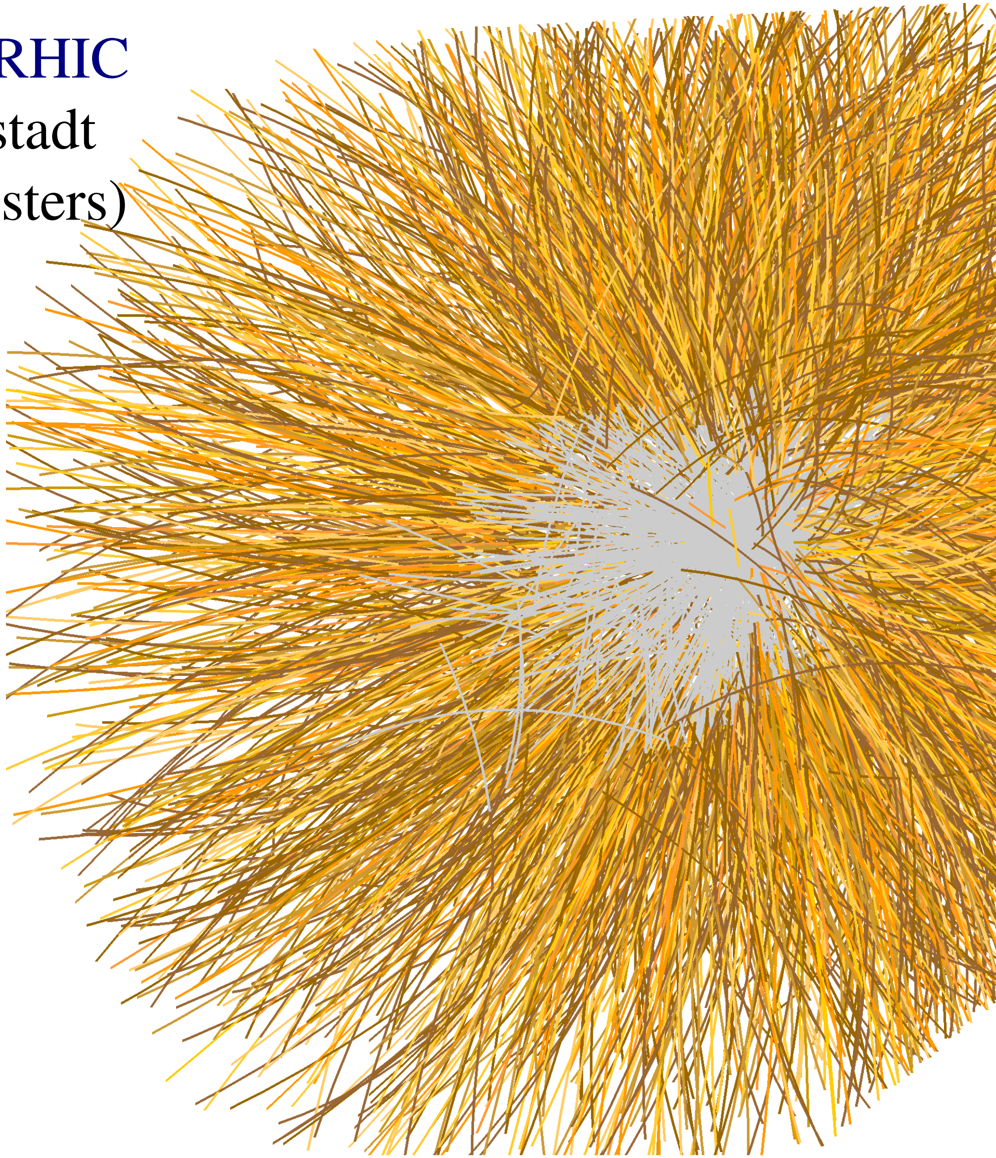
Quark-Gluon Plasma: from RHIC to LHC energies

a wealth of results from LHC Run1 and from RHIC
(see recent QM 2014 conference in Darmstadt
31 plenary and 180 parallel talks, 300 posters)

a personal selection of just a few observables
with thanks to my colleagues from
ALICE, ATLAS, CMS, PHENIX, STAR

where are we and where do we go from here?



the objective:
study the phase diagram of
strongly interacting matter
properties of the quark-gluon plasma matter
nature of the QCD phase transition

Johanna Stachel – Universität Heidelberg

11th ICFA Seminar on Future Perspective in High-Energy Physics, Beijing, Oct 2014

Heavy ion runs at RHIC and LHC

LHC: PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV   ALICE, ATLAS, CMS

2010 about 9 μb^{-1}

2011 about 150 μb^{-1} ≅ 10^9 collisions

pPb at $\sqrt{s_{NN}}$ = 5.02 TeV   ALICE, ATLAS, CMS, LHCb

2013 about 30 nb-1 ≅ $5 \cdot 10^{10}$ collisions

total of about 12 weeks in 3 years of running

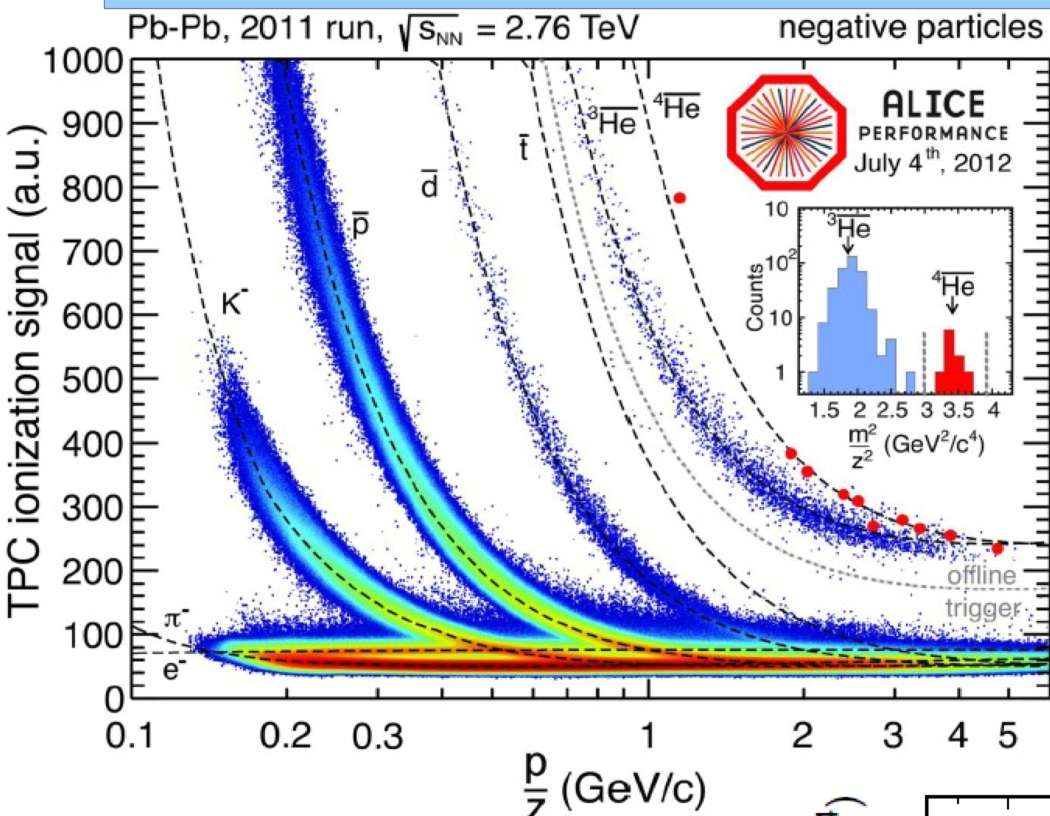
RHIC: AuAu at $\sqrt{s_{NN}}$ =7.7 - 200 GeV BRAHMS*, PHENIX, PHOBOS*, STAR

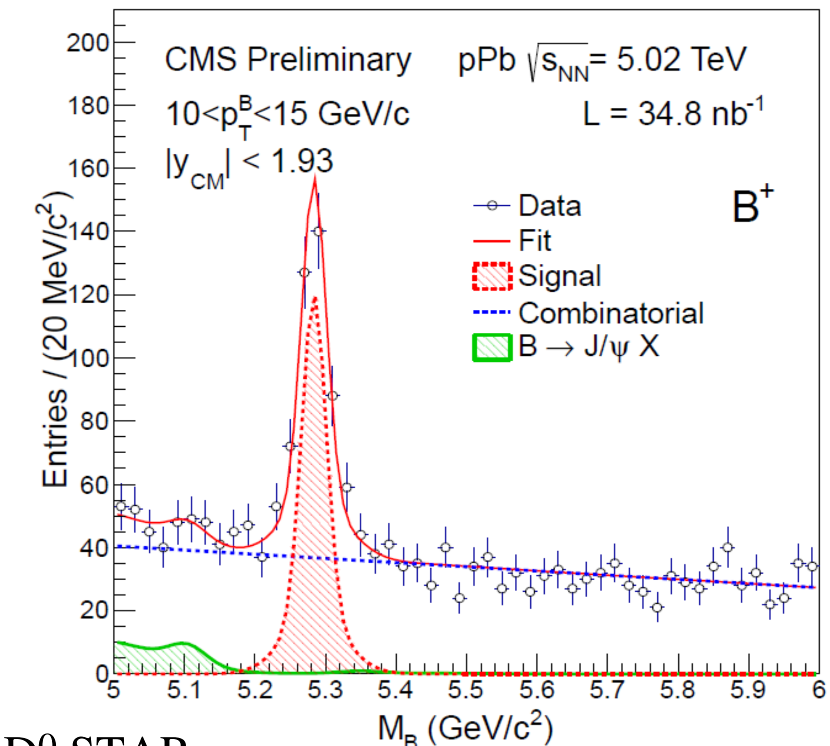
from 2000	77 nb^{-1}	about 60% of it in 2014!
other nuclei	71 nb^{-1}	
dAu	510 nb^{-1}	

total of 132 weeks in 15 year of running

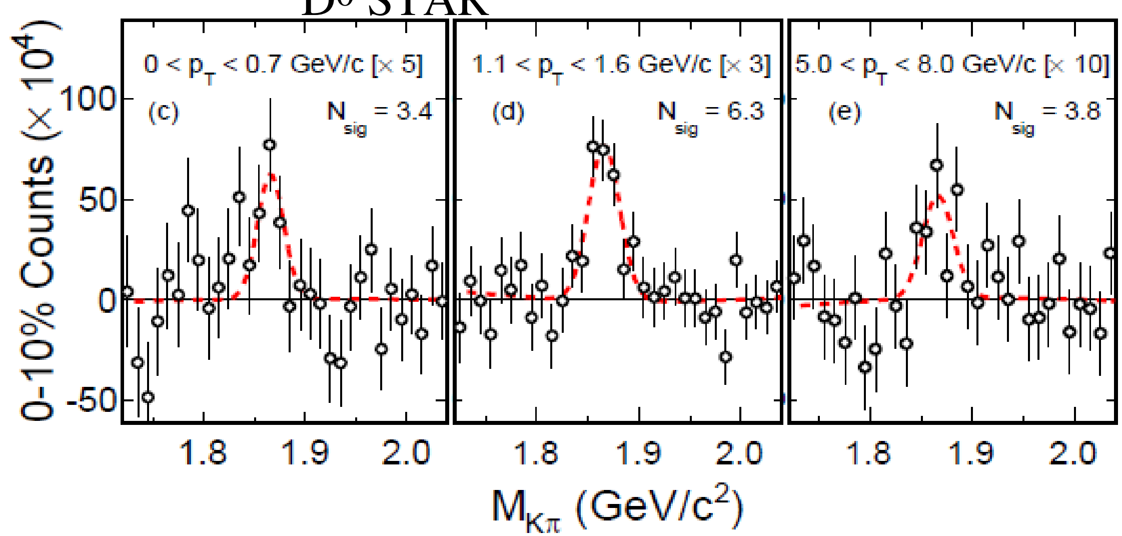
*completed

Particle identification is a key tool





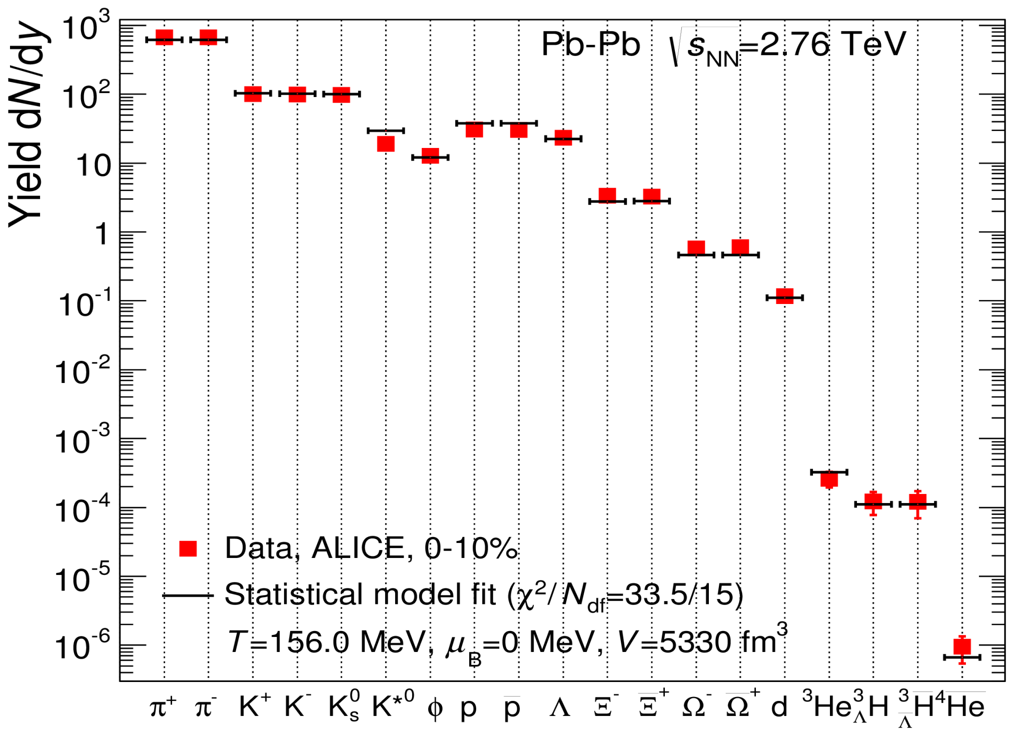
D⁰ STAR

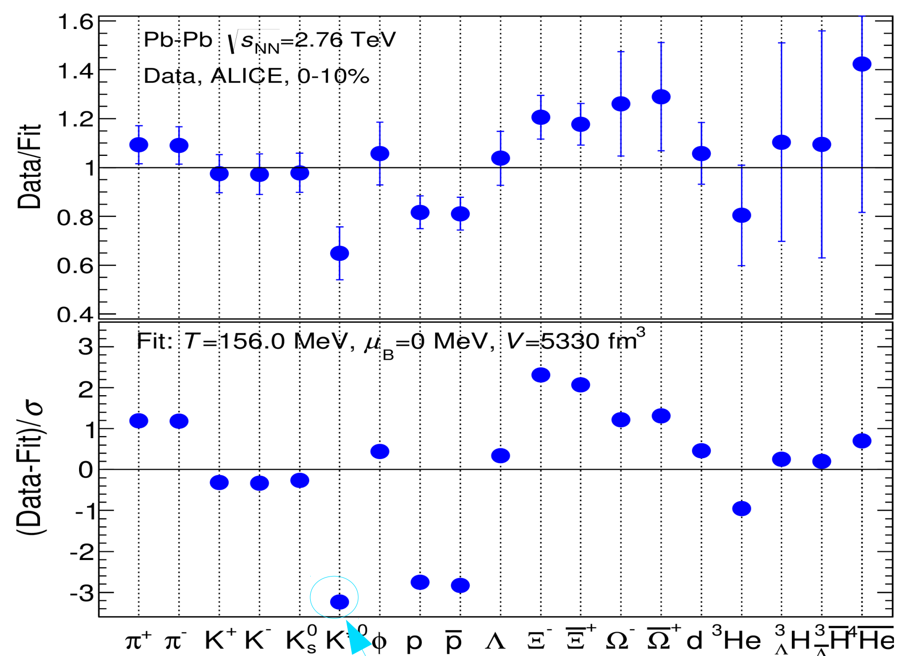


specific ionization in TPCs and silicon
time-of-flight
transition radiation
RICHes
reconstruction m_{inv} from decay products

Production of hadrons and nuclei at LHC

model: J.S., A. Andronic, P. Braun-Munzinger, K. Redlich, arXiv: 1311.4662



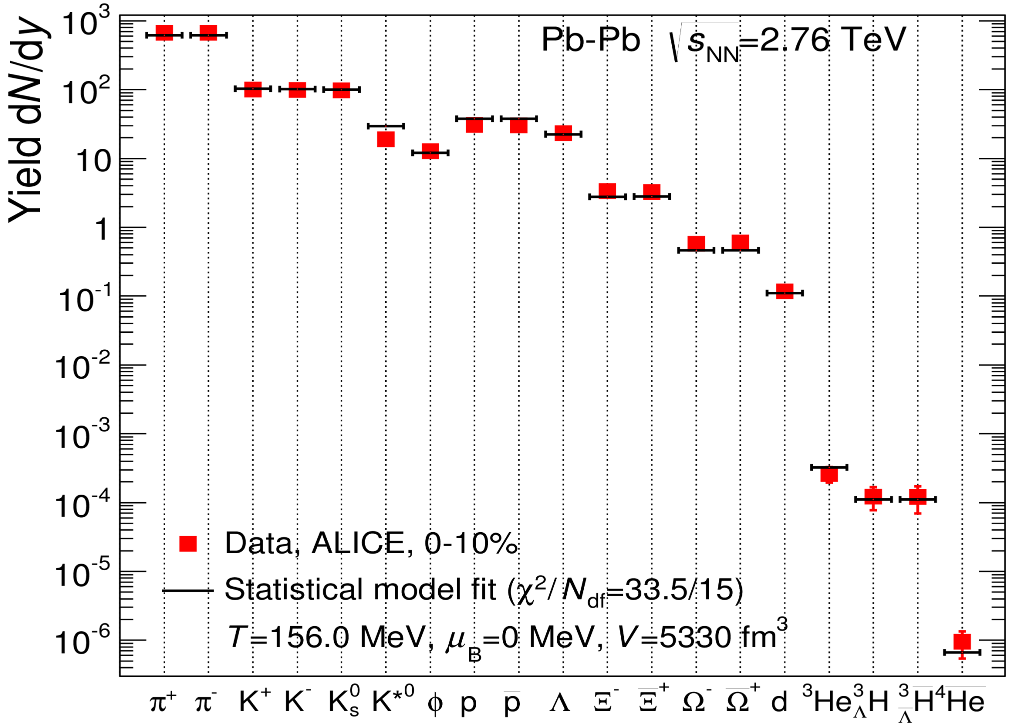


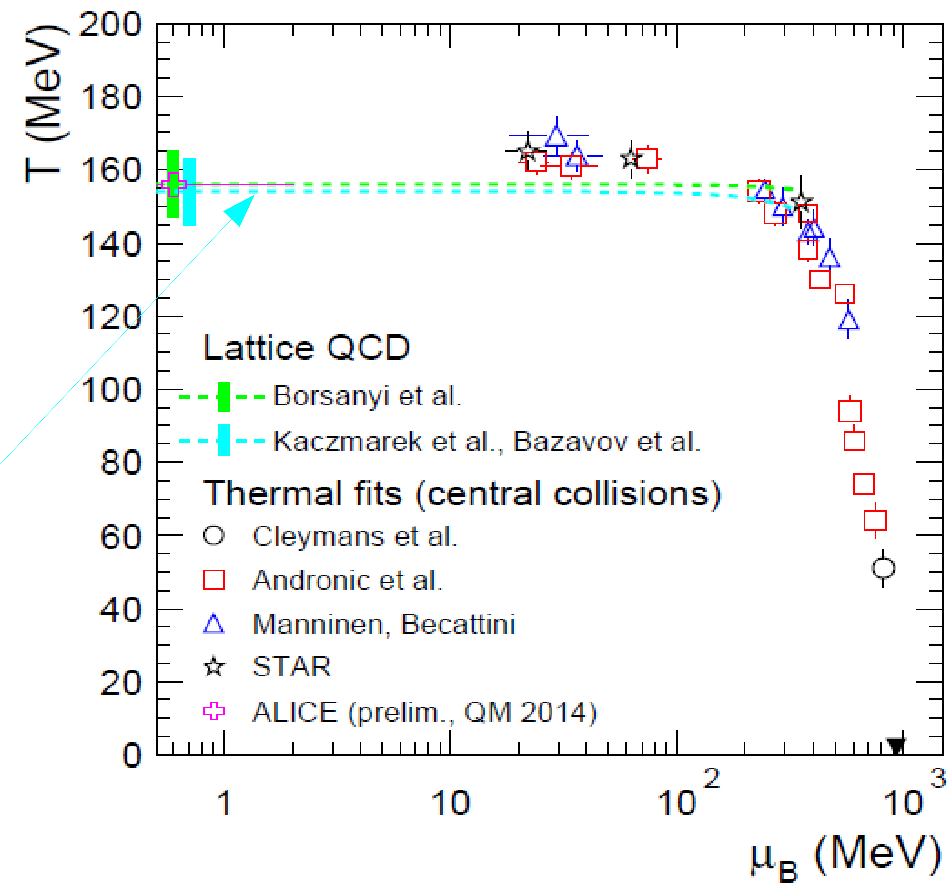
strongly decaying resonance, not included in fit

statistical model of hadronization employing full QCD statistical operator (partition function) reproduces hadron and nuclei yields over 9 orders of magnitude

protons 2.7 sigma low – is it an indication of incompletely know baryon spectrum?

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

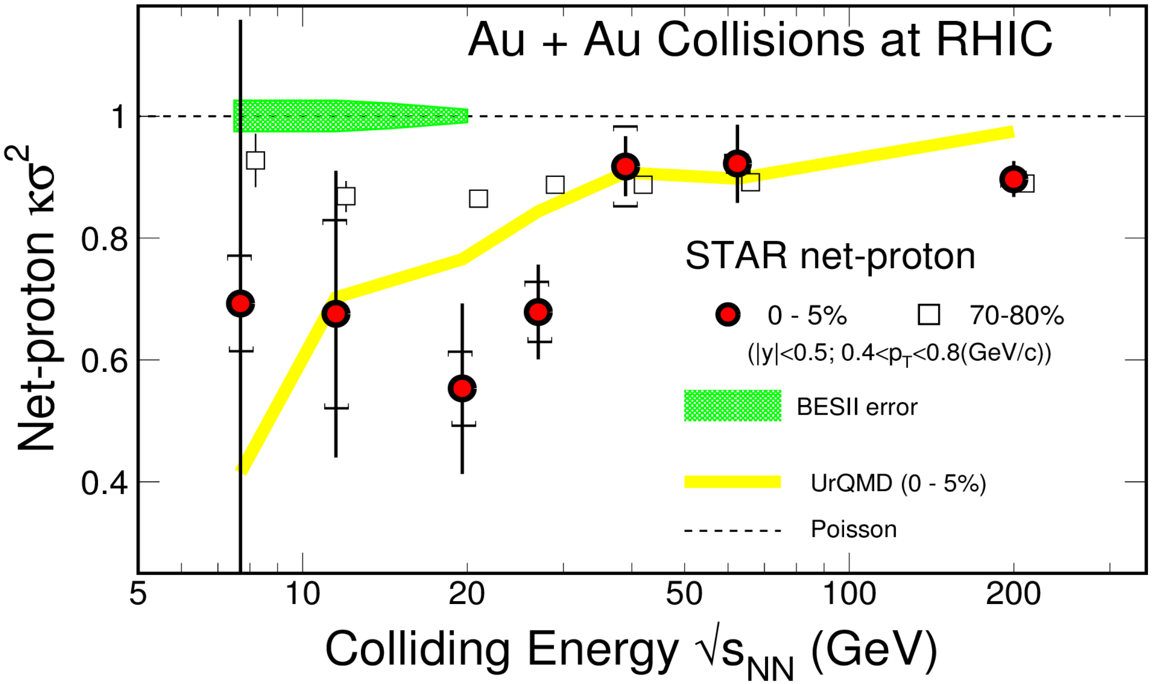
$T = 156$ MeV and $\mu_b < 1$ MeV, very close to predictions from lattice QCD for T_c

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

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

Fluctuations in net baryon number

Phys. Rev. Lett. 112 (2014) 32302



moments of (p-pbar) distribution can be linked to quark number susceptibilities from lattice QCD

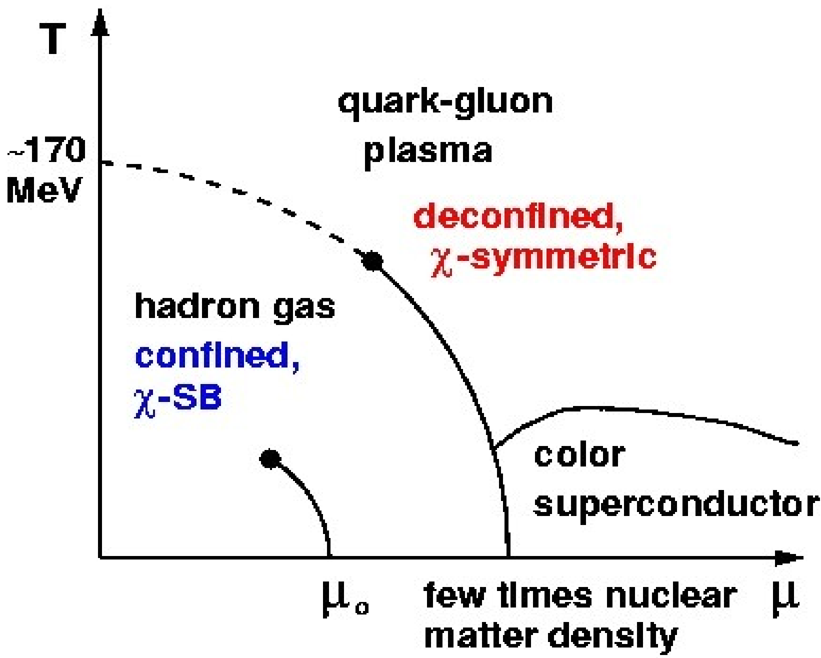
$$\text{variance}: \sigma^2 = \chi_2$$

$$\text{kurtosis}: \kappa = \chi_4/\chi_2^2$$

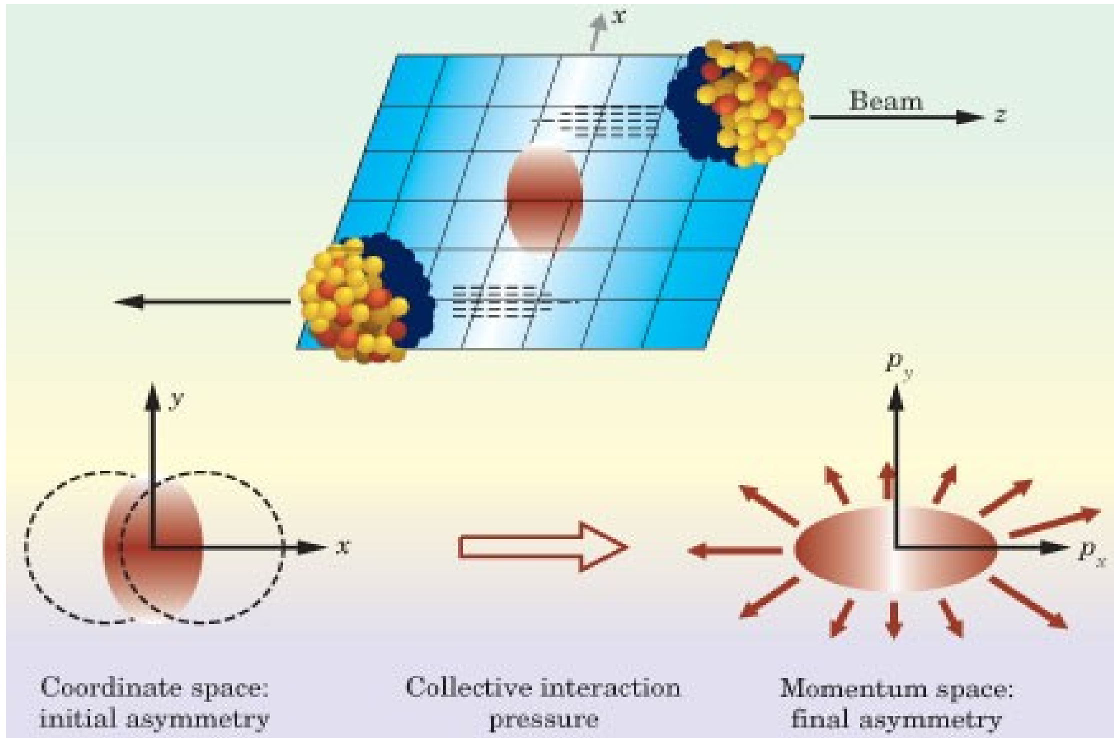
$$\kappa\sigma^2 = \chi_4/\chi_2$$

$$\chi_{lmn}^{BSQ} = \frac{\partial^{\,l+m+n} p/T^4}{\partial(\mu_B/T)^l \partial(\mu_S/T)^m \partial(\mu_Q/T)^n}$$

- in lattice QCD dip near critical point expected because χ_4 negative, χ_2 positive (preserved for chiral cross over)
- could lower point(s) near 20 GeV be due to fluctuations near a critical point? intriguing
- such studies will be priority for BES-II at RHIC



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

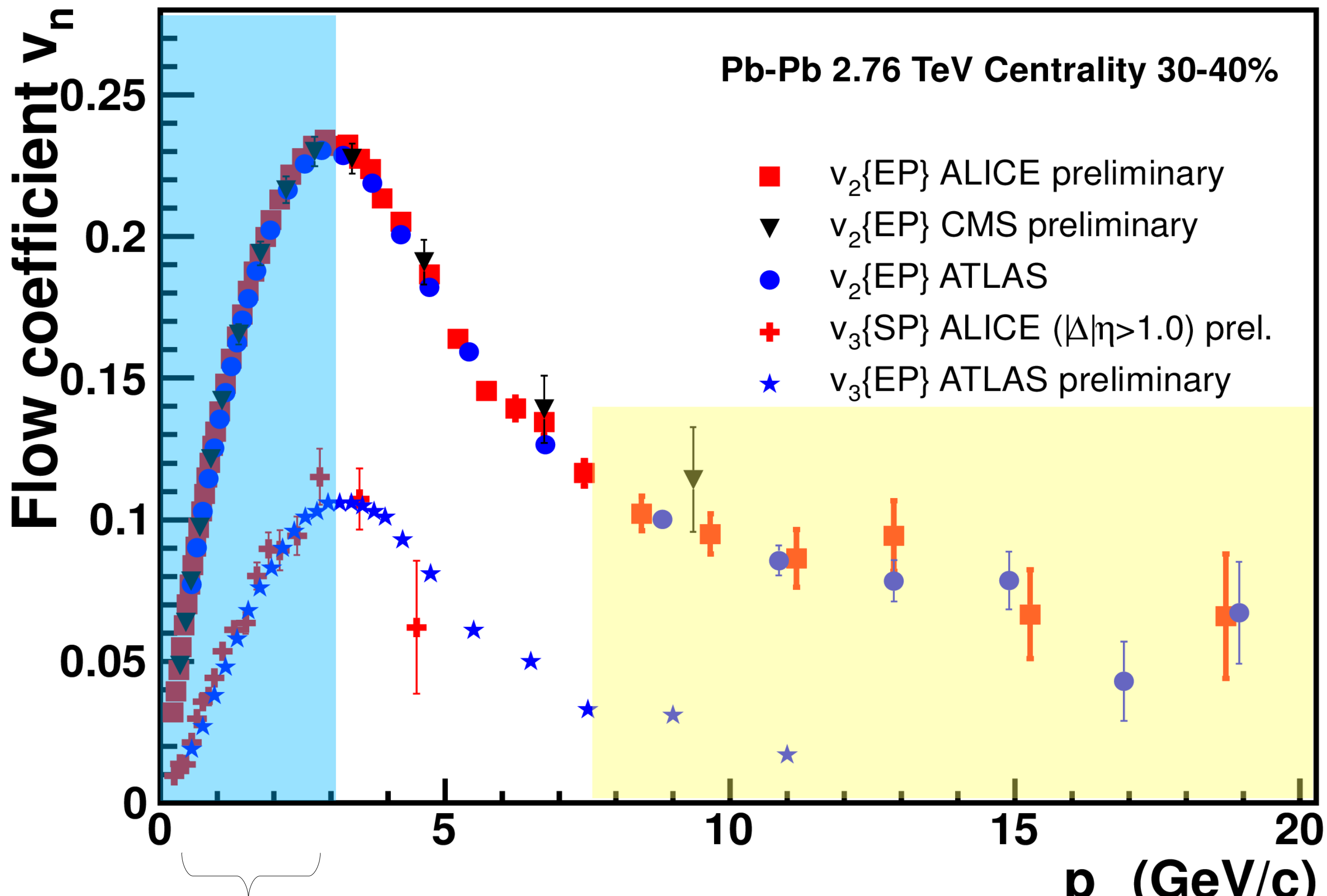
"elliptic flow"

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



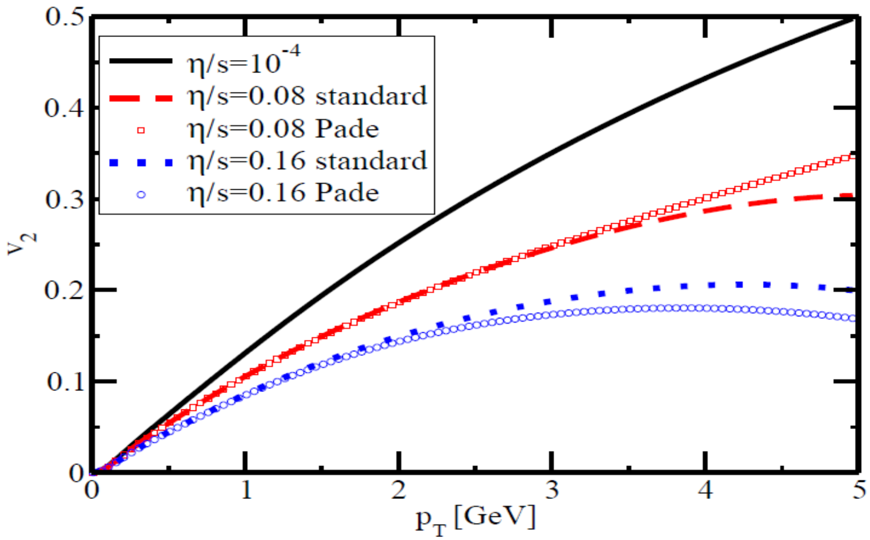
elliptic flow (v_2) as function of p_t :
- excellent agreement between all 3 LHC experiments
- same for v_3

hydrodynamic regime
v_2 driven by pressure gradient

jet fragmentation regime
v_2 driven by energy loss

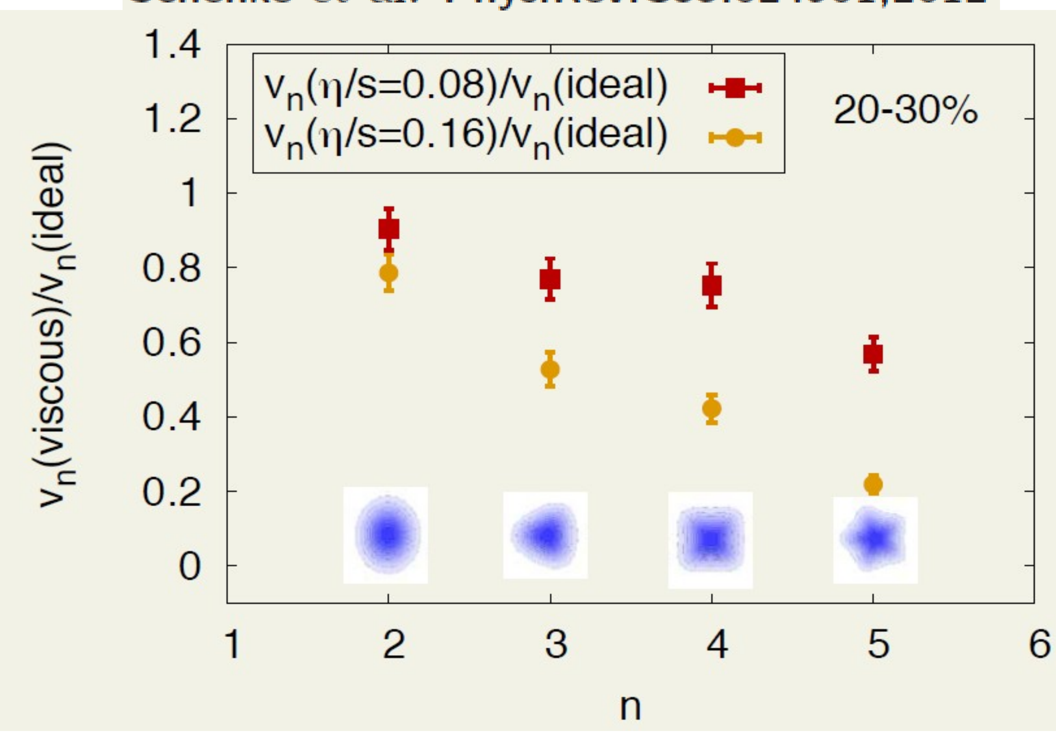
Sensitivity to viscosity of the fluid

Luzum, Romatschke PRC 78 (2008) 034915



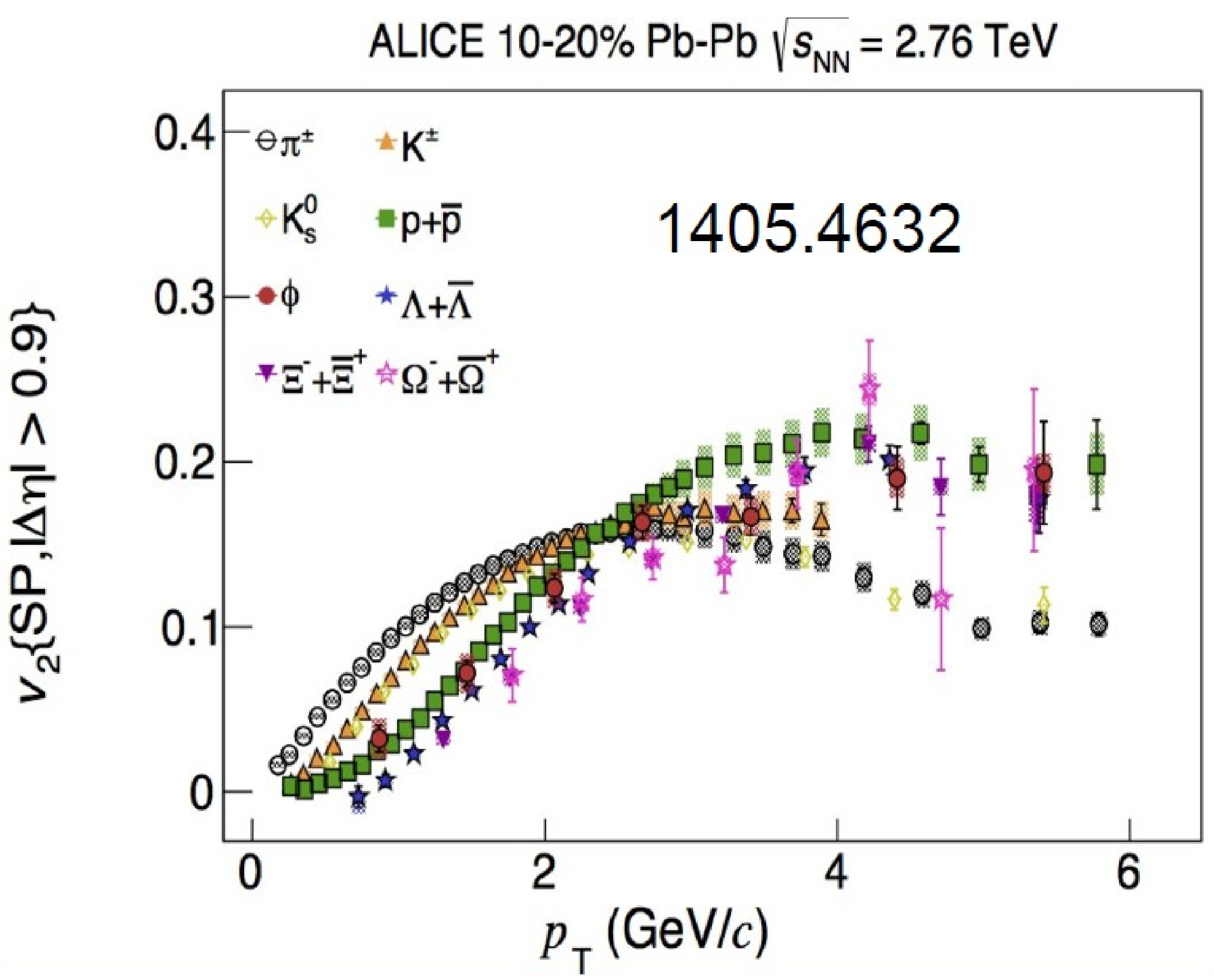
in hydro regime v_2 driven by initial condition and properties of the liquid
$\rightarrow$ ratio of viscosity to entropy density η/s

Schenke *et al.* Phys.Rev.C85:024901,2012



viscosity suppresses v_2
higher moment suppressed more strongly

Elliptic flow for identified hadrons



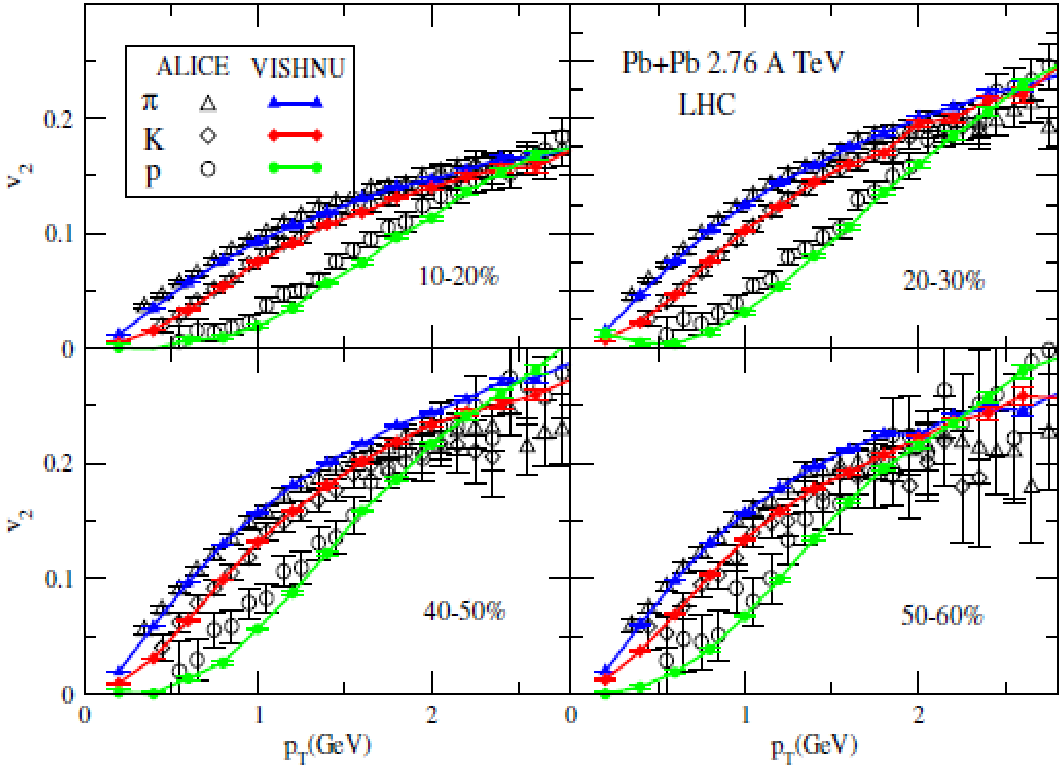
beyond v_2 for charged particles, data available for identified hadrons

- mass ordering observed
- characteristic feature of hydrodynamic expansion

Elliptic flow of identified hadrons compared to hydrodynamics

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

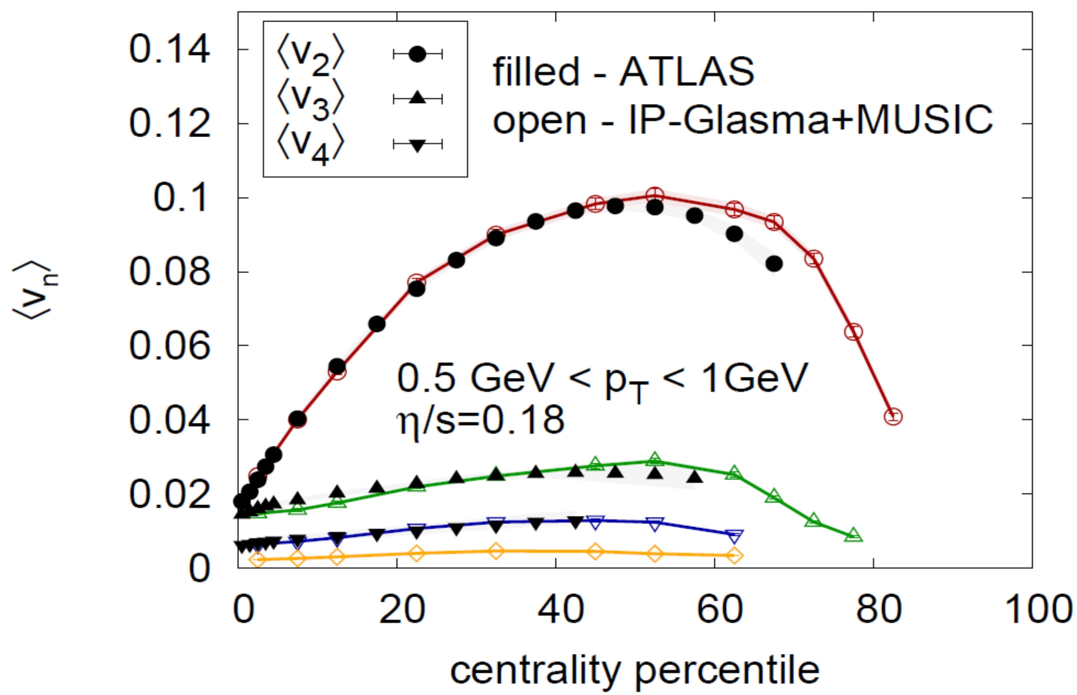
calculations: (2+1)-D hydro plus UrQMD (VISHNU)
H. Song, S. Bass and U. W. Heinz, Phys. Rev. C **89**, 034919 (2014)



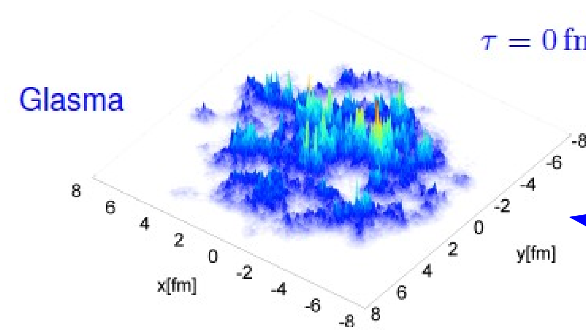
mass dependence is a genuine prediction of hydrodynamics
calculations with η/s = 0.20 reproduce data very well
but: uncertainty due to initial condition
color glass initial condition ↔ Glauber
η/s = 0.20 ↔ 0.08

Higher flow harmonics and their fluctuations

data: ATLAS JHEP 1311 (2013) 183
calc: B. Schenke, R. Venugopalan, Phys. Rev. Lett. 113 (2014) 102301

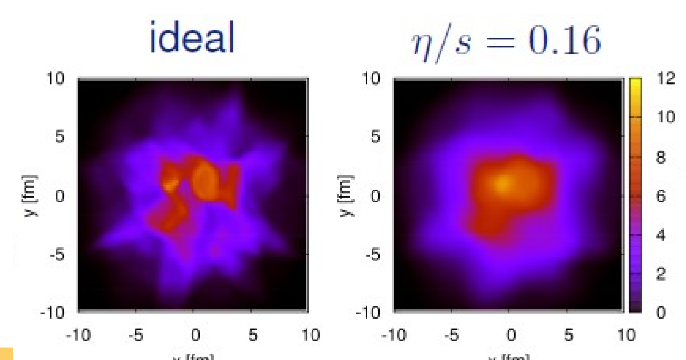


ratios of v_2/v_n and their fluctuations depend on initial condition



initial

final



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

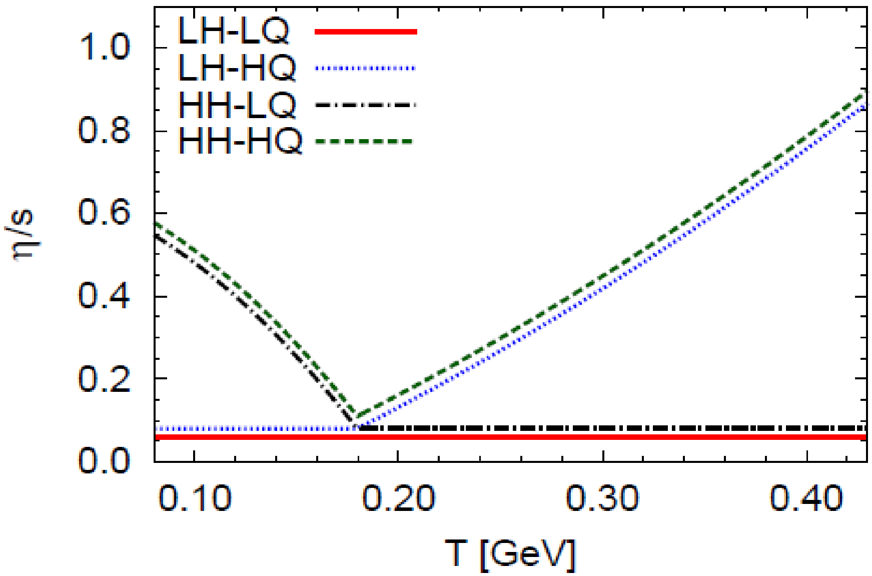
for LHC η/s = 0.18 for RHIC η/s = 0.12

indication of temperature dependence of η/s?

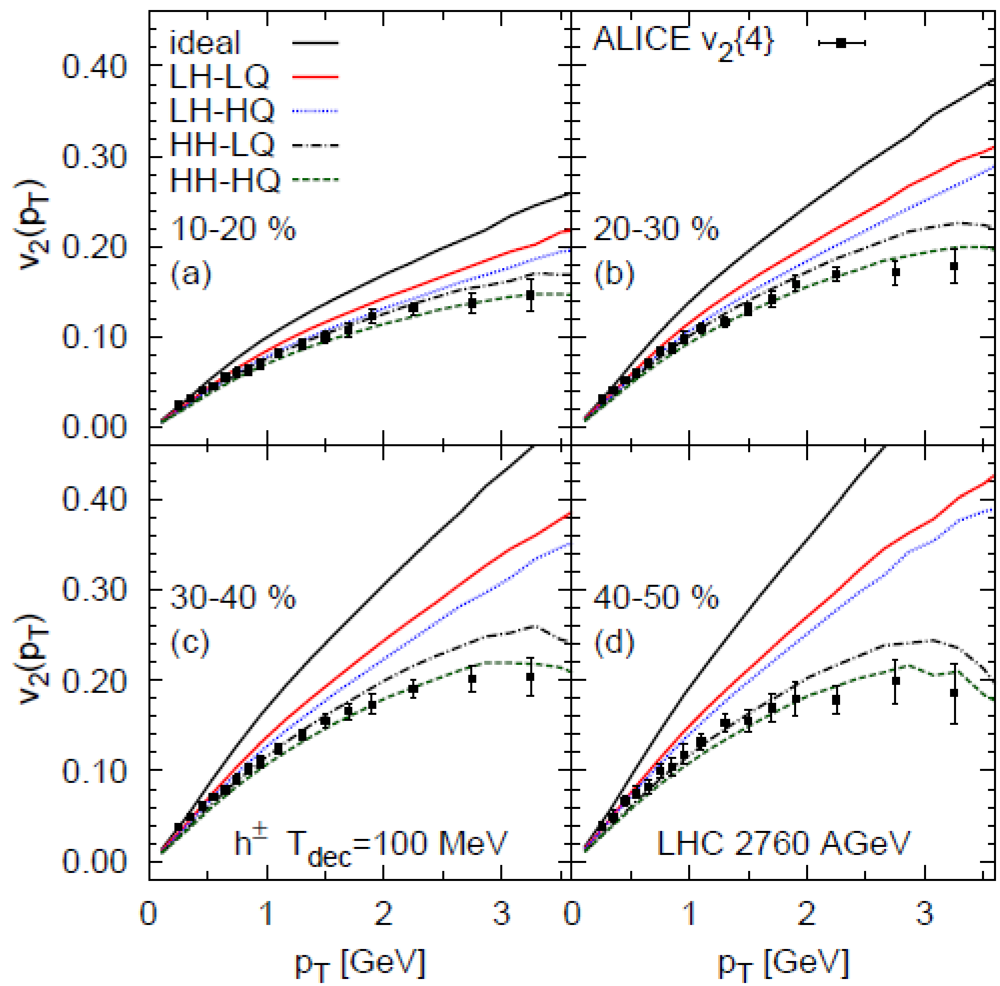
Sensitivity of temperature dependence of eta/s

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

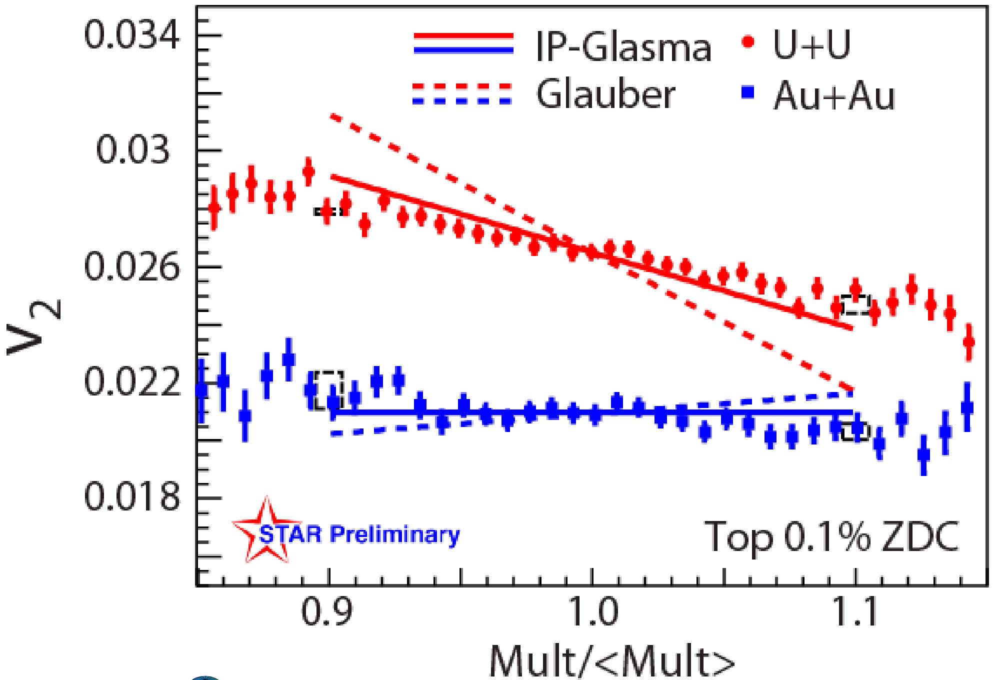
v_2, v_4, as function of rapidity and p_t

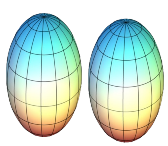
fix hadron gas η/s(T) with RHIC data

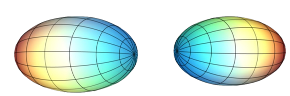
then proceed to extract η/s(T) for QGP with LHC data as well as minimal value

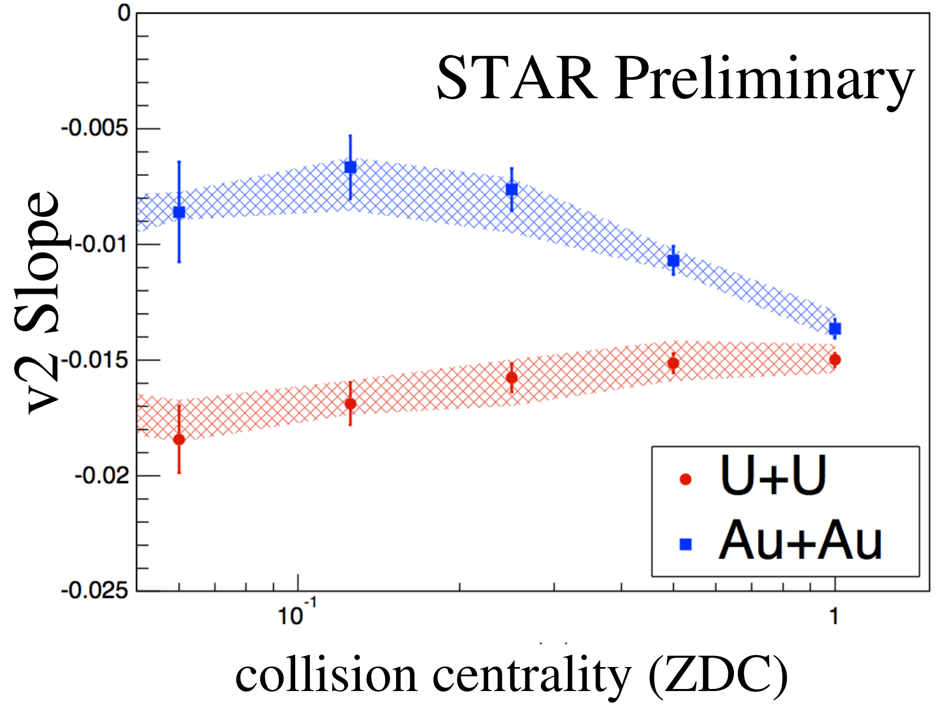
Shape and orientation of colliding nuclei - U+U collisions

Hui Wang (for the STAR Collaboration) Quark Matter 2014



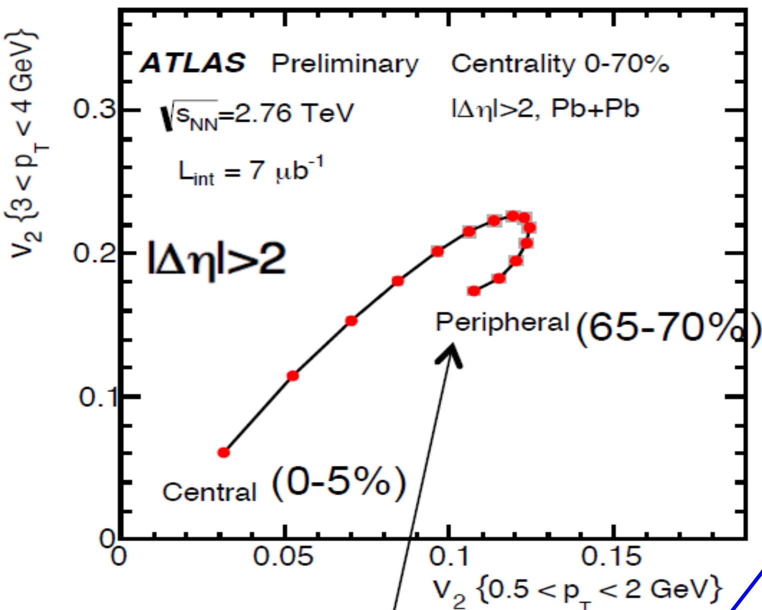




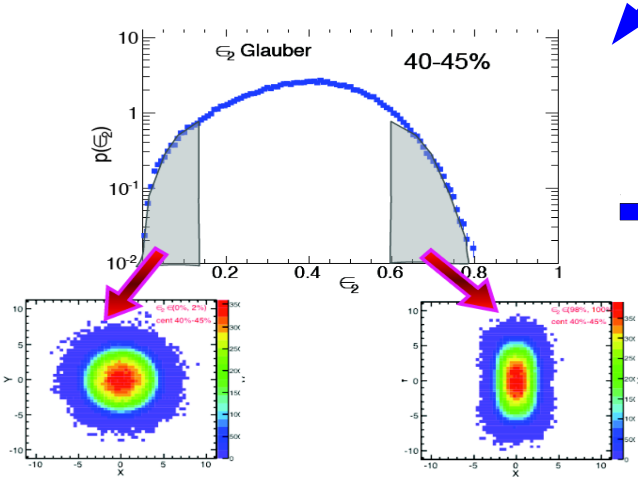


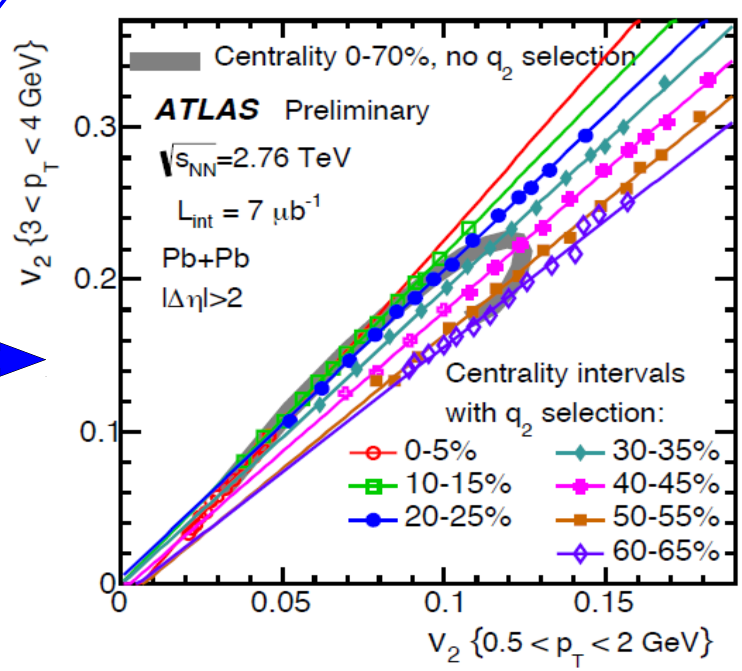
- for tip-on-tip collisions expect 20% increase in energy density
- selection of near-complete overlap via (absence of) forward neutrons in ZDC, then look for highest multiplicity events
- reveals sensitivity to initial condition - color glass initial condition (IP Glasma) ok

Does fluctuating shape of overlap region affect viscosity?



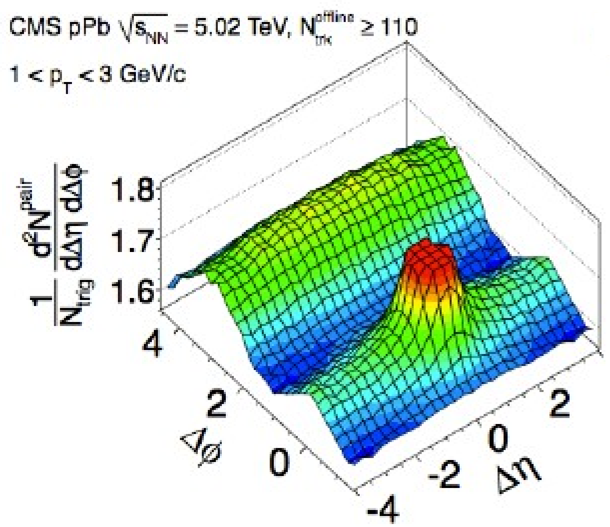
for a given collision centrality (impact parameter):
correlate v_2 for different p_t intervals
(boomerang instead of straight line due to p_t dependence of viscous effects)
then change for each centrality shape of overlap region by binning in v_2 at forward rapidity

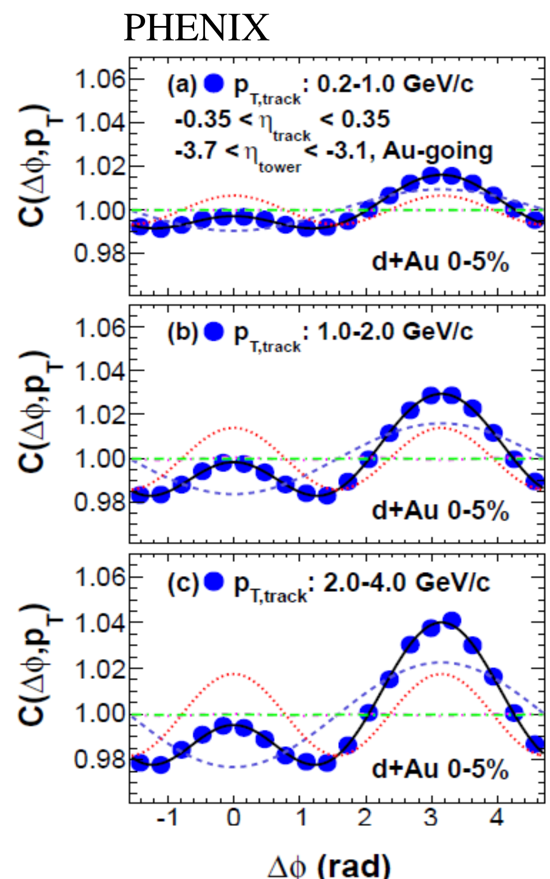


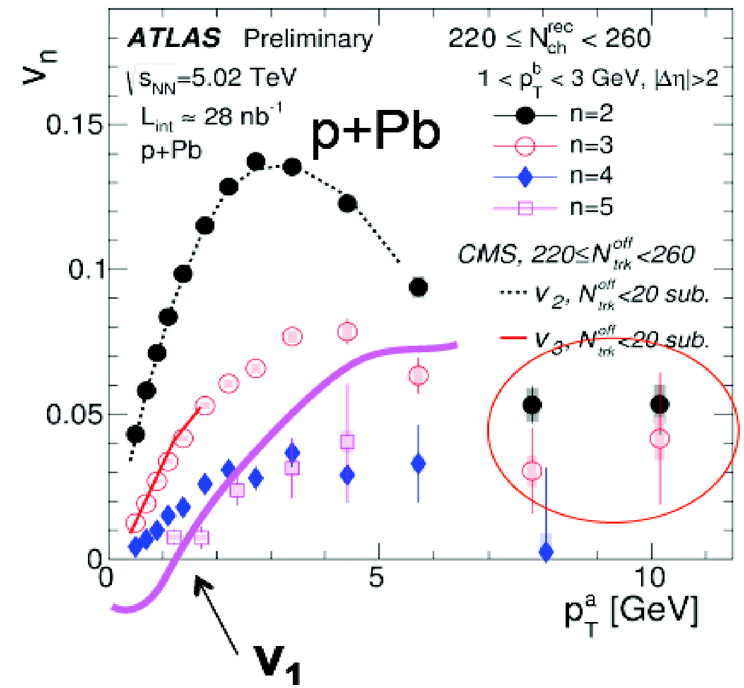


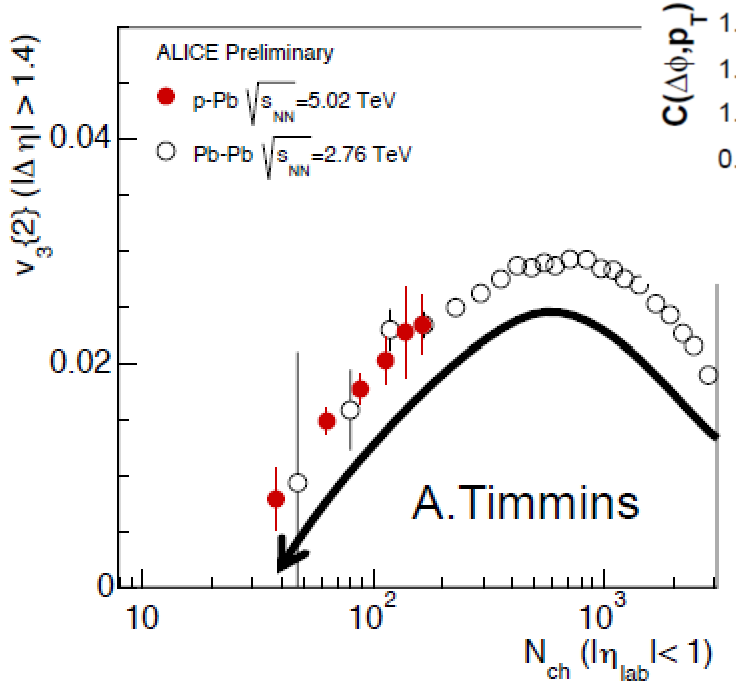
linear correlation for forward-v_2 selected bins
→ viscous damping same for all these shapes

Ridge in pPb and dAu collisions







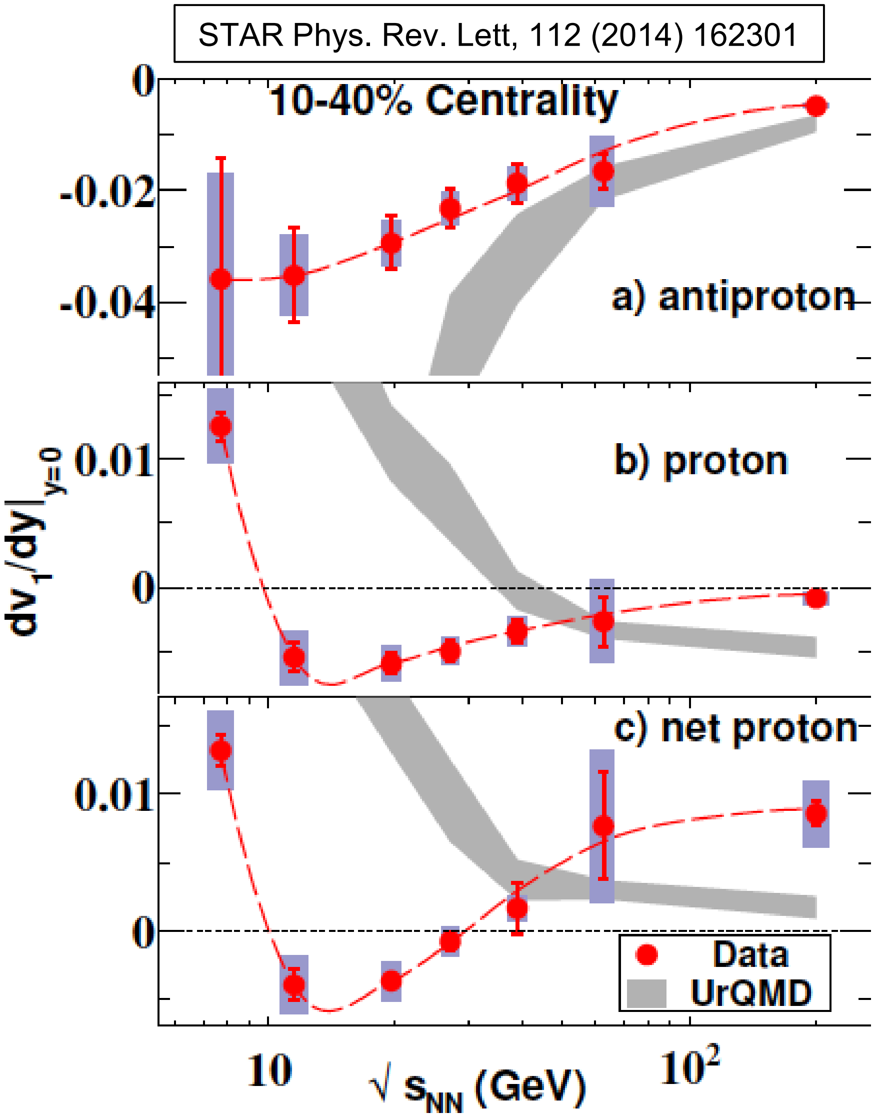


correlations are long range in rapidity, causality demands they must them from early times

initial fluctuations amplified by collective expansion?

qualitatively similar features observed in pp and AuAu/PbPb collisions

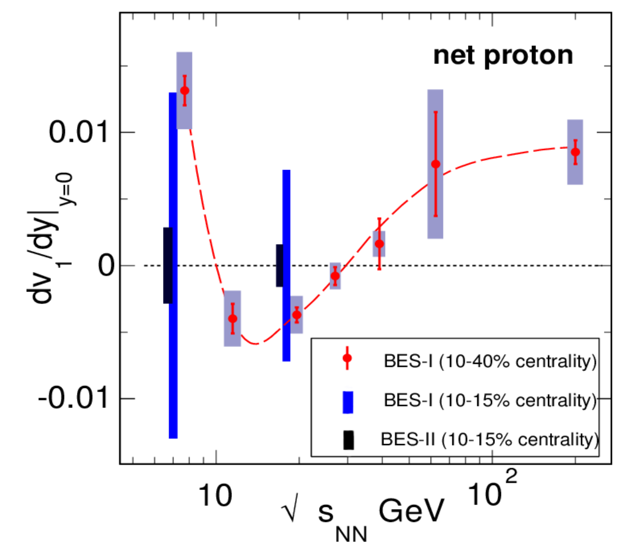
Softening of the equation of state: v_1



- v_1 (sideways kick) considered sensitive to equation of state
- a softest point (very strong minimum in v_1) predicted 20 years ago (D. Rischke et al.)
- now an effect observed for the first time, albeit much weaker

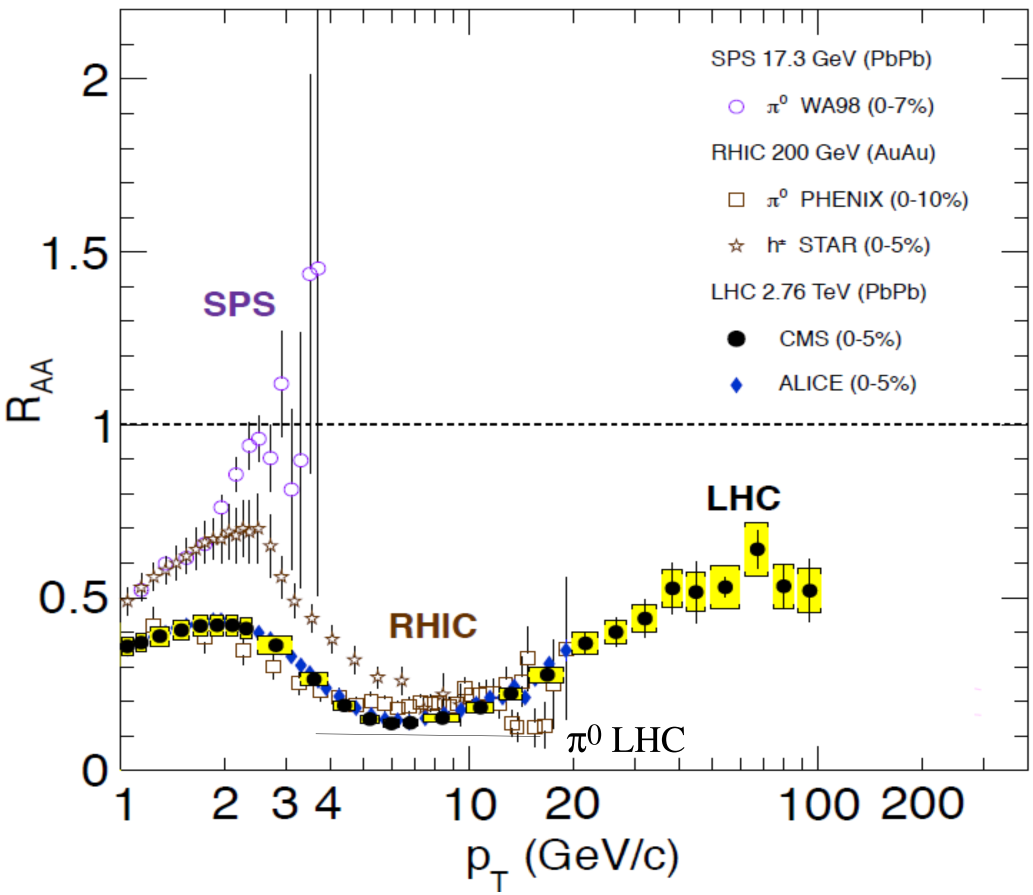
could it be a signal of a first order phase transition?

➔ study this in smaller centrality bins in BES-II



Jet quenching – parton energy loss in QGP

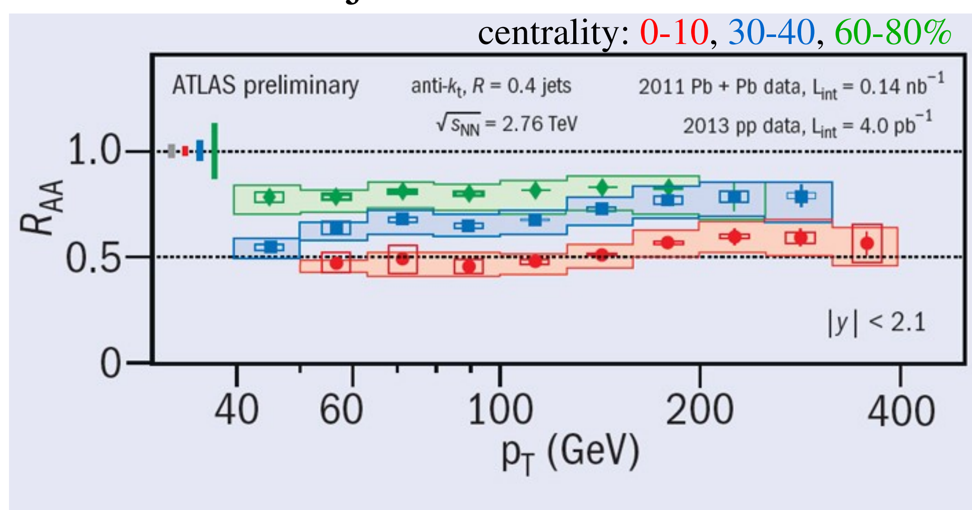
leading particles



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

- suppression of leading particles first observed at RHIC
- still stronger at LHC
- upturn beyond 7 GeV new at LHC
- levels off at 0.5

reconstructed jets



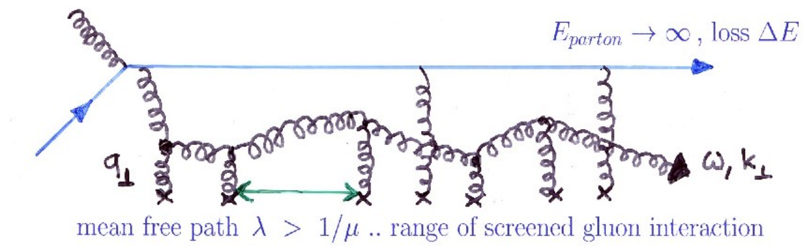
factor 2 suppression of jets up to 400 GeV!

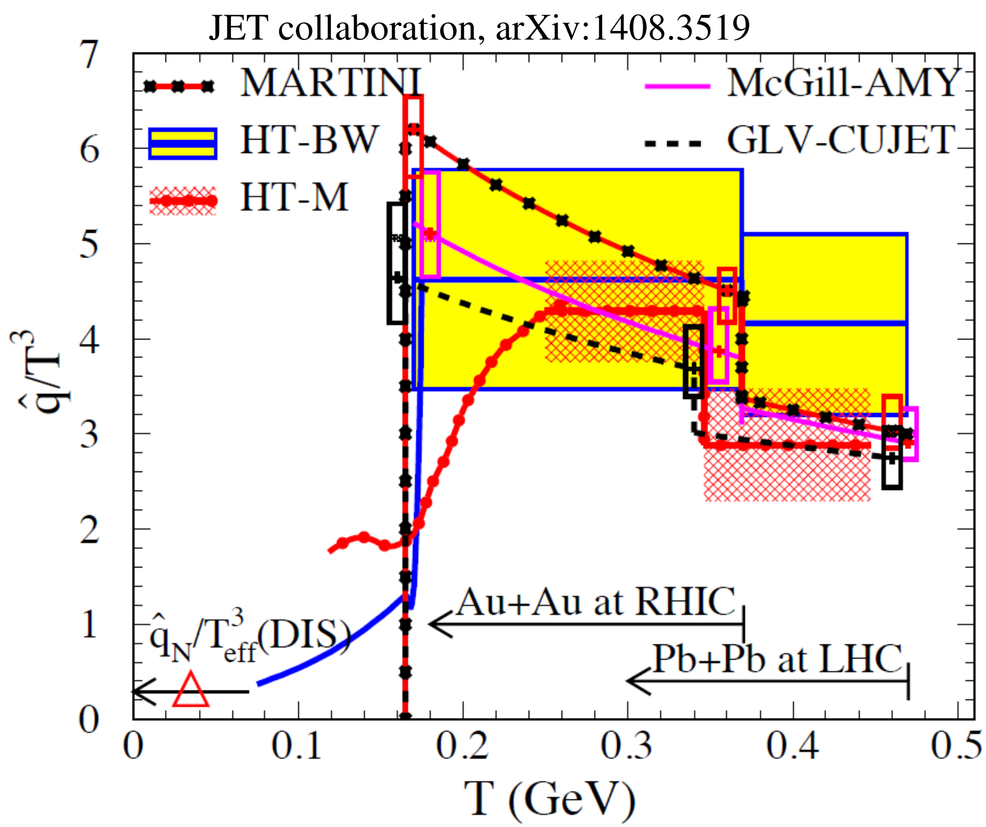
Extracting the jet quenching parameter

$dE/dx \propto \rho\, \sigma \langle k_t^2 \rangle\, L$

density of color charge carriers

transport coefficient $\hat{q} \propto \rho\, \sigma \langle k_t^2 \rangle$





determine transport coefficient from comparing transport model calculations to R_{AA} data

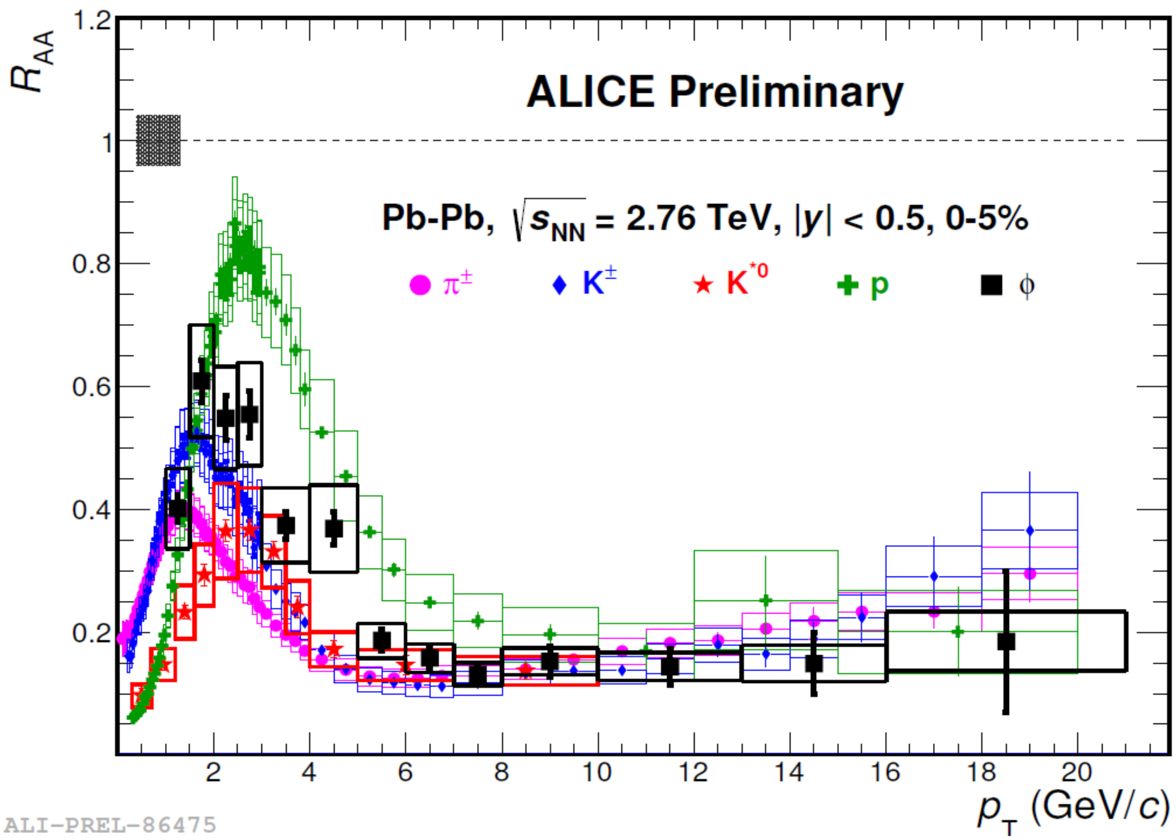
at center of nuclear fireball at τ_0=0.6 fm/c

obtain for RHIC and LHC

$$\hat{q} = \begin{array}{ll} 1.2\pm0.3\ \mathrm{GeV^2/fm} & \text{at T = 370 MeV} \\ 1.9\pm0.7\ \mathrm{GeV^2/fm} & \text{470 MeV} \end{array}$$

2 orders of magnitude larger than in nuclear matter (from DIS)!

Suppression of identified hadrons

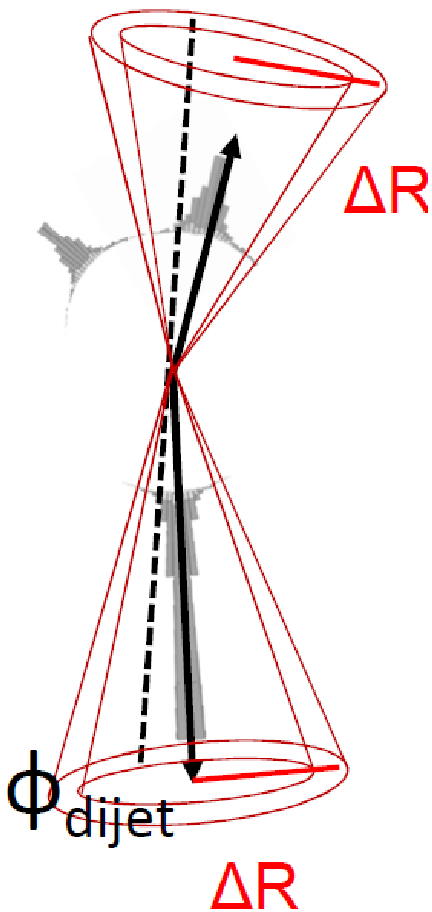


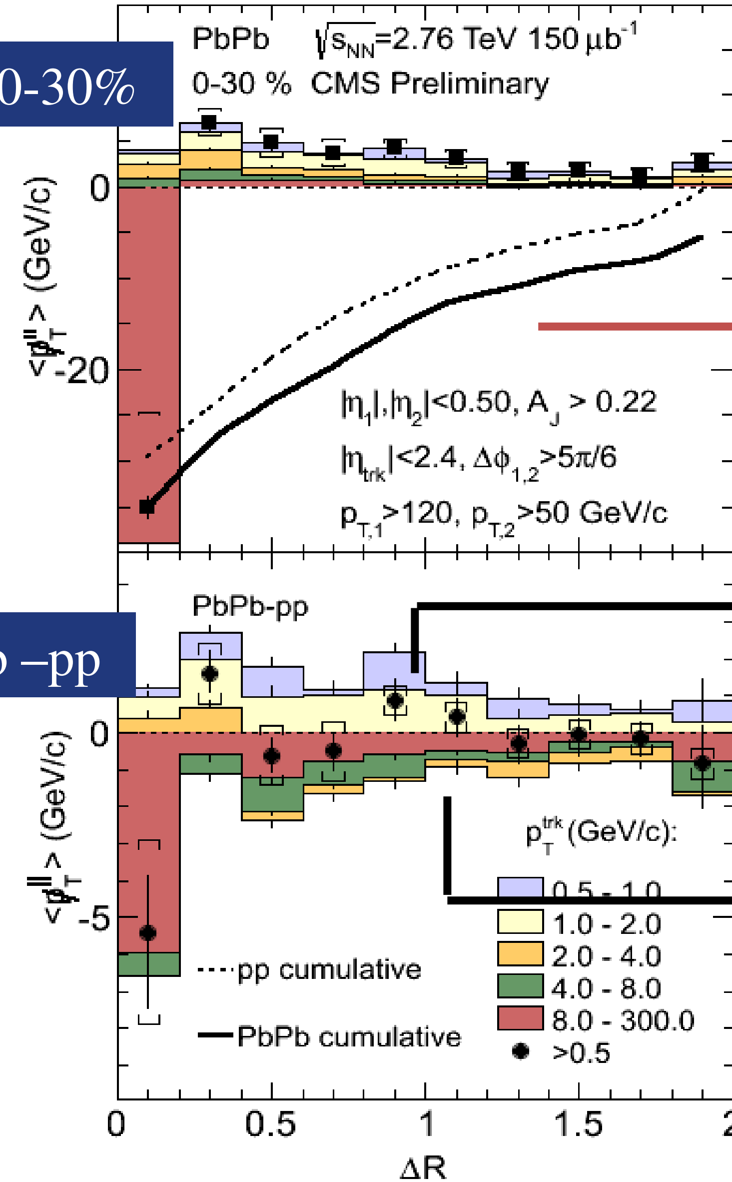
all converge at high p_t (within current errors)
in few GeV range see radial flow (expansion velocity) effects

Jet quenching: where does lost energy go?

PbPb 0-30%

PbPb –pp





asymmetric dijet
$A_J > 0.22$

measurement of the radiated energy up to ΔR=2.0 !

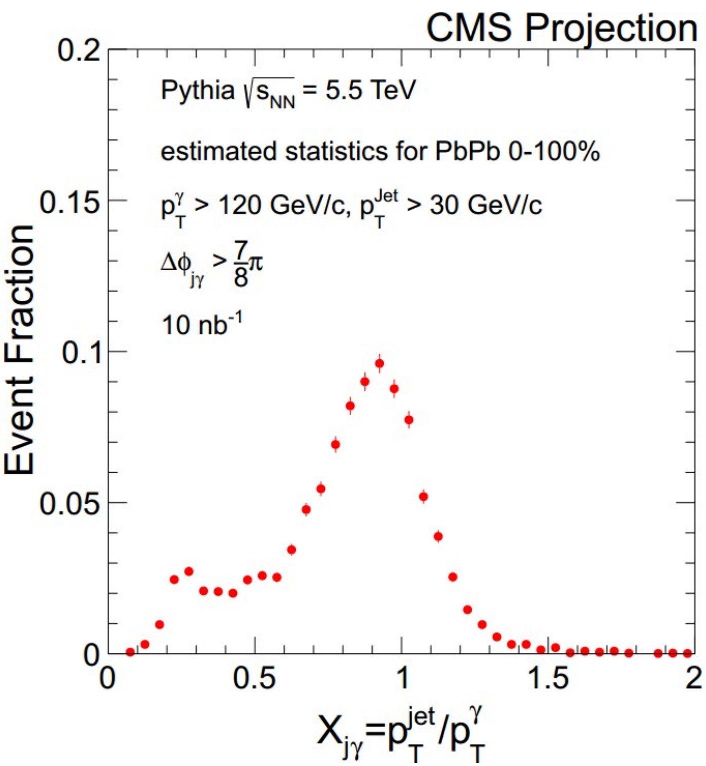
enhancement of low p_t particles in PbPb

out of cone radiation is carried by a third jet in pp

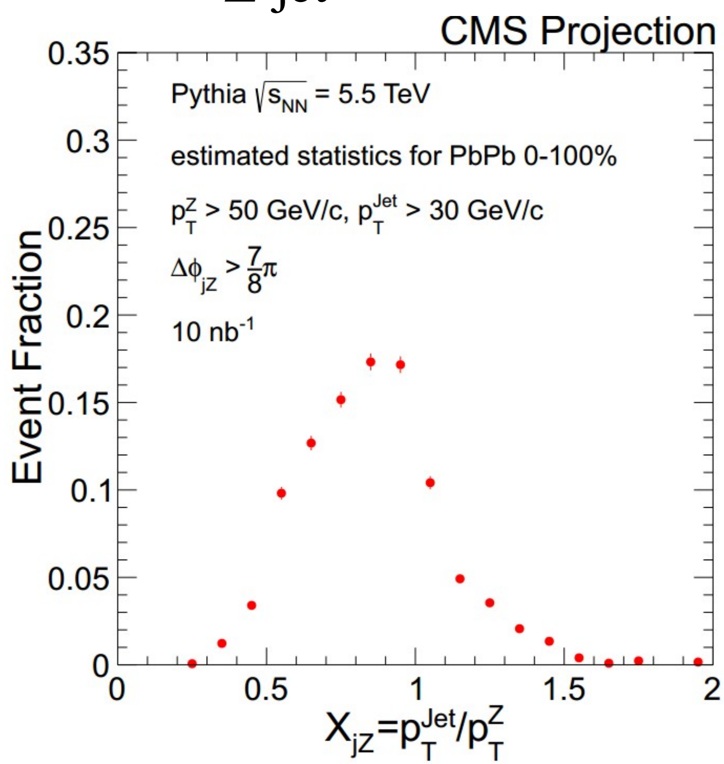
CMS-PAS-HIN-14-010

CMS prospects for Run2/Run3

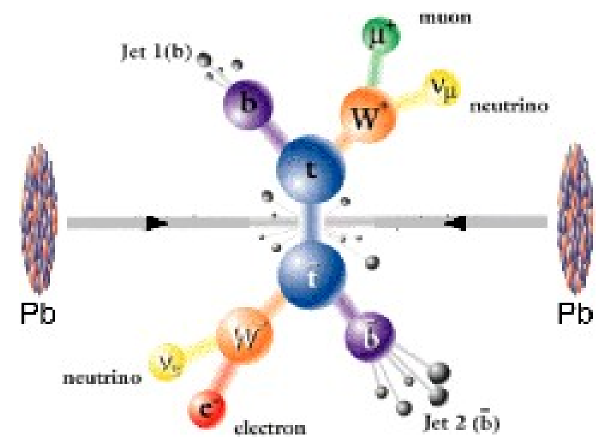
photon-jet



Z-jet



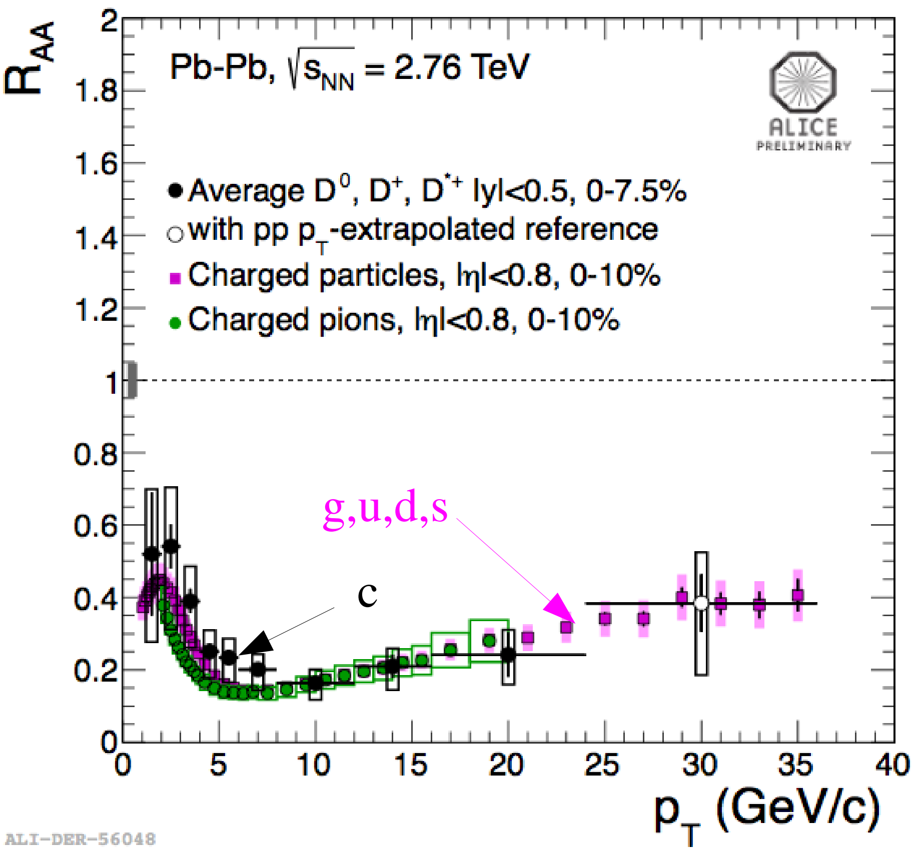
top production

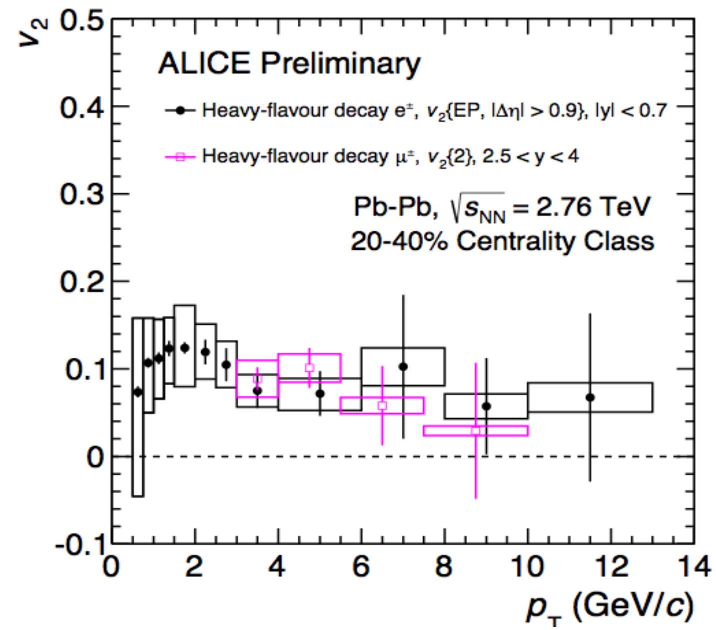


upgraded Level 1 trigger system for jet triggers
high statistics photon-jet, Z-jet measurements
first measurement of top production in PbPb collisions

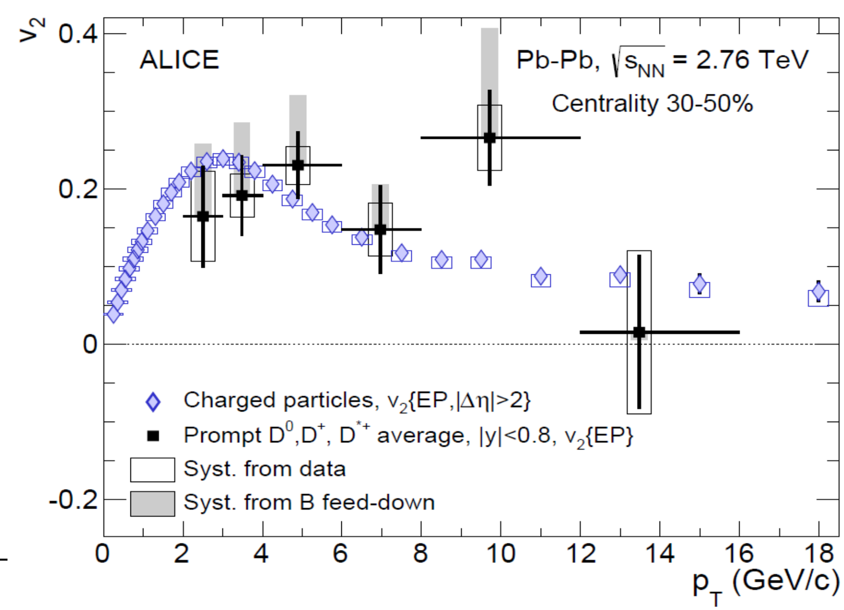
Charm quarks thermalize to large degree in QGP

strong energy loss of charm quarks





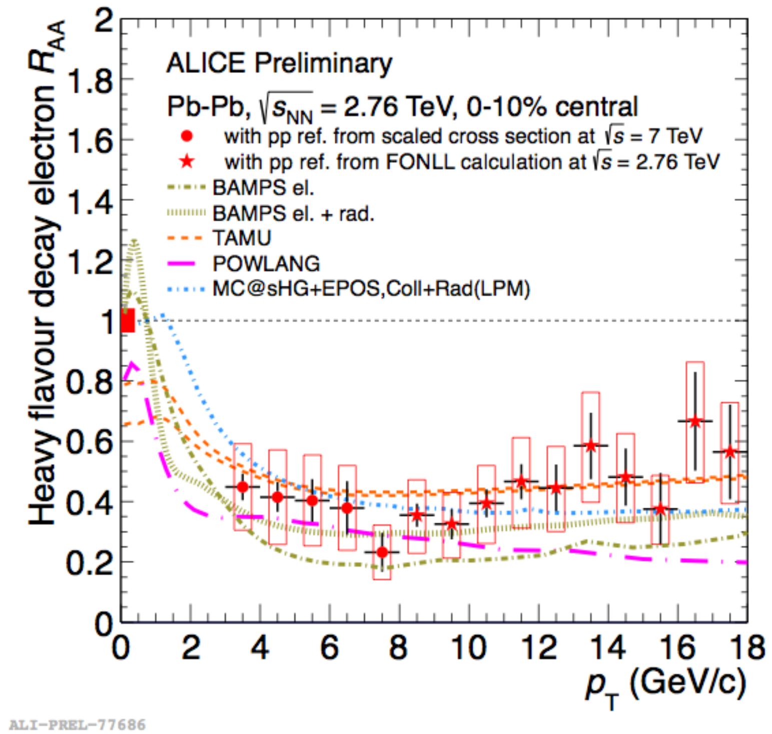
elliptic flow for charm – participation in coll. flow

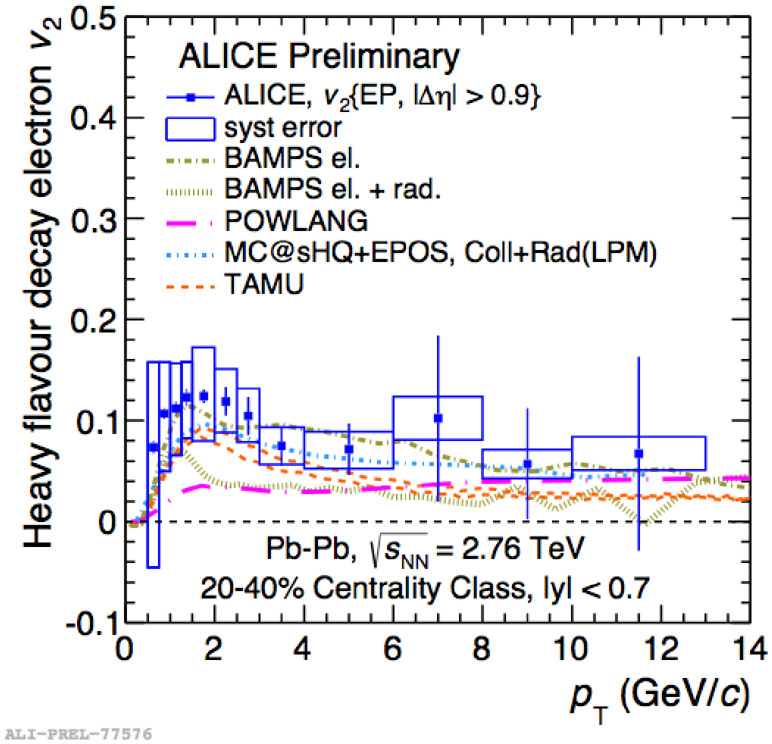


Phys. Rev. Lett. 111 (2013) 102301

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

On the way towards transport coefficients for c-quarks





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

Energy loss and flow of charm quarks at RHIC energy

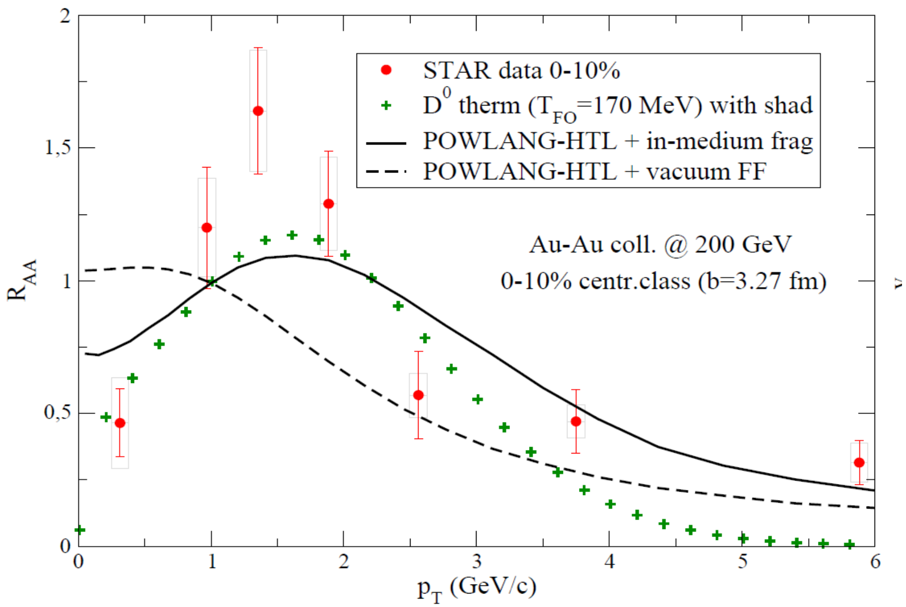
STAR D^0 production in $\sqrt{s_{NN}}$=200 GeV AuAu

PRL 113 (2014) 142301

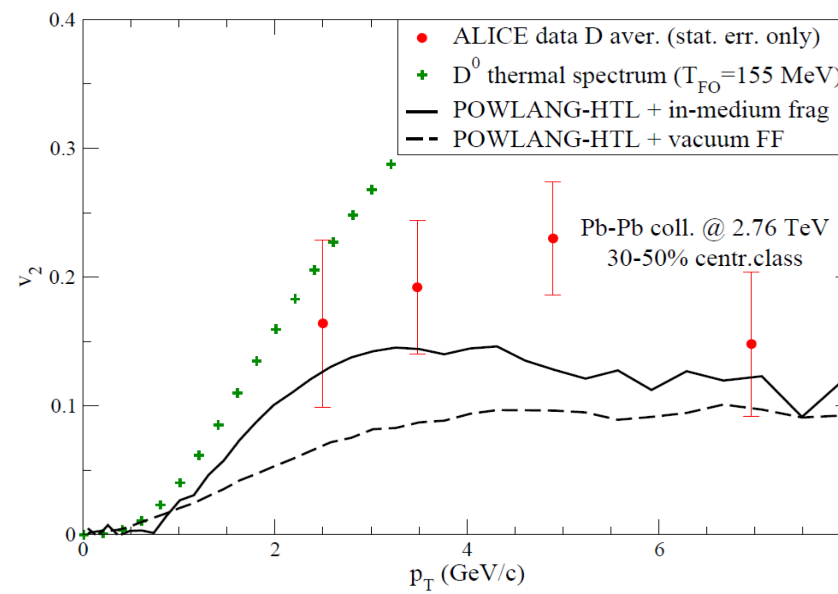
! measurement down to p_t close to 0 !

calc: A. Beraudo et al. 1407.5918, 1410.6082

calculations with charm quark energy loss in QGP using Langevin equation with weak coupling transport coefficients and hadronization in an expanding medium lead to enhancement in low p_t region



current LHC data start above 2 GeV/c
but elliptic flow of D mesons reproduced by the same approach wo new parameters

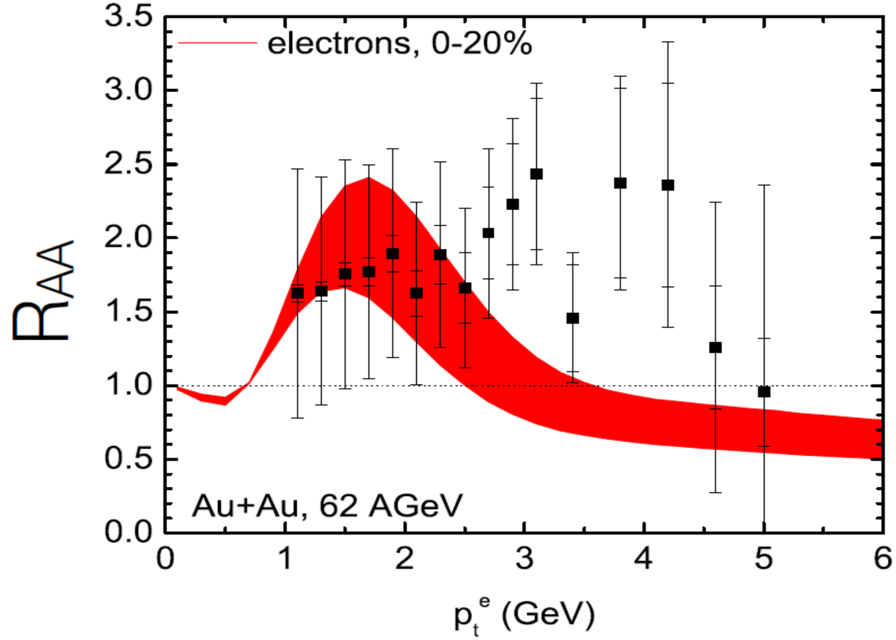


ALICE PbPb $\sqrt{s_{NN}}$=2.76 TeV D mesons

PRL 111 (2013) 102301

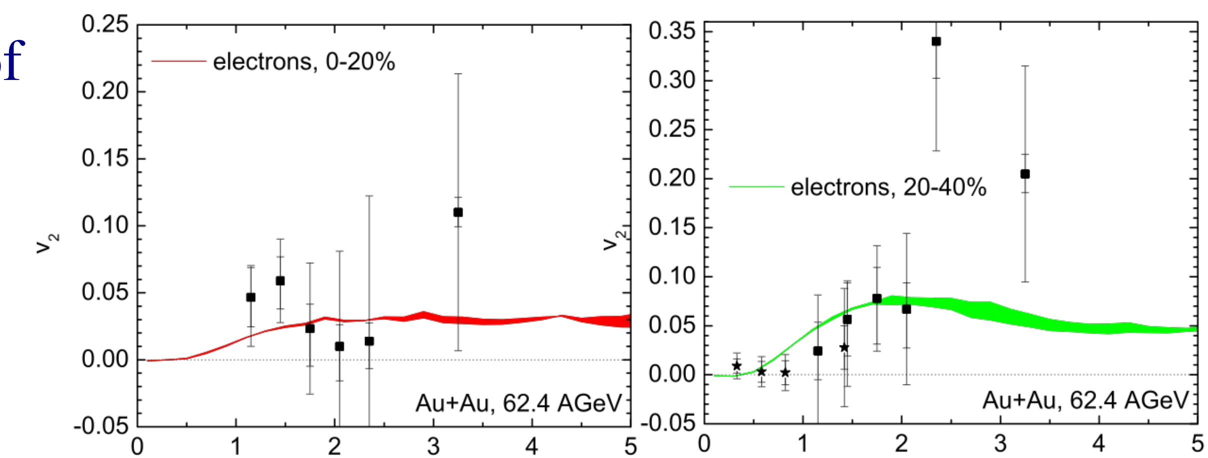
Charm measurements at even lower energy

data: PHENIX 1405.3301 calc: Rapp, Fries, He 1409.4539



- an indication of R_{AA}>1 and elliptic flow for electrons from heavy flavor decays
- do charm quarks thermalize in the medium at this low energy and get dragged along by the collective expansion?

calculations suggest that coupling of charm quark to expanding medium could be strongest near T_c
drives interest in AuAu and pp collisions at $\sqrt{s_{NN}}$ = 62 GeV for 2016 RHIC run

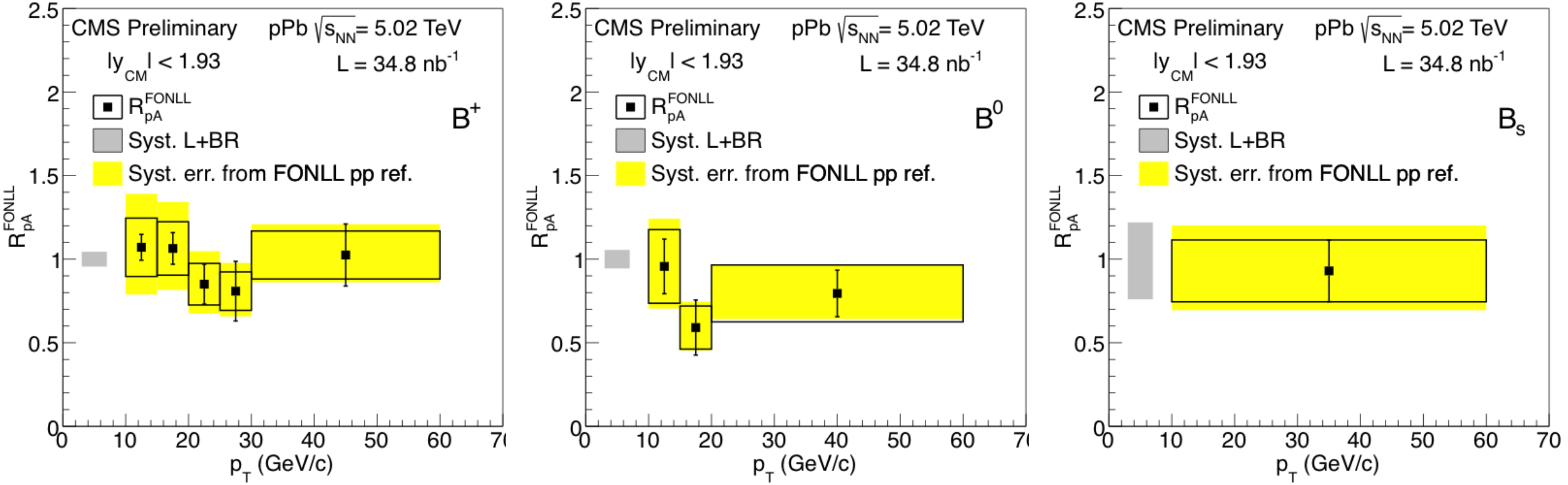


What about b-quark energy loss and thermalization?

so far in PbPb only measured in CMS via J/ψ from B-decay above 7 GeV/c

CMS recent result: first B-meson direct reconstruction in pPb collisions!

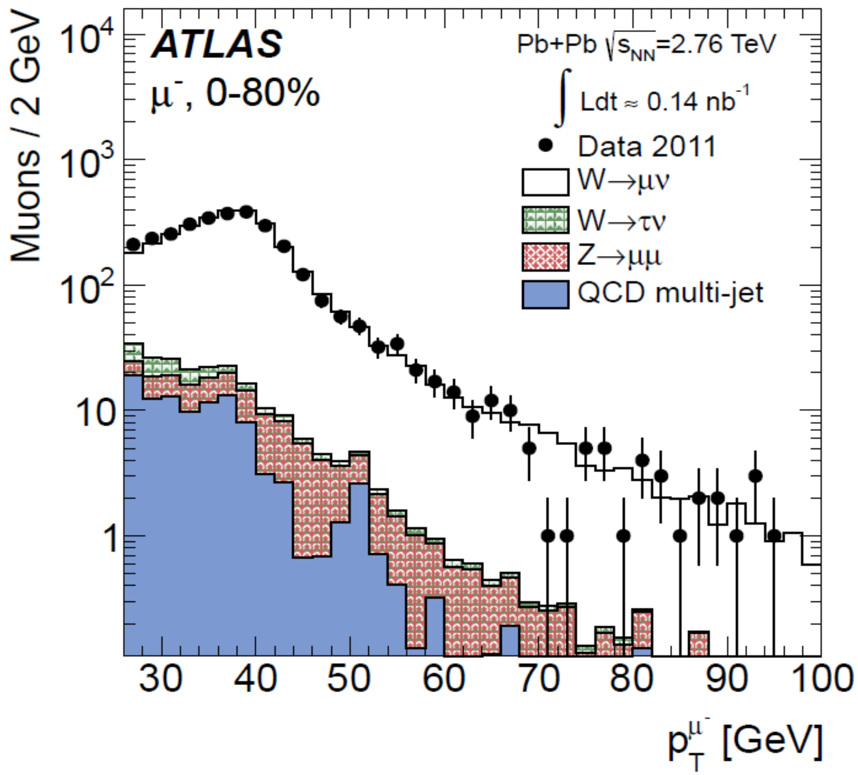
CMS-PAS-HIN-14-004

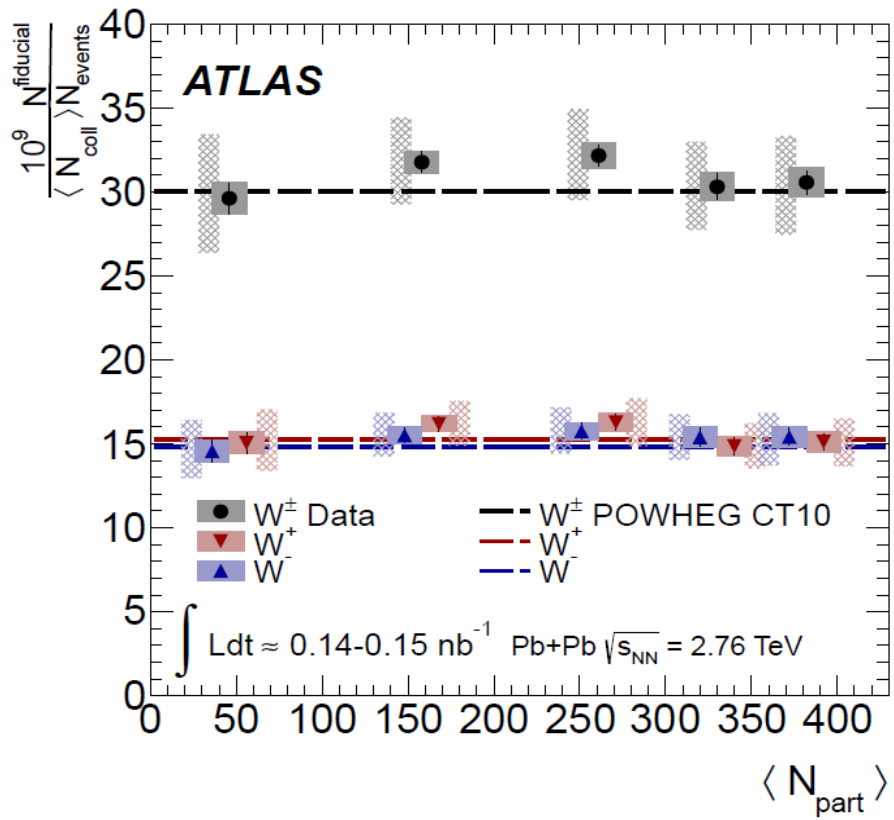


important baseline for PbPb data - to be repeated in Run2 for PbPb

W-production tests: is energy loss a QGP medium effect?

arXiv:1408.4674

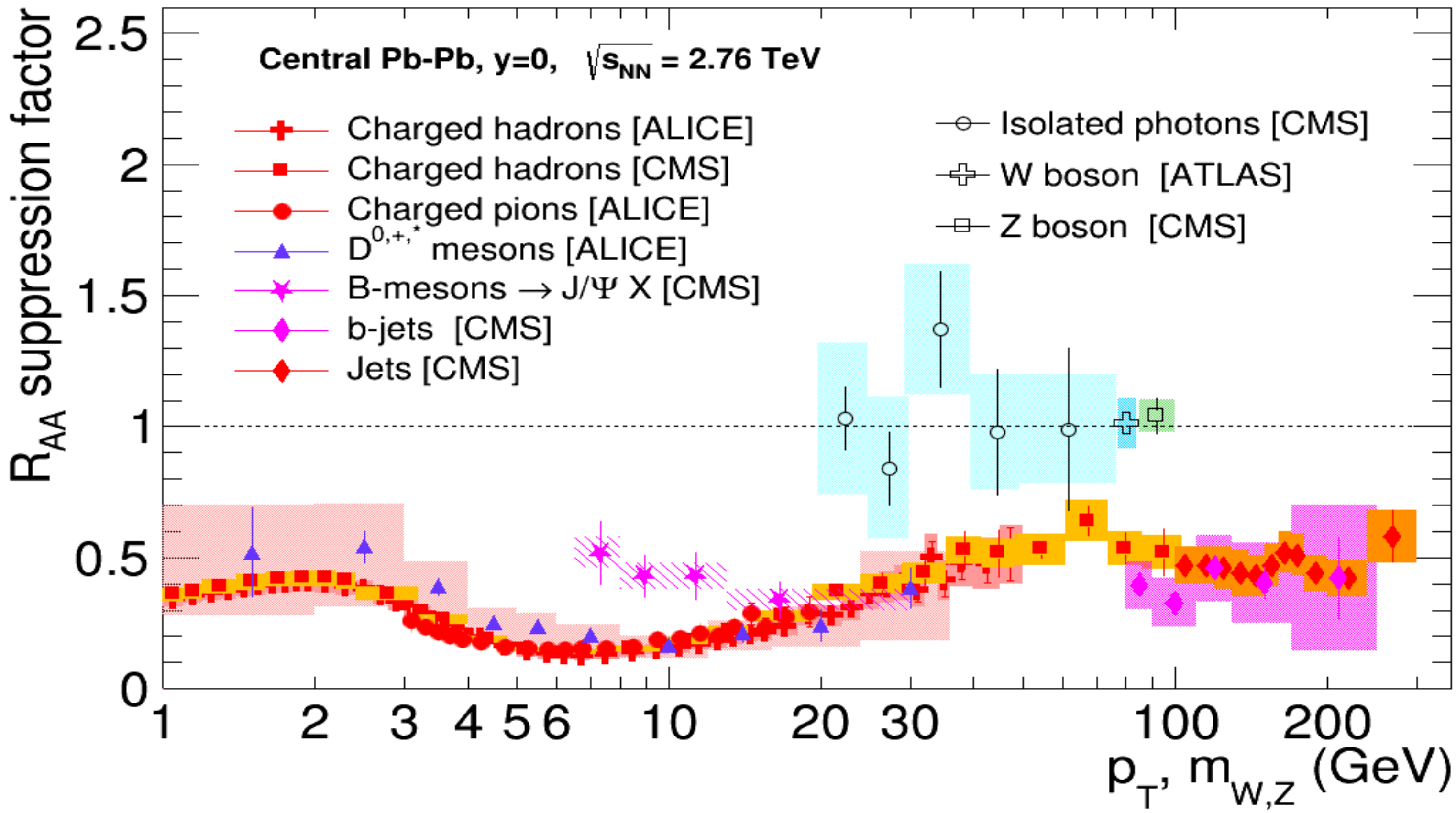




data compared to a NLO pQCD calculation: agreement at all collision centralities
more on electroweak probes to come from Run2 and Run3

Suppression only for strongly interacting hard probes

prepared by D. d'Enterria for ICFA2014



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

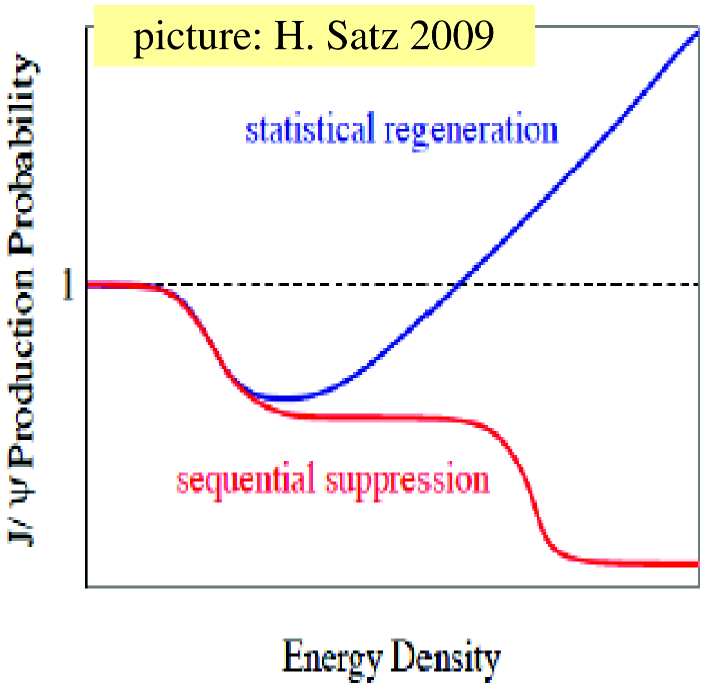
→ demonstrates that hadron and jet suppression is medium effect: energy loss in QGP

Charmonia as a probe of deconfinement

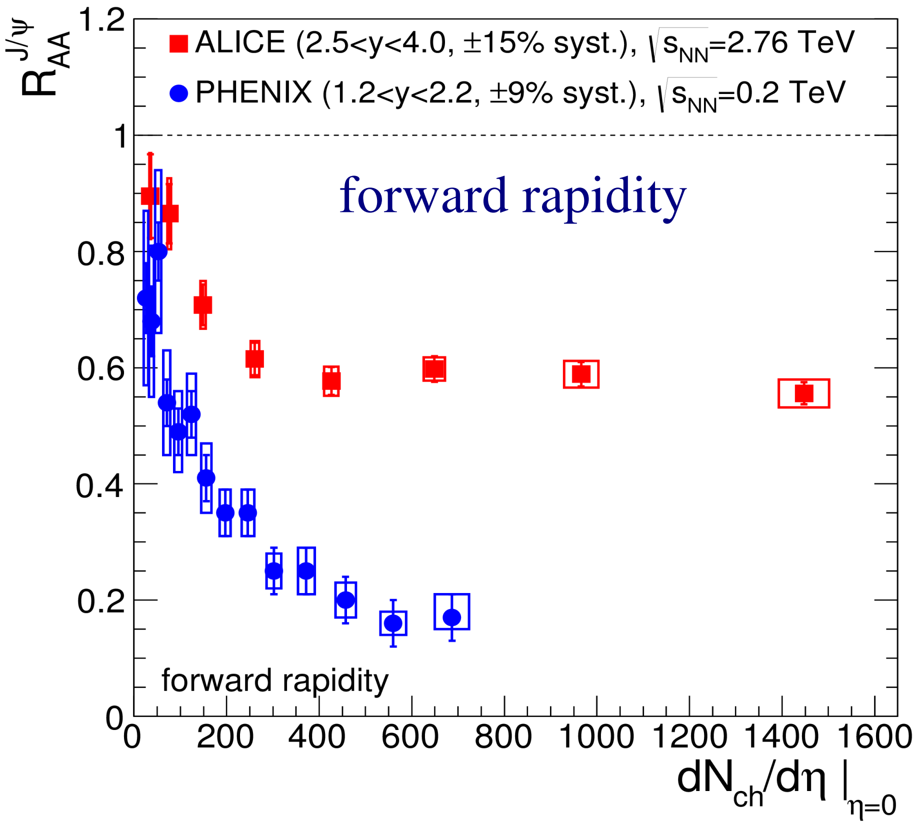
the original idea (Matsui and Satz 1986): implant charmonia into the QGP and observe their modification (Debye screening of QCD), in terms of suppressed production in nucleus-nucleus collisions; larger states are suppressed at lower T – sequential melting

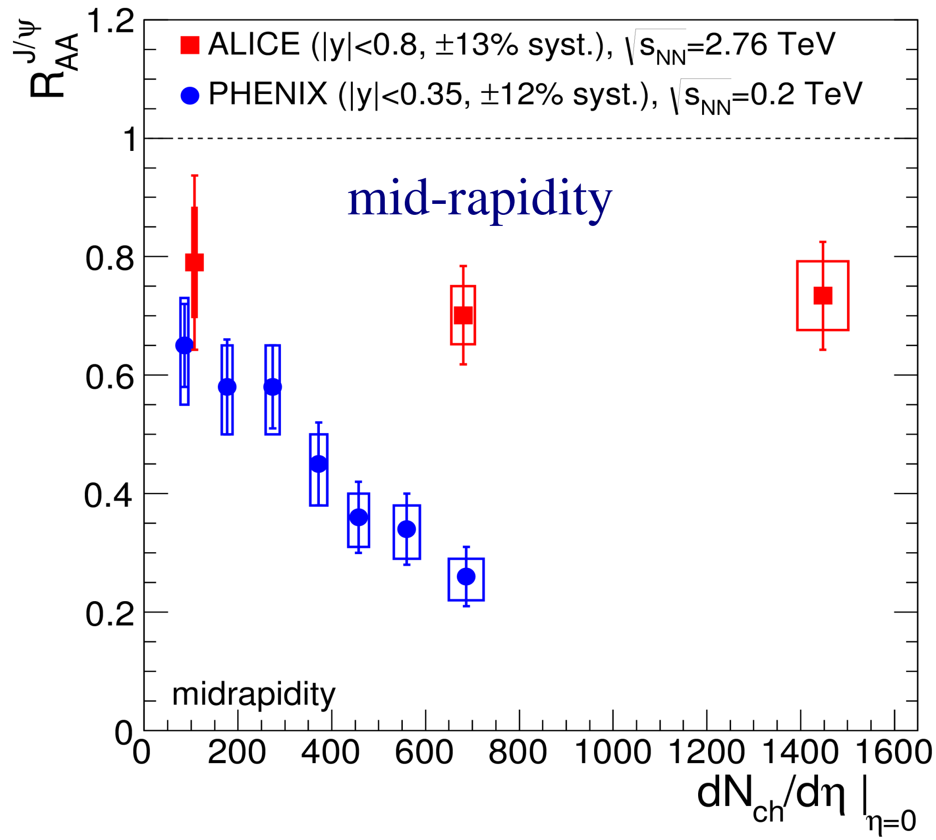
new insight (Braun-Munzinger, J.S. PLB490(2000)186): QGP may screen all charmonia, but charmonium production takes place at the phase boundary, enhanced production at colliders

– signal for deconfinement



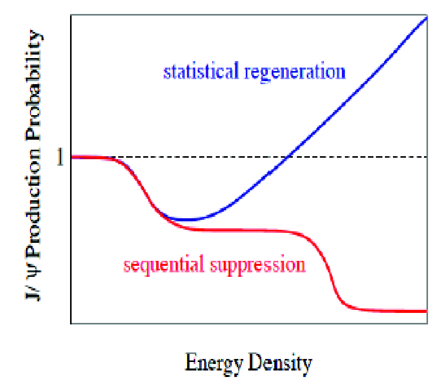
J/psi production in PbPb collisions: LHC relative to RHIC



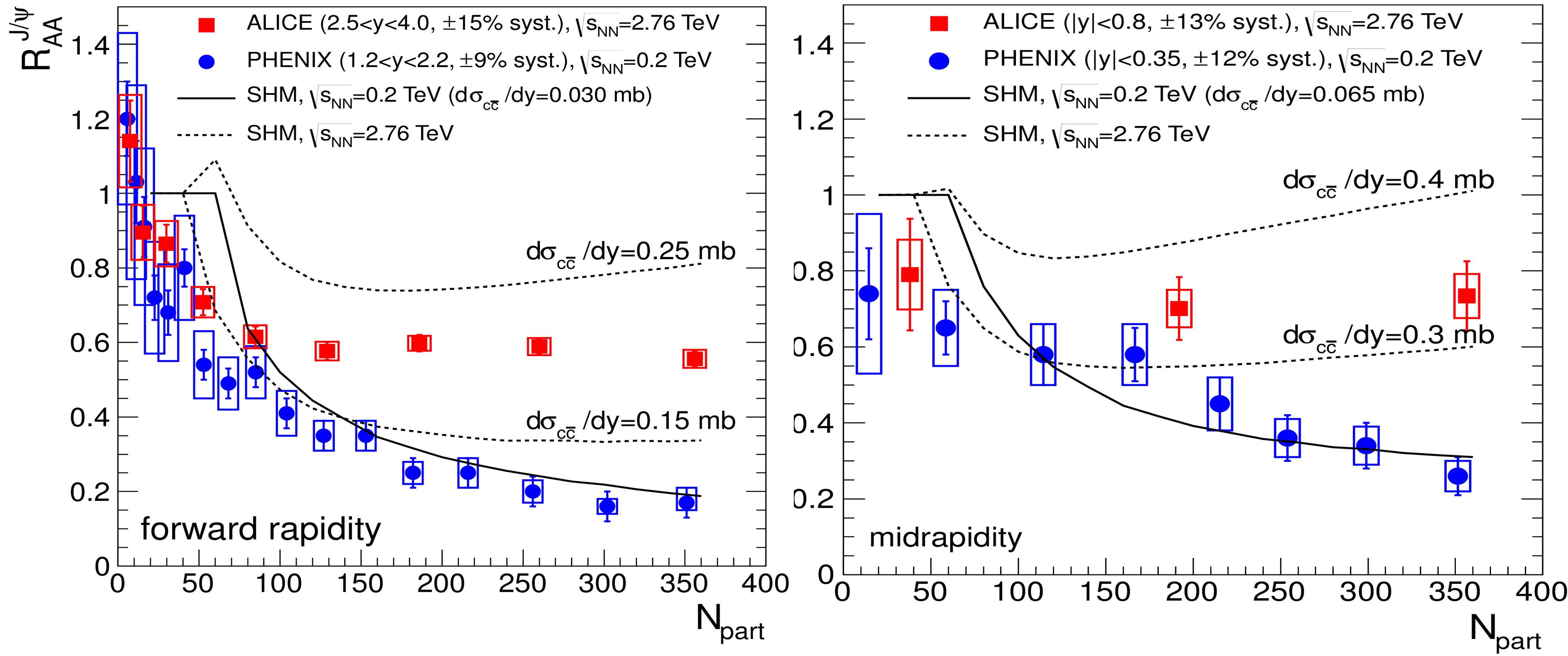


energy density -->

enhancement with increasing energy density!
(from RHIC to LHC and from forward to mid-rapidity)
deconfinement and stat. hadronization at phase boundary



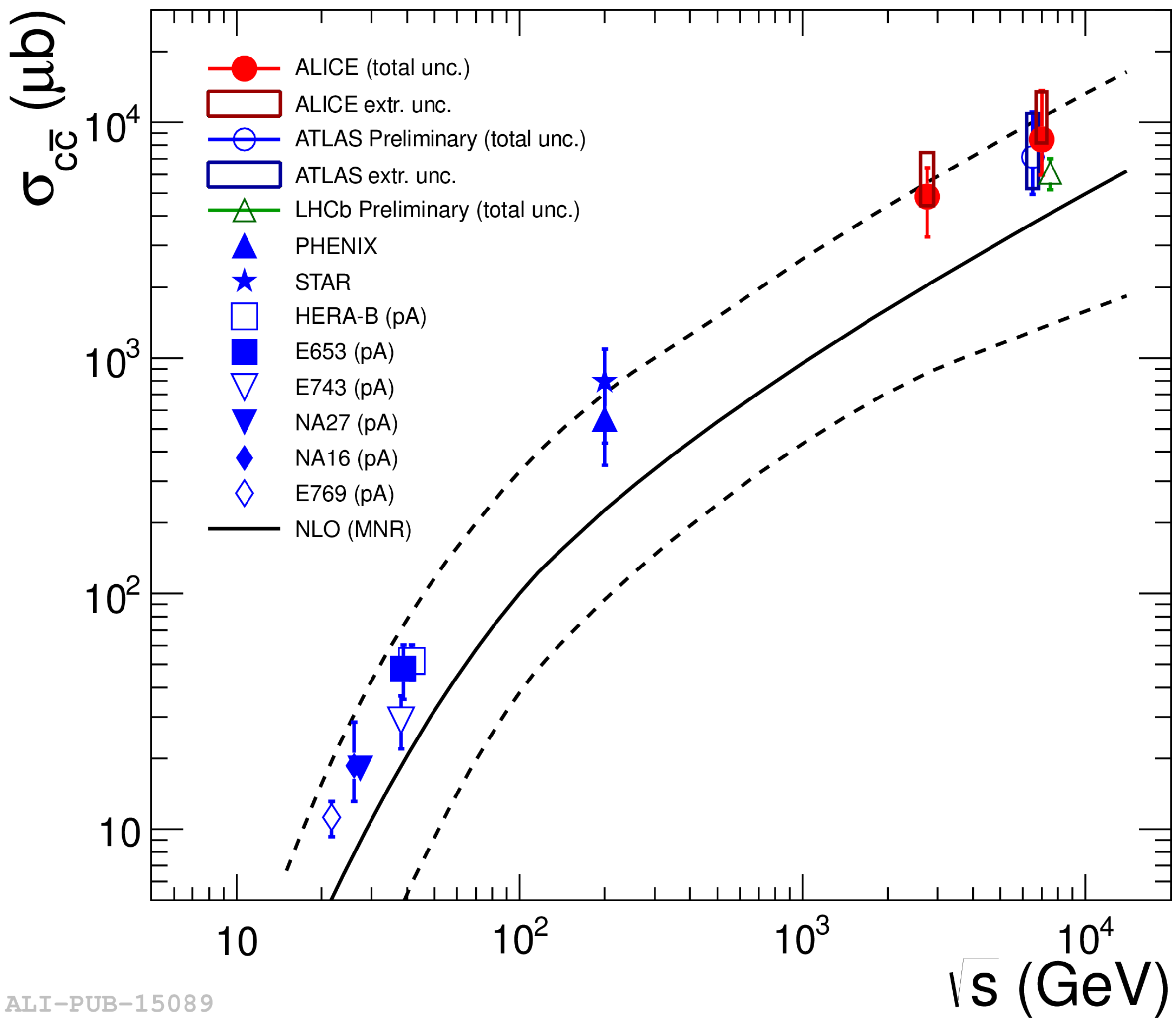
J/psi and statistical hadronization



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

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

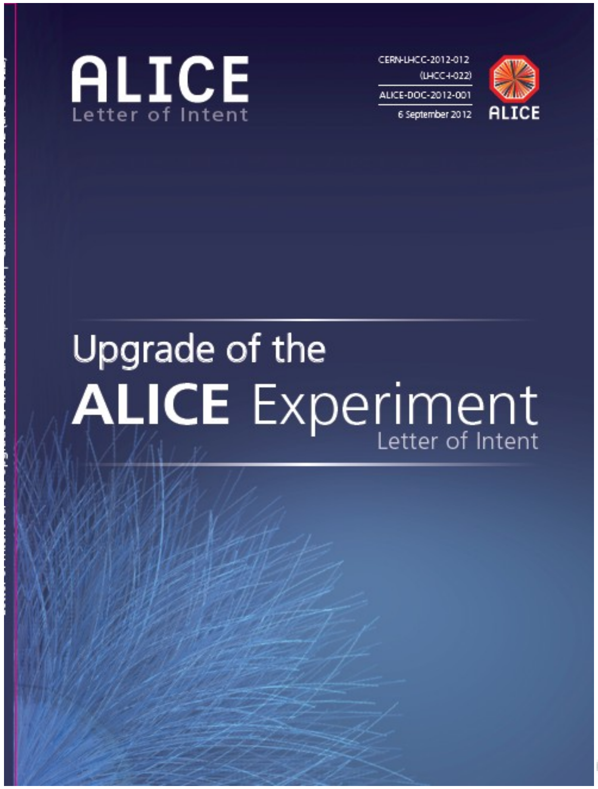
JHEP 1207 (2012) 191



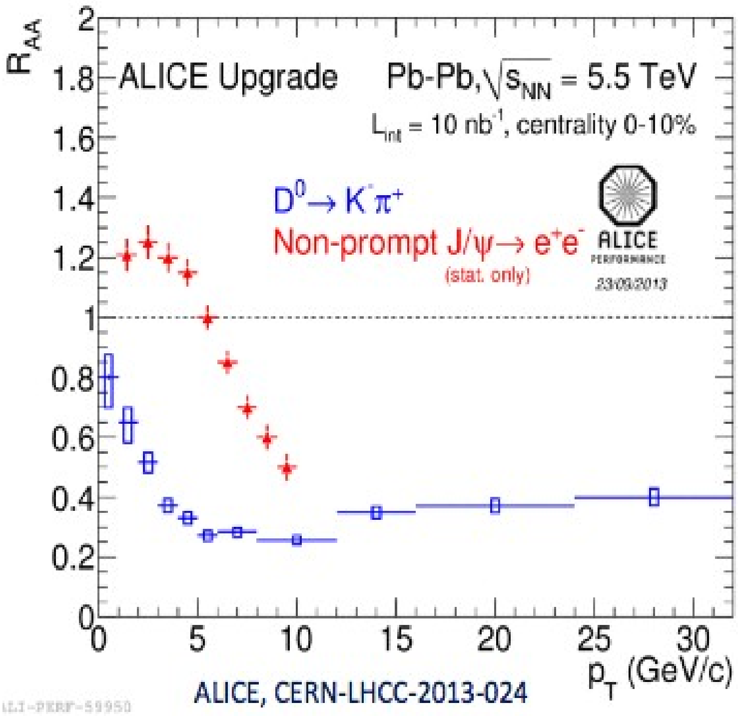
- good agreement between ALICE, ATLAS and LHCb
- large syst. error due to extrapolation to low pt, need to push measurements in that direction
- data factor 2 ± 0.5 above central value of FONLL but well within uncertainty
- beam energy dependence follows well FONLL
- soon more accurate 4π extrapolation at 7 TeV
- aim for 10% syst error with Run3 data

Outlook open heavy flavor – LHC Run3

new high performance ITS plus rate increase (TPC upgrade)



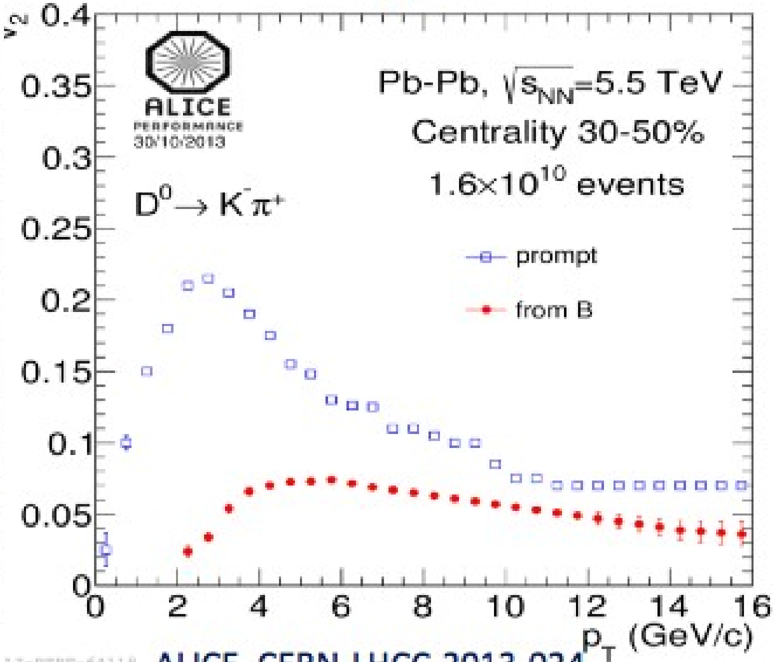
Upgrade



ALICE, CERN-LHCC-2013-024

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

Upgrade



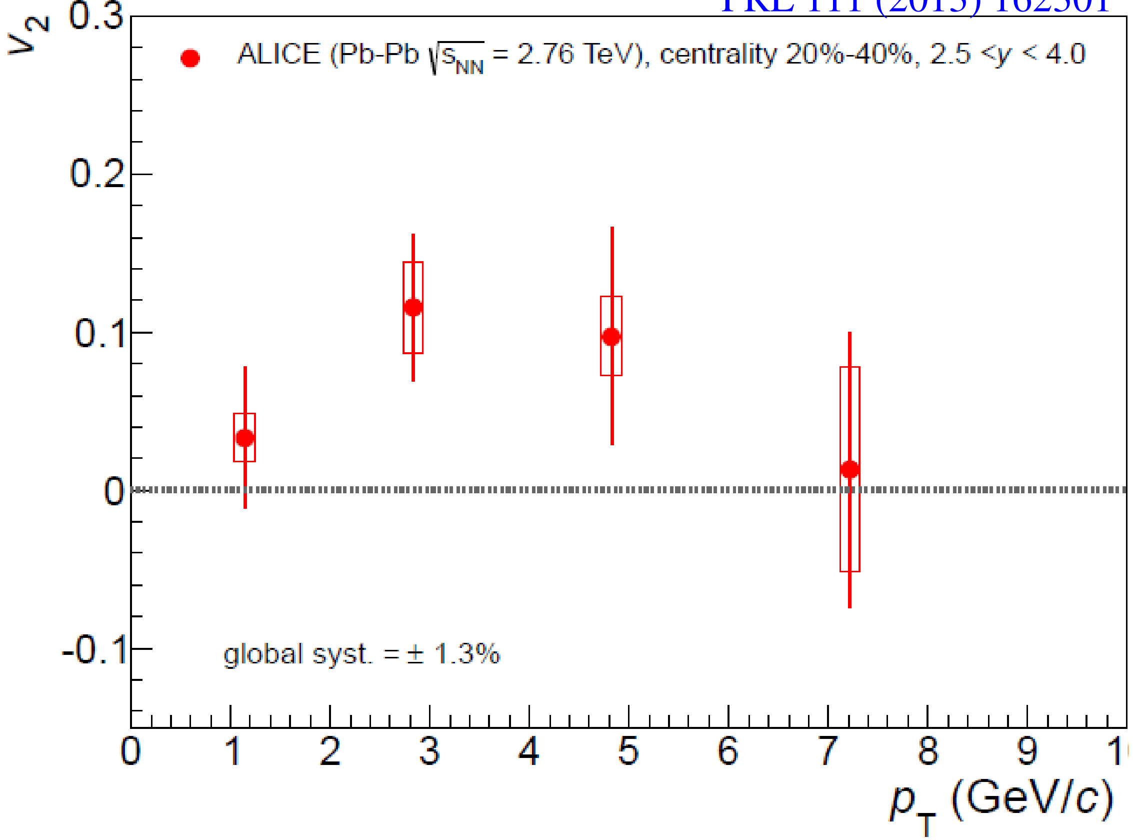
ALICE, CERN-LHCC-2013-024

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

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

elliptic flow of J/psi vs p_t

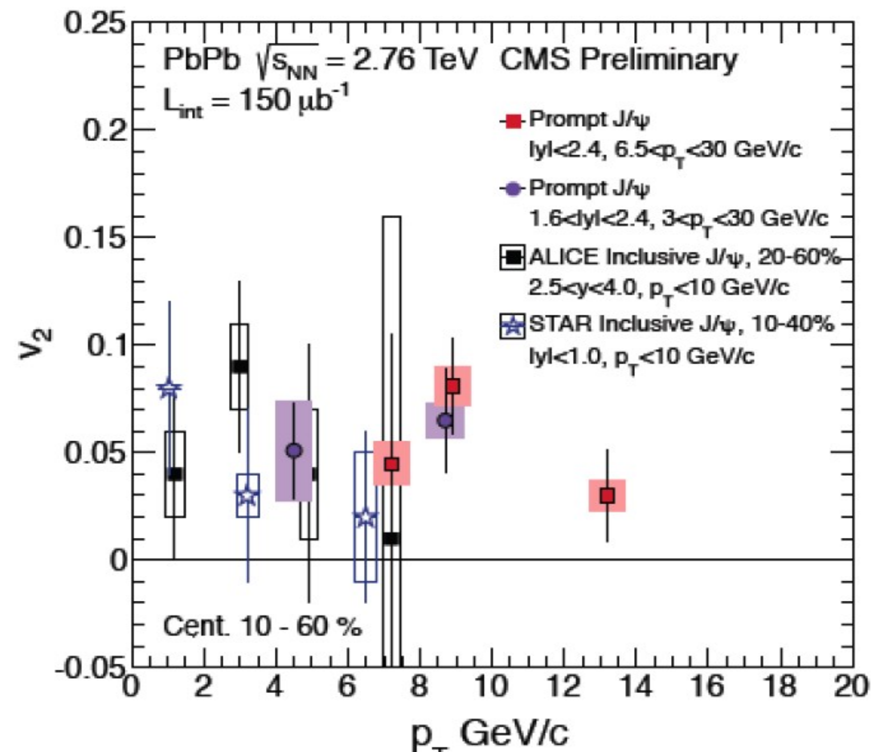
PRL 111 (2013) 162301



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

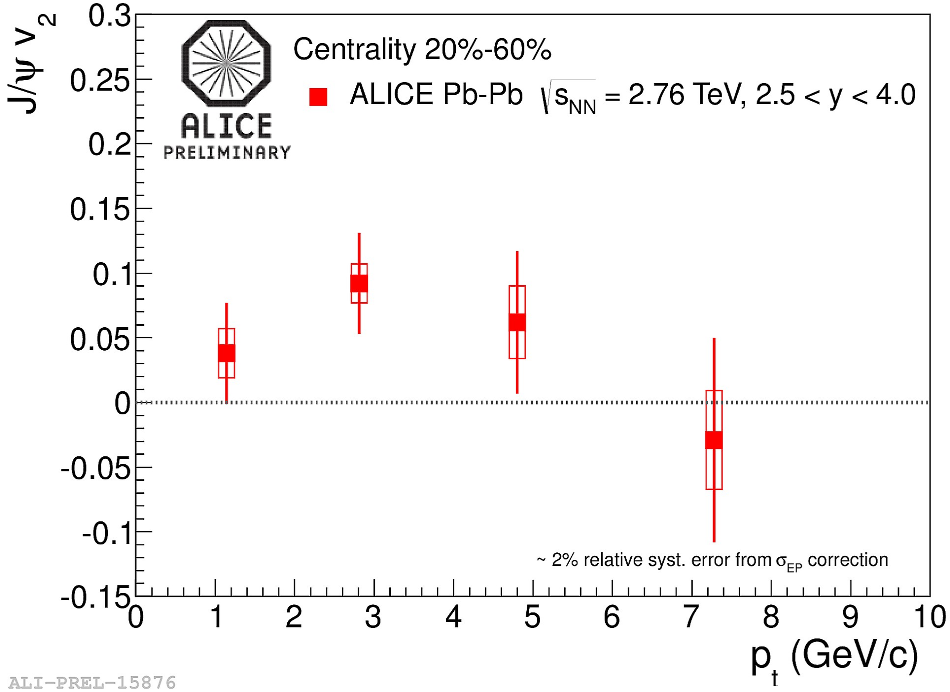
somewhat surprizing: nonzero v_2 also at high p_t observed by CMS

is it path length effect on energy loss?



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

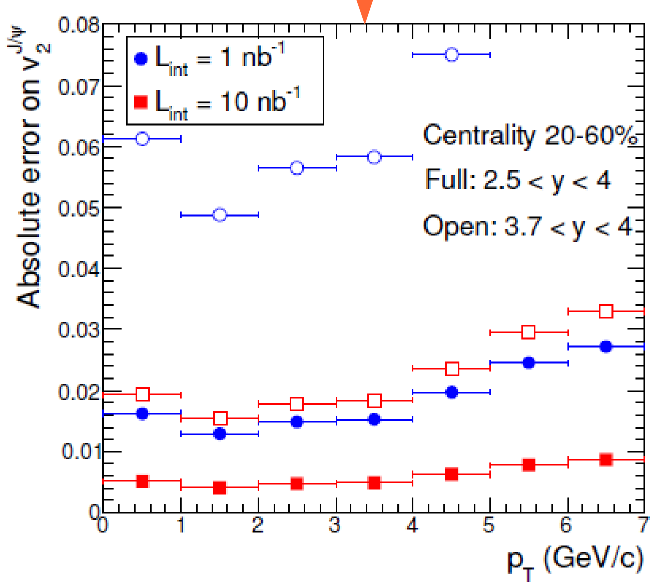
J/psi elliptic flow outlook



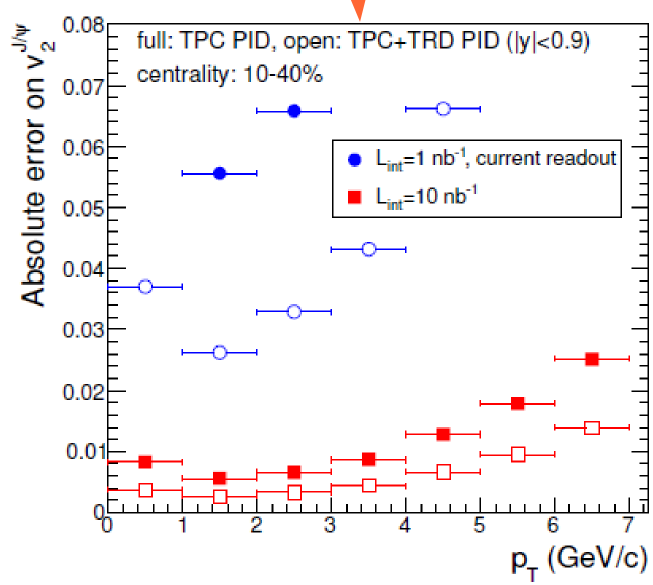
observation of flow with muon arm
presently 3 sigma
needs statistics to make model comparison
meaningful

future statistical errors

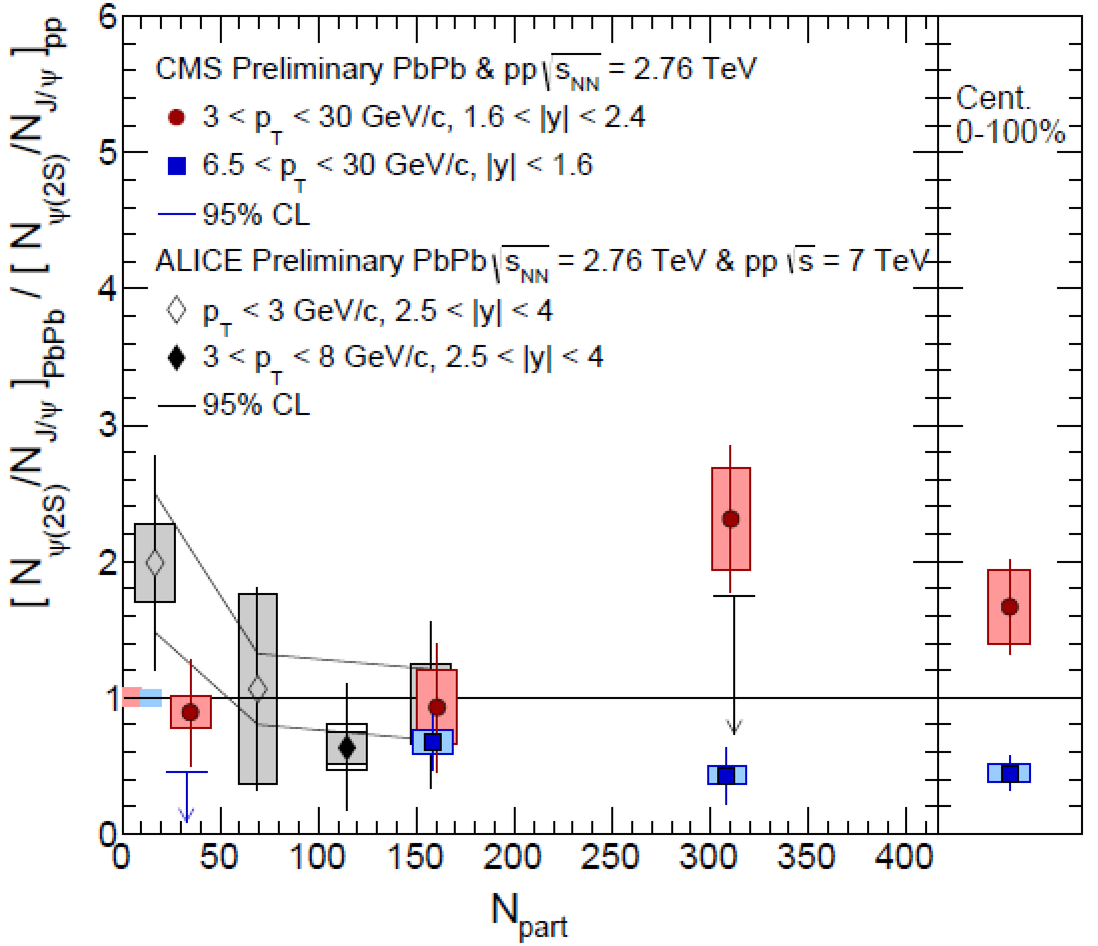
muon arm



central barrel



psi' to J/psi at LHC

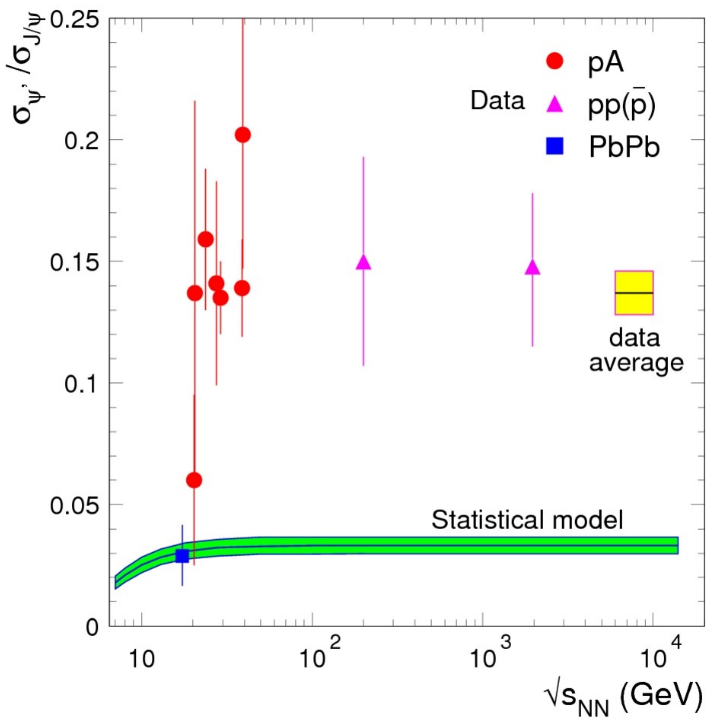


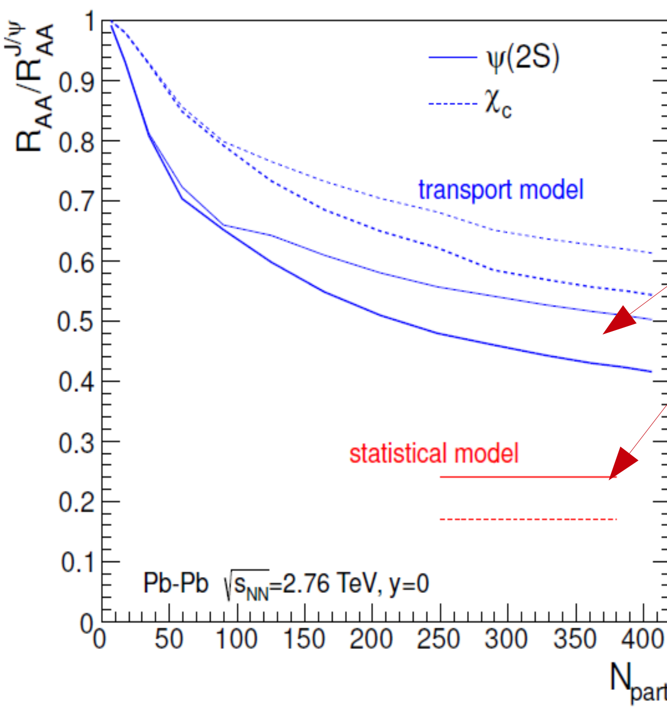
for statistical hadronization expect suppression of higher charmonia due to Boltzmann factors, so for ψ' relative to pp factor 3 reduction

CMS sees value larger 1 for pt>3 GeV
ALICE for pt 0-3 only upper limit for central collisions

not yet conclusive

Excited charmonia - outlook



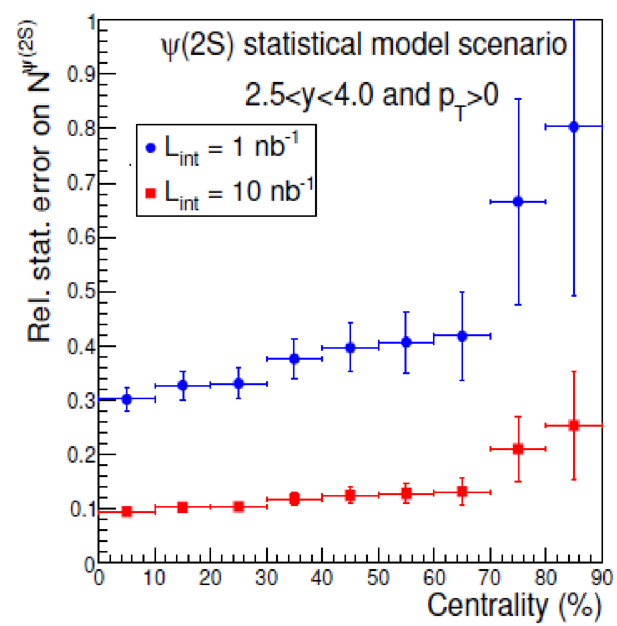


in fact here one can distinguish between the transport models that form charmonia already in QGP and statistical hadronization at phase boundary!

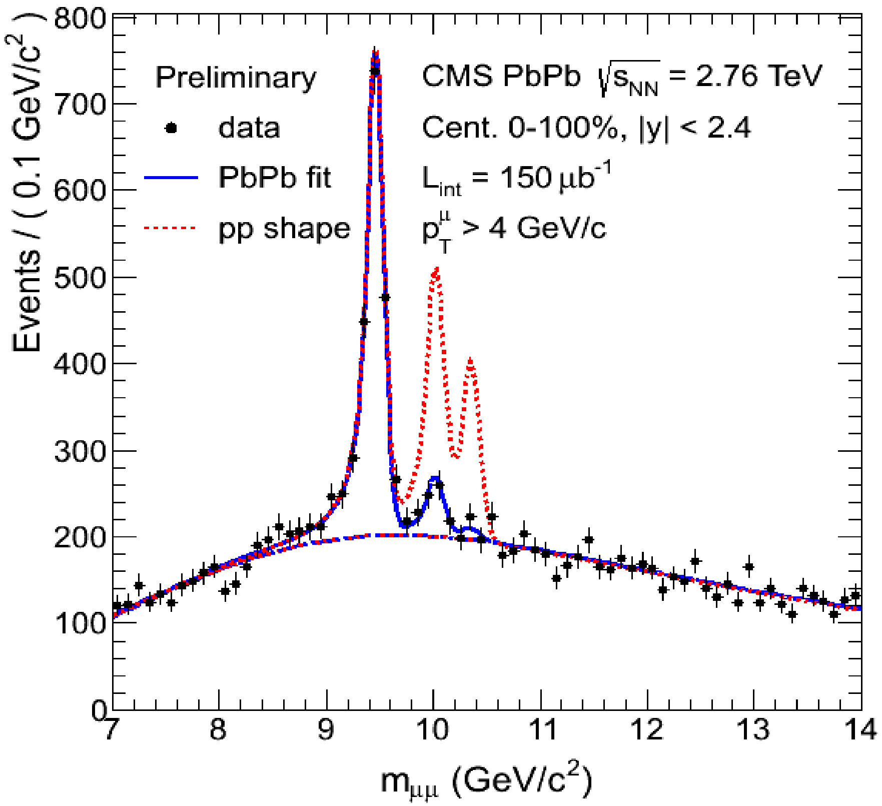
for statistical hadronization need to see suppression by Boltzmann factor

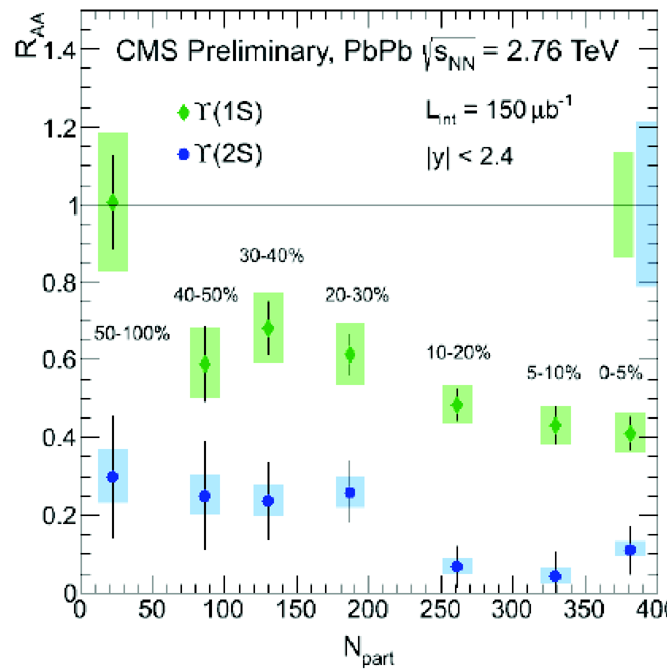
χ_c even bigger difference

expected ALICE performance muon arm Run2 and Run3 →



Suppression of Upsilon states





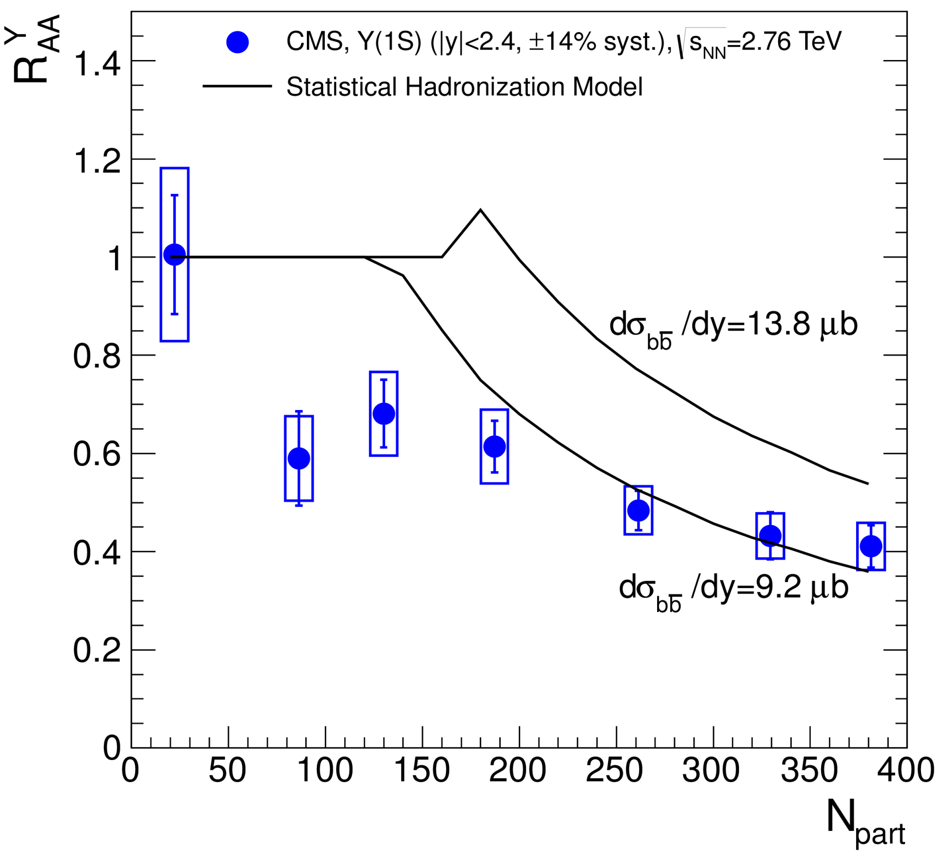
consistent with excited state suppression (50% feed-down)

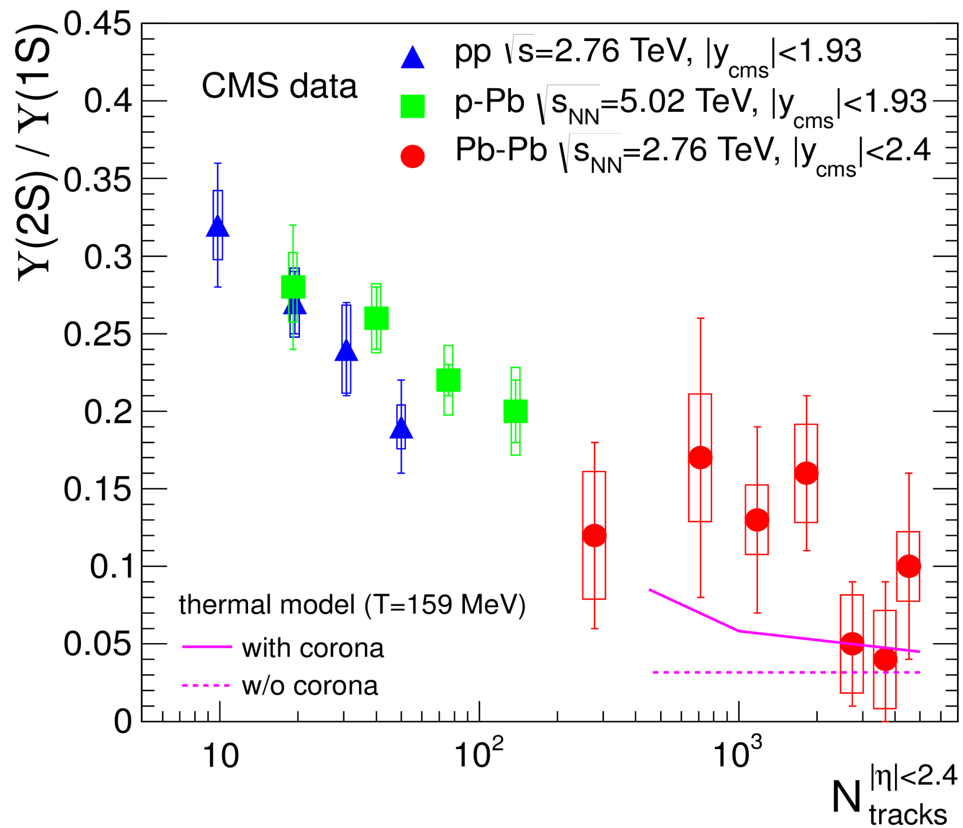
centrality integrated:
2S/1S PbPb relative to pp 0.21+-0.07+-0.02
3S/1S " < 0.1 95% C.L.

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.





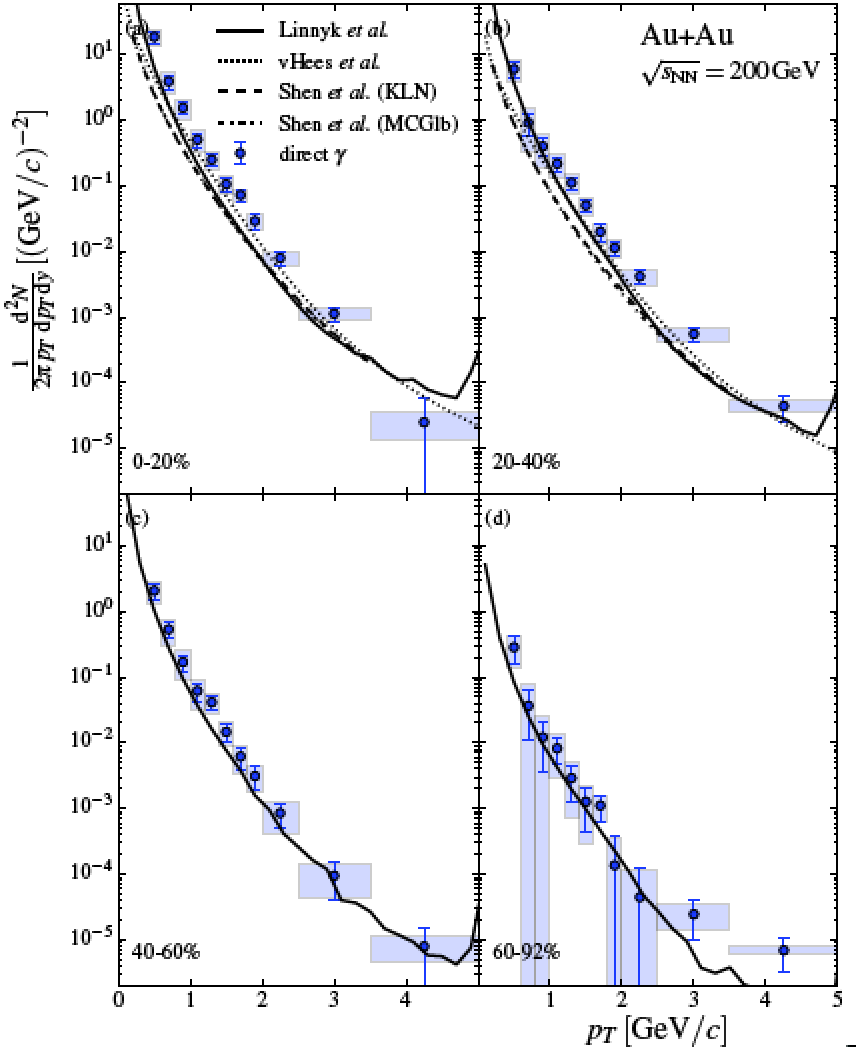
in this picture the entire Upsilon family is formed from deconfined b at hadronization
but: need to know first – do b-quark thermalize at all?

- total b-cross section in PbPb

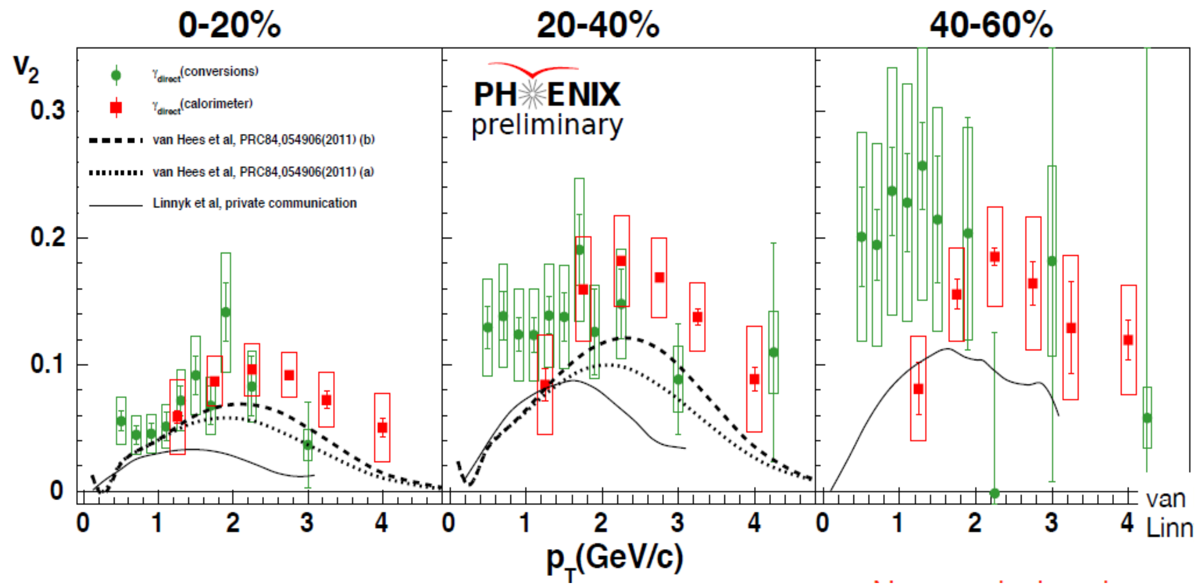
future measurements in Run2 and Run3, focus for ALICE, ATLAS and CMS

Direct photon excess and elliptic flow at RHIC

arXiv:1405.3940

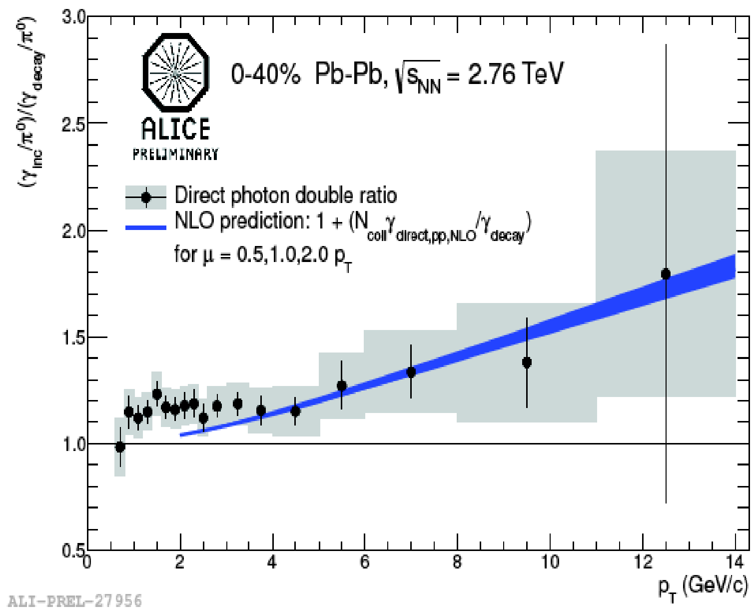


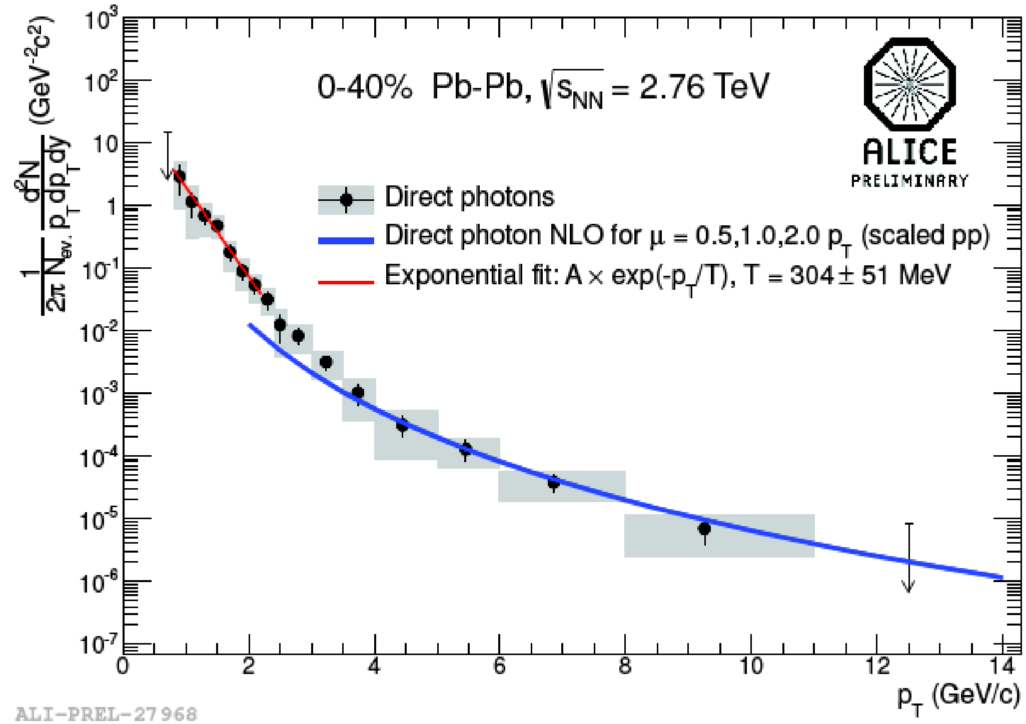
data: S. Mizuno, PHENIX, QM2014
calc: van Hees et al: PRC **84**, 054906 (2011)
and Linnyk et al.: PHSD model (priv. comm.)

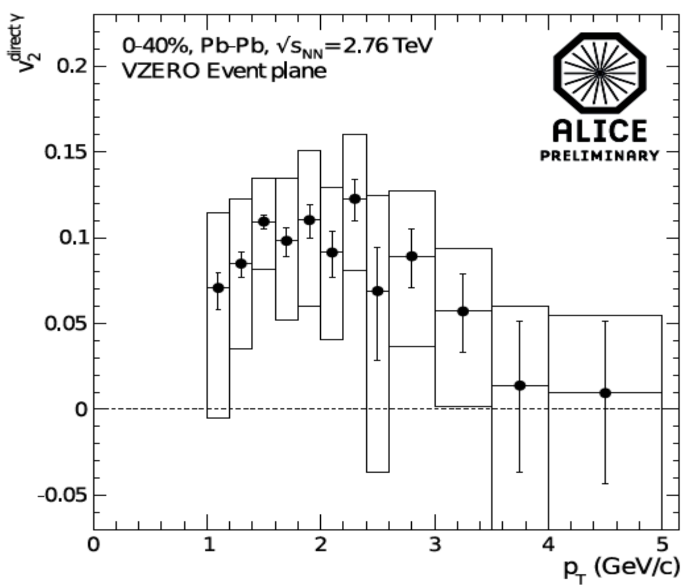


- new measurements using photon conversions extend data to significantly lower p_t
- confirm earlier measurements, different systematics
- the challenge for theories remains

direct photons in PbPb collisions at the LHC







a hot photon (300 MeV) source, the QGP

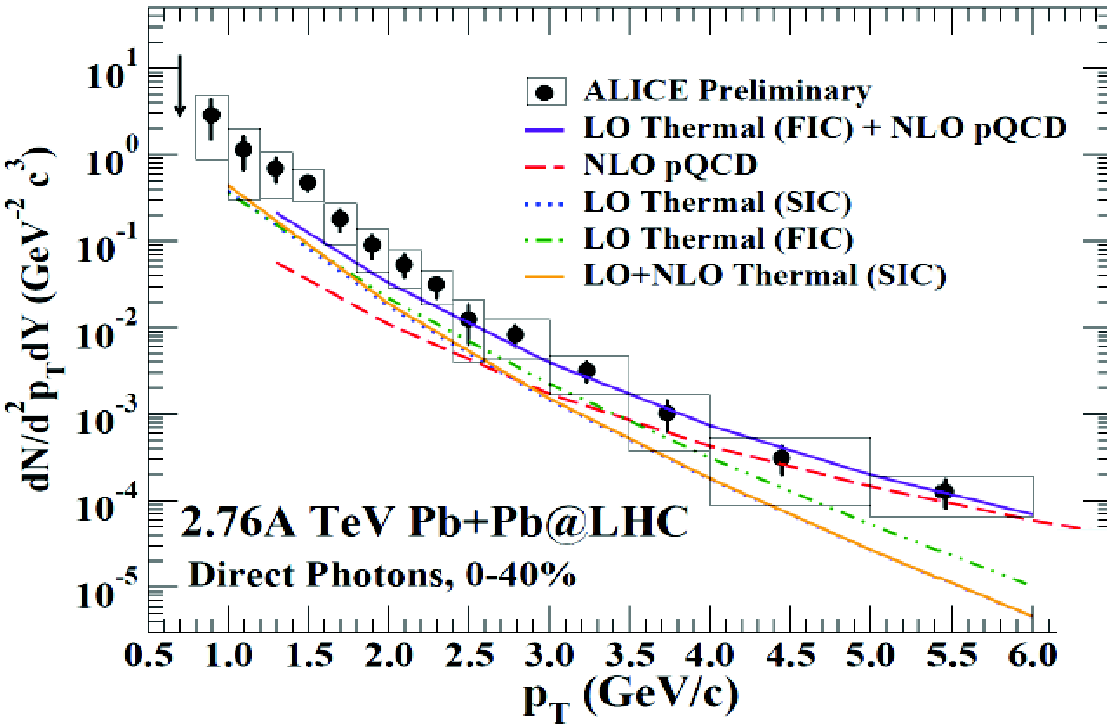
- or are they blueshifted photons from a later stage?

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^-

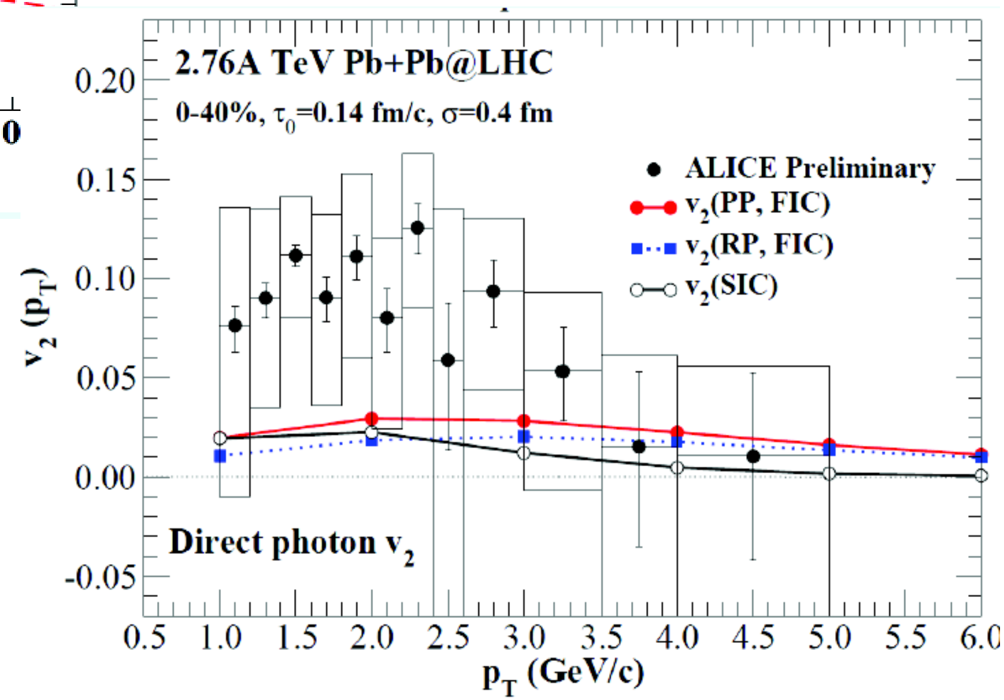
Direct photons at LHC (and RHIC) challenge models



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

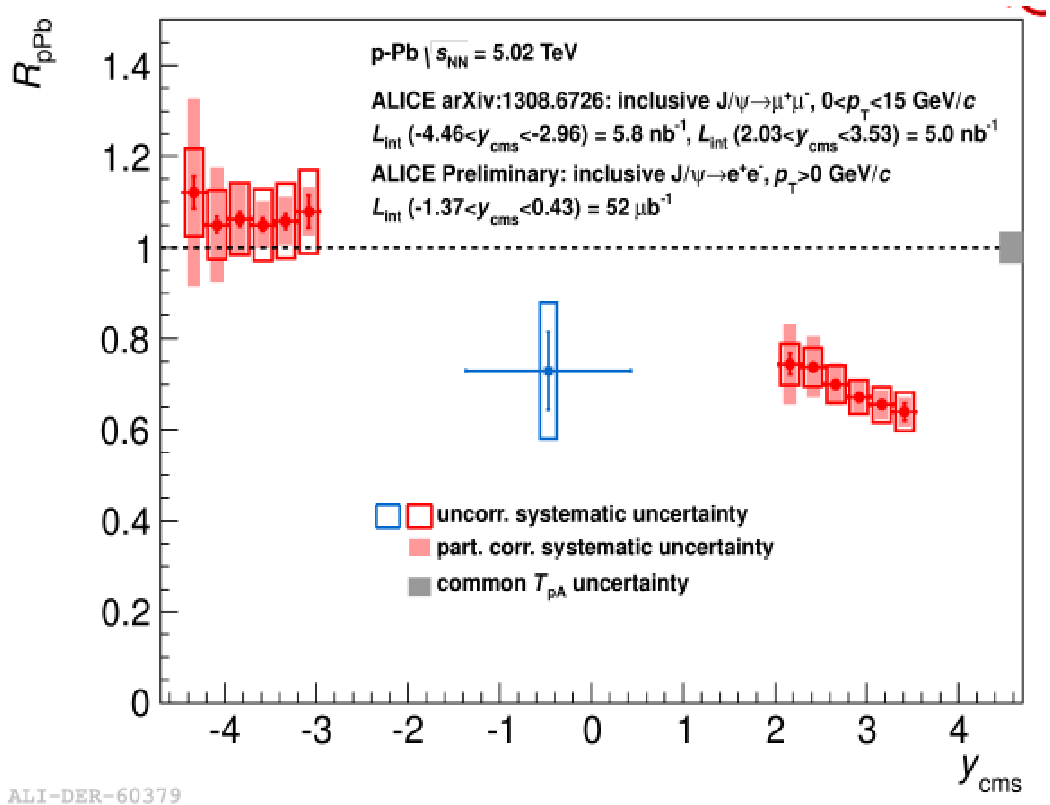
spectra and elliptic flow high as compared to models – a real challenge
but: systematic errors largely correlated and error in v_2 dominated by error in direct photon yield



pPb collisions

1. for hard probes proper normalization to include nuclear effects on parton distributions (shadowing)

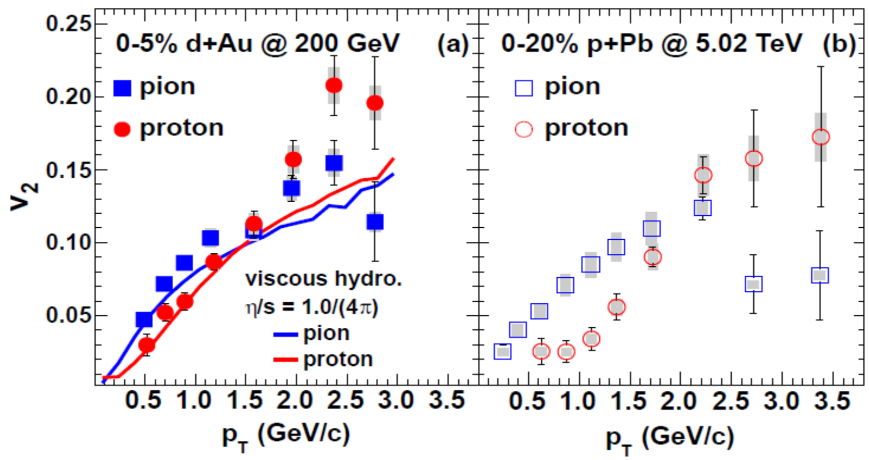
    example: J/psi production



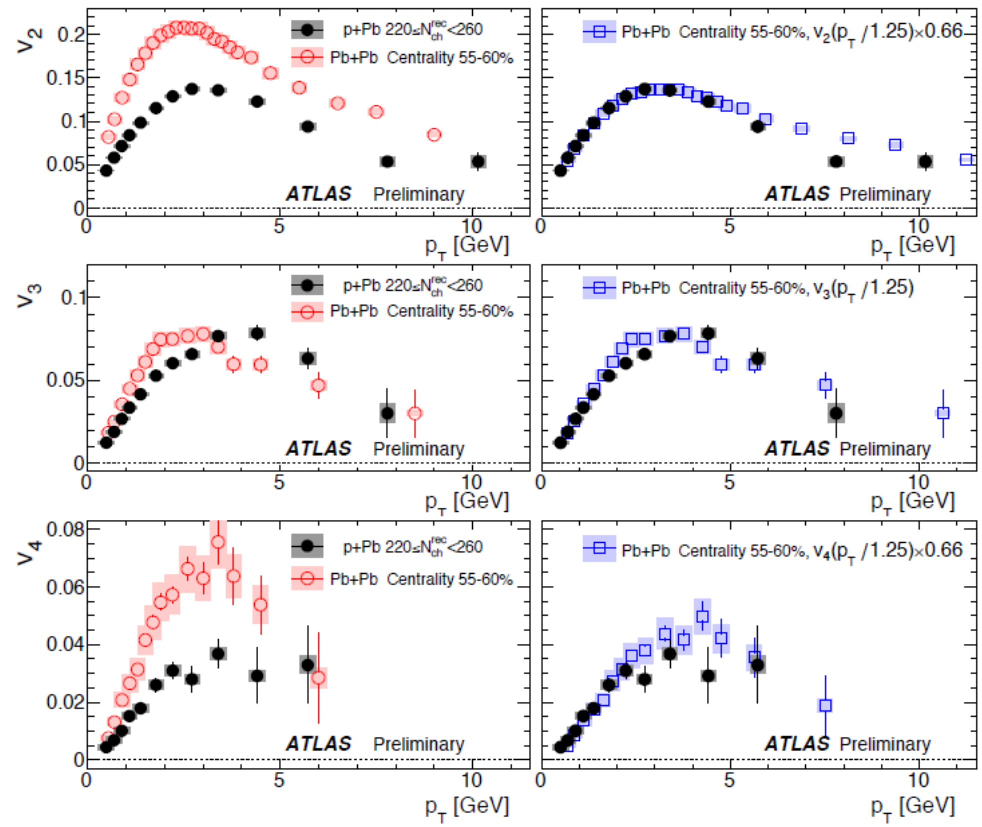
ALICE forward/backward arXiv:1308.6726
good agreement with LHCb arXiv:1308.6729
ALICE mid-y hard probes 2013

2. pPb collisions for very high multiplicity events - collective features?

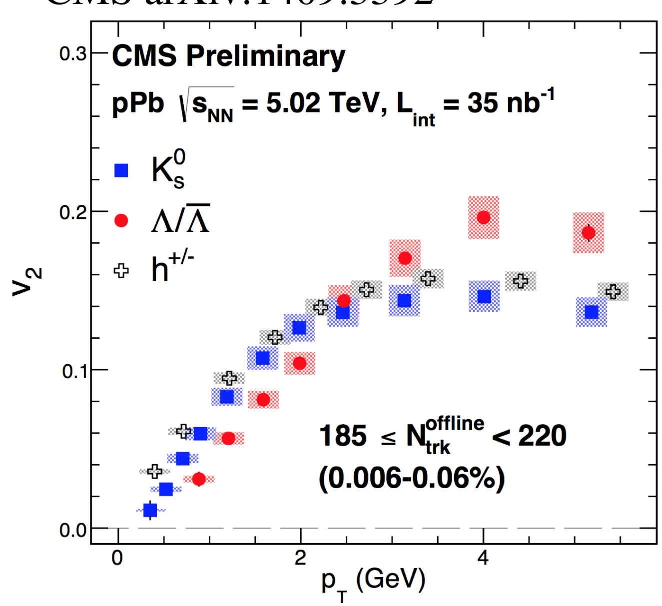
PHENIX arXiv:1404.7461 ALICE Phys. Lett. B726, 164 (2013)



ATLAS arXiv:1409.1792 0.003% highest mult



CMS arXiv:1409.3392



multipole moments with similar features as observed in PbPb collisions – spectra show similar features as well
a real surprize and still a matter of much discussion

Conclusions and outlook

results from Run1 at the LHC and 15 years of RHIC:

LHC has already surpassed luminosity goal at Run1 $\sqrt{s}$, RHIC has reached unanticipated luminosities

experiments zeroing in on the properties of the Quark-Gluon Plasma

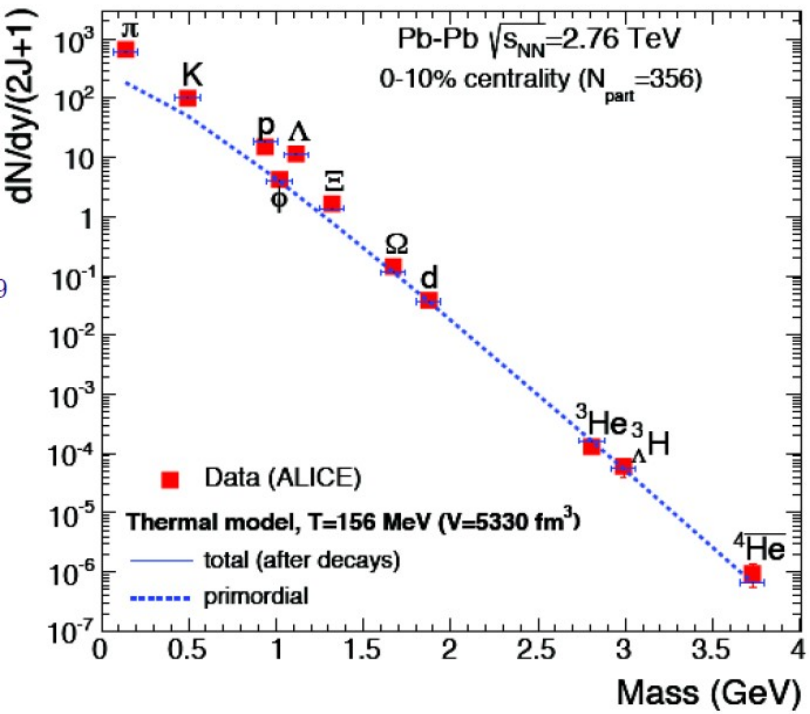
- transport coefficients
- deconfinement

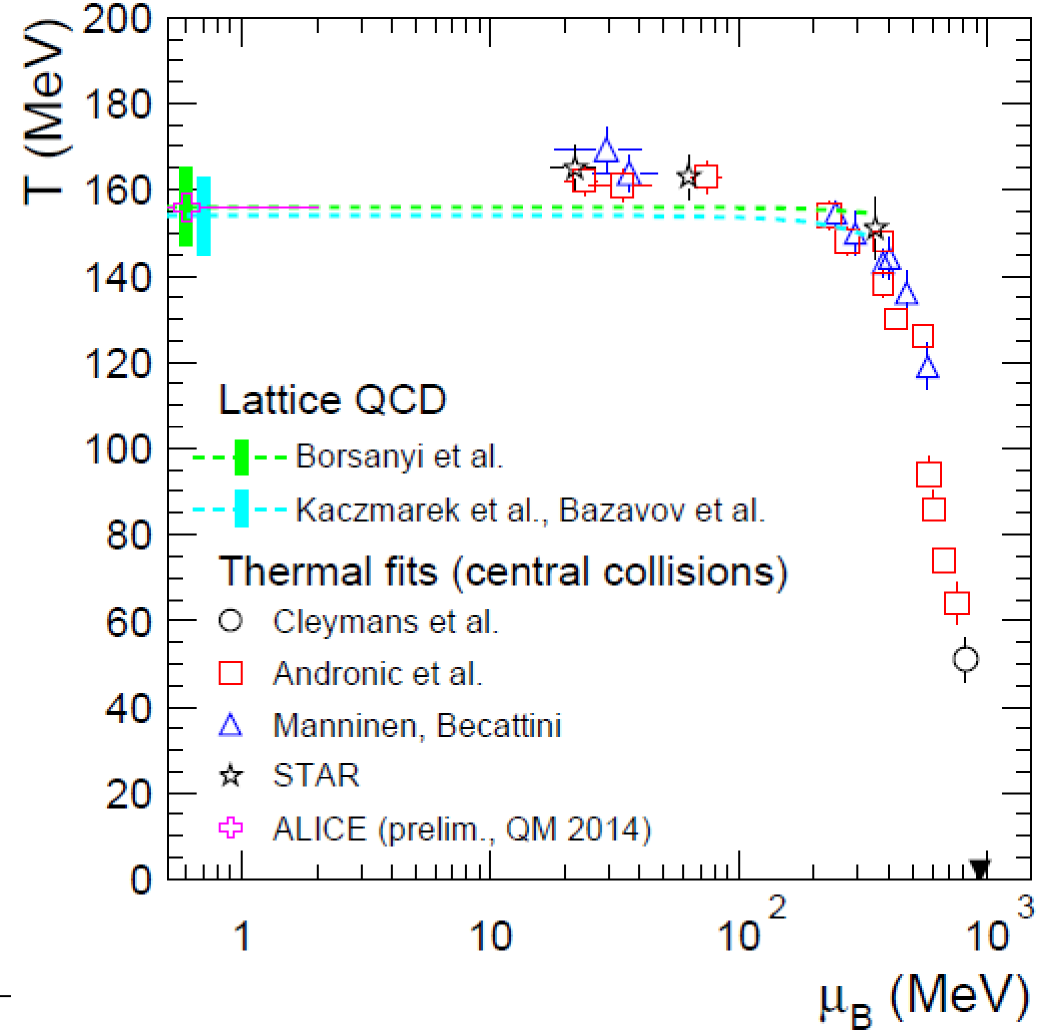
RHIC will much increase low $\sqrt{s}$ performance by cooling
STAR and PHENIX – BES-II fluctuations, possible effects of critical point, heavy flavor with new vertex trackers, MPC-EX for forward photons, PHENIX new detector proposal, explore regime of possibly strongest coupling with jet observables

LHC expect continuous increase in PbPb luminosity, 50 kHz for Run3
ATLAS and CMS precision measurements at medium and high p_t, jets in QGP
ALICE low p_t heavy flavor, electron pairs, and photons, upgrade during LS2

backup

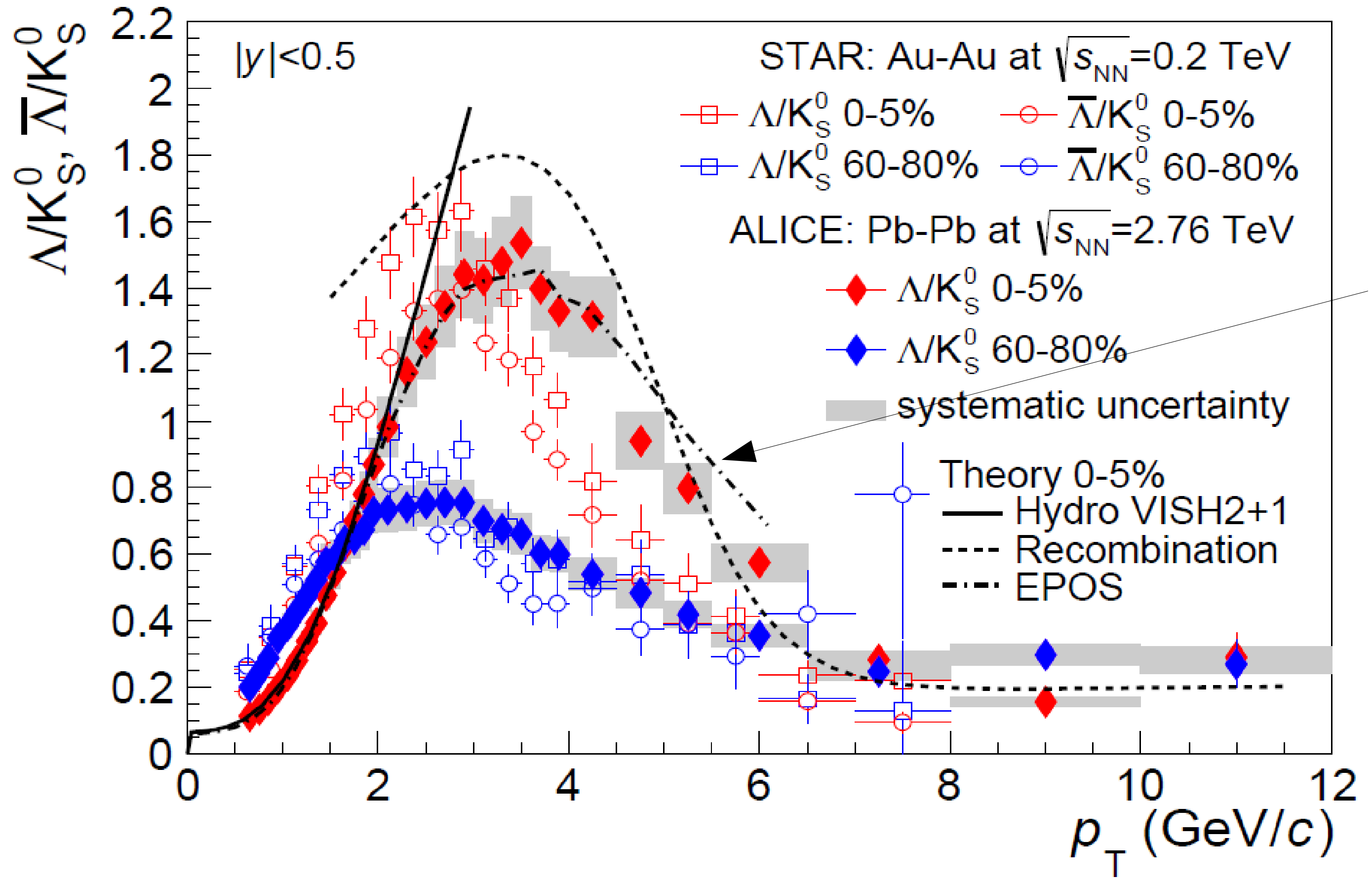
Production of hadrons and nuclei at LHC





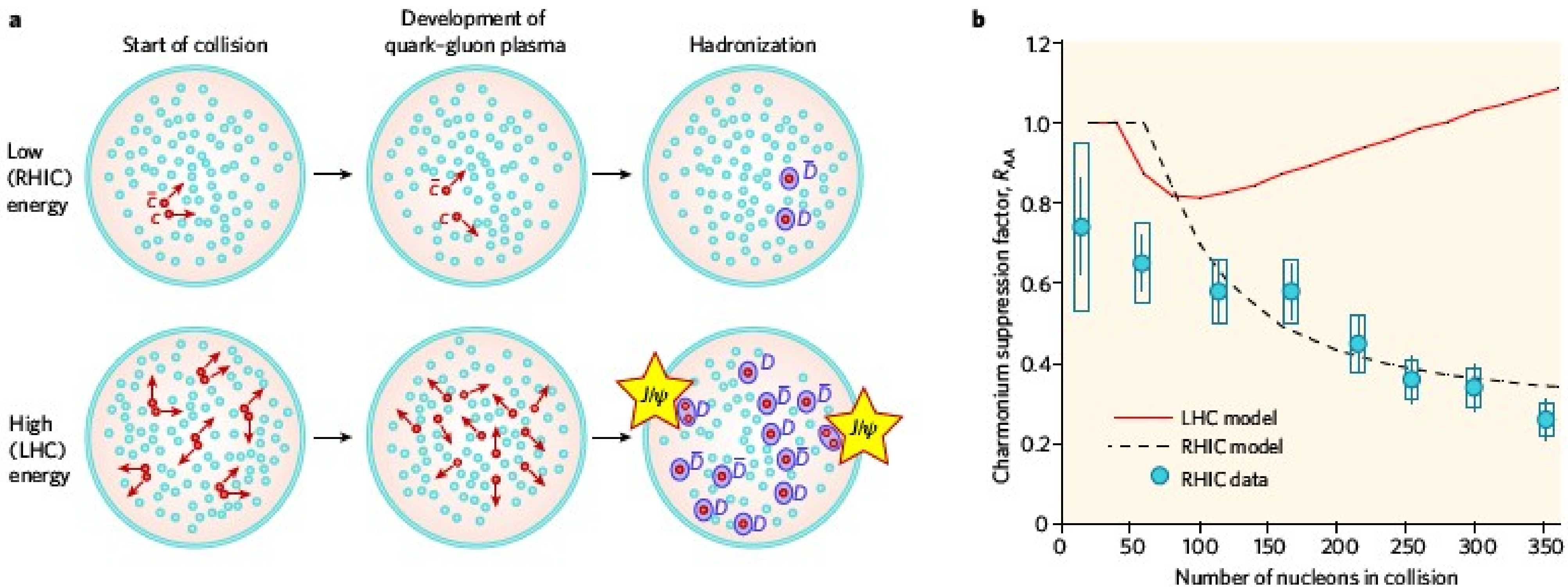
hadron yields for Pb-Pb central collisions from LHC run1 are well described by assuming equilibrated matter at T = 156 MeV and μ_b < 1 MeV, very close predictions from lattice QCD for T_c

Need for additional coalescence mechanism?



peak in Λ/K needs no additional mechanism statistically hadronizing string segments get pushed by collective flow - could be the entire picture

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



charmonium enhancement as fingerprint of deconfinement at LHC energy

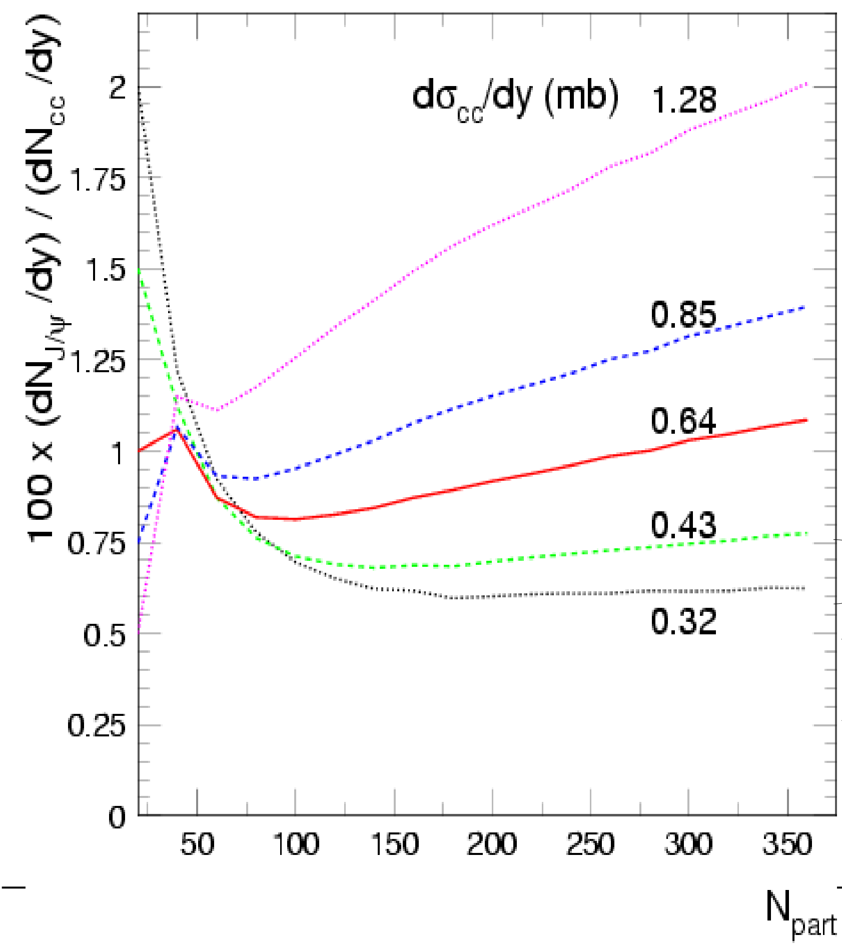
only free parameter: open charm cross section in nuclear collision

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

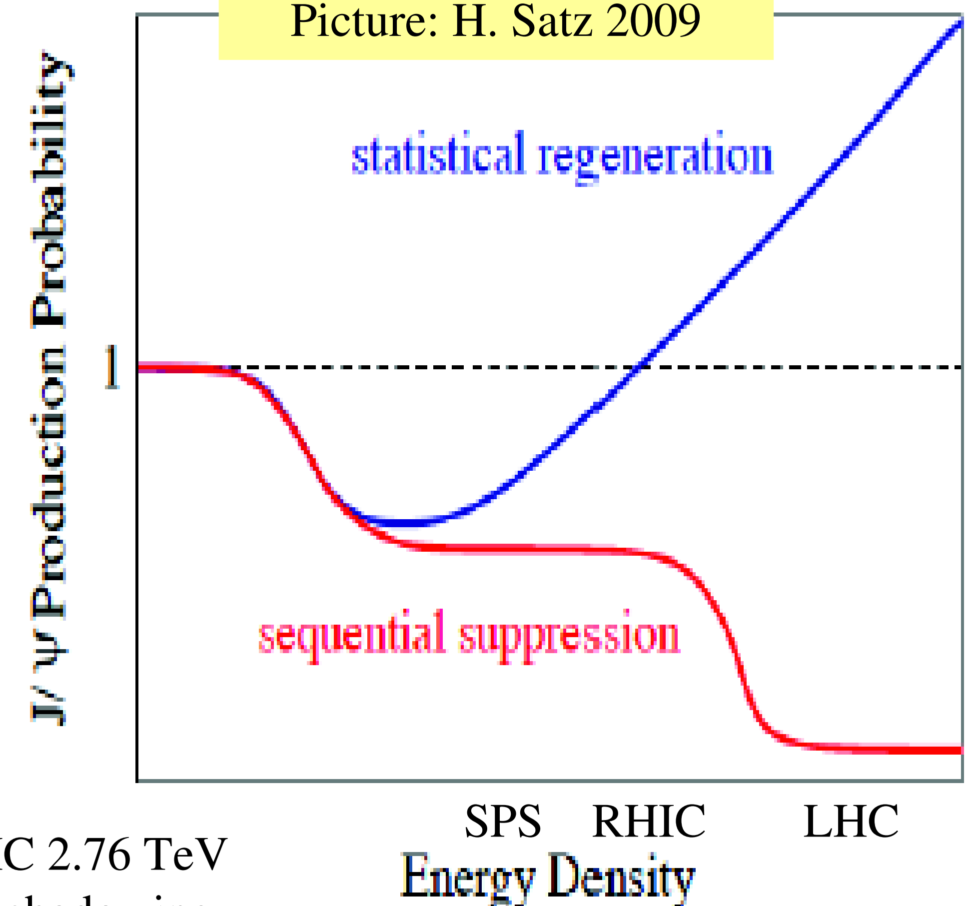
A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel Phys. Lett. B652 (2007) 259



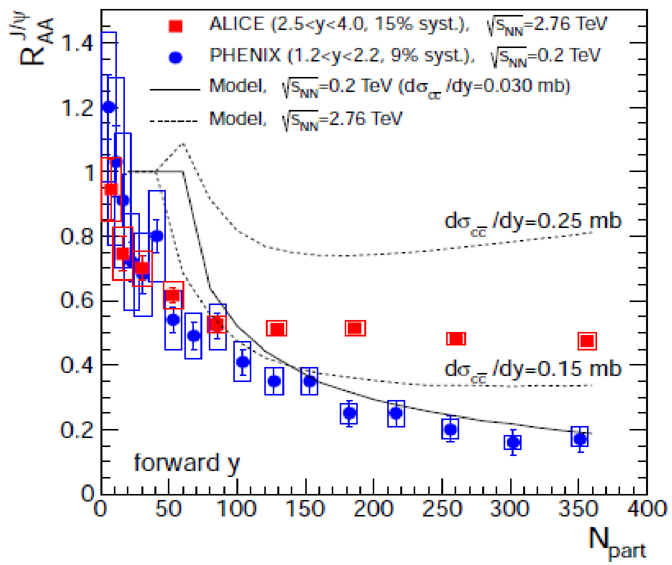
mid-y LHC 2.76 TeV including shadowing

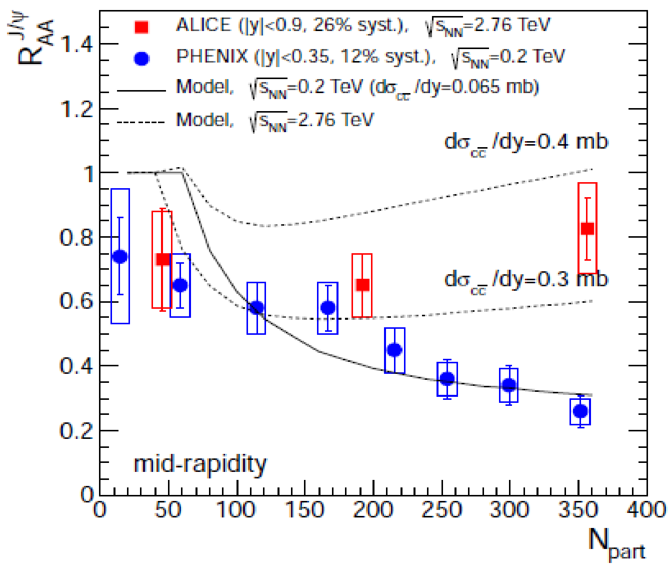
forward-y LHC 2.76 TeV including shadowing

Picture: H. Satz 2009



J/psi as probe of deconfinement



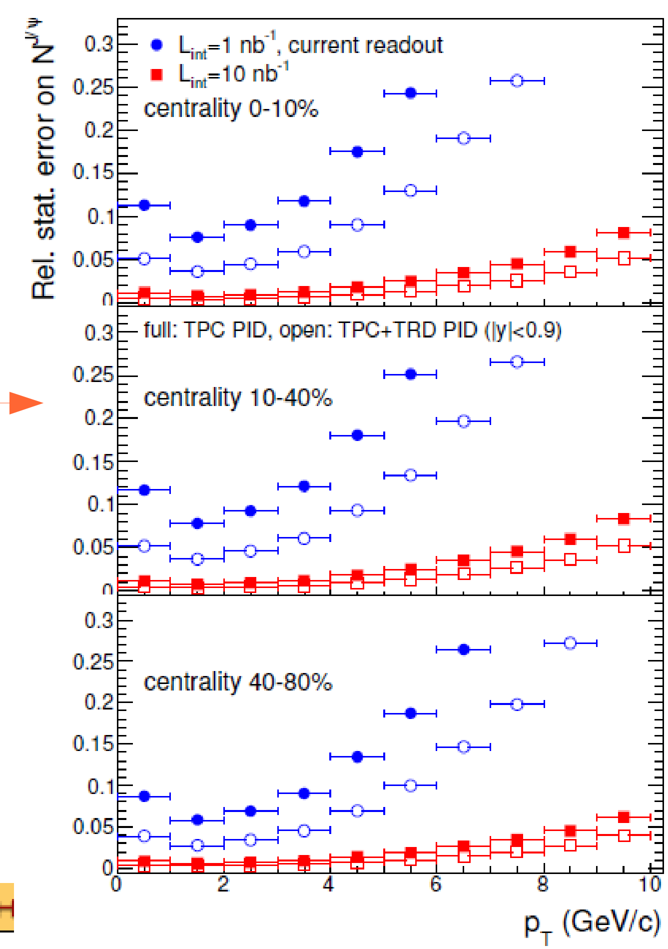


di-electrons statistics limited, 10 nb-1 will have huge effect

but also syst uncertainties will decrease with upgrade:

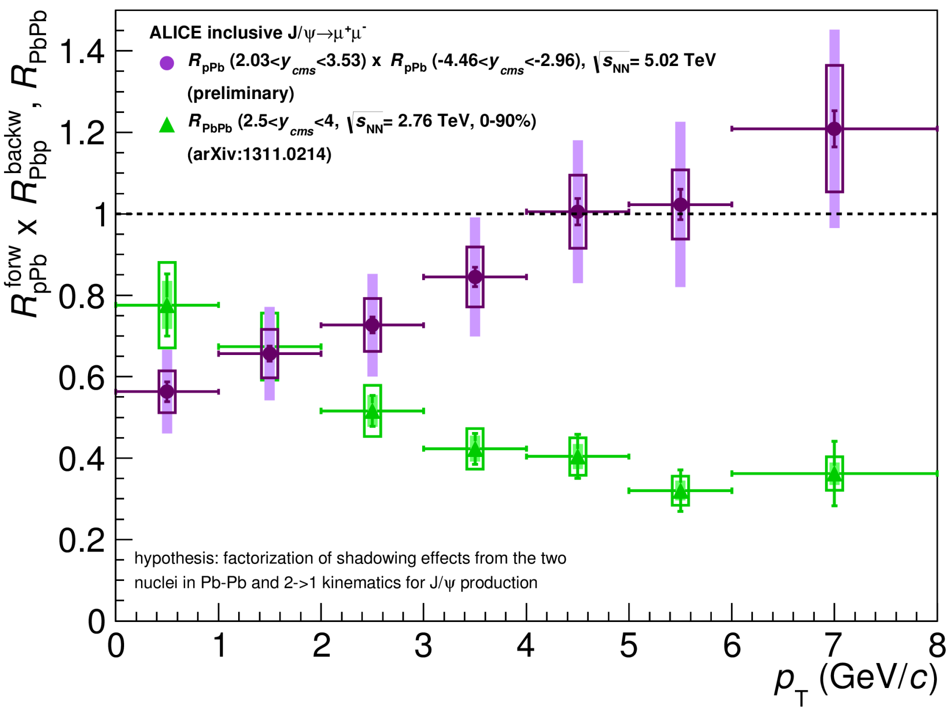
- will also add TRD for electron id - reduced comb background
- thinner ITS reduced radiation tail

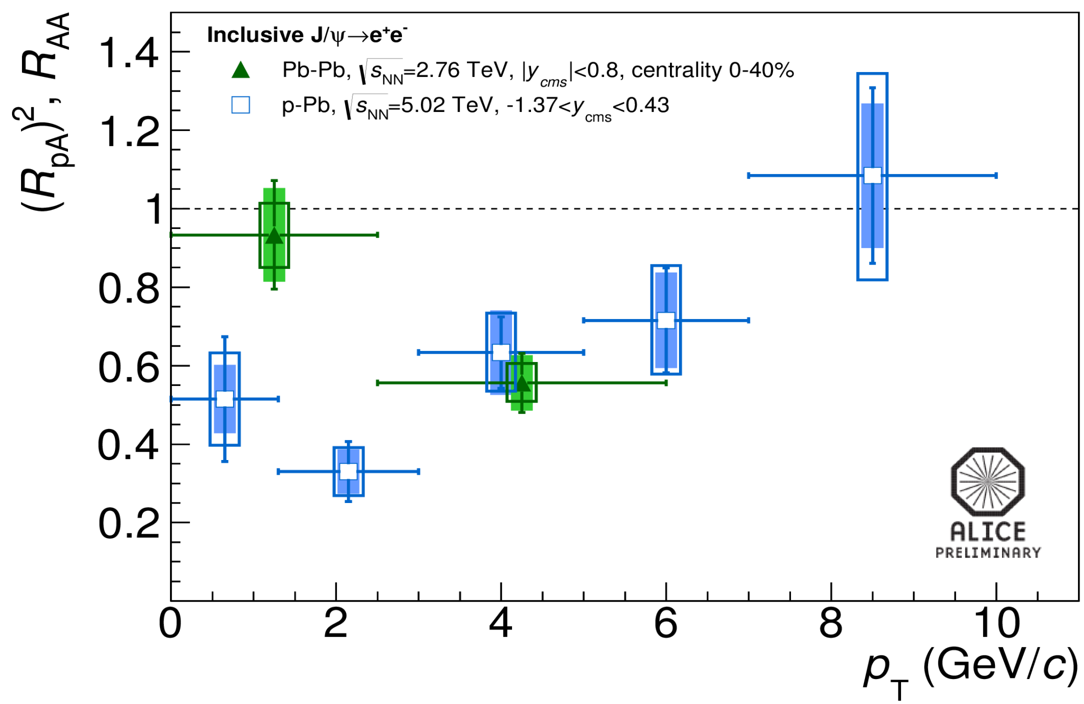
both affect signal extraction



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

arXiv:1405.1177

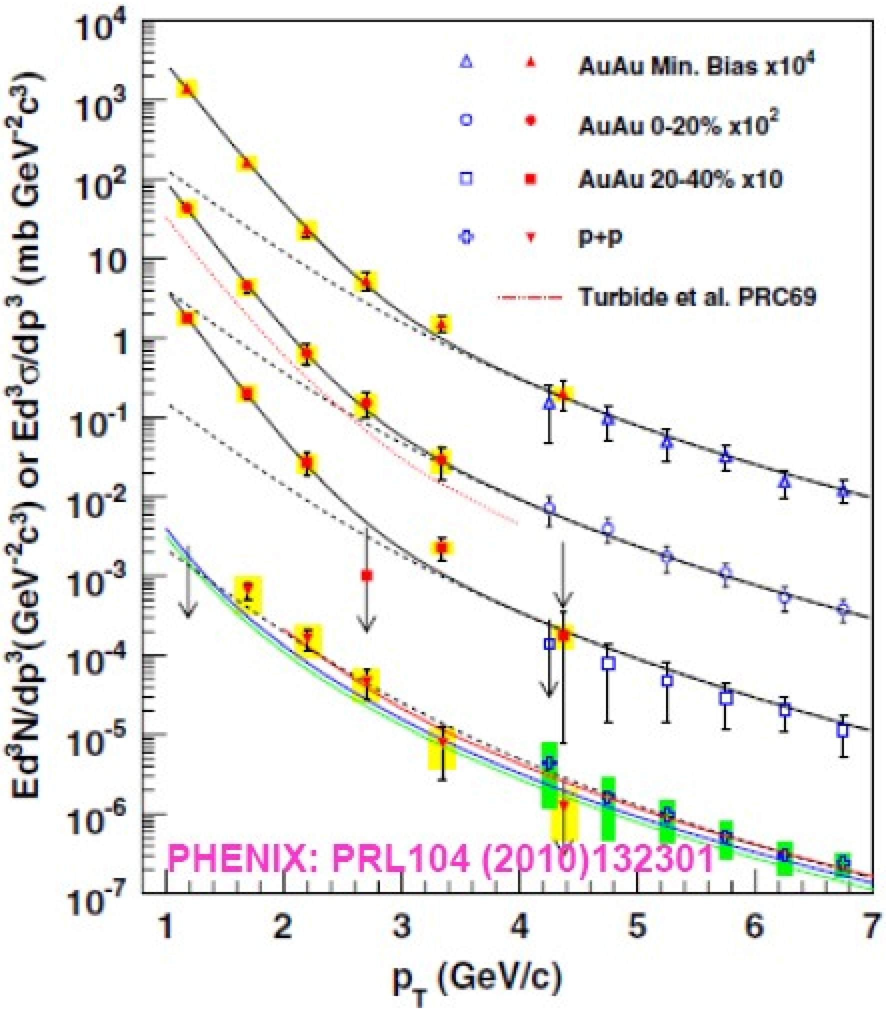


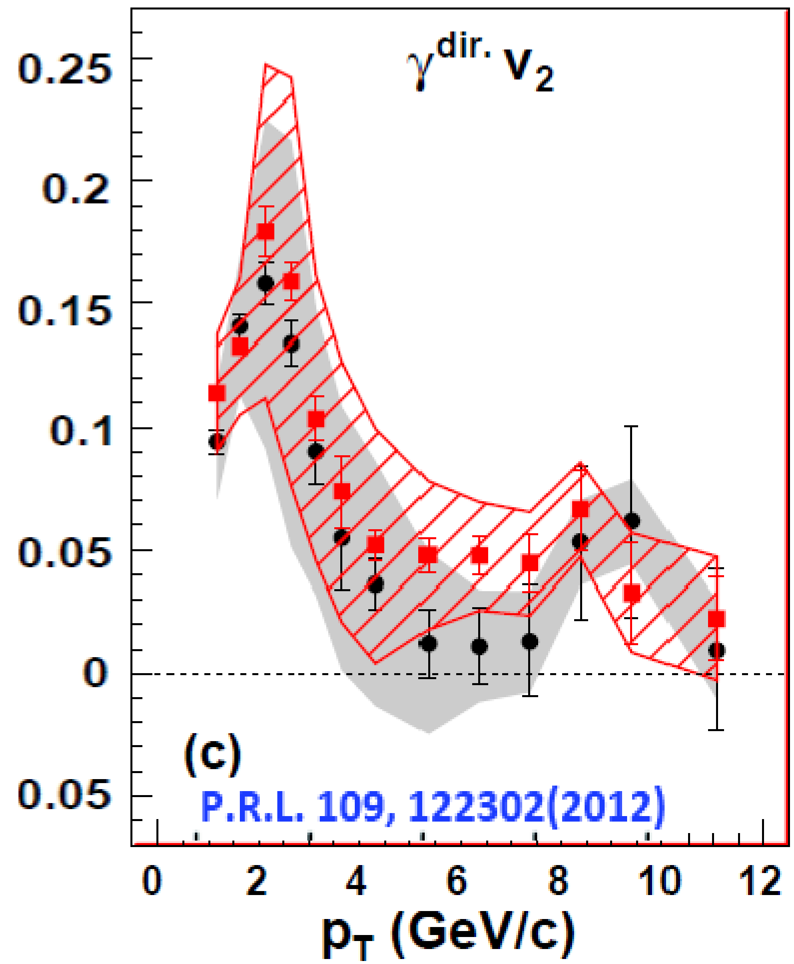


at low pt yield in nuclear collisions above pPb collisions

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

Direct photon excess and elliptic flow at low p_t at RHIC



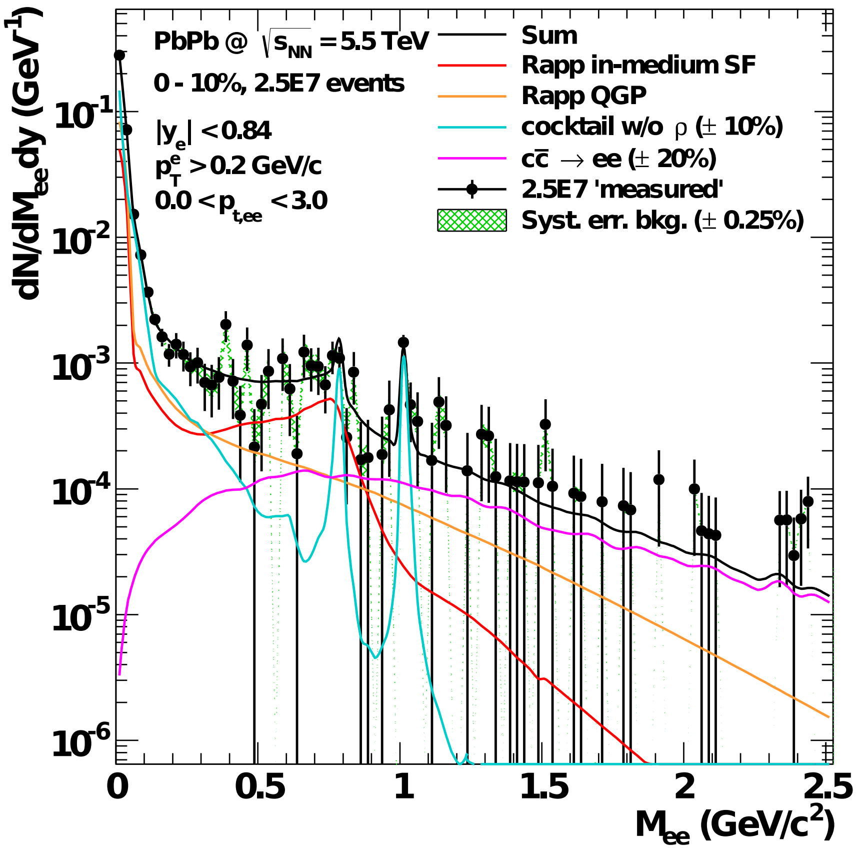


models underpredict photon yield and even more the photon v2

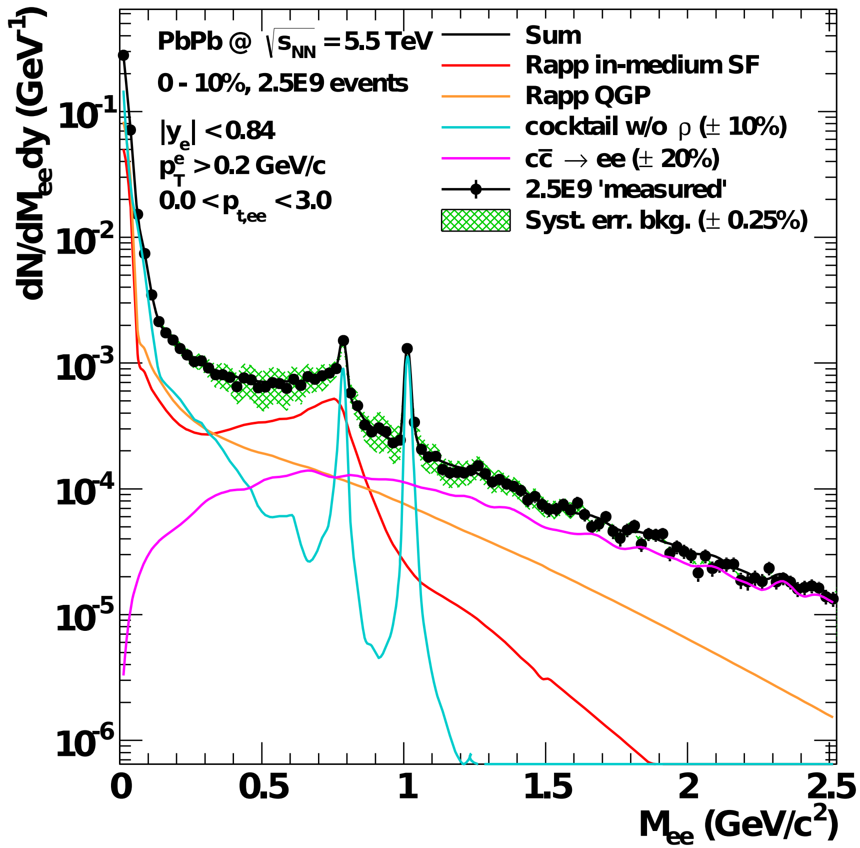
Electron pairs of low and intermediate mass
- experimentally very difficult – so far not addresses in PbPb at LHC

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