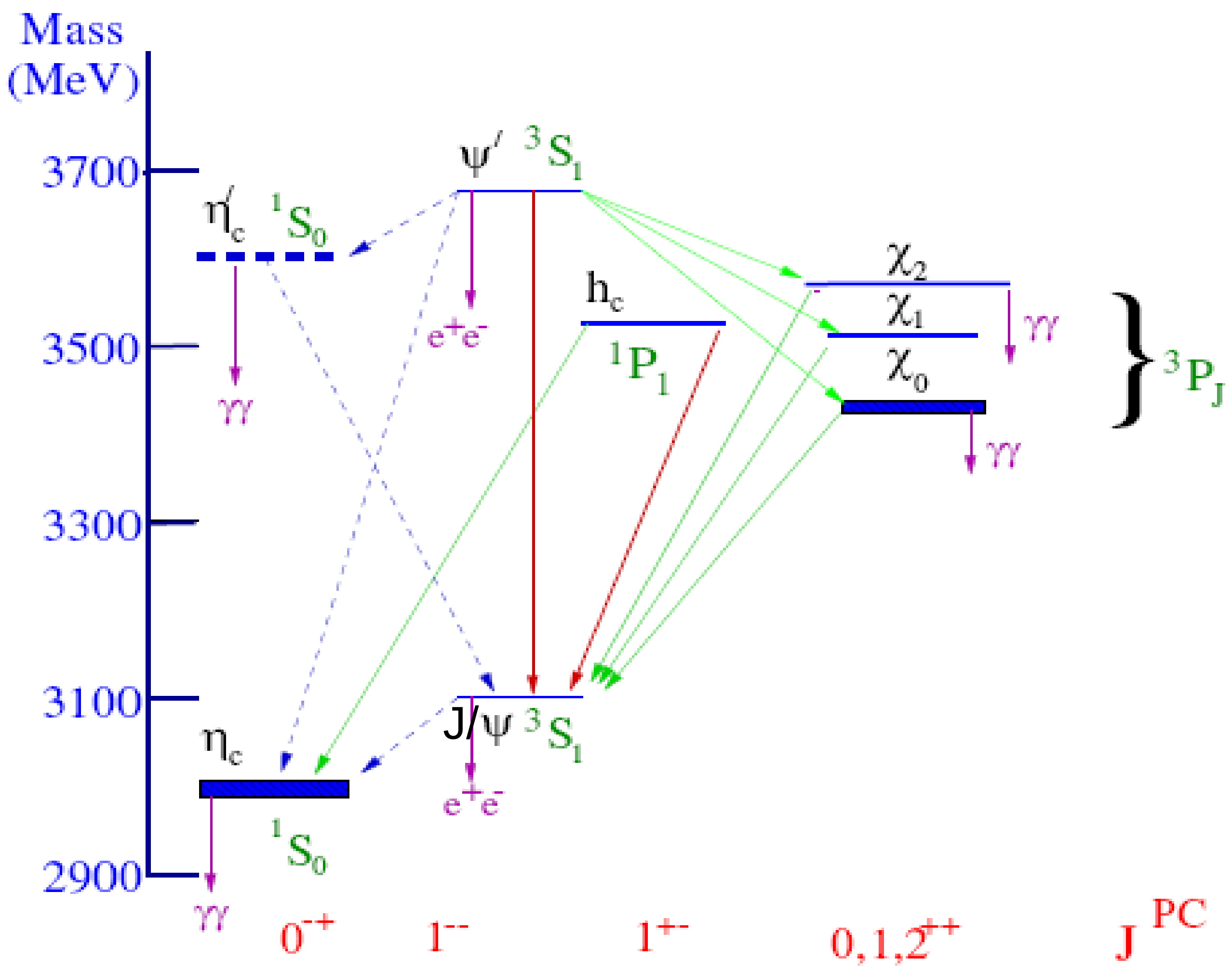
Schrödinger equation $\left\{2m_c - \frac{1}{m_c}\nabla^2 + V(r)\right\}\Phi_i(r) = M_i\Phi_i(r)$

confining ("Cornell") potential $V(r) = \sigma\ r - \frac{\alpha}{r}$

string tension $\sigma \simeq 0.2$ GeV^2, gauge coupling $\alpha \simeq \pi/12$

$\Rightarrow$ quarkonium masses M_i and radii r_i

charmonium, a bound state of charm and anti-charm quarks



Quarkonium Properties and Debye Screening

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

table from H. Satz, J. Phys. G32 (2006) R25

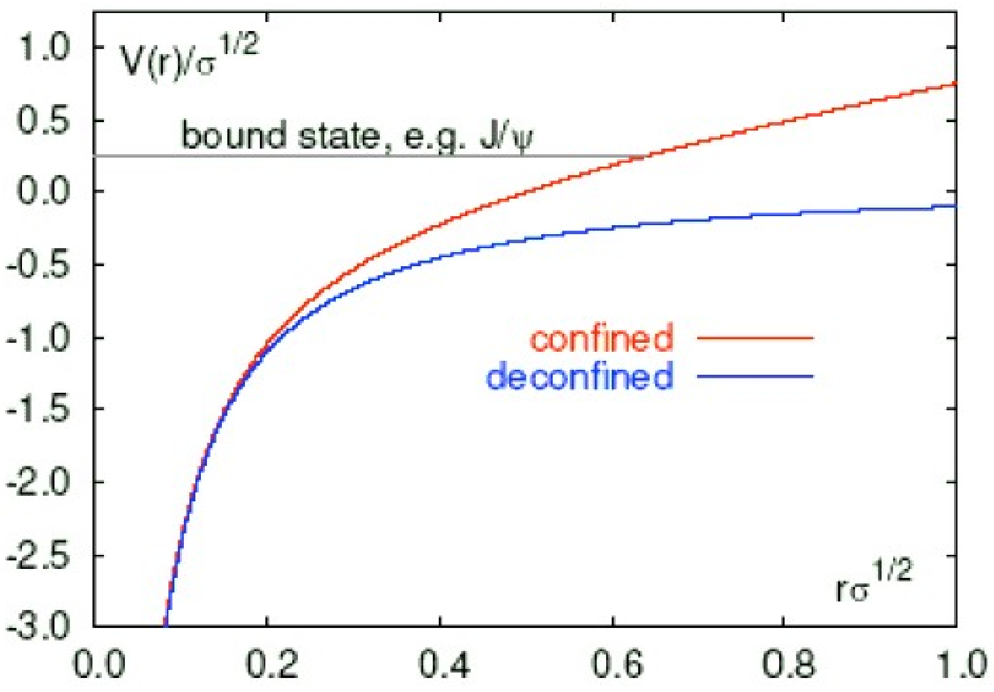
In the QGP, the screening radius $r_{Debye}(T)$ decreases with increasing T. If $r_{Debye}(T) < r_{charmonium}$ the system becomes unbound $\rightarrow$ suppression compared to charmonium production without QGP. The screening radius can be computed using potential models or solving QCD on the lattice.

Debye screening

V(r,T large)   no bound state

V(r,T small) bound state

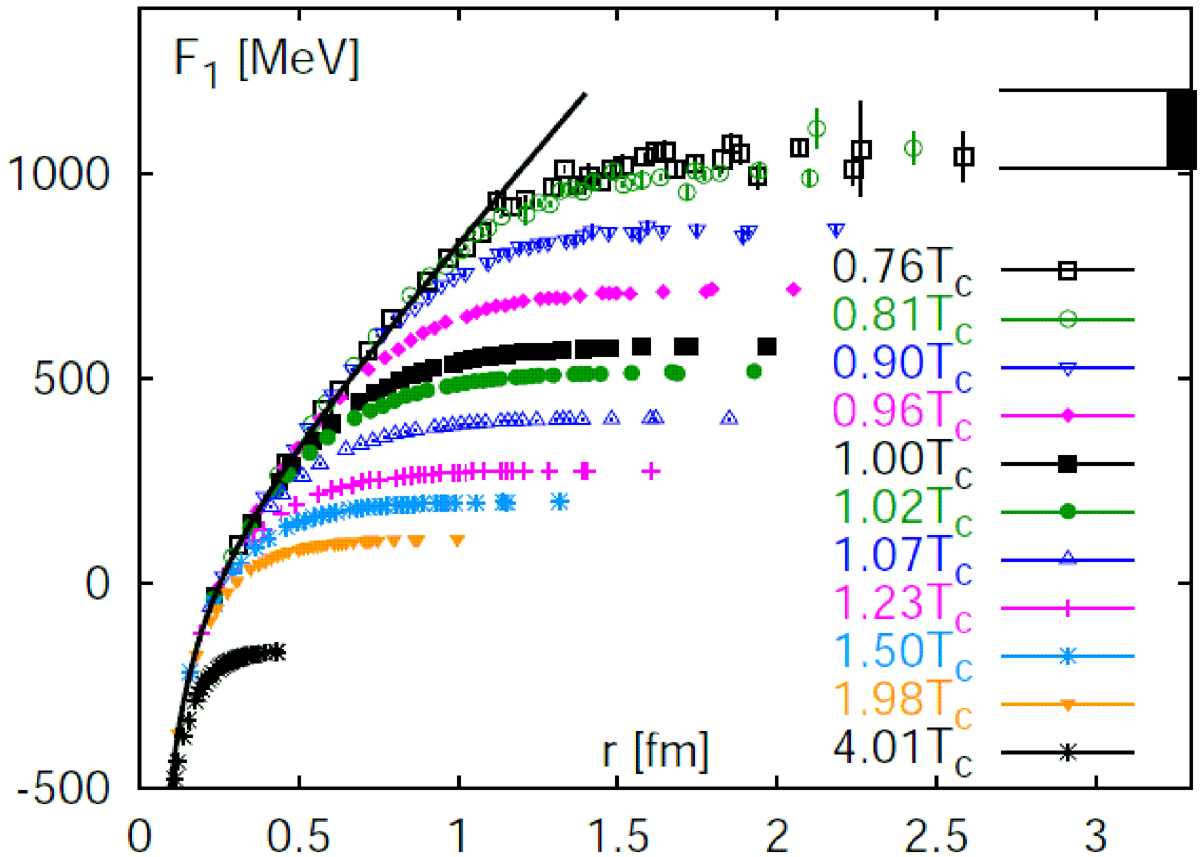
σ = string tension = 1 GeV/fm
= 0.2 GeV^2



Free energy of a heavy quark-antiquark pair

color singlet free energy
$F_1(T) = U(T) - T\,S(T)$

note: J/ψ is bound
by 640 MeV



J/ψ disappears for T > 1.6 T_c

O. Kaczmarek, F.Zantow, PRD 71(2005)114510

Debye Screening

screened potential for heavy quark-antiquark pair

$$V_{q\bar{q}}(r,T) = \frac{\sigma}{\mu}\left(1 - e^{-\mu(T)r}\right) - \frac{\alpha}{r} e^{-\mu(T)r}$$

Debye radius $r_{Debye} = 1/\mu(T)$

$r_{Debye} \propto 1/n_g^{1/3} \propto 1/(g(T)\,T)$

state	J/ψ	χ_c	ψ'	
E_s^i [GeV]	0.64	0.20	0.05	
T_d/T_c	1.1	0.74	0.1 - 0.2	using F_1
T_d/T_c	~ 2.0	~ 1.1	~ 1.1	using U

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?

at LHC energy, clean separation of time scales

collision time << QGP formation time < charmonium formation time

are charmonia (and charmed hadrons) produced thermally?

ratios of charmed and beauty hadrons exhibit thermal features (Becattini 1997)
but: psi'/psi ratio is far from thermal in pp collisions
see also Sorge&Shuryak, Phys. Rev. Lett. 79 (1997) 2775, where it is further noted that the psi'/psi ratio reaches a thermal value (T=170 MeV) in central PbPb collisions at SPS energy

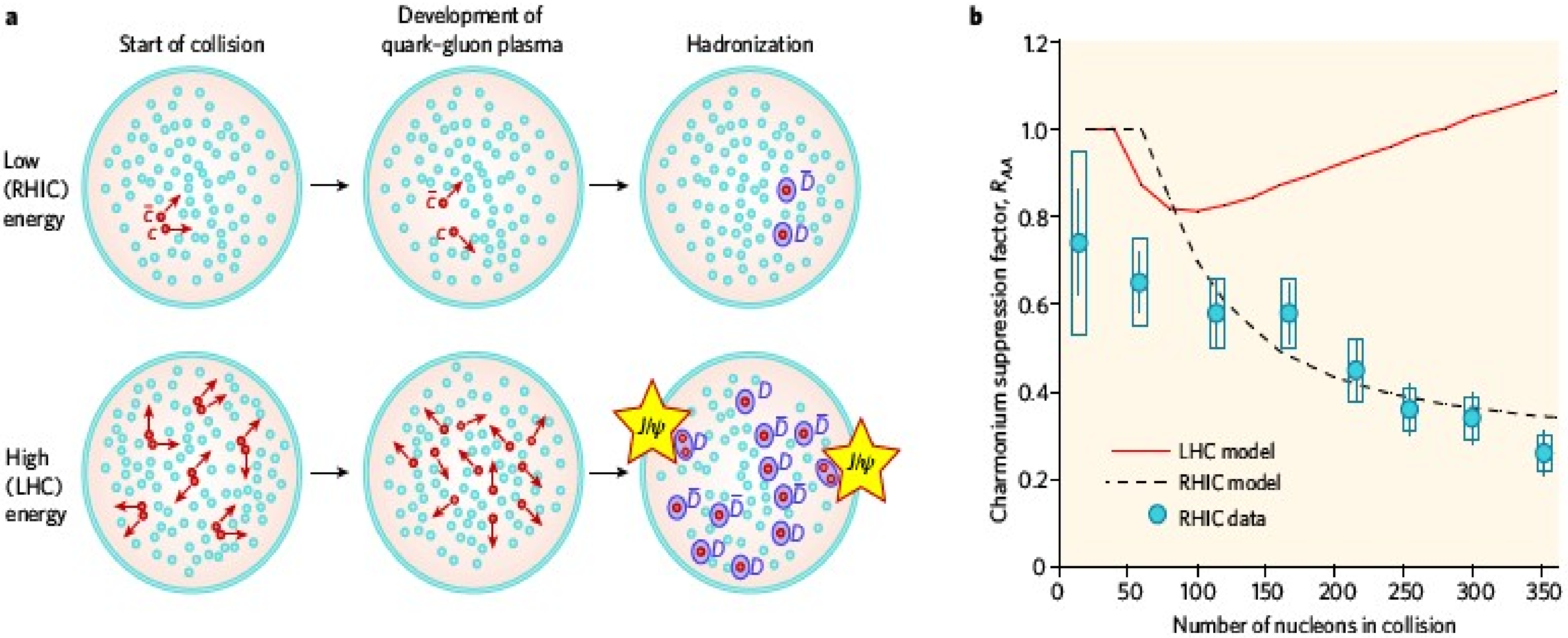
further analysis by Gorenstein and Gazdzicki, Phys. Rev. Lett. 83 (1999) 4003
result: (J/psi)/pi is approximately constant at SPS energy for PbPb

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

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

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

P. Braun-Munzinger, J. Stachel, The Quest for the Quark-Gluon Plasma, Nature **448** Issue 7151, (2007) 302-309.



charmonium enhancement as fingerprint of color screening and 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

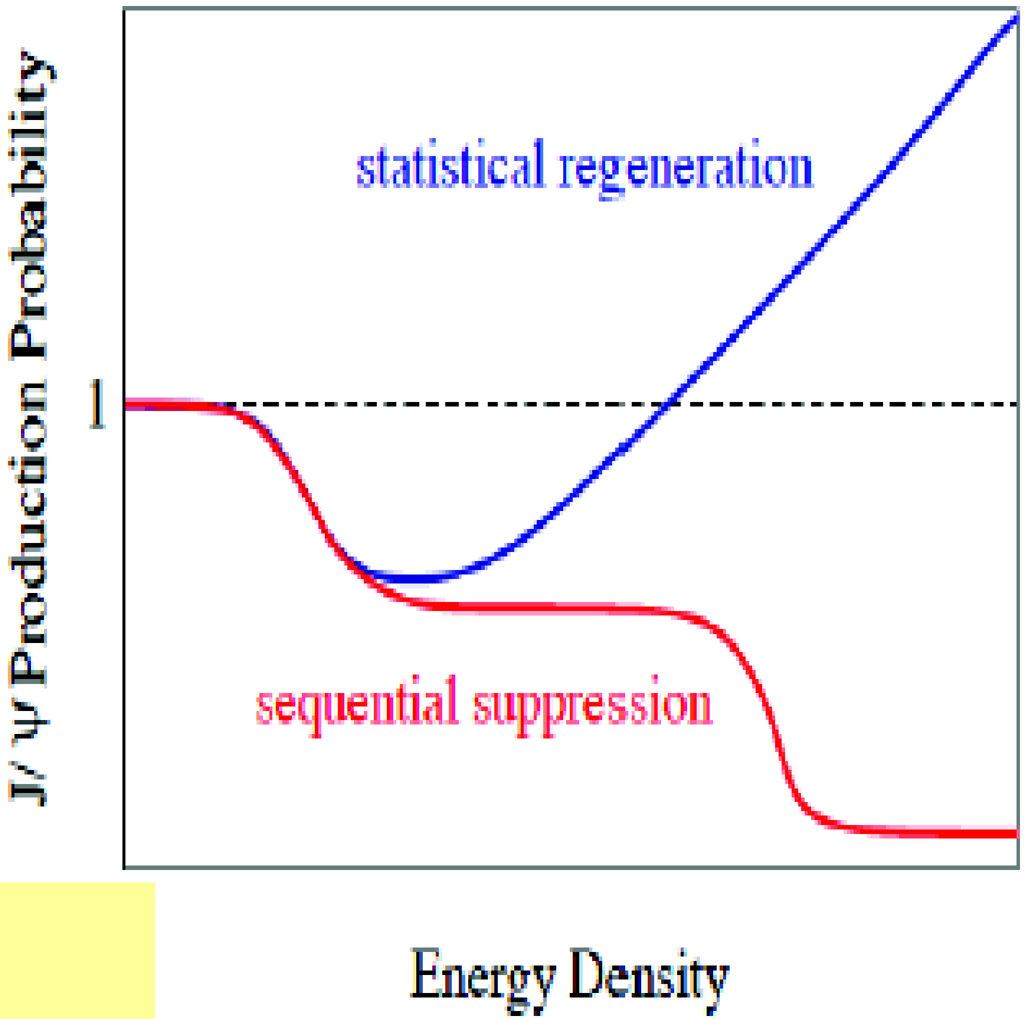
charm balance equation

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

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



Picture:
H. Satz 2009

SPS RHIC LHC

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

now brief survey of SPS and RHIC results

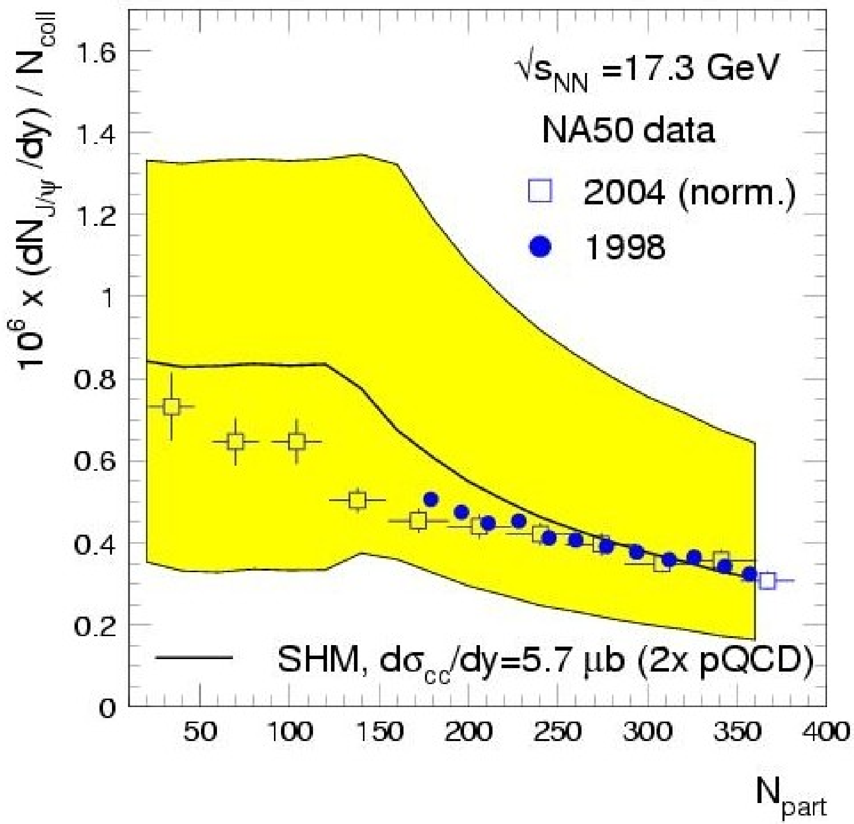
note: charmonium suppression or enhancement is quantified via the nuclear modification factor R_{AA}

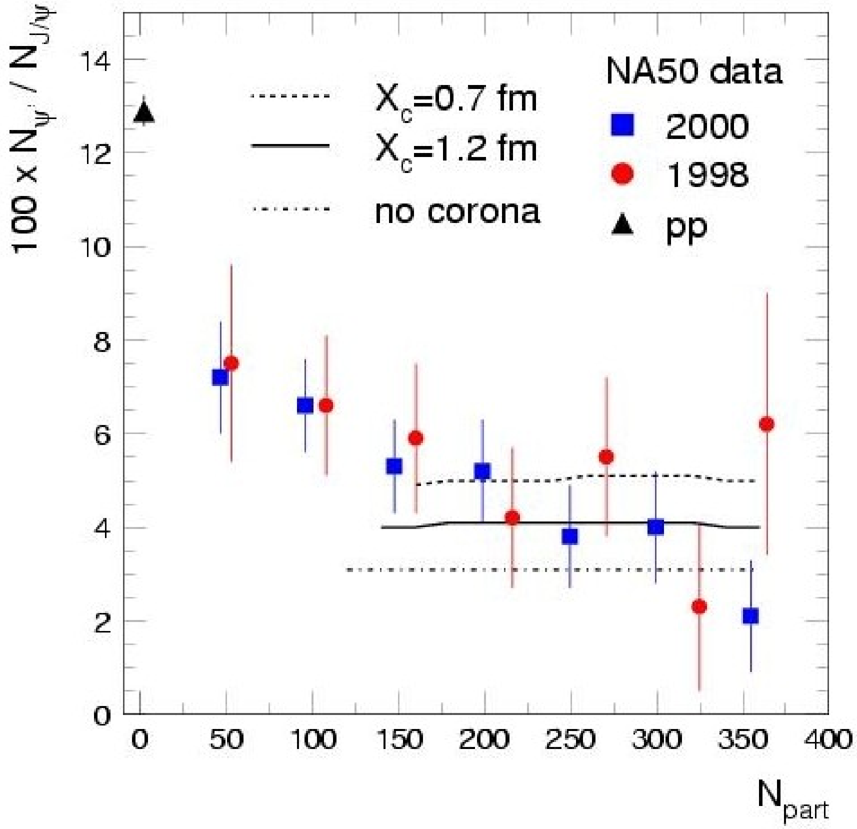
$$R^i_{\mathrm{AA}} = \frac{Y^i_{\mathrm{J}/\psi}(\Delta p_{\mathrm{t}}, \Delta y)}{\langle T^i_{\mathrm{AA}} \rangle \times \sigma^{\mathrm{PP}}_{\mathrm{J}/\psi}(\Delta p_{\mathrm{t}}, \Delta y)}$$

Here, T_{AA} is the nuclear thickness function

by construction, R_{AA} = medium/vacuum

results for SPS energy



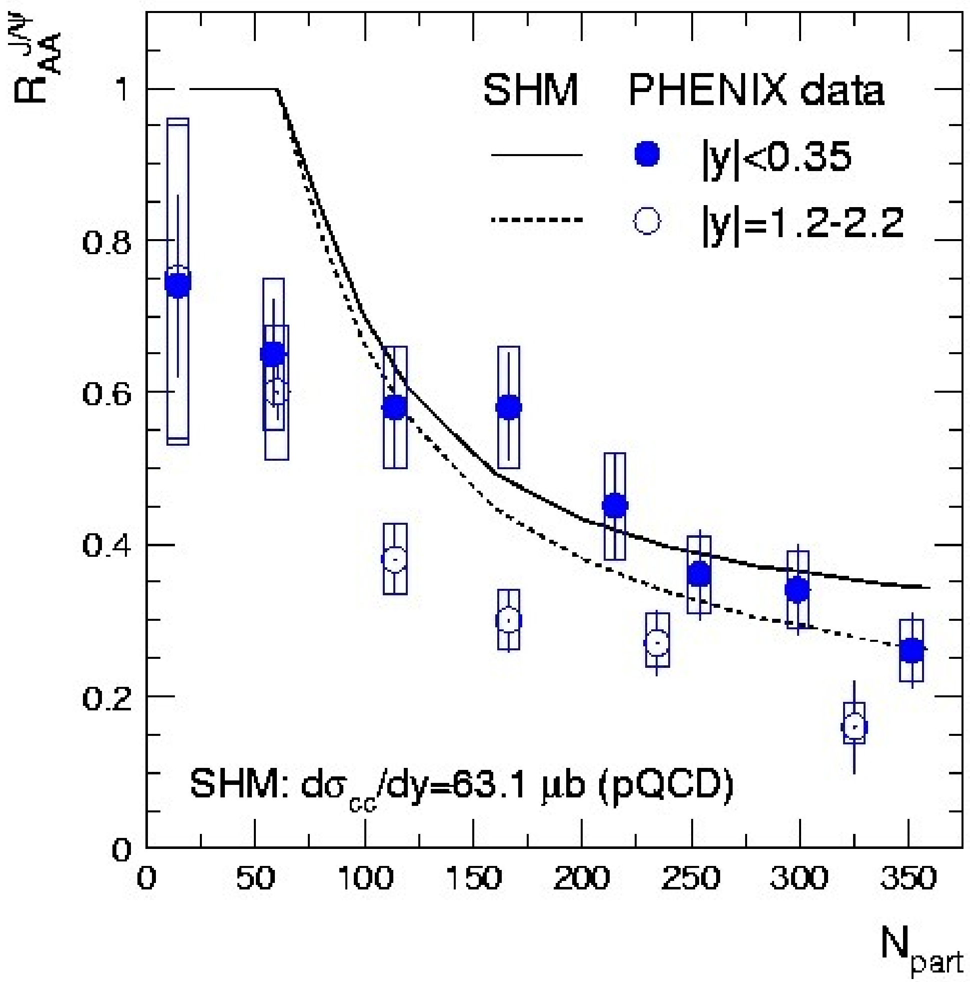


only moderately enhanced (2 x pQCD) cc_bar cross section needed

psi'/psi ratio is expected from a thermal scenario

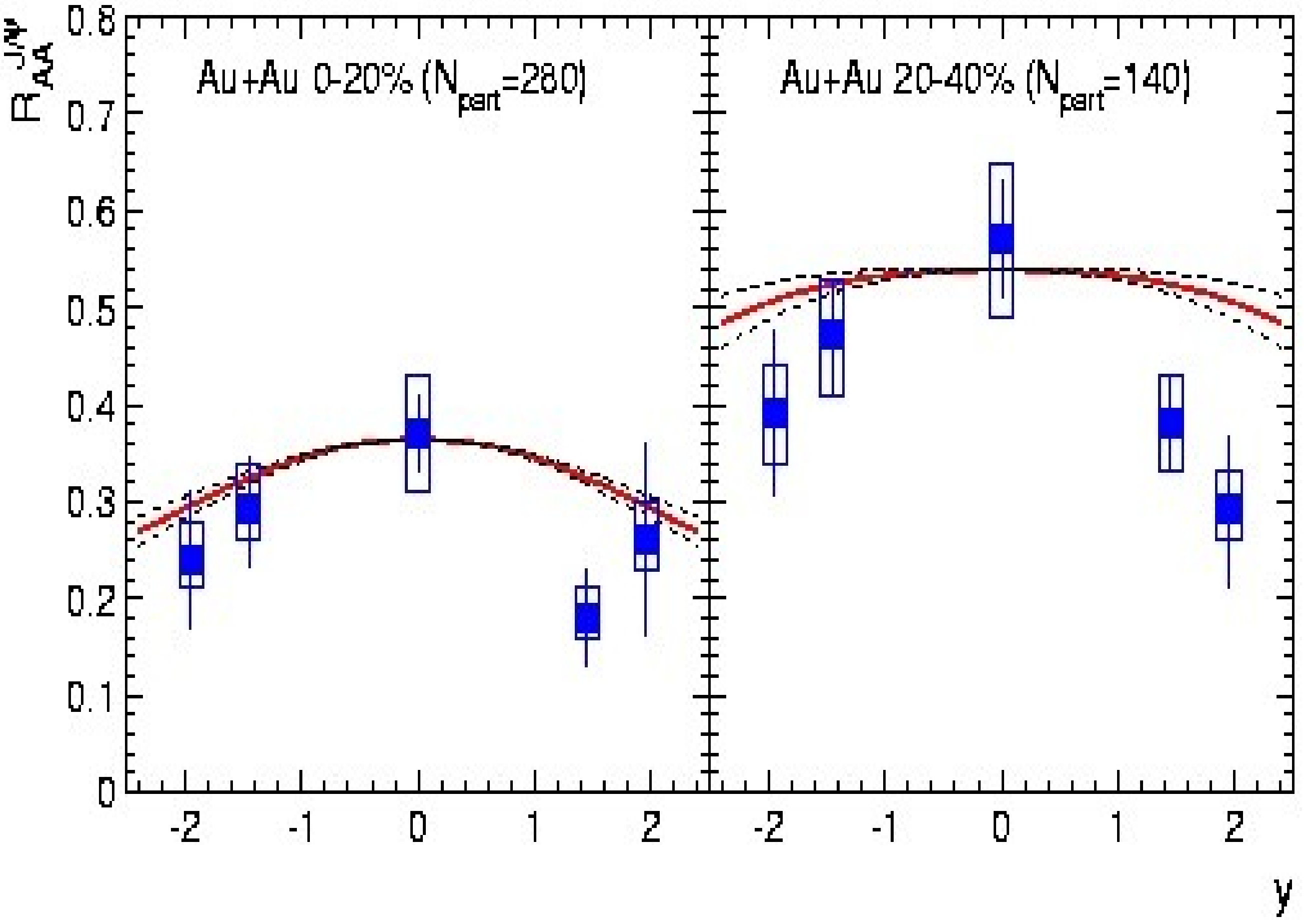
a brief look at RHIC data

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

summary of low energy (SPS, RHIC) results

first indications for (re-)generation picture

interpretation not unique

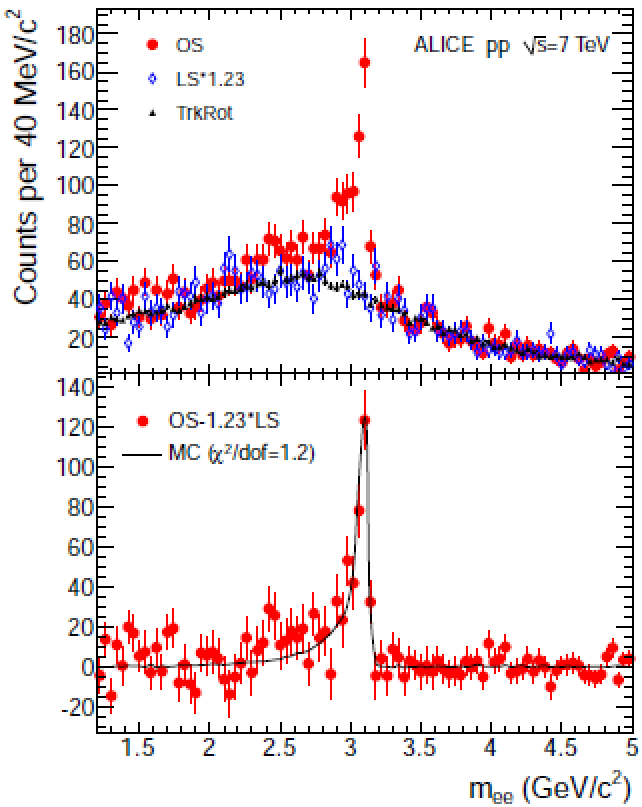
now to LHC data

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

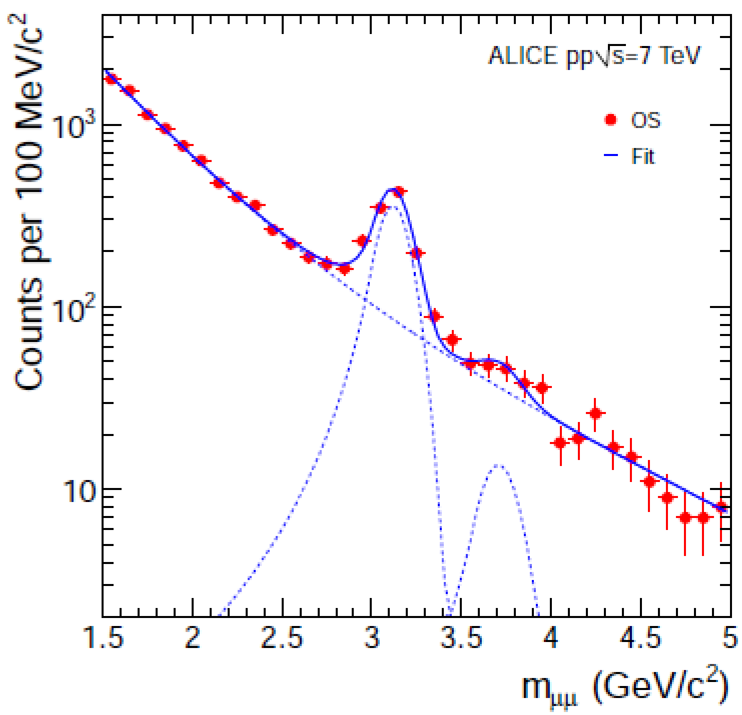
attempt full measurement including polarization of all quarkonia
in pp, pPb, PbPb as function of centrality, rapidity and transverse momentum

...we are on the way

J/psi identification in pp collisions with ALICE



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

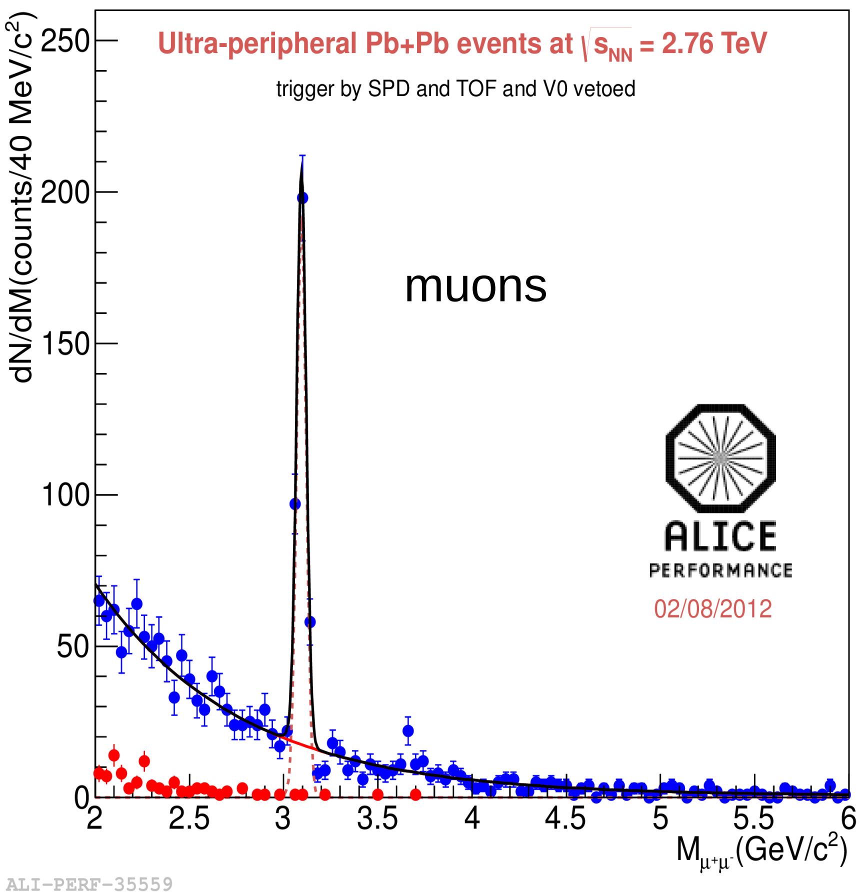


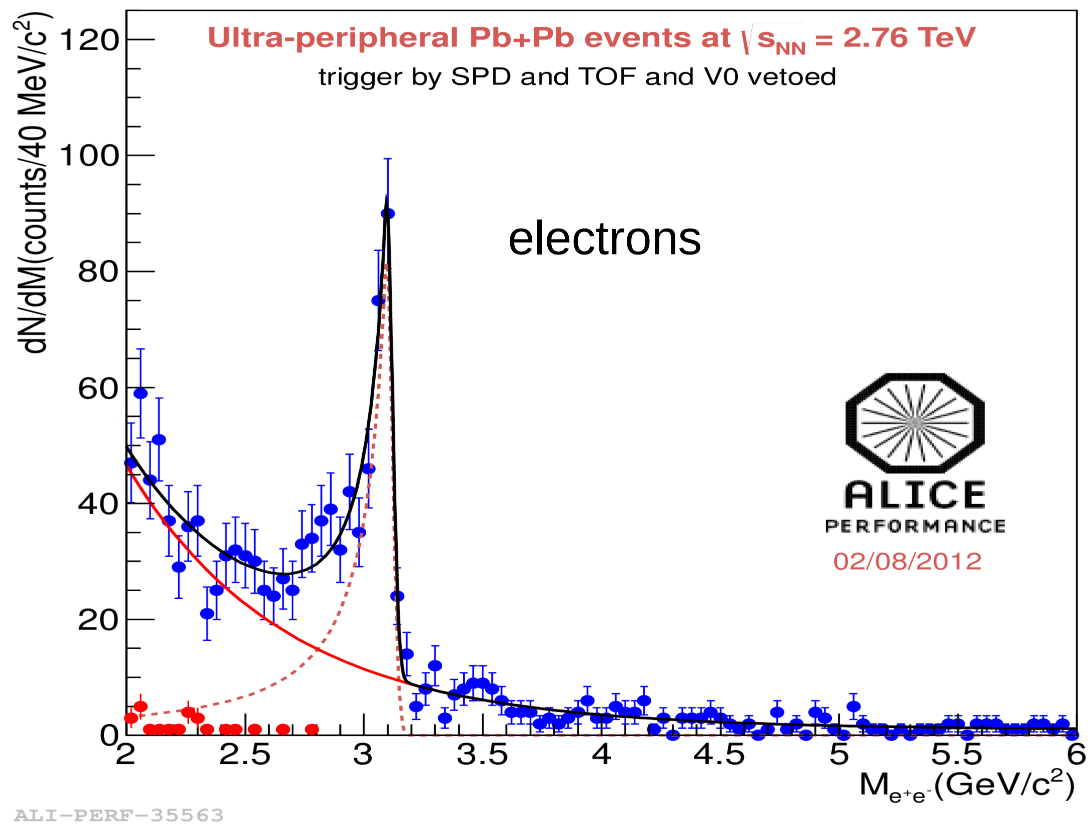
$N_{J/psi} = 957 \pm 56$ for L_{int}=7.9 nb^{-1}

Phys. Lett. B 704 (2011) 442

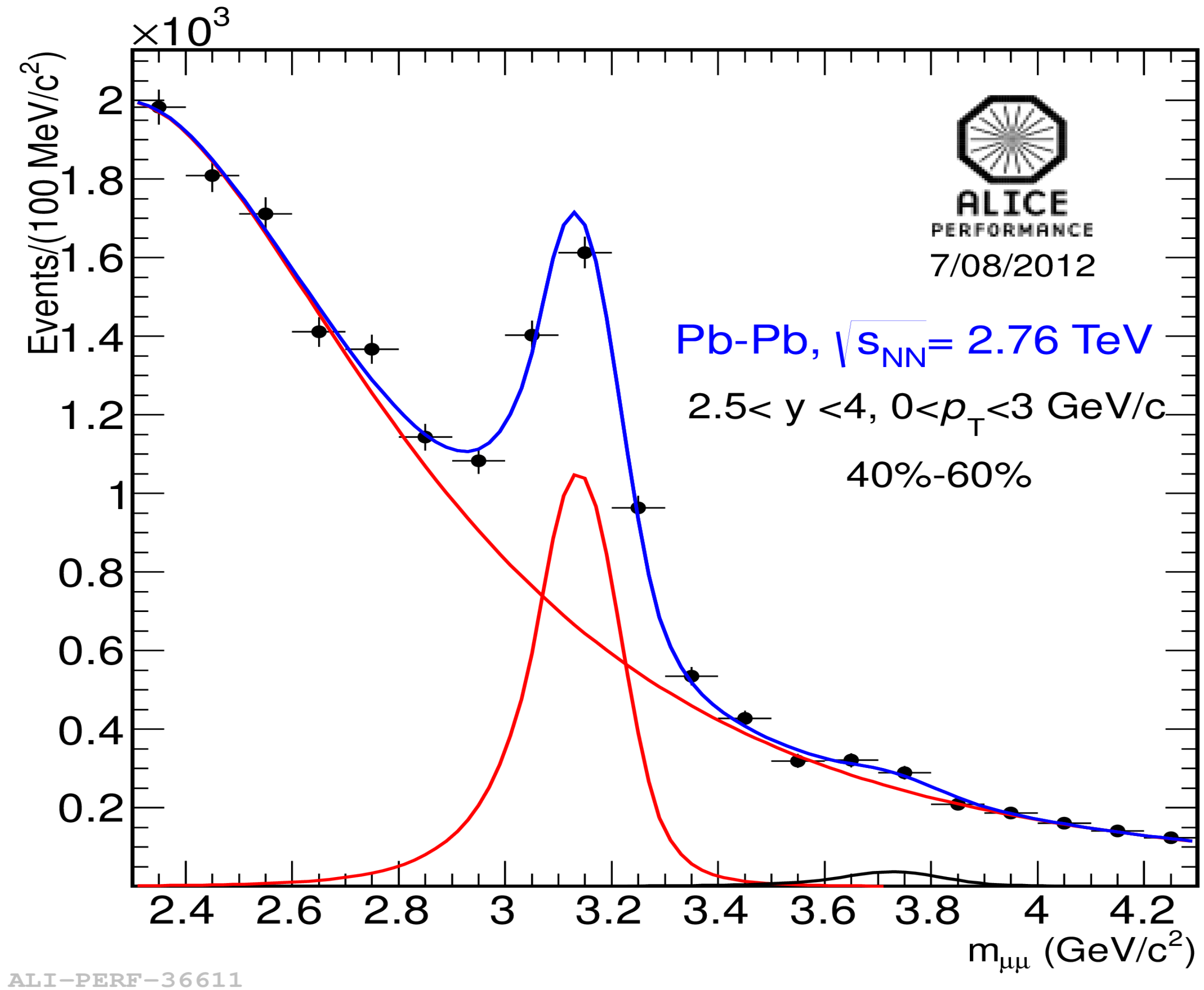
J/psi line shape in ultra-peripheral Pb—Pb collisions

resolution: about 23 MeV for J/psi, precision determination of tail due to internal and external bremsstrahlung



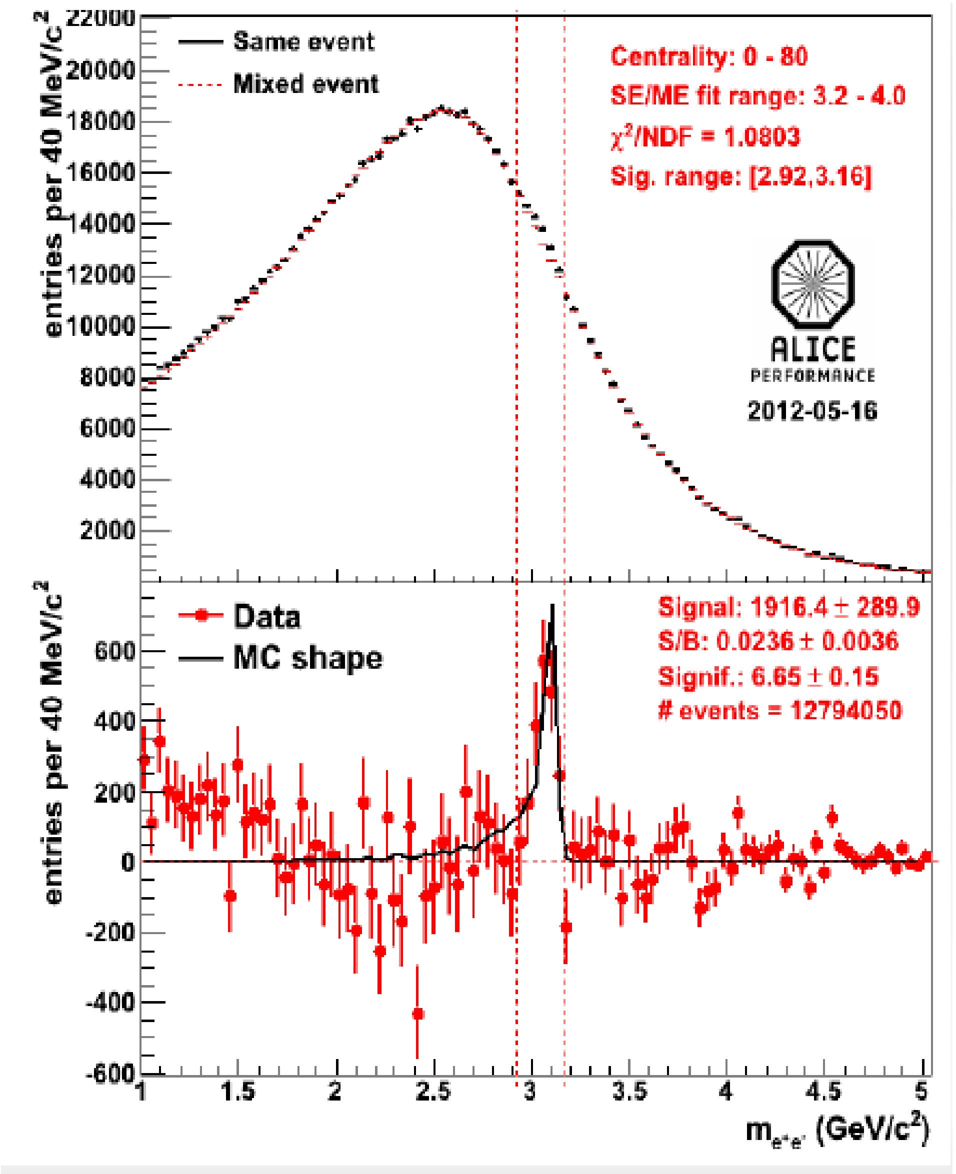


J/psi → mumu in PbPb collisions



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

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



most challenging: PbPb collisions

in spite of significant combinatorial background

(true electrons, not from J/y decay but e.g. D- or B-mesons) resonance well visible

in Pb—Pb collisions 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

Normalization

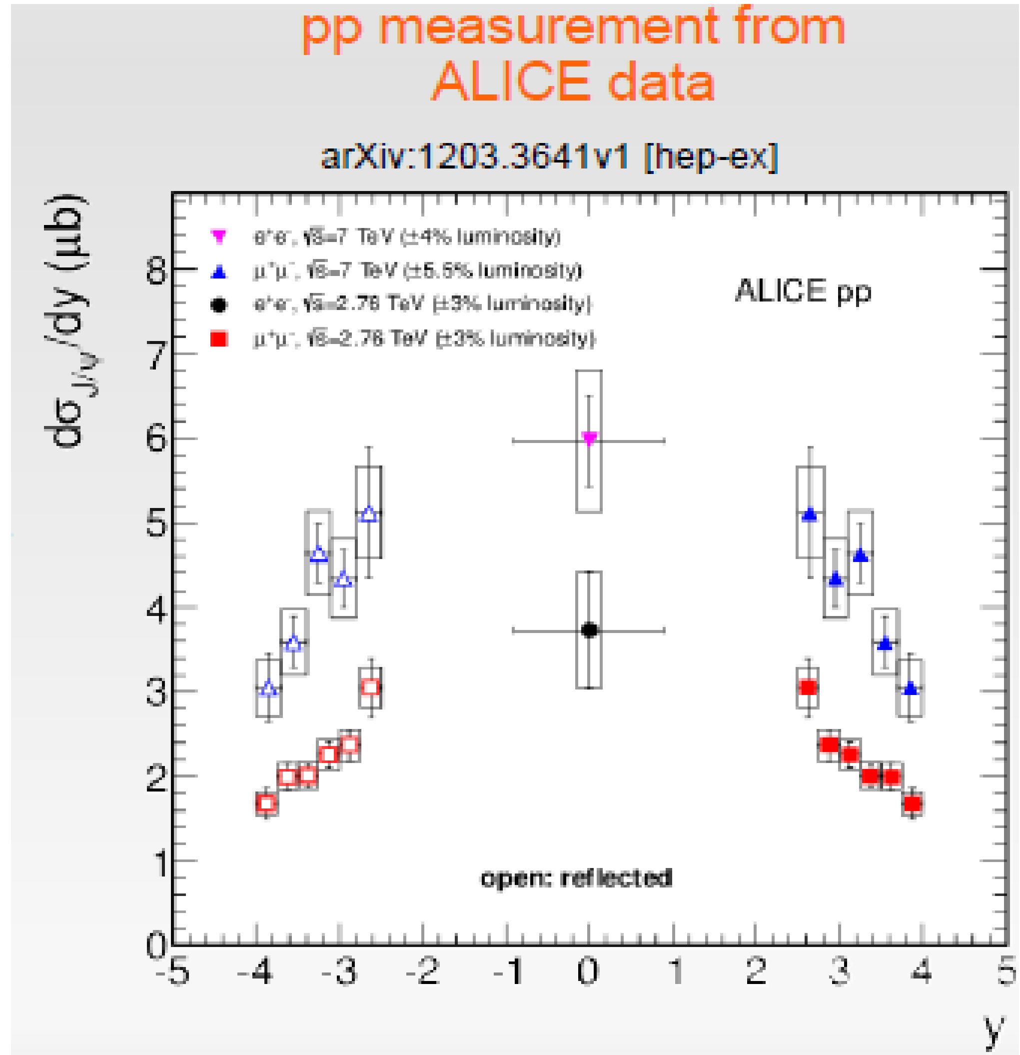
pp @ 2.76 TeV reference for the nuclear modification factor R_{AA} in Pb-Pb collisions

$$R^i_{\mathrm{AA}} = \frac{Y^i_{\mathrm{J}/\psi}(\Delta p_{\mathrm{t}}, \Delta y)}{\langle T^i_{\mathrm{AA}} \rangle \times \sigma^{\mathrm{PP}}_{\mathrm{J}/\psi}(\Delta p_{\mathrm{t}}, \Delta y)}$$

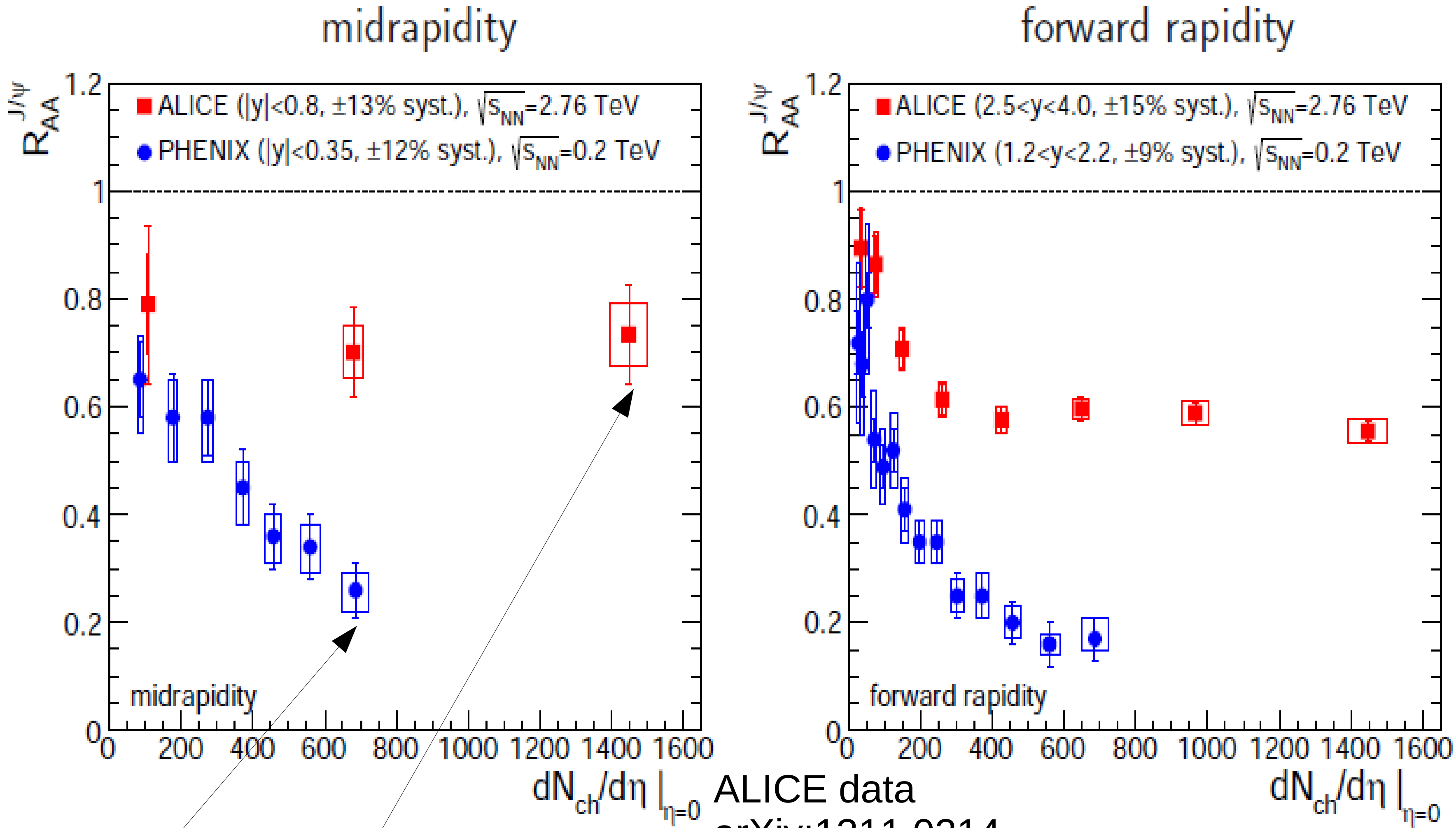
the pp reference is also the main source of systematic uncertainty in the R_{AA} computation:

J/Ψ (2.5<y<4), total syst. uncertainty of 9%

J/Ψ (|y|<0.9), total syst. uncertainty of 26%



less suppression when increasing the energy density

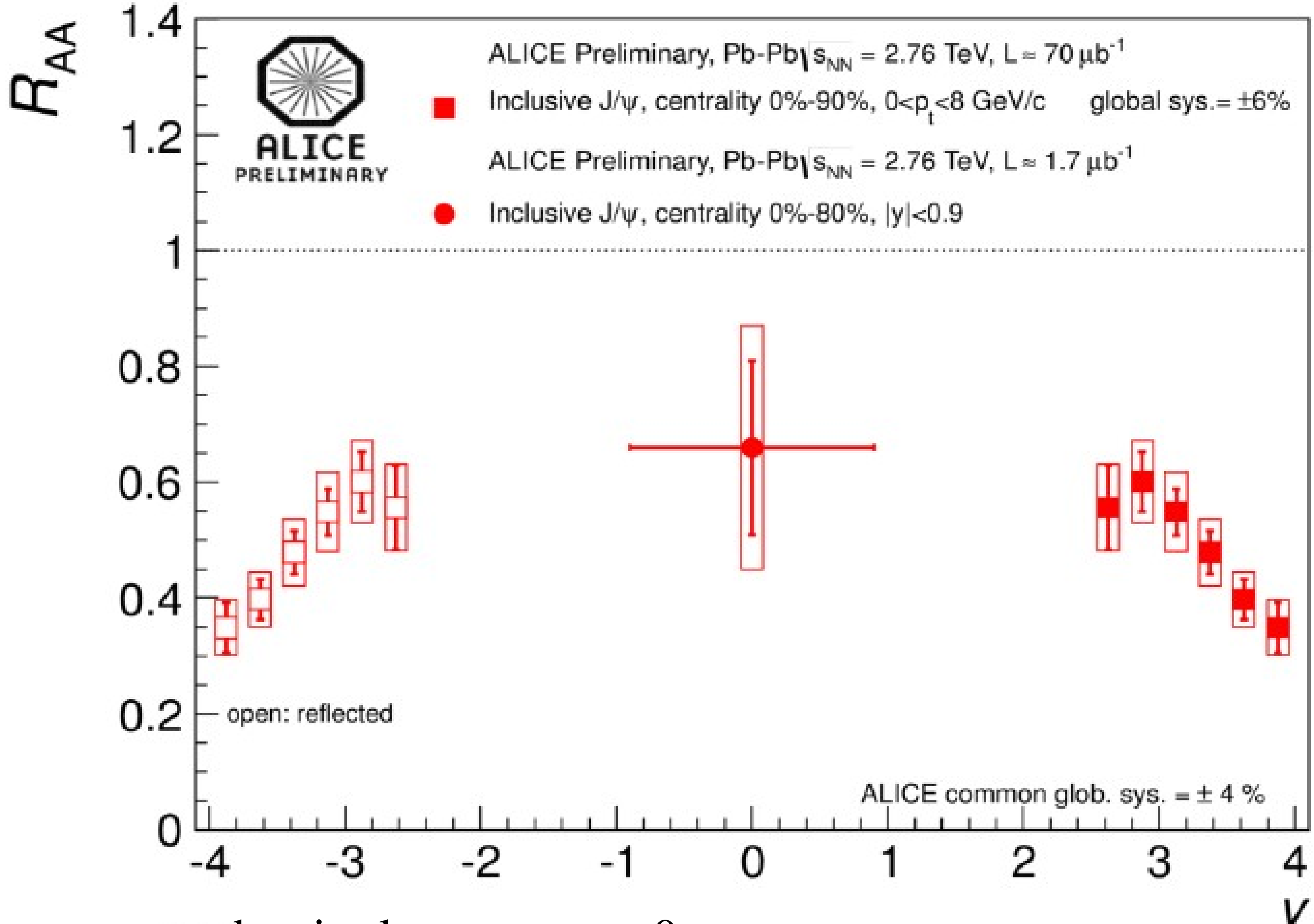


ALICE data
arXiv:1311.0214
PLB, in print

from here to here more than factor of 2 increase in energy density, but R_{AA} increases by more than a factor of 3

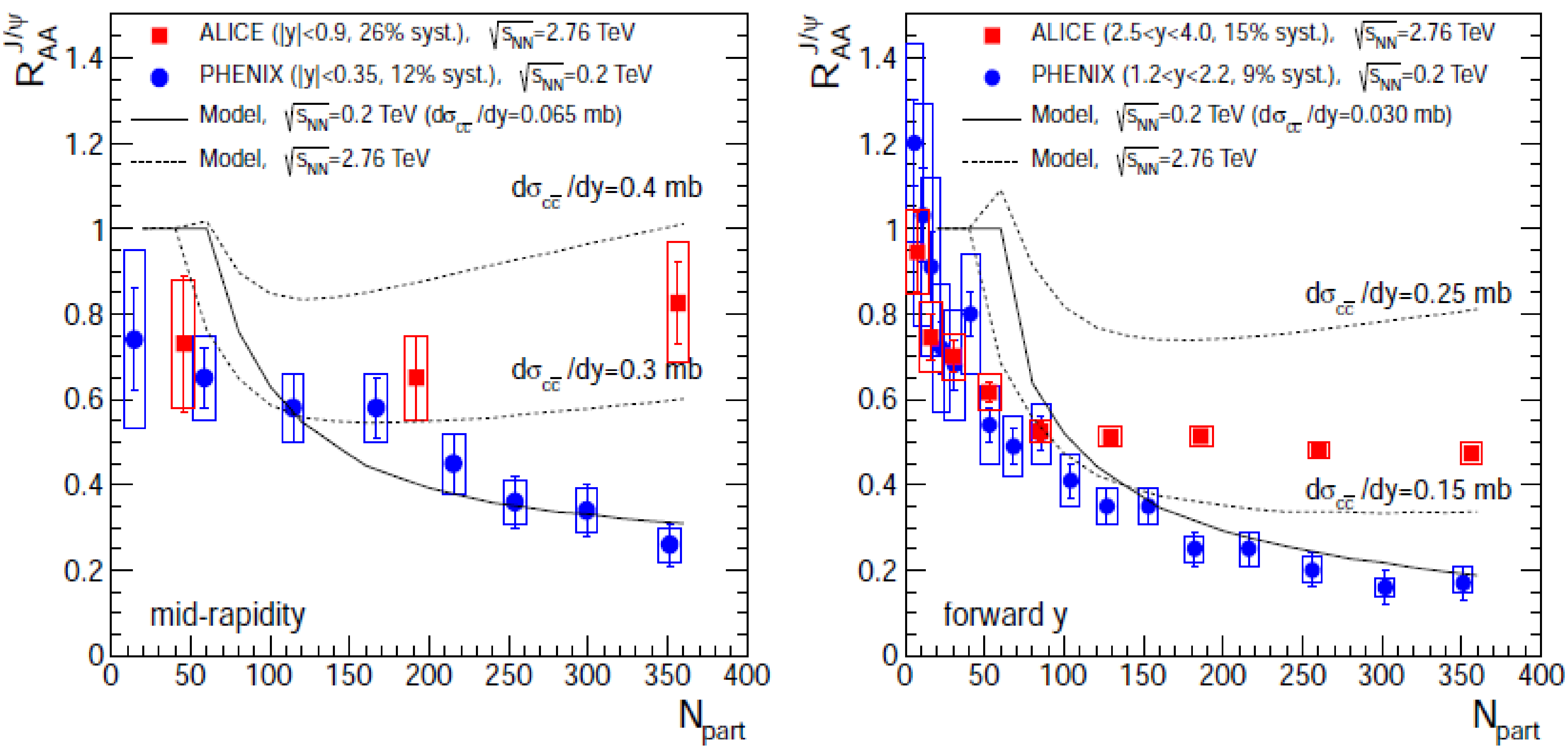
2007 prediction impressively confirmed by LHC data

Rapidity dependence



note: energy density largest at y = 0

statistical hadronization model



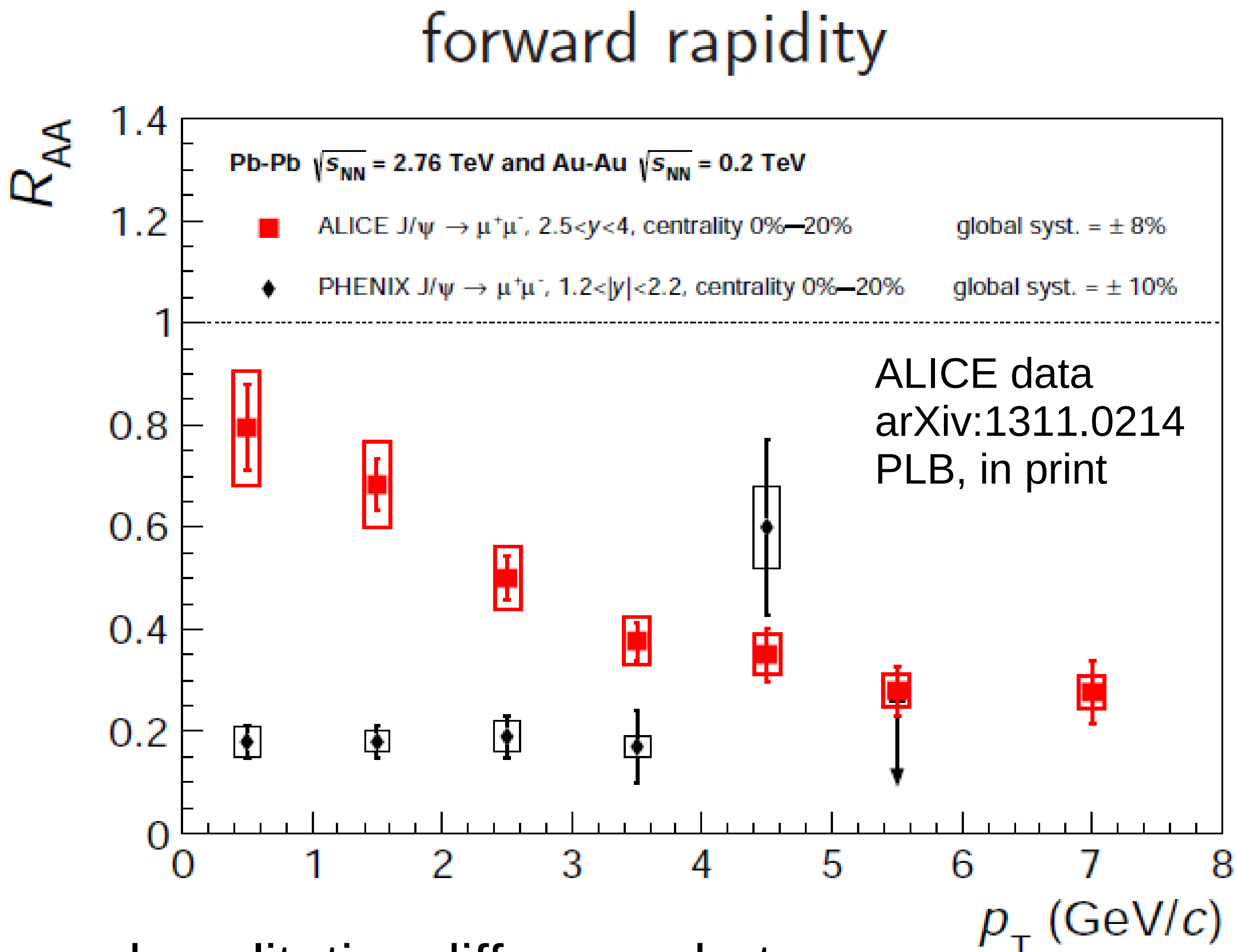
ALICE data and evolution from RHIC to LHC energy described quantitatively

back to J/psi data – what about spectra and hydrodynamic flow of charm and charmonia?

if charmonia are produced via statistical hadronization of charm quarks at the phase boundary, then:

- charm quarks should be in thermal equilibrium
    - low pt enhancement
    - flow of charm quarks
    - flow of charmonia

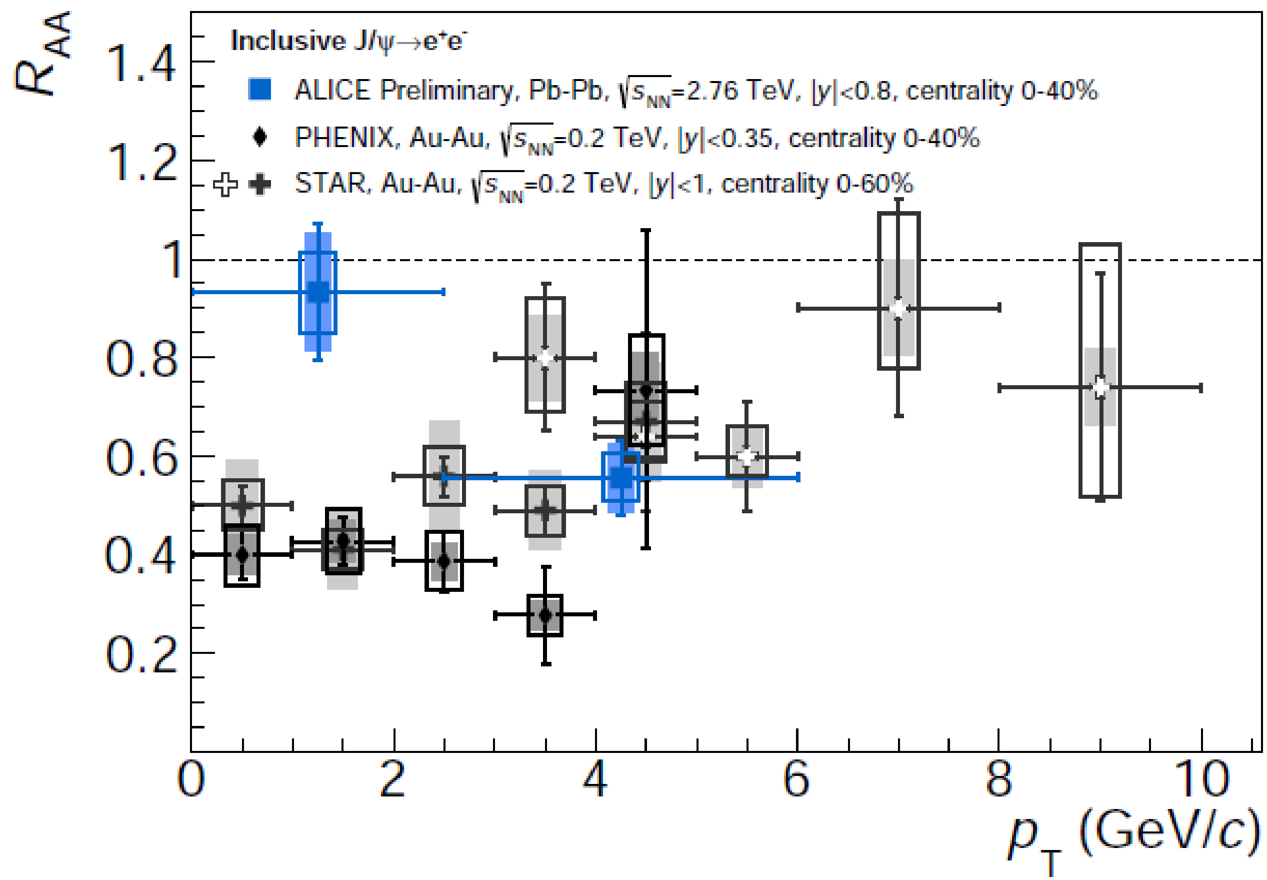
Comparison of transverse momentum spectra at RHIC and LHC



dramatic and qualitative difference between RHIC and LHC results

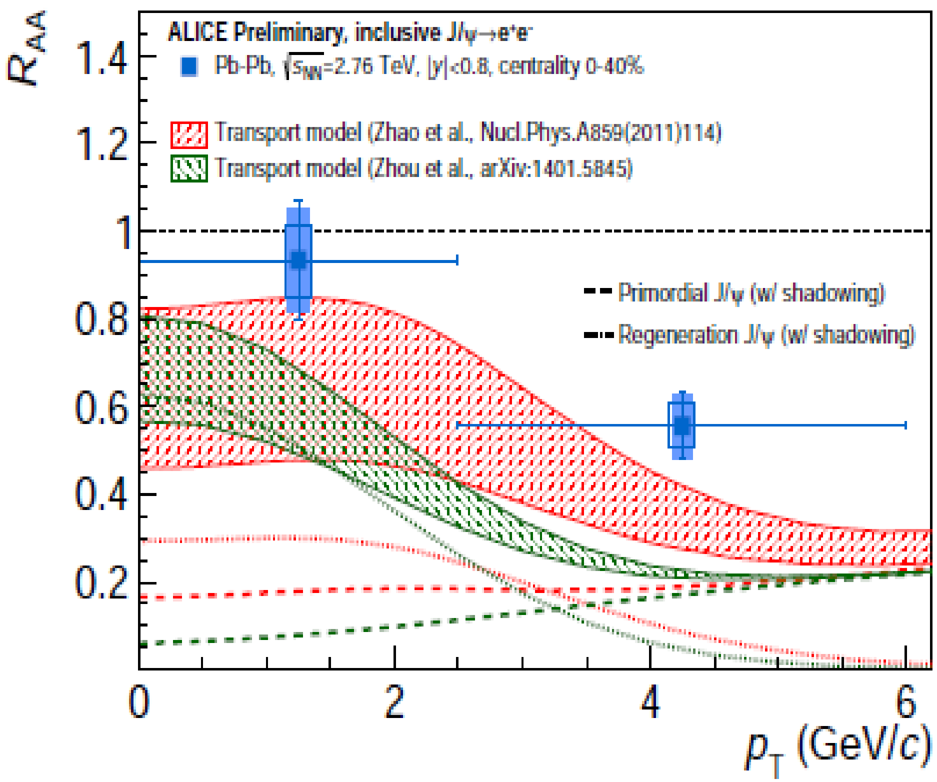
Comparison of transverse momentum spectra at RHIC and LHC

midrapidity

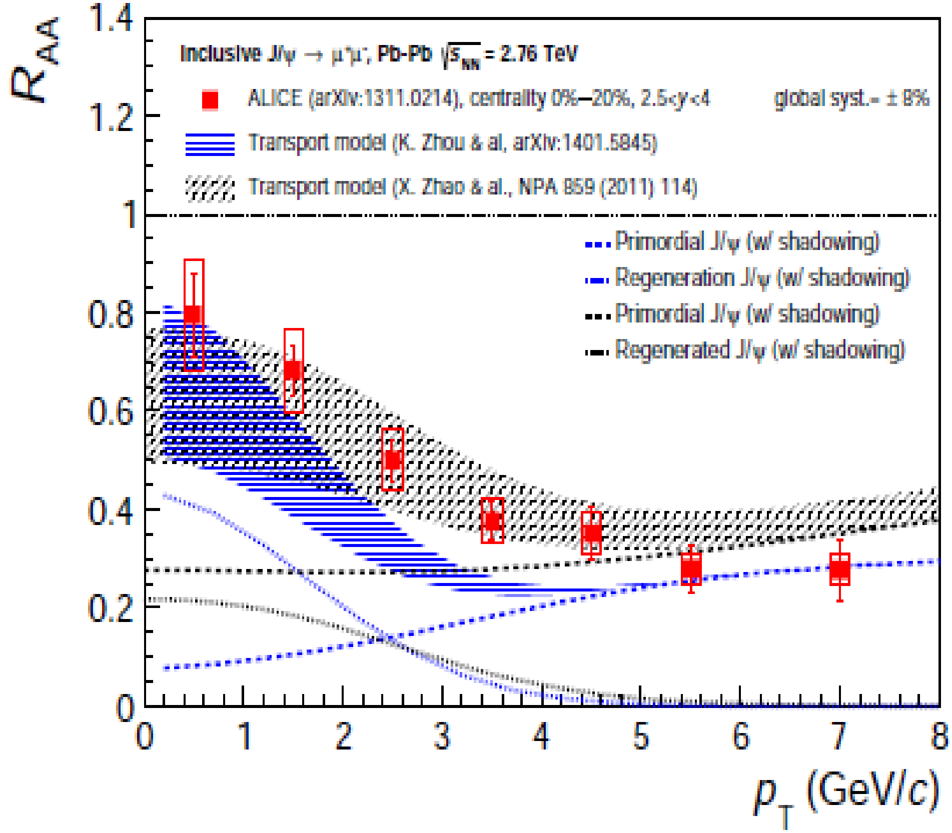


comparison with (re-)generation models

midrapidity



forward rapidity



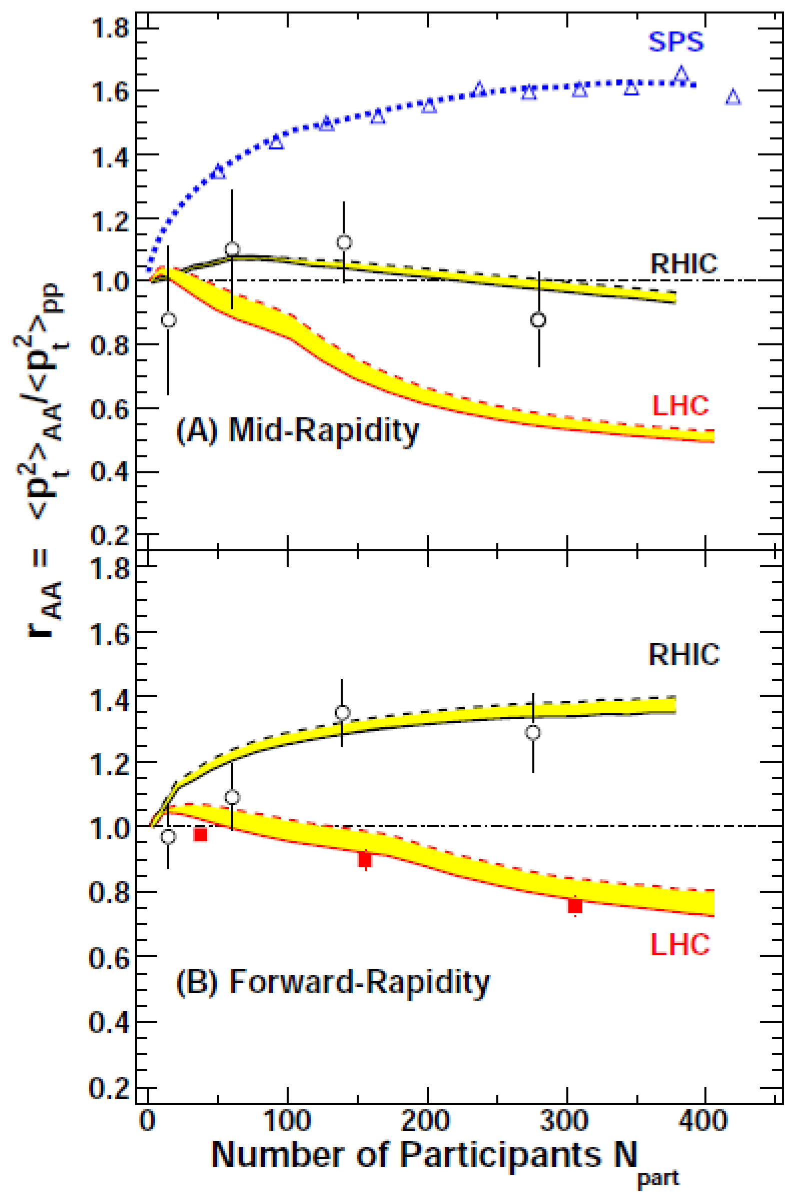
good agreement lends further strong support to the 'full color screening and late J/psi production' picture

analysis of transverse momentum spectra

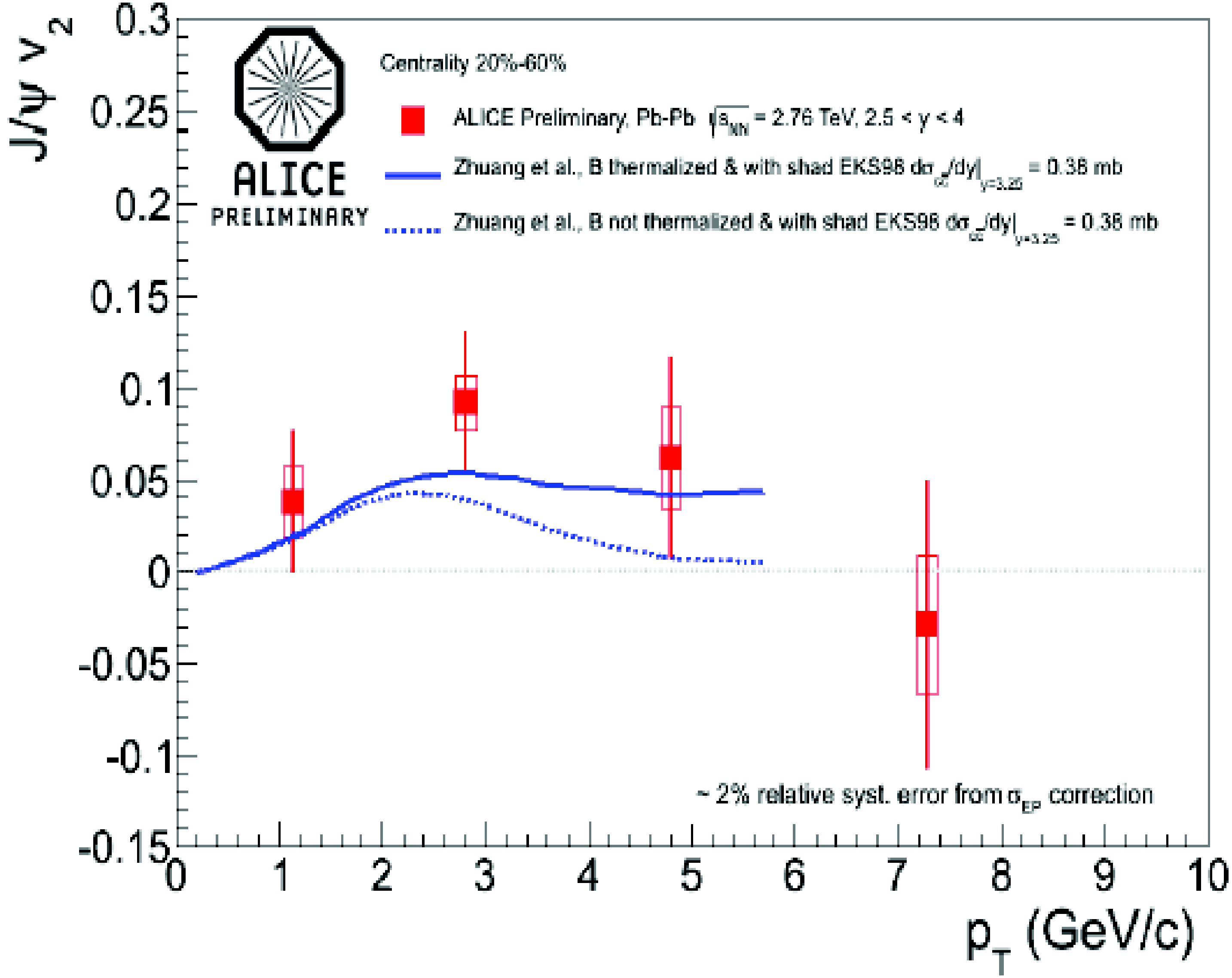
arXiv:1309.7520v1 [nucl-th] 29 Sep 2013

Zhou, Xu, Zhuang

at LHC energy, mostly (re-) generation of charmonium, p_t distribution exhibits features of strong energy loss and approach to thermalization for charm quarks



J/psi flow compared to models including (re-) generation



hydrodynamic flow of J/psi consistent with (re-)generation

Charmonium production at LHC energy: deconfinement,and color screening

- Charmonia formed at the phase boundary → full color screening at T_c

- Debye screening length < 0.4 fm near T_c

- Combination of uncorrelated charm quarks into J/psi → deconfinement

statistical hadronization picture of charmonium production provides most direct way towards information on the degree of deconfinement reached as well as on color screening and the question of bound states in the QGP

Debye mass, LQCD, and J/psi data

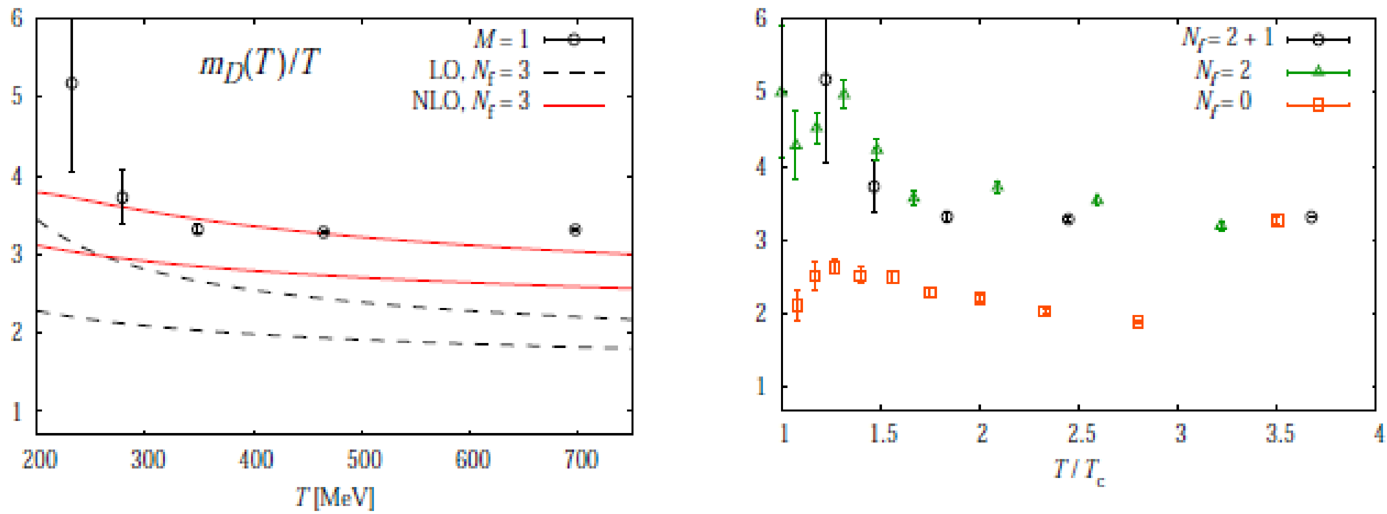


Fig. 6. (Left) The Debye screening mass on the lattice in the color-singlet channel together with that calculated in the leading-order (LO) and next-to-leading-order (NLO) perturbation theory shown by dashed-black and solid-red lines, respectively. The bottom (top) line expresses a result at $\mu = \pi T$ $(3\pi T)$, where μ is the renormalization point. (Right) Flavor dependence of the Debye screening masses. We assume the pseudo-critical temperature for $2+1$-flavor QCD as $T_c \sim 190$ MeV.

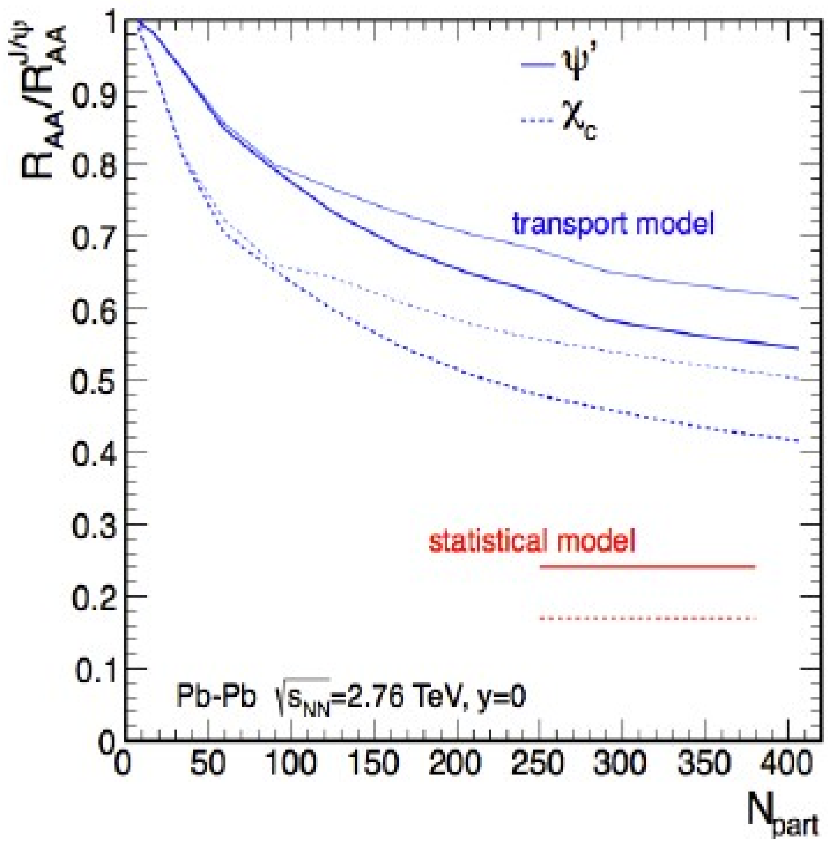
arXiv:1112.2756 WHOT-QCD Coll.

from J/psi data and statistical hadronization analysis:

$m_{Debye}/T > 3.3$

at T = 0.15 GeV

Are there hadronic bound states in the QGP?



transport model:

X. Zhao, R. Rapp,

NPA 859 (2011) 114

statistical model:

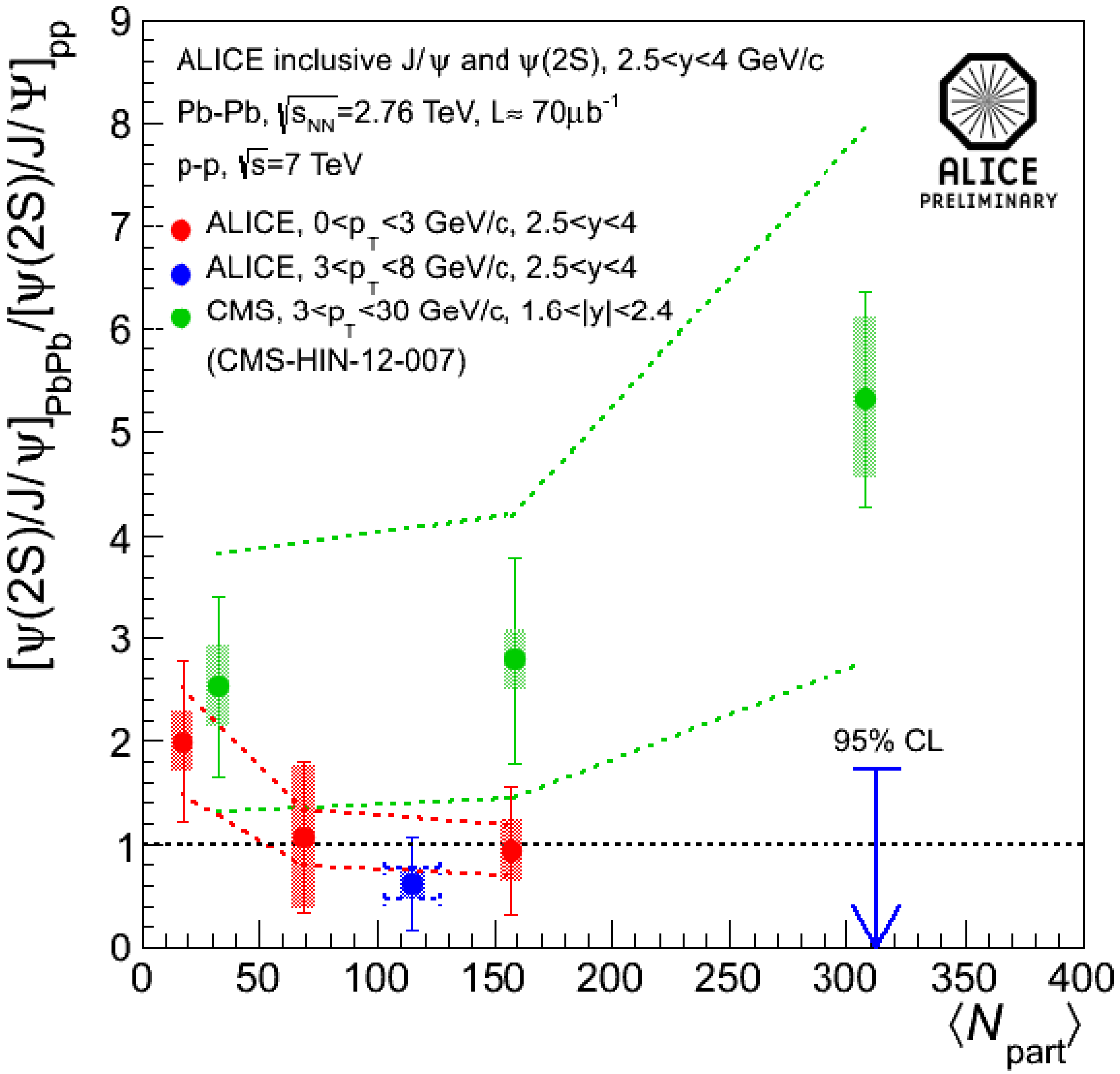
A. Andronic et al.,

PLB 678 (2009) 350

Possible resolution of a fundamental question:
can there be bound states of colorless hadrons in the QGP or are all hadrons formed at the phase boundary?

measurement of psi'/psi and chi_c/psi ratio will settle the issue → ALICE upgrade

First results on psi'/(J/psi) ratio

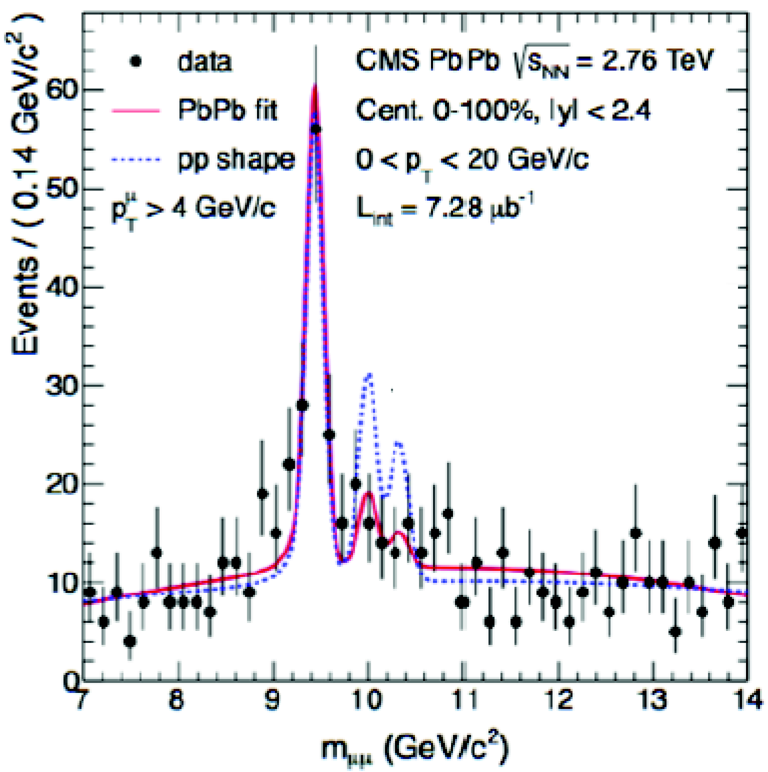


dramatic enhancement in CMS data not confirmed by ALICE measurements

Sequential Upsilon suppression

2010 data

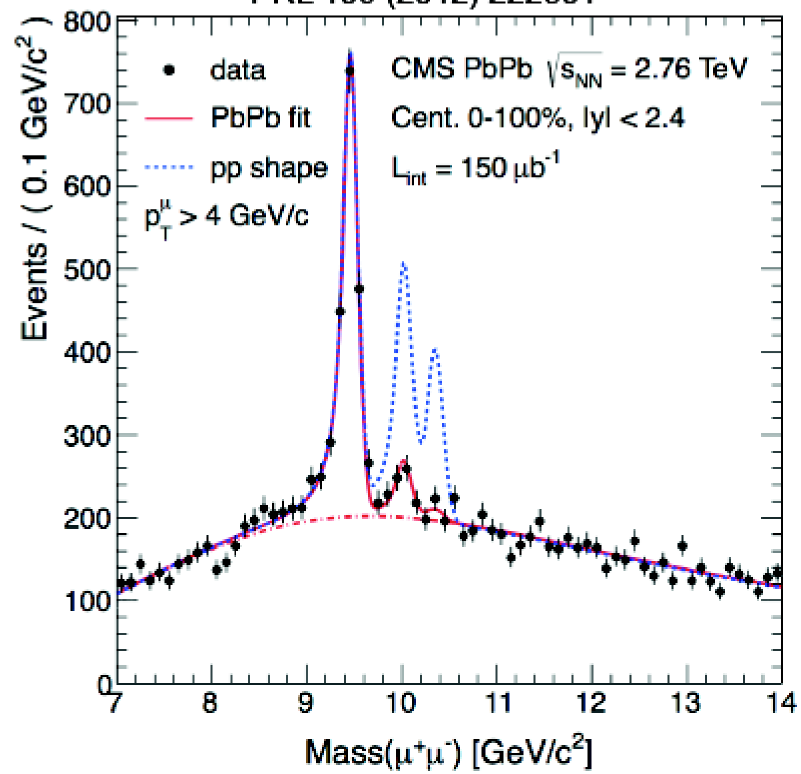
PRL 107 (2011) 052302



Indication of suppression of (Y(2S)+Y(3S)) relative to Y(1S)
→ 2.4σ significance

2011 data

PRL 109 (2012) 222301

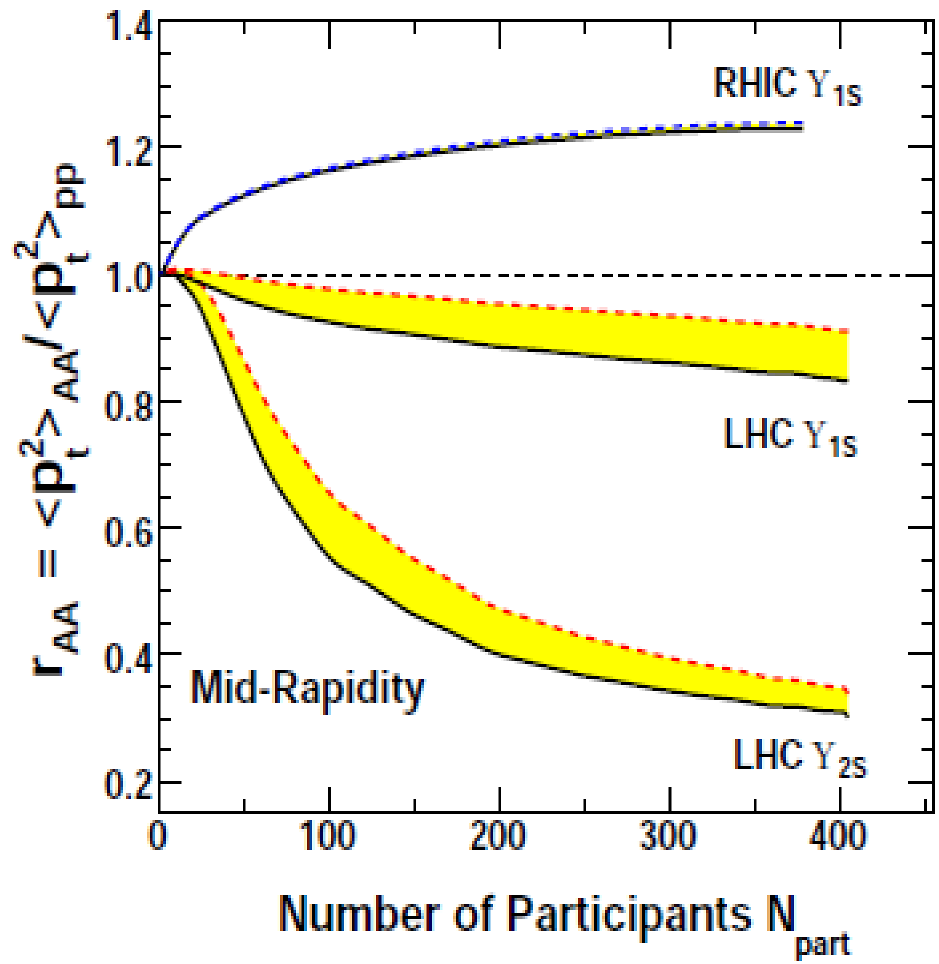


Observation of sequential suppression of Y family
→ Detailed studies

transverse momentum distributions for Y states

if picture of Debye screening and (re-)generation also applies to Y states, expect similar p_t pattern as for charmonia

needs approach to thermalization for b quarks!



predictions by Zhou, Xu, Zhuang
arXiv:1309.7520 [nucl-th]

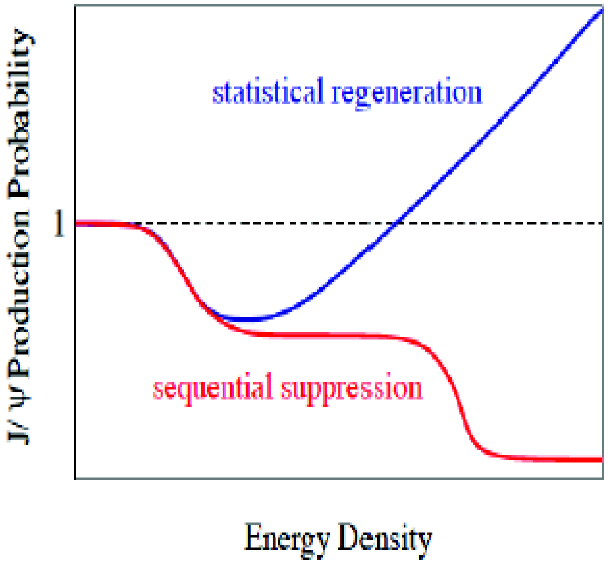
summary 1 – quarkonium production

- spectacular difference between results from RHIC and LHC
- J/psi production is consistent with complete Debye screening and (re-)generation at the QCD phase boundary
- charm quarks are thermalized and deconfined
- Y production: also suppressed but unclear relation to color screening
  are b quarks and/or Y thermalized?

summary 2

- charmonium production – a fingerprint for deconfined quarks and gluons

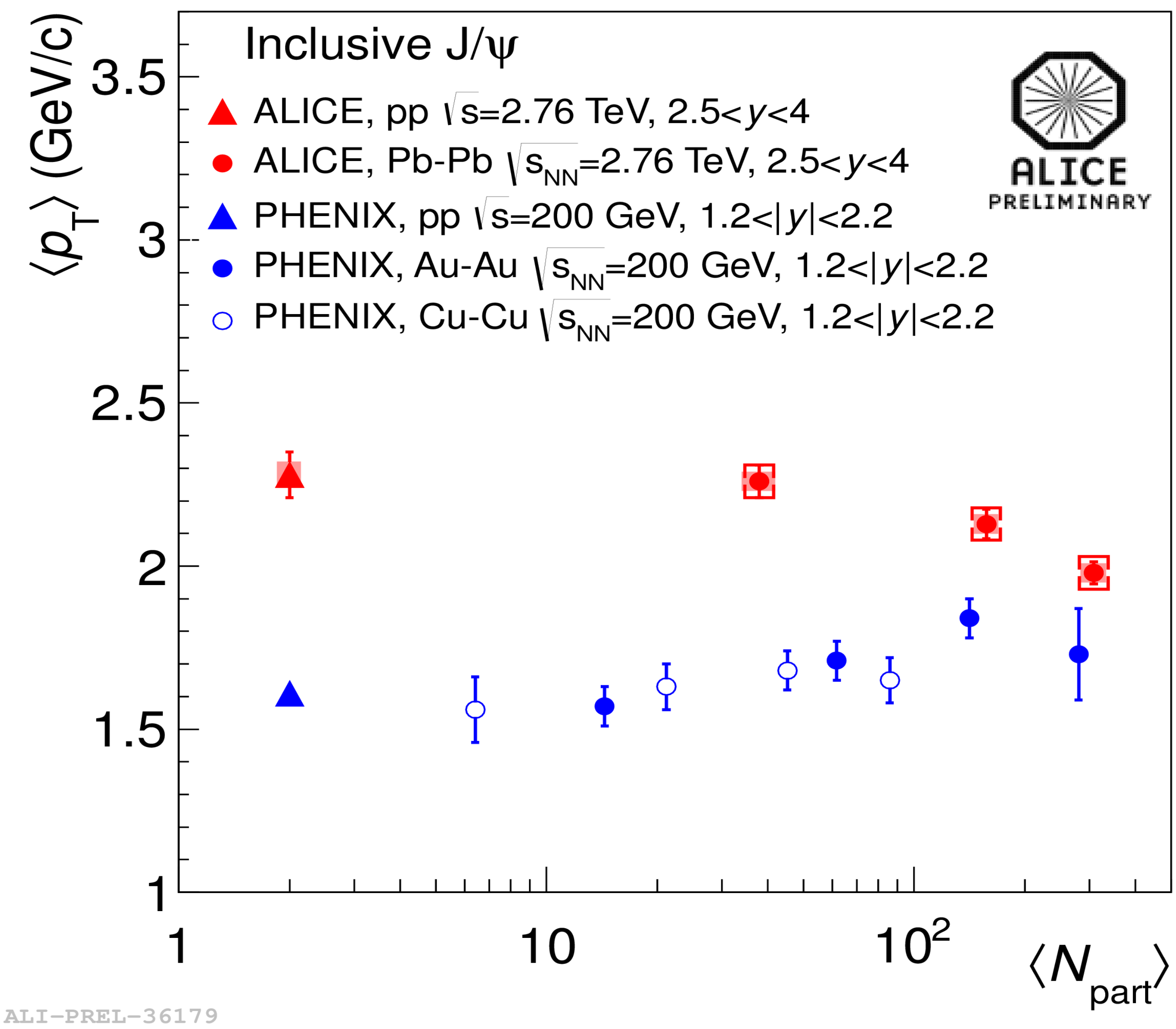
- evidence for energy loss and flow of charm quarks -->
thermalization
- charmonium generation at the phase boundary – a new process
- first indications for this from psi'/(J/psi) SPS and J/psi RHIC data
- evolution from RHIC to LHC described quantitatively
- charmonium enhancement at LHC – J/psi color-screened at T_c,
deconfined QGP



cartoon Helmut Satz, 2009 SPS RHIC LHC

extra slides

Evolution of J/psi transverse momentum spectra – evidence for thermalization and charm quark coalescence at the phase boundary



Evolution of J/psi transverse momentum spectra – evidence for thermalization and charm quark coalescence at the phase boundary