PHENIX results on collectivity in small systems

Sylvia Morrow, for the PHENIX collaboration

PRC 96, 064905 (2017)
PRL 120, 062302 (2018)
arXiv:1710.09736, *accepted PRC*
arXiv:1805.02973, submitted *Nature Physics*

What is the origin of collectivity in small systems?

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

Can we turn it off?	Common velocity field?	Geometry-driven flow?

Multiple measurements to test the flow hypothesis

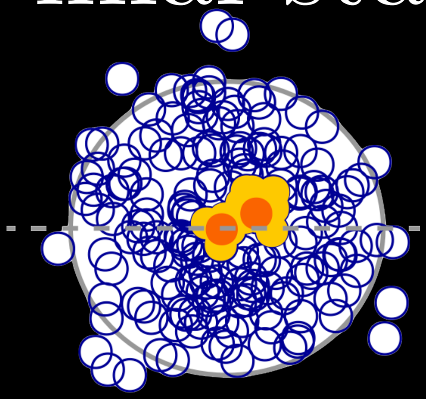
Can we turn it off?

Beam energy scan

S. Morrow

Q How long does a quark-gluon plasma droplet have to last to see final state effects?

$\sqrt{s_{NN}}$ [GeV]	d+Au
200	✓
62.4	✓
39	✓
19.6	✓

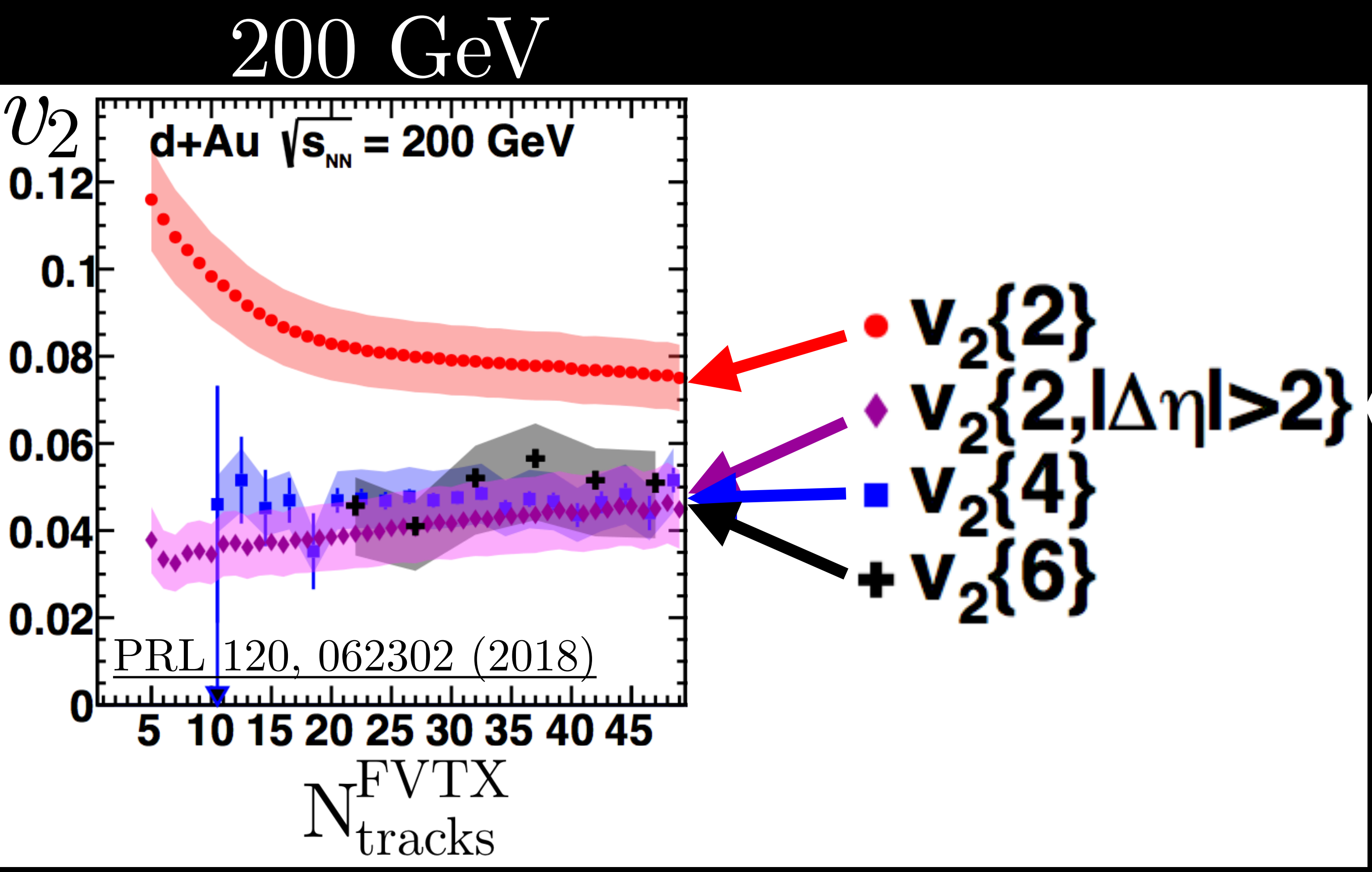


As energy decreases, system spends less time as hot matter

A **Lower limit seems to have not been reached in this BES**

d+Au 200 GeV $v_2(\mathrm{N_{tracks}})$: data

PHENIX
S. Morrow



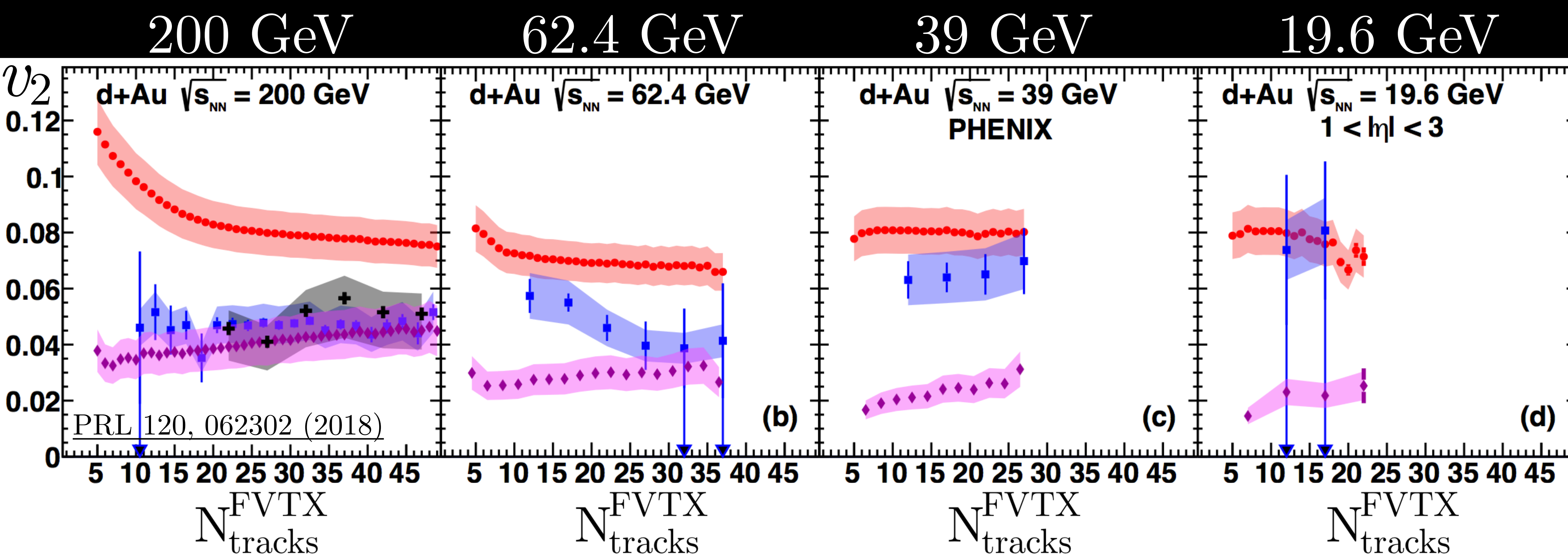
- η separation reduces non-flow contributions
- Different kinematics

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

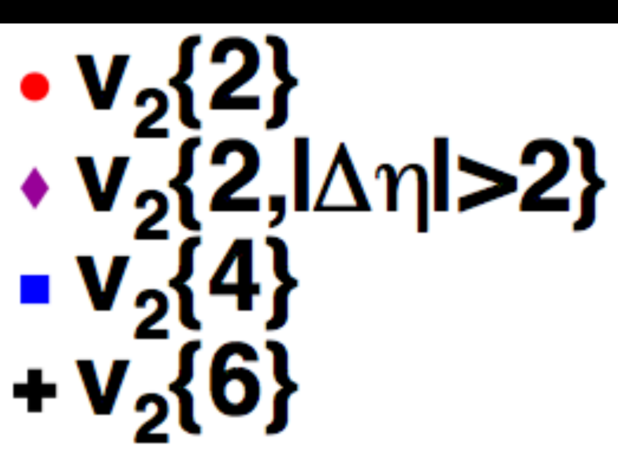
$\therefore$ $v_2\{4\}$ dominated by flow

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

PHENIX
S. Morrow

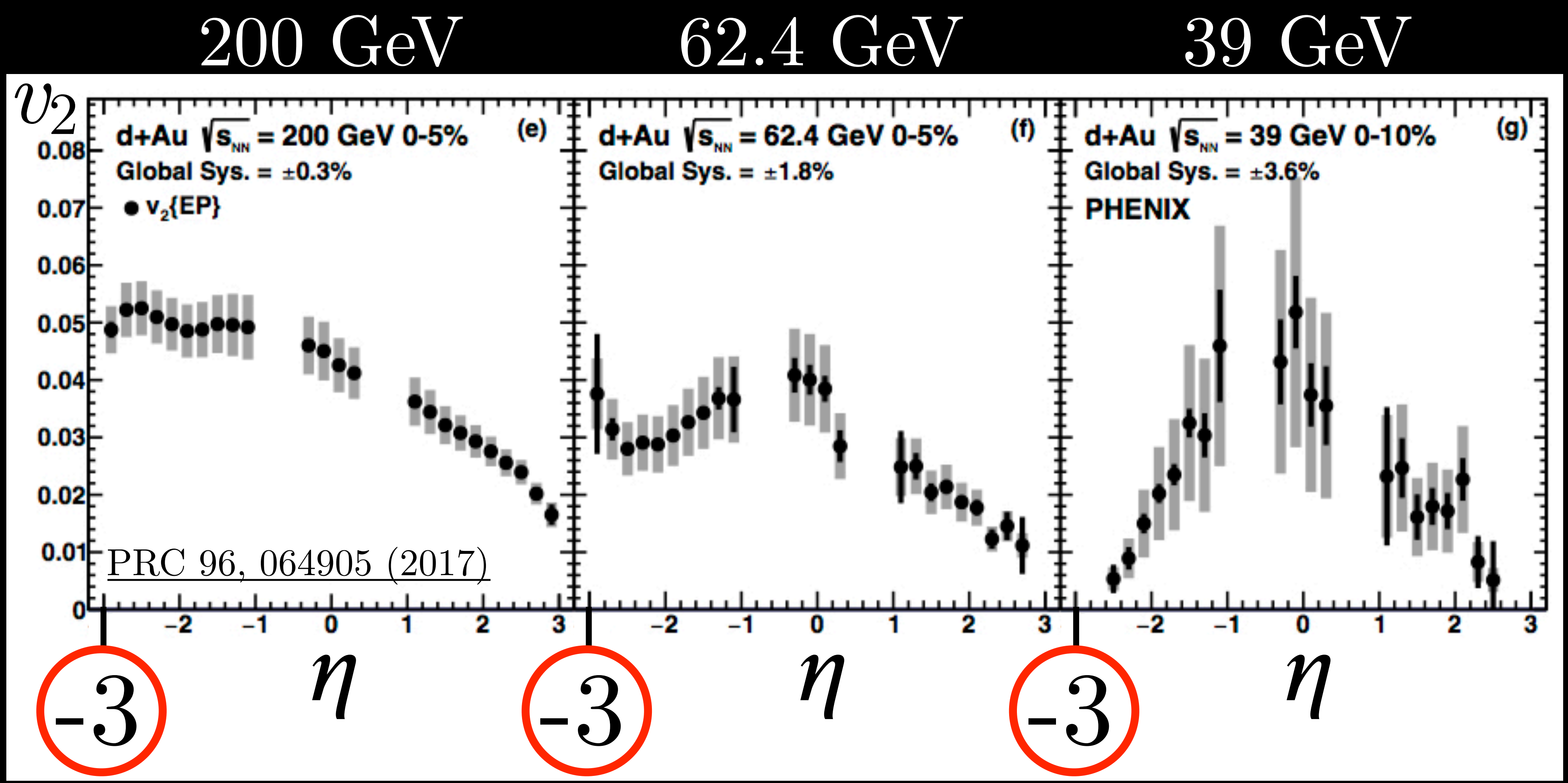


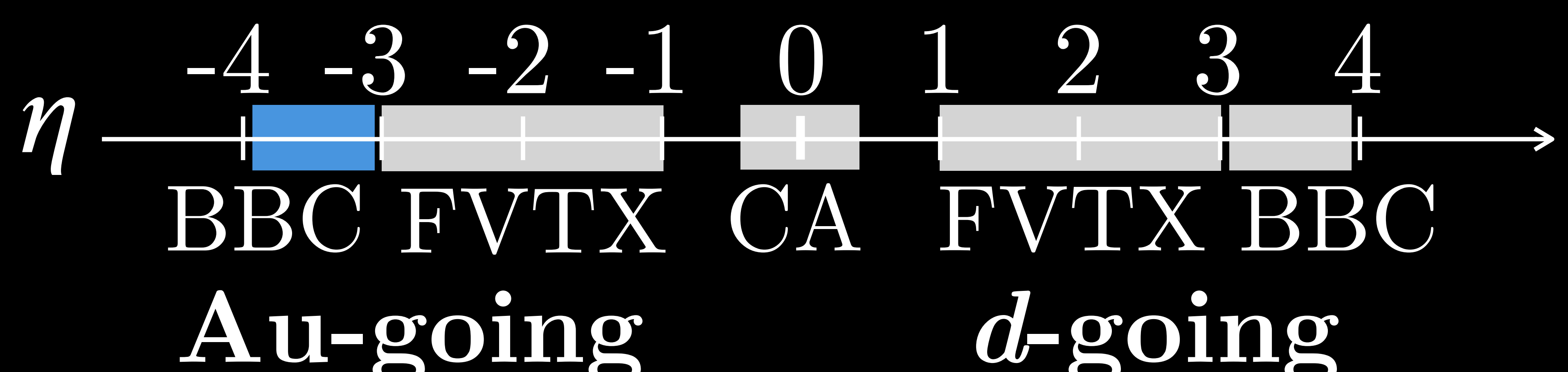
Real $v_2\{4\}$ for all energies



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

d+Au BES $v_2(\eta)$: data

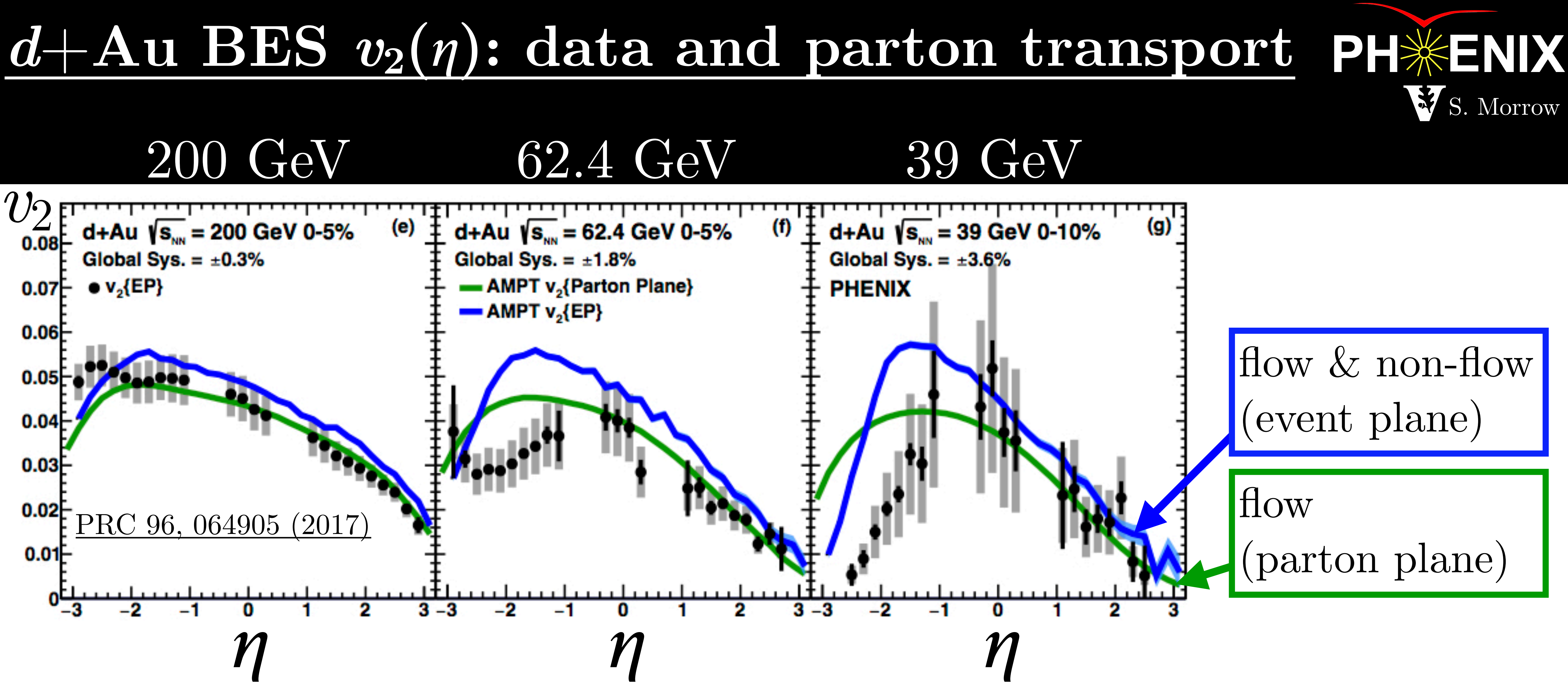




BBCS (Au-going side) used as event plane detector

d+Au BES $v_2(\eta)$: data and parton transport

PHENIX
S. Morrow



- AMPT replicates asymmetric shape
- For lower energies at $\eta < 0$, EP crosses parton plane: non-flow decreases signal magnitude

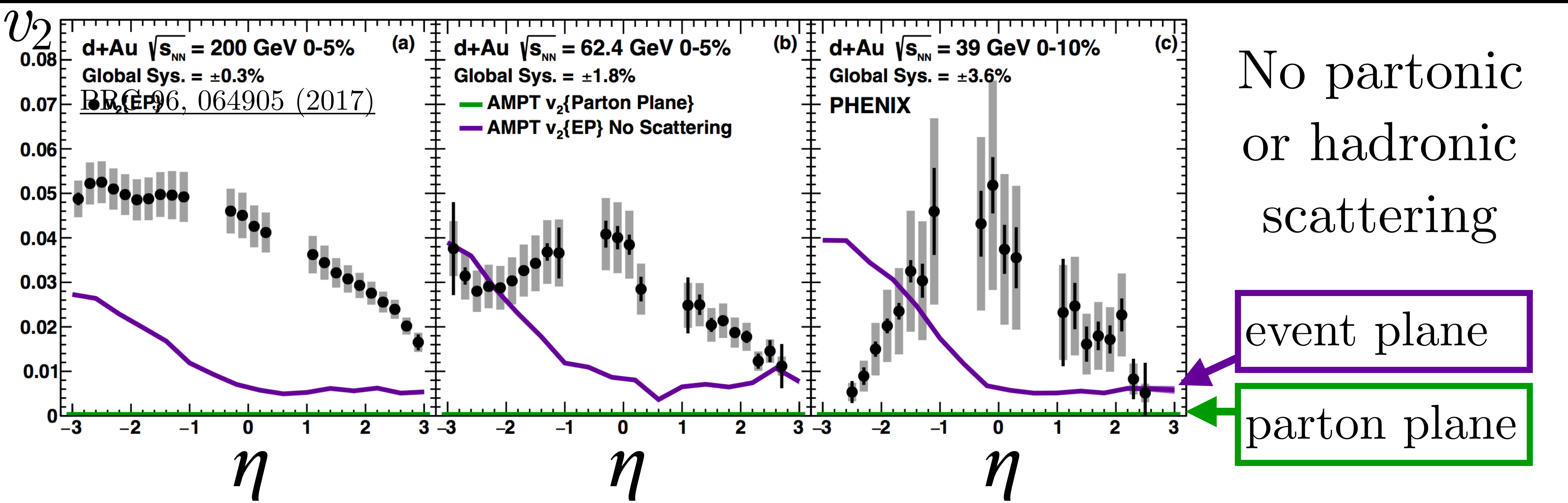
parton cross section: 0.75 mb

d+Au BES $v_2(\eta)$: data and parton transport

PHENIX

S. Morrow

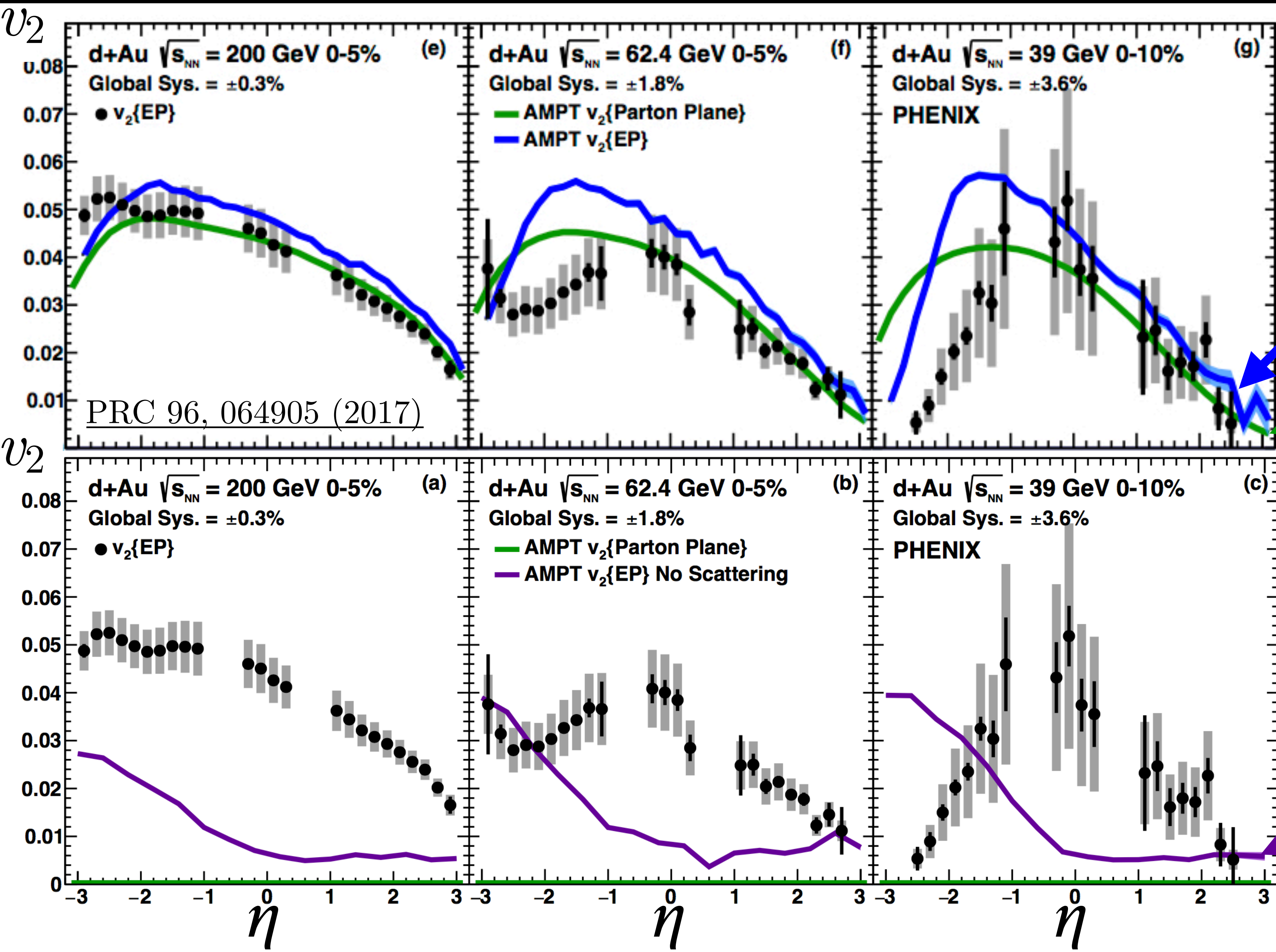
200 GeV 62.4 GeV 39 GeV



- Parton plane gives $v_2 = 0$, consistent with expectations
- Event plane has signal (larger for $\eta < 0$)

d+Au BES $v_2(\eta)$: role of nonflow

200 GeV | 62.4 GeV | 39 GeV



with scattering

flow & nonflow (event plane)

flow (parton plane)

without scattering

nonflow (event plane)

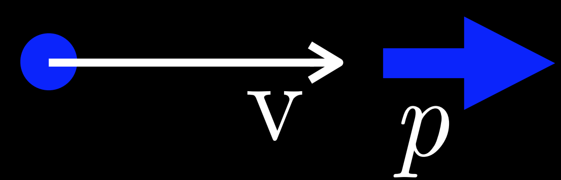
Can't simply add flow (**green**) and non-flow (**purple**) to get flow & non-flow combination (**blue**)

Common velocity field?

Identified particles

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

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



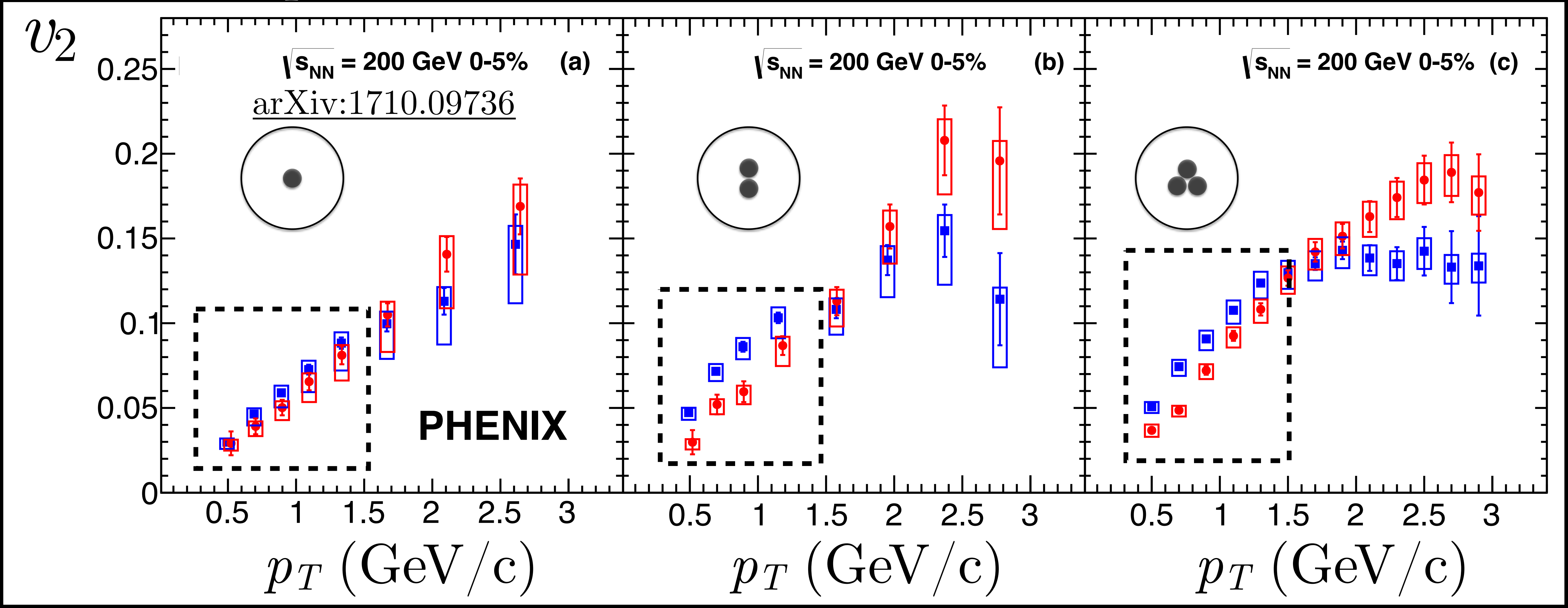
p mass = 938 MeV/c

A **Perhaps — alternative explanations exist**

π and p $v_2(p_T)$: data

S. Morrow

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

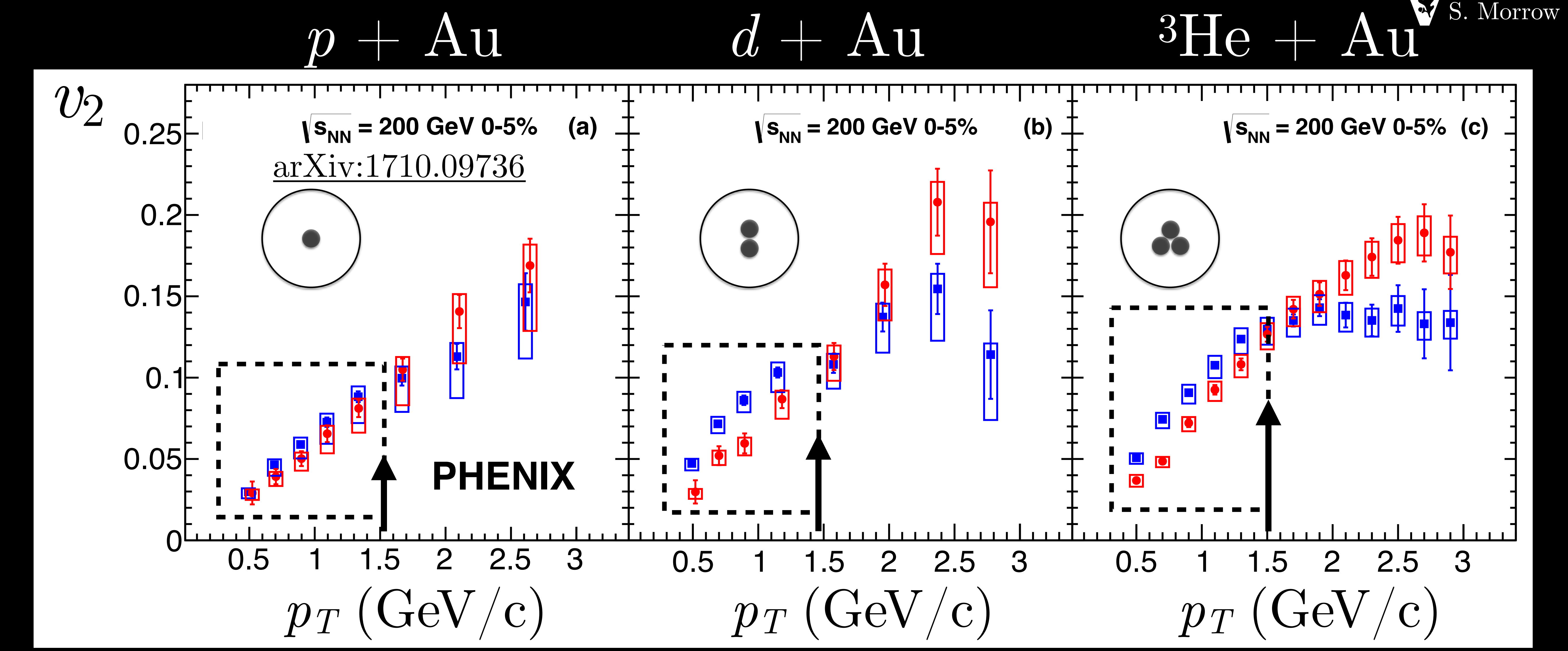


p_T [GeV/c]	< 1.5
v_2 ordering	$\pi > p$

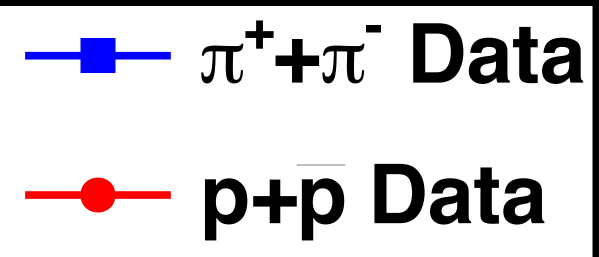
$\pi^+ + \pi^-$ Data
$p + \bar{p}$ Data

π and p $v_2(p_T)$: data

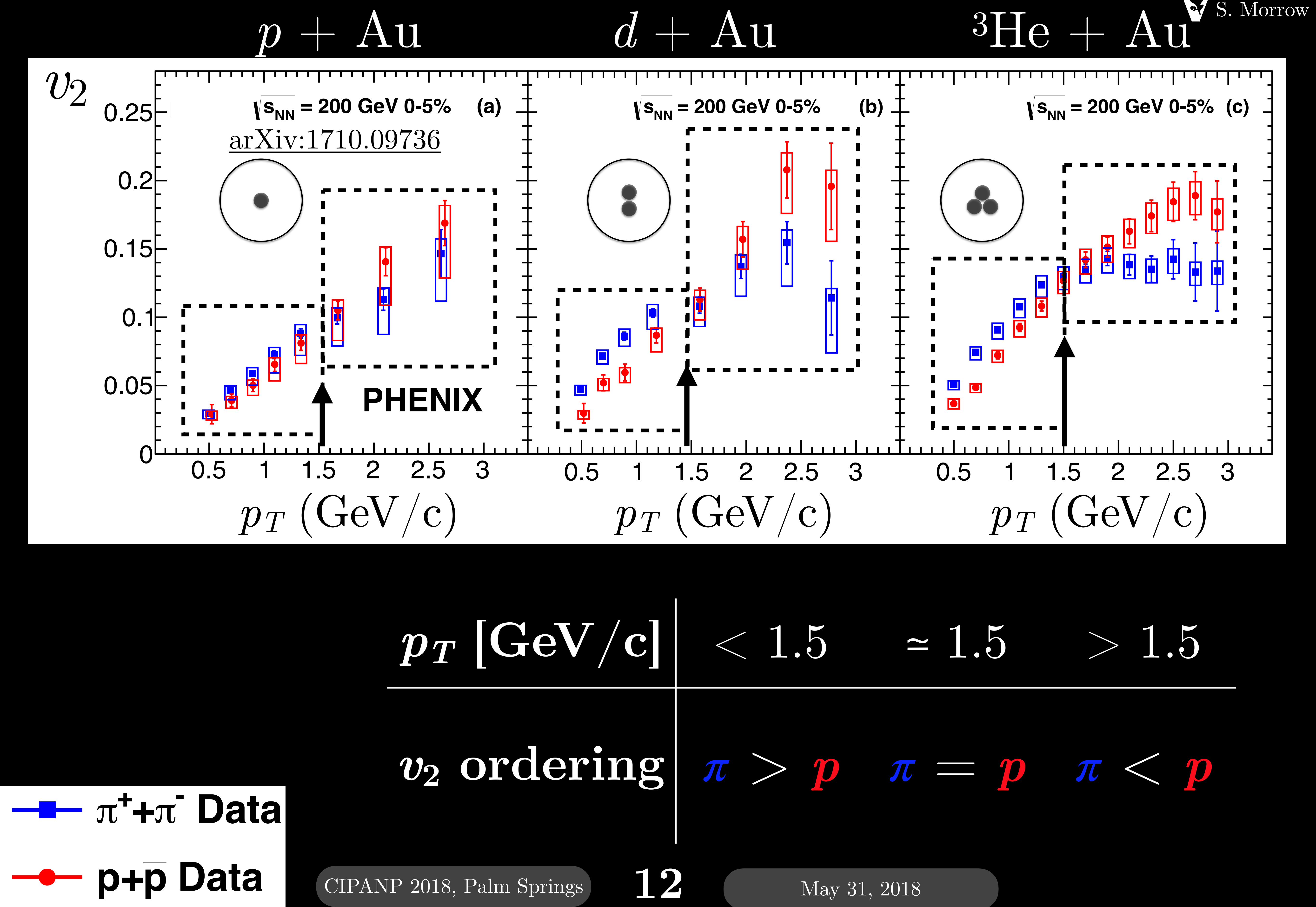
S. Morrow



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

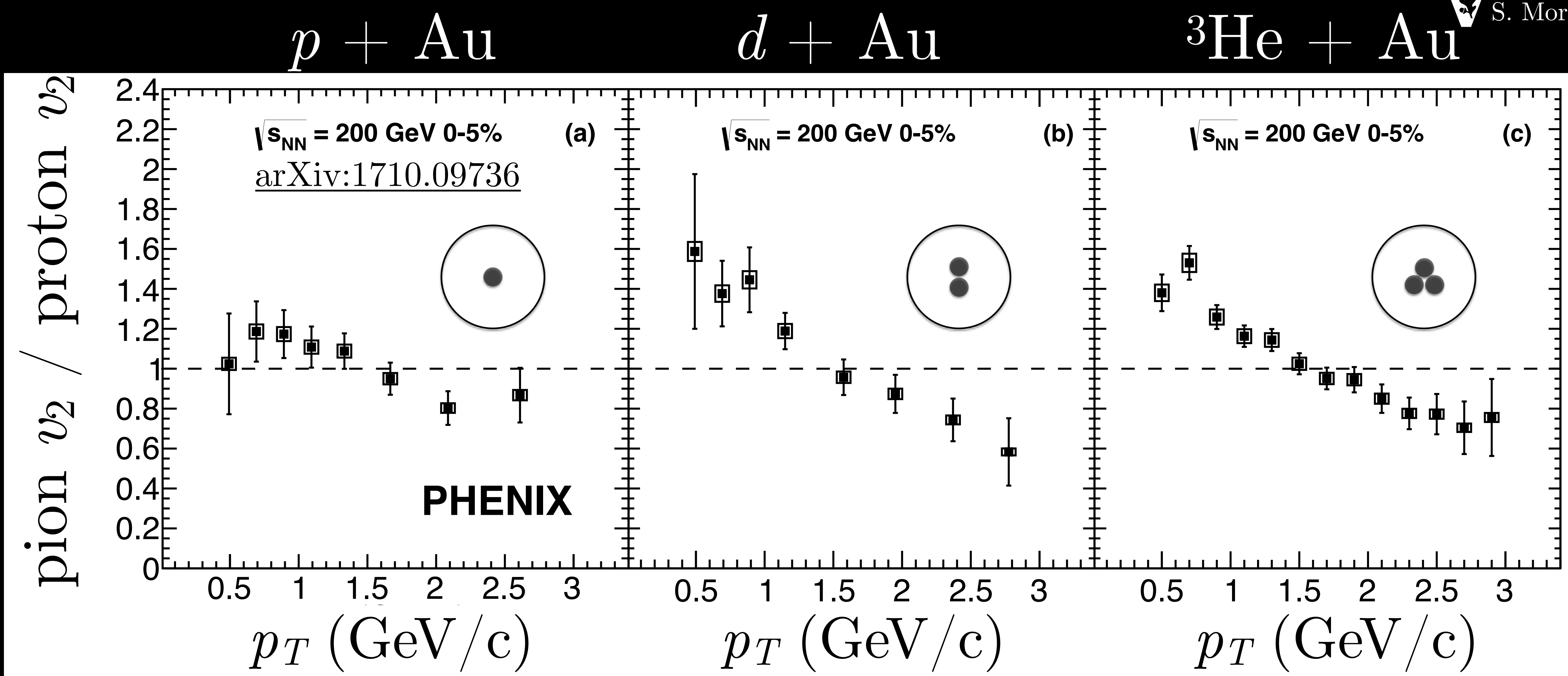


π and p $v_2(p_T)$: data



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

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

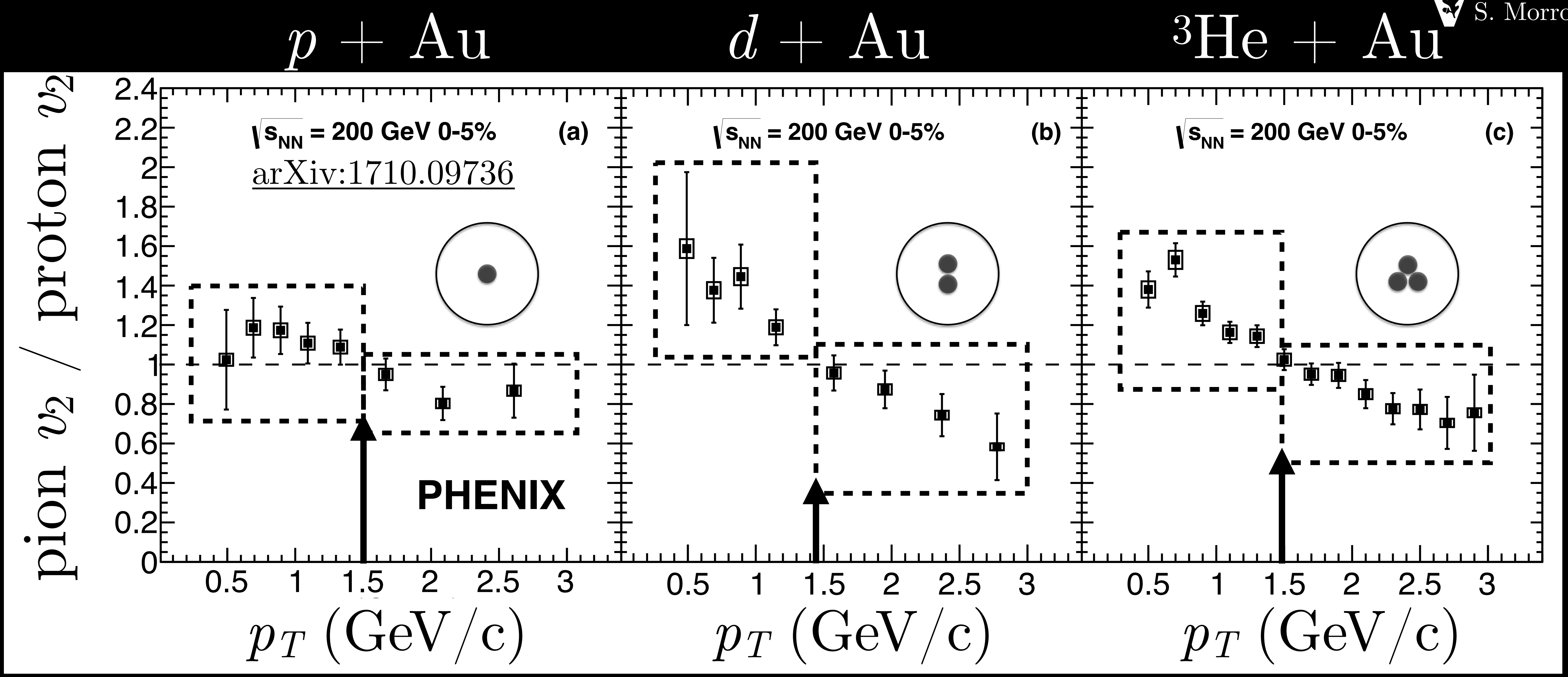


Ratio of pion $v_2(p_T)$ to proton $v_2(p_T)$ — some uncertainty cancels

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

PHENIX

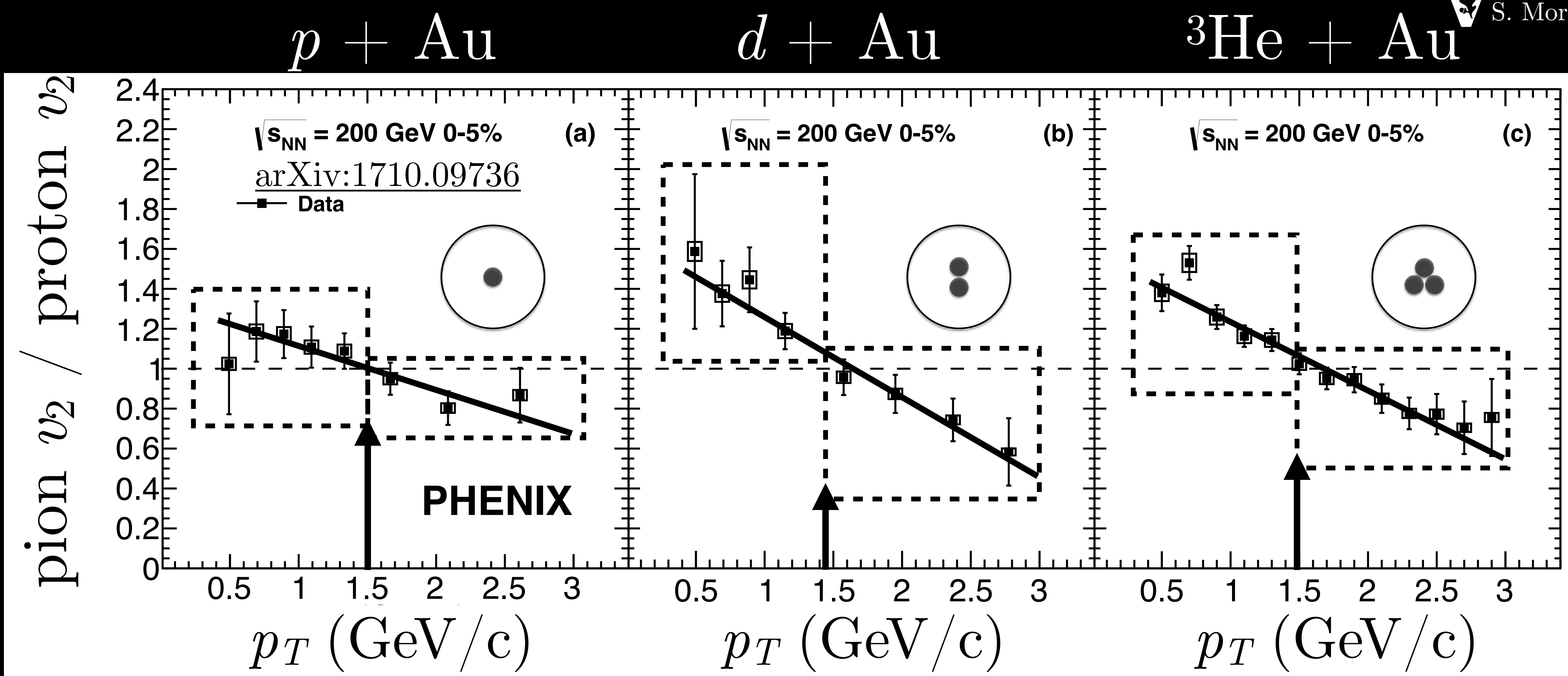
S. Morrow



p_T [GeV/c]	< 1.5	$\simeq 1.5$	> 1.5
v_2 ordering	$\pi > p$	$\pi = p$	$\pi < p$
ratio	> 1	1	< 1

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

PHENIX
S. Morrow



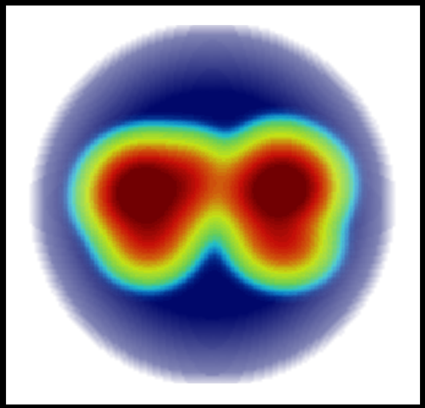
Slope quantifies amplitude of mass splitting

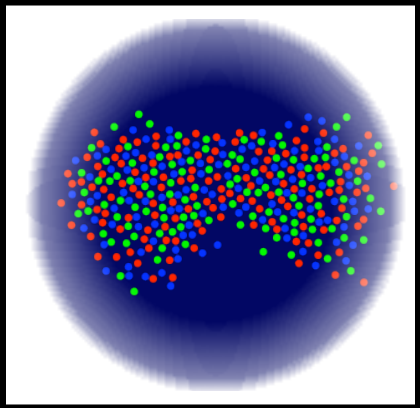
p_T [GeV/c]	< 1.5	$\simeq 1.5$	> 1.5
v_2 ordering	$\pi > p$	$\pi = p$	$\pi < p$
ratio	> 1	1	< 1

Two model formalisms

	Hydrodynamic	Parton transport
	SONIC	**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





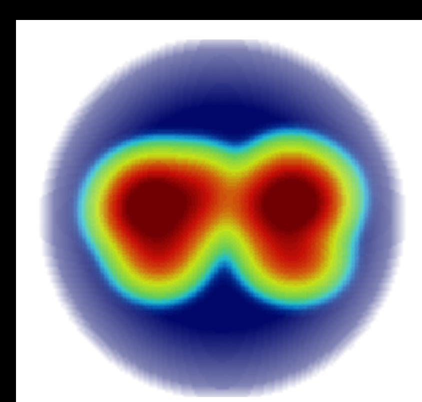
Microscopic

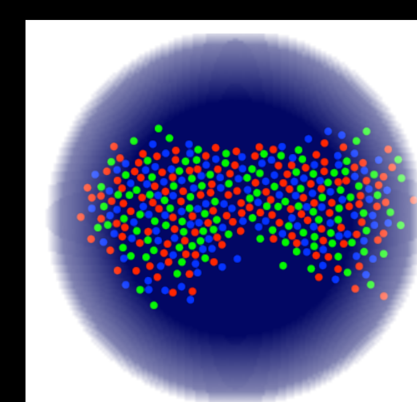
Two model formalisms

S. Morrow

	Hydrodynamic	Parton transport
	SONIC	**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

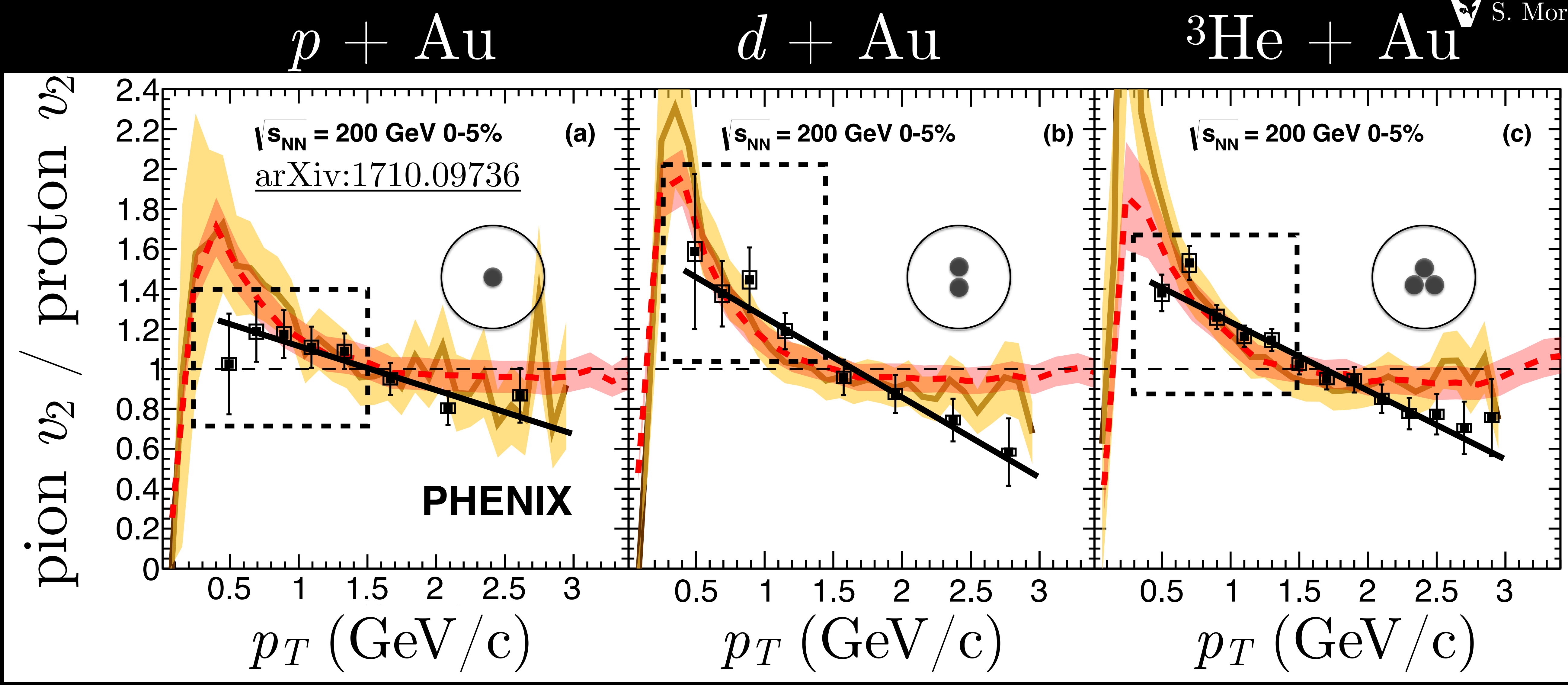
Macroscopic





Microscopic

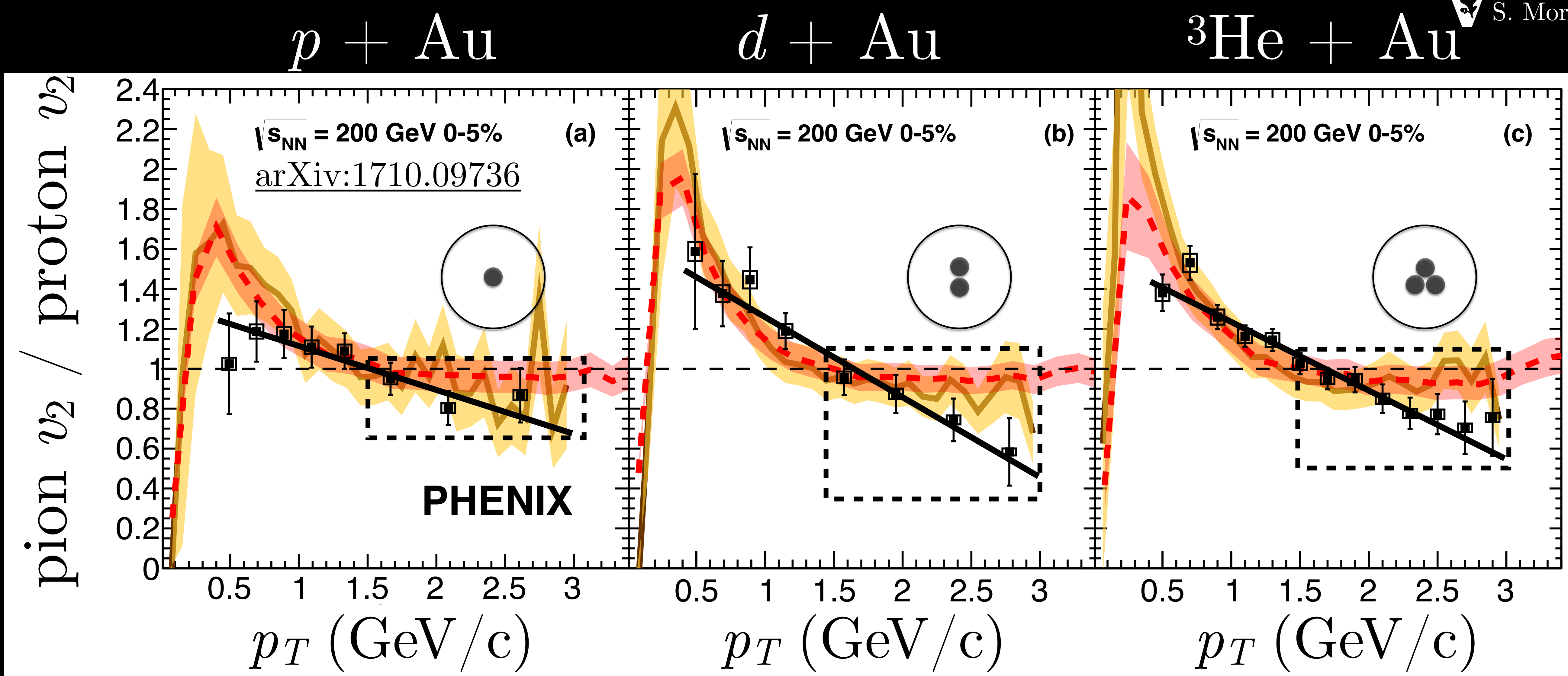
$v_2(p_T)$ pion/proton ratio in small systems



Low p_T is well-described

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

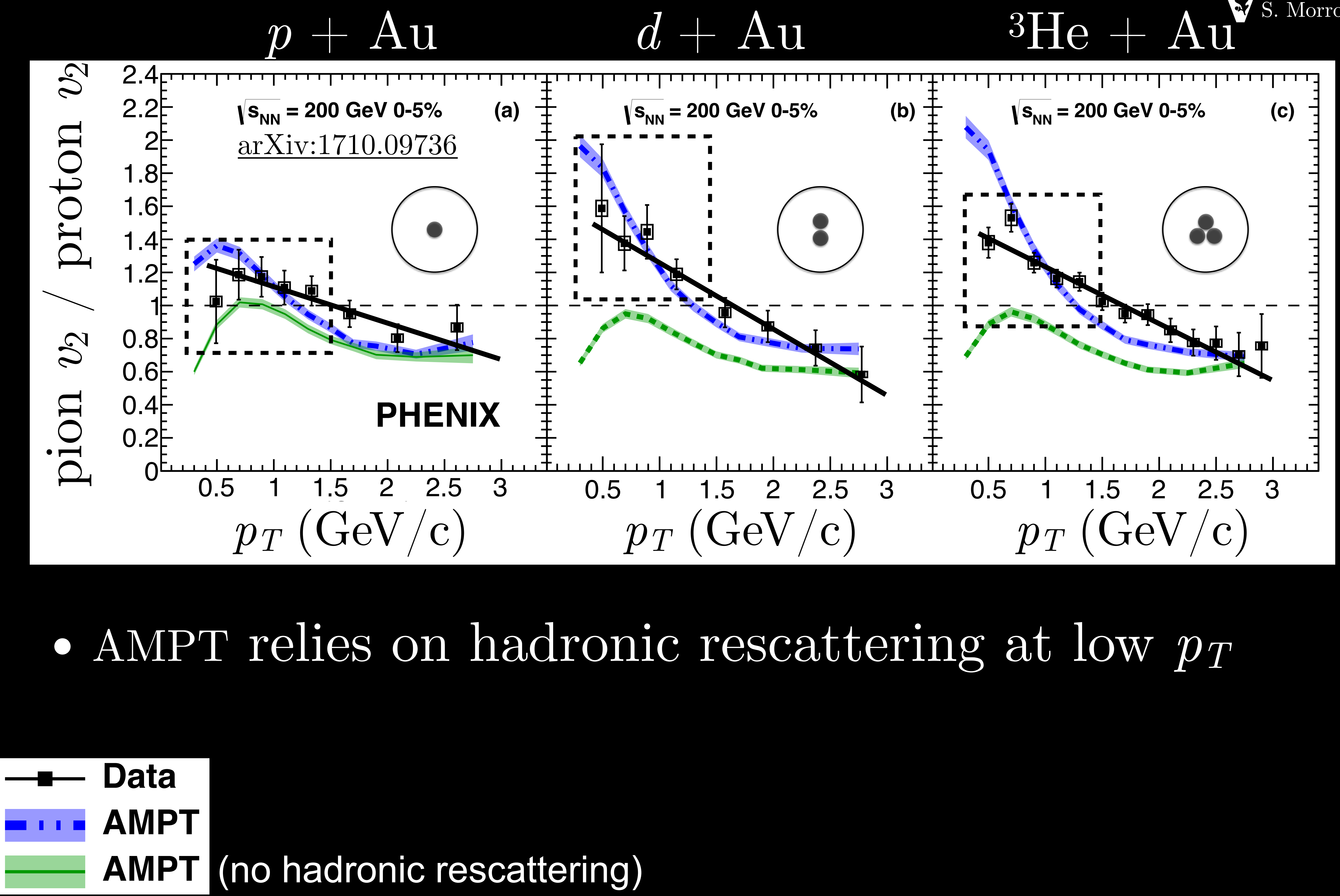
PHENIX
S. Morrow



Low p_T is well-described

Misses slope at high p_T

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



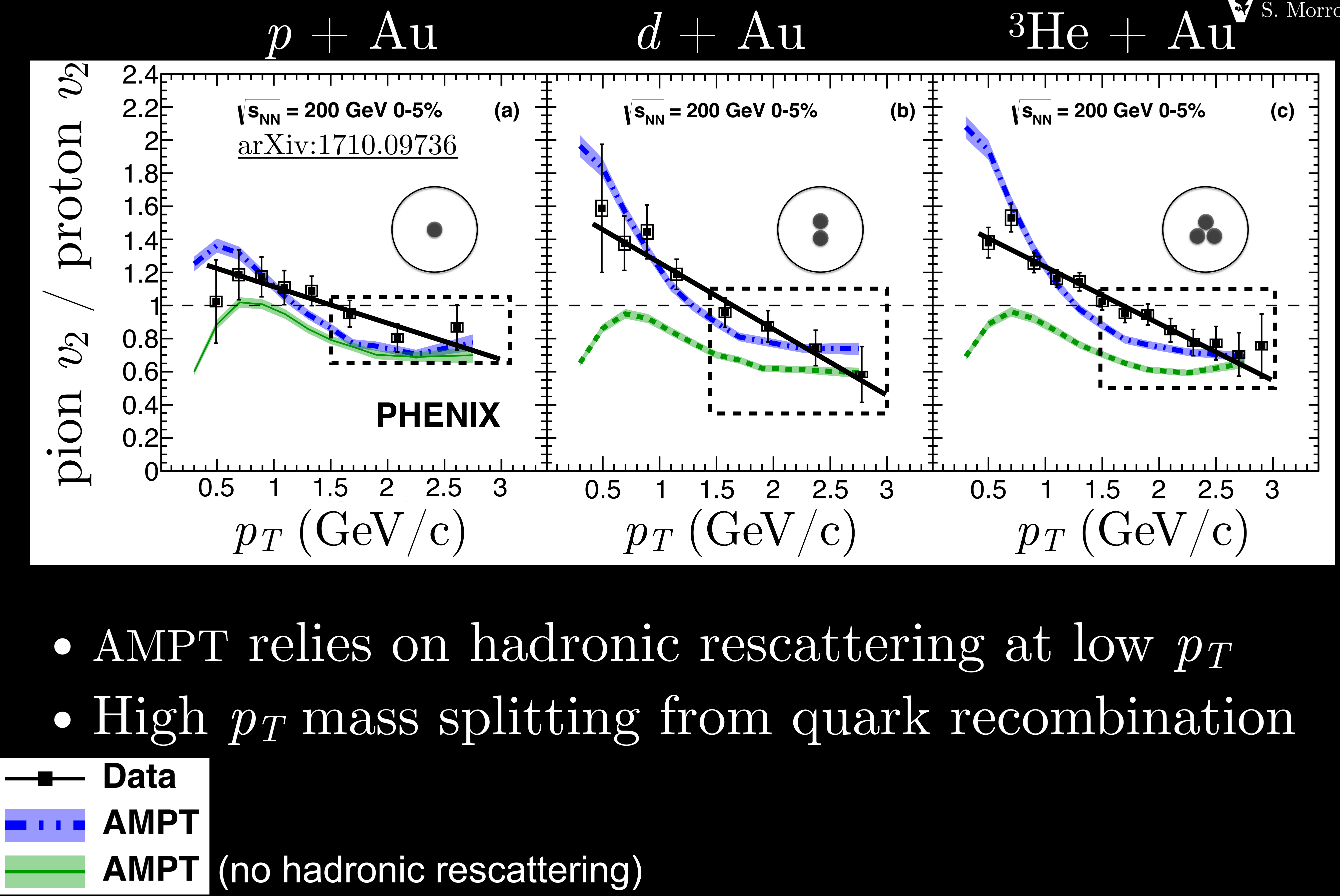
(no hadronic rescattering)

- AMPT relies on hadronic rescattering at low p_T

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

PHENIX

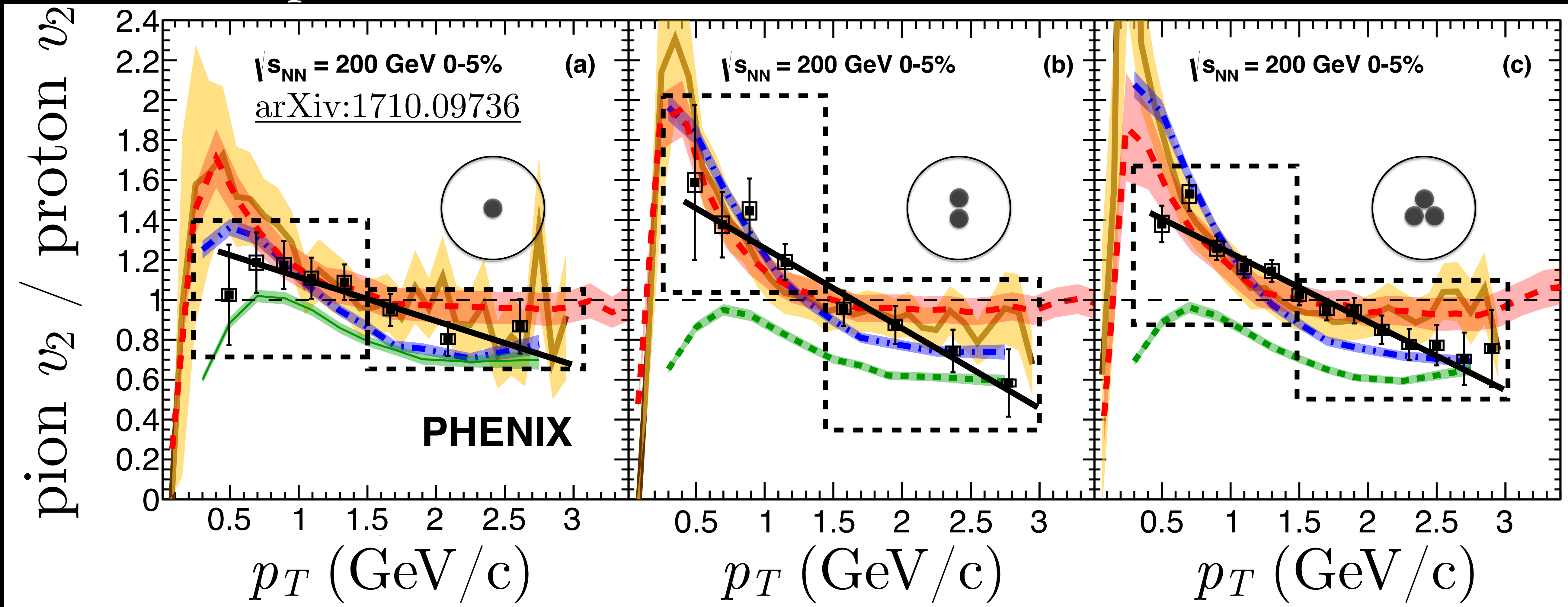
S. Morrow



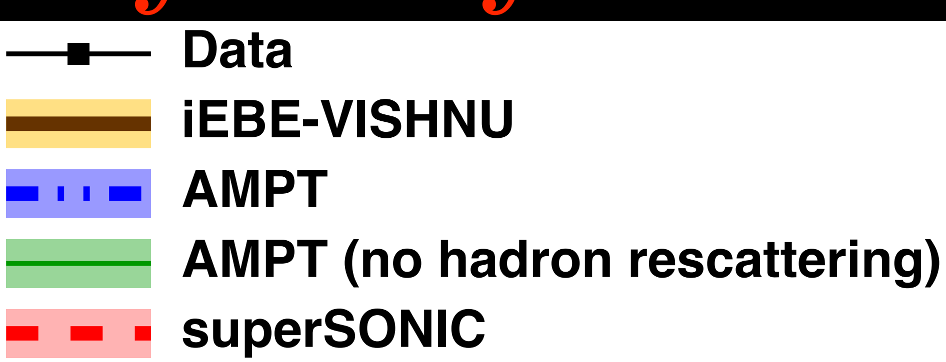
- AMPT relies on hadronic rescattering at low p_T
- High p_T mass splitting from quark recombination

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

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



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

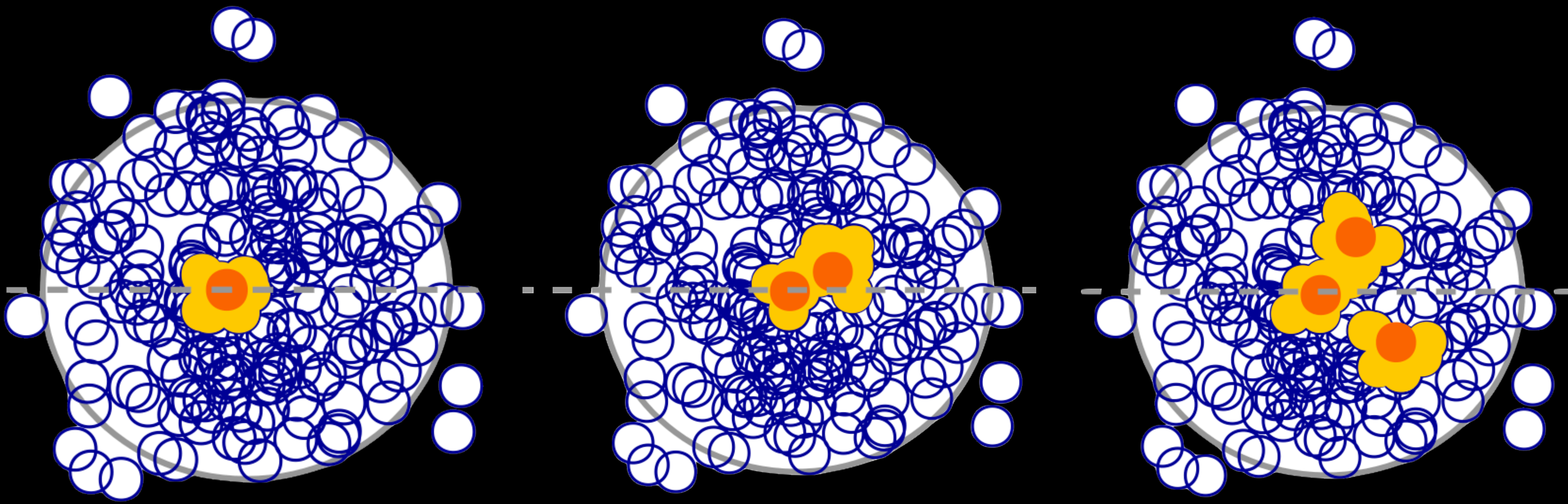


Geometry-driven flow?

Geometry scan

PHENIX
S. Morrow

Q Are final state momentum correlations driven by initial state geometry?



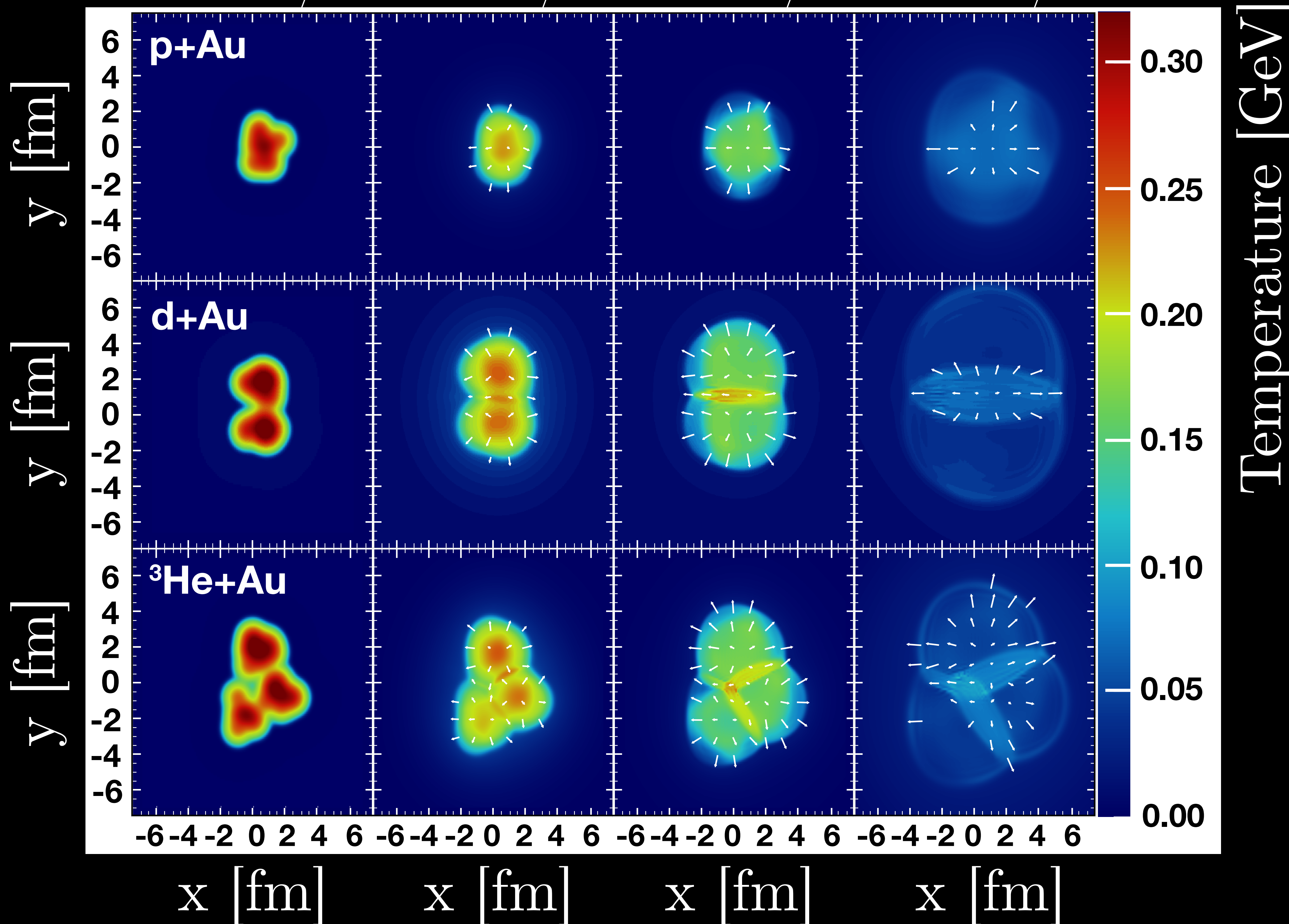
A **Strong evidence indicating YES!**

Hydrodynamic description

PHENIX
S. Morrow

SONIC evolution

$t =$ 1.0 fm/c 1.7 fm/c 3.2 fm/c 4.5 fm/c

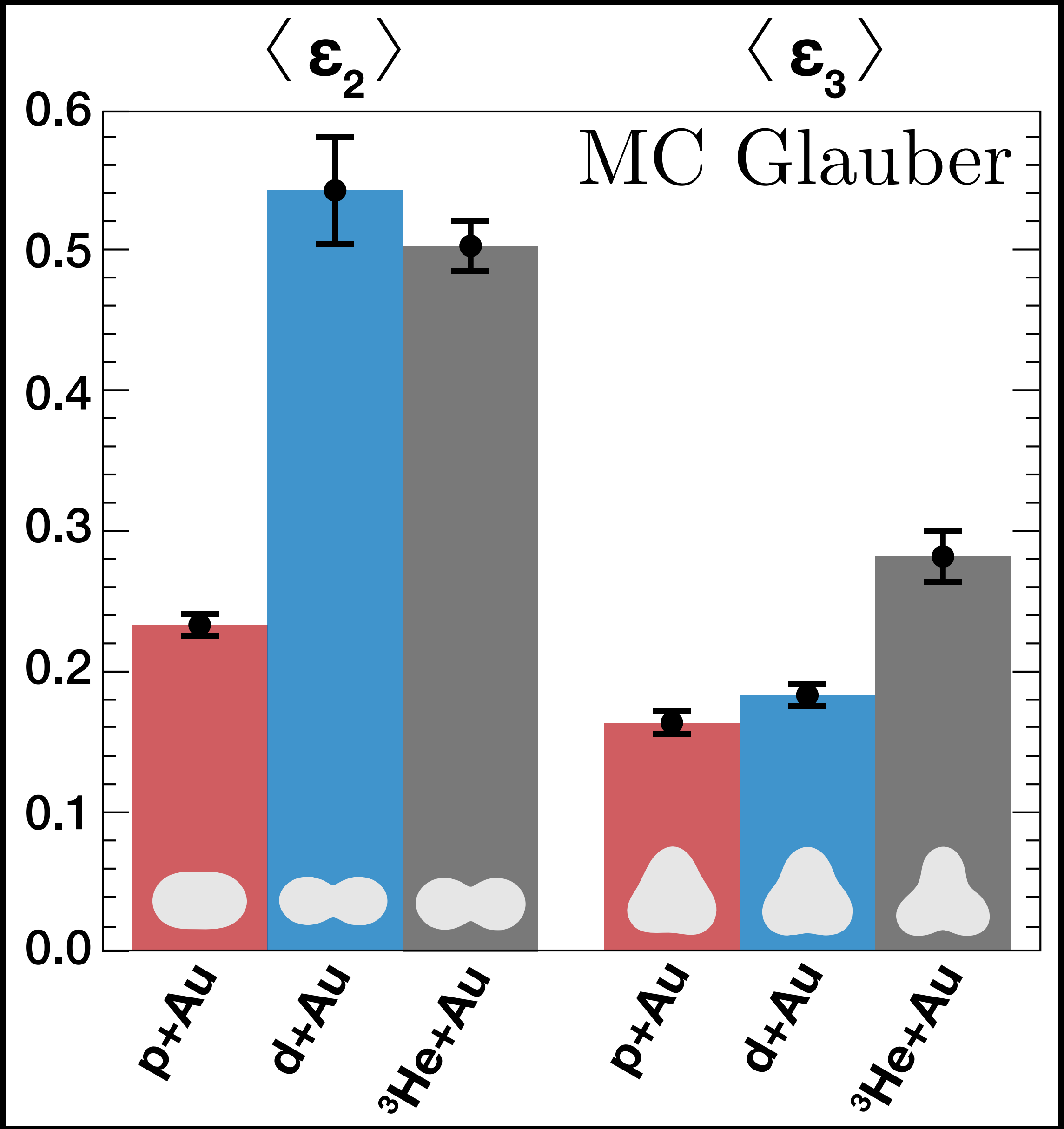


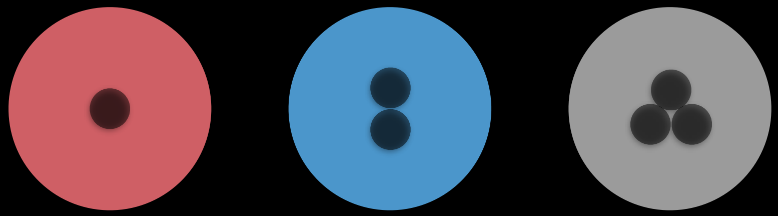
arXiv:1805.02973

Eccentricities

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

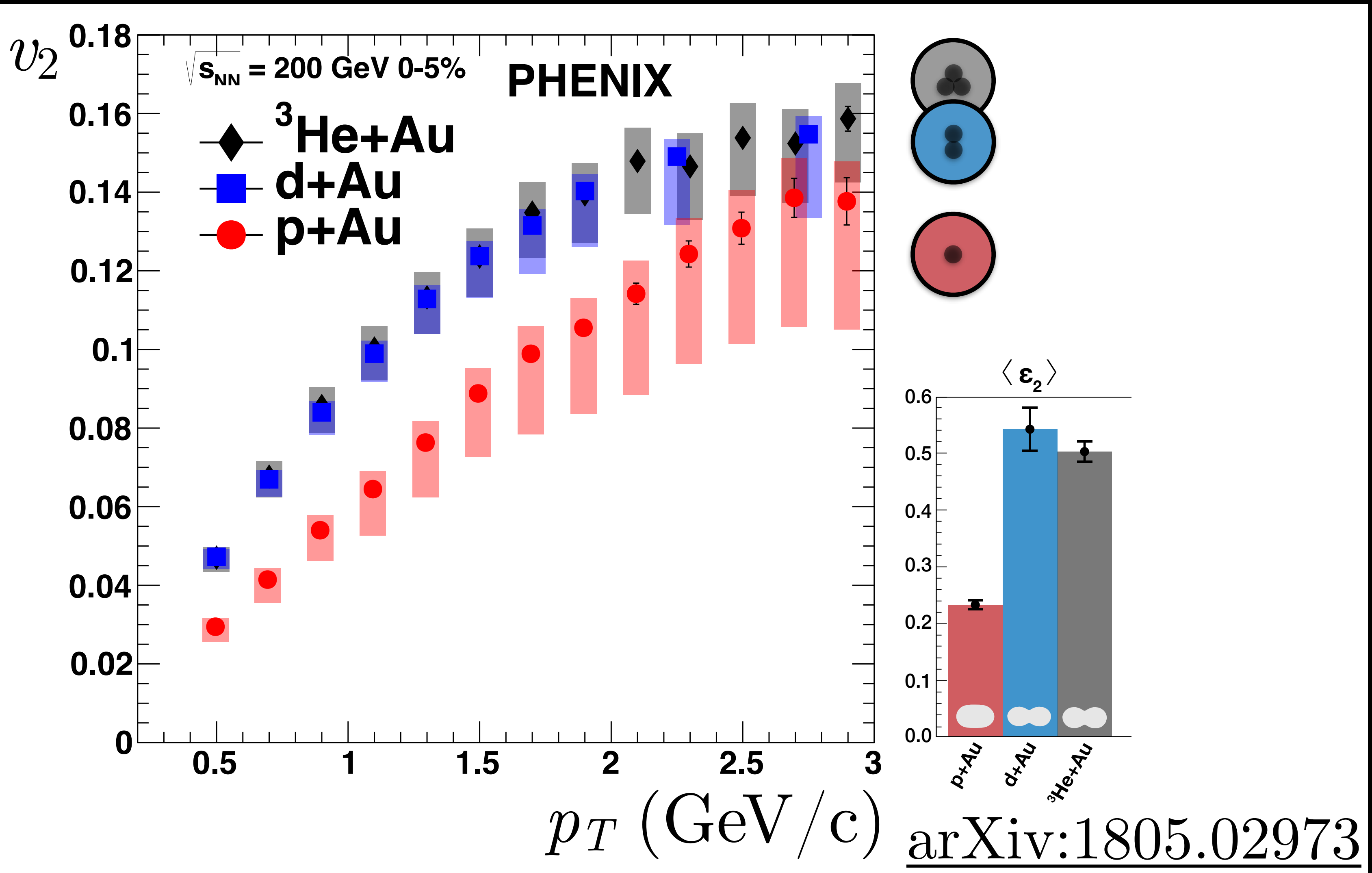
$$\varepsilon_3^{p+\mathrm{Au}} \approx \varepsilon_3^{d+\mathrm{Au}} < \varepsilon_3^{^3\mathrm{He+Au}}$$





arXiv:1805.02973

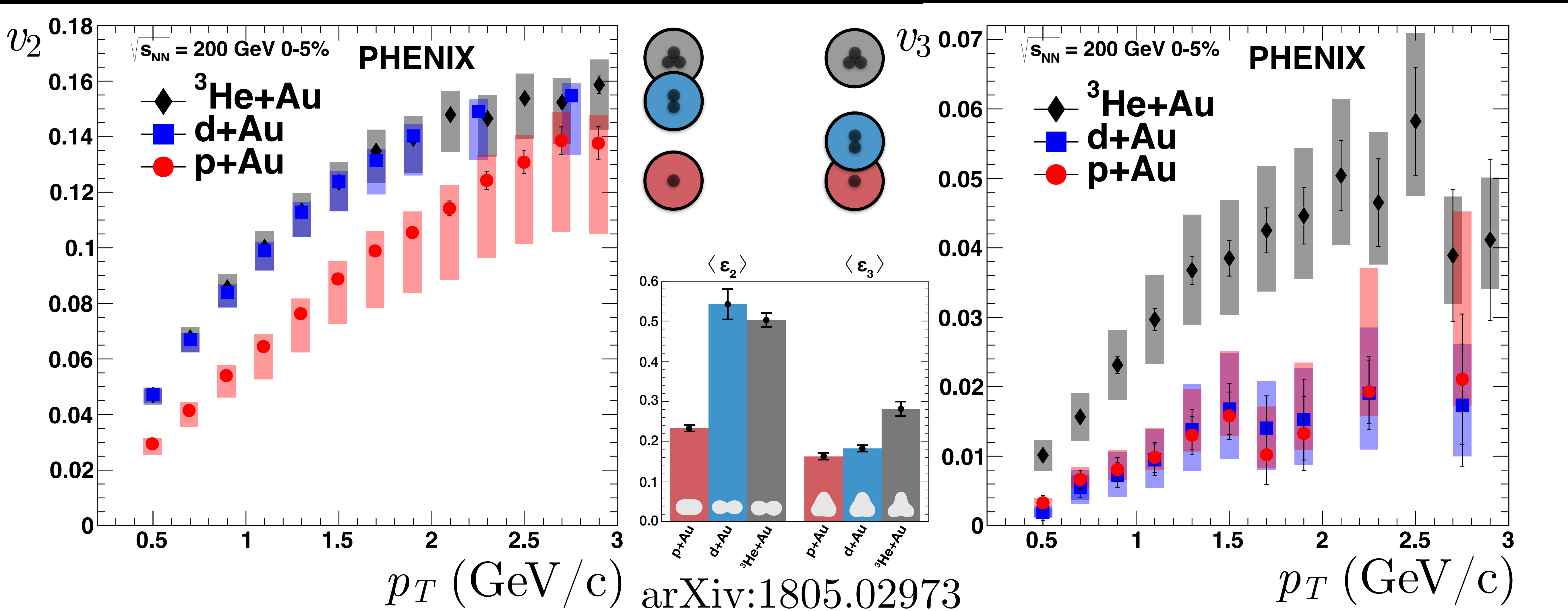
$v_n(p_T)$ measurement in small systems



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

$v_n(p_T)$ measurement in small systems

PHENIX S. Morrow



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

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

Confirms flow as geometric in origin

Final state correlation mechanism

Hydrodynamics

initial spatial correlation $\twoheadrightarrow\!\!\!\!\rightarrow$ v_n^{system}

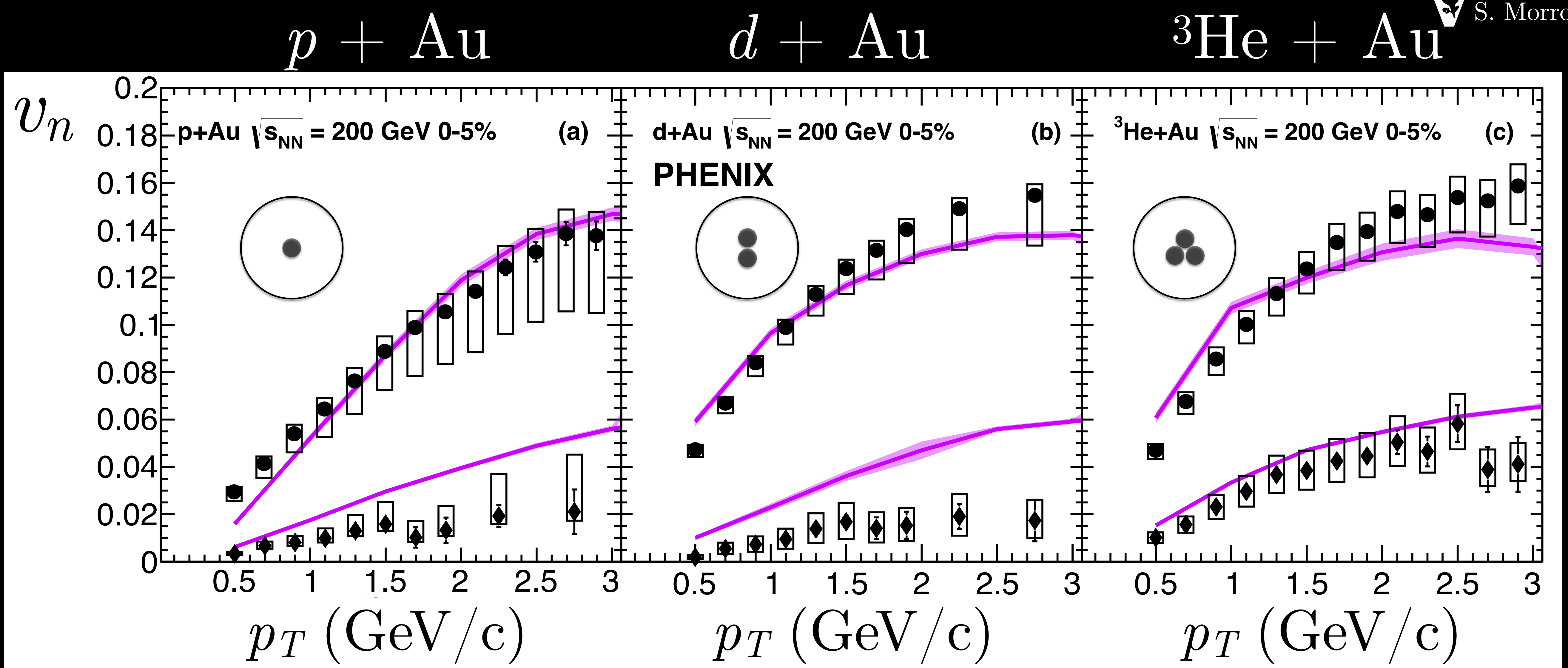
Initial state momentum correlation model

initial momentum correlation $\twoheadrightarrow\!\!\!\!\rightarrow$ v_n^{system}

Alternative? A CGC postdiction

PHENIX

S. Morrow



Reasonable description of $v_2(p_T)$, but misses strong geometry dependence in $v_3(p_T)$

- v_2 Data
- v_3 Data
- v_n CGC postdiction arXiv:1805.09342

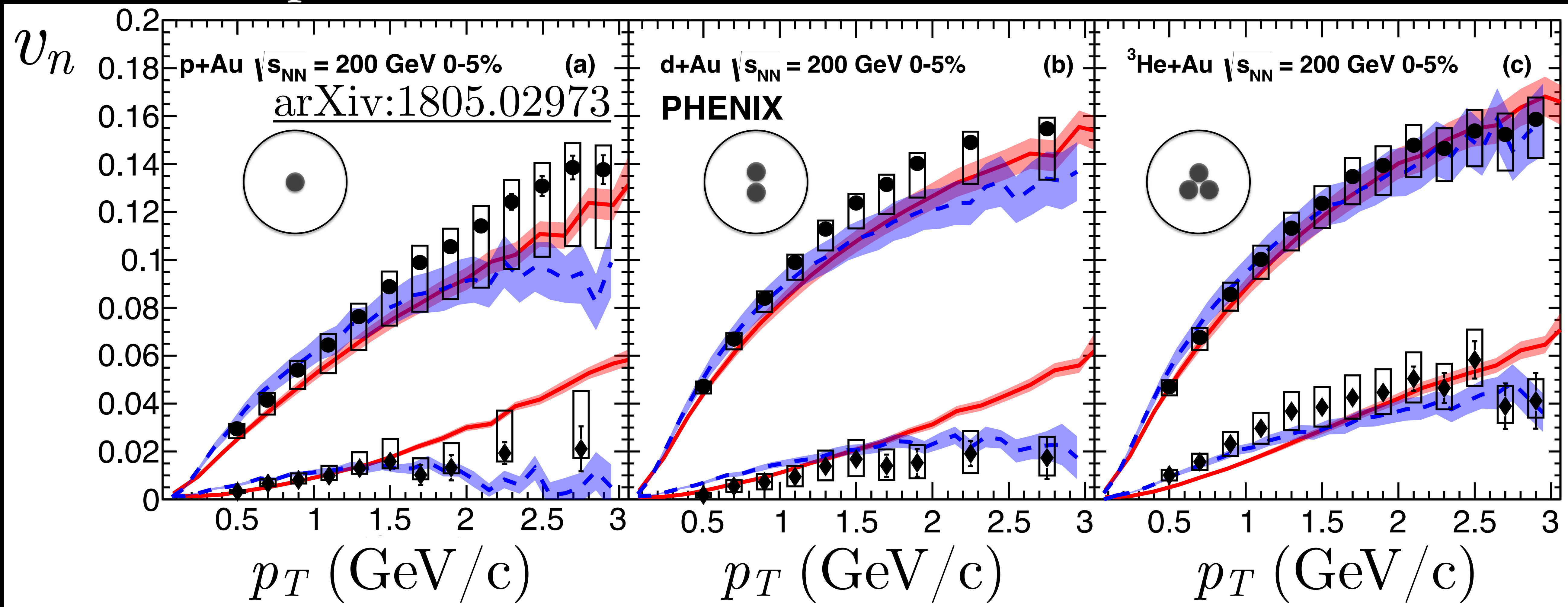
- Systematic uncertainty not quantified
- Assumes Q_s (deuteron) > Q_s (proton) and that domains not resolved individually (Q_s = saturation scale)

$v_n(p_T)$ from hydrodynamics and data

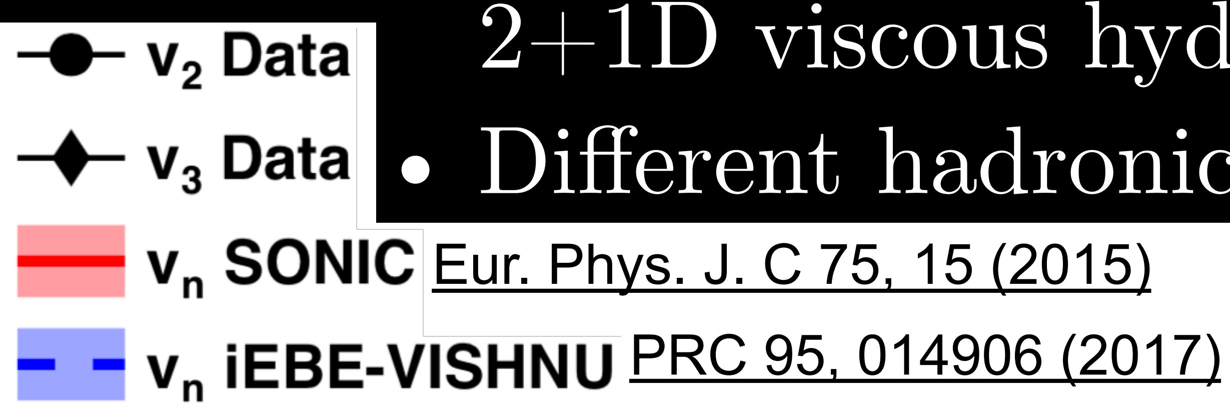
PHENIX

S. Morrow

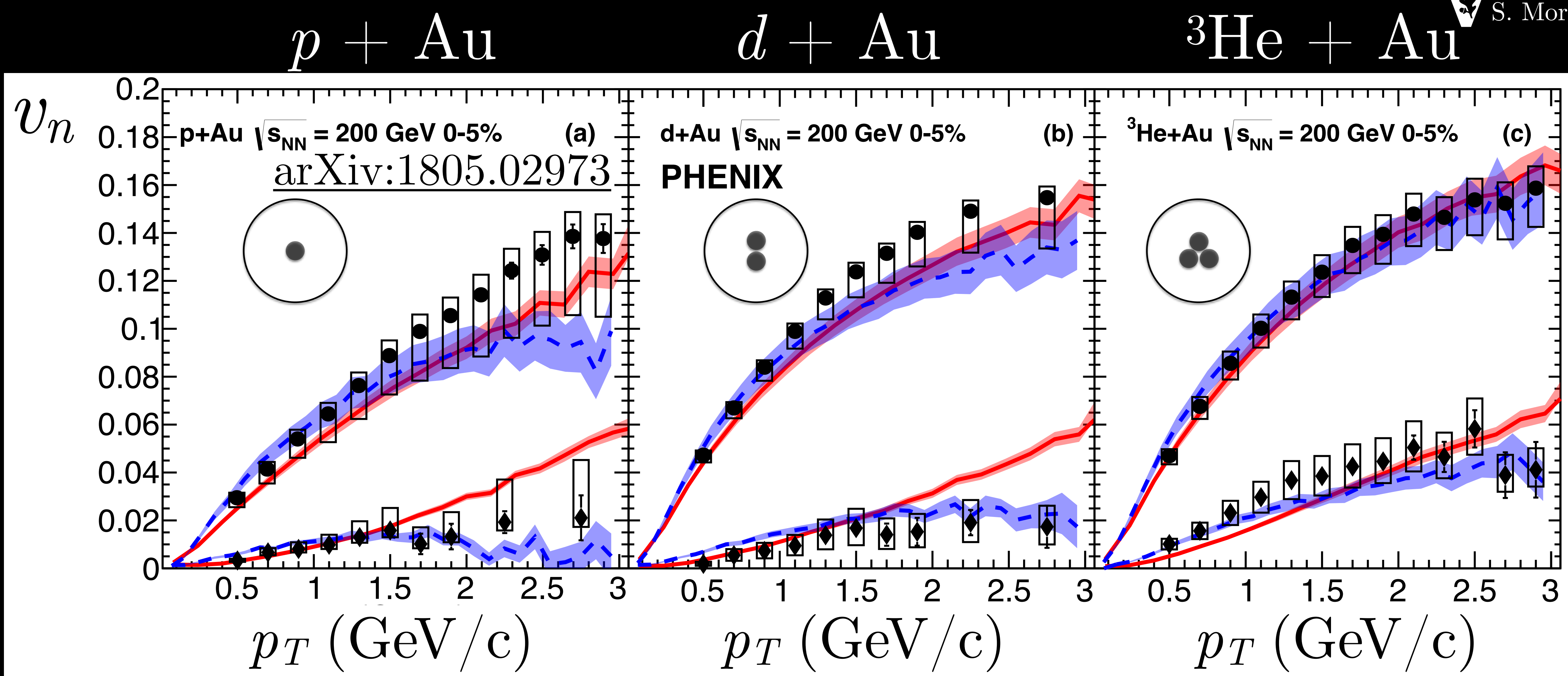
p + Au d + Au ^{3}He + Au



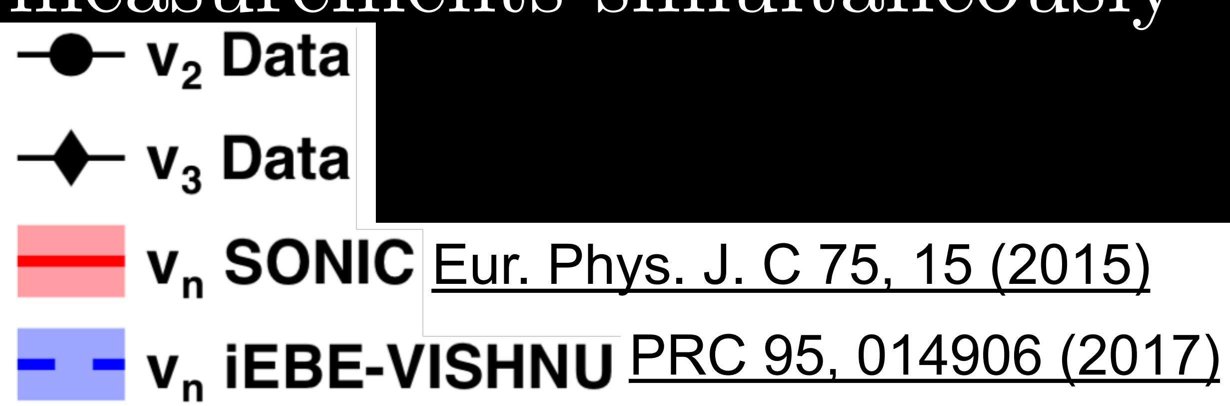
- Both use η/s=0.08, MC Glauber initial conditions, 2+1D viscous hydrodynamic evolution
- Different hadronic rescattering packages



$v_n(p_T)$ from hydrodynamics and data



Unprecedented model discrimination: model predictions describe six measurements simultaneously



Presence of QGP droplet best describes measurement

Conclusion

PHENIX

Final state correlations at all BES energies

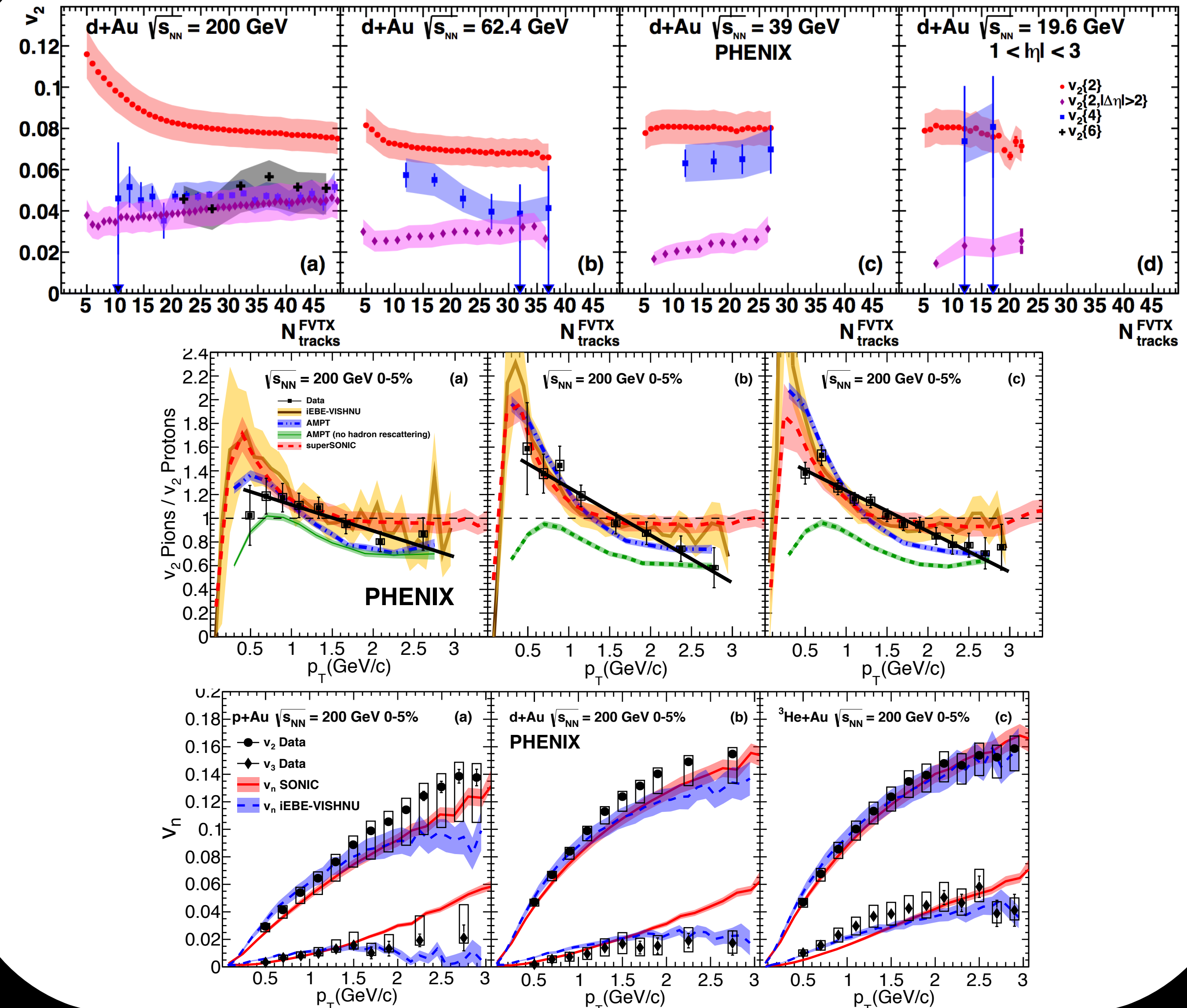
PRC 96, 064905 (2017) and PRL 120, 062302 (2018)

Mass ordering consistent with common velocity field

arXiv:1710.09736

Flow is geometric

arXiv:1805.02973



- **The collection of measurements is best described by hydro which includes QGP**
- **Strong evidence for QGP in small systems**

Backup

PHENIX small systems papers

- Creating small circular, elliptical, and triangular droplets of quark-gluon plasma arXiv:1805.02973, submitted *Nature Physics*
- 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, *accepted PRC*
- Measurements of multiparticle correlations in d+Au collisions at 200, 62.4, 39, and 19.6 GeV and p+Au collisions at 200 GeV and implications for collective behavior PRL 120, 062302 (2018)
- Measurements of azimuthal anisotropy and charged-particle multiplicity in d+Au collisions at $\sqrt{s_{NN}} = 200$, 62.4, 39, and 19.6 GeV PRC 96, 064905 (2017)
- Measurement of long-range angular correlations and azimuthal anisotropies in high multiplicity p+Au collisions at $\sqrt{s_{NN}} = 200$ GeV PRC 95, 034910 (2017)
- Measurements of elliptic and triangular flow in high-multiplicity ^{3}He+Au collisions at $\sqrt{s_{NN}} = 200$ GeV PRL 115, 142301 (2015)
- Quadrupole anisotropy in dihadron azimuthal correlations in central d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV PRL 111, 212301 (2013)
- Measurement of long-range angular correlation and quadrupole anisotropy of pions and (anti)protons in central d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV PRL 114, 192301 (2015)

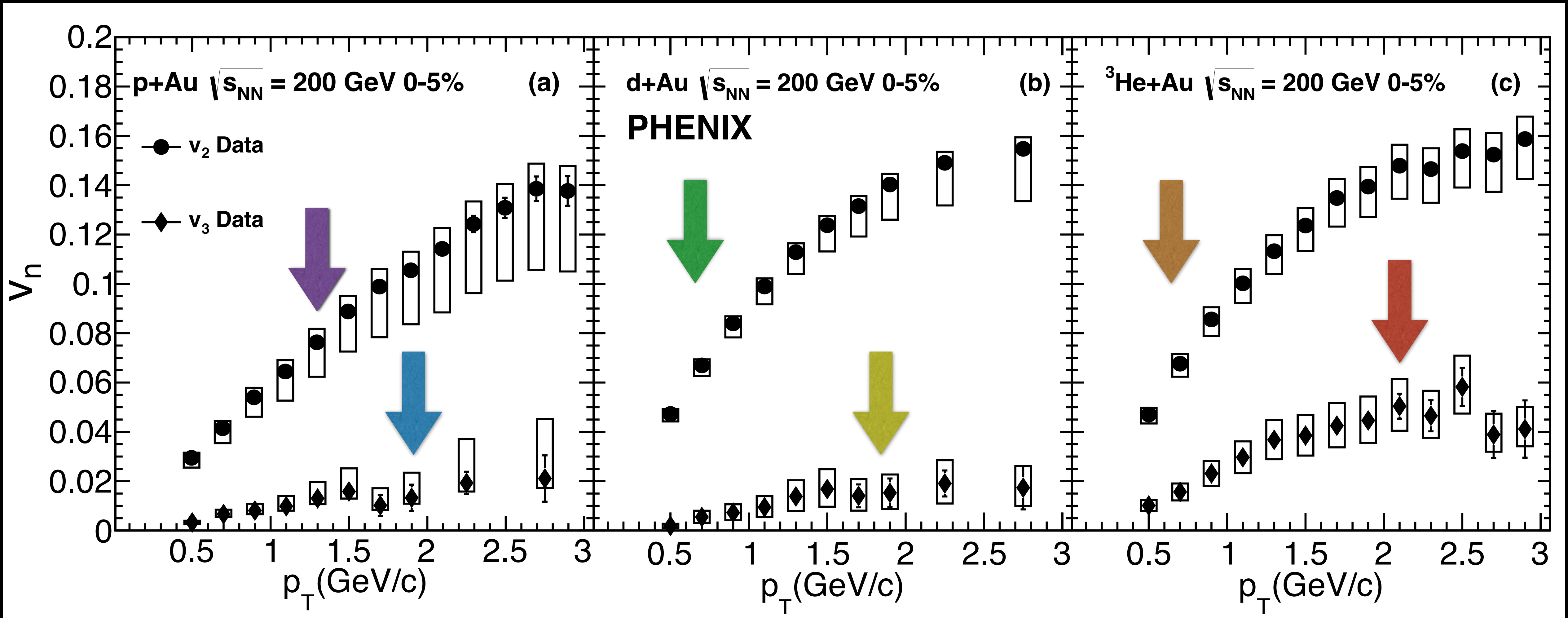
$v_n(p_T)$ measurement in small systems

PHENIX
S. Morrow

PRC 95, 034910 (2017)

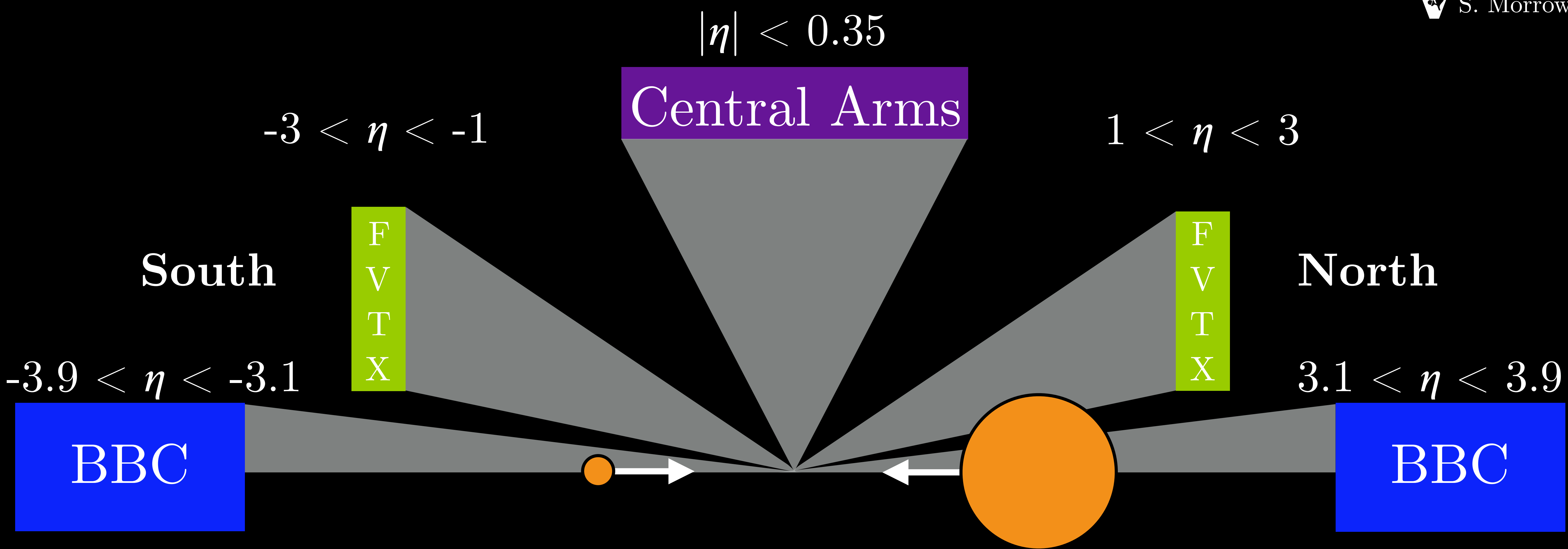
PRC 96, 064905 (2017) new nonflow estimate

PRL 115, 142301 (2015)



brand new in arXiv:1805.02973

Cartoon of (some) PHENIX sub-detectors

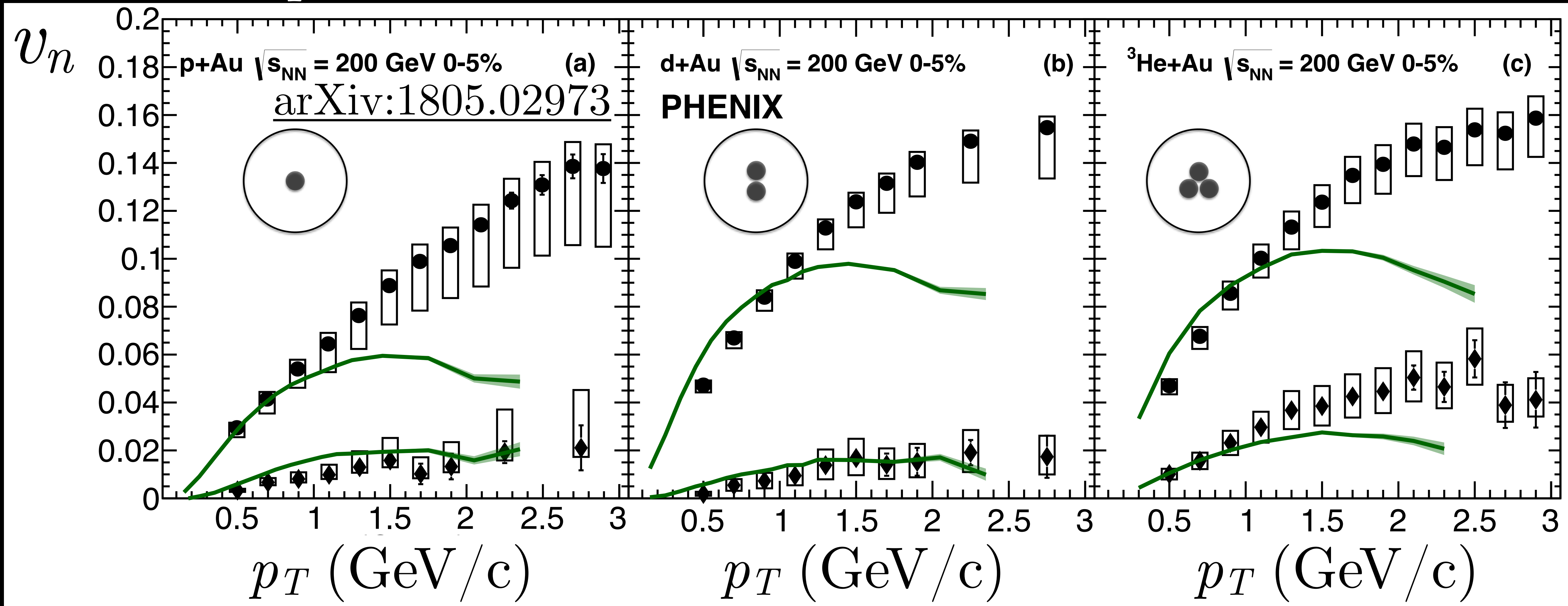


- Event plane measured in south BBC (beam-beam counter) and/or south FVTX (forward vertex detector)
- Particle tracks measured in the central arms
- Measure in south (Au-going side) because multiplicity is greater

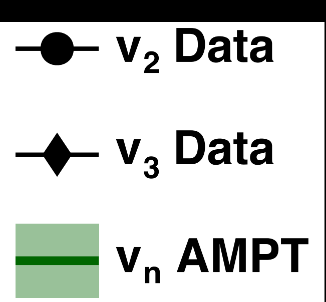
$v_n(p_T)$ from AMPT and data

PHENIX
S. Morrow

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



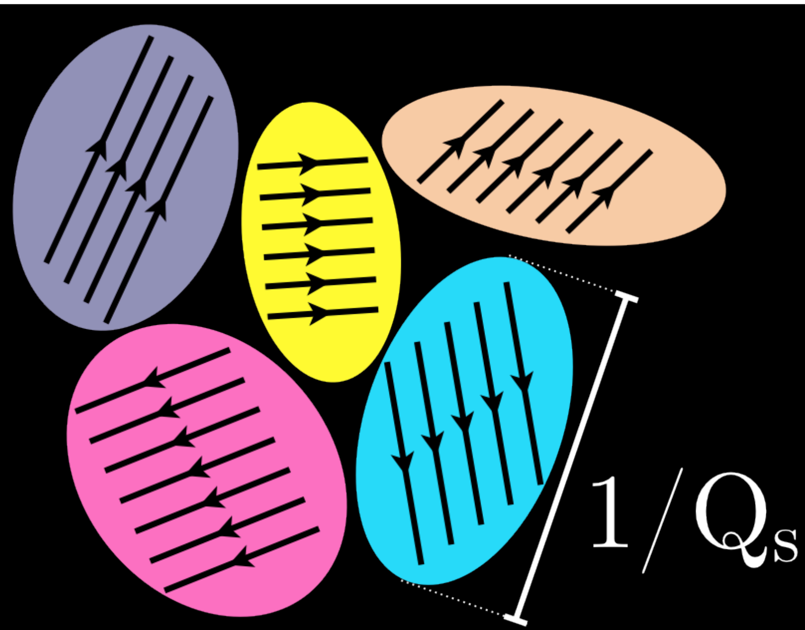
- Parton transport model with the same parameters for all systems (above) doesn't well-describe all measurements simultaneously
- Not clear that AMPT can describe small and large systems with a common set of parameters
- Calculated using parton plane ∴ doesn't include nonflow



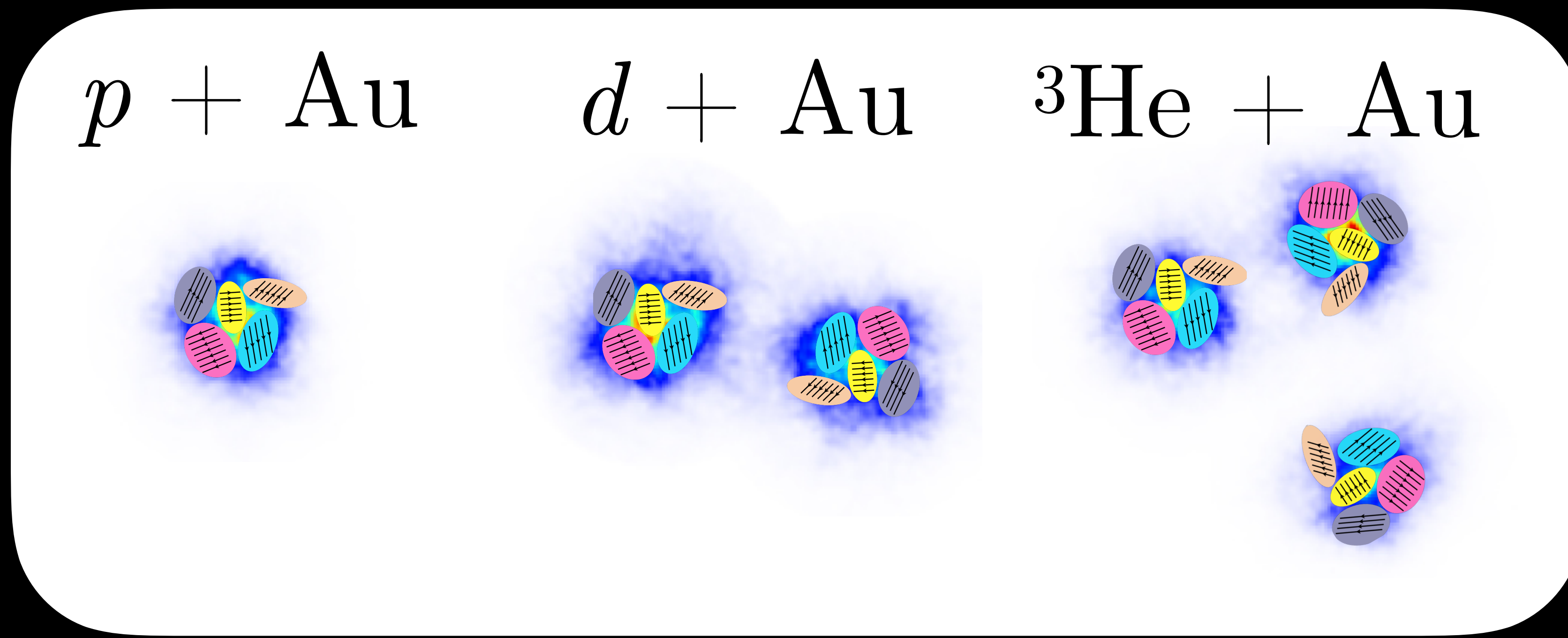
PRC 92, 054903 (2015)

Initial state momentum correlation model

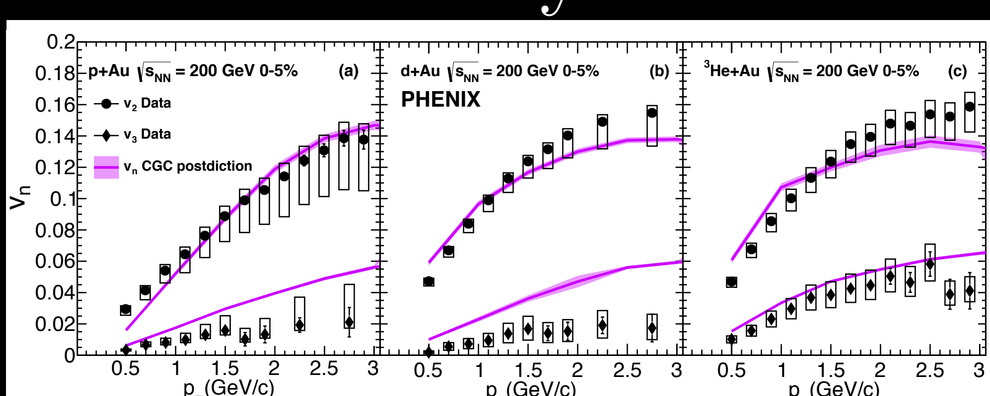
PHENIX
S. Morrow



- 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: $v_n^{p+\mathrm{Au}} > v_n^{d+\mathrm{Au}} > v_n^{^3\mathrm{He}+\mathrm{Au}}$
which is clearly not the case in the data

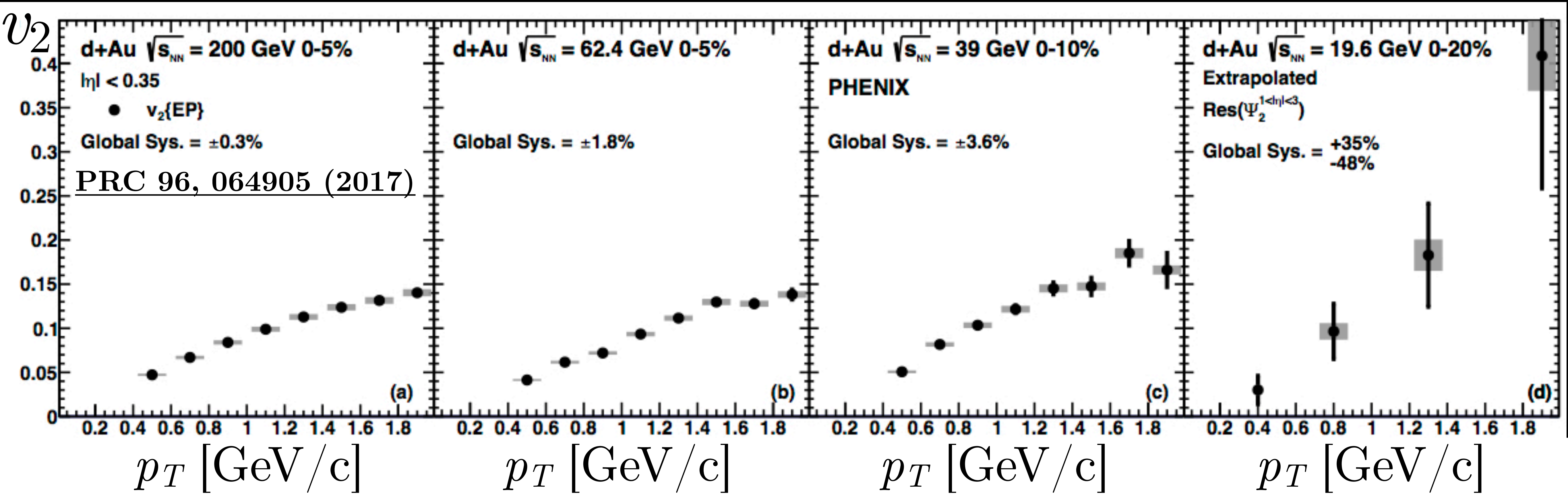


CGC calculation on slide 25 assumes Q_s (deuteron) > Q_s (proton) and that domains not resolved individually in this p_T range

d+Au BES $v_2(p_T)$: data and hydro

PHENIX
S. Morrow

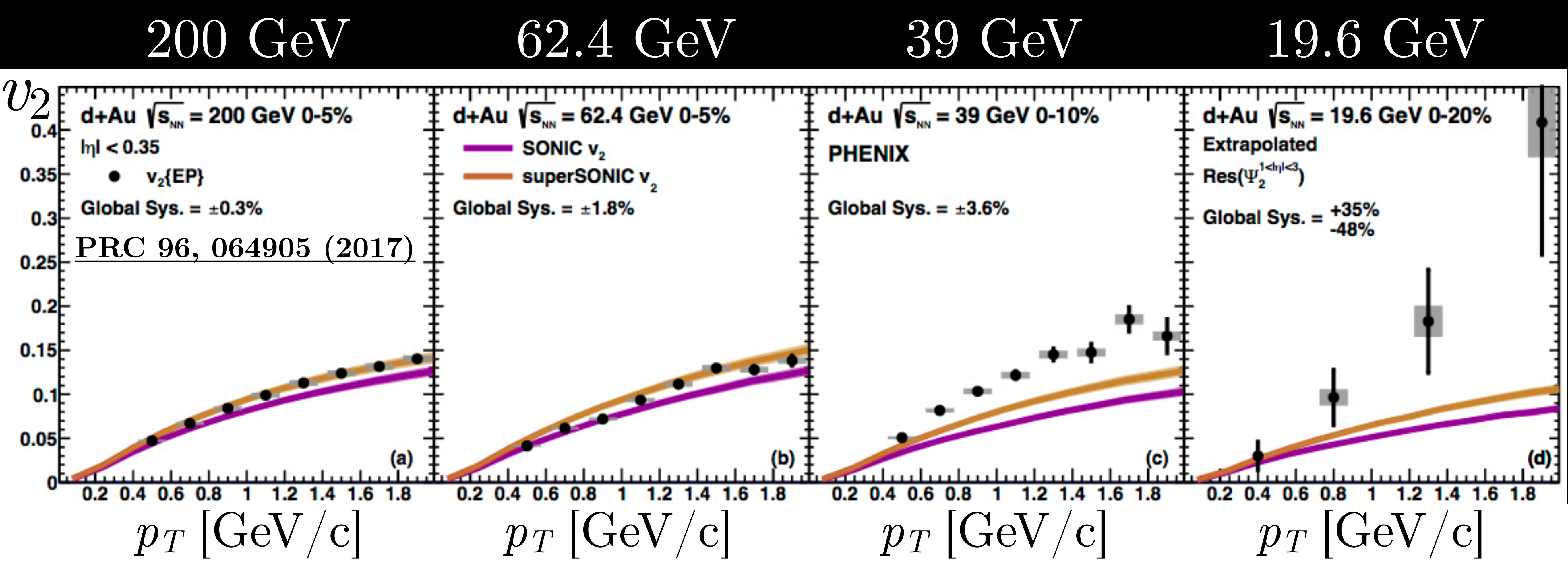
200 GeV 62.4 GeV 39 GeV 19.6 GeV



- Measured signal at all energies (similar magnitude)
- Flow & non-flow

d+Au BES $v_2(p_T)$: data and hydro

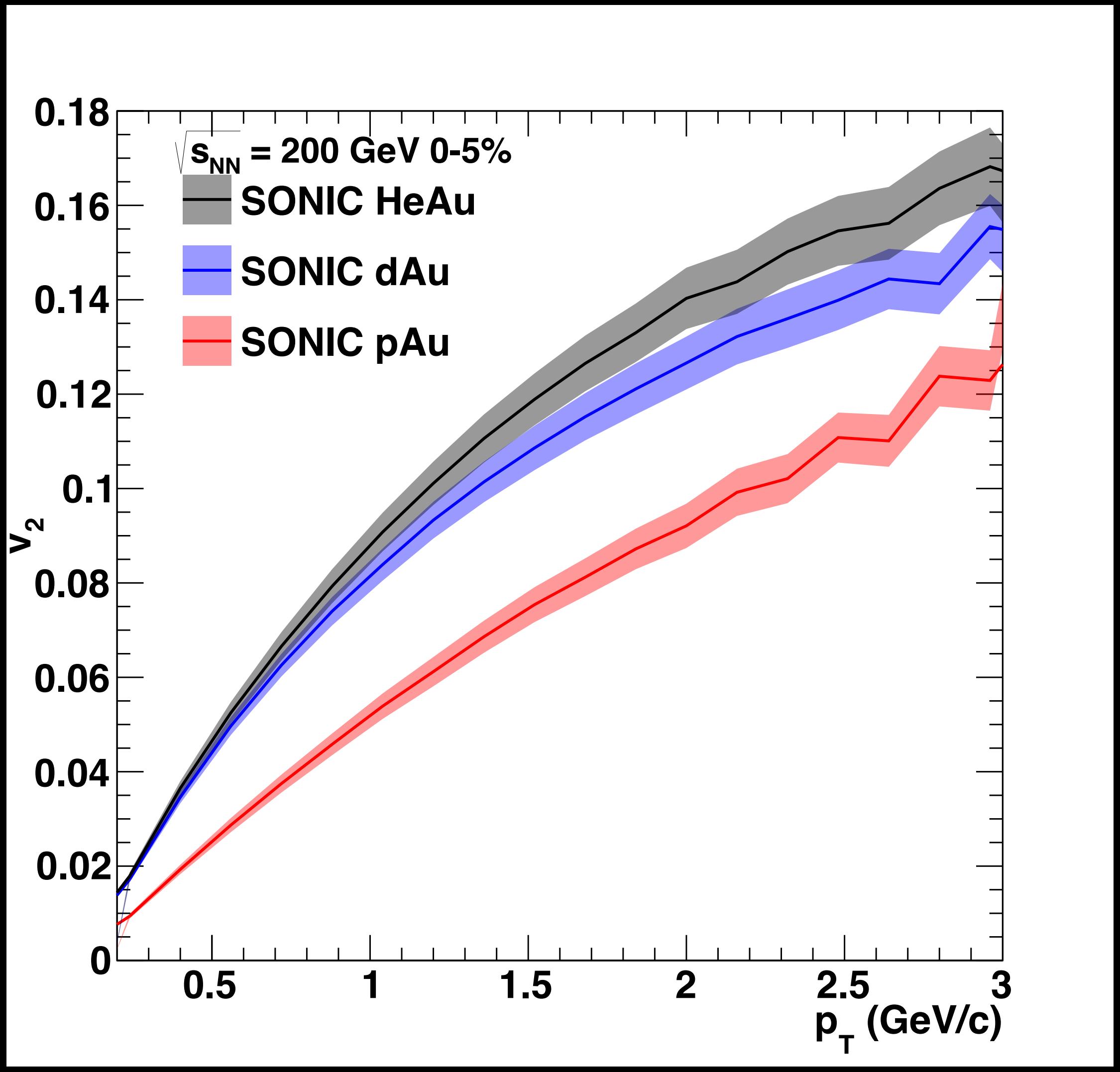
PHENIX
S. Morrow

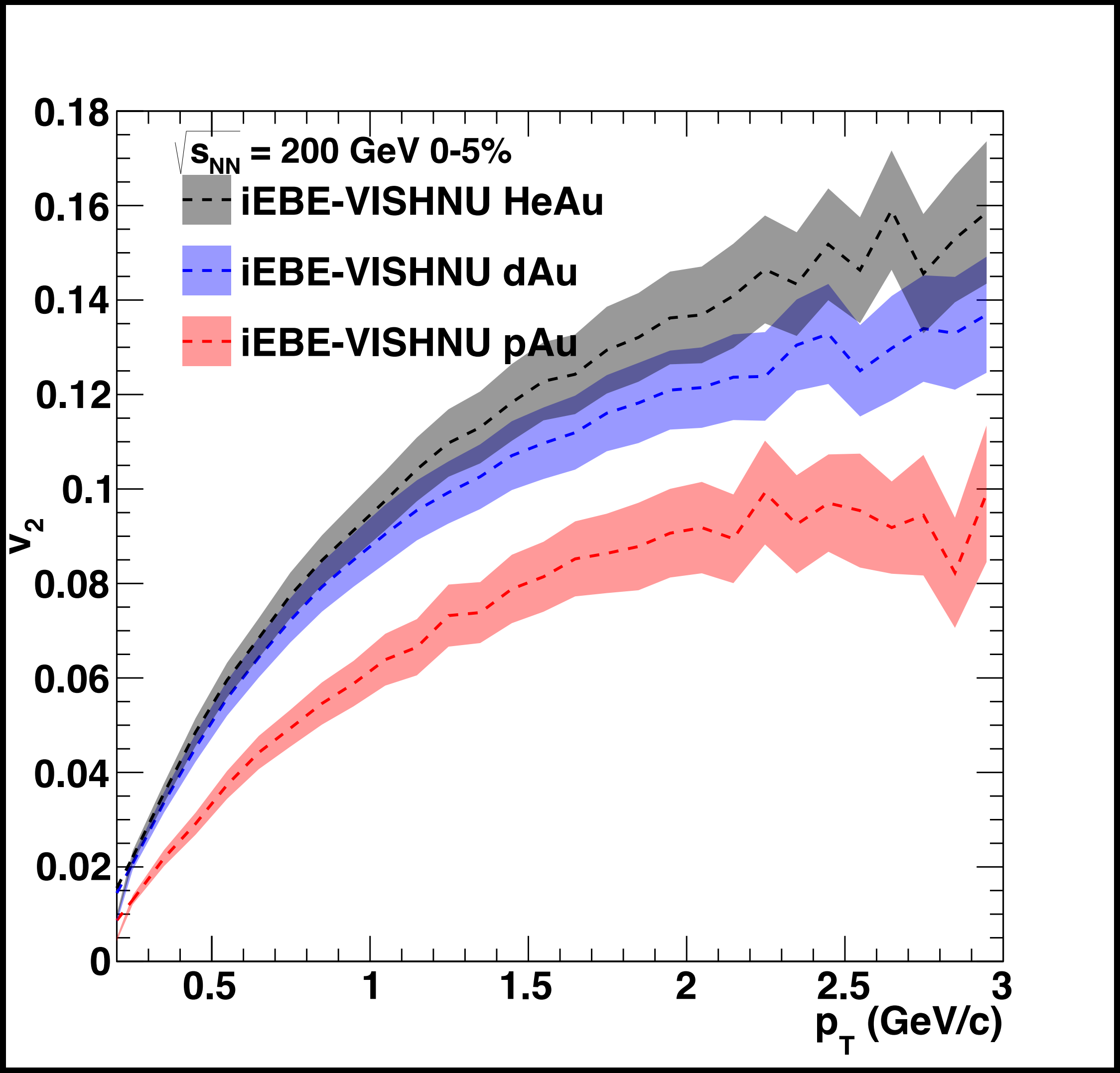


Macroscopic models (flow)

- Describe measured signal at high energies
- Underestimate measure signal at low energies

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



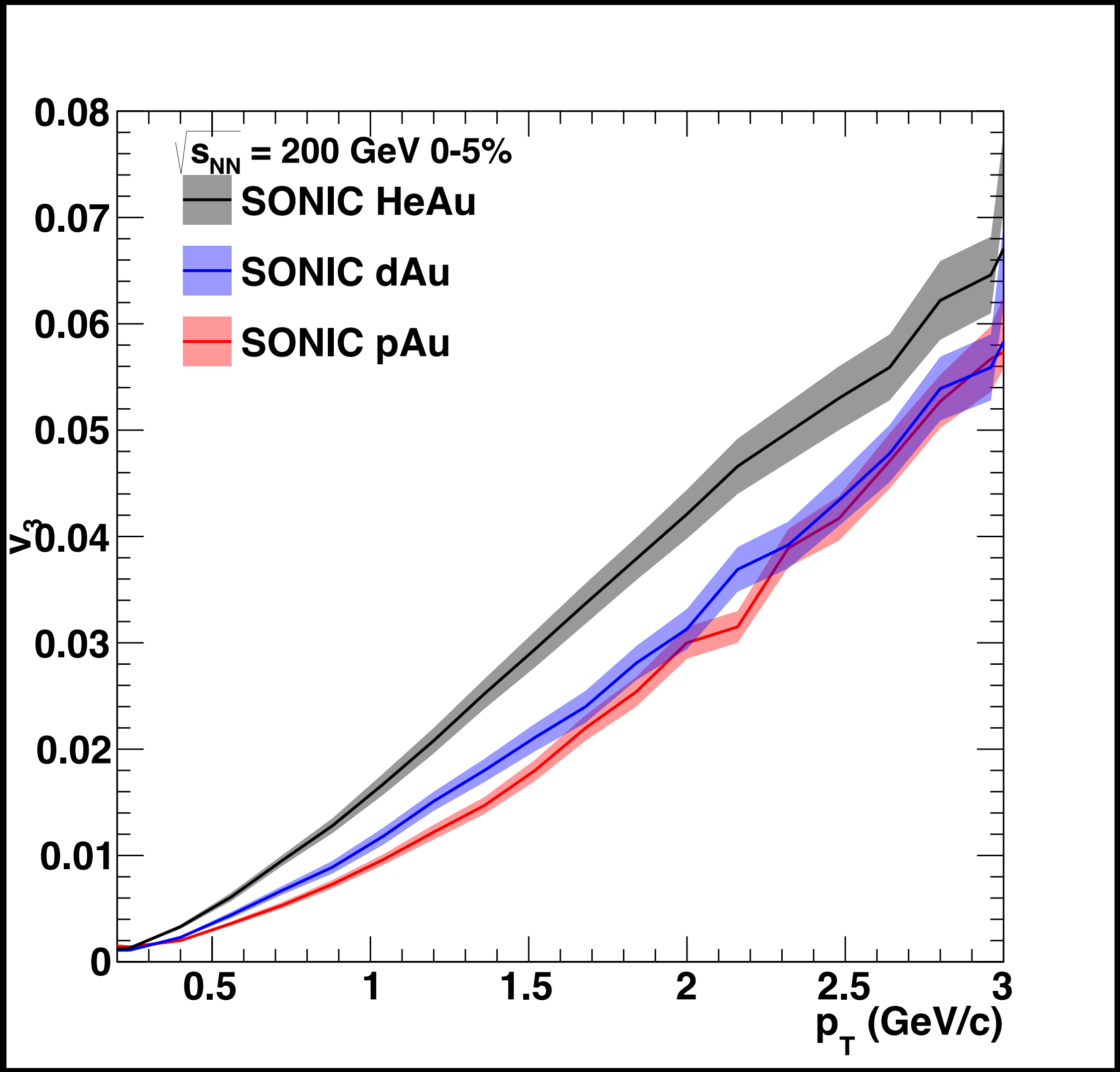


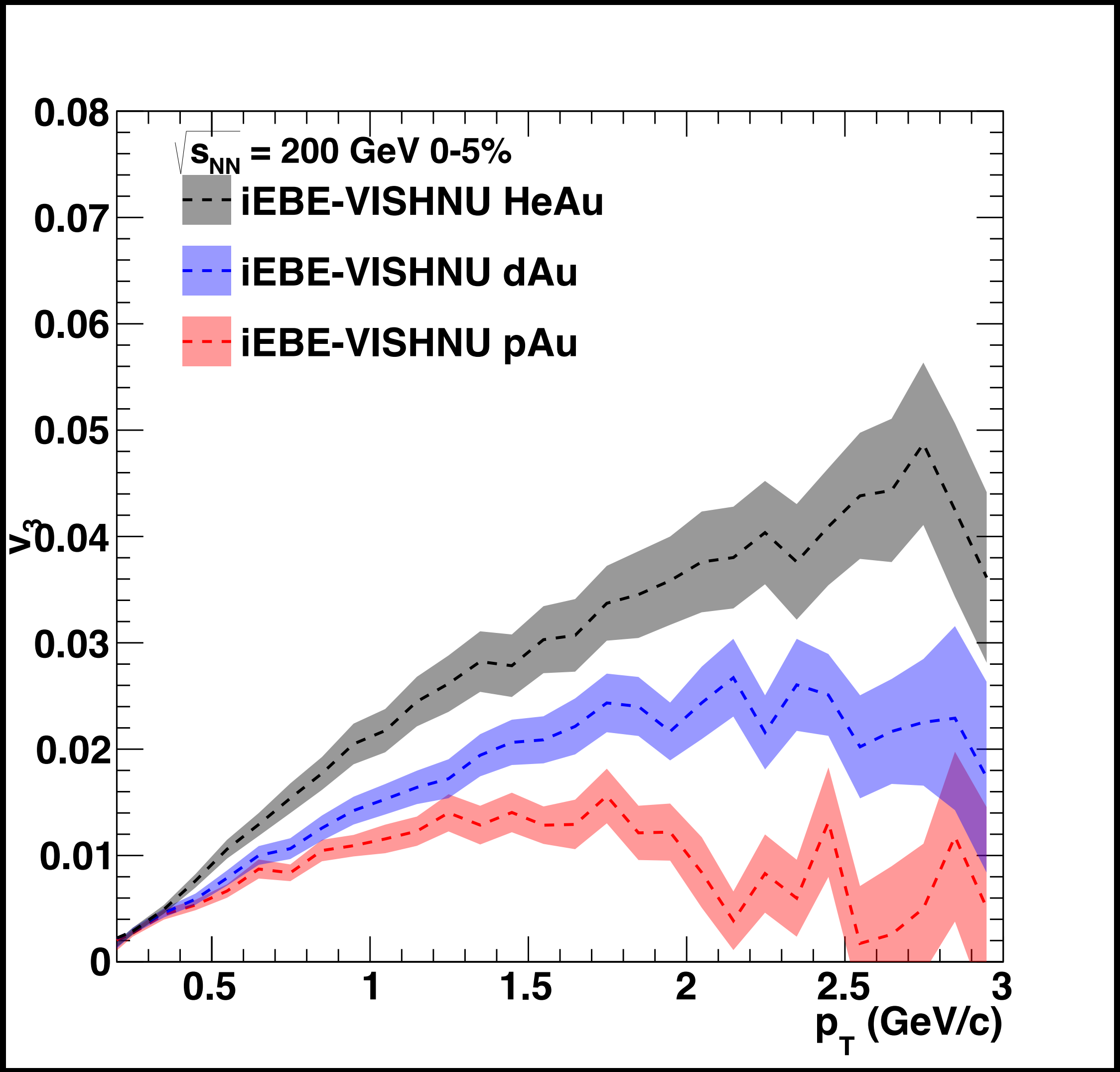
- Both hydrodynamic models predict flow ordering that matches eccentricity ordering: $v_2^{p+\text{Au}} < v_2^{d+\text{Au}} \approx v_2^{^3\text{He+Au}}$

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

PHENIX

S. Morrow





- SONIC flow ordering matches eccentricity ordering:

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

- iEBE-VISHNU does not predict: $v_3^{p+\mathrm{Au}} \approx v_3^{d+\mathrm{Au}}$

Abstract

PHENIX

S. Morrow

To answer the question of how small a system can be while still exhibiting collective behavior, the PHENIX experiment has used RHIC's extraordinary versatility to design a set of experiments controlling the initial geometry of the collisions by selecting different colliding species, $p/d/^{3}$He+Au. In addition, a beam energy scan with d+Au collisions was done to vary the lifetime of the system while keeping the initial geometry constant.

In this talk we show PHENIX measurements of elliptic and triangular flow of charged hadrons and elliptic flow of identified hadrons at midrapidity as a function of transverse momentum in $p/d/^{3}$He+Au collisions at 200 GeV per nucleon center-of-mass energy. Measurements of elliptic flow of charged hadrons in d+Au collisions at 200, 62.4, 39, and 19.6 GeV per nucleon center-of-mass energy will also be presented as a function of transverse momentum and pseudorapidity.

In order to asses the origin of collectivity in the smallest systems, these results are compared with several theoretical models that produce azimuthal particle correlations based on initial and/or final state effects. Hydrodynamical models which include a droplet of quark gluon plasma provide the best simultaneous description of our observations.