Hard QCD Probes in Heavy-Ion Collisions at RHIC and LHC

Sonia Kabana

University of Nantes and SUBATECH, France

6th International Workshop on High Energy Physics in the LHC Era
6-12 January 2016, Universidad Técnica Federico Santa Maria, Valparaiso, Chile

Outline

I Introduction

II Accelerator facilities and experiments

III Selected physics results from RHIC and LHC:

1. Jet quenching

   Single Hadrons (light, heavy quarks)

   Jets

2. Quarkonia

   J/Psi, Psi’

   Y

IV Conclusions and Perspectives

I Introduction

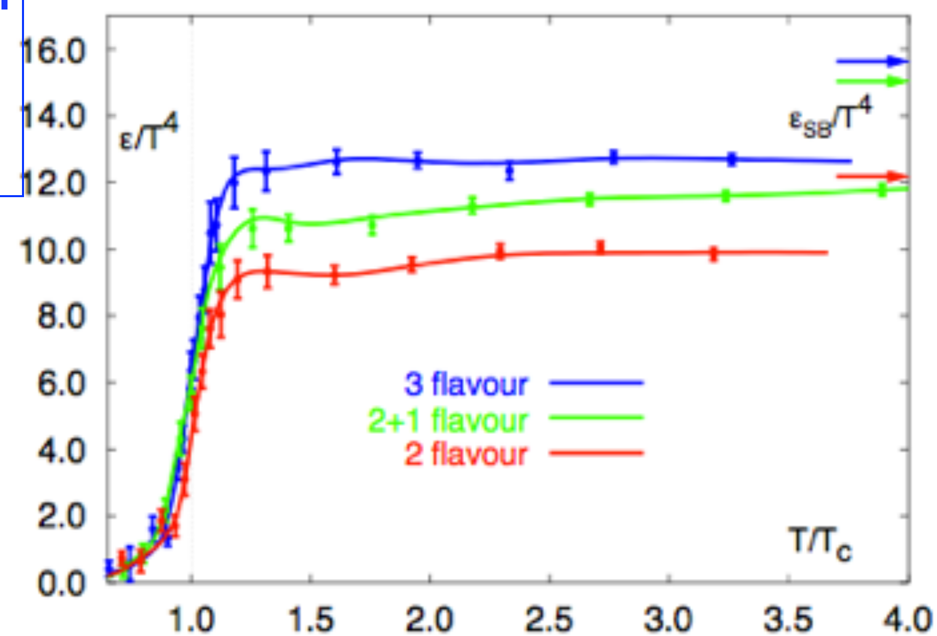
The QCD phase transition between hadronic and partonic phase

QCD on the lattice predicts a cross over at zero net baryon density with critical temperature Tc~154+-9 MeV (2014), critical energy density ~0.6 GeV/fm^3

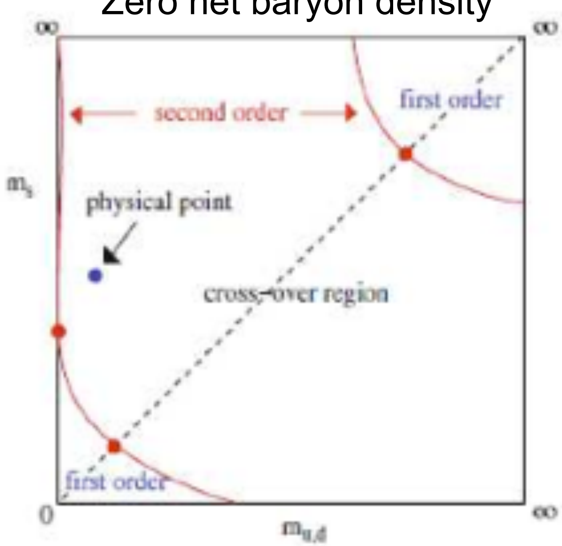
(Nuclear Density: rho=0.15 GeV/fm^3
Density inside Nucleon: rho=0.5 GeV/fm^3)

Zero net baryon density

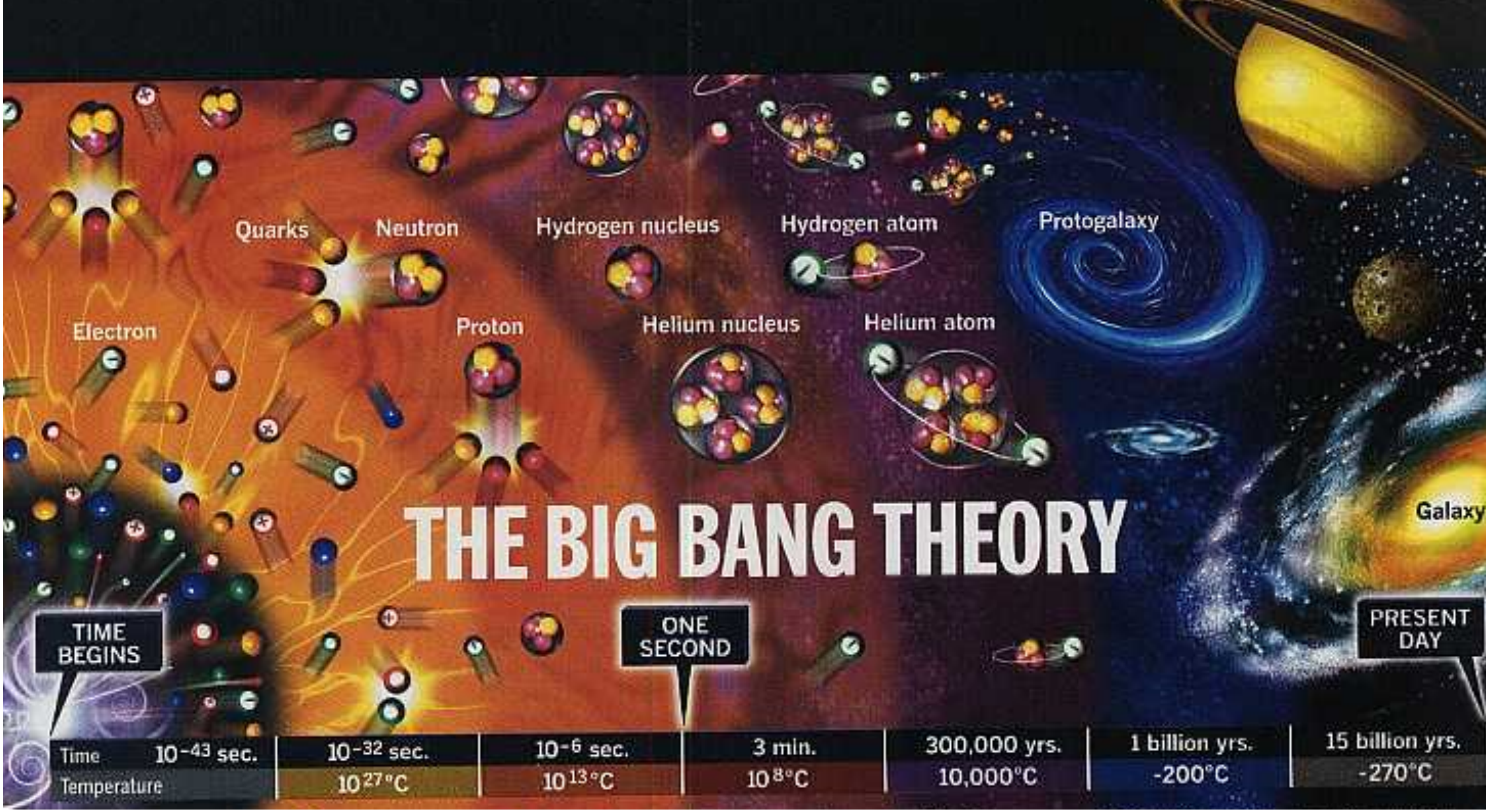
F. Karsch, Lect. Notes Phys. 583 (2002) 209, hep-lat/0106019



Zero net baryon density



The order of the transition depends on the parton masses. A cross over is expected for the physical point (for the physical u,d,s masses).

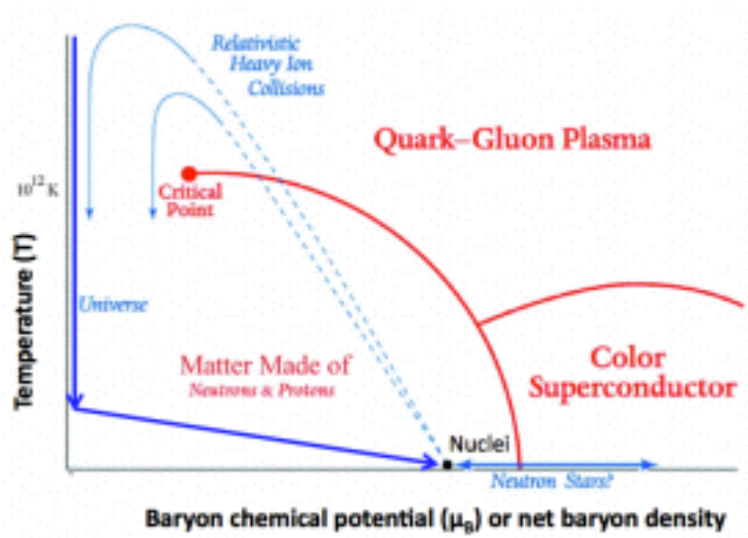


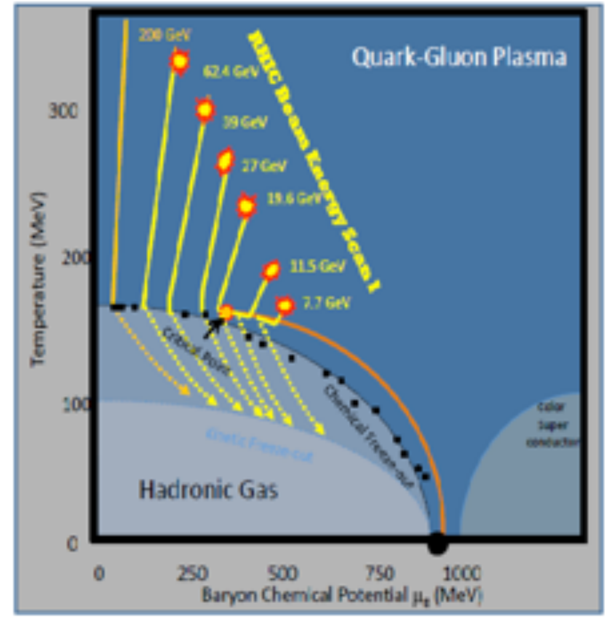
Big Bang - Inflation - Grand unification, SUSY? - electroweak symmetry breaking and mass generation - QCD phase transition - nucleosynthesis - Recombination/formation of atoms - CMB photons decoupling

The transition from quarks and gluons to hadrons is believed that took place few 10-6 sec after the Big Bang.
The QCD phase transition is the only phase transition of the early universe that can be reproduced in the Lab today

The expected QCD phase diagram

Ph. Rosnet,1510.04200





First calculation of path of early universe in the (T, muB) plane:

S.K., P. Minkowski, J Phys G 28 (2002) 2063-2067.

Phases of QCD Matter

Areas of different net baryon densities and temperatures can be probed using different collision energies and nuclei.

The order of the transition is expected to change with the net baryon density.

Goal: explore experimentally the QCD phase diagram (order, critical point, properties of the QGP).

Signatures of the Quark Gluon Plasma

A. Signatures originating "from the QGP itself" :

Direct photons from QGP → T(QGP)

Strangeness enhancement (Mueller, Rafelski 1981) → K/pi

U,d,s yields for T(freeze out) or pT slopes (Van Hove, H Stoecker et al) → plateau vs energy at Tc → e_init(crit), sqrt(s)("crit")

Multiquark states from QGP (Greiner et al) → 'small QGP-lumps'

Critical fluctuations near the critical point, Tc → K/pi, <pT>, etc

Hadronic mass/width changes (Pisarski 1982) → rho etc

Flow -> shear viscosity (eta/S), etc

B. Signatures of high pT probes altered by the QGP, "Hard Probes" :

Charmonia suppression (Satz, Matsui 1987) → T(dissociation) of ccbar, bbbar

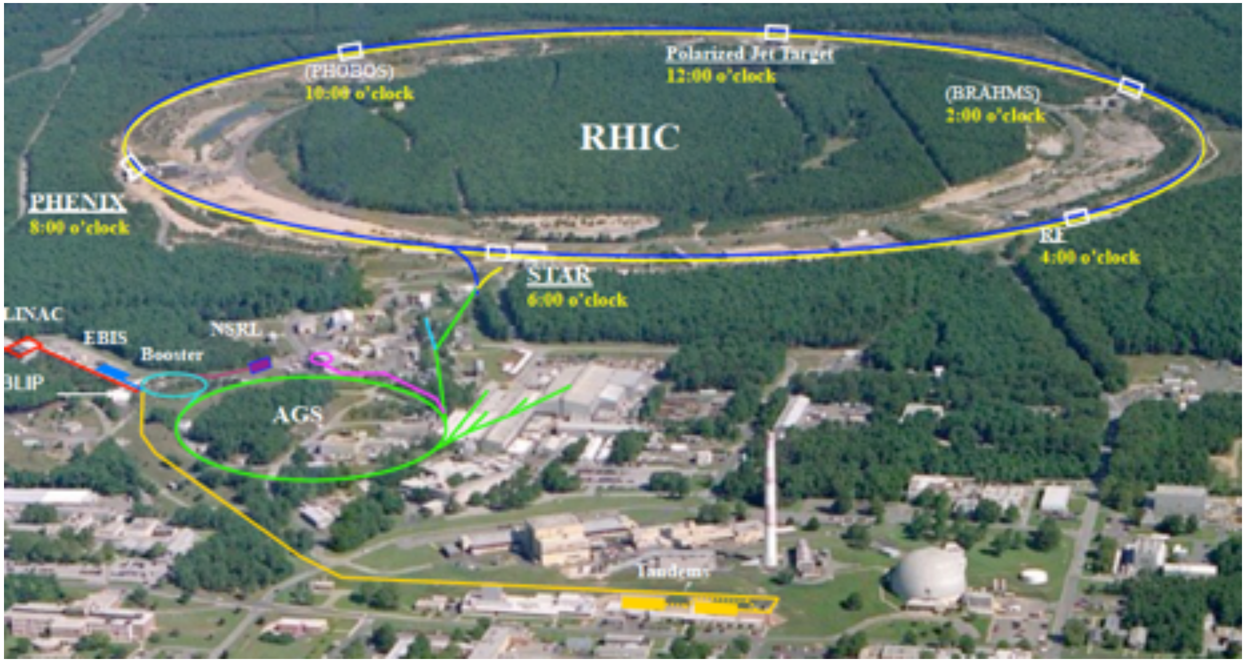
Jet quenching (J D Bjorken 1982) → medium density and properties

--> Goal is to achieve a combination of many signatures and measure the characteristic properties via multiple observables

II Accelerator facilities and experiments

Relativistic Heavy Ion Collider

at the Brookhaven Lab, Long Island, New York, USA



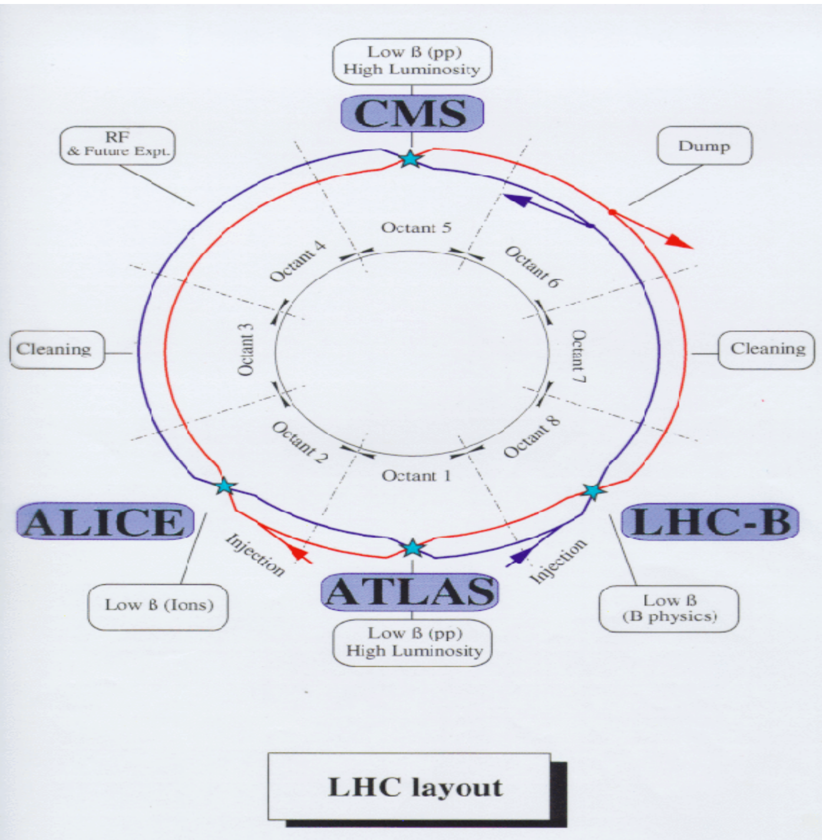
RHIC has been exploring nuclear matter at extreme conditions over the last 15 years 2000-2015

4 experiments initially:
STAR PHENIX
BRAHMS PHOBOS

Still runing: STAR and PHENIX

Colliding systems:
p+p, d+Au, Cu+Cu, Au+Au, Cu+Au, U+U, 3He+Au, p+Al/Au
Energies A+A :
$\sqrt{s_{NN}}$ = 62, 130, 200 GeV
and low energy scan e.g. 7.7, 11.5, 19.6, 22.4, 27, 39 GeV
Energies p+p : 200, 500 GeV
Energies d/p+A : 200 GeV

Large Hadron Collider (LHC) at CERN

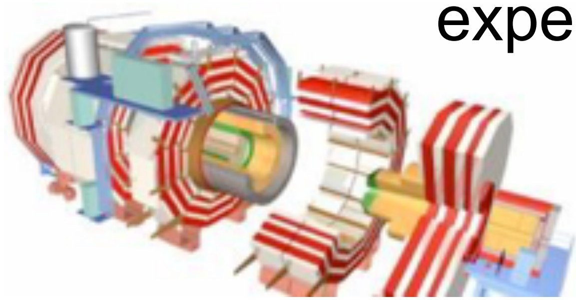


run-1: p+p $\sqrt{s_{NN}}$ =0.9, 2.76, 7, 8 TeV, p+Pb $\sqrt{s_{NN}}$ =5.02 TeV, Pb+Pb at $\sqrt{s_{NN}}$ =2.76 TeV
run-2; p+p $\sqrt{s_{NN}}$ = 13 TeV Dec 2015: Pb+Pb at $\sqrt{s_{NN}}$ =5.1 TeV

Current Experiments with Heavy Ion program

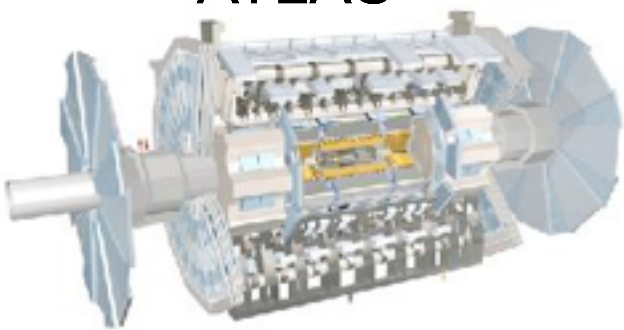
LHC experiments

CMS



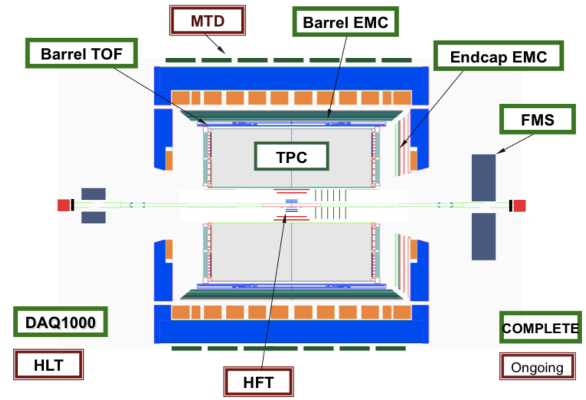
LHCb

ATLAS

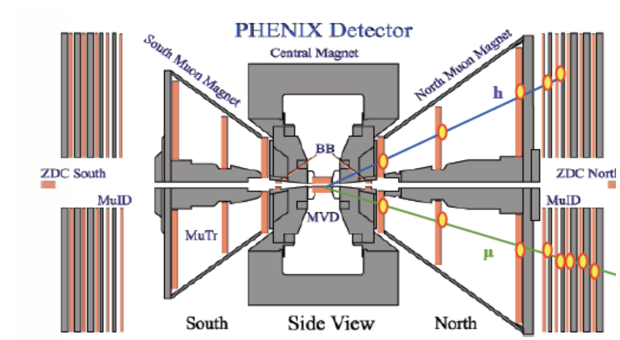


ALICE

STAR at RHIC

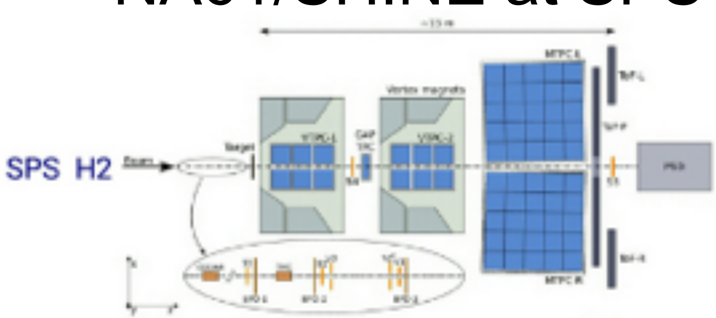


PHENIX at RHIC



$1.2<|y|<2.2 \quad \Delta\Phi=2\pi$

NA61/SHINE at SPS

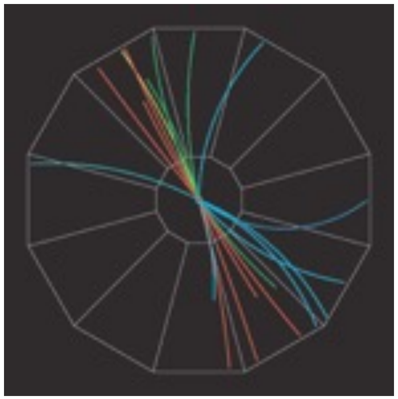


III Selected physics results:

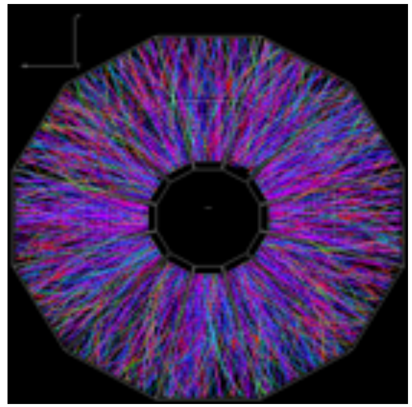
1. Jet quenching

Jet quenching

p+p Collision



Au+Au Collision

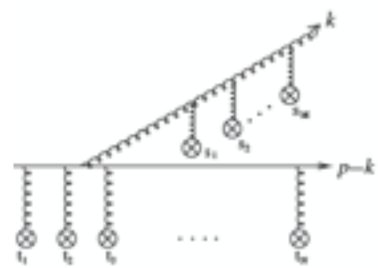


Partons interact with the medium and loose energy through eg gluon radiation

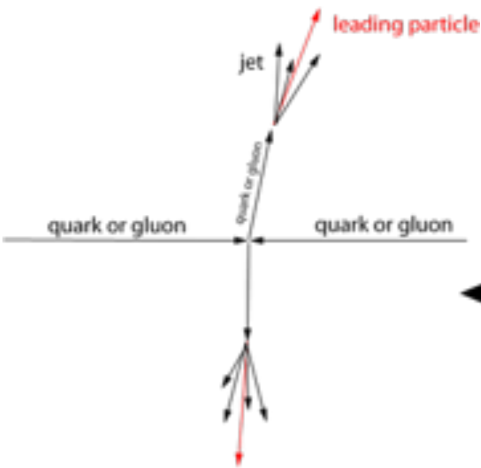
Collisional "elastic" energy loss: elastic interaction with the medium

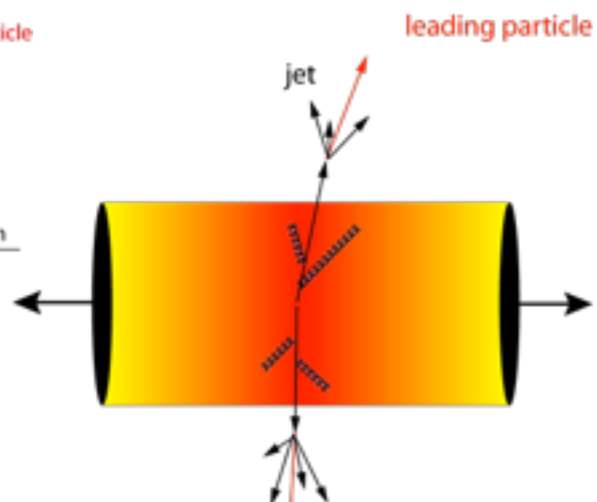
Energy loss
$DE \sim L$

Radiative energy loss: parton radiation due to interaction with the medium



$DE \sim L^2$





Baier et al (BDMPS), Gyulassy et al (GLV+D), Arnold et al (AMY), JP Blaizot et al, U Wiedemann et al, J. Aichelin et al, B. Kopeliovich et al, AdS/CFT, etc

Jet quenching

We compare A+A to expectations from p+p, using often the "nuclear modification factor" R_{AA} defined as:

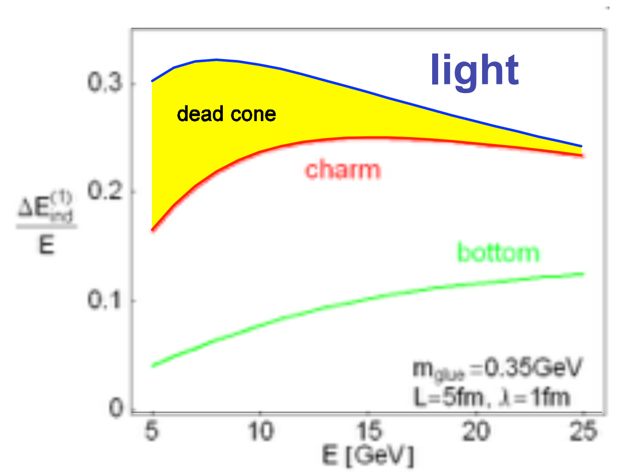
$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times \langle N_{coll} \rangle}$$

N coll : Average number of NN collisions in AA collision

Suppression of jets in A+A: $R_{AA} < 1$

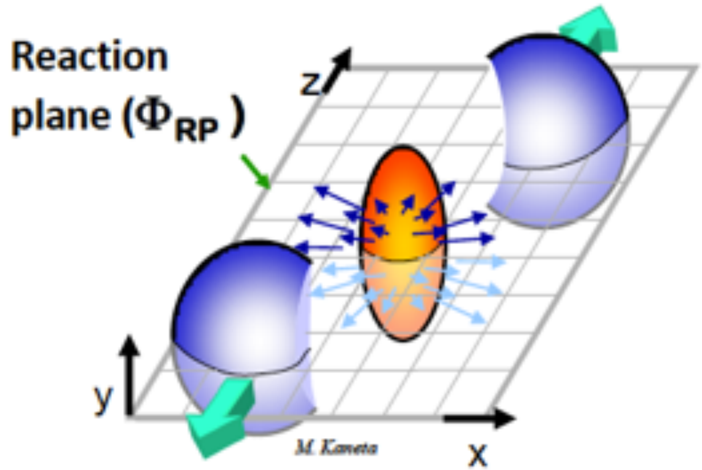
Mass dependence

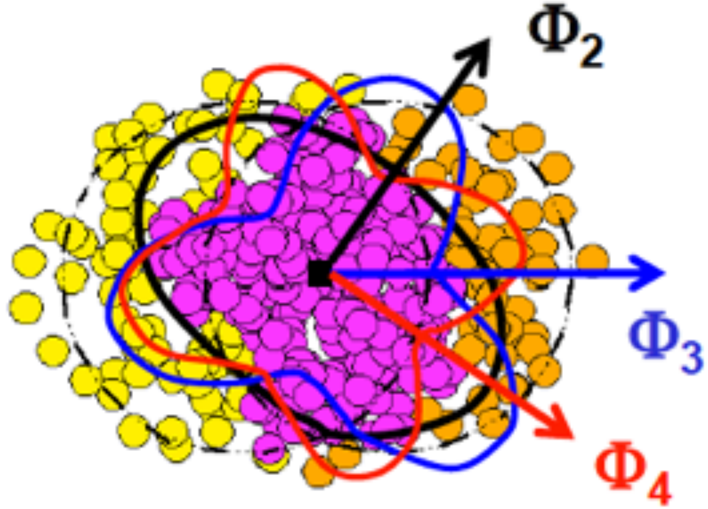
Quarks are expected to exhibit different radiative energy loss depending on their mass (**D.Kharzeev et al. Phys Letter B. 519:1999**)



M.Djordjevic PRL 94 (2004)

Flow coefficients v_n, n=1,2,3..





Matter in the overlapp area of two colliding nuclei gets compressed and heated

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \Phi_n)]$$

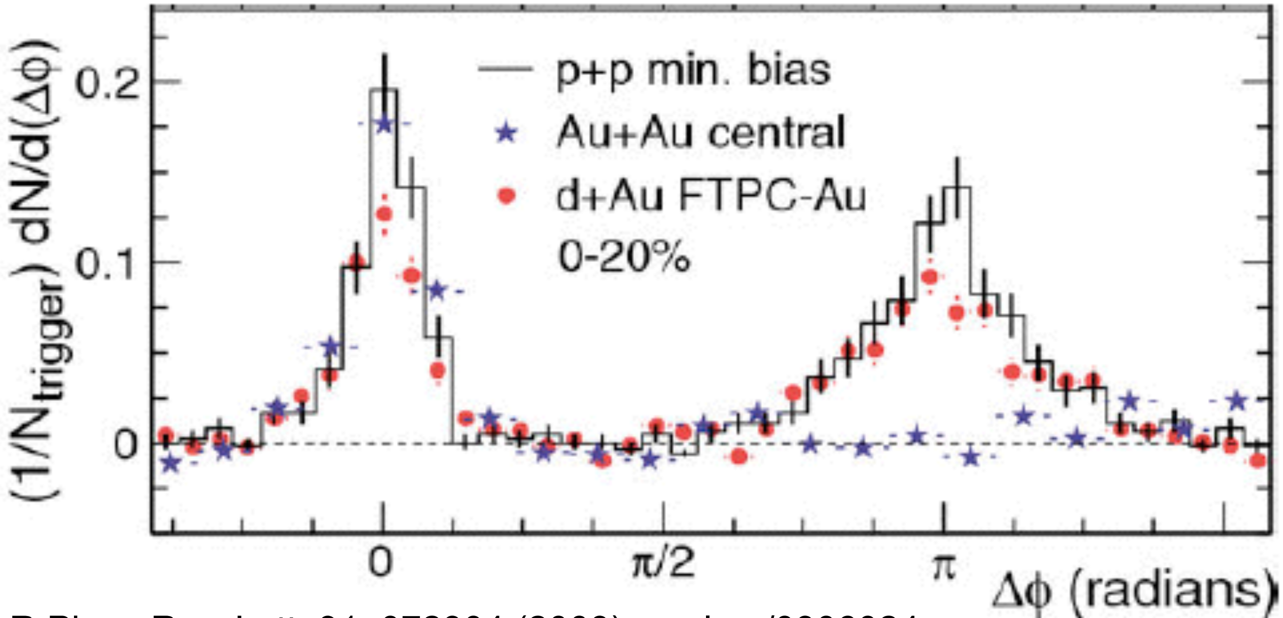
$$v_n = \langle \cos[n(\phi - \Phi_n)] \rangle$$

v : flow coefficients
(v1: directed flow, v2: elliptic flow, ...)

Discovery of jet quenching at RHIC (2003)

Jet quenching was discovered at RHIC

RHIC white papers for the 4 RHIC experiments 2005

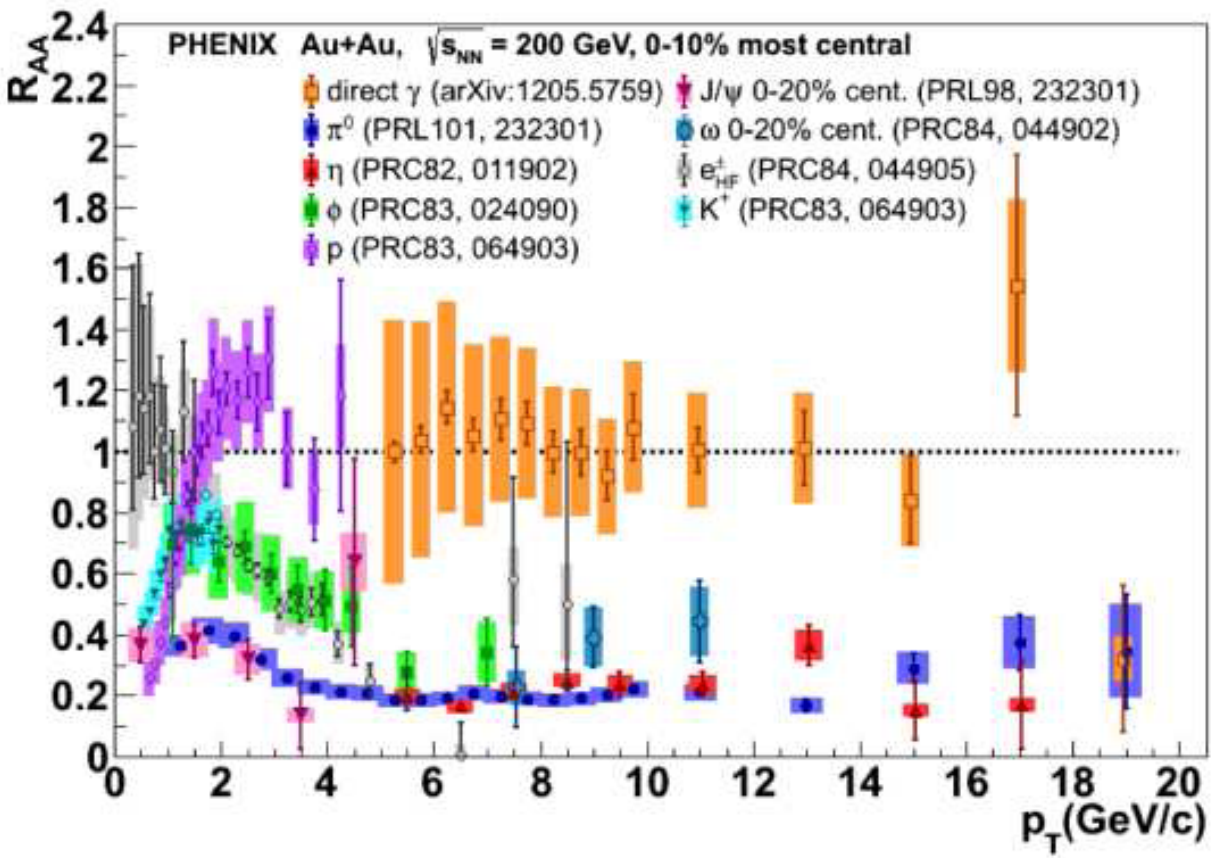


STAR Phys. Rev. Lett. 91, 072304 (2003), nucl-ex/0306024.

Dihadron correlations for pT(trig)=(4,6 GeV) and pT(associated)=(2 GeV,pT(trig))

Single hadrons

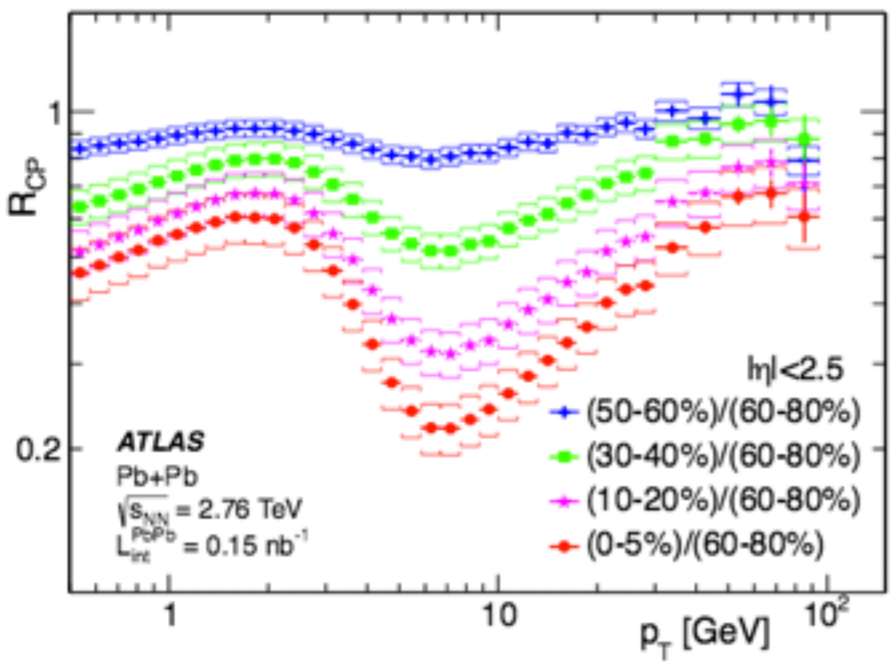
Jet quenching of light hadrons at RHIC

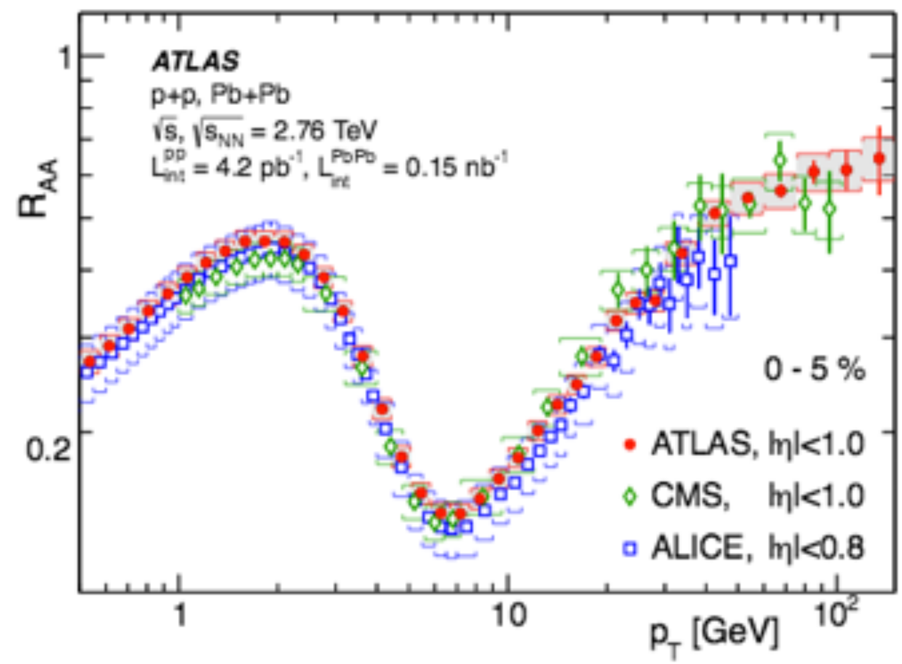


*** Light hadrons are quenched**
*** Photons are not quenched**

RAA of charged particles in Pb+Pb at LHC

ATLAS, arXiv: 1504.0337

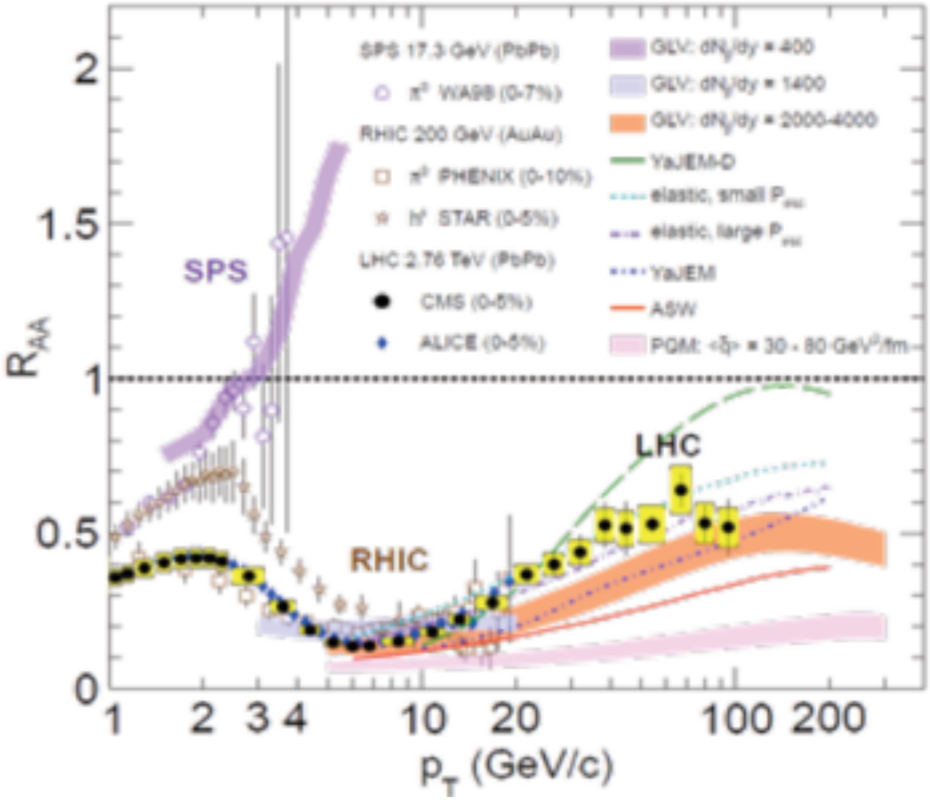




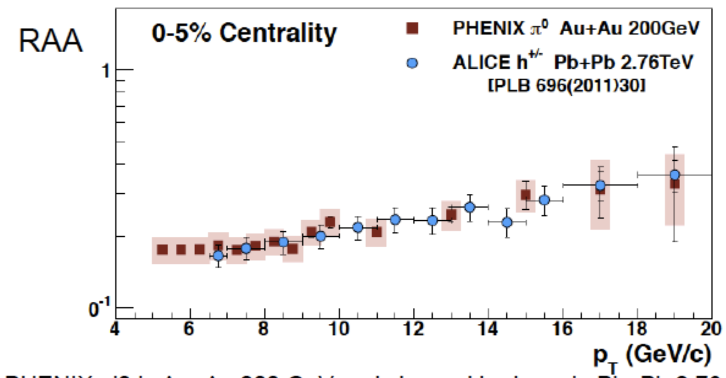
RAA vs pT in Pb+Pb by ATLAS study of centrality dependence

RAA in 0-5% Pb+Pb by ATLAS, ALICE, CMS

Jet quenching hadrons
Collision energy dependence



Sakaguchi, PHENIX, QM2012



PHENIX pi0 in Au+Au 200 GeV and charged hadrons in Pb+Pb 2.76 TeV 0-5% look very similar

Same RAA for pions at RHIC and LHC at high pT

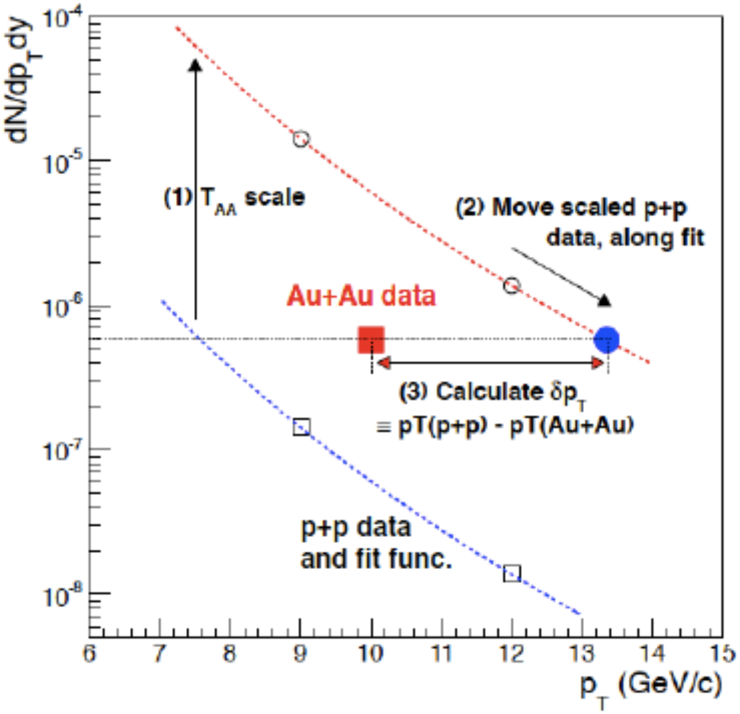
RAA compared to models for energy loss allows for an estimate of gluon density dN/dy(gluon)
Here as an example we get (GLV model):

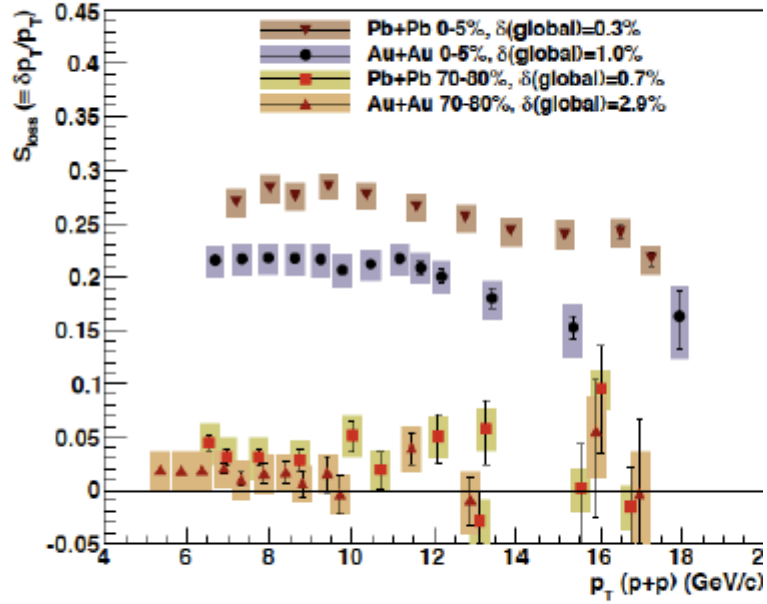
dN/dy(g)=400 for SPS
dN/dy(g)=1400 for RHIC
dN/dy(g)=2000-4000 for LHC

To estimate with confidence dN/dy(g), we should understand the mechanism of jet quenching via studies of its dependence from pT, energy, event plane, path length, centrality, quark mass etc

Fractional momentum loss is different at RHIC and LHC

PHENIX exp.





Measure fractional momentum loss instead of RAA

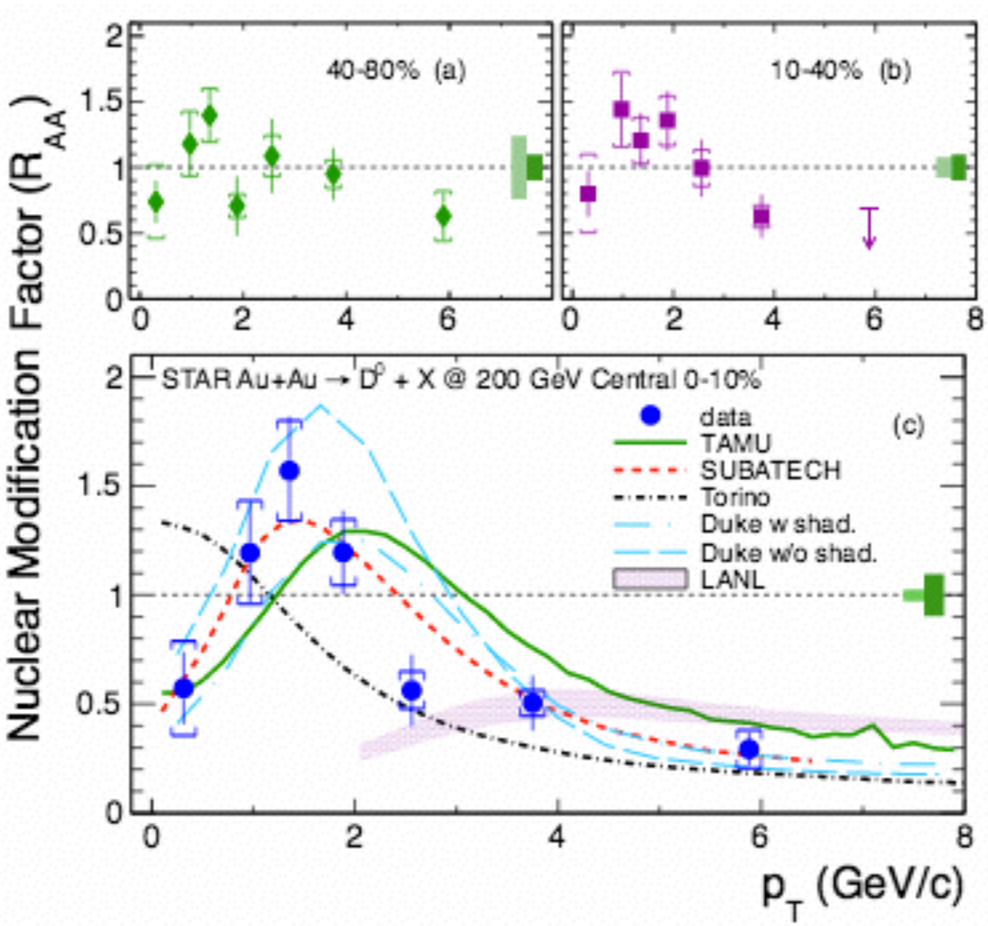
arXiv 1208.2254

- Different dpT/pt for RHIC and LHC, for same RAA
- dpt/pt is 25% higher for ALICE
- dpt/pt decreases slightly with increasing pt (where rise of RAA occurs)

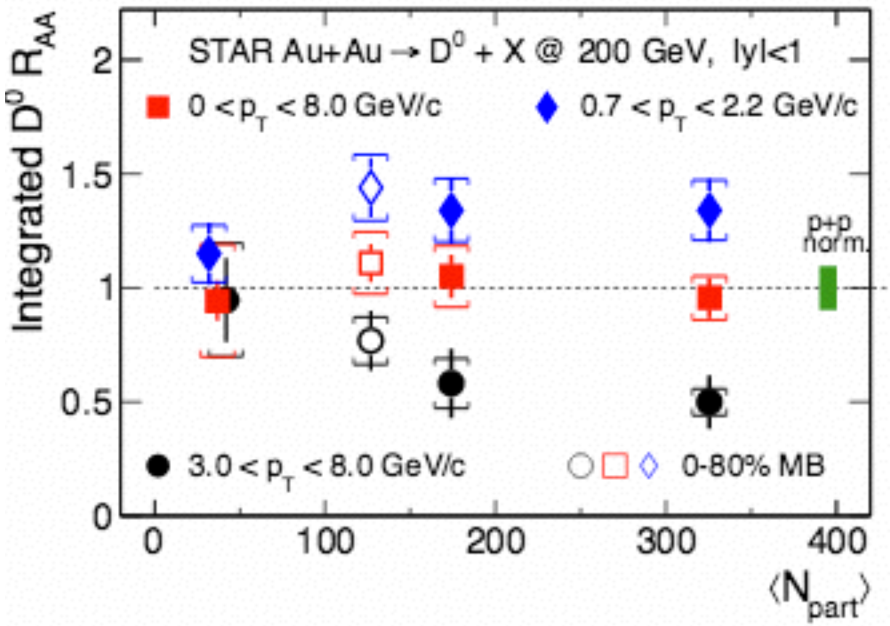
Fract. momentum loss : dpt(LHC) ~ 1.25 dpt(RHIC)
Charged multiplicity: dN/dy(LHC) ~ 2.2 dN/dy(RHIC)

M. Tannenbaum and PHENIX collaboration

STAR R_{AA} of D_0 in Au+Au 200 GeV



STAR: Phys. Rev. Lett. **113** (2014) 142301 and 1404.6185

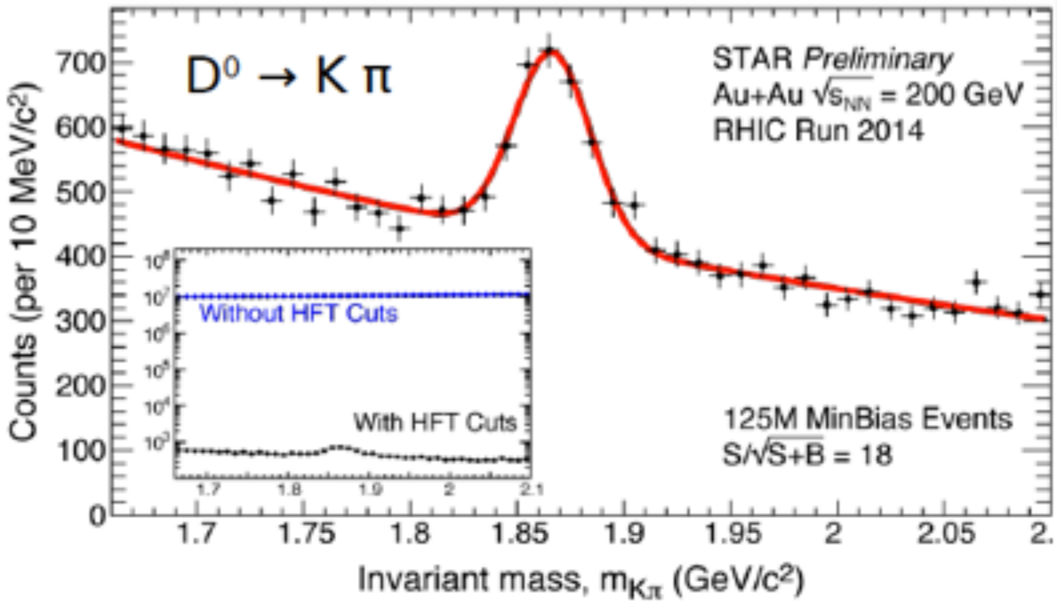


- RAA D0 suppression in central Au+Au 200 GeV
- suppression at high p_T similar to pions
- Enhancement at pT~0.7-2 GeV (described eg by models with charm quark coalescence with light quarks)

New results from Heavy Flavor Tracker of STAR run-14

Secondary vertex reconstruction of D mesons with HFT

STAR, QM15

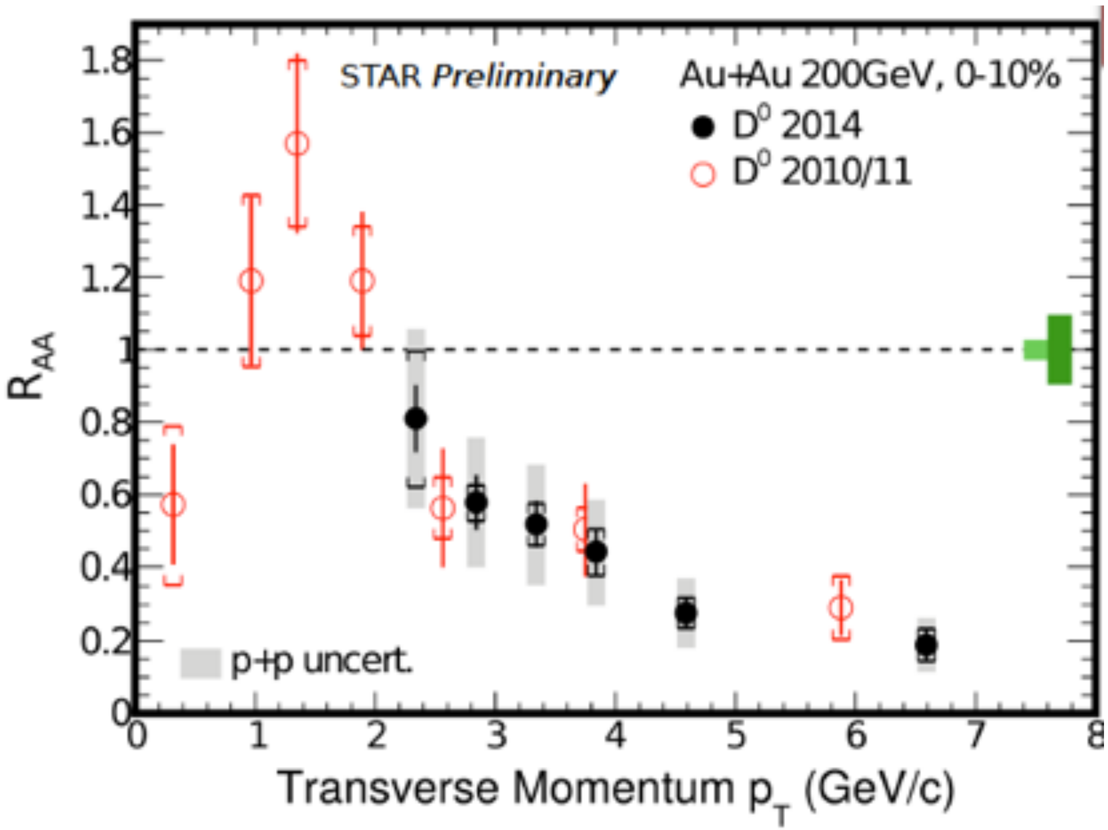


~ 4 orders of magnitude reduction of combinatorial background

Significance per billion events : without HFT= 13, with HFT= 51

Total significance ~ 39 (min bias all pt)

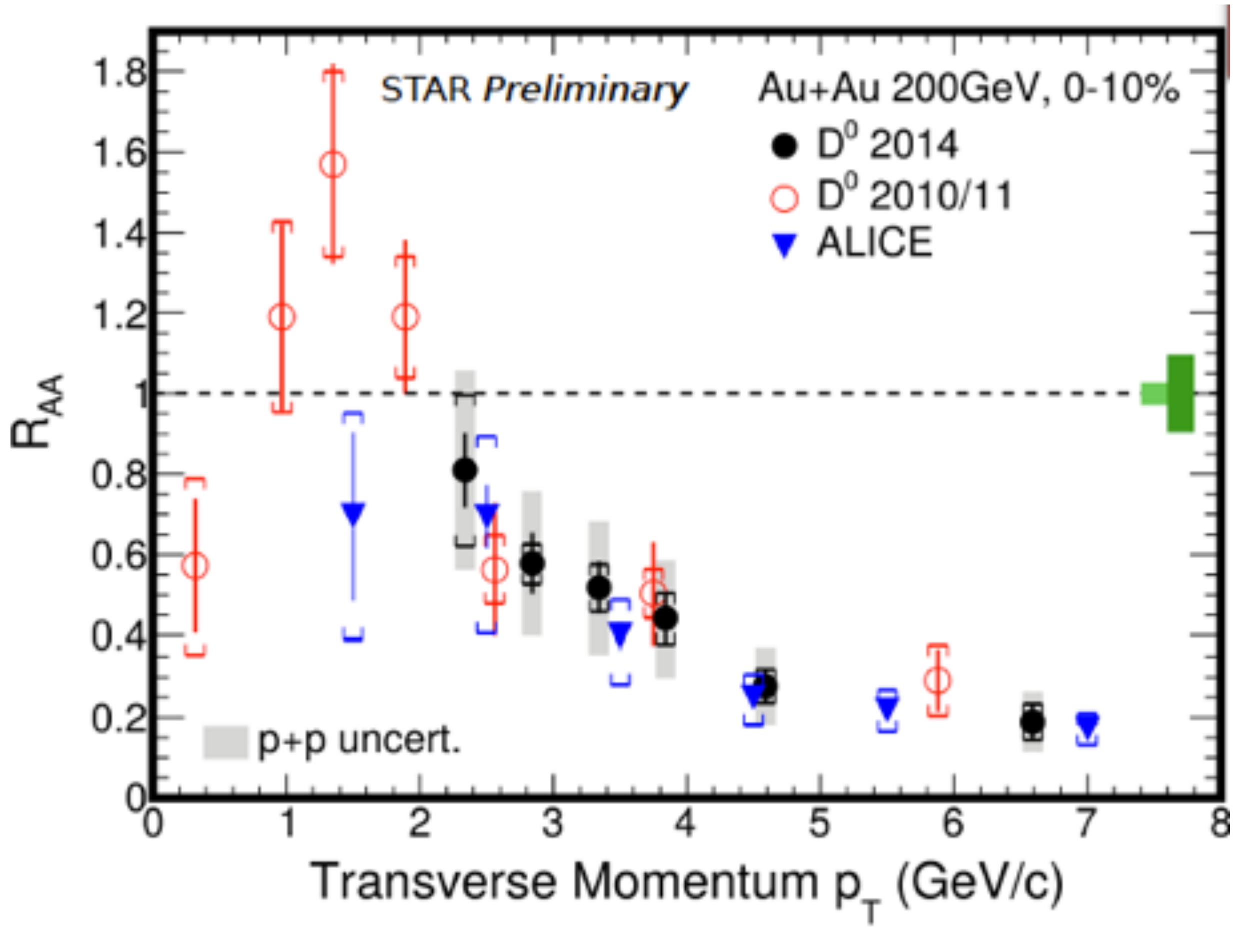
D0 nuclear modification factor in Au+Au 200 GeV from HFT



STAR, QM15

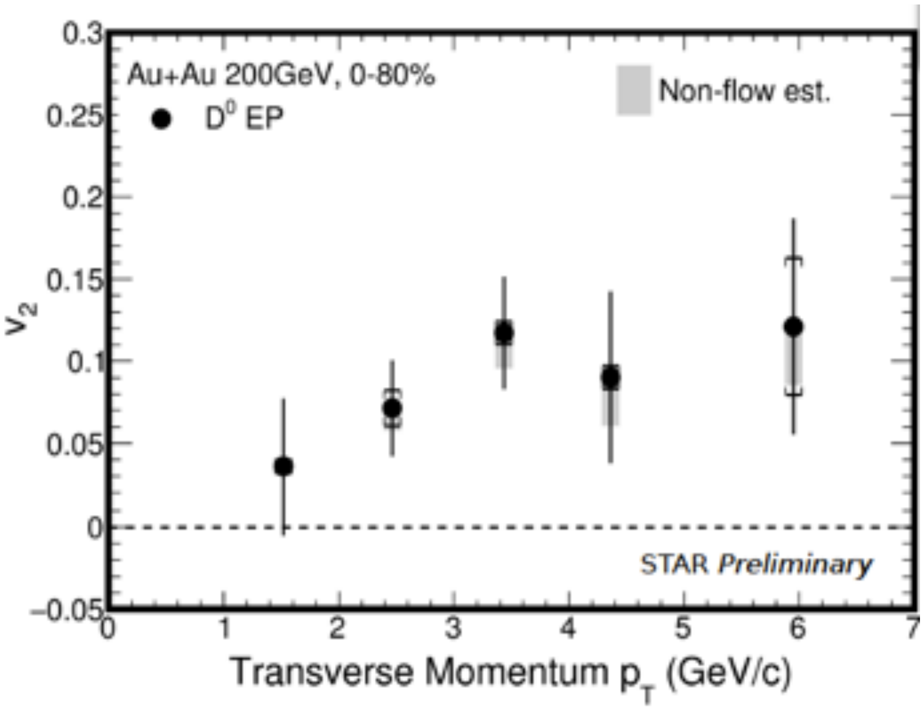
Suppression of D0 at high pT
Enhancement of D0 at pT<2 GeV/c pointing to charm coalescence with a flowing medium

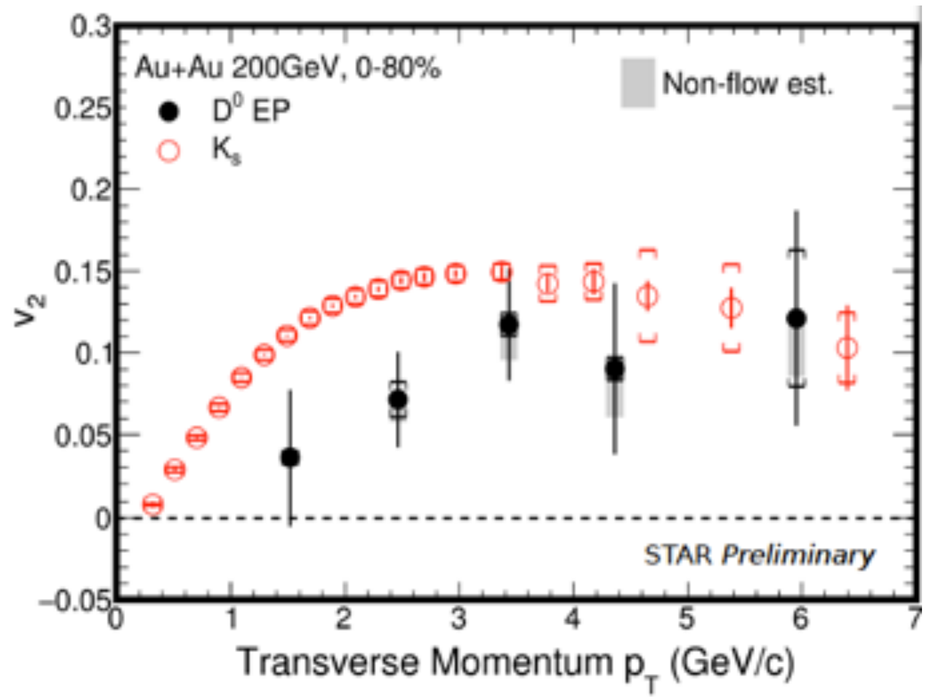
Comparison RHIC to LHC



RAA of D0 mesons is similar in RHIC and LHC at pT>2 GeV/c

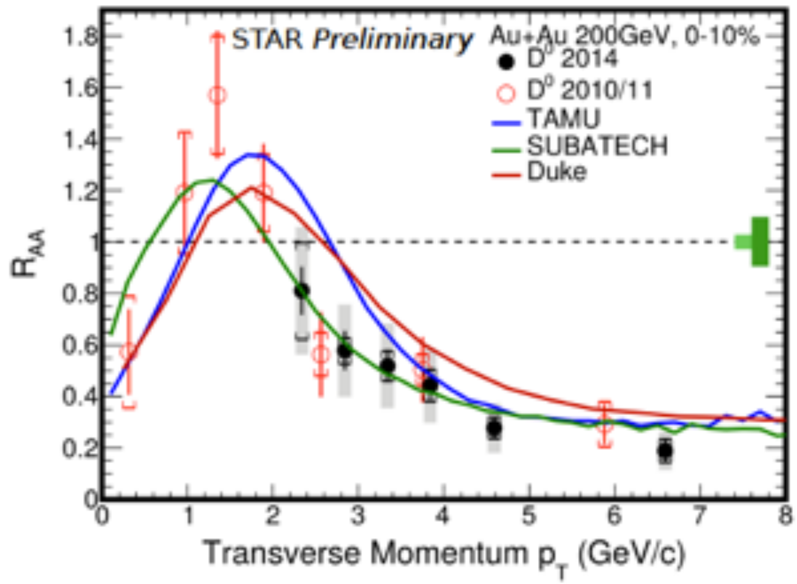
D0 v2 with the HFT

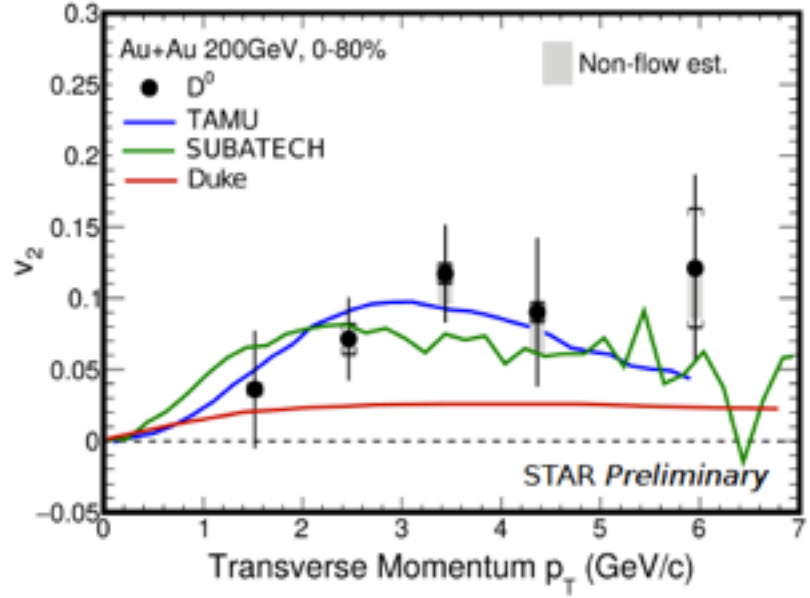


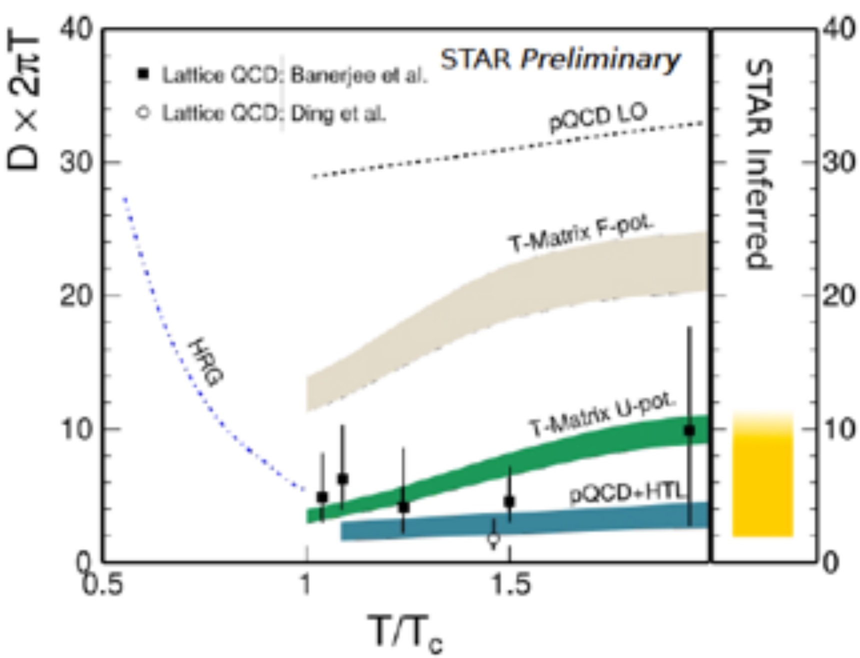


Observation of finite v2 of D0 mesons at pT>2 GeV/c
The v2 of D0 is lower than v2 of light hadrons at pT<3 GeV/c

Comparison to theory



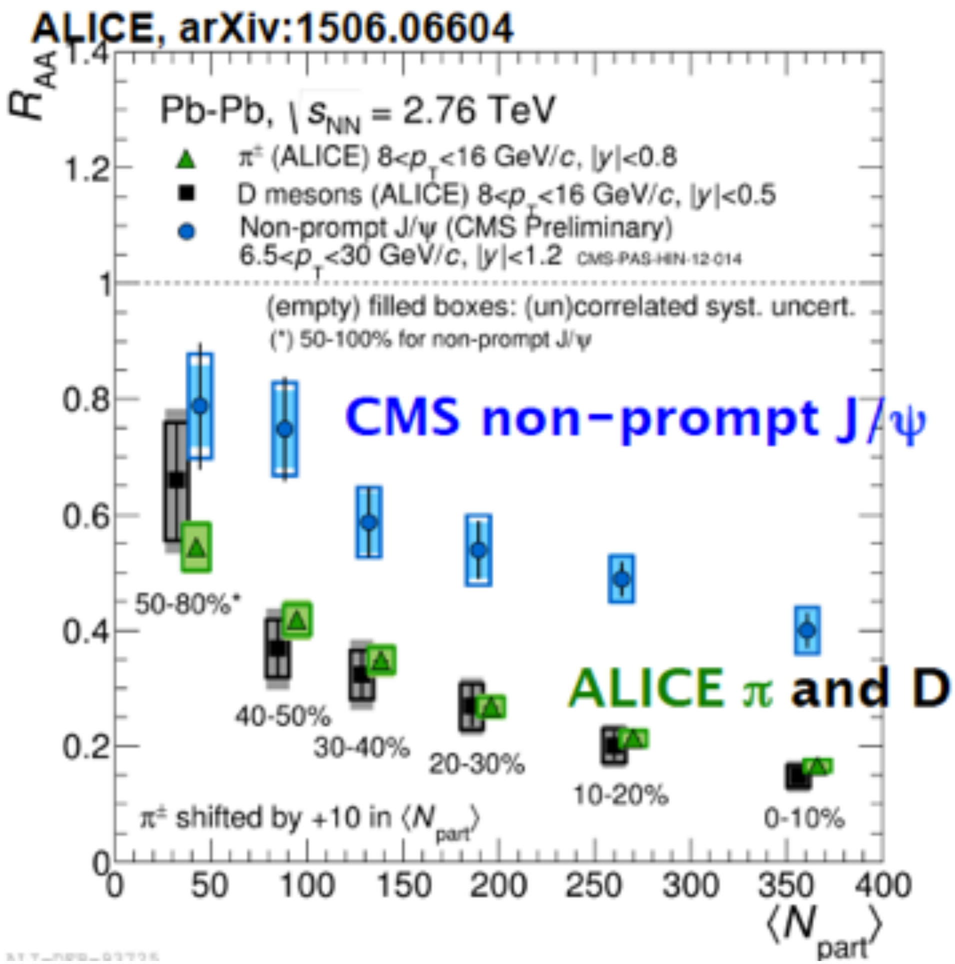




Models with charm diffusion coefficient of 2-10 agree with STAR data on RAA and v2

Lattice calculations are consistent with the values that agree with STAR data

RAA of open charm and beauty at the LHC



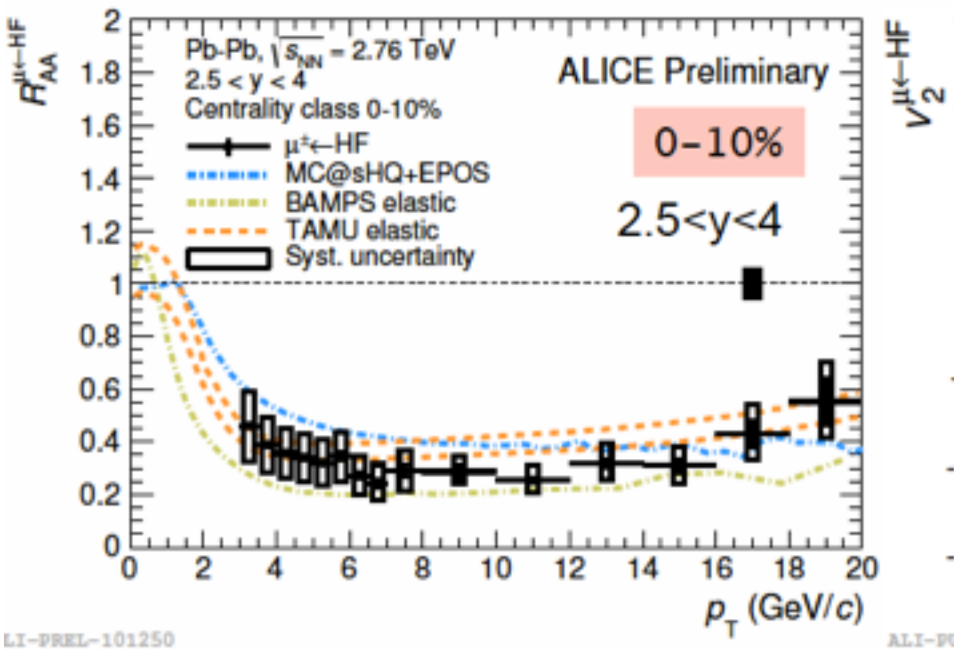
ALICE, QM2015

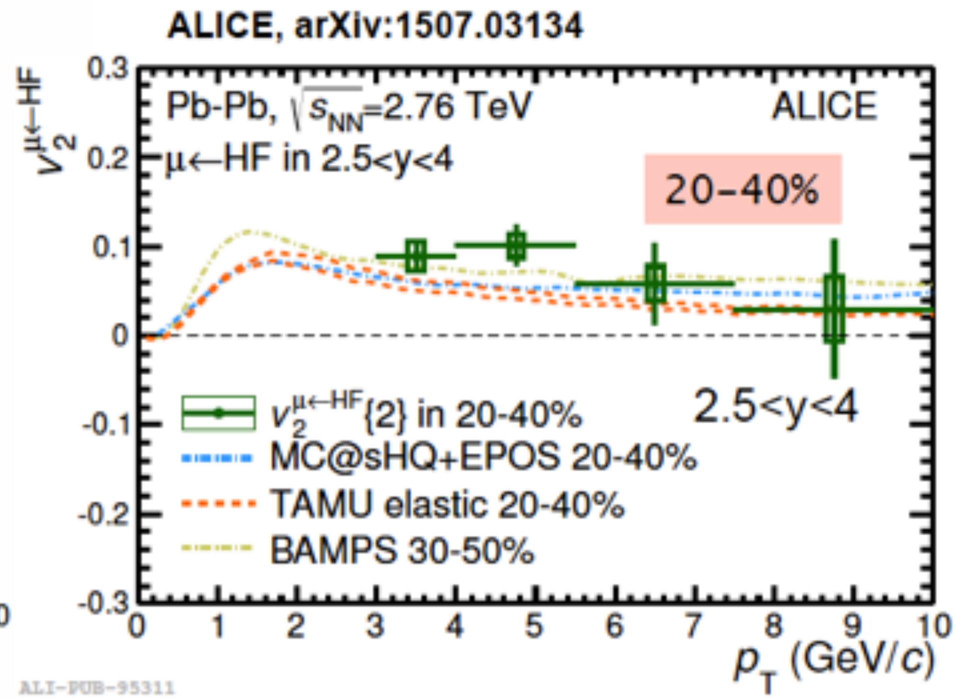
Pb+Pb ALICE, CMS:

RAA of D mesons is much smaller than RAA of non-prompt J/Psi representing open beauty (B->J/Psi X) (but pT range different)

RAA of pions and D mesons is consistent (pT range is the same)

Heavy flavor (c,b) -> muon ALICE

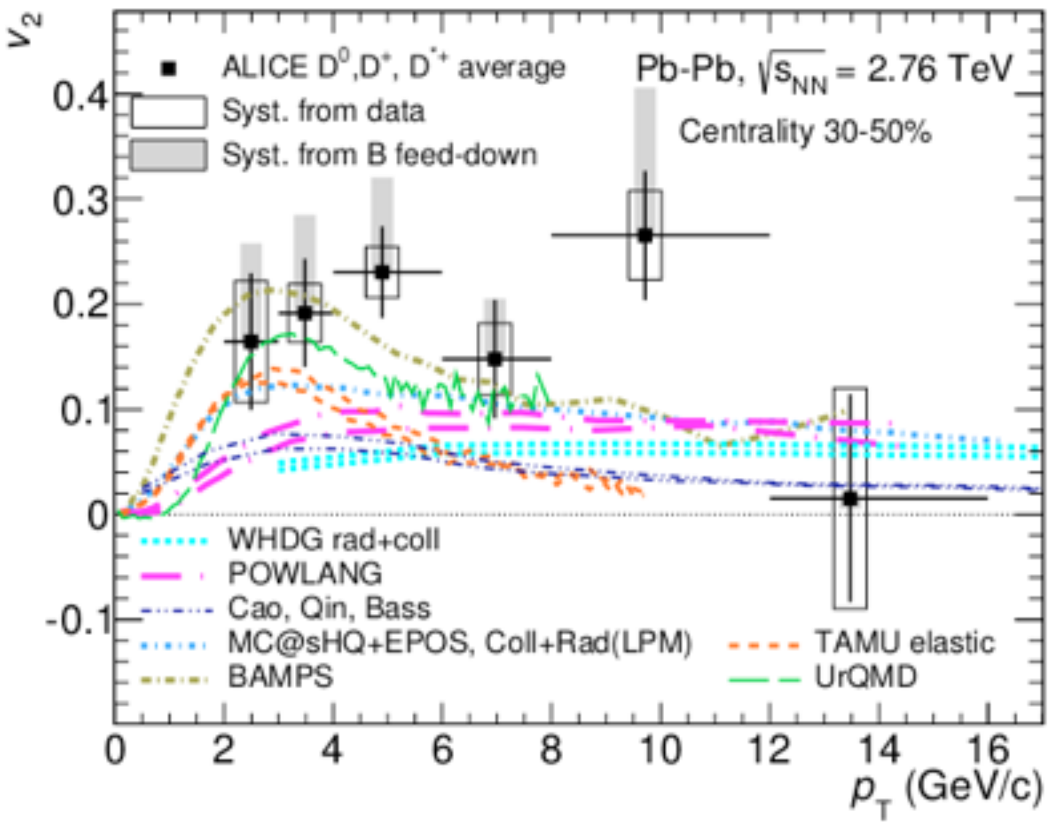




A. Dubla

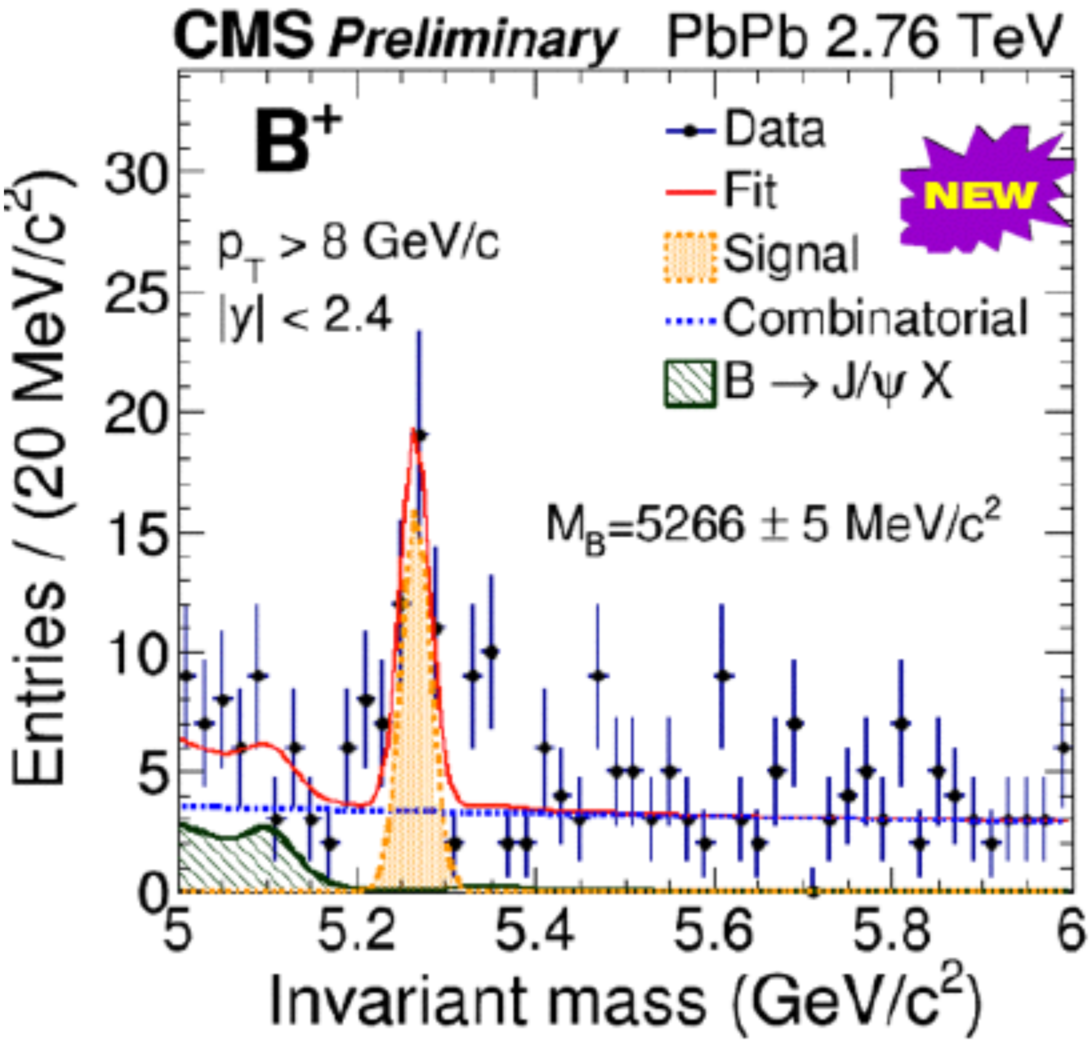
RAA extended up to pT 20 GeV
RAA and v2 described by transport model calculations

Flow of heavy flavor at LHC



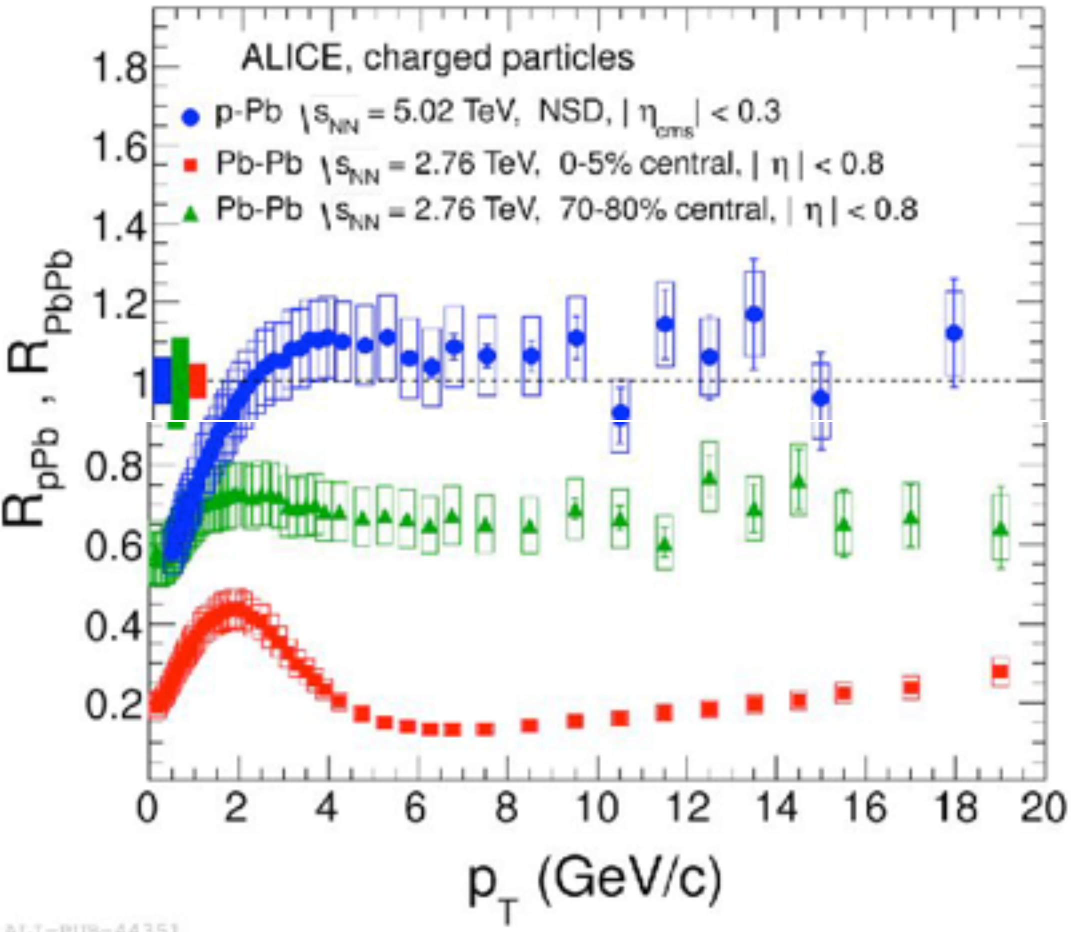
D mesons exhibit a strong v2 component
-> charm quarks participate in the collective evolution of the system?

First measurement of a B meson in A+A collisions



Ta-Wei Wang, CMS Hard Probes 2015

p+Pb and Pb+Pb data at LHC



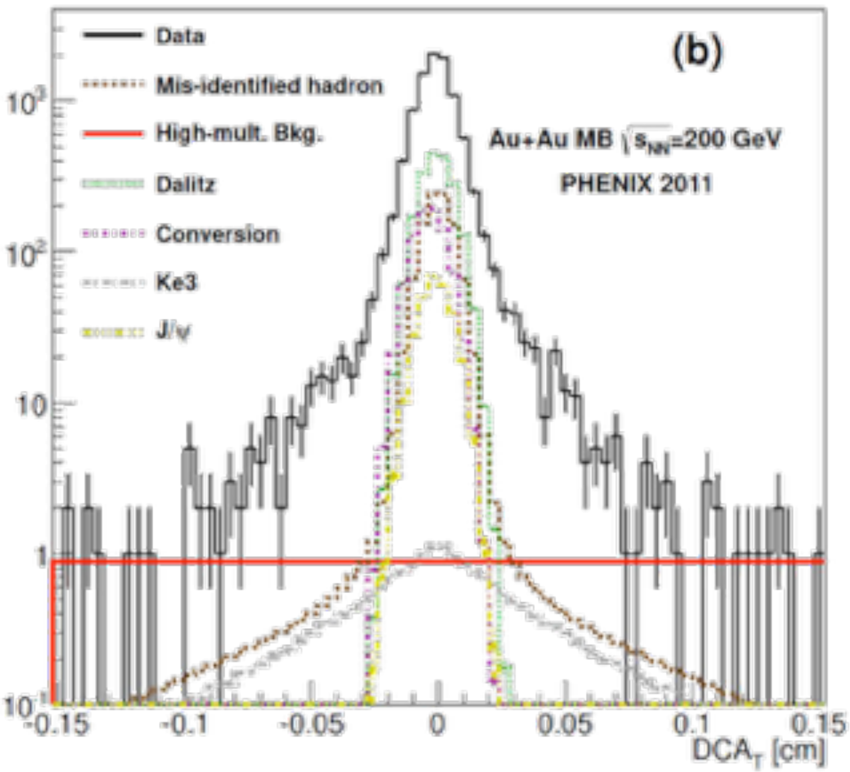
R(PbPb) suppressed at high pT

R(pPb) for charged particles is compatible with 1 at hight pT
no jet quenching in p+PB

The jet quenching seen in Pb+Pb is not due to cold nuclear matter effects

PHENIX: Charm and Beauty in Au+Au at 200 GeV using the Silicon Vertex Tracker

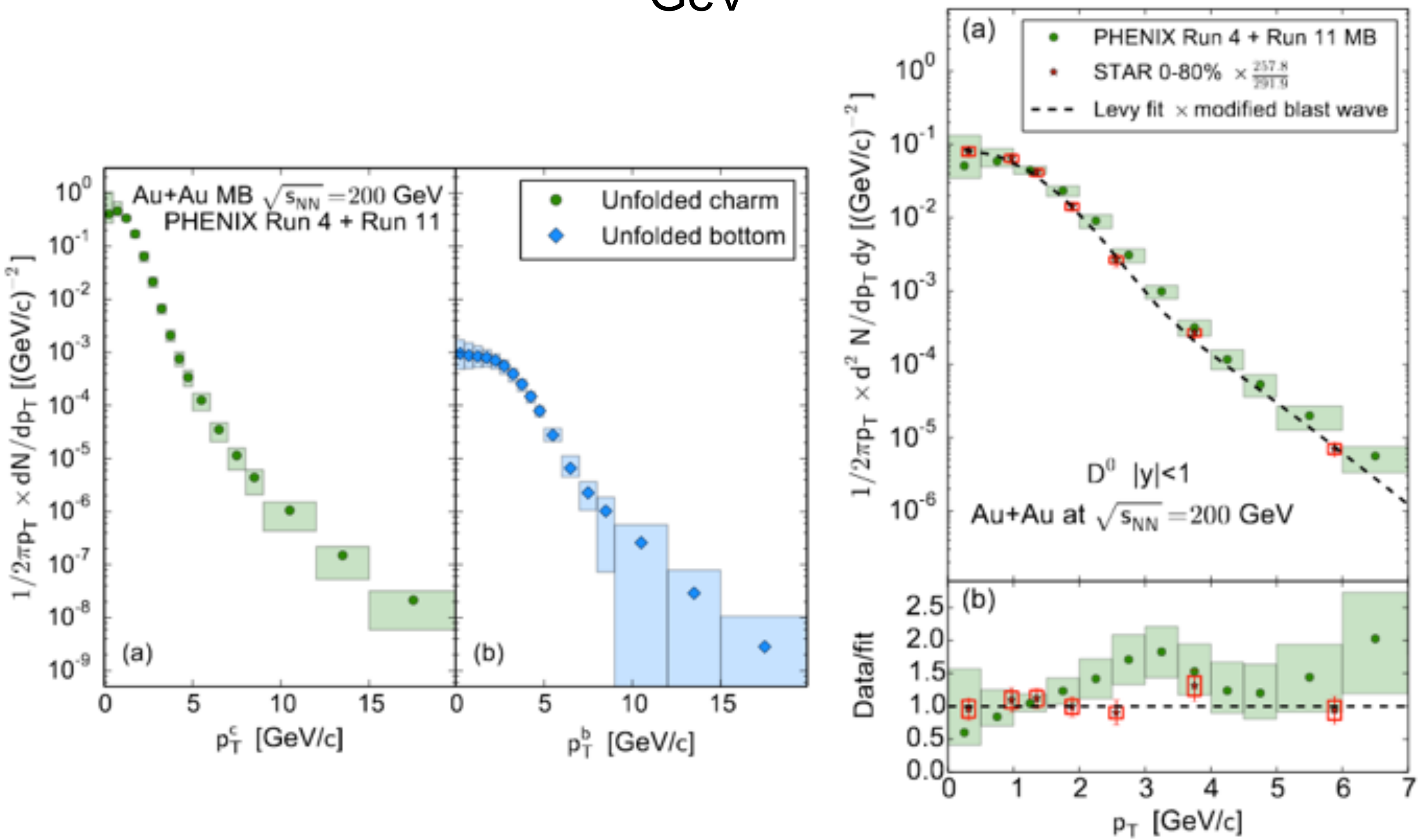
PHENIX: arXiv:1509.04662 (2015)



Analysis of data sets 2004+2011 runs

Used the information of Distance of Closest Approach (DCA) of electrons, measured with the Silicon Vertex Tracker (VTX) (available from 2011), to unfold charm and beauty contributions in min. bias Au +Au 200 GeV

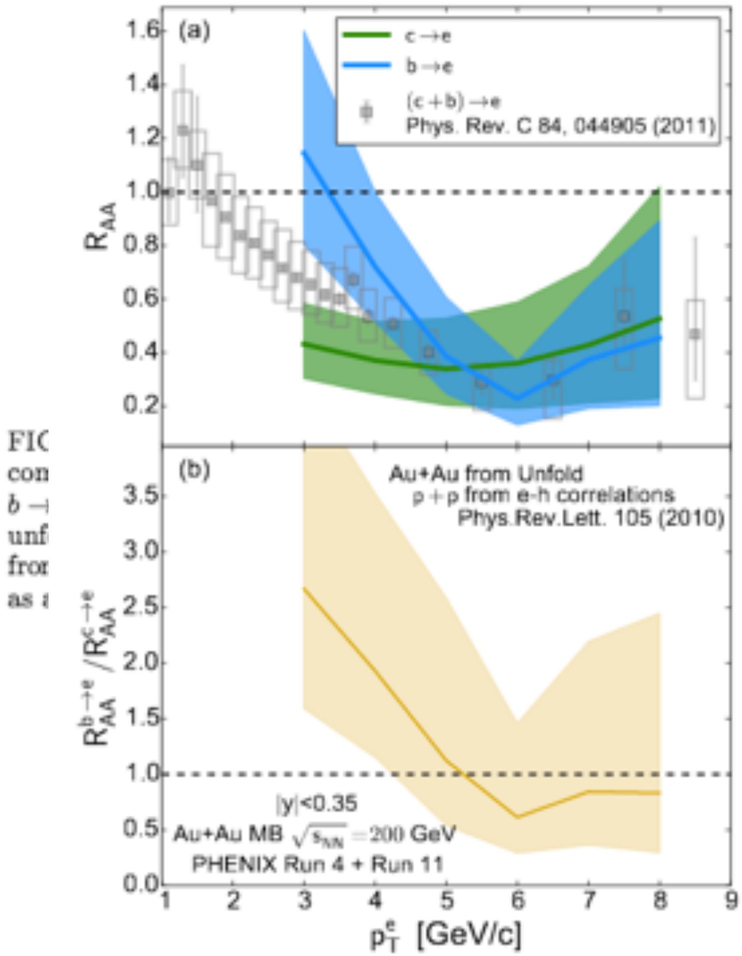
Unfolded charm and beauty in min. bias Au+Au 200 GeV



PHENIX unfolded charm in Au+Au min. bias is similar to STAR direct charm measurement (0-80%)

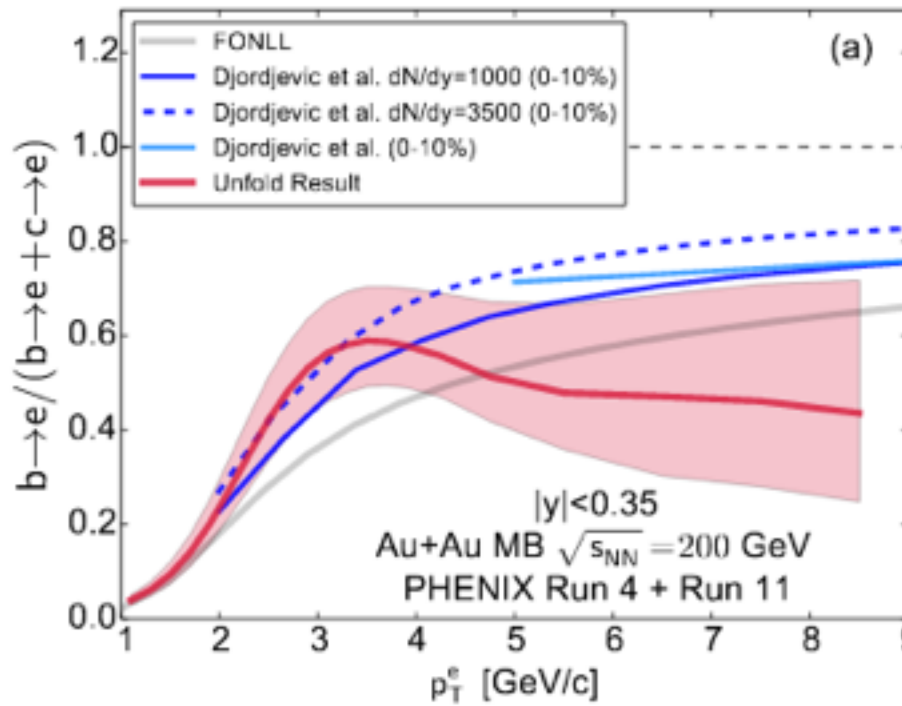
RAA of Charm and Beauty in min. bias Au+Au at 200 GeV

PHENIX: arXiv:1509.04662 (2015)



RAA of (b->e) is less suppressed than RAA of (c->e) in pT=3-4 GeV/c

Example of comparison with models: model with energy loss (however for 0-10% Au+Au)

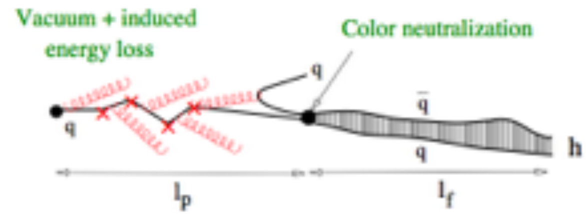


Future: 2014 Au+Au and 2015 p+p data analysis (with VTX). Centrality dependence.

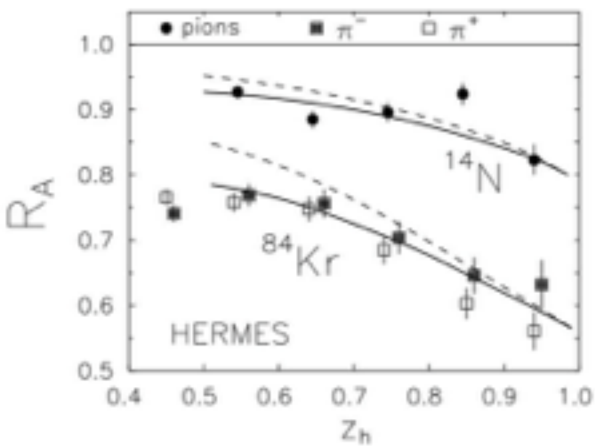
Jet quenching in a non-energy loss scenario

B. Kopeliovich et al, EPJ Web Conf. 71 (2014) 00070 , 1402.2012

Gluon radiation -> color neutralization -> colourless pre-hadron -> inelastic collisions with the medium -> attenuation

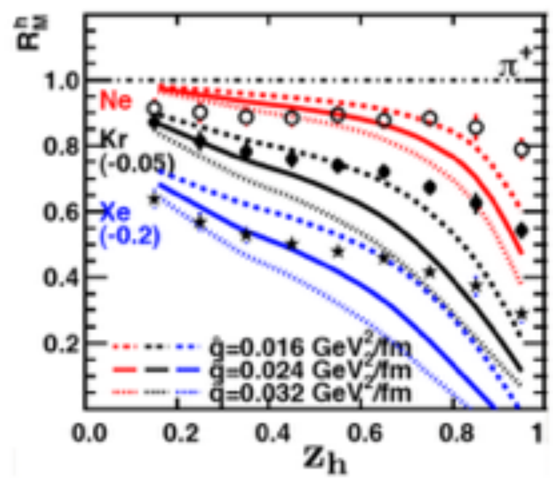


This model agrees with nuclear suppression factor of HERMES



Below an energy loss scenario assuming long hadronization time does not agree well with nuclear suppression factor of HERMES

W. T. Deng and X. N. Wang, Phys. Rev. C **81**, 024902 (2010).

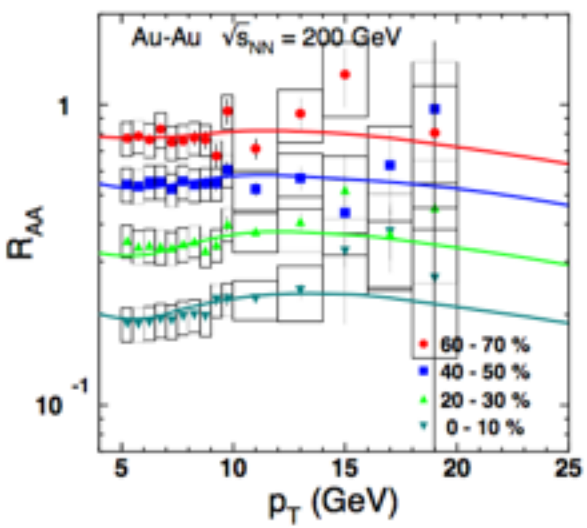


Jet quenching in a non-energy loss scenario

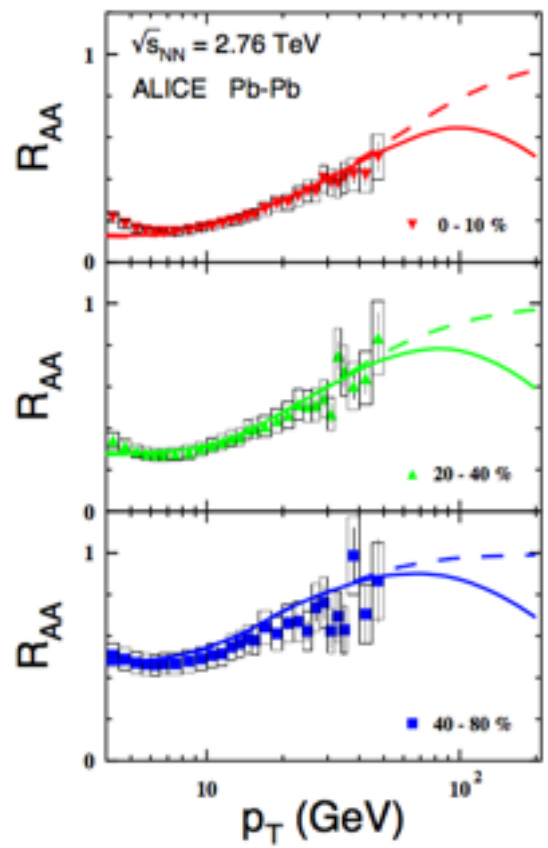
B. Kopeliovich et al, EPJ Web Conf. 71 (2014) 00070 , 1402.2012

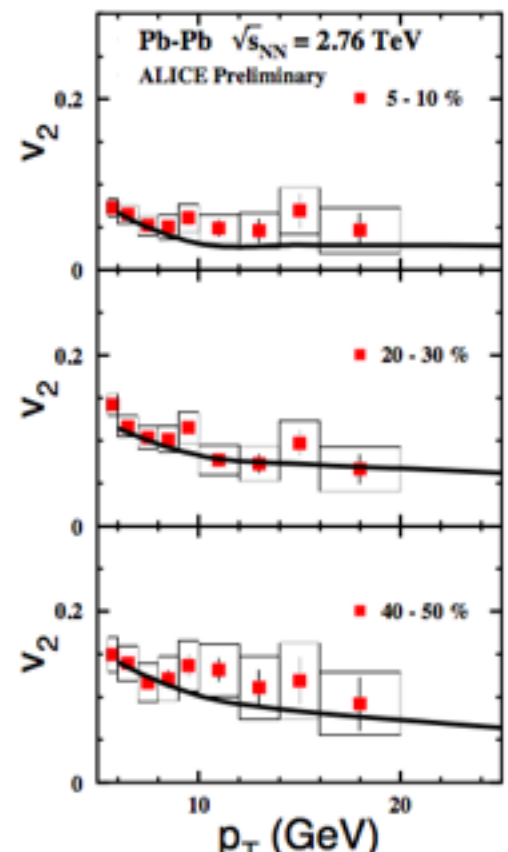
The model agrees with RAA and v2 data at RHIC AND LHC
One parameter: transport coefficient q-hut
Extracted values of q-hut: 1.2, 1.6, 2 GeV^2/fm for sqrt(s)=62, 200, 2760 GeV
They extract similar values for the q-hut of the medium from J/Psi analysis

PHENIX



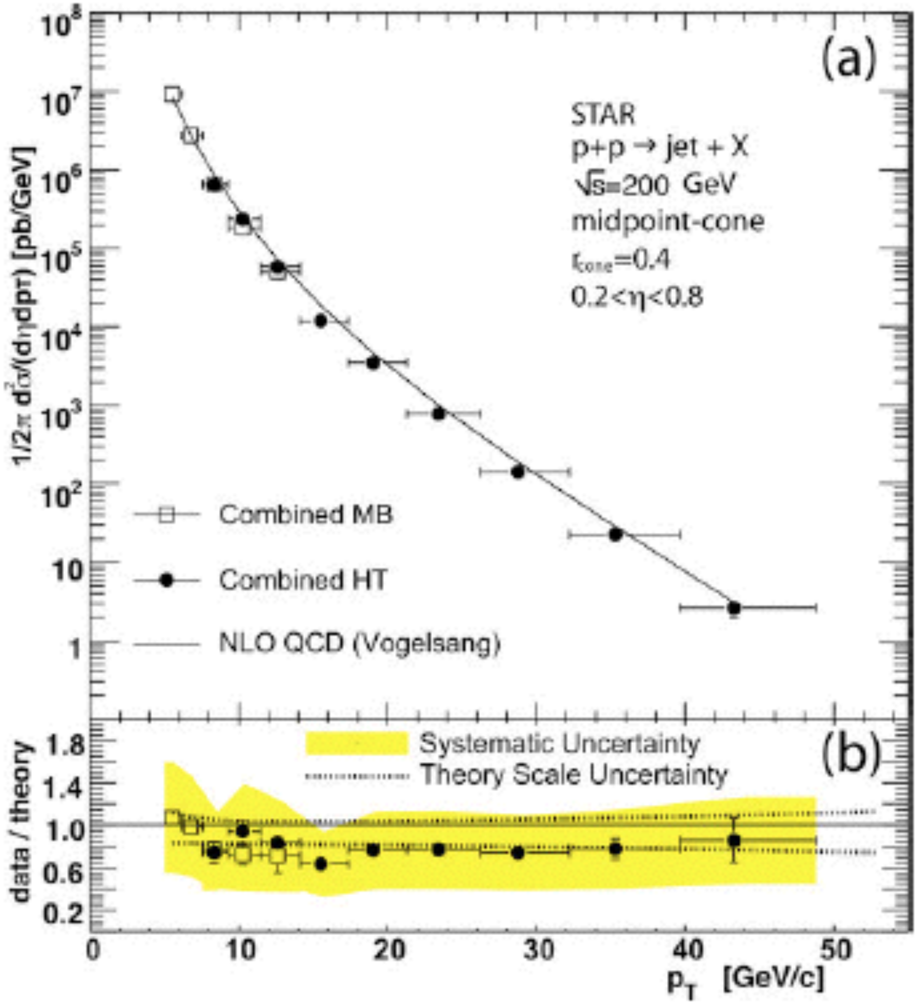
ALICE





Reconstructed jets

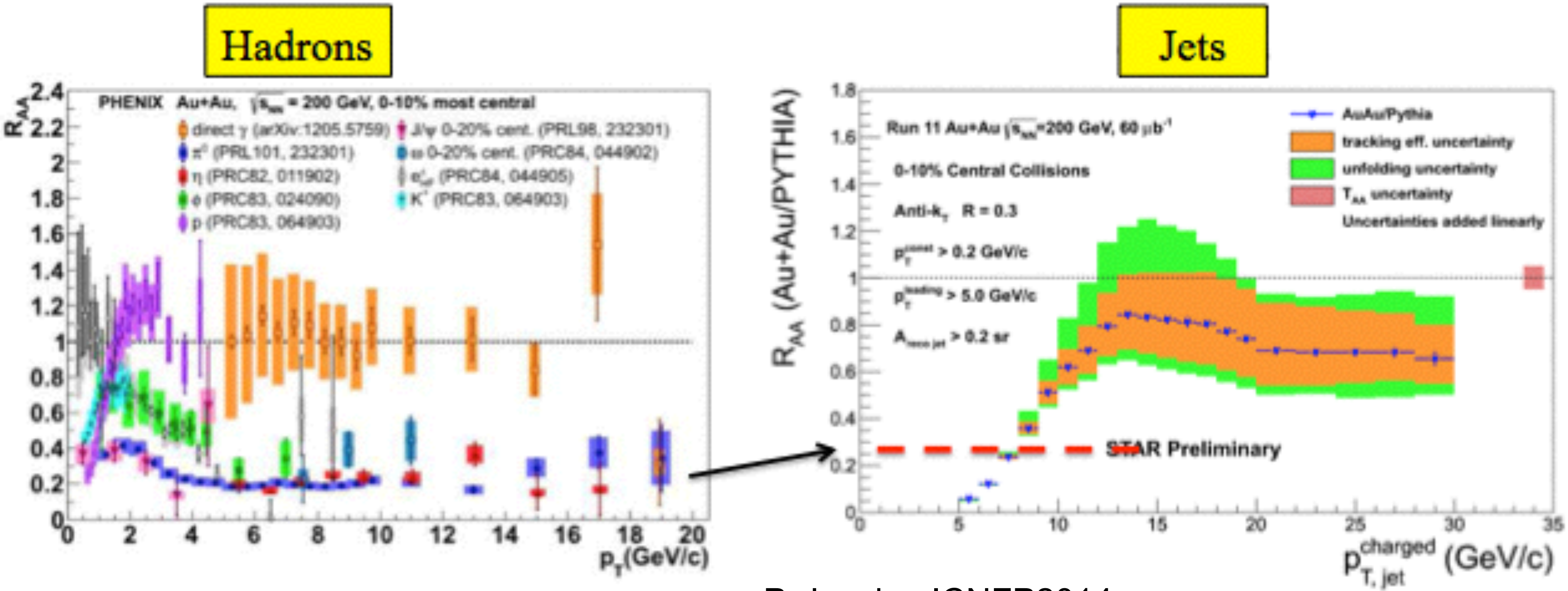
Jet cross section in p+p 200 GeV RHIC



STAR, Phys. Rev. Lett. 97, 252001 (2006), hep-ex/0608030.

The jet cross section in p+p 200 GeV is described by NLO pQCD over seven orders of magnitude

Hadron vs jet suppression RHIC

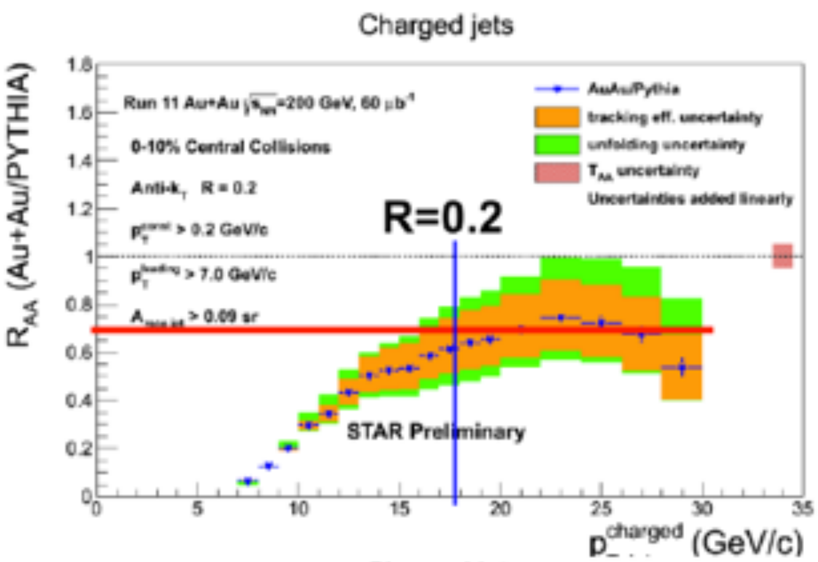


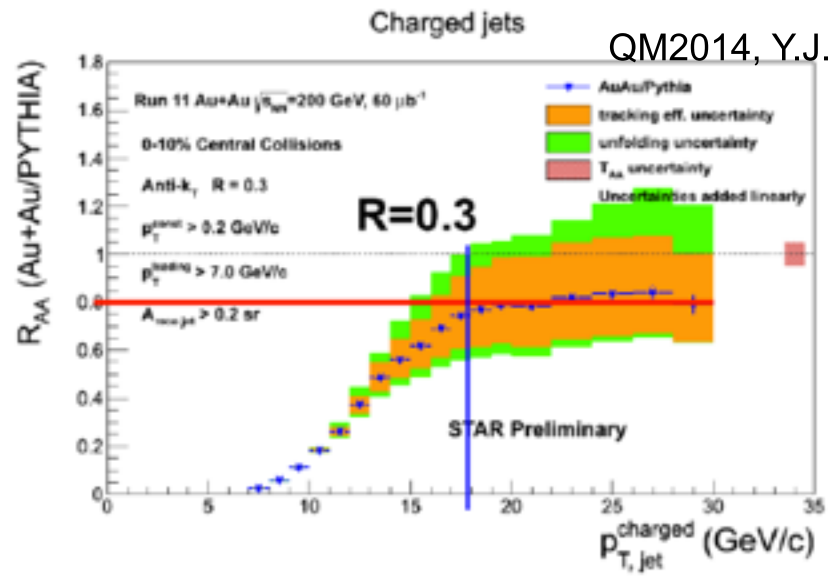
P. Jacobs, ICNFP2014

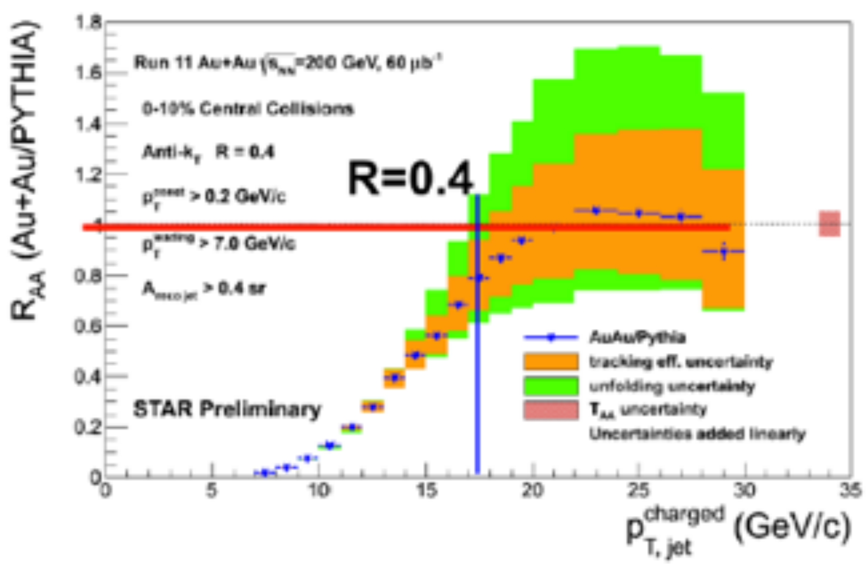
Jets are less suppressed than hadrons at RHIC, while in LHC they are suppressed the same.
Less out of cone radiation at RHIC?

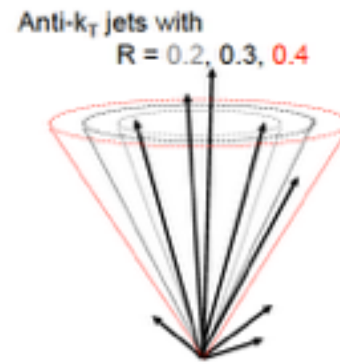
STAR: Effect of changing the R

QM2014, Y.J. Lee



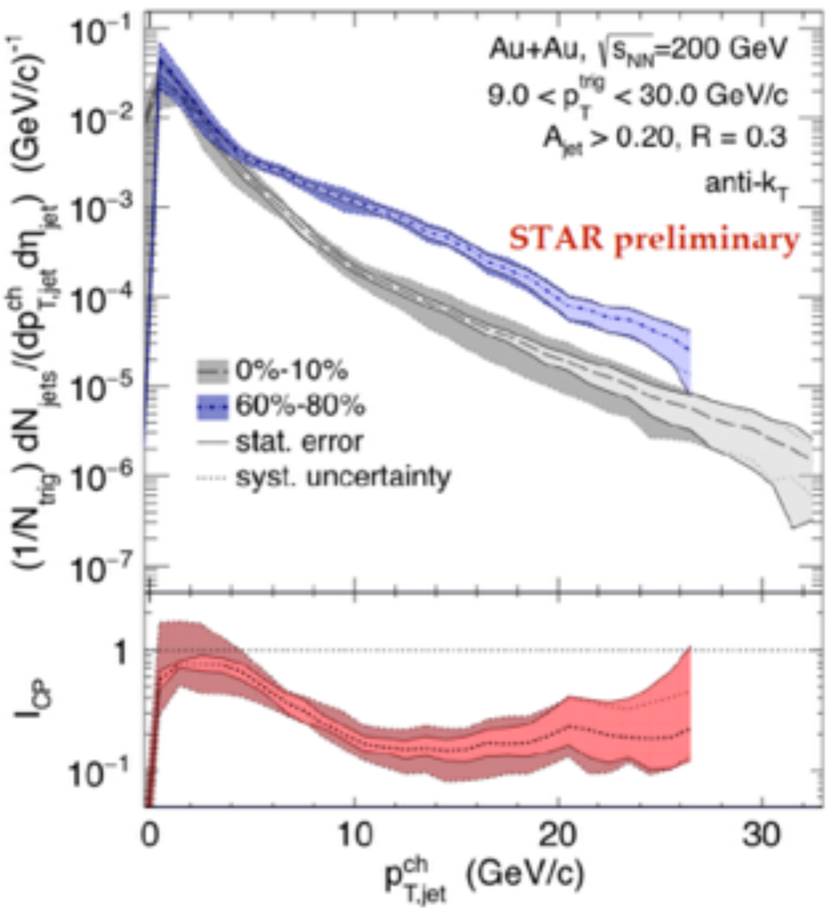






STAR observes a change of RAA(Au+Au/Pythia) with R from 0.2 to 0.4.

New: semi-inclusive charged jet measurement in Au+Au at 200 GeV

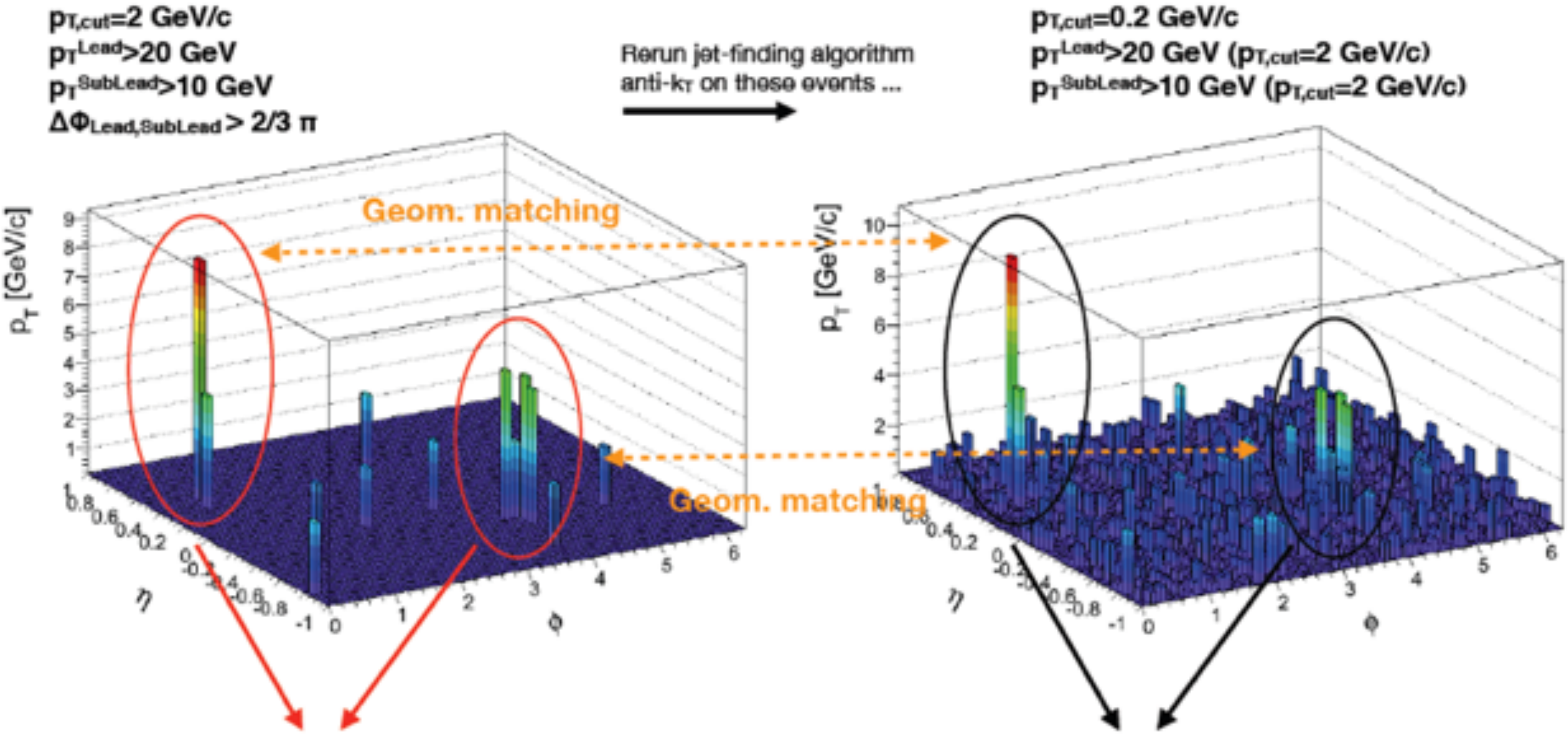


STAR, P Jacobs et al, 1512.08784

Corrected recoil-jet distributions show significant suppression at high pT in 0-10% Au+Au as compared to peripheral Au+Au

Dijets

Dijet imbalance in STAR: A_J



Calculate A_j with constituent $p_{T,cut}$>2 GeV/c

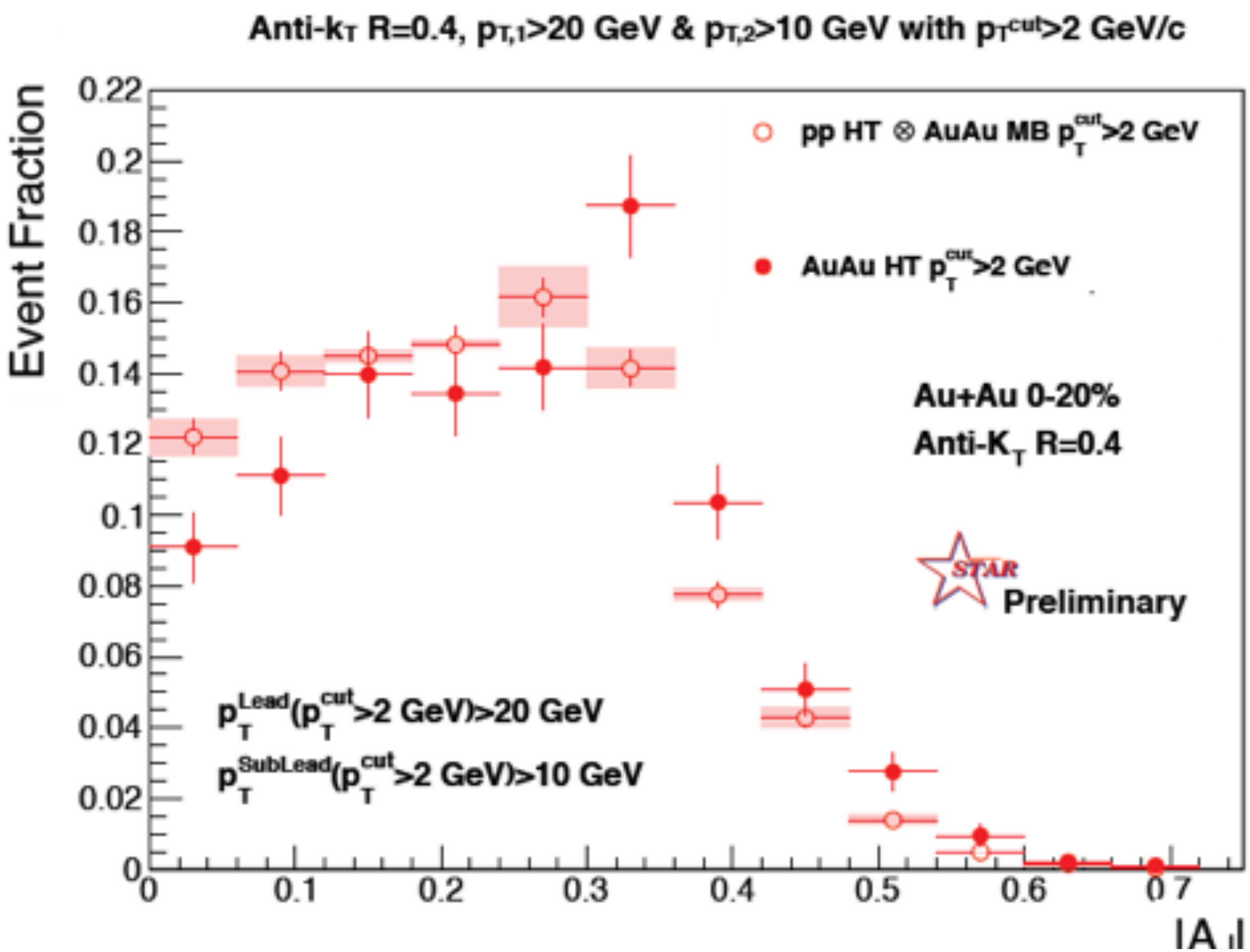
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \qquad p_T = p_T^{rec} - \rho \times A$$

Calculate "matched" $|A_j|$ with constituent $p_{T,cut}$>0.2 GeV/c.

J. Putschke, STAR, QM14

STAR, Dijet imbalance Au+Au 0-20% R=0.4

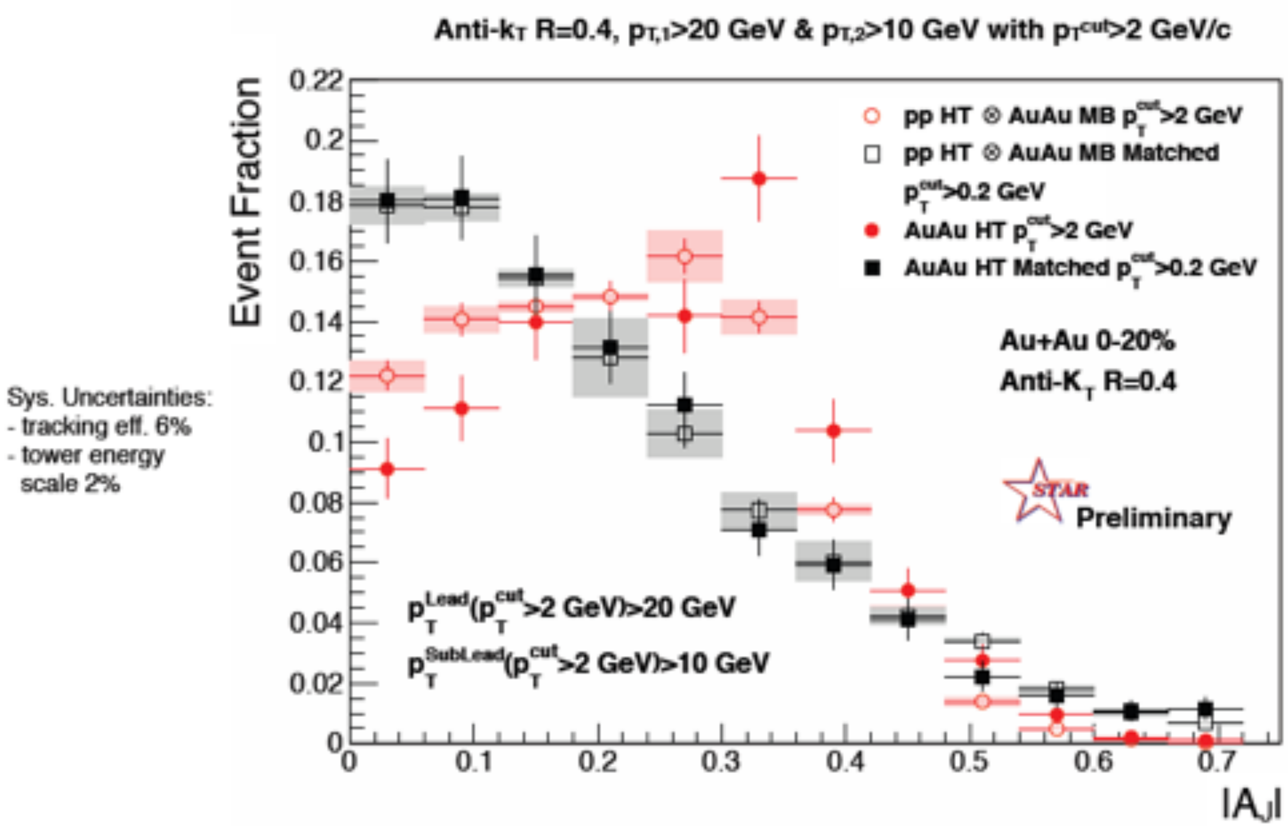
Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%



Au+Au di-jets more imbalanced than p+p for p_T^{cut}>2 GeV/c

J. Putschke, STAR, QM14 also STAR, QM2015

STAR, Dijet imbalance Au+Au 0-20% R=0.4



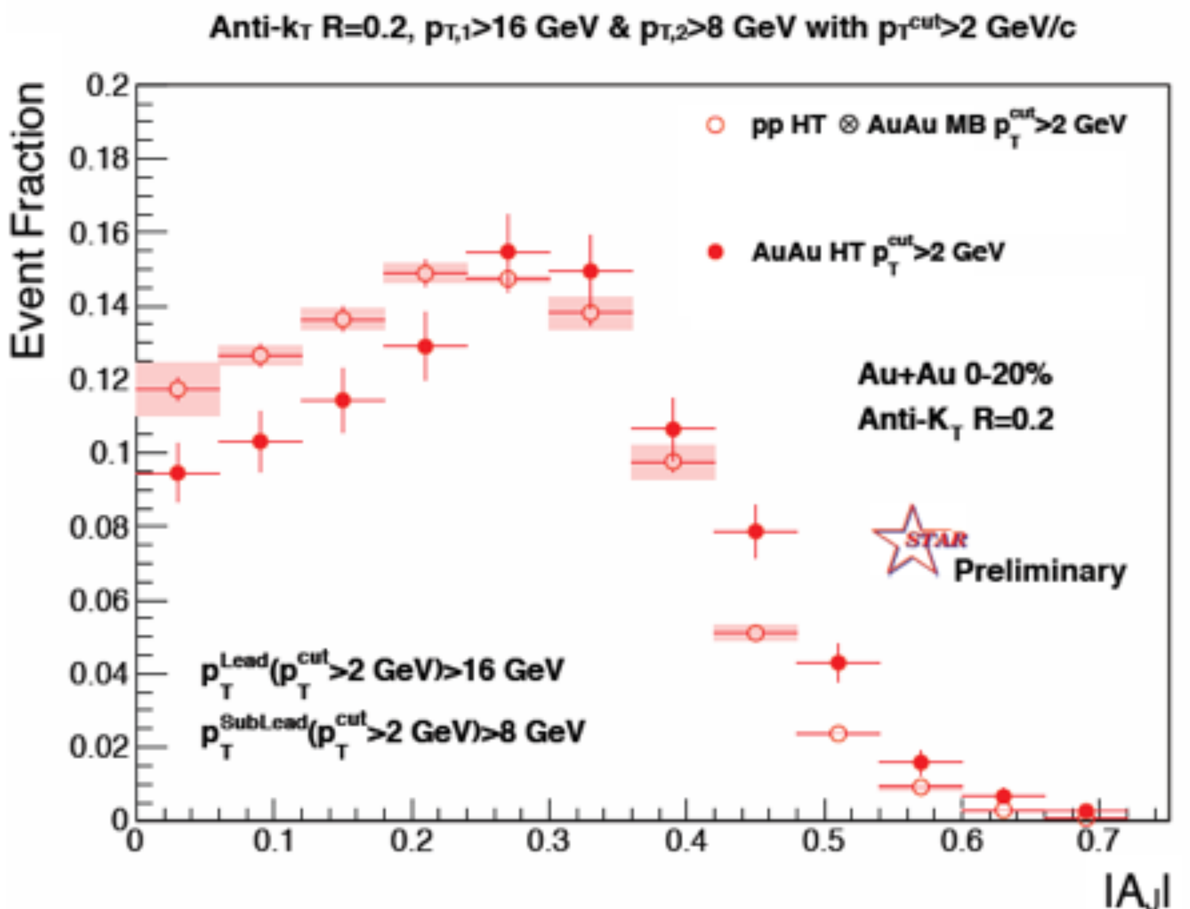
J. Putschke, STAR, QM14

Au+Au di-jets more imbalanced than p+p for p_T^{cut}>2 GeV/c

Au+Au A_J ~ p+p A_J for matched di-jets (R=0.4)

Quenched jet energy is recovered at low pT within a cone of R=0.4

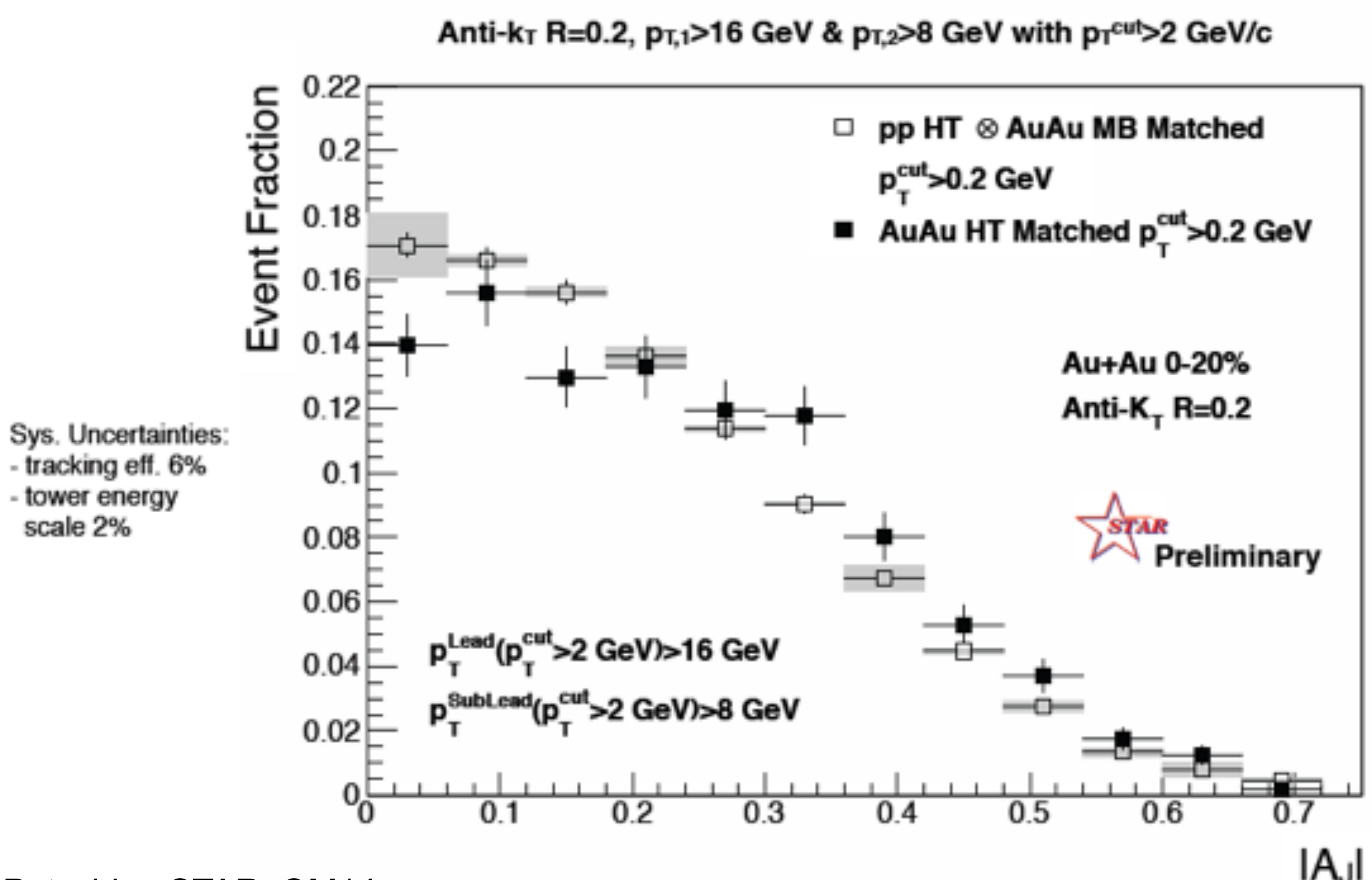
Dijet imbalance with R=0.2



Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

J. Putschke, STAR, QM14

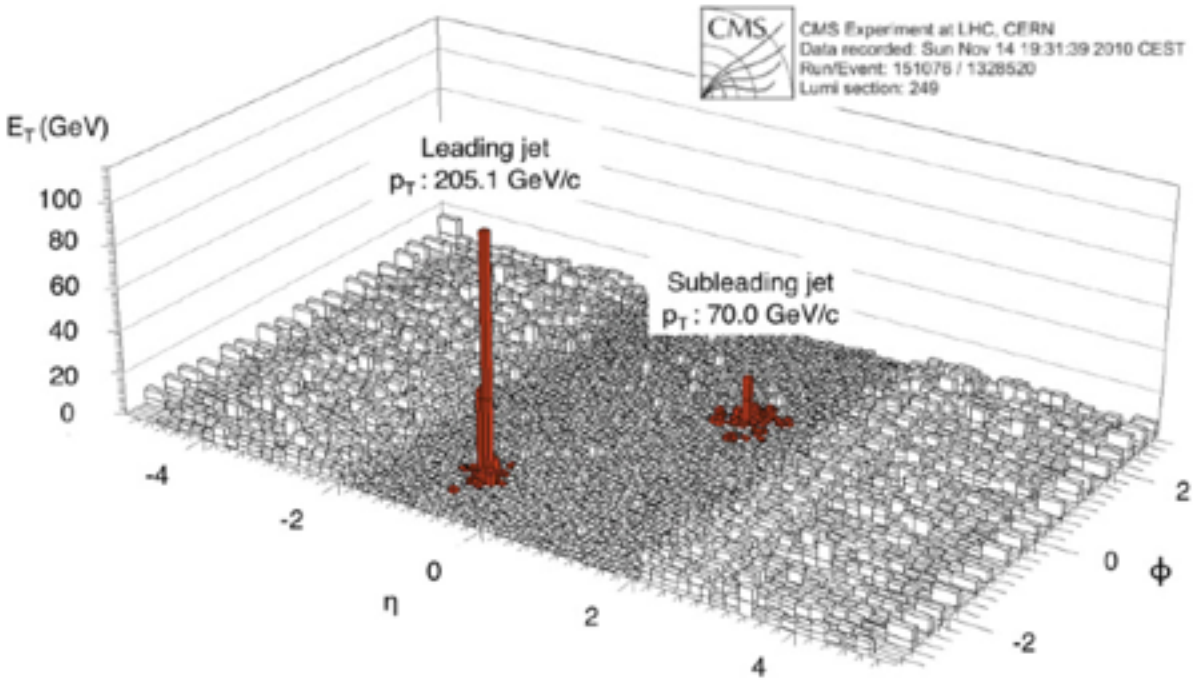
Dijet imbalance with R=0.2, matched



J. Putschke, STAR, QM14

Matched Au+Au $A_J \neq$ p+p A_J for R=0.2
→ (recoil) Jet broadening in 0.2 – 0.4

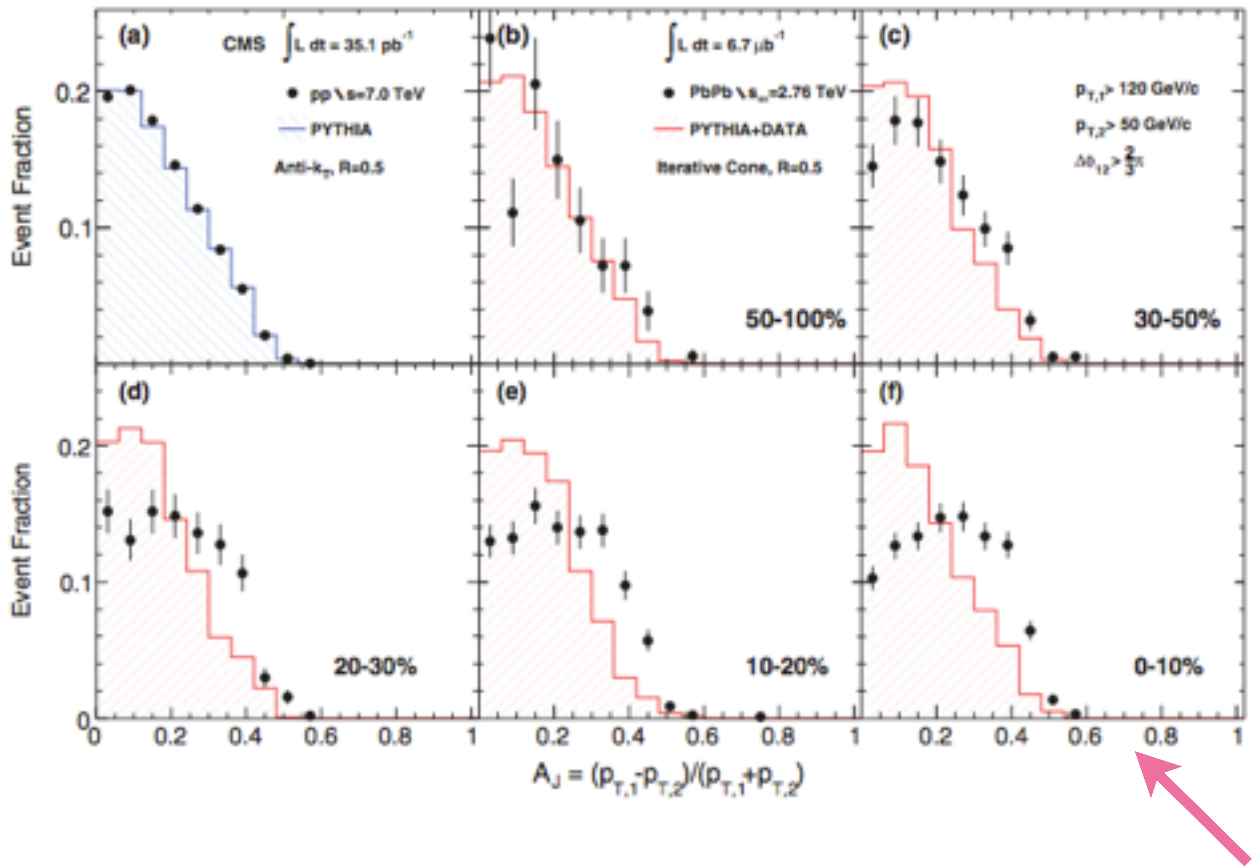
Comparison to LHC: first LHC results



Asymmetry parameter AJ defined to characterize dijet balance (or imbalance):

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}},$$

Jet quenching via dijet imbalance



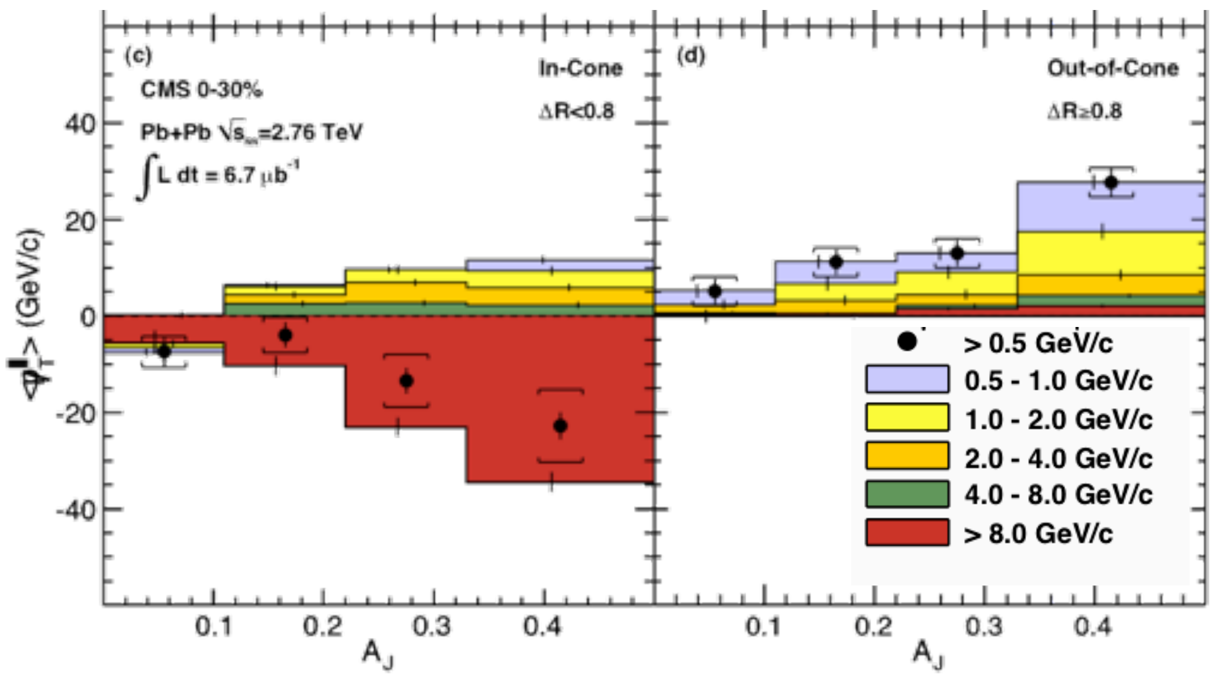
Observation of highly unbalanced dijet events in central PbPb collisions -> evidence for energy loss in medium or "jet quenching"

Where did the lost energy go?

CMS: Look at track-jet correlations

-> RHIC and LHC differ: **in LHC lost energy is moved from large to small PT and from small to large angles namely outside the leading and subleading jets cones.**

CMS, PRC 84 (2011) 024906



Color decoherence can lead to large angle emission

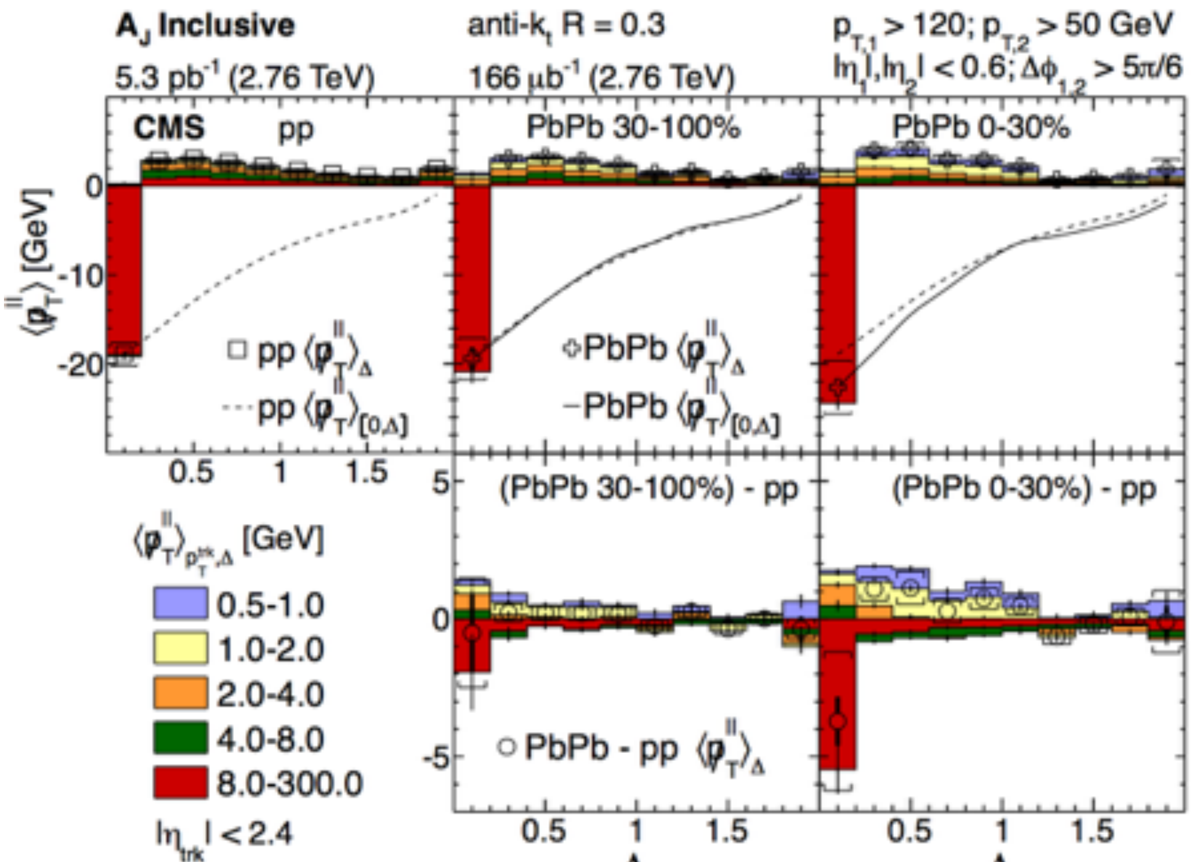
N. Armesto et al, 1207.0984
K. Tywokiuk et al 1401.8293

Colored bands show contribution to pT for five pT ranges

Dijet balance (or imbalance) characterization:

$$A = (p_{T1} - p_{T2}) / (p_{T1} + p_{T2})$$

Where did the lost energy go? Compare to p+p



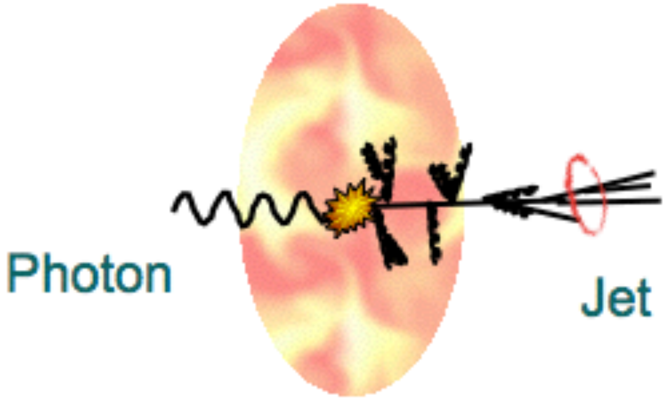
CMS, 1509.09029

Dashed line (pp) and solid line (PbPb)= cumulative values demonstrating the overal pT balance vs angle.
Balance is restored when the lines reach zero (at large angles)

CMS, 1509.09029:
For a given dijet asymmetry The imbalance in pT in PbPb is compensated by particles in pT range 0.5-2 GeV while in pp in the range 2-8 GeV -> softening of radiation responsible for the imbalance inPbPb

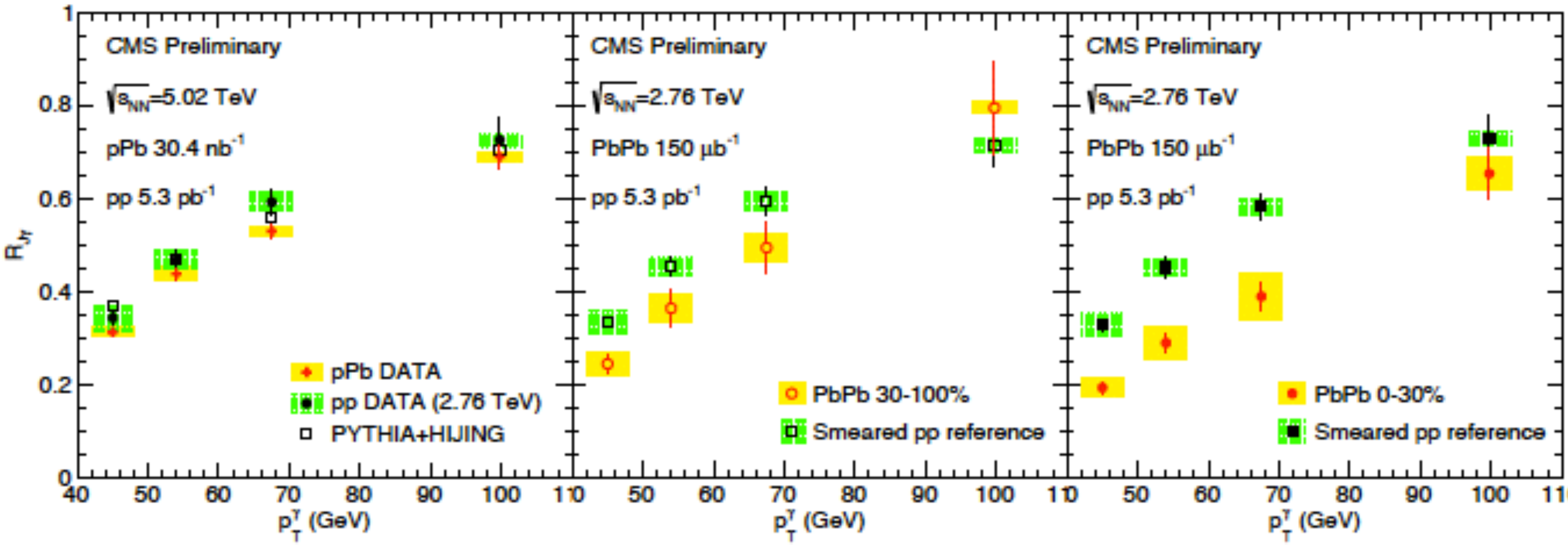
Average of track pT projections on the dijet axis as a function of the variable: $\Delta = \sqrt{(\phi_{trk} - \phi_{jet})^2 + (\eta_{trk} - \eta_{jet})^2}$
which is used to define annular regions around the axis

Gamma-jet



CMS: Is gamma-jet showing jet quenching in pPb and PbPb ?

Fraction of isolated photons that do not find an associated jet of pT > 30 GeV :



pPb show no jet suppression as compared to pp

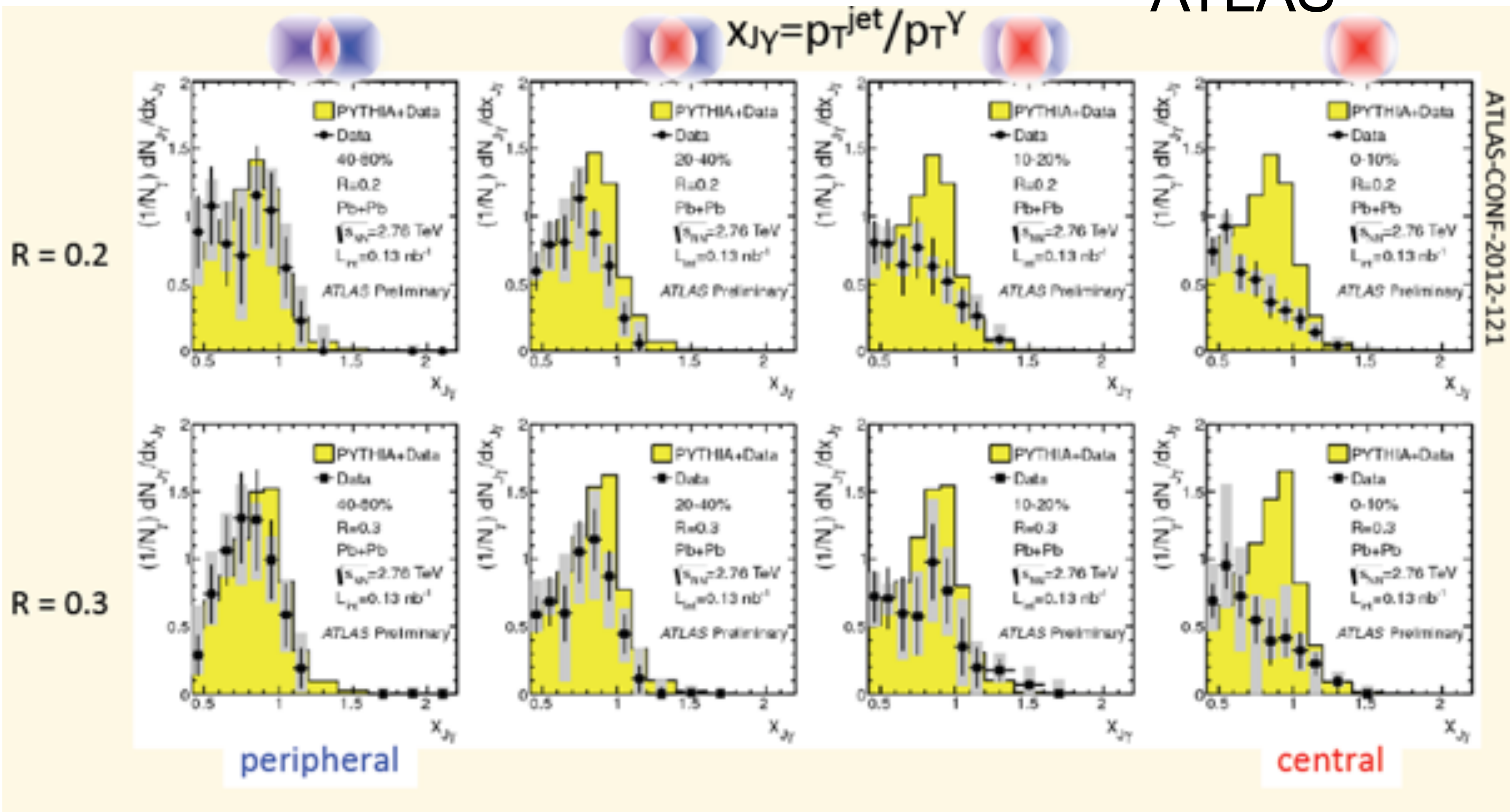
PbPb 30-100% show jet suppression as compared to pp

PbPb 0-30% show even more jet suppression as compared to pp

CMS-PAS-HIN-13-006

Jet quenching via gamma-jet

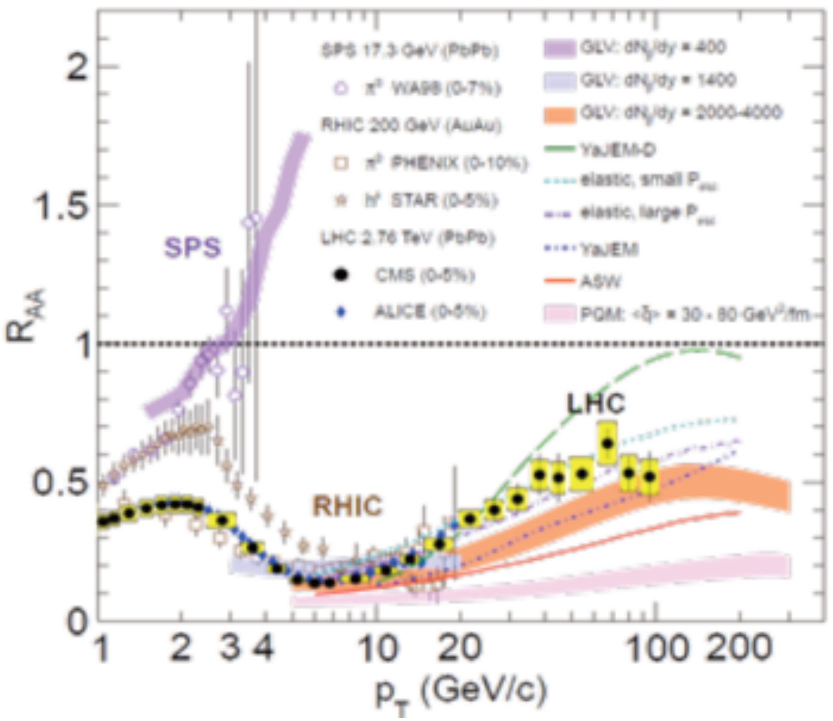
ATLAS

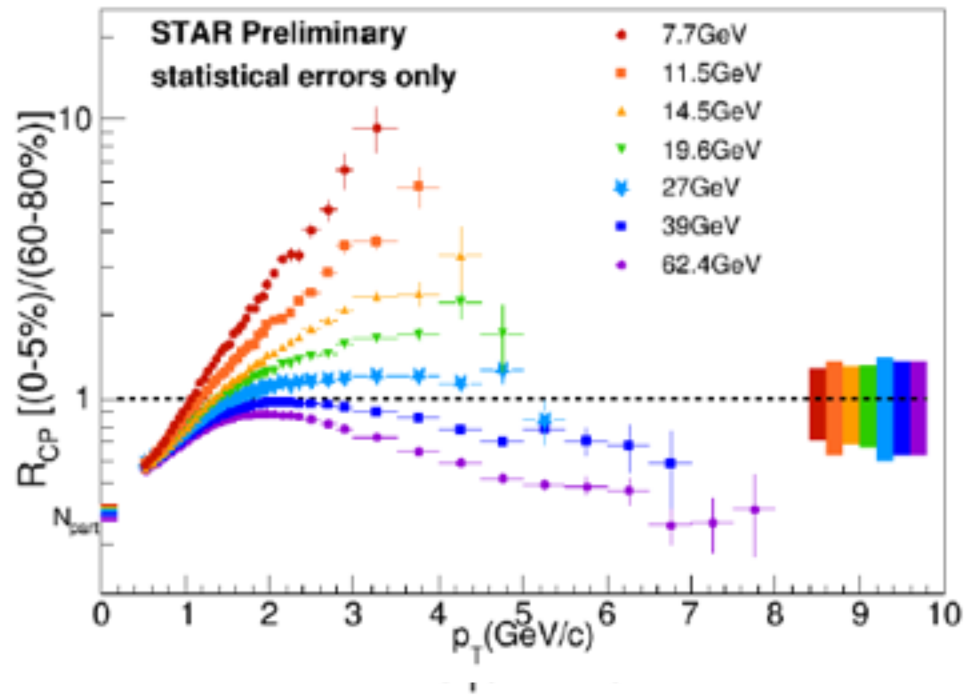


Peripheral Pb+Pb: data like Pythia

Central Pb+Pb: Smaller energy fraction of jet with respect to the photon and reduction of the integral.

STAR: At which energy does jet quenching switch off?





New data at 14.5 GeV added (in the right plot)
Smooth transition from suppression to enhancement

R_{CP} suppression at high pT sets in from $\sqrt{s}$=39 GeV on

Jet transport coefficient at RHIC and LHC

Extracting jet transport coefficient from data and models at RHIC and LHC

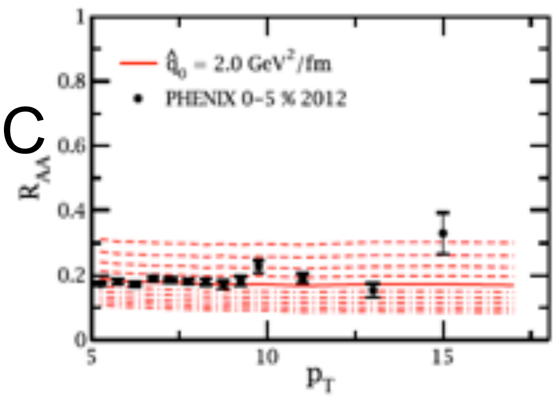
Karen M. Burke,[1] Alessandro Buzzatti,[2,3] Ningbo Chang,[4,5] Charles Gale,[6] Miklos Gyulassy,[3] Ulrich Heinz,[7] Sangyong Jeon,[6] Abhijit Majumder,[1] Berndt Müller,[8] Guang-You Qin,[5,1] Björn Schenke,[8] Chun Shen,[7] Xin-Nian Wang,[5,2] Jiechen Xu,[3] Clint Young,[9] and Hanzhong Zhang[5]

K. Burke et al, JET collaboration, 1312.5003

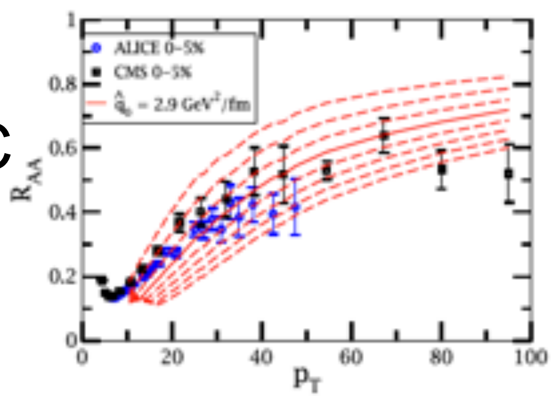
In last years the JET collaboration of groups using different models has made an important step forward evaluating for the first time q-hut with a fit to both RHIC and LHC and reaching a good agreement of all models while fiting the experimental data at RHIC and LHC.
Models: GLV-CUJET, HT-M, HT-BW, MARTINI and McGill-AMY. GLV and its recent CUJET implementation.
Jet transport coefficient for a jet initiated by a light quark considered (10 GeV jet assumed).
For the QGP medium viscous hydrodynamics (VISH2+1) is employed (Ohio State group).

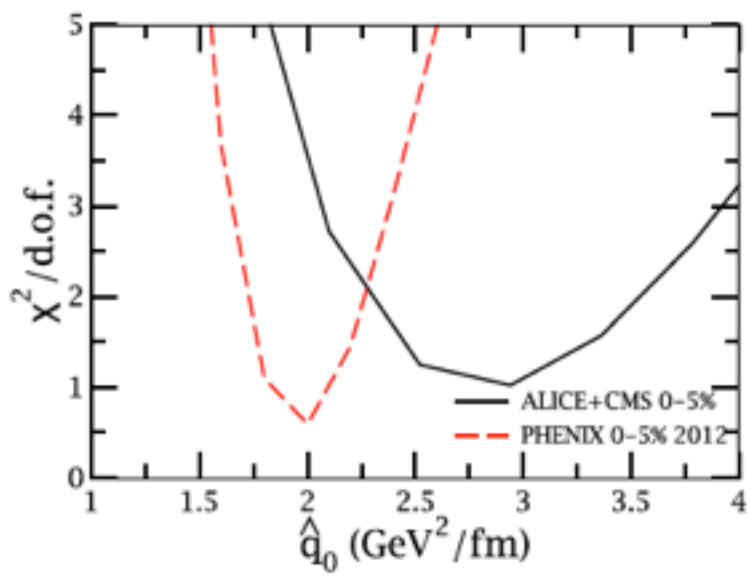
Example results from the Higher-Twist-Majumder (HT-M) model

RHIC



LHC



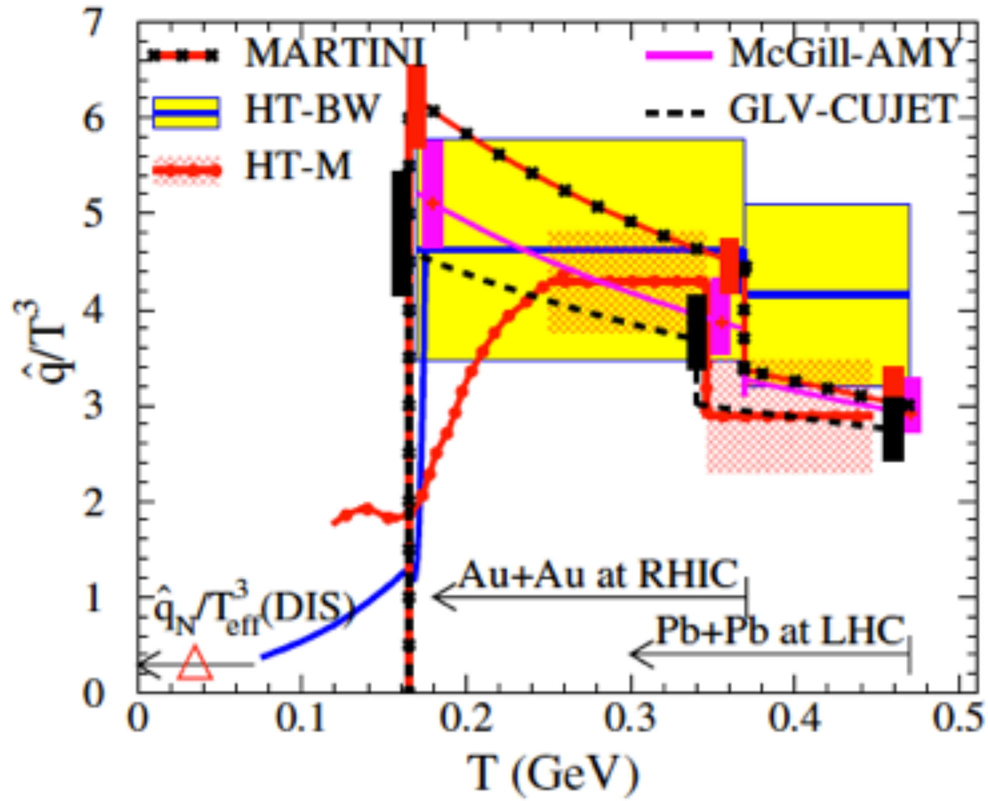


Dedx(radiative)~ q-hut

Example of fit to pi0 in central 0-5% Au+Au and Pb+Pb for the Higher-Twist-Majumder (HT-M) model.

The model calculates the medium modified fragmentation function including multiple induced gluon emission.

Assumed temperature dependence of the scaled jet transport parameter q-hut/T^3, with q-hut estimated from fits to data from RHIC and LHC

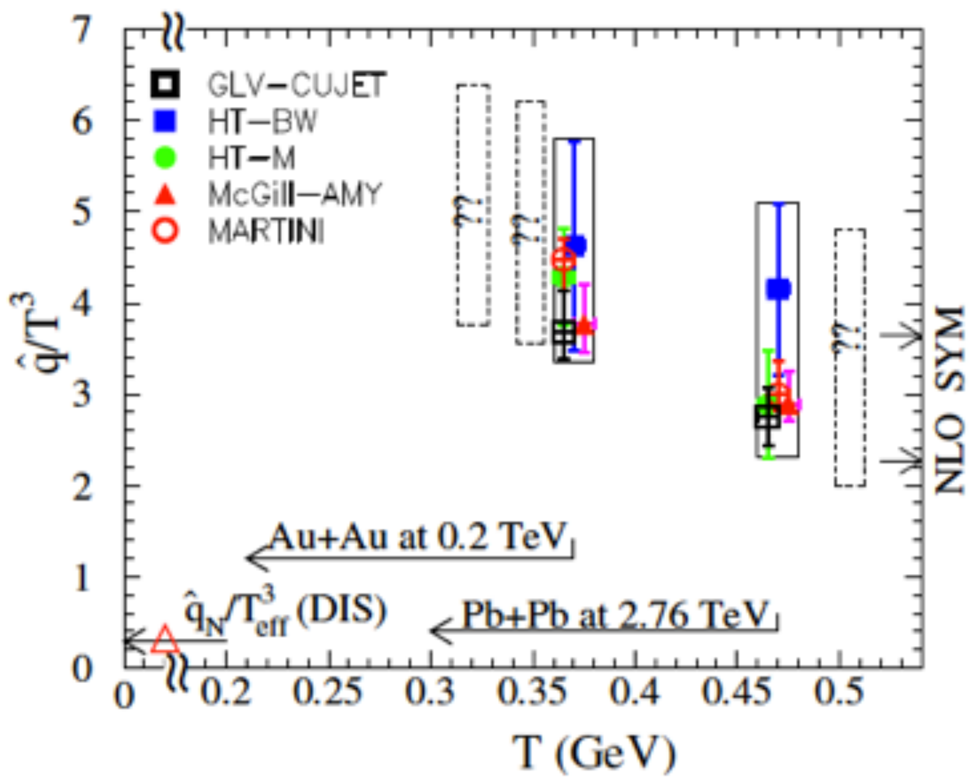


Triangle: value in cold nuclei from DIS experiments

Calculation at initial time 0.6 fm/c

$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \mathrm{GeV}^2/\mathrm{fm} \;\; \text{at} \;\; \begin{matrix} T{=}370\ \mathrm{MeV} \\ T{=}470\ \mathrm{MeV} \end{matrix}$$

Scaled jet transport parameter q-hut/T^3

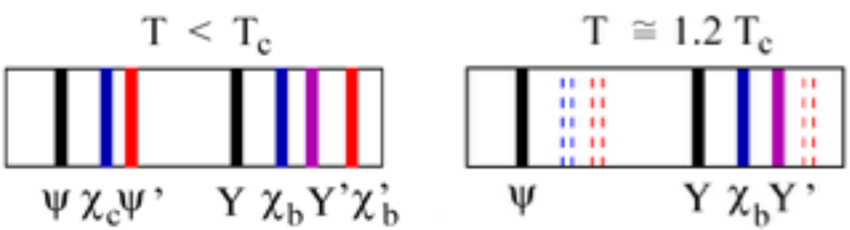


Dashed boxes show expected values for sqrt(s)=0.063, 0.130 and 5.5 TeV

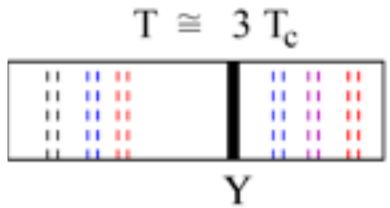
Results from JET collaboration agree with results from AdS/CFT correspondance shown here with the arrows named NLO SYM

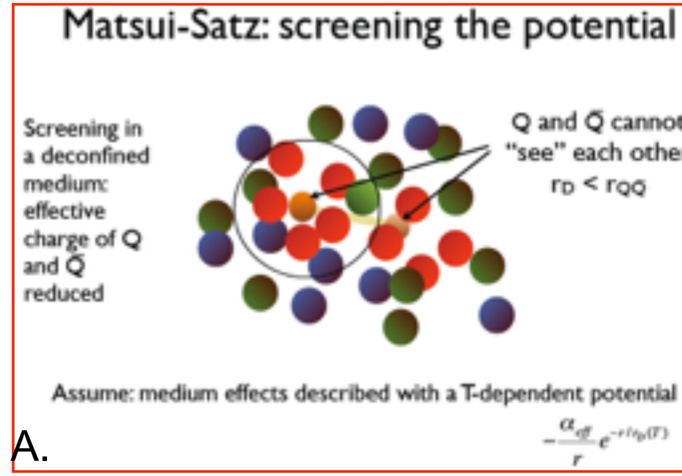
5. Quarkonia suppression

Quarkonia

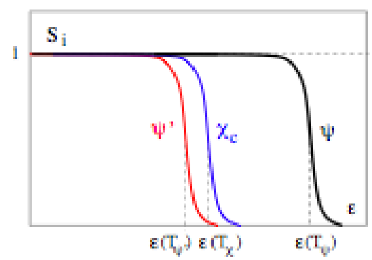


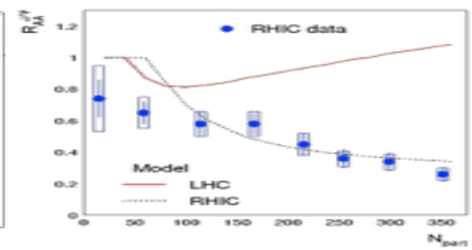
H. Satz, Nucl. Phys. A (783): 249-260(2007)





state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17



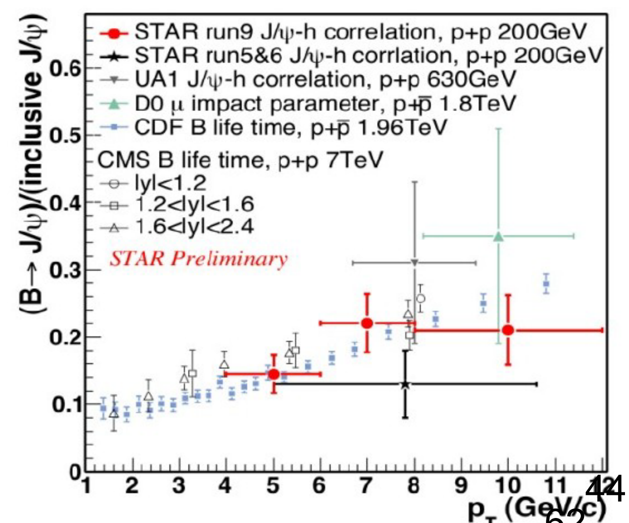


Quarkonia: Thermometer of QGP via their suppression pattern (Satz, Matsui)

Many effects play a role like dissociation in QGP, cold matter absorption, recombination/ coalescence from c, cbar, feeding, eg B mesons carry 10-25% of charmonia yields (B->J/Psi from J/Psi-h correlation STAR measurement) etc

ccbar pairs can also be destroyed before formation of J/Psi (S. Brodsky).

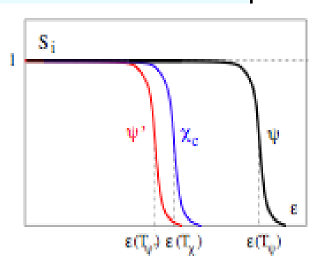
Other models: B. Kopeliovich et al, D. Kharzeev, E. Ferreiro, A. Capella, A. Kaidalov et al etc.



J/Ψ suppression and coalescence

J/ψ suppression at low p_T maybe from excited stats (ψ', χ_c) F. Karsch, D. Kharzeev and H. Satz, PLB 637, 75 (2006); B. Alessandro et al. (NA50), Eur. Phys. J. C 39 (2005) 335; R. Arnaldi et al. (NA60), Quark Matter 2005; PHENIX: Phys.Rev.Lett.98, 232301,2007.

60% of all J/Psi comes from direct J/ψ. (30% of all J/Psi come from χ_c and 10% ψ')
χ_c and ψ' T(dissociation) ~Tc, while J/Psi T(dissociation)~ 2 Tc

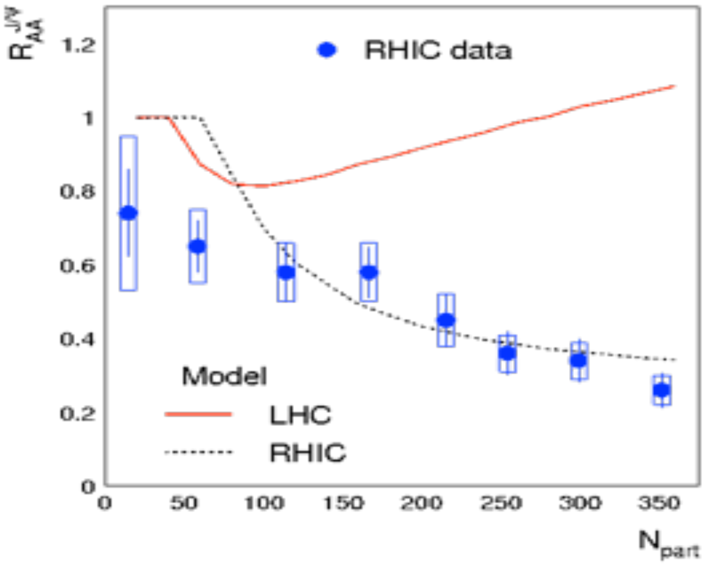


Suppression of J/Psi observed, maybe due to χ_c and ψ' dissociation
Directly produced J/Psi may not be suppressed at SPS and RHIC
One can then expect more suppression at LHC due to direct J/Psi dissociation
(but must account for possible c,cbar coalescence-> J/Psi)

J/Psi assumed completely suppressed and resurrected by c,cbar "coalescence" :

S.K., New J. of Phys. 3 (2001) 16, 0004138

A Andronic et al, Phys Lett B 652 2007, p 259



- **J/Psi assumed to be completely suppressed**
- **R_AA(J/Psi) is estimated for the process of c, cbar coalescence to J/Psi, within a thermal model**

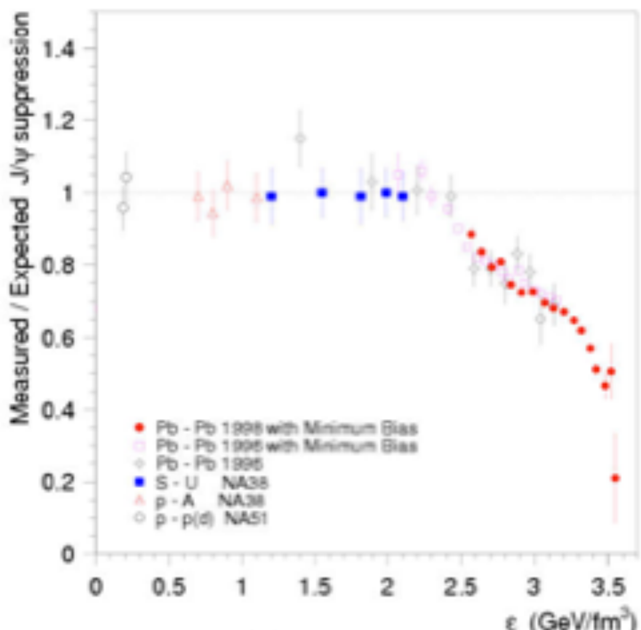
→This estimate can describe R_AA(J/Psi) at RHIC

→ It predicts a great enhancement of R_AA(J/Psi) at LHC

CERN press release 2000

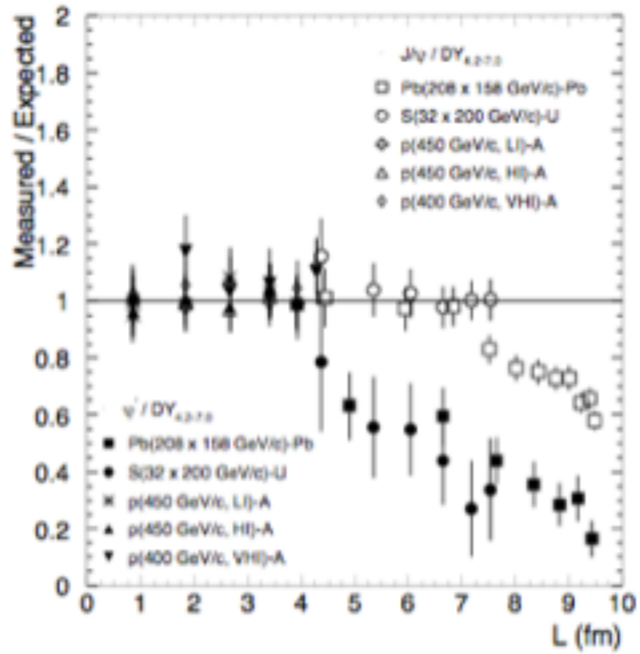
Sequential Psi prime and J/Psi suppression has been observed at CERN SPS Pb+Pb 158 A GeV

NA50, Phys Lett B 477 (2000) 28

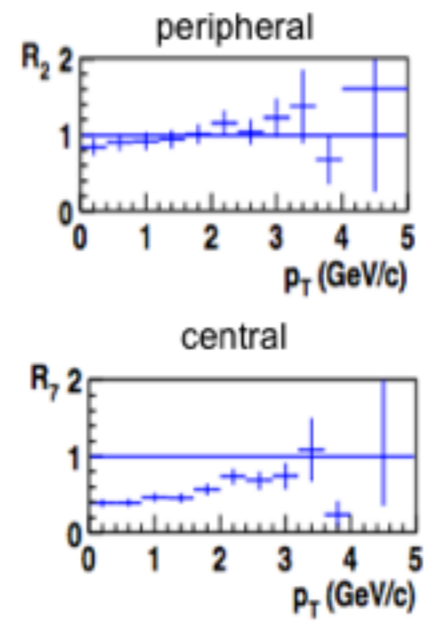


$$\varepsilon_{Bj}(\tau) = \frac{1}{A\tau}\frac{\mathrm{d}E_T(\tau)}{\mathrm{d}y},$$

Eur Phys J C 49 (2007) 559



J/Psi/DY n-bin/1st bin

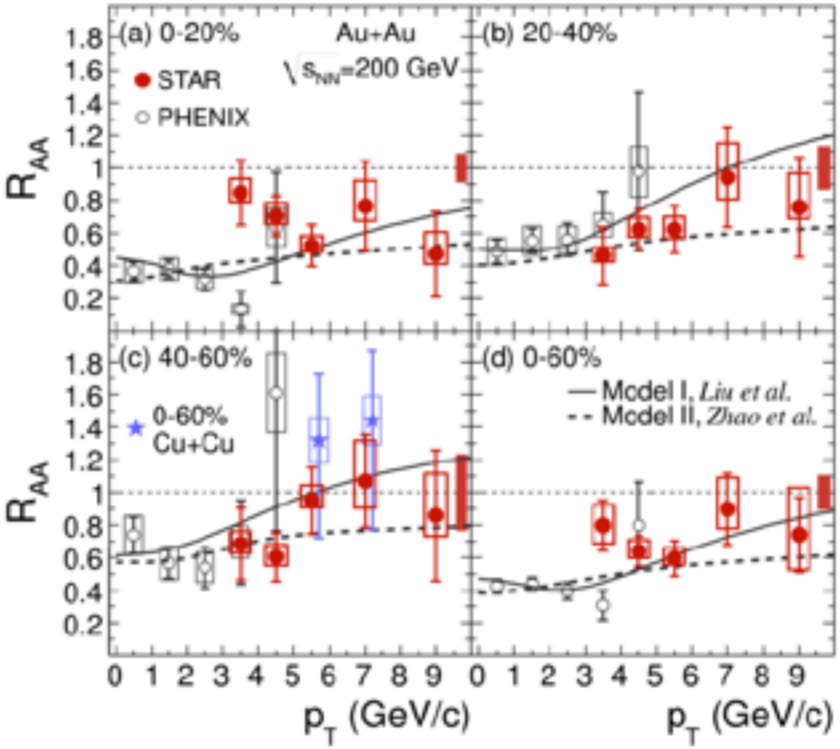


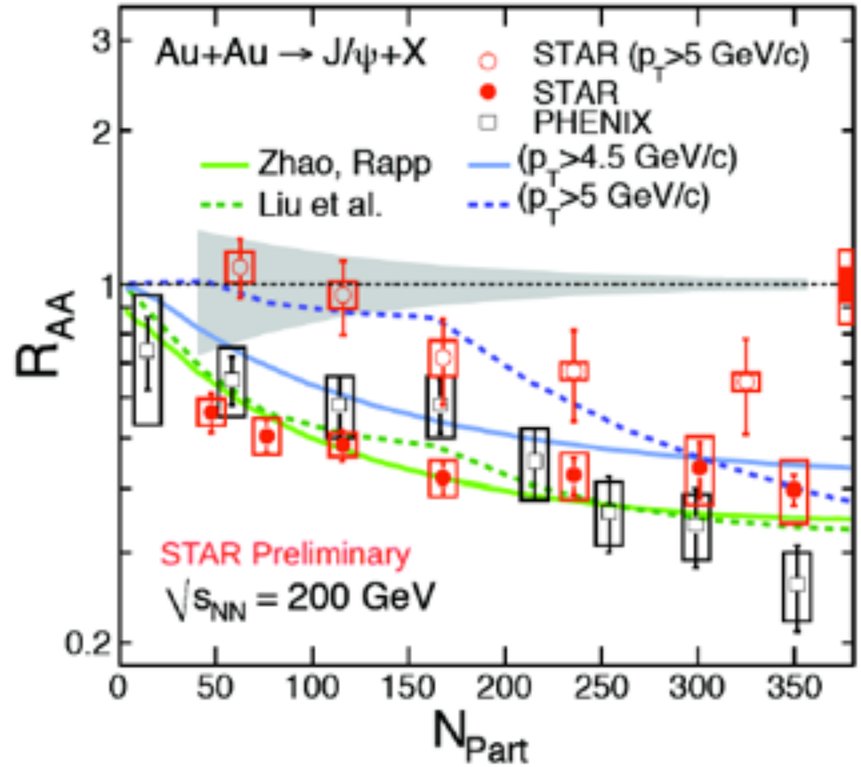
A Kurepin, 18th Nucl Phys Div Conf of EPS, Aug 23-29, 2004

- * **Psi prime is suppressed from 1.23 GeV/fm^3 on**
- * **J/Psi is suppressed from ~2.4 GeV/fm^3 on**
- * **J/Psi supression occurs mainly at low pT**

p_T dependence of J/Psi suppression in Au+Au, Cu+Cu 200 GeV

PLB 722 (2013) 55





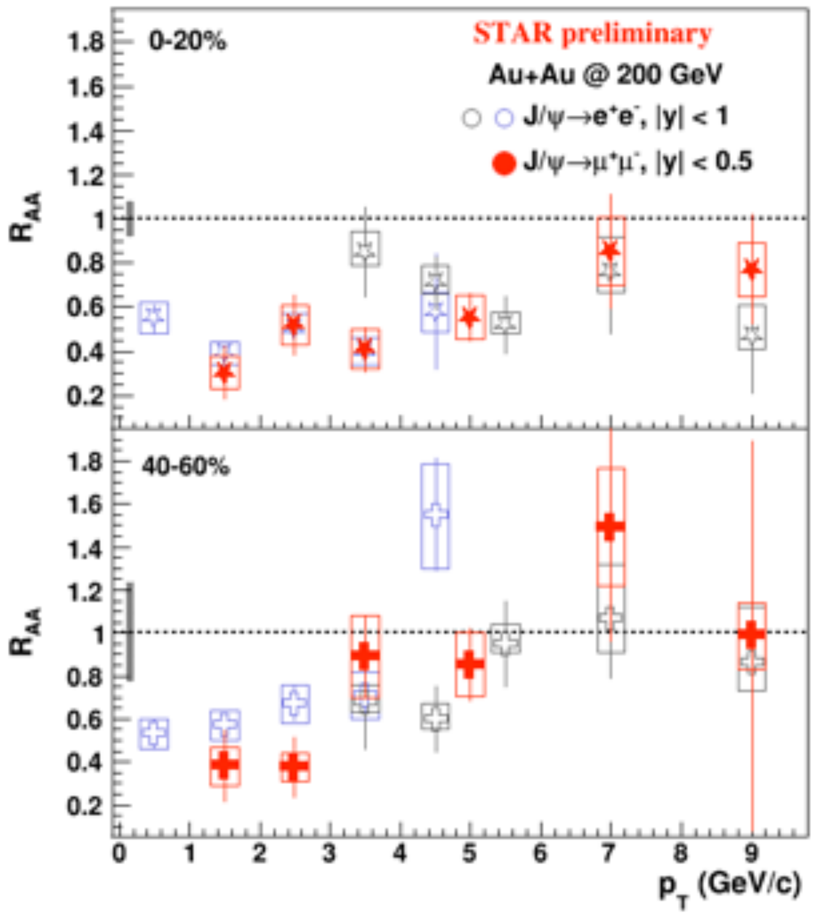
Liu et al, PLB 678 (2009) 72
Zhao et al, PRC 82 (2010) 064905

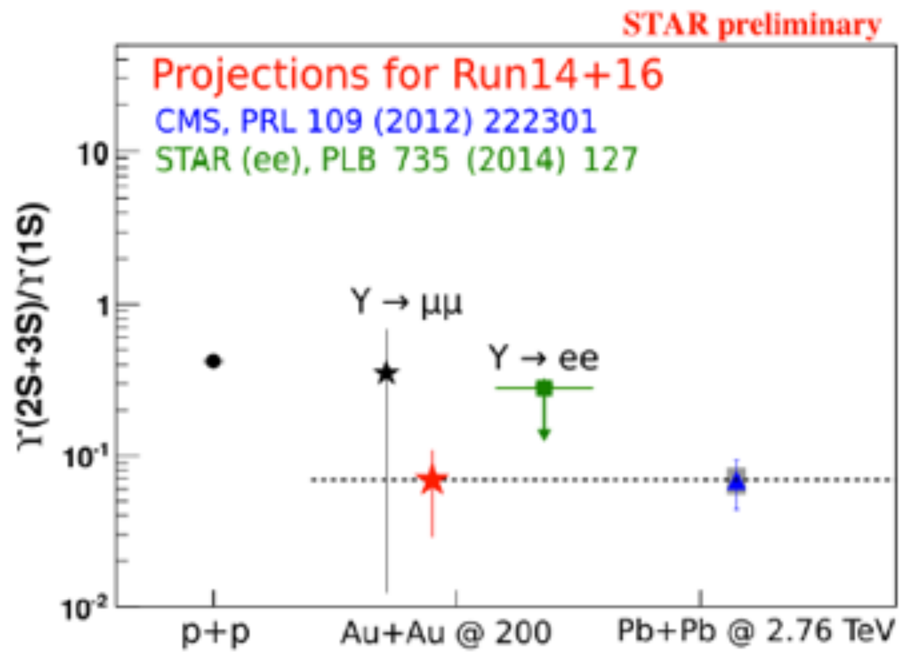
- J/Psi not suppressed at high p_T's in non-central collisions

- J/Psi suppressed at all p_T's for most central events

- R_{AA} of J/Psi is systematically larger for higher p_T. Low pT J/Psi is more suppressed

STAR quarkonia in the dimuon channel from Muon detector (MTD)



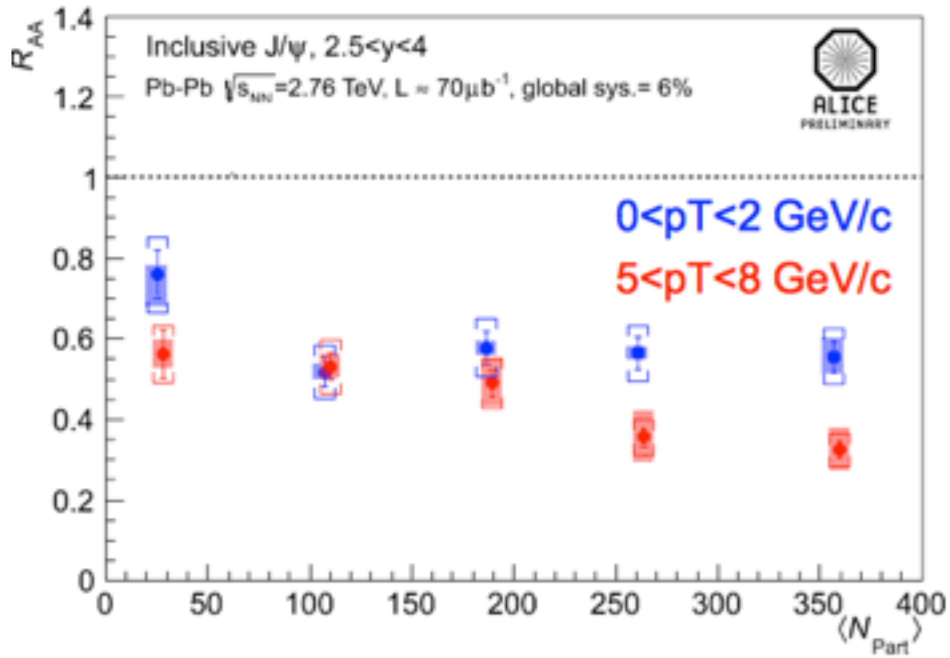


J/Psi: Suppression in all centralities at pt<5 GeV/c
RAA of J/Psi is consistent in the dimuon and dielectron channels

Υ(2S+3S)/Υ(1S) measured in dimuon channel
In red: expectations for run-14+16

STAR,QM2015

LHC is different
J/Psi recombination at LHC ? p_T and Npart dependence



RAA of J/Psi in Pb+Pb at LHC is below 1

Low pT is less suppressed
RAA of J/Psi is higher at low pT, in central collisions ->

Indication of J/Psi regeneration at LHC at low pT?

Which is the right normalization for quarkonia ?

1. J/Psi AA/pp : RAA(J/Psi)

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times \langle N_{coll} \rangle}$$

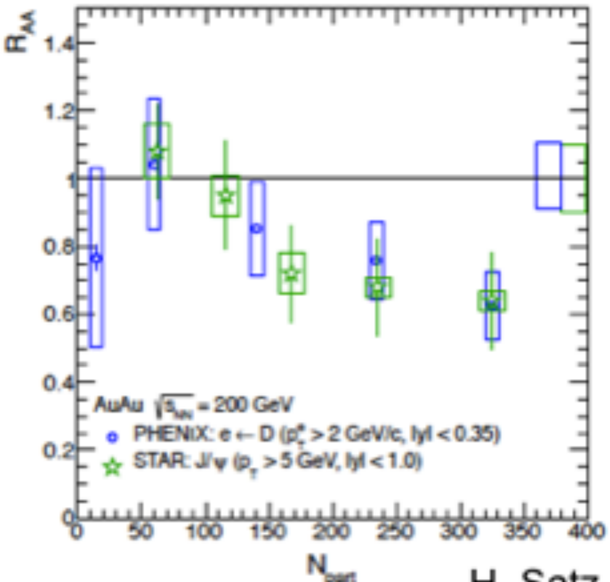
2. Jpsi AA/pA : RpA
(J/Psi AA measured)/(expected from pA) (NA50)
to subtract Cold Nuclear Matter effects (CNM)

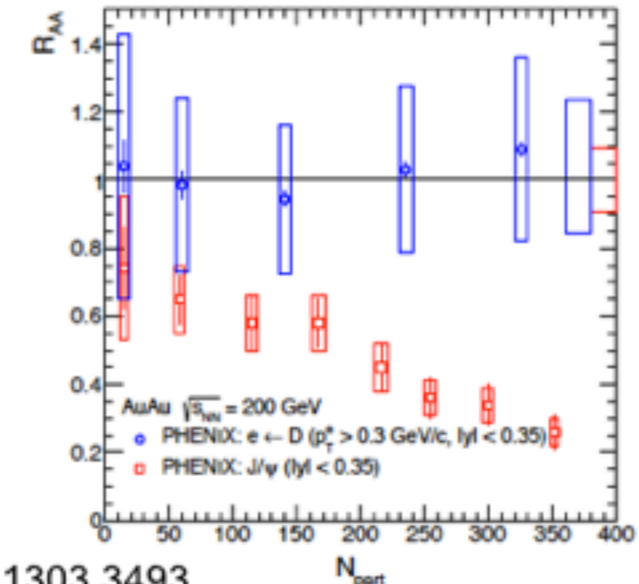
3. (J/Psi AA/pp) / (open charm AA/pp) :
RAA(J/Psi) / RAA(open charm)

4. (J/Psi AA/pA) / (open charm AA/pA):
(RpA (J/Psi))/ (RpA (open charm))

Very different conclusions can be drown depending on normalization

J/Psi compared to open charm - RHIC



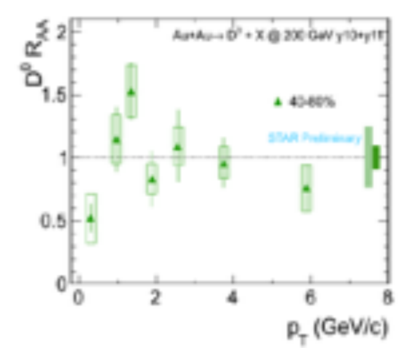


H. Satz, arXiv 1303.3493

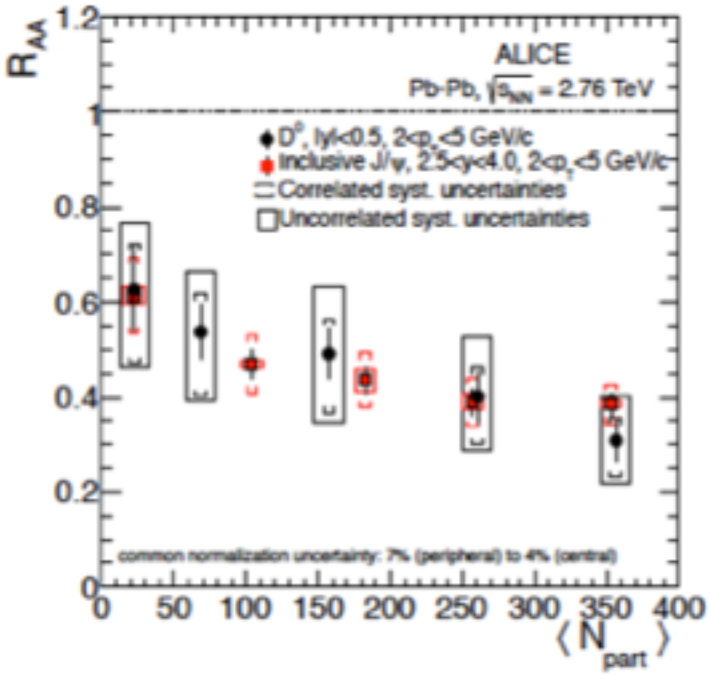
*** J/Psi seems to be neither suppressed nor enhanced with respect to open charm at all centralities at high pT (However pT range is not exactly the same)**

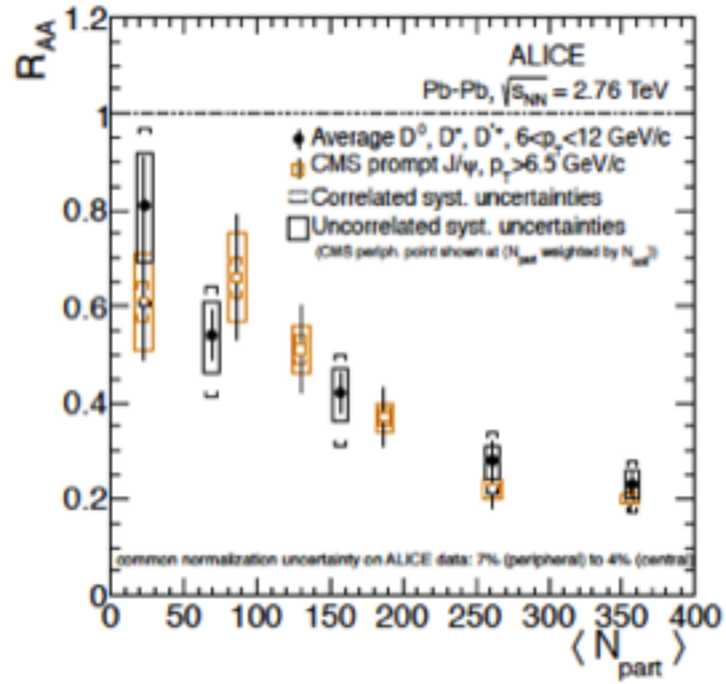
*** J/Psi seems to be significantly suppressed with respect to open charm at low pT in central Au+Au events (same acceptance here)**

STAR : RAA(D0) shows no suppression for peripheral collisions



J/Psi compared to open charm - LHC



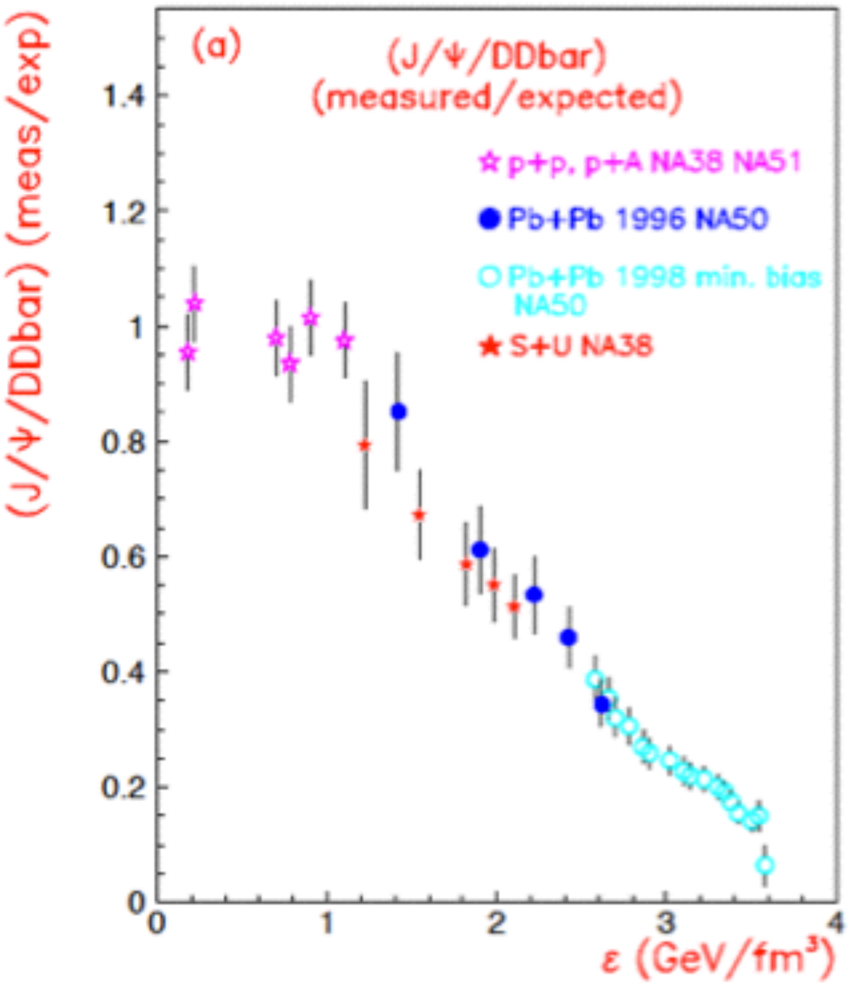


H. Satz, arXiv 1303.3493

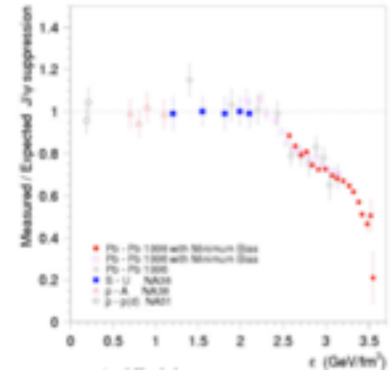
J/Psi seems to be neither suppressed nor enhanced with respect to open charm at all centralities, at intermediate (pT=2-5 GeV) and high pT>6.5 GeV

However experiments should compare more precisely within exactly same acceptance (here different y) and at low pT too

First study of the ratio of J/Psi to open charm (SPS)



S.K., New J. of Physics, Vol. 3, (2001), 16, arXiv 0004138



- Open charm measured by dimuons in region 1.6-2.5 GeV

The J/Psi/(DDbar) estimate is suppressed at 1 GeV/fm^3
Critical energy density from Lattice QCD for the QCD phase transition is ~ 0.6 GeV/fm^3

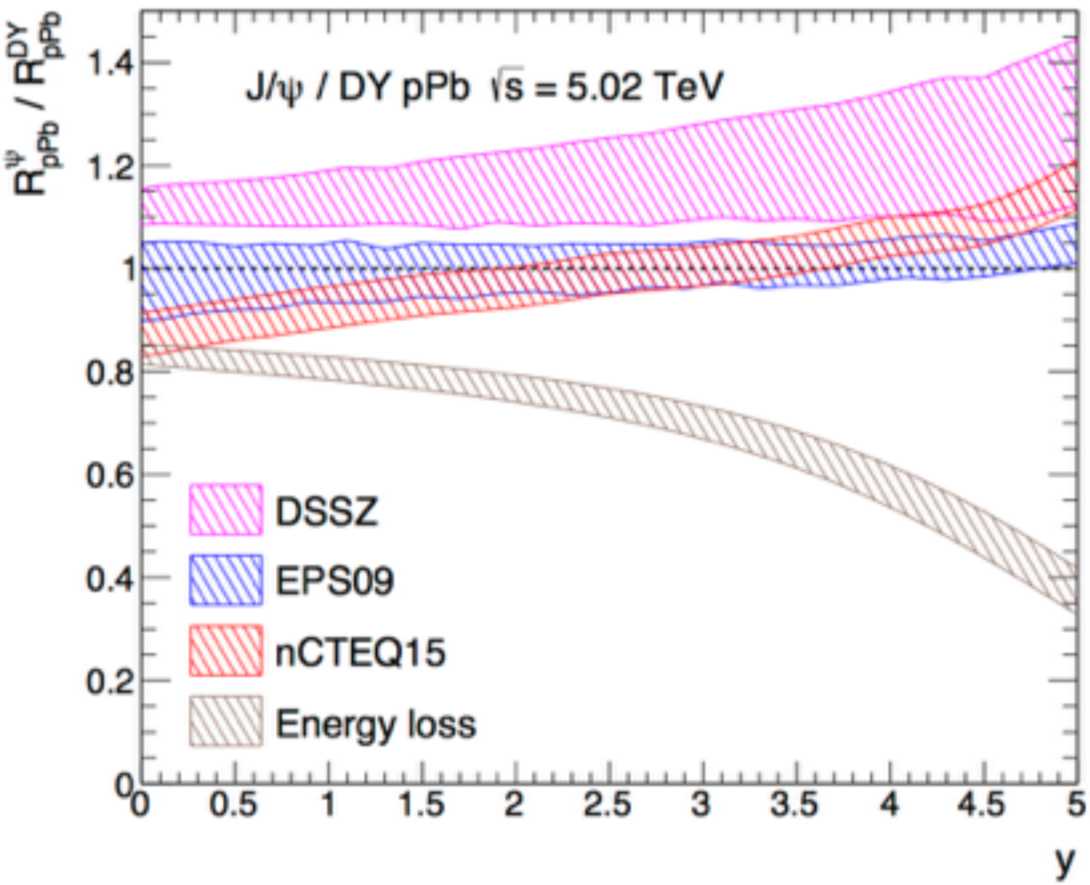
We need hidden and open charm measurements at low energy to understand quarkonia onset of suppression.

F. Fleuret et al: LHCb SMOG program will address chi_c at lower energies

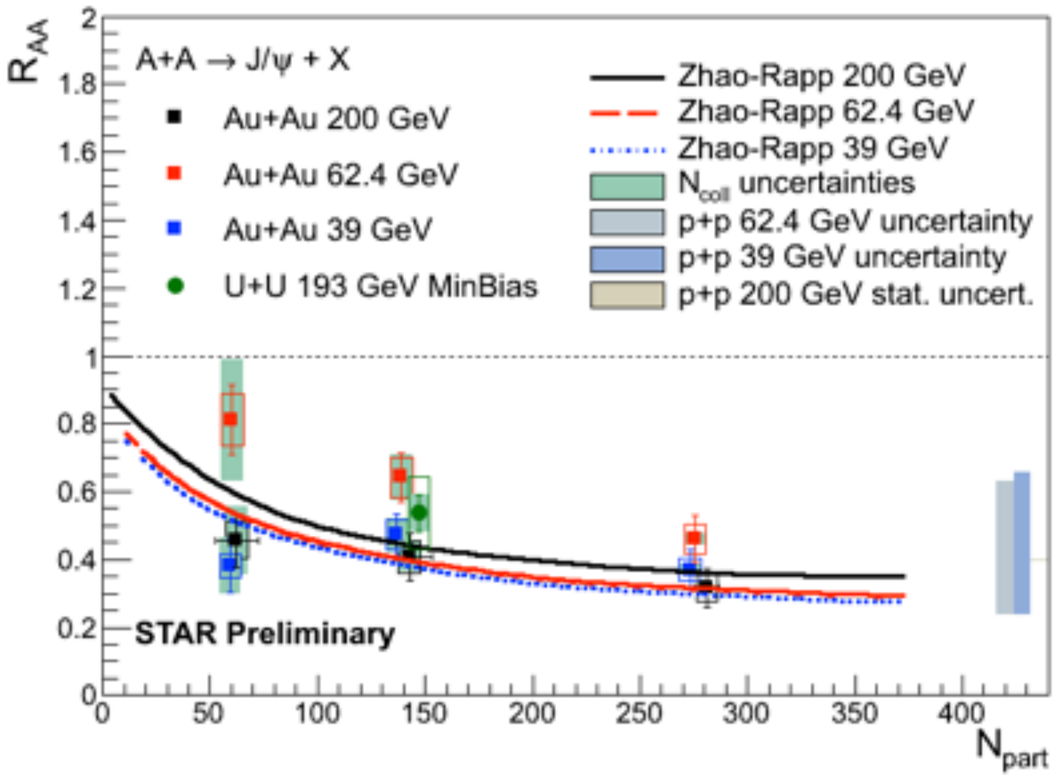
J/Psi/DY

F. Arleo, S. Peigne, 1512.0179

Measuring the J/Ps/DY ratio in p+Pb (instead of the RpA) allows to disentangle shadowing effects from coherent energy loss

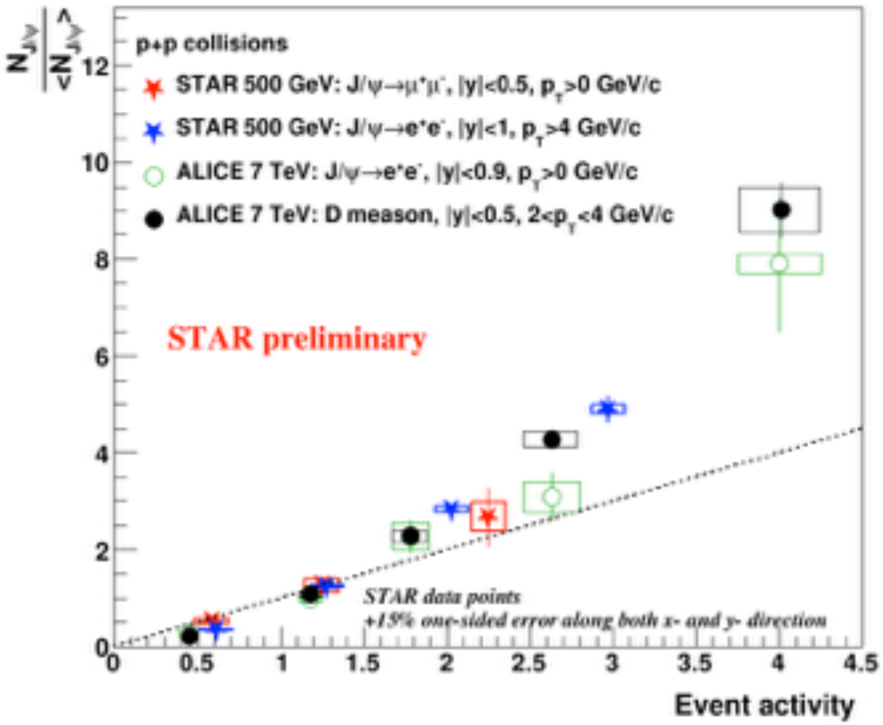


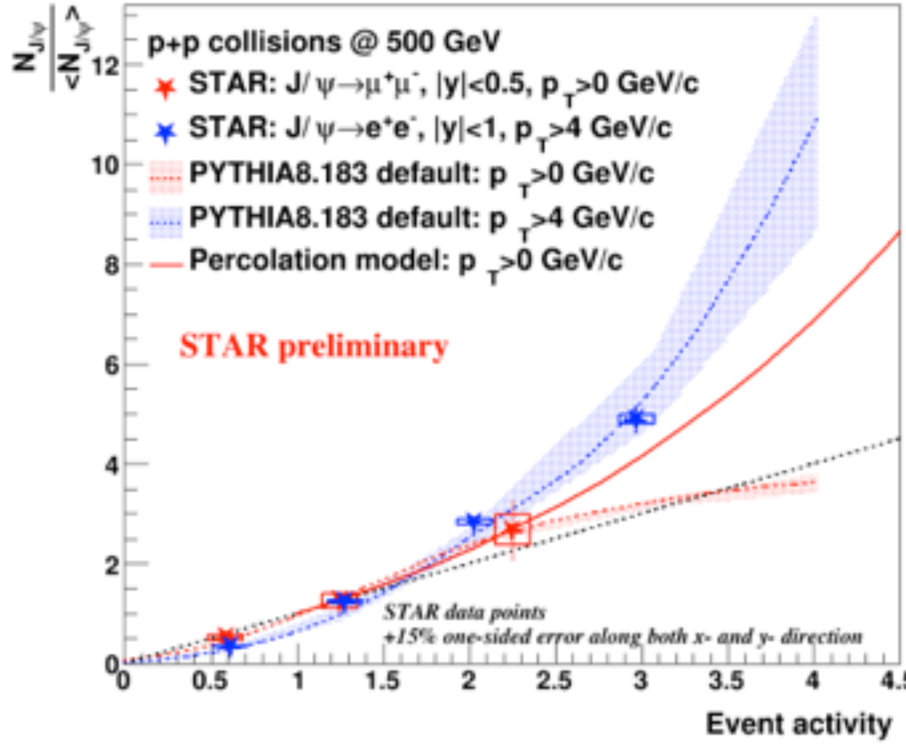
RHIC Beam Energy Scan:
At which energy does J/Psi suppression turn off?



Color Evaporation Model (CEM) estimate for p+p reference used for 39, 62 GeV
R_{AA} in U+U 193 GeV is consistent within errors with Au+Au 200 GeV
R_{AA} of J/Psi is suppressed in similar way at 39, 62 and 200 GeV

J/Psi in pp collisions at RHIC and LHC vs event activity

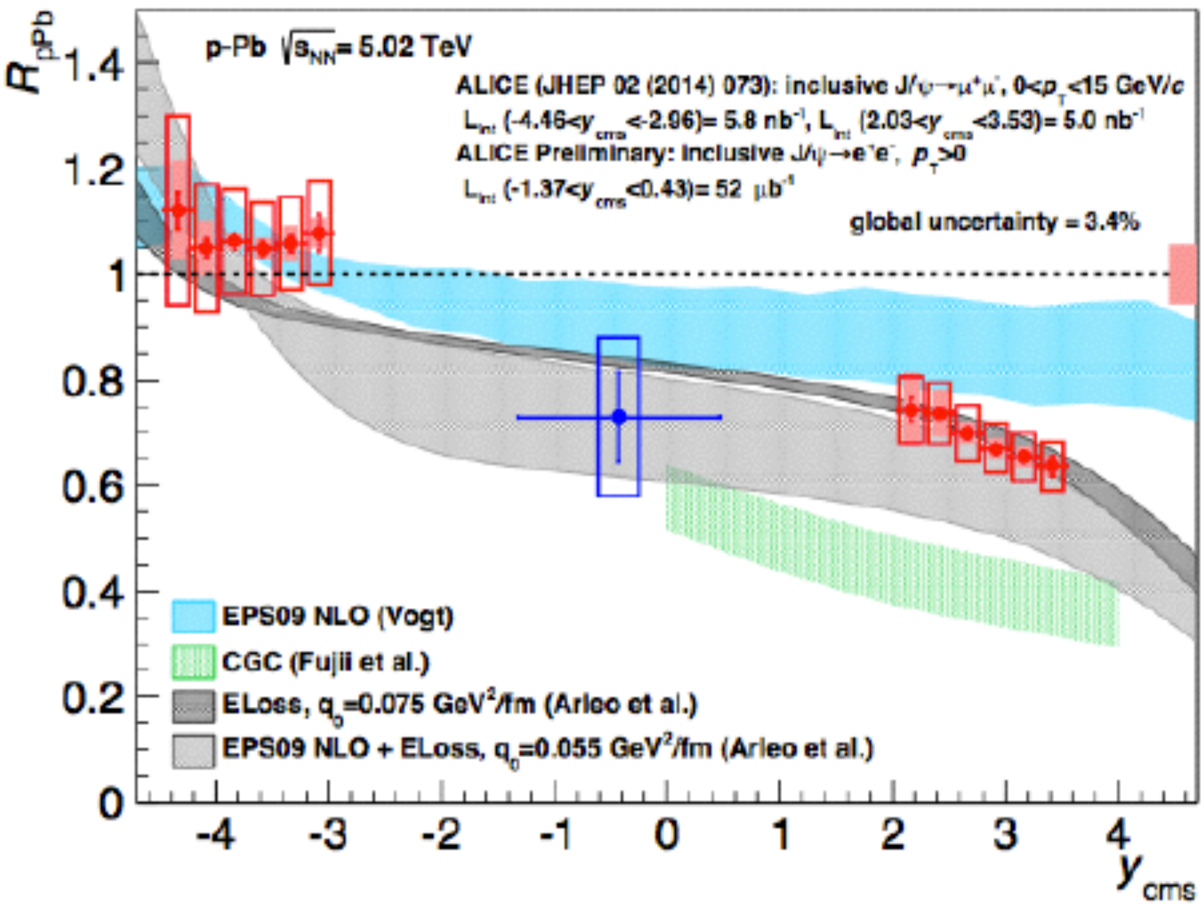




- J/psi increases more than linearly with the multiplicity ("event activity") in p+p collisions at 500 GeV
-The rising seem to be faster for high pT at RHIC and LHC

Models shown:
Multiple parton-parton interactions - PYTHIA 8
String screening – percolation model, PRC 86 (2012) 034903

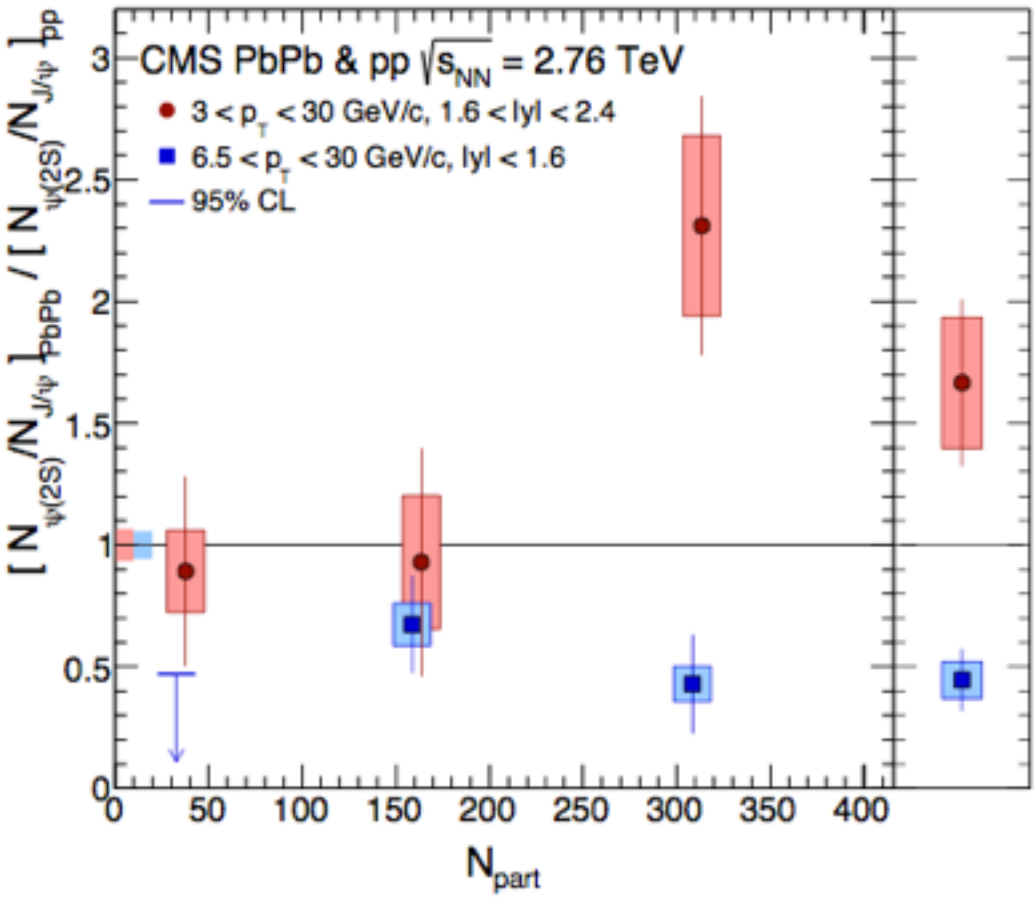
J/Psi in p+Pb



* Models with energy loss in cold nuclear matter and shadowing can describe the data on J/Psi in p+Pb at LHC
* pT dependence of R(pPb) not easy to reproduce at same time

Psi(2S)/(J/Psi) (PbPb/pp)

CMS results

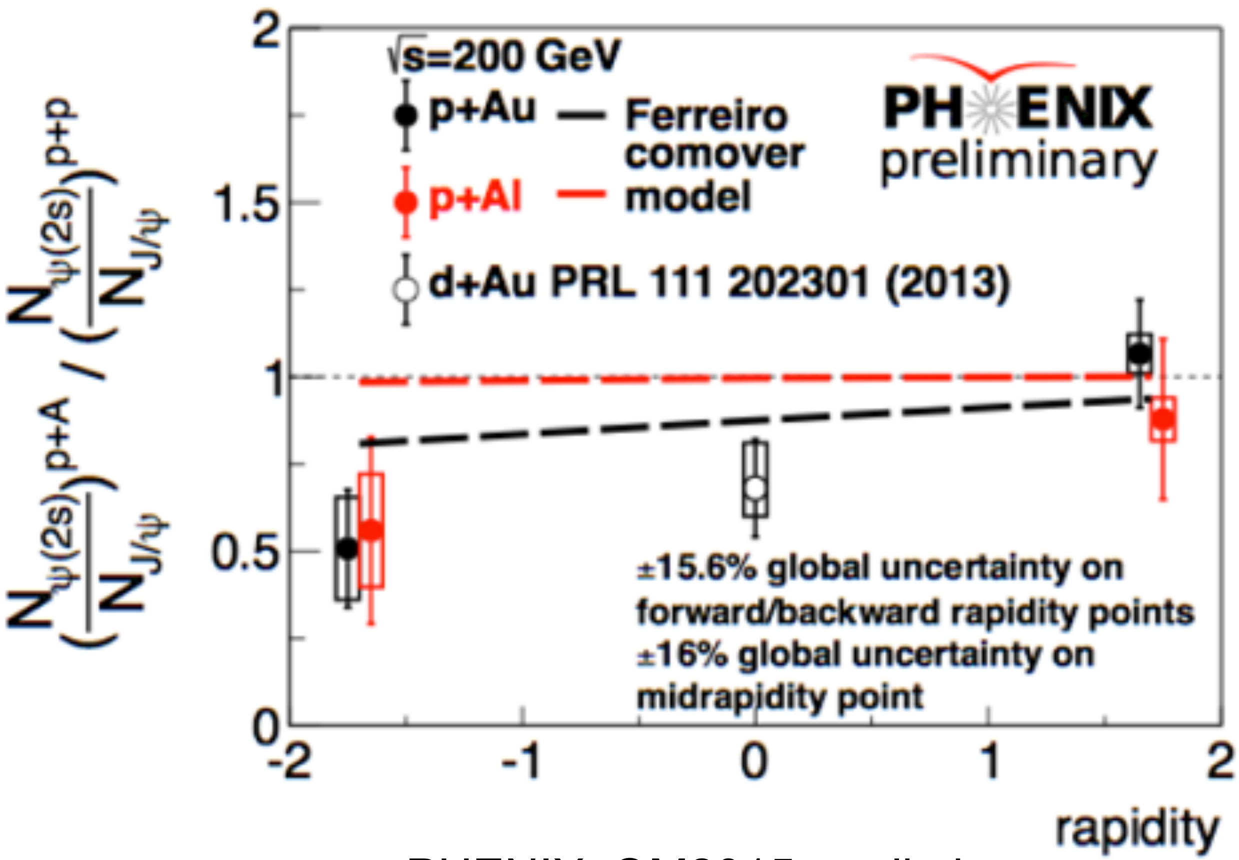


1410.1804 CMS

- Psi(2S) more suppressed than J/Psi in central PbPb collisions compared to pp collisions, for |y| <1.6 and pT=(6.5,30) GeV

- while it is enhanced for more forward |y|=(1.6,2.4) and pT=(3,30) GeV

New results from 2015 run
Psi(2S)/J/Psi in p+A

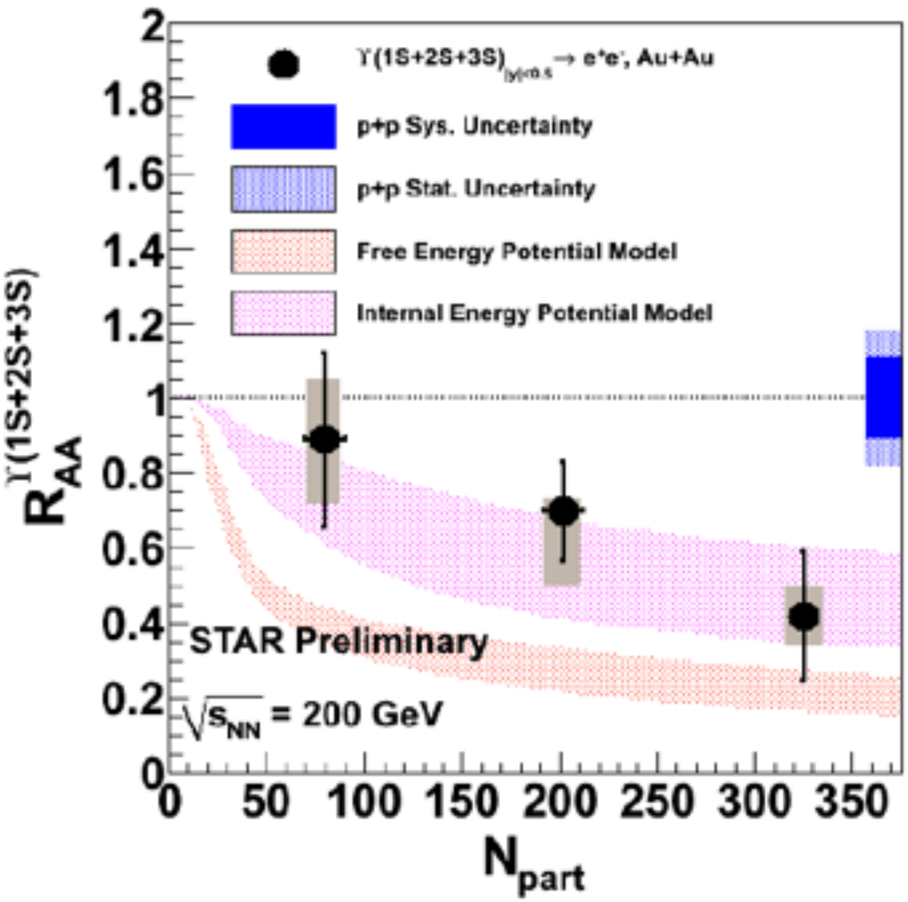


PHENIX, QM2015, preliminary

Double ratio of psi(2S) to J/Psi in p+A over p+p: ~0.5 in backward rapidity
-> Psi(2S) strongly suppressed in backward rapidity in p+Au, p+Al 200 GeV

Upsilon in Au+Au 200 GeV

Y suppression was discovered both at RHIC (STAR) and LHC (CMS) in 2011



state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

Y(1S+2S+3S) in Au+Au collisions at 200 GeV :

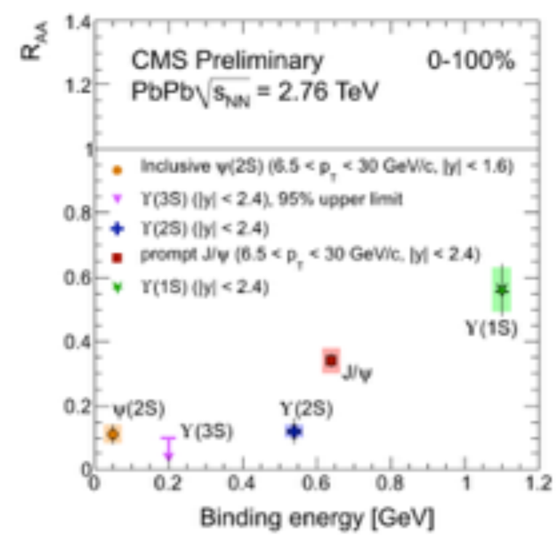
* No suppression in most peripheral collisions

* Exhibits suppression in more central collisions increasing with centrality

* The suppression observed is consistent with model assuming Y(2S) and Y(3S) suppression

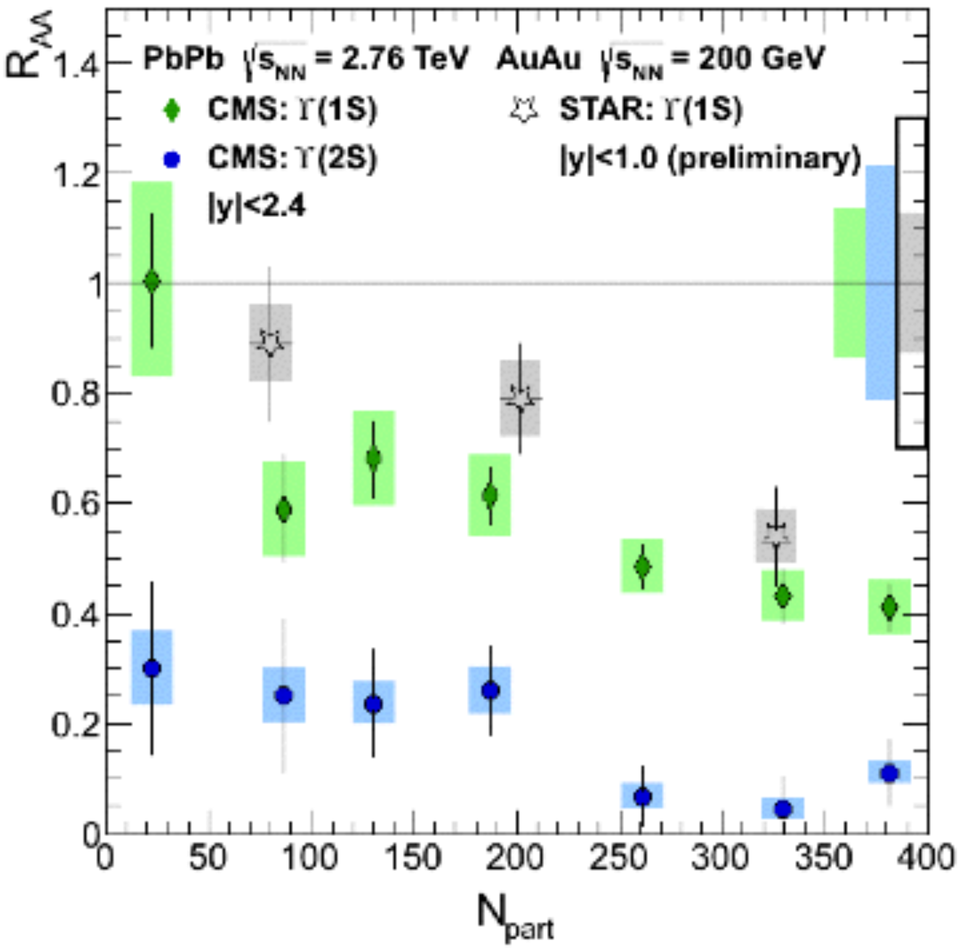
Model by Strickland et al (PRL 107, 132301, 2011, Nucl. Phys. A879 (2012) 25, arXiv:1112.2761) :

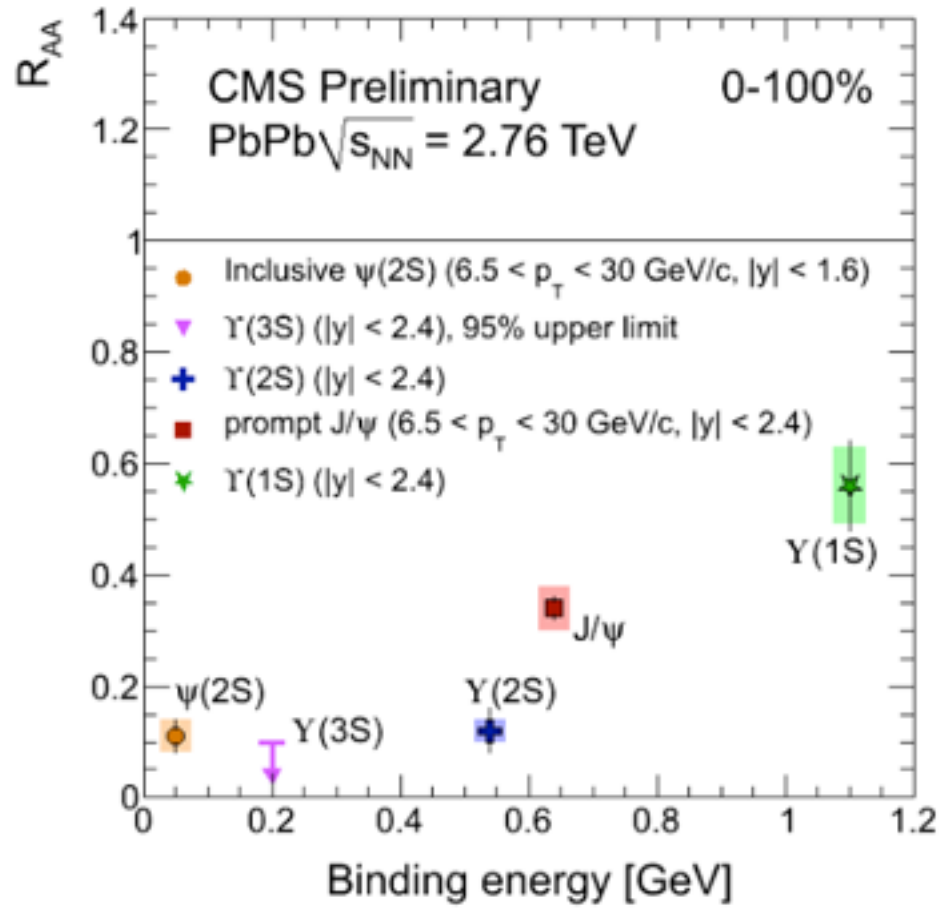
Assumes T_0= 428-442 MeV and 1/4π < η/S < 3/4π



PRL 109, 222301 (2012)

Y states LHC

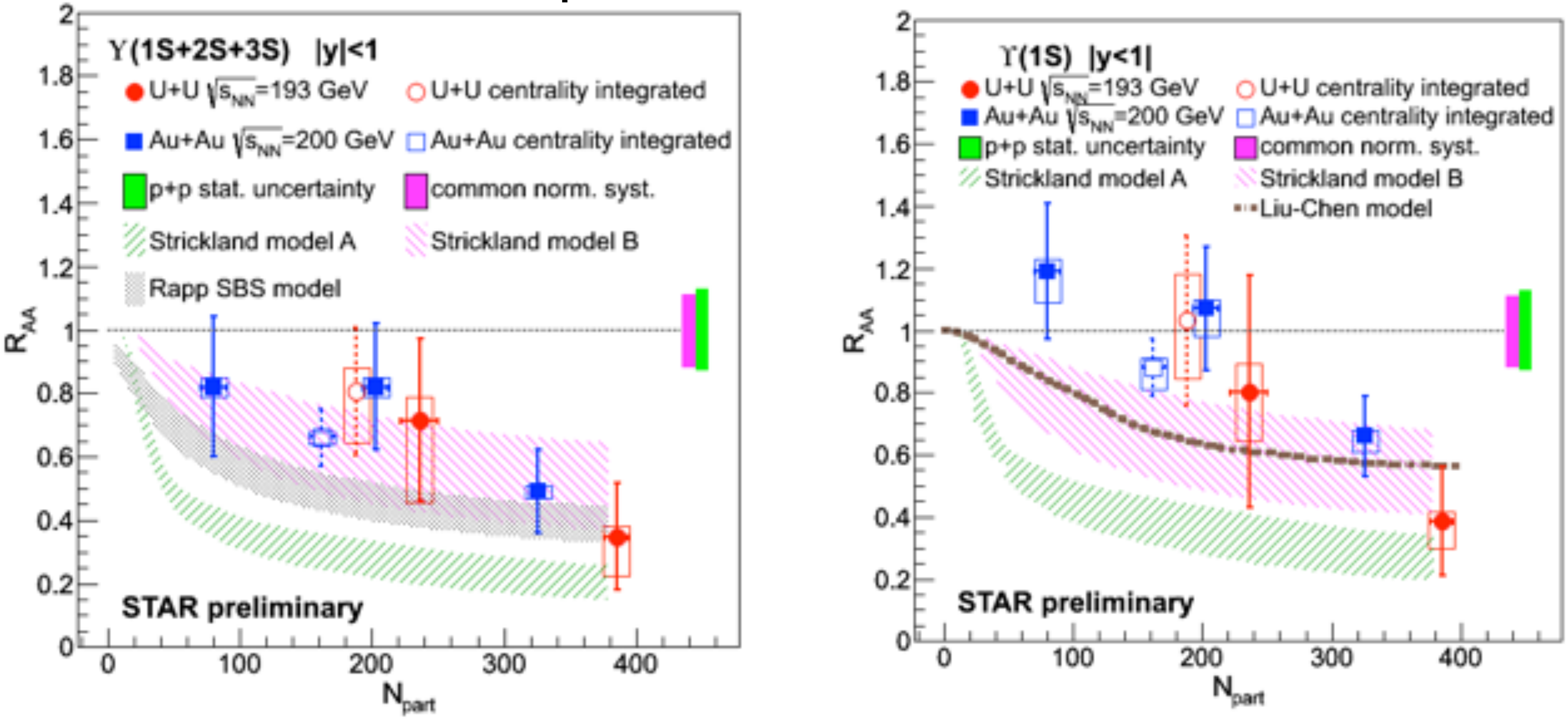




***Larger suppression of Y(2S) as compared to Y(1S) (CMS)**
*** Y(1S) CMS and STAR similar in central collisions**

*** Hierarchy of suppression as expected for quarkonia dissosiation !**

Upsilon vs models at RHIC



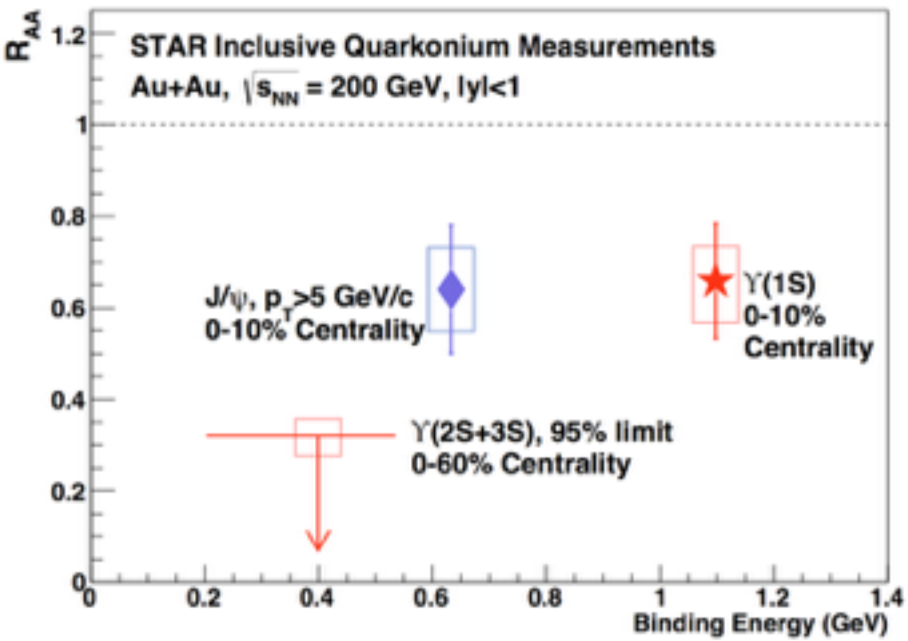
Model of Strickland, Bazov (Nucl. Phys. A 879, 25 (2012))
No Cold Nuclear Matter effects
T(initial)=428-443 MeV
Potential model A is based on heavy quark free energy (disfavored)
Potential model B is based on heavy quark internal energy

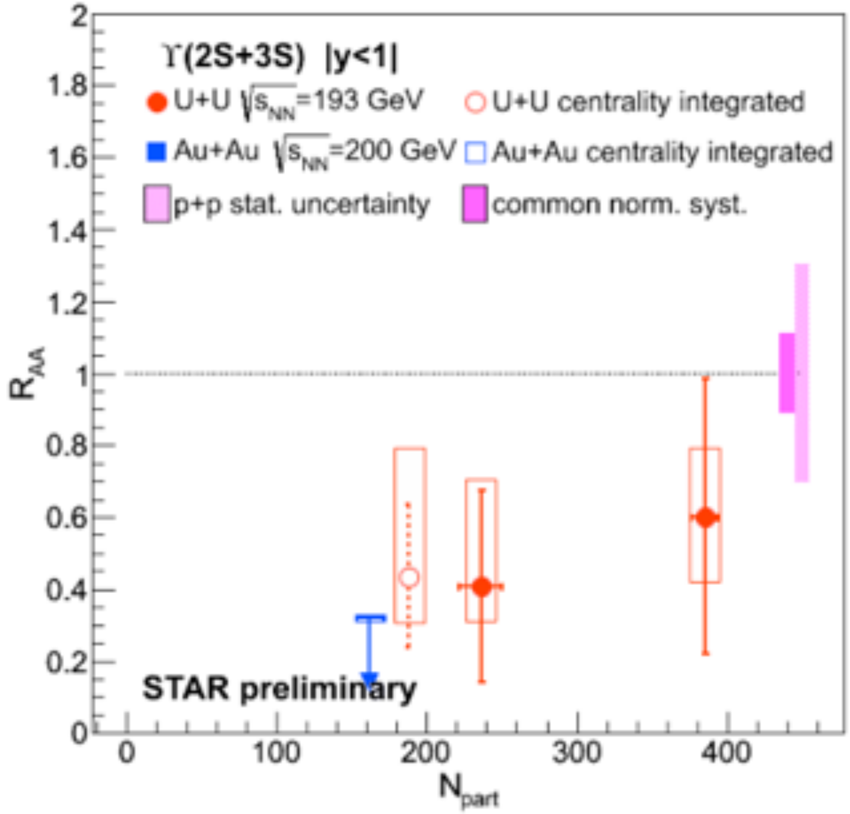
Model of Liu, Chen, Xu, Zhuang (Phys Lett B 697, 32 (2011)
Potential model, no Cold Nuclear Matter effects. T= 340 MeV

Model of Emerick, Zhaon, Rapp (Eur. Phys. J A48, 72 (2012))
Cold Nuclear Matter effects included

Y data in agreement with Y melting scenario

Quarkonia sequential suppression at RHIC ?



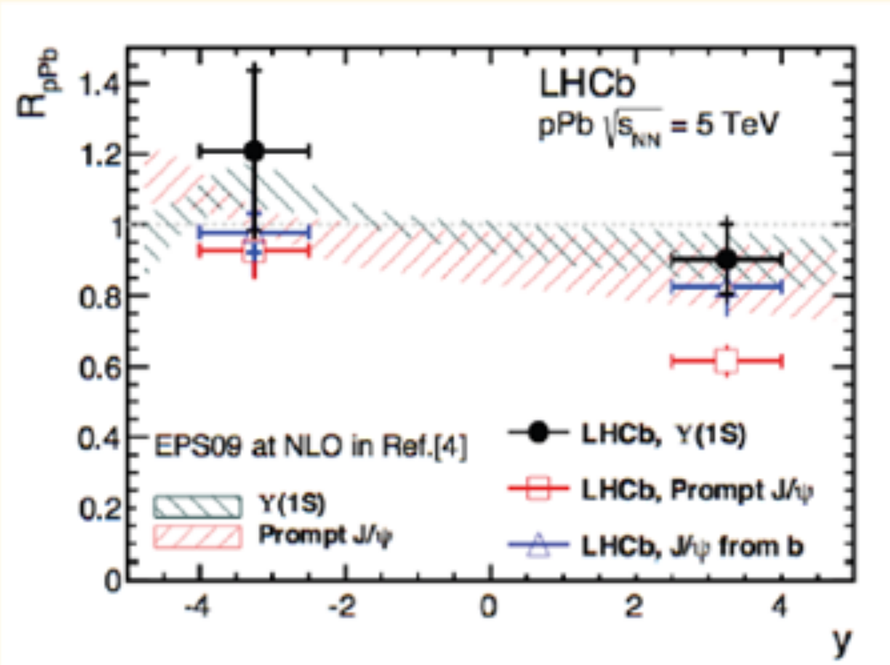


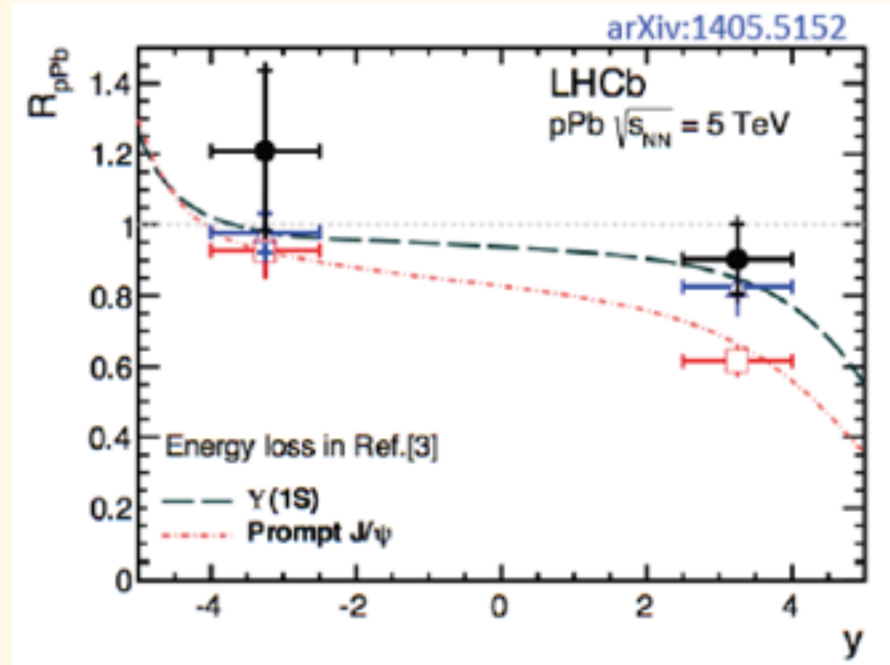
- Au+Au 0-10%: Y(1S) similarly suppressed as J/Psi at high pT.
- Au+Au 0-60% upper limit: Y(2S+3S) consistent with complete melting/suppression (upper limits)
- U+U: centrality dependence pattern of Y(2S+3S) consistent with Au+Au Upper Limits

- J/Psi, Y(1S), Y(2S+3S) suppression pattern supports sequential melting.

b-bbar in p+Pb

- Υ production in pPb collisions
- kinematics: 2.5 <|y|<4.0, p_T < 15 GeV/c

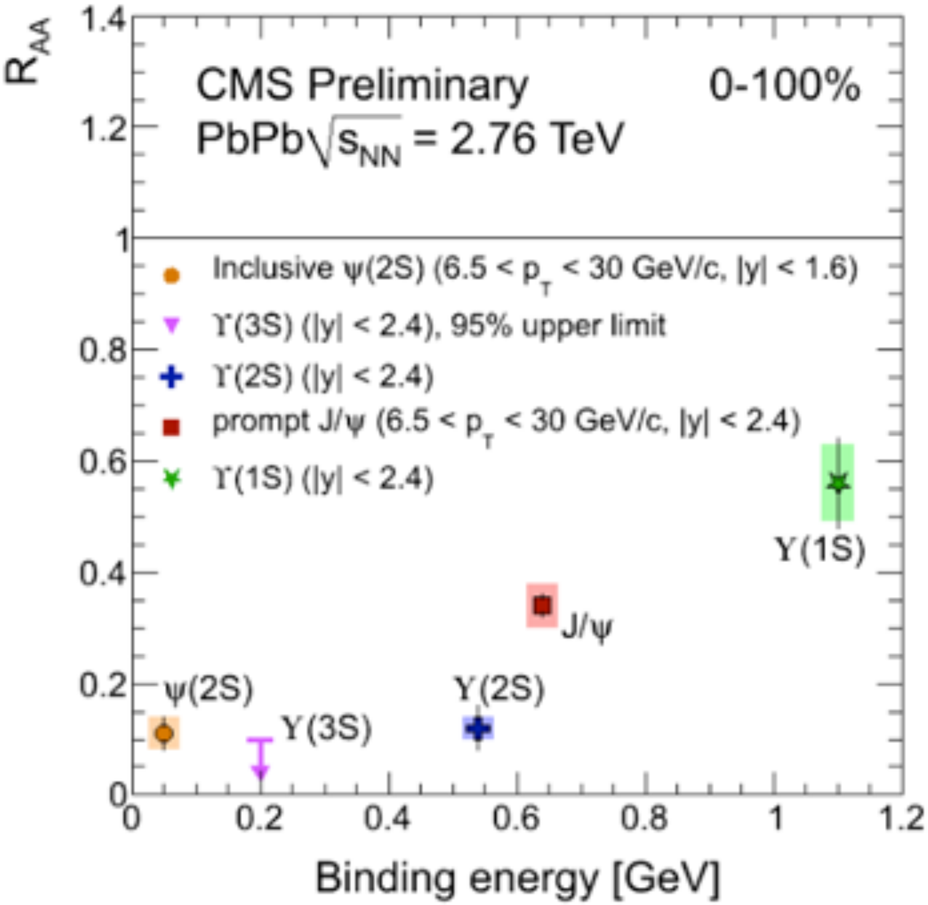


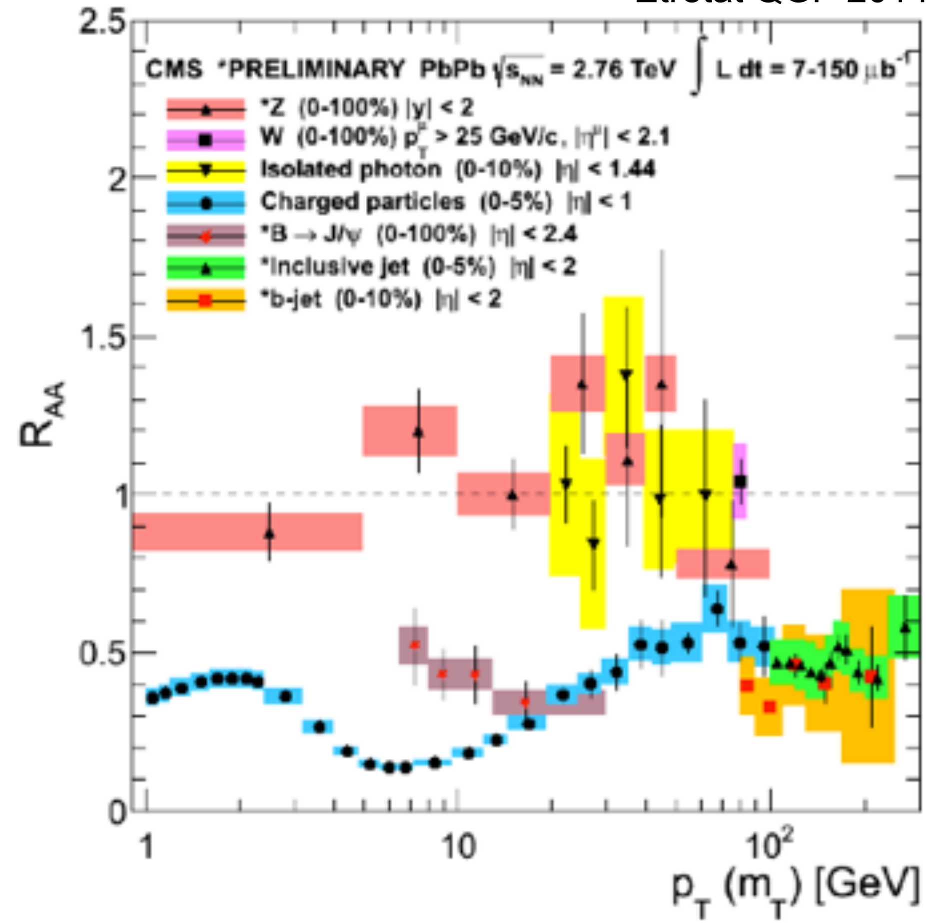


- data consistent with NLO EPS09 plus coherent energy loss
- very similar suppression for Υ(1S) and J/ψ from b
- dominated by statistical uncertainties

Are Upsilons supressed more than open beauty ?

M. Jo et al CMS, Etretat QGP 2014



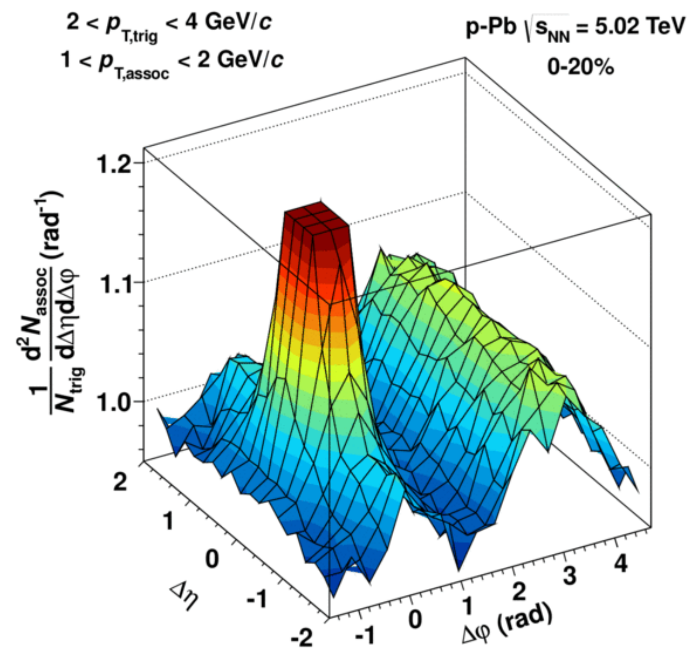


Y(1S) in PbPb within errors seem similarly suppressed as open beauty in PbPb (needs better stat)

Y(2S), Y(3S) in PbPb more suppressed than open beauty in PbPb

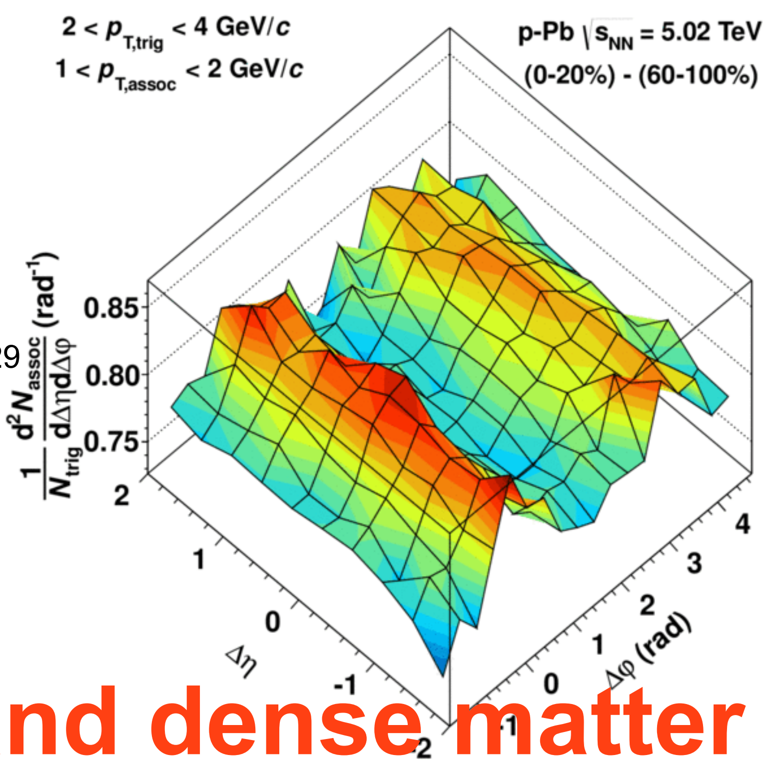
Small systems

The ridge in p+p, p+A, A+A



First observed by CMS
PLB718 (2013) 795

After taking out jet-effects: Double Ridge



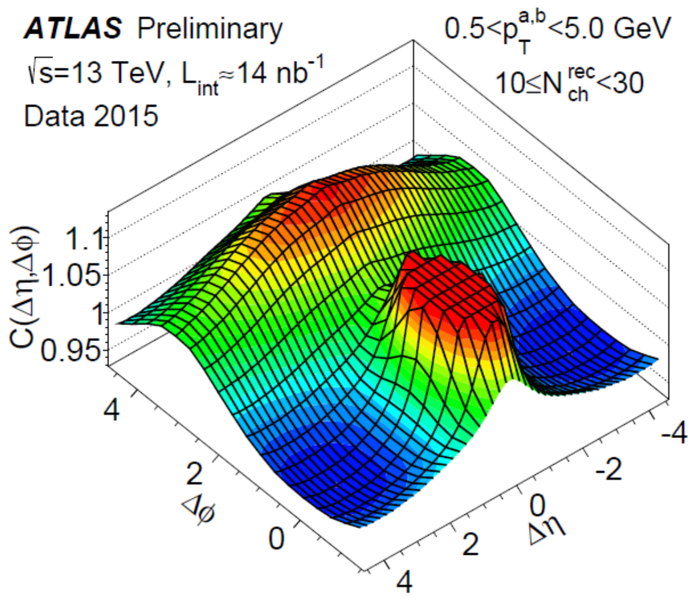
ALICE PLB719 (2013) 29

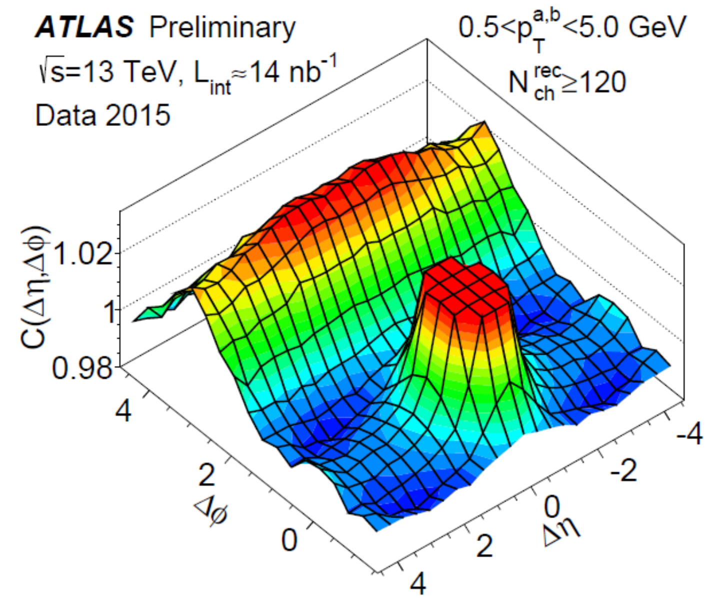
* Interpretation of ridge structure
in p+p, p+Pb remains open

CGC ? hydrodynamic flow ?

Possibility of hot and dense matter formation in small systems ?

Run-2 news: the ridge seen in p+p collisions at 13 TeV





Low mult

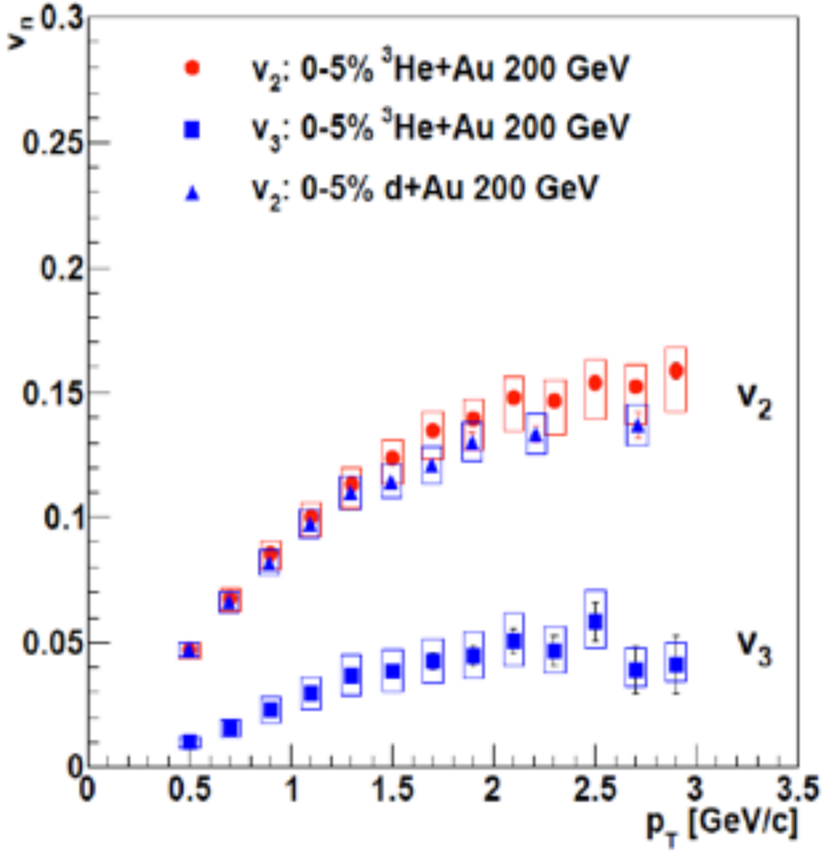
High mult

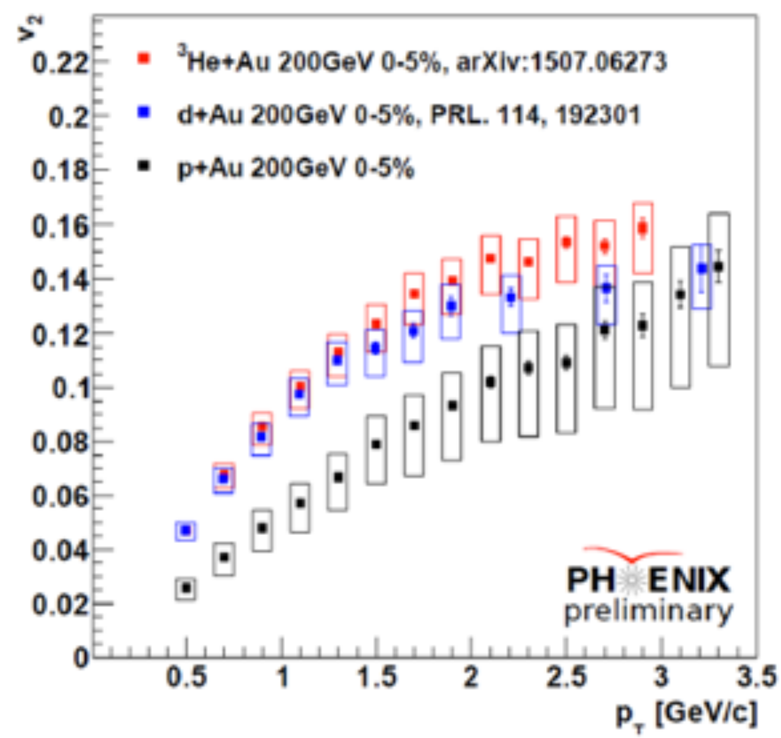
M. Arratia et al , ATLAS
EPS2015

Ridge: Similar in p+p 13 and 7 TeV

RHIC: First results from 2015 p+Au run and results from 2014 3He+Au at 200 GeV

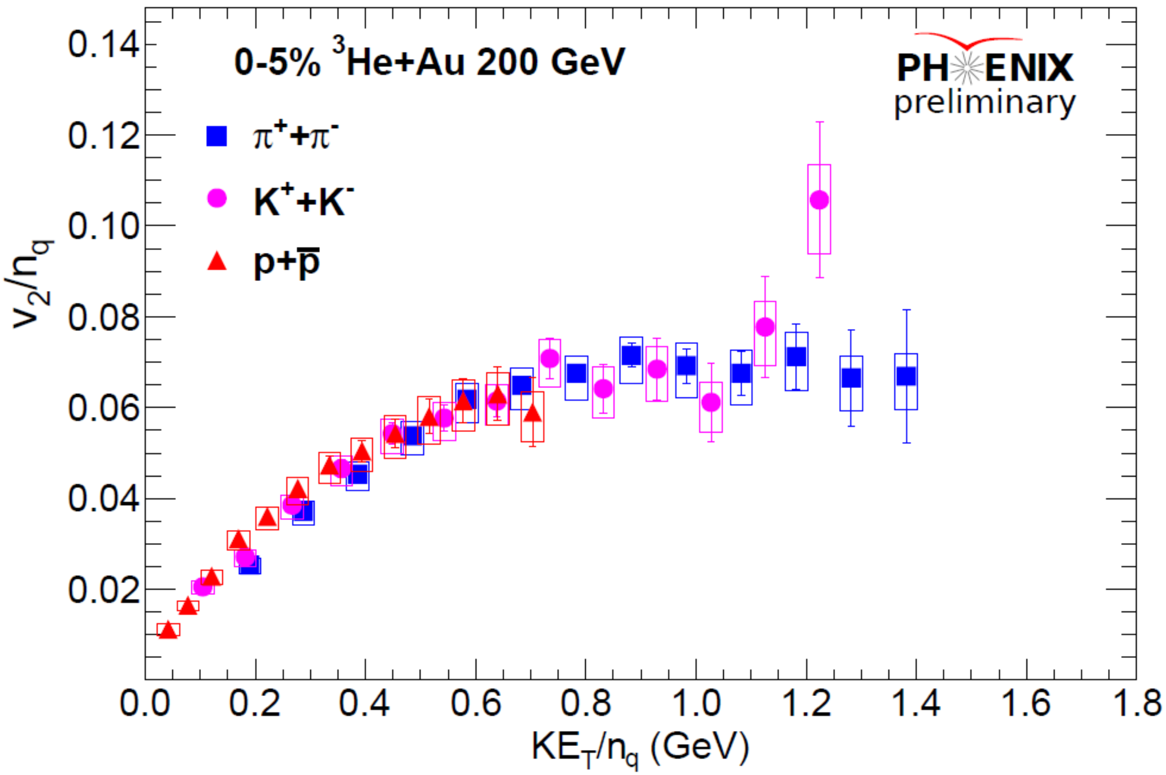
PHENIX 3HeAu: Phys. Rev. Lett. 115, 142301 (2015)
PHENIX dAu: Phys. Rev. Lett. 114, 192301 (2015)





Large v2, v3 components in 0-5% 3He+Au, d+Au and p+Au from 2015 run

Number of quark scaling in 3He+Au

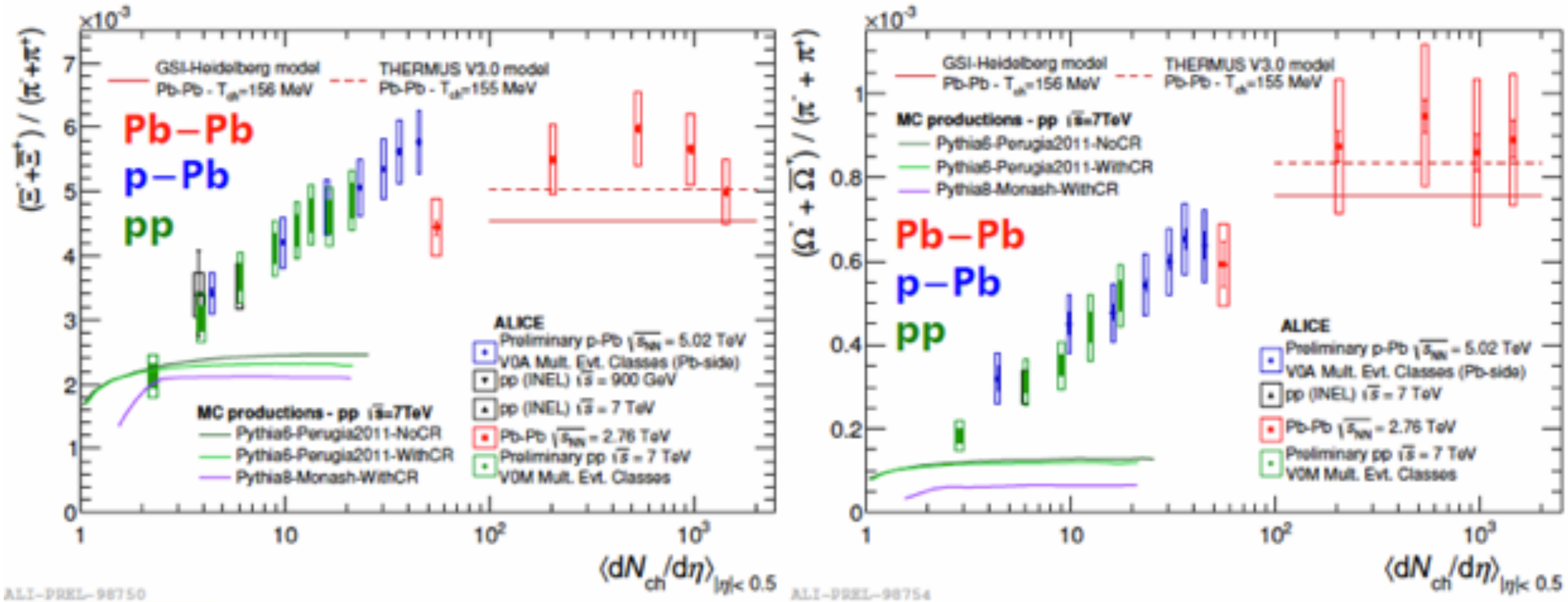


S Huang,
STAR,
QM15

The familiar behavior of number of quark scaling observed in Au+Au collisions is also seen in the small ^{3}He+Au system

ALICE strangeness

Ξ/π and Ω/π vs. $dN_{ch}/d\eta$



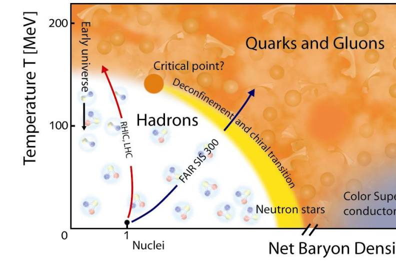
L. Bianchi
QM2015

- Ξ/π and Ω/π reach Grand Canonical limit in Pb−Pb
- Similar multiplicity dependence in pp and p−Pb
  - ✓ Neither PYTHIA6 nor 8 reproduce data in any of the tunes tested

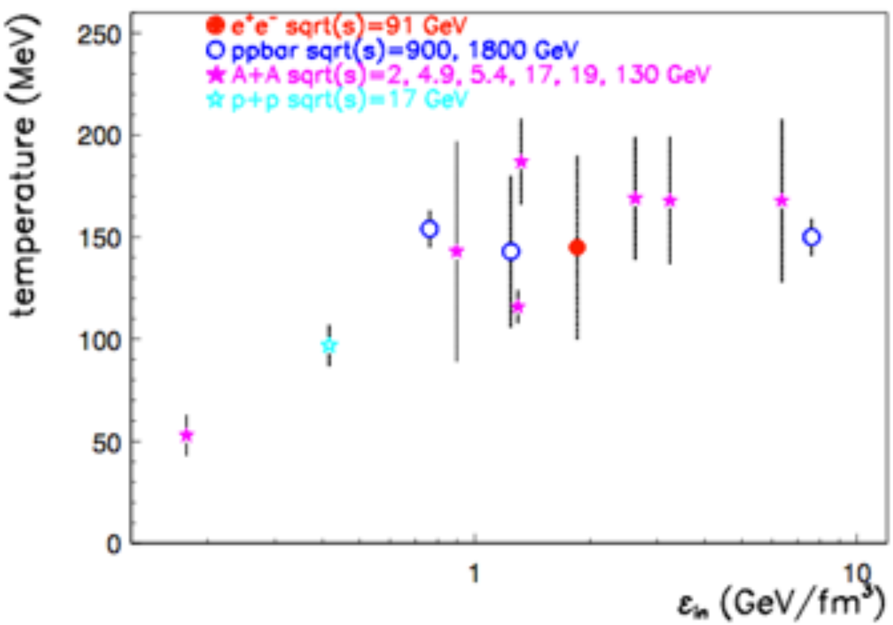
QGP forming in small systems ?

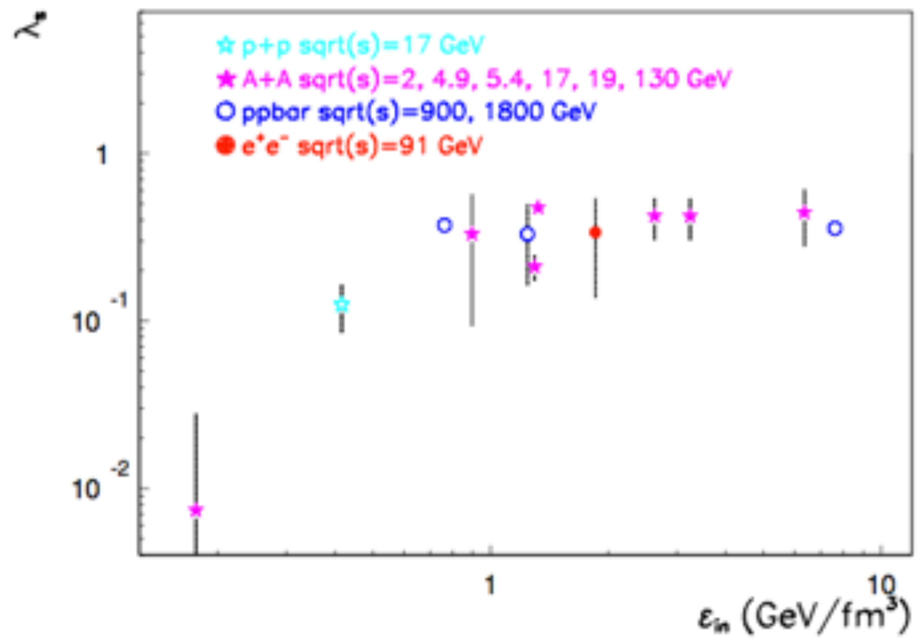
First time proposed in:

S.K., P. Minkowski, 2001 New J. Phys. 3 4



Universality of the QCD phase transition in p+p, p+A, A+A





First time found that small systems with initial energy density > 0.8 GeV/fm^3 seem to reach the critical conditions for QGP formation. Extrapolating all data to mu$_B$=0 :

-> Universality of onset of phase transition near ~0.8 GeV/fm^3

-> Universality of onset of saturation of strangeness suppression factor

Differences of AA, pp, pA dissappears at high enough initial energy density and at same mu$_B$

IV Conclusions and perspectives

- A wealth of data on Hard Probes at RHIC and LHC are available and are confronted to theoretical estimates.

- Further studies are needed to study in detail and understand jet quenching, quarkonia suppression and other phenomena.

- RHIC: accelerator and experimental upgrades -> wait for new results from 2014, 2015 run data with Au+Au, p+Au/Al, p+p and coming Au+Au 200 GeV and d+Au run in 2016 at few energies

- - LHC: run-2 started. First results from p+p 13 TeV out, Pb+Pb run in dec. 2015

- Further data taking and upgrades of existing experiments at RHIC, SPS and LHC, as well as new accelerator facilities and corresponding new experiments, NICA in Dubna, Russia and FAIR in GSI, Germany and J-PARC in Japan, will allow to progress in significant way in the next decades.

(Center of mass energy (sqrt(s)NN):
FAIR: 2-6 (10) GeV, NICA: 4-11 GeV, RHIC: 7 (2.5) - 200 GeV LHC: 2.76, 5 TeV)
J-PARC: 1-10 GeV

Thank you very much for your attention