Observation of collectivity in p+Au, d+Au and ^{3}He+Au collisions with PHENIX

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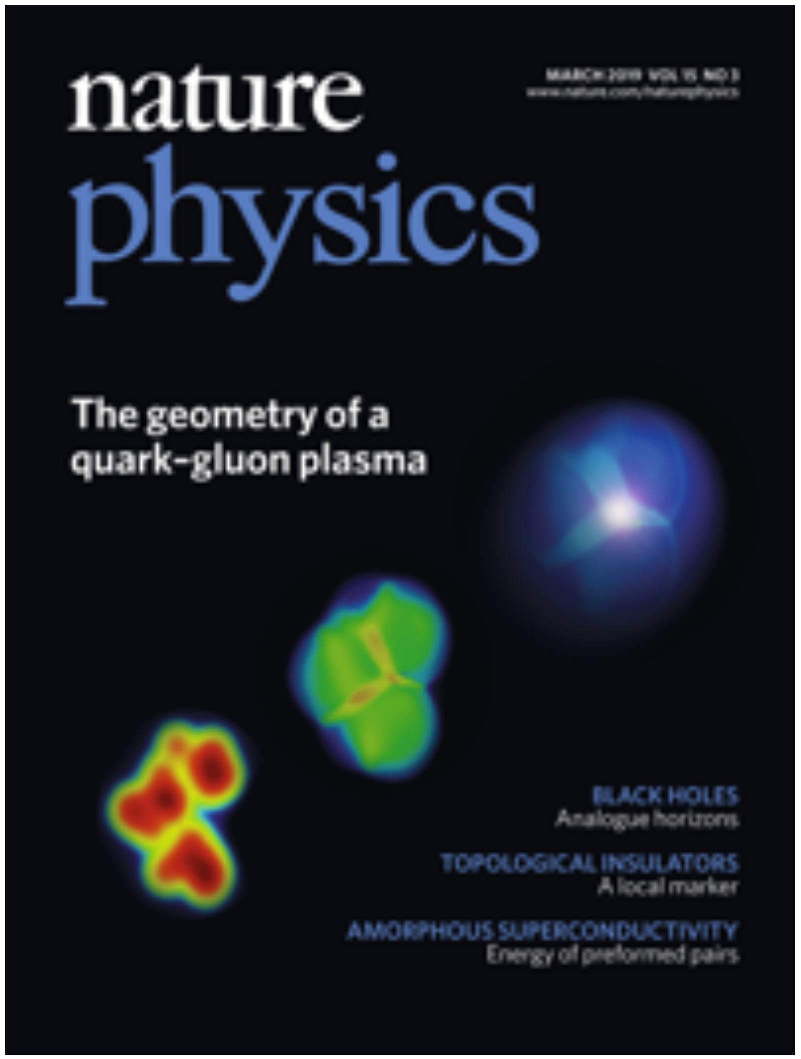

nature physics LETTERS
https://doi.org/10.1038/s41567-018-0360-0

Creation of quark–gluon plasma droplets with three distinct geometries

PHENIX Collaboration*

Experimental studies of the collisions of heavy nuclei at relativistic energies have established the properties of the quark–gluon plasma (QGP), a state of hot, dense nuclear matter in which quarks and gluons are not bound into hadrons[1–4]. In this state, matter behaves as a nearly inviscid fluid[5] that efficiently translates initial spatial anisotropies into correlated momentum anisotropies among the particles produced, creating a common velocity field pattern known as collective flow. In recent years, comparable momentum anisotropies have been measured in small-system proton–proton (p+p) and proton–nucleus (p+A) collisions, despite expectations that the volume and lifetime of the medium produced would be too small to form a QGP. Here we report on the observation of elliptic and triangular flow patterns of charged particles produced in proton–gold (p+Au), deuteron–gold (d+Au) and helium–gold (^{3}He+Au) collisions at a nucleon–nucleon centre-of-mass energy $\sqrt{s_{NN}} = 200$ GeV. The unique combination of three distinct initial geometries and two flow patterns provides unprecedented model discrimination. Hydrodynamical models, which include the formation of a short-lived QGP droplet, provide the best simultaneous description of these measurements.

anisotropy to momentum correlations generated at the earliest stages of the collision, hence referred to as initial-state momentum correlation models (see refs [12,13] for recent reviews).

A projectile geometry scan utilizing the unique capabilities of the RHIC was proposed in ref. [14] to discriminate between hydrodynamical models that couple to the initial geometry and initial-state momentum correlation models that do not. Varying the collision system from p+Au, to d+Au, to ^{3}He+Au changes the initial geometry from dominantly circular, to elliptical, to triangular configurations, respectively, as characterized by the second- and third-order spatial eccentricities, which correspond to ellipticity and triangularity, respectively. The *n*th order spatial eccentricity of the system, ε_n, typically determined from a Monte Carlo (MC) Glauber model of nucleon–nucleon interactions (see for example ref. [15]), can be defined as

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

where r and ϕ are the polar coordinates of participating nucleons[16]. The eccentricity fluctuates event-by-event and is generally dependent on the impact parameter of the collision and the number of

STRONG EVIDENCE FOR QGP IN SMALL SYSTEMS

$v_2(p_T)$ measurement in small systems

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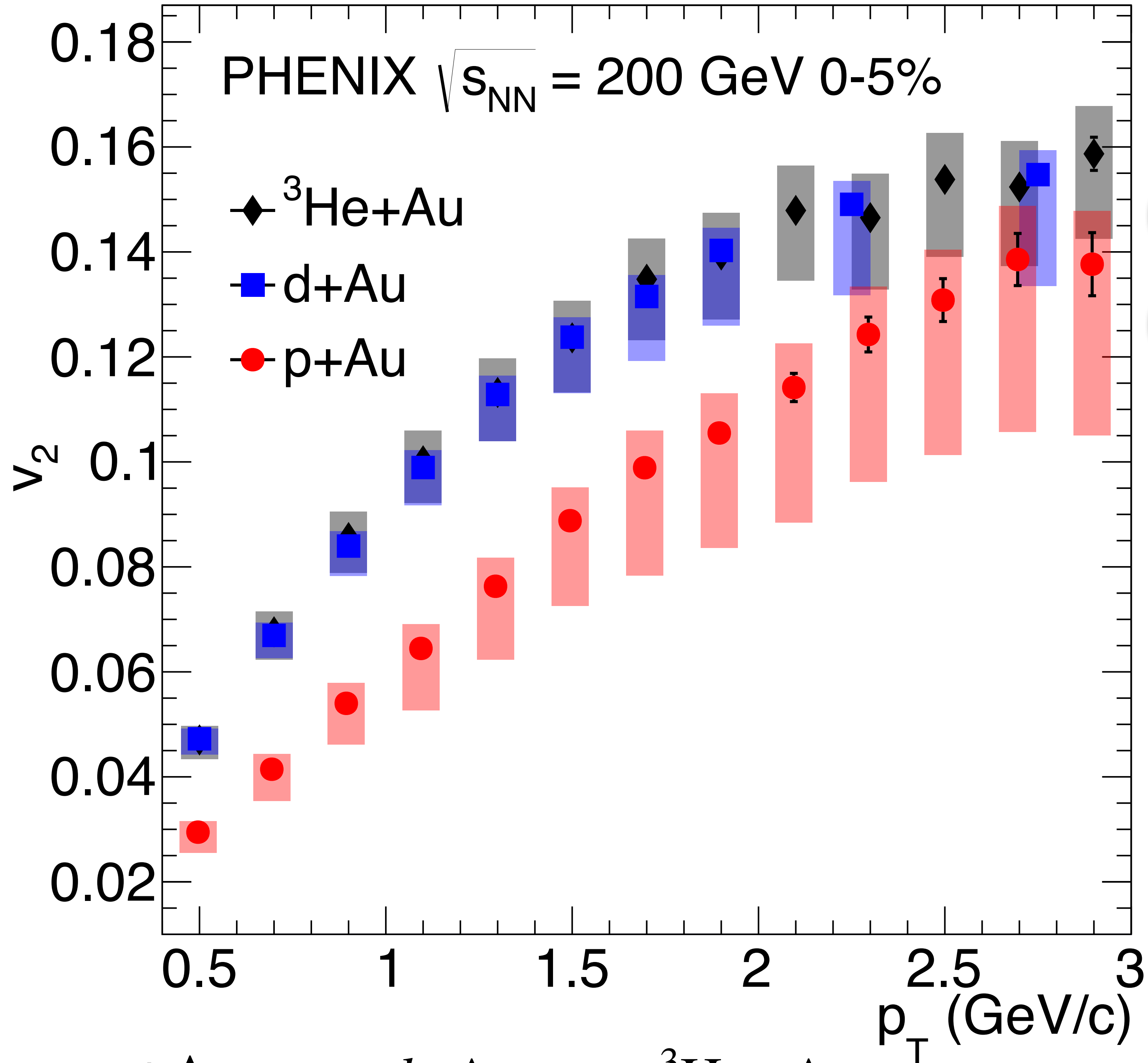
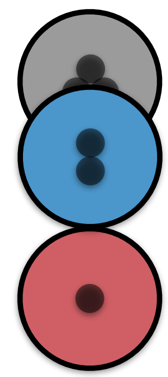
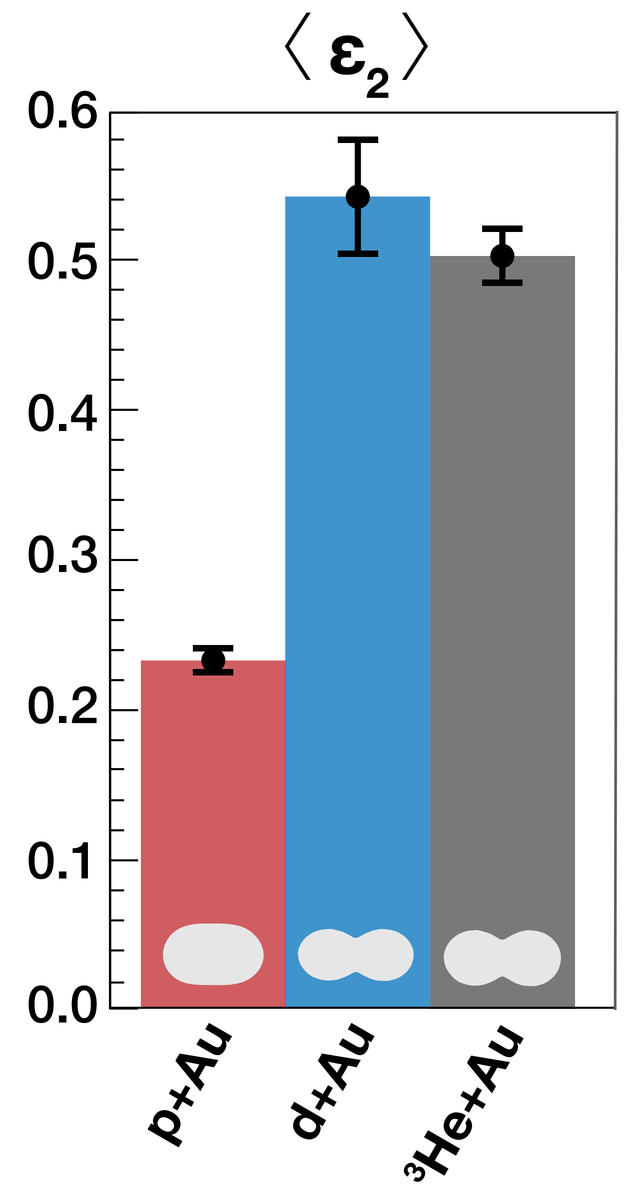






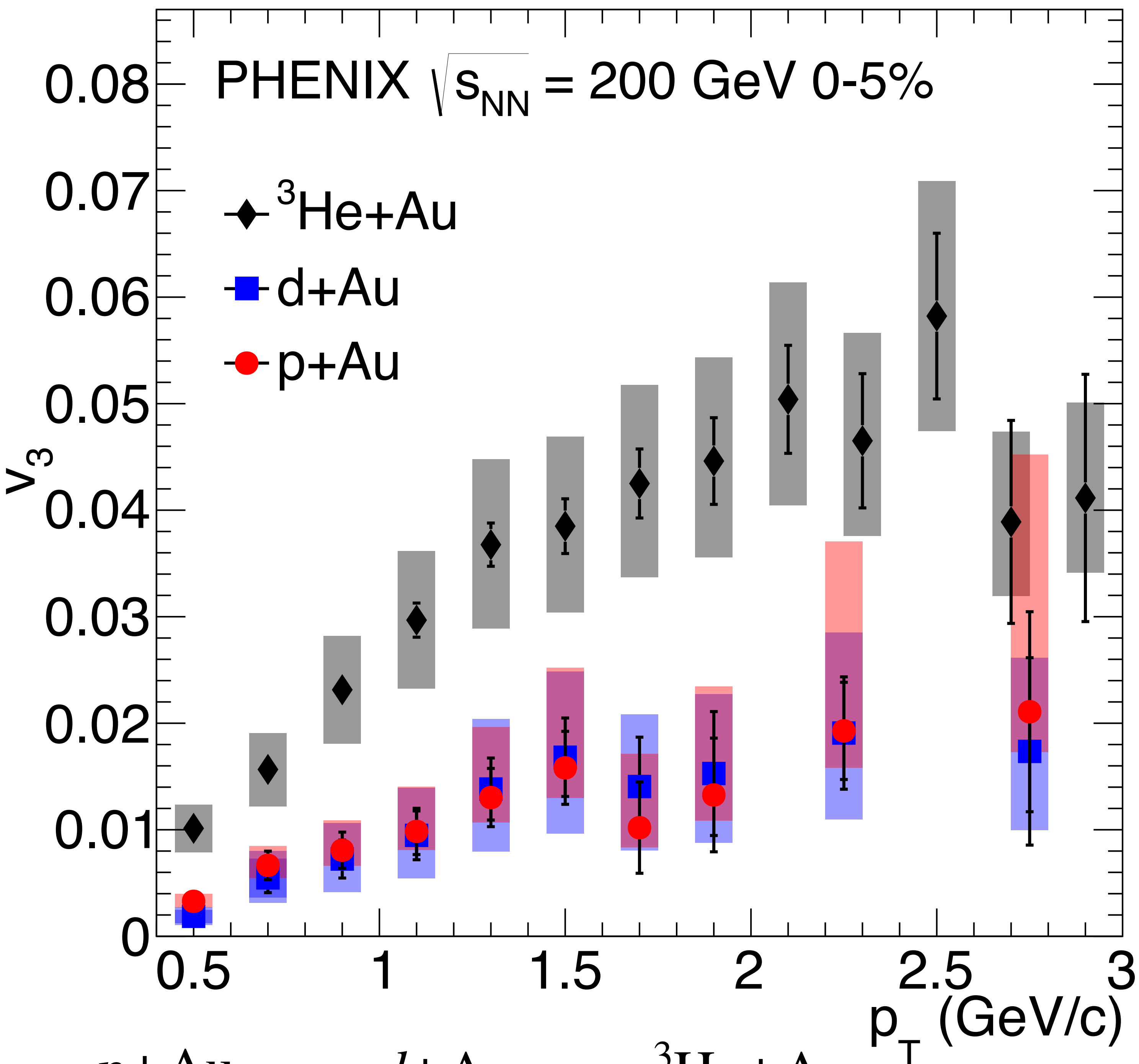
Glauber Model calculations

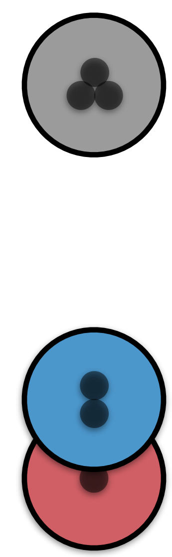
$$v_2^{p+\mathrm{Au}} < v_2^{d+\mathrm{Au}} \approx v_2^{^3\mathrm{He+Au}}$$

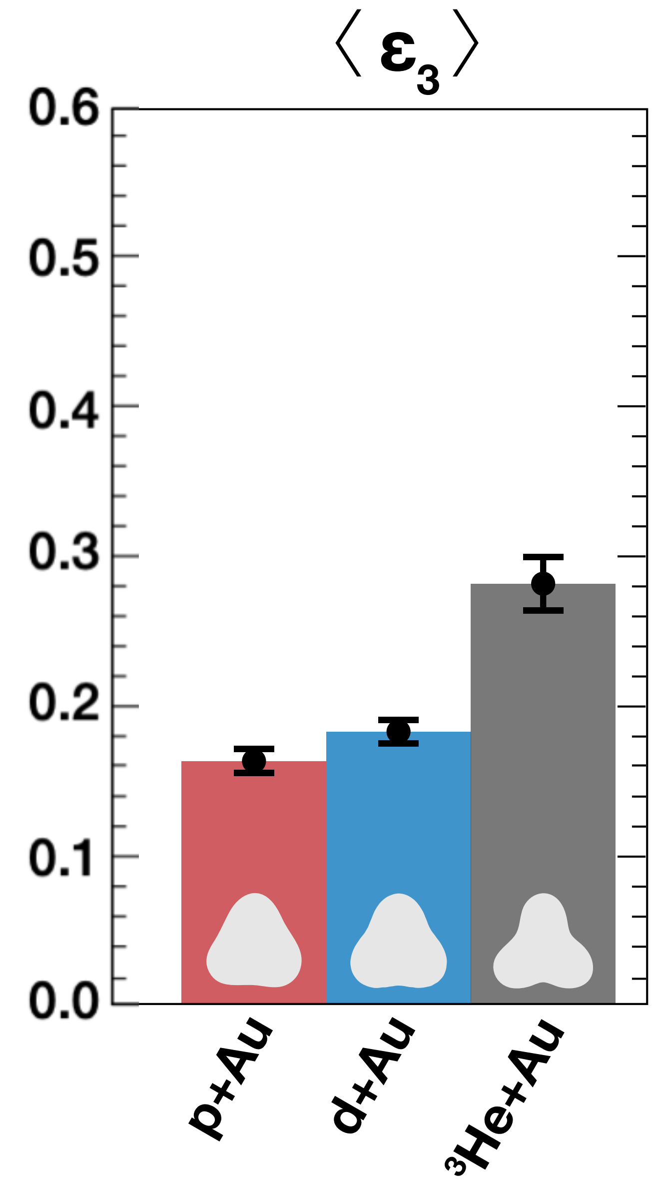
$$\varepsilon_2^{p+\mathrm{Au}} < \varepsilon_2^{d+\mathrm{Au}} \approx \varepsilon_2^{^3\mathrm{He+Au}}$$

Nature Physics vol. 15, 214–220 (2019)

$v_3(p_T)$ measurement in small systems







Glauber Model calculations

$$v_3^{p+\mathrm{Au}} \approx v_3^{d+\mathrm{Au}} < v_3^{^3\mathrm{He+Au}}$$

$$\varepsilon_3^{p+\mathrm{Au}} \approx \varepsilon_3^{d+\mathrm{Au}} < \varepsilon_3^{^3\mathrm{He+Au}}$$

Nature Physics vol. 15, 214–220 (2019)

$v_n(p_T)$ measurement in small systems

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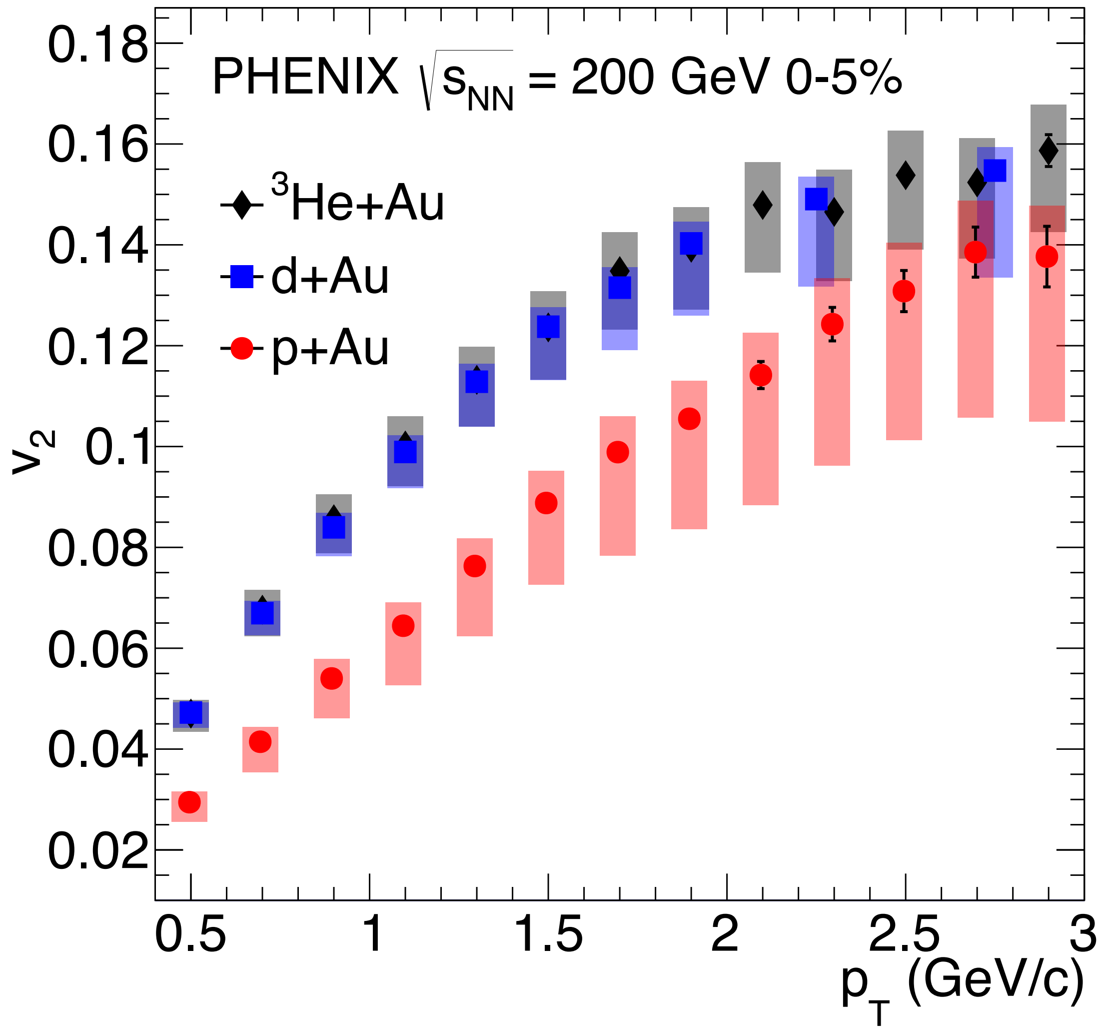
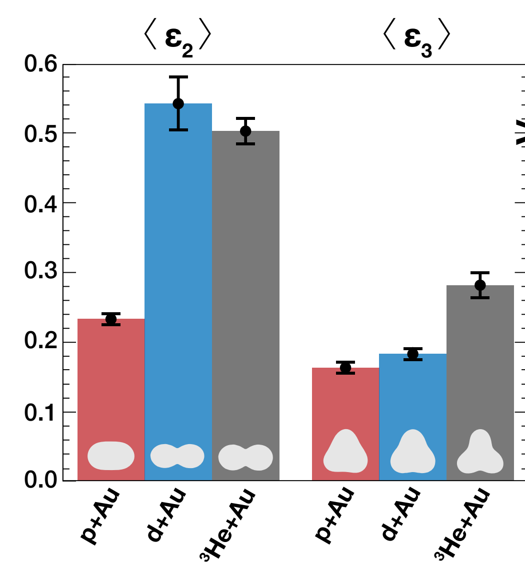
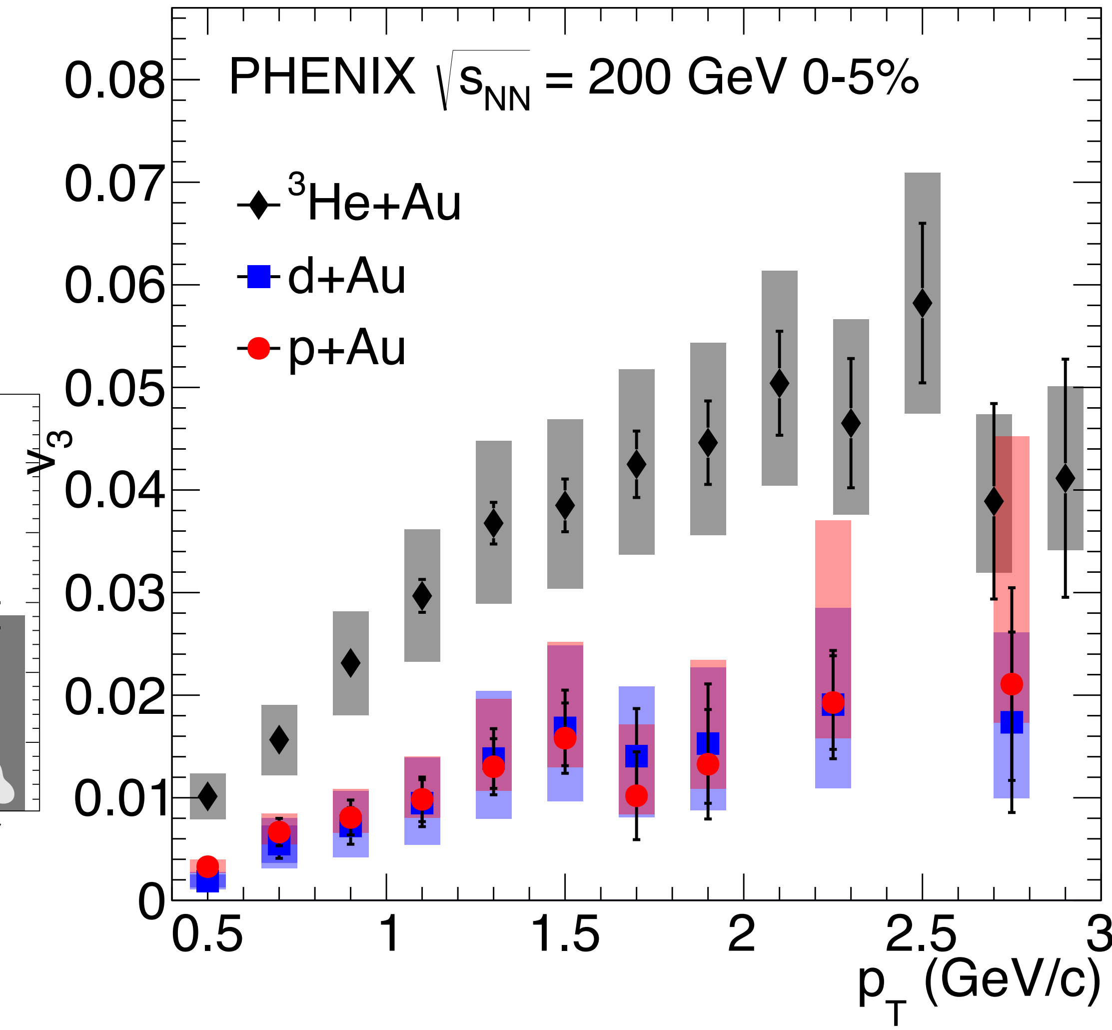




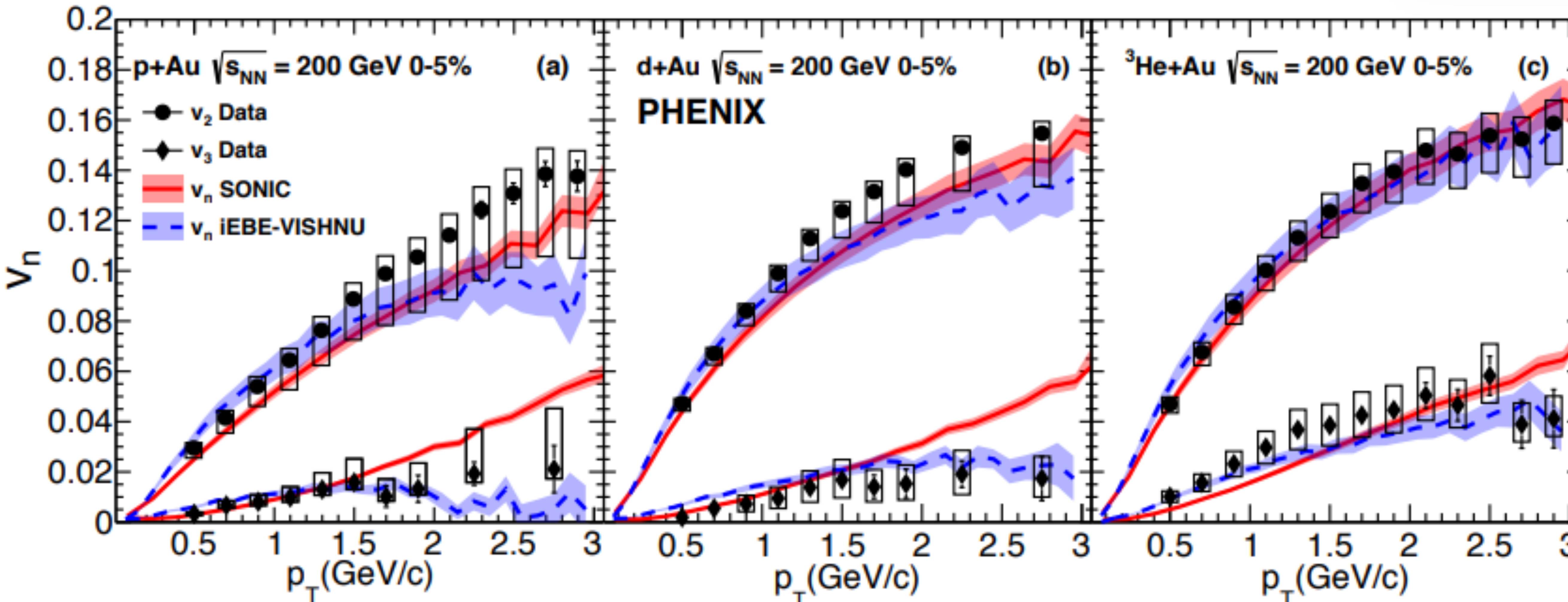


$$v_2^{p+\mathrm{Au}} < v_2^{d+\mathrm{Au}} \approx v_2^{^3\mathrm{He+Au}}$$

$$v_3^{p+\mathrm{Au}} \approx v_3^{d+\mathrm{Au}} < v_3^{^3\mathrm{He+Au}}$$

Suggests flow is geometric in origin

$v_n(p_T)$ measurement comparing to hydro models



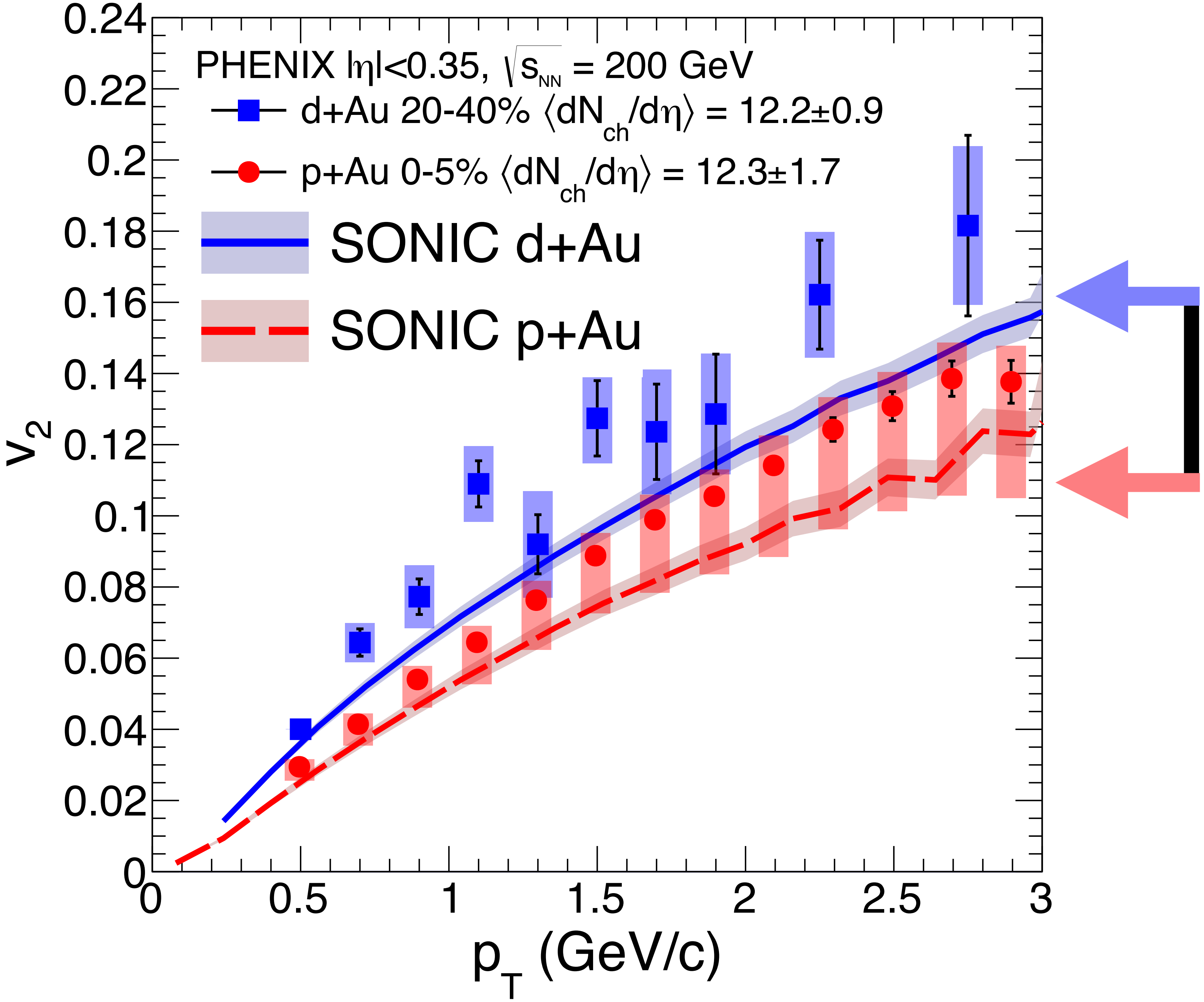
iEBE-VISHNU: C. Shen et al., Phys. Rev. C 95, 014906 (2017).
SONIC: M. Habich et al., Eur. Phys. J. C 75, 15 (2015).

hydrodynamical models provide a simultaneous and quantitative description of the data in all three

p/d+Au at same $\langle dN_{ch}/d\eta \rangle$

d+Au 20-40% $\langle dN_{ch}/d\eta \rangle = 12.2 \pm 0.9$ PRC 96, 064905 (2017)

p+Au 0-5% $\langle dN_{ch}/d\eta \rangle = 12.3 \pm 1.7$ PRC 95, 034910 (2017)

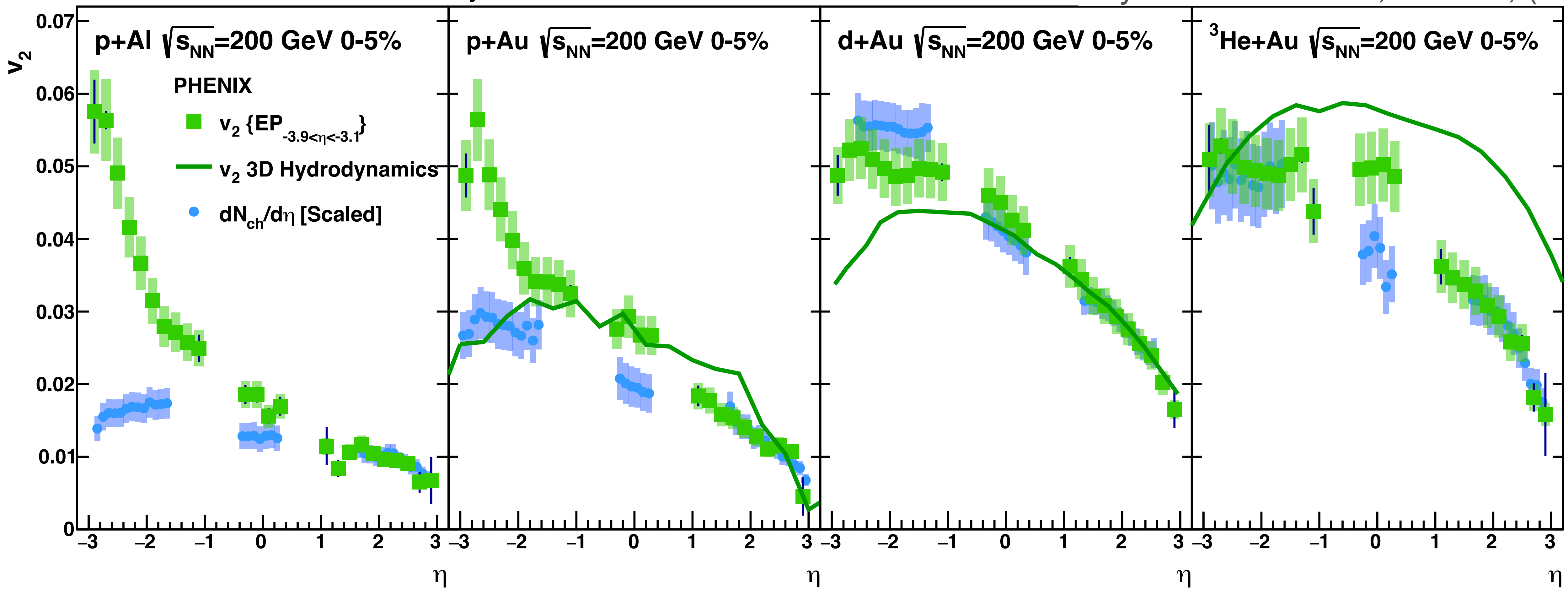


Good qualitative agreement of systematic difference between p+Au and d+Au

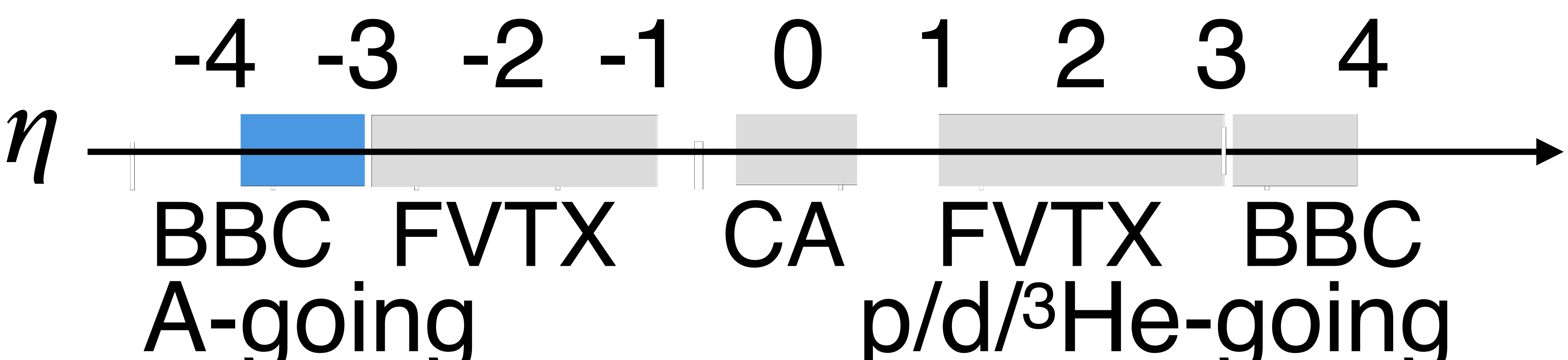
$v_2(\eta)$ measurement comparing to hydro models

P. Bozek etc.'s 3D hydro model

Phys. Rev. Lett. **121**, 222301, (2018)



$v_2(\eta)$ is correlated with $dN_{ch}/d\eta$ but not exact scaling
3D Hydrodynamics predicts the trend



$v_2(\eta)$ measurement comparing to hydro models

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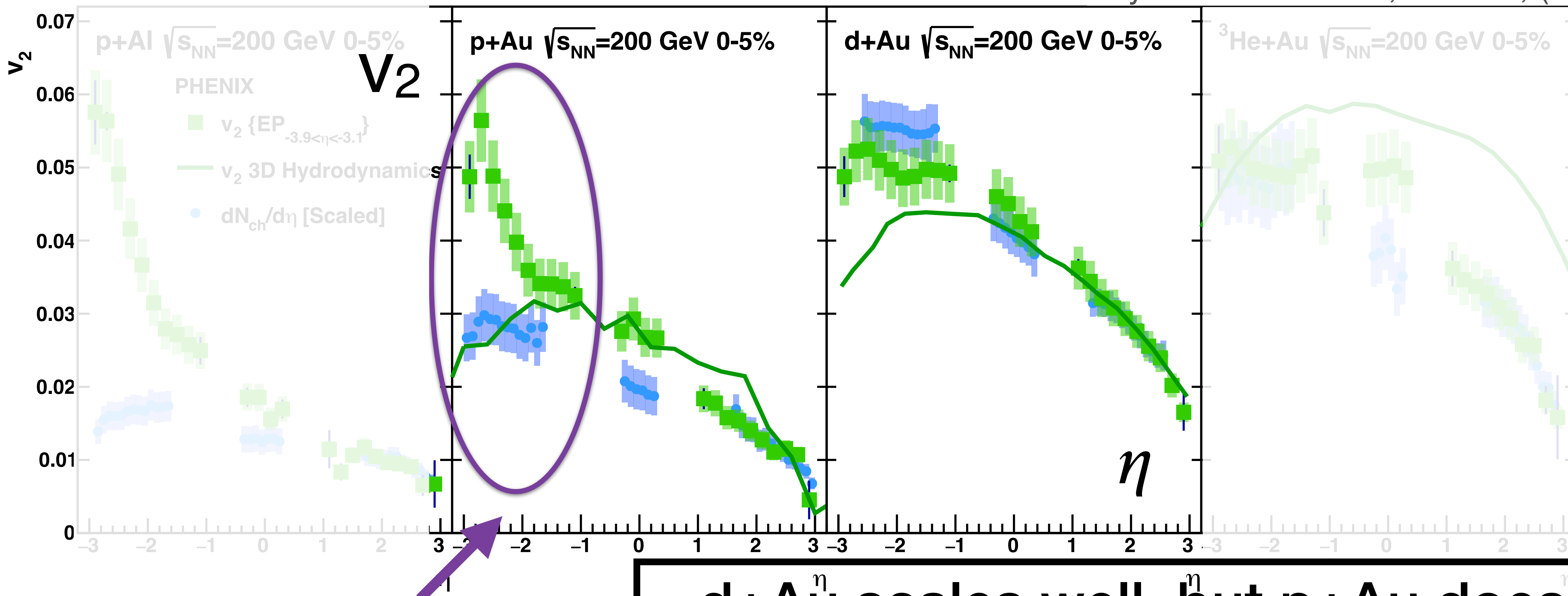
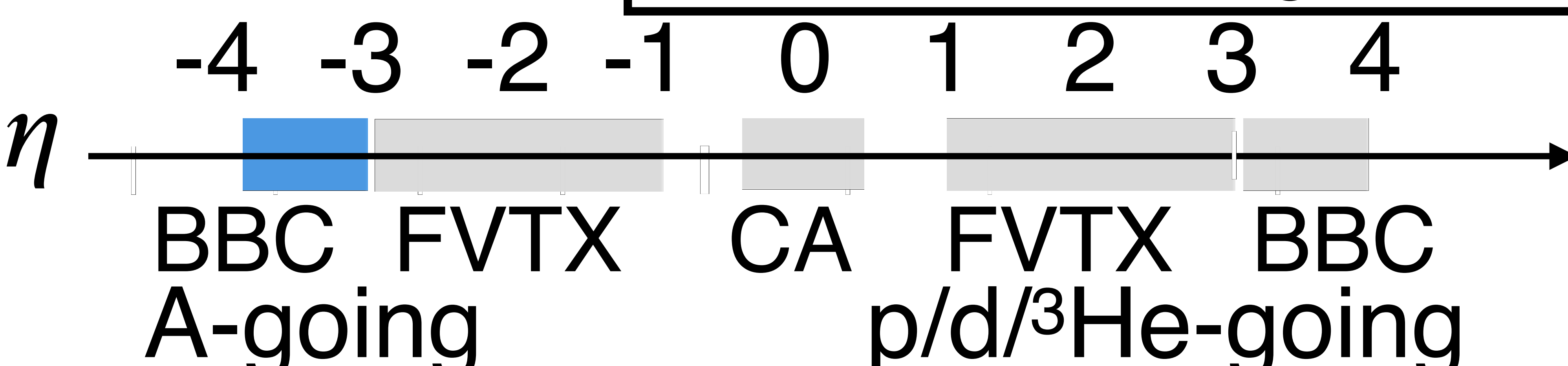
Phys. Rev. Lett. **121**, 222301, (2018)



Non-flow dominates near the EP detector

d+Au scales well, but p+Au does not at backward rapidity, non-flow becomes more significant



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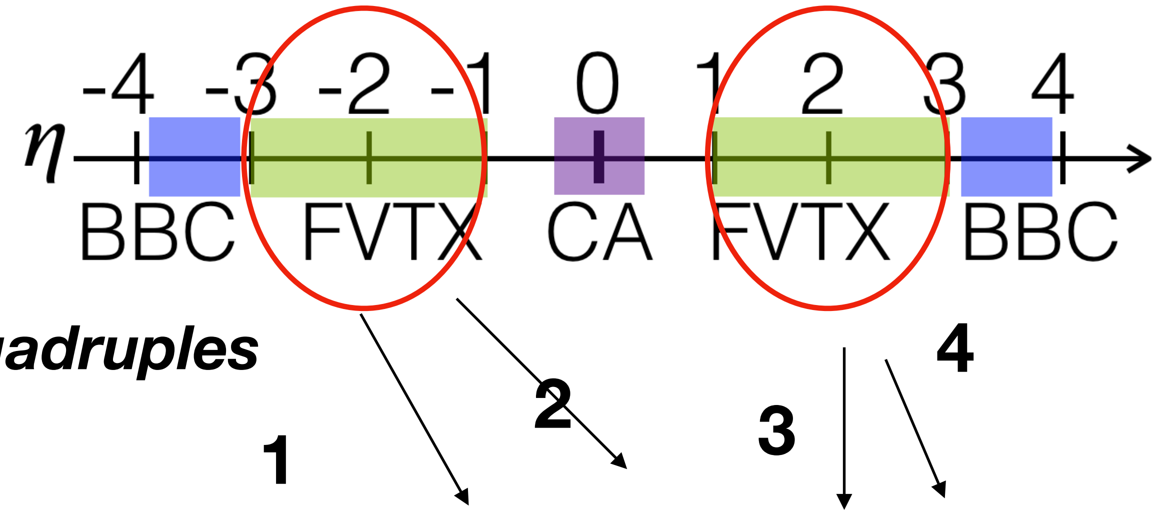
Multi-particle correlation method

4-p correlation as an example:



All quadruples

$$\langle\langle 4\rangle\rangle = \langle\langle e^{in(\phi_1 + \phi_2 - \phi_3 - \phi_4)}\rangle\rangle$$

$$\langle\langle 2\rangle\rangle = \langle\langle e^{in(\phi_1 - \phi_2)}\rangle\rangle$$

$$c_2\{4\} = \langle\langle 4\rangle\rangle - 2 * \langle\langle 2\rangle\rangle^2$$

$$v_2\{4\} = (-c_2\{4\})^{-1/4}$$

Multi-particle correlations suppress non-flow effectively

Multi-particle correlations also provide information about how flow fluctuate event-by-event

$$\mathbf{v_2\{4\}^2 \approx v_2\{6\}^2 \approx <v_2>^2 - \sigma_{v2}^2}$$

$$\mathbf{v_2\{2\}^2 \approx <v_2>^2 + \sigma_{v2}^2 + \delta^2}$$

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Multi-particle correlations in d+Au@200GeV

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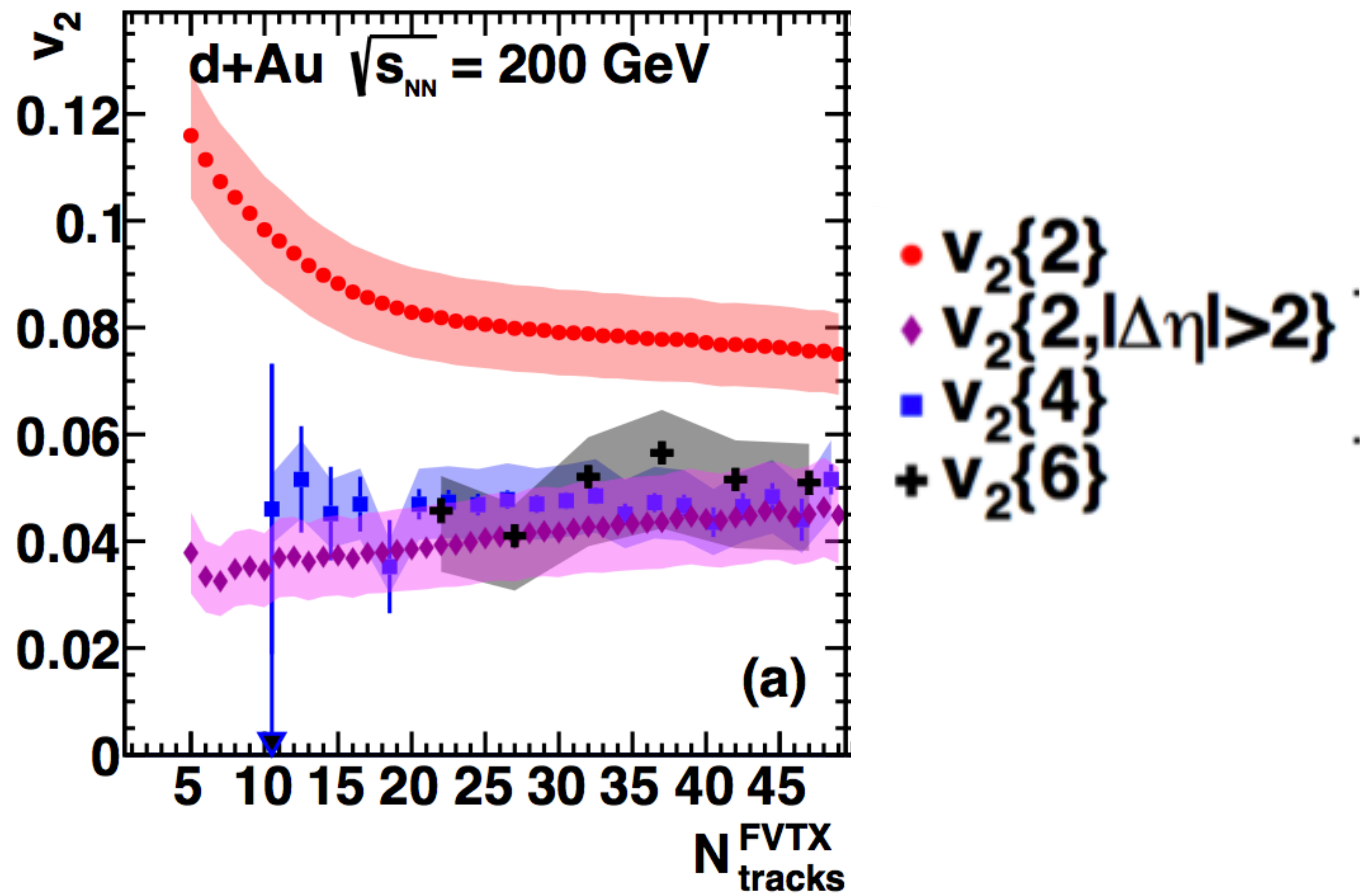
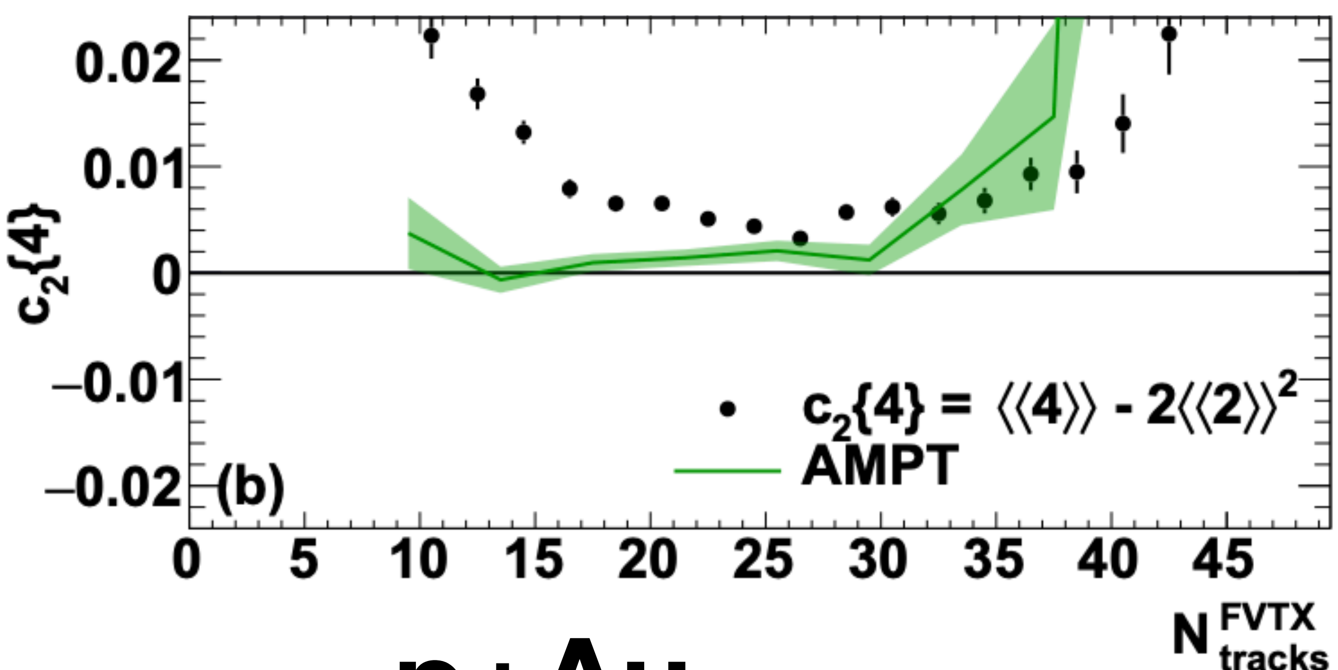
200 GeV

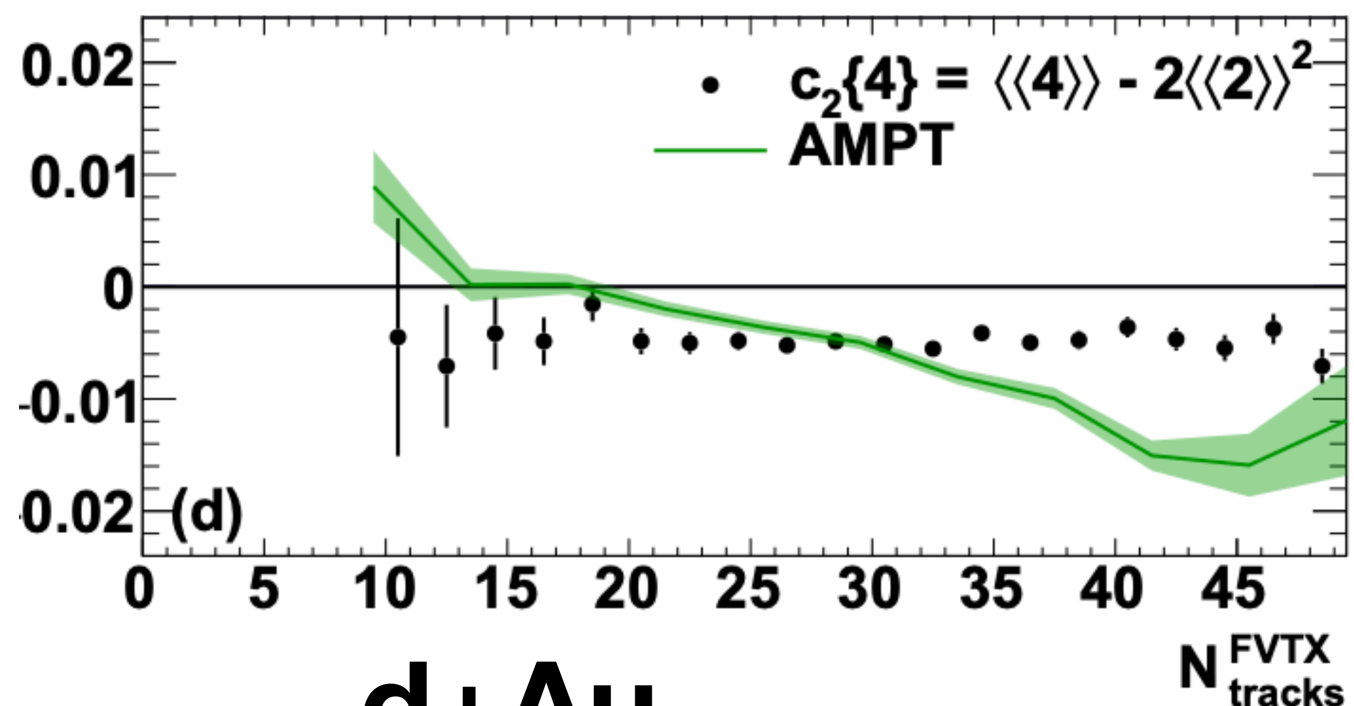


- 200 GeV $v_2\{2\}[\eta$ gap$] \approx v_2\{4\} \approx v_2\{6\}$, indication of strong collectivity
- 200 GeV $v_2\{4\}$ dominated by flow, not non-flow

Flow fluctuations in p/d+Au@200GeV

Phys. Rev. Lett. 120, 062302 (2018)





p+Au

Positive $c_2\{4\}$

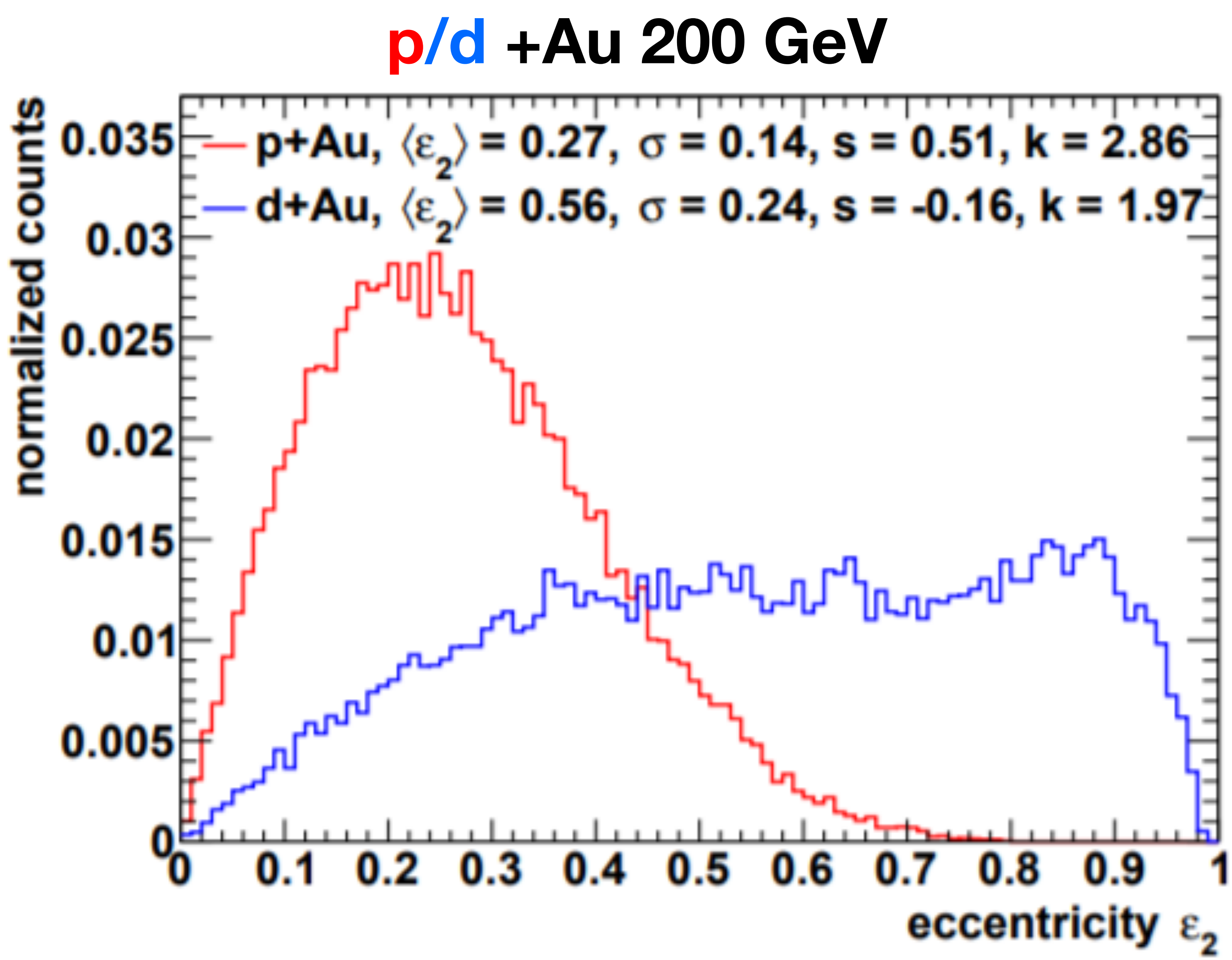
d+Au

Negative $c_2\{4\}$

- $v_2\{4\}^2 \approx \langle v_2\rangle^2 - \sigma_{v2}^2$, If fluctuation σ_{v2} > mean v_2, $c_2\{4\}$ is positive
- Implies $c_2\{4\}$ in p+Au is dominated by fluctuations
- AMPT (A Multi-phase transport model) describes the sign

Initial eccentricity distribution

Monte Carlo Glauber



High positive skewness in p+Au
Significantly platykurtic in d+Au

- Initial eccentricity distribution is highly non-Gaussian.
- Fluctuations are highly non-trivial in small systems

Phys. Rev. Lett. 120, 062302 (2018)

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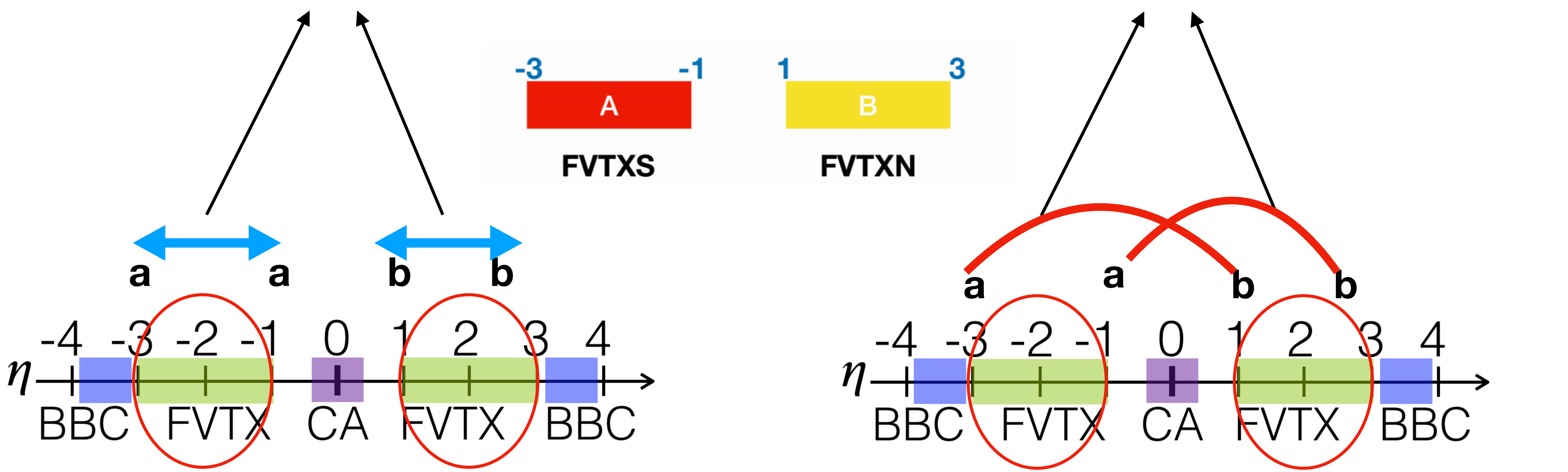
Subevent cumulant method

- To further suppress non-flow and investigate the role of fluctuations, 2-subevent cumulant method is used
- These 2 subevents already has an η gap > 2
- Two types depending on how we correlate particles are studied
- Typically non-flow contained: **aa|bb < ab|ab < standard method**

ab | ab $e^{in(\phi_1^a+\phi_2^b-\phi_3^a-\phi_4^b)}$

aa | bb $e^{in(\phi_1^a+\phi_2^a-\phi_3^b-\phi_4^b)}$



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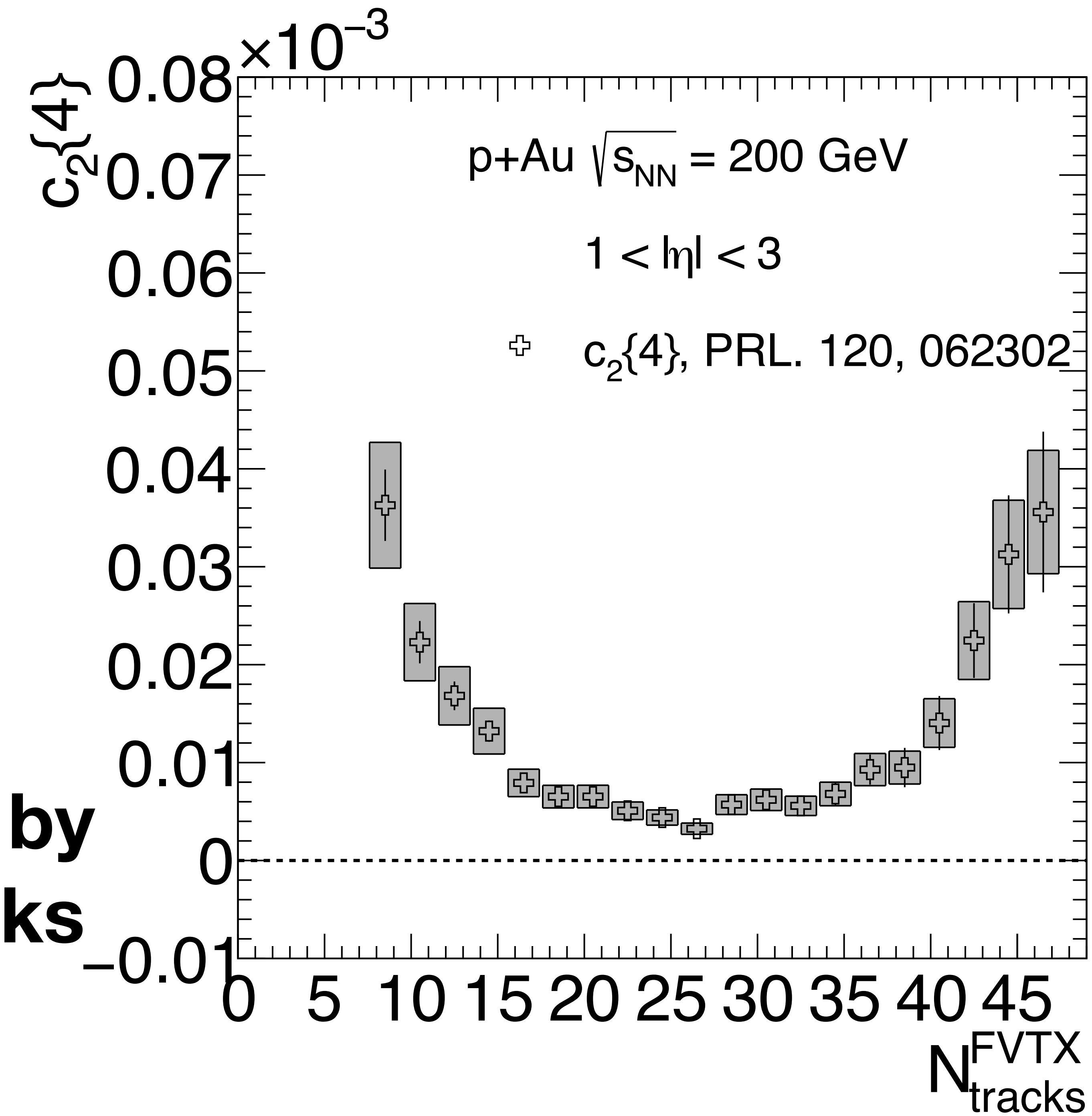
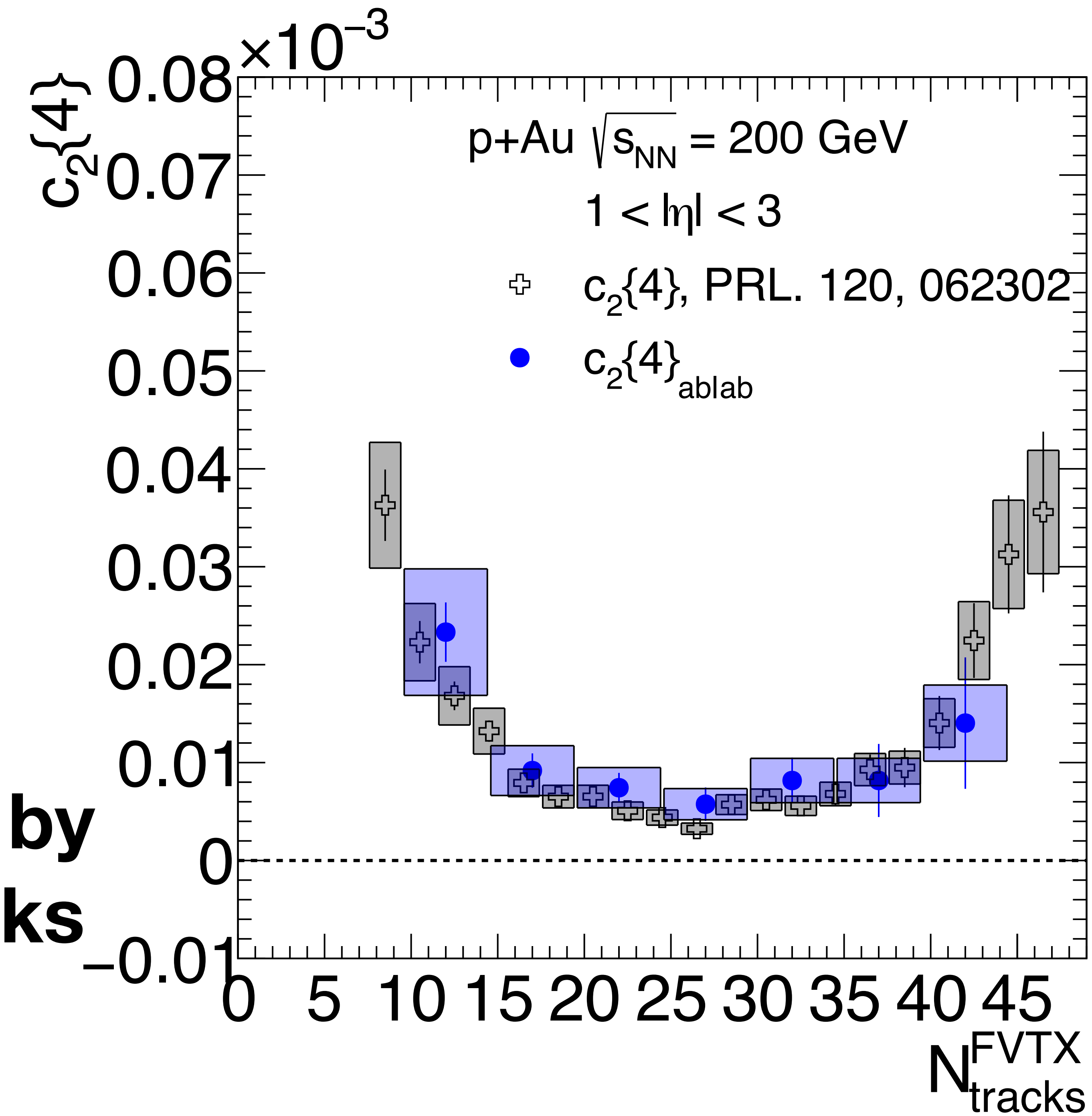
Subevent cumulants in p+Au@200GeV



dominated by low p_T tracks

- **Standard $c_2\{4\}$ in p+Au is positive**

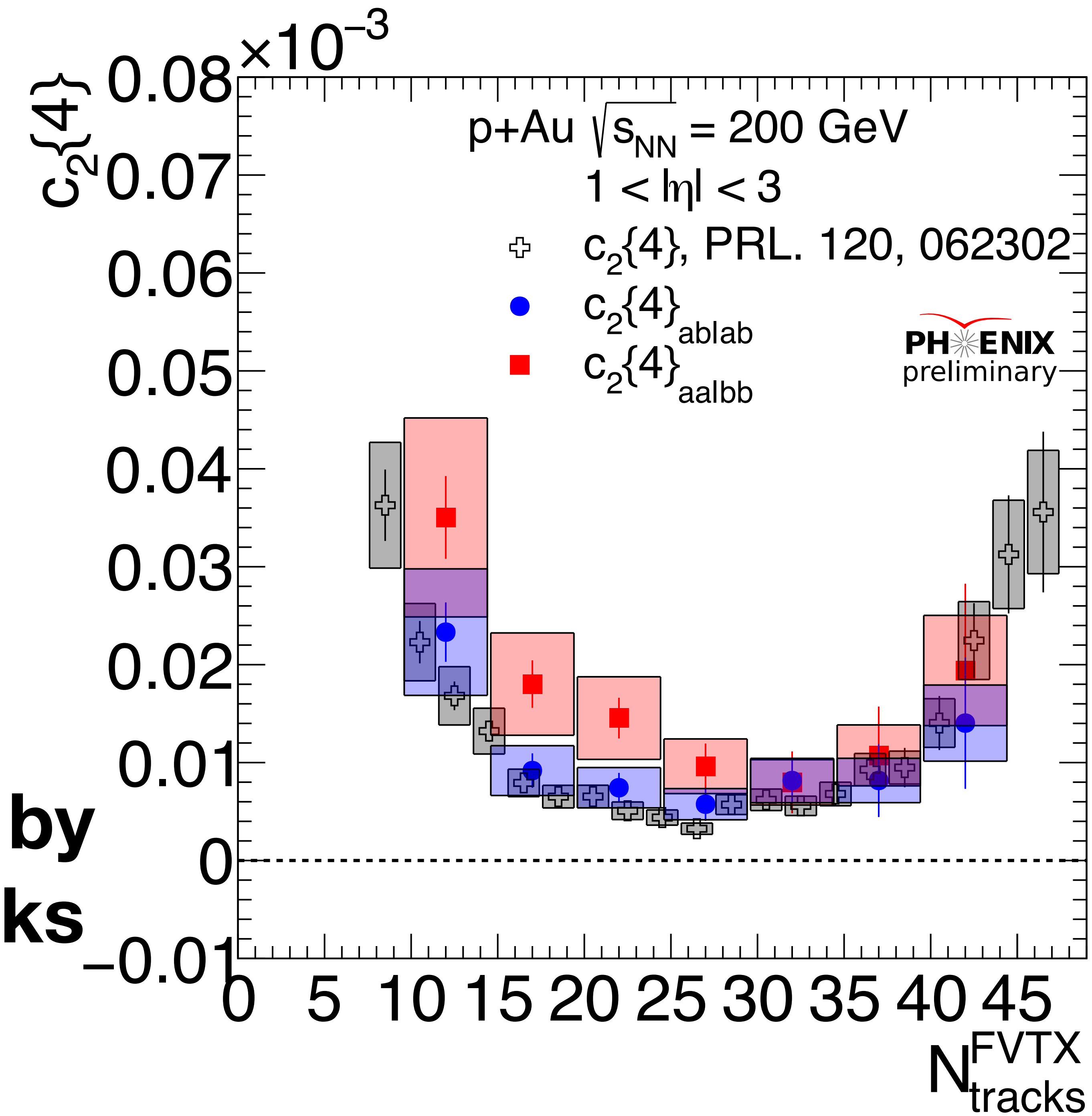
Subevent cumulants in p+Au@200GeV



dominated by low p_T tracks

- Two sub-event $c_2\{4\}$ in p+Au are still positive
- Consistent with standard $c_2\{4\}$ without subevent

Subevent cumulants in p+Au@200GeV



Our PRL results are very robust!

dominated by low p_T tracks

- Two sub-event $c_2\{4\}$ in p+Au are still positive
- Further confirm that flow fluctuations are important in p+Au

Conclusions

- **Initial Geometry** is the driving force of the final correlations
- **Small variance limit** breaks in p+Au and in d+Au
- **Flow fluctuations are significant in $c_2\{4\}$** in p+Au collisions confirmed by **sub-event cumulant analysis**

Back Up

Small system measurements in PHENIX

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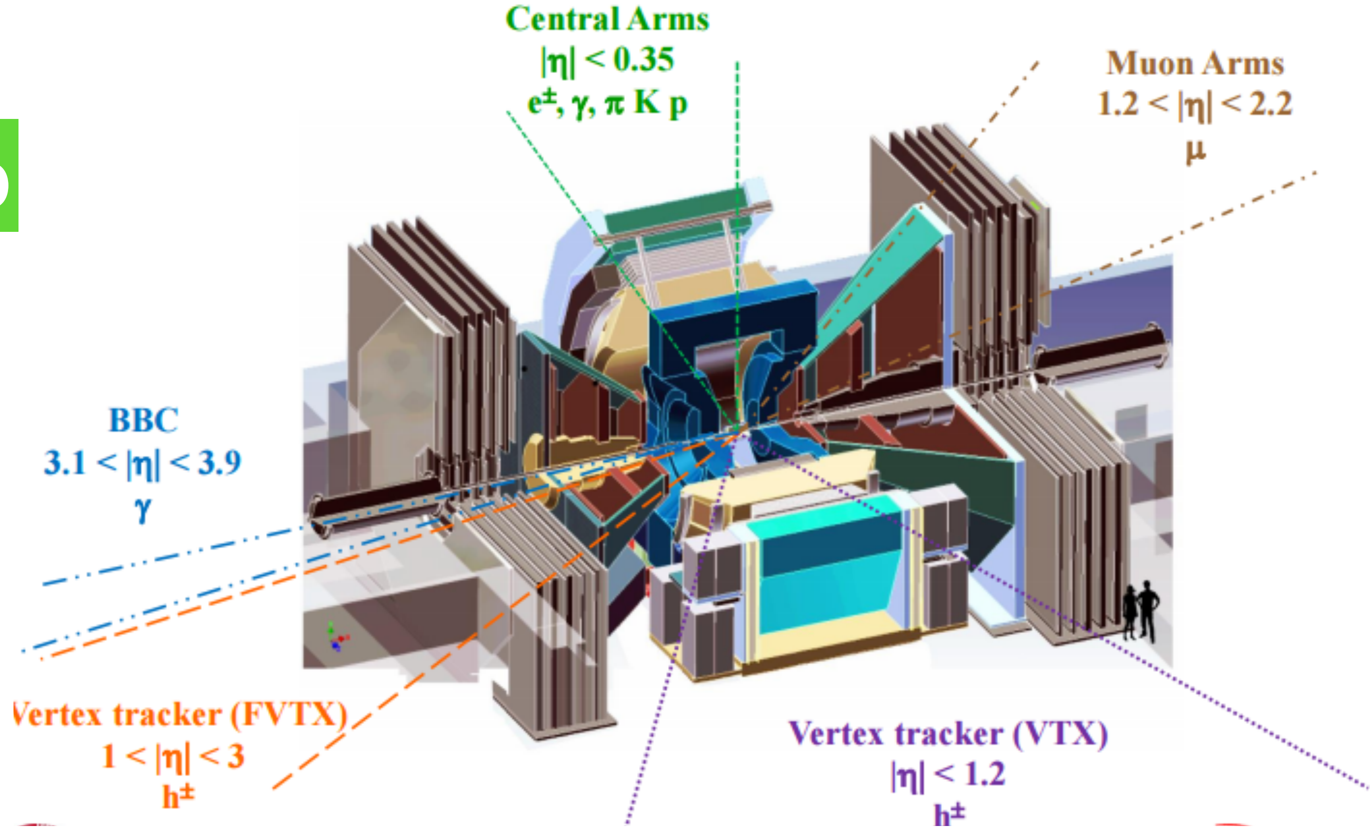
Detector Setup

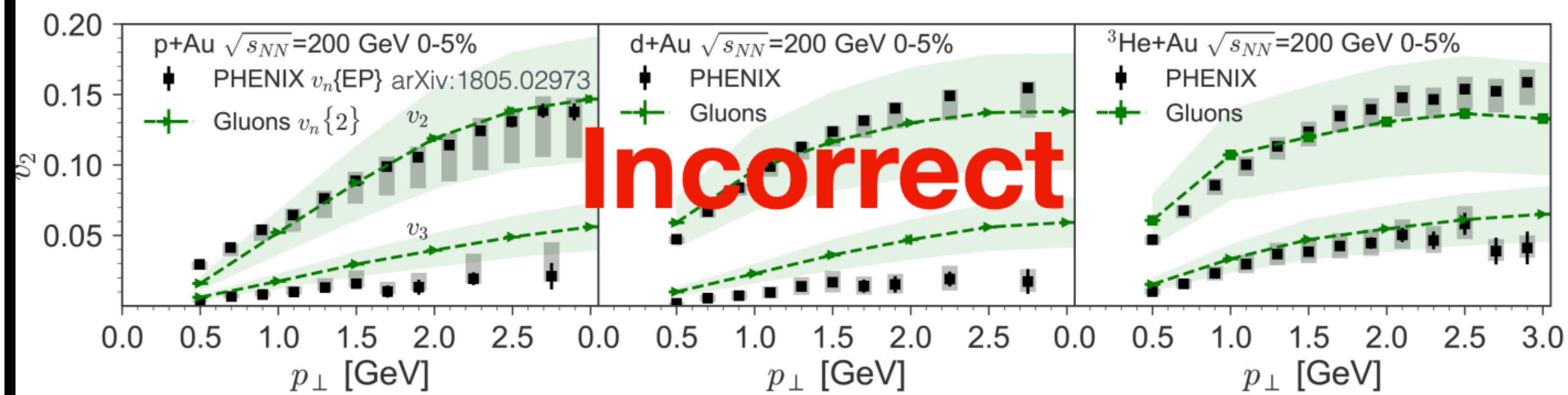


- Midrapidity: DC, PC, TOF -> tracking and PID
- Forward: BBC, FVTX -> triggering, event selection, correlations with midrapidity particles, event plane determination
- Muon arm: FVTX, Muon Tracking, Muon ID -> heavy flavor tracking and identification

From Latest development for CGC models

from M.Mace at INT - May 2, 2019 Origins of Correlations in High Energy Collisions

An error



Digging deeper in the code in answer questions raised in small systems workshop in Houston and preparing to make code public, a bug was found in the units

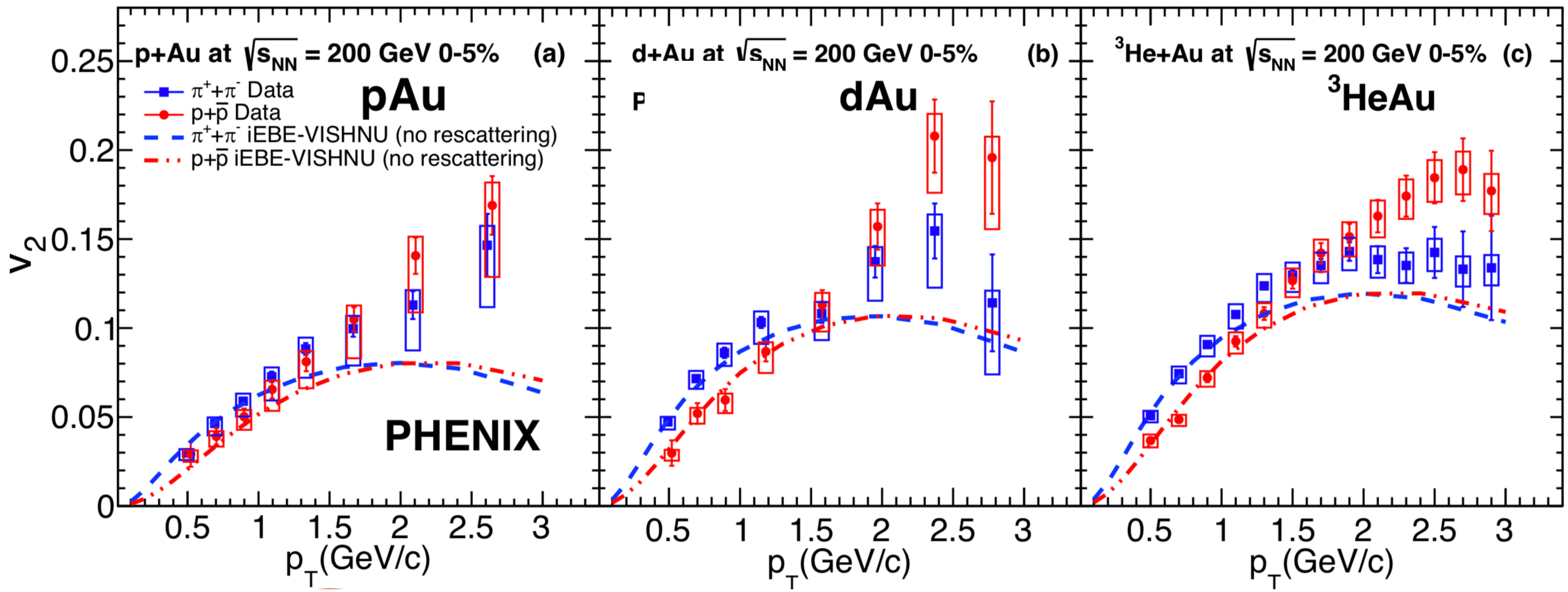
$$\frac{dN}{d^2k}[\mathrm{GeV}^{-2}] \stackrel{!}{=} f(k')[\mathrm{fm}^2]$$

Effectively, all results were off by in momenta factor of $\hbar c$

$v_2(p_T)$ for identified $\pi^\pm$ and protons

System Size Increases

Phys. Rev. C 97, 064904 (2018)

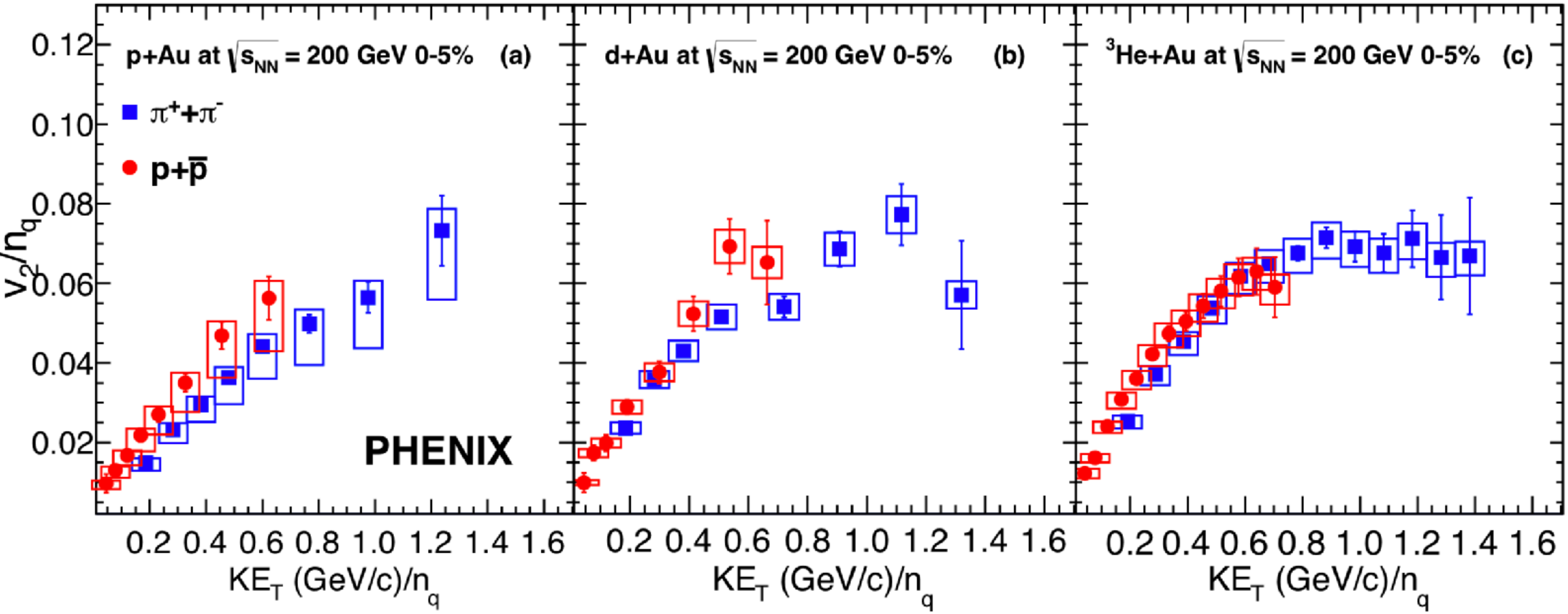


- $v_2(\pi^\pm) > v_2(\text{proton})$ at $p_T < 1.5$ GeV/c, reversed at higher p_T
- The hydro model describes the low-p_T mass-ordering in $v_2(p_T)$ well
- hydro doesn't get the intermediate pT splitting so well because of the hadronization

Quark number scaling of v_2 in p/d/^{3}He+Au

Is there a common velocity field?

PRC 97, 064904 (2018)



Quark number scaling observed similar to AA holds better as the system size increases

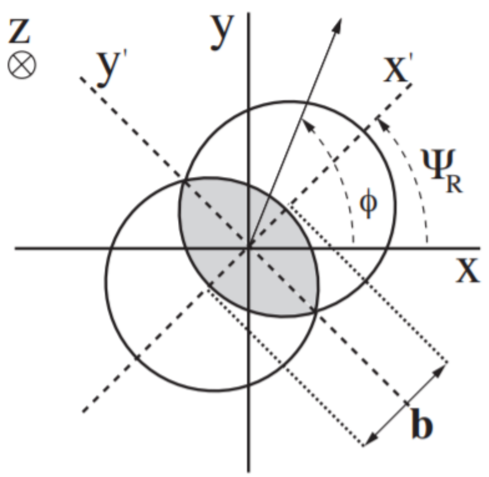
Analysis methods for Flow

Two – particle correlation method

Pairs: $$\frac{dN}{d\Delta\phi} \propto 1 + \sum_n 2 v_n^a v_n^b \cos(n\Delta\phi)$$ **2PC method**

Event plane method:

$$dN/d\phi = 1 + \sum_n 2v_n \cos(n(\phi - \Psi_n))$$



Multi-particle correlation method:

$$\langle 2\rangle \equiv \left\langle e^{in(\phi_1-\phi_2)}\right\rangle \equiv \frac{1}{P_{M,2}} \sum_{i,j}{}' e^{in(\phi_i-\phi_j)},$$

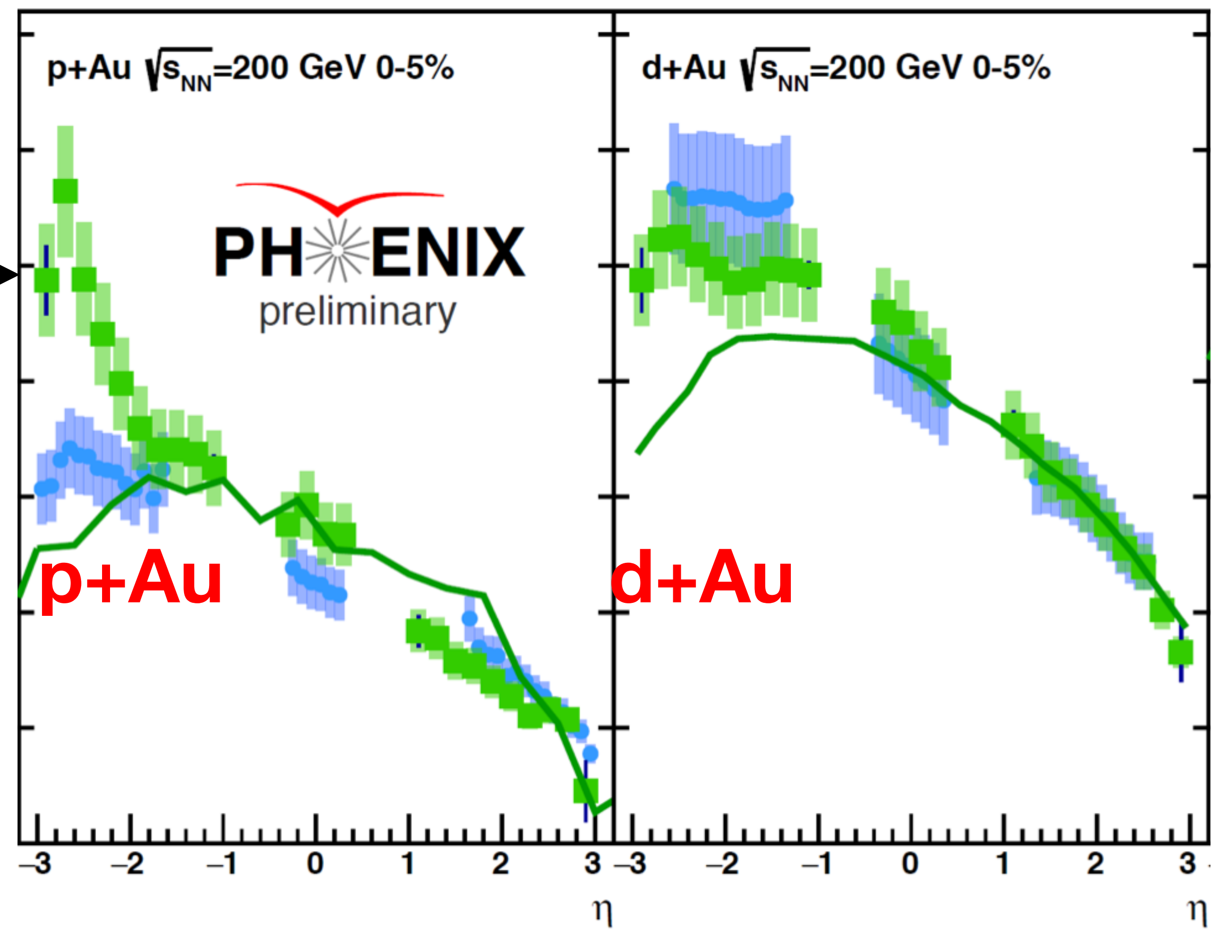
$$\langle 4\rangle \equiv \langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle \equiv \frac{1}{P_{M,4}} \sum_{i,j,k,l}{}' e^{in(\phi_i+\phi_j-\phi_k-\phi_l)},$$

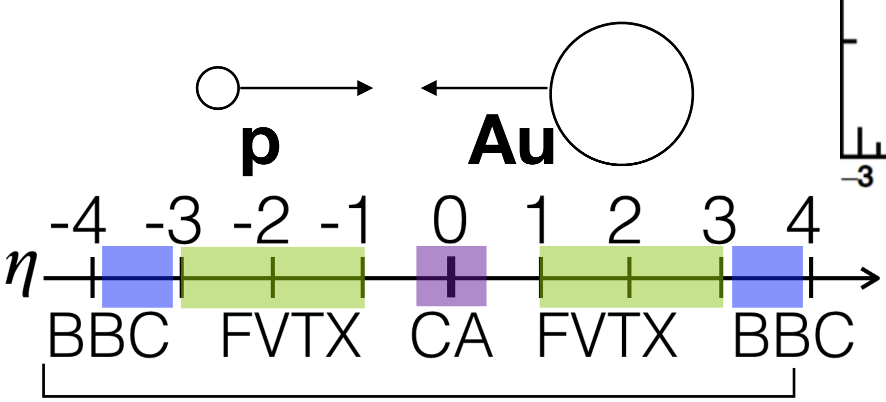
$v_2(\eta)$ vs $dN_{ch}/d\eta$ in Geometry Control Scan

green: $v_2(\eta)$

blue: $dN_{ch}/d\eta$

Curve: 3D hydro





Wide rapidity range

- d+Au scales well, but p+Au does not at backward rapidity
- 3D hydrodynamics quantitatively describes the data in p+Au and d+Au

The event plane is measured in $-3.9 < \eta < -3.1$

Multi-particle correlations in p+A comparing RHIC and LHC results

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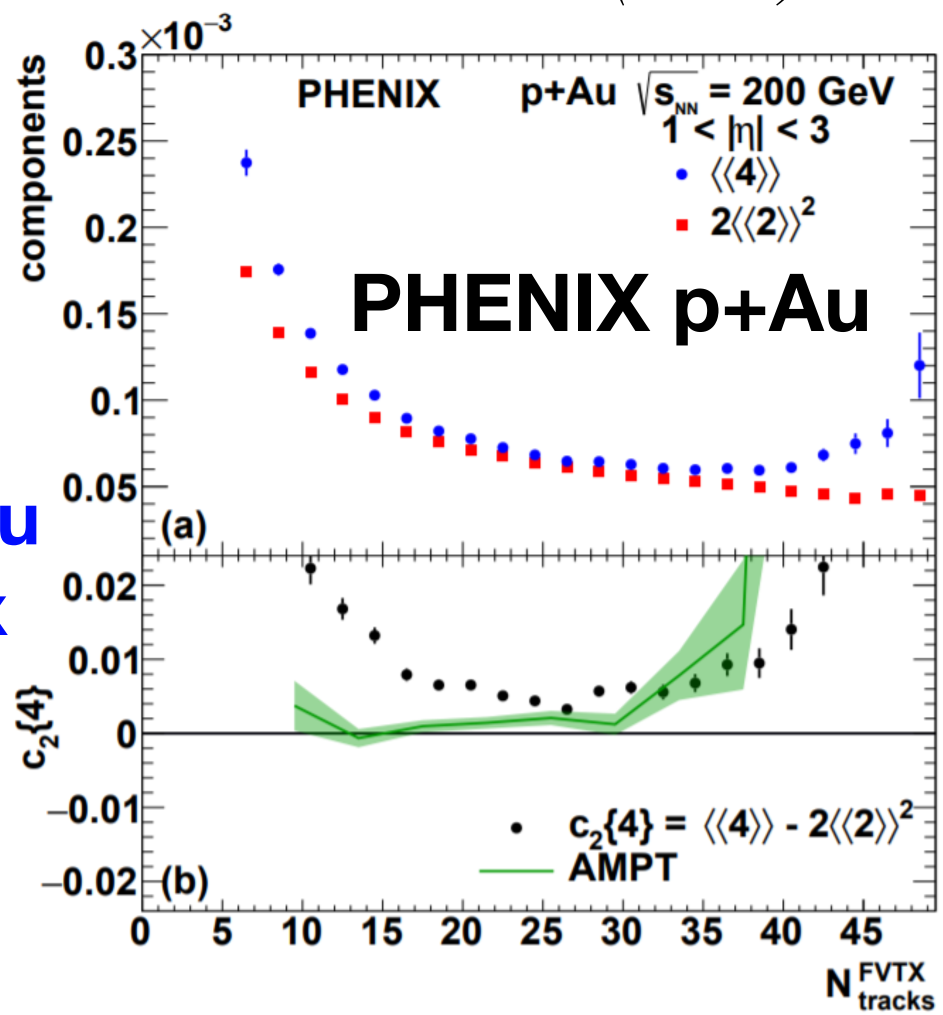
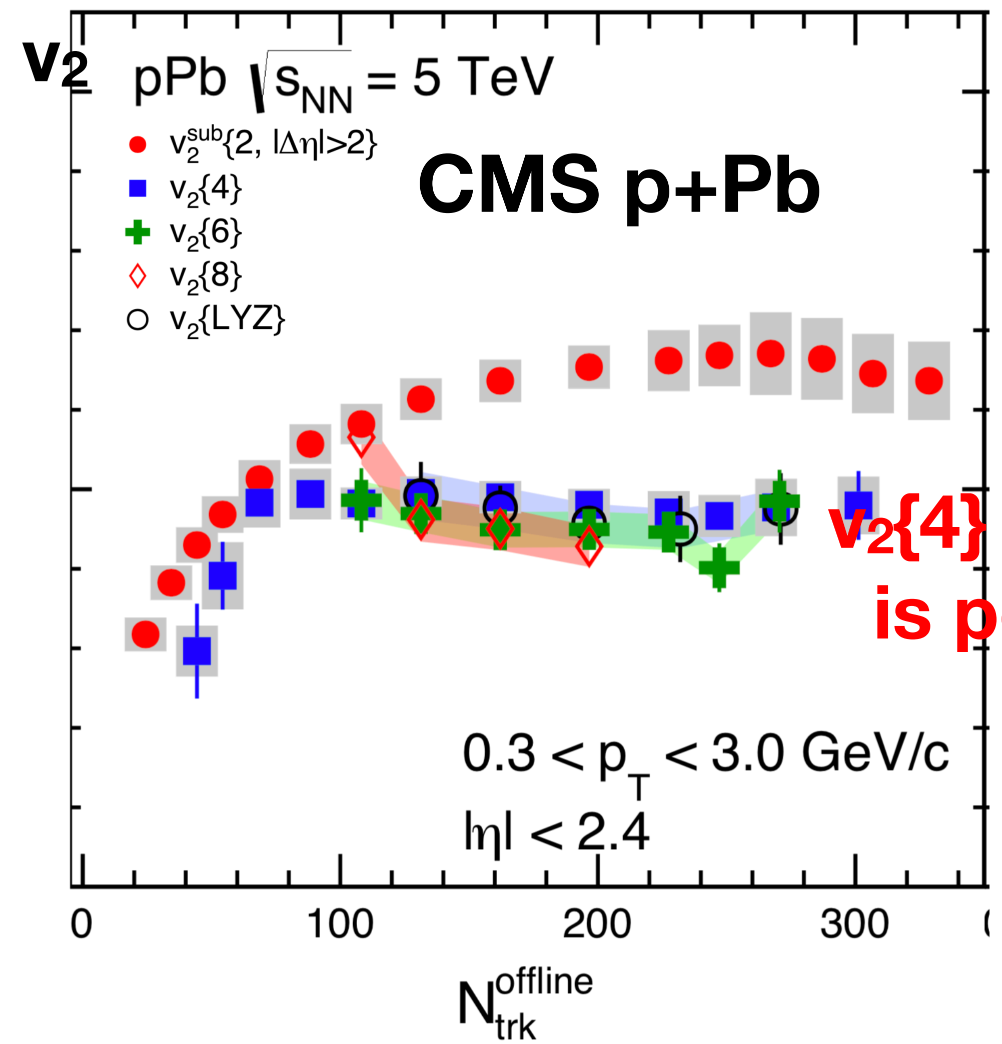
Phys. Rev. Lett. 120, 062302 (2018)



$v_2\{4\}$ in p+Au is complex

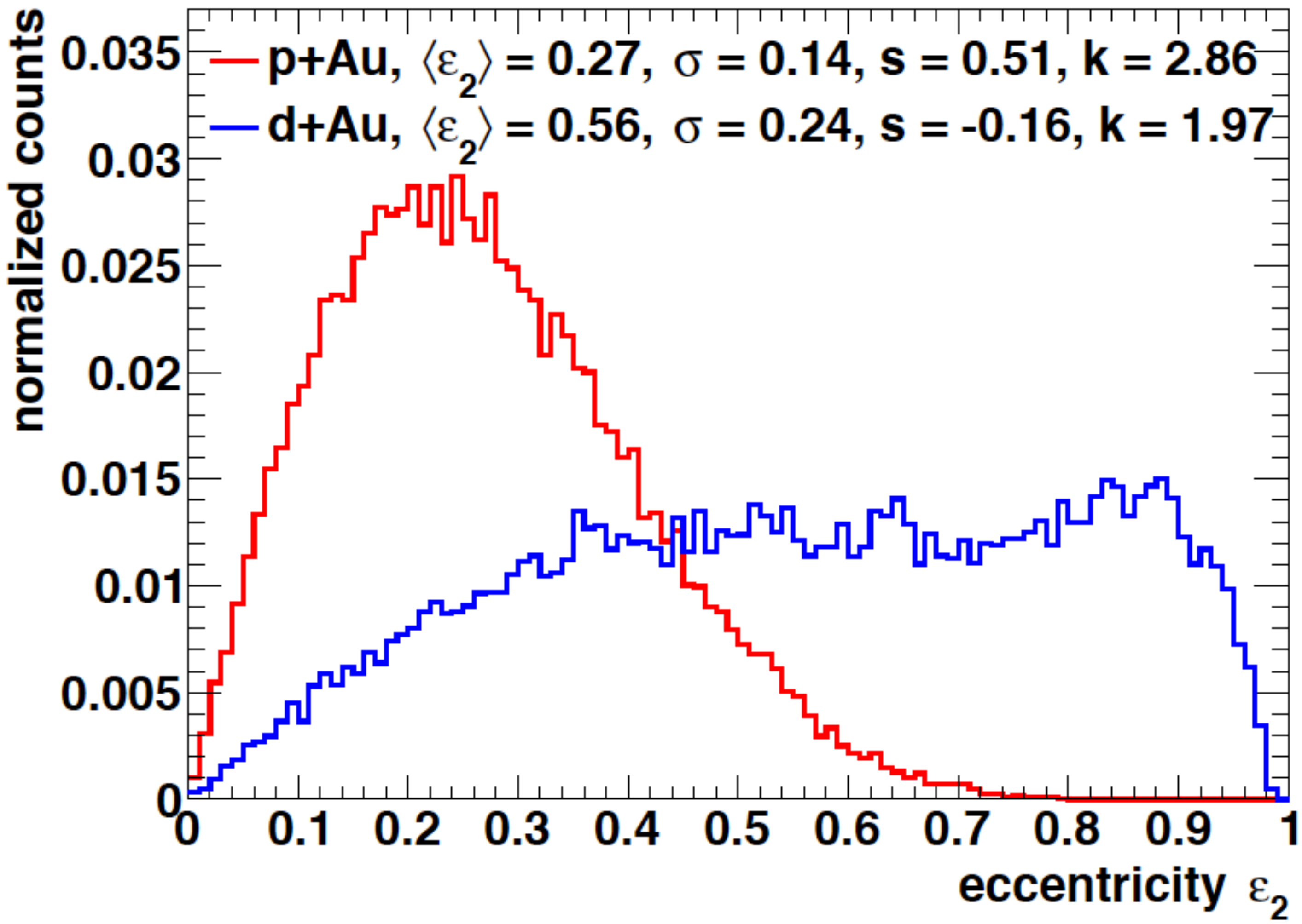
Phys. Lett. B 765 (2017) 193-220



$v_2\{4\}$ in p+Pb is positive

- p+A at RHIC enengy has more contributions from fluctuations than LHC energy

Figure from Ronald Belmont



	p+Au	d+Au
ε_2^4	0.00531	0.0983
$2\varepsilon_2^2\sigma^2$	0.00277	0.0370
$4\varepsilon_2 s\sigma^3$	0.00147	-0.0053
$(k-2)\sigma^4$	0.00031	-0.0001

$$\varepsilon_2\{4\} = (\varepsilon_2^4 - 2\varepsilon_2^2\sigma^2 - 4\varepsilon_2 s\sigma^3 - (k-2)\sigma^4)^{1/4}$$

- the variance brings $\varepsilon_2\{4\}$ down (this term gives the usual $\sqrt{v_2^2 - \sigma^2}$)
- positive skew brings $\varepsilon_2\{4\}$ further down, negative skew brings it back up
- kurtosis > 2 brings $\varepsilon_2\{4\}$ further down, kurtosis < 2 brings it back up —recall Gaussian has kurtosis $= 3$

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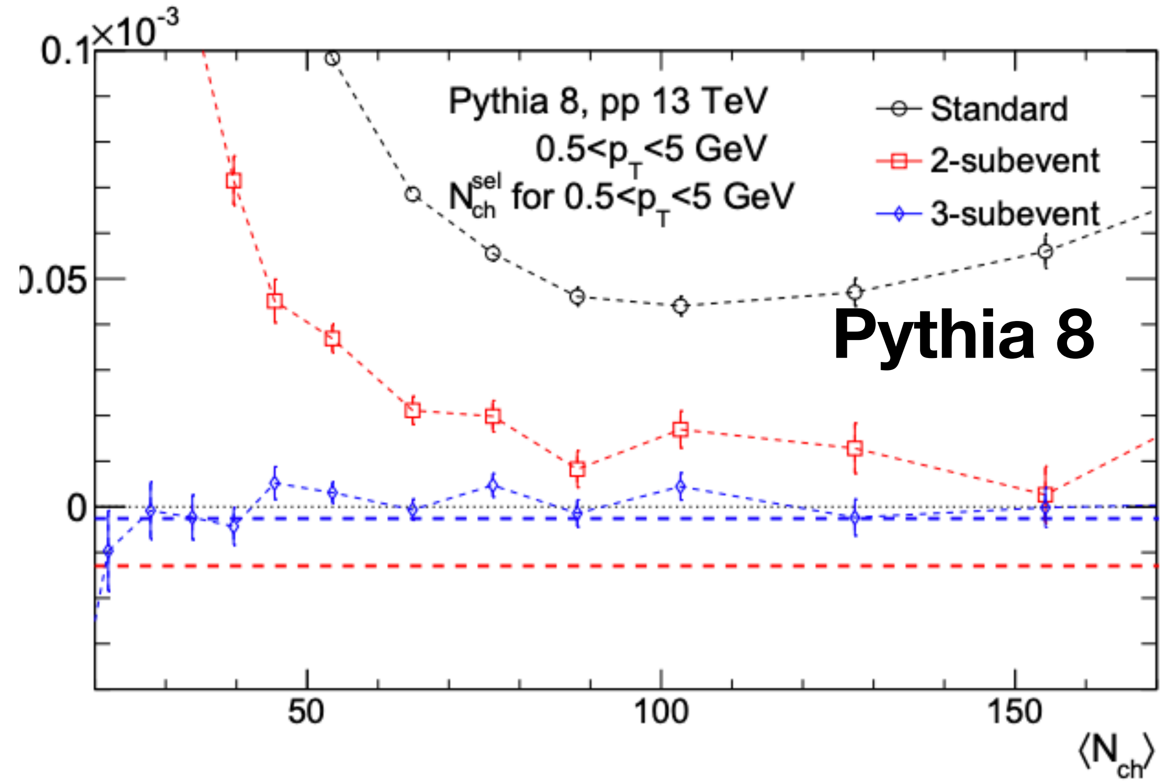
Sub-event cumulant method



The second type of four-particle cumulant has a larger contribution from non-flow

Introduced to further reduce non-flow correlations in multi-particle cumulant in small systems

Pythia does not have flow correlations —> expectation is $c_2\{4\} \sim 0$

Standard $c_2\{4\} > 0$ —> non-flow remains

2-subevent closer to 0 , but still positive

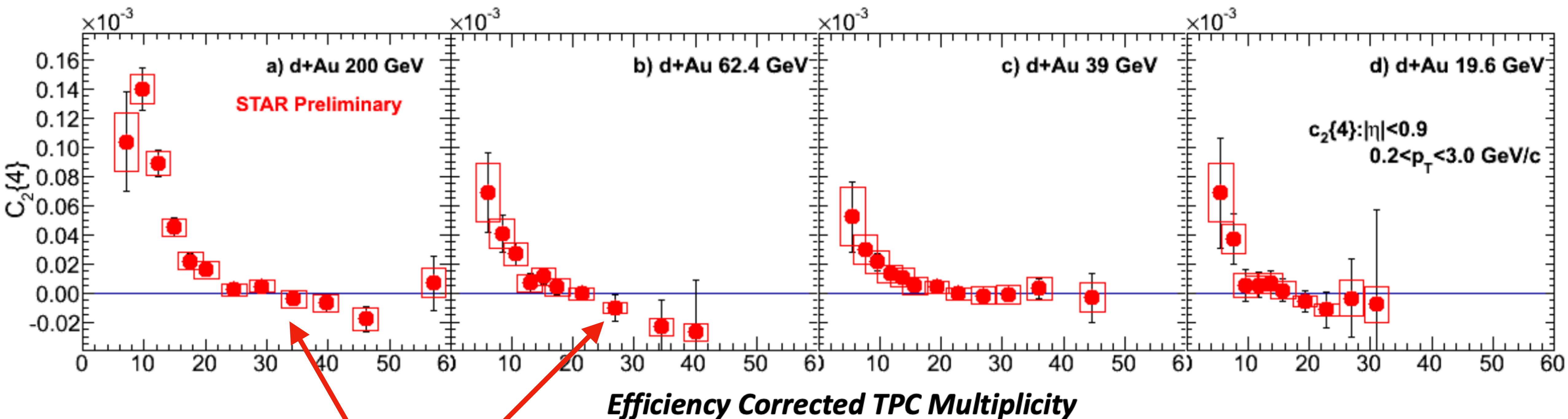
3-subevent - close to 0

Reference: Revealing long-range multi-particle collectivity in small collision systems via subevent cumulants. Phys. Rev. C 96, 034906 (2017)

Small system multi-particle correlations in STAR

$c_2\{4\}$ vs. $<dN/d\eta>$

Standard cumulant



indication of negative $c_2\{4\}$ in d+Au

200 GeV d+Au 3sub-events