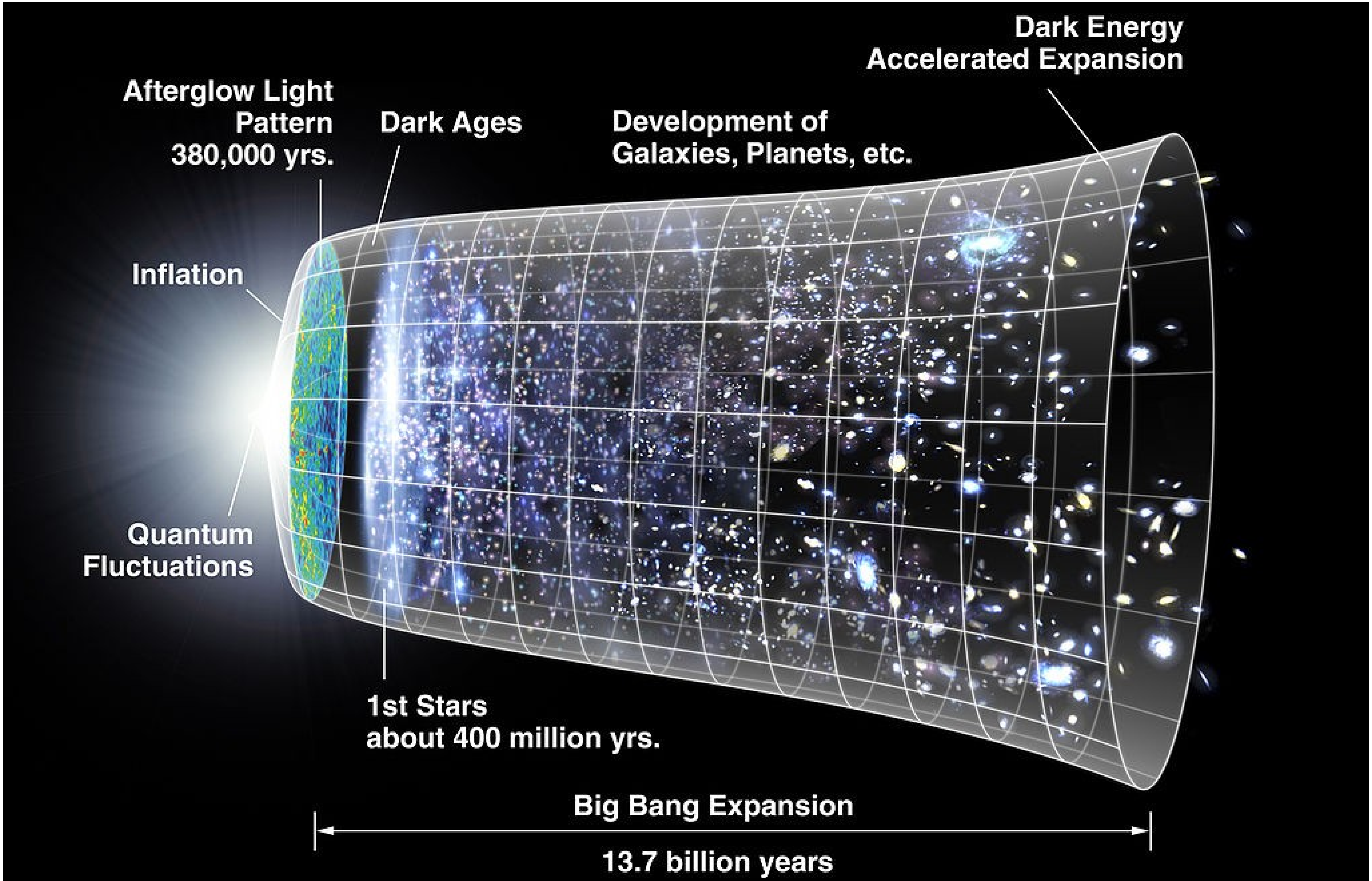
Quarkonia, QGP, and Deconfinement

- introductory remarks and context
- a few words on open heavy flavor production
- the charmonium story – deconfinement and color screening
  - SPS and RHIC energies
  - LHC results
- remarks on Y production
- the Debye screening radius and LQCD
- summary

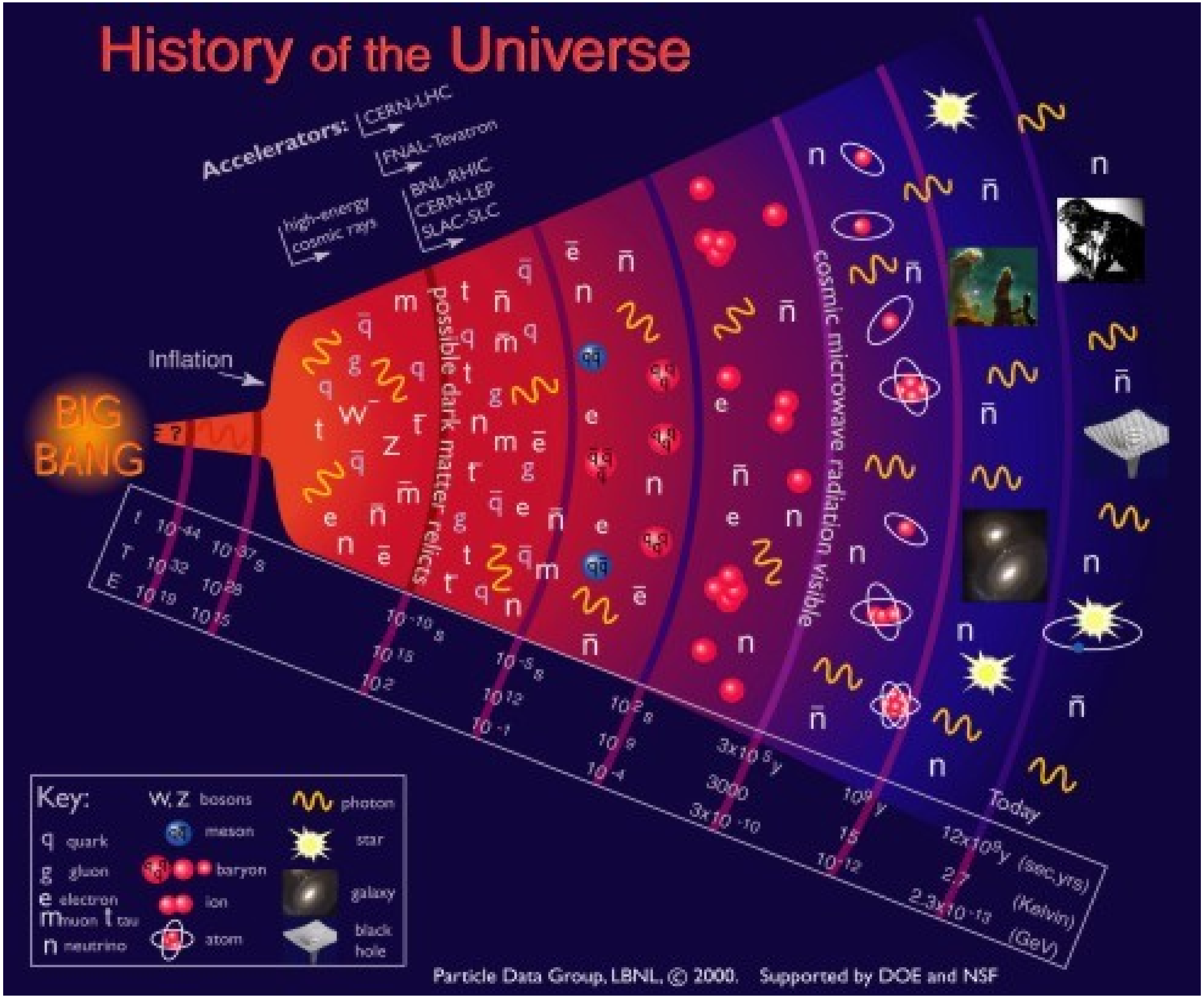
work based on collaboration with
A. Andronic, K. Redlich, and J. Stachel

Workshop on QCD Thermodynamics
in High-Energy Collisions
July 27 - 31, 2015
College of Physical Science and Technology
Central China Normal University, Wuhan, China

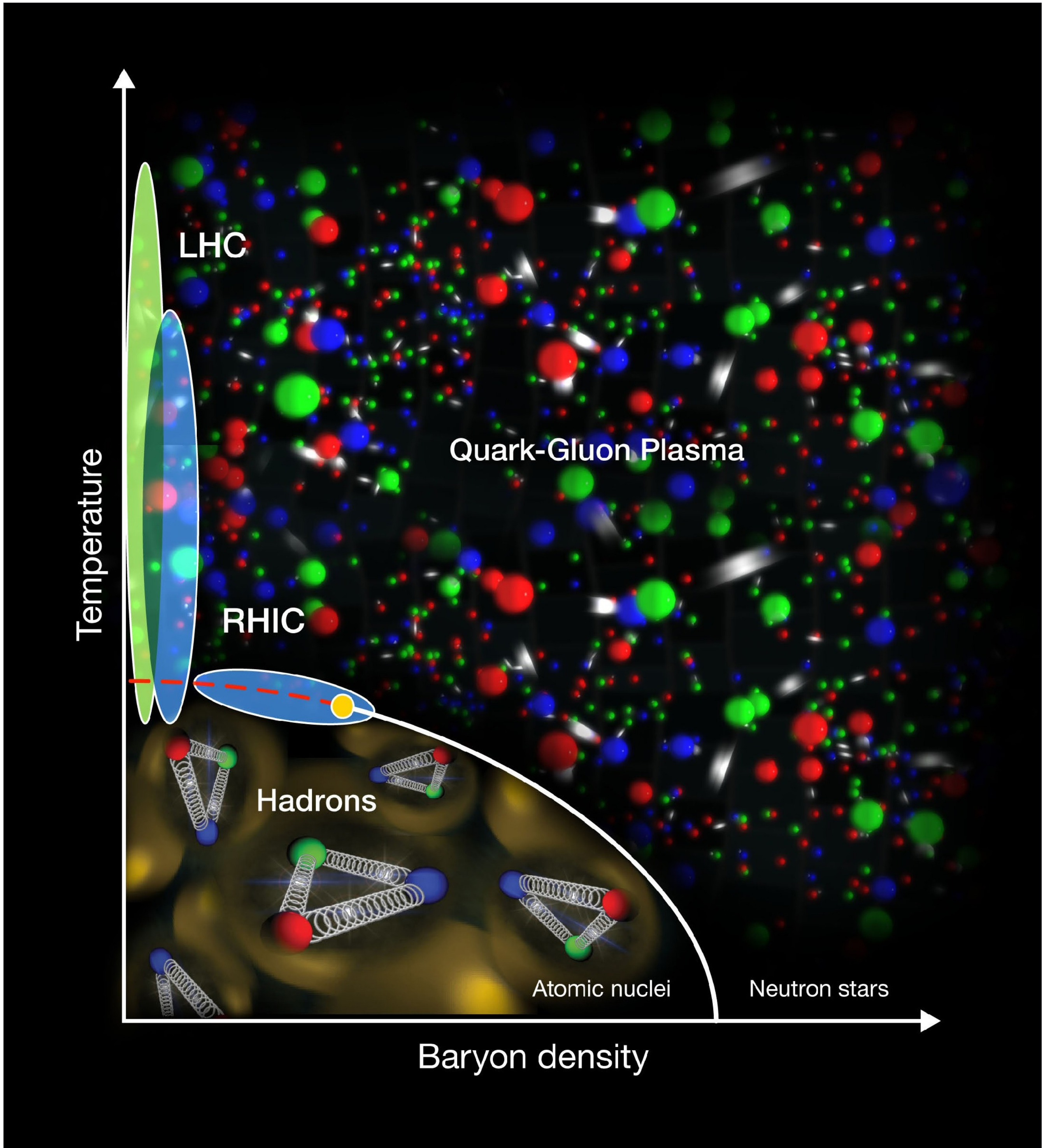
Peter Braun-Munzinger



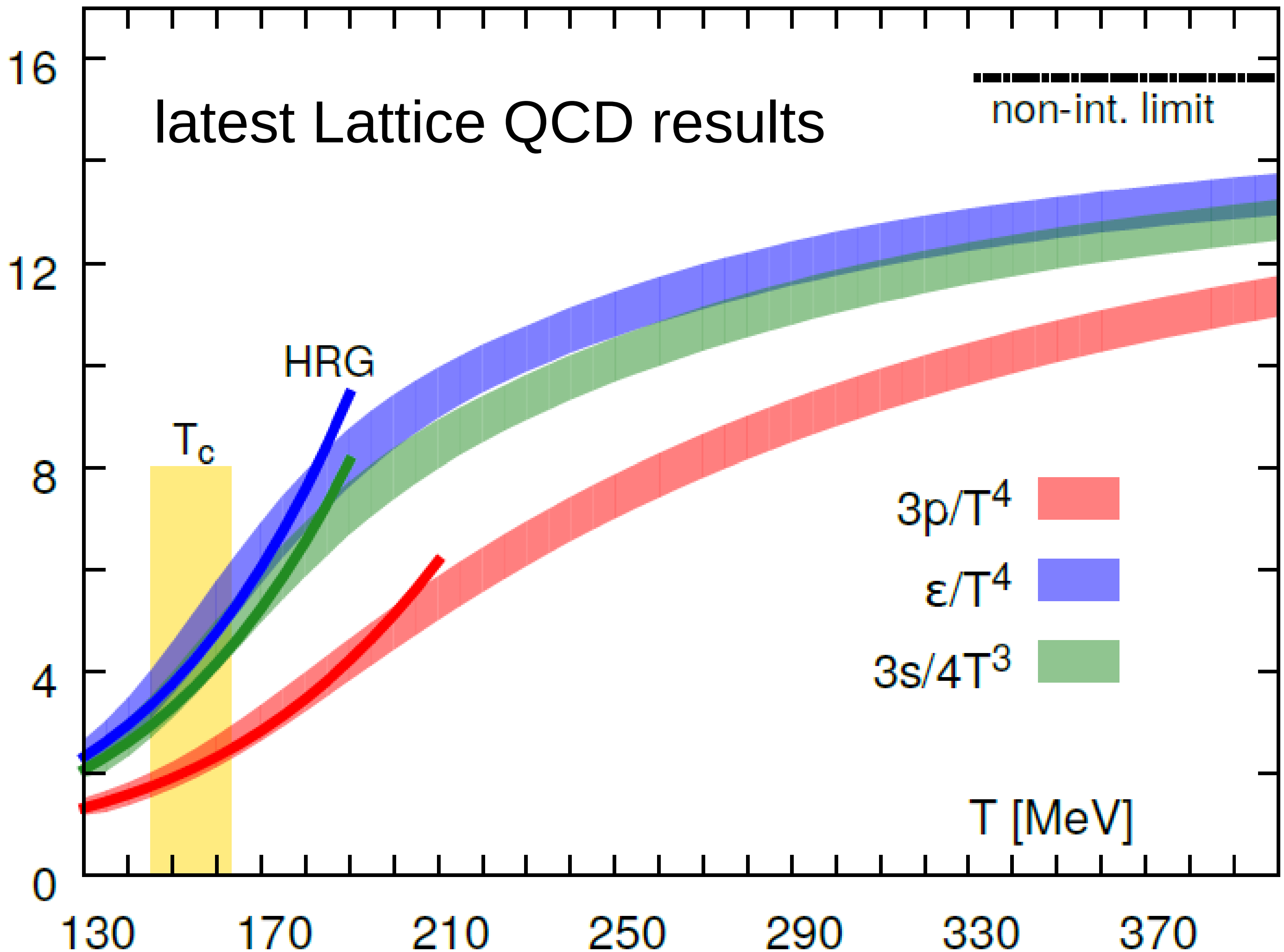
Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
Today
(sec,yrs)
(Kelvin)
(GeV)
Key:
q quark
g gluon
e electron
m muon
t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

The phase diagram of quantum chromodynamics



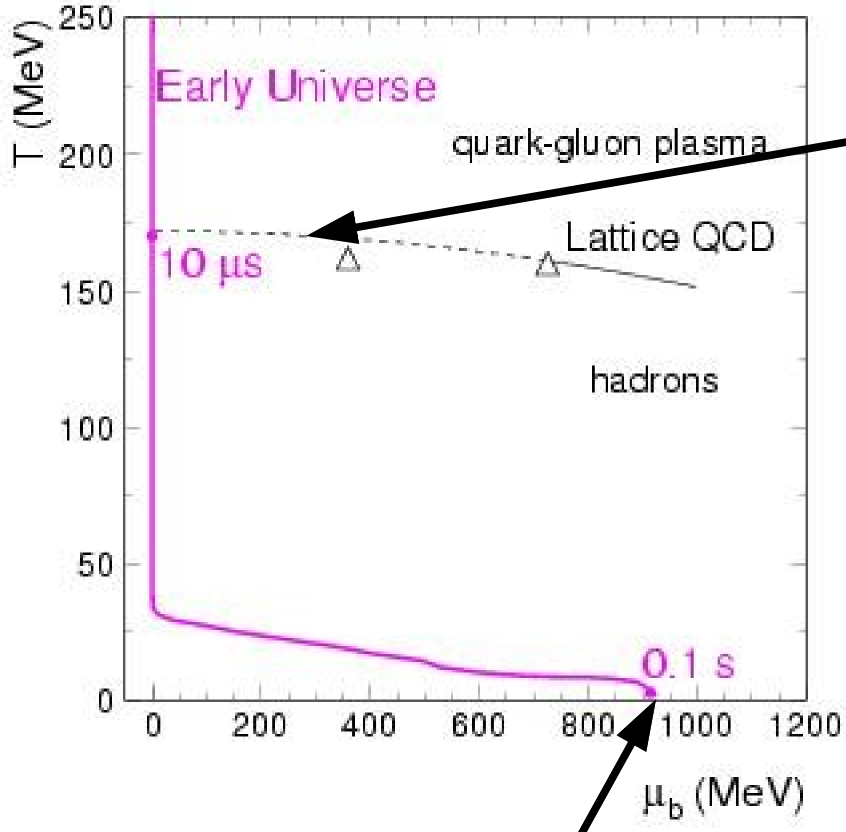
The equation of state of hot QCD matter – a chiral (cross over) phase transition between hadron gas and the QGP



critical region: T_c = (154 ± 9) MeV ε_{crit} = (340 ± 45) MeV/fm^3

HOTQCD coll., Phys.Rev. D90 (2014) 9, 094503

Evolution of the Early Universe and the QCD phase Diagram



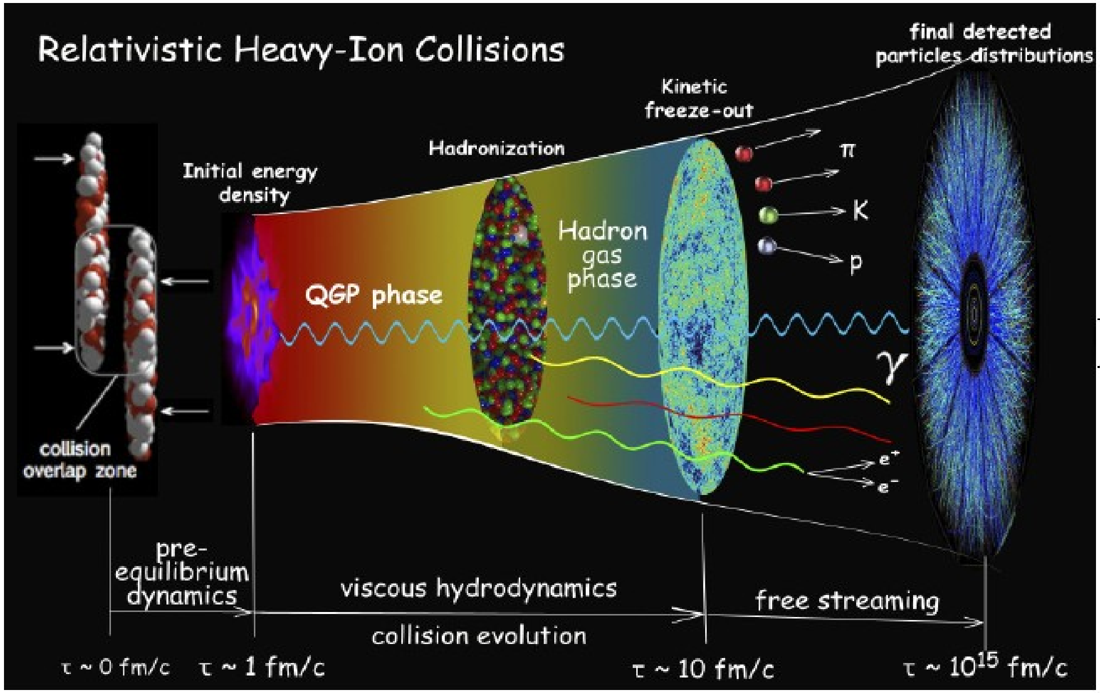
QCD Phase Boundary

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

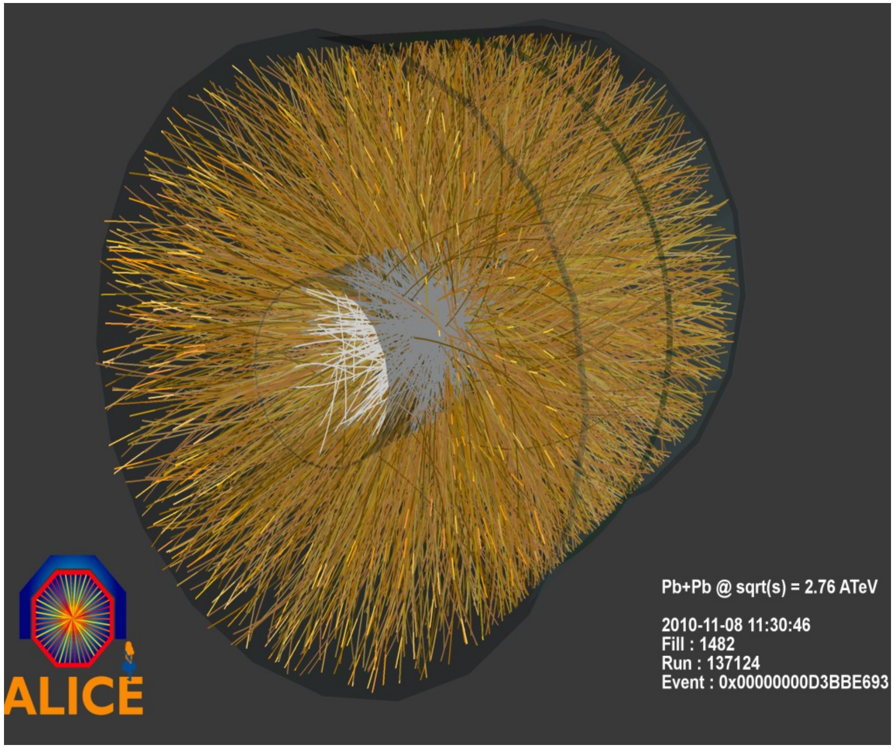
- Charge neutrality
- Net lepton number = net baryon number
- Constant entropy/baryon

neutrinos decouple and light nuclei begin to be formed

The Quark-Gluon Plasma formed in Nuclear Collisions at very high Energy



Paul Sorensen and Chun Shen



2a) Open heavy flavor, charmonium production and the QGP – some general remarks

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

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) $\rightarrow \Delta E_{gluon} > \Delta E_{quark}$
  - parton mass dependent (dead cone effect: Dokshitzer & Kharzeev, PLB 519(2001)199) $\rightarrow \Delta E_{u,d,s} > \Delta E_{c} > \Delta E_{b}$
- 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

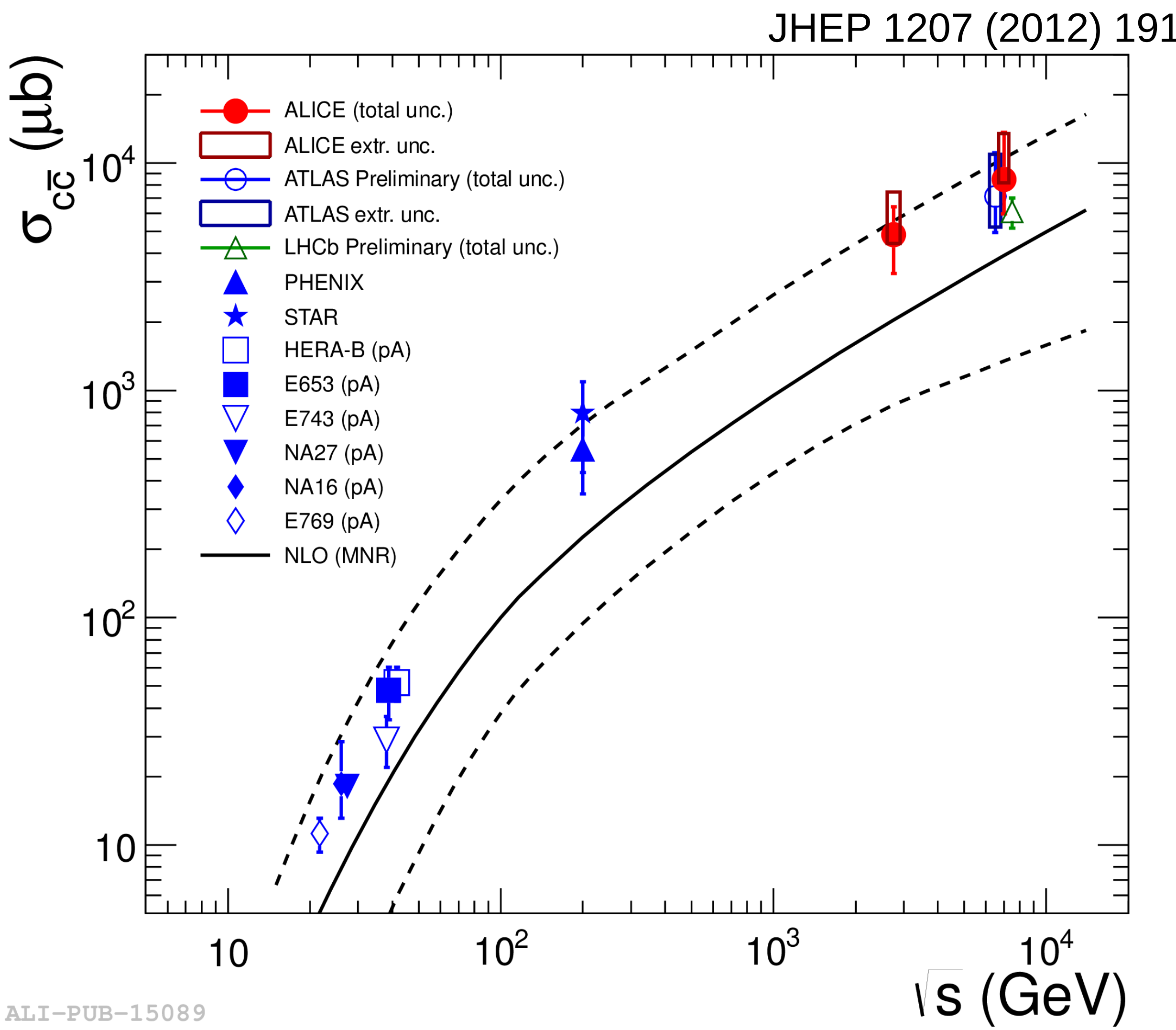
no medium effect

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

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

total ccbar cross section in pp at LHC energy



- good agreement between ALICE, ATLAS and LHCb
- syst. error due to extrapolation to low pt,
- data about factor 2 above central value of FONLL
- beam energy dependence follows well FONLL prediction
- significant improvement of accuracy expected in LHC Run2

how to quantify the effect of the medium?

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

R_AA = medium/vacuum

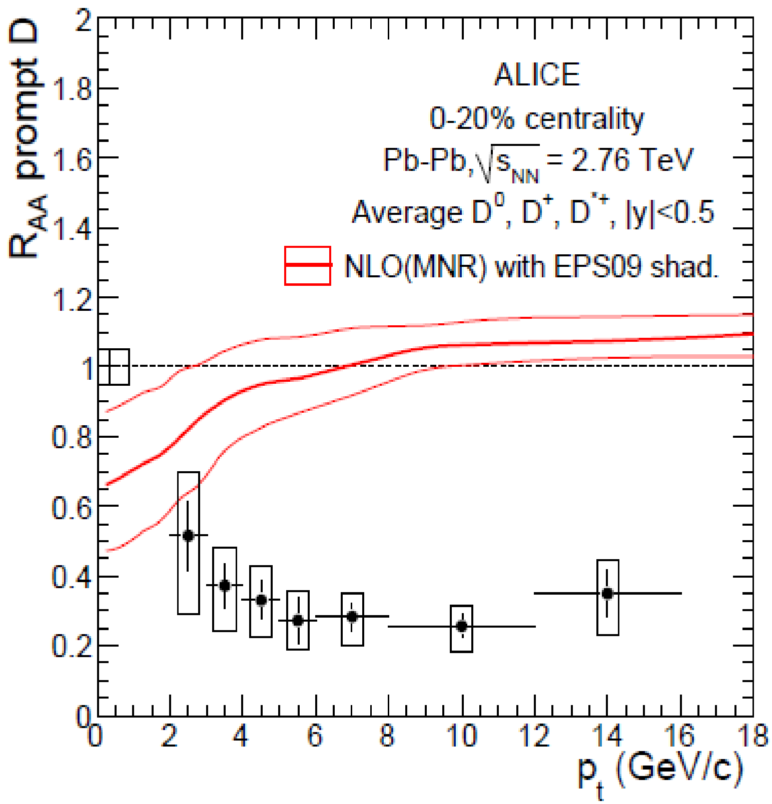
R_AA = 1 if no dense medium is formed

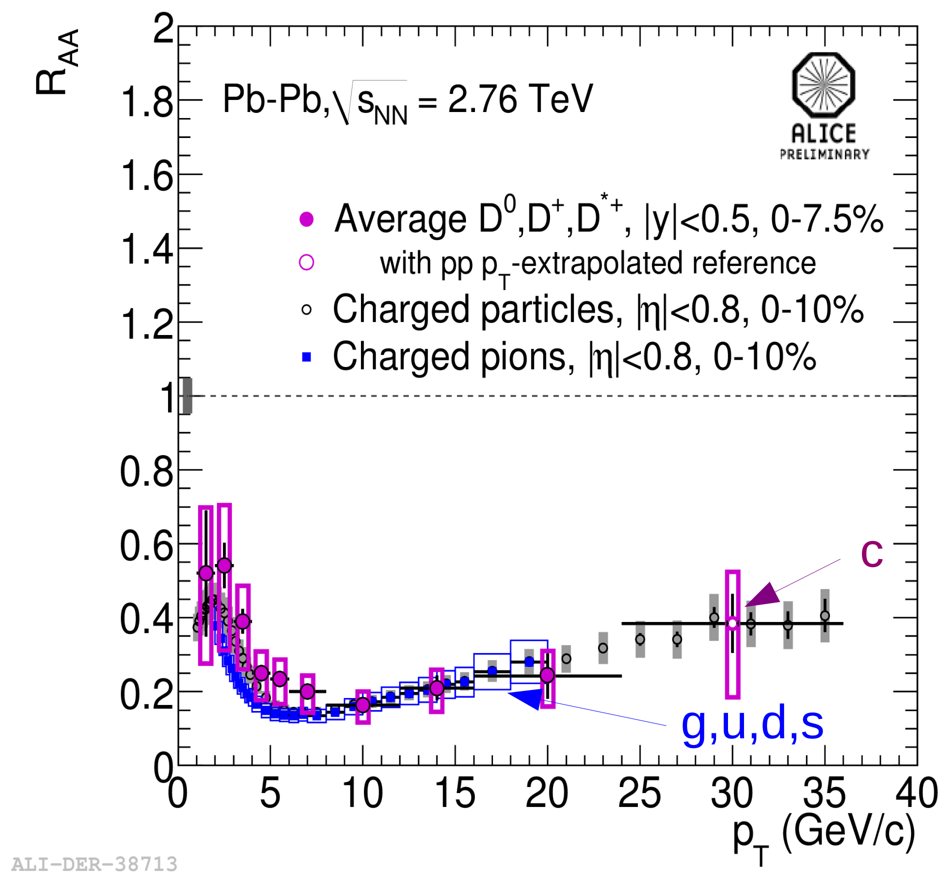
or

if one looks at electro-weak probes

suppression of charm at LHC energ

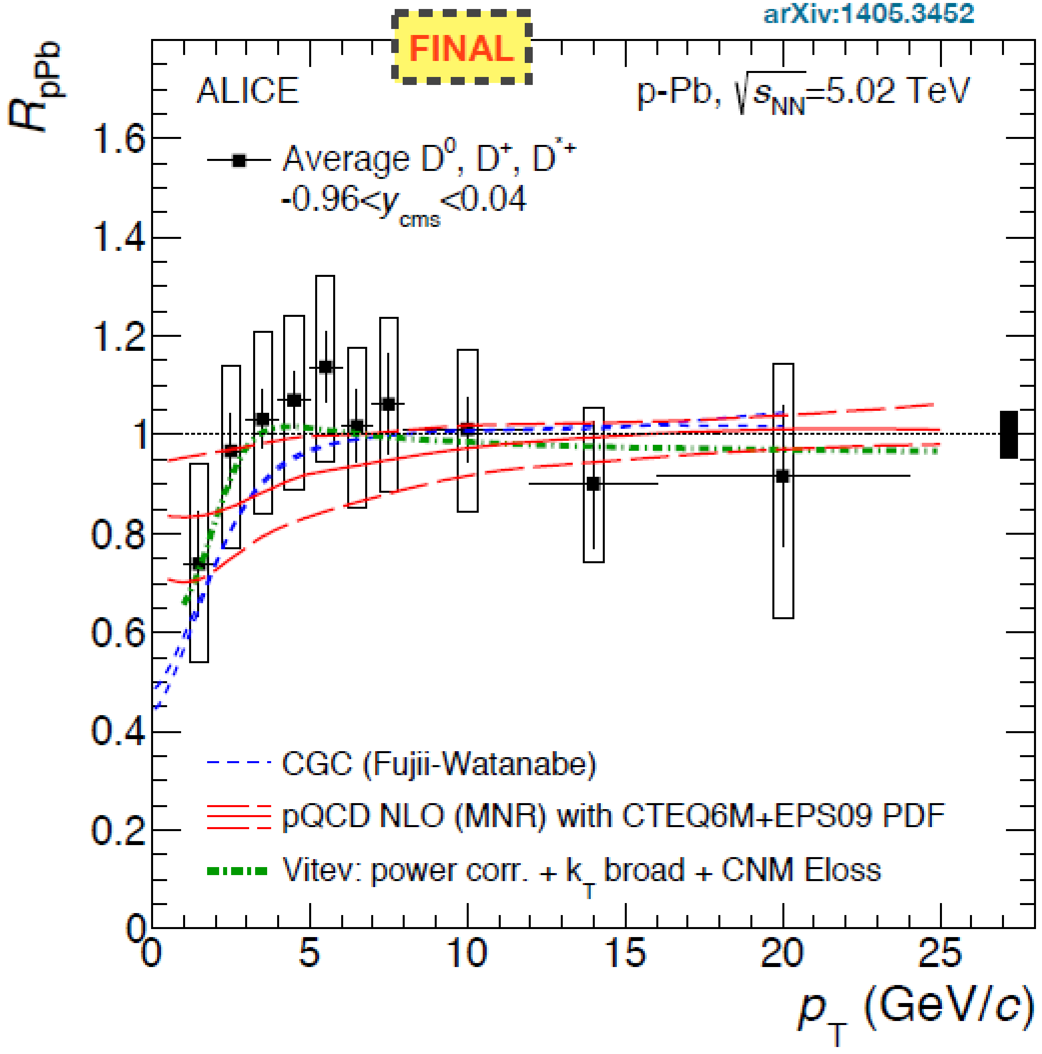
comparison to EPS09 shadowing:
suppression not an initial state effect
will be measured directly in pPb collisions



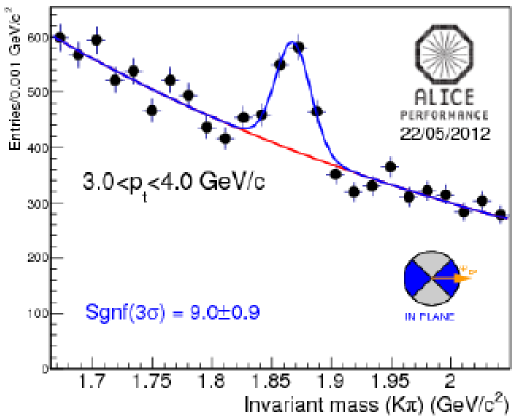


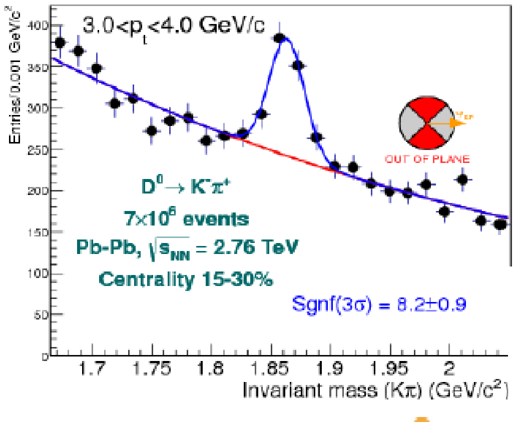
energy loss of charm quarks only slightly less than that for light quark → thermalization

no charm modification in p-Pb collisions



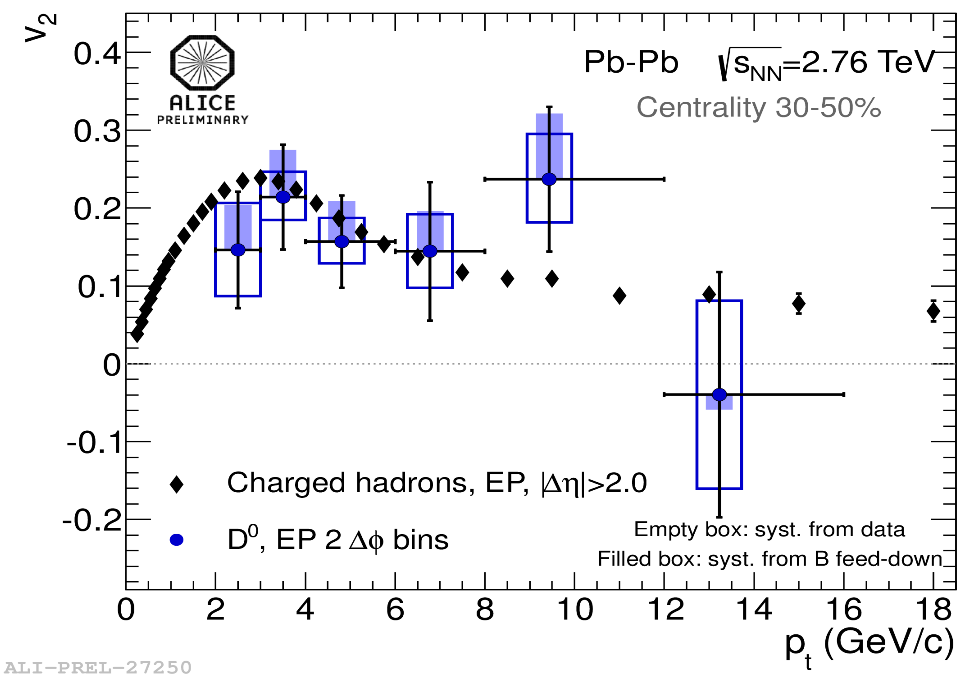
charm Quarks also Exhibit Elliptic Flow





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

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



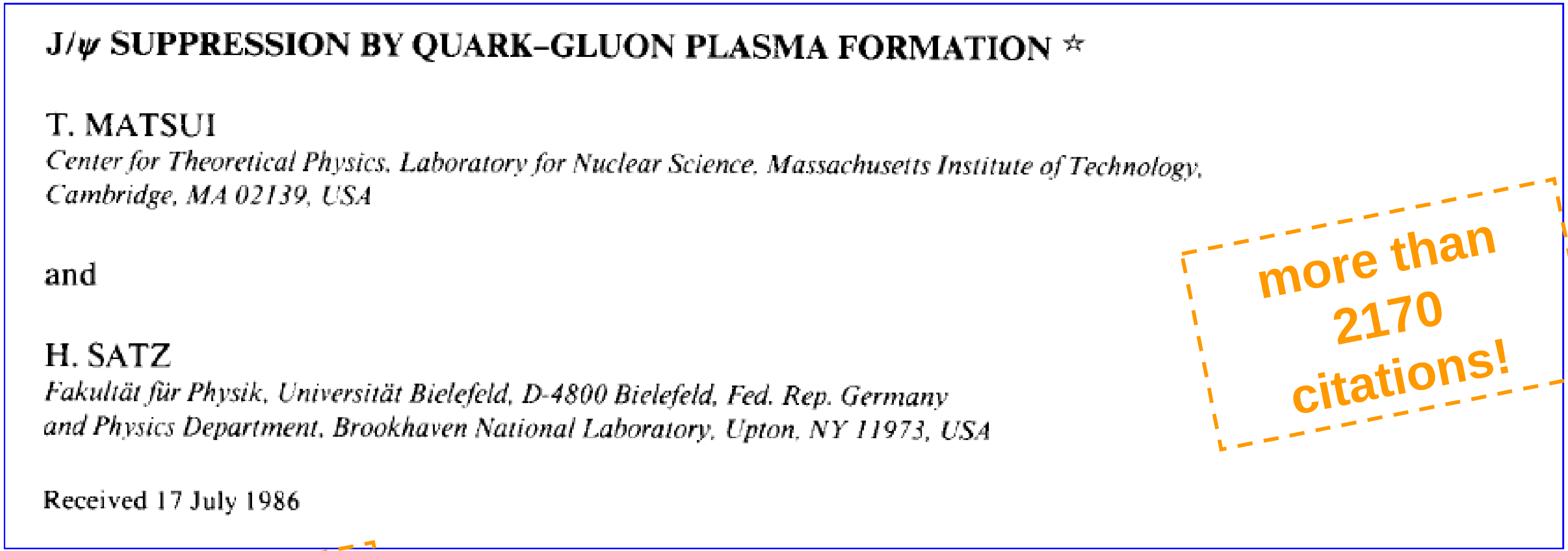
non-zero elliptic flow for 3 σ effect for D^0 2-6 GeV/c
within errors charmed hadron v_2 equal to that of all charged hadrons

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

J/ψ suppression and QGP formation

In 1986, Matsui and Satz argued that the possible suppression of the J/ψ production yield in nuclear collisions should be a clear signal of the phase transition from confined hadronic matter to a deconfined plasma of quarks and gluons.


J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

T. MATSUI
Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

and

H. SATZ
Fakultät für Physik, Universität Bielefeld, D-4800 Bielefeld, Fed. Rep. Germany and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Received 17 July 1986

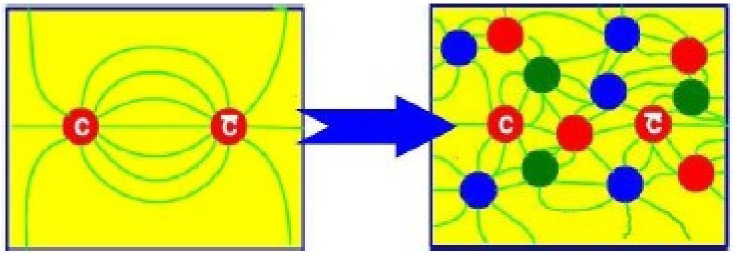
more than 2170 citations!

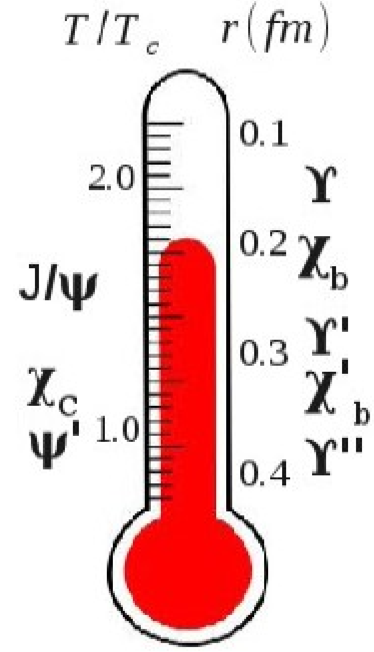
29 years ago!

"...we thus conclude that:

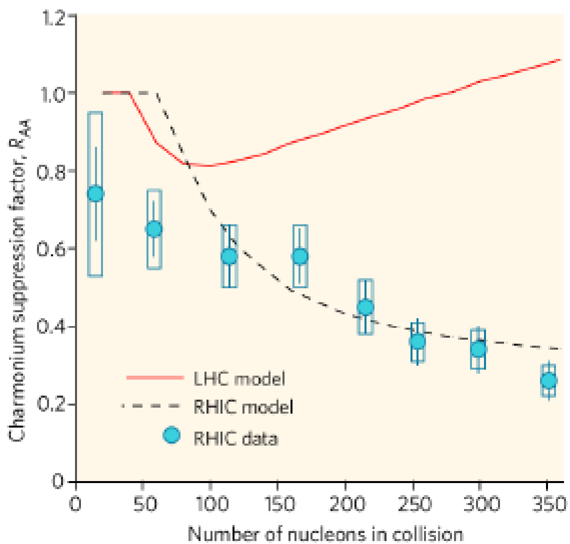
- there appears to be no mechanism for J/ψ suppression in a nuclear collision except the formation of a plasma
- and if such a plasma is produced, there seems to be no way to avoid J/ψ suppression"

color screening





sequential suppression



deconfined charm quarks and
(re-)combination

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 production probability scales with $N(_{ccbar})^2$

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

n.b. at collider energies there is a complete separation of time scales

$t_{coll} << t_{QGP} < t_{Jpsi}$

implanting charmonia into QGP is an inappropriate notion

this issue was already anticipated by Blaizot and Ollitrault in 1988

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?

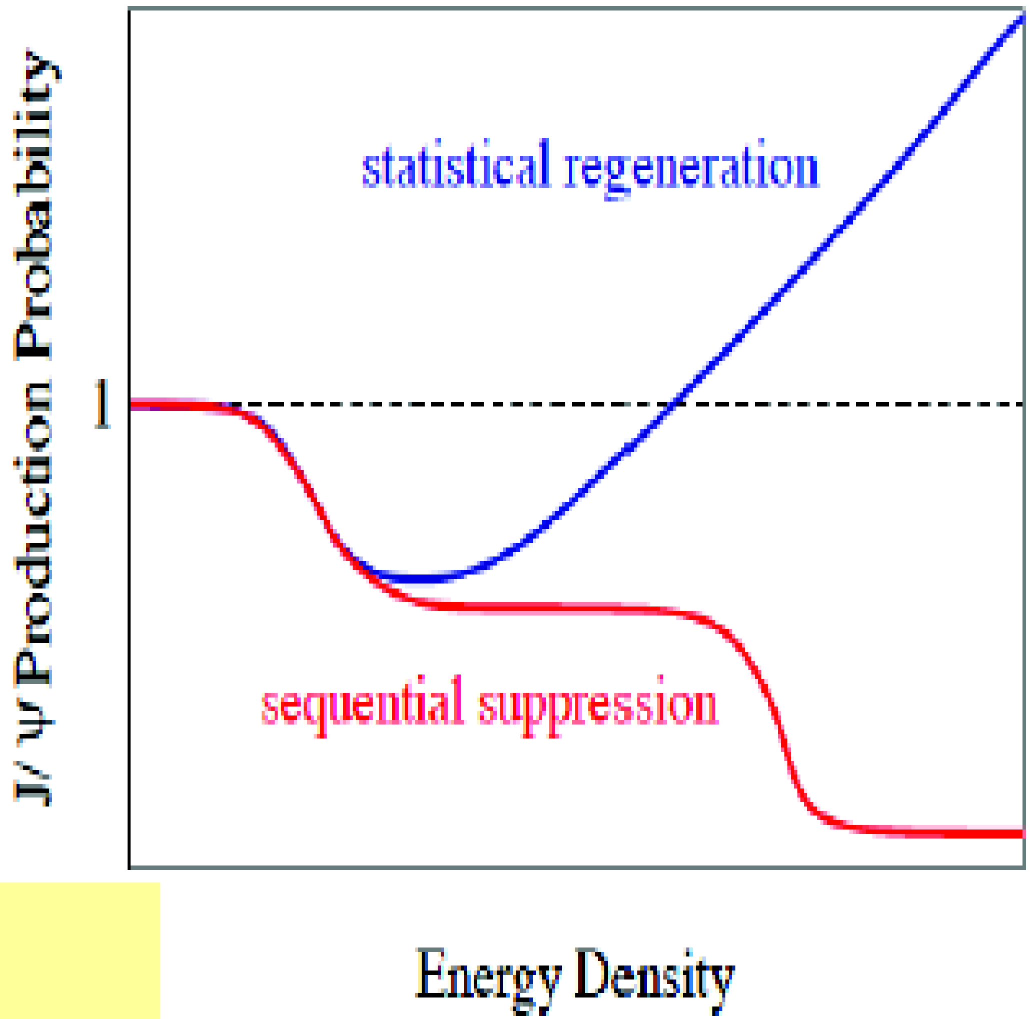
ratios of charmed and beauty hadrons exhibit thermal features (Becattini 1997)
but: psi'/psi ratio is far from thermal in pp collisions
see also Sorge&Shuryak, Phys. Rev. Lett. 79 (1997) 2775, where it is further noted that the psi'/psi ratio reaches a thermal value (T=170 MeV) in central PbPb collisions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

decision on regeneration vs sequential suppression from LHC data



SPS RHIC LHC

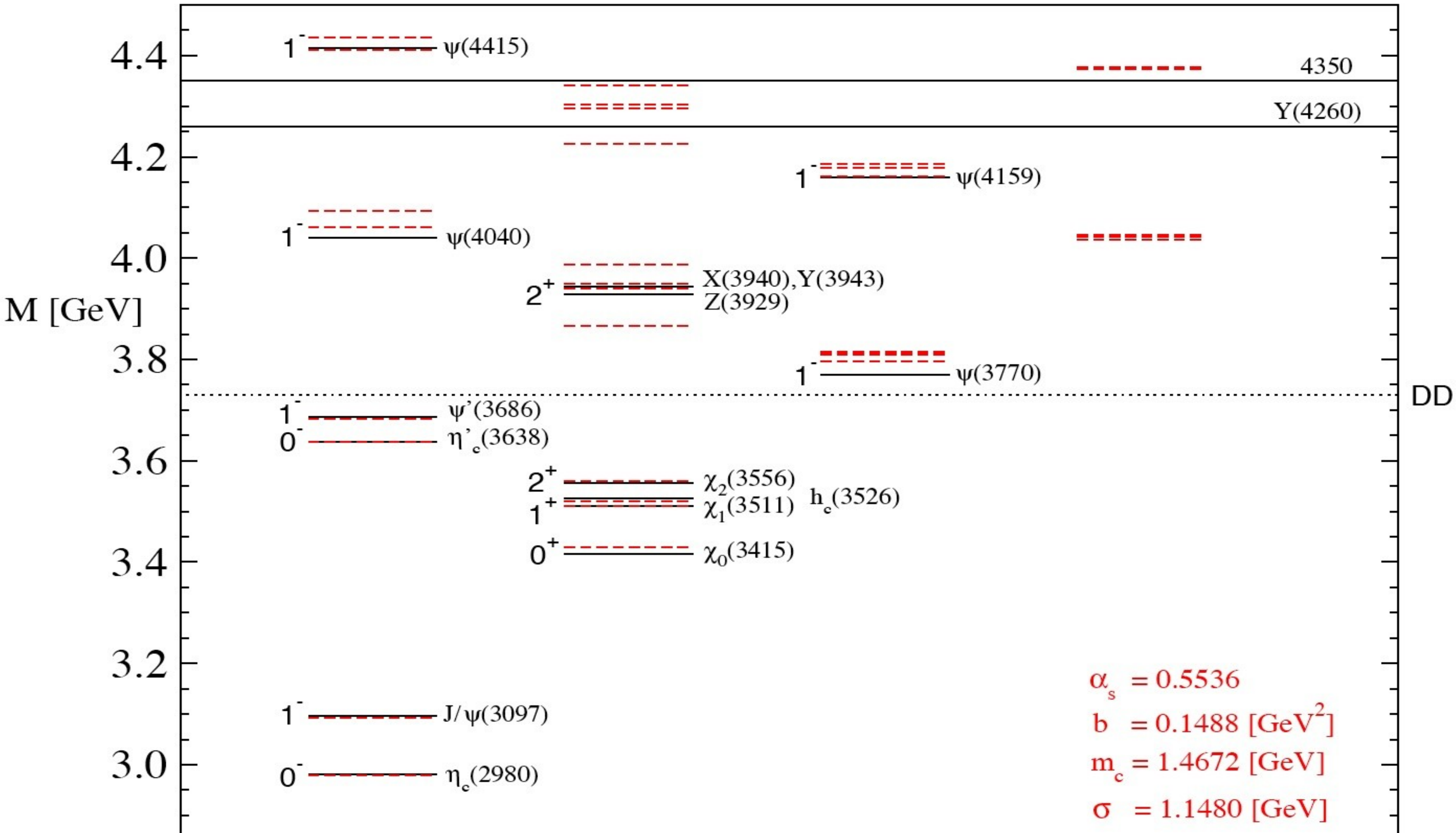
Picture:
H. Satz 2009

Charmonium

- a bound state of charm and anti-charm quarks
- mass of lowest 1- state (J/ψ) = 3.1GeV
  but its width is only 93 keV
- mass of charm quark 1.2 – 1.3 GeV
- binding energy about 600 MeV
- charm quarks move non-relativistically

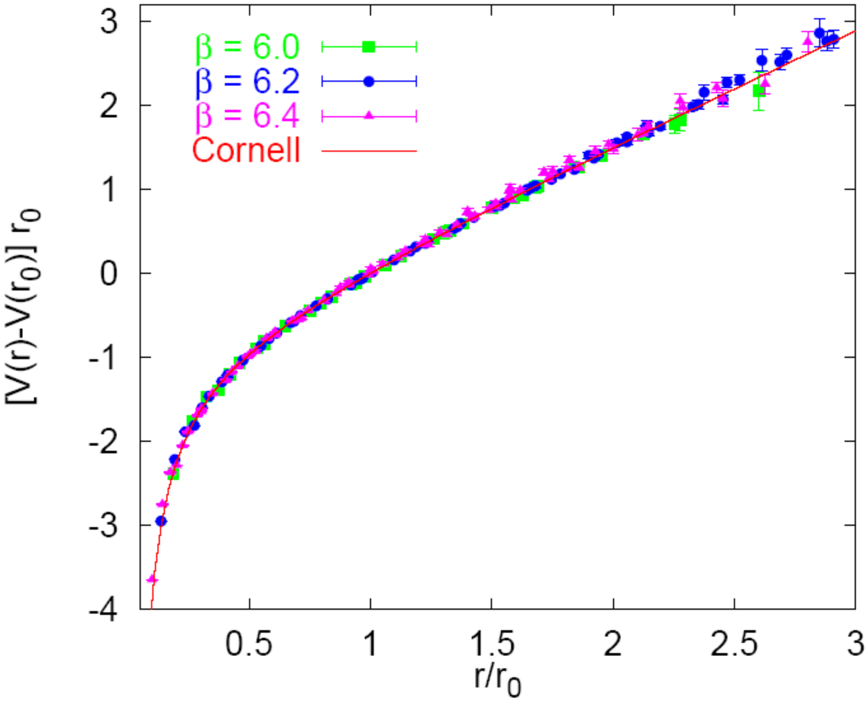
The charmonium spectrum and non-relativistic potential models

(courtesy Ted barnes)

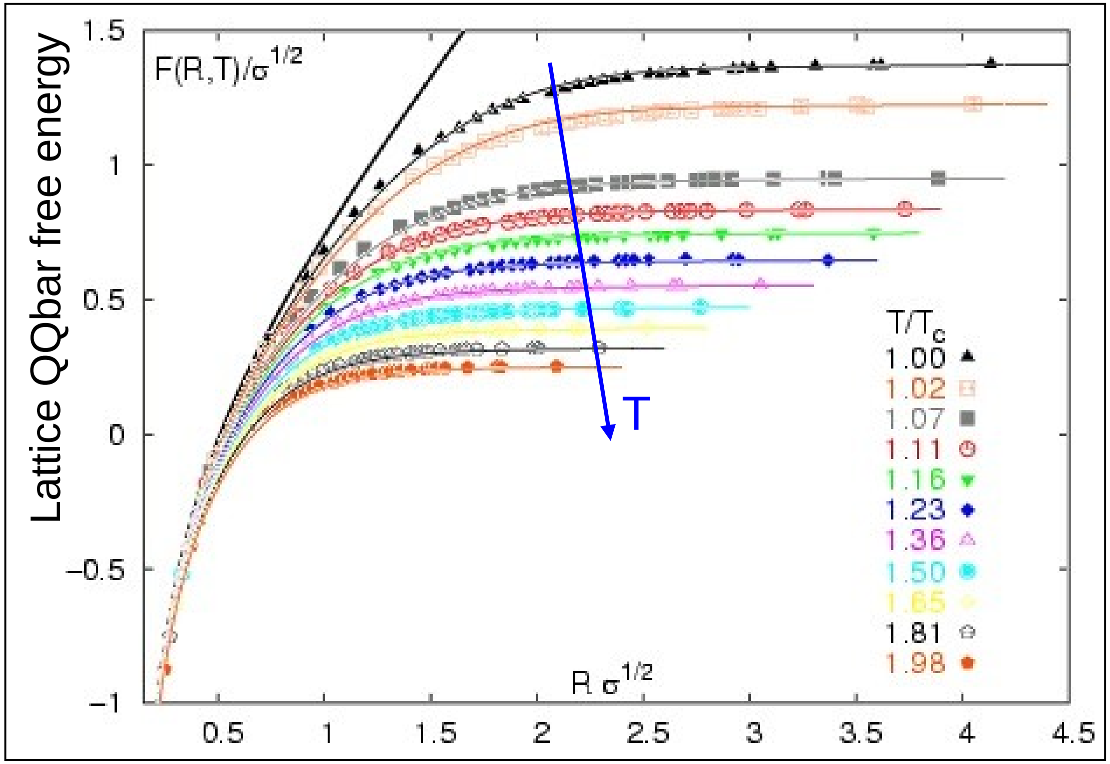


The c-cbar potential

in the vacuum



in the medium



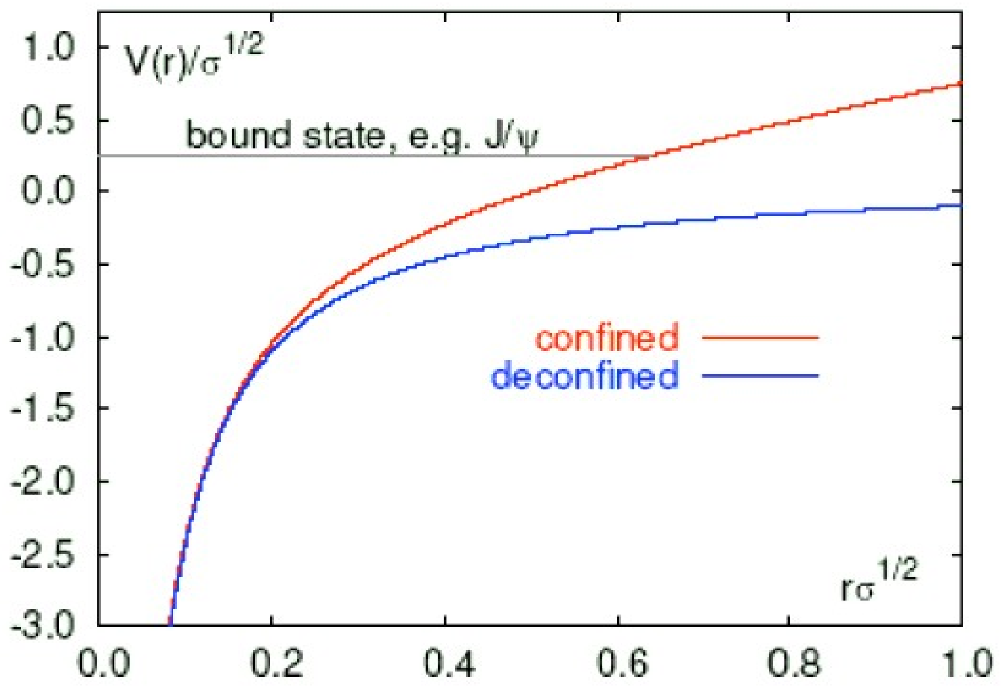
clear evidence for color screening in a static medium with full thermal equilibrium

simulations: Hot QCD coll.

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

Debye screening

for the medium to change the binding potential the J/psi must interact with it strongly

lattice calculation: complete equilibrium at temperature T

rough estimate:
potential period: $\hbar\omega$ = 400 MeV

$T_p = \pi$ fm/c

J/psi should be near equilibrium with medium for Debye screening potential to build up and should interact with the medium for a time of at least T_p

There is no Debye screening without equilibration of the heavy quarkonium!

Can this ever be achieved for the Y family?
The p_t spectrum should approach a thermal distribution.

Statistical hadronization in one page

Thermal model calculation (grand canonical) T, μ_B: $\rightarrow n_X^{th}$

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

$N_{c\bar{c}} << 1 \rightarrow$ <u>Canonical:</u> 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, $\quad V = N_{ch}^{exp} / n_{ch}^{th}$, $\quad N_{c\bar{c}}^{dir}$ (pQCD)

related approaches

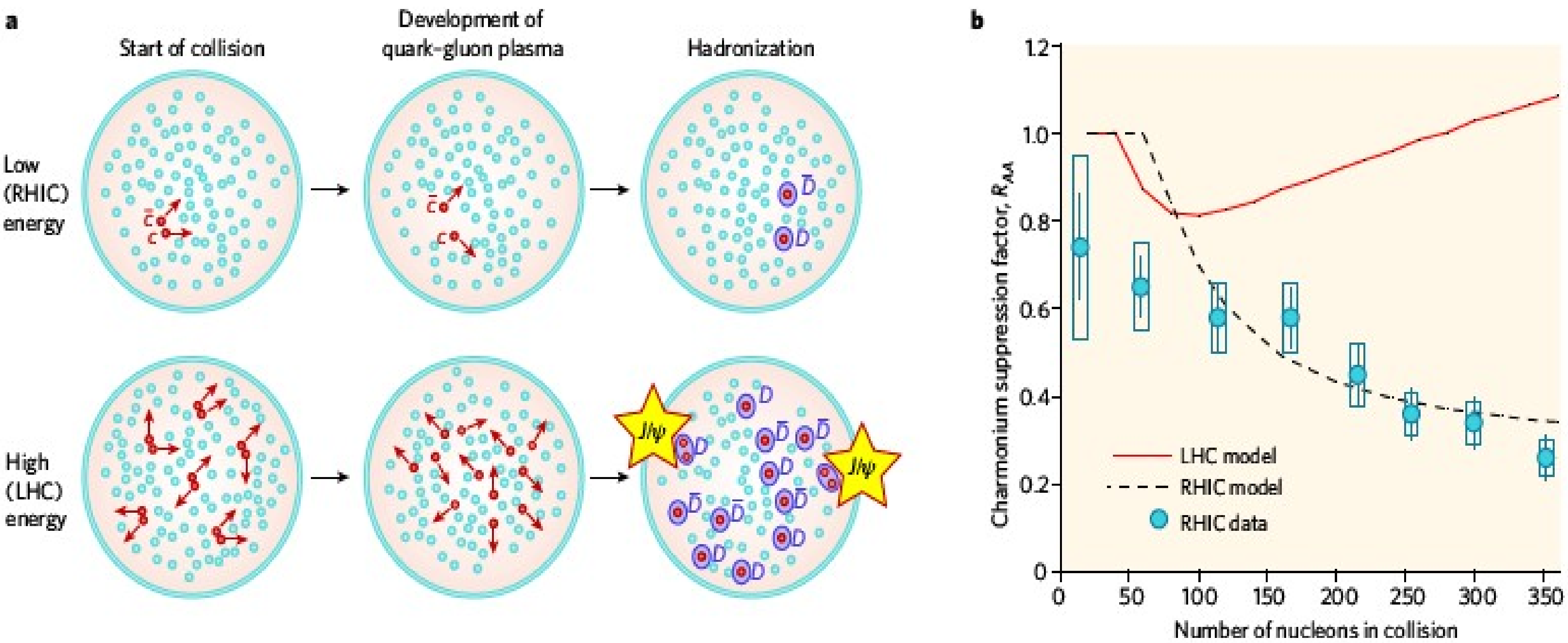
alternative to statistical hadronization: implementation of screening into space-time evolution of the fireball – continuous destruction and (re)generation

Thews et al, 2001, Rapp et al. 2001, Gorenstein et al. 2001, P.F. Zhuang et al. 2005

for a very recent new approach see Blaizot et al, arXiv:1503.03857.

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

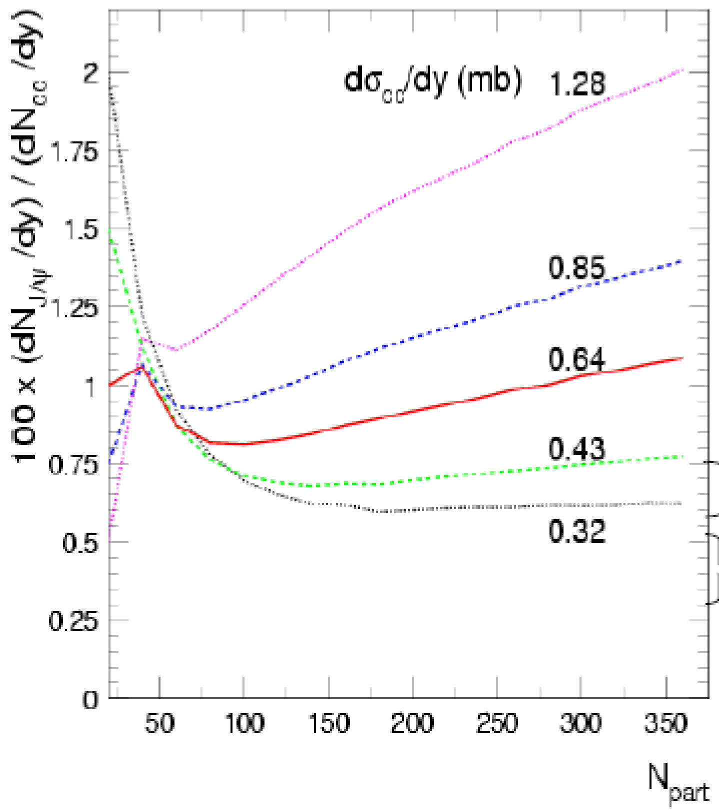
P. Braun-Munzinger, J. Stachel, The Quest for the Quark-Gluon Plasma, Nature **448** Issue 7151, (2007) 302-309.



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

dependence of enhancement on charm cross section



open charm is natural and essential normalization

precision measurement needed

mid-y LHC 2.76 TeV including shadowing

forward-y LHC 2.76 TeV including shadowing

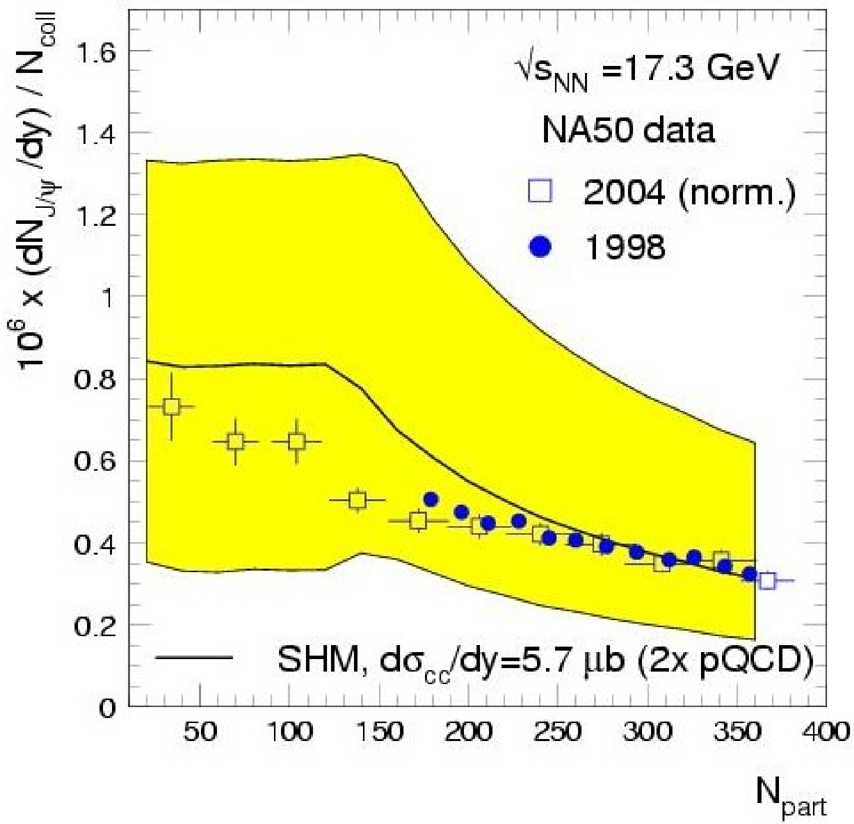
A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel Phys. Lett. B652 (2007) 259

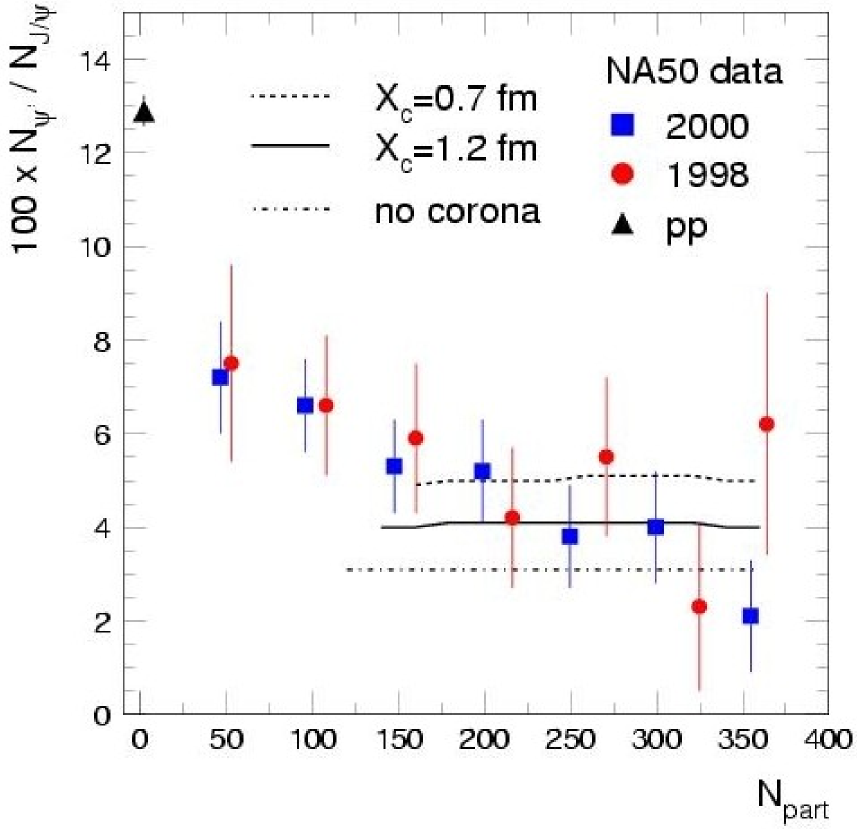
ingredients for prediction of quarkonium and open charm cross sections

• 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

results for SPS energy



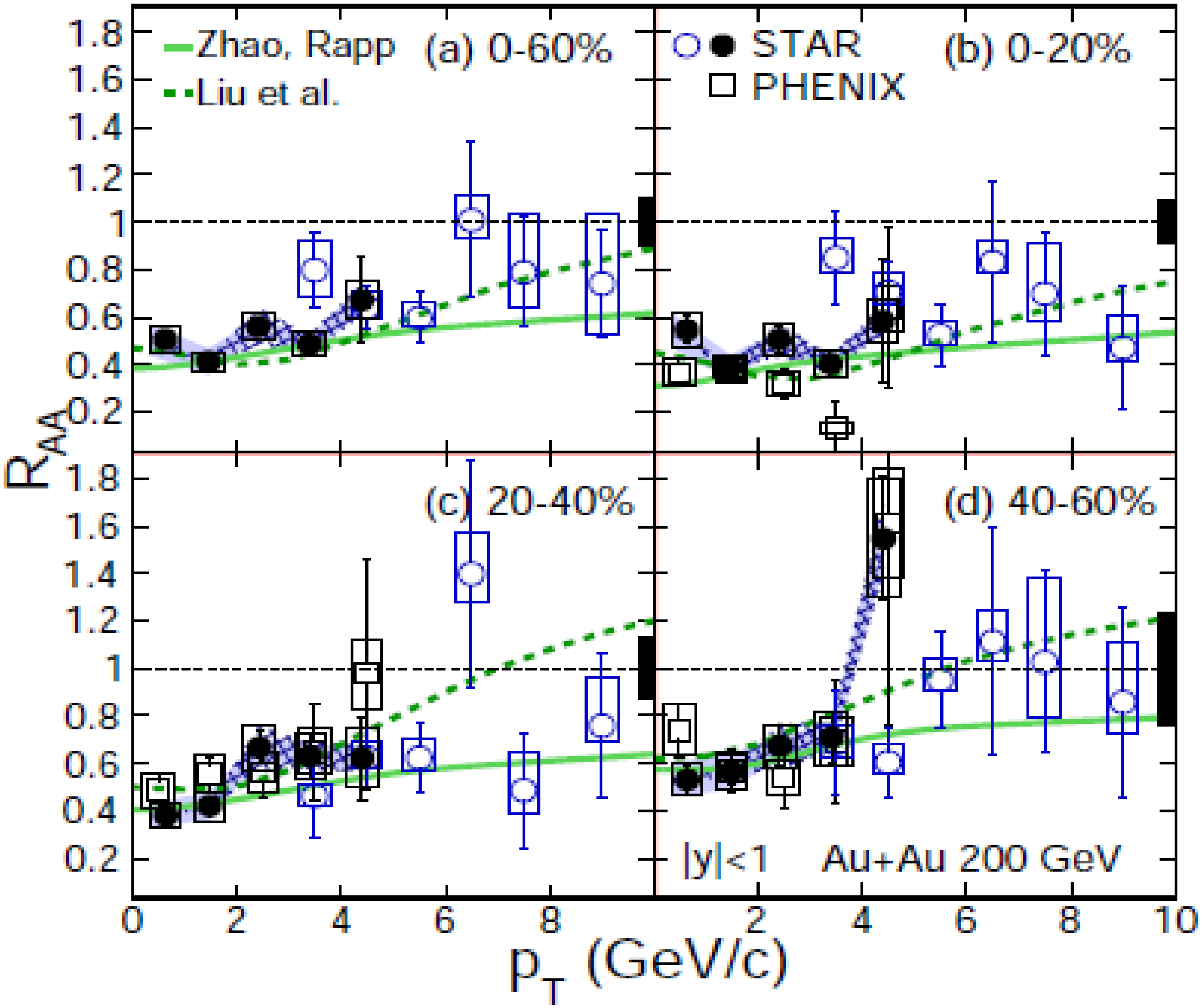


only moderately enhanced (2 x pQCD) cc_bar cross section needed

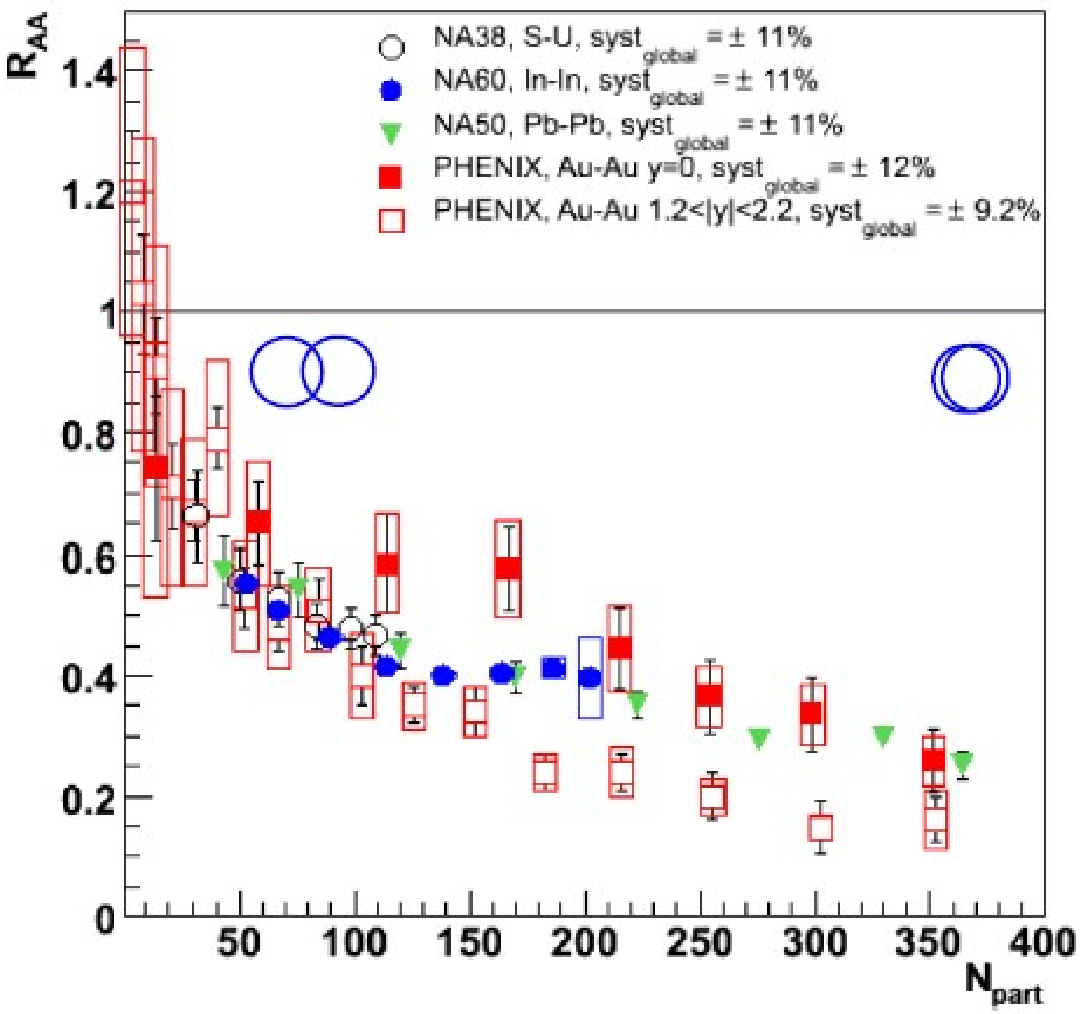
psi'/psi ratio is expected from a thermal scenario

a brief look at RHIC data

Star and Phenix results: similar picture

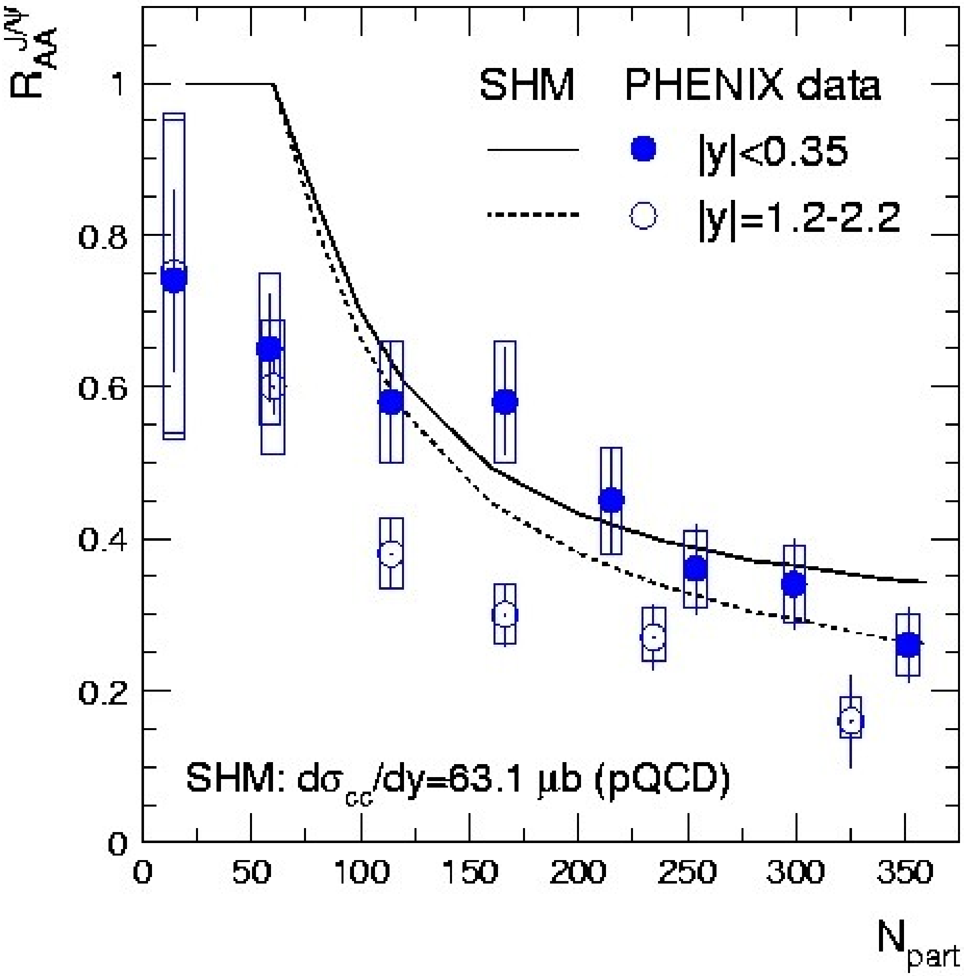


now brief survey of SPS and RHIC results



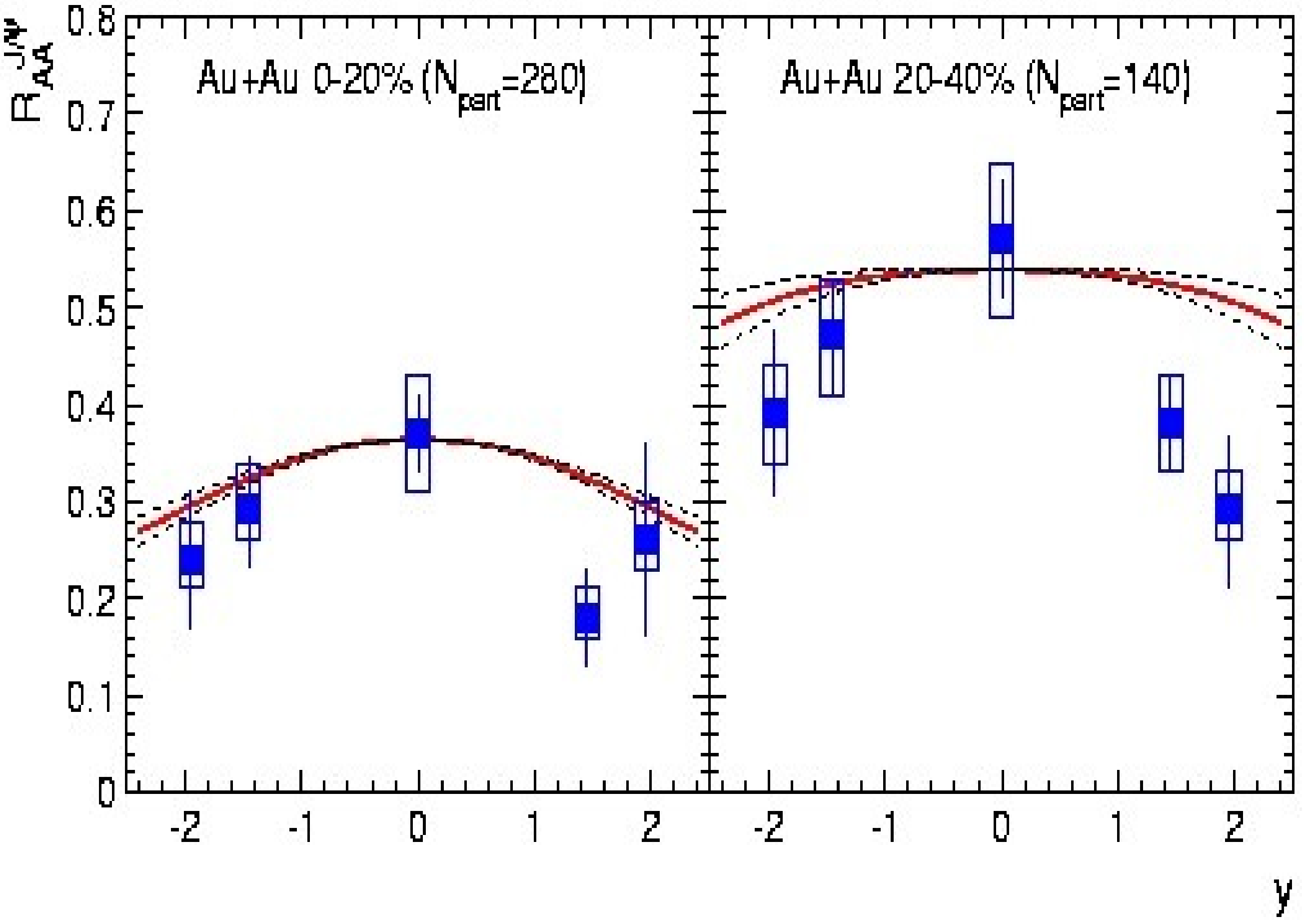
nuclear modification factor nearly unchanged between SPS and RHIC energies, unanticipated rapidity dependence, apparently no scaling with energy density

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 lower energy (SPS, RHIC) results

first indications for (re-)generation picture

interpretation not unique

now to LHC data

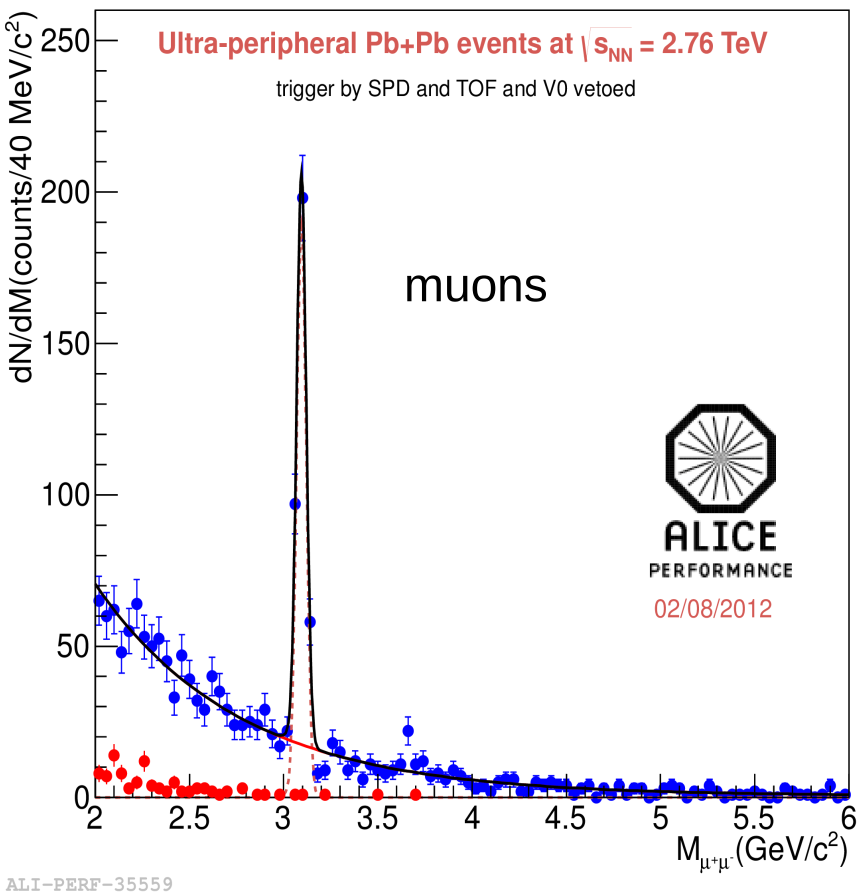
attempt full measurement of open charm and open beauty
in pp, pPb, PbPb as function of centrality, rapidity and transverse momentum

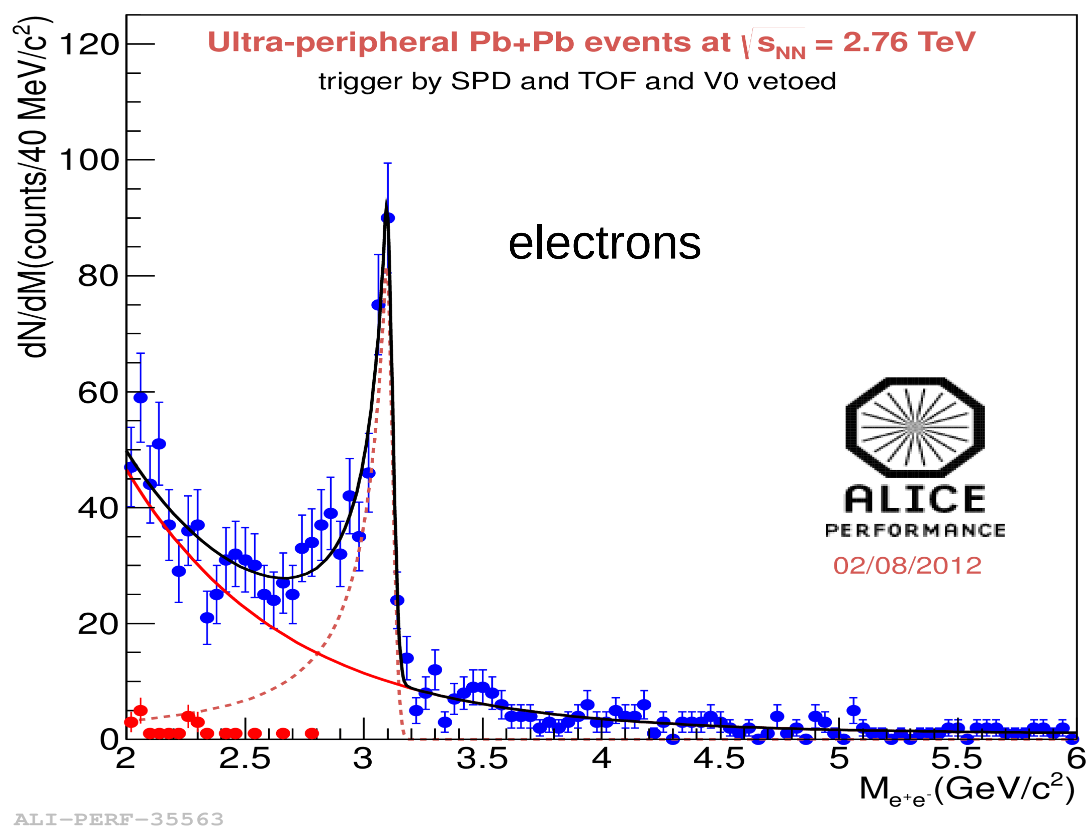
attempt full measurement including polarization of all quarkonia
in pp, pPb, PbPb as function of centrality, rapidity and transverse momentum

...we are on the way

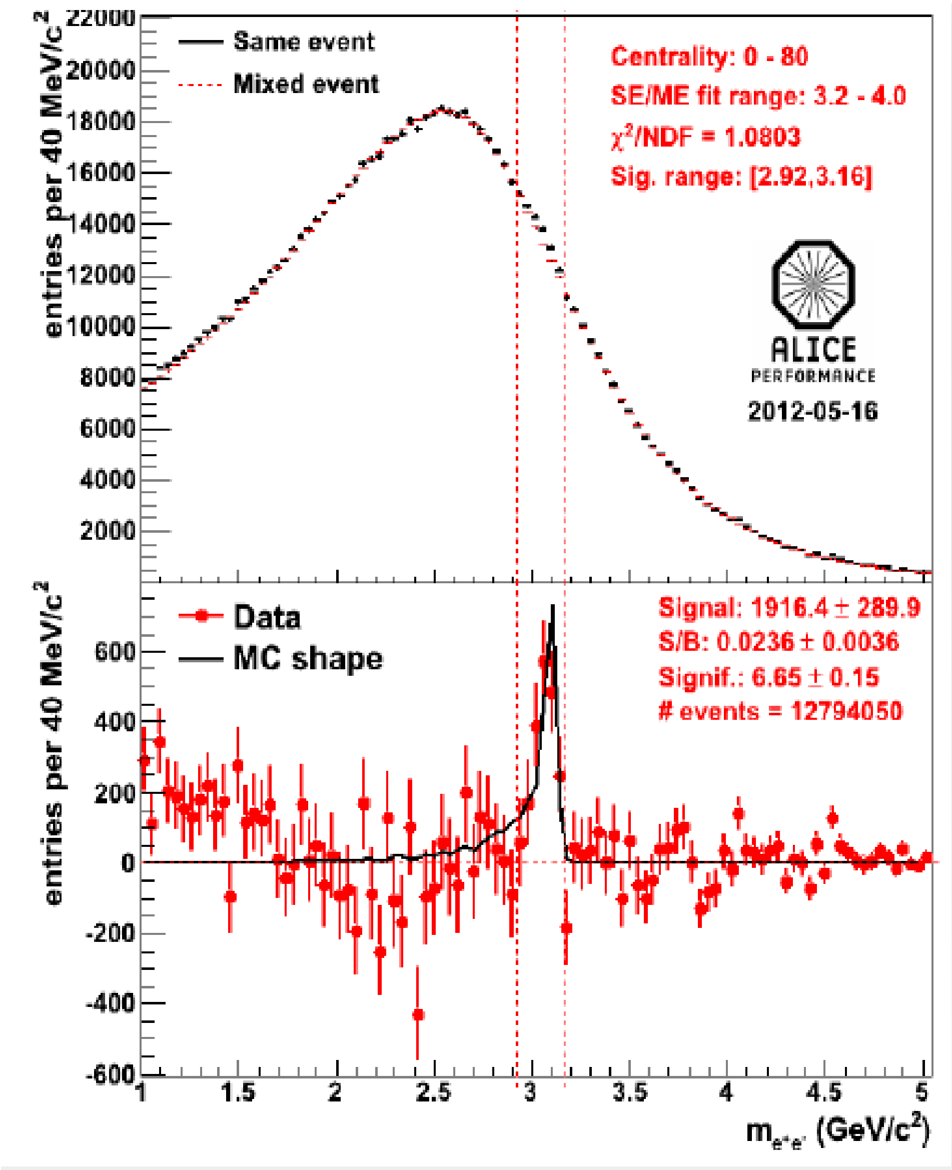
J/psi line shape in ultra-peripheral Pb—Pb collisions

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





J/psi 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

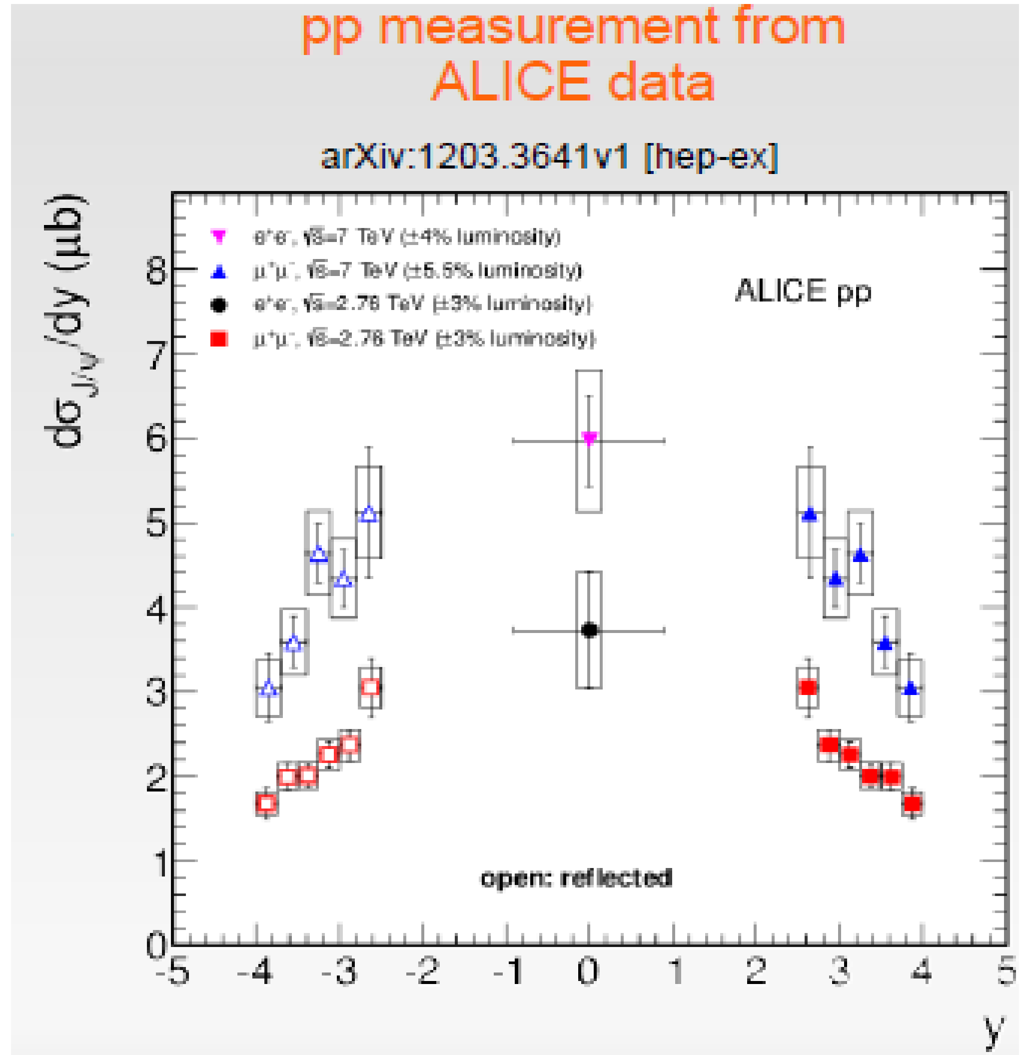
pp @ 2.76 TeV reference for the nuclear modification factor R_{AA} in Pb-Pb collisions

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

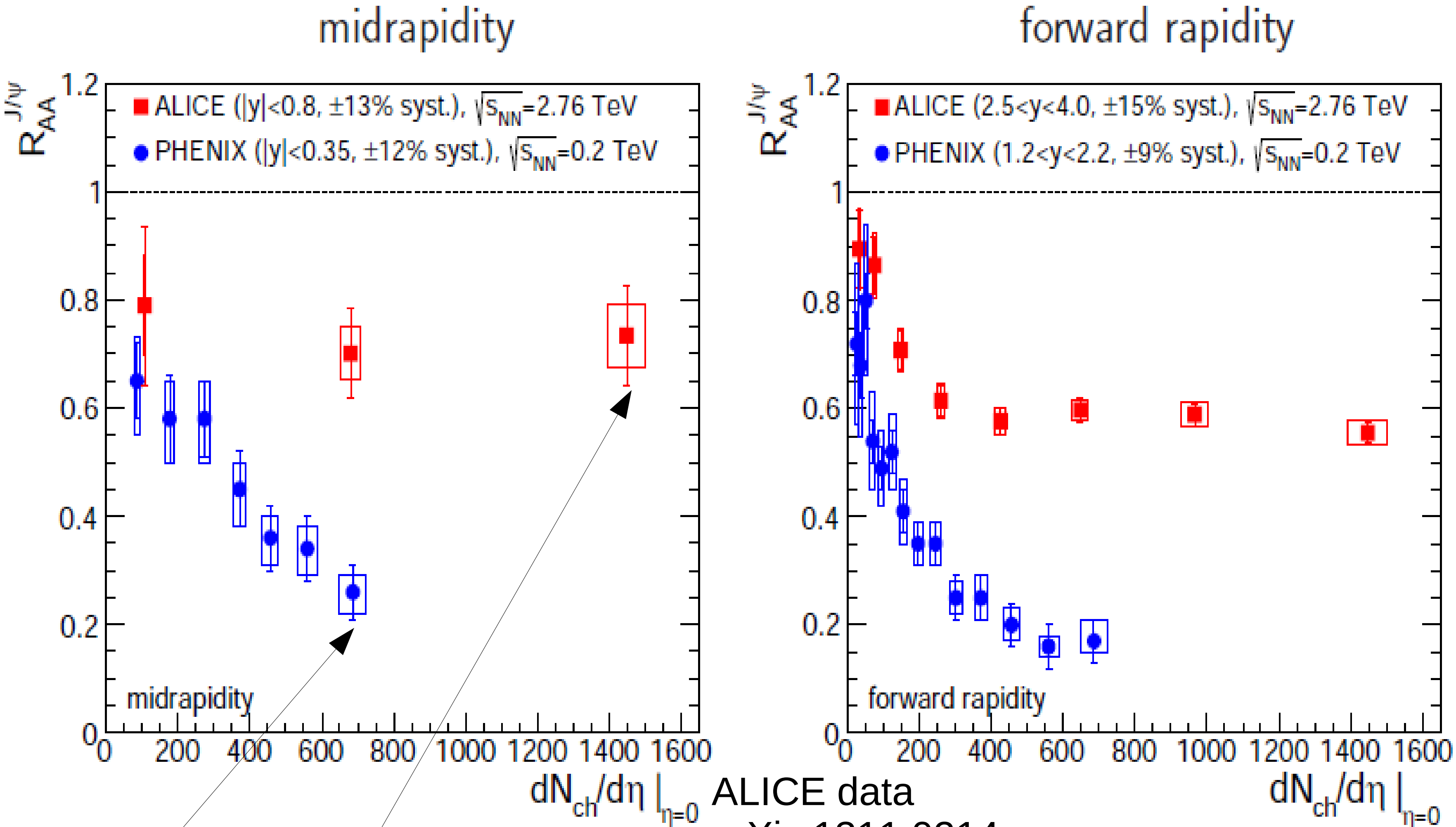
the pp reference is also the main source of systematic uncertainty in the R_{AA} computation:

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

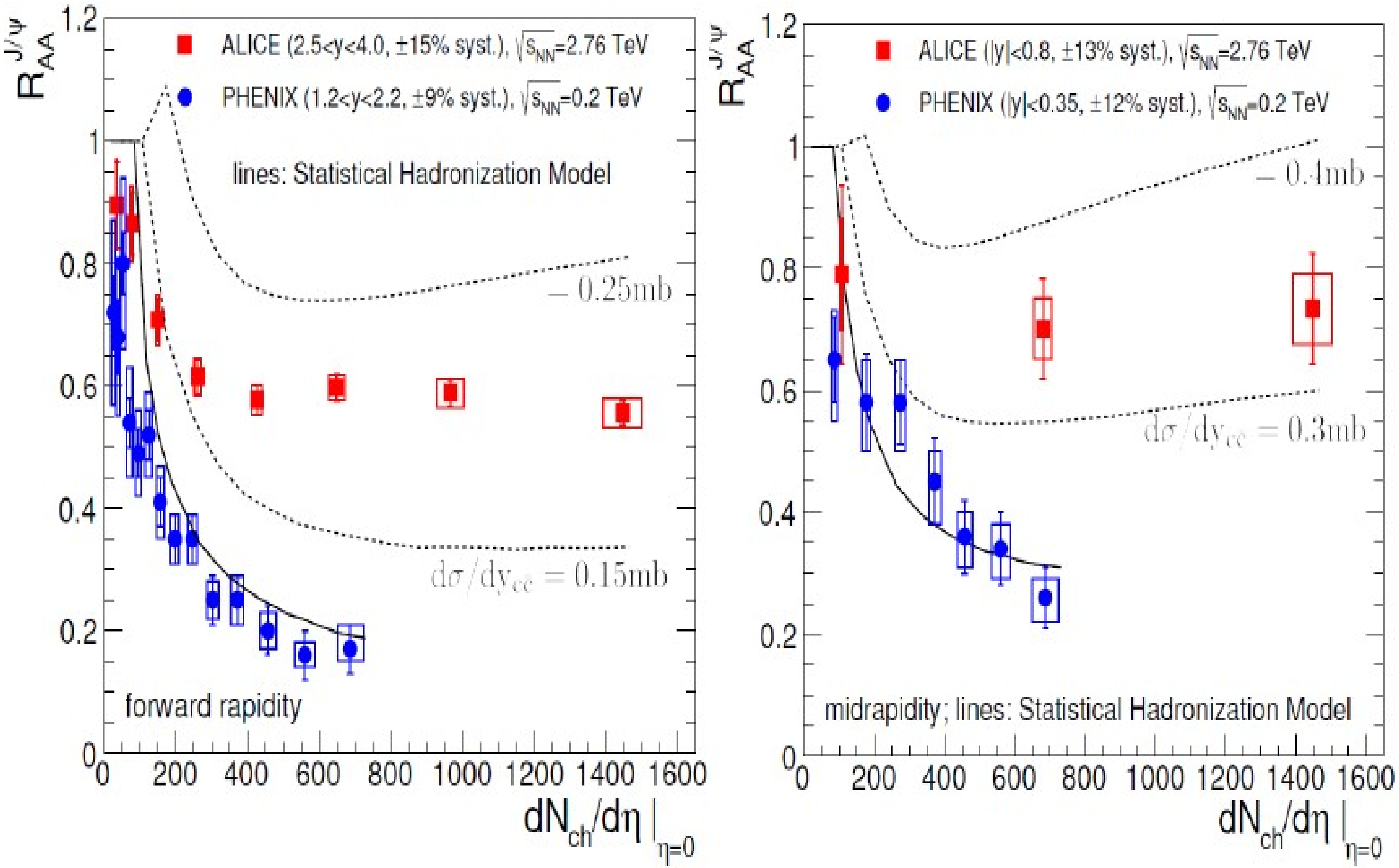


ALICE data
arXiv:1311.0214
PLB 743 (2014) 314

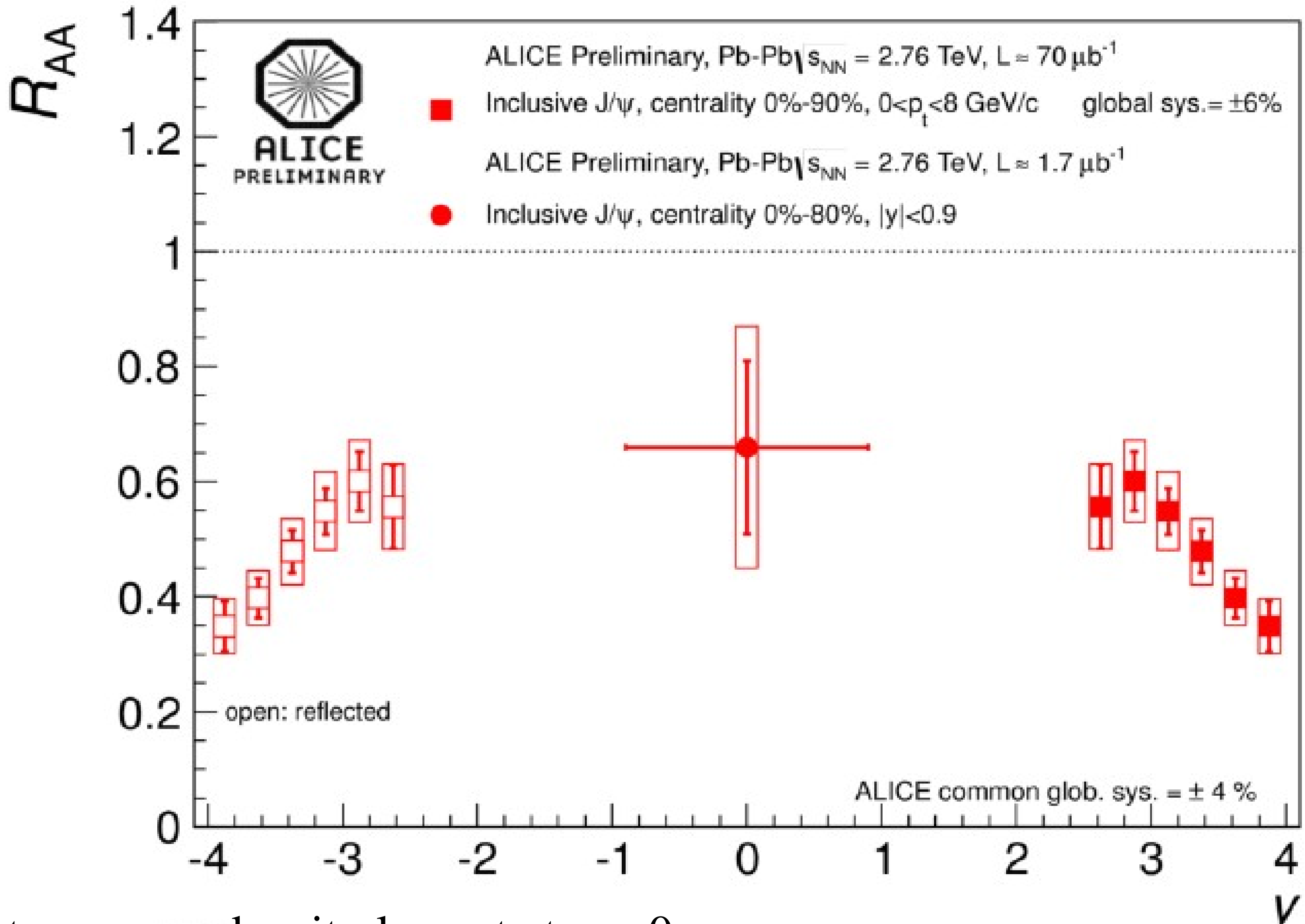
from here to here more than factor of 2 increase in energy density, but R_{AA} increases by more than a factor of 3

2007 prediction impressively confirmed by LHC data

Comparison to Statistical Hadronization Model Prediction



Rapidity dependence



note: energy density largest at y = 0

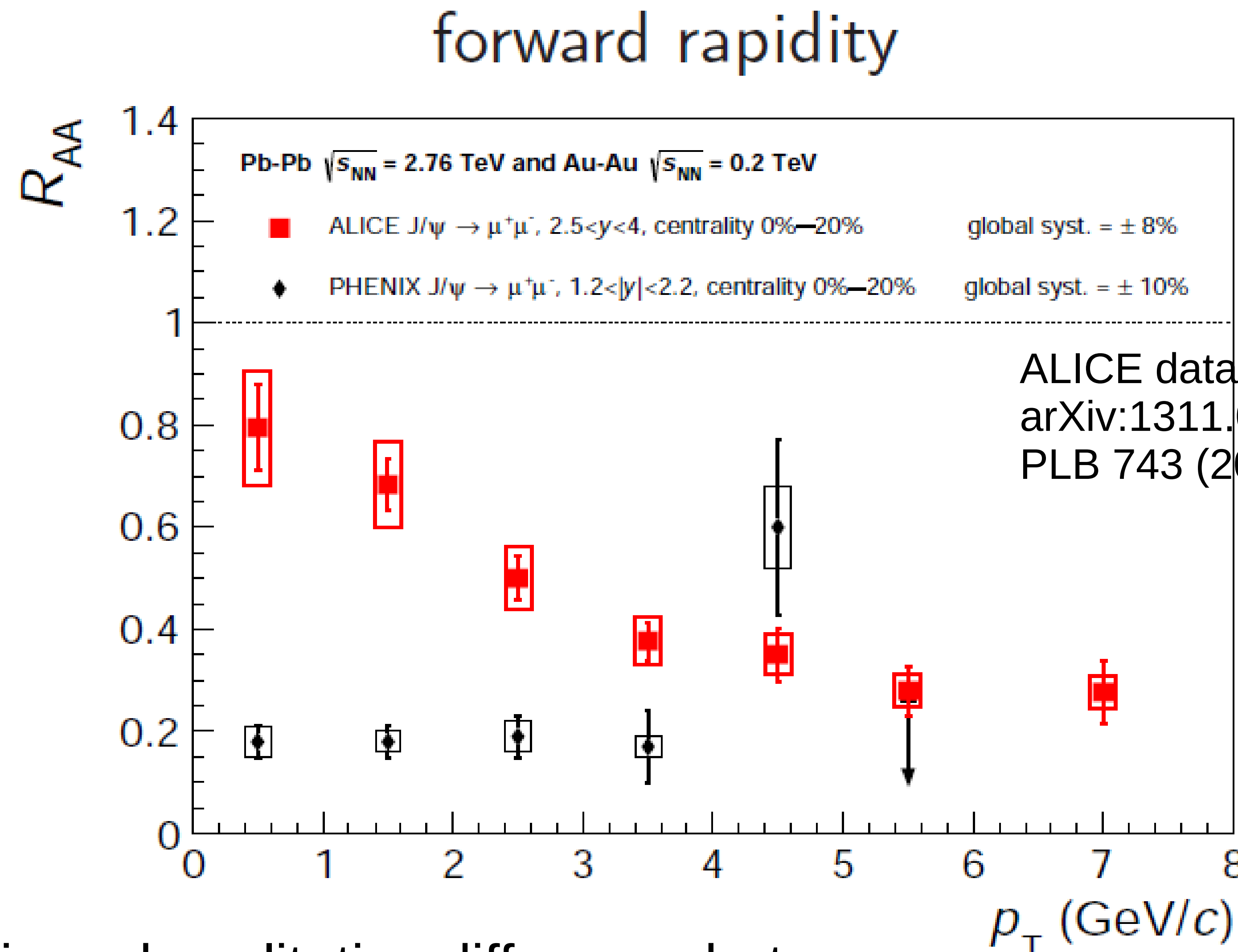
back to J/psi data – what about spectra and hydrodynamic flow of charm and charmonia?

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

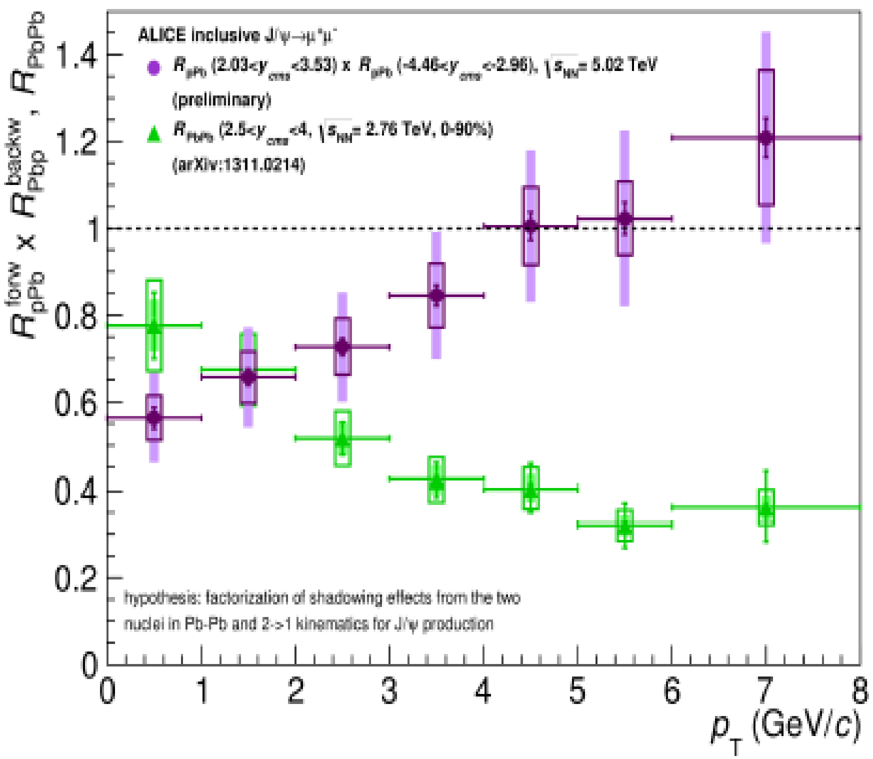


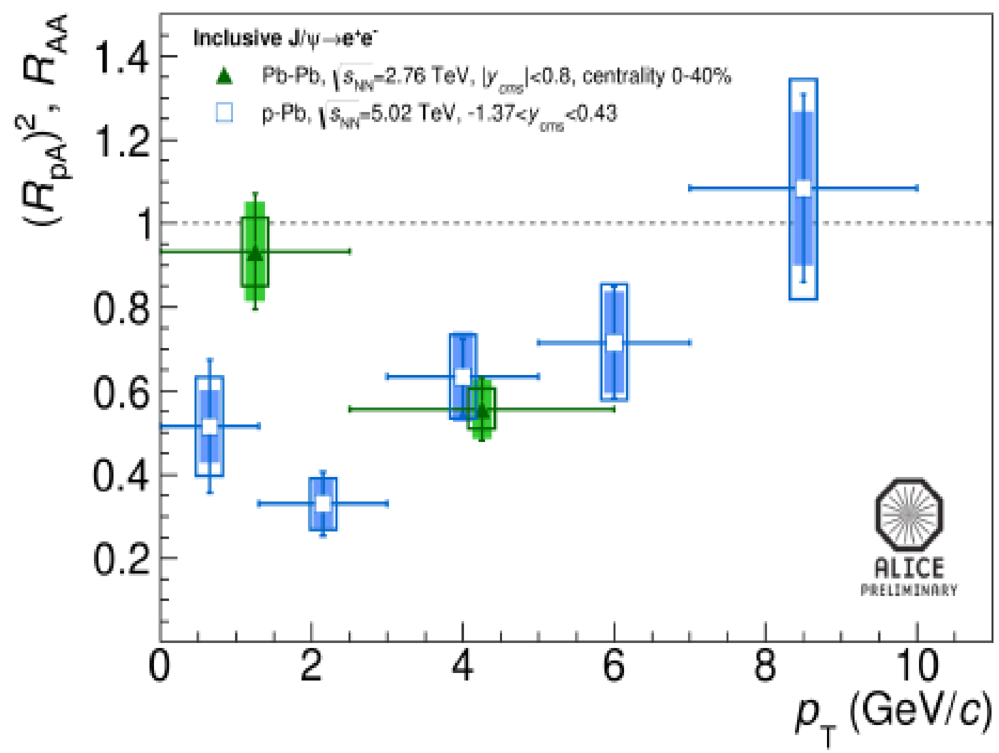
ALICE data
arXiv:1311.0214
PLB 743 (2014) 314

dramatic and qualitative difference between RHIC and LHC results

Comparison Pb-Pb to pPb

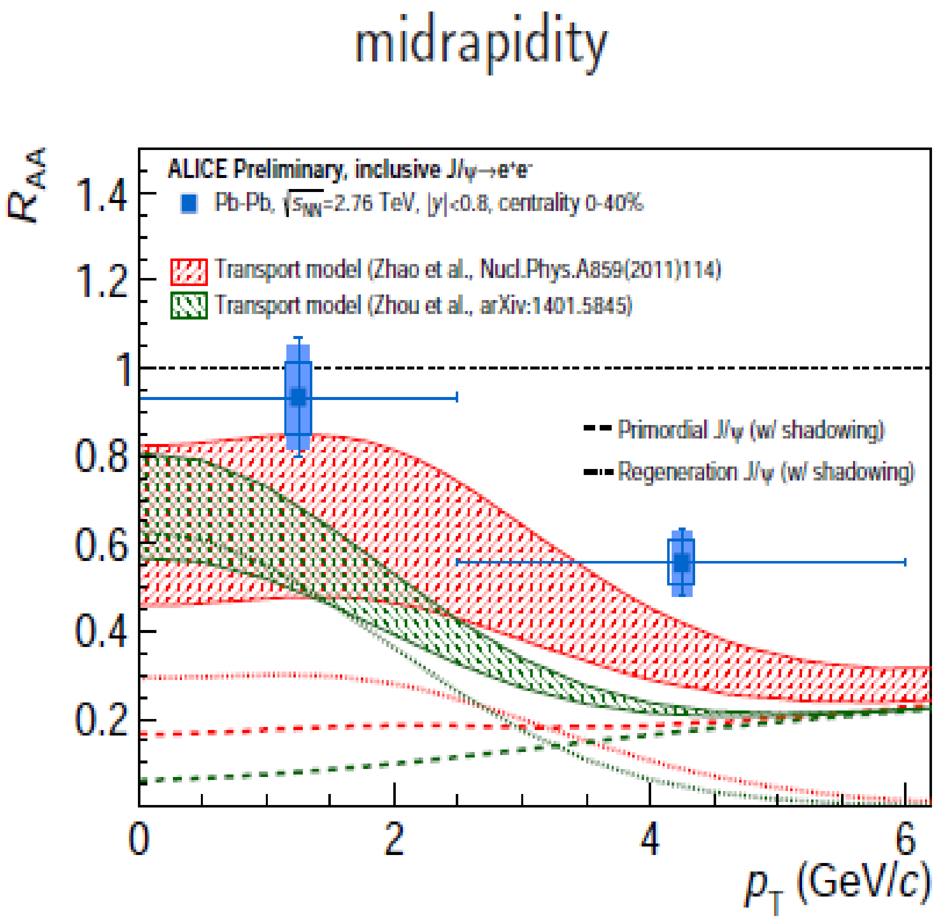
data: ALICE JHEP 1402, arXiv:1308.6726 and arXiv:1405.1177 and arXiv:1404.1615

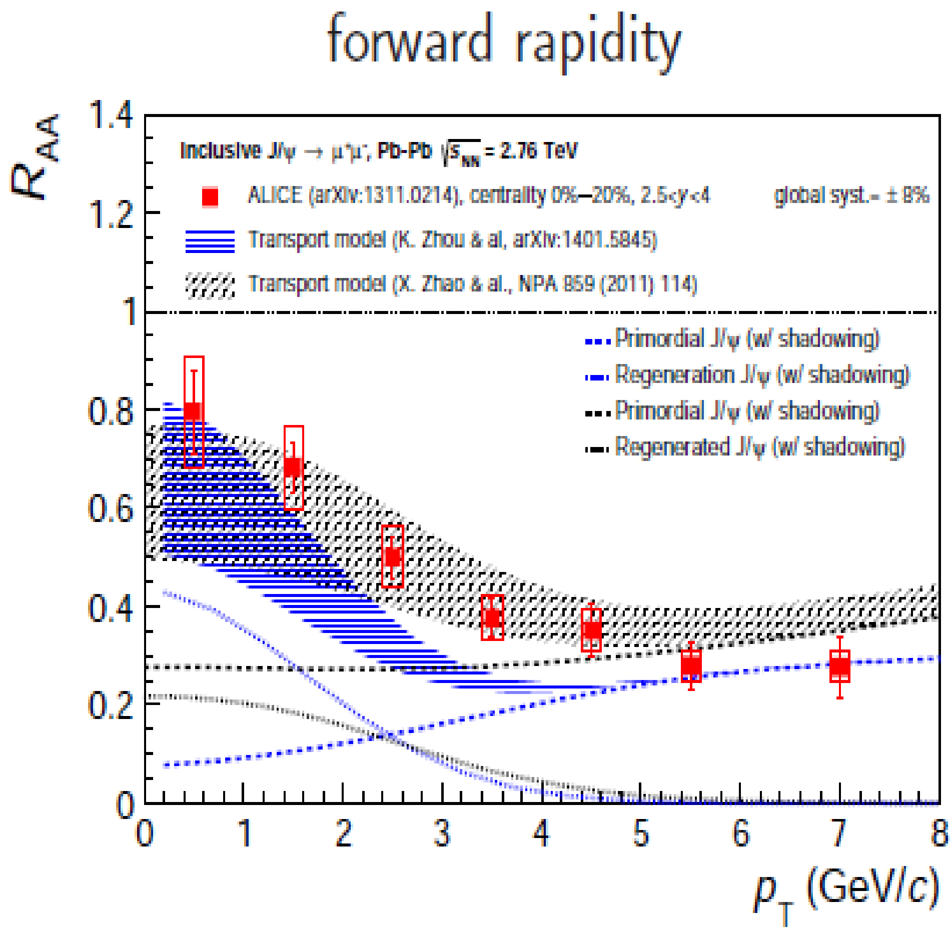




J/psi production in Pb-Pb is enhanced beyond shadowing

comparison with (re-)generation models





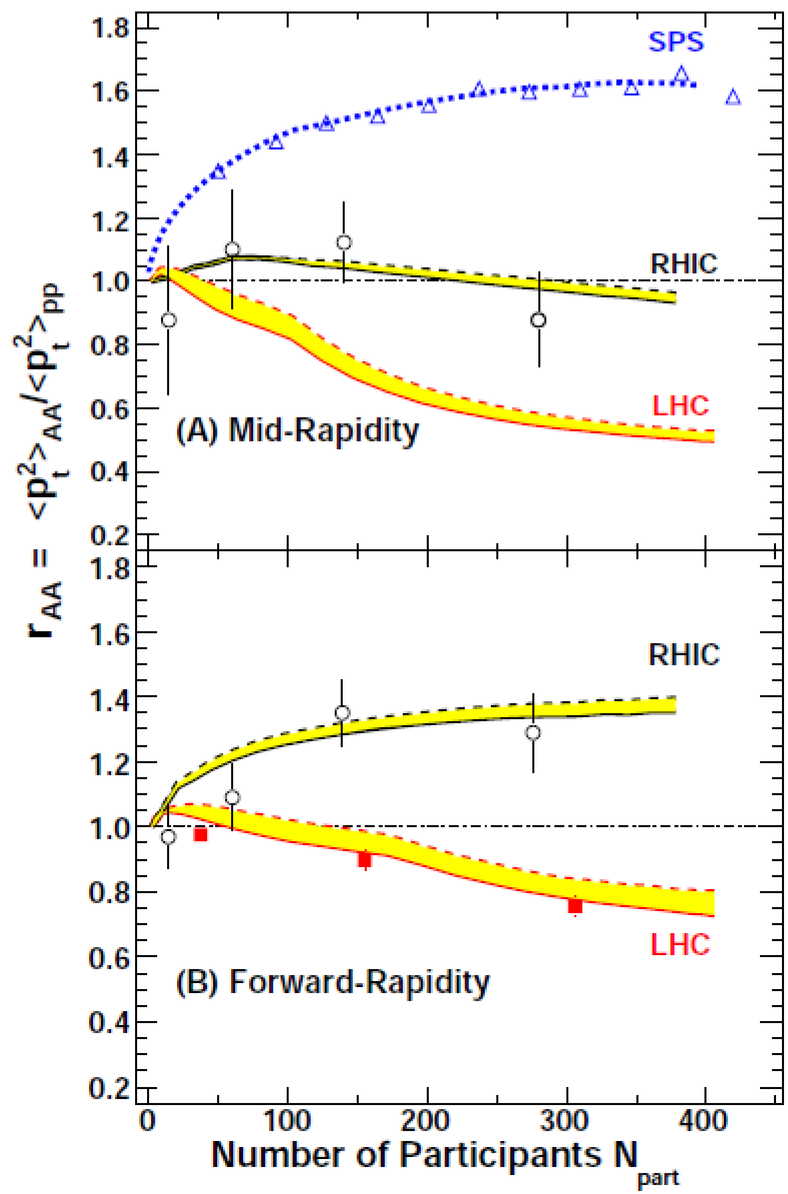
good agreement lends further strong support to the
'full color screening and late J/psi production' picture

analysis of transverse momentum spectra

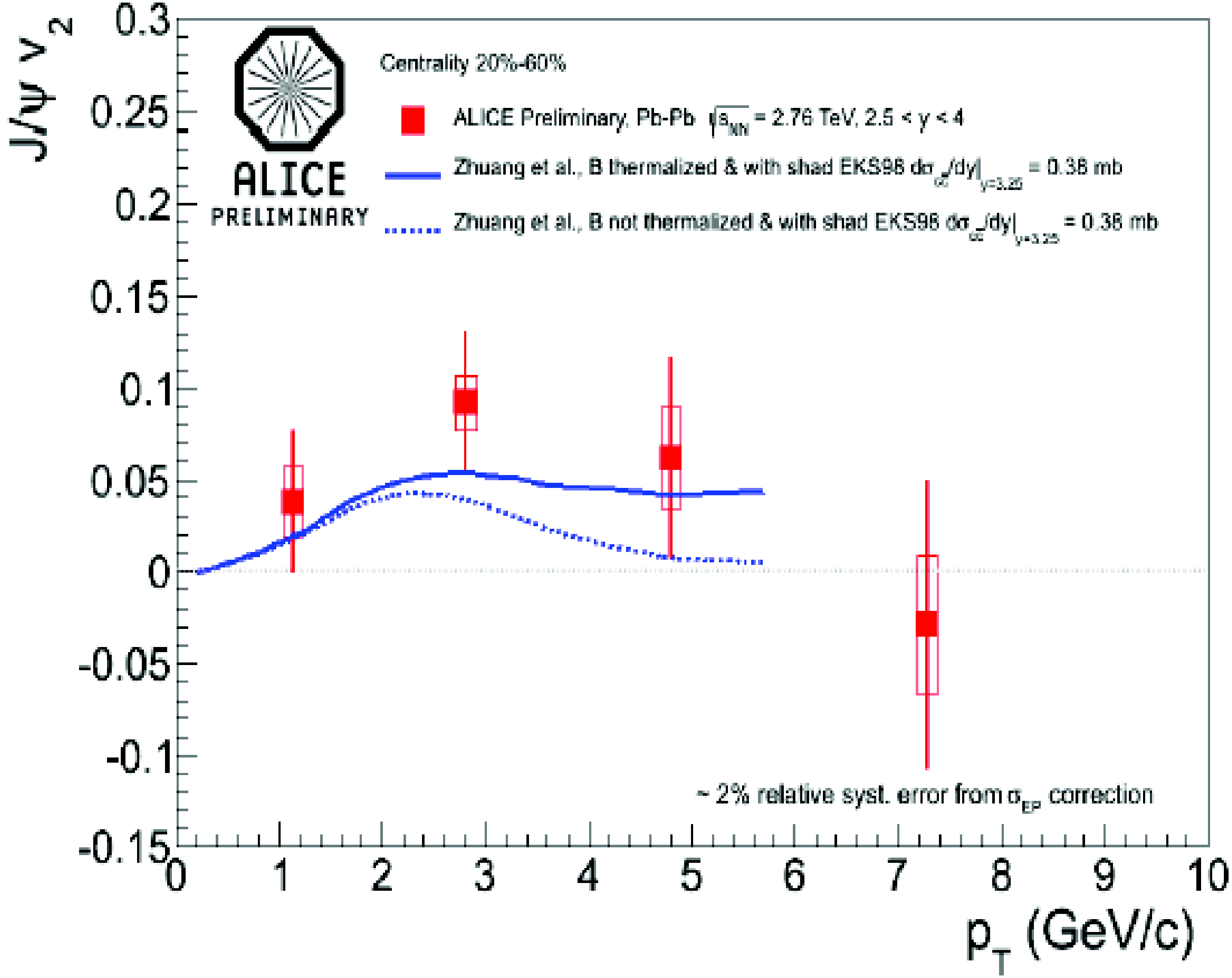
arXiv:1309.7520v1 [nucl-th] 29 Sep 2013

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

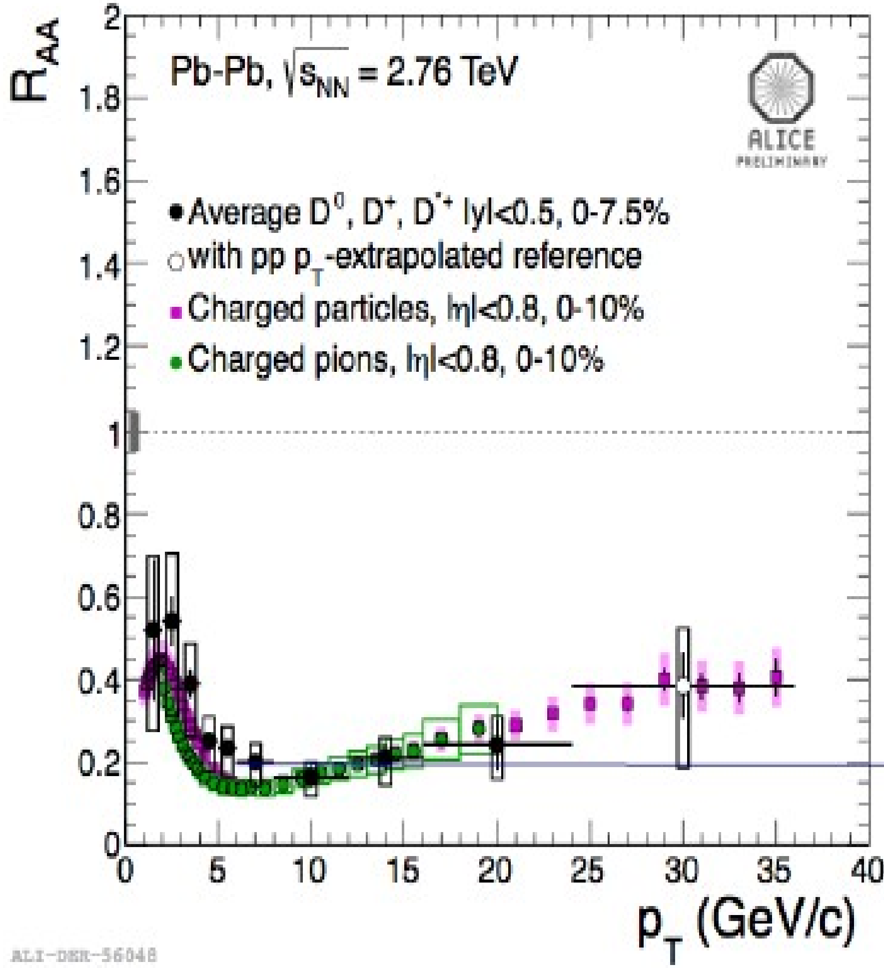


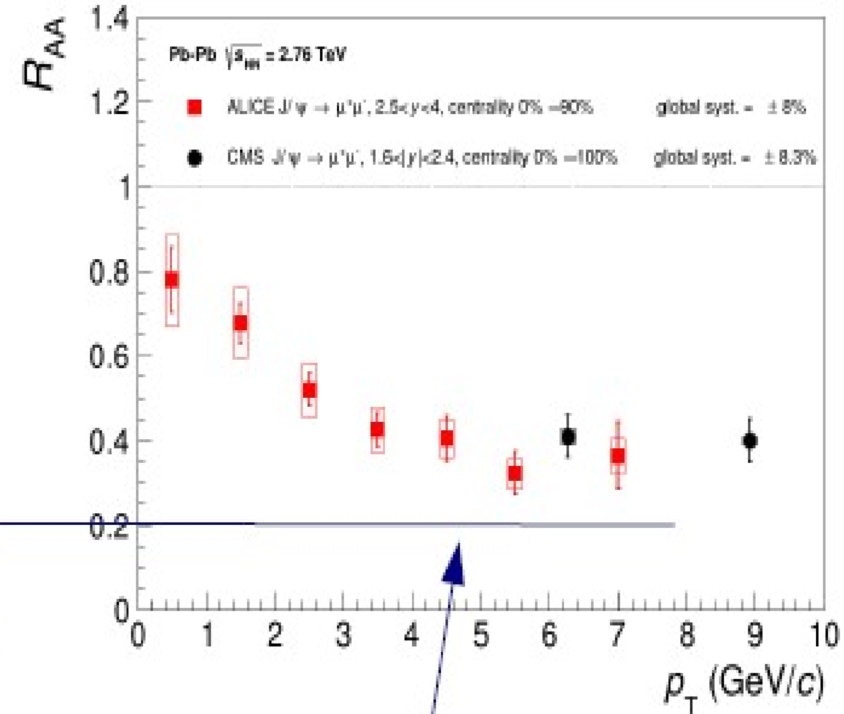
J/psi flow compared to models including (re-) generation



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

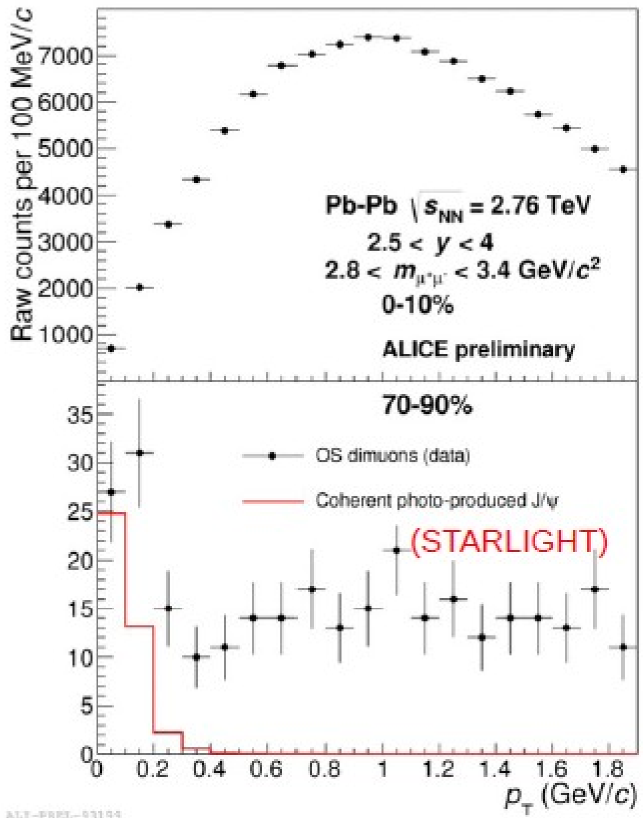
Comparison R_AA for D-mesons, charged particles, and J/psi

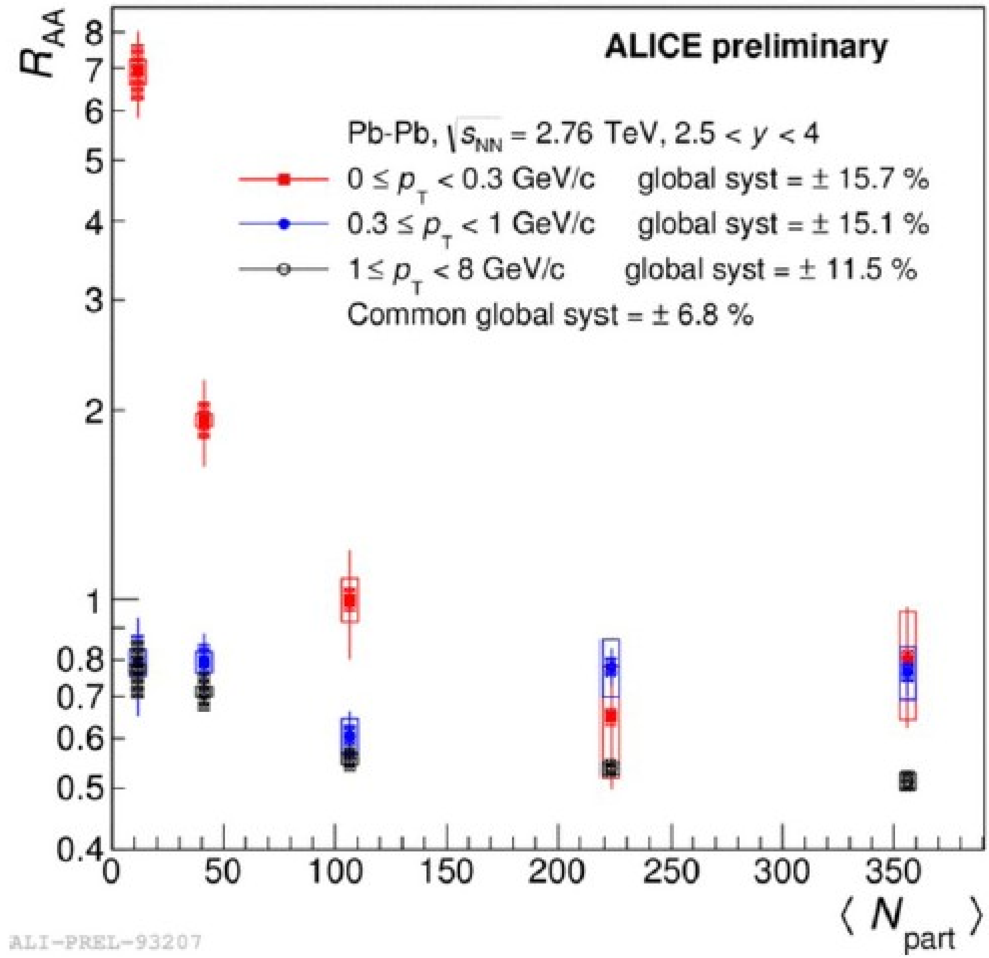




what is the role of energy loss of charmonium production? Is (re-)combination important at p_t = 10 GeV?

Enhancement for ultra-low transverse momenta in peripheral collisions





most likely photoproduction, needs quantitative understanding

<p_t> < 1/R for R = 7 fm this corresponds to 30 MeV
can one implant a source of cold J/psi into the QGP?

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

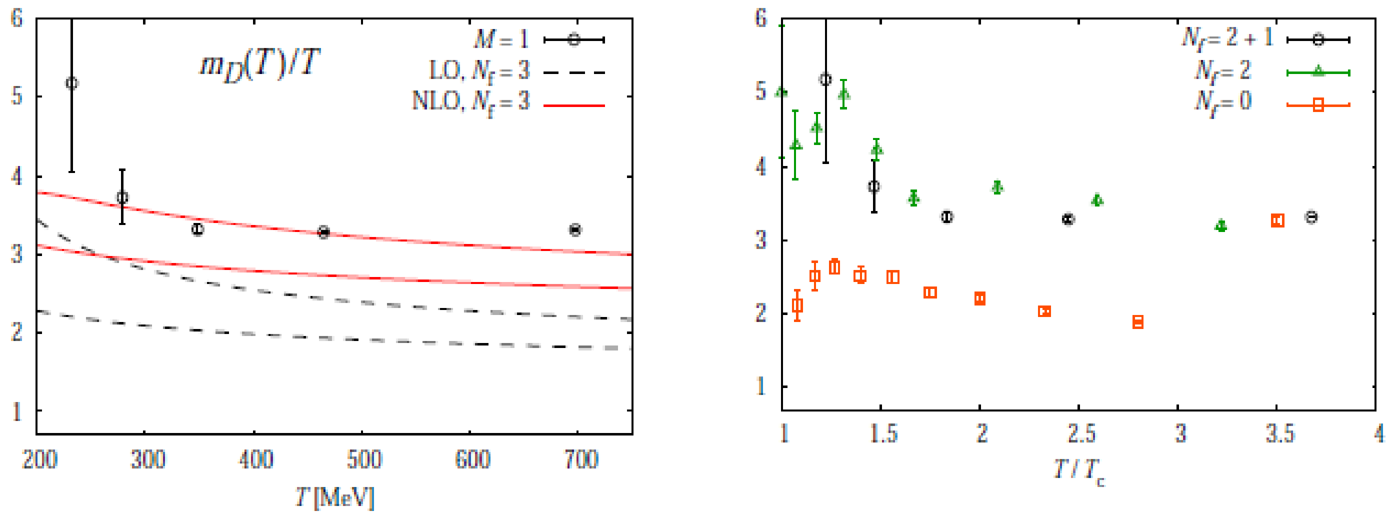


Fig. 6. (Left) The Debye screening mass on the lattice in the color-singlet channel together with that calculated in the leading-order (LO) and next-to-leading-order (NLO) perturbation theory shown by dashed-black and solid-red lines, respectively. The bottom (top) line expresses a result at $\mu = \pi T$ $(3\pi T)$, 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.

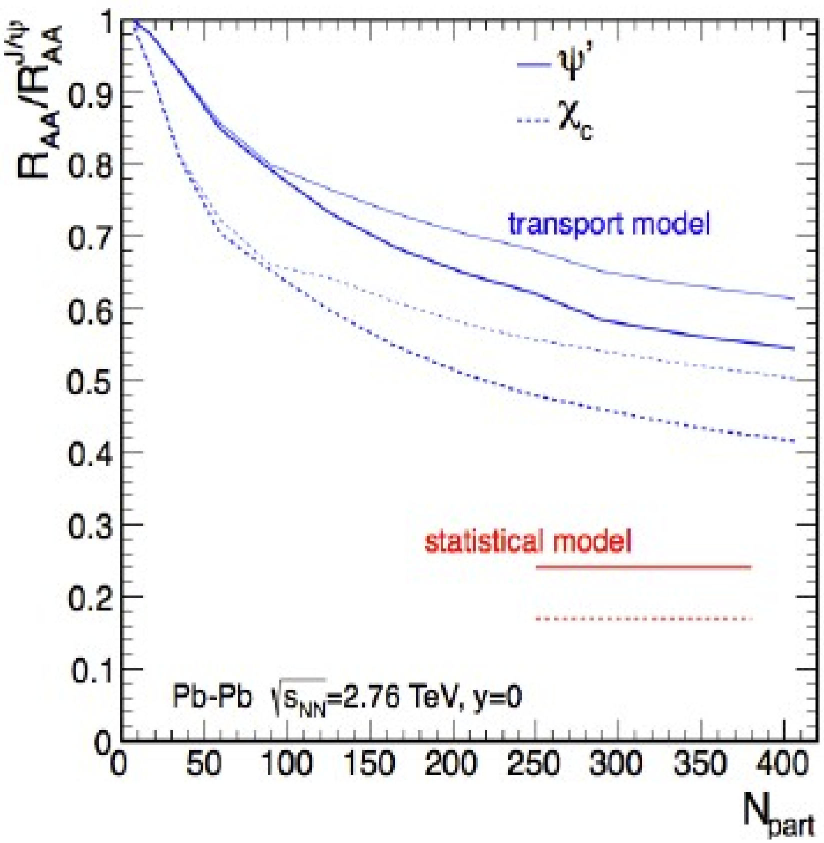
arXiv:1112.2756 WHOT-QCD Coll.

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

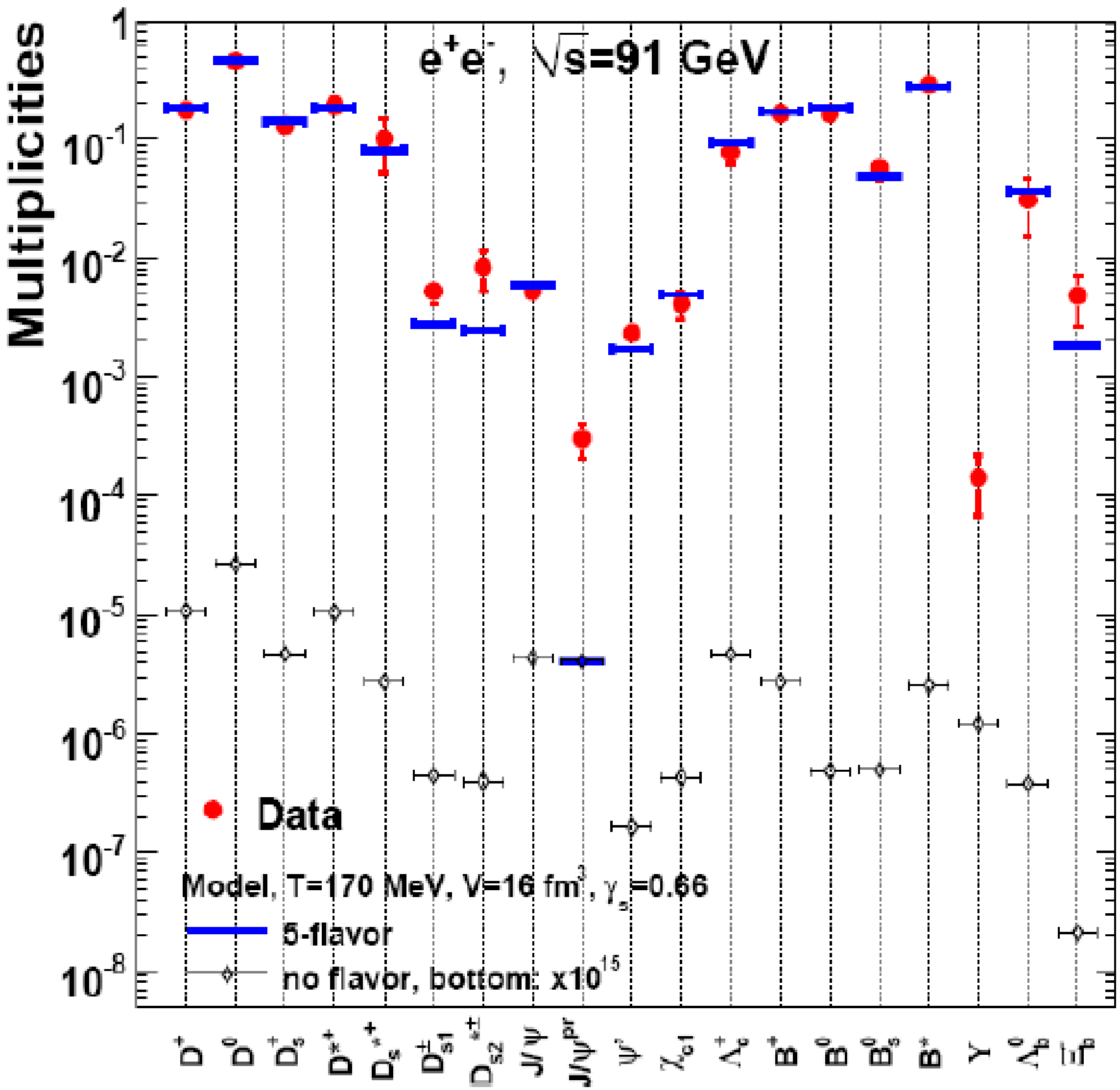
Hadronization of charm quarks – a special case?

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.

hadronization of heavy quarks in e+e- collisions



Comparison of stat. model calcs. with data

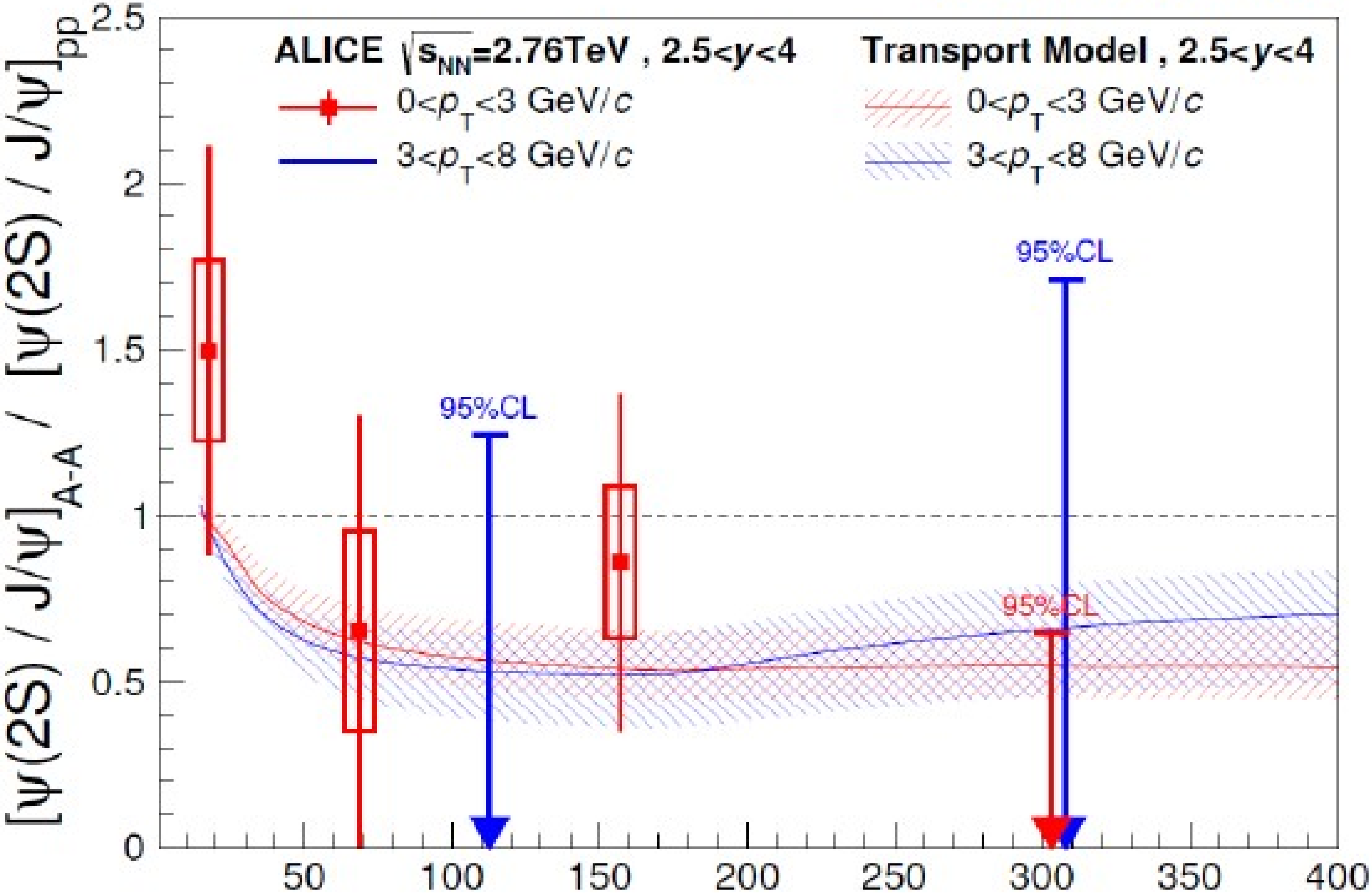
Phys. Lett. B678 (2009) 350, arXiv:0903.1610 [hep-ph]

charmonium cannot be described at all in this approach

But: all charm quarks hadronize at 170 MeV

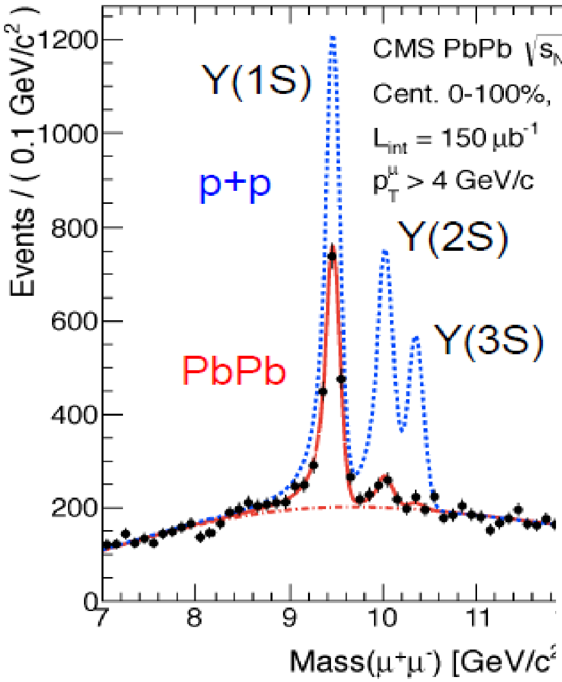
First results on psi'/(J/psi) ratio

arXiv: 1506.08804



possible enhancement in CMS data not supported by ALICE measurements but errors still very large. No strong conclusions yet.

The bottomonium puzzle (I)

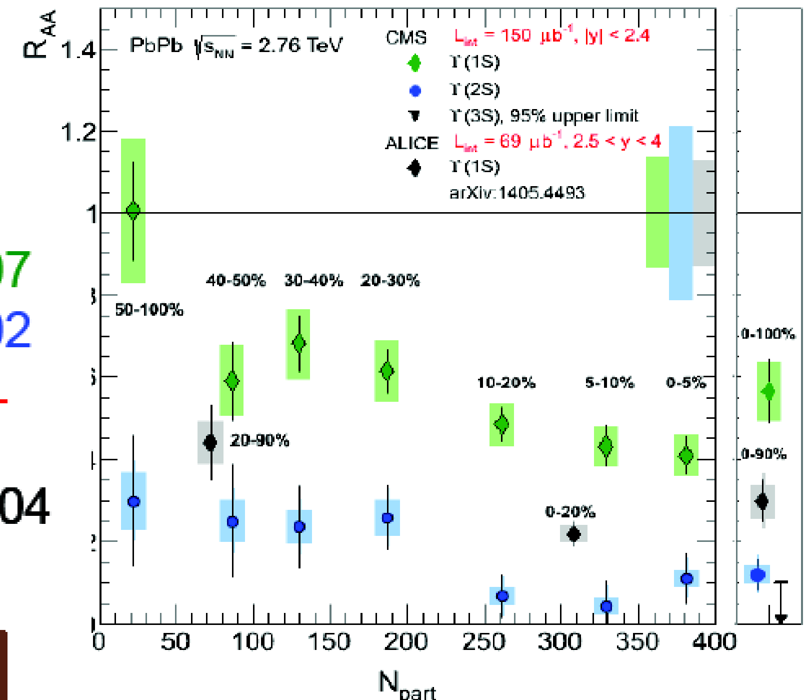


R_{AA} (Y(1S)) = 0.56 ± 0.08 ± 0.07

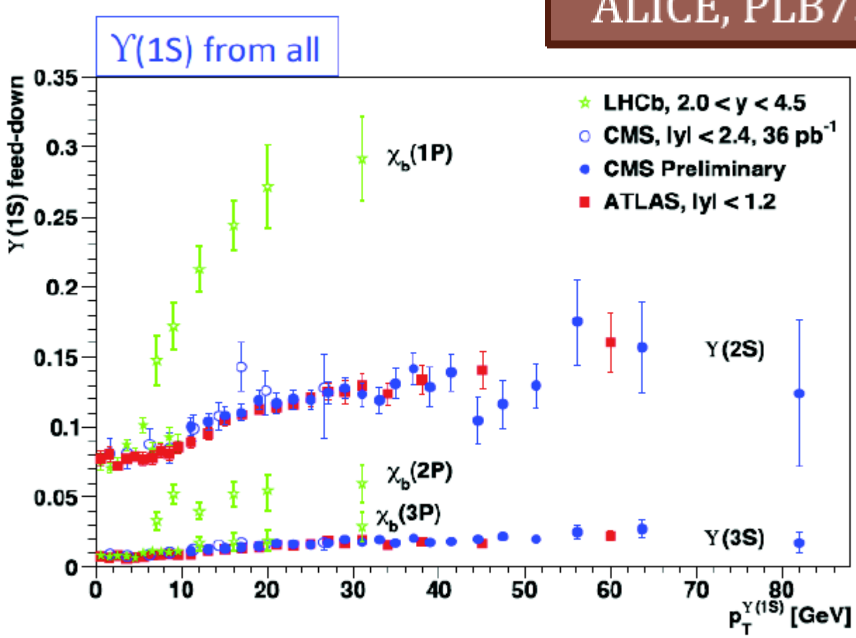
R_{AA} (Y(2S)) = 0.12 ± 0.04 ± 0.02

R_{AA} (Y(3S)) < 0.10 @ 95% CL

+ R_{AA} (Y(1S)) = 0.30 ± 0.05 ± 0.04 (at forward rapidity)

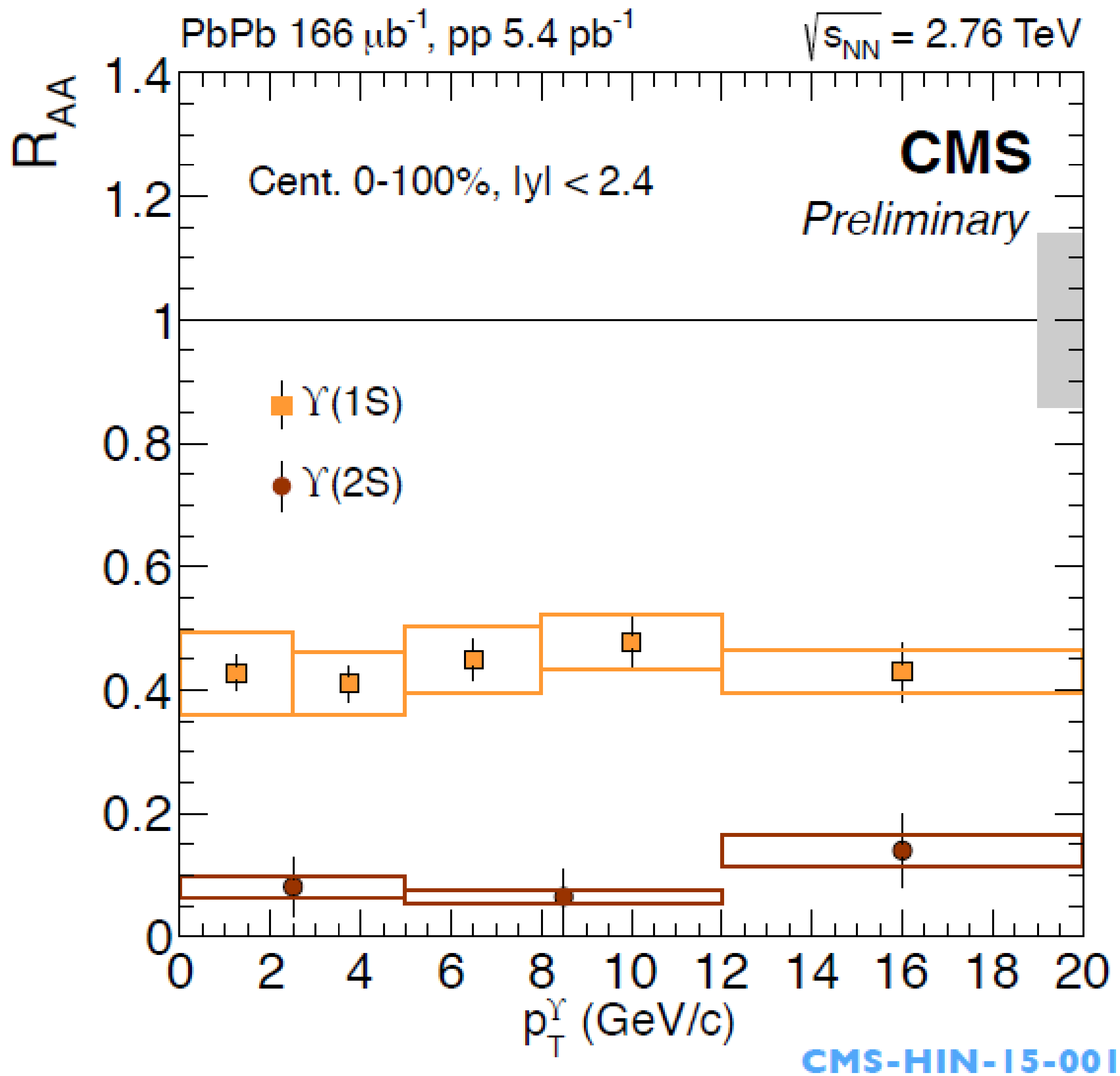


CMS, PRL109 (2012) 222301
ALICE, PLB738 (2014) 361



New results from LHCb: feeding into Y(1s) only about 30% → Y(1s) suppression not due to reduced feeding in Pb—Pb collisions

Bottomonium puzzle (ii)
CMS data on RAA vs transverse momentum



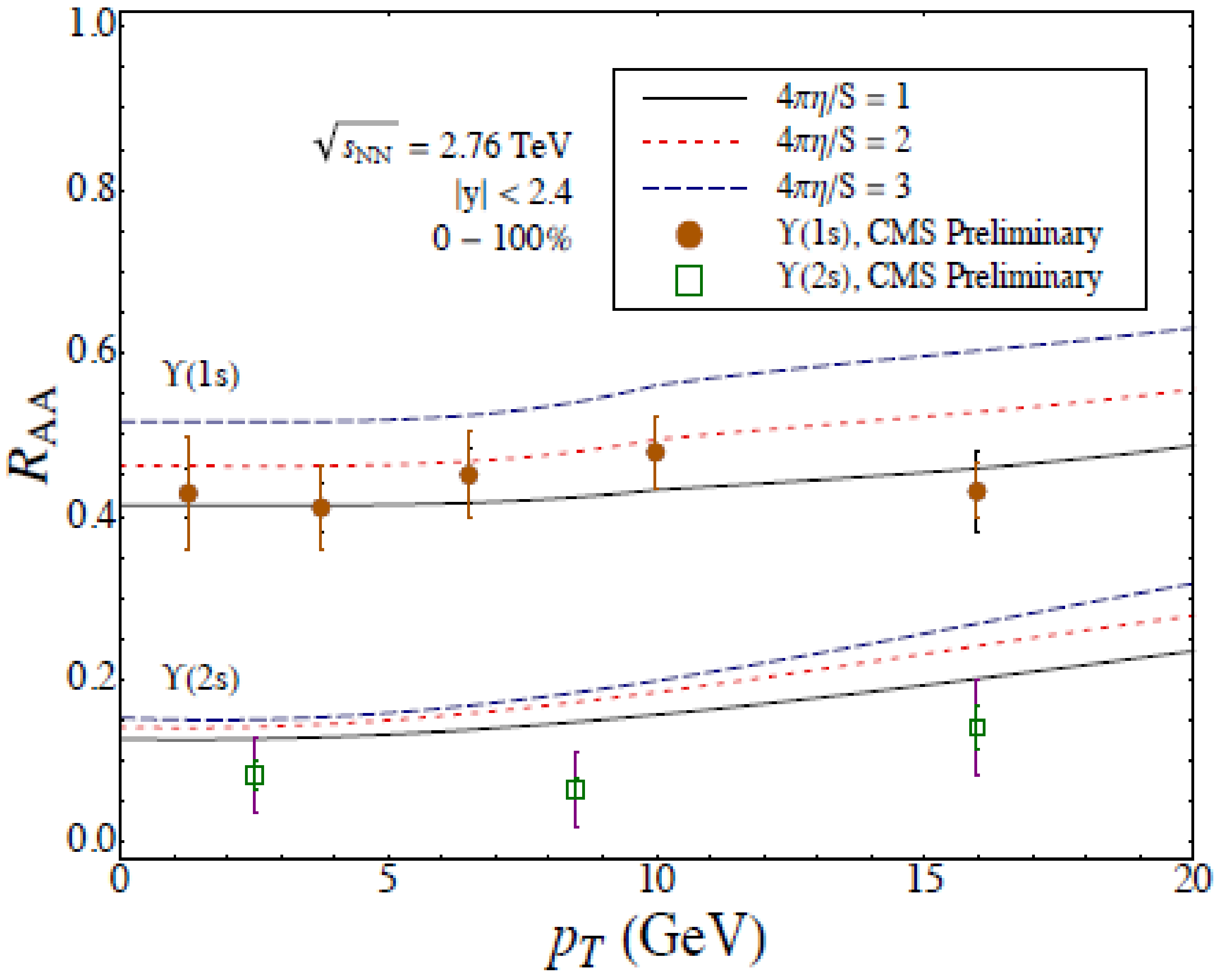
Y pt spectrum in Pb-Pb same as in pp, little evidence for thermalization

Observed suppression for Y(1s) is too large for 'feeding explanation', flat pt dependence challenges 'Debye screening' interpretation

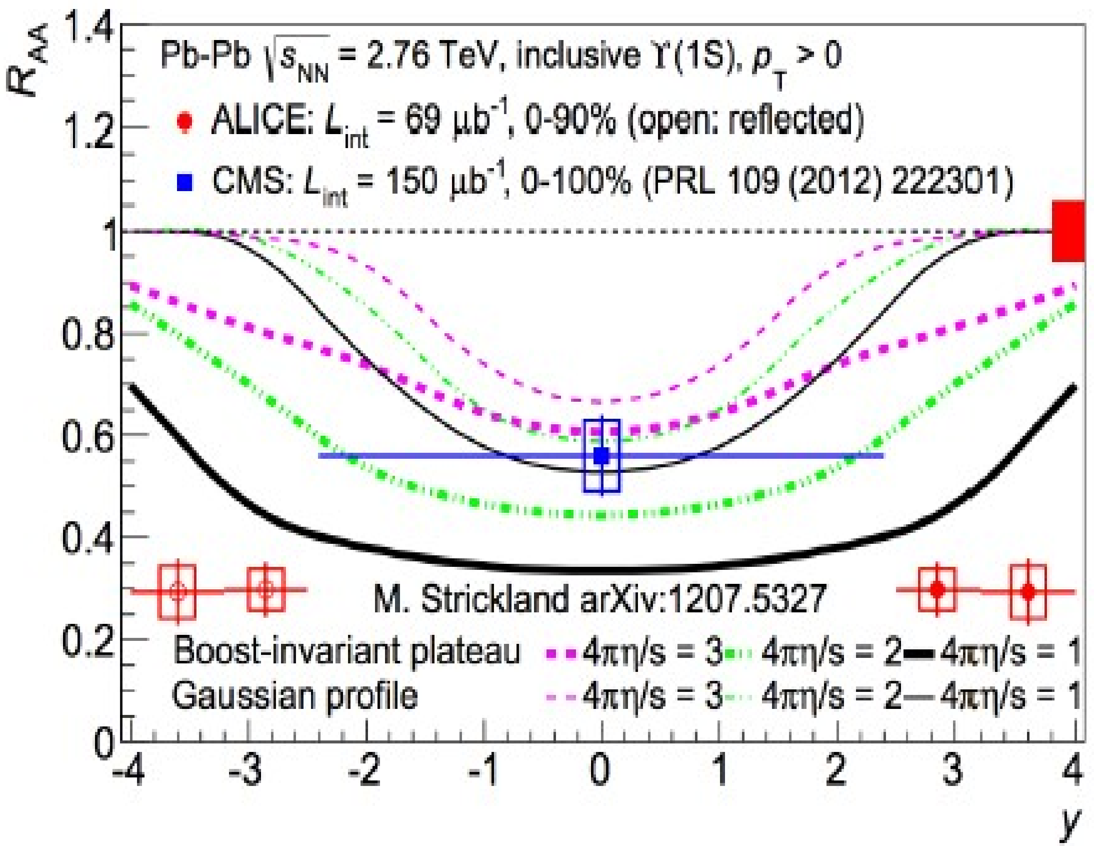
Newest results from M. Strickland, arXiv:1507.03951

feeding consistent with latest measurements, anisotropic hydro, Y in-medium potential based on internal energy prescription, both real and imaginary part momentum-independent

measured pt dependence is (surprizingly?) reproduced



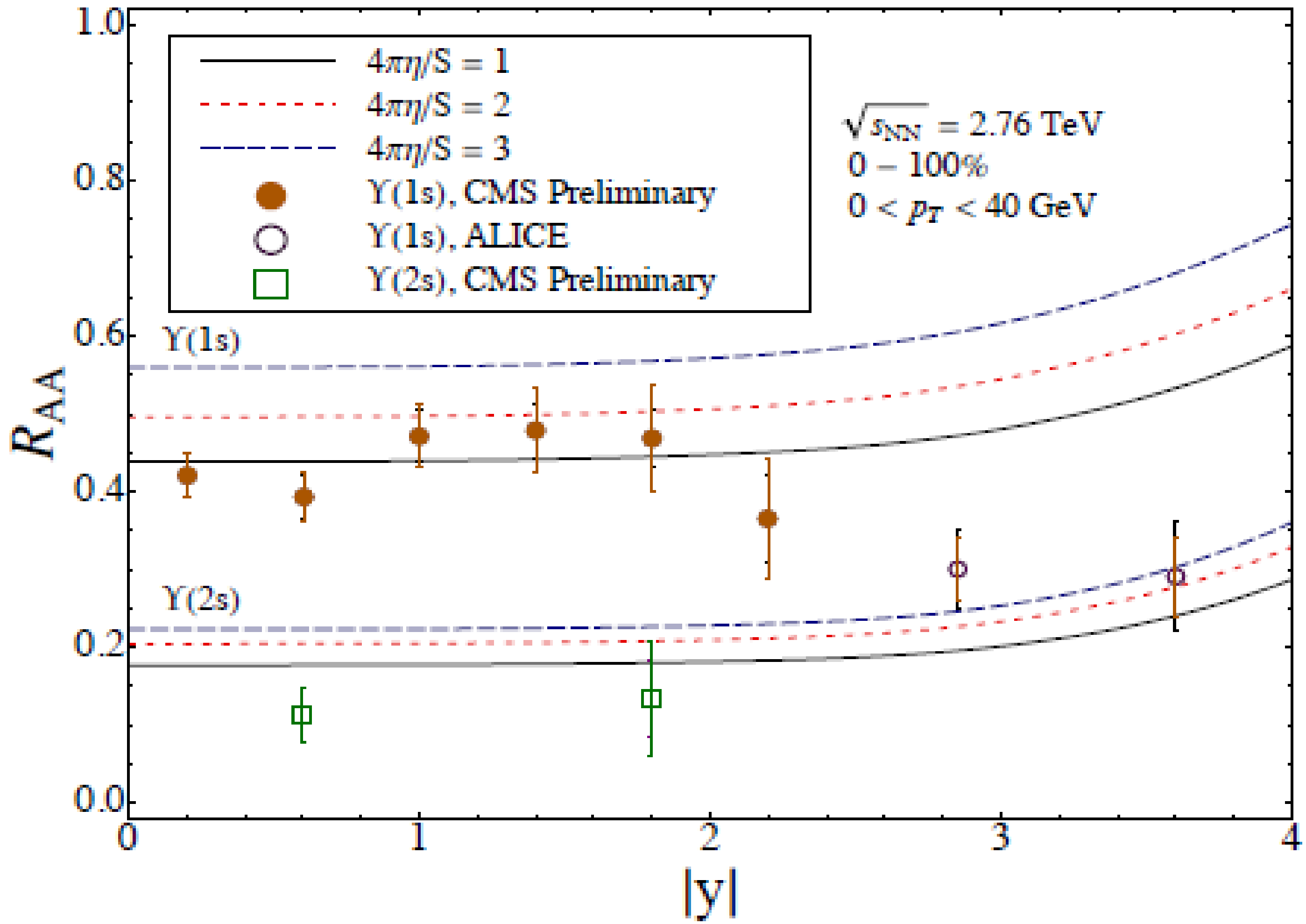
The bottomonium puzzle (III)



Rapidity distribution of RAA for Y(1s) is peaked at y=0, not consistent with suppression scenarios

Measurements at large rapidity (ALICE muon arm) are crucial!

The bottomonium puzzle (III)



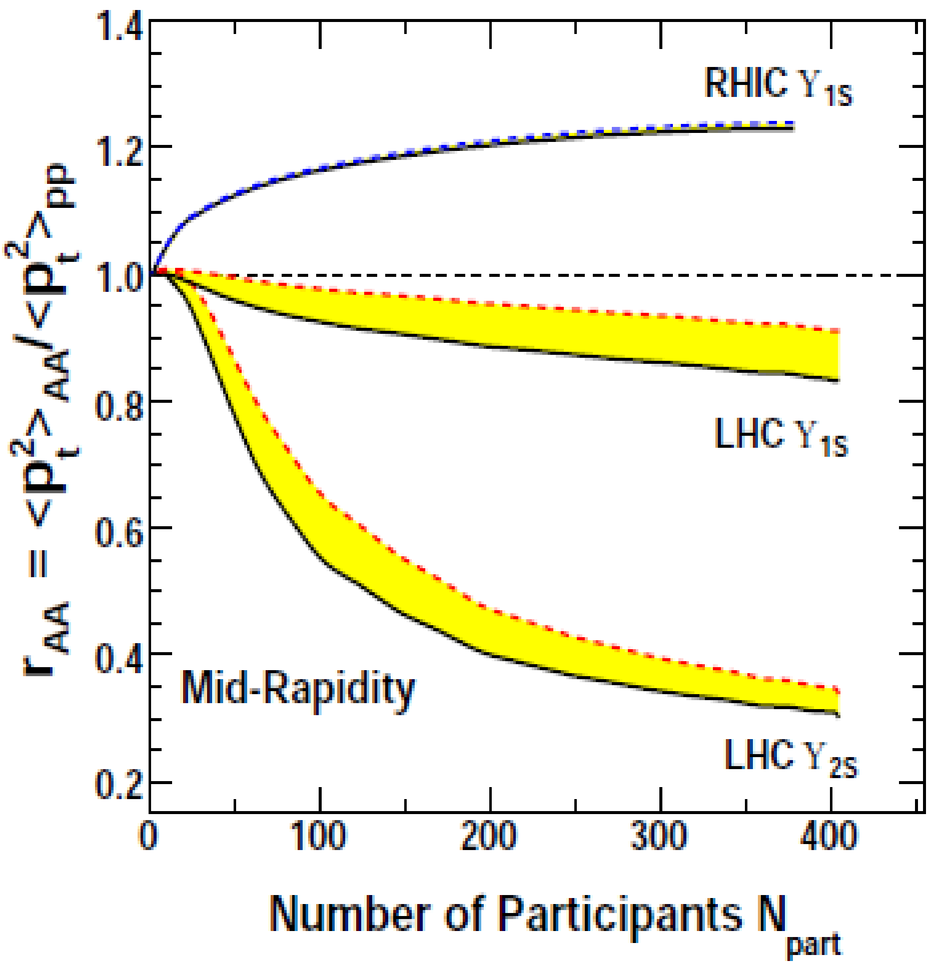
Newest result from Strickland after HP2015, arXiv:1507.03951, still not consistent with measured rapidity dependence

Measurements at large rapidity (ALICE muon arm) are crucial!

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

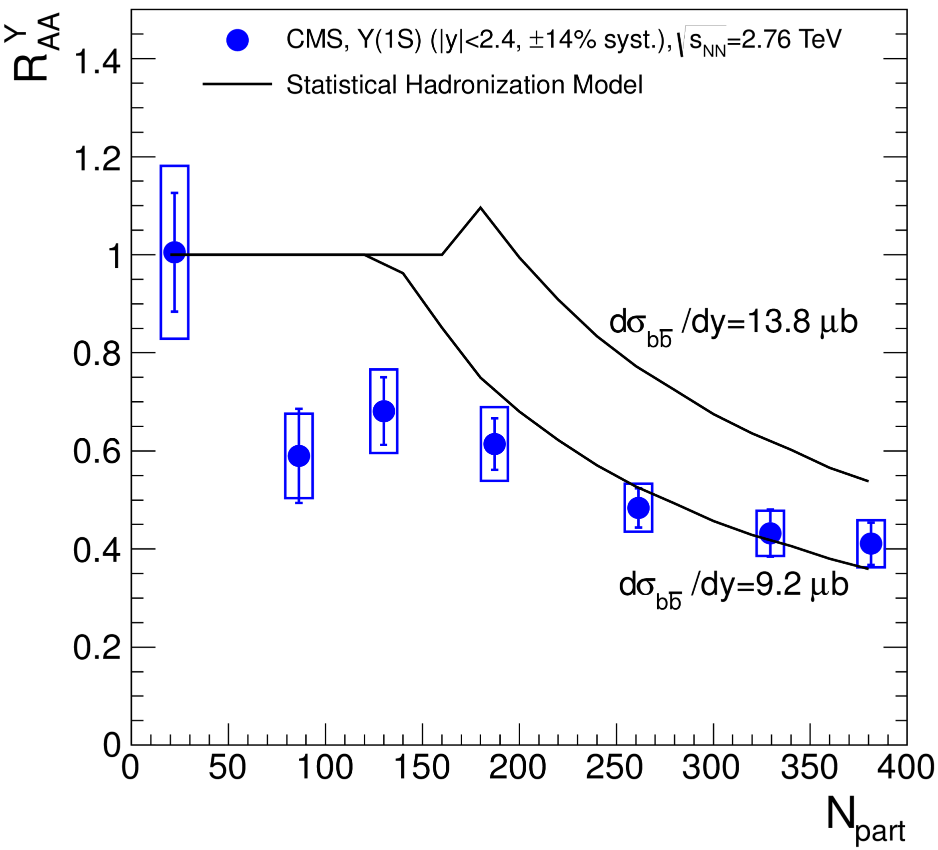
needs approach to thermalization for b quarks!

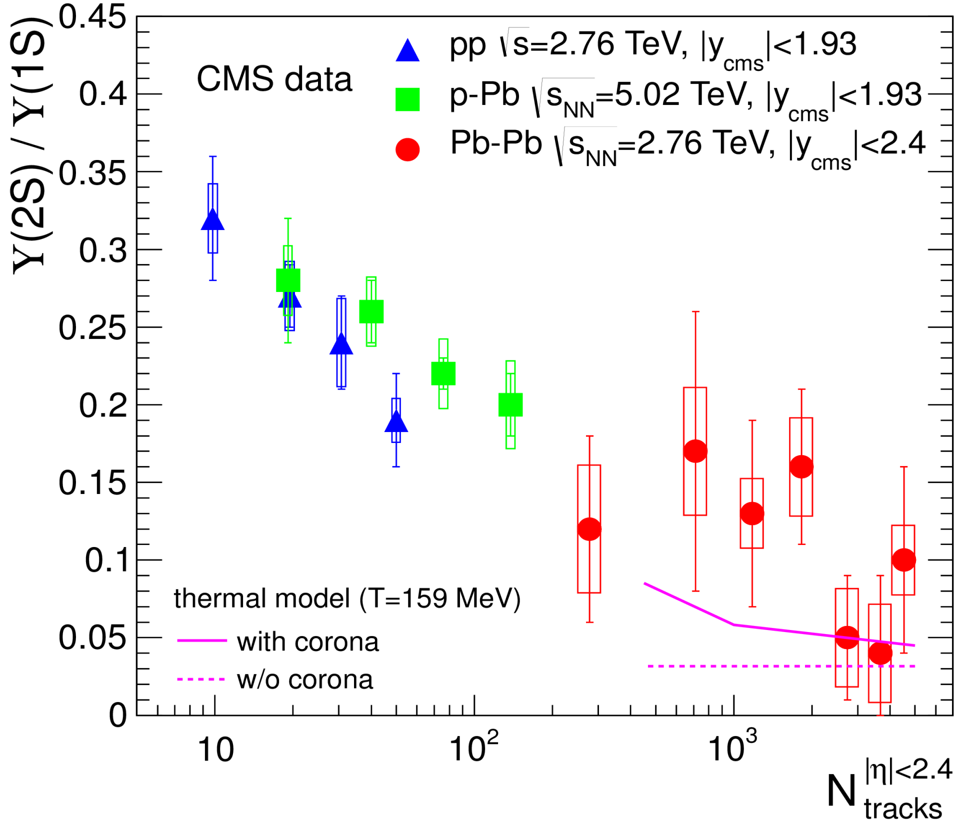


predictions by Zhou, Xu, Zhuang
arXiv:1309.7520 [nucl-th]

Upsilon production and statistical hadronization

SHM/thermal model: Andronic et al.





are b quarks thermalized?
no connection to color screening with equilibrium!

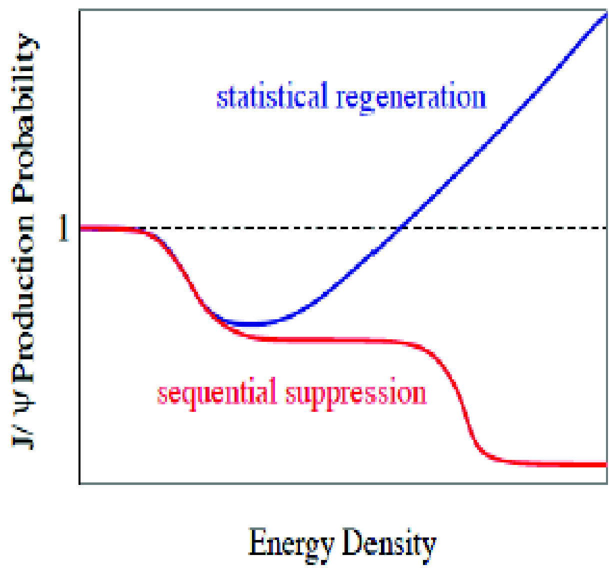
summary 1 – quarkonium production

- 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

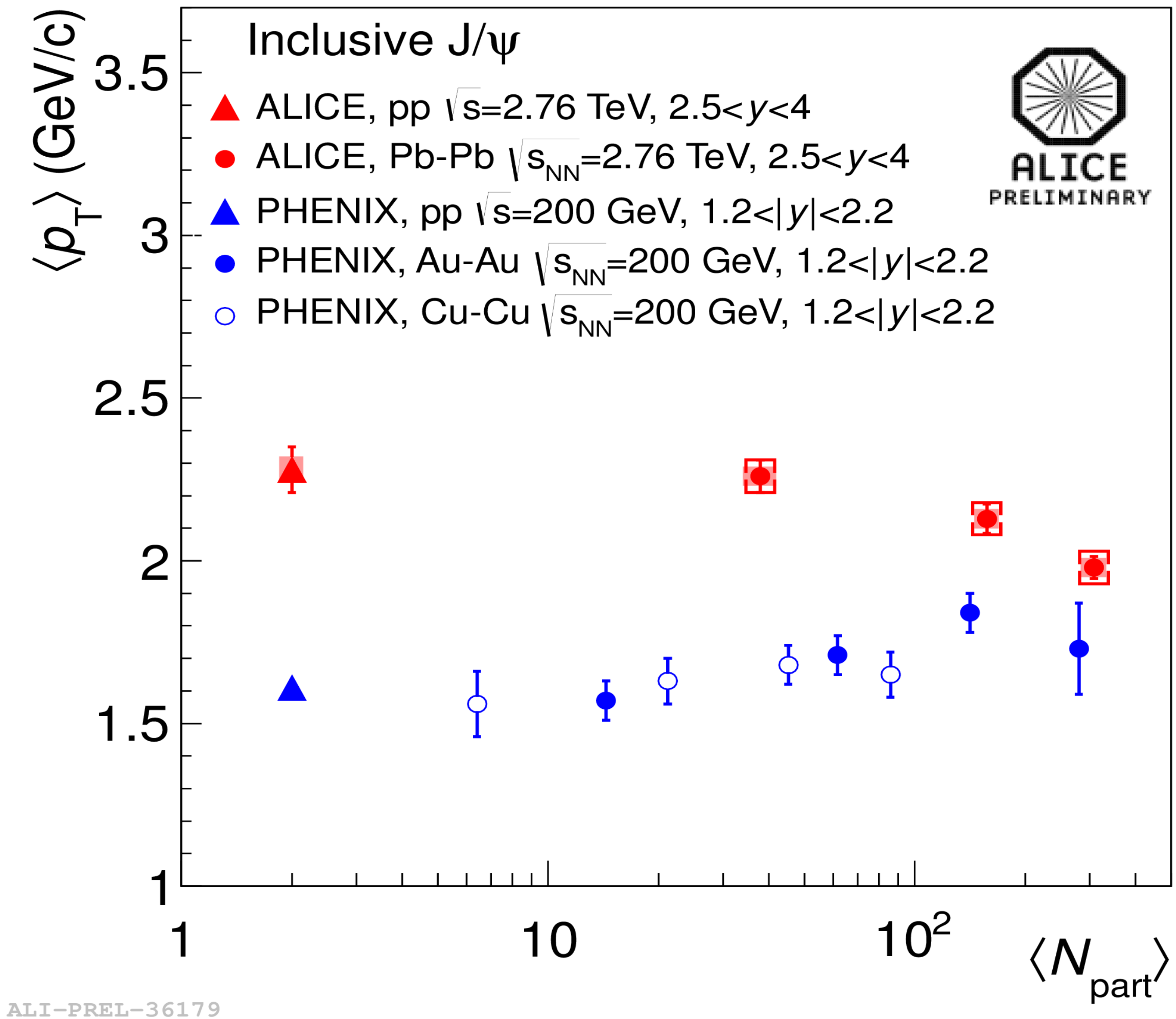
- evidence for energy loss and flow of charm quarks --> thermalization
- charmonium generation at the phase boundary – a new process
- first indications for this from psi'/(J/psi) SPS and J/psi RHIC data
- evolution from RHIC to LHC described quantitatively
- charmonium enhancement at LHC – J/psi color-screened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