Small systems collectivity: QGP or not ?

PHENIX

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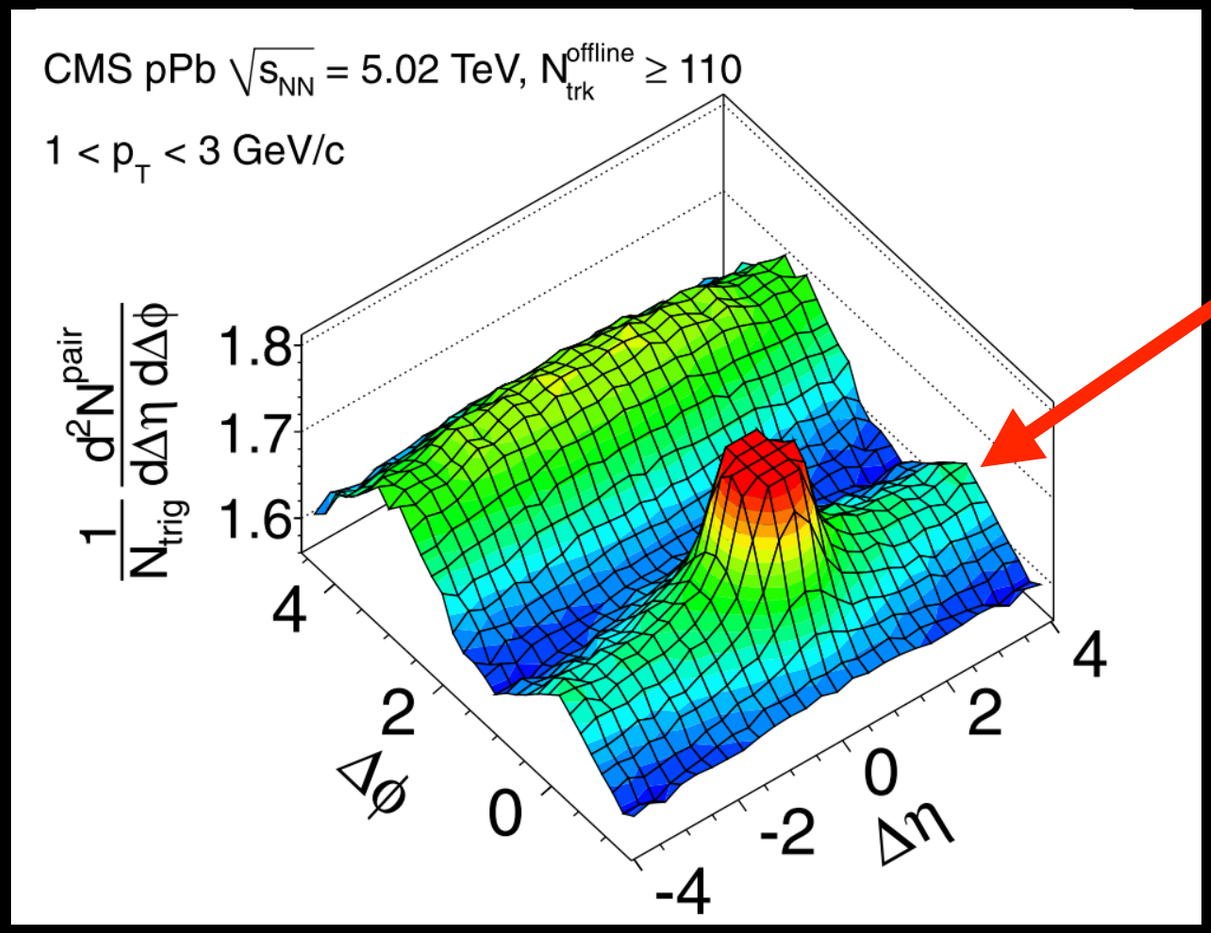
(Vanderbilt)

RHIC/AGS User Meeting
BNL, June 4, 2019

Small Systems Motivation

- Originally: cold nuclear matter effects
- However, correlations similar to those in large systems were also seen in small systems



Near-side ridge

Revised: understand the limits of the most prominent feature of QGP - near perfect fluidity

PHENIX papers on small-system collectivity

1. Nature Physics vol. 15, 214–220 (2019) - pAu,dAu, ^{3}HeAu - charged hadron v_2 and v_3, and model discrimination
2. PRL 121, 222301 (2018) - pAl, pAu, dAu,^{3}HeAu $dN_{ch}/d\eta$,$v_2(\eta)$
3. PRL 120, 062302 (2018) - v_2 with multi-particle cumulants in dAu BES, and cumulants in pAu
4. Phys. Rev. C 98, 014912 (2018) - pi0 - h correlations in dAu
5. Phys. Rev. C 97, 064904 (2018) - v_2 of identified hadrons quark number scaling in pAu, dAu , ^{3}HeAu
6. Phys. Rev. C 96, 064905 (2017) - v_2 and dN_{ch}/deta of charged hadrons in dAu BES; also as a function of centrality
7. Phys. Rev. C 95, 034910 (2017) - charged hadron v_2 in pAu
8. PRL 115, 142301 (2015)- charged hadron v_2 and v_3 in ^{3}HeAu
9. PRL 114,192301 (2015) - charged hadron v_2 in dAu; EP
10. PRL 111, 212301 (2013)- charged hadron v_2 in dAu; 2PC

What is the origin of collectivity in small systems?

If it's quark-gluon plasma we expect to see signatures of a perfect fluid…

Is the whole system collective ?

Geometry-driven flow?

Is the whole system collective ?

Correlations are long-range ?

Is the whole system collective ?

All particles are correlated ?

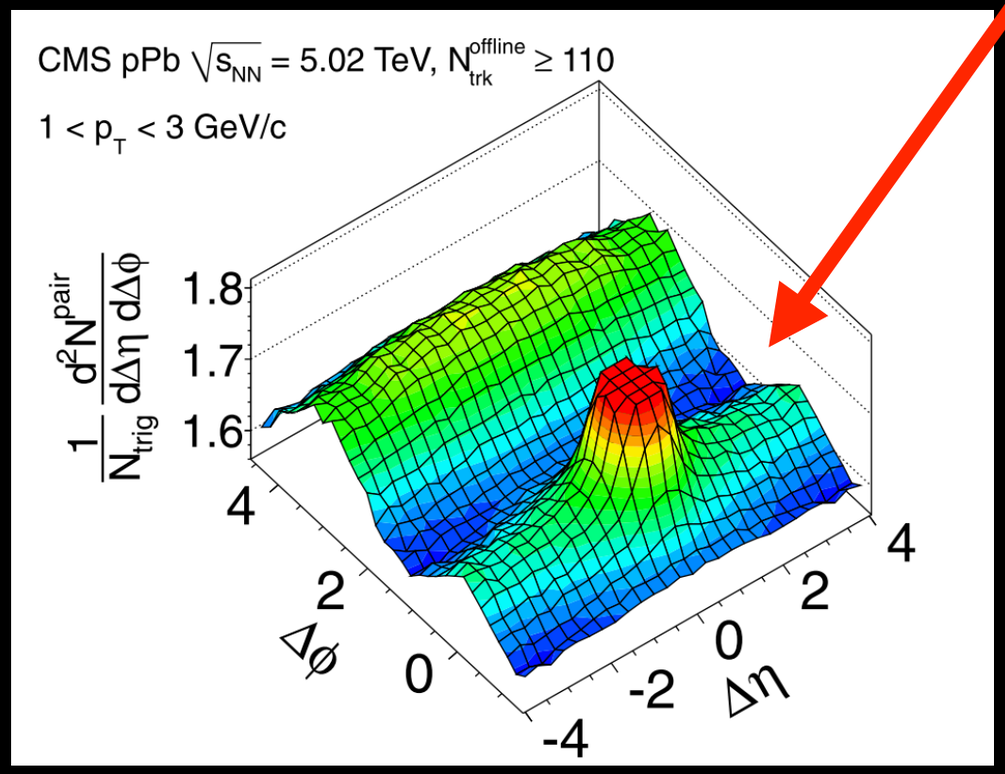
Common velocity field ?

Q

Are there long-range correlations in small systems at RHIC?

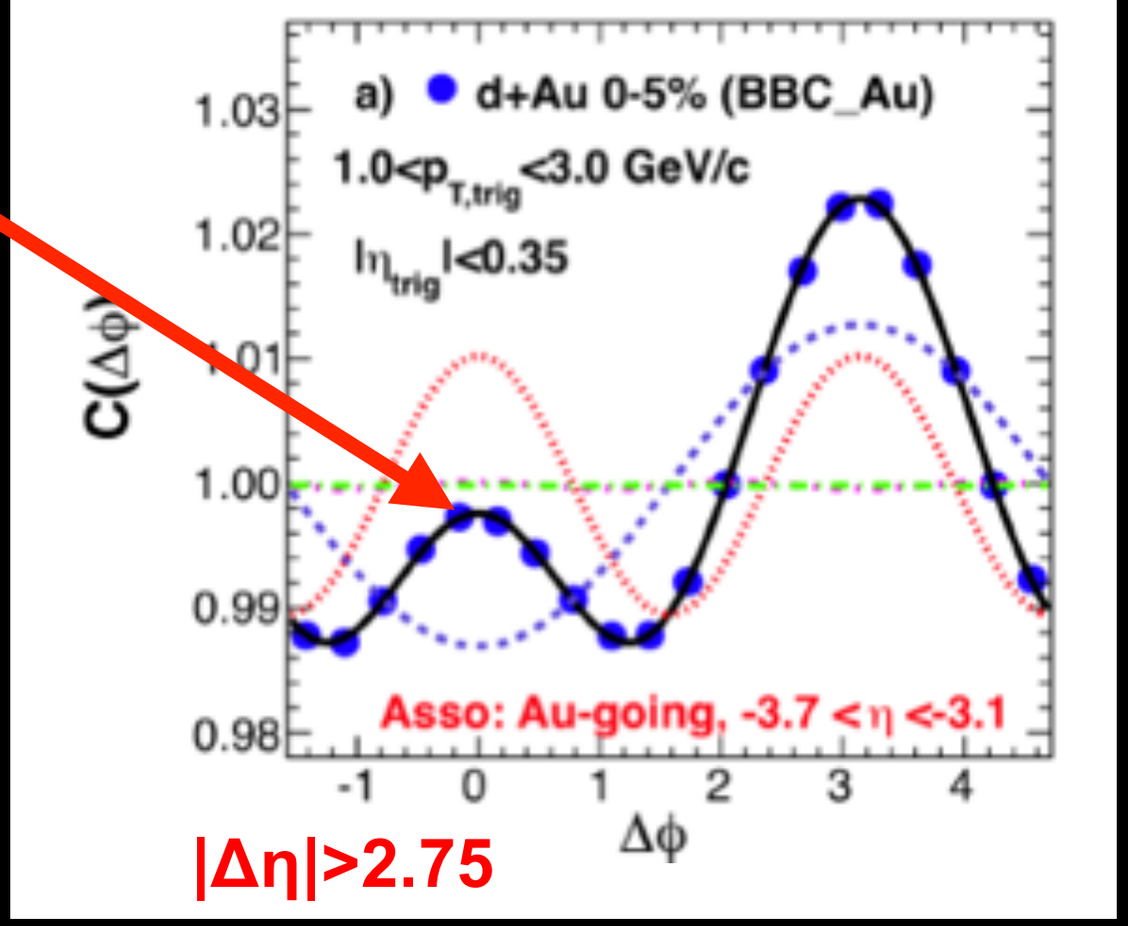
pPb at LHC

near-side ridge



PHENIX 2008 d+Au data

Phys. Rev. Lett. 114, 192301, 2015



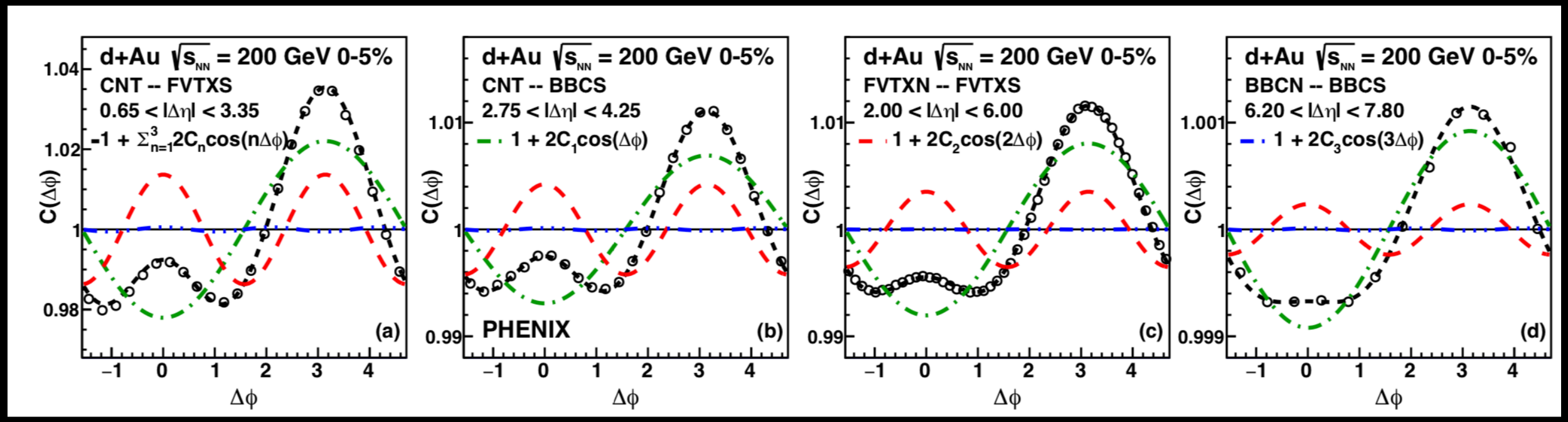
A

Yes. A near-side ridge is observed in d+Au.

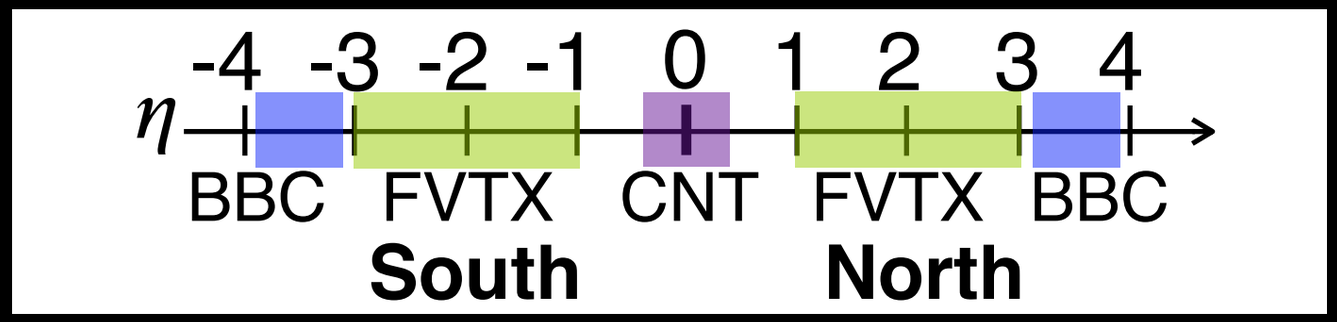
larger Δη range studied with 2016 d+Au data

PRC 96, 064905 (2017)

2016 d+Au data



a) **0.65 < |Δη| < 3.35**, (b) **2.75 < |Δη| < 4.25**, (c) **2.0 < |Δη| < 6.0**, (d) **6.2 < |Δη<7.8**

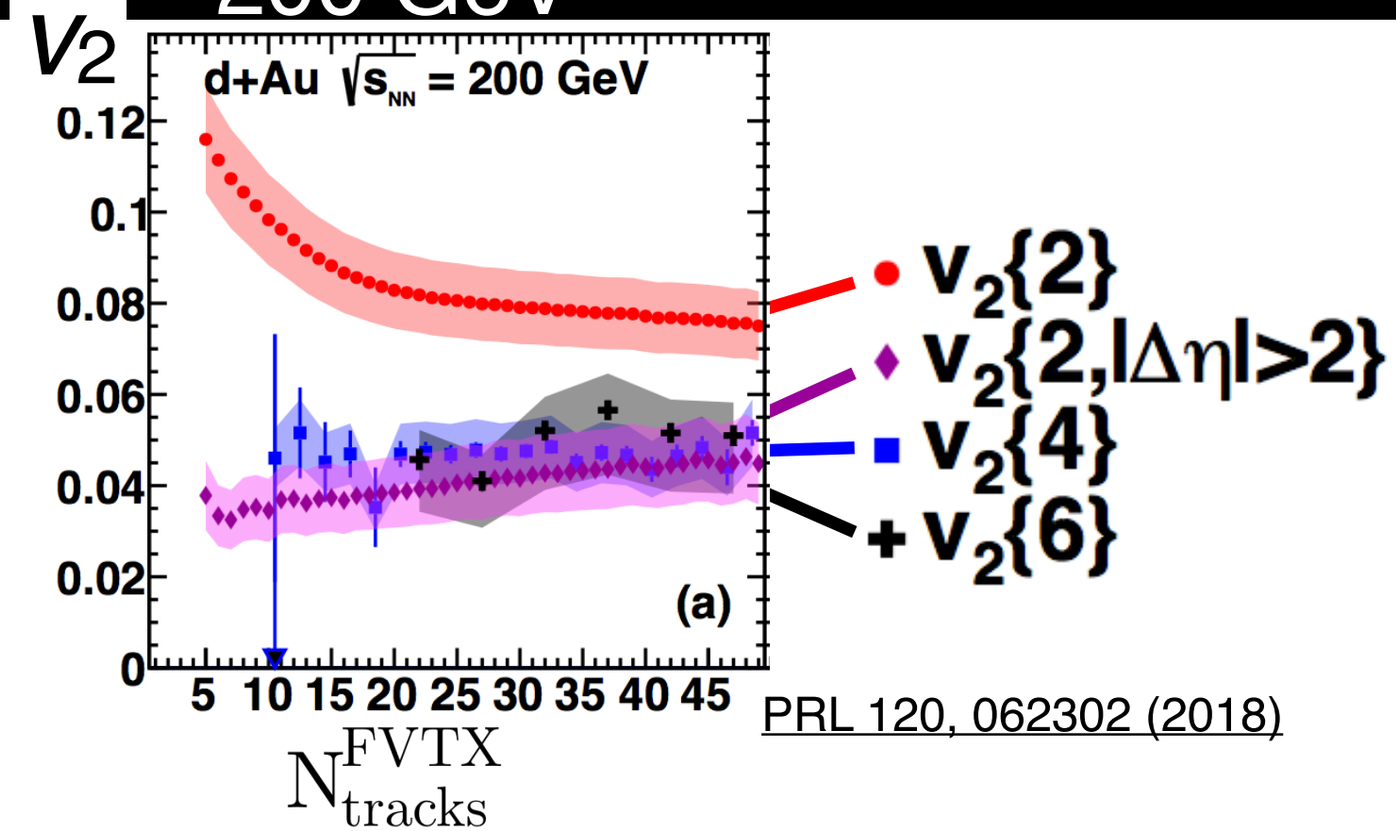


A sizable c_2 component is seen even for 6.2 < |Δη<7.8

Q Are all particles correlated ?

Are all particles correlated ?

200 GeV



PRL 120, 062302 (2018)

- η separation reduces non-flow contributions
- Different kinematics

- $v_2\{2\}$ is above $v_2\{2,|\eta|>2\}$, $v_2\{4\}$, and $v_2\{6\}$
- $v_2\{4\}$ is consistent with $v_2\{6\}$

$\therefore$ $v_2\{4\}$ dominated by flow

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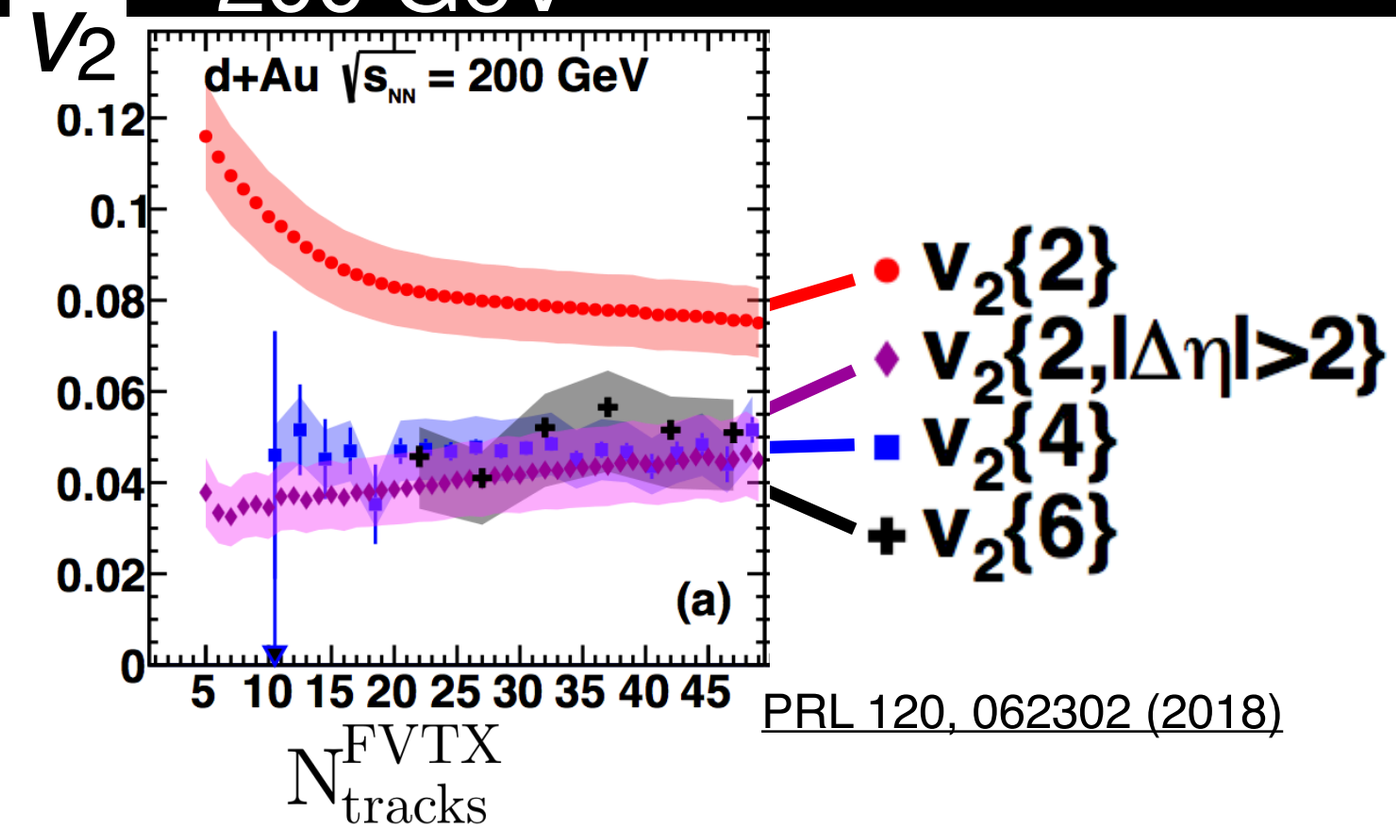

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$\therefore$ $v_2\{4\}$ dominated by flow

A Yes! Multi-particle correlations !

d+Au BES $v_2(N_{tracks})$: data

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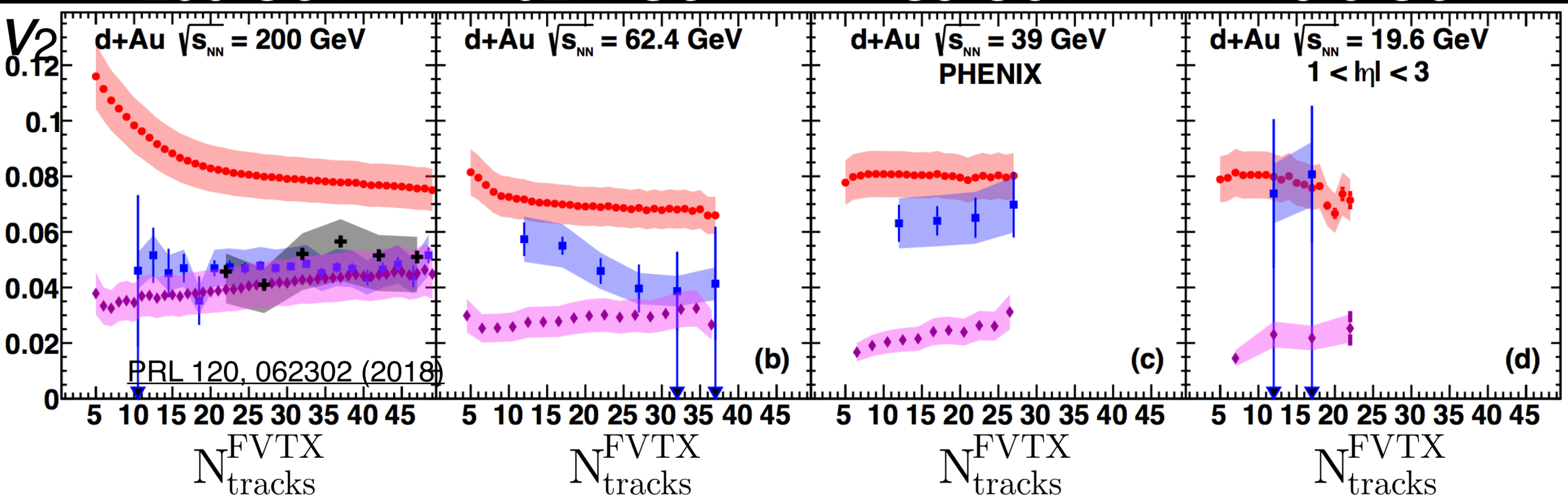
200 GeV 62.4 GeV 39 GeV 19.6 GeV



Real $v_2\{4\}$ for all energies

Appears to be flow correlations down to lowest energy measured (19.6 GeV)

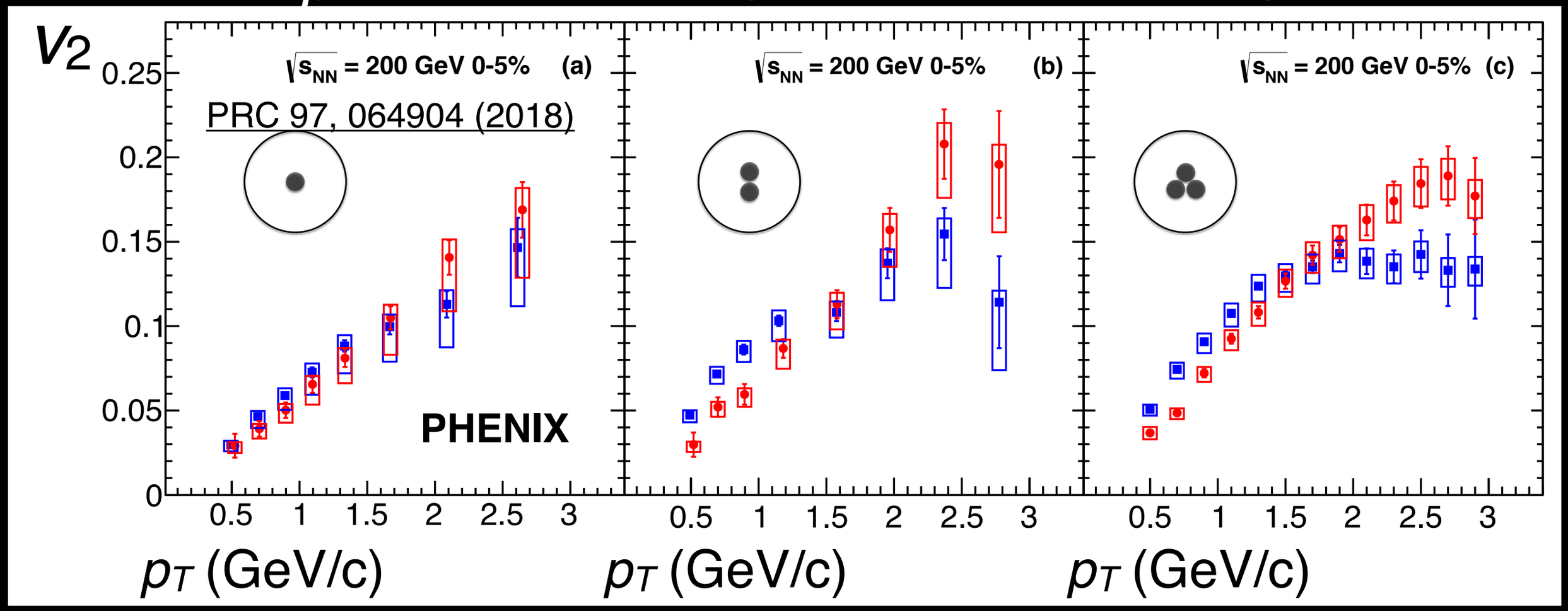
- $v_2\{2\}$
- $v_2\{2,|\Delta\eta|>2\}$
- $v_2\{4\}$
- $v_2\{6\}$

Q

Is there a mass ordering due to a common velocity field?

Measure flow of identified particles

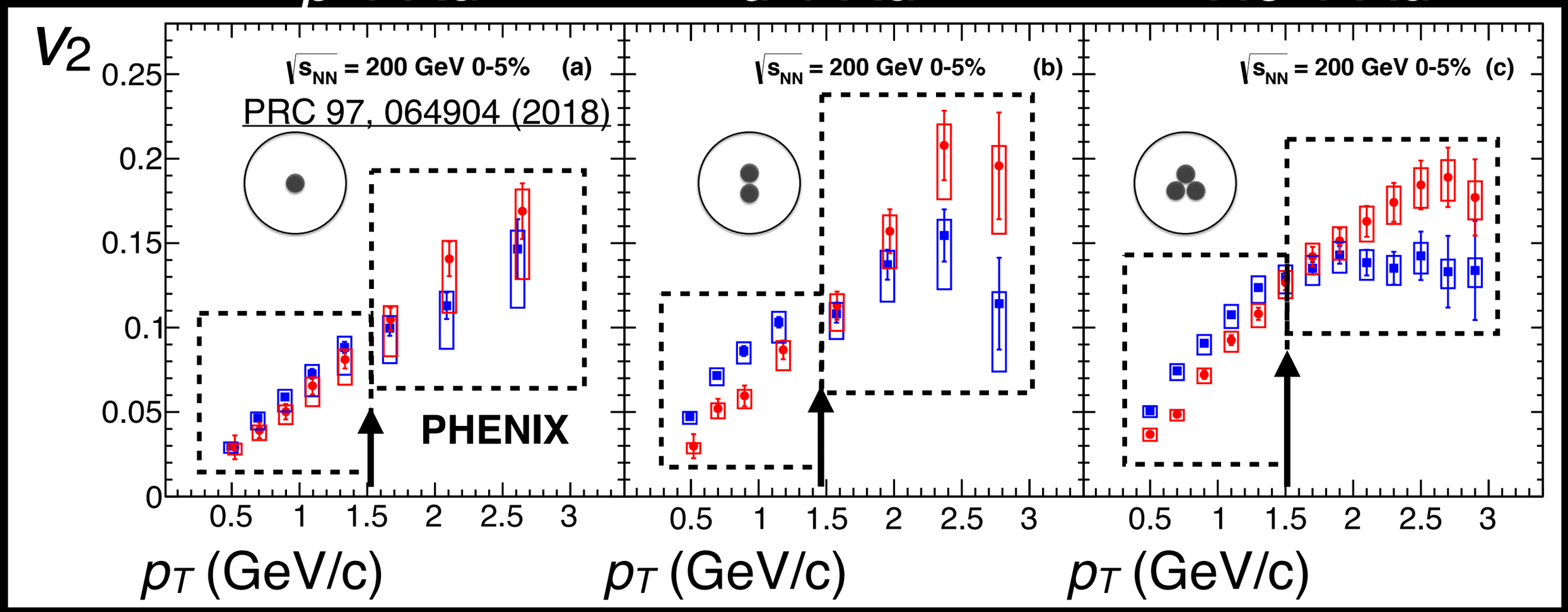
π and p $v_2(p_T)$: data



$\pi^+ + \pi^-$ Data

$p + \bar{p}$ Data

π and p $v_2(p_T)$: data

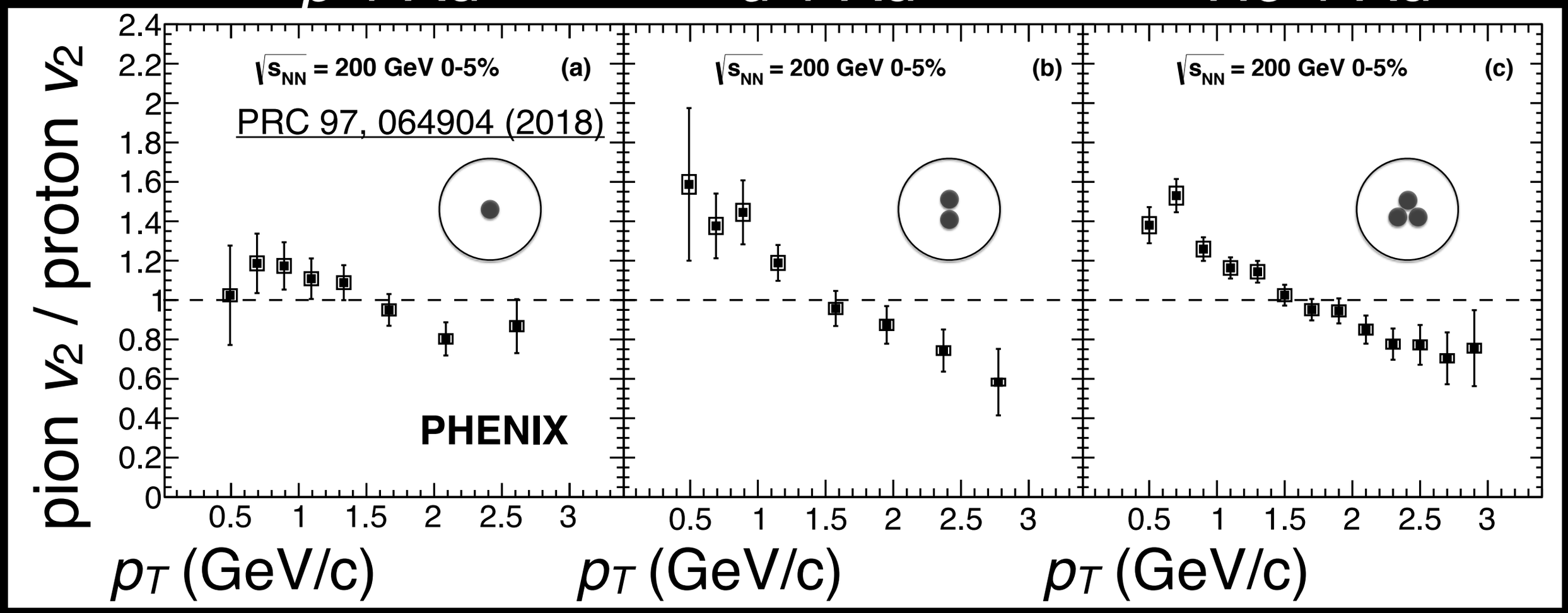


p_T [GeV/c]	< 1.5	$\simeq 1.5$	> 1.5
v_2 ordering	$\pi > p$	$\pi = p$	$\pi < p$

$\pi^+ + \pi^-$ Data

$p + \bar{p}$ Data

$v_2(p_T)$ pion/proton ratio in small systems

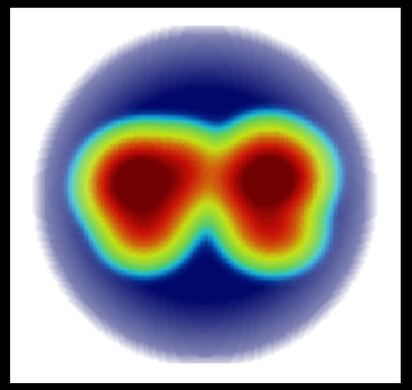


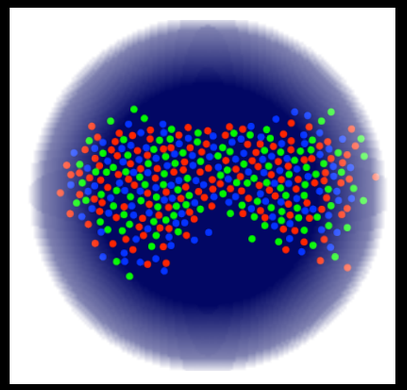
Ratio of pion $v_2(p_T)$ to proton $v_2(p_T)$ —
some uncertainty cancels
mass splitting both at low and high-p_T

Two model formalisms compared to data

	Hydrodynamic	Parton transport
	SONIC, iEBE-VISHNU	**AMPT**
Initial conditions	MC Glauber	MC Glauber
Particle production	N/A	String melting
Expansion	Viscous hydrodynamics	Parton scattering
Hadronization	Cooper-Frye	Spatial coalescence/quark recombination
Final stage	Hadron cascade	Hadron cascade

Macroscopic

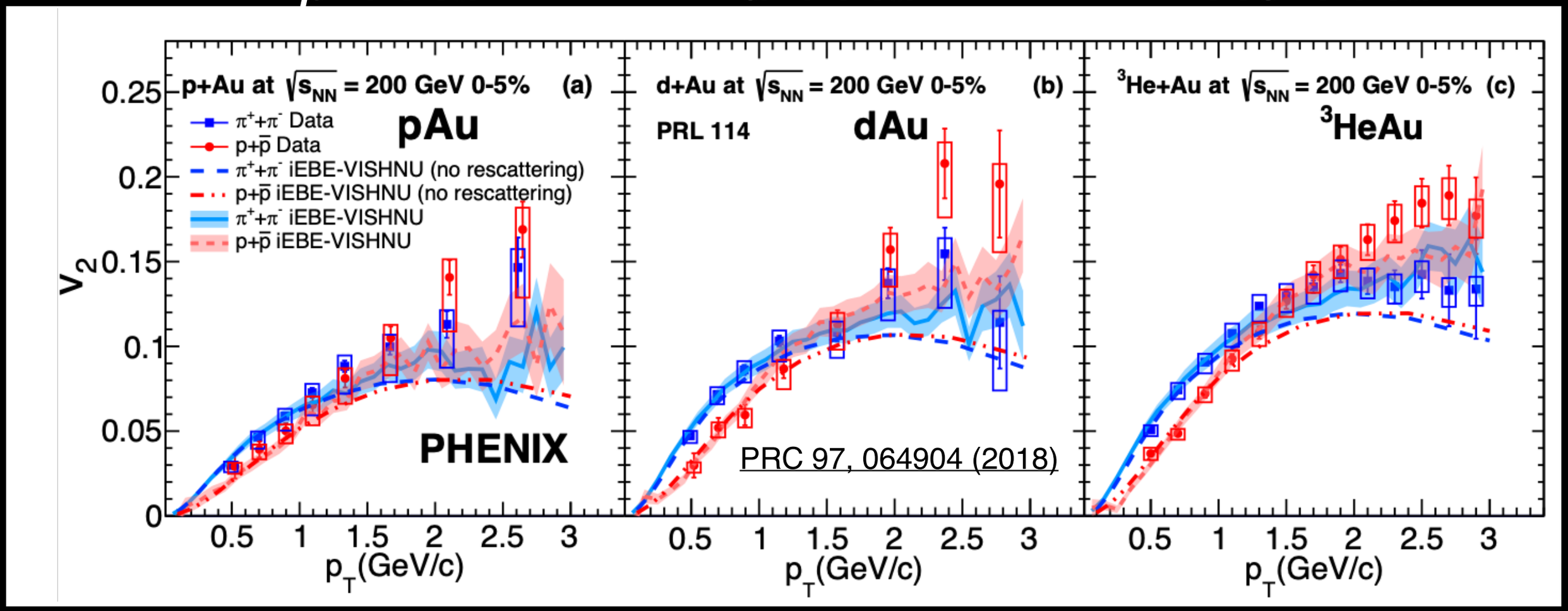


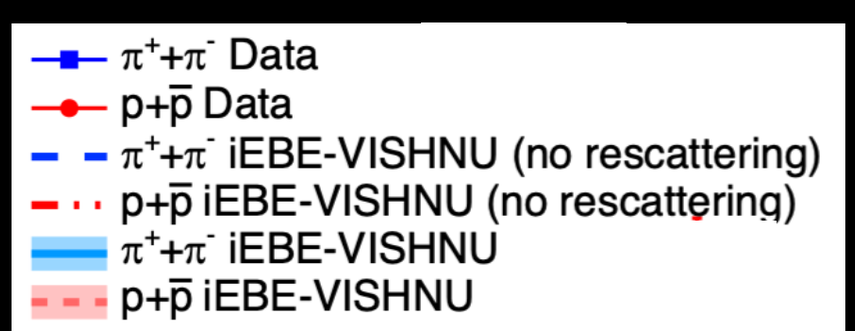


Microscopic

π and p $v_2(p_T)$: data and hydro

p + Au | d + Au | ^{3}He + Au





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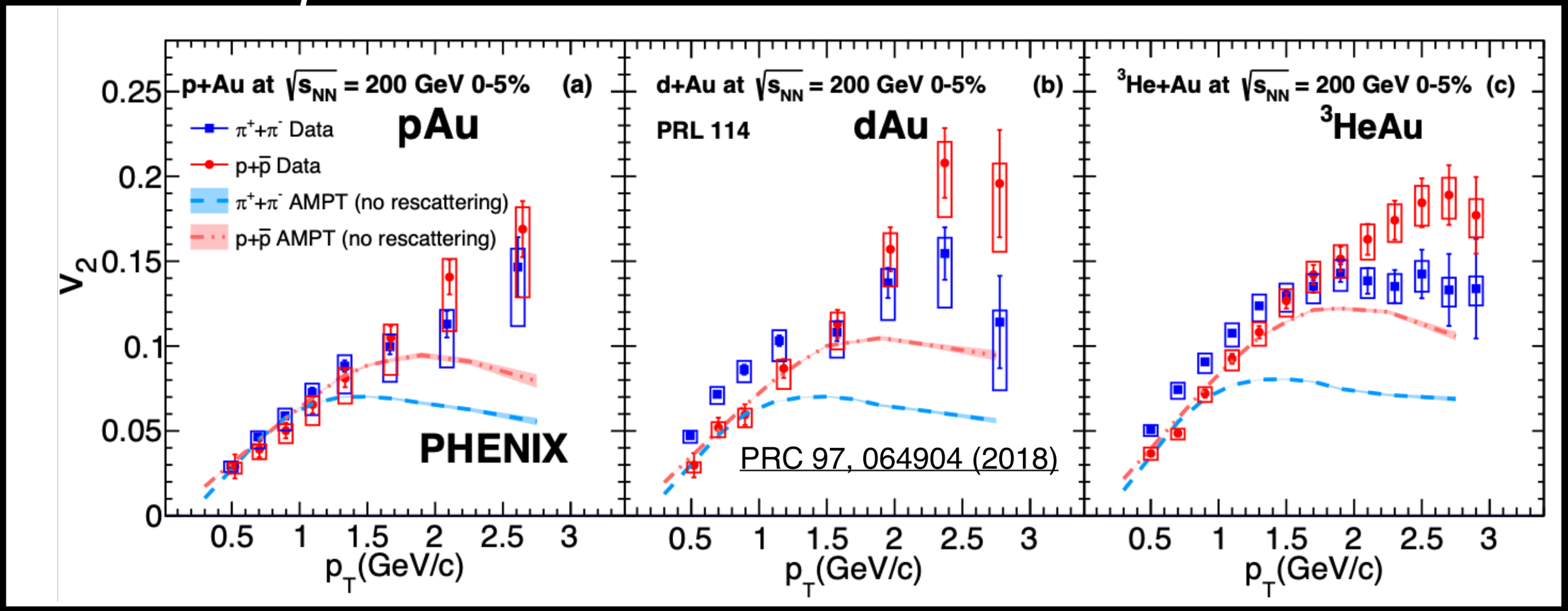
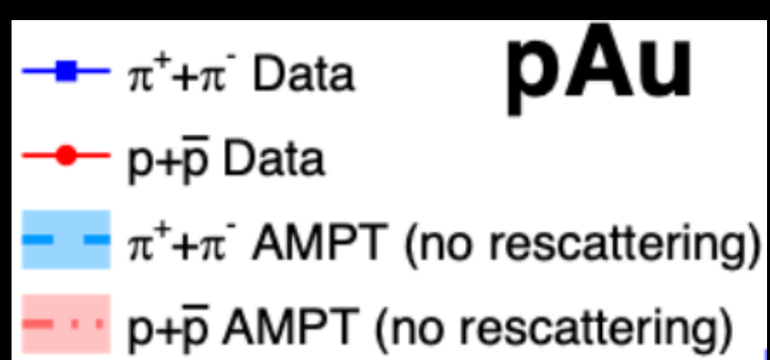
v_2 ordering hydro	$\pi > p$	$\pi = p$	$\pi \simeq p$

π and p $v_2(p_T)$: AMPT (no hadronic rescattering)

p + Au | d + Au | ^{3}He + Au





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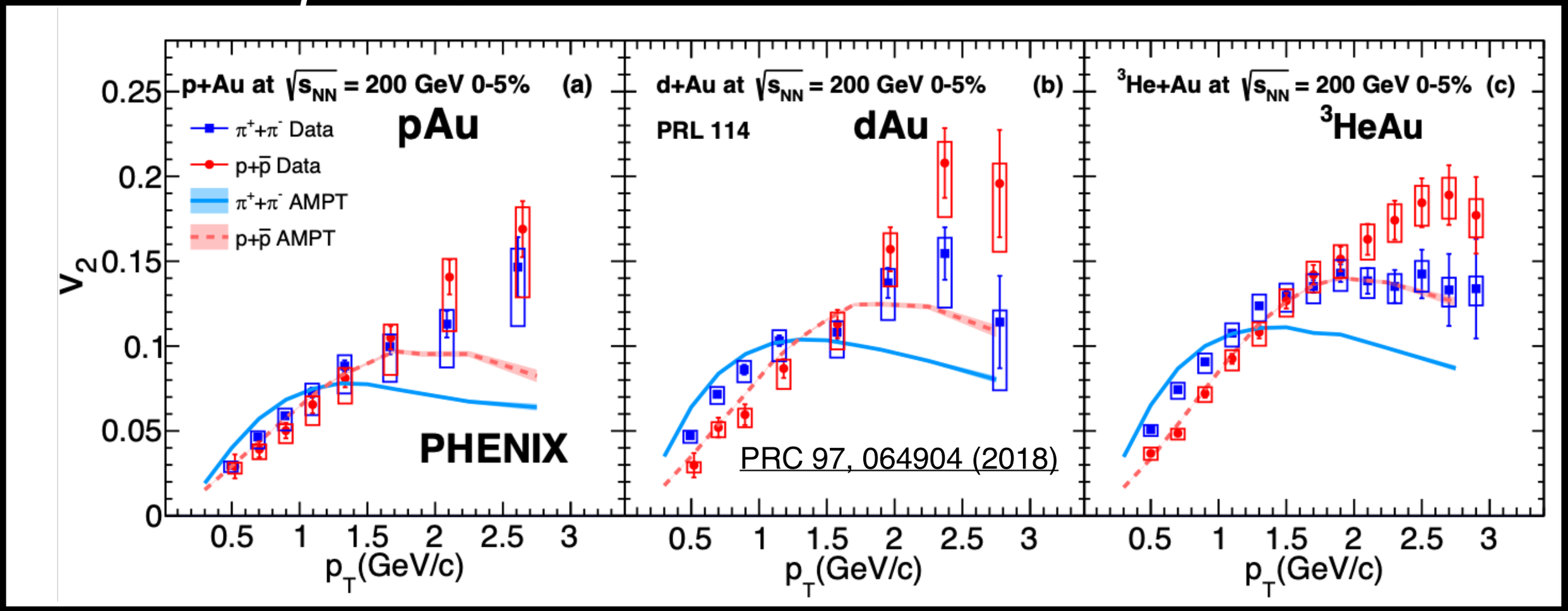
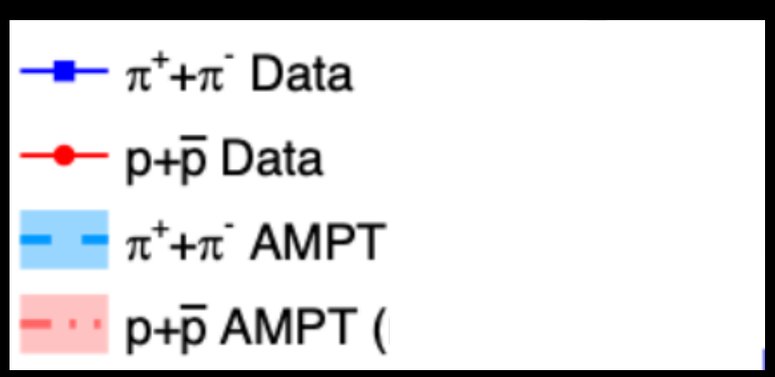
v_2 ordering AMPT	$\pi = p$	$\pi < p$	$\pi < p$

π and p $v_2(p_T)$: AMPT with hadronic rescattering

p + Au | d + Au | ^{3}He + Au





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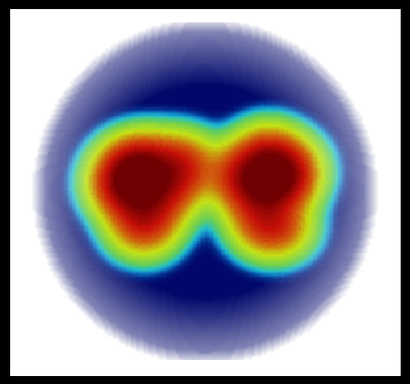
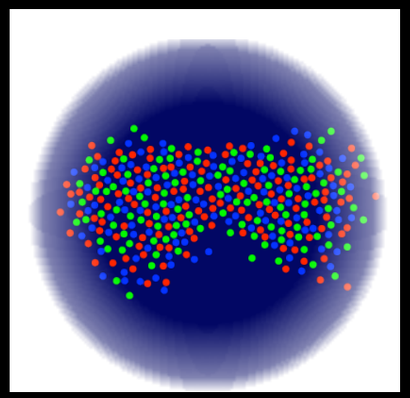
Final stage	Hadron cascade	Hadron cascade low-p_T mass splitting

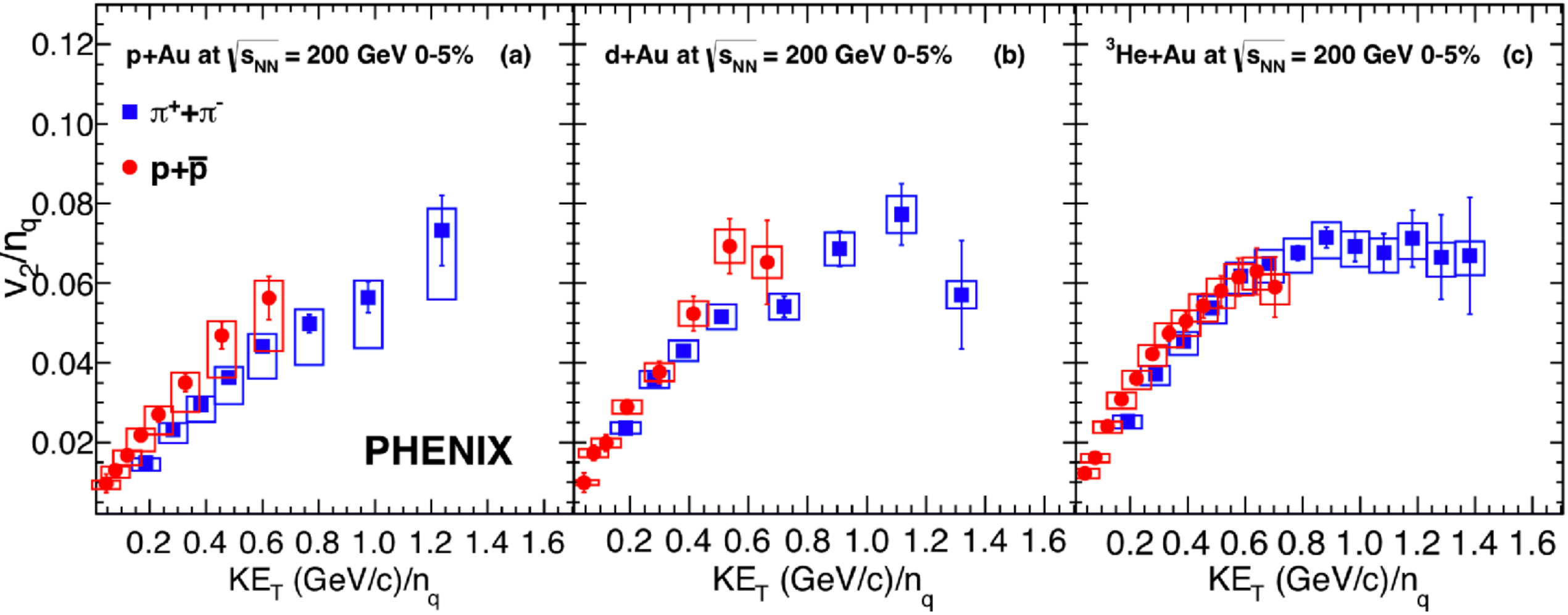
Macroscopic





Microscopic

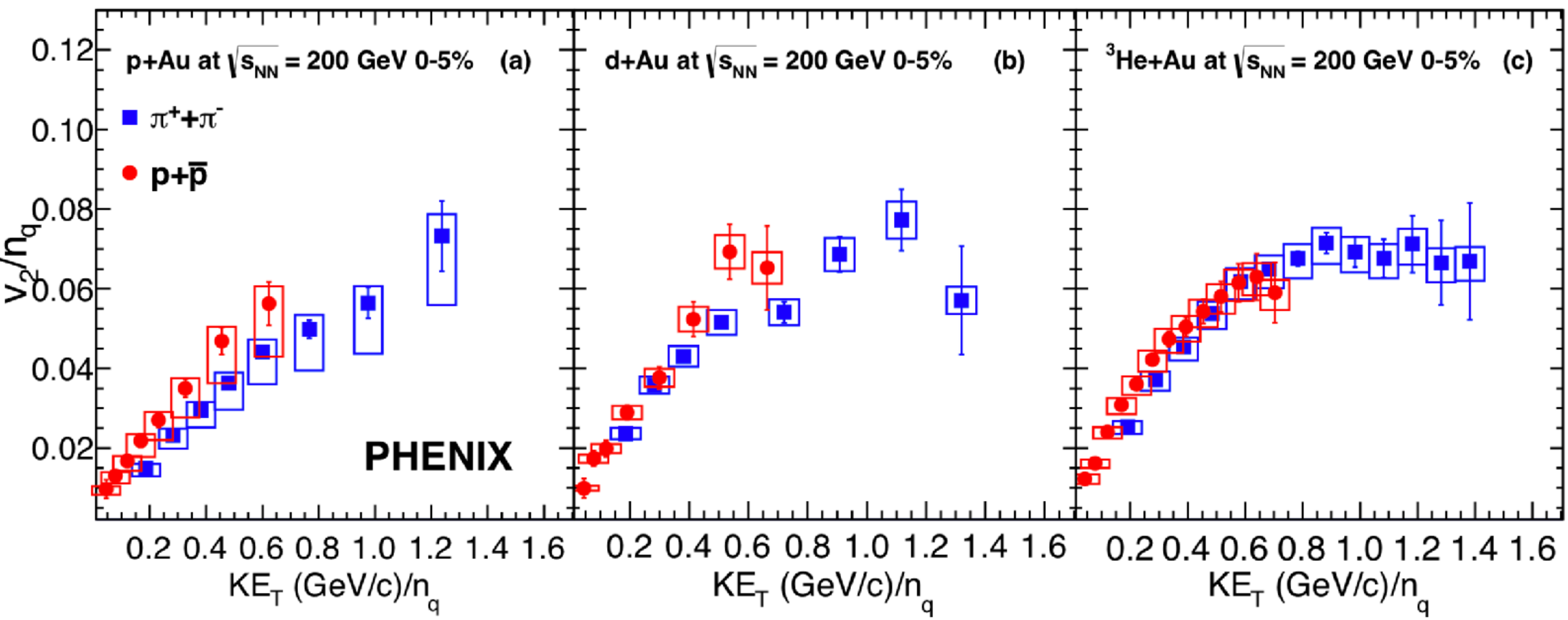
Quark number scaling of v2 in p/d/^{3}He+Au



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

Quark number scaling of v2 in p/d/^{3}He+Au

Q Is there a common velocity field?



A Mass ordering and quark number scaling consistent with flow, but hadron rescattering can also have an effect

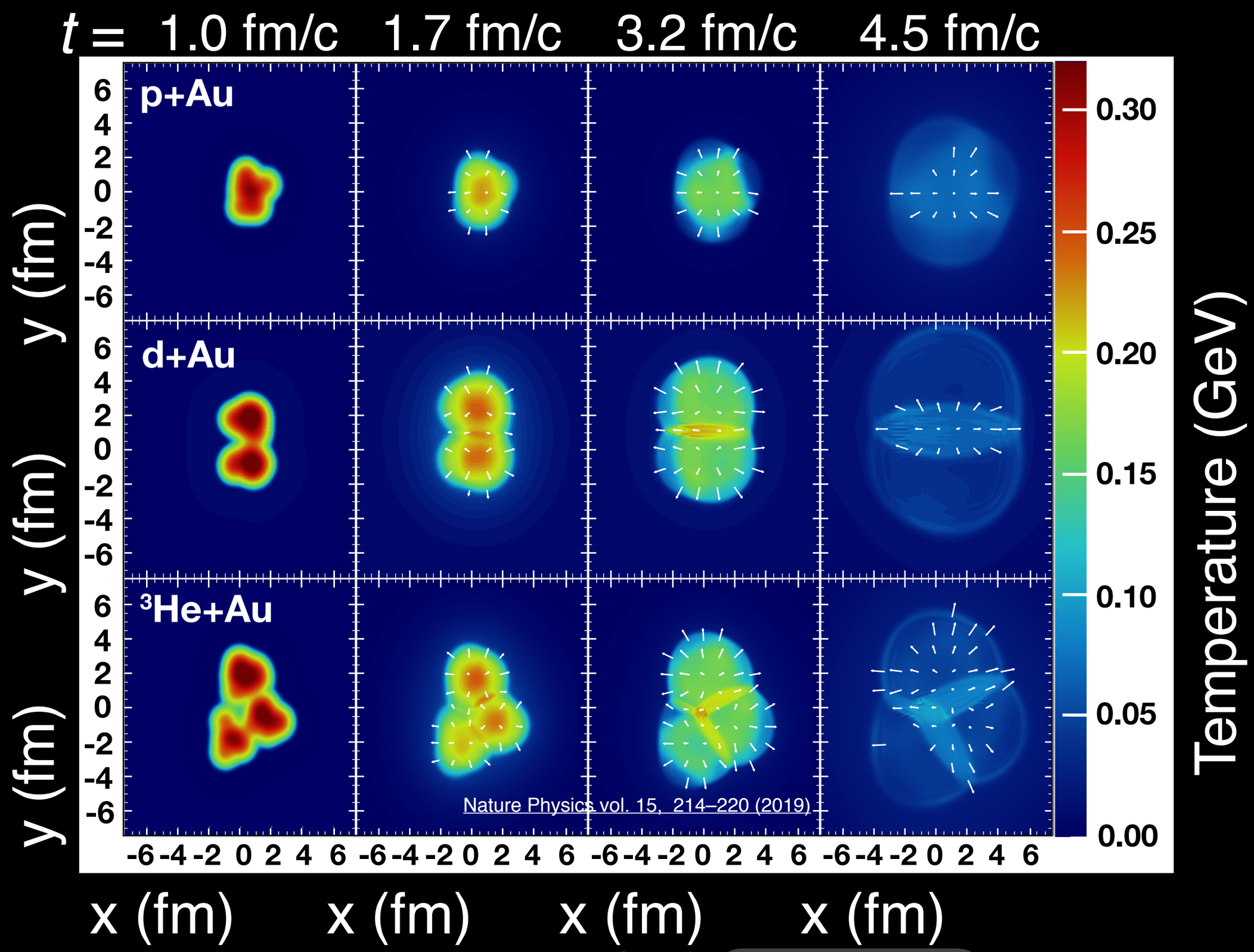
Is the initial state geometry the primary driver of final state momentum correlations in small systems?

Strong evidence indicating YES!

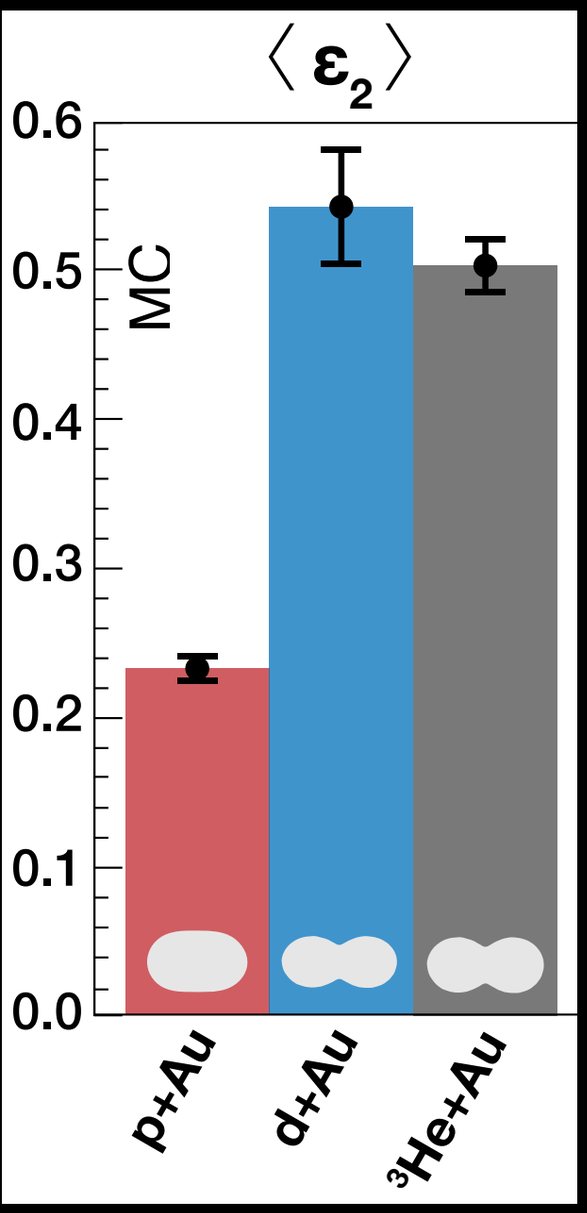
Nature Physics vol. 15, 214–220 (2019)

Hydrodynamic description (SONIC)

$\sqrt{s_{NN}}$ = 200 GeV, central collisions



Eccentricities



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

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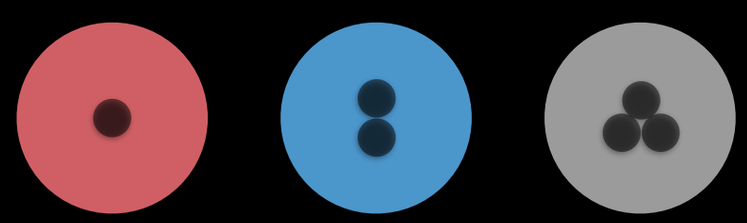

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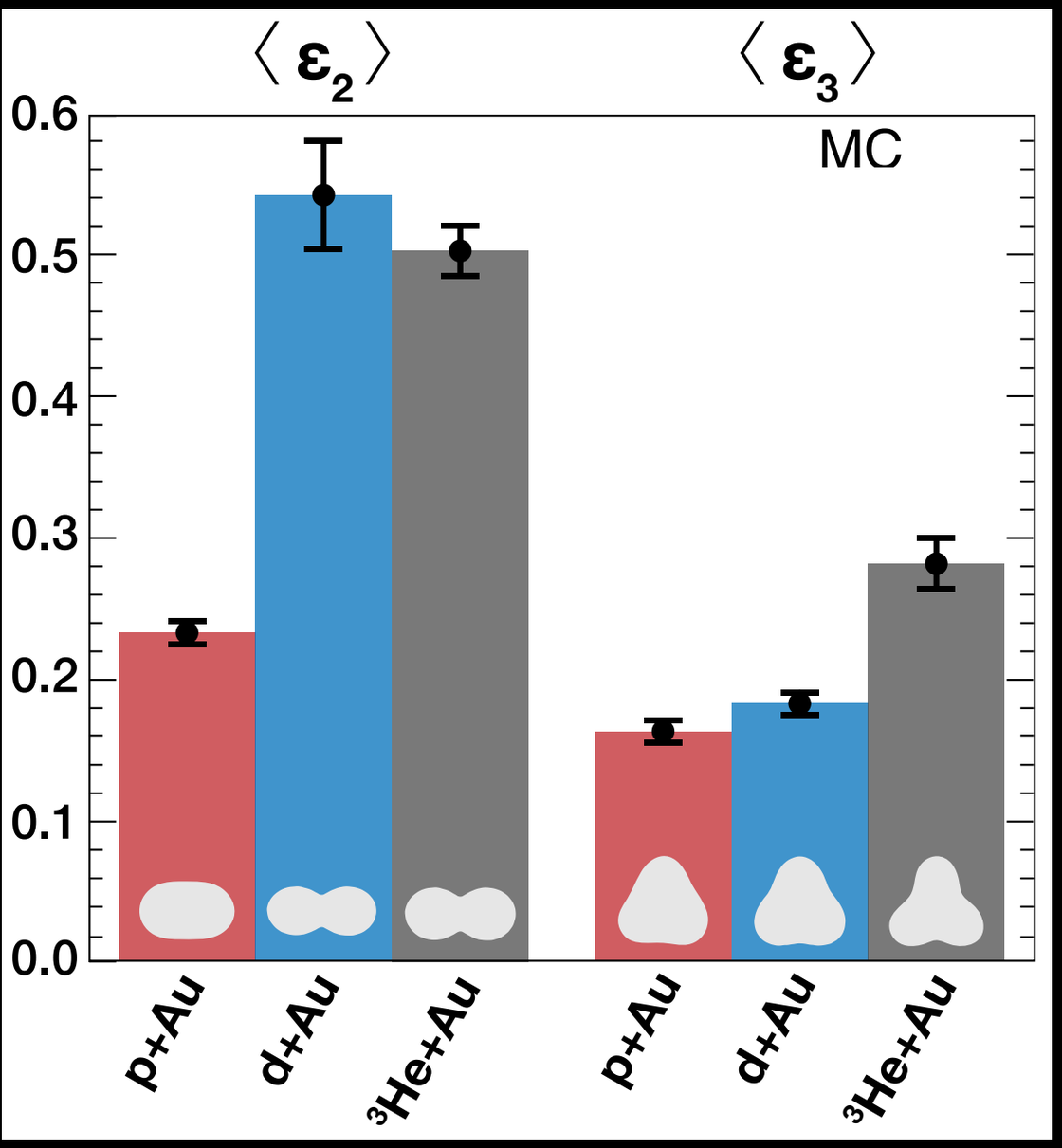

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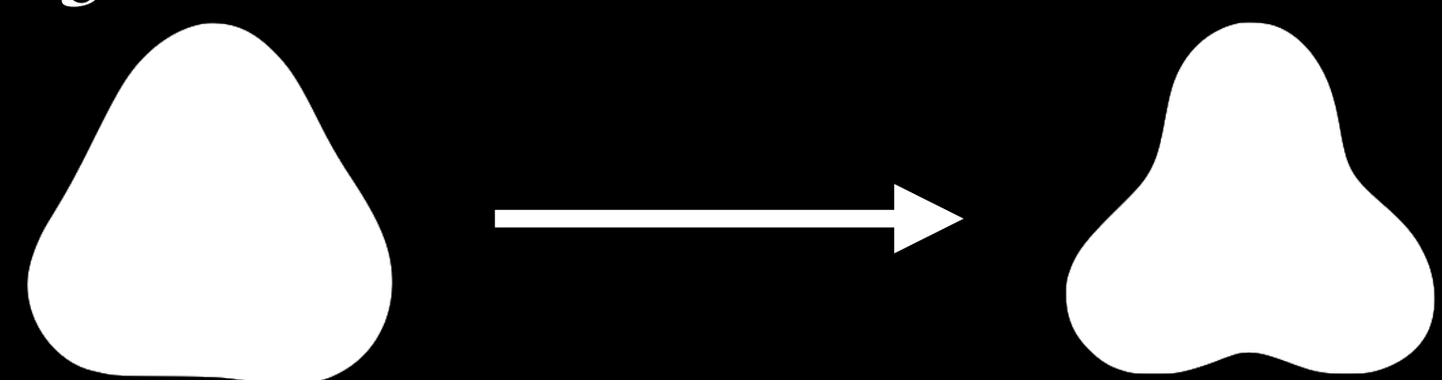
$$\varepsilon_3^{p+\mathrm{Au}} \approx \varepsilon_3^{d+\mathrm{Au}} < \varepsilon_3^{^3\mathrm{He}+\mathrm{Au}}$$



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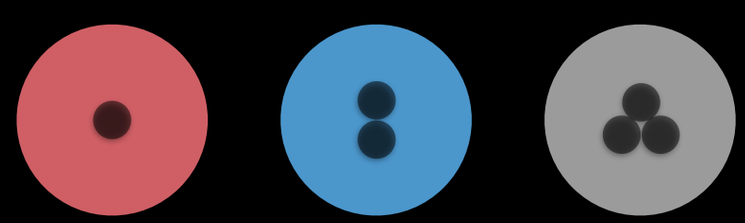
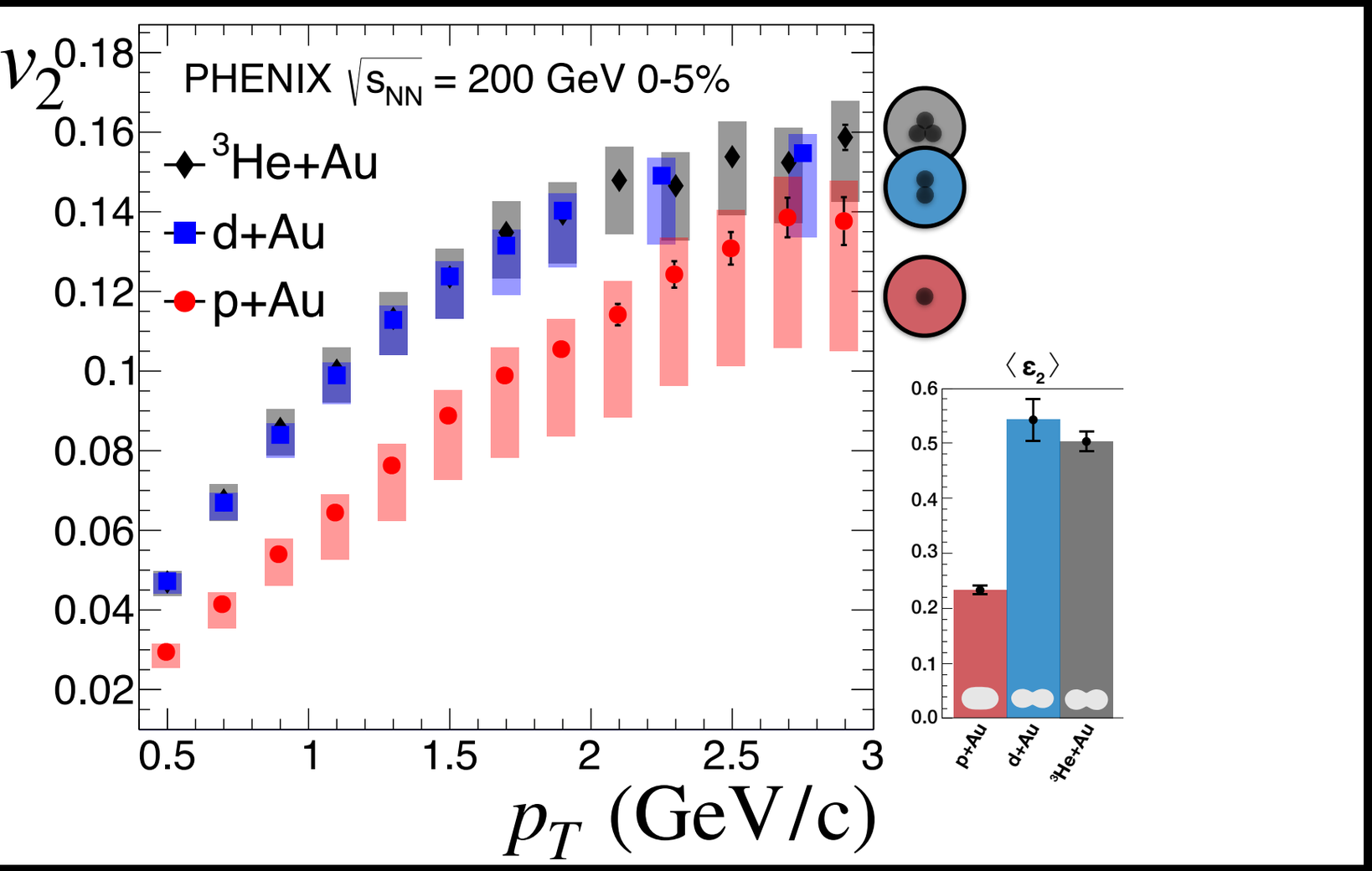


$v_n(p_T)$ measurement in small systems



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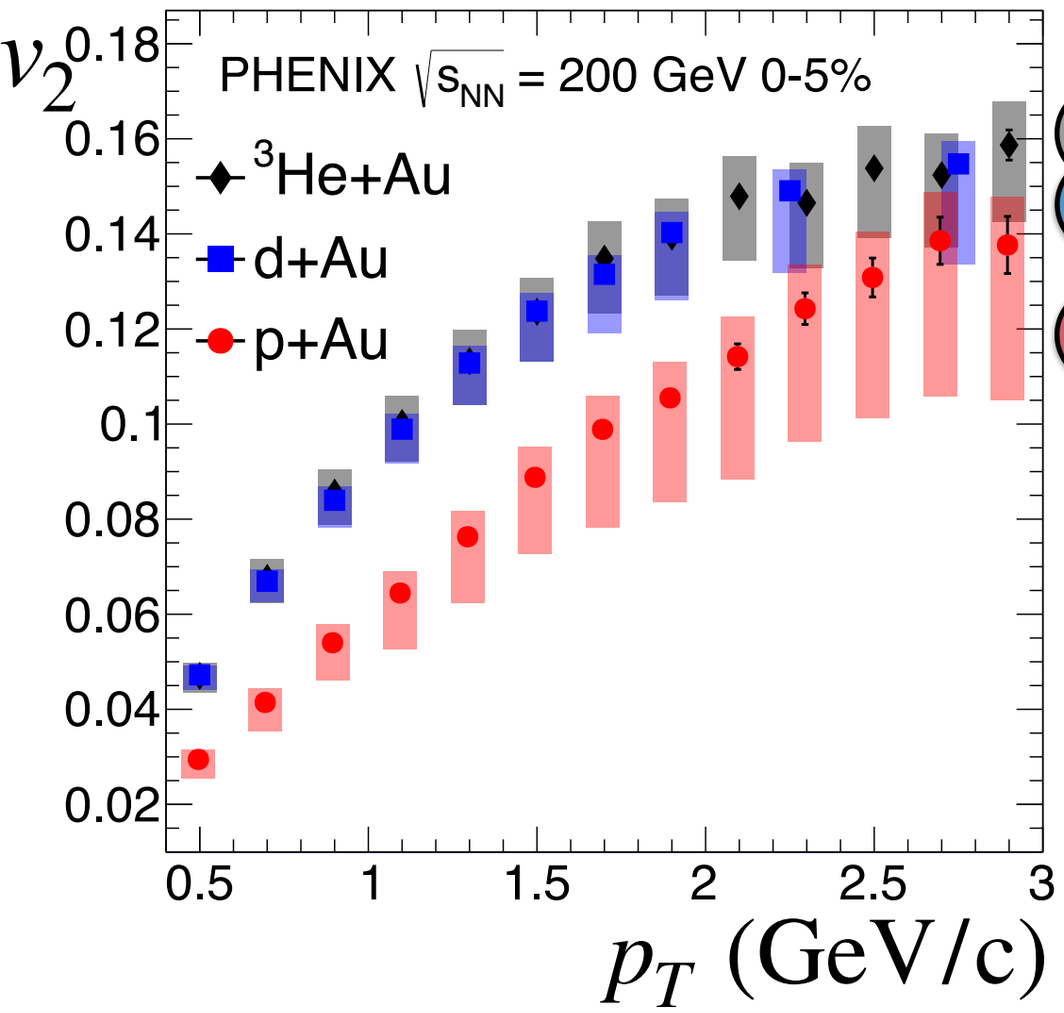
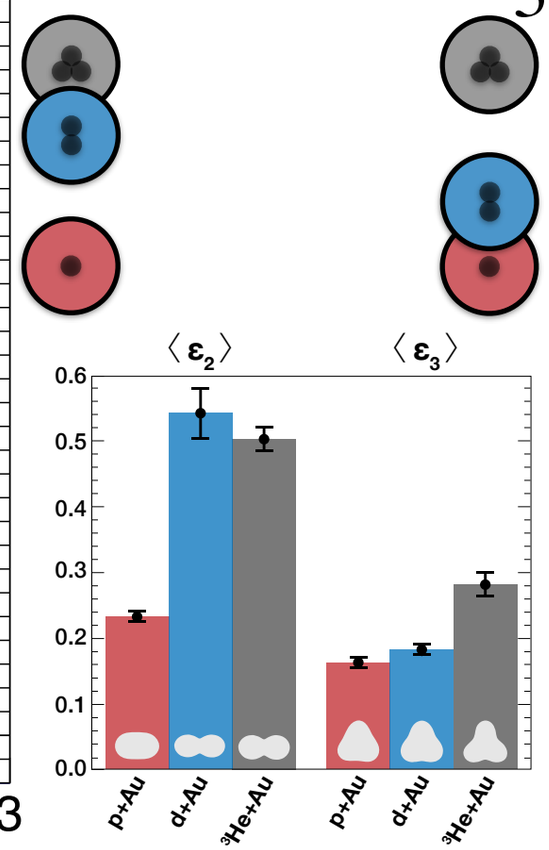
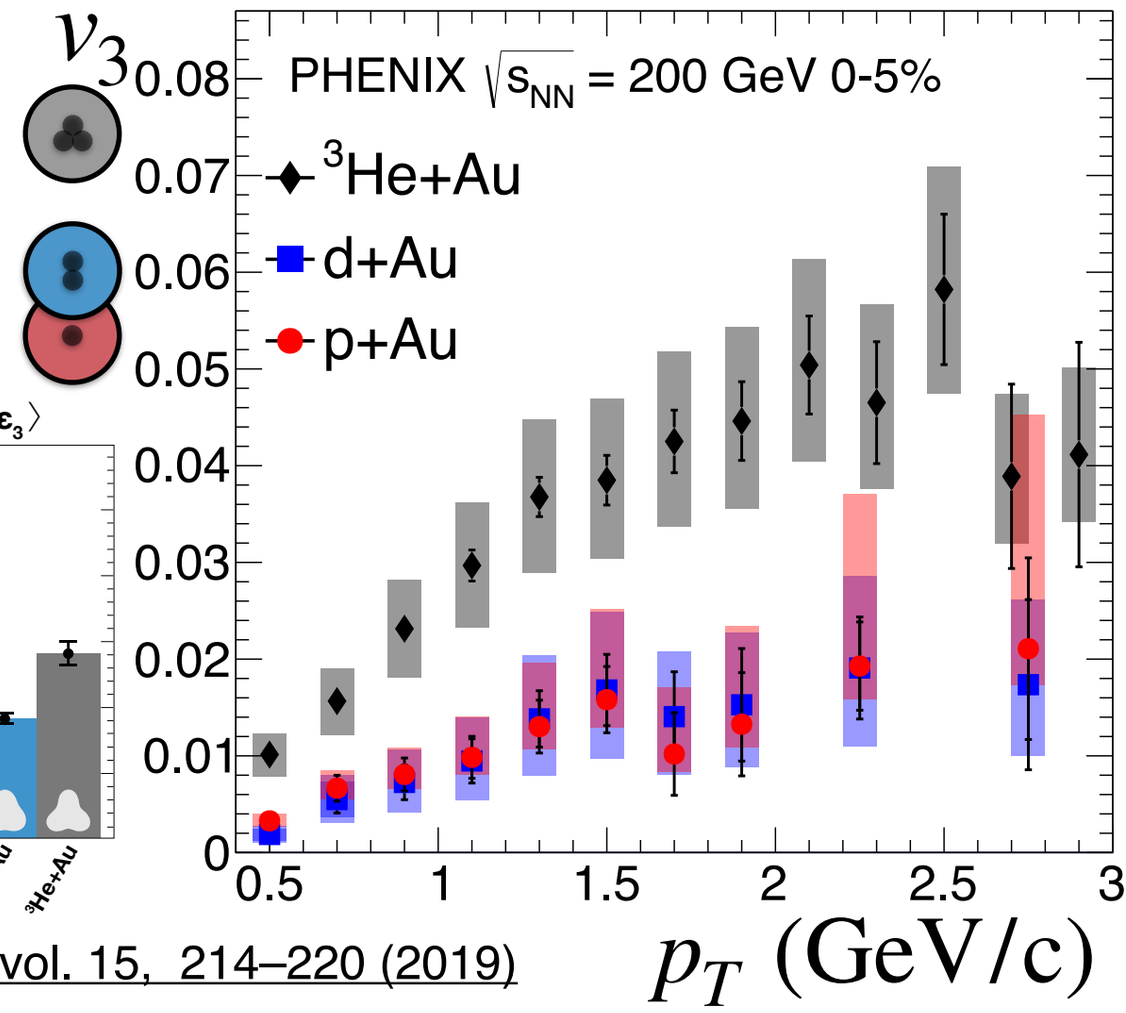






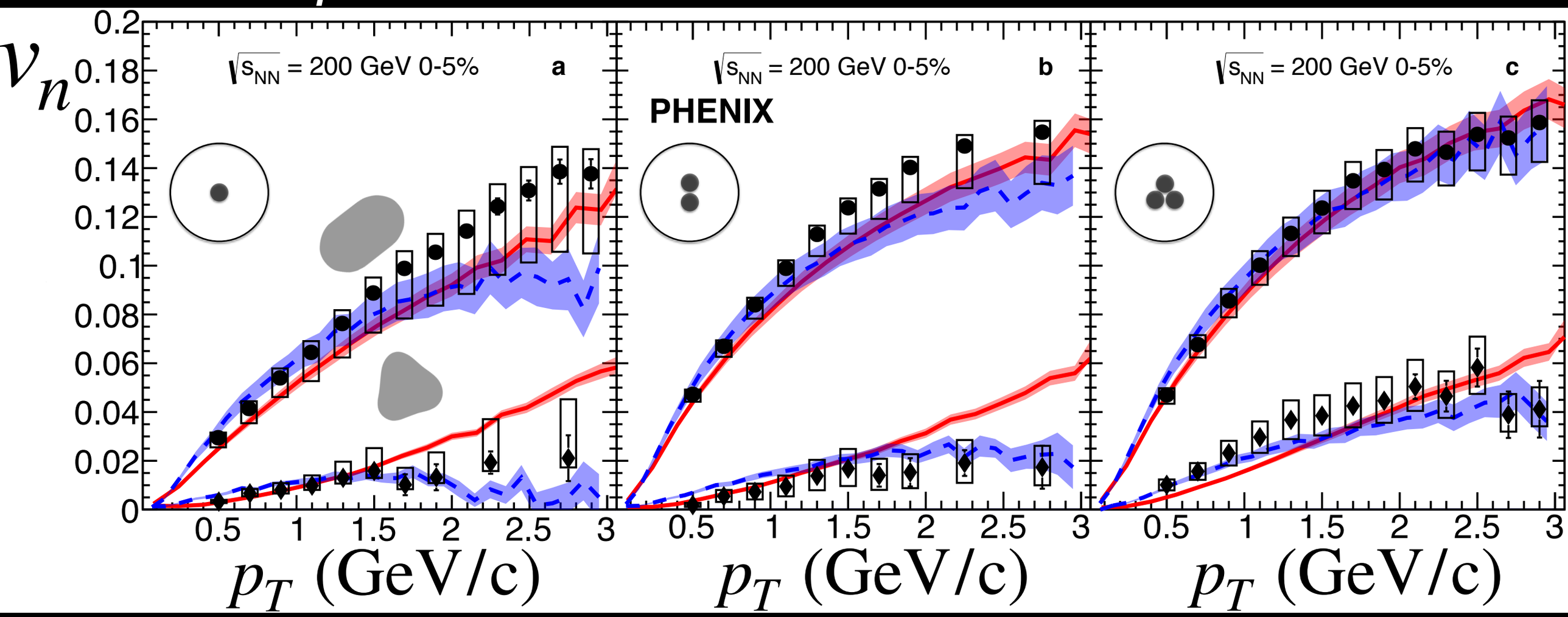
Nature Physics vol. 15, 214–220 (2019)

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

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

Suggests flow is geometric in origin

$v_n(p_T)$ from hydrodynamics and data



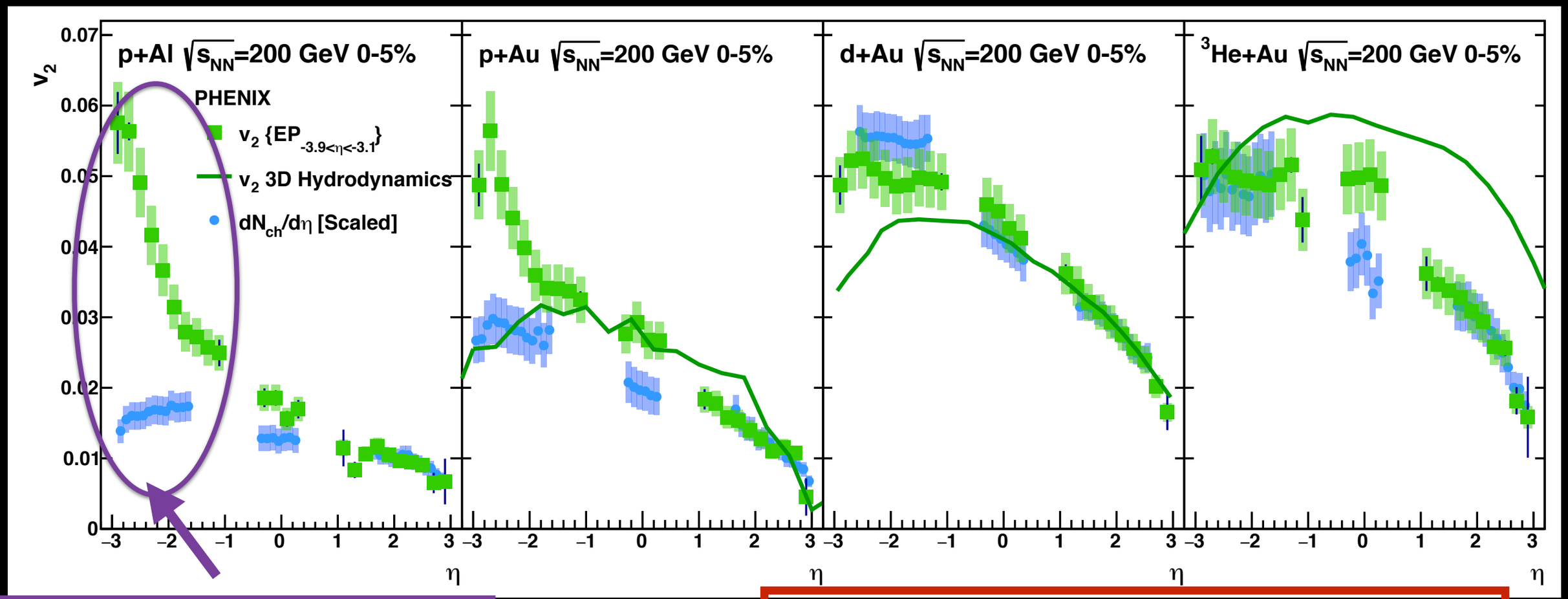
Hydrodynamics provides simultaneous description

- v_2 Data
- v_3 Data
- v_n SONIC Eur. Phys. J. C 75, 15 (2015)
- v_n iEBE-VISHNU PRC 95, 014906 (2017)

- Both use η/s=0.08, MC Glauber initial conditions, 2+1D viscous hydrodynamic evolution
- Different hadronic rescattering packages

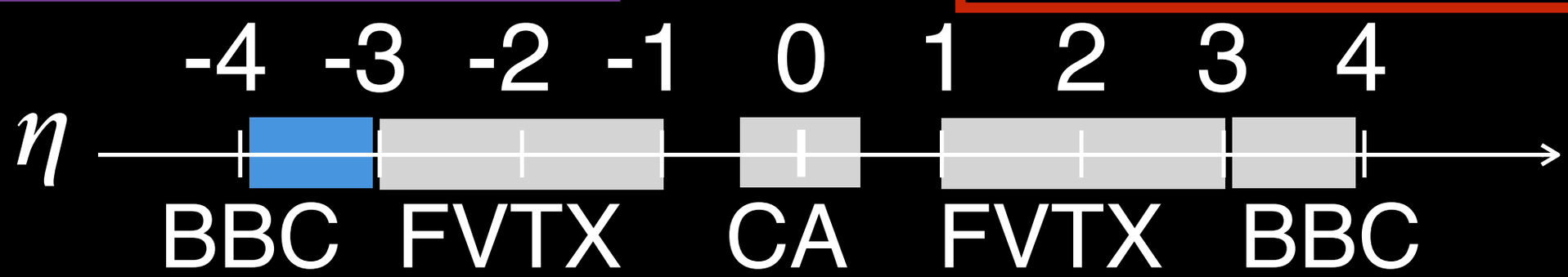
Eccentricity or multiplicity ?

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



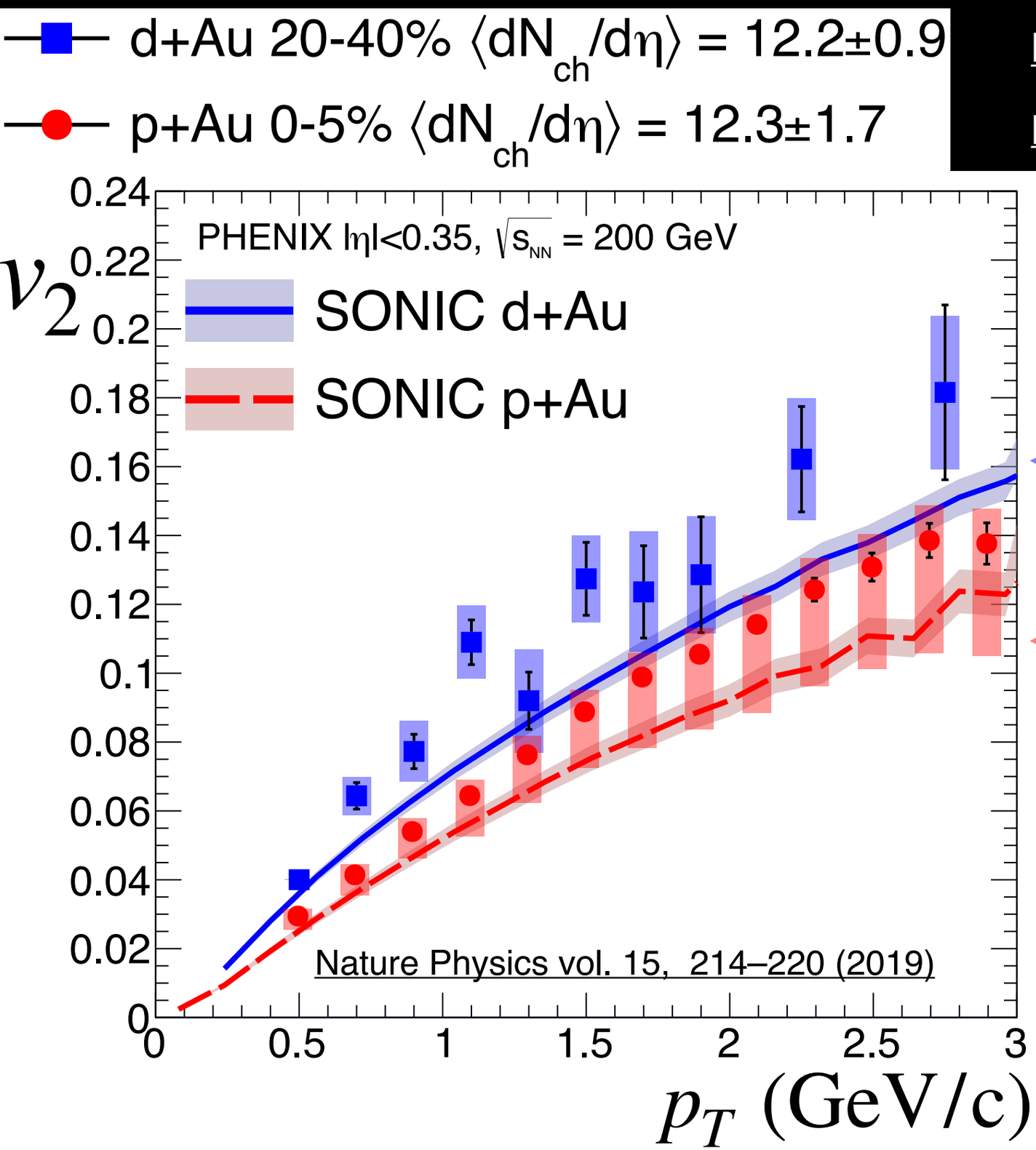
Nonflow dominates near the EP detector

v_2 is correlated with $dN_{ch}/d\eta$ but not exact scaling



Au-going ***d*-going**

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



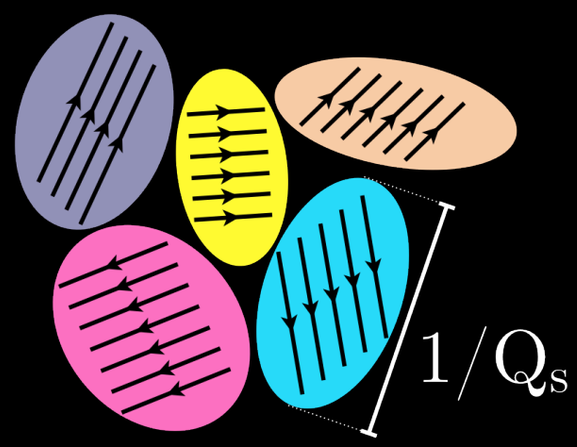
PRC 96, 064905 (2017)

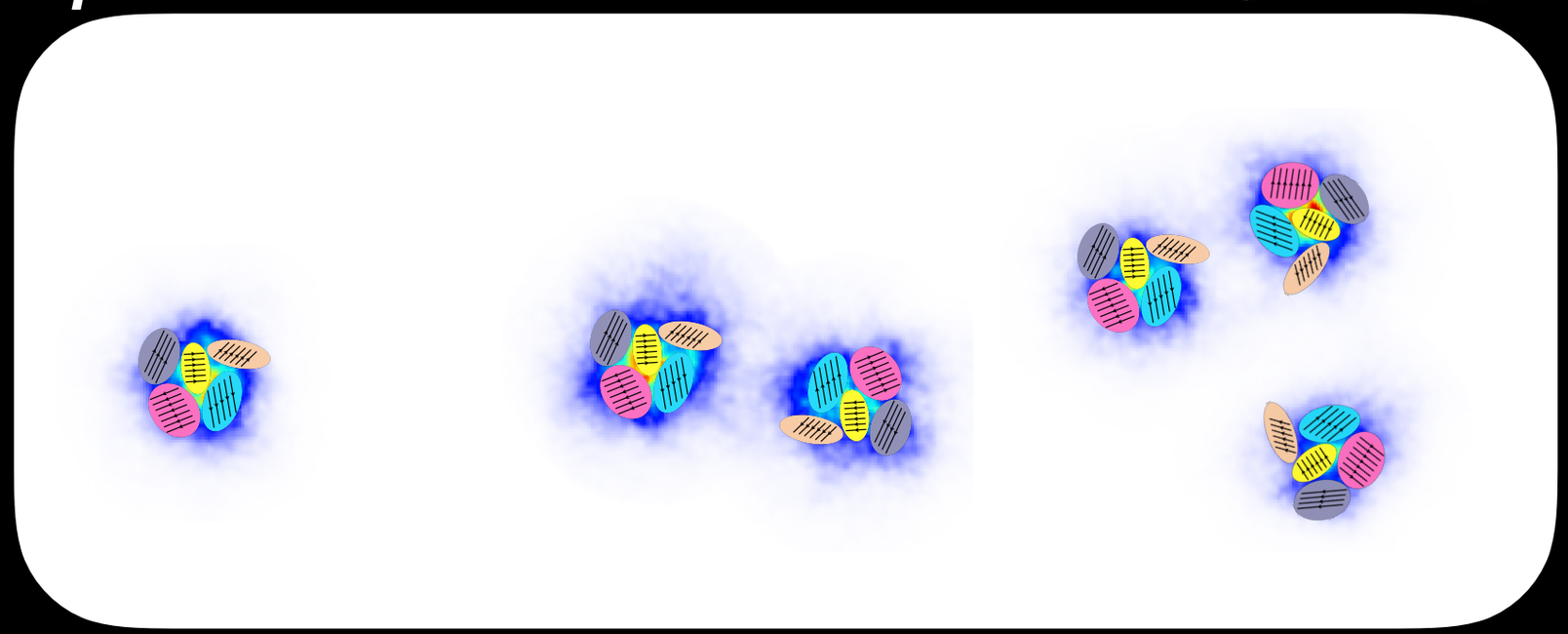
PRC 95, 034910 (2017)

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

Alternatives ?

Initial state momentum correlation model





- Uncorrelated momentum domains in a nucleon
- Q_s = saturation scale

If each nucleon creates a well-separated (individually resolved) hot spot, uncorrelated nucleon momenta dilute overall initial state momentum correlations which, if translated to final state momentum correlations, suggests:

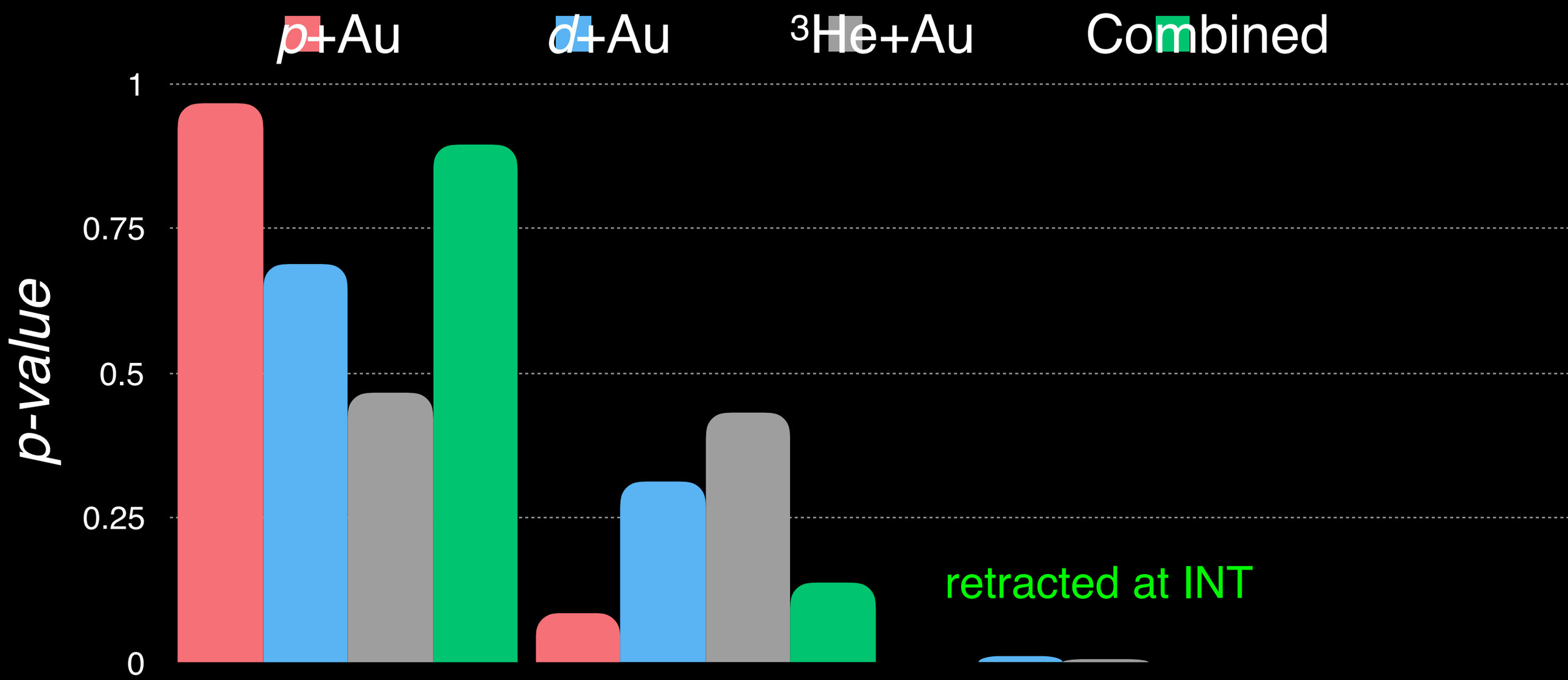
$$v_n^{p+\mathrm{Au}} > v_n^{d+\mathrm{Au}} > v_n^{^3\mathrm{He}+\mathrm{Au}}$$

After several iterations of CGC-based calculations, MSTV now agree that this is the theoretical result

see INT slides: http://www.int.washington.edu/talks/WorkShops/int_19_1b/People/Mace_M/Mace.pdf

Calculated *p*-values

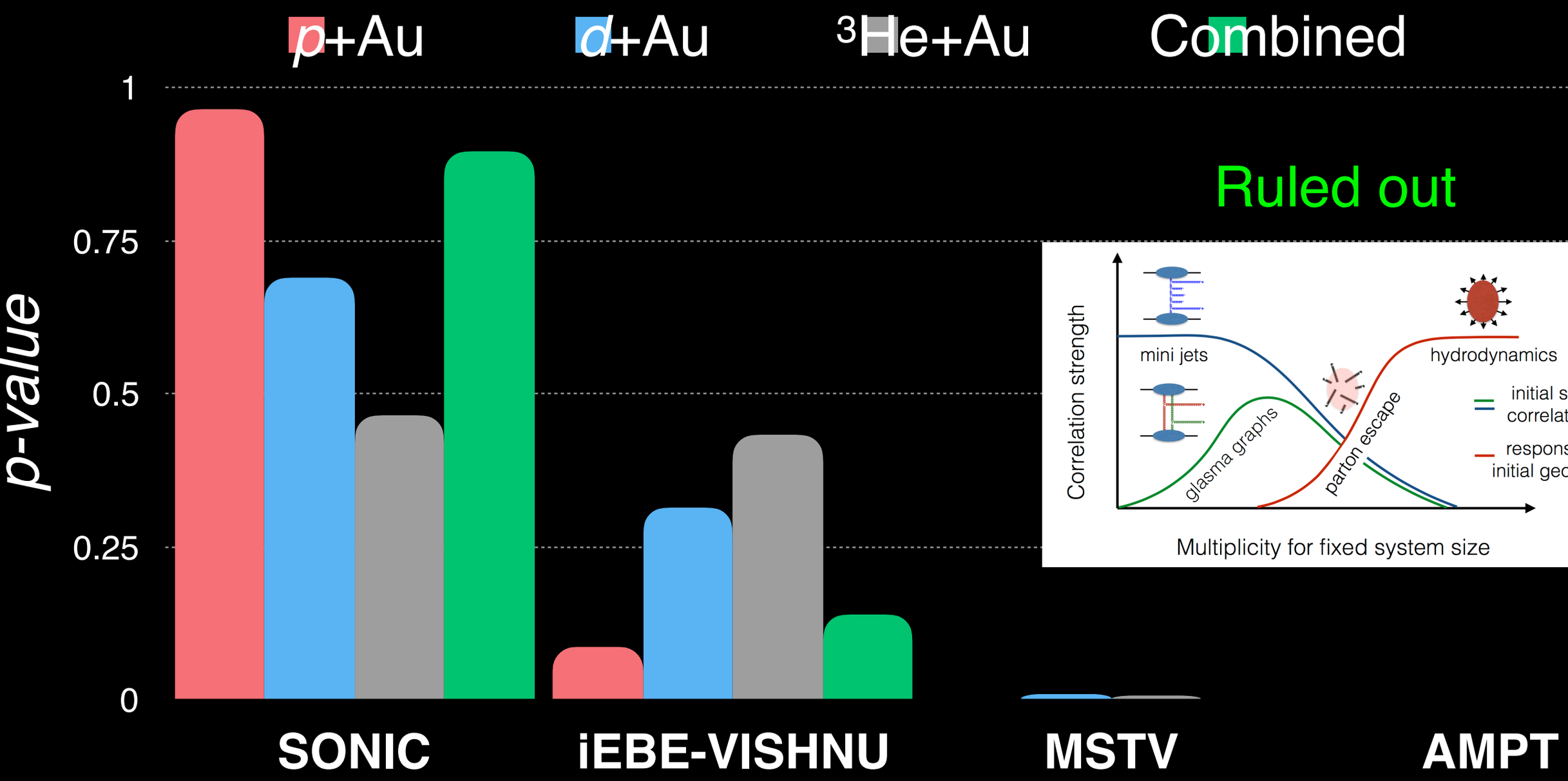
Nature Physics vol. 15, 214–220 (2019)

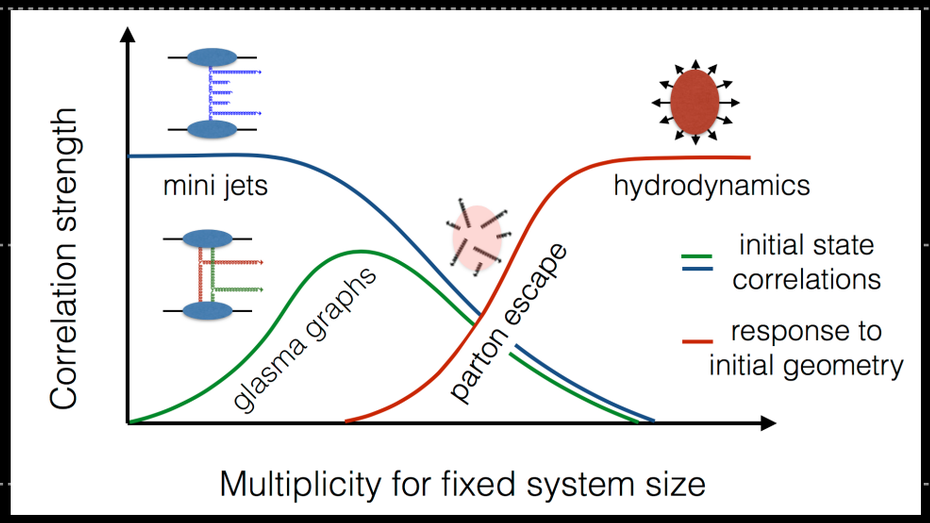


	SONIC	iEBE-VISHNU	MSTV	AMPT
p+Au	0.966	0.086	7.07×10^{-17}	2.09×10^{-7}
d+Au	0.689	0.313	0.011	1.58×10^{-18}
^{3}He+Au	0.465	0.432	0.007	2.17×10^{-22}
Combined	0.896	0.139	9.8×10^{-17}	2.67×10^{-43}

Calculated *p*-values

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

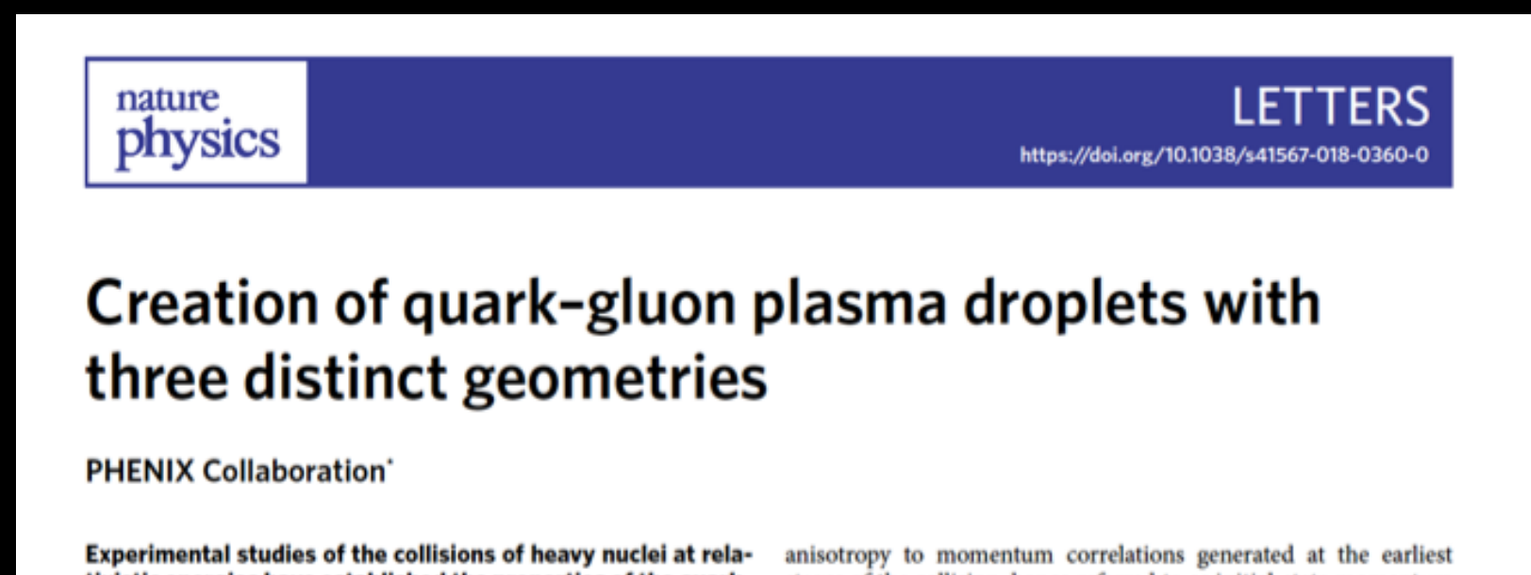




Presence of QGP droplet best describes measurement

Conclusion

- Correlated particle emission over the whole system
- Flow is geometric
- Hydrodynamics provides simultaneous description



nature physics — LETTERS

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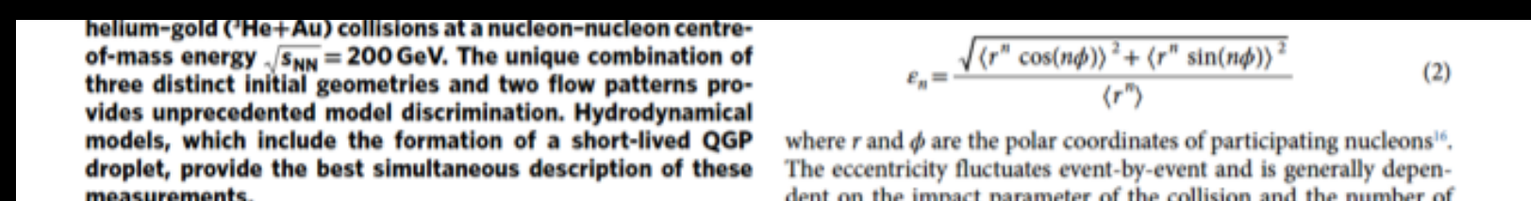
Creation of quark–gluon plasma droplets with three distinct geometries

PHENIX Collaboration*

Experimental studies of the collisions of heavy nuclei at rela-

anisotropy to momentum correlations generated at the earliest

STRONG EVIDENCE FOR QGP IN SMALL SYSTEMS



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.

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

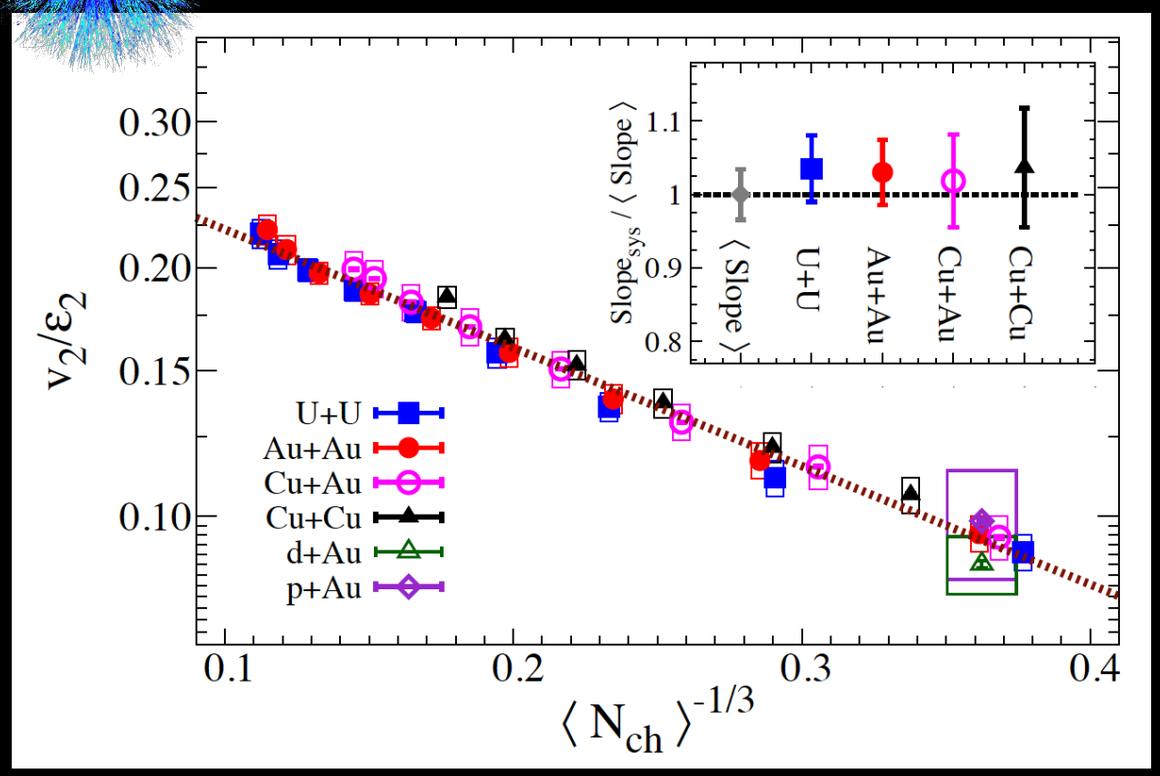
where r and ϕ are the polar coordinates of participating nucleons[16]. The eccentricity fluctuates event-by-event and is generally dependent on the impact parameter of the collision and the number of

Backup

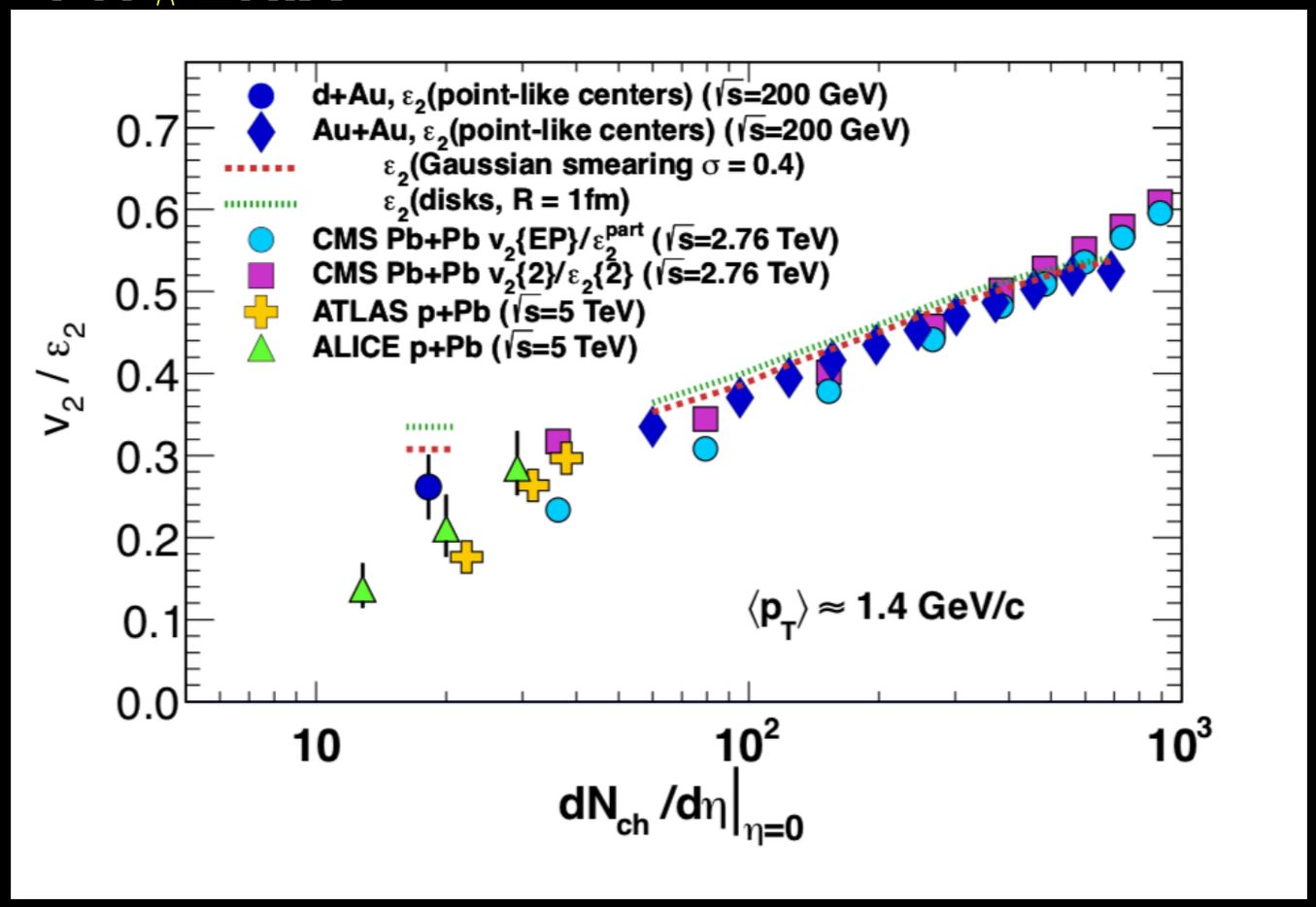
Eccentricity or multiplicity ?

STAR

arXiv:1901.08155



PHENIX Phys. Rev. Lett. 111, 212301 (2013)



- Common multiplicity scaling of v_2/ecc for large and small systems
- Note: direct STAR/PHENIX comparison is difficult due to large systematic uncertainties and different kinematic cuts

arXiv:1901.10506v1

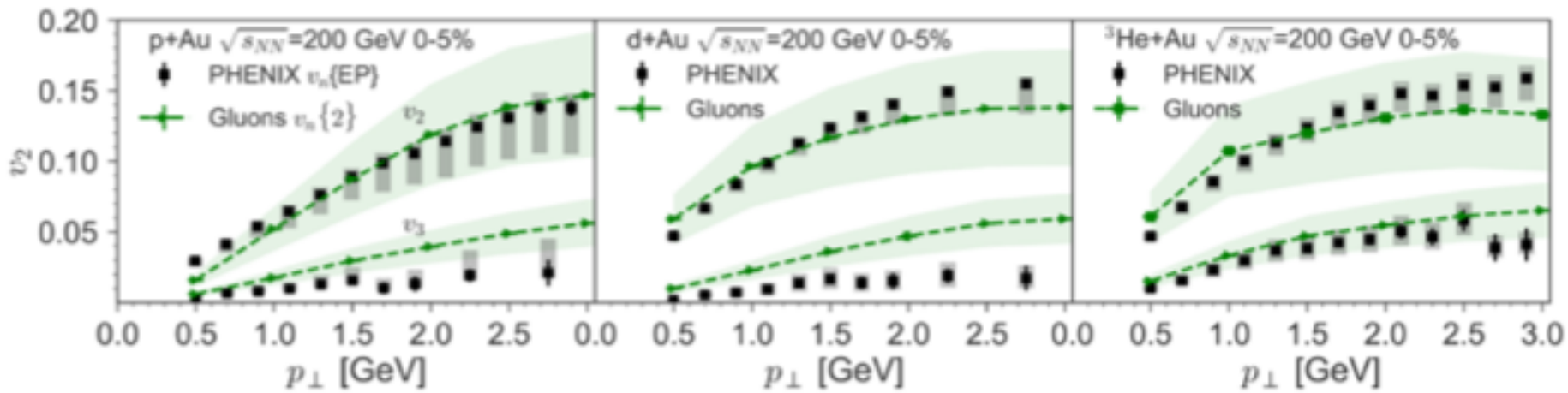
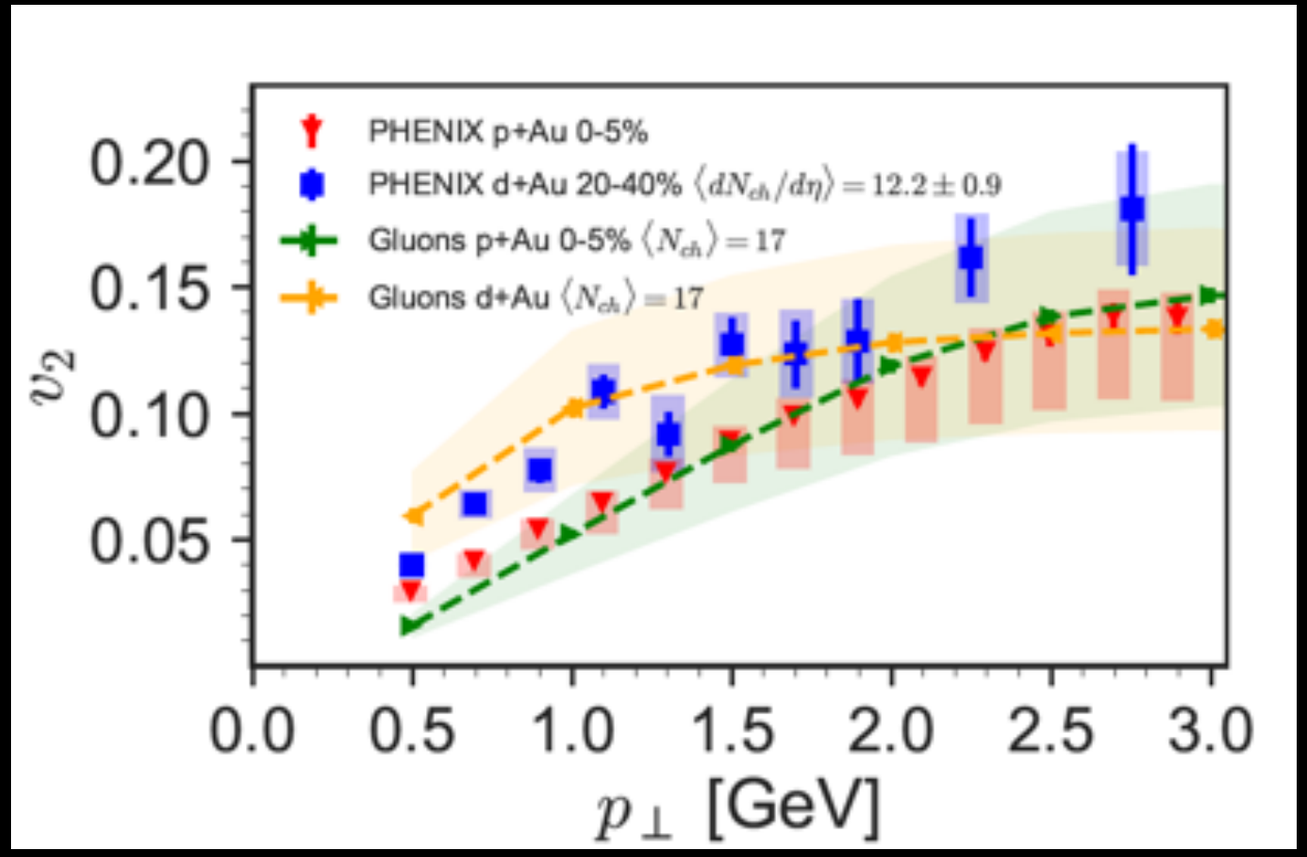
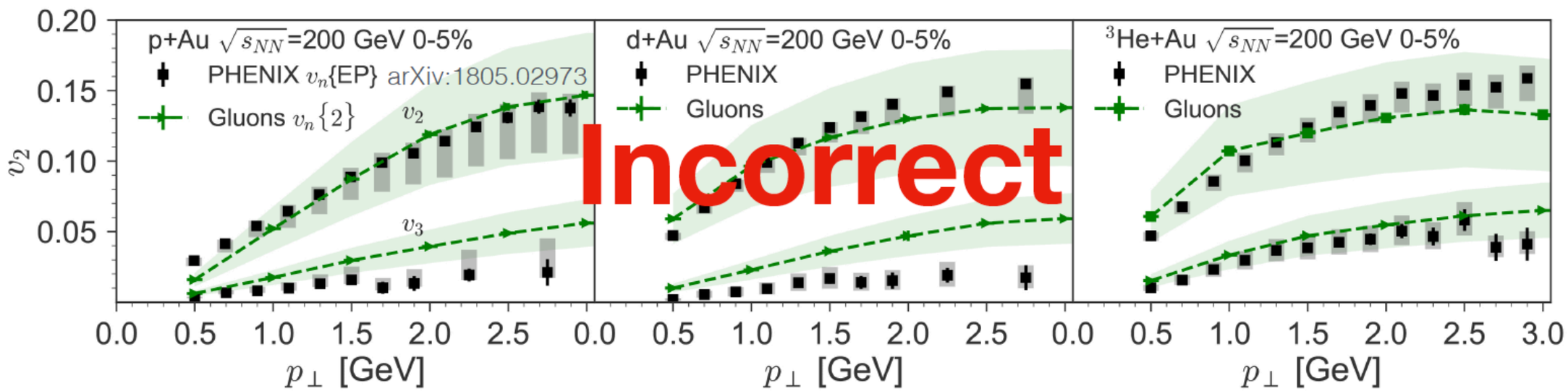


FIG. 3: Comparison of 0-5% multiplicity class $v_n\{2\}(p_\perp)$ for $n = 2, 3$ for gluons [1], compared to recent PHENIX results on charged hadrons [4, 5]. The light colored (in green) bands correspond to a 30% theory uncertainty.



“ In [1], we predicted that for the same Nch that v2;3 would be identical for different small systems at fixed Nch .This prediction was however based upon a color domain argument rather than explicit computation;”

An error



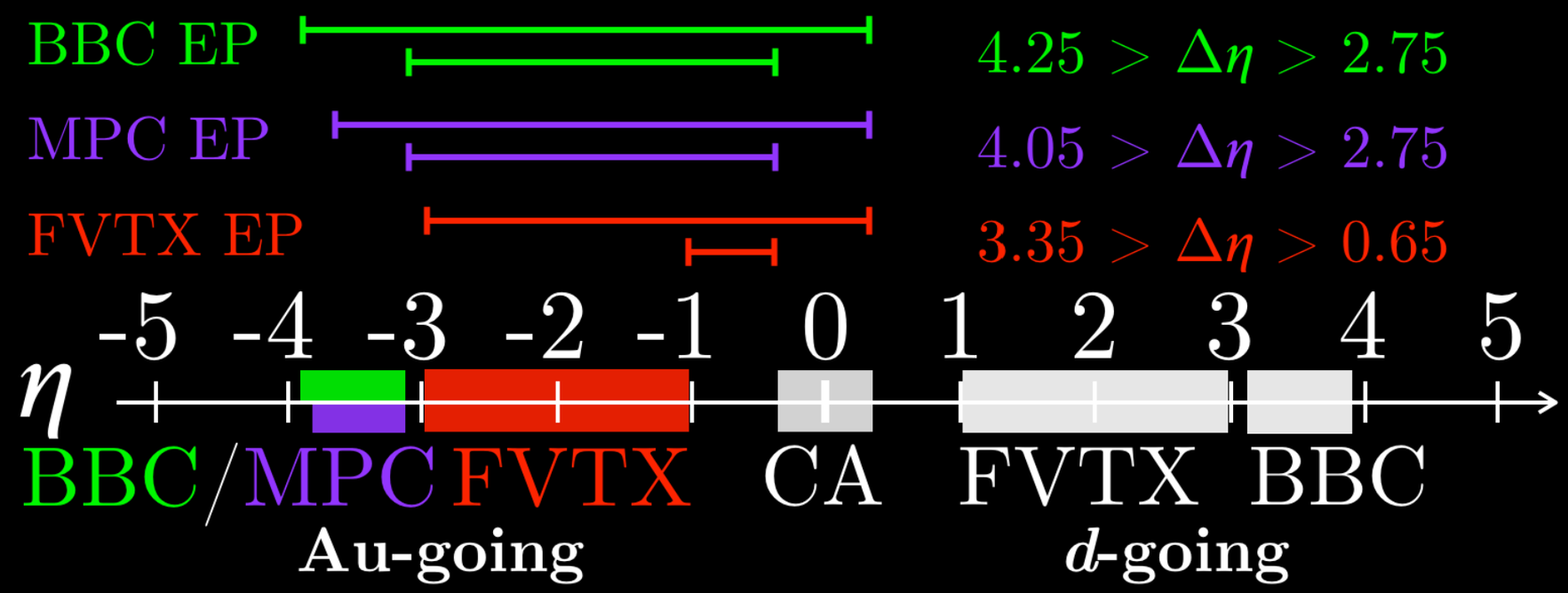
Digging deeper in the code in answer questions raised in small systems workshop in Houston and preparing to make code public, a bug was found in the units

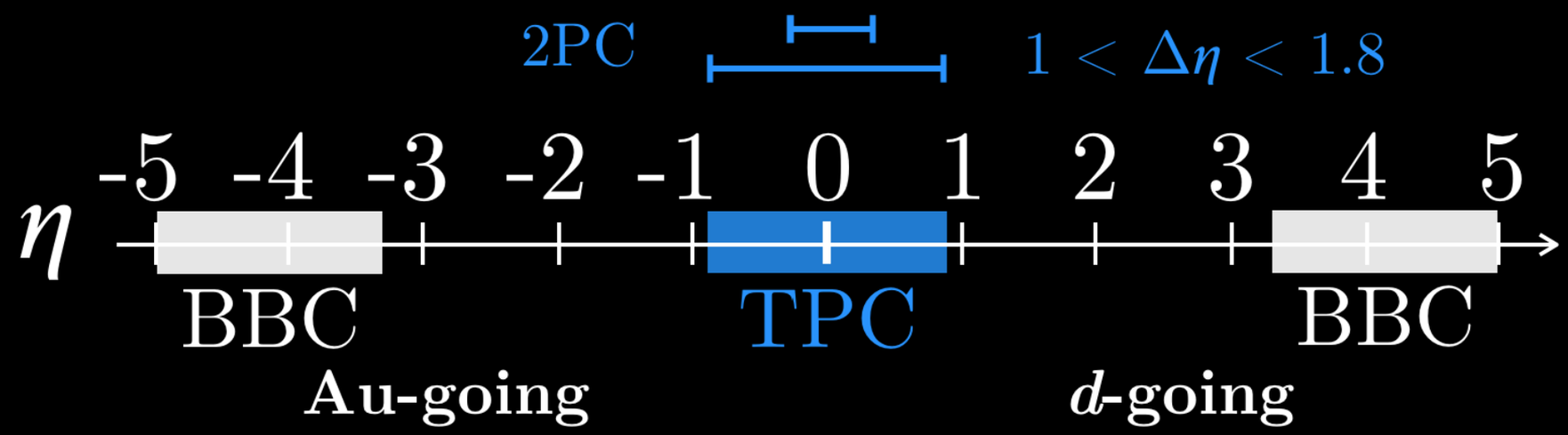
$$\frac{dN}{d^2k}[\mathrm{GeV}^{-2}] \stackrel{!}{=} f(k')[\mathrm{fm}^2]$$

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

Do we understand nonflow contributions?

η separation: PHENIX and STAR



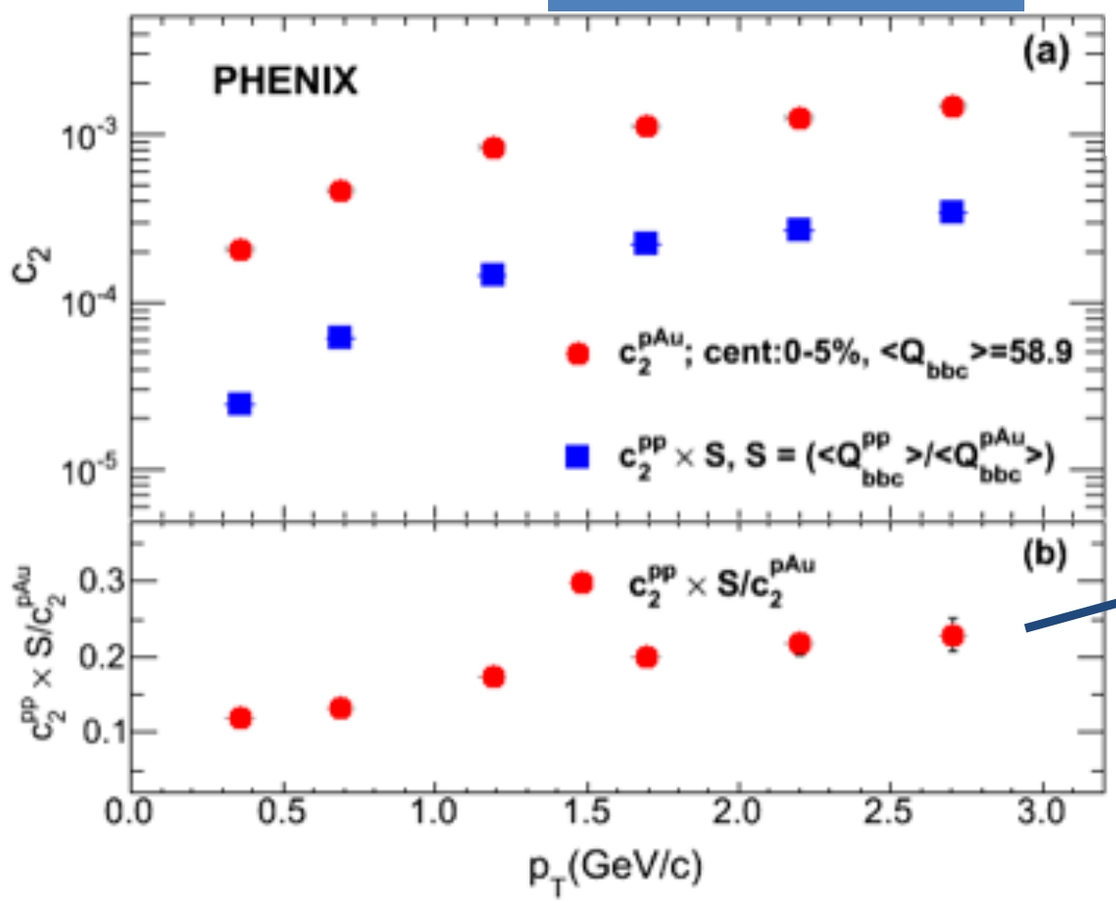


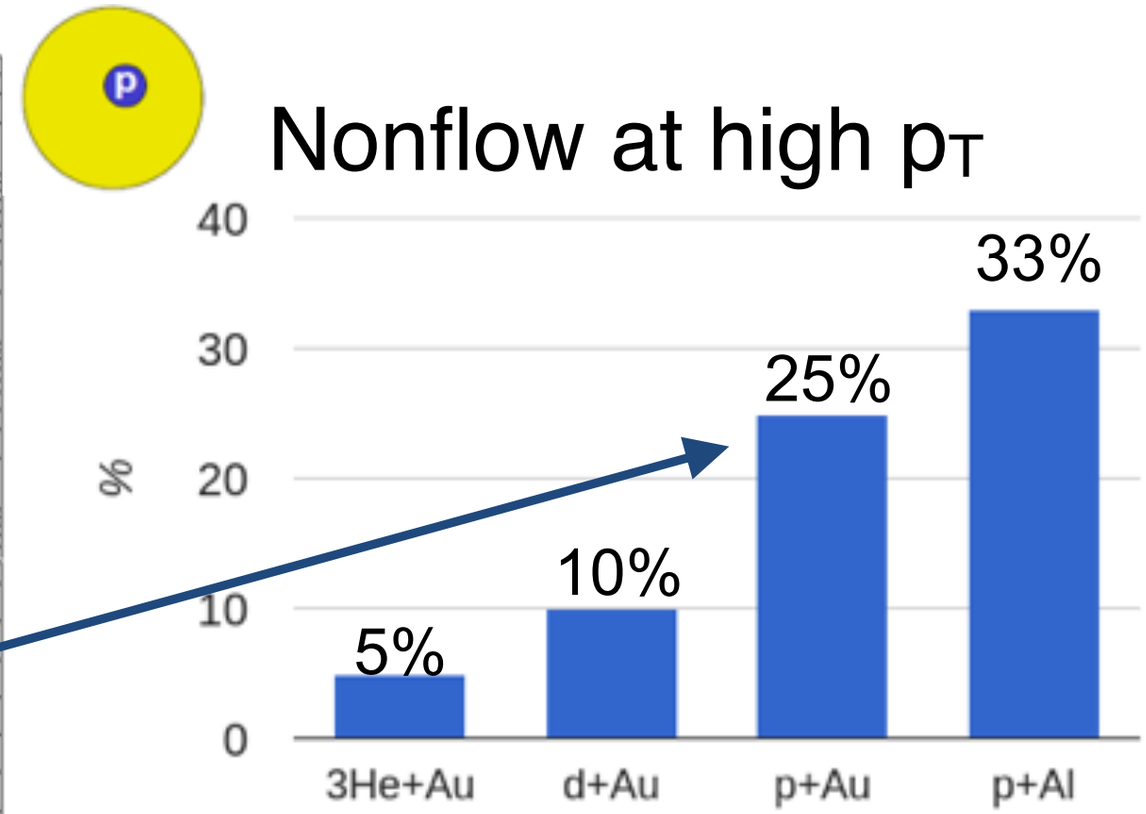
- $\Delta\eta$ range means STAR has a much larger issue with nonflow than PHENIX

nonflow in PHENIX data: $v_2(p_T)$

arXiv:1609.02894

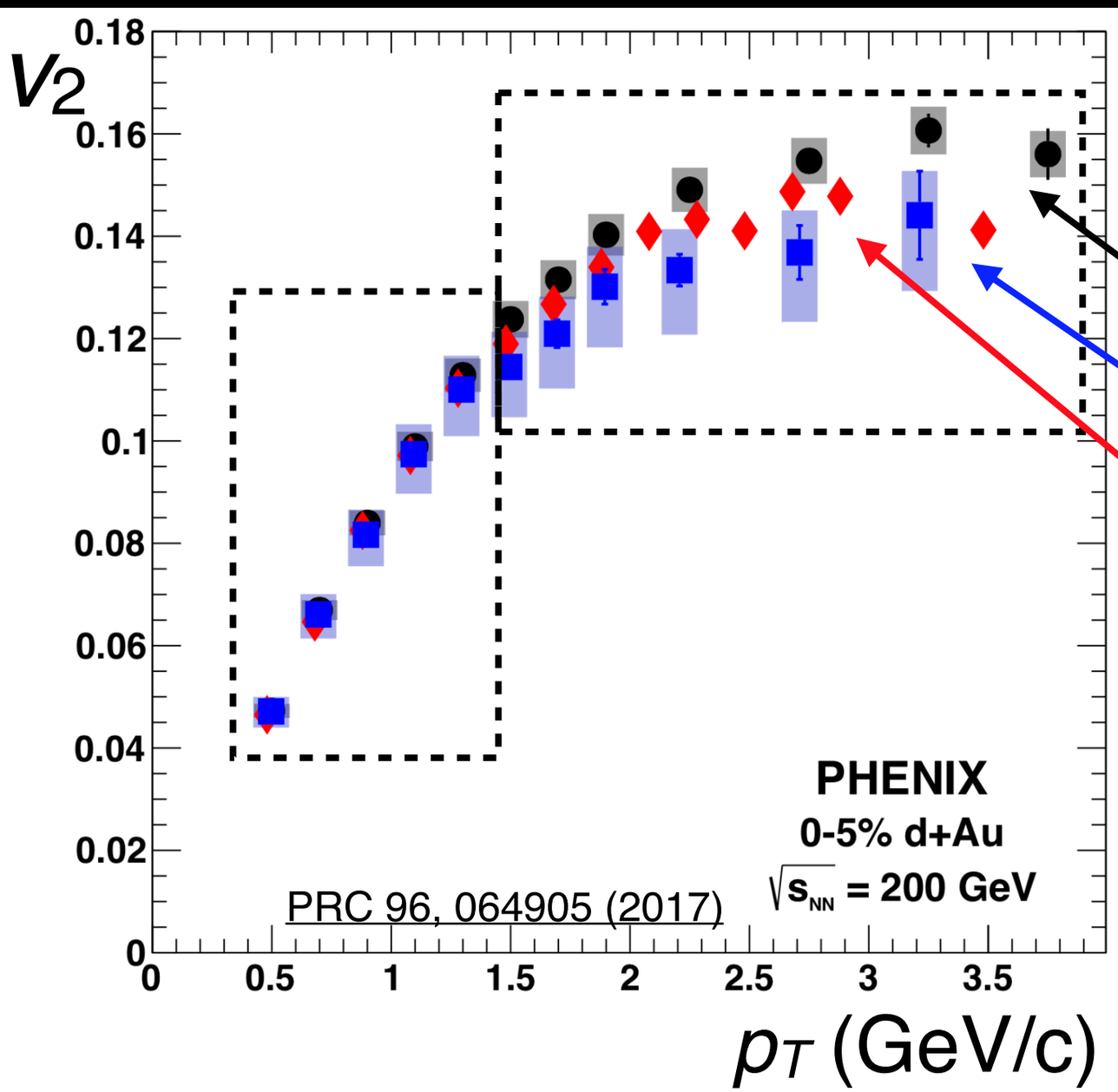
Central p+Au





- Estimated based on p+p minbias scaled by multiplicity
- Same reference for all collisions systems
- Included in systematic uncertainty
- the PHENIX results are undersubtracted by construction

PHENIX nonflow



- v_2\{EP\} Global Sys. = ±0.3%
- v_2\{EP\} PRL 114 (2015)
- v_2\{2PC\}

FVTX EP: $0.65 < \Delta\eta < 3.35$

MPC EP: $2.75 < \Delta\eta < 4.05$

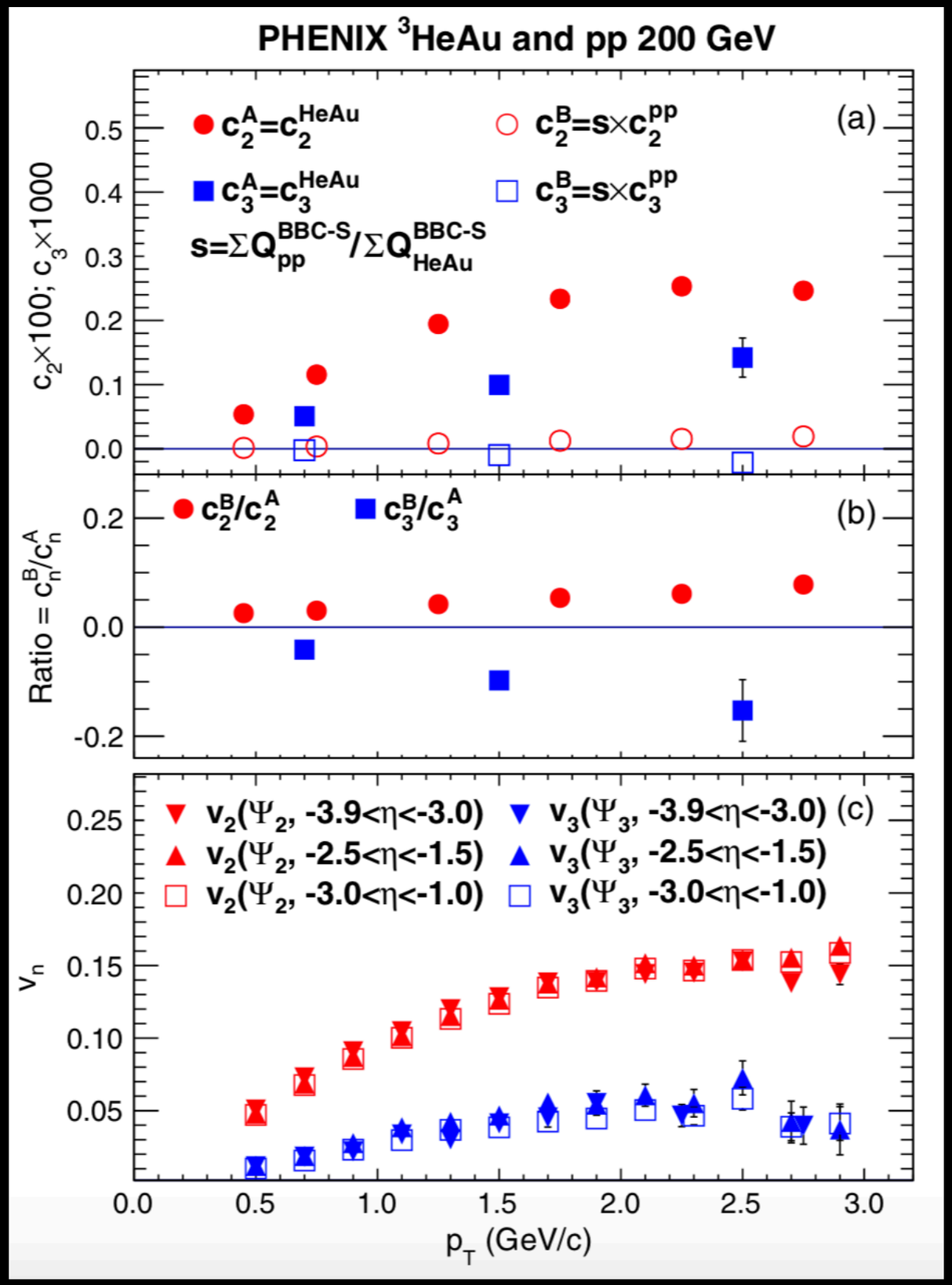
2PC: 3-sub event method with BBC, FVTX, CA

Low p_T: nonflow is not an issue

High p_T: difference between measurements gives an idea of the nonflow effect

- Note: Nonflow systematic not shown for FVTX EP measurement; it is < 15% (value reached at high p_T)

nonflow in PHENIX data: $v_2(p_T)$ and $v_3(p_T)$



^{3}He+Au

v_2 and v_3 nonflow anti-correlated

robust measurement of both v_2 and v_3 using several detectors