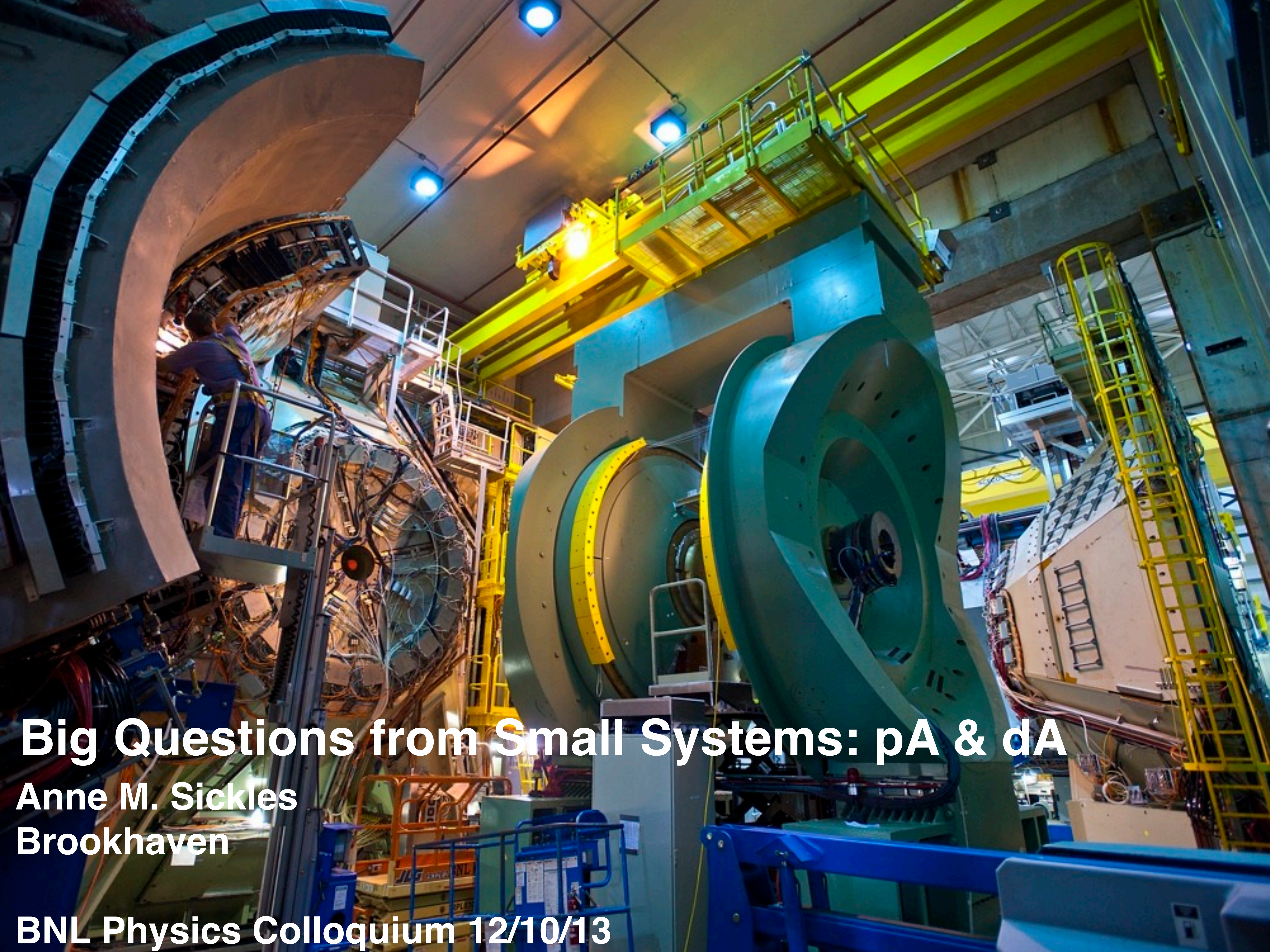

Big Questions from Small Systems: pA & dA

Anne M. Sickles
Brookhaven

BNL Physics Colloquium 12/10/13

why heavy ion collisions?

- goal: describe and understand QCD at extremely high temperatures
- create matter where protons and neutrons are not the applicable degrees of freedom: Quark Gluon Plasma
- use heavy ions (gold & lead, ~200 nucleons each) and accelerators to create as big and long lived instance of this matter as possible

why heavy ion collisions?

- goal: describe and understand QCD at extremely high temperatures
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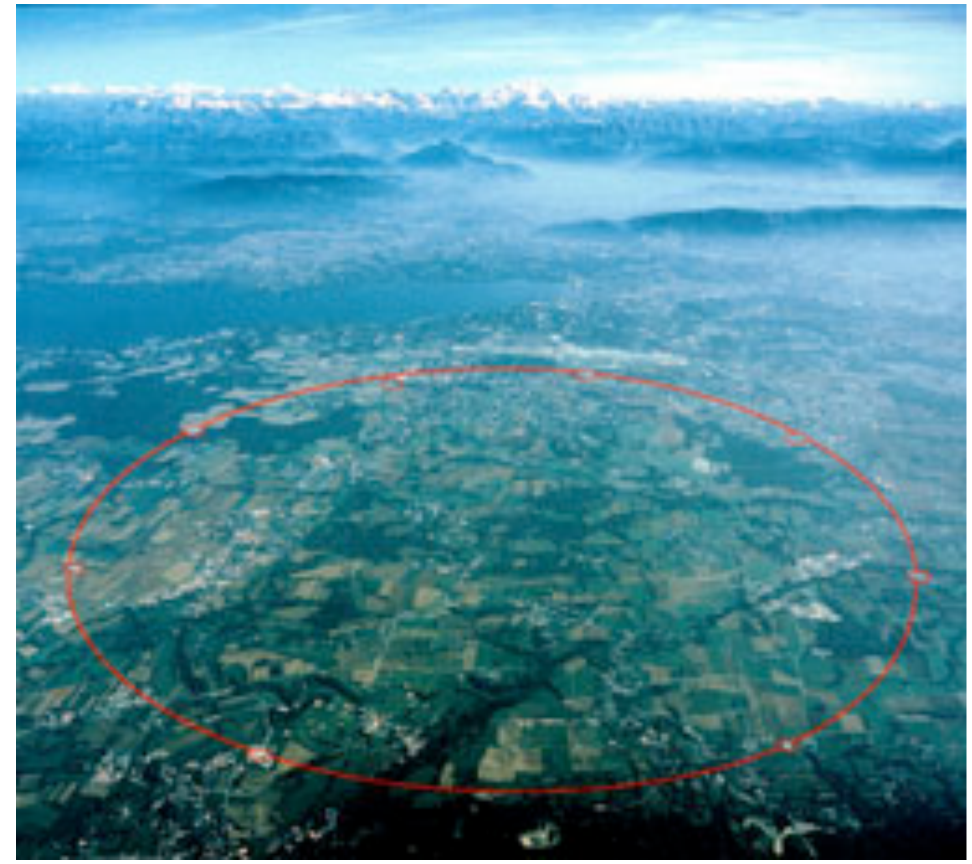
big **+** ***speed*** $\rightarrow$ **QGP**

how big is big enough?

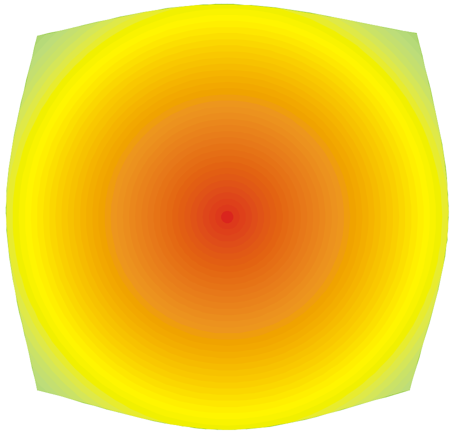
Heavy Ion Programs at RHIC and LHC



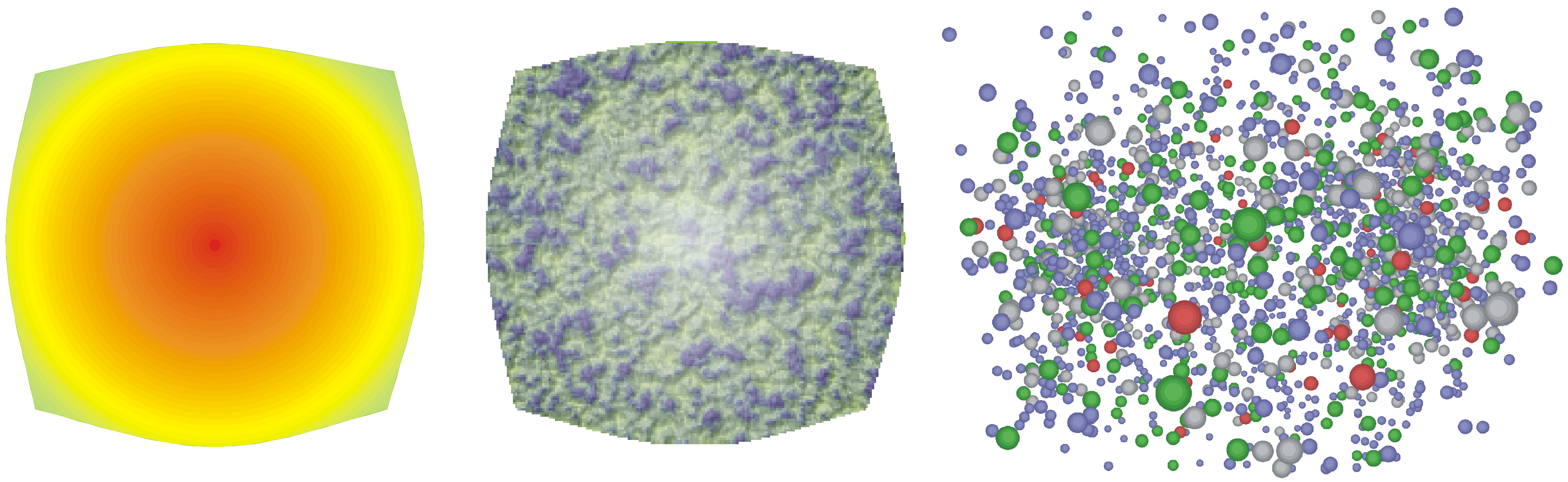
2000 - present
7.7-510 GeV collision energy
AuAu, dAu, pp, CuCu, UU, CuAu

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

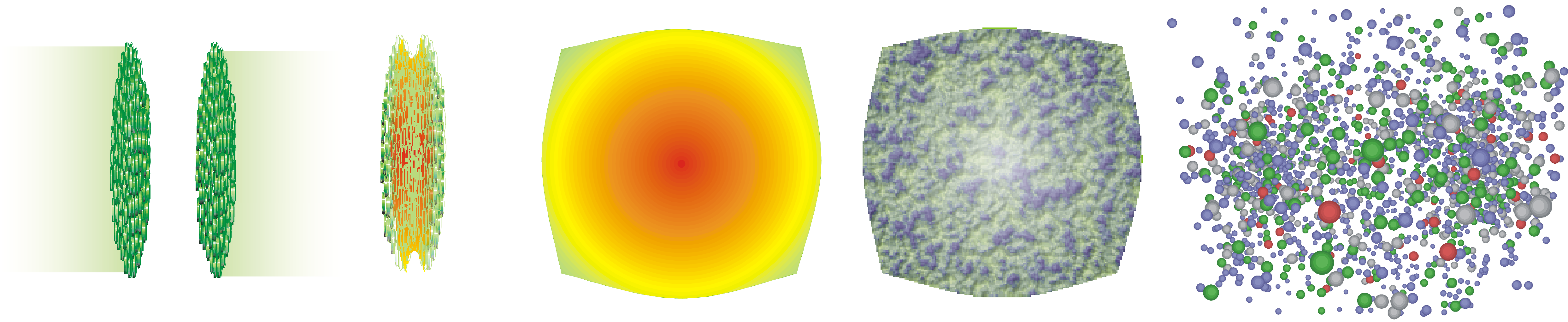
relativistic **heavy** ion collisions



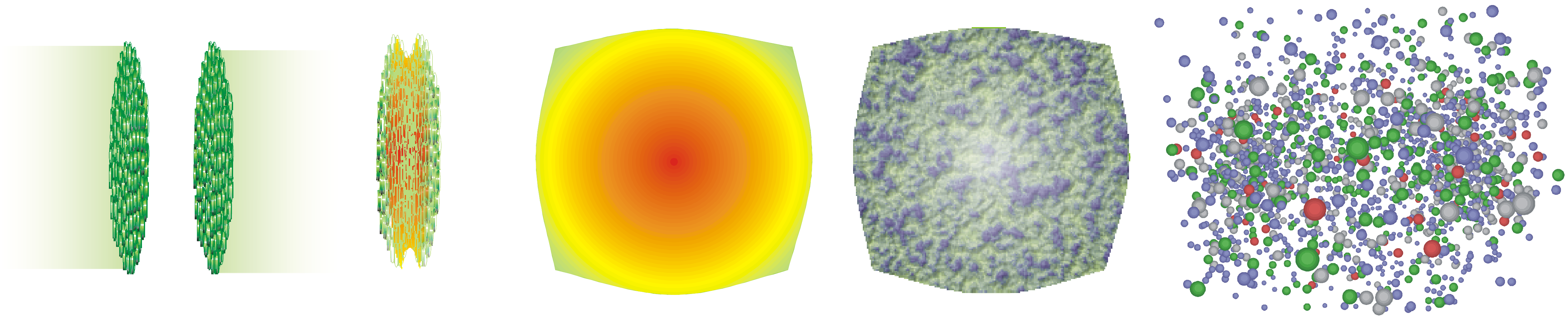
relativistic **heavy** ion collisions



relativistic **heavy** ion collisions



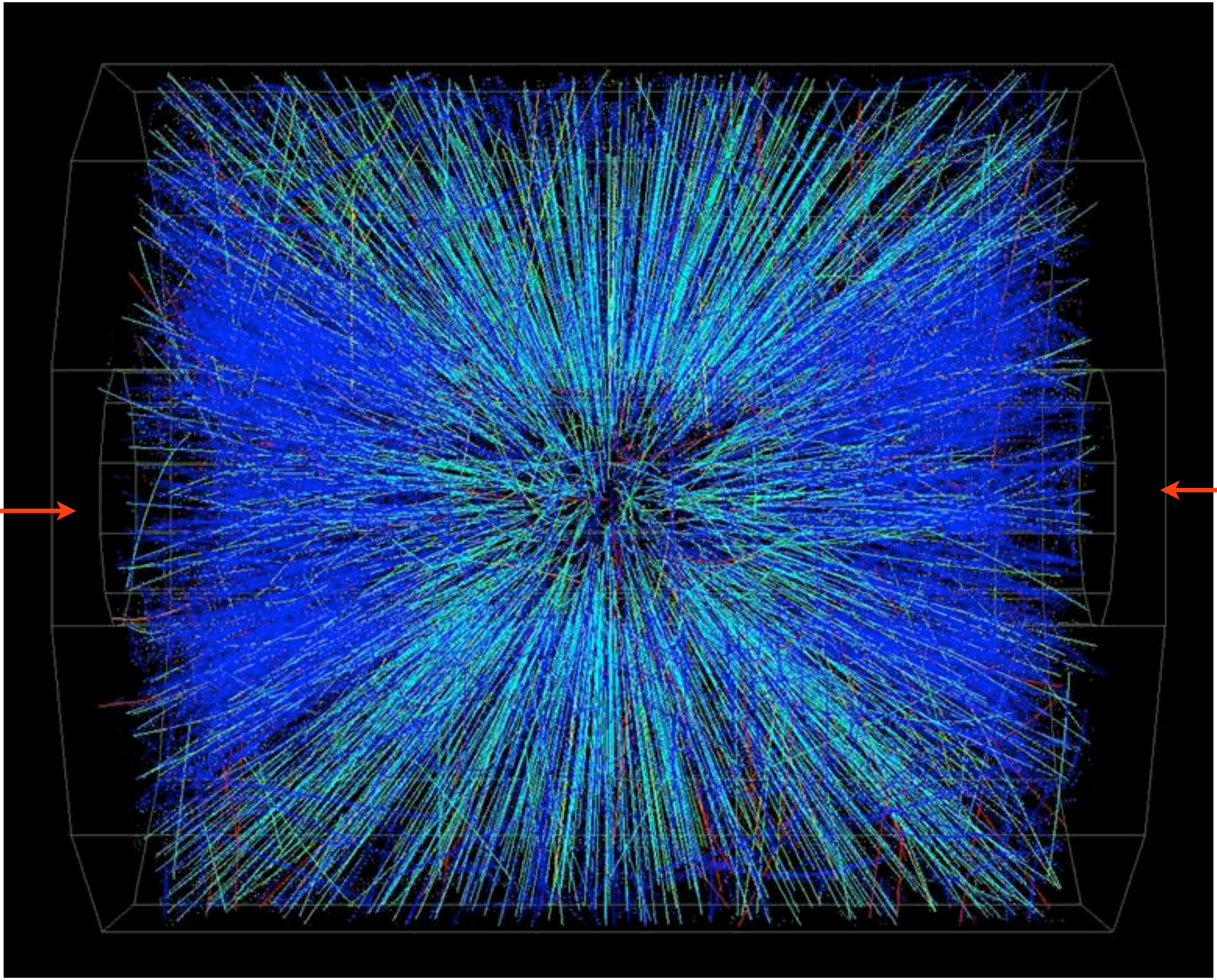
relativistic **heavy** ion collisions



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

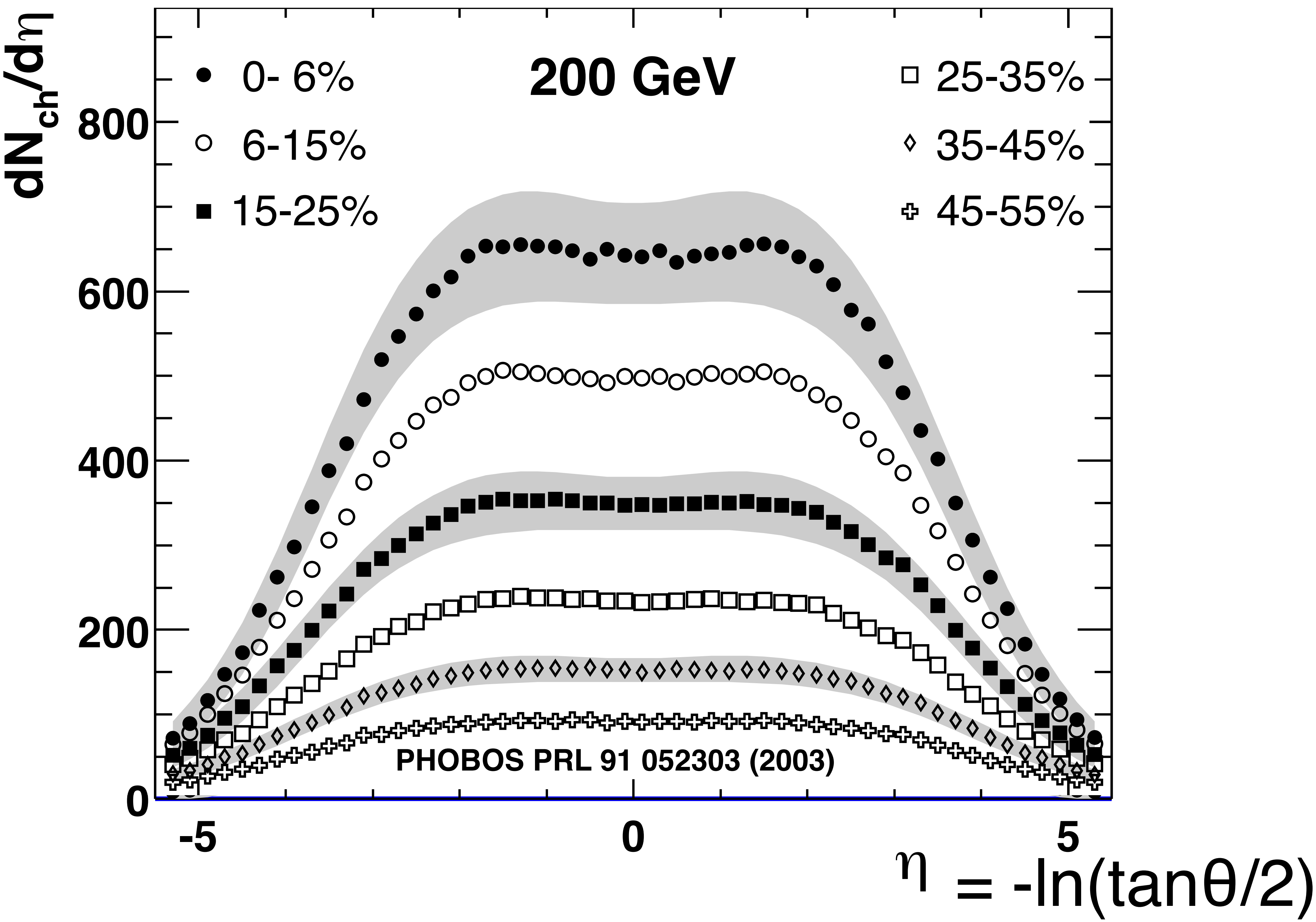
the aftermath

the aftermath



charged particle multiplicity

Au+Au



charged particle multiplicity

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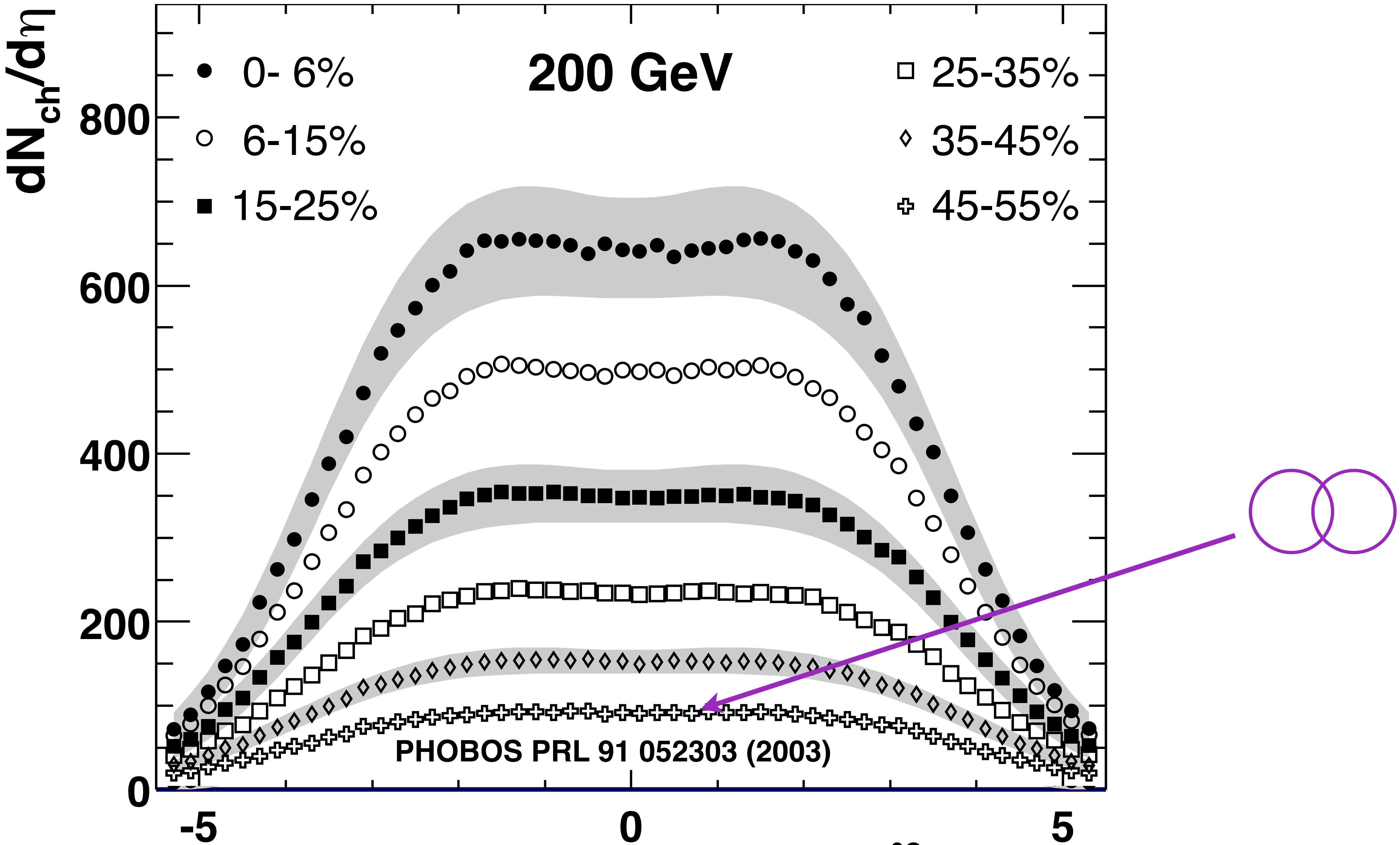
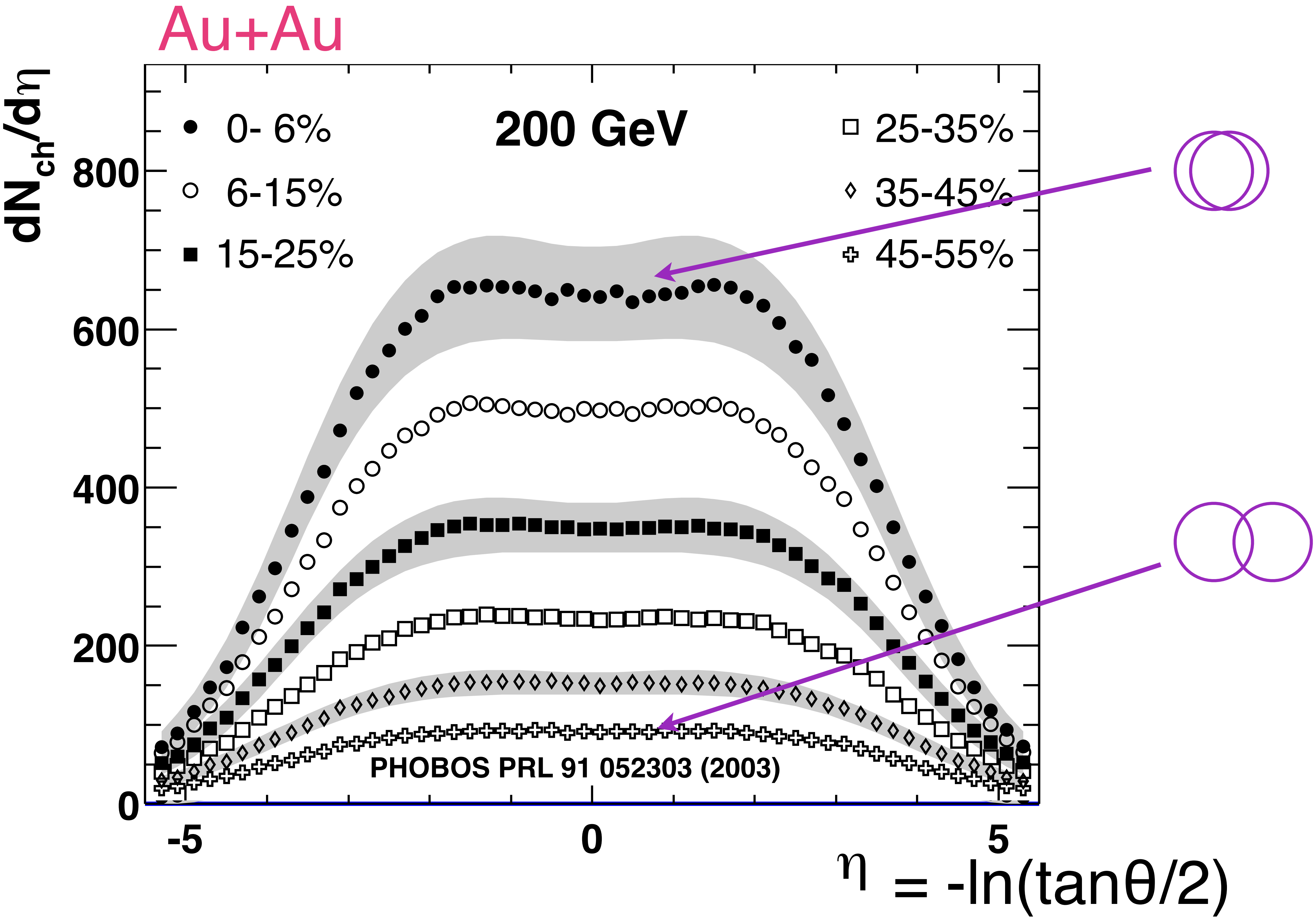


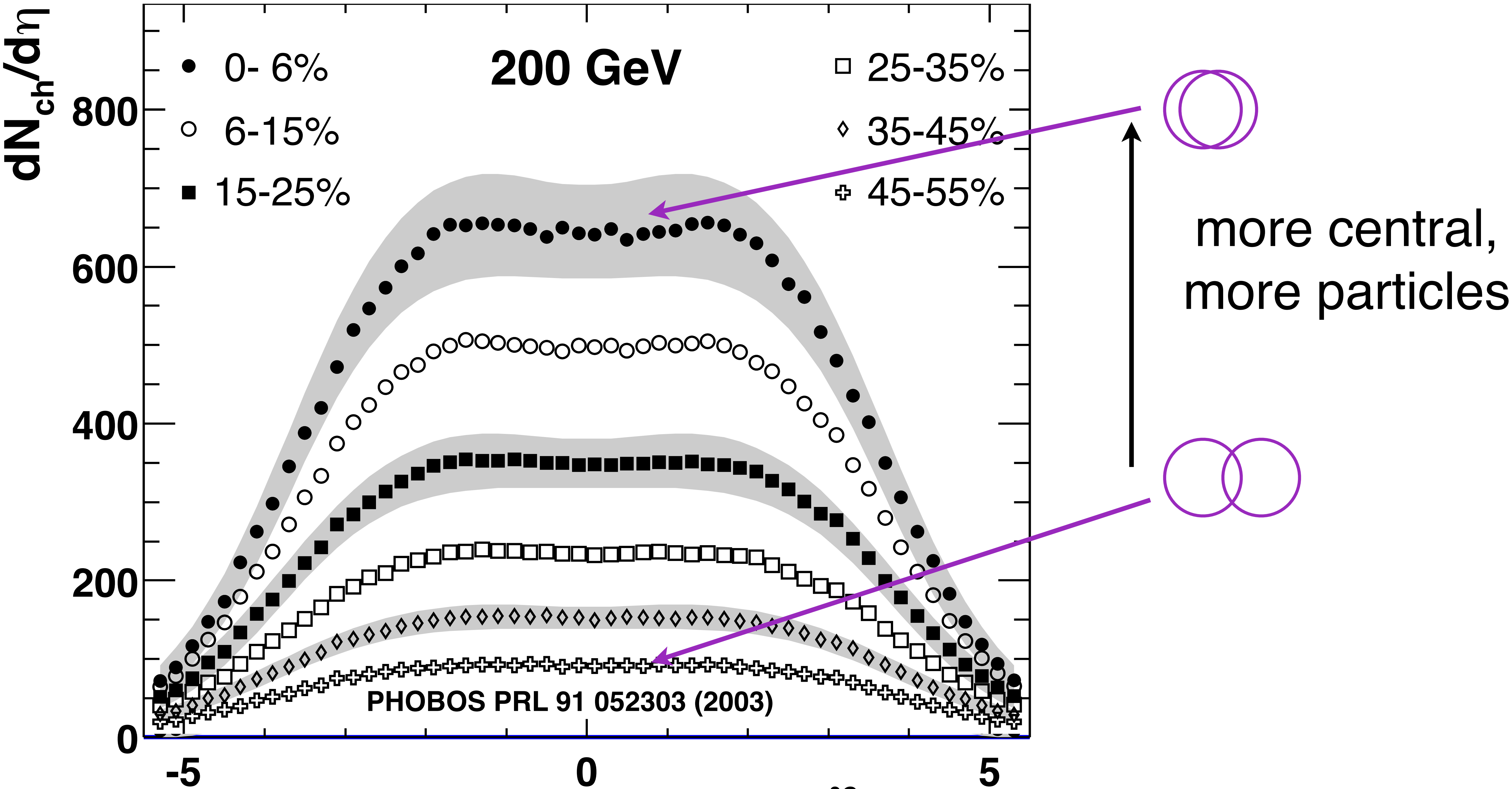
$\eta = -\ln(\tan\theta/2)$

charged particle multiplicity



charged particle multiplicity

Au+Au



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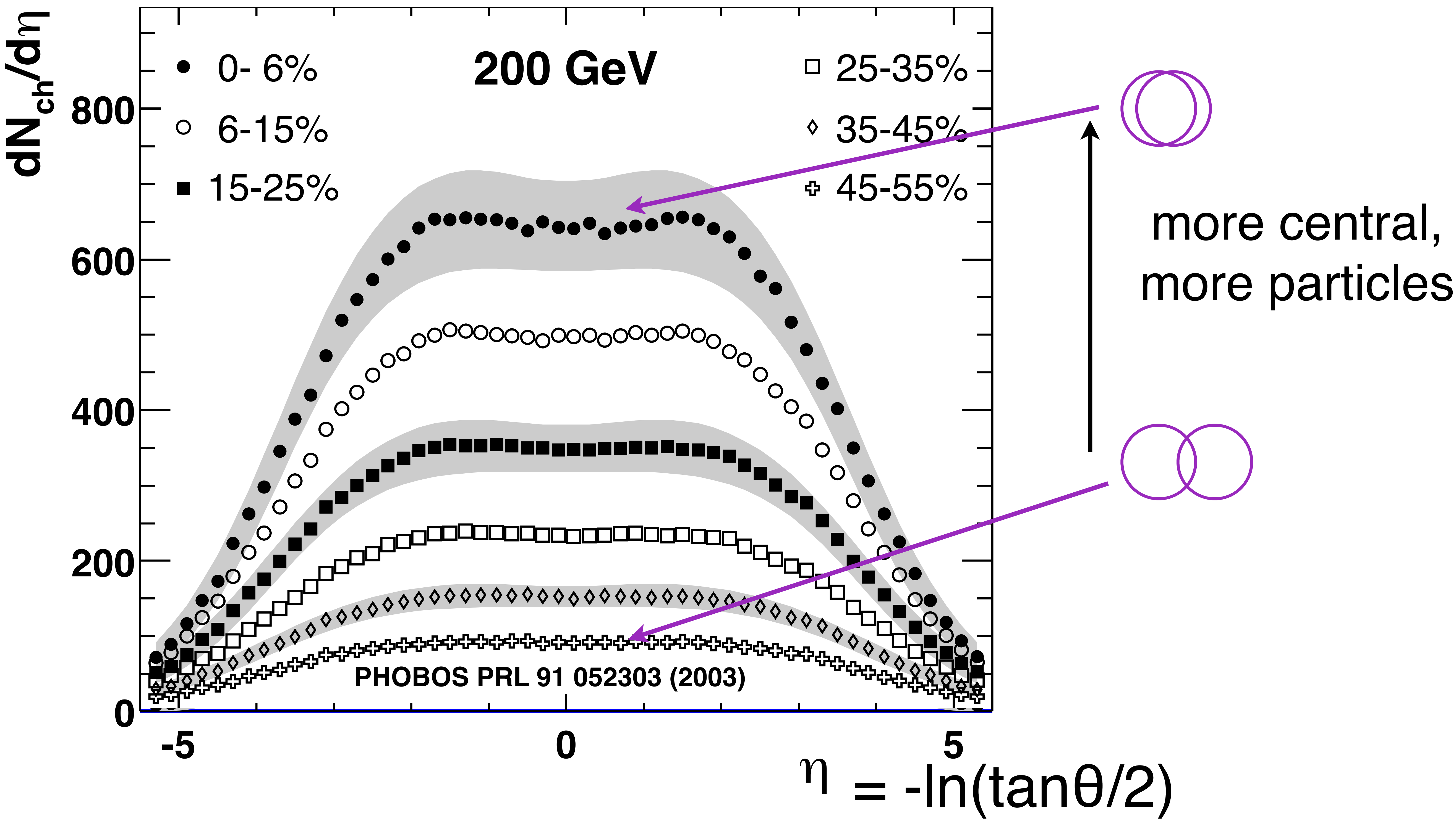
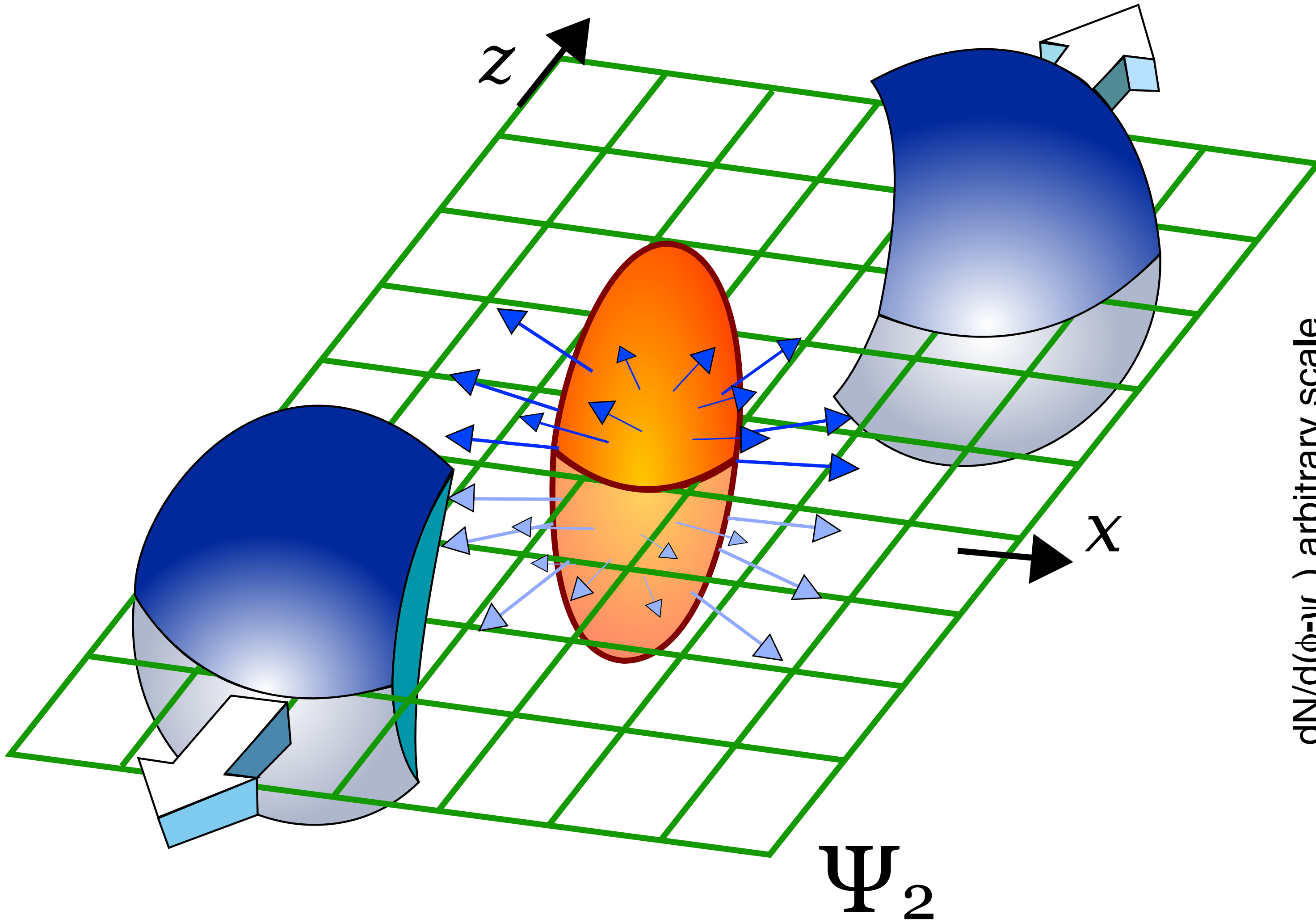


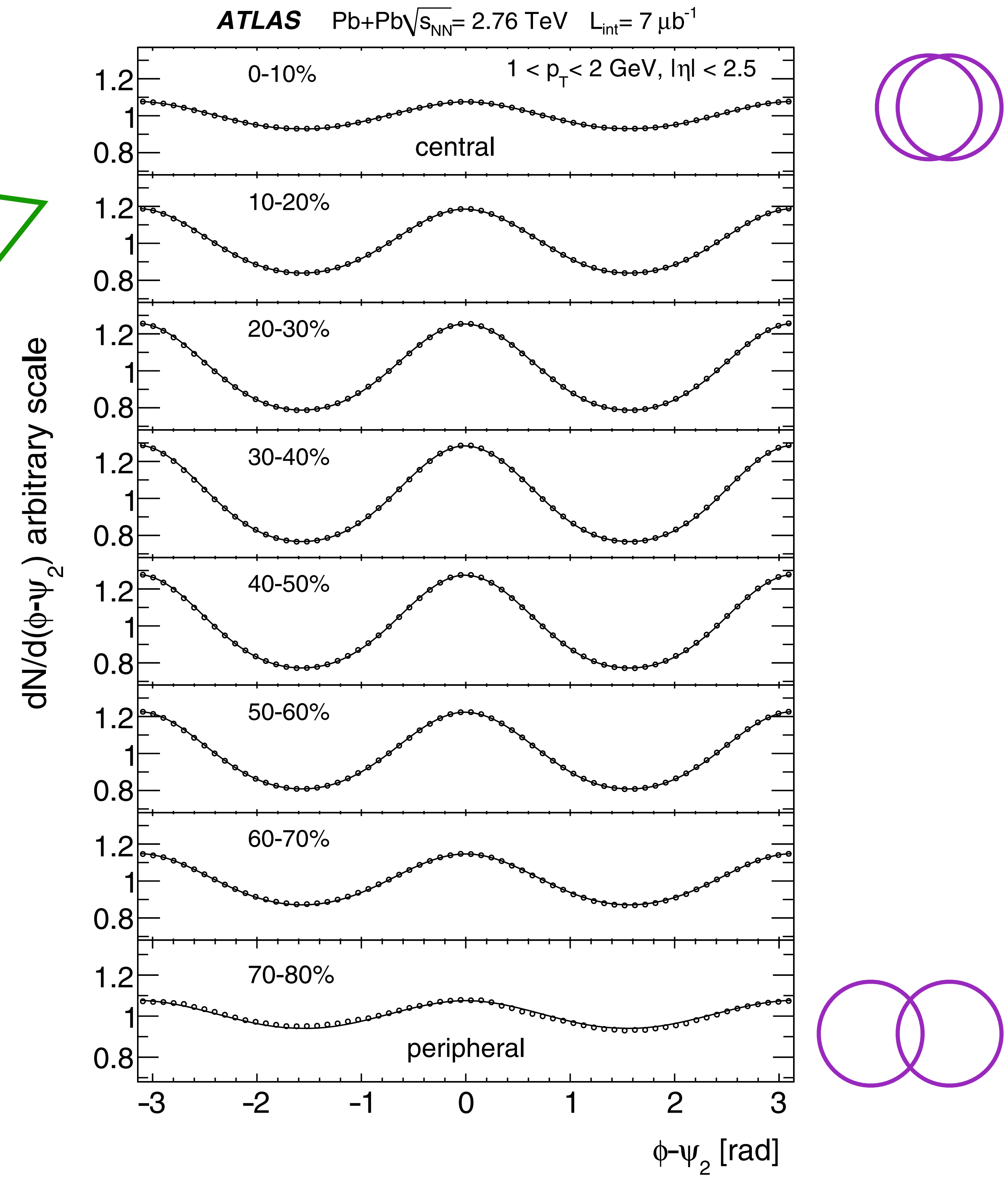
use the correlations between these particles to understand the QGP

characterizing the QGP

- characterization of the hot dense matter created in heavy ion collisions relies on a number of observables
  - here we focus on two:
- **hydrodynamic behavior of the QGP**
- **jet quenching**: can't bring in a truly external probe, but we can observe the modification of hard quarks and gluons by the QGP

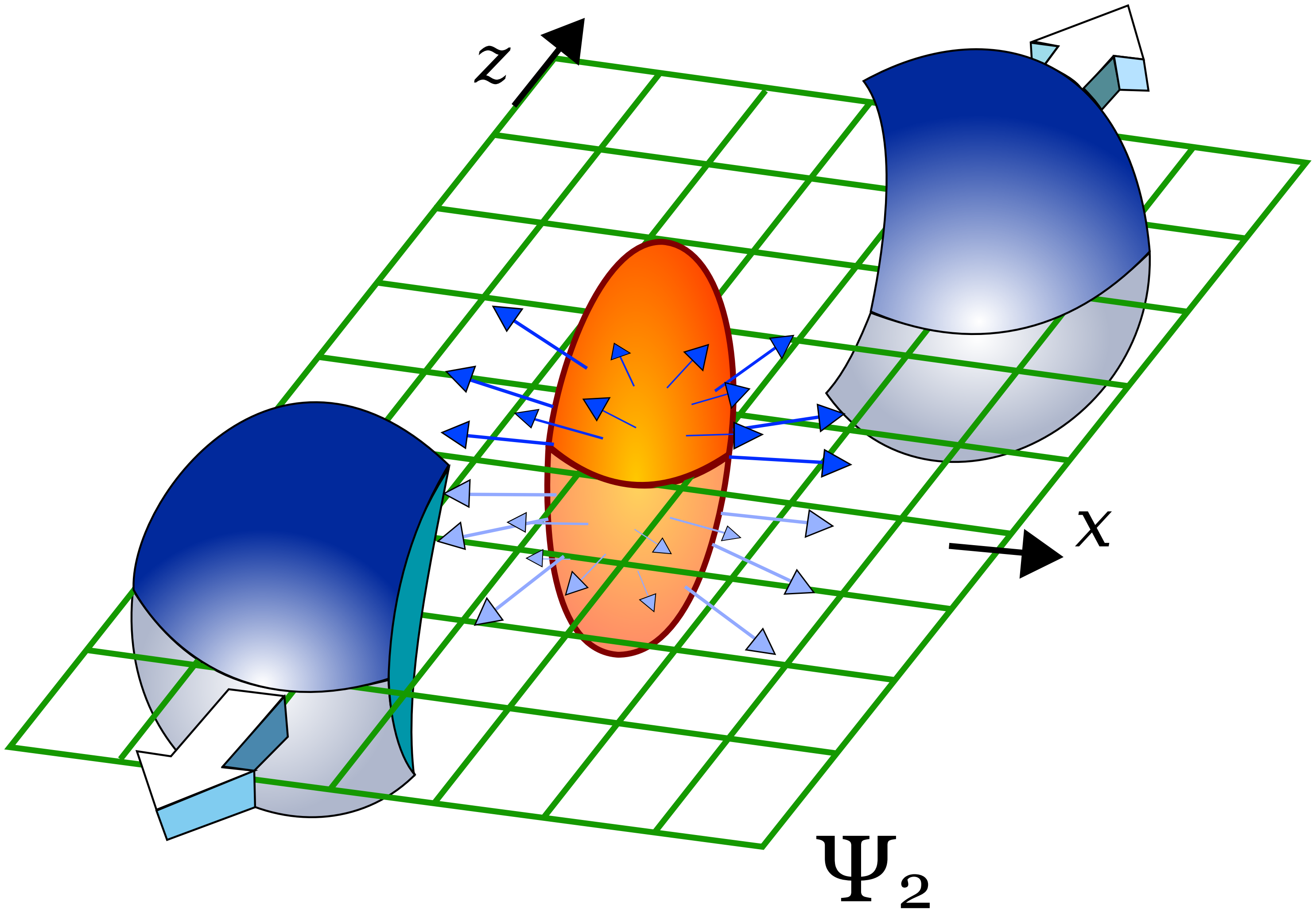
heavy ion collision



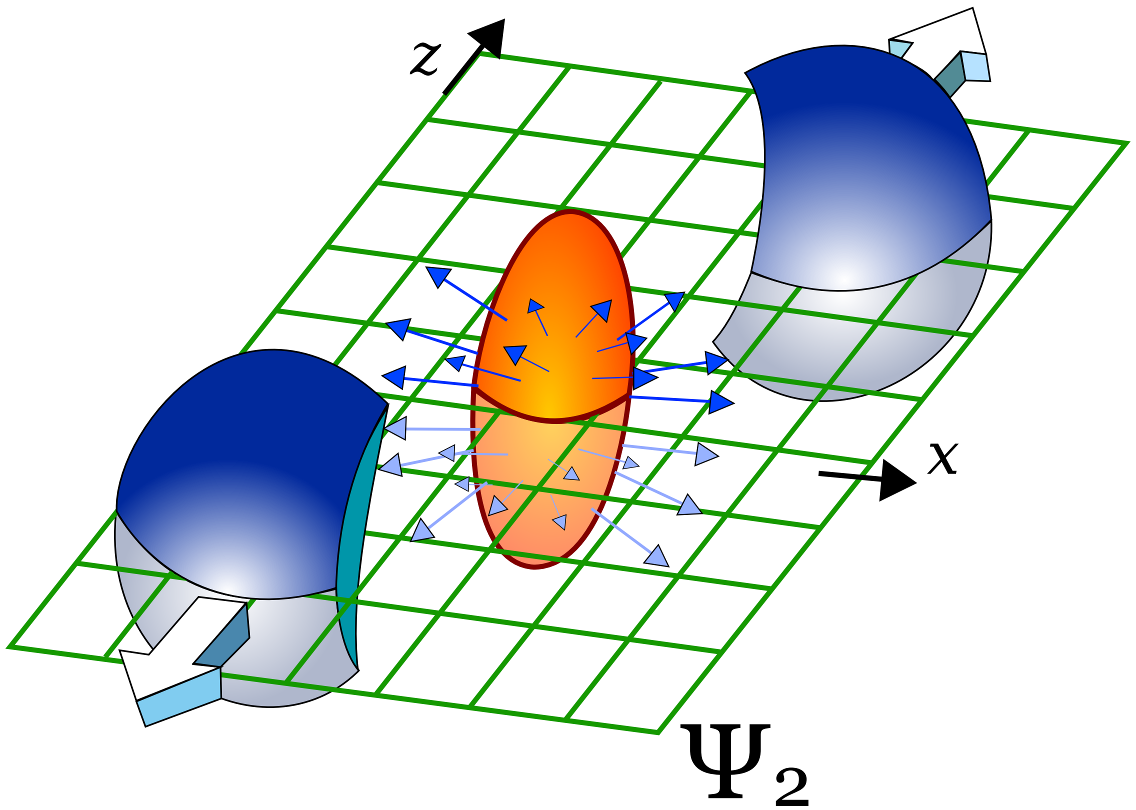


PLB 707 330 (2012)

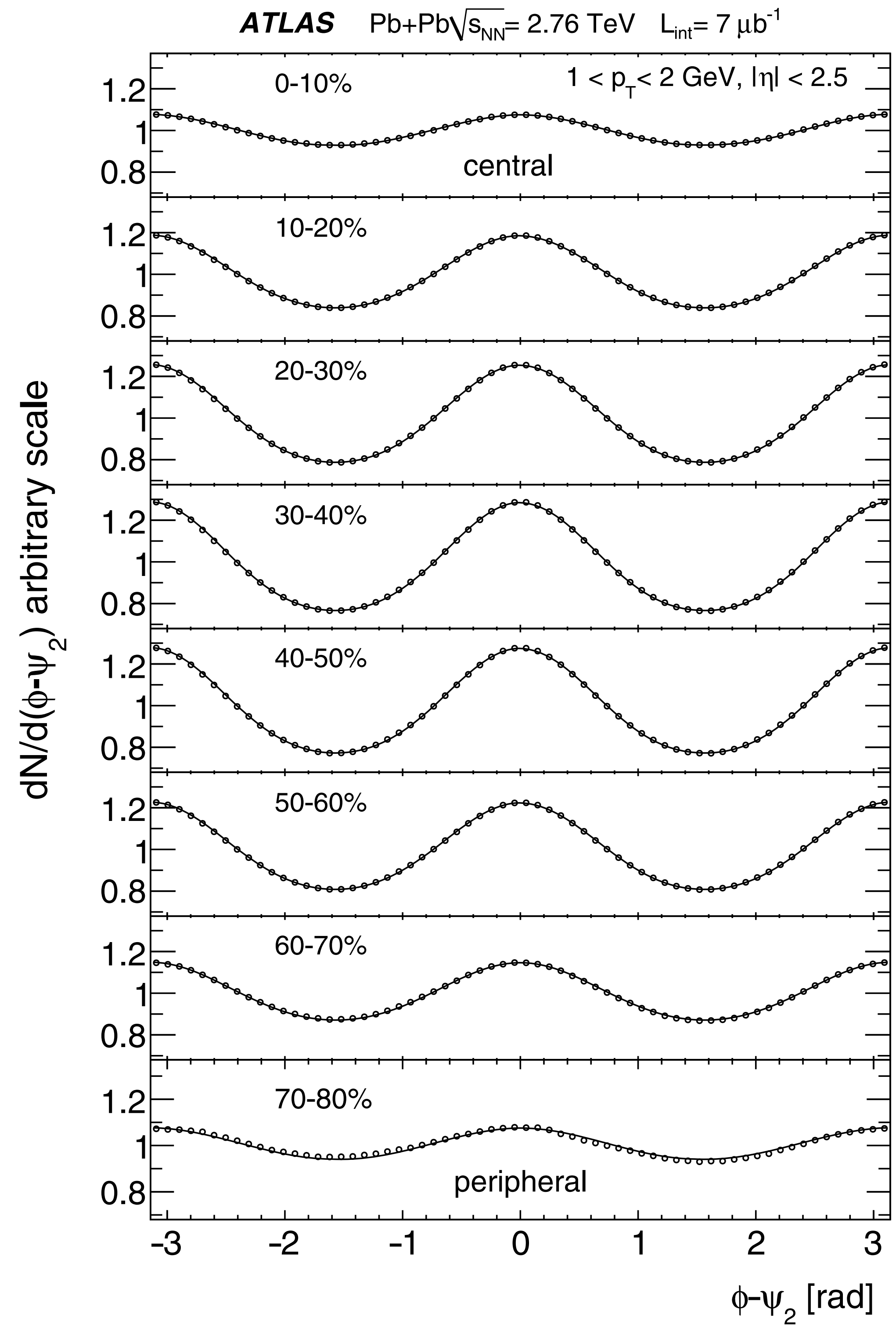
hydrodynamics



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

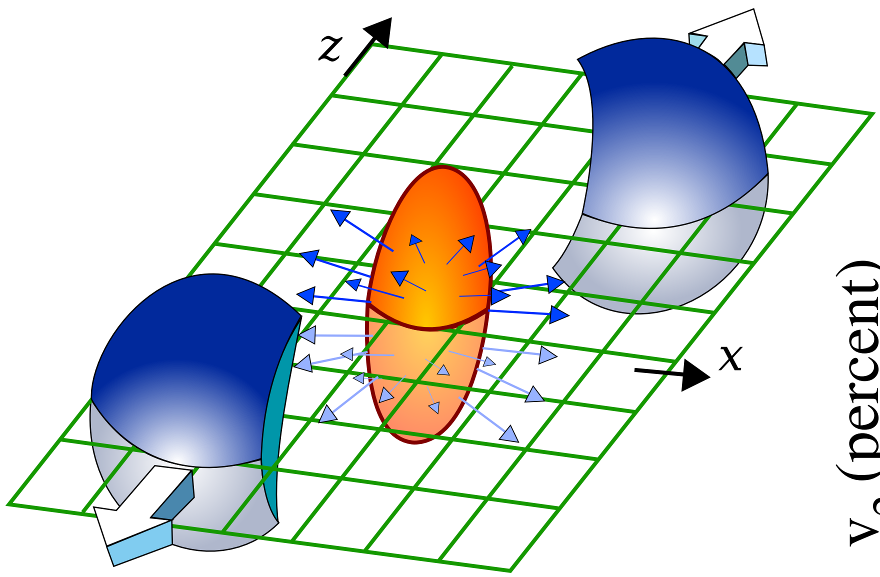


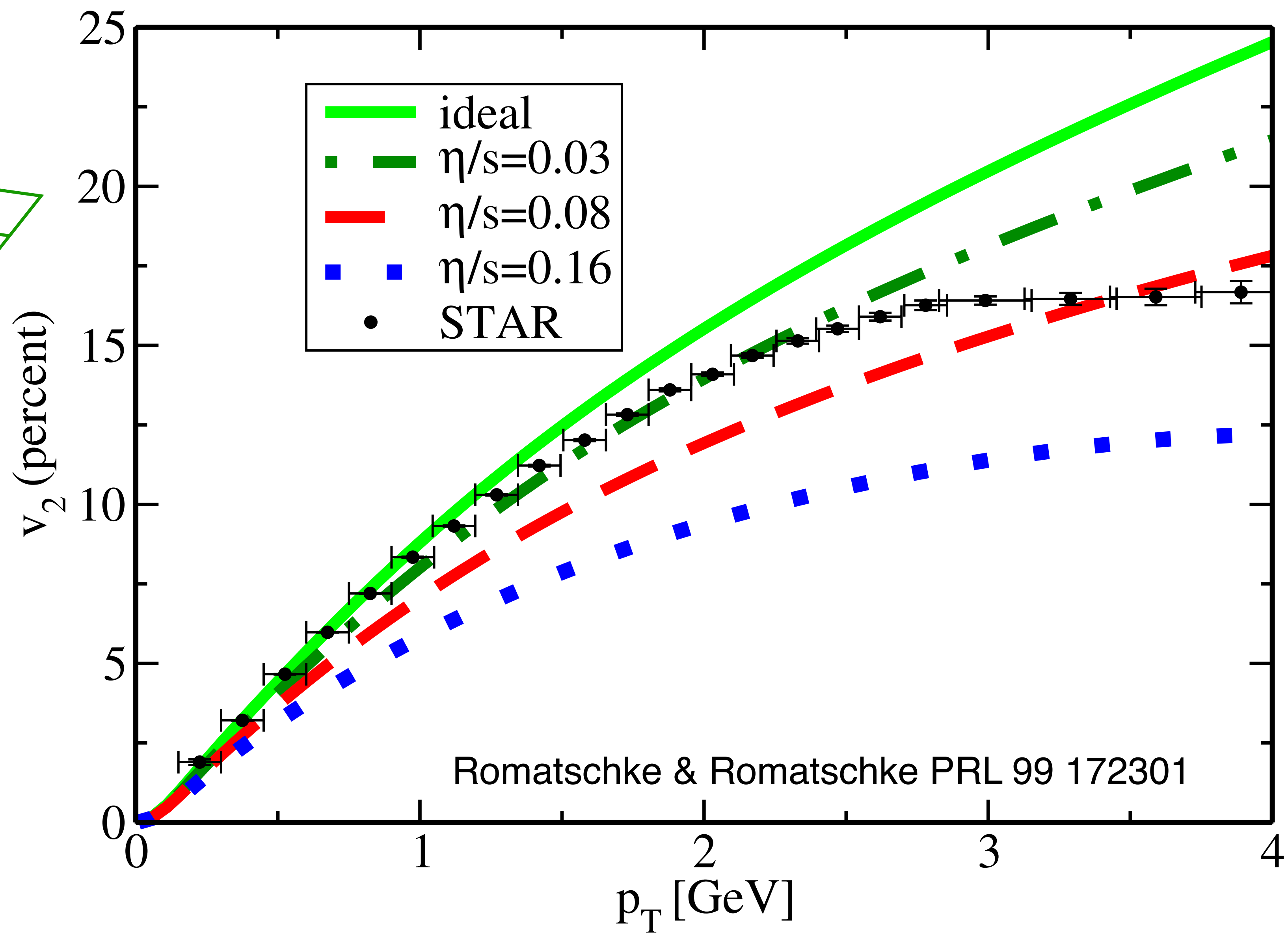
$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2\left(\phi - \Psi_2\right)$$



PLB 707 330 (2012)

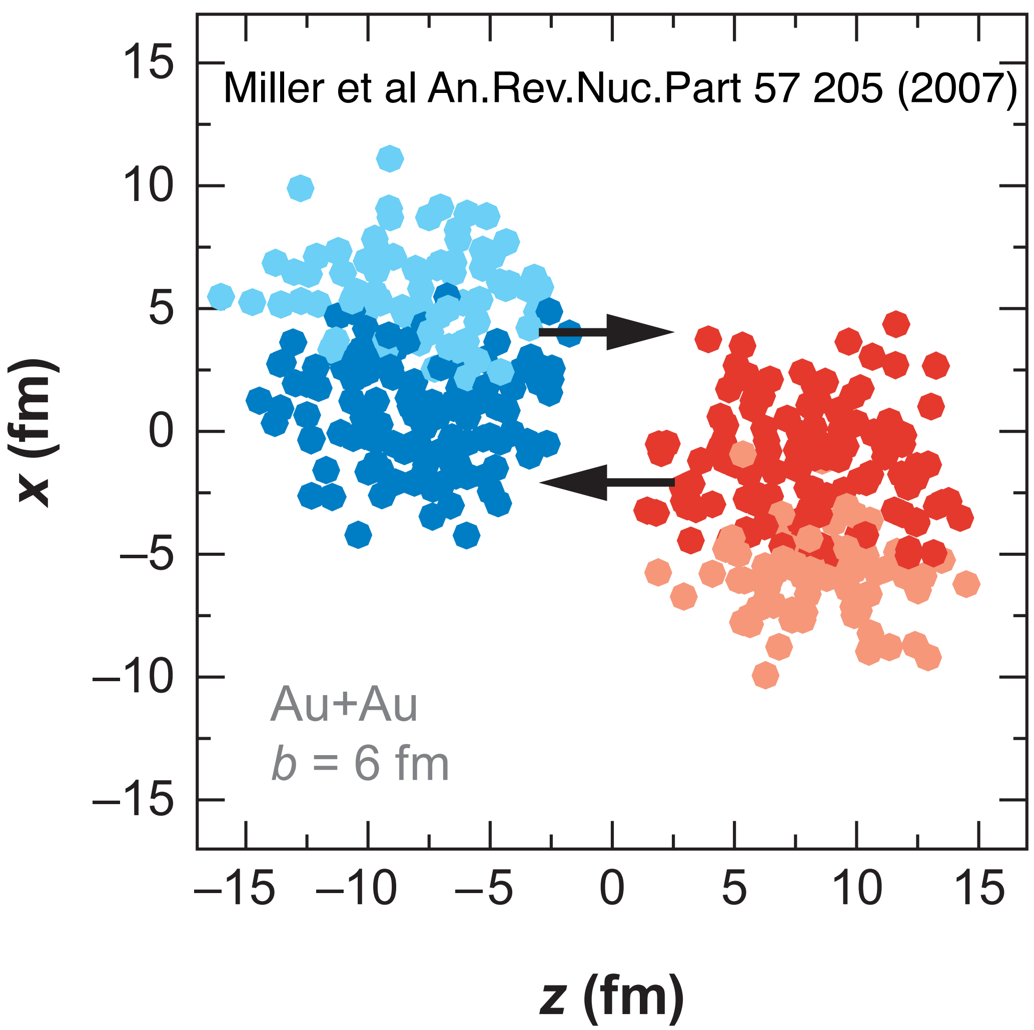
hydrodynamic calculations



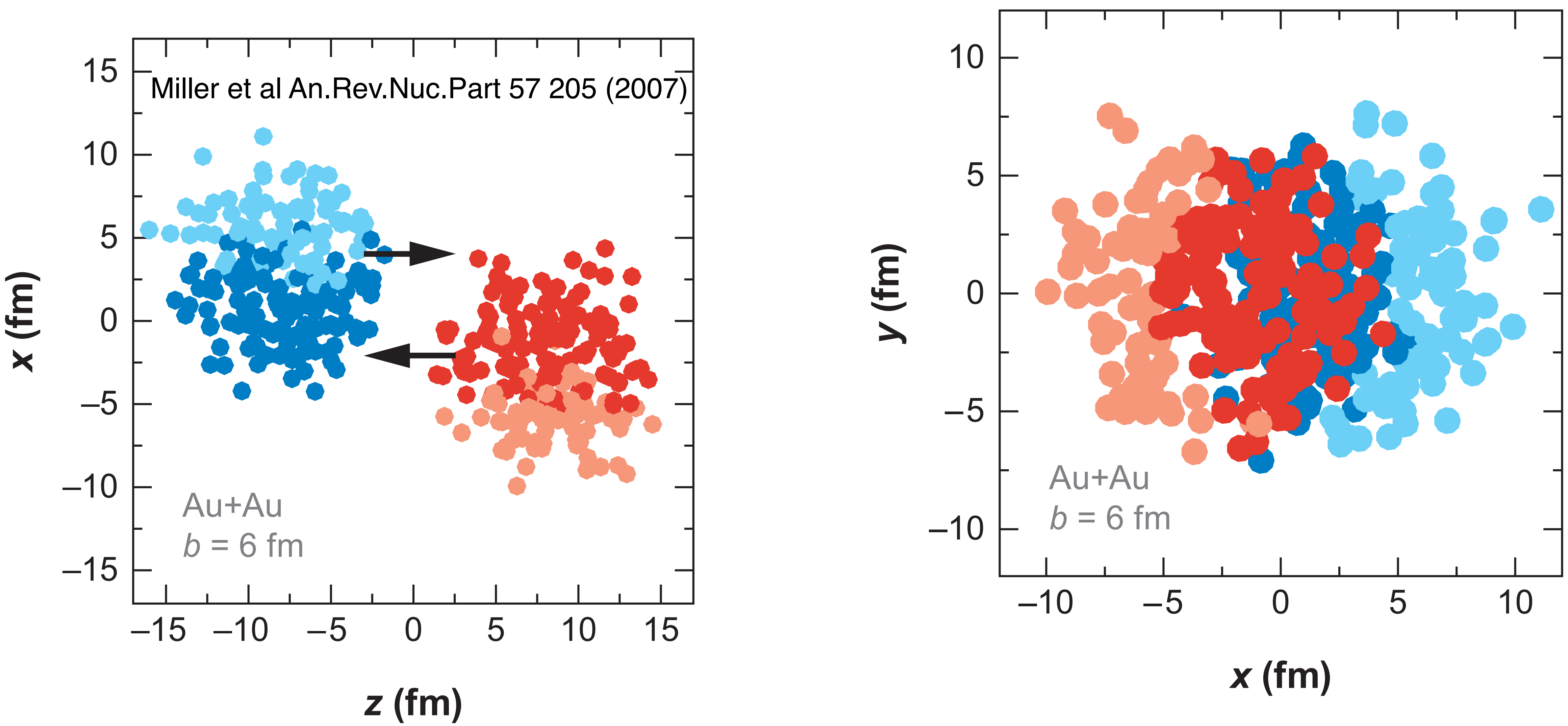


hydrodynamics works, v2 sensitive to viscosity

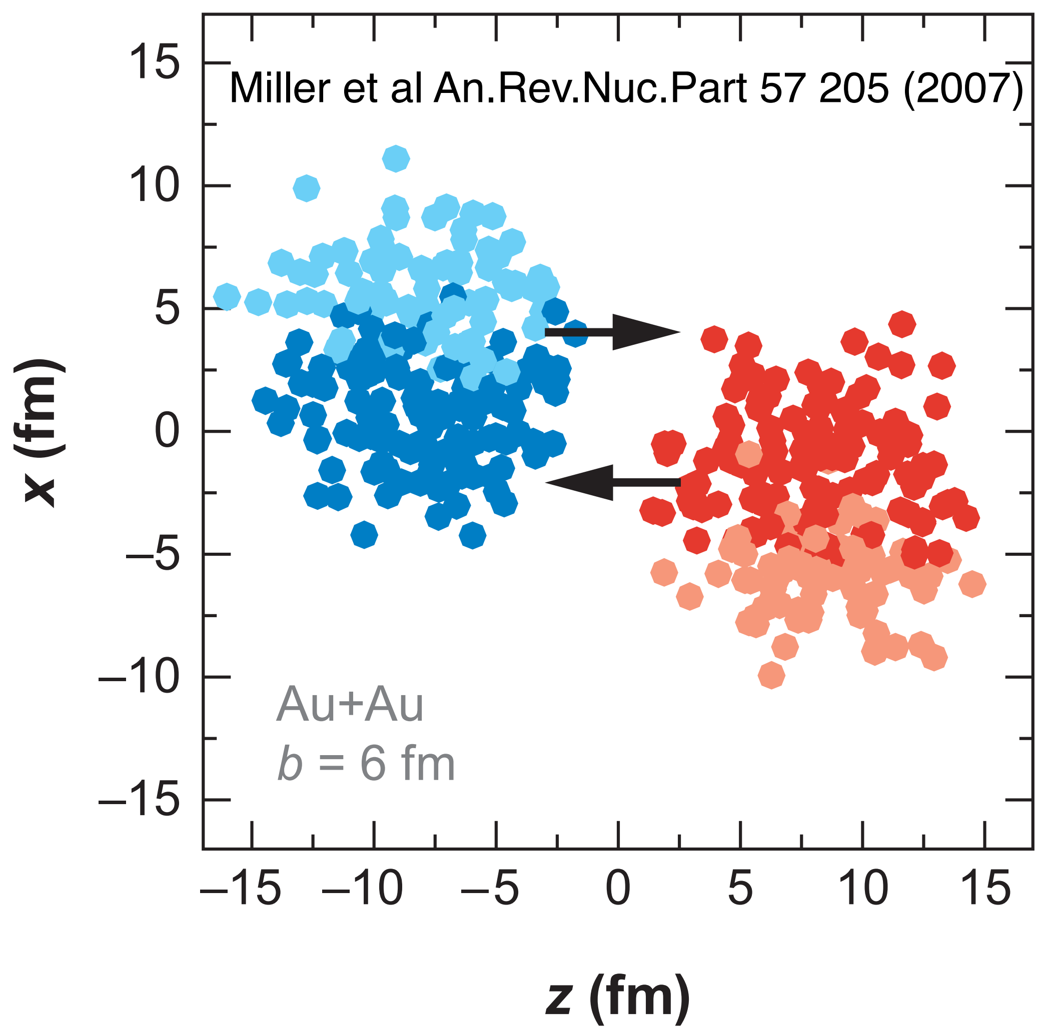
Glauber model: nucleon position fluctuations

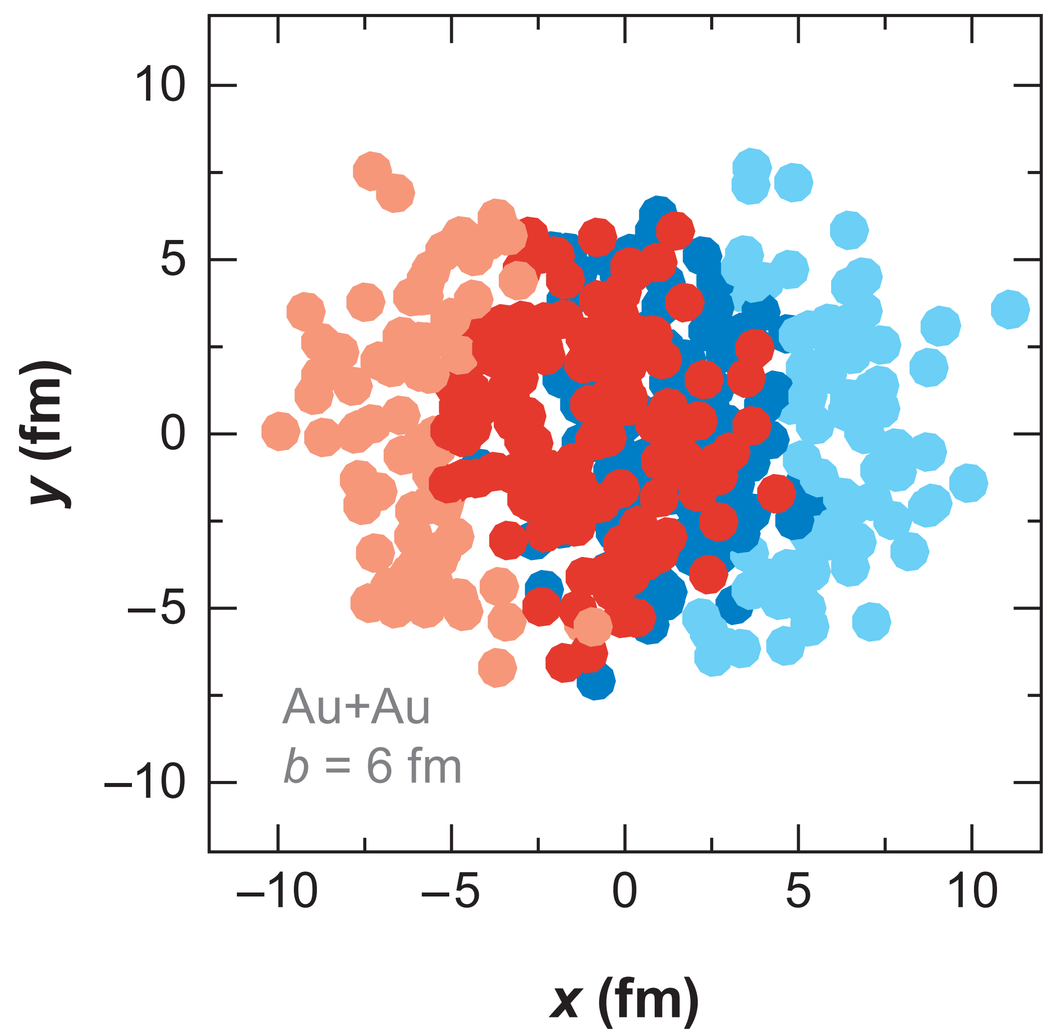


Glauber model: nucleon position fluctuations



Glauber model: nucleon position fluctuations

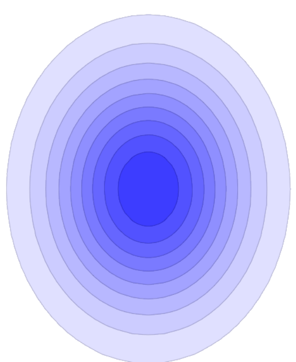




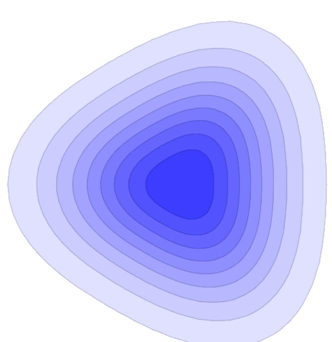
- not necessarily elliptical, smooth, or oriented around impact parameter plane...
  - more complicated geometry, leads to more complicated particle distributions

shape can be decomposed

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

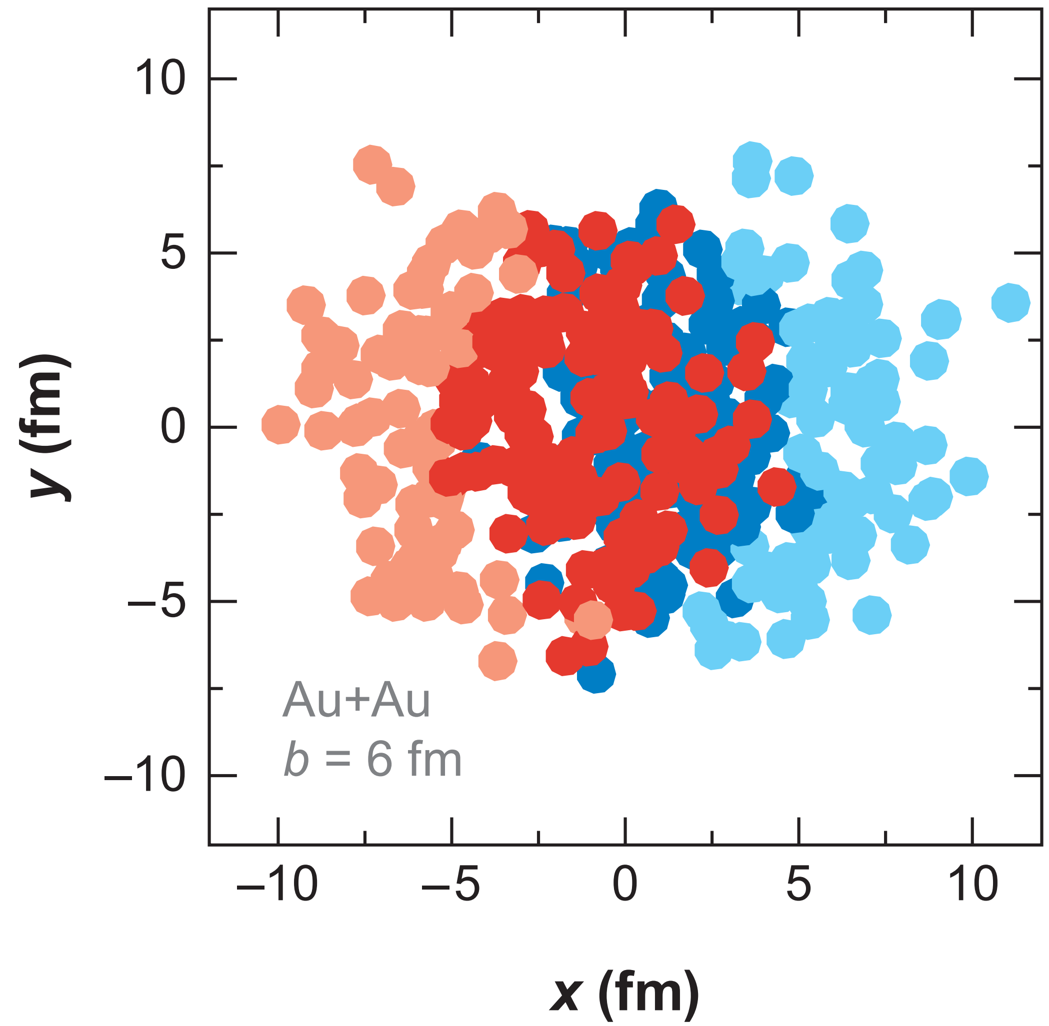


ε_2



ε_3

...

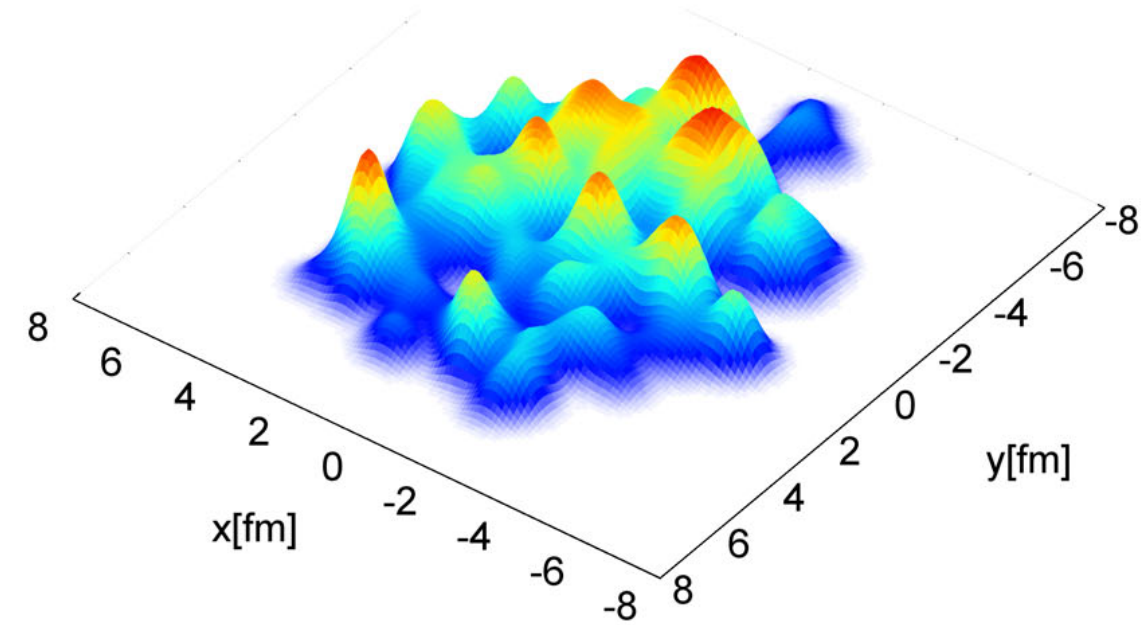


these shapes can then be seen in the observed particle distributions

nucleon positions to energy density

single event initial energy density

nucleons: Gaussians,
σ = 0.4fm



Schenke, Tribedy & Venugopalan PRL 108 252301 (2012)

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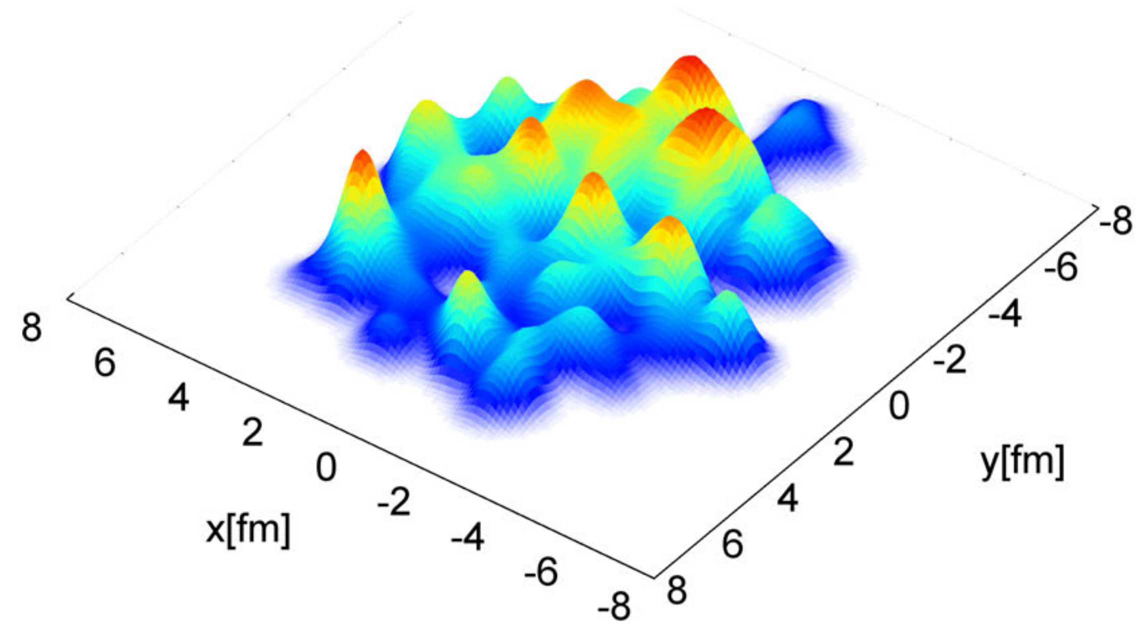
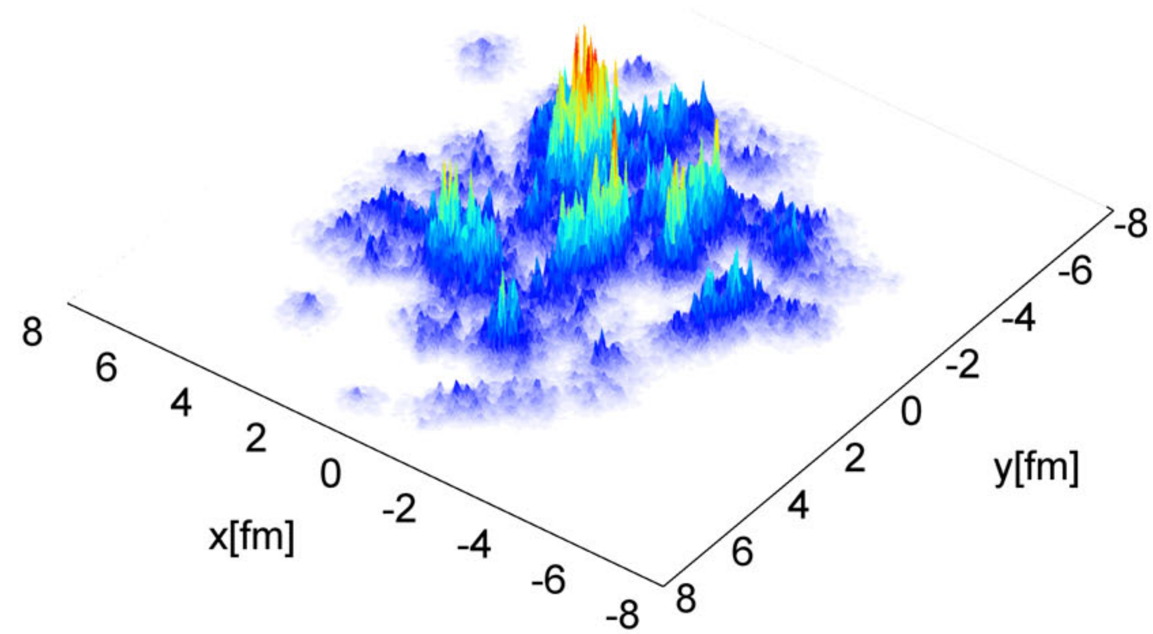
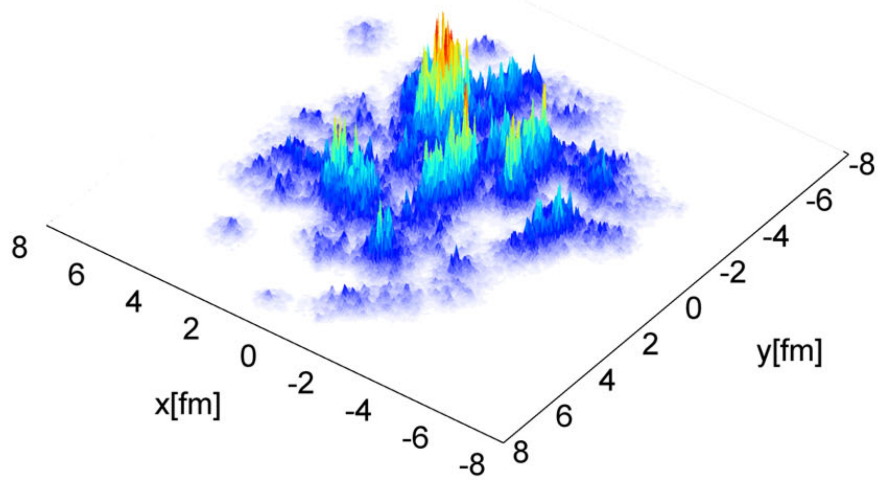


subnucleonic fluctuations:
IP-Glasma model

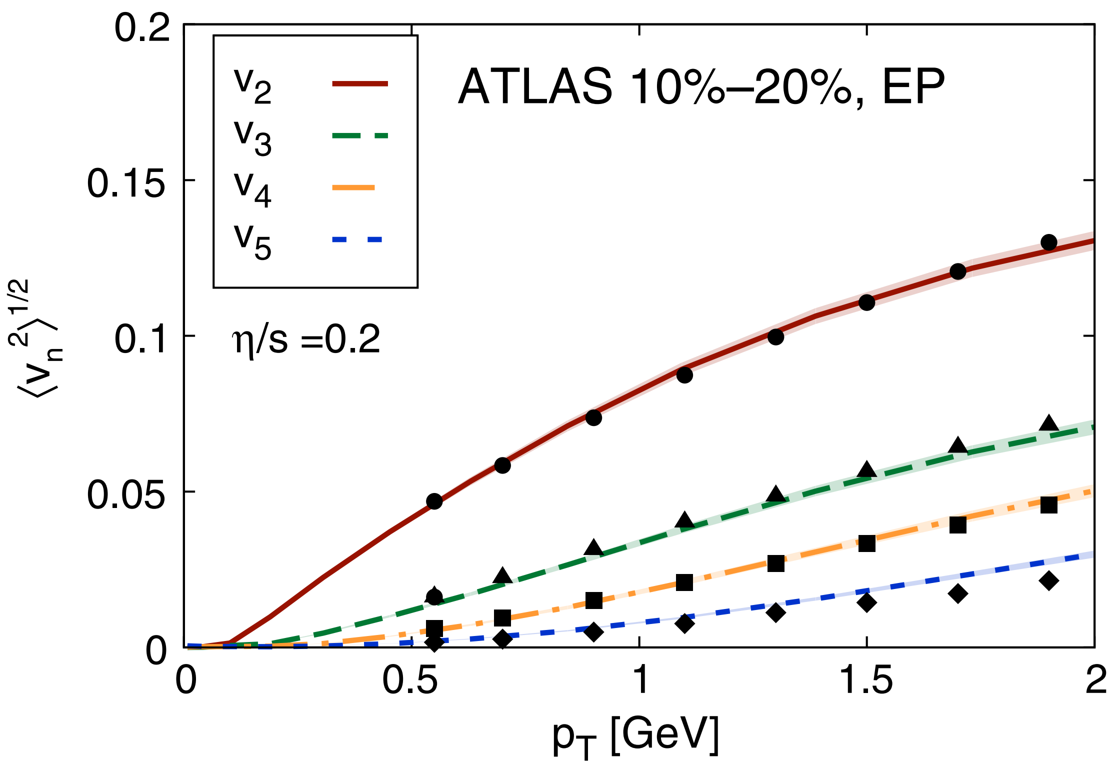


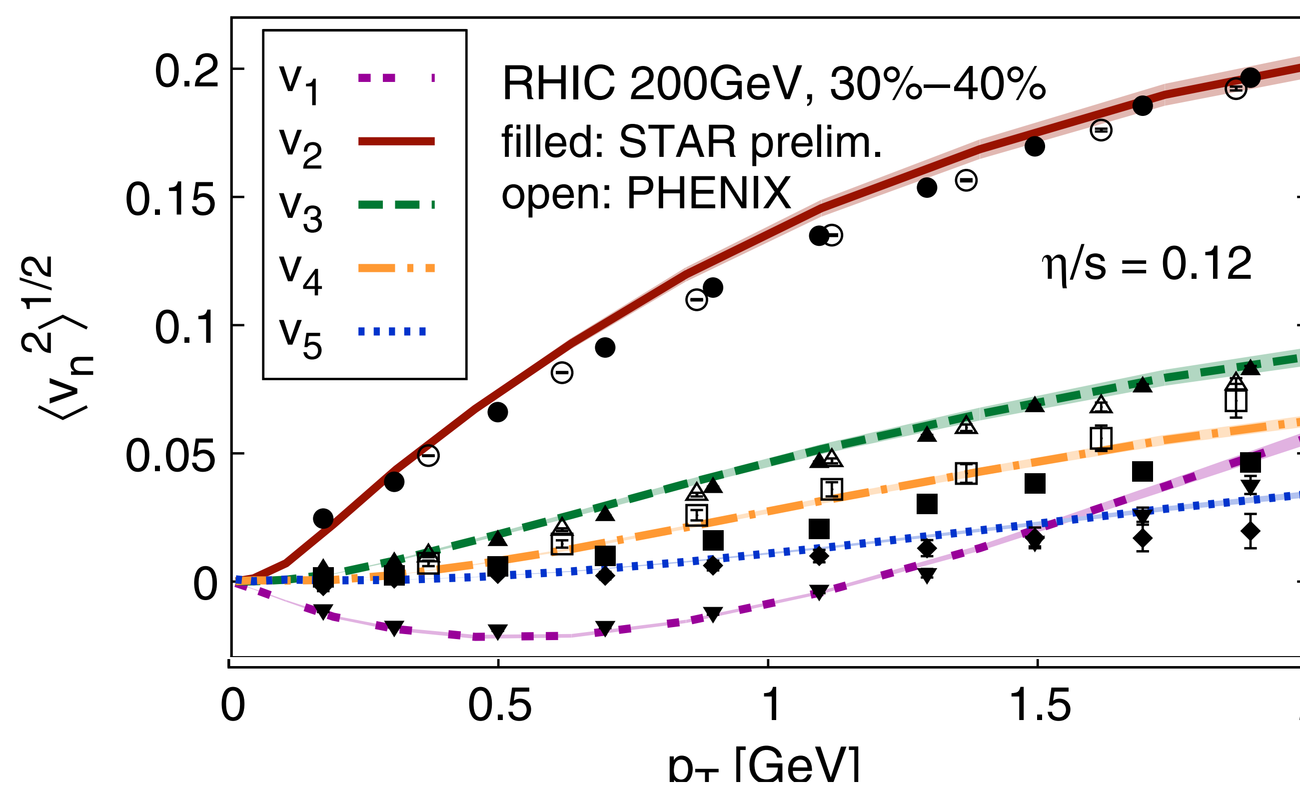
Schenke, Tribedy & Venugopalan PRL 108 252301 (2012)

state of the art hydrodynamic calculations



& 3 +1d viscous hydrodynamics



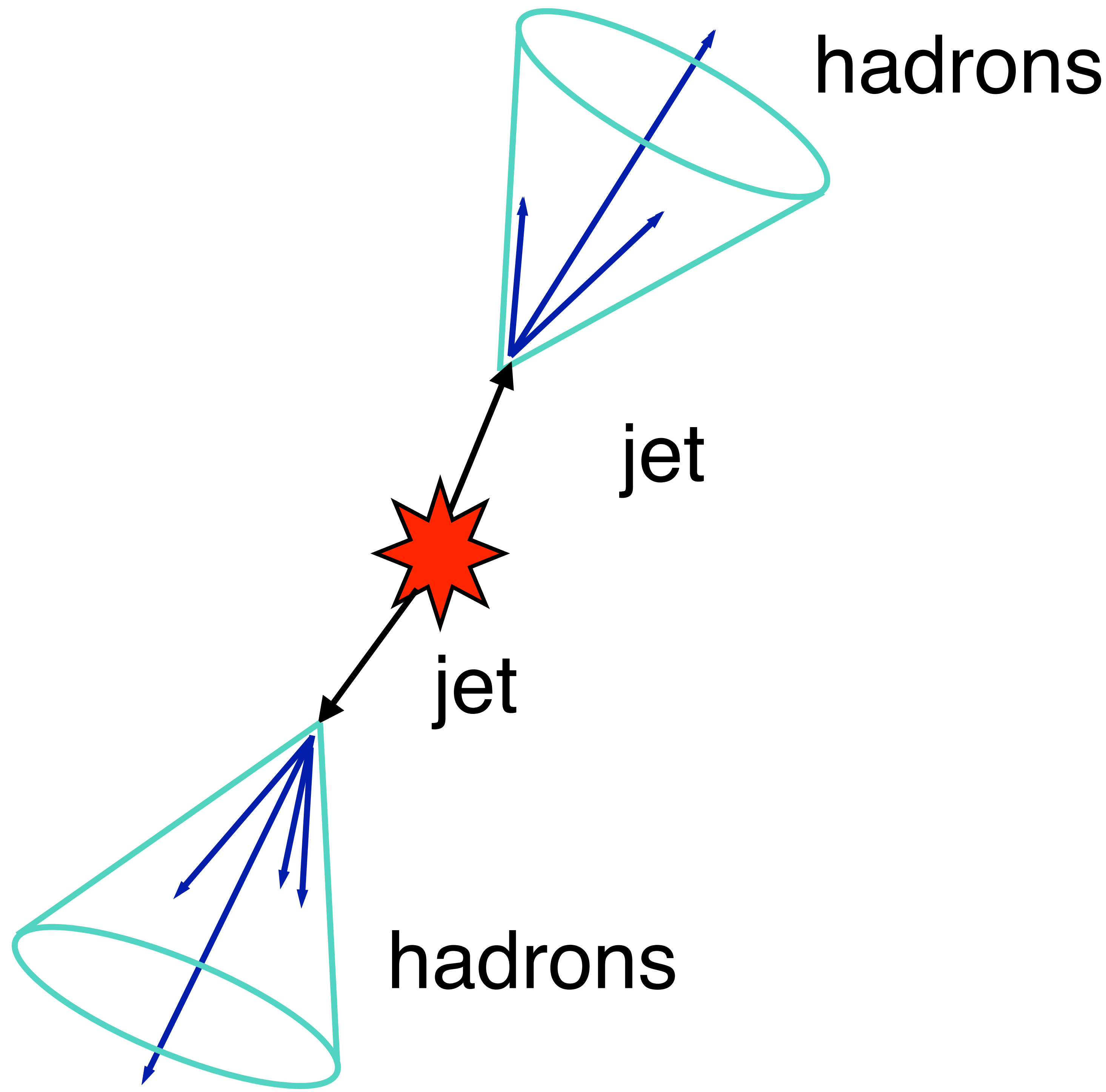


quantitative description of v_1 - v_5 at both RHIC and LHC

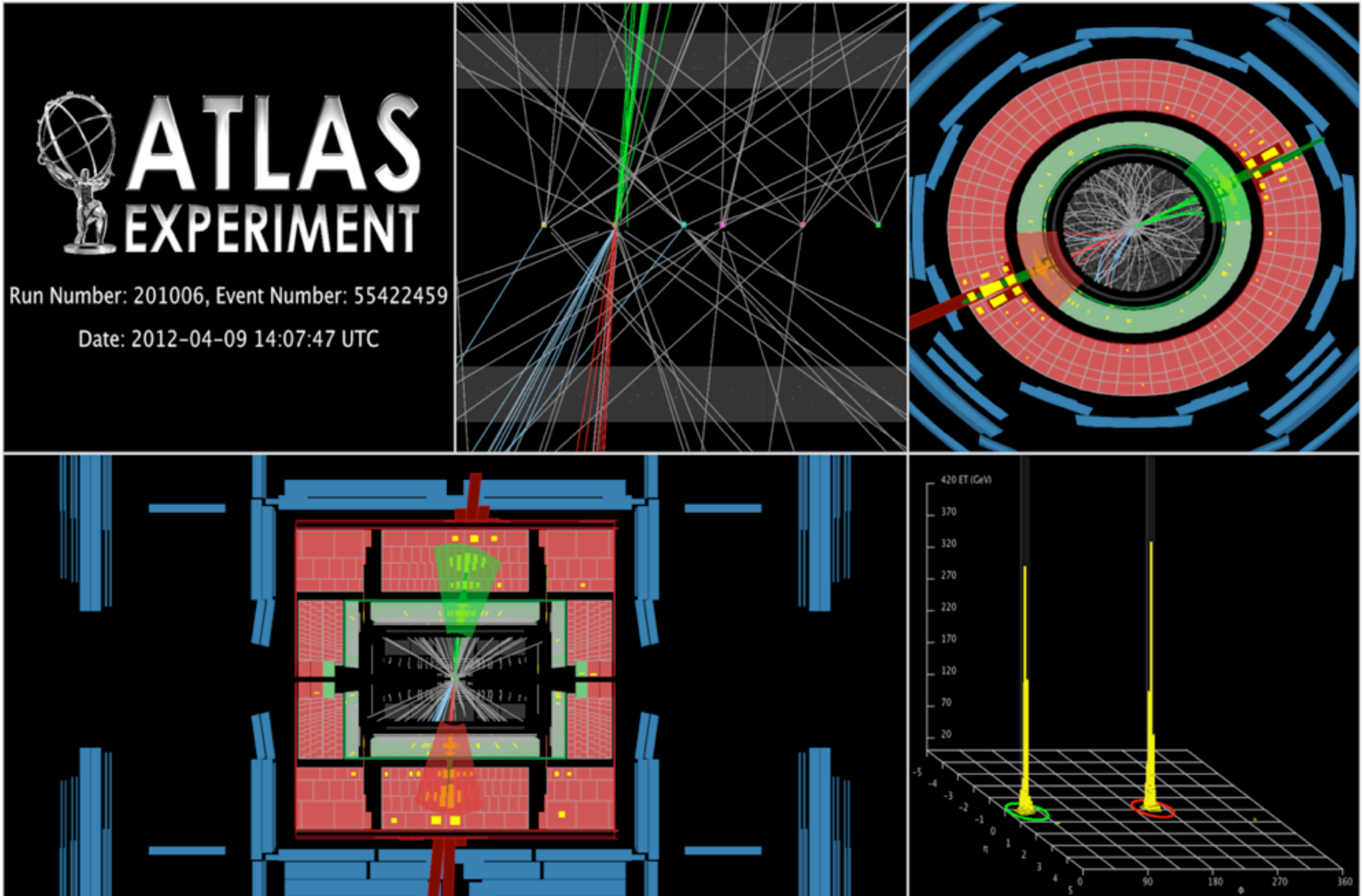
Gale, Jeon, Schenke, Tribedy, Venugopalan PRL 110 012302

probing the QGP with jets

p+p collisions

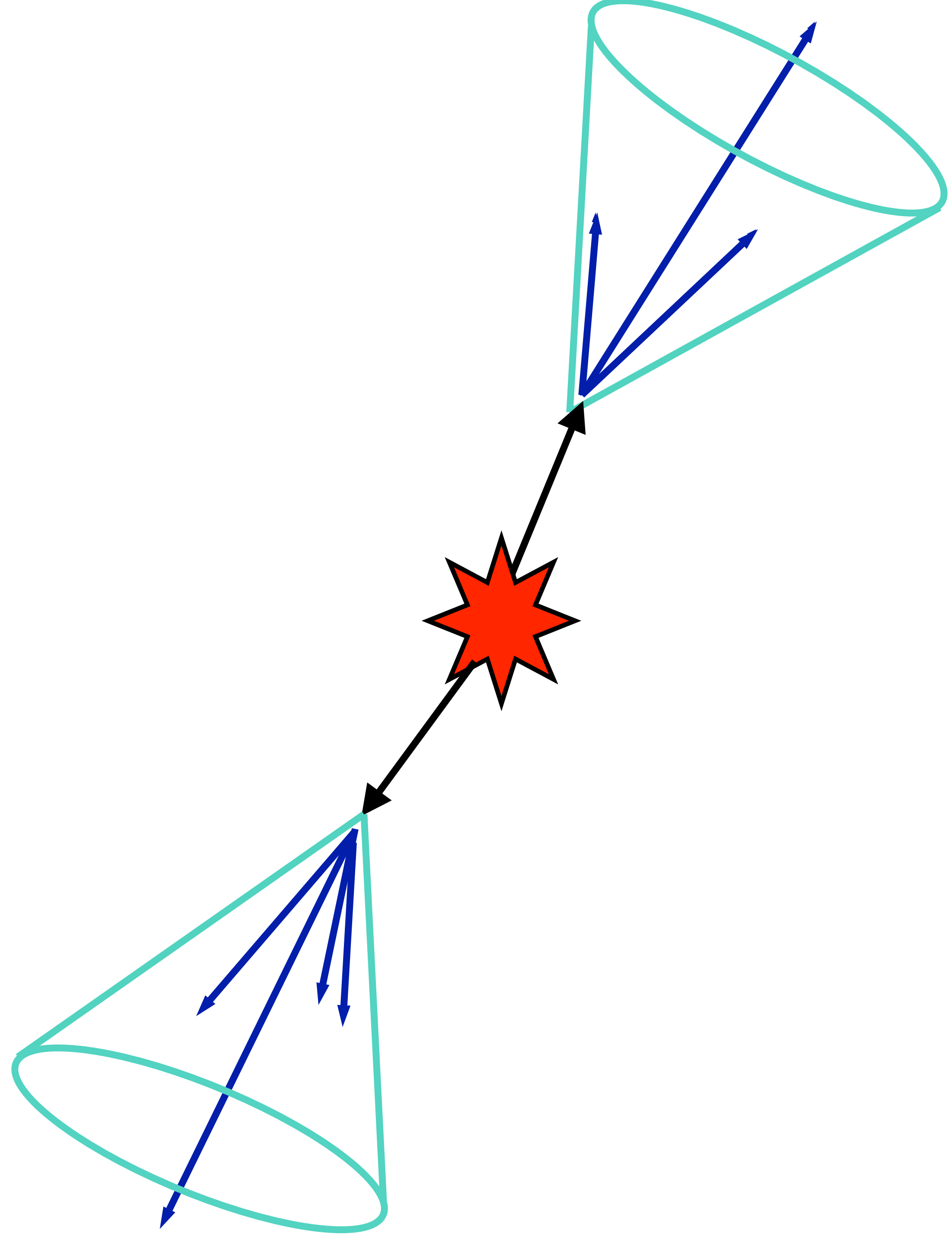


jets in proton-proton collisions

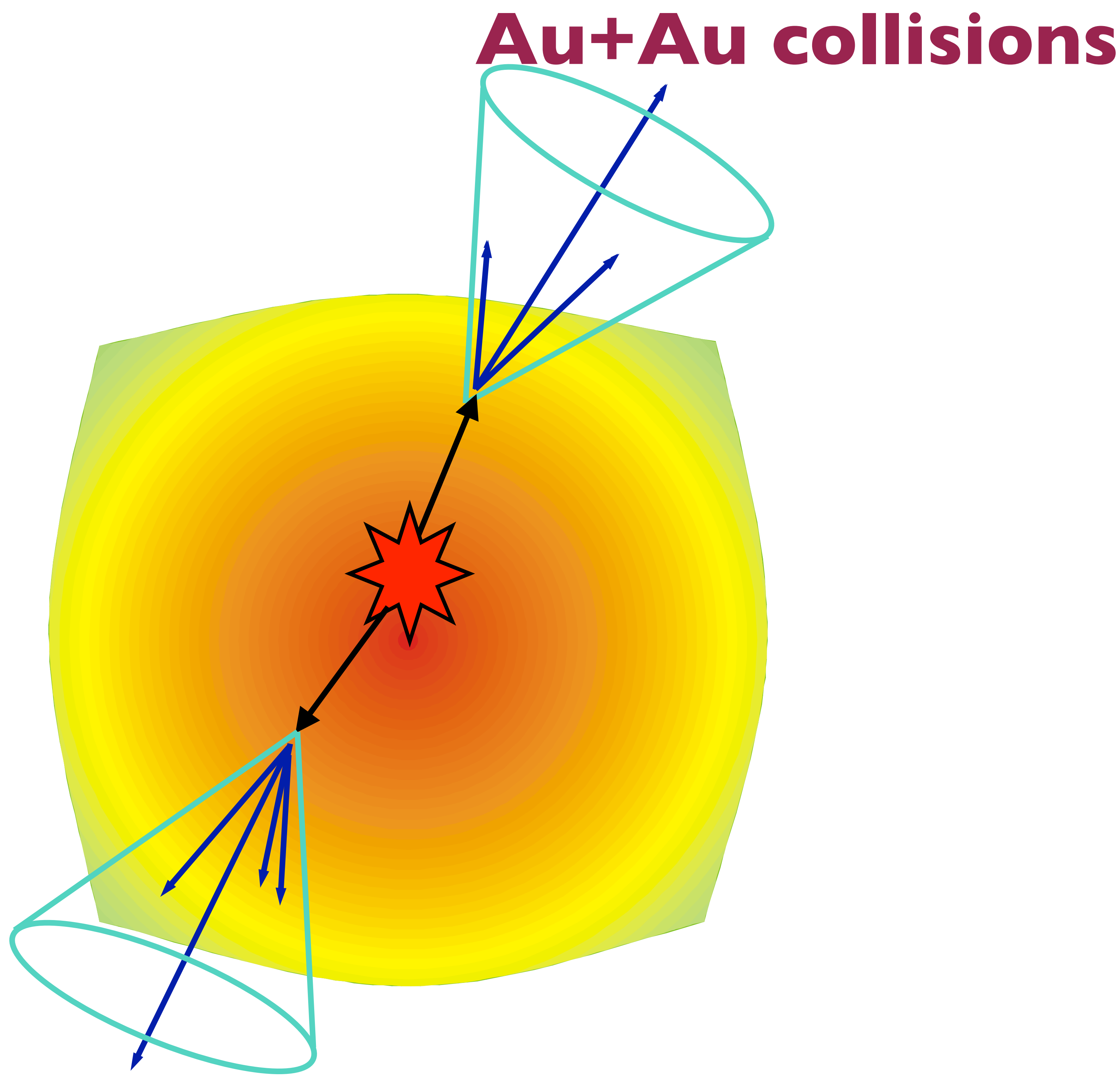


probing the QGP with jets

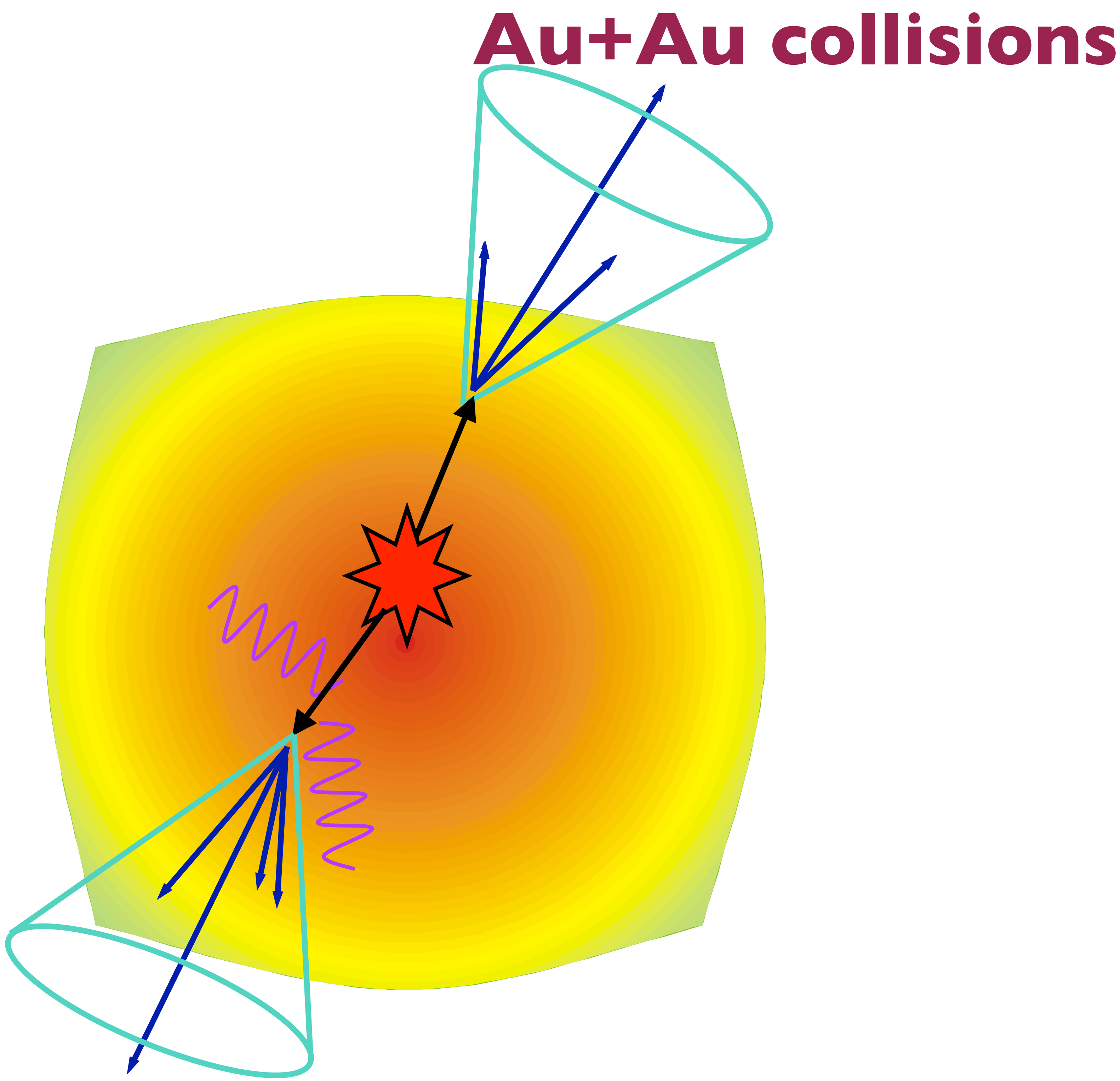
Au+Au collisions



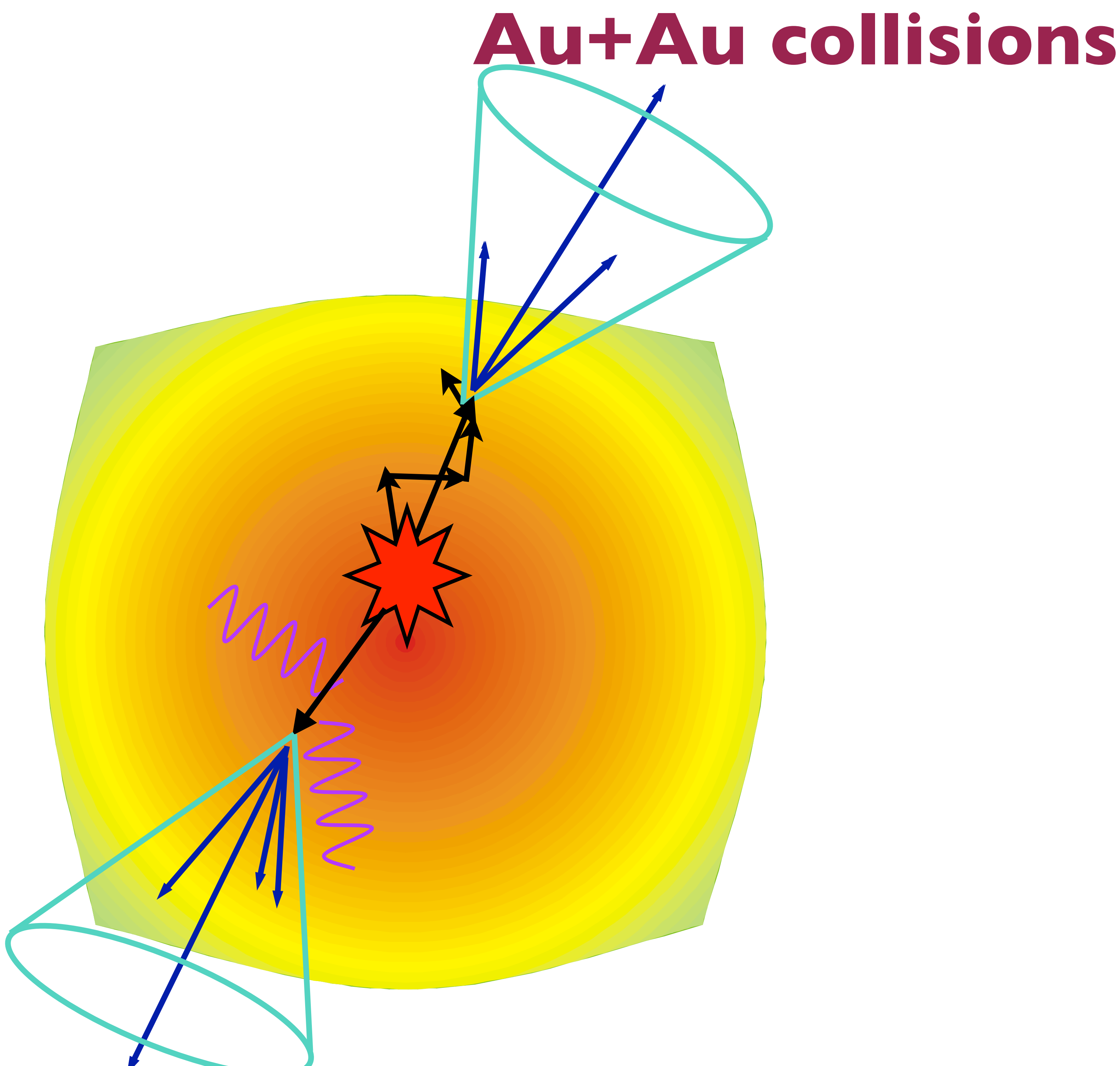
probing the QGP with jets



probing the QGP with jets

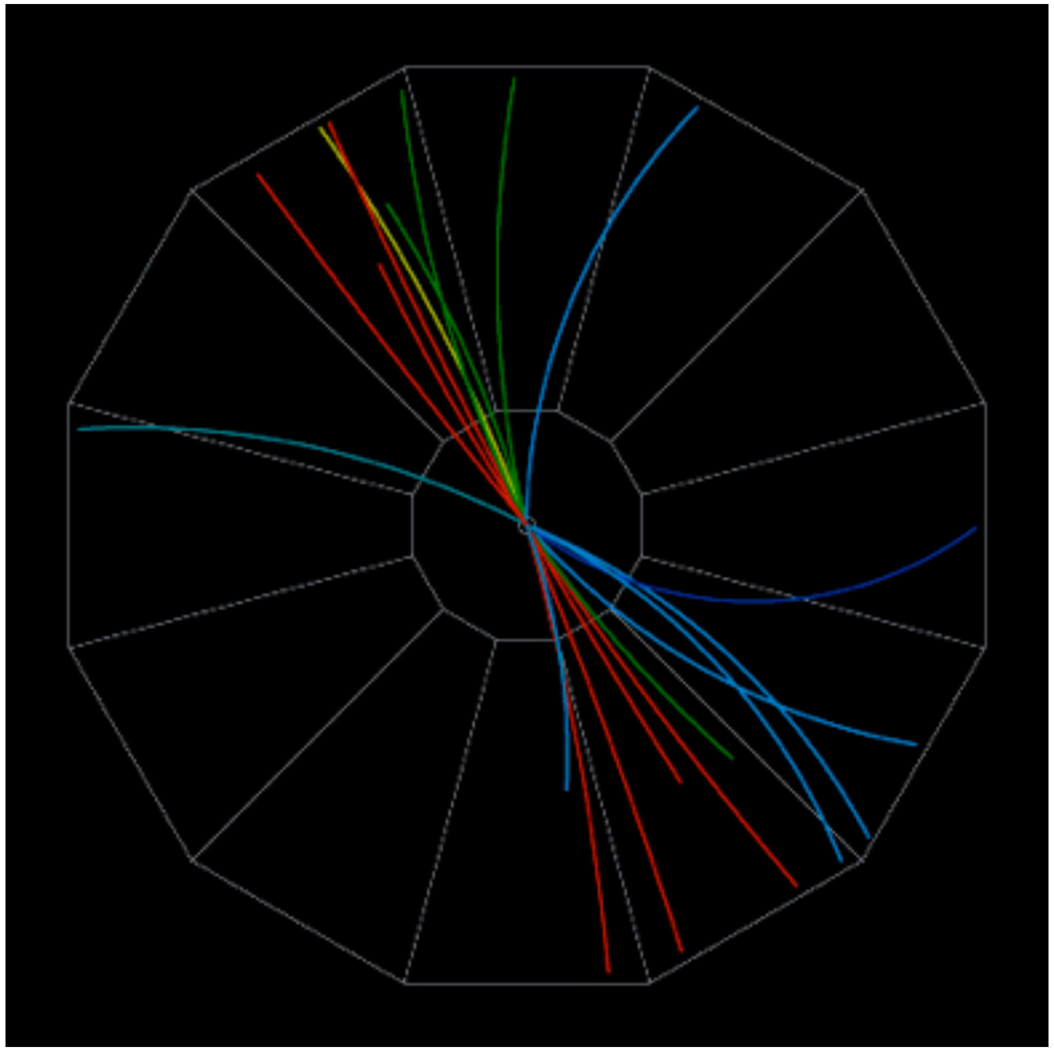


probing the QGP with jets



experimental challenge!

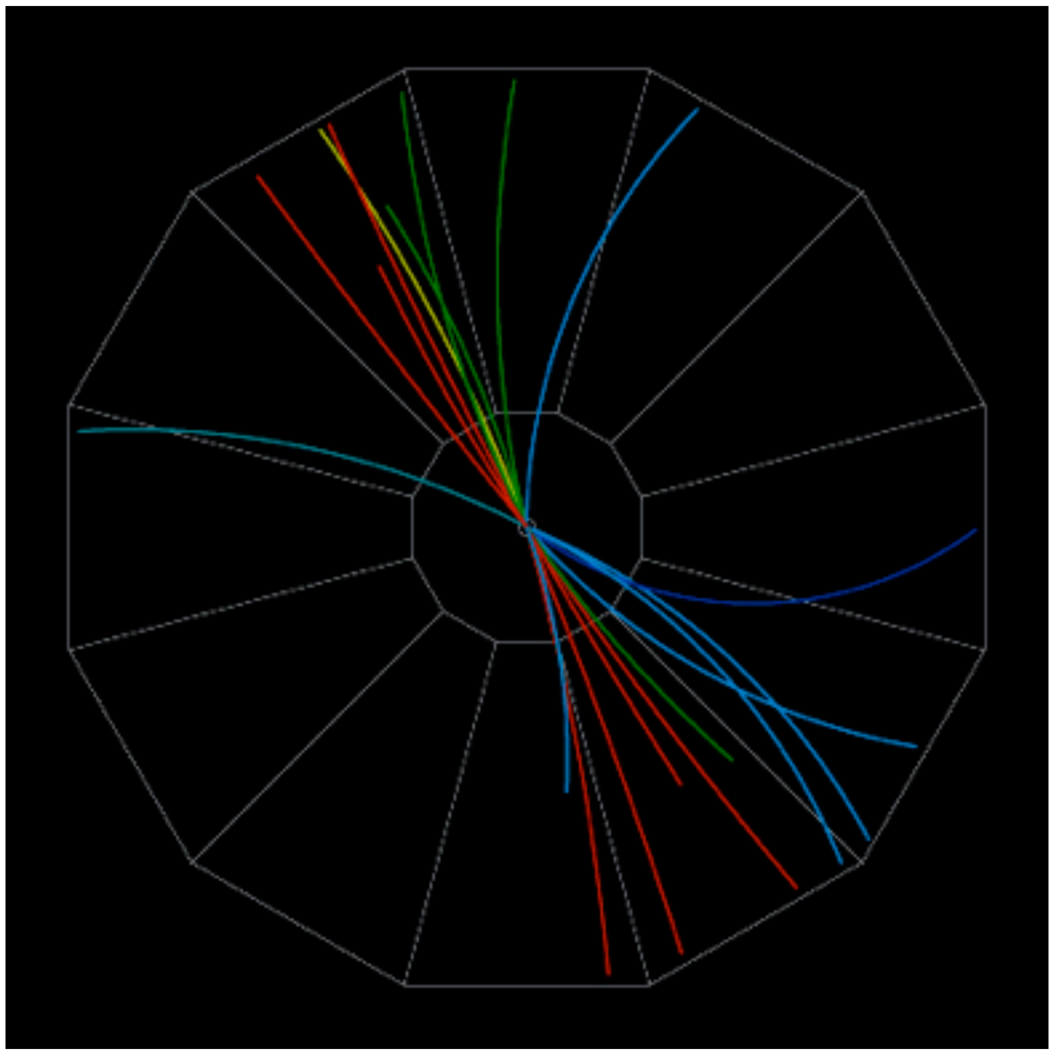
find this...



jet in 200GeV p-p collision

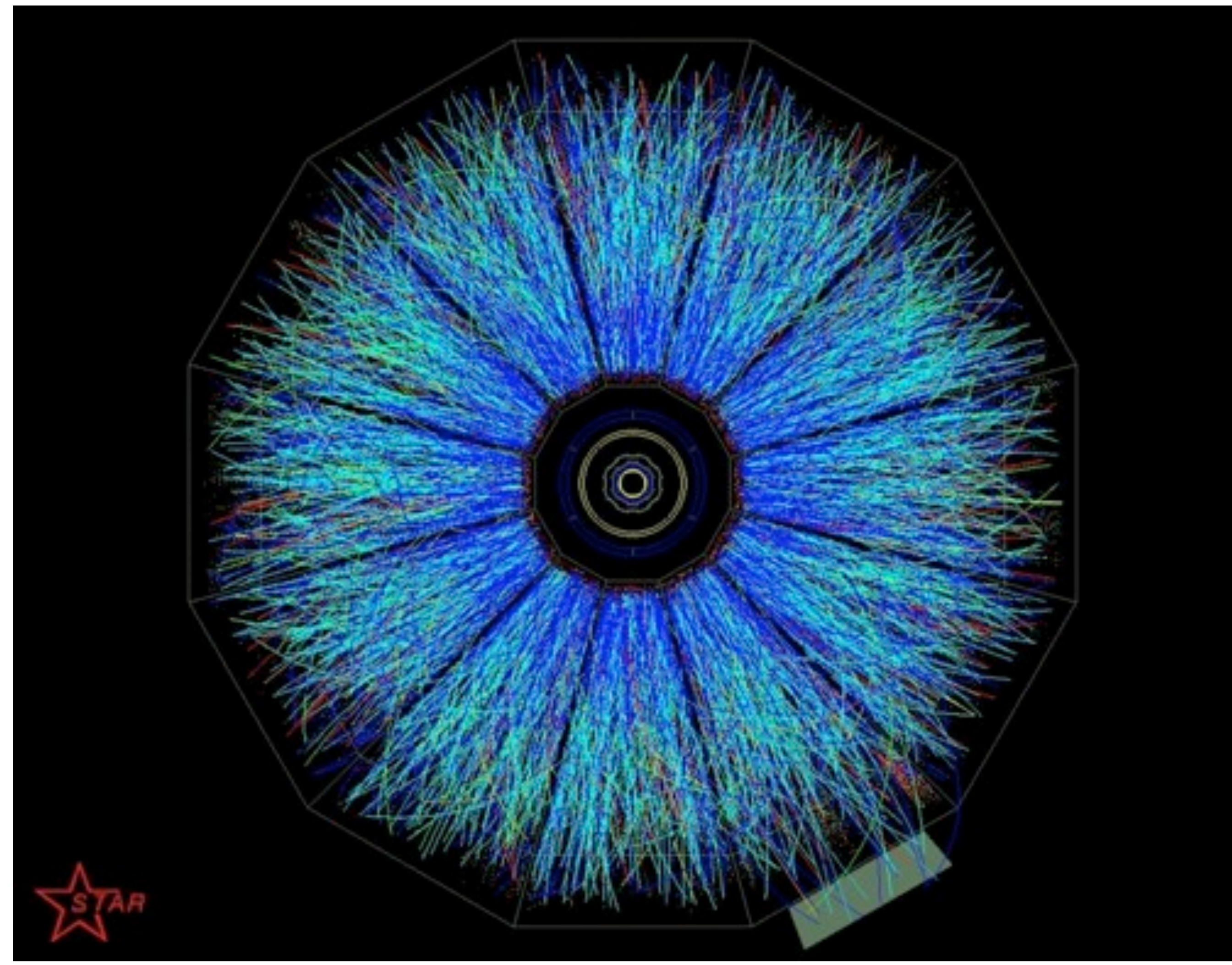
experimental challenge!

find this...



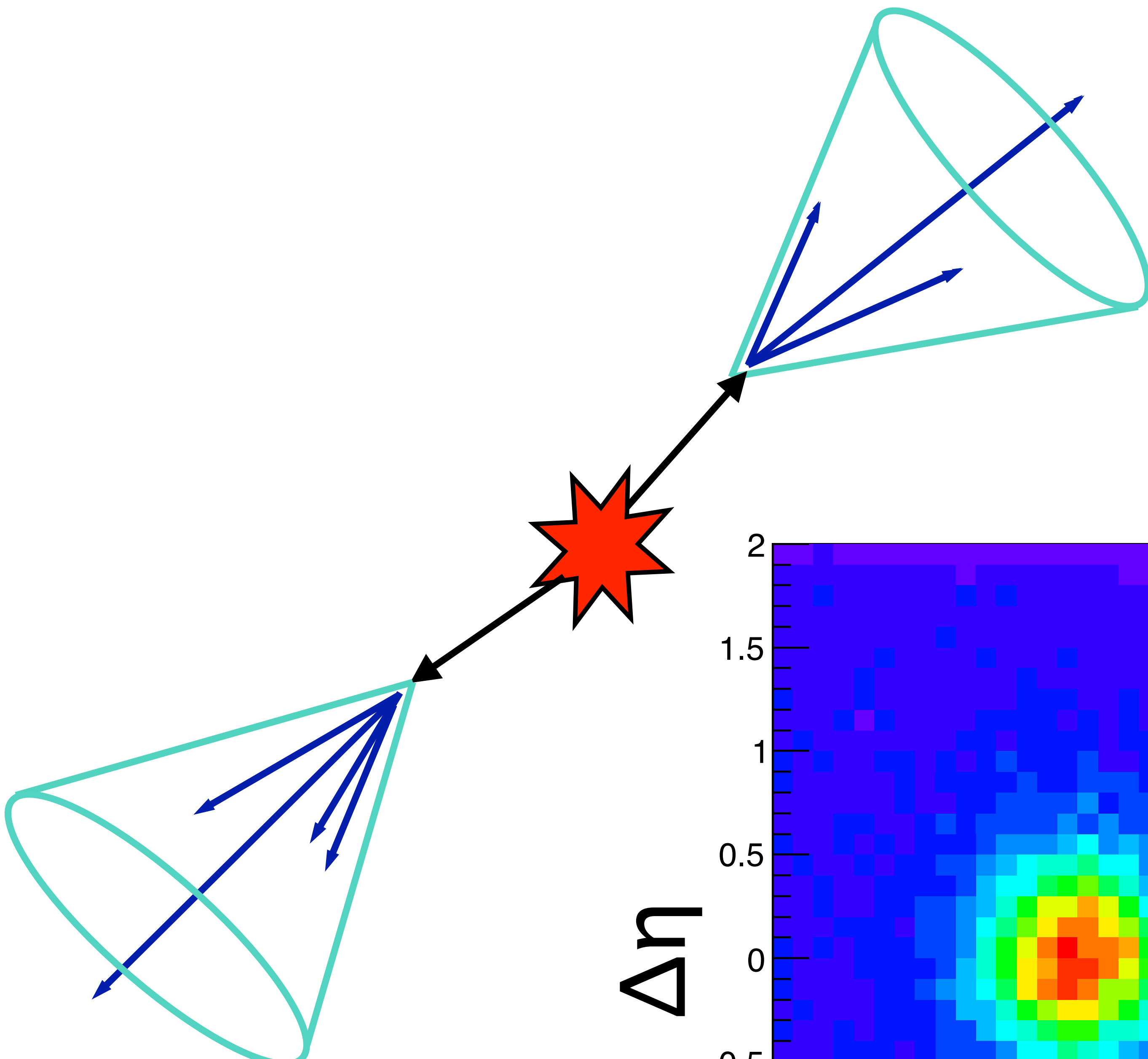
jet in 200GeV p-p collision

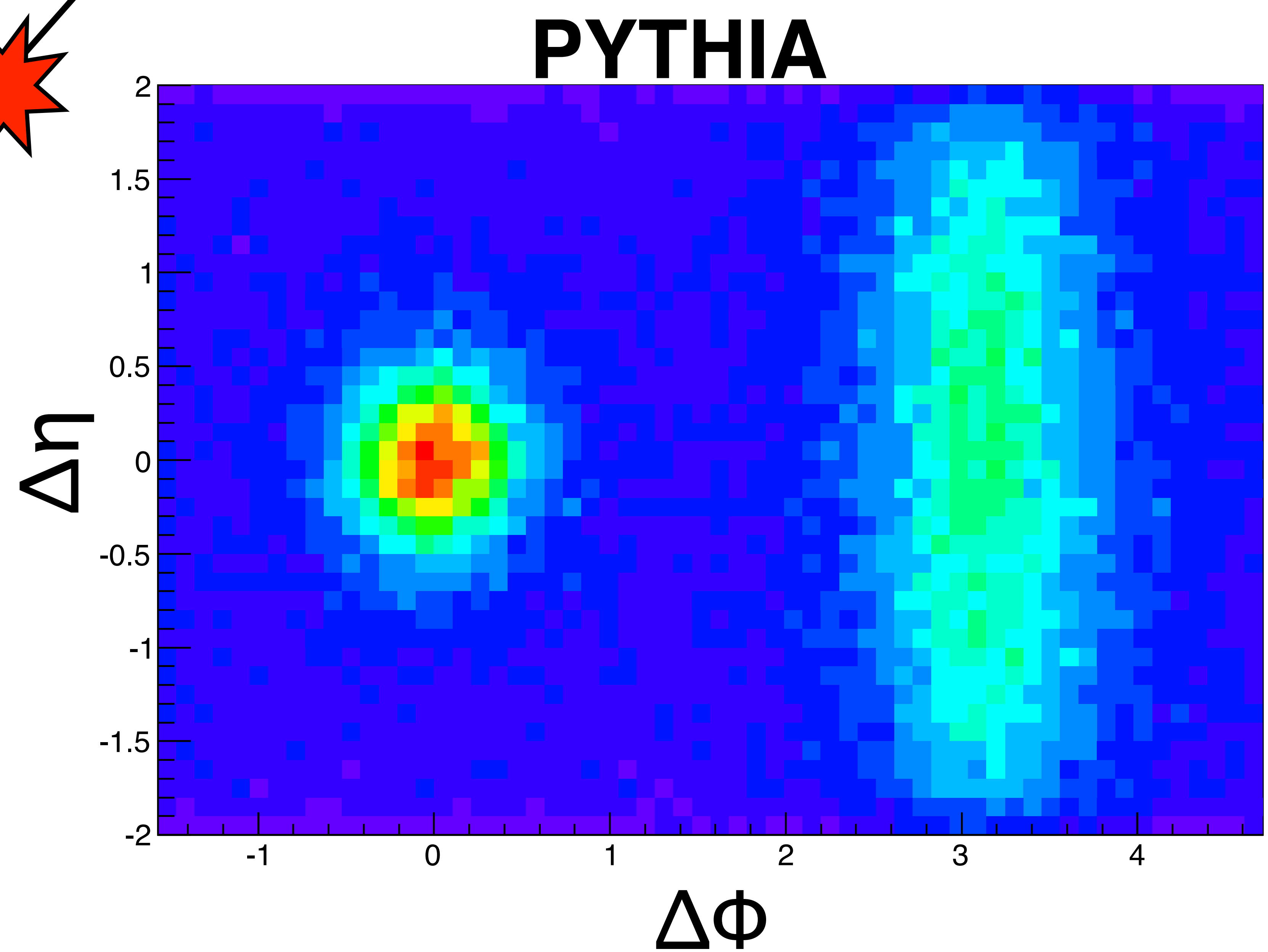
in here!



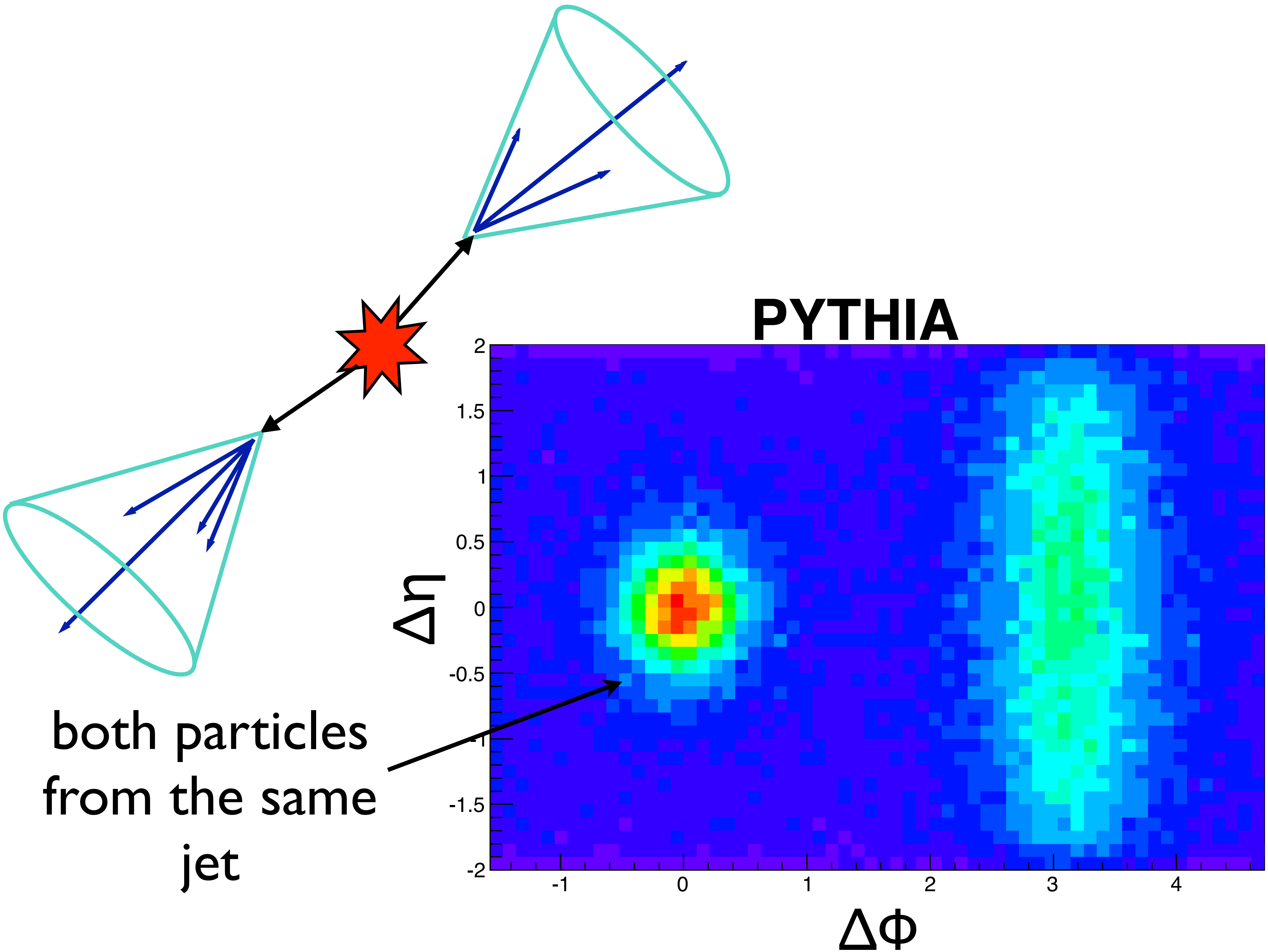
200GeV Au-Au collision

two particle correlations



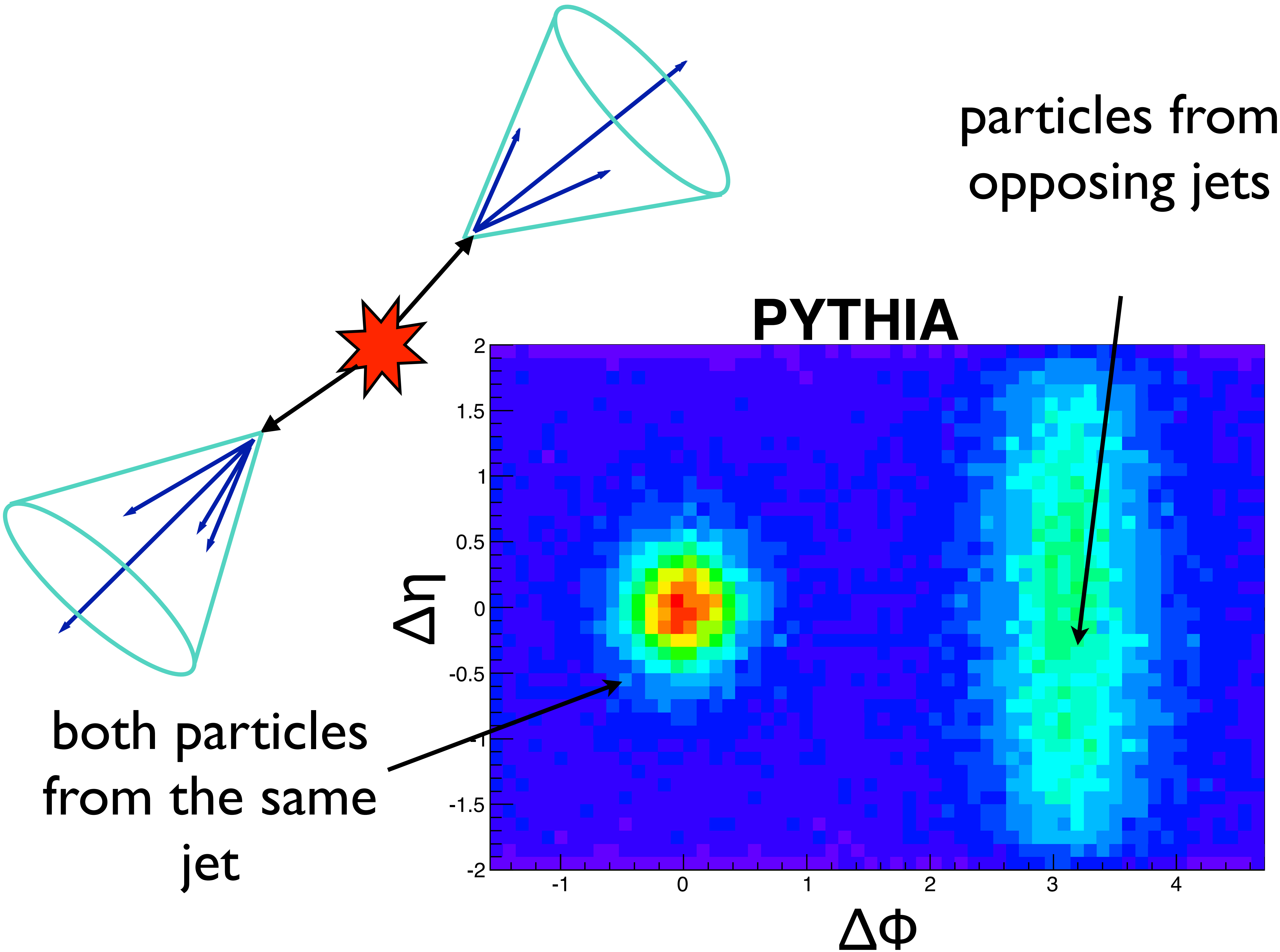


two particle correlations

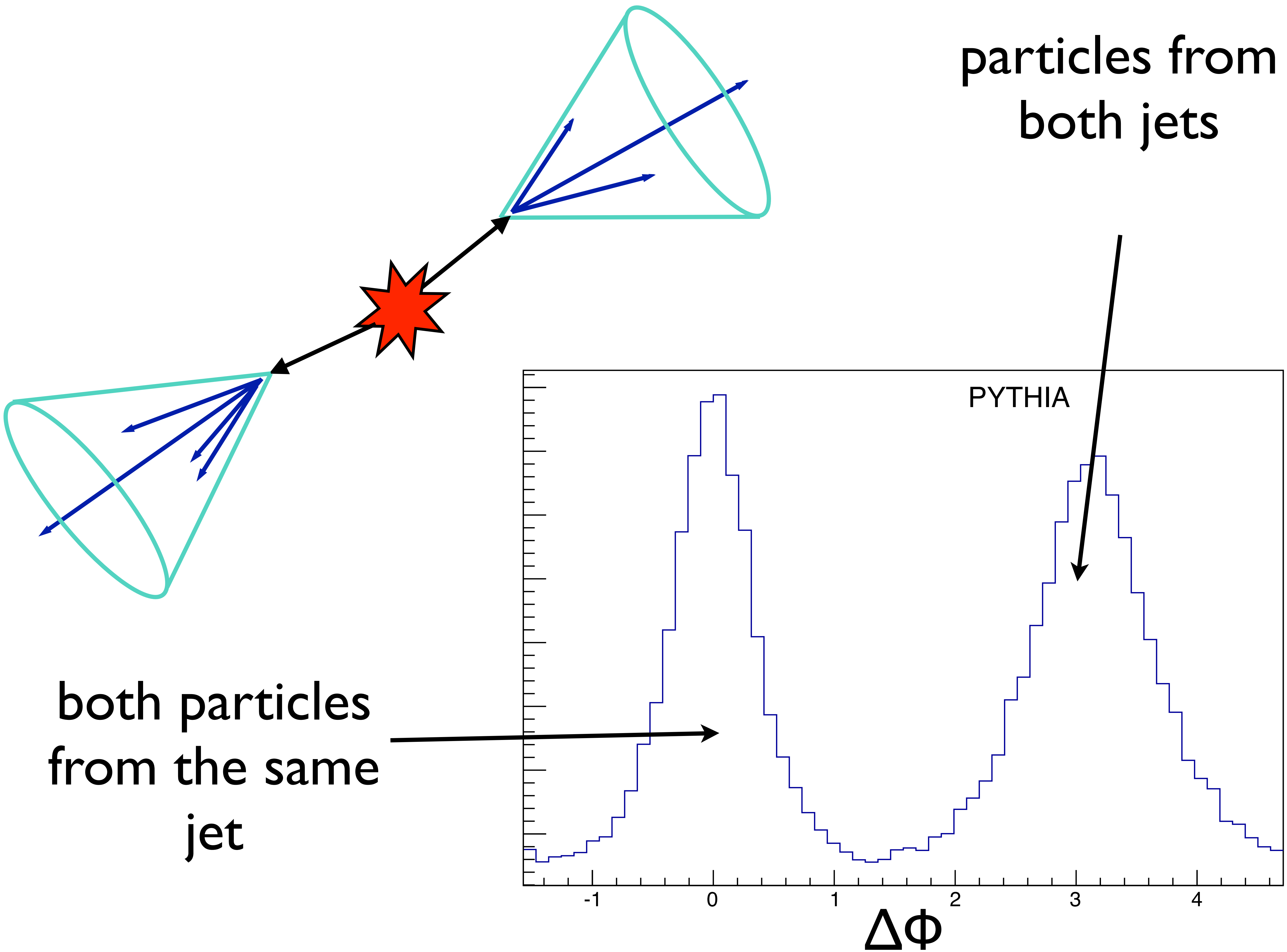


both particles from the same jet

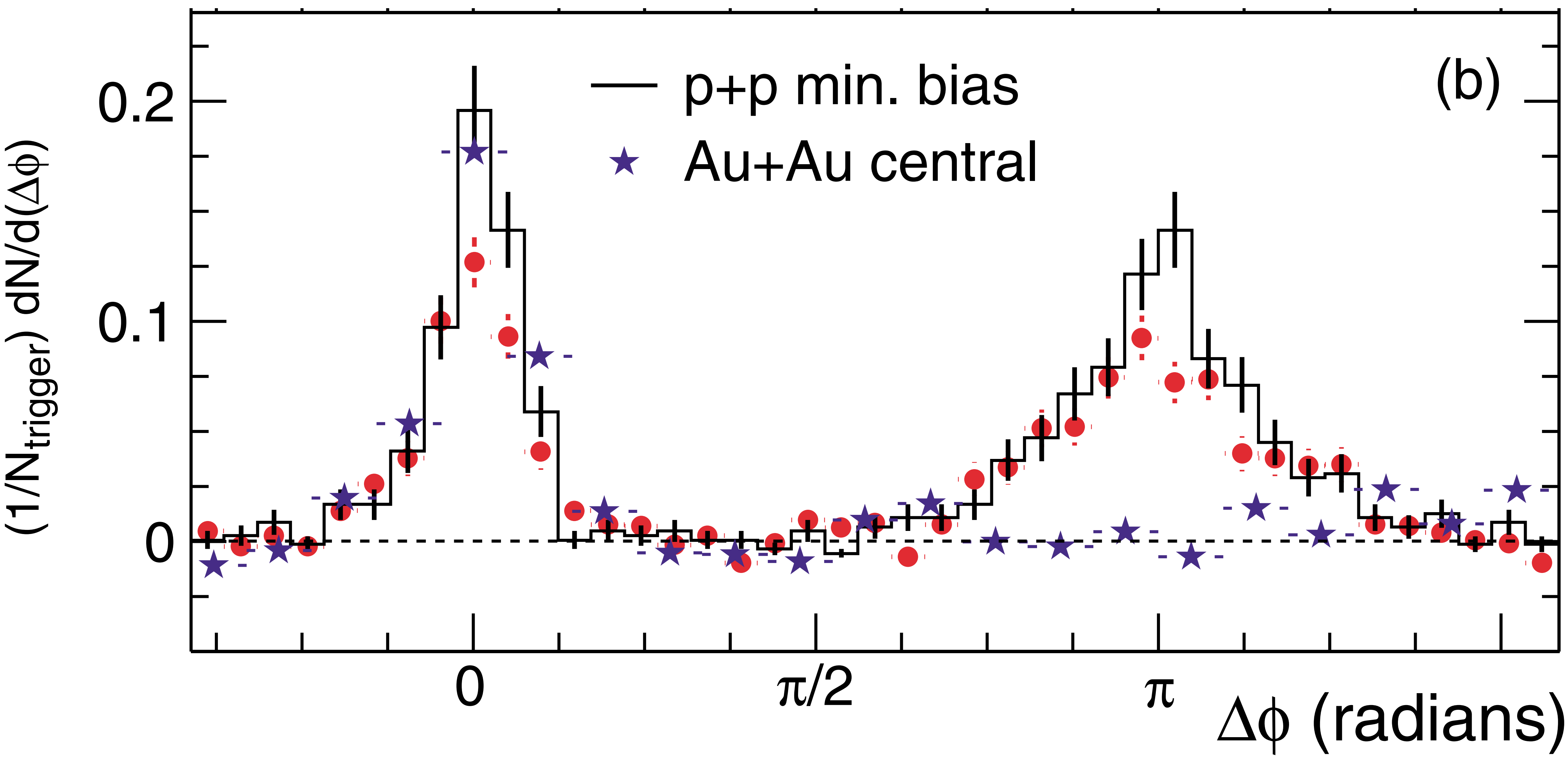
two particle correlations

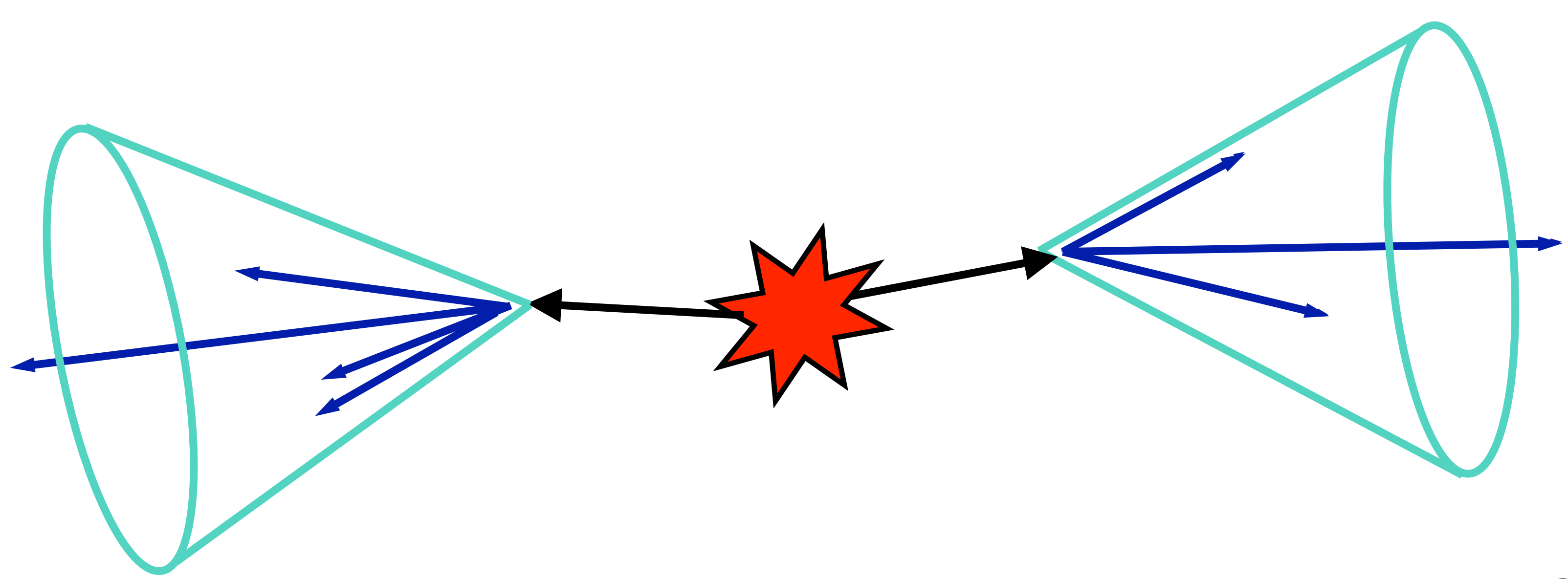


two particle correlations



jet quenching





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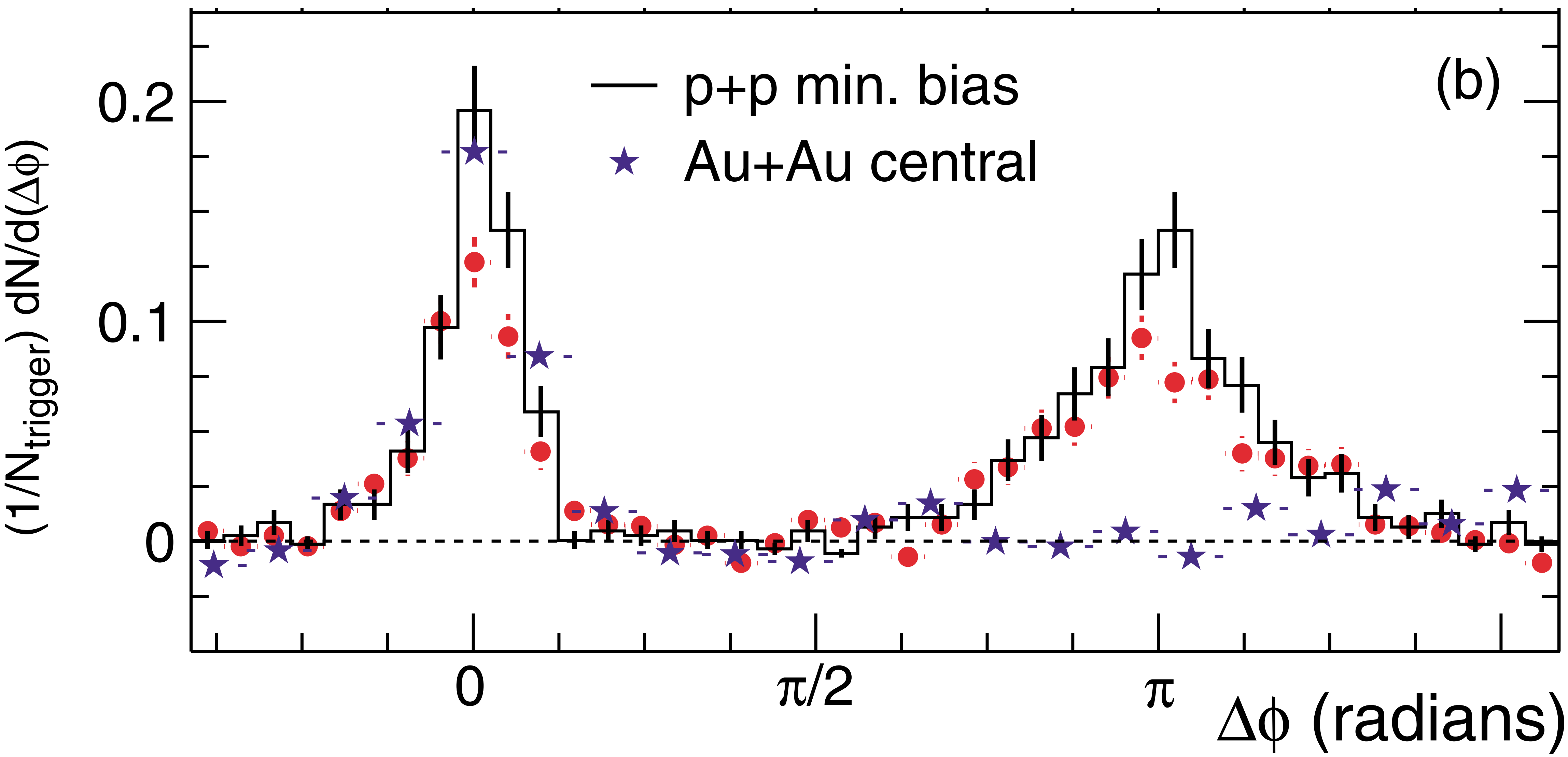
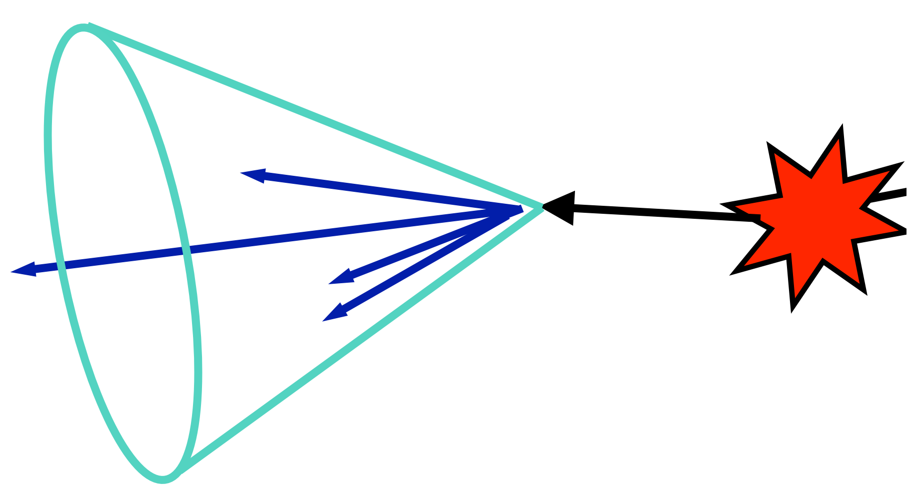
jet quenching





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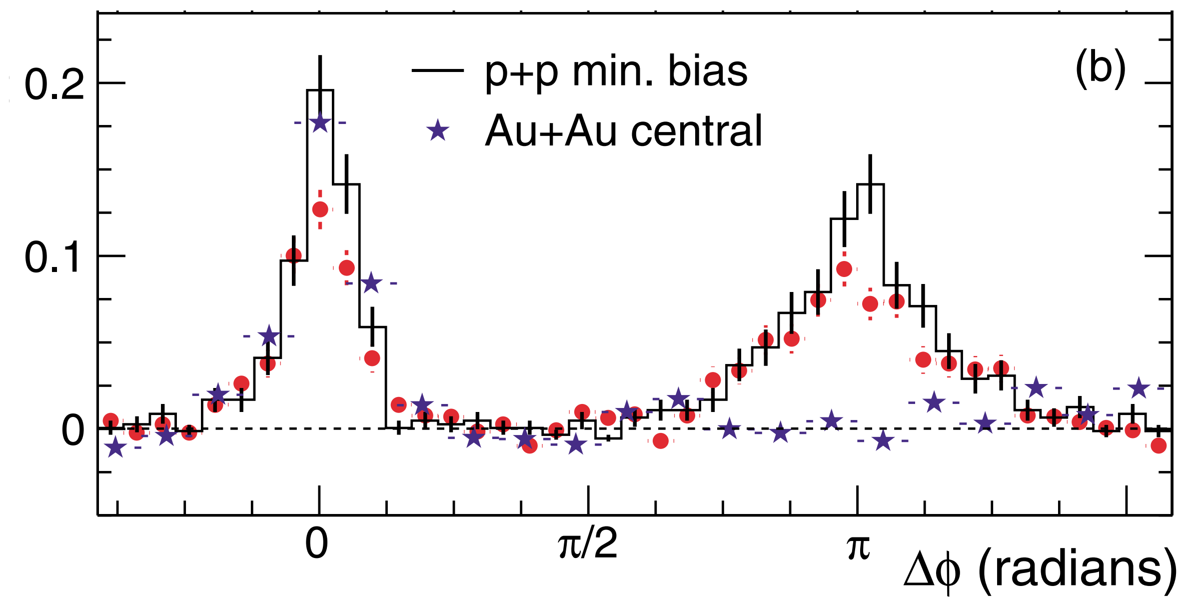
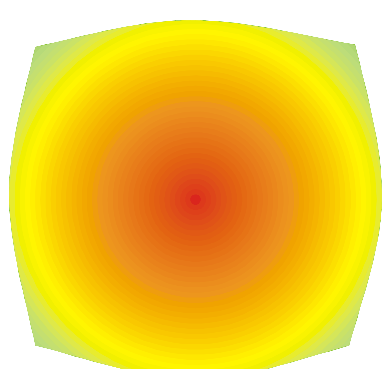
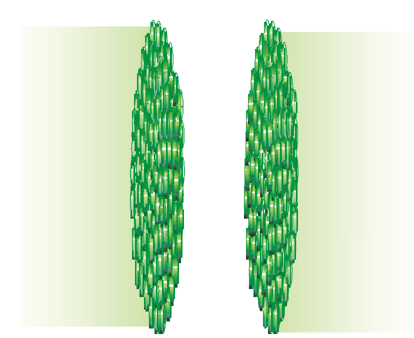
a remaining question



what if the missing jet wasn't the result of jet quenching in the QGP, but rather some feature of the initial state caused it not to be created in the first place?



or

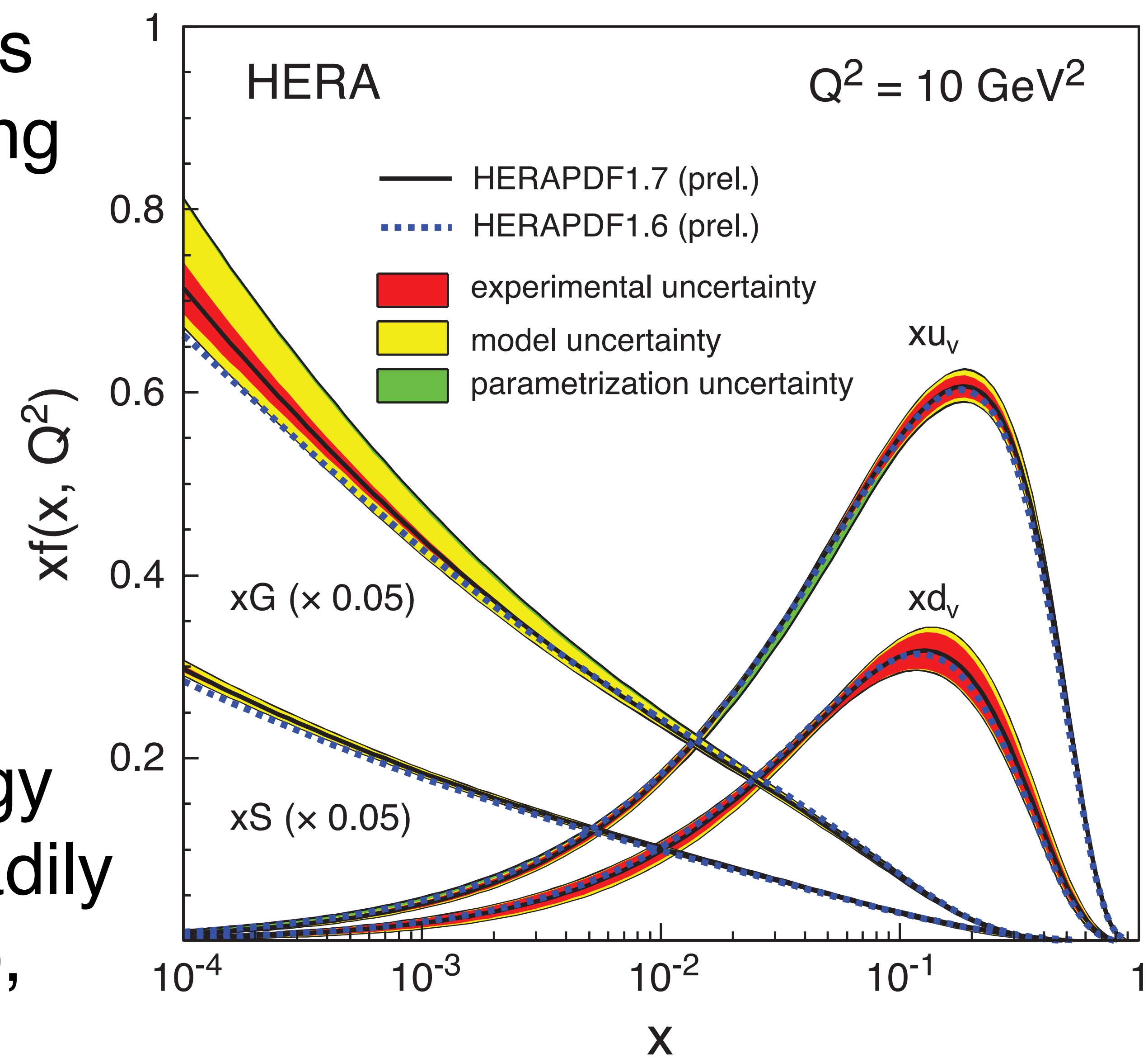


?

saturation of low x gluons

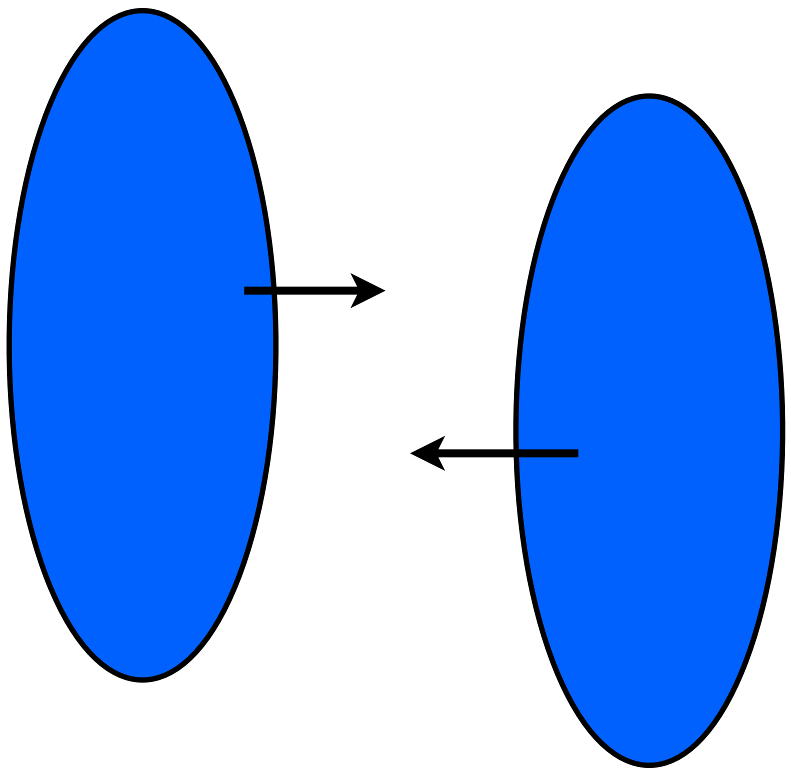
- basic idea: the number of gluons increases quickly with decreasing x. At some point there are so many gluons that the recombination rate becomes significant, saturating the distribution

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

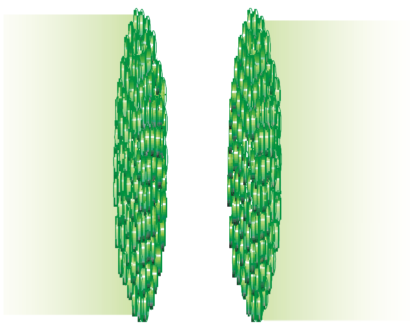


some calculations expected that in this scenario what looked like jet quenching could be a feature of the incoming nucleus

a control experiment



AuAu



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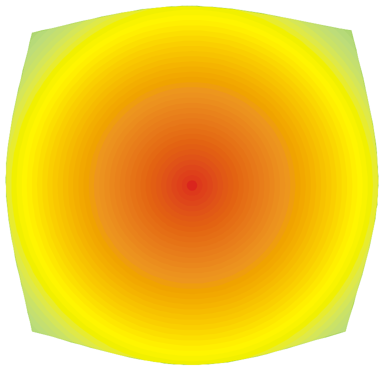
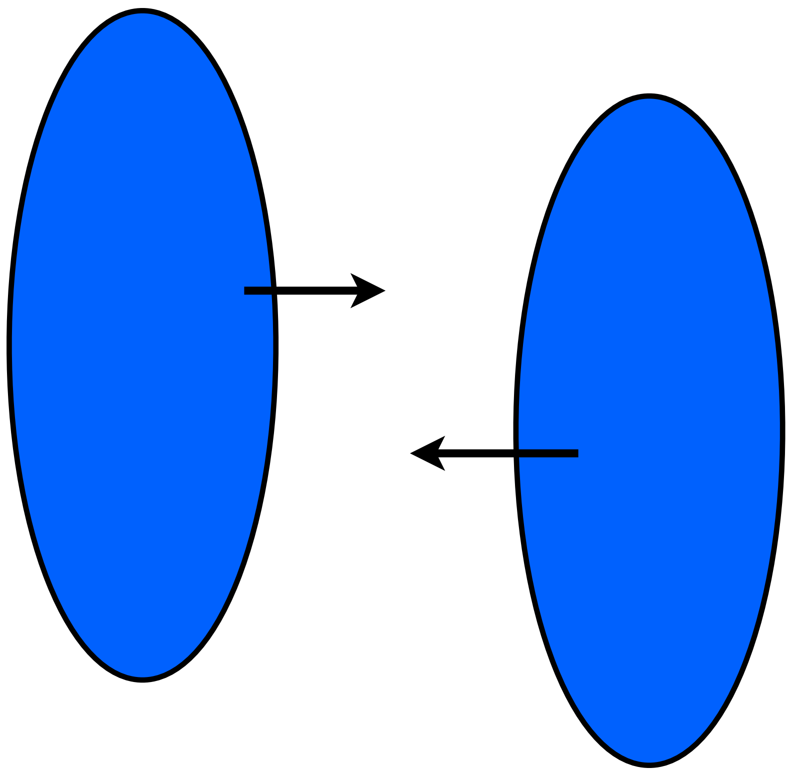
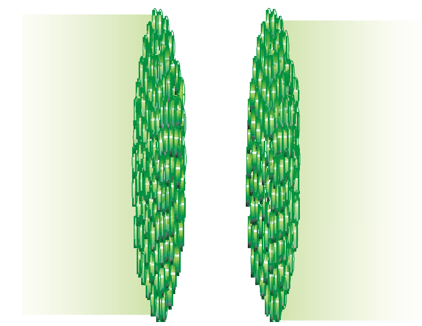


a control experiment



AuAu



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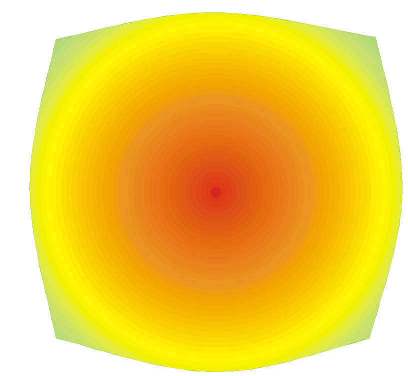
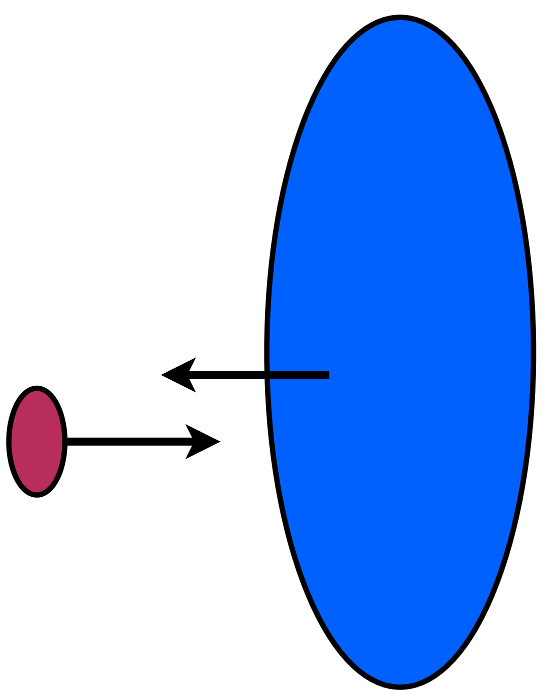
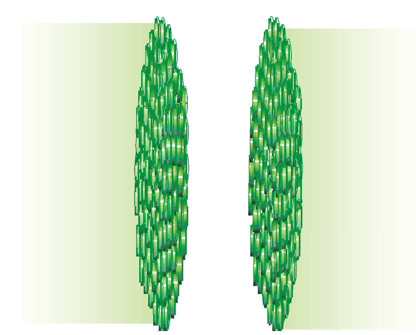
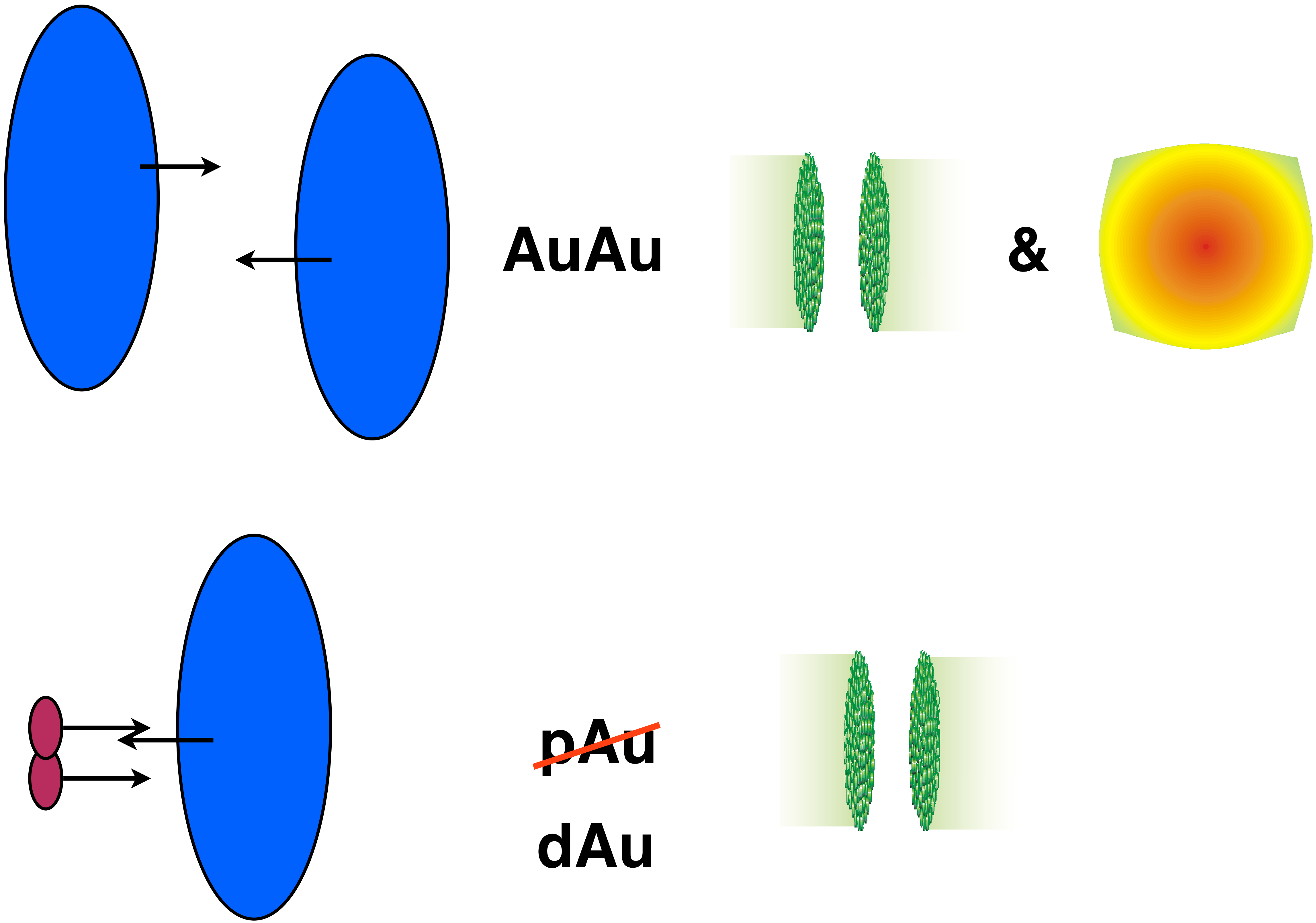


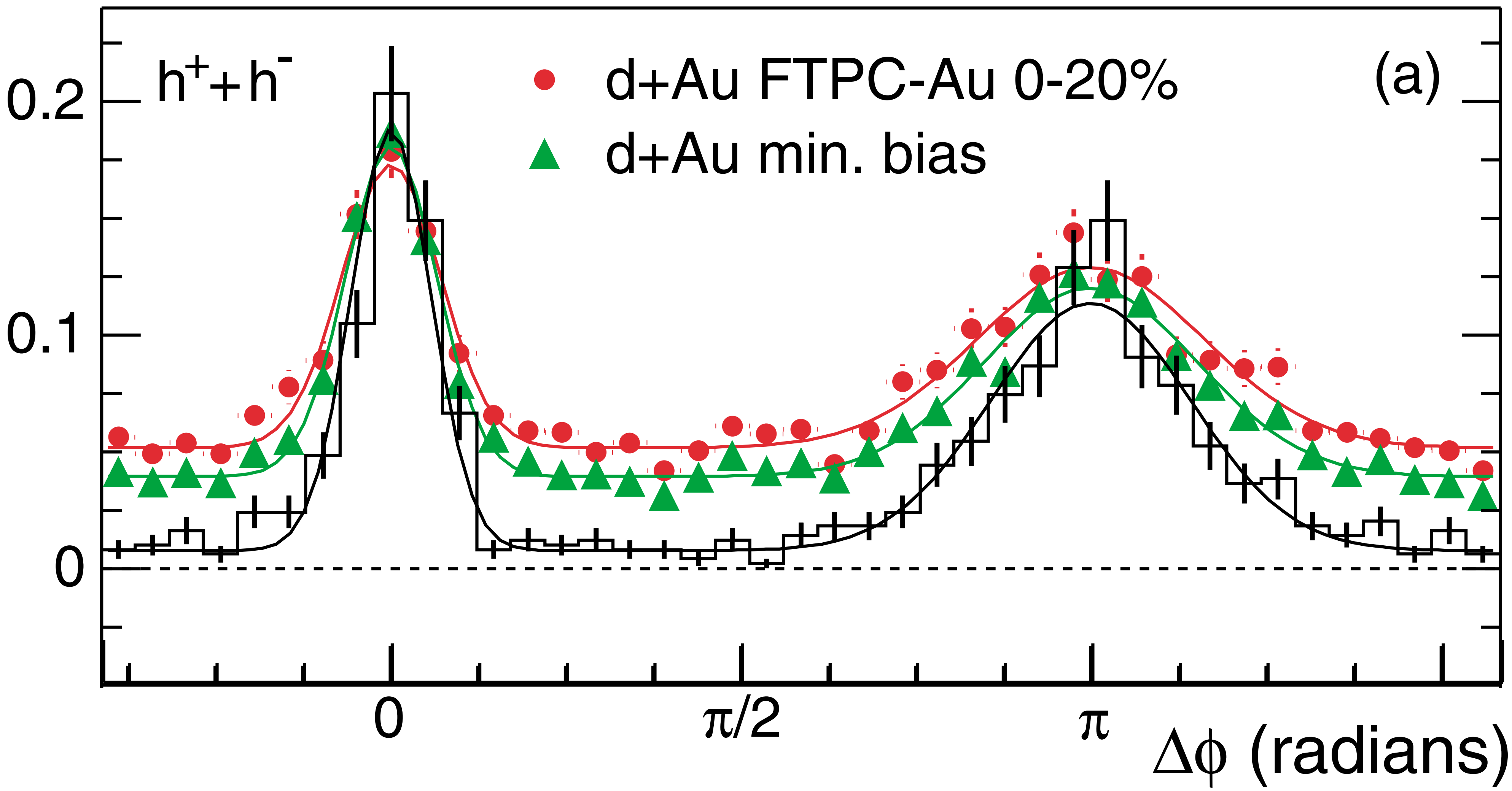


pAu



a control experiment





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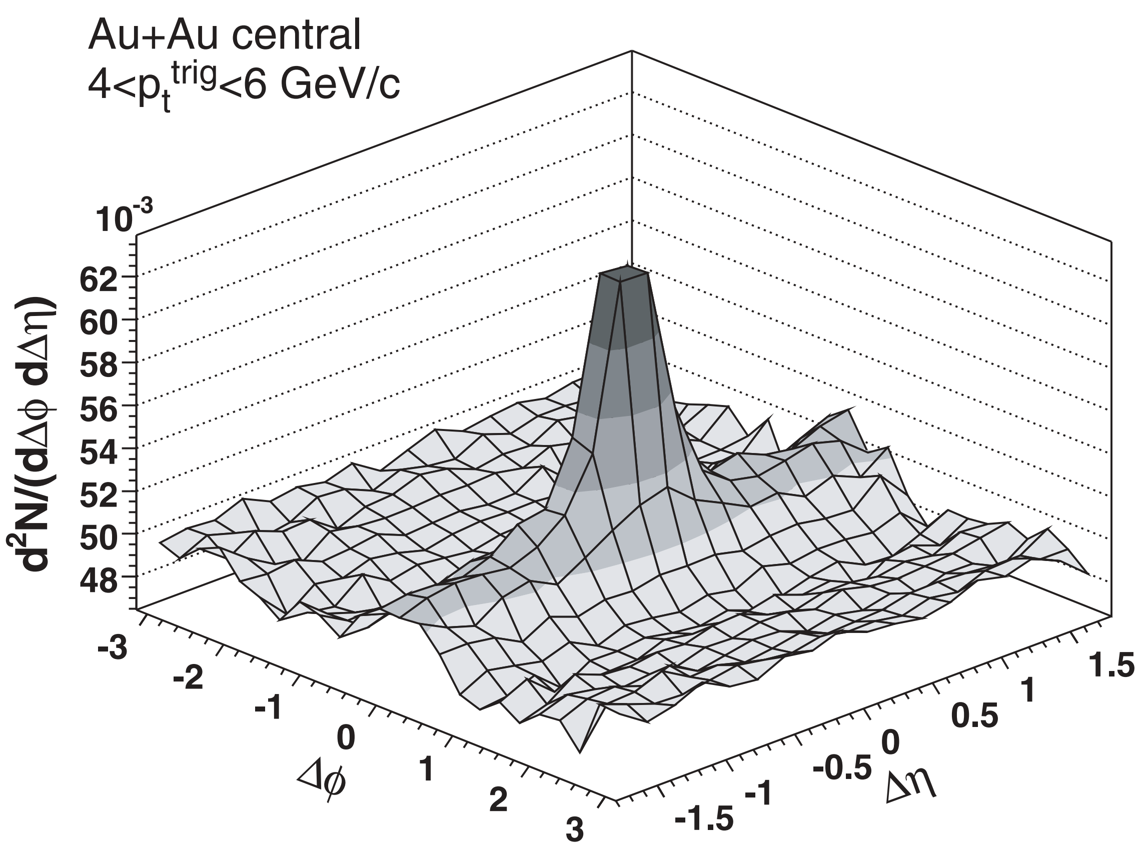
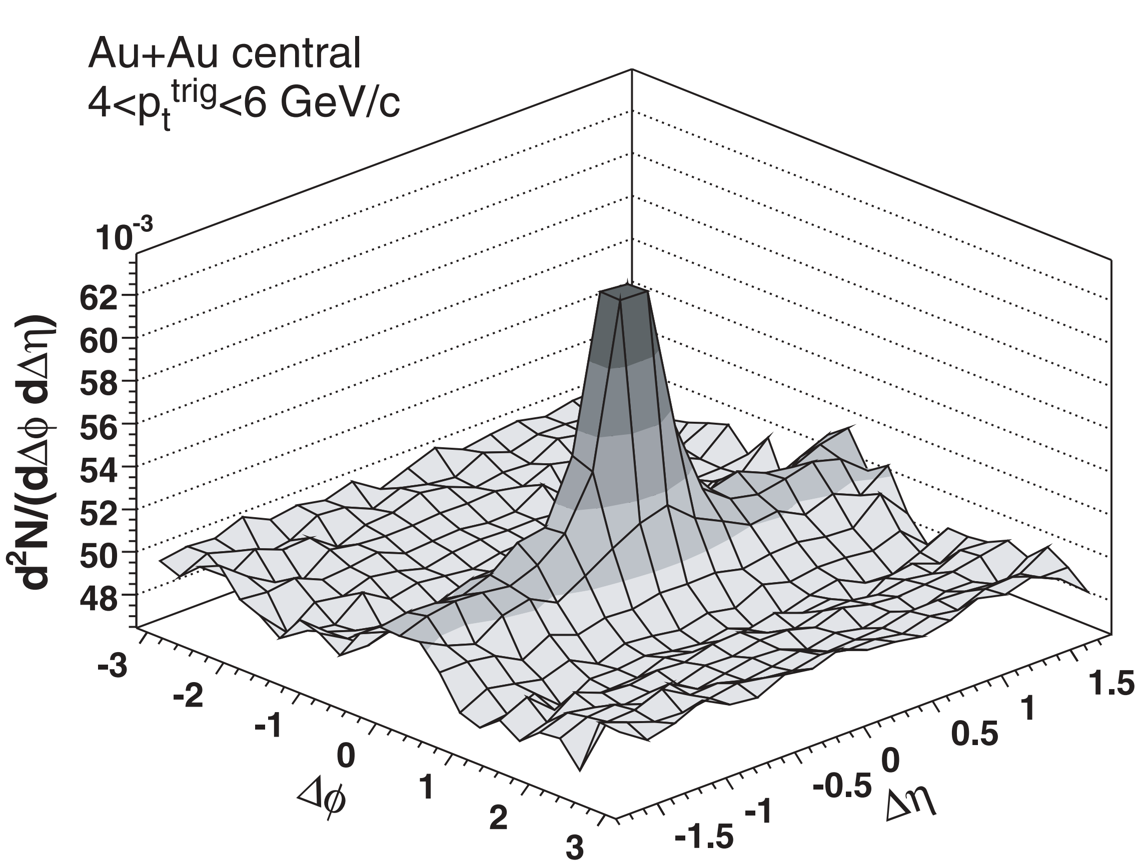
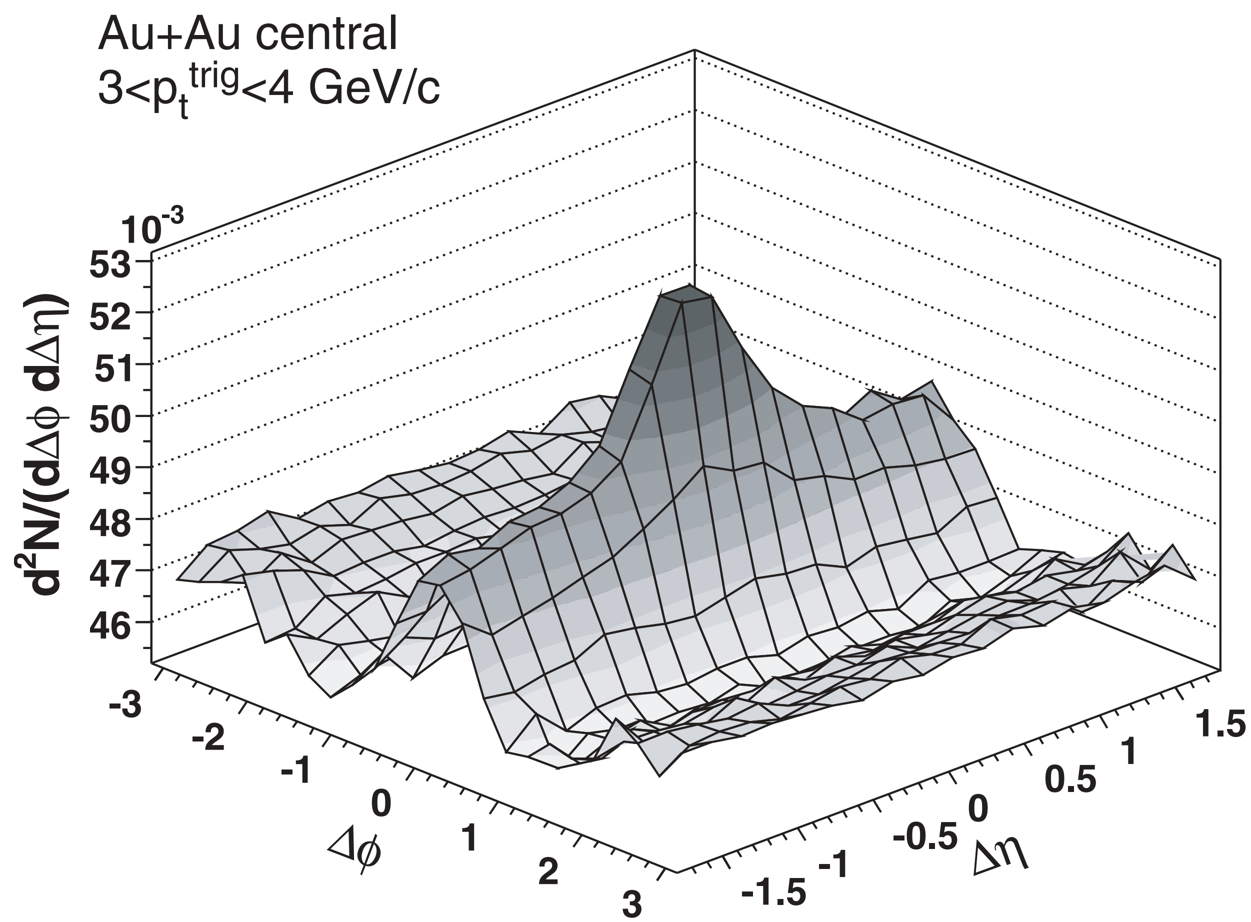
something strange--the ridge



STAR PRC 80 064912

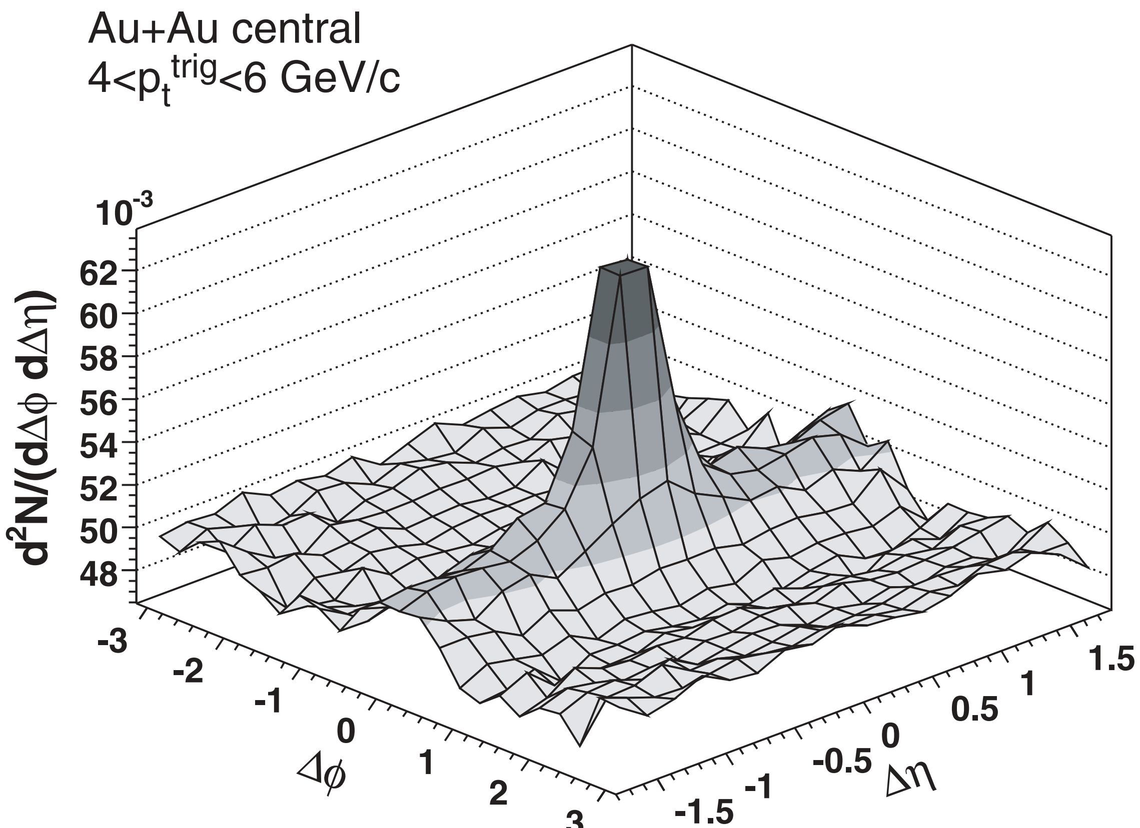
something strange--the ridge

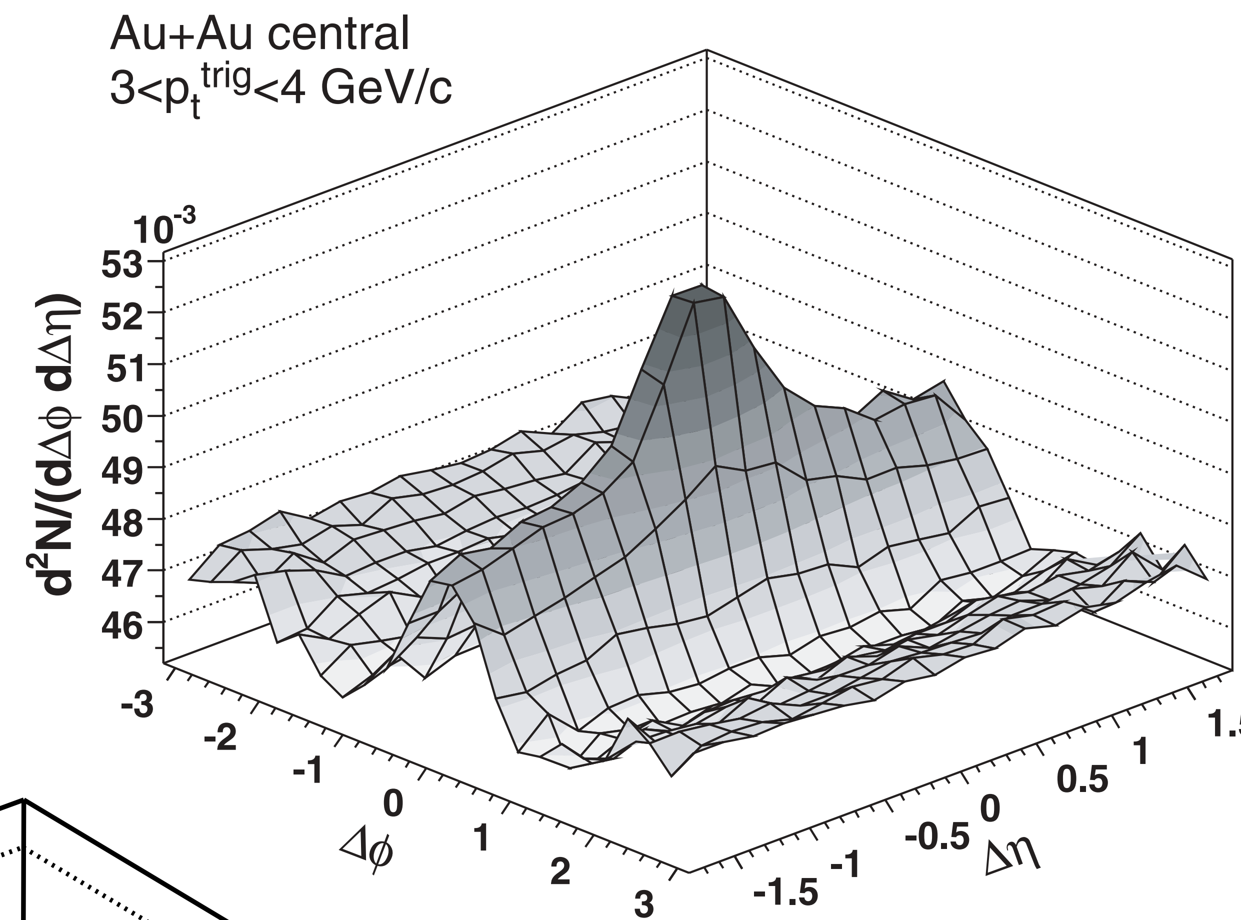




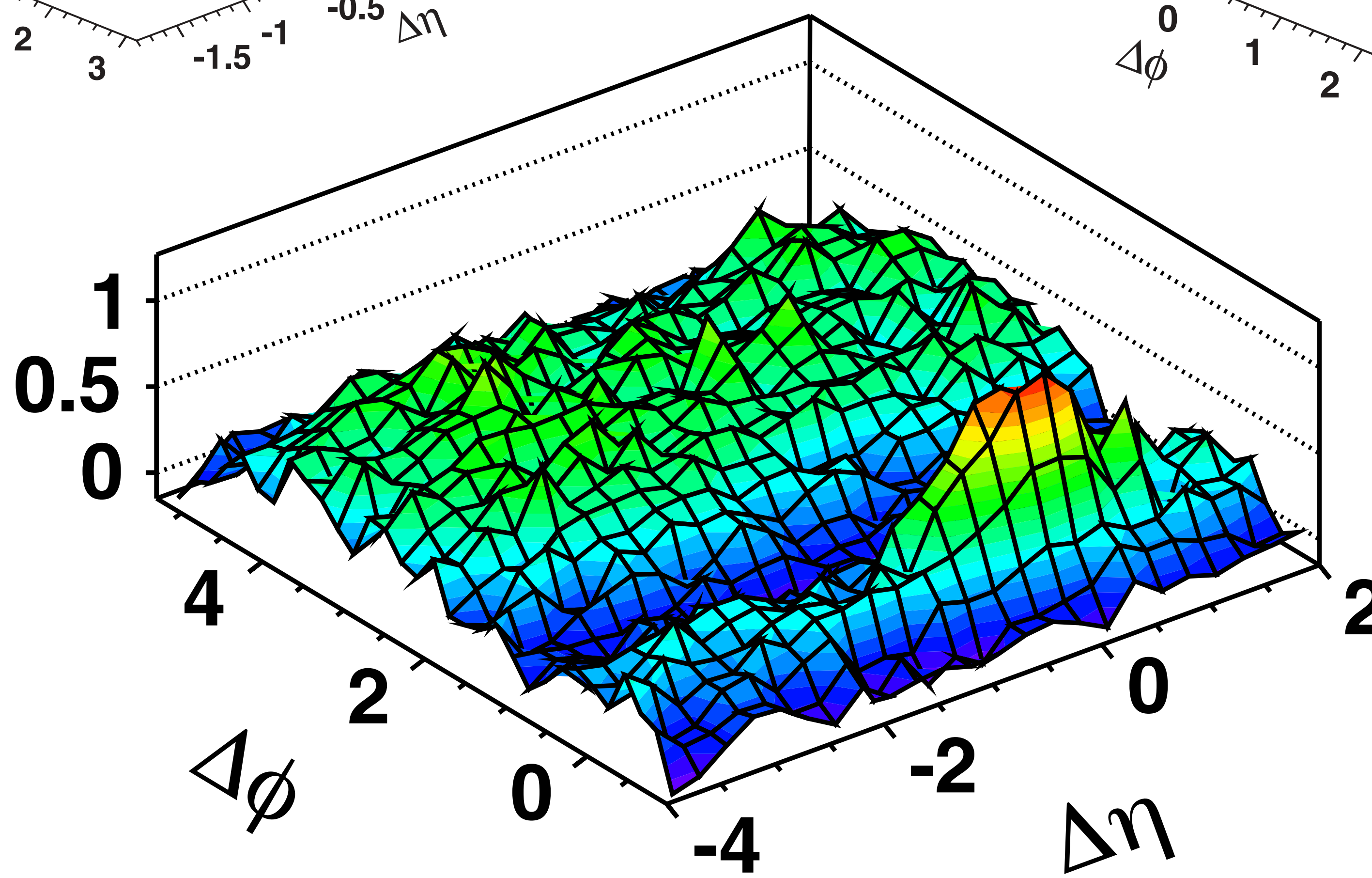
STAR PRC 80 064912

something strange--the ridge



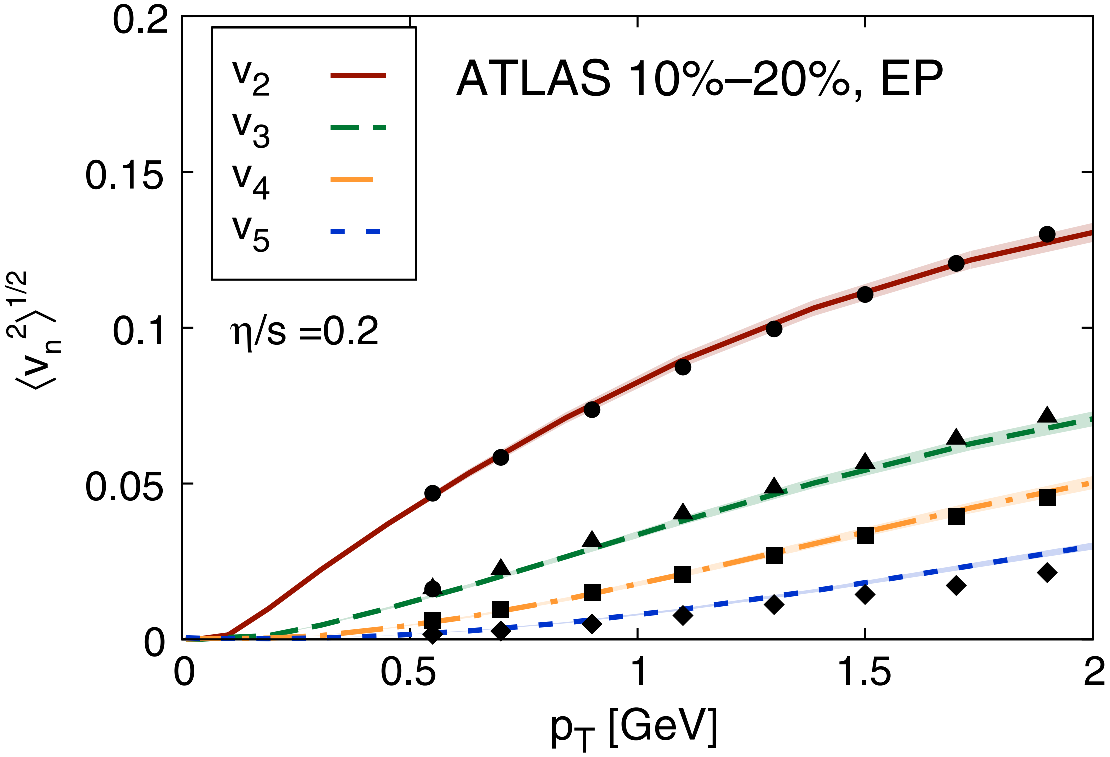


STAR PRC 80 064912



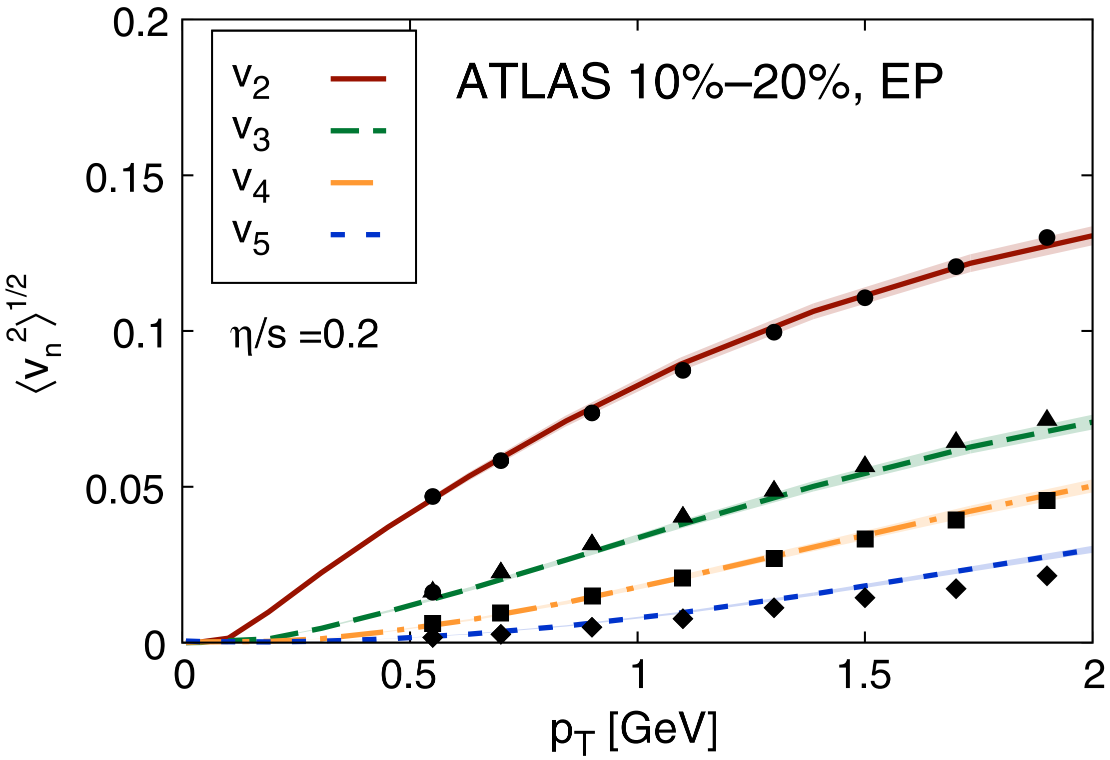
PHOBOS PRL 104 062301

hydrodynamics & correlations



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

hydrodynamics & correlations

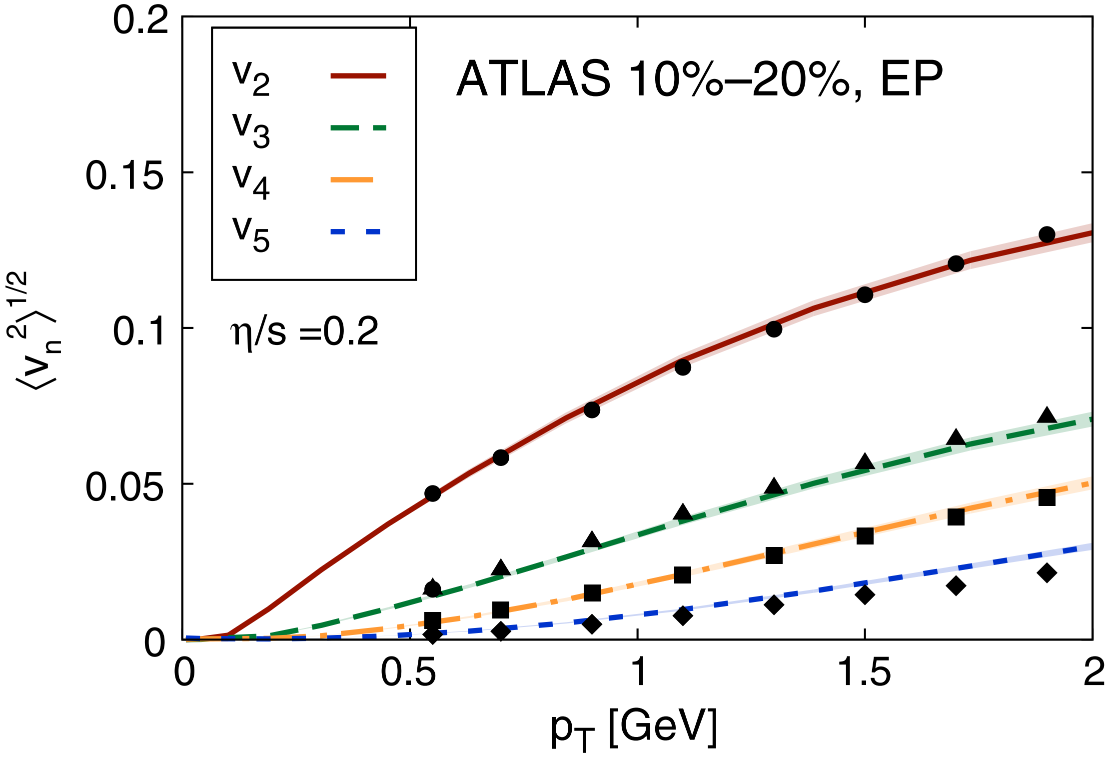


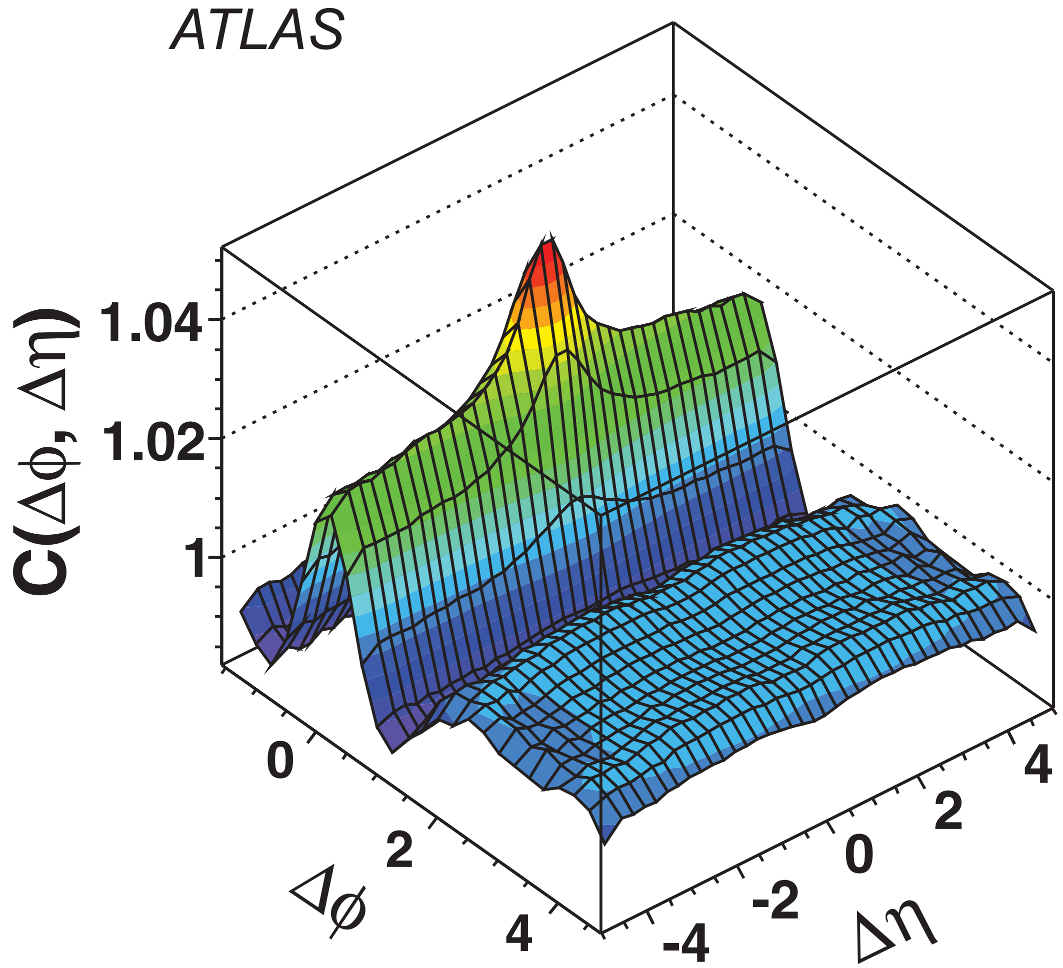
$$\frac{dN}{d\phi} \propto 1 + \sum^{n} 2v_n \cos n\left(\phi - \Psi_n\right)$$

pairs

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

hydrodynamics & correlations



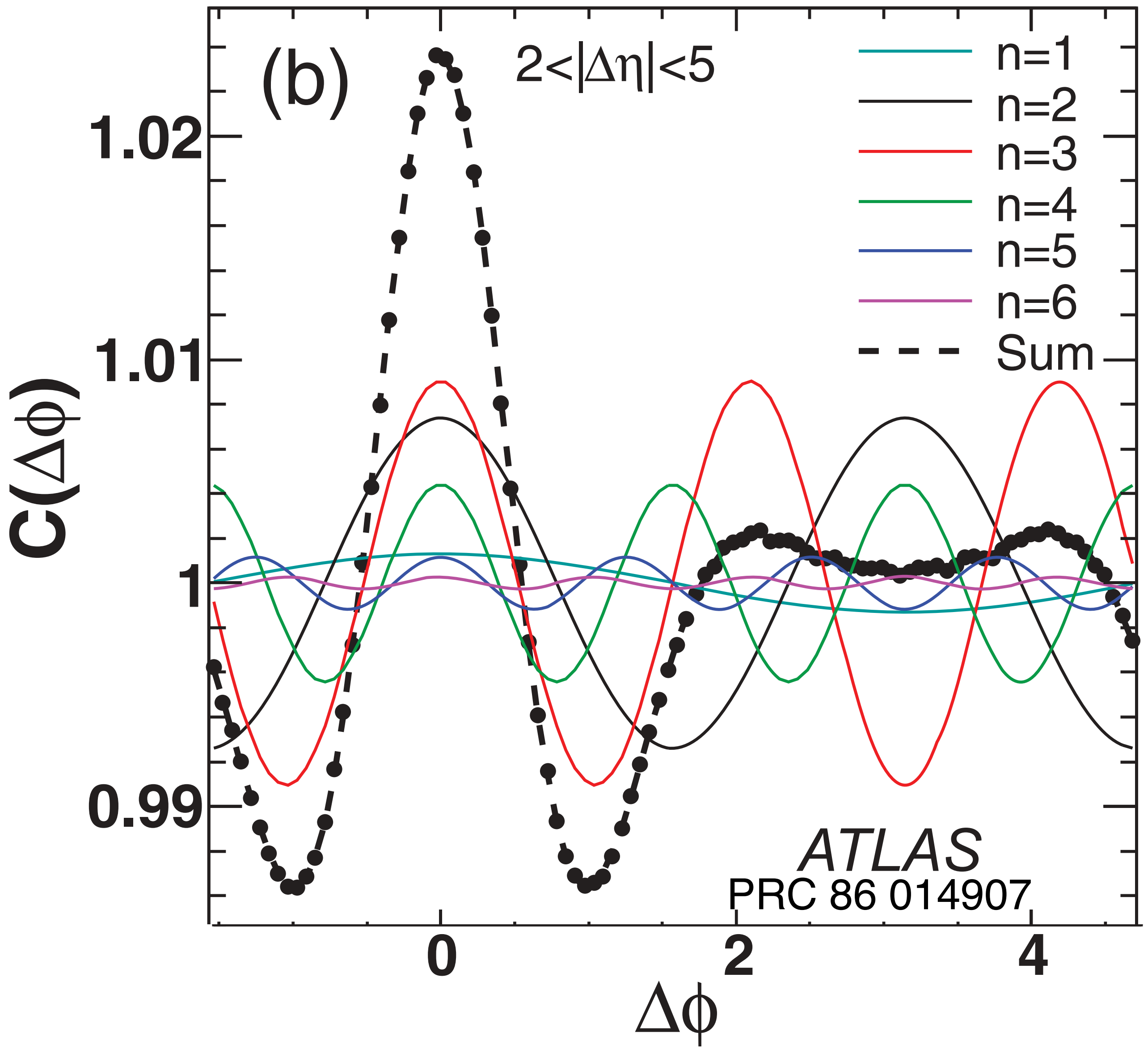


$$\frac{dN}{d\phi} \propto 1 + \sum^{n} 2v_n \cos n\left(\phi - \Psi_n\right)$$

pairs

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

ridge: v_N & two particle correlations



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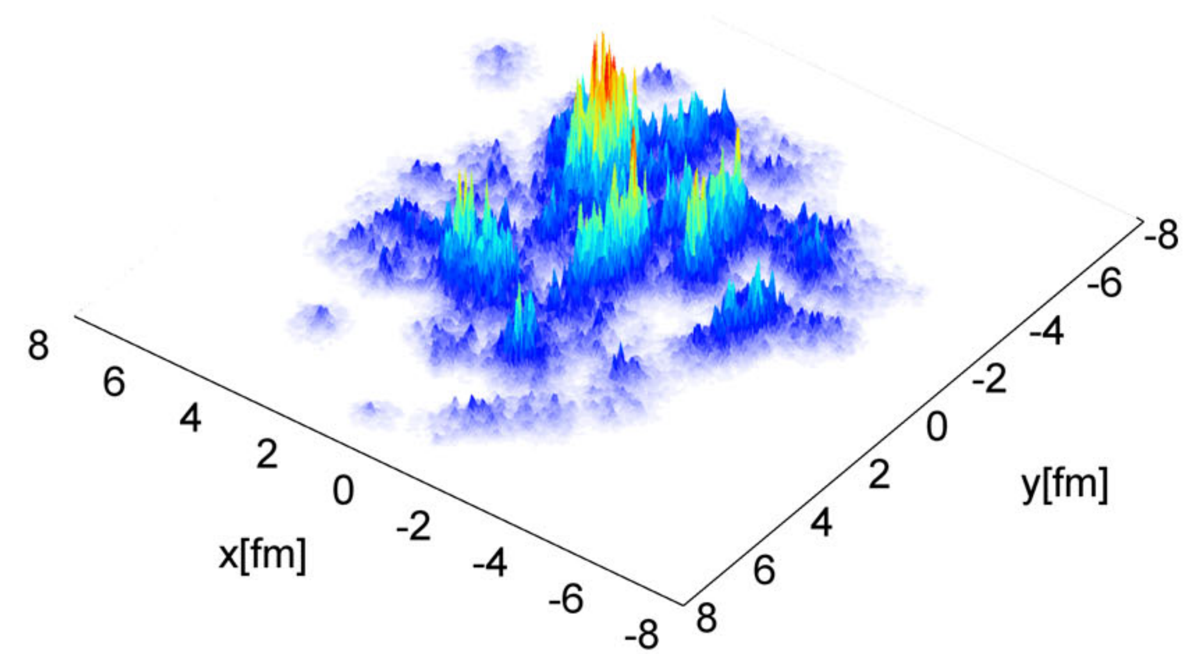
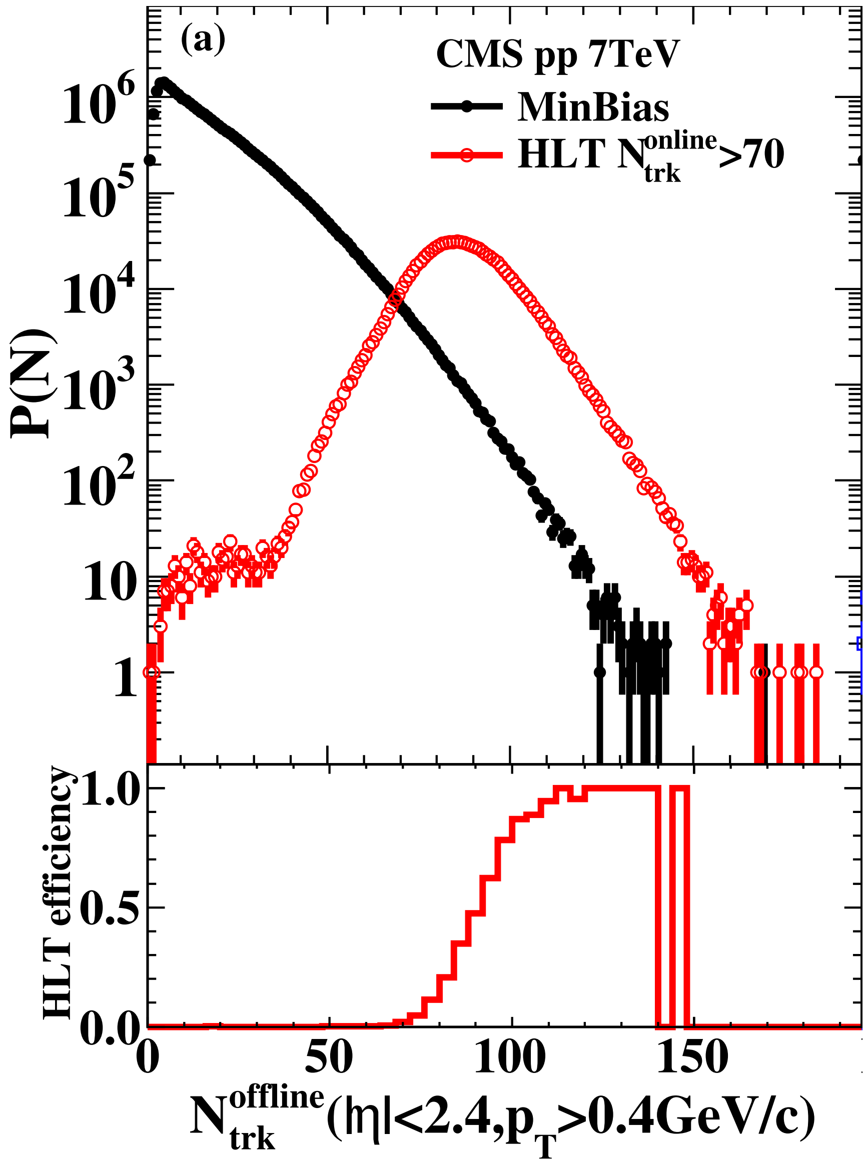


ridge explained as initial state geometry + hydrodynamics

Alver & Roland PRC81 054905

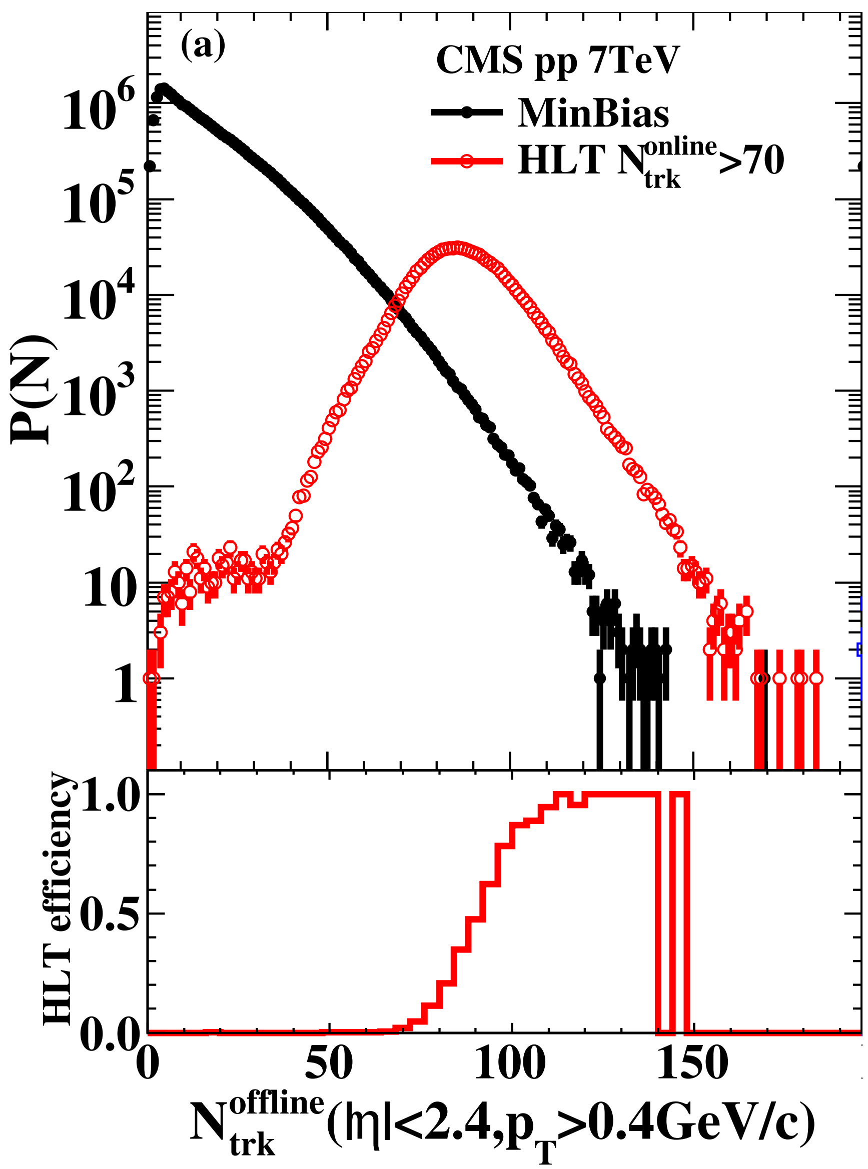
7 TeV pp collisions

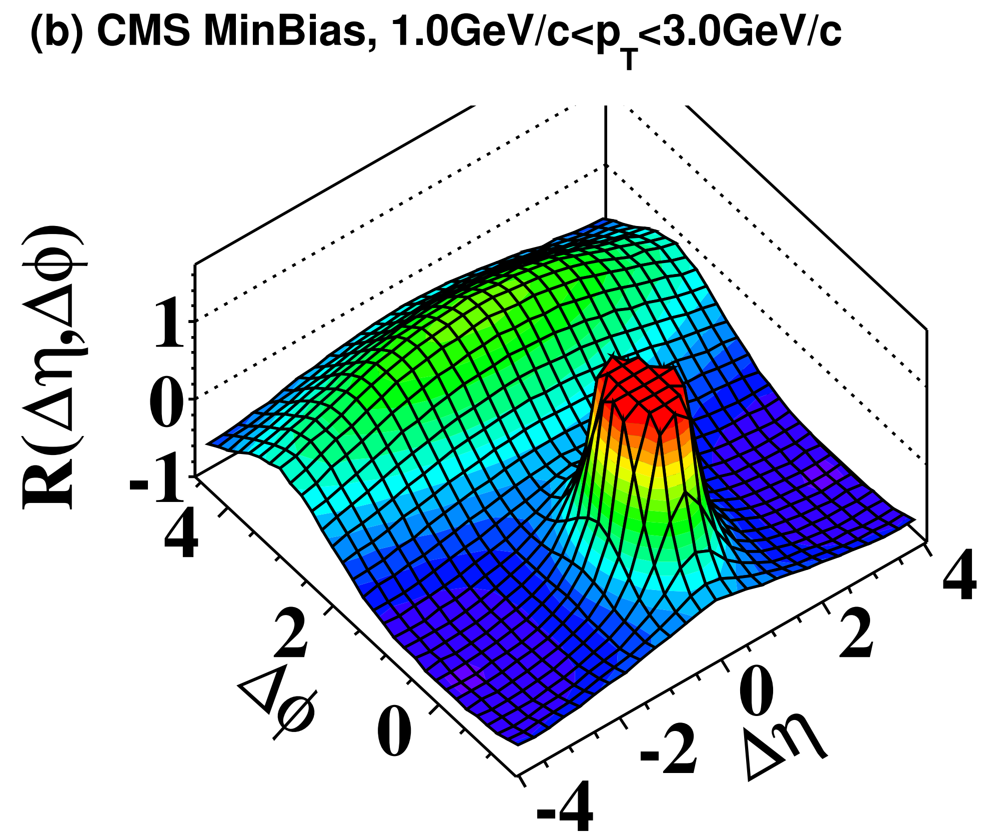


multiplicity

CMS JHEP 1009 (2010) 091

7 TeV pp collisions

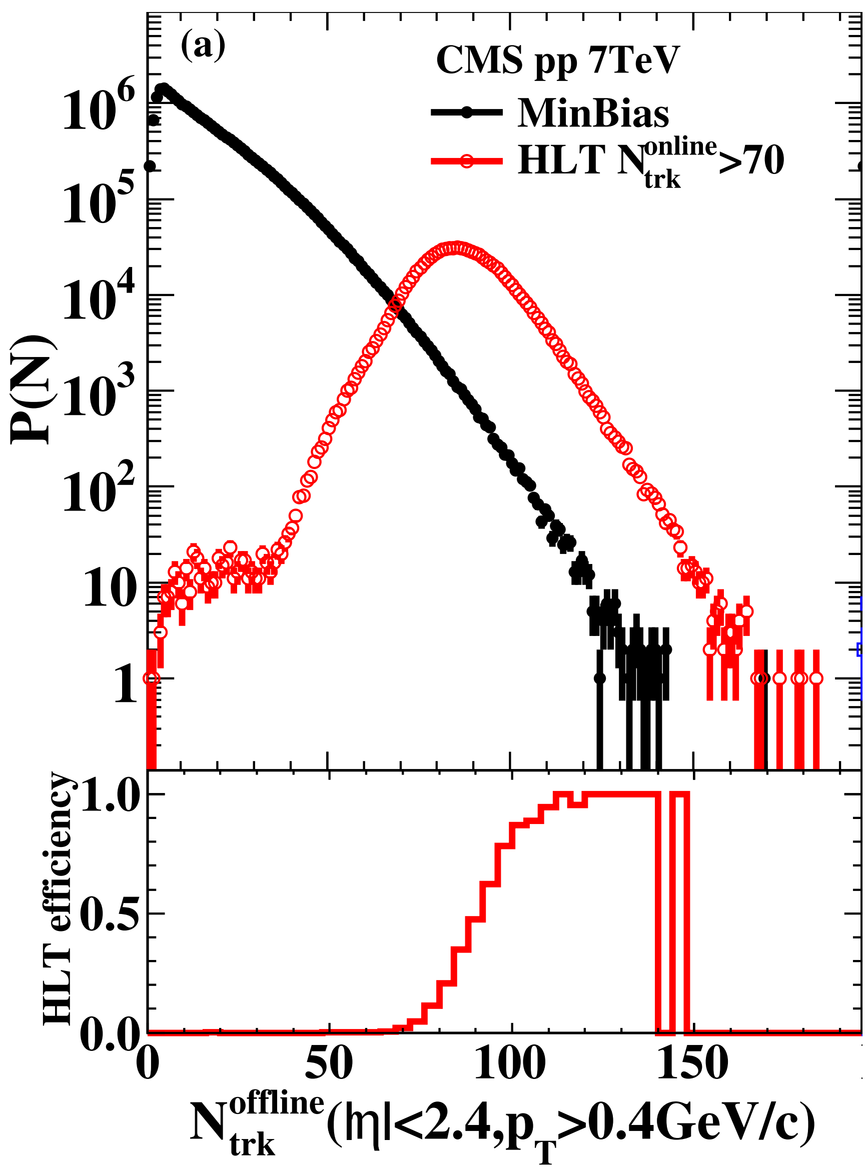




multiplicity

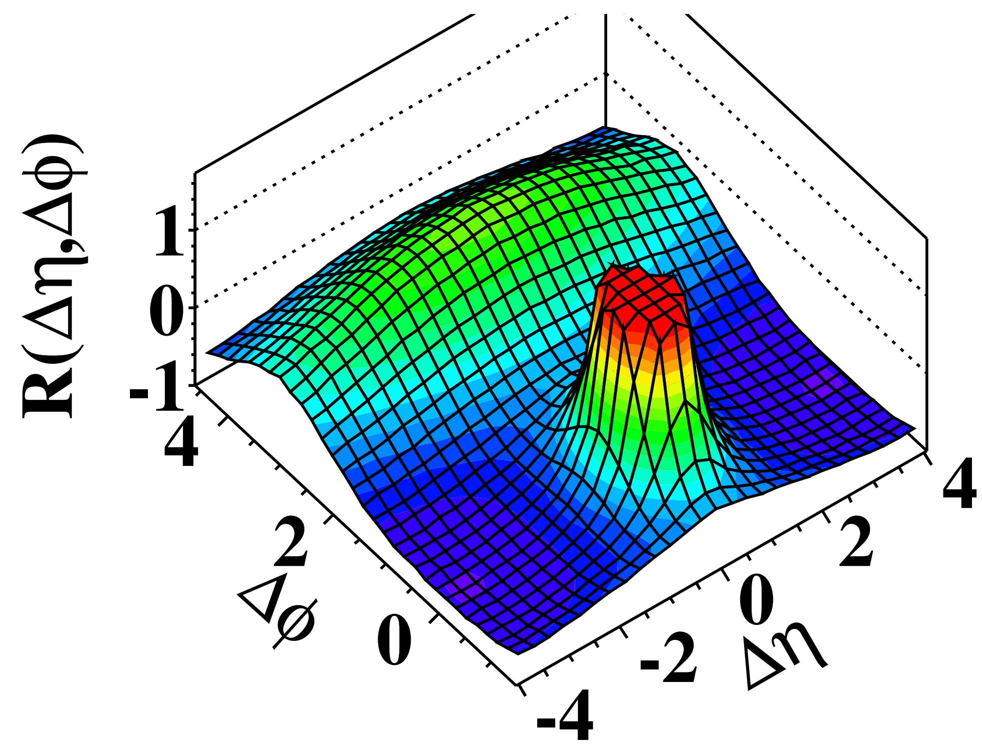
CMS JHEP 1009 (2010) 091

7 TeV pp collisions

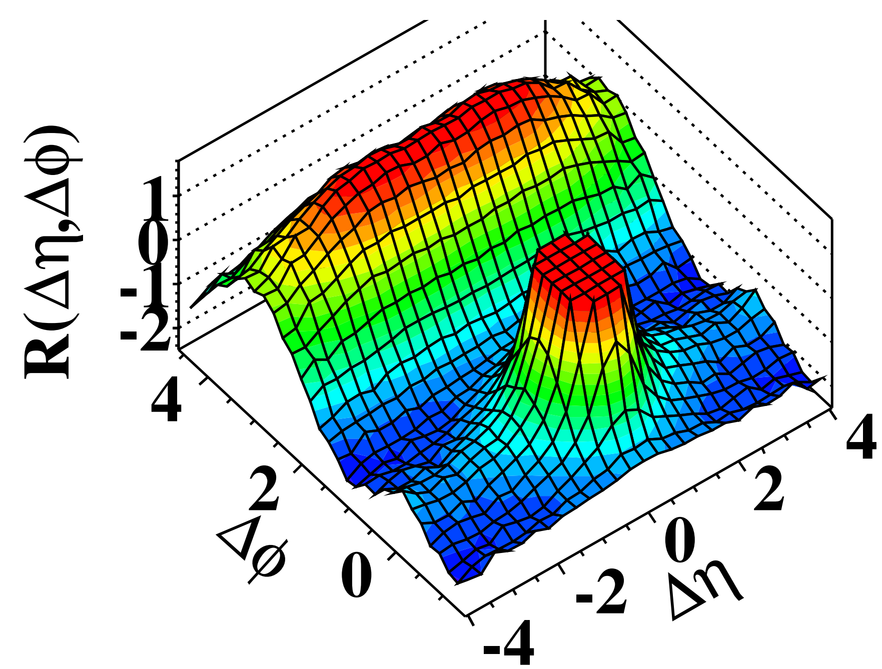


multiplicity

(b) CMS MinBias, 1.0GeV/c<p_T<3.0GeV/c



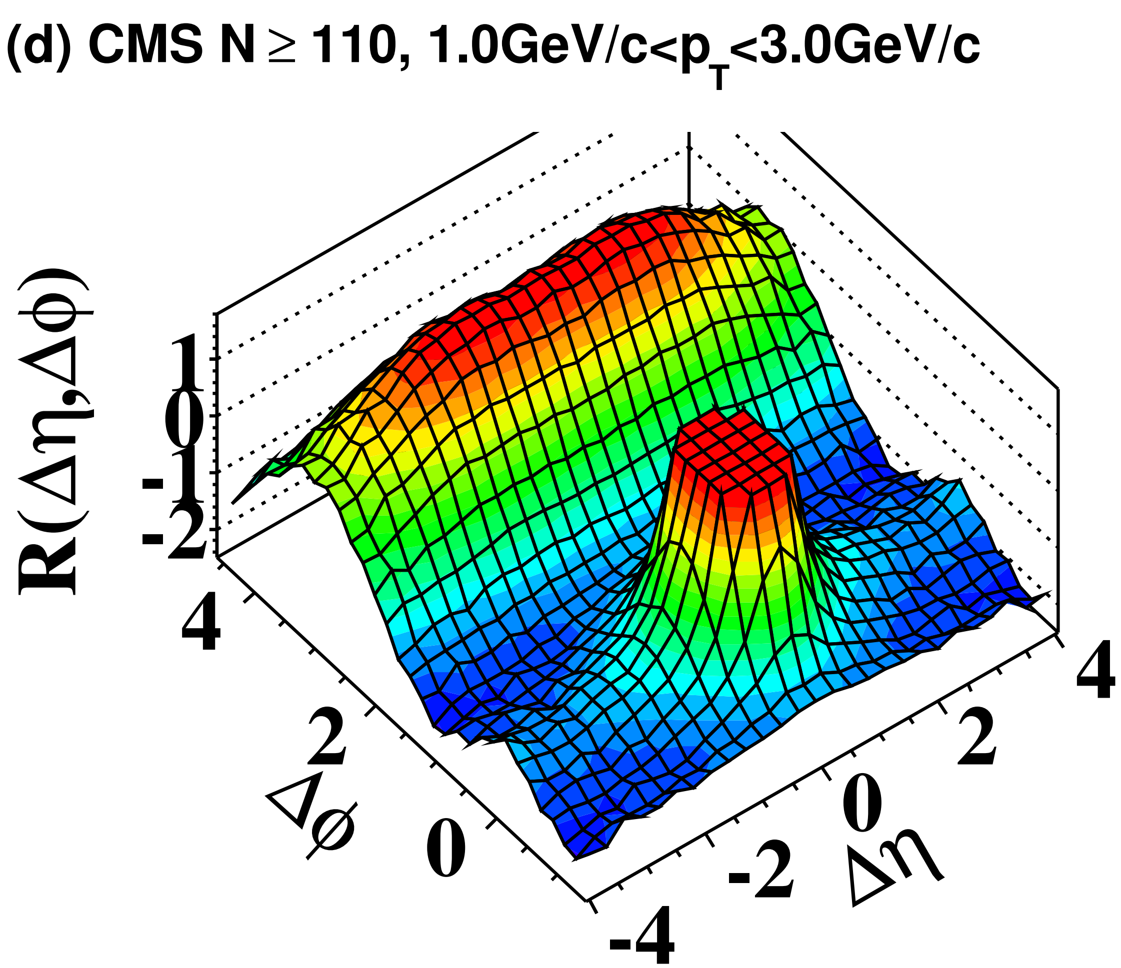
(d) CMS N ≥ 110, 1.0GeV/c<p_T<3.0GeV/c



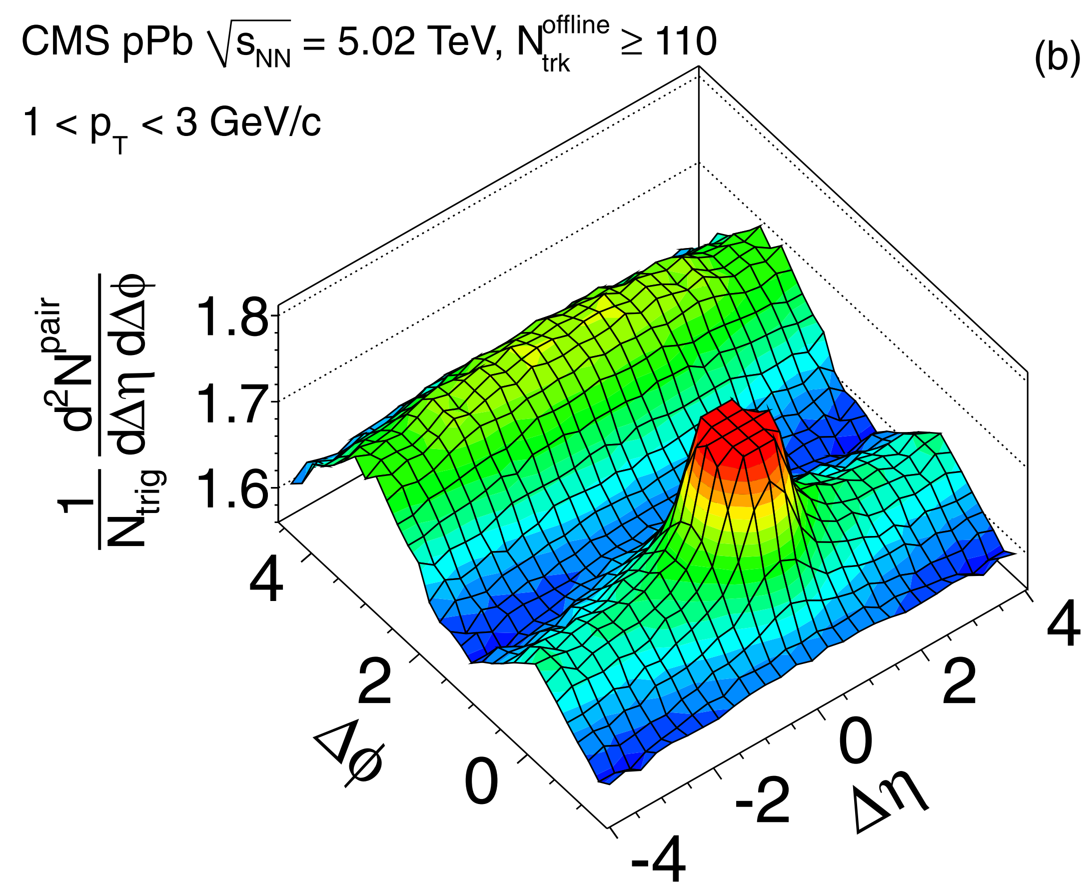
CMS JHEP 1009 (2010) 091

and in pPb

7 TeV proton-proton collisions



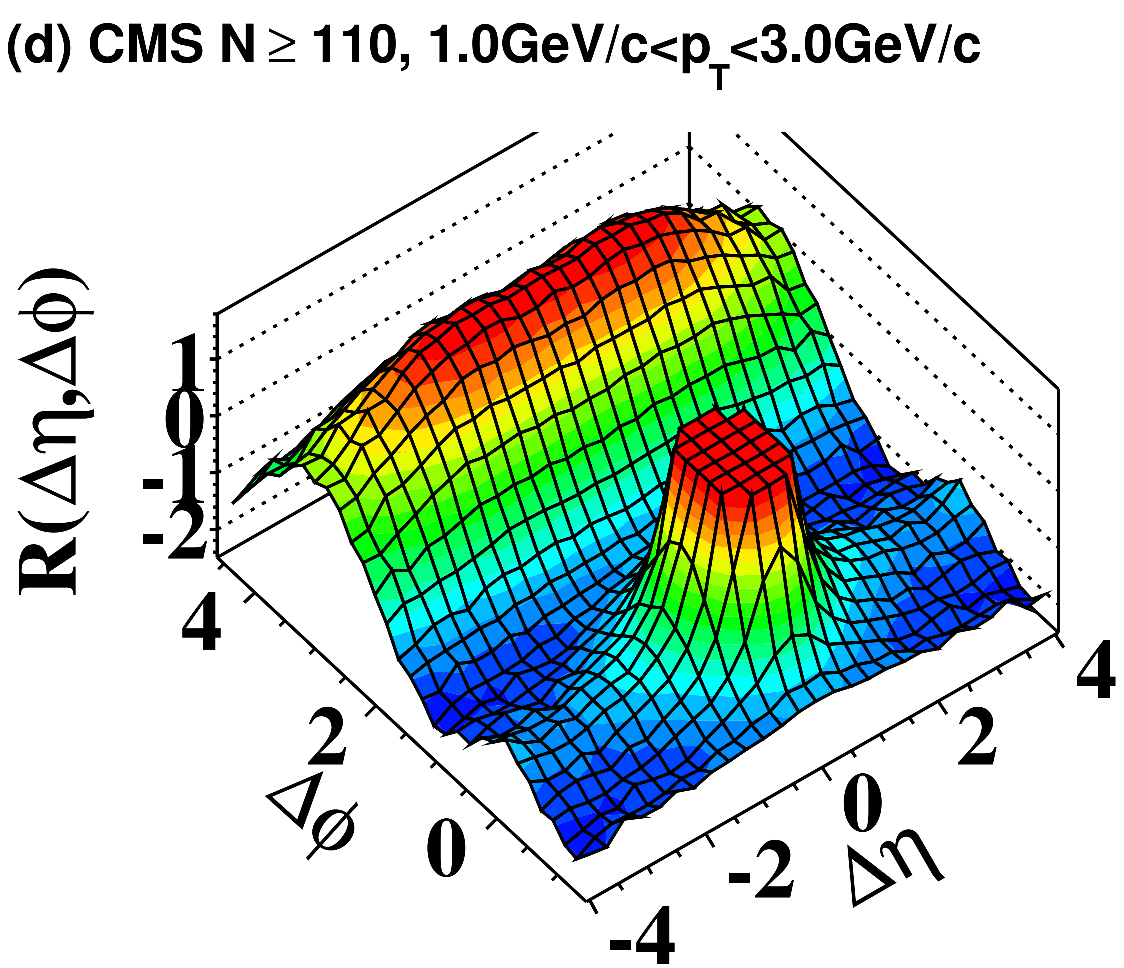
5 TeV proton-Pb collisions



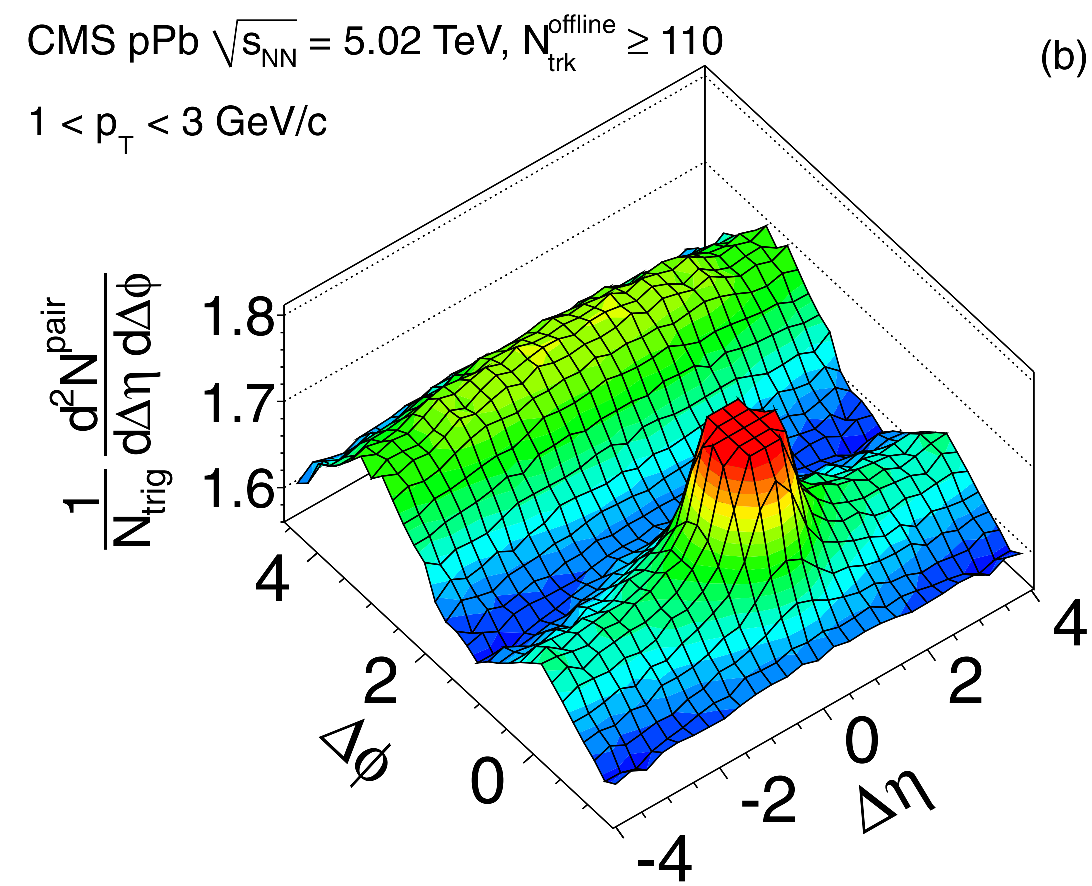
CMS JHEP 1009 (2010) 091, PLB 718 795

and in pPb

7 TeV proton-proton collisions



5 TeV proton-Pb collisions



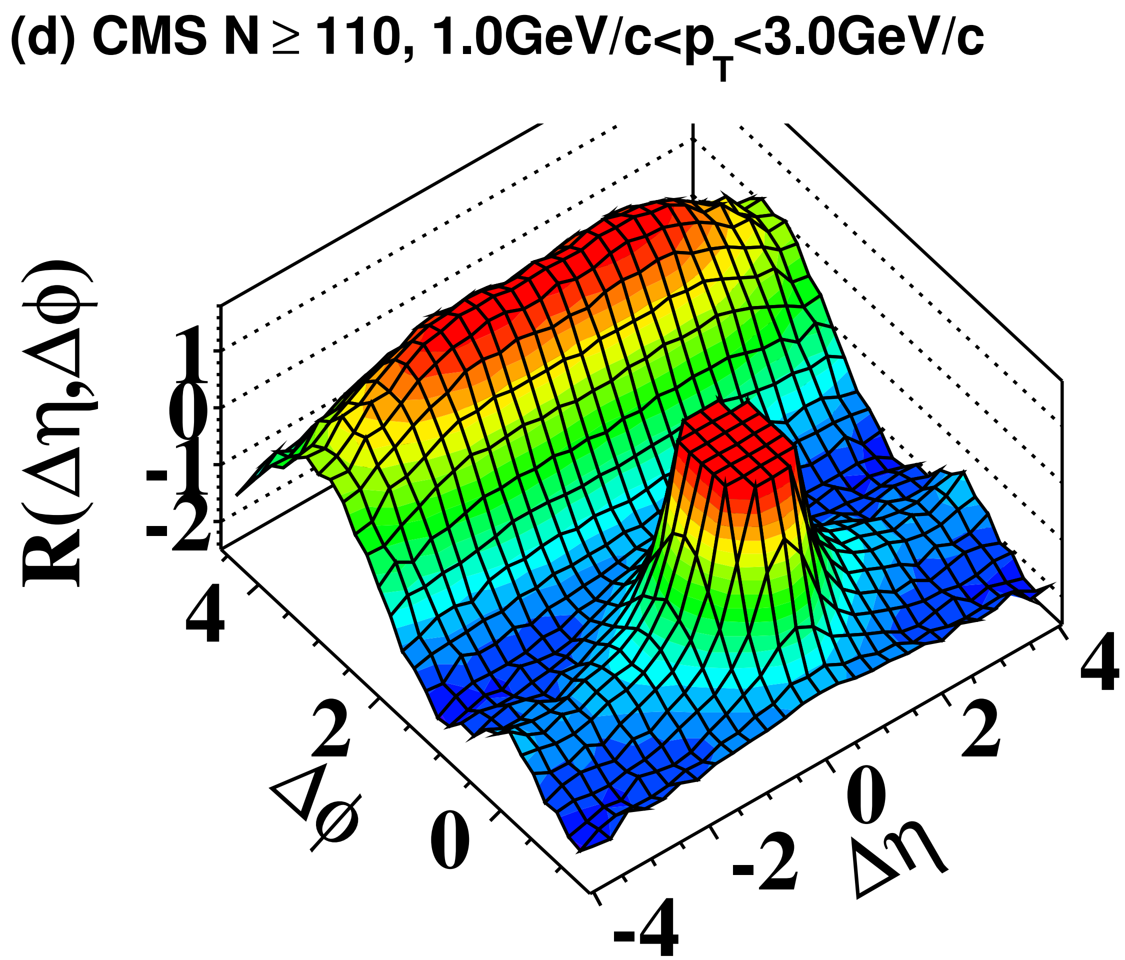
but if the ridge in nucleus-nucleus collisions is due to hydrodynamic flow

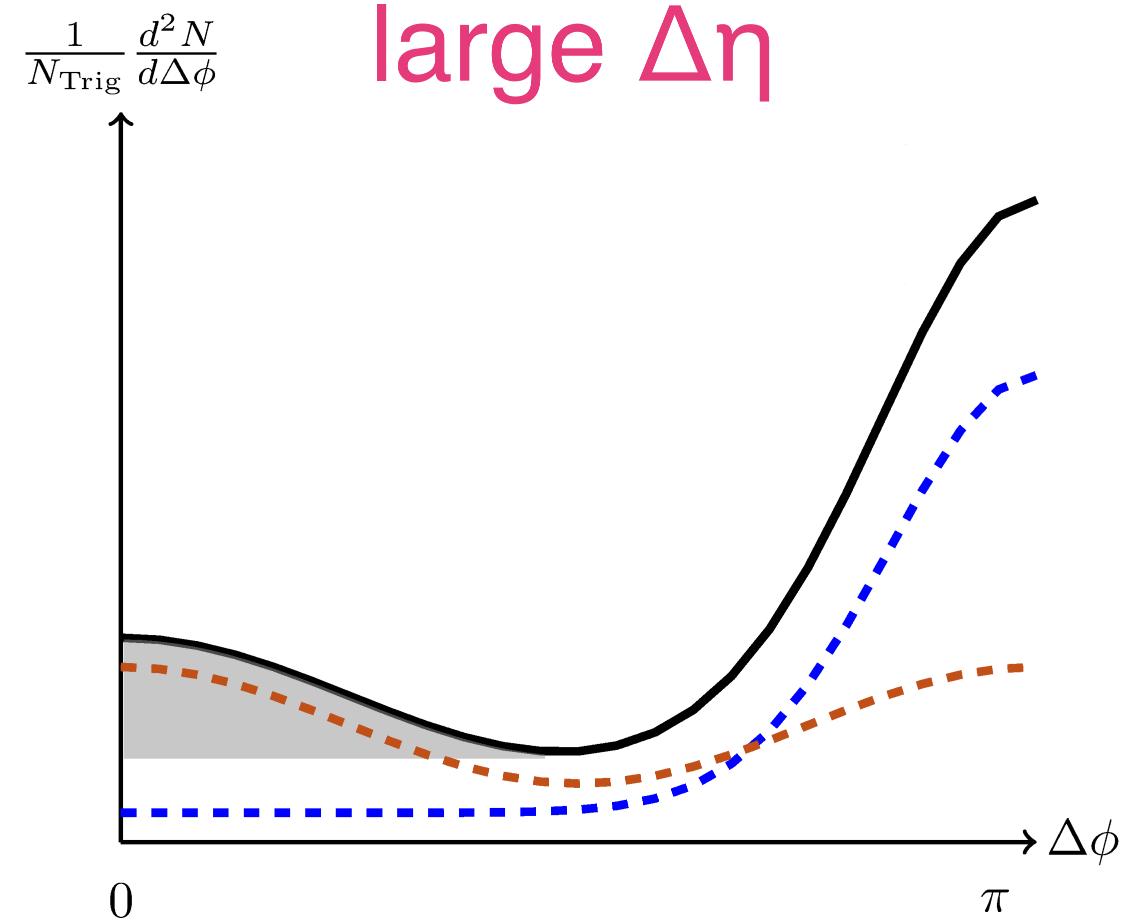
what's it doing in p-p and p-Pb collisions?

CMS JHEP 1009 (2010) 091, PLB 718 795

ridge in pp/pPb from color glass condensate?

Color Glass Condensate: calculational framework for saturation

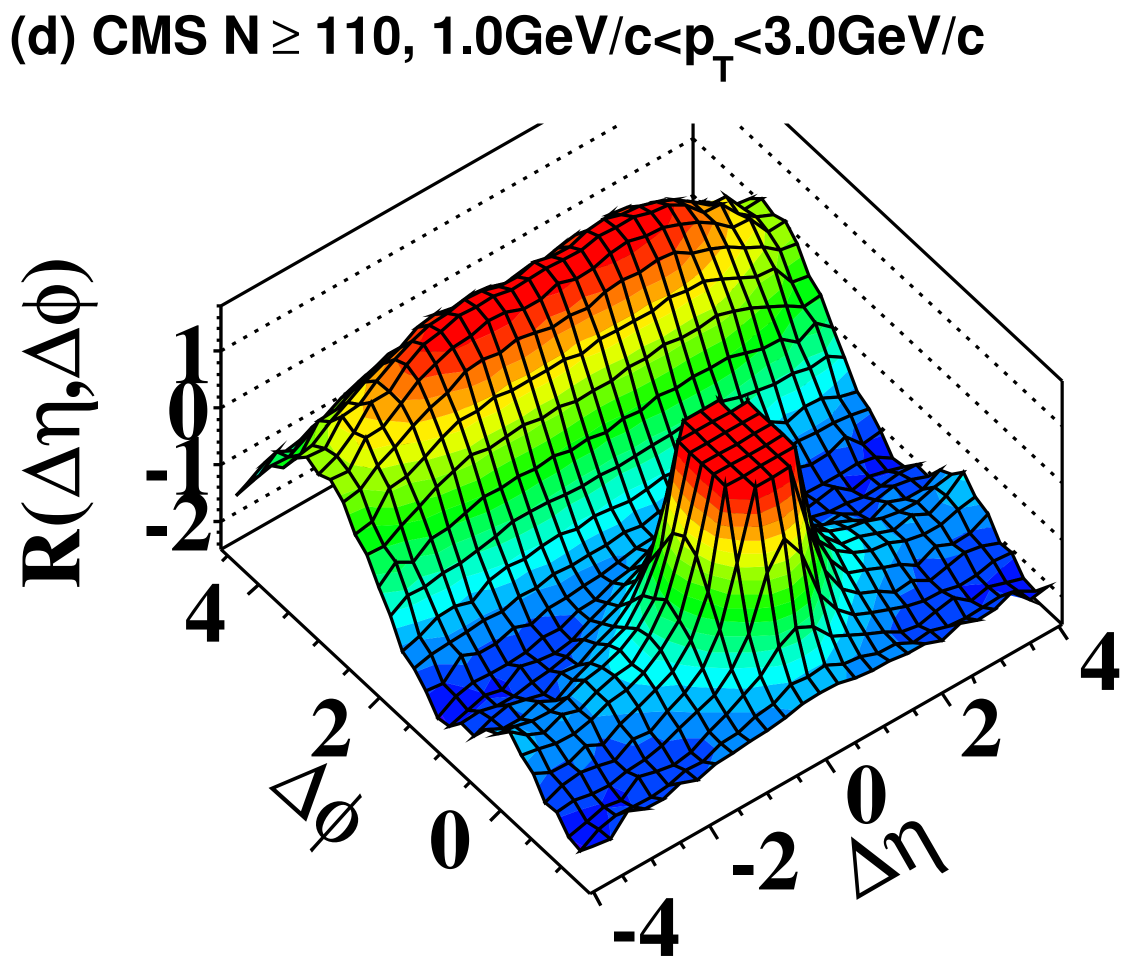


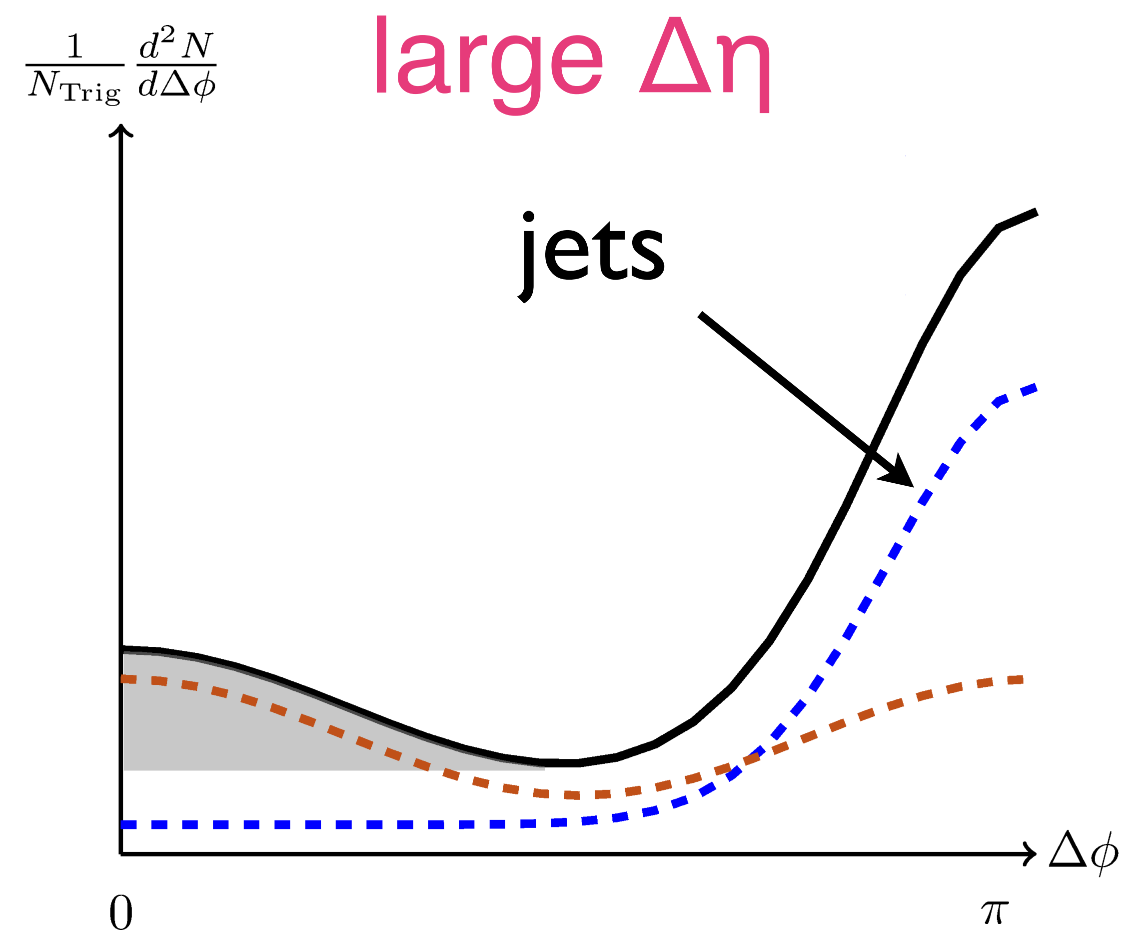


Dusling & Venugopalan PRL 104 262301, PRD 87 054014, PRD 87 094034

ridge in pp/pPb from color glass condensate?

Color Glass Condensate: calculational framework for saturation





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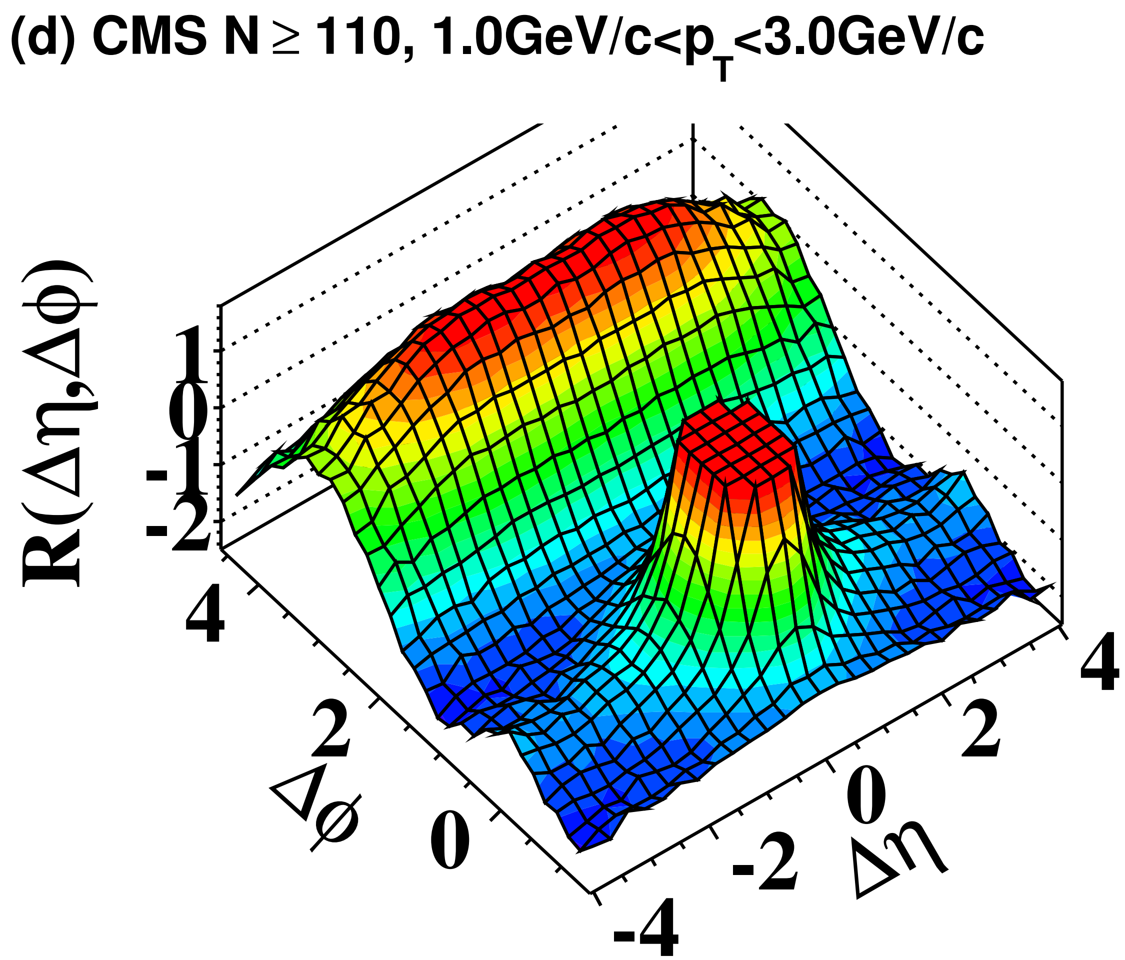

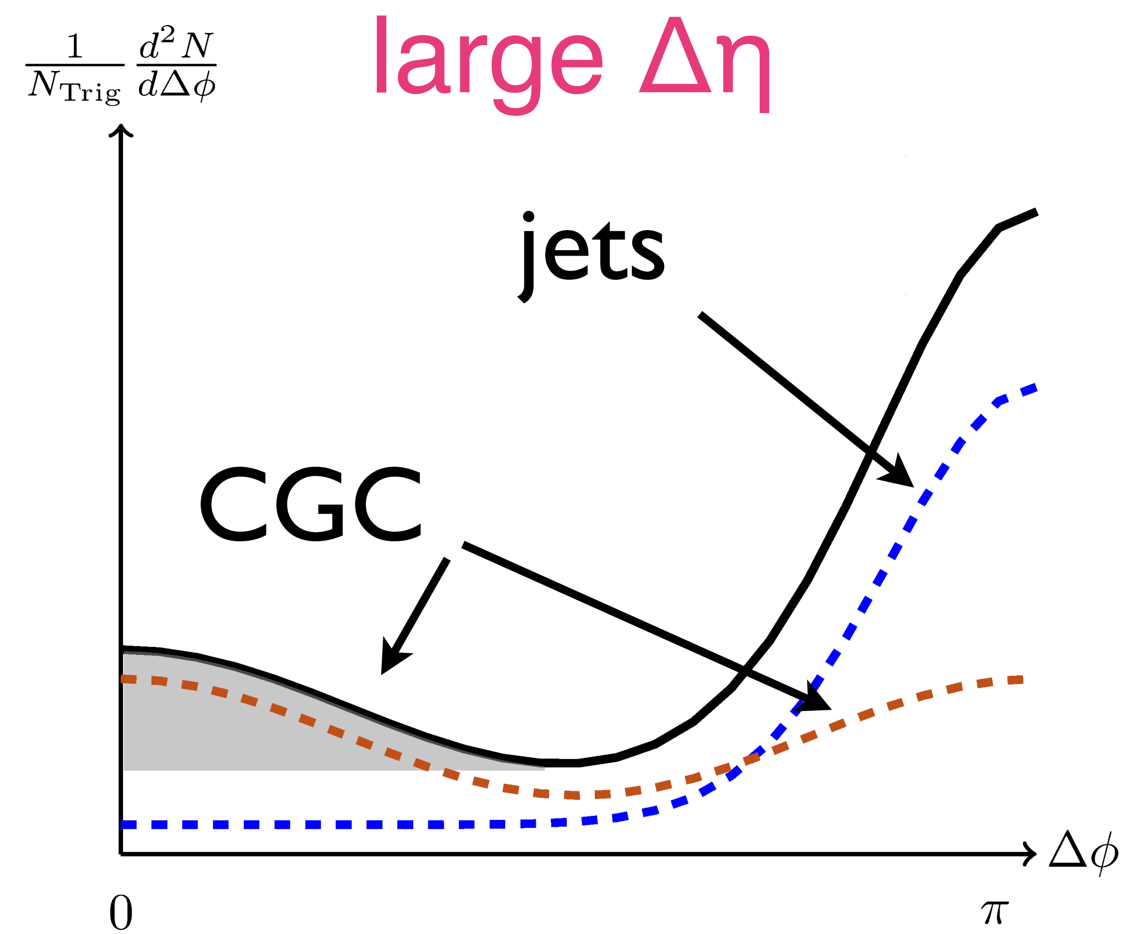

Dusling & Venugopalan PRL 104 262301, PRD 87 054014, PRD 87 094034

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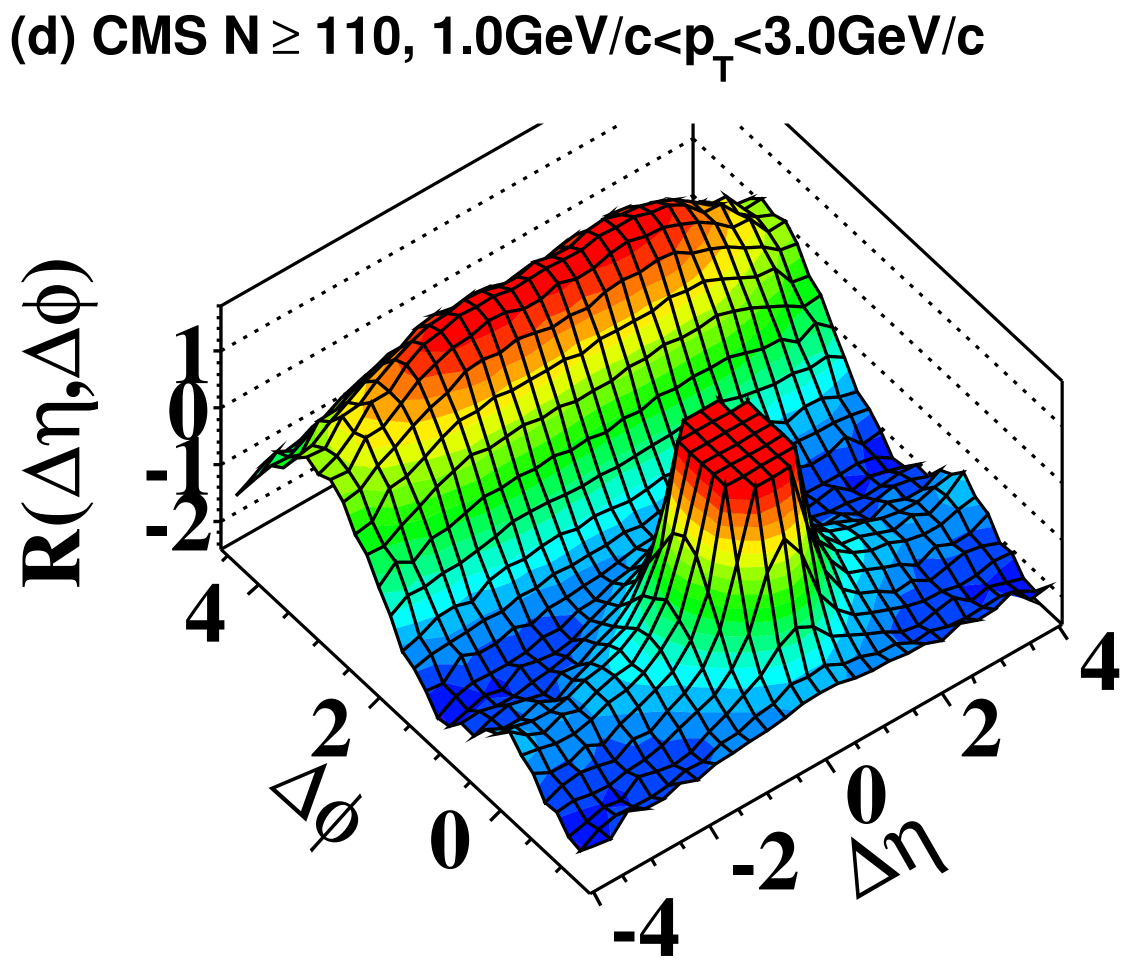
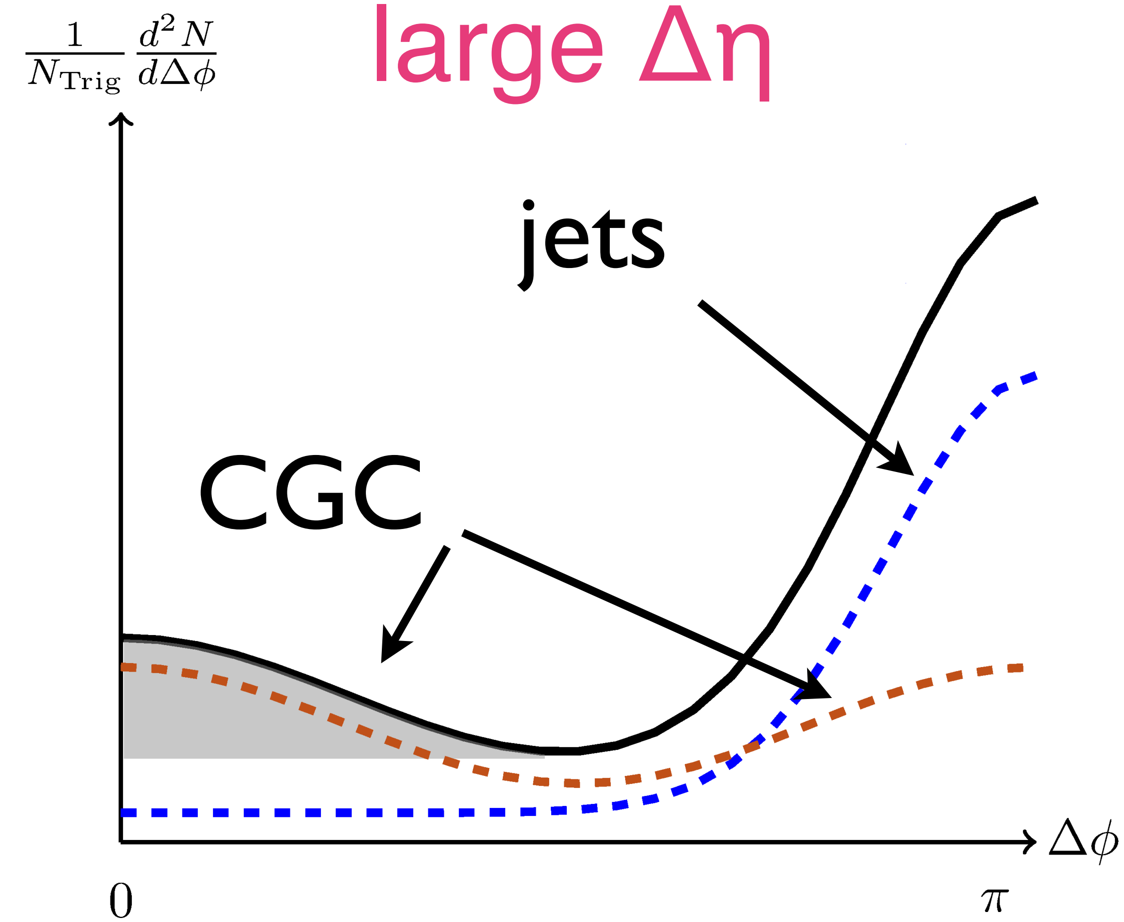
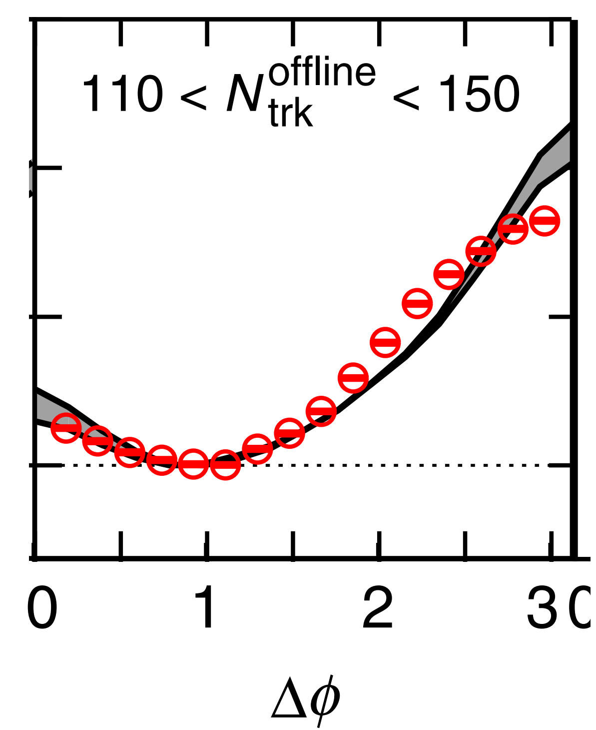
Color Glass Condensate: calculational framework for saturation







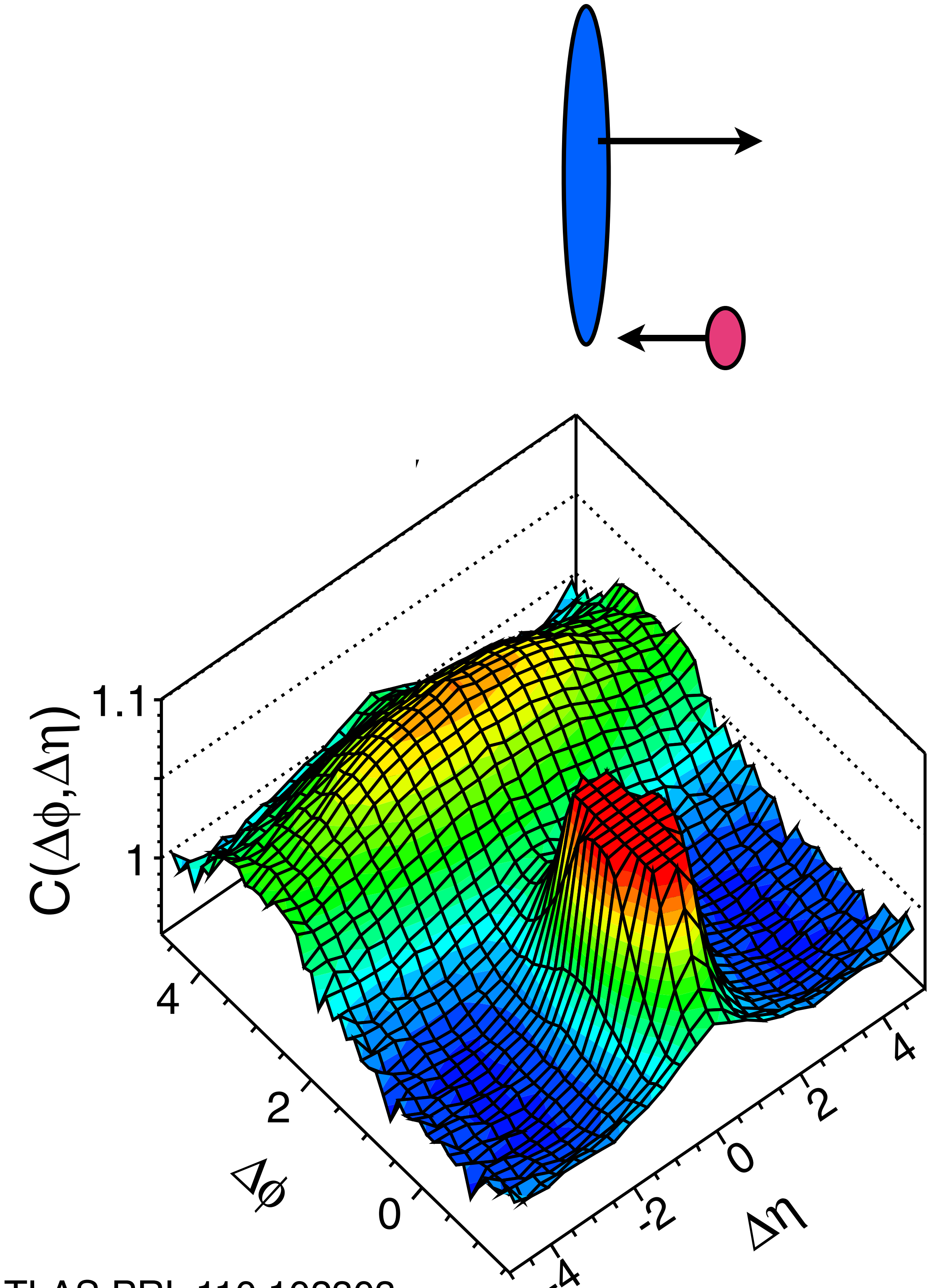
good description of the data in pp & pPb

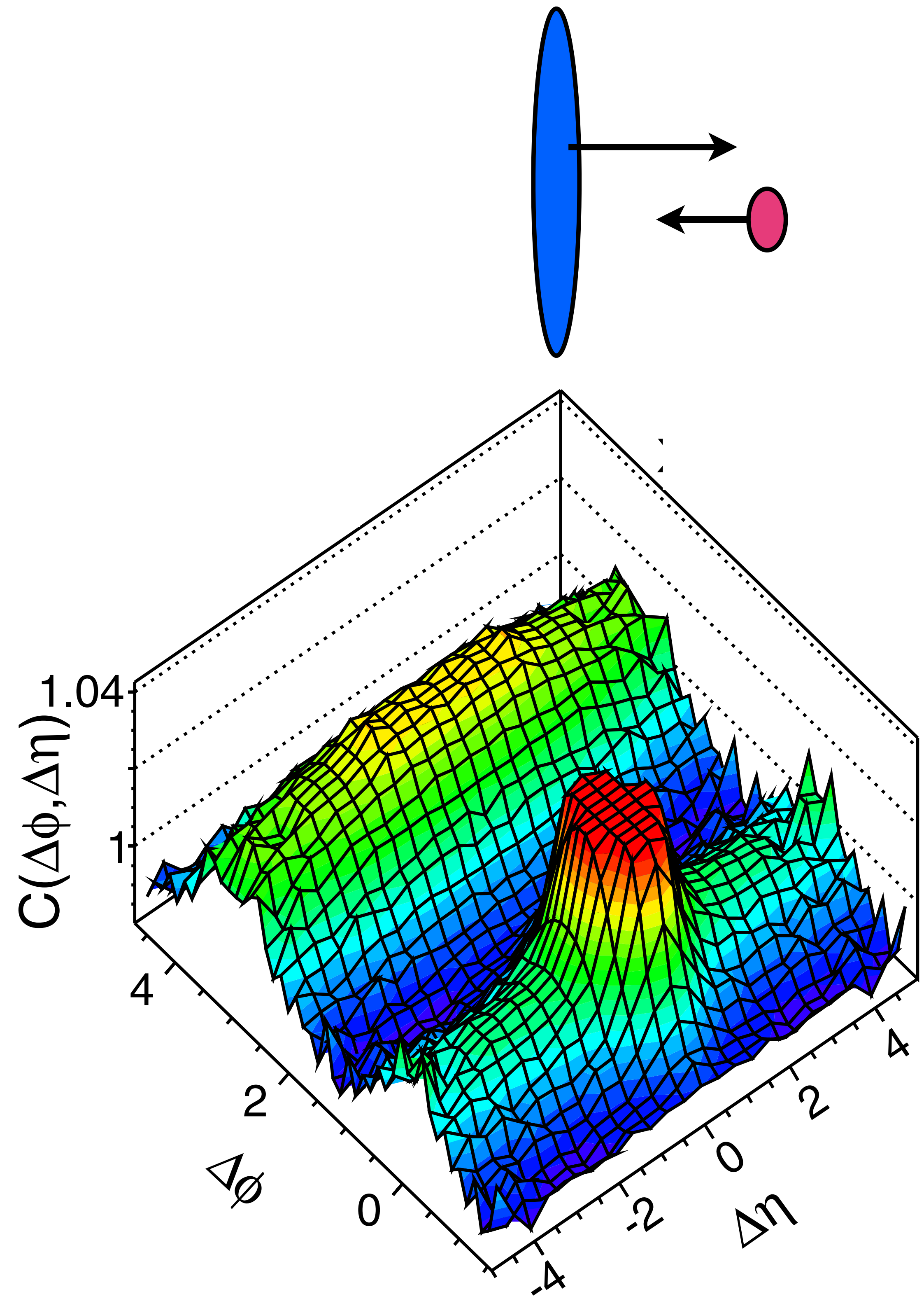
Dusling & Venugopalan PRL 104 262301, PRD 87 054014, PRD 87 094034

a closer look at pPb

peripheral collisions

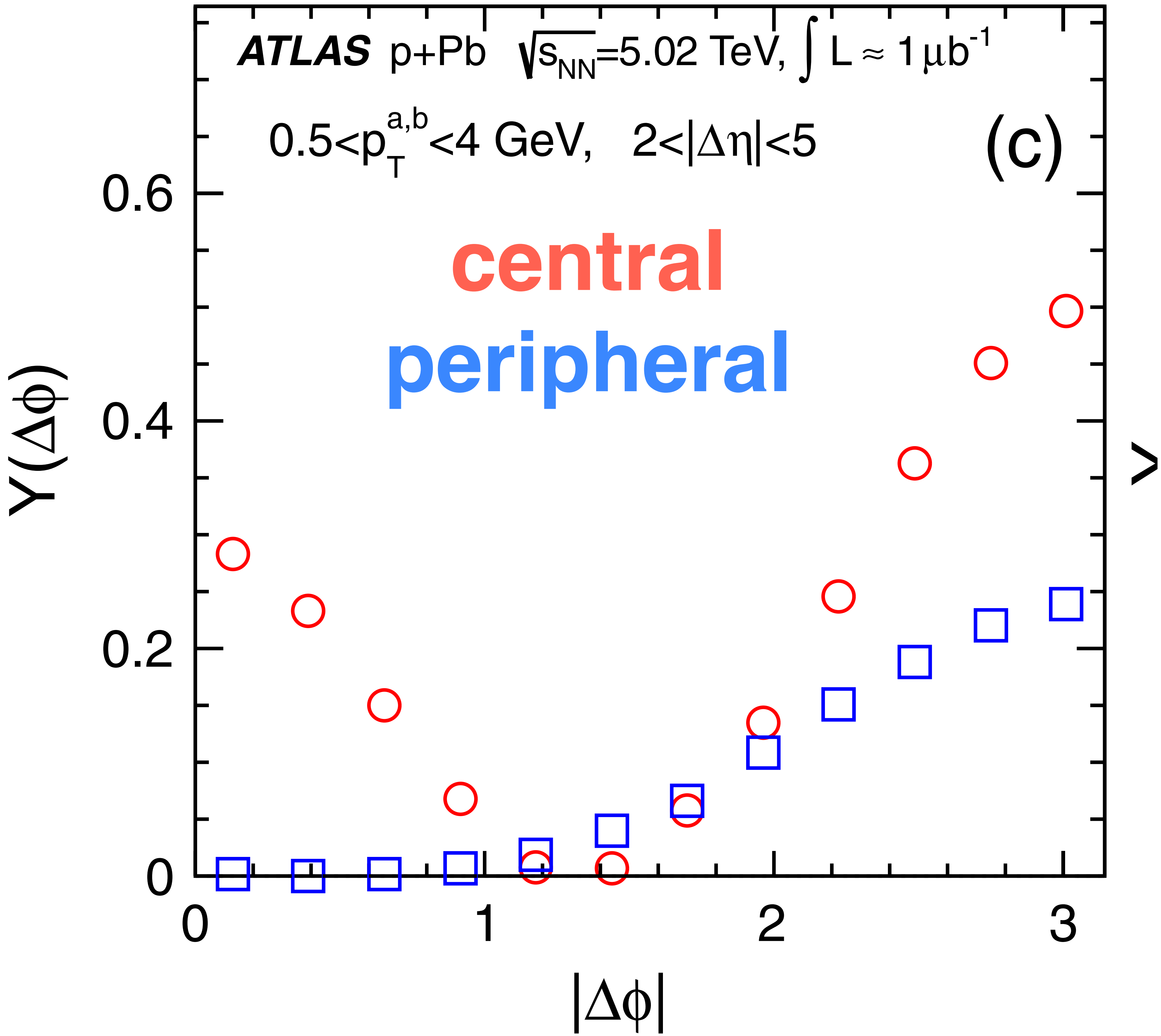
central collisions





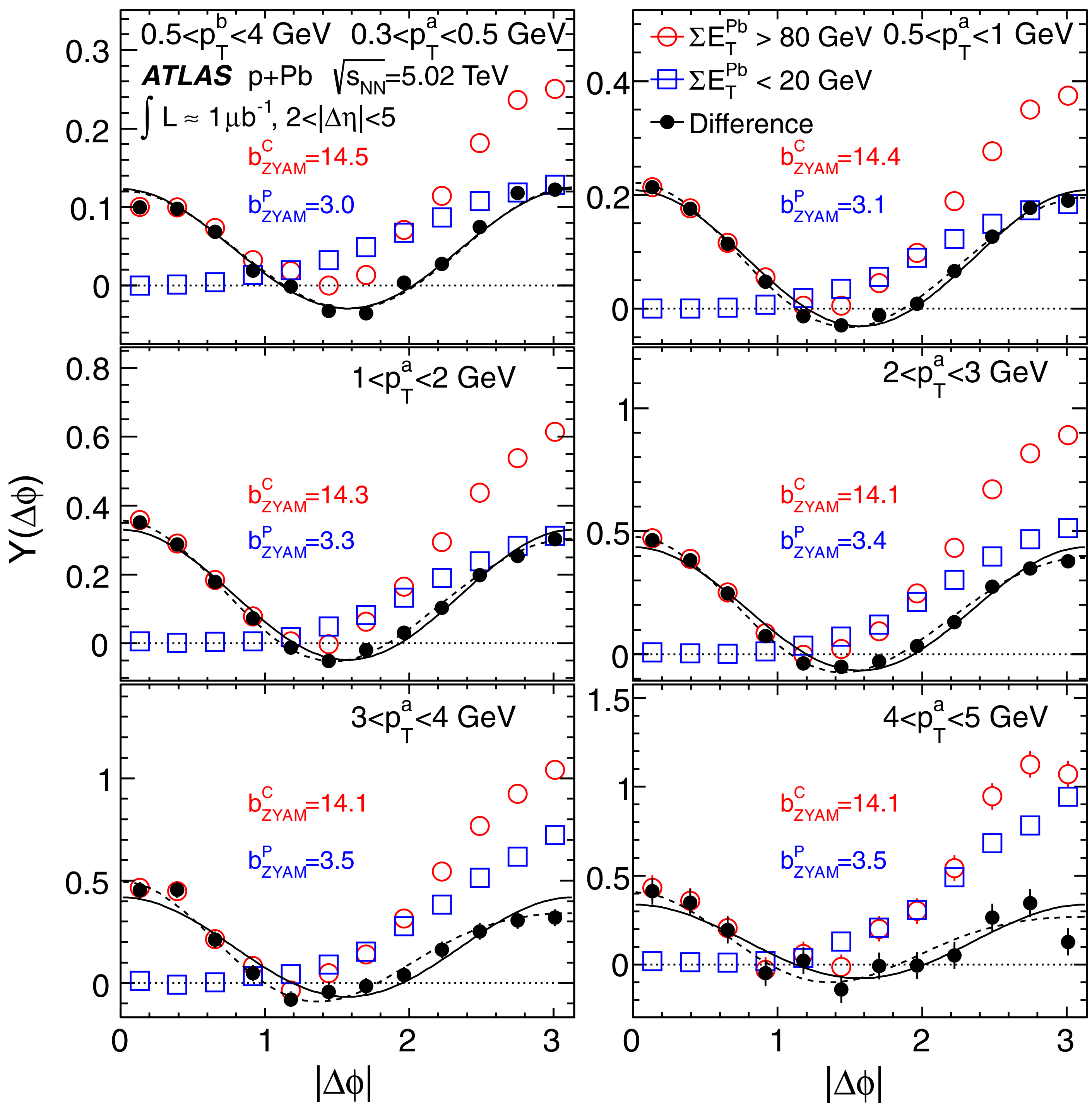
ATLAS PRL 110 102303

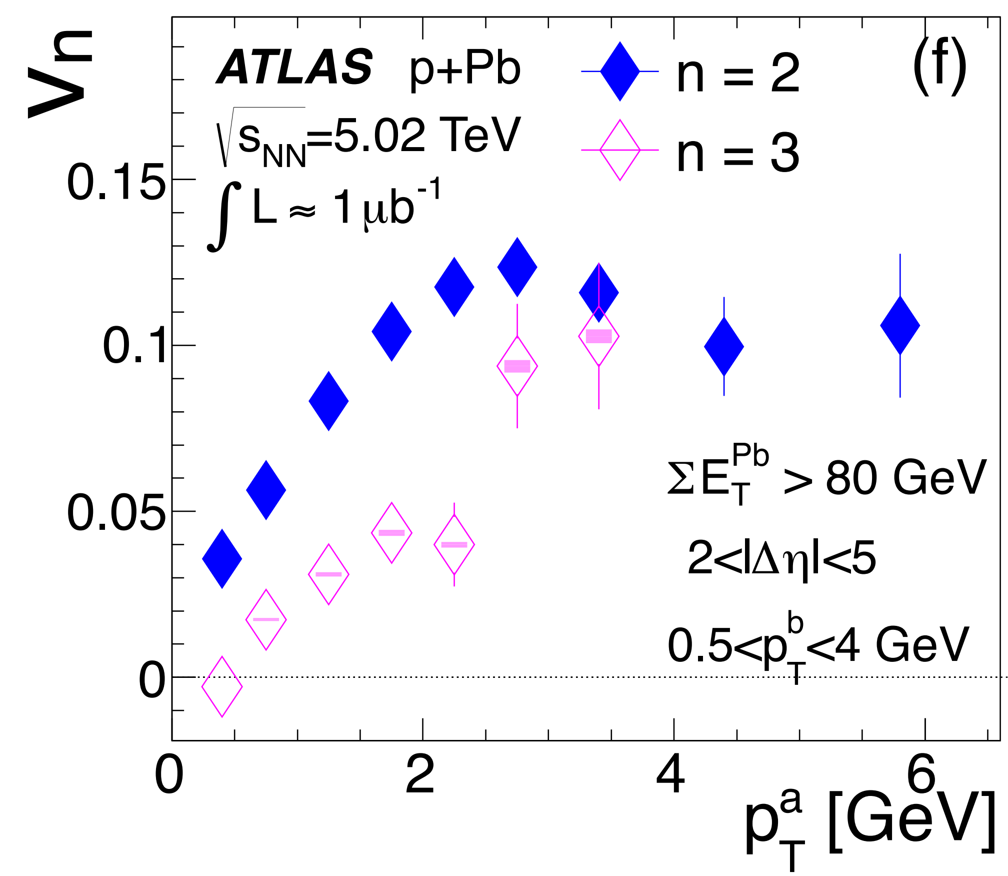
a closer look at pPb



ATLAS PRL 110 102303

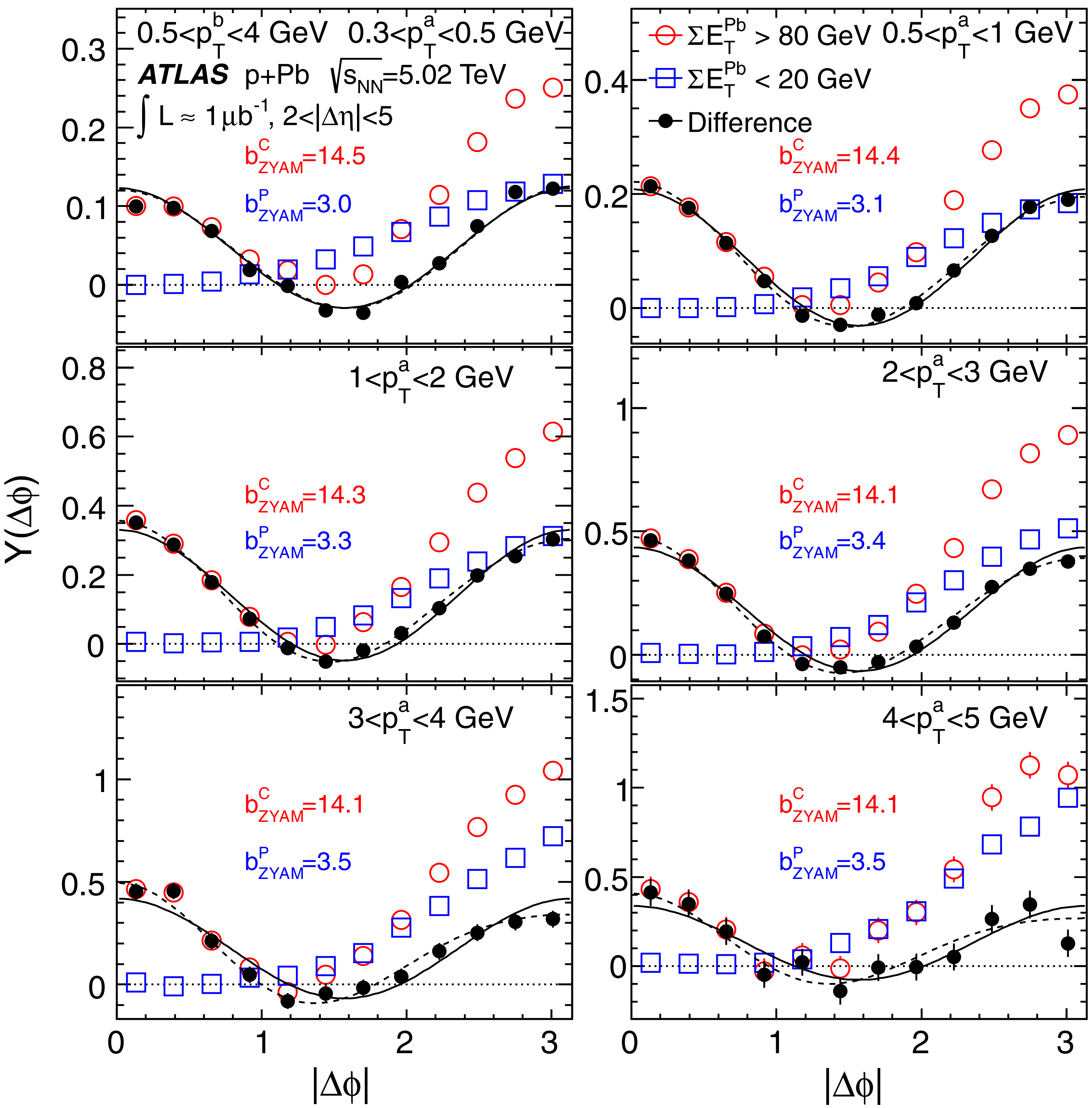
v_2 & v_3 in pPb collisions

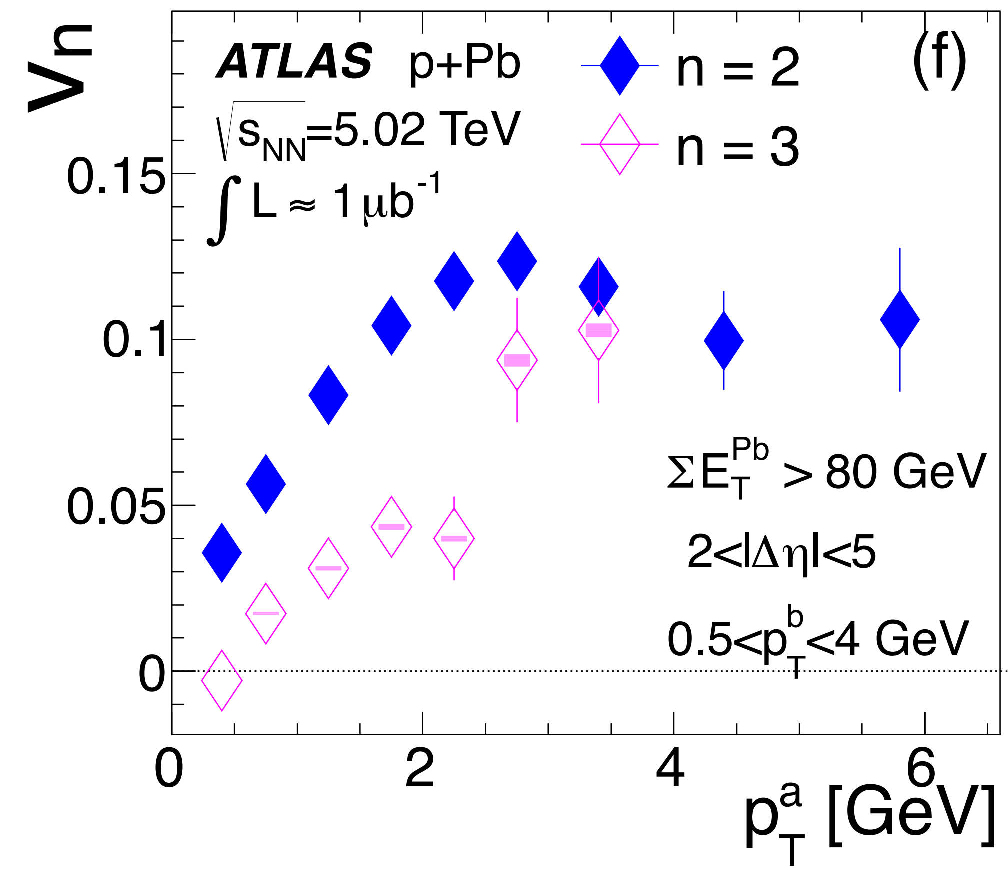




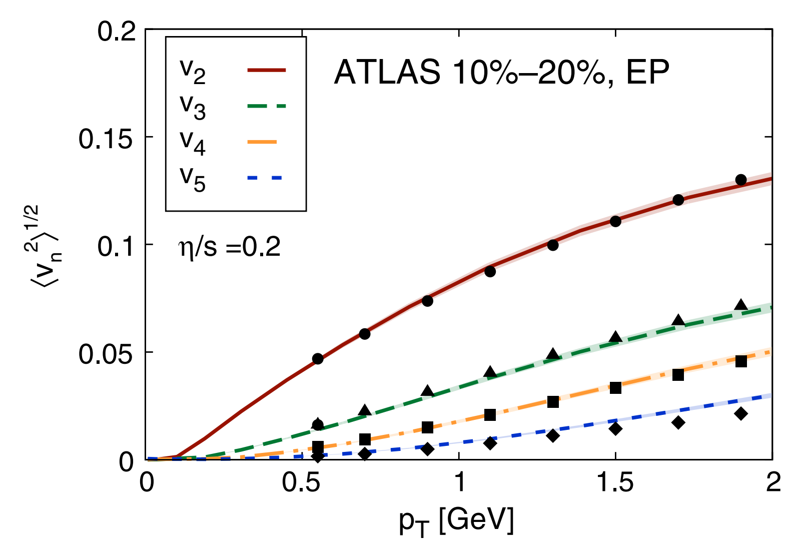
ATLAS PRL 110 102303

v_2 & v_3 in pPb collisions



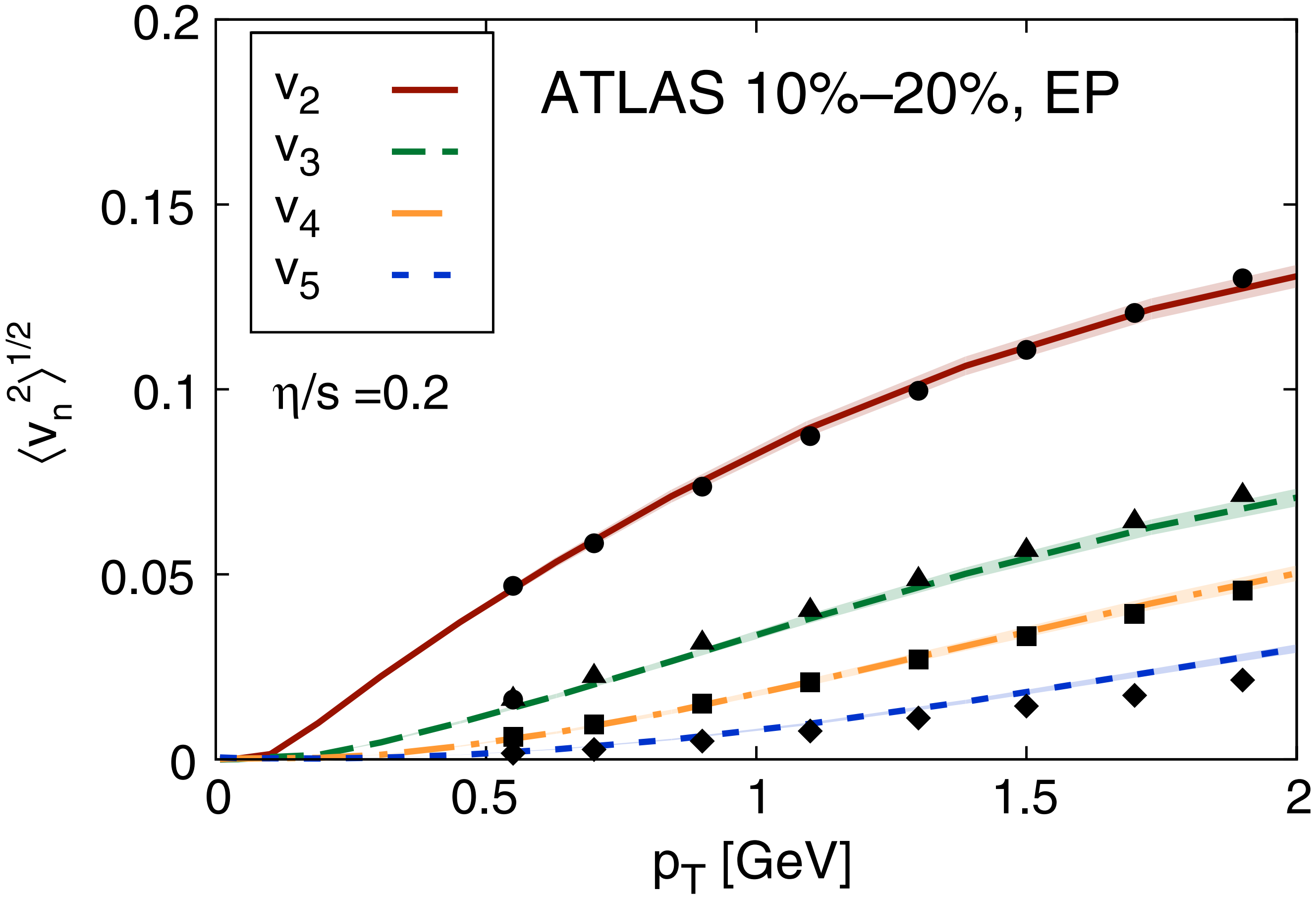


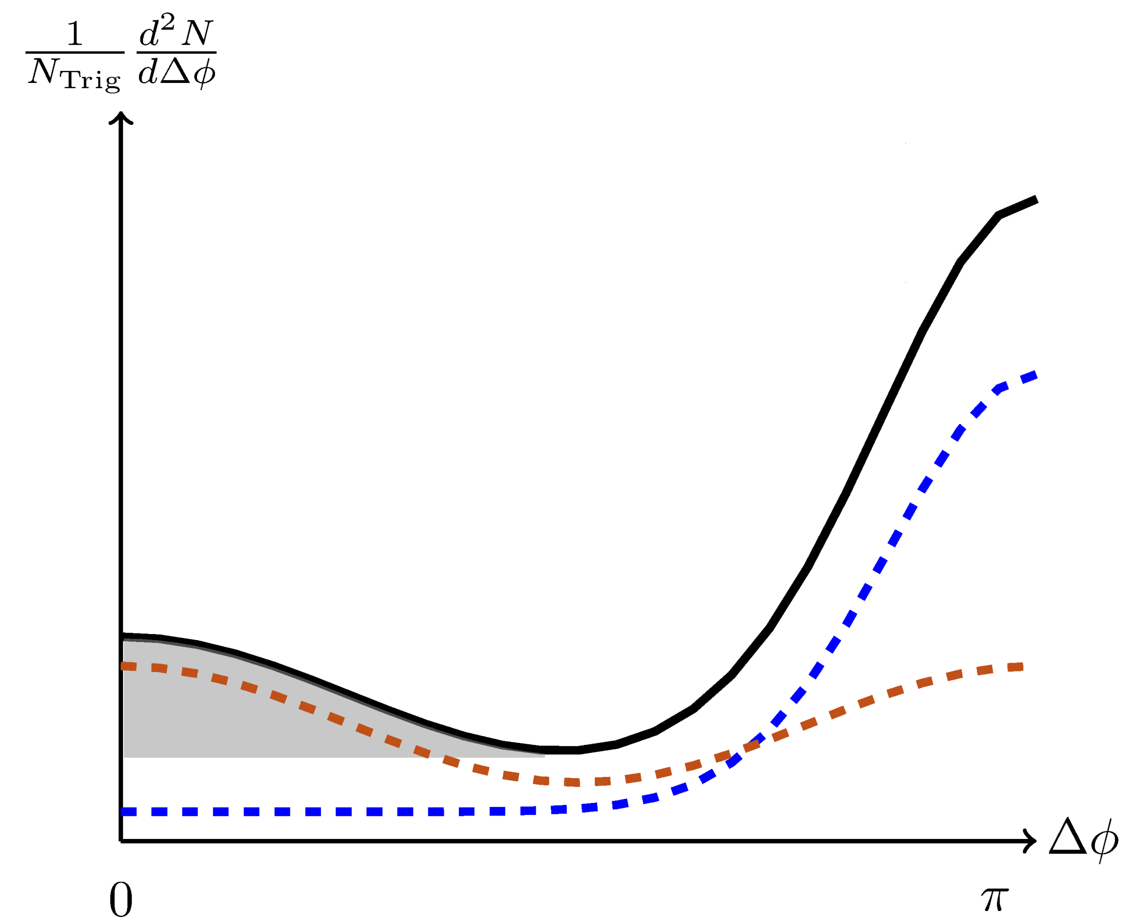
very similar to AA results



ATLAS PRL 110 102303

what is the origin of the ridge in pPb?





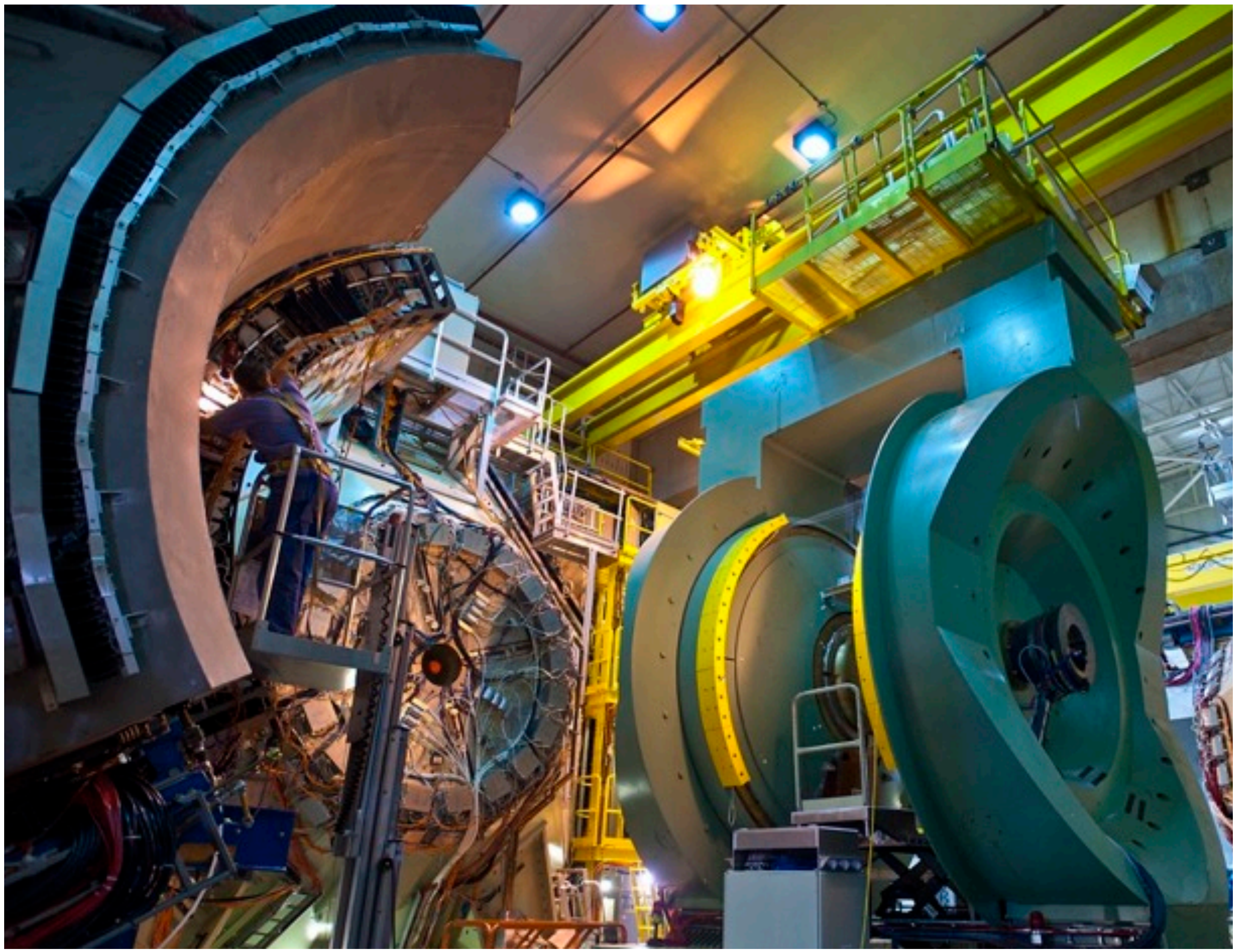
geometry & flow as in AA collisions or CGC correlations

what can RHIC add?

RHIC had dAu data at 200 GeV

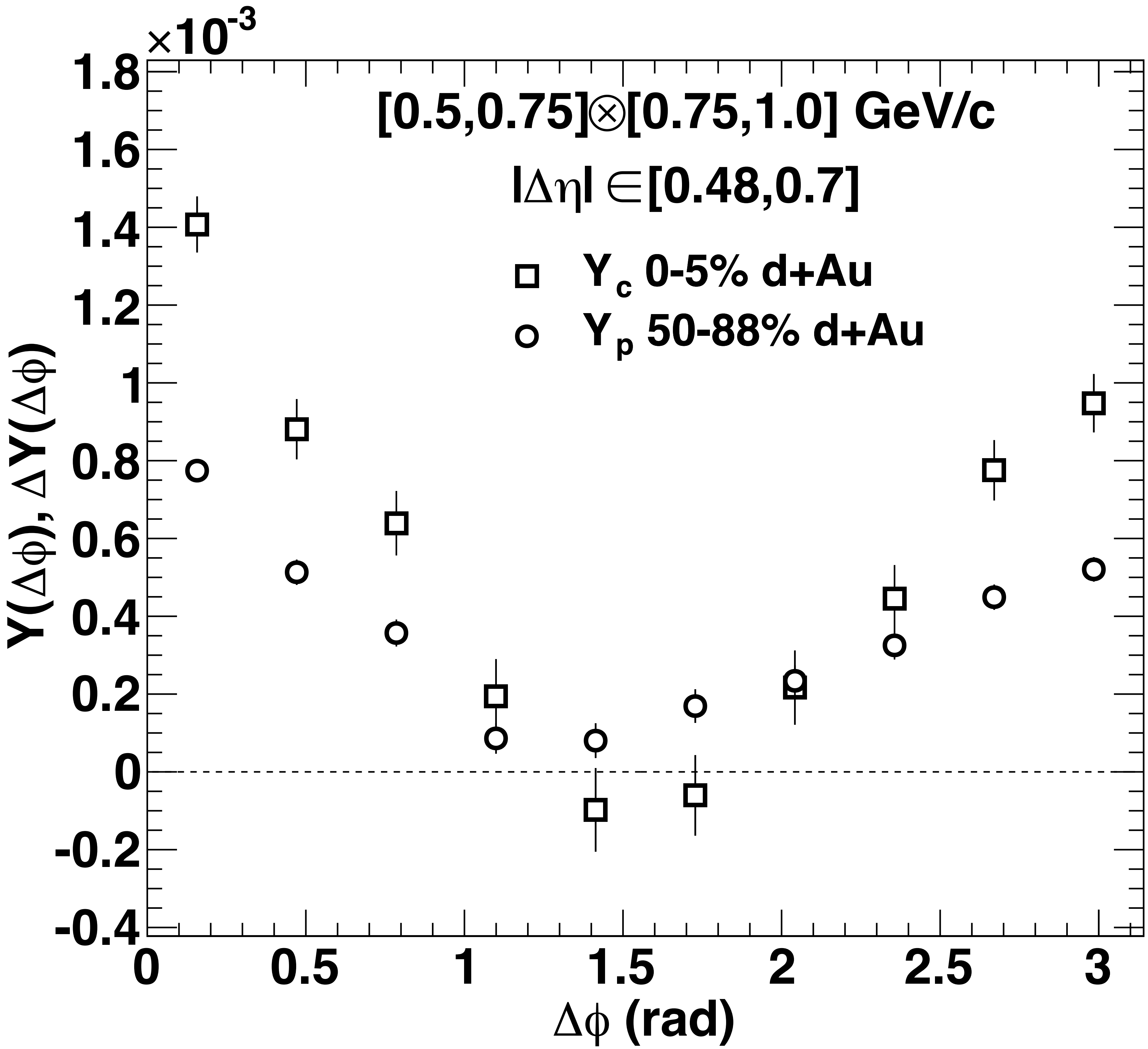
25x smaller collision energy than the LHC

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

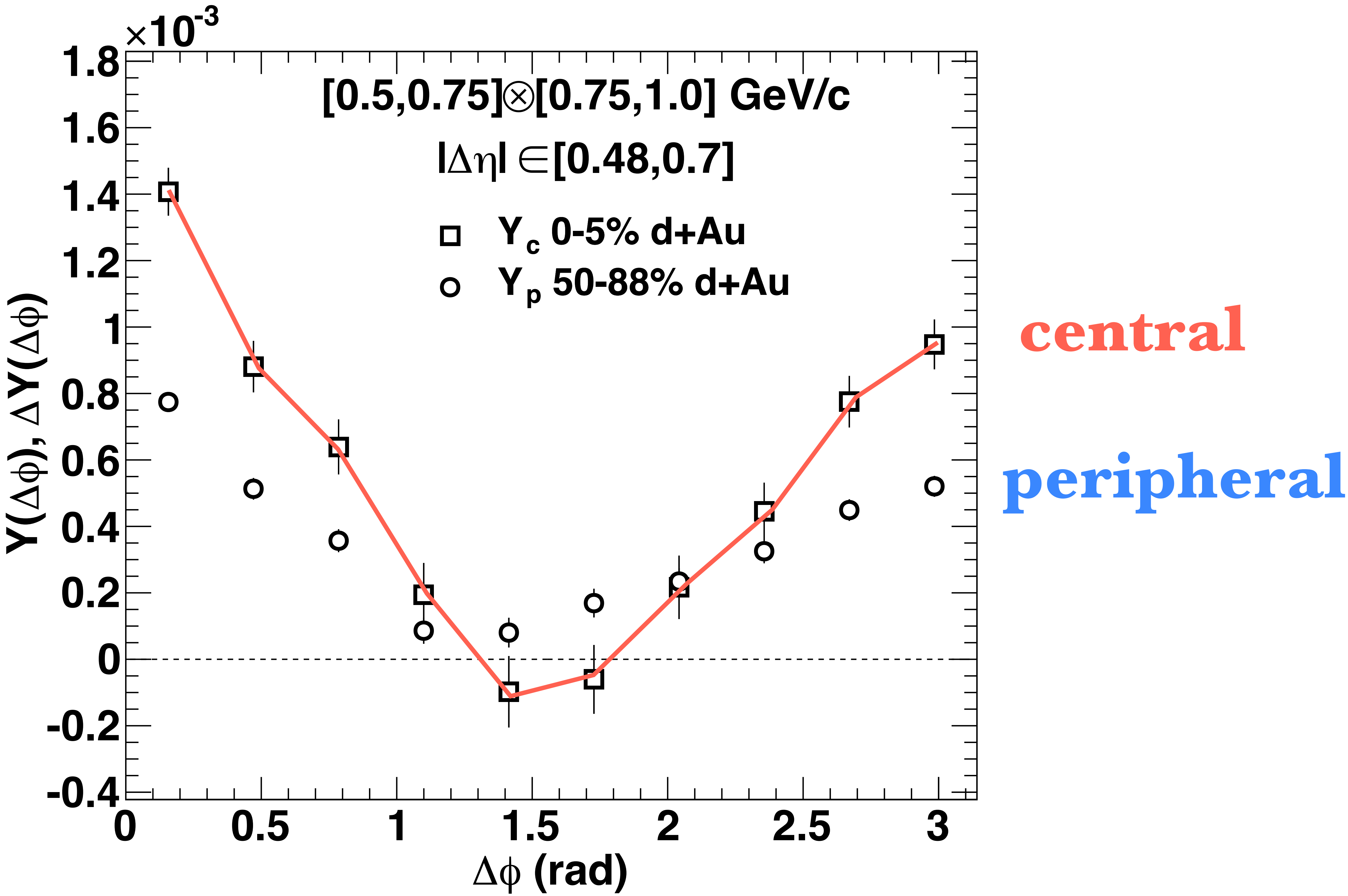


central

peripheral

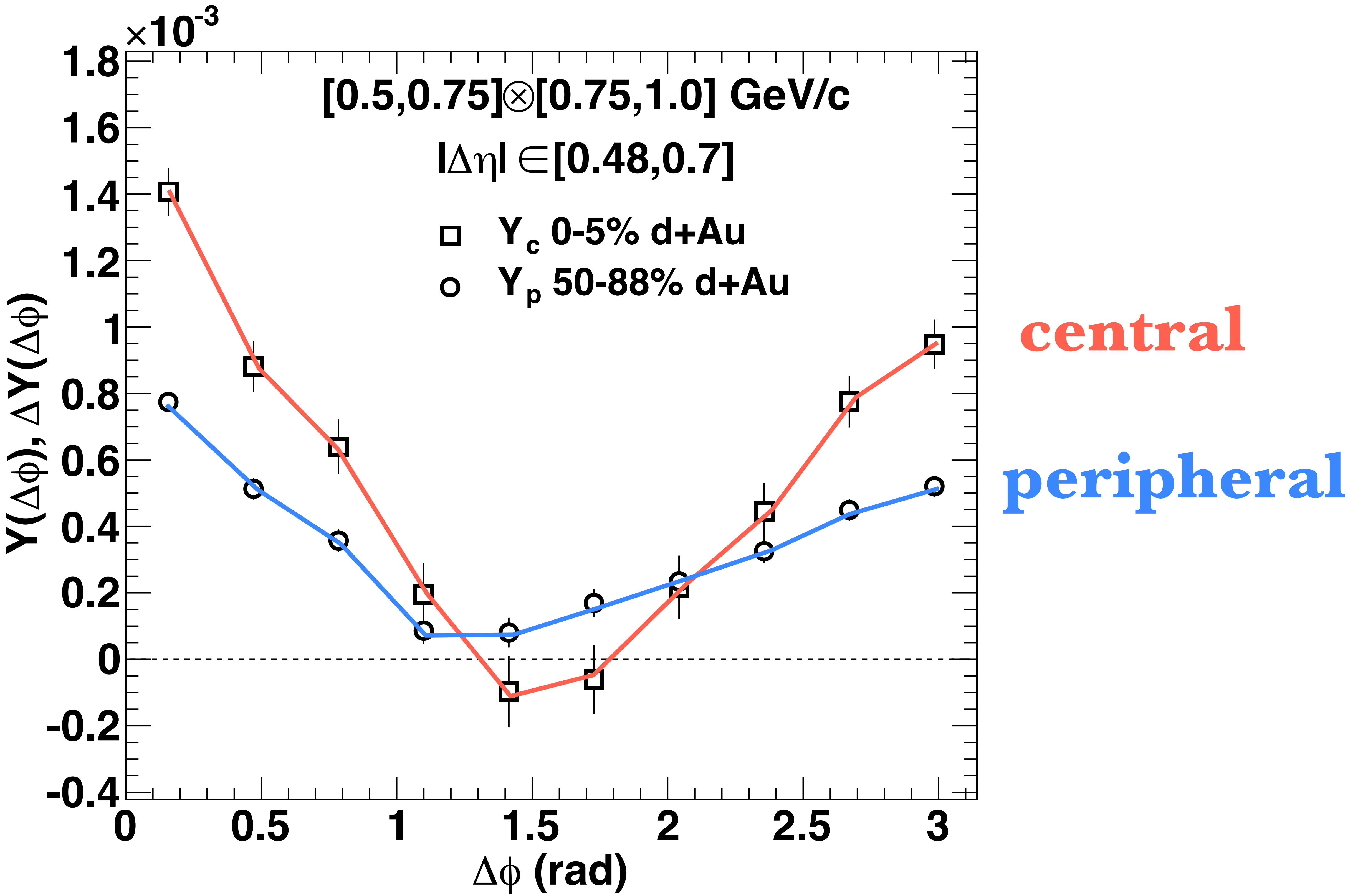
PHENIX PRL 111 212301

two particle correlations in dAu



PHENIX PRL 111 212301

two particle correlations in dAu



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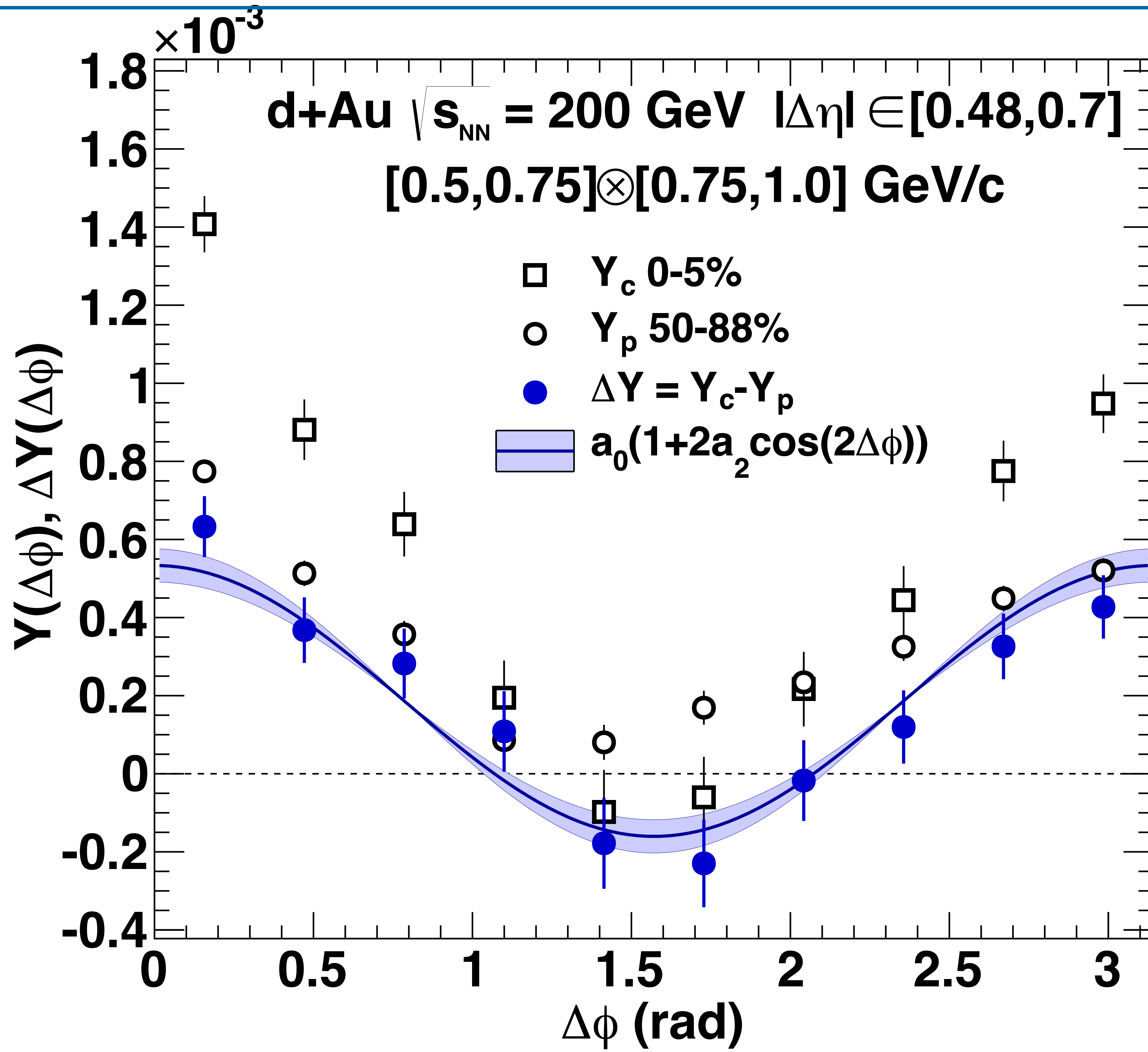
centrality dependence



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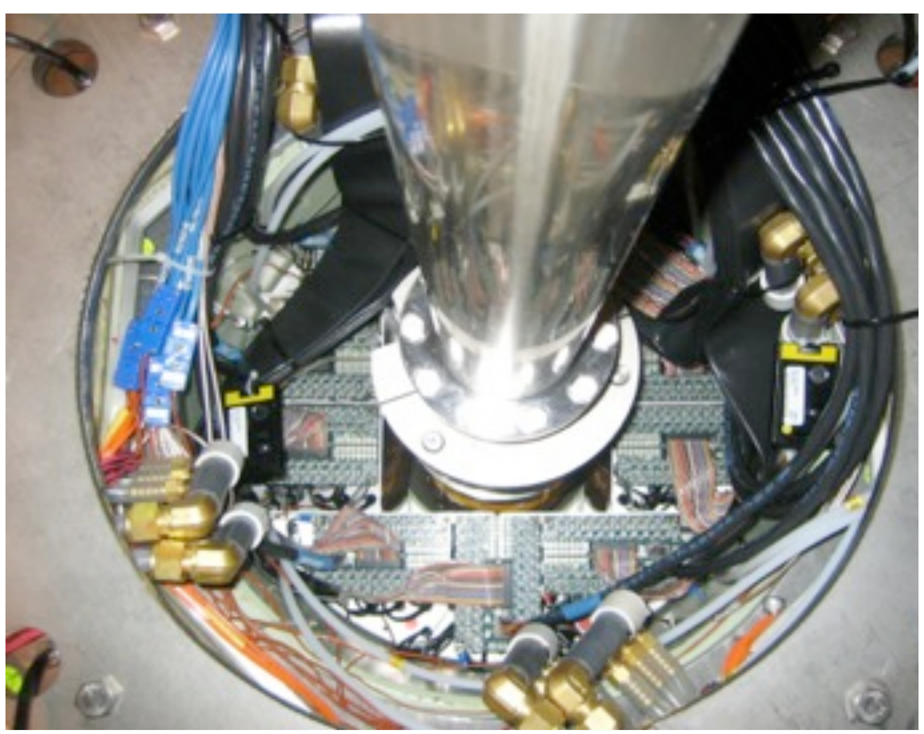
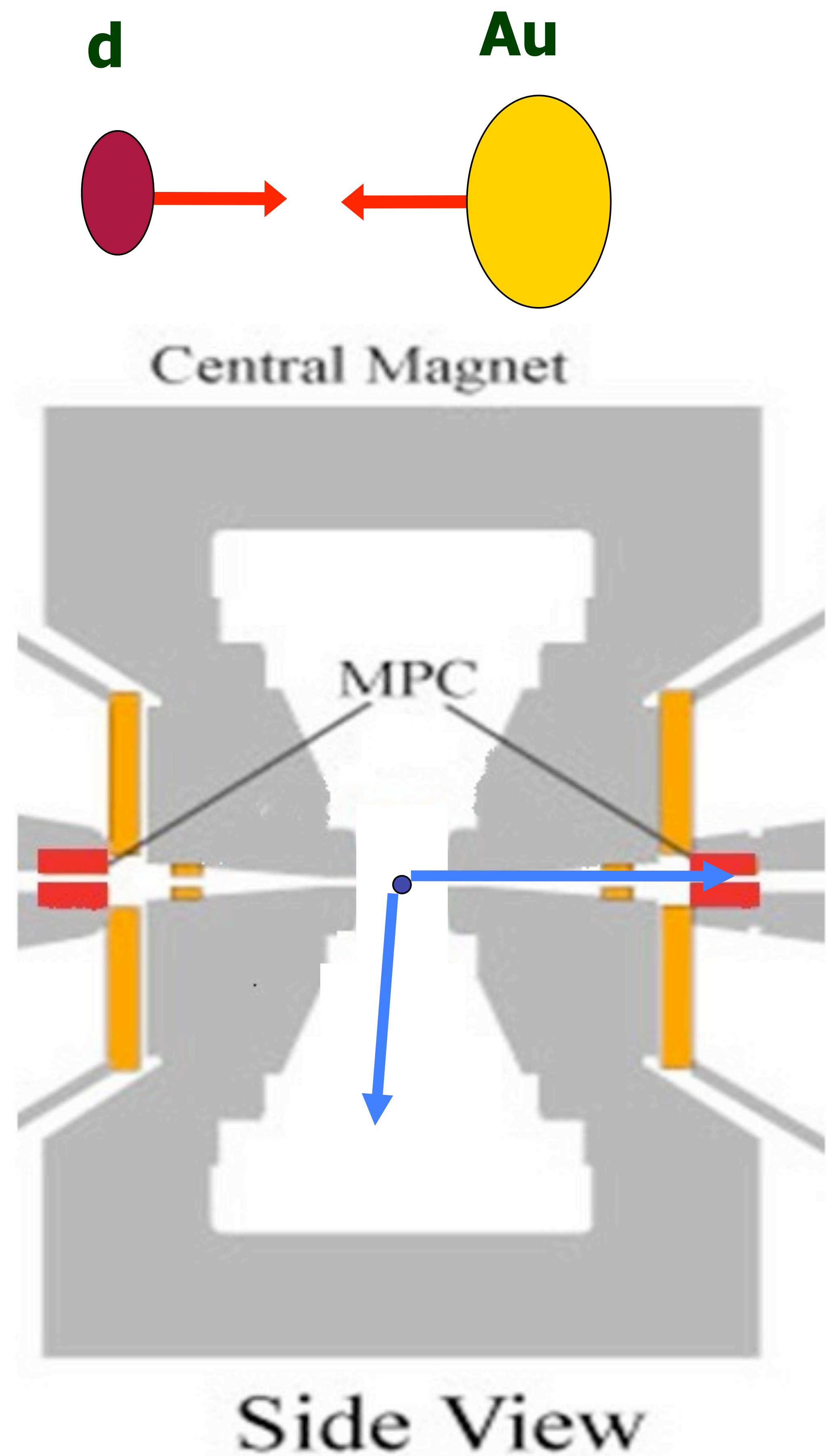
rapidity separated correlations

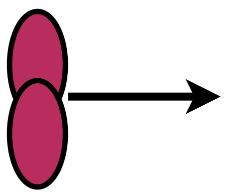
Muon Piston Calorimeters

both d-going & Au-going directions
$3 < |\eta| < 4$

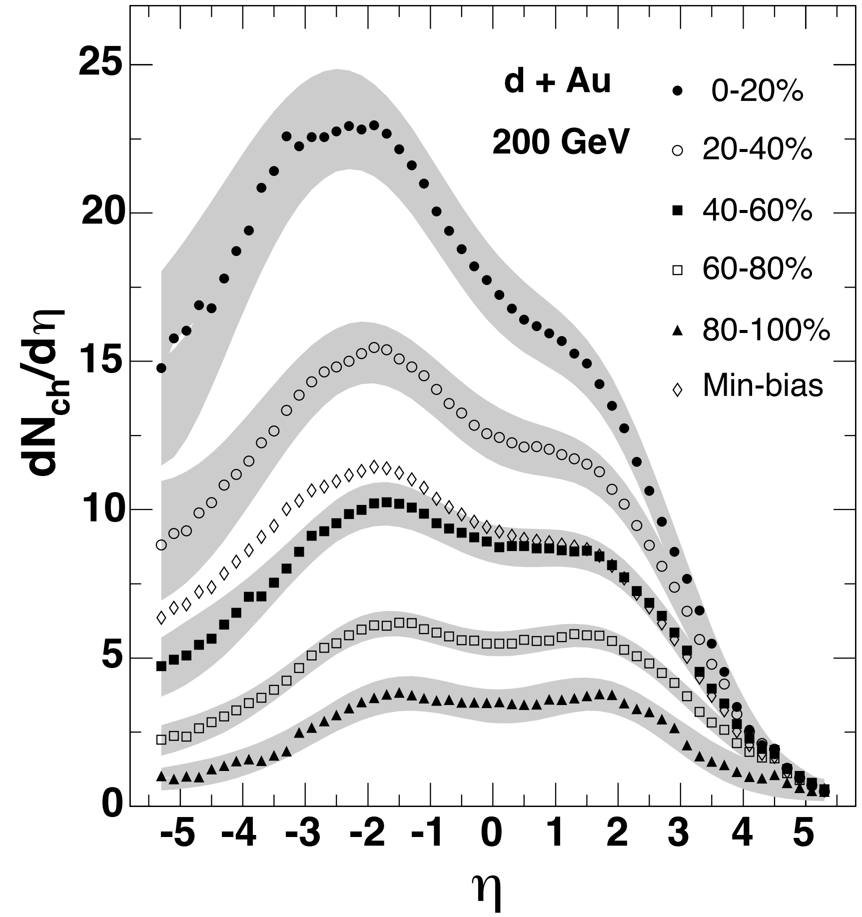


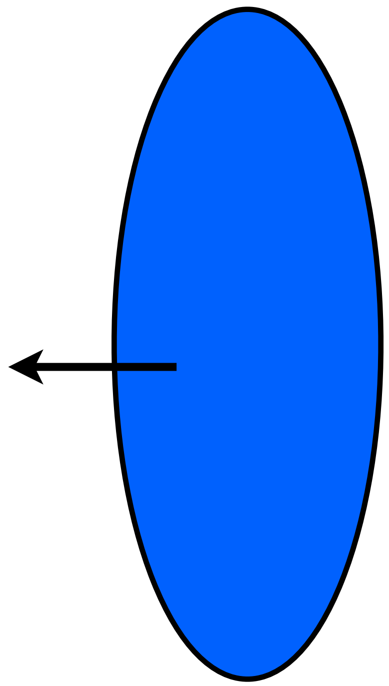


long range correlations in dAu

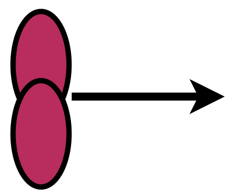


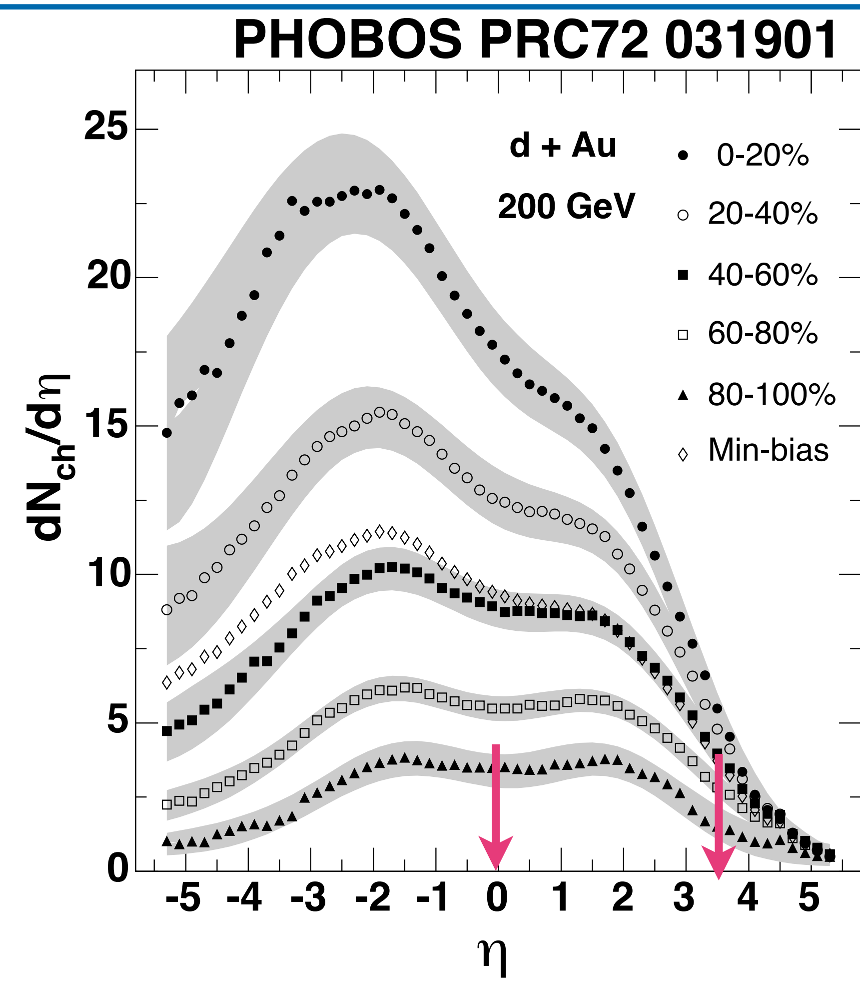
PHOBOS PRC72 031901

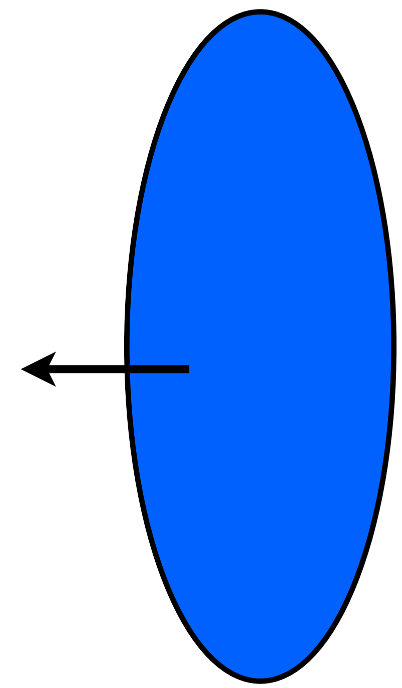


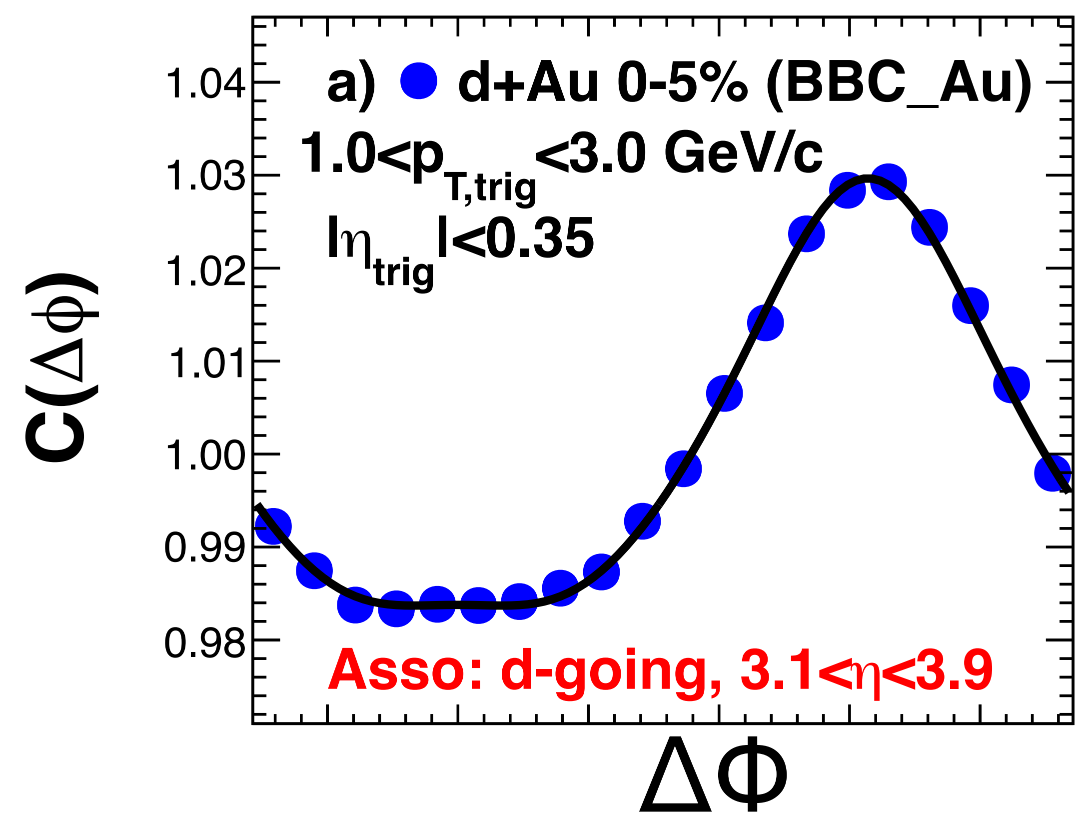


long range correlations in dAu

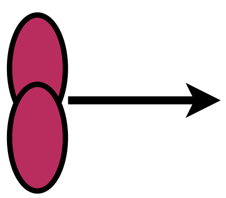


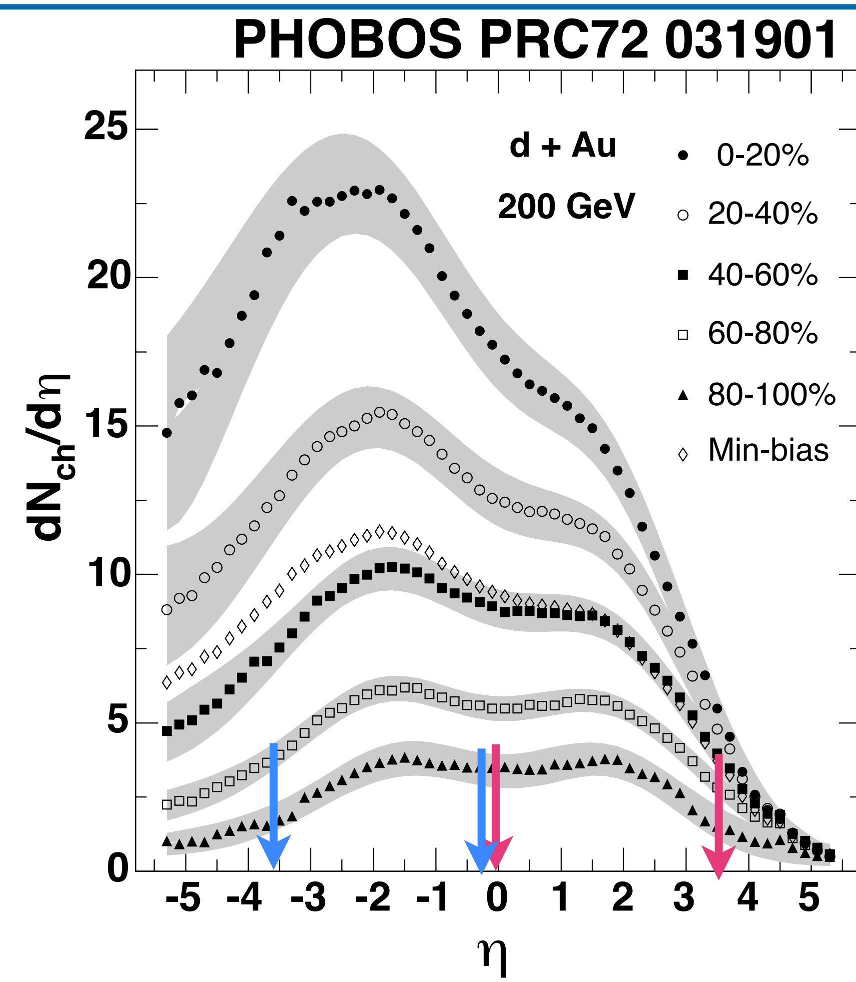


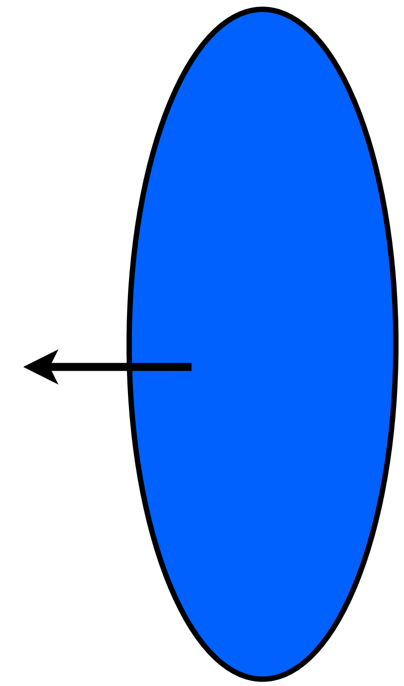


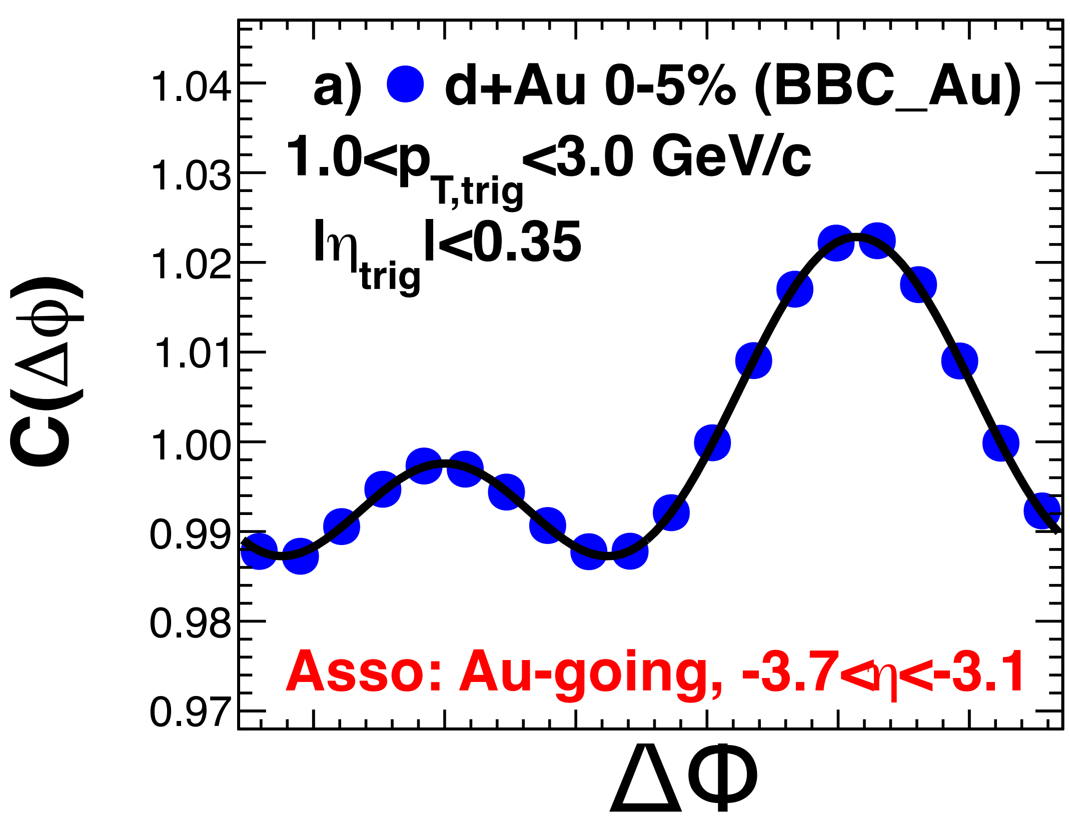


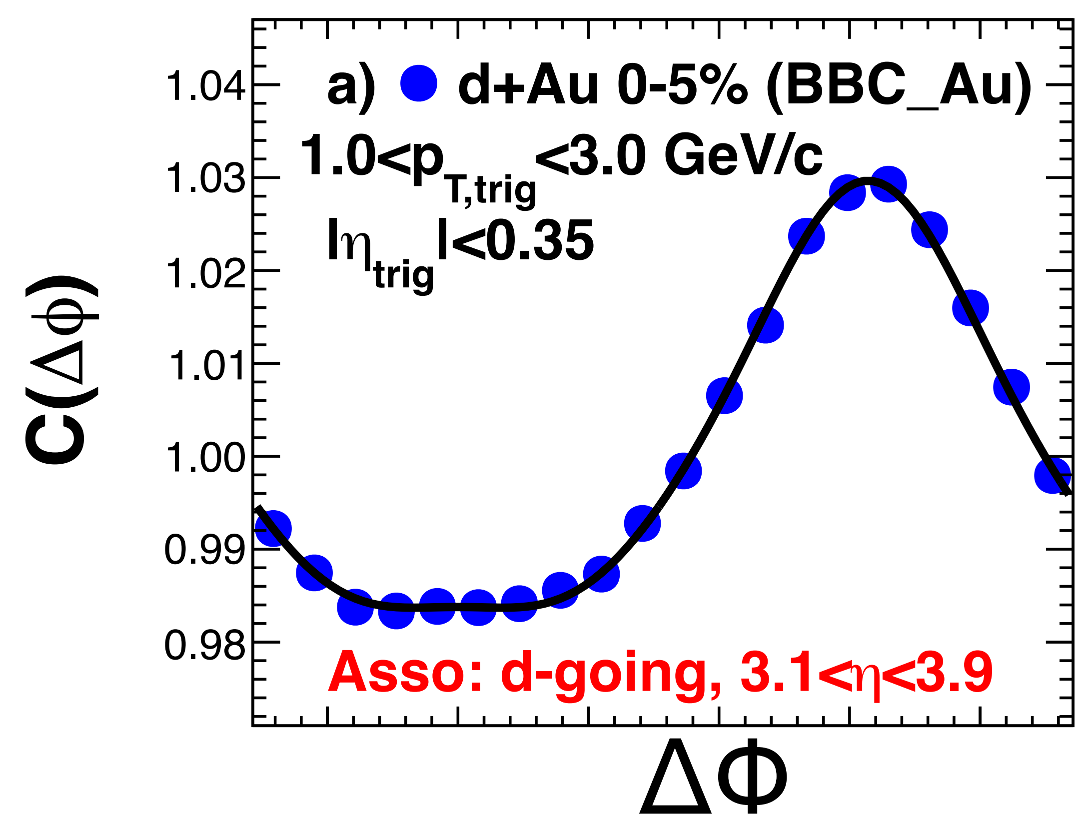
long range correlations in dAu



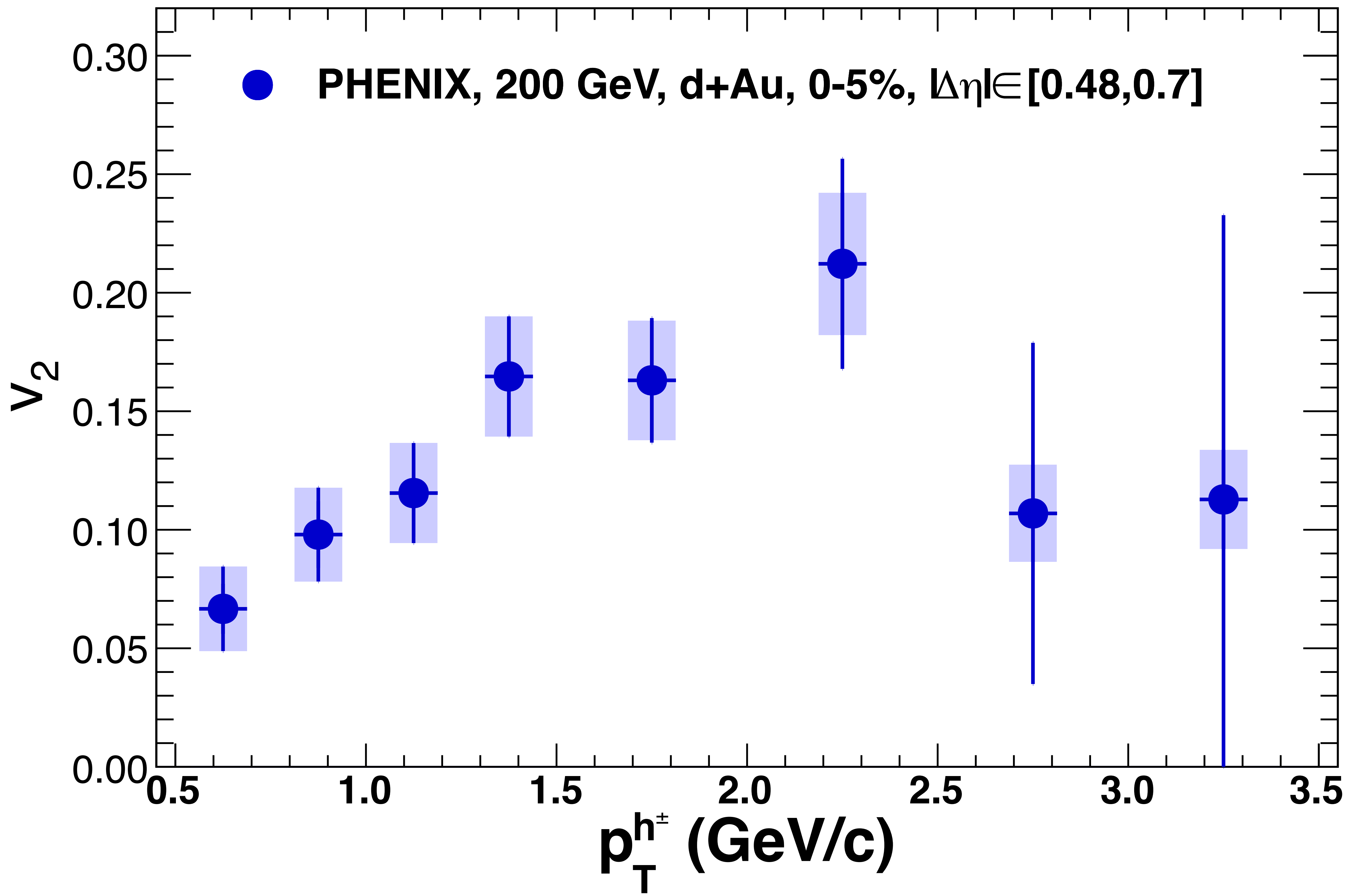






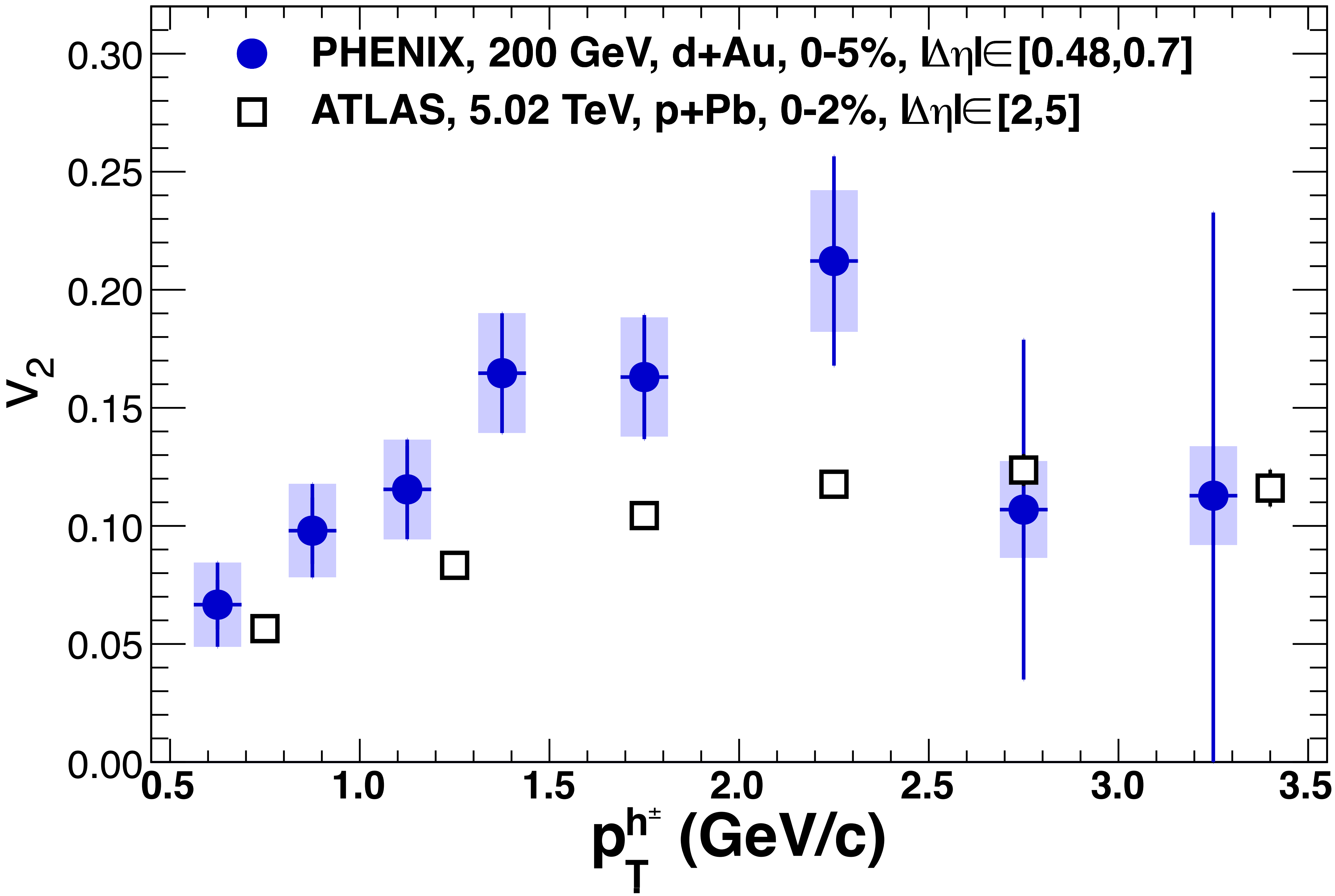


midrapidity v_2 results



PHENIX PRL 111 212301

midrapidity v_2 results



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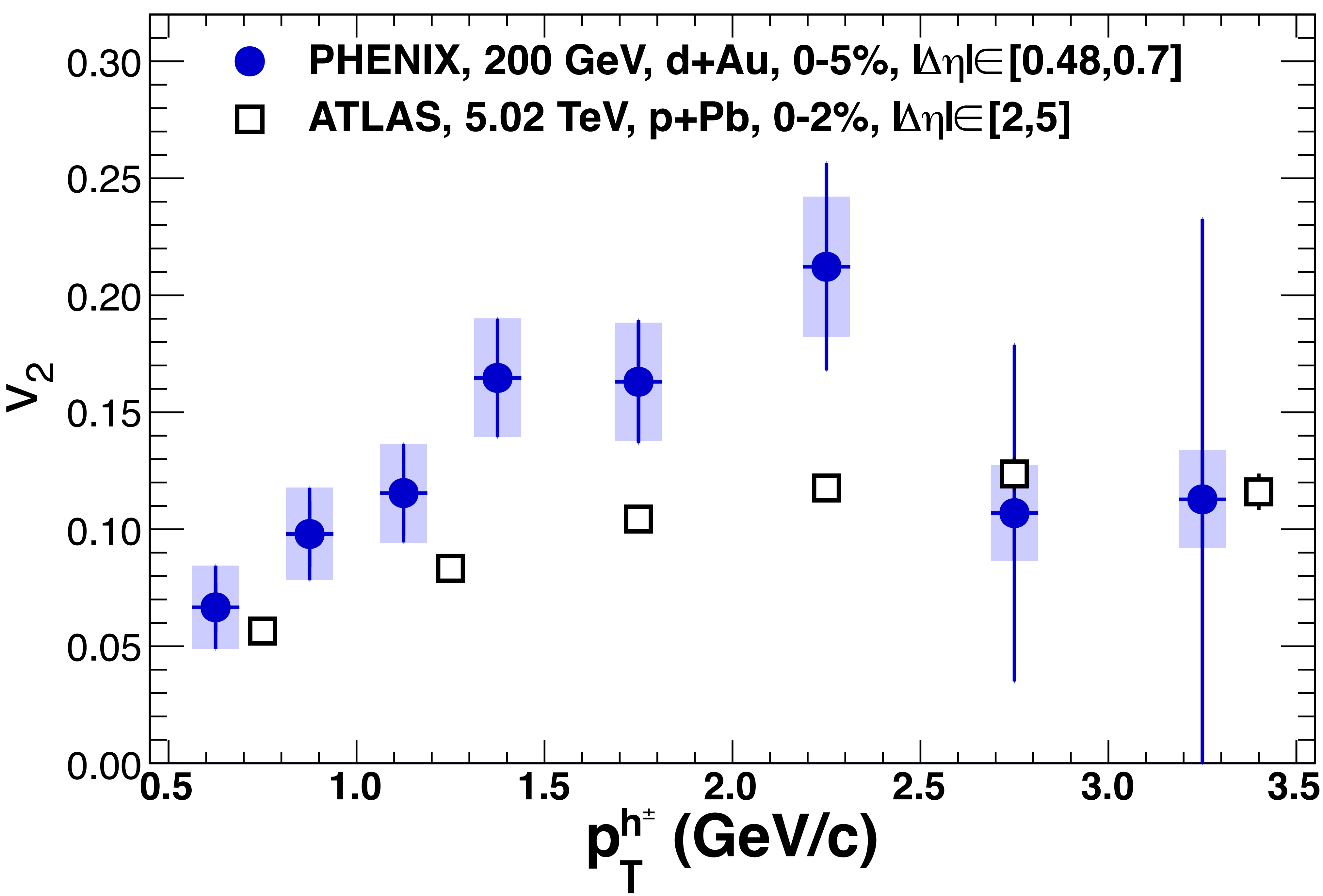
midrapidity v_2 results



larger v_2 observed at RHIC

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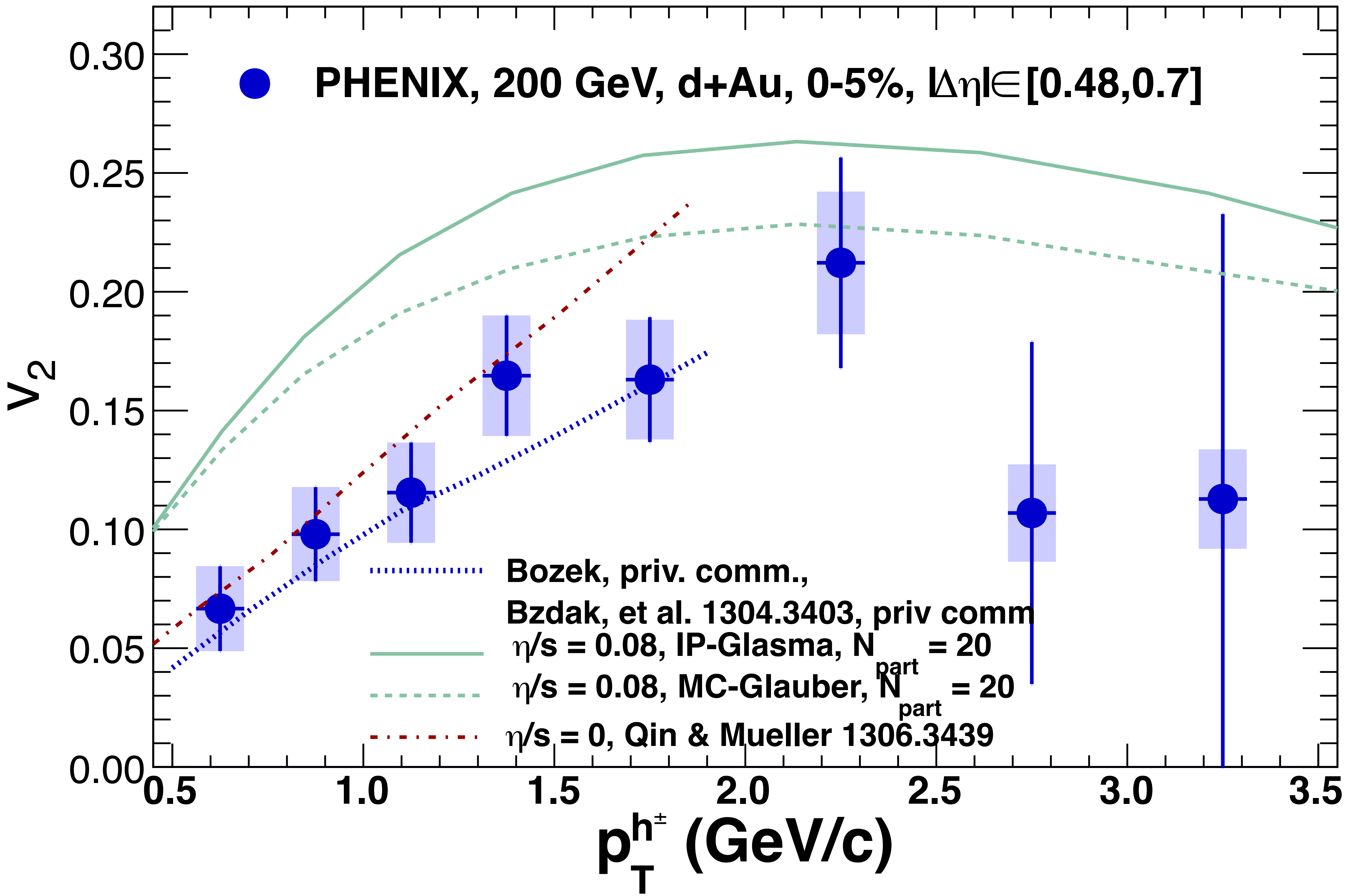
v_2 in dAu compared to hydro. calculations



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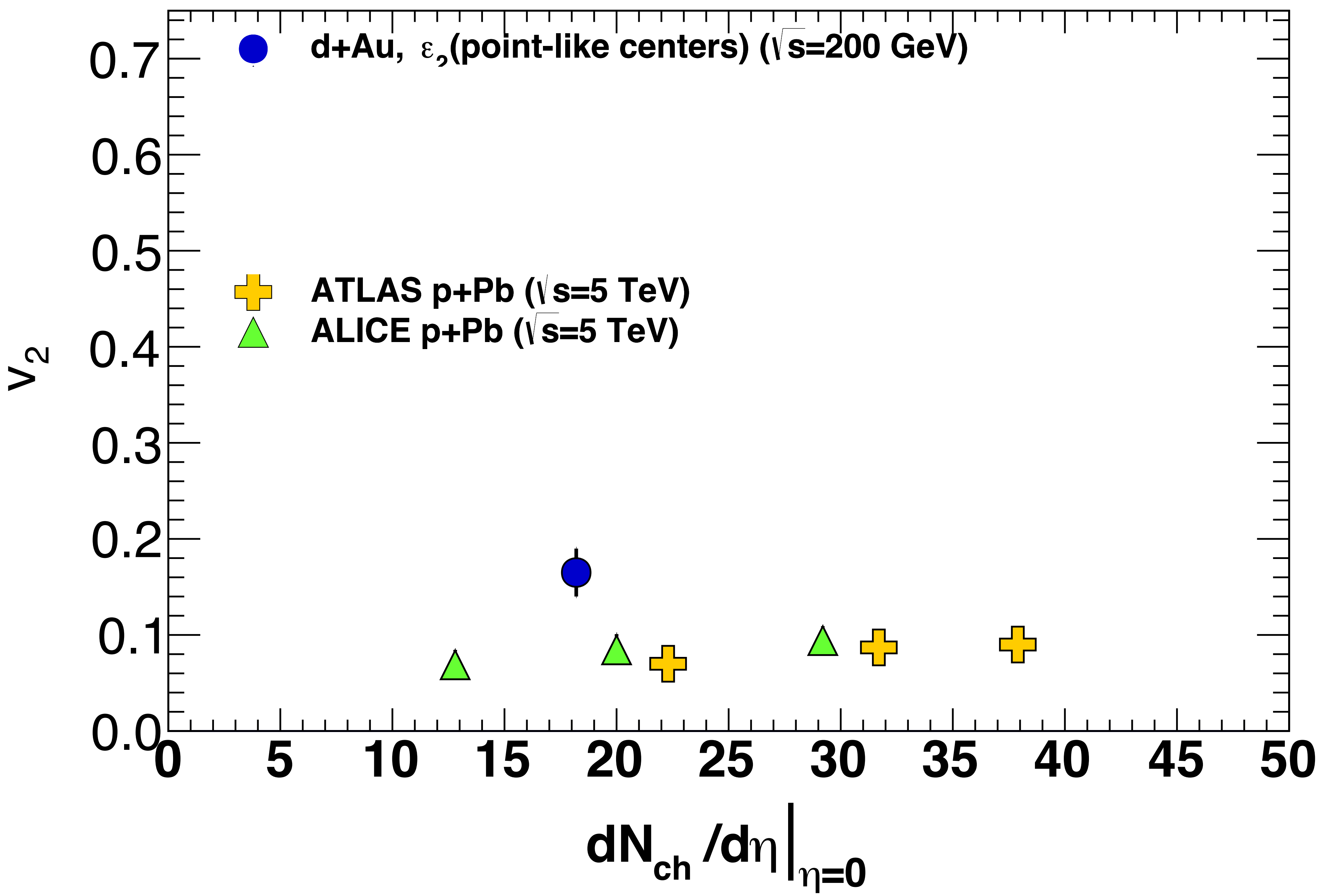
v_2 dAu & pPb



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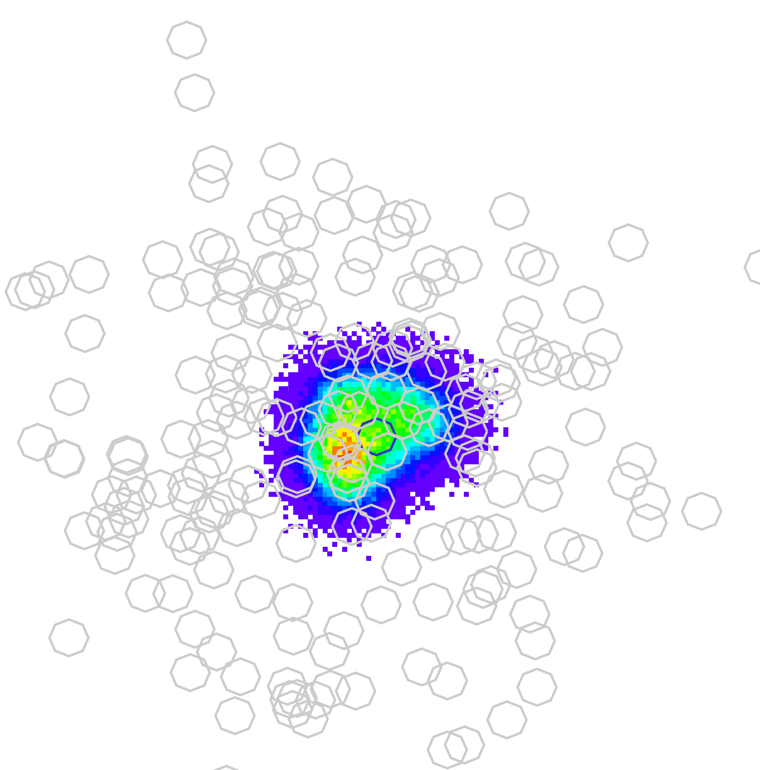
eccentricity

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

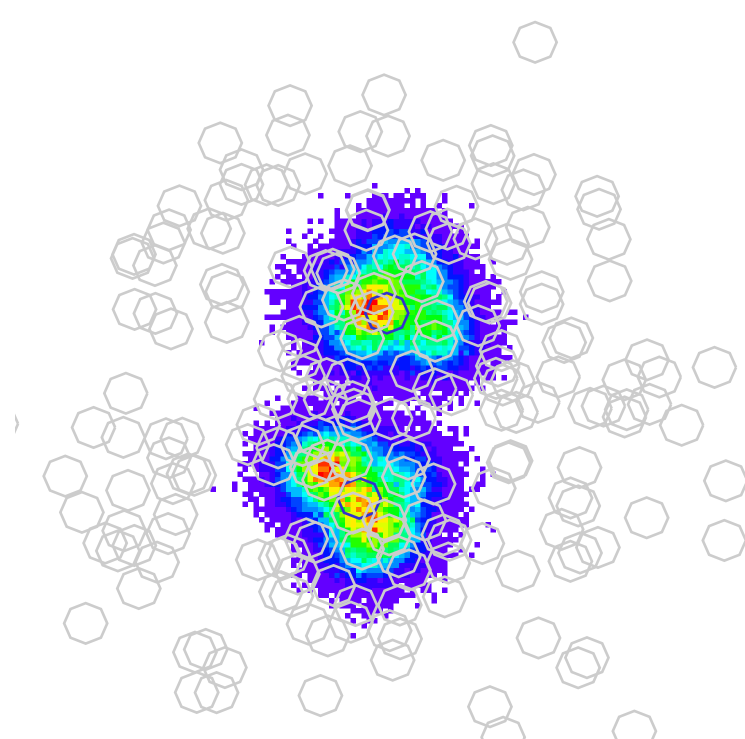
Glauber Monte Carlo used to generate single event initial energy density distributions

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

pA, small ε_2

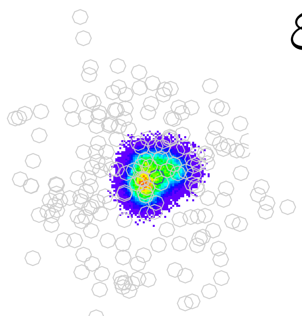


dA, large ε_2

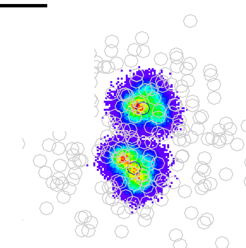


v_2 scaled by eccentricity, dAu & pPb

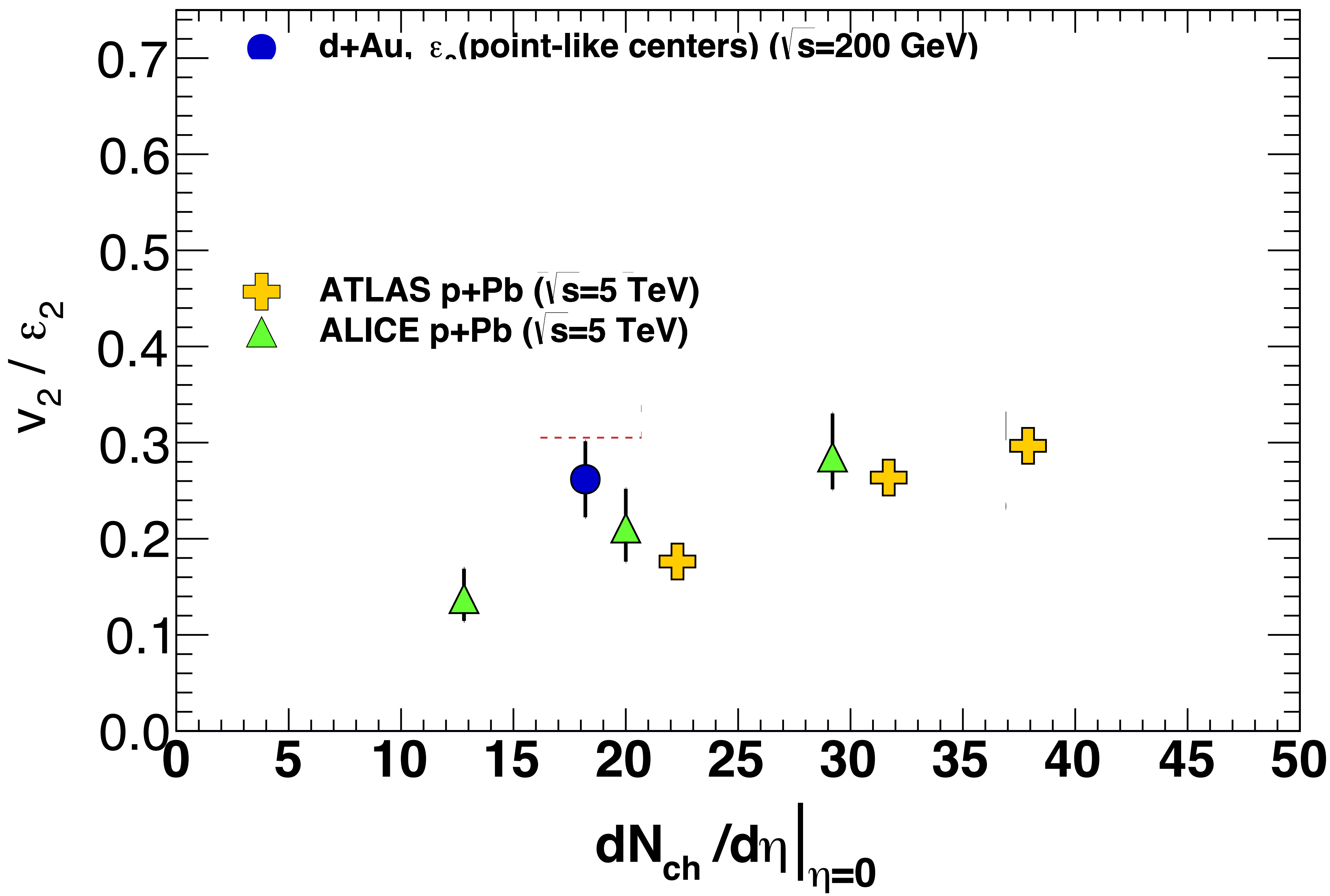
$$\varepsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \sin(n\phi)\rangle^2}}{\langle r^n \rangle}$$



pA, rounder, small ε_2

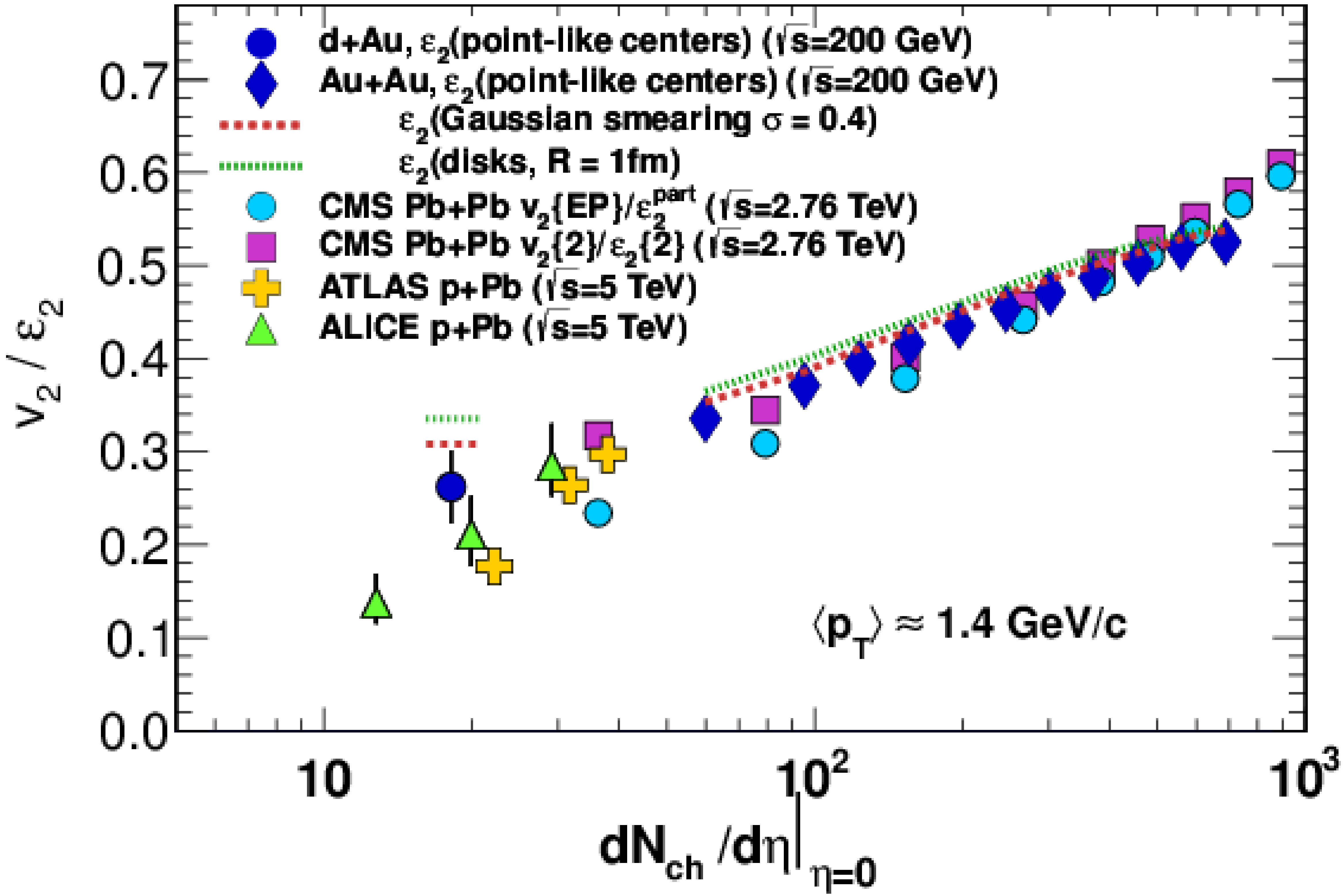


dA, elongated, large ε_2



PHENIX PRL 111 212301

dAu, pPb, AuAu & PbPb



single trend, AA data understood as initial geometry + hydrodynamics

$\varepsilon_3 \rightarrow v_3$?

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

no significant v3 in dAu collisions at PHENIX

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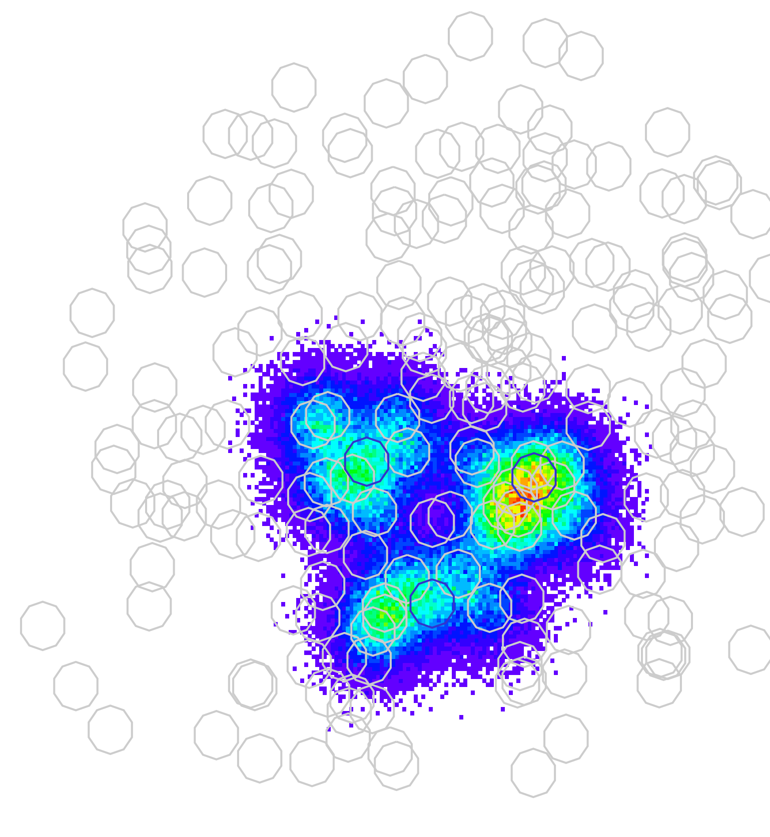
no significant v3 in dAu collisions at PHENIX

question: can we induce a v_3 with ^{3}He+Au collisions?



Tentative Run Schedule for RHIC

Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2013	• 510 GeV pol p+p	• Sea quark and gluon polarization	• upgraded pol'd source • STAR HFT test
2014	• 200 GeV Au+Au • 15 GeV Au+Au	• Heavy flavor flow, energy loss, thermalization, etc. • Quarkonium studies • QCD critical point search	• Electron lenses • 56 MHz SRF • full STAR HFT • STAR MTD
2015-2016	• p+p at 200 GeV • p+Au, d+Au, ^{3}He+Au at 200 GeV • High statistics Au+Au	• Extract η/s(T) + constrain initial quantum fluctuations • More heavy flavor studies • Sphaleron tests	• PHENIX MPC-EX • Coherent electron cooling test
2017	• No Run		• Electron cooling upgrade
2018-2019	• 5-20 GeV Au+Au (BES-2)	• Search for QCD critical point and deconfinement onset	• STAR ITPC upgrade
2020	• No Run		• sPHENIX installation
2021-2022	• Long 200 GeV Au+Au w/ upgraded detectors • p+p, p(d)+Au at 200 GeV	• Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism • Color screening for different QQ states	• sPHENIX
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B. Muller

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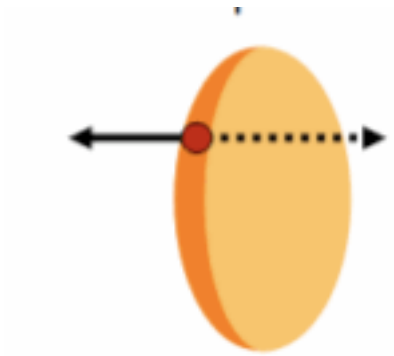
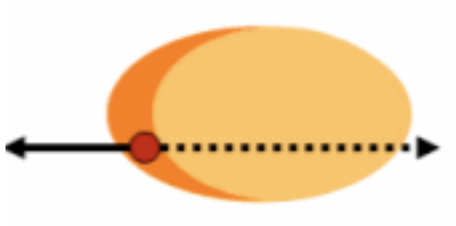
B. Muller

jets in dAu

AA collisions: quenching depends on L



less quenching

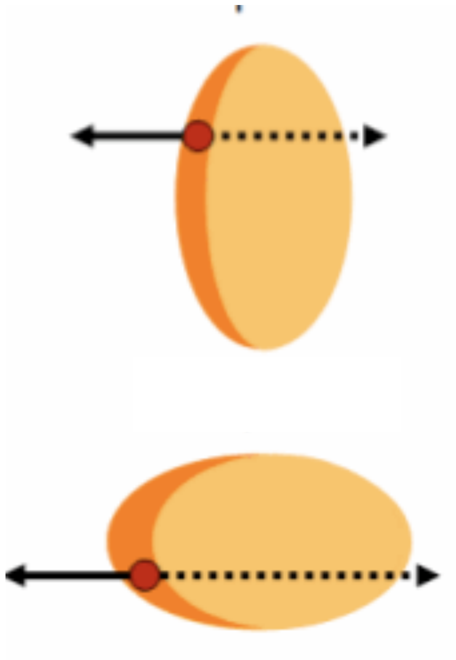


more quenching

jets in dAu

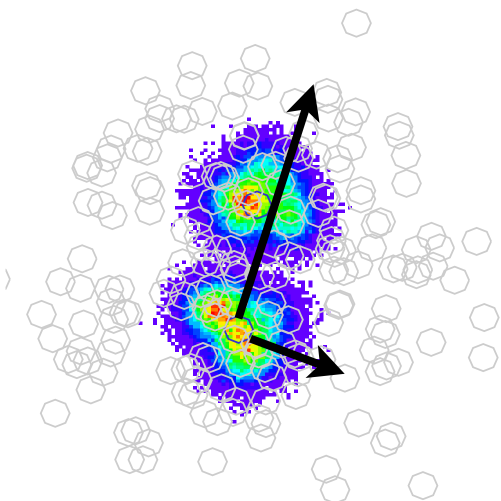
AA collisions: quenching depends on L

could something similar happen in dA?



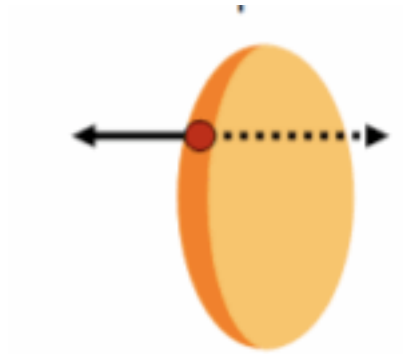
less quenching

more quenching

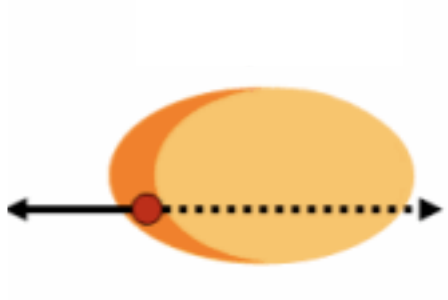


jets in dAu

AA collisions: quenching depends on L

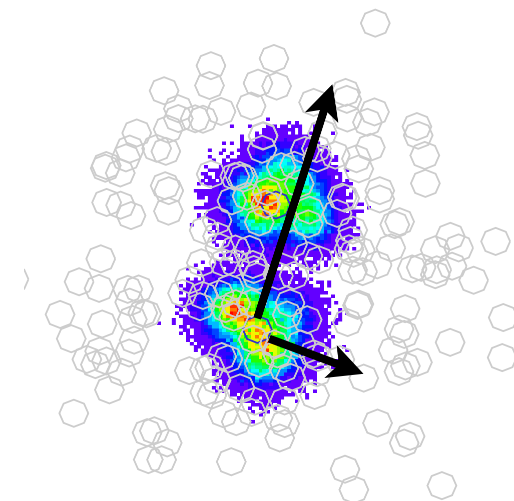


less quenching



more quenching

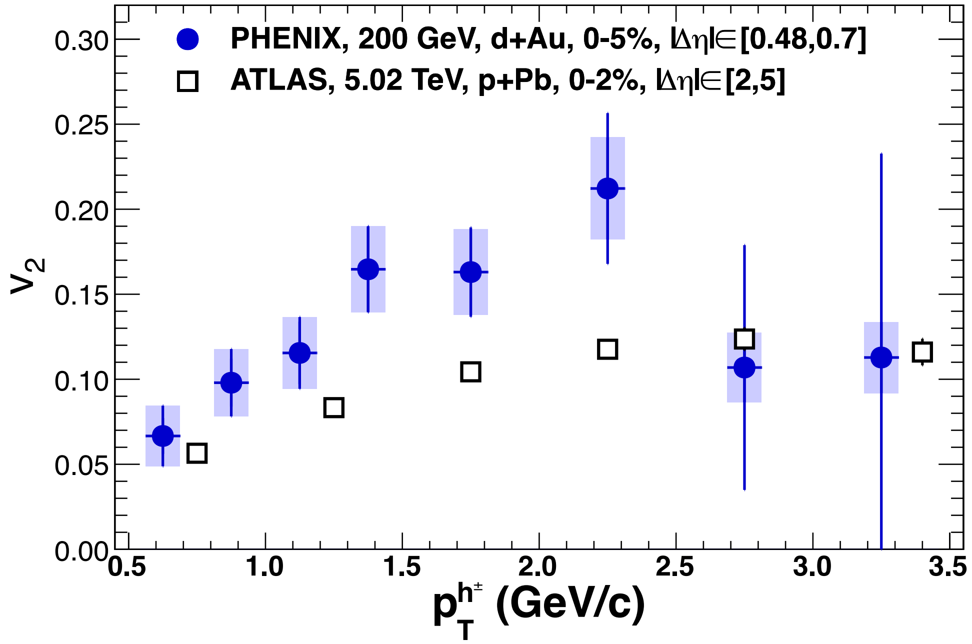
could something similar happen in dA?

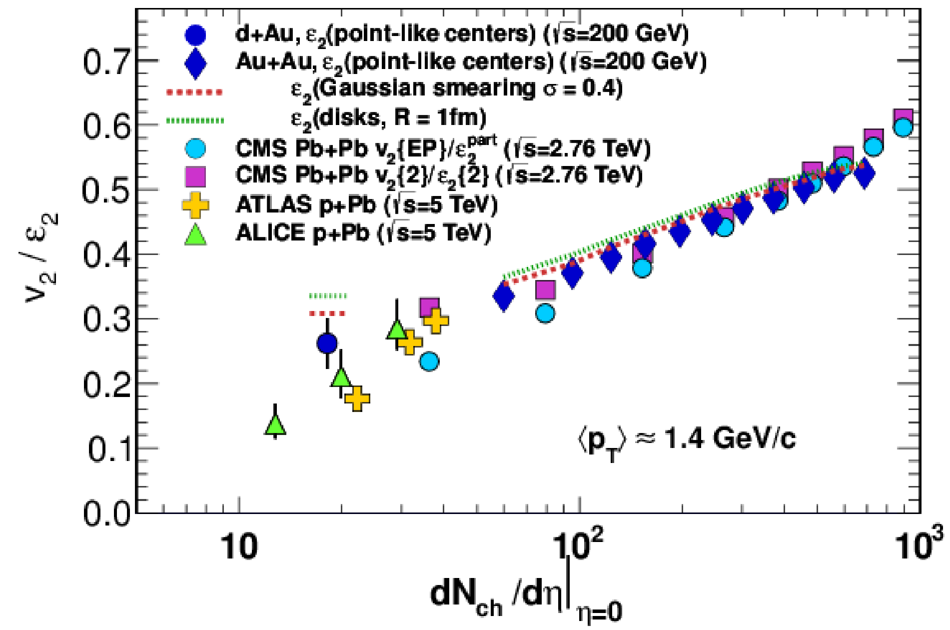


geometrical dependence might be observable **even though we know the overall level of quenching is small in dAu**

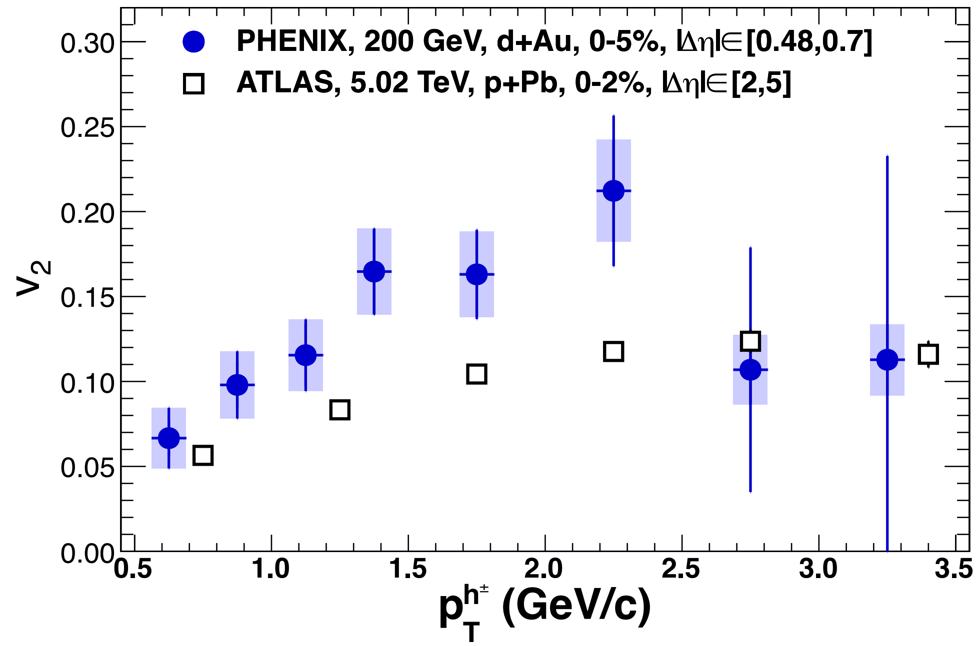
recent calculations for pPb (Zhang & Liao, 1311.5463), but any effect should be larger in dA than in pA

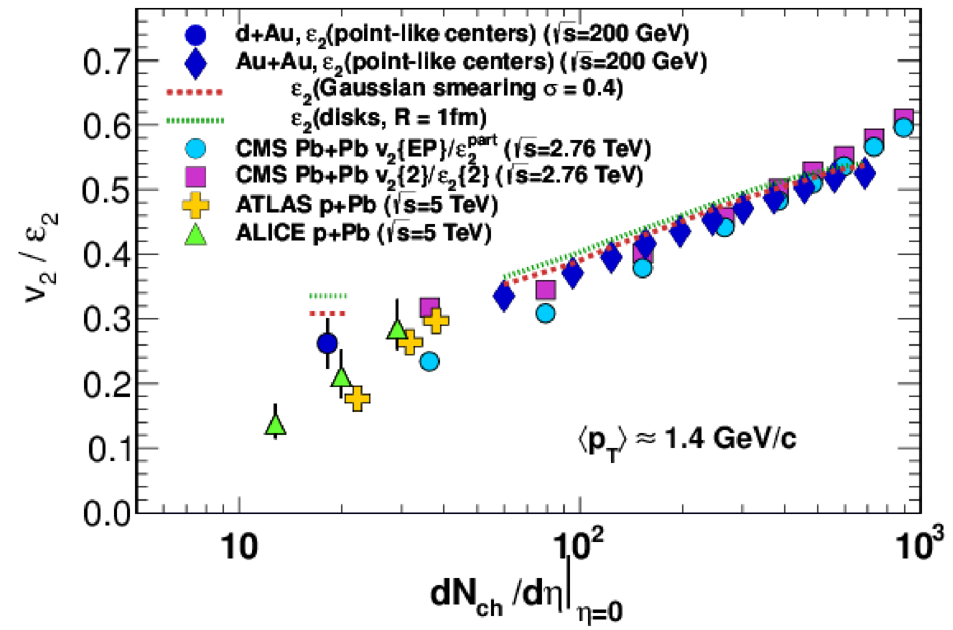
conclusions





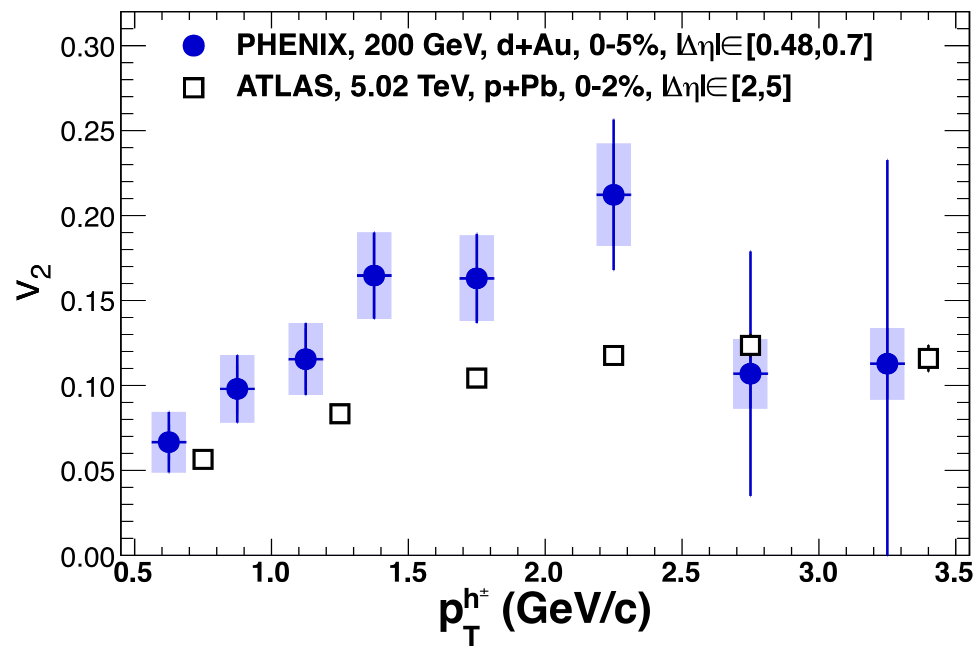
conclusions

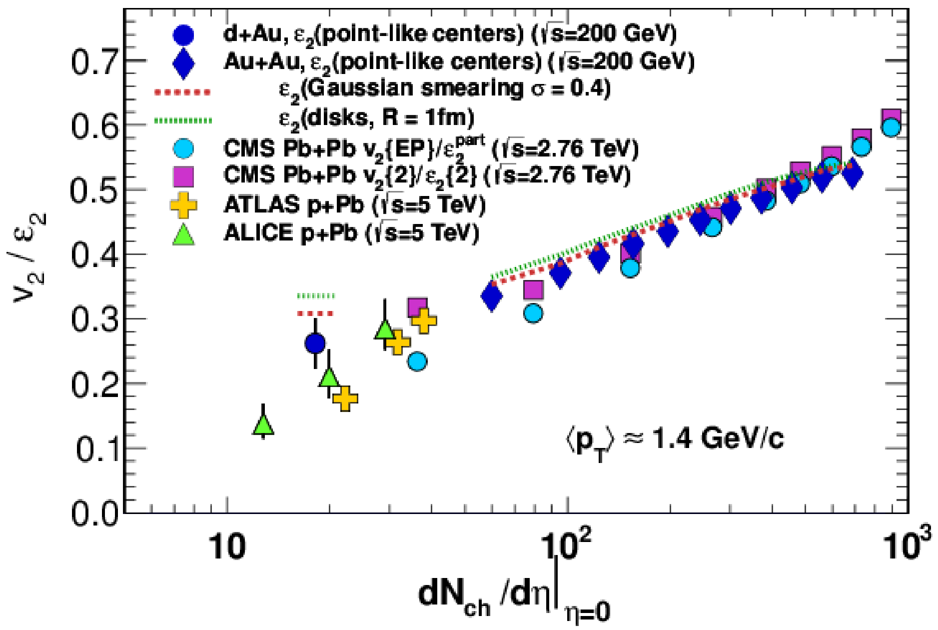




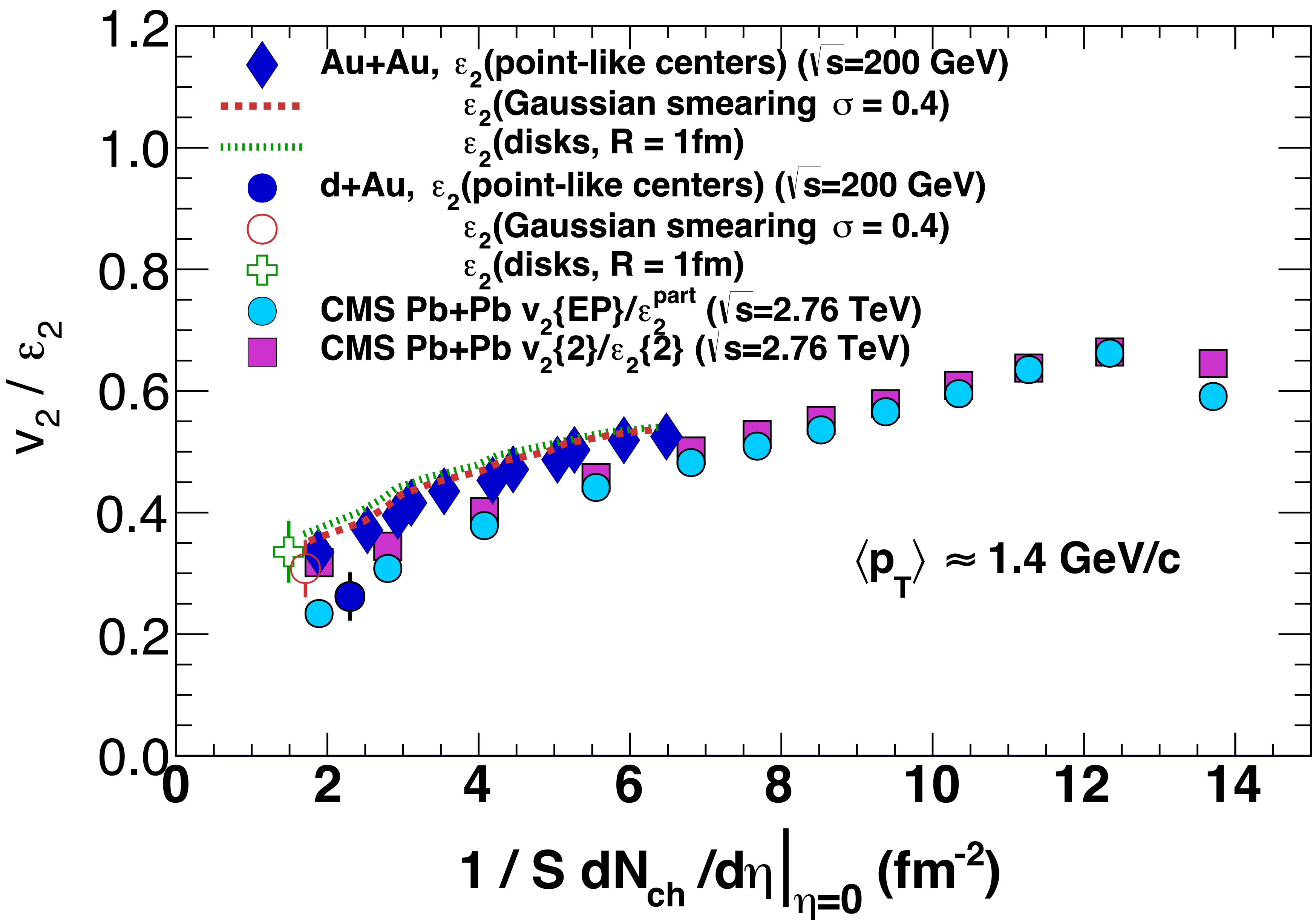
- two particle correlations have led to discovery of ridge in pp, pPb & dAu systems

conclusions





- two particle correlations have led to discovery of ridge in pp, pPb & dAu systems
- surprising scaling between eccentricity and v_2 from pPb & dAu to AuAu & PbPb
  - clear illustration of the synergy between RHIC & LHC
  - extremely fortuitous to have dAu data at RHIC
  - looking forward to pA, dA, ^{3}HeA at RHIC in 2015-16 will determine the connection between initial geometry and final state correlations

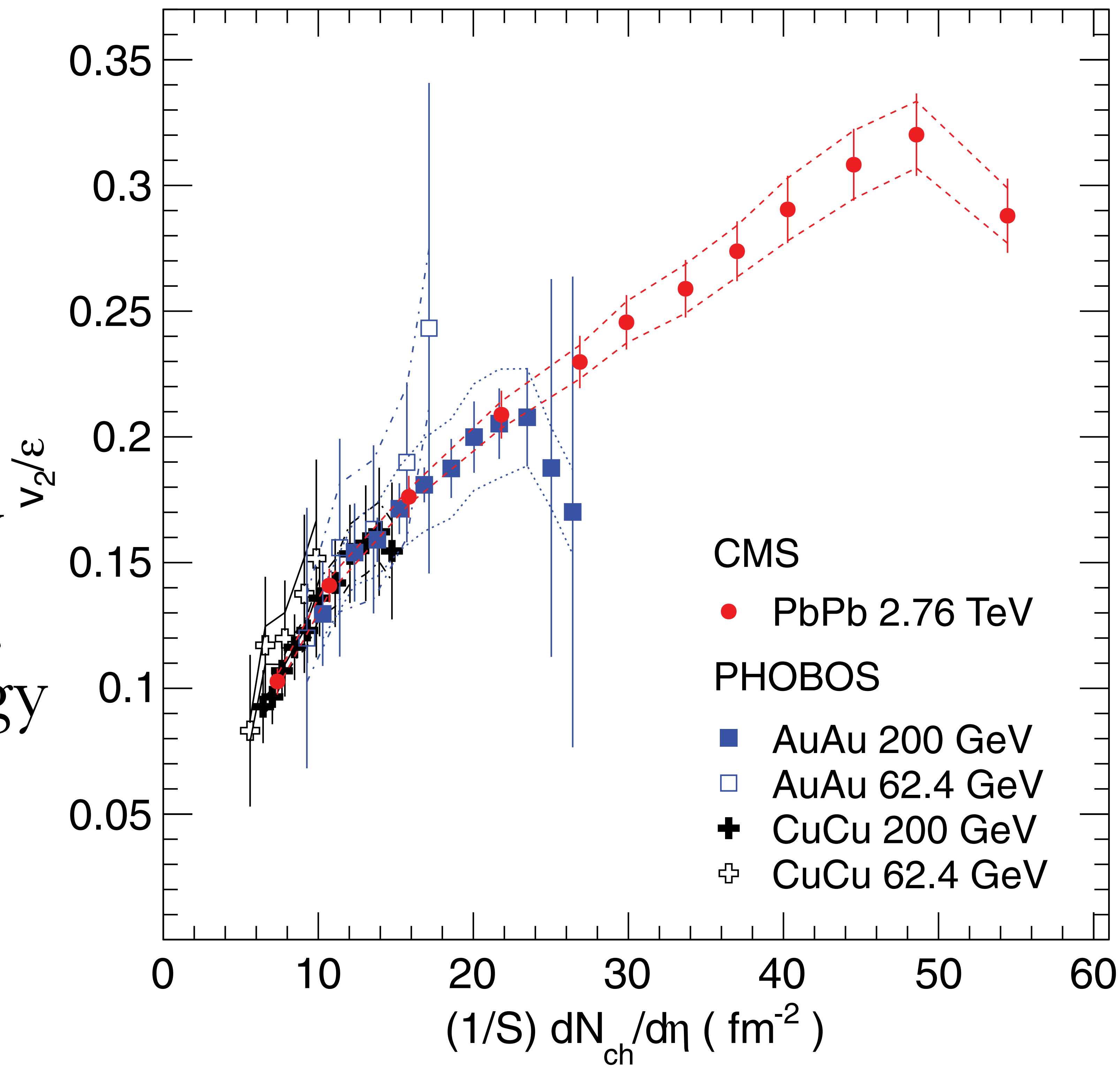


Au+Au, ε_2(point-like centers) ($\sqrt{s}$=200 GeV)
ε_2(Gaussian smearing σ = 0.4)
ε_2(disks, R = 1fm)
d+Au, ε_2(point-like centers) ($\sqrt{s}$=200 GeV)
ε_2(Gaussian smearing σ = 0.4)
ε_2(disks, R = 1fm)
CMS Pb+Pb $v_2\{EP\}/\varepsilon_2^{part}$ ($\sqrt{s}$=2.76 TeV)
CMS Pb+Pb $v_2\{2\}/\varepsilon_2\{2\}$ ($\sqrt{s}$=2.76 TeV)
$\langle p_T \rangle \approx$ 1.4 GeV/c
v_2 / ε_2
$1 / S\, dN_{ch} / d\eta|_{\eta=0}$ (fm^{-2})
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
2
4
6
8
10
12
14

scaling with overlap area?

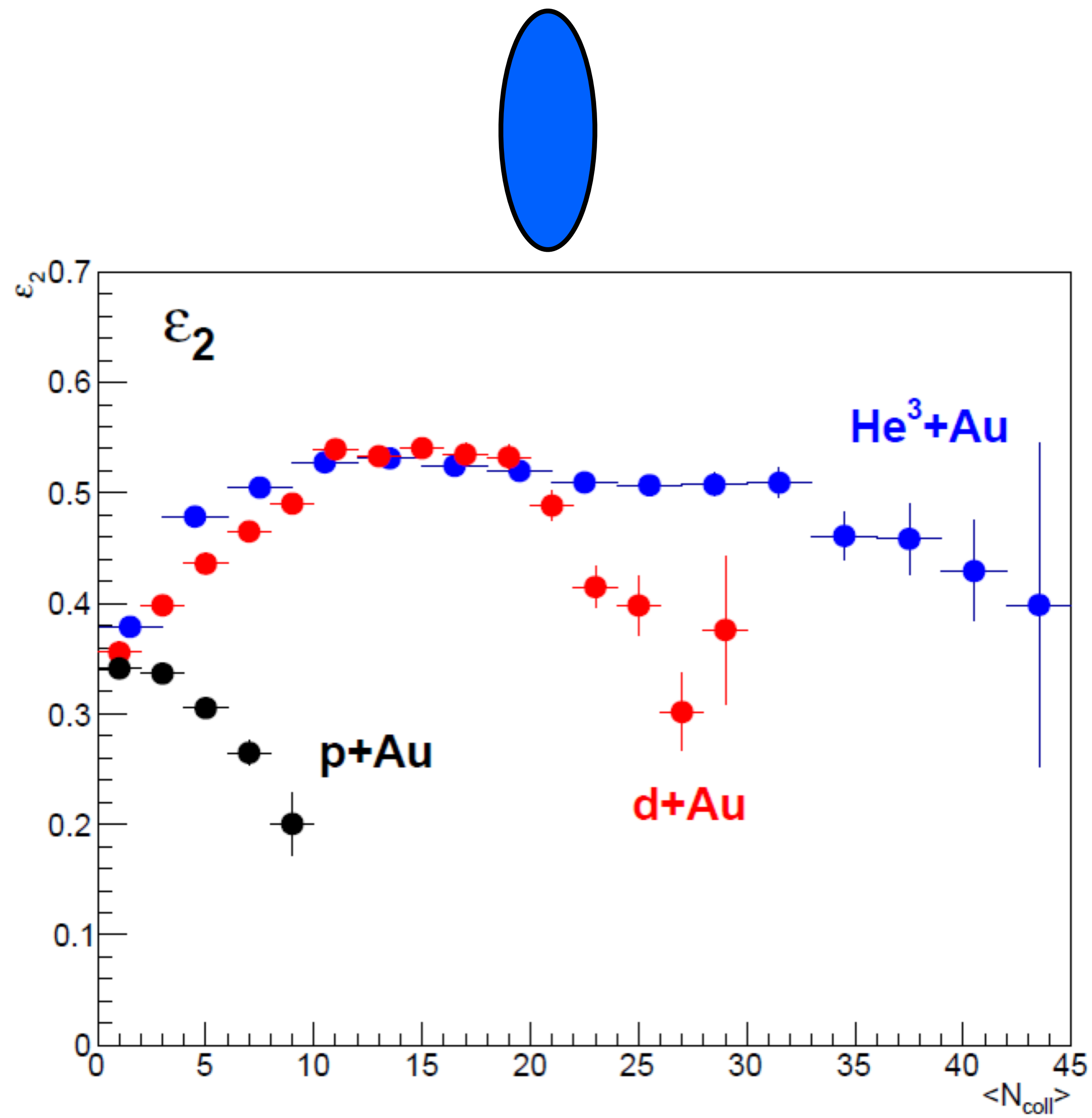
$$S = 4\pi\sqrt{\sigma_x^2\sigma_y^2 - \sigma_{xy}^2}$$

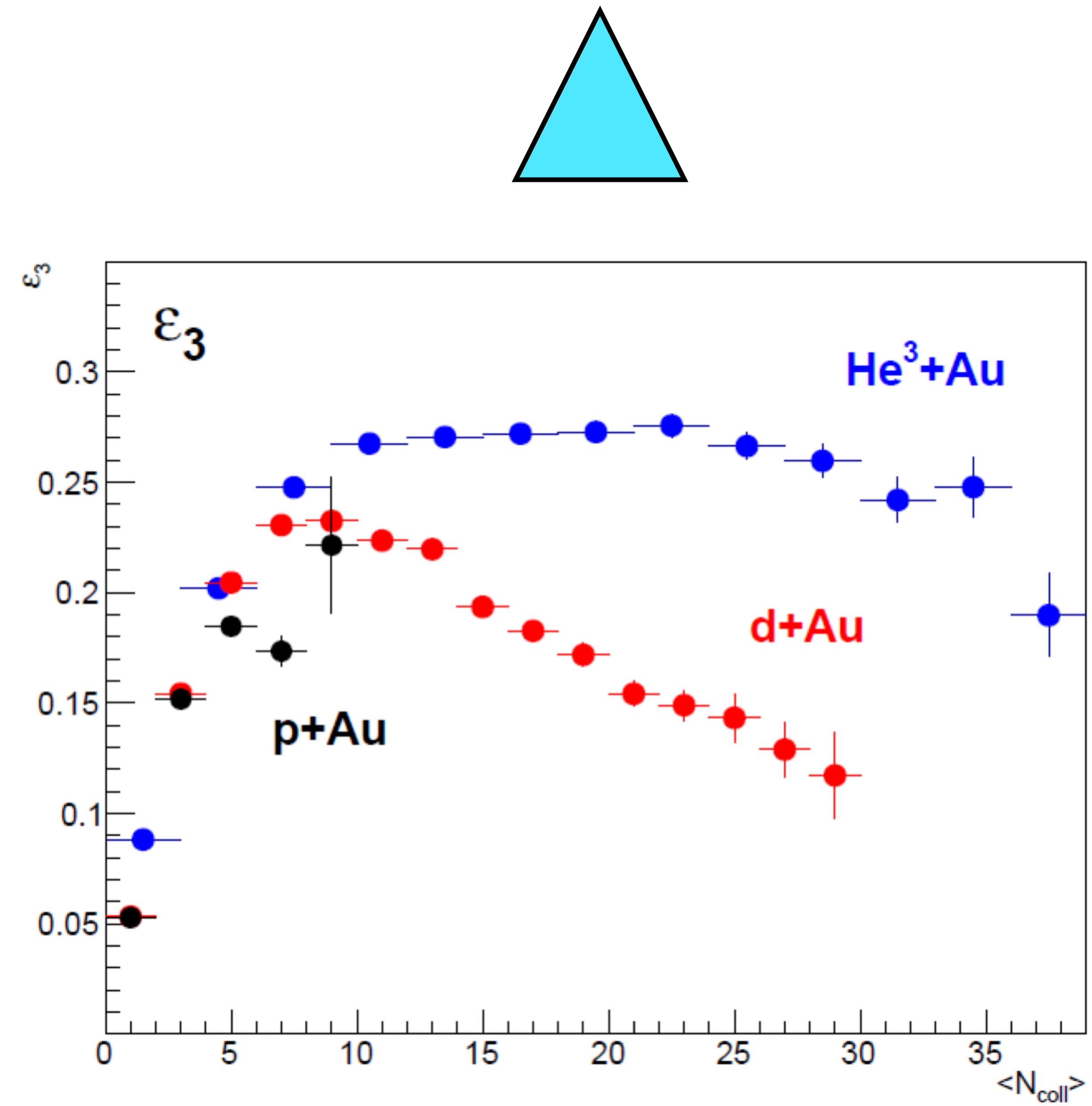
p_T integrated v_2 data found to scale in heavy ions with $1/S\ dN_{ch}/d\eta$ over wide collision energy



CMS PRC 87 014902

ε_2 & ε_3: (p, d, ^{3}He) + A

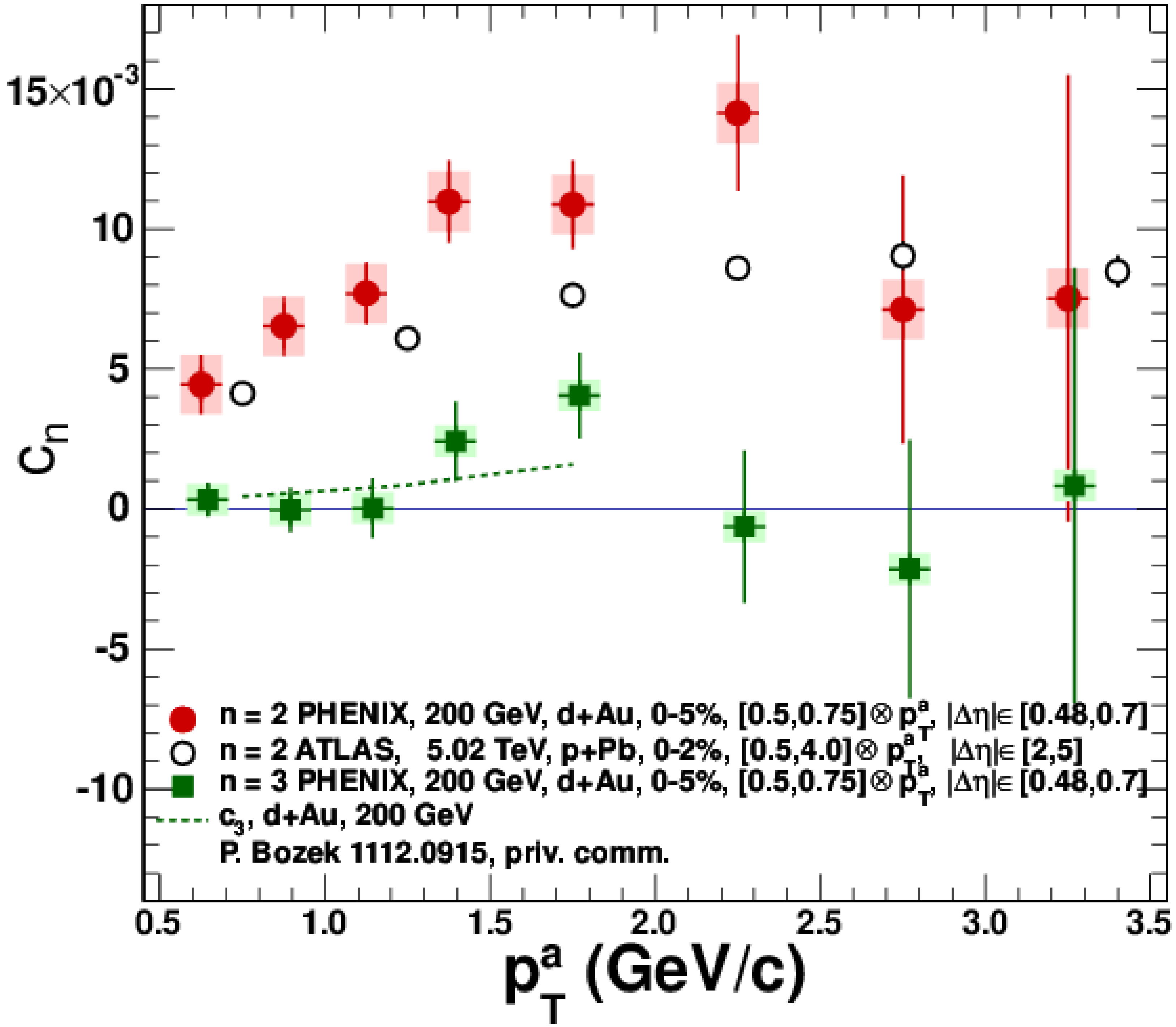




$$\varepsilon_2 = \frac{\sqrt{\langle r^2\cos(2\phi_{\rm part})\rangle^2 + \langle r^2\sin(2\phi_{\rm part})\rangle^2}}{\langle r^2\rangle}$$

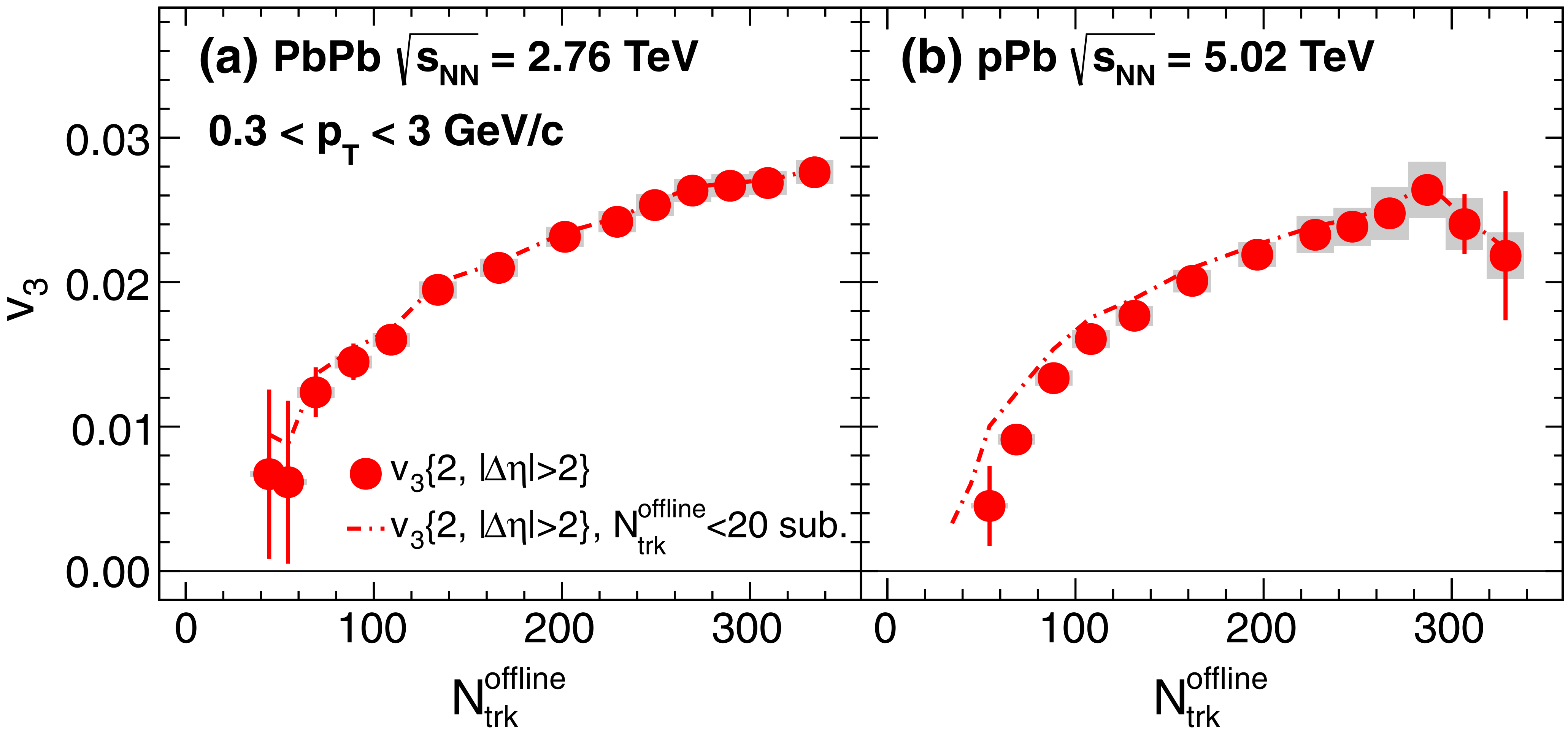
$$\varepsilon_3 \equiv \frac{\sqrt{\langle r^2\cos(3\phi_{\rm part})\rangle^2 + \langle r^2\sin(3\phi_{\rm part})\rangle^2}}{\langle r^2\rangle}$$

v_3 at RHIC?



no evidence for significant v3, consistent with hydro expectations

PHENIX: 1303.1794


(a) PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
0.3 < p_T < 3 GeV/c
(b) pPb $\sqrt{s_{NN}}$ = 5.02 TeV
v_3
0.03
0.02
0.01
0.00
0
100
200
300
$N_{trk}^{offline}$
$v_3\{2, |\Delta\eta|>2\}$
$v_3\{2, |\Delta\eta|>2\}$, $N_{trk}^{offline}$<20 sub.

remaining jet effects?

issue: short range effects from centrality dependent jet modifications could modify near side correlations within small $|\Delta\eta|$

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issue: short range effects from centrality dependent jet modifications could modify near side correlations within small $|\Delta\eta|$

- vary the minimum $|\Delta\eta|$ cut from 0.36 to 0.60
- look at the charge sign dependence:
    - jet correlations are enhanced for opposite sign pairs and suppressed for same sign pairs
- further studying with event generators

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issue: short range effects from centrality dependent jet modifications could modify near side correlations within small $|\Delta\eta|$

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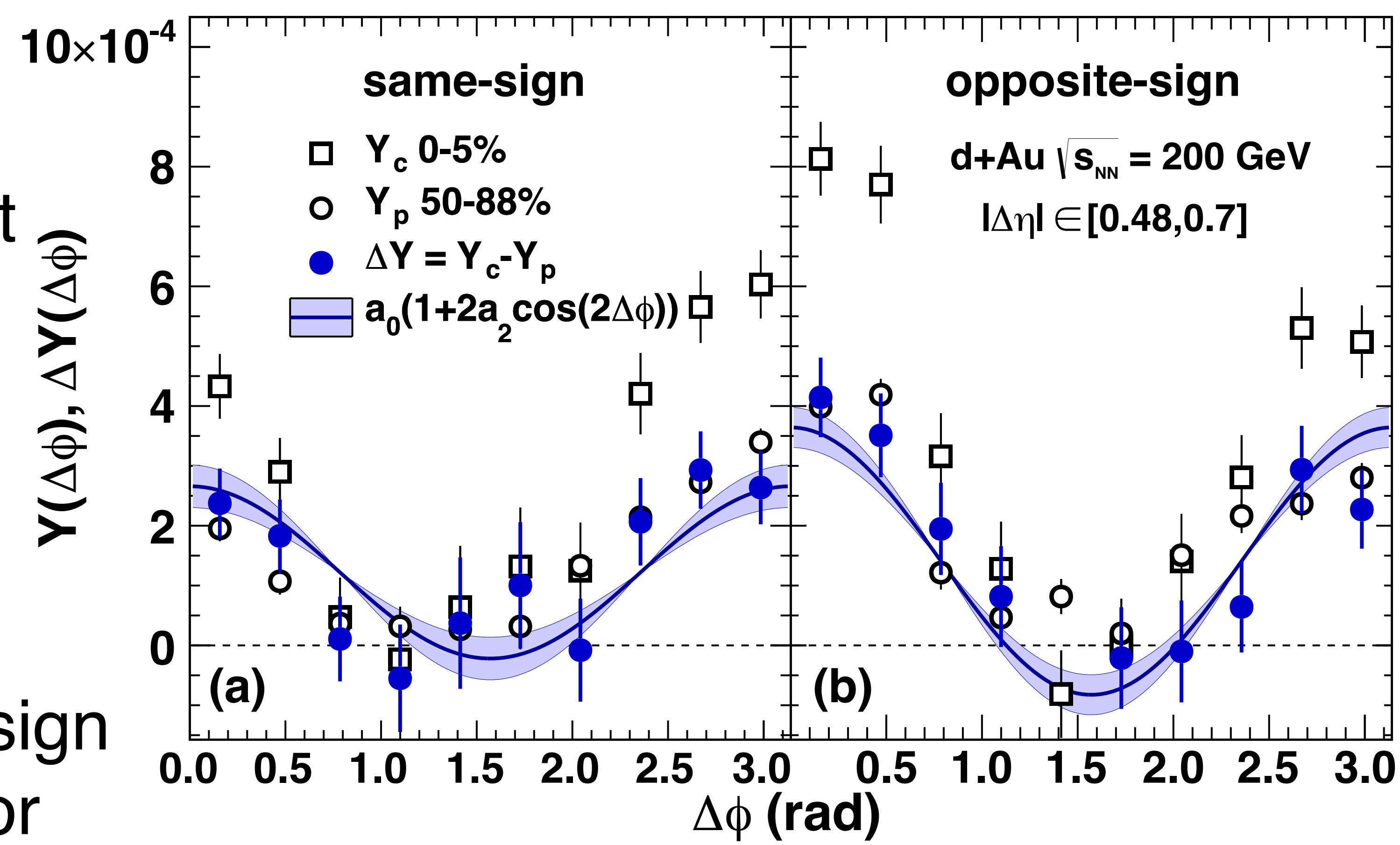

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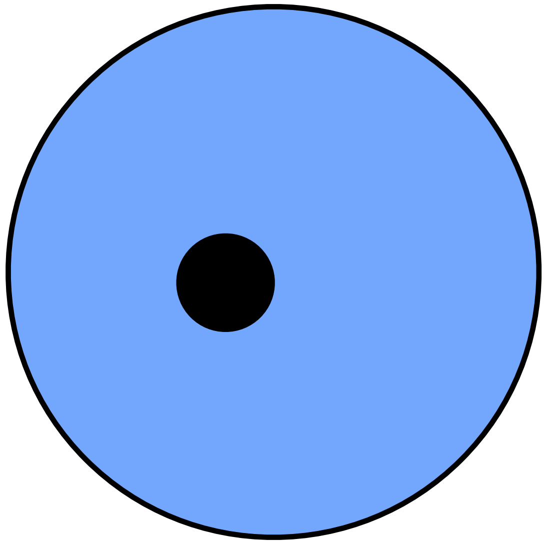
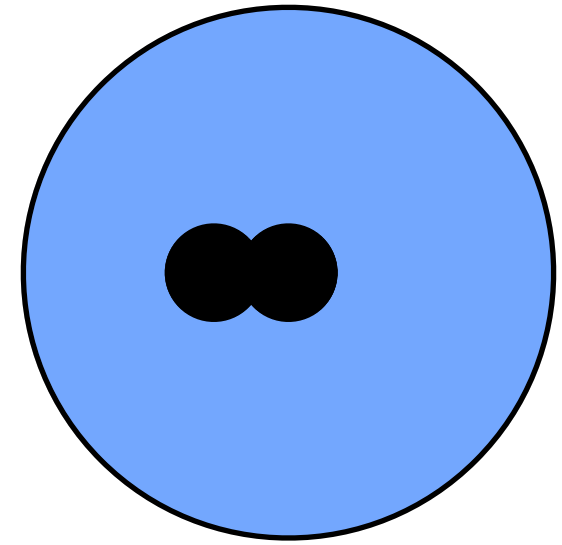
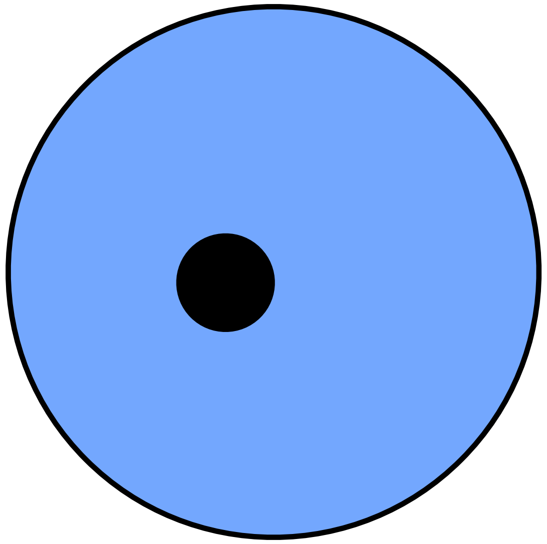
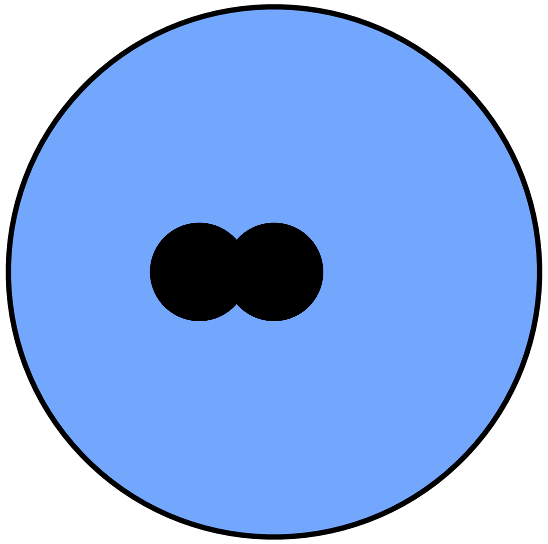
pPb vs dAu

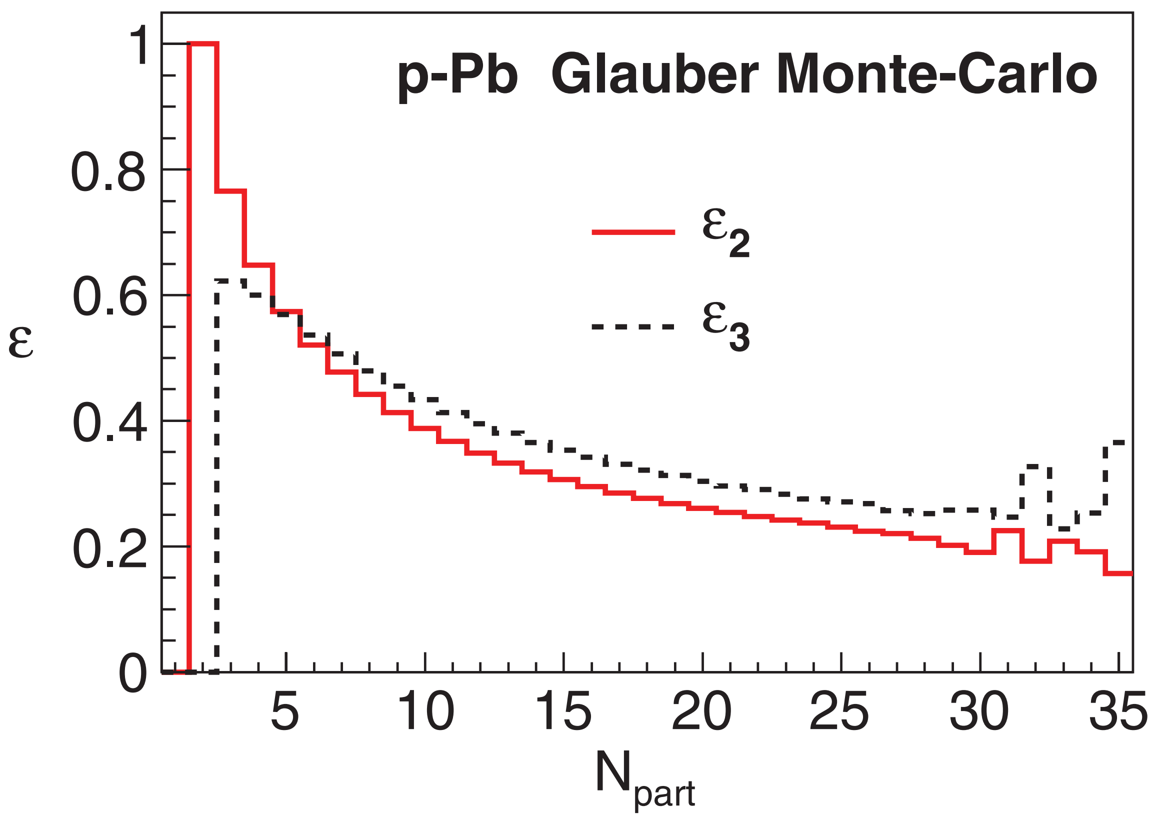


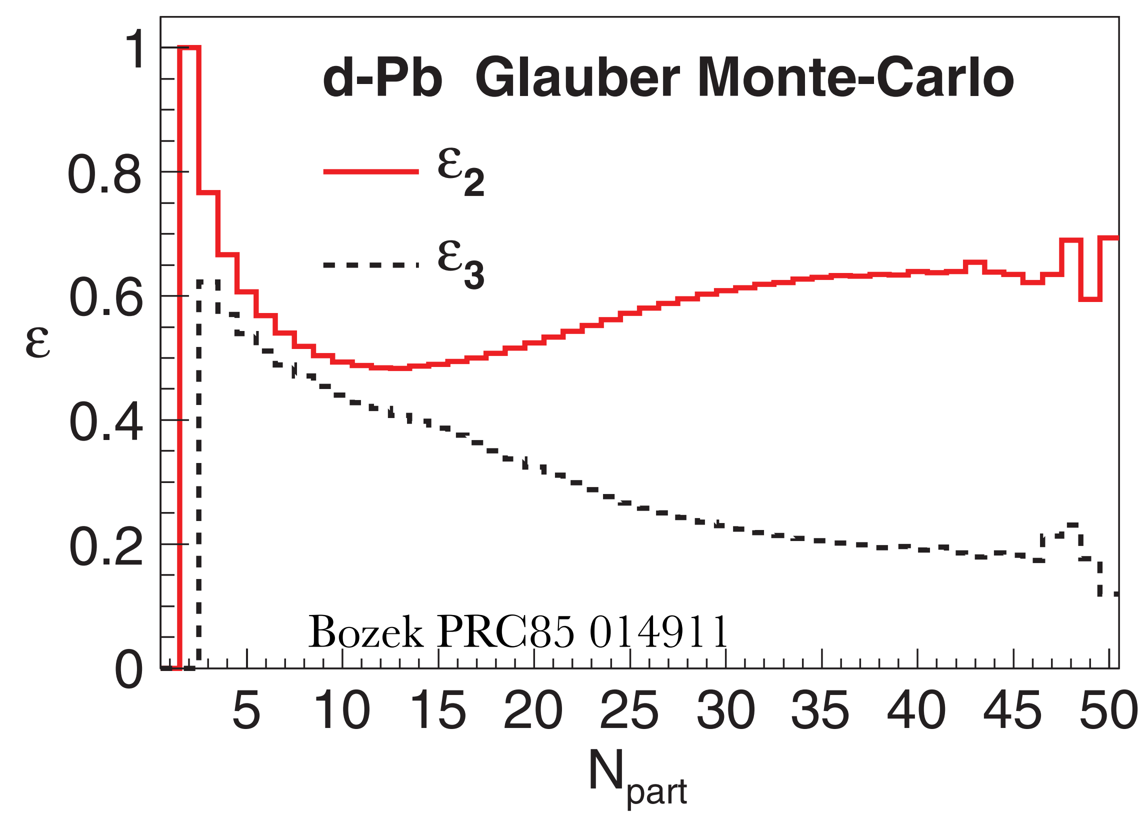


pPb vs dAu

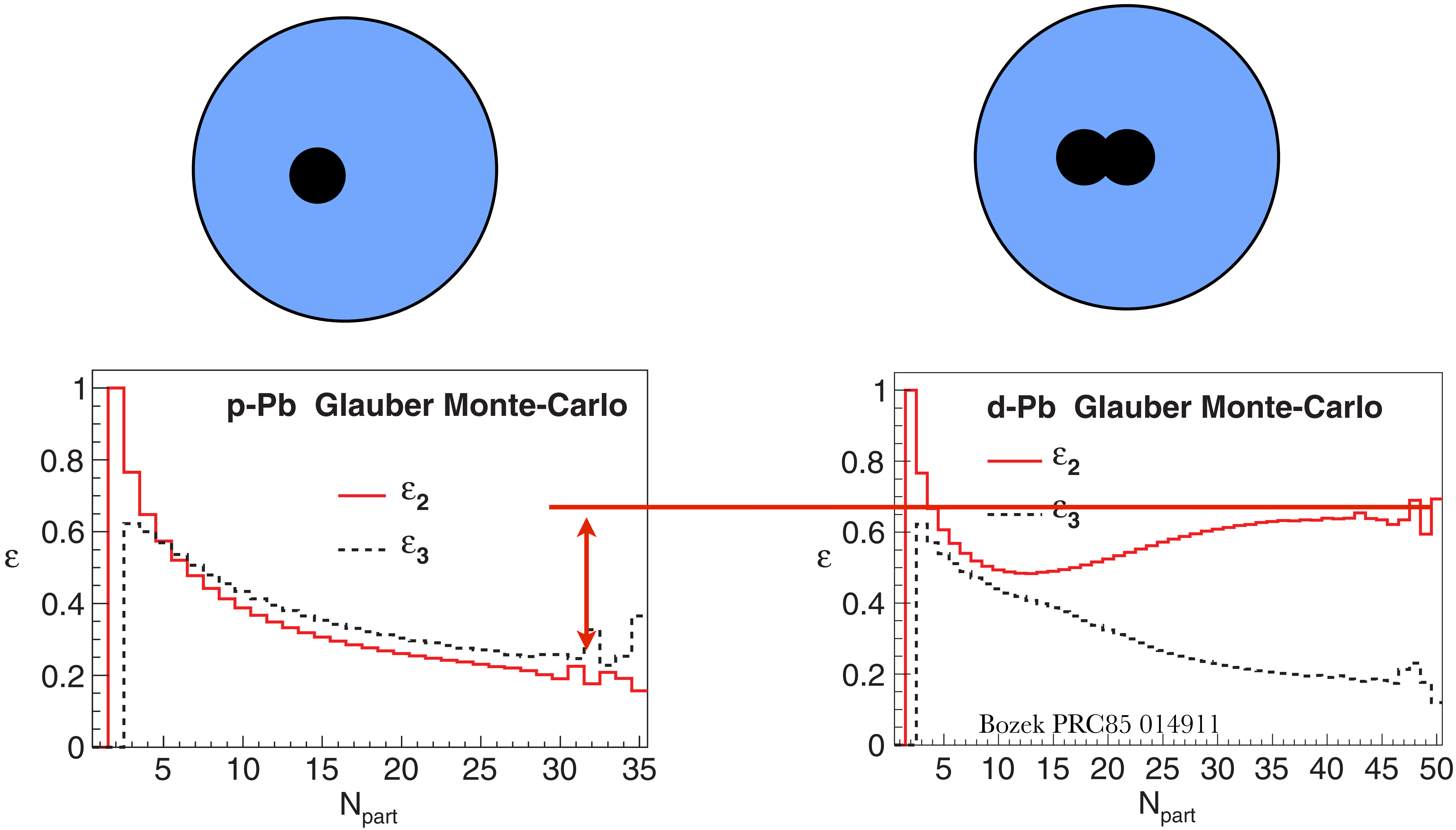





p-Pb Glauber Monte-Carlo
ε_2
ε_3
ε
1
0.8
0.6
0.4
0.2
0
5
10
15
20
25
30
35
N_{part}

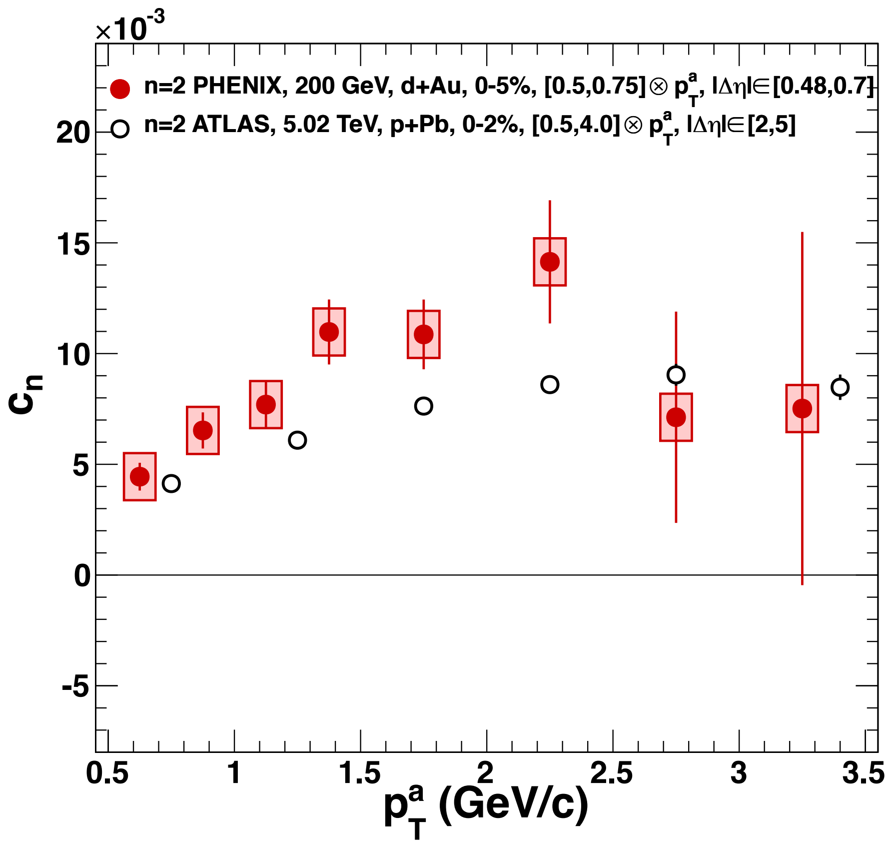

d-Pb Glauber Monte-Carlo
ε_2
ε_3
ε
Bozek PRC85 014911
1
0.8
0.6
0.4
0.2
0
5
10
15
20
25
30
35
40
45
50
N_{part}

pPb vs dAu



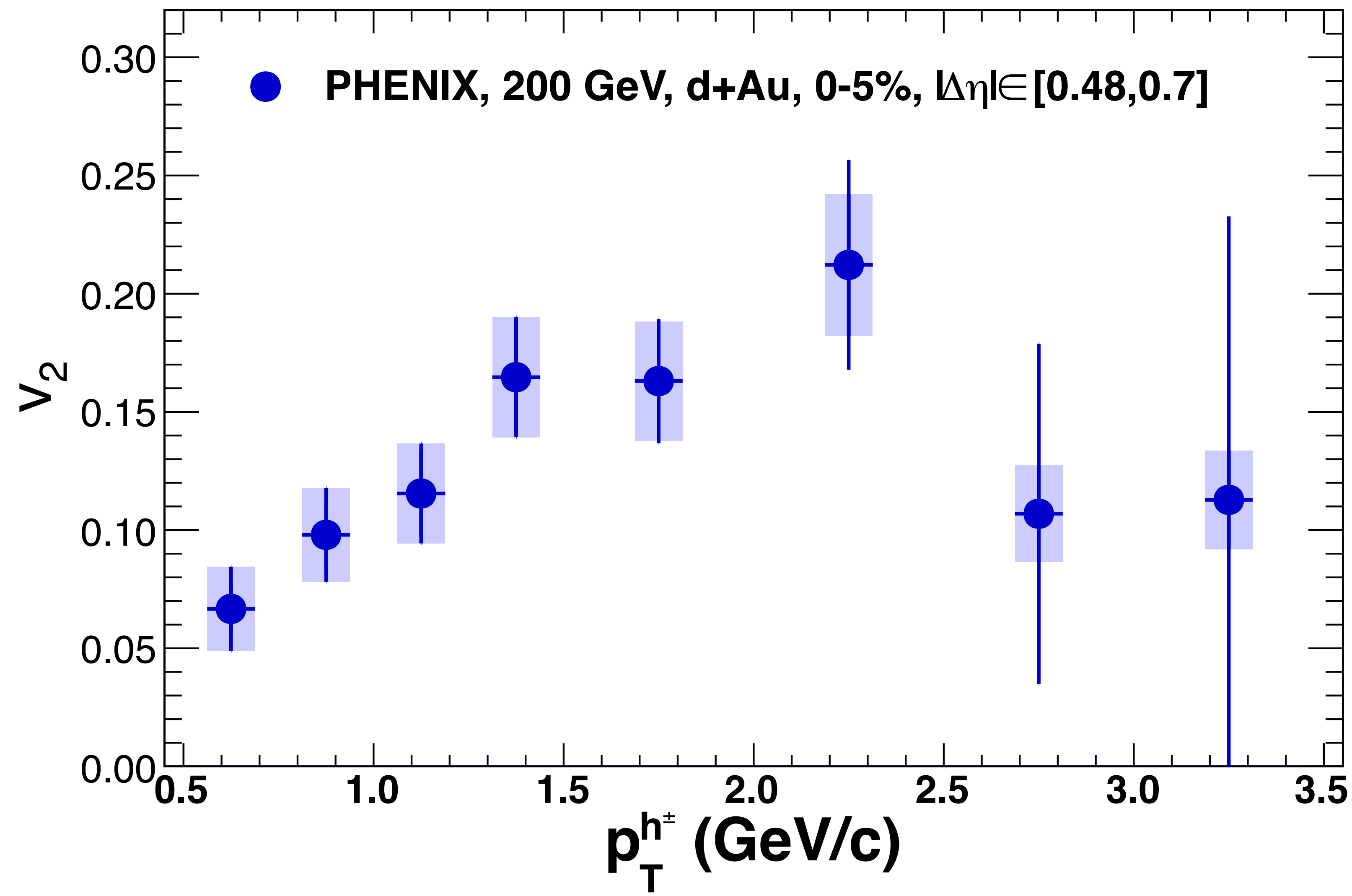
d+A central collisions have much larger ε_2 than p+A

extract v_2 via factorization



$$c2(p_{T,a},p_{T,b}) = v2(p_{T,a})v2(p_{T,b})$$

→factorization assumption: two particle modulation is the product of the single particle anisotropies, no inconsistencies with this assumption found



PHENIX: 1303.1794

Hijing expectations?

- HIJING has no flow, no CGC
- perform the same study with HIJING as in the data

HIJING c_2 consistent with 0, much smaller than in data