Collectivity in Small Systems at RHIC

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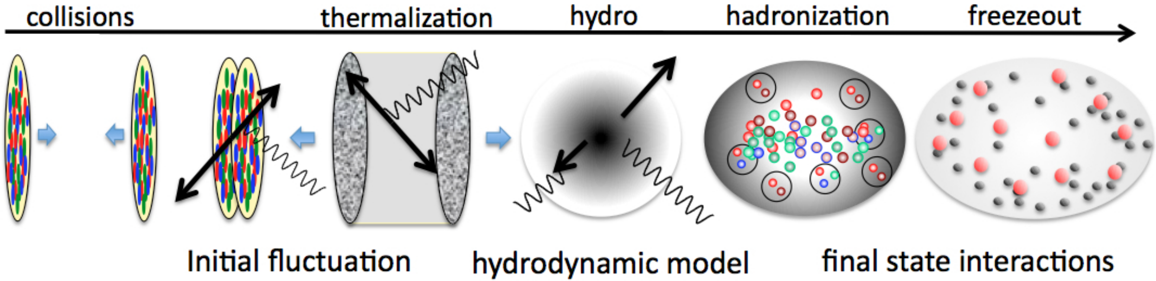
University of North Carolina at Greensboro

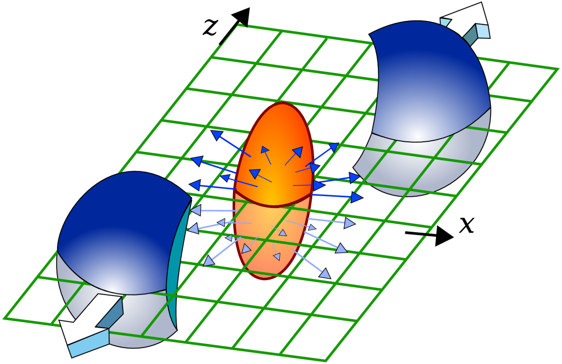
MPI@LHC 2023
20 November 2023

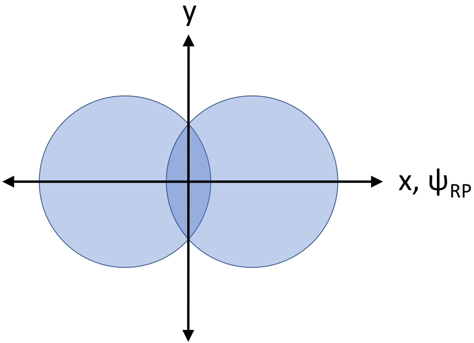
Standard model of heavy ion physics



Based on developments in hydro theory over the last few years, we should replace "thermalization" with "hydrodynamization"

Azimuthal anisotropy measurements

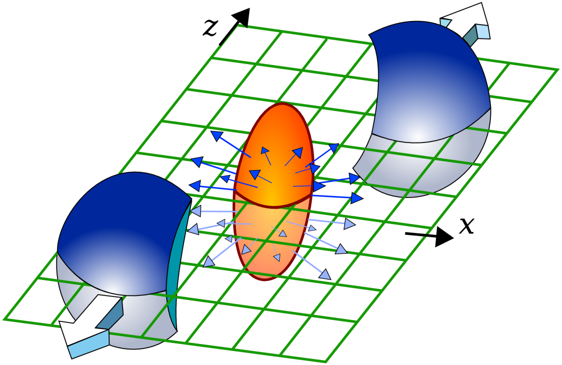


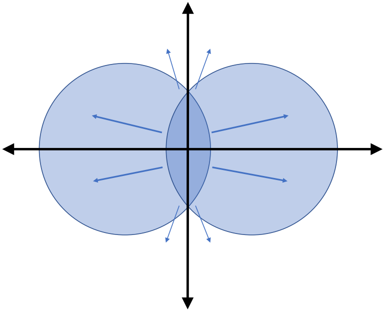


$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos n\varphi \qquad v_n = \langle \cos n\varphi \rangle \qquad \varepsilon_n = \frac{\sqrt{\langle r^n \cos n\varphi \rangle + \langle r^n \sin n\varphi \rangle}}{\langle r^n \rangle}$$

- Hydrodynamics translates initial shape (including fluctuations) into final state distribution

Azimuthal anisotropy measurements





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- Hydrodynamics translates initial shape (including fluctuations) into final state distribution

Small systems geometry scan

PHYSICAL REVIEW LETTERS

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Exploiting Intrinsic Triangular Geometry in Relativistic $^{3}\mathrm{He} + \mathrm{Au}$ Collisions to Disentangle Medium Properties

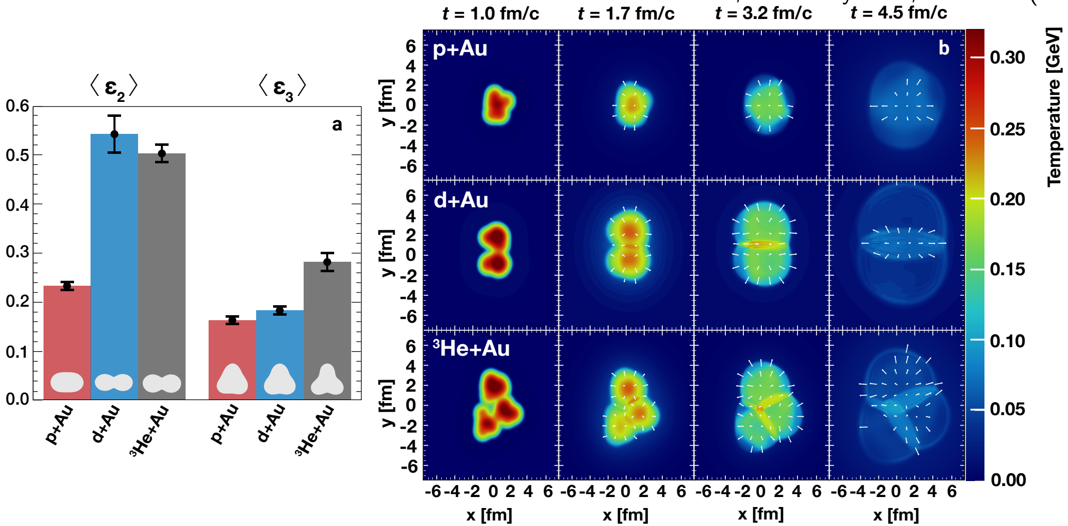
J. L. Nagle, A. Adare, S. Beckman, T. Koblesky, J. Orjuela Koop, D. McGlinchey, P. Romatschke, J. Carlson, J. E. Lynn, and M. McCumber

Phys. Rev. Lett. **113**, 112301 – Published 12 September 2014

- Collective motion translates initial geometry into final state distributions
- To determine whether small systems exhibit collectivity, we can adjust the geometry and compare across systems
- We can also test predictions of hydrodynamics with a QGP phase

Small systems geometry scan

PHENIX, Nat. Phys. 15, 214–220 (2019)



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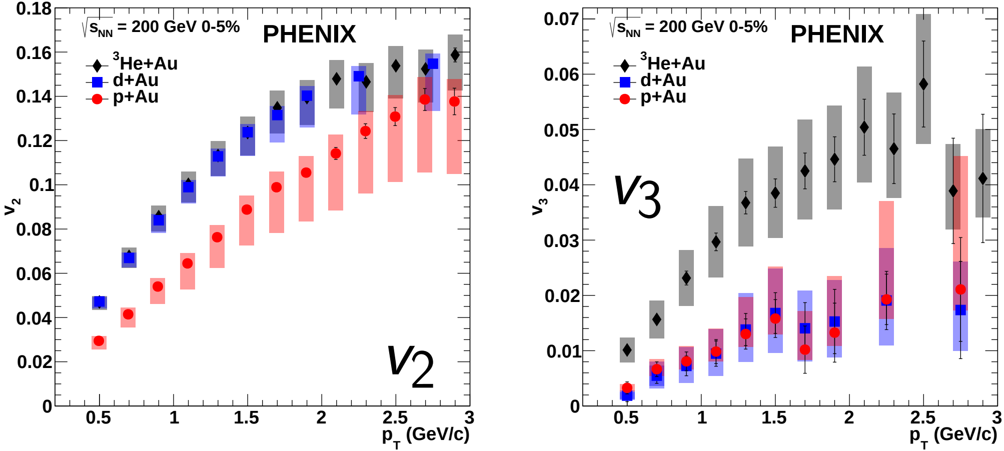
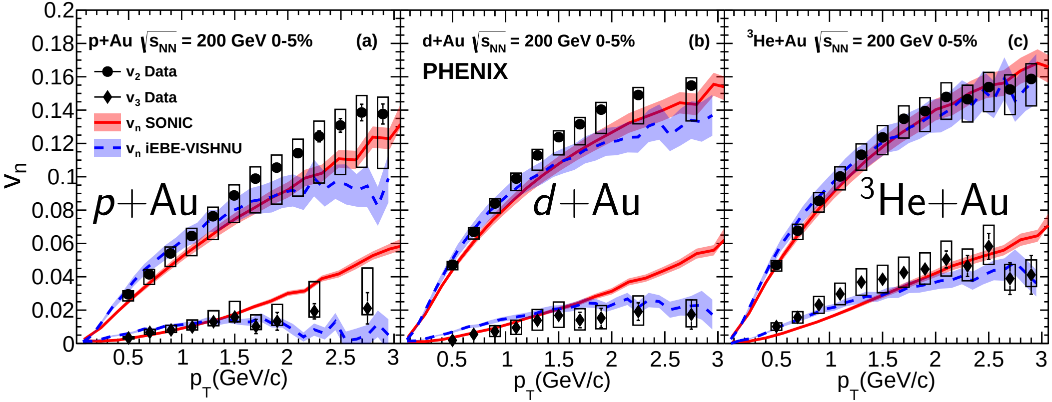


- v_2 and v_3 ordering matches ε_2 and ε_3 ordering in all three systems
  —Collective motion of system translates the initial geometry into the final state

Small systems geometry scan

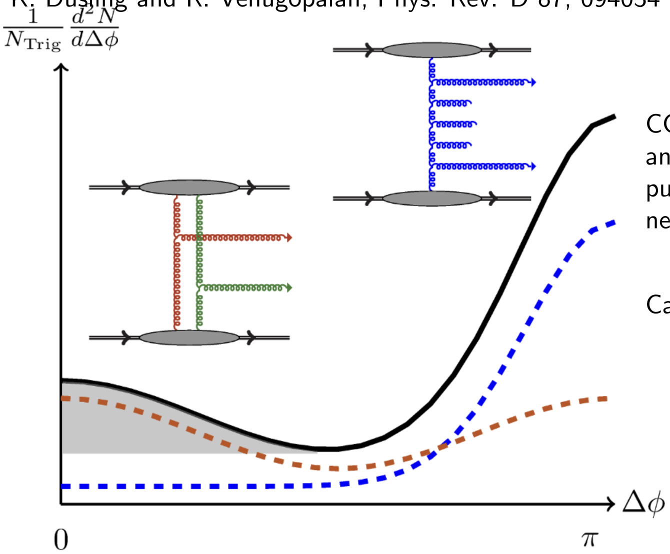
PHENIX, Nat. Phys. 15, 214–220 (2019)



- v_2 and v_3 vs p_T predicted or described very well by hydrodynamics in all three systems
  —All predicted (except v_2 in d+Au) in J.L. Nagle et al, PRL 113, 112301 (2014)
  —v_3 in p+Au and d+Au predicted in C. Shen et al, PRC 95, 014906 (2017)

Can initial state effects explain the data?

K. Dusling and R. Venugopalan, Phys. Rev. D 87, 094034 (2013)

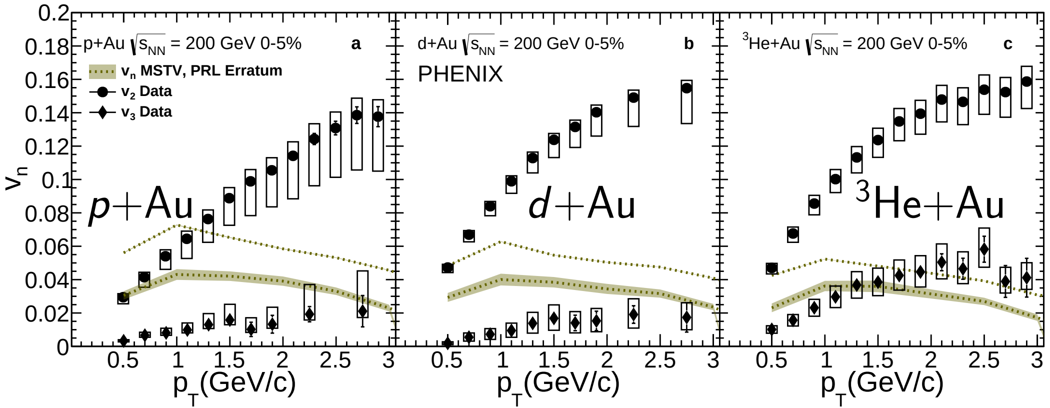


CGC framework: glasma diagrams produce angular correlations like the ridge and v_n purely from initial state correlations, with no need for final state interactions (hydro)

Can they explain the data?

Initial state effects cannot explain the data

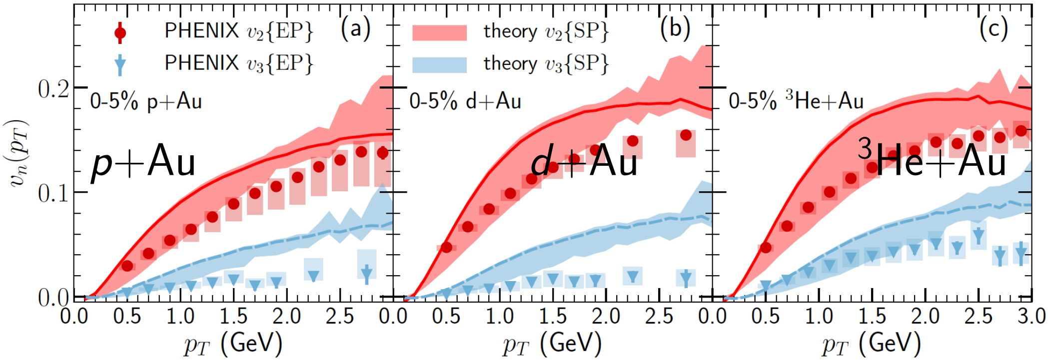
PHENIX, Nat. Phys. 15, 214–220 (2019)



- Initial state effects (CGC/Glasma) alone do not describe the data —Phys. Rev. Lett. 123, 039901 (Erratum) (2019)

How important are initial state effects?

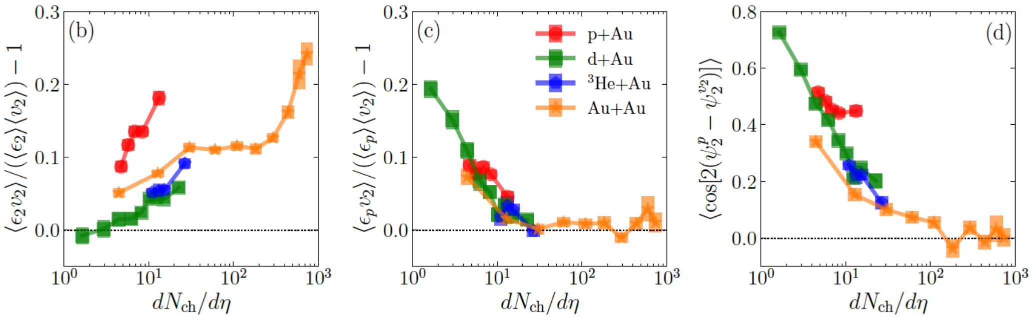
B. Schenke et al, Phys. Lett. B 803, 135322 (2020)



- Initial state effects important for theory, but make little contribution for central collisions
- Overestimation of data assumed to be related to fluid choice parameters and/or longitudinal dynamics

How important are initial state effects?

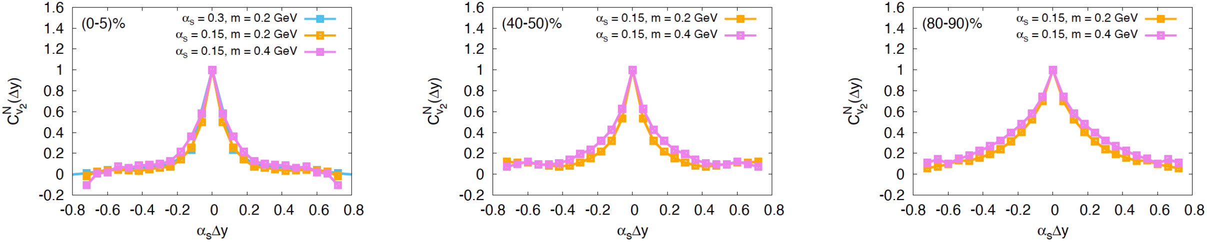
B. Schenke et al, Phys. Lett. B 803, 135322 (2020)



- For central p+Au, modest correlation between ε_p and v_2
- For central d+Au and ^{3}He+Au, no correlation between ε_p and v_2

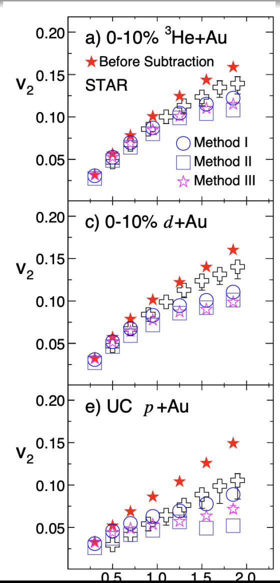
How important are initial state effects?

B. Schenke et al, Phys. Rev. D 105, 094023 (2022)



- The CGC/Glasma correlations appear to be too narrow in (pseudo)rapidity to have any significant impact on the data
  —The PHENIX data are measured with three detectors spanning $-3.9 < \eta < +0.35$
- We'll talk more about the importance of the pseudorapidity acceptance of experiments soon

Comparisons with STAR



STAR, Phys. Rev. Lett. 130, 242301 (2023)

Good agreement between STAR and PHENIX for v_2

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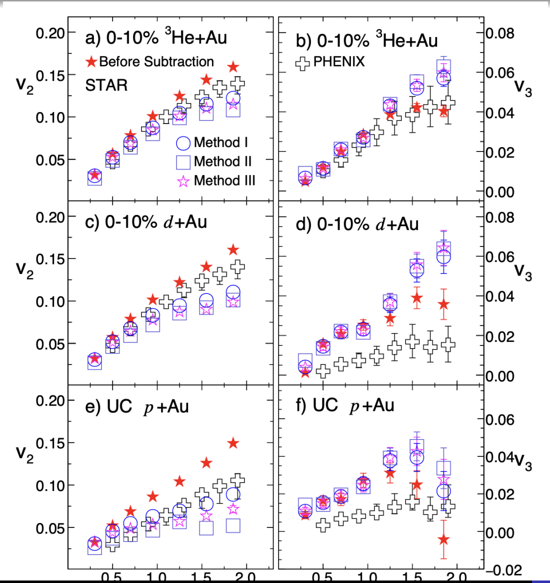


STAR, Phys. Rev. Lett. 130, 242301 (2023)

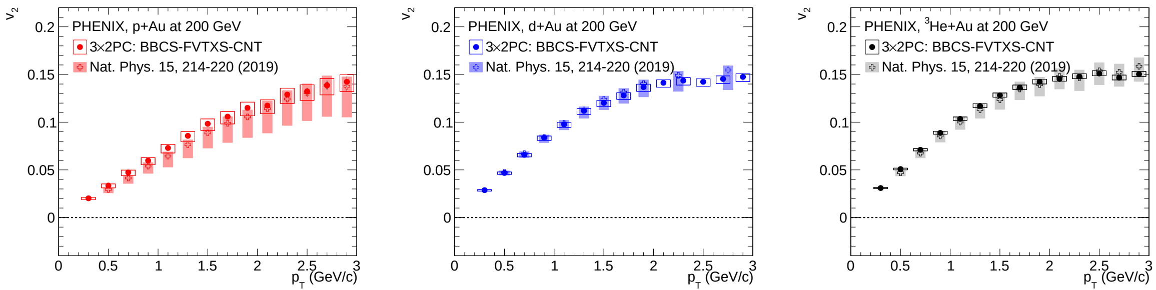
Good agreement between STAR and PHENIX for v_2

Large difference between STAR and PHENIX for v_3 in p+Au and d+Au

Large subnucleonic fluctuations can overwhelm the intrinsic geometry in some models, leading to similar ε_3 for all systems

PHENIX data update

PHENIX, Phys. Rev. C 105, 024901 (2022)



- PHENIX has completed a new analysis confirming the results published in Nature Physics
- All new analysis using two-particle correlations with event mixing instead of event plane method
  —Completely new and separate code base
  —Very different sensitivity to key experimental effects (beam position, detector alignment)

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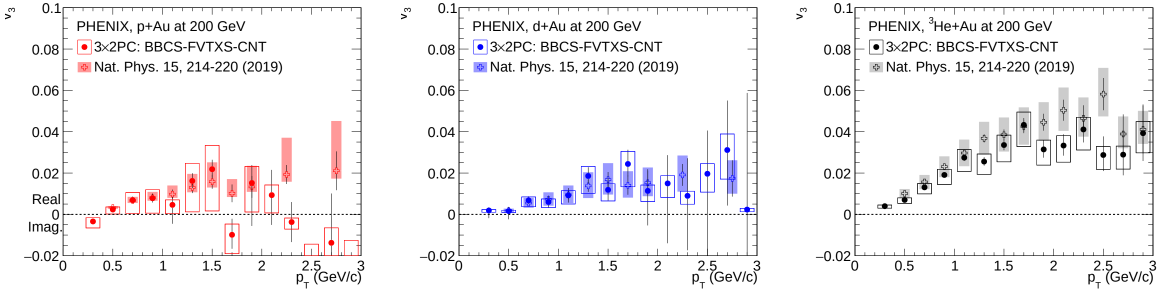

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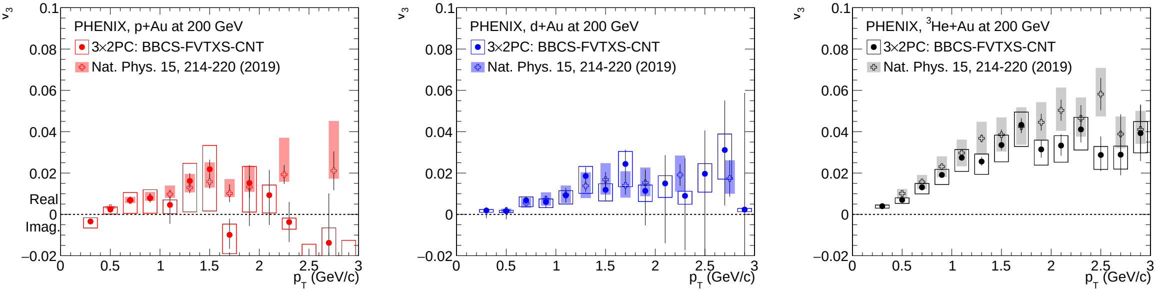

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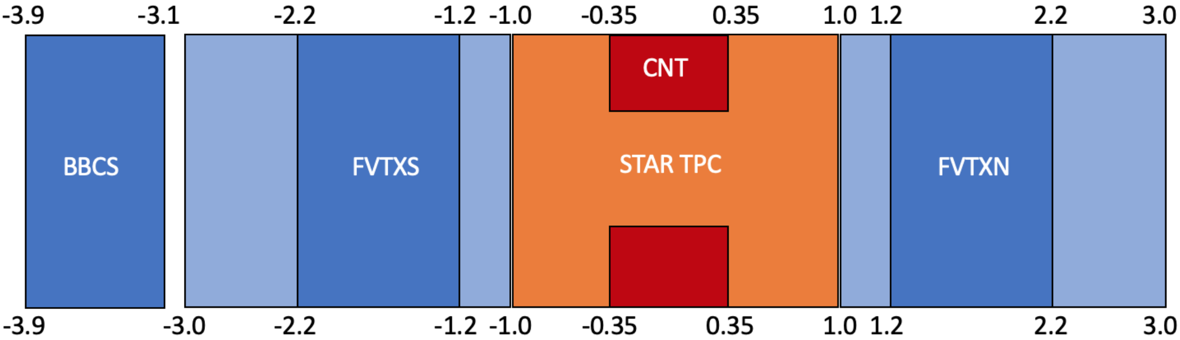
- All new analysis using two-particle correlations with event mixing instead of event plane method
  —Completely new and separate code base
  —Very different sensitivity to key experimental effects (beam position, detector alignment)
- It's essential to understand the two experiments have very different acceptance in pseudorapidity
  —STAR-PHENIX difference actually reveals interesting physics

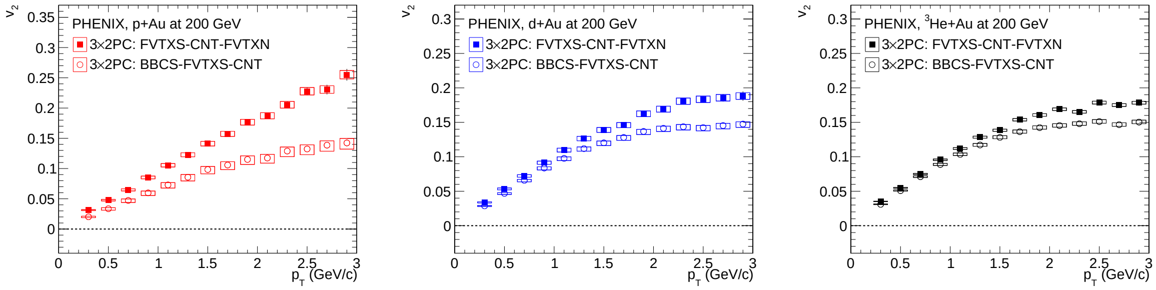
STAR and PHENIX detector comparison



- The PHENIX Nature Physics paper uses the BBCS-FVTXS-CNT detector combination —This is very different from the STAR analysis (TPC only)
- We can try to use FVTXS-CNT-FVTXN detector combination to better match STAR —Closer, and "balanced" between forward and backward, *but still different*

More STAR and PHENIX data comparisons

PHENIX, Phys. Rev. C 105, 024901 (2022)



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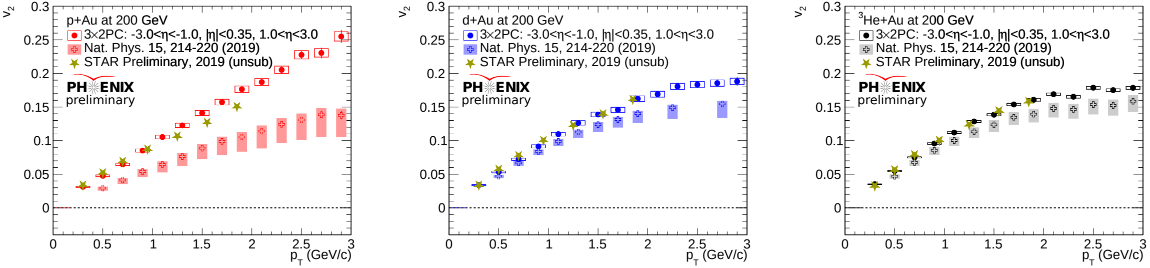

- Good agreement with STAR for v_2

  —Similar physics for the two different pseudorapidity acceptances

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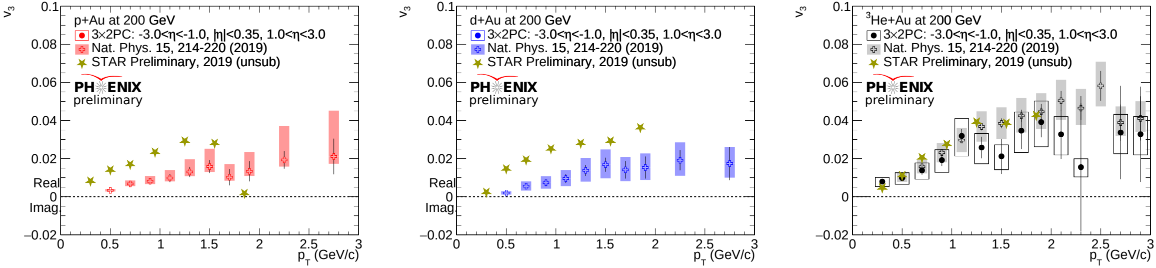

- Good agreement with STAR for v_2
  —Similar physics for the two different pseudorapidity acceptances
- Strikingly different results for v_3
  —Rather different physics for the two different pseudorapidity acceptances
  —Longitudinal effects apparently much stronger for v_3 than v_2

More STAR and PHENIX data comparisons

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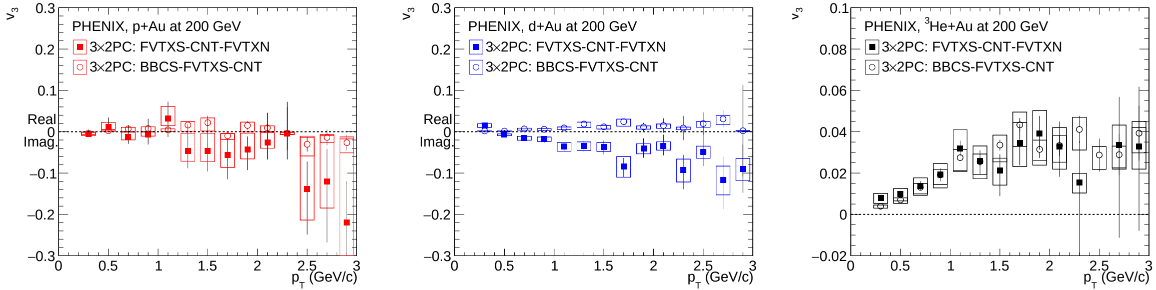

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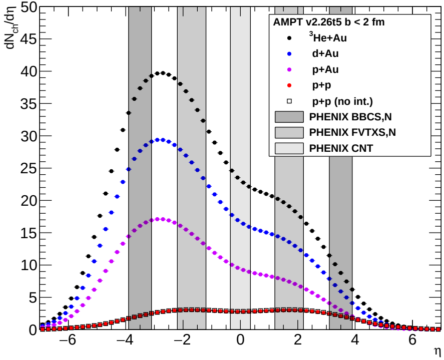
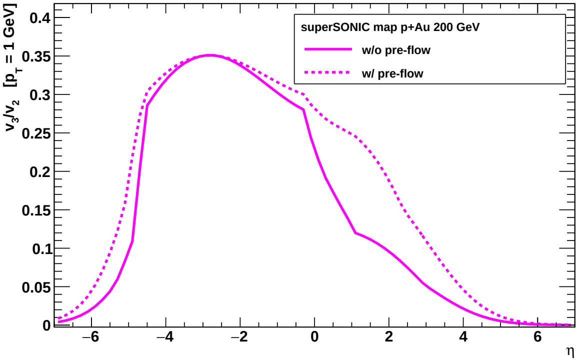
Pseudorapidity dependence in small systems

J.L. Nagle et al, Phys. Rev. C 105, 024906 (2022)

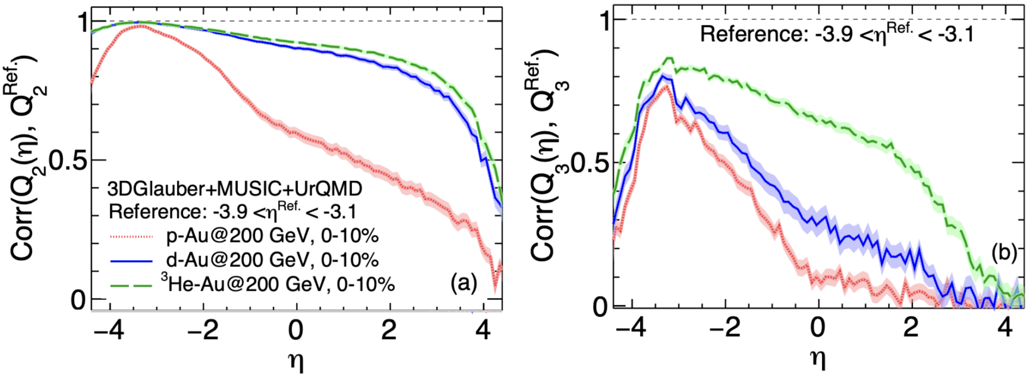




- $dN_{ch}/d\eta$ from AMPT, $v_3(\eta)$ from (super)SONIC
- The likely much stronger pseudorapidity dependence of v_3 compared to v_2 is an essential ingredient in understanding different measurements

Pseudorapidity dependence in small systems

W. Zhao et al, Phys. Rev. C 107, 014904 (2023)



- Flow vectors become decorrelated with increasing pseudorapidity separation
  —The effect is much stronger for v_3 than for v_2
- The hierarchy of the measured v_n depends on that of the geometry *and* decorrelations
  —Interesting that the decorrelation hierarchy matches that of the geometry...

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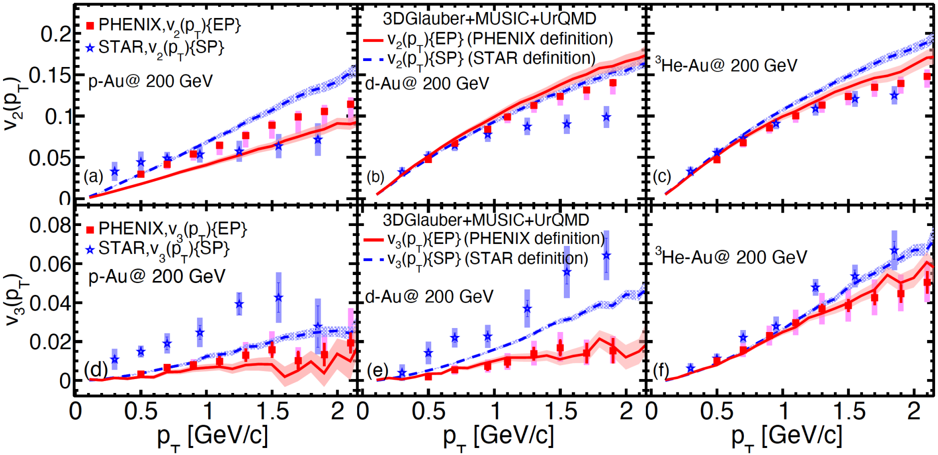
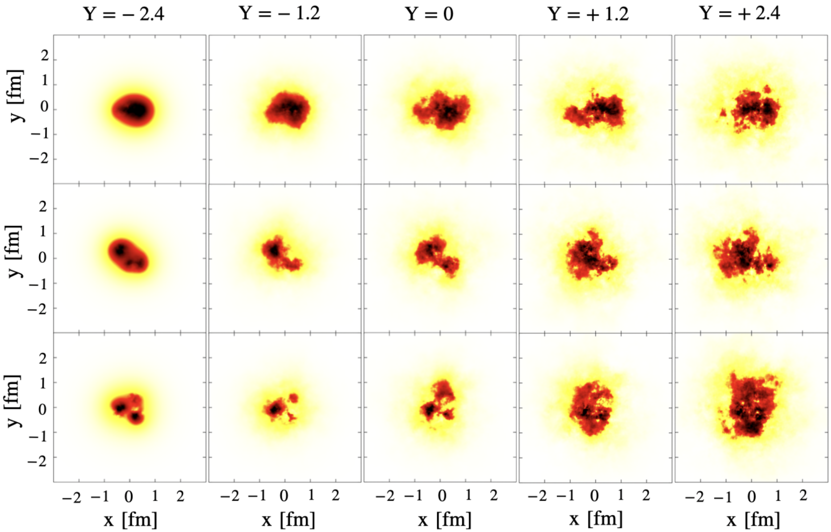


- Flow decorrelations lead to larger v_3 for STAR, explaining ∼50% of the difference between the experiments in this particular model

Pseudorapidity dependence in small systems

B. Schenke et al, Phys. Rev. D 105, 094023 (2022)



- Intrinsic geometry likely persists over all pseudorapidity ranges
- Fluctuations in the geometry vary as a function of rapidity (p from a p+Pb collision shown)
- PHENIX data follow intrinsic geometry, STAR data follow subnucleonic fluctuations

Brief Summary

- Long established role of geometry and hydrodynamics in large systems
- Role of geometry and hydrodynamics in small systems also now established
- Understanding the pseudorapidity dependence is an essential part of understanding the overall dynamics
  —Longitudinal decorrelation leads to major differences between measurements
  —The intrinsic geometry likely persists over long ranges in pseudorapidity
  —Fluctuations in the geometry vary over pseudorapidity
- Initial state effects, though important from a theoretical standpoint, have minimal impact on the measured v_n
  —This is in part due to their rather small range in pseudorapidity
- We've learned a lot from 2+1D hydro, but we have ever-increasing need for 3+1D hydro

Additional Material

Additional Material

A few other things of possible interest

- $v_2(p_T)$ with diffferent detector combinations in p+p and for all centralities in p+Au, d+Au, ^{3}He+Au at 200 GeV
  —PHENIX, Phys. Rev. C 107, 024907 (2023)

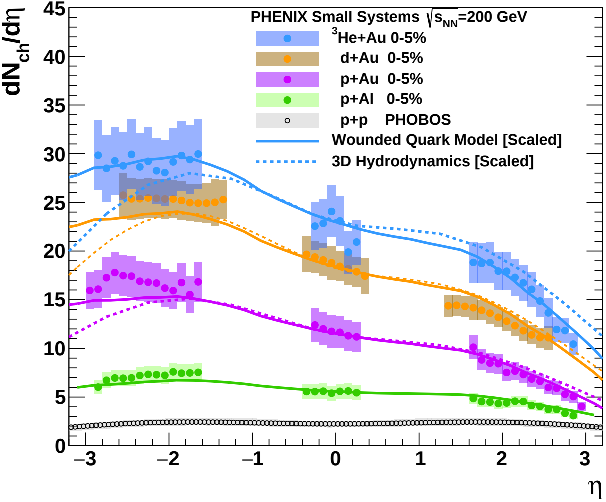
- $v_2(\eta)$ for central and $dN_{ch}/d\eta$ for all centralities in p+Al, p+Au, d+Au, and ^{3}He+Au at 200 GeV
  —PHENIX, Phys. Rev. Lett. 121, 222301 (2018)

- $v_2(\eta)$ and $dN_{ch}/d\eta$ for central and $v_2(p_T)$ for all centralities in d+Au at 200, 62.4, 39, and 19.6 GeV
  —PHENIX, Phys. Rev. C 96, 064905 (2017)

- The $dN_{ch}/d\eta$ measurements across many different systems, centralities, and energies can help constrain 3+1D modes for BES-II

Pseudorapidity dependence in small systems

PHENIX, Phys. Rev. Lett. 121, 222301 (2018)



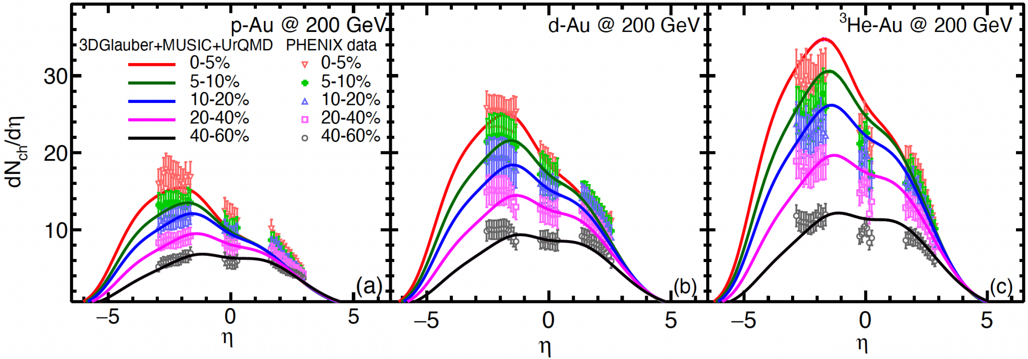
p+Al, p+Au, d+Au, ^{3}He+Au

Good agreement with wounded quark model (M. Barej et al, Phys. Rev. C 97, 034901 (2018))

Good agreement with 3D hydro (P. Bozek et al, Phys. Lett. B 739, 308 (2014))

Pseudorapidity dependence in small systems

W. Zhao, S. Ryu, C. Shen and B. Schenke, Phys. Rev. C 107, 014904 (2023)



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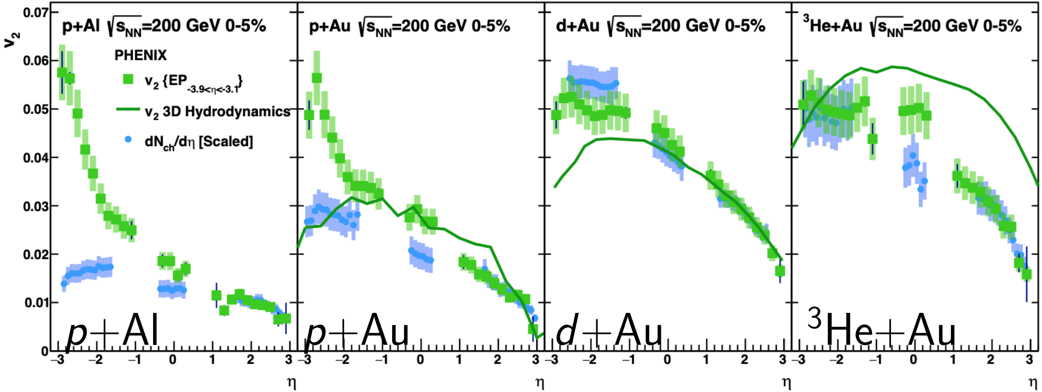

- v_2 vs η in p+Al, p+Au, d+Au, and ^{3}He+Au
- Good agreement with 3D hydro for p+Au and d+Au (Bozek et al, PLB 739, 308 (2014))

Pseudorapidity dependence in small systems

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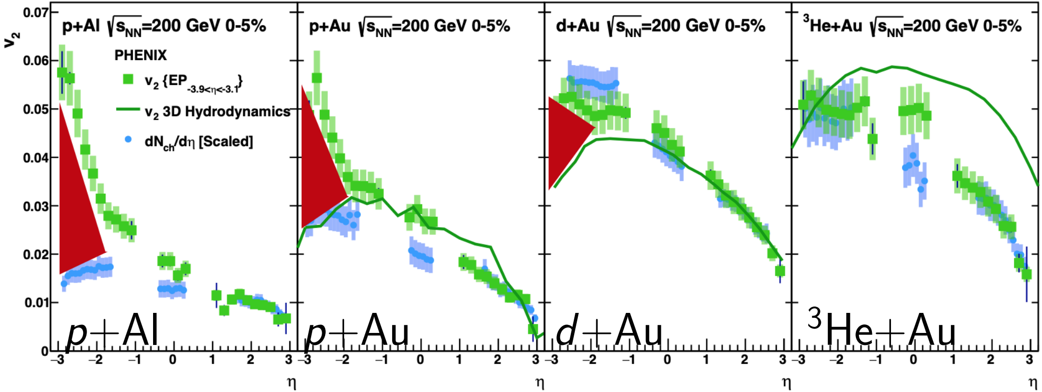

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- Prevalence of nonflow near the EP detector ($-3.9 < \eta < -3.1$)

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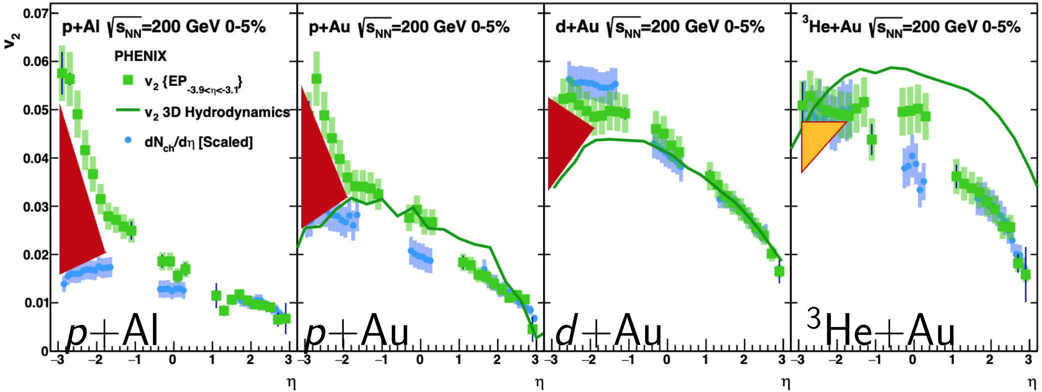

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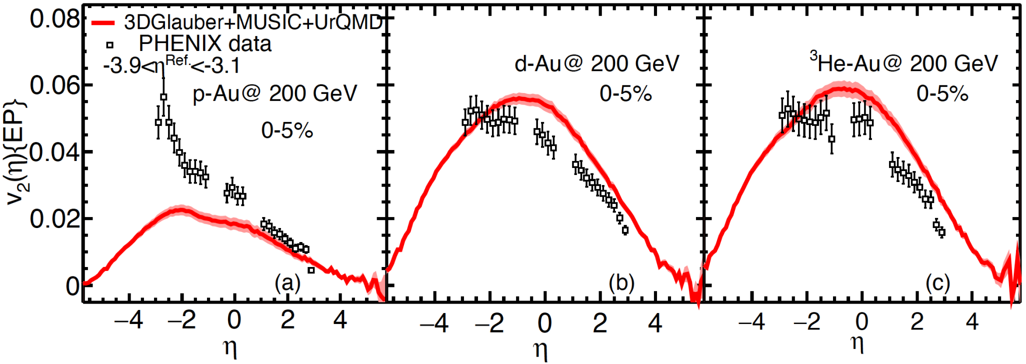
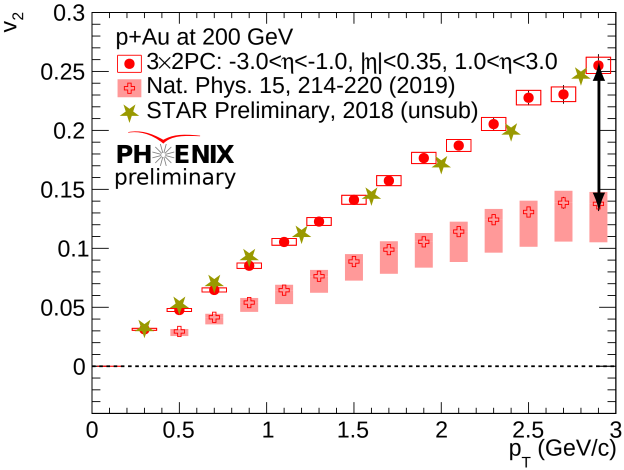


- Good agreement with 3D hydro for $v_2(\eta)$ in p+Au, p+Au, ^{3}He+Au

Understanding the nonflow contribution: v_2 in p+Au as a case study



- The large difference between the PHENIX published and STAR preliminary in this case is nonflow
- PHENIX suppresses nonflow via kinematic selection

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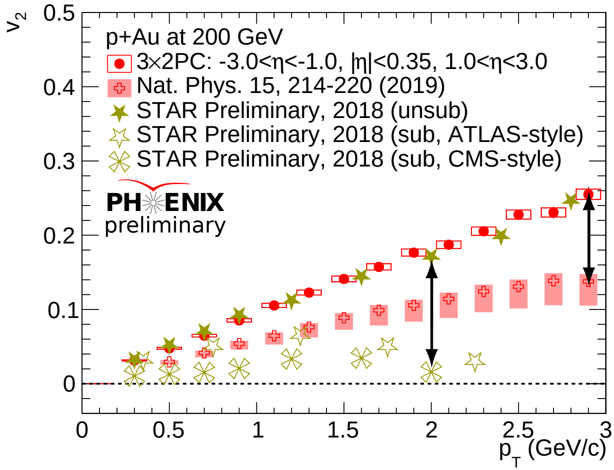

- The large difference between the PHENIX published and STAR preliminary in this case is nonflow
- PHENIX suppresses nonflow via kinematic selection
- STAR applies non-flow subtraction procedure
- One needs to be careful about the risk of over-subtraction methods—S. Lim et al, Phys. Rev. C 100, 024908 (2019)

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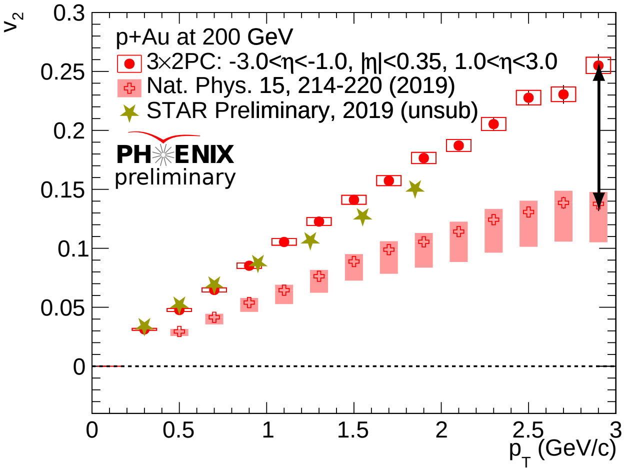

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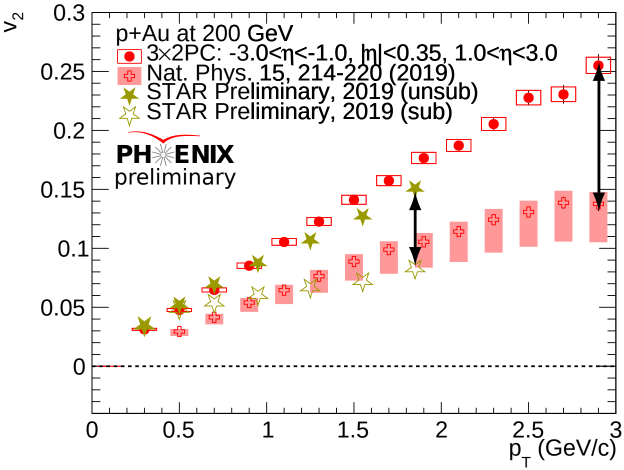


- The large difference between the PHENIX published and STAR preliminary in this case is nonflow
- PHENIX suppresses nonflow via kinematic selection
- STAR applies non-flow subtraction procedure
- Considerable improvement in nonflow subtraction in STAR 2019 preliminary, reasonable agreement with PHENIX

Additional non-flow studies using published data tables

Checking Non-Flow Assumptions and Results via PHENIX Published Correlations in p+p, p+Au, d+Au, ^{3}He+Au at $\sqrt{s_{NN}}$ = 200 GeV

J.L. Nagle,[1] R. Belmont,[2] S.H. Lim,[3] and B. Seidlitz[1]

[1] *University of Colorado, Boulder, Colorado 80309, USA*
[2] *University of North Carolina, Greensboro, North Carolina 27413, USA*
[3] *Pusan National University, Busan, 46241, South Korea*

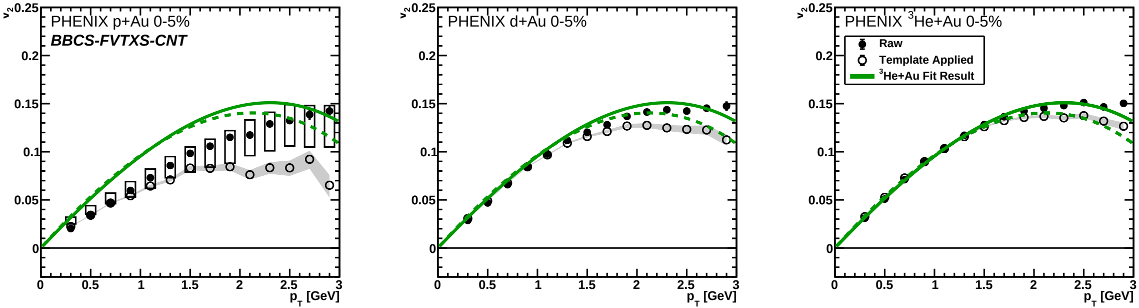
(Dated: July 16, 2021)

https://arxiv.org/abs/2107.07287

- To enable additional study, the new PHENIX publication (Phys. Rev. C 105, 024901 (2022)) includes the complete set of $\Delta\phi$ correlations and extracted coefficients c_1, c_2, c_3, c_4
- A new paper uses these data tables to explore non-flow subtraction of these data as well as to assess the degree of (non-)closure of non-flow subtraction methods

Additional non-flow studies using published data tables

J.L. Nagle et al, Phys. Rev. C 105, 024906 (2022)



- The BBCS-FVTXS-CNT combination minimizes non-flow, so subtraction doesn't make too much difference

Additional non-flow studies using published data tables

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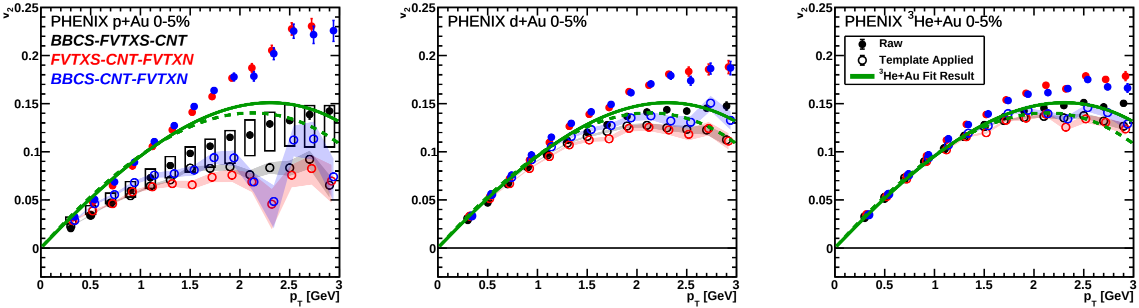

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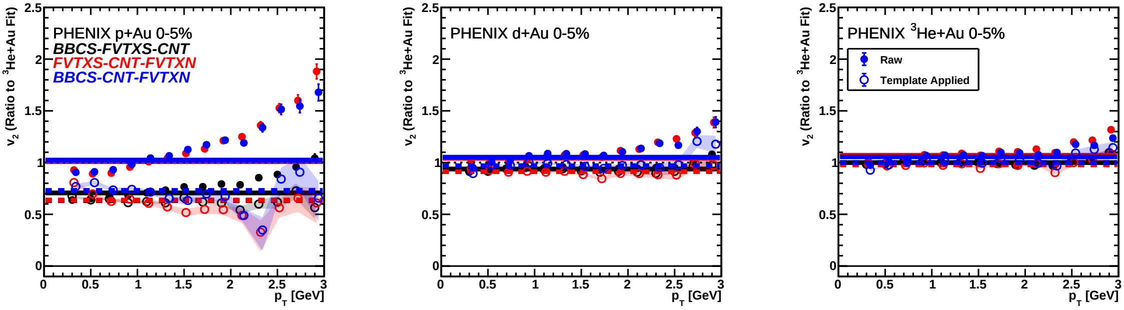
- The FVTXS-CNT-FVTXN combination has more non-flow, and the subtraction does much more
- That the three different combinations all line up after non-flow subtraction seems to lend some credence thereto, but one must be careful...

Additional non-flow studies using published data tables

J.L. Nagle et al, Phys. Rev. C 105, 024906 (2022)



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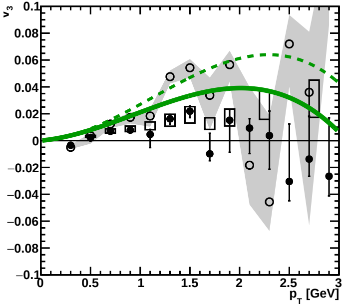

- There's a larger relative change for v_3 compared to v_2, but the smaller value of v_3 makes the non-flow subtraction more sensitive to non-closure

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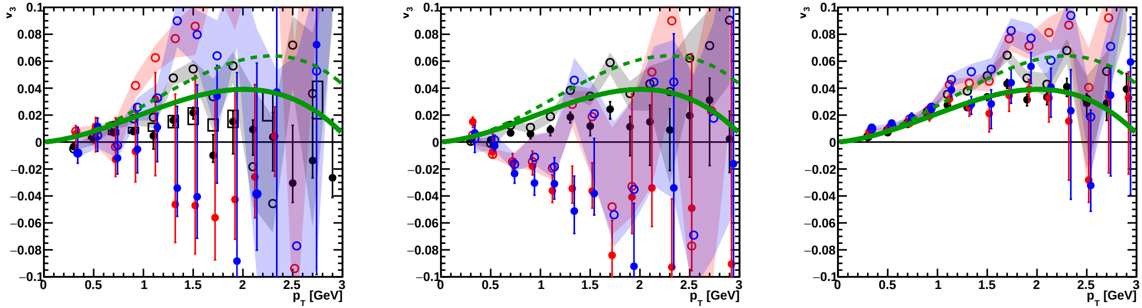

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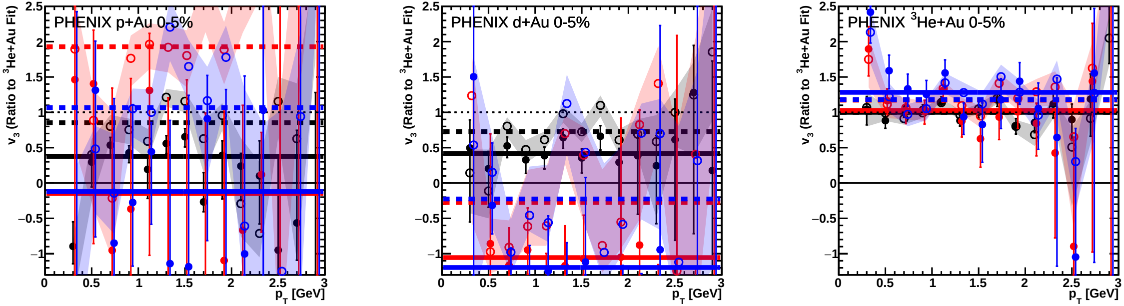

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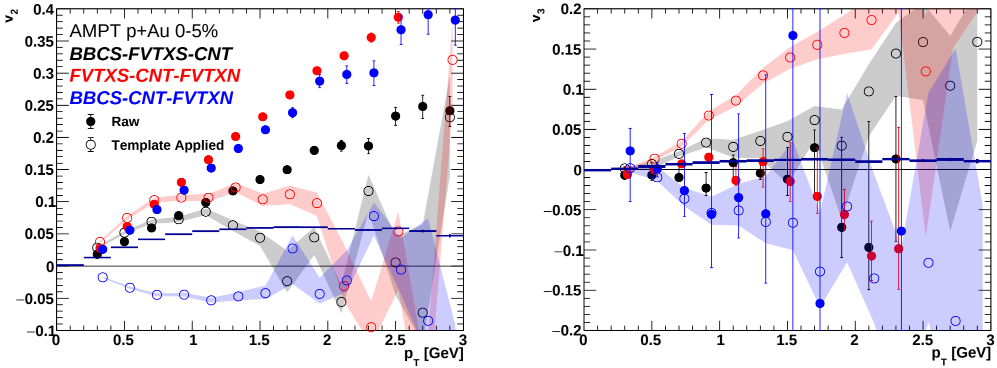

- Closure is considerably violated in AMPT

Additional non-flow studies using published data tables

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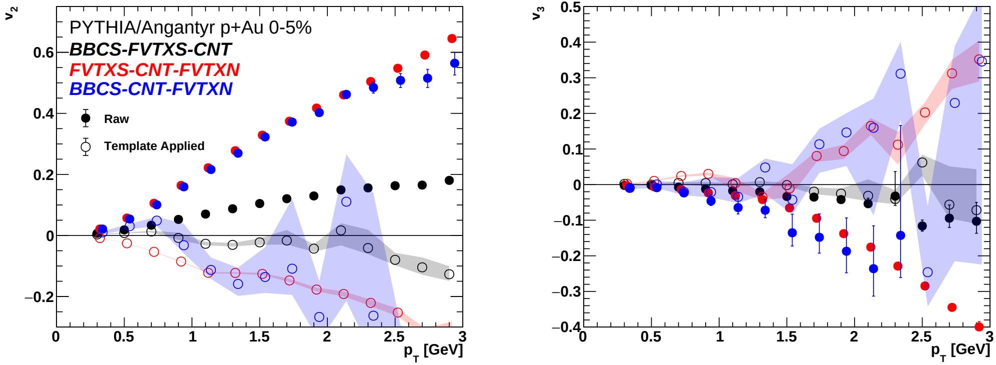

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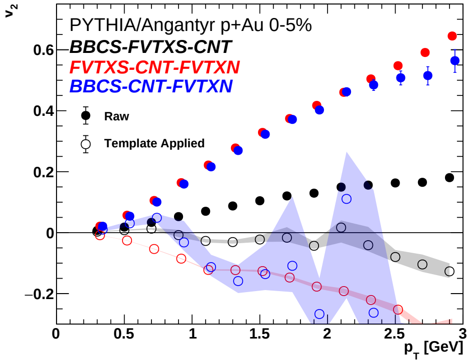

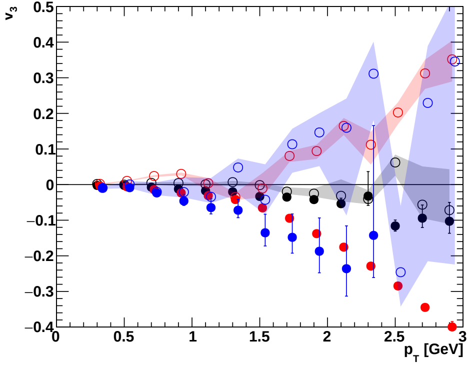

- Closure is considerably violated in AMPT and PYTHIA/Angantyr
- Since AMPT has too much non-flow and PYTHIA doesn't have any flow, the degree of overcorrection in real data is likely not as bad as it is with these generators

Additional non-flow studies using published data tables

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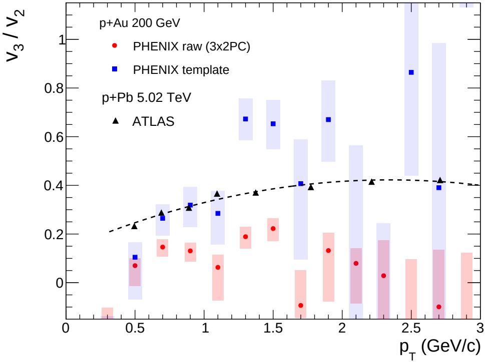

- The standard PHENIX v_3/v_2 is lower than the ATLAS, while the non-flow corrected is above

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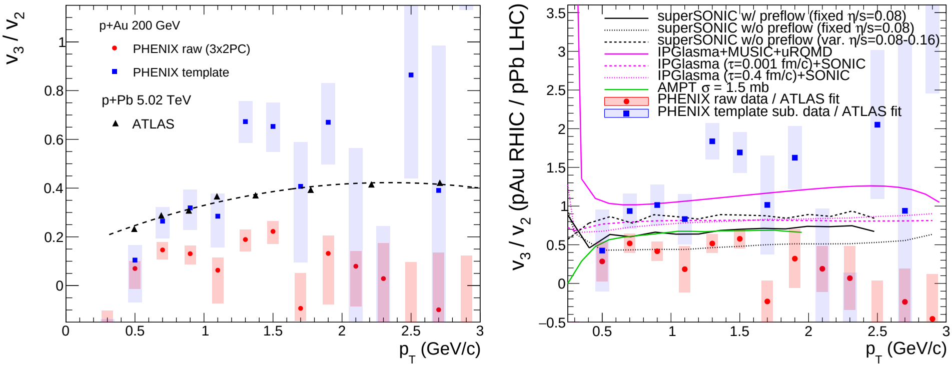

- The standard PHENIX v_3/v_2 is lower than the ATLAS, while the non-flow corrected is above
- The ratio is expected to be lower for lower collision energies in almost all physics scenarios
  —Lower energy, shorter lifetime, more damping of higher harmonics