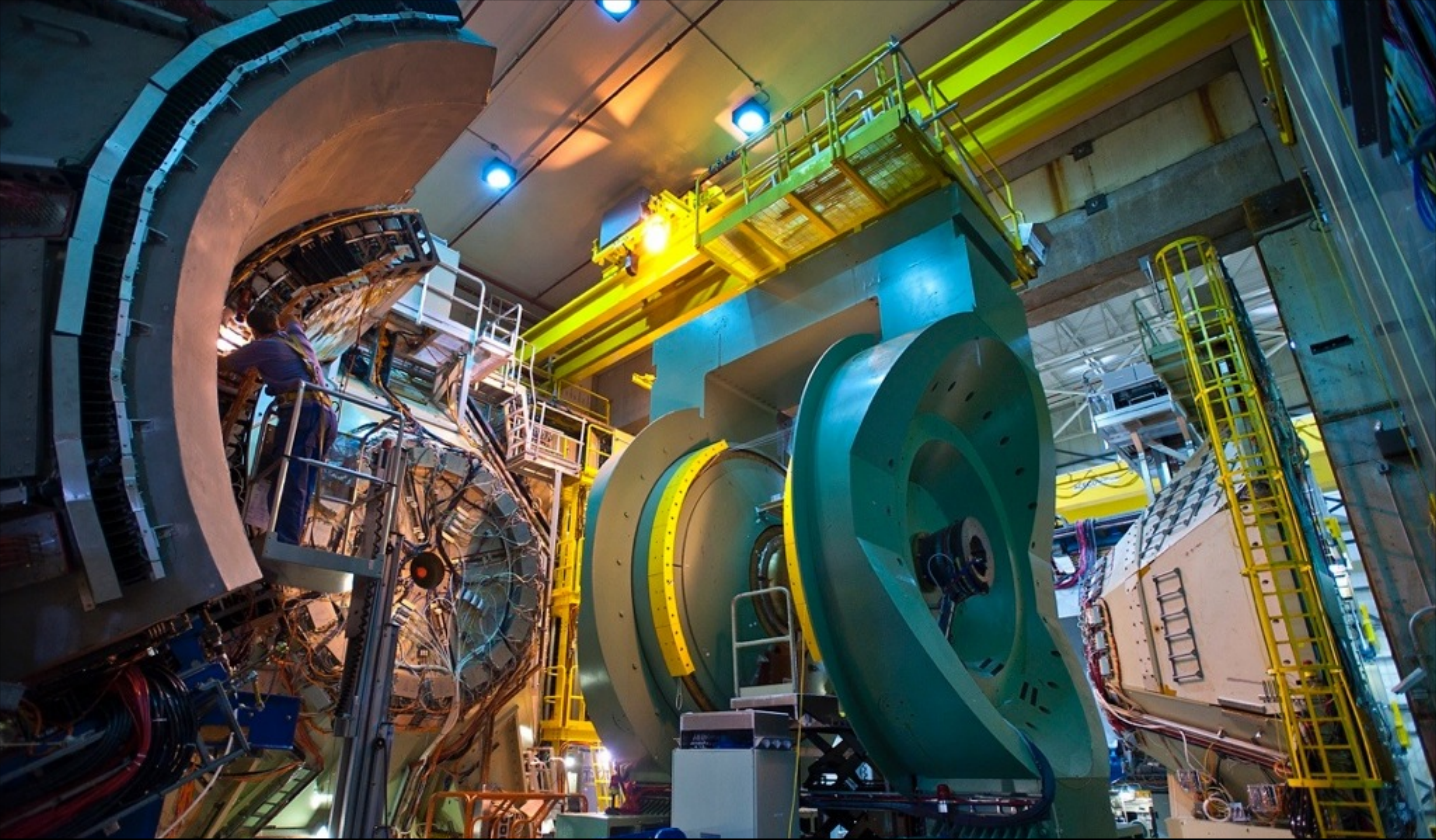
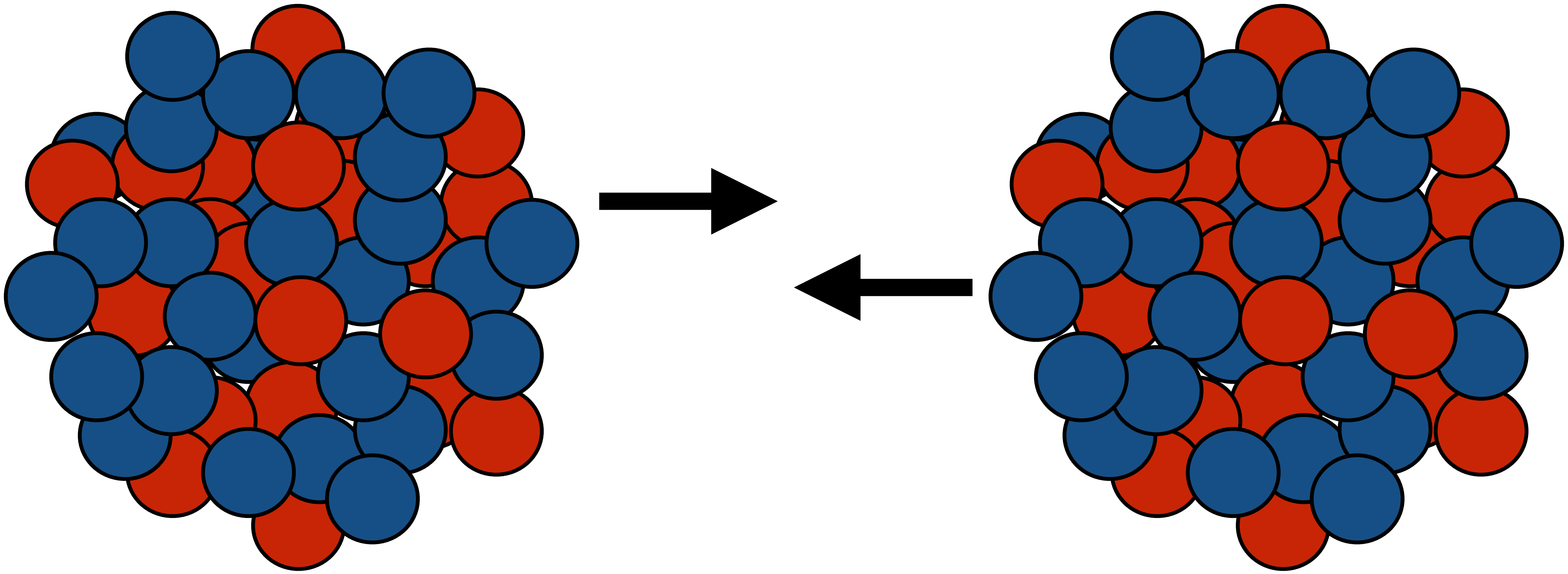


The Lighter Side of Heavy Ions

News from p/d+A Collisions

Anne M. Sickles, BNL

March 10, 2014



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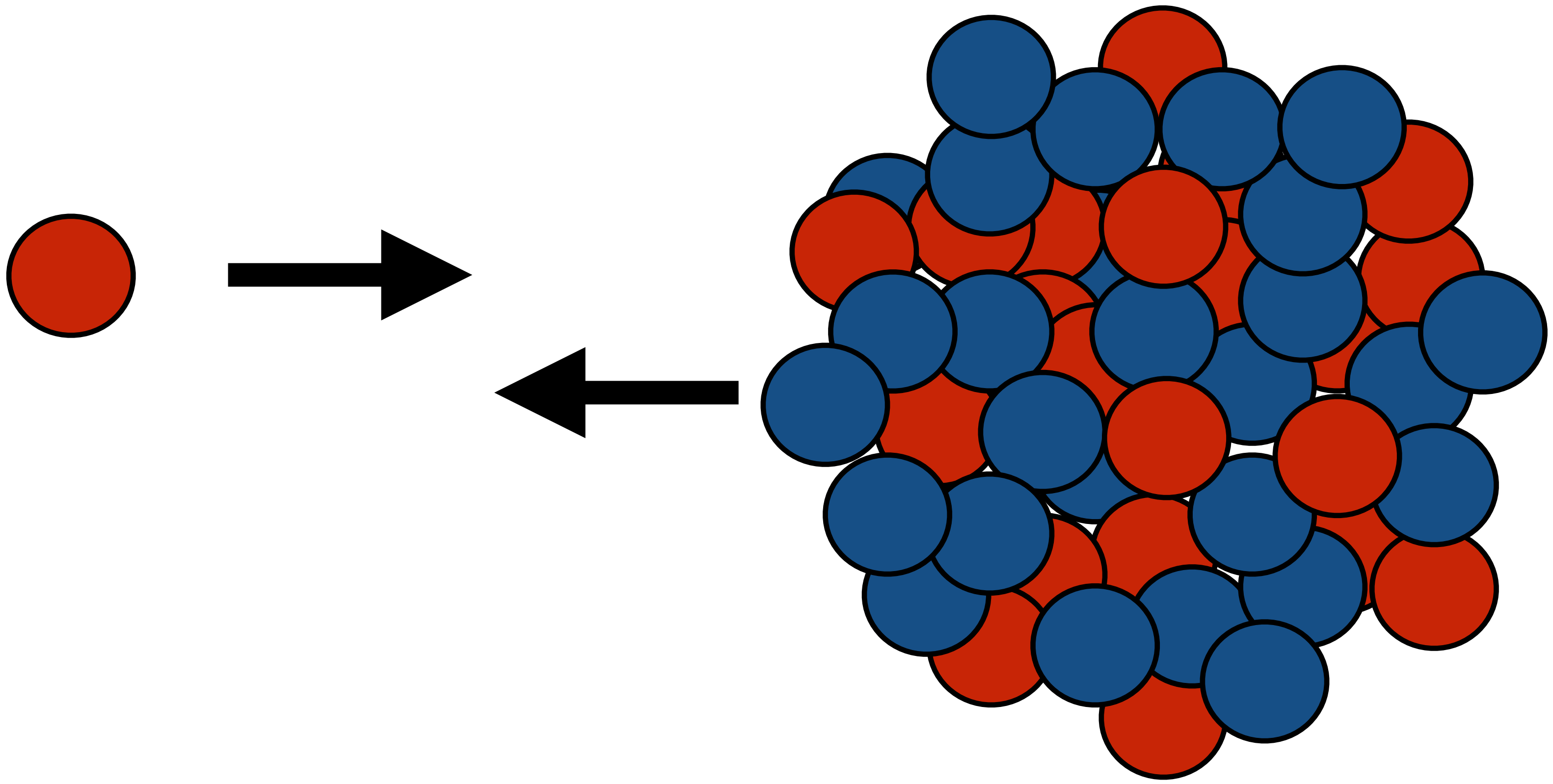

The Lighter Side of Heavy Ions

News from p/d+A Collisions

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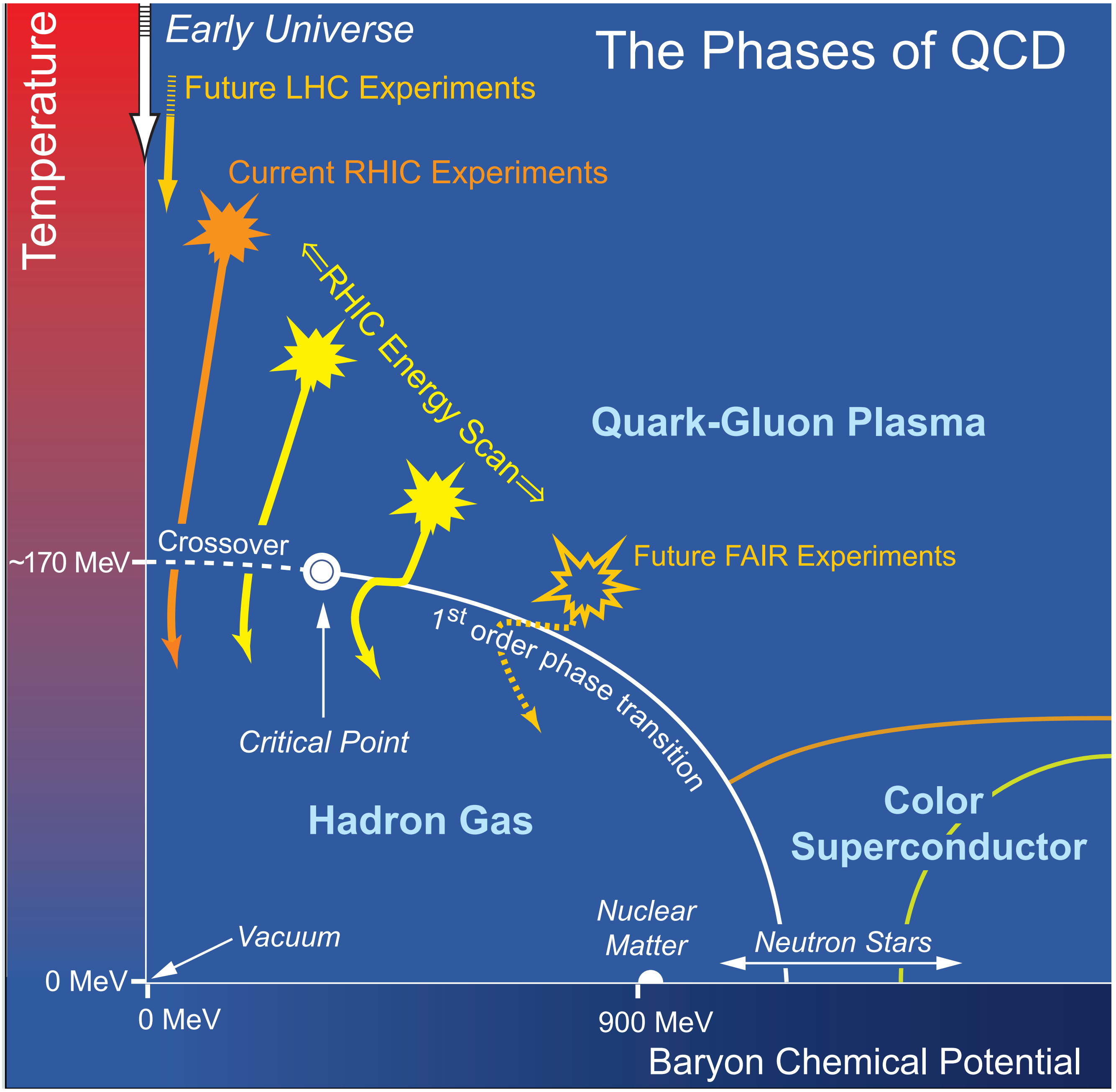
March 10, 2014

why heavy ion collisions?

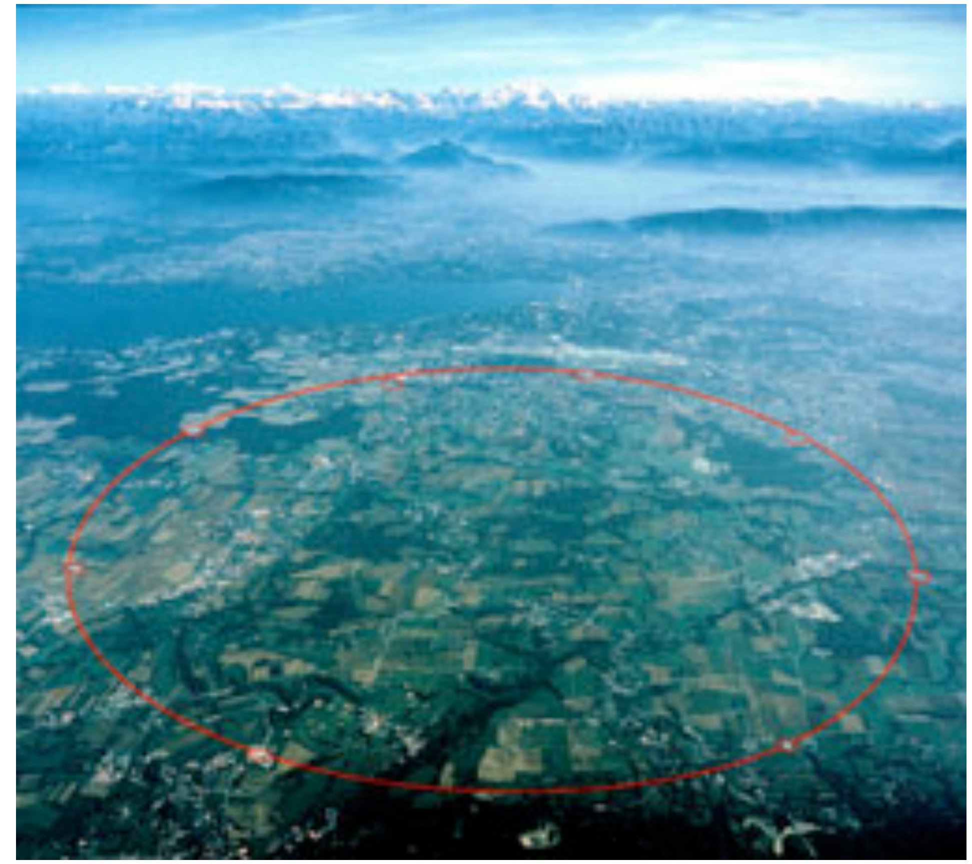
- study the phase structure of QCD
  - here we will focus on the high temperature side, but there are also exciting new investigations at lower temperatures and higher baryon densities
- quantitative understanding of the properties of QCD matter at extreme temperatures



Heavy Ion Programs at RHIC and LHC

2000 - present
7.7-510 GeV collision energy
AuAu, dAu, pp, CuCu, UU, CuAu

strengths: collision system & energy versatility and long running times



2010 - present
2.76 TeV collision energy PbPb
5.02 TeV pPb
pp @ multiple energies

strengths: excellent detectors and very high energy

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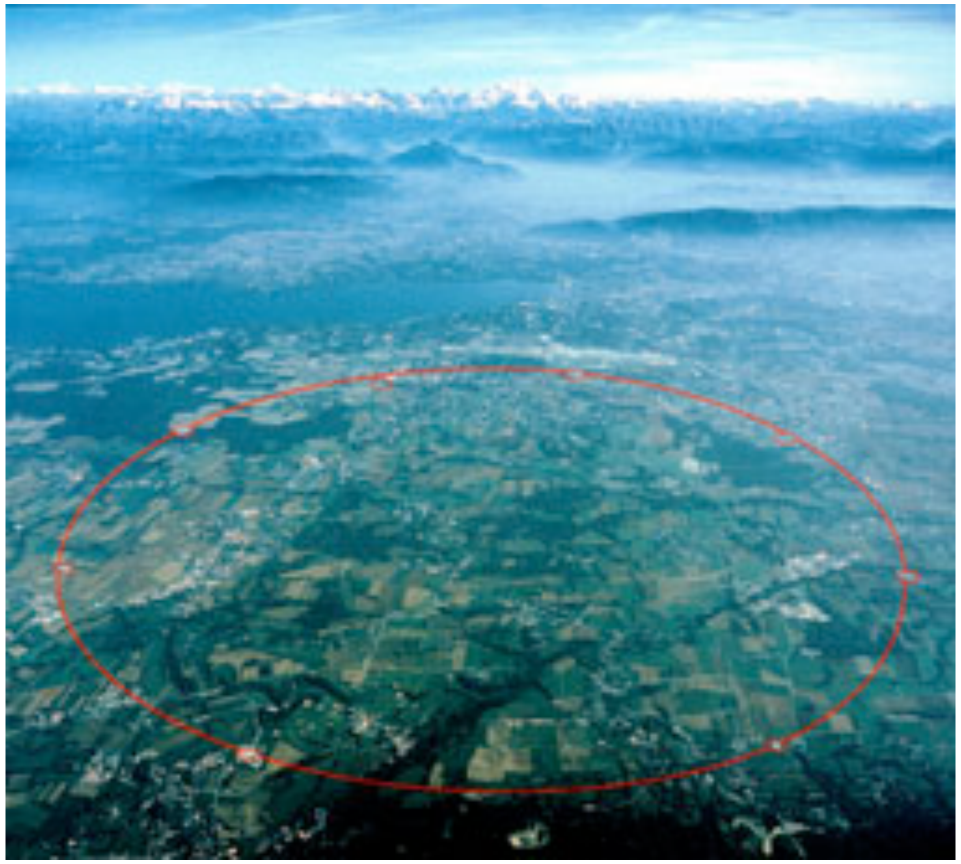

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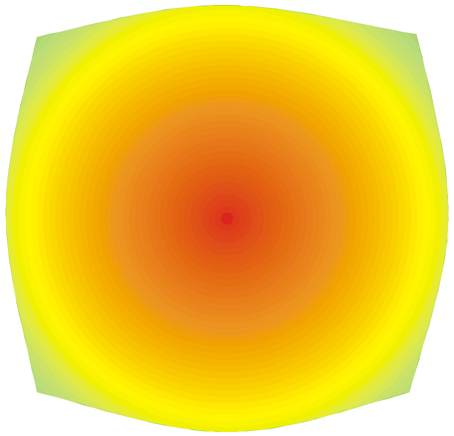
relativistic **heavy** ion collisions

quark gluon plasma



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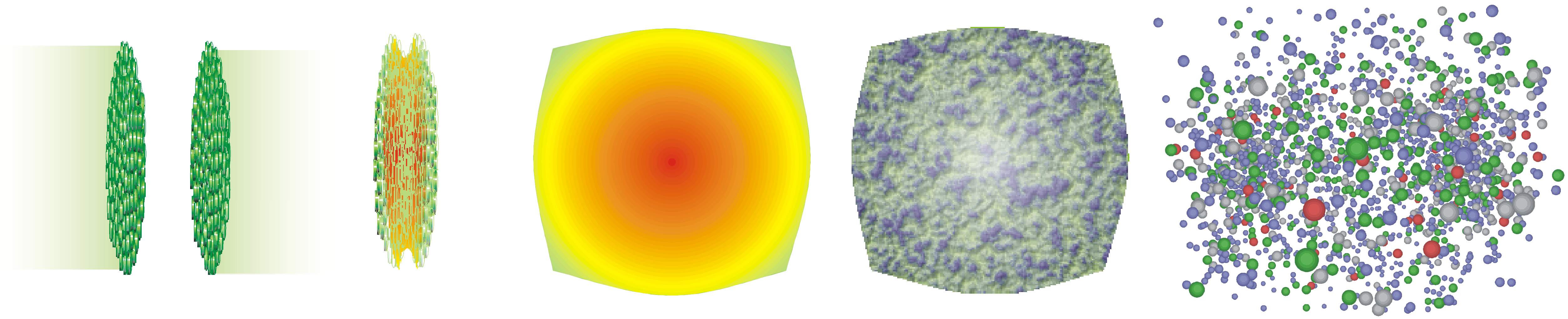

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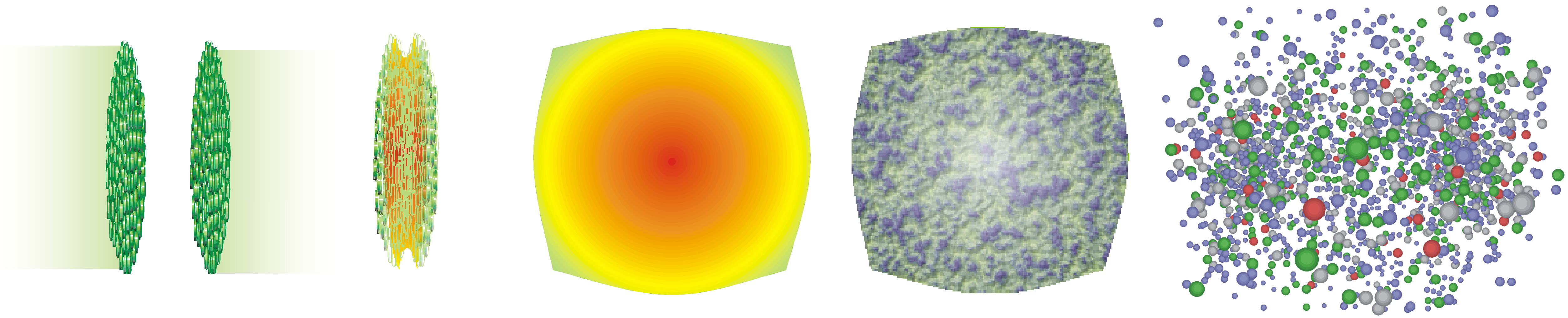
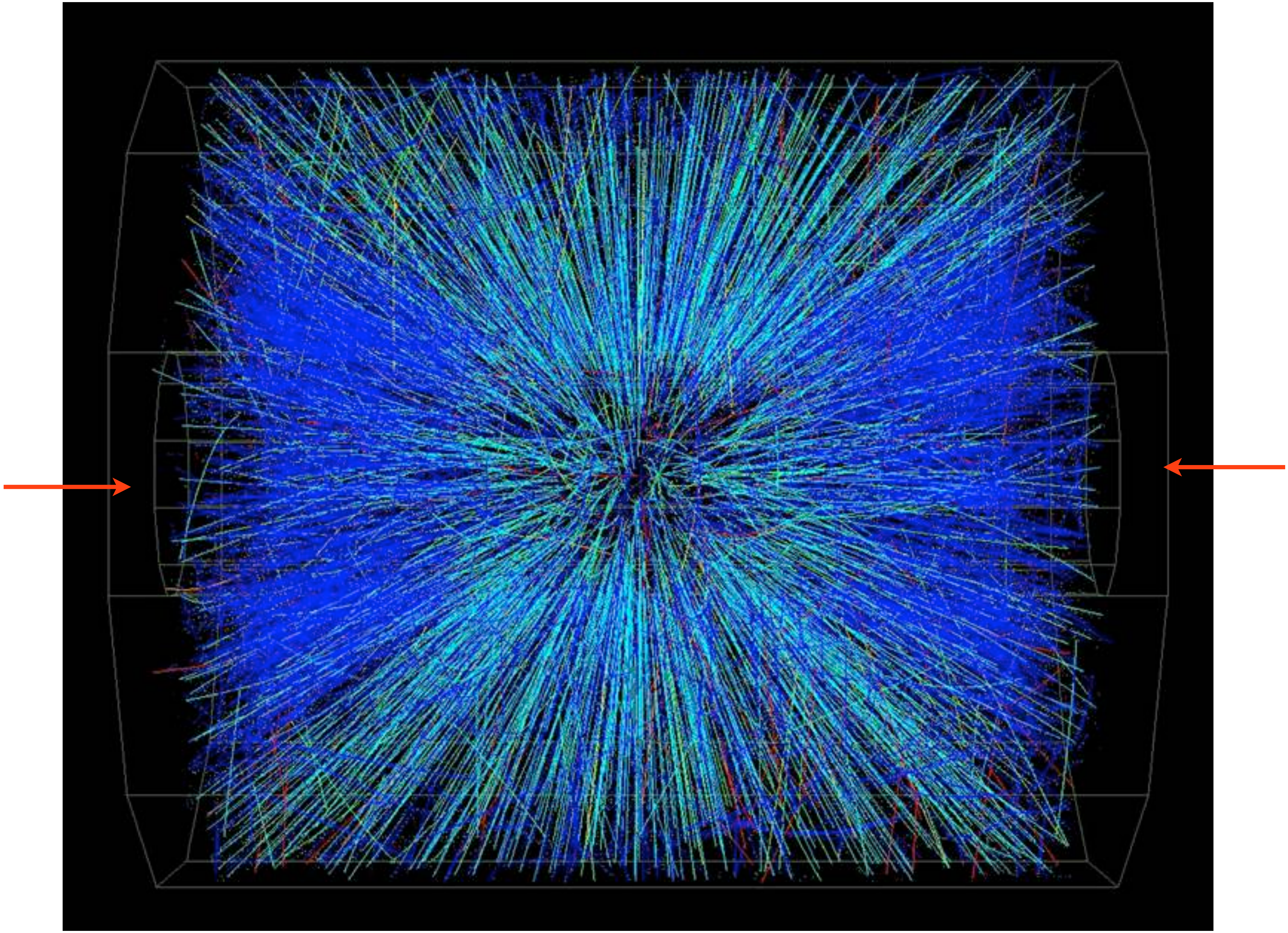


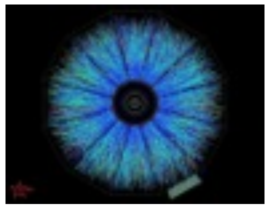
want to untangle QGP effects from effects of initial nucleus and hadronic matter

the aftermath

the aftermath

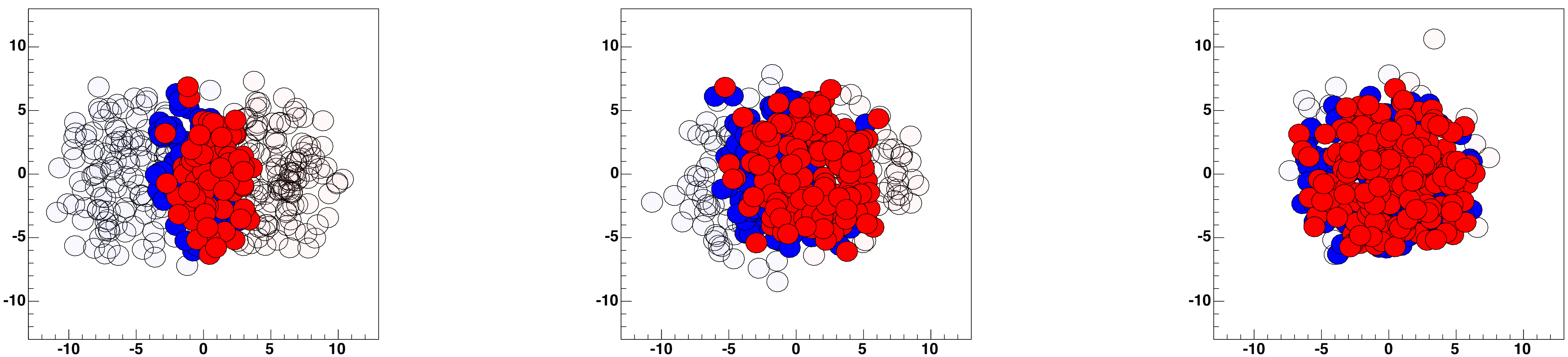


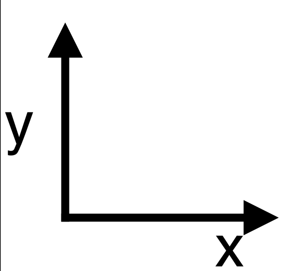
collision geometry



view: one nuclei going into the screen and one coming out

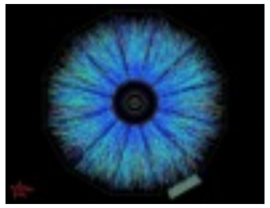
nucleon positions for the colliding nuclei for three different collisions





varying the distance between the nuclei, changes the shape and size of the region where the nuclei overlap

collision geometry



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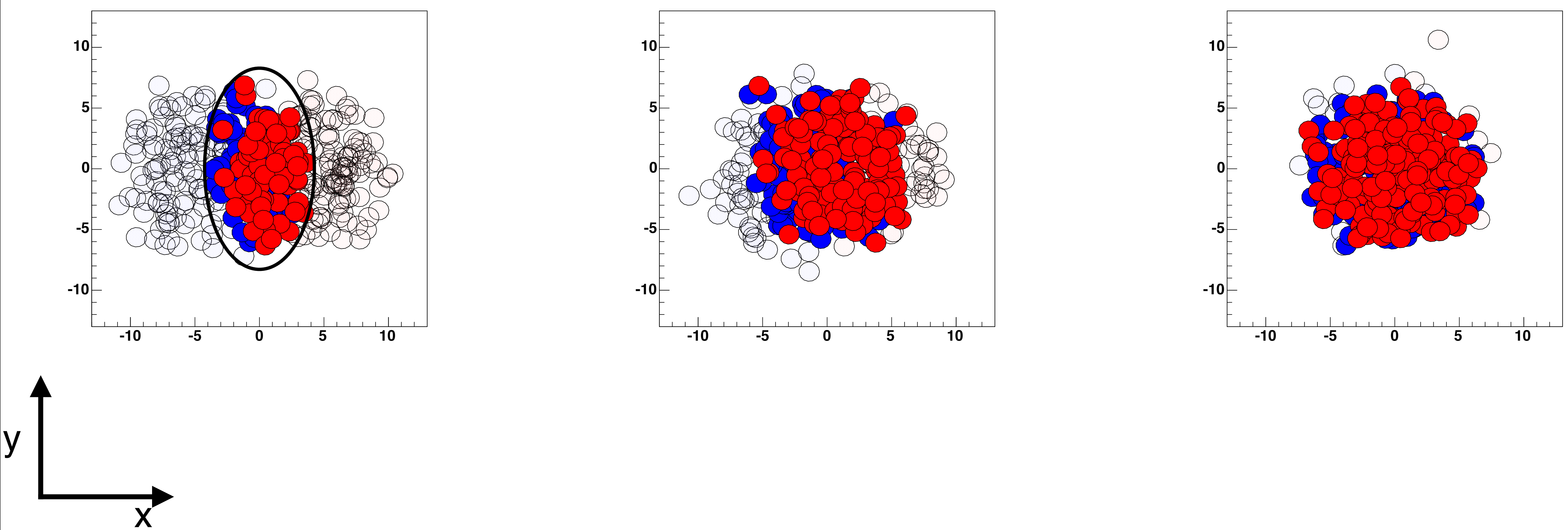

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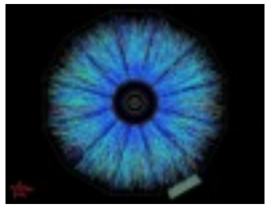

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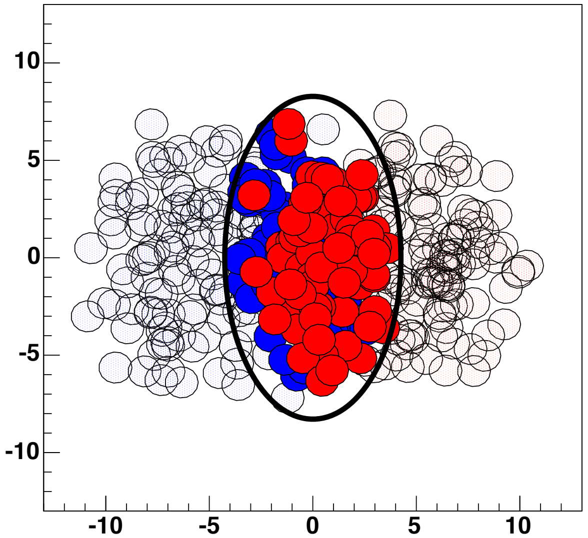
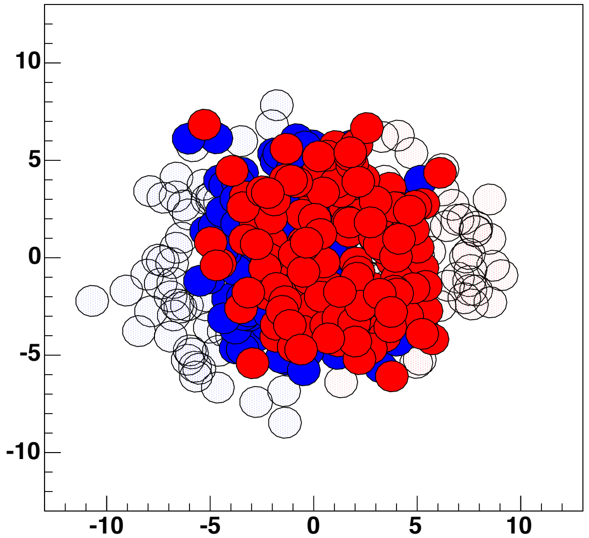
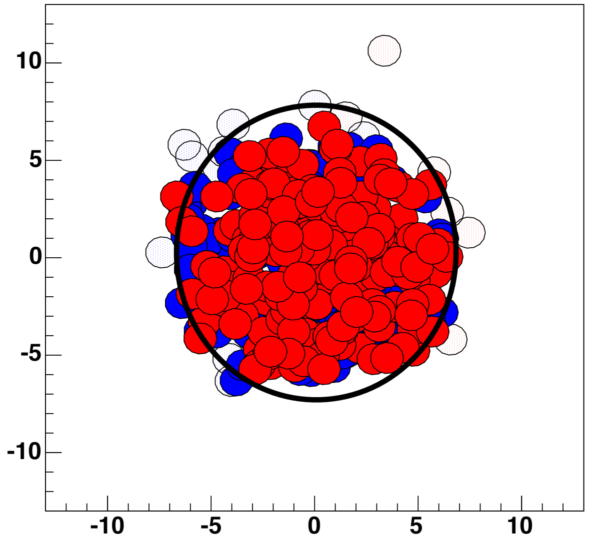
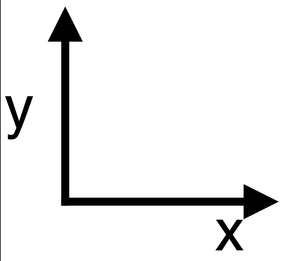




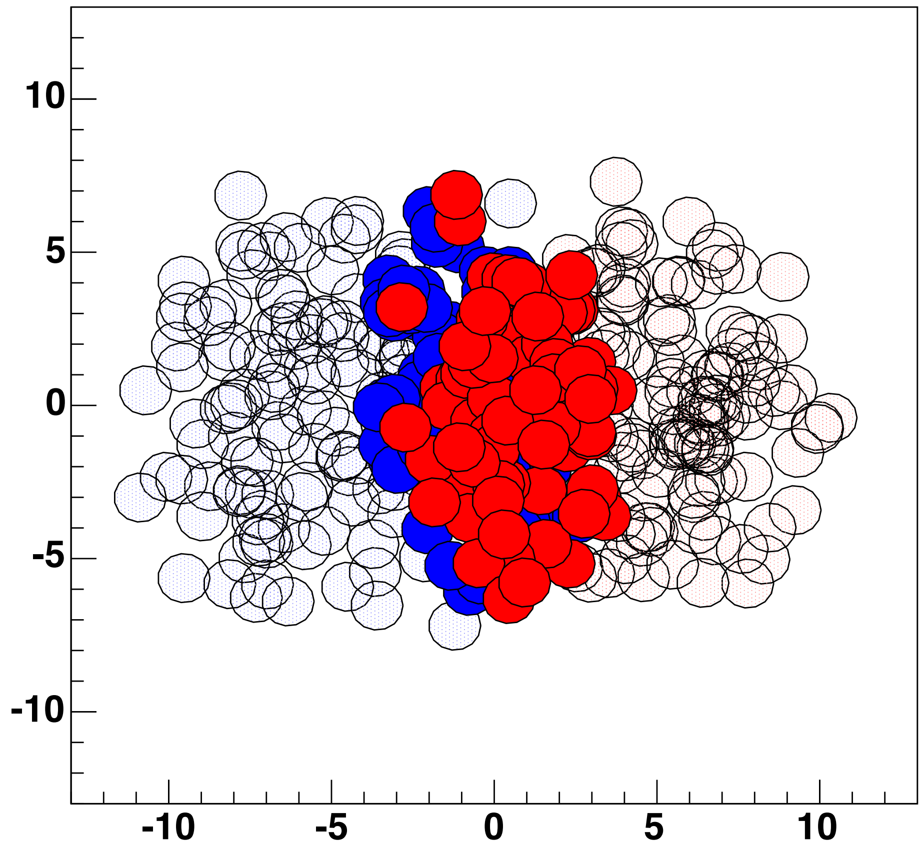




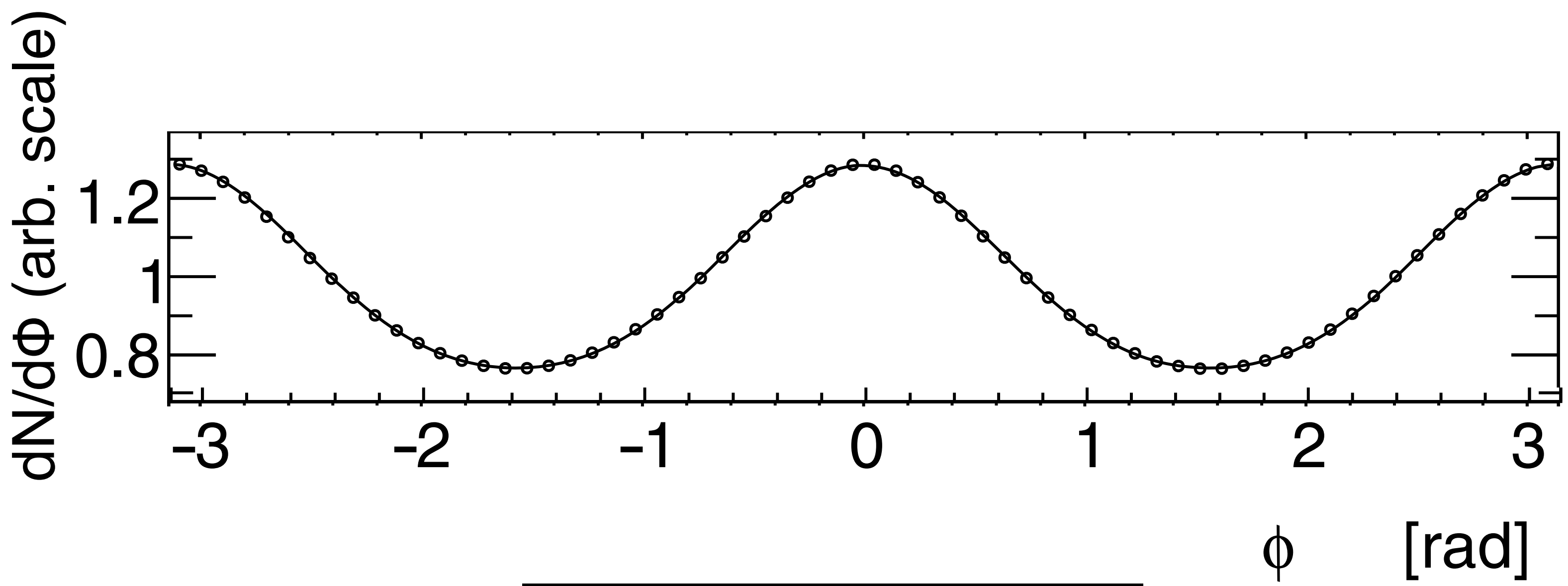
varying the distance between the nuclei, changes the shape and size of the region where the nuclei overlap

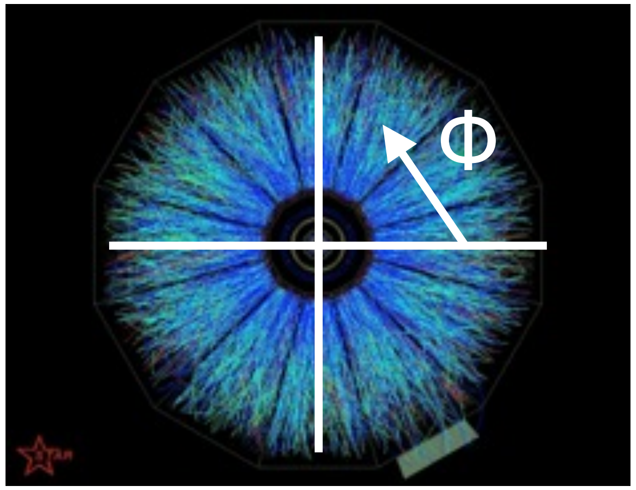
collision geometry → measured particles

initial collision geometry



measured hadron distributions





PLB 707 330 (2012)

collision geometry → measured particles

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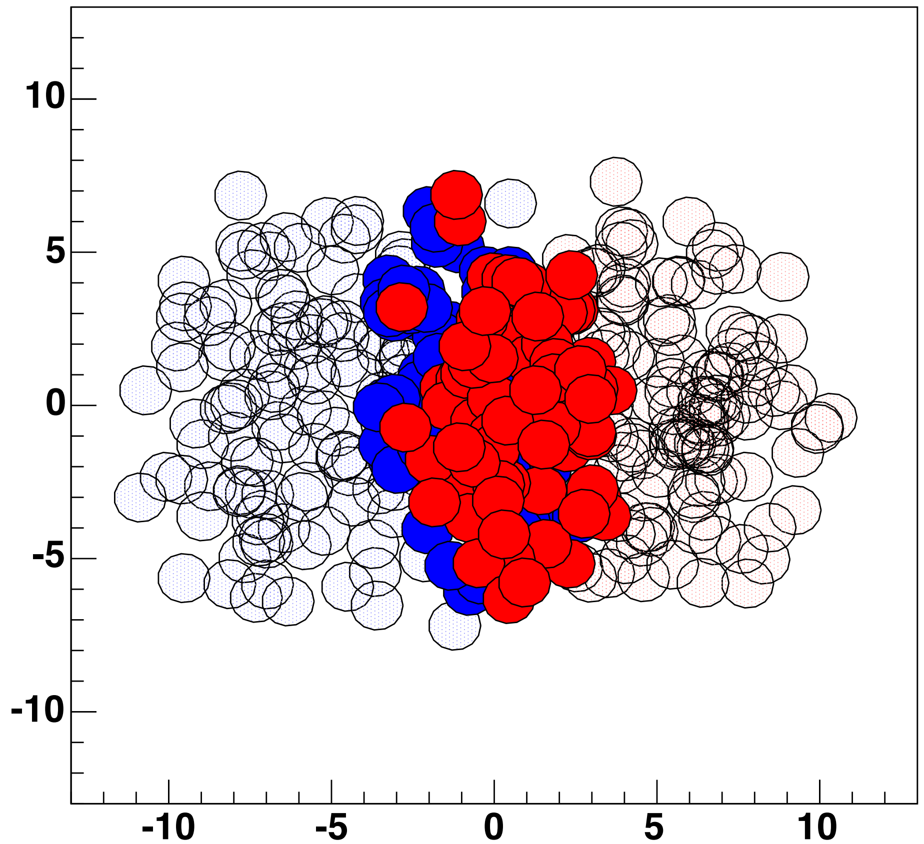

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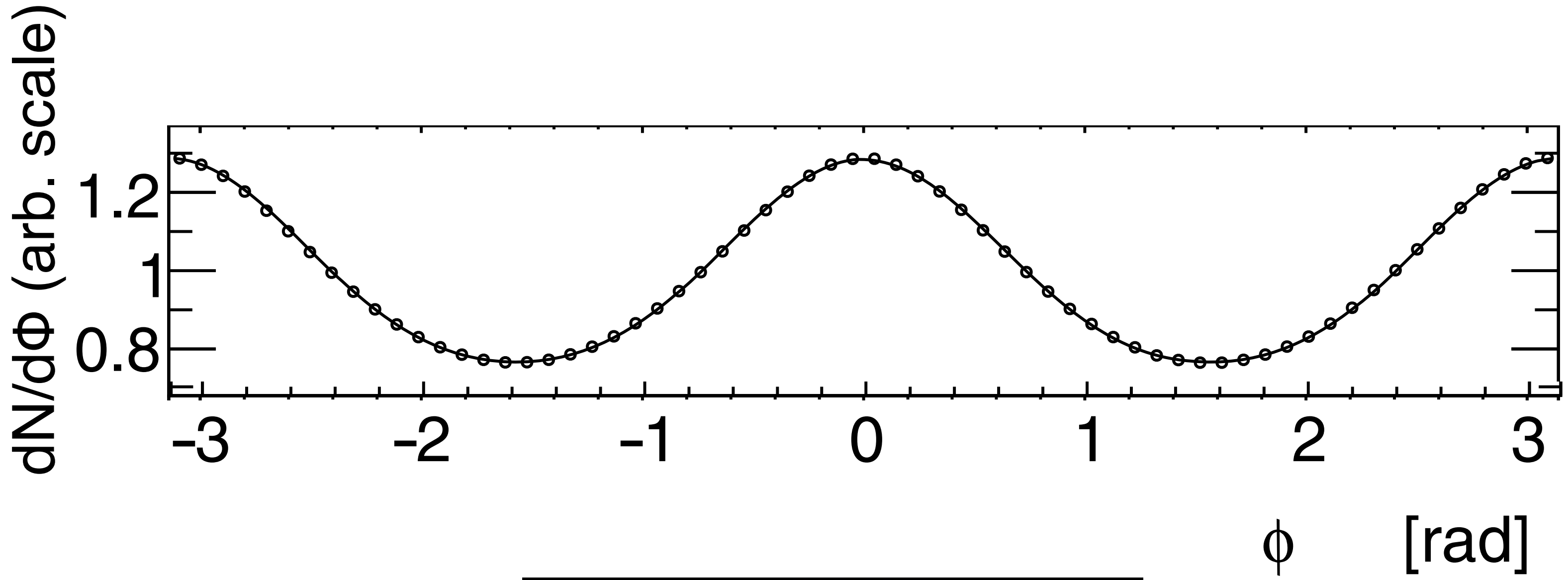
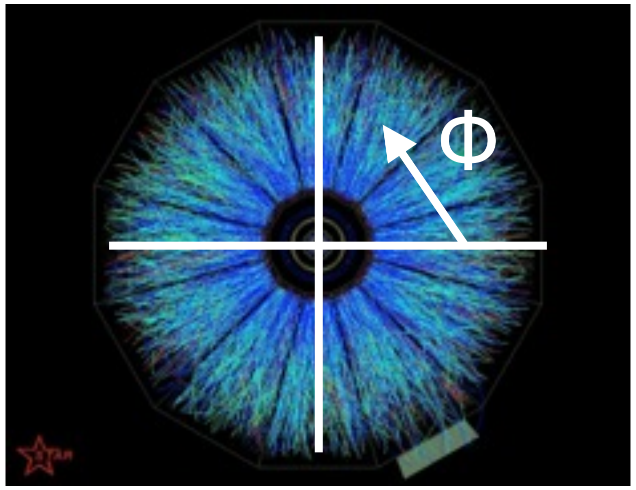
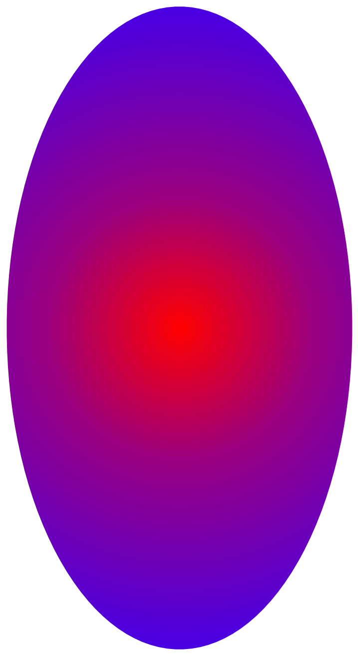


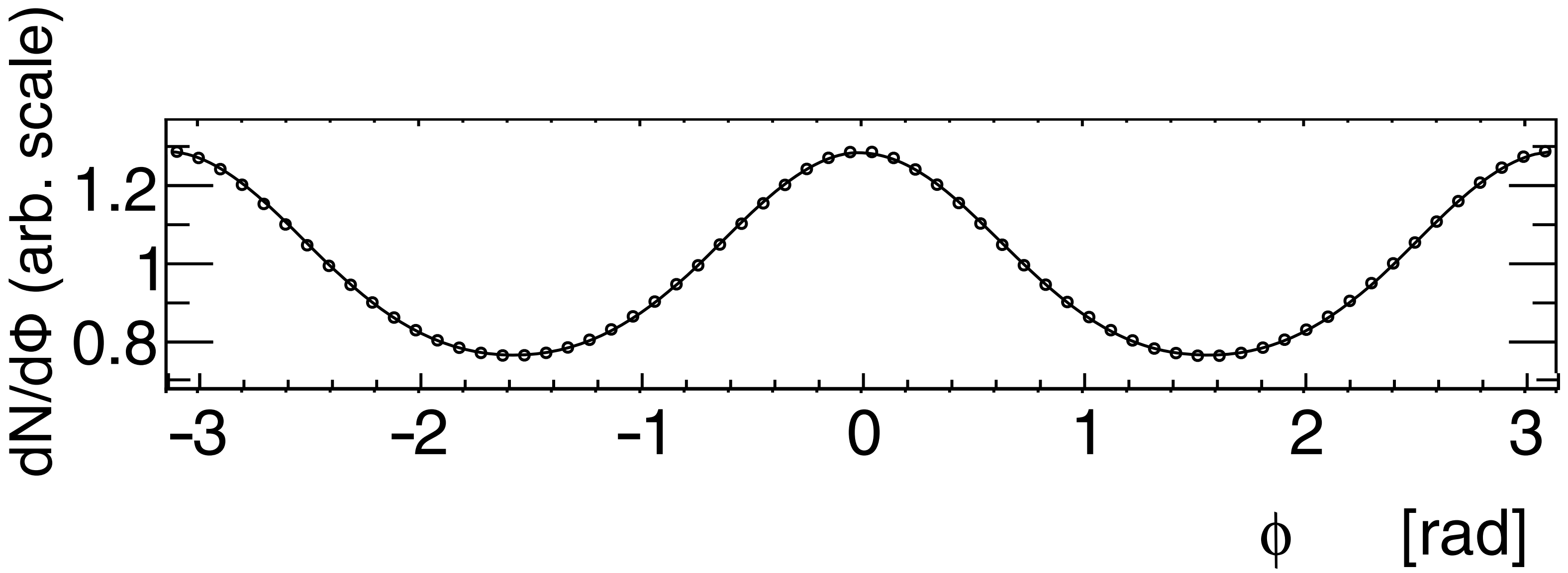


the shape of the initial collision geometry is imprinted on the final particle distributions

PLB 707 330 (2012)

strong interactions

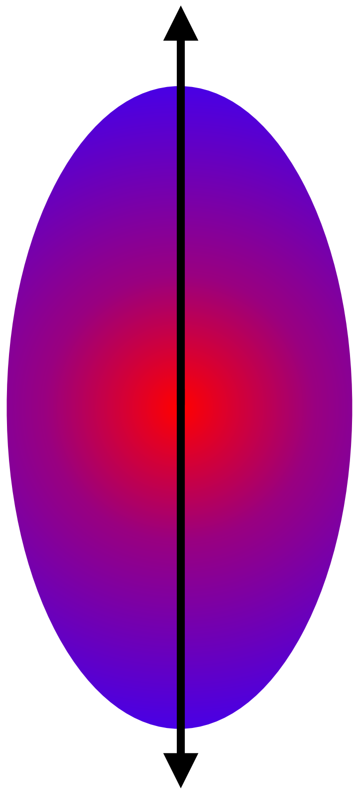




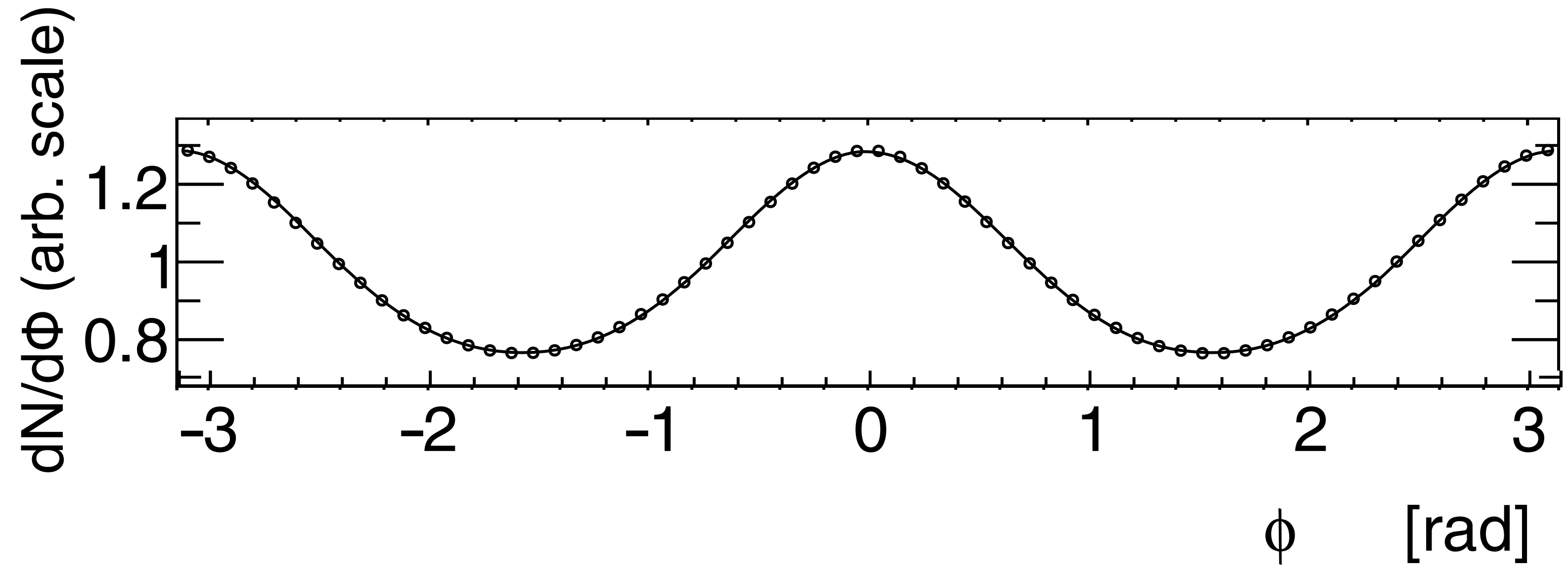
- large observed anisotropies → strong interactions:
  - **fluid behavior, hydrodynamics**
- larger pressure gradients push more particles out in the x direction than in y

PLB 707 330 (2012)

strong interactions



gradual
pressure
change



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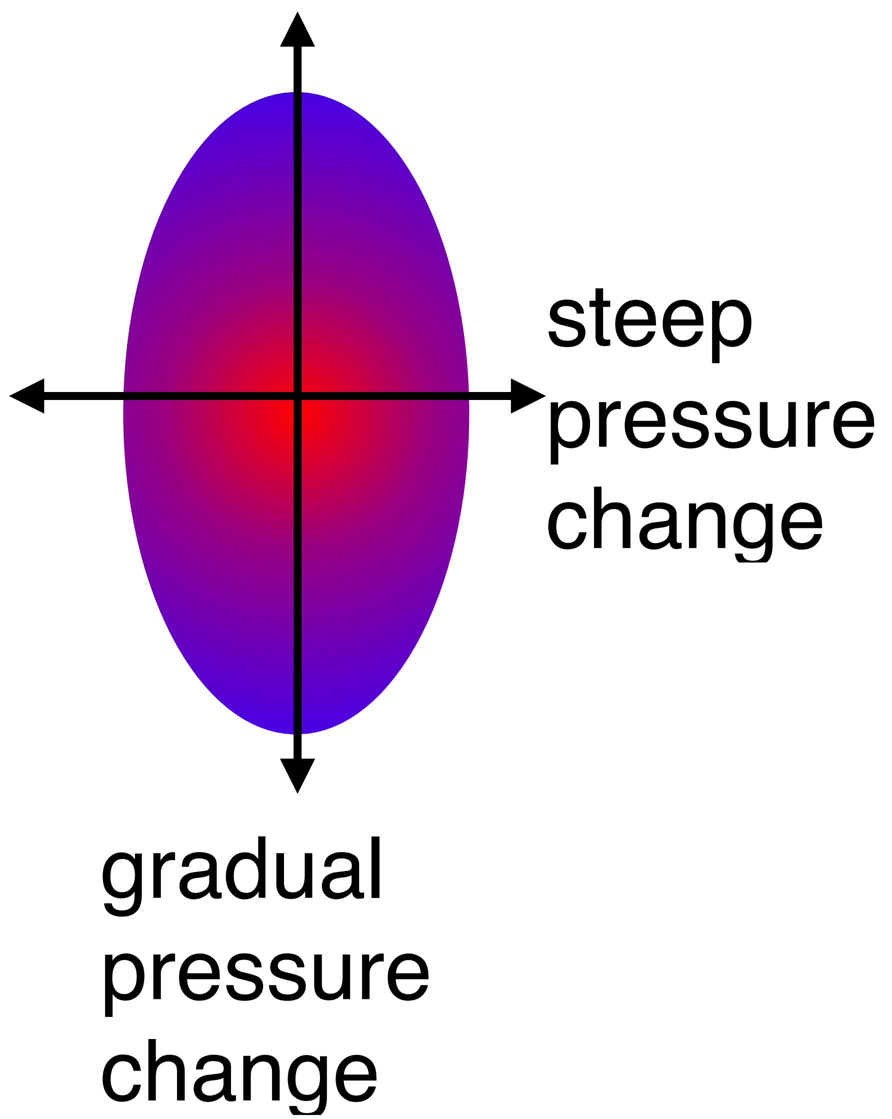

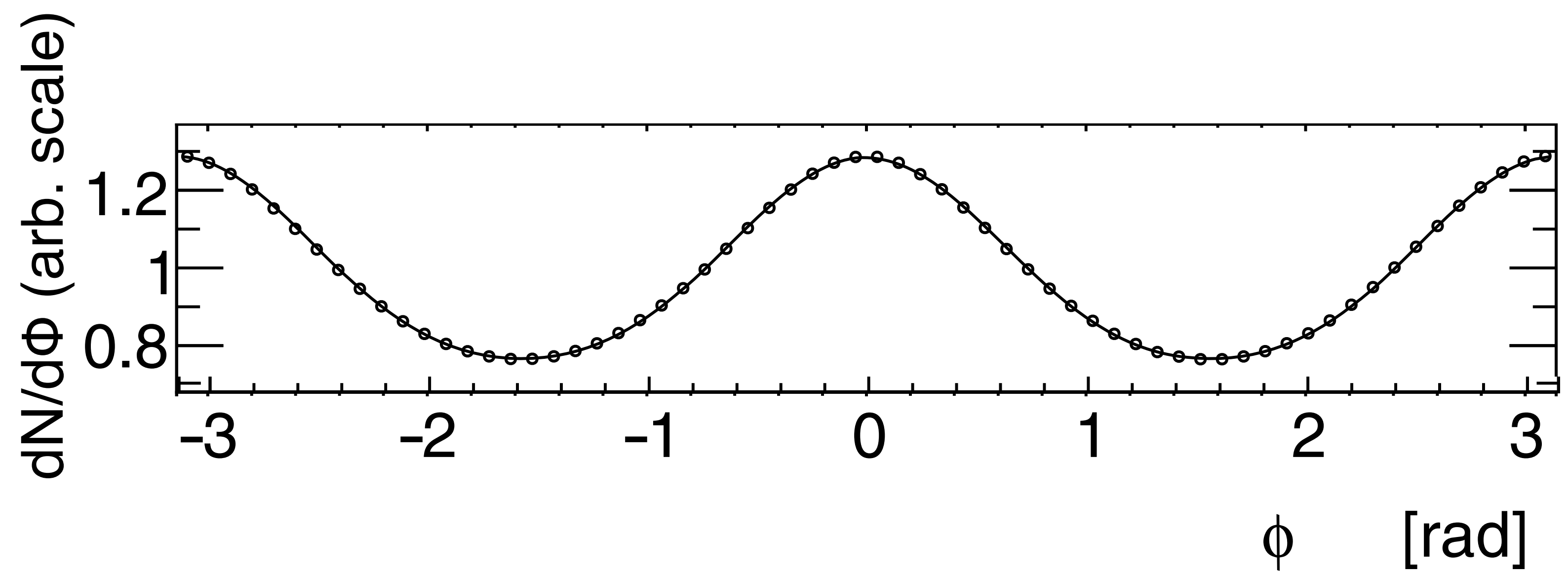

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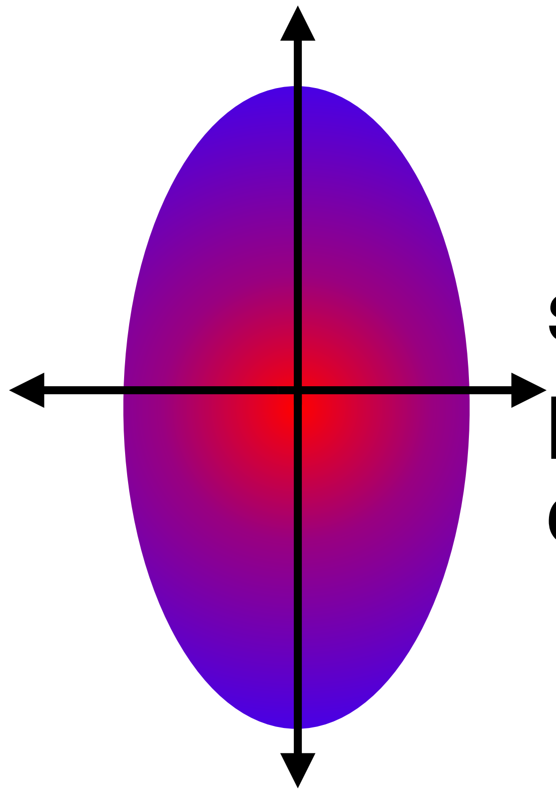

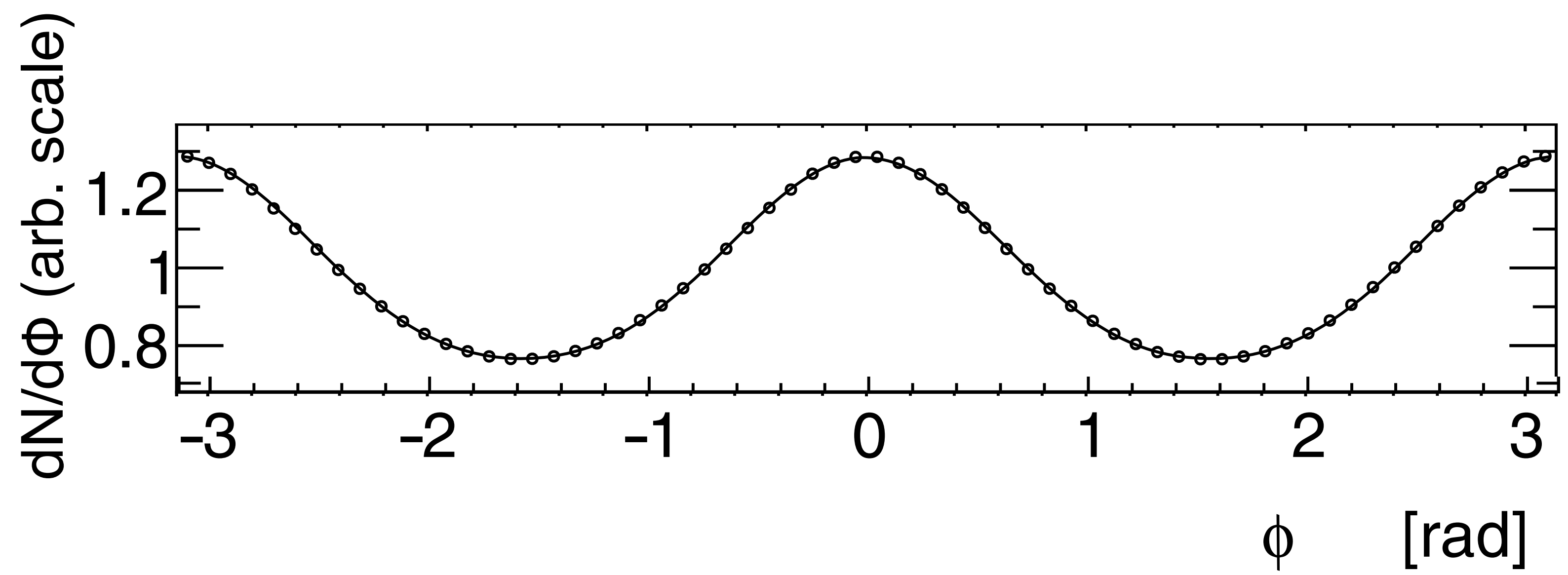

$$\frac{dN}{d\phi} = 1 + 2v_2 \cos 2\phi$$

- large observed anisotropies → strong interactions:
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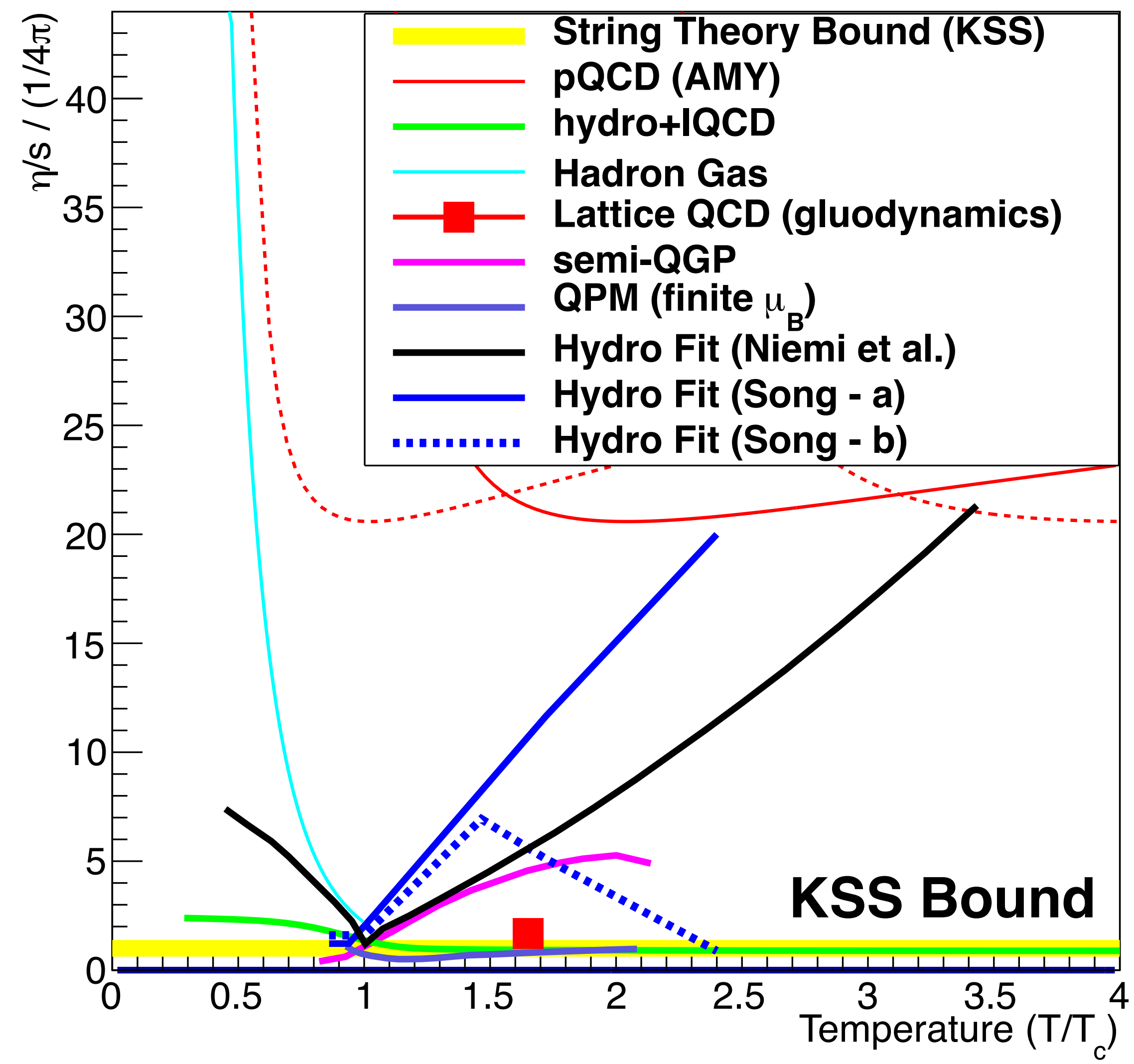
PLB 707 330 (2012)

the viscosity of the QGP

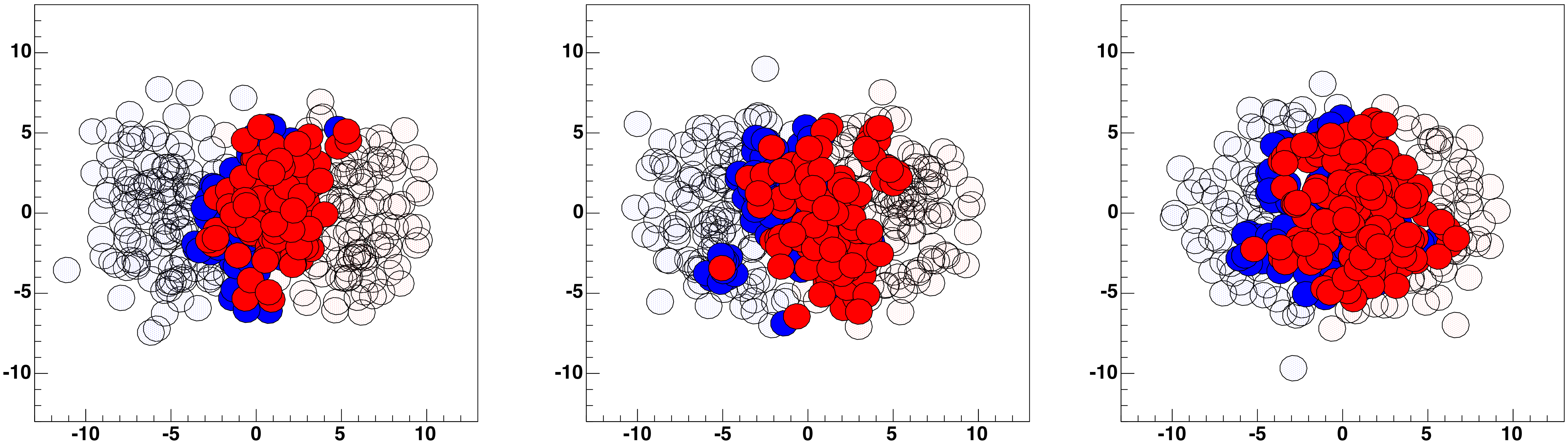
- what kind of fluid is the QGP?
  - more like water or honey?
- characterize by ratio of shear viscosity to entropy density: η/s
  - we know that η/s(QGP) is very small near the critical T
  - but how does that change with temperature?



arXiv: 1207.638

each collision is unique

nucleon distributions for 3 single collisions (xy-plane)



each collision evolves in isolation without knowing what the “typical” collision is

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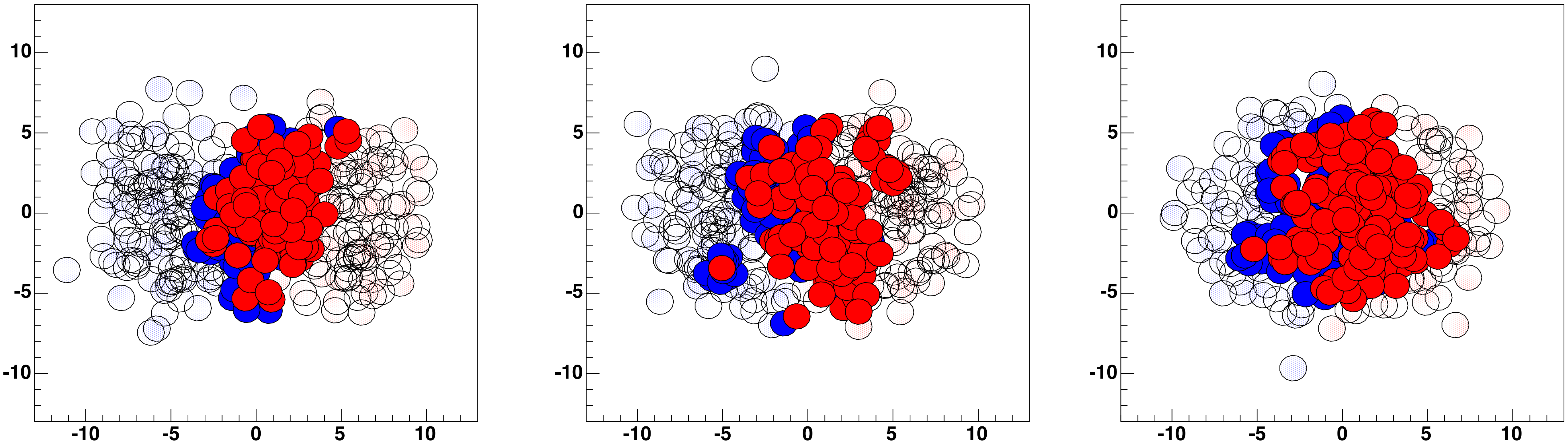
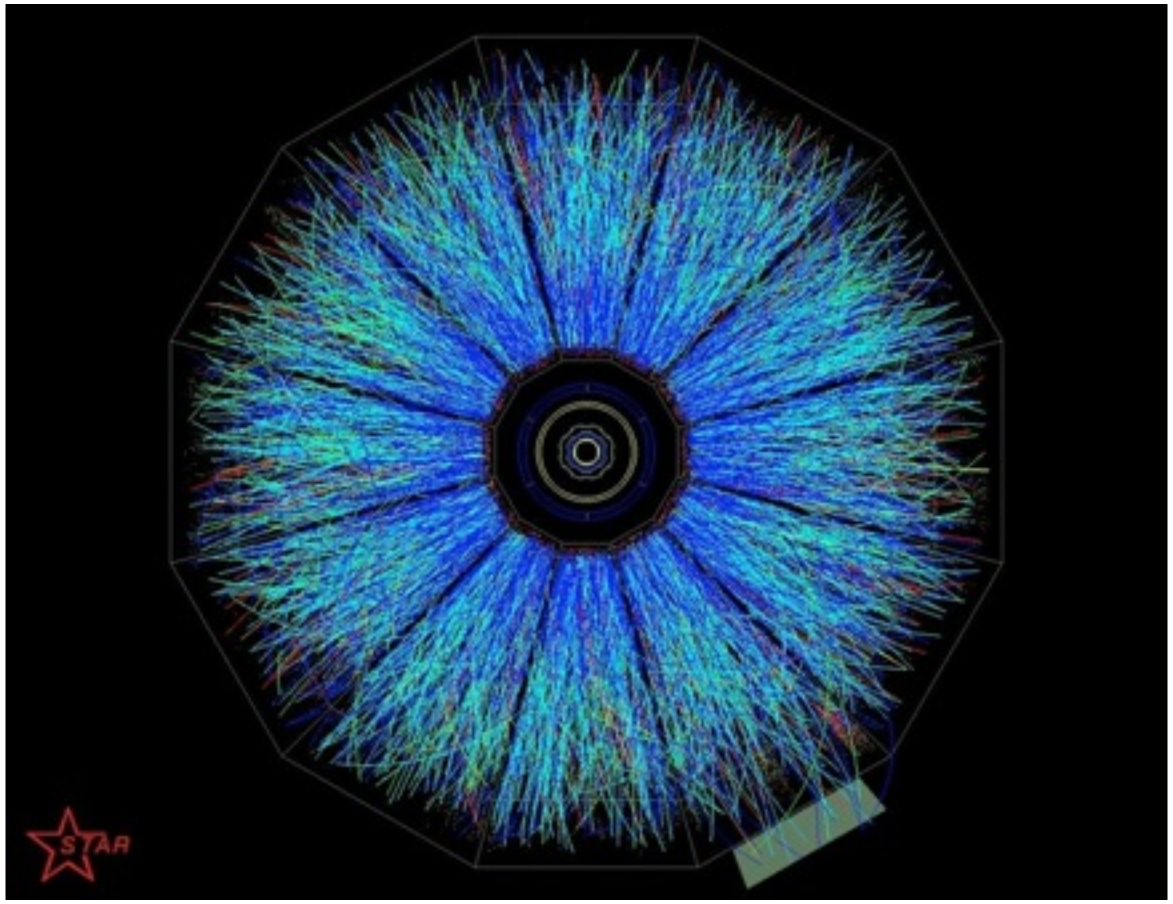


each collision evolves in isolation without knowing
what the “typical” collision is

not just v_2 describing cos2Φ, but v_n:

$$\frac{dN}{d\phi} \propto 1 + \sum^{n} 2v_n \cos n\left(\phi - \Psi_n\right)$$

two particle correlations



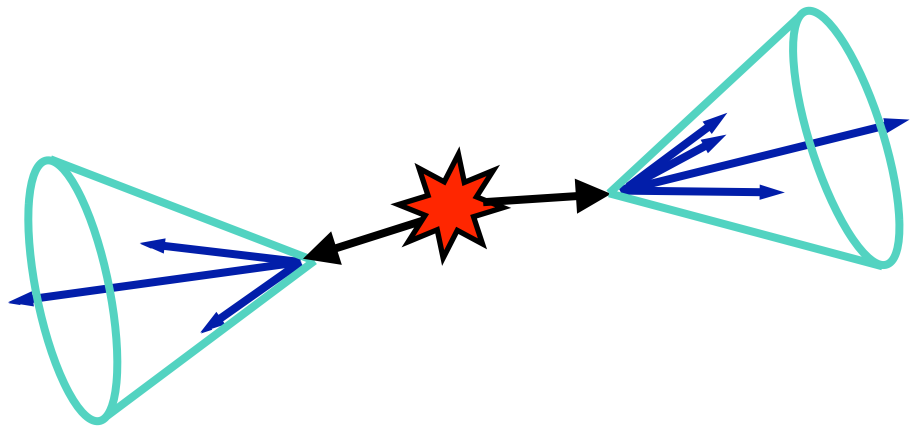
$$\frac{dN}{d\phi} \propto 1 + \sum^{n} 2v_n \cos n\left(\phi - \Psi_n\right)$$

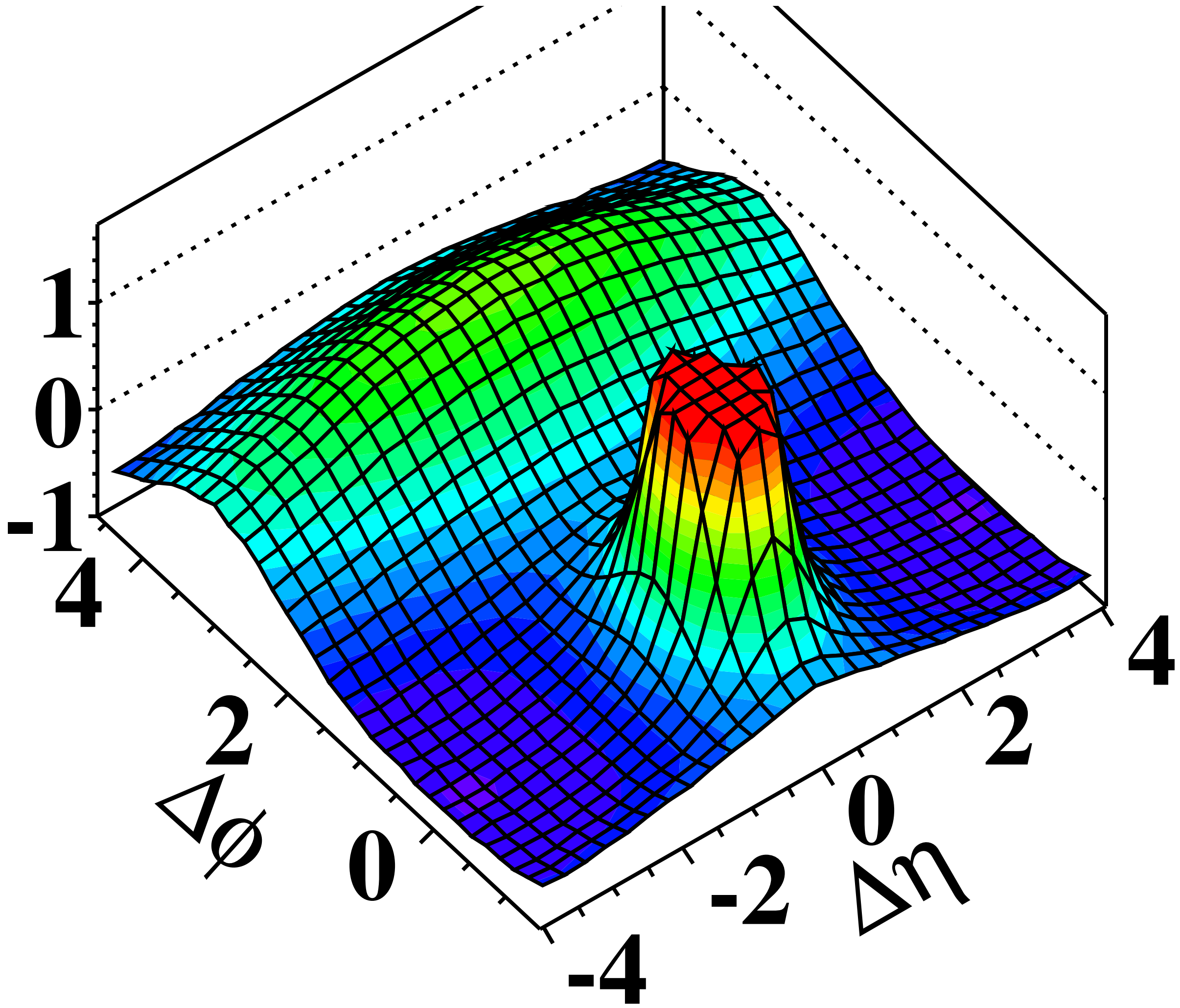
$$\downarrow$$

$$\frac{dN_{AB}}{d\Delta\phi} \propto 1 + \sum^{n} 2v_{n,A}v_{n,B} \cos\left(n\Delta\phi\right)$$

two particle correlations

jets in pp collisions





flow

single particles

$$\frac{dN}{d\phi} \propto 1 + \sum^{n} 2v_n \cos n\left(\phi - \Psi_n\right)$$

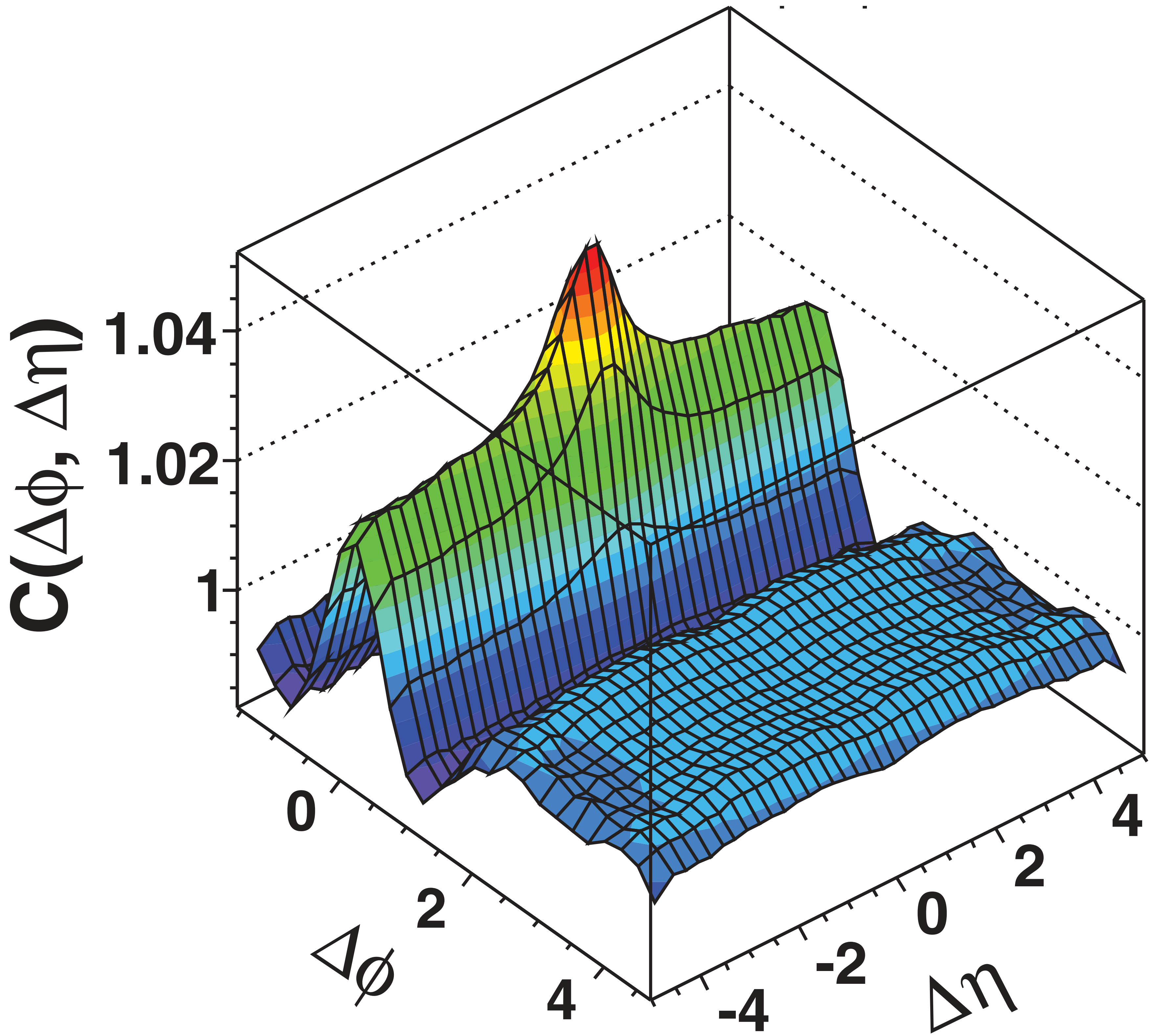
pairs of particles

$$\frac{dN_{AB}}{d\Delta\phi} \propto 1 + \sum^{n} 2v_{n,A}v_{n,B} \cos\left(n\Delta\phi\right)$$

flow correlations should be long range η

CMS JHEP 1009 (2010) 091

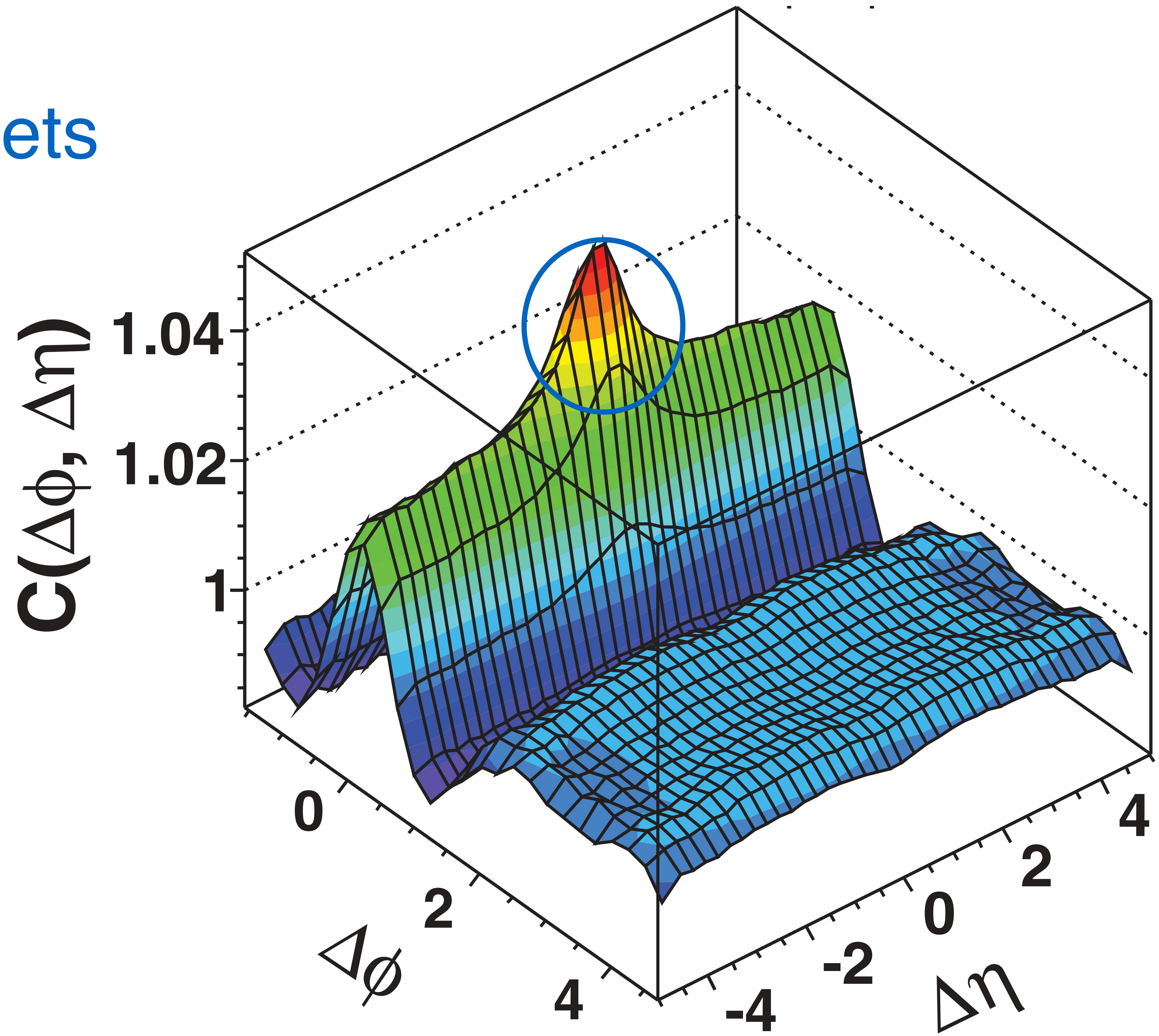
correlations in PbPb



ATLAS PRC 86 014907

correlations in PbPb

jets



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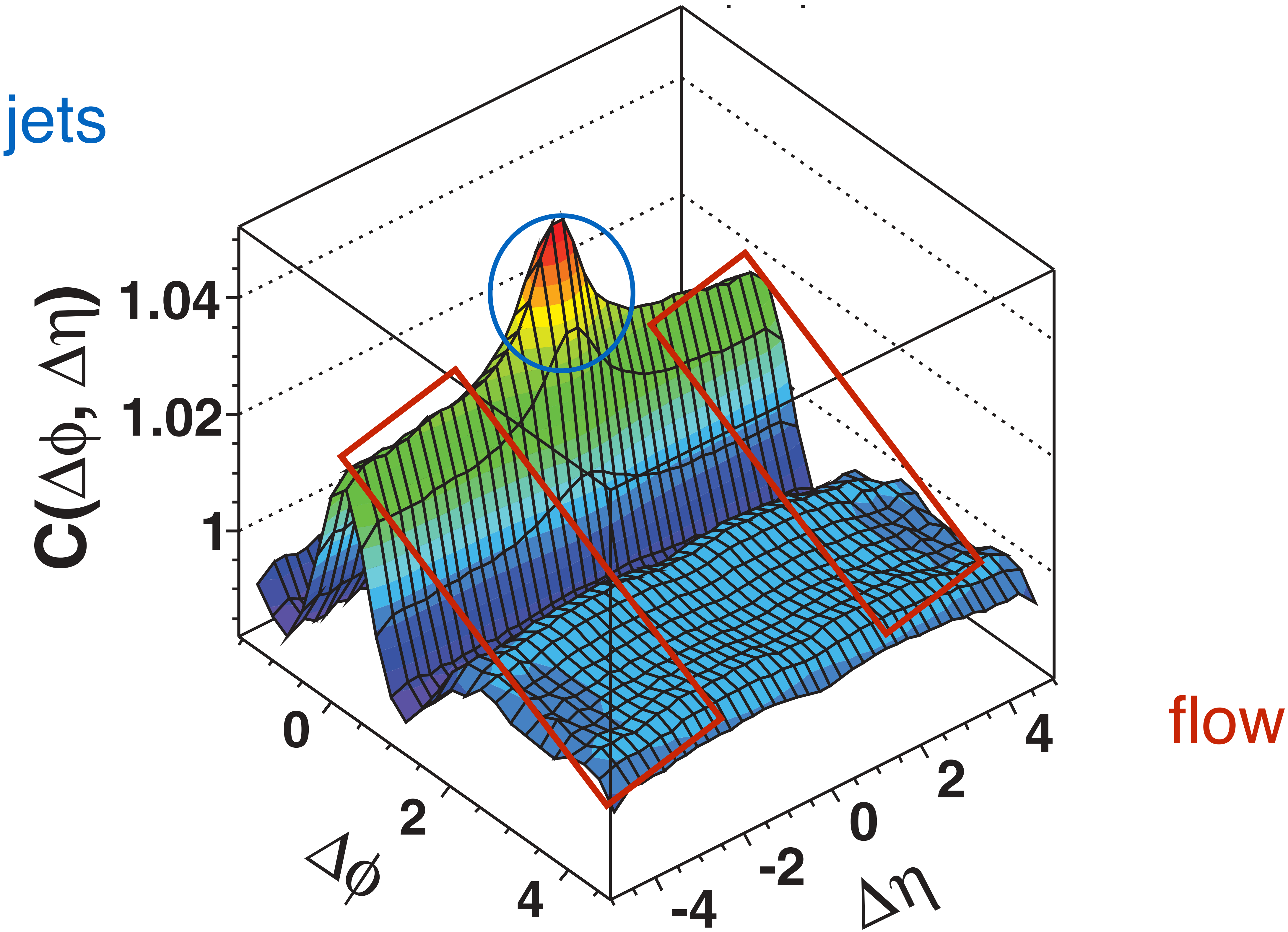
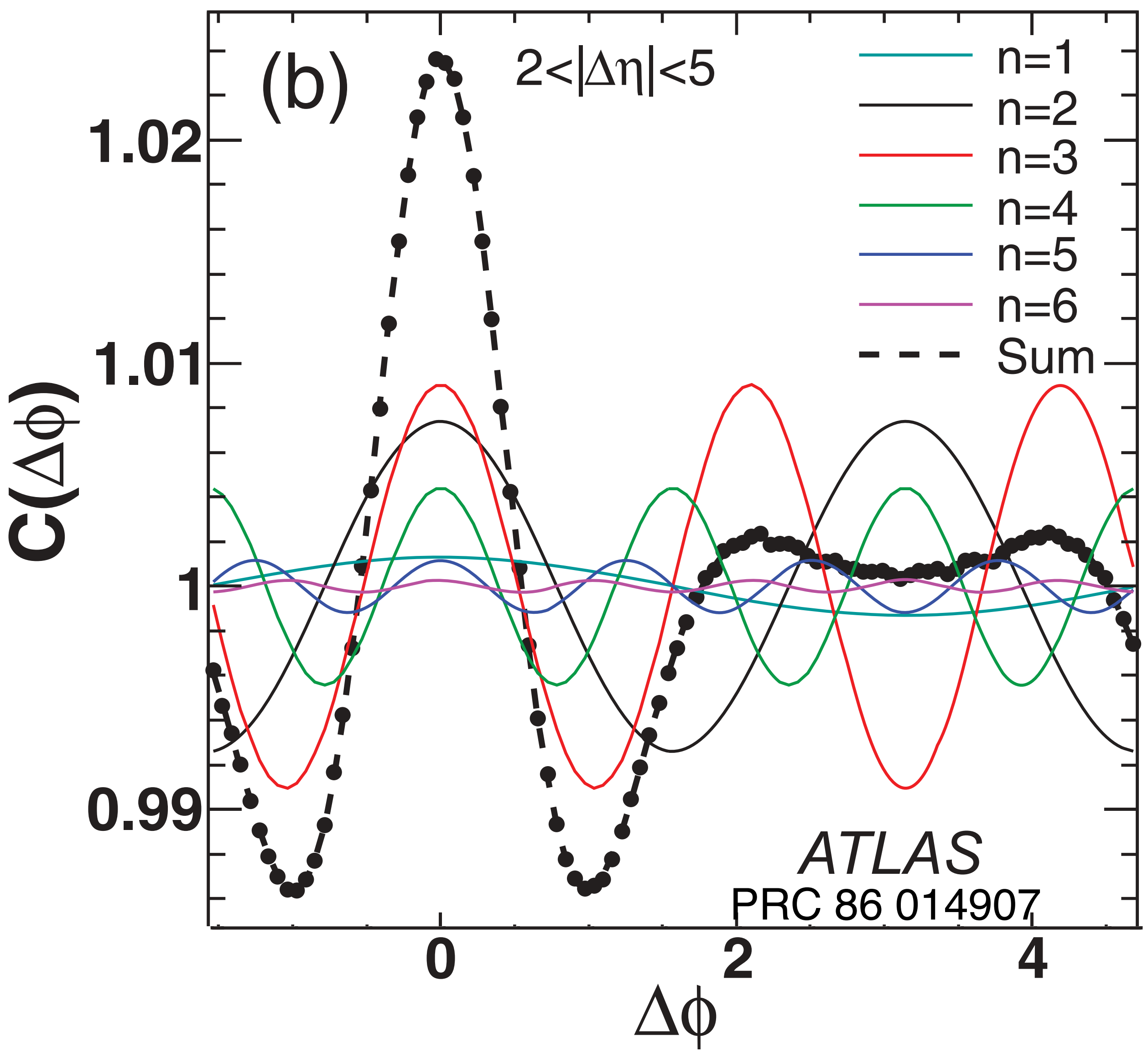
correlations in PbPb



ATLAS PRC 86 014907

ridge: v_N & two particle correlations



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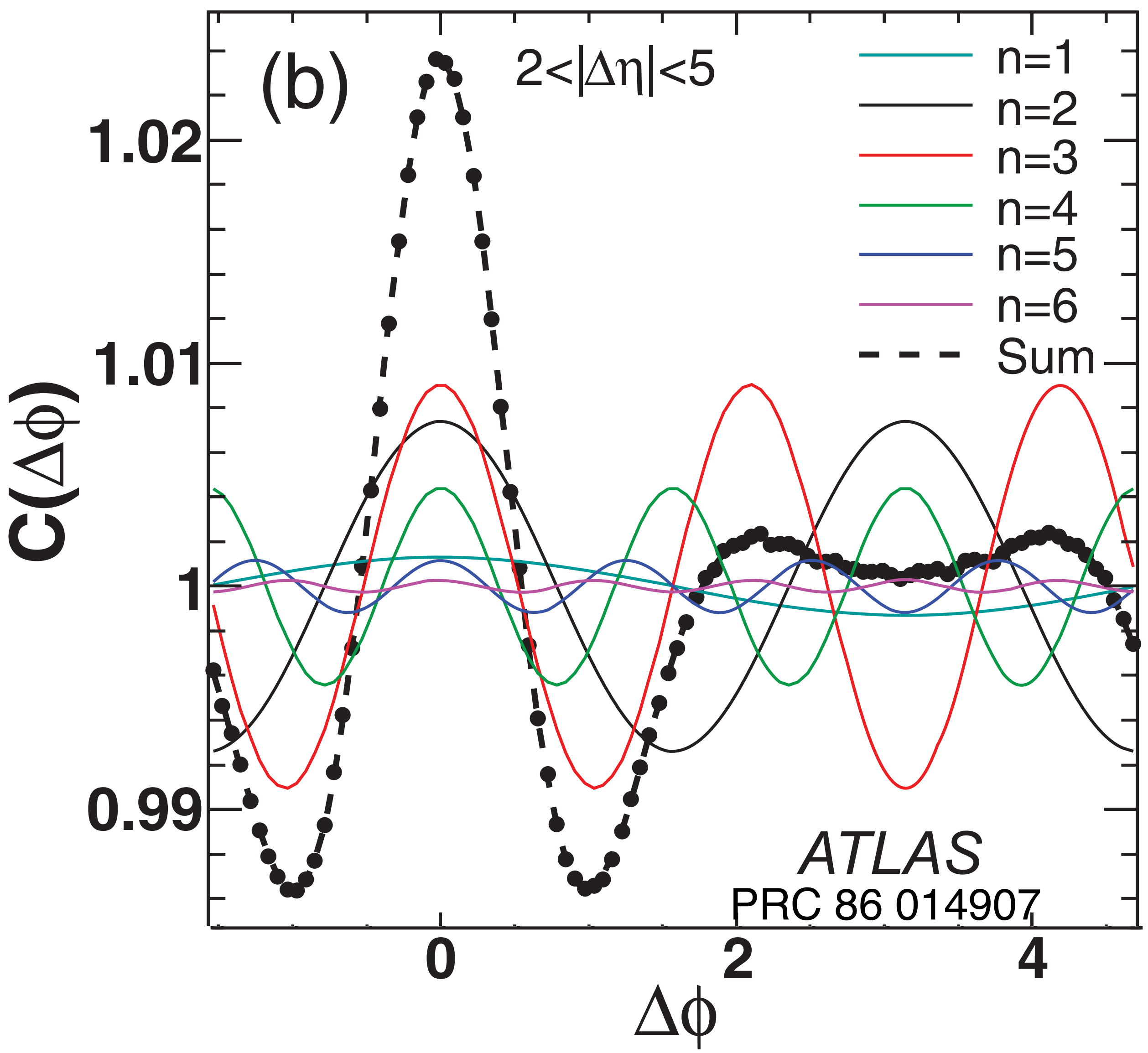
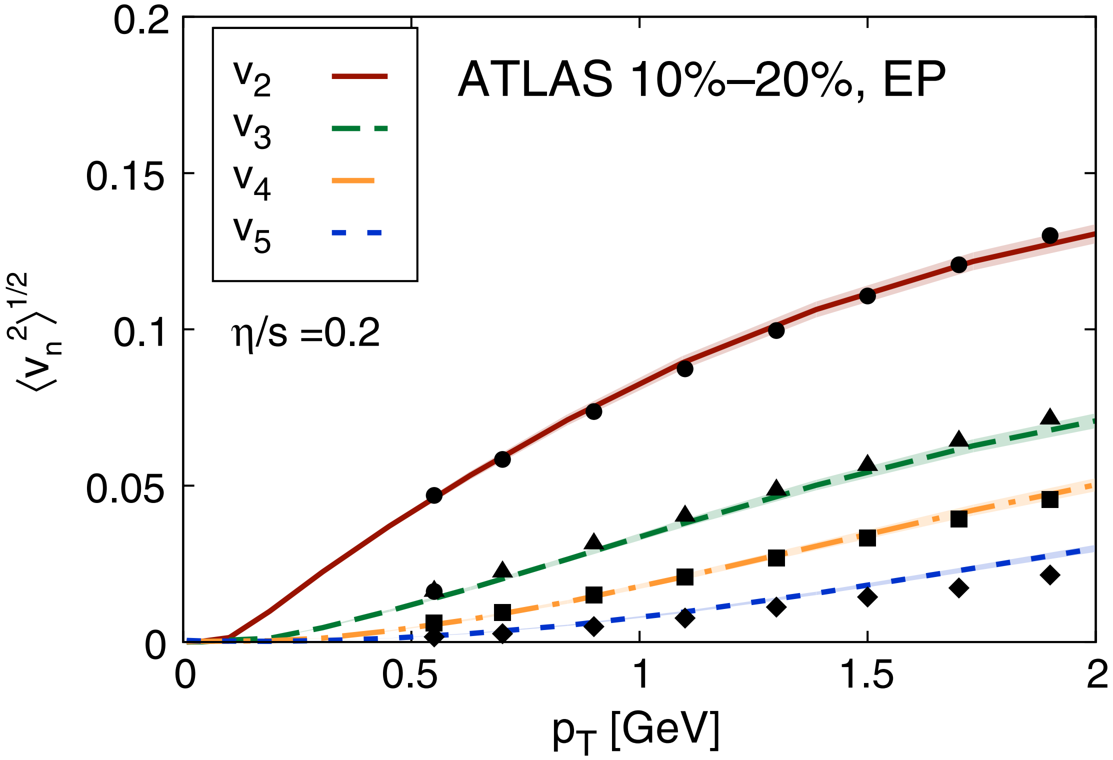


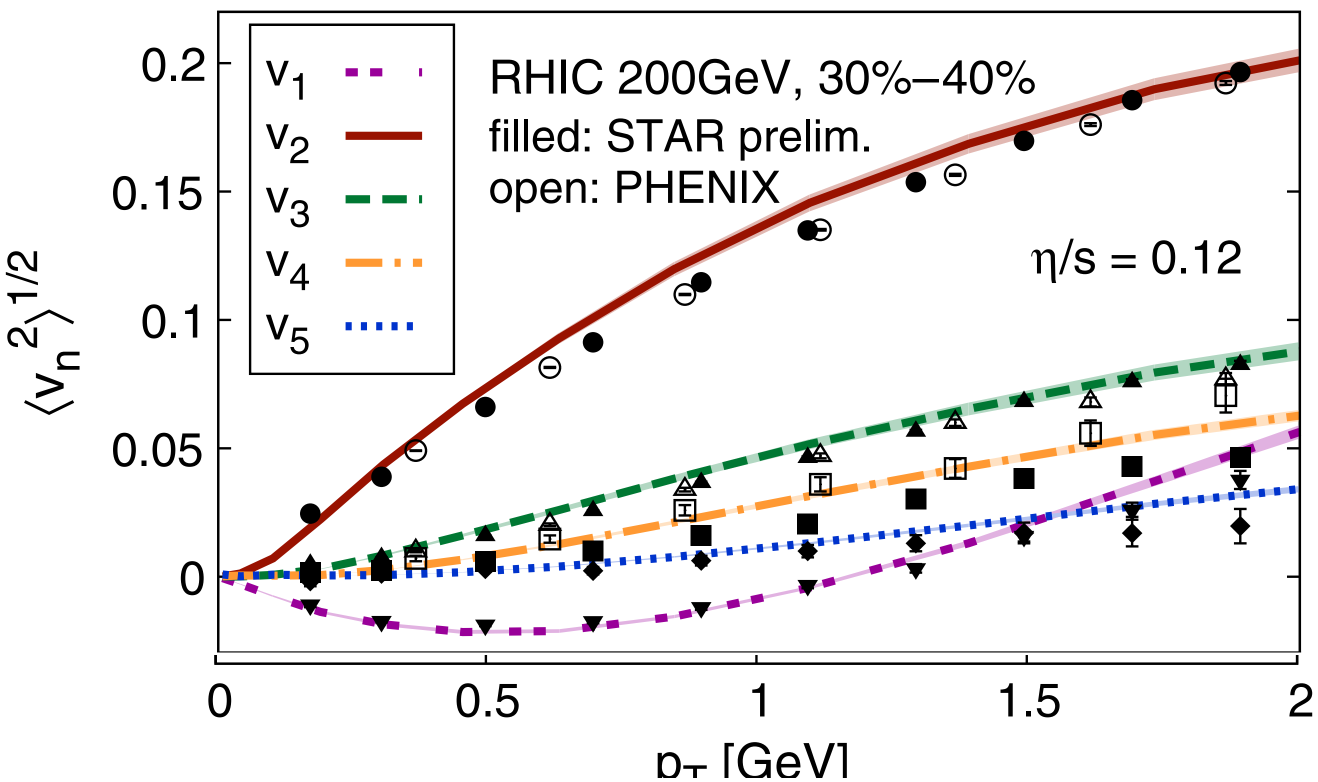
$$\frac{dN_{AB}}{d\Delta\phi} \propto 1 + \sum^{n} 2 v_{n,A} v_{n,B} \cos(n\Delta\phi)$$

evidence for many higher order terms in particle correlations

state of the art hydrodynamic calculations

3 +1d viscous hydrodynamics

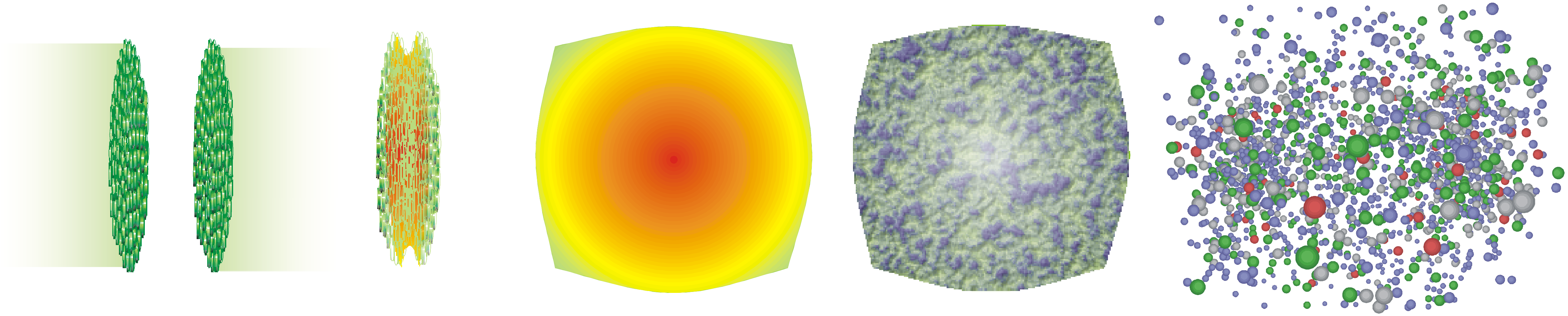


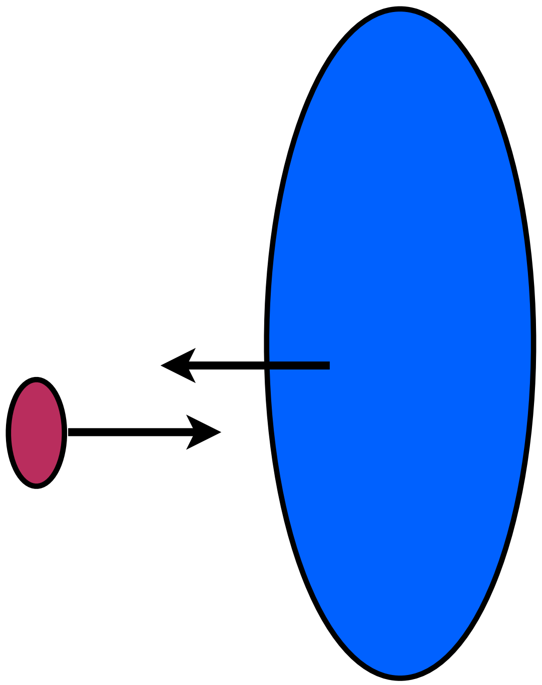


quantitative description of v_1 - v_5 at both RHIC and LHC
sensitivity to η/s

Gale, Jeon, Schenke, Tribedy, Venugopalan PRL 110 012302

pA physics



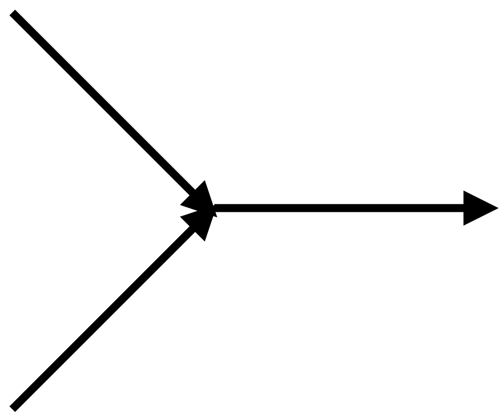


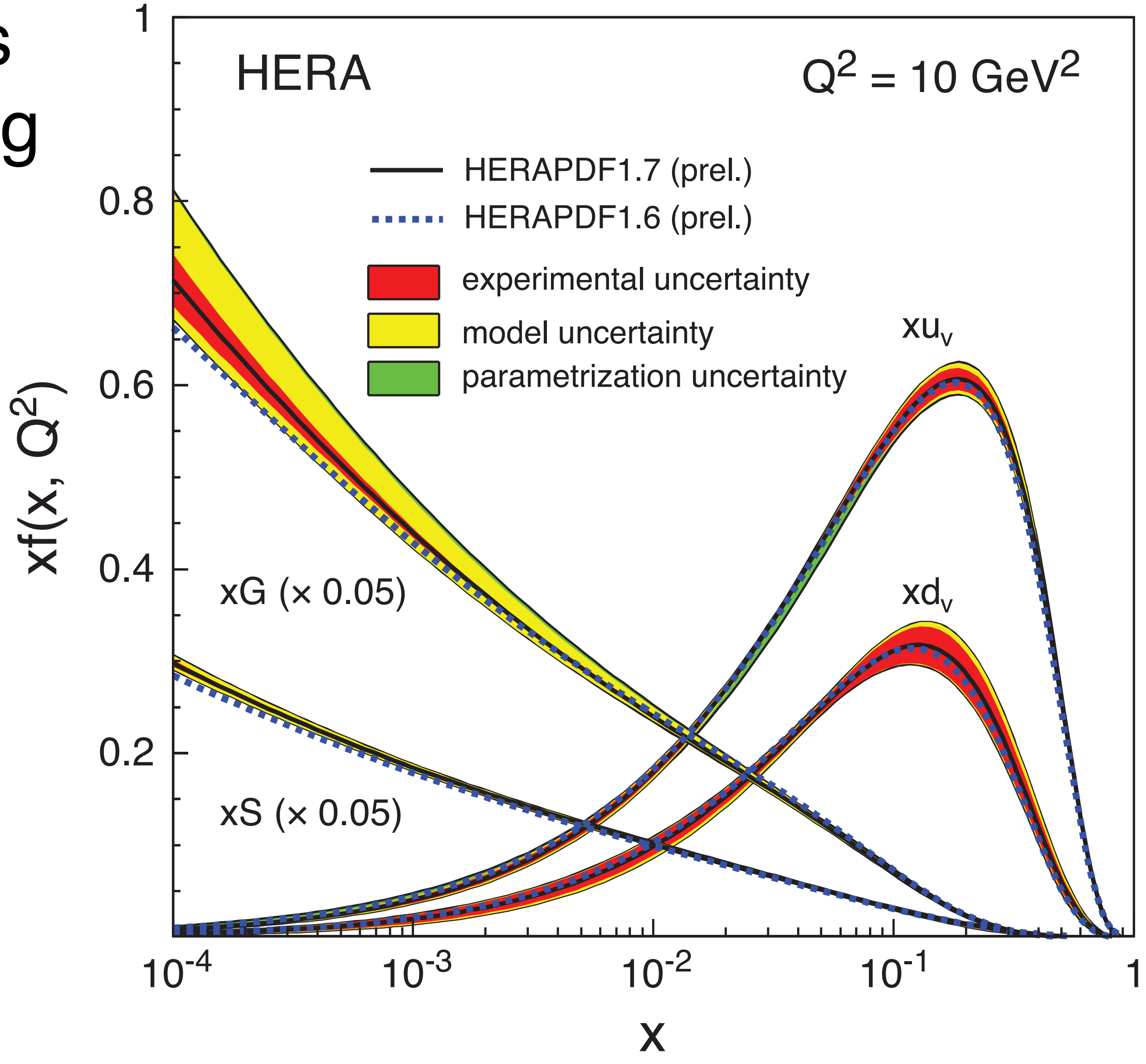
pA

- isolate QGP effects from something present in the incoming nuclei

saturation of low x gluons

- basic idea: the number of gluons increases quickly with decreasing x. At some point there are so many gluons that the recombination rate becomes significant, saturating the distribution



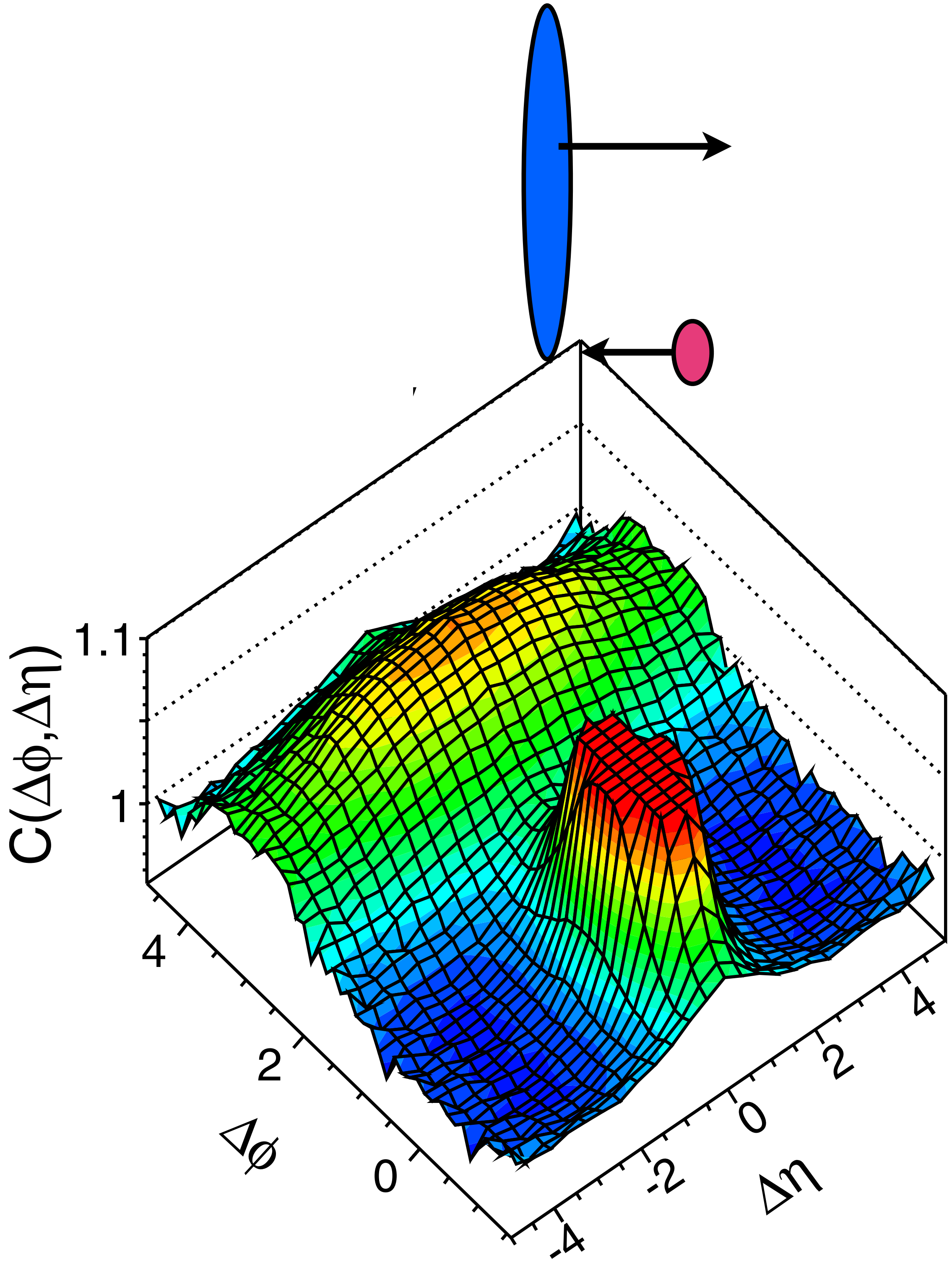


in a large nucleus in high energy collisions, this happens more readily because the nucleons overlap, increasing the density

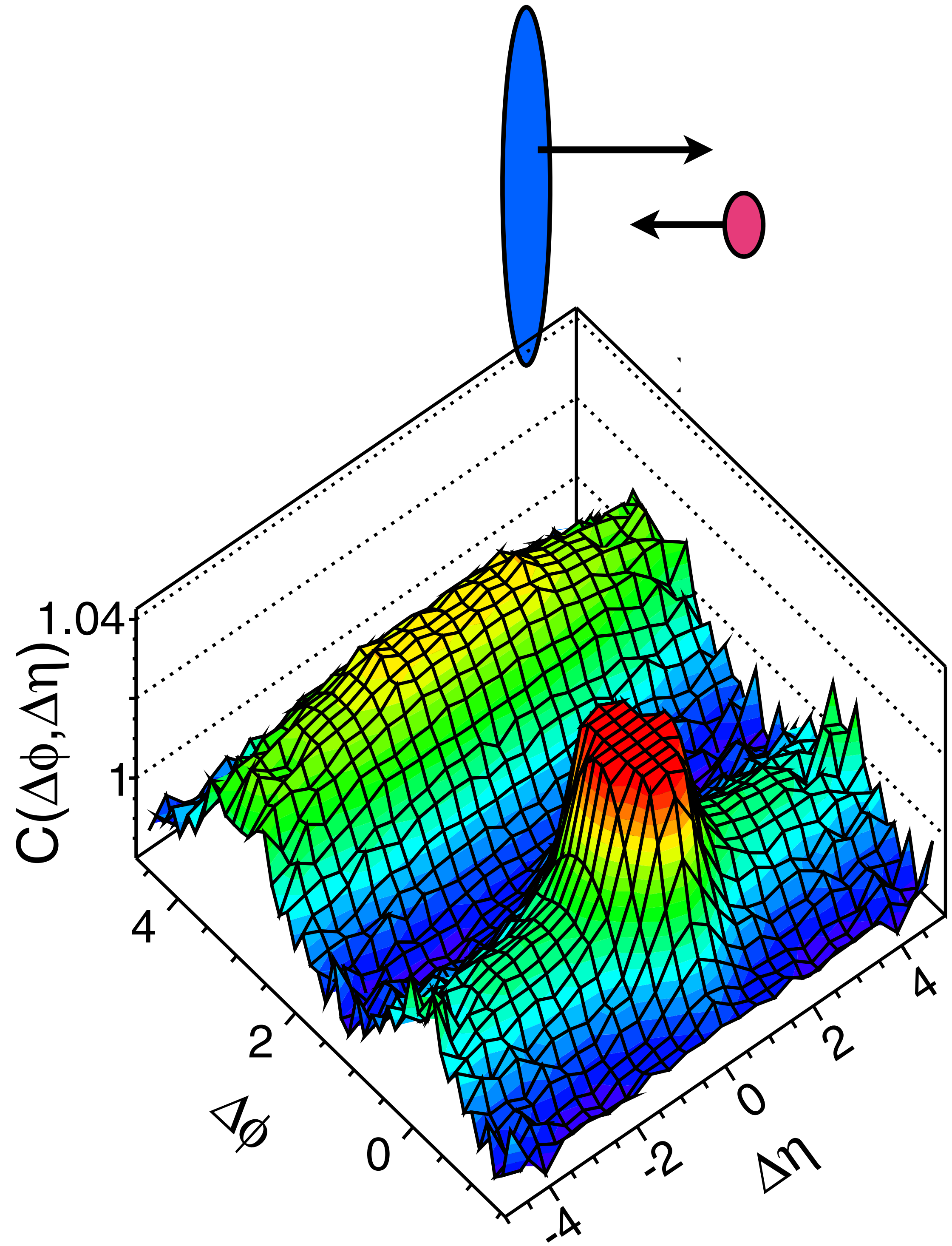
a closer look at pPb

peripheral collisions

central collisions



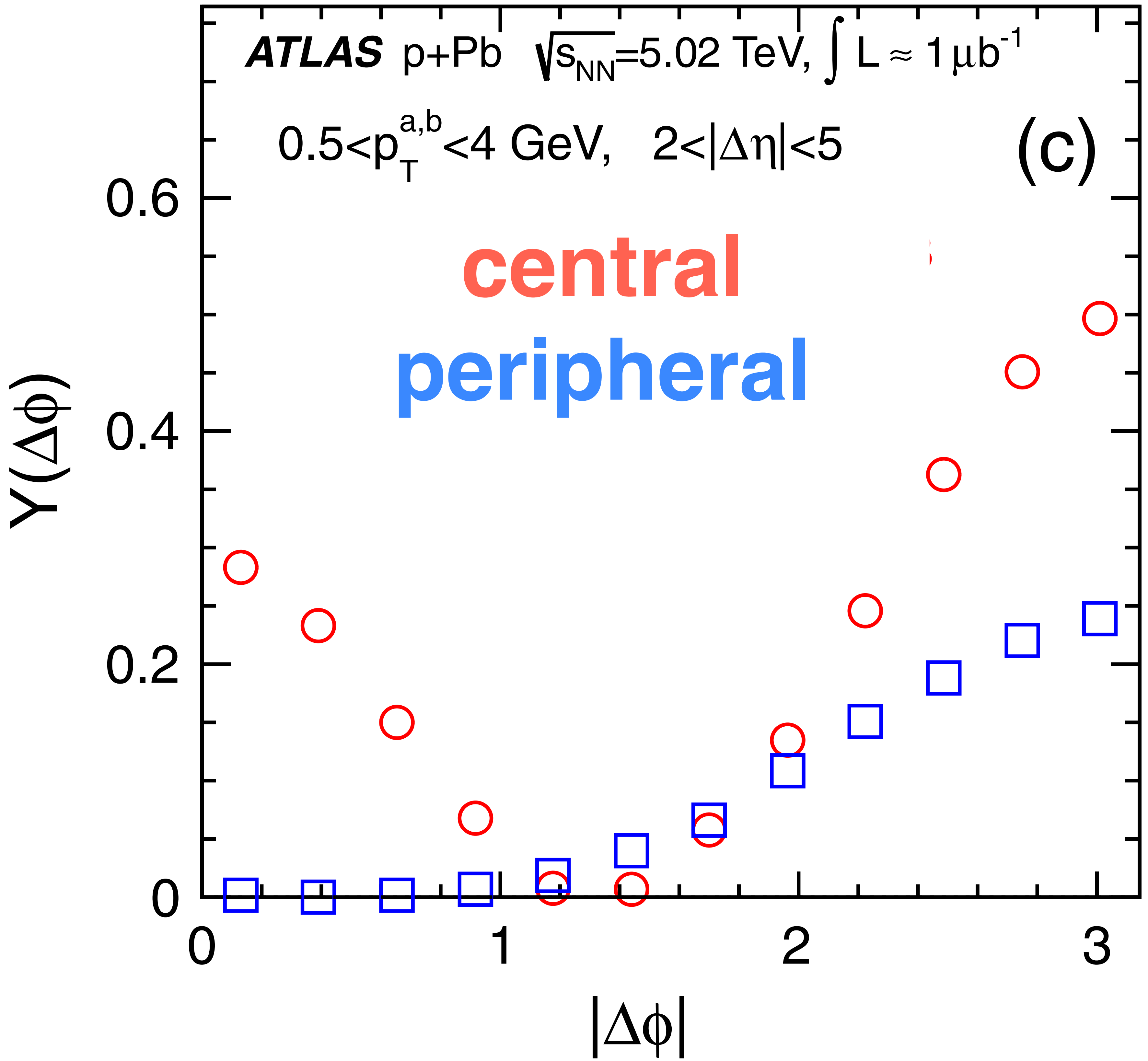
jets



jets + flow

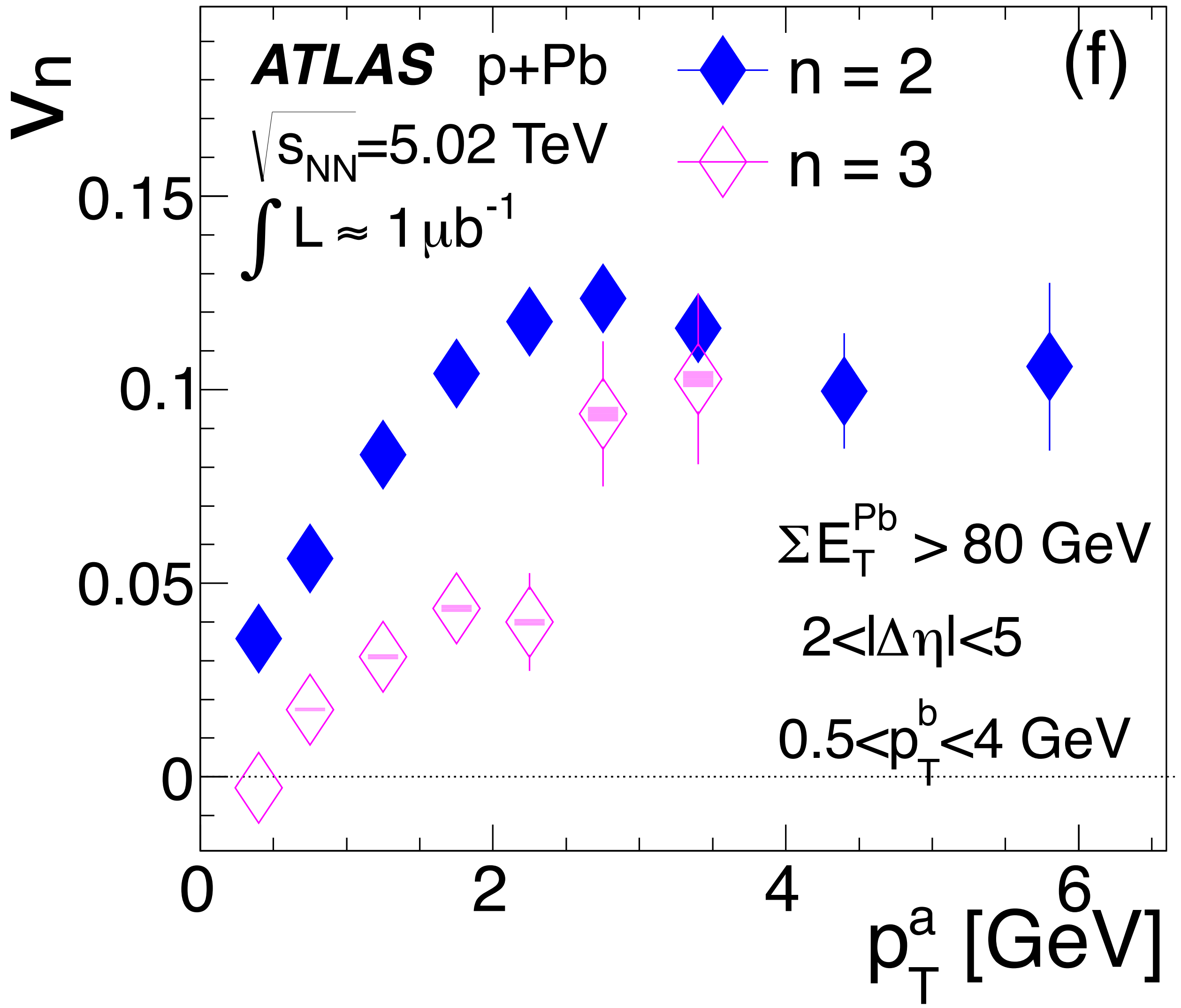
ATLAS PRL 110 102303

a closer look at pPb



ATLAS PRL 110 102303

v_2 & v3 in pPb collisions



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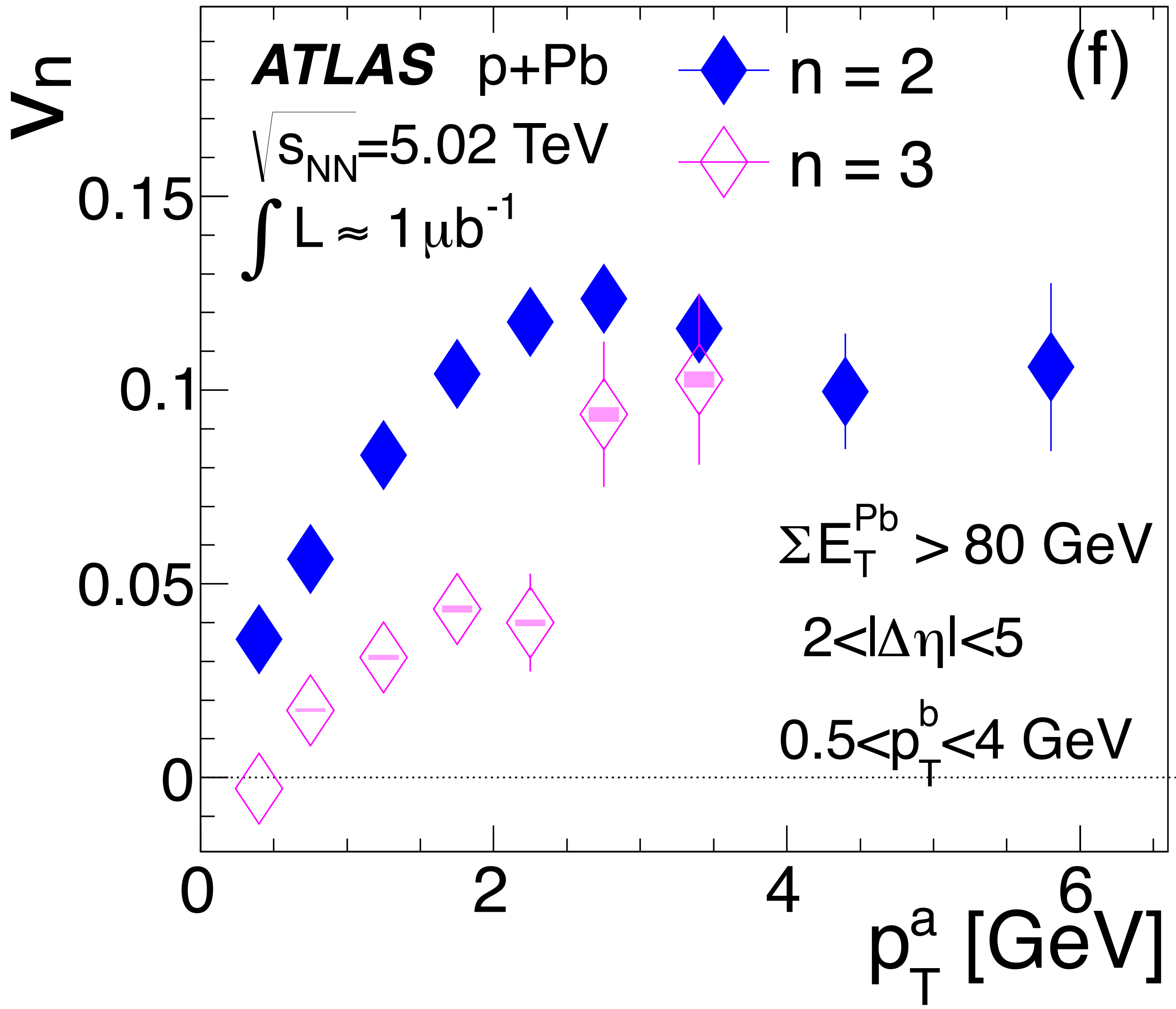
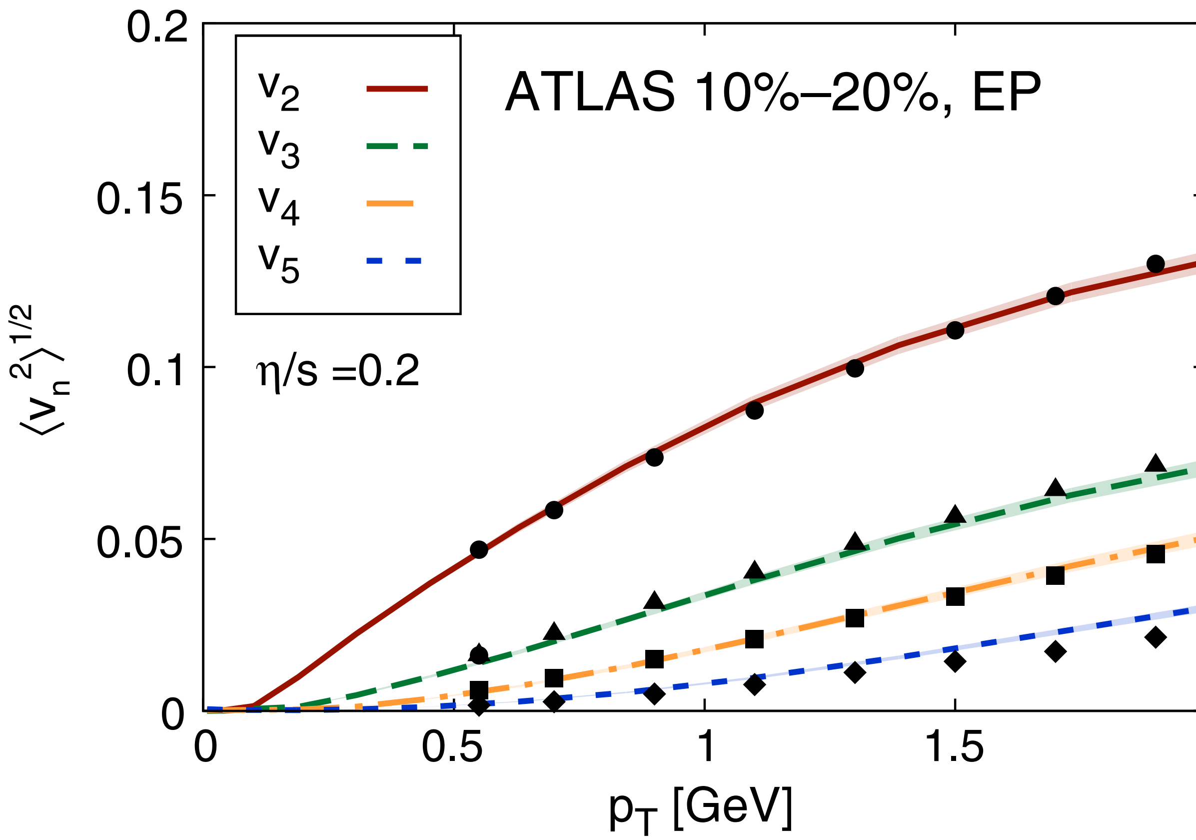


very similar to AA results



ATLAS PRL 110 102303

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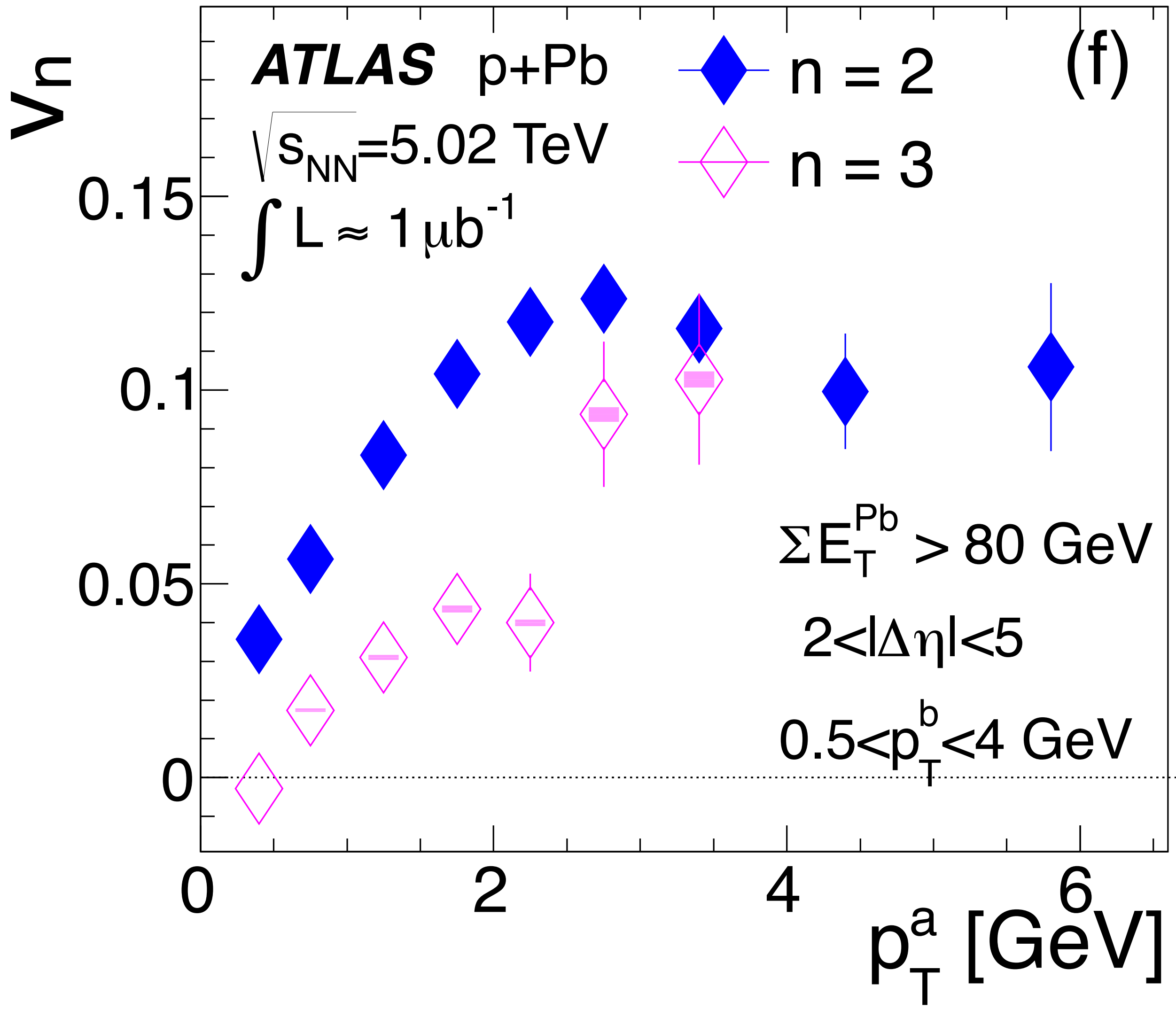

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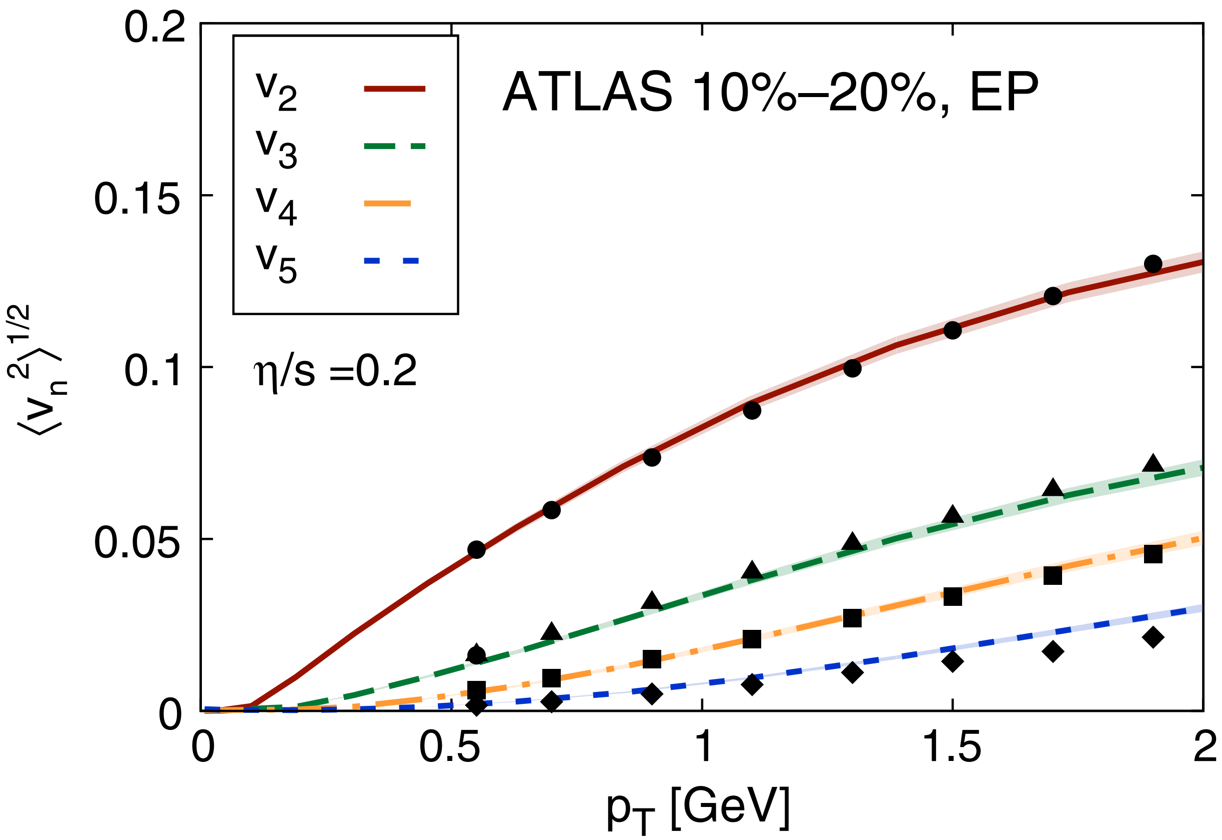
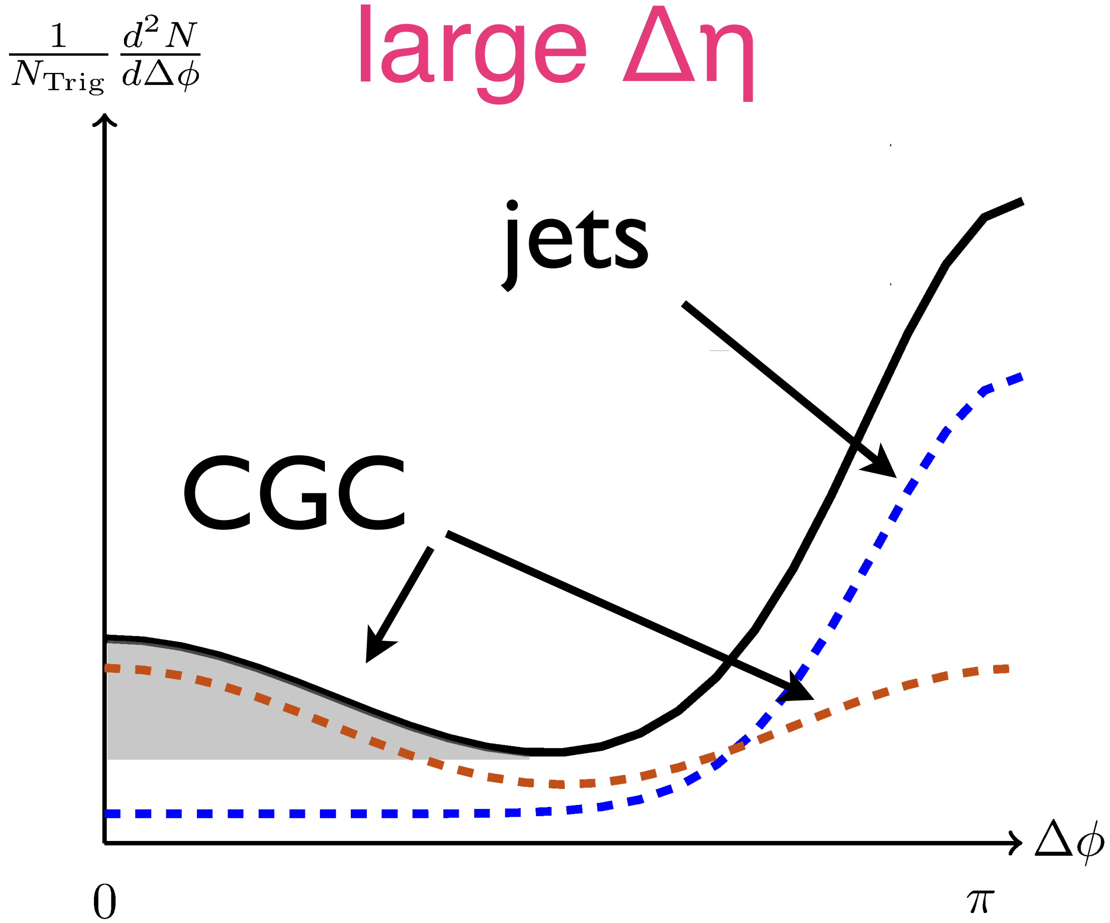
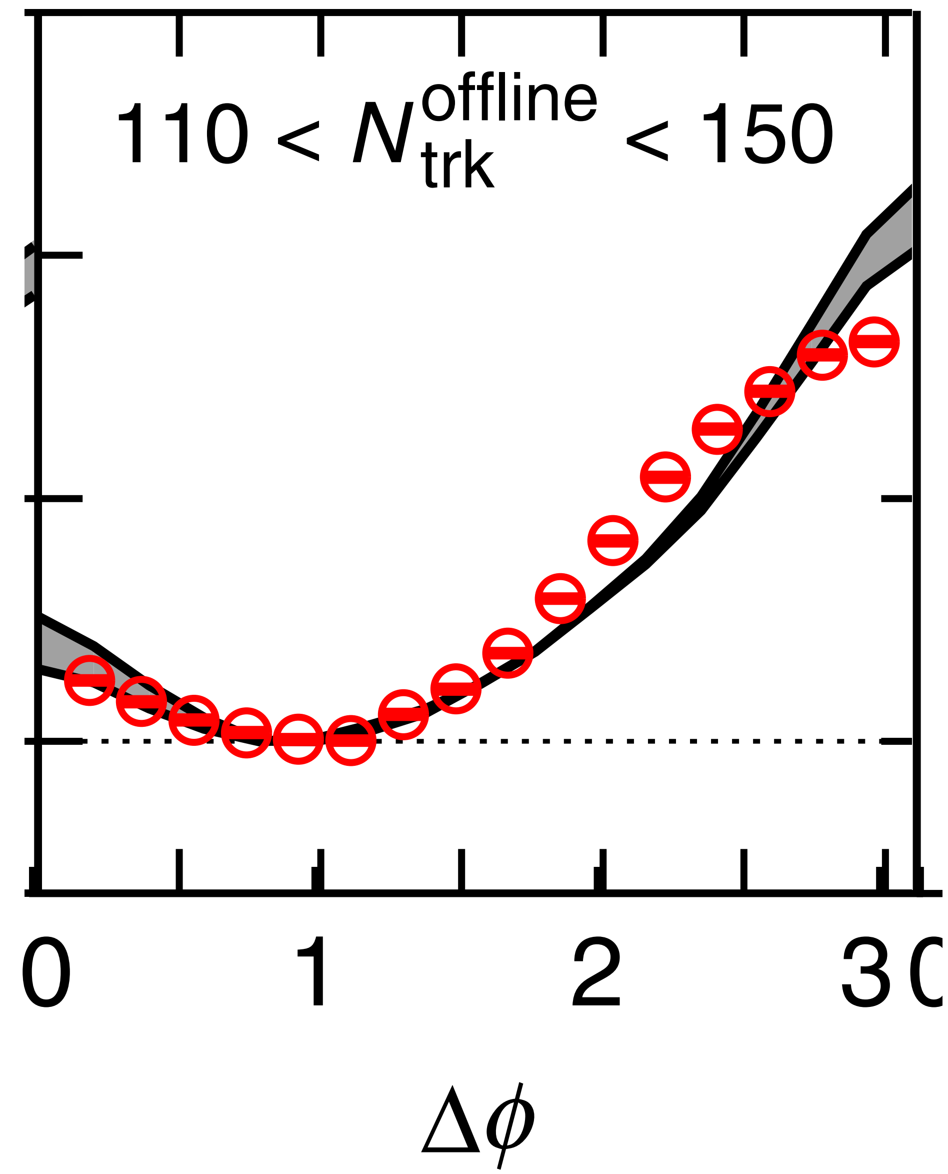


are the pA and AA v2 related to the same physics?

ridge in pp/pPb from color glass condensate?

Color Glass Condensate: calculational framework for saturation





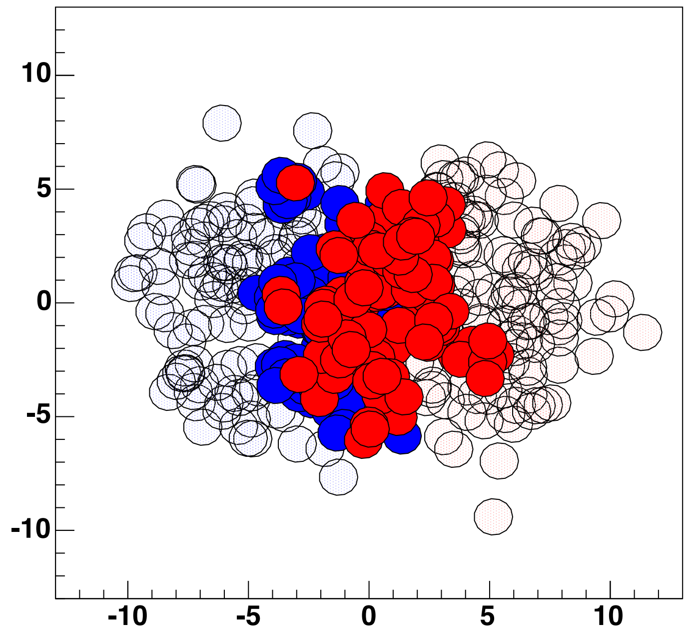
good description of the data in pPb

Dusling & Venugopalan PRL 104 262301, PRD 87 054014, PRD 87 094034

geometry in AA & pA

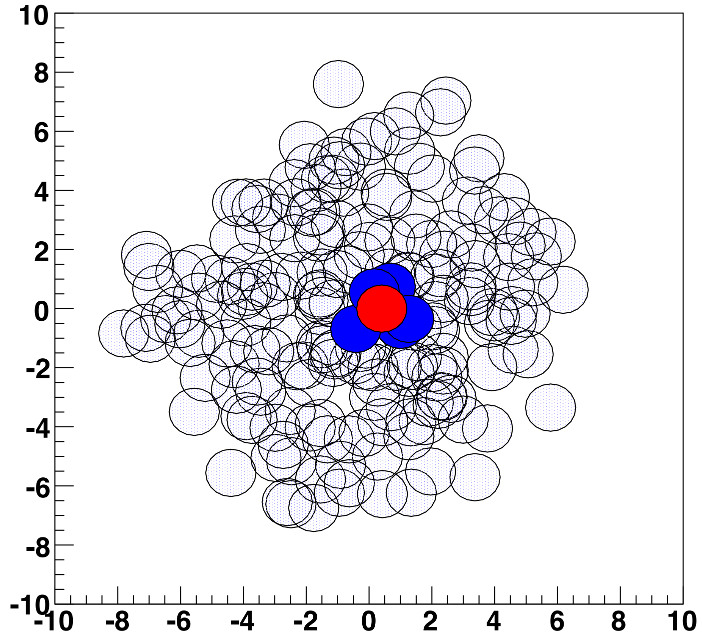
AA

impact parameter + fluctuations



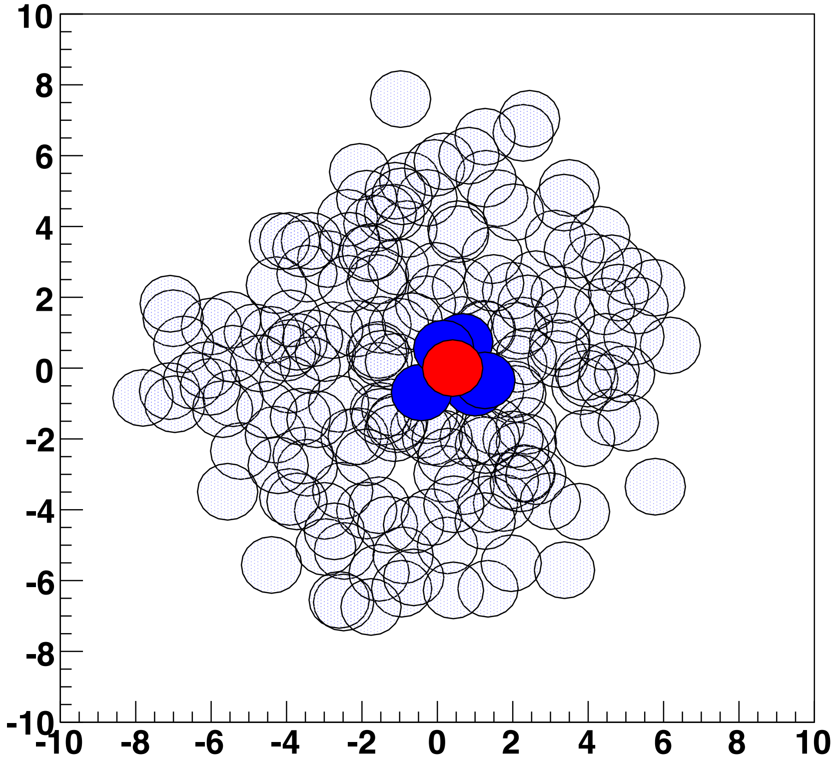
pA

fluctuations

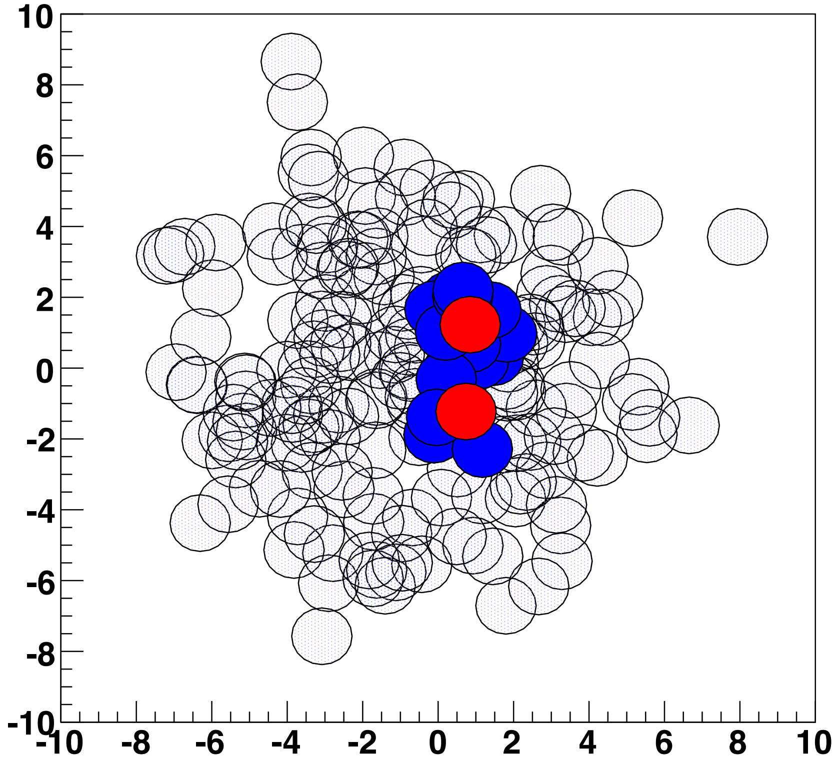


variation of the small nucleus

pA



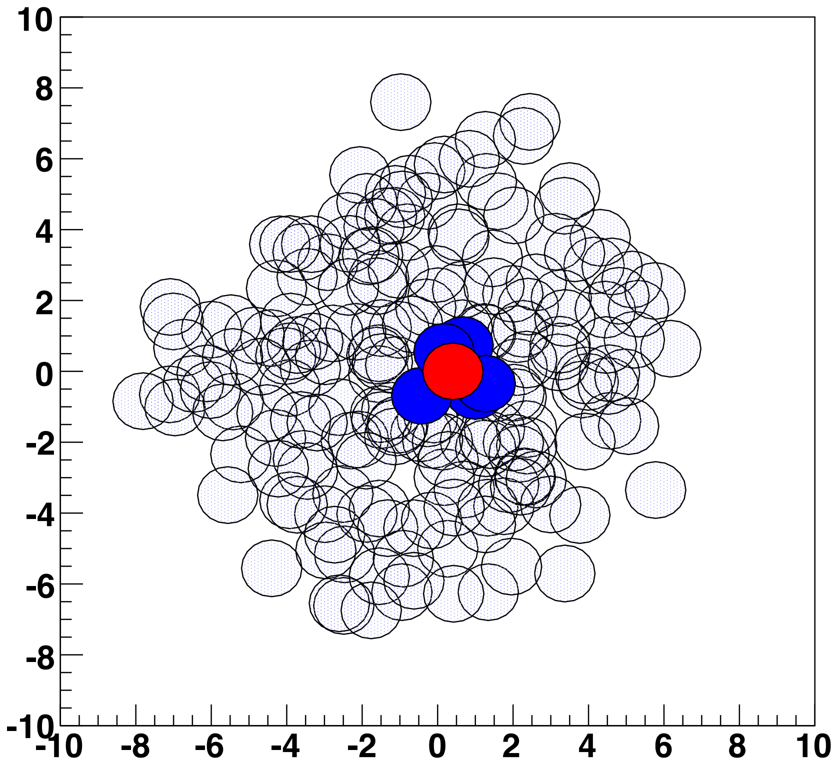
dA



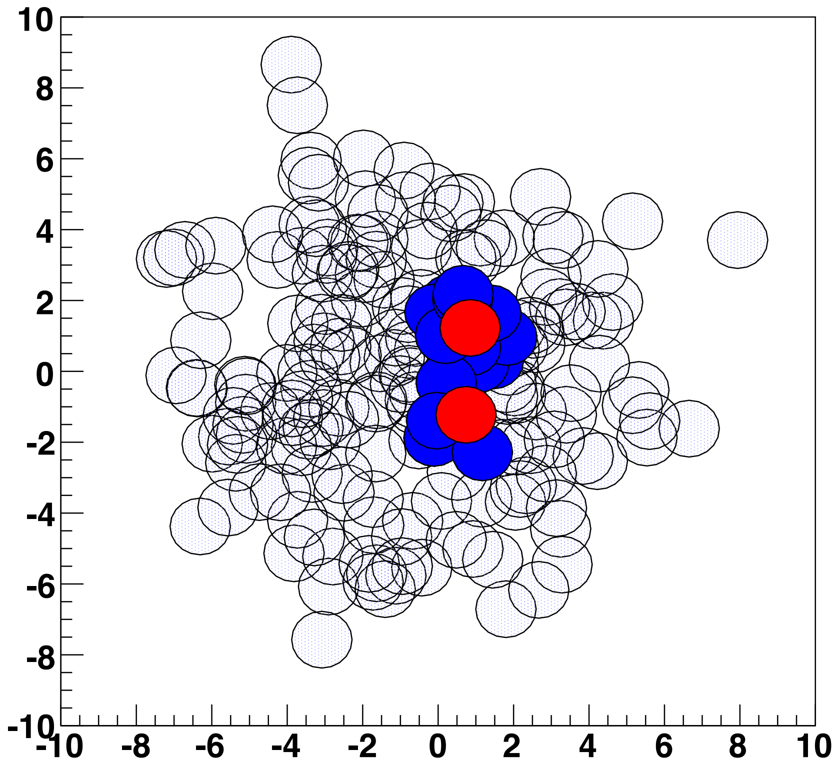
control the collision geometry by varying the small nucleus

variation of the small nucleus

pA



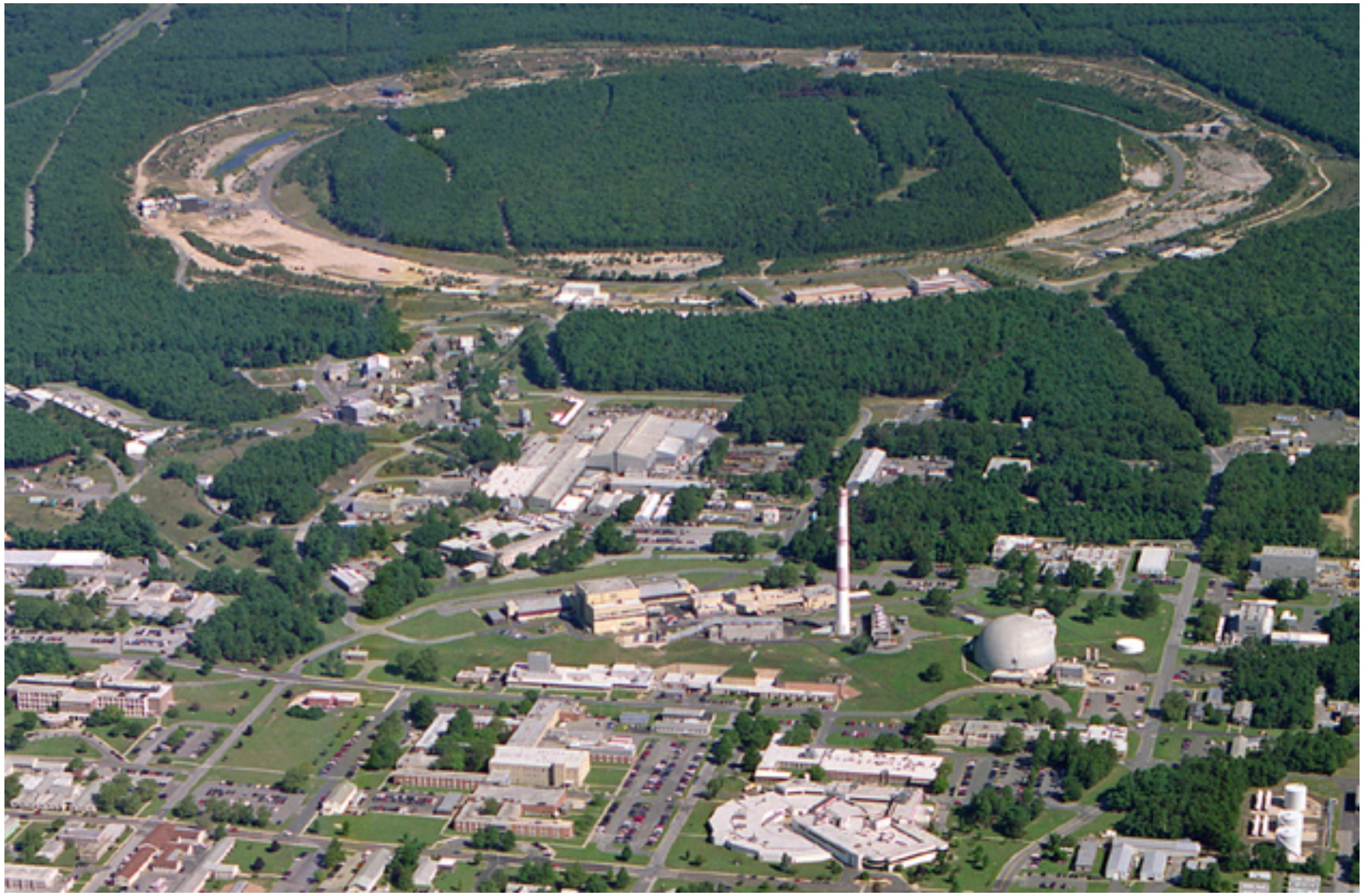
dA



control the collision geometry by varying the small nucleus

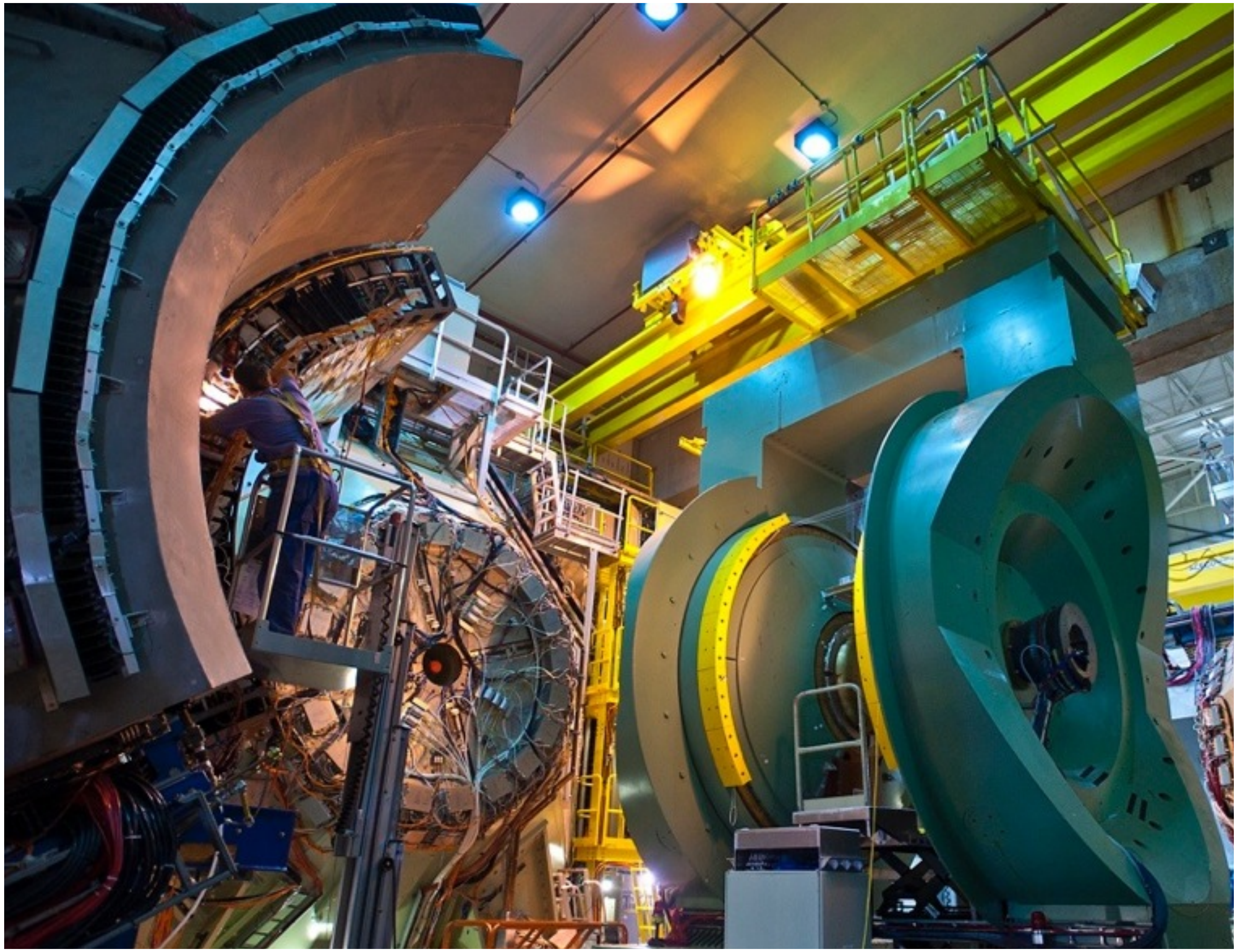
does v2 reflect the geometry of the initial state in p/d+A as in A+A?

what can RHIC add?



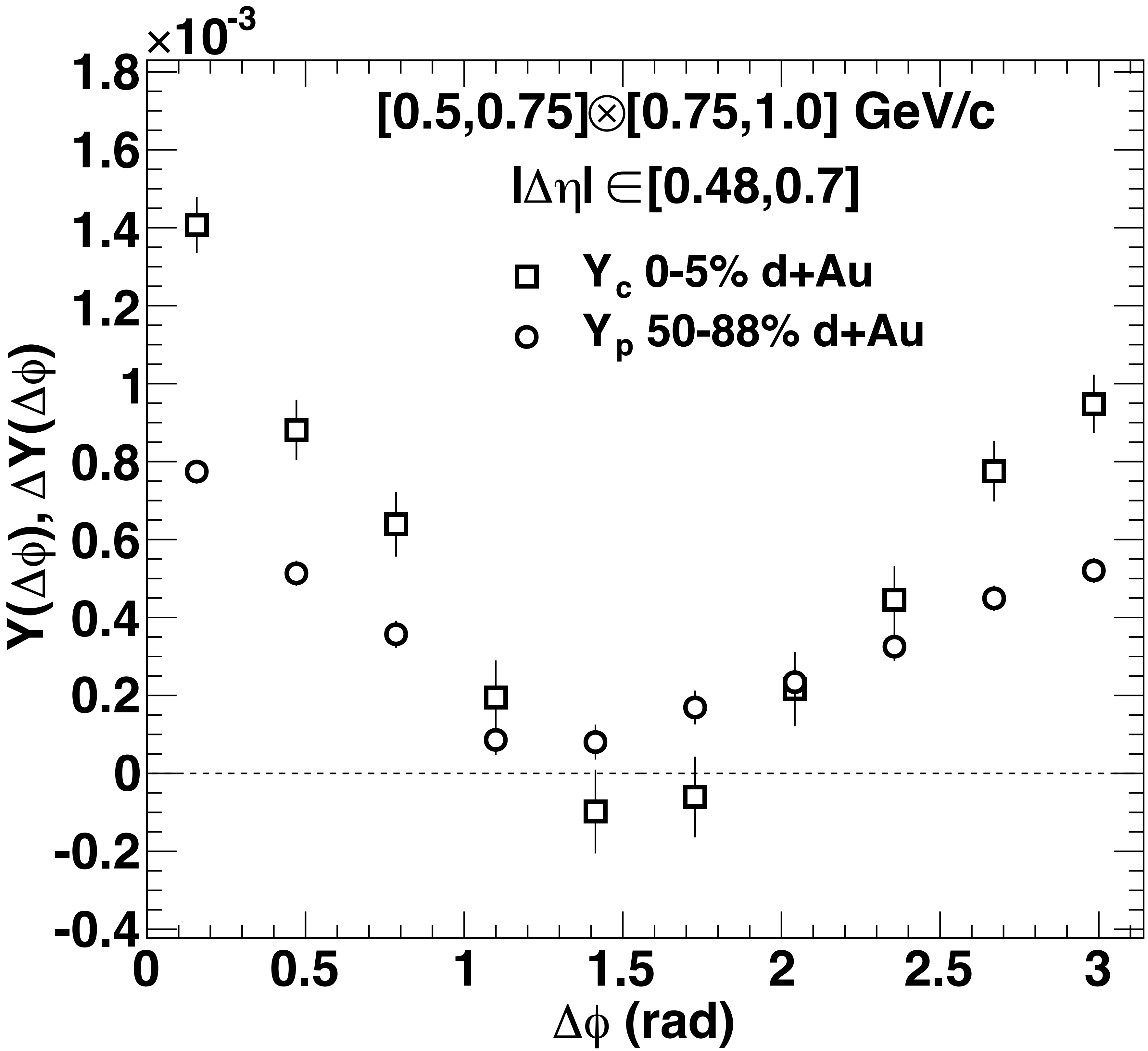
RHIC had huge d+Au sample
25x smaller collision energy than the LHC

PHENIX



- charged hadrons
  - $|\eta| < 0.35$
  - $|\Delta\eta| < 0.7$
- centrality determined by charged particles in the Au going direction: $3 < |\eta| < 4$
- 1.6B minimum bias events

two particle correlations in dAu

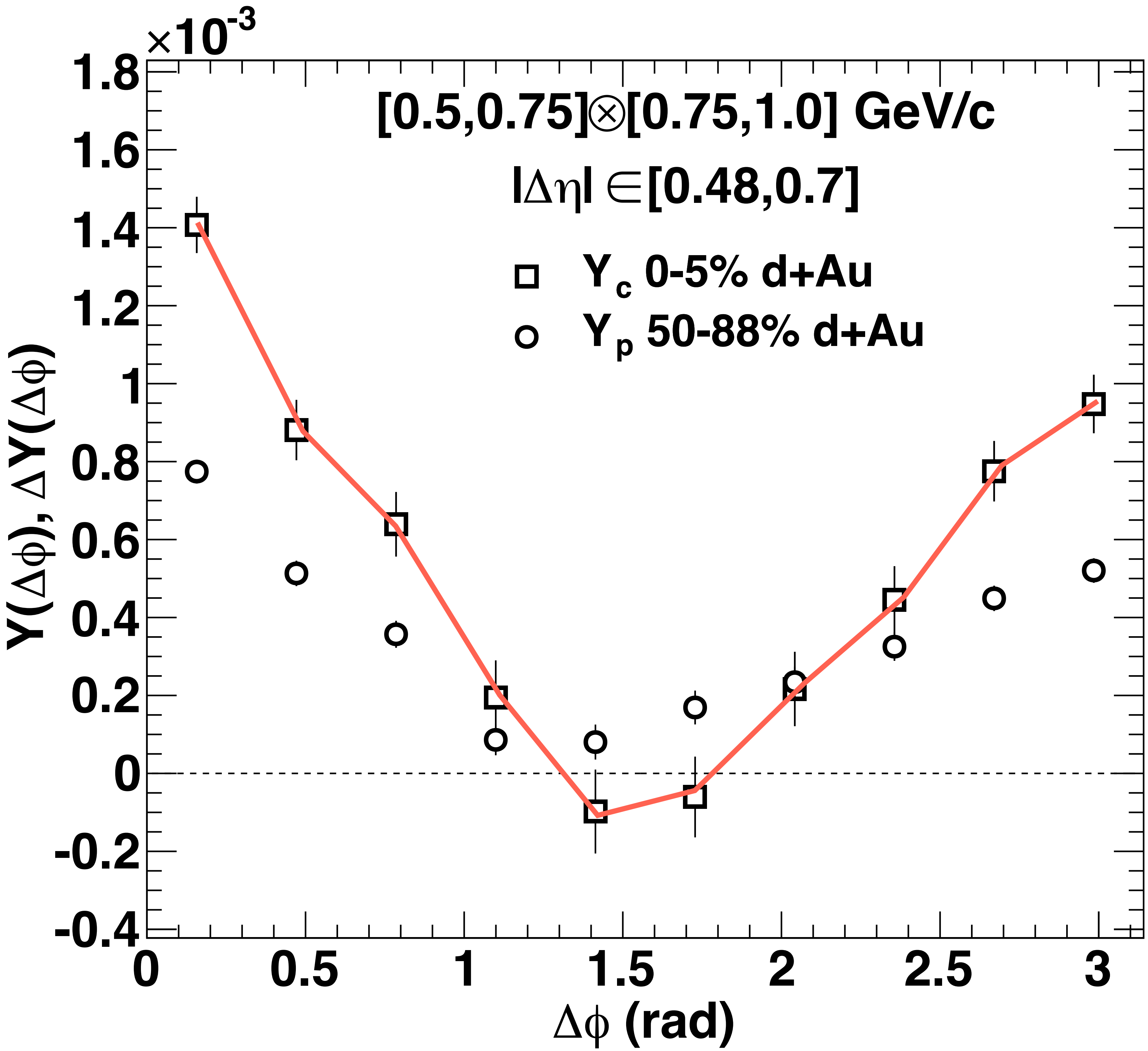


central

peripheral

PHENIX PRL 111 212301

two particle correlations in dAu

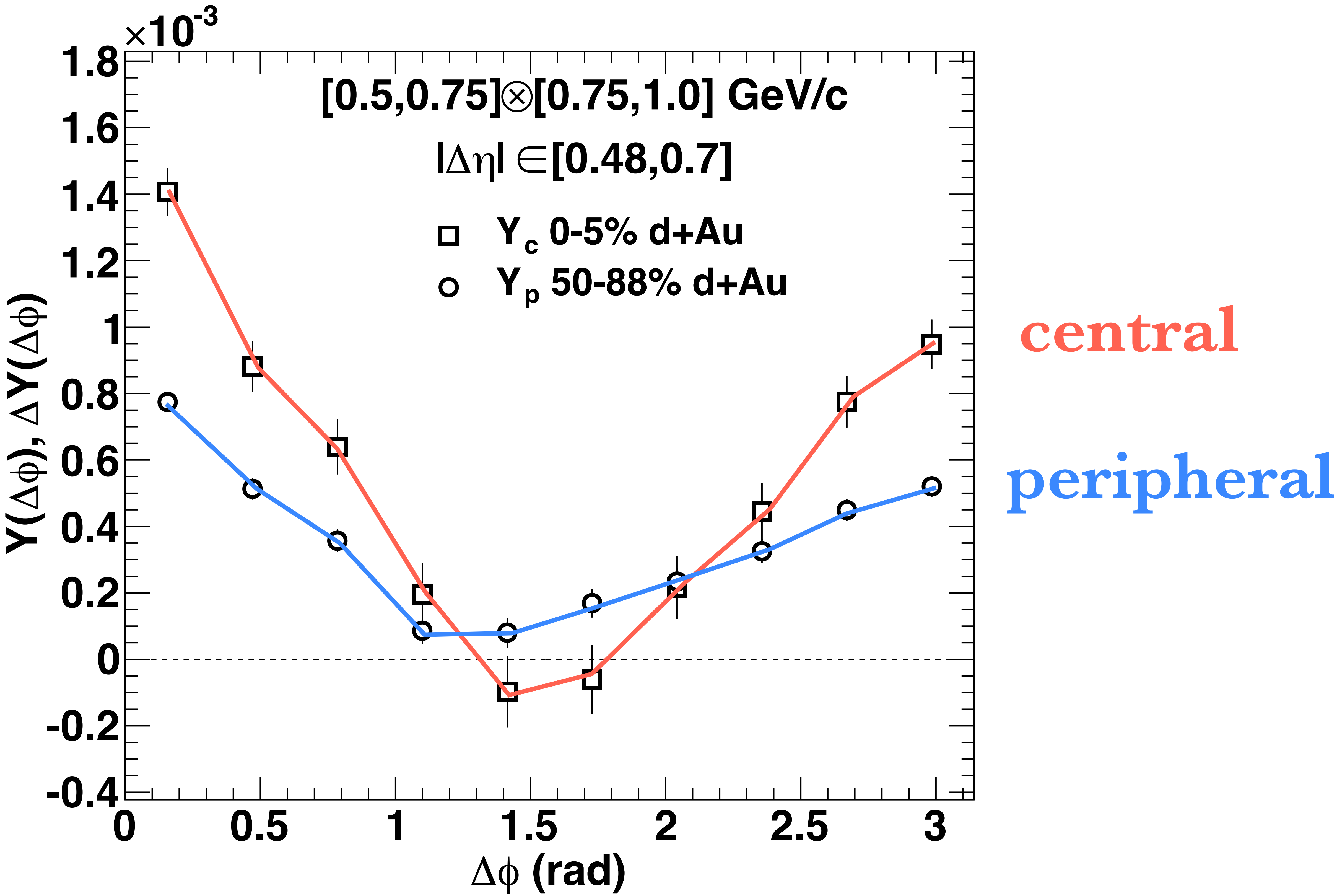


central

peripheral

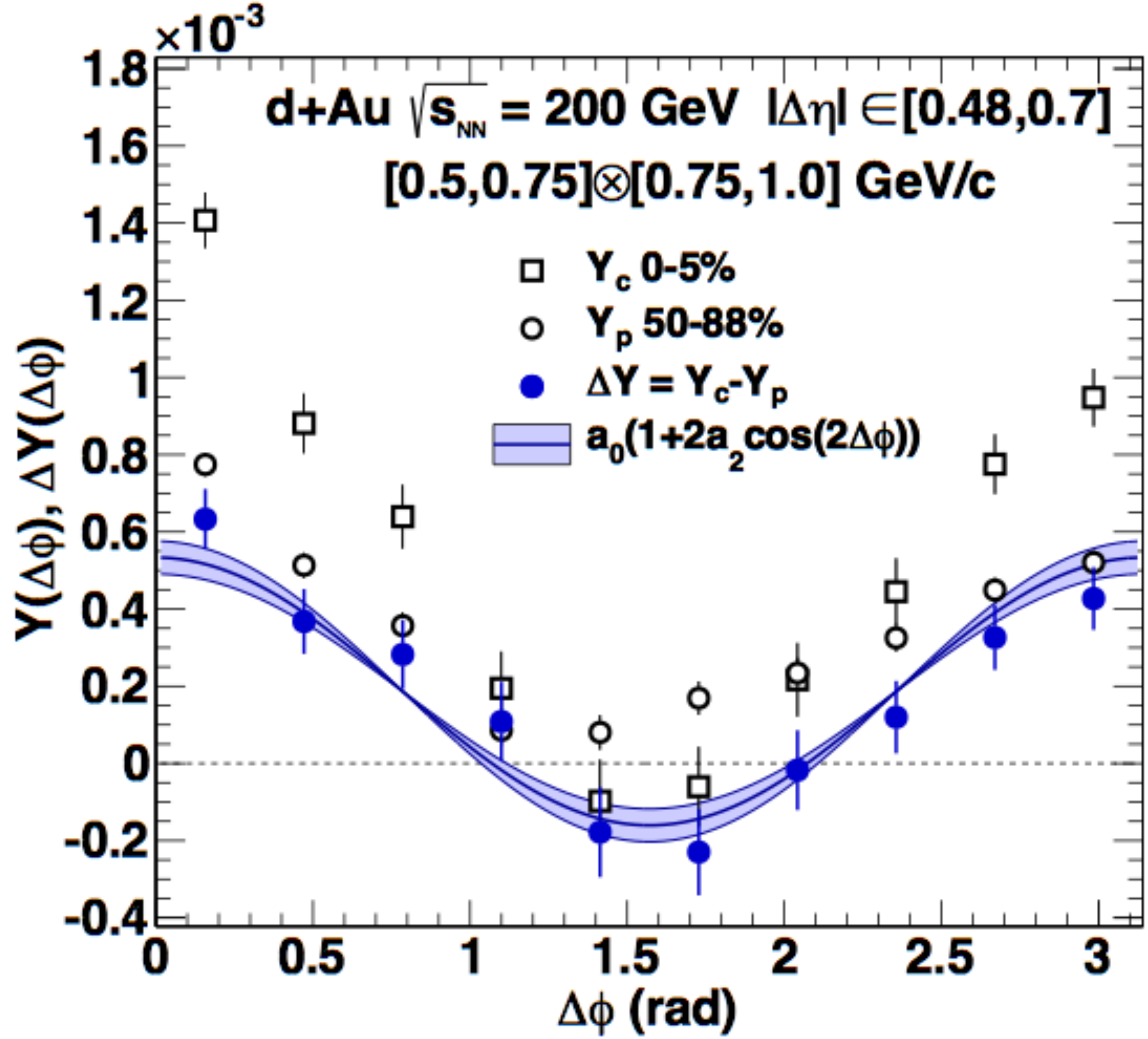
PHENIX PRL 111 212301

two particle correlations in dAu



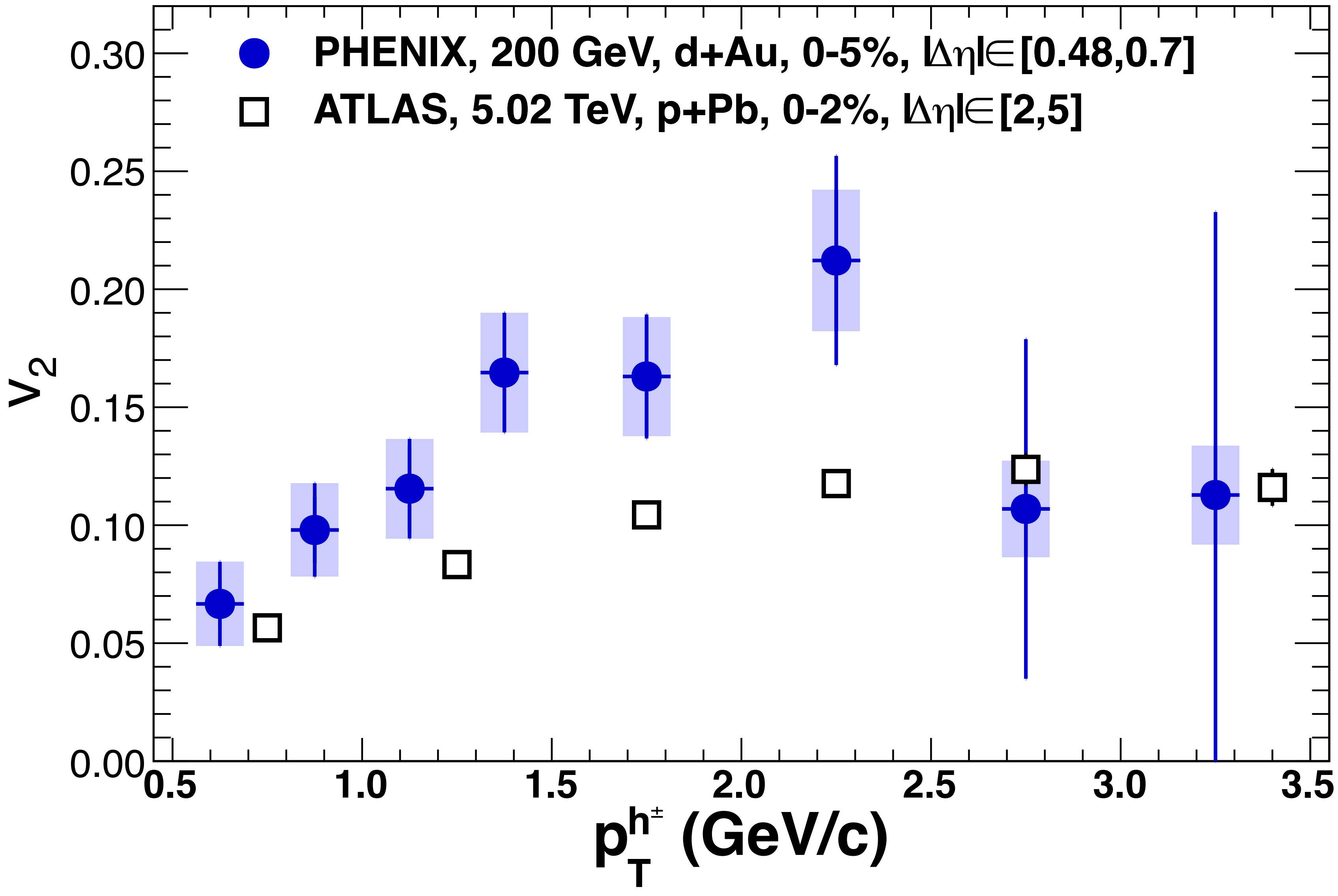
PHENIX PRL 111 212301

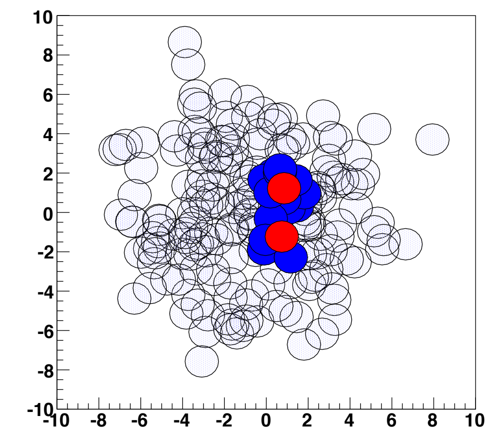
centrality dependence

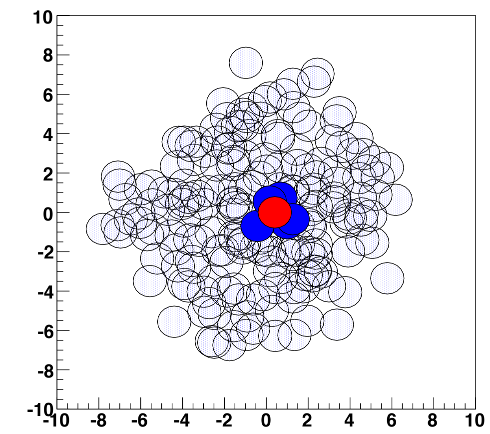


PHENIX PRL 111 212301

v2: pPb & dAu







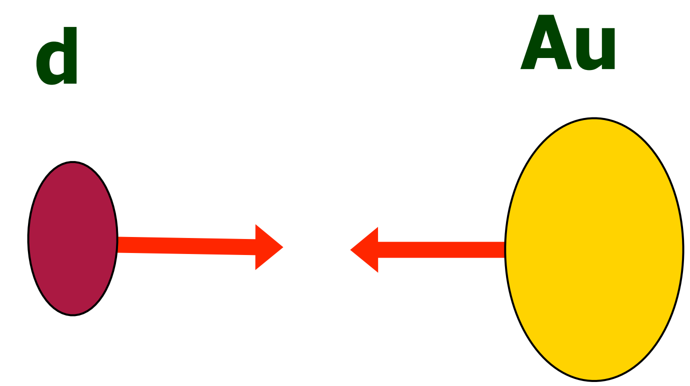
PHENIX PRL 111 212301 (2013)
ATLAS PRL 110 182302 (2013)

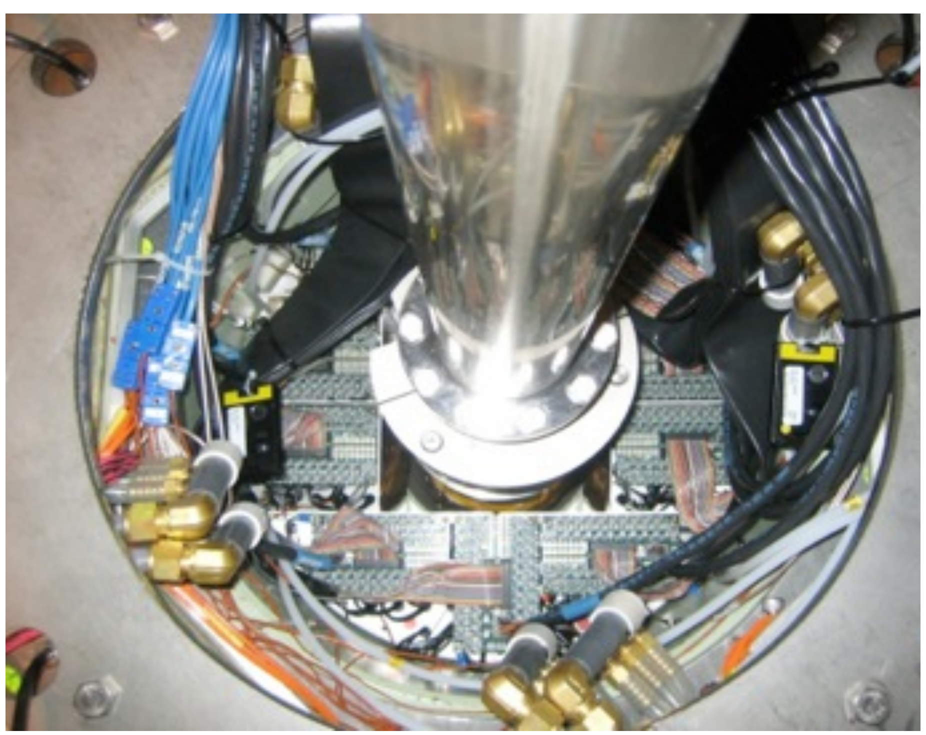
rapidity separated correlations

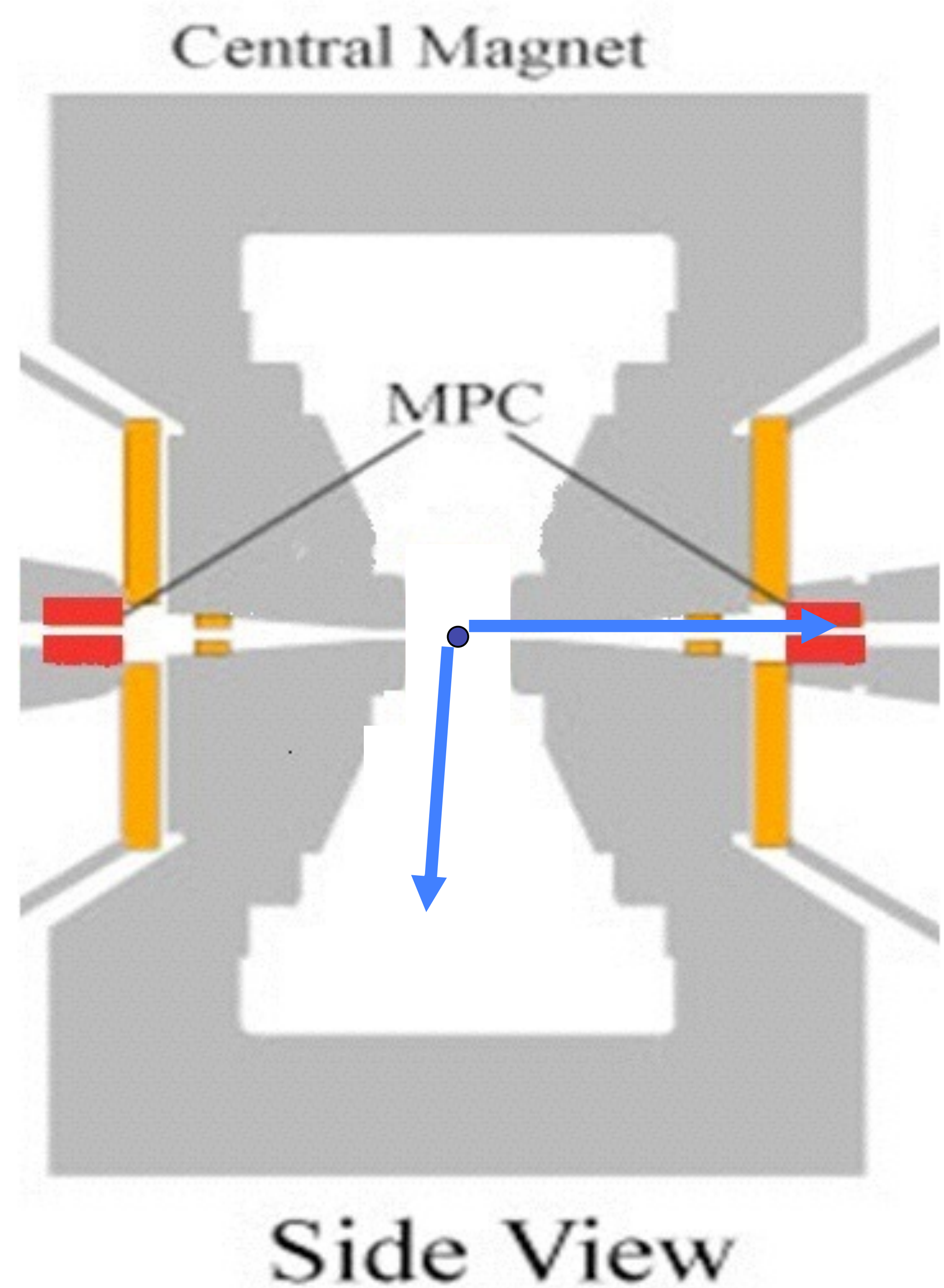
Muon Piston Calorimeters

both d-going & Au-going directions

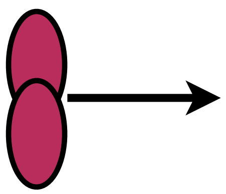
$3 < |\eta| < 4$



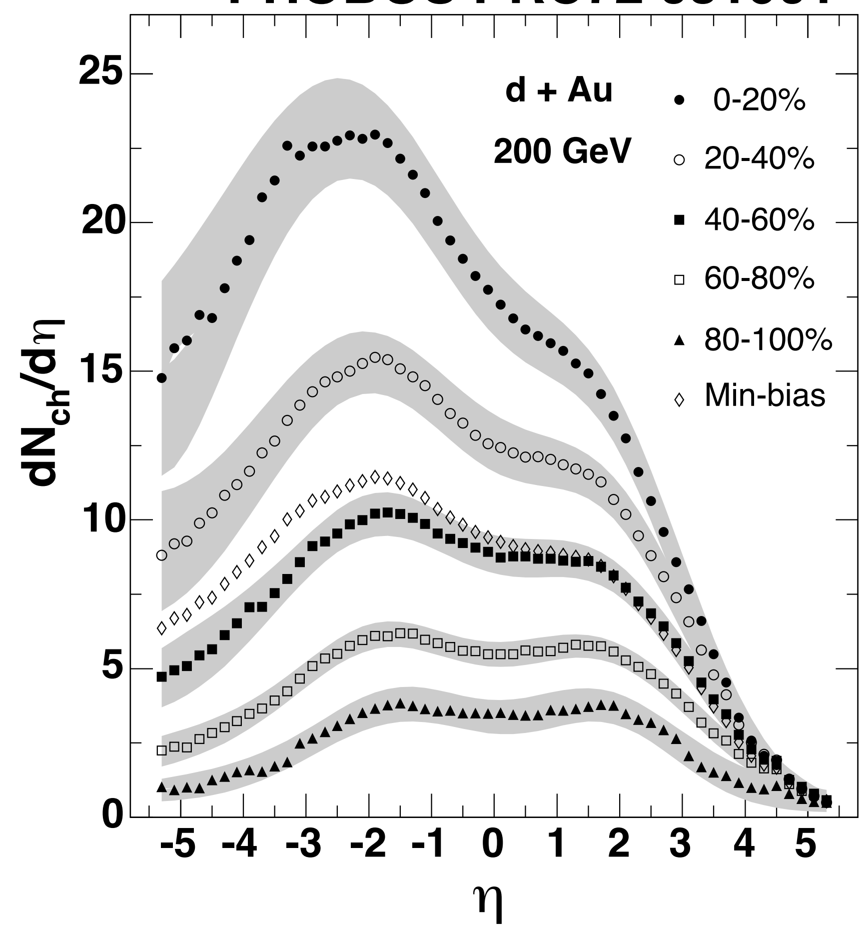


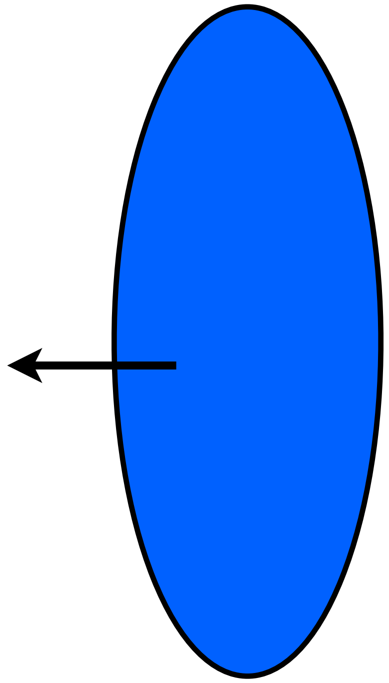


long range correlations in dAu

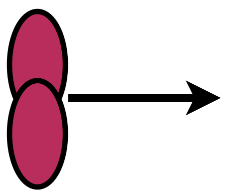


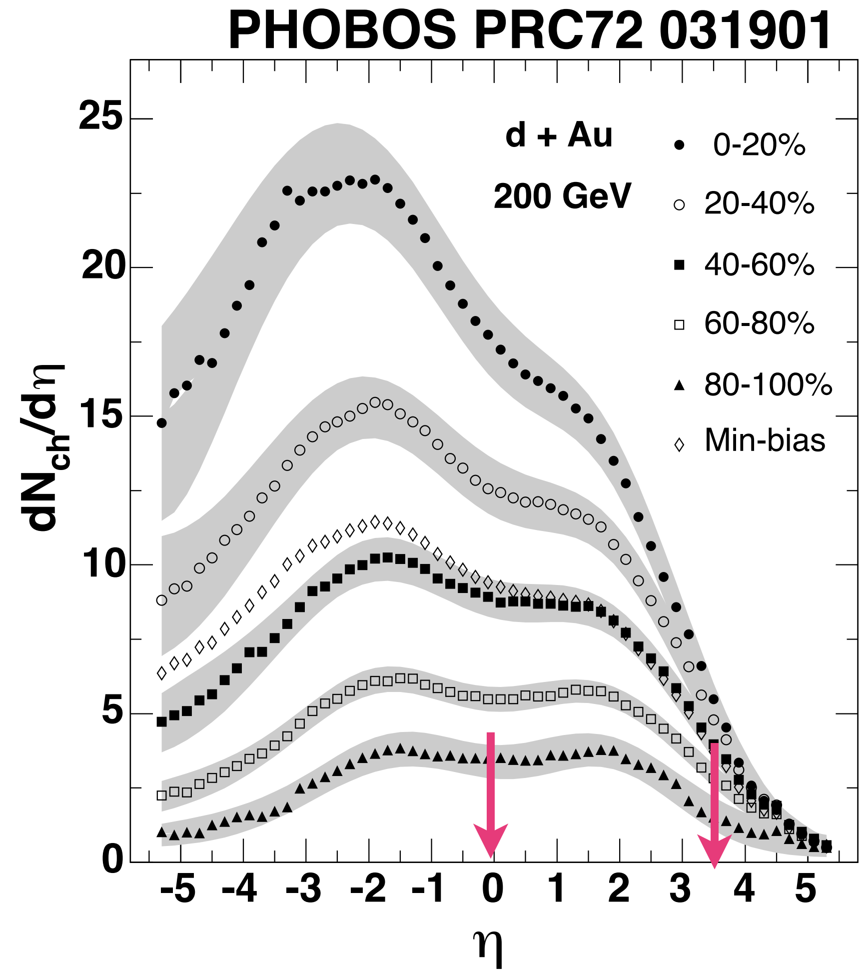
PHOBOS PRC72 031901

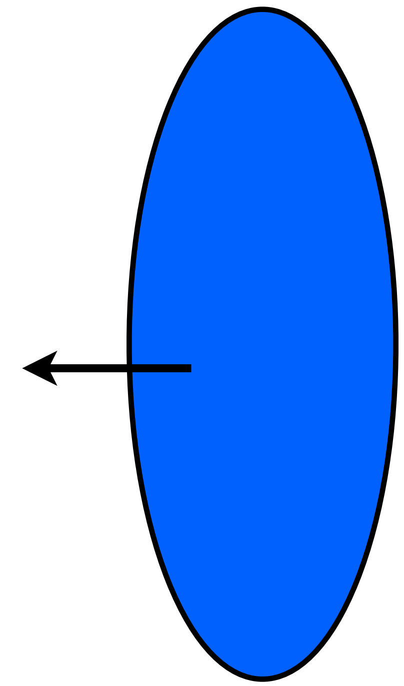


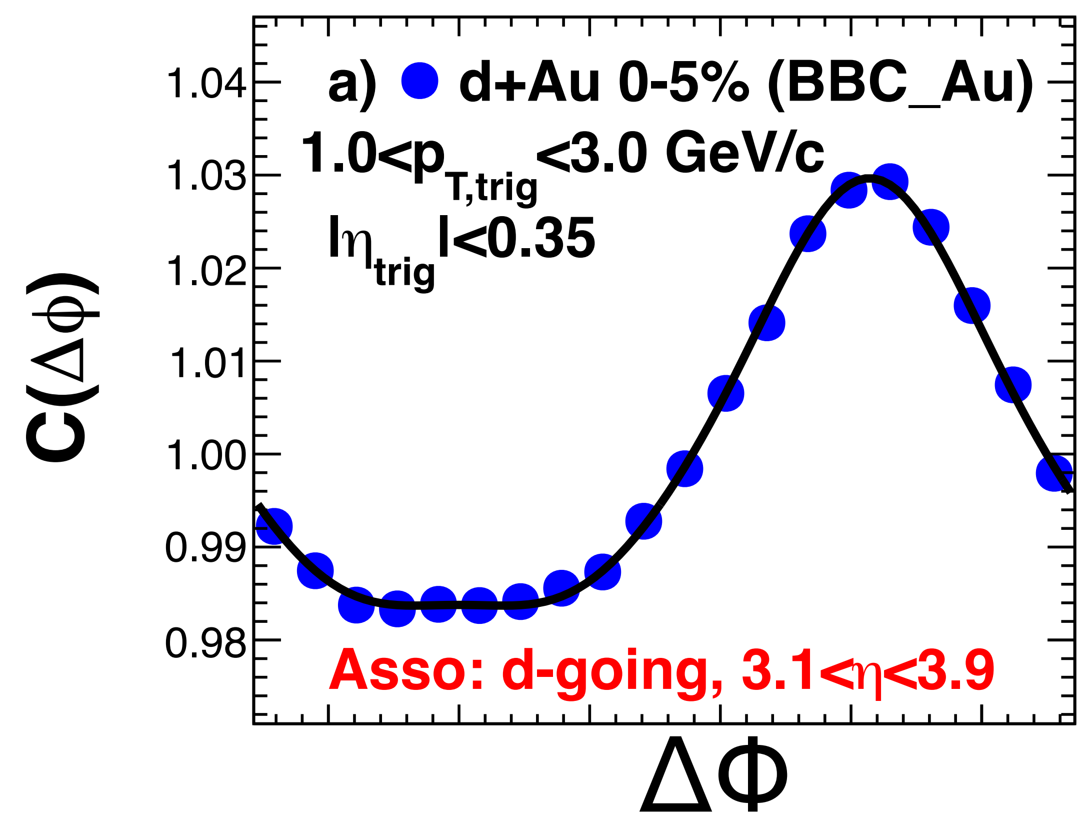


long range correlations in dAu

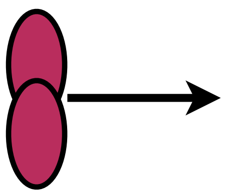


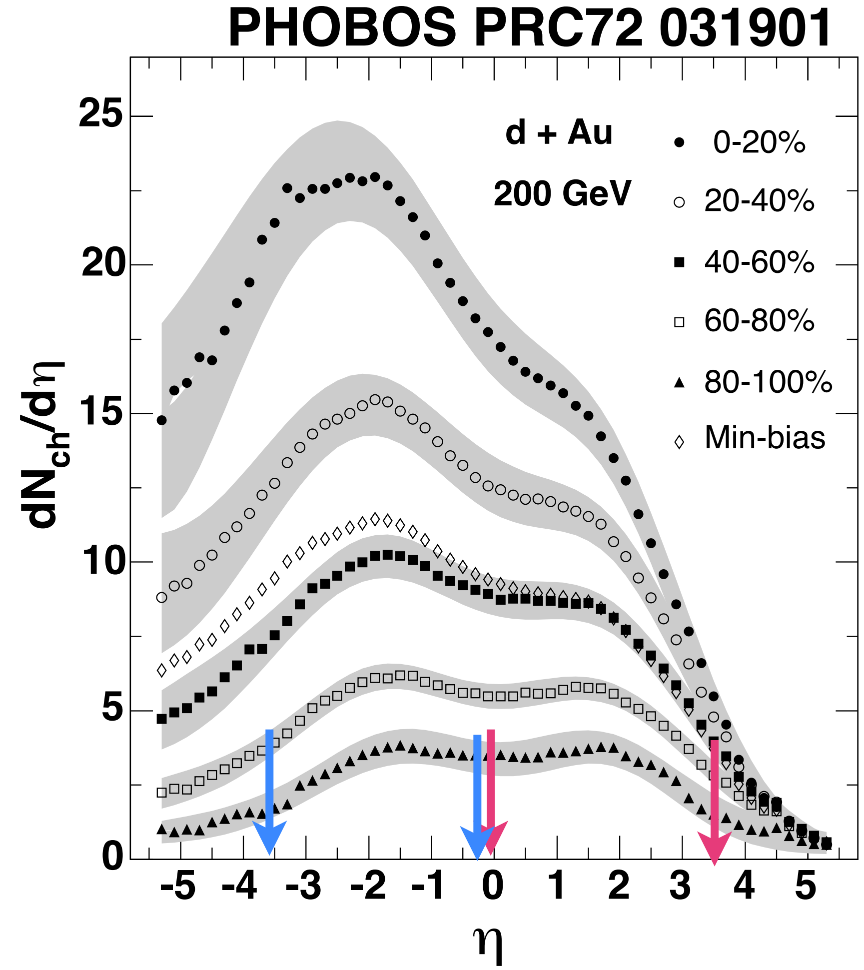


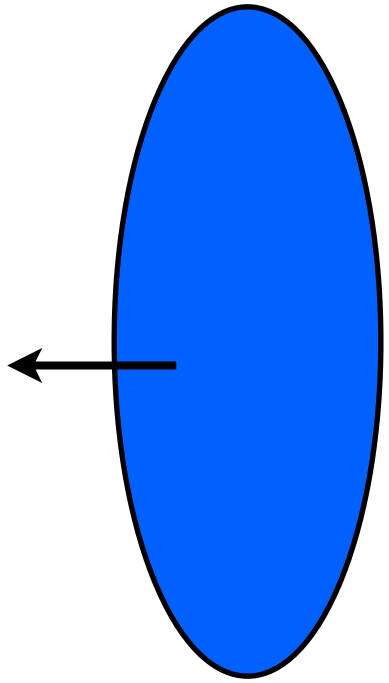


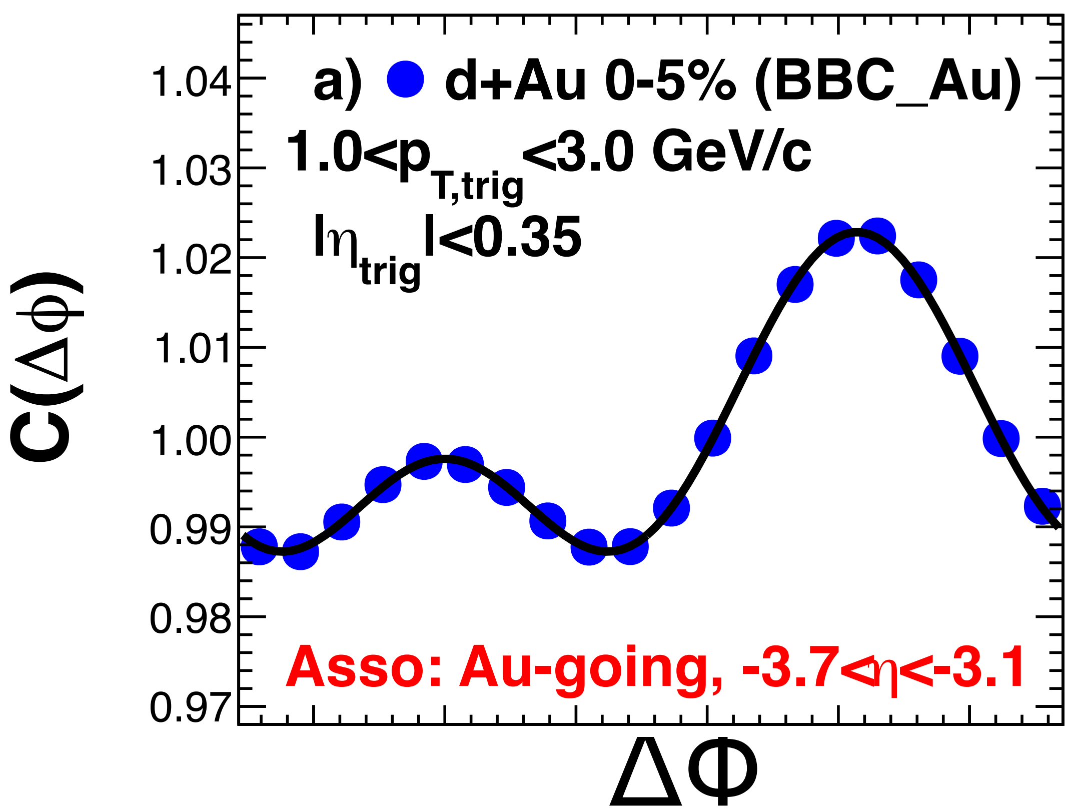


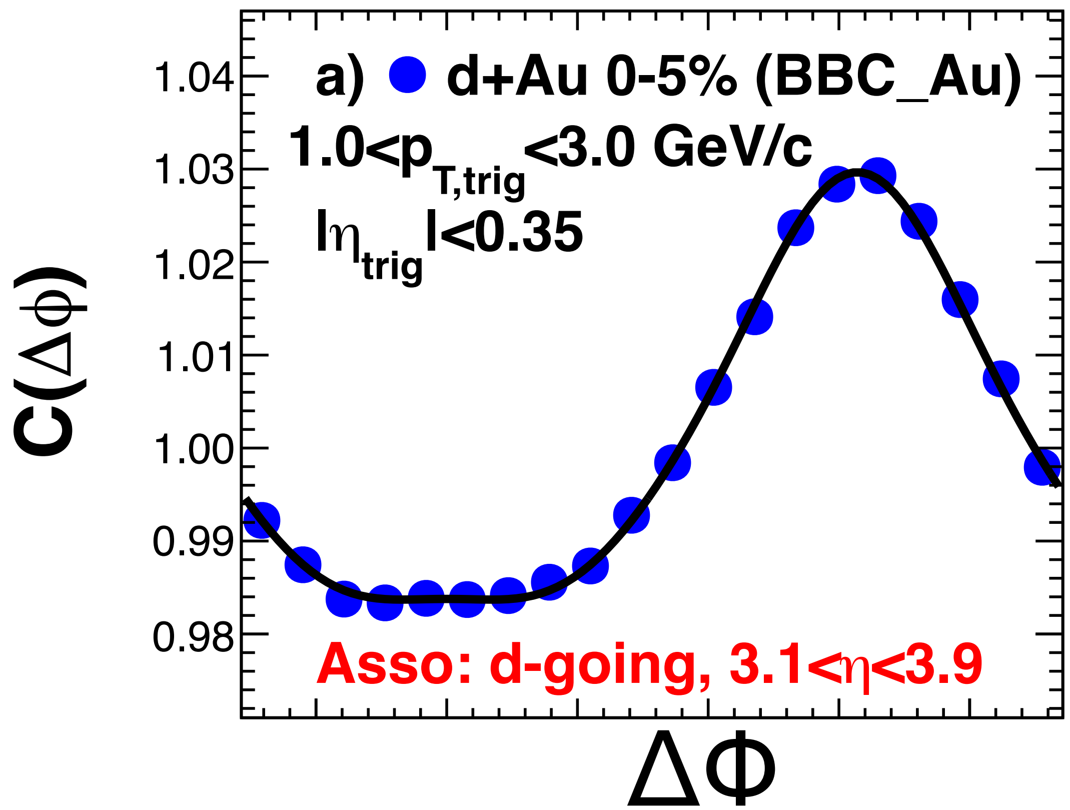
long range correlations in dAu



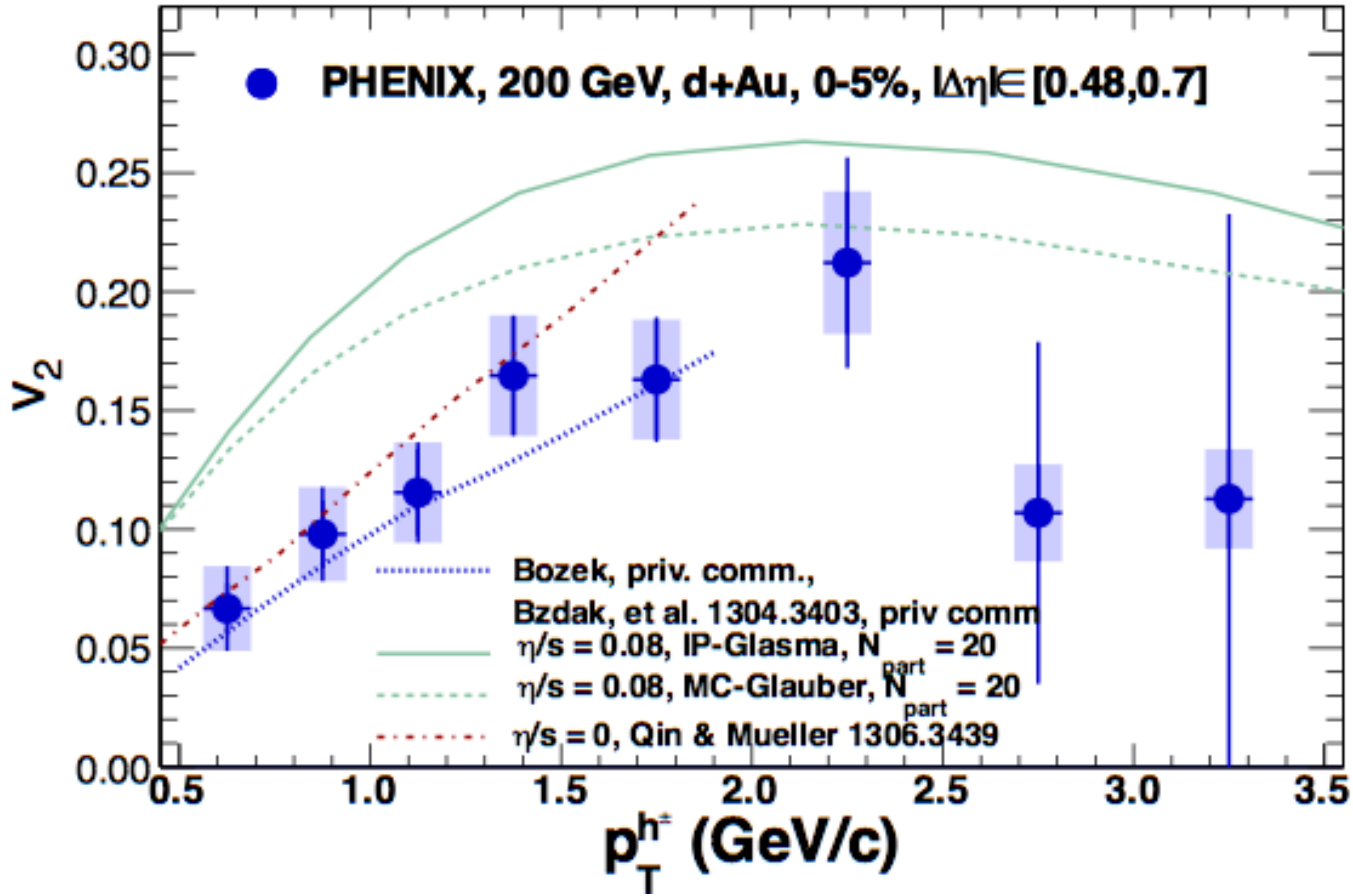








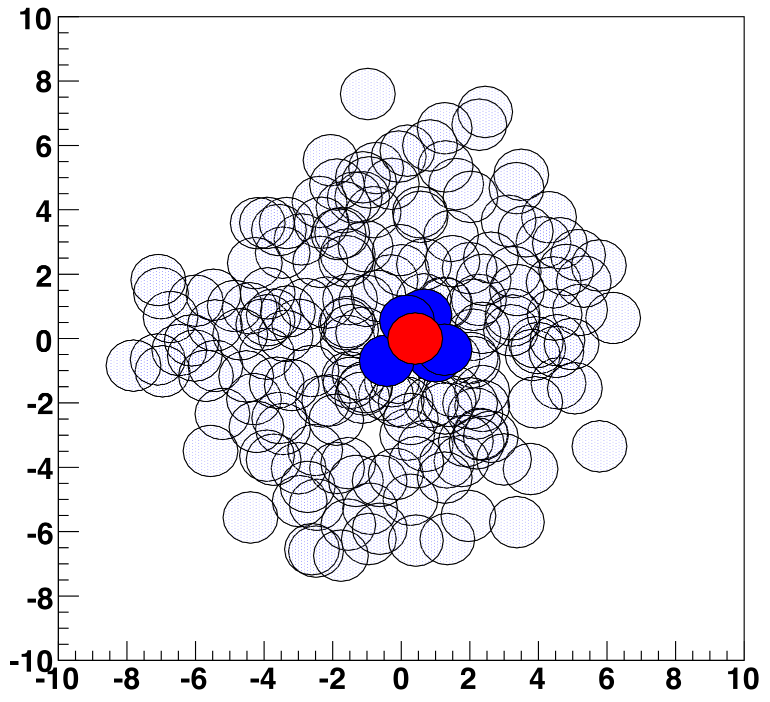
v_2 in dAu compared to hydro. calculations



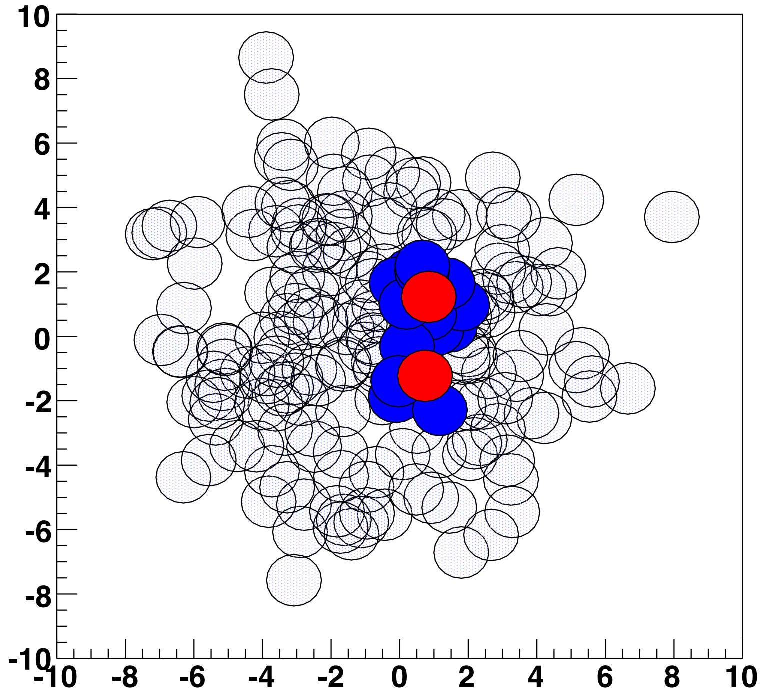
PHENIX PRL 111 212301

shapes of pA & dA

pA, small ε_2



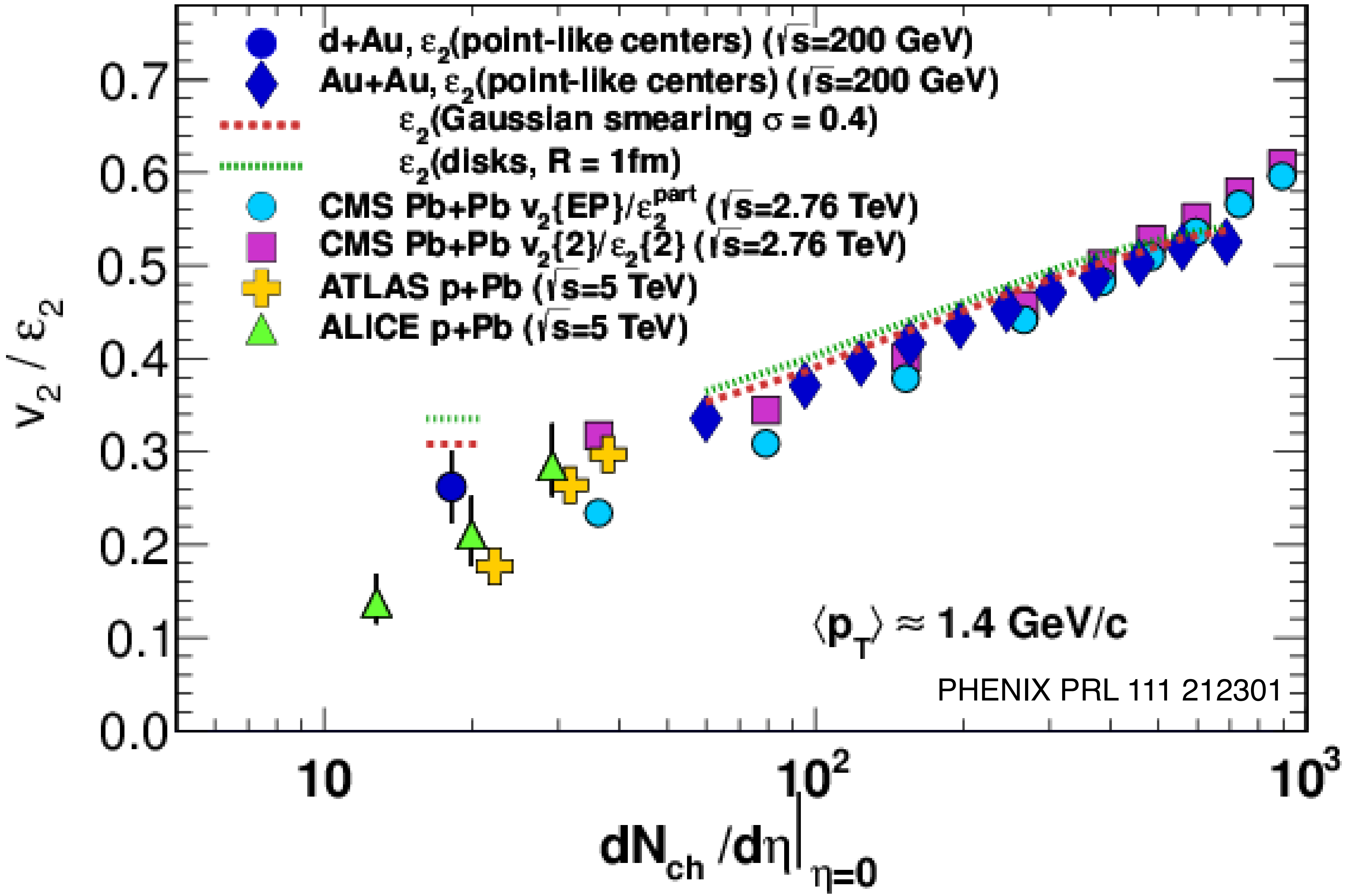
dA, large ε_2



Glauber Monte Carlo used to generate single event initial energy density distributions

used to determined $<\varepsilon_n>$ values for event selections

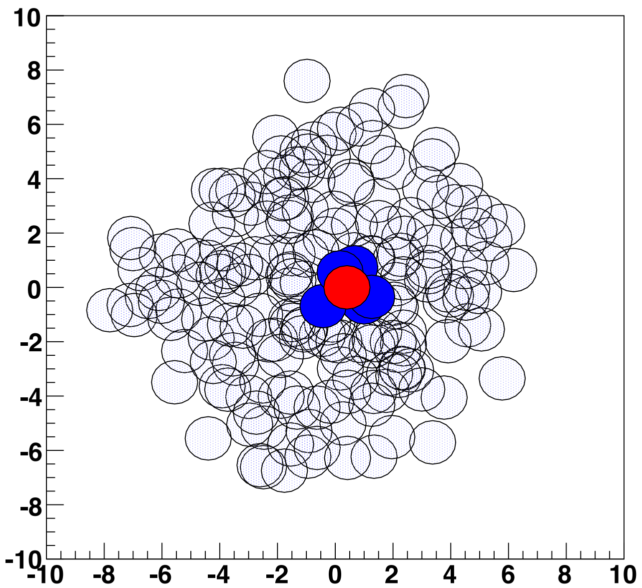
dAu, pPb, AuAu & PbPb



single trend, AA data understood as initial geometry + hydrodynamics

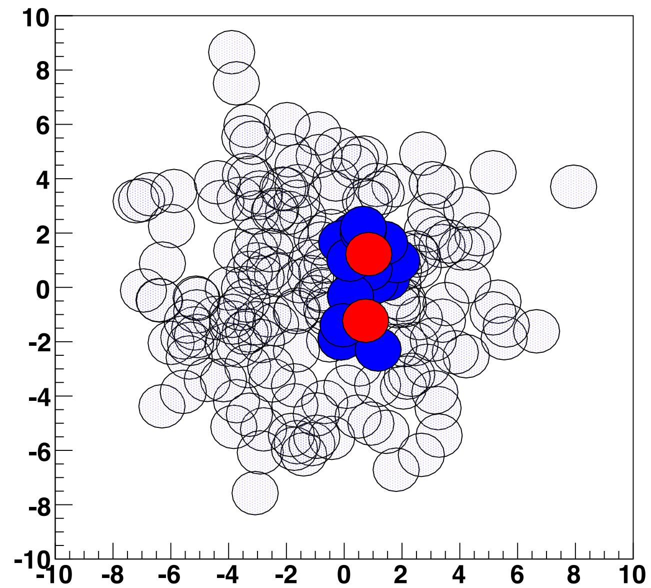
variation of the small nucleus

pA



small ε$_2$

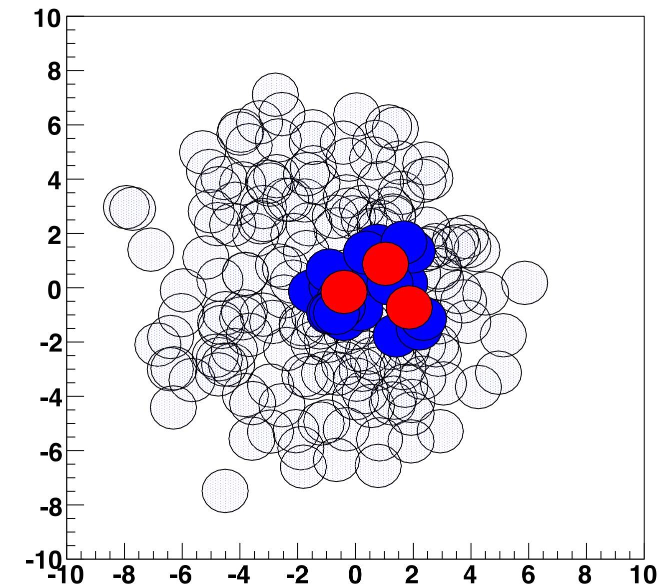
dA



large ε$_2$

small ε3

^{3}HeA

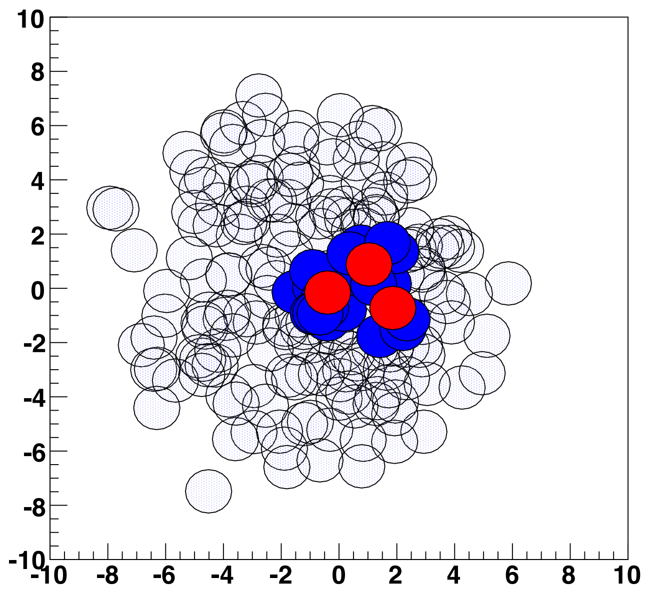


large ε3

$$\varepsilon_n = \frac{\sqrt{\langle r^2 \cos n\phi \rangle^2 + \langle r^2 \sin n\phi \rangle^2}}{\langle r^2 \rangle}$$

control the collision geometry by varying the small nucleus

importance of v_3

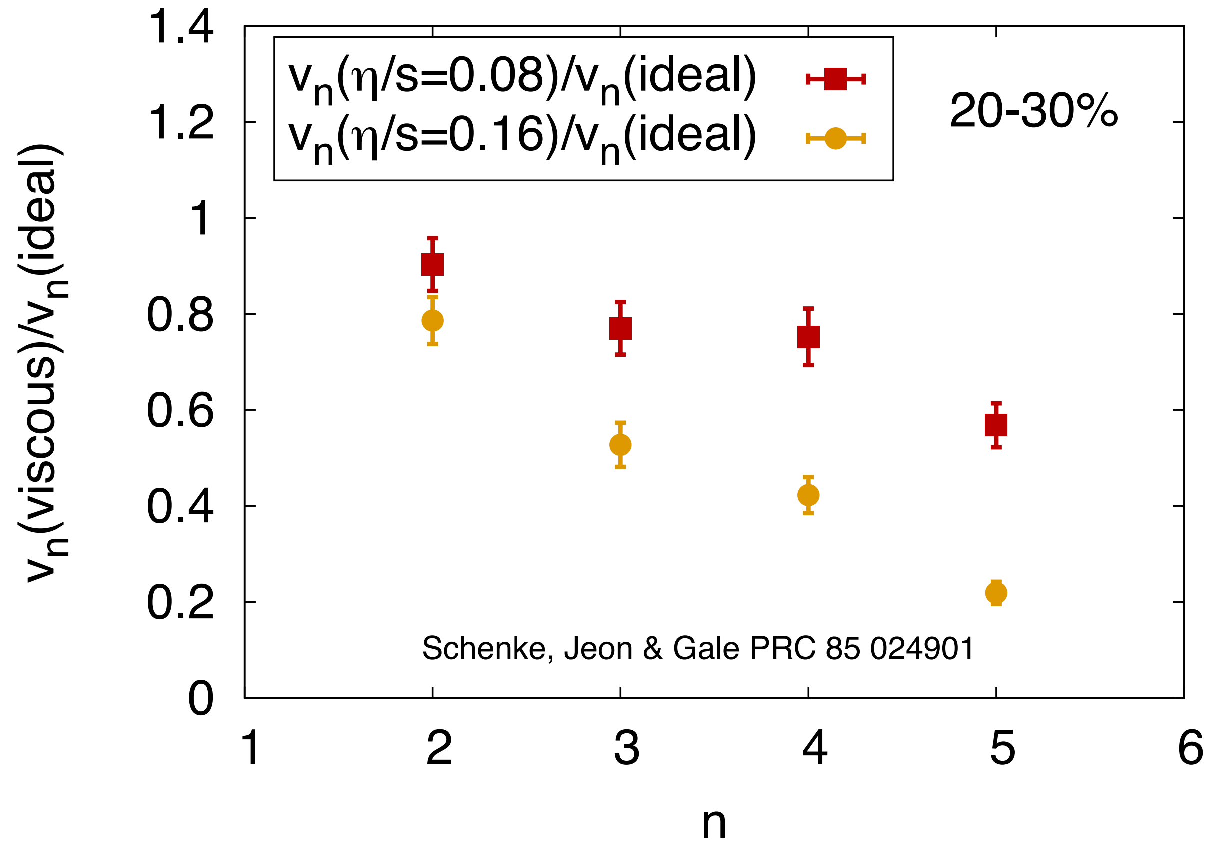


if: $\varepsilon_3 \rightarrow \cos 3\Delta\Phi$ modulation

direct confirmation of hydrodynamic behavior in small systems

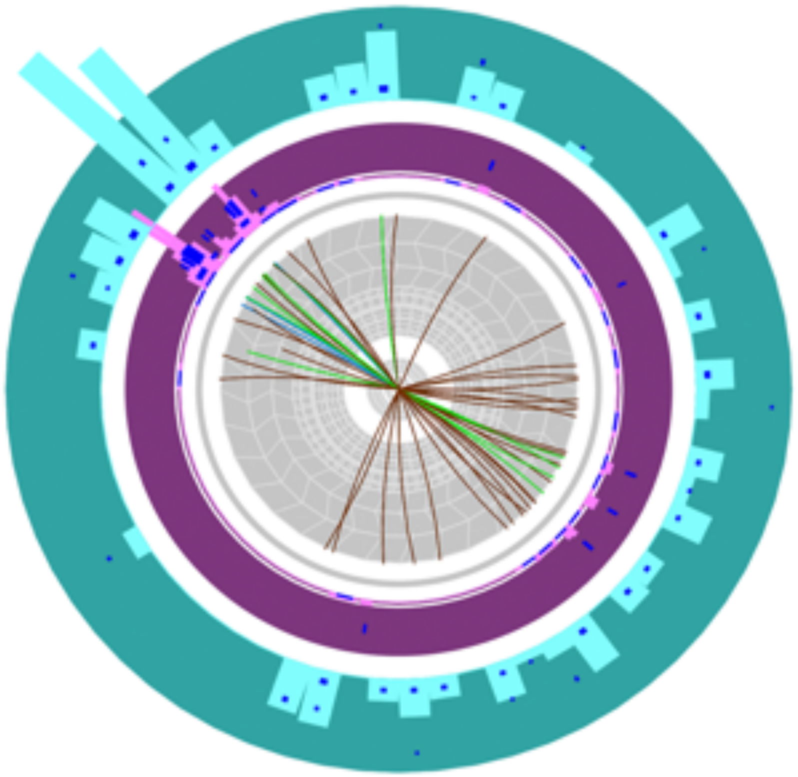
new handle on viscosity

higher moments,
more sensitive to viscous effects

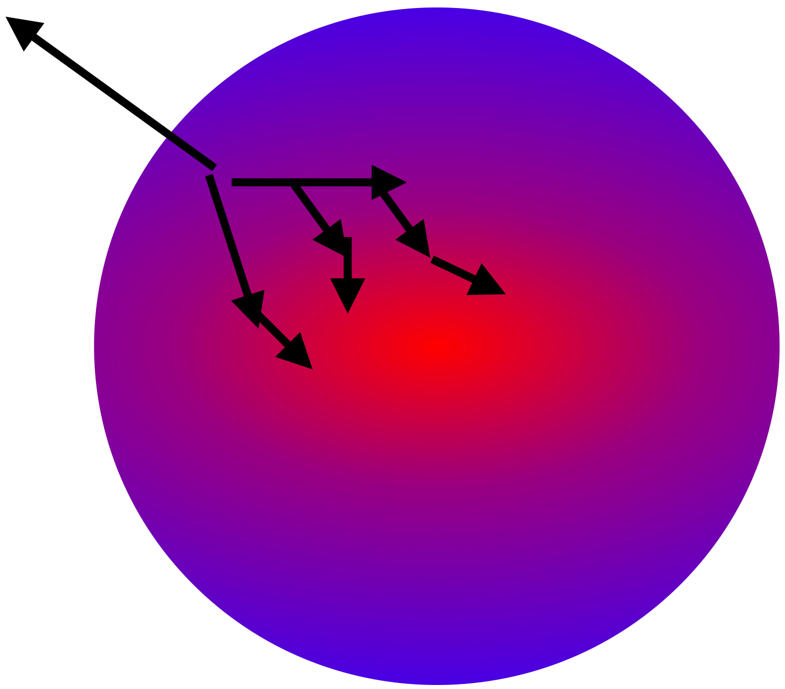


jet quenching

jets act as an external probe of the QGP and lose energy as they go through the matter
quenching is sensitive to the **matter** itself and how **long** the jet is in the matter



ATLAS PRL 105 252303 (2011)

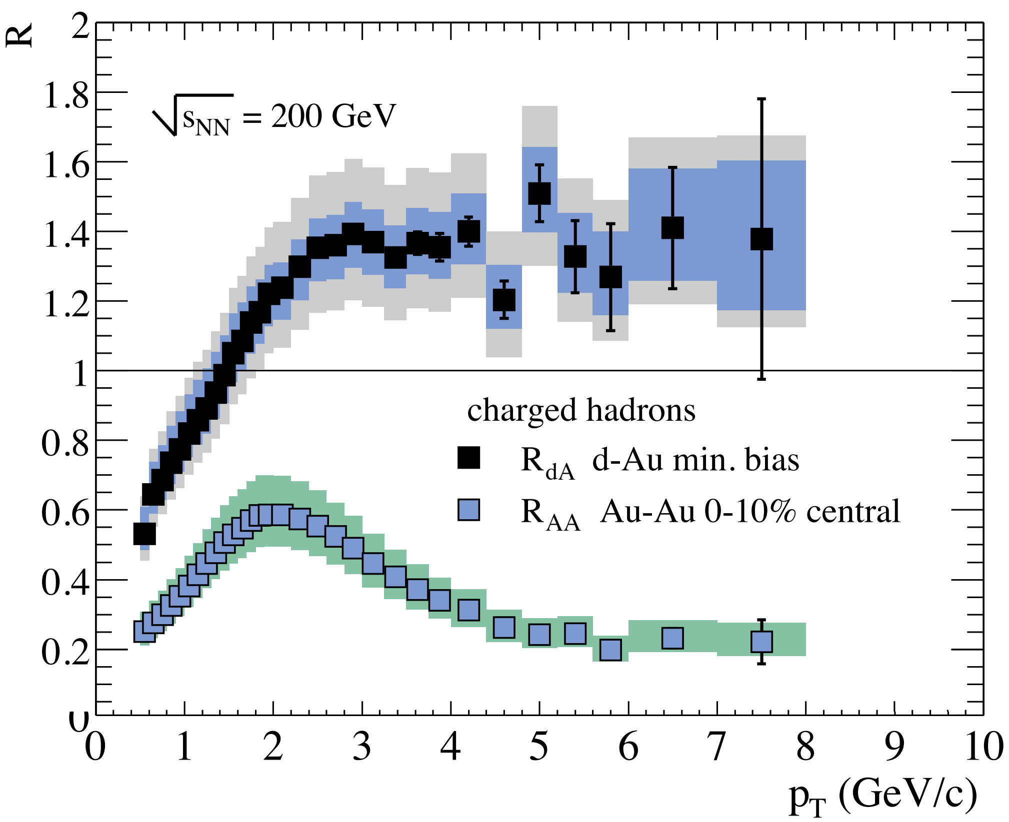


jet quenching

jets act as an external probe of the QGP and lose energy as they go through the matter

quenching is sensitive to the matter itself and how long the jet is in the matter

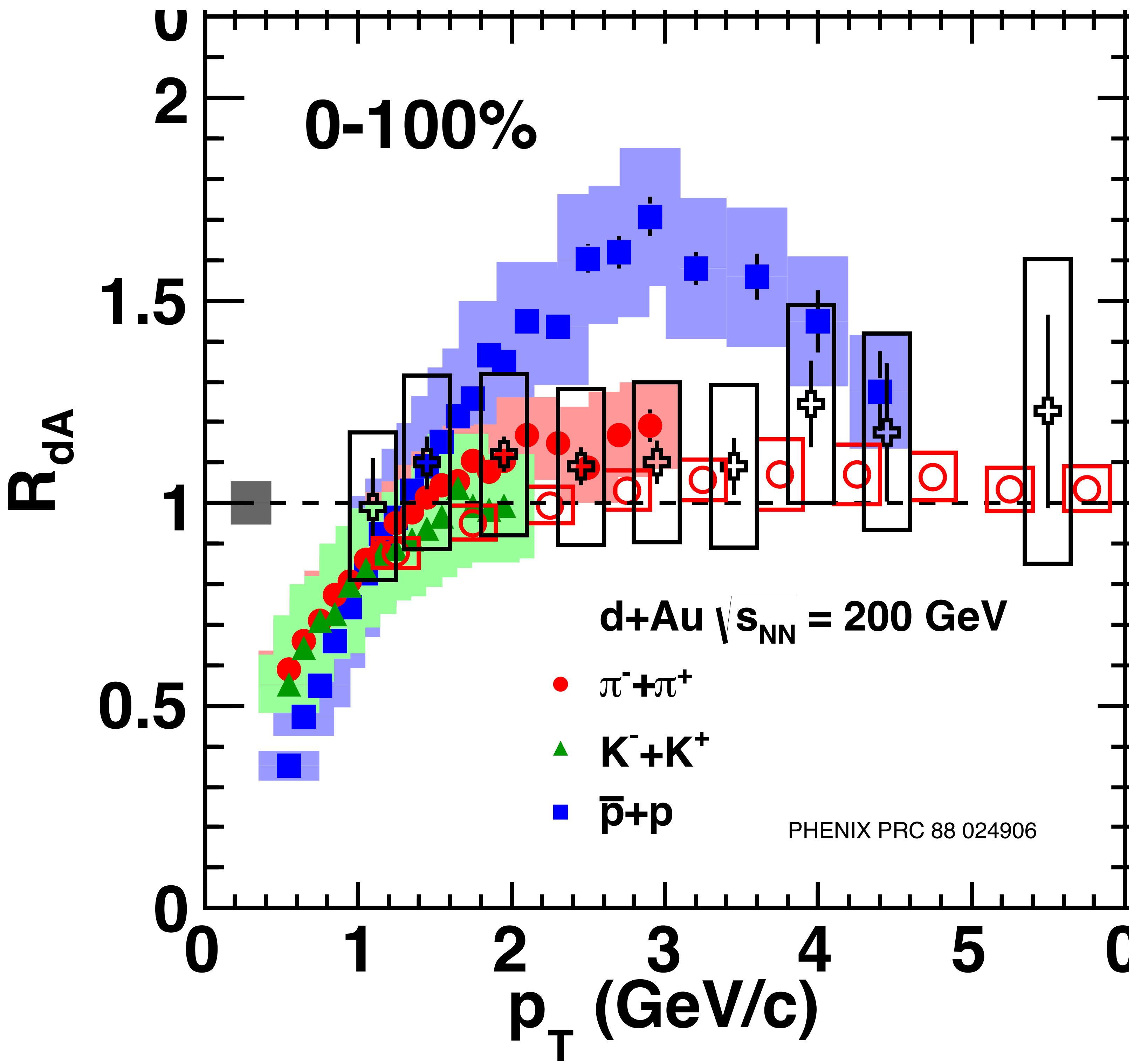
$$R_{AA} = \frac{\text{observed in AA}}{\text{expectation from pp}}$$



dAu:
no quenching

AuAu: quenching

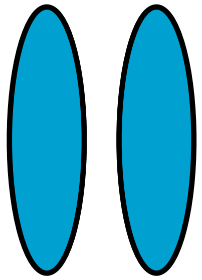
particle species dependence



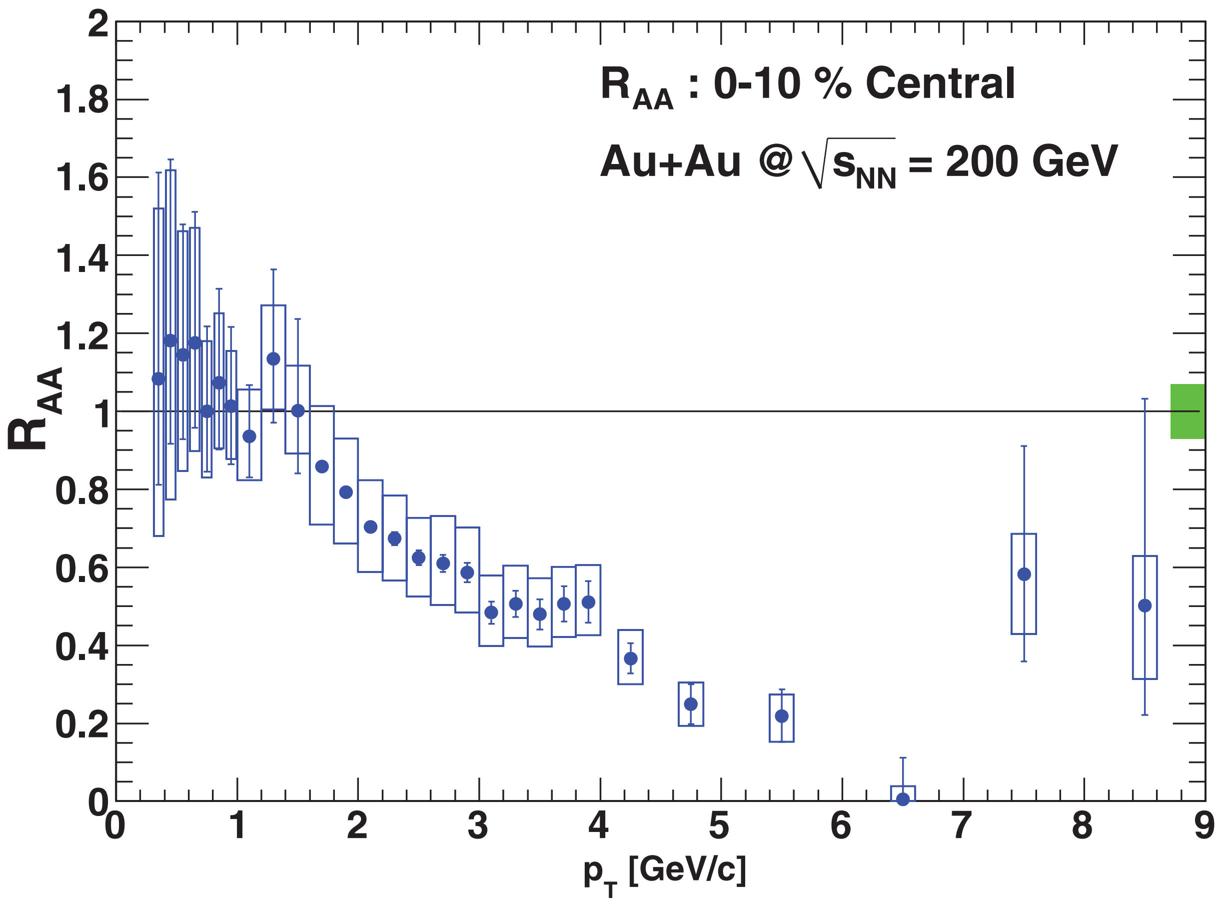
charged hadron enhancement in protons

...and heavy flavor

electrons from heavy flavor decays



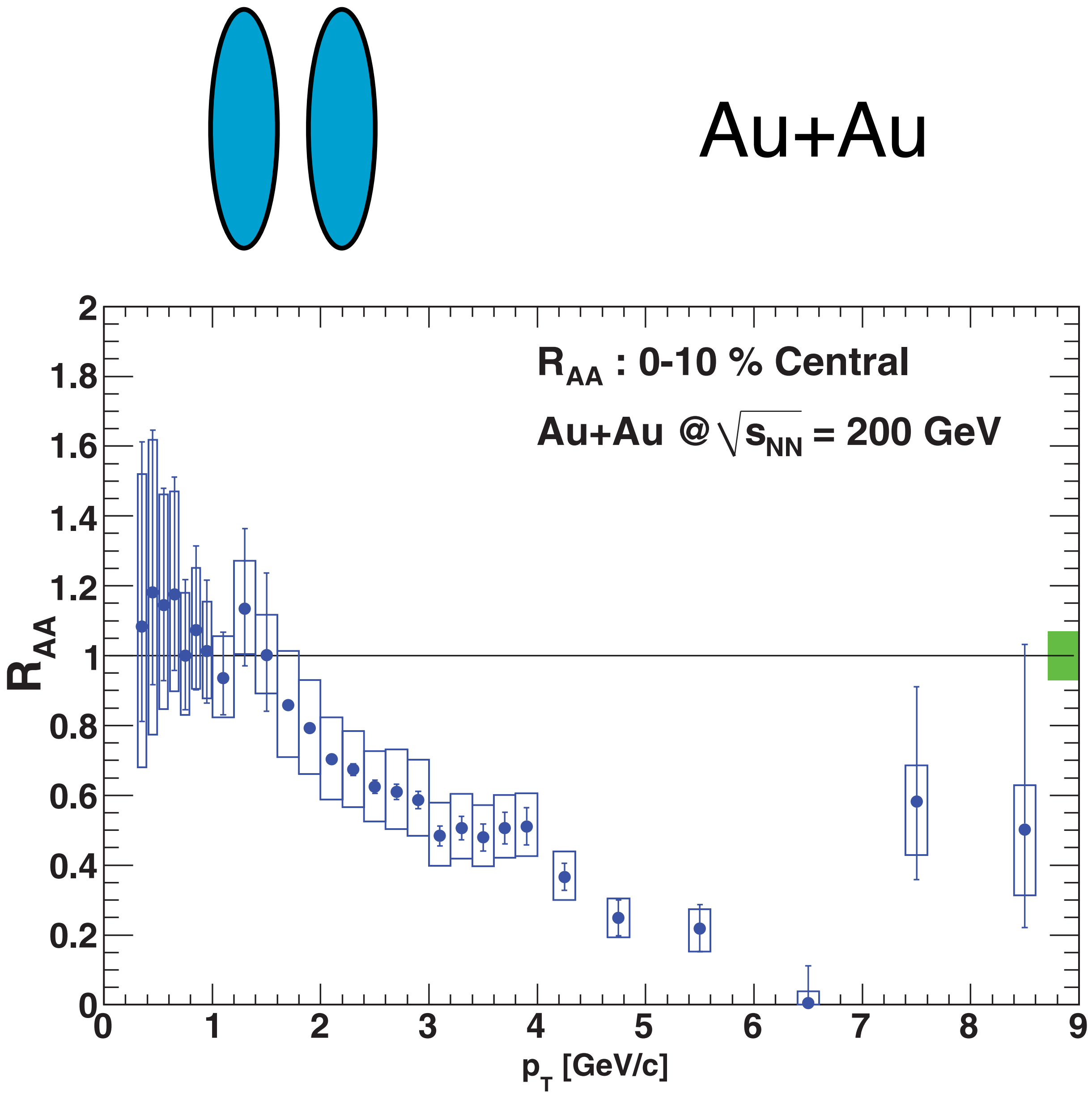
Au+Au

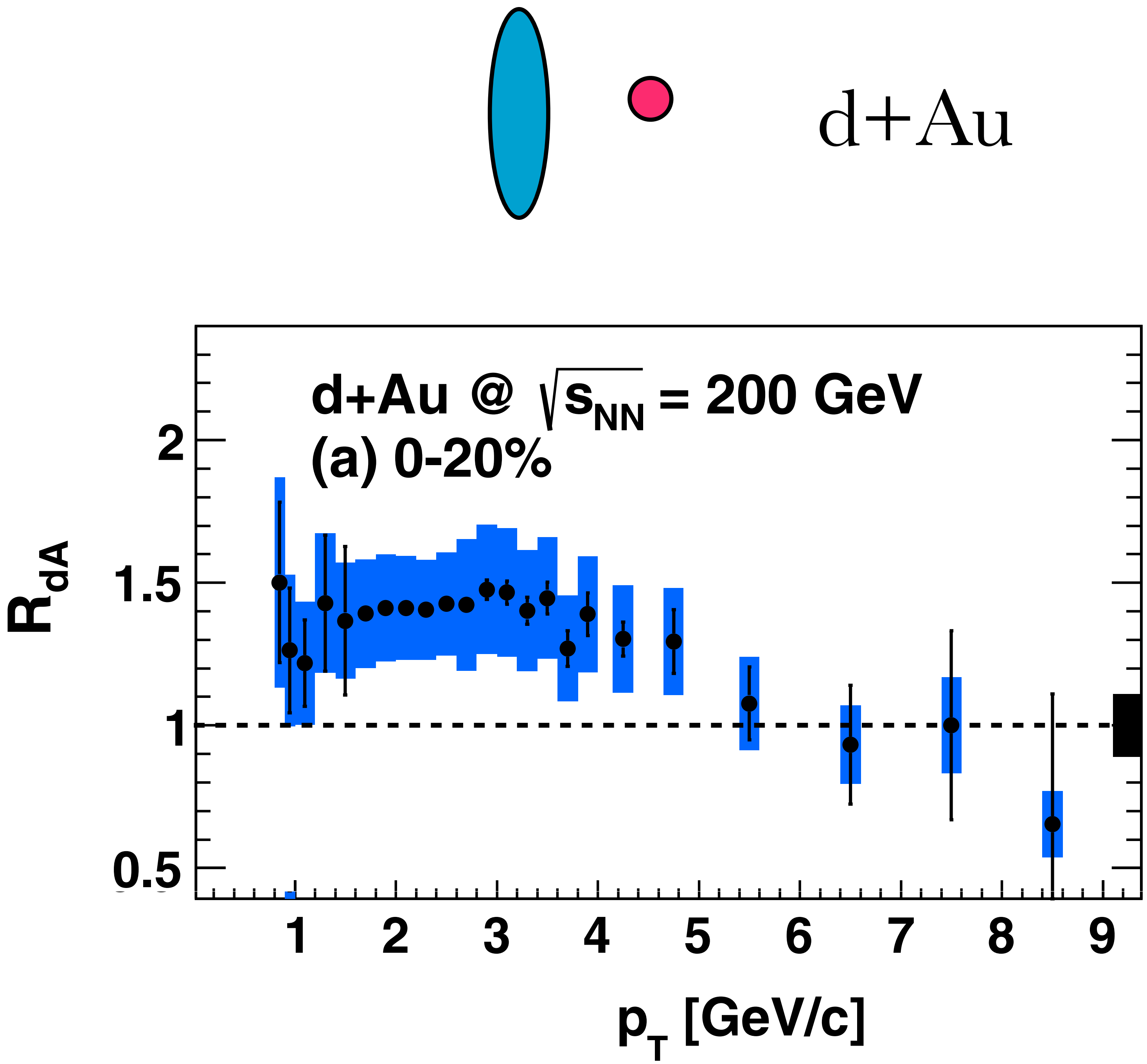


PHENIX PRL 109 242301
PHENIX PRC 84 044905

...and heavy flavor

electrons from heavy flavor decays

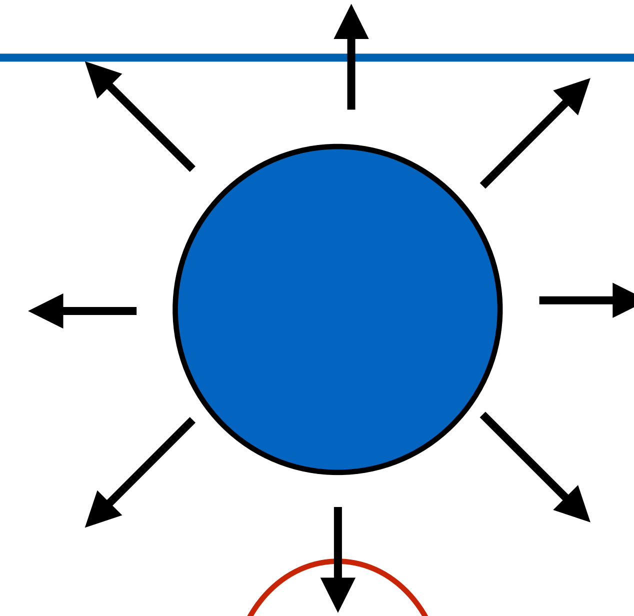




PHENIX PRL 109 242301
PHENIX PRC 84 044905

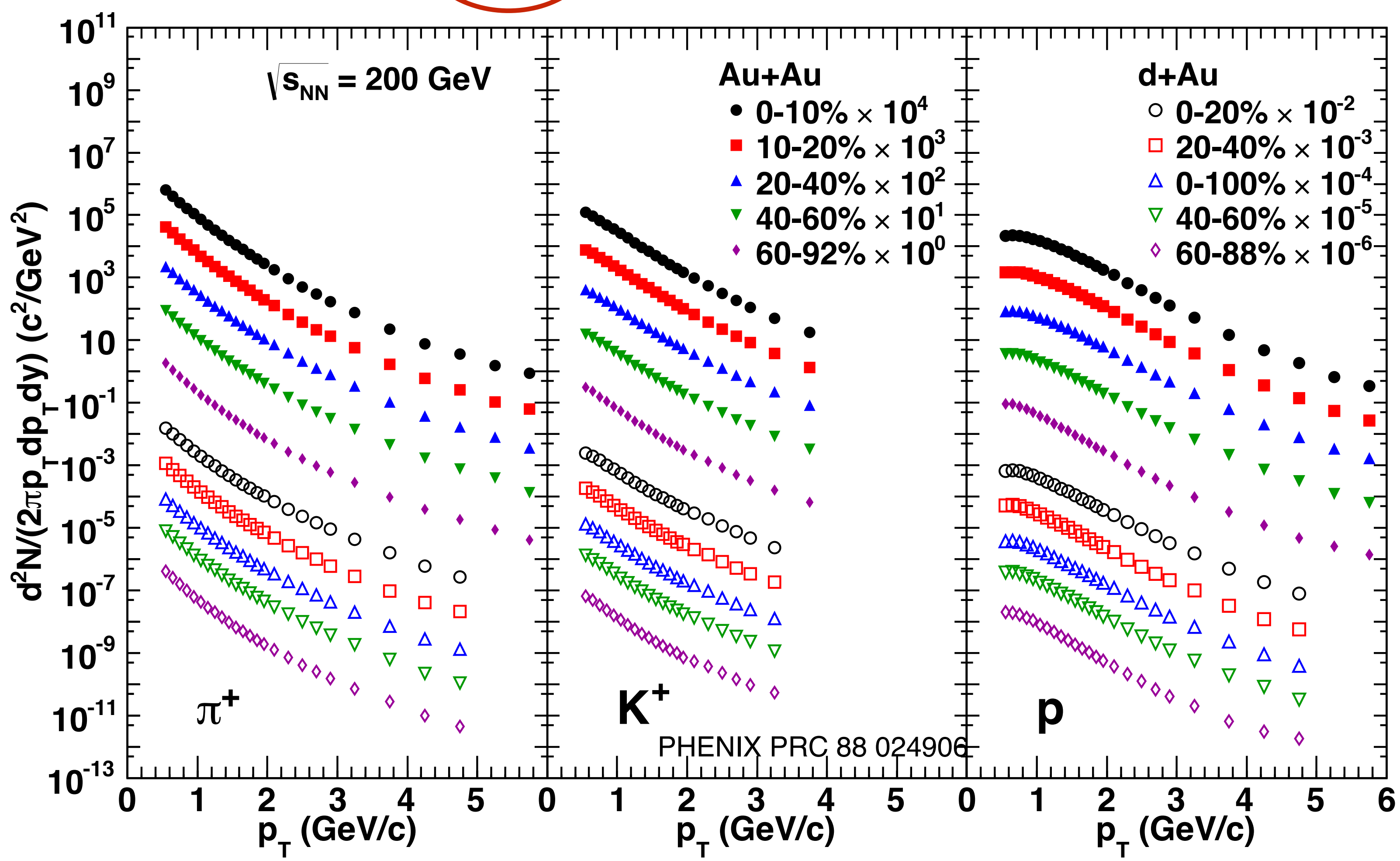
what about radial flow?

the Blast-Wave: outward velocity boost, from a hydrodynamic source

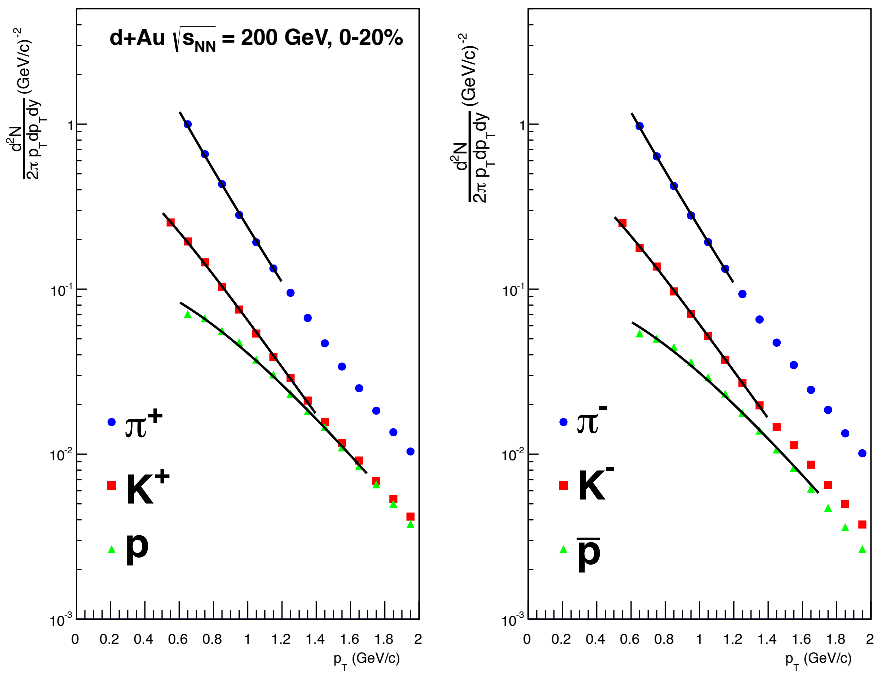


$$\frac{1}{p_T}\frac{dN}{dp_T} \propto \int_0^R r\,dr\,m_T\,I_0\left(\frac{p_T \sinh\rho}{T_{fo}}\right) K_1\left(\frac{m_T \cosh\rho}{T_{fo}}\right) \qquad \rho = \tanh^{-1}(\beta_{max}(r/R)^n)$$

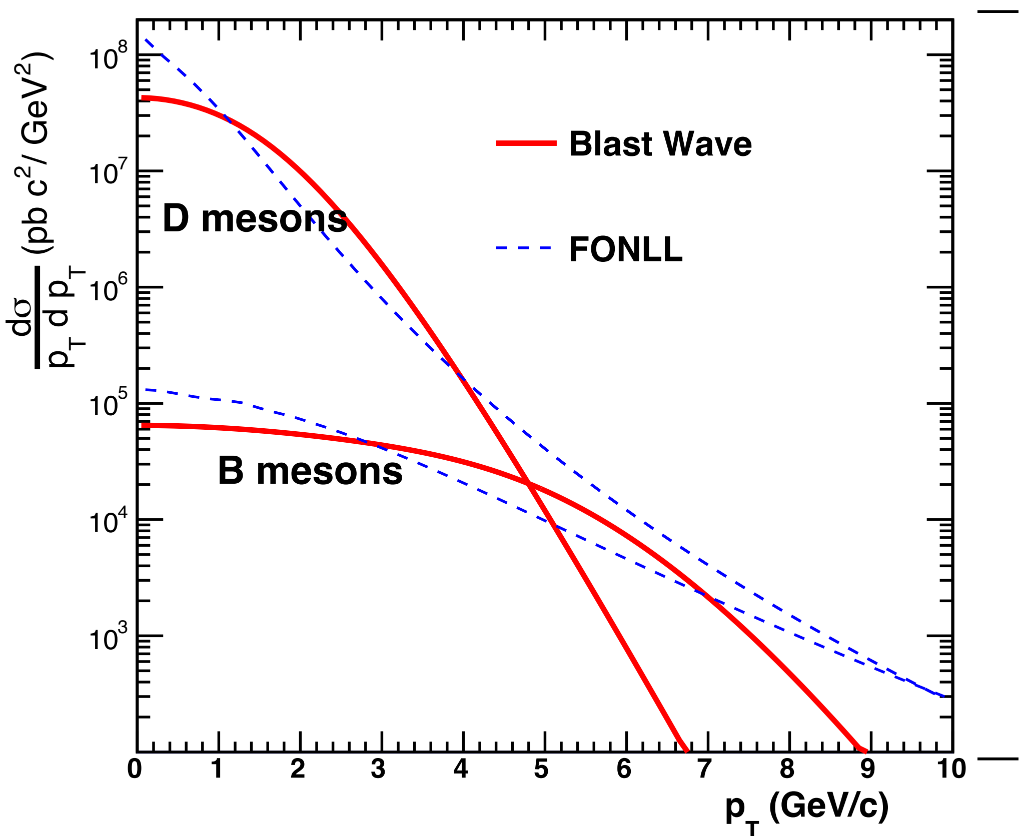
Schnedermann, Sollfrank, & Heinz PRC48 2462 (1993)

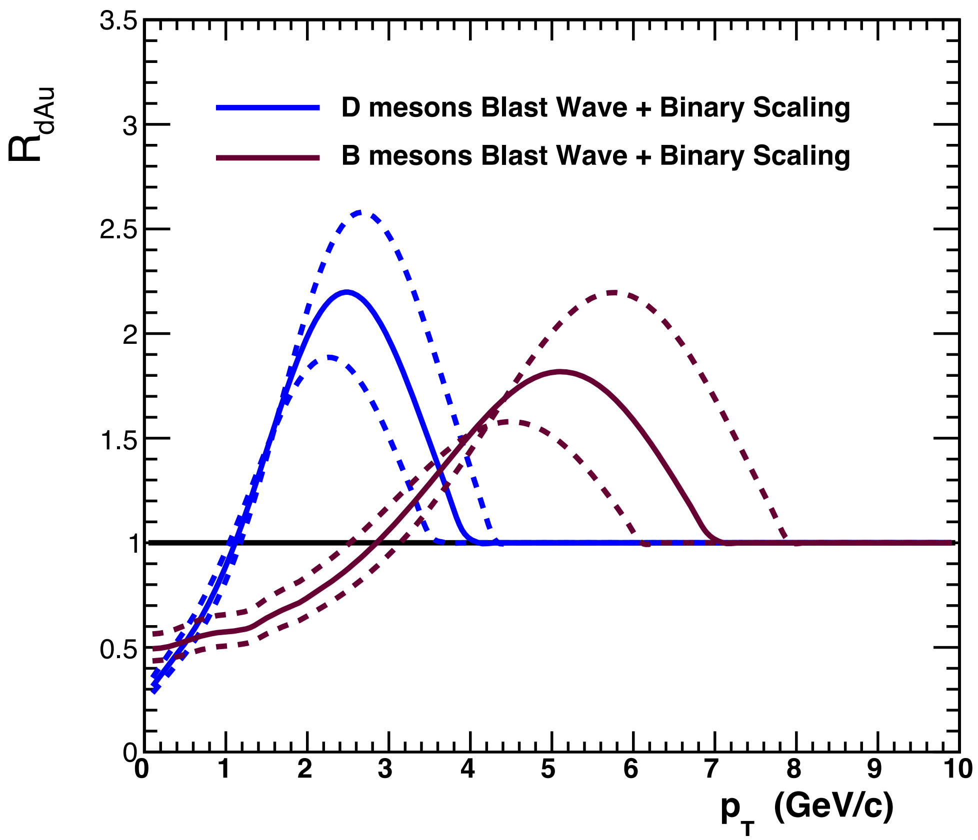


blast-wave fit to dAu data



0-20% d+Au
simultaneous fit to π, K, p
$\beta_{max} = 0.70$
T_{fo} = 139MeV

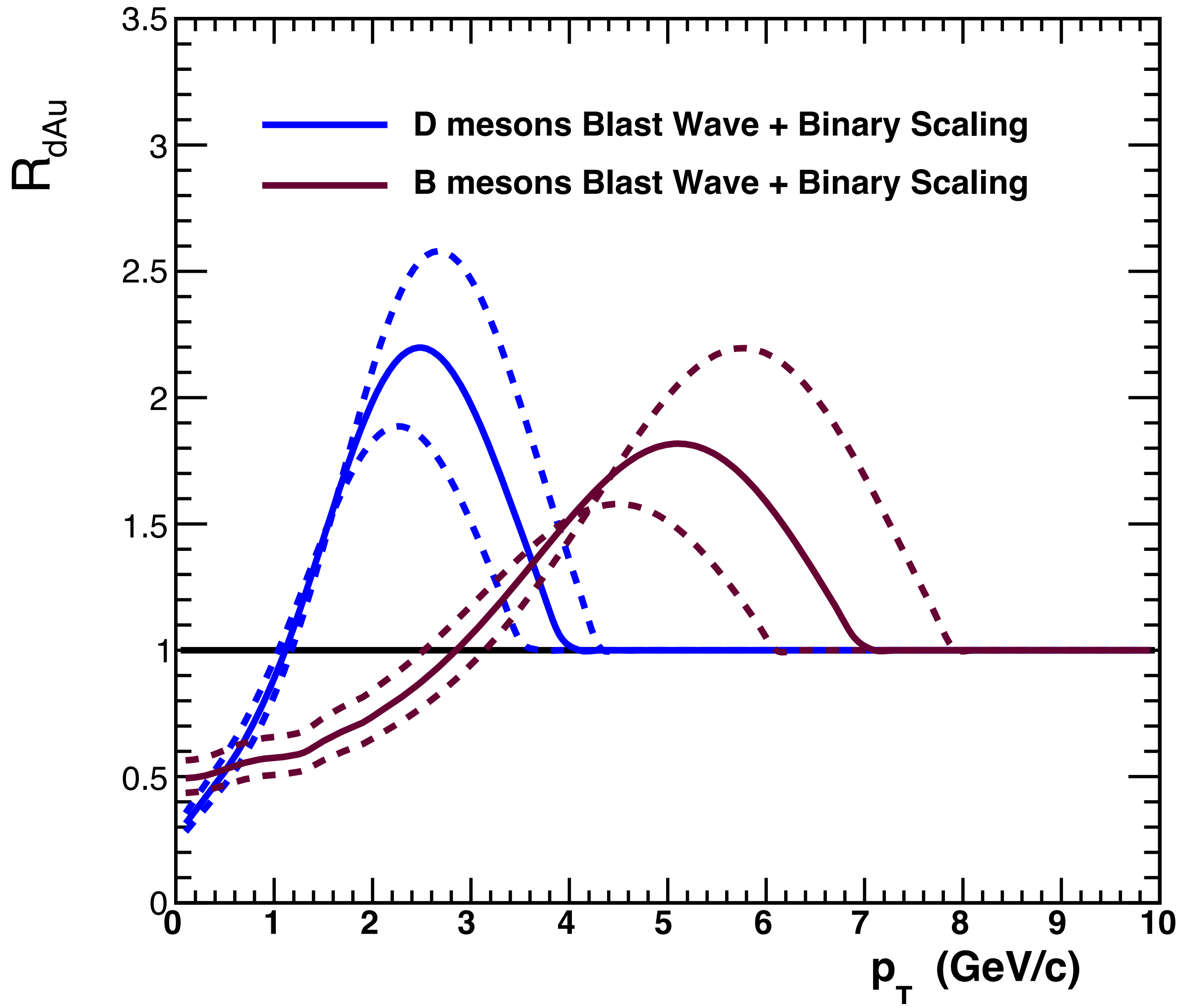


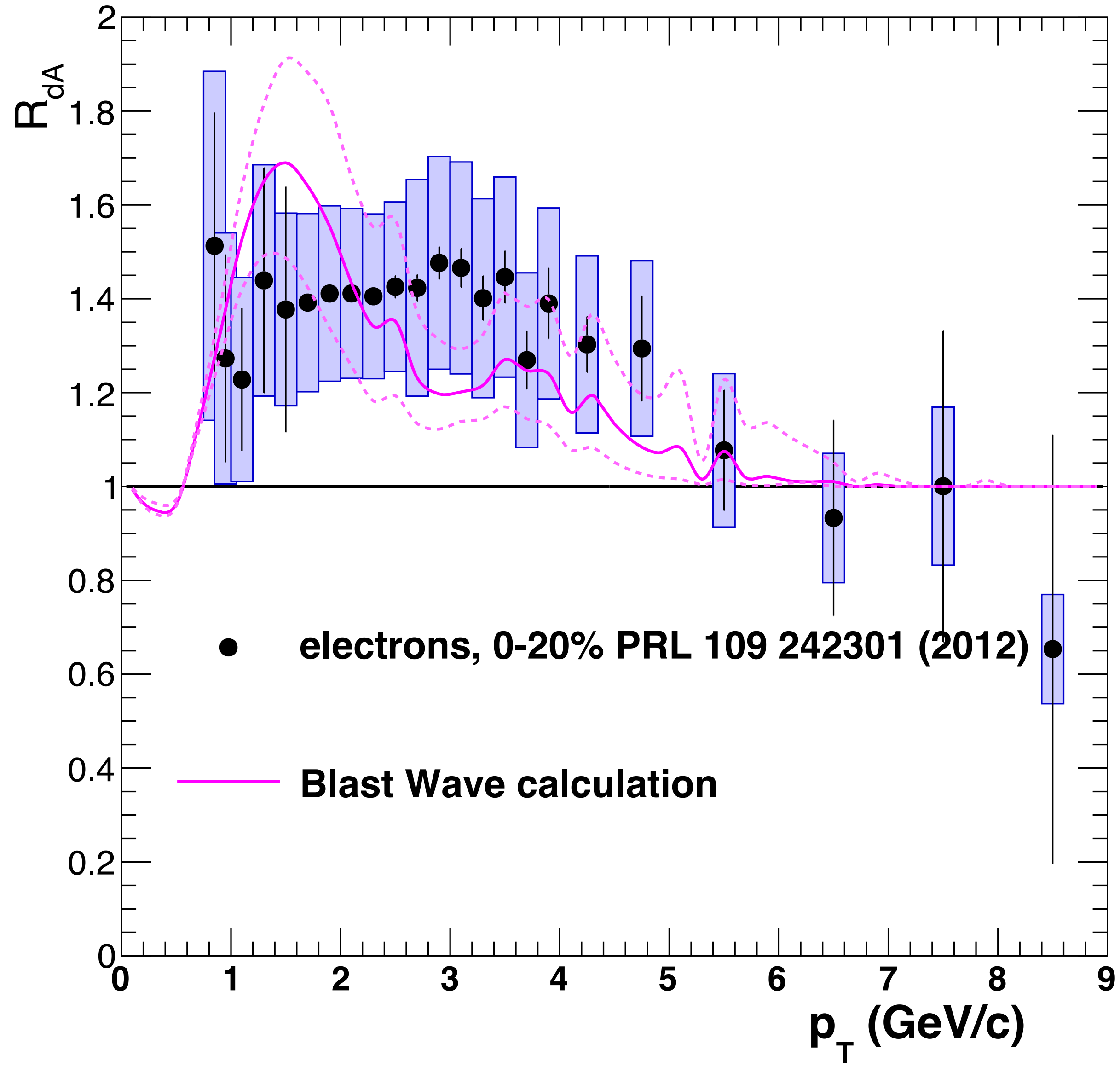


large enhancement of heavy mesons!

data: PHENIX PRC 88 024906
AMS: PLB 731 51 (2014)

and for the electrons?





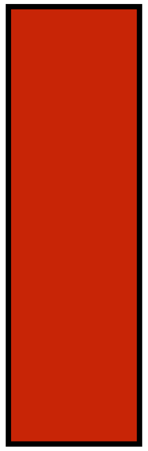
another flow effect?

charm and bottom separated measurements key to clarifying

data: PHENIX PRL 109 242301
AMS: PLB 731 51 (2014)

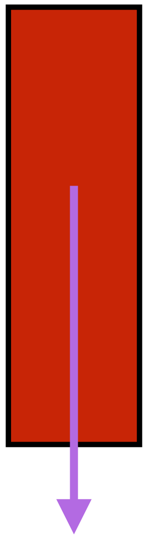
jets in dAu

AA collisions: quenching depends on L



jets in dAu

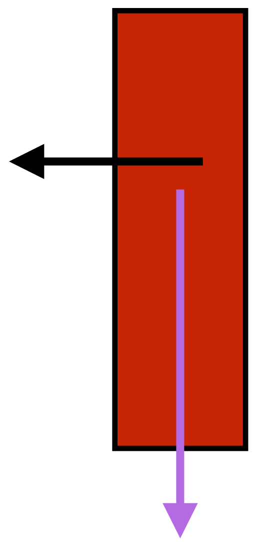
AA collisions: quenching depends on L



a lot of quenching

jets in dAu

AA collisions: quenching depends on L

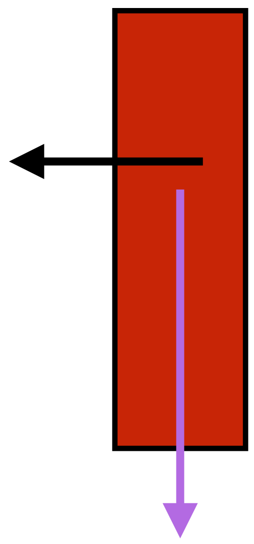


a little quenching

a lot of quenching

jets in dAu

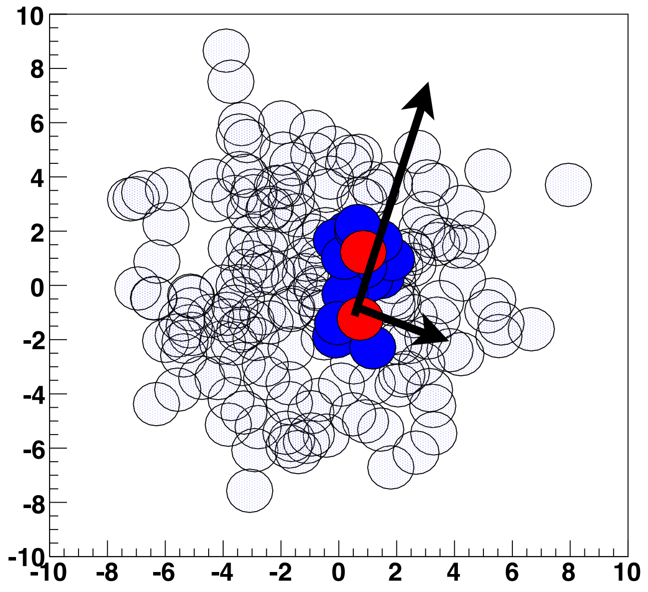
AA collisions: quenching depends on L



a little quenching

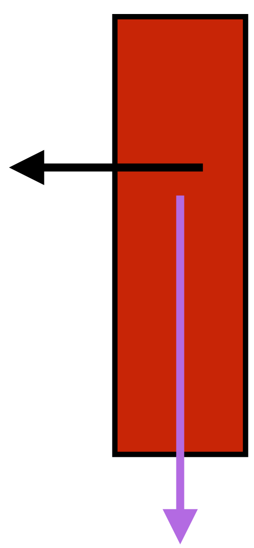
a lot of quenching

could something similar happen in dA?



jets in dAu

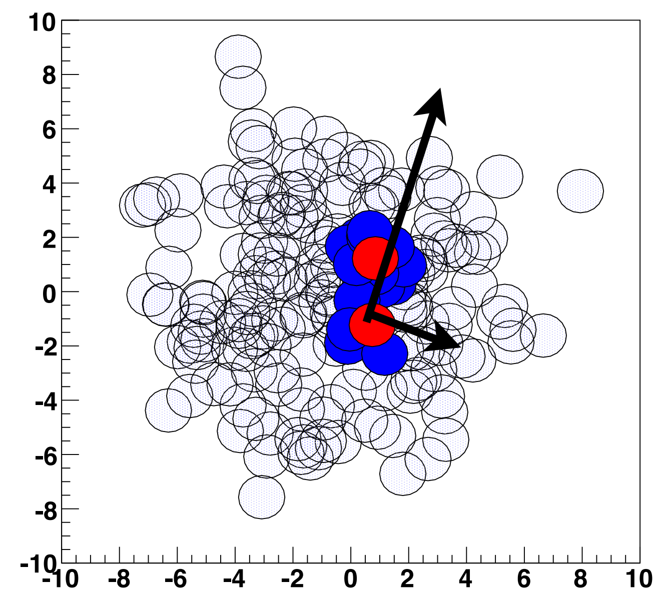
AA collisions: quenching depends on L



a little quenching

a lot of quenching

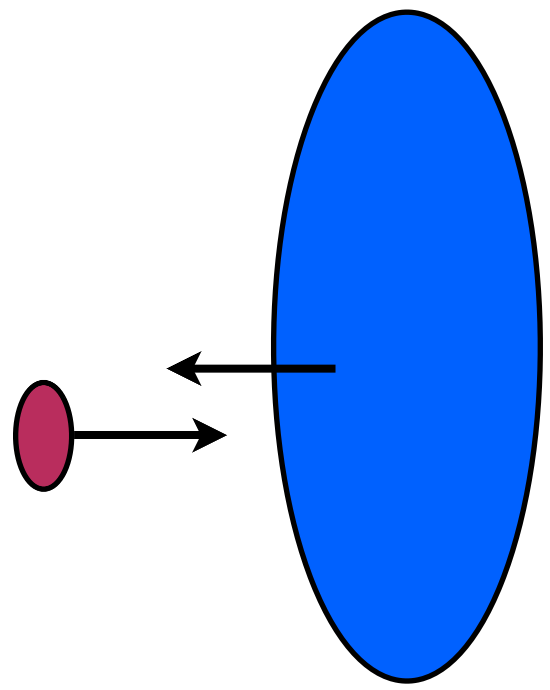
could something similar happen in dA?



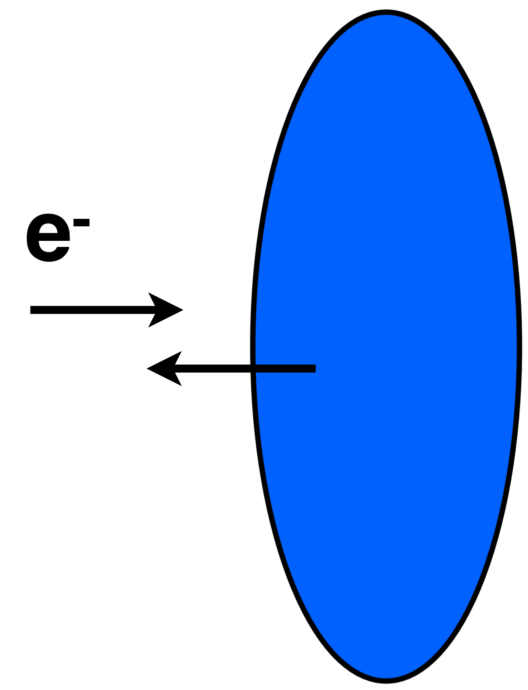
geometrical dependence might be observable **even though we know the overall level of quenching is small in dAu**

recent calculations (Zhang & Liao, 1311.5463), show **~10x** bigger effect in dAu than pPb

investigating initial state of the nucleus?



investigating initial state of the nucleus?



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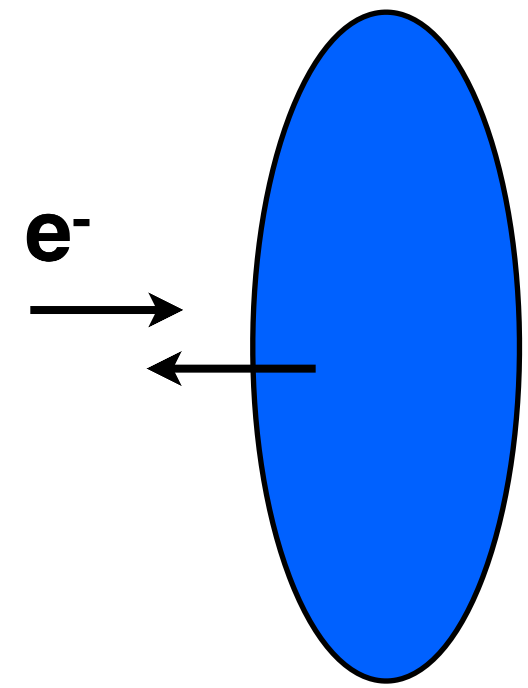
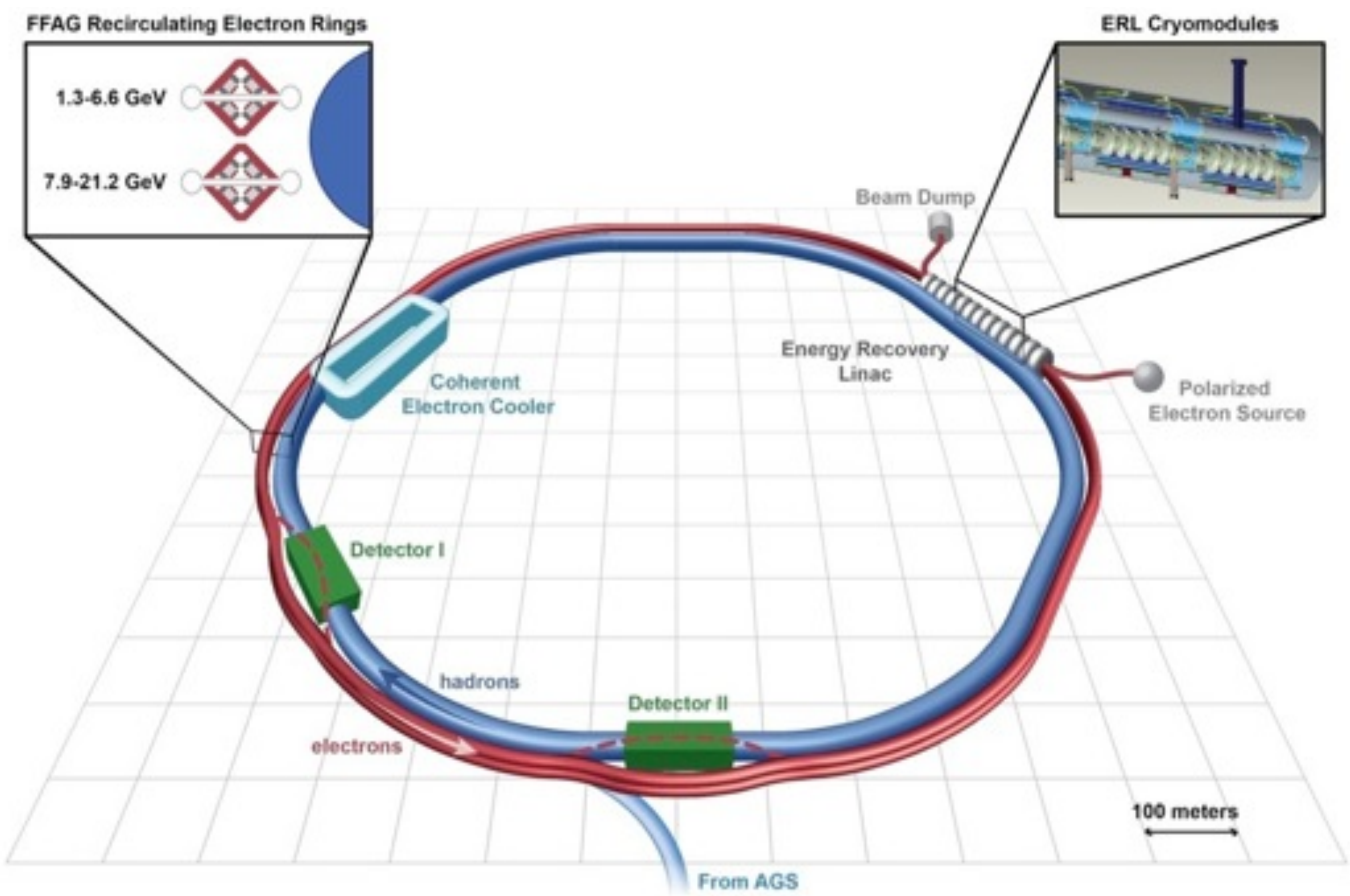


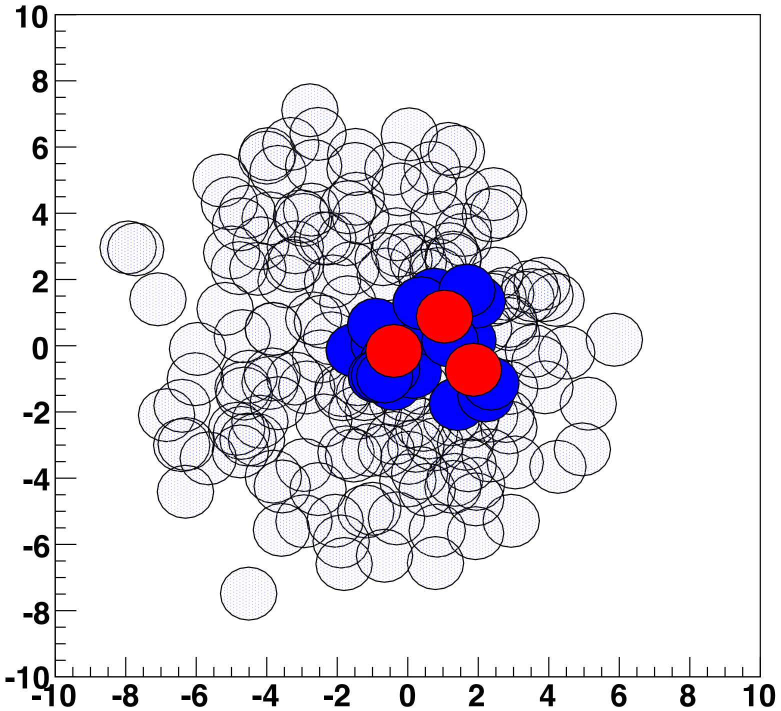


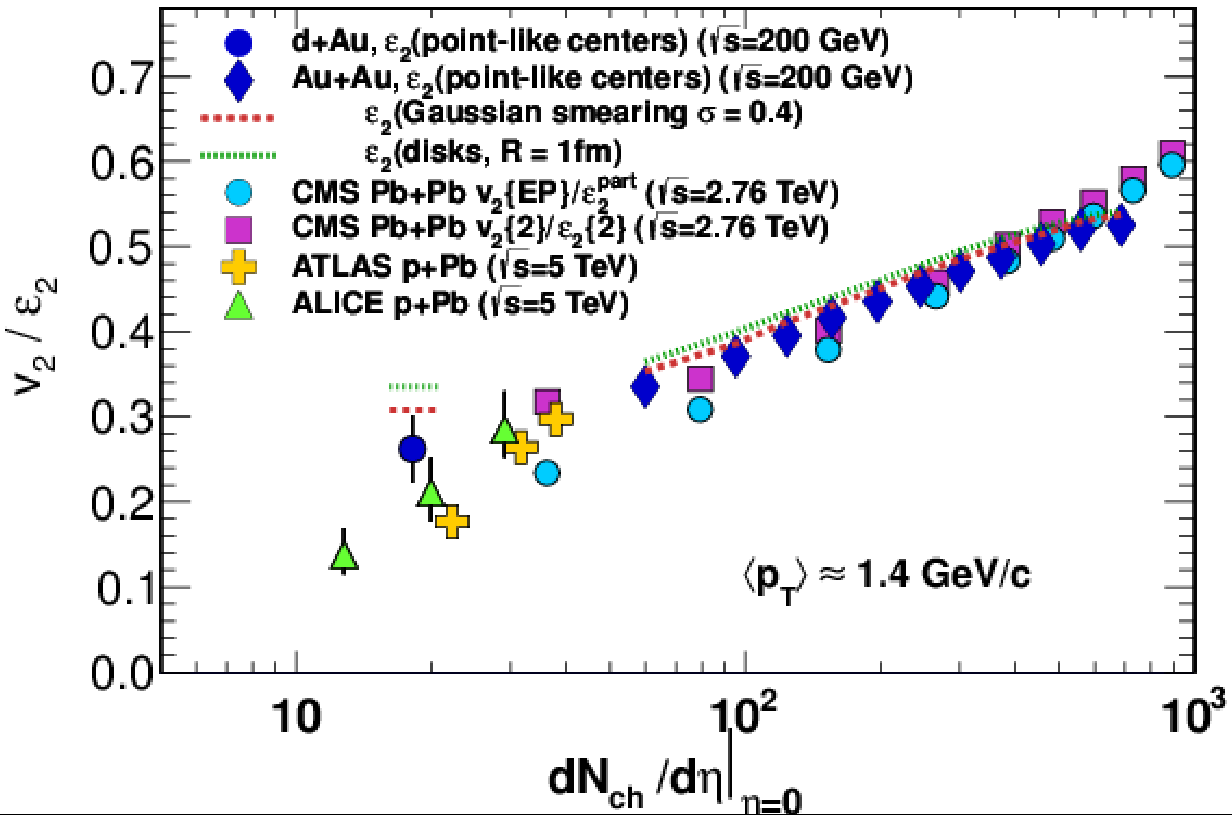
eRHIC

upgrade to allow electrons at RHIC timescale ~ 2025

pushing the limits of the QGP

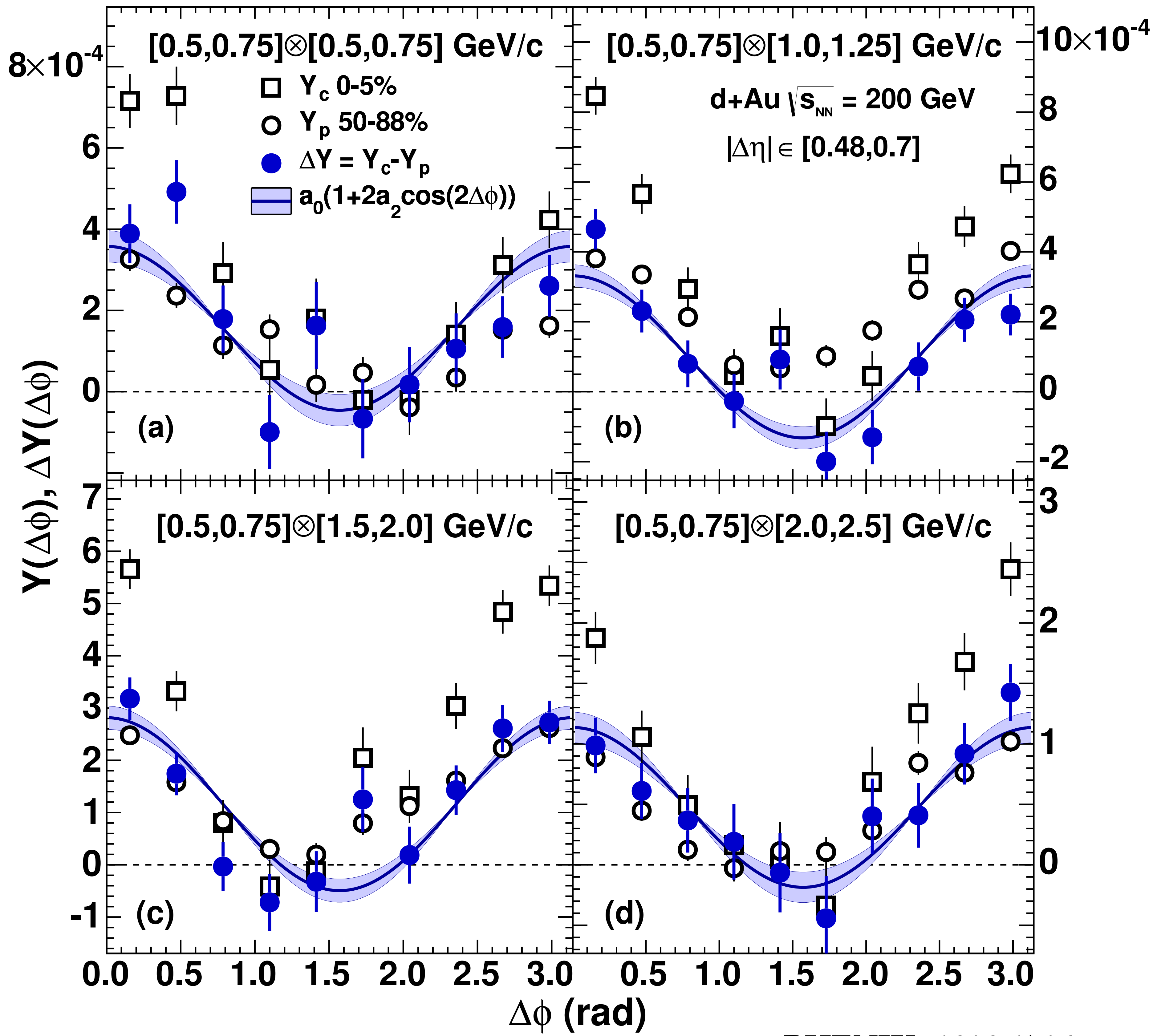
- RHIC and the LHC are pushing the size limits of the quark gluon plasma
  - suggestive of evolution, rather than a transition, from big to small systems
  - looking forward to new measurements very soon to support/challenge this interpretation and quantitative understanding





- backups

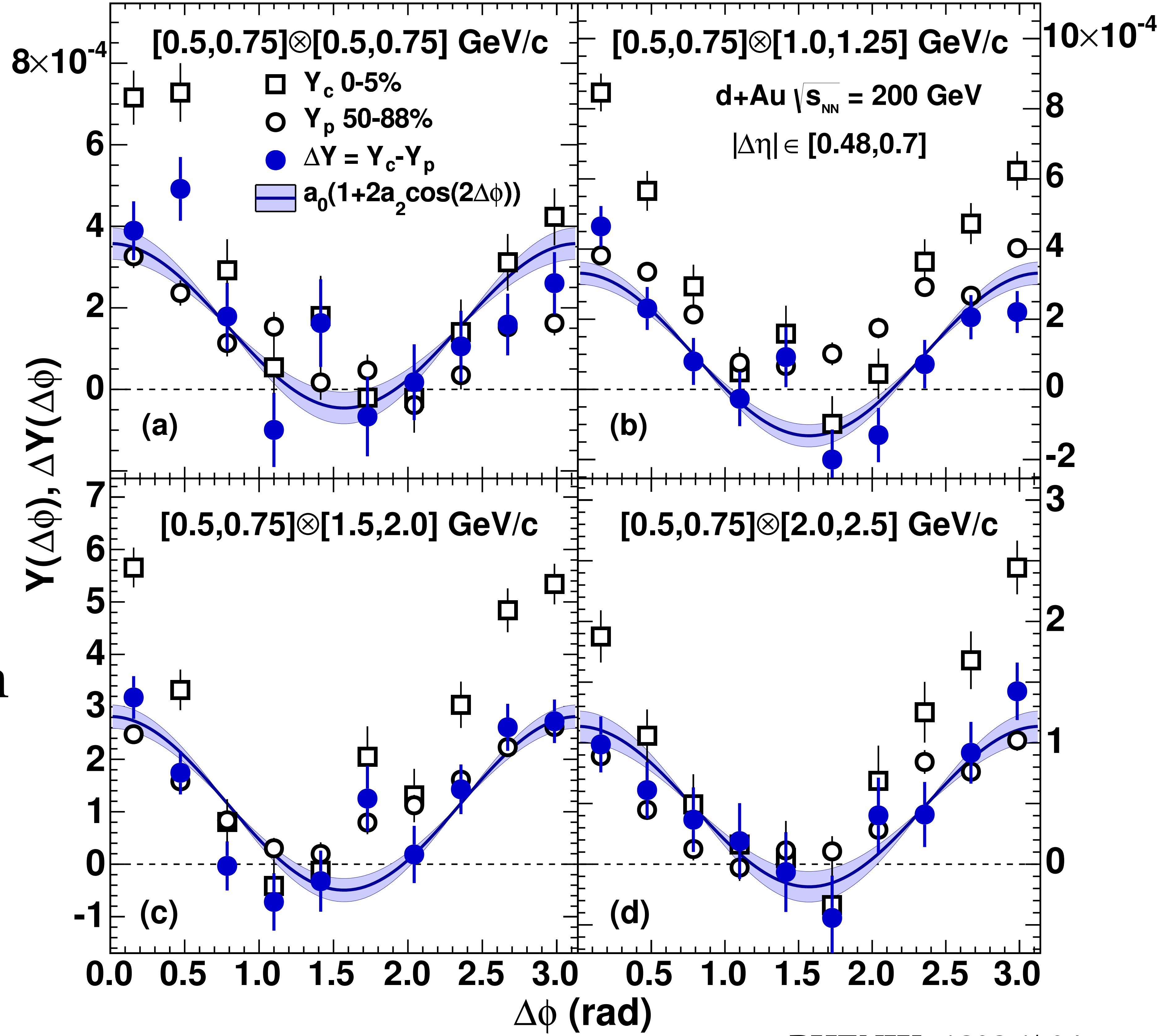
centrality dependence consistently described by cos2Δφ shape evidence for double ridge



PHENIX: 1303.1794

centrality dependence consistently described by cos2Δϕ shape evidence for double ridge

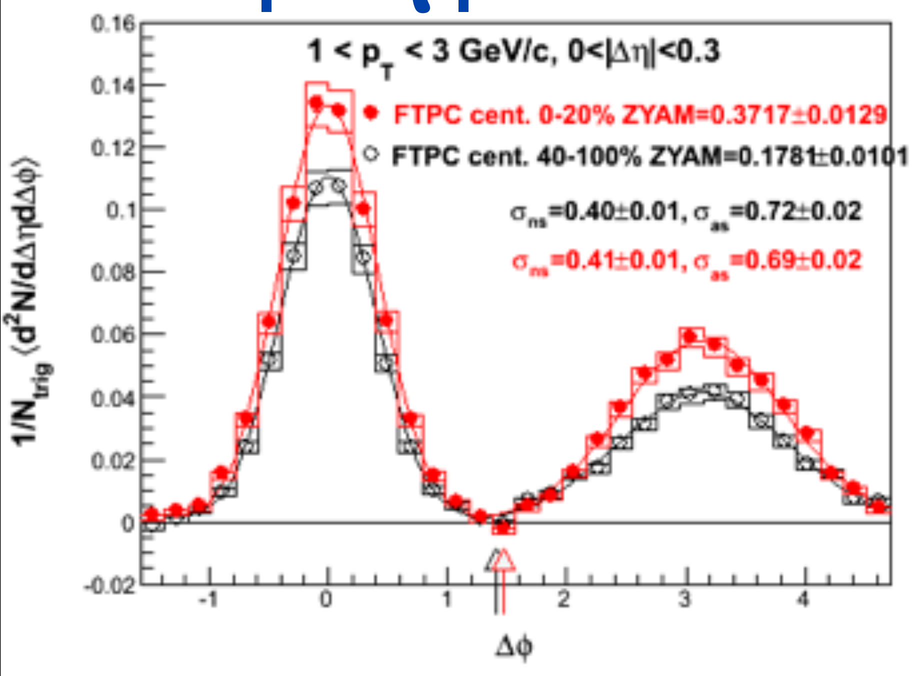
but is this just an artifact of the small |Δη| acceptance?



PHENIX: 1303.1794

results from STAR

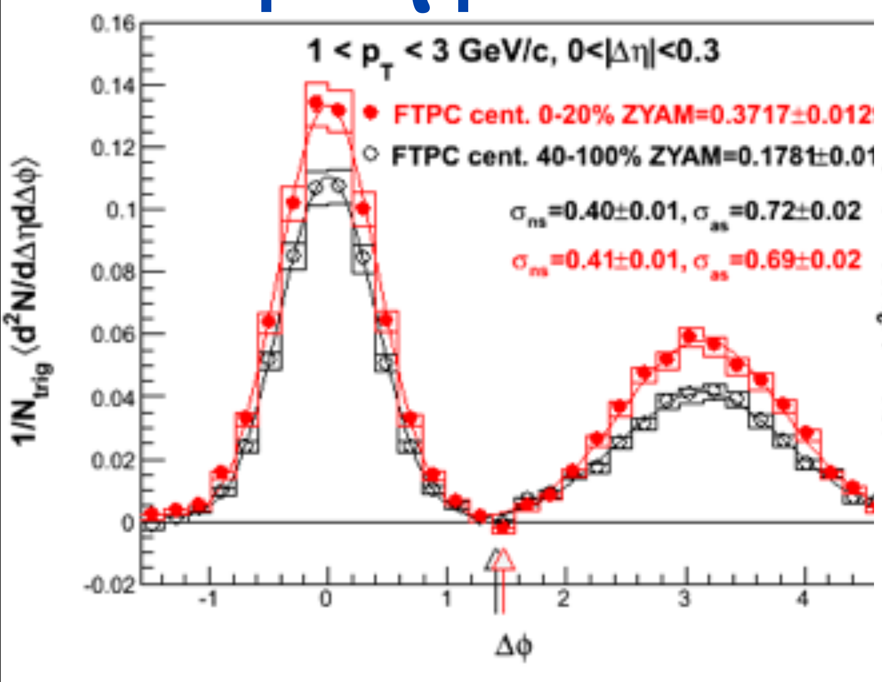
|Δη|<0.3

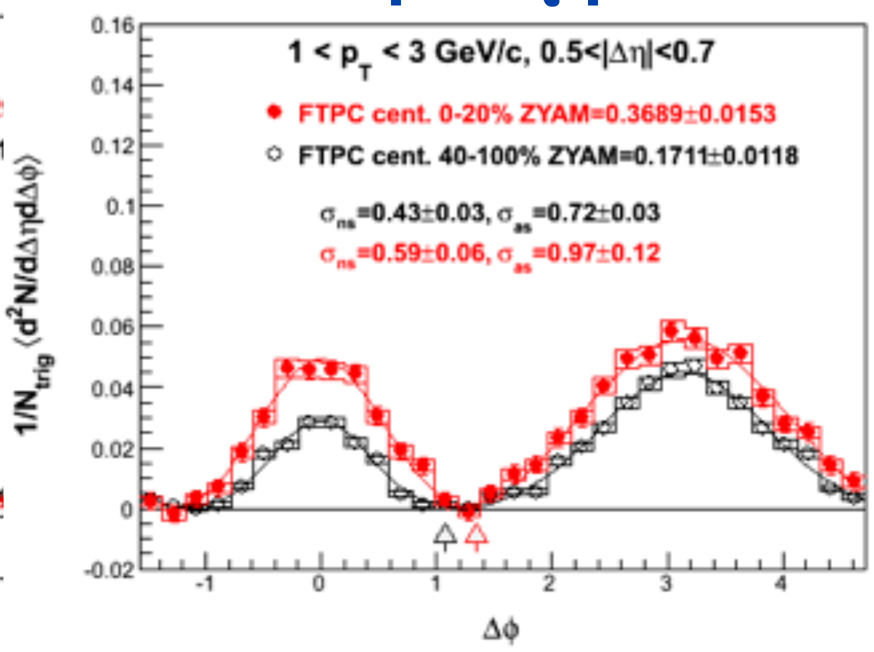


F. Wang IS2013

results from STAR

|Δη|<0.3 **0.5<|Δη|<0.7**

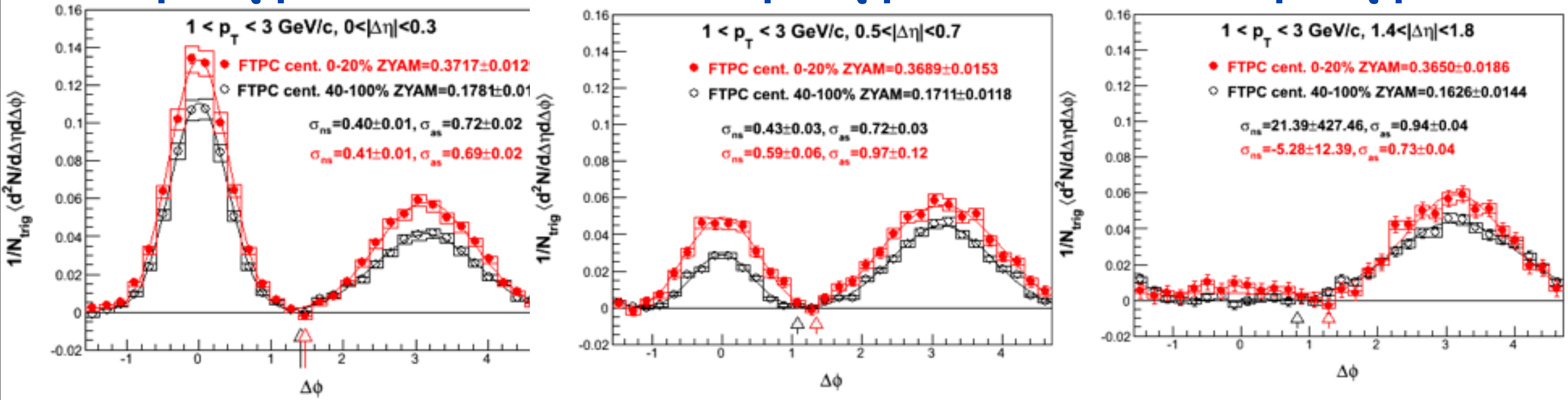




F. Wang IS2013

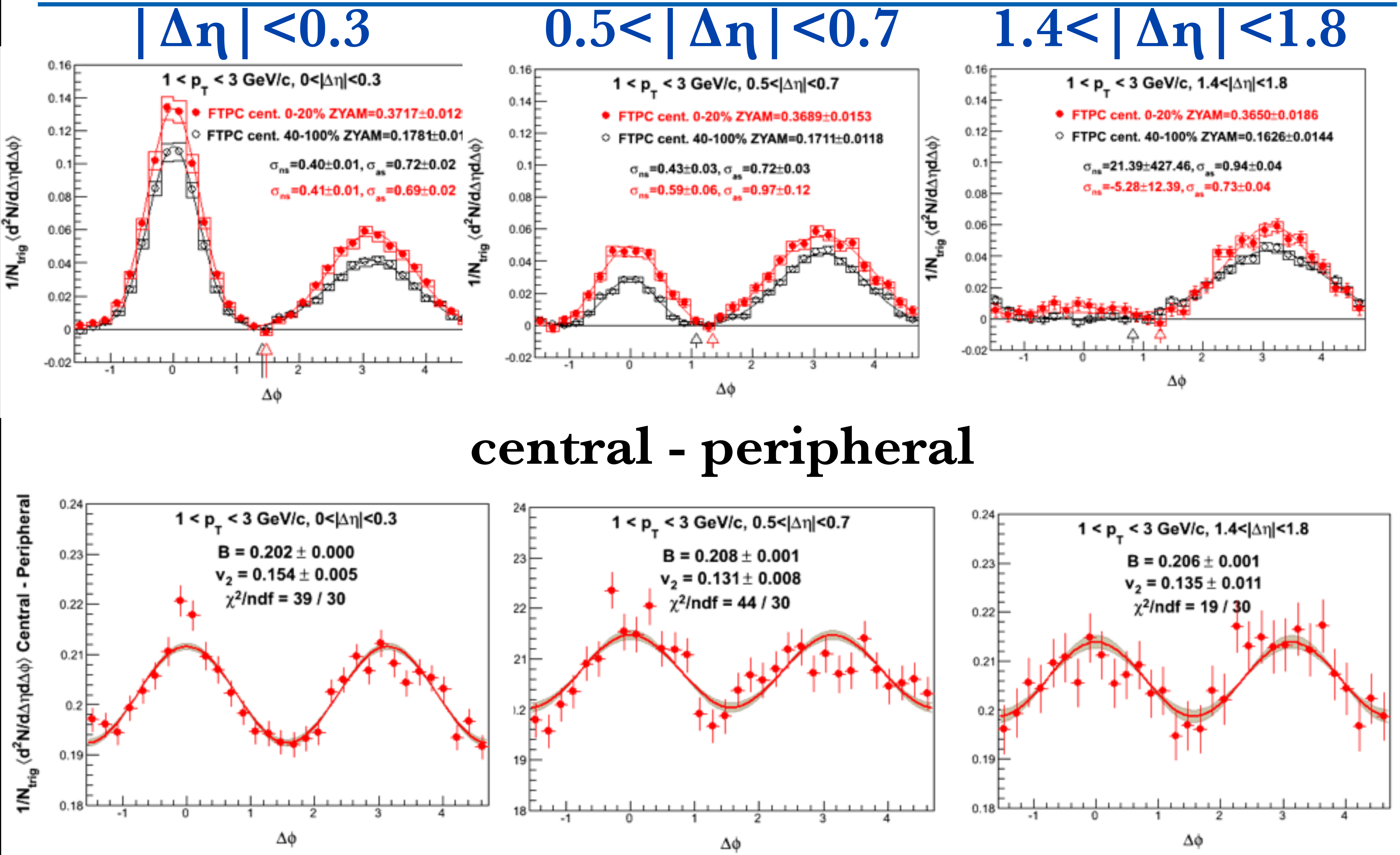
results from STAR

|Δη|<0.3 **0.5<|Δη|<0.7** **1.4<|Δη|<1.8**



F. Wang IS2013

results from STAR



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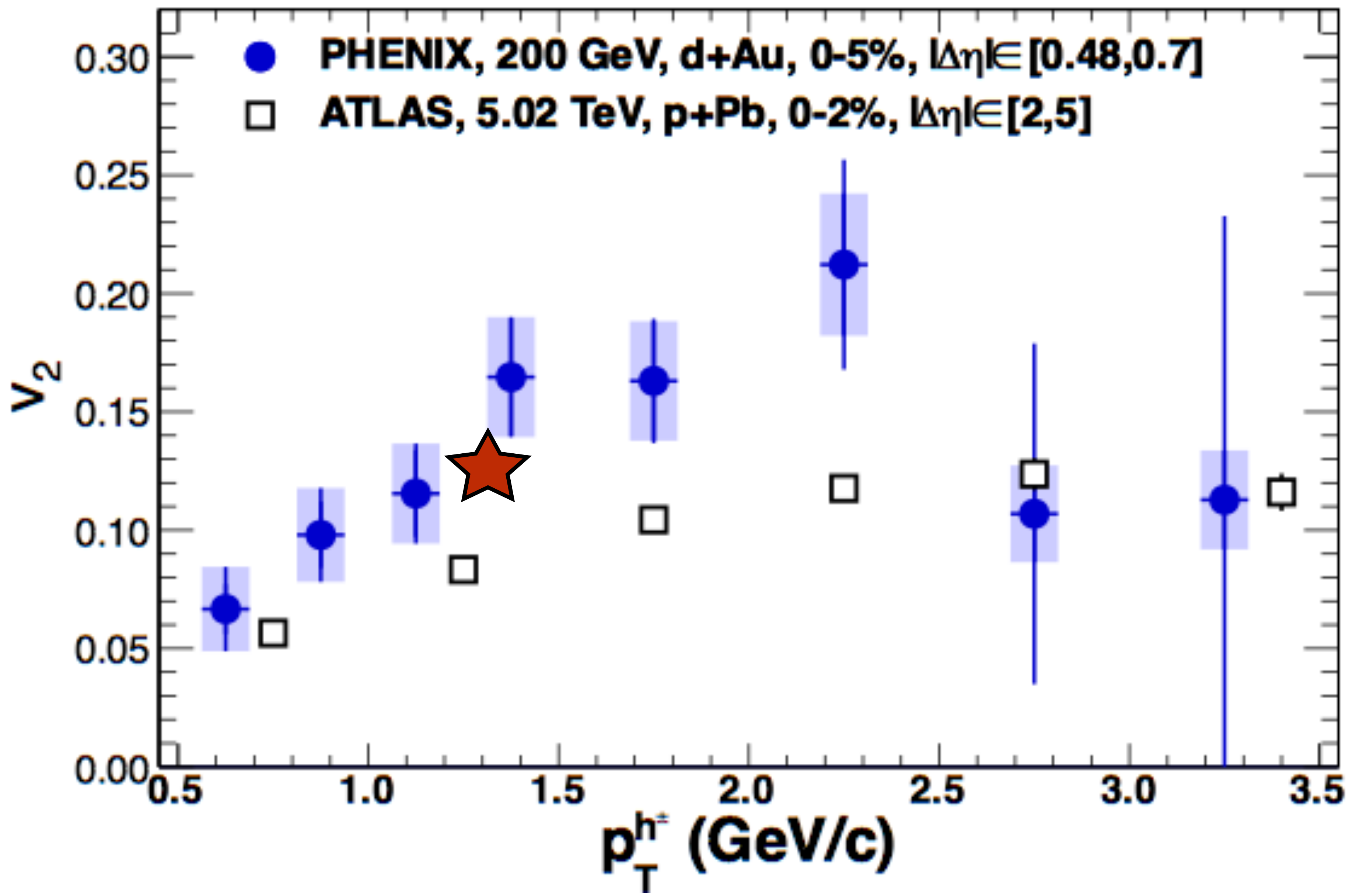
RHIC comparisons



STAR v_2: ~13±1% 1<p_T<3GeV/c
good consistency at RHIC!

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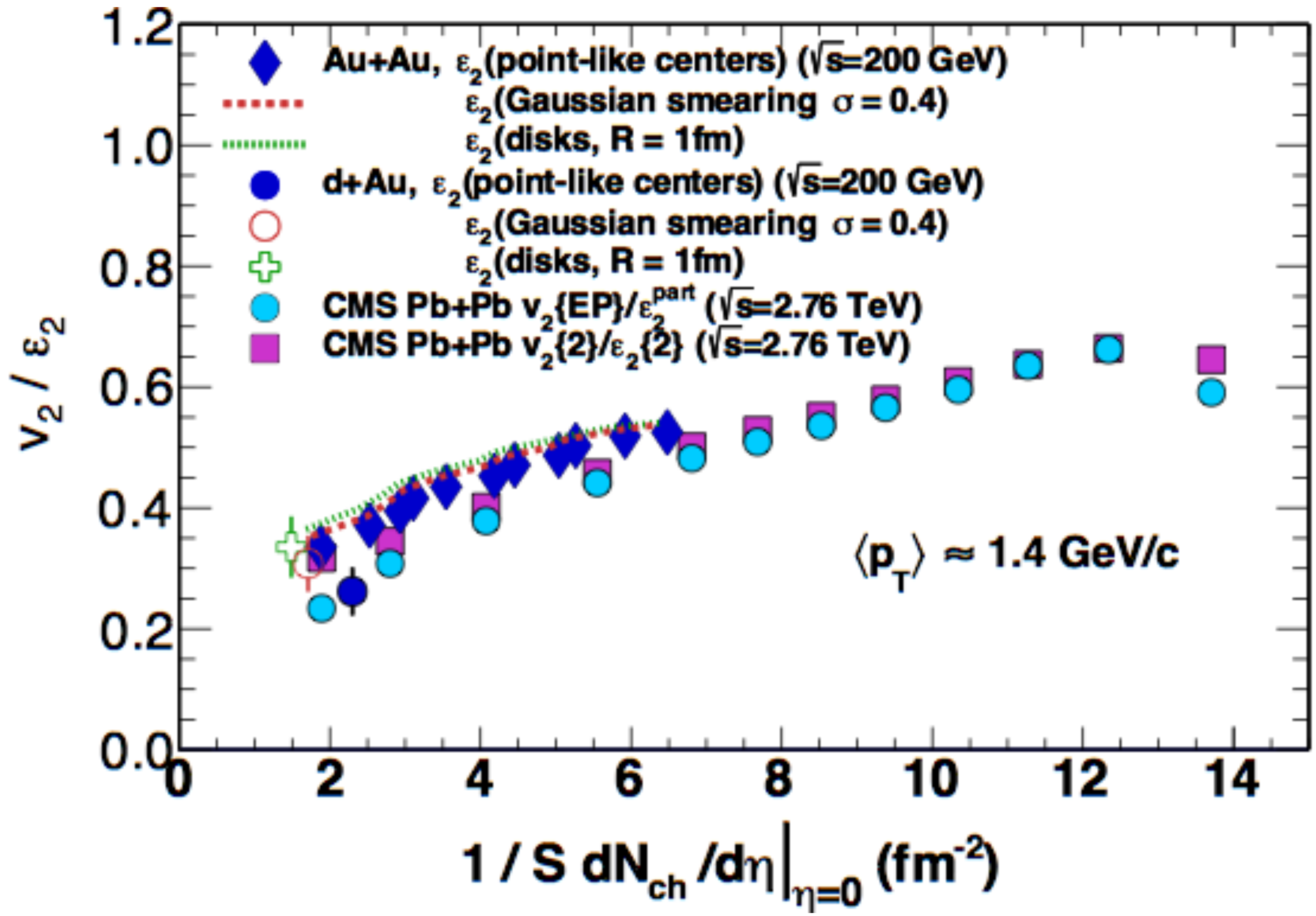
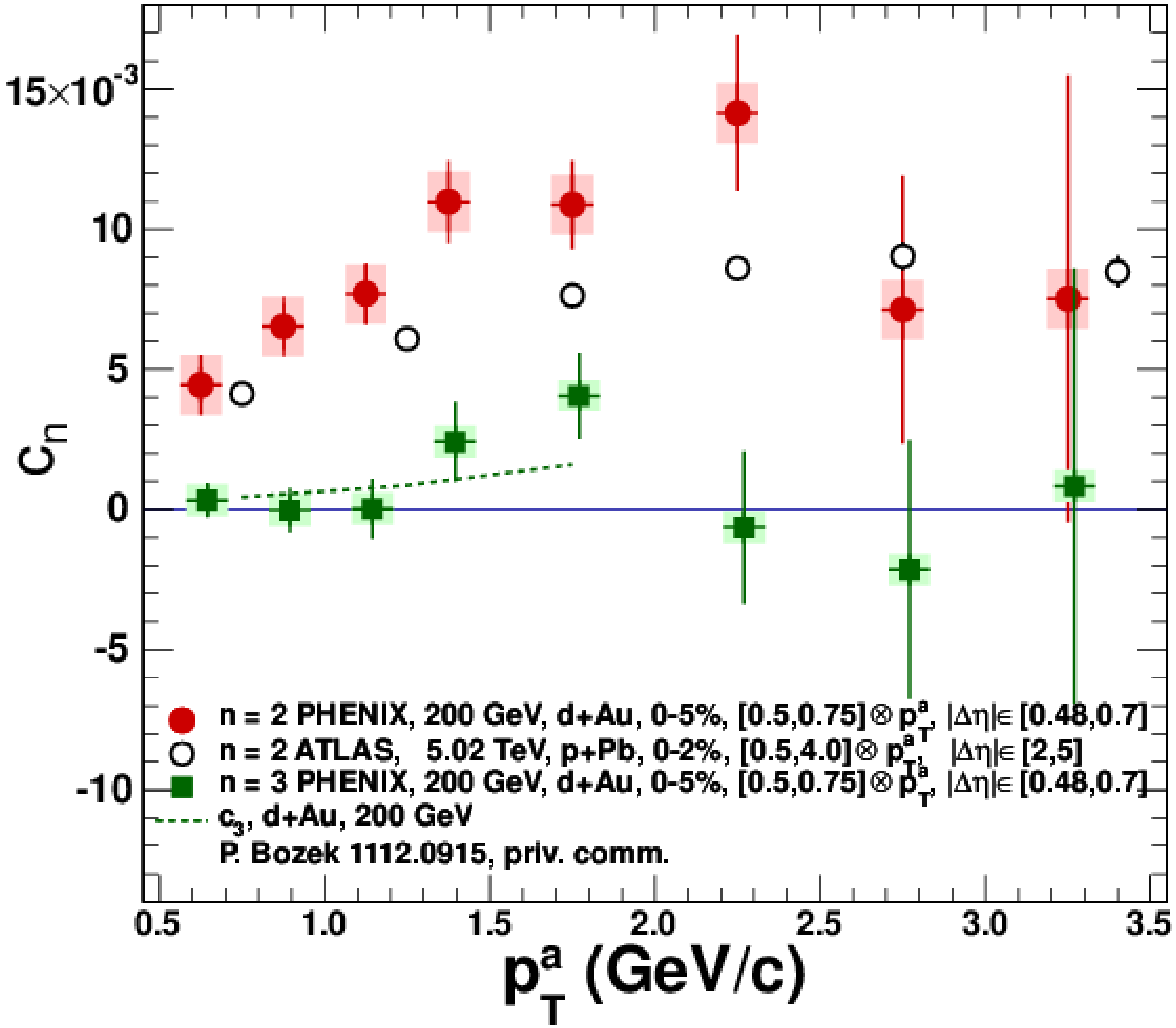
scaling with overlap area?



- approximate scaling with $1/S \; dN_{ch}/d\eta$
  - significant uncertainties due to nucleon representations in d+Au
  - n.b. not directly comparable to other 1/S plots, here v_2 at fixed p_T!

v_3 at RHIC?



no evidence for significant v3, consistent with hydro expectations

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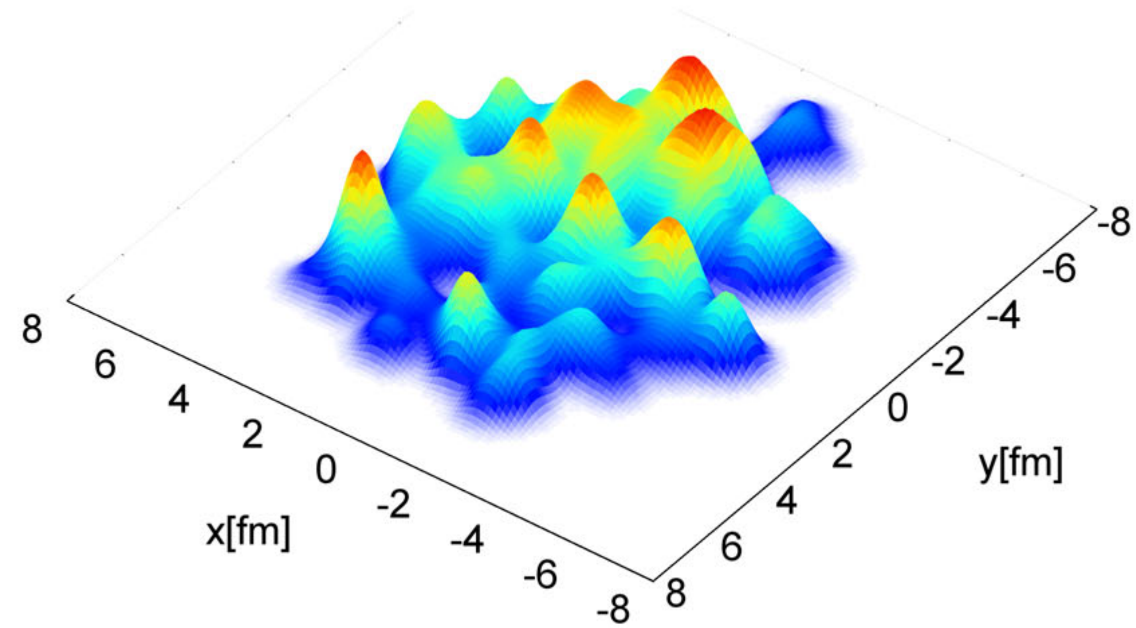
nucleon positions to energy density

single event initial energy density

nucleons: Gaussians,
σ = 0.4fm



Schenke, Tribedy & Venugopalan PRL 108 252301 (2012)

nucleon positions to energy density

single event initial energy density

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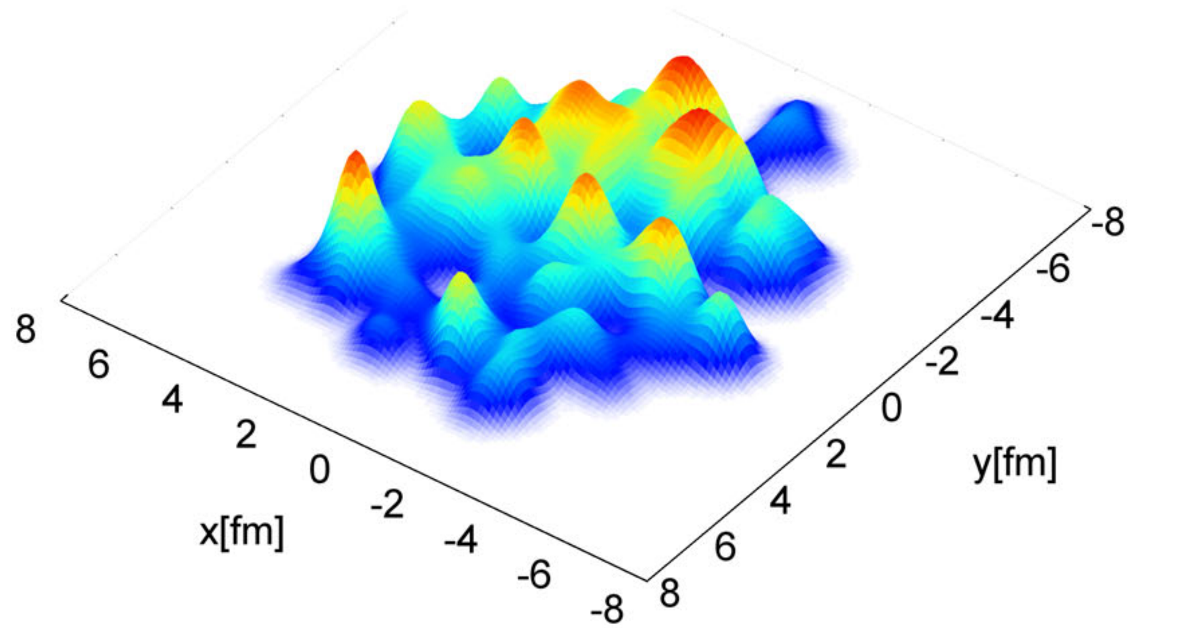
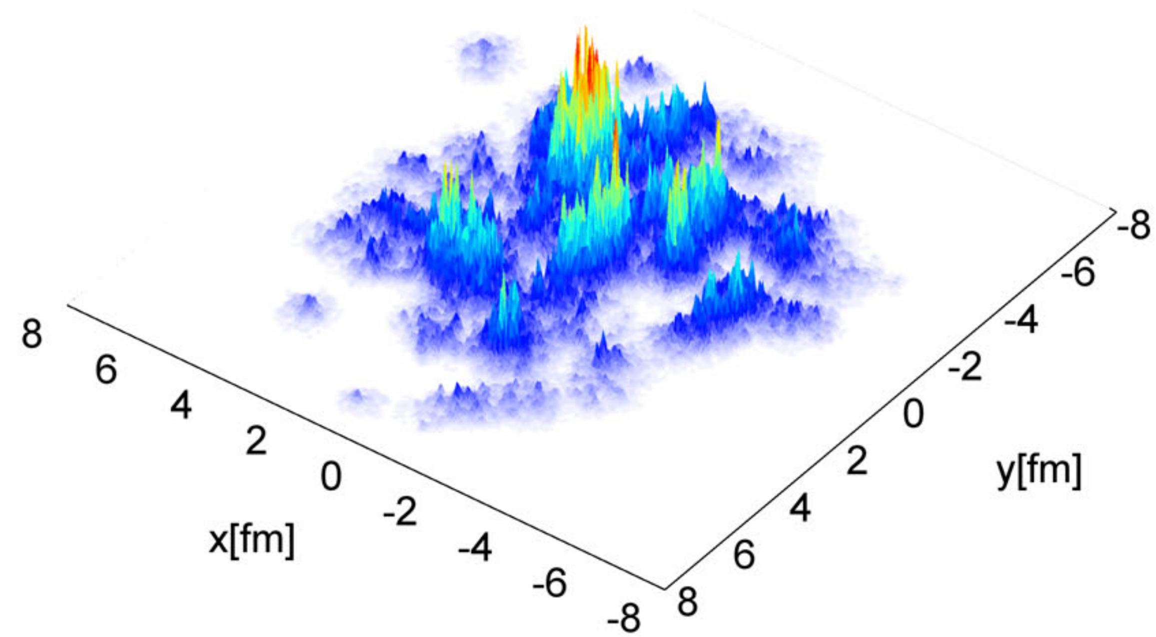


subnucleonic fluctuations:
IP-Glasma model



Schenke, Tribedy & Venugopalan PRL 108 252301 (2012)