

# A Big Surprise in Small Drops of Quark-Gluon Plasma

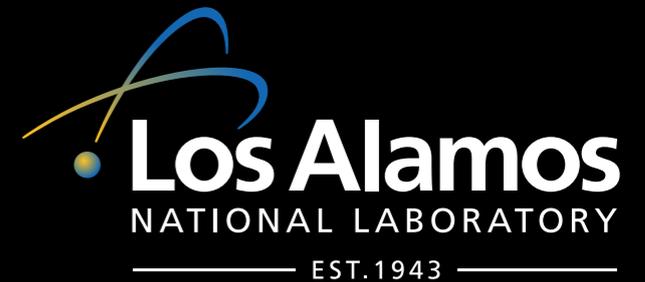
*Or: Flow in d+Au at RHIC?*

**Michael P. McCumber**

(Los Alamos National Laboratory)

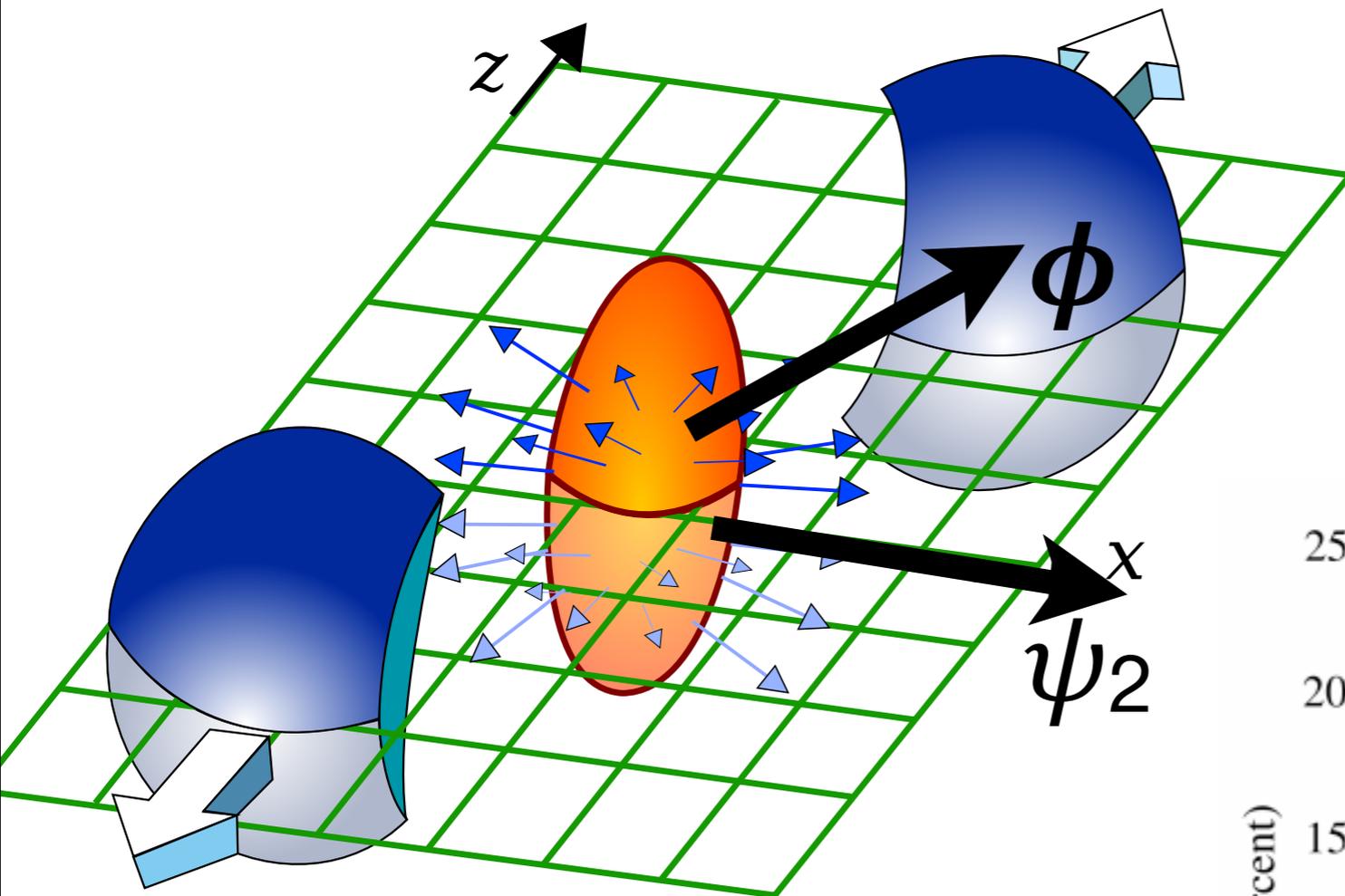
for the PH $\star$ ENIX Collaboration

**Moriond QCD**  
La Thuile, Italy  
March 28 2014



# Collective Behavior

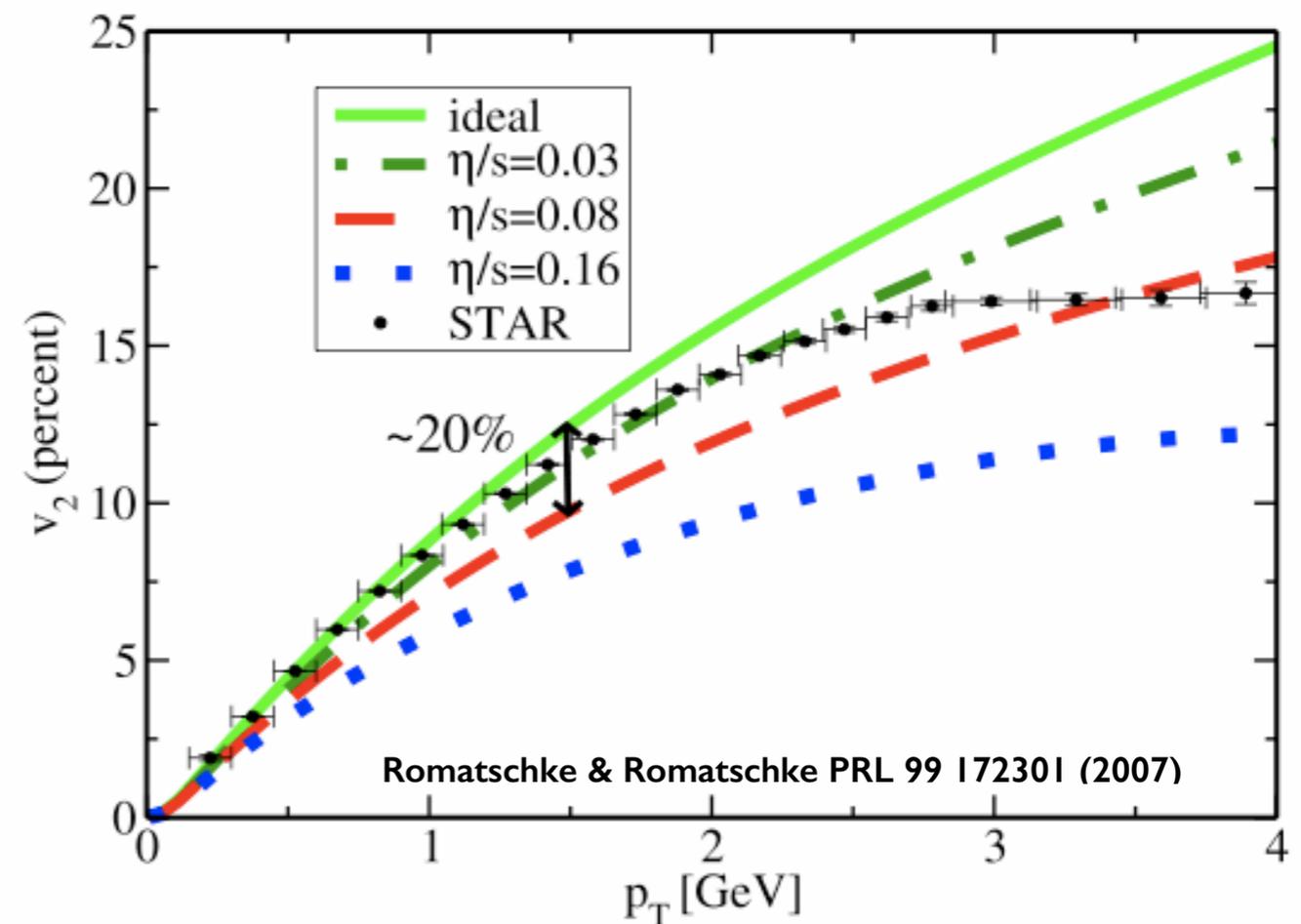
## in Heavy Ion Collisions



**Goal to extract system properties:**  
 initial eccentricity  
 equation of state  
 shear viscosity ratio,  $\eta/s$

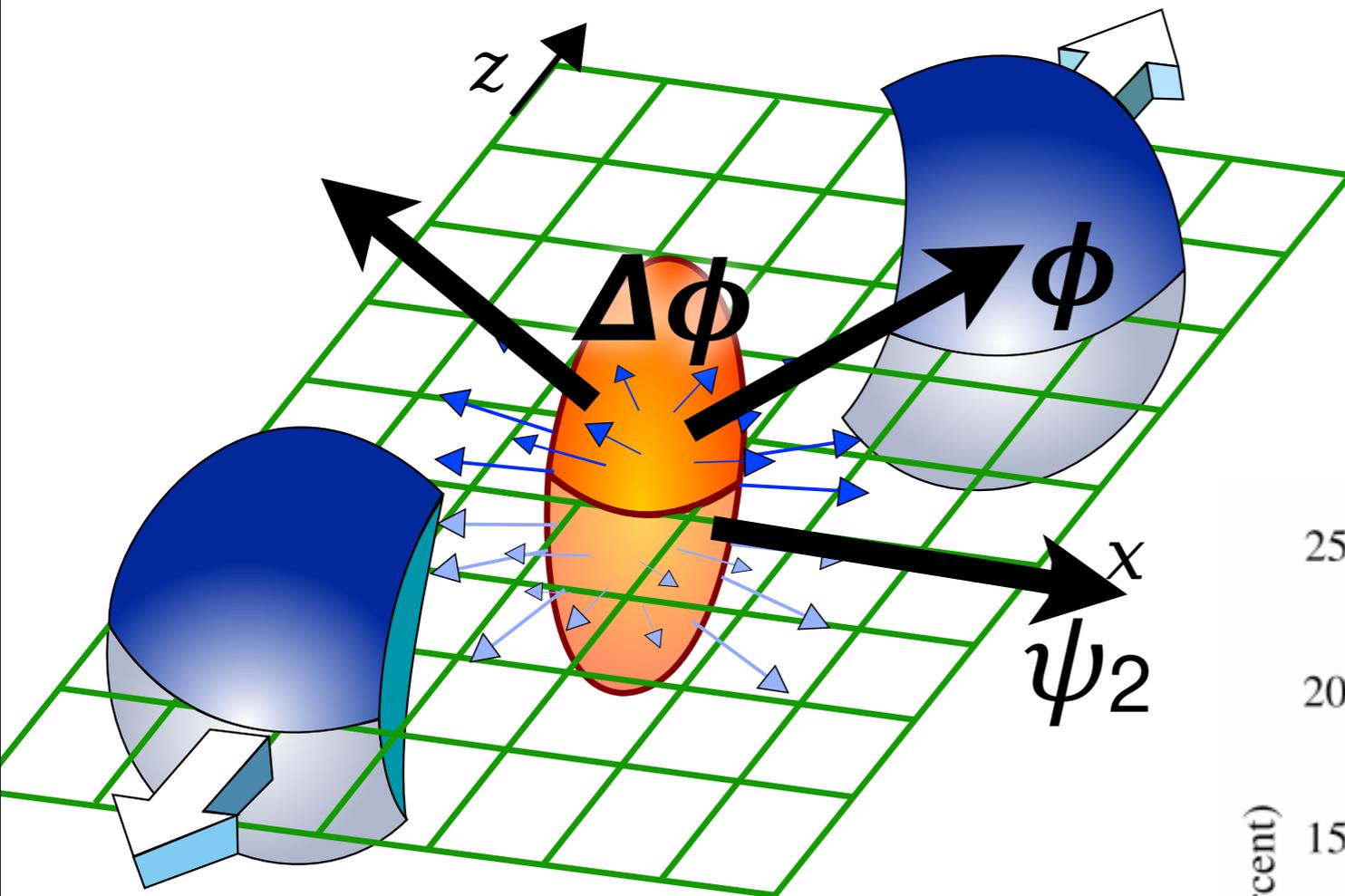
**Measure particle production:**

$$\frac{dN}{d\phi} \sim 1 + 2 \sum \cos n (\phi - \psi_n)$$



# Collective Behavior

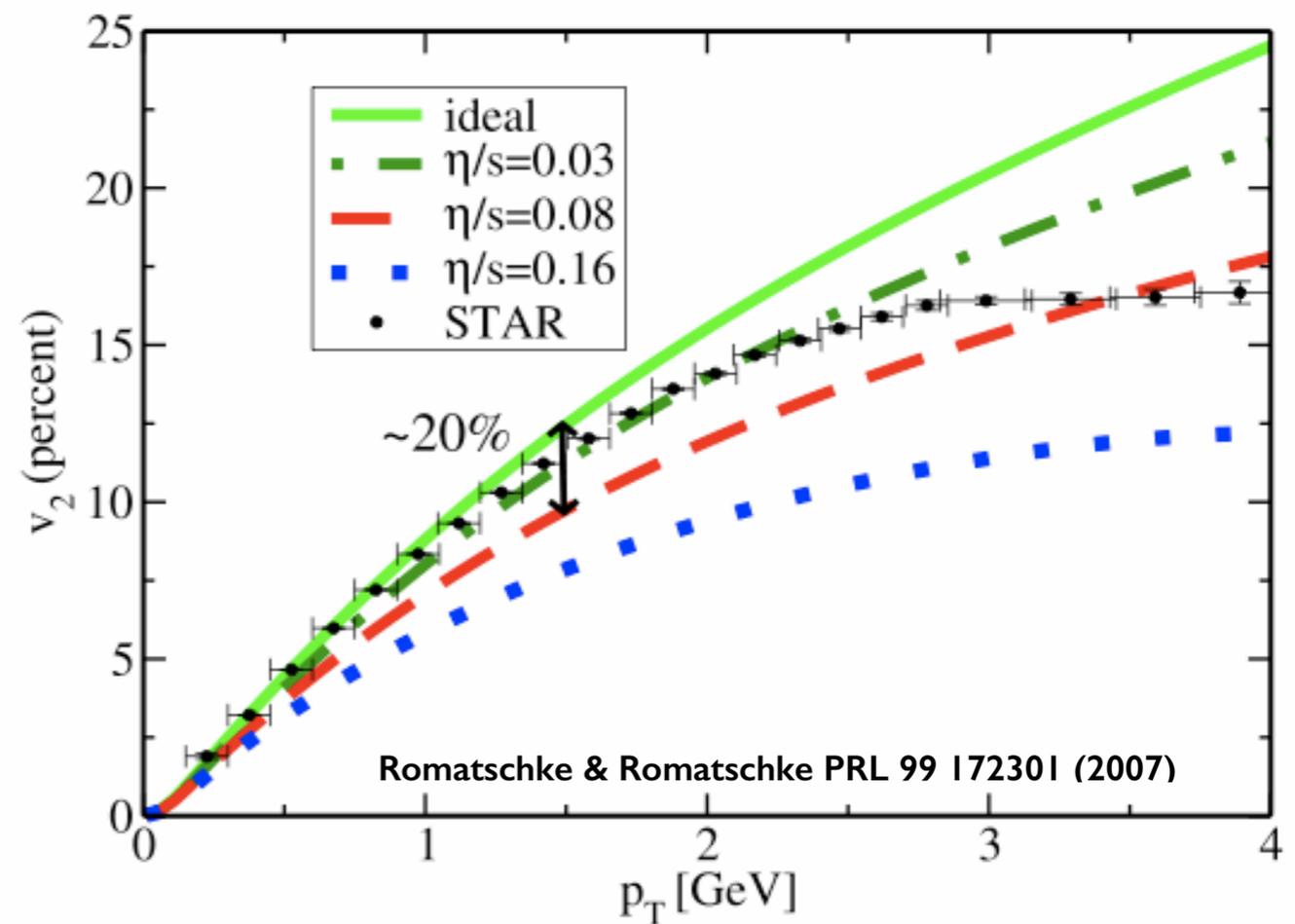
## in Heavy Ion Collisions



Goal to extract system properties:  
 initial eccentricity  
 equation of state  
 shear viscosity ratio,  $\eta/s$

Pair amplitude modulation ( $c_2$ ):

$$c_2 = v_2^a \times v_2^b$$



# Perspective & Motivation

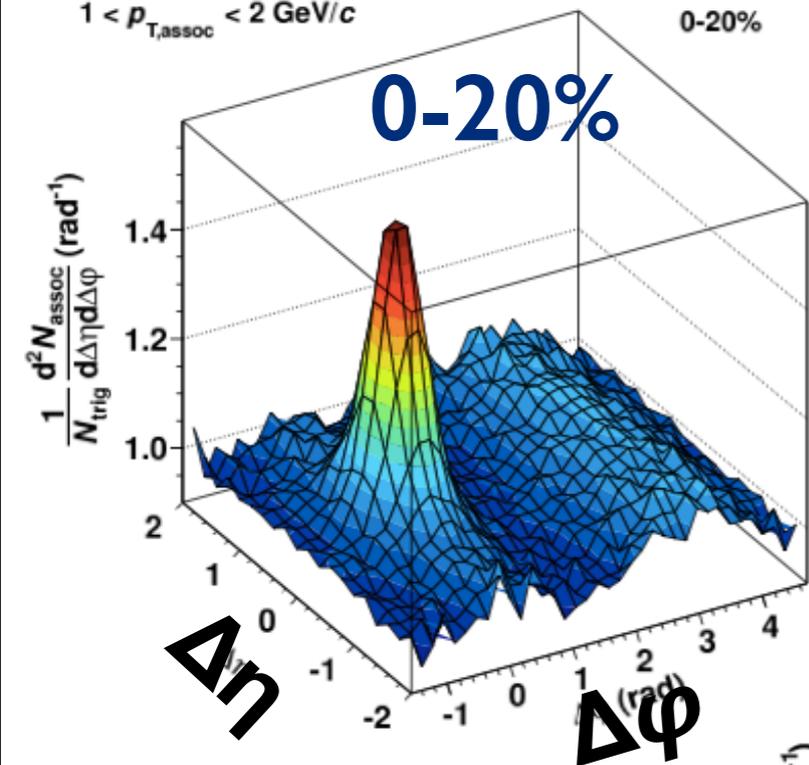
p+Pb

from ALICE, Phys.Lett. B719 (2013) 29-41

$2 < p_{T,\text{trig}} < 4 \text{ GeV}/c$   
 $1 < p_{T,\text{assoc}} < 2 \text{ GeV}/c$

p-Pb  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$   
0-20%

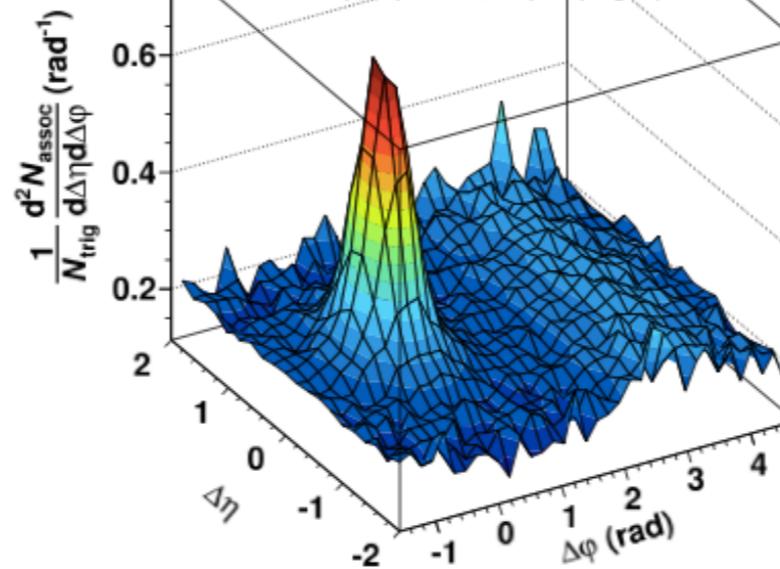
0-20%



$2 < p_{T,\text{trig}} < 4 \text{ GeV}/c$   
 $1 < p_{T,\text{assoc}} < 2 \text{ GeV}/c$

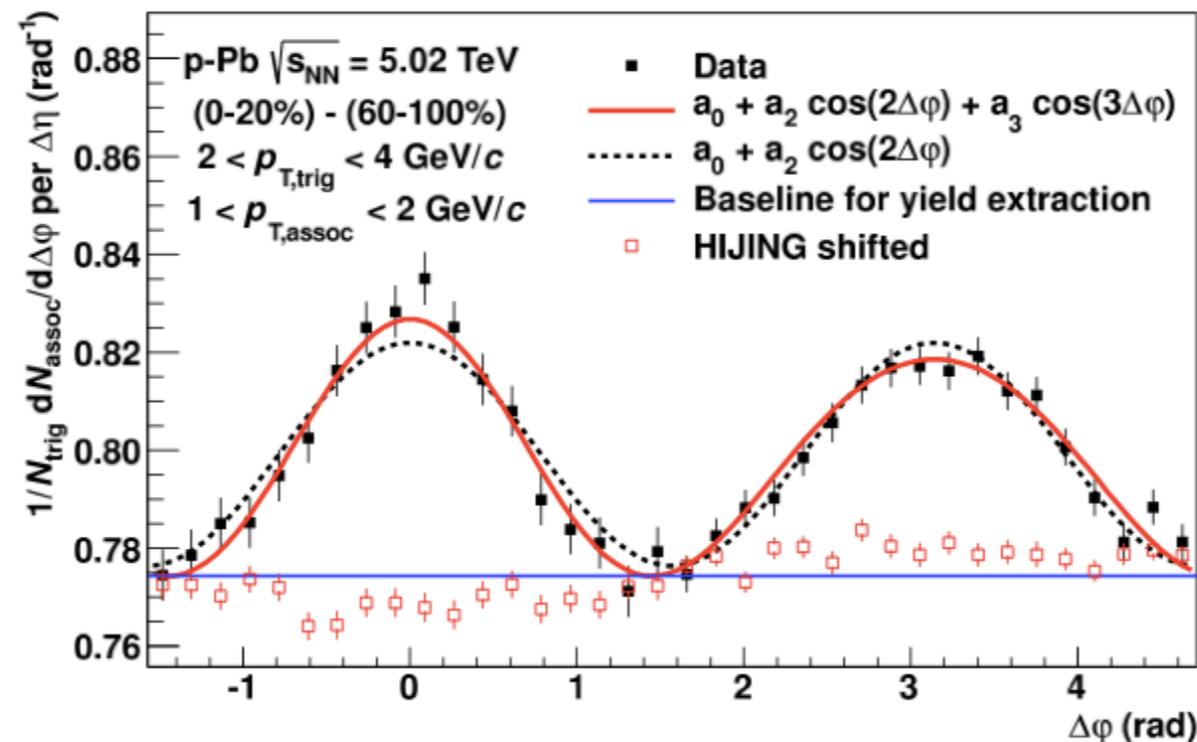
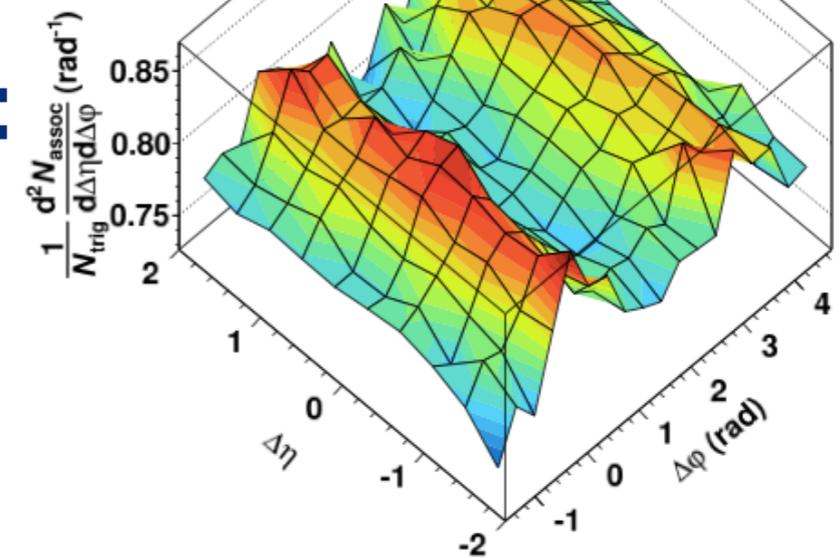
p-Pb  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$   
60-100%

60-100%



$2 < p_{T,\text{trig}} < 4 \text{ GeV}/c$   
 $1 < p_{T,\text{assoc}} < 2 \text{ GeV}/c$

p-Pb  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$   
(0-20%) - (60-100%)



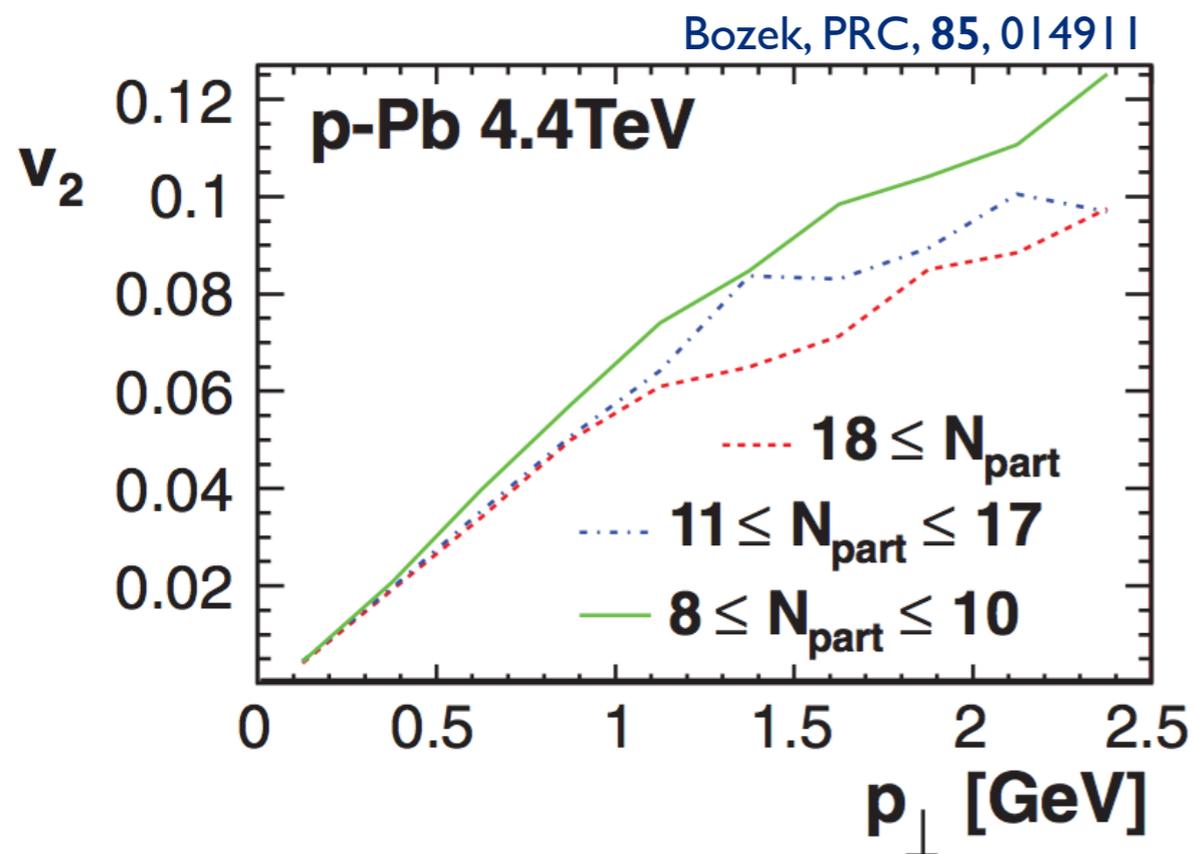
*pair excess in central events well-described by small order moments*

# Physical Mechanisms

*competing theoretical descriptions of the effect...*

## Hydrodynamics

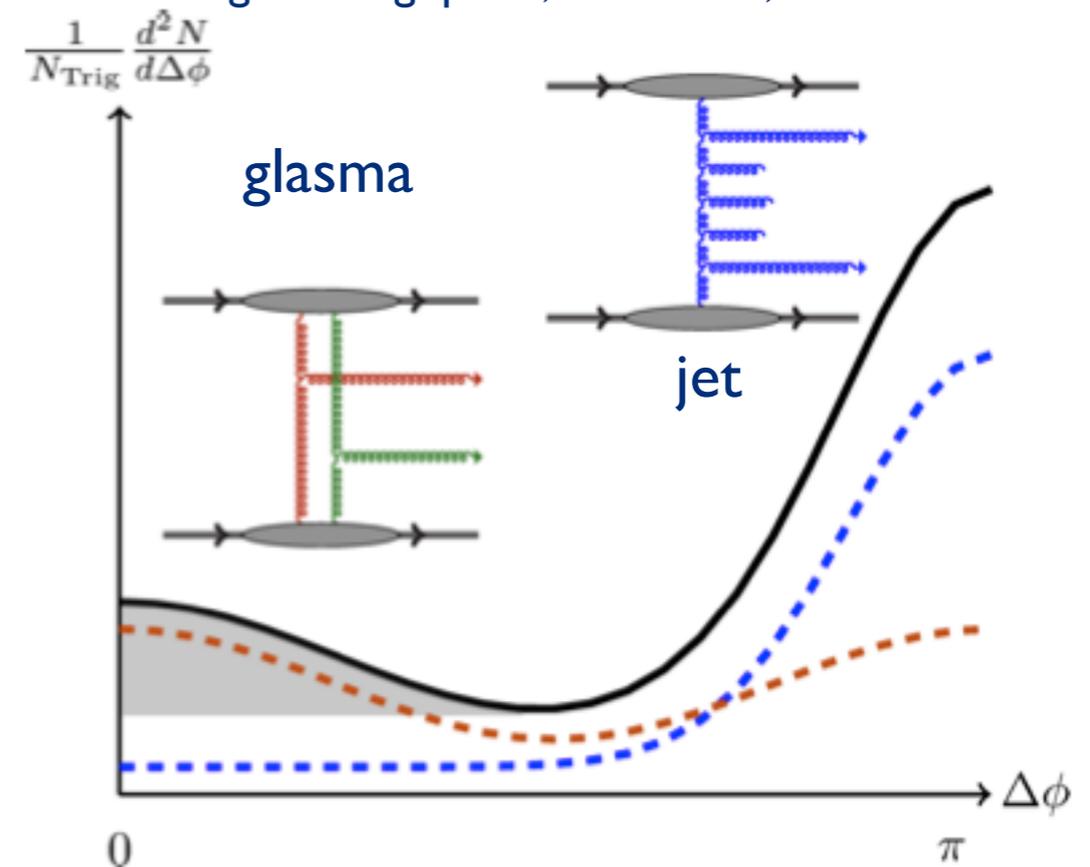
(final state re-scattering and thermal expansion)



## CGC/Glasma

(correlated emission off a flux tube)

Dusling & Venugopalan, 1211.3701, 1302.7018



*so is this phenomena present at RHIC energies?*



New York

Switzerland

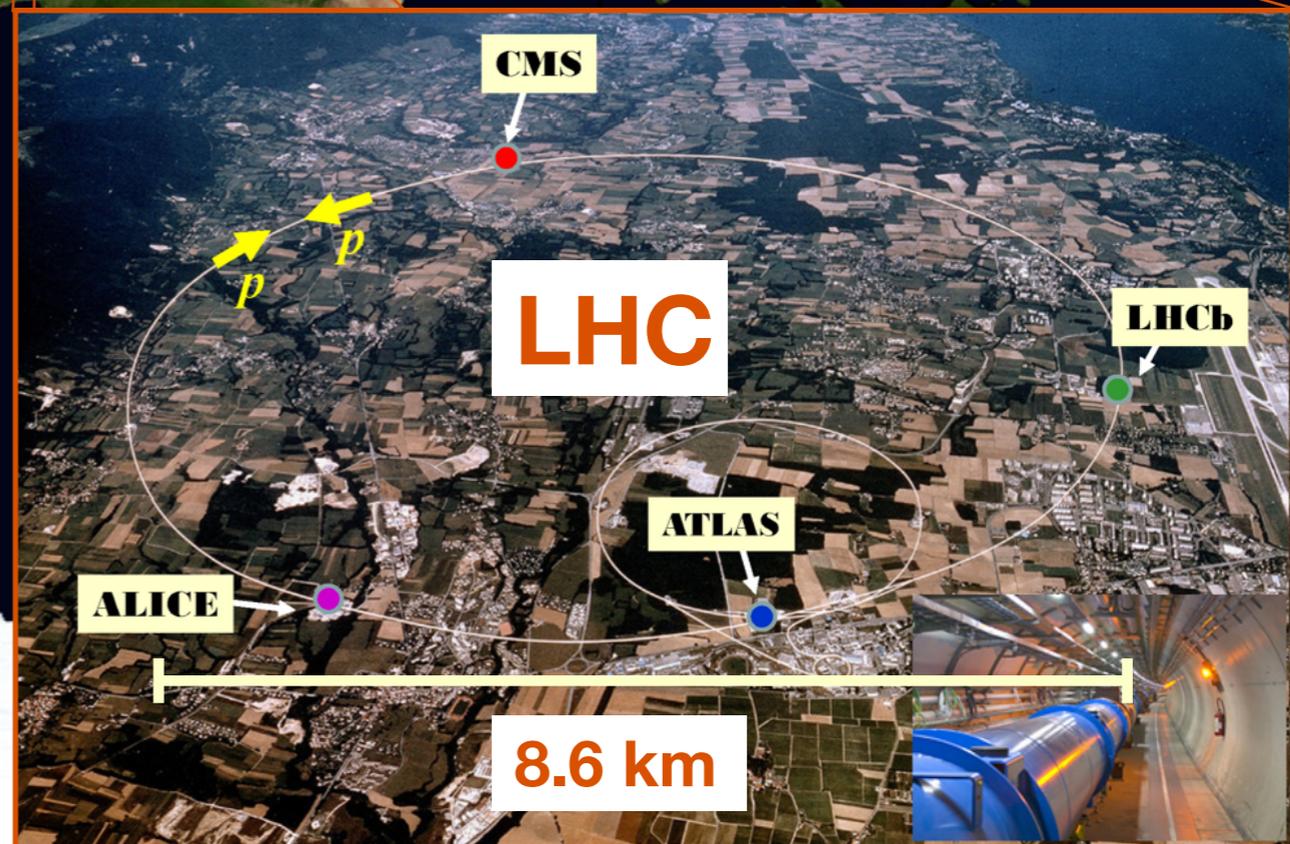


**RHIC**

**PHENIX**

**STAR**

**1.2 km**



**CMS**

**LHC**

**LHCb**

**ALICE**

**ATLAS**

**8.6 km**

**today's topic** →

beam	energy (GeV)
$\vec{p}+\vec{p}$	62 - 510
<b>d+Au</b>	<b>200</b>
Cu+Cu	22 - 200
Cu+Au	200
Au+Au	7 - 200
U+U	193

beam	energy (GeV)
p+p	7000-8000
p+Pb	5020
Pb+Pb	2760

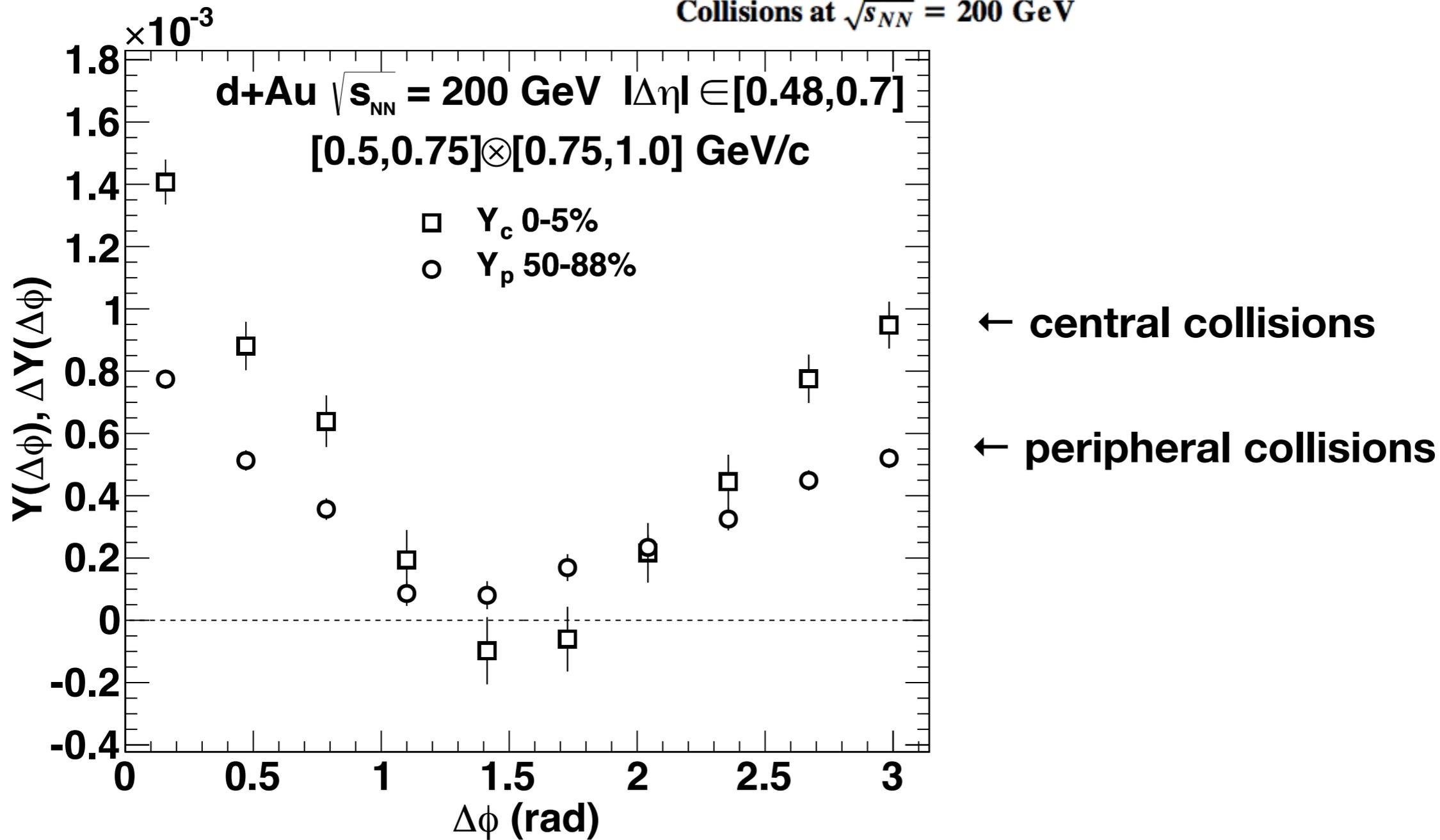
# Azimuthal Excess

PRL 111, 212301 (2013)

PHYSICAL REVIEW LETTERS

week ending  
22 NOVEMBER 2013

Quadrupole Anisotropy in Dihadron Azimuthal Correlations in Central  $d + Au$   
Collisions at  $\sqrt{s_{NN}} = 200$  GeV



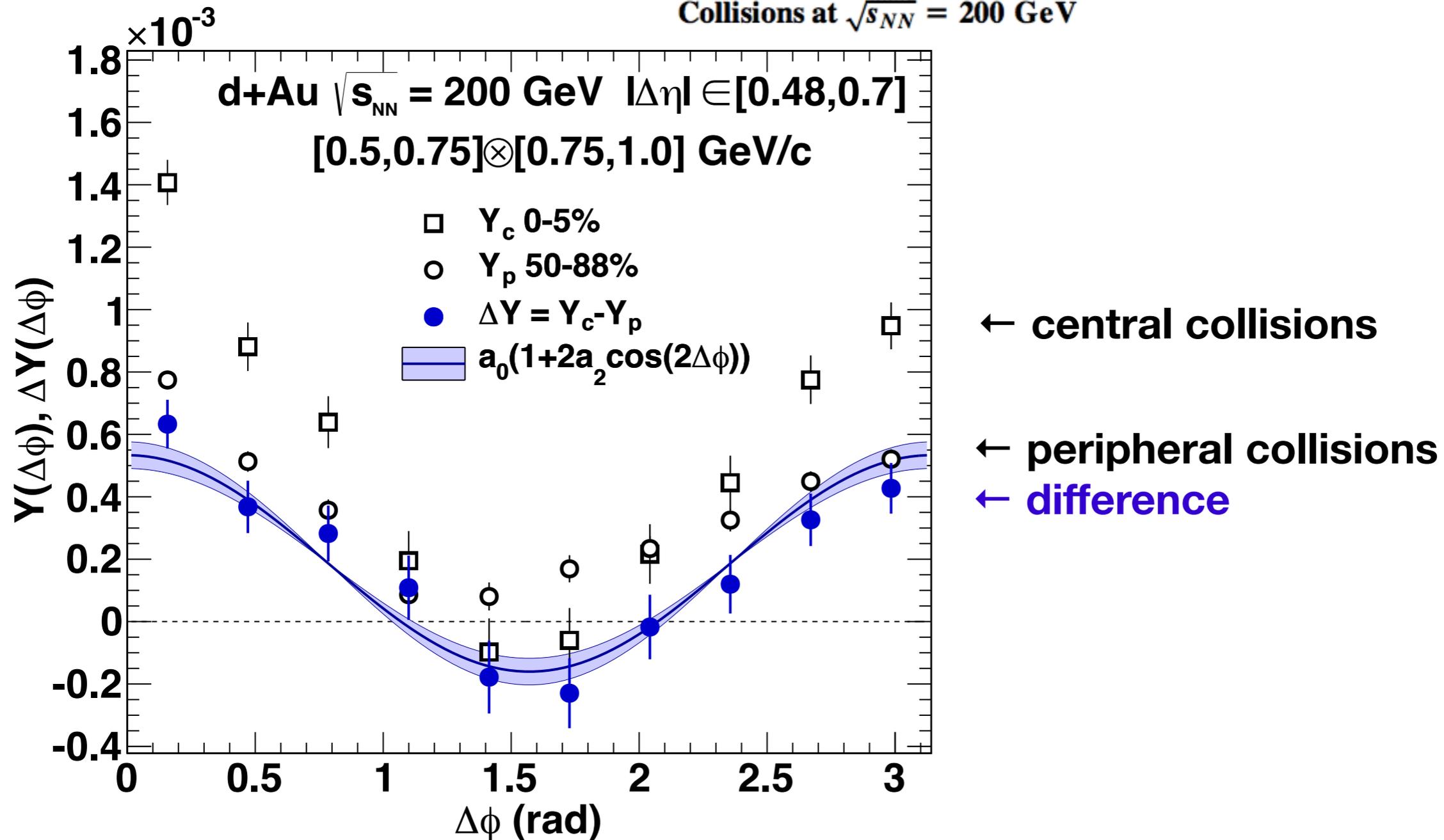
# Azimuthal Excess

PRL 111, 212301 (2013)

PHYSICAL REVIEW LETTERS

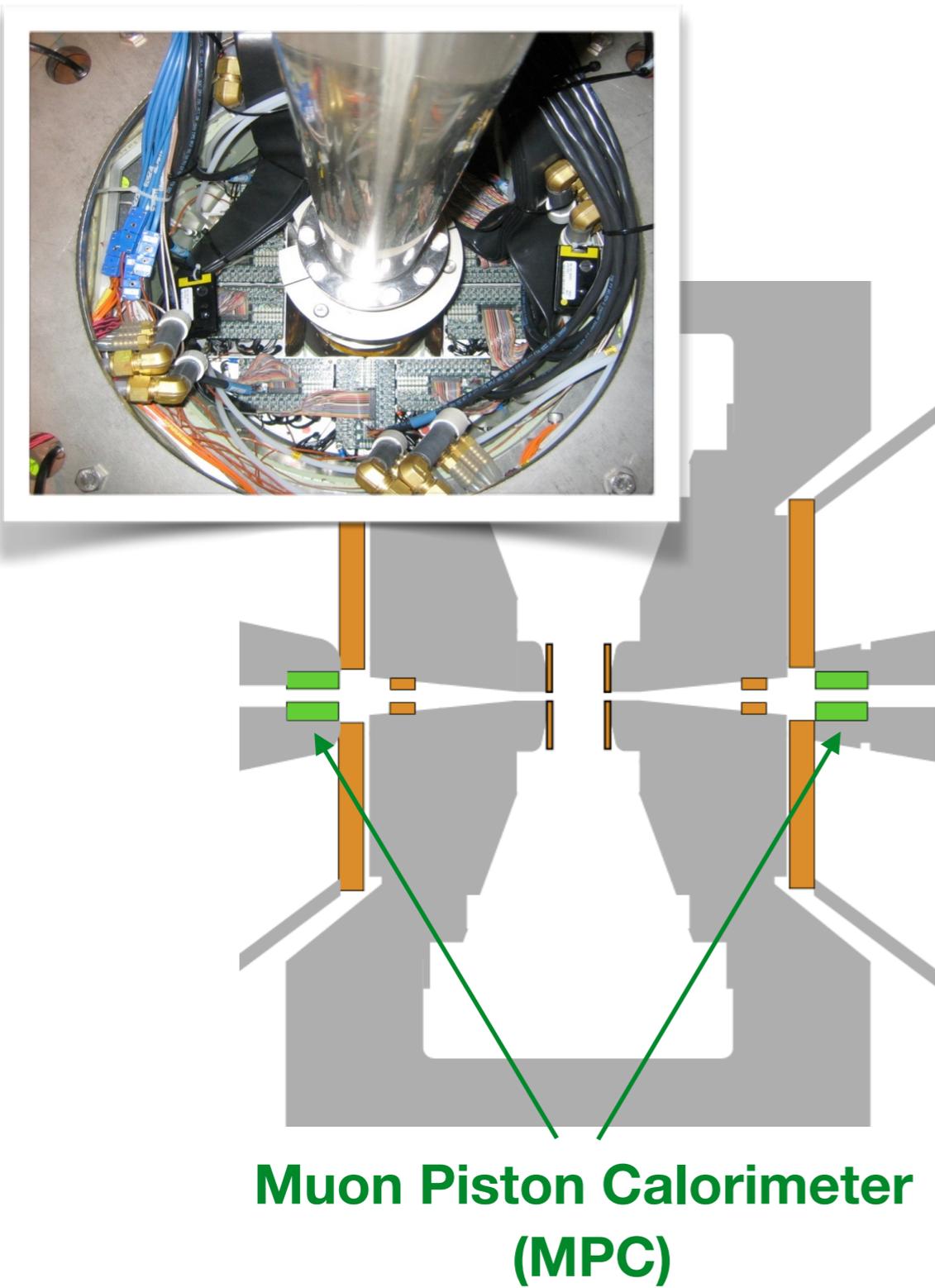
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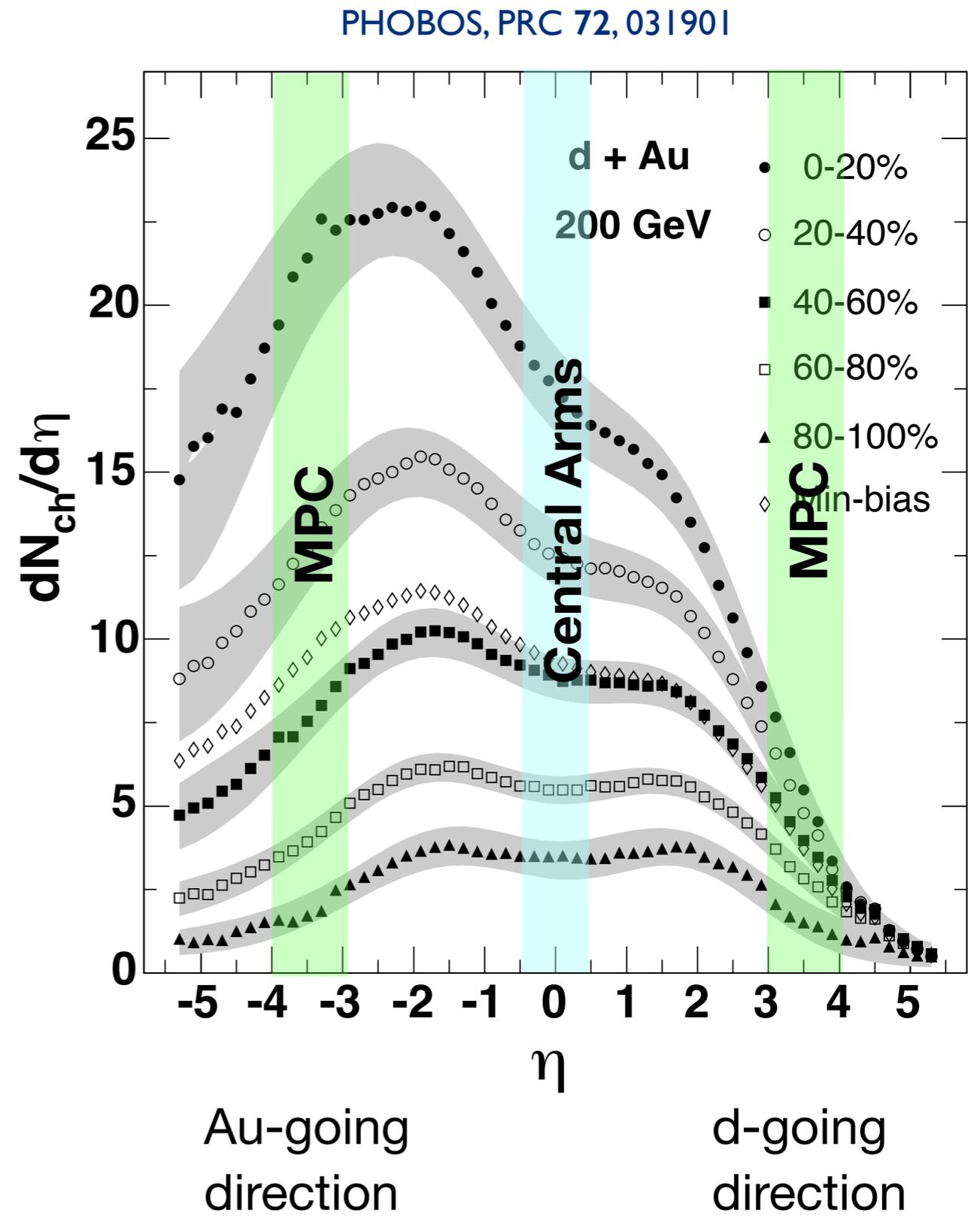


*the centrality difference is well-described by a 2nd-order moment*

# Large Rapidity Gap

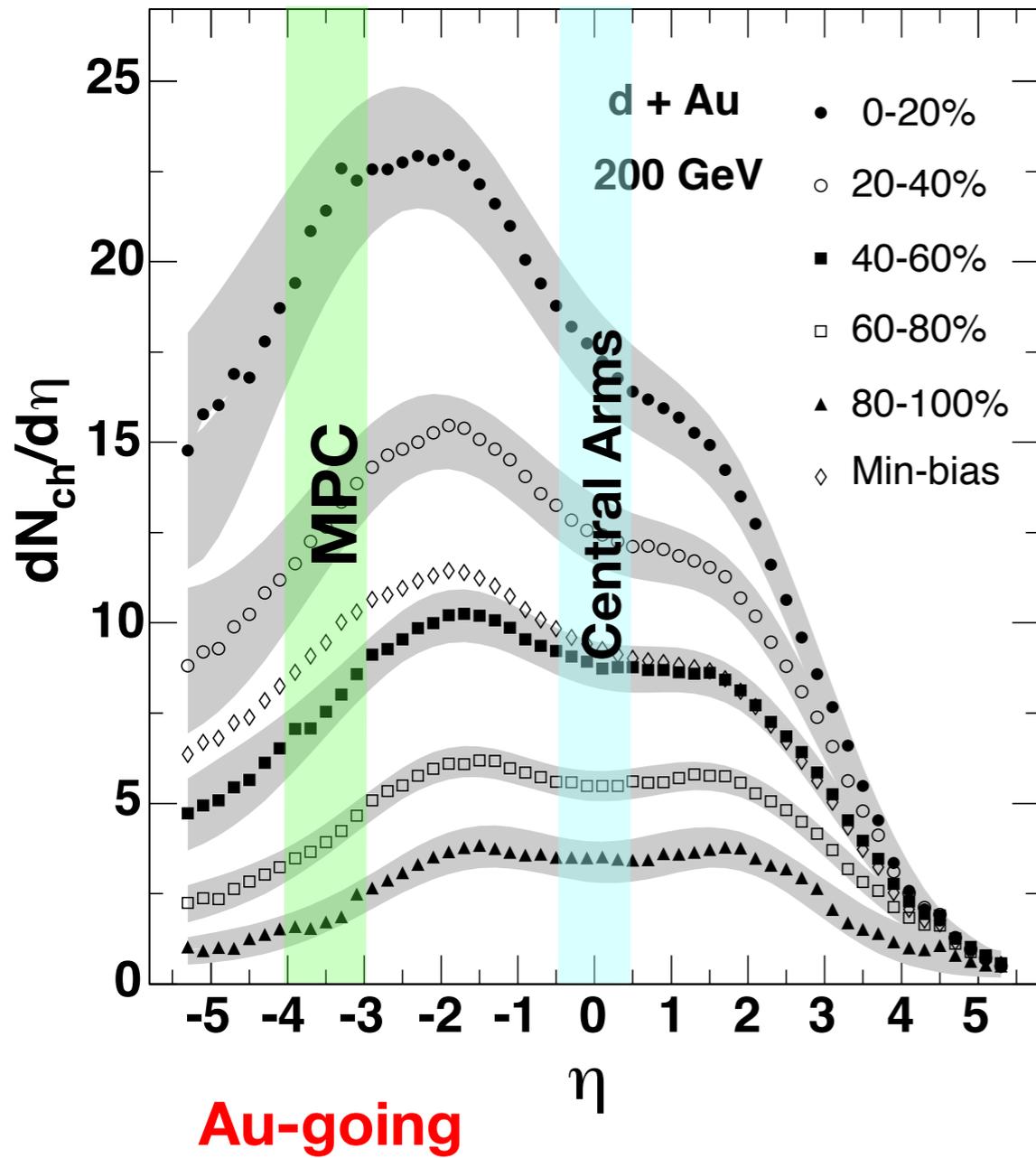


*expect small  $v_2$  bias from jets*

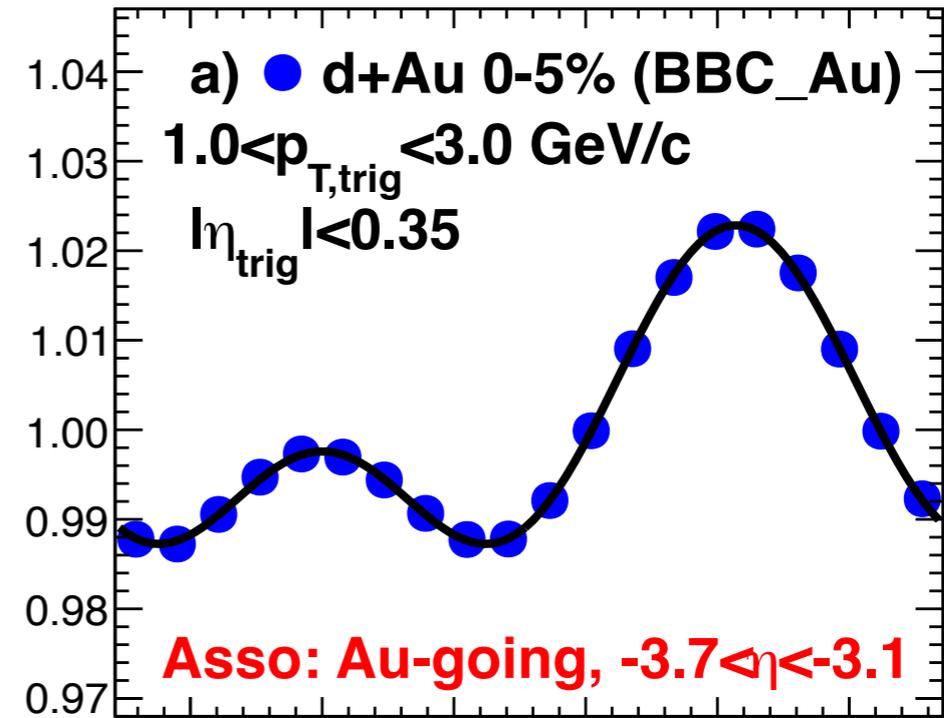


# Backward Rapidity

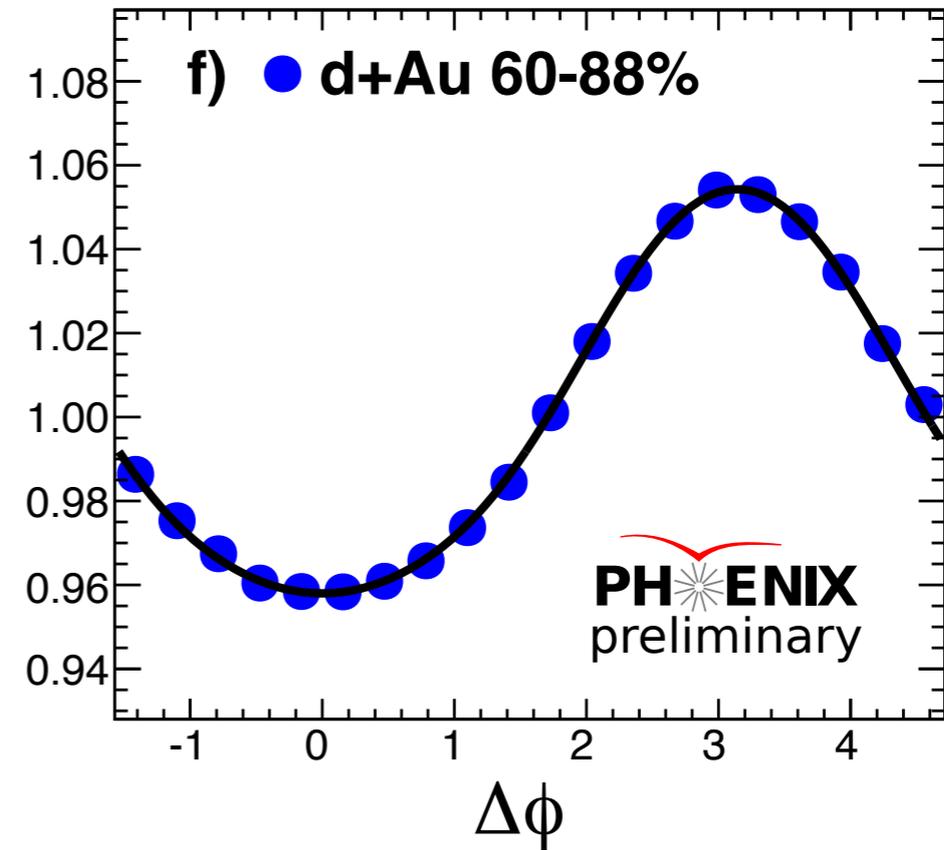
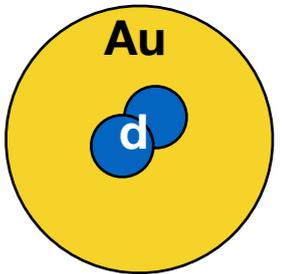
PHOBOS, PRC 72, 031901



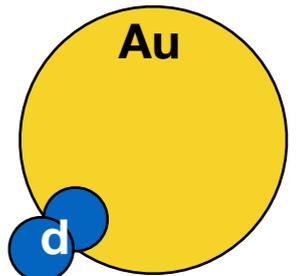
$C(\Delta\phi)$



central collisions

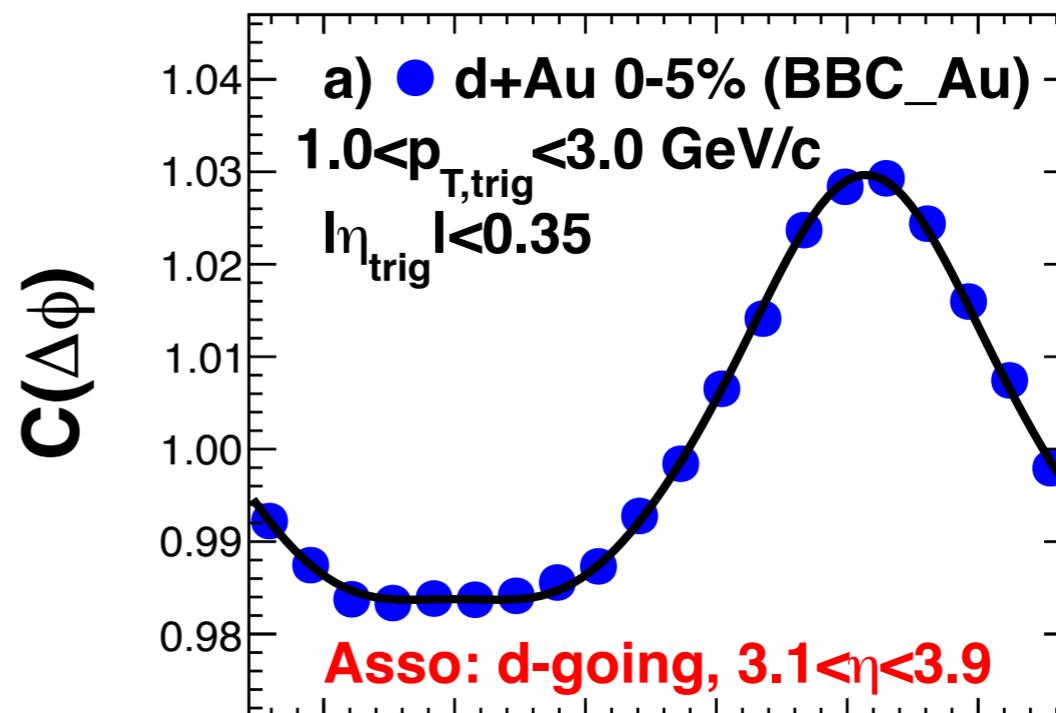
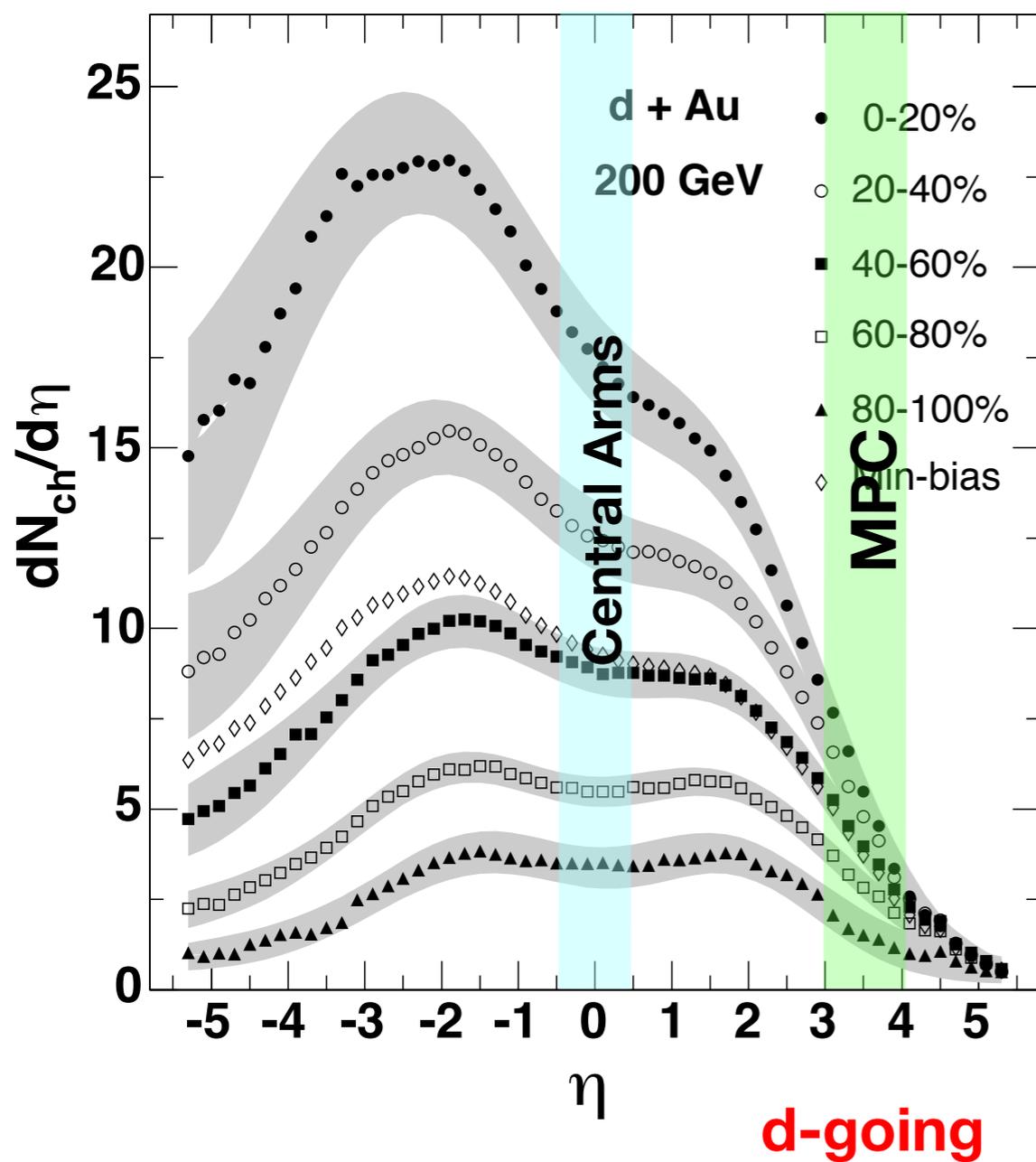


peripheral collisions

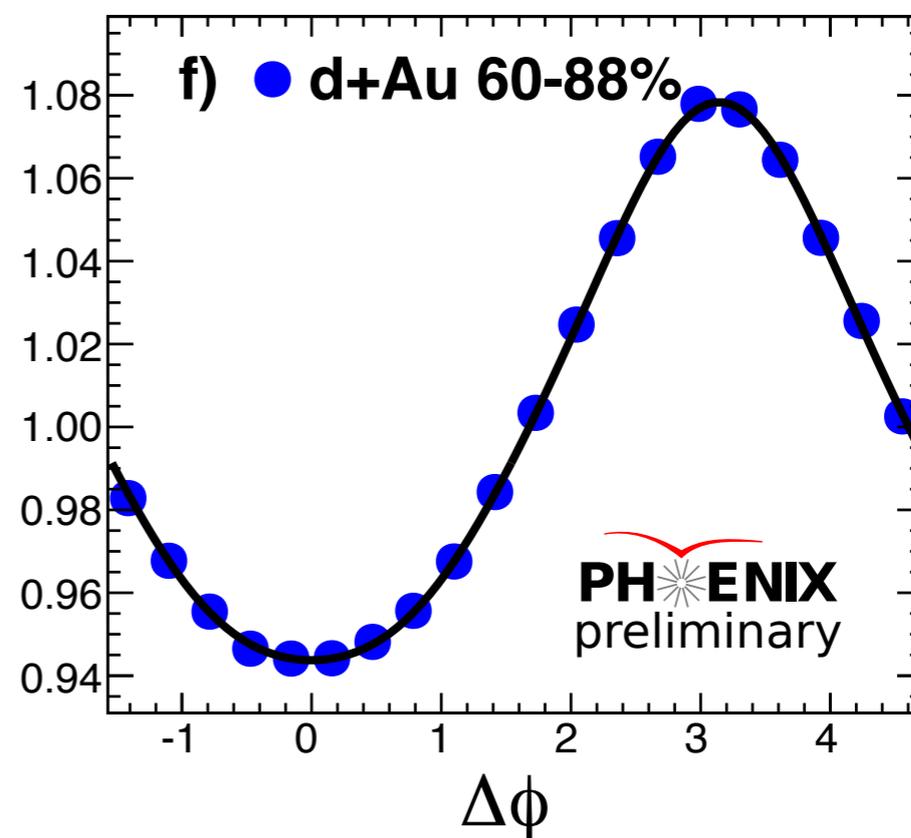
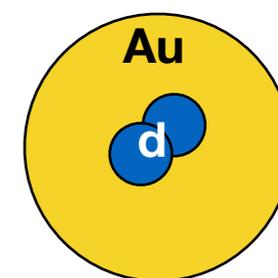


# Forward Rapidity

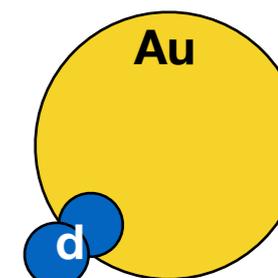
PHOBOS, PRC 72, 031901



central collisions



peripheral collisions



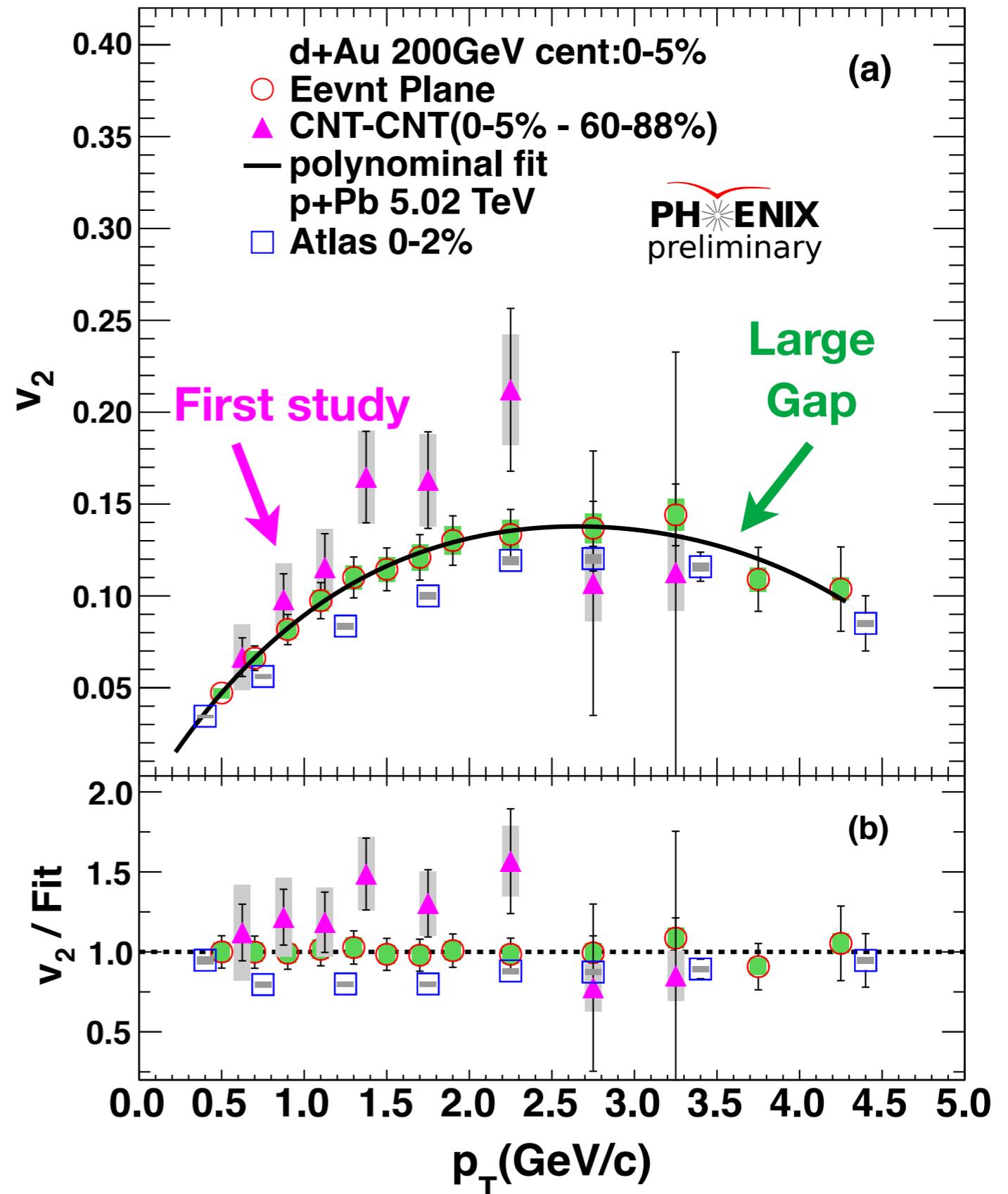
*effect extends across many units of pseudorapidity*

# Anisotropies

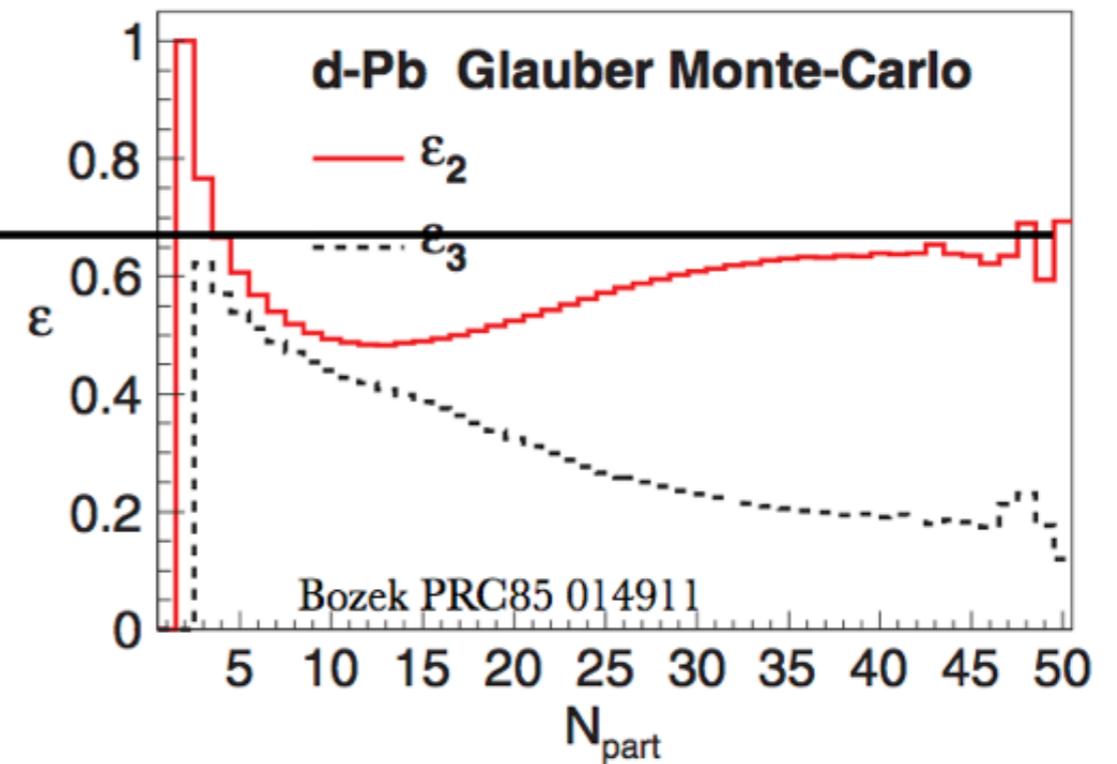
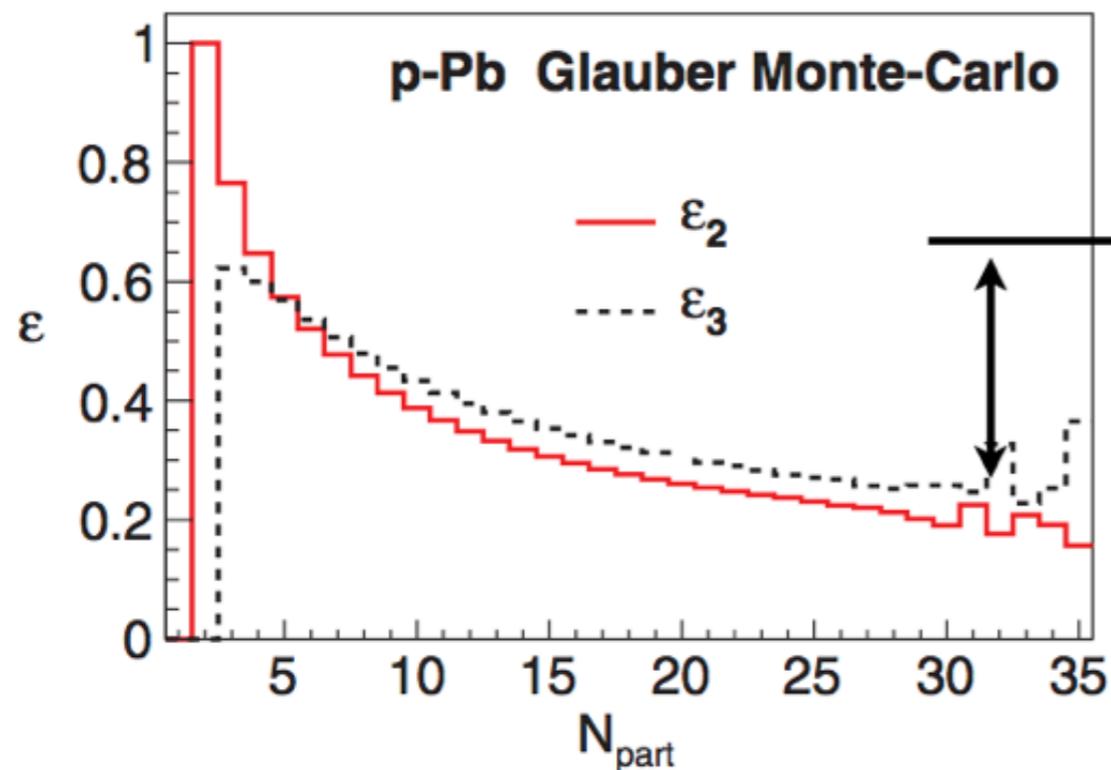
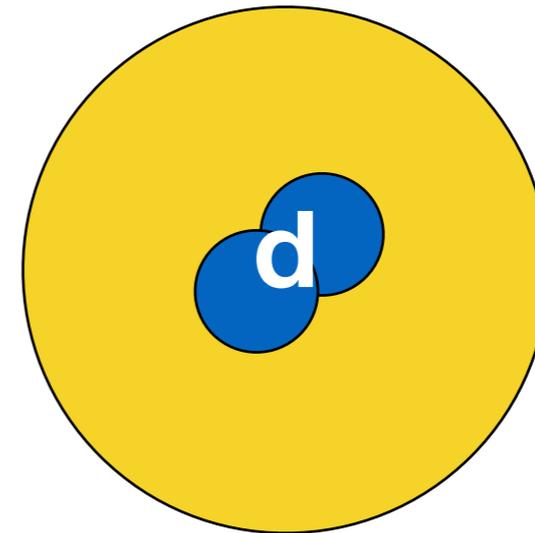
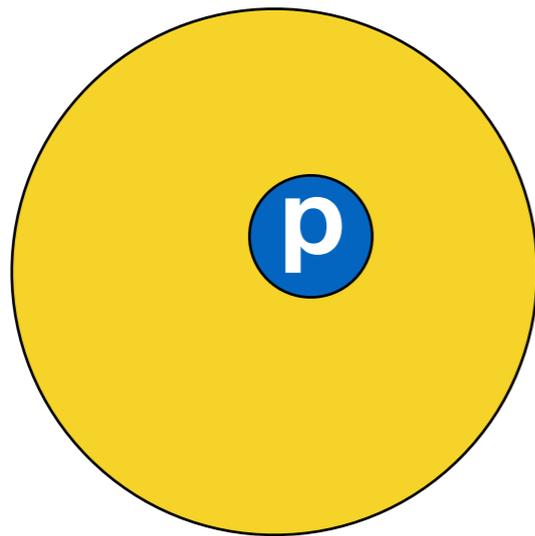
*tension between studies covered by correlated systematic*

*still larger than LHC values after improving jet separation*

*Reason? - deuteron gives larger eccentricities*



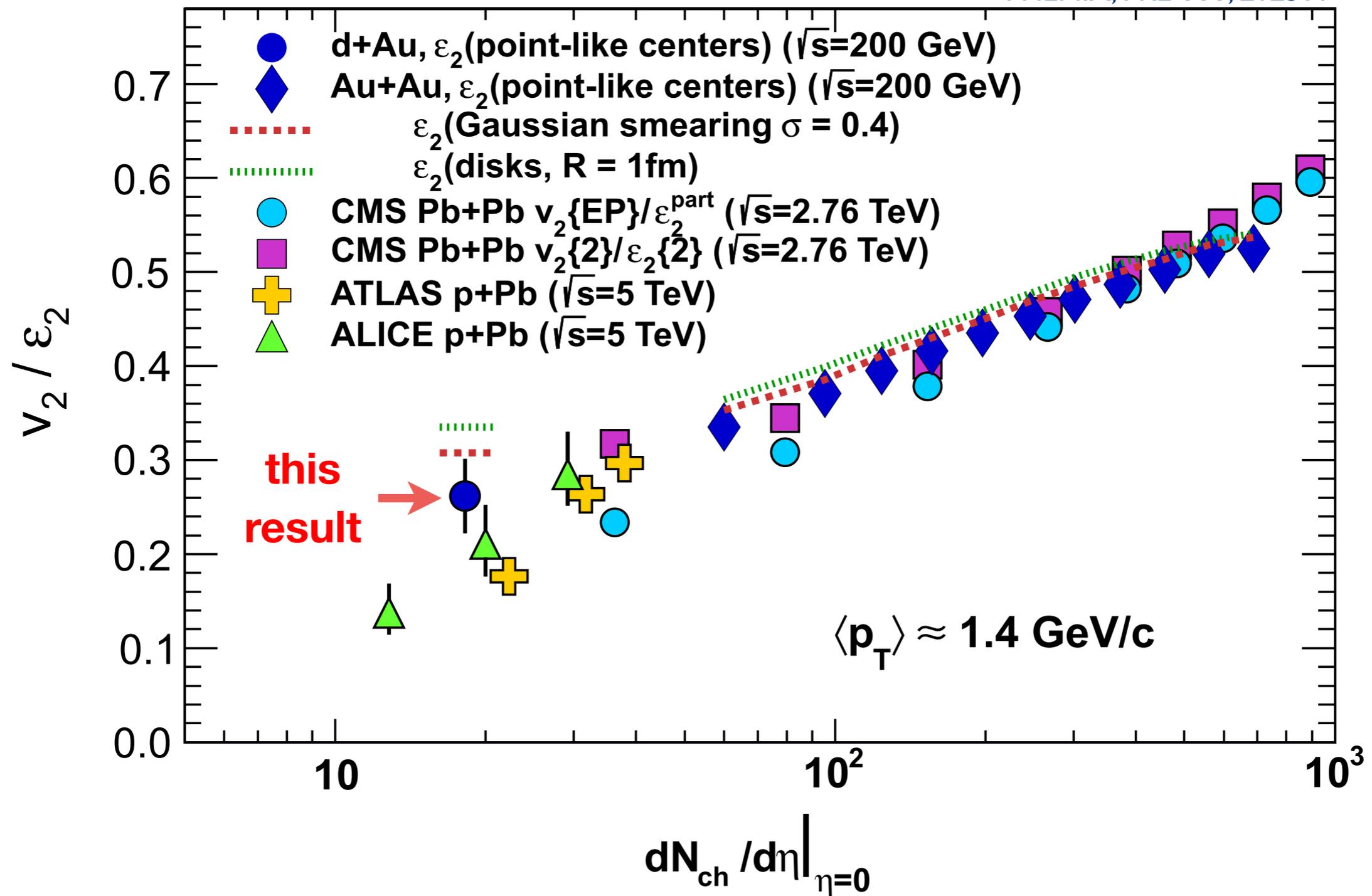
# Eccentricity Differences



*larger 2nd order eccentricity is expected from deuteron projectile  
only small 3rd order is expected*

# Scaling

PHENIX, PRL 111, 212301

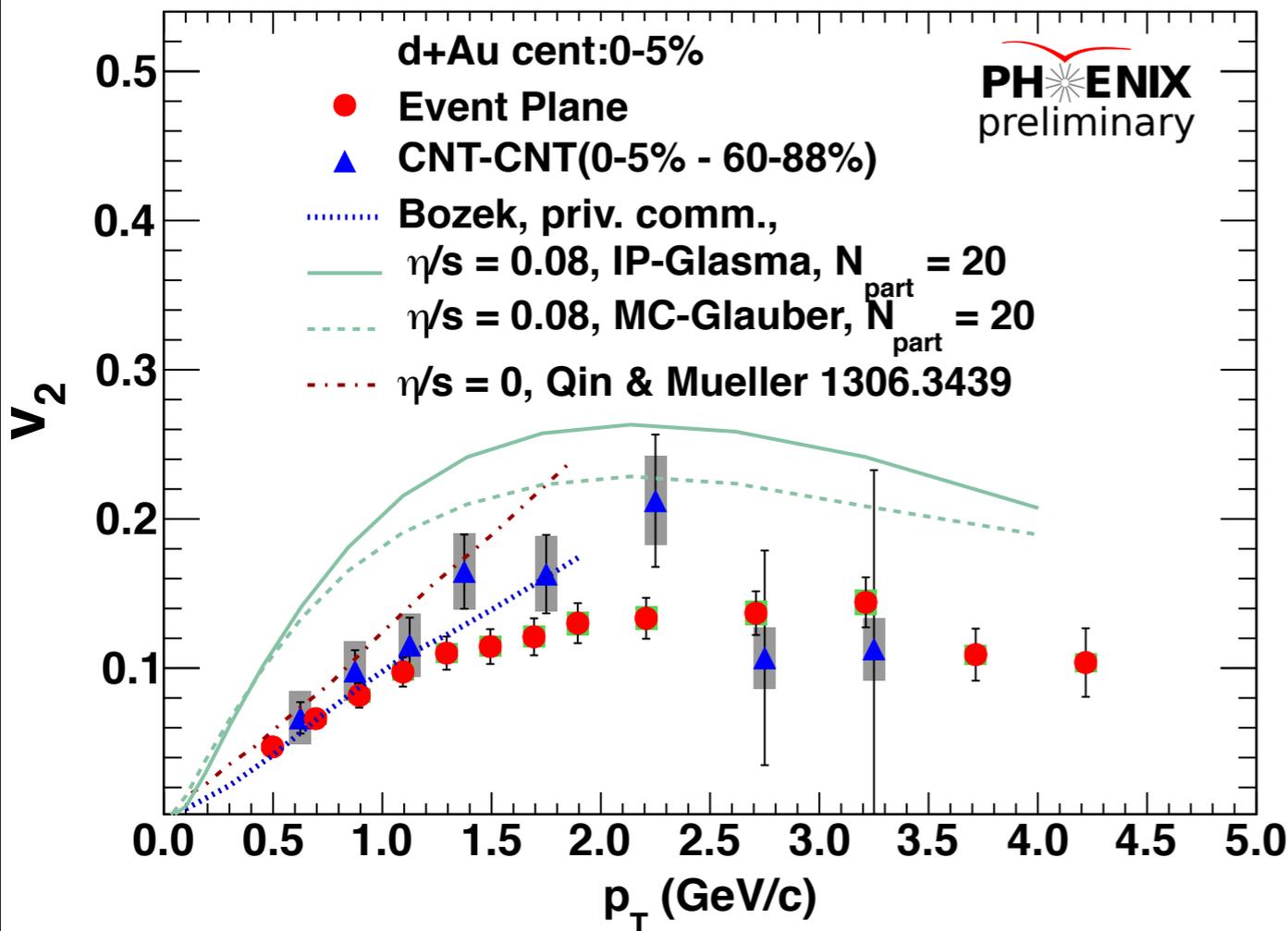


*system size conversion of eccentricity  
into anisotropy similar to world data*

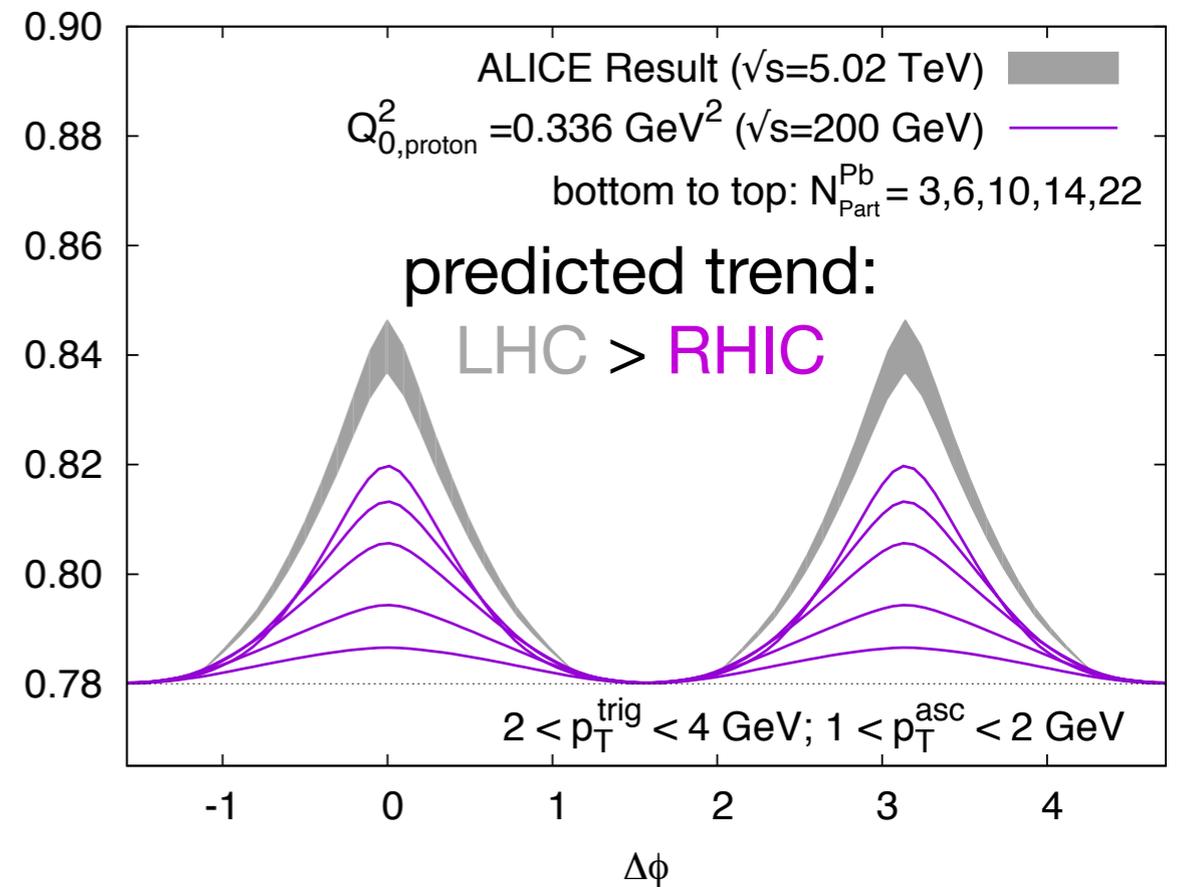
# Physical Mechanisms Revisited

## Hydrodynamics

PHENIX, PRL 111, 212301



## CGC/Glasma

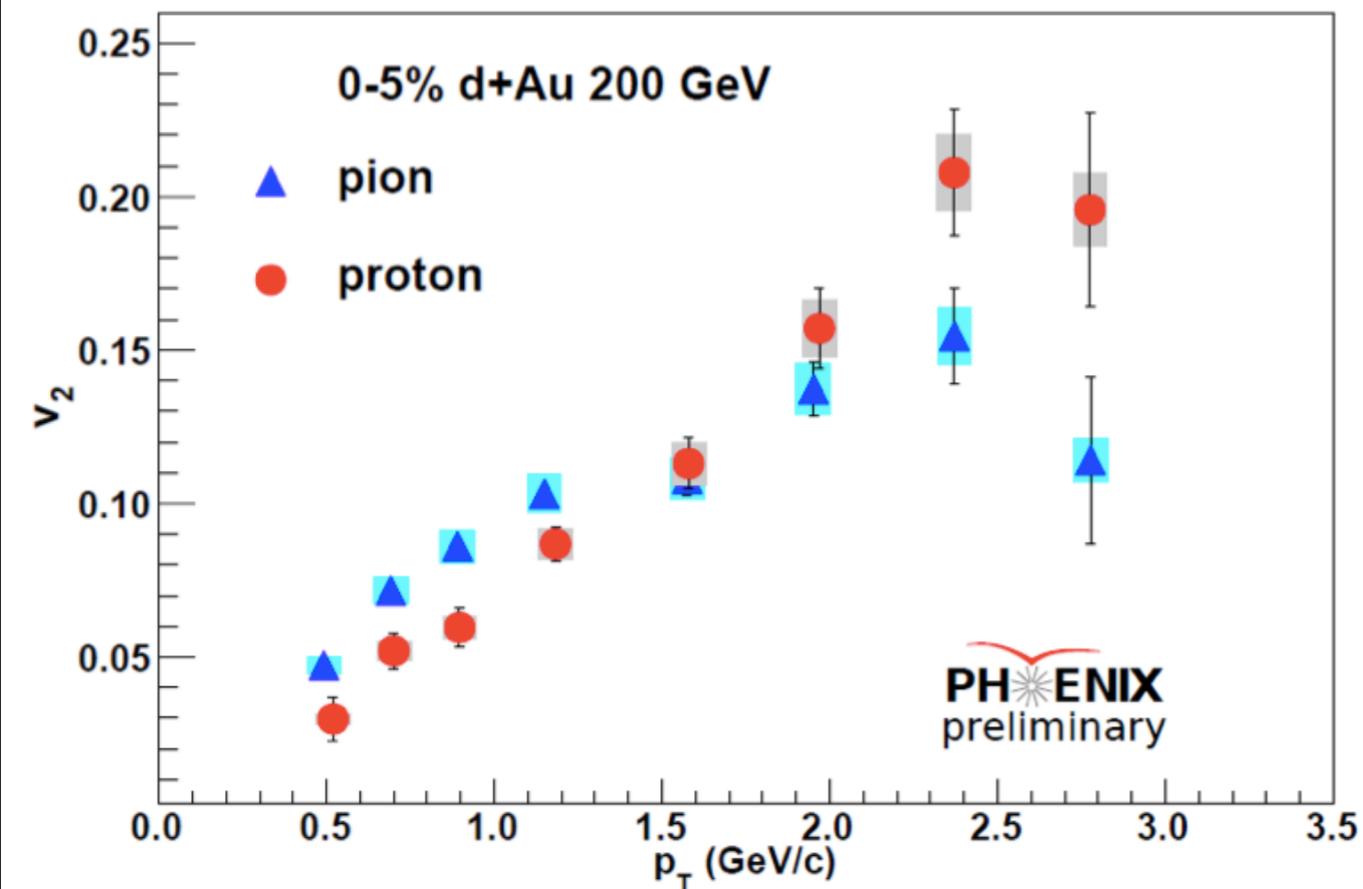


*qualitative consistency with hydrodynamics*

# Particle Content

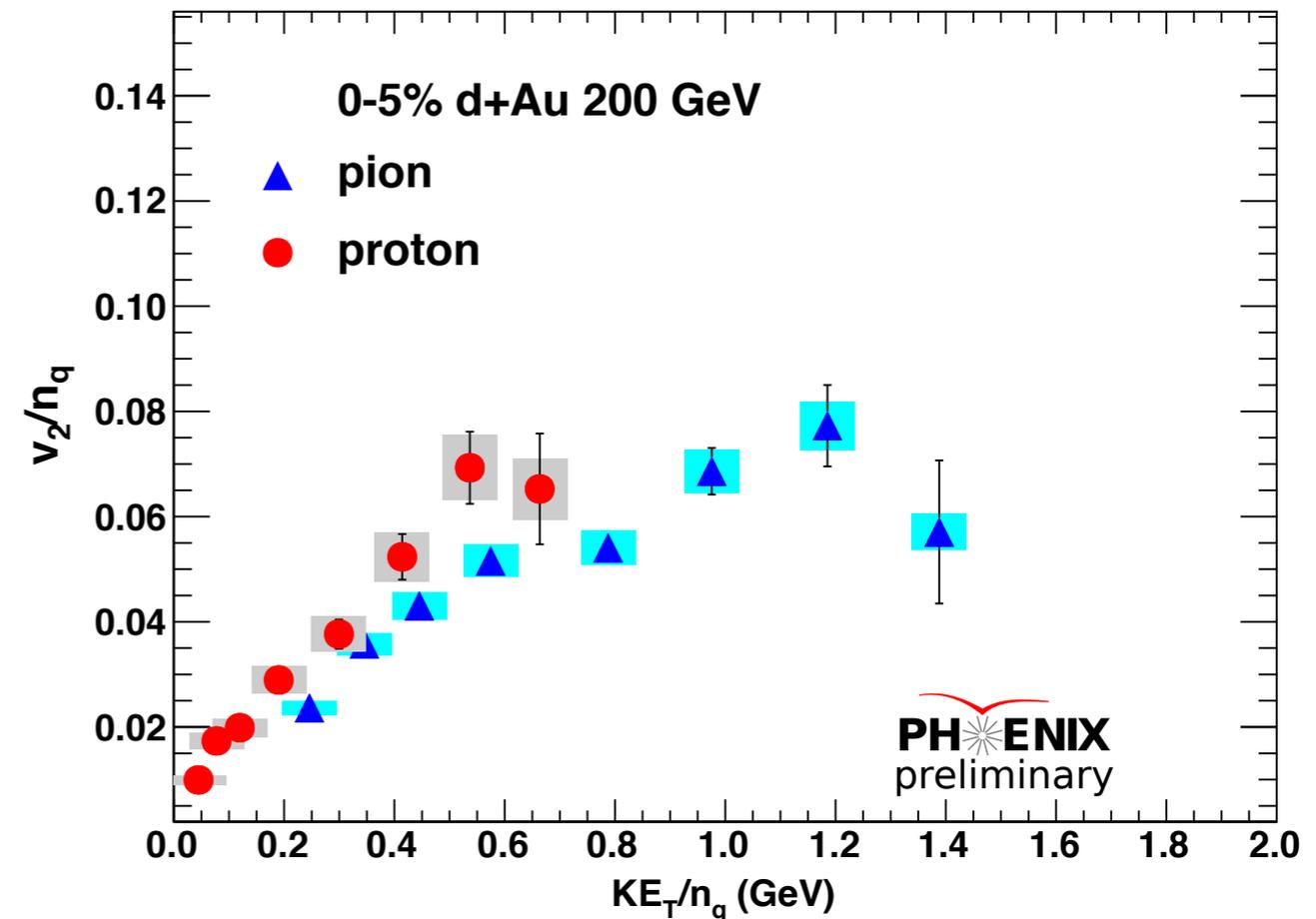
using identified pions and protons

## Large $\eta$ -gap results



*mass ordering  
a hydro hallmark!*

## Quark-scaling test

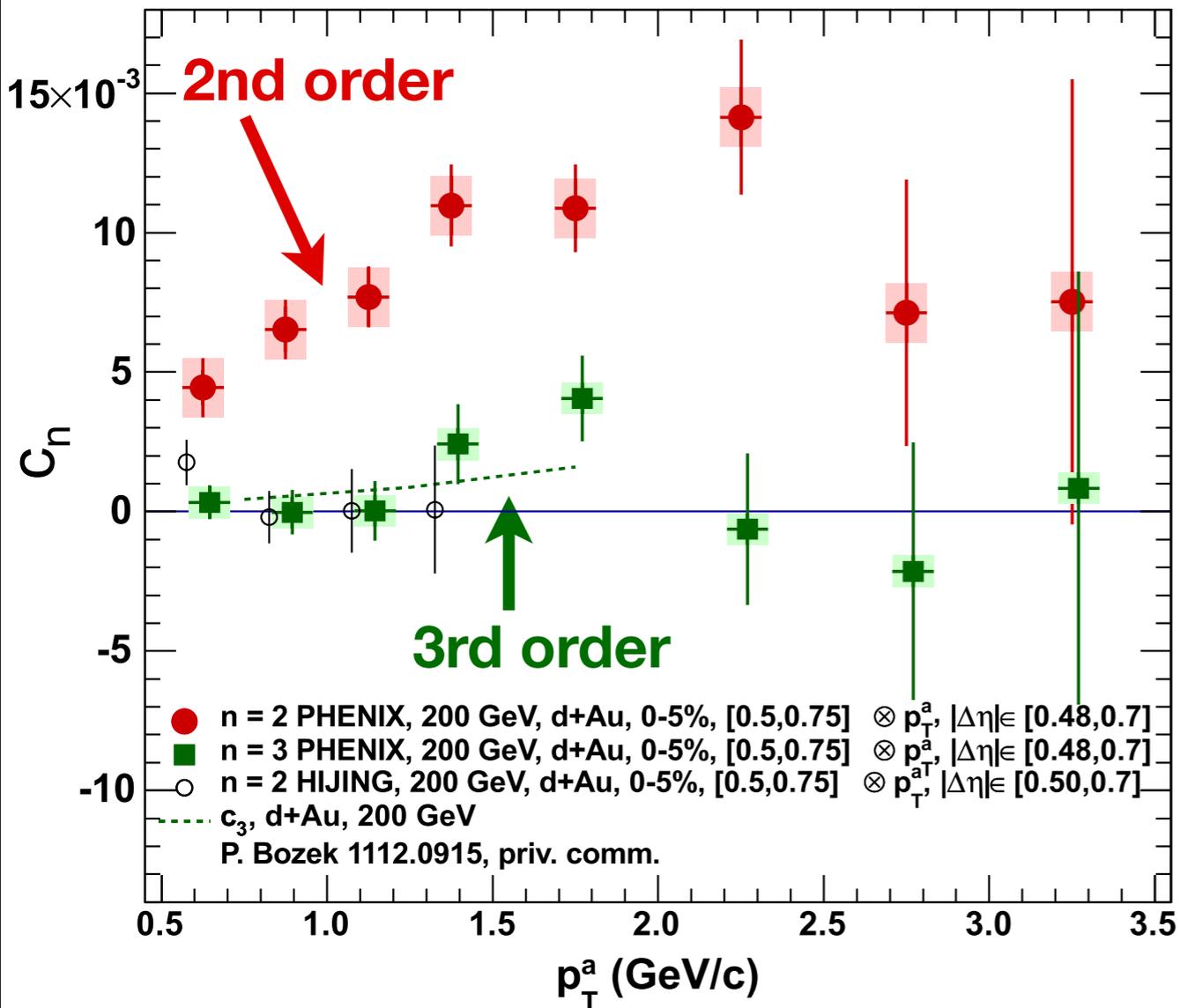


*almost scales with  
quark content*

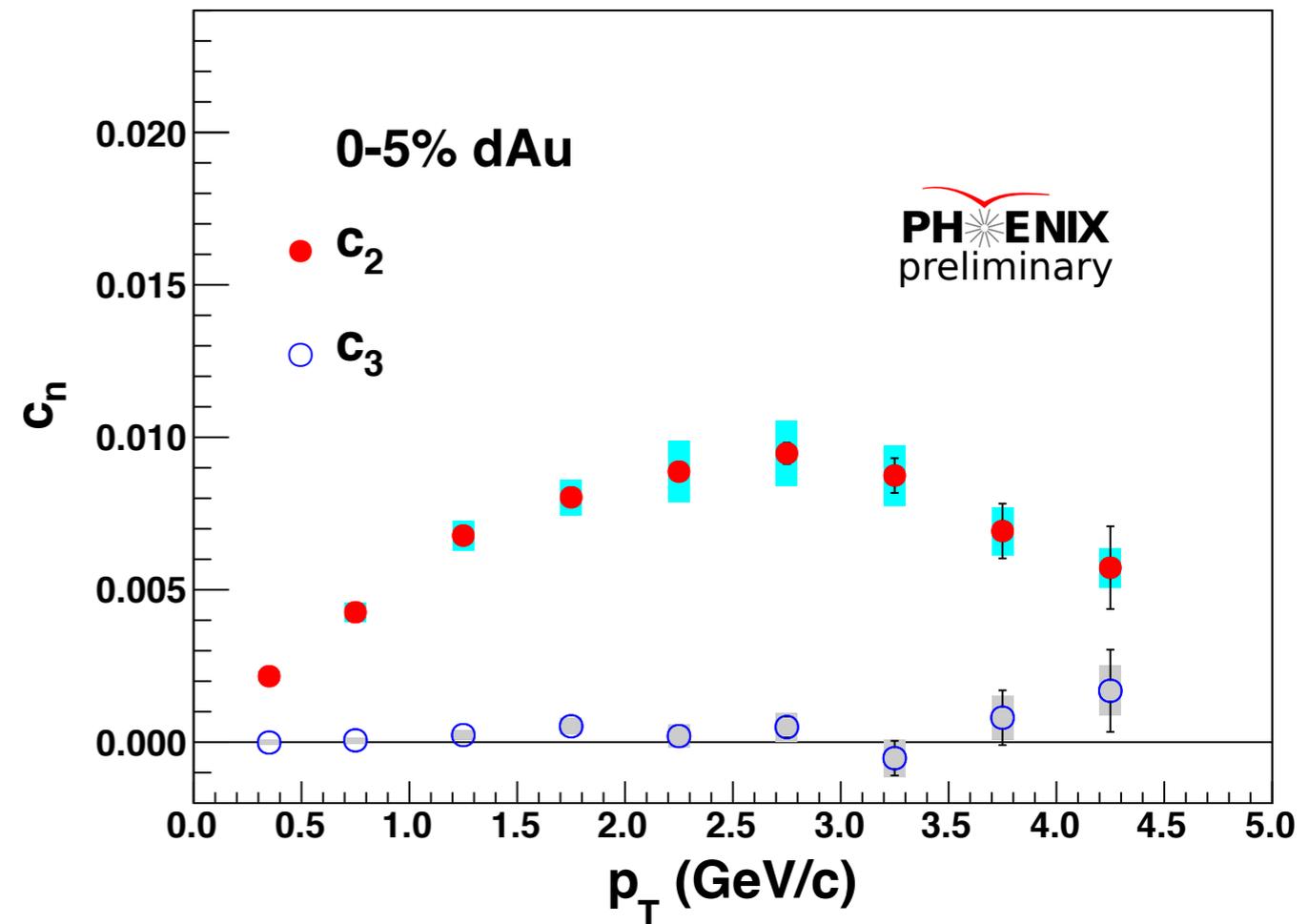
# Higher Moments

## Published results

PHENIX, PRL 111, 212301



## Large $\eta$ -gap results

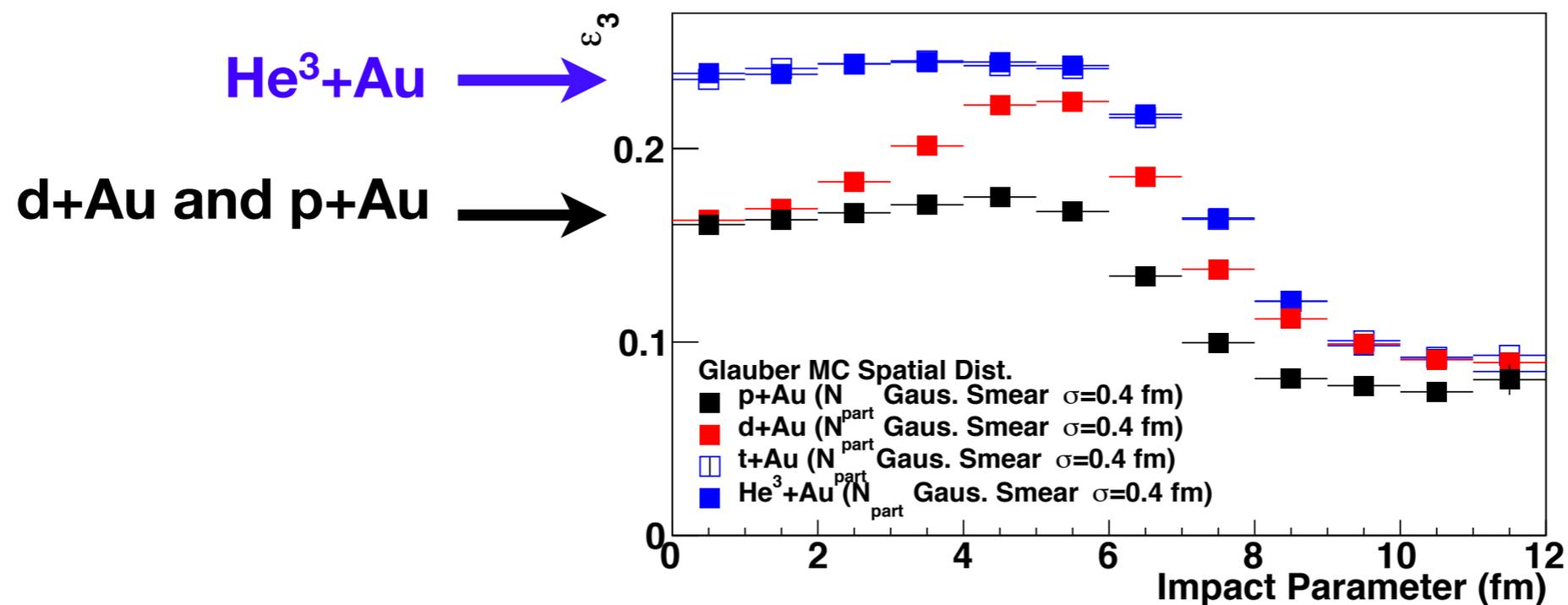
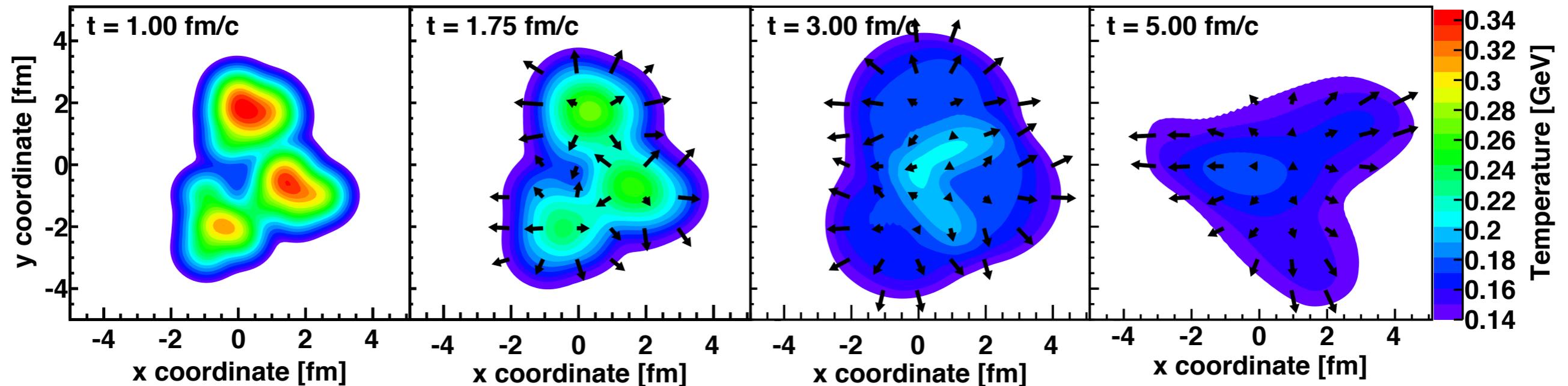


*no significant 3rd order contribution measured*

# Future

**He<sup>3</sup>+Au** provides an larger, intrinsic triangular collision geometry

Nagle, et al (MM), arXiv:1312.4565



could run with p+A at RHIC as early as 2015

# Summary

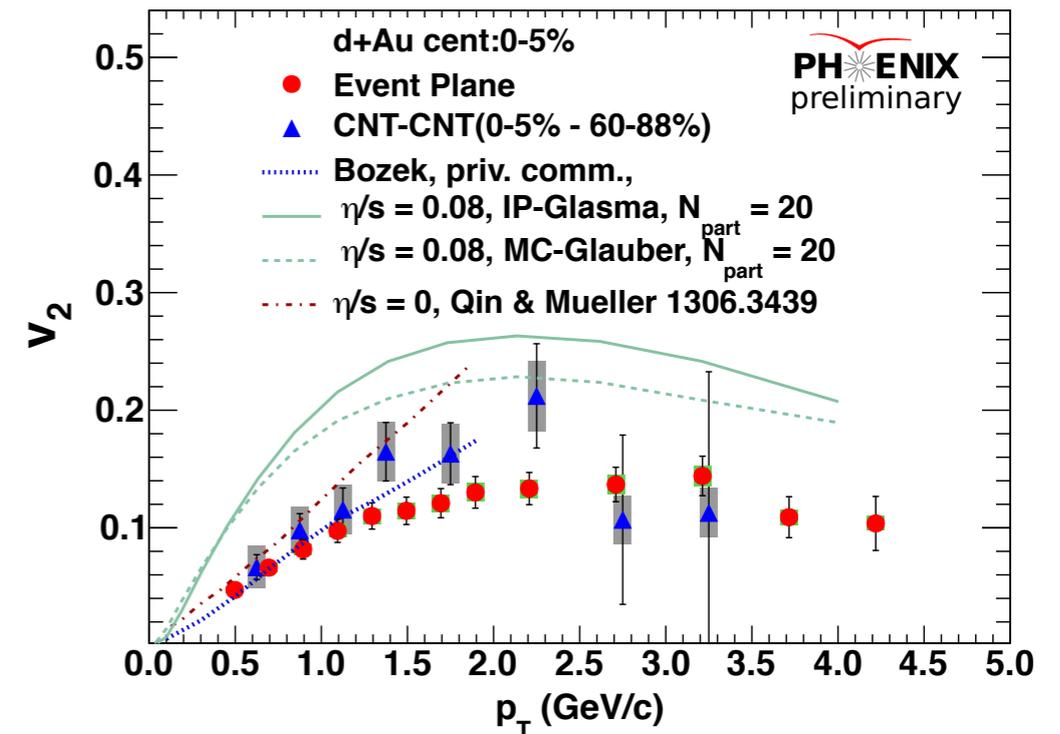
We have observed a strong 2nd-order moment difference between central and peripheral d+Au events

This feature extends across rapidity

These data show qualitative features of hydrodynamic models and eccentricity scaling

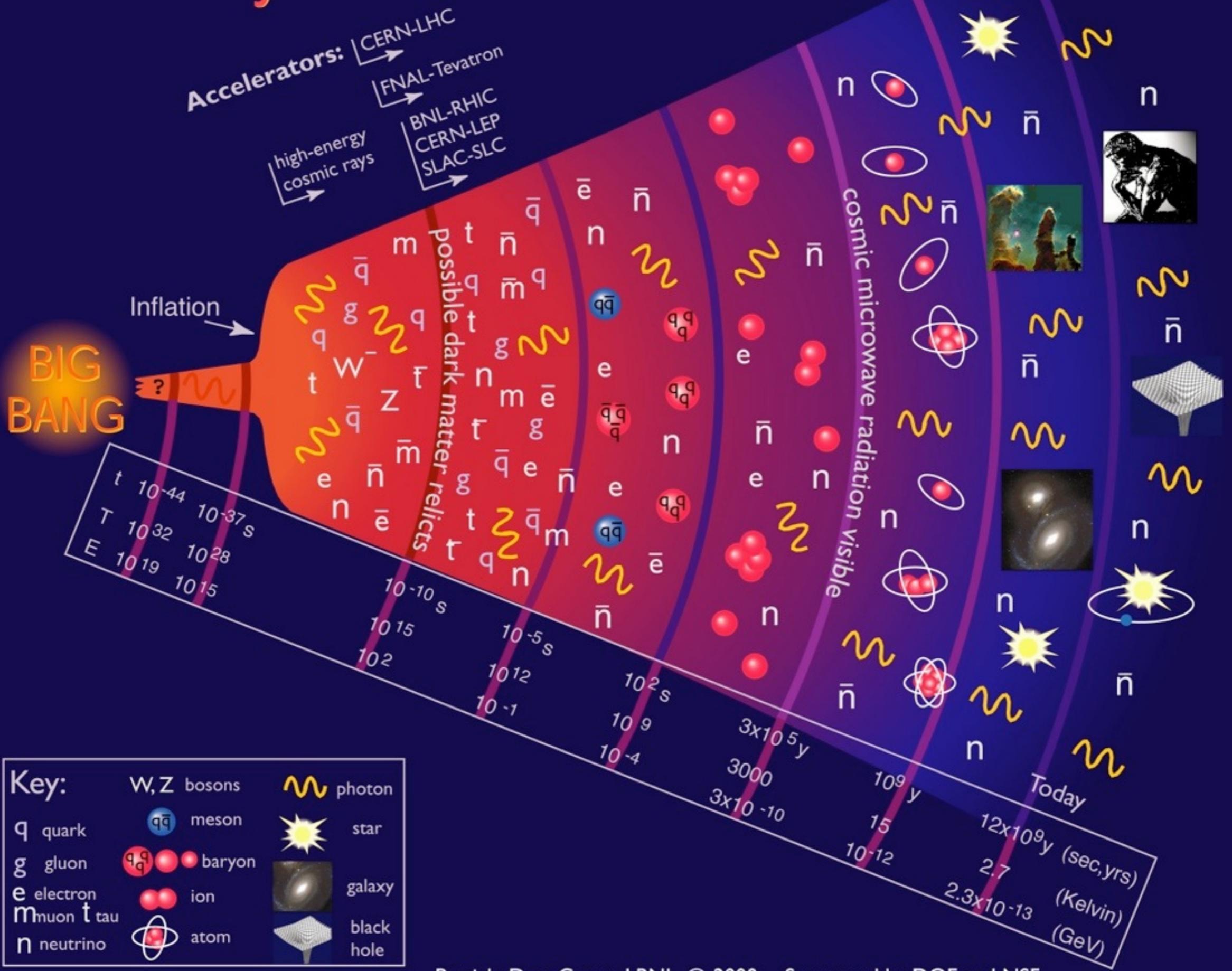
The particle content ( $\pi^\pm, p$ ) of the signal also shows hydrodynamic features

RHIC can run p+Au, He<sup>3</sup>+Au and test a change in eccentricity directly, ~2015

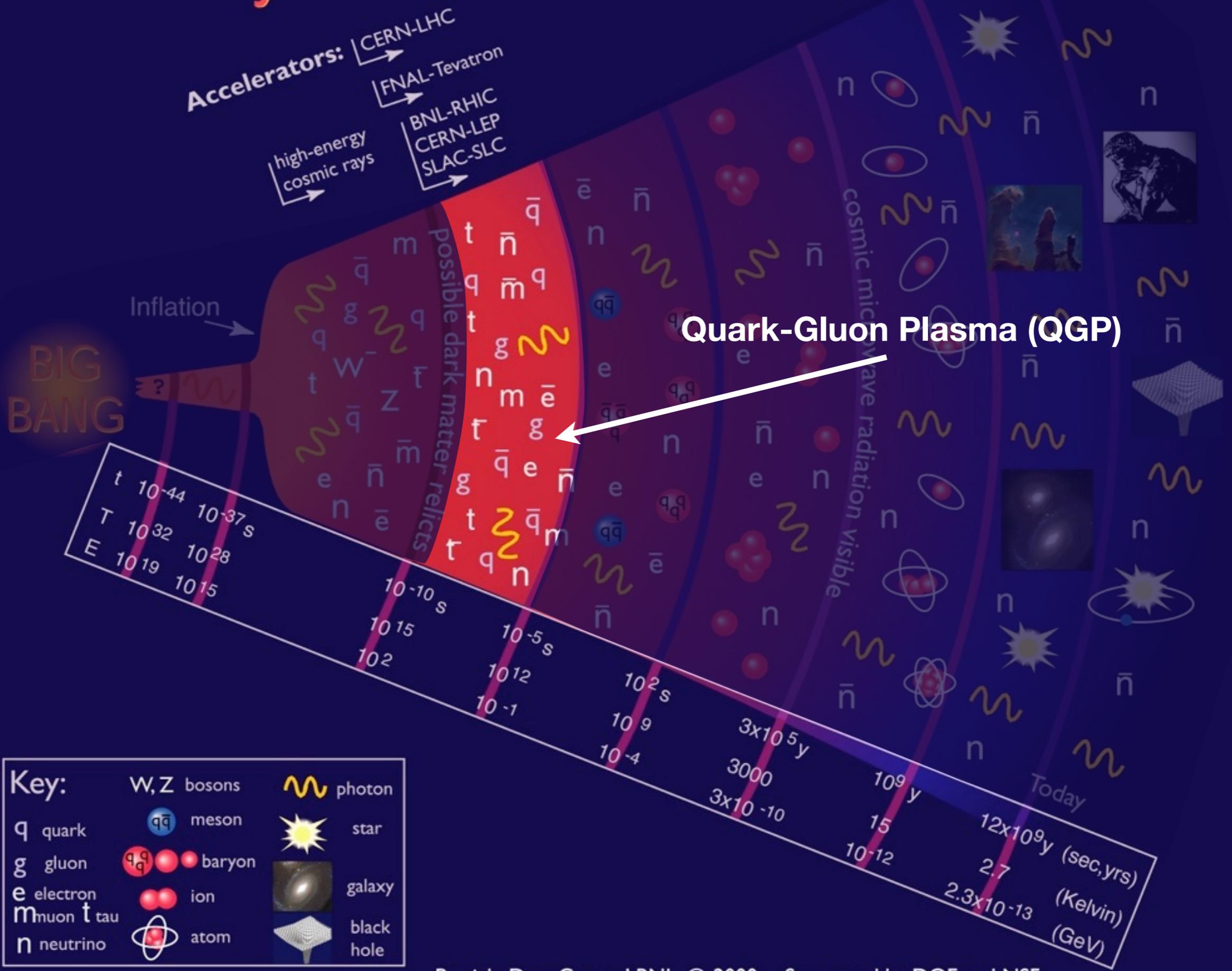


BACKUP SLIDES

# History of the Universe



# History of the Universe



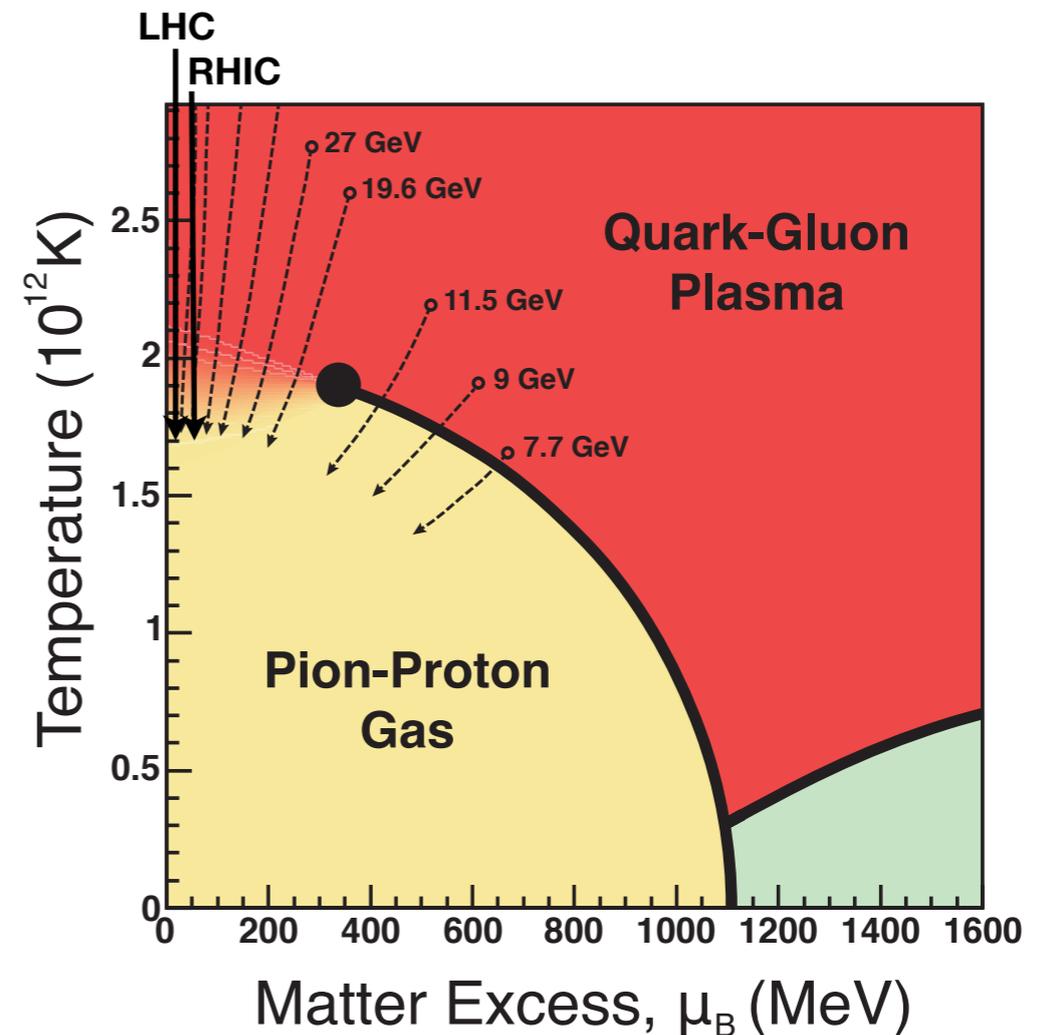
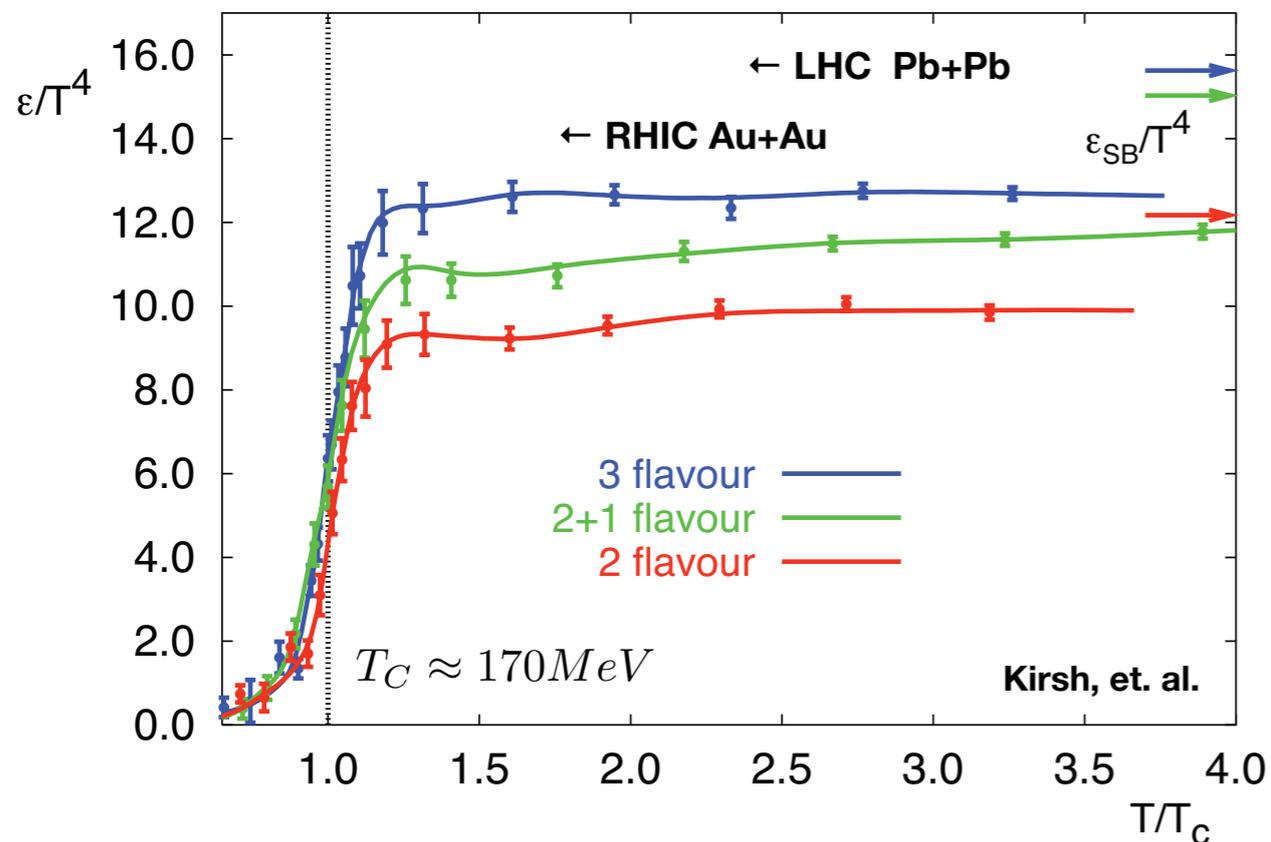
# Heavy Ion Collisions

## QCD Phase Diagram

Quark-gluon plasma above a few  $10^{12}$  K

Reachable by collider facilities

Critical point being sought



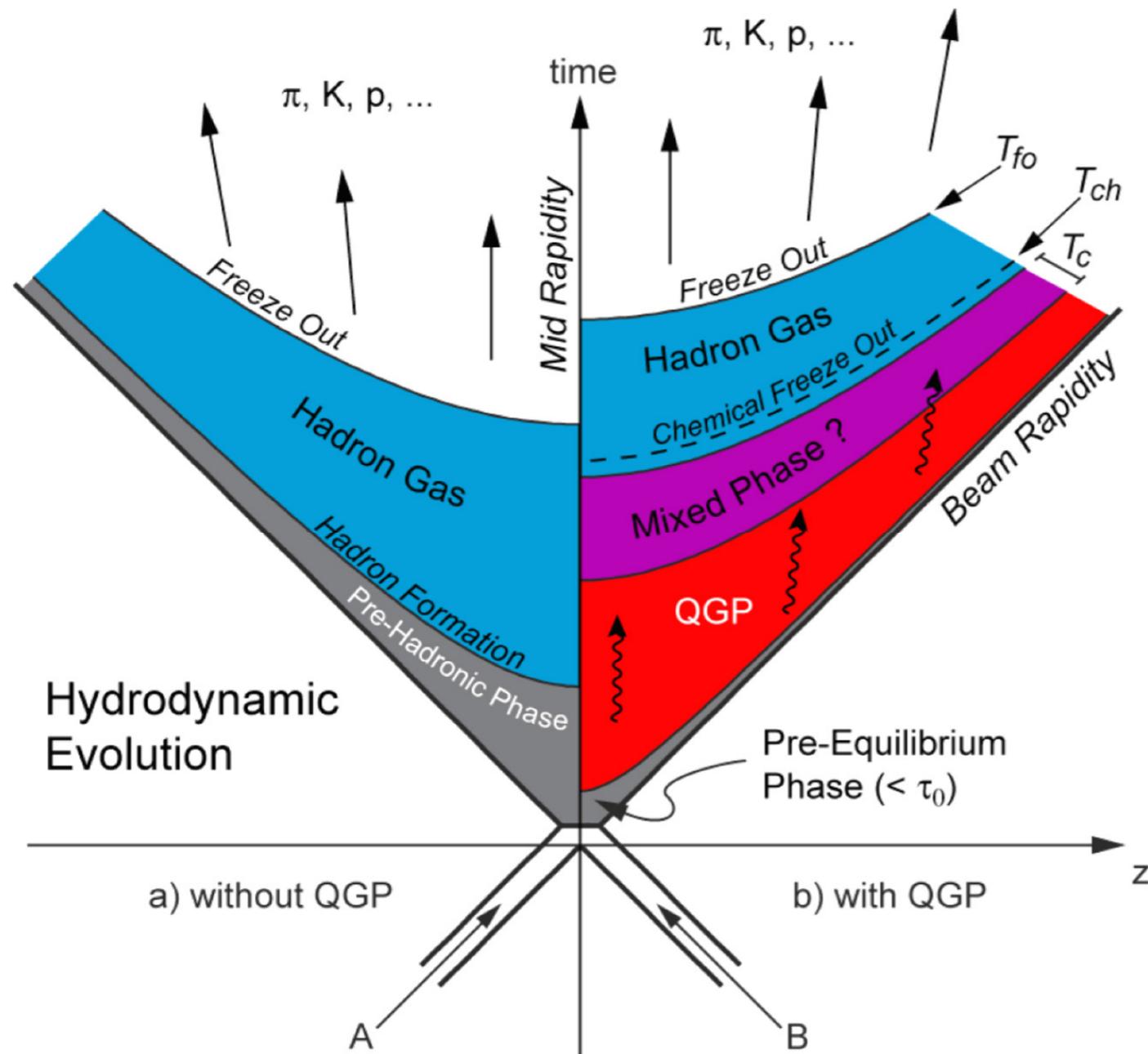
## Lattice QCD Calculations

Energy density indicates partonic degrees of freedom open at  $T_c \approx 170 \text{ MeV}$

Ideal gas of quarks and gluons at arbitrarily large  $T$

(Data) Strongly-coupled fluid near  $T_c$

# Space-Time Evolution



**Kinetic Freeze Out ( $\sim 10-15$  fm/c)**

**Chemical Freeze Out ( $\sim 7$  fm/c)**

**Hadron Gas**

**Phase Transition ( $\sim 4$  fm/c)**

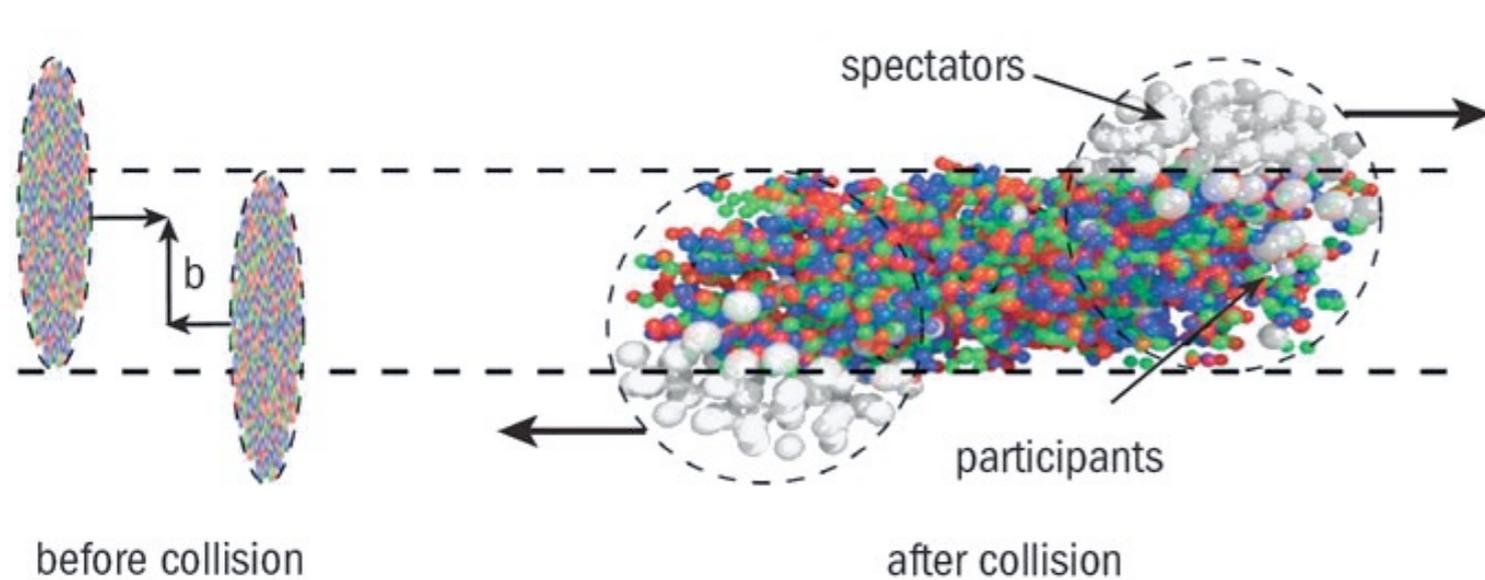
**QGP**

**Thermalization ( $\sim 0.6$  fm/c)**

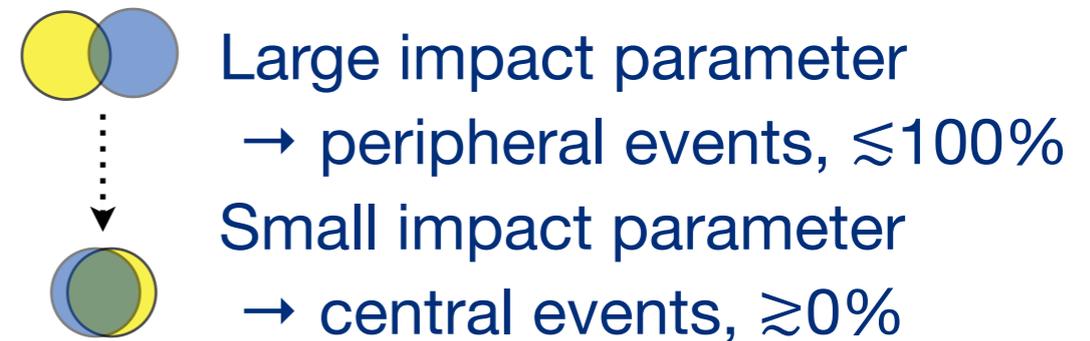
**Nuclear Crossing ( $\sim 0.1$  fm/c)**

\*values for RHIC at 200 GeV

# Event Geometry Controls



Impact parameter studied via **centrality** selection



Measured at large pseudorapidity

Tool: Glauber Monte Carlo simulation

Simple geometric description of A+A

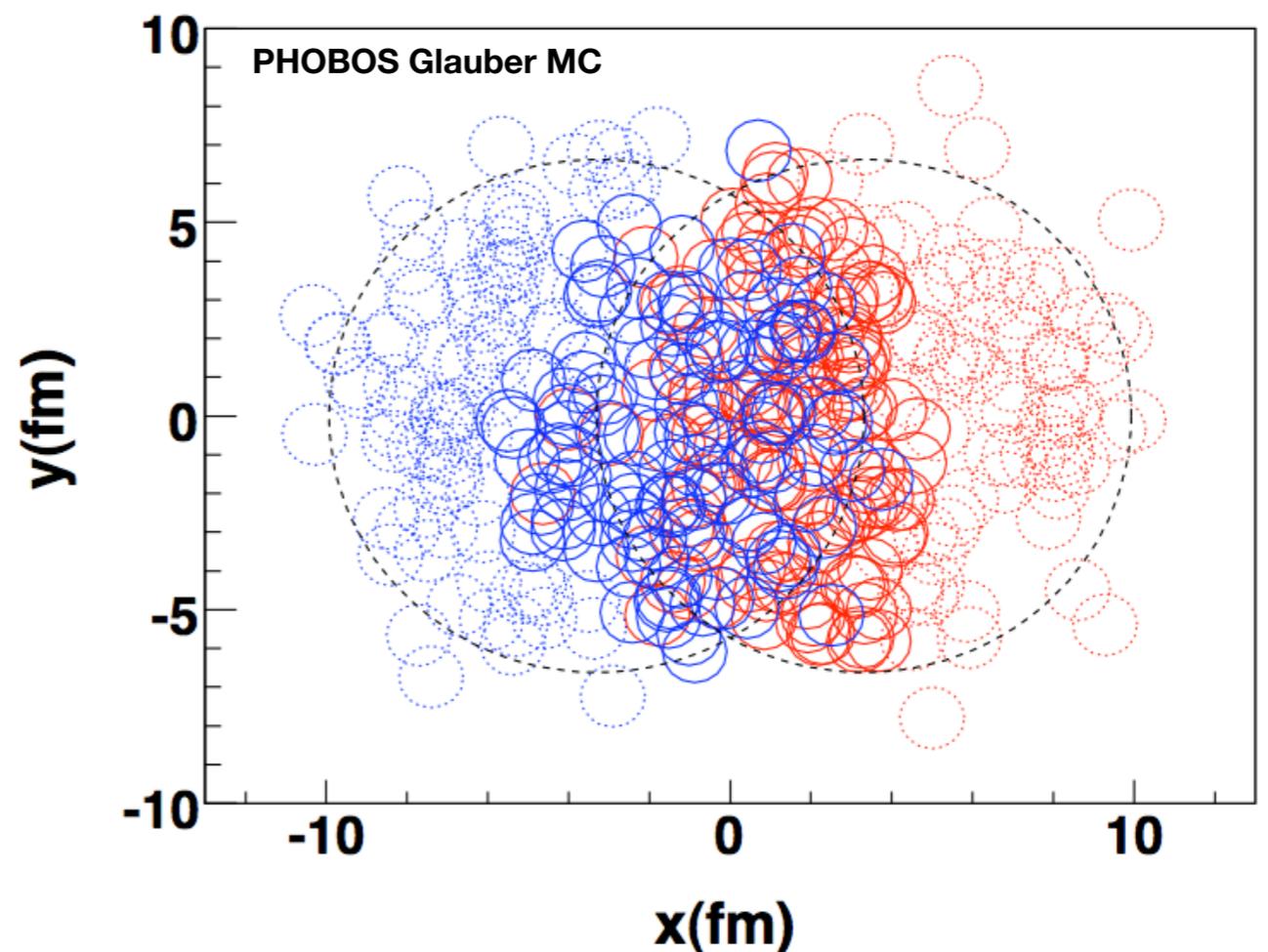
Includes statistical fluctuations

**Number of Participating Nucleons,  $N_{\text{part}}$**

~ system size

**Number of Binary Scatterings,  $N_{\text{coll}}$**

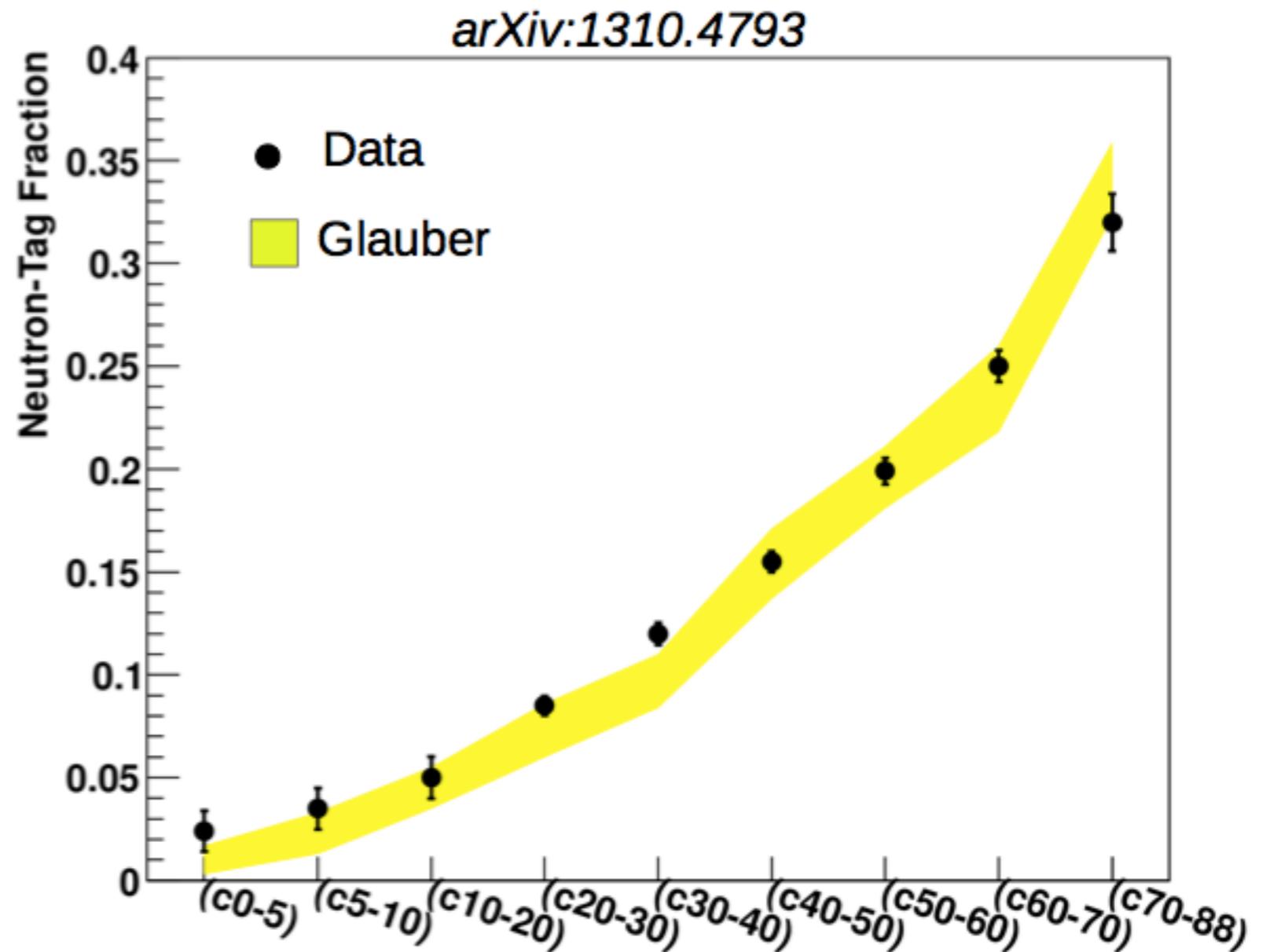
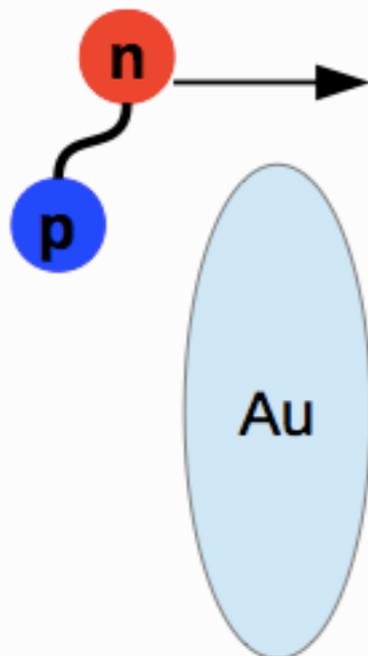
~ hard process cross-section



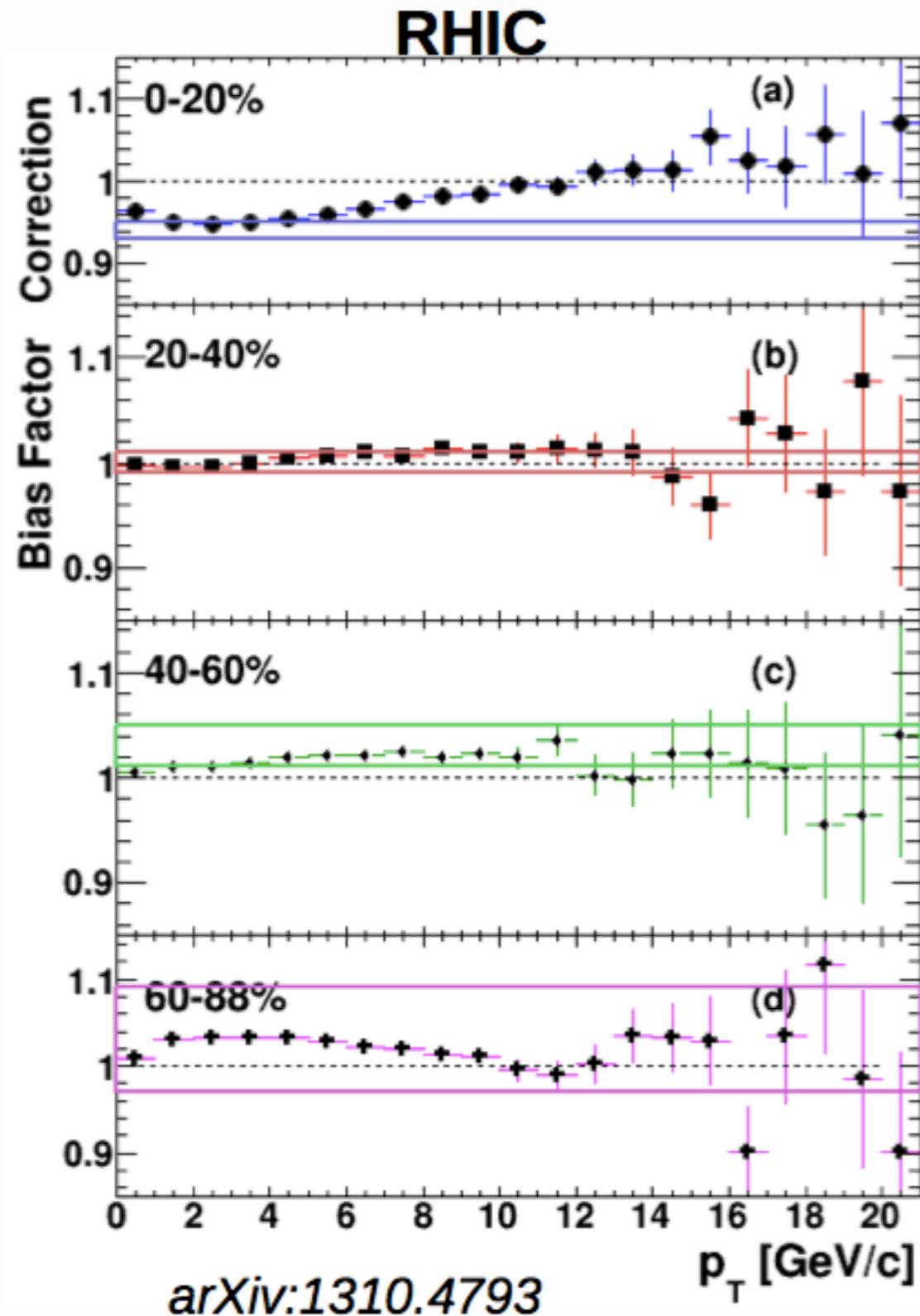
# Centrality in d+Au

Measure fraction of events with a neutron in the ZDC.

Compares well with expectations from Glauber model.



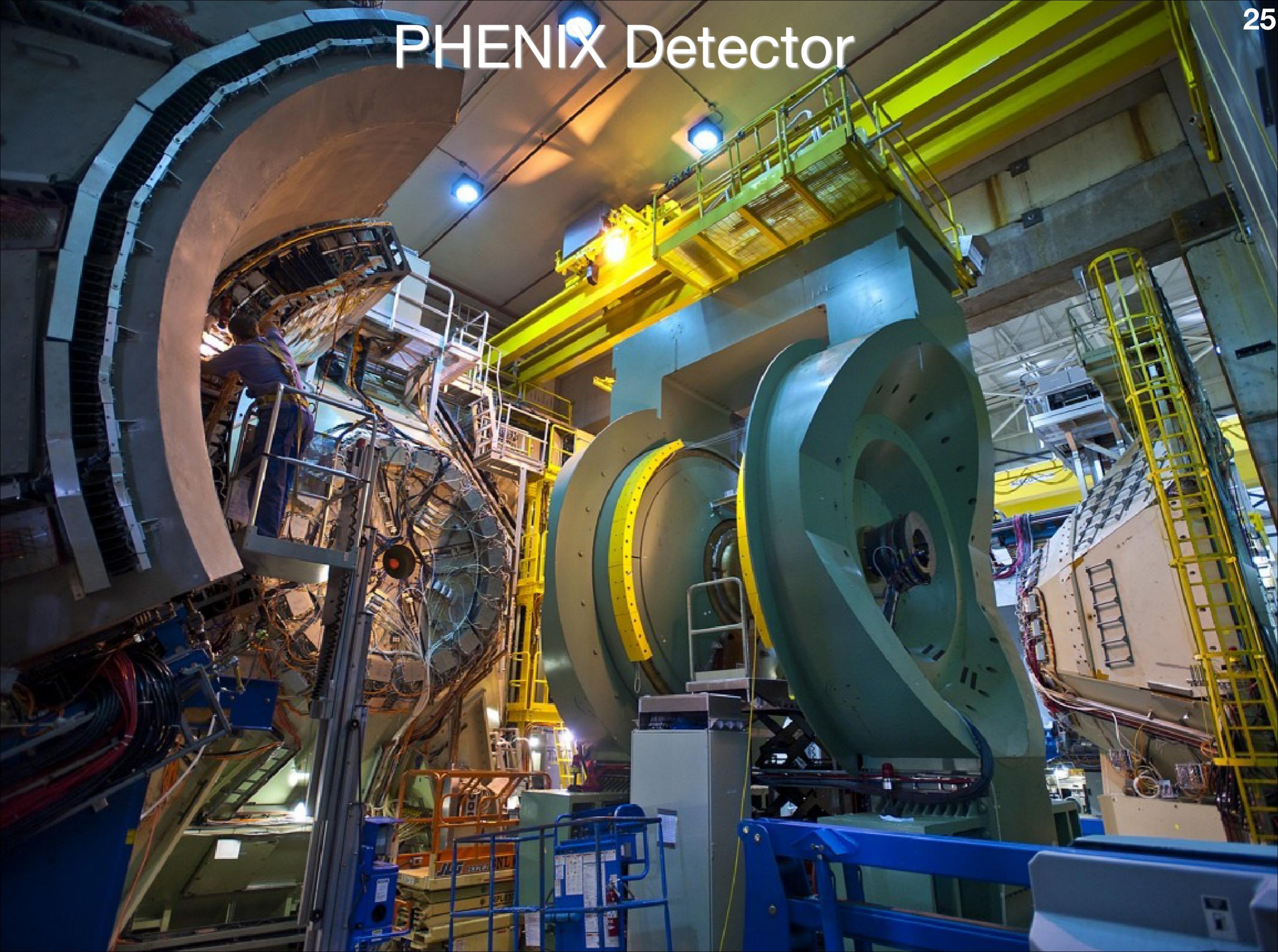
# Centrality Bias in d+Au



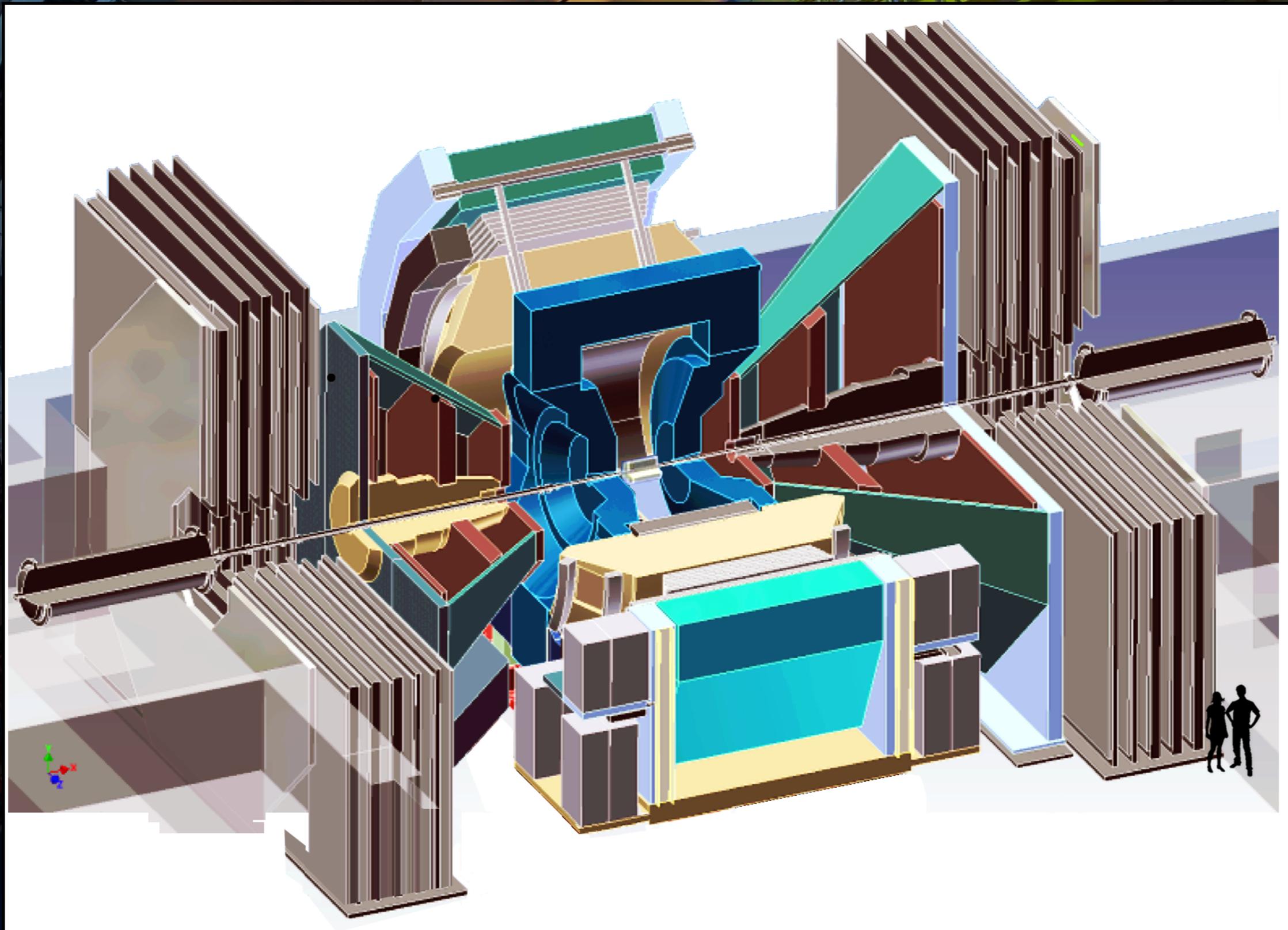
- Large interest in correlations between the process of interest and the measured centrality (i.e. bias factors)
- Determined using data+Glauber model
- **Included in PHENIX 2003 & 2008 d+Au results.**
- Now test results using HIJING
- Minimal  $p_T$  dependence at RHIC for  $p_T < 10$  GeV.
- **Good agreement with Glauber results.**

**~5% Effect at RHIC!**

# PHENIX Detector



# PHENIX Detector



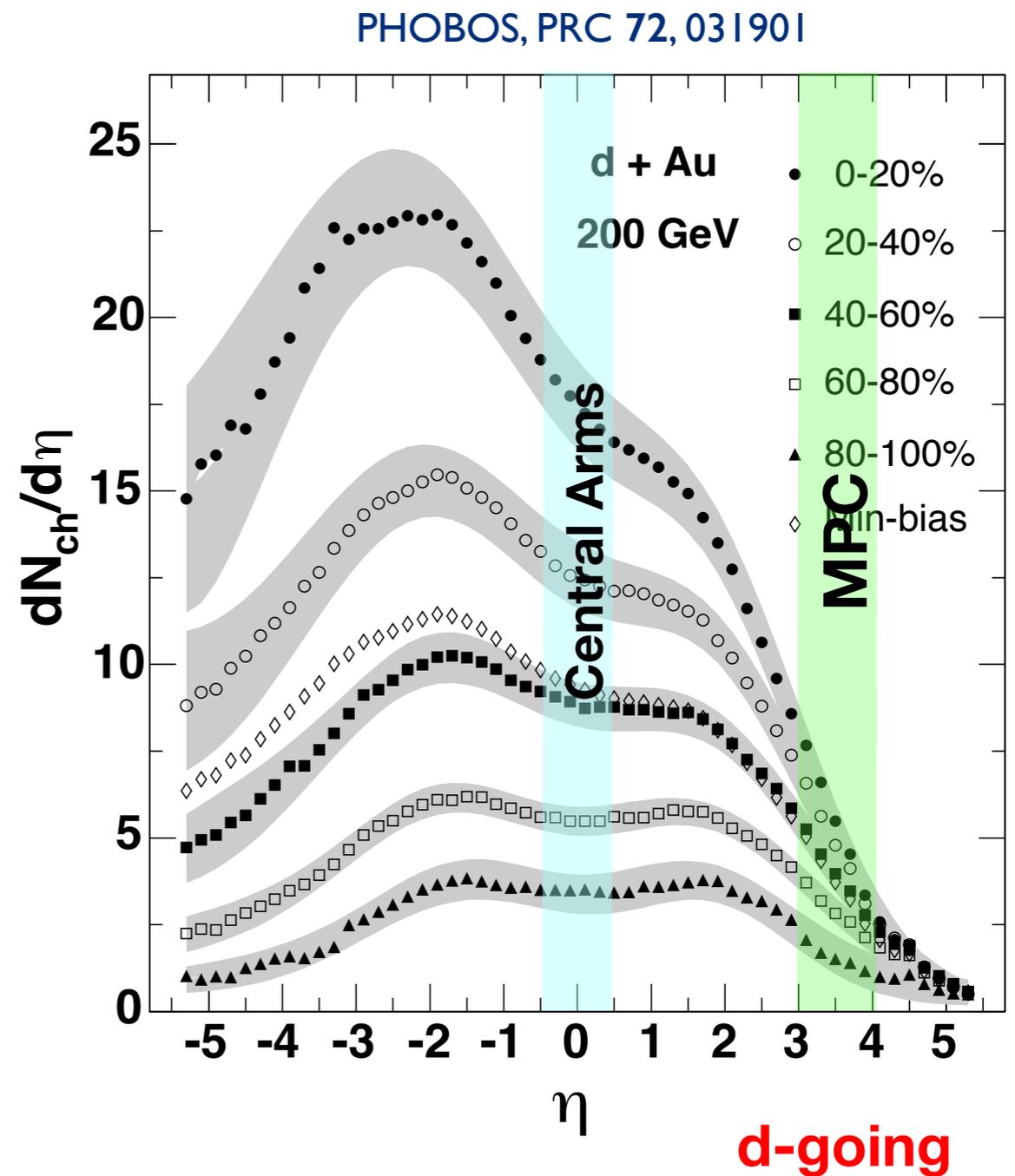
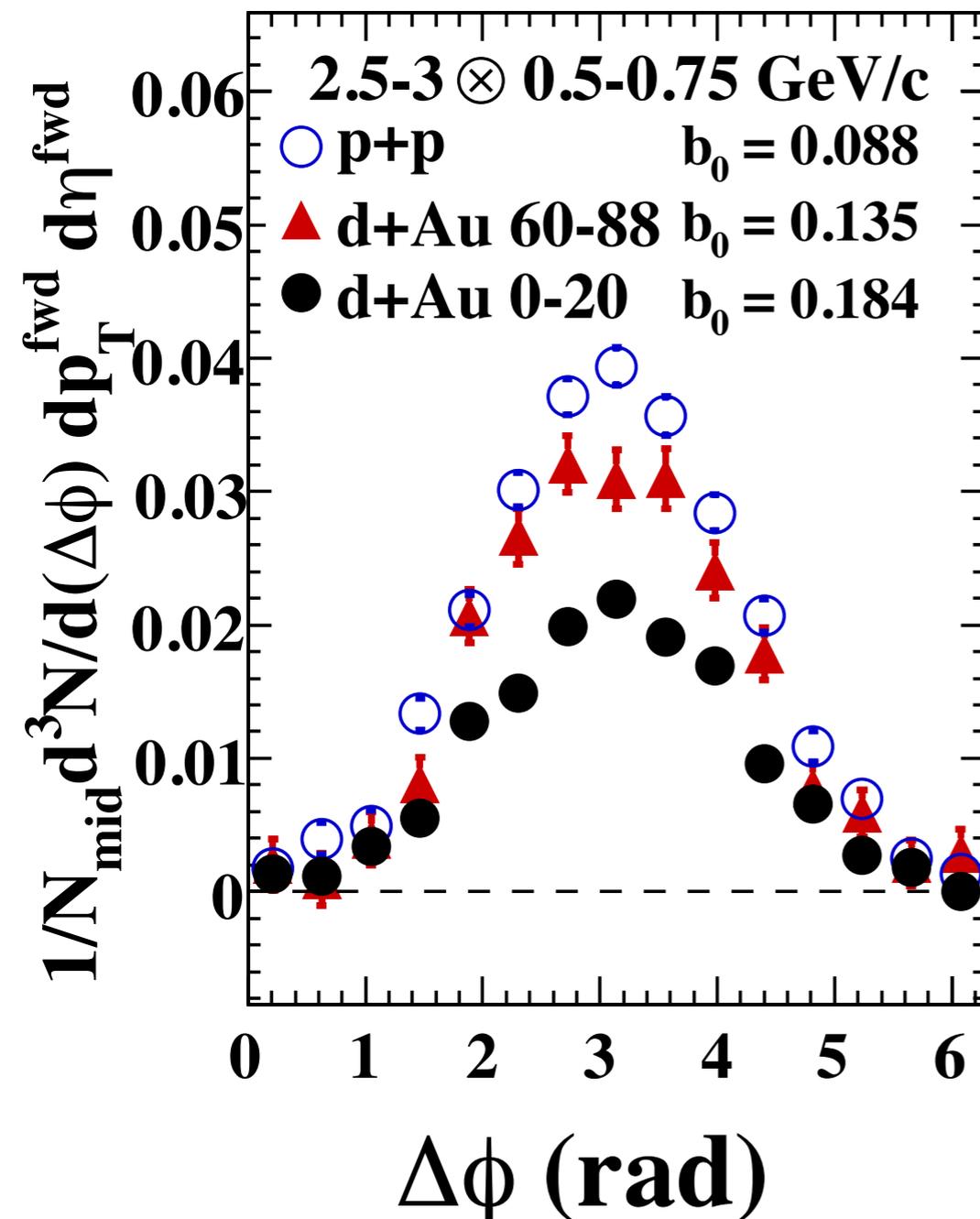
# Previous PHENIX studies

PRL 107, 172301 (2011)

PHYSICAL REVIEW LETTERS

week ending  
21 OCTOBER 2011

Suppression of Back-to-Back Hadron Pairs at Forward Rapidity  
in  $d + \text{Au}$  Collisions at  $\sqrt{s_{NN}} = 200 \text{ GeV}$



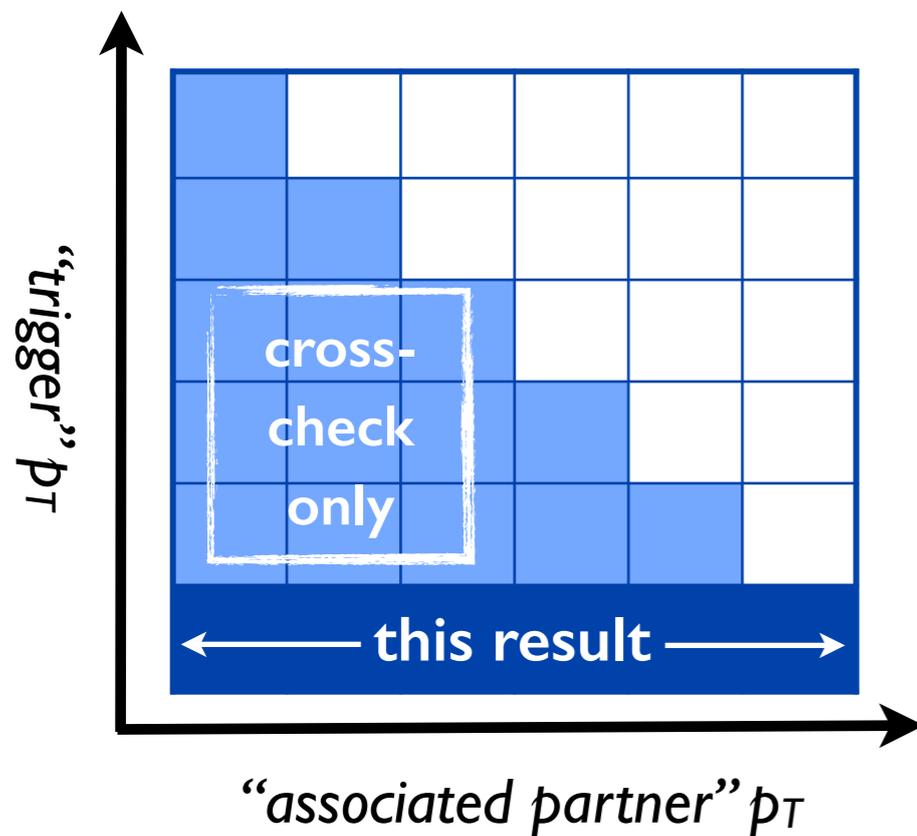
Focus: dijet at small  $x$  in Au

# Transverse Momentum

Pair amplitude modulation:

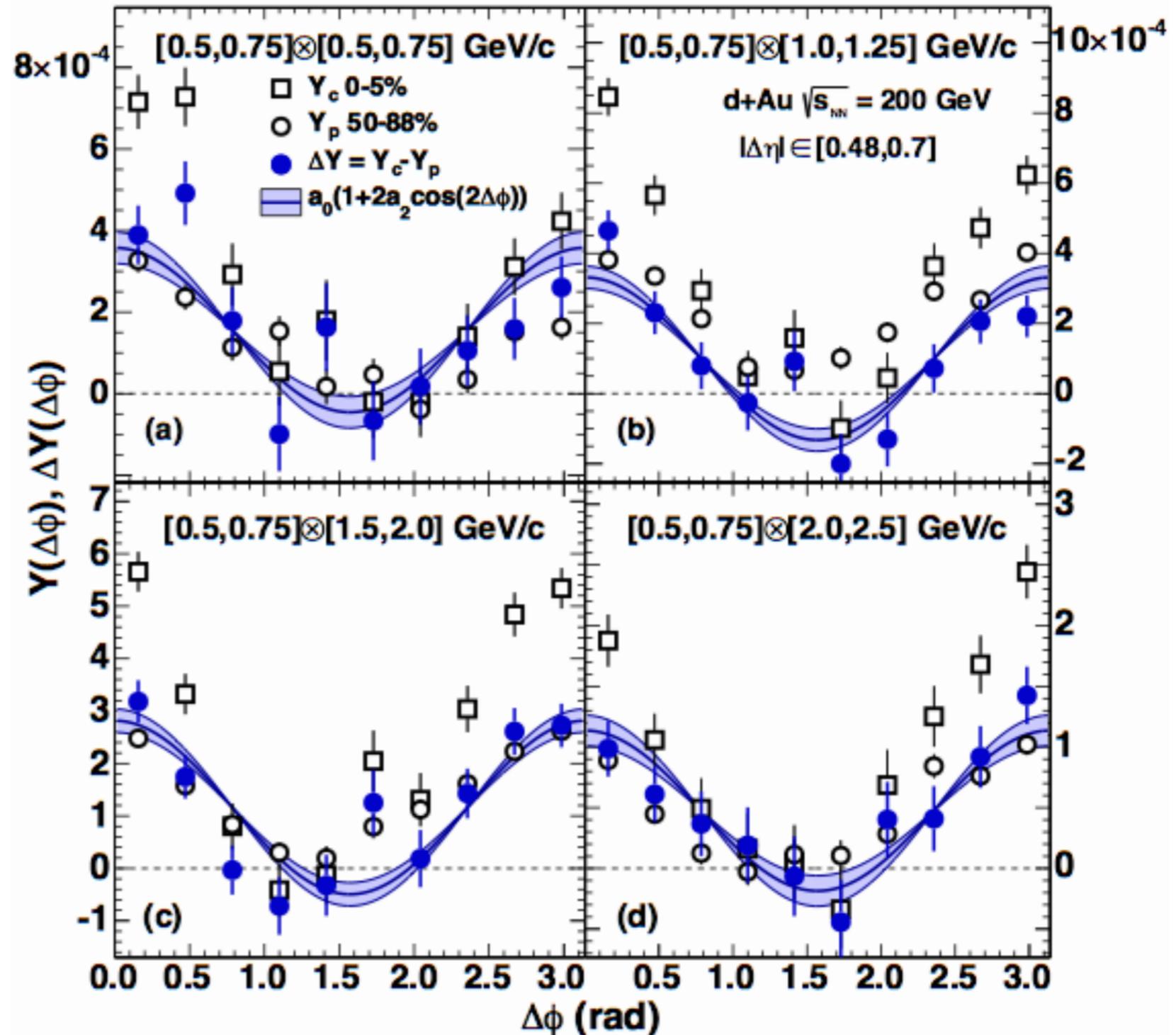
$$c_2 = v_2^a \times v_2^b$$

possible pair combinations



some examples...

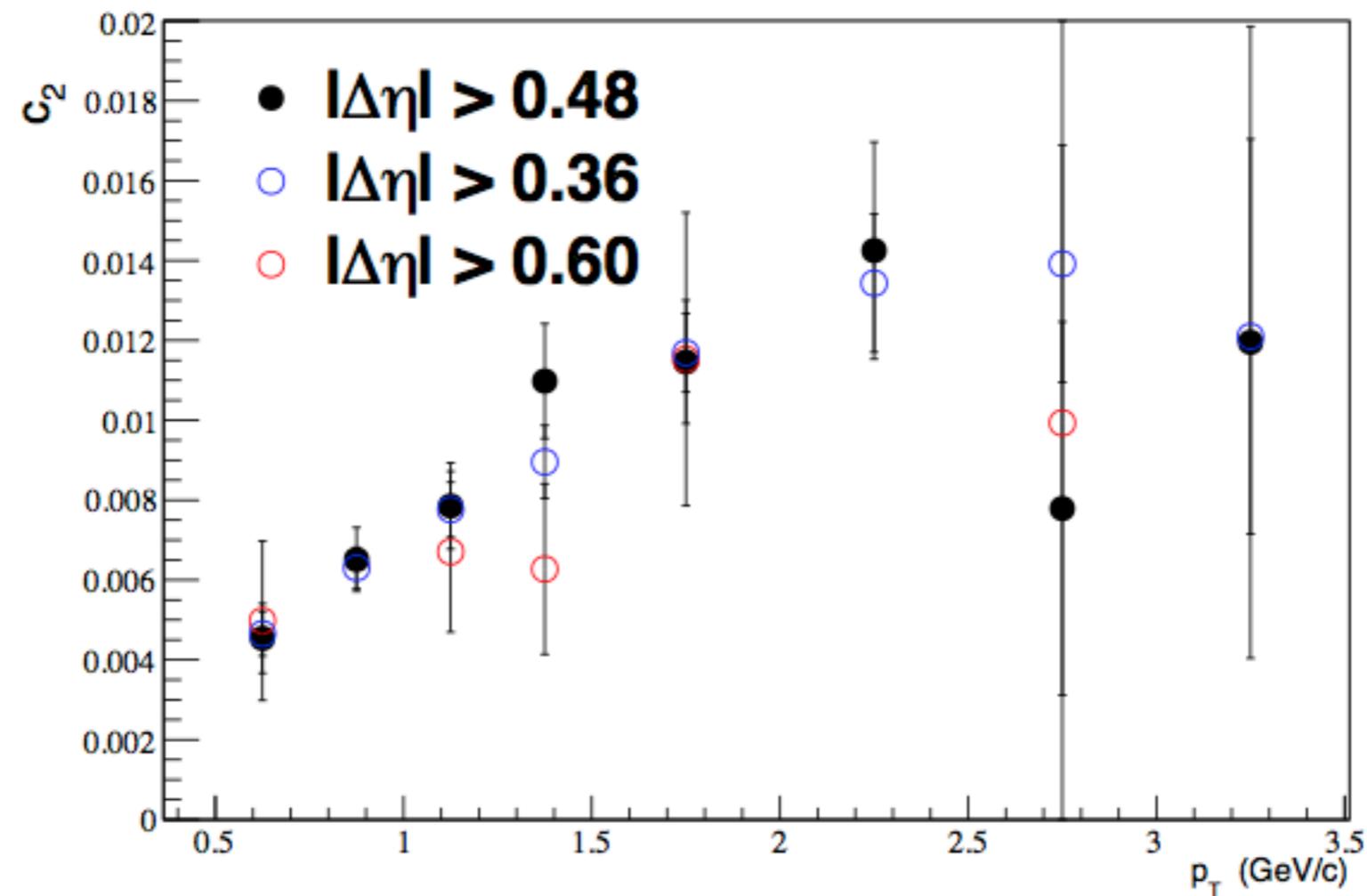
PHENIX, PRL 111, 212301



*a similar effect found across multiple  $p_T$  values*

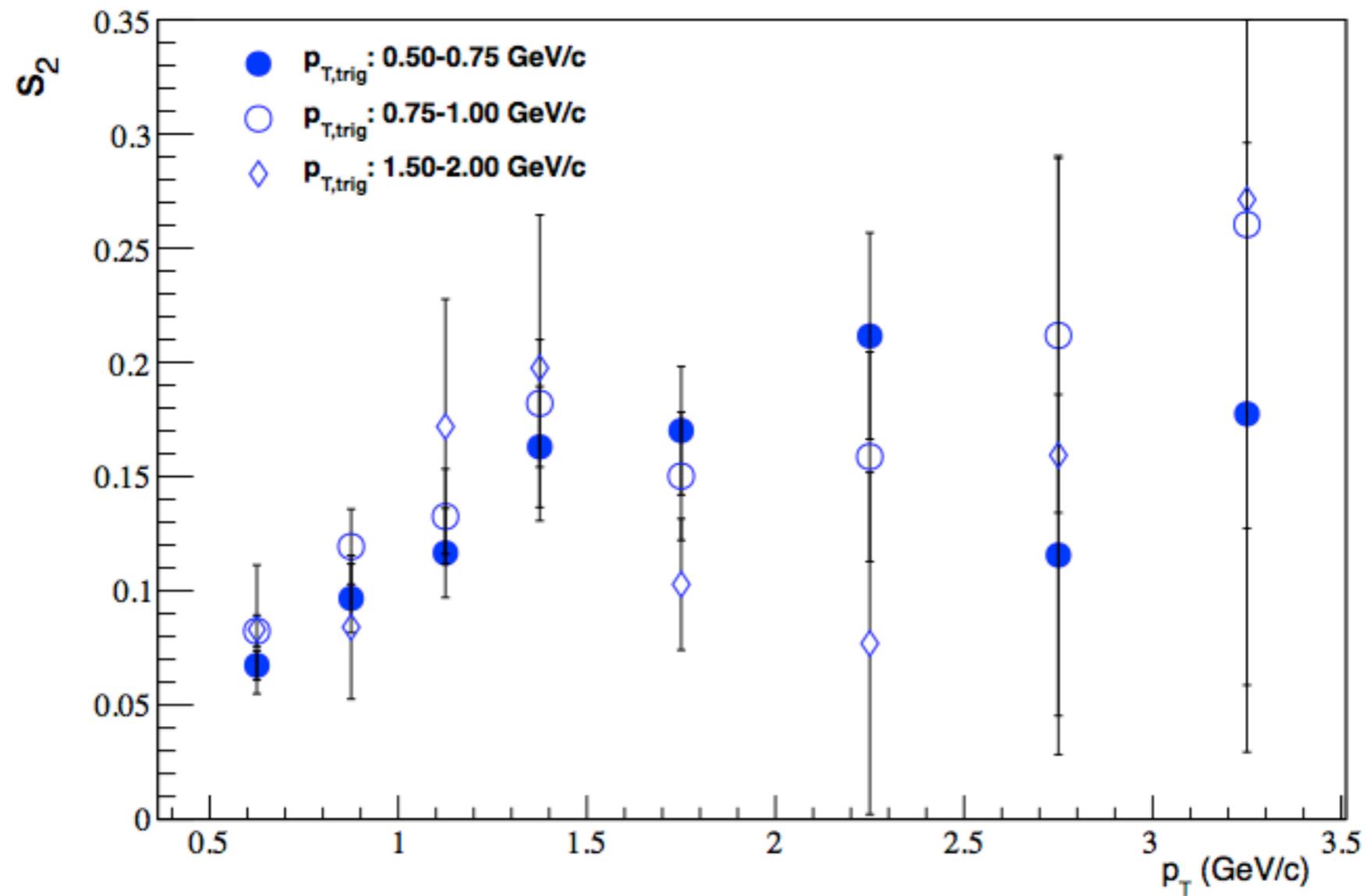
# Eta Gap Cross Check

Extract flow moments and test eta-separation and subtraction with a variety of different pseudorapidity separations



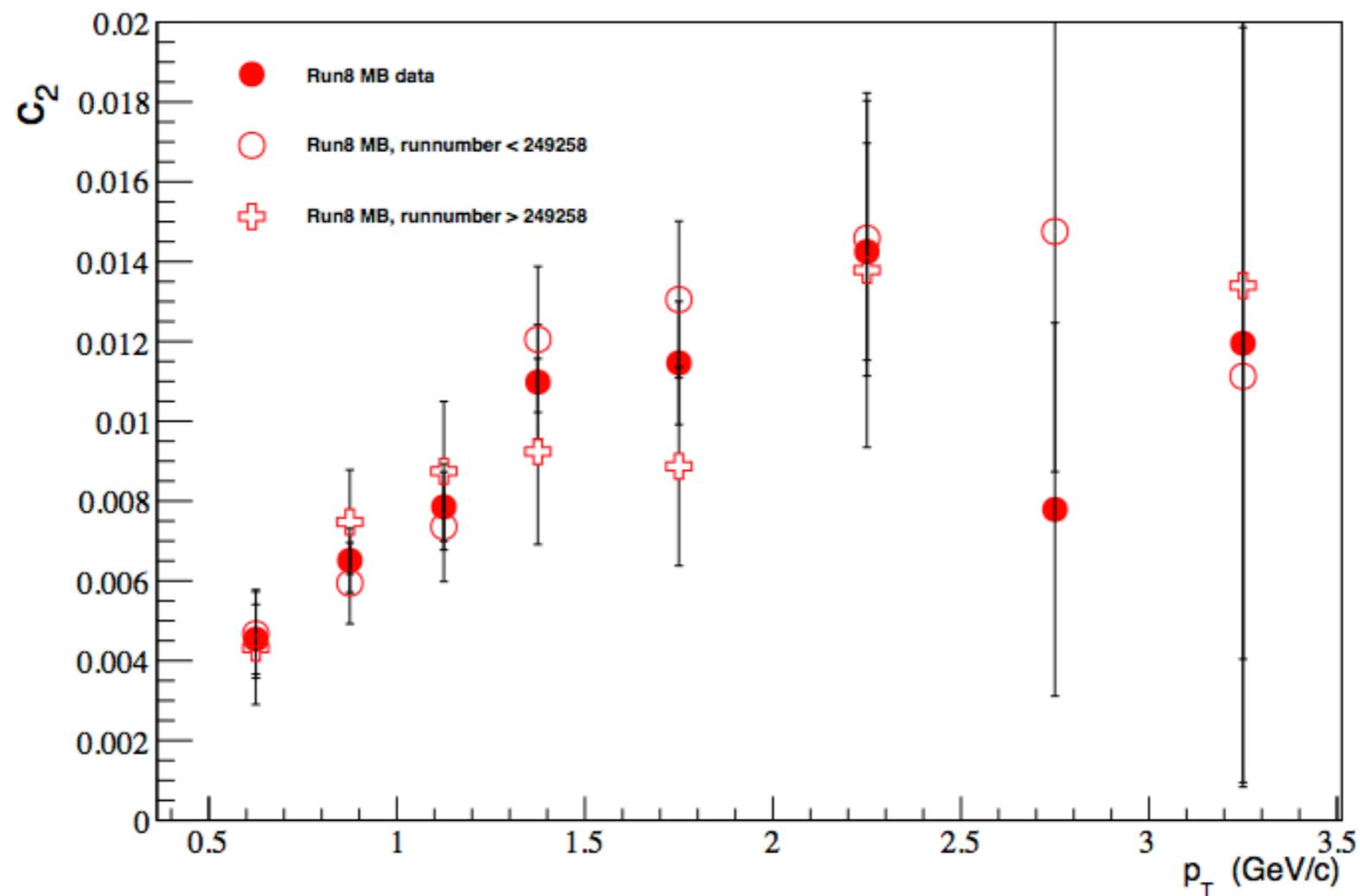
# Factorization Cross Check

Extract flow moments to test factorization with a  
different trigger  $p_T$



# Luminosity Cross Check

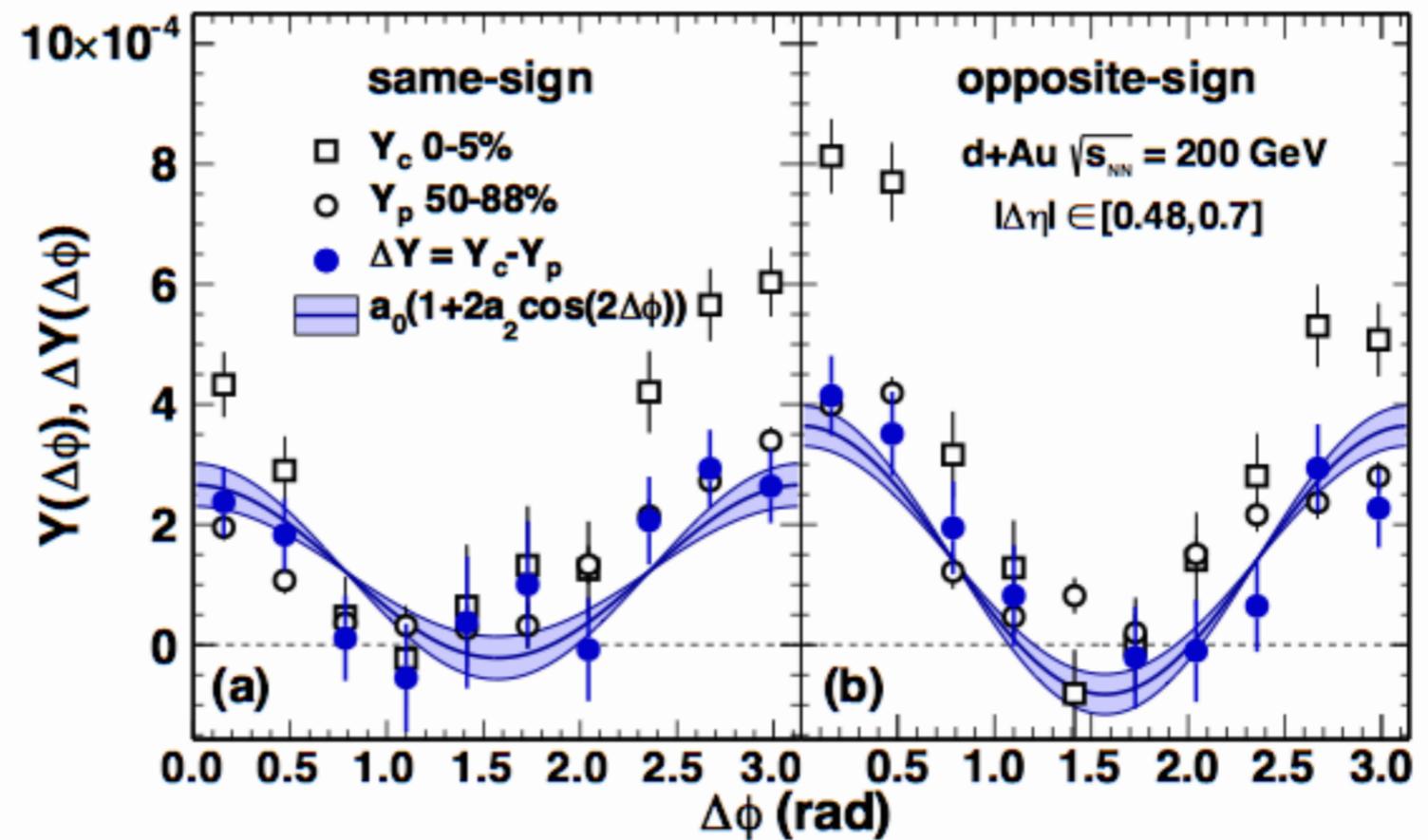
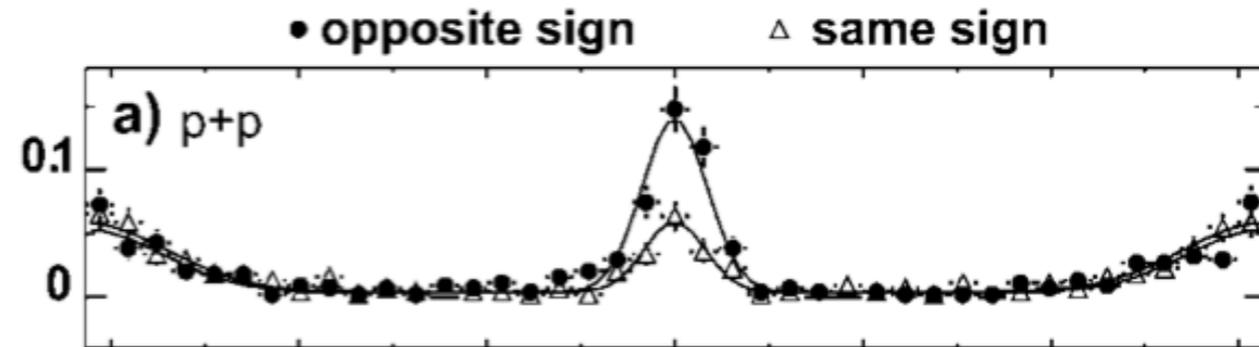
Extract flow moments and test double-interaction contamination with a different beam luminosity



# Charge Sign Cross Check

Jet pair correlations have a well-known charge-ordering and remaining contamination should show this signature

Not clear if the signal also has a correlation of this kind, we assume a worst case scenario



# p+p analysis cross check

