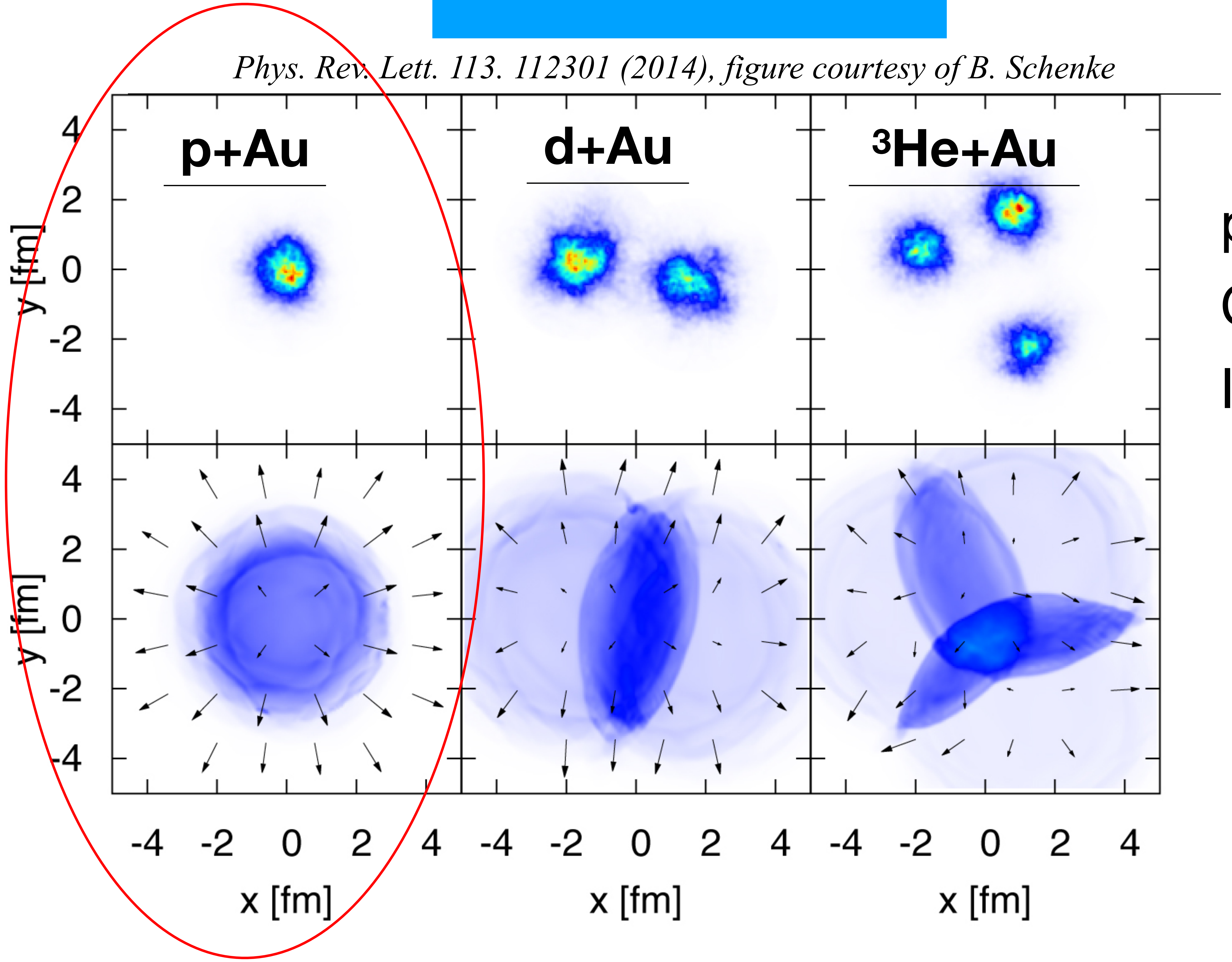
Implications for small-system collectivity from wide-range soft physics measurements in p+A collisions by PHENIX

Qiao Xu
for the PHENIX Collaboration
2018/05/14

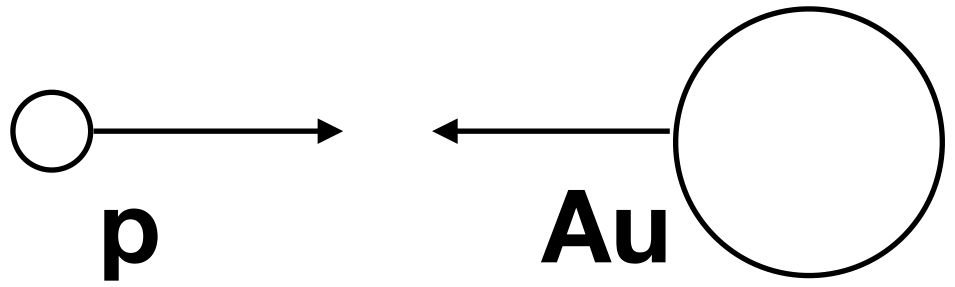
Motivation

Geometry Control Scan

Phys. Rev. Lett. 113. 112301 (2014), figure courtesy of B. Schenke

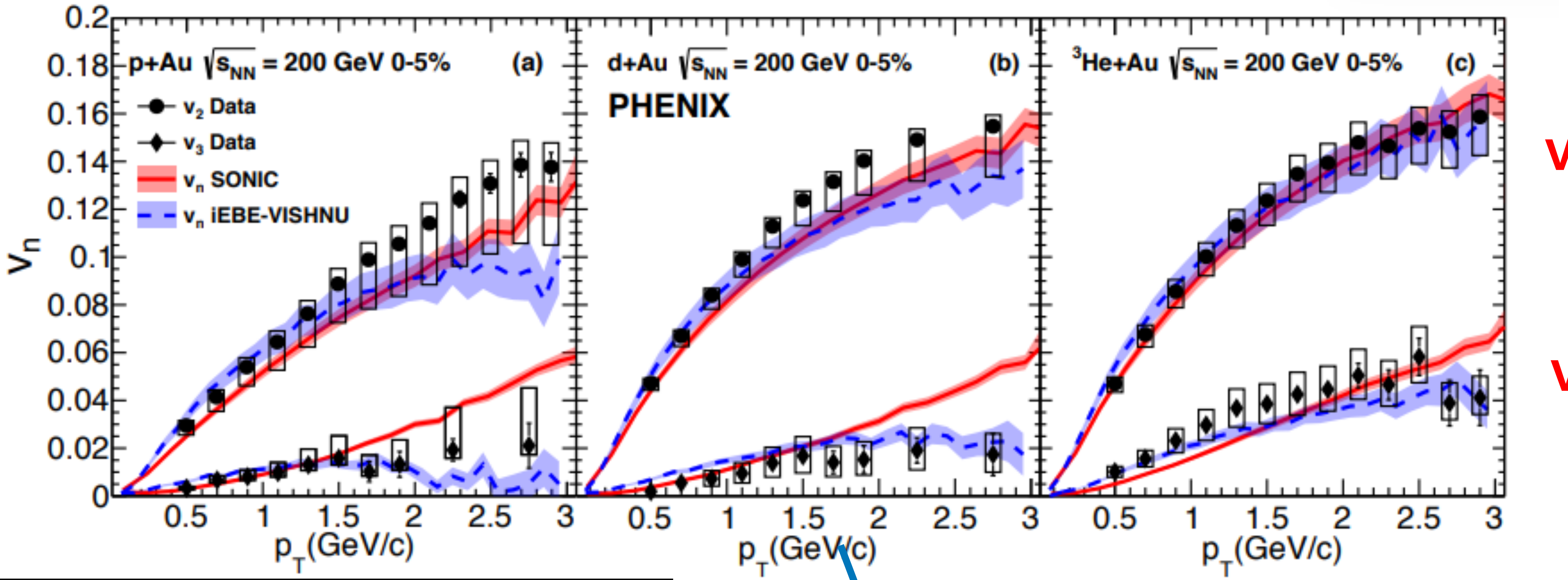


p+A collisions ->
Cold Nuclear Effect &
Important handle for collectivity



Motivation

arxiv:1805.02973, submitted to Nature Physics

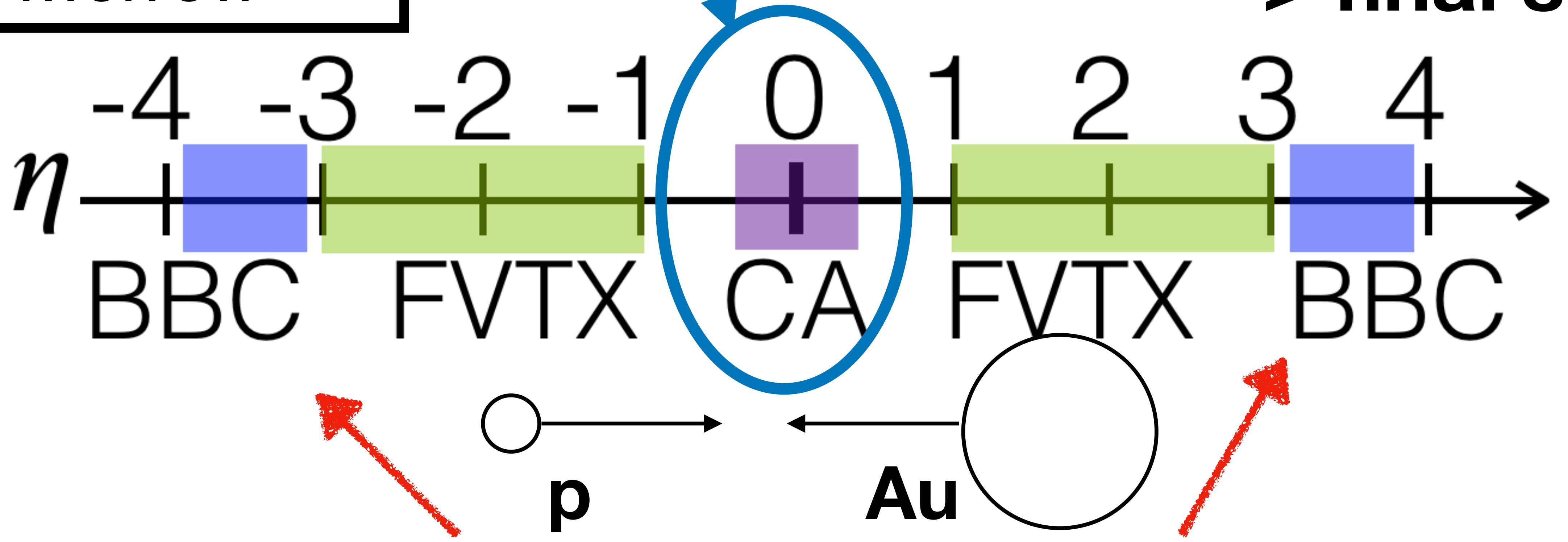


v_2 in p/d/^{3}He+Au

v_3 in p/d/^{3}He+Au

See more at session 'Collectivity in small systems' 11:10am 15th by Sylvia Morrow

Mid-rapidity, Initial geometry -> final state collectivity



Extend collectivity study to different kinetic ranges in p+A

Do we have more soft observables?

A wide range of longitudinal observables are needed to understand soft processes in p+A

Question: How is the flow related to longitudinal particle production?

- Longitudinal dynamics

Question: How do fluctuations contribute to the collectivity?

- Flow fluctuations

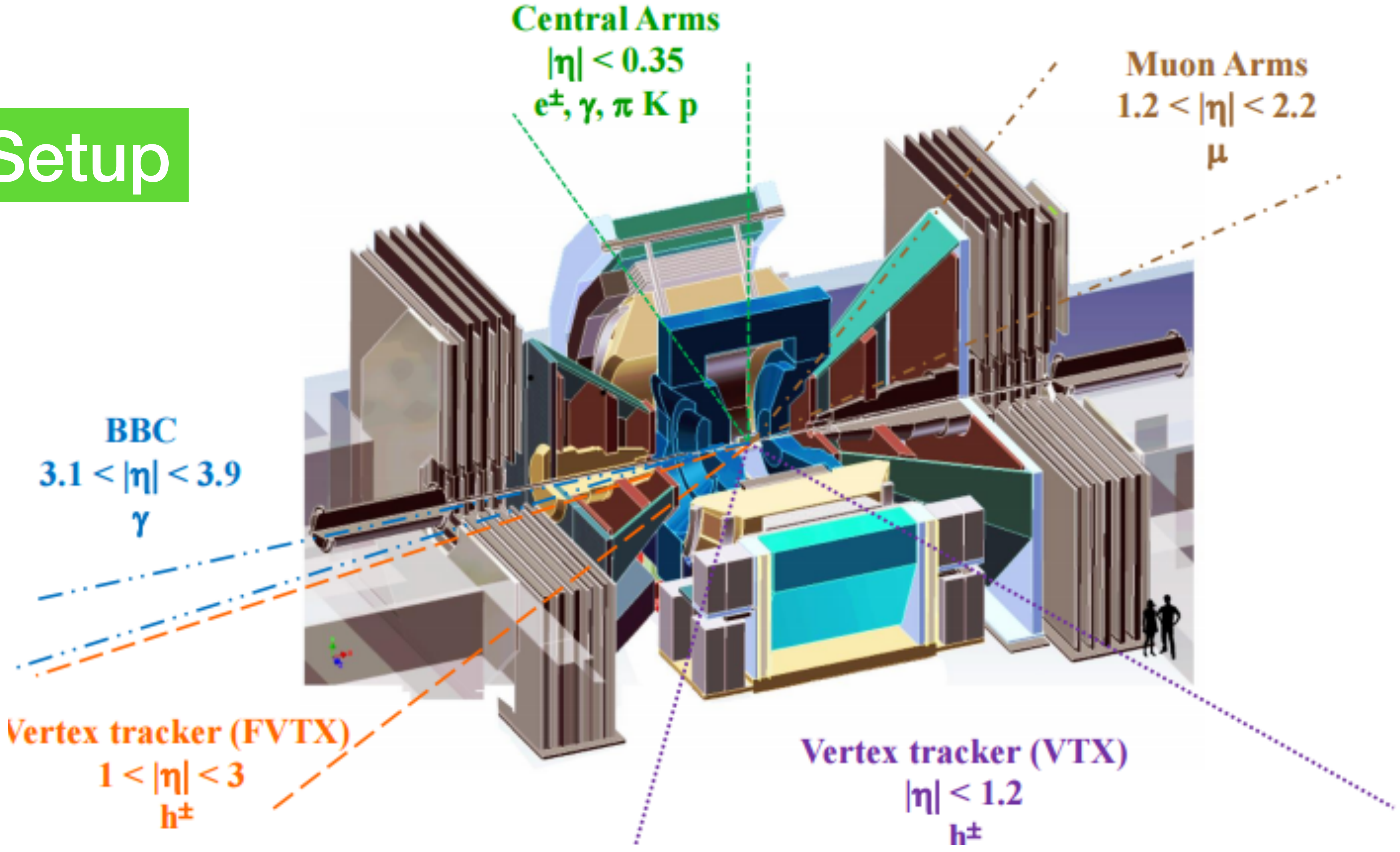
Question: In what degrees of freedom does the particle flow collectively in p+A?

- Flow for identified particles

A Coherent Picture in p+A !

Small system measurements in PHENIX

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

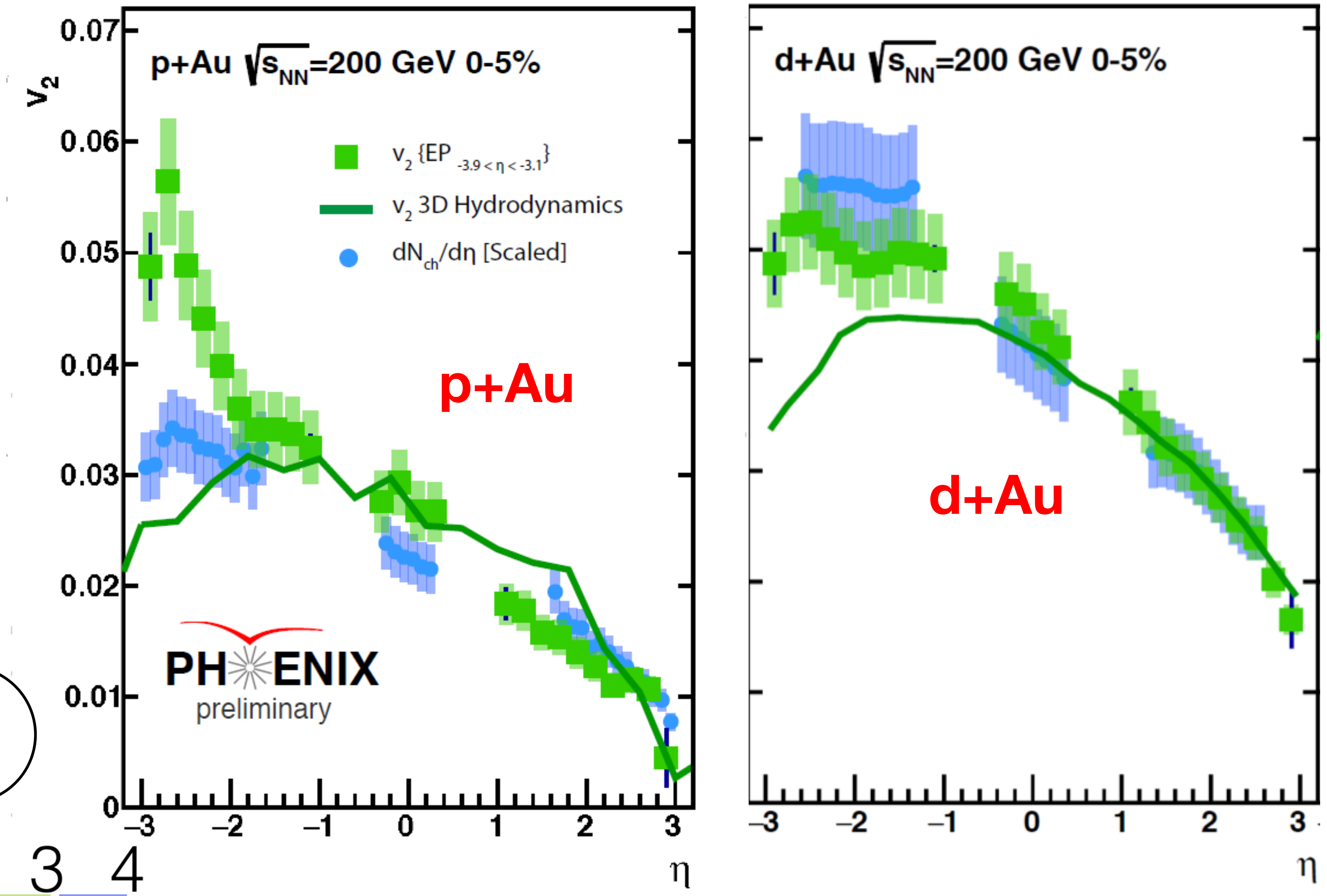
Longitudinal dynamics

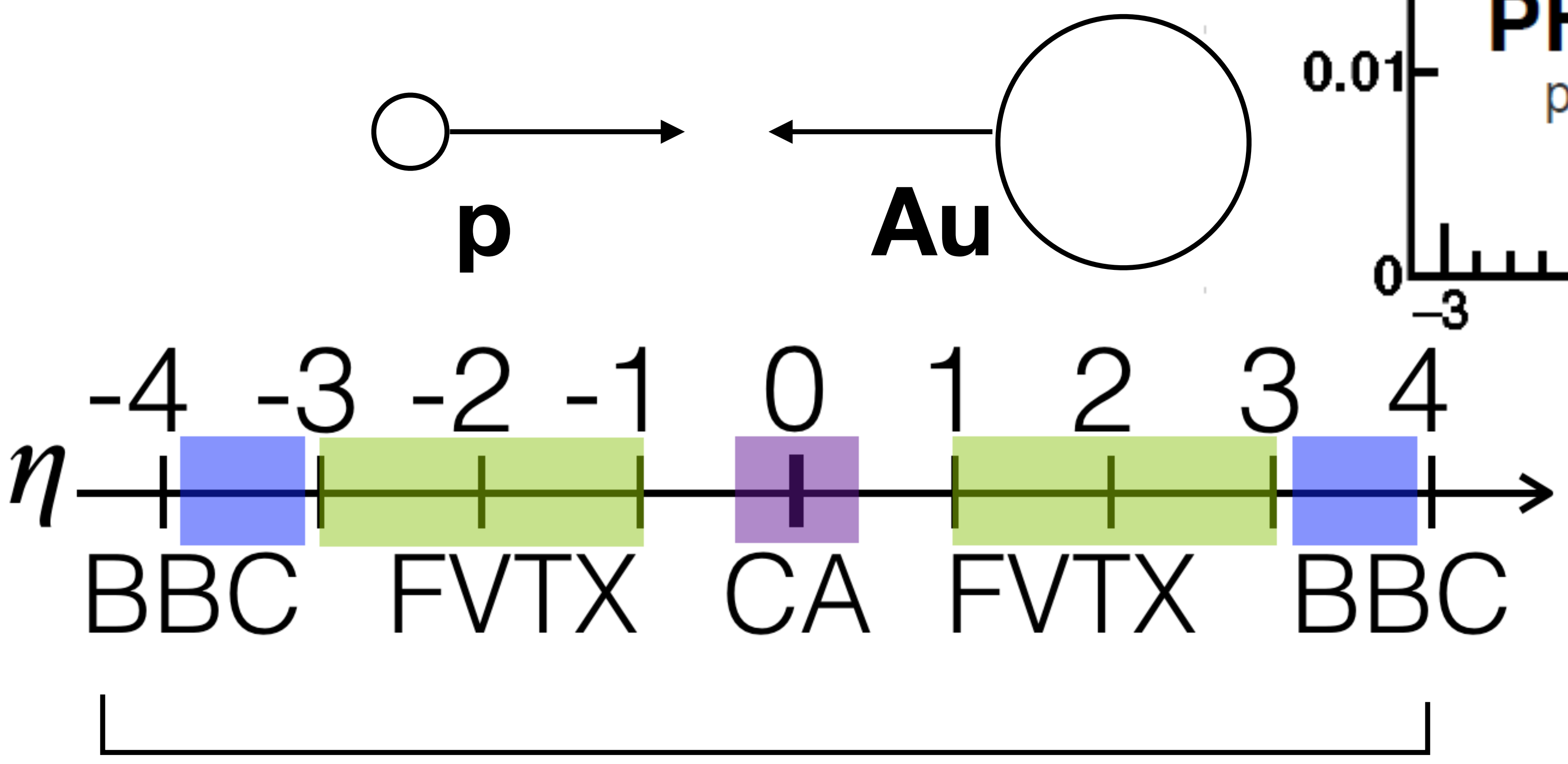
$v_2(\eta)$ vs $dN_{ch}/d\eta$ in Geometry Control Scan

green: $v_2(\eta)$

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

Curve: v_2 3D hydro





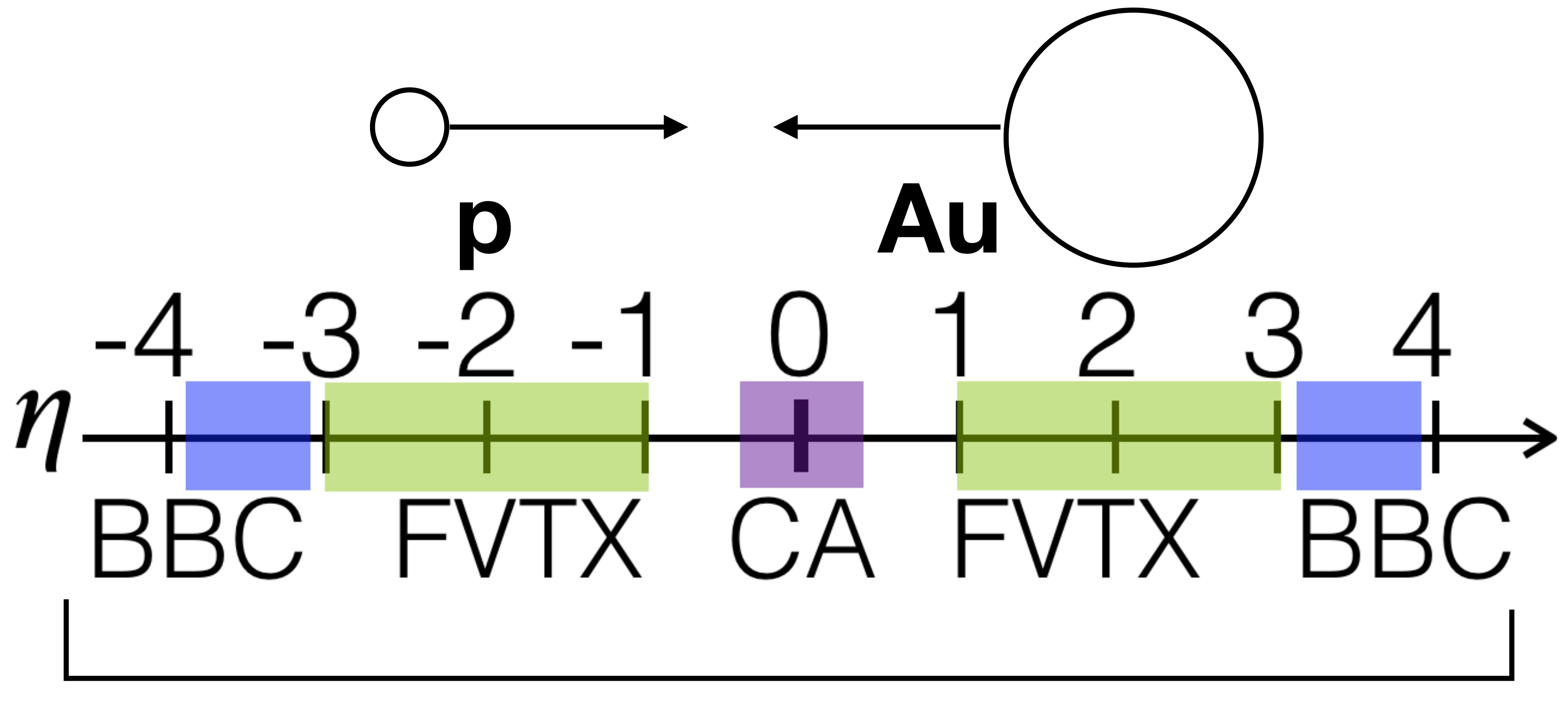
Wide rapidity range

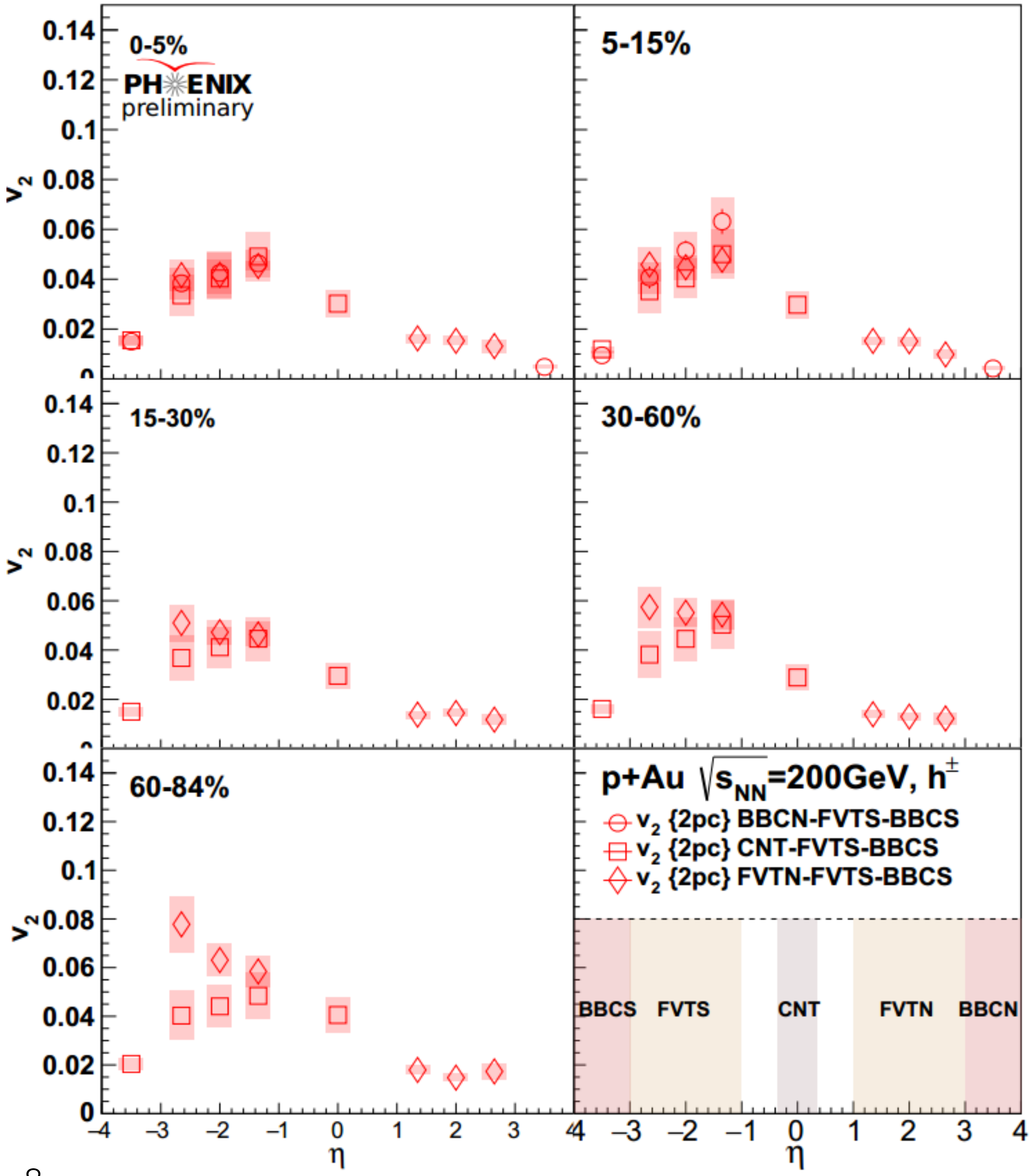
- d+Au scales well, but p+Au does not at backward rapidity
- 3D hydrodynamics quantitatively describes the data in p+Au

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

$v_2(\eta)$ at different centrality bins in p+Au

- $v_2(\eta)$ is enhanced at backward rapidity where the multiplicities are higher
- Peripheral events exhibit more non-flow effect





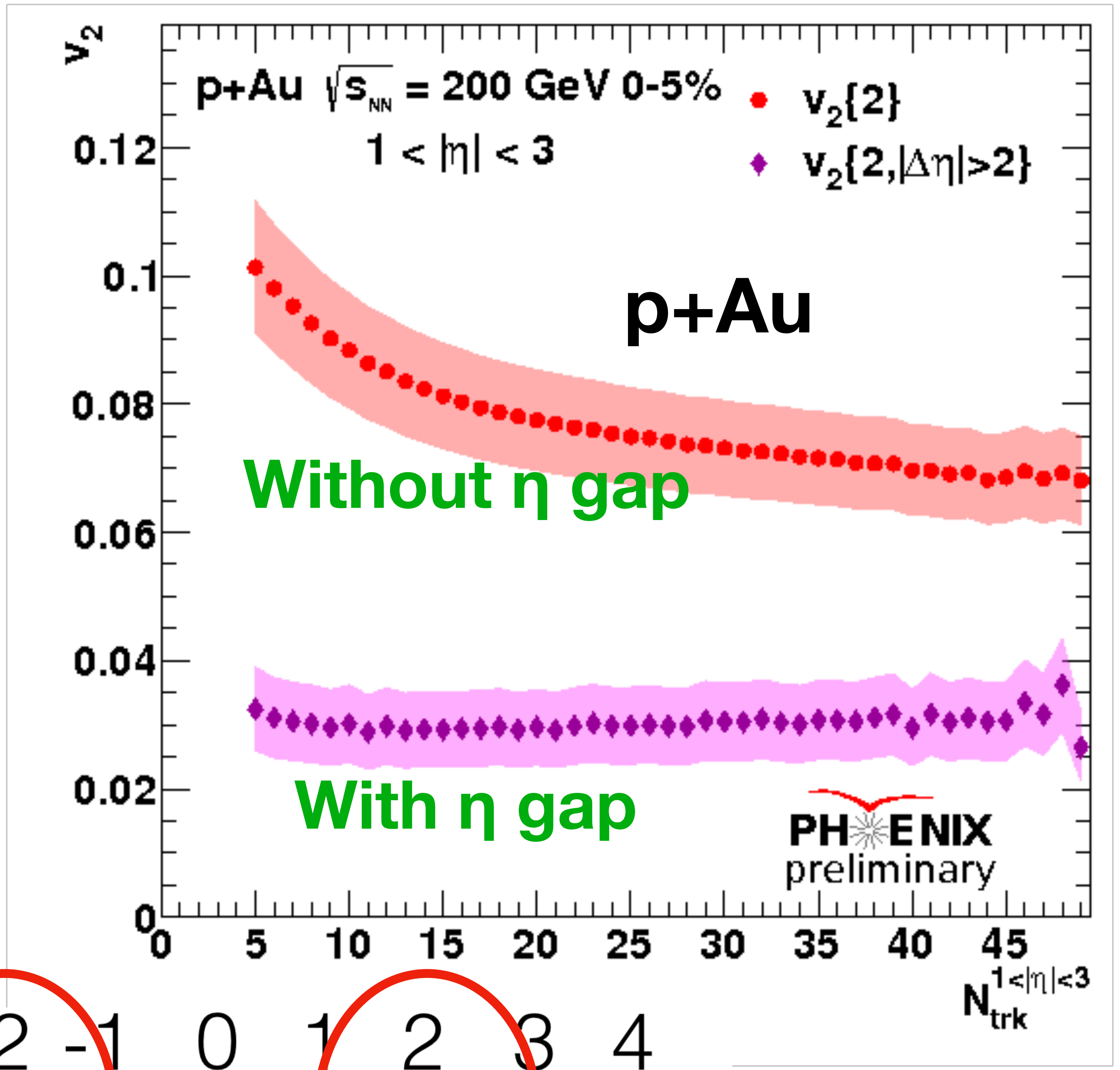
Longitudinal dynamics

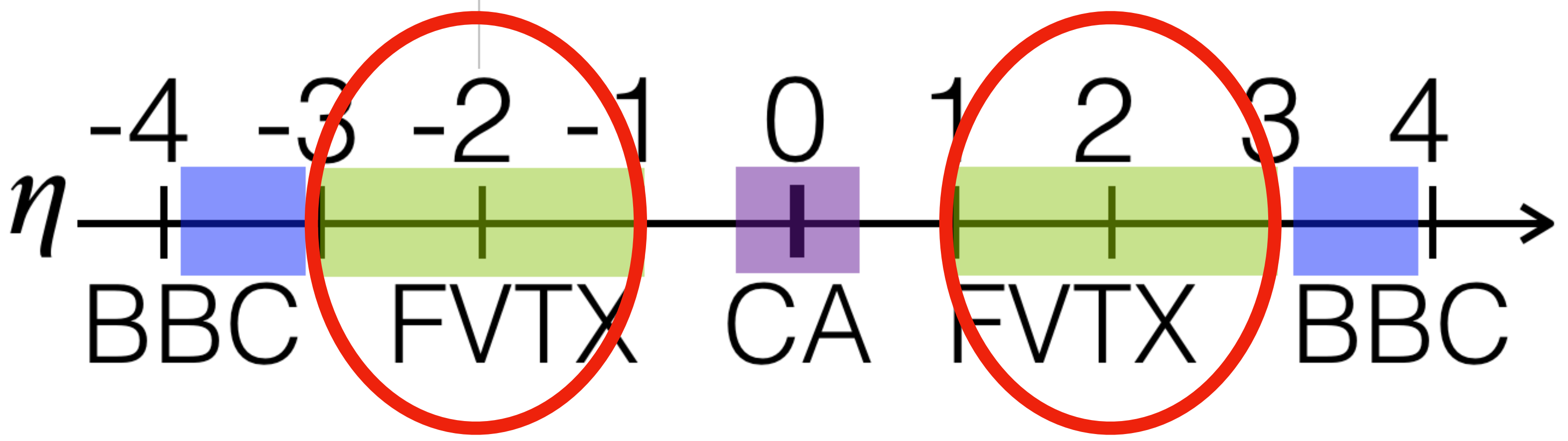
- Larger flow in backward region than in forward region
- Flow and longitudinal particle productions do not scale well in p+A
- non-flow effects are important

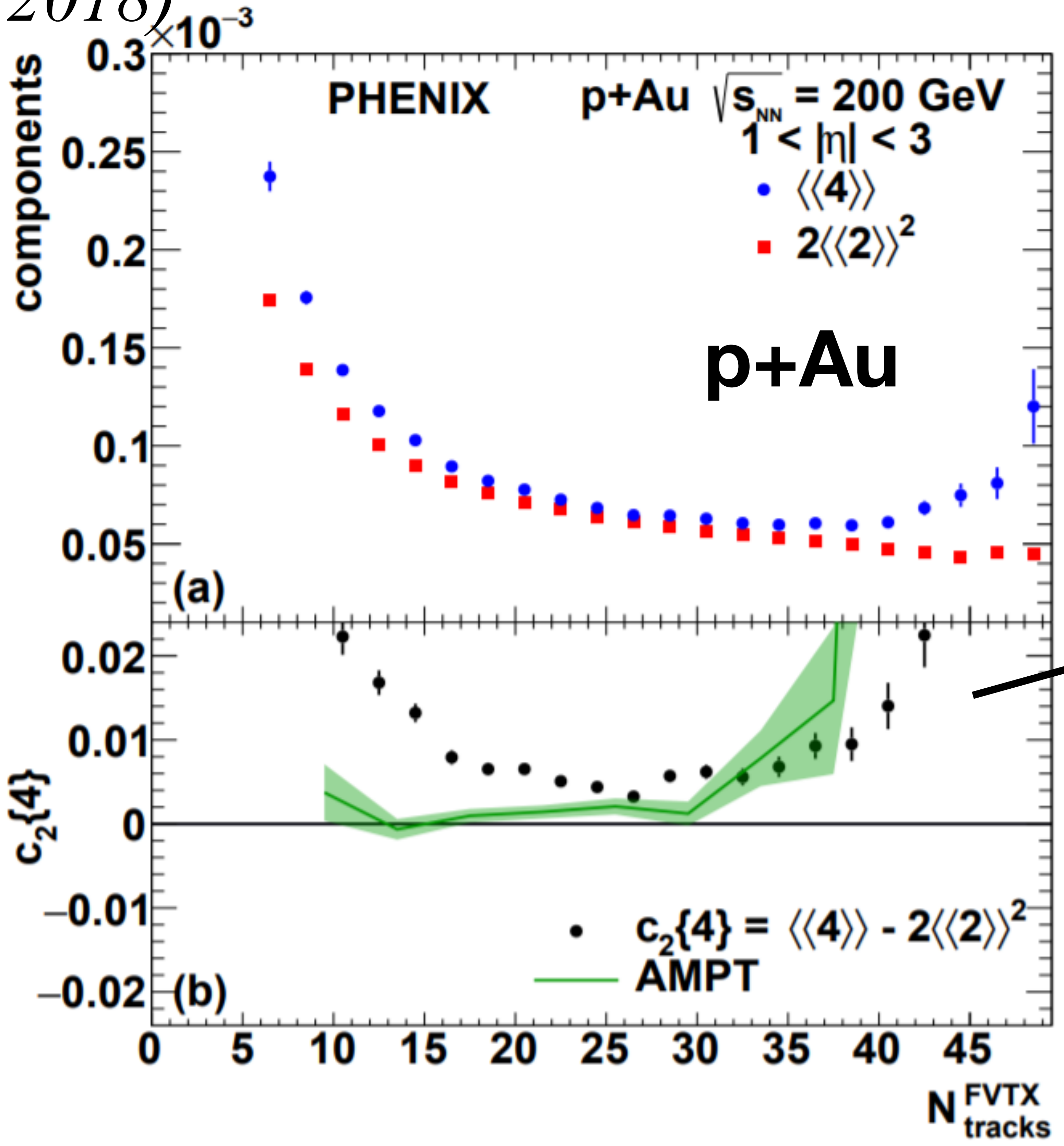
Flow fluctuations

Multi-particle correlations in p+Au

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







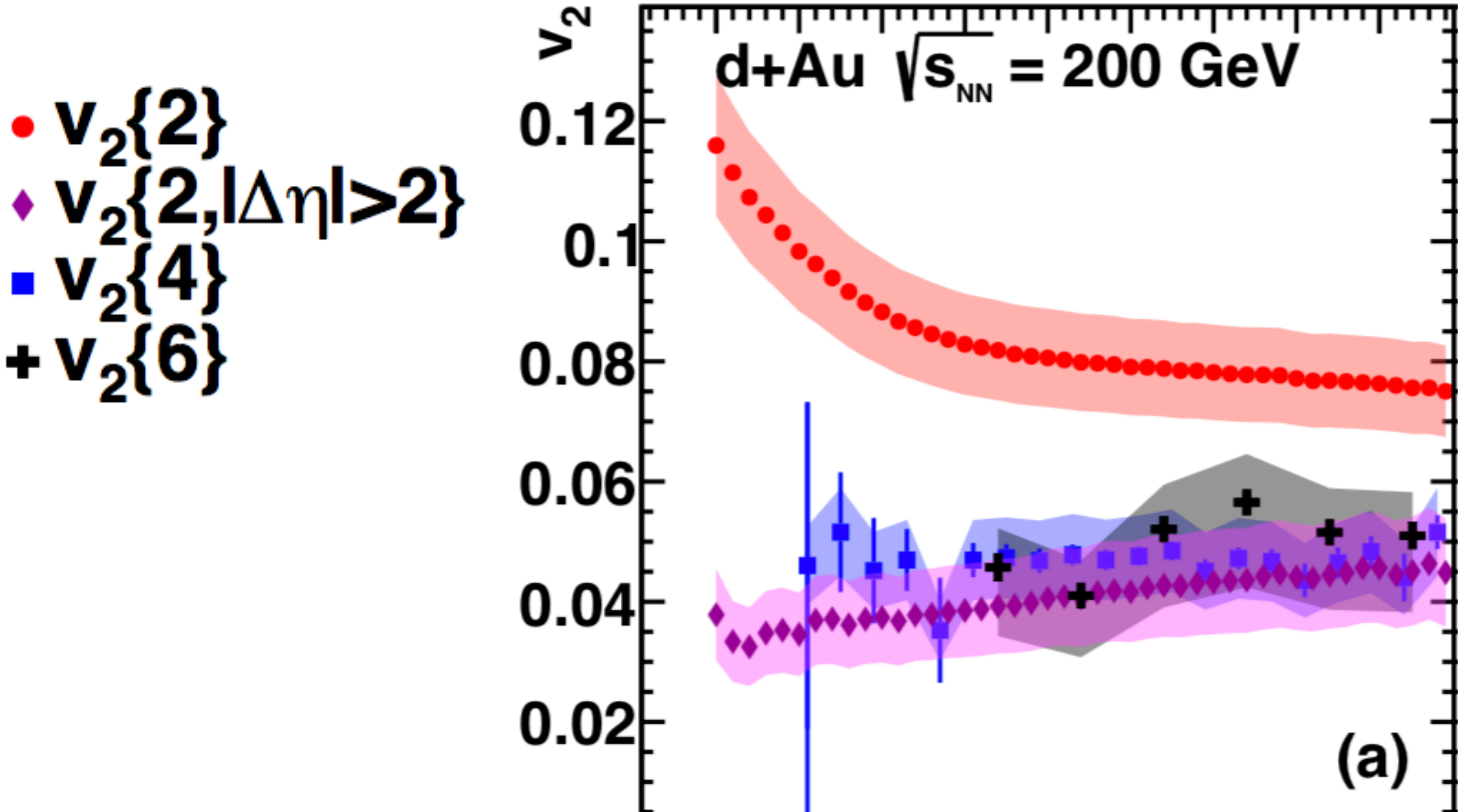
Why is $v_2\{4\}$ in p+Au complex?

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

$c_2\{4\}$ positive <-> $v_2\{4\}$ complex

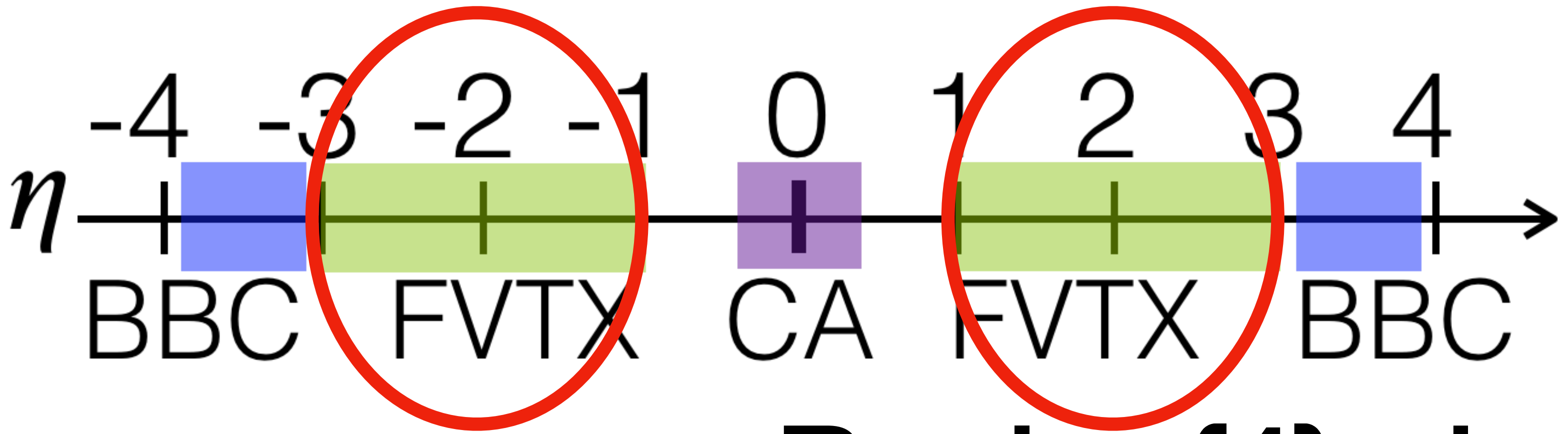
- Adding η gap suppresses non-flow
- Multi-particle correlation suppresses non-flow quite effectively

Multi-particle correlations in d+Au



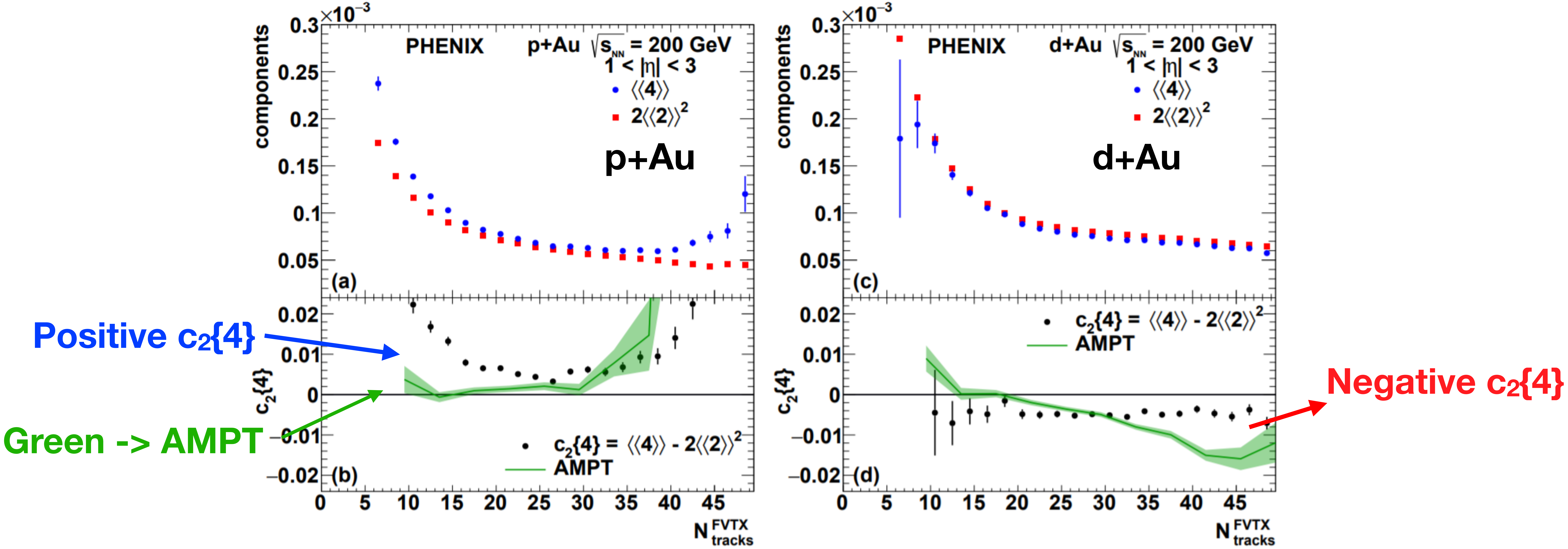
Phys. Rev. Lett. 120, 062302 (2018)

Why are they different?



- Real $v_2\{4\}$ observed
- $v_2\{4\} \approx v_2\{6\}$, strong indication of collectivity

Flow fluctuation from multi-particle correlations



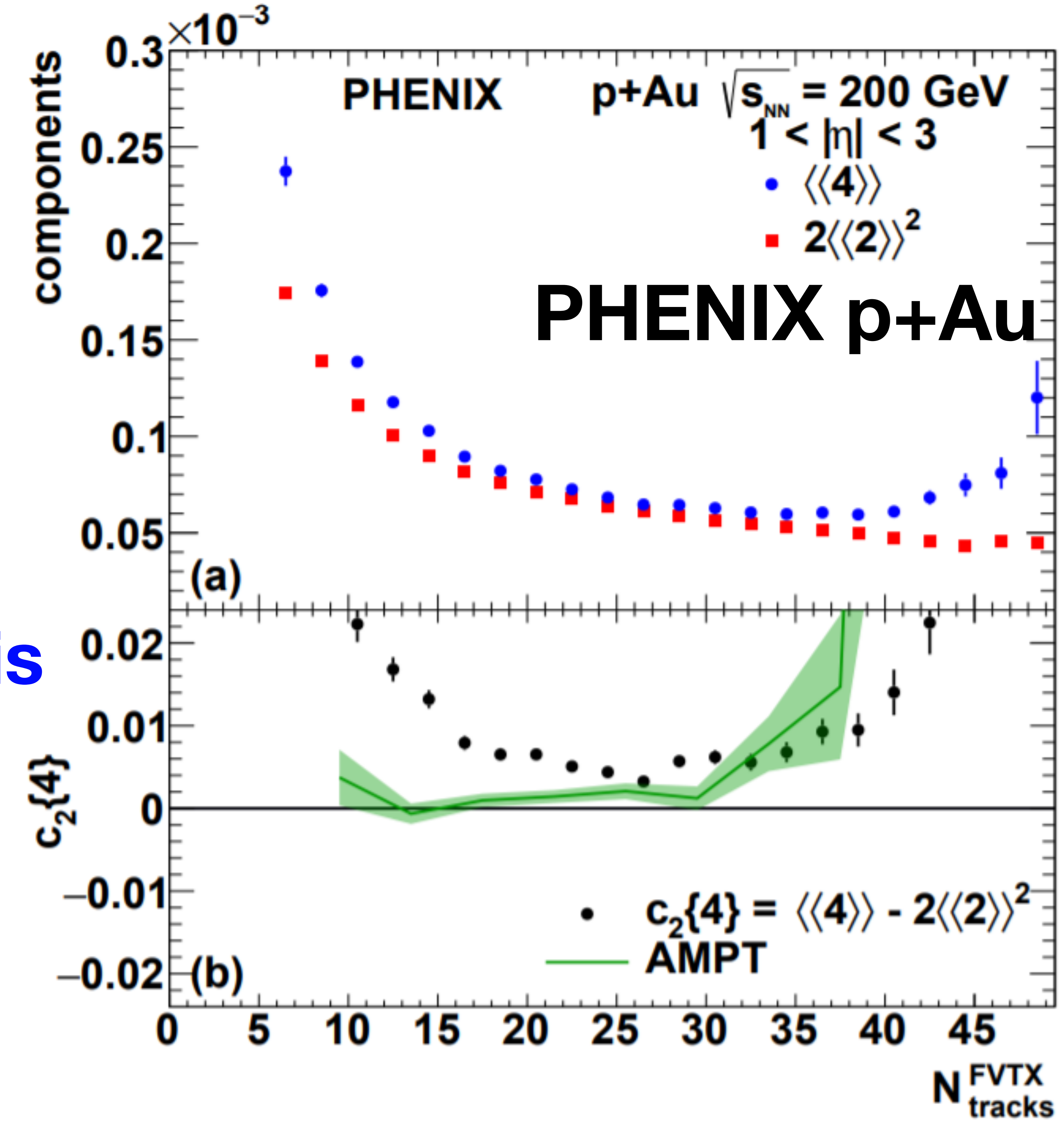
- $v_2\{2\}[\eta\ gap]^2 \approx v_2^2 + \sigma_{v2}^2$ $v_2\{4\}^2 \approx v_2^2 - \sigma_{v2}^2$

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

- If fluctuation σ_{v2} > mean v_2, $c_2\{4\}$ is positive
- Implies collectivity in p+Au is dominated by fluctuations, while d+Au is not
- AMPT (A Multi-phase transport model) describes the sign

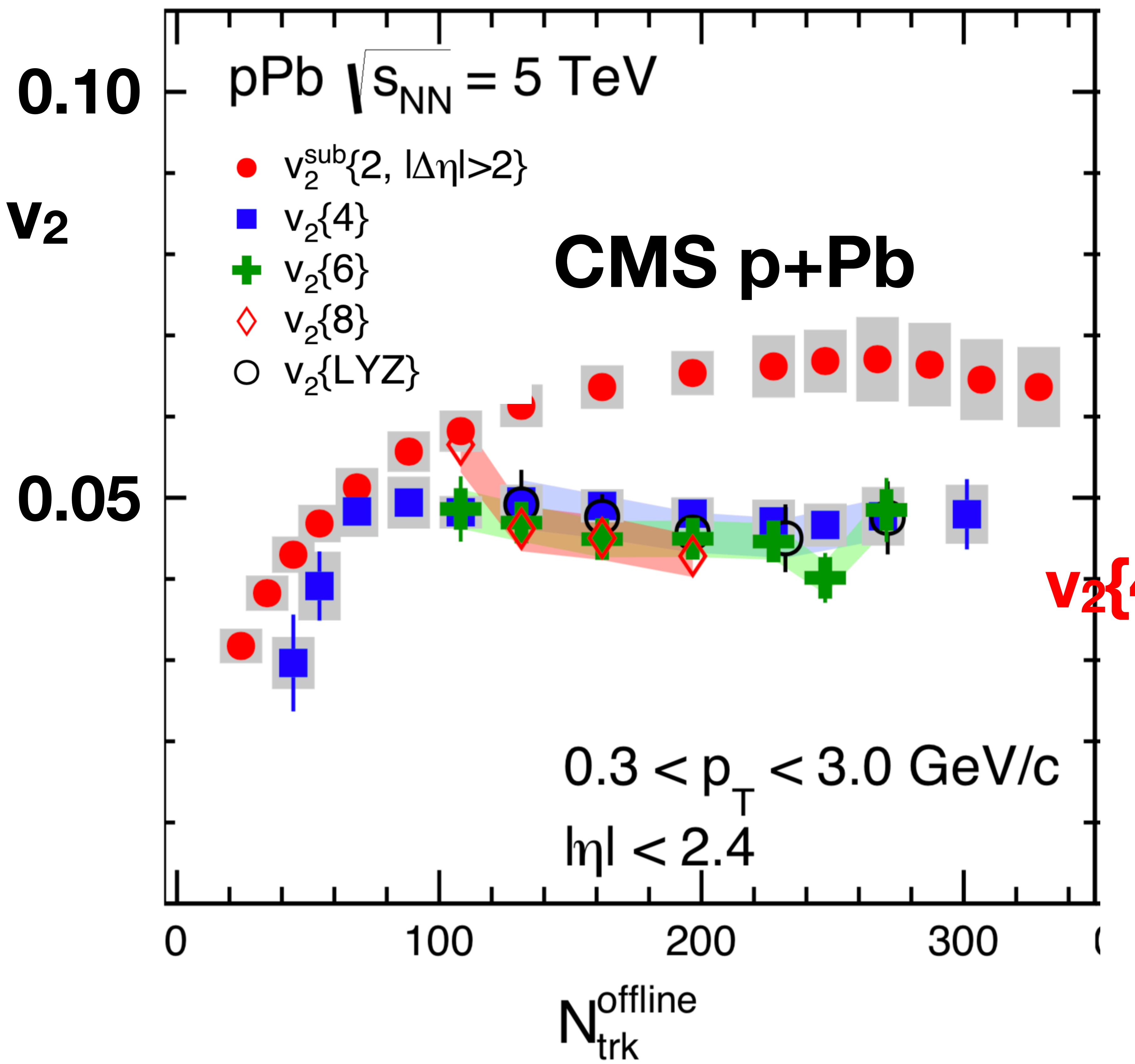
Multi-particle correlations in p+A

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

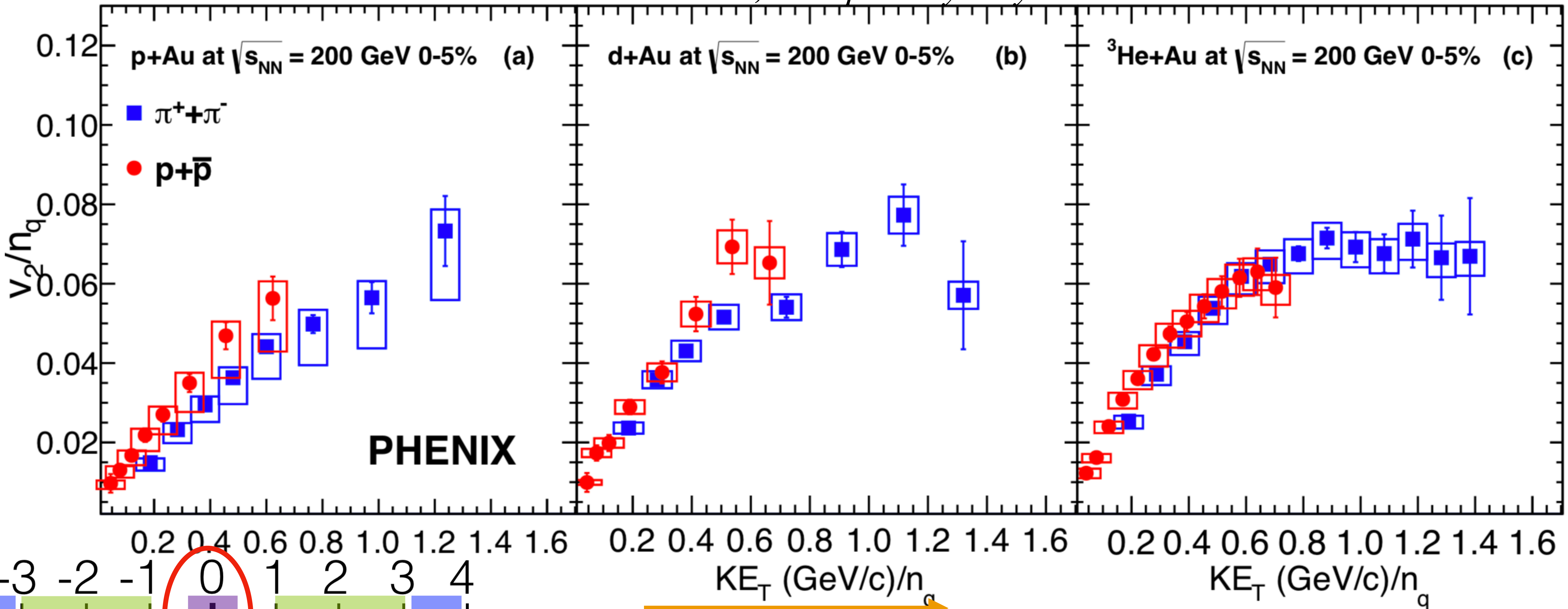
Flow fluctuations

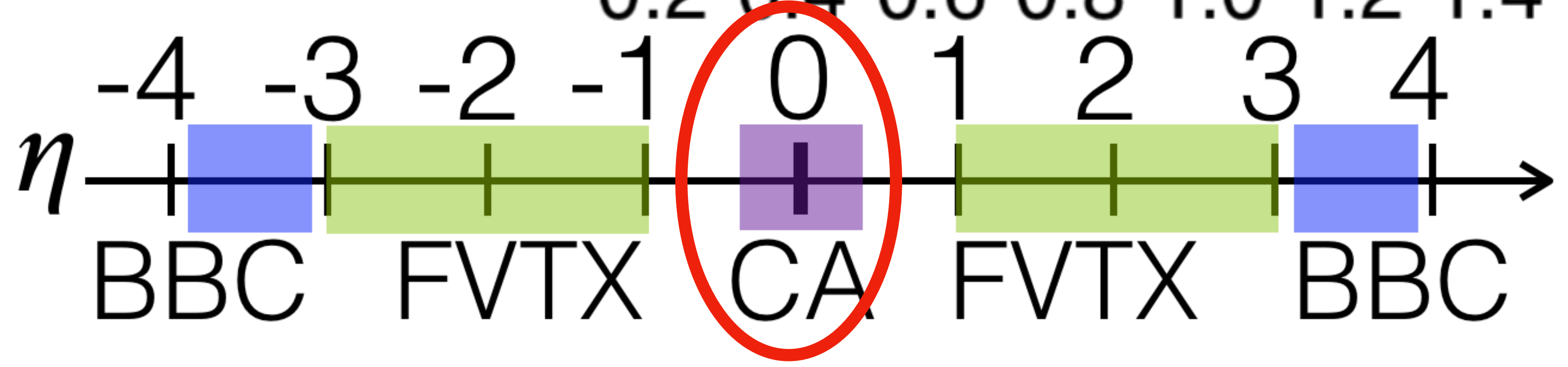
- Small variance limit breaks in p+Au but not d+Au
- Flow fluctuations are the main source of collectivity in p+Au forward/backward rapidities

Flow for identified particles

$v_2(p_T)$ KET scaling for identified $\pi^{\pm}$ and protons

arXiv:1710.09736, accepted by Phys. Rev. C

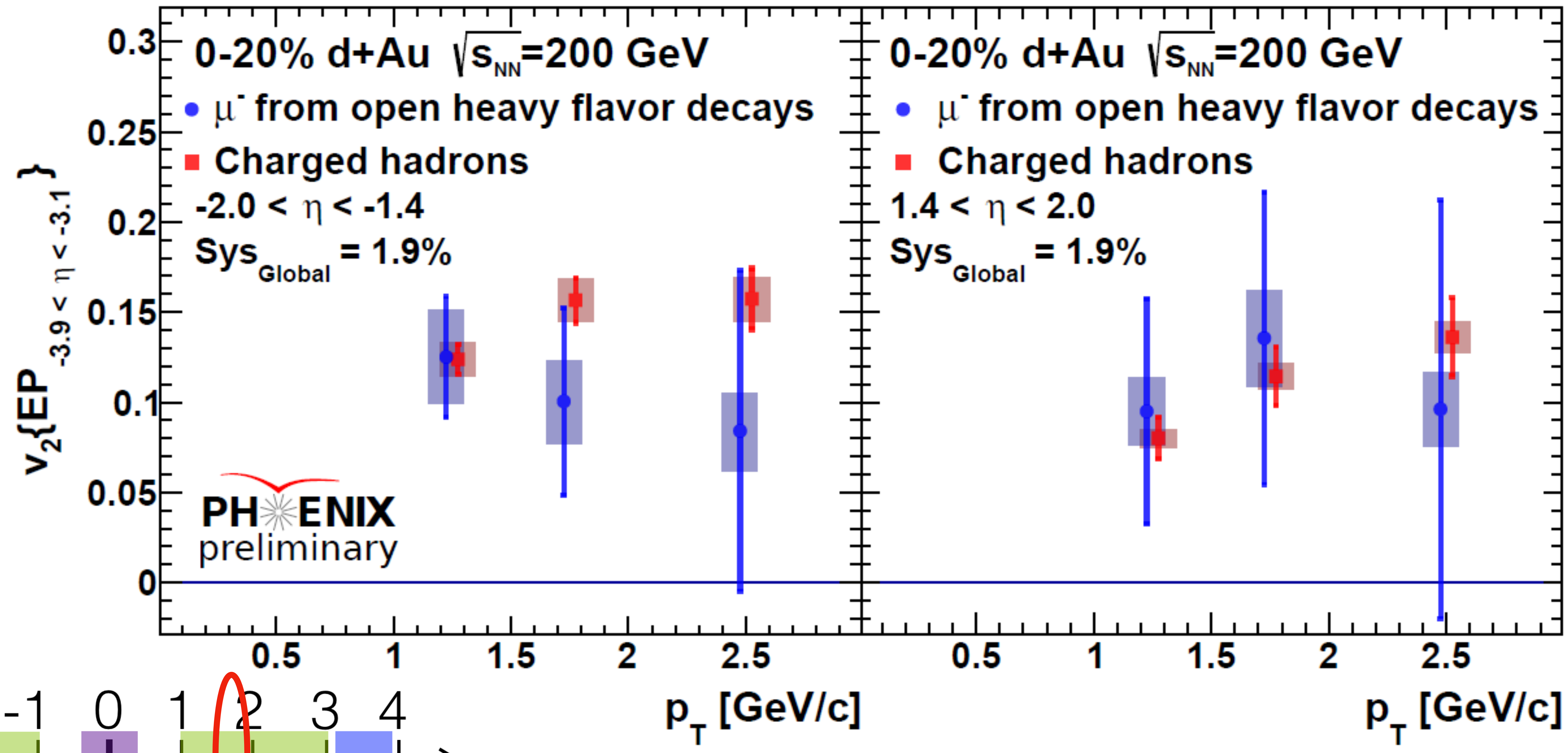


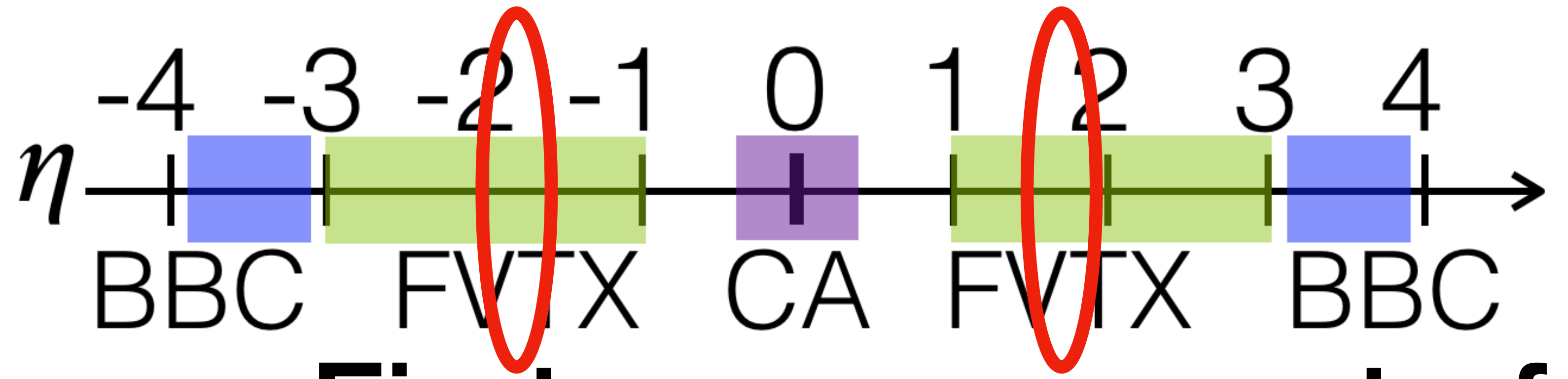


System Size Increases

- Approximate quark number scaling, similar to A+A collisions
- The scaling in larger systems holds better generally

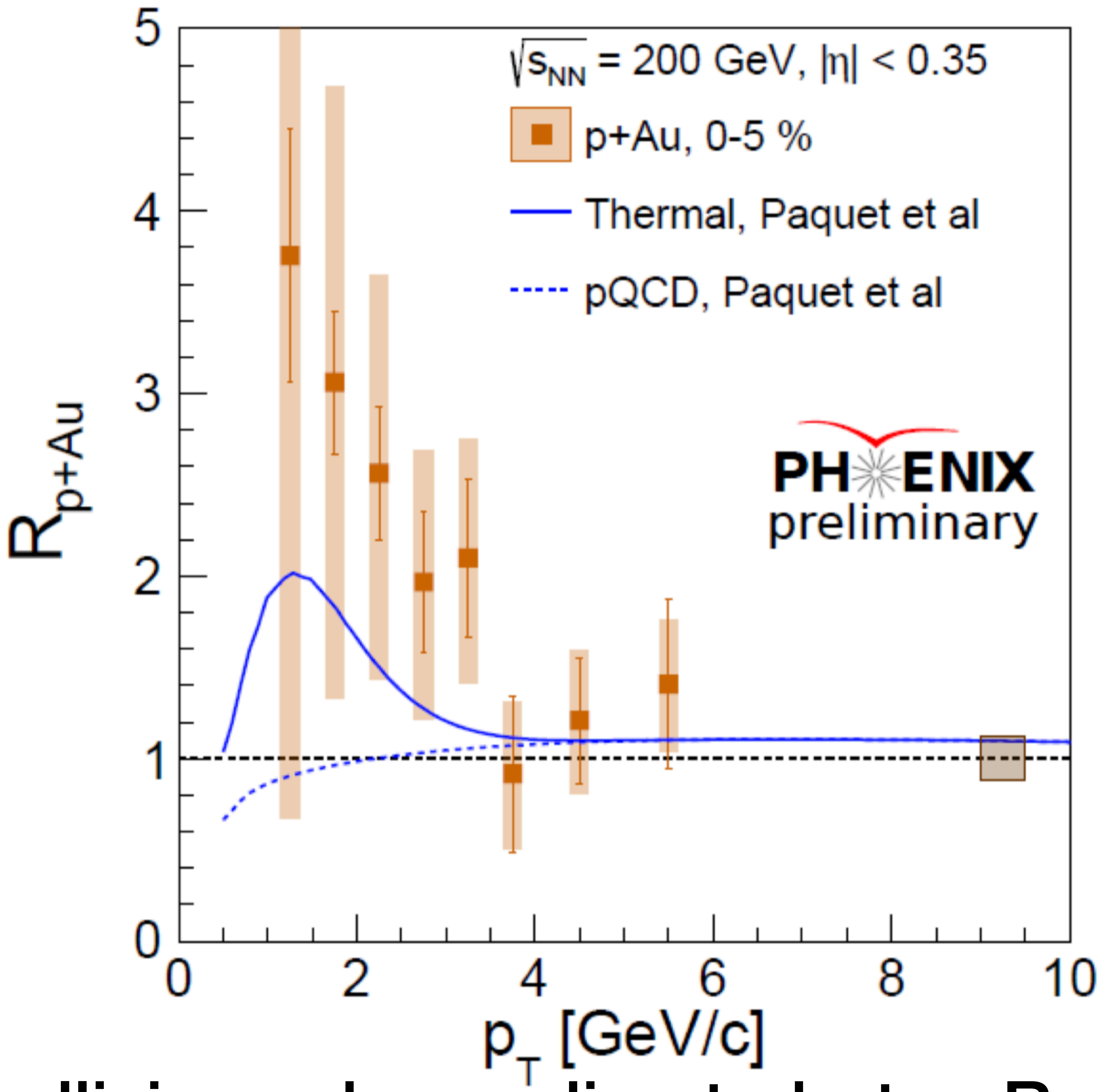
$v_2(p_T)$ for heavy flavor muons

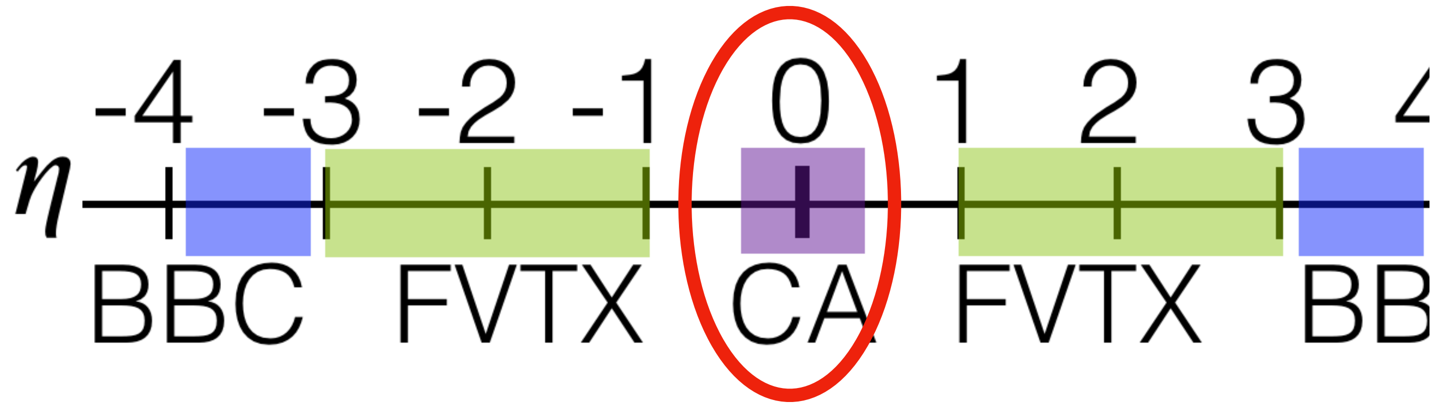




- First measurement of heavy flavor v_2 in small collision systems at RHIC
- Heavy quarks flow even in small collision systems!

R_{pAu} for direct photons





- Central p+Au collisions shows direct photon R_{pAu} > 1
- Data suggests thermal photon yields

Flow for identified particles

- Identified particles flow in a wide range in p+A at RHIC
- Thermal photons yields indicates the existence of QGP
- Flow shows quark number degrees of freedom in p+A

Summary and Conclusions

- Flow and longitudinal particle productions do not scale well in p+A and non-flow effects are important
- Small variance limit breaks in p+A and fluctuations are the main source of collectivity
- Identified particles flow in a wide range in p+A at RHIC
- Flow shows quark number degrees of freedom in p+A
- Hydrodynamics describes (nearly) all the observables
- Any model should describe all the observables simultaneously

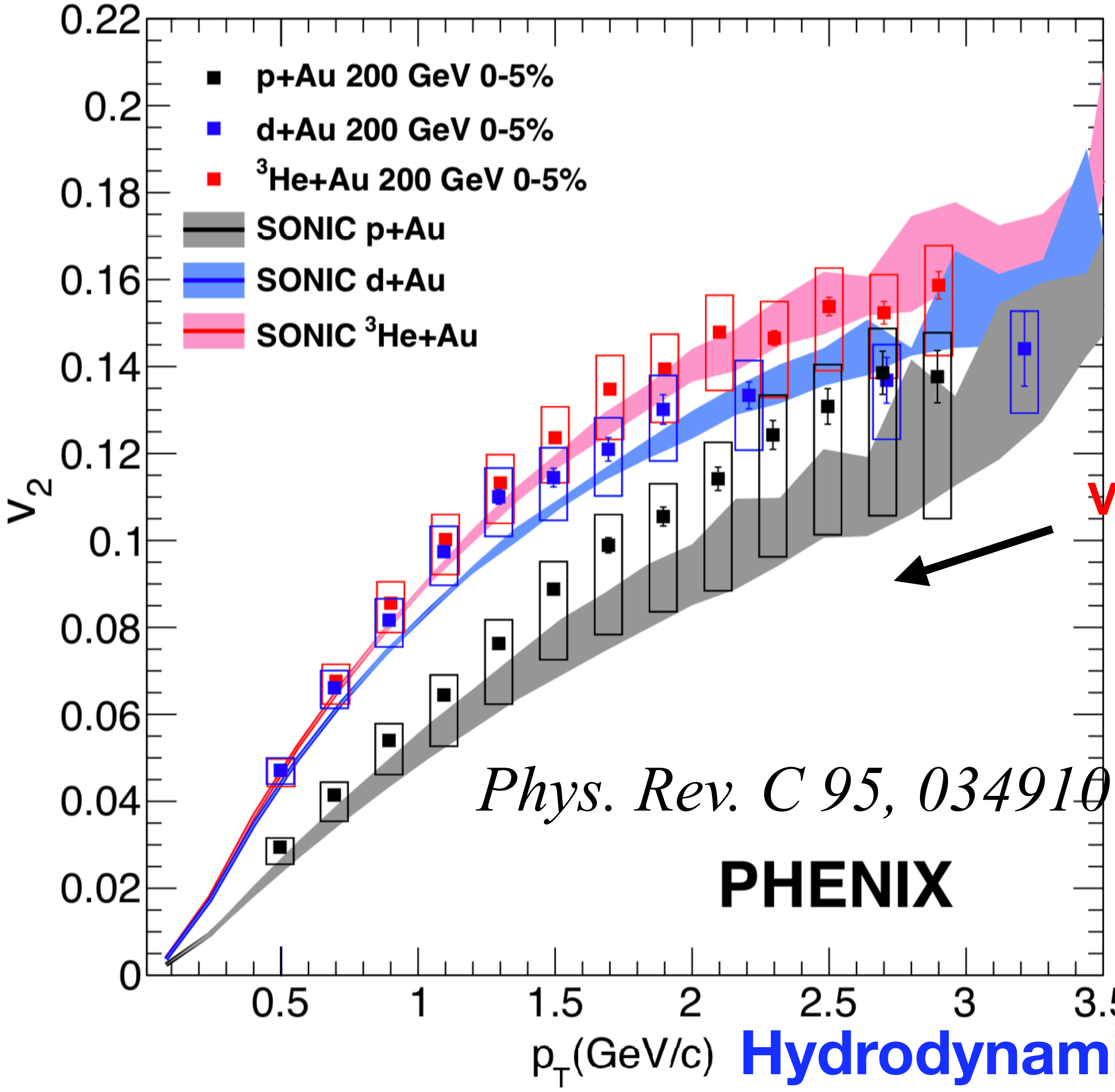
Back Up

p+A collisions ->

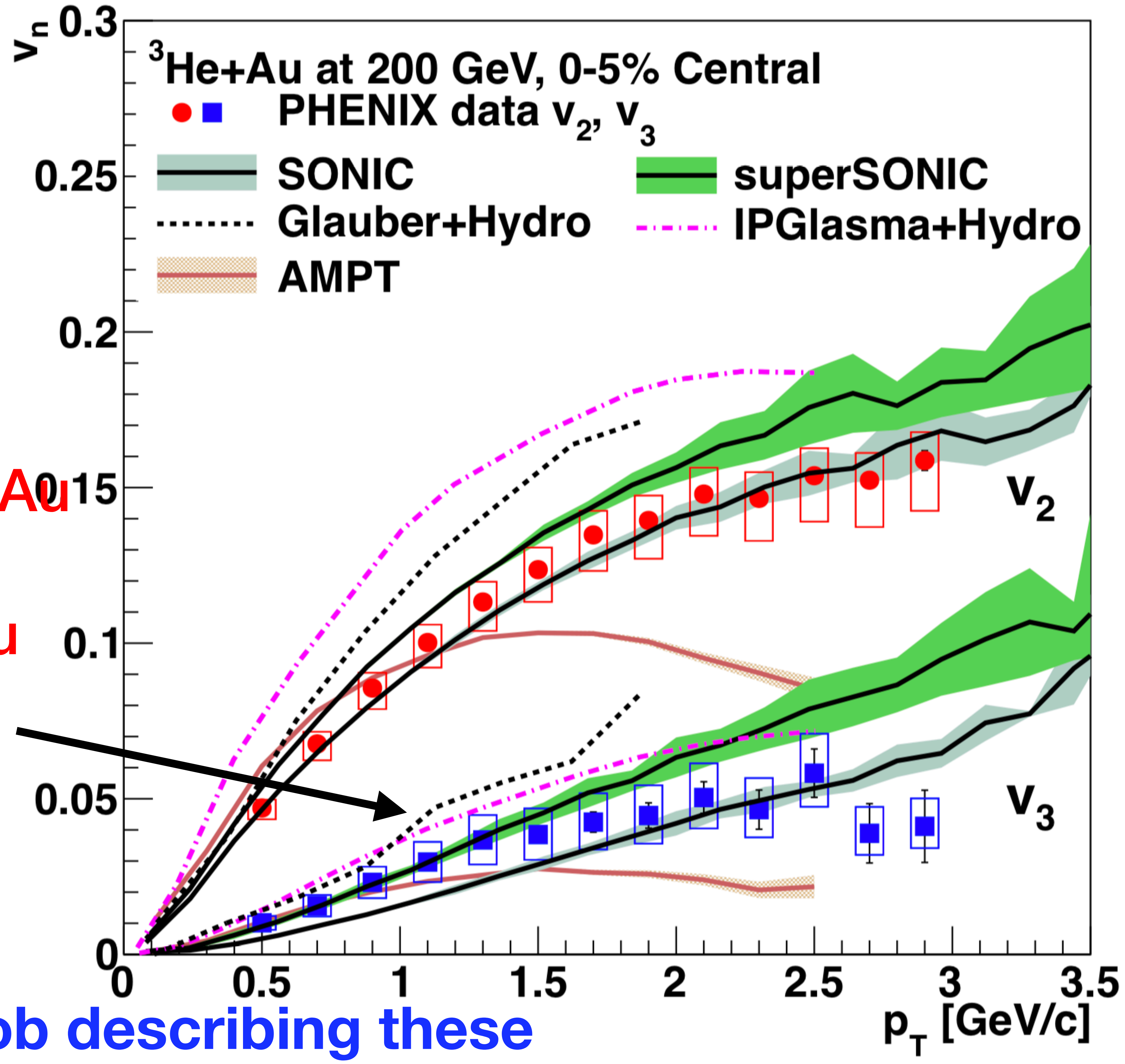
Earlier: Cold Nuclear Effect

Now: Important handle for collectivity

Motivation



Phys. Rev. Lett. 115, 142301 (2015)



v_2 vs p_T in p/d/^{3}He+Au

v_3 vs p_T in ^{3}He+Au

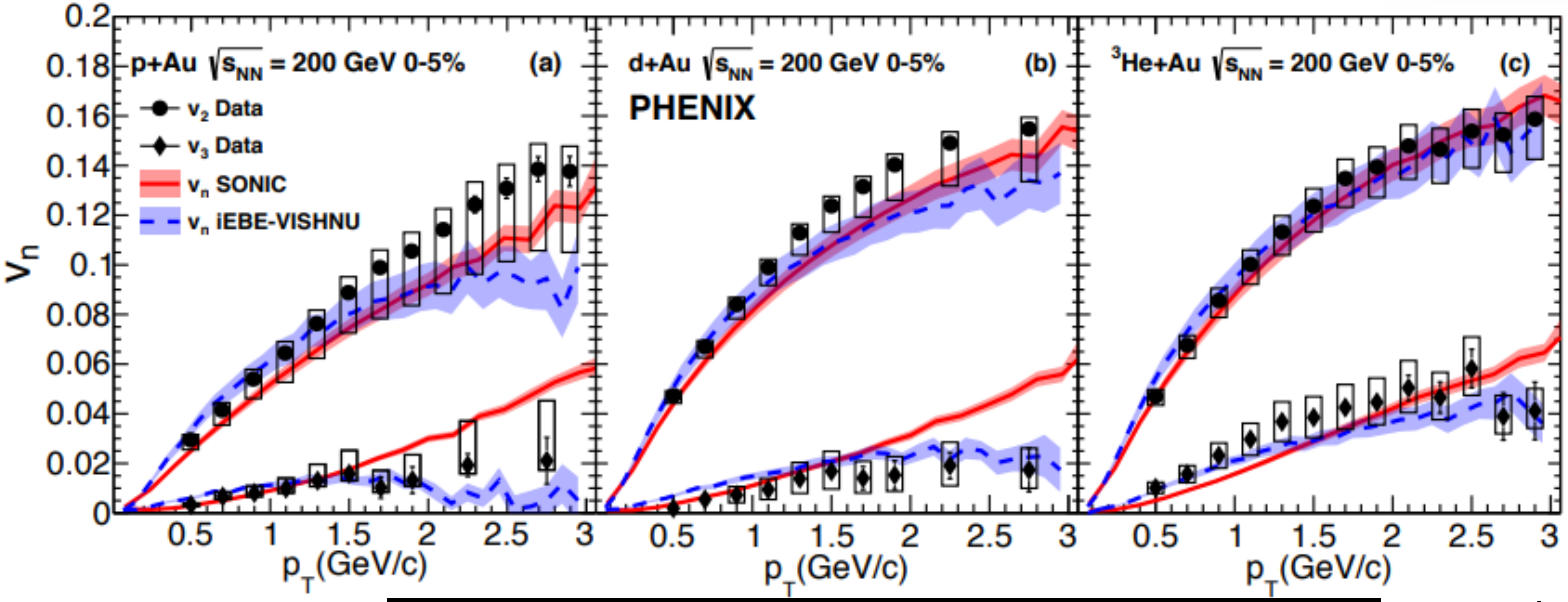
Hydrodynamics does a good job describing these

Some other models also work

At RHIC, two important control experiments are done:

- **Geometry Control Scan -> Change the projectiles and/or targets**
- **Beam Energy Scan on d+Au -> Ranges from 20 GeV to 200 GeV**

Complete sets of GCS



arxiv:1805.02973

η/s = 0.08 in both models

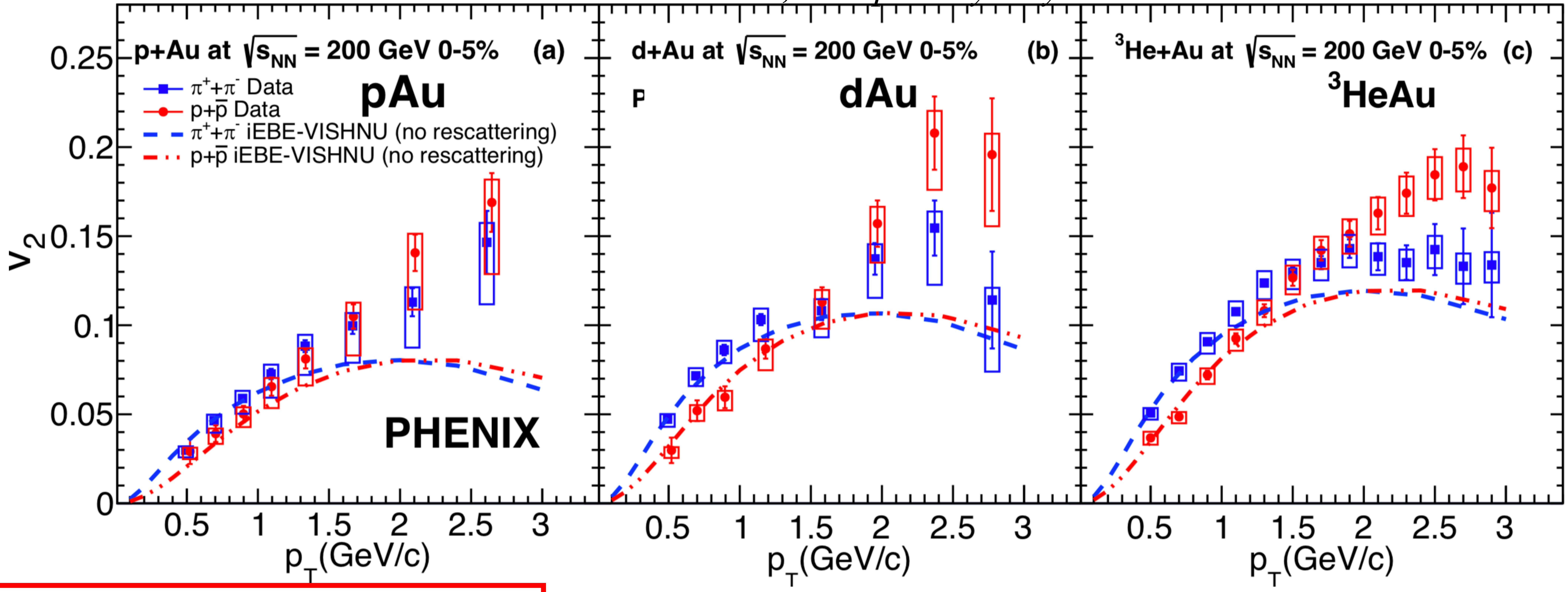
- **hydrodynamical models provide a simultaneous and quantitative description of the data in all three systems.**

At RHIC, two important control experiments are done:

- Geometry Control Scan -> see Sylvia's presentation tomorrow
- Beam Energy Scan on d+Au -> ranges from 20 GeV to 200 GeV

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

arXiv:1710.09736, accepted by Phys. Rev. C

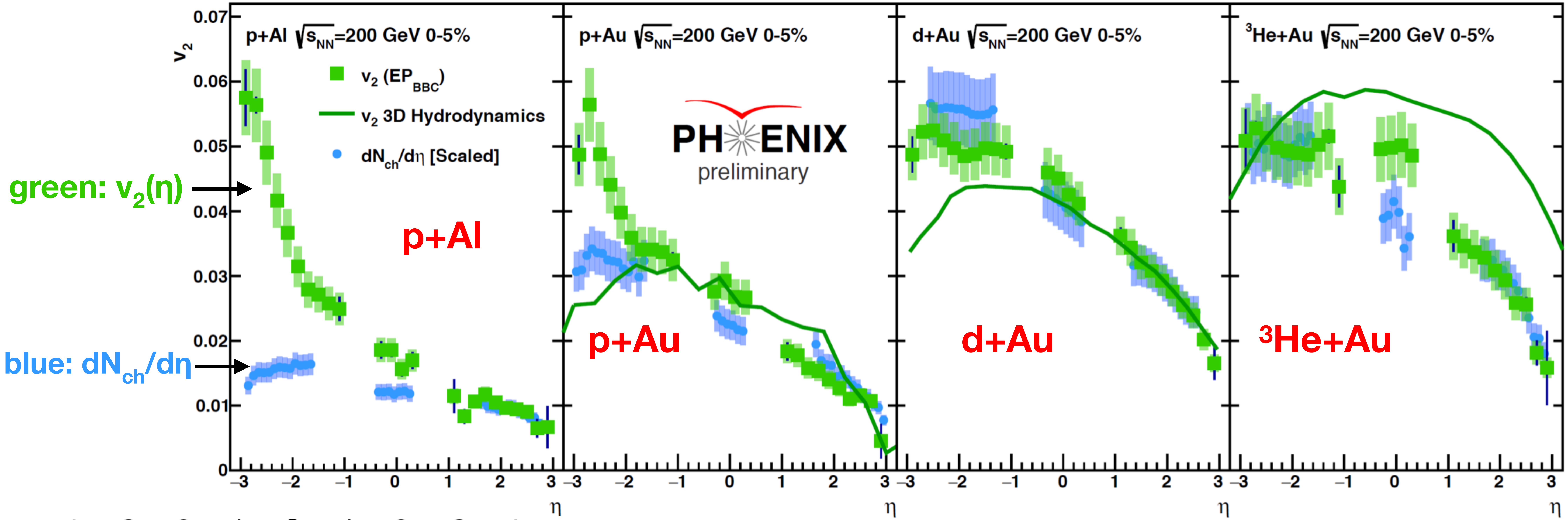


See more at session 'Collectivity in small systems' 11:10am 15th by Sylvia Morrow

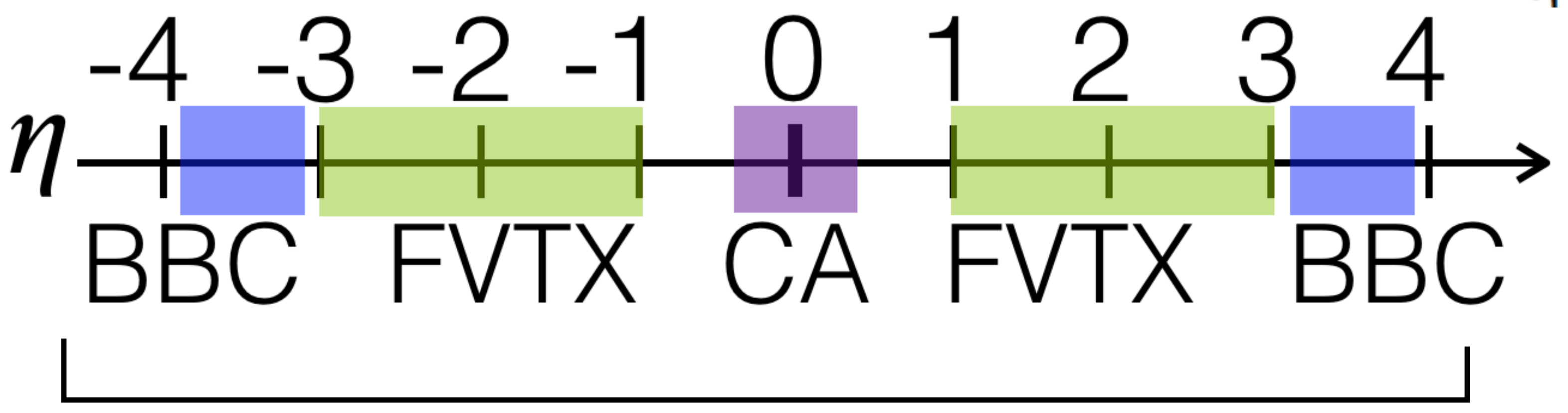
System Size Increases

- $v_2(\pi^\pm) > v_2(\text{proton})$ 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

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



System Size Increases



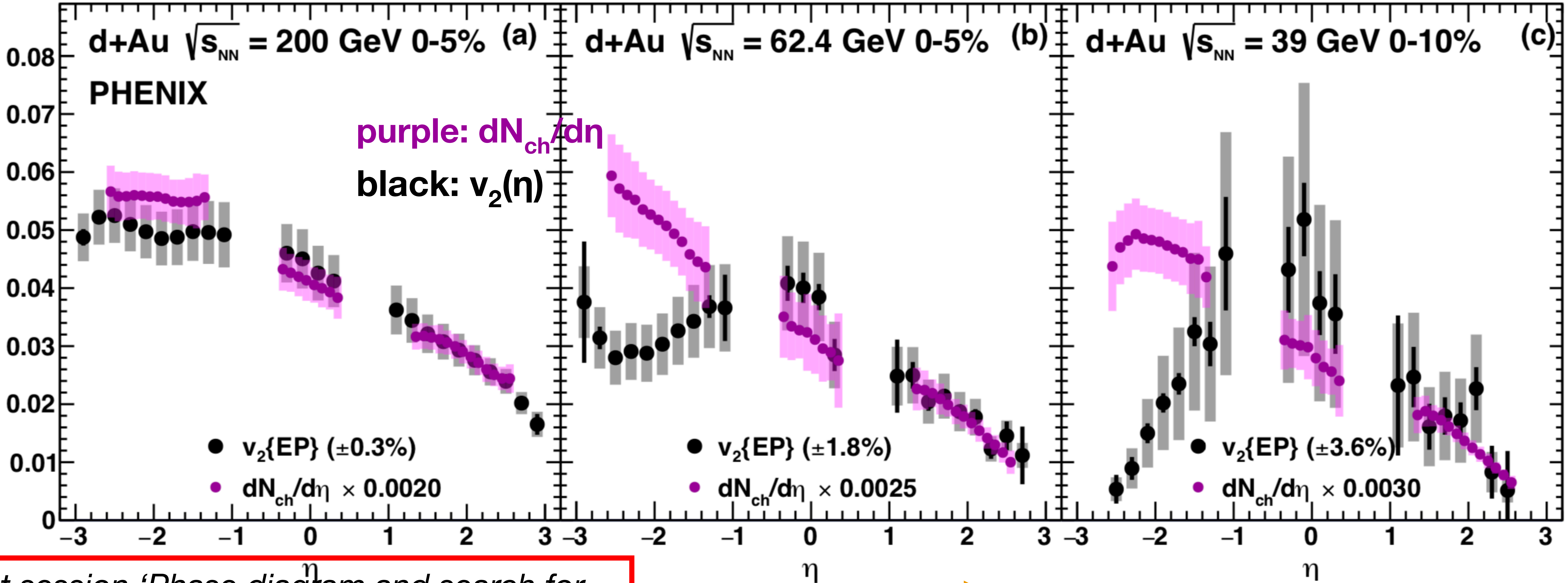
Wide rapidity range

- d+Au scales well, but p+Au does not at backward rapidity, non-flow becomes more significant
- 3D hydrodynamics quantitatively describes the data in p+Au

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

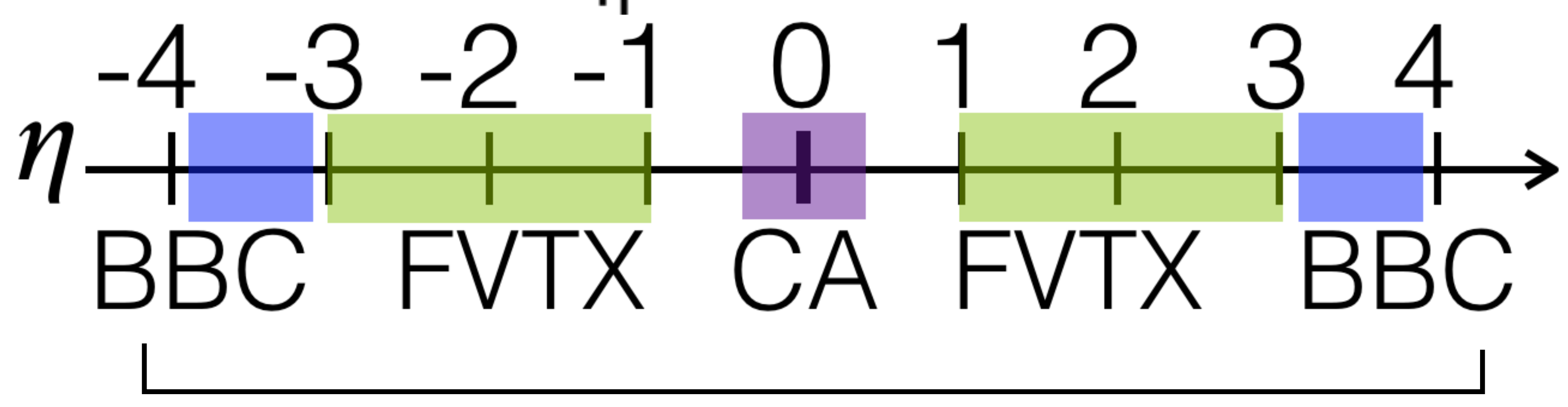
$v_2(\eta)$ vs $dN_{ch}/d\eta$ in Beam Energy Scan

Phys. Rev. C 96, 064905 (2017)



See more at session 'Phase diagram and search for the critical point' 10:20am 16th by Darren McGlinchey

Energy Decreases



Wide rapidity range

- Scaling holds, except at lower energy backward rapidity
- v2(η) contains non-flow
- Flow & non-flow anti-correlation?

The event plane is measured in $-3.0 < \eta < -1.0$

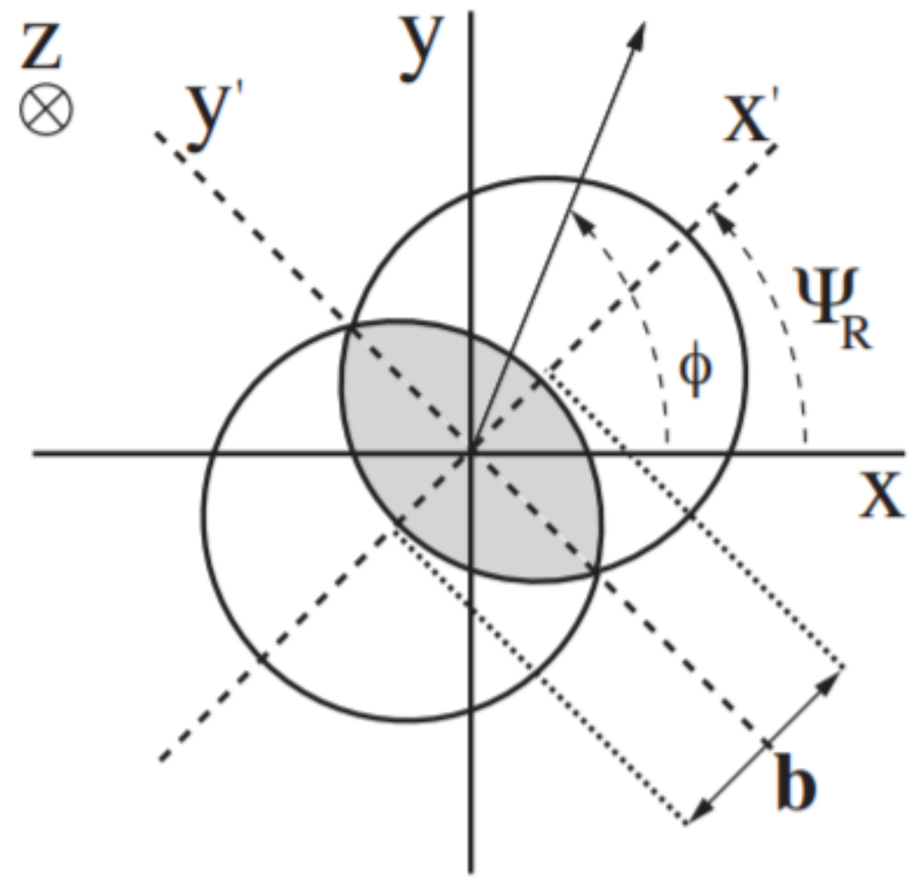
Analysis methods for Flow

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:

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

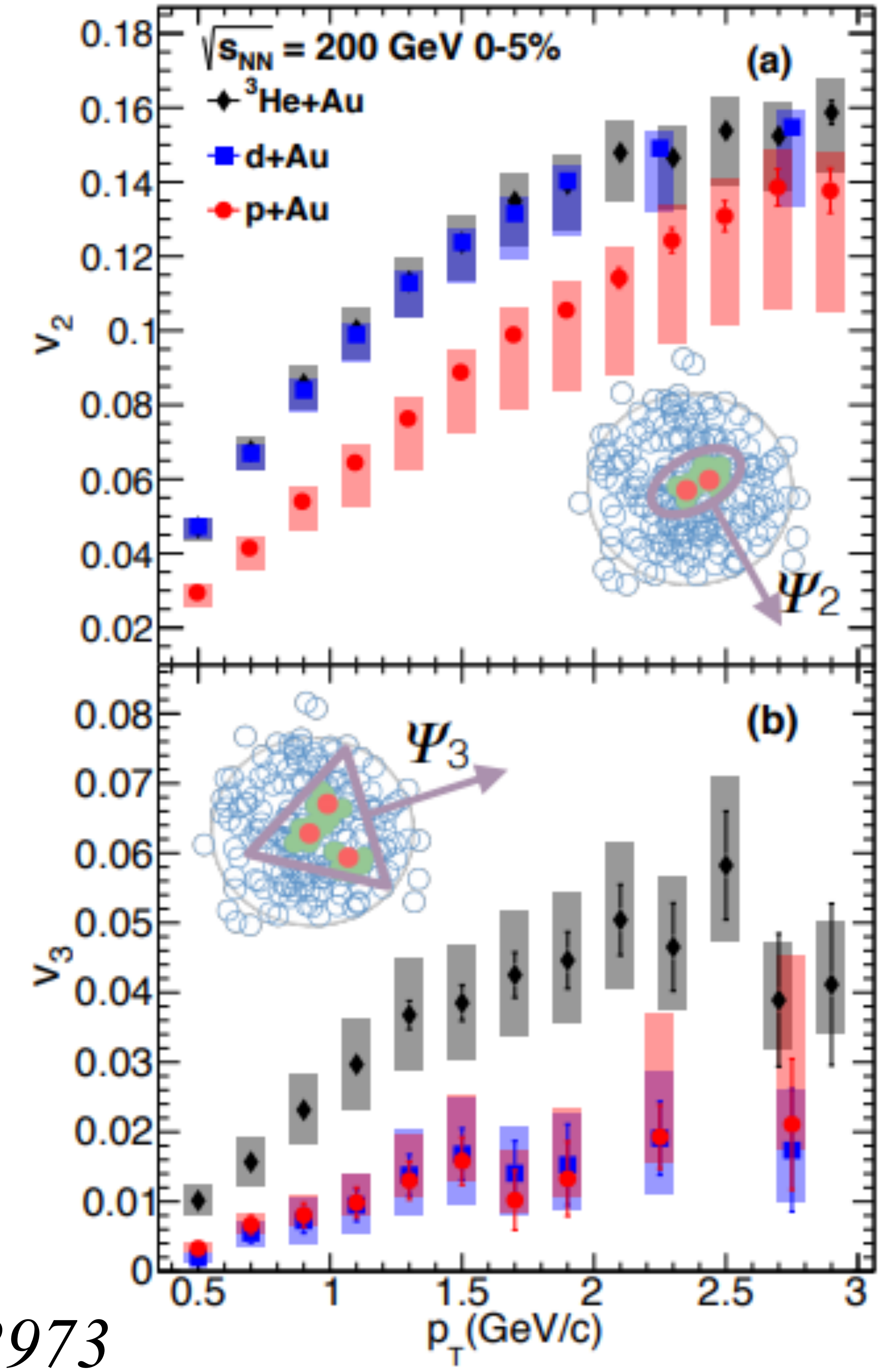
$$\langle 4 \rangle \equiv \langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)} \rangle \equiv \frac{1}{P_{M,4}} \sum_{i,j,k,l}{}' e^{in(\phi_i+\phi_j-\phi_k-\phi_l)},$$

$v_2(p_T)$ and $v_3\,(p_T)$ for hadrons

$$v_2^{p+\mathrm{Au}} < v_2^{d+\mathrm{Au}} \approx v_2^{^3\mathrm{He+Au}},$$
$$v_3^{p+\mathrm{Au}} \approx v_3^{d+\mathrm{Au}} < v_3^{^3\mathrm{He+Au}}.$$

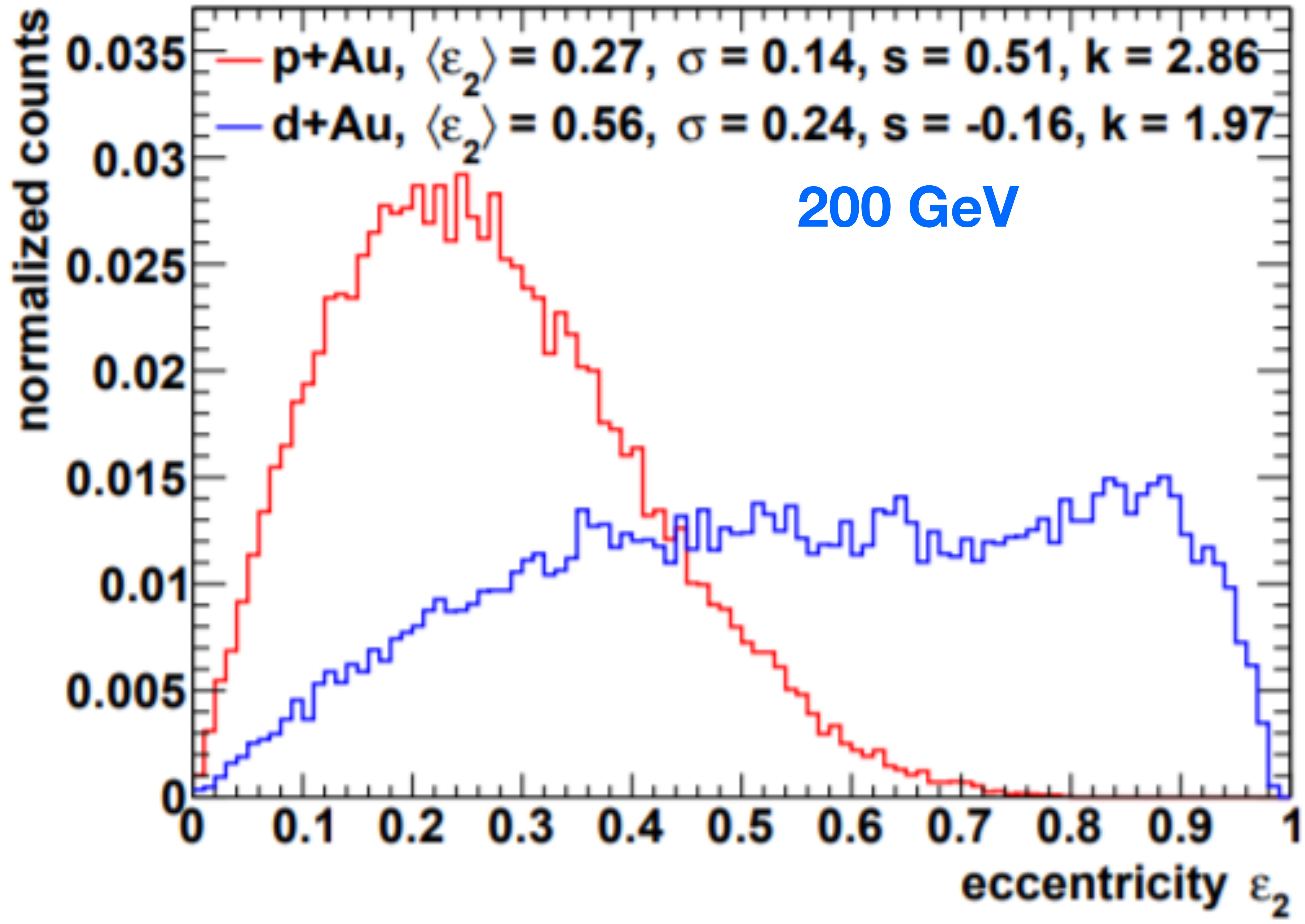
- Hydrodynamics can efficiently translate the initial geometric ε_n's into v_n's
- Rule out initial moment correlation picture where we expect:

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



arxiv:1805.02973

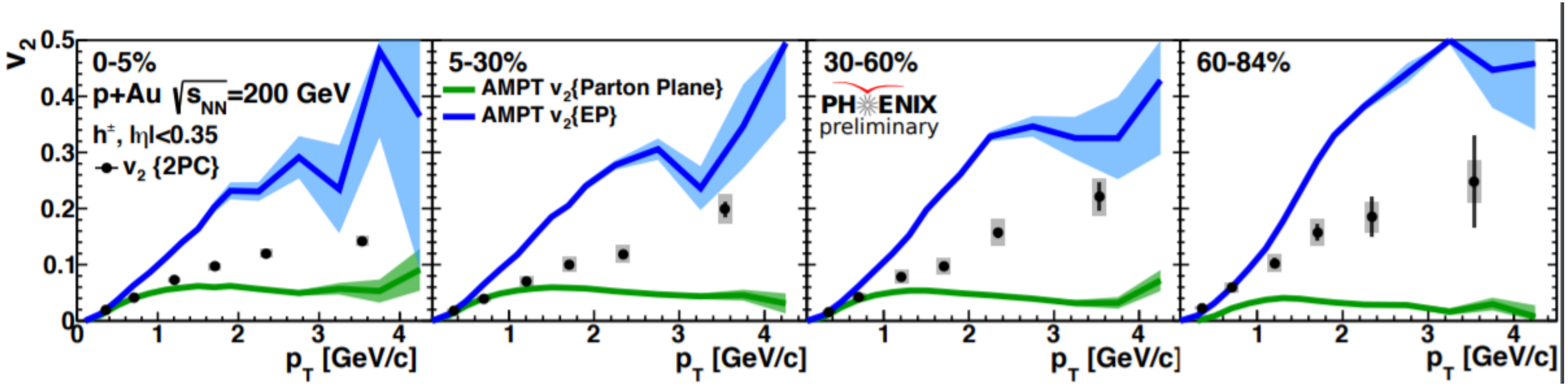
Eccentricity distribution



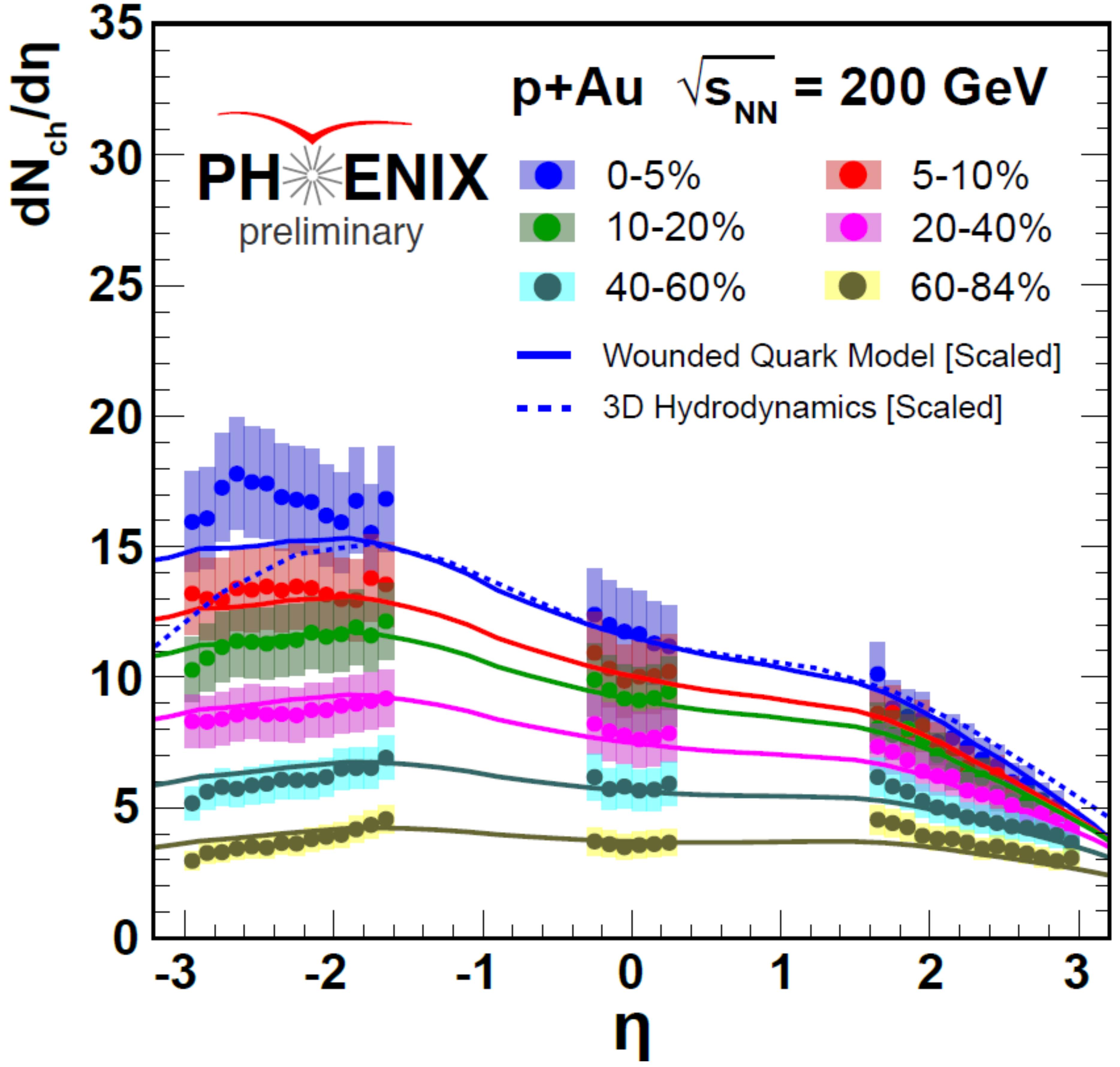
- High skewness in p+Au, deviates from Gaussian
- Additional flow fluctuation in p+Au must take place

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

$v_2(p_T)$ in different centrality bins



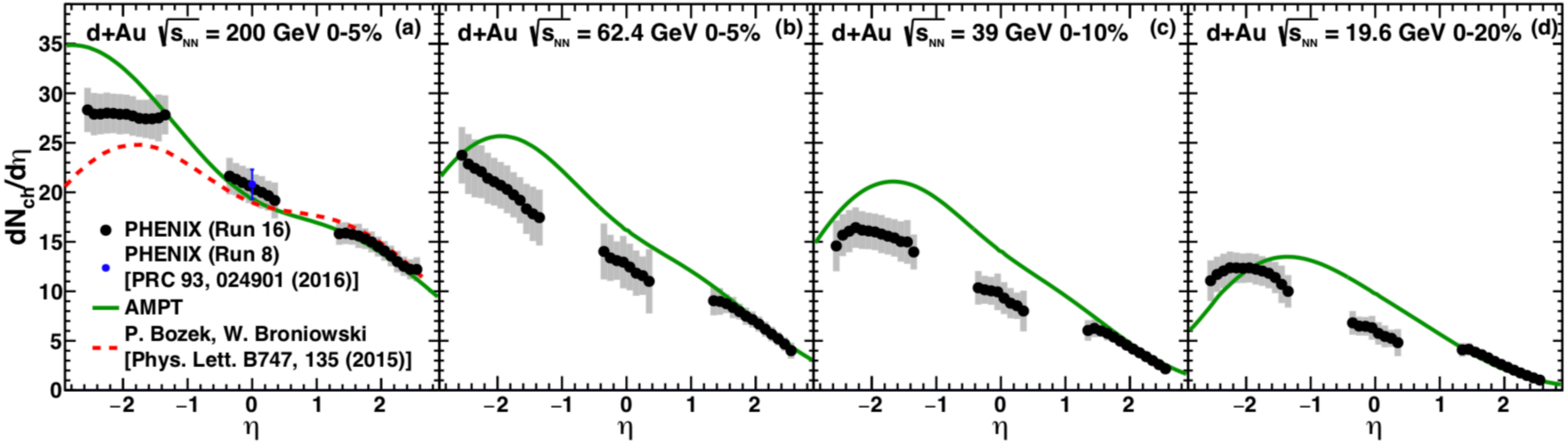
$dN_{ch}/d\eta$ vs centrality in p+Au



***arXiv:1712.02618* [hep-ph]**

- Wounded Quark Model: Heavy-Ion collisions consists of independent quark-quark collisions
- Assuming a common quark source

$dN_{ch}/d\eta$ in BES



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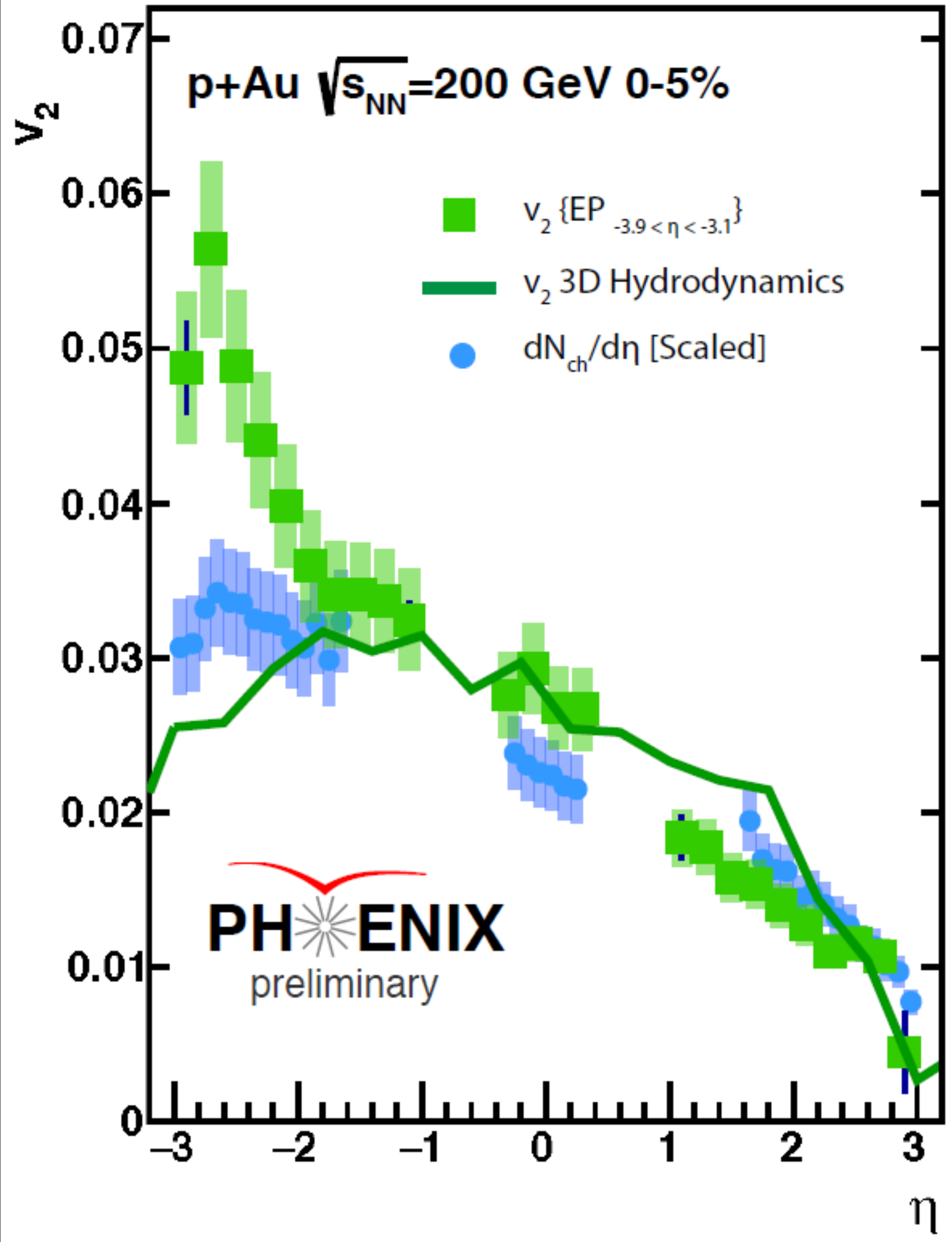
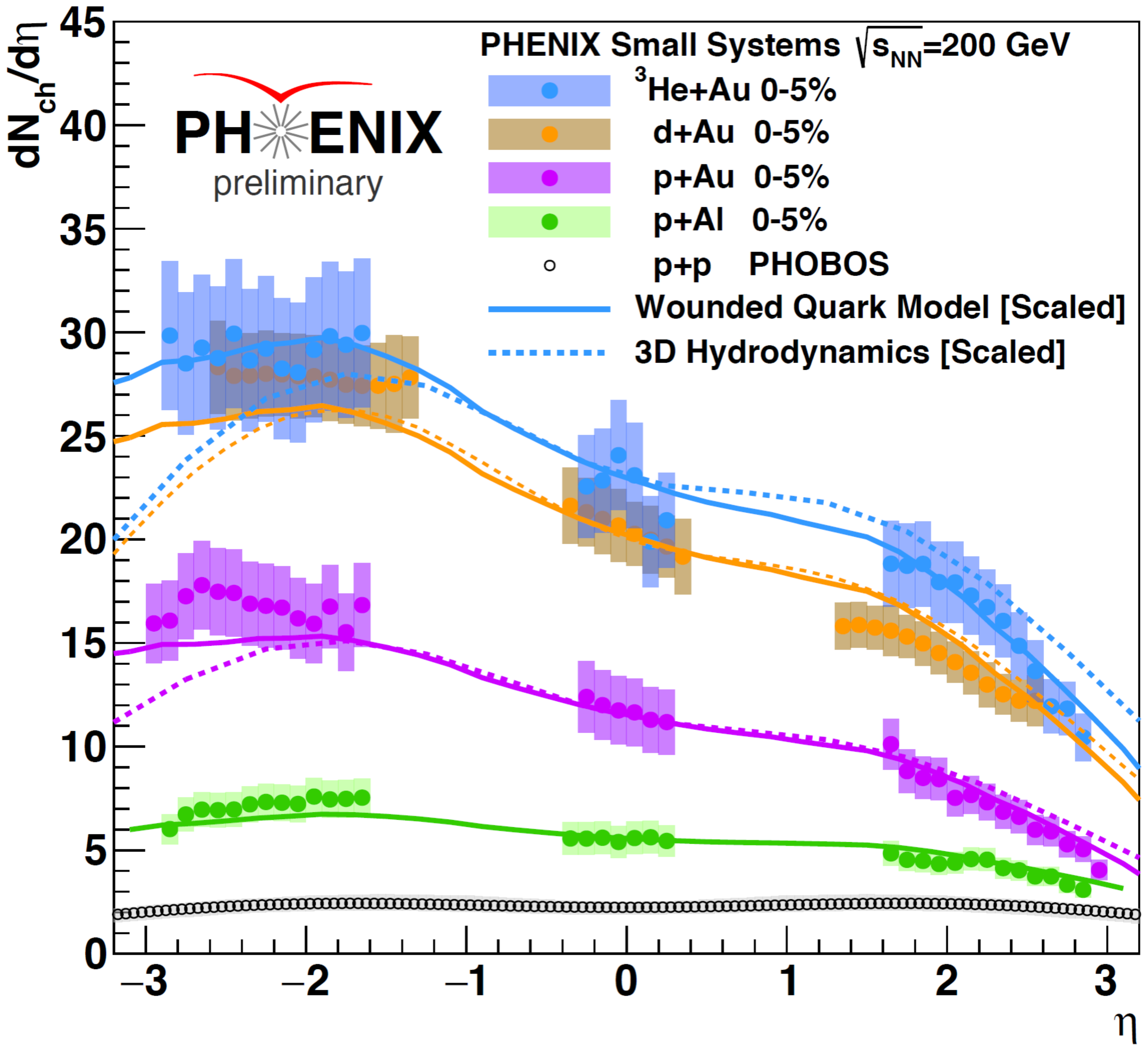
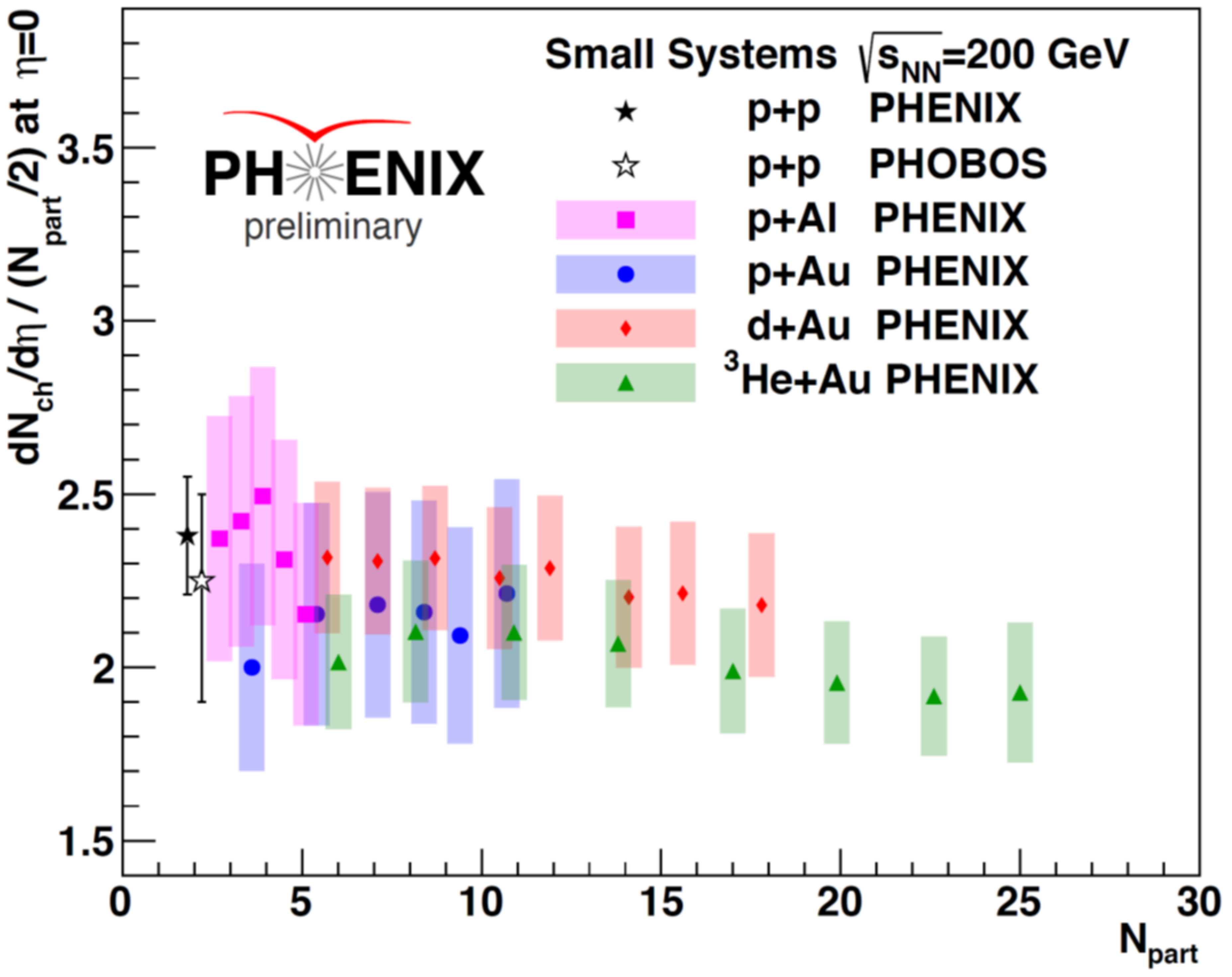
$dN_{ch}/d\eta$ vs $v_2(\eta)$ in small systems



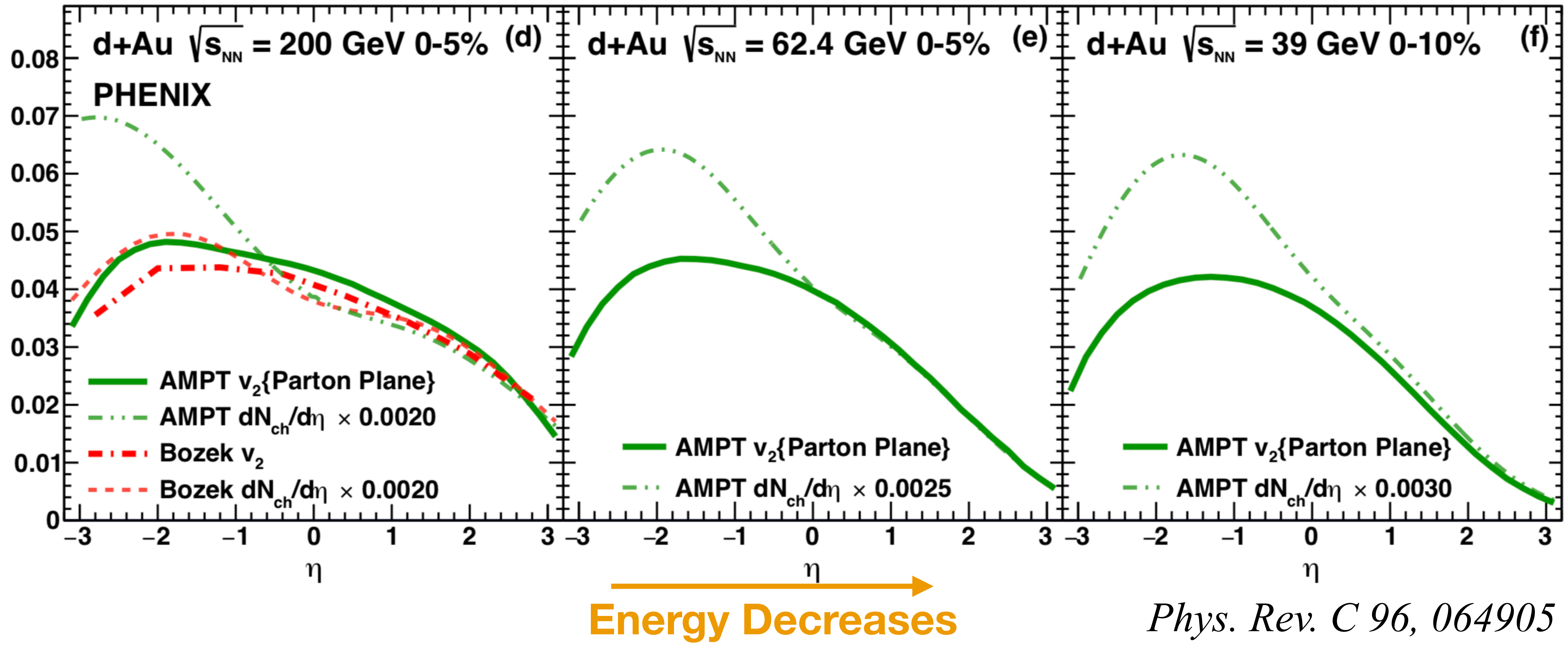




- Hydro describes the shape well, although deviation in the very backward region

- All the small system $dN_{ch}/d\eta$ scales with N_{part}

$v_2(\eta)$ and $dN_{ch}/d\eta$ in models



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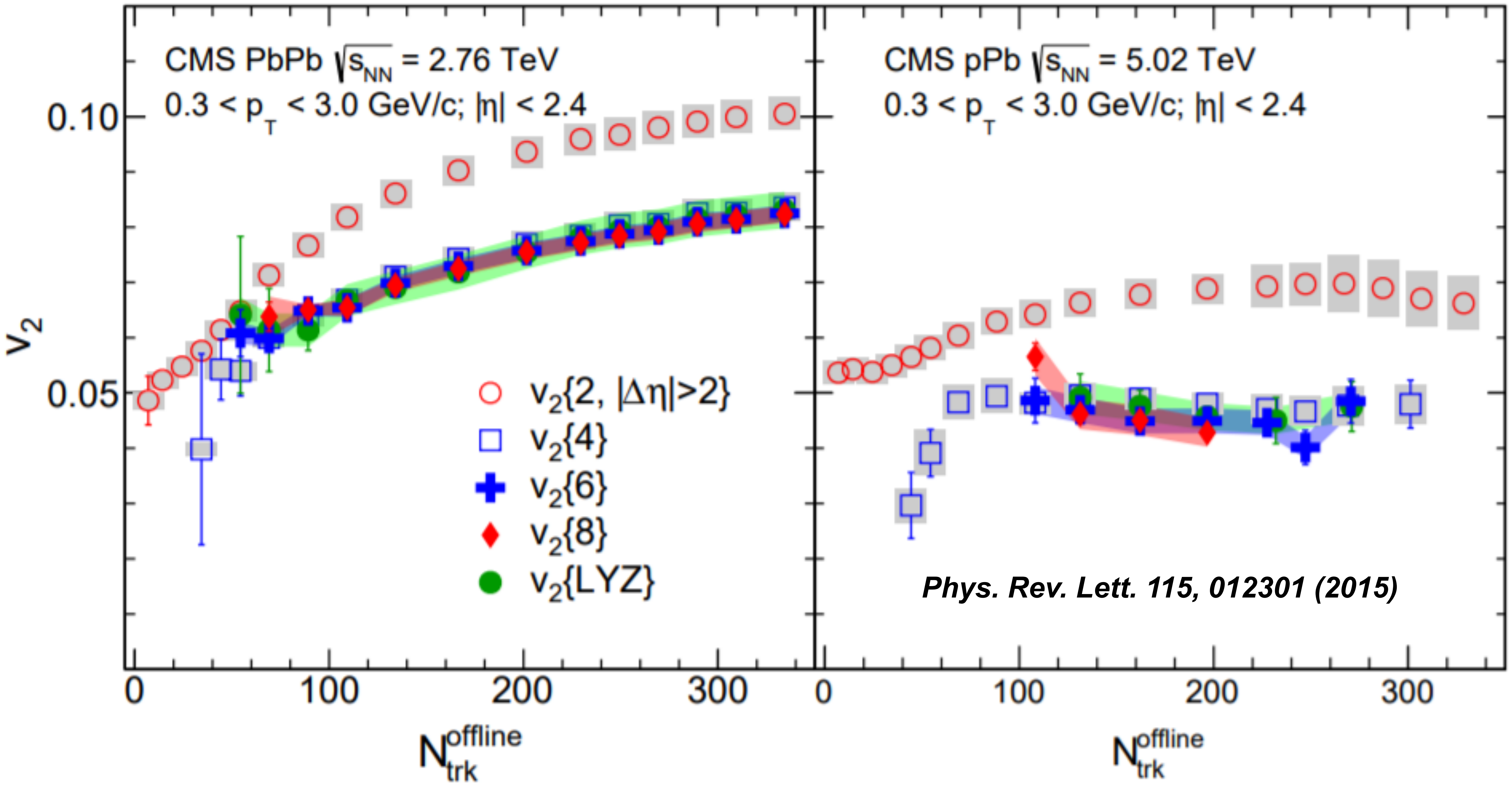
- Bozek model is a hydrodynamics model
- The trend in data is well captured by AMPT/Hydro model

Multi-particle correlation in Pb+Pb and p+Pb



$v_2(\eta)$ and v_2(centrality) for hadrons