Selected prospects in relativistic nuclear collisions at LHC

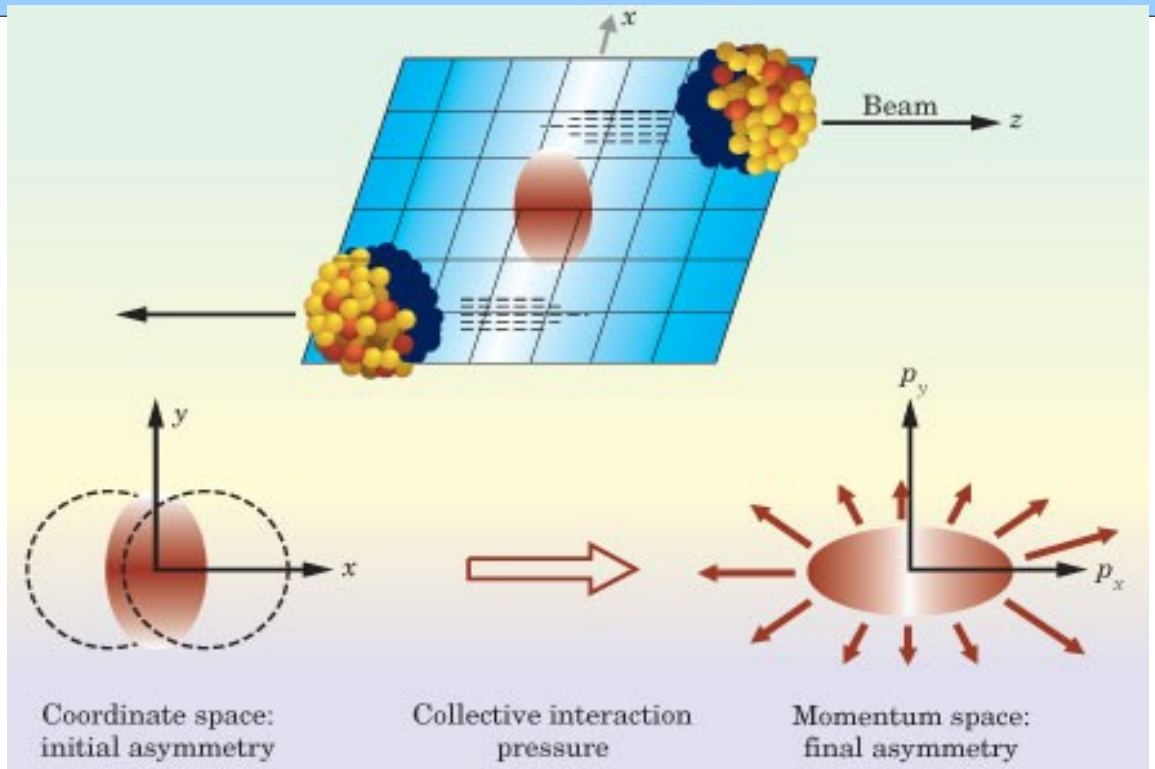
a wealth of results from run1 at the LHC (see recent Quark Matter Conference in Darmstadt)
where do we go from here? LHC run2 and run3
a very personal selection of just a few observables*

- azimuthal correlations
- open heavy flavor
- quarkonia
- photons and di-leptons

* due to time constraint mostly focused on ALICE

Johanna Stachel – Universität Heidelberg
3rd International Conference on New Frontiers in Physics
special session celebration the 60th anniversary of CERN
Kolymbari, Greece, August 5, 2014

Azimuthal Anisotropy of Transverse Spectra



Fourier decomposition of momentum distributions rel. to reaction plane:

$$\frac{dN}{dp_t\, dy\, d\phi} = N_0 \cdot \left[1 + \sum_{i=1} 2\, v_i(y, p_t) \cos(i\phi) \right]$$

quadrupole component v_2

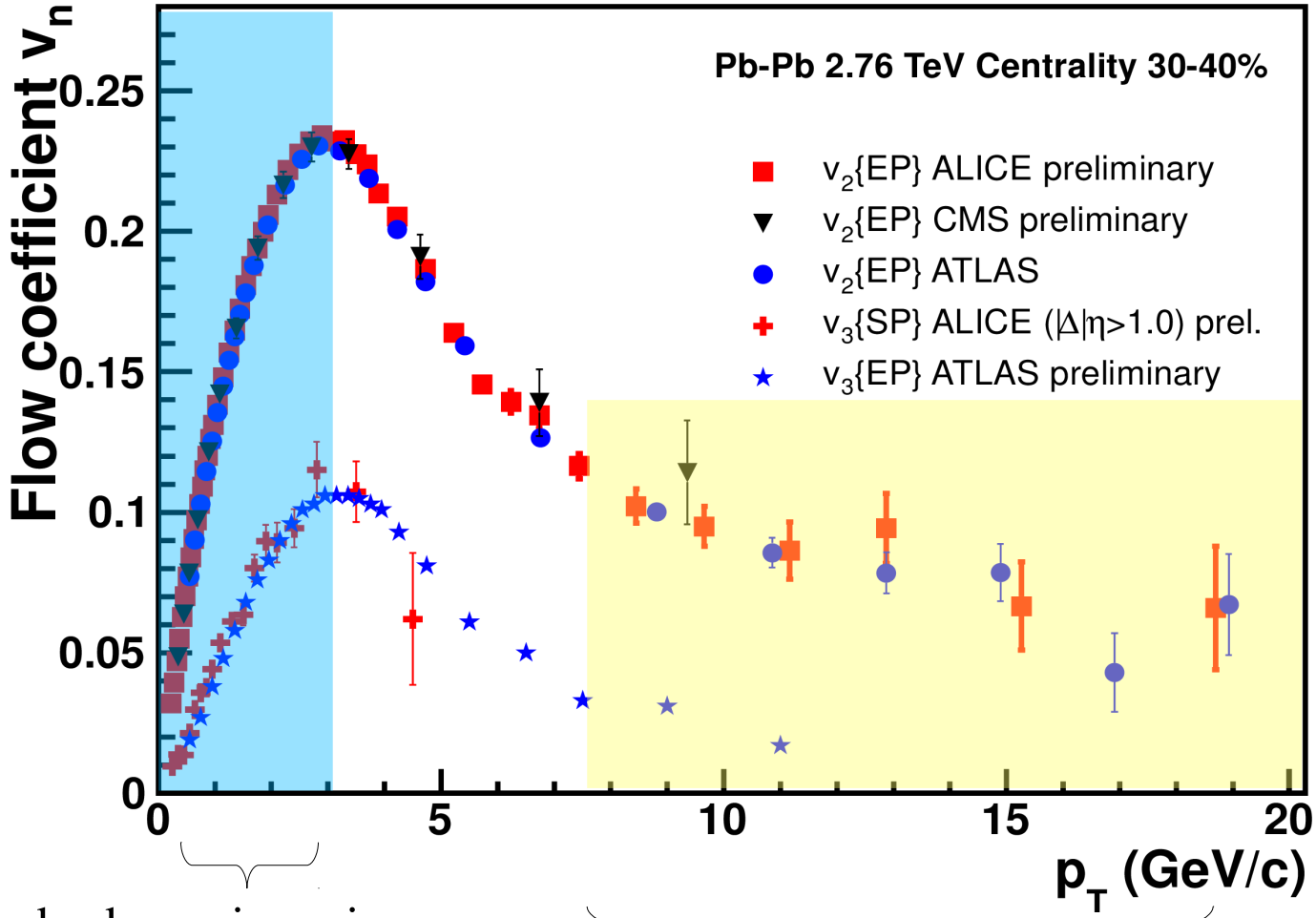
"elliptic flow"

effect of expansion (positive v_2) seen from top AGS energy upwards

the v_n are the equivalent of the power spectrum of cosmic microwave rad.

Elliptic Flow of Charged Particles at LHC

figure modified from B. Muller, J. Schukraft, B. Wyslouch, arXiv:1202.3233v1



elliptic flow (v2) as function of p_t :

- excellent agreement between all 3 LHC experiments
- same for v3

hydrodynamic regime
v2 driven by pressure gradient

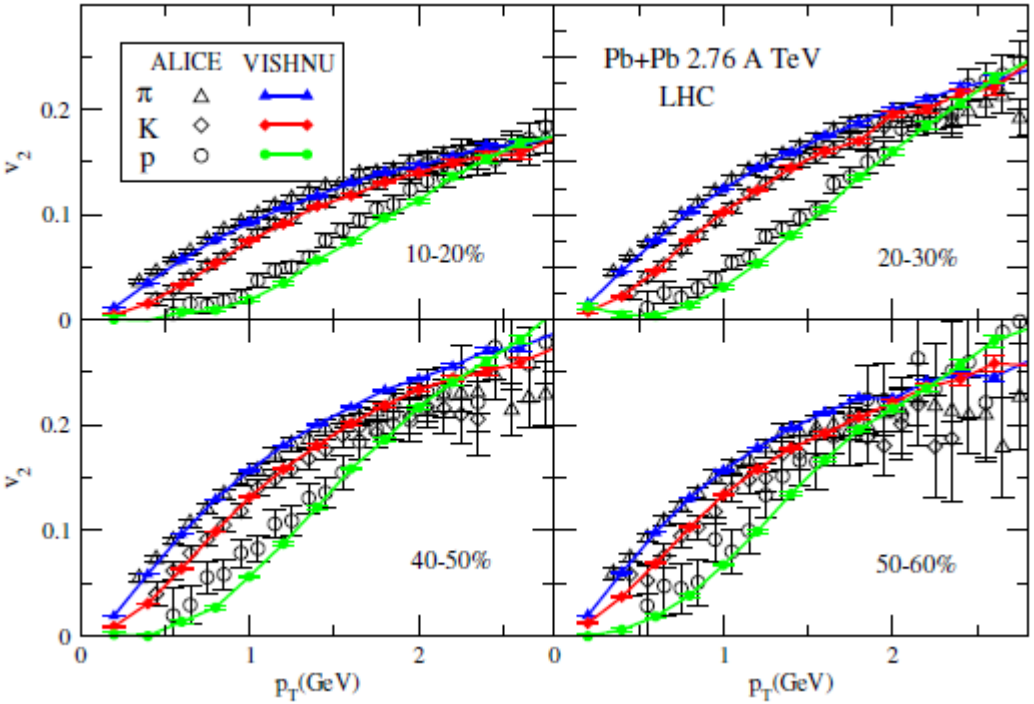
jet fragmentation regime
v2 driven by energy loss

Elliptic flow of identified pions, kaons, protons

the quest to extract the ratio of shear viscosity over entropy density η/s
note: minimum value of $1/4\pi \approx 0.08$ predicted with AdS/CFT correspondence

data: ALICE
calculations: (2+1)-D hydro plus UrQMD (VISHNU)

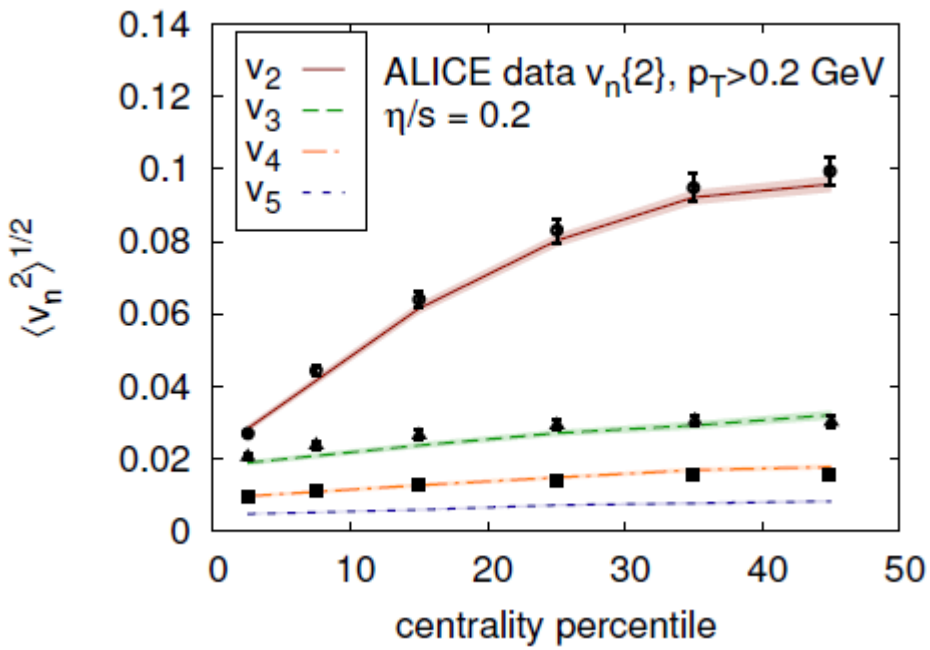
H. Song, S. Bass and U. W. Heinz, Phys. Rev. C **89**, 034919 (2014)



mass dependence is a genuine prediction of hydrodynamics
calculations with shear viscosity to entropy density $\eta/s = 0.20$ reproduce data very well
but: uncertainty due to initial condition
color glass initial condition $\leftrightarrow$ Glauber
$\eta/s = 0.20 \leftrightarrow 0.08$

Higher flow harmonics and their fluctuations

Gale, Jeon, Schenke, Tribedy and Venugopalan, PRL **110**, 012302 (2013)



higher harmonics:
ratios of v_2/v_n and their fluctuations depend on initial condition

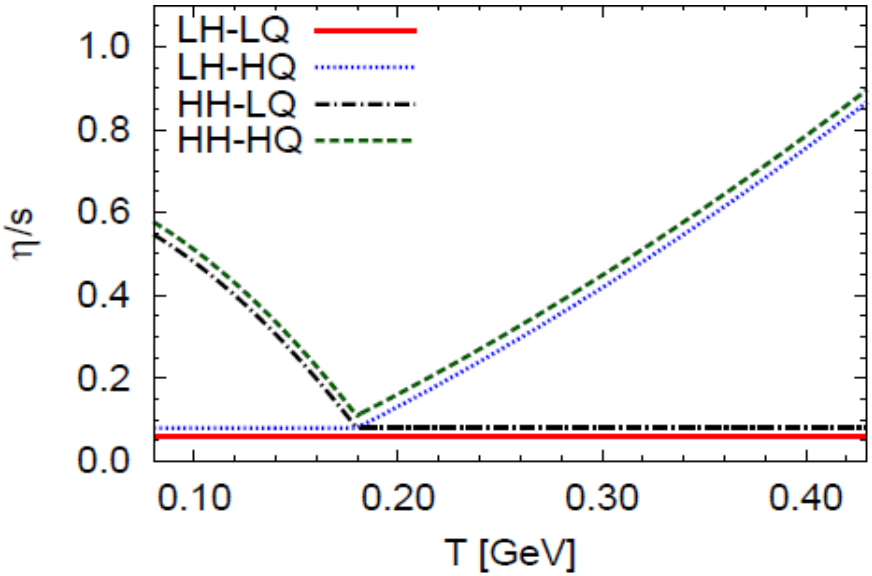
very well reproduced by viscous hydrodynamics (MUSIC) with fluctuating IP Glasma initial condition (including initial quantum fluctuations of gluon fields)

for LHC $\eta/s = 0.20$ for RHIC $\eta/s = 0.12$

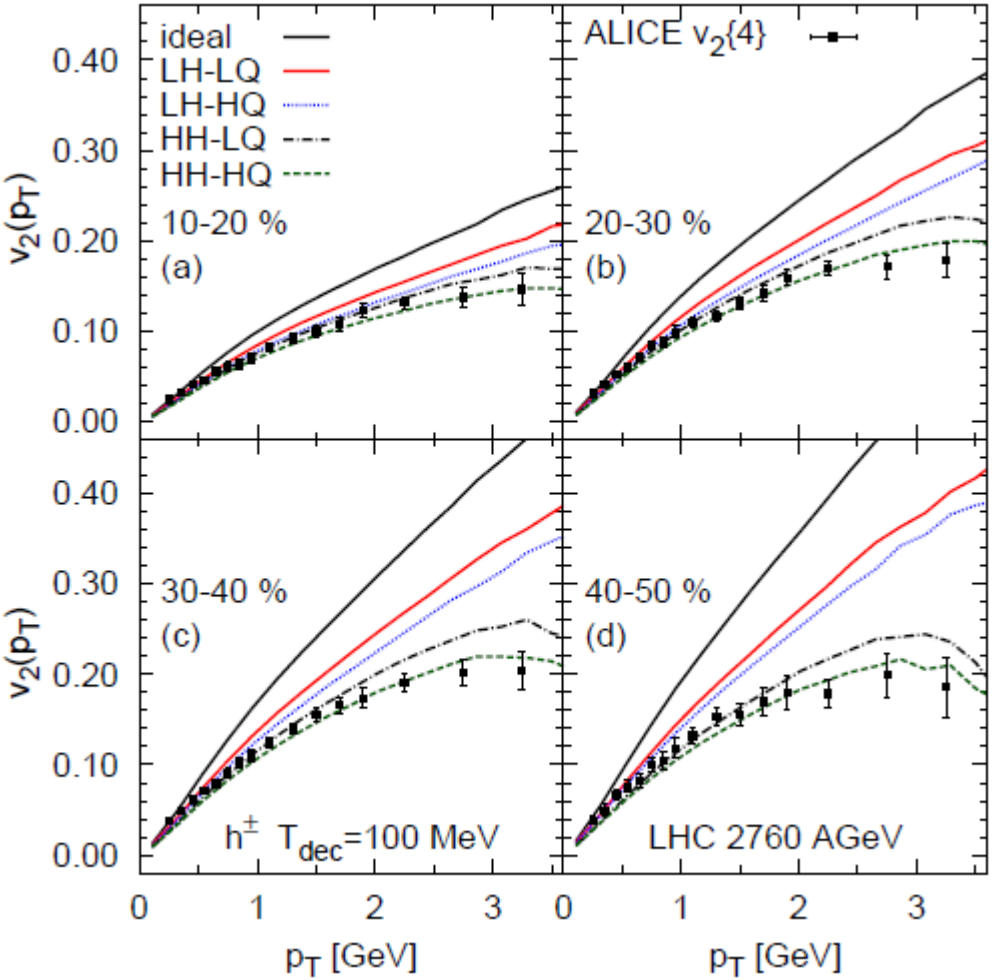
indication of temperature dependence of η/s?

Sensitivity of temperature dependence of eta/s

E. Molnar, H. Holopainen, P. Huovinen, H. Niemi, arXiv:1407.8152
(3+1)-D viscous hydro, initial cond fixed to dN/deta, freeze-out to spectra, EOS from lattice QCD



while RHIC data show no sensitivity to QGP η/s at LHC there is sensitivity, but less to hadron gas



on the other hand, can always rescale η/s to reproduce data at one energy and centrality

recipe: multi-differential measurements

v_2, v_4, as function of rapidity and p_t

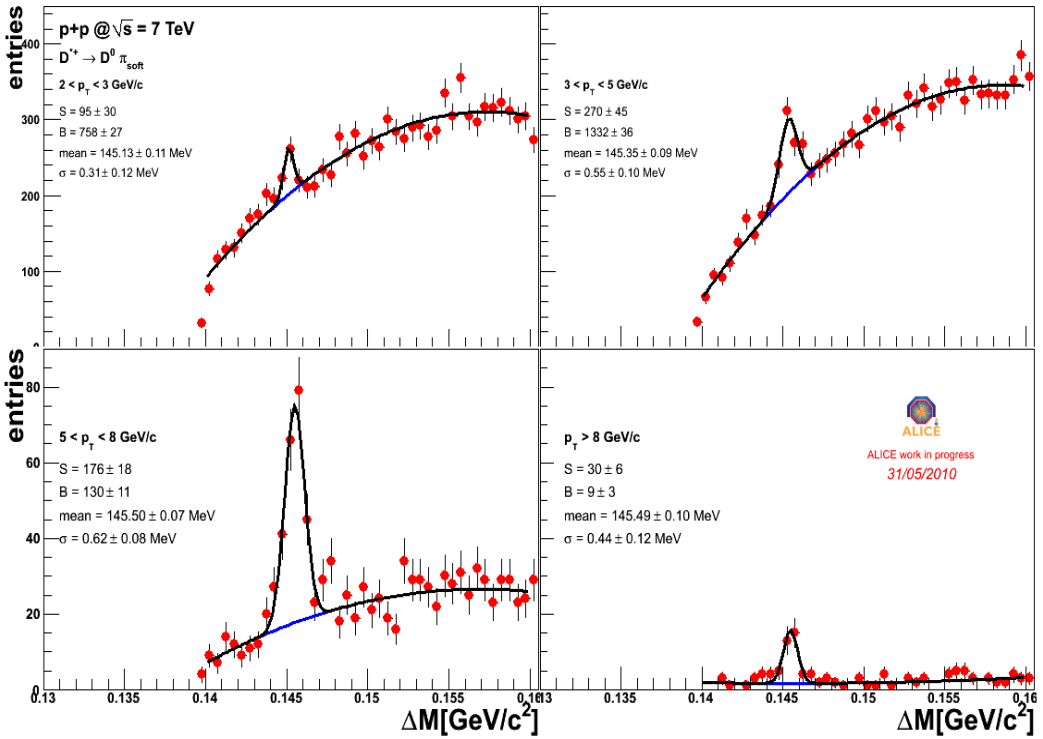
fix hadron gas η/s(T) with RHIC data

then proceed to extract η/s(T) for QGP with LHC data as well as minimal value

Measurement of open charm cross section in pp collisions at the LHC

2 different methods:
- reconstruction of D-mesons
- e or μ from semileptonic D-decays

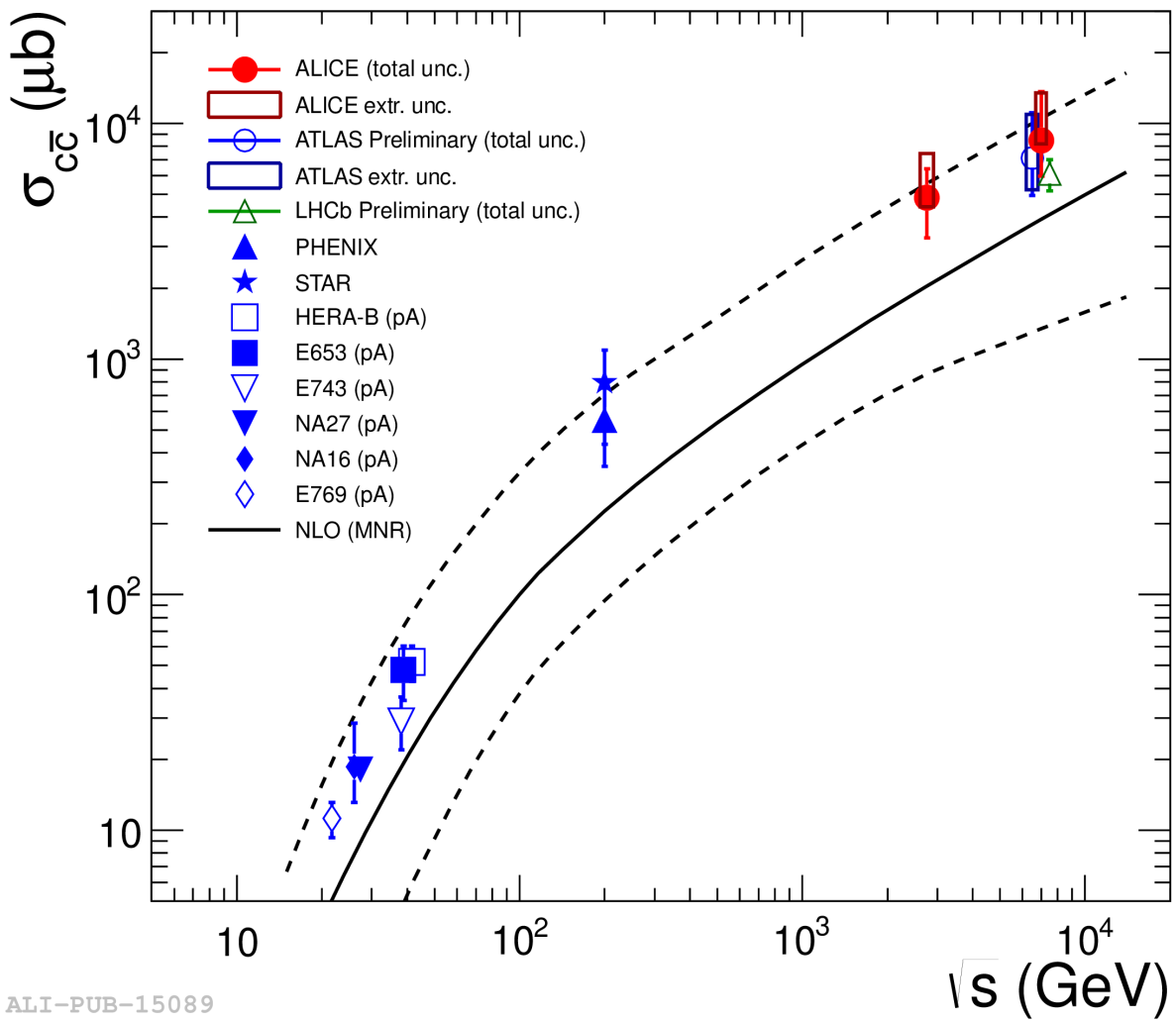
all LHC experiments contribute
for published data:
ALICE at $p_t > 2$ GeV/c and $0 < y < 4$
ATLAS and CMS at $p_t > 6$ GeV/c $0 < y < 2.5$
LHCb at $p_t > 2$ GeV/c and $2.5 < y < 4$



all detectors employ sophisticated Si vertex detectors

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

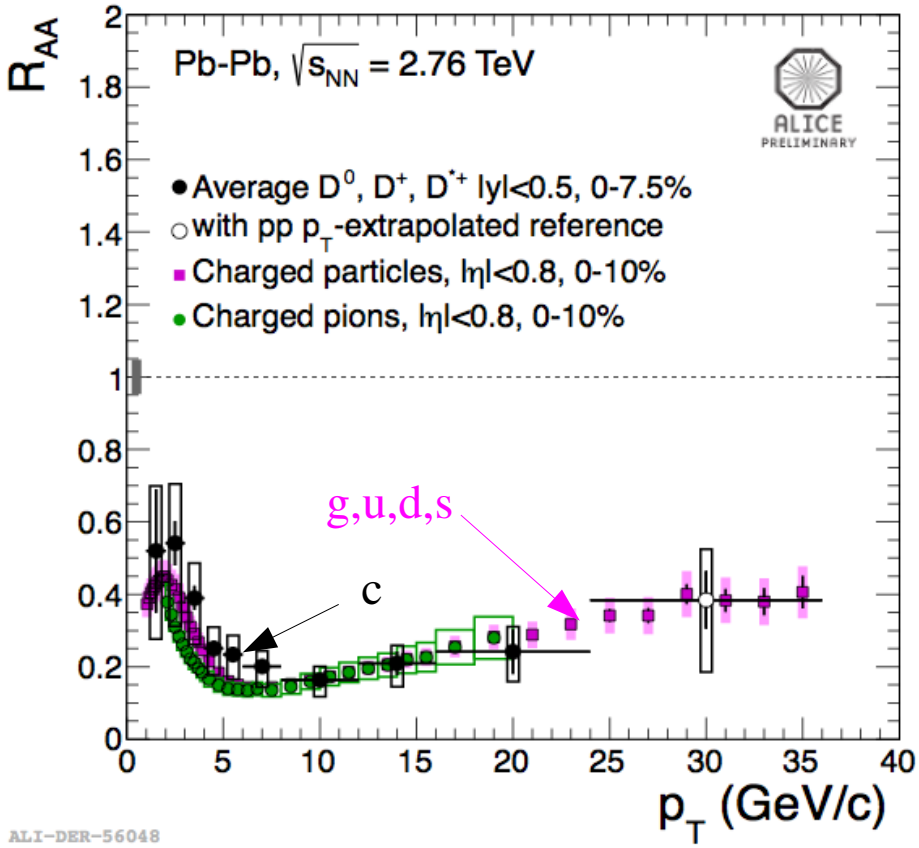
JHEP 1207 (2012) 191

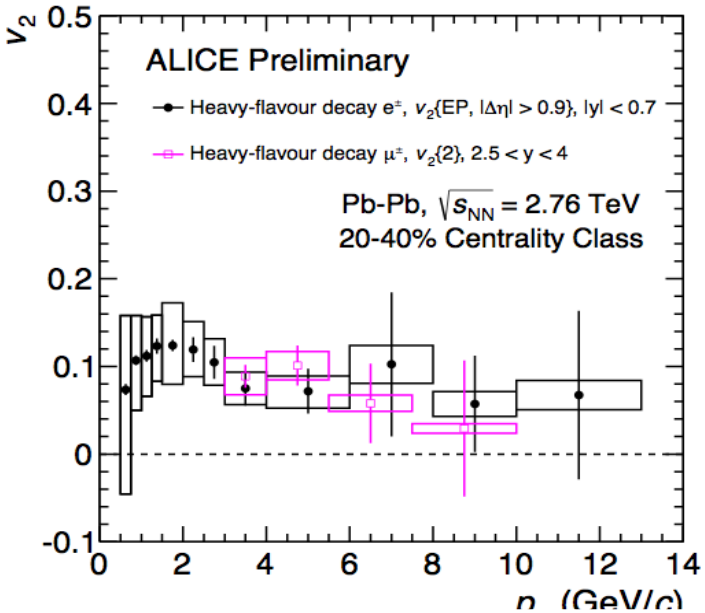


- good agreement between ALICE, ATLAS and LHCb
- large syst. error due to extrapolation to low pt, need to push measurements in that direction
- data factor 2 ± 0.5 above central value of FONLL but well within uncertainty
- beam energy dependence follows well FONLL
- soon more accurate 4π extrapolation at 7 TeV
- aim for 10% syst error with run3 data

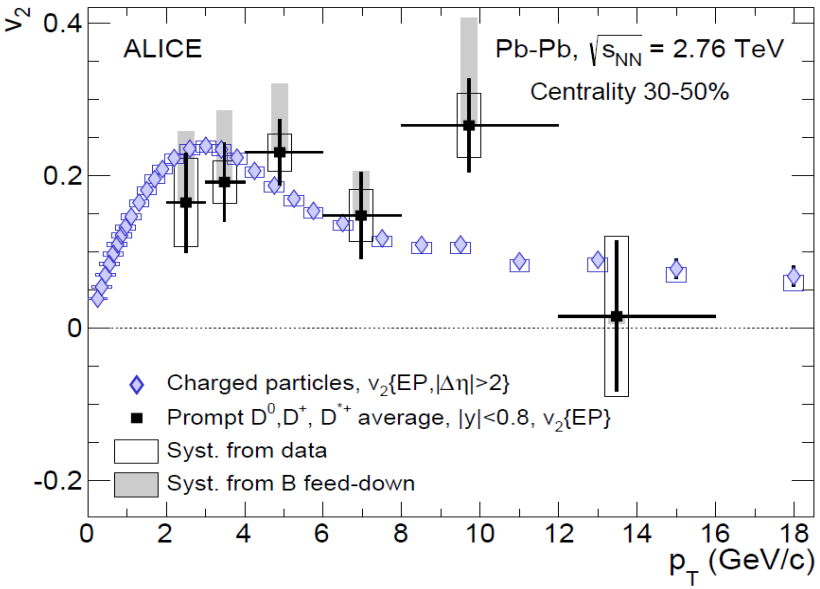
Charm quarks thermalize to large degree in QGP

strong energy loss of charm quarks





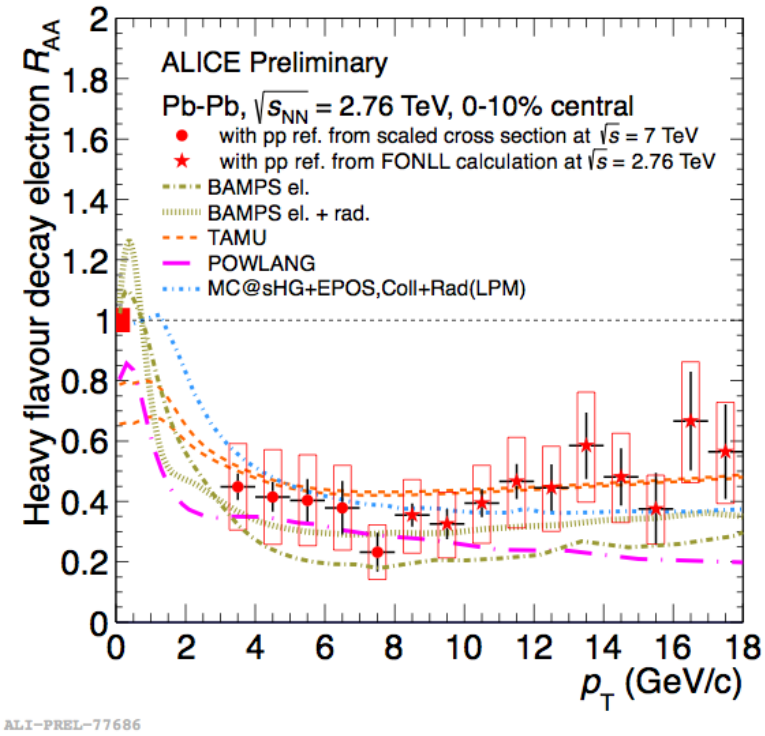
elliptic flow for charm – participation in coll. flow

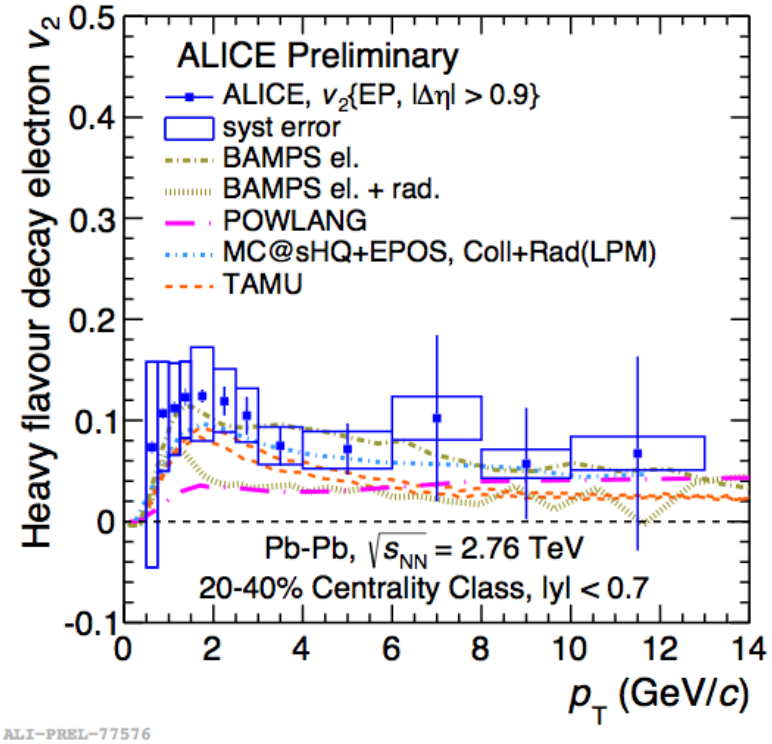


Phys. Rev. Lett. 111 (2013) 102301

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

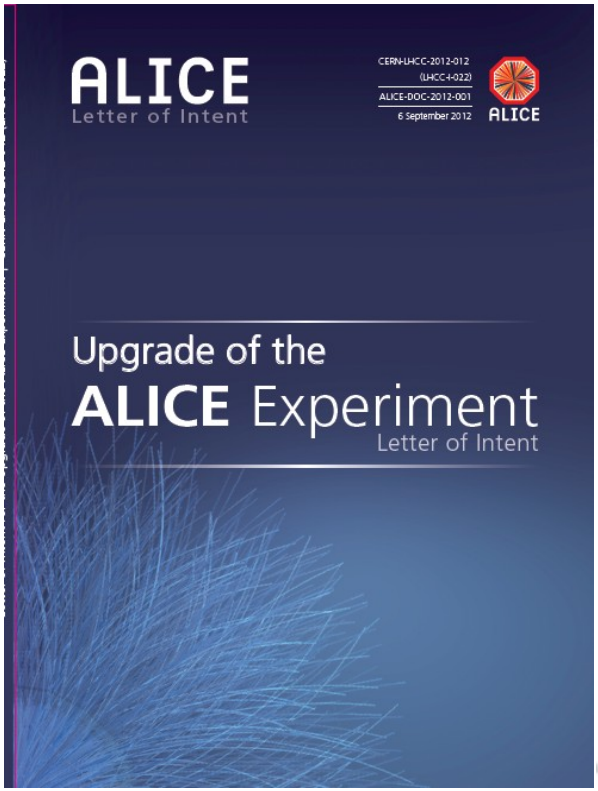
Models constrained by simulataneous fit of R_{AA} and v_2

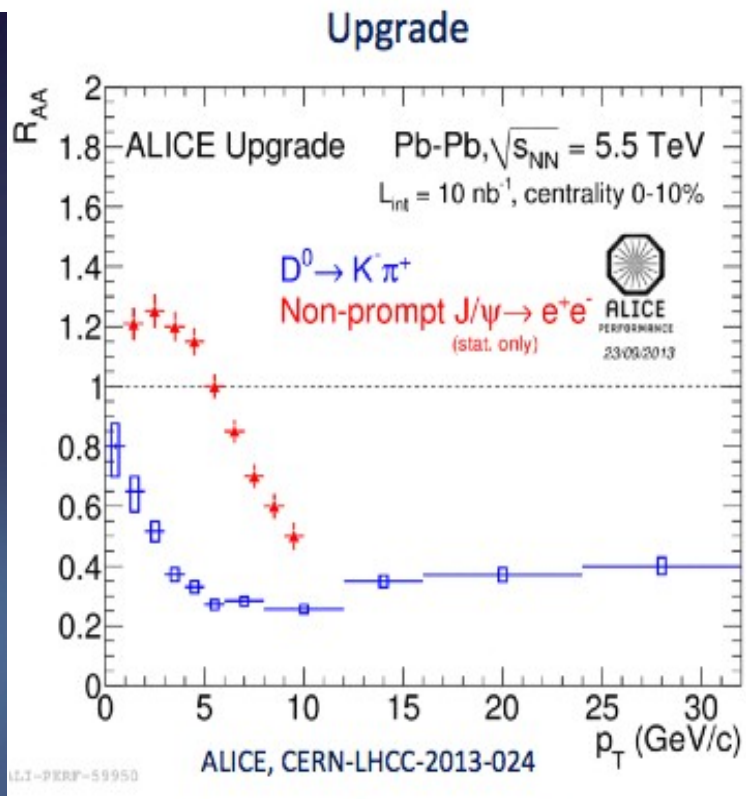


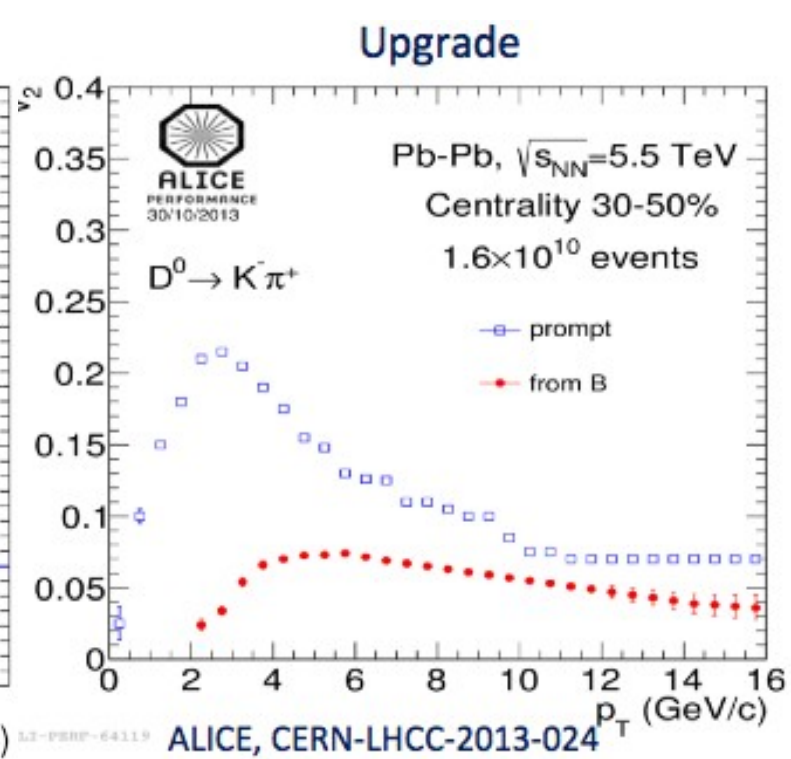


Outlook open heavy flavor – LHC run3

new high performance ITS plus rate increase (TPC upgrade)







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

Charmonia as a probe of Deconfinement

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

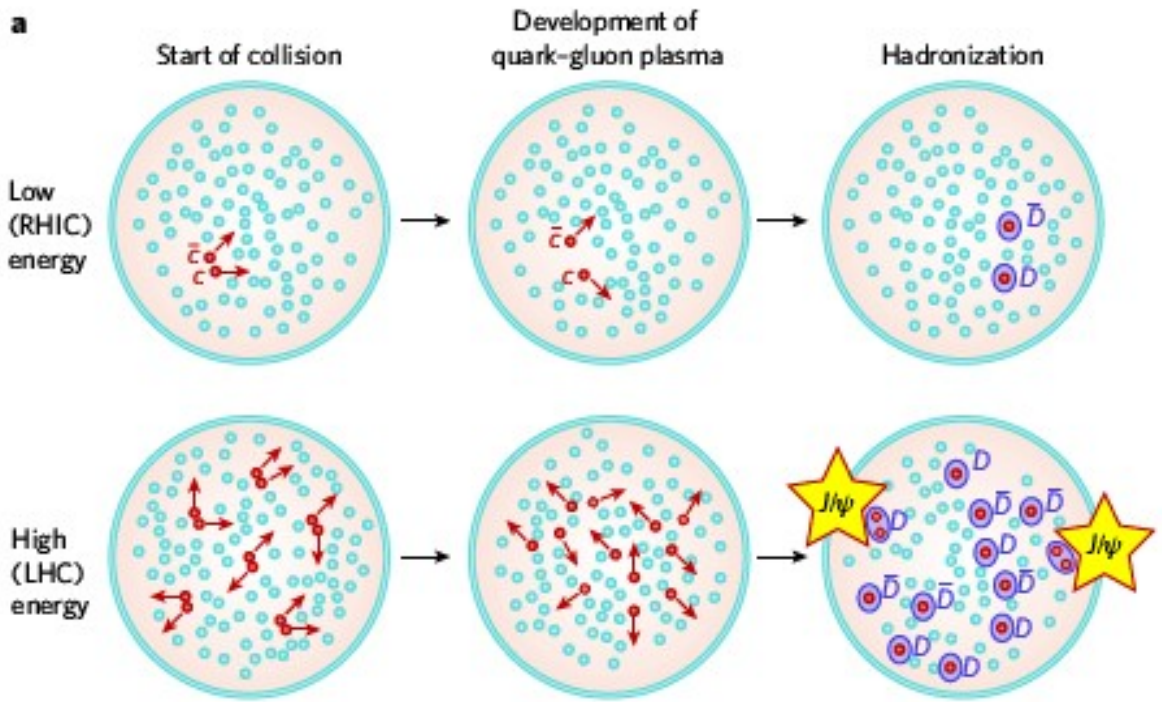
J/ψ 1s state of ccbar
mass 3.1 GeV
radius 0.45 fm

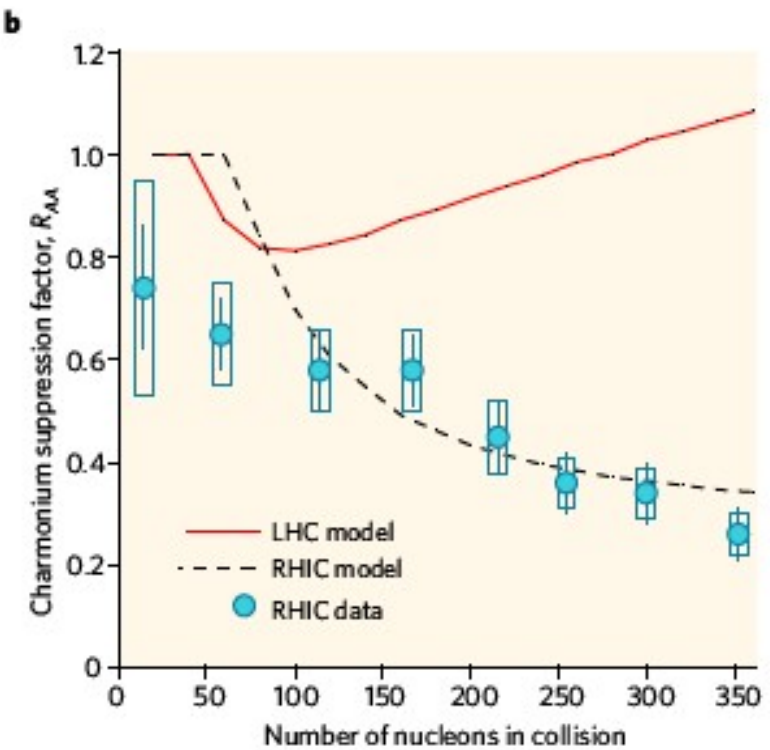
the original idea (Matsui and Satz 1986): implant charmonia into the QGP and observe their modification (Debye screening of QCD), in terms of suppressed production in nucleus-nucleus collisions with or without plasma formation – sequential melting

"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."

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

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





charmonium enhancement as fingerprint of deconfinement at LHC energy

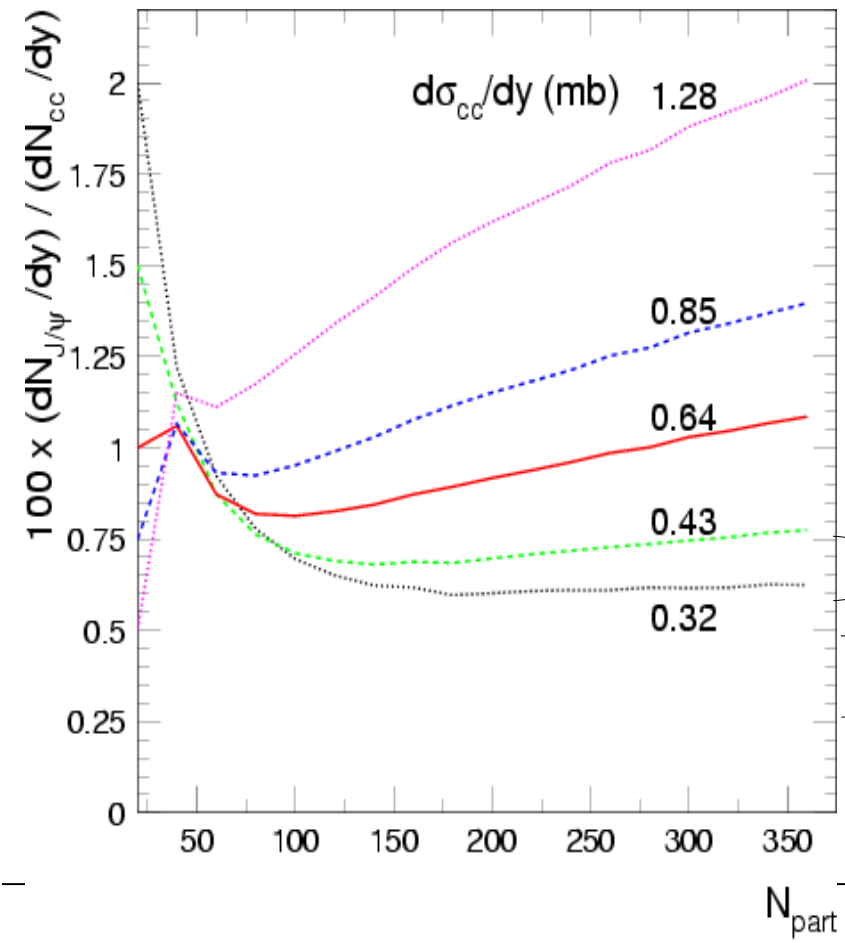
only free parameter: open charm cross section in nuclear collision

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

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

Decision on Regeneration vs. Sequential Suppression from LHC Data

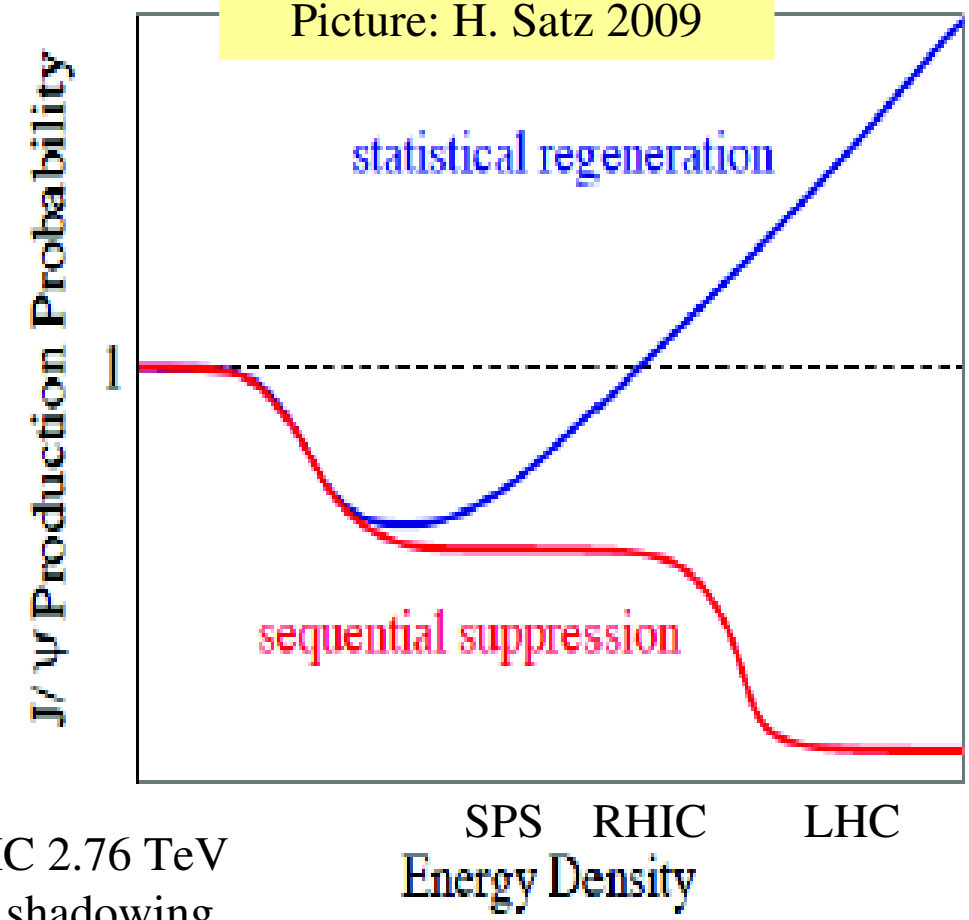
A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel Phys. Lett. B652 (2007) 259



mid-y LHC 2.76 TeV including shadowing

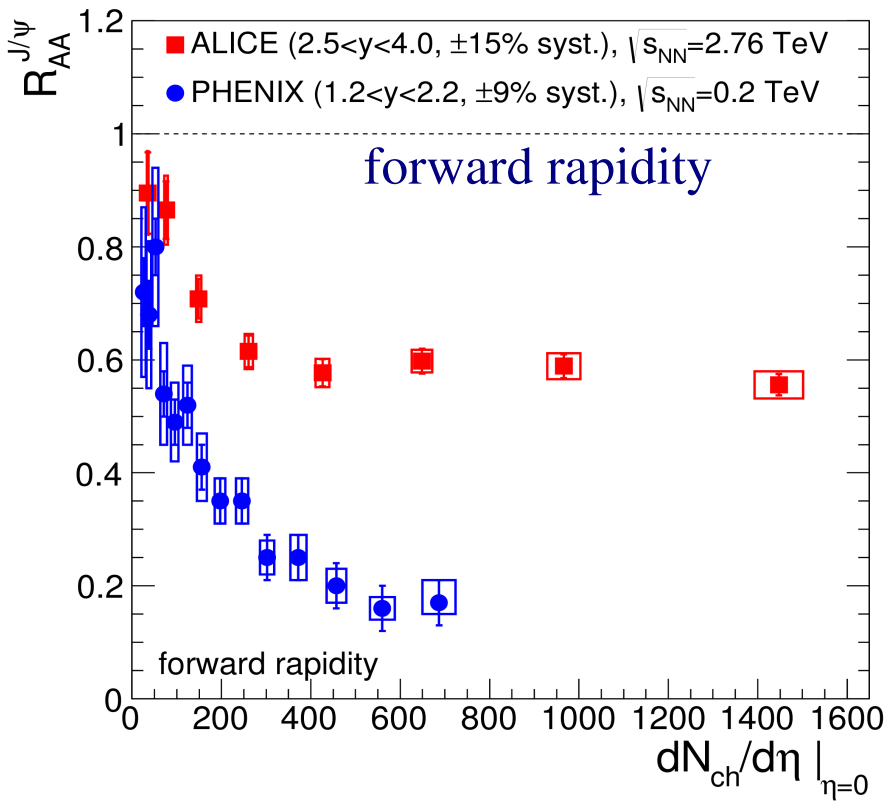
forward-y LHC 2.76 TeV including shadowing

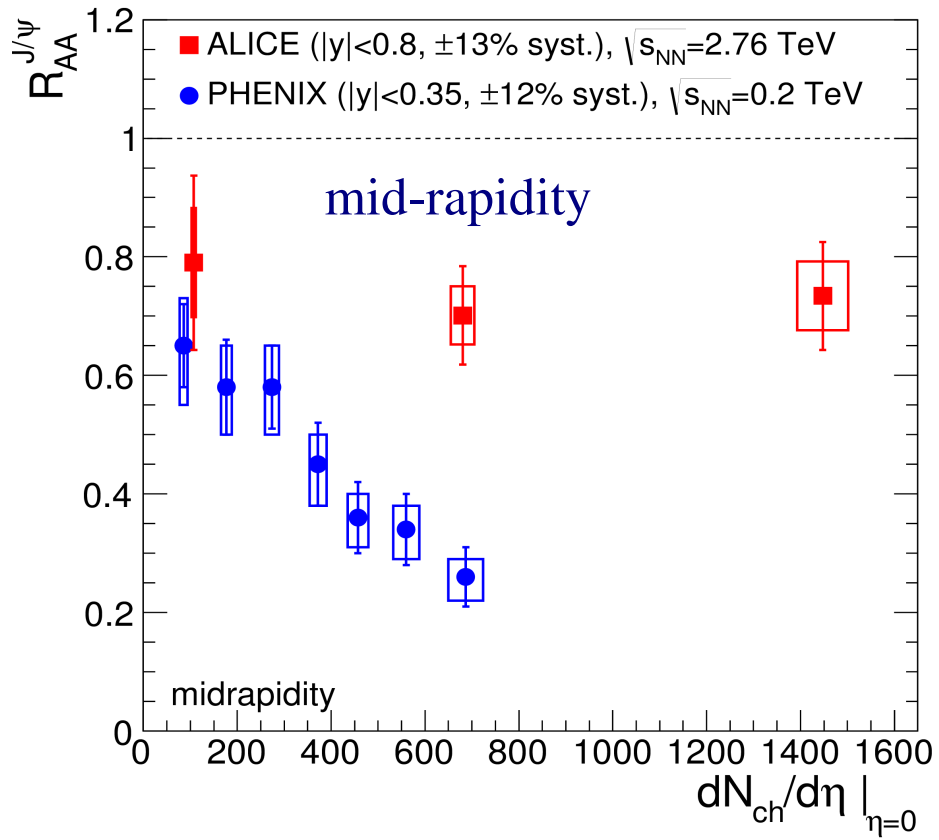
Picture: H. Satz 2009



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

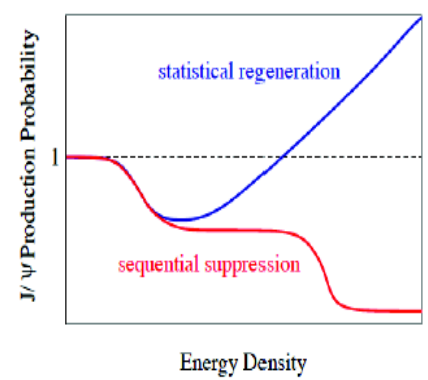
$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta dp_T}{\langle N_{coll}\rangle (1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta dp_T}$$



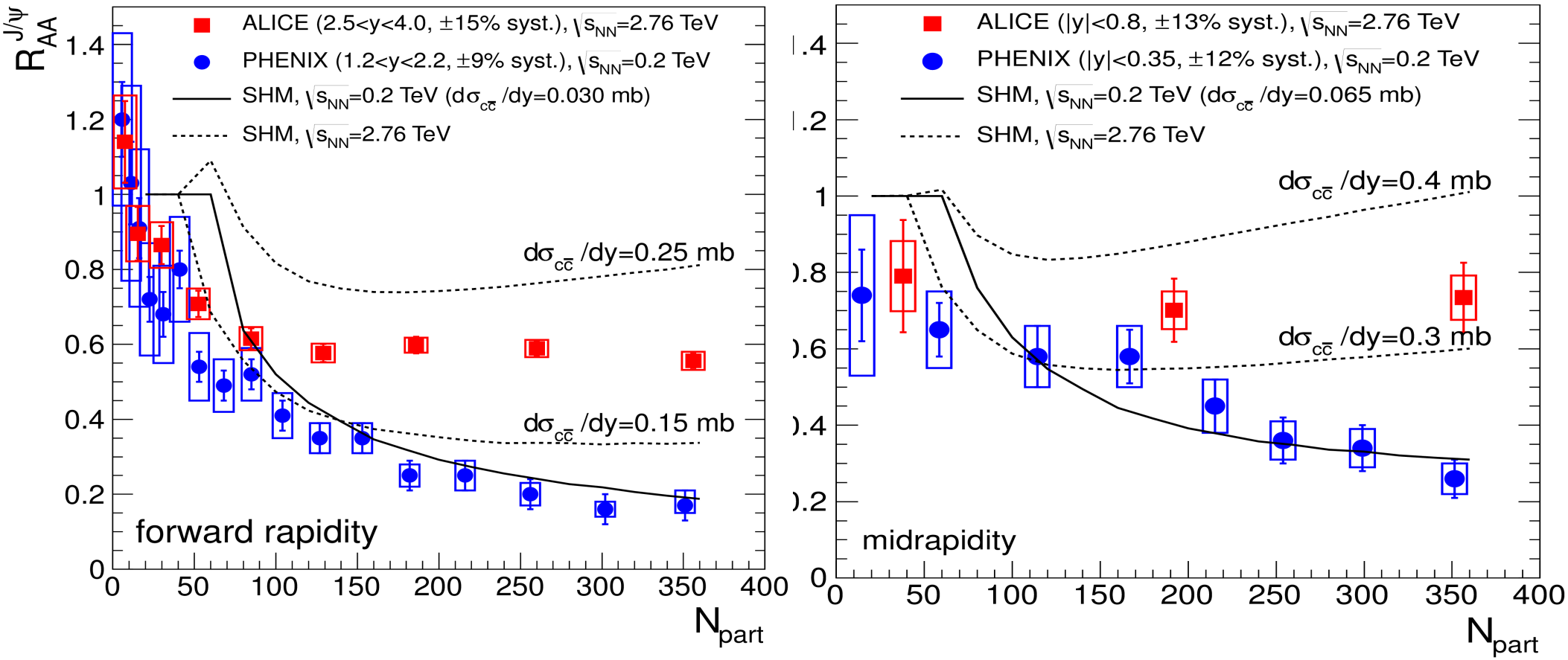


energy density -->

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

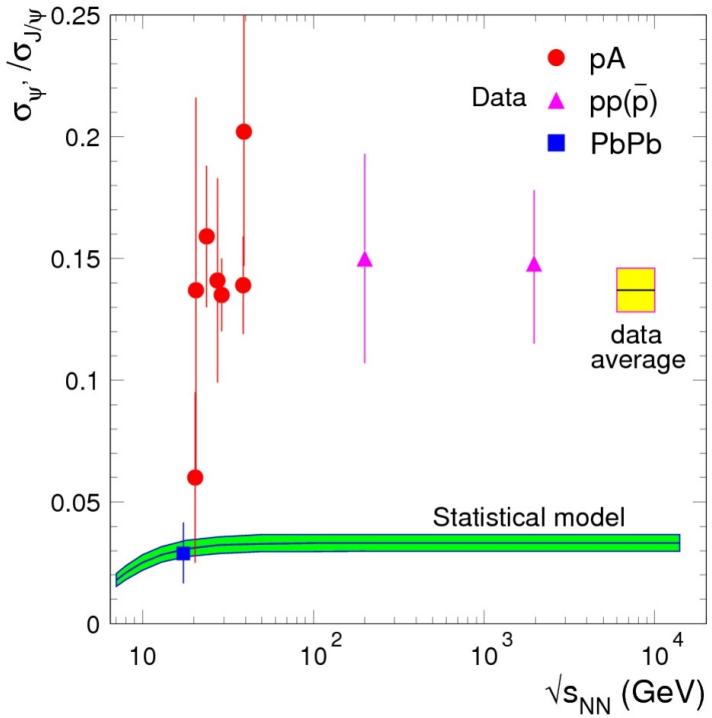


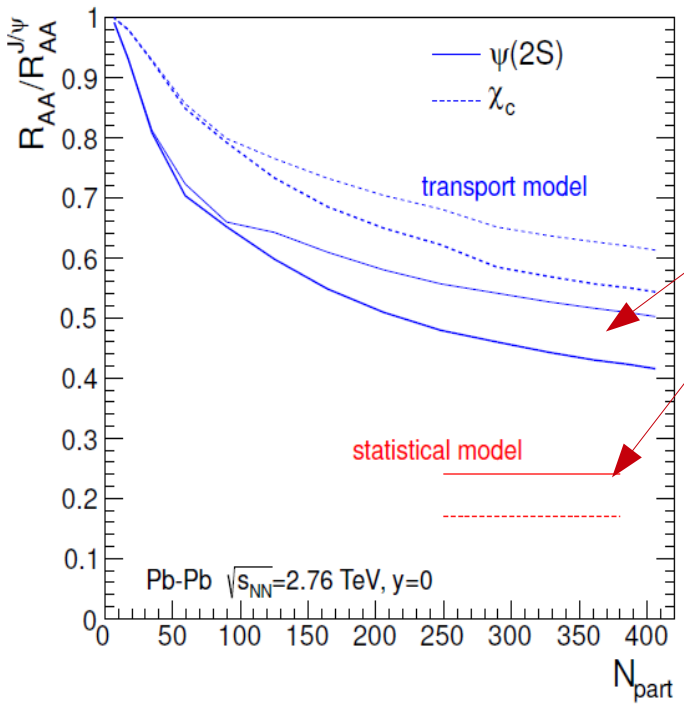
J/psi and Statistical Hadronization



- 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)
- transport codes that produce and destroy charmonia in the QCG also reproduce data, albeit with about twice the charm cross section

Progress in the charmonium sector: excited charmonia



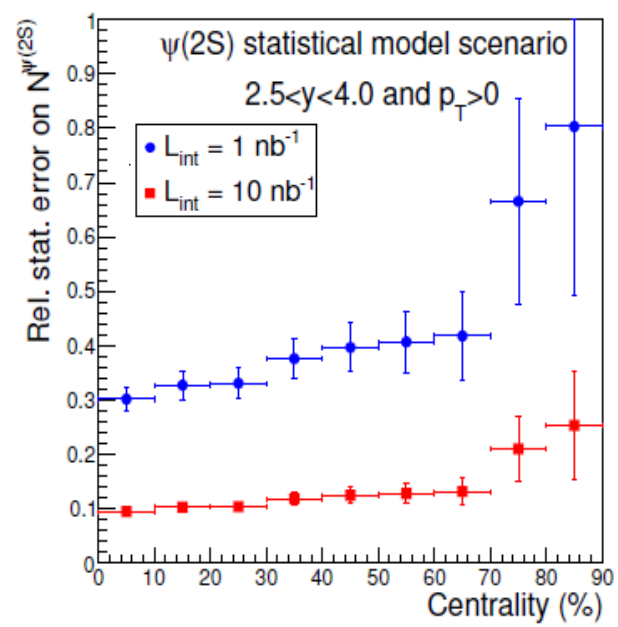


in fact here one can distinguish between the transport models that form charmonia already in QGP and statistical hadronization at phase boundary!

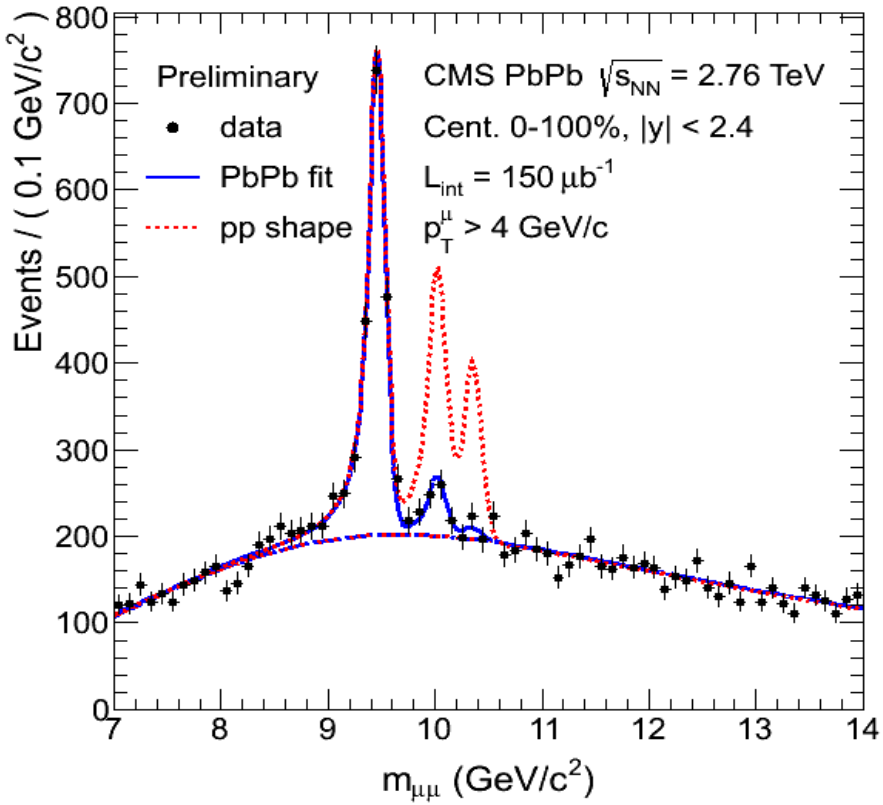
for statistical hadronization need to see suppression by Boltzmann factor

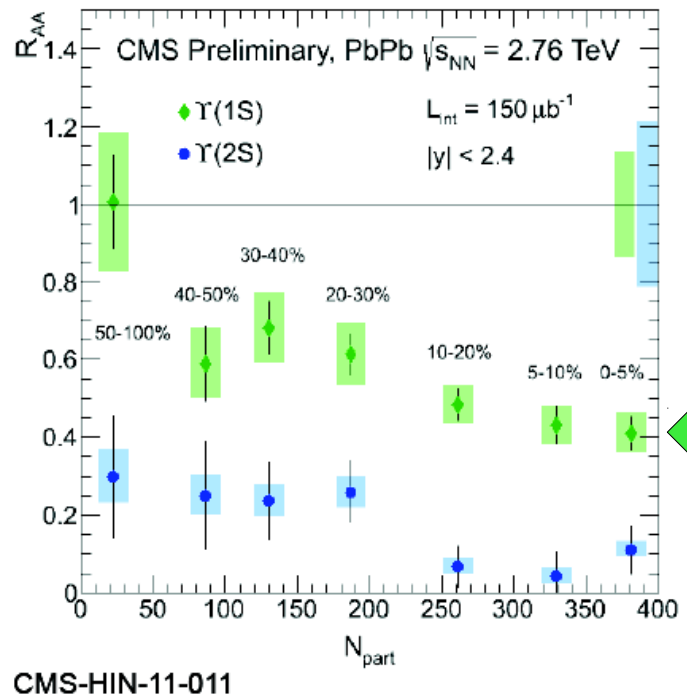
χ_c even bigger difference

expected ALICE performance muon arm run2 and run3



Suppression of Upsilon States





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

centrality integrated:

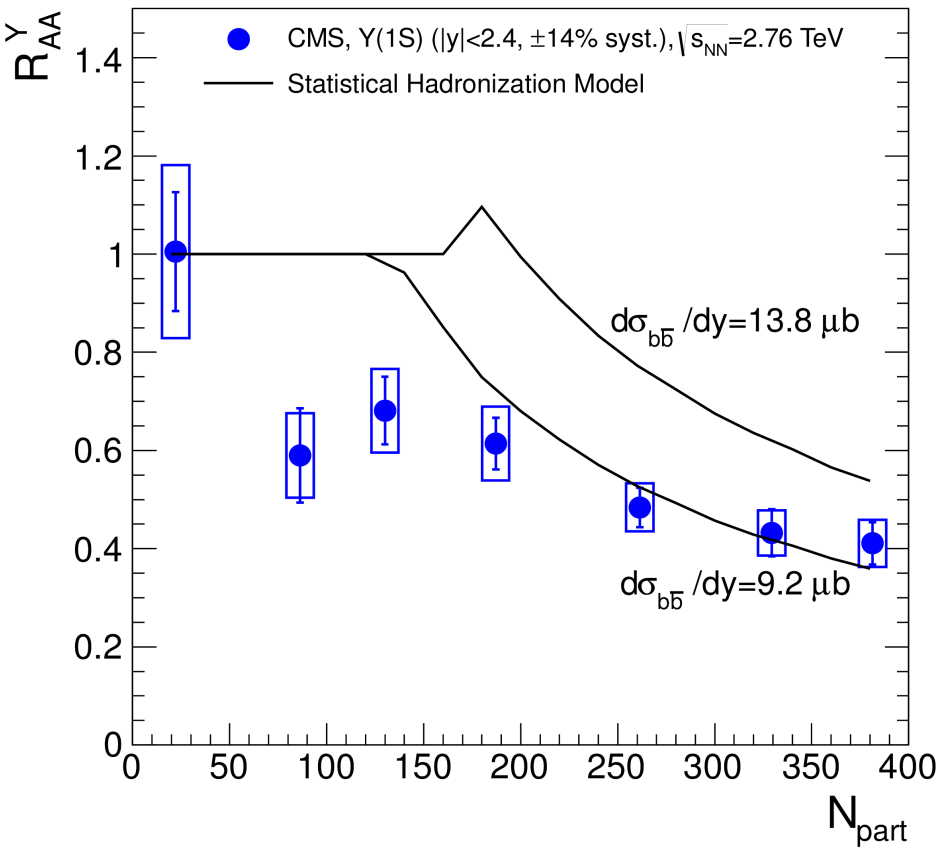
2S/1S PbPb relative to pp 0.21+-0.07+-0.02

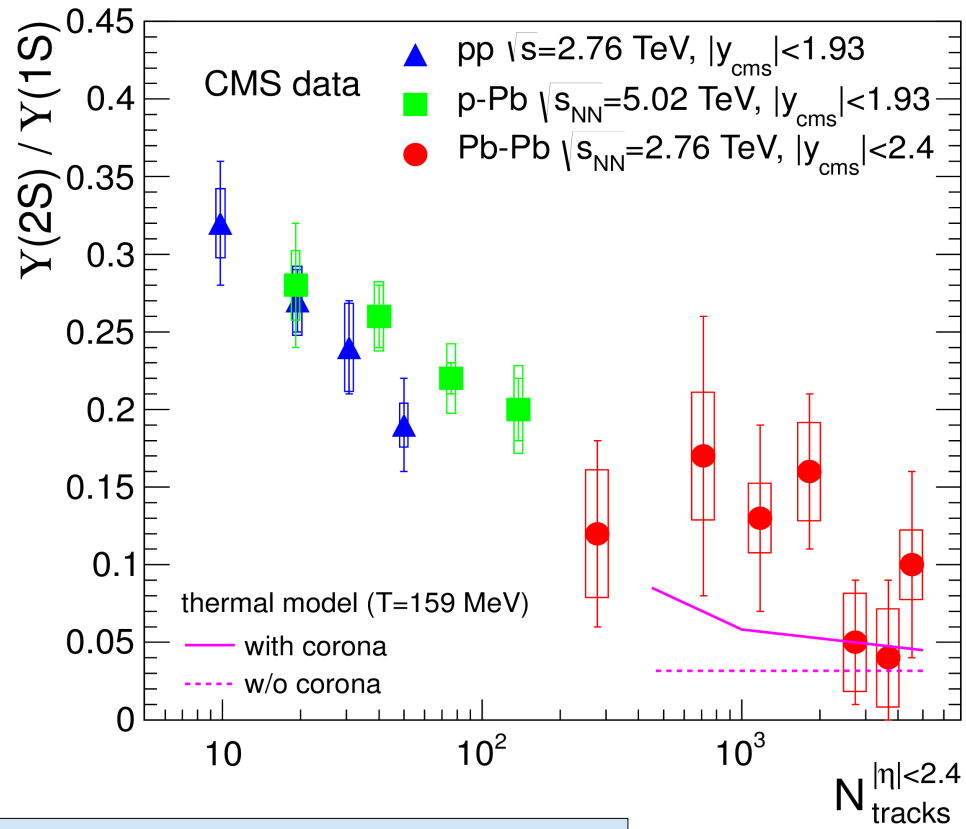
3S/1S " < 0.1 95% C.L.

higher upsilon states expected to melt earlier because of larger radius

the Upsilon could also come from statistical hadronization

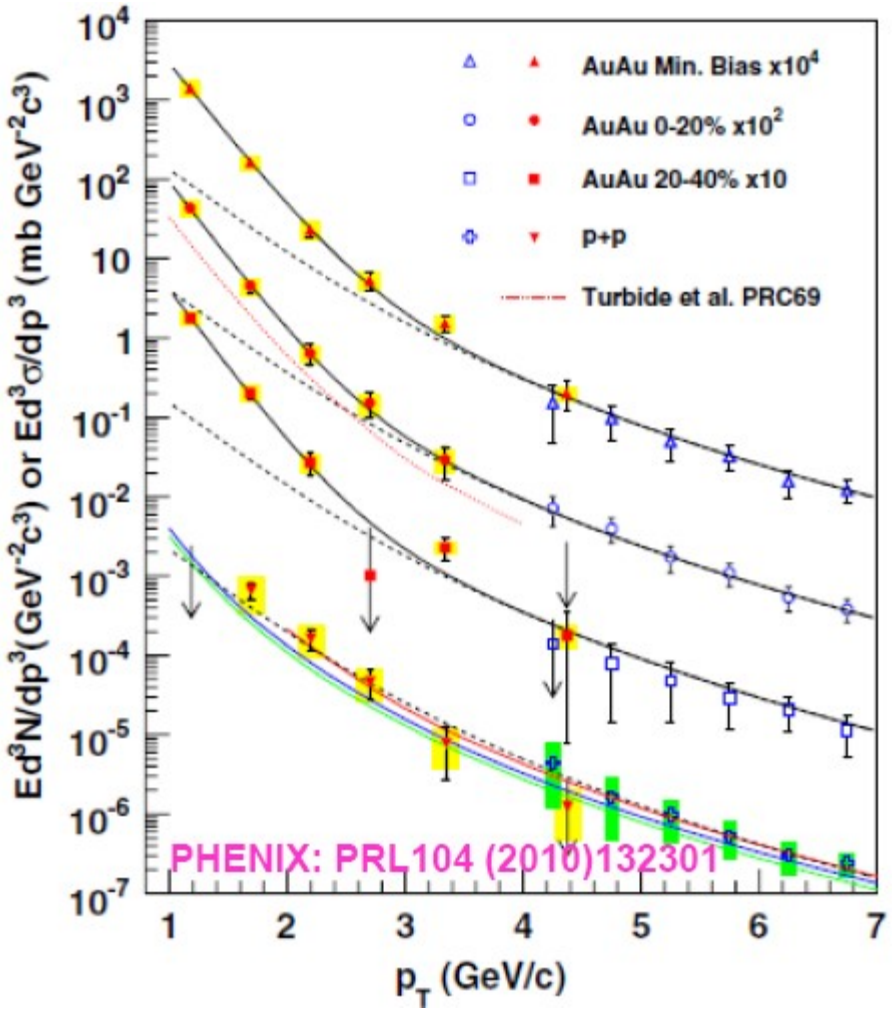
SHM/thermal model: Andronic, Braun-Munzinger, Redlich, J.S.

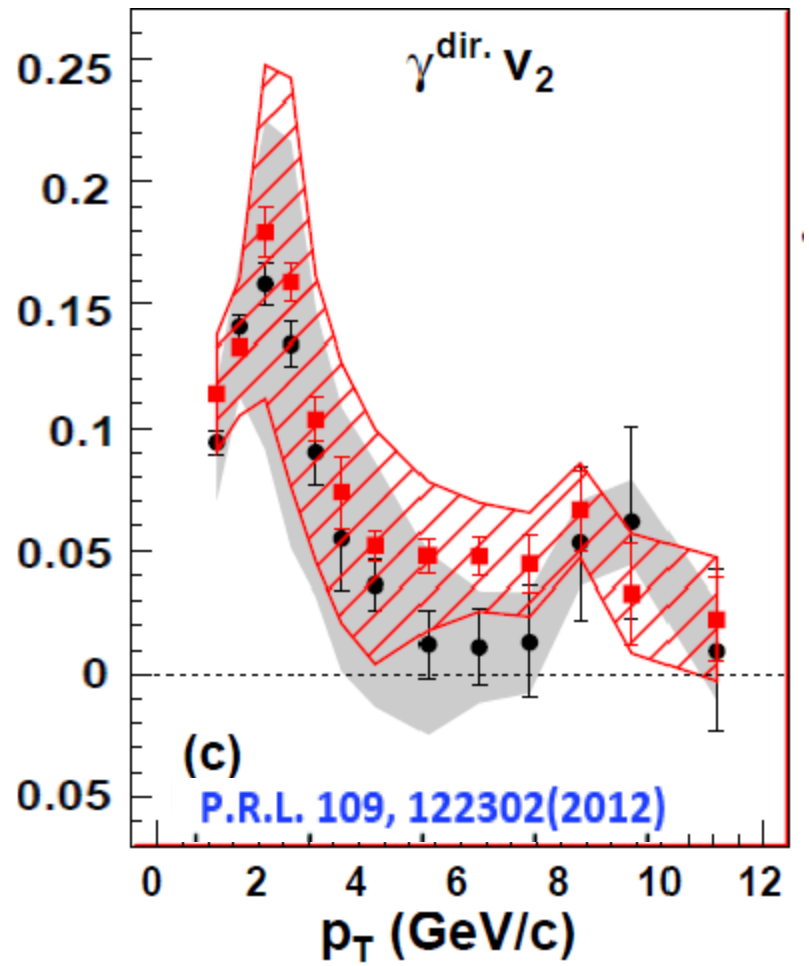




in this picture the entire Upsilon family is formed at hadronization
but: need to know first – do b-quark thermalize at all?
- total b-cross section in PbPb
future measurements in run2 and run3

Direct photon excess and elliptic flow at low p_t at RHIC

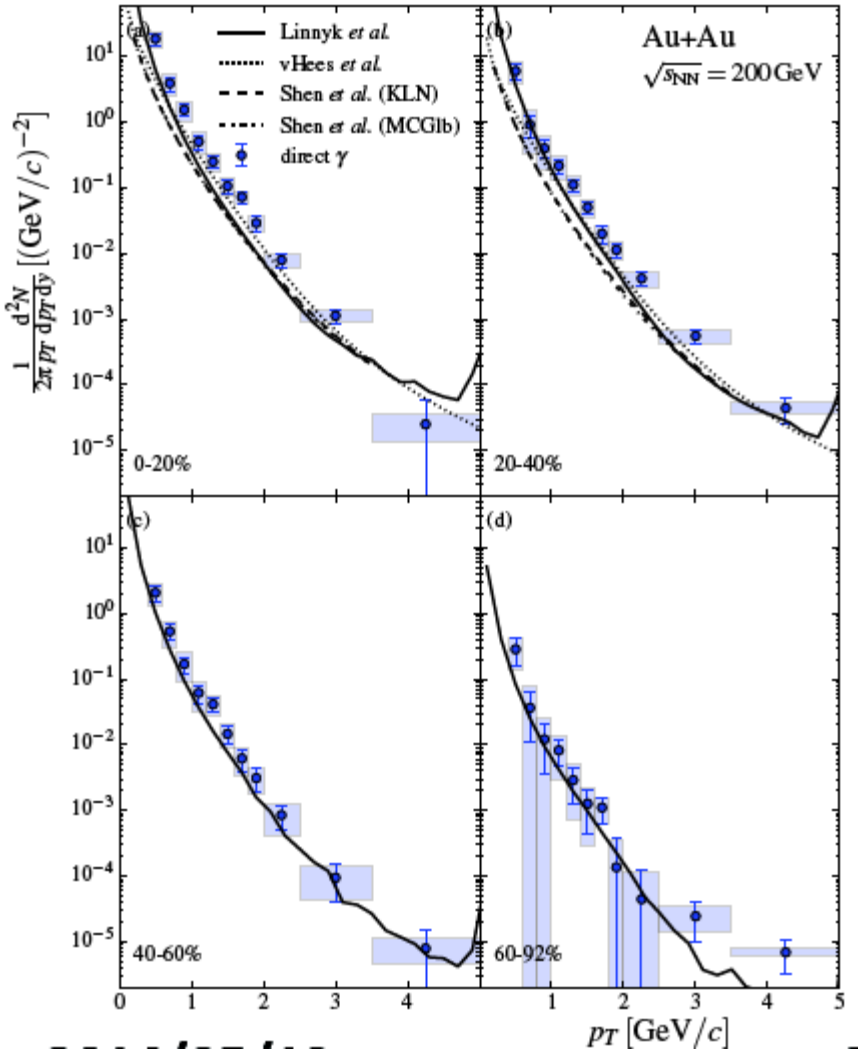




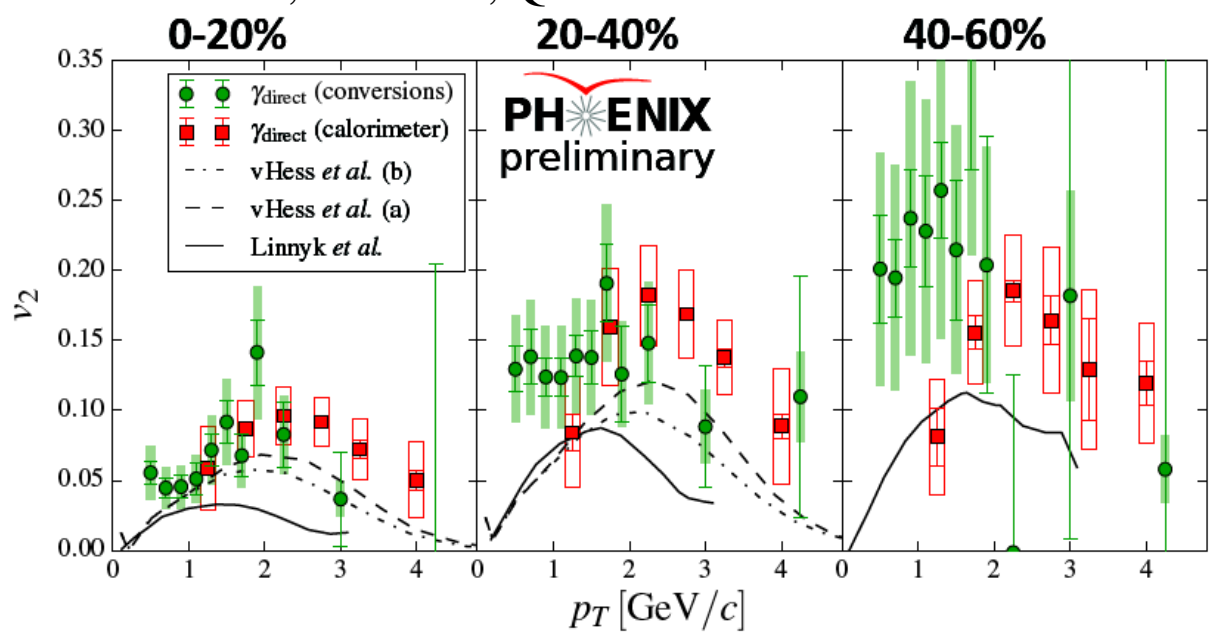
models underpredict photon yield and even more the photon v2

Much improved measurements: the puzzle remains

arXiv:1405.3940



S. Mizuno, PHENIX, QM2014

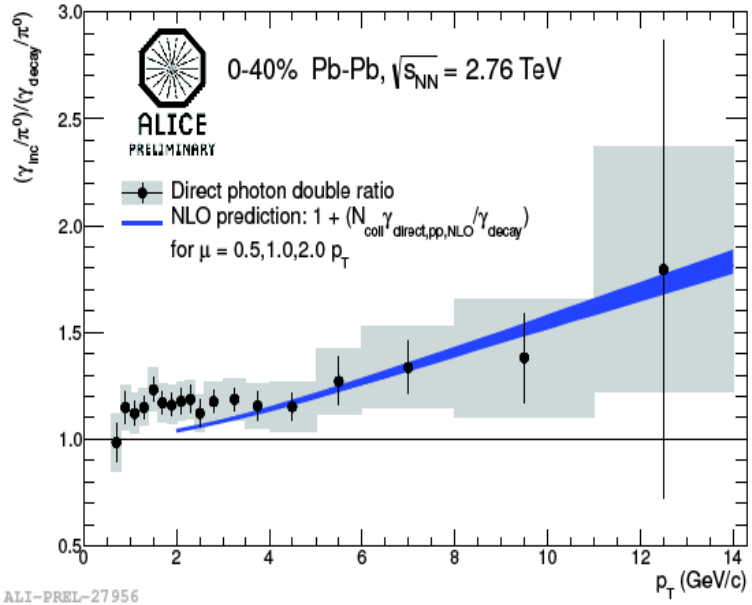


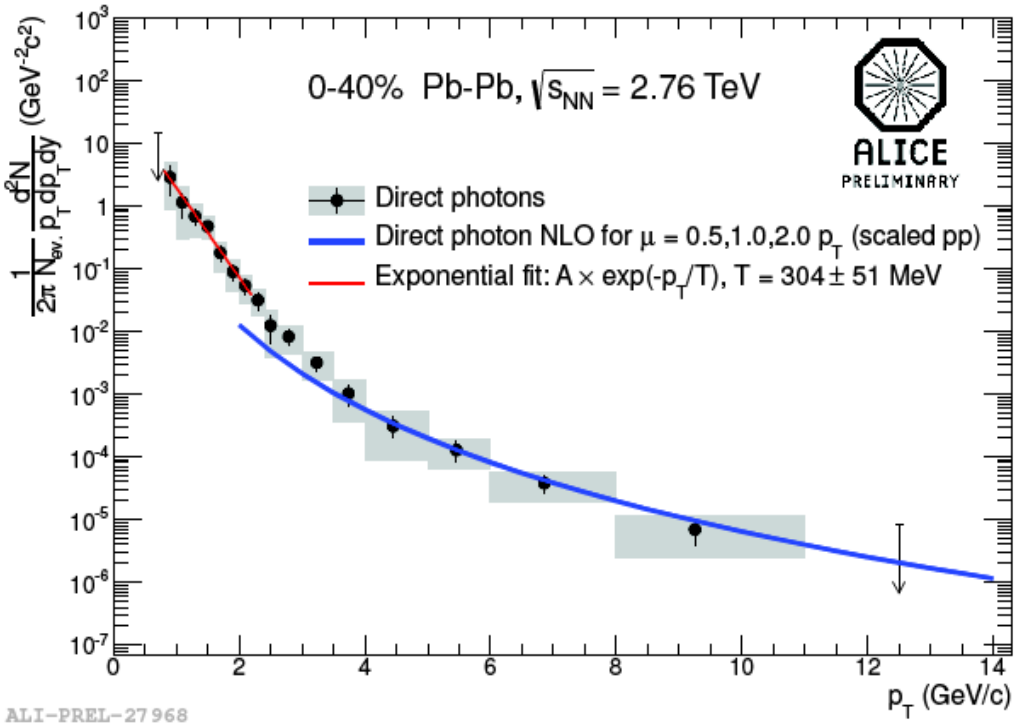
measurements using photon conversions extend data to significantly lower pt

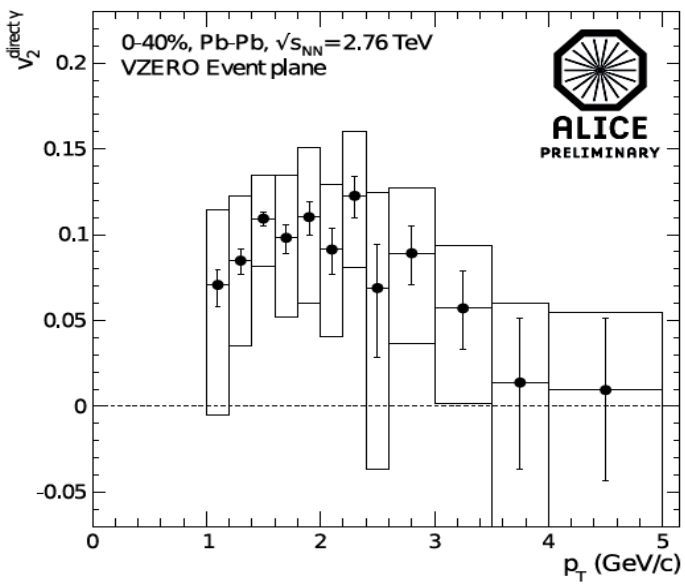
confirm earlier measurements, different systematics

the challenge for theories remains

direct photons in PbPb collisions at the LHC







a hot photon (300 MeV) source, the QGP

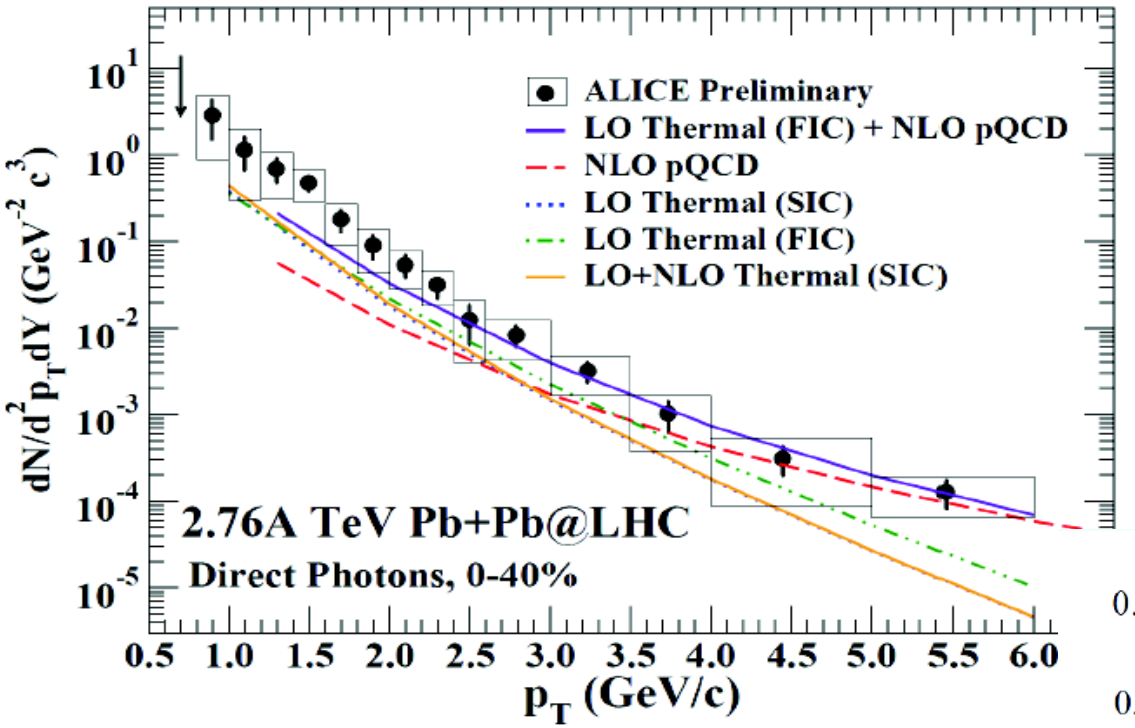
- or are they blueshifted photons from a later stage?

elliptic flow of photons a puzzle, v_2 measurement very good, but significance of direct photon signal at low p_t?

measurements in run2 and run3:

- reduction of systematic error
- measurement of complementary observable: virtual photon to e^+e^-

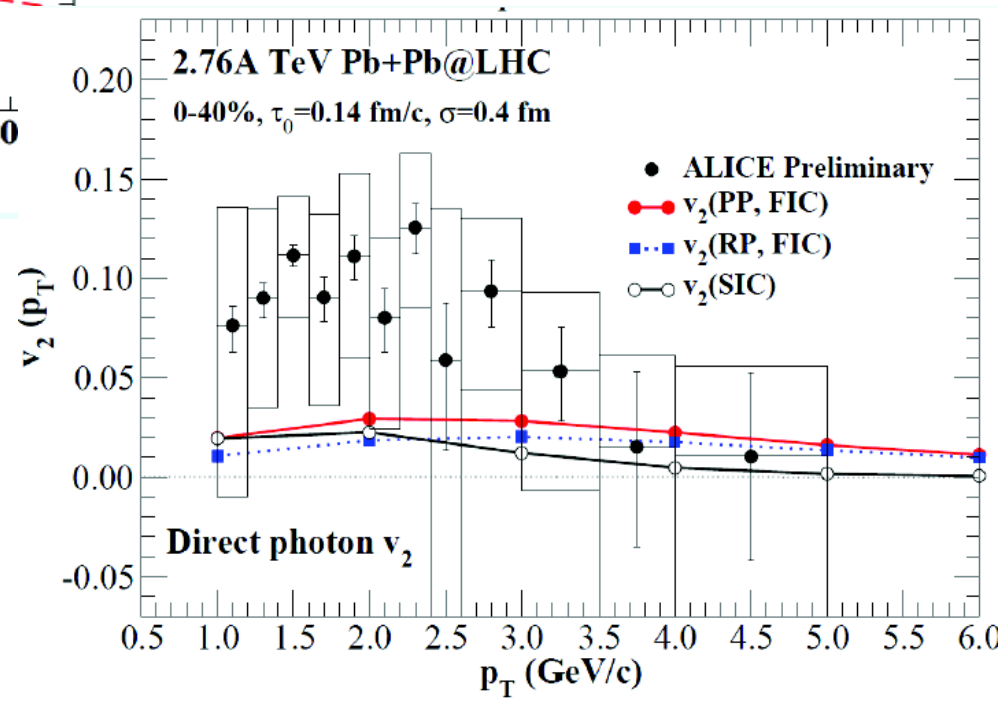
Direct photons at LHC (and RHIC) challenge models



R. Chatterjee, D.K. Srivastava, T. Renk arXiv:1401.7464

R. Chatterjee, H. Holopainen, I. Helenius, T. Renk, K. Escola PRC 88 (2013) 034901

it helps to introduce fluctuating initial conditions, but barely enough

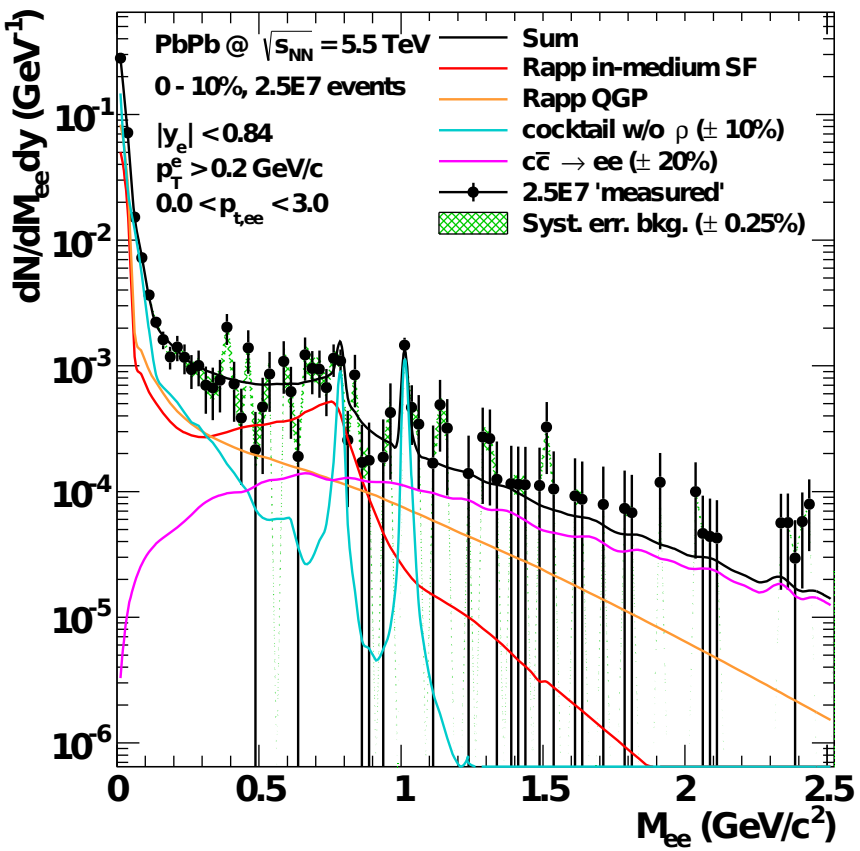


Spectra and elliptic flow high as compared to models – a real challenge
but: systematic errors largely correlated and error in v2 dominated by error in direct photon yield

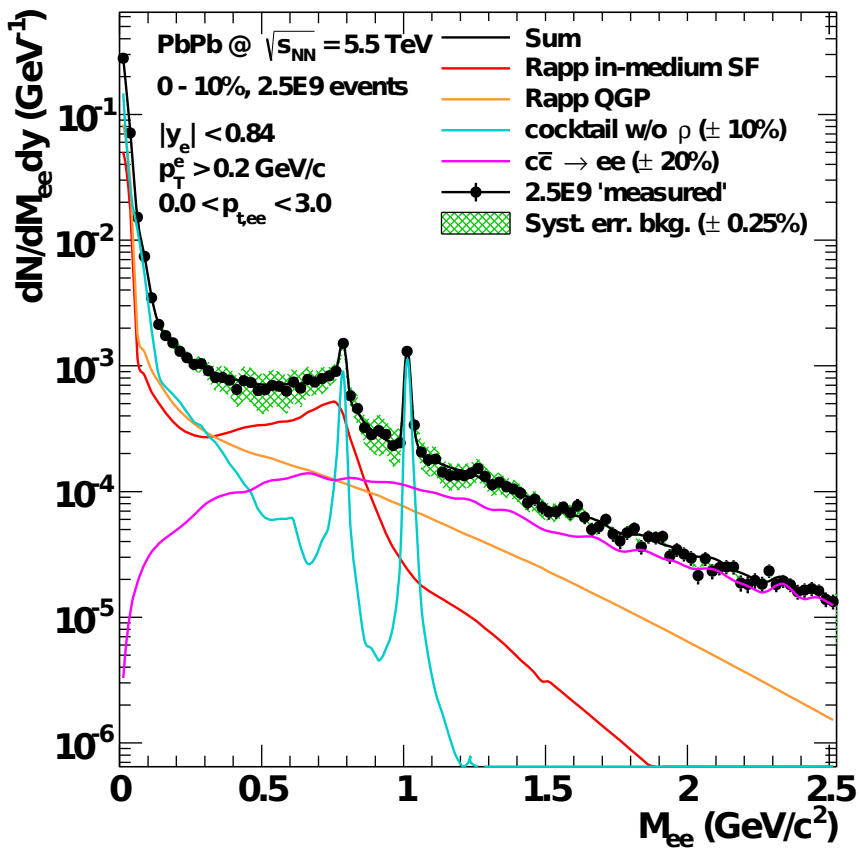
Electron pairs of low and intermediate mass
- experimentally very difficult – so far not addresses in PbPb at LHC

simulation!

2.5×107 Pb-Pb (0-10%)



2.5×109 Pb-Pb (0-10%)



- new ITS allows suppression of Dalitz, conversion and charm contributions
- continuous TPC read-out with 50 kHz in run3 increases event rate by a factor 100
- allows detailed investigation of thermal radiation from hadronic phase and QGP

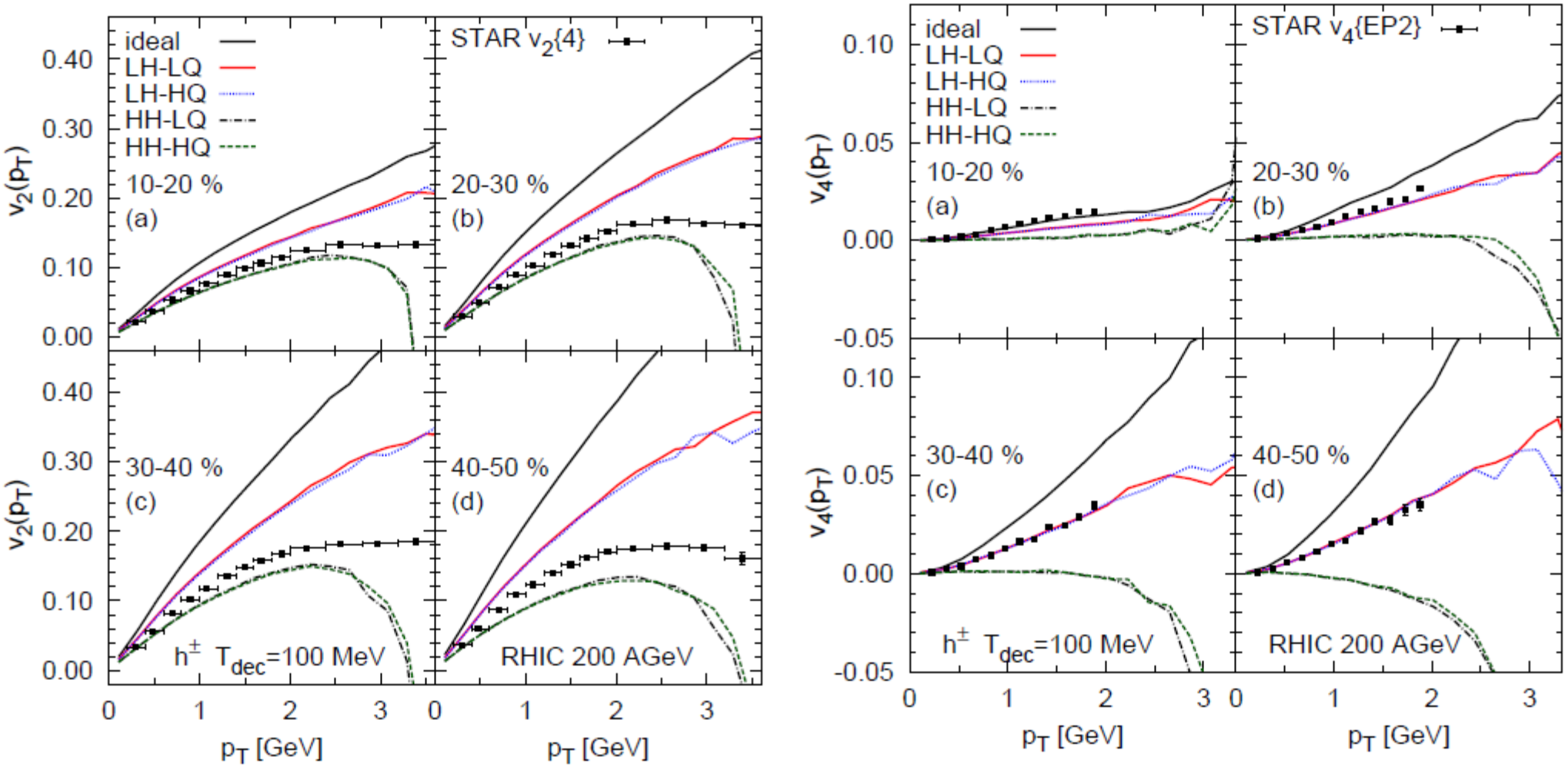
outlook

results for PbPb collisions from run1 at the LHC:
zeroing in on the properties of the Quark-Gluon Plasma
- transport coefficients
- deconfinement

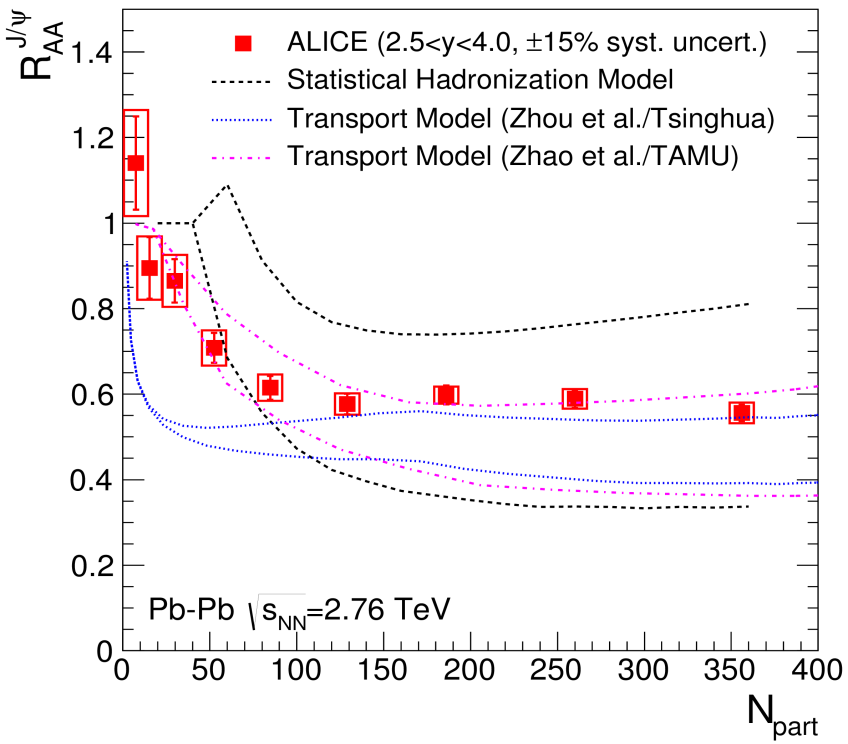
while we celebrate 60 years of CERN, we are looking forward to the next 10 years of studying the QGP at the LHC

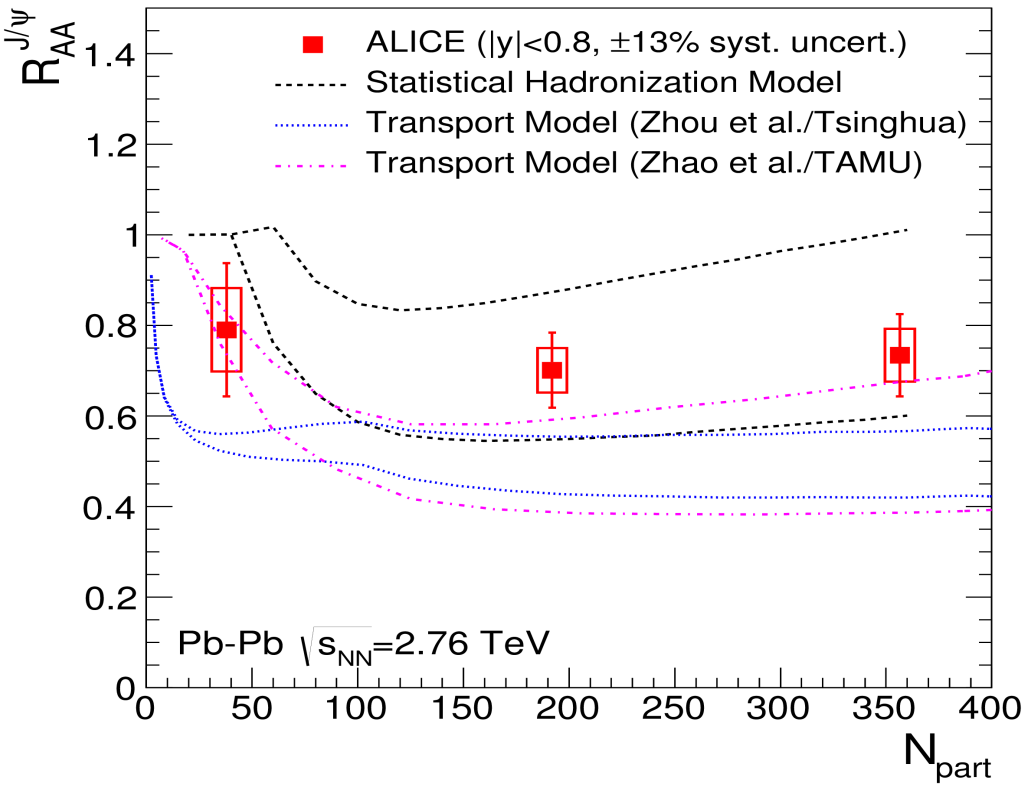
backup

RHIC data show no sensitivity to shear viscosity of QGP



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

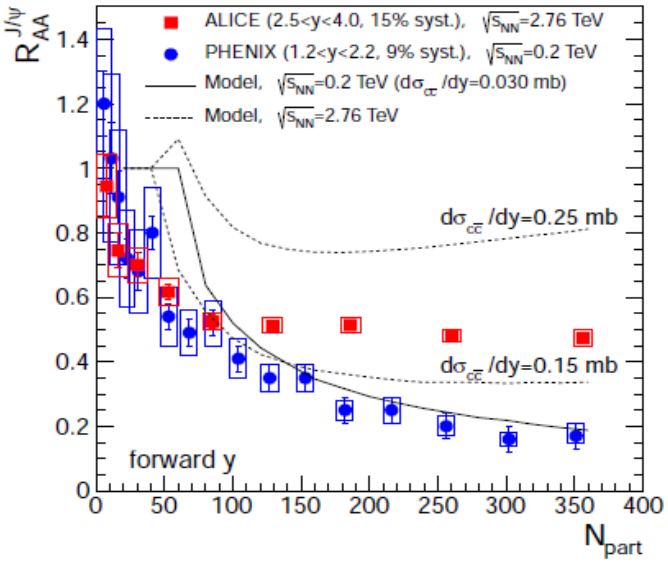
- transport models also in line with R_{AA}

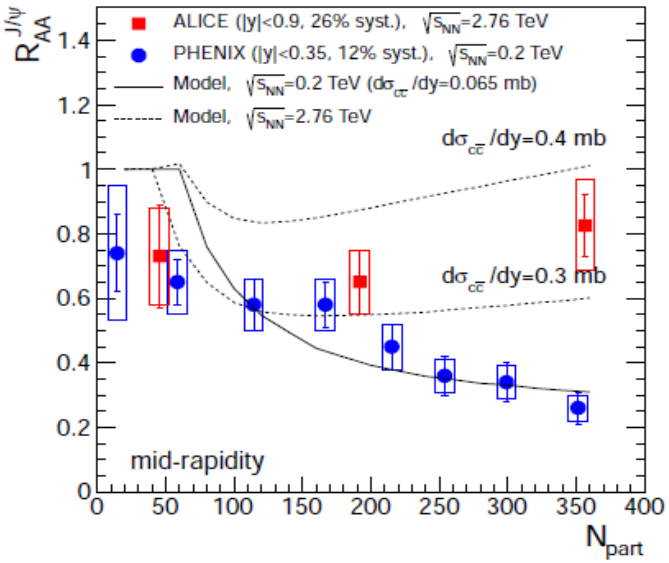
  part of J/psi from direct hard production, part dynamically generated in QG

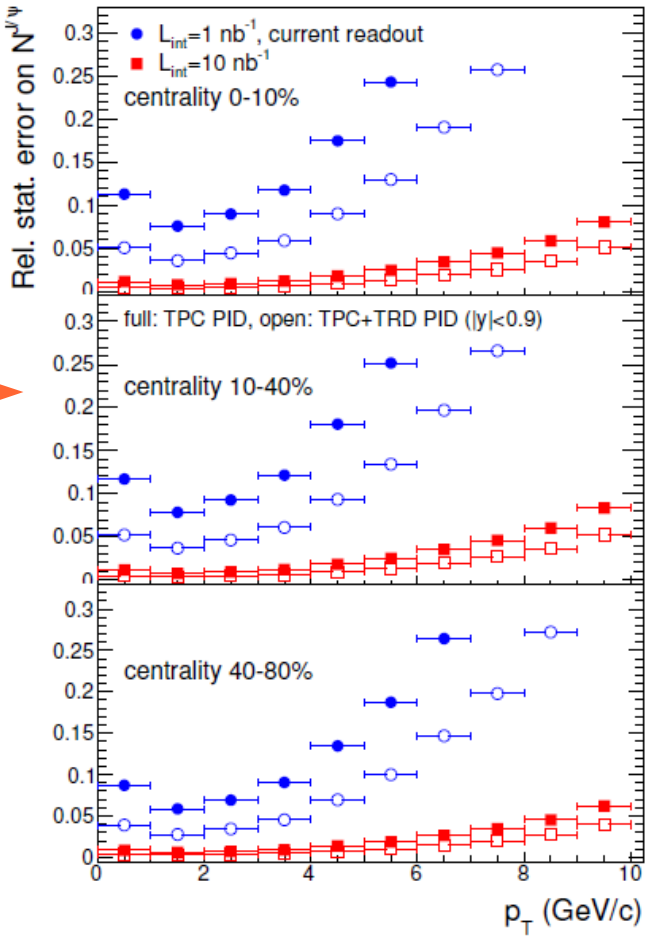
  but different open charm cross section used

  (0.5-0.75mb TAMU and 0.65-0.8 mb Tsinghua vs. 0.3-0.4 mb SHM)

J/psi as probe of deconfinement







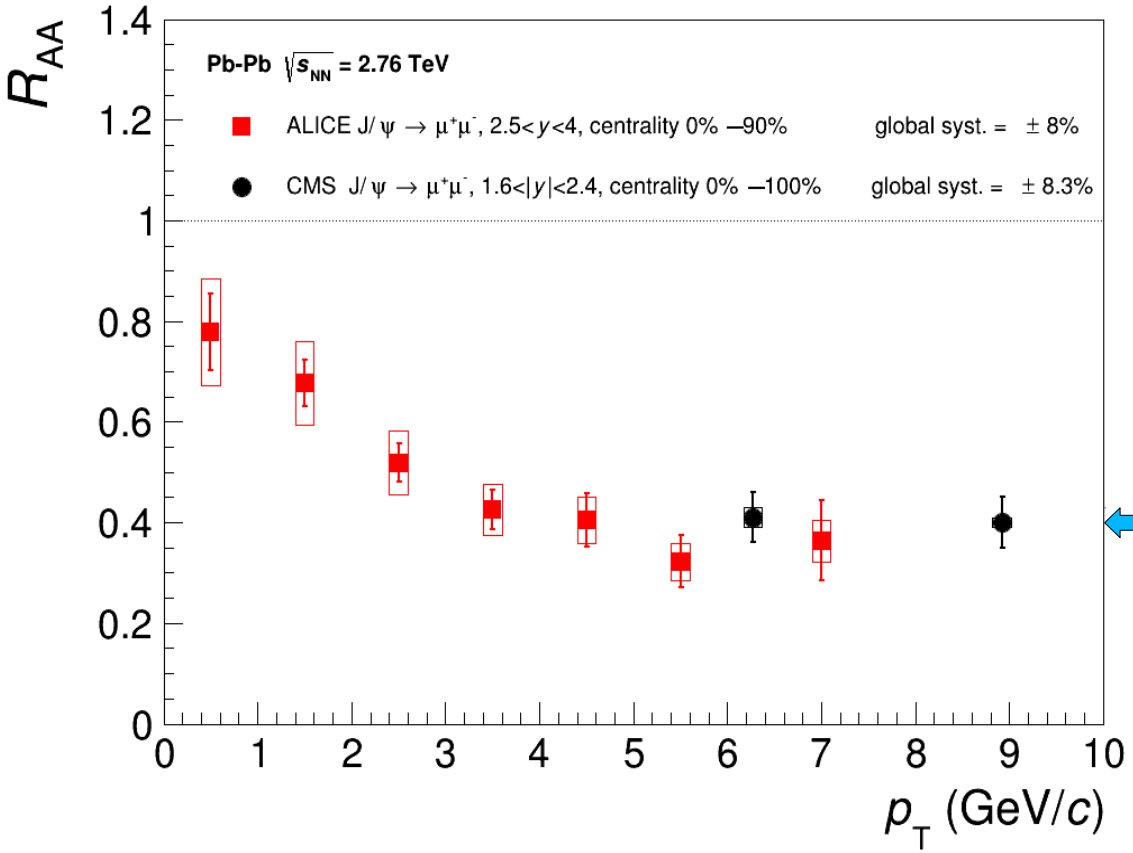
di-electrons statistics limited, 10 nb-1 will have huge effect

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

p_t dependence of R_{AA}

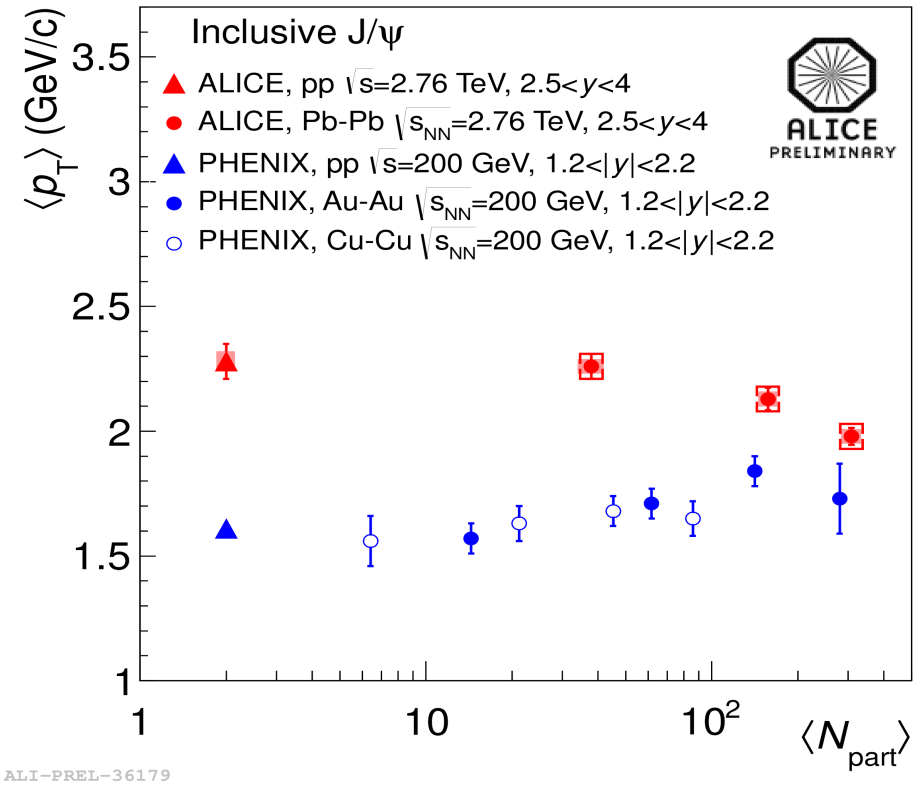


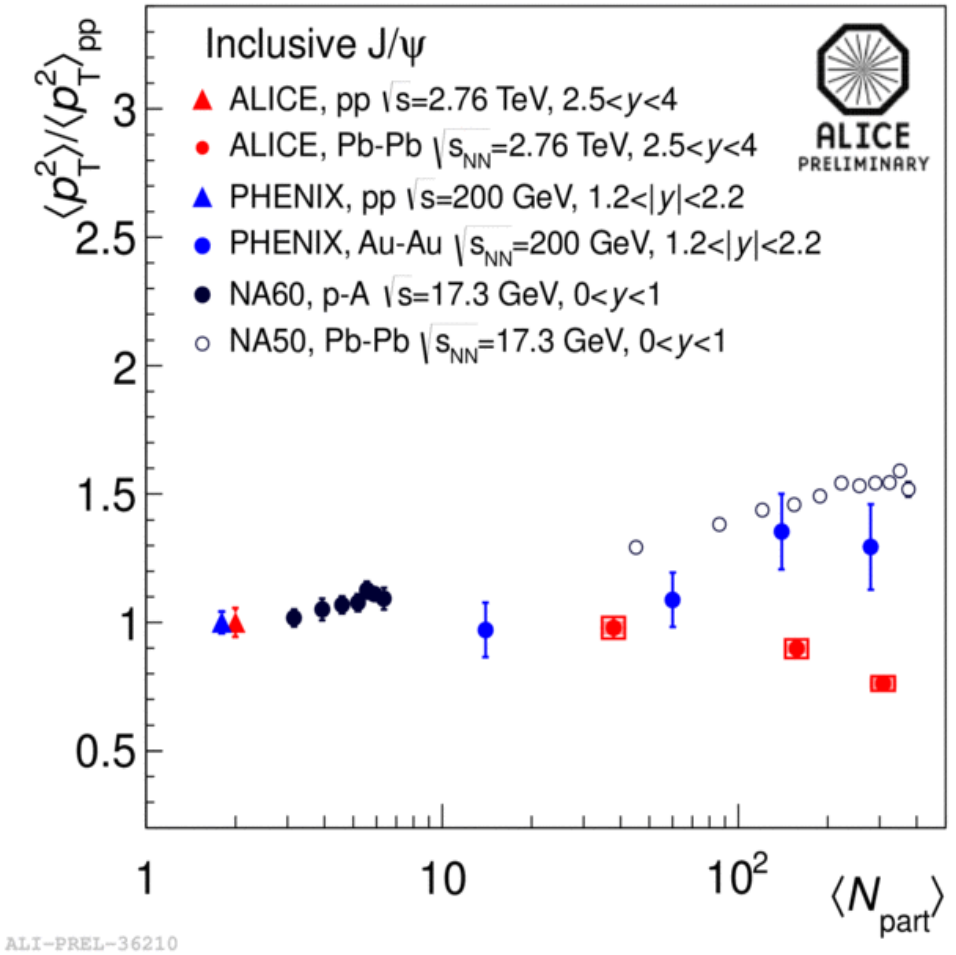
relative yield larger at low p_t in nuclear collisions

good agreement with CMS at high p_t

argument: thermalized deconfined charm quarks hadronize into J/ψ

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

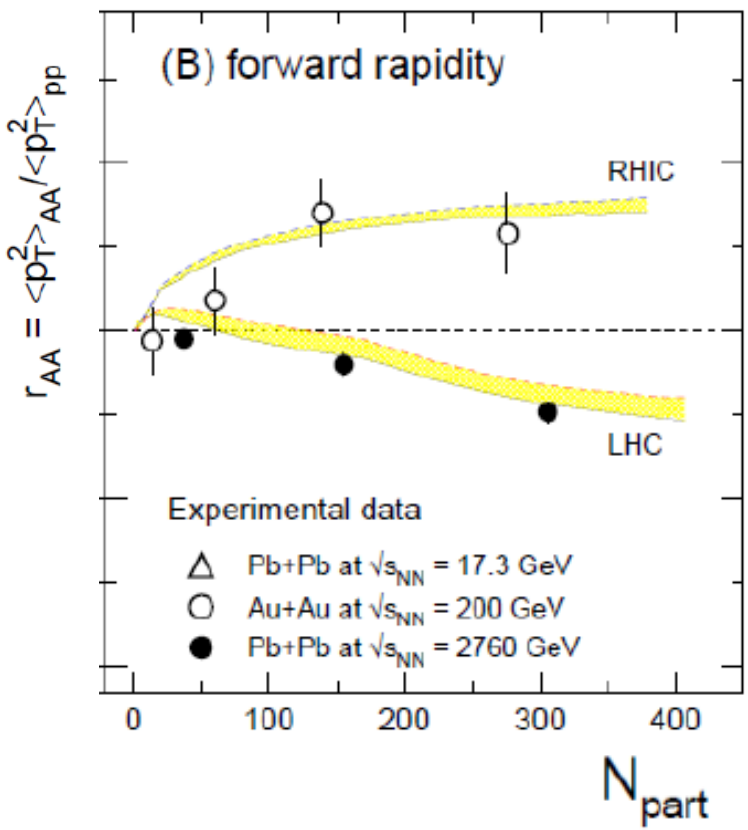


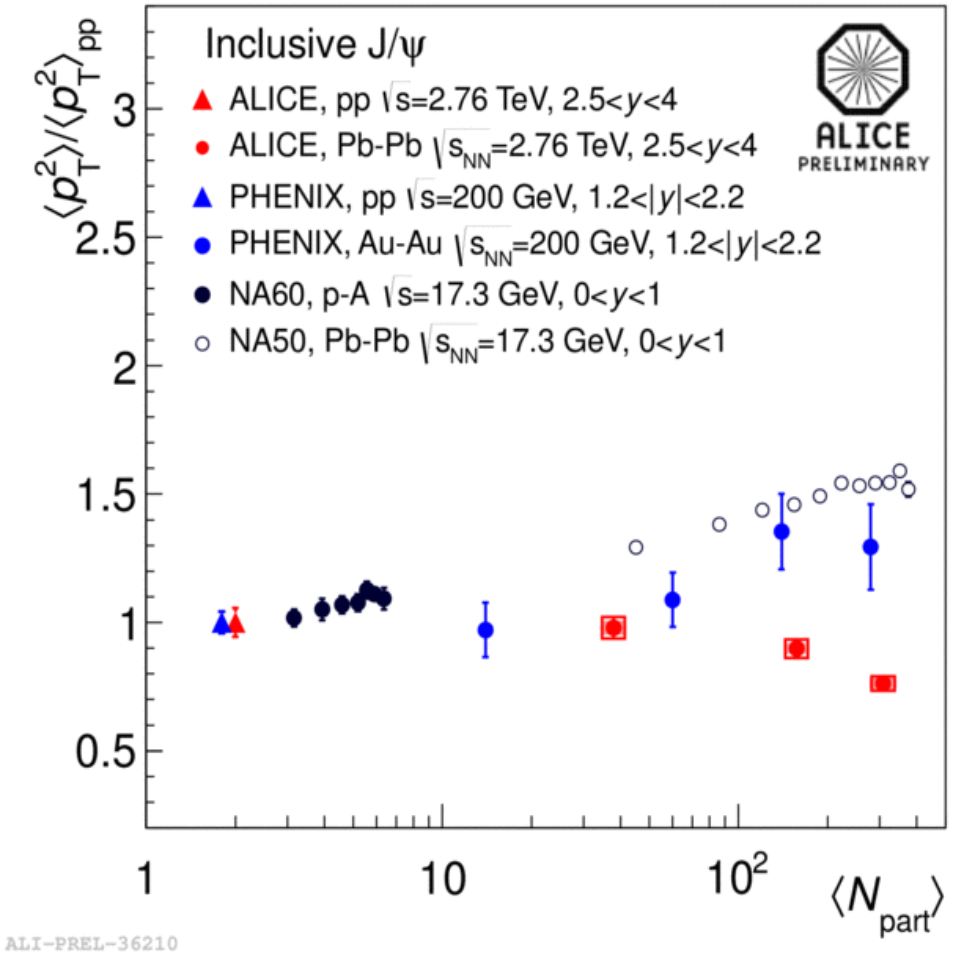


At LHC for central collisions softening relative to peripheral collisions and relative to pp (opposite trend to RHIC) - consistent with formation of J/psi from thermalized c-quarks

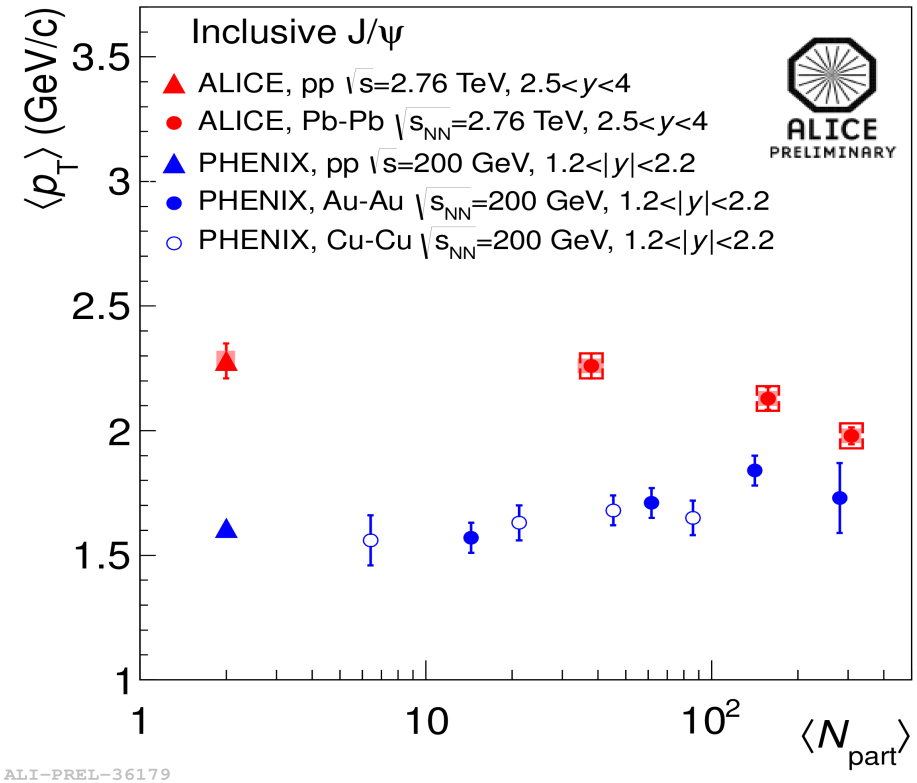
Softening of J/psi p_t distributions for central PbPb coll.

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



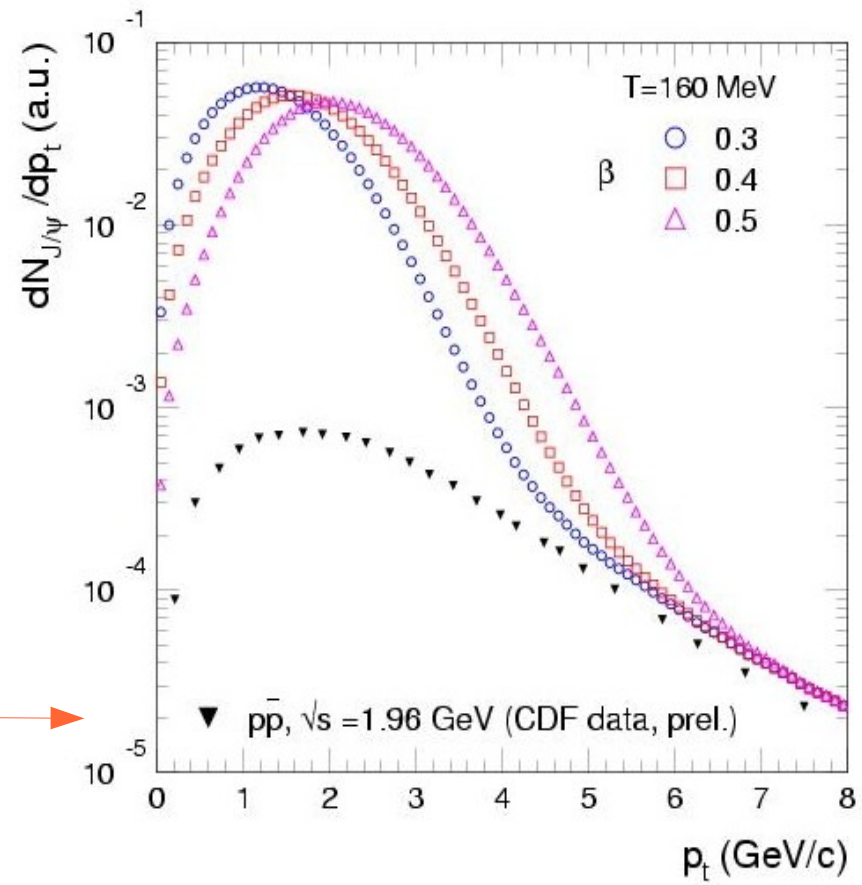


Spectral distribution is key to thermalization



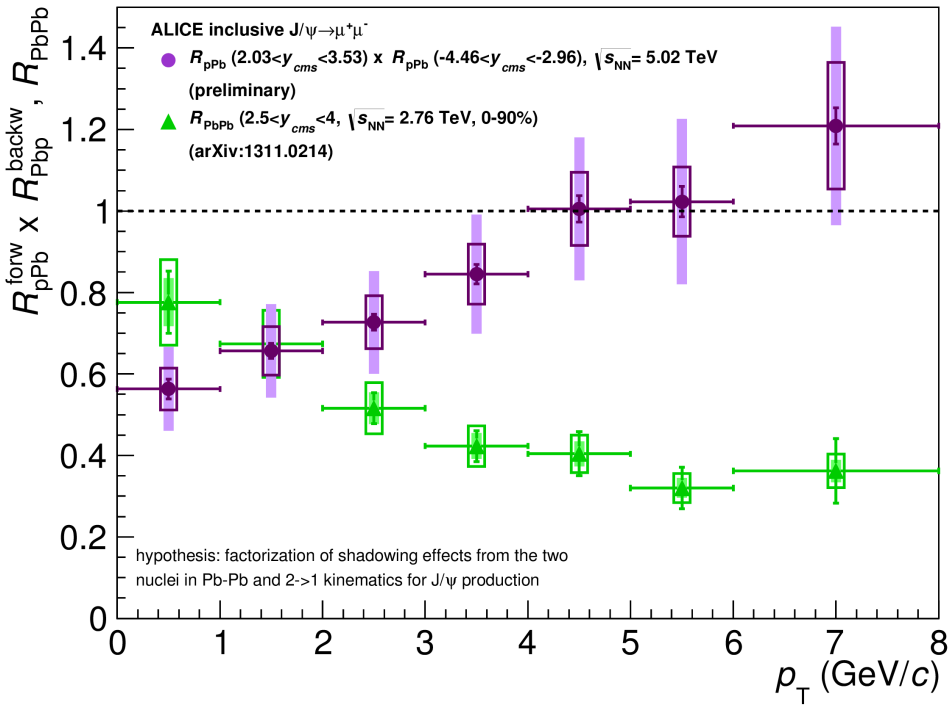
at LHC shift of paradigm: more central collision → narrower momentum distribution
my interpretation: thermalization

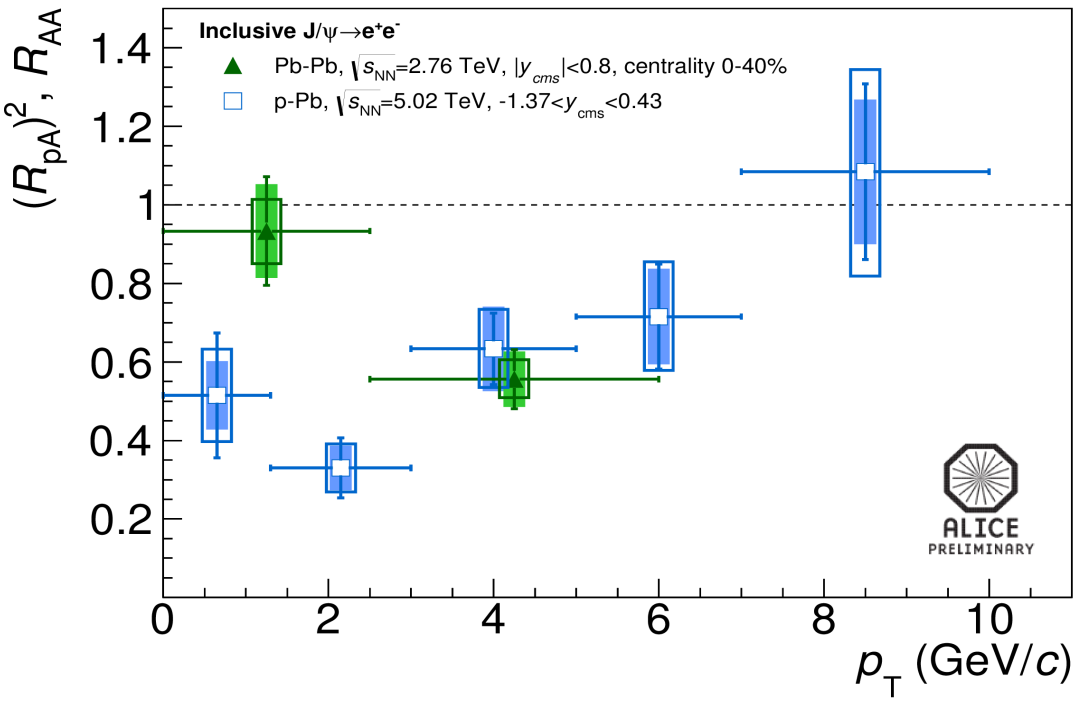
but if charm quark thermalize, their spectral distributions should also reflect collective flow of liquid



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

arXiv:1405.1177



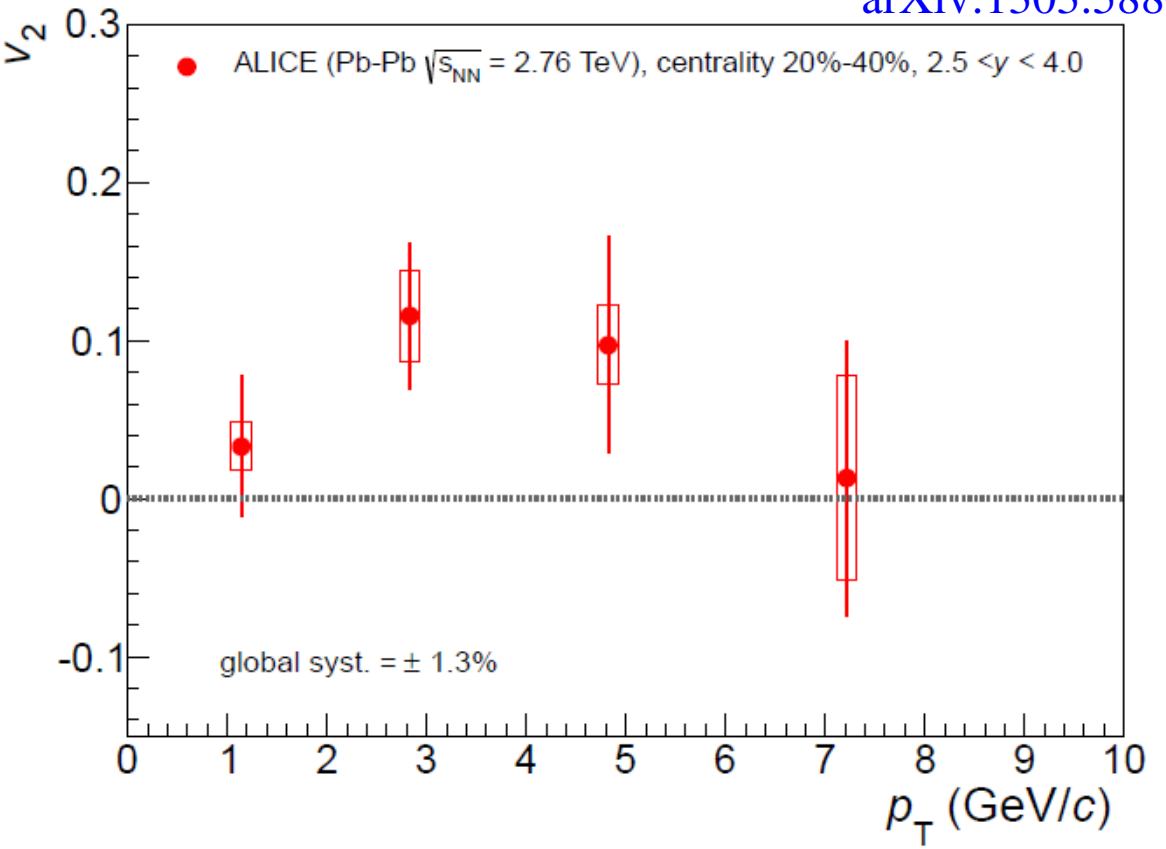


at low pt yield in nuclear collisions above pPb collisions

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

Elliptic Flow of J/psi vs pt

arXiv:1303.5880

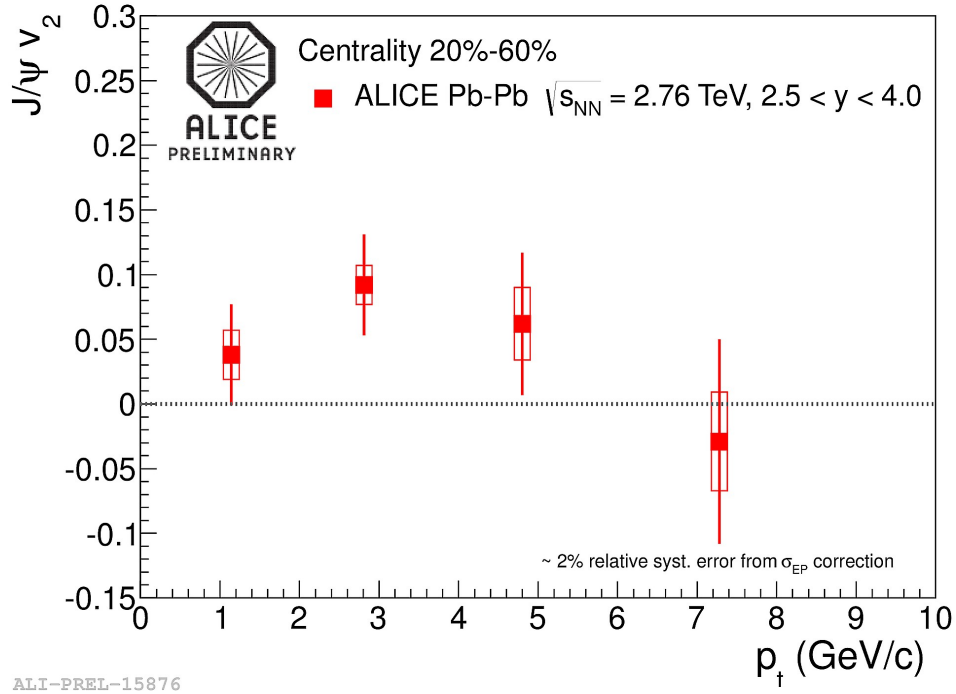


charm quarks thermalized in the QGP should exhibit the elliptic flow generated in this phase

- expect build-up with p_t as observed for π, p. K, Λ, … and vanishing signal for high p_t region where J/ψ not from hadronization of thermalized quarks

first observation of J/ψ v_2
in line with expectation from statistical hadronization

J/psi from thermalized charm quarks should exhibit collective flow

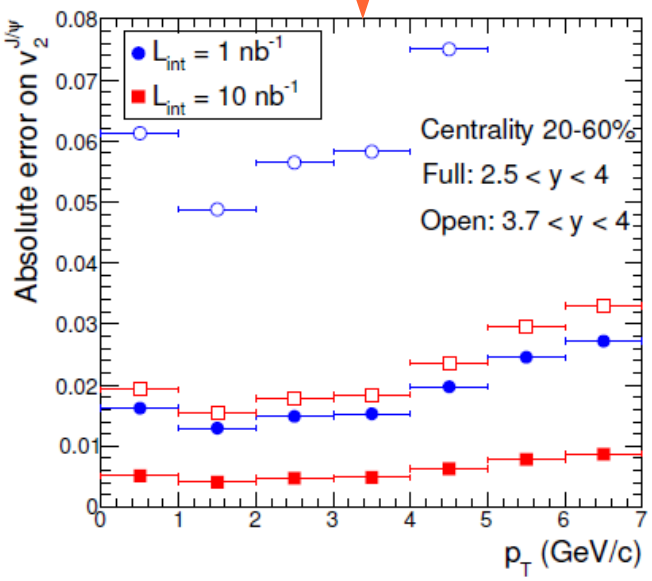


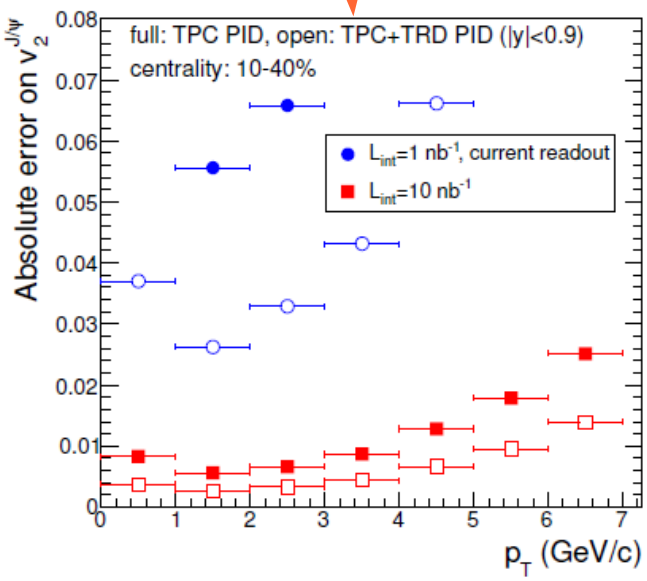
observation of flow with muon arm
presently 3 sigma
needs statistics to make model comparison meaningful

future statistical errors

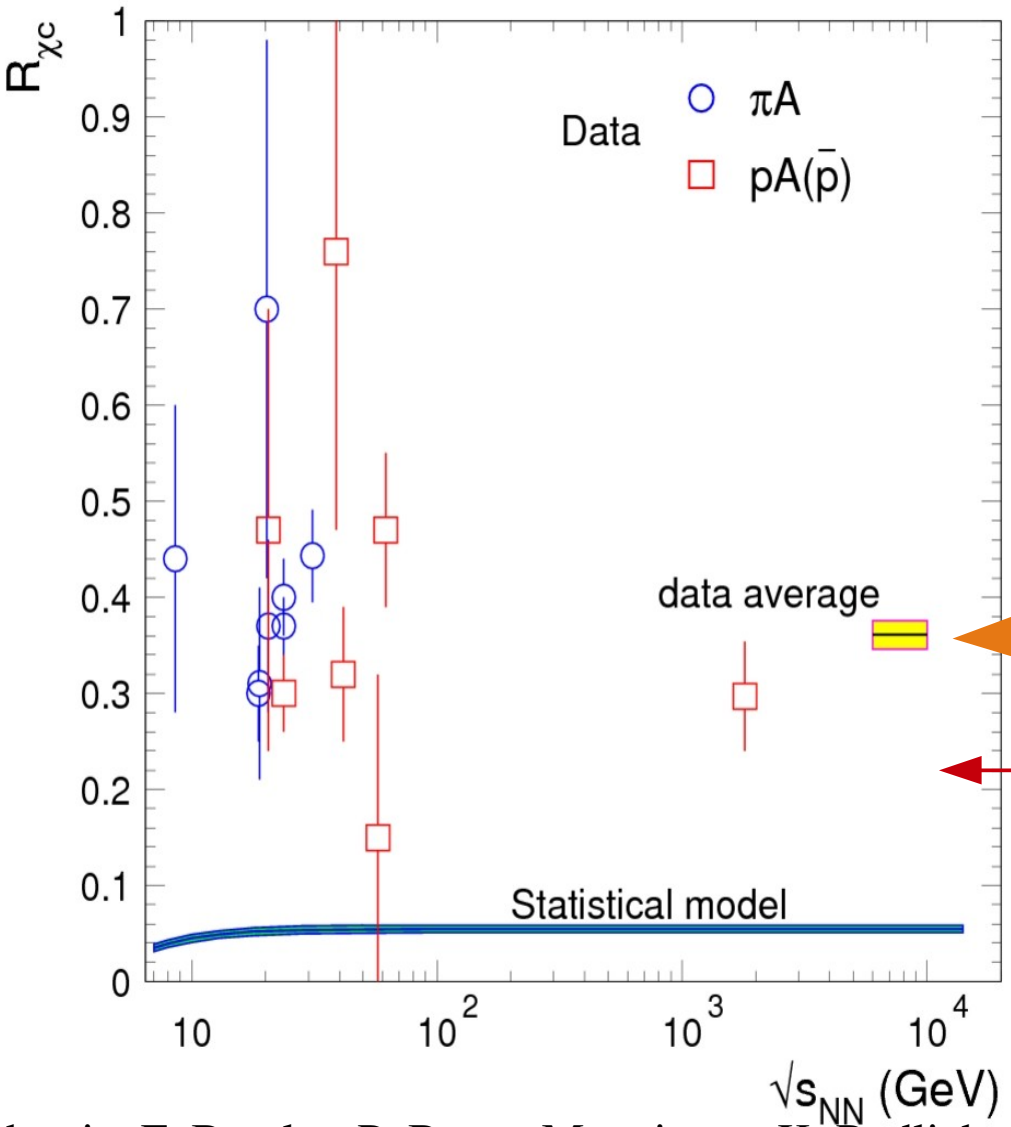
muon arm

central barrel





Situation even more dramatic for P-states



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

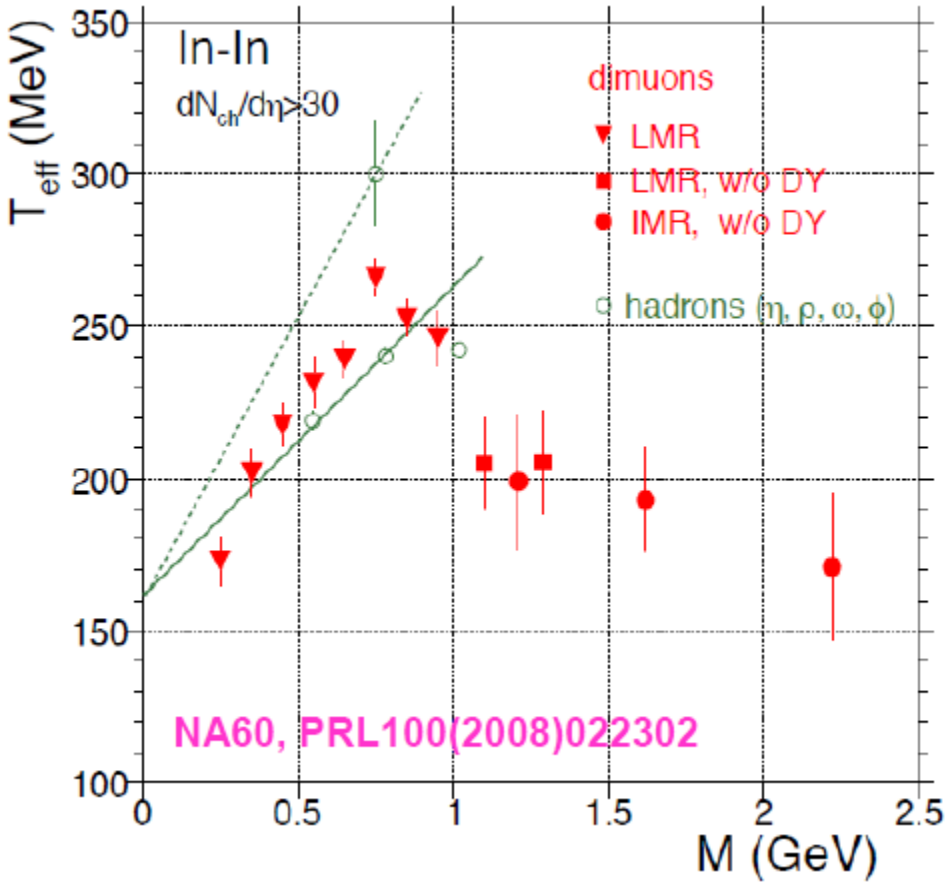
Transport model (Rapp)

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

Physics reach after ALICE upgrade

Topic	Observable	Approved (1/nb delivered, 0.1/nb m.b.)	Upgrade (10/nb delivered, 10/nb m.b.)
Heavy flavour	D meson RAA	pT>1, 10%	pT>0, 0.3%
	D from B RAA	pT>3, 30%	pT>2, 1%
	D meson elliptic flow (for v2=0.2)	pT>1, 50%	pT>0, 2.5%
	D from B elliptic flow (for v2=0.1)	not accessible	pT>2, 20%
	Charm baryon/meson ratio (Λc/D)	not accessible	pT>2, 15%
	Ds RAA	pT>4, 15%	pT>1, 1%
Charmonia	J/ψ RAA (forward y)	pT>0, 1%	pT>0, 0.3%
	J/ψ RAA (central y)	pT>0, 5%	pT>0, 0.5%
	J/ψ elliptic flow (forward y, for v2 =0.1)	pT>0, 15%	pT>0, 5%
	ψ'	pT>0, 30%	pT>0, 10%
Dielectrons	Temperature IMR	not accessible	10% on T
	Elliptic flow IMR (for v2=0.1)	not accessible	10%
	Low-mass vector spectral function	not accessible	pT>0.3, 20%
Heavy nuclei	hyper(anti)nuclei, H-dibaryon	35% (4ΛH)	3.5% (4ΛH)

stat. error at min pt


In-In
dN_ch/dη>30
dimuons
LMR
LMR, w/o DY
IMR, w/o DY
hadrons (η, ρ, ω, φ)
NA60, PRL100(2008)022302
T_eff (MeV)
M (GeV)
350
300
250
200
150
100
0
0.5
1
1.5
2
2.5