PHENIX results on collectivity in small systems

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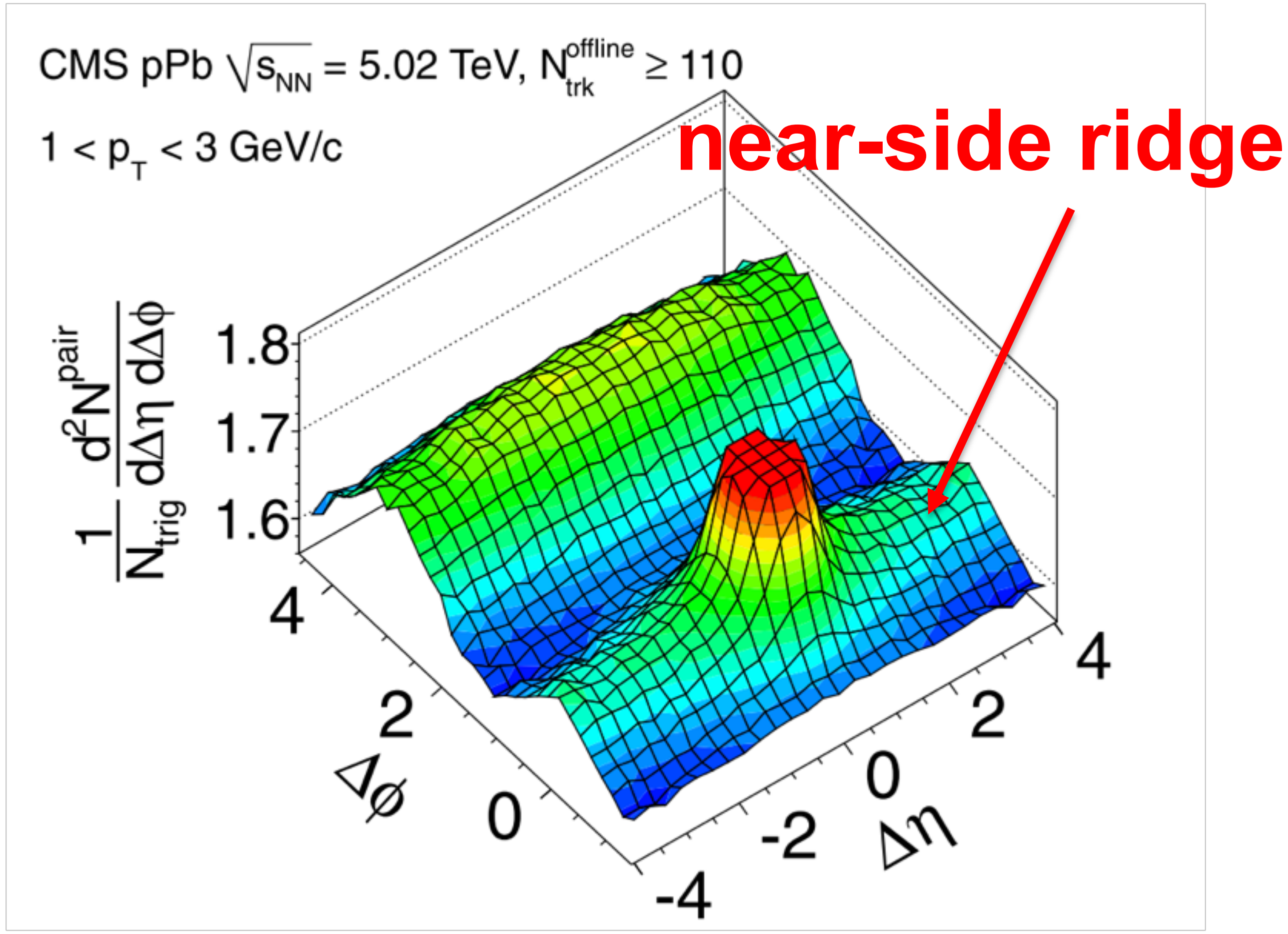
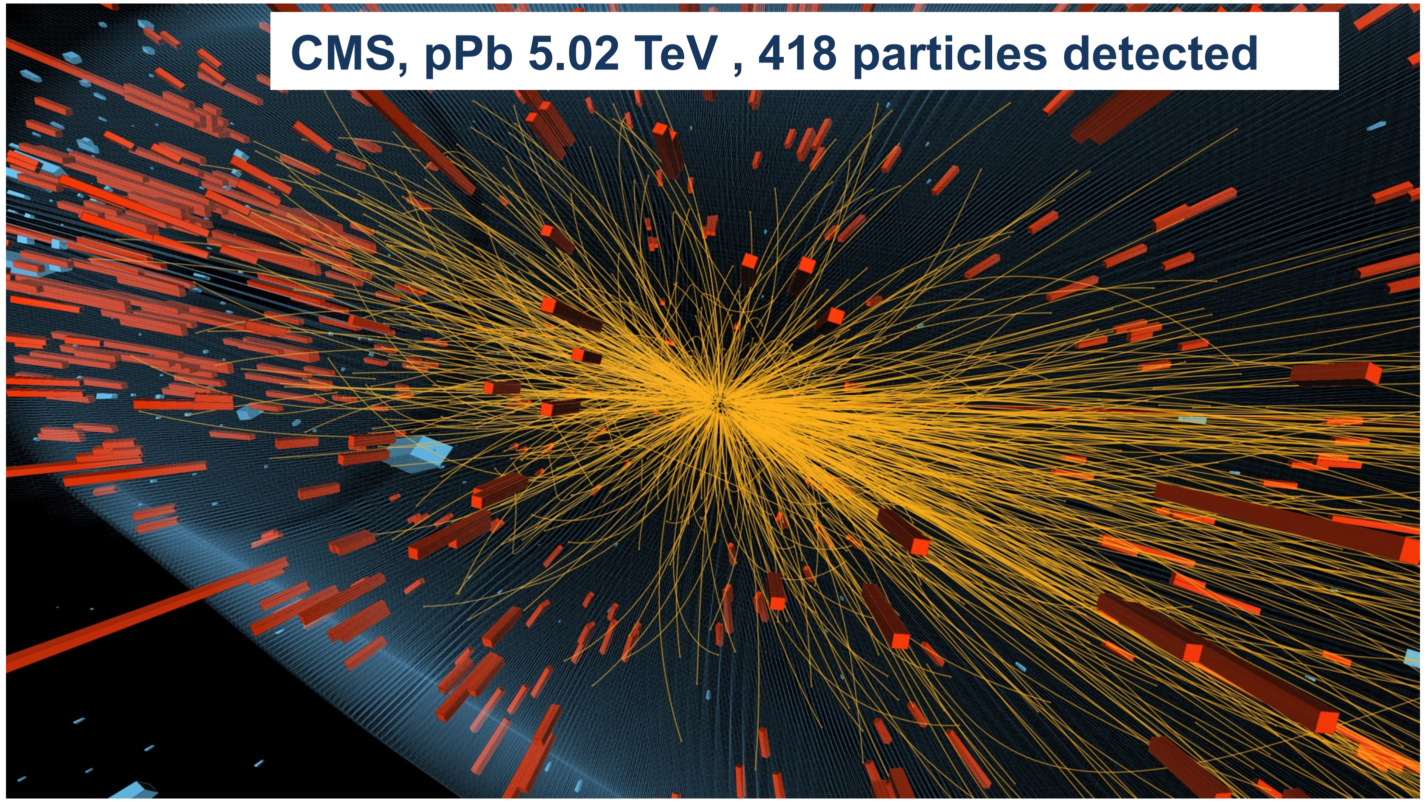
PHENIX

Motivation to study small systems

- Originally: to investigate ”cold nuclear matter effects” in the initial state
- However, “ridge” was also discovered in pp and pPb collisions at LHC





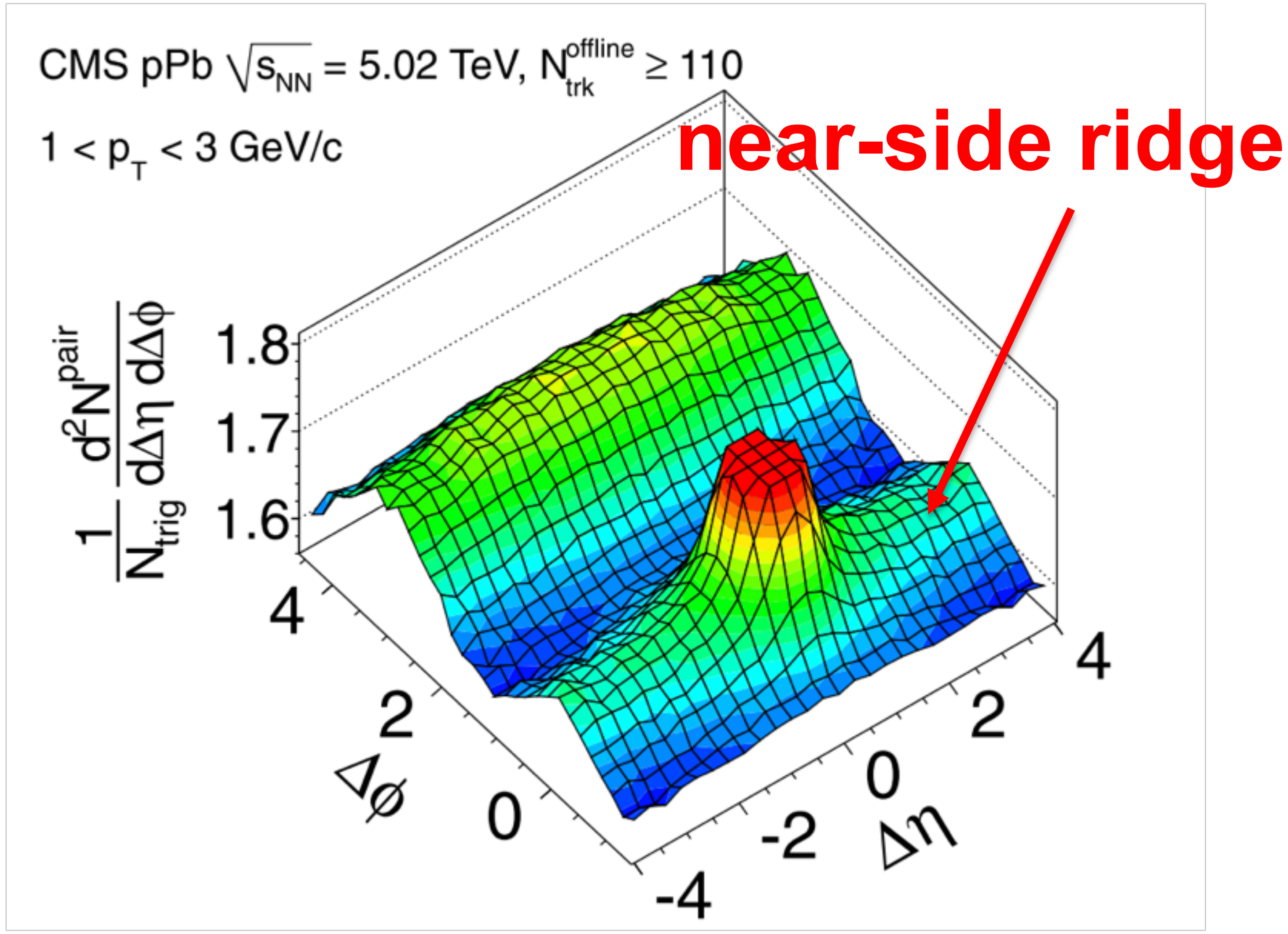
- Revised: to understand the origin of the near-perfect fluidity of QGP

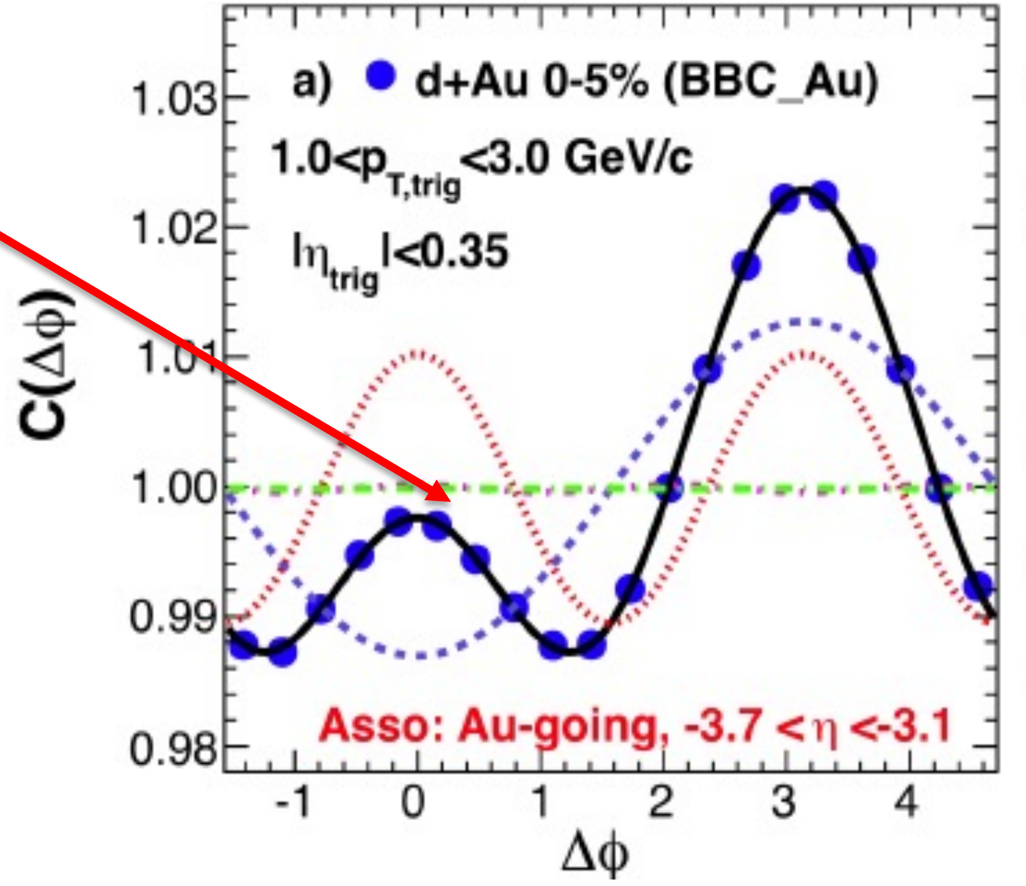
Do we see long-range correlations in small systems at RHIC?

PLB 718 (2013) 795

2008 d+Au data

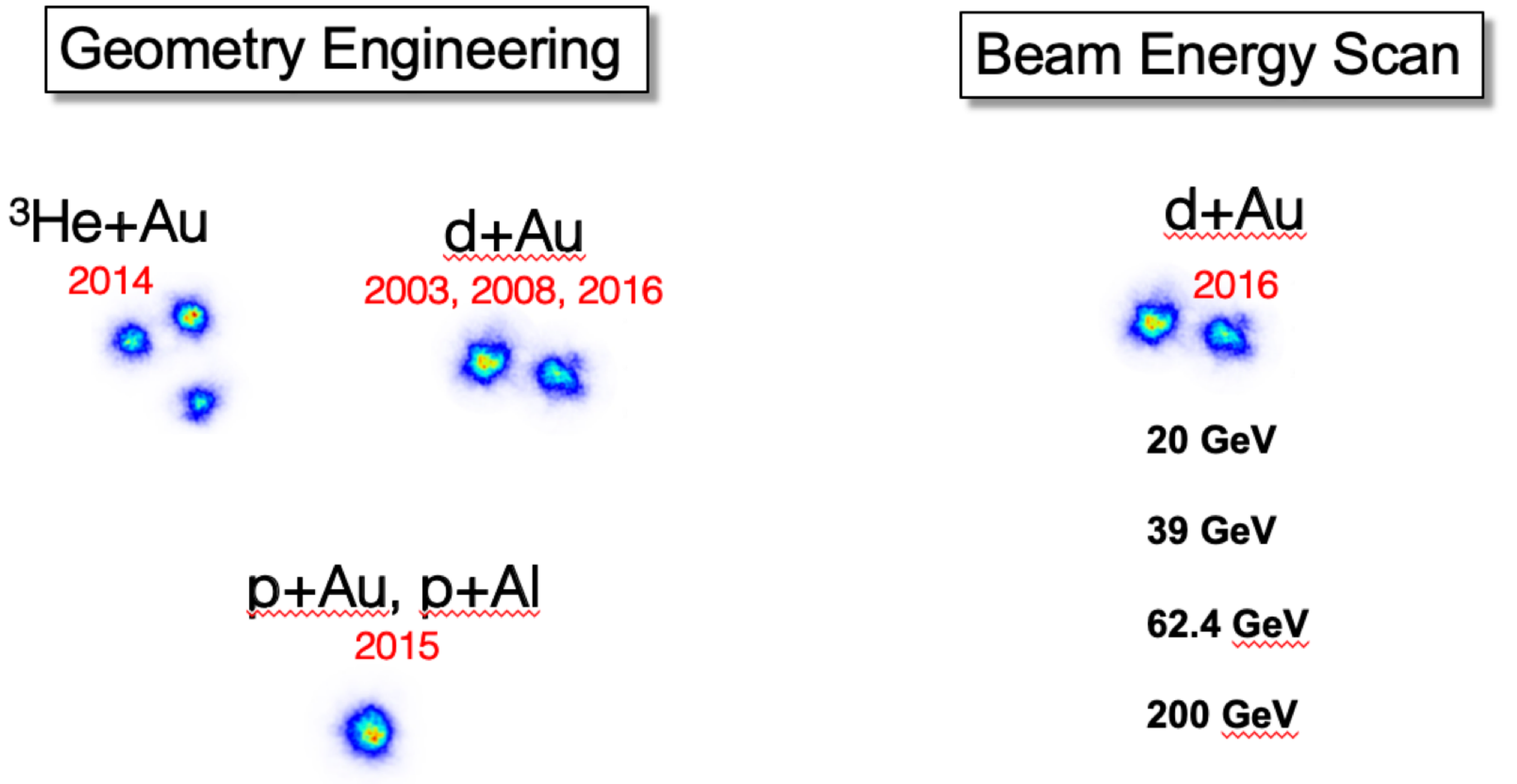
Phys. Rev. Lett. 114, 192301 (2015)





PHENIX small-systems program

- RHIC has unique versatility in collision systems and beam energy



- Opportunity for detailed studies of correlation phenomena and multi-faceted quantitative comparisons to theory

QGP or new origins of collectivity in small systems ?

- If the system forms a near-perfect fluid QGP we expect:
  - Long-range correlations
  - All particles are correlated
  - A common velocity field (mass-dependence of flow)
  - Initial geometry and its fluctuations are propagated to the final state
    - Higher order effects: non-linear mode mixing (v_n not proportional to ε_n), and event-plane decorrelations
  - Experimental challenge: separate flow and nonflow at lower multiplicity
- Some of these features also reported from initial state CGC
- Quantitative comparison to the data is crucial

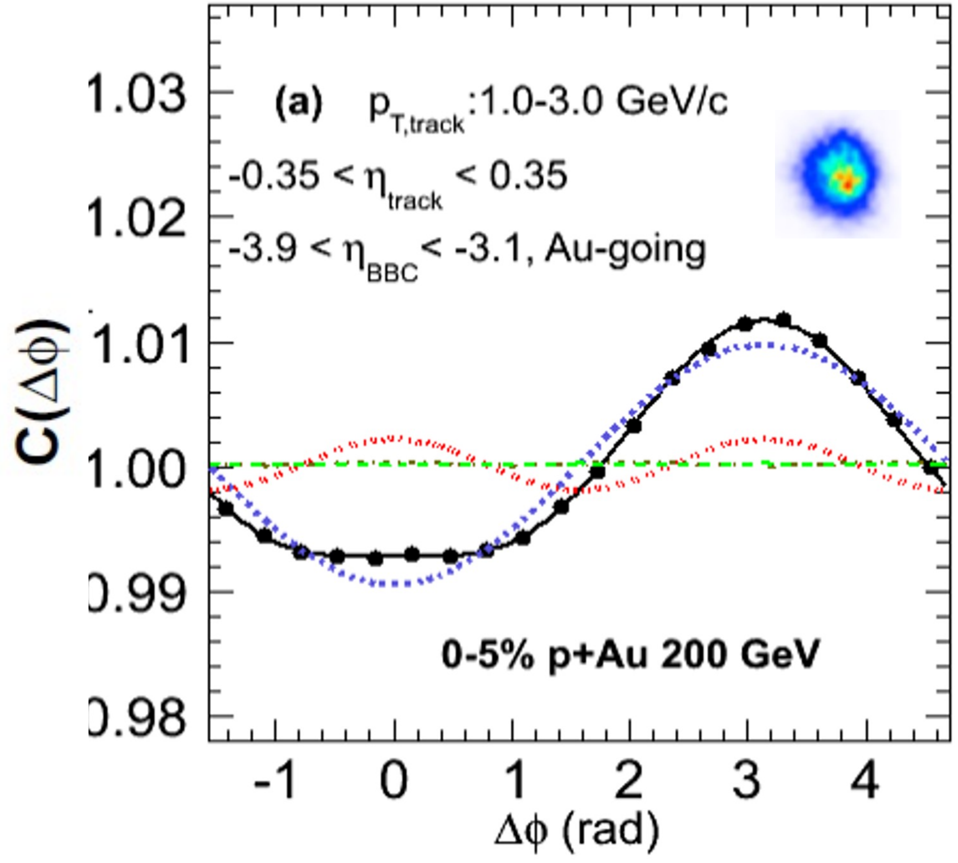
PHENIX papers on collectivity in small systems

1. Phys. Rev. C 105, 024901 (2022) – (PHENIX) 3x2PC, kinematic dependence v2, v3
2. Nature Physics vol. 15, 214–220 (2019) - (PHENIX) pAu,dAu, ^{3}HeAu - charged hadron v_2 and v_3, and model discrimination
3. PRL 121, 222301 (2018) - (PHENIX) pAl, pAu, dAu,^{3}HeAu $dN_{ch}/d\eta$,$v_2(\eta)$
4. PRL 120, 062302 (2018) - (PHENIX) v_2 with multi-particle cumulants in dAu BES, and cumulants in pAu
5. Phys. Rev. C 98, 014912 (2018) - (PHENIX) pi0 - h correlations in dAu
6. Phys. Rev. C 97, 064904 (2018) - (PHENIX) v_2 of identified hadrons quark number scaling in pAu, dAu , ^{3}HeAu
7. Phys. Rev. C 96, 064905 (2017) - (PHENIX) v_2 and dN_{ch}/deta of charged hadrons in dAu BES; also as a function of centrality
8. Phys. Rev. C 95, 034910 (2017) - (PHENIX) charged hadron v_2 in pAu
9. PRL 115, 142301 (2015) - (PHENIX) charged hadron v_2 and v_3 in ^{3}HeAu
10. PRL 114,192301 (2015) - (PHENIX) - charged hadron v_2 in dAu; EP
11. PRL 111, 212301 (2013) - (PHENIX) - charged hadron v_2 in dAu; 2PC

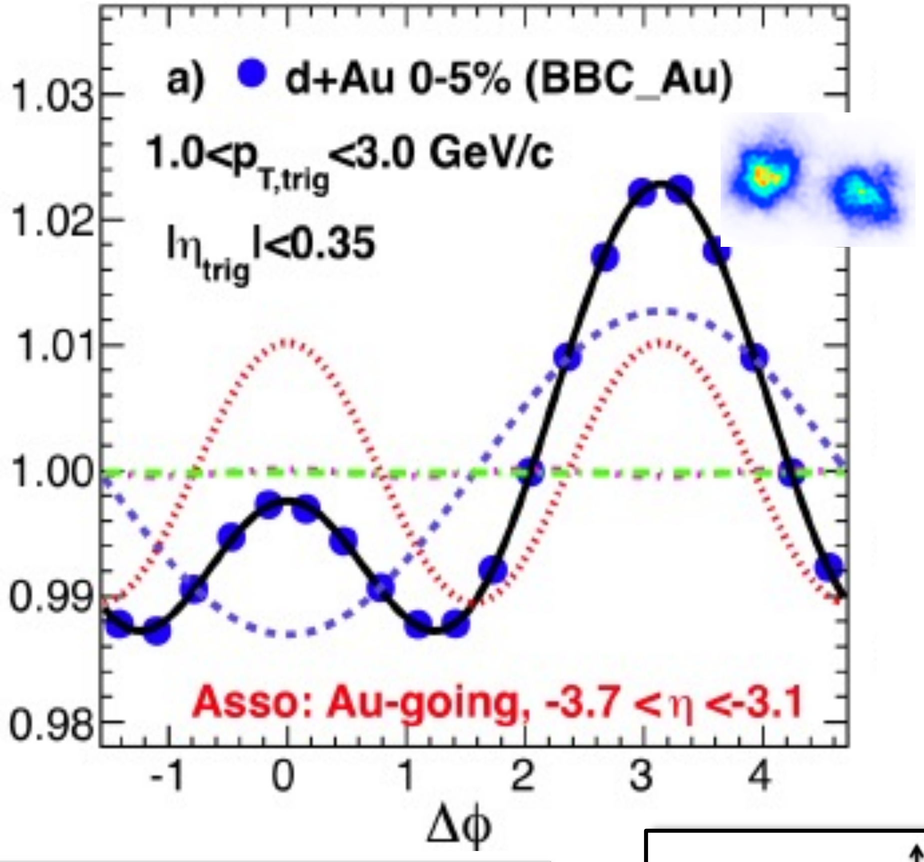
+ papers reporting identified particle spectra, e.g. Phys. Rev. C 88, 024906 (2013) – dAu spectra, and arXiv:2111.05756 p/d/^{3}He+Au, pAl

The small-system Ridge in PHENIX

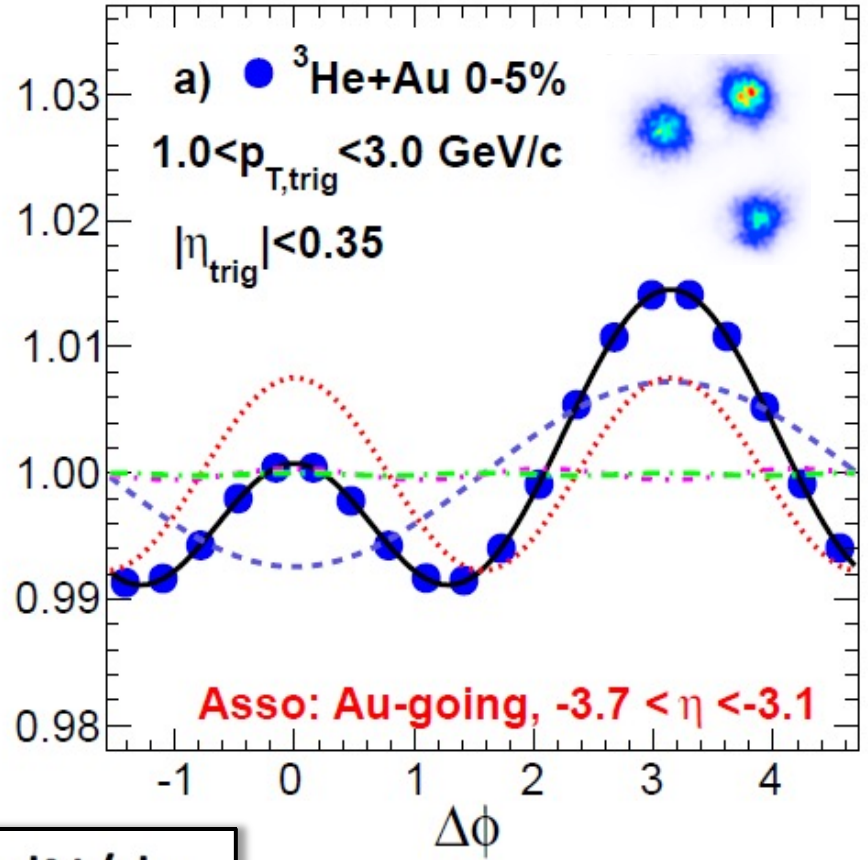
Phys. Rev. C 95, 034910 (2017)

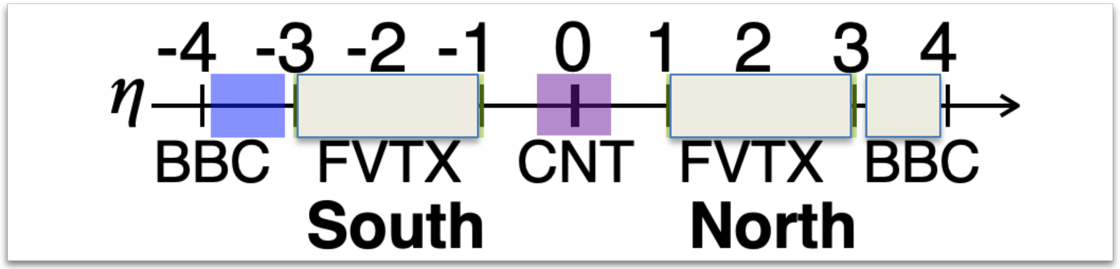


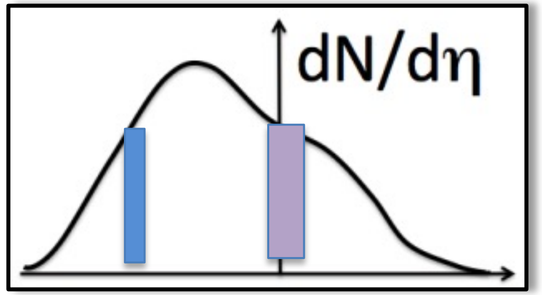
Phys. Rev. Lett. 114, 192301 (2015)



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





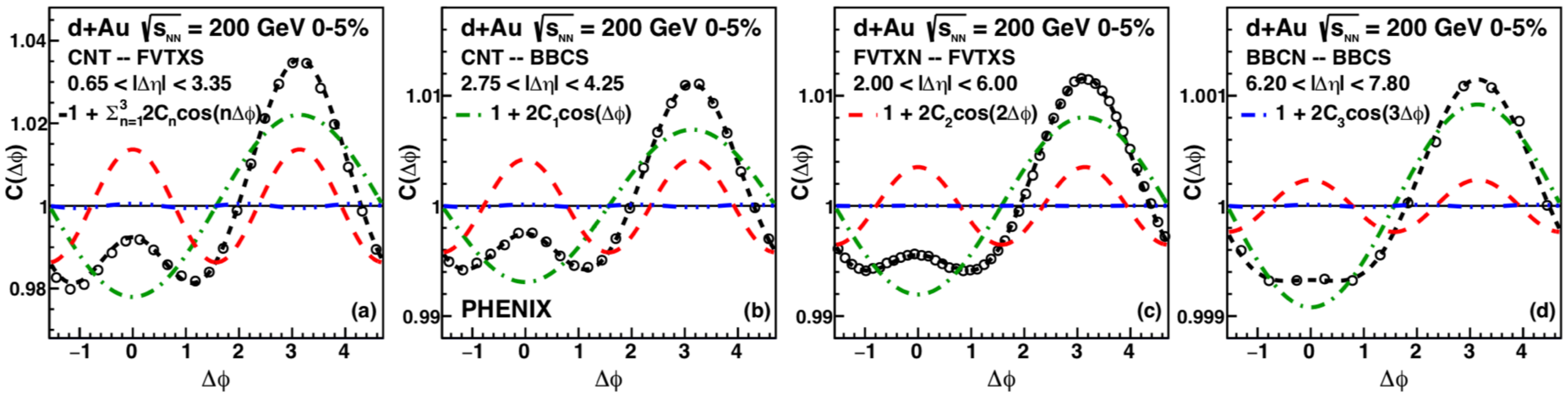


- A clear ridge on the Au-going side in central d+Au, ^{3}He+Au
- a more subtle effect in p+Au

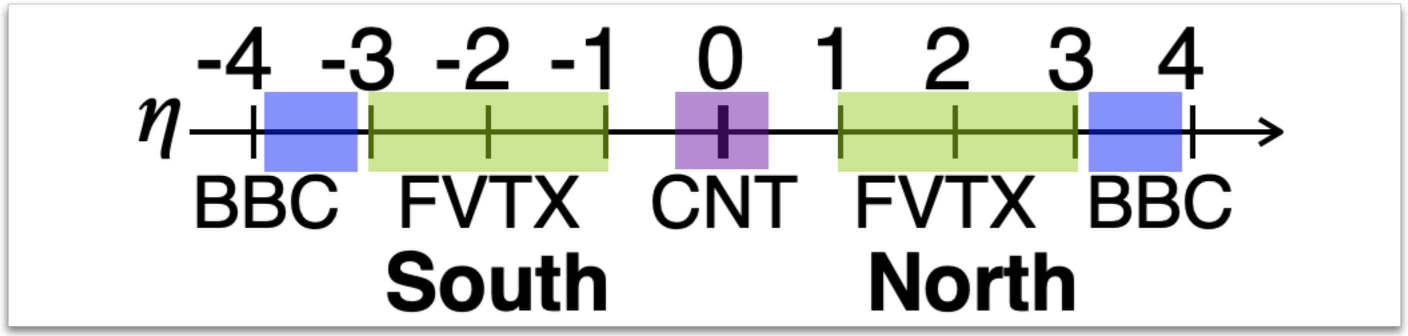
larger Δη range studied with 2016 d+Au data

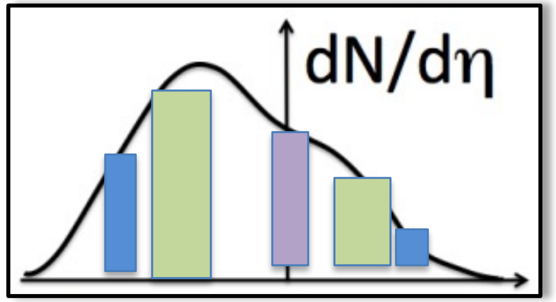
PRC 96, 064905 (2017)

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

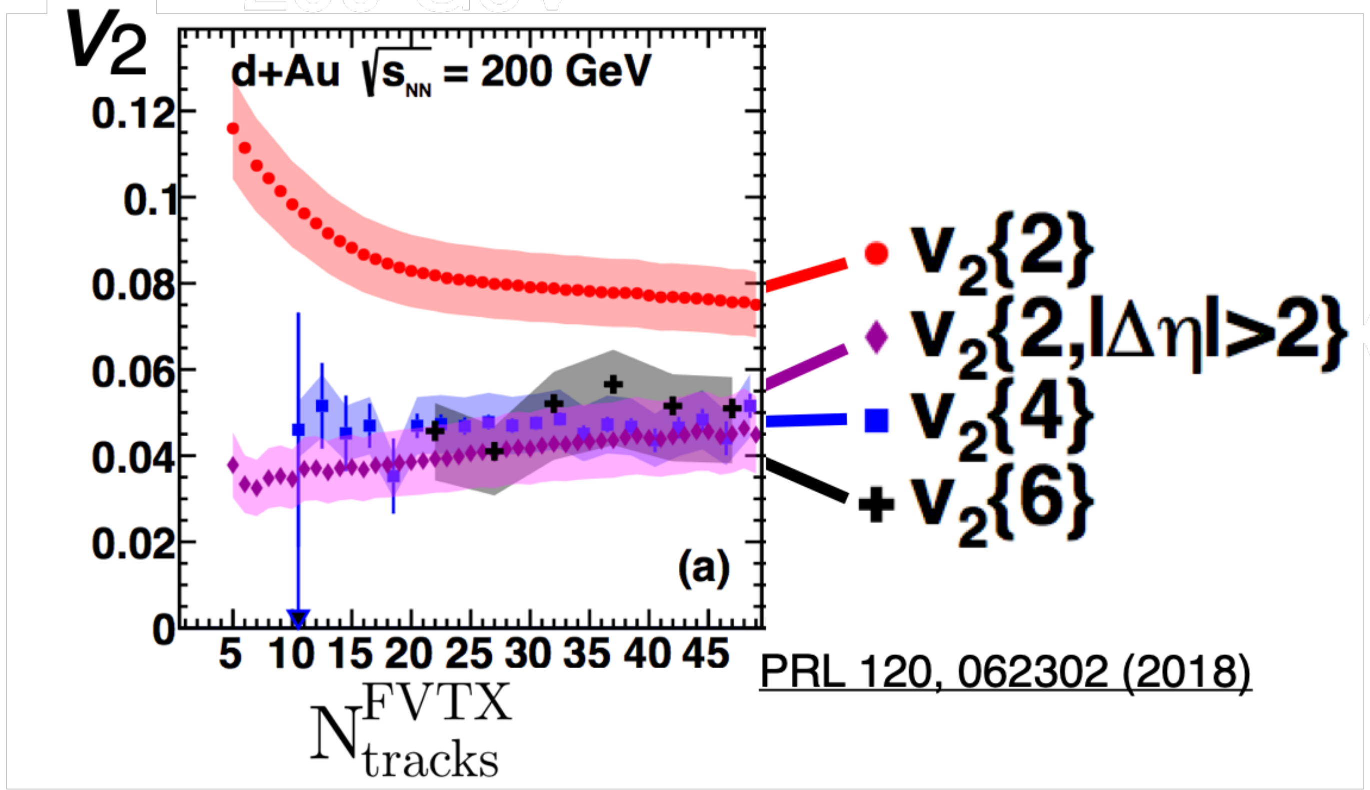




A sizable c_2 component is seen even for 6.2 < |Δη|<7.8

Are all particles correlated ?

PRL, 120, 062302, (2018)



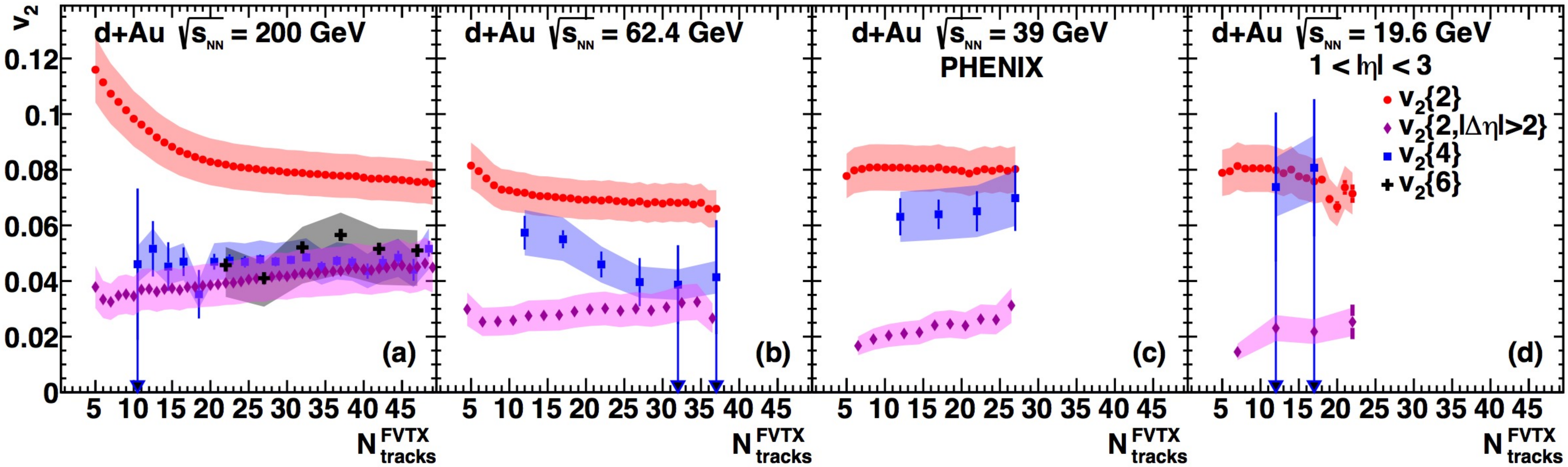
PRL 120, 062302 (2018)

η separation reduces non-flow contributions
Note: different kinematics

- $v_2\{2\}$ is above $v_2\{2,|\Delta\eta|>2\}$, $v_2\{4\}$, and $v_2\{6\}$
- $v_2\{4\}$ is consistent with $v_2\{6\}$ and likely dominated by collective flow

Multi-particle correlations at lower energy

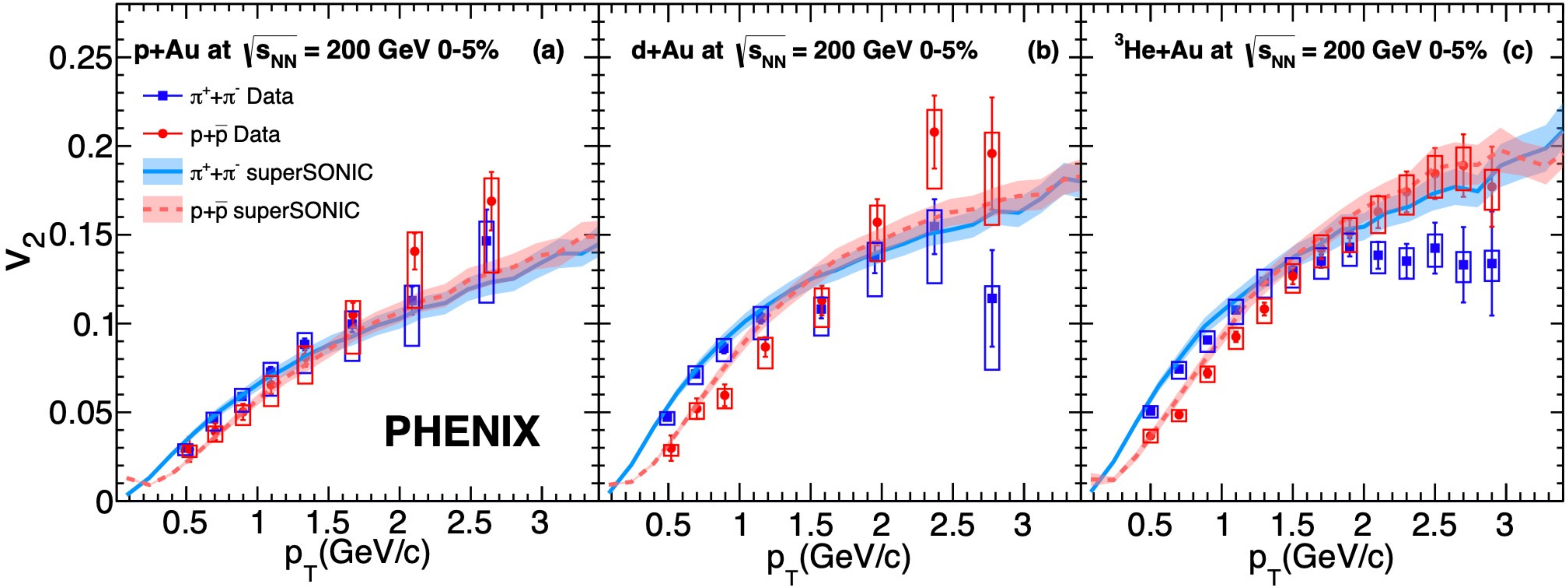
PRL, 120, 062302, (2018)



- Real $v_2\{4\}$ for all energies
- Consistent with collective flow

Is there a common velocity field ?

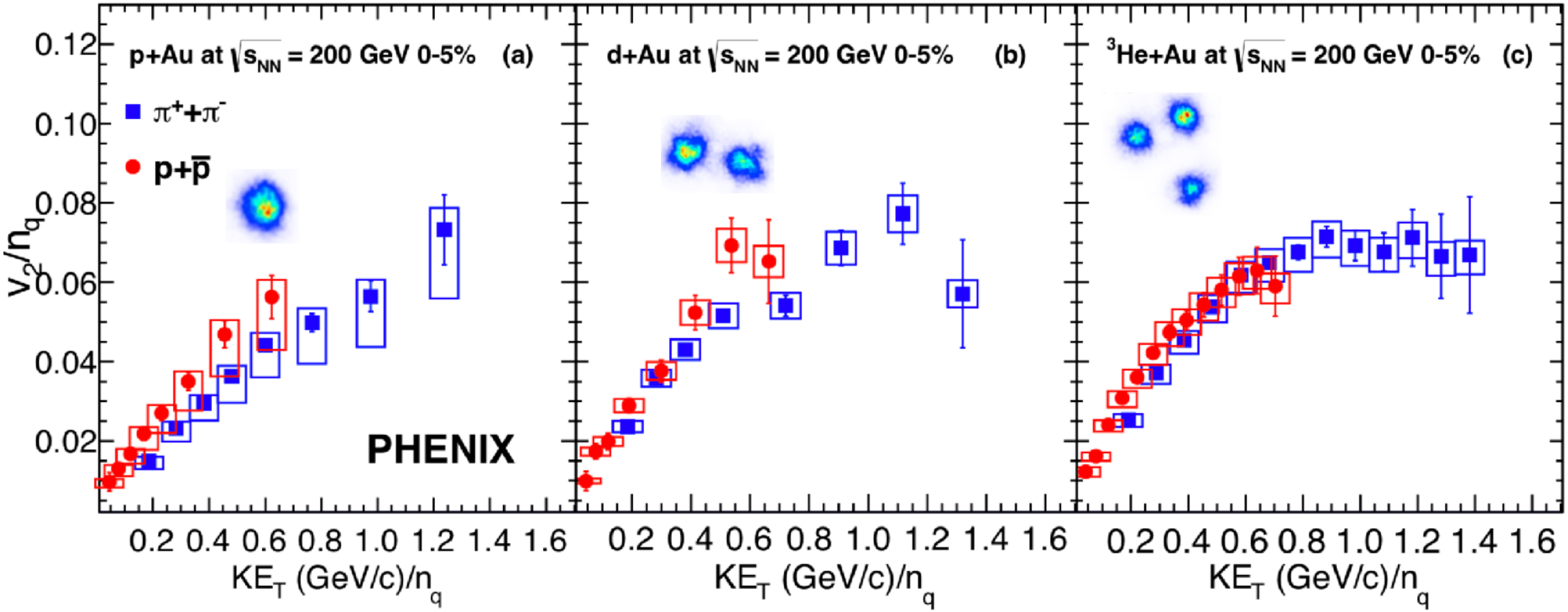
Phys. Rev. C 97, 064904 (2018)



- Mass dependence at low p_T well described by viscous hydro
  - no recombination in SONIC → No baryon/meson splitting for p_T> 2 GeV
  - High-p_T baryon/meson splitting well described by AMPT (see backup slides)

Is there a common velocity field ?

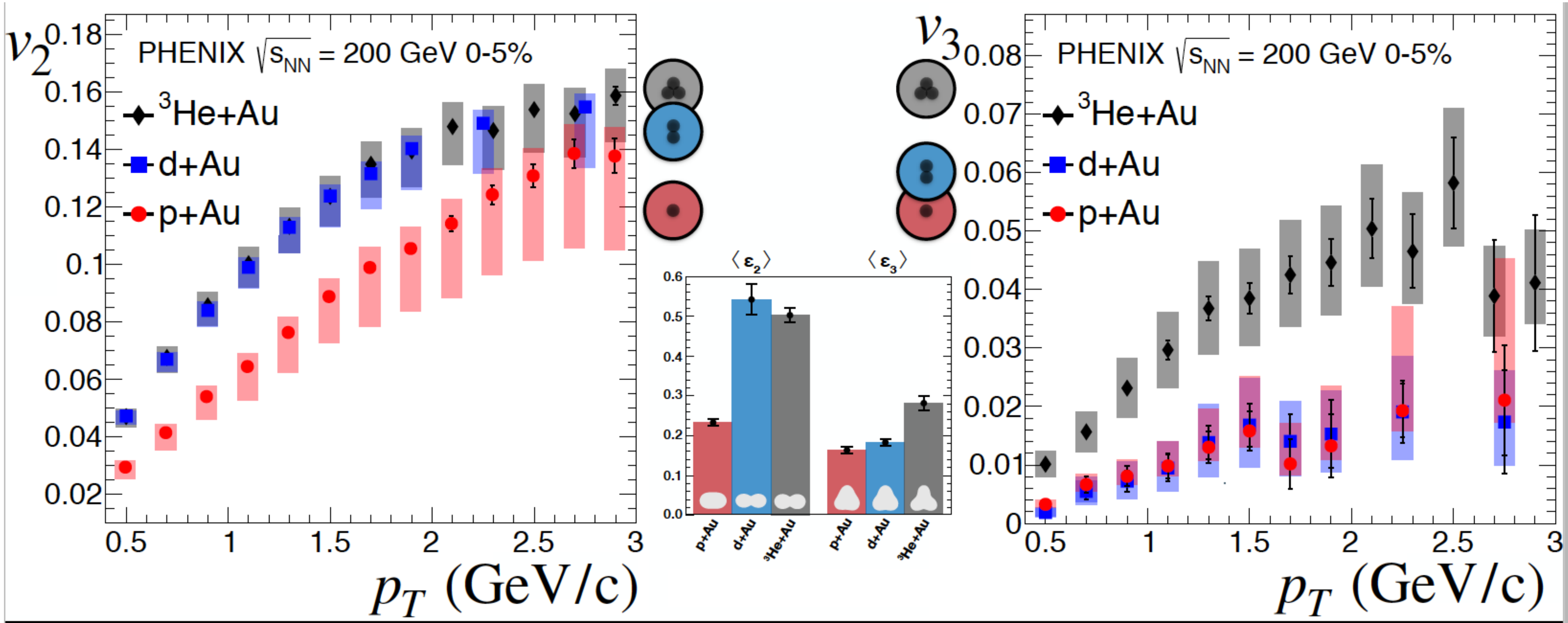
PRC 97, 064904 (2018)



- Quark number scaling observed similar to AA
- holds better as the system size increases
- Mass dependence well described by viscous hydro, and hadronic rescattering

The role of the initial geometry: elliptic and triangular flow data

Nature Phys. 15 (2019) no.3, 214-220

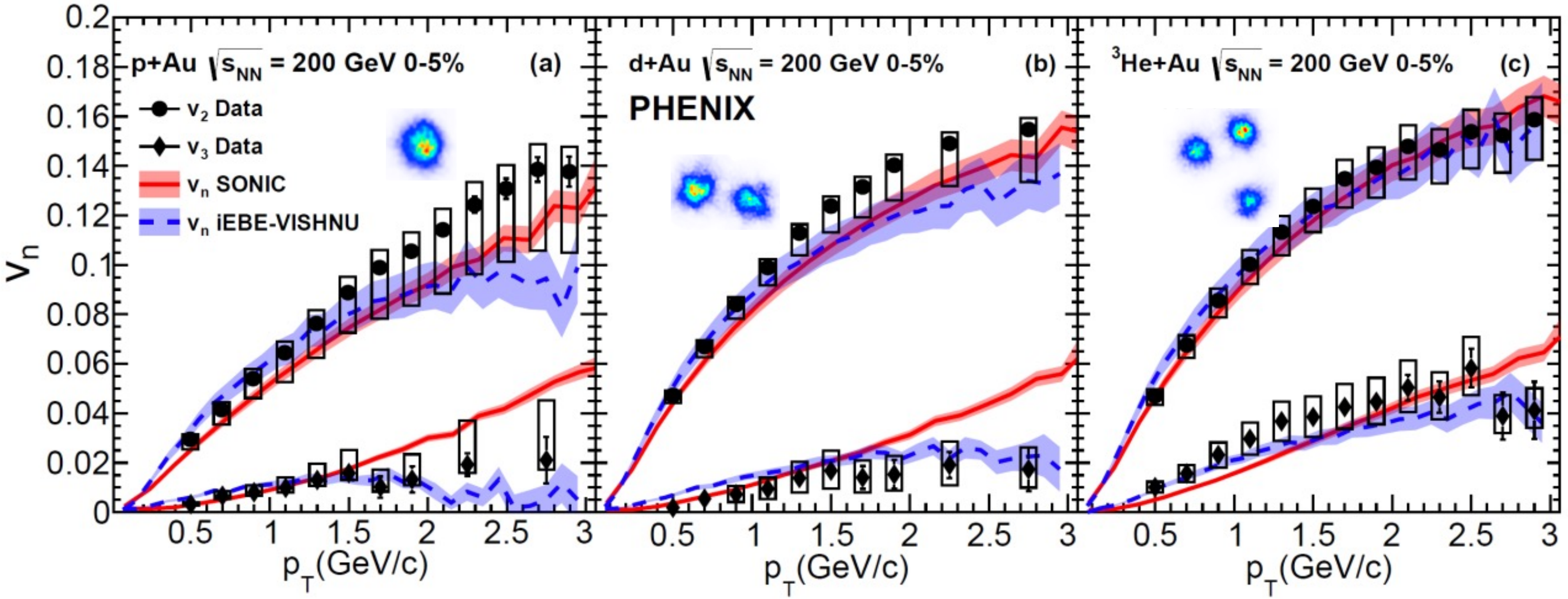


$$v_2^{p+Au} < v_2^{d+Au} \approx v_2^{^3He+Au} \qquad v_3^{p+Au} \approx v_3^{d+Au} < v_3^{^3He+Au}$$

The v_2 and v_3 values follow the initial spatial eccentricity order

Hydrodynamic description of $v_n(p_T)$ in p/d/^{3}He +Au

Nature Phys. 15 (2019) no.3, 214-220

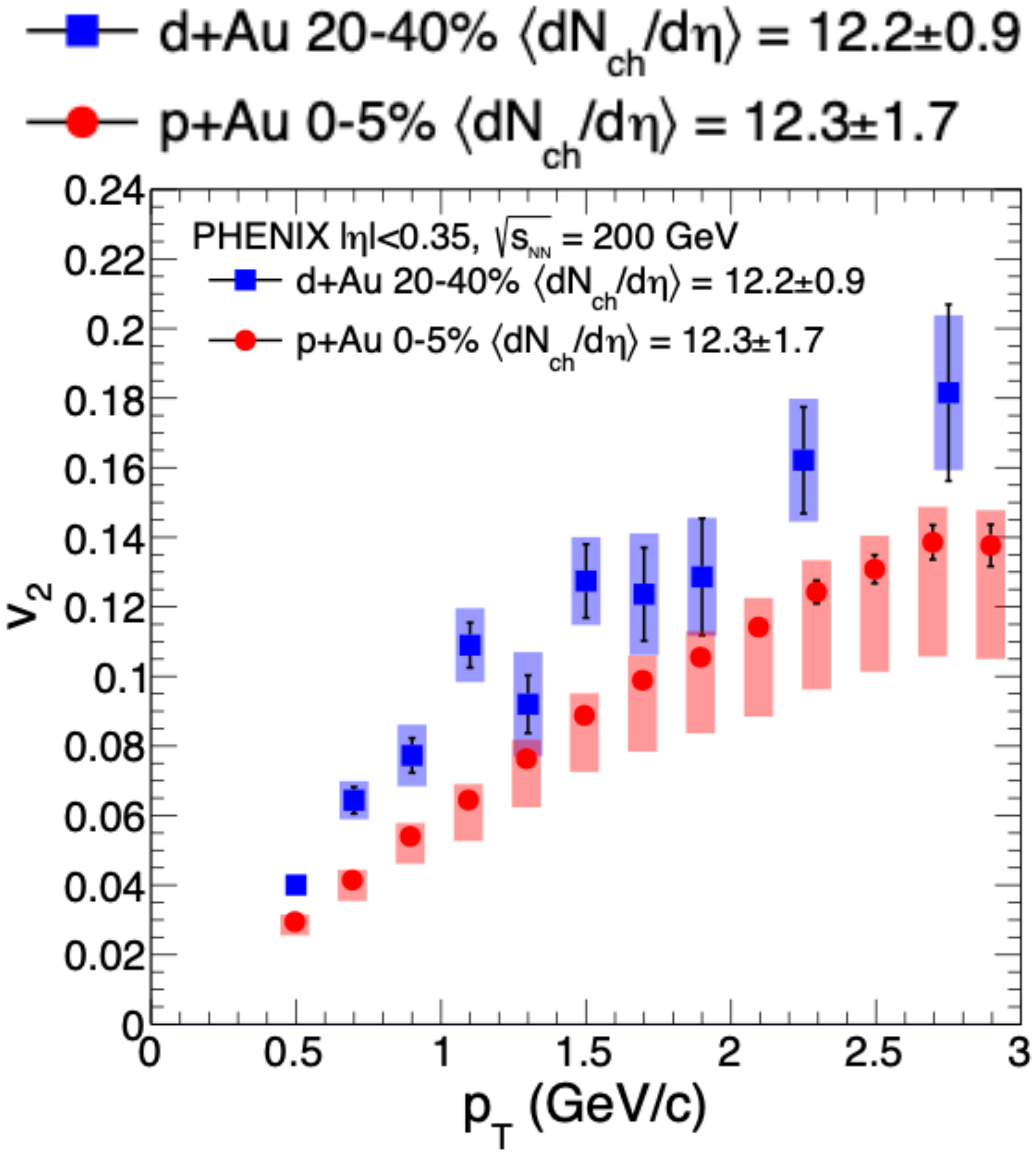


- Hydrodynamics provides a quantitative simultaneous description of v_2 and v_3 in three systems with different initial geometry

Geometry or multiplicity ? v_2 in p/d+Au at the same multiplicity

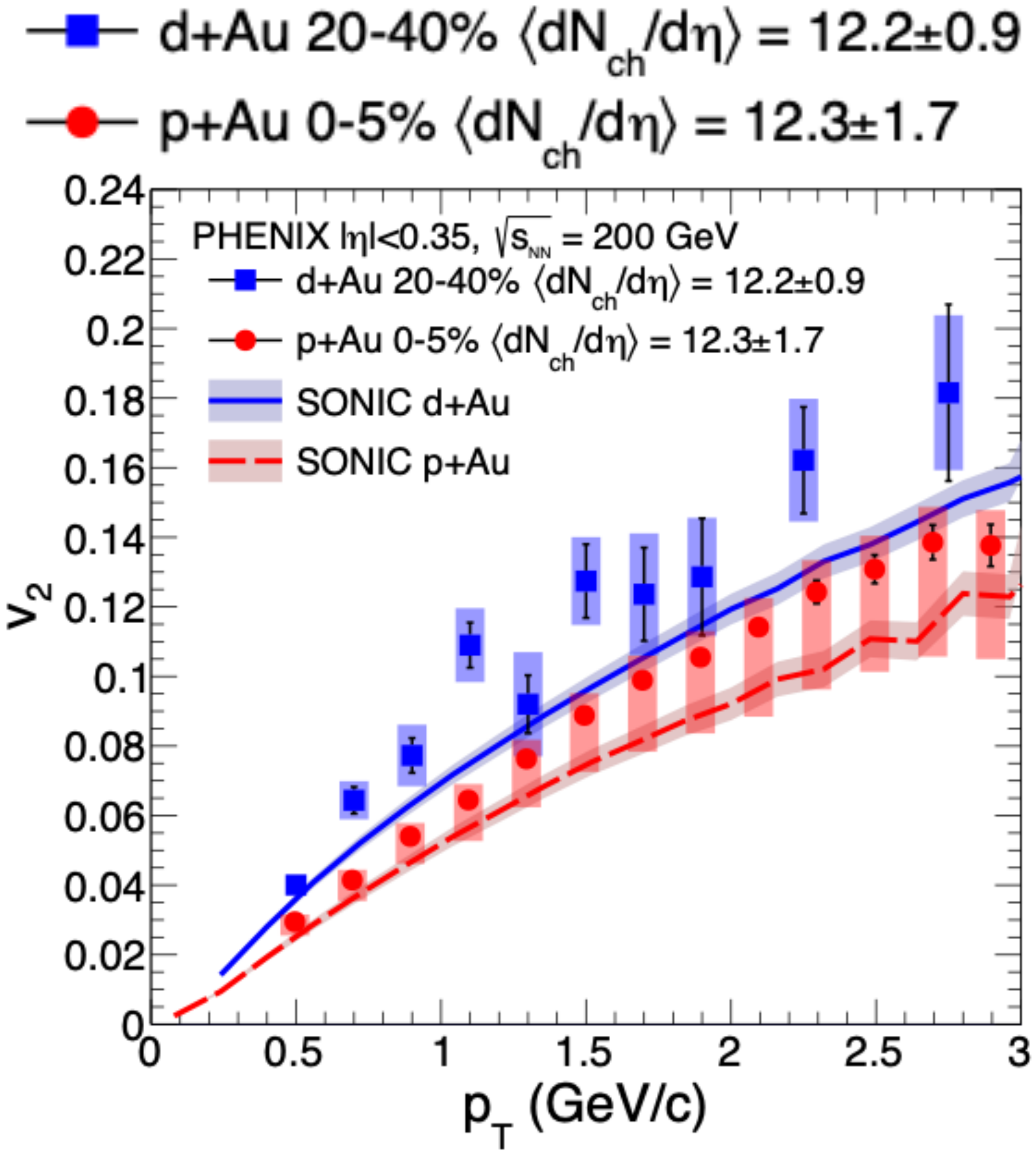
PRC 96, 064905 (2017)

PRC 95, 034910 (2017)



These are NOT the same

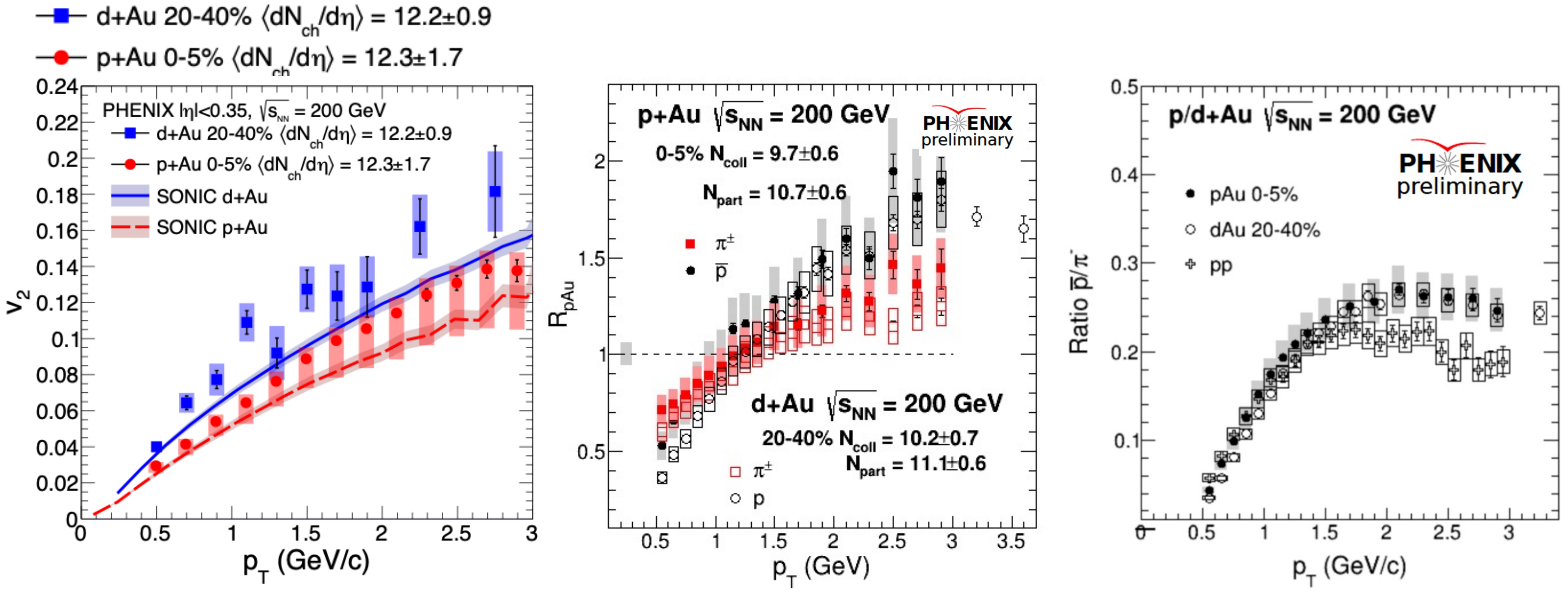
Geometry or multiplicity ? v_2 in p/d+Au at the same multiplicity



Nature Phys. 15 (2019) no.3, 214-220

Qualitative agreement with hydro

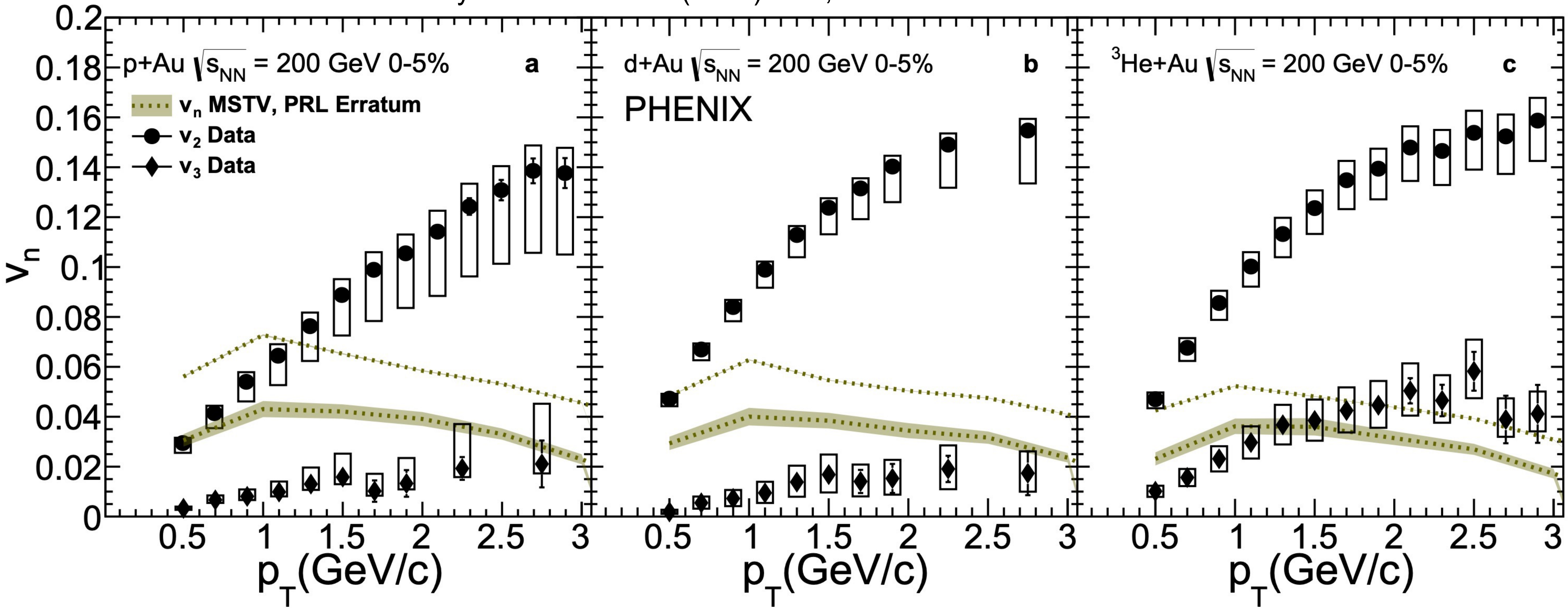
p+Au and d+Au at the same multiplicity



- **different** v_2 , but similar radial flow and hadronization in p/d+Au
- Consistent with geometry-driven anisotropic flow

The role of the initial state

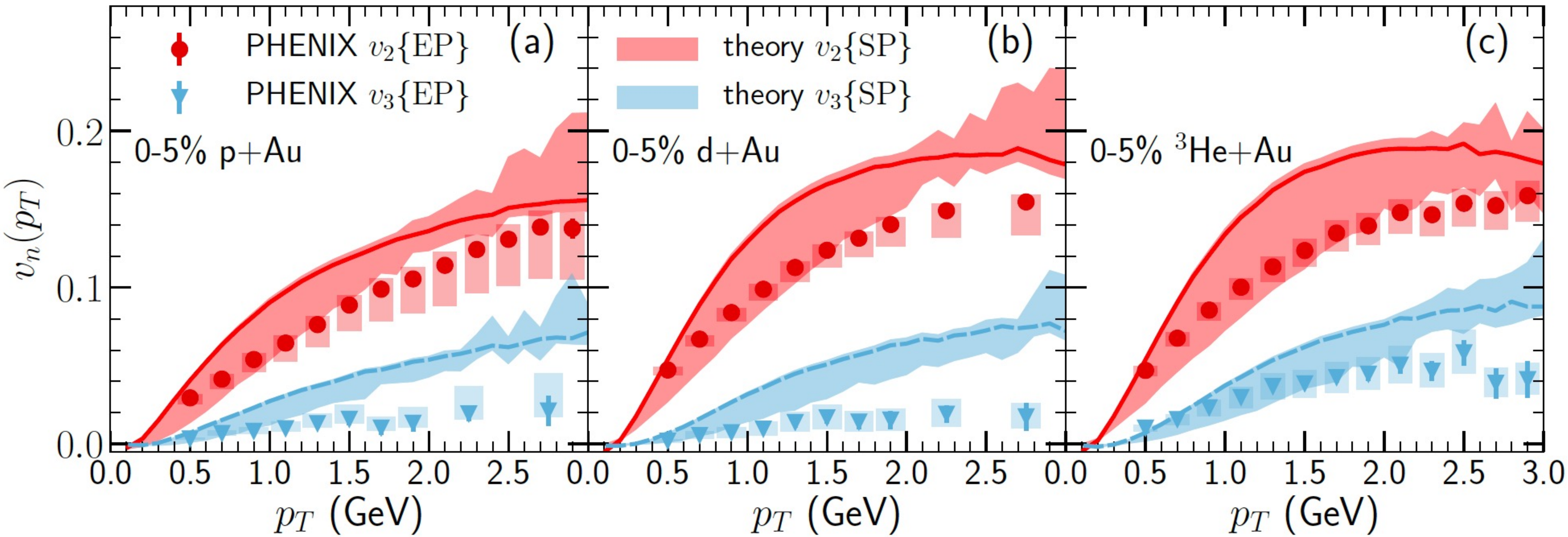
Erratum: Phys. Rev. Lett. 121 (2018) no.5, 052301



- CGC does not provide a viable explanation of the data

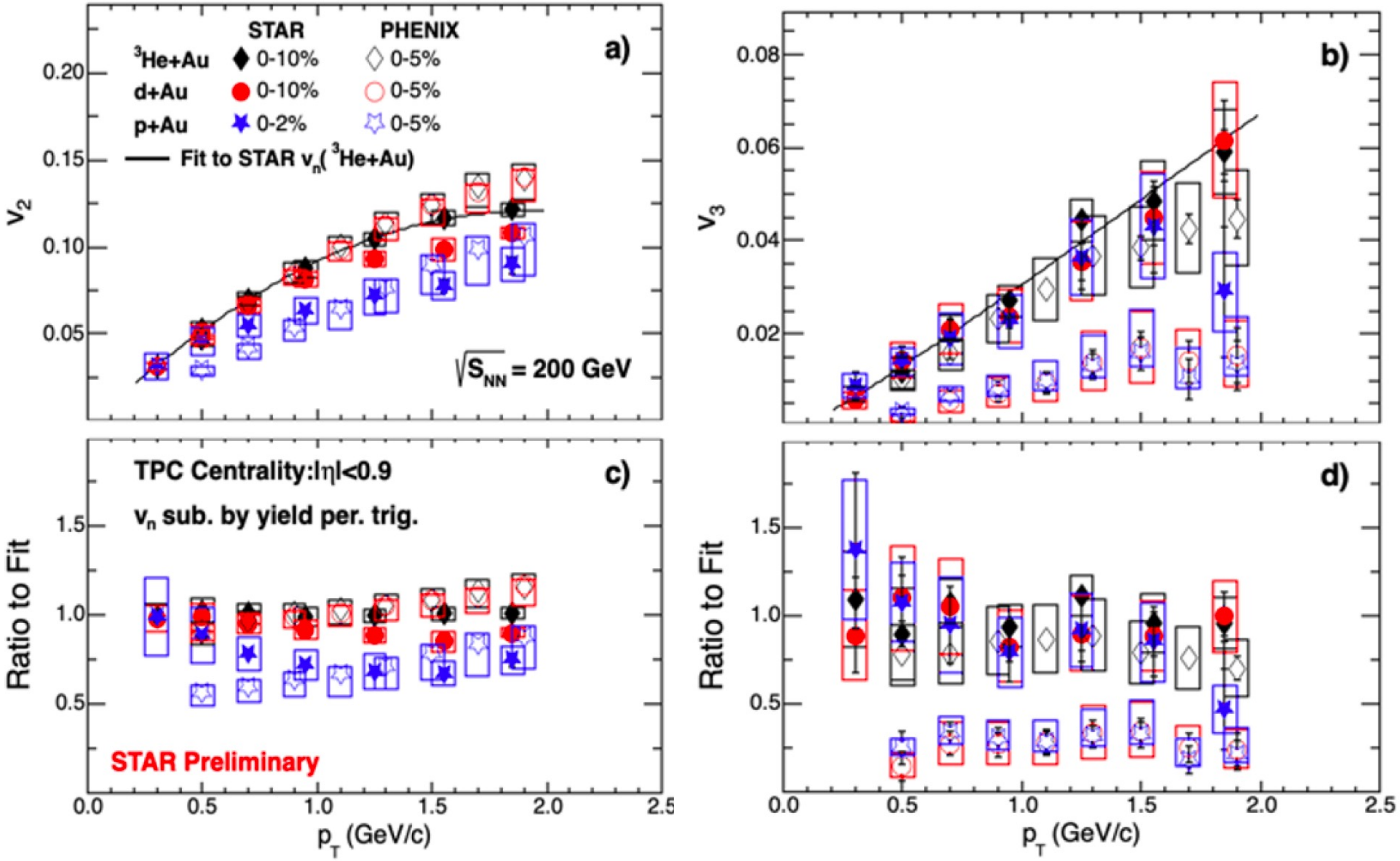
Initial + final state effects

B. Schenke et al, Phys. Lett. B 803, 135322 (2020)



Describing qualitative features of the experimental data require final state interactions; details of the initial state (CGC) also important, but not so much for the central collisions measured by PHENIX

PHENIX- STAR comparison: QM19



Task force formed in 2020 to investigate the differences

The work has concluded in June 2021

Measurement errors ruled out

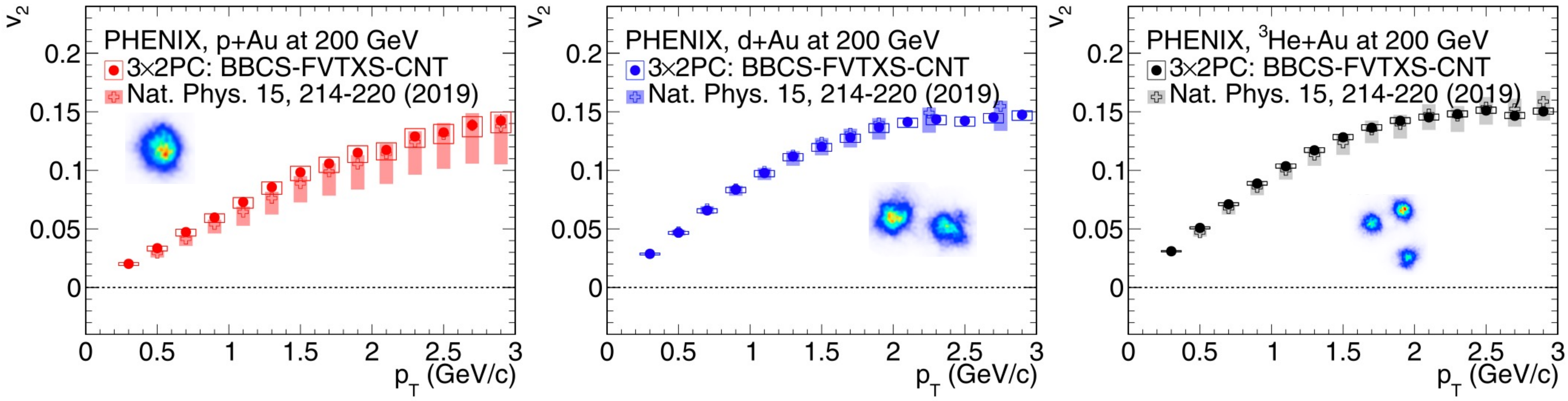
Differences to be understood in terms of physics

We are still awaiting a STAR publication 2+ years after QM19

Reasonable agreement in v_2

Large discrepancy in v_3

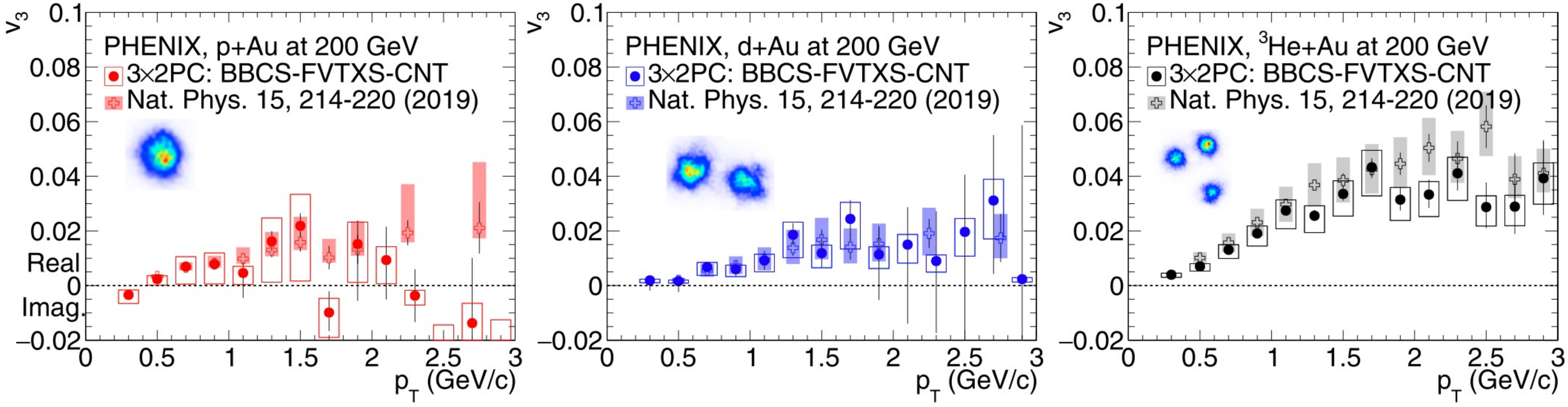
New PHENIX publication confirms previous results



Phys. Rev. C 105, 024901 (2022)

- New analysis based on two-particle correlations with event mixing instead of EP
  - not subject to observed bias in event-plane resolution caused by beam offset and beam angle
  - completely new and separate code; measurement using FVTX tracks rather than clusters

New PHENIX publication confirms previous results

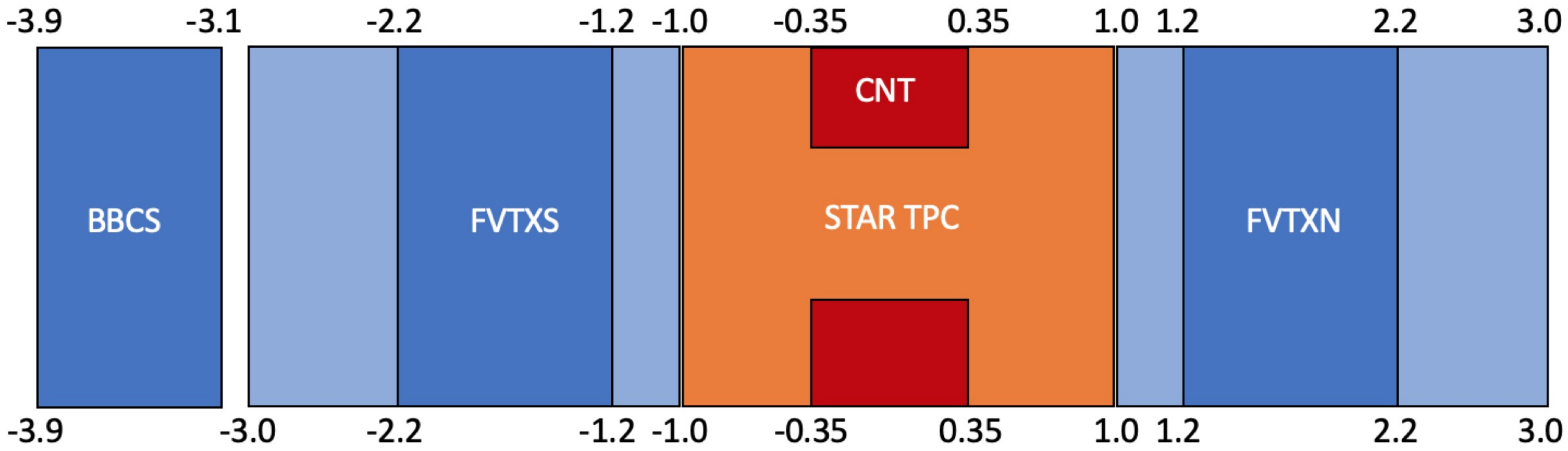


Phys. Rev. C 105, 024901 (2022)

- New analysis based on two-particle correlations with event mixing instead of EP
  - not subject to observed bias in event-plane resolution caused by beam offset and beam angle
  - completely new and separate code; measurement using FVTX tracks rather than clusters

Physics differences between STAR and PHENIX

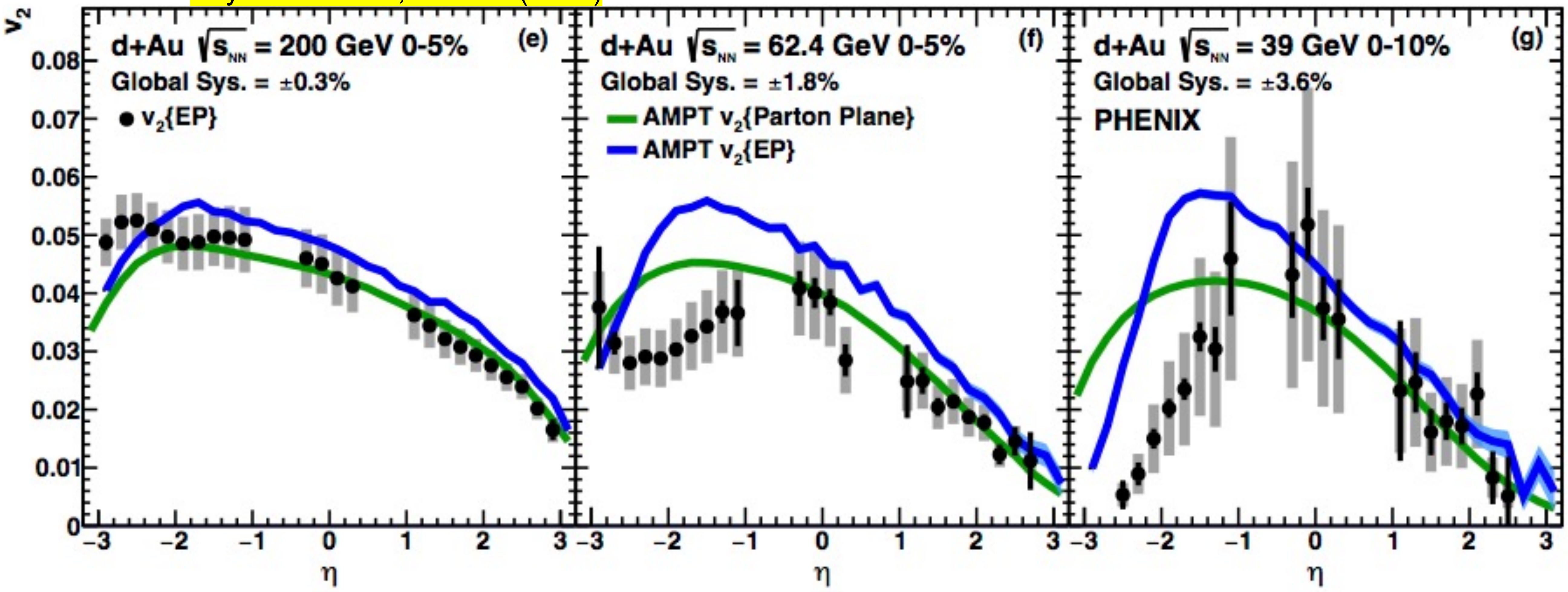
- Kinematic coverage

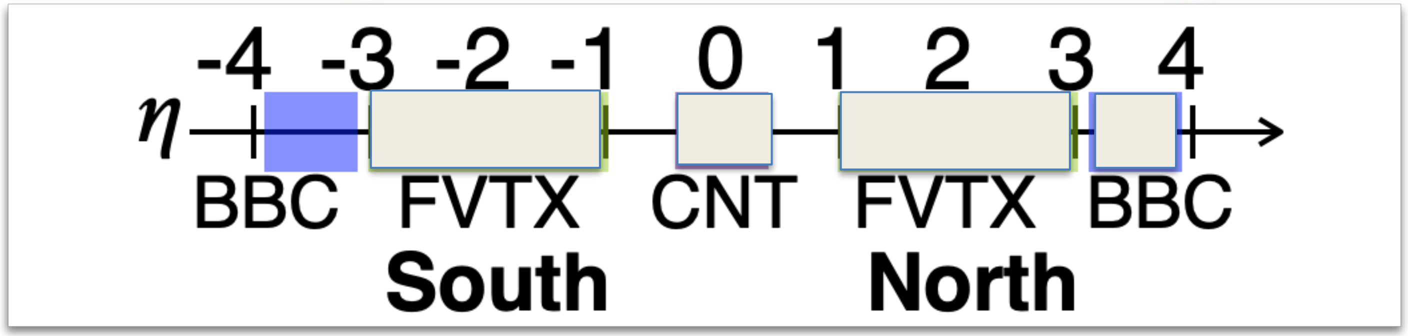


- Nonflow treatment
  - PHENIX - nonflow suppressed by large pseudorapidity gaps, not subtracted – included in the systematic uncertainty
  - STAR – nonflow subtracted by template fits
    - QM18 – using peripheral events
    - QM19 – using pp reference
  - Detour in next few slides: a PHENIX study of longitudinal dynamics and nonflow for v_2 in d+Au PRC 96, 064905 (2017)

Longitudinal dynamics and nonflow

Phys. Rev. C 96, 064905 (2017)



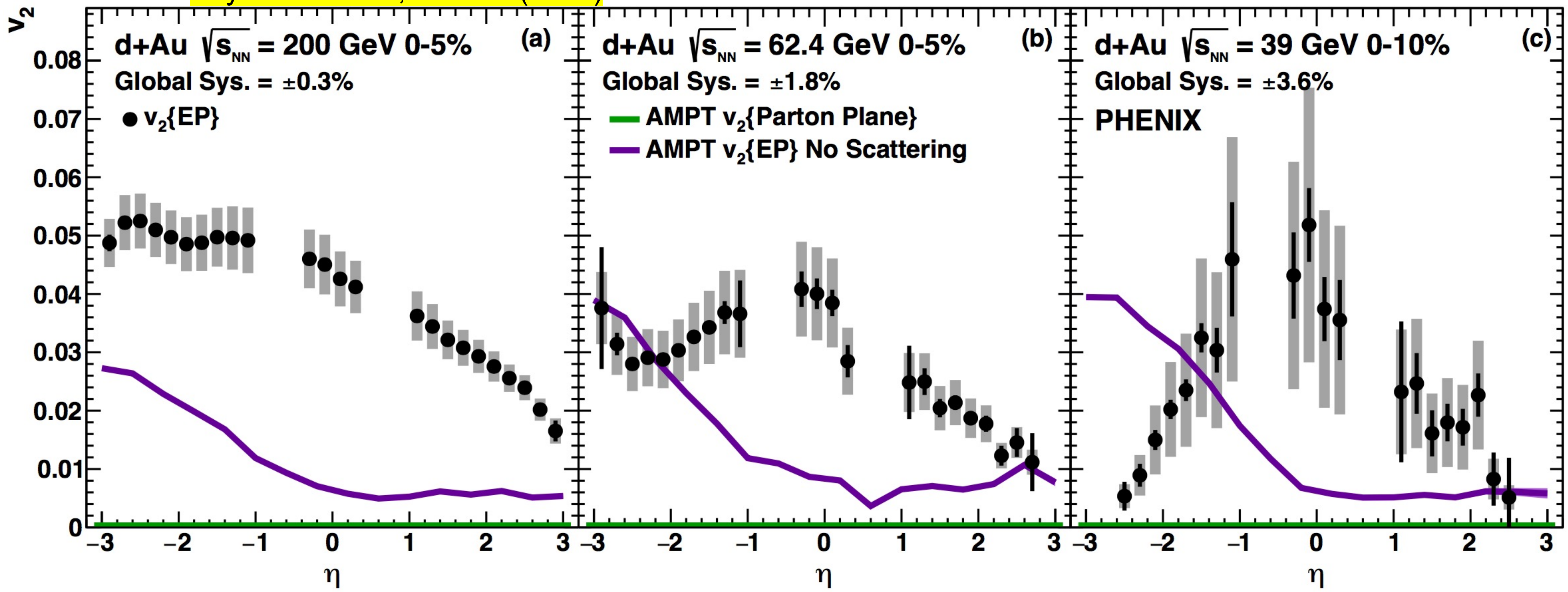


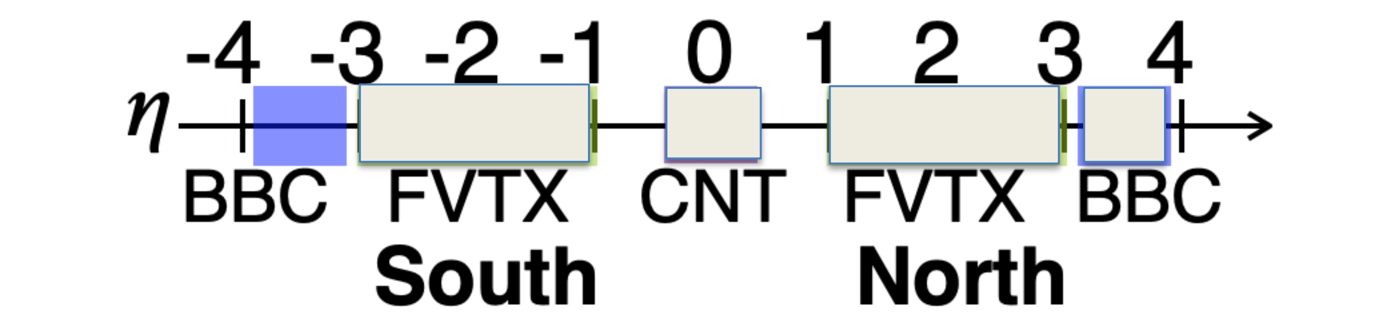
flow & non-flow
(event plane)

flow
(parton plane)

Longitudinal dynamics and nonflow

Phys. Rev. C 96, 064905 (2017)



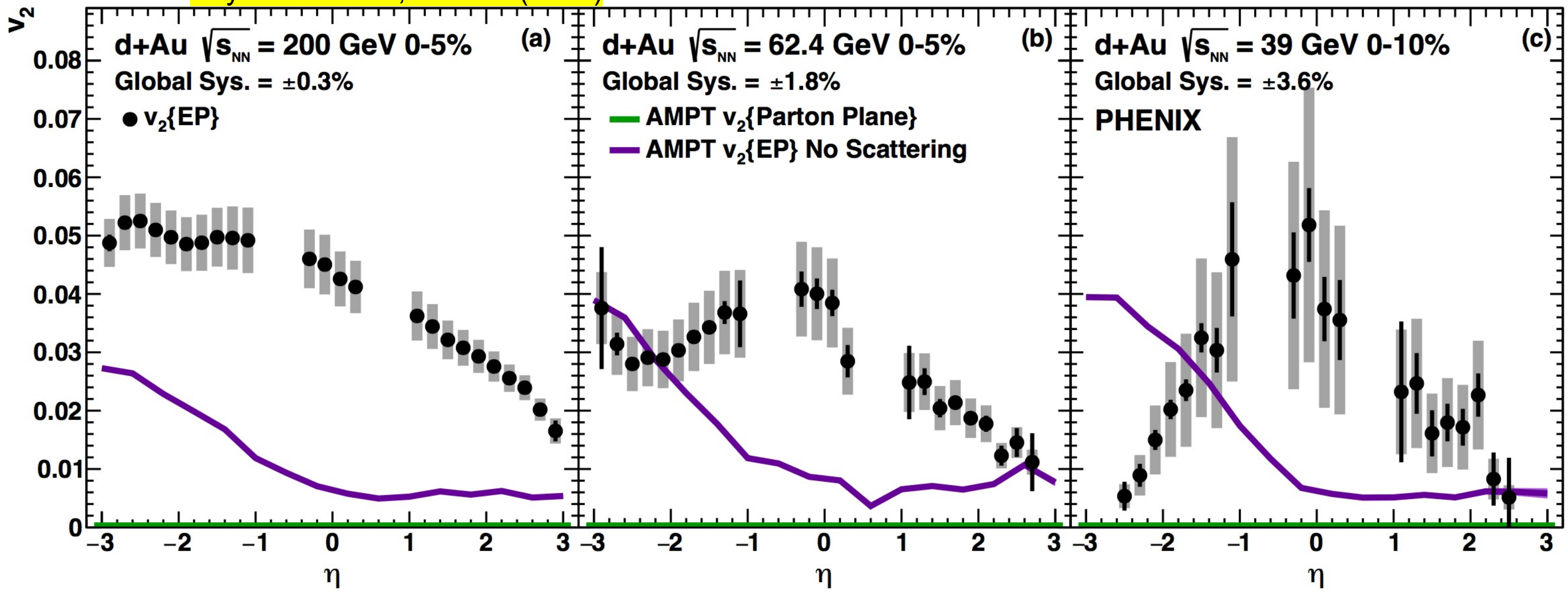


pure nonflow
event plane

zero flow
parton plane

Longitudinal dynamics and nonflow

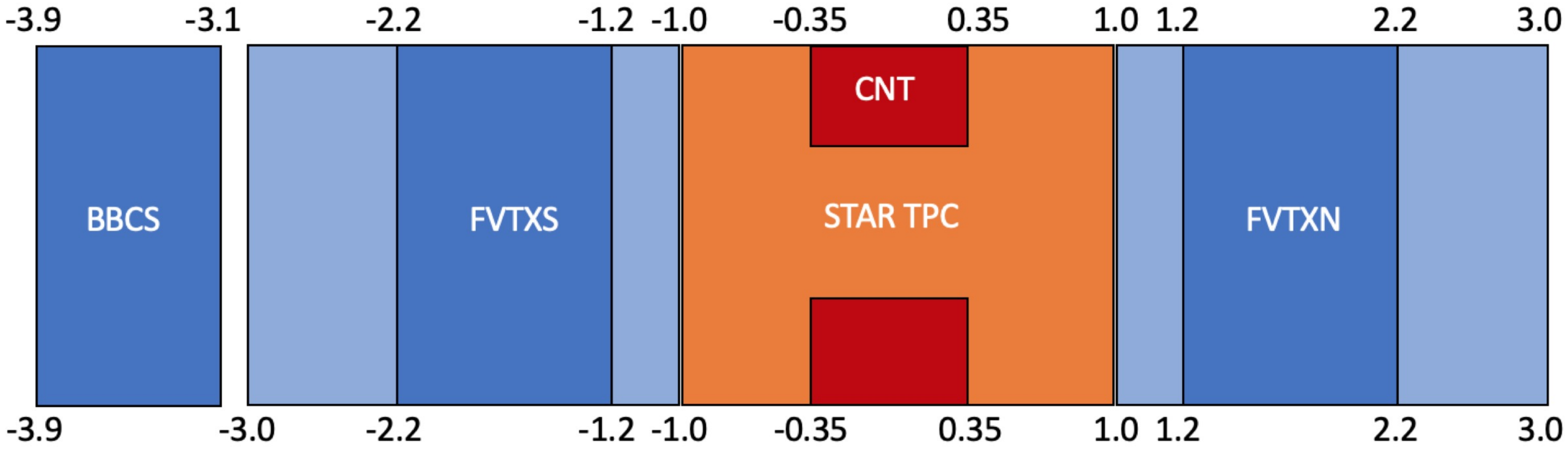
Phys. Rev. C 96, 064905 (2017)



- Large $\Delta\eta$ needed to suppress nonflow
- Flow and nonflow may not be additive

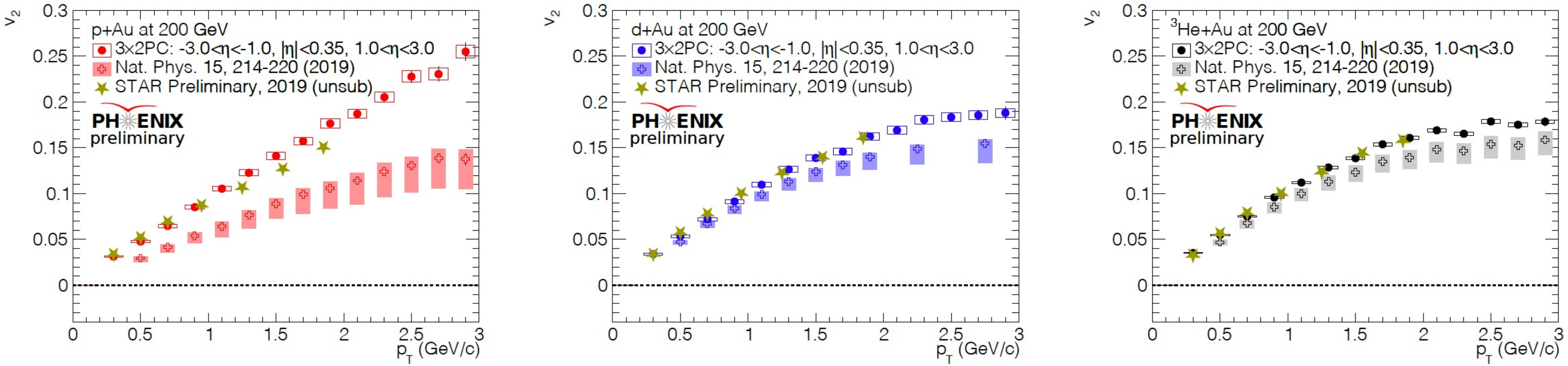
An attempt at matching STAR-PHENIX acceptance

- Matching the acceptance is not possible with 2014-2016 data, but PHENIX studied a symmetric combination: FVTXS – CNT – FVTXN
- Compared to STAR data before nonflow subtraction



An attempt at matching acceptance: v_2

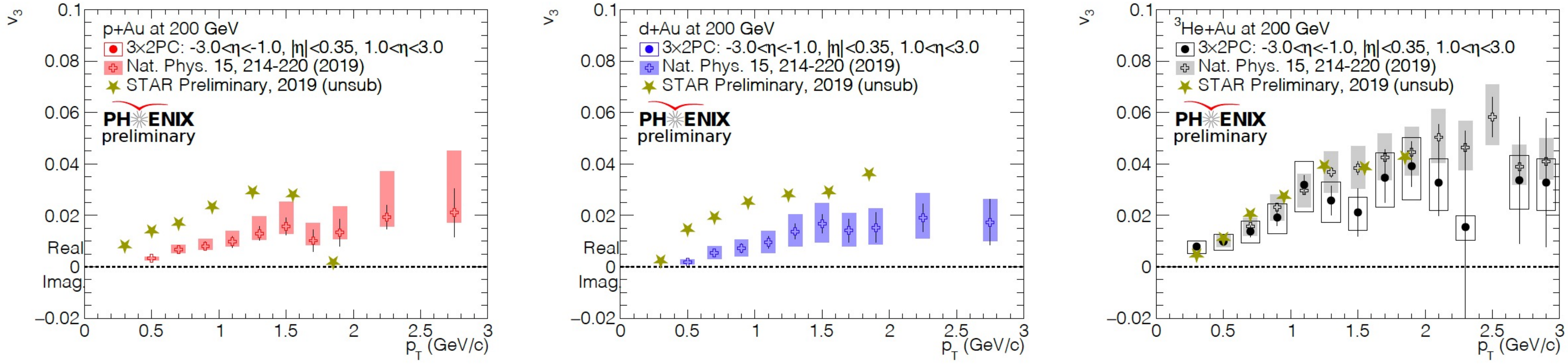
- Matching the acceptance is not possible with 2014-2016 data, but PHENIX studied a symmetric combination: FVTXS – CNT – FVTXN
- Compared to STA R preliminary data before nonflow subtraction
  - PHENIX data: Phys. Rev. C 105, 024901 (2022)



- Good agreement in v_2

An attempt at matching acceptance: v_3

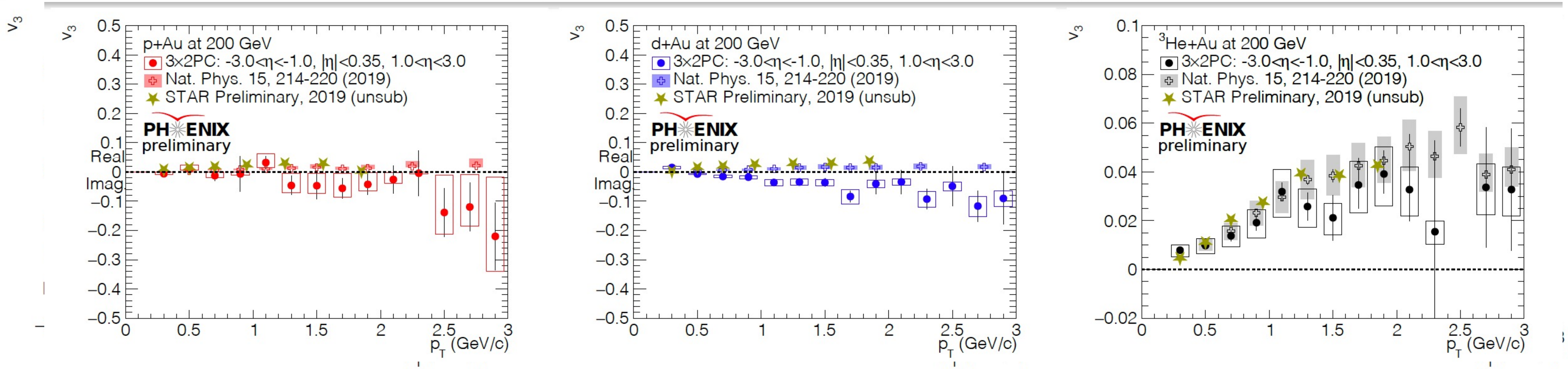
- Matching the acceptance is not possible with 2014-2016 data, but PHENIX studied a symmetric combination: FVTXS – CNT – FVTXN
- Compared to STA R preliminary data before nonflow subtraction
  - PHENIX data: Phys. Rev. C 105, 024901 (2022)



- Large difference in v_3
- Different physics at play in two different pseudorapidity acceptances

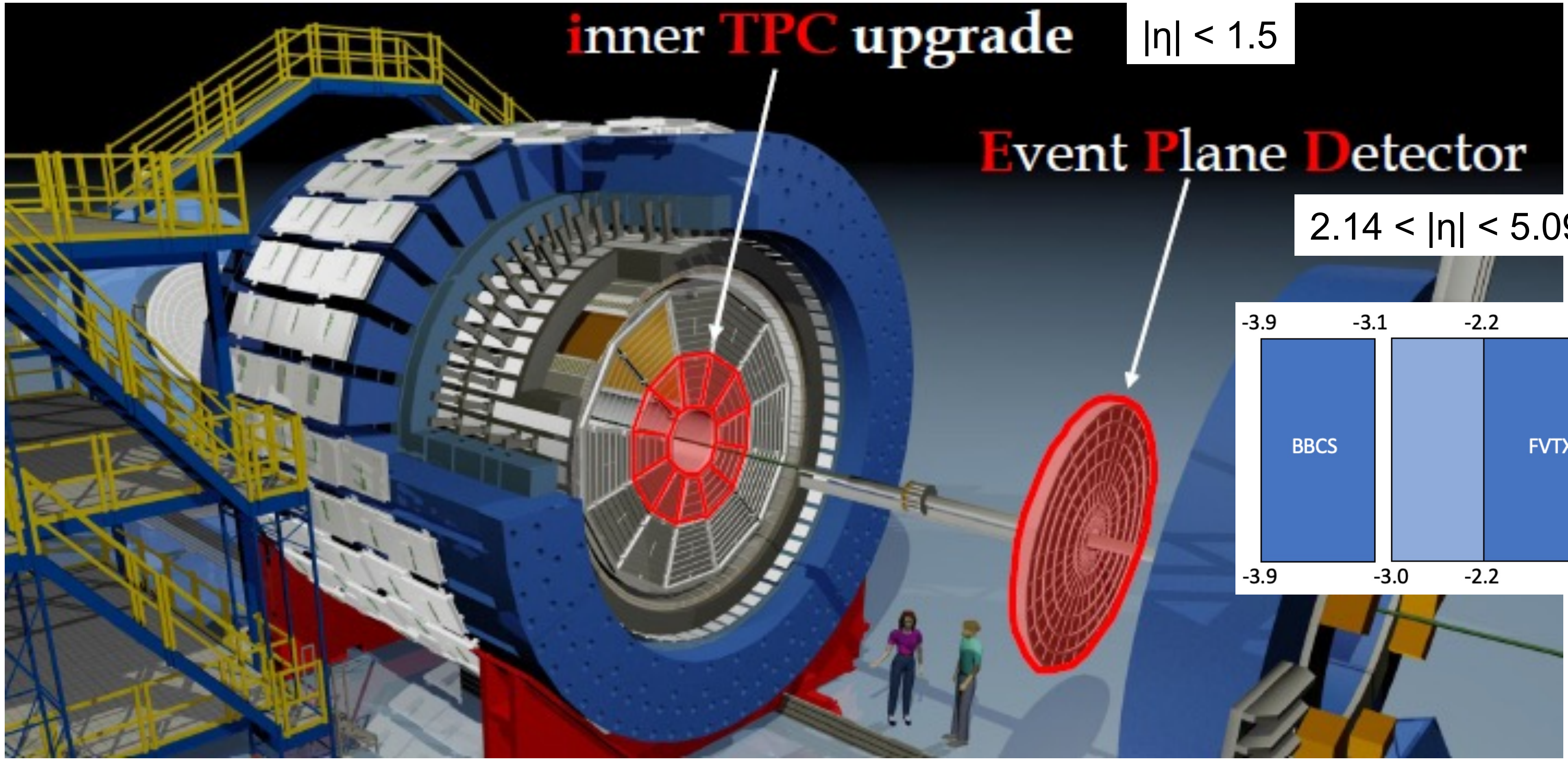
An attempt at matching acceptance: v_3

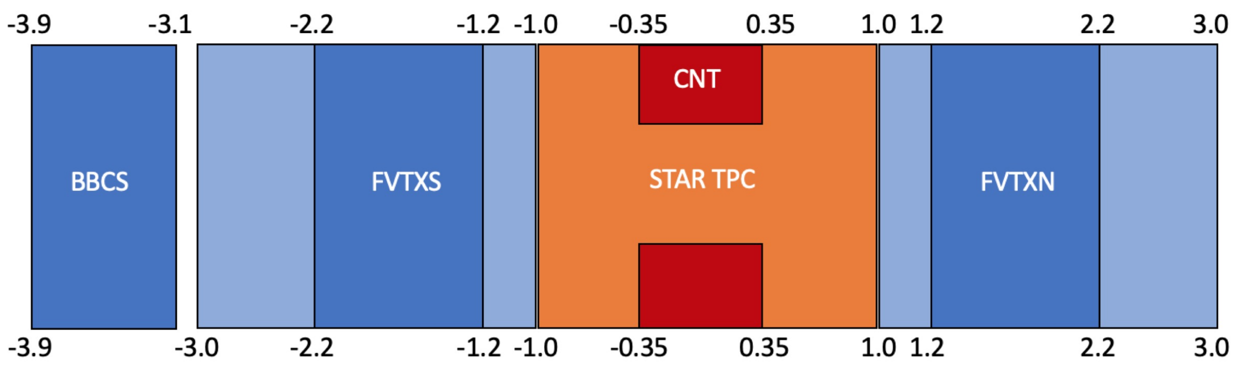
- Matching the acceptance is not possible with 2014-2016 data, but PHENIX studied a symmetric combination: FVTXS – CNT – FVTXN
- Compared to STA R preliminary data before nonflow subtraction
  - PHENIX data: Phys. Rev. C 105, 024901 (2022)



- v_3 can not be extracted in p/d+Au; imaginary value
- In addition to nonflow, decorrelation effects could also play a role in v_3

The upgraded STAR detector





- New d+Au data in 2021
- p+Au data expected in 2024
- Direct STAR - PHENIX comparisons will be possible

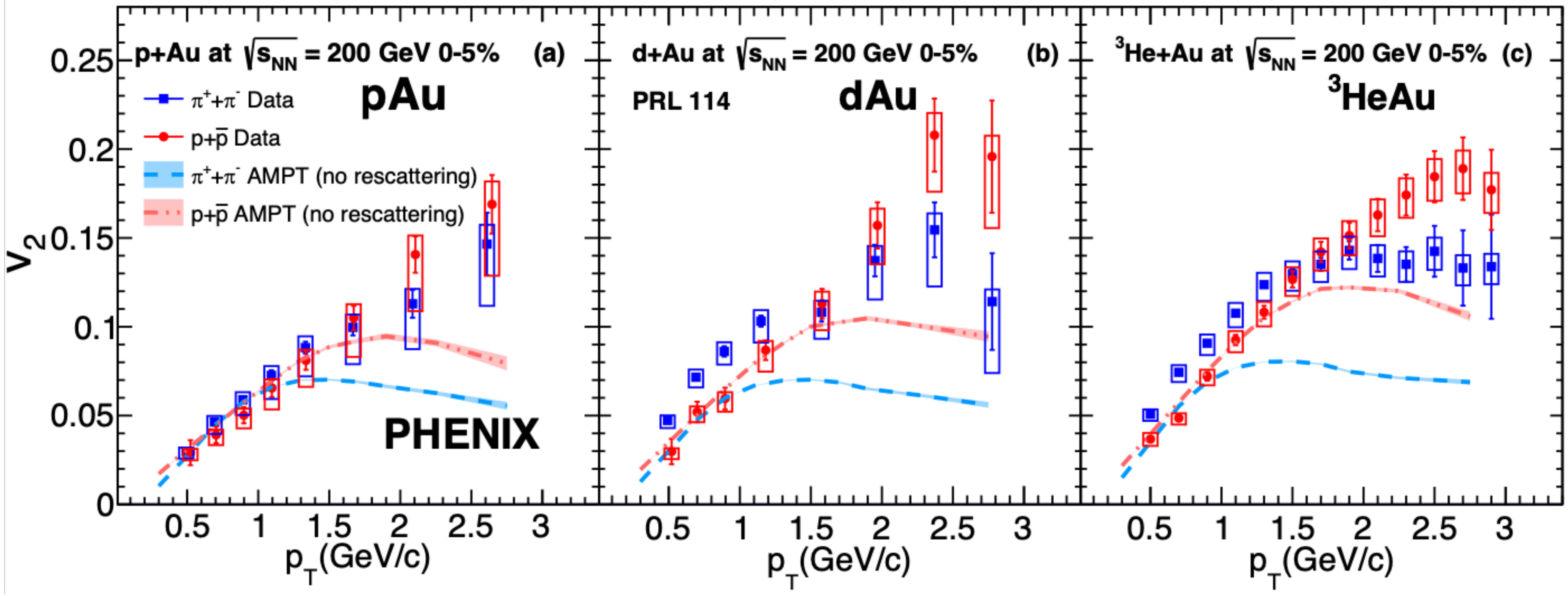
Summary

- A wealth of PHENIX results on collectivity in small systems
- Compelling evidence for formation of hot QGP droplets
- Detailed STAR – PHENIX data comparison offers opportunities for deeper understanding of the physics

- d+Au (2021) and p+Au (2024) data will provide further insights
  – STAR upgraded detector
  – sPHENIX coming online

Identified particle flow in AMPT

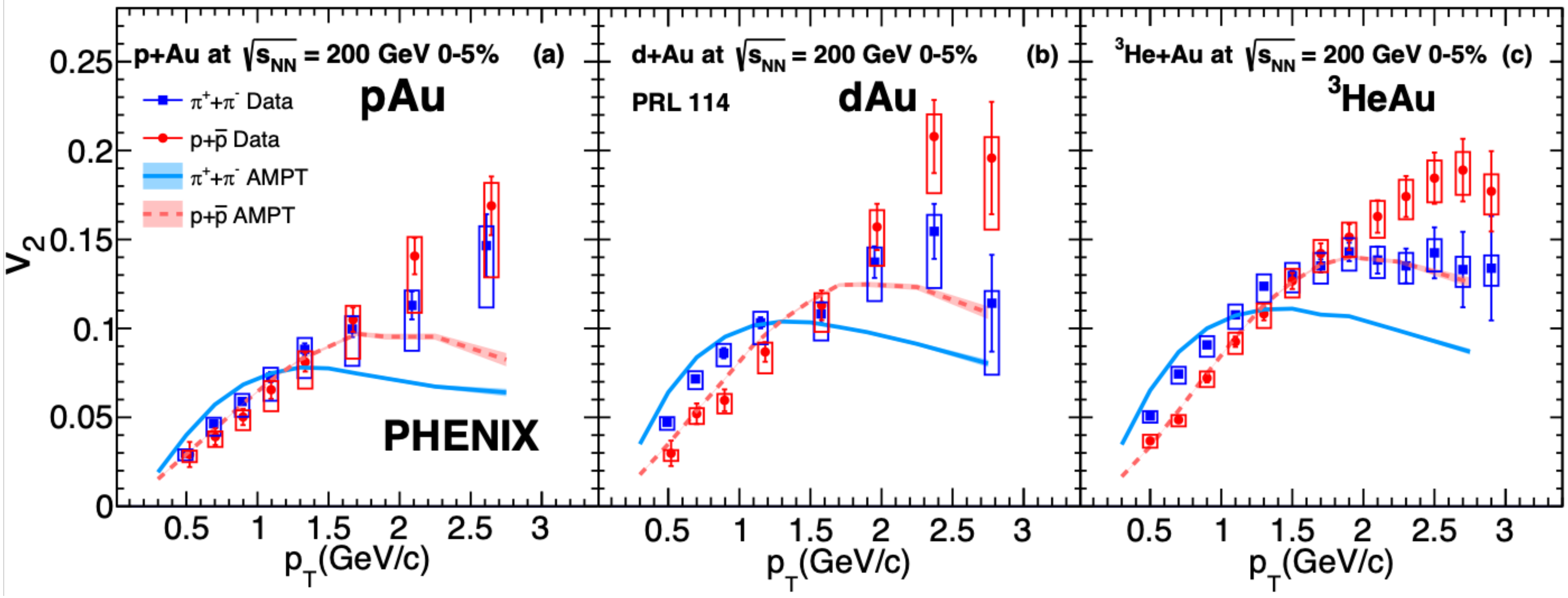
Phys. Rev. C 97, 064904 (2018)



In AMPT, hadronization by recombination results in baryon/meson splitting for p_T> 2 GeV consistent with the data

Identified particle flow in AMPT

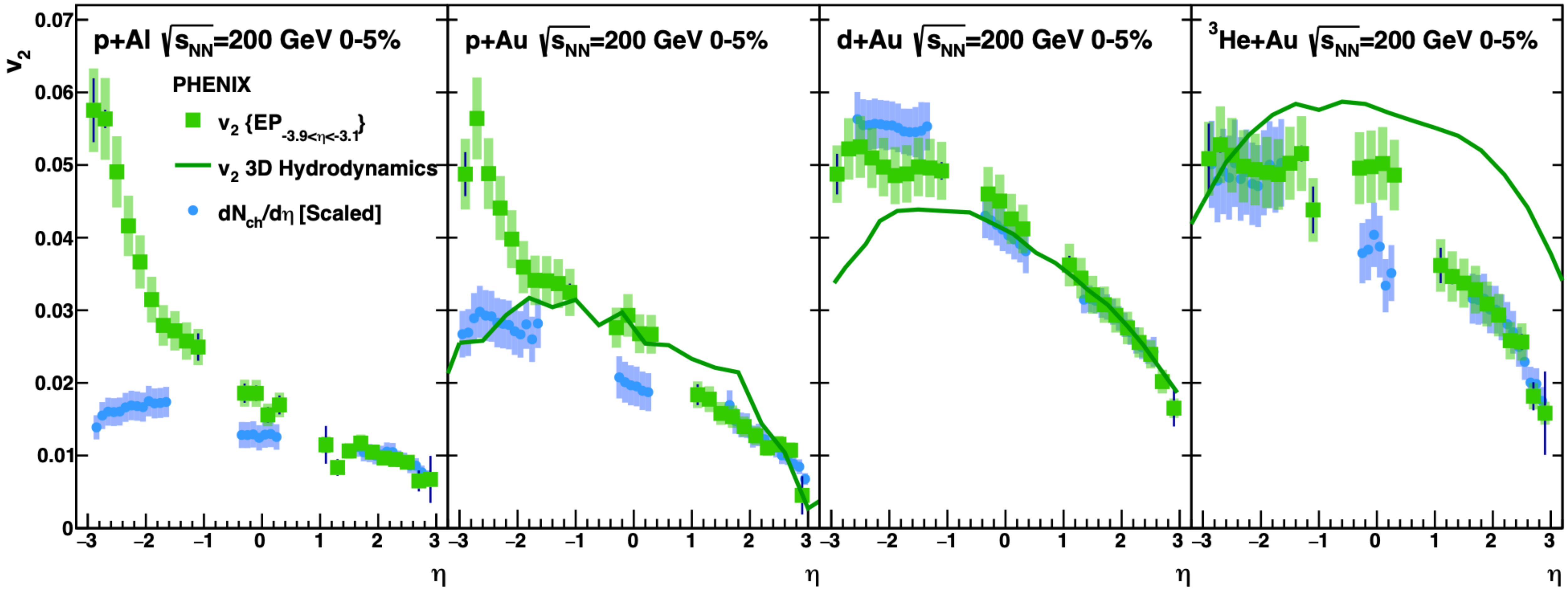
Phys. Rev. C 97, 064904 (2018)



In AMPT, late-stage hadronic rescattering results in pion/proton v_2 splitting for p_T < 2 GeV consistent with the data

multiplicity and v_2

PRL 121, 222301 (2018)



STAR v_2 and v_3 with different $\Delta\eta$ gaps

Phys. Rev. C **105** (2022) 14901