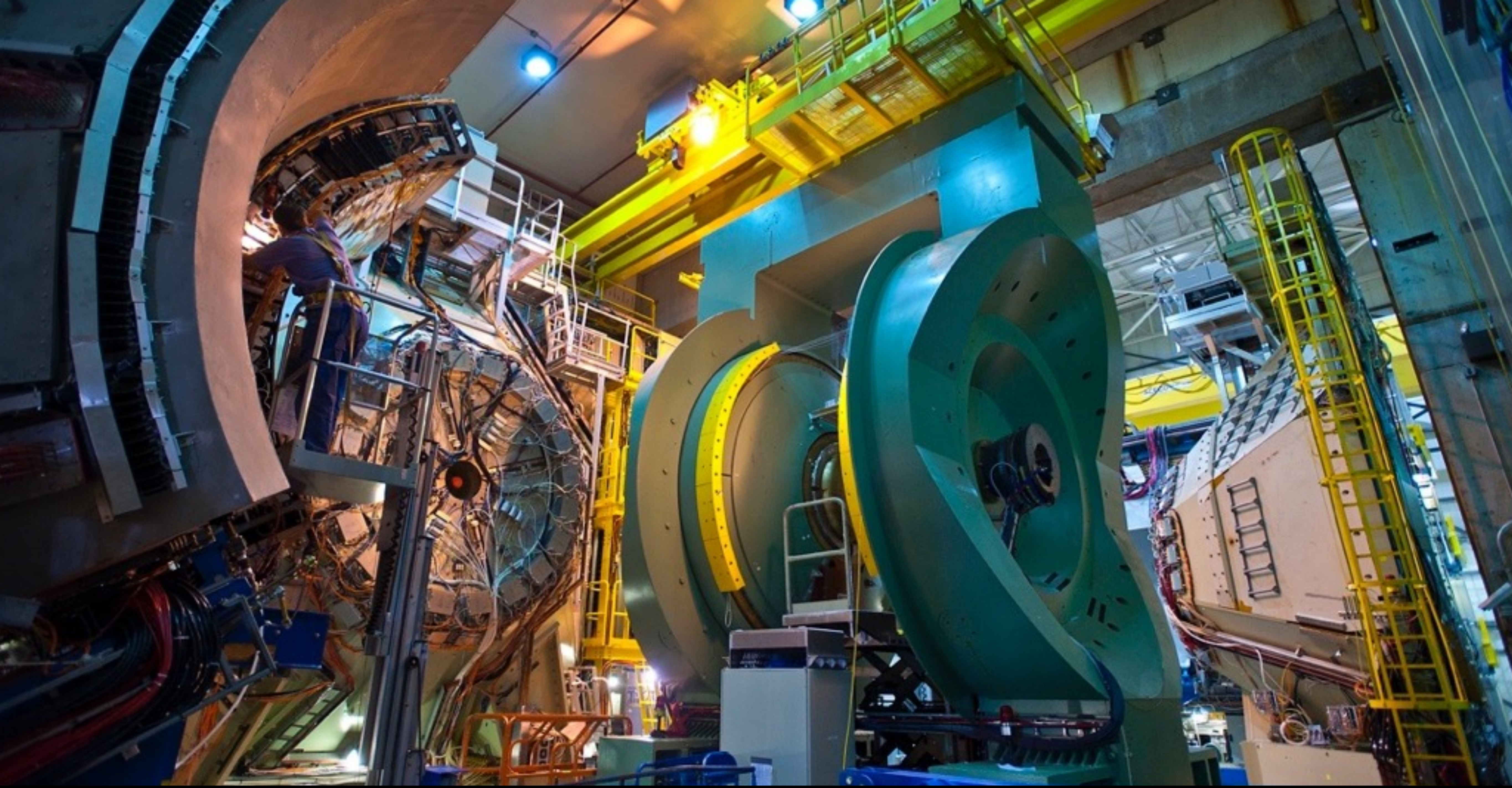
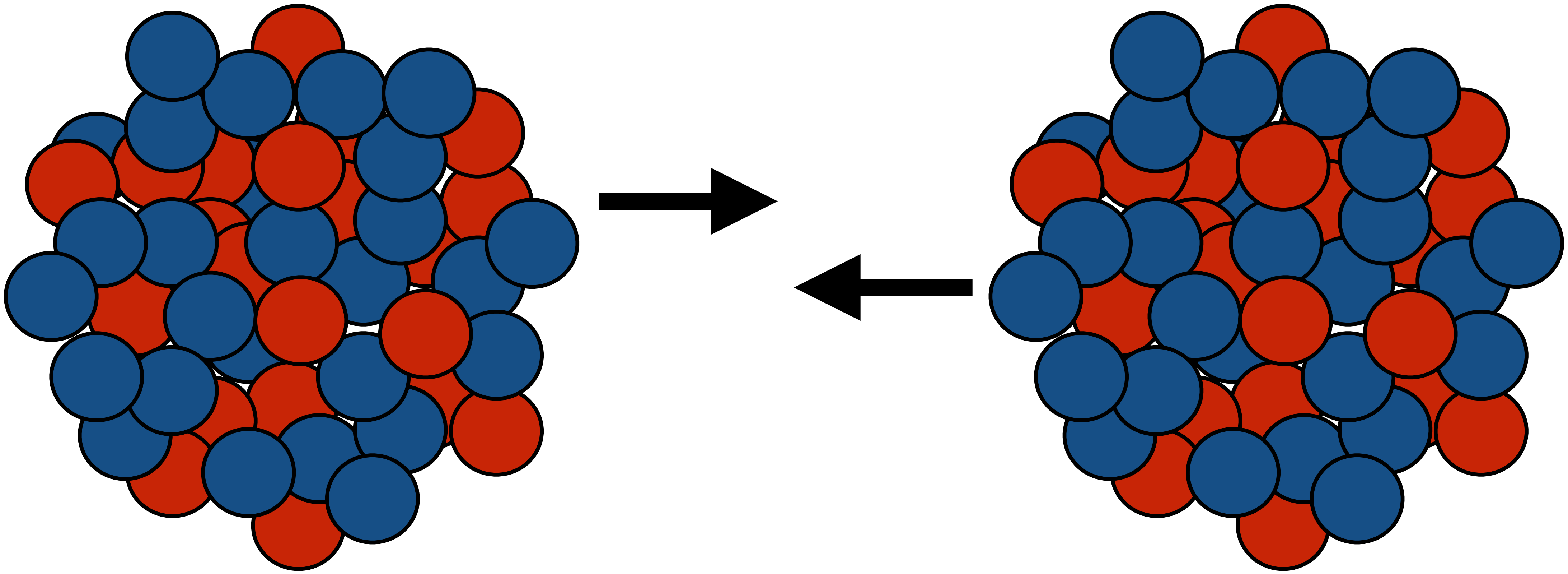


The Lighter Side of Heavy Ions

What have we learned from colliding large nuclei with protons, deuterons and He3?

ILLINOIS

Anne M. Sickles
February 6, 2015



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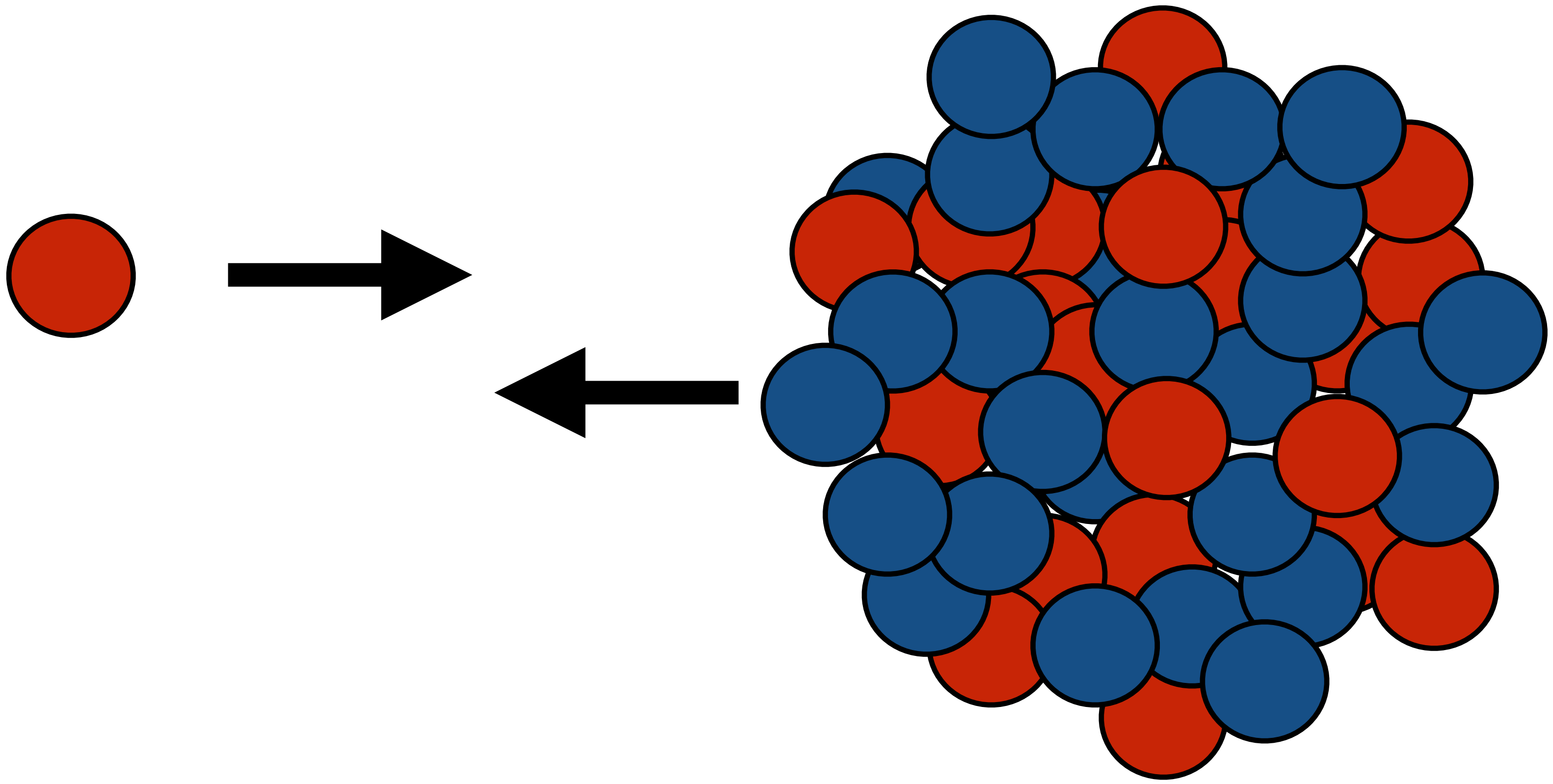

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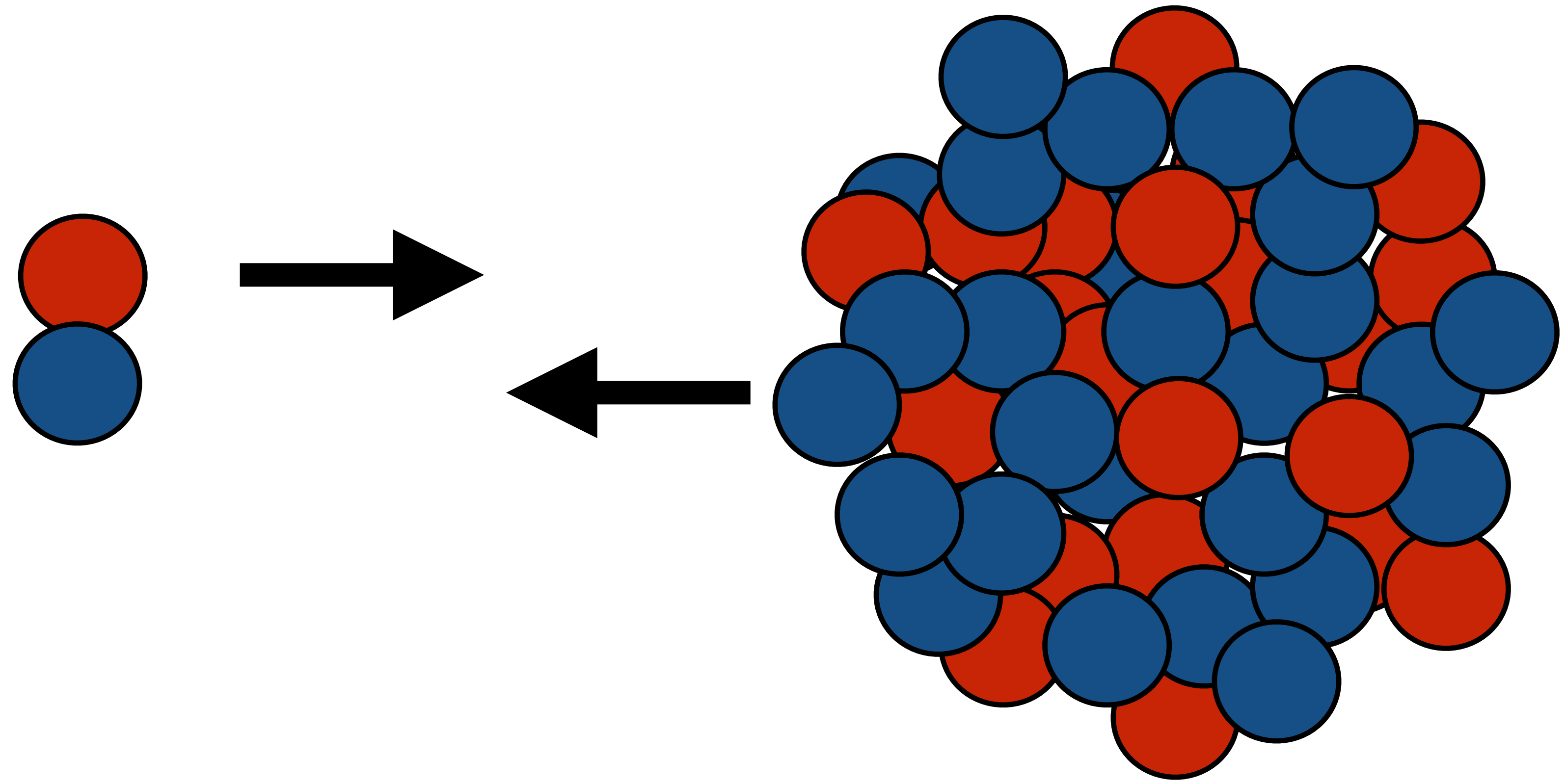

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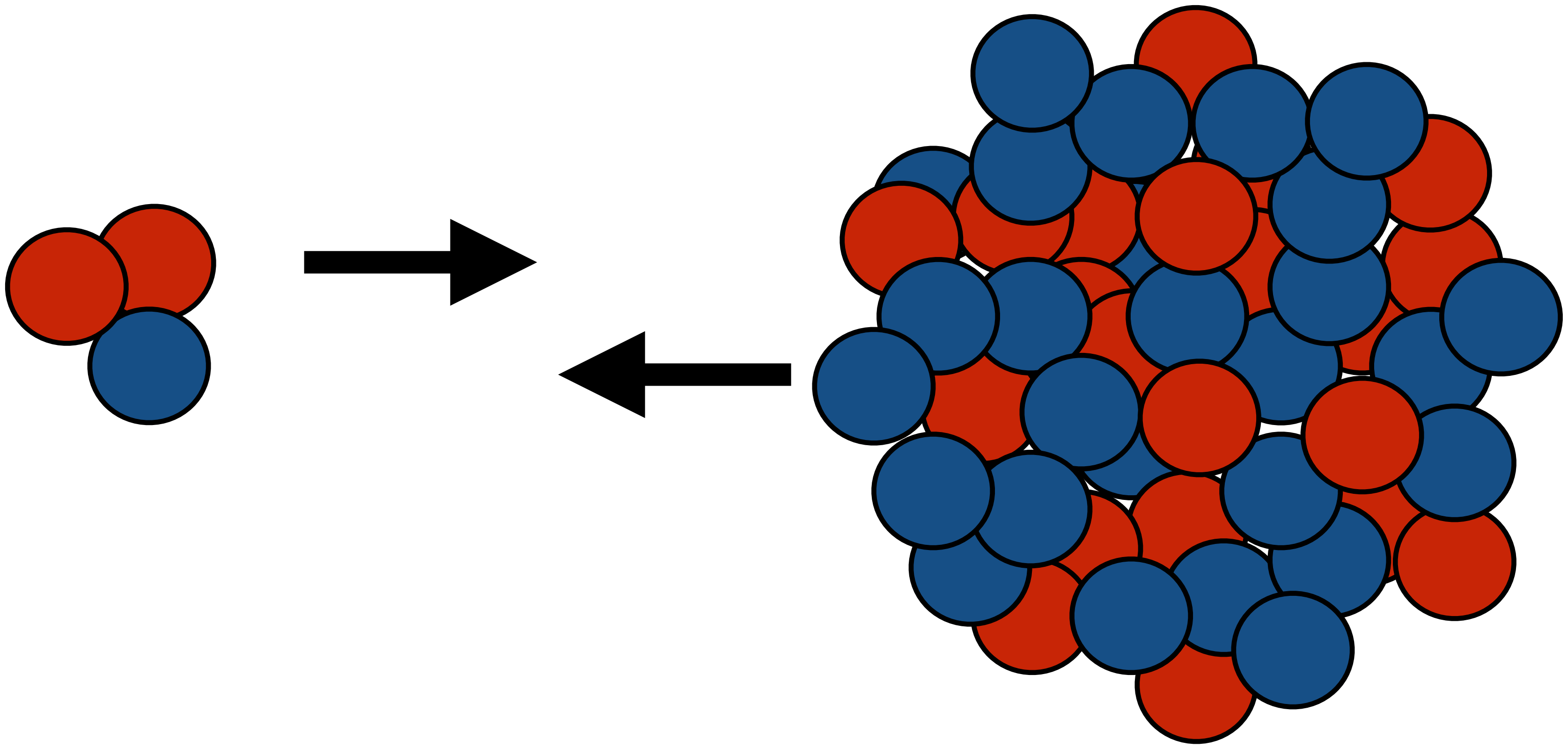


The Lighter Side of Heavy Ions

What have we learned from colliding large nuclei with protons, deuterons and He3?

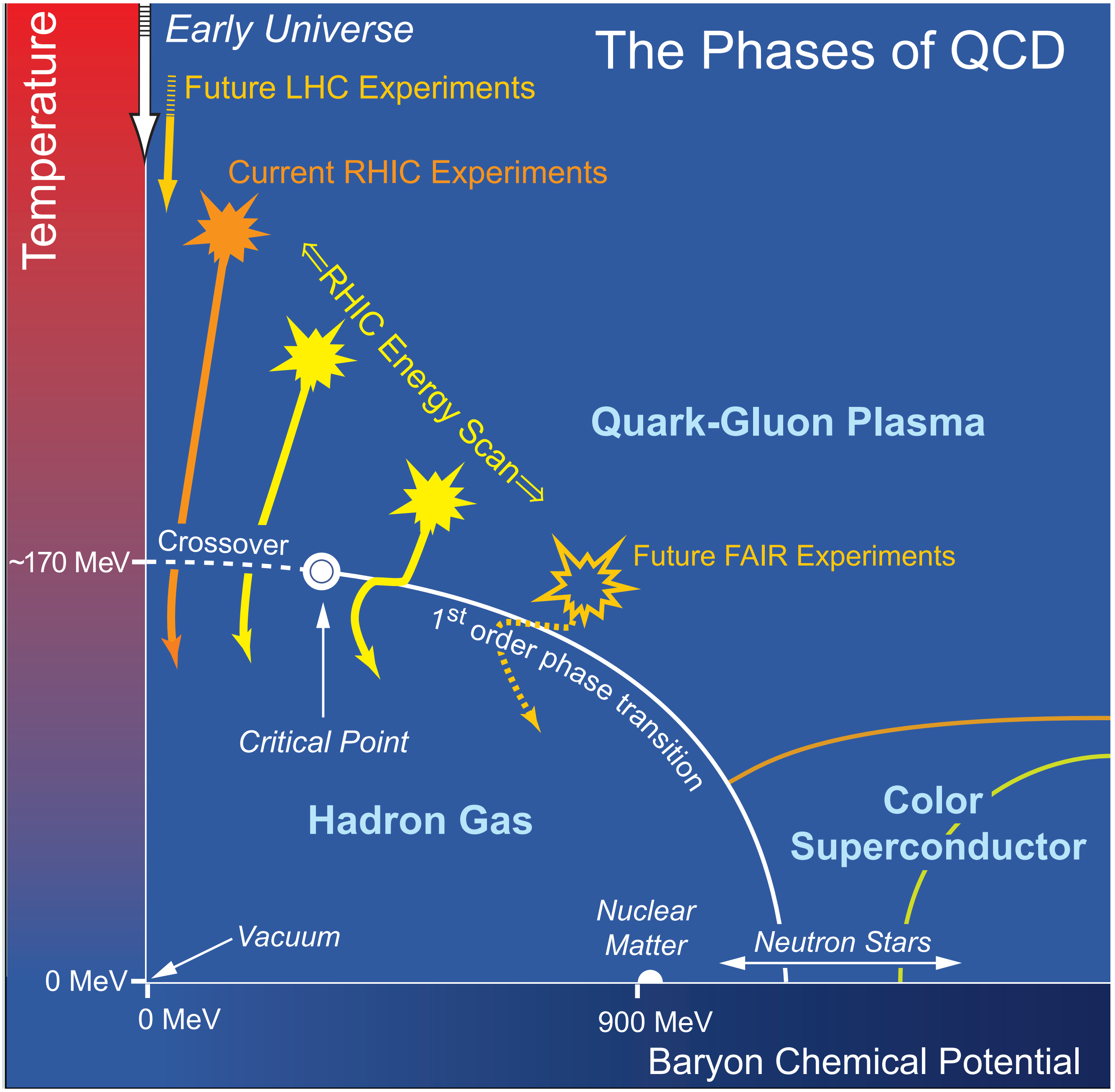
ILLINOIS

Anne M. Sickles

February 6, 2015

why heavy ion collisions?

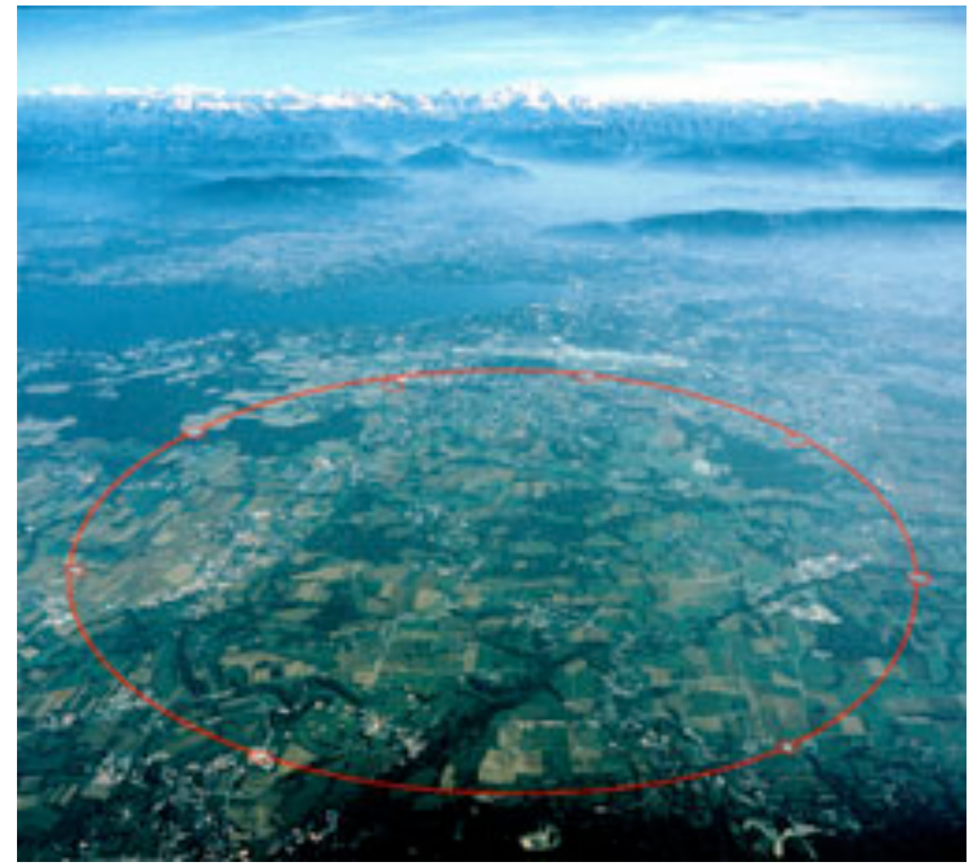
- explore QCD away from normal bound states
- only “large” system we can study with partonic degrees of freedom



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

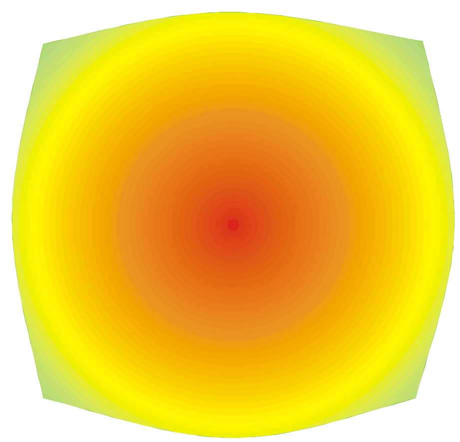


2010 - present
2.76 TeV collision energy PbPb
5.02 TeV pPb
pp @ multiple energies

strengths: excellent detectors and very high energy

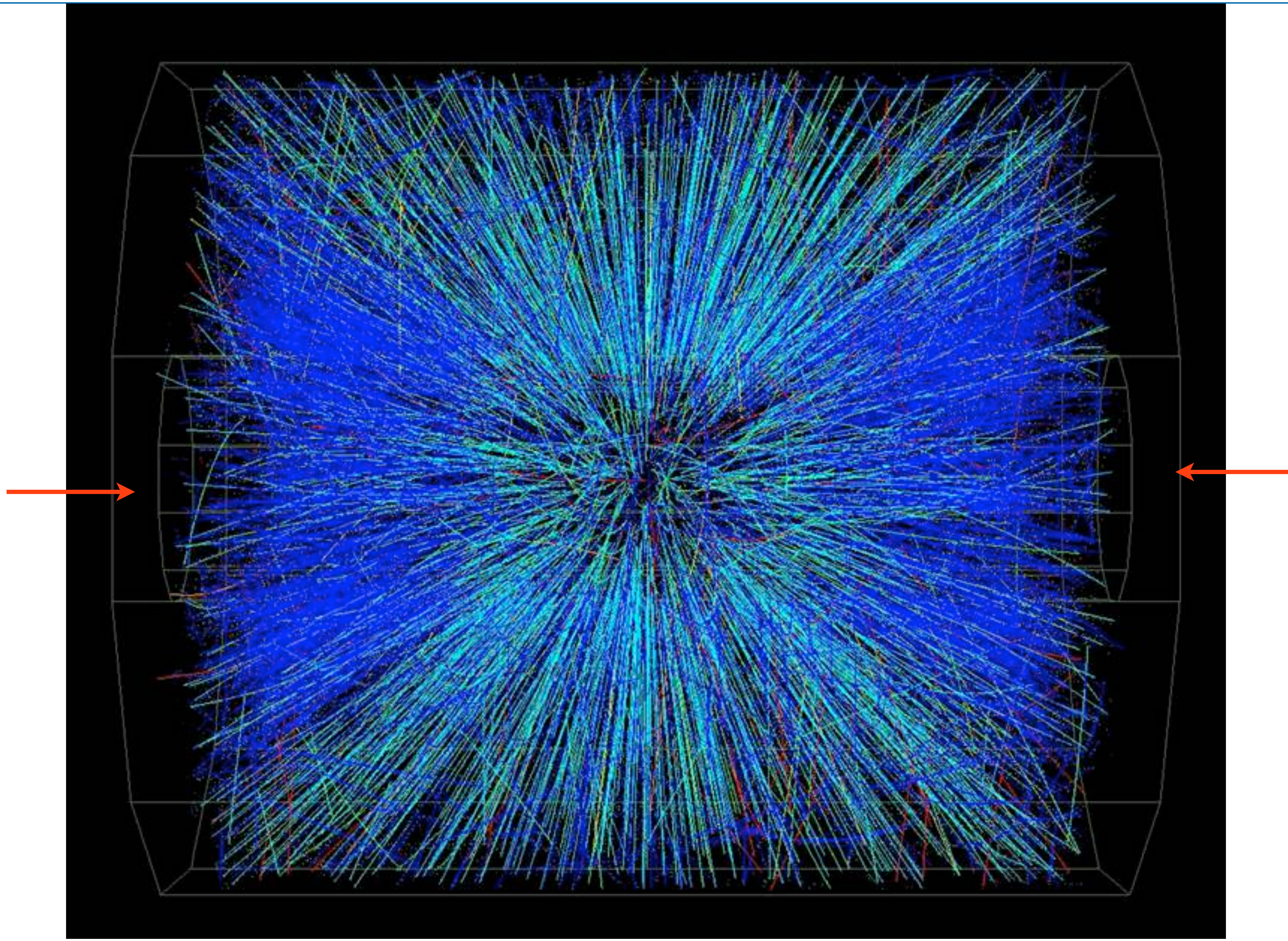
relativistic **heavy** ion collisions

quark gluon plasma

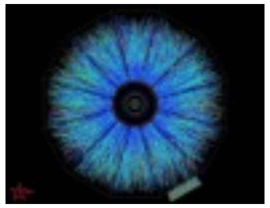


want to untangle QGP effects from effects of initial nucleus and hadronic matter

the aftermath

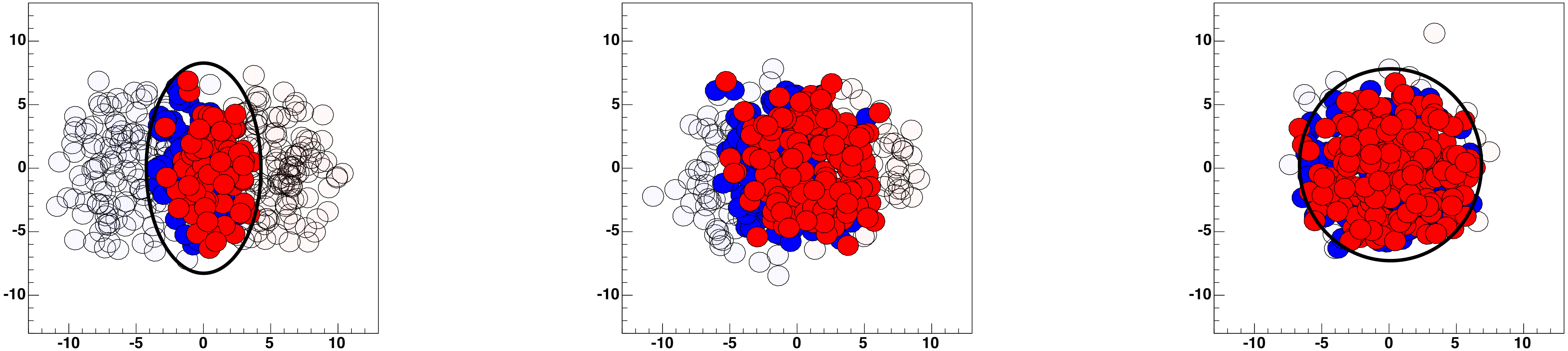


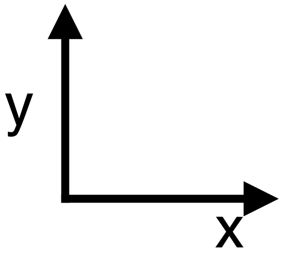
collision geometry



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

nucleon positions for the colliding nuclei for three different collisions

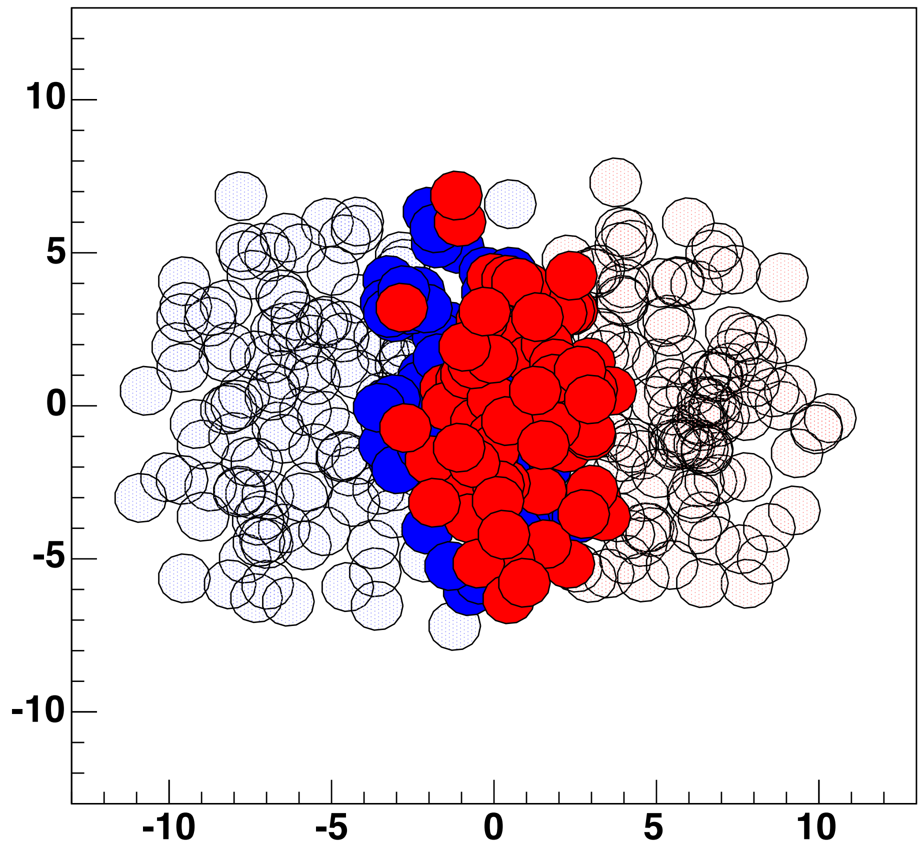




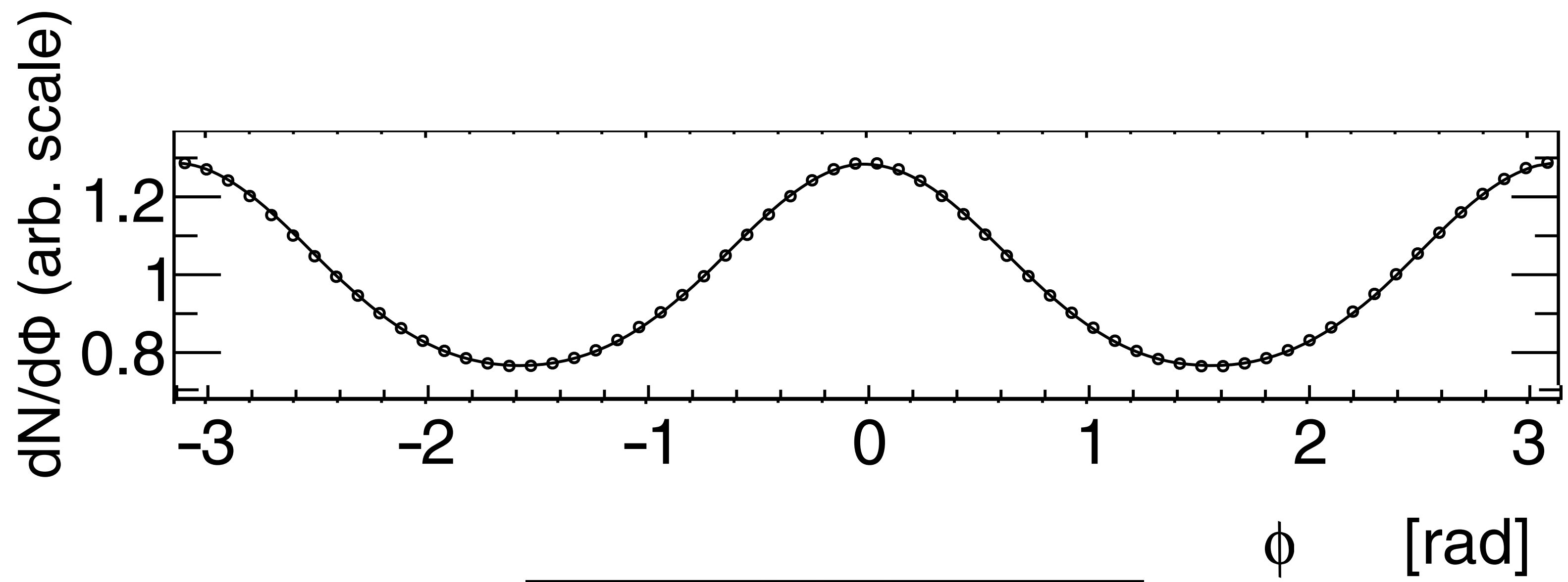
varying the distance between the nuclei, changes the shape and size of the region where the nuclei overlap

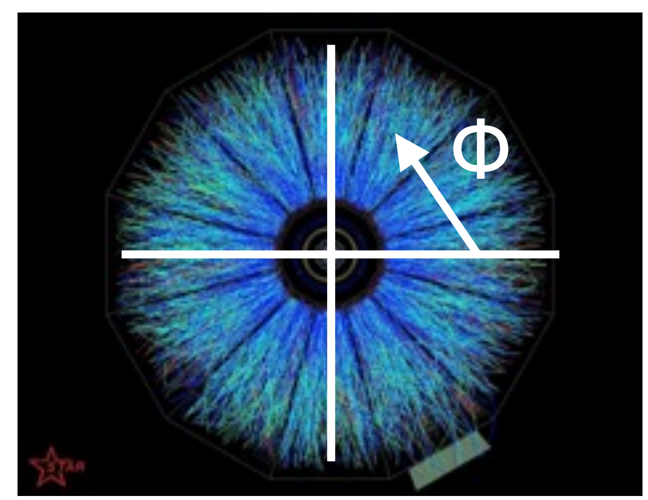
collision geometry → measured

initial collision geometry



measured hadron distributions

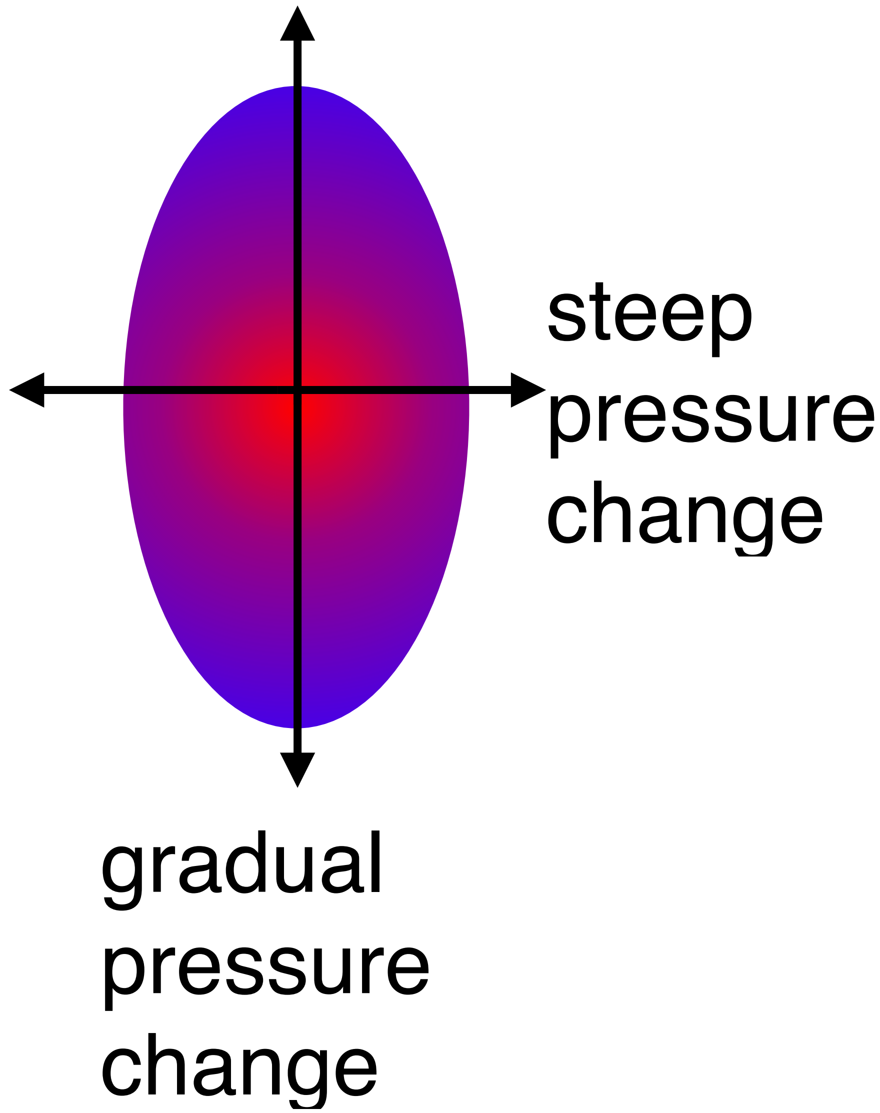


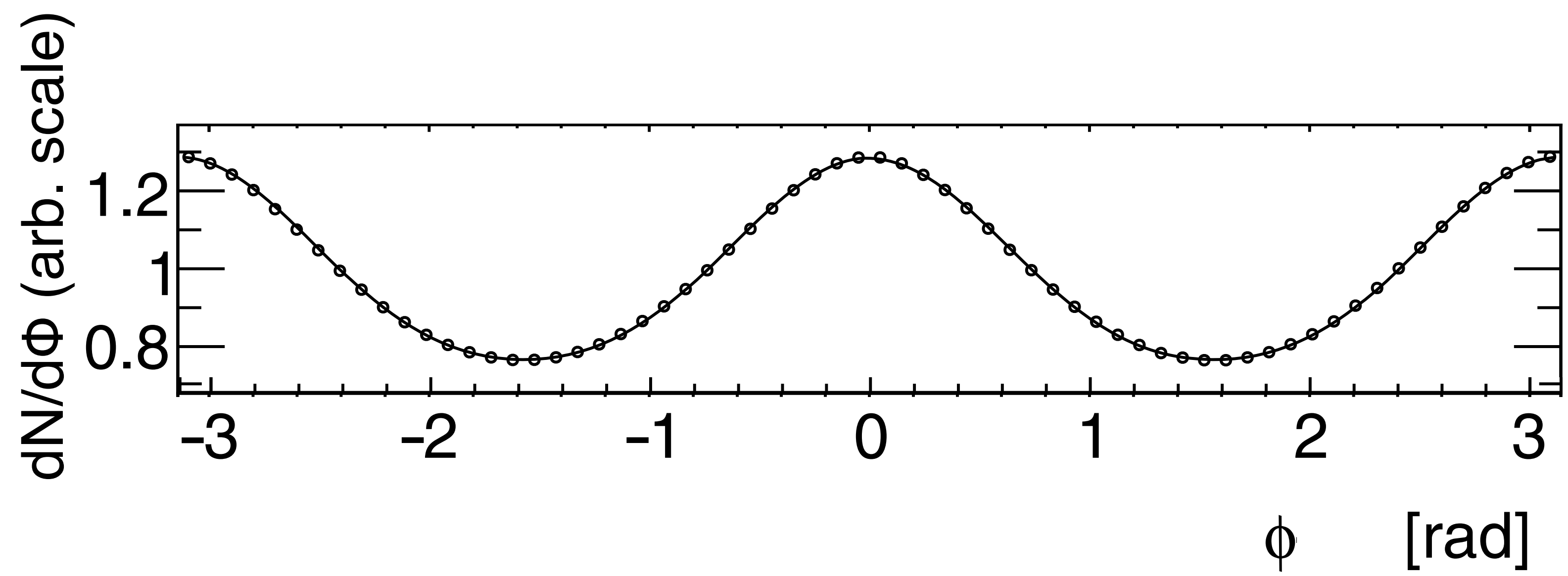


the shape of the initial collision geometry is imprinted on the final particle distributions

PLB 707 330 (2012)

strong interactions





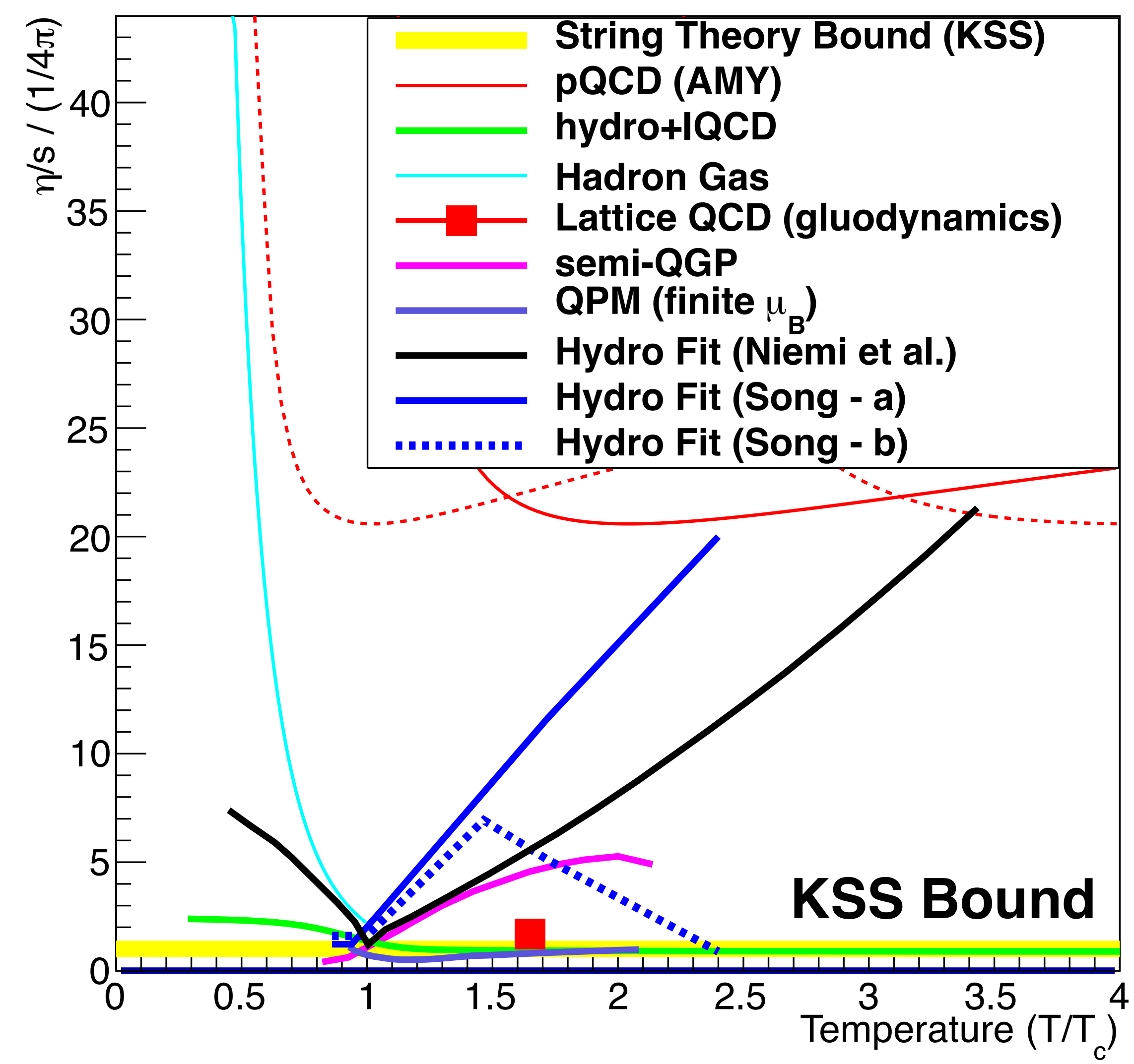
$$\frac{dN}{d\phi} = 1 + 2v_2 \cos 2\phi$$

- 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)

the viscosity of the QGP

- what kind of fluid is the QGP?
  - nearly ideal
  - viscosity within a factor of a few of what's allowed by quantum mechanics



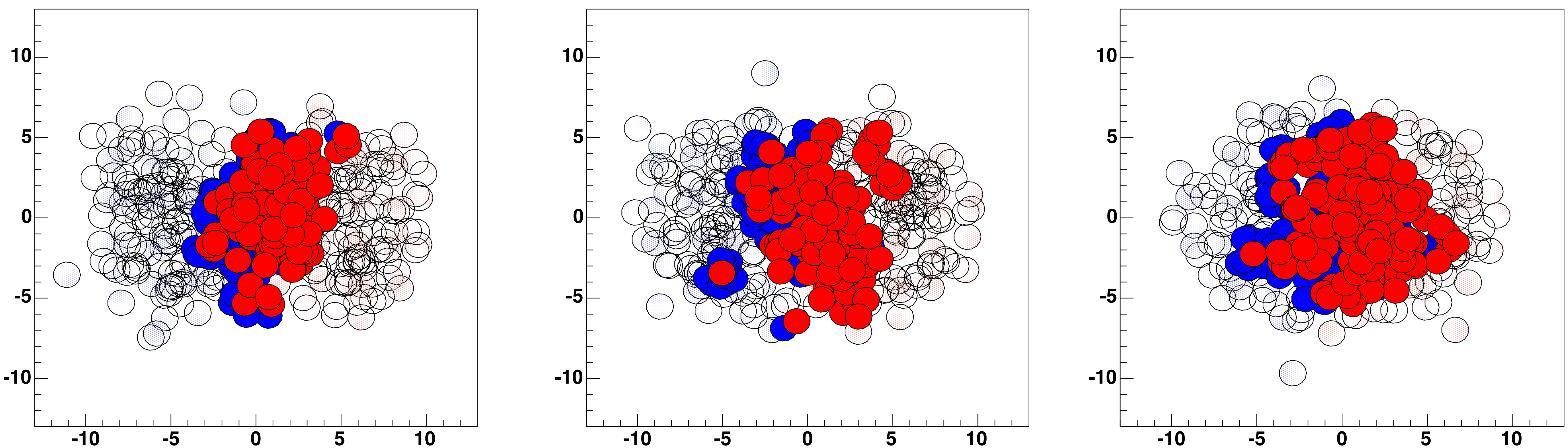
what is viscosity as a function of T?

why does the QGP behave as such?

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

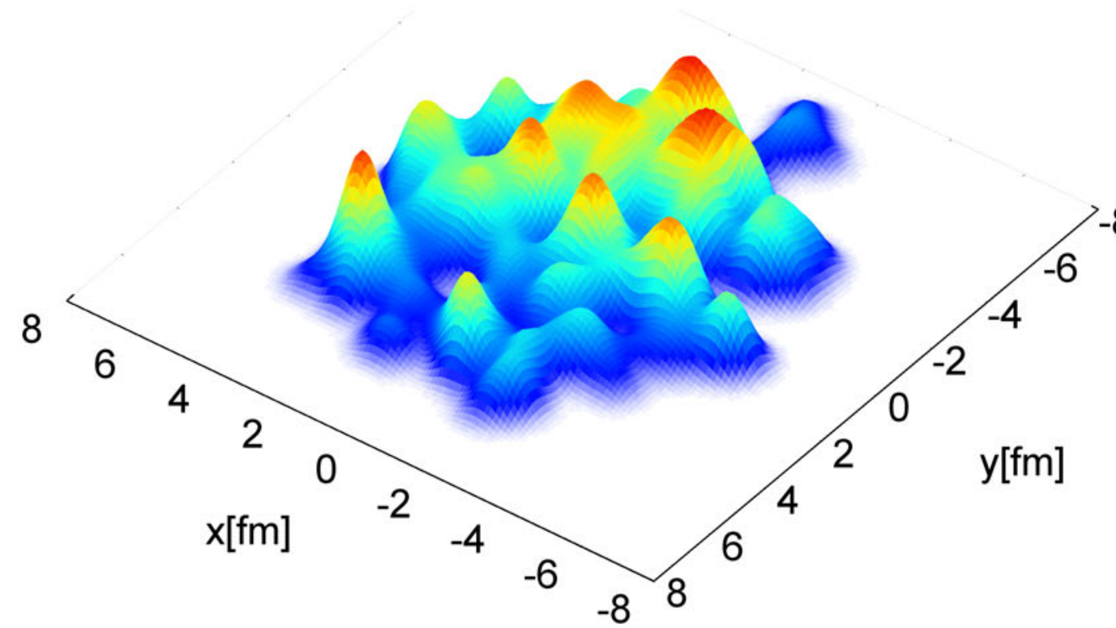
not just v_2 describing cos2Φ, but v_n:

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

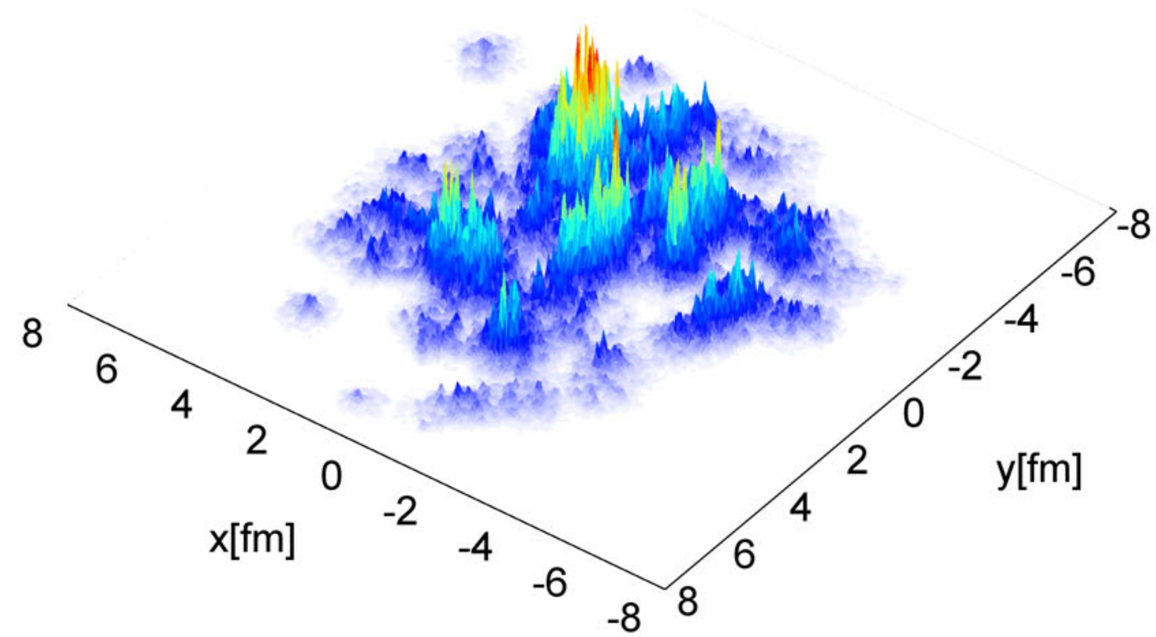
what is initial energy density distribution?

single event initial energy density

nucleons: Gaussians,
σ = 0.4fm

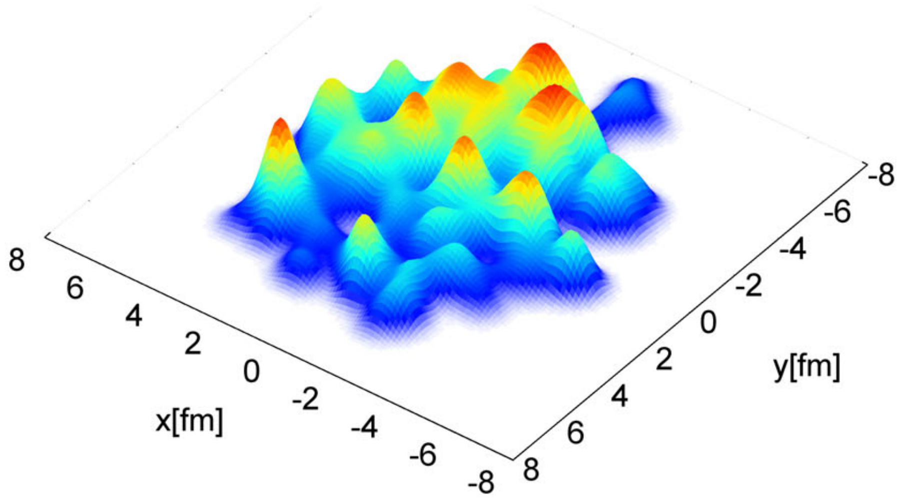


subnucleonic fluctuations:
IP-Glasma model

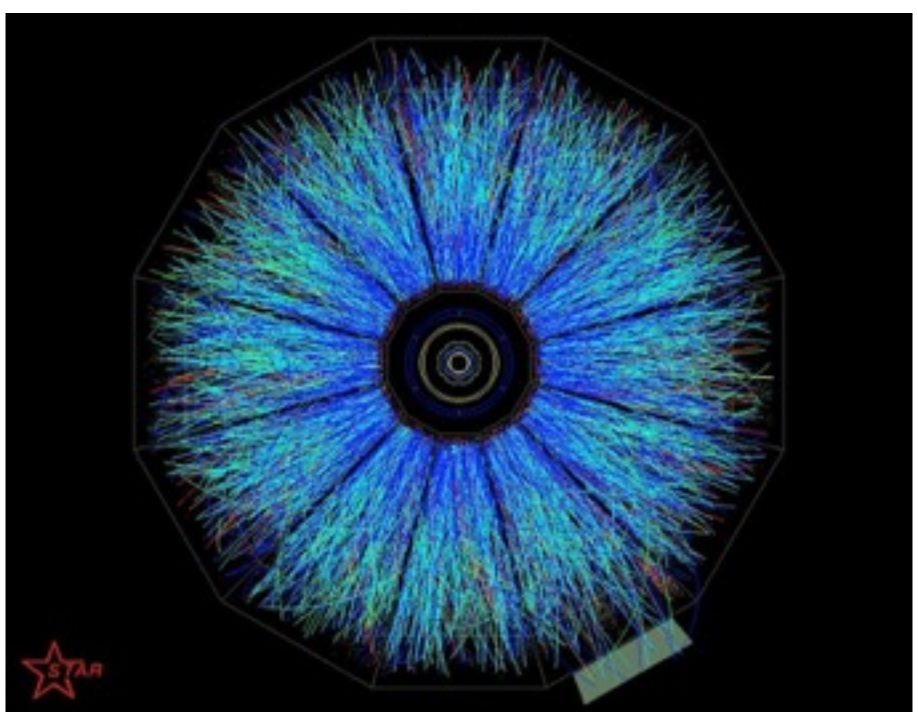


Schenke, Tribedy & Venugopalan PRL 108 252301 (2012)

two particle correlations



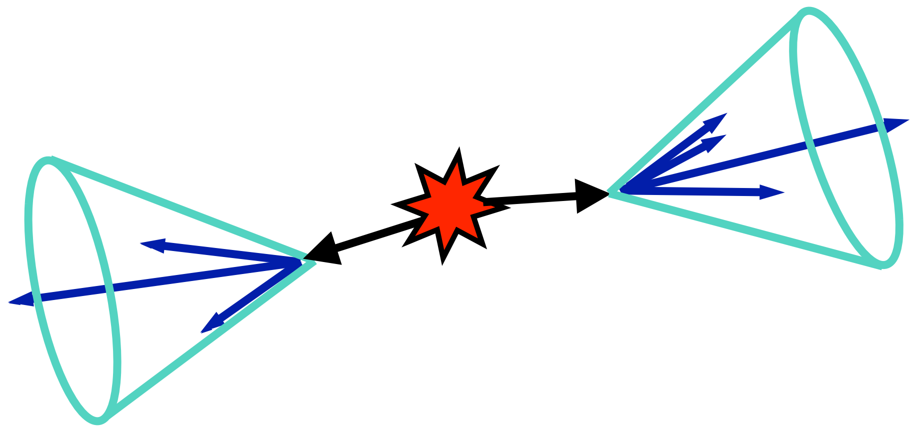
$$\frac{dN}{d\phi} \propto 1 + \sum^{n} 2v_n \cos n\left(\phi - \Psi_n\right)$$

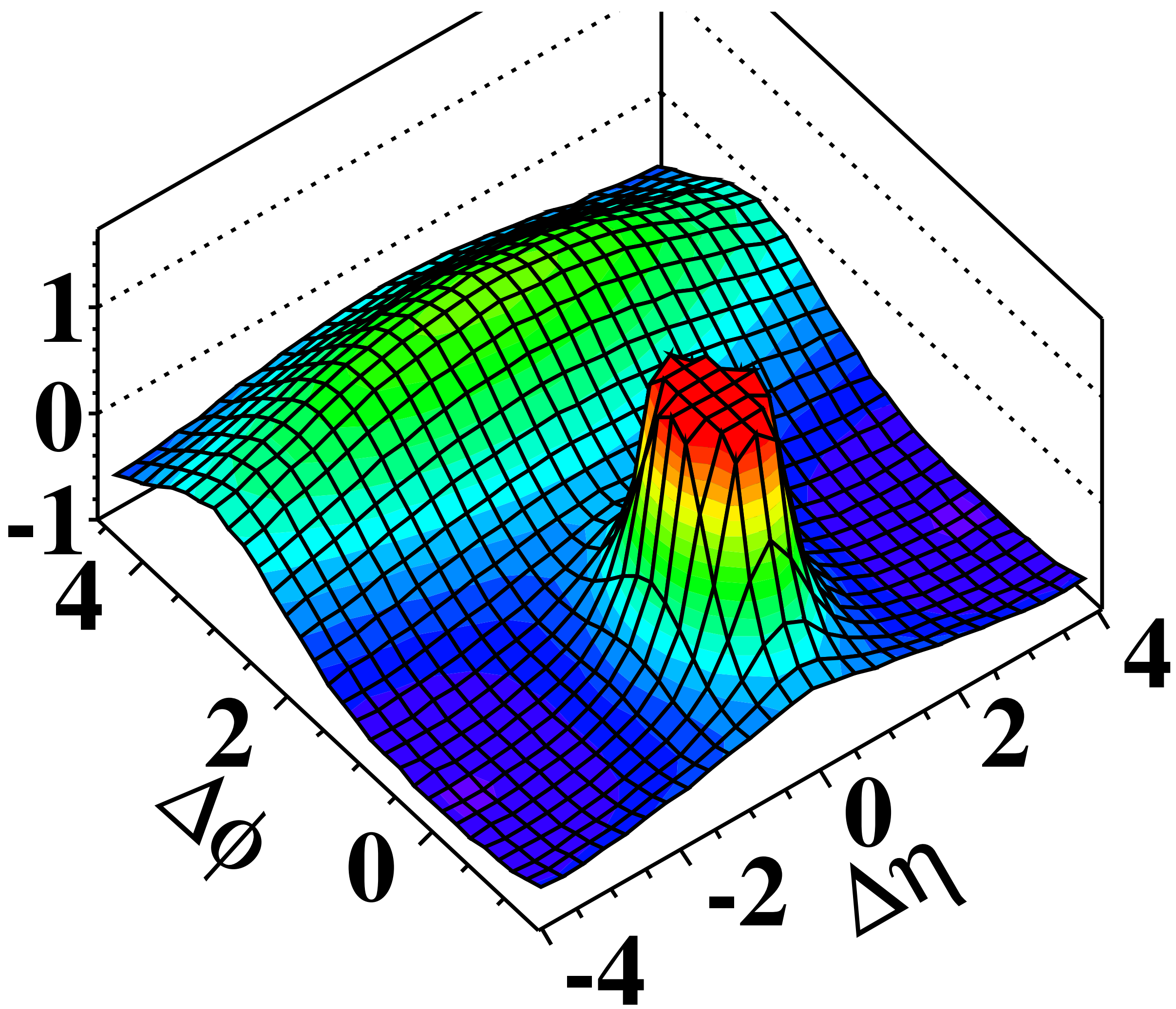


$$\frac{dN_{AB}}{d\Delta\phi} \propto 1 + \sum^{n} 2v_{n,A}v_{n,B} \cos\left(n\Delta\phi\right)$$

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

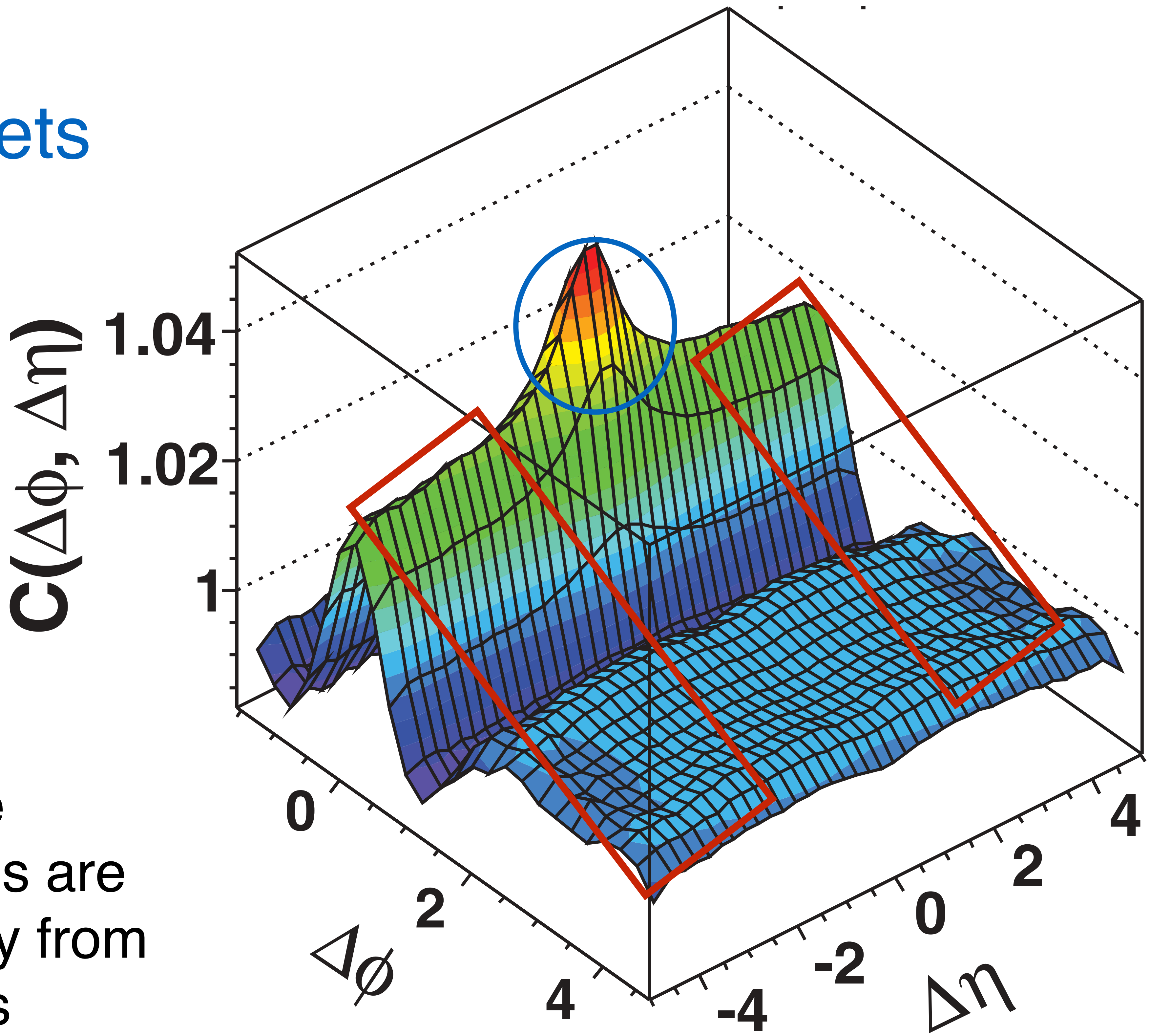
$$\frac{dN_{AB}}{d\Delta\phi} \propto 1 + \sum^{n} 2v_{n,A}v_{n,B} \cos\left(n\Delta\phi\right)$$

flow correlations should be long range η

CMS JHEP 1009 (2010) 091

correlations in PbPb

jets

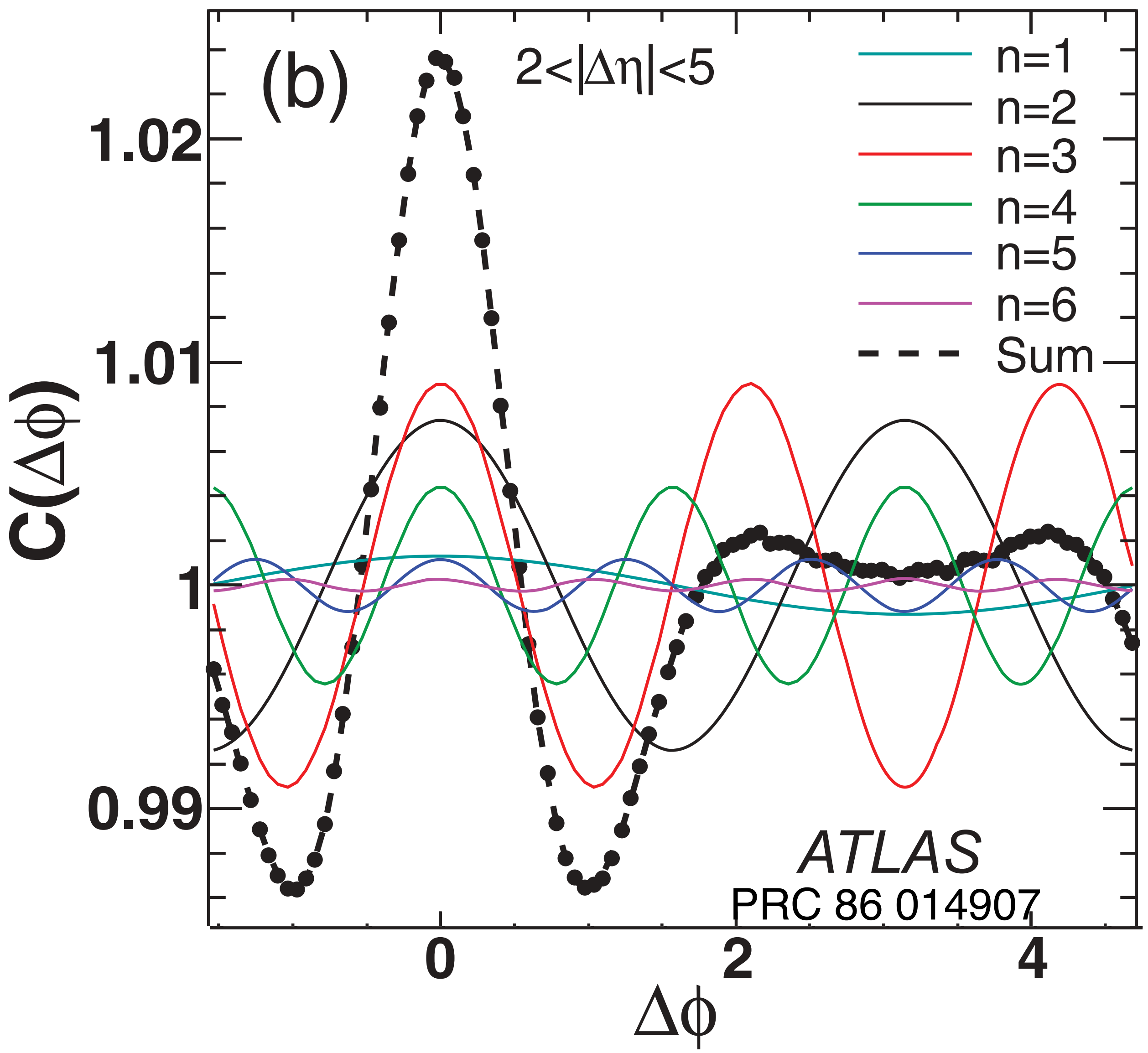


flow

long range correlations are necessarily from early times

ATLAS PRC 86 014907

A+A: v_N & two particle correlations

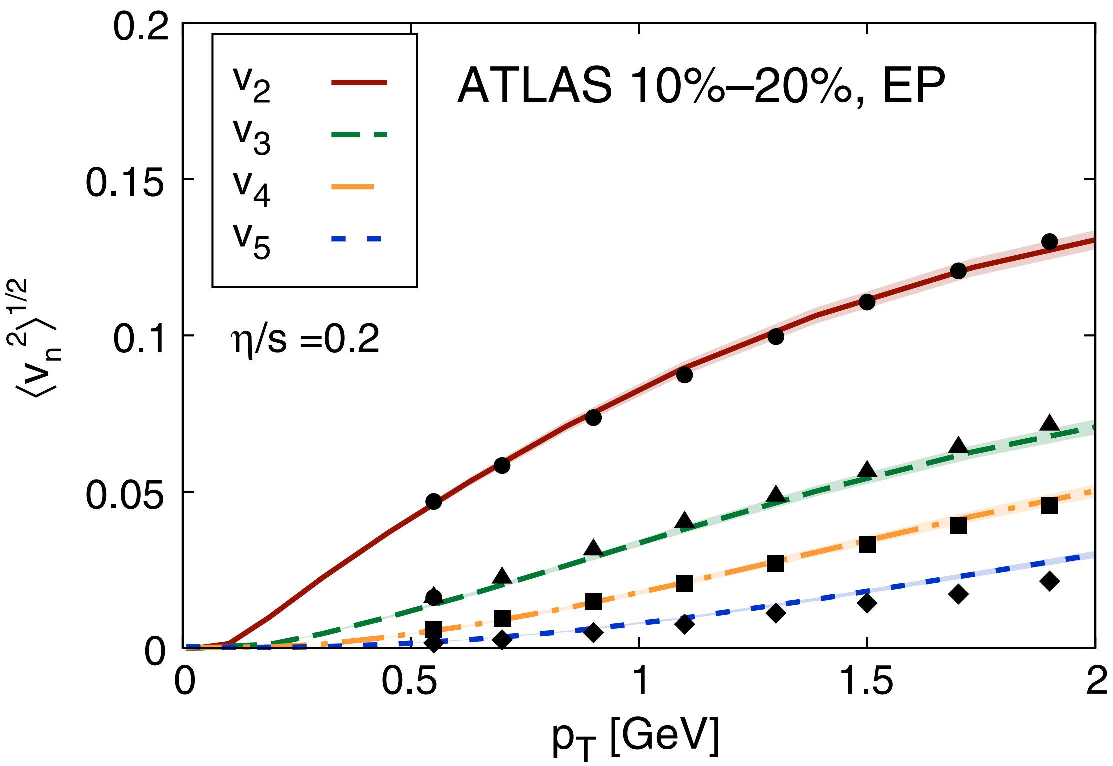


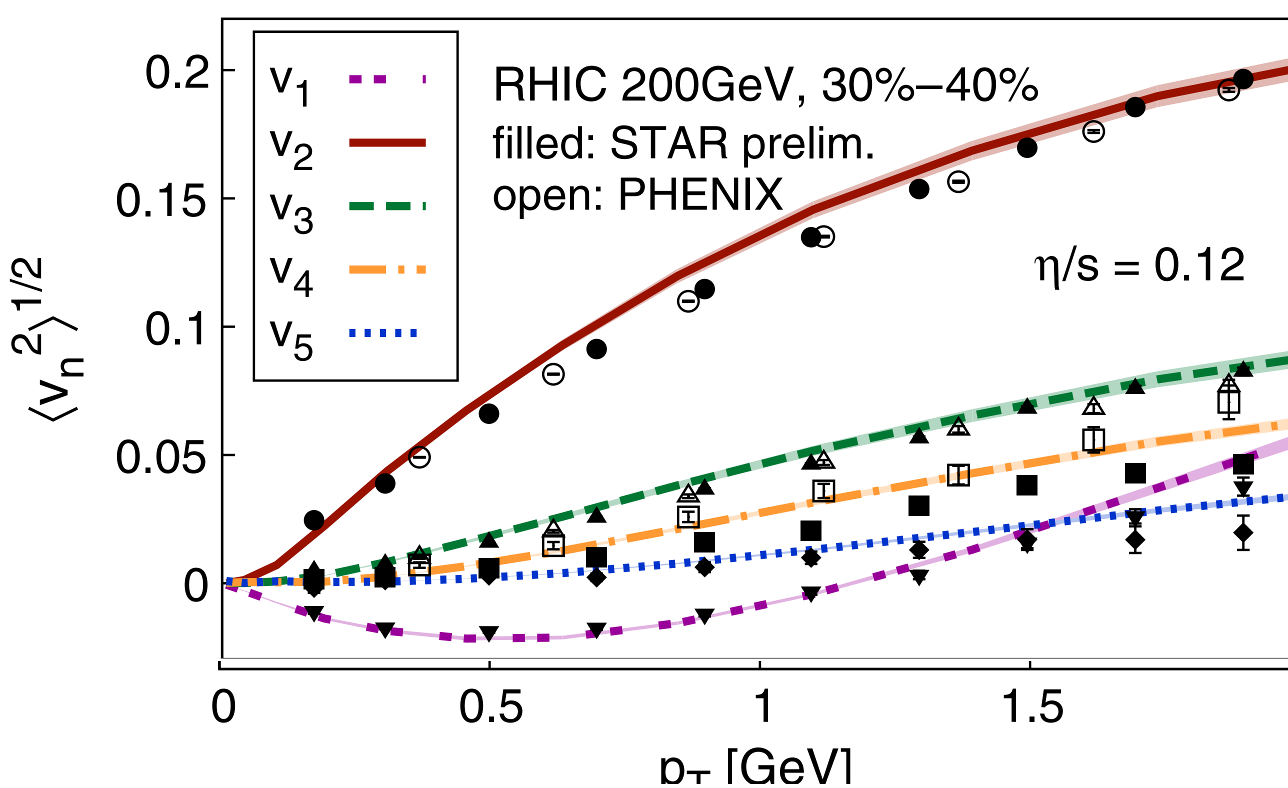
$$\frac{dN_{AB}}{d\Delta\phi} \propto 1 + \sum^{n} 2v_{n,A}v_{n,B}\cos(n\Delta\phi)$$

evidence for many higher order terms in particle correlations

state of the art hydrodynamic calculations

3 +1d viscous hydrodynamics





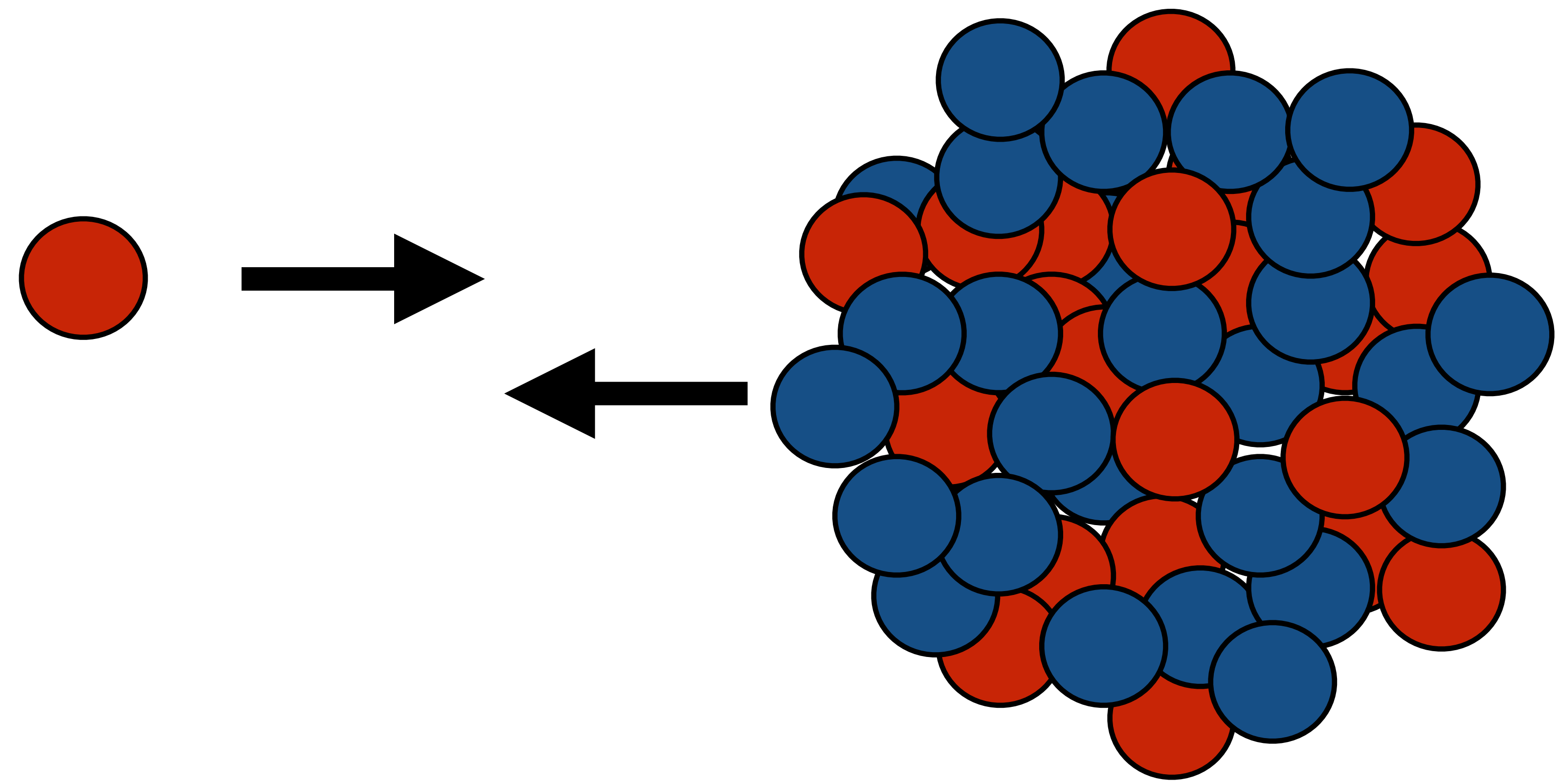
quantitative description of v_1 - v_5 at both RHIC and LHC

sensitivity to η/s

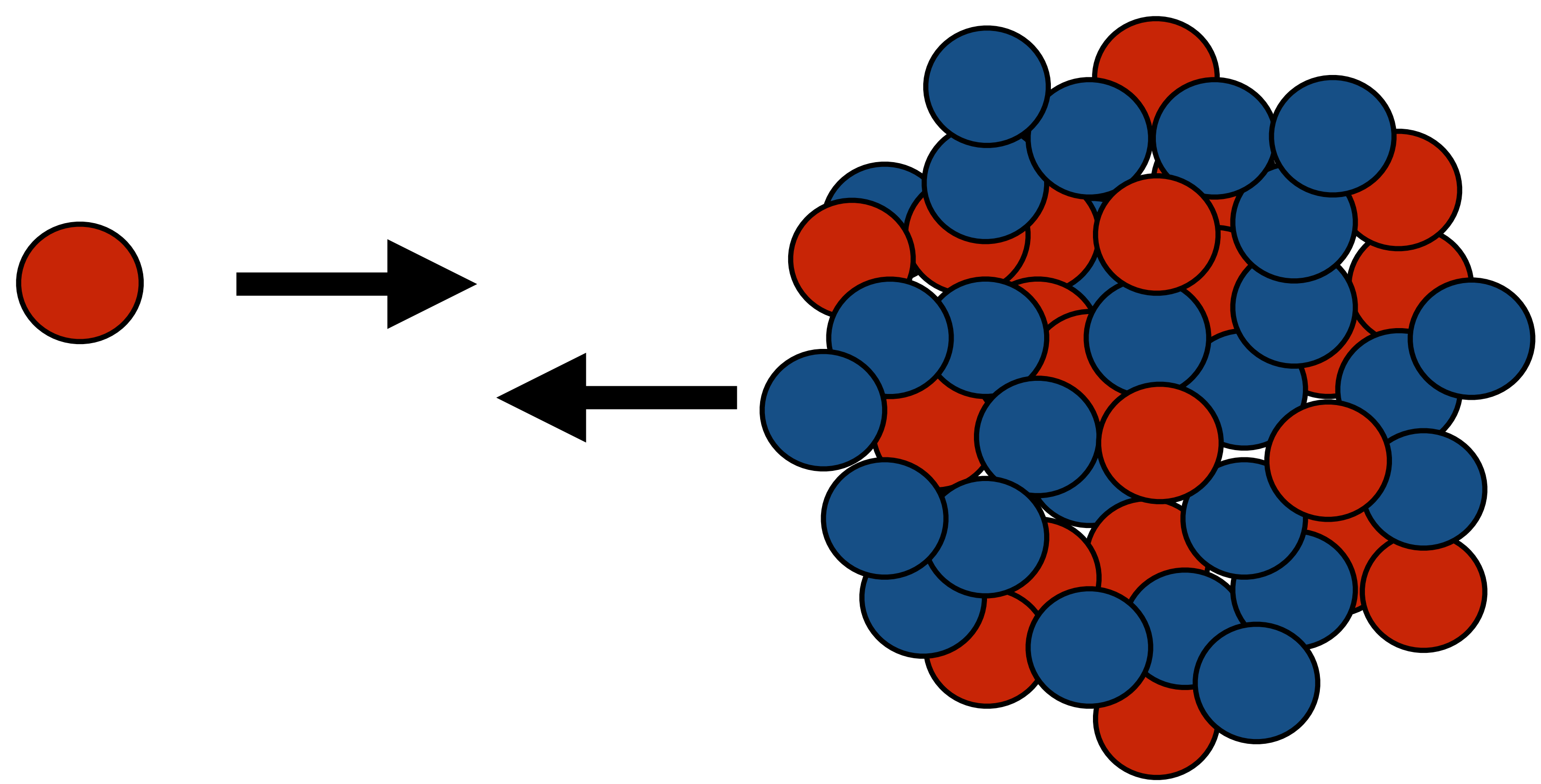
Gale, Jeon, Schenke, Tribedy, Venugopalan PRL 110 012302

p + A collisions

small probe,
big target
study how nuclear environment is different than free nucleons (e.g. EMC effect)



small, **but finite probe**,
big target
create a small amount of QGP



p + A collisions

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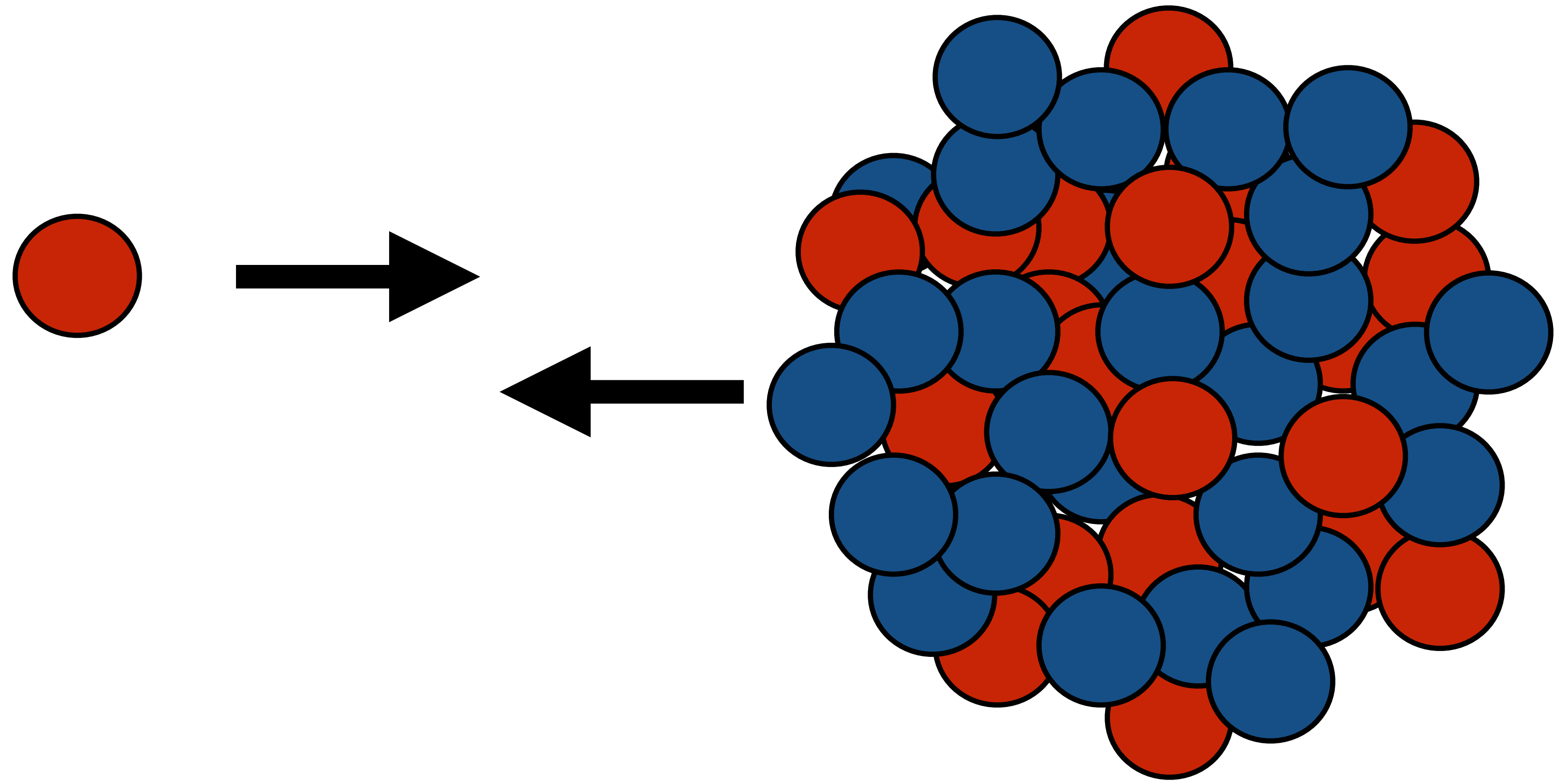
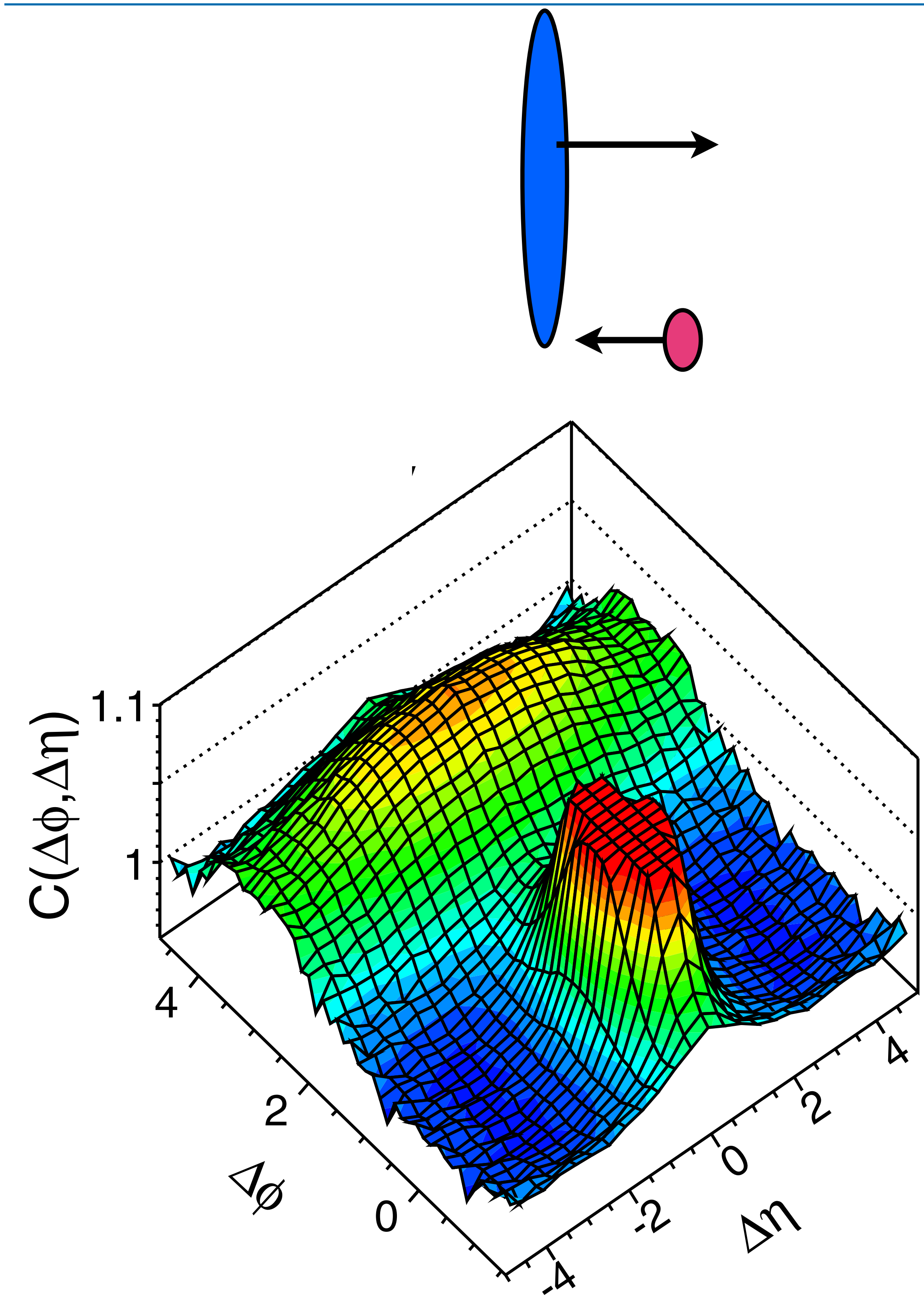
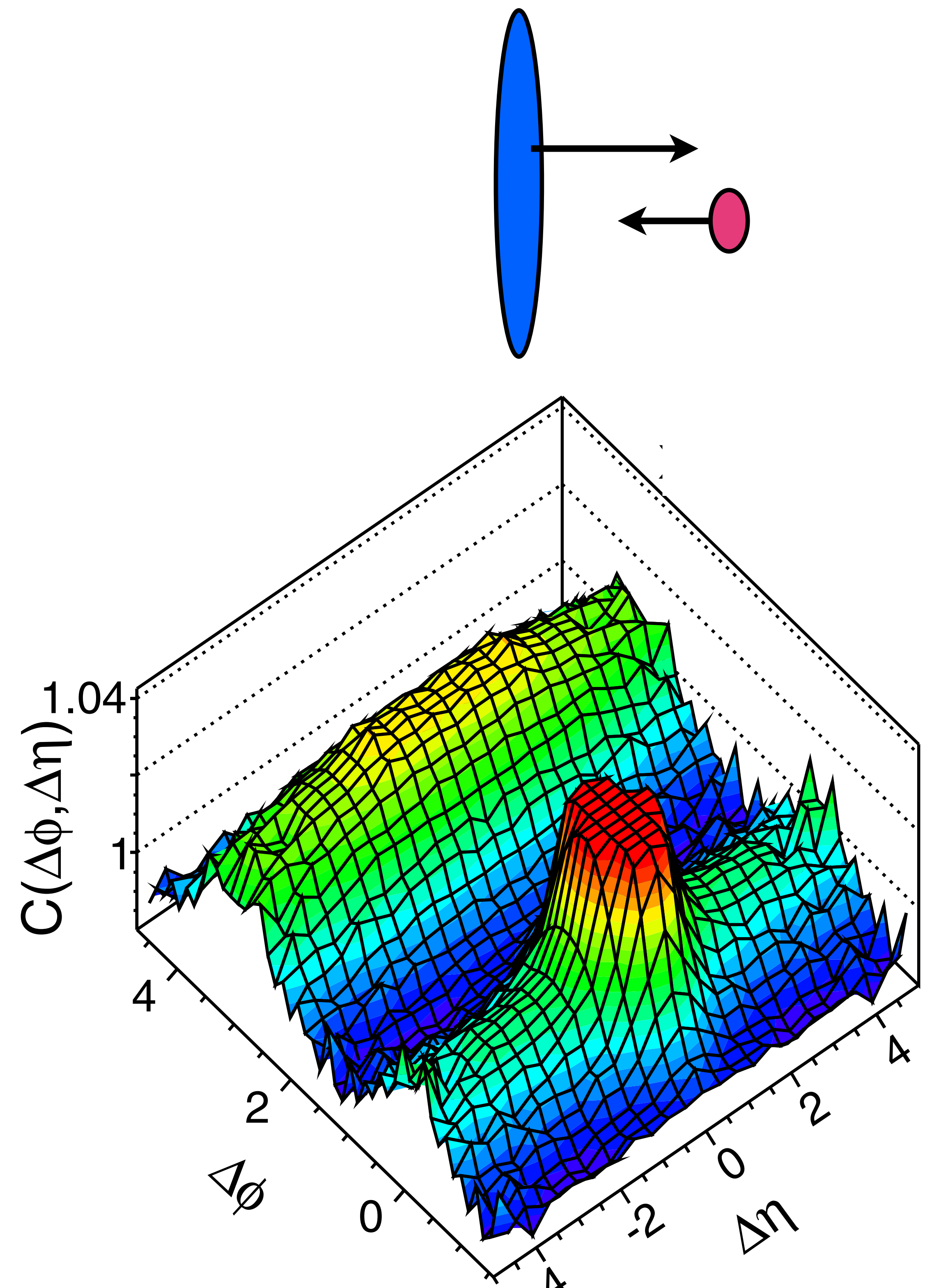


small, **but finite probe**,
big target
create a small tube of amount of QGP

a closer look at pPb



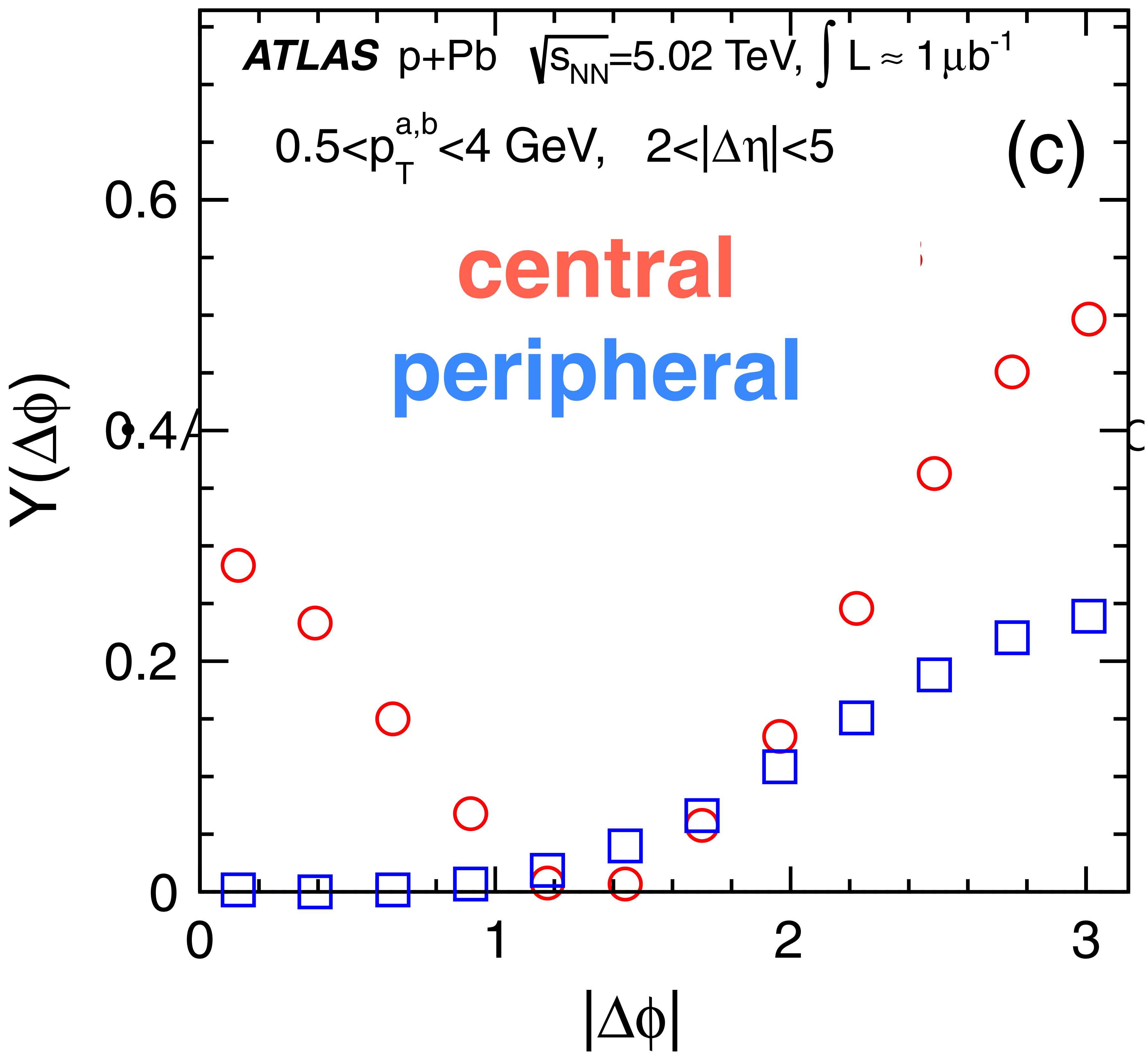
jets



jets + flow

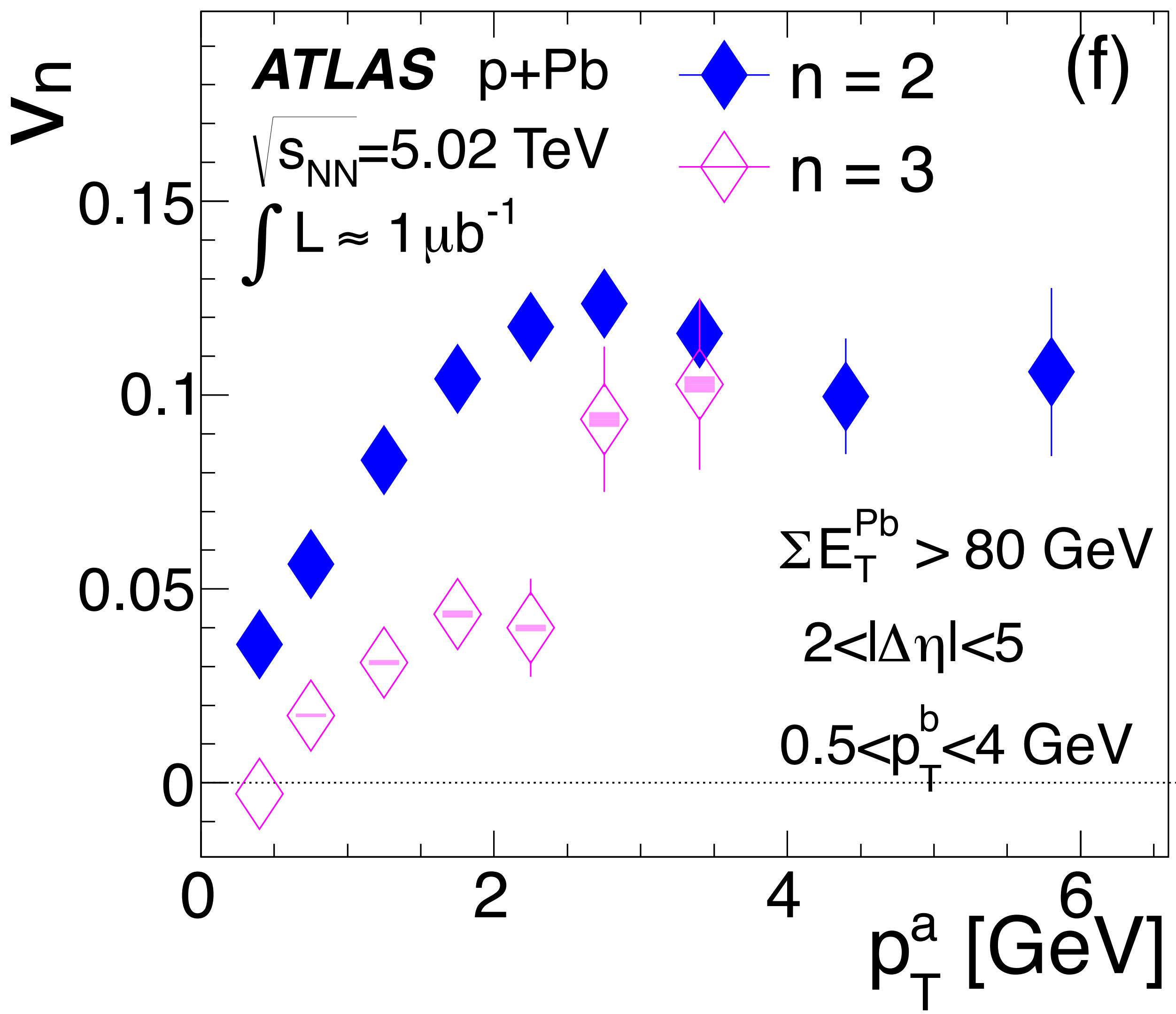
ATLAS PRL 110 102303

a closer look at pPb

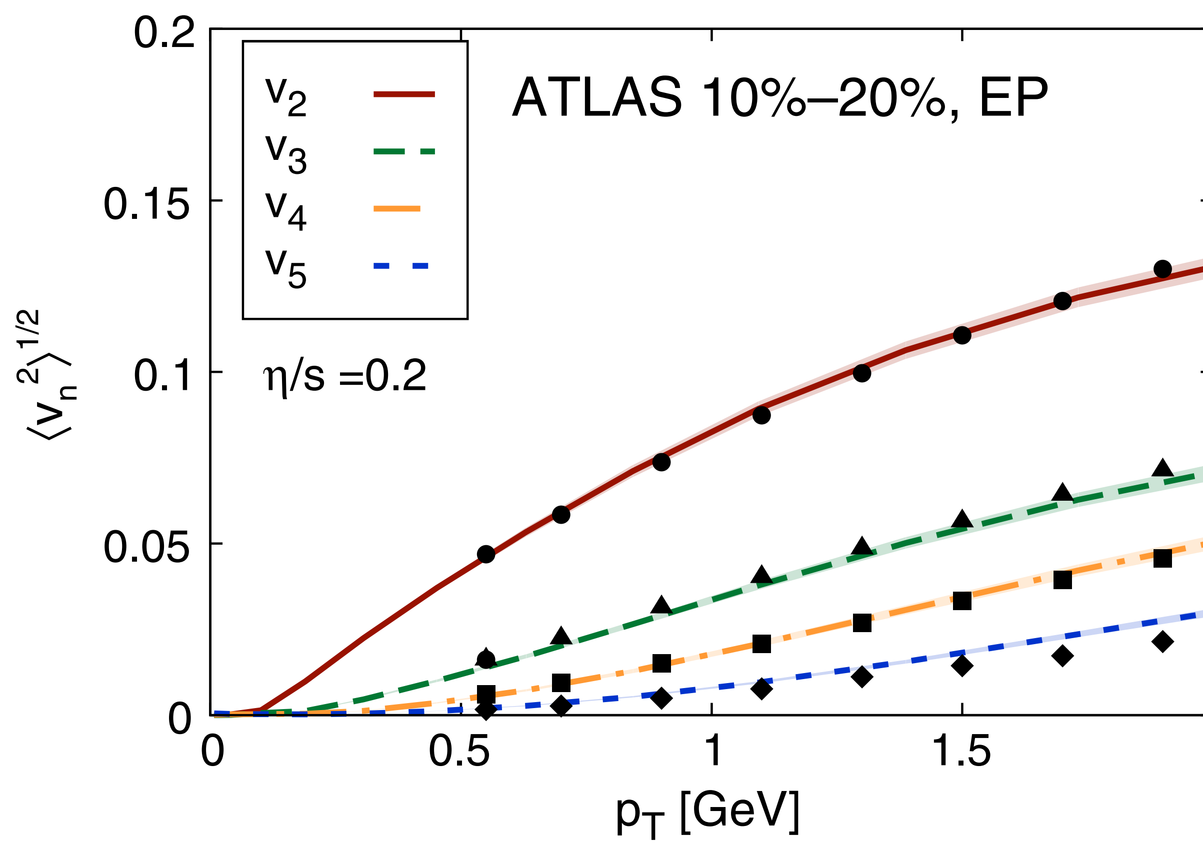


ATLAS PRL 110 102303

v_2 & v3 in pPb collisions



very similar to AA results



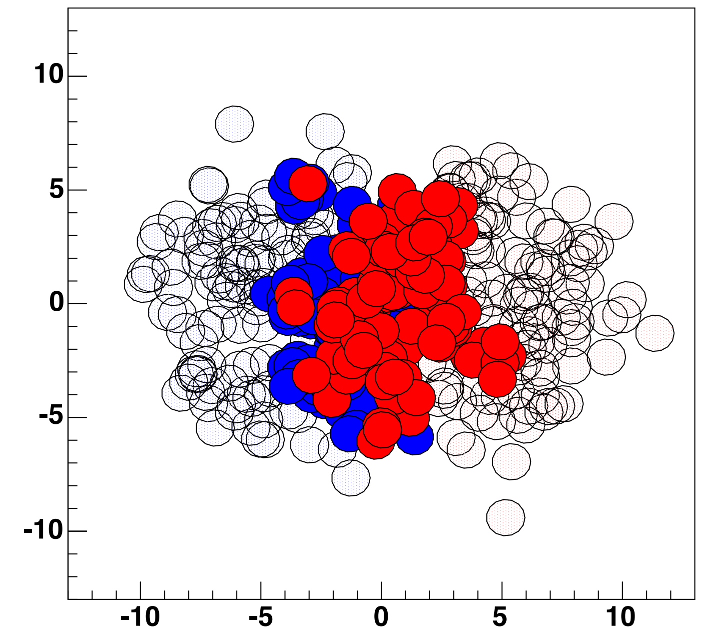
are the pA and AA v_2 related to the same physics?

ATLAS PRL 110 102303

geometry in AA & pA

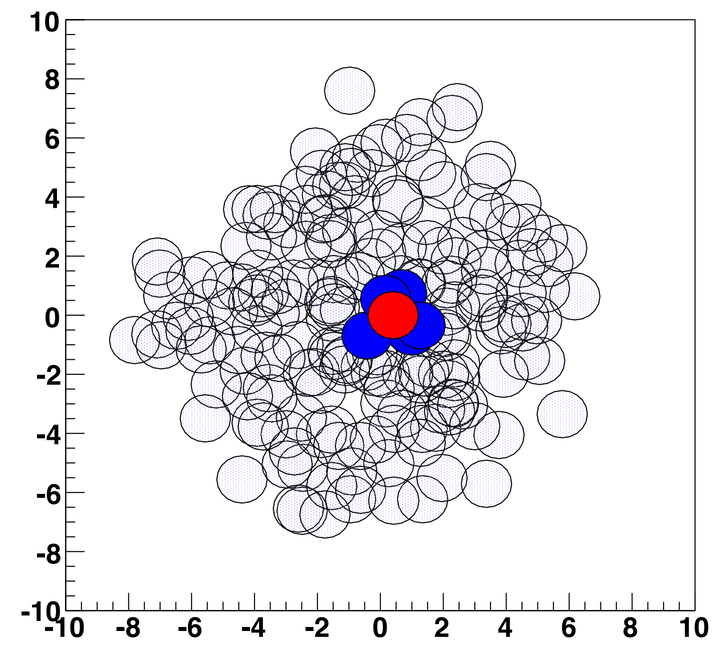
AA

impact parameter
+ fluctuations



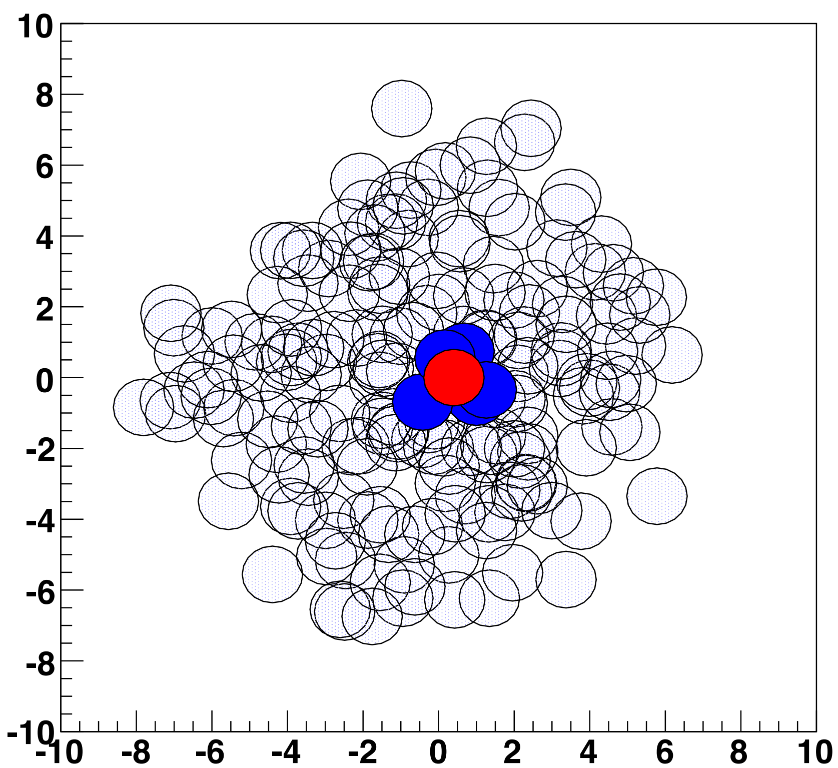
pA

fluctuations

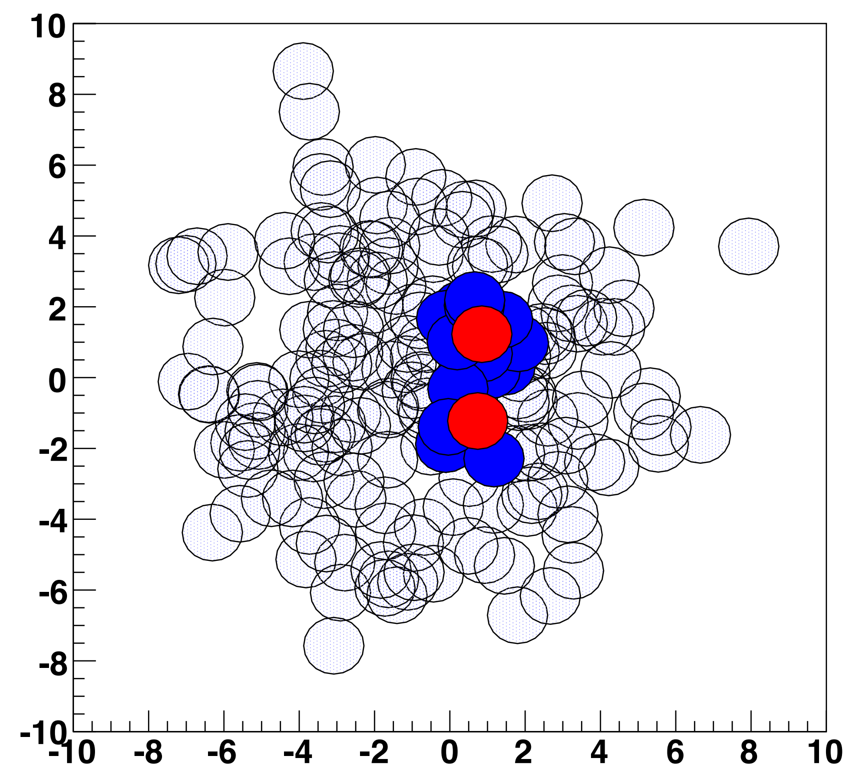


variation of the small nucleus

pA



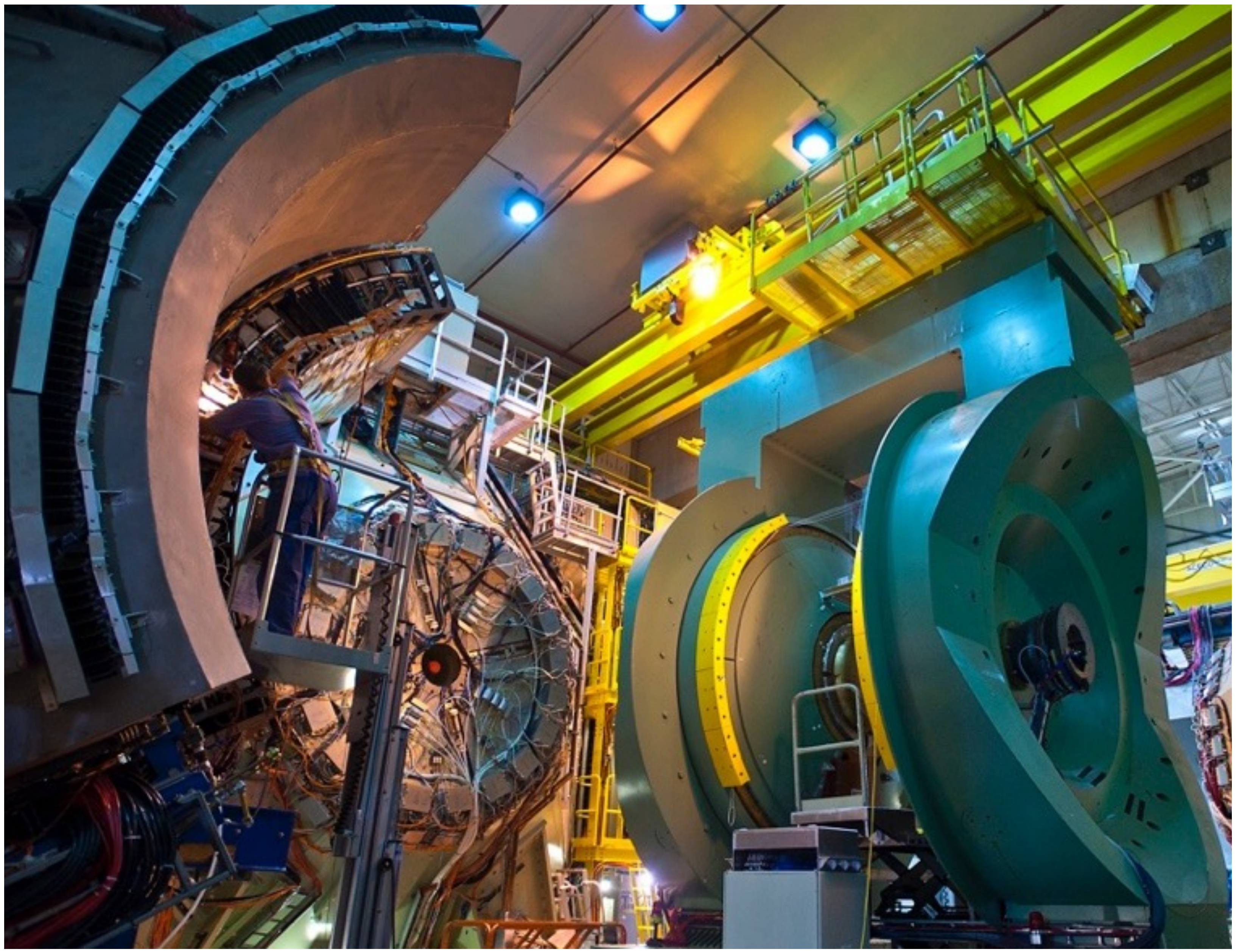
dA



control the collision geometry by varying the small nucleus

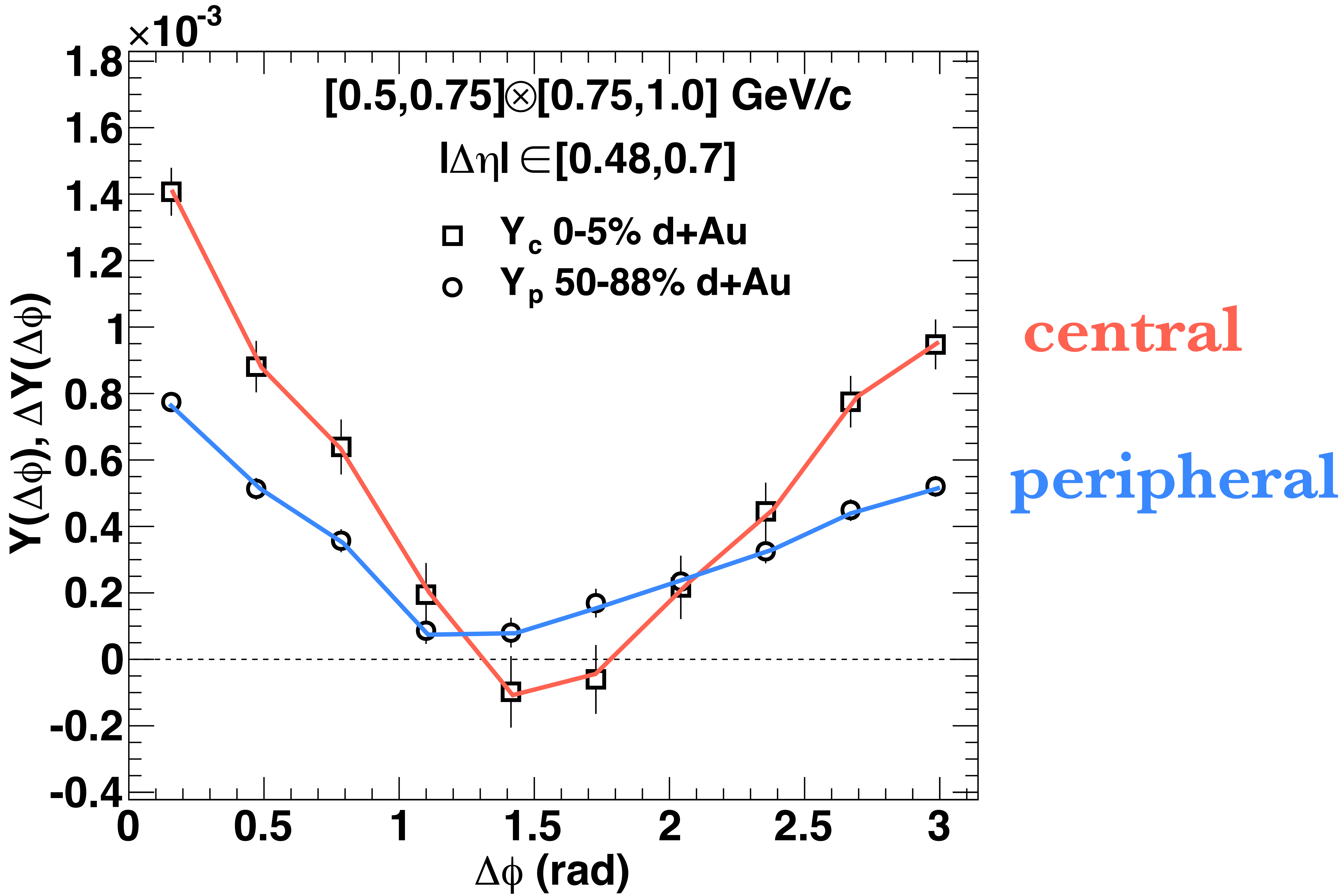
does v2 reflect the geometry of the initial state in p/d+A as in A+A?

PHENIX



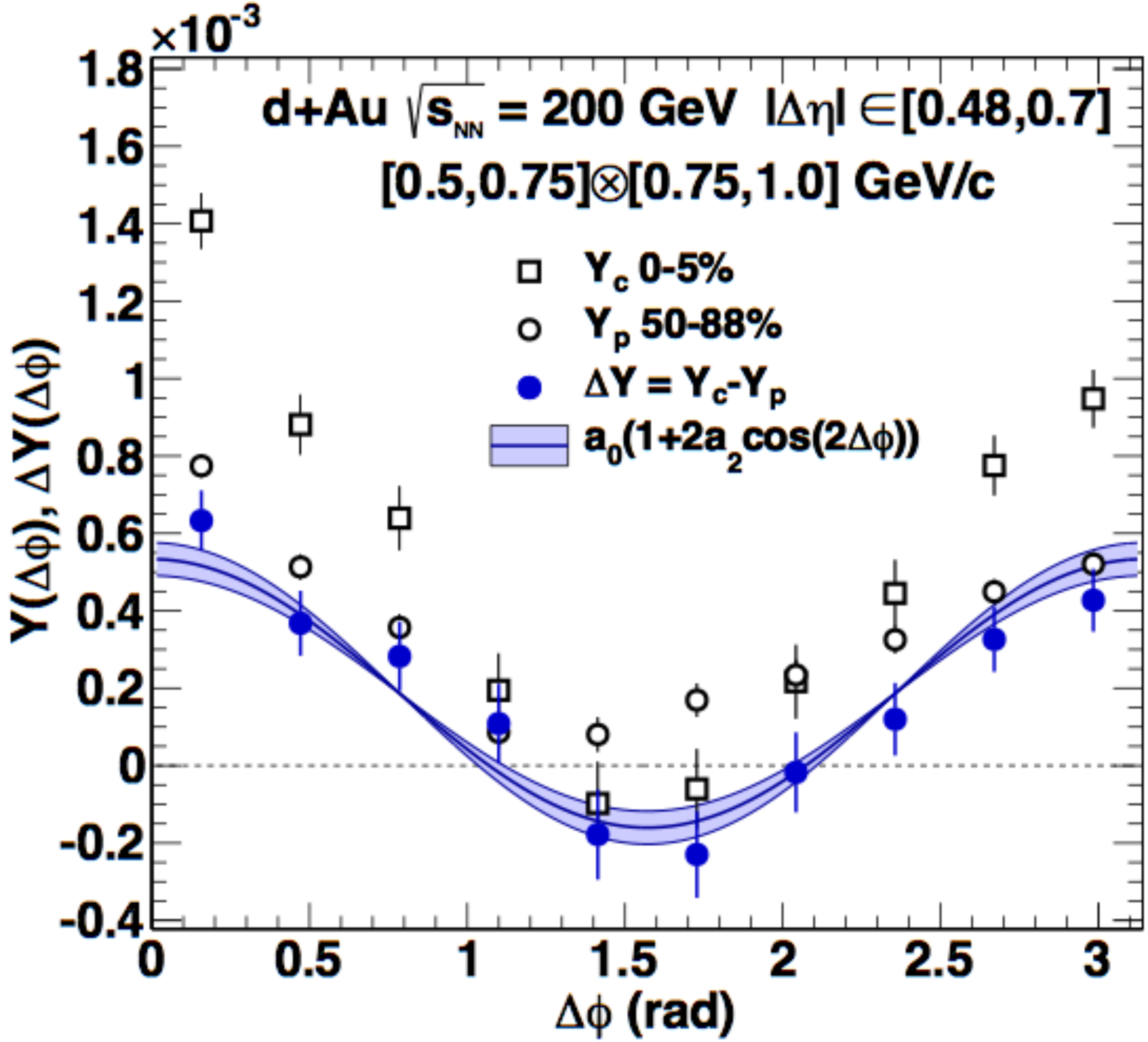
- charged hadrons
  - $|\eta| < 0.35$
  - $|\Delta\eta| < 0.7$
- → no long range sensitivity with only charged particles

two particle correlations in dAu



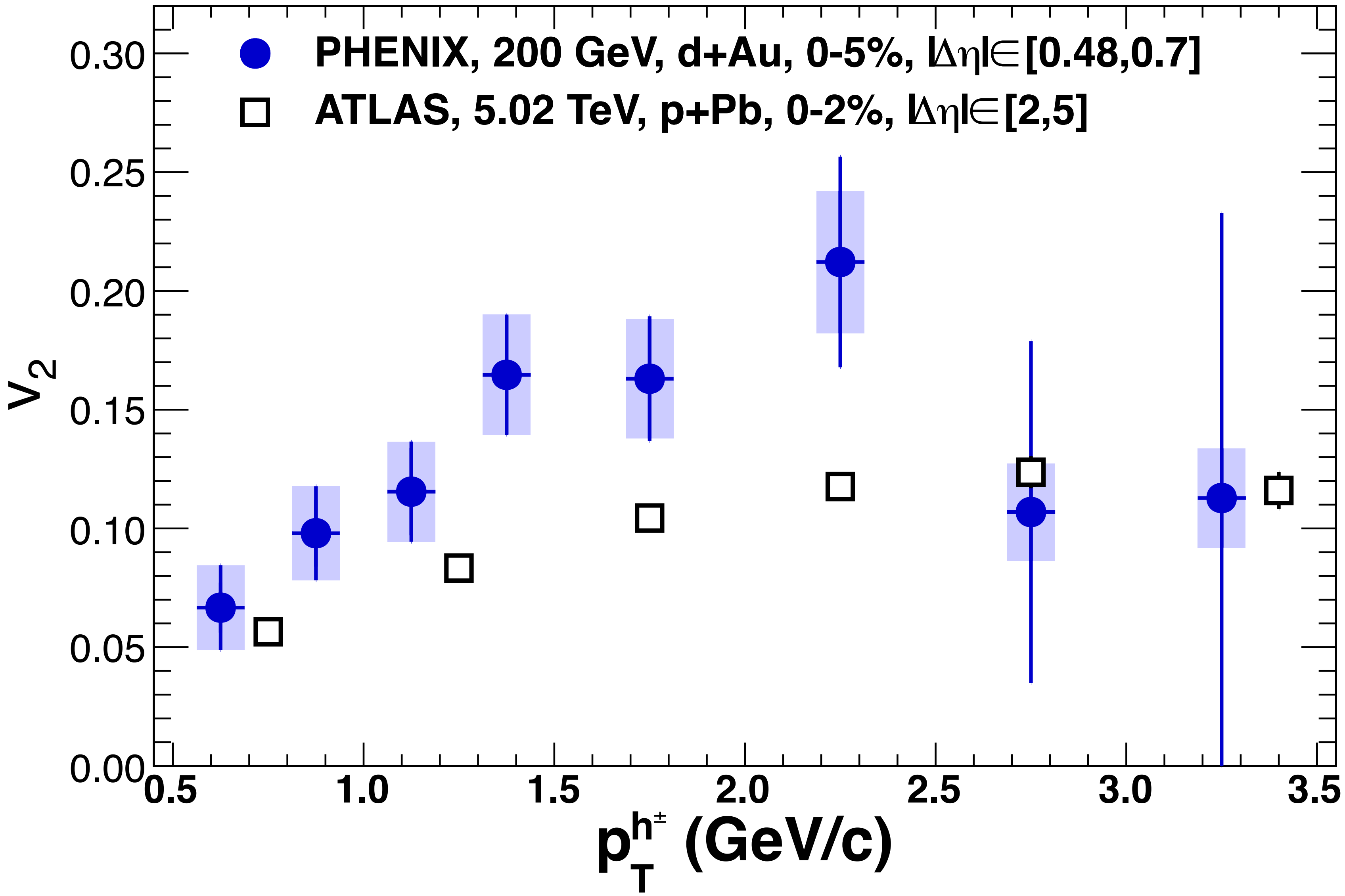
PHENIX PRL 111 212301

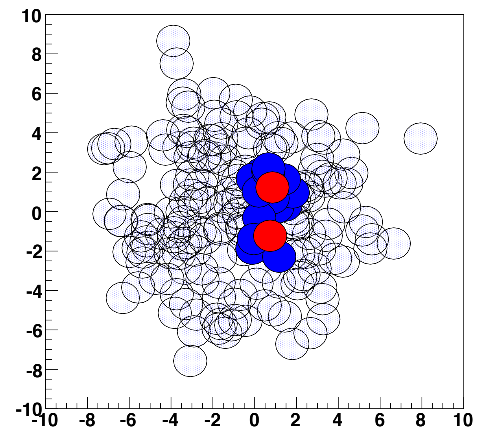
centrality dependence

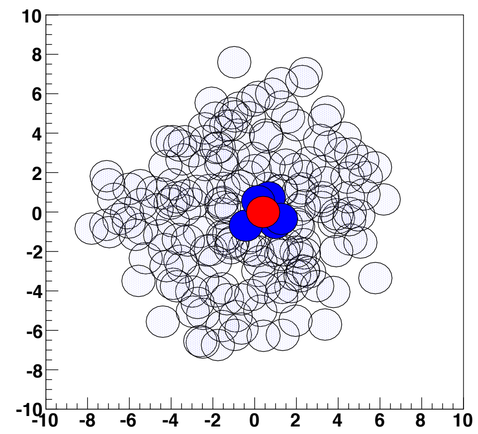


PHENIX PRL 111 212301

v2: pPb & dAu





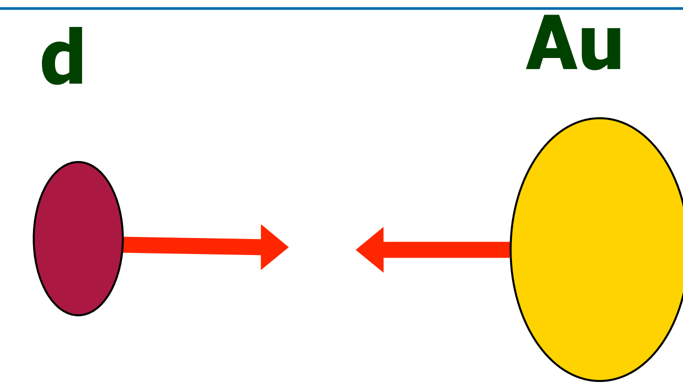


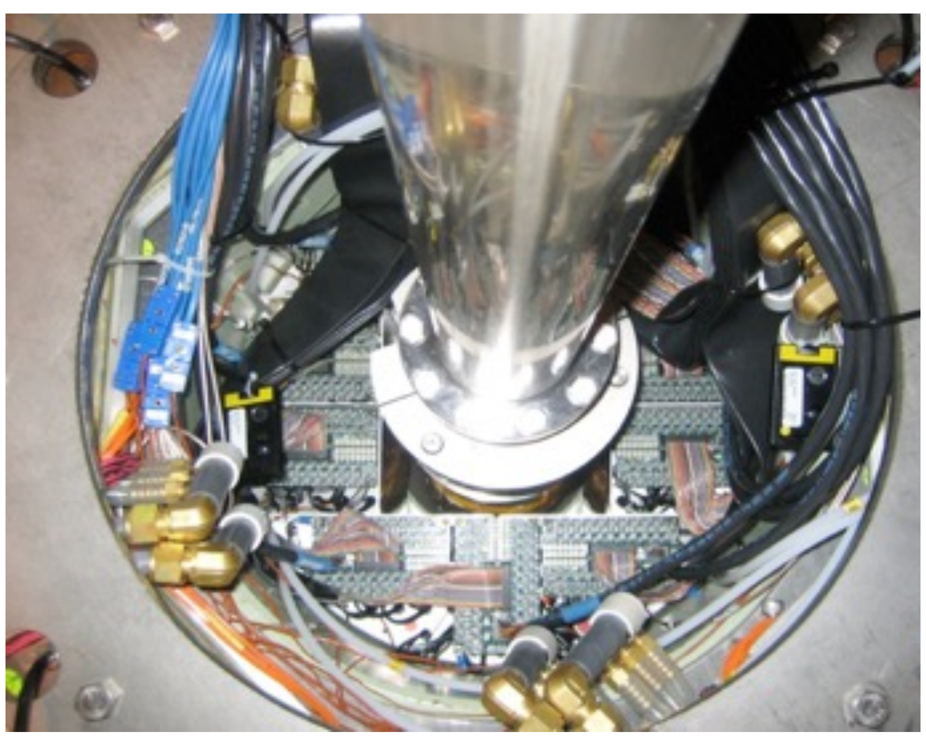
PHENIX PRL 111 212301 (2013)
ATLAS PRL 110 182302 (2013)

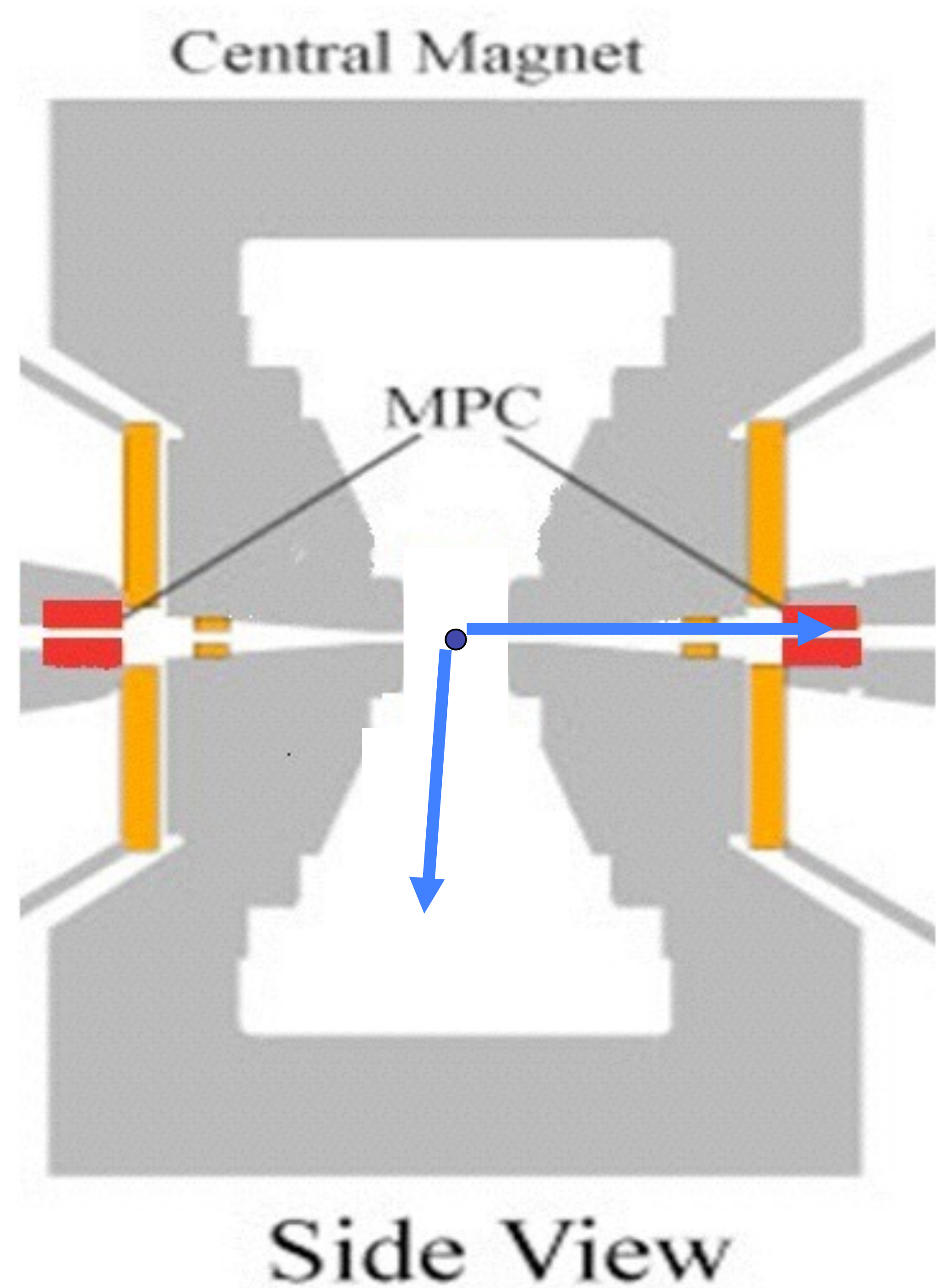
rapidity separated correlations

Muon Piston Calorimeters

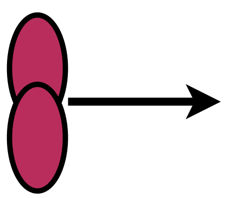
both d-going & Au-going directions
3 < |η| < 4



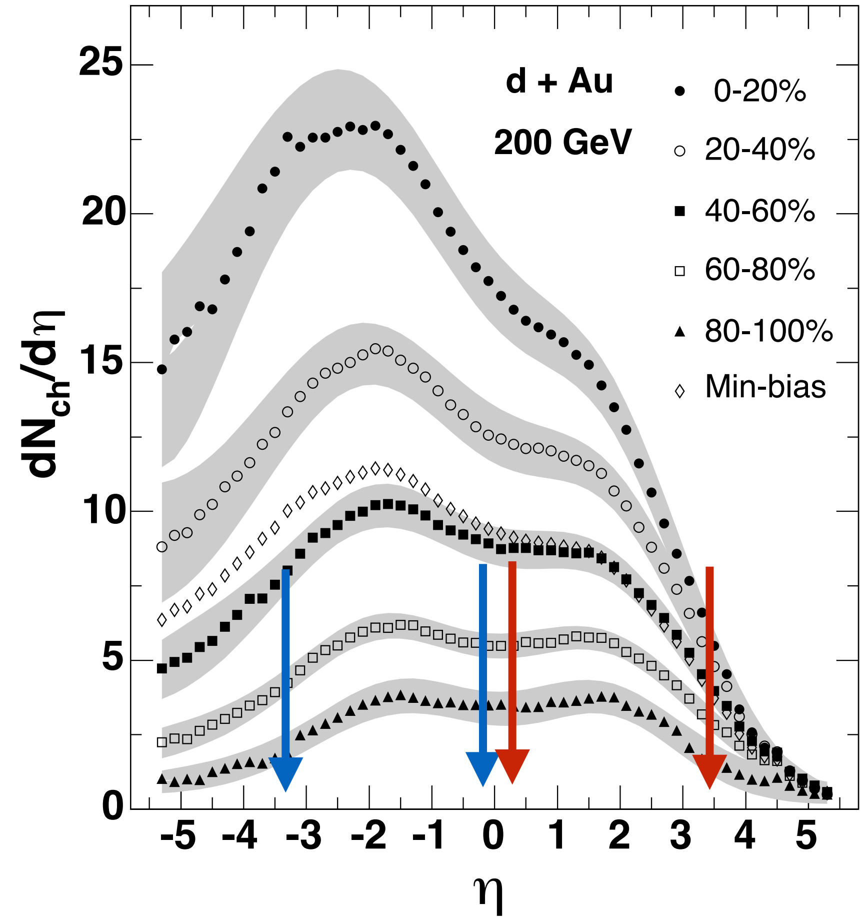


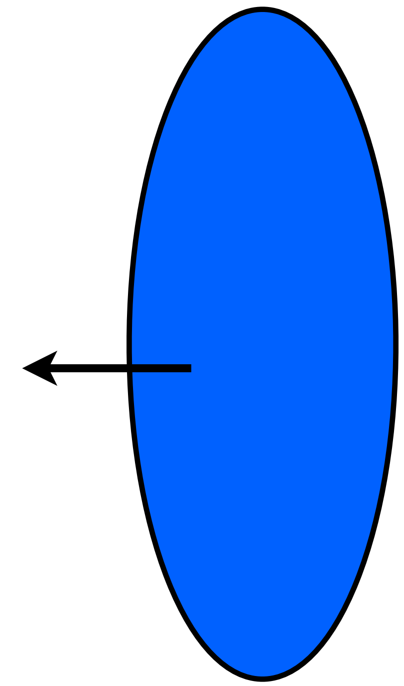


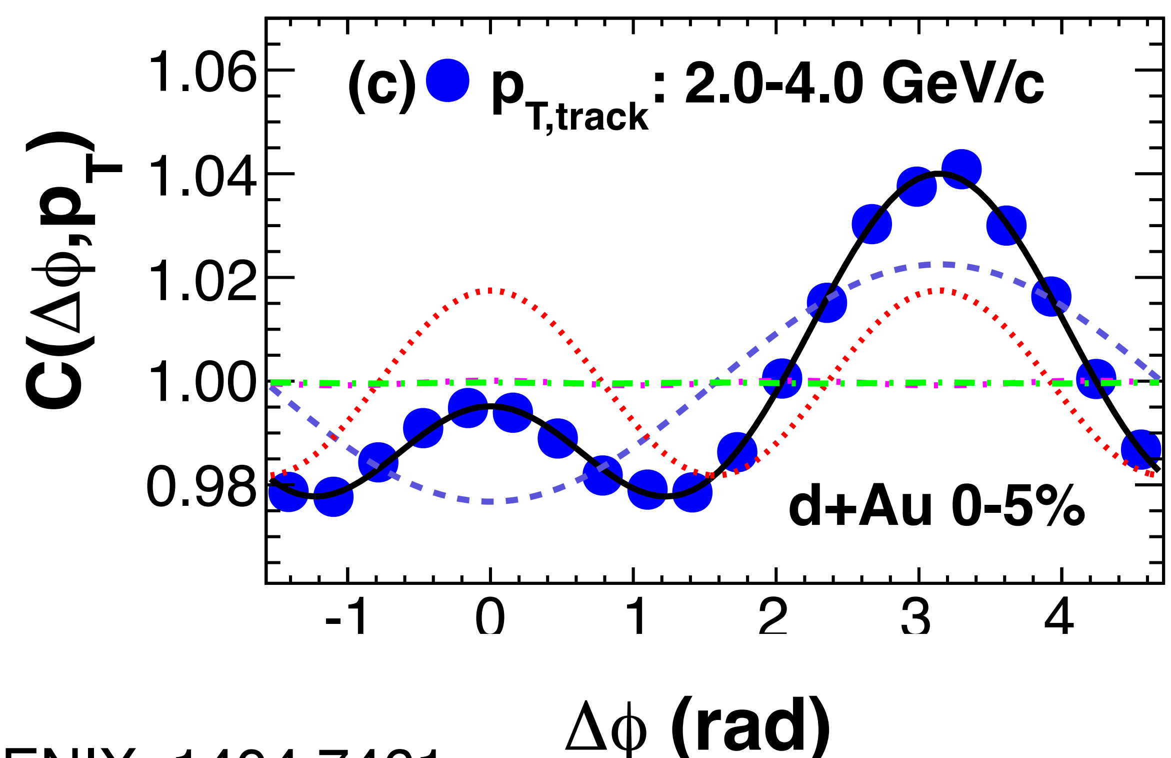
long range correlations in dAu

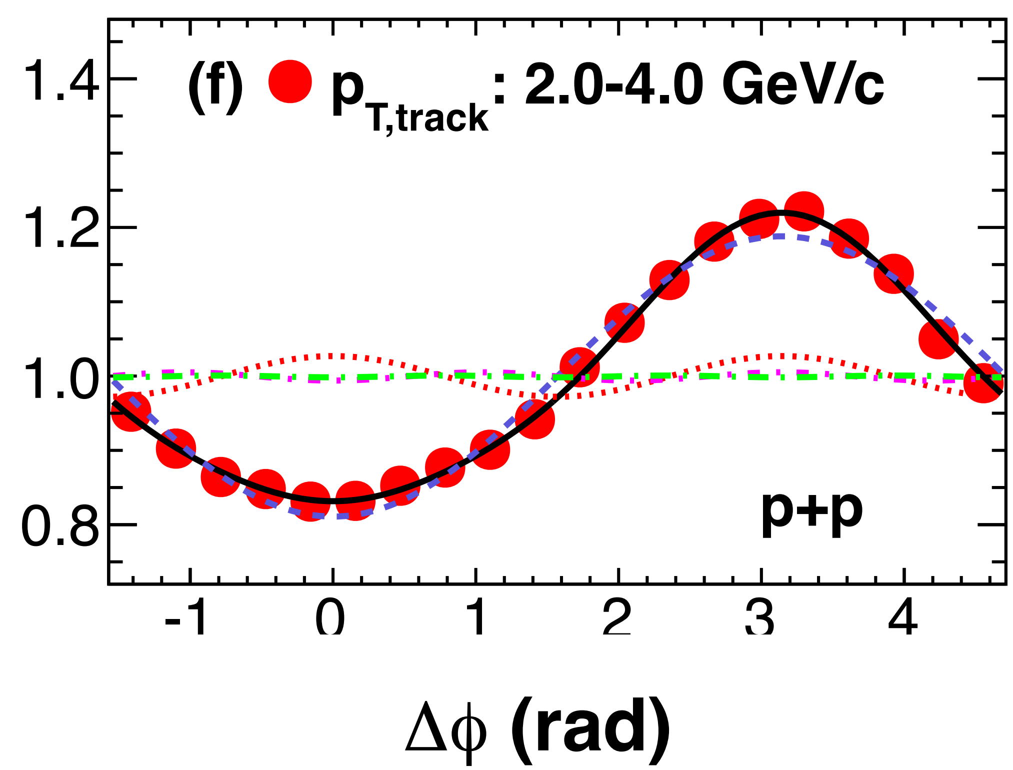


PHOBOS PRC72 031901



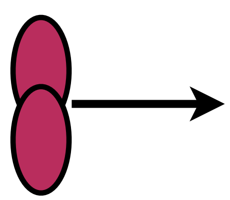


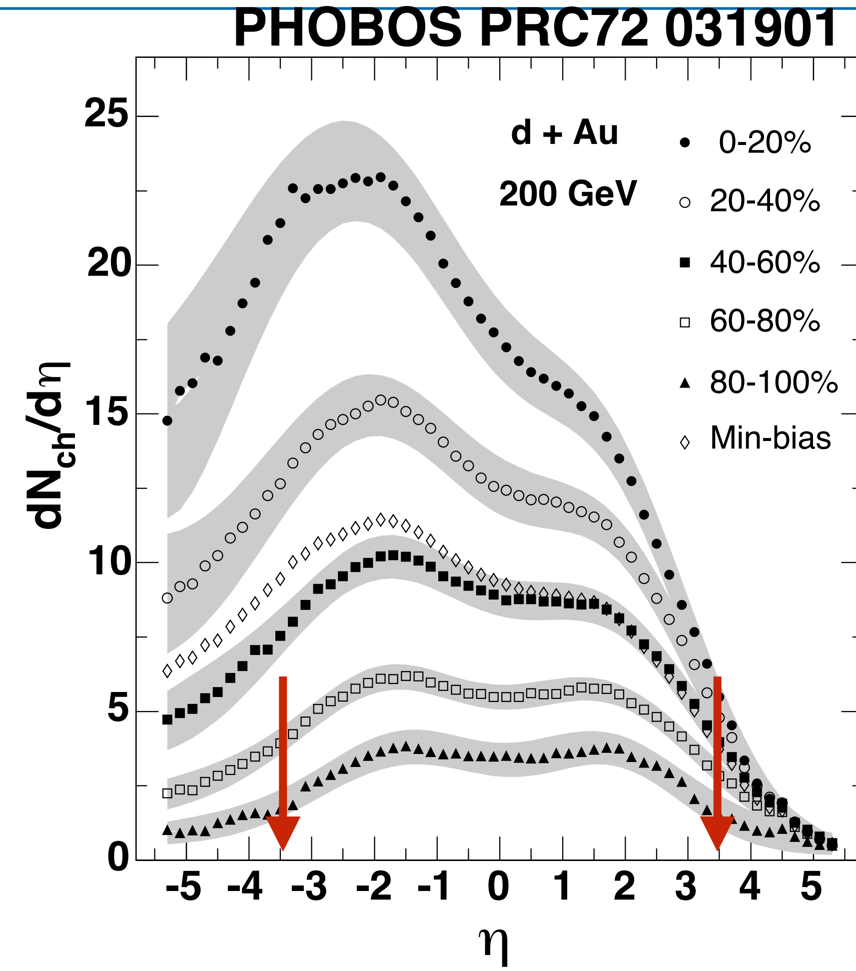


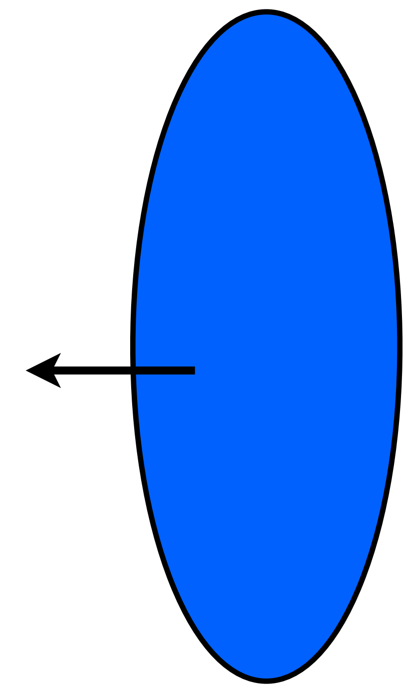


PHENIX: 1404.7461

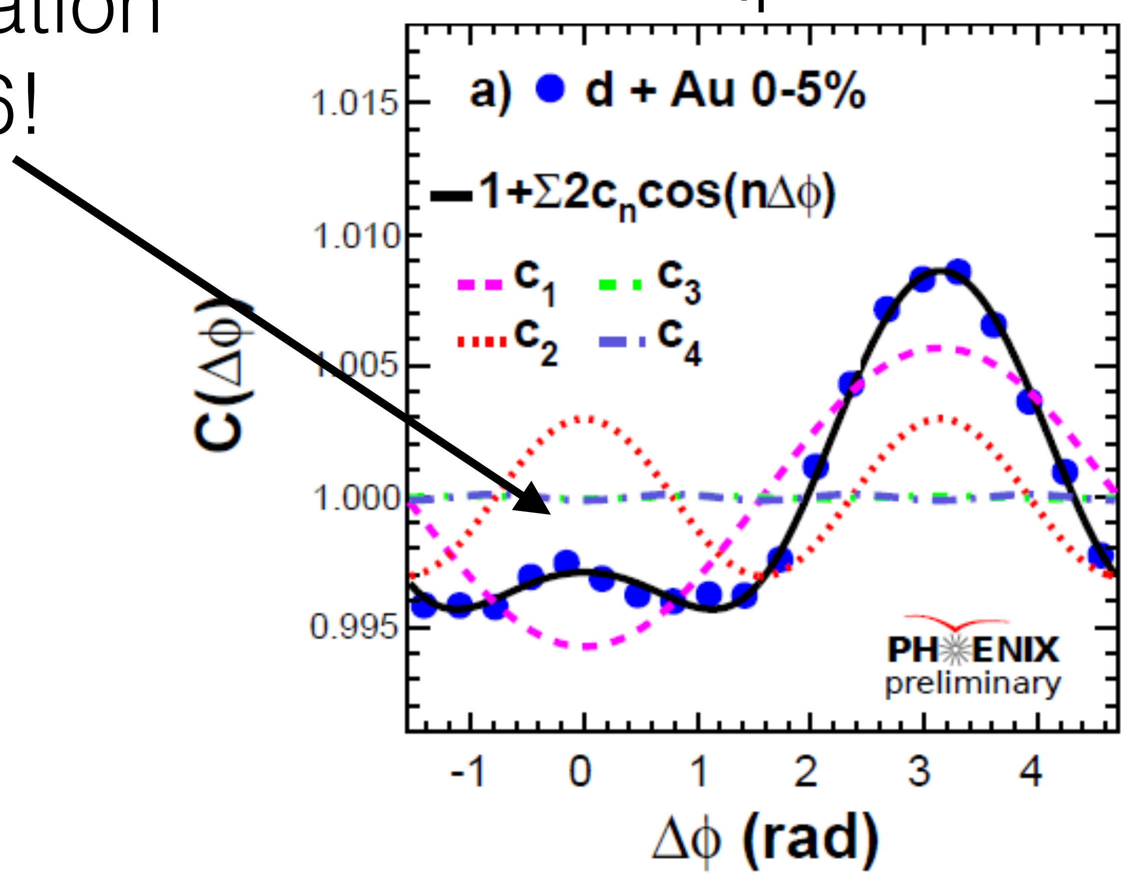
long range correlations in dAu





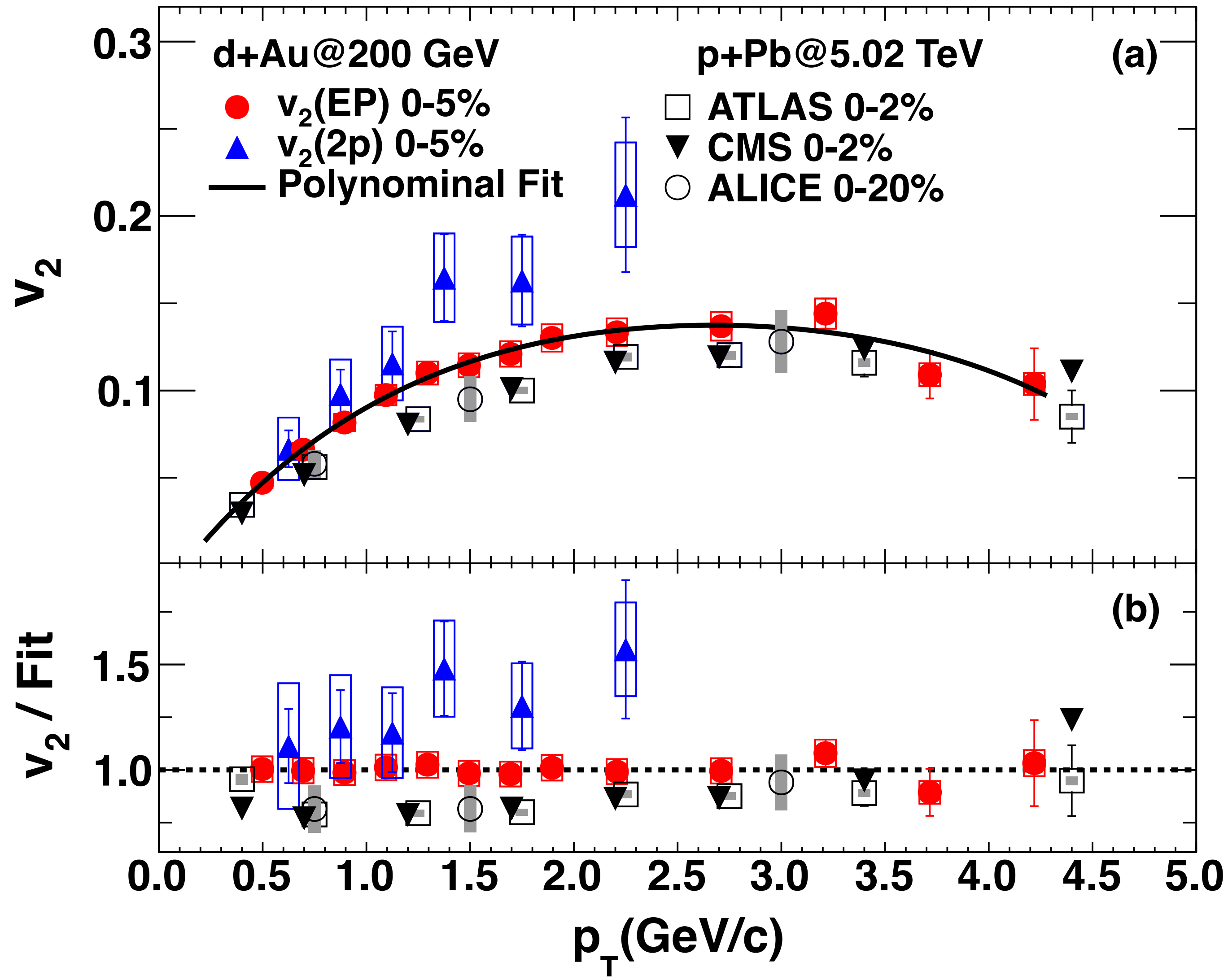


ridge correlation
for |η| > 6!



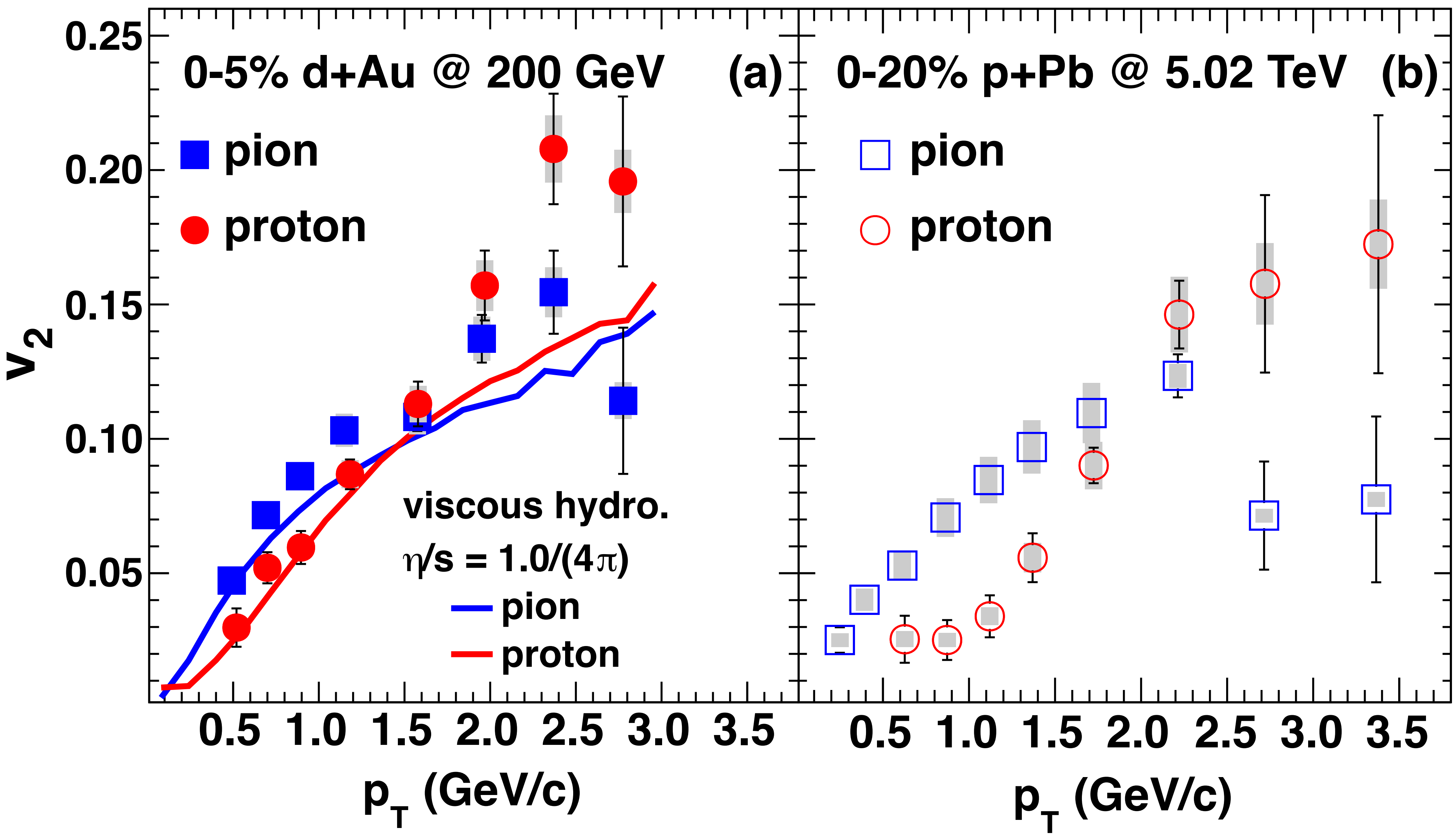
long range d+Au v_2

- event plane reconstructed @ η = 3-4, v_2 of particles @ |η| < 0.35
- true long range correlations
- v_2 slightly reduced from 2PC method



PHENIX: 1404.7461

particle mass dependence

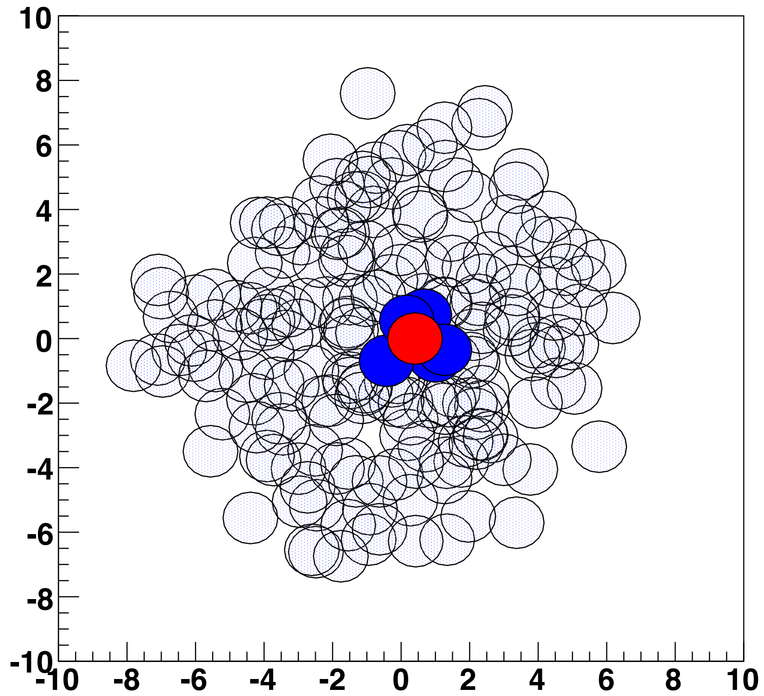


- characteristic flow particle mass dependence
  - stronger radial flow at the LHC

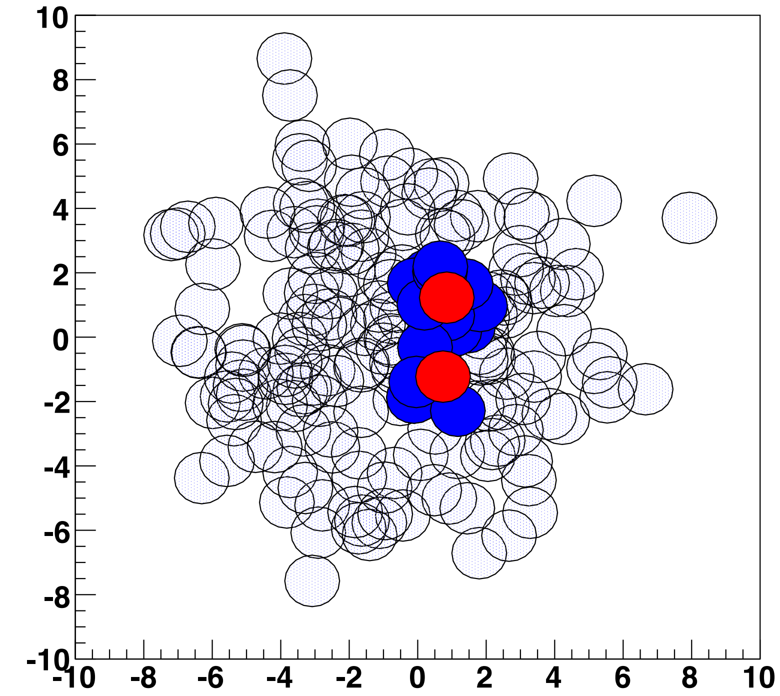
PHENIX: 1404.7461

shapes of pA & dA

pA, small ε_2



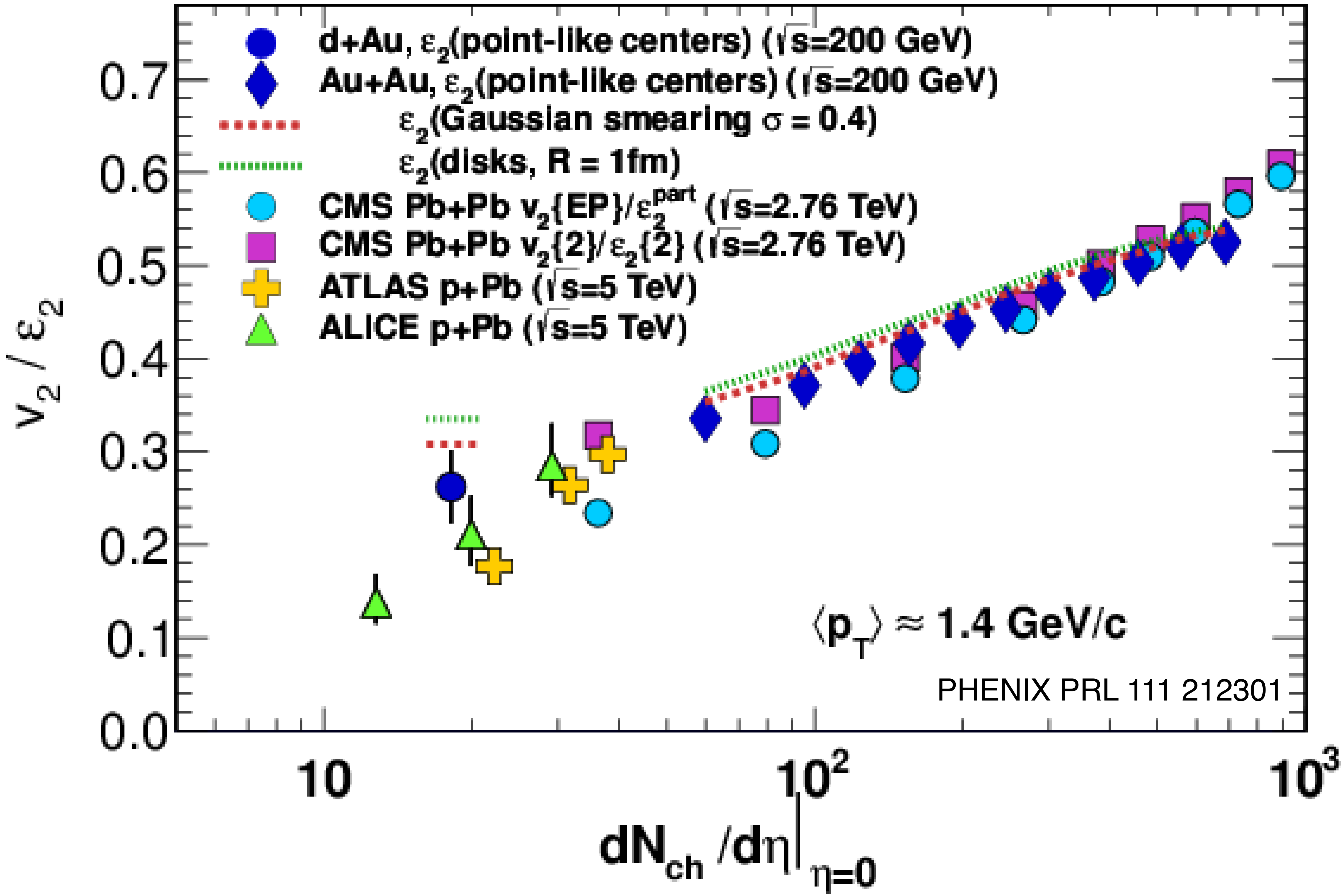
dA, large ε_2



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

used to determined $\langle \boldsymbol{\varepsilon}_n \rangle$ values for event selections

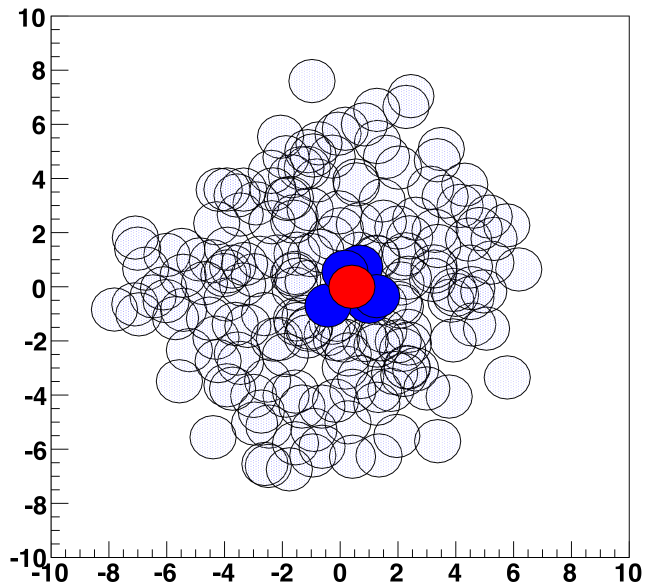
dAu, pPb, AuAu & PbPb



single trend, AA data understood as initial geometry + hydrodynamics

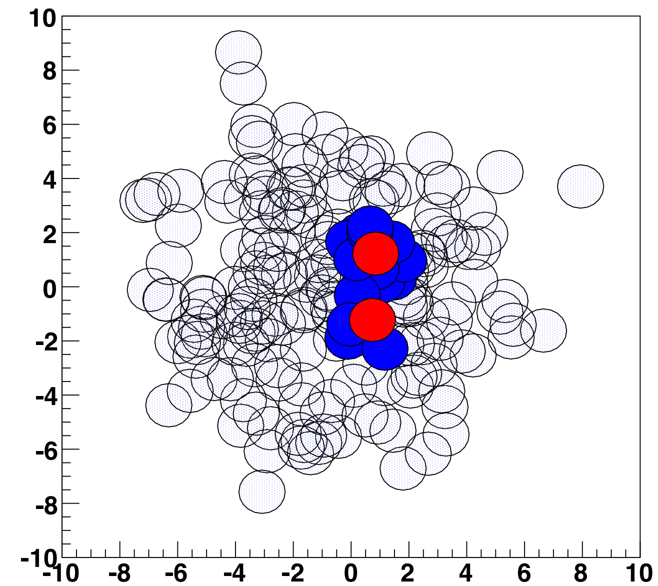
variation of the small nucleus

pA



small ε_2

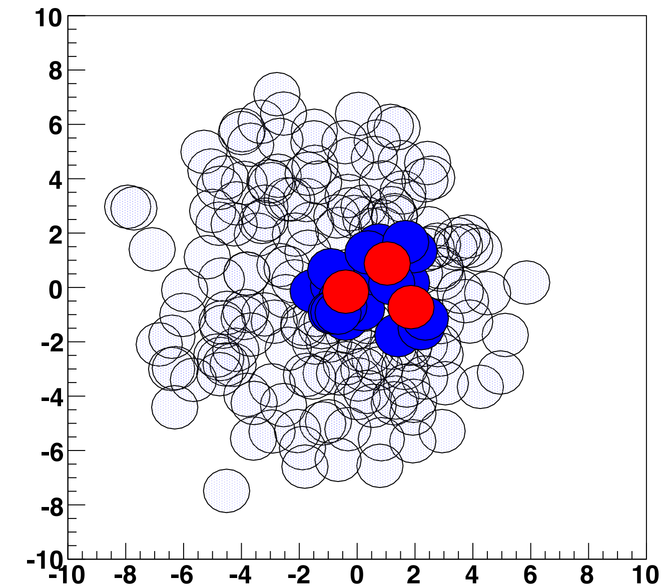
dA



large ε_2

small $\varepsilon 3$

^{3}HeA



large $\varepsilon 3$

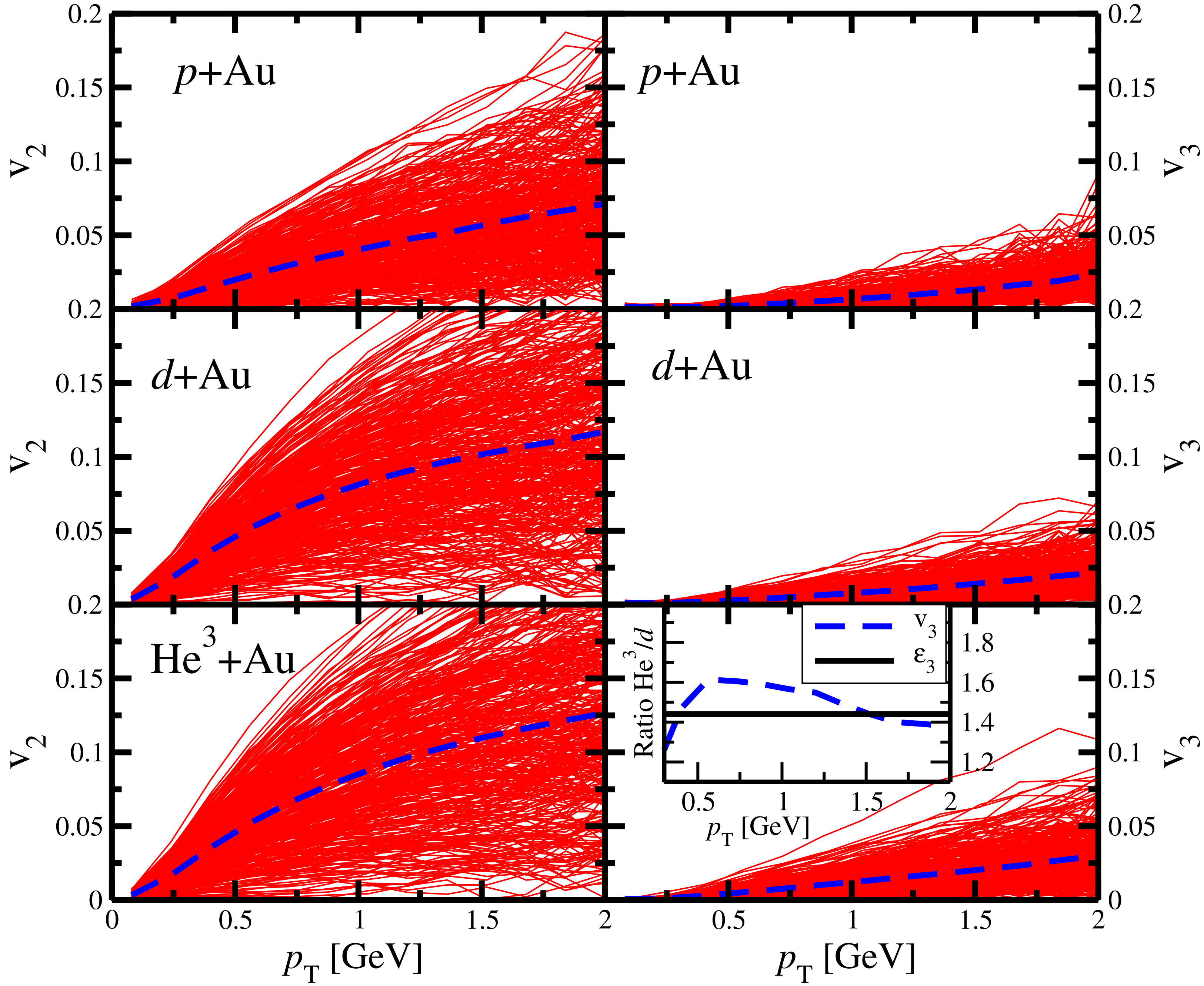
$$\varepsilon_n = \frac{\sqrt{\langle r^2 \cos n\phi \rangle^2 + \langle r^2 \sin n\phi \rangle^2}}{\langle r^2 \rangle}$$

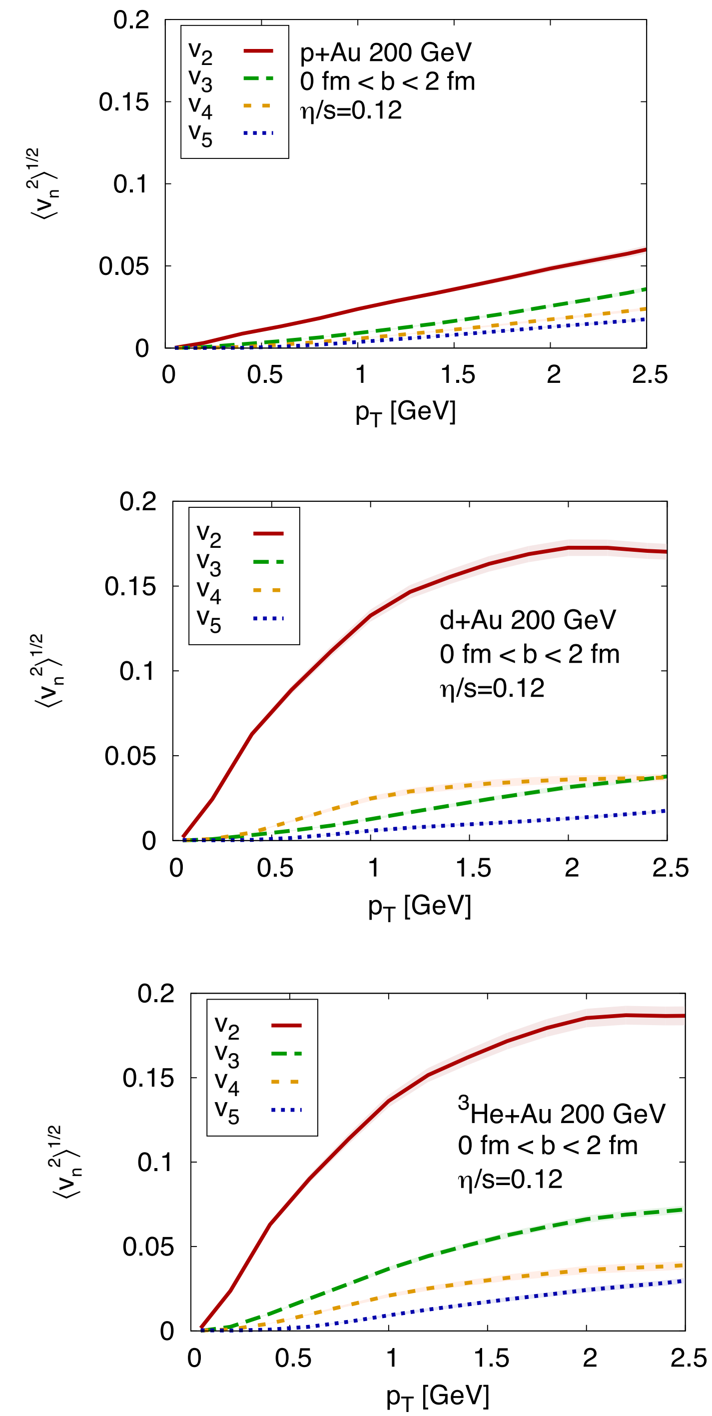
control the collision geometry by varying the small nucleus

theory calculations, b<2fm

IP-Glasma + MUSIC (2+1d)

nucleons: Gaussians, σ = 0.7fm

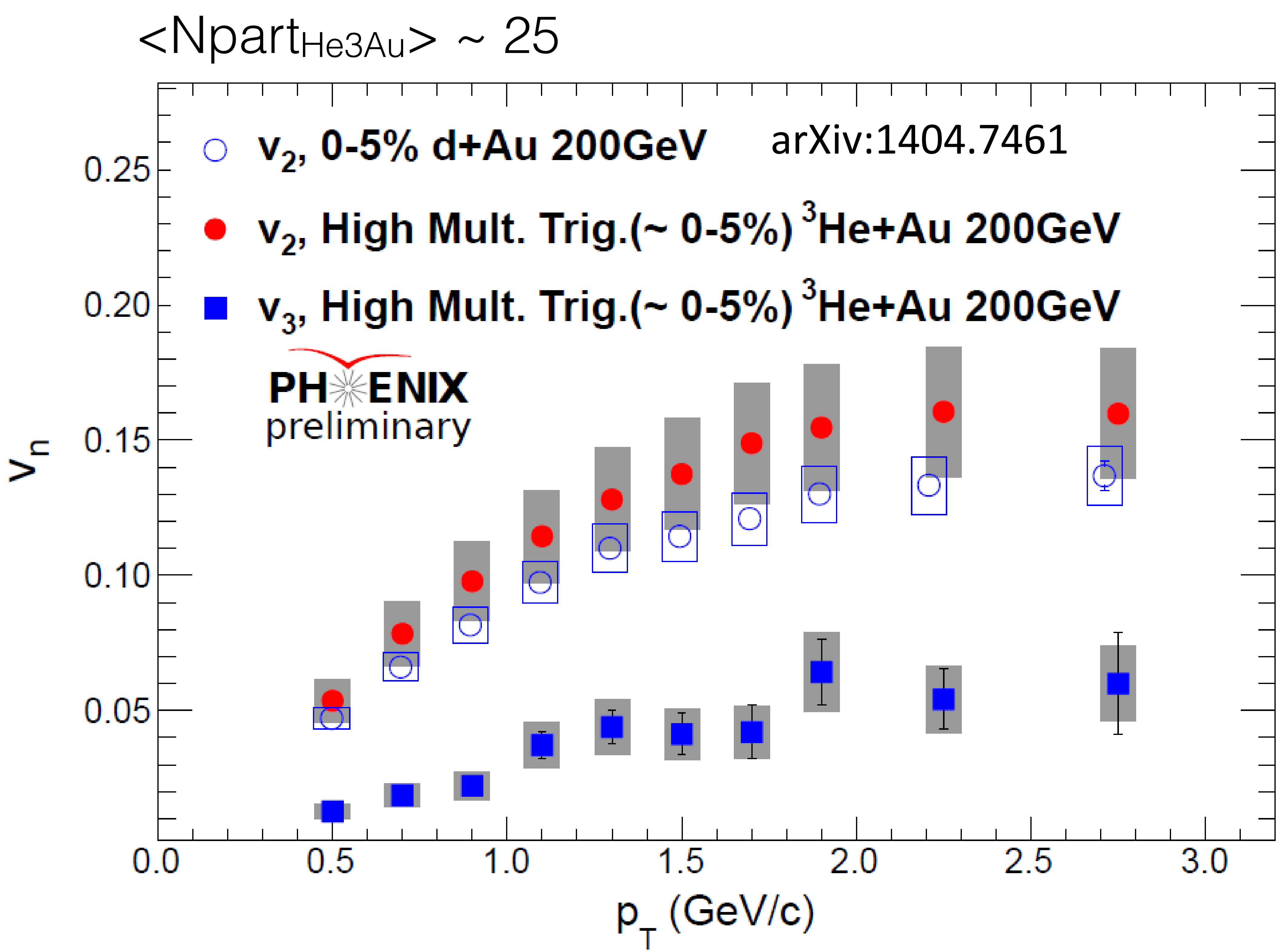




J.L. Nagle, et al PRL 113 112301

Schenke & Venugopalan: 1407.7557

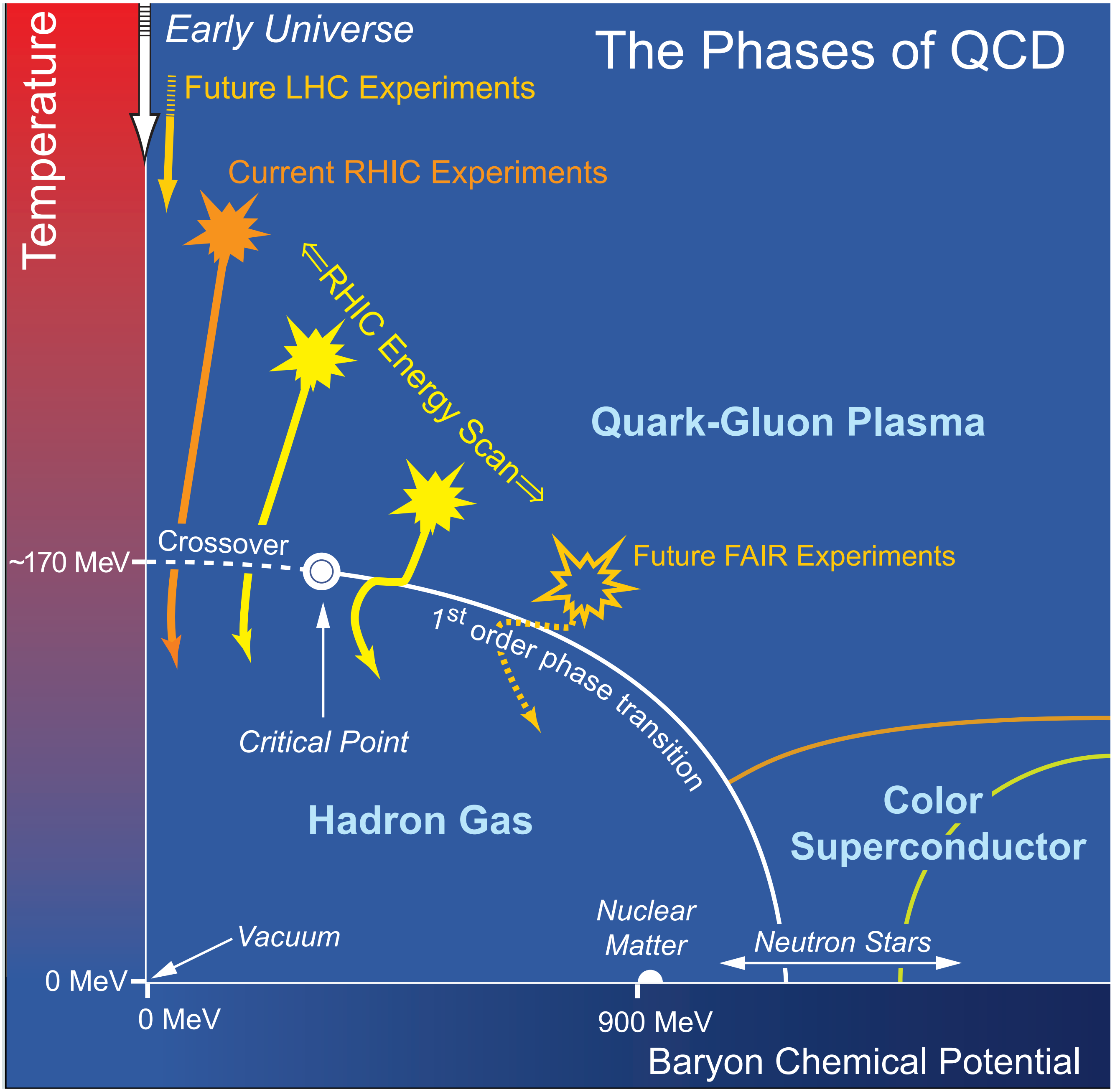
He3+Au: first data!



v3 ~ hydrodynamic expectations

why heavy ion collisions?

- explore QCD away from normal bound states
- only "large" system we can study with partonic degrees of freedom

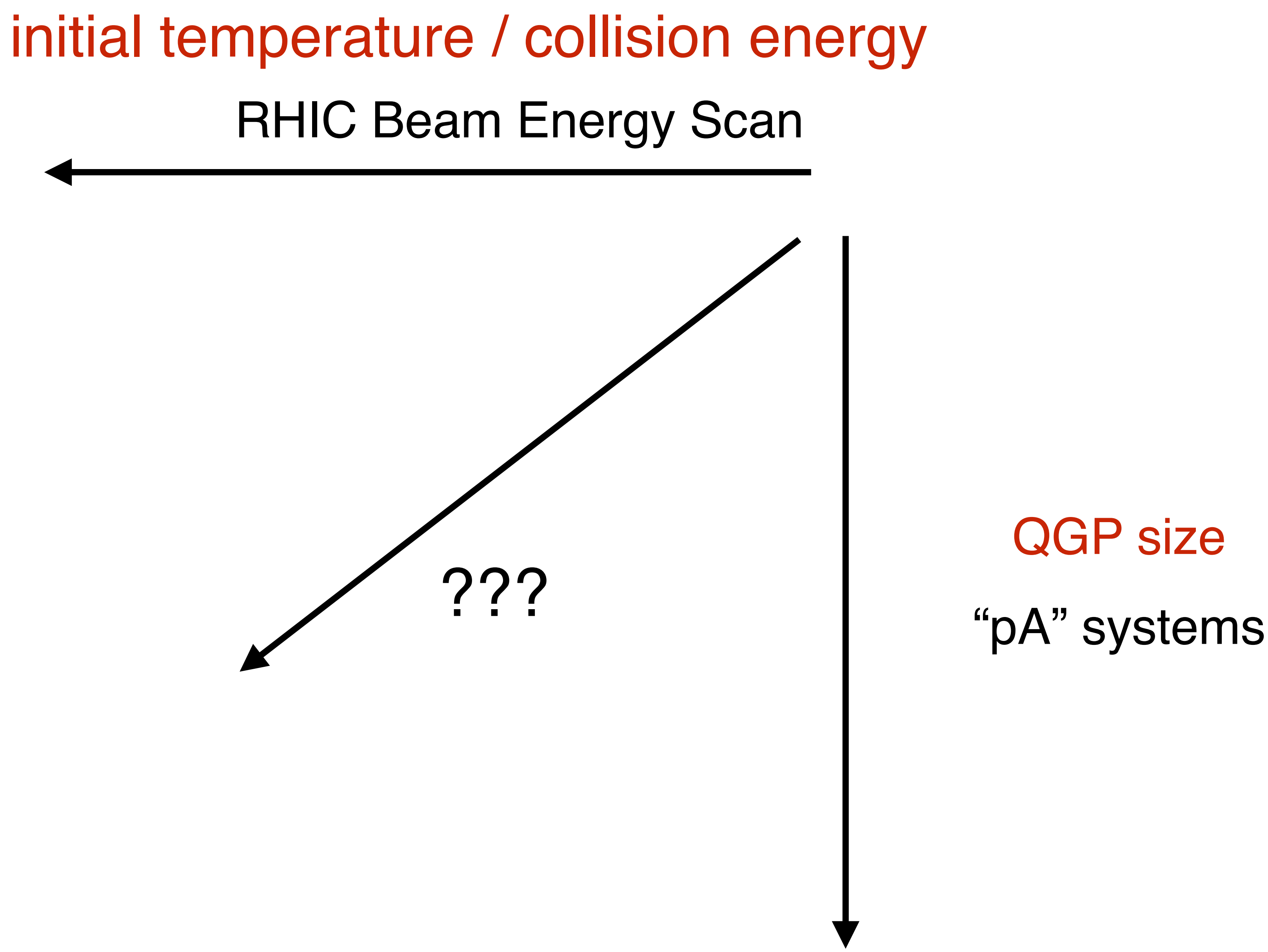


what does "large" mean?

how does the system become a QGP?

challenge to theory, suggestive experimentally, great opportunity to learn

smaller and cooler



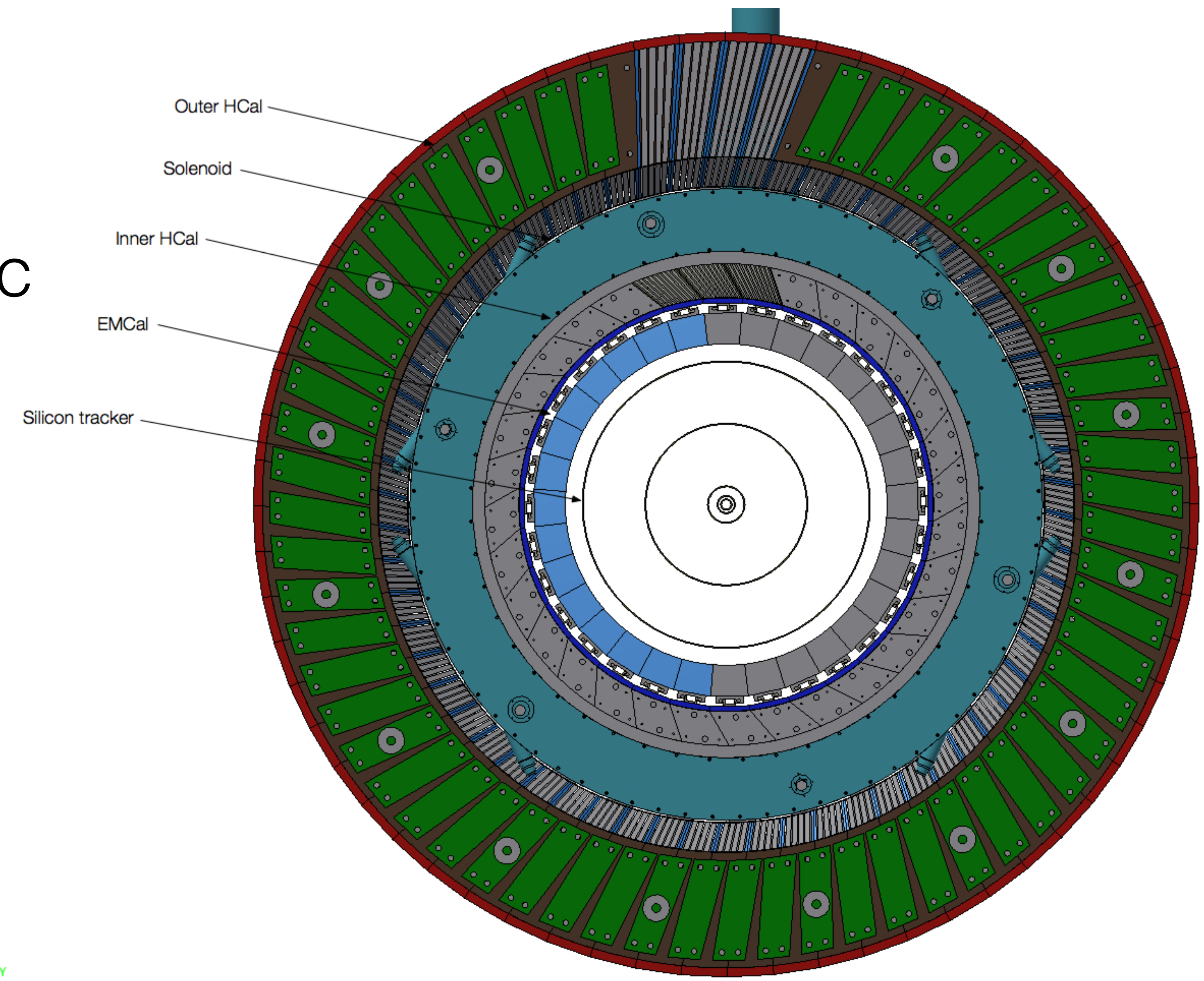
pA collisions: how is the QGP formed, how does it thermalize, what is the initial energy density distribution?

importance of RHIC & LHC

slide from Peter Steinberg JQRL 4/13

sPHENIX

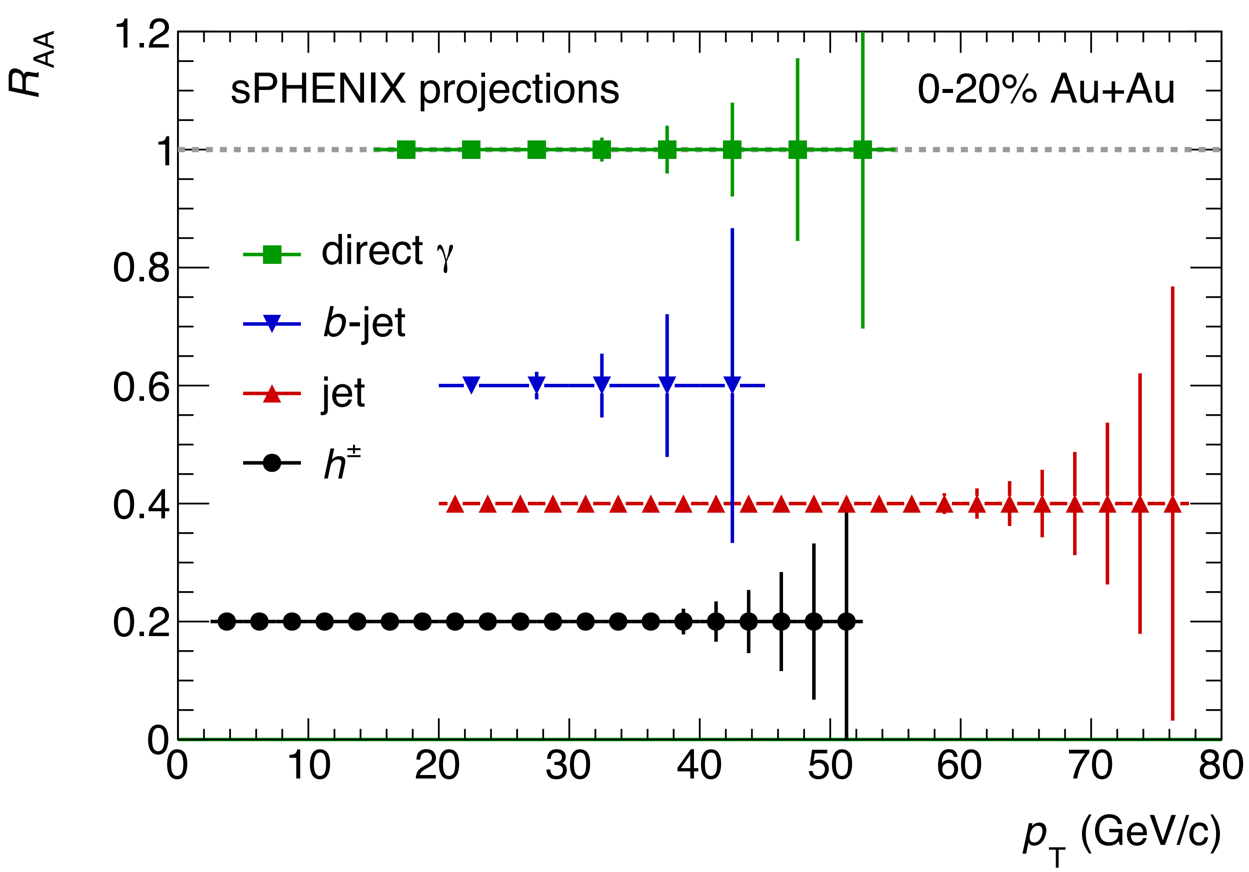
- EMCal + HCal
- used at ATLAS & CMS
- triggering on EM & hadronic energy
- high efficiency → maximal kinematic reach
- minimal bias on how the jet fragments
- independent of tracking measurements

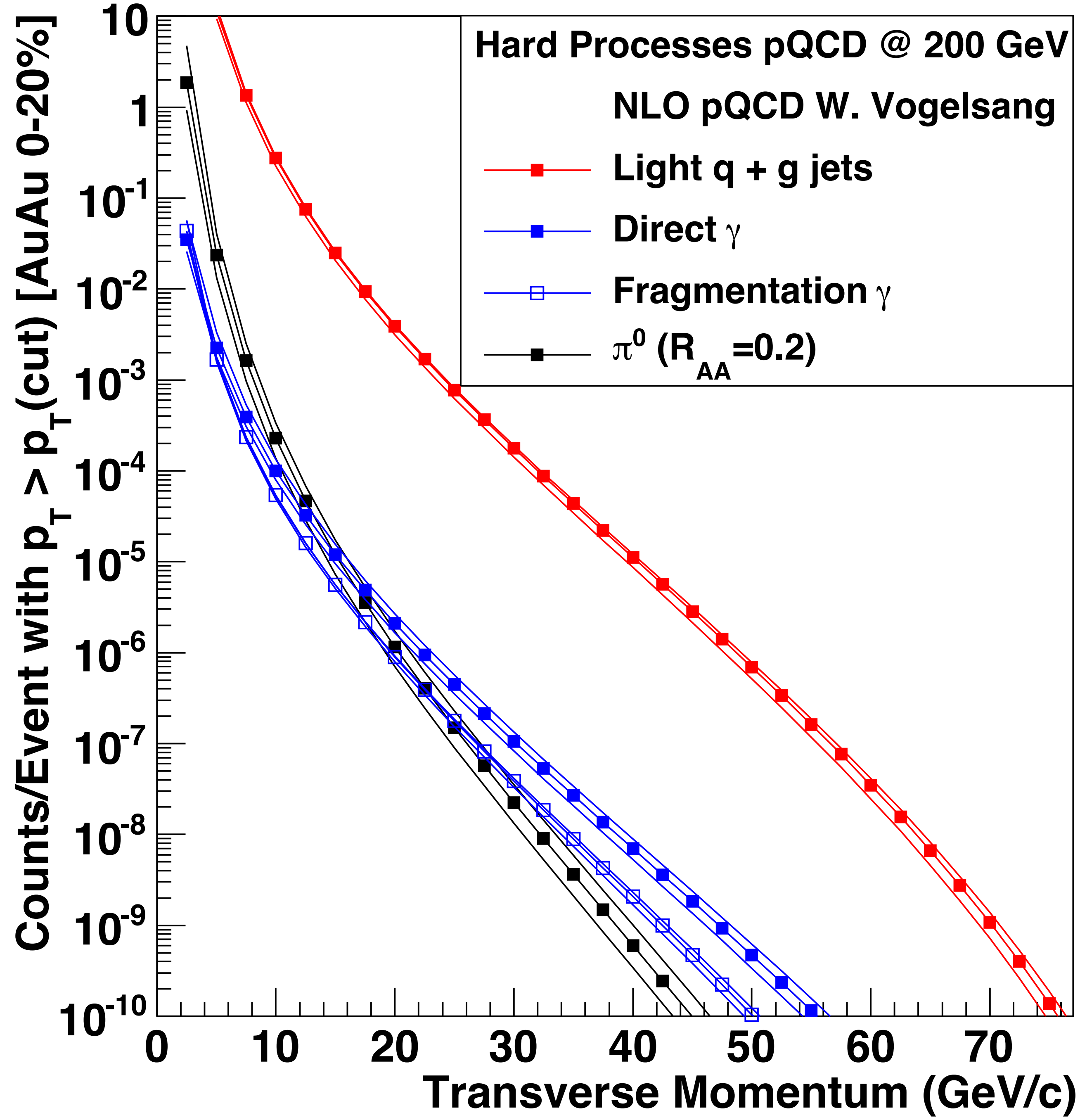


proposal: 1501.06197

jet rates

- record 100 B events / 22 weeks, AuAu
  - sample 0.6 T events
- comparable pp/pA sample





magnet at BNL

symmetry
dimensions of particle physics

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Photo by Andy Freeberg, SLAC National Accelerator Laboratory

breaking

January 16, 2015

20-ton magnet heads to New York

A superconducting magnet begins its journey from SLAC laboratory in California to Brookhaven Lab in New York.

By Justin Eure

SLAC, January 16

at BNL Gate on Tuesday night

looking ahead…

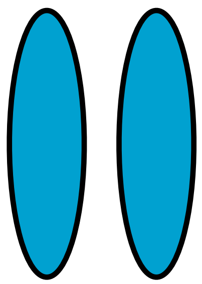
- strong evidence for AA hydrodynamics in pA, dA, & He3A systems
  - is a mini QGP created?
  - RHIC will figure that out:
    - He3A on tape
    - pA to be taken this month at RHIC
- strong interplay between RHIC & LHC
  - both are necessary
  - sPHENIX will be crucial for jet physics in the 2020s

pA, jets and the beam energy scan provide will provide the data necessary to understand why hot QCD is a low viscosity fluid and how it forms

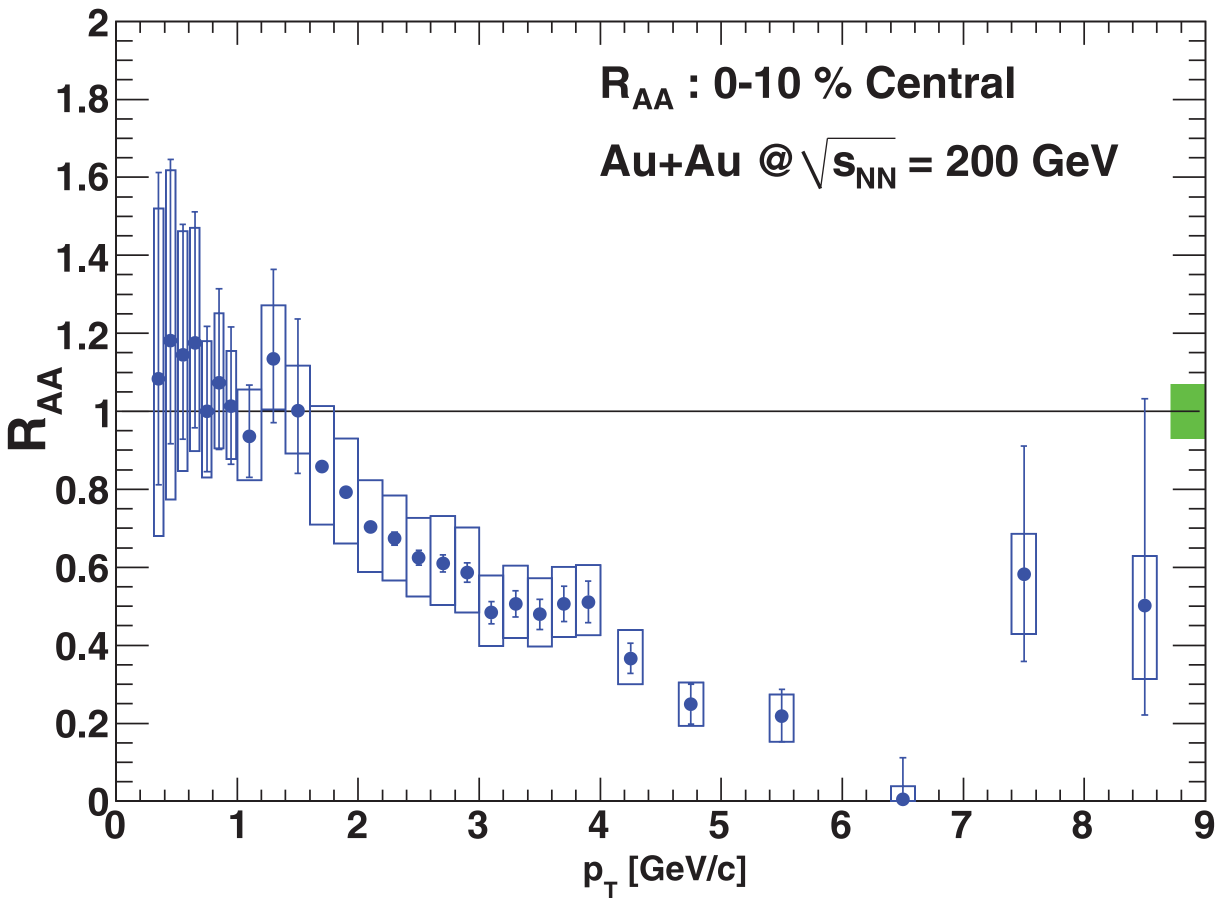
extras

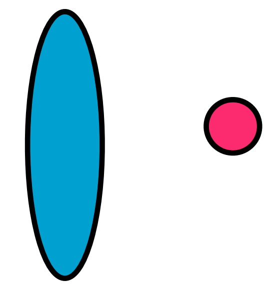
…and charm and bottom?

electrons from heavy flavor decays: e.g. c quark→ D→ e^- + X

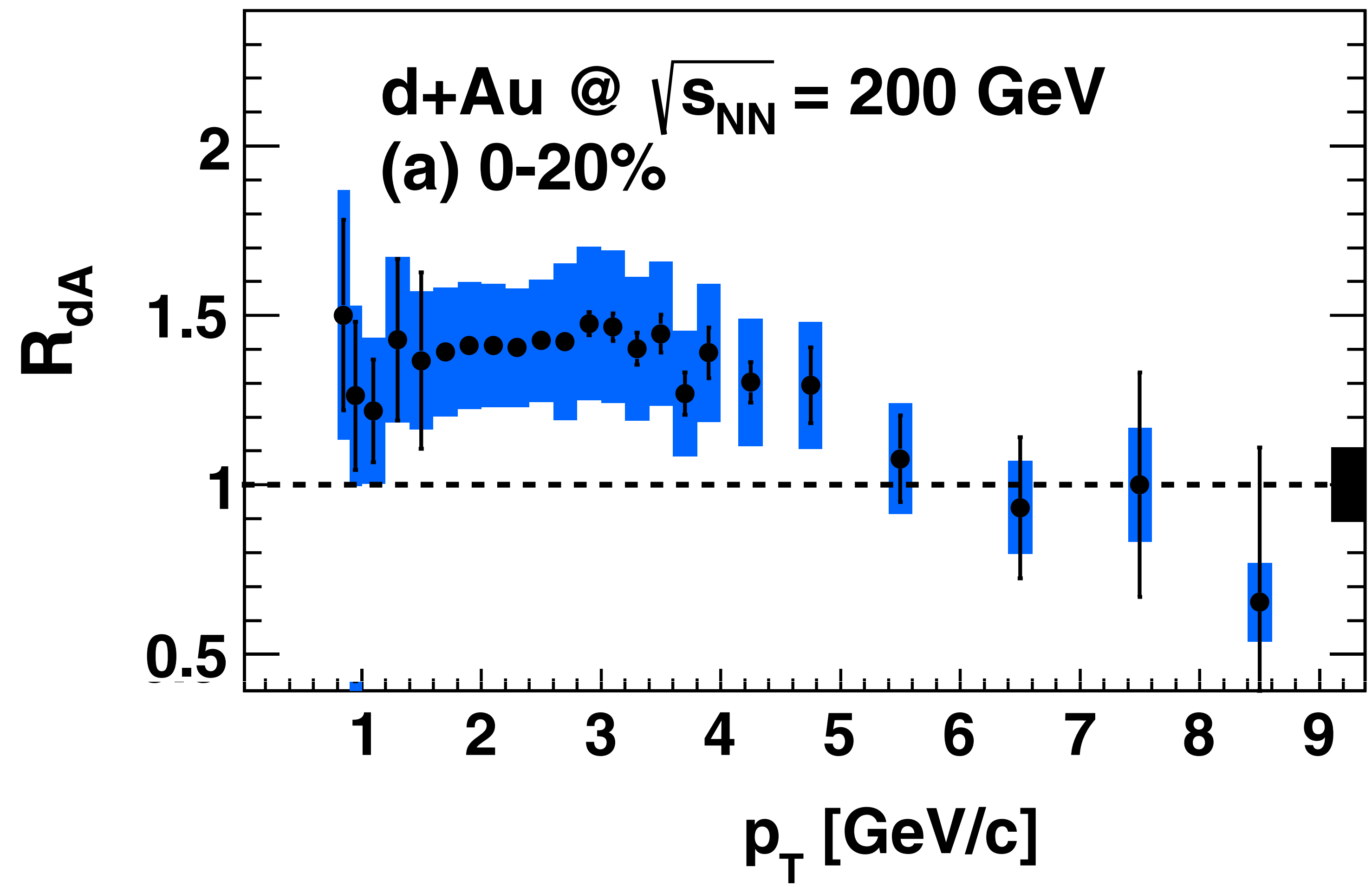


Au+Au



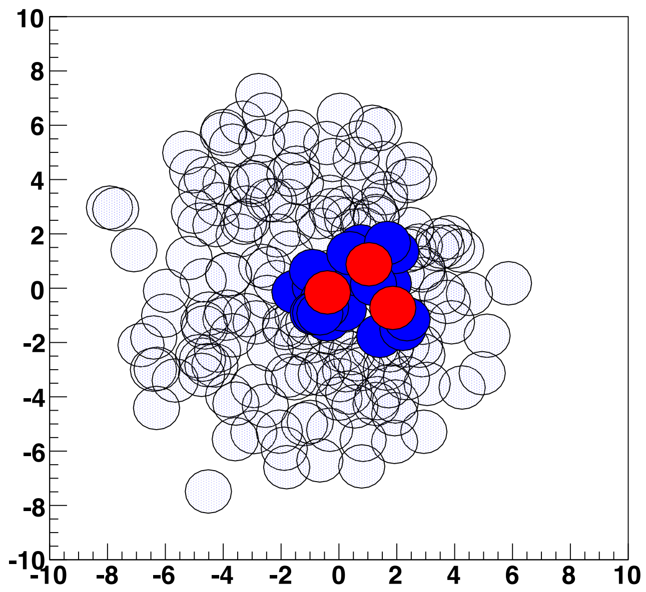


d+Au



PHENIX PRL 109 242301
PHENIX PRC 84 044905

importance of v_3

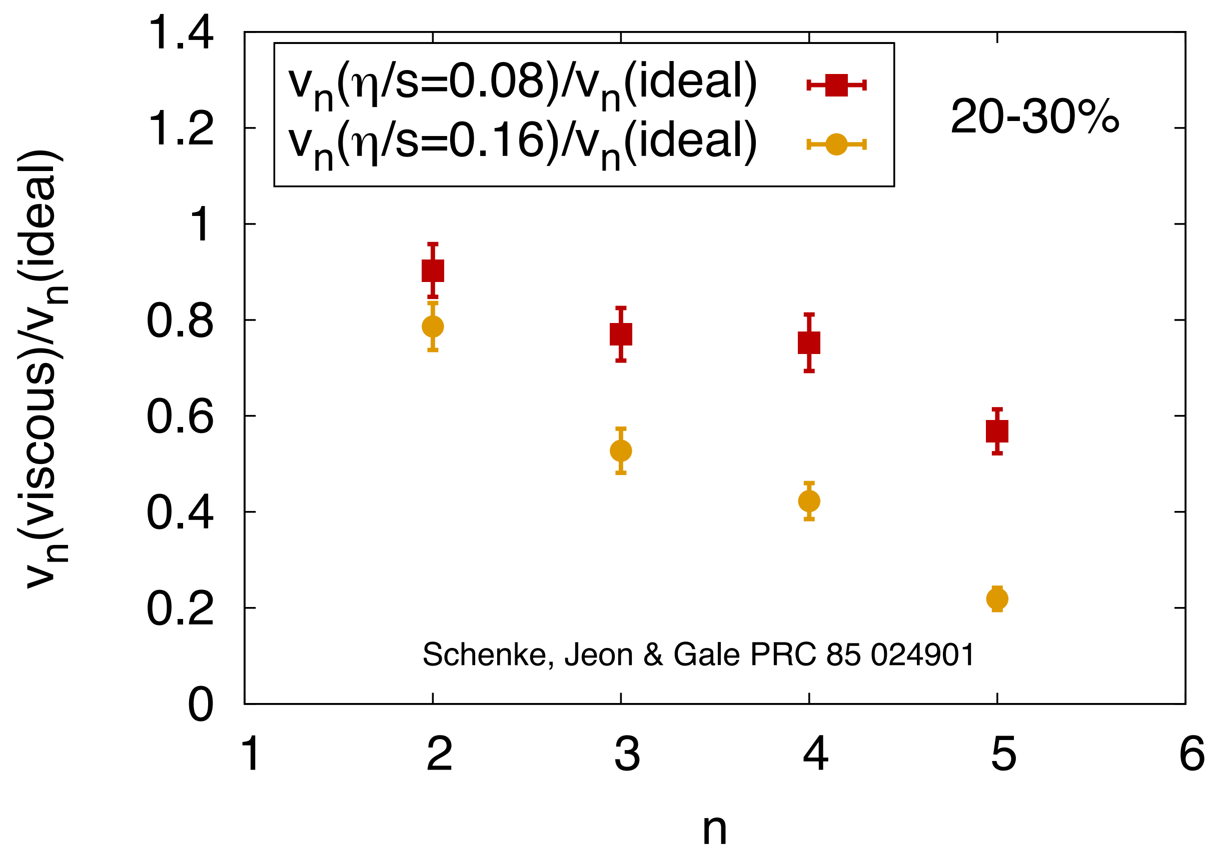


if: $\varepsilon_3 \rightarrow \cos 3\Delta\Phi$ modulation

direct confirmation of hydrodynamic behavior in small systems

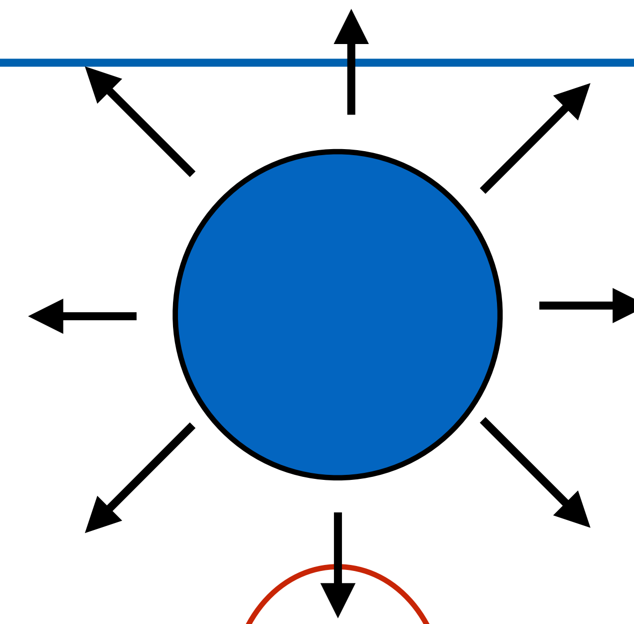
new handle on viscosity

higher moments,
more sensitive to viscous effects



what about radial flow?

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

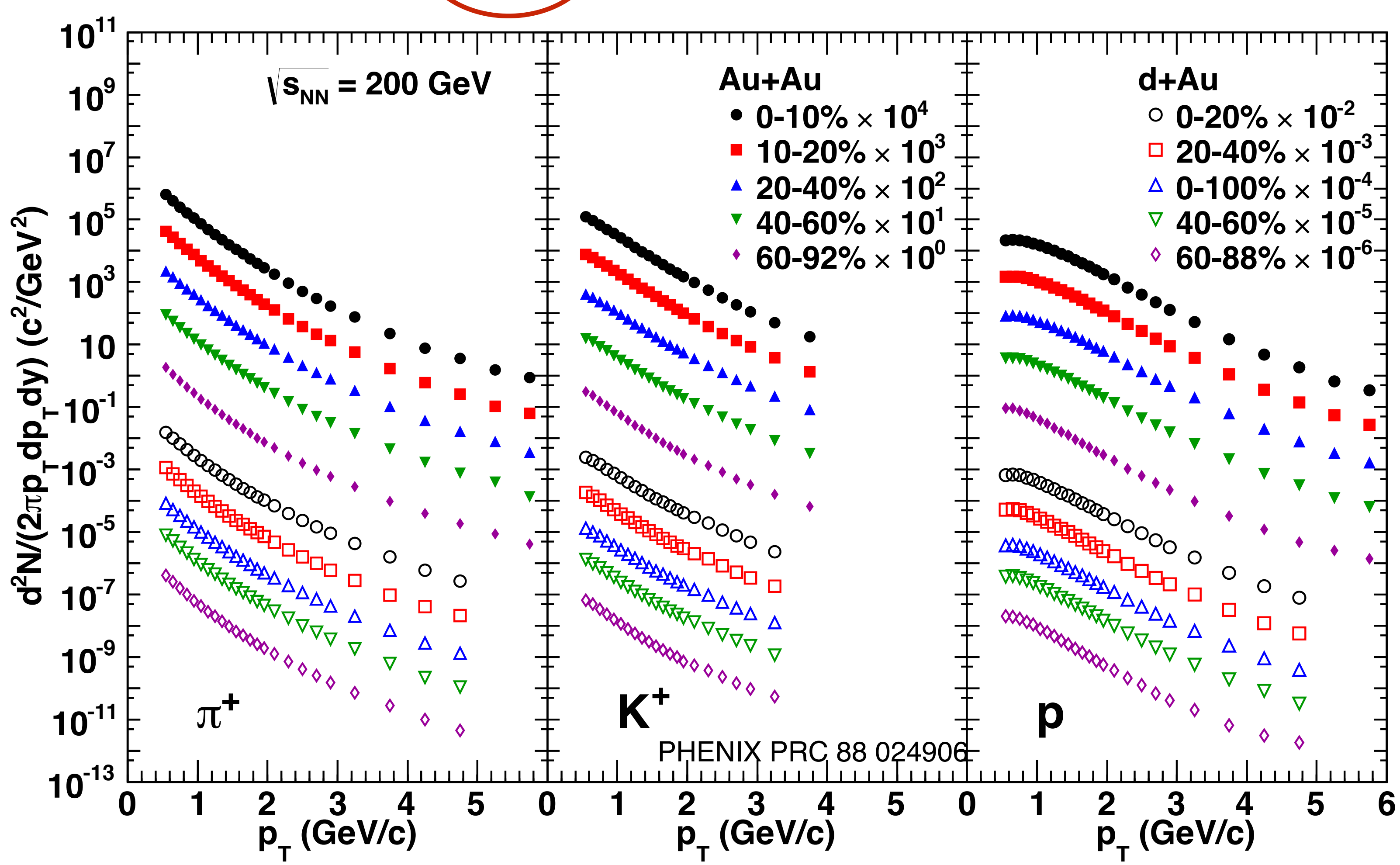


$$\frac{1}{p_T}\frac{dN}{dp_T} \propto \int_0^R r\,dr\,m_T\,I_0\left(\frac{p_T \sinh\rho}{T_{fo}}\right) K_1\left(\frac{m_T \cosh\rho}{T_{fo}}\right) \qquad \rho = \tanh^{-1}\left(\beta_{max}(r/R)^n\right)$$

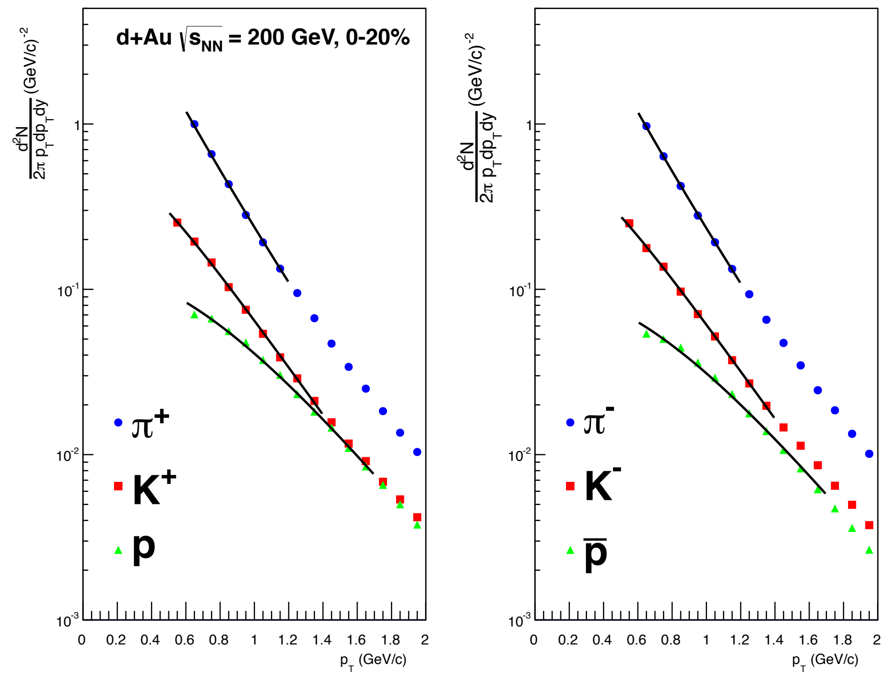
Schnedermann, Sollfrank, & Heinz PRC48 2462 (1993)

- pA systems especially sensitive to radial flow

(

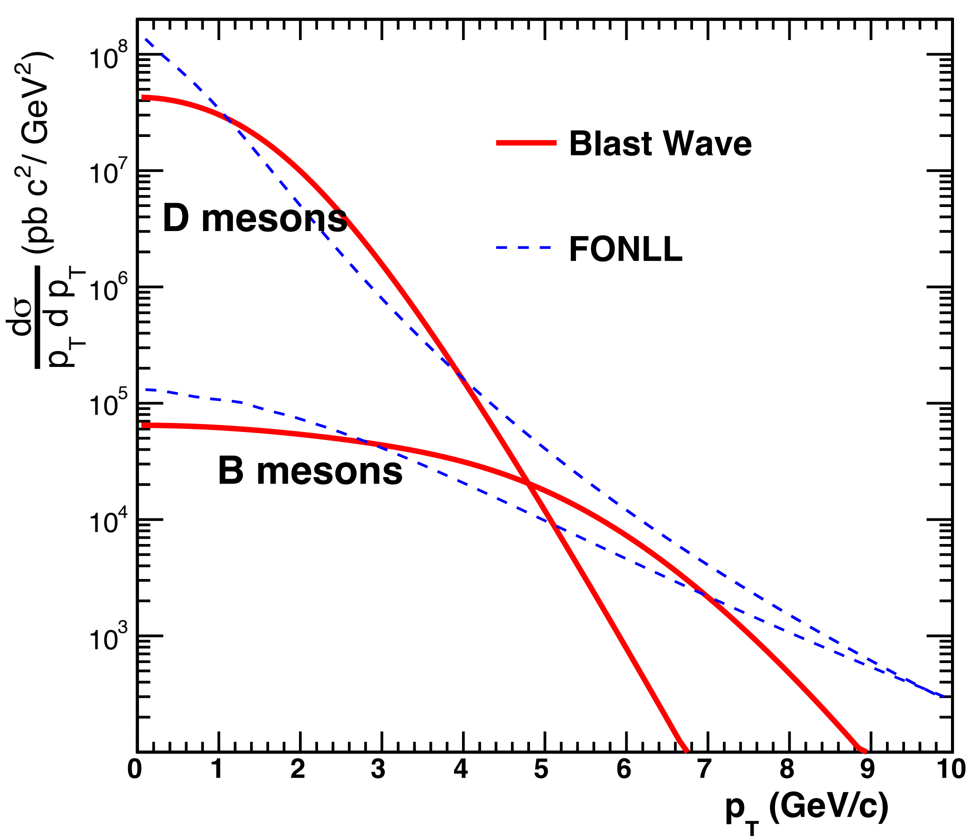


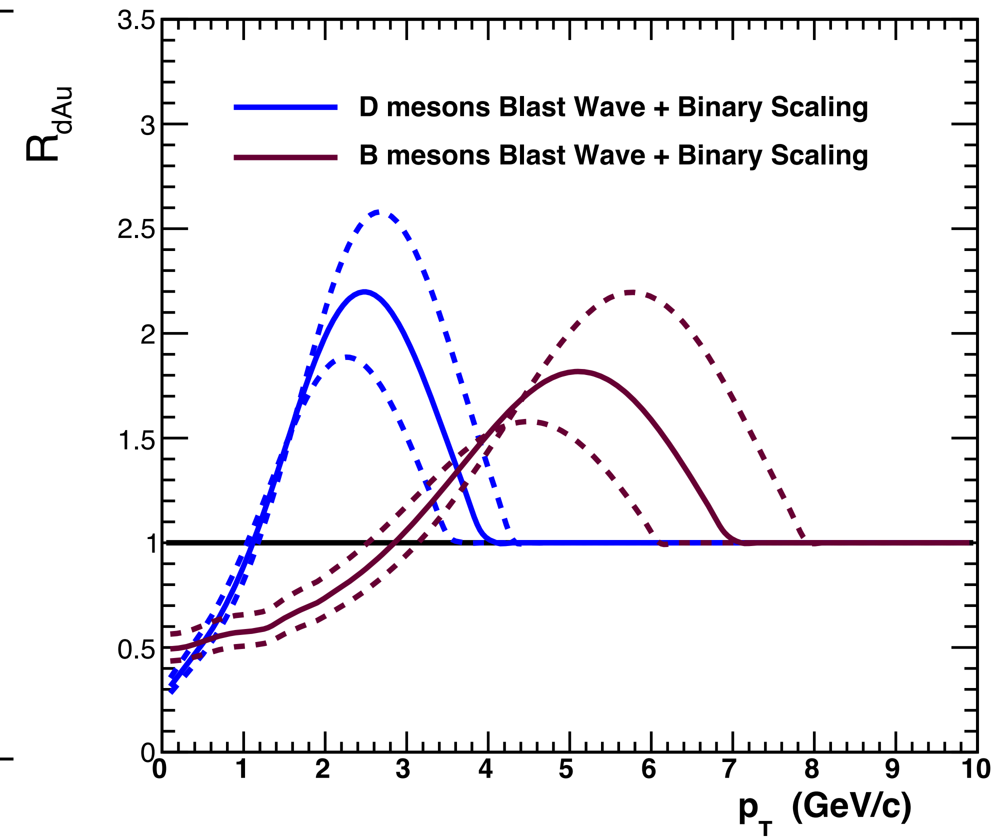
blast-wave fit to dAu data



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

st wave!

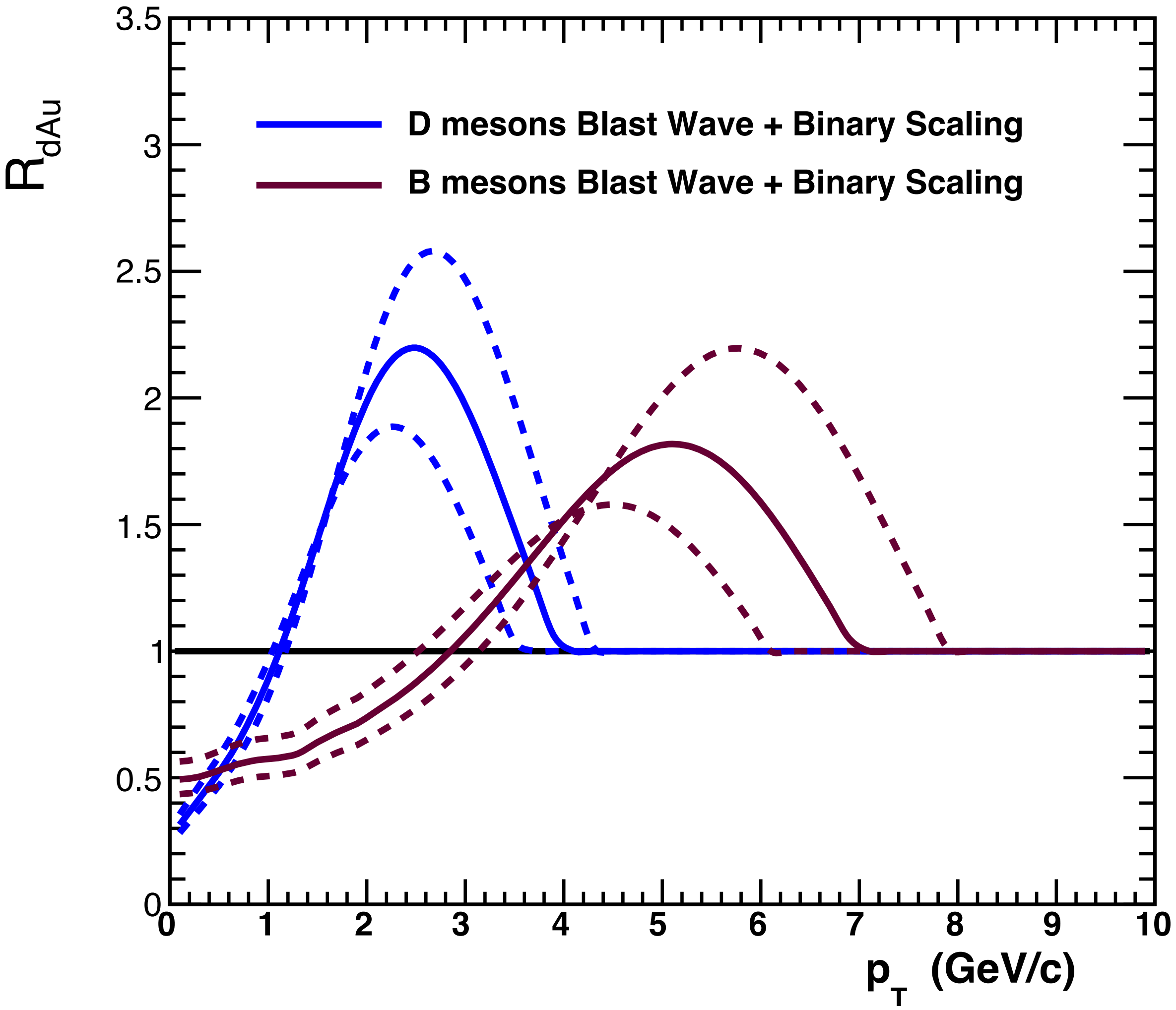




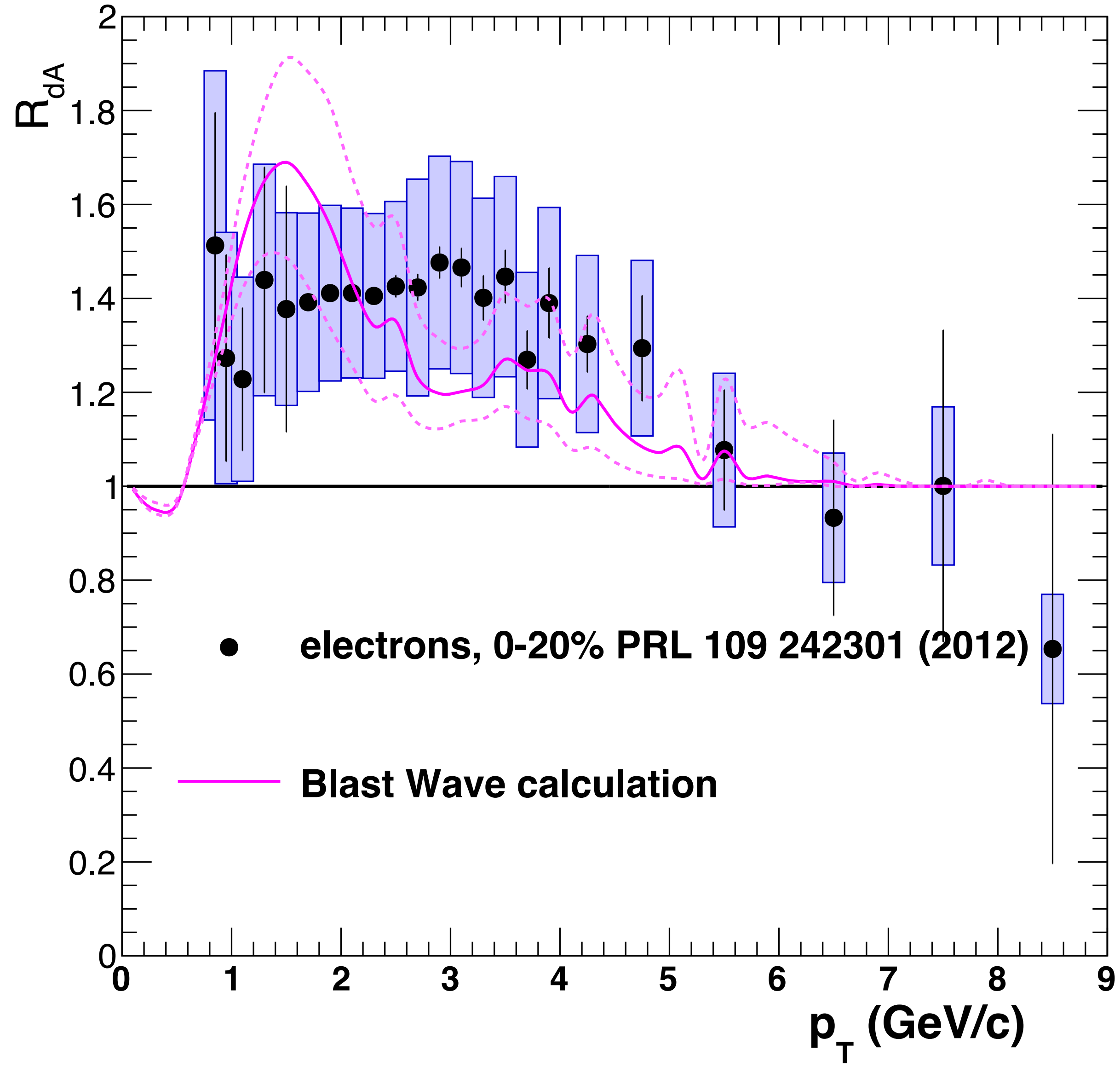
large enhancement of D & B mesons!

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

and for the electrons?



ave!



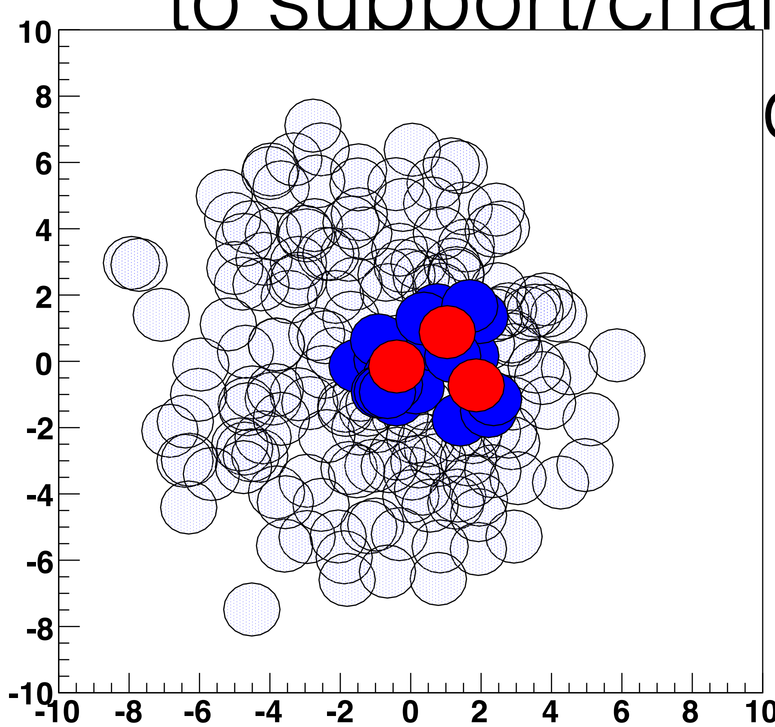
another flow effect?

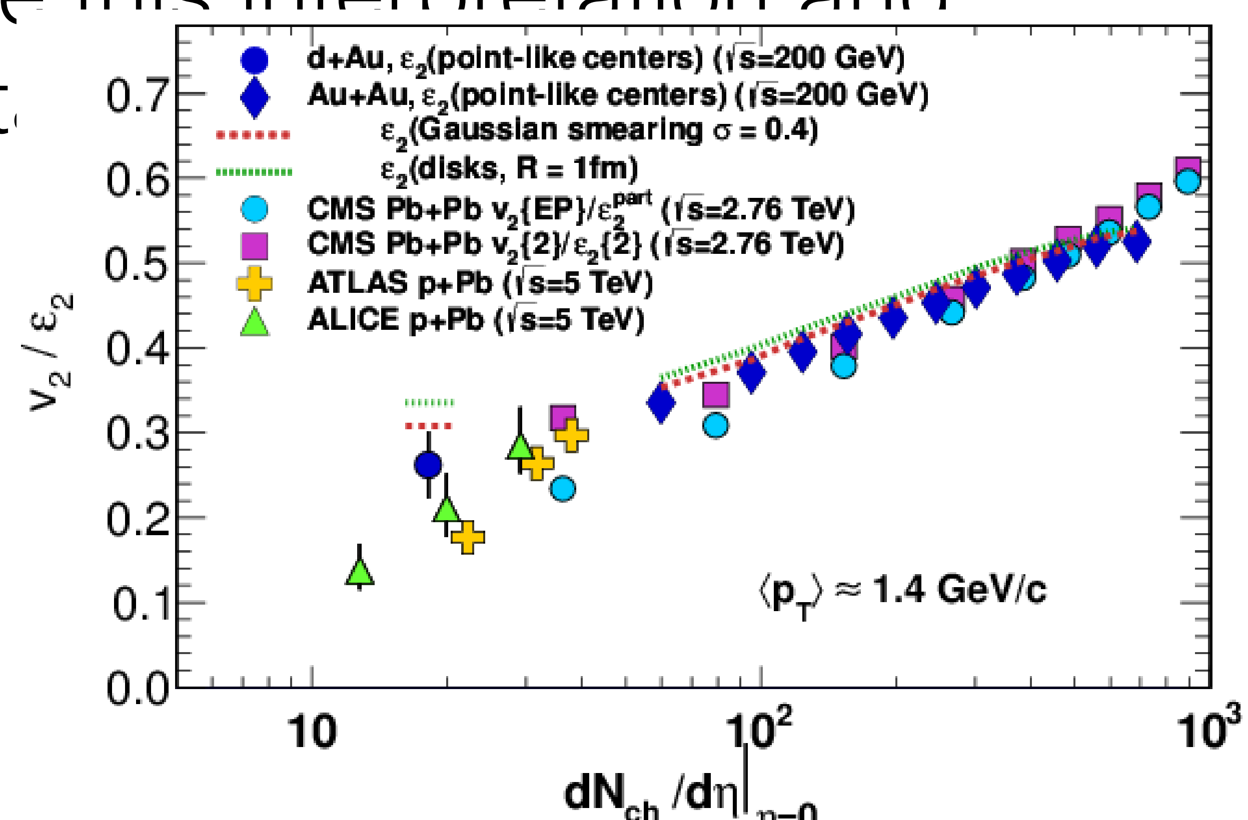
charm and bottom separated measurements key to clarifying

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

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 … derst…

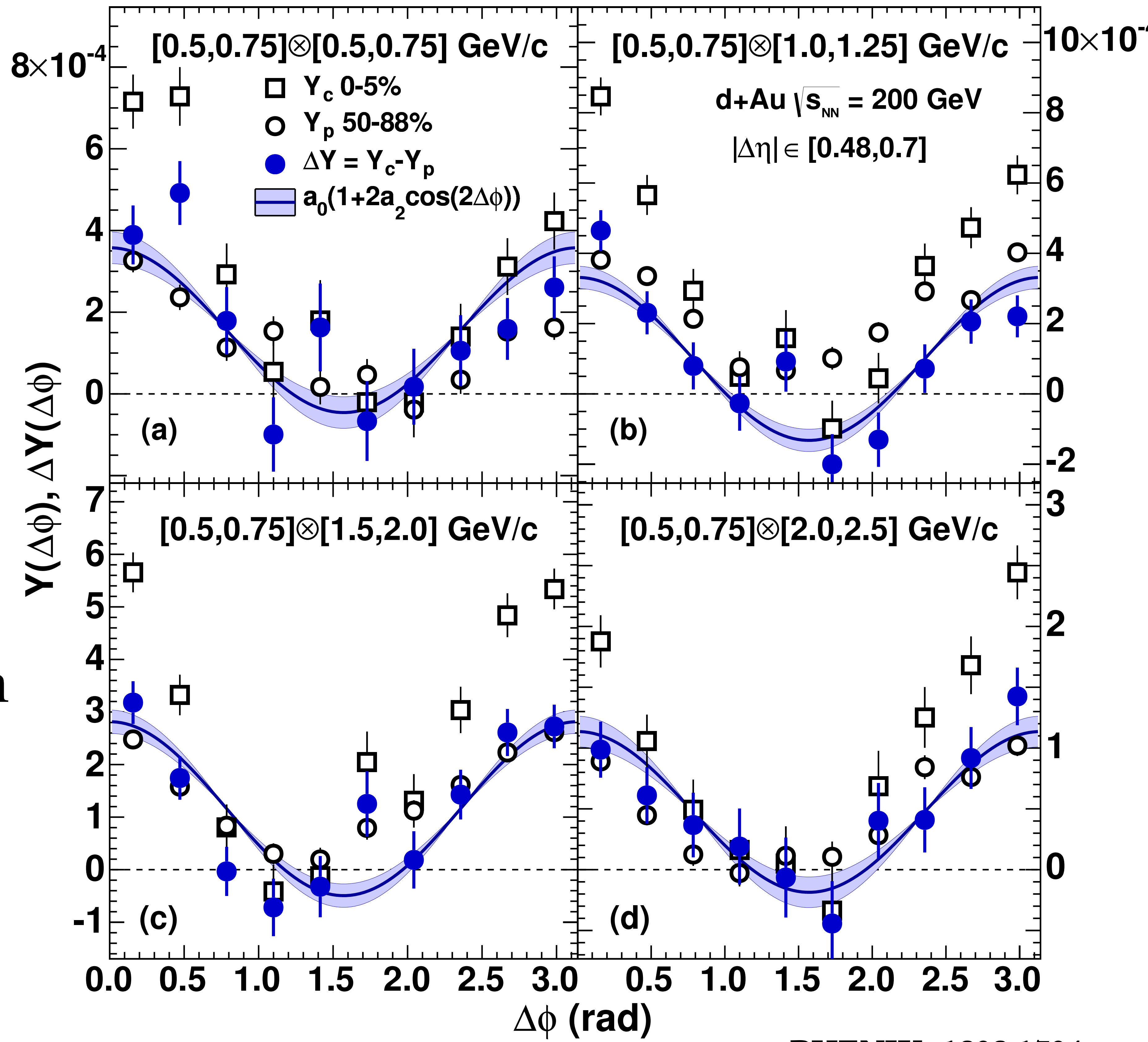




- backups

centrality dependence consistently described by cos2Δϕ shape evidence for double ridge

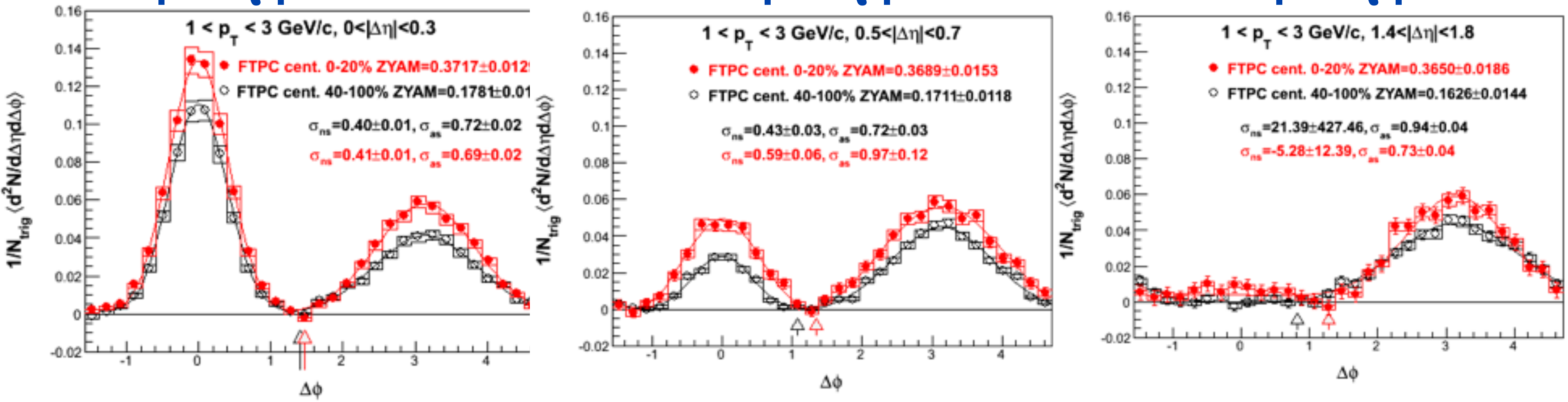
but is this just an artifact of the small |Δη| acceptance?



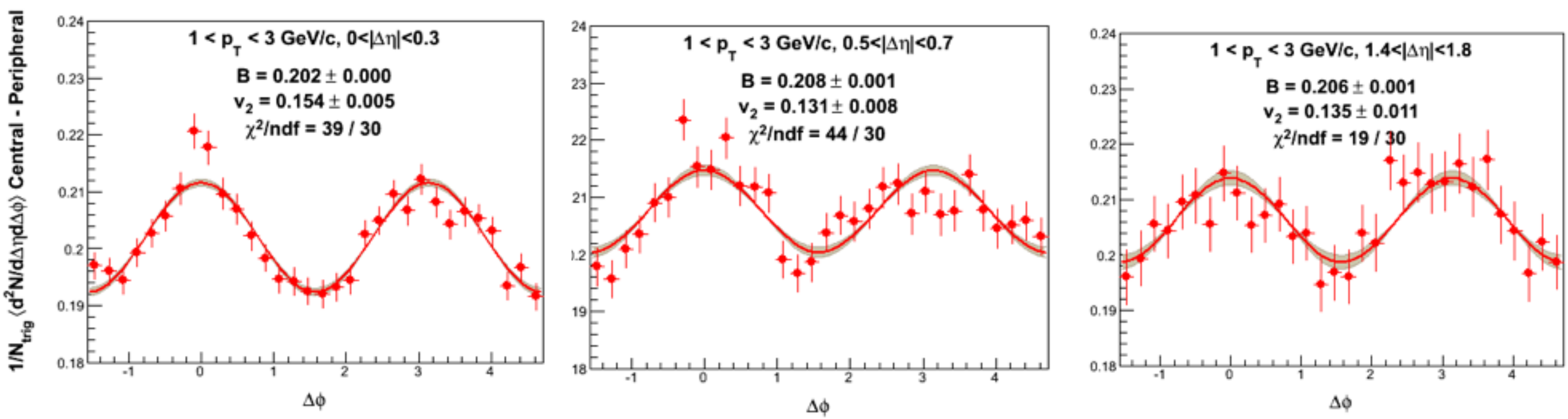
PHENIX: 1303.1794

results from STAR

$|\Delta\eta|<0.3$ $0.5<|\Delta\eta|<0.7$ $1.4<|\Delta\eta|<1.8$

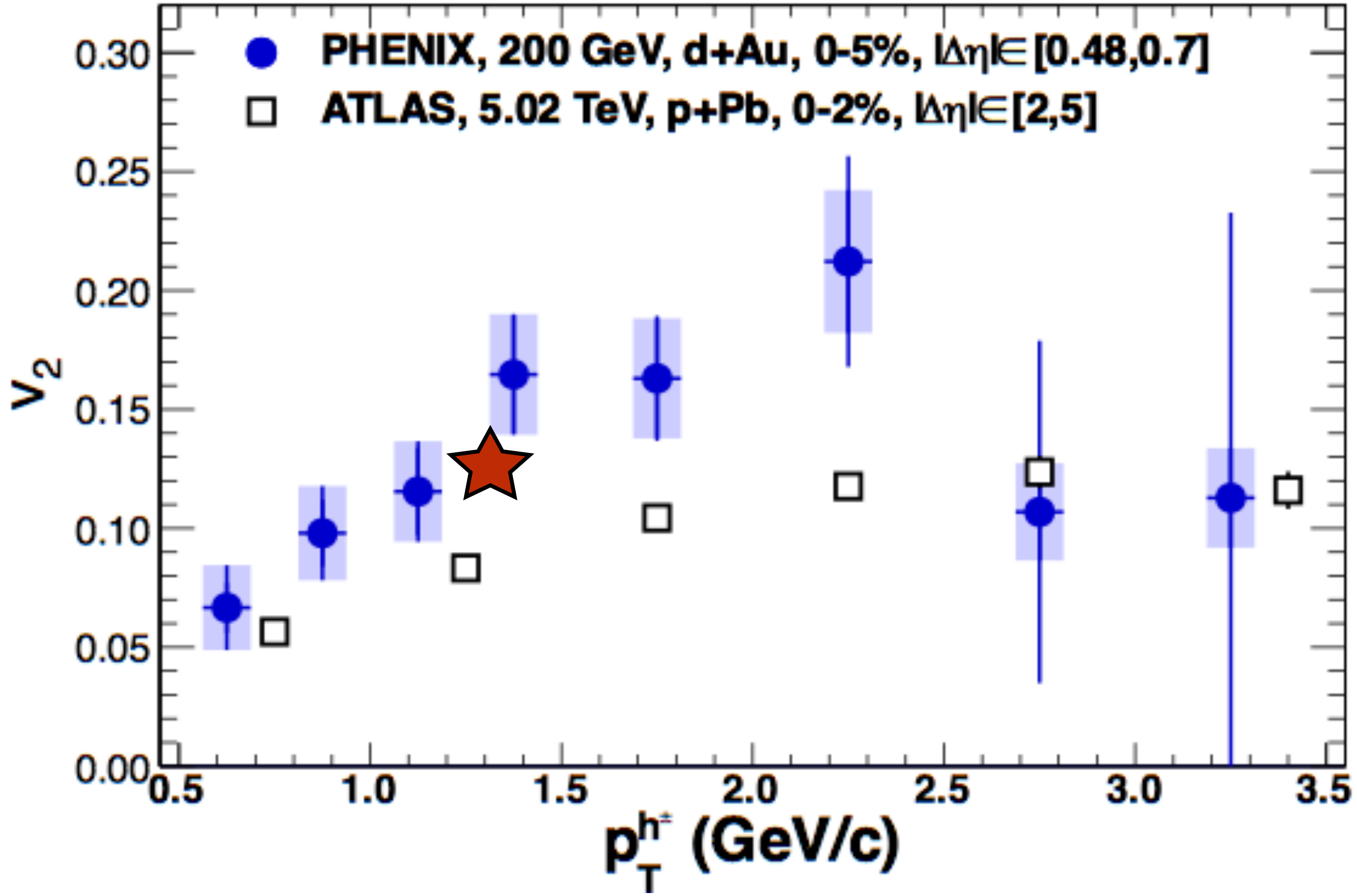


central - peripheral



F. Wang IS2013

RHIC comparisons



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

PHENIX: 1303.1794
F. Wang IS2013

scaling with overlap area?

- app
- si d
  +
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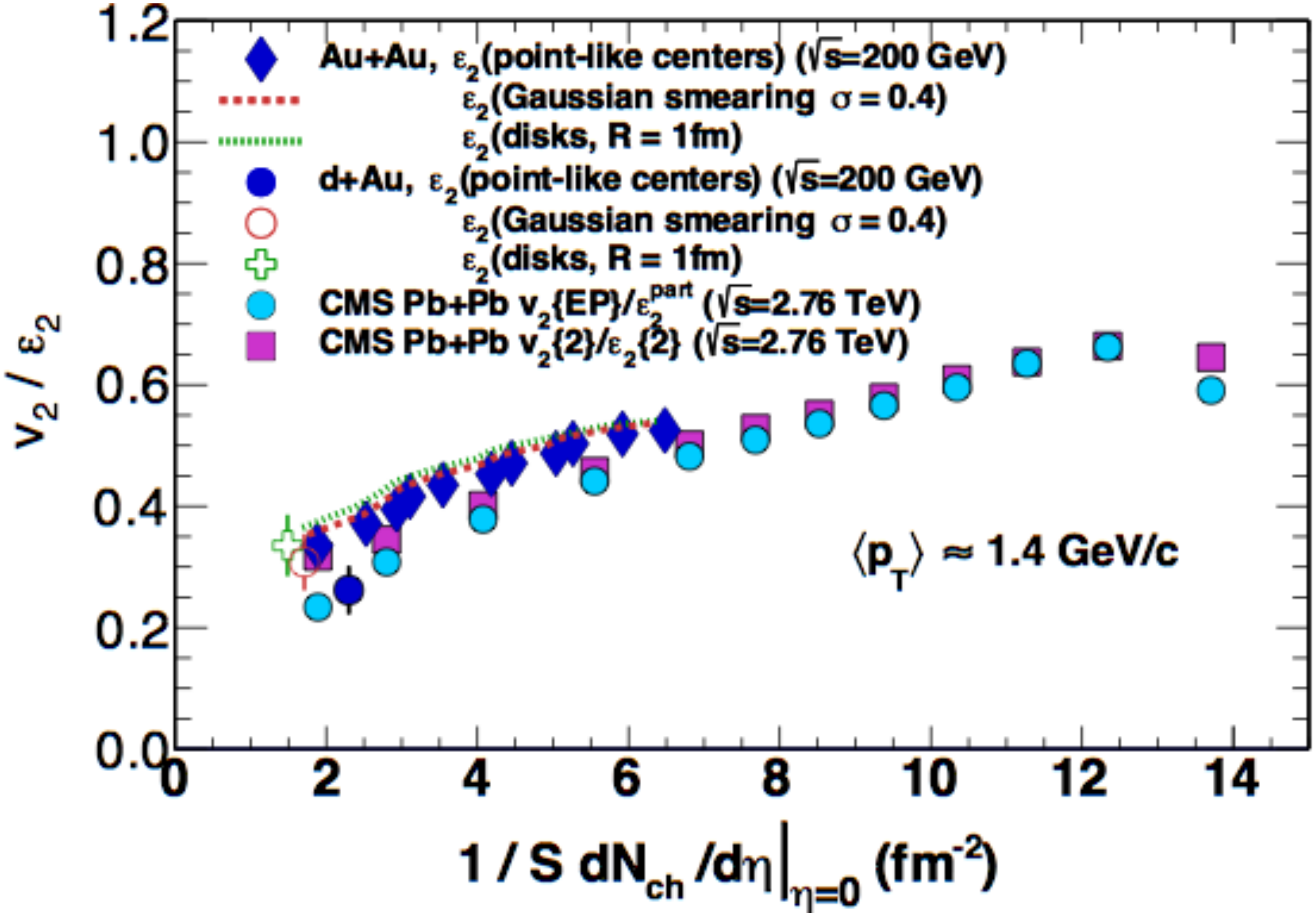
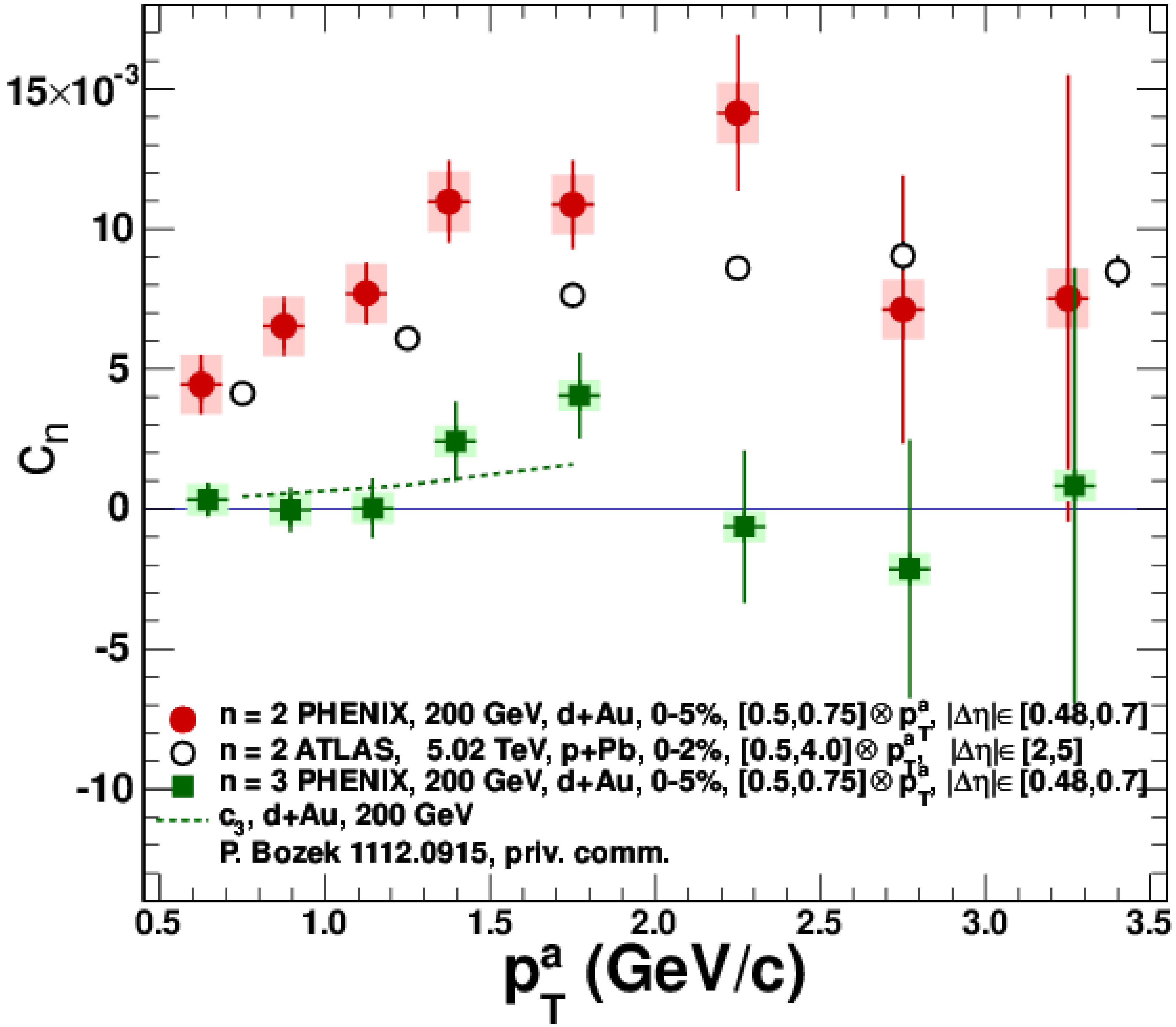


v_3 at RHIC?

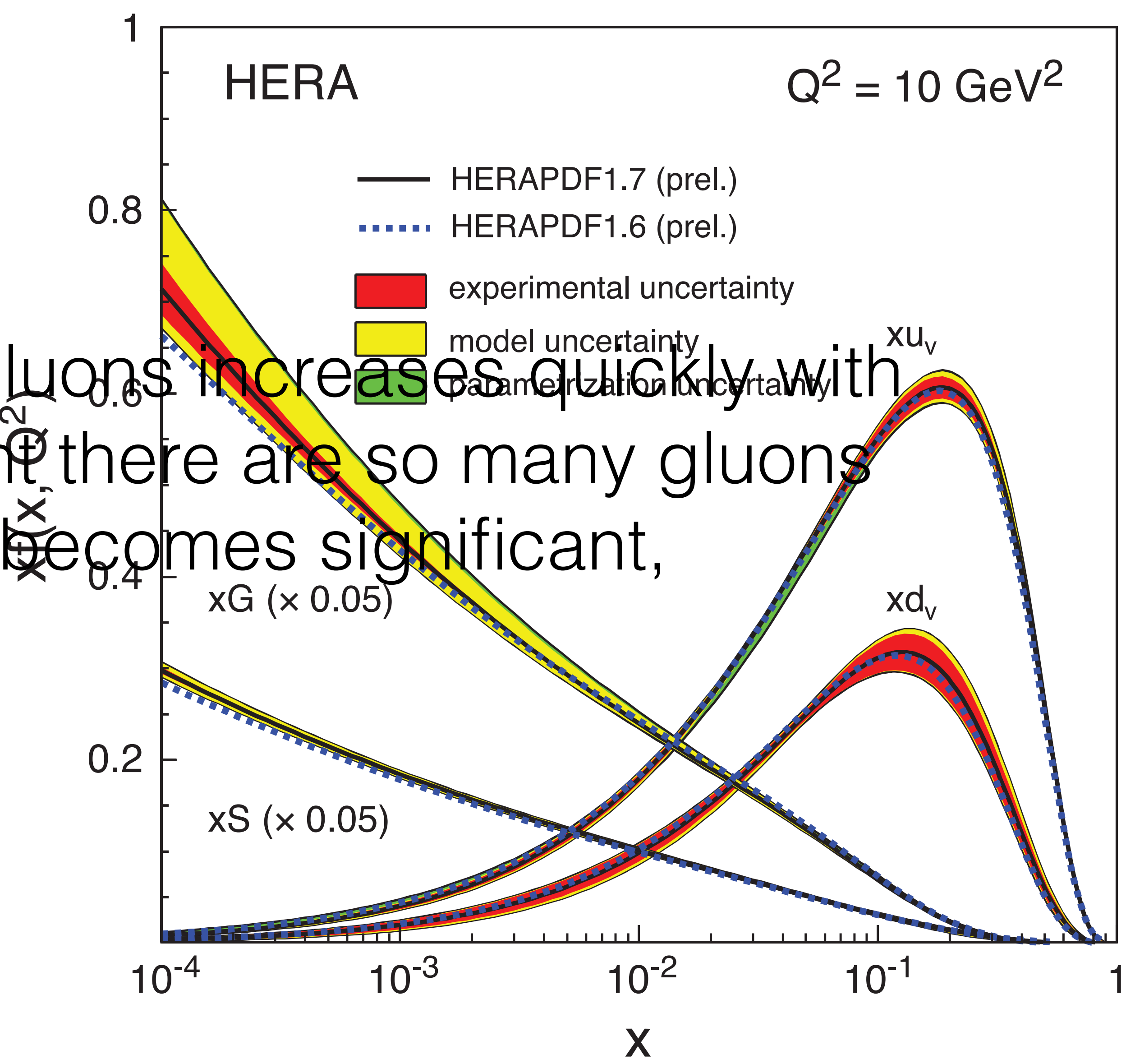


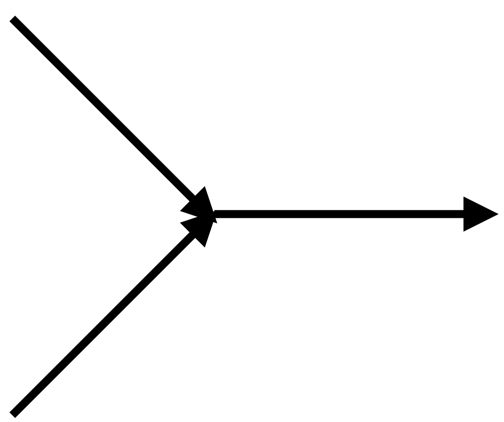
no evidence for significant v3, consistent with hydro expectations

PHENIX: 1303.1794

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

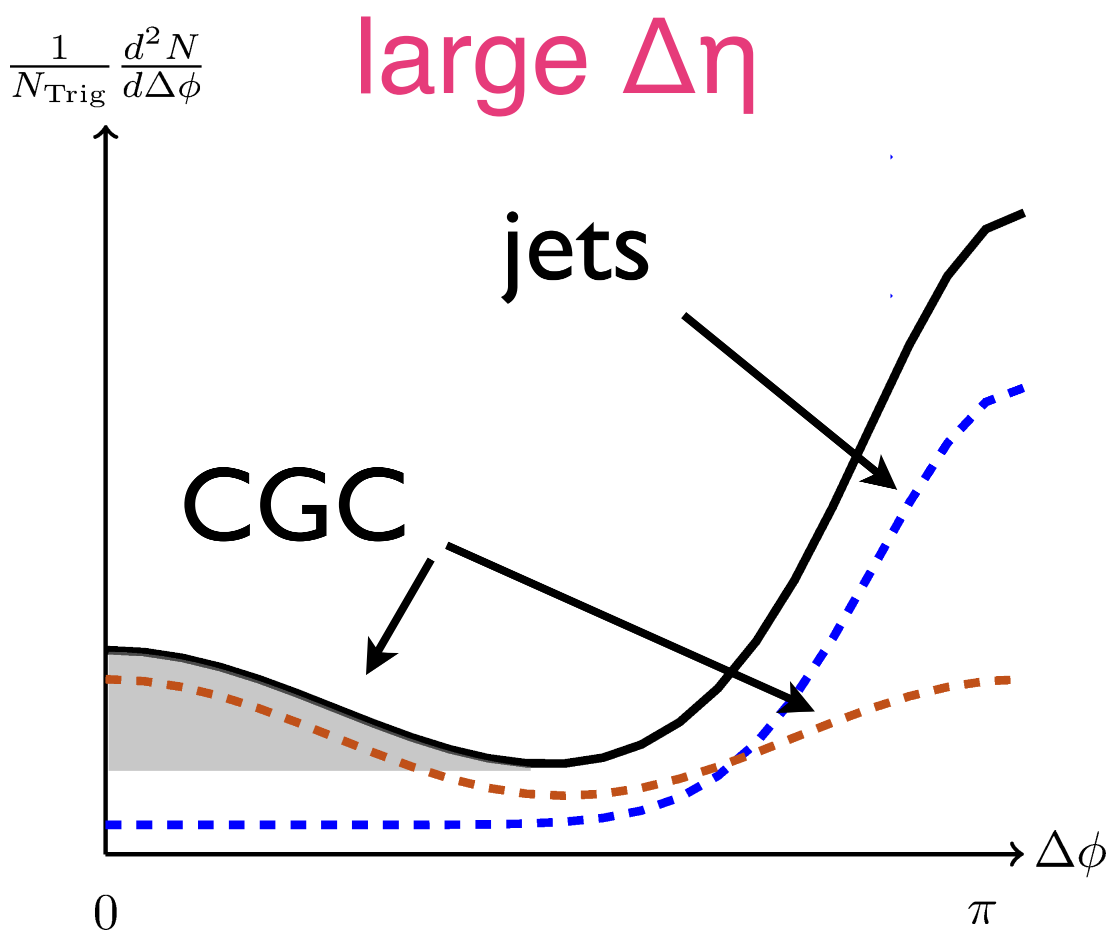


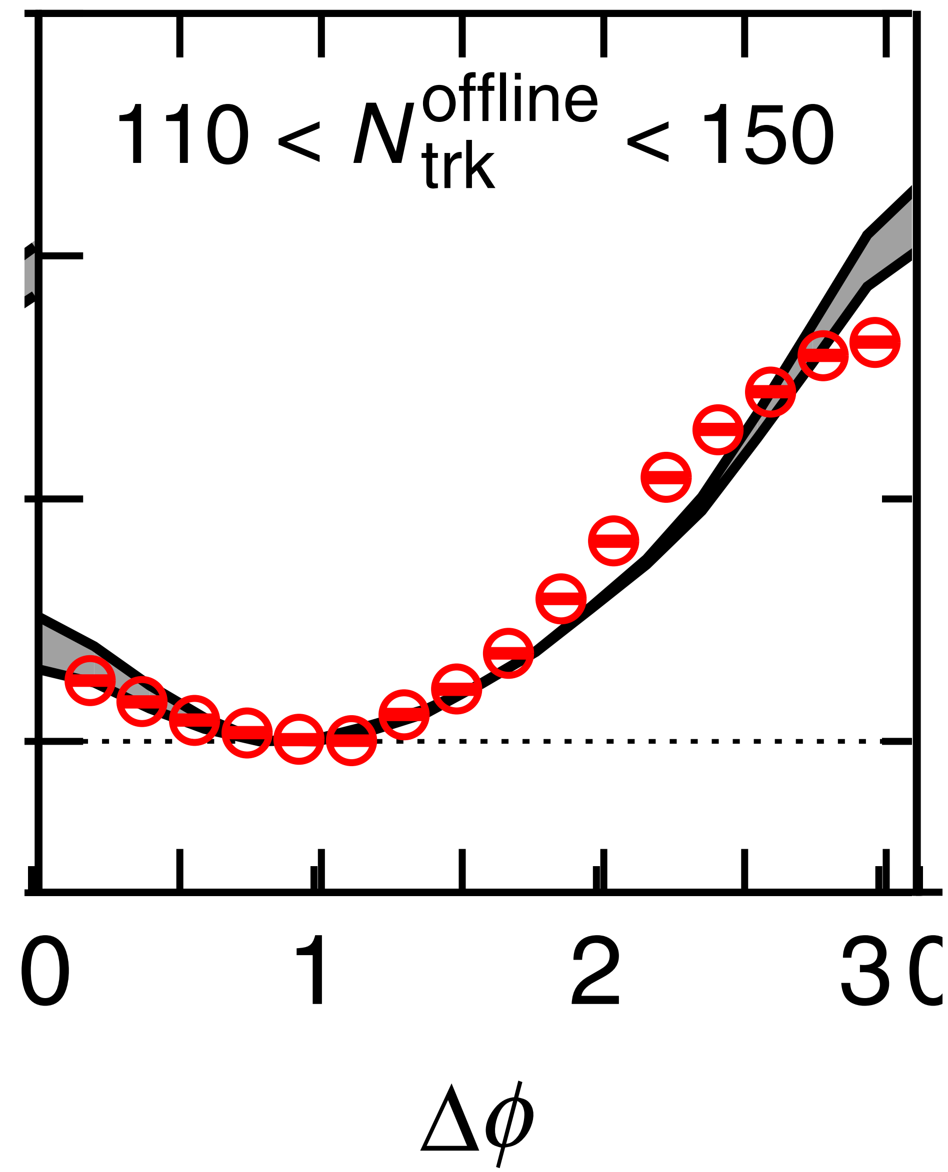


in a large nucleus in high energy collisions, this happens more readily because the nucleons overlap, increasing the density

ridge in pp/pPb from color glass

Color Glass Condensate: calculational framework for saturation

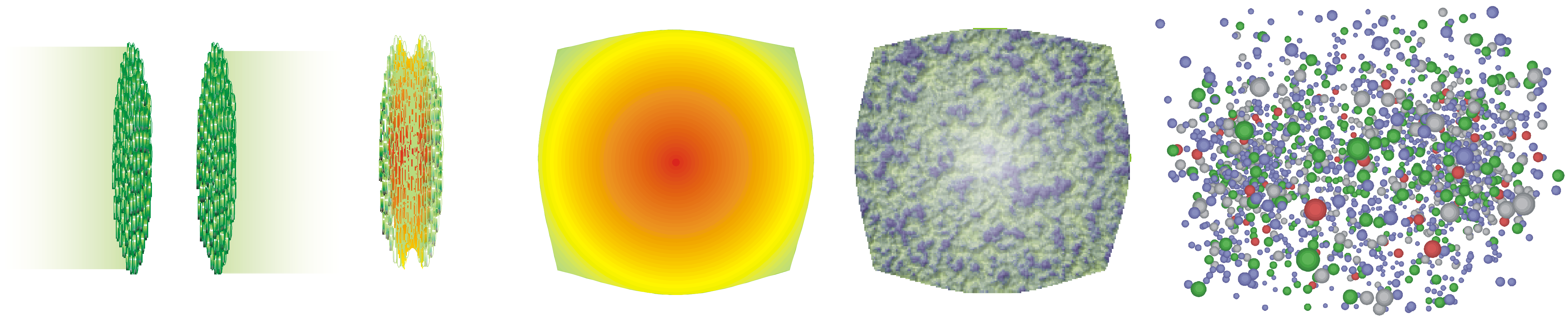




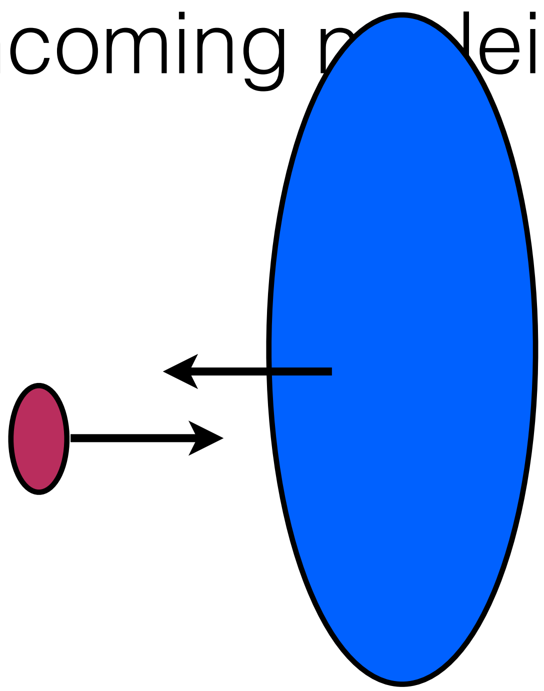
good description of the data in pPb

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

pA physics



- isolate QGP effects from something present in the incoming nuclei



pA