Quarkonia as Probe of Deconfinement in High Energy Nuclear Collisions

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Charmonia as a Probe of Deconfinement

Charmonia: bound states of charm and anticharm quarks, e.g. →

J/ψ 1s state of ccbar
mass 3.1 GeV
radius 0.45 fm

the original idea (Matsui and Satz 1986): implant charmonia into the QGP and observe their modification (Debye screening of QCD), in terms of suppressed production in nucleus-nucleus collisions with plasma formation
– sequential melting signature as QGP thermometer

"If high energy heavy-ion collisions lead to the formation of a hot quark-gluon-plasma, then color screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. ... It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon-plasma formation."

Quarkonia

- Quarkonia are heavy quark antiquark bound states, i.e. ccbar and bbar
- since masses of charm and beauty quarks are high as compared to QCD scale parameter Λ_{QCD} ~ 200 MeV
  non-relativistic Schrödinger equation can be used to find bound states

$$(-\frac{\nabla^2}{2(m_Q/2)} + V(r))\Psi(\vec{r}) = E\Psi(\vec{r})$$

with quark-quark potential of the form

$$V(r) = \sigma r - \frac{4}{3}\frac{\alpha_s}{r} + \frac{32\pi\alpha_s}{9}\frac{\vec{s}_1 \cdot \vec{s}_2}{m_Q^2}\delta(\vec{r}) + \ldots$$

confinement

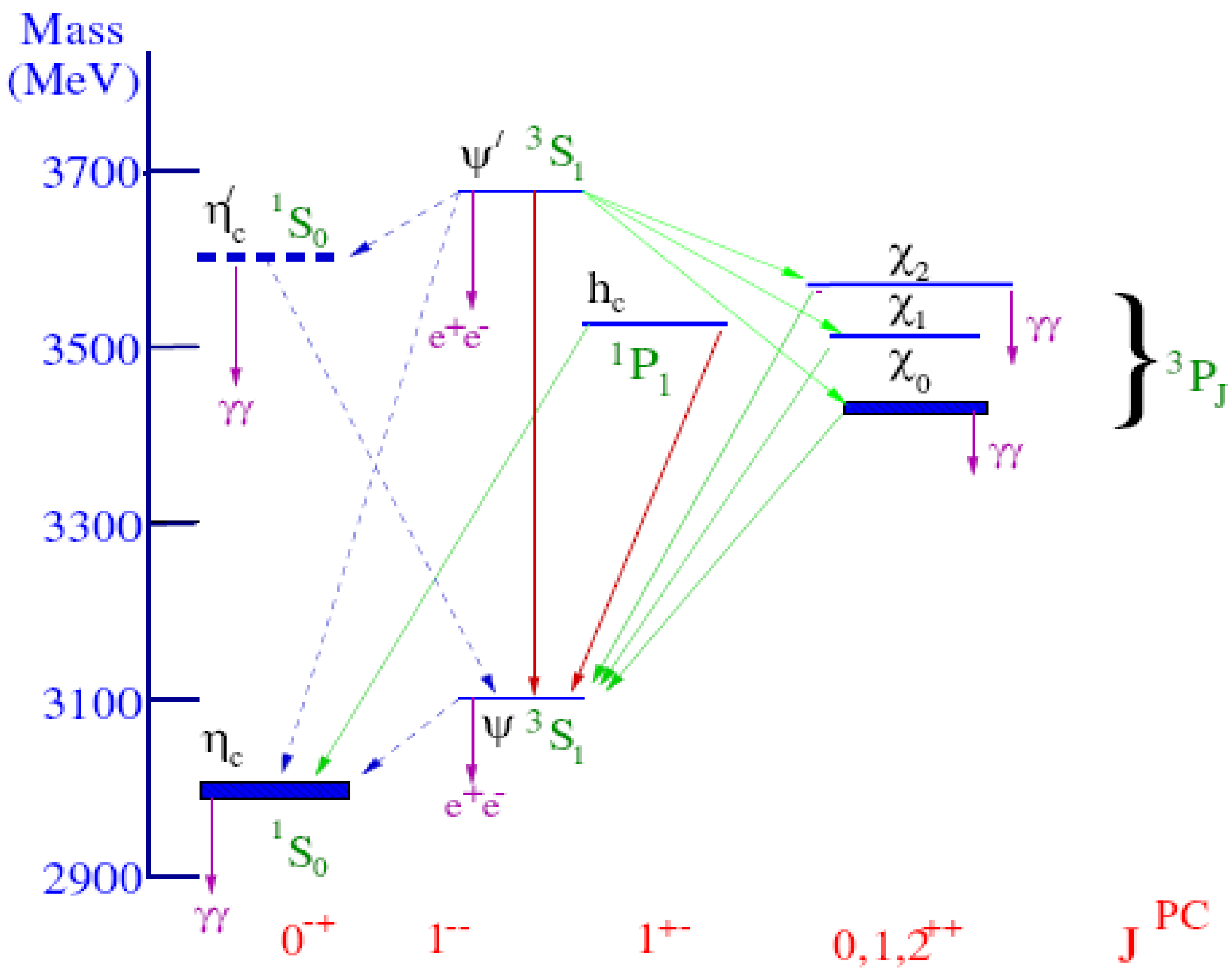
color Coulomb int.

spin-spin int.

tensor, spin-orbit, higher order rel. corr.

- with σ ~ 0.9 GeV/fm, $\alpha_s(m_Q)$ ~ 0.35 and 0.20 for m_c=1.5 and m_b=4.6 GeV
  obtain spectrum of quarkonia

Charmonium spectrum



Charmonia at finite temperature

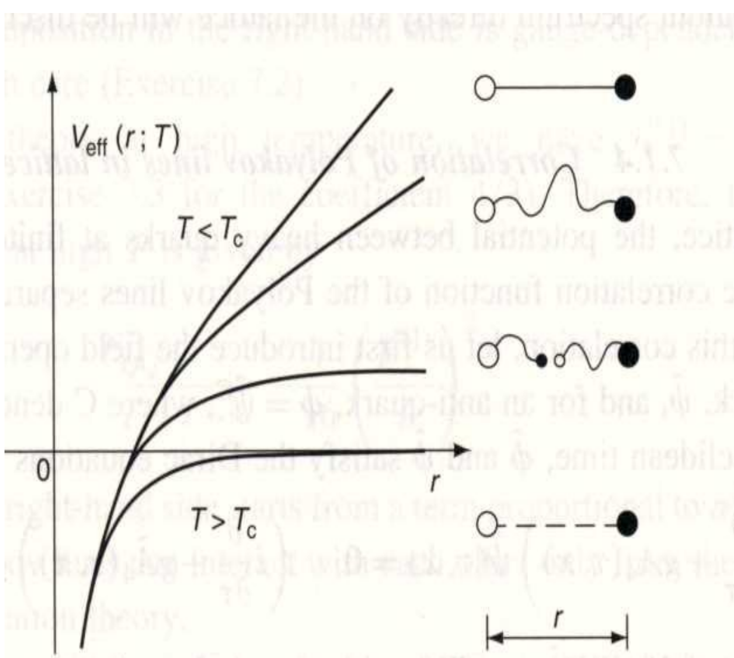
Consider T« m_c so QGP of gluons, u,d,s quarks and antiquarks, no thermal heavy quarks

Consider c cbar in environment of gluons and light quarks

$$V(r) \rightarrow V_{eff}(r,T) \text{ and } m_Q \rightarrow m_Q(T)$$

In QGP color singlet and color octet ccbar states can mix by absorption or emission of a soft gluon

Modification of V_{eff}



- reduced string tension at T approaches Tc
- string breaking due to thermal qqbar and gluons leading to D and Dbar
- for T>Tc confining part disappears and short range Coulomb part is Debye screened to give Yukawa type potential

$$V_{eff}(r,T) \rightarrow -\frac{4}{3}\frac{\alpha_s}{r}e^{-r/\lambda_D}$$

$$\omega_D = 1/\lambda_D$$

Debye screening mass and length

Debye screening of quarkonia

unlike Coulomb potential, Yukawa potential does not always have bound states

→ dissociation of quarkonia if ω_D sufficiently large at high T

(idea: T. Matsui, H. Satz, Phys. Lett. B 178 (1986) 416 :
compare Bohr radius of charmonia r_B and Debye screening length λ_D

for r_B smaller than λ_D bound states exist even for $\sigma=0$

for r_B larger than λ_D no bound states

equivalently to QED where $r_B(\text{hydrogen}) = 1/(m_e\alpha)$ we have: $r_B = 3/(2m_Q\alpha_s)$
and the Debye screening mass: $\omega_D^2 = \frac{4\pi}{3}\alpha_s T^2(N_c + \frac{1}{2}N_f)$

bound states then disappear for

$$T \geq 0.15 \times m_Q\sqrt{\alpha_s} \approx 0.16\,\text{GeV for J}/\psi\text{ and }0.46\text{ for }\Upsilon$$

Different quarkonia melt at different temperatures

using $$V(r,T) = \frac{\sigma}{\omega_D(T)}(1 - \exp(-\omega_D(T)r)) - \frac{\alpha}{r}\exp(-\omega_D(T)r)$$

F. Karsch and H. Satz (Z.Physik C51 (1991) 209) obtain:

	J/ψ	ψ'	χ_c	Υ	Υ'
state	1s	2s	1p	1s	2s
mass(GeV)	3.1	3.7	3.5	9.4	10.0
r (fm)	0.45	0.88	0.70	0.23	0.51
T_D/T_c	1.17	1.0	1.0	2.62	1.12
ϵ_D (GeV/fm^3)	1.92	1.12	1.12	43.3	1.65

exact values very model dependent, but basic feature: J/psi, psi', chic, Upsilon' not bound at or little above T_c, Upsilon survives much longer

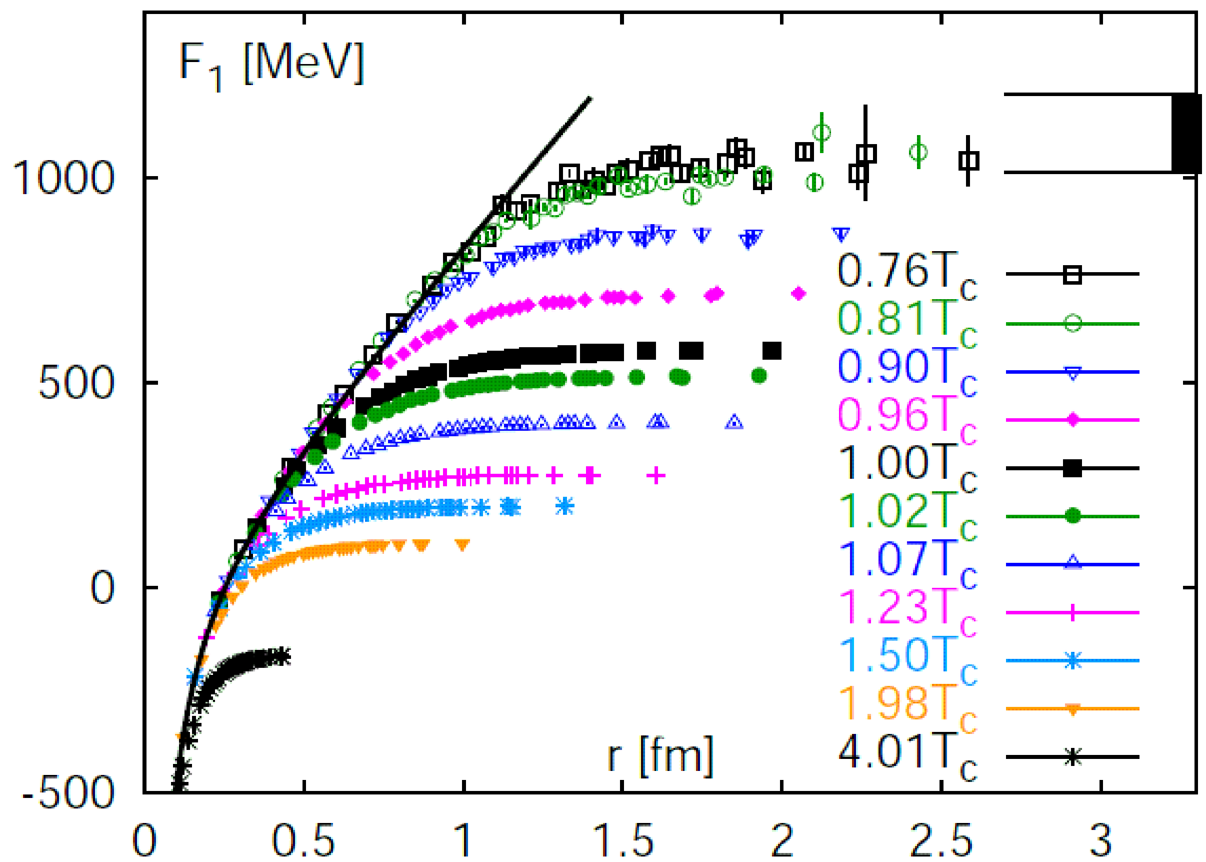
Results on Debye screening from lattice QCD

agree qualitatively, quantitatively still a lot of debate, unclear, how to extract effective heavy quark potential (free energy vs internal energy)
One attempt: correlation of Polyakov lines but there are others

color singlet free energy

J/ψ disappears for
$T > 1.1\ T_c$ using F
$2\ T_c$ using U

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

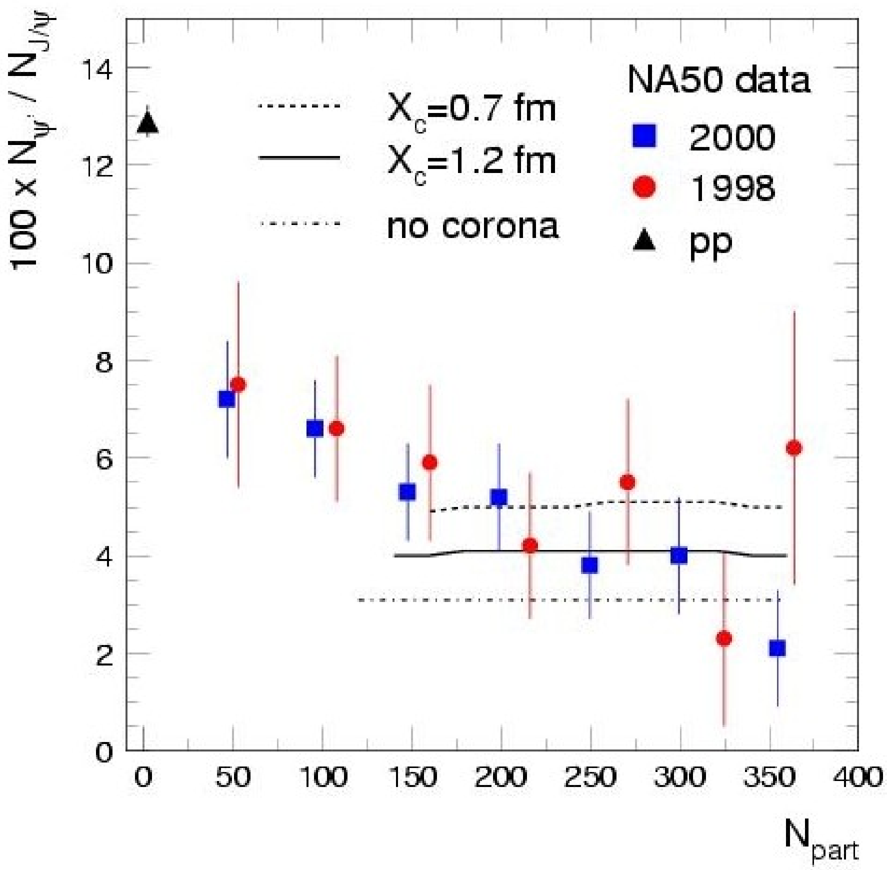


Charmonia as a Probe of Deconfinement

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

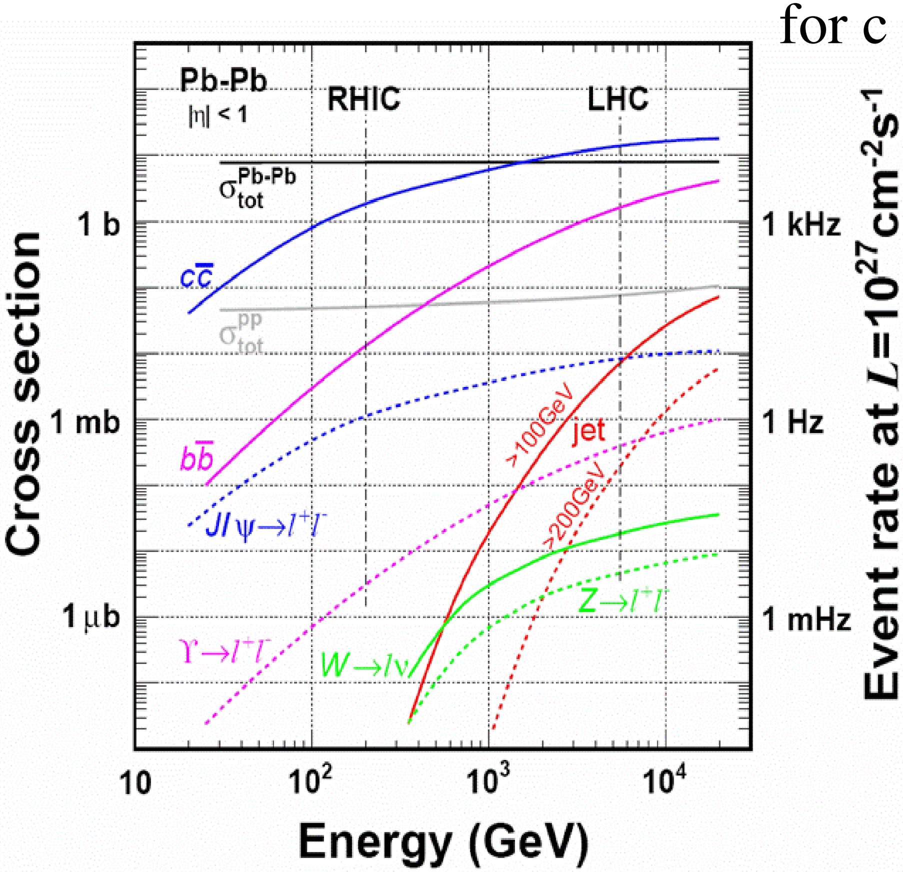
inspiration: ψ' to J/ψ for central PbPb collisions at the SPS looks thermal

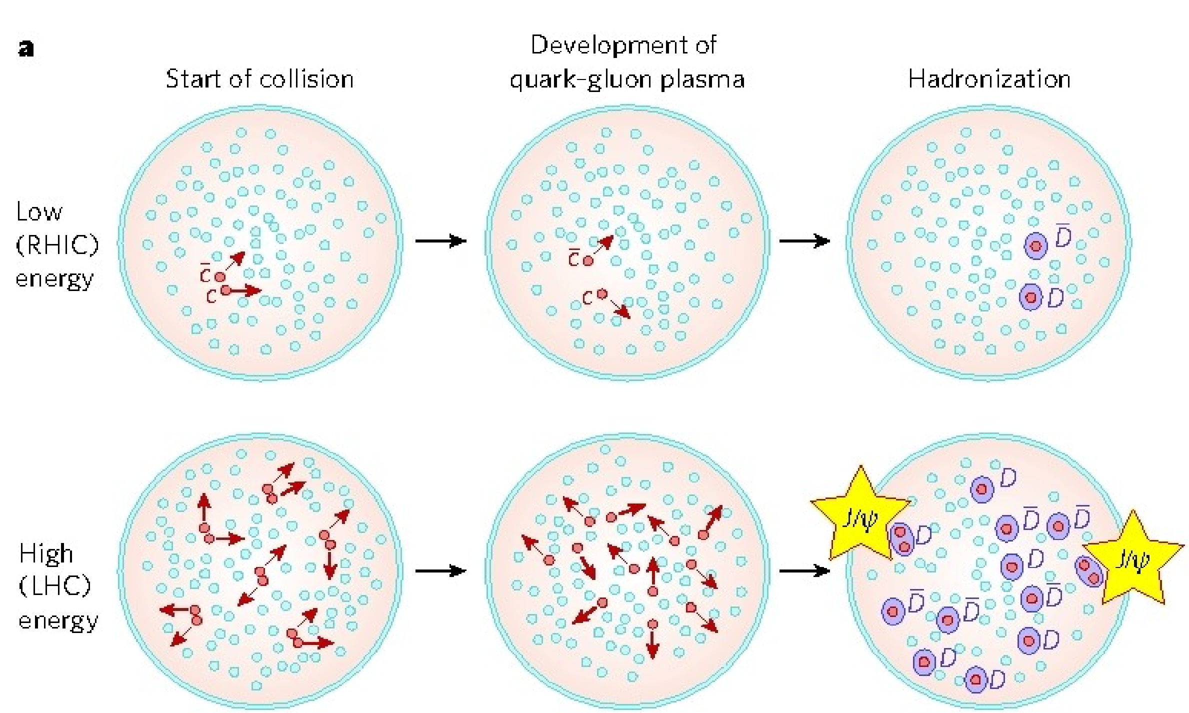
observation M. Gazdzicki: J/ψ to π ratio looks thermal
(note: this is not our conclusion)



what happens to deconfined charm quarks at higher beam energy?

as more and more charm quarks produced, probability for c and cbar to hadronize into J/psi grows quadraticaly





low energy: few c-quarks per collision → **suppression** of J/ψ

high energy: many " " → **enhancement** "

unambiguous signature for QGP!

starting point: the statistical model – grand canonical

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

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

for every conserved quantum number there is a chemical potential:

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

but can use conservation laws to constrain V, μ_S, μ_{I_3}

→ **fit at each energy provides values for T and μ_b**

- get yields of all hadrons

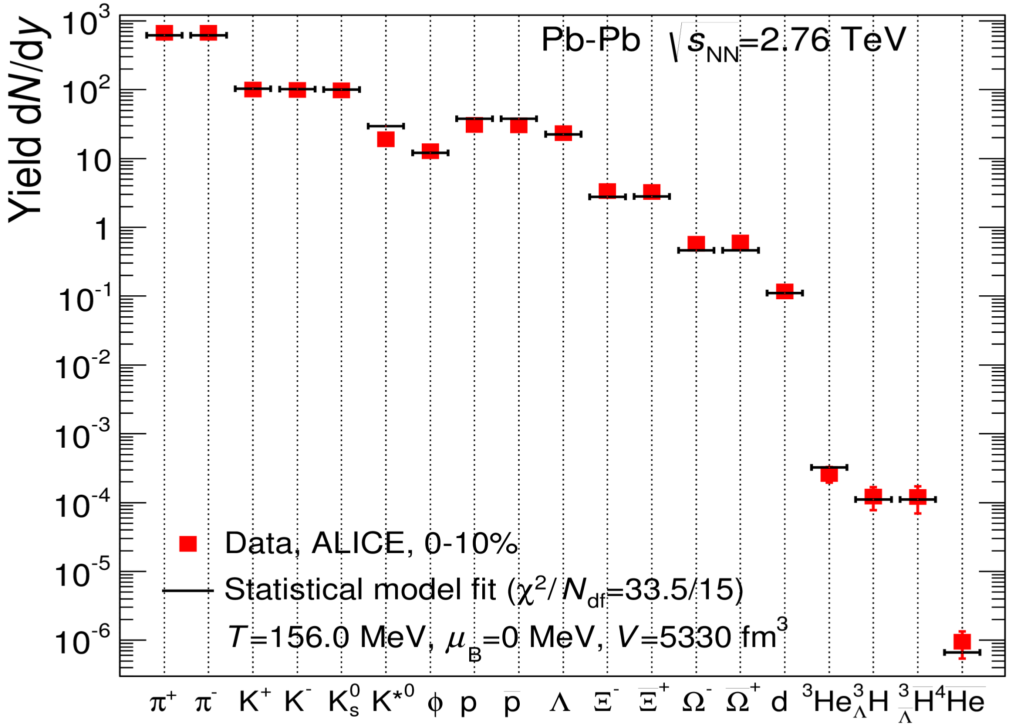
for dN/dy need in addition volume per unit y - fix to dN_{ch}/deta

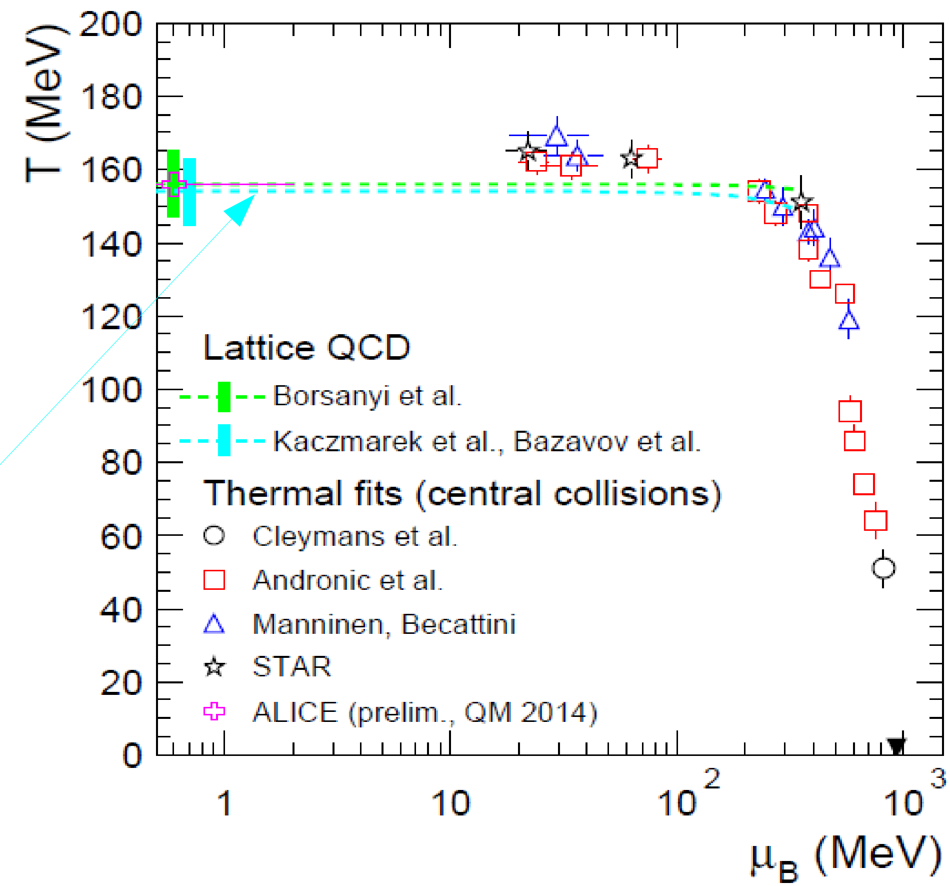
good fit to data for central collisions of heavy nuclei at AGS, SPS, RHIC

see e.g.

A. Andronic, P. Braun-Munzinger, J.S. Nucl. Phys. A722(2006)167 nucl/th/0511071

Production of hadrons and nuclei at LHC





hadron yields for Pb-Pb central collisions from LHC Run1 are well described by assuming equilibrated matter at

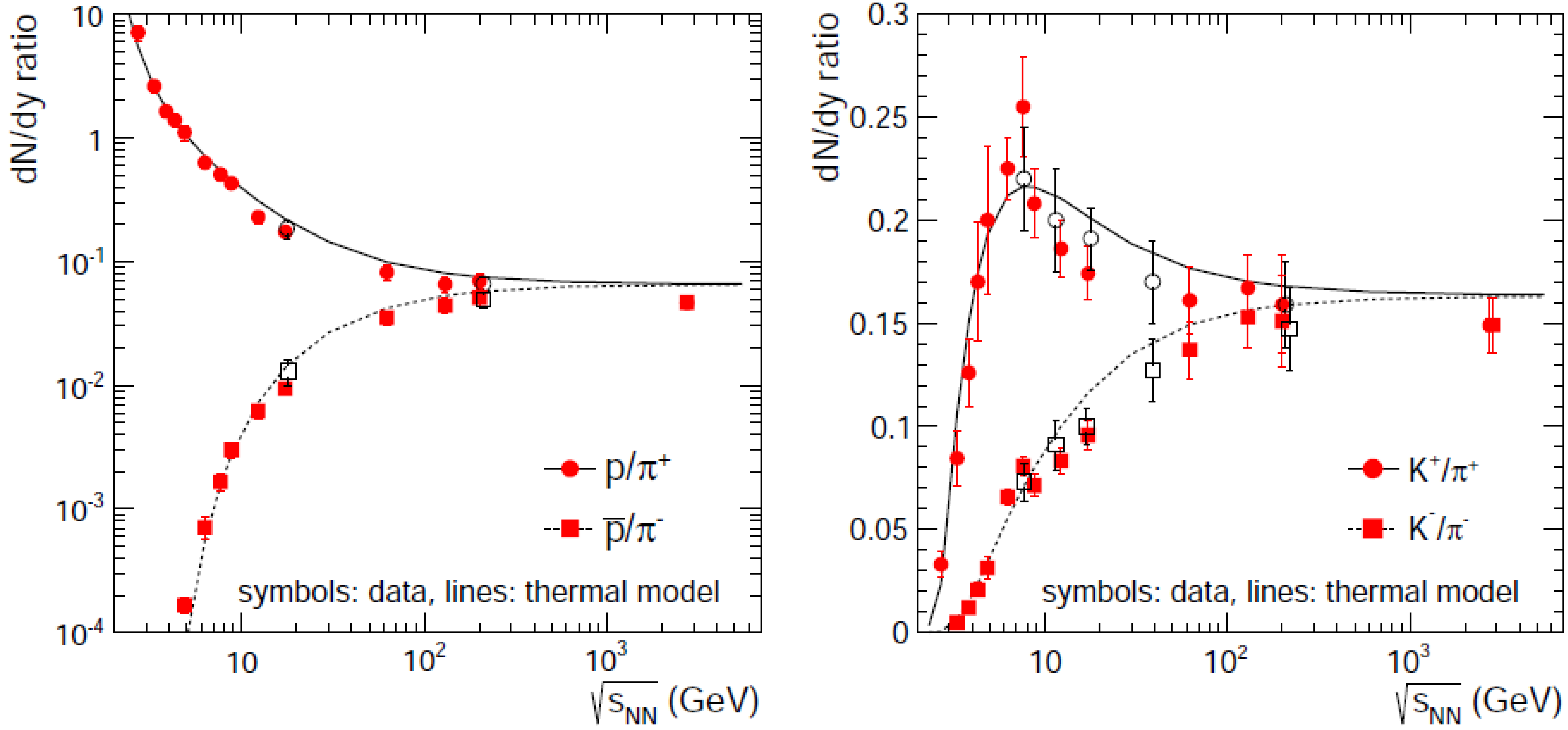
T = 156 MeV and μ_b < 1 MeV, very close to predictions from lattice QCD for T_c

multi-hadron collisions in dense regime near Tc bring hadrons into equilibrium

(JS, P.Braun-Munzinger, K. Wetterich)

beam energy dependence of hadron yields from AGS to LHC

following the above T and μ_b evolution, features of proton/pion and kaon/pion ratios reproduced in detail



extension of statistical model to include charmed hadrons

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

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

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

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

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

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

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

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

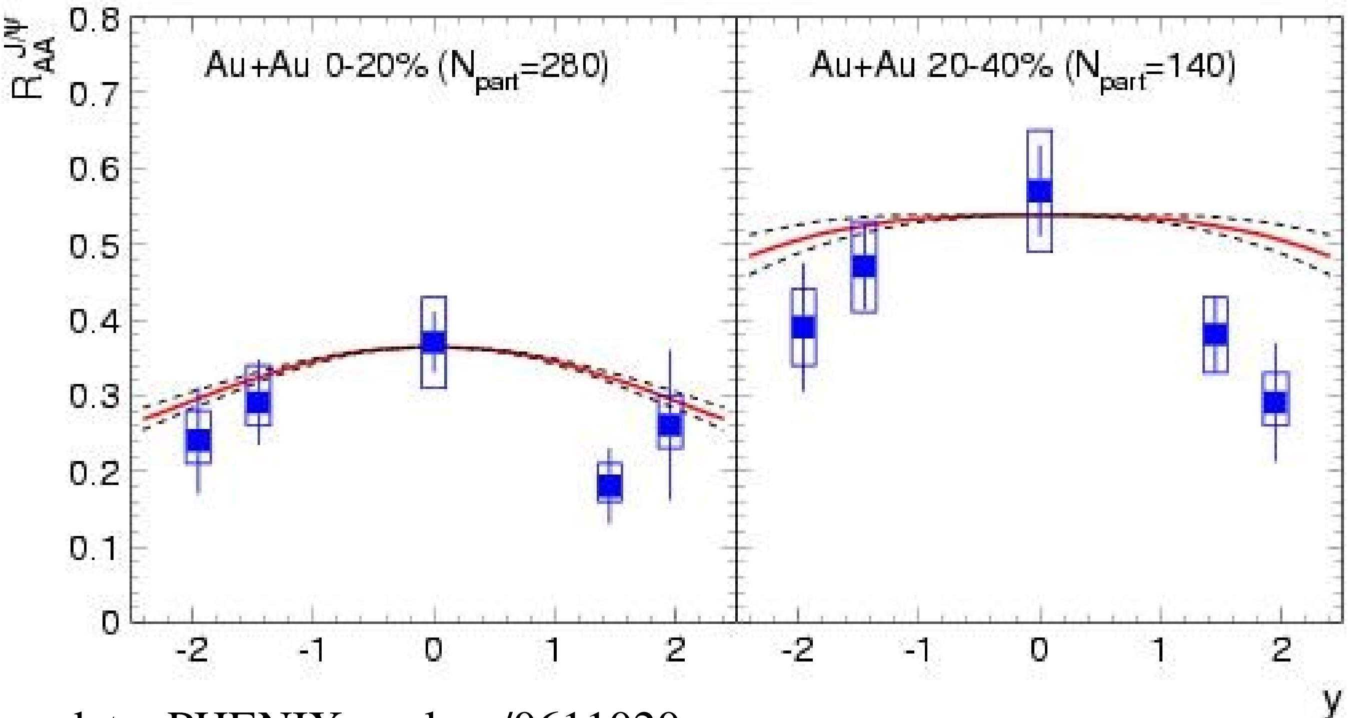
Destruction and regeneration in transport models

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

comparison of model predictions to RHIC data:

R_{AA}: J/ψ yield in AuAu / J/ψ yield in pp times N_{coll}



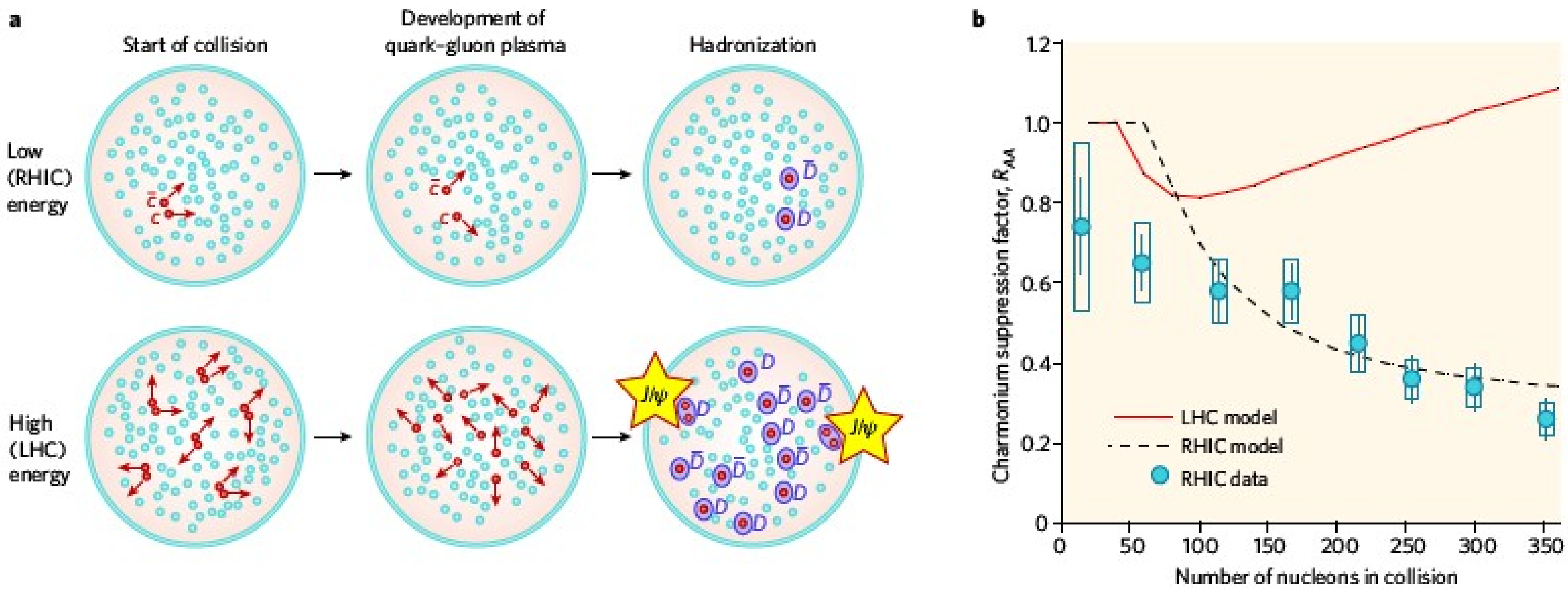
good agreement, no free parameters

data: PHENIX nucl-ex/0611020
additional 14% syst error beyond shown

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

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

Quarkonium as a Probe for Deconfinement at the LHC the Statistical Hadronization Picture



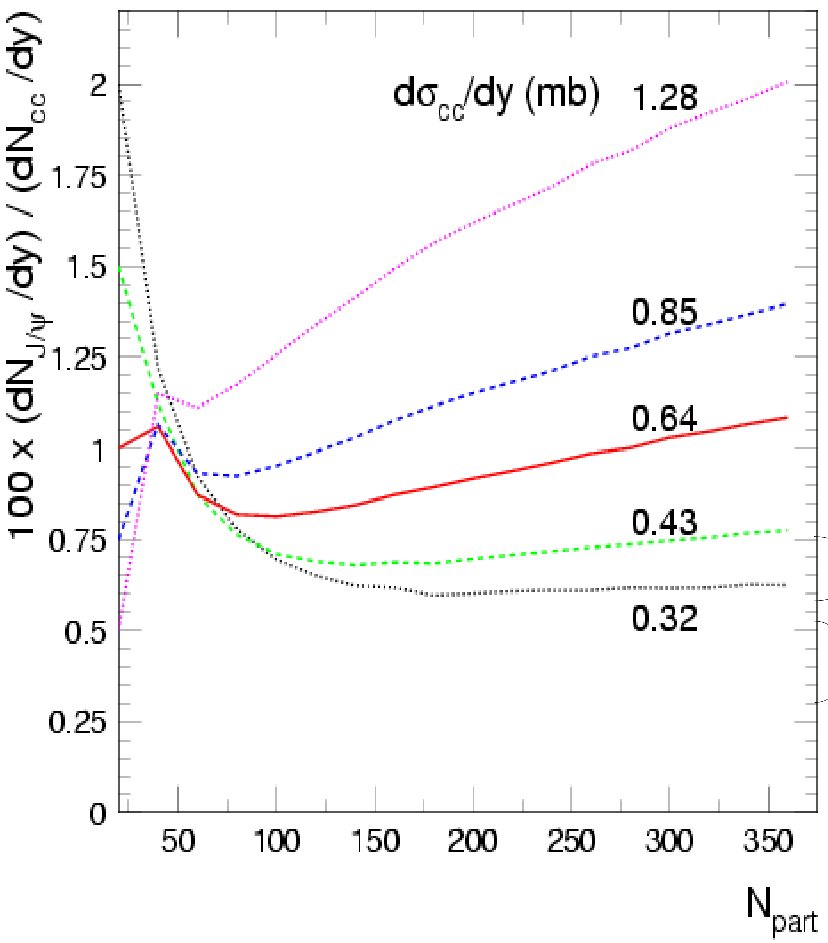
charmonium enhancement as fingerprint of deconfinement at LHC energy

only free parameter: open charm cross section in nuclear collision

Braun-Munzinger, J.S., Phys. Lett. B490 (2000) 196 and

Andronic, Braun-Munzinger, Redlich, J.S., Phys. Lett. B652 (2007) 659

Predictions for LHC energies



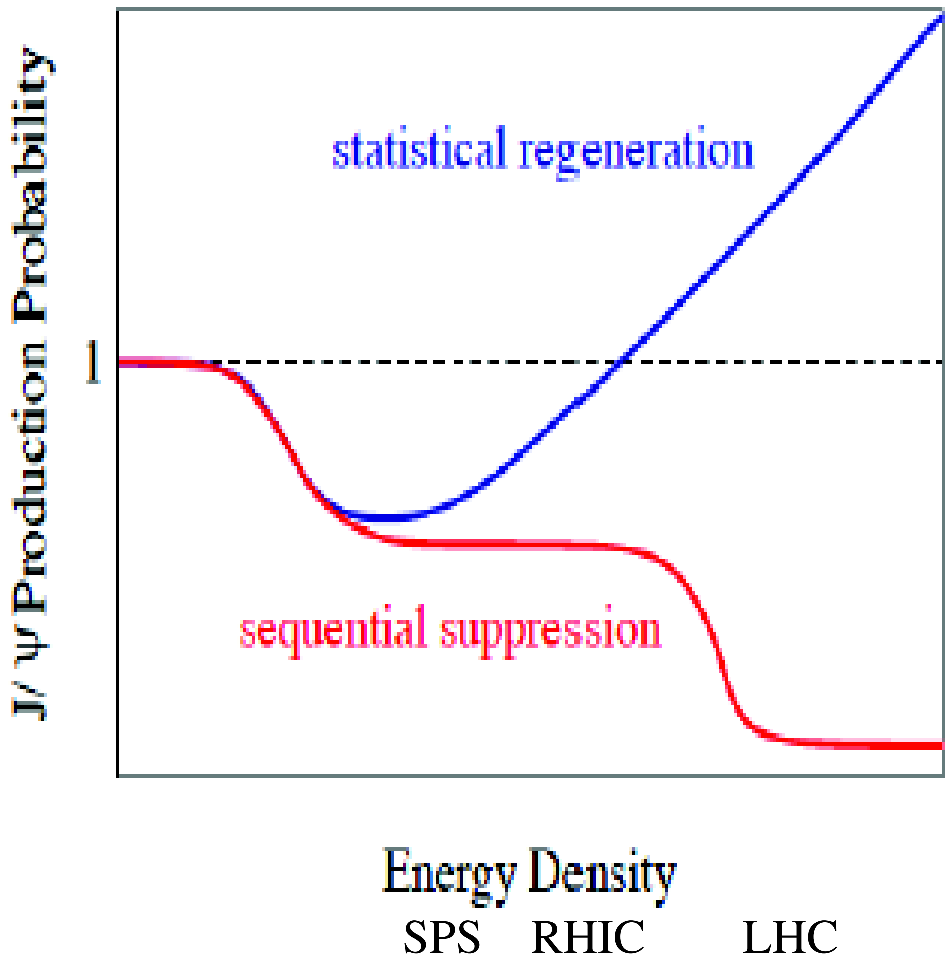
open charm is natural and essential normalization
precision measurement needed

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

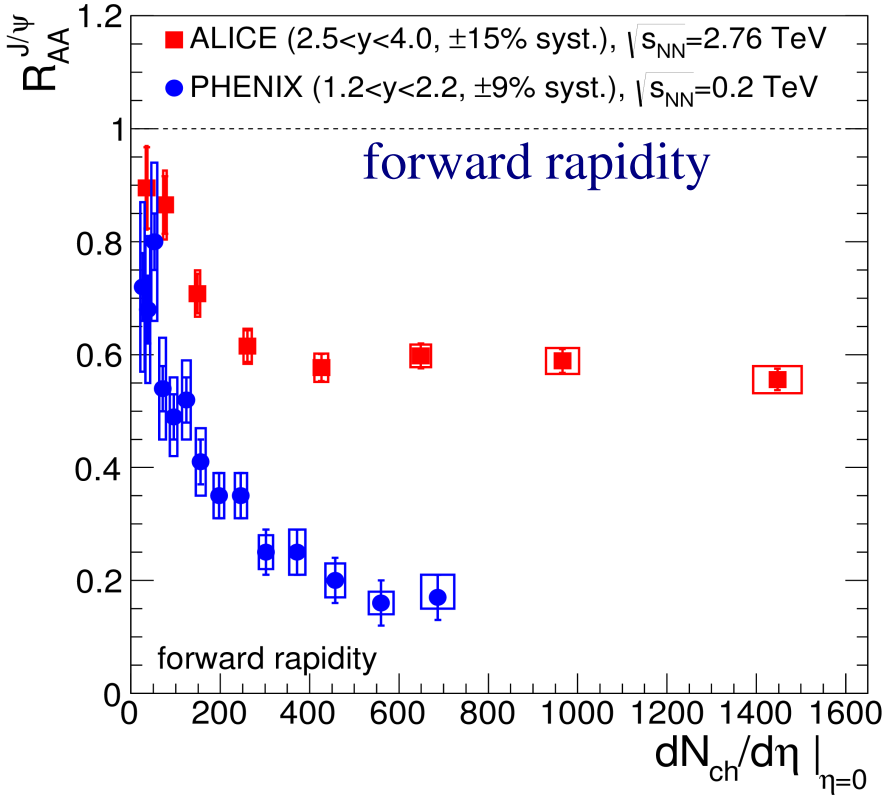
Decision on Regeneration vs. Sequential Suppression from LHC Data

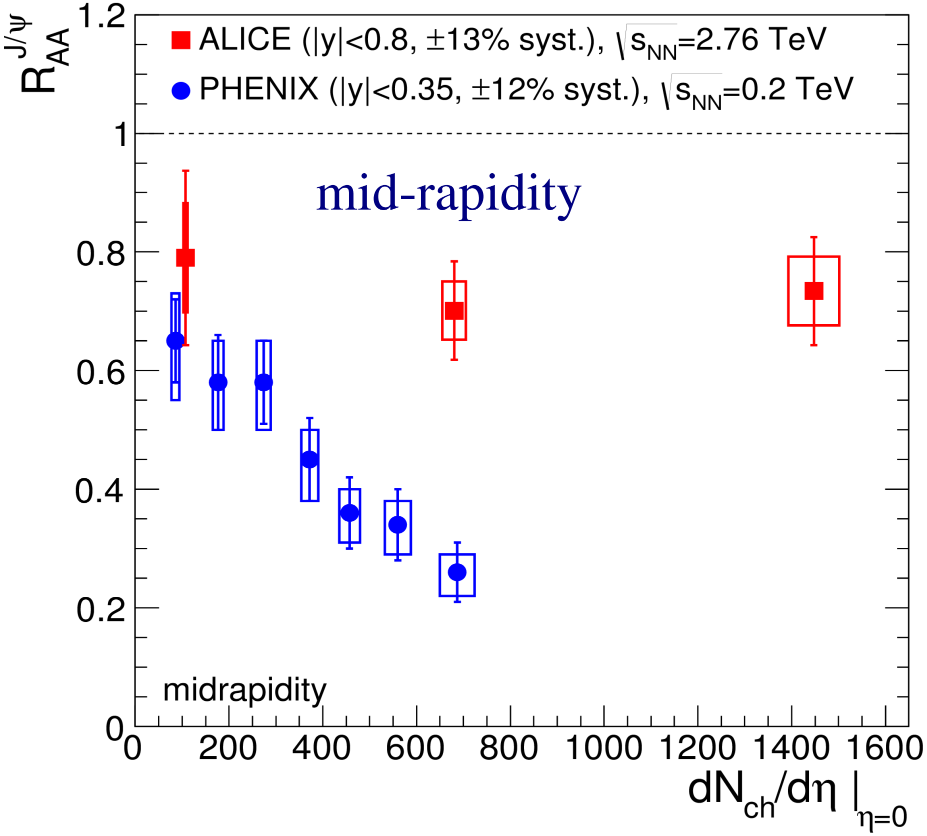


Picture:
H. Satz 2009

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

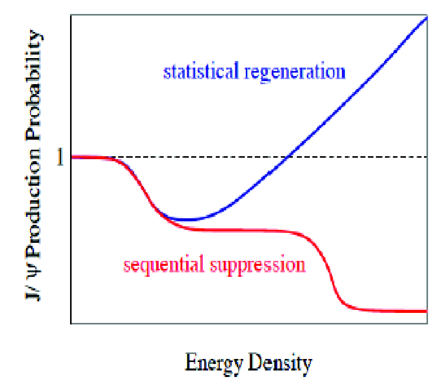
$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta\, dp_T}{\langle N_{coll}\rangle\, (1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta\, dp_T}$$





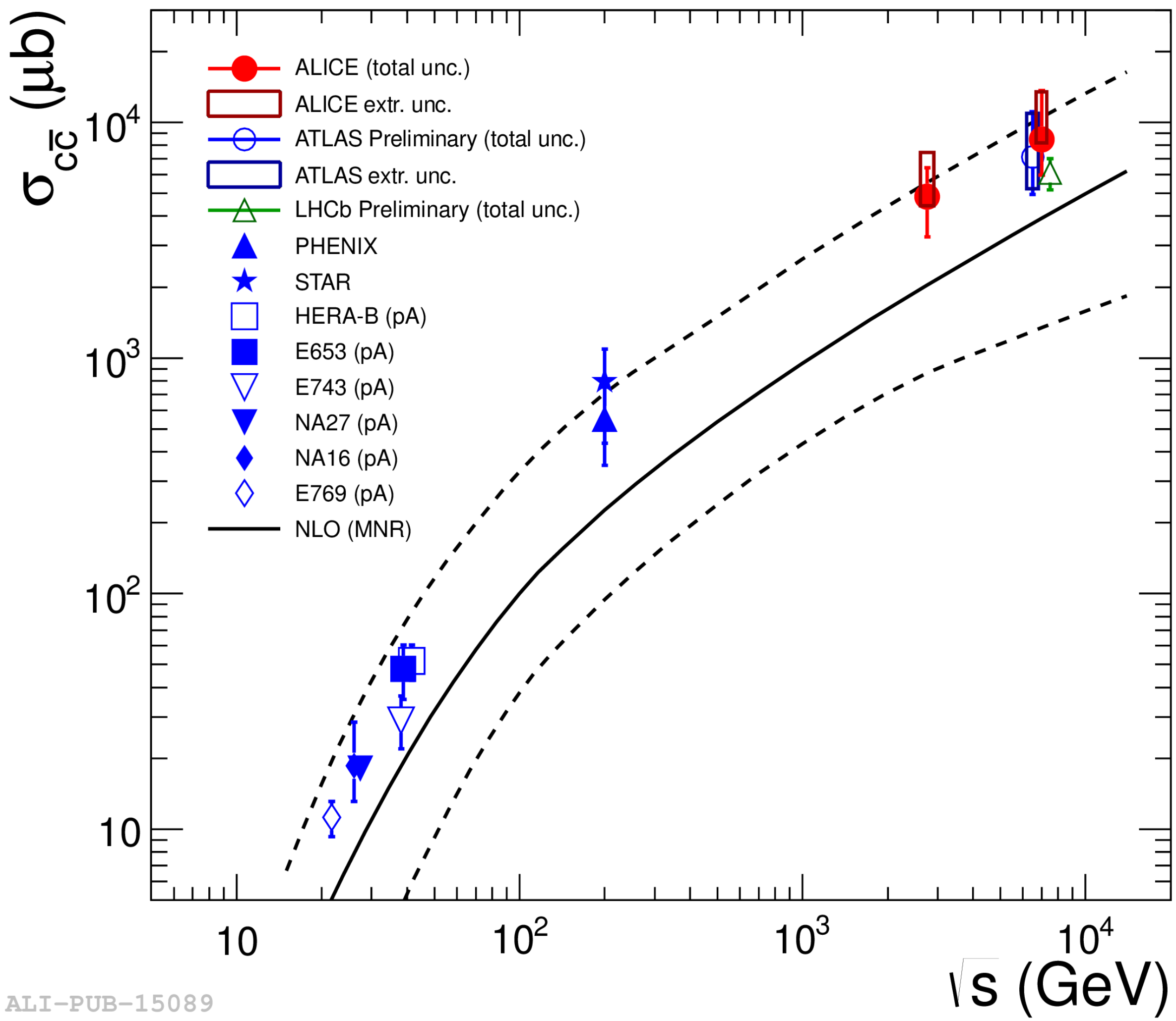
energy density -->

melting scenario not observed
rather: enhancement with increasing energy density!
(from RHIC to LHC and from forward to mid-rapidity)



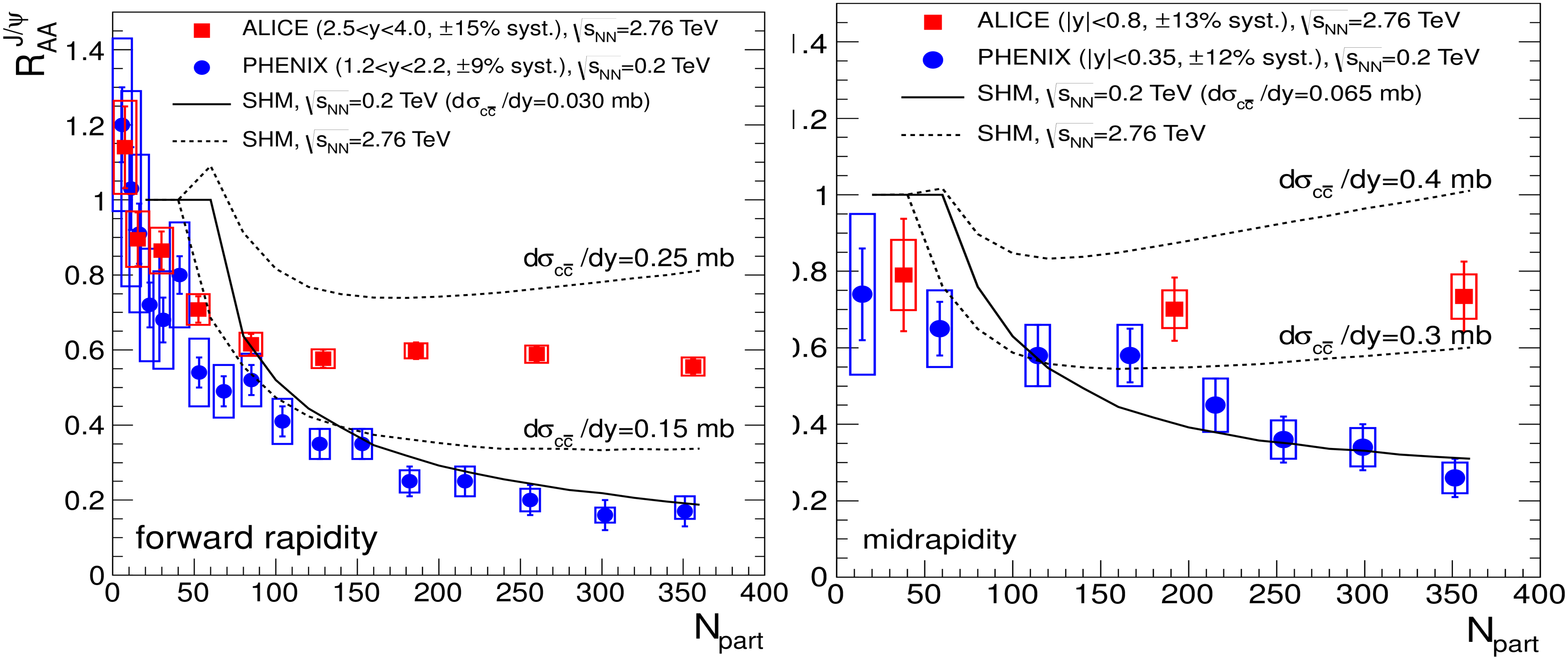
a first try at the total ccbar cross section in pp at LHC

JHEP 1207 (2012) 191



- good agreement between ALICE, ATLAS and LHCb
- large syst. error due to extrapolation to low pt, need to push measurements in that direction
- data factor 2 ± 0.5 above central value of FONLL but well within uncertainty
- beam energy dependence follows well FONLL
- soon more accurate 4pi extrapolation at 7 TeV

J/psi and Statistical Hadronization



- production in PbPb collisions at LHC consistent with deconfinement and subsequent statistical hadronization within present uncertainties
- main uncertainties for models: open charm cross section, shadowing in Pb
- shadowing from pPb collisions: forward y: R_{AA} = 0.76(12) mid-y R_{AA} (estim) =0.72(15)

First determination of Debye mass from data

J/psi formation via statistical hadronization at Tc implies
experimental determination of Debye length (mass) and temperature

$\lambda_D < 0.4$ fm at T = 156 MeV

$\omega_D/T > 3.3$

can compare to theory:

quite ok

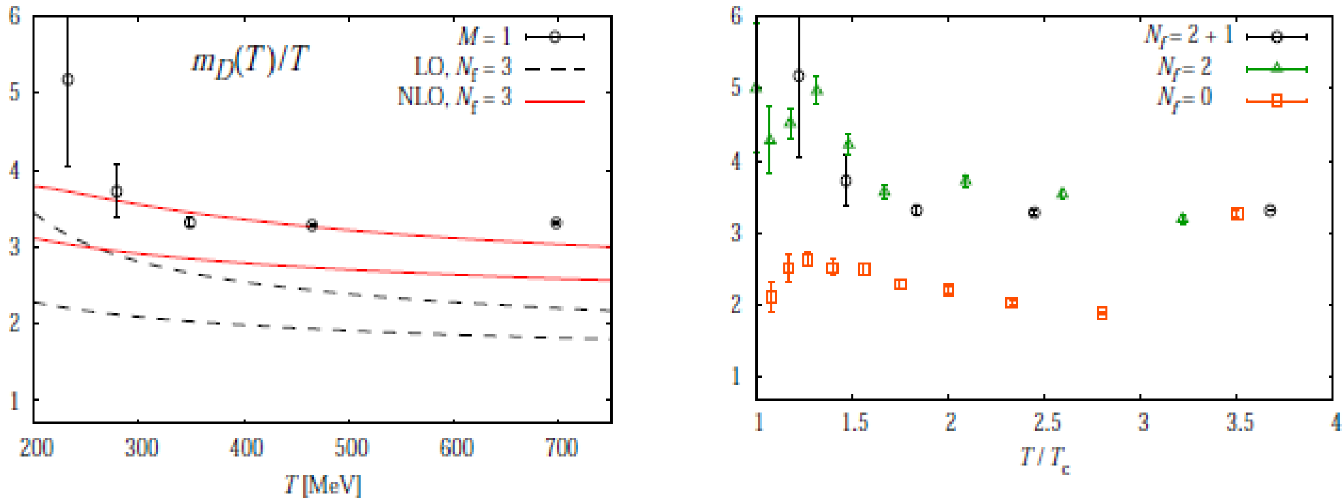
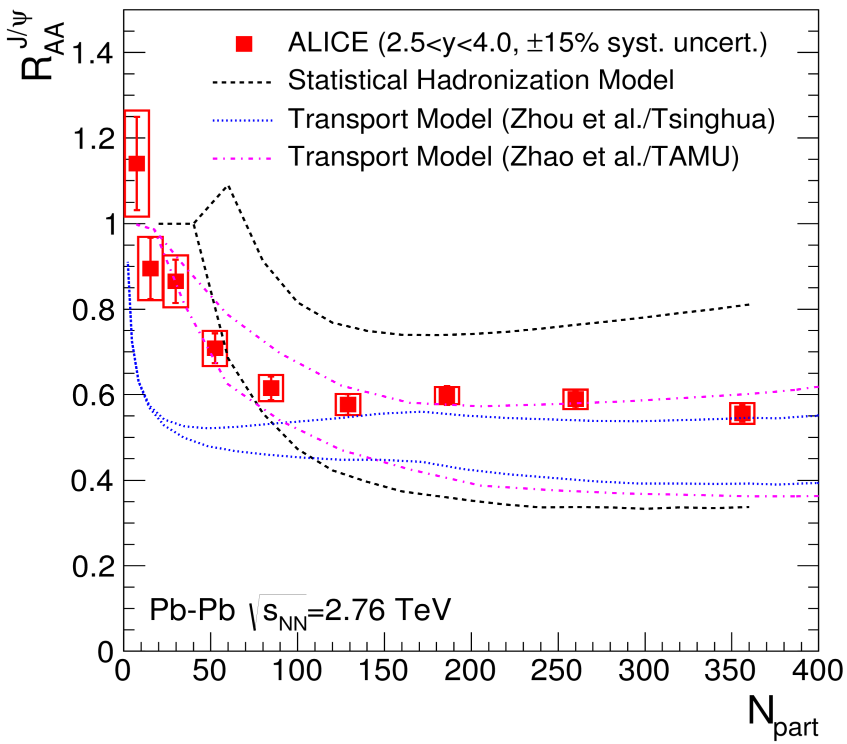
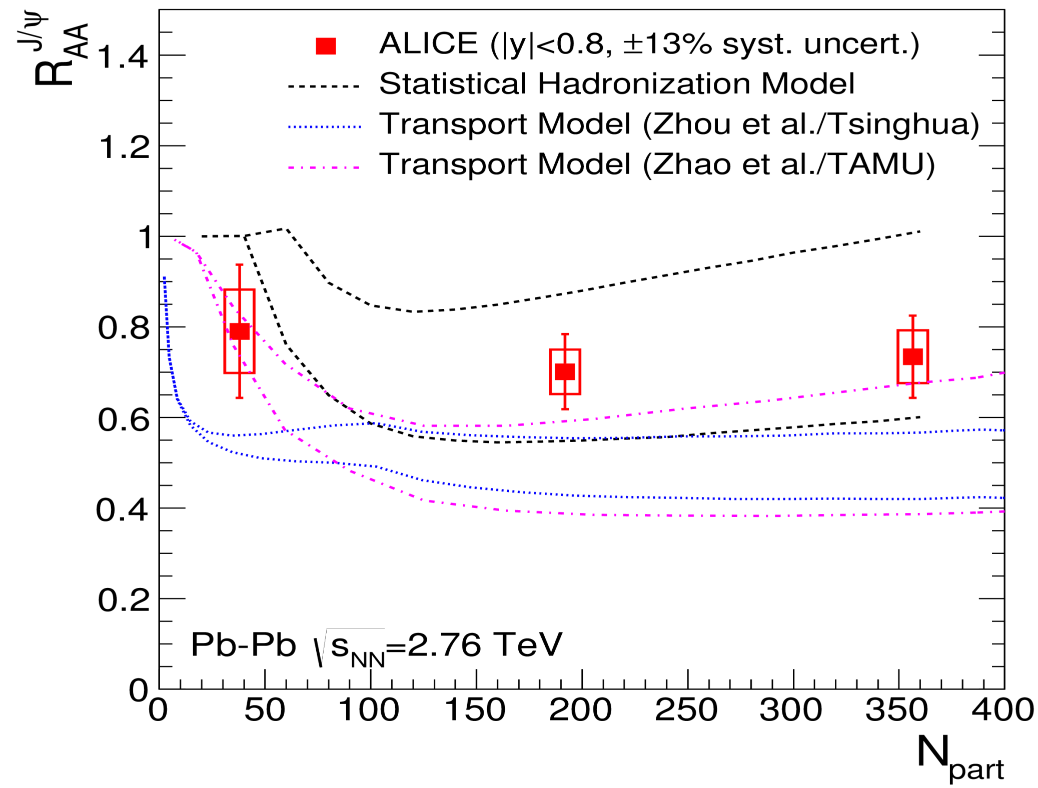


Fig. 6. (Left) The Debye screening mass on the lattice in the color-singlet channel together with that calculated in the leading-order (LO) and next-to-leading-order (NLO) perturbation theory shown by dashed-black and solid-red lines, respectively. The bottom (top) line expresses a result at $\mu = \pi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

J/psi and transport models (and stat hadronization)



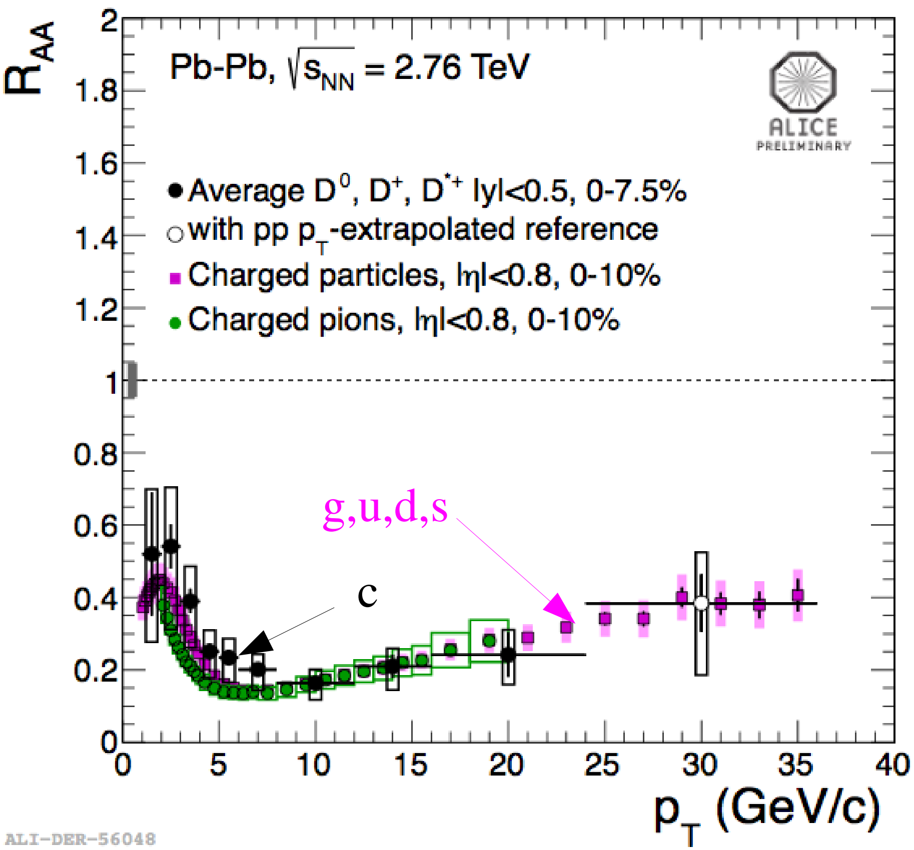


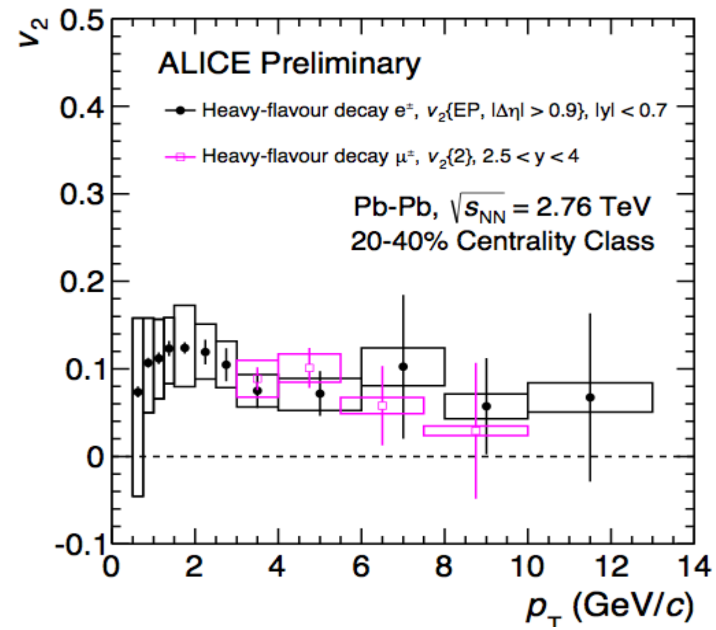
in transport models (Rapp et al. & P.Zhuang, N.Xu et al.) J/psi generated both in QGP and at hadronization

- transport models also in line with R_{AA}
  part of J/psi from direct hard production, part dynamically generated in QG
  but different open charm cross section used
  (0.5-0.75mb TAMU and 0.65-0.8 mb Tsinghua vs. 0.3-0.4 mb SHM)

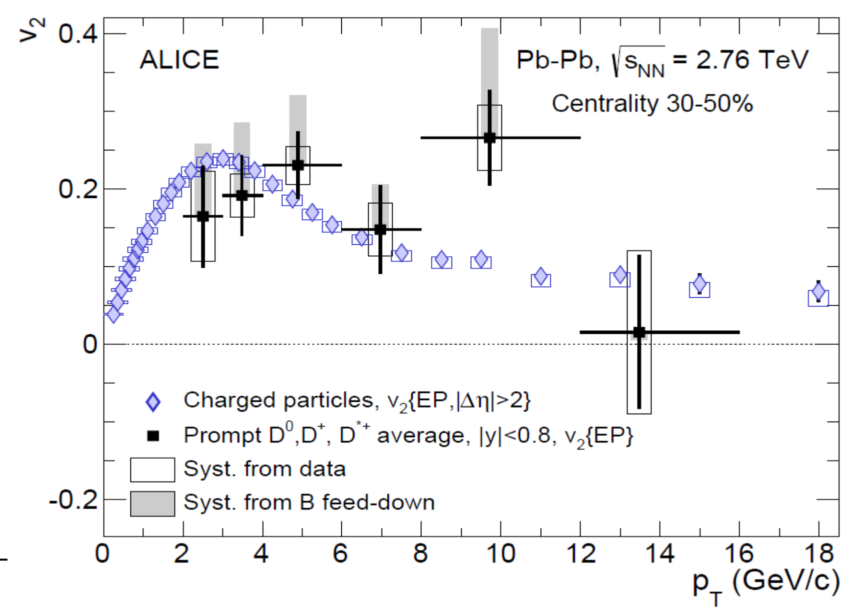
Charm quarks thermalize to large degree in QGP

strong energy loss of charm quarks





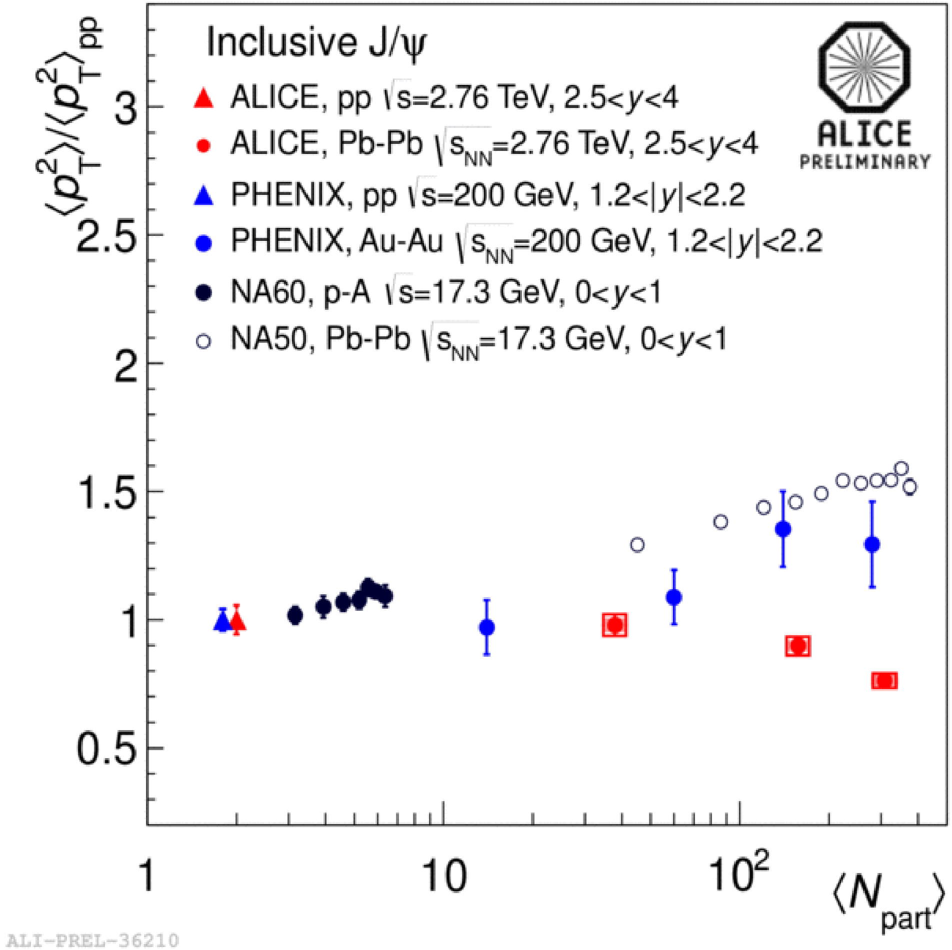
elliptic flow for charm – participation in coll. flow



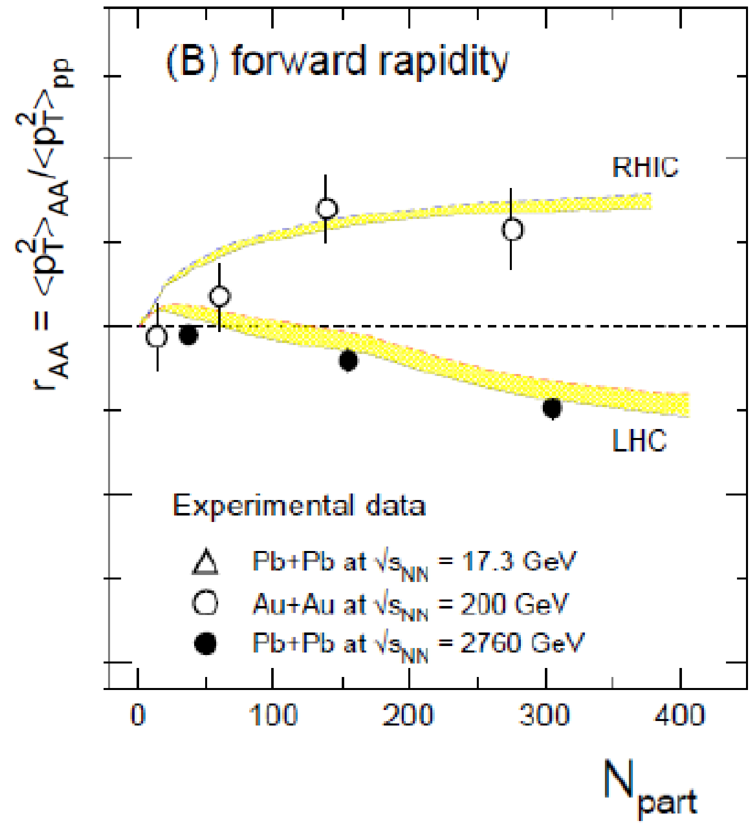
Phys. Rev. Lett. 111 (2013) 102301

M.Djordjevic, arXiv:1307.4098: equal R_{AA} is a conspiracy of different fragmentation functions of light quarks, gluons, charm and different color factors in energy loss

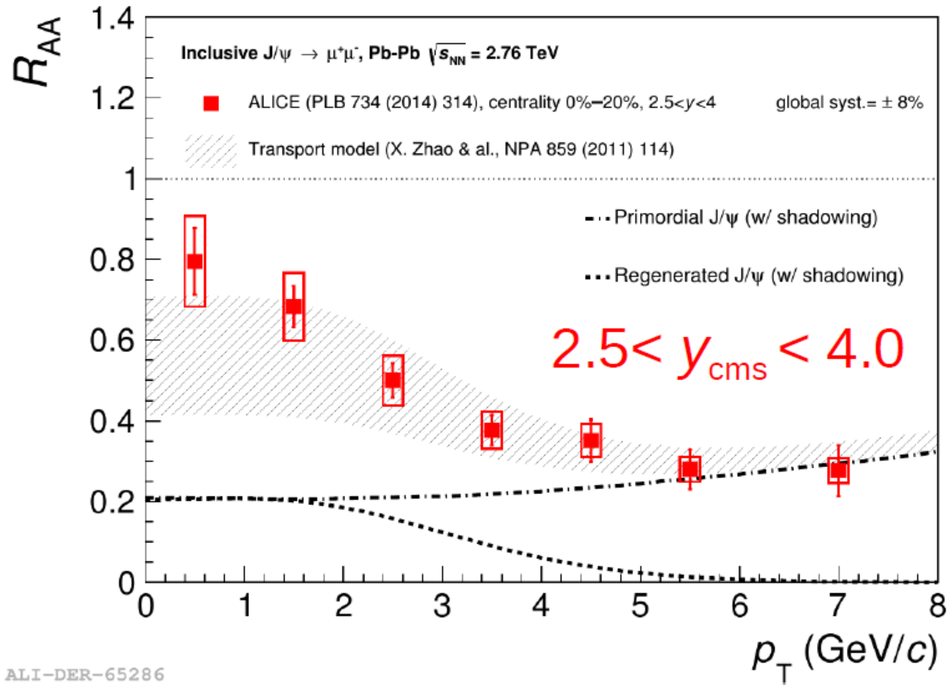
Softening of J/psi p_t distributions for central PbPb coll.

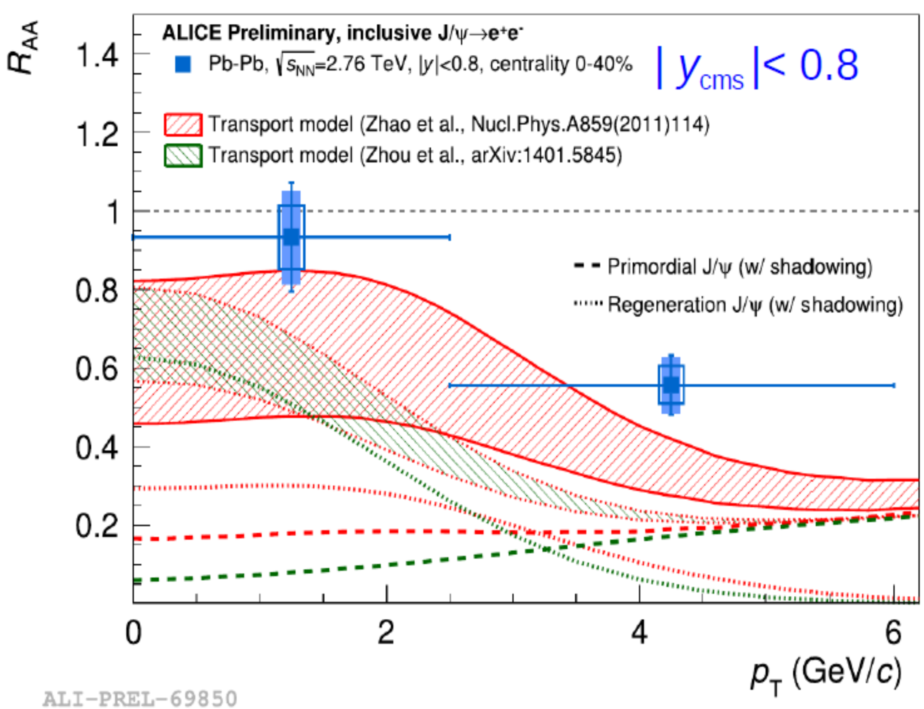


P.Zhuang et al. regeneration of J/psi
90% at mid-y, > 60% at forward y



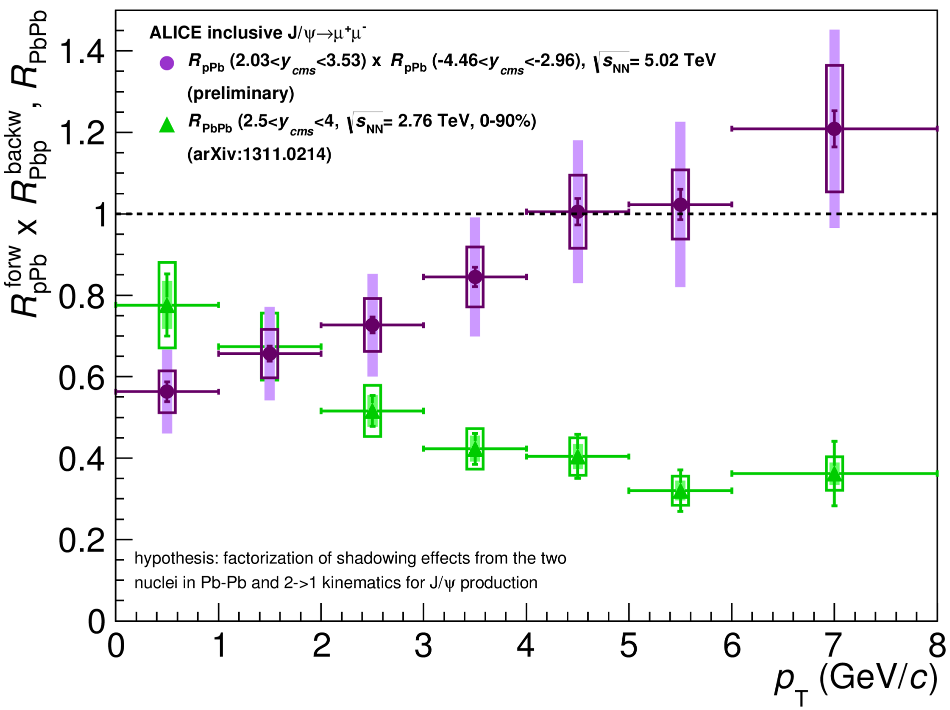
p_t dependence of R_{AA} supports dominance of new production mechanism at LHC at small p_t

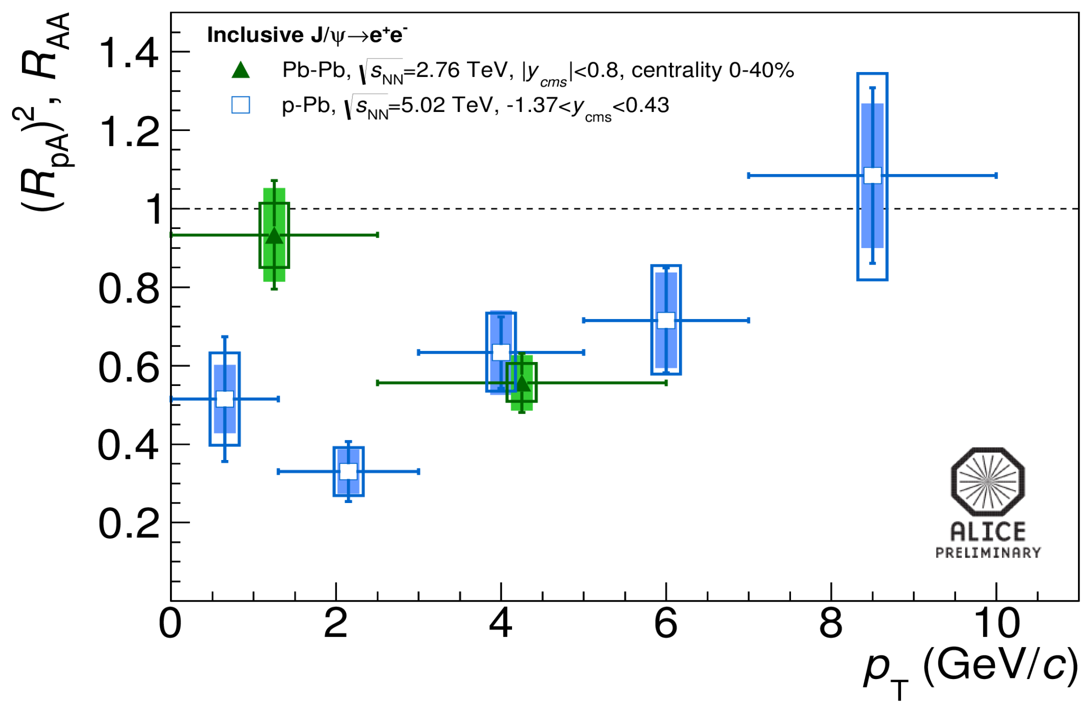




J/psi vs p_t in PbPb collisions relative to pPb collisions

arXiv:1405.1177



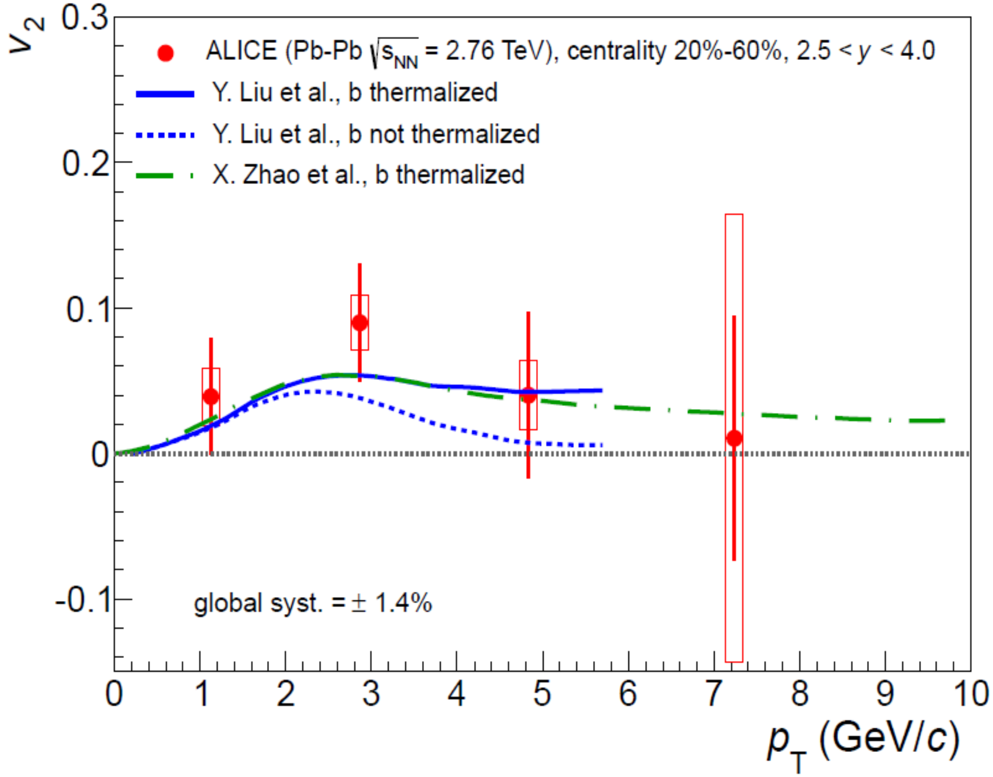


at low pt yield in nuclear collisions above pPb collisions

J/psi production **enhanced** in nuclear collisions **over mere shadowing effect**

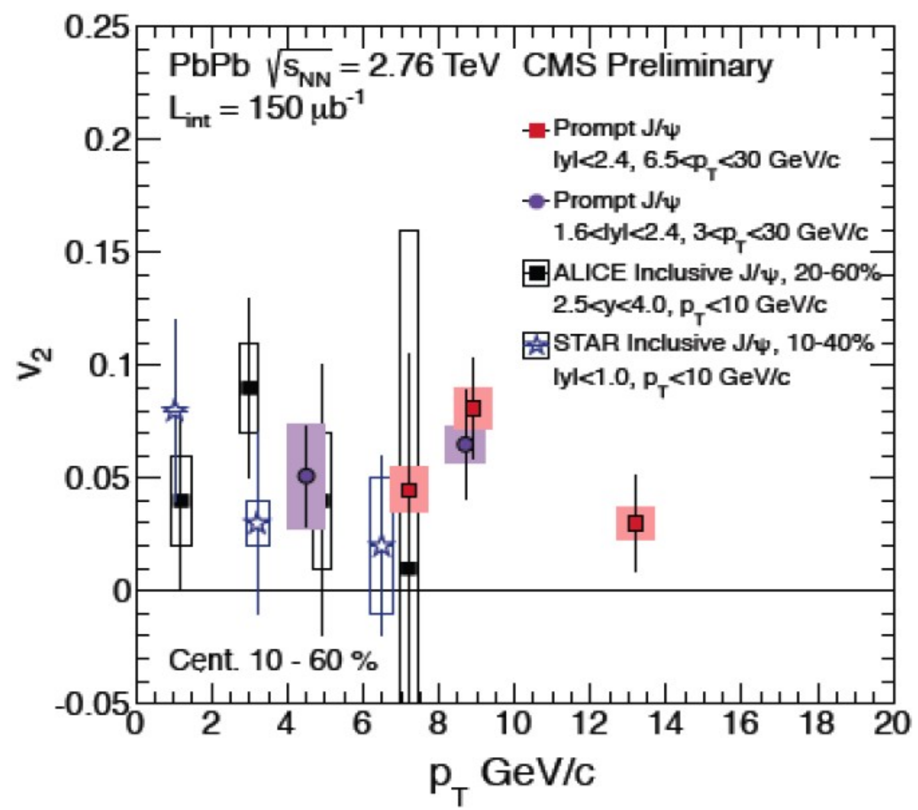
J/psi flow compared to models including (re-) generation

arXiv:1303.5880



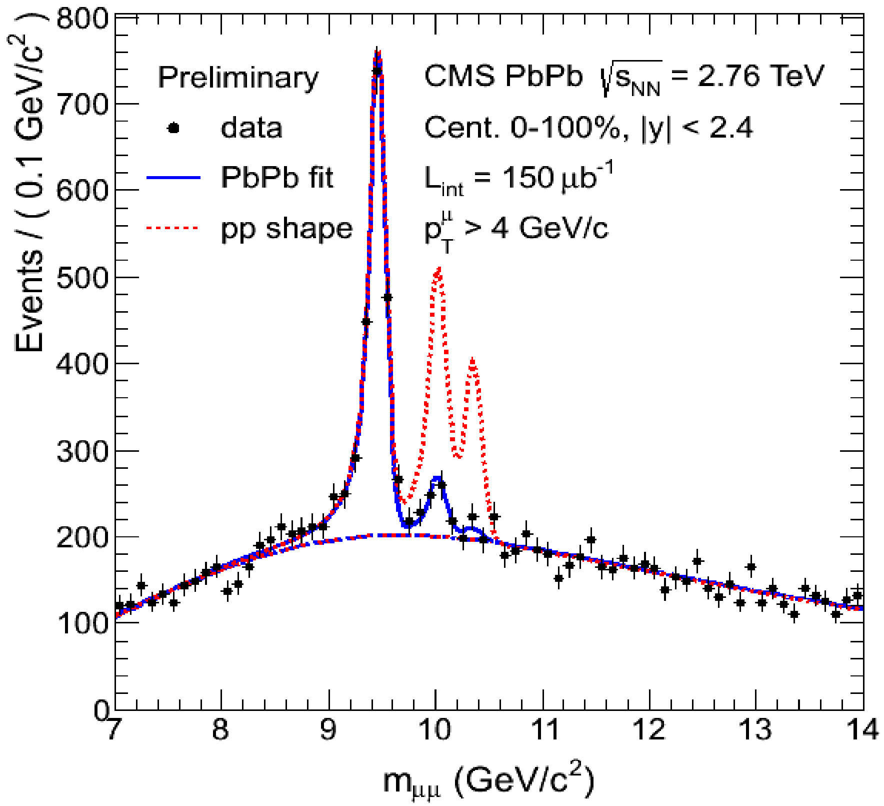
v_2 of J/ψ consistent with hydrodynamic flow of charm quarks in QGP
and statistical (re-)generation

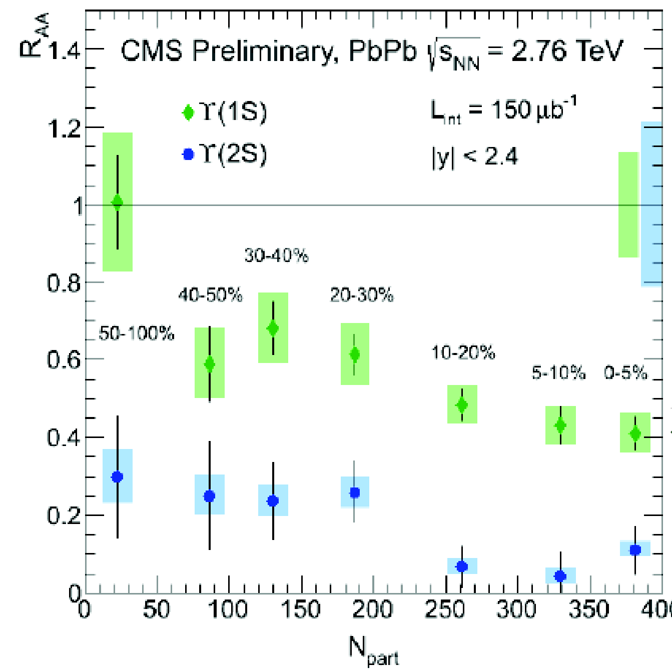
but:
CMS observes similar v_2 at higher p_t



this calls for
more and better data

Suppression of Upsilon States





CMS-HIN-11-011

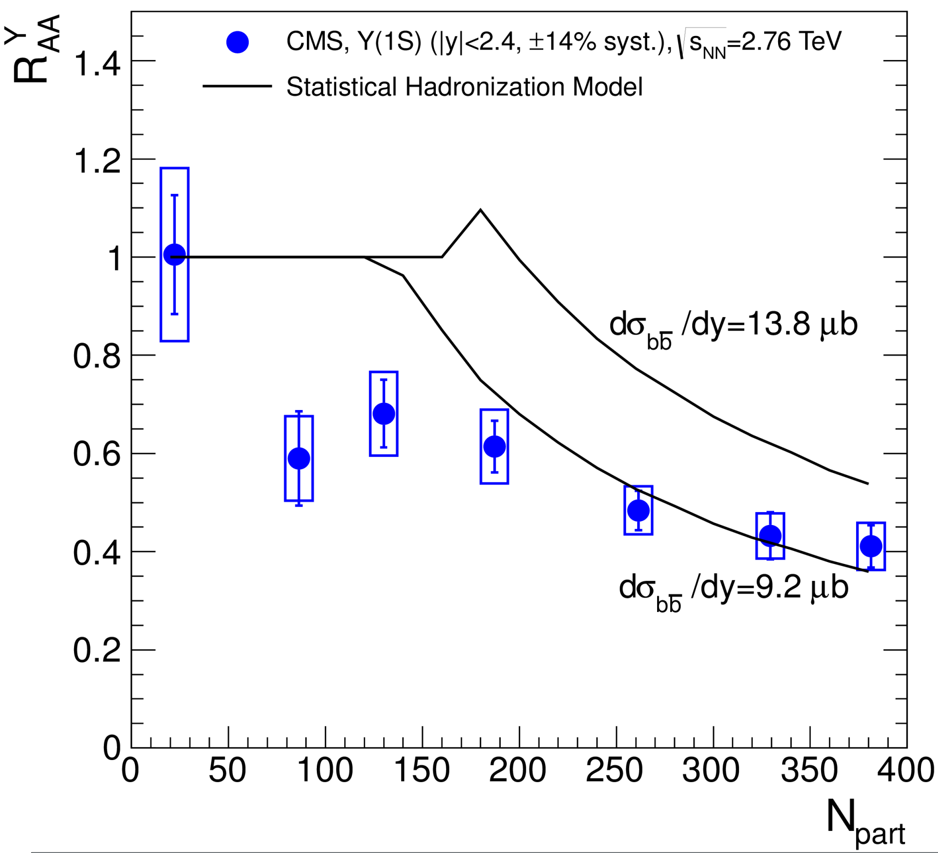
consistent with excited state suppression (50% feed-down)

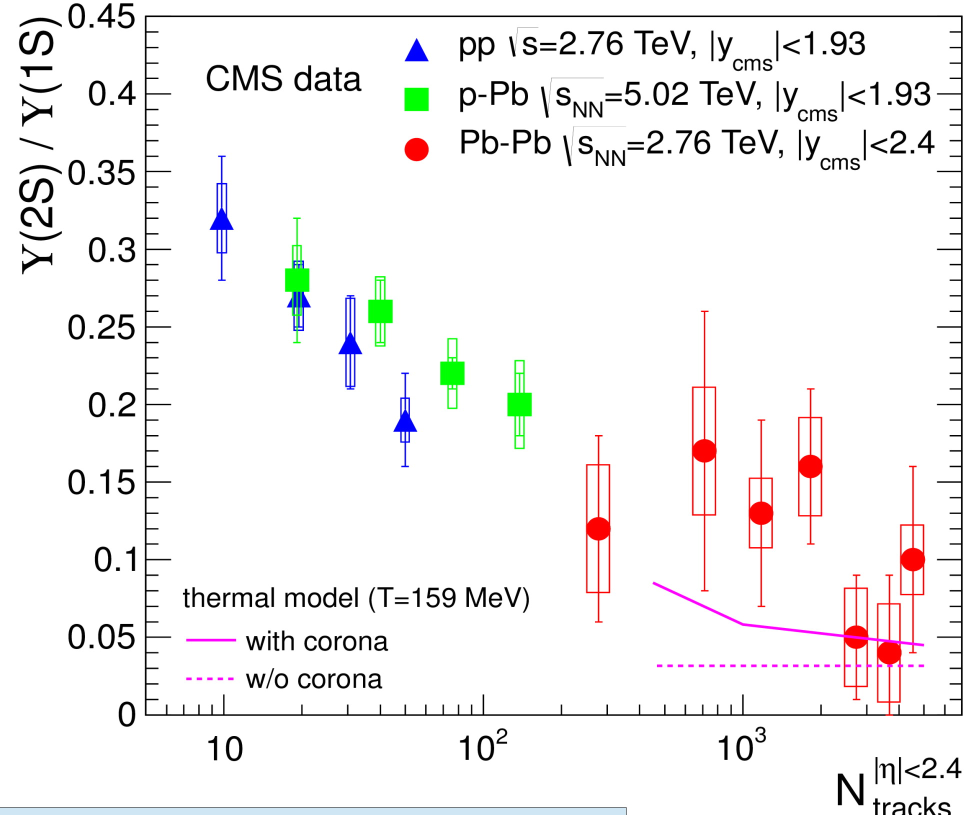
centrality integrated:
2S/1S PbPb relative to pp 0.21+-0.07+-0.02
3S/1S " < 0.1 95% C.L.

higher upsilon states expected to melt earlier because of larger radius

the Upsilon could also come from statistical hadronization

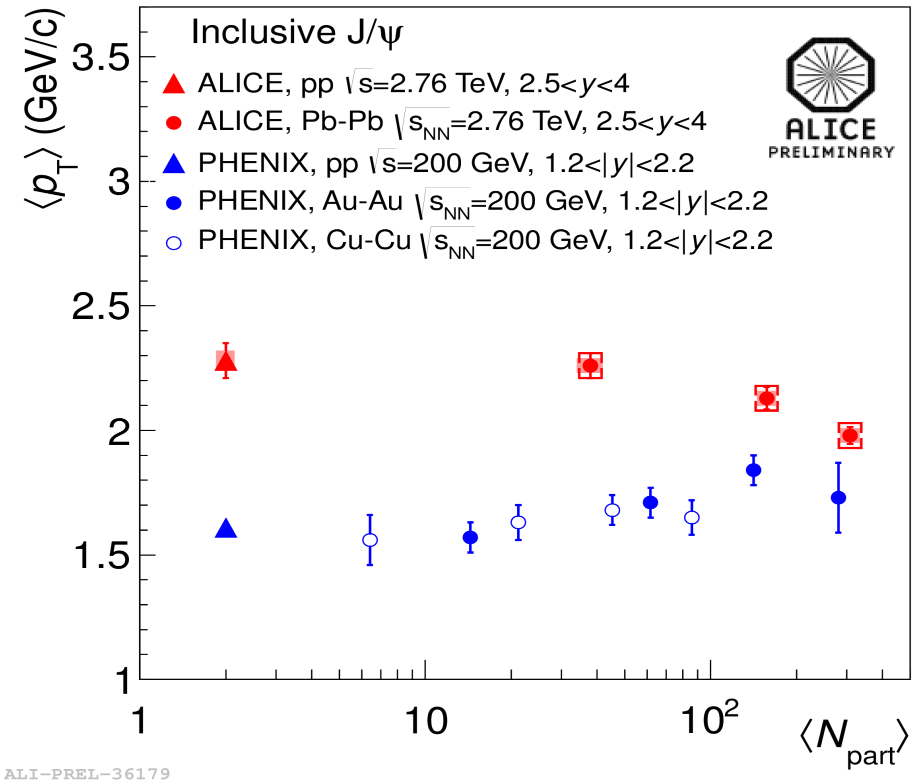
SHM/thermal model: Andronic et al.





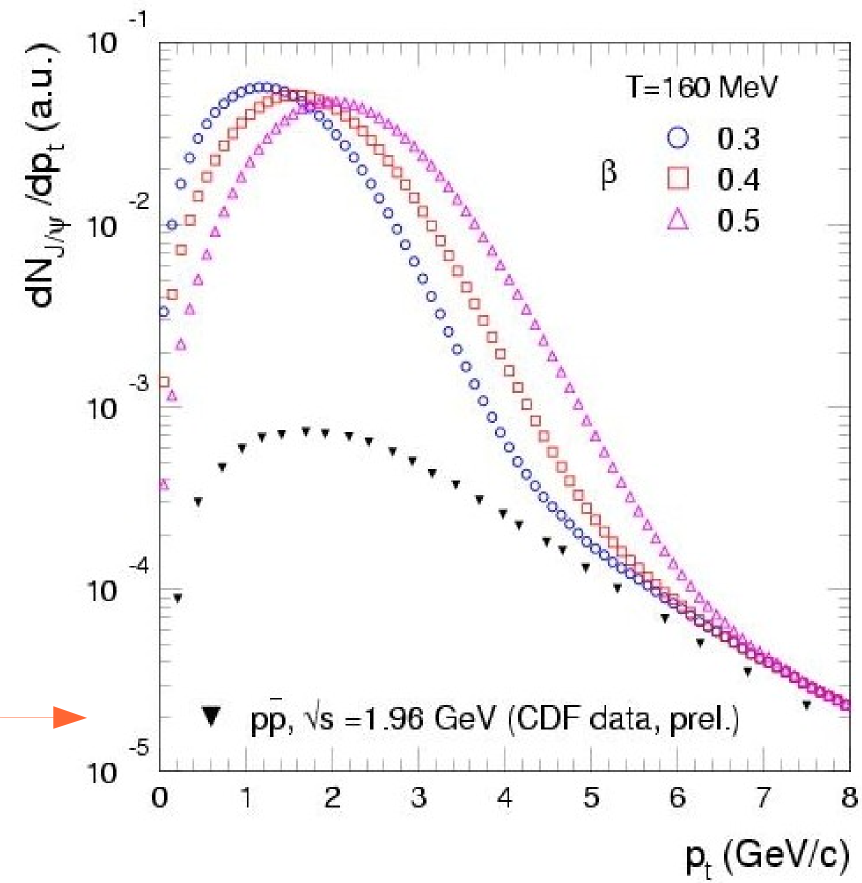
in this picture the entire Upsilon family is formed at hadronization
but: need to know first – do b-quark thermalize at all
- total b-cross section in PbPb

Outlook: spectral distribution is key to thermalization

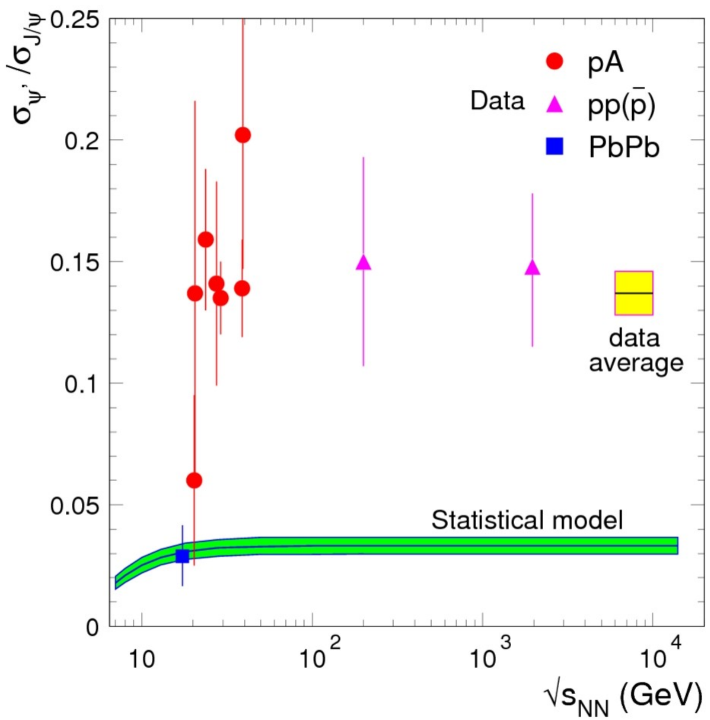


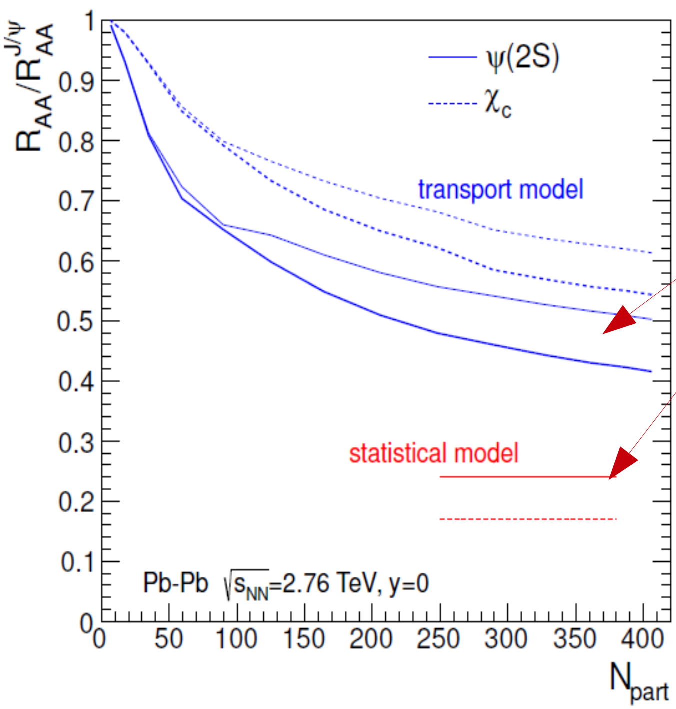
at LHC shift of paradigm: more central collision → narrower momentum distribution
my interpretation: thermalization

but if charm quark thermalize, their spectral distributions should also reflect collective flow of liquid



Outlook: excited charmonia



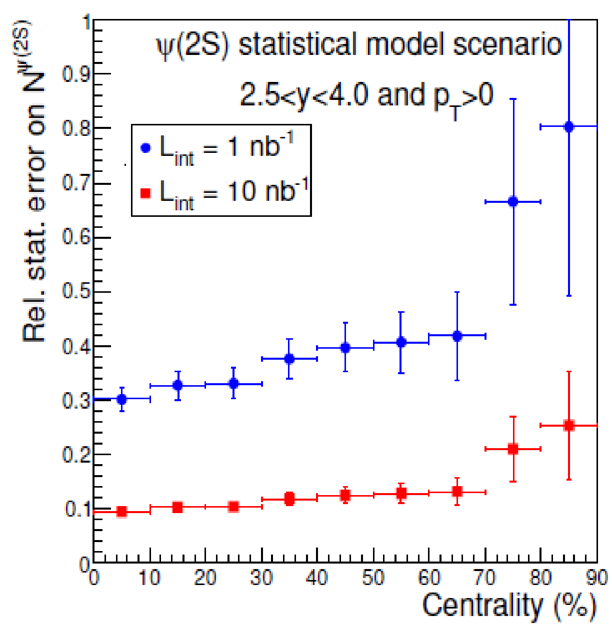


in fact here one can distinguish between the transport models that form charmonia already in QGP and statistical hadronization at phase boundary!

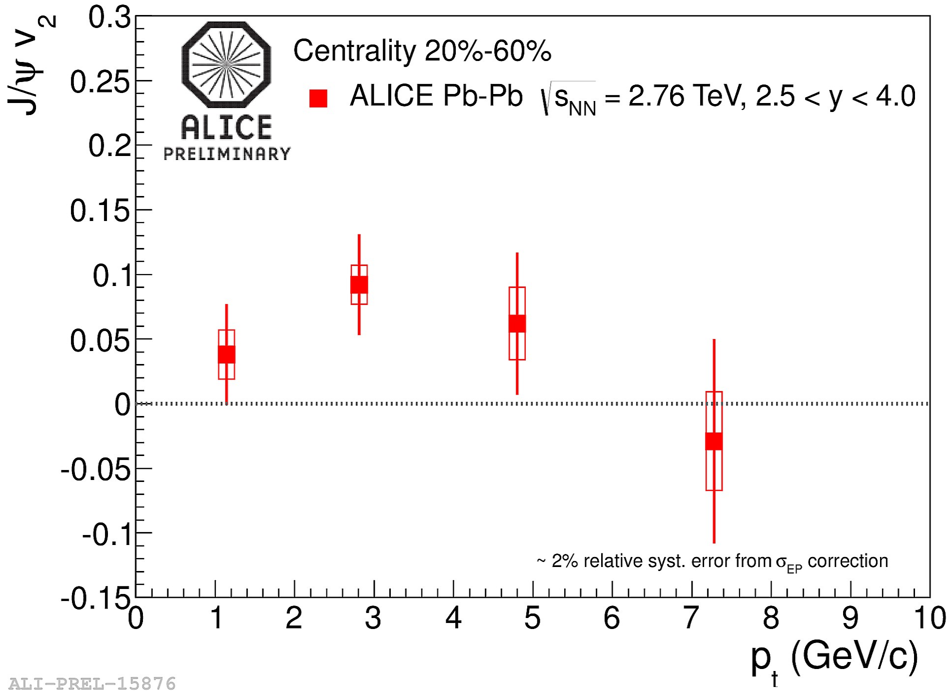
for statistical hadronization need to see suppression by Boltzmann factor

χ_c even bigger difference

expected ALICE performance muon arm run2 and run3



J/psi elliptic flow

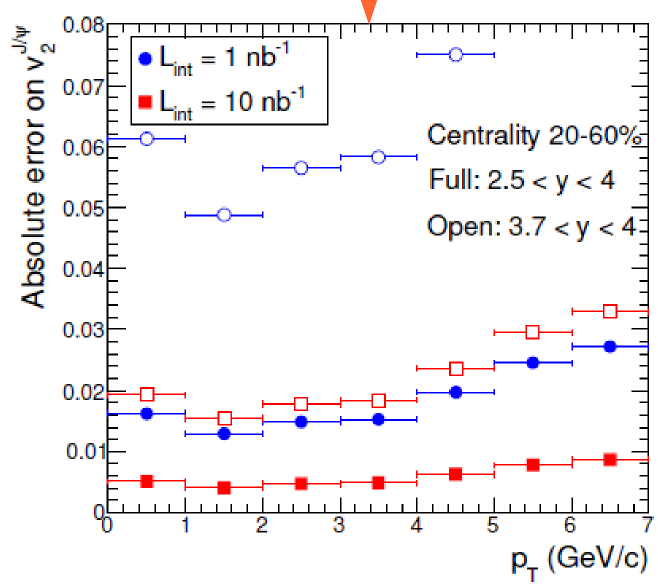


observation of flow with muon arm presently 3 sigma

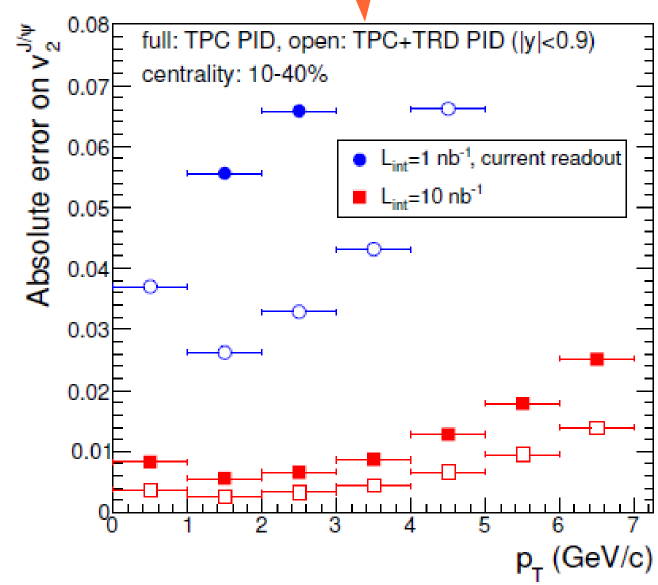
needs statistics to make model comparison meaningful

future statistical errors

muon arm



central barrel



summary

- J/psi good probe of deconfinement

though contrary to initial expectation not via sequential suppression, but reversal of suppresssion to enhancement at high beam energy

- within current uncertainties all J/psi observables at LHC consistent with formation from deconfined charm quarks

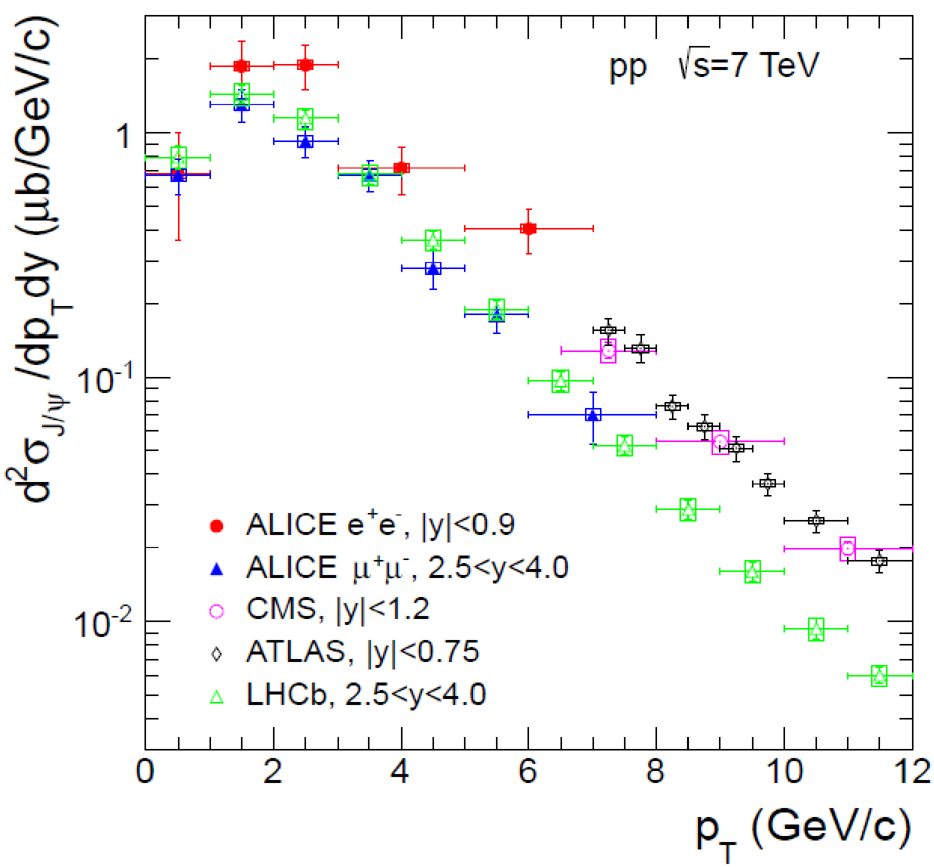
- significant progress expected within next decade, will allow models tests with a precision to constitute a proof of deconfinement

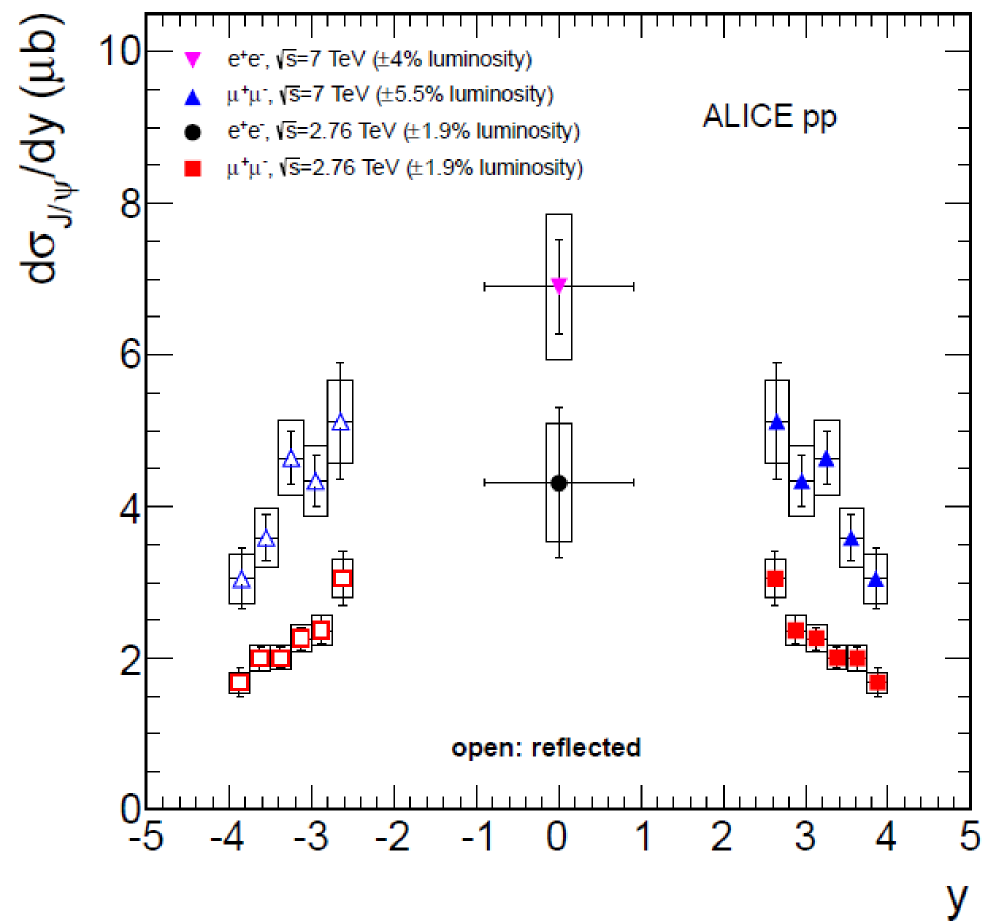
expect experimental determination of Debye screening mass

backup

J/psi spectrum and cross section in pp collisions

ALICE PLB704 (2011) 442 arXiv:1105.0380 and PLB718 (2012) 295

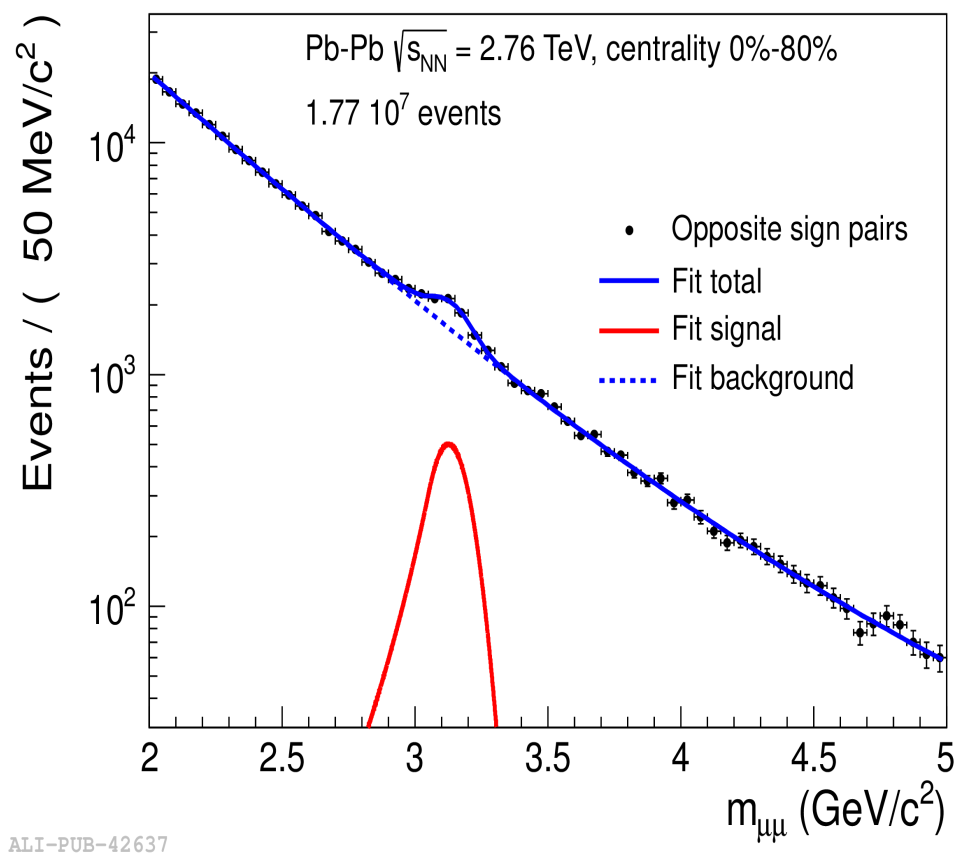


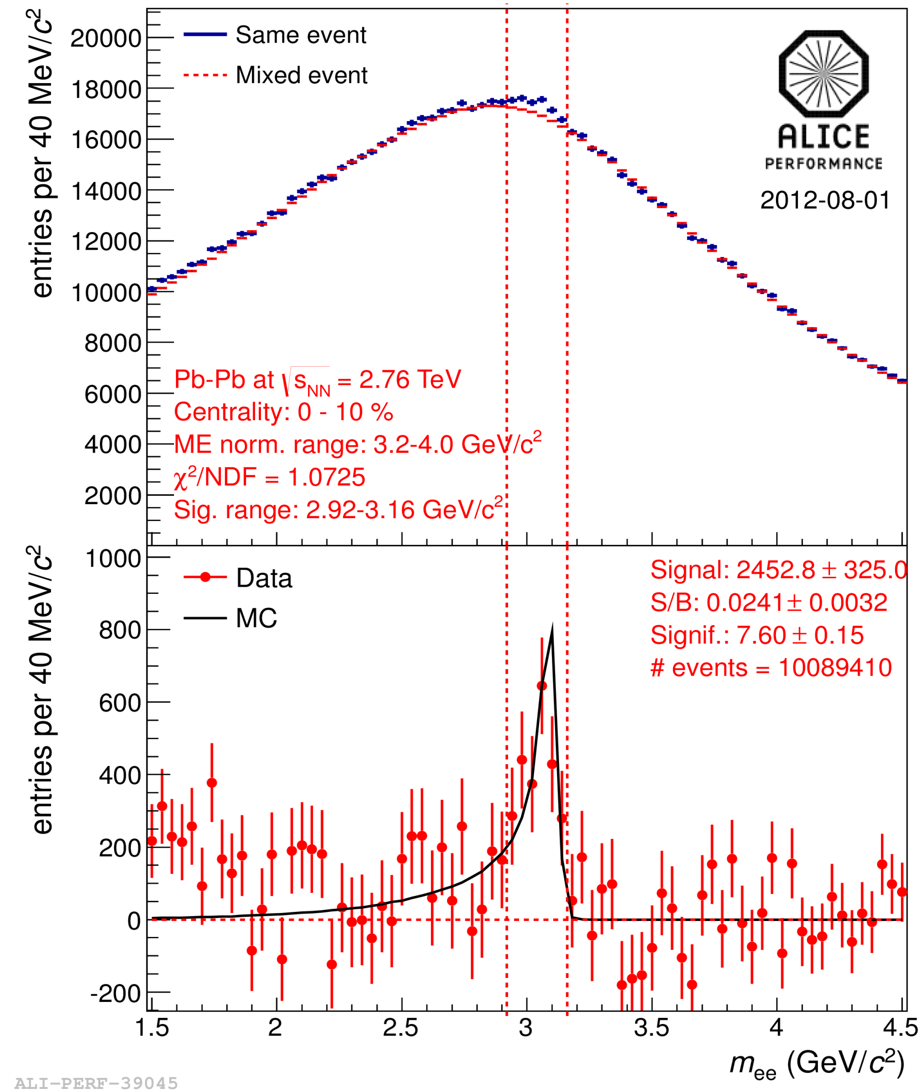


- good agreement between experiments
- complementary in acceptance:
  only ALICE has acceptance below
  6 GeV at mid-rapidity

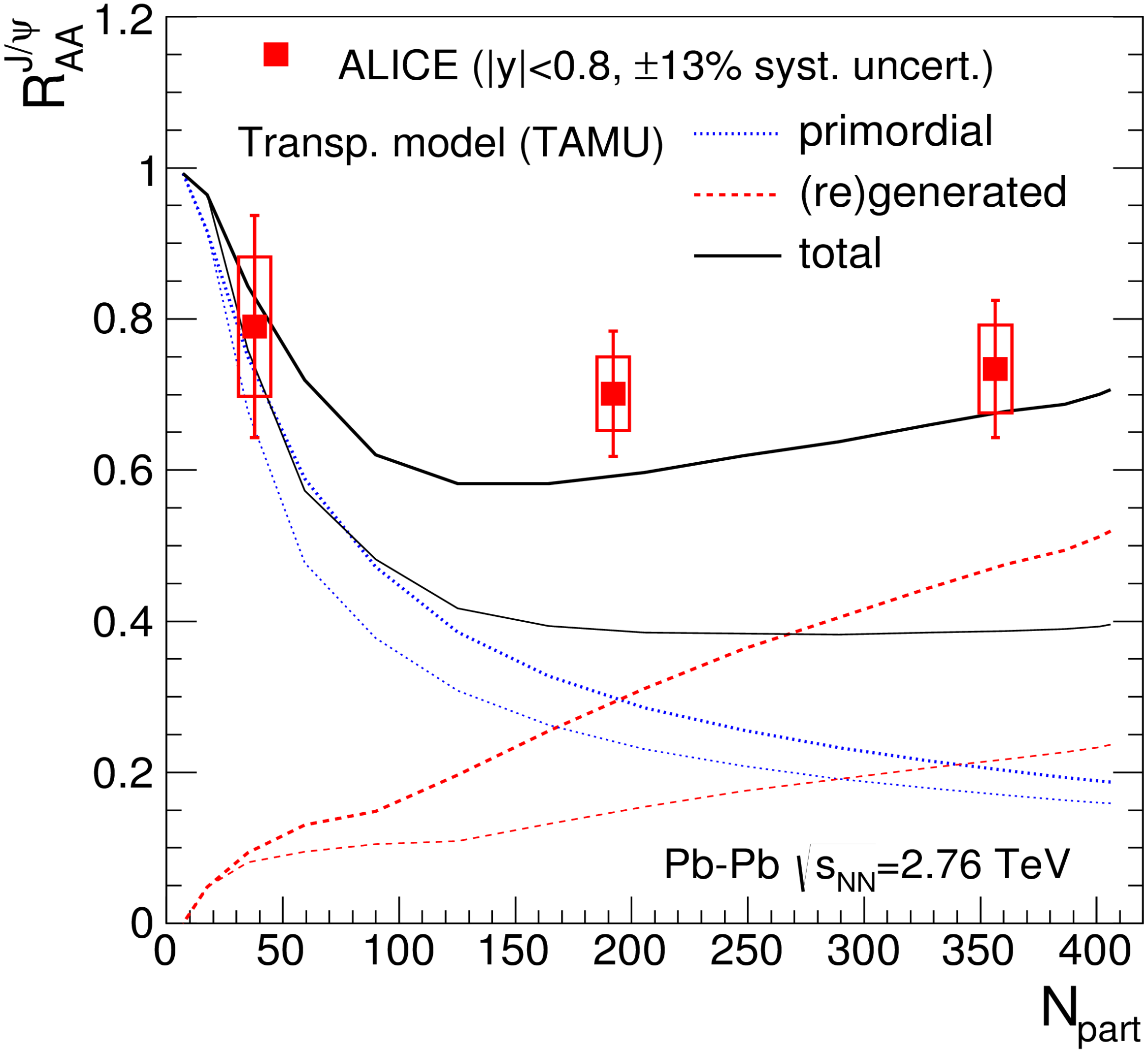
measured both at 7 and 2.76 TeV
<u>open issues:</u> statistics at mid-rapidity
polarization (biggest source of syst error)

Reconstruction of J/psi via mu+mu- and e+e- decay





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

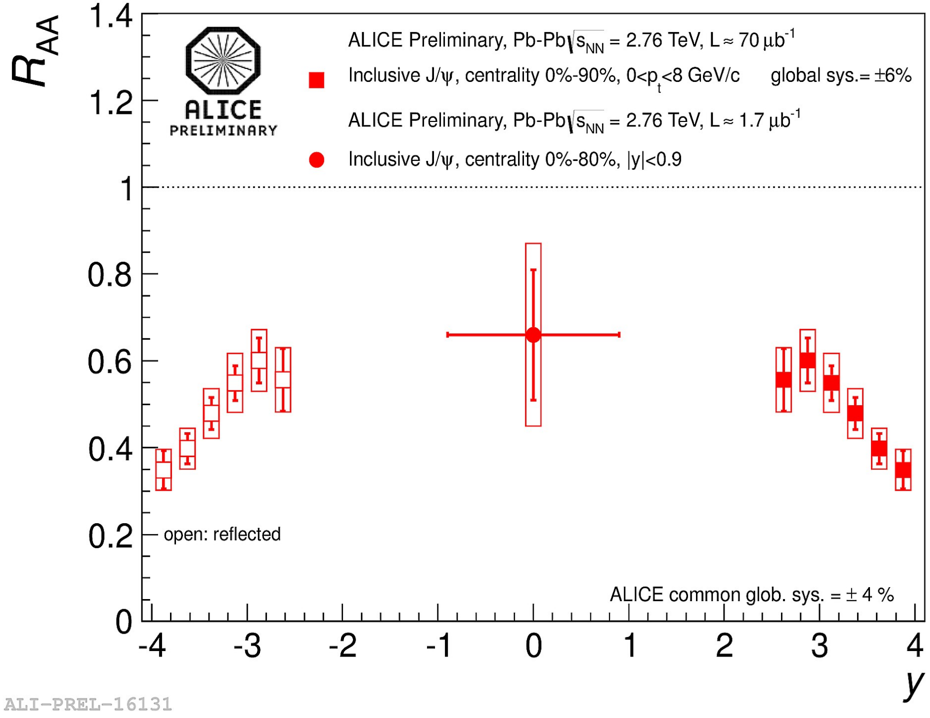


TAMU transport model:

Zhao et al., NPA 859 (2011) 114 and priv. comm.

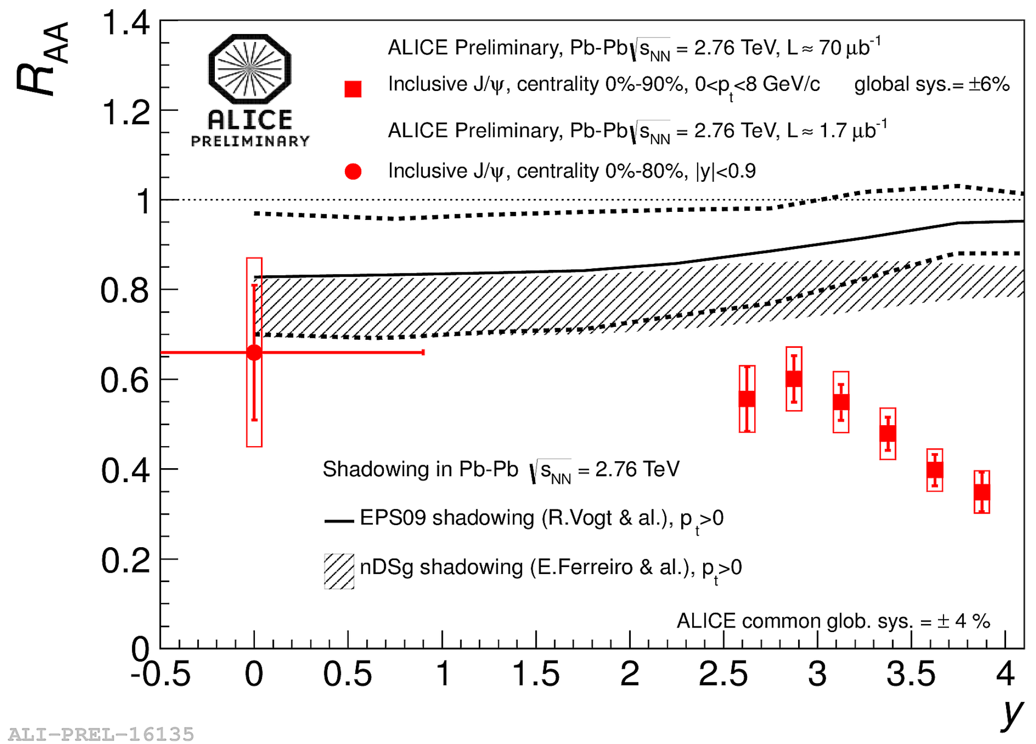
similar fractions in the Tsinghua model

Rapidity Dependence of J/psi R_{AA}

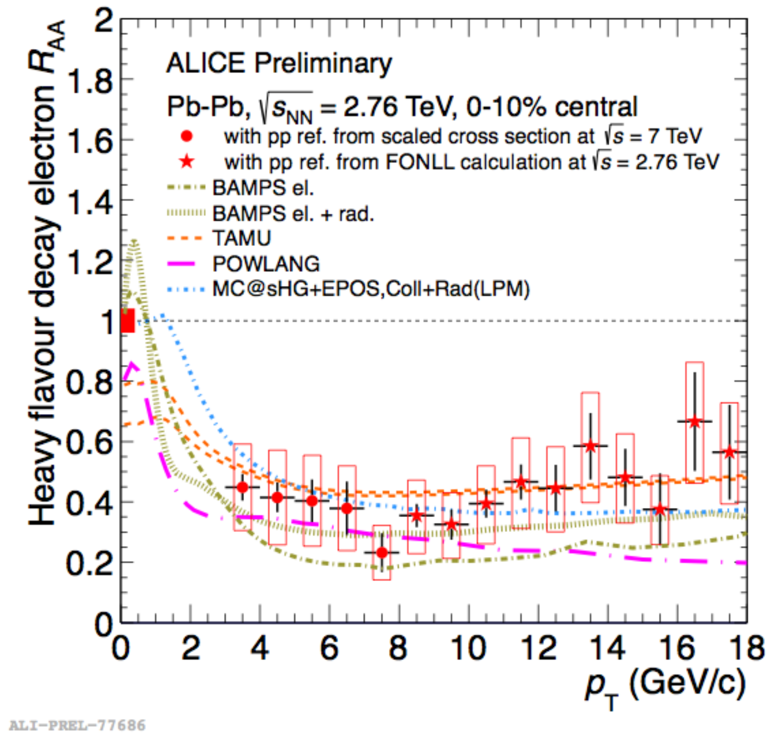


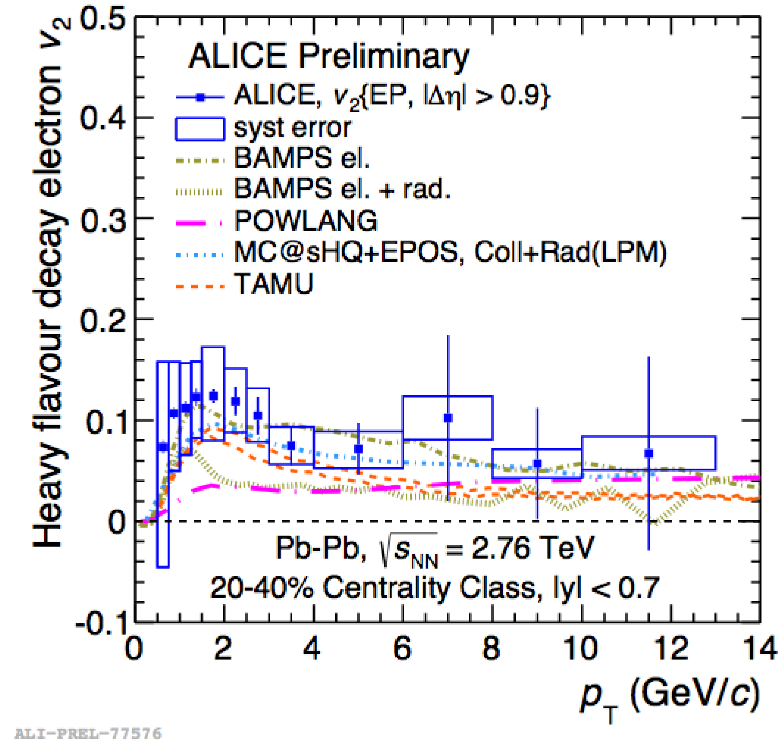
for statistical hadronization J/ψ yield proportional to N_c^2
higher yield at mid-rapidity predicted in line with observation

comparison to shadowing calculations:
- at mid-rapidity suppression could be explained by shadowing only
- at forward rapidity there seems to be additional suppression
- need to measure shadowing



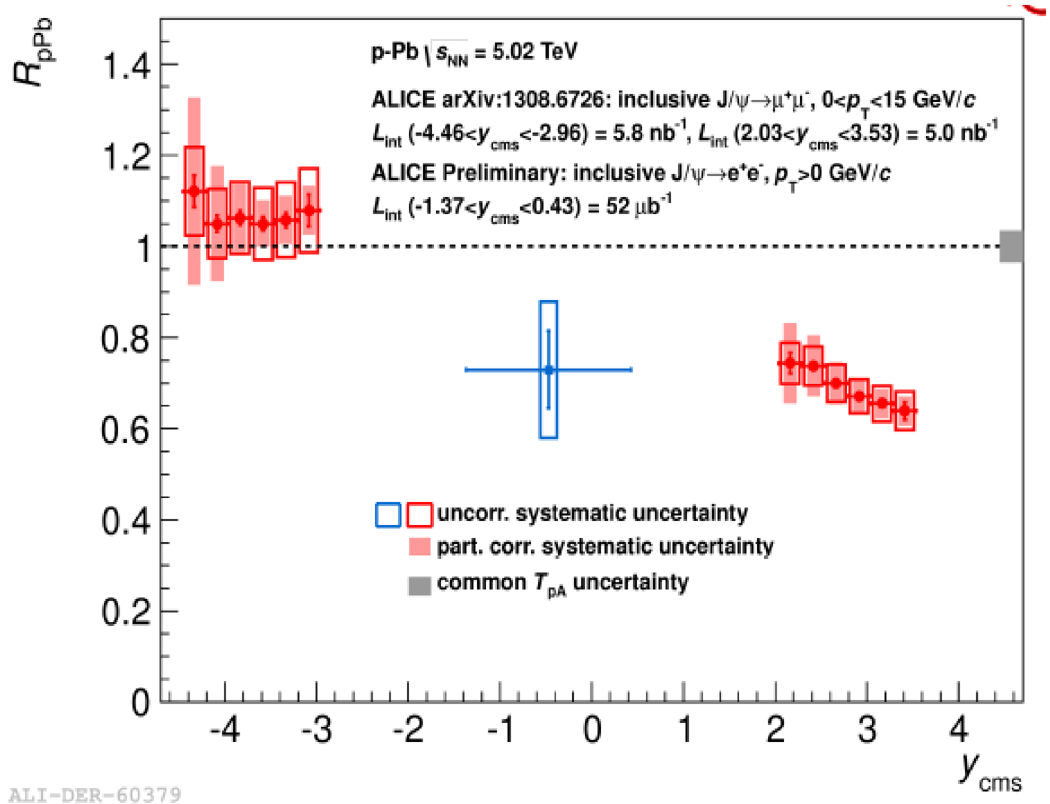
On the way towards transport coefficients for c-quarks





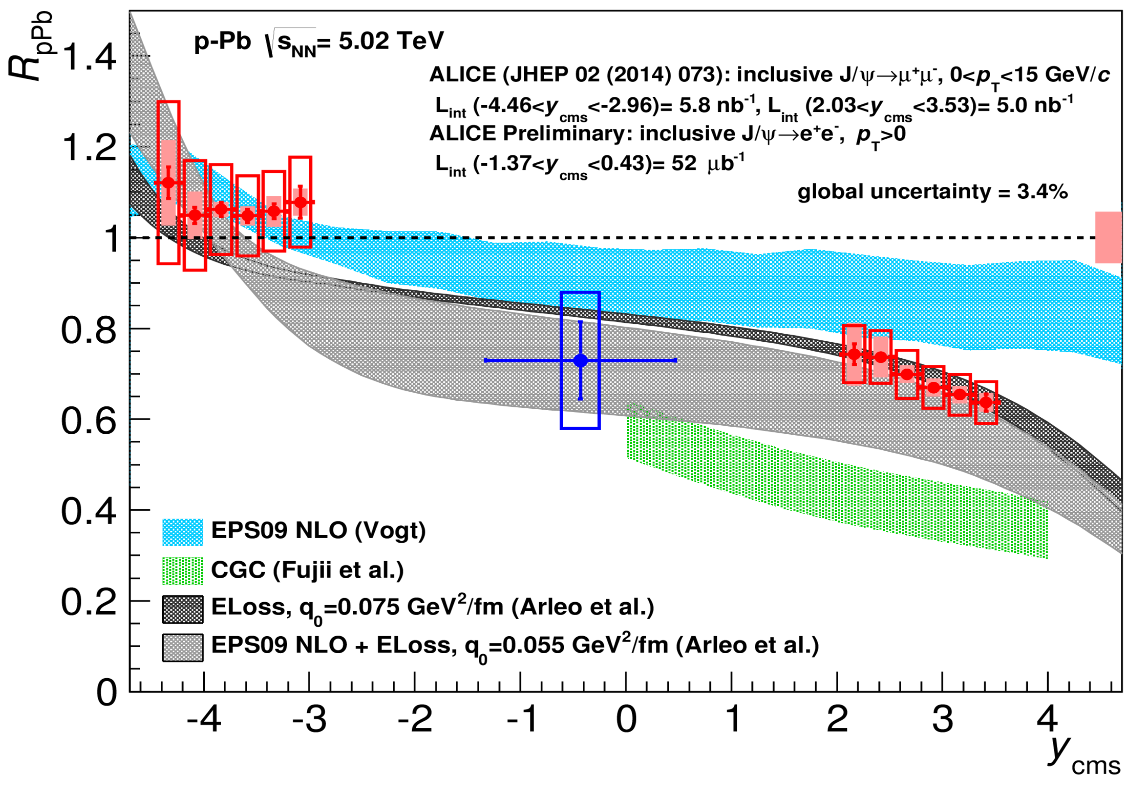
models constrained by simultaneous fit of R_{AA} and v_2

J/psi rapidity distribution in pPb compared to pp



ALICE forward/backward arXiv:1308.6726
good agreement with LHCb arXiv:1308.6729
ALICE mid-y hard probes 2013

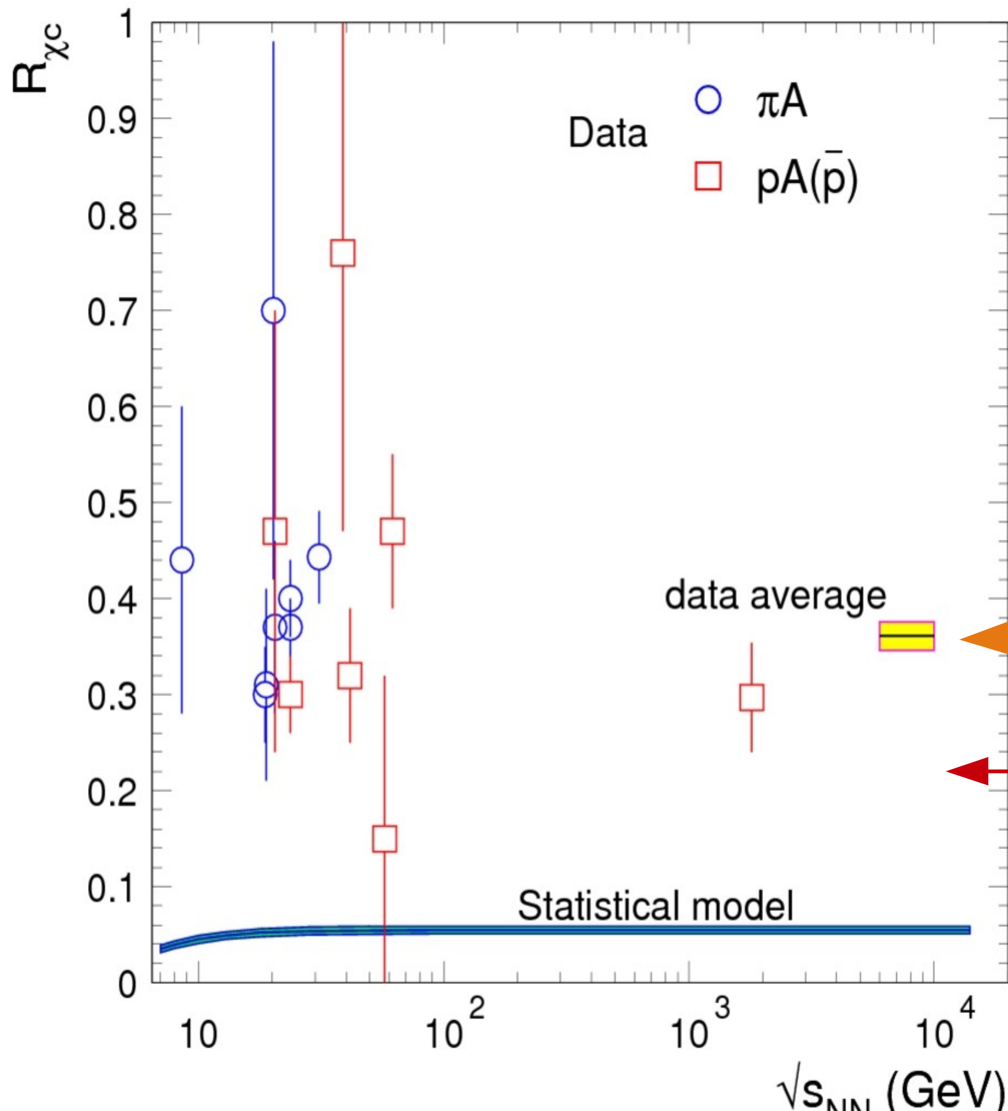
J/psi rapidity distribution in pPb compared to pp



ALICE forward/backward arXiv:1308.6726
good agreement with LHCb arXiv:1308.6729
ALICE mid-y hard probes 2013

good agreement with EPS09 shadowing wo absorption (Ferreiro)
also consistent w energy loss models wo shadowing (Arleo)
CGC calculation disfavored (Fuji)

situation even more dramatic for P-states



pA and πA data on average factor 7 avove statistical model prediction

Transport model (Rapp)

A. Andronic, F. Beutler, P. Braun-Munzinger, K. Redlich, J. Stachel Phys. Lett. B678 (2009) 350

outlook – what ALICE can do in the future

LHC run1:

2 PbPb runs

- 2010 $O(10\ \mu b^{-1})$
- 2011 $O(150\ \mu b^{-1})$

luminosity reached $\mathscr{L}=2\ 10^{26}\ cm^{-2}\ s^{-1}$ twice design lumi at this energy

1 pPb run

- 2012/2013 $O(30\ nb^{-1})$

from 2/2013 until end of 2014 LS1: consolidation of LHC to allow full energy ⇦ we are here

LHC run2: 2015-2018 PbPb running at $\sqrt{s_{NN}} = 5.5$ TeV

to achieve approved initial goal of 1 nb^{-1}

late 2018 start LS2 – increase of LHC luminosity und experiment upgrade

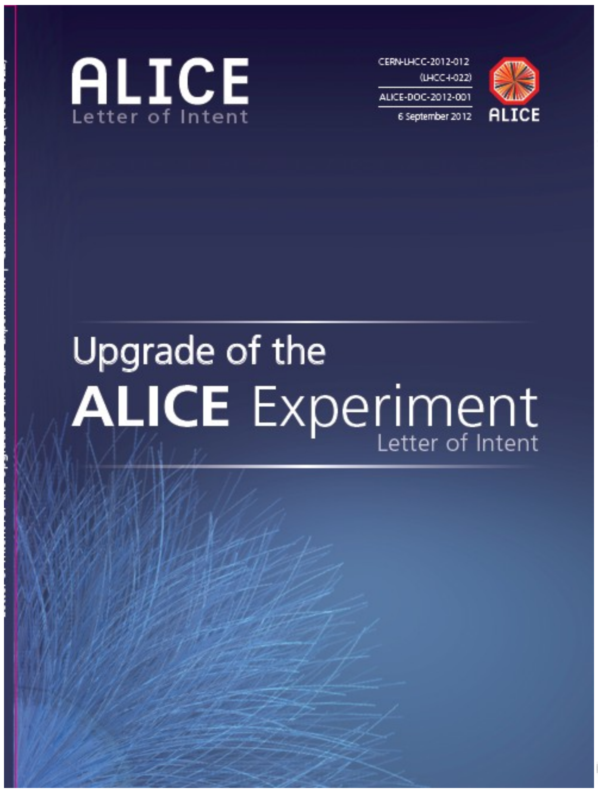
LHC run3: 2020 onwards - expect $\mathscr{L}=6\ 10^{27}\ cm^{-2}\ s^{-1}$ or PbPb interactions at 50 kHz

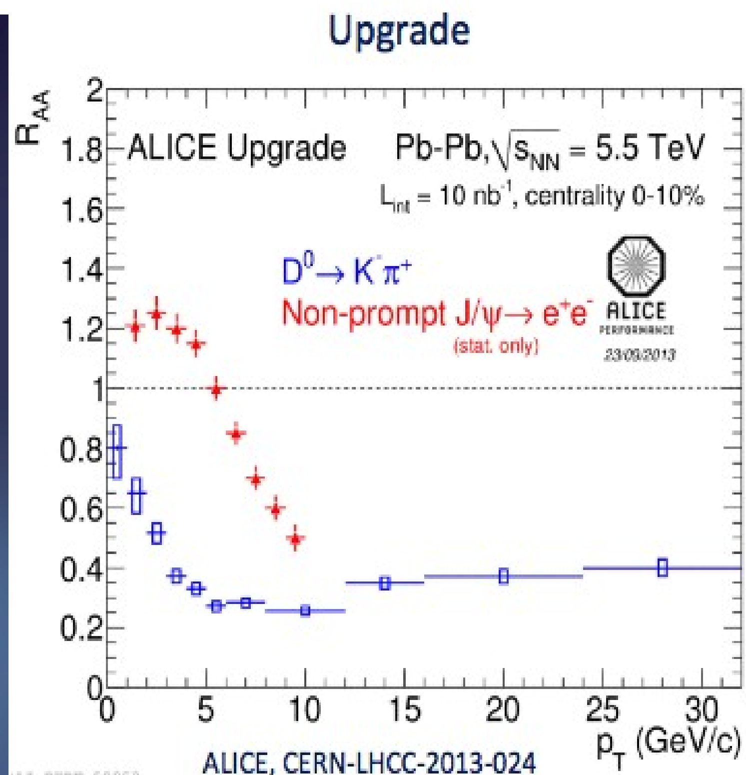
achieve for PbPb 10 nb^{-1} corresponding to 8 10^{10} collisions sampled

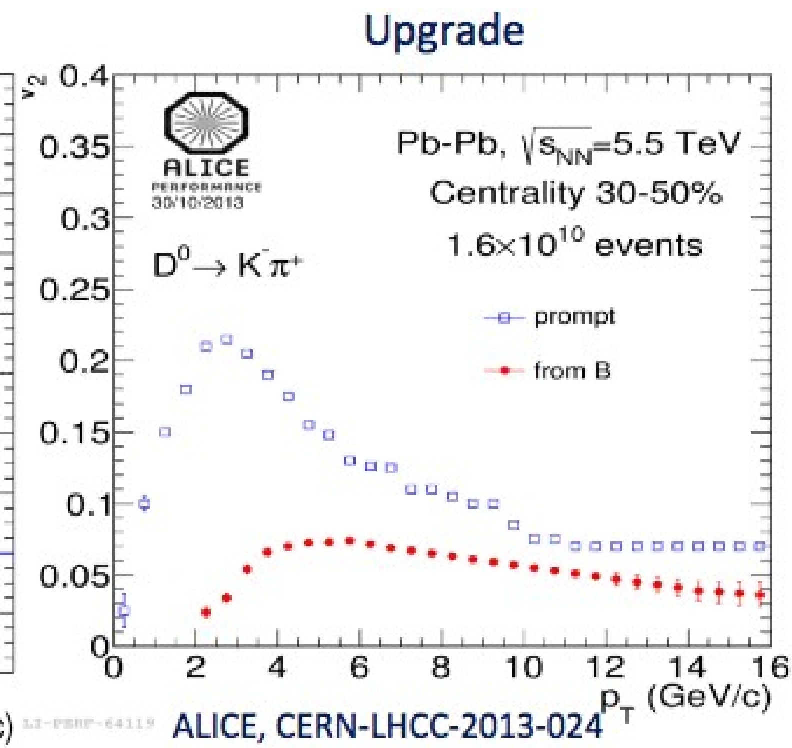
plus a low field run of 3 nb^{-1} + pp reference running + pPb - a program for about 6 years

outlook open heavy flavor – LHC run3

new high performance ITS plus rate increase by 2 oom (TPCwith GEMs)





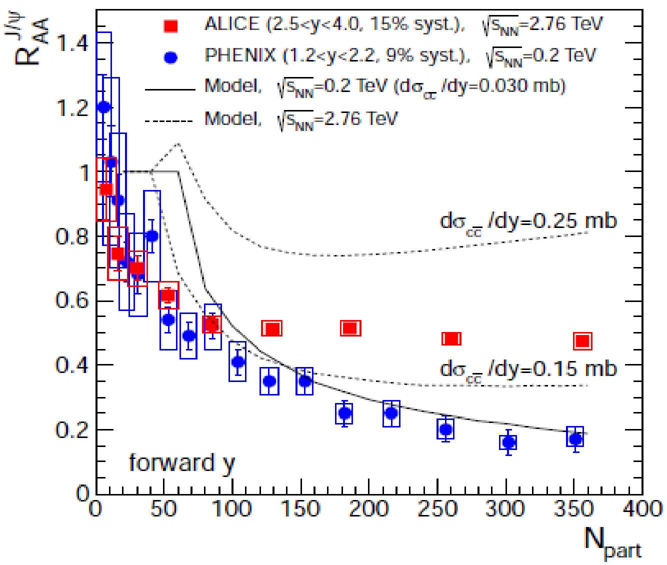


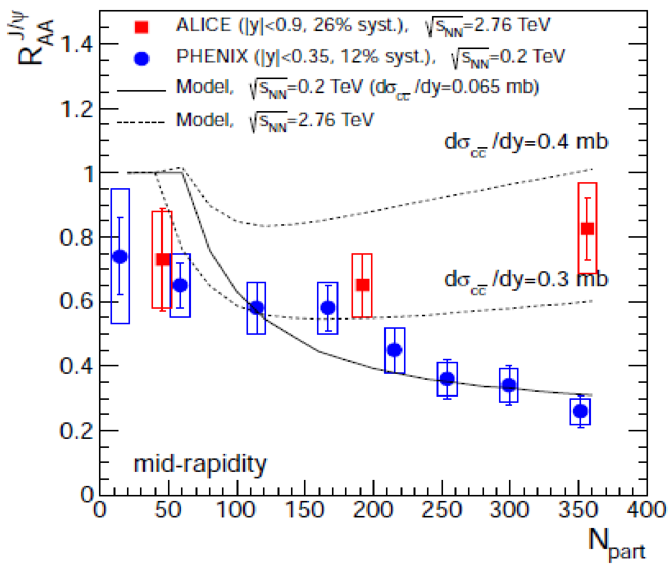
Input values from BAMPS model: C. Greiner et al. arXiv:1205.4945

Charm and beauty R_{AA} down to p_T~0 using D^0 and B-decay J/ψ

Charm v_2 down to p_T~0 using prompt and beauty v_2 down to B p_T~0 using B-decay D^0

J/psi as probe of deconfinement





di-electrons statistics limited, 10 nb^{-1} will have huge effect

but also syst uncertainties will decrease with upgrade:

- will also add TRD for electron id - reduced comb background
- thinner ITS reduced radiation tail

both affect signal extraction