PHENIX results on elliptic and triangular flow from the small-system geometry scan at 200 GeV

Sylvia Morrow, for the PHENIX collaboration

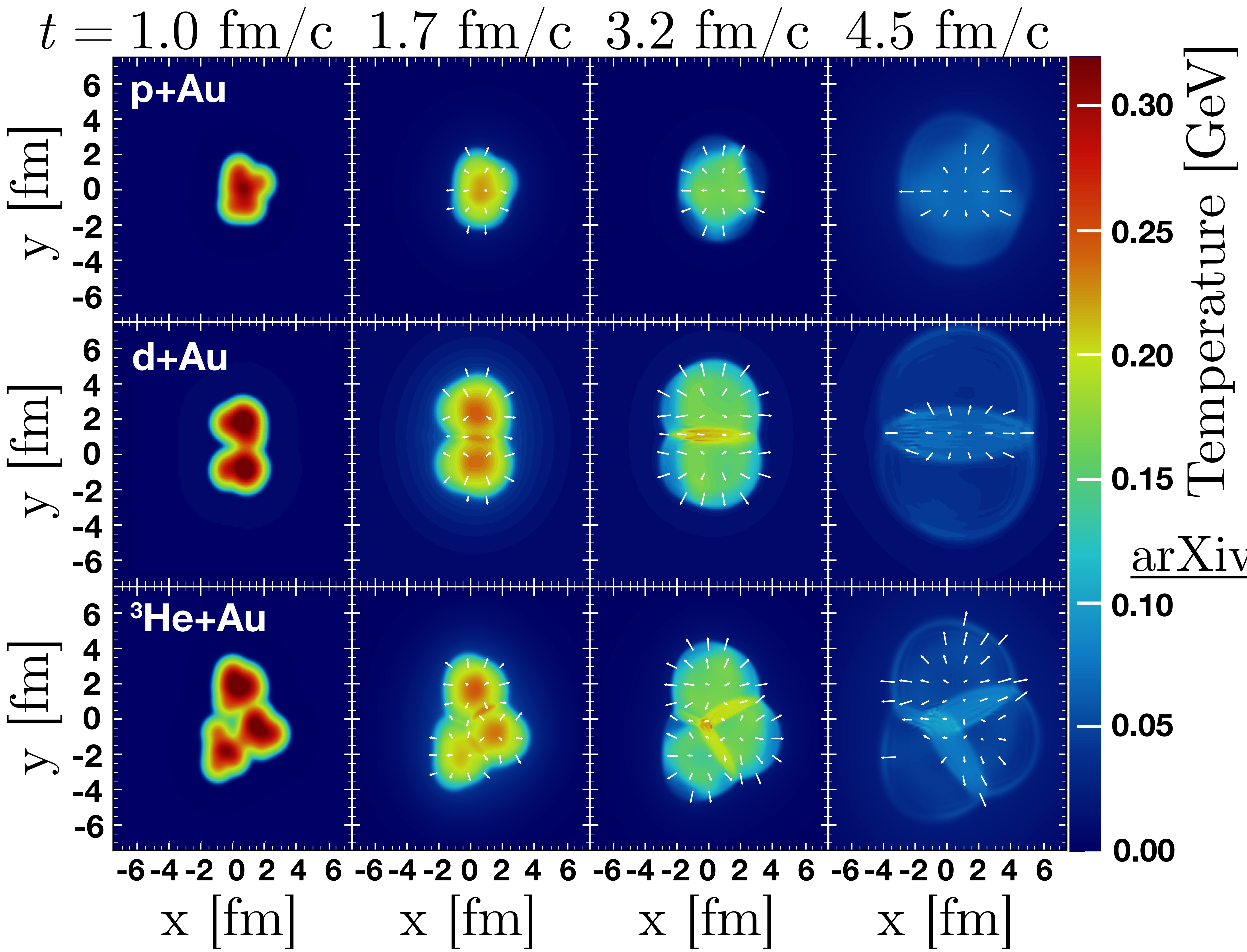
2018 Quark Matter Venezia

NEW! arXiv:1805.02973, submitted *Nature Physics*

arXiv:1710.09736, accepted *PRC*

PHENIX

RHIC collision species versatility allows for controlled geometry in small systems



arXiv:1805.02973

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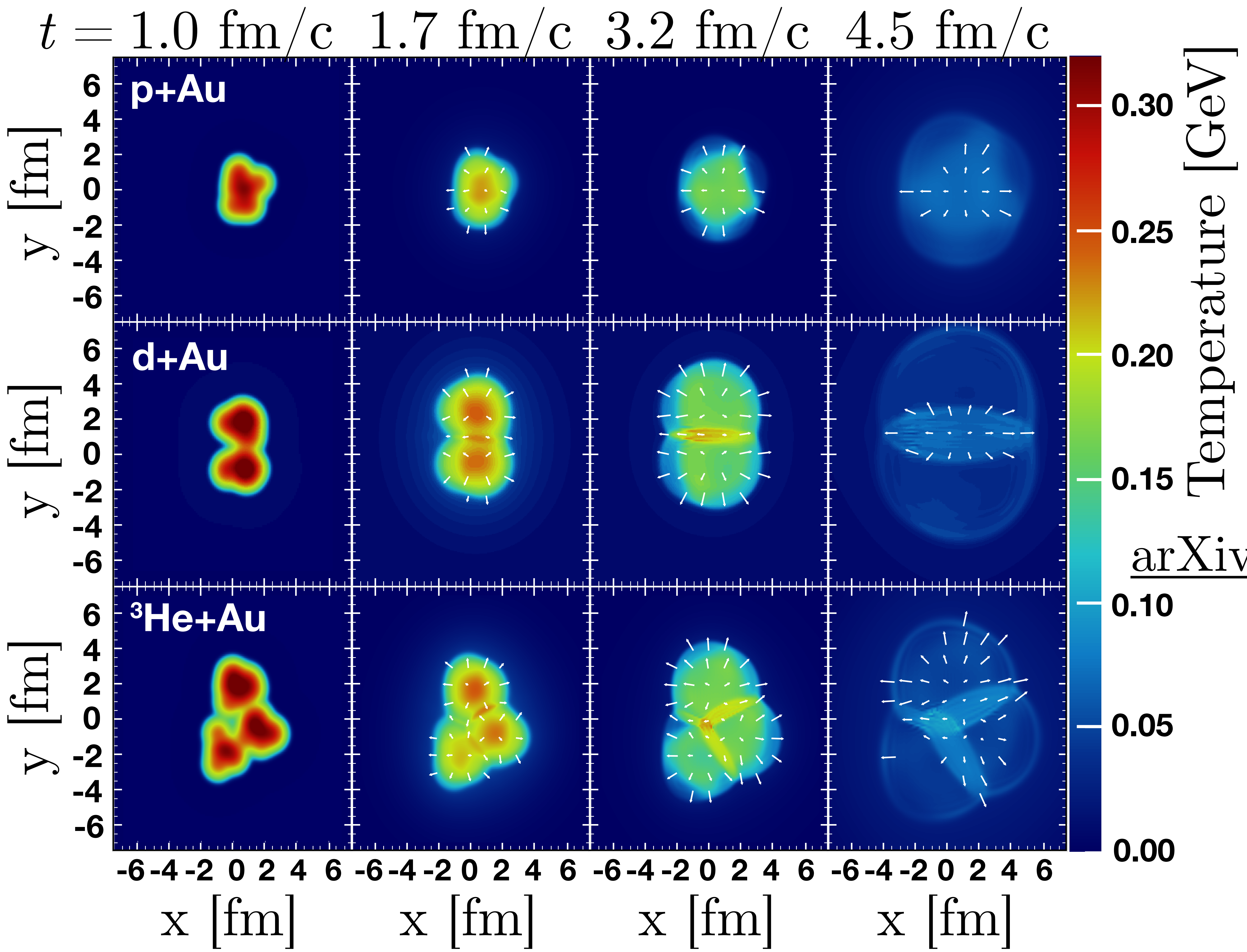

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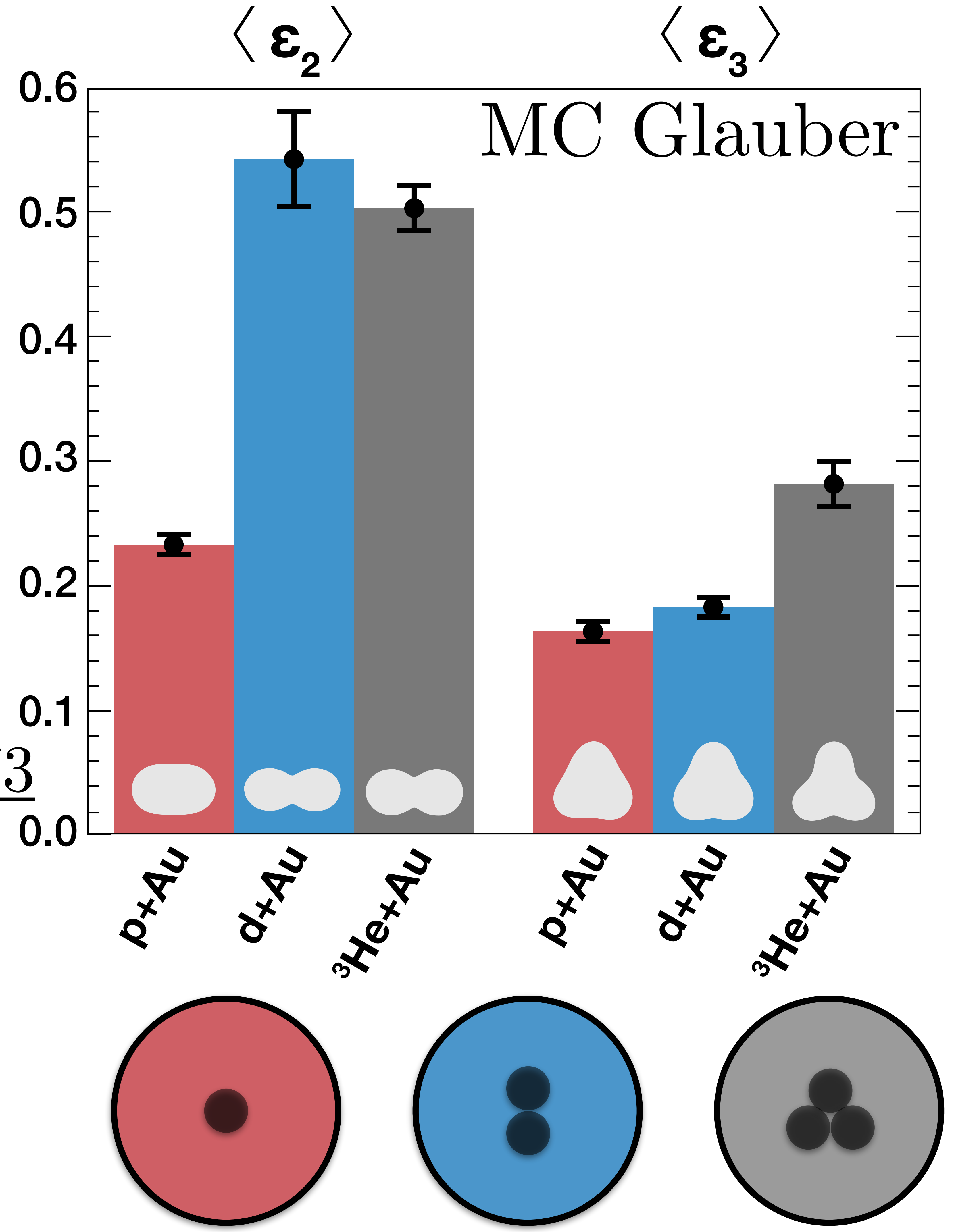

RHIC collision species versatility allows for controlled geometry in small systems

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

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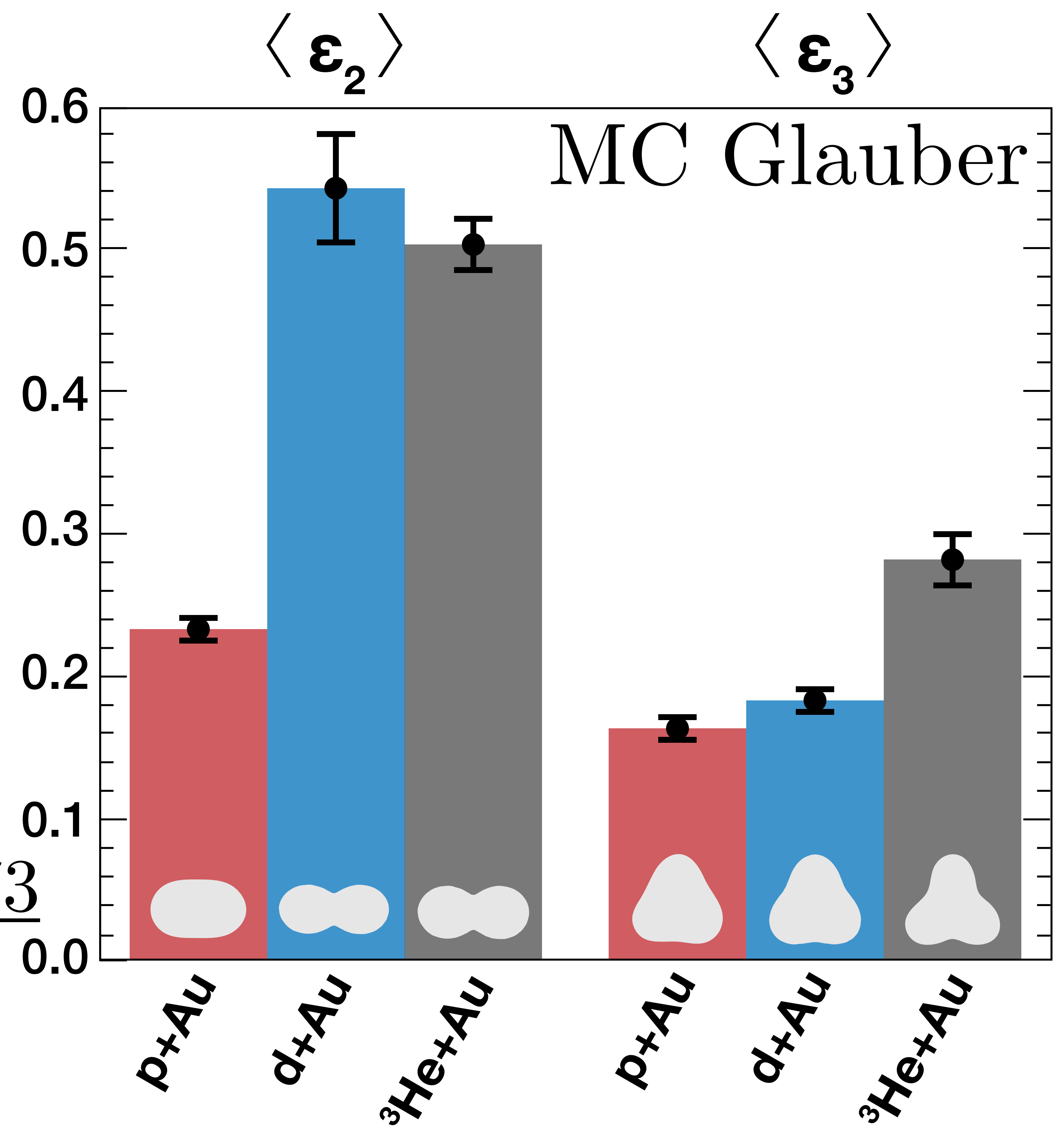
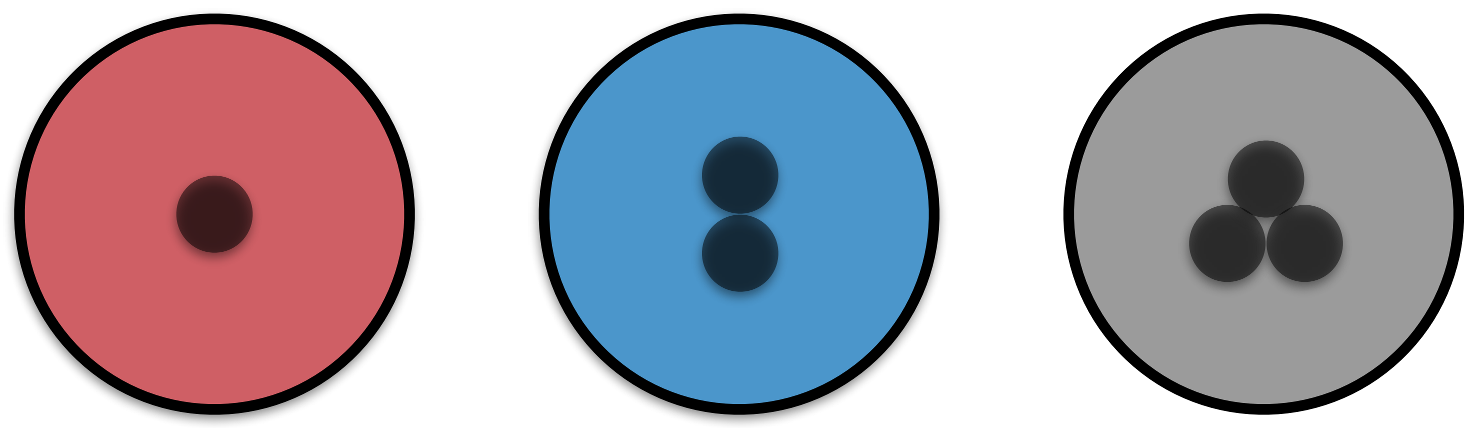
arXiv:1805.02973





$v_2(p_T)$ ordering in $p/d/{}^3$He+Au

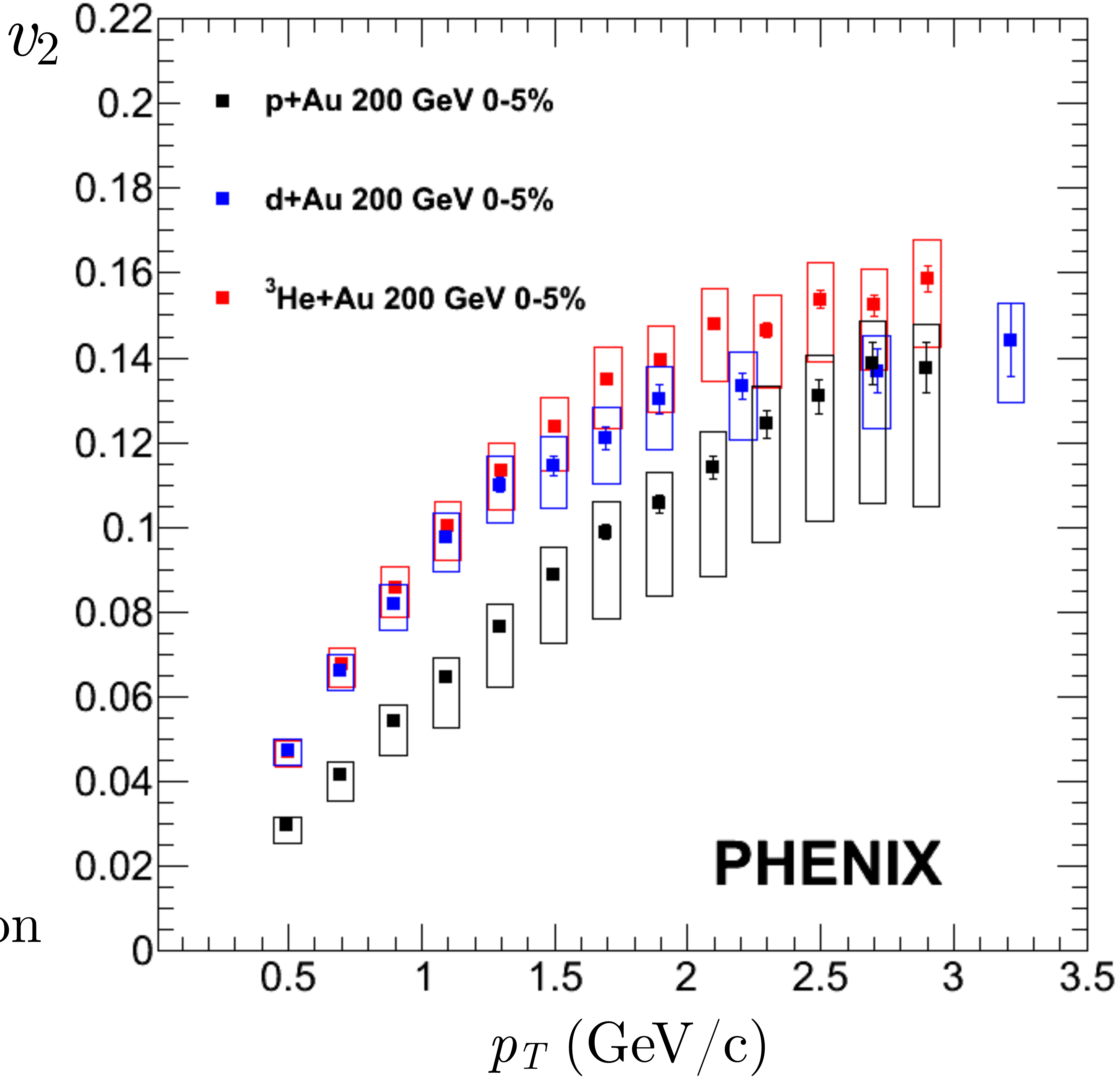
PRC **95**, 034910 (2017)

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

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

ε_2: ellipticity of initial state spatial distribution

v_2: ellipticity of final state momentum distribution



$v_2(p_T)$ ordering in $p/d/^3$He+Au

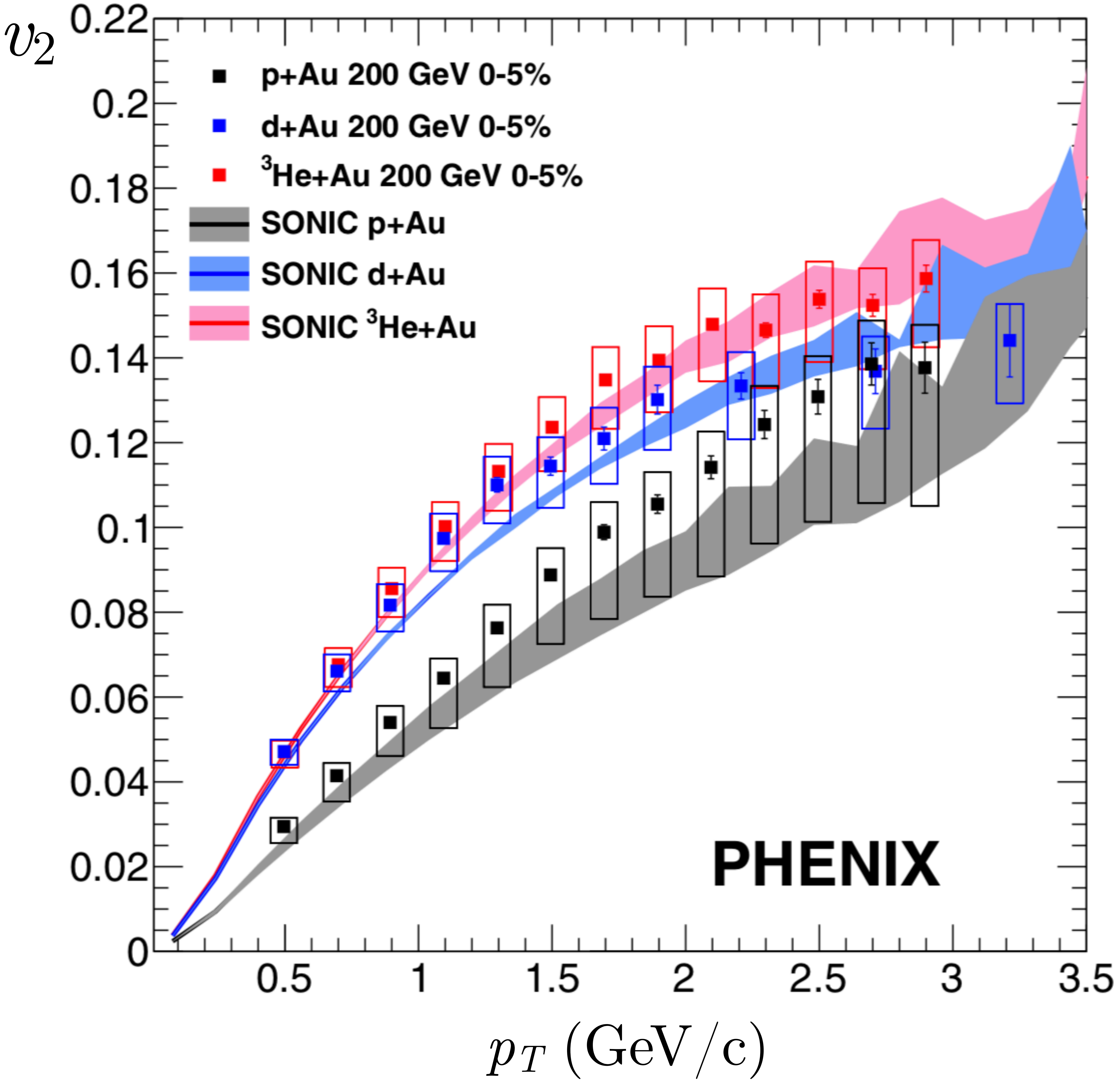
PRC **95**, 034910 (2017)

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

$$\Downarrow$$

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

Hydrodynamic calculation describes data



What is the origin of collectivity in small systems?

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- Identified particle flow

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

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- Charged hadron flow

Are there quark-gluon plasma droplets in central small systems collisions?

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- Identified particle flow

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

Perhaps — alternative explanations exist

arXiv:1710.09736, accepted *PRC*

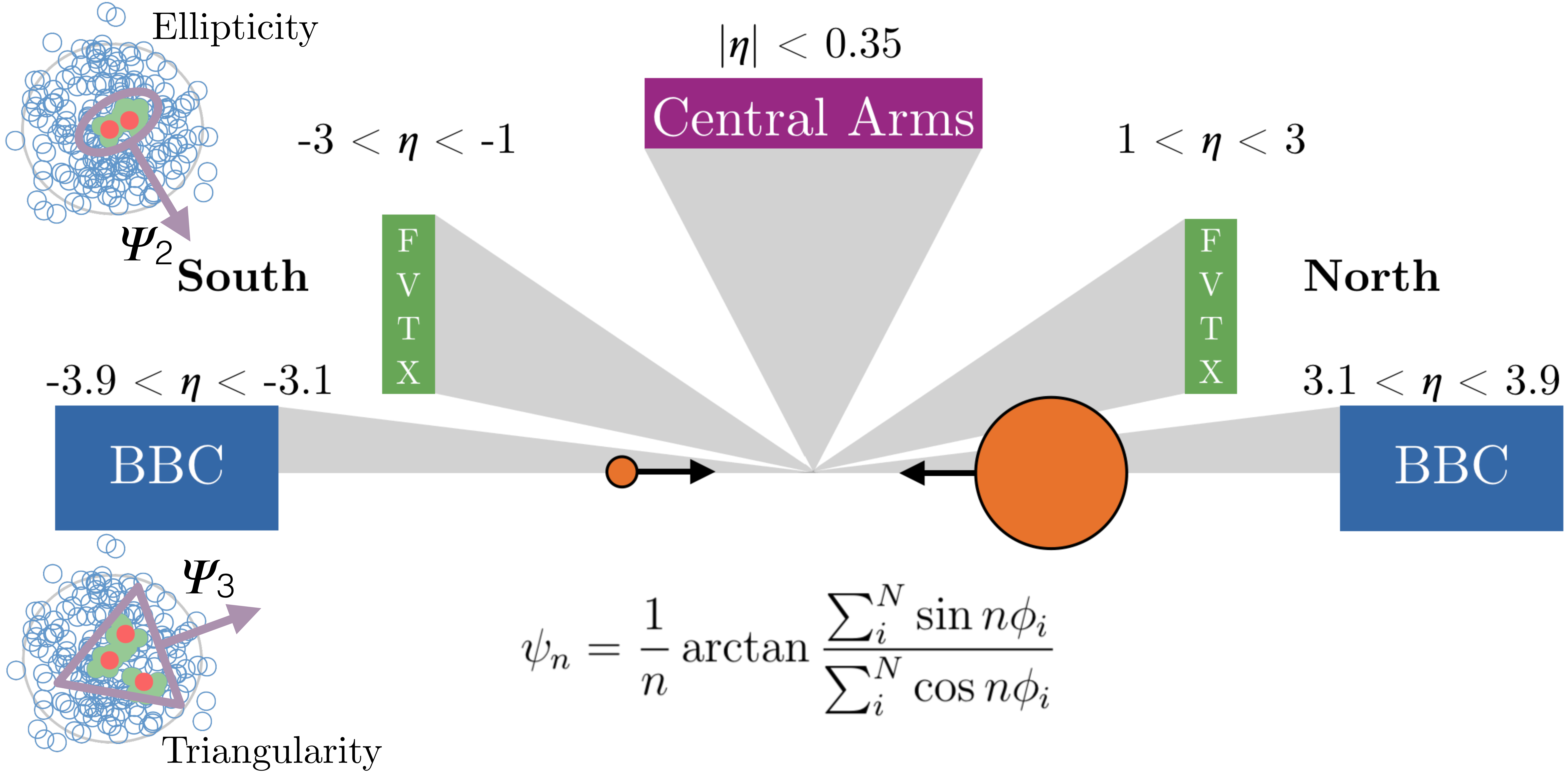
- Charged hadron flow

Are there quark-gluon plasma droplets in central small systems collisions?

Strong evidence indicating YES!

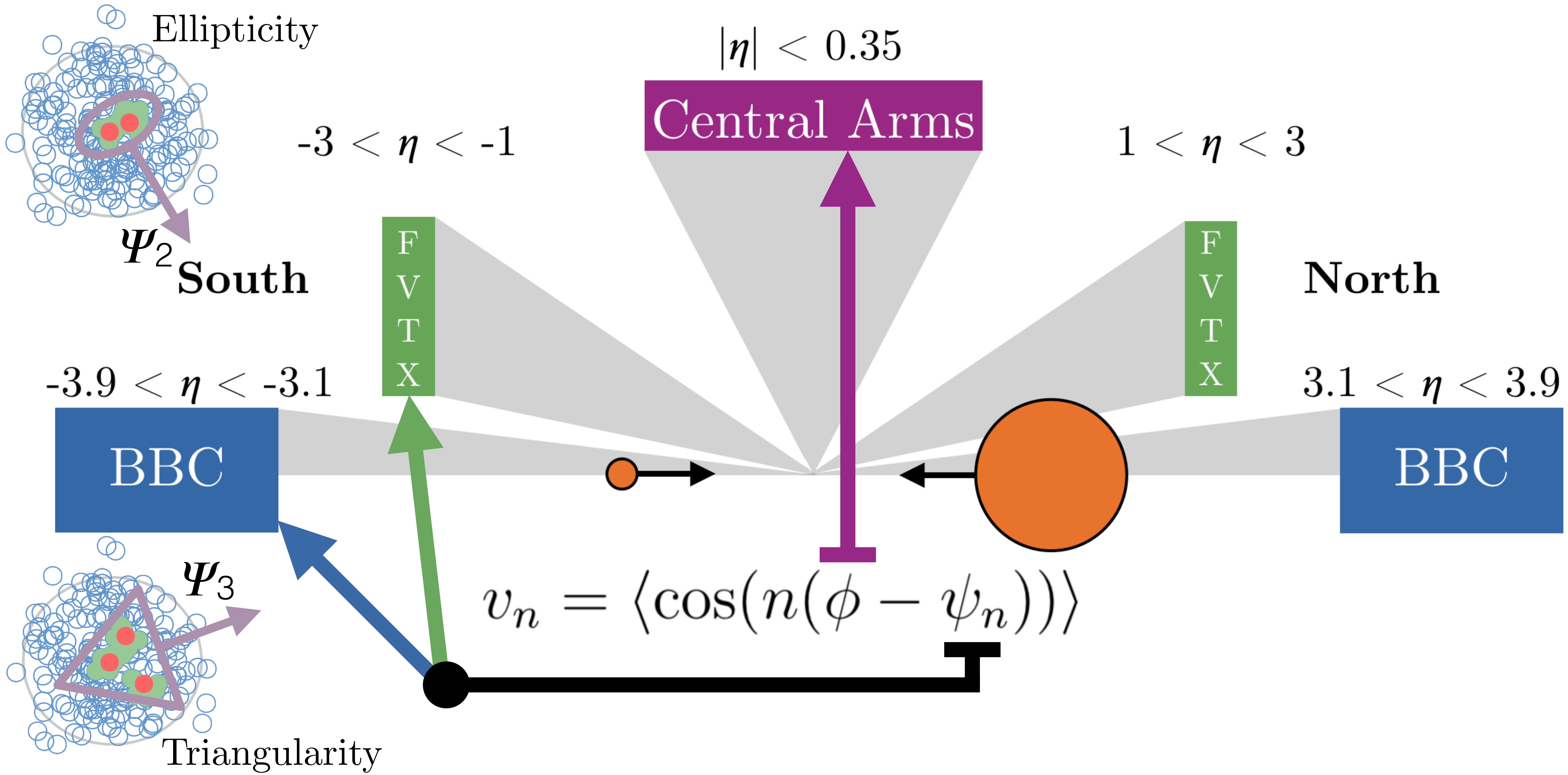
arXiv:1805.02973, submitted *Nature Physics*

Event plane angle and PHENIX detector



$$\psi_n = \frac{1}{n} \arctan \frac{\sum_i^N \sin n\phi_i}{\sum_i^N \cos n\phi_i}$$

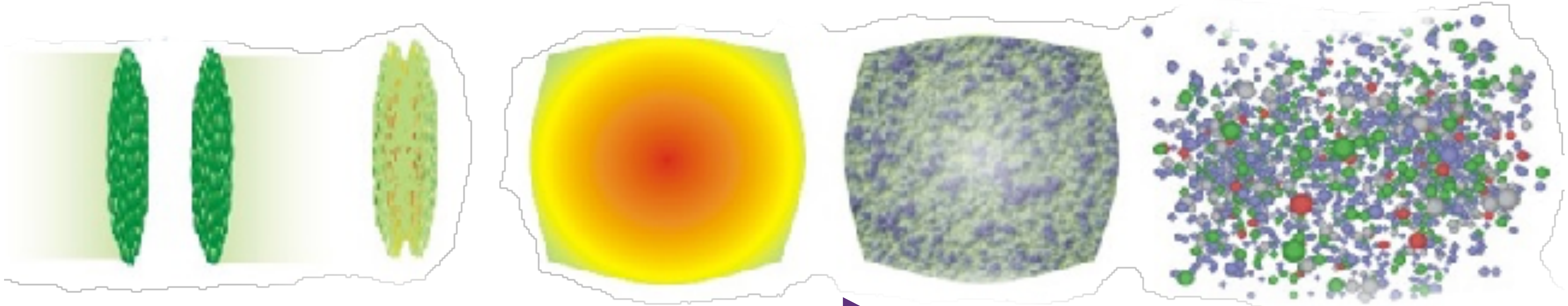
Event plane angle and PHENIX detector



$$v_n = \langle \cos(n(\phi - \psi_n)) \rangle$$

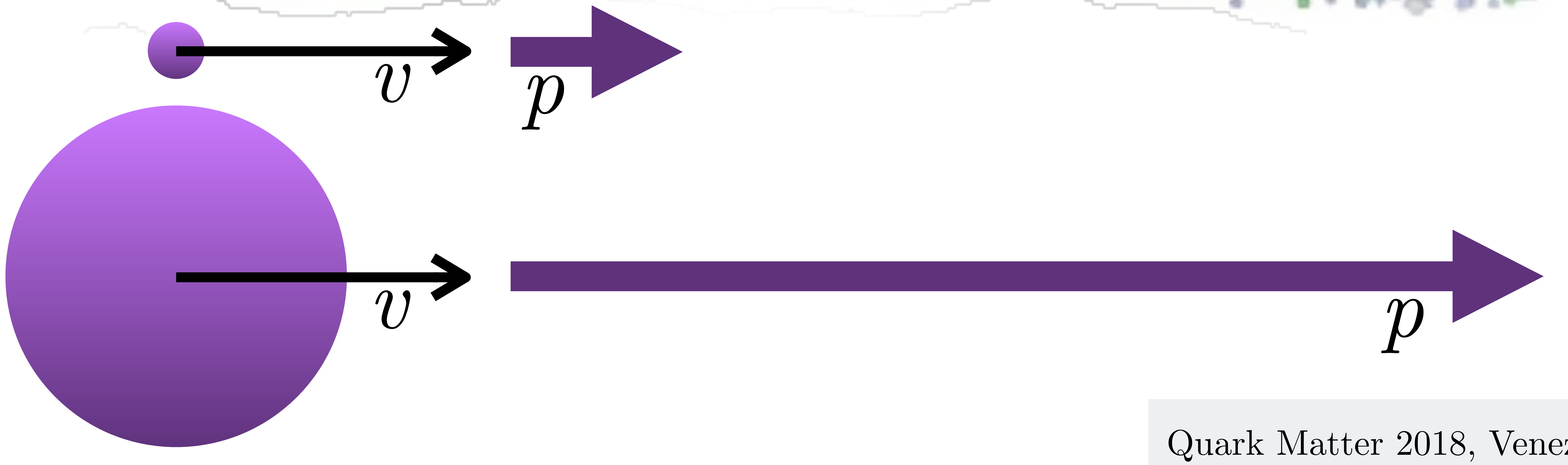
Identified particle flow

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



$\pi^{\pm}$ mass = 140 MeV/c

p mass = 938 MeV/c



π and p $v_2(p_T)$: data

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

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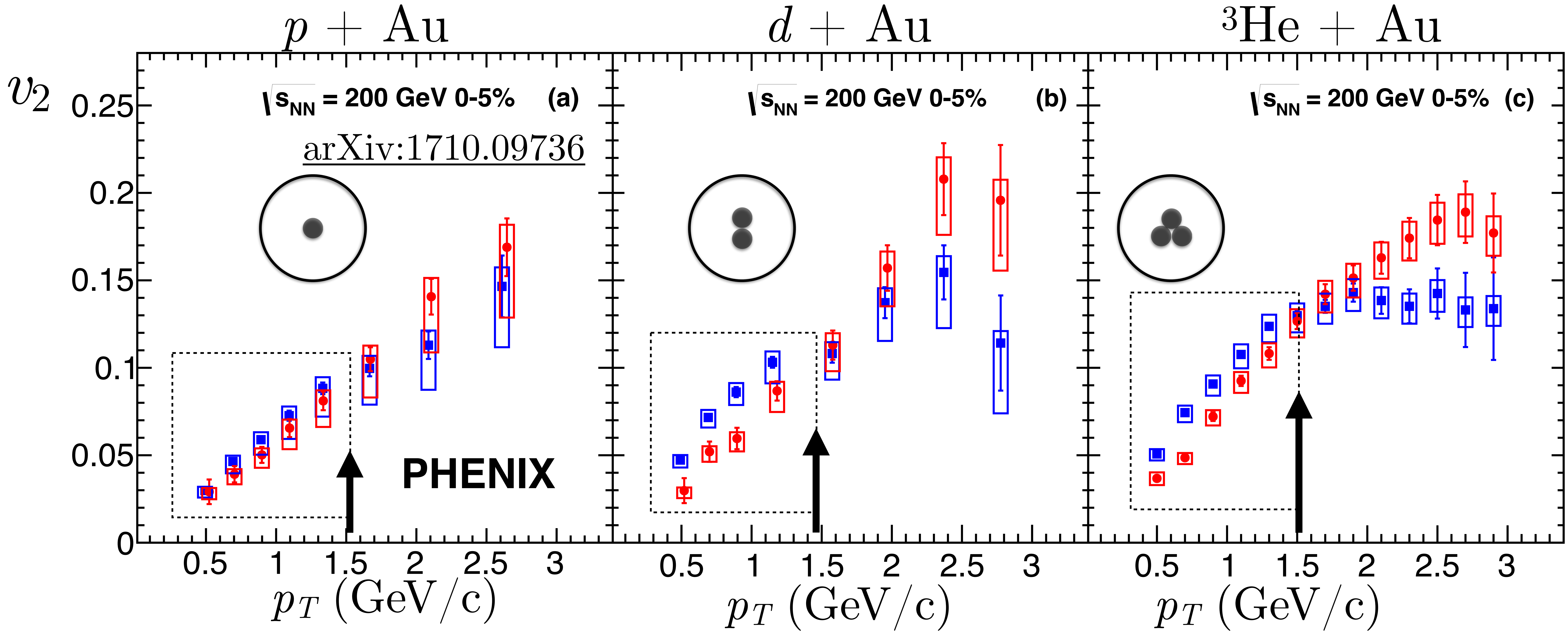

$\pi^+ + \pi^-$ Data

$p + \bar{p}$ Data

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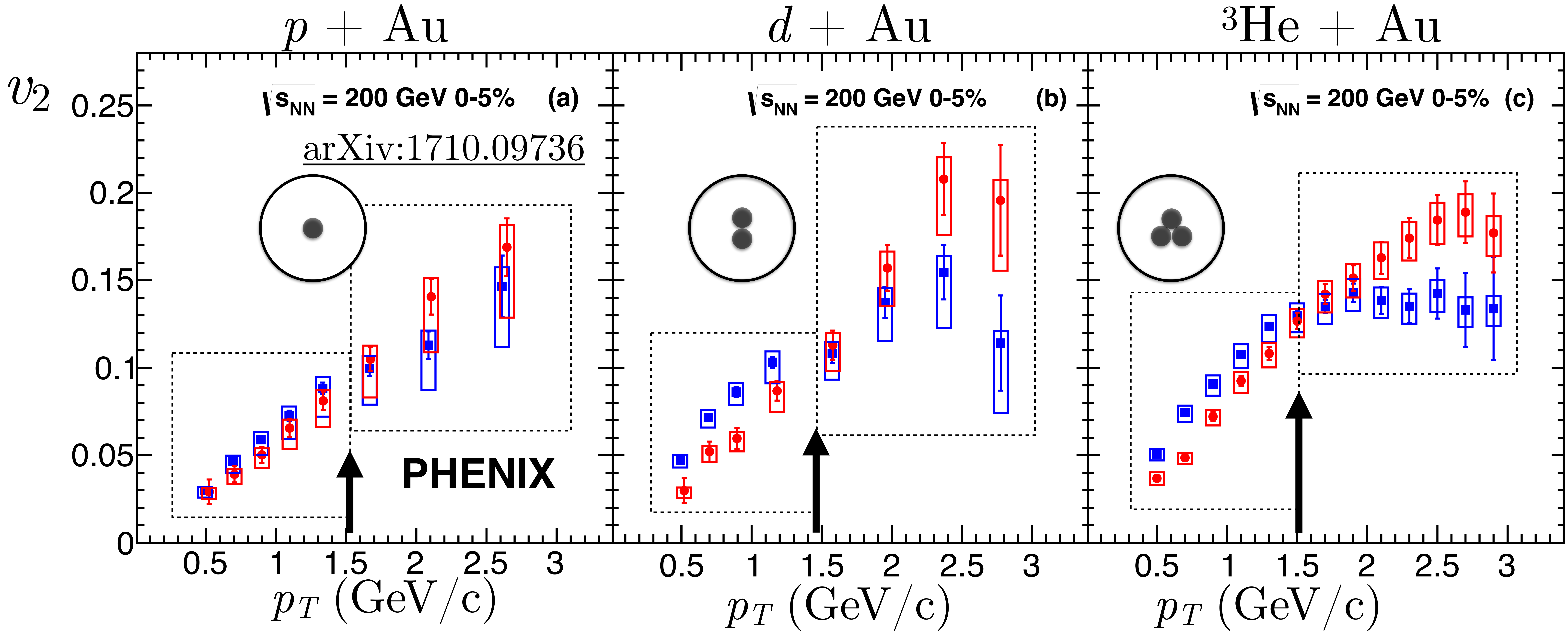

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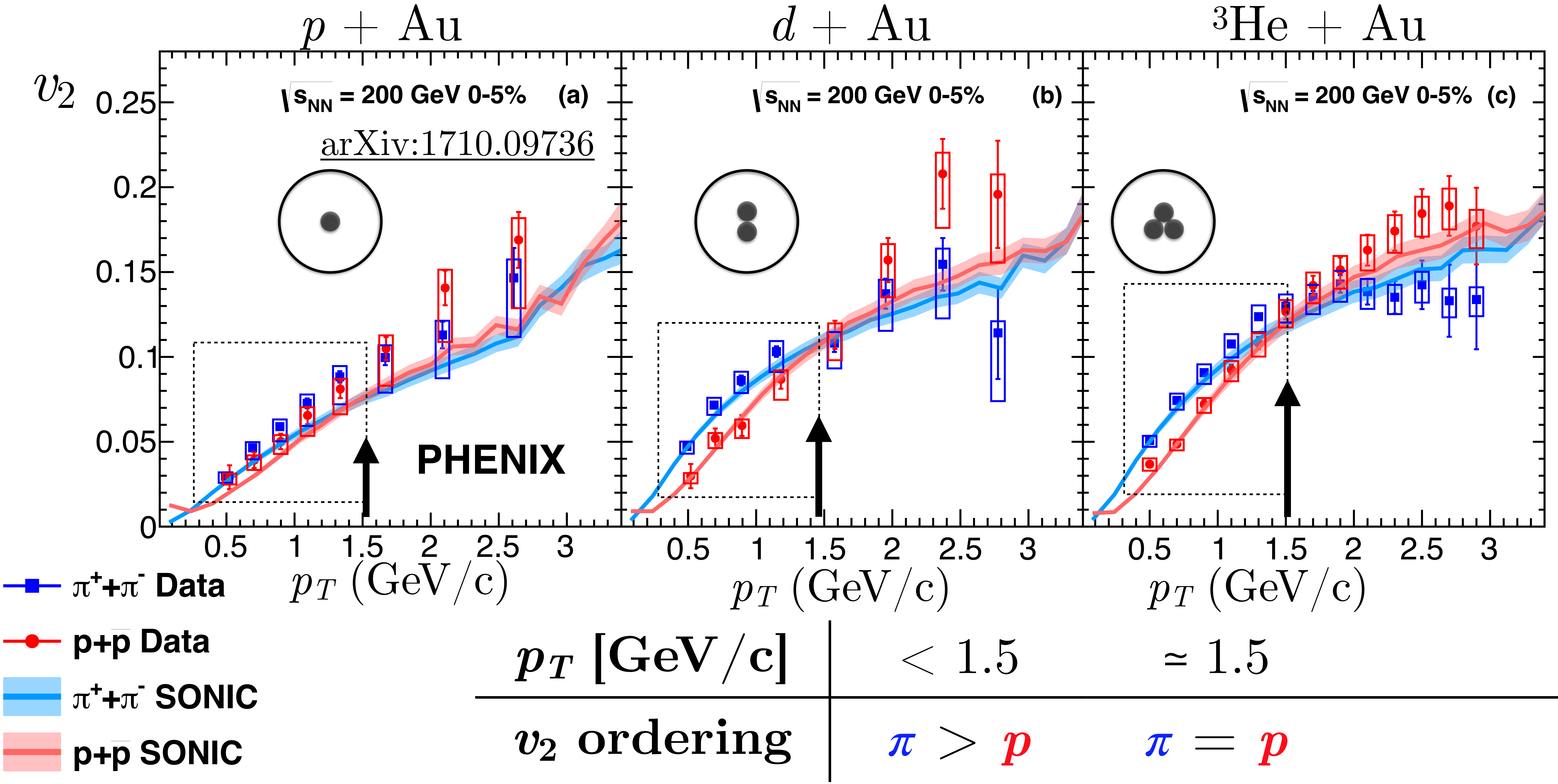
π and p $v_2(p_T)$: hydrodynamics and data



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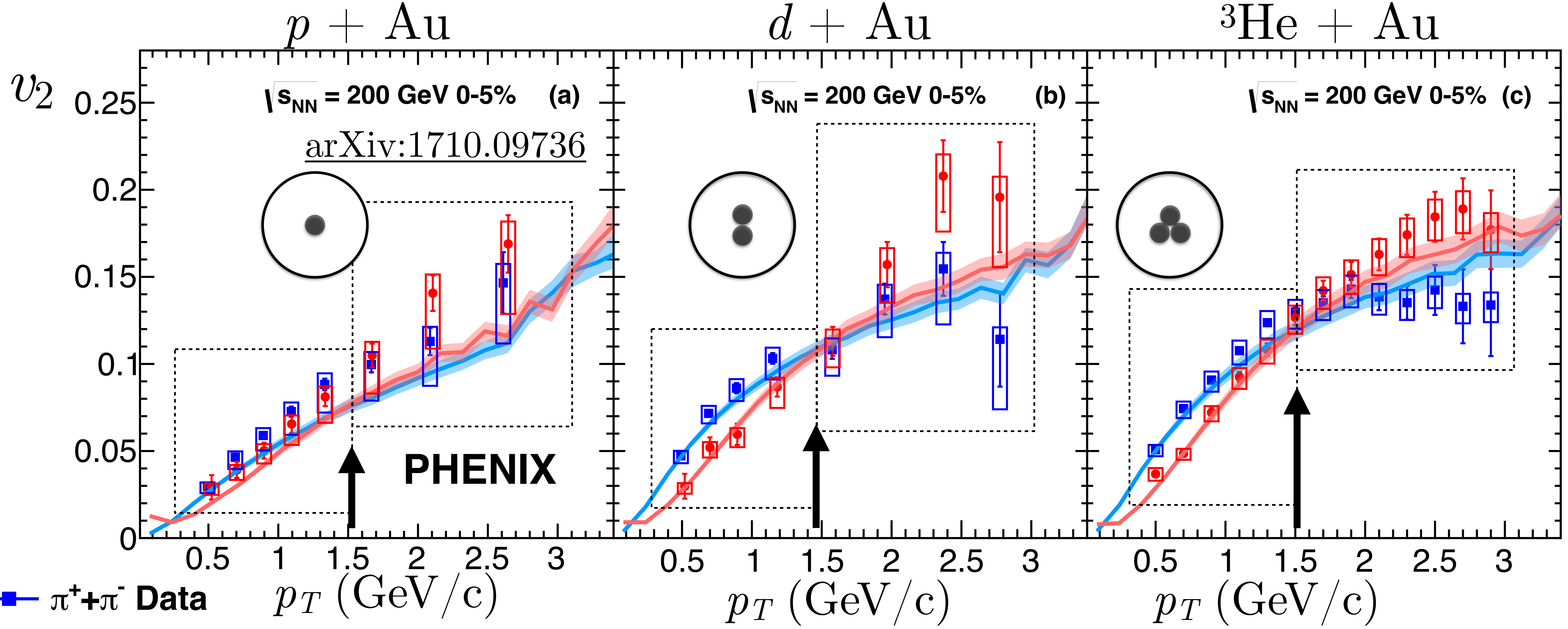

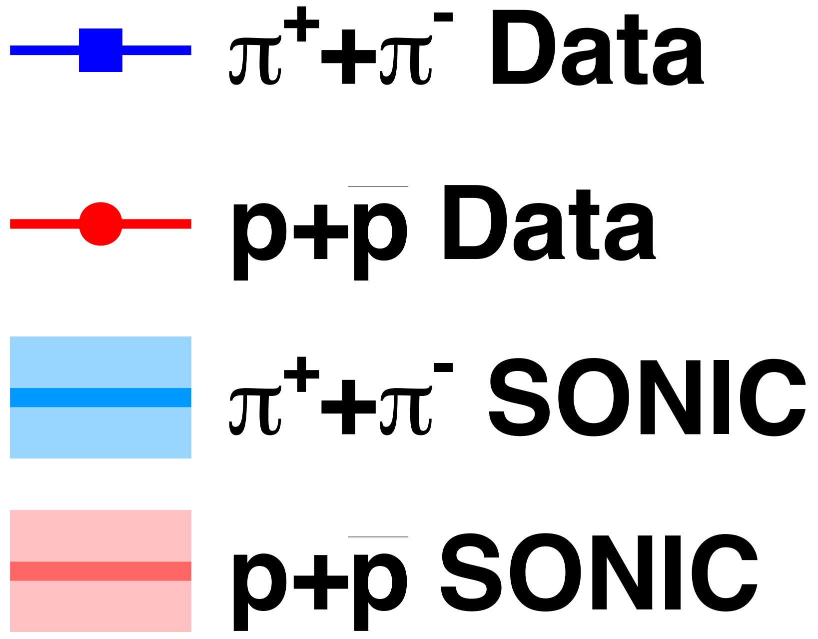

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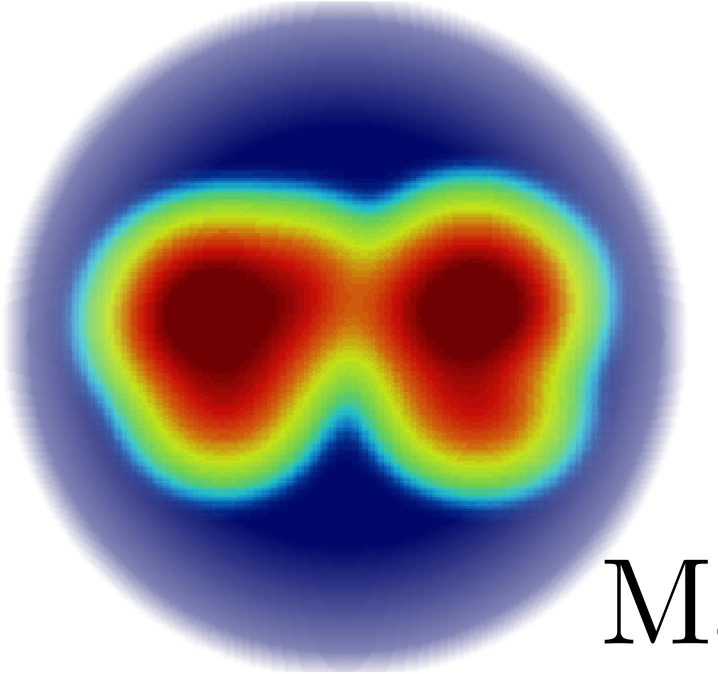
v_2 ordering	$\pi > p$	$\pi = p$	$\pi = p$

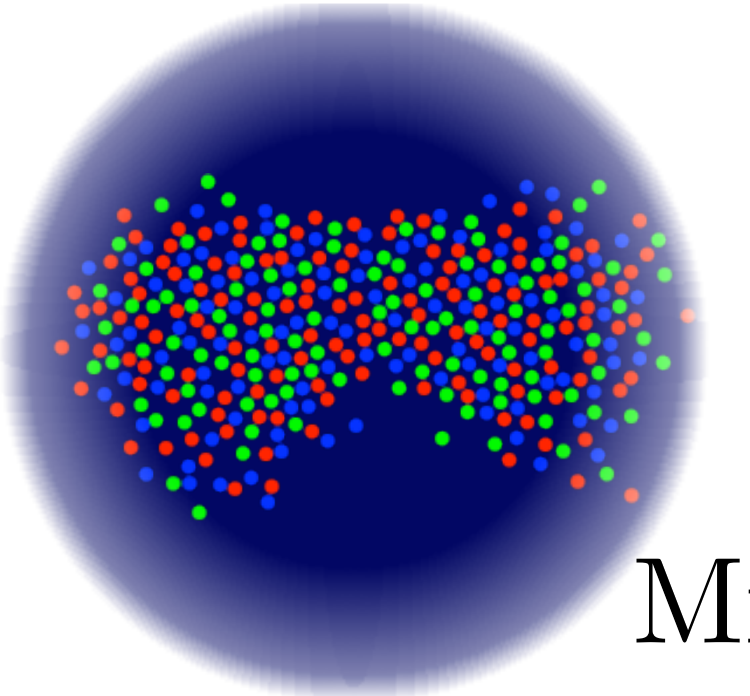
Microscopic formalism: A Multi-Phase Transport model

AMPT successfully describes many low p_T and p_T- integrated flow signatures in small systems

	Hydrodynamic	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



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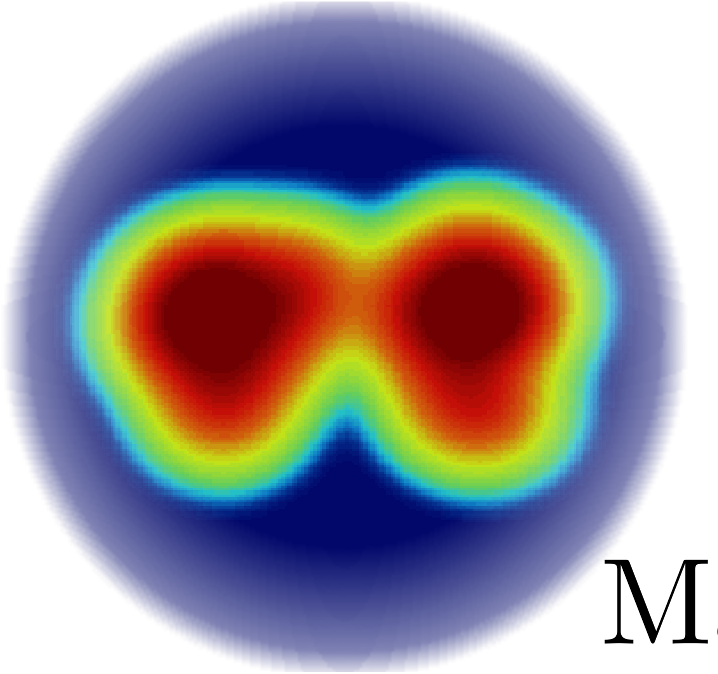
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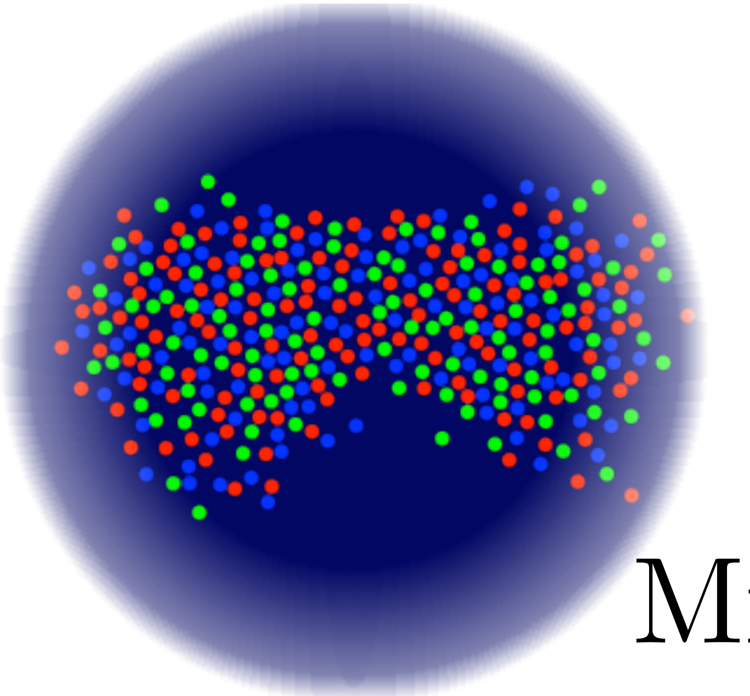
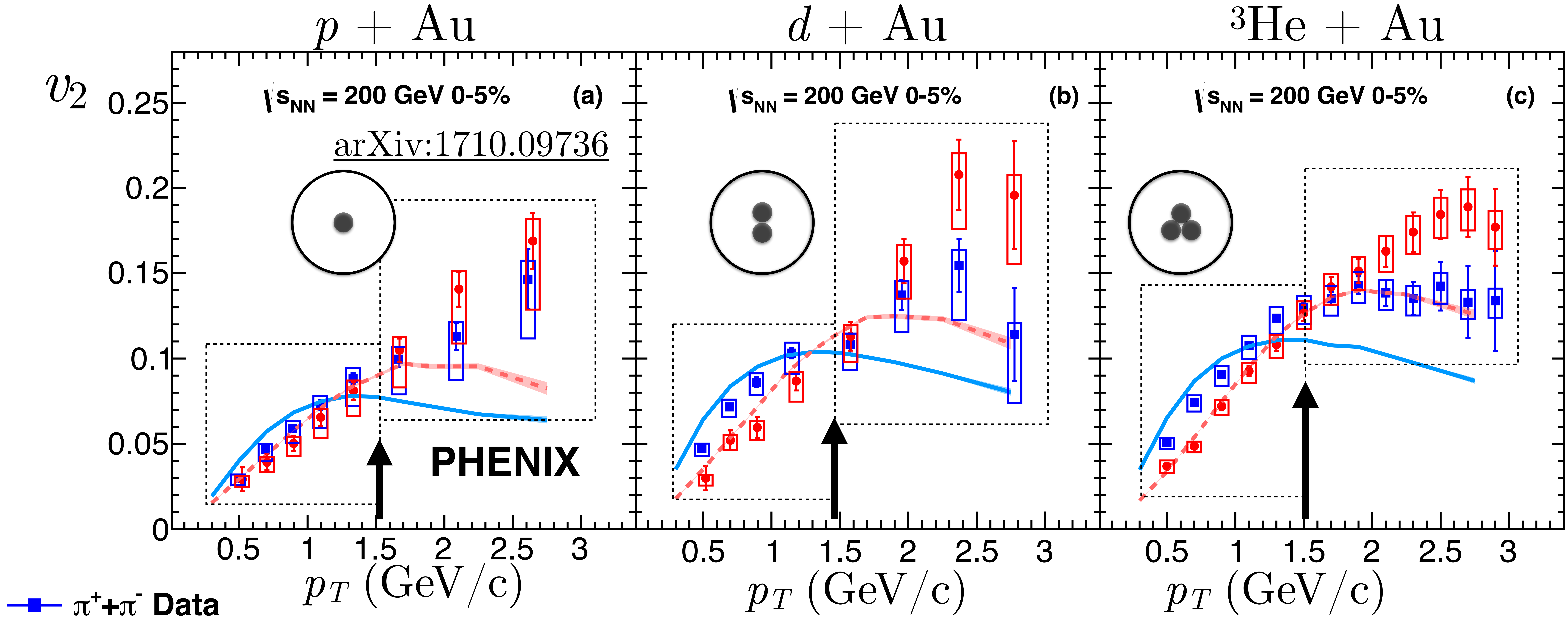
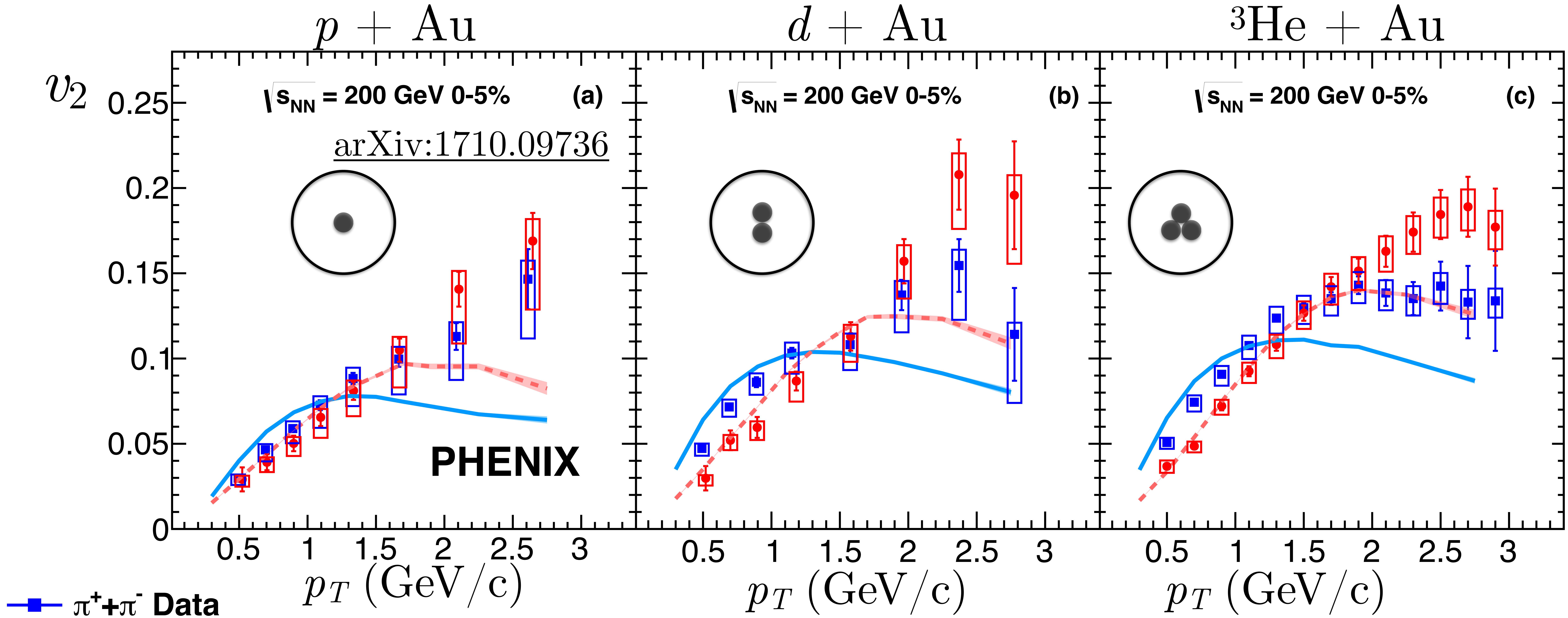

Microscopic

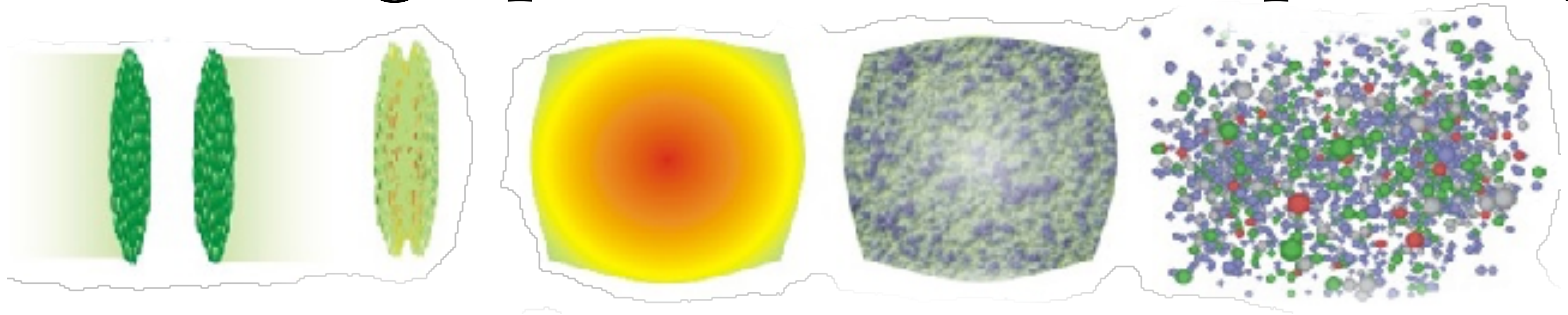
π and p $v_2(p_T)$: parton transport model and data PHENIX 21



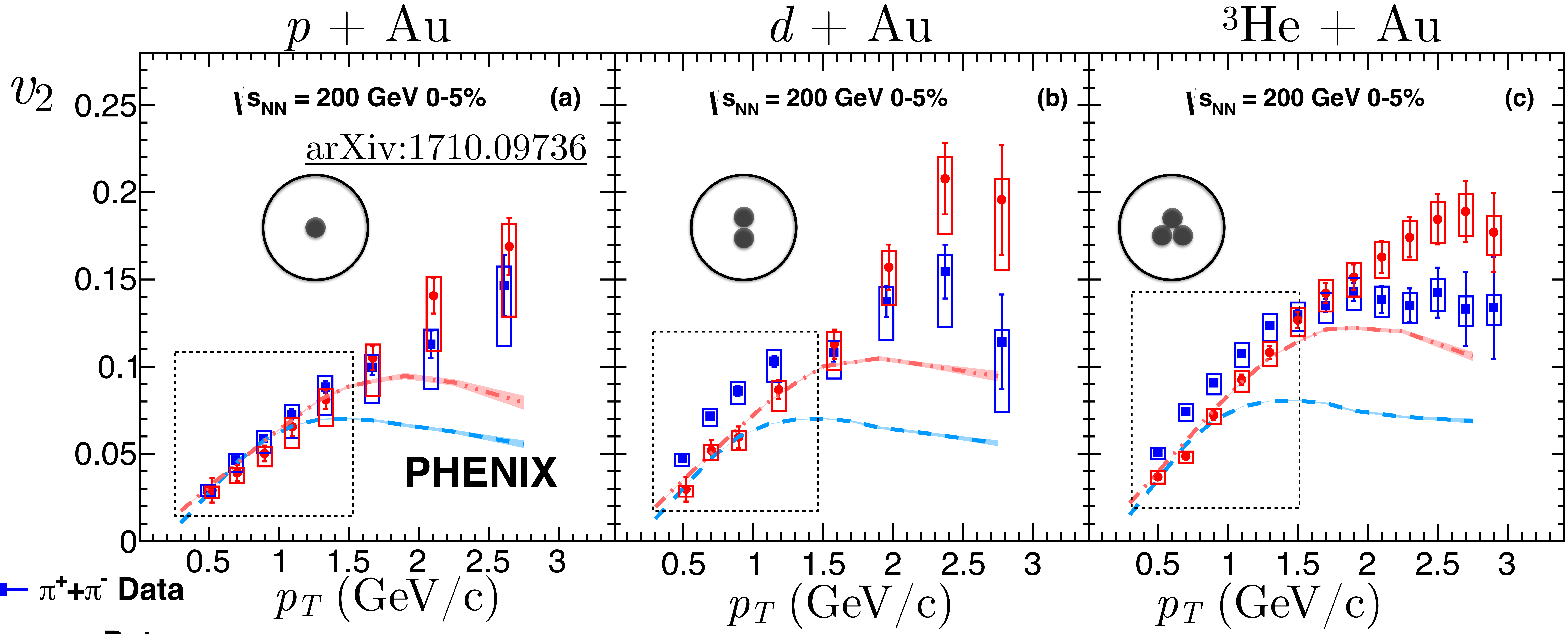
p_T [GeV/c]	< 1.5	$\simeq 1.5$	> 1.5
v_2 ordering	$\pi > p$	$\pi = p$	$\pi < p$

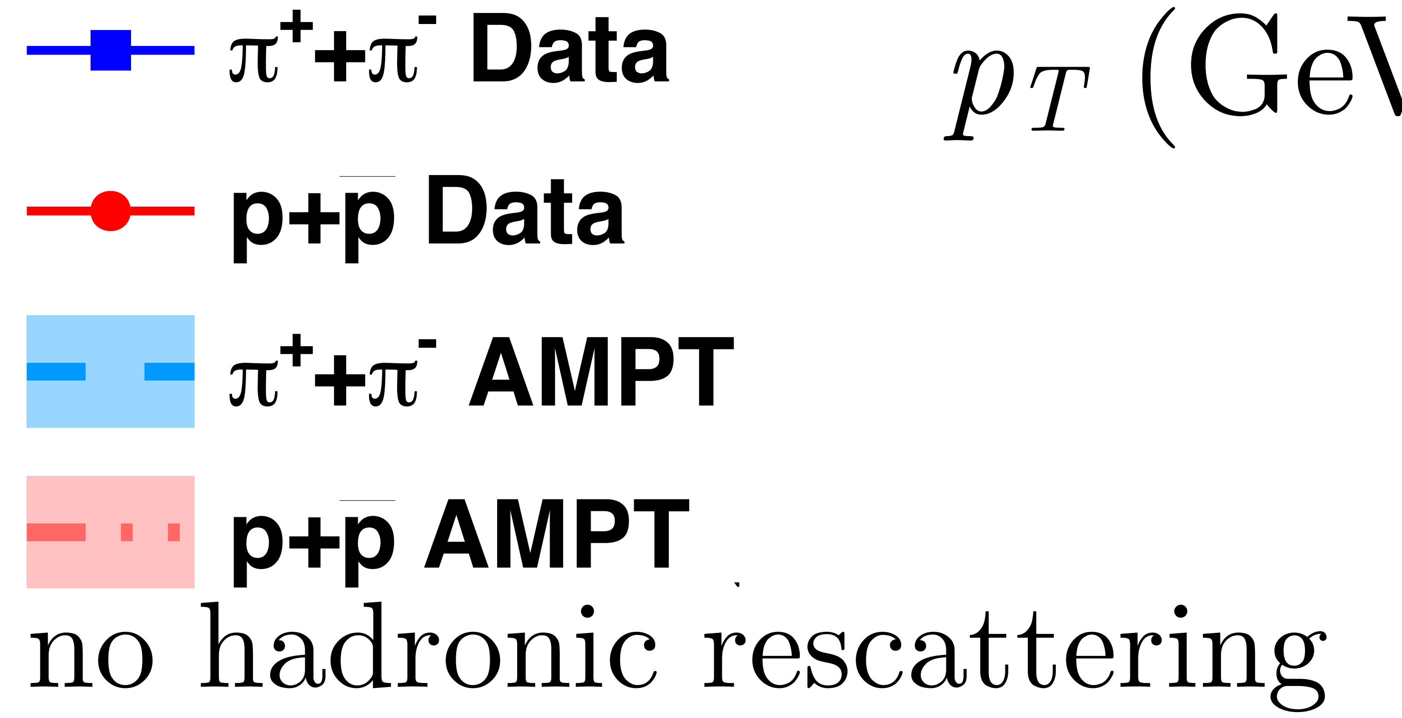


Which stage produces mass splitting?



π & p $v_2(p_T)$: AMPT w/o rescattering and data

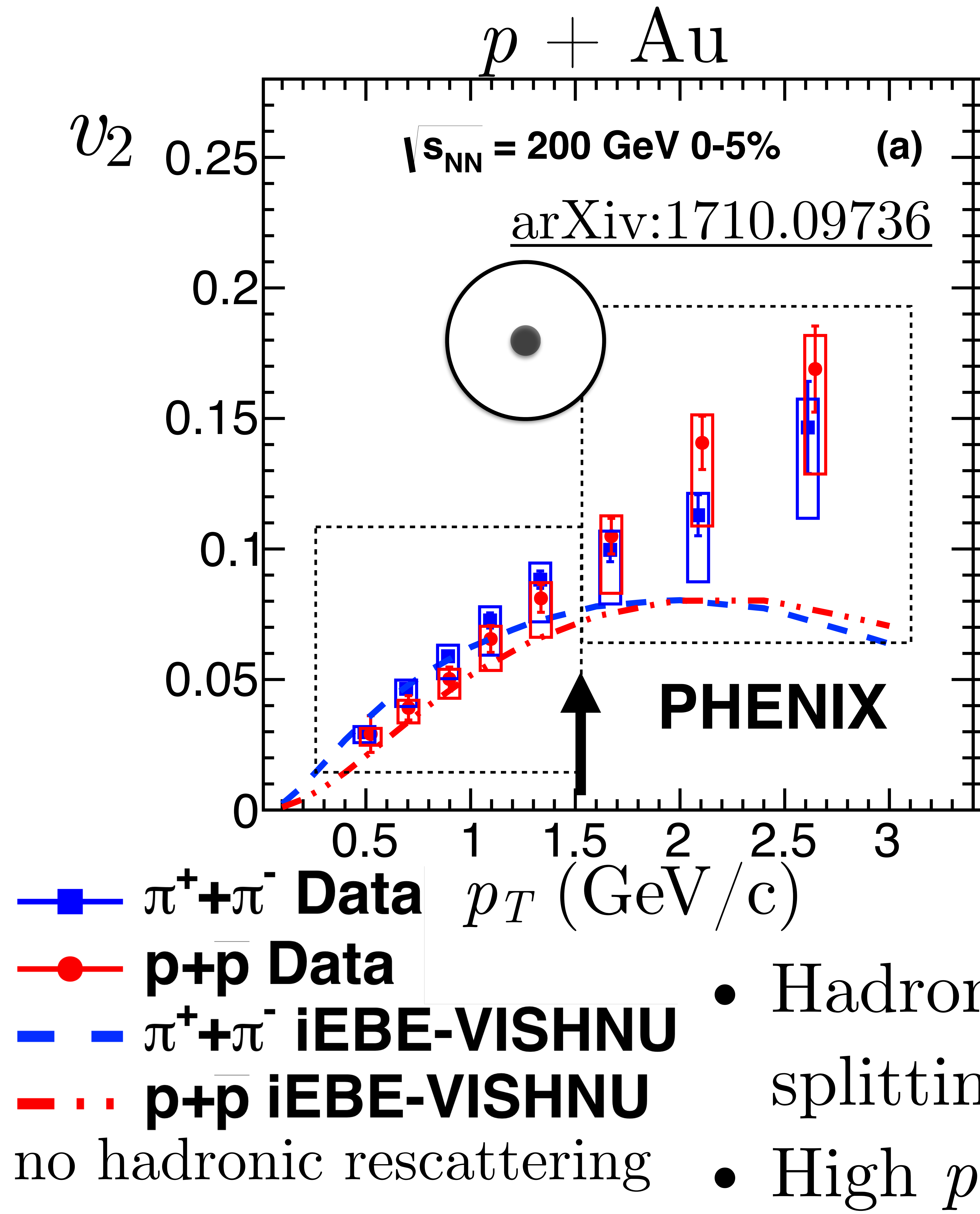




p_T [GeV/c]	< 1.5	$\simeq 1.5$	> 1.5
v_2 ordering	$\pi = p$	$\pi = p$	$\pi < p$

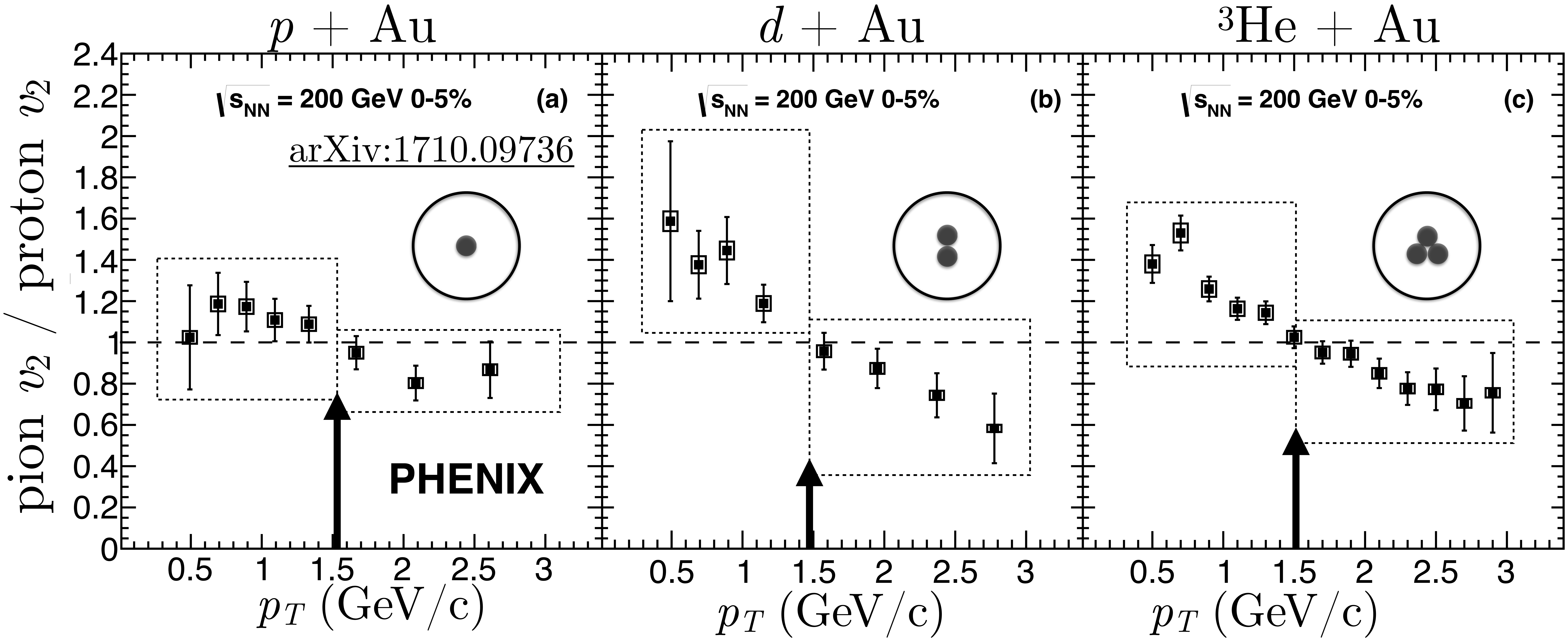
π and p $v_2(p_T)$: hydro w/o rescattering and data

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



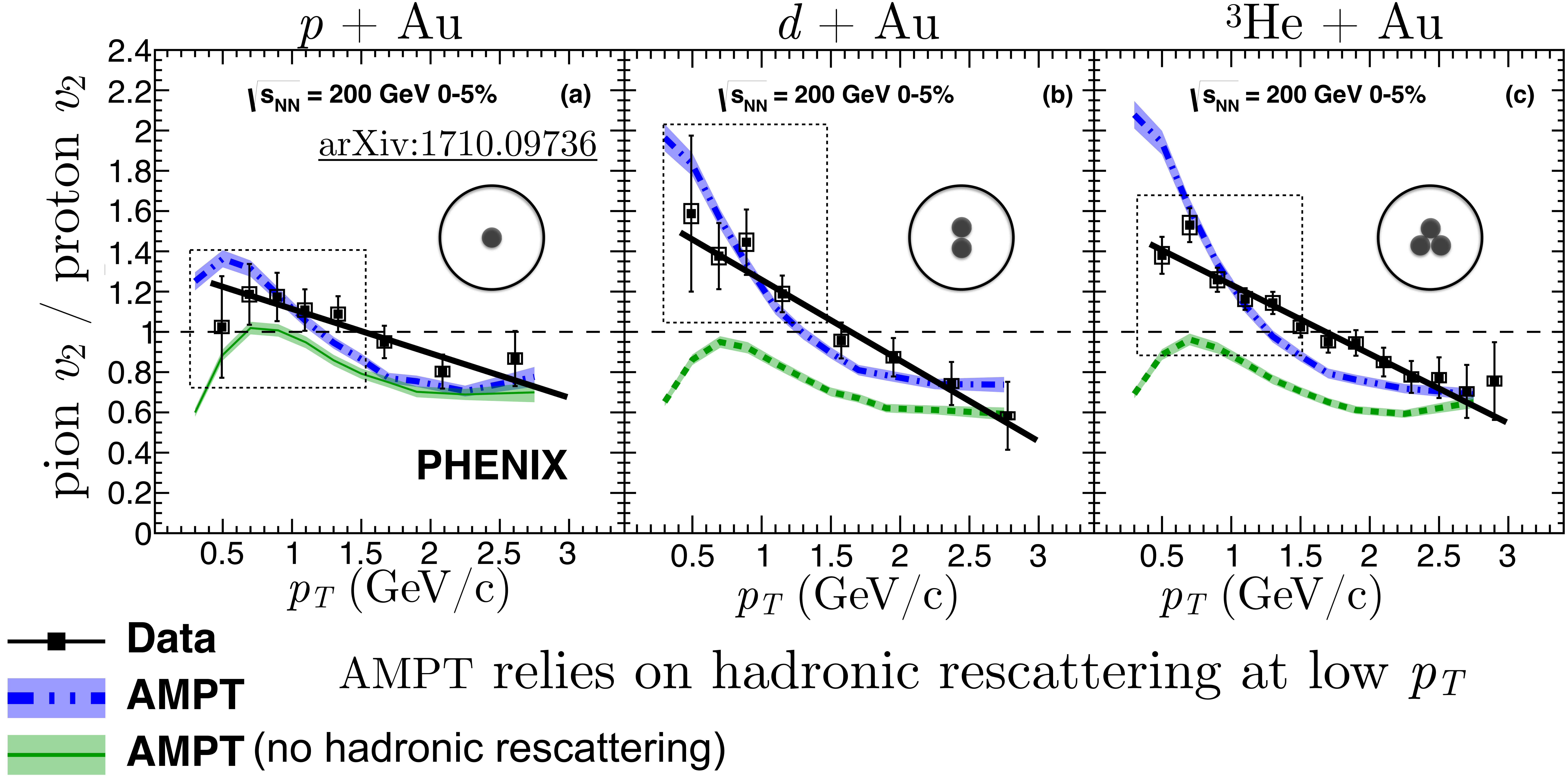
- Hadronic rescattering is responsible for low p_T mass splitting in AMPT, but not necessarily in general
- High p_T mass splitting is from quark recombination

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



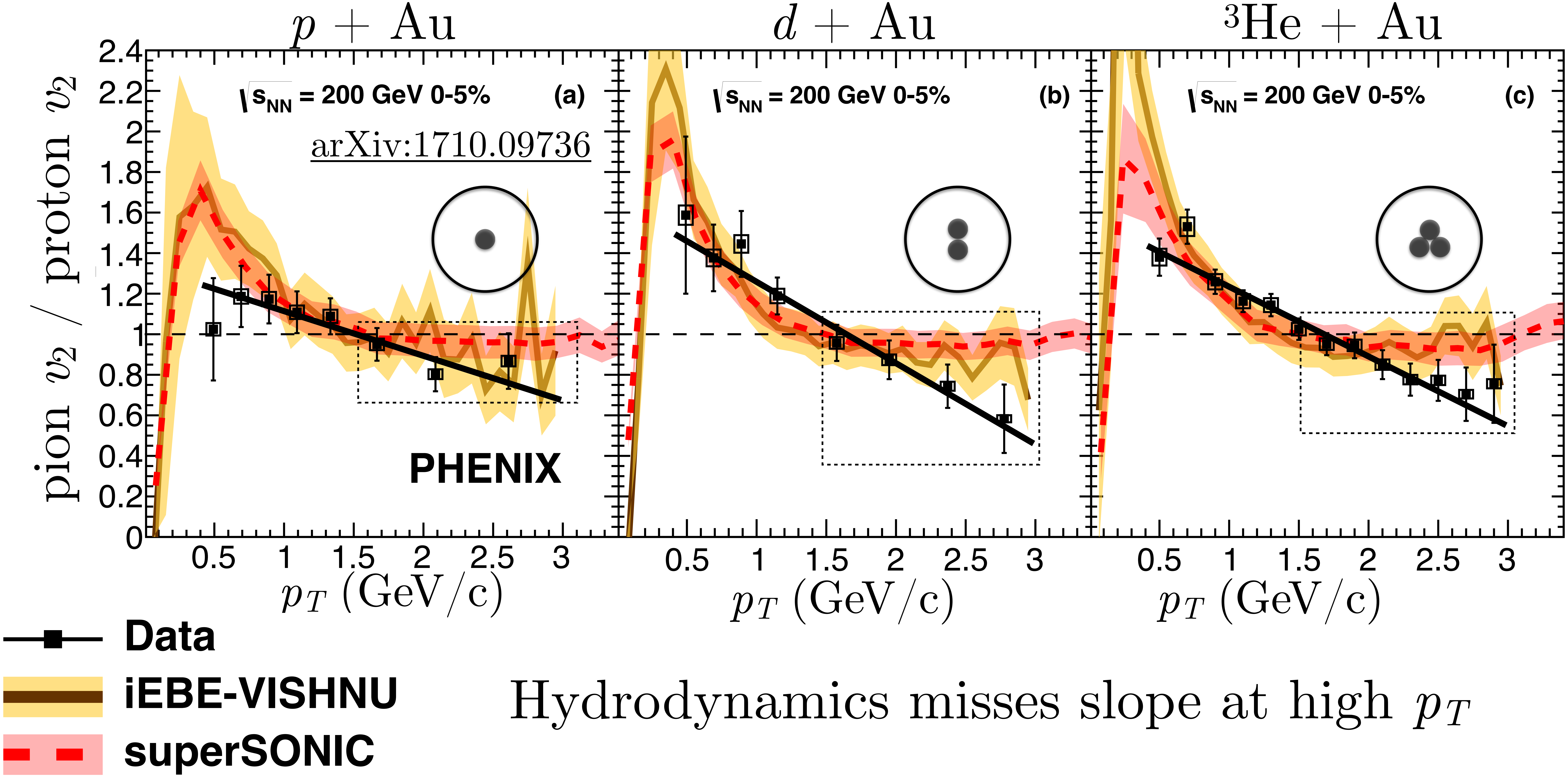
Ratio of pion $v_2(p_T)$ over proton $v_2(p_T)$ — some uncertainty cancels

$v_2(p_T)$ pion/proton ratio with AMPT



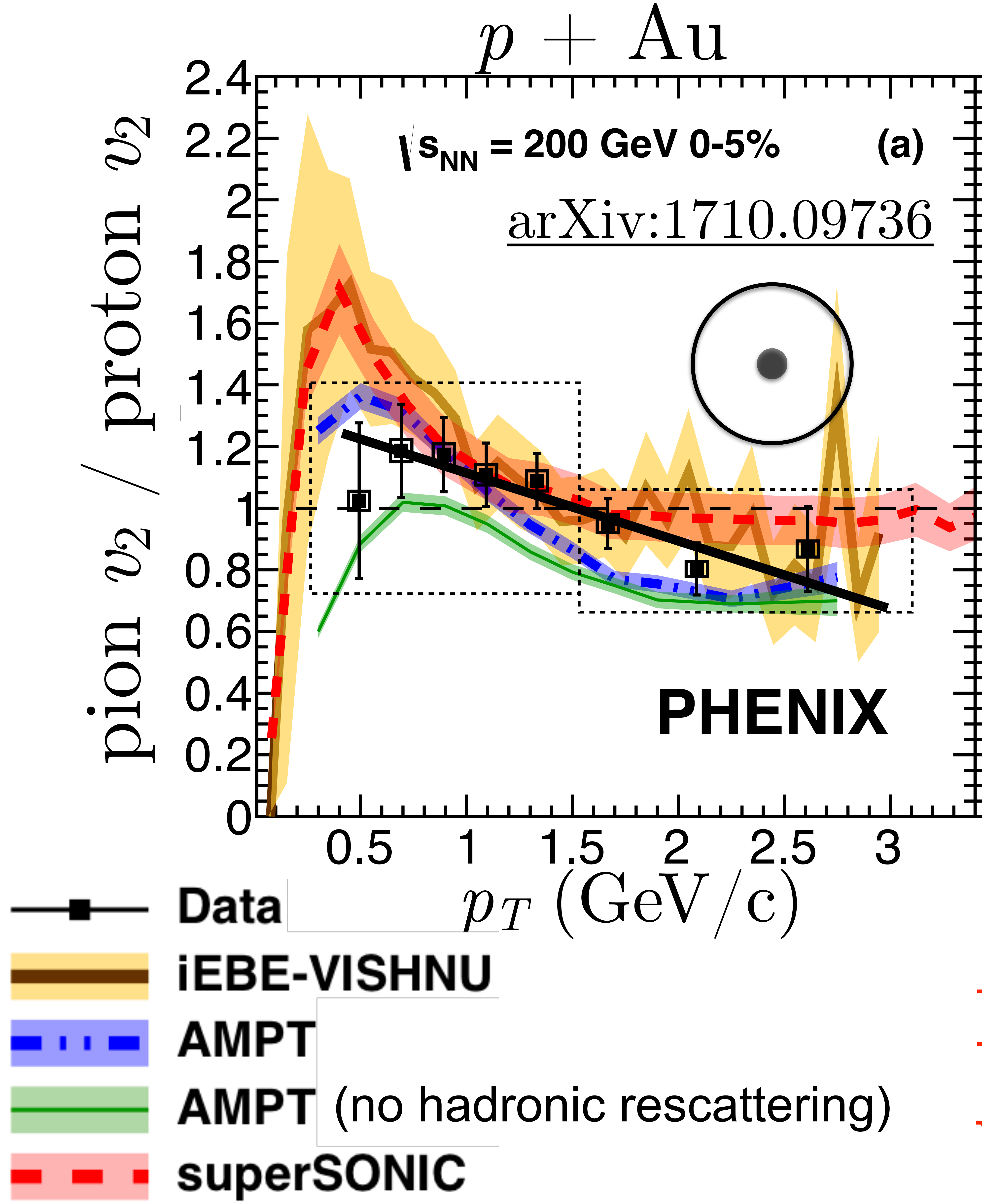
AMPT relies on hadronic rescattering at low p_T

$v_2(p_T)$ pion/proton ratio with hydrodynamics



Hydrodynamics misses slope at high p_T

$v_2(p_T)$ pion/proton ratio compared to models



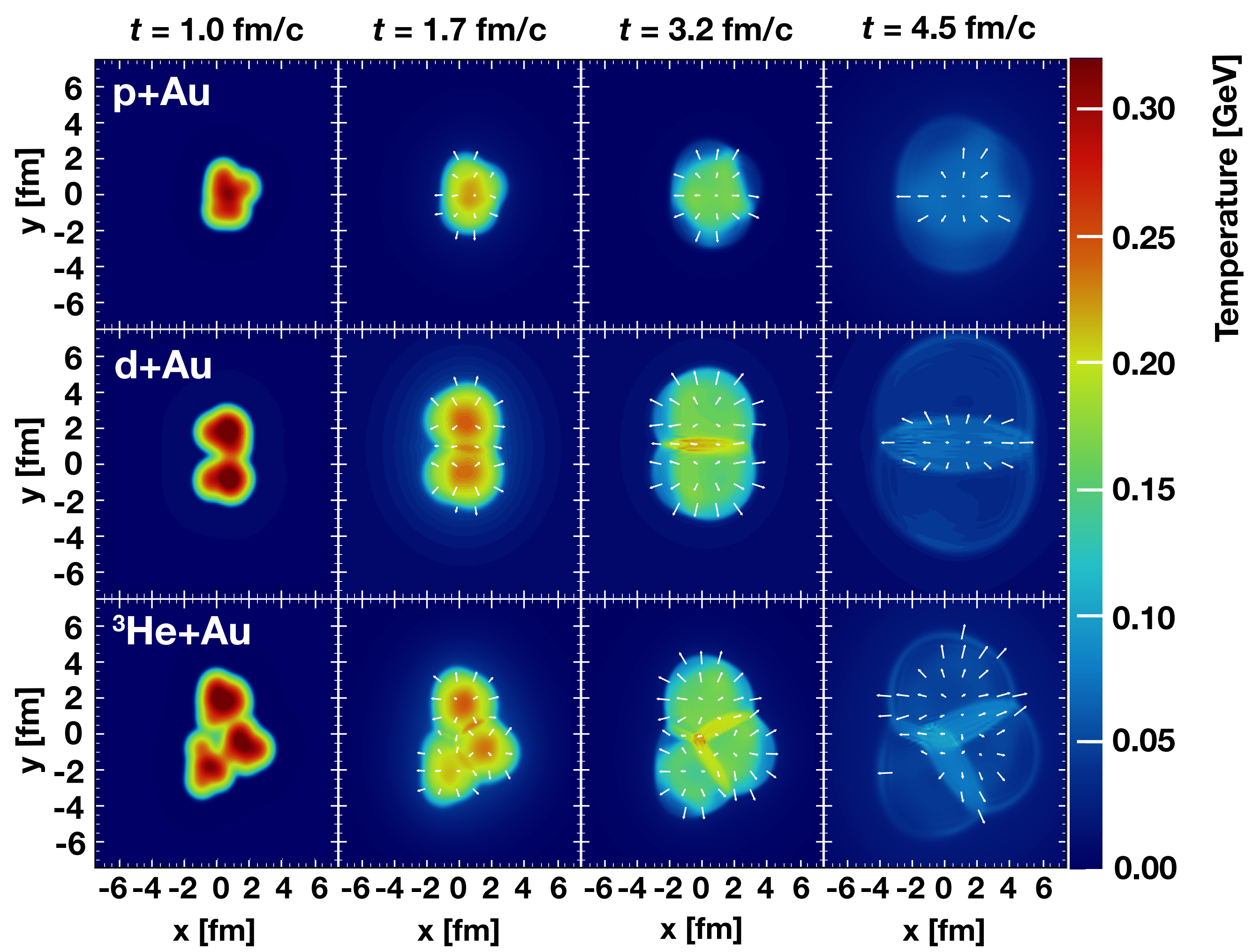
Mass-dependent $v_2(p_T)$ is consistent with hydrodynamics, though alternative explanations exist

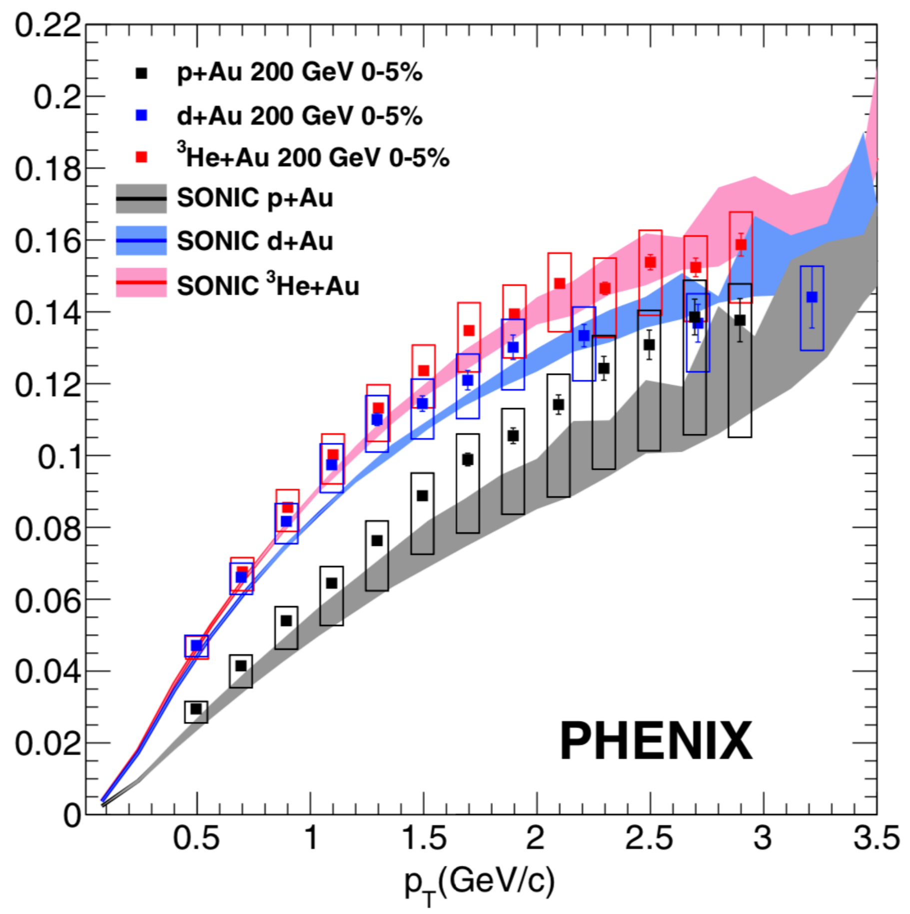
Charged hadron flow

Are there quark-gluon plasma droplets in central small systems collisions?

Hydrodynamics predicts:

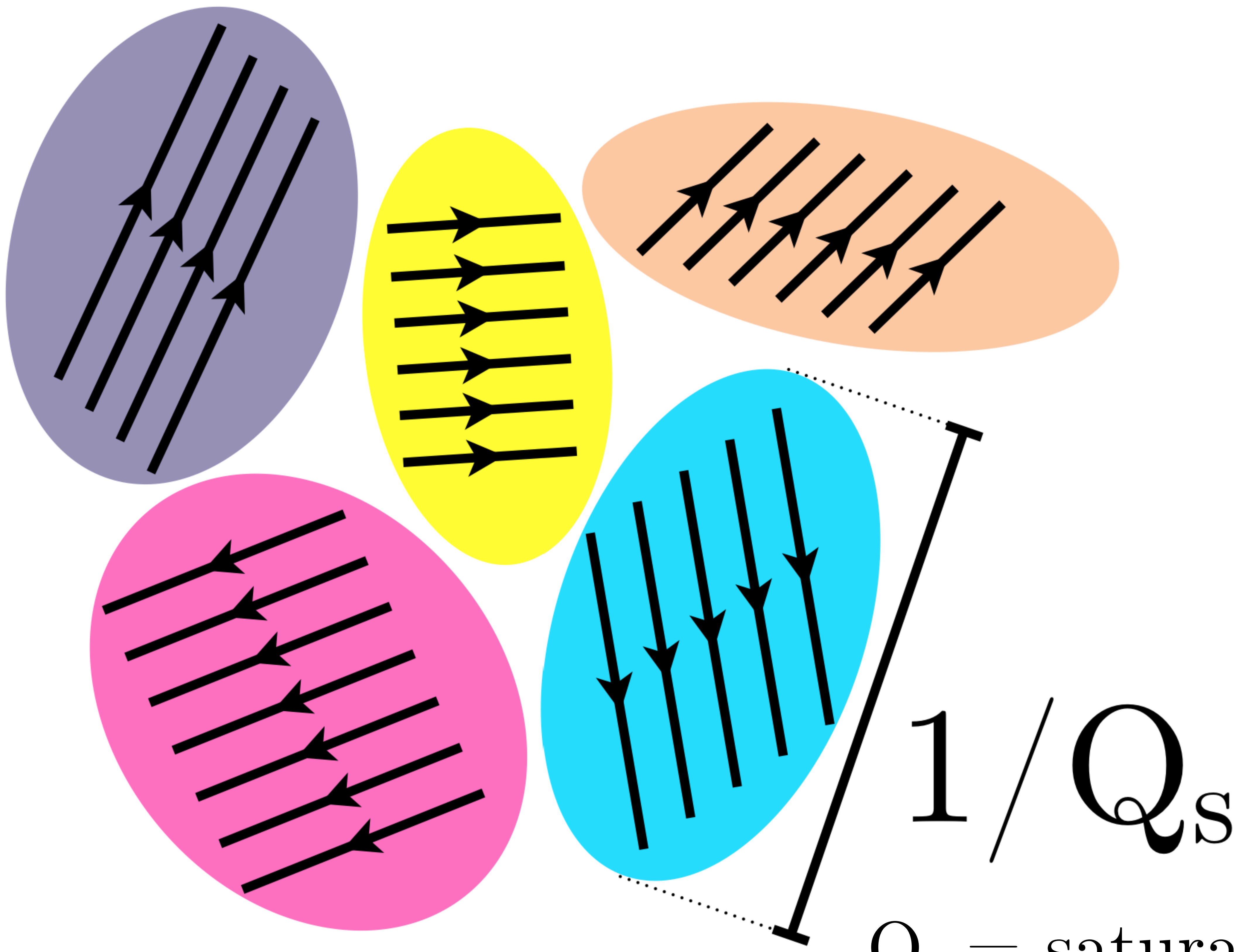
$$\varepsilon_n^{\mathrm{system}} \twoheadrightarrow v_n^{\mathrm{system}}$$





momentum correlations in the initial state $\twoheadrightarrow$ v_n^{system}

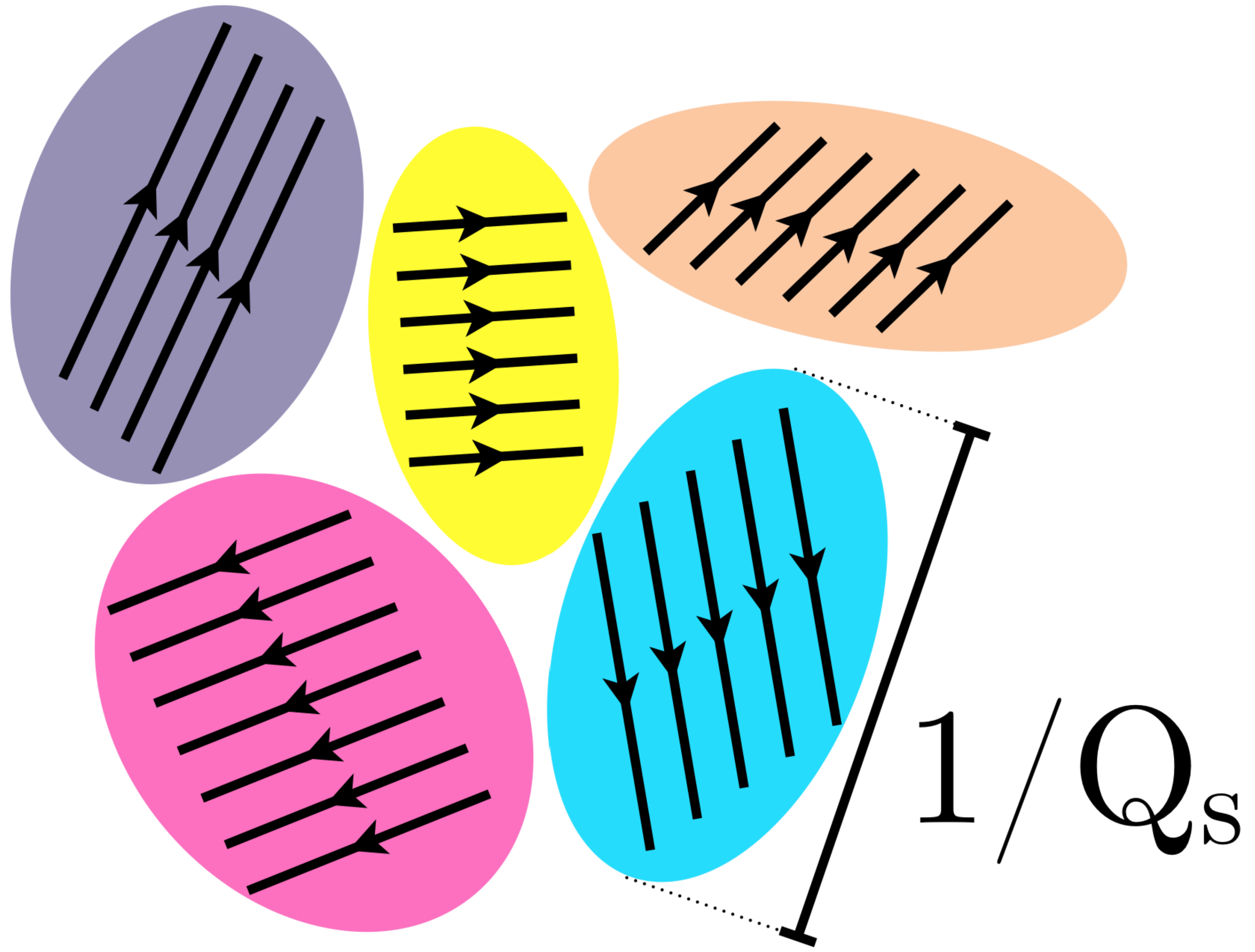
Initial state momentum correlation models

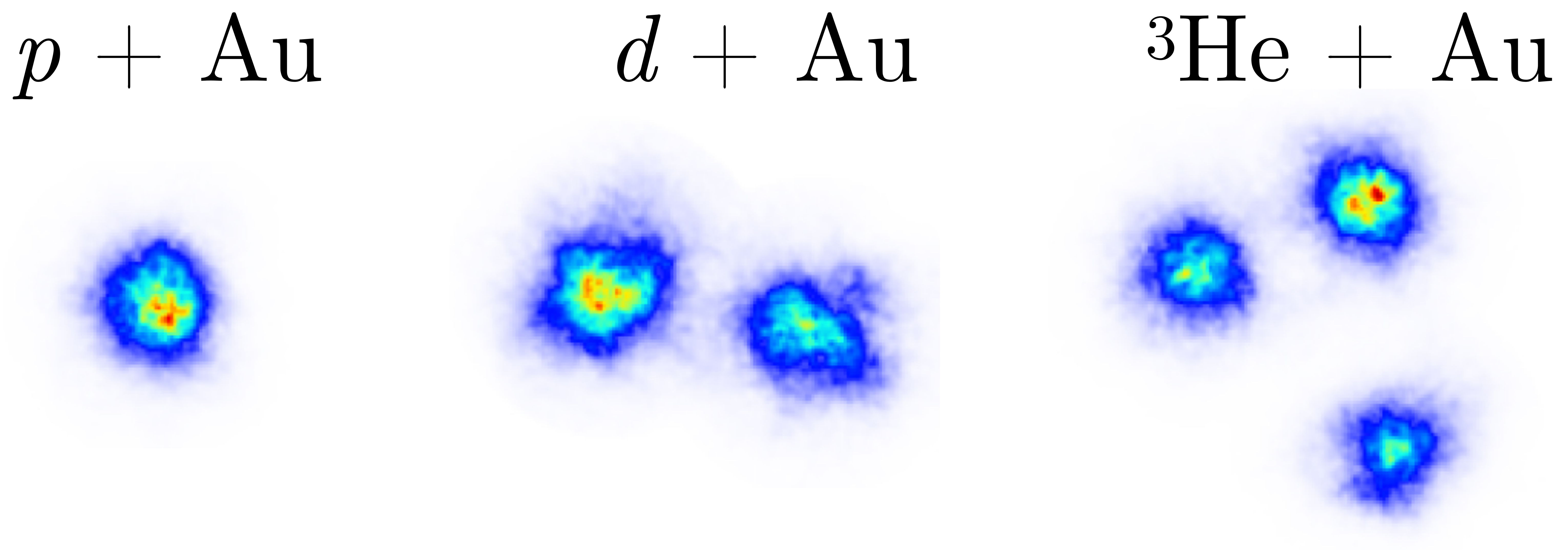


Q_s = saturation scale

- Size of domains < size of nucleon
- Analogous to domains in ferromagnetic materials

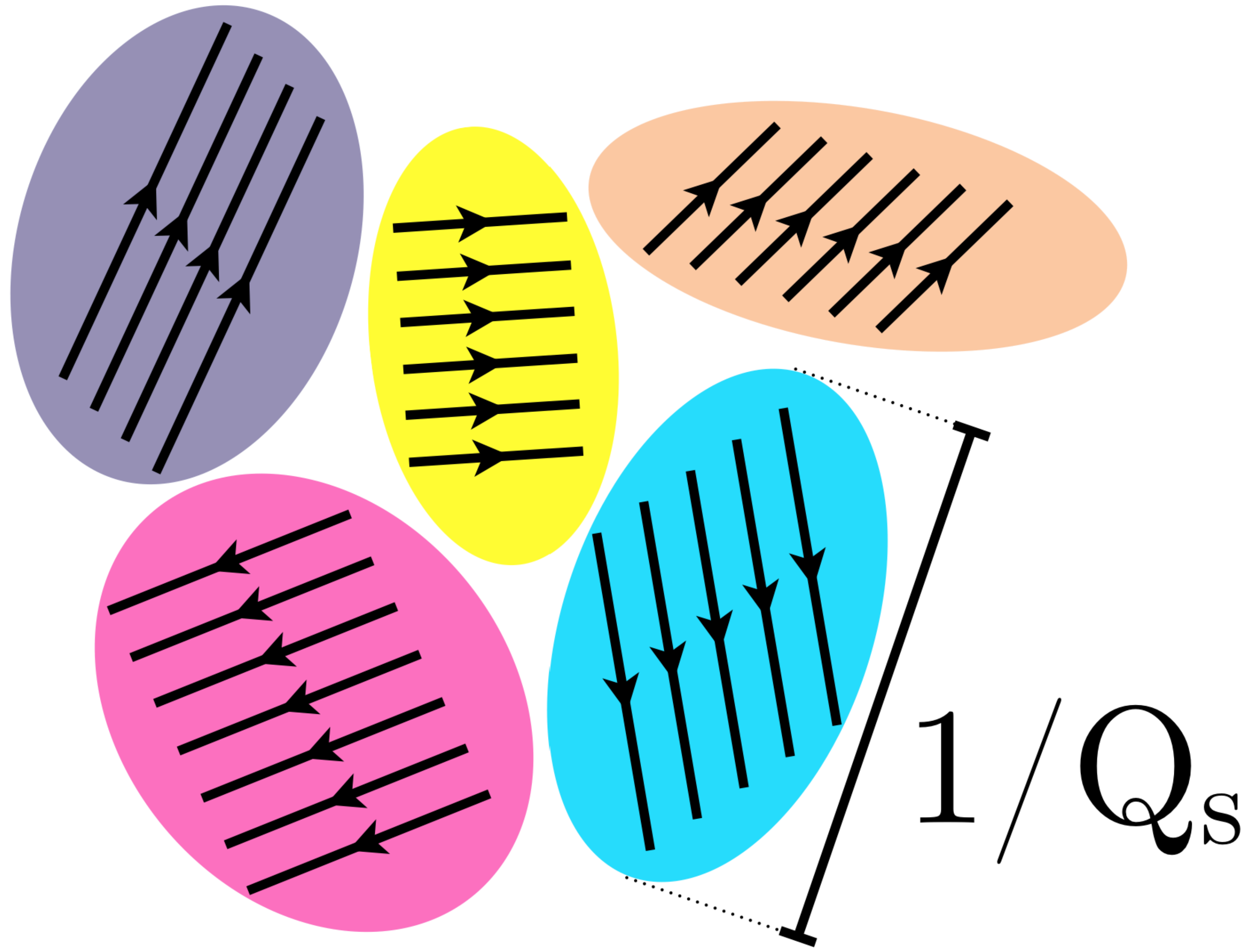
Uncorrelated momentum domains in a nucleon

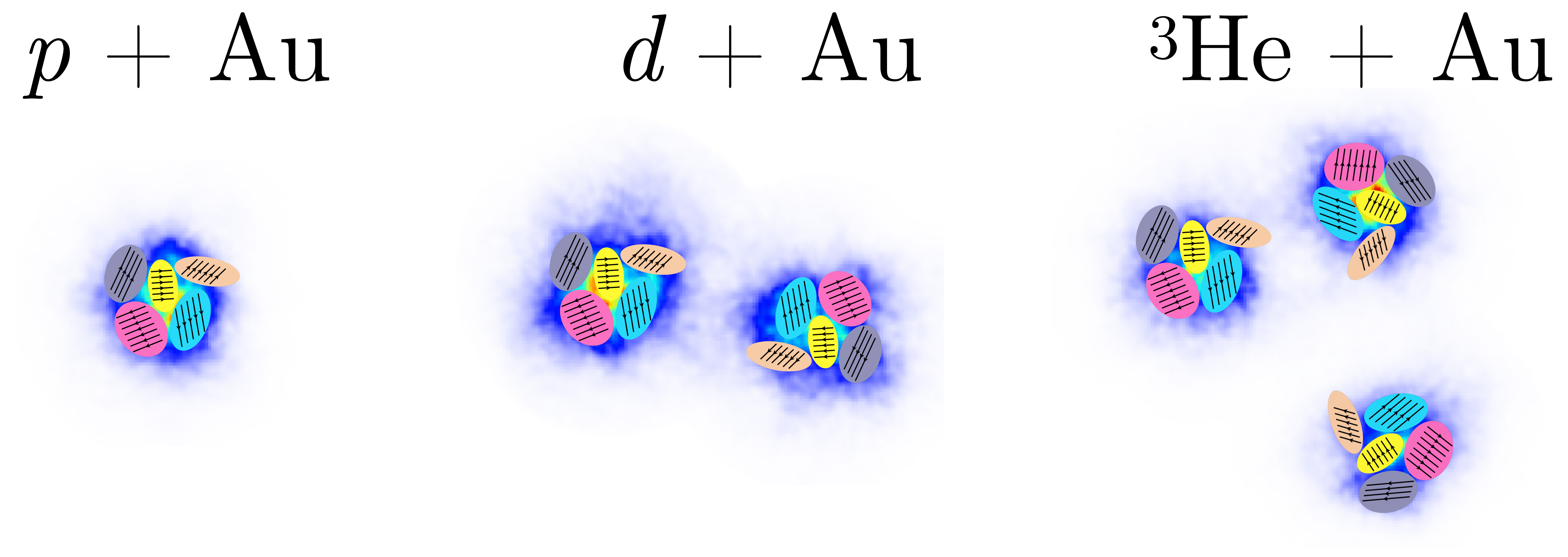




B. Schenke

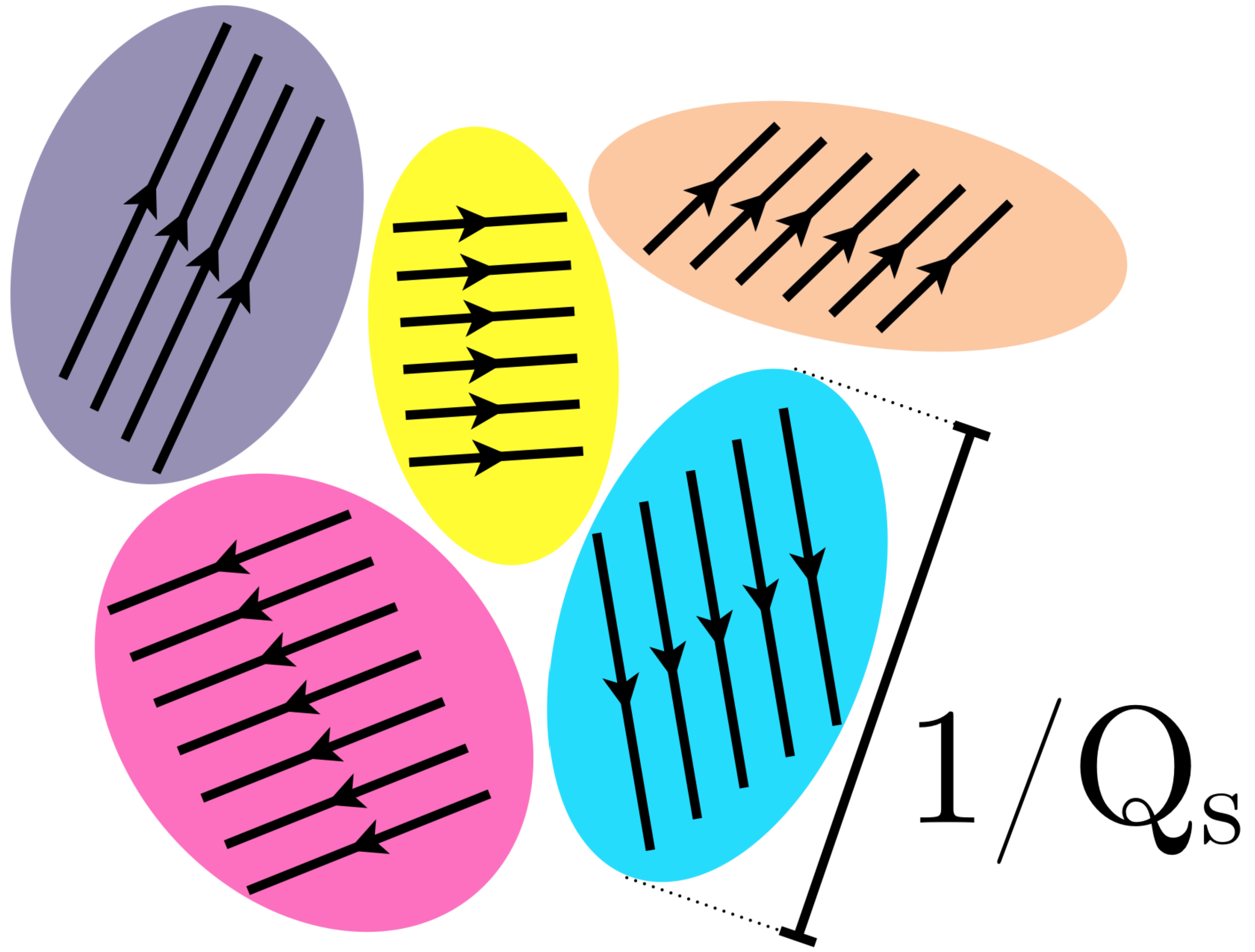
- If each nucleon creates a well-separated hot spot...

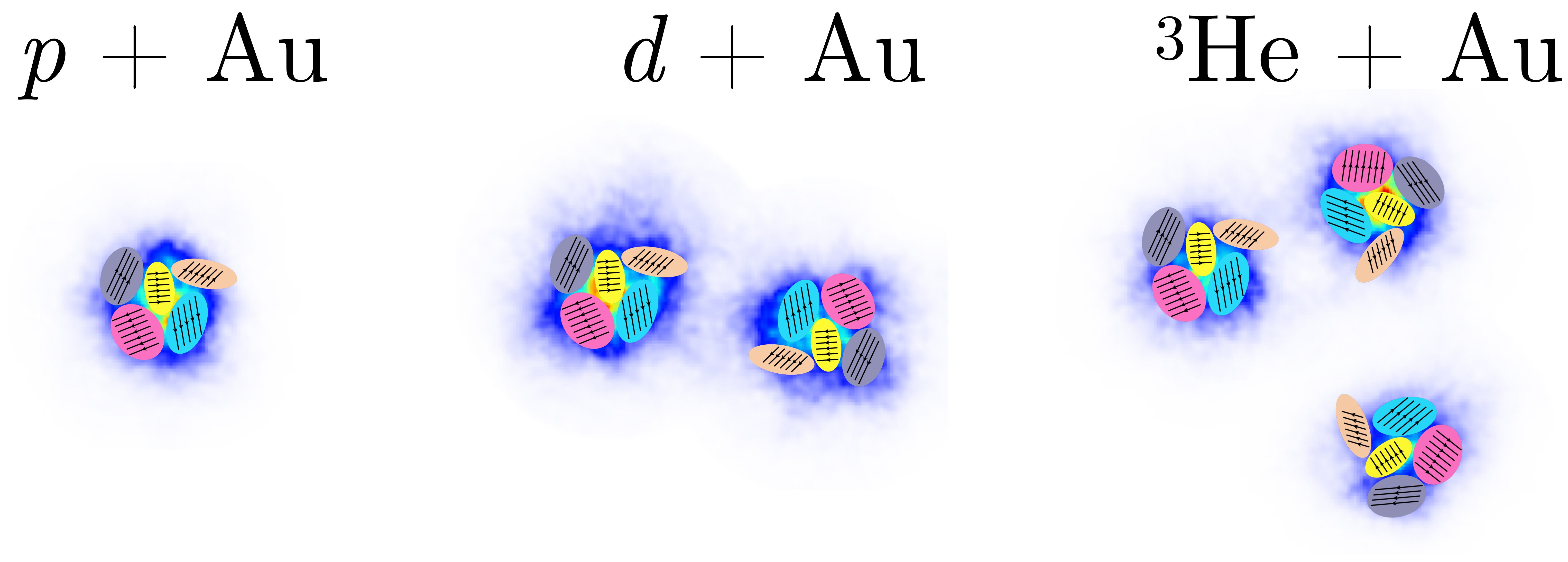




- If each nucleon creates a well-separated hot spot, uncorrelated nucleon momenta dilute overall initial state momentum correlations

Initial state momentum correlation models

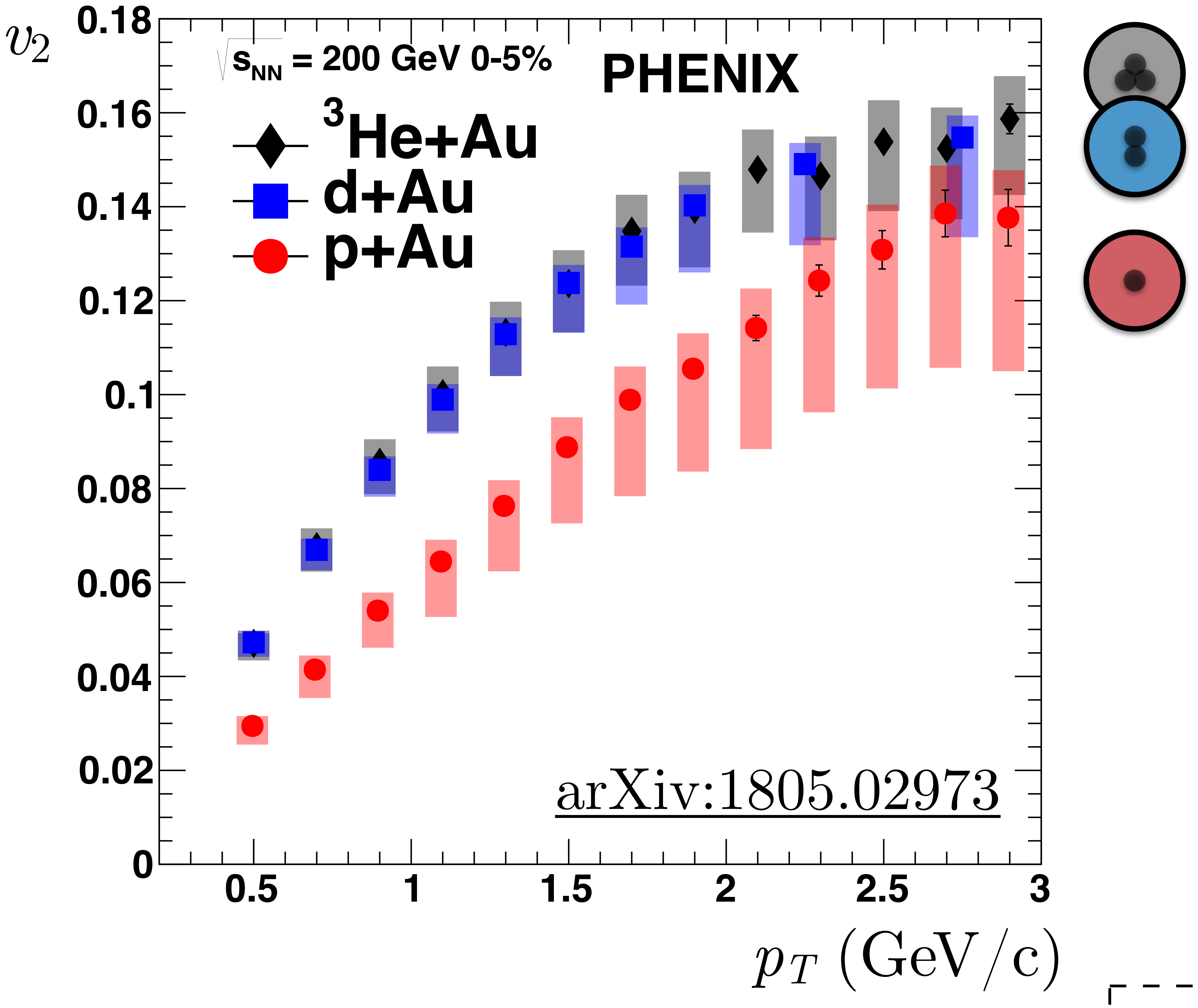


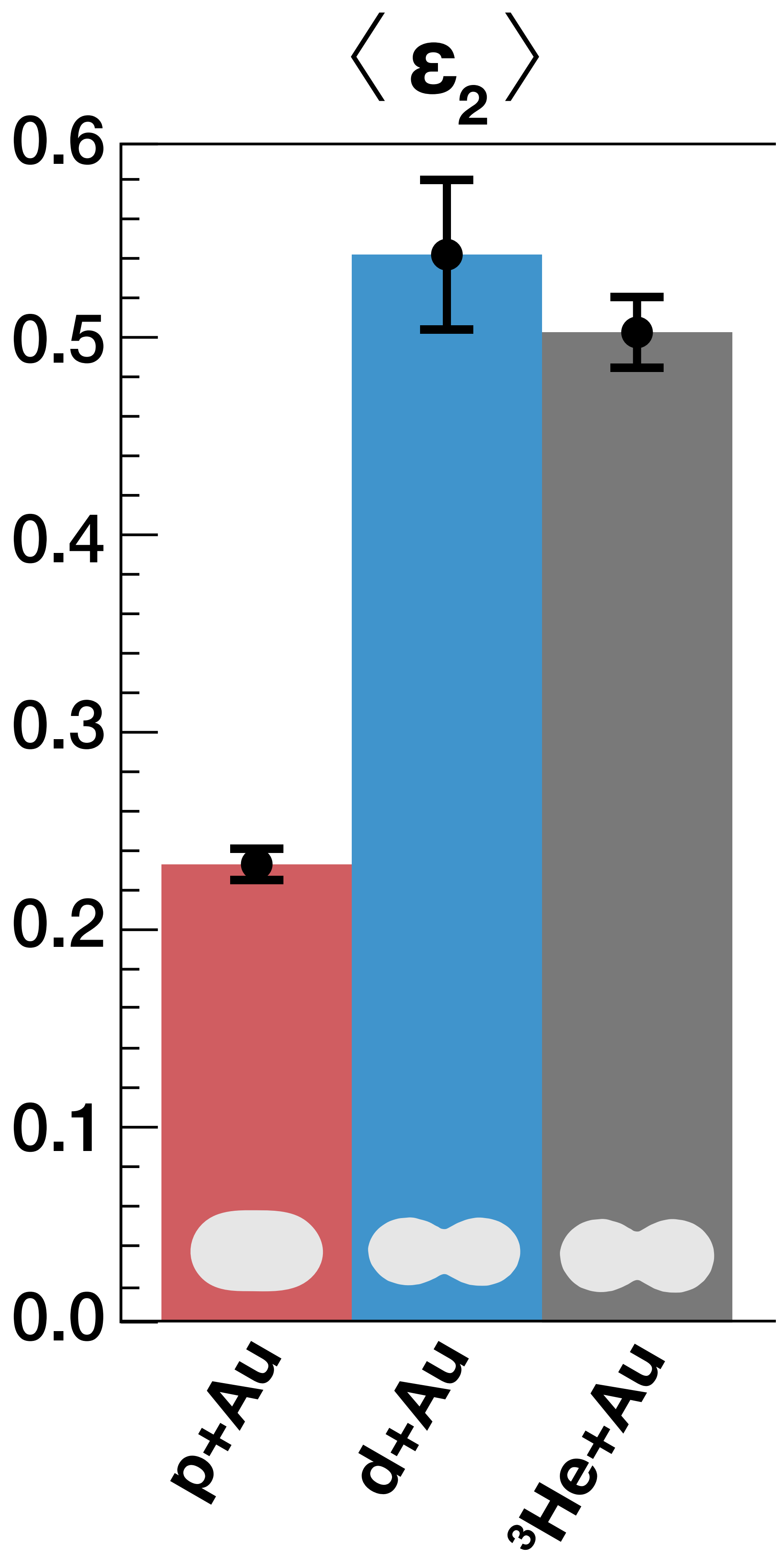


- If each nucleon creates a well-separated hot spot, uncorrelated nucleon momenta dilute overall initial state momentum correlations which, if translated to final state momentum correlations, suggests:

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

$v_2(p_T)$ measurement in small systems



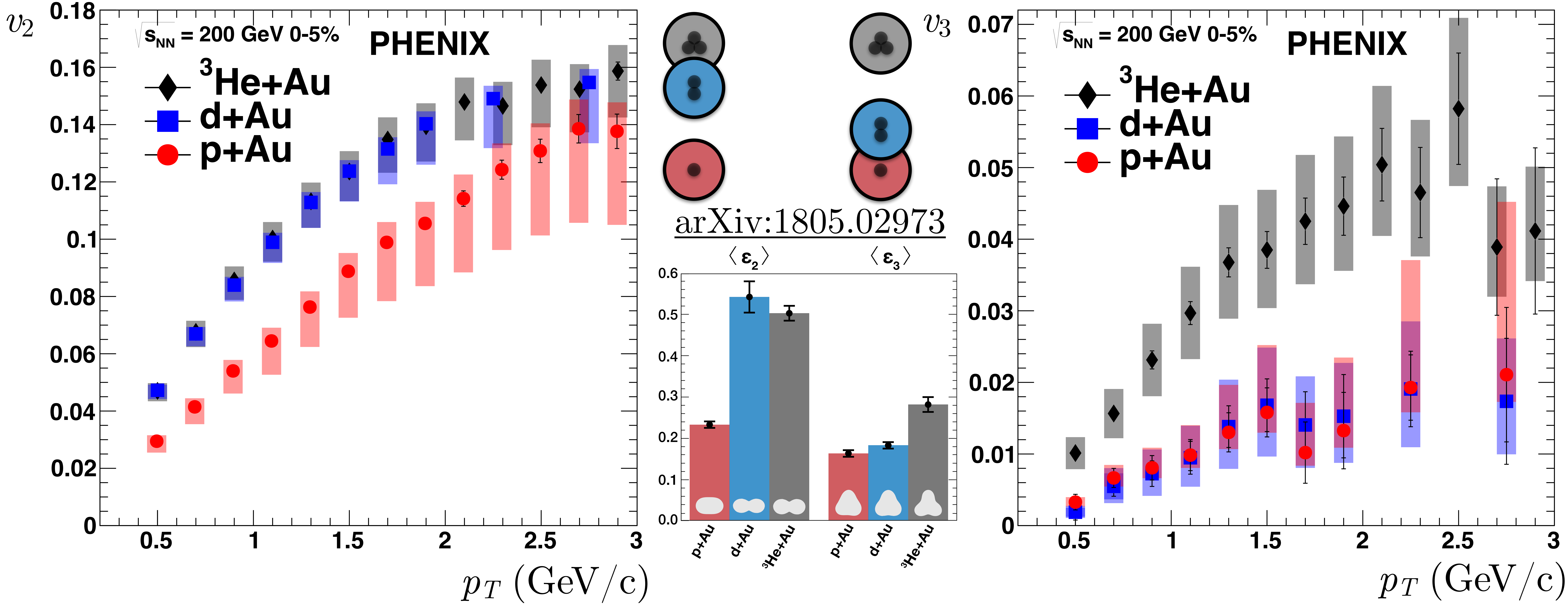


$$v_2^{p+\mathrm{Au}} < v_2^{d+\mathrm{Au}} \approx v_2^{^3\mathrm{He+Au}}$$

d+Au $v_2(p_T)$

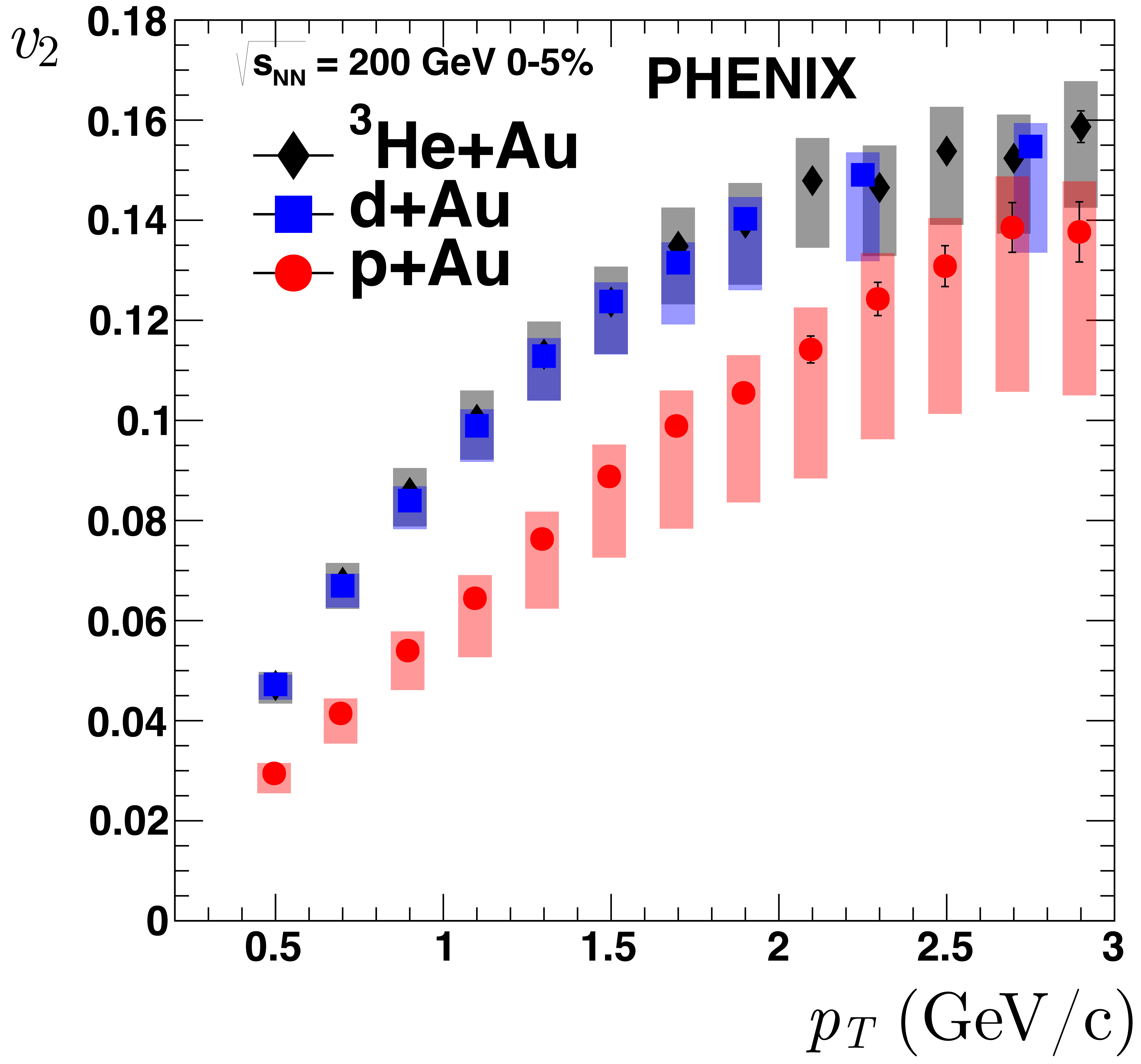
- Updated from Run8 to Run16 data
- First published in Phys. Rev. C **96**, 064905 (2017)
- New nonflow estimate

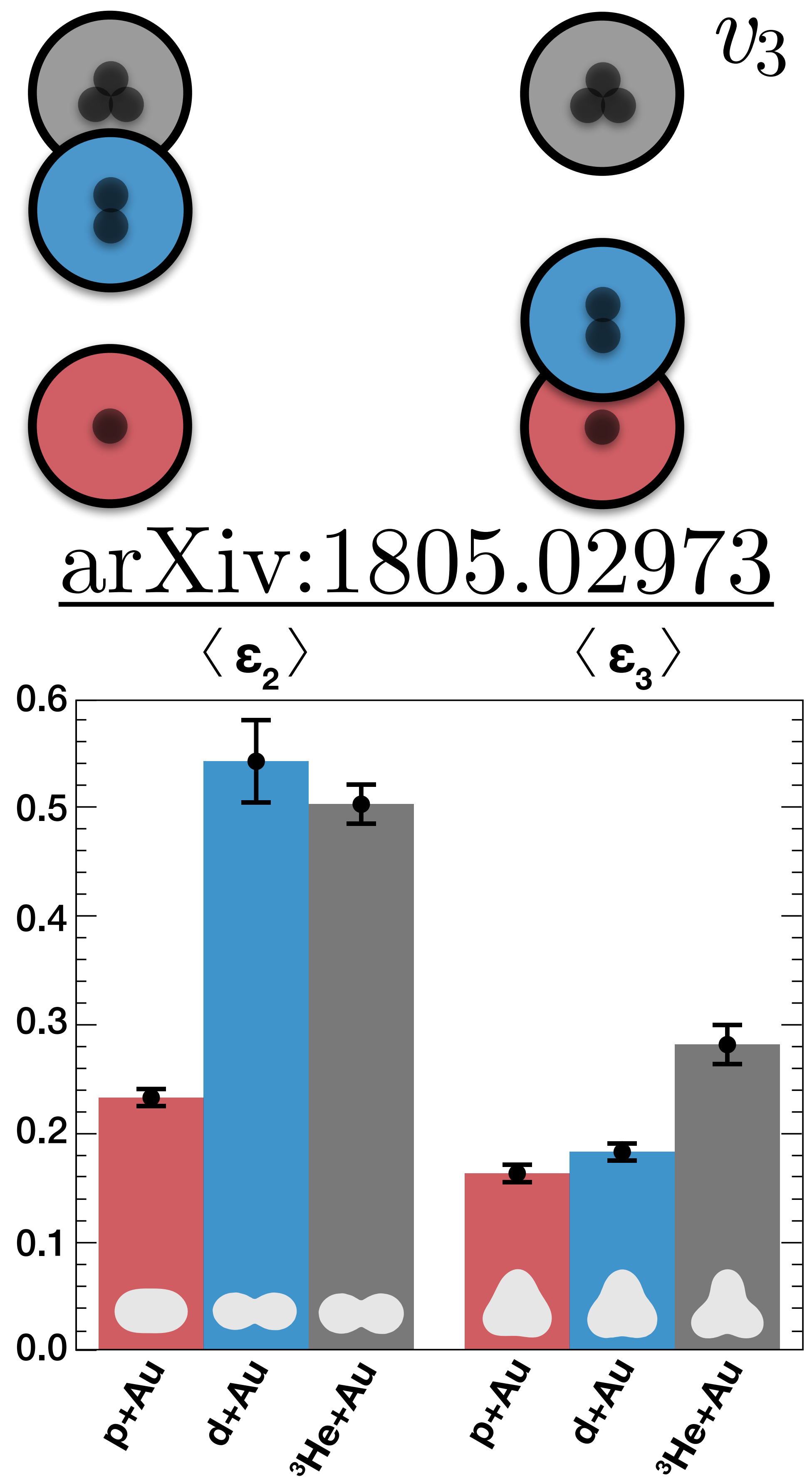
$v_n(p_T)$ measurement in small systems

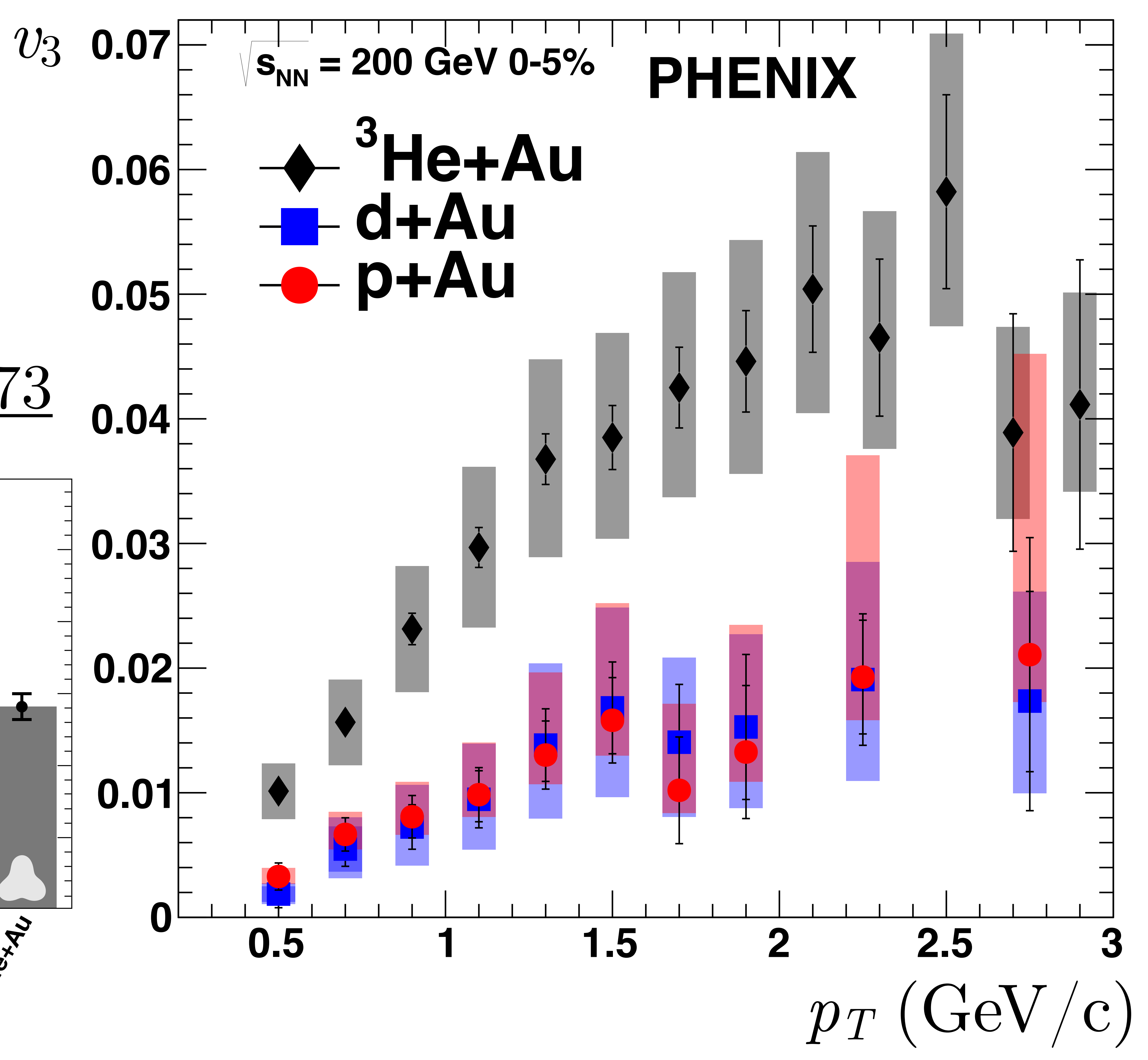


$$v_3^{p+\text{Au}} \approx v_3^{d+\text{Au}} < v_3^{^3\text{He+Au}}$$

$v_n(p_T)$ measurement in small systems



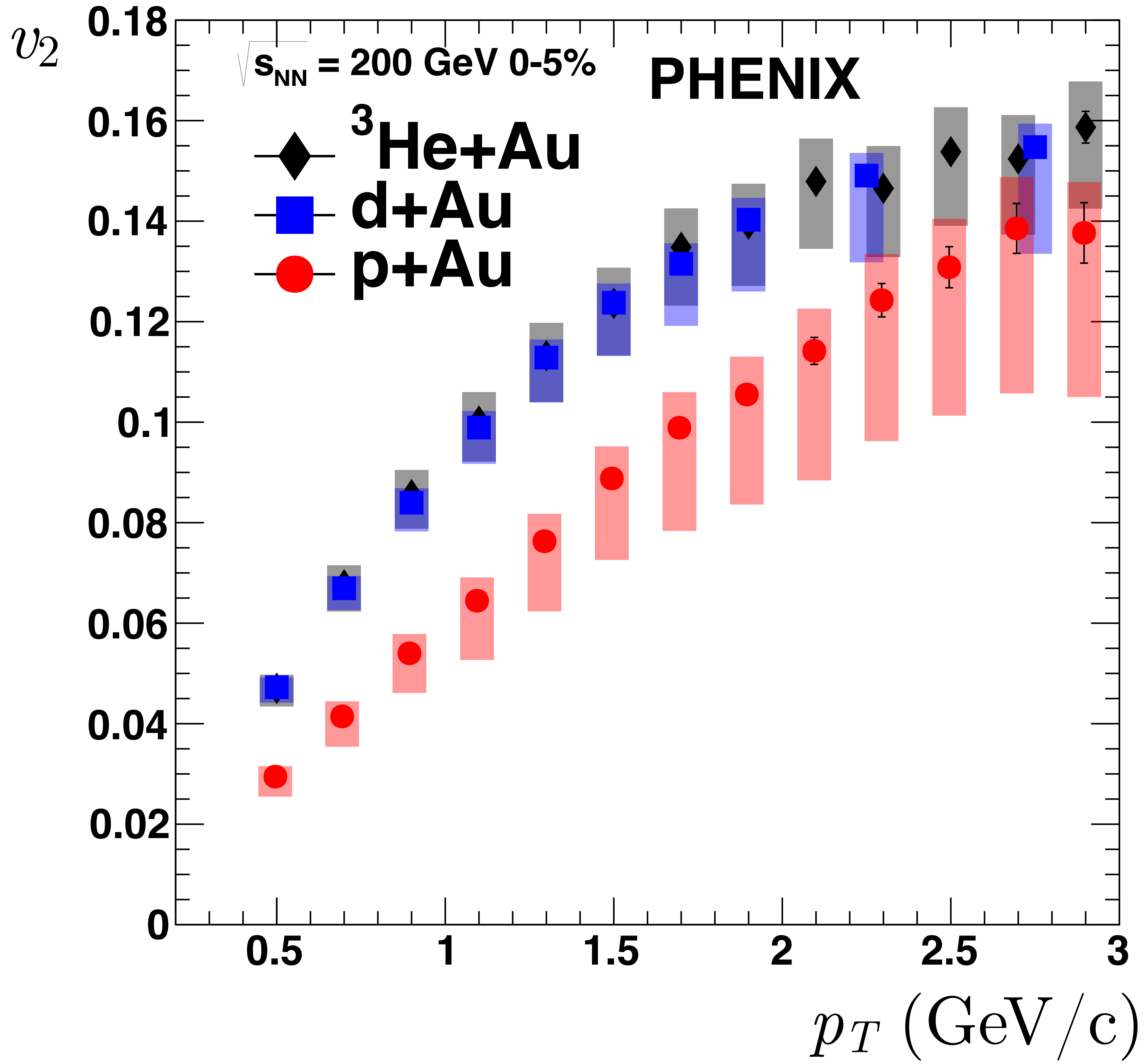


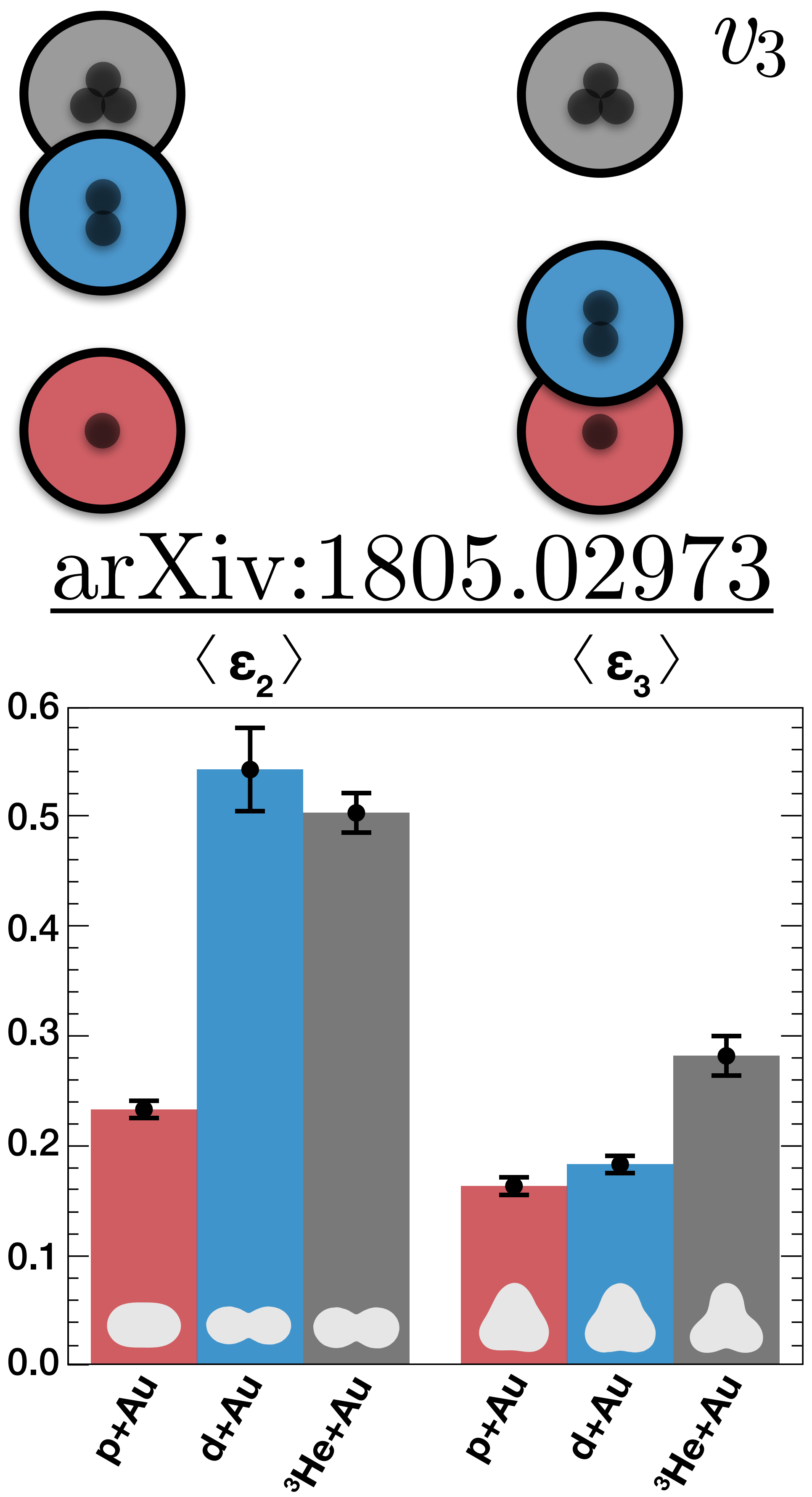


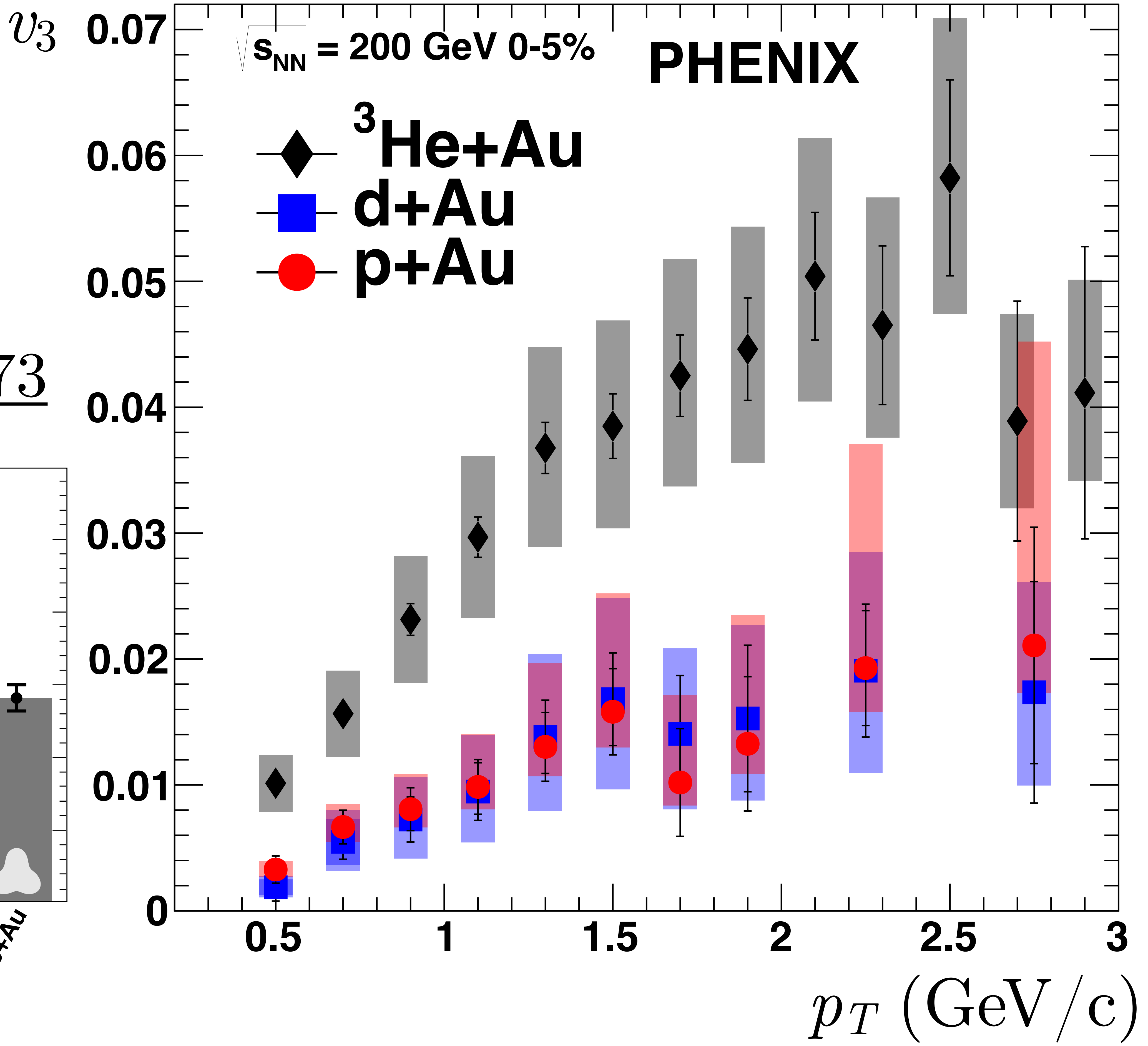
Initial state momentum correlation models predict: $v_n^{p+\mathrm{Au}} > v_n^{d+\mathrm{Au}} > v_n^{^3\mathrm{He+Au}}$

Ruled out as dominant mechanism

$v_n(p_T)$ measurement in small systems



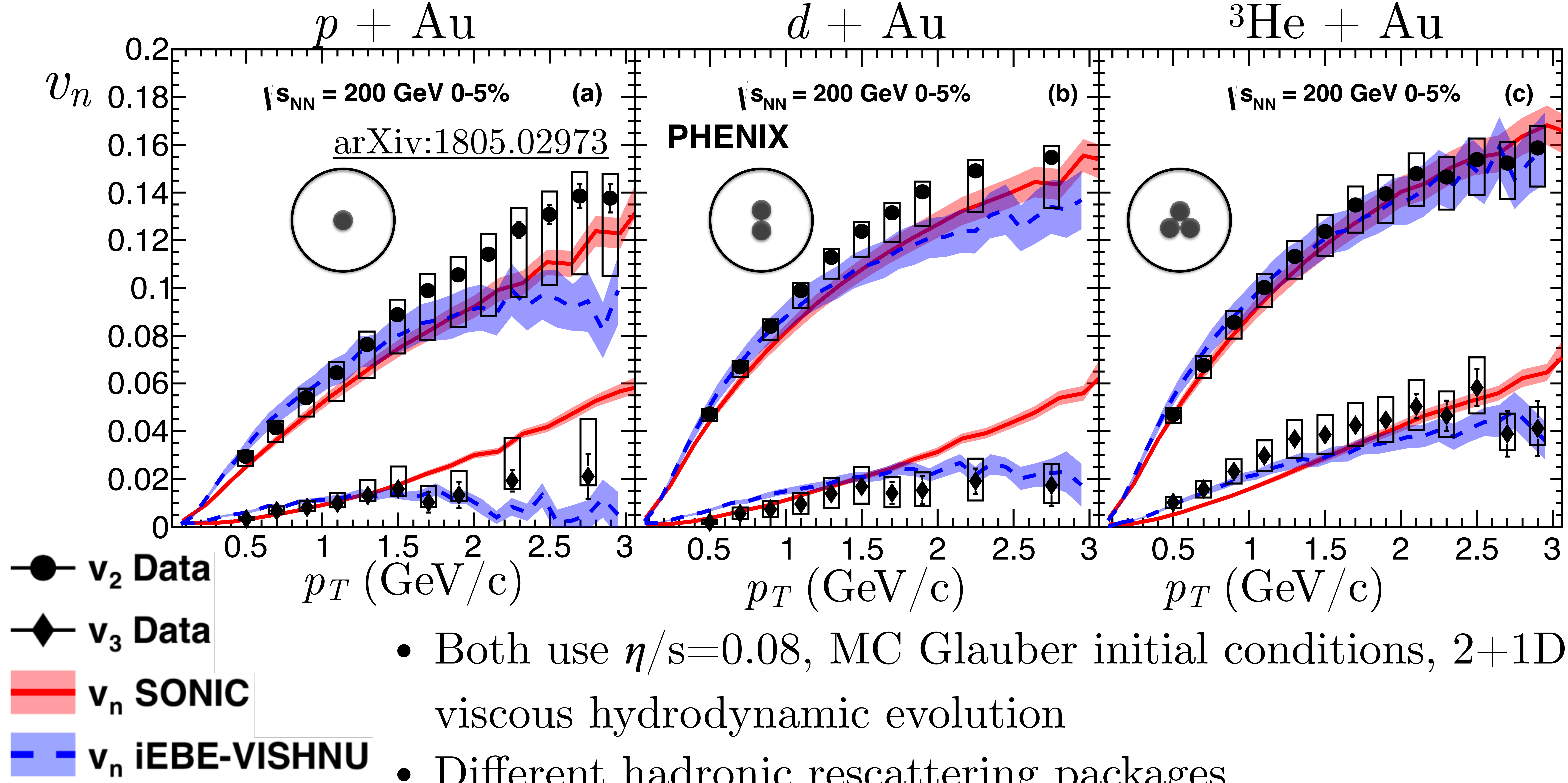




Confirms flow as geometric in origin,

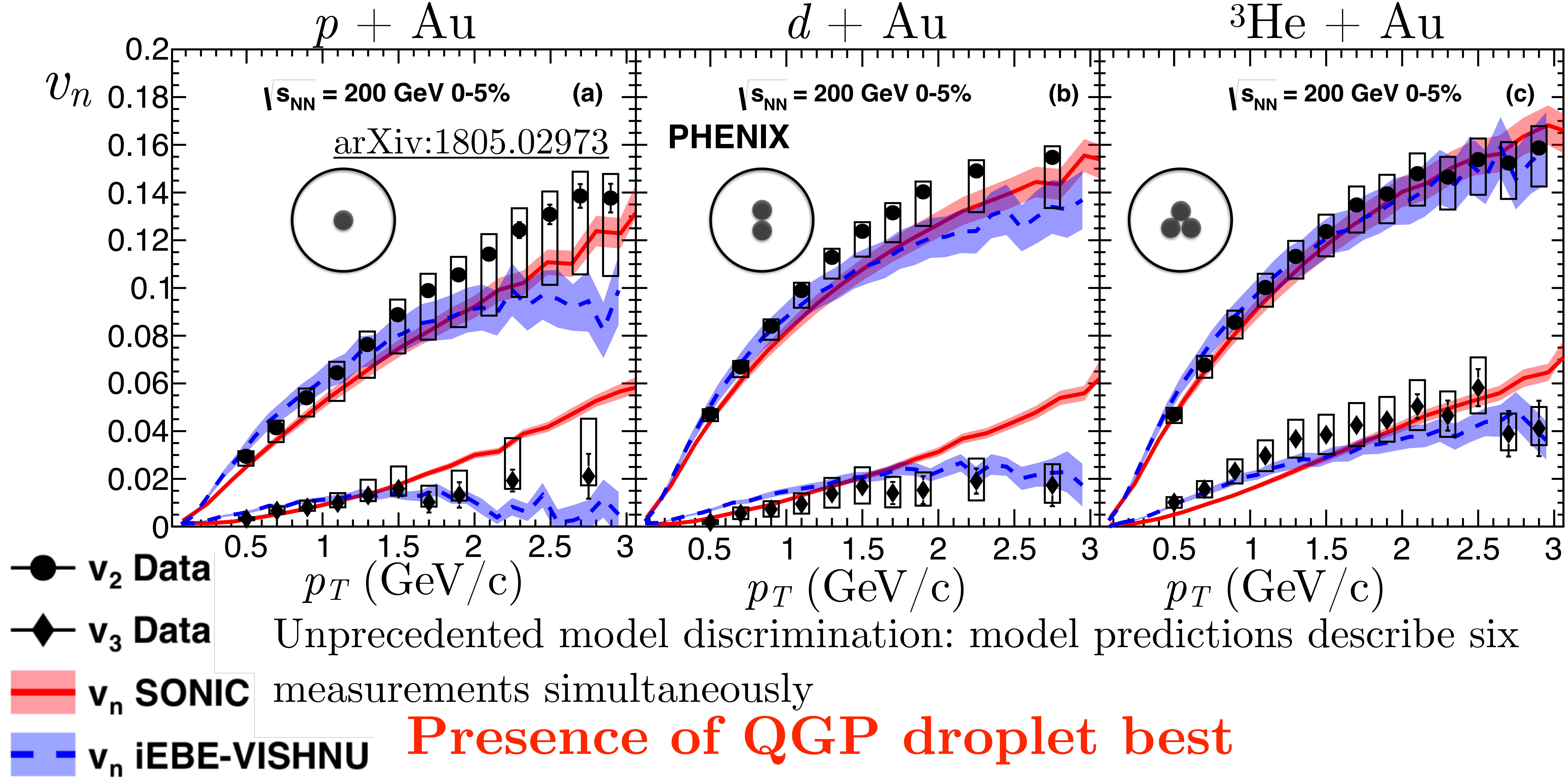
but mechanism driving this is inconclusive

$v_n(p_T)$ from hydrodynamics and data



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

$v_n(p_T)$ from hydrodynamics and data



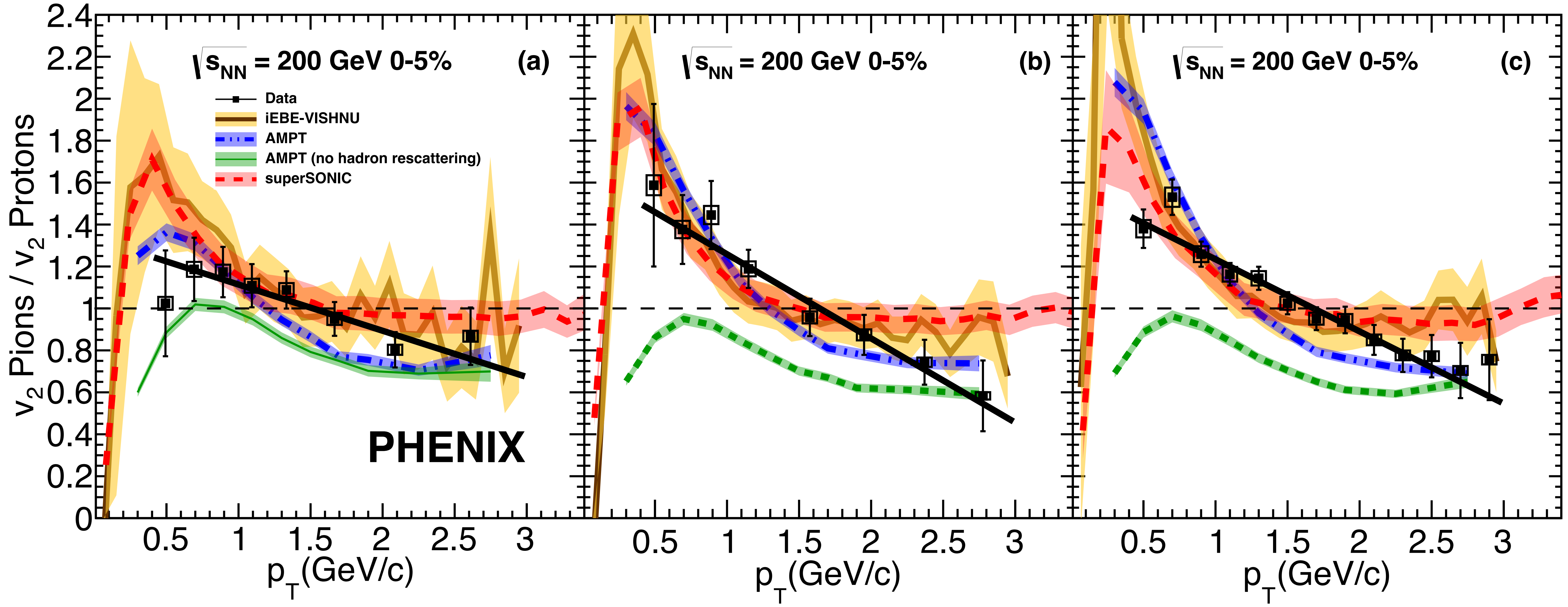
Unprecedented model discrimination: model predictions describe six measurements simultaneously

Presence of QGP droplet best describes measurement

Conclusion

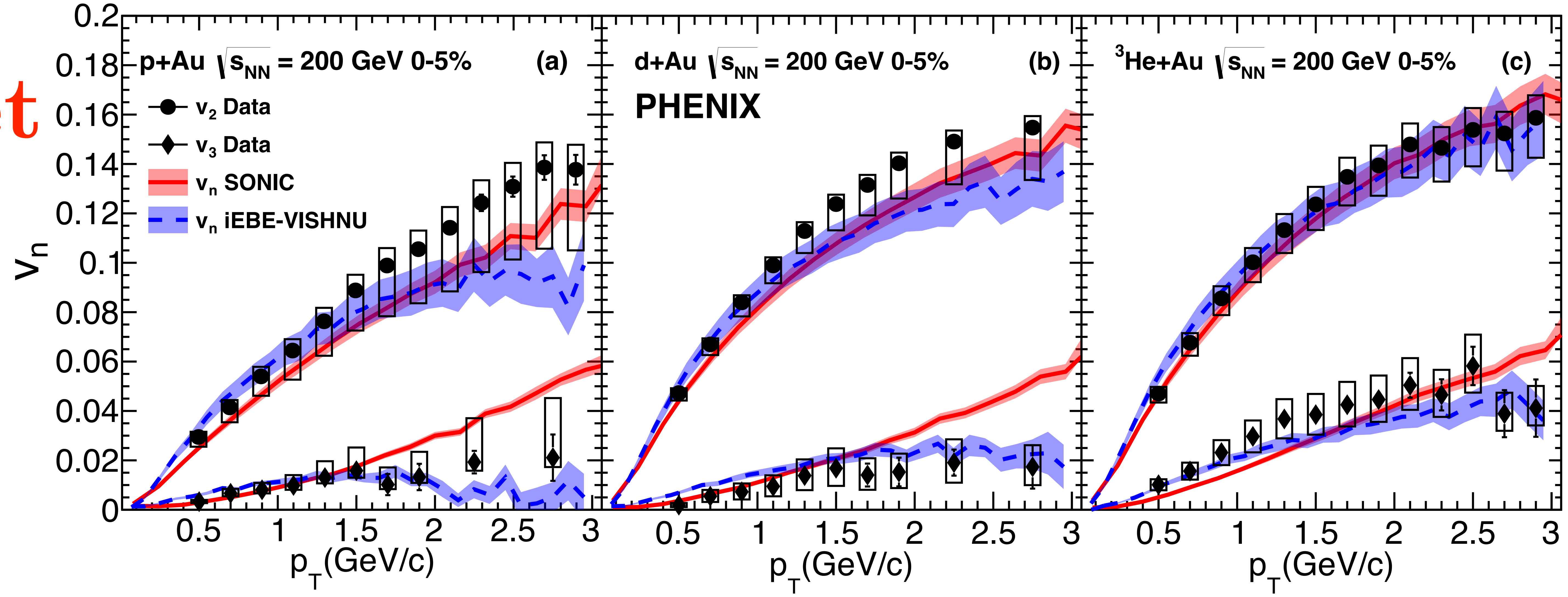
Mass ordering strengthens case for QGP droplets

arXiv:1710.09736



- **Flow is geometric**
- **Measurement best described by QGP droplet**
- **Initial state momentum correlations ruled out as dominant mechanism**

arXiv:1805.02973



Backup

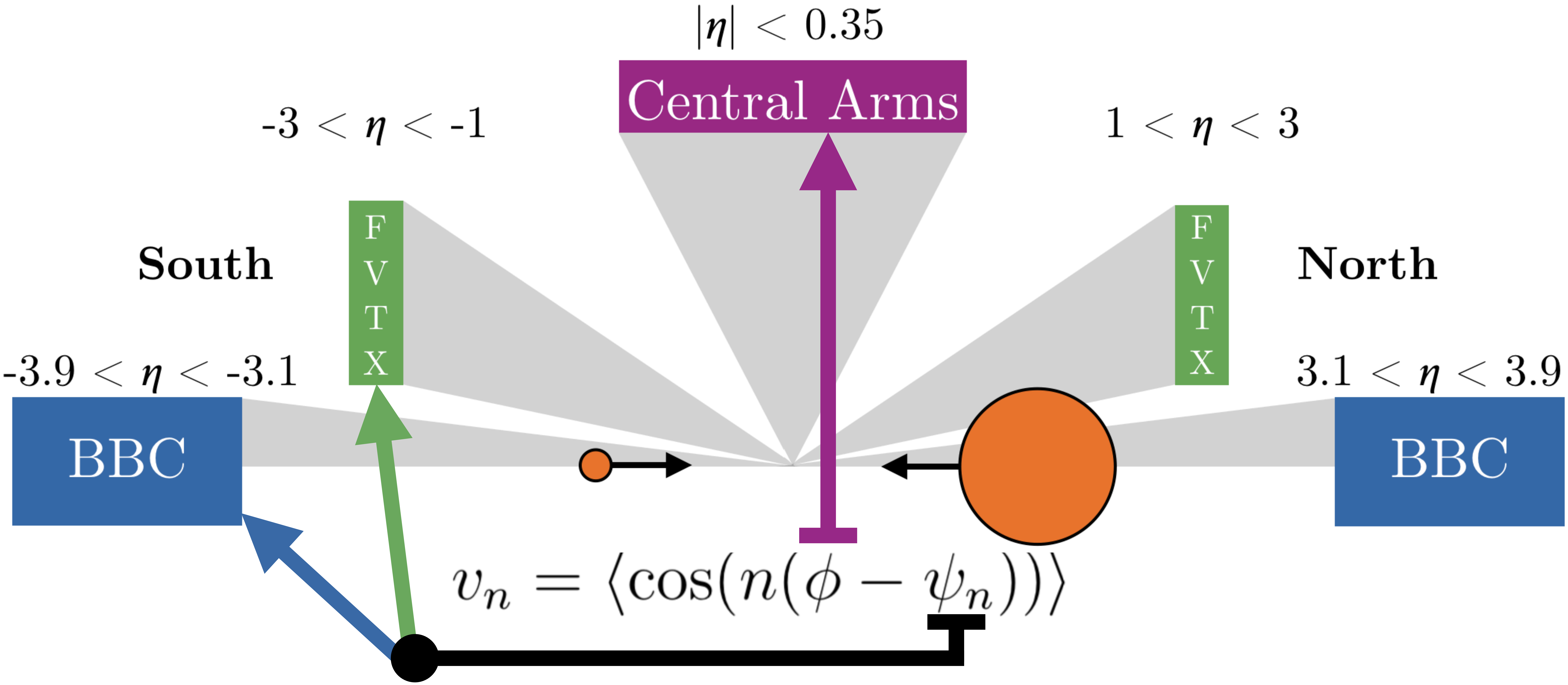
Abstract

Using the extraordinary versatility of RHIC in selecting different colliding species, the PHENIX experiment has collected data in p+Al, p+Au, d+Au, and ^{3}He+Au at 200 GeV center-of-mass energy and conducted a comprehensive set of anisotropic flow measurements. These geometry-controlled experiments provide a unique testing ground for theoretical models that produce azimuthal particle correlations based on initial and/or final state effects.

New results that will be presented at this conference include a complete set of triangular anisotropies of inclusive charged particles and final results on identified pion, kaon and proton $v_2(p_T)$. The v_3 measurements are particularly sensitive to the initial-state fluctuations and the duration of the hot matter stage; the mass-ordered splitting in $v_2(p_T)$ provides information about the role of early-stage collective flow and late-stage hadronic rescattering. Detailed model comparisons with all observables will be discussed.

- Creating small circular, elliptical, and triangular droplets of quark-gluon plasma arXiv:1805.02973
- Measurement of mass-dependent azimuthal anisotropy in central p+Au, d+Au, and ^{3}He+Au collisions at $\sqrt{s_{NN}} = 200$ GeV arXiv:1710.09736

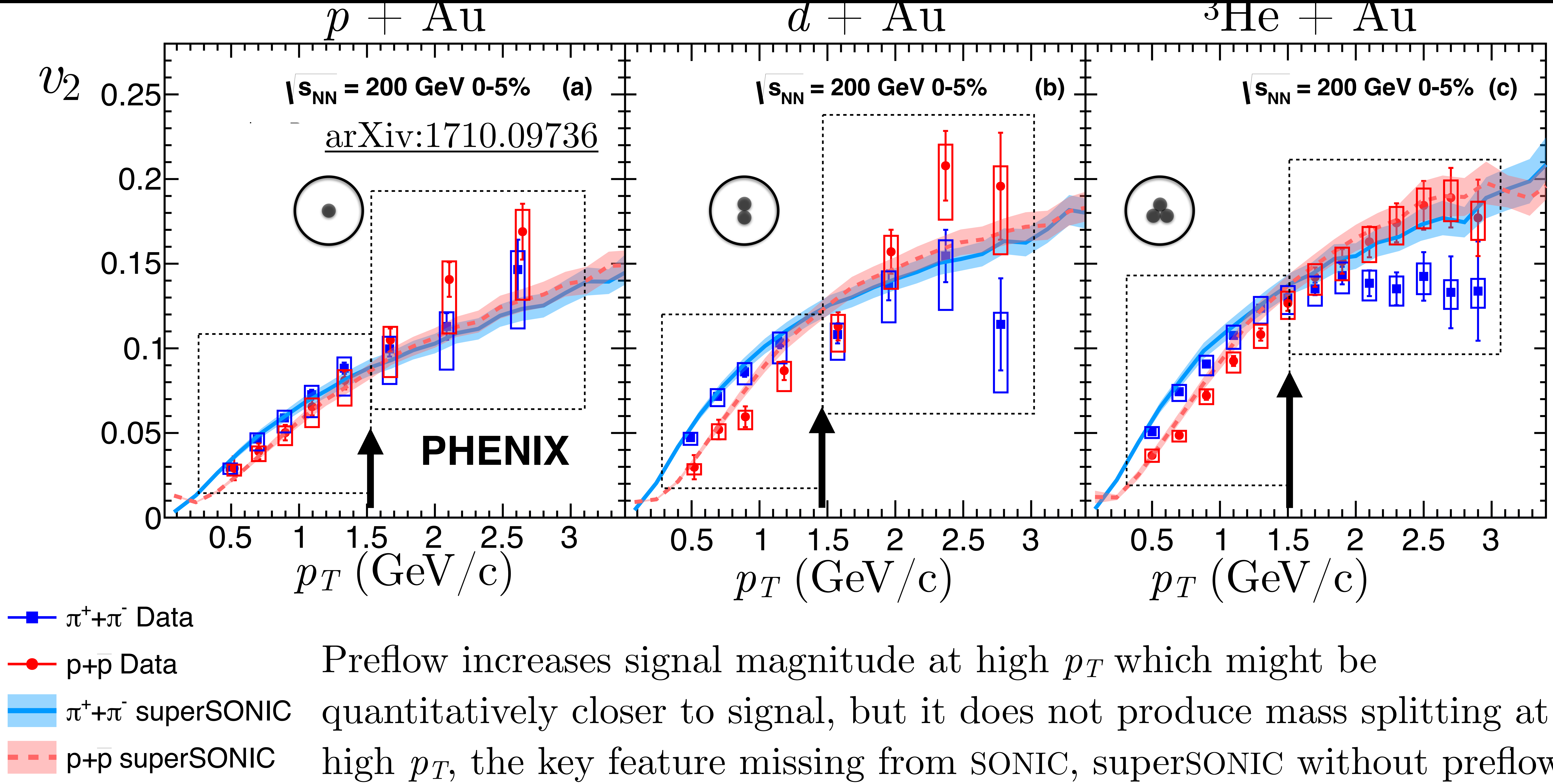
Event plane resolution



$$v_n = \langle \cos(n(\phi - \psi_n)) \rangle$$

$$\mathrm{Res}(\psi_n)^2 = \frac{\langle \cos(n(\psi_n^a - \psi_n^b)) \rangle \langle \cos(n(\psi_n^a - \psi_n^c)) \rangle}{\langle \cos(n(\psi_n^b - \psi_n^c)) \rangle}$$

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

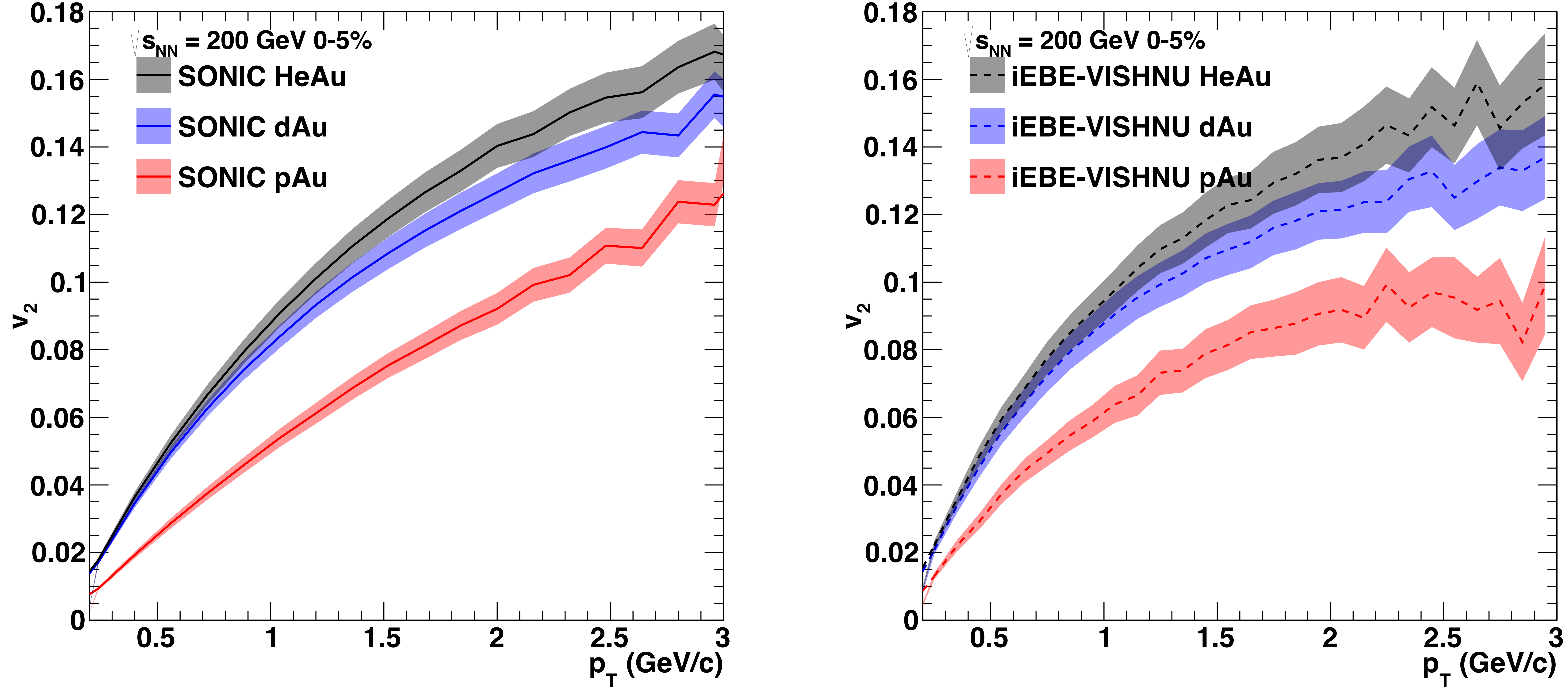


Preflow increases signal magnitude at high p_T which might be quantitatively closer to signal, but it does not produce mass splitting at high p_T, the key feature missing from SONIC, superSONIC without preflow

π and p $v_2(p_T)$: hydrodynamics w/ & w/o rescattering

	p_T [GeV/c]	< 1.5	$\simeq 1.5$	> 1.5
iEBE-VISHNU (rescat)	v_2 ordering	$\pi > p$	$\pi = p$	$\pi = p$
iEBE-VISHNU (no rescat)	v_2 ordering	$\pi > p$	$\pi = p$	$\pi = p$

$v_2(p_T)$ in $p/d/{}^3$He+Au from hydrodynamics



- Both hydrodynamic models predict flow ordering that matches eccentricity ordering: $v_2^{p+\mathrm{Au}} < v_2^{d+\mathrm{Au}} \approx v_2^{^3\mathrm{He+Au}}$

$v_3(p_T)$ in $p/d/^3$He+Au from hydrodynamics

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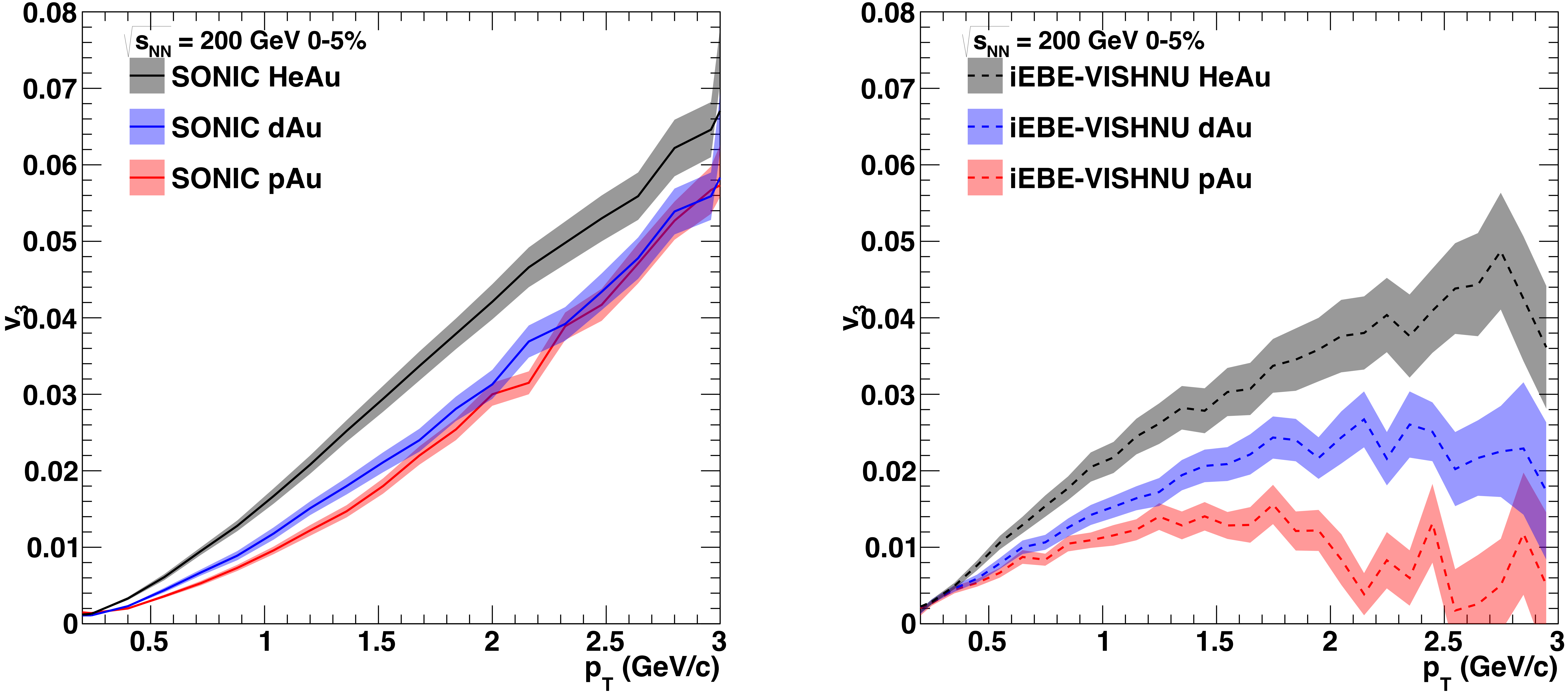
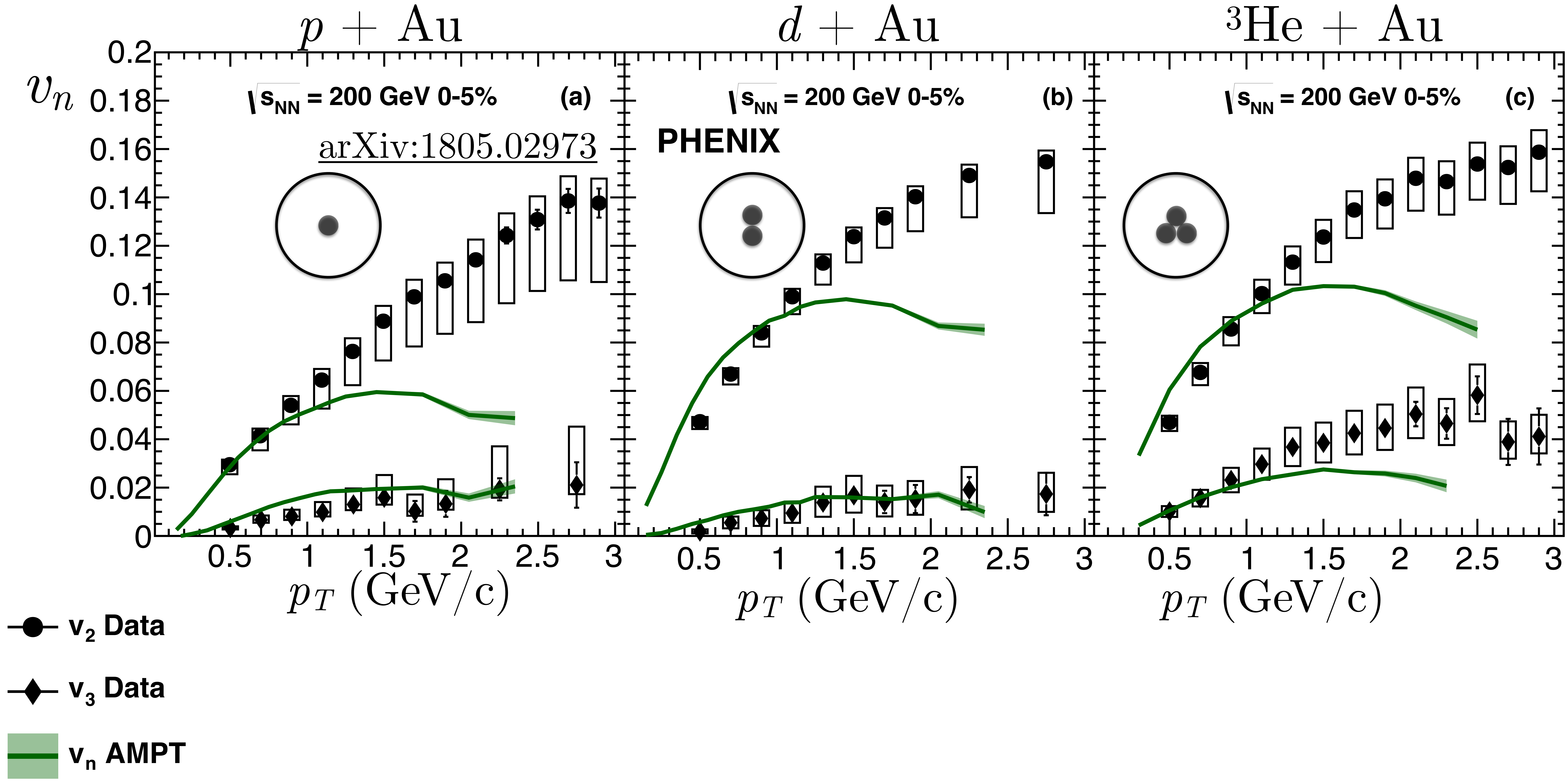


- SONIC flow ordering matches eccentricity ordering: $v_3^{p+\mathrm{Au}} \approx v_3^{d+\mathrm{Au}} < v_3^{^3\mathrm{He+Au}}$
- iEBE-VISHNU does not predict $v_3^{p+\mathrm{Au}} \approx v_3^{d+\mathrm{Au}}$



p + Au
d + Au
3He + Au
vn
√sNN = 200 GeV 0-5%
(a)
(b)
(c)
arXiv:1805.02973
PHENIX
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.5
1
1.5
2
2.5
3
pT (GeV/c)
v2 Data
v3 Data
vn AMPT