Collectivity in small systems at RHIC

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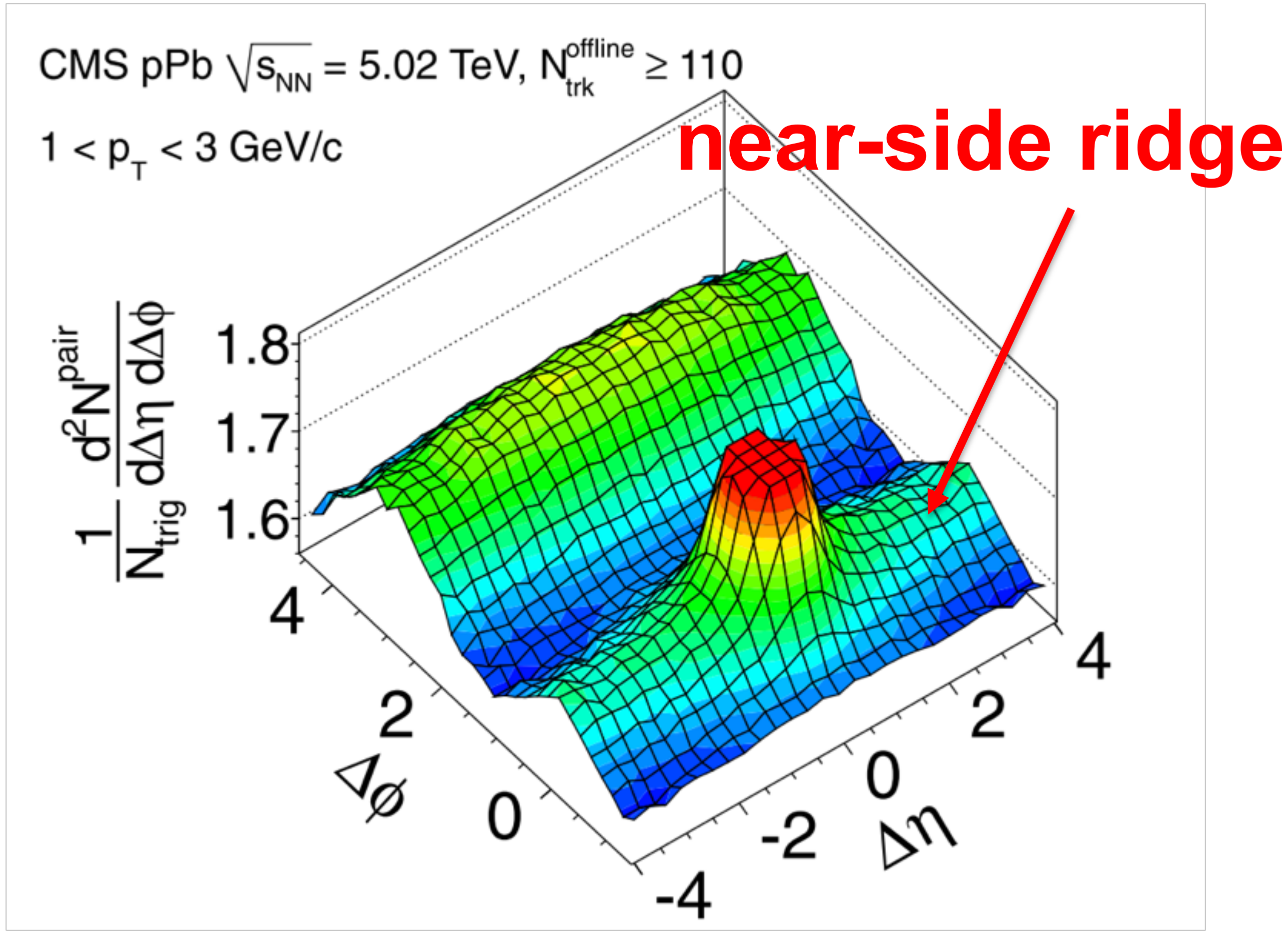
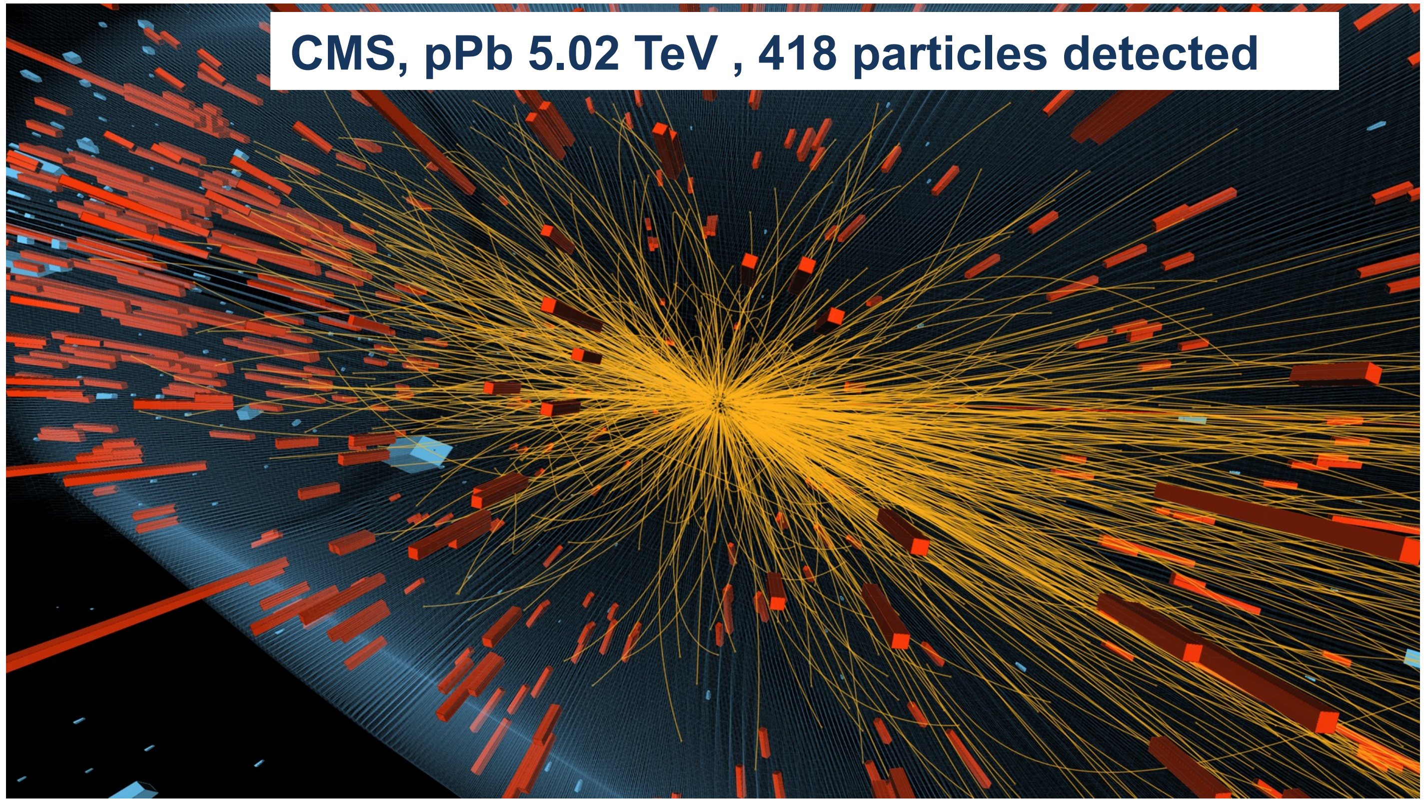
Motivation to study small systems

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





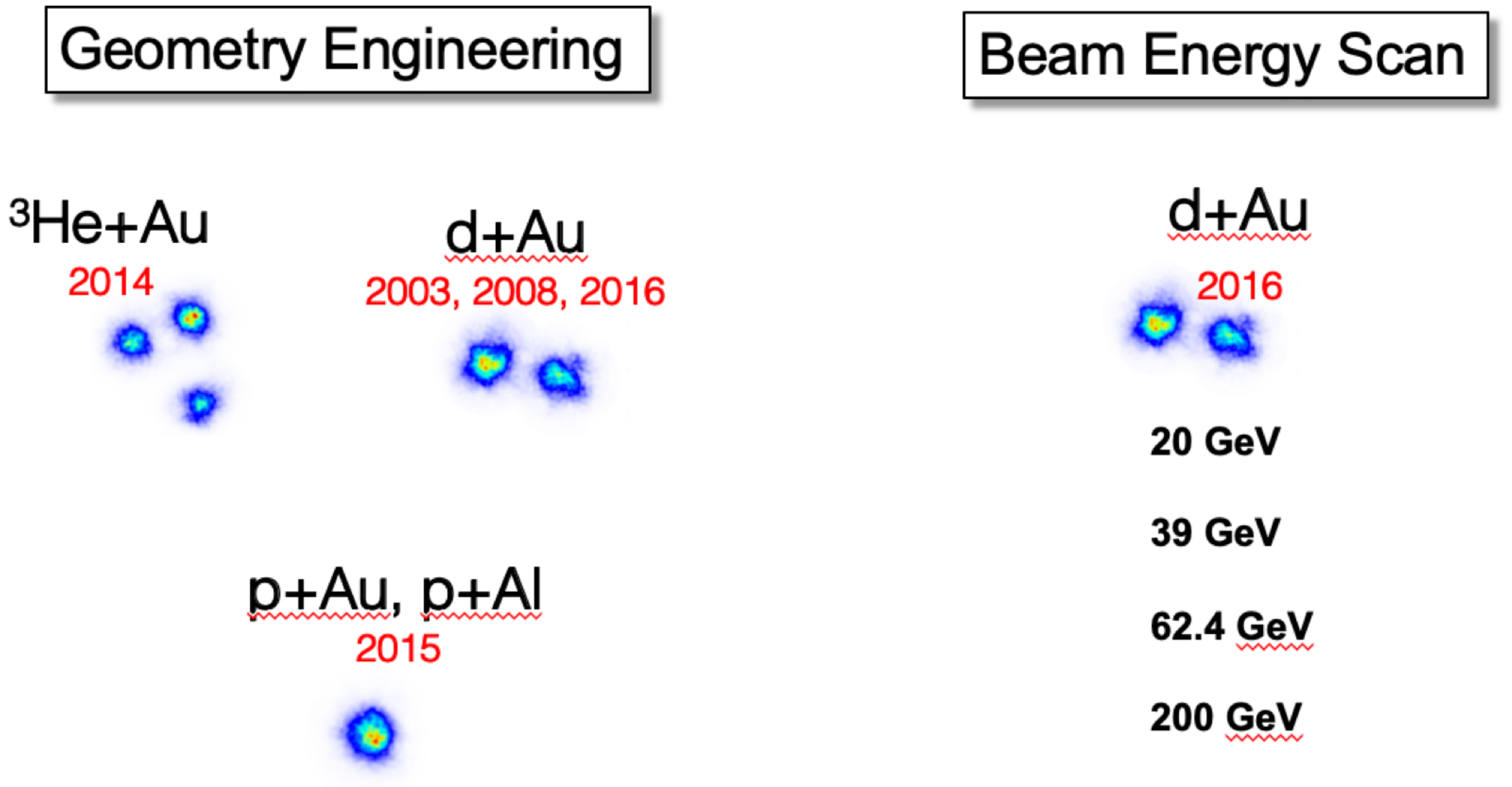
- Revised: to understand the origin of the near-perfect fluidity of QGP

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 ($v_n \neq \varepsilon_n$), 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

Why study small systems at RHIC ?

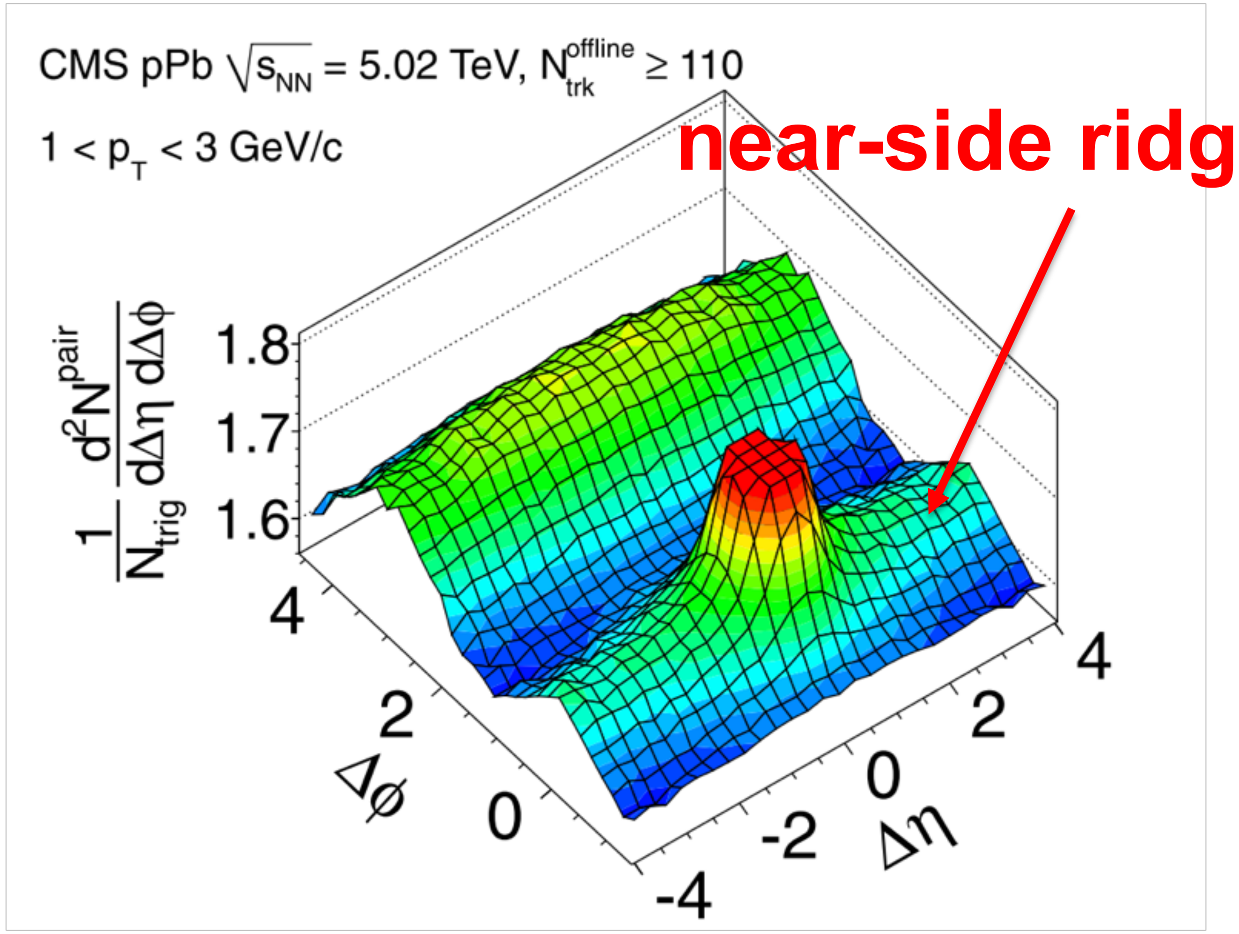
- Unique versatility in collision systems and beam energy



+ not yet analyzed STAR data from 2021, d+Au and O+O at 200 GeV
    - Opportunity for detailed studies of correlation phenomena and multi-faceted quantitative comparisons to theory

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

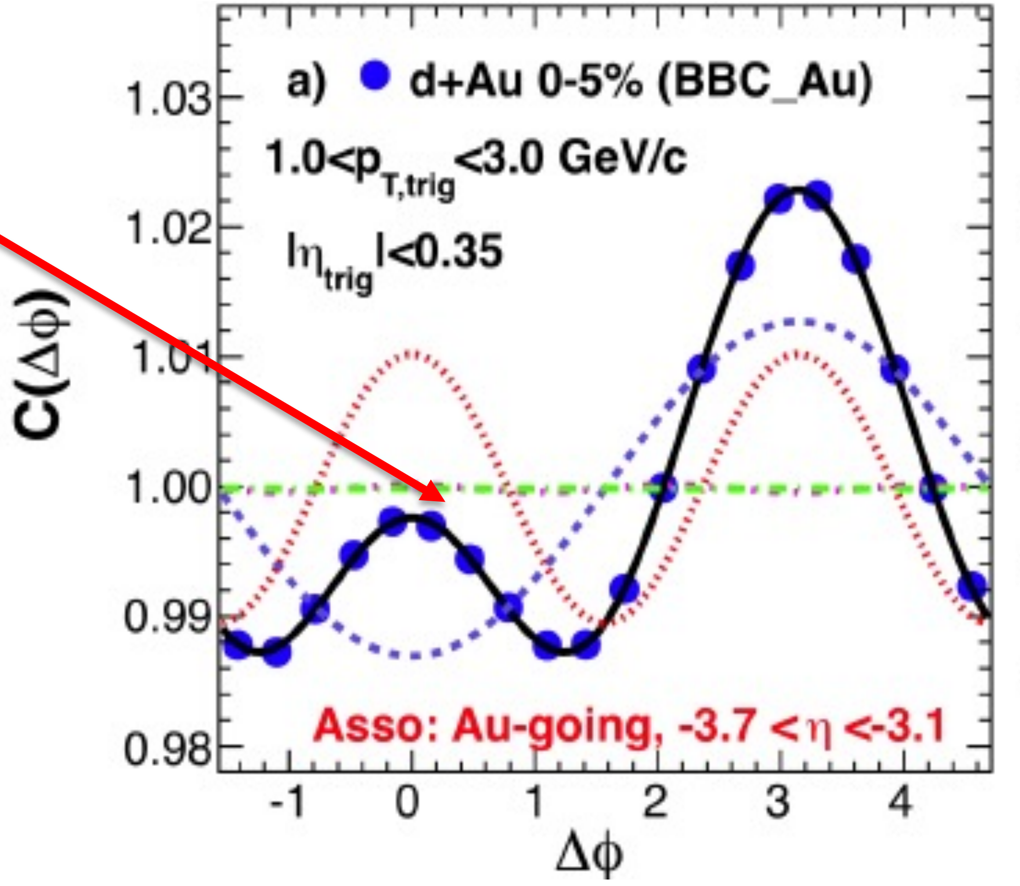
PLB 718 (2013) 795



near-side ridge

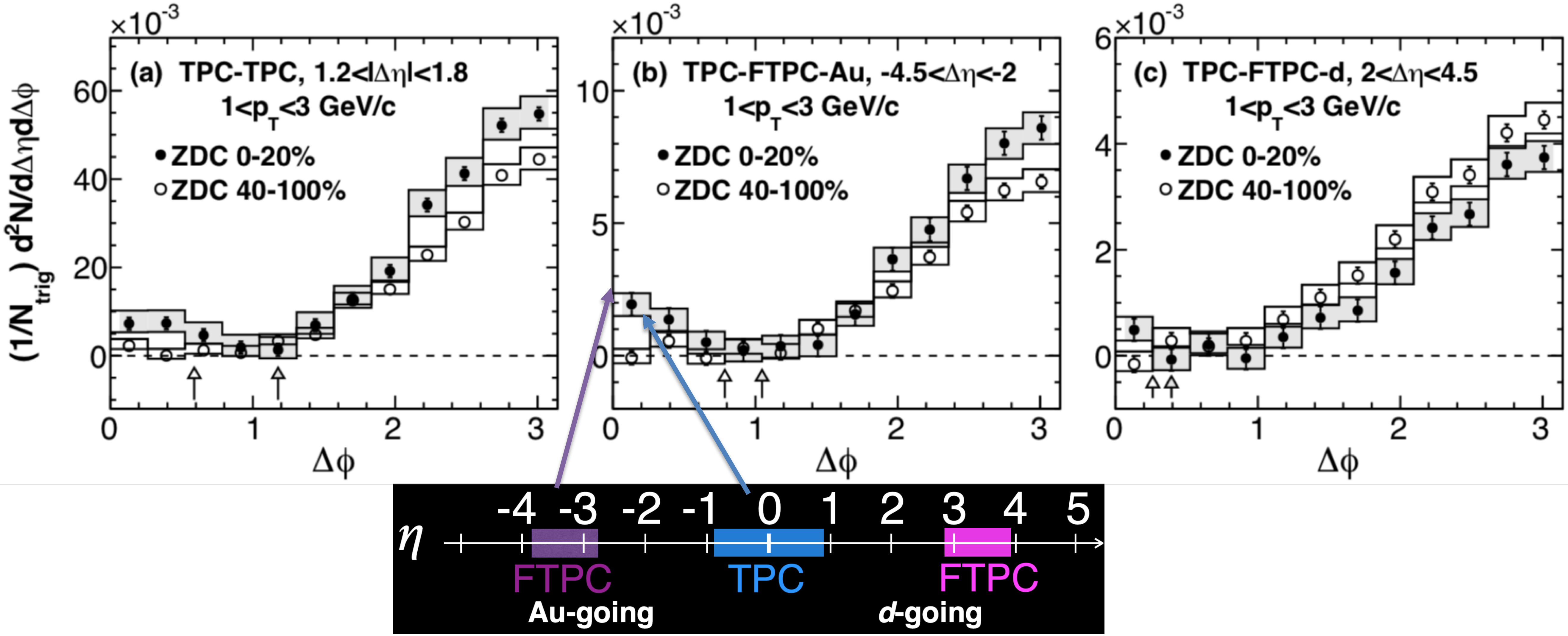
2008 d+Au data

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



Long-range 2-particle correlations in STAR

Phys. Lett. B 747 (2015) 265 - (2003 d+Au data)

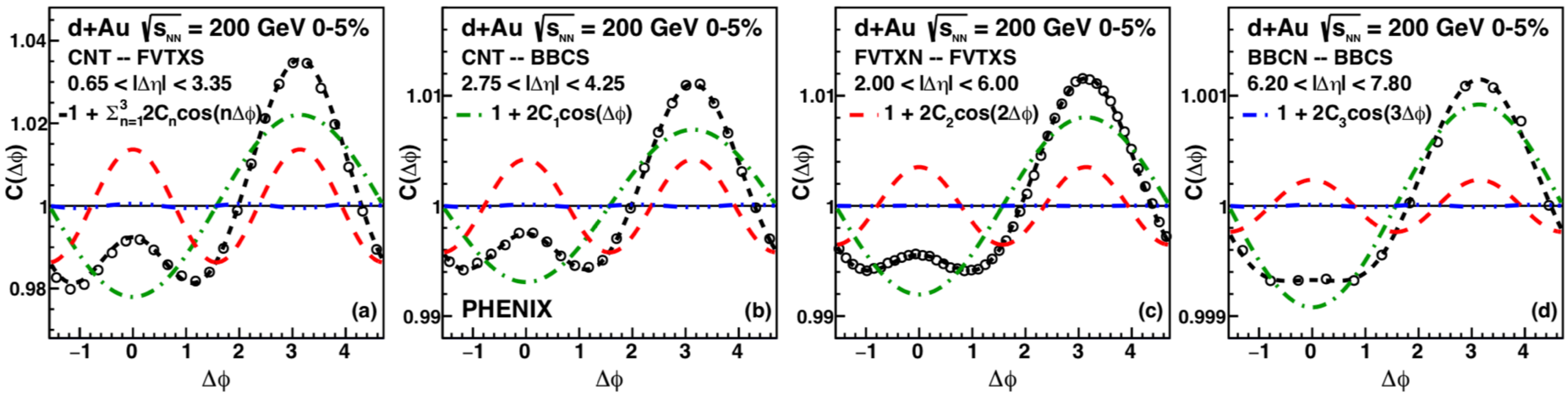


Excess in near-side yield extending long-range in Δη in high-multiplicity events

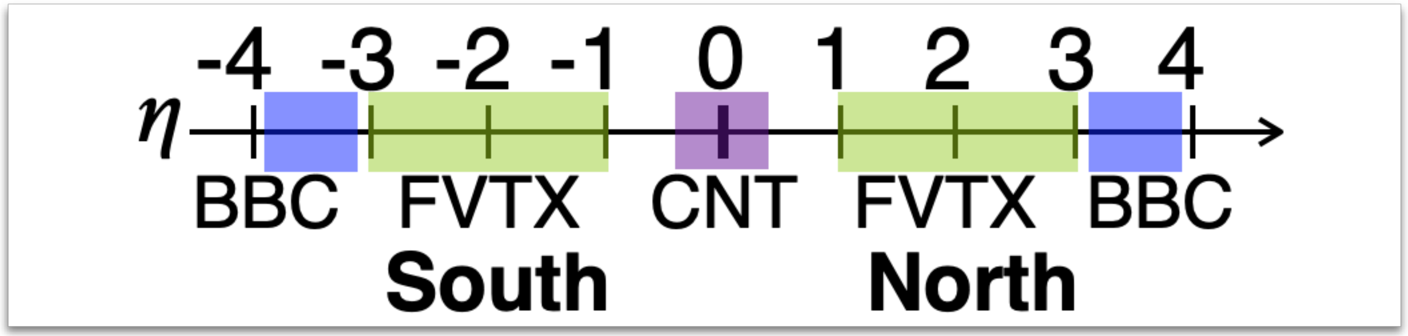
larger Δη range studied with 2016 d+Au data

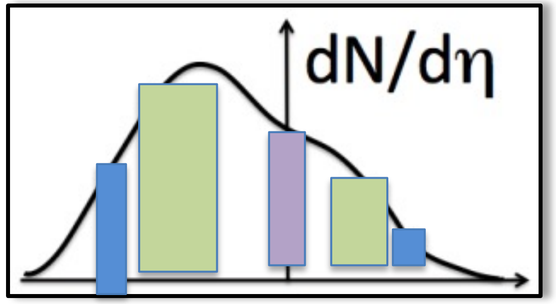
PRC 96, 064905 (2017)

2016 d+Au data



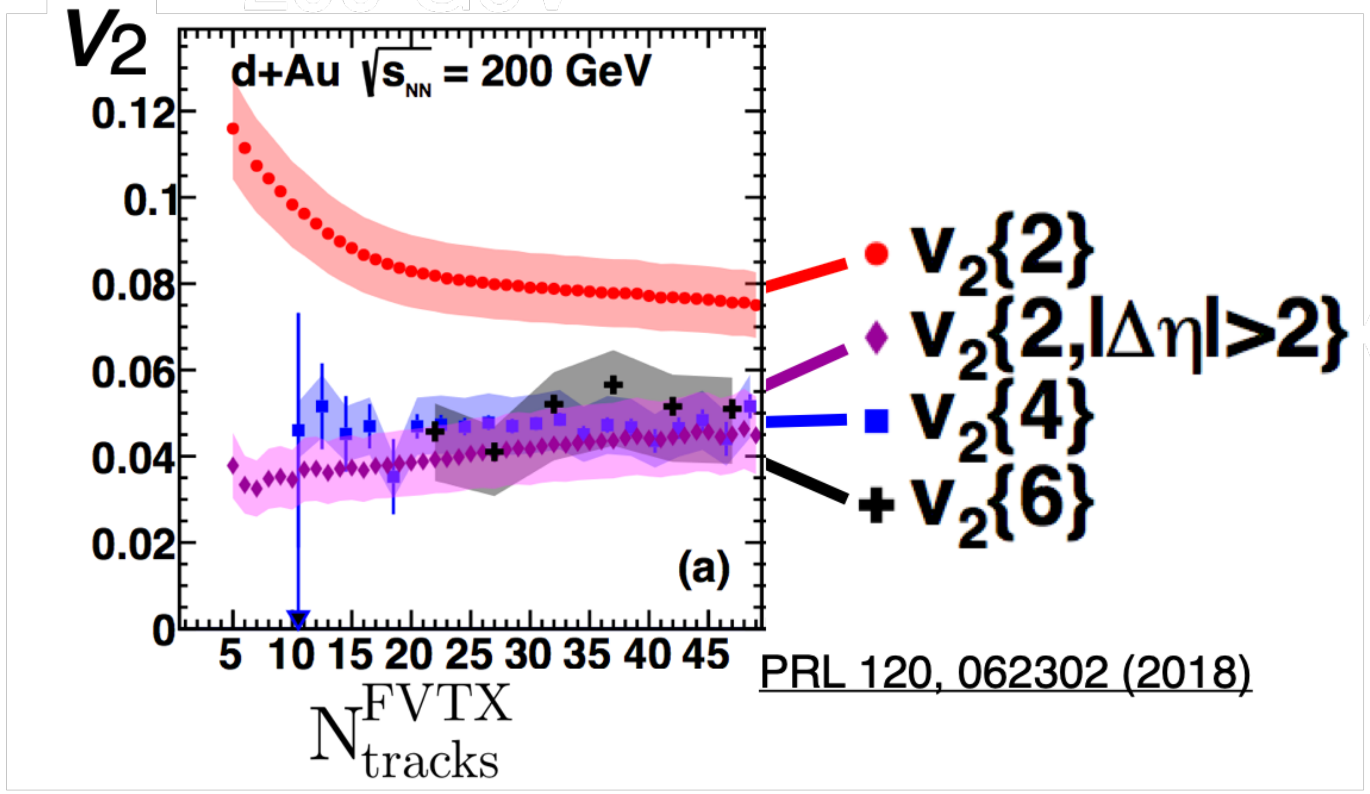
(a) 0.65 < |Δη| < 3.35, (b) 2.75 < |Δη| < 4.25, (c) 2.0 < |Δη| < 6.0, (d) 6.2 < |Δη<7.8





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

Are all particles correlated ?



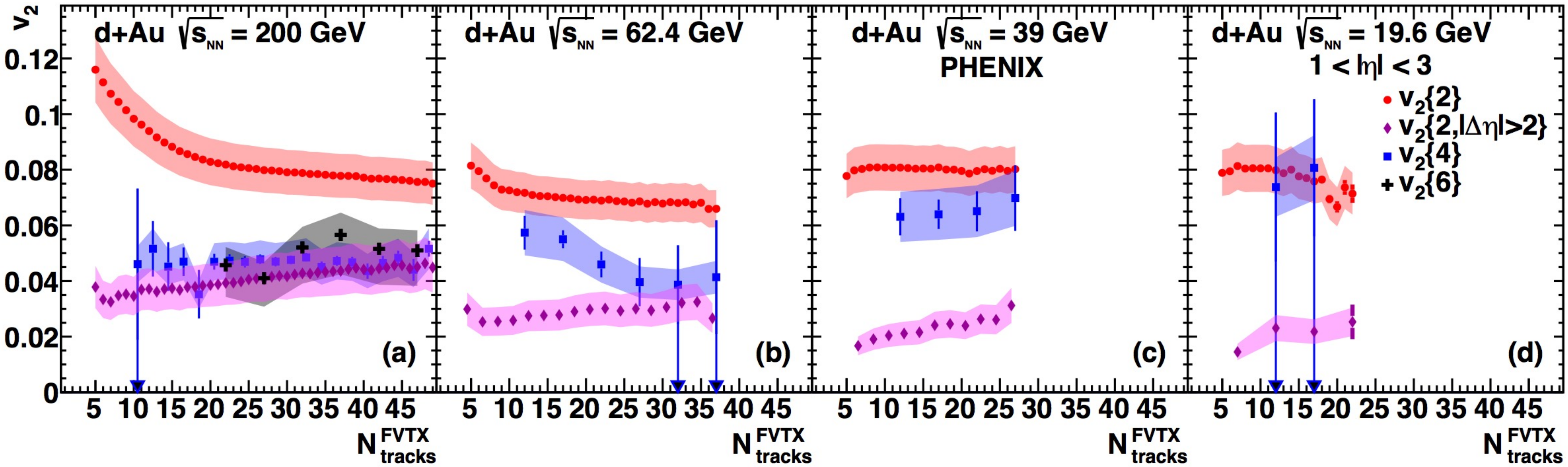
PRL 120, 062302 (2018)

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

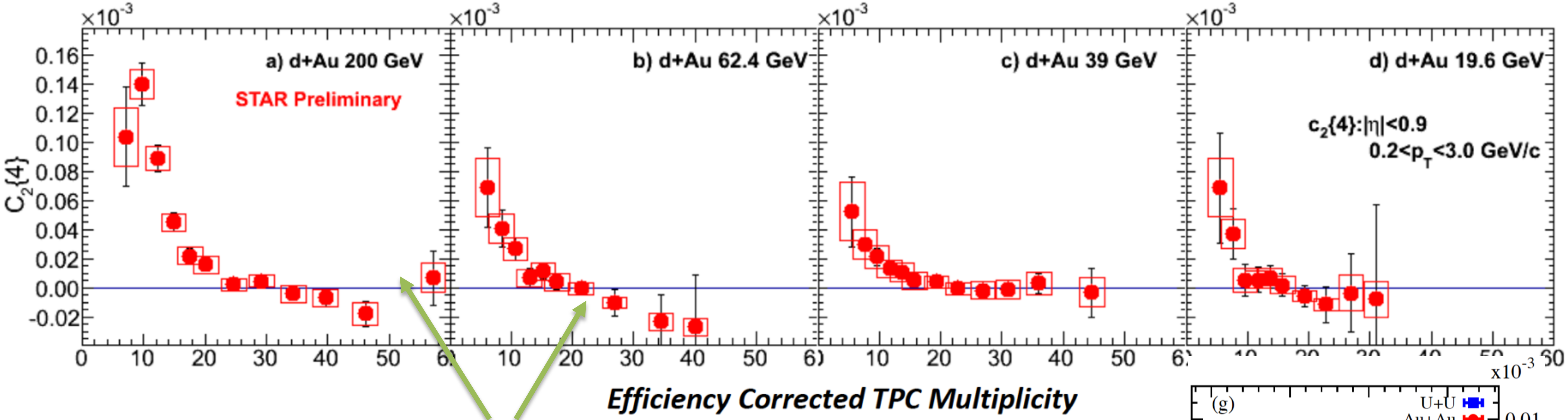
PRL, 120, 062302, (2018)



- Real v2{4} for all energies
- Consistent with collective flow

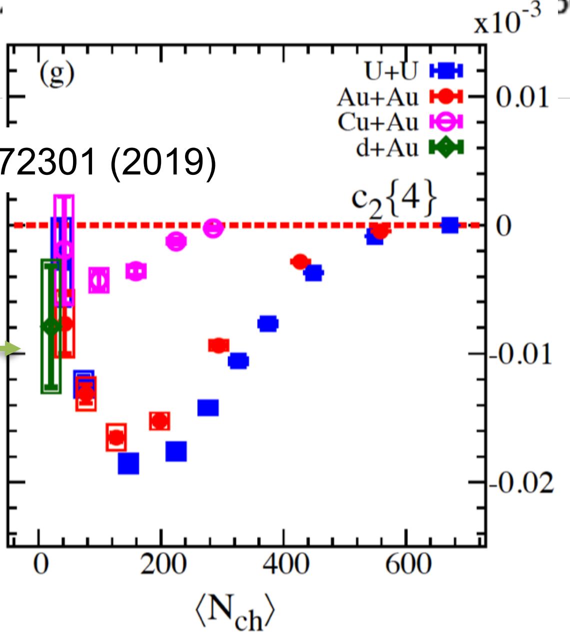
Star: multi-particle correlations, $v_2\{4\}$

$c_2\{4\}$ vs. $<dN/d\eta>$



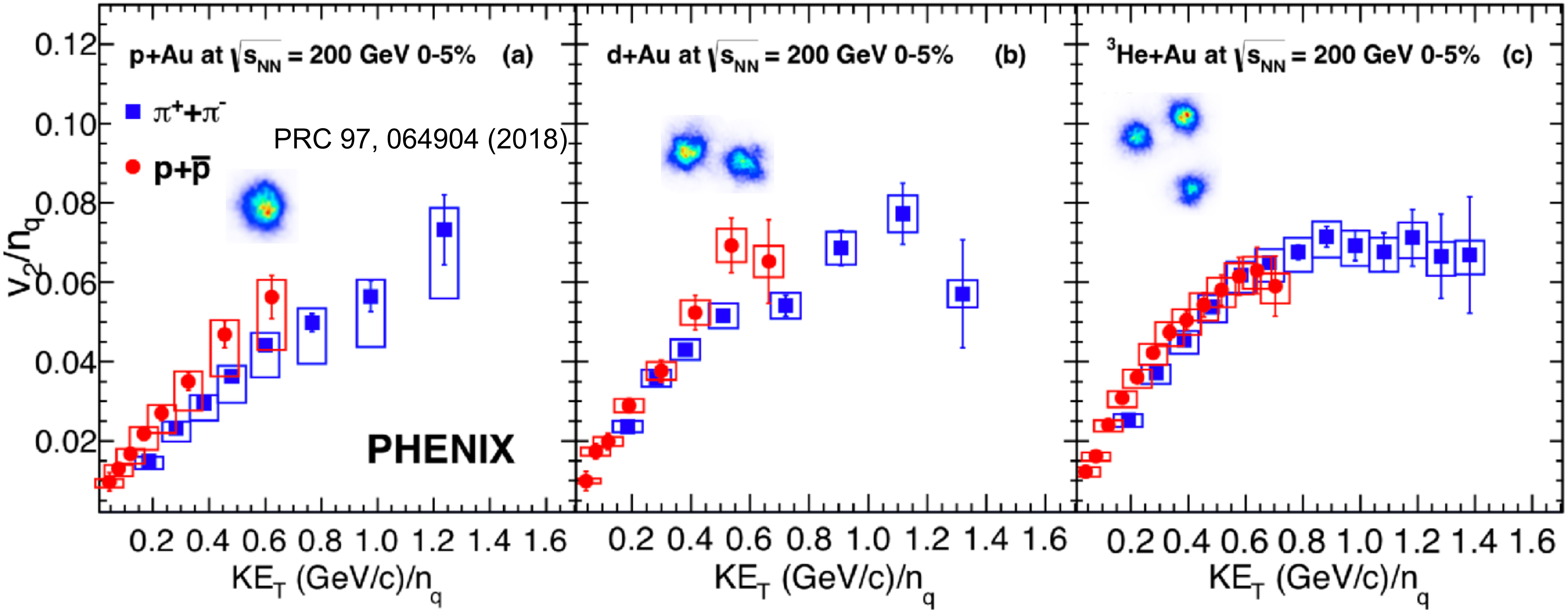
- Indication of negative c2{4}

Phys. Rev. Lett. 122, 172301 (2019)



Note: different kinematic range for STAR & PHENIX

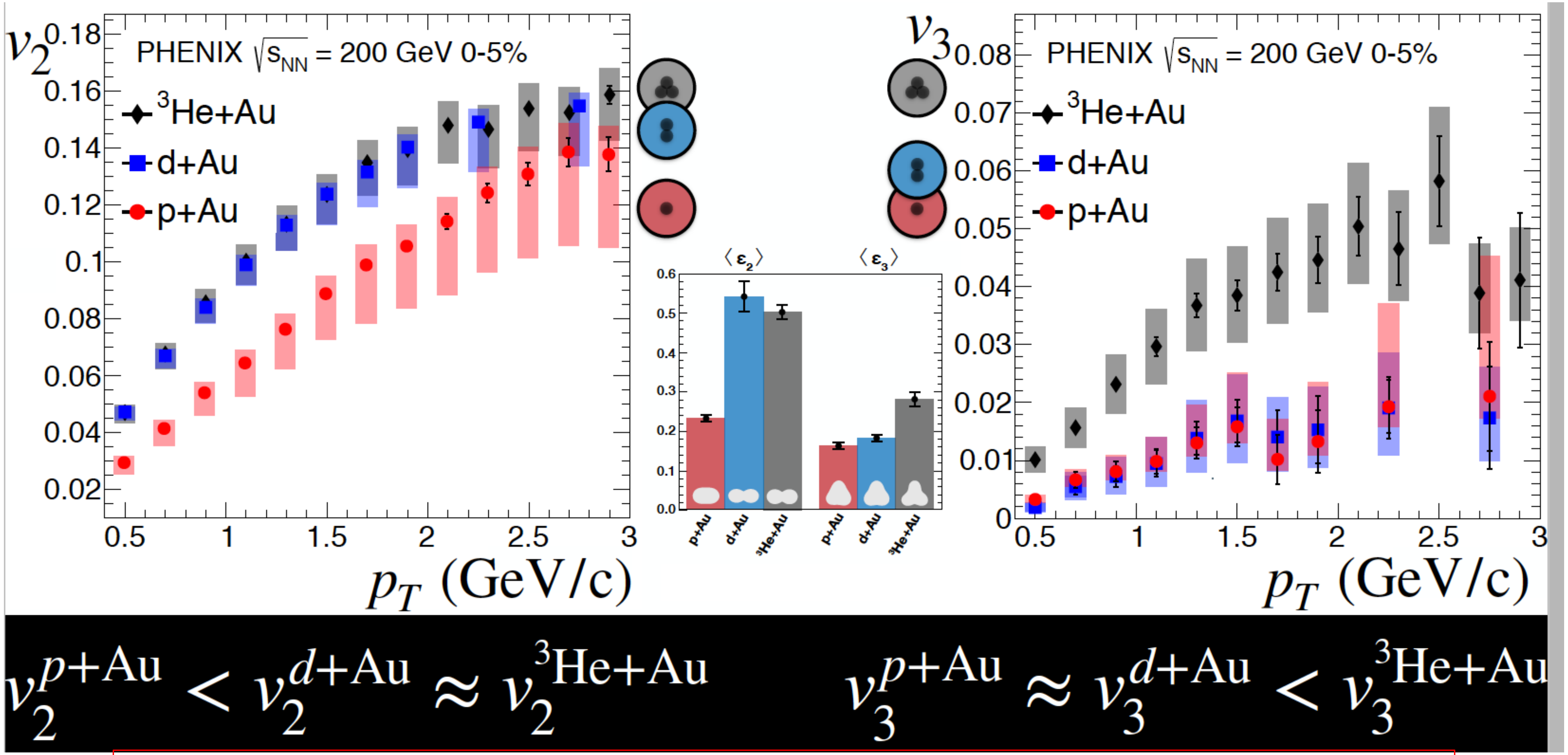
Is there a common velocity field ?



- 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

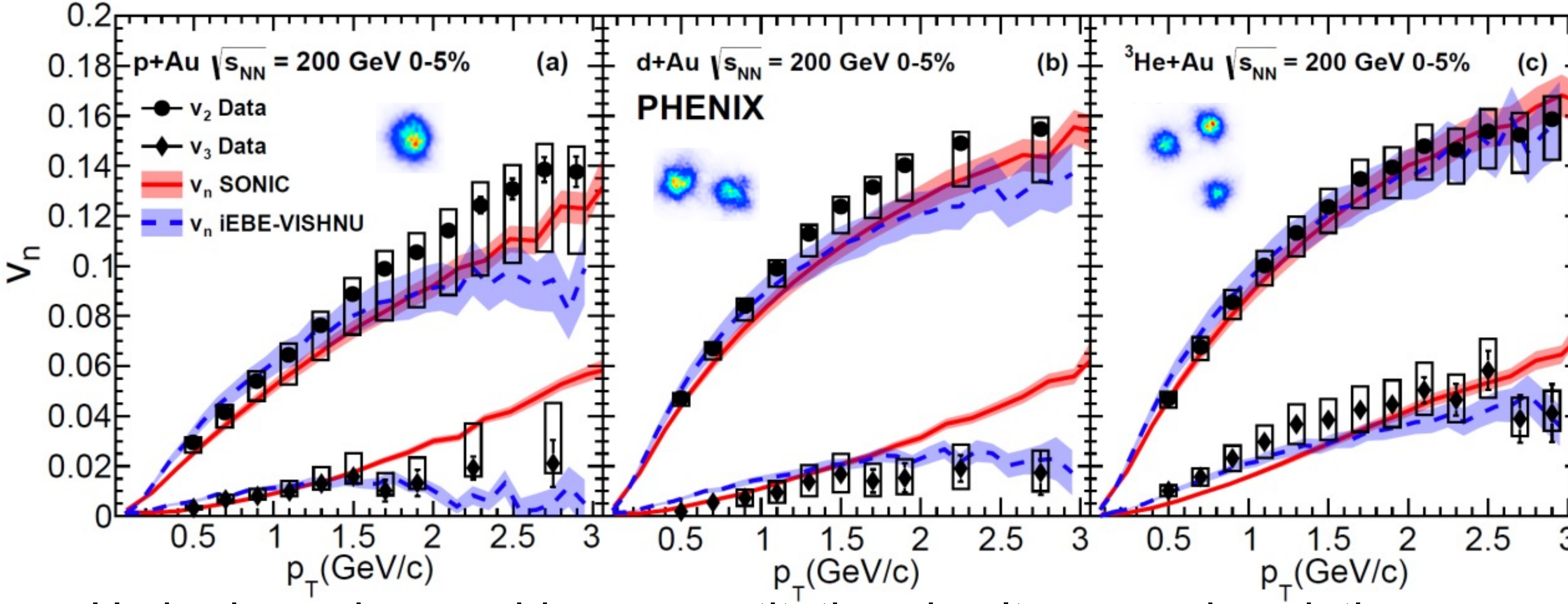
Nature Phys. 15 (2019) no.3, 214-220



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

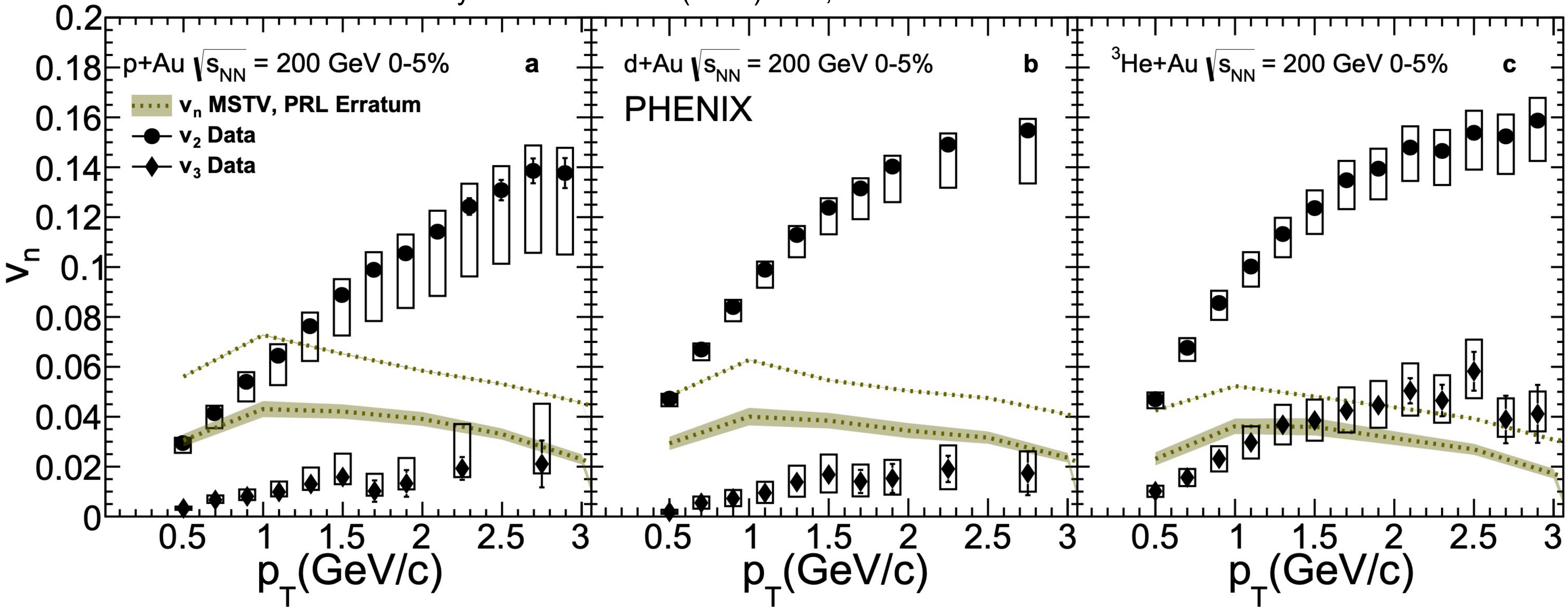
Nature Phys. 15 (2019) no.3, 214-220



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

The role of the initial state

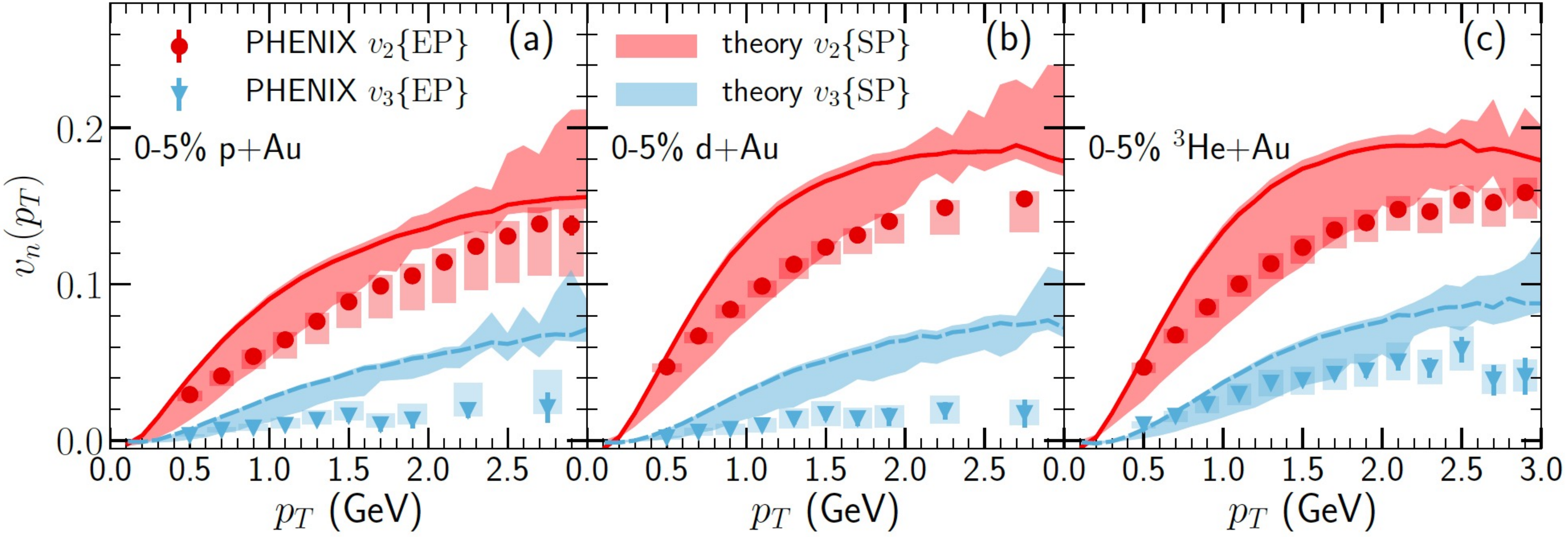
Erratum: Phys. Rev. Lett. 121 (2018) no.5, 052301



- CGC does not provide a viable explanation

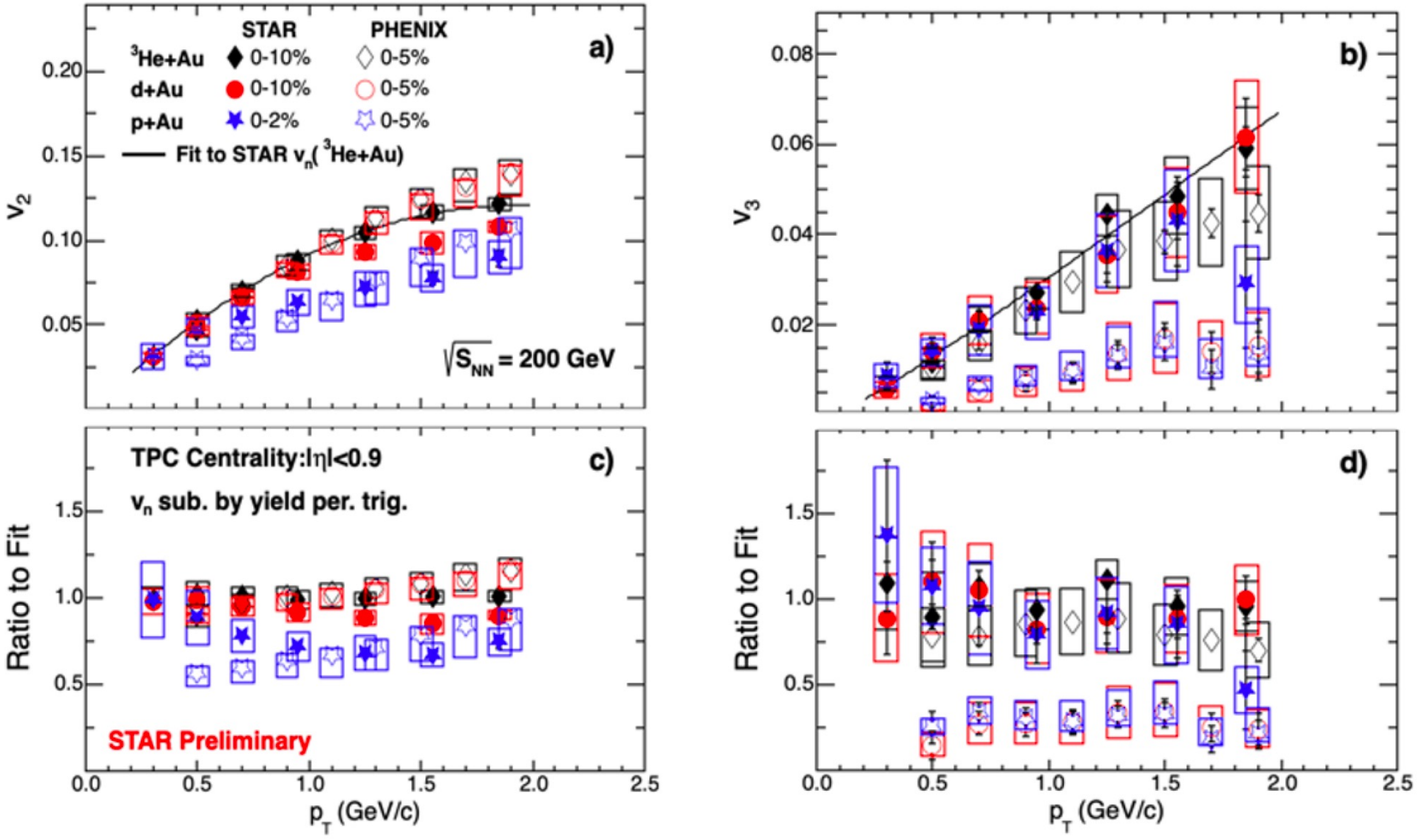
Initial + final state effects

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

PHENIX- STAR comparison: QM19



Reasonable agreement in v_2

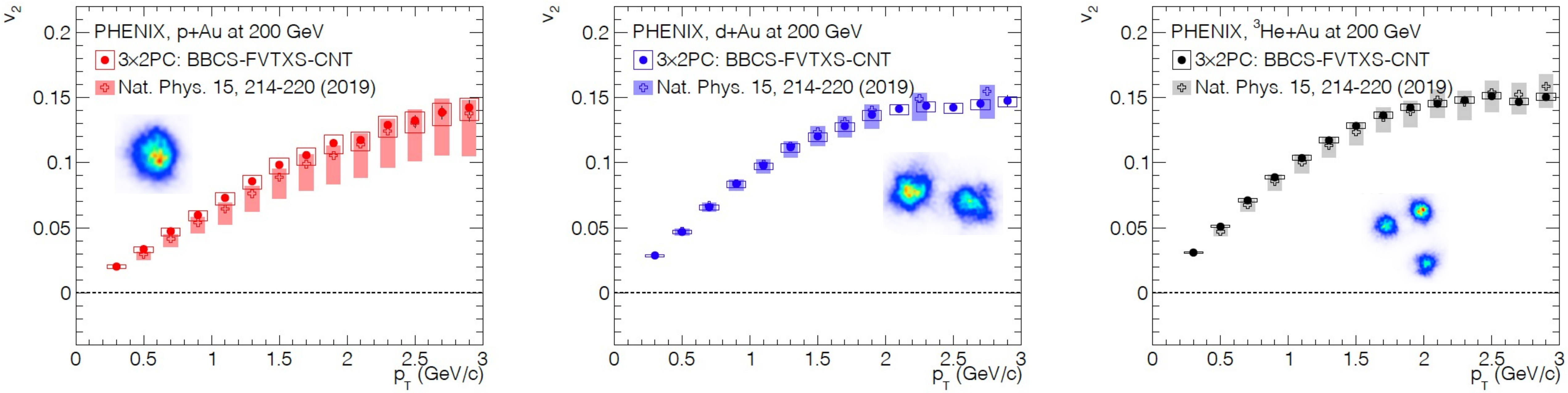
Large discrepancy in v_3

Task force formed in 2020 to investigate the differences

The work has concluded in June 2021

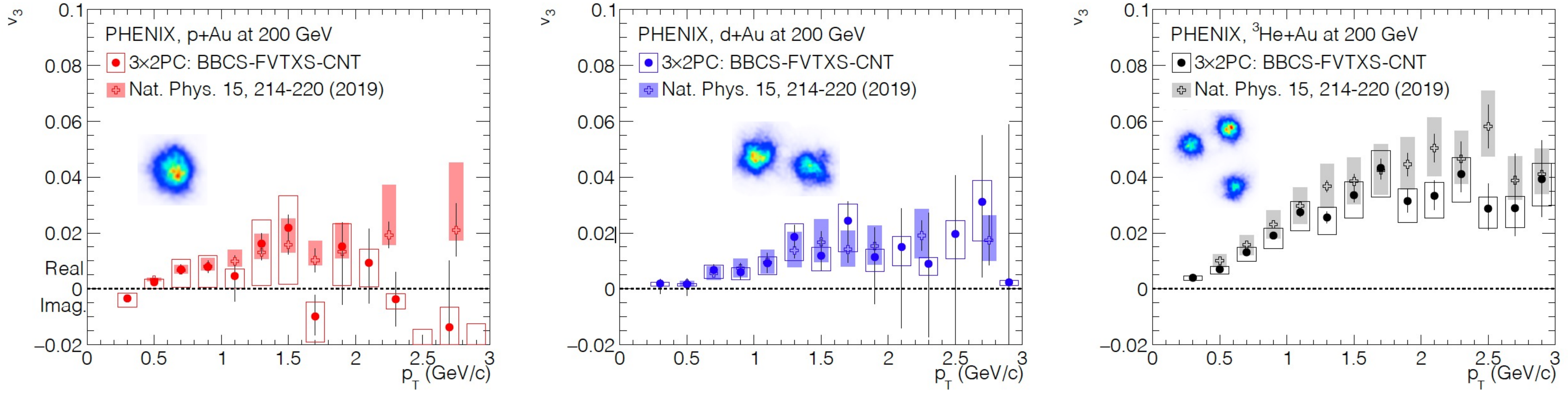
Publications to follow

PHENIX new analysis confirms results: arXiv:2107.06634



- PHENIX has completed and submitted for publication a new analysis confirming the results published in Nature Physics
- 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
- Measurement error ruled out

PHENIX new analysis confirms results: arXiv:2107.06634



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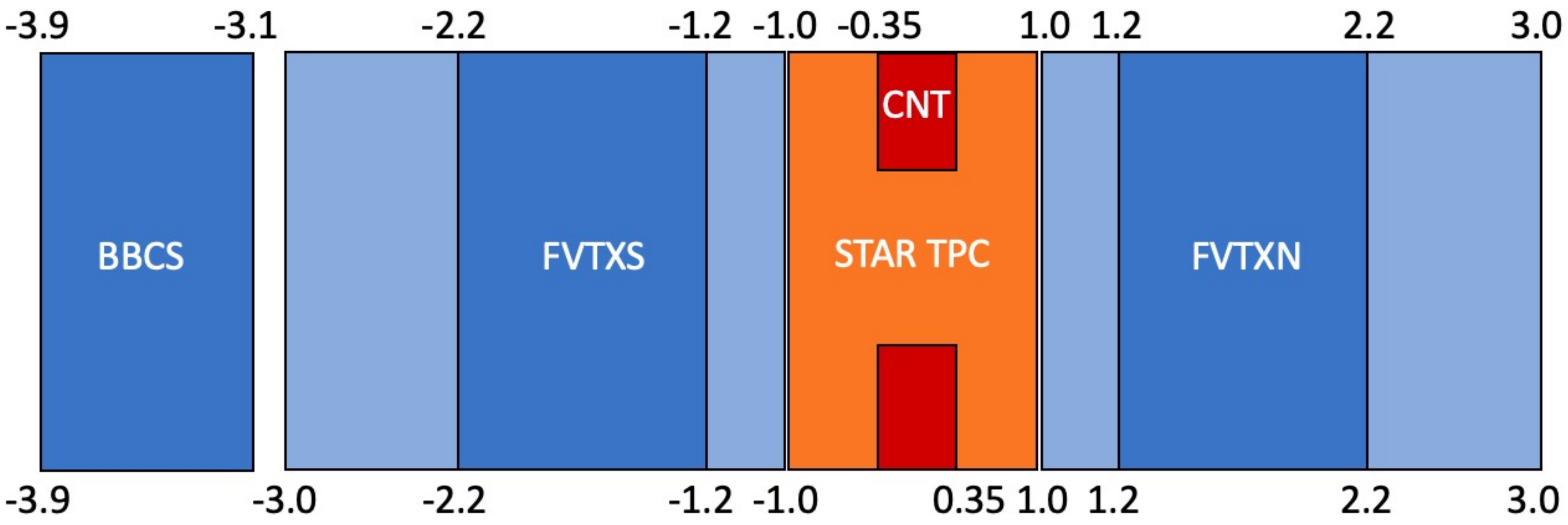
  - completely new and separate code; measurement using FVTX tracks rather than clusters
- Measurement error ruled out; ; STAR also confirmed their result

Physics differences between STAR and PHENIX

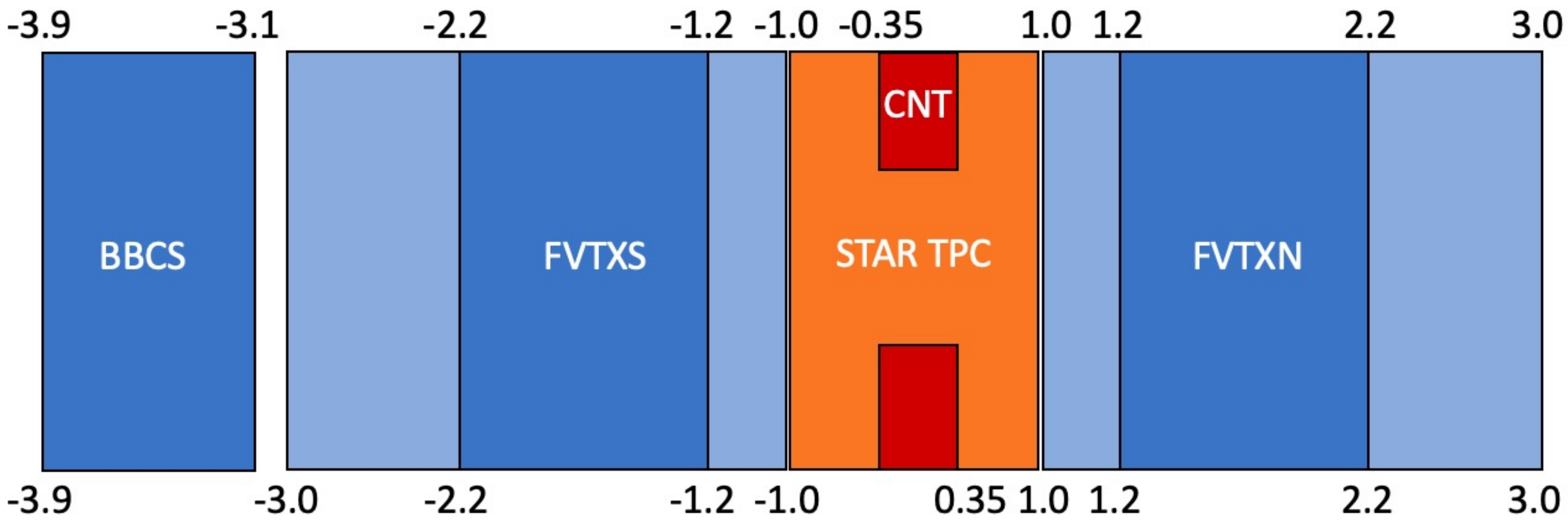
- Kinematic coverage



- 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

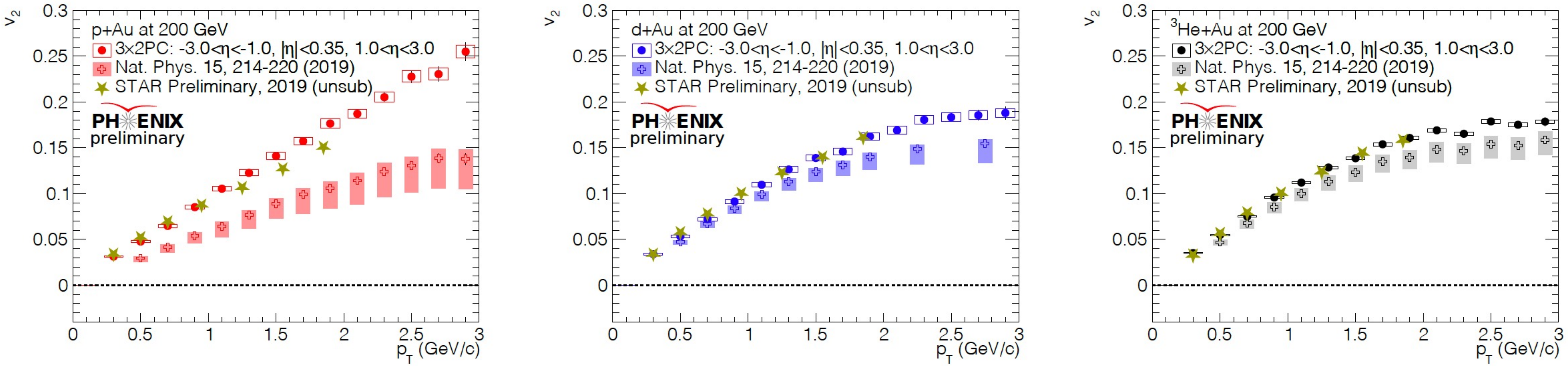
An attempt at matching acceptance

- 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

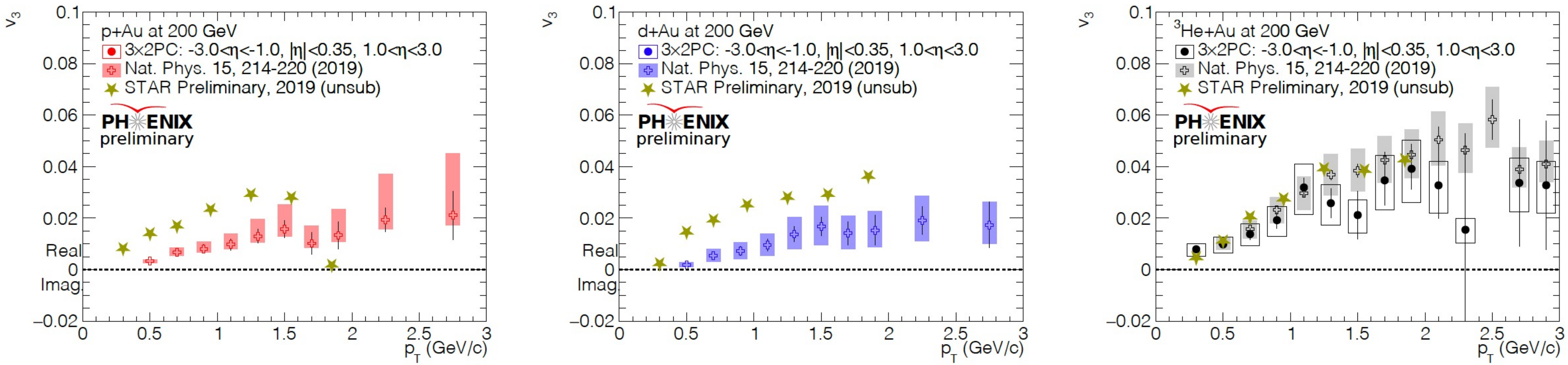
- Matching the acceptance is not possible with 2014-2016 data, but PHENIX studied a symmetric combination: FVTXS – CNT – FVTXN
- Compared to STA R data before nonflow subtraction
  - PHENIX arXiv:2107.06634



- Good agreement in v_2

An attempt at matching acceptance: v_3

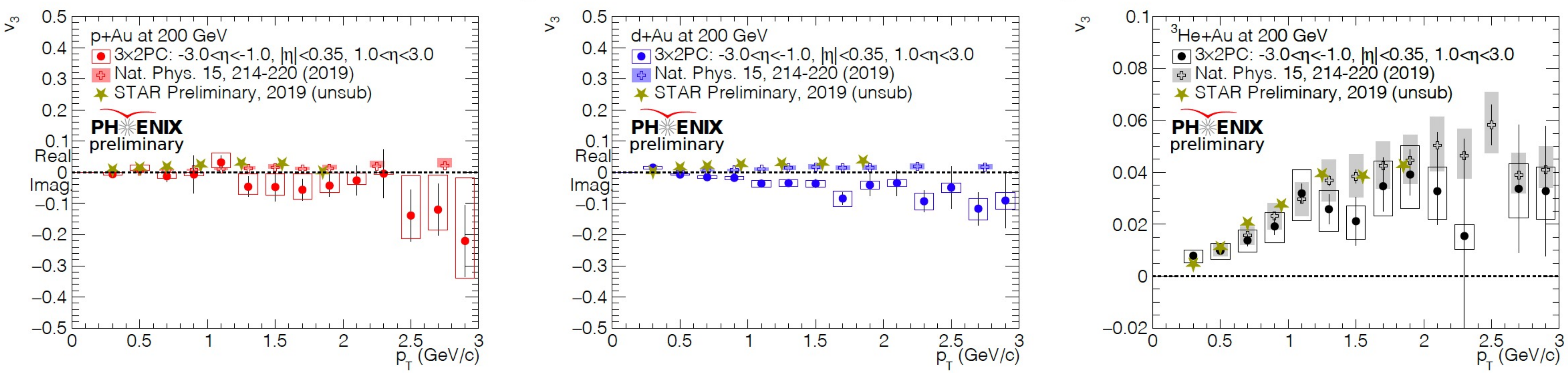
- Matching the acceptance is not possible with 2014-2016 data, but PHENIX studied a symmetric combination: FVTXS – CNT – FVTXN
- Compared to STAR data before nonflow subtraction
  - PHENIX arXiv:2107.06634



- Large difference in v_3 in p/d+Au

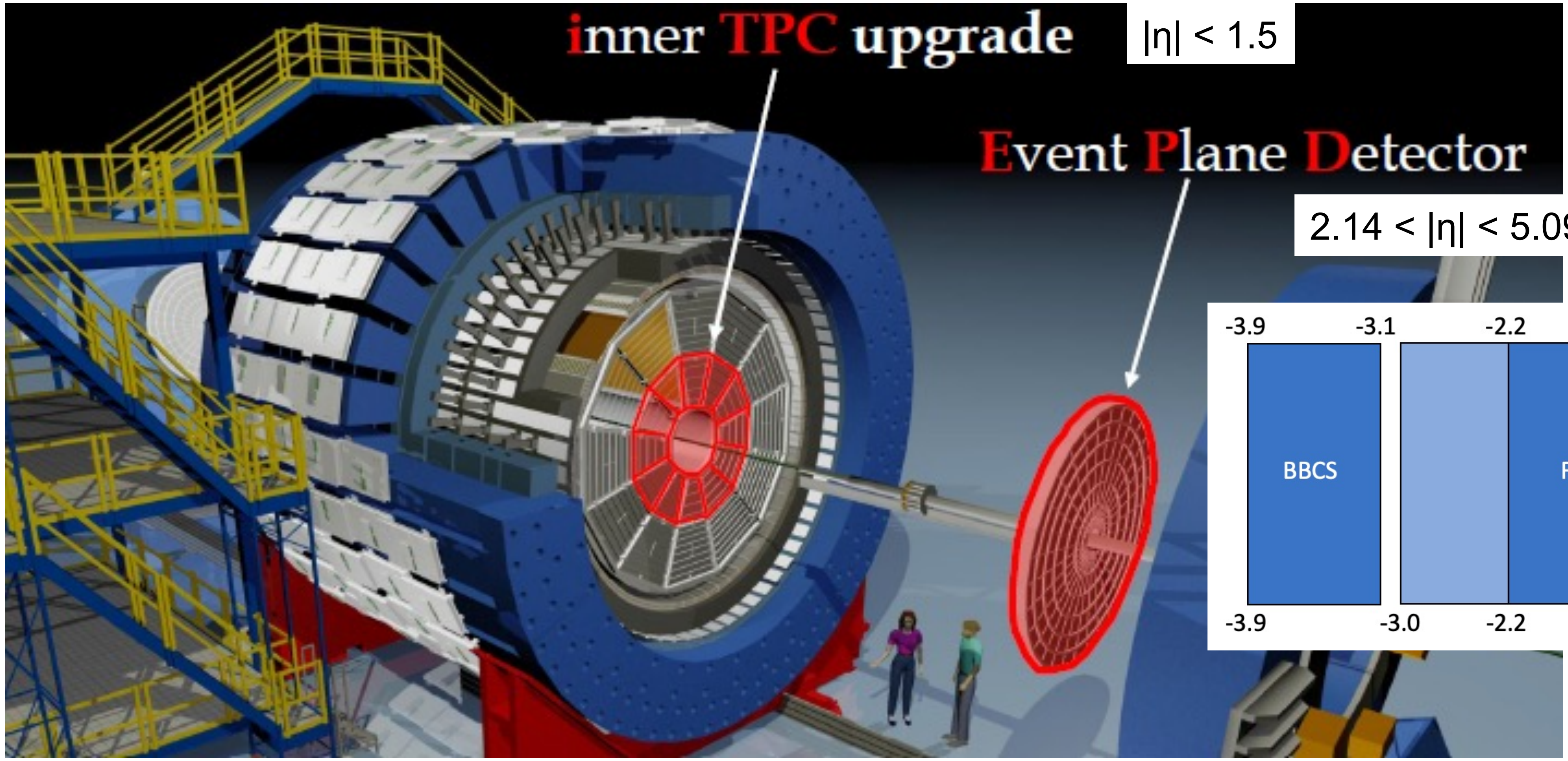
An attempt at matching acceptance: v_2

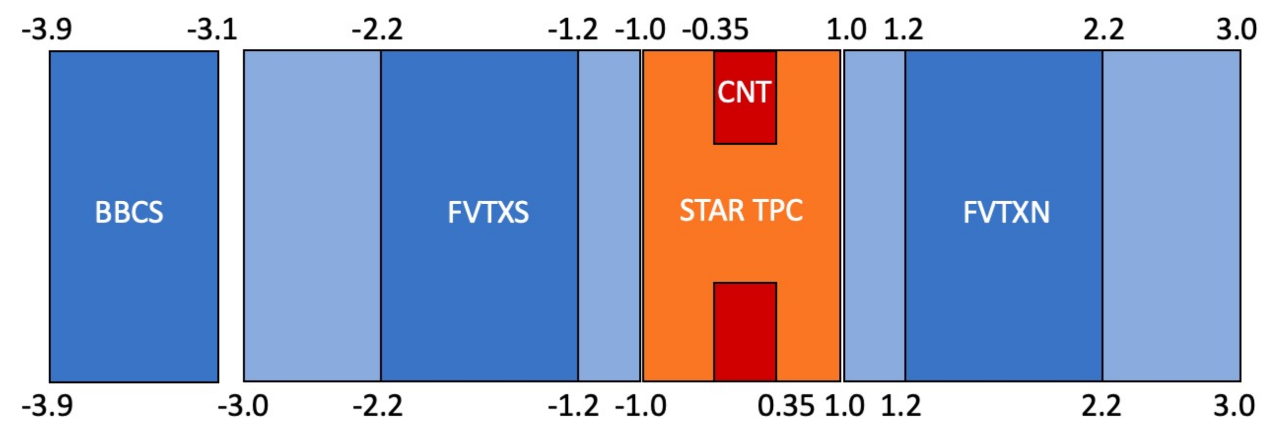
- Matching the acceptance is not possible with 2014-2016 data, but PHENIX studied a symmetric combination: FVTXS – CNT – FVTXN
- Compared to STA R data before nonflow subtraction
  - PHENIX arXiv:2107.06634



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

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 RHIC 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
  - Both experiments confirmed their results
  - Measurement errors are ruled out
- Stay tuned for d+Au (2021) and p+Au (2024) data
  - STAR upgraded detector
  - sPHENIX coming online

RHIC papers on small-system collectivity

1. arXiv: 2107.06634 (submitted to PRC) – (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. Phys. Rev. Lett. 122, 172301 (2019) – (STAR) v_n in different systems - common scaling
4. PRL 121, 222301 (2018) - (PHENIX) pAl, pAu, dAu,^{3}HeAu $dN_{ch}/d\eta$,$v_2(\eta)$
5. PRL 120, 062302 (2018) - (PHENIX) v_2 with multi-particle cumulants in dAu BES, and cumulants in pAu
6. Phys. Rev. C 98, 014912 (2018) - (PHENIX) pi0 - h correlations in dAu
7. Phys. Rev. C 97, 064904 (2018) - (PHENIX) v_2 of identified hadrons quark number scaling in pAu, dAu , ^{3}HeAu
8. 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
9. Phys. Rev. C 95, 034910 (2017) - (PHENIX) charged hadron v_2 in pAu
10. PRL 115, 142301 (2015) - (PHENIX) charged hadron v_2 and v_3 in ^{3}HeAu
11. PRL 114,192301 (2015) - (PHENIX) - charged hadron v_2 in dAu; EP
12. Phys. Lett. B 747 (2015) 265 - (STAR) - charged long range 2PC v_2
13. PRL 111, 212301 (2013) - (PHENIX) - charged hadron v_2 in dAu; 2PC