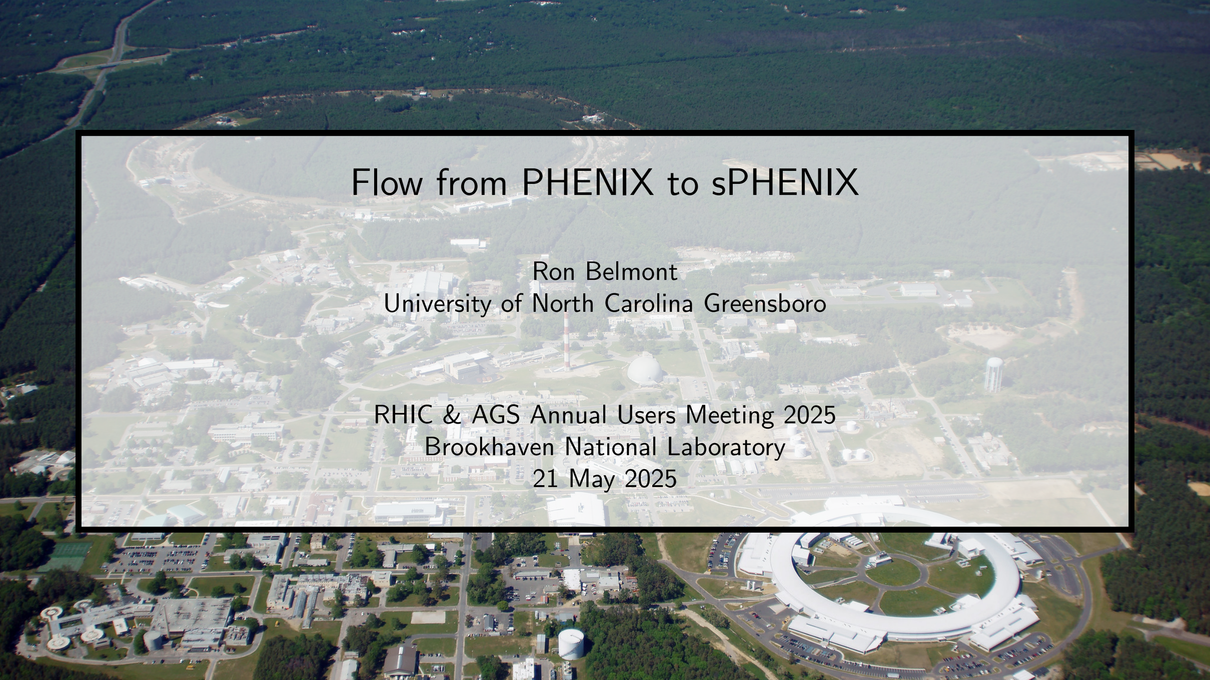
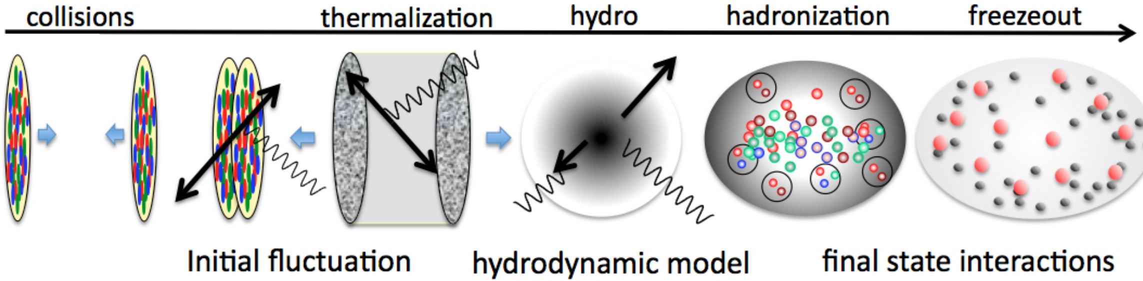


Flow from PHENIX to sPHENIX

Ron Belmont
University of North Carolina Greensboro

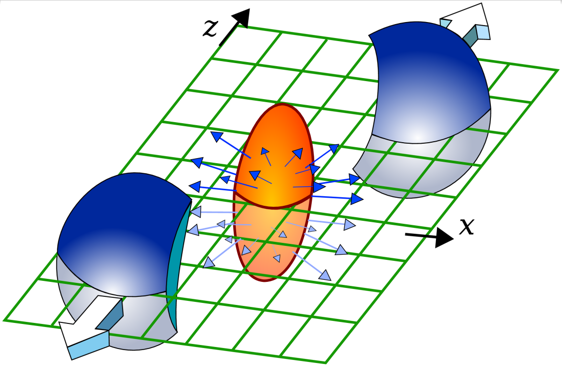
RHIC & AGS Annual Users Meeting 2025
Brookhaven National Laboratory
21 May 2025

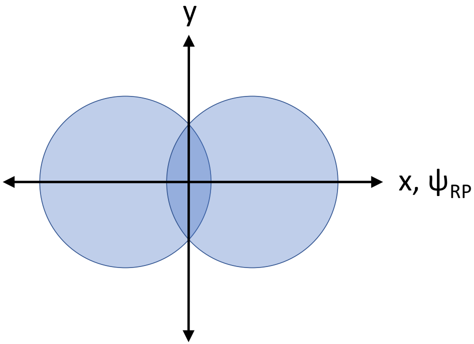
Standard model of heavy ion physics



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

Azimuthal anisotropy measurements

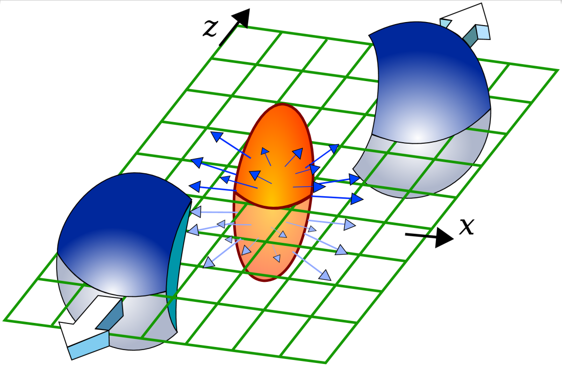


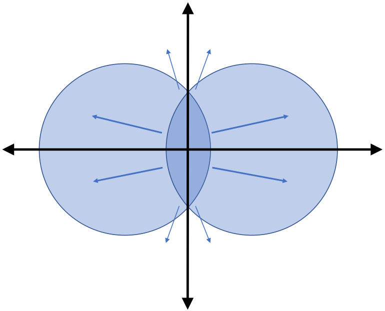


$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos n\varphi \qquad v_n = \langle \cos n\varphi \rangle \qquad \varepsilon_n = \frac{\sqrt{\langle r^n \cos n\varphi \rangle + \langle r^n \sin n\varphi \rangle}}{\langle r^n \rangle}$$

Hydrodynamics translates initial shape (including fluctuations) into final state distribution
In $A{+}A$, the shape is mostly elliptical, so $n = 2$ dominates

Azimuthal anisotropy measurements



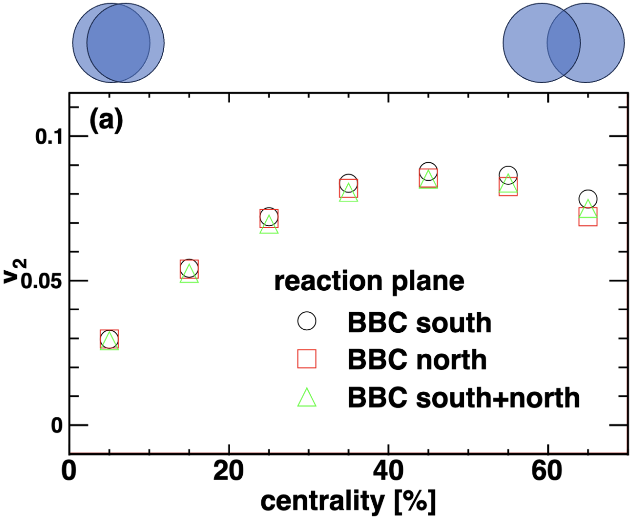


$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2 v_n \cos n\varphi \qquad v_n = \langle \cos n\varphi \rangle \qquad \varepsilon_n = \frac{\sqrt{\langle r^n \cos n\varphi \rangle + \langle r^n \sin n\varphi \rangle}}{\langle r^n \rangle}$$

Hydrodynamics translates initial shape (including fluctuations) into final state distribution
In $A{+}A$, the shape is mostly elliptical, so $n = 2$ dominates

v_2 vs Centrality

PHENIX, Phys. Rev. C 92, 034913 (2015)



Non-monotonic behavior because of competing effects

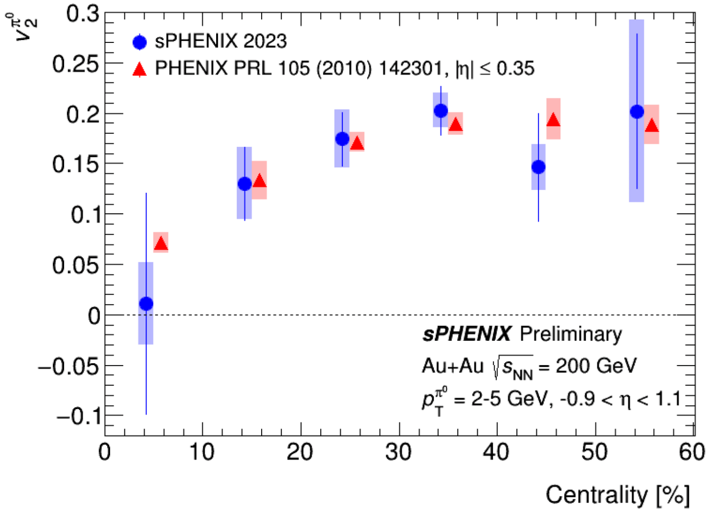
More peripheral = higher eccentricity → higher v_2

More peripheral = smaller system size → lower v_2

π^0 v_2 vs Centrality

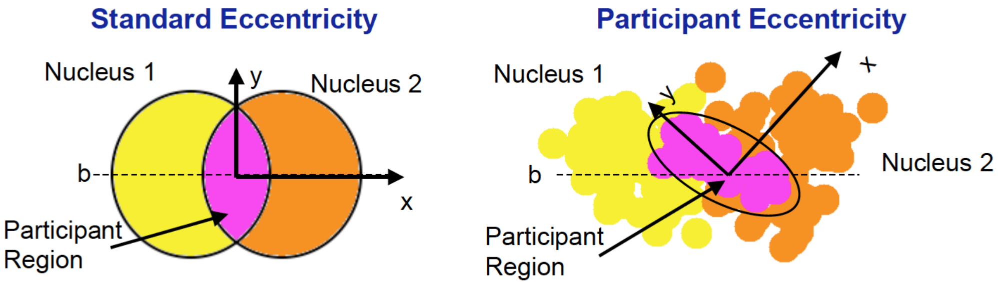
Successful extraction of π^0 v_2 from sPHENIX Run 2023 Commissioning dataset with very limited statistics

Excellent agreement to PHENIX measurement for all centralities



Important discovery in 2005

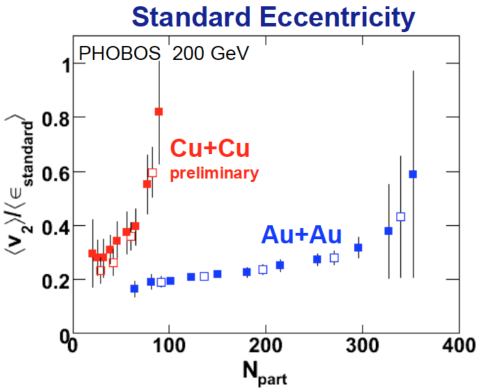
PHOBOS Plenary, Quark Matter 2005 (see also Phys.Rev.C 77, 014906 (2008))



A nucleus isn't just a sphere

Important discovery in 2005

PHOBOS Plenary, Quark Matter 2005 (see also Phys.Rev.C 77, 014906 (2008))



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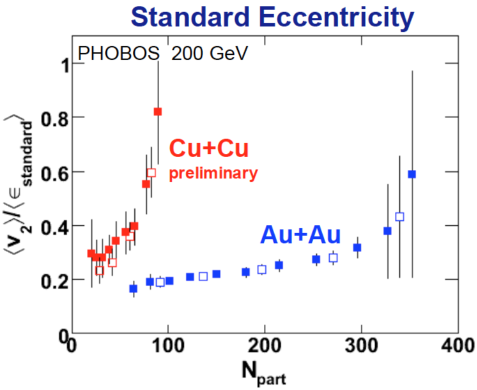
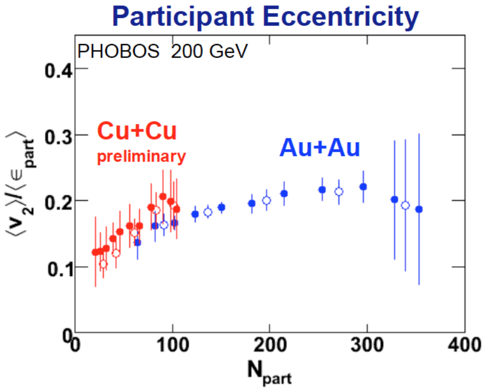




A nucleus isn't just a sphere

Important discovery in 2005

R. Andrade et al, Eur. Phys. J. A 29, 23-26 (2006)

NeXSPheRIO results on elliptic flow at RHIC and connection with thermalization

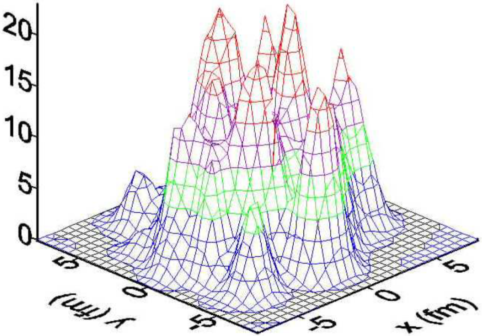
R.Andrade[1], F.Grassi[1], Y.Hama[1], T.Kodama[2], O.Socolowski Jr.[3], and B.Tavares[2]

[1] Instituto de Física, USP,
C. P. 66318, 05315-970 São Paulo-SP, Brazil

[2] Instituto de Física, UFRJ,
C. P. 68528, 21945-970 Rio de Janeiro-RJ , Brazil

[3] CTA/ITA,
Praça Marechal Eduardo Gomes 50, CEP 12228-900 São José dos Campos-SP, Brazil

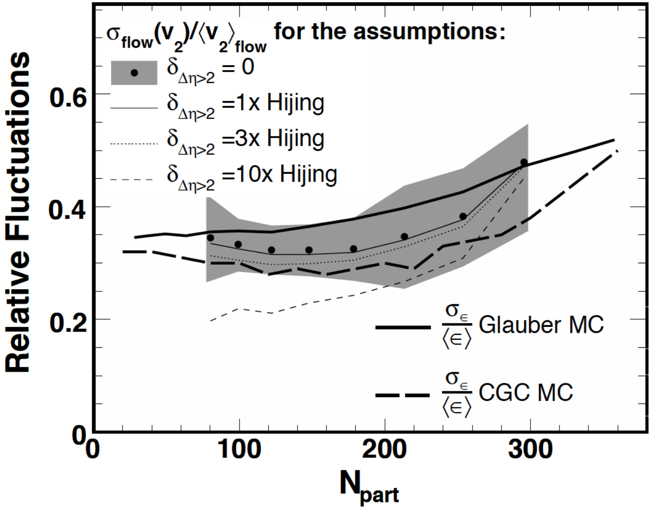
Received 1 January 2004



Worth noting that lumpy initial conditions were predicted some time in 2003

Fluctuations in large systems

PHOBOS, Phys. Rev. C 81, 034915 (2010)



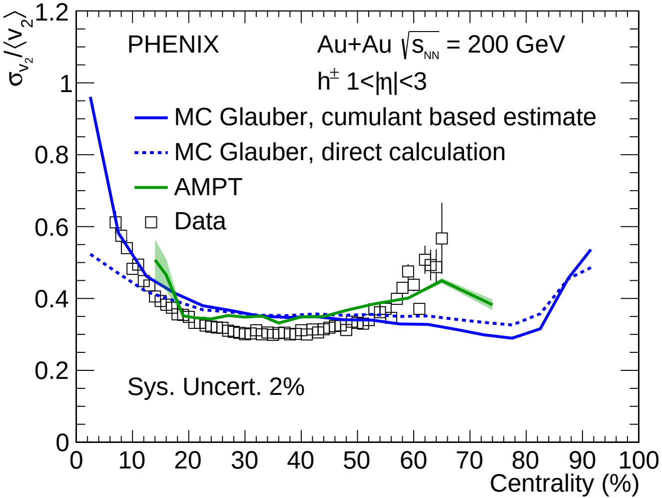
Fluctuations should also be translated, so measure $\sigma_{v_2}/\langle v_2 \rangle$

$|\eta| < 1$

Generally good agreement with models of initial geometry

Fluctuations in large systems

PHENIX, Phys. Rev. C 99, 024903 (2019)



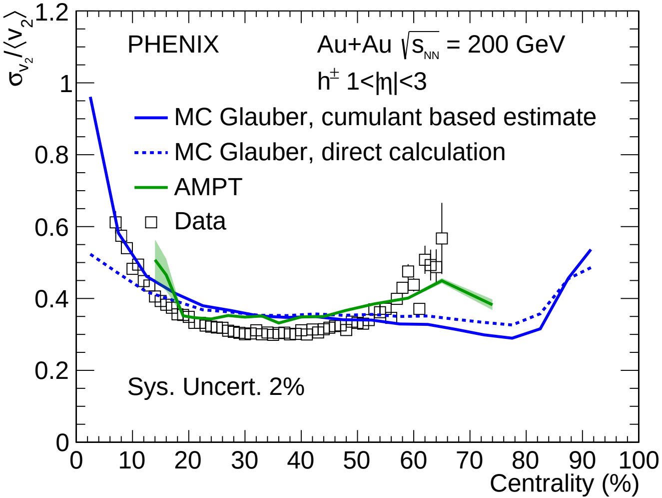
Fluctuations should also be translated, so measure $\sigma_{v_2}/\langle v_2 \rangle$

$1 < |\eta| < 3$

Generally good agreement with models of initial geometry

Fluctuations in large systems

PHENIX, Phys. Rev. C 99, 024903 (2019)



Fluctuations should also be translated, so measure $\sigma_{v_2}/\langle v_2 \rangle$

$1 < |\eta| < 3$

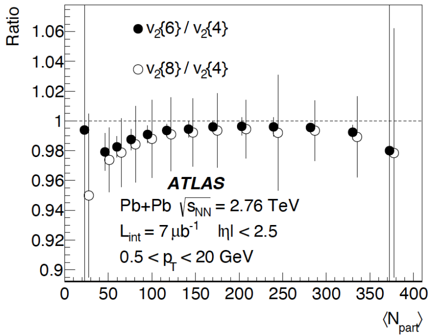
Central: breakdown of small-variance limit (assumed in data and solid line)

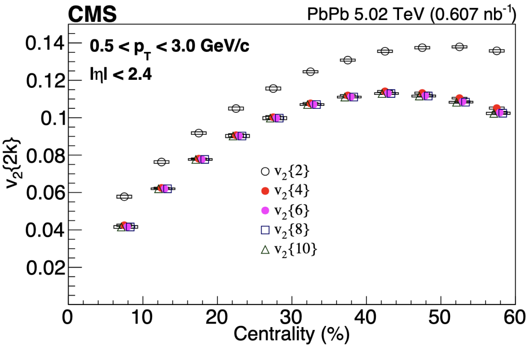
Peripheral: non-linearity in hydro response (e.g. J. Noronha-Hostler et al Phys. Rev. C 93, 014909 (2016))

Flow measurements in Au+Au

ATLAS Eur. Phys. J. C (2014) 74: 3157

CMS JHEP 02, 106 (2024)





sPHENIX can measure $v_2\{2,4,6,8\}$ with very high precision

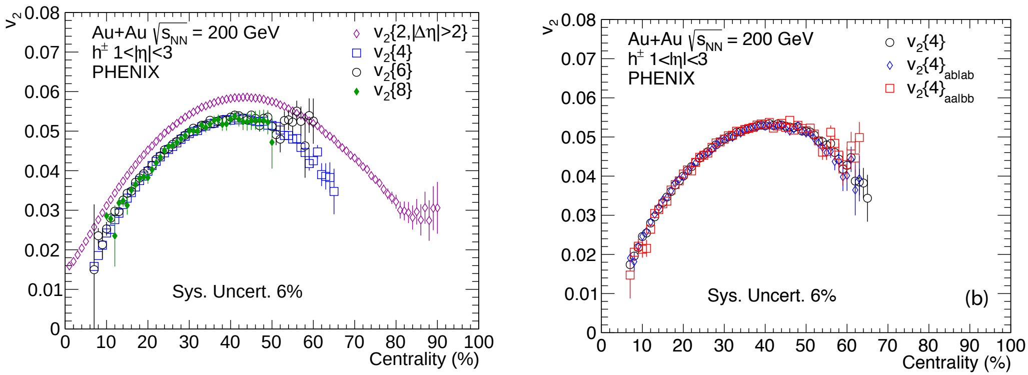
—Roughly, $v_2\{2\} = \sqrt{v_2^2 + \sigma^2}$ and $v_2\{4,6,8\} \approx \sqrt{v_2^2 - \sigma^2}$

—Deviations of ratios from unity give insights into higher moments of v_2 distribution

Can definitely measure $v_2\{10\}$, but not clear (yet) what level of sensitivity can be obtained

Flow measurements in Au+Au

PHENIX, Phys. Rev. C 99, 024903 (2019)

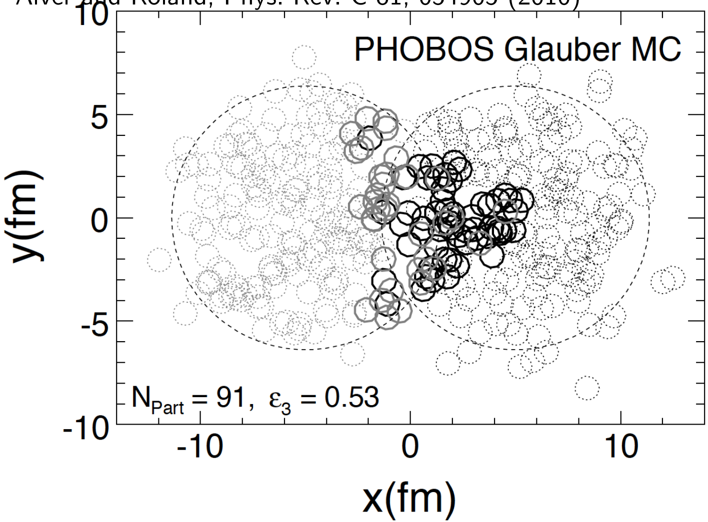


You can do a lot with ∼1 billion events...

...so you can do a lot more with ≈50 billion events!

Important discovery in 2010

Alver and Roland, Phys. Rev. C 81, 054905 (2010)



Nucleon fluctuations can produce non-zero ε_n for odd n

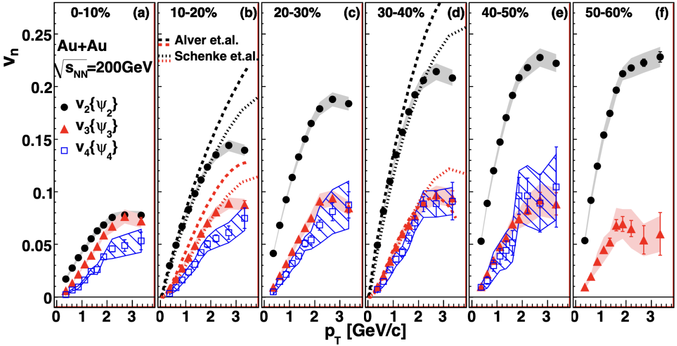
Symmetry planes ψ_n can be different for different harmonics

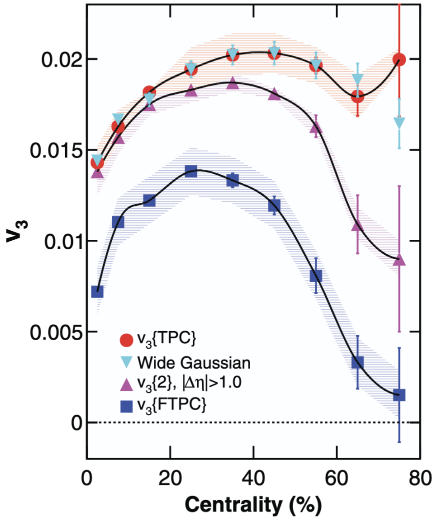
$$\varphi = \phi_{lab} - \psi_n$$

v_3 in Au+Au collisions

PHENIX, Phys. Rev. Lett. 107, 252301 (2011)

STAR, Phys. Rev. C 88, 014904 (2013)

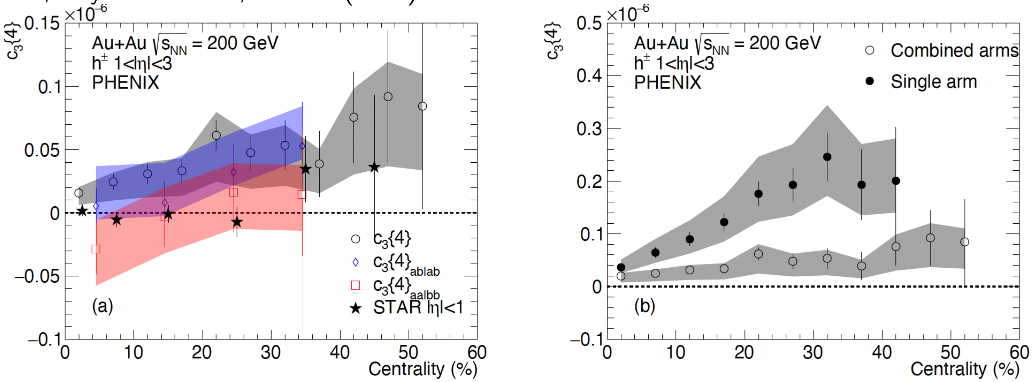




Sure enough, v_3 isn't zero

v_3 in Au+Au collisions

PHENIX, Phys. Rev. C 99, 024903 (2019)

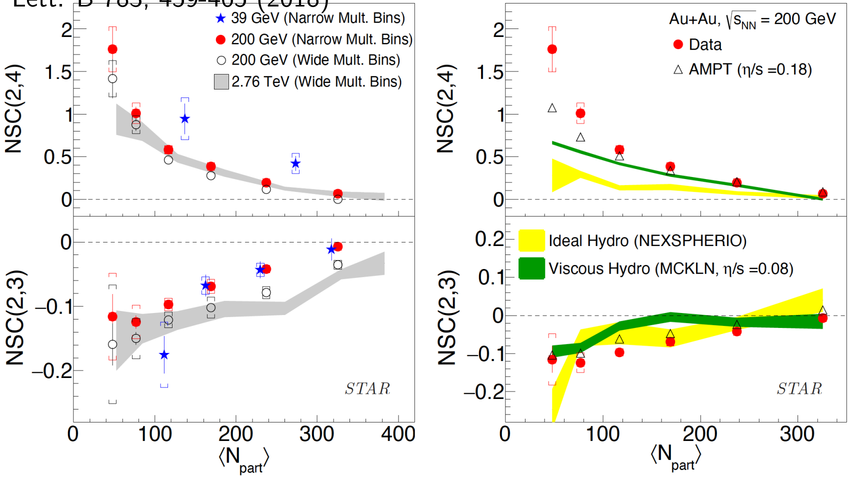


Previous observation of interesting rapidity dependence of $c_3\{4\} = -v_3^4\{4\}$ comparing STAR $|\eta| < 1$ and PHENIX $1 < |\eta| < 3$

sPHENIX can do high precision measurement with $|\eta| < 1.1$ (central barrel) and $2.0 < |\eta| < 4.9$ (sEPD)

Harmonic correlations in Au+Au

STAR, Phys. Lett. B 783, 459-465 (2018)



NSC(n,m) gives correlations between n-th and m-th harmonics

sPHENIX can improve these with more statistics, add higher harmonics, etc

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

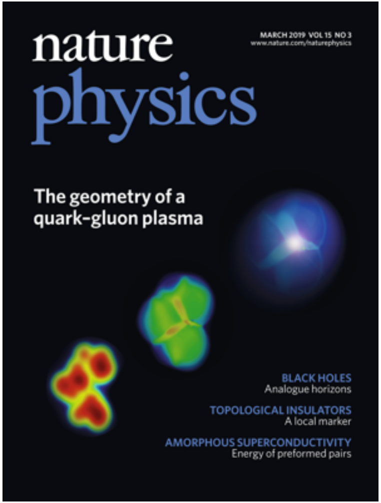
nature physics

Letter | Published: 10 December 2018

Creation of quark–gluon plasma droplets with three distinct geometries

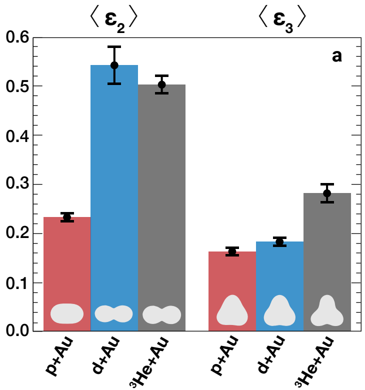
PHENIX Collaboration

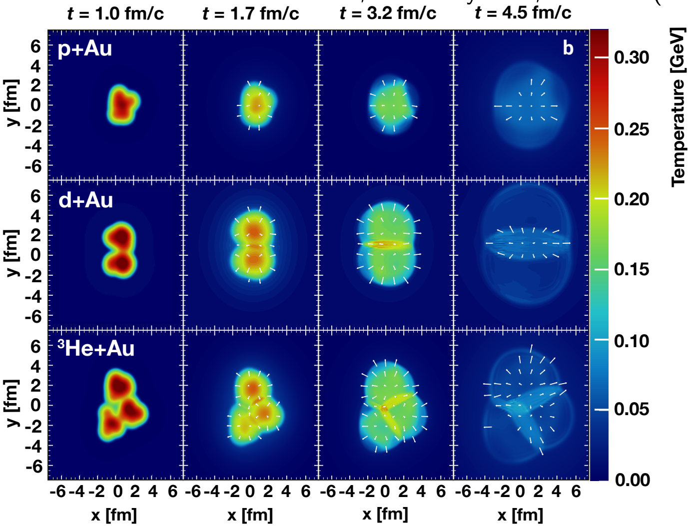
Nature Physics **15**, 214–220(2019) | Cite this article



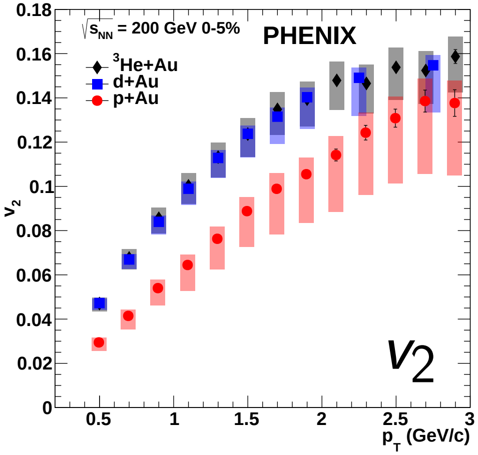
Small systems geometry scan

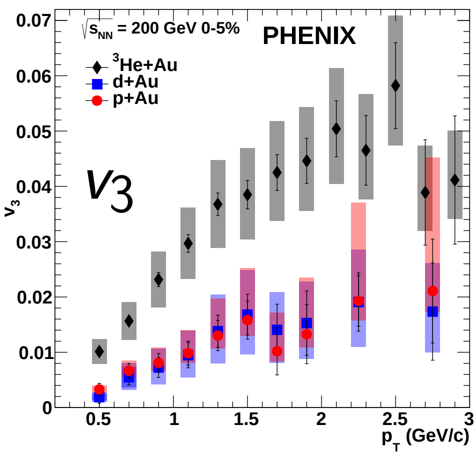
PHENIX, Nat. Phys. 15, 214–220 (2019)





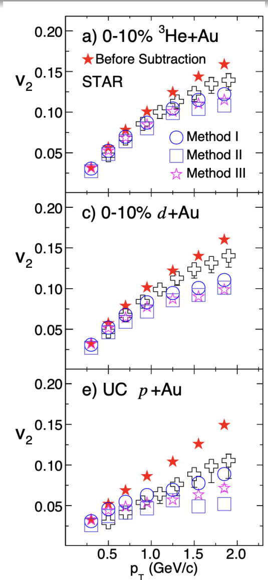
PHENIX, Nat. Phys. 15, 214–220 (2019)





v_2 and v_3 ordering matches ε_2 and ε_3 ordering in all three systems

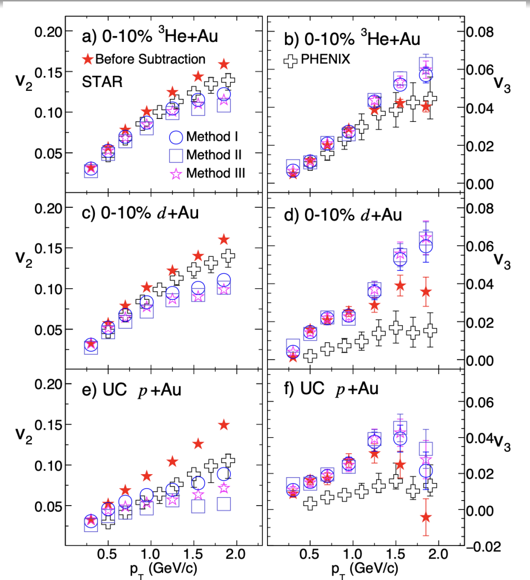
Comparisons with STAR



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

Good agreement between STAR and PHENIX for v_2

Comparisons with STAR



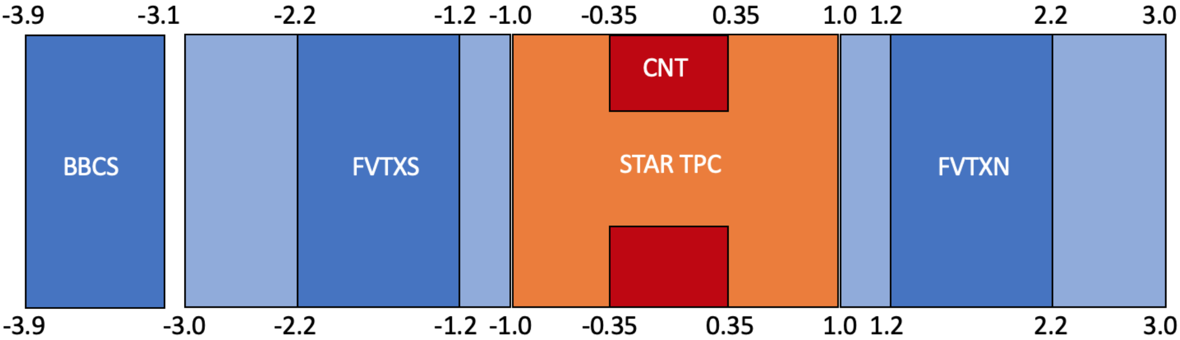
STAR, Phys. Rev. Lett. 130, 242301 (2023)

Good agreement between STAR and PHENIX for v_2

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

The kinematic acceptance between the two experiments is very different, and longitudinal dynamics plays a big role in the observables

STAR and PHENIX detector comparison

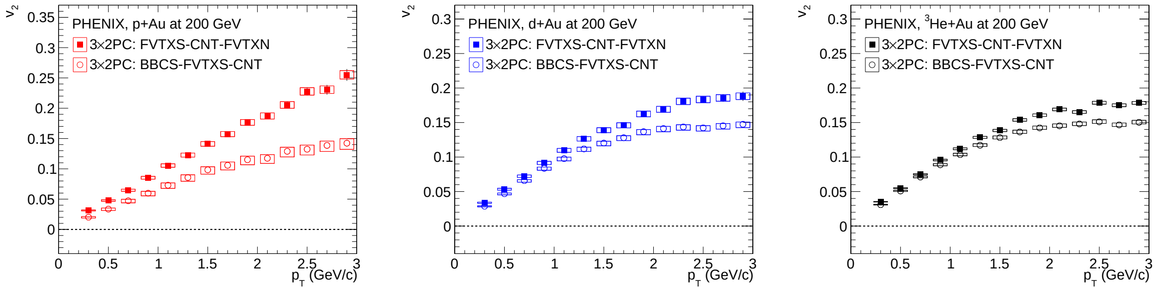


The PHENIX Nature Physics paper uses the BBCS-FVTXS-CNT detector combination
—This is very different from the STAR analysis (TPC only)

We can try to use FVTXS-CNT-FVTXN detector combination to better match STAR
—Closer, and "balanced" between forward and backward, *but still different*

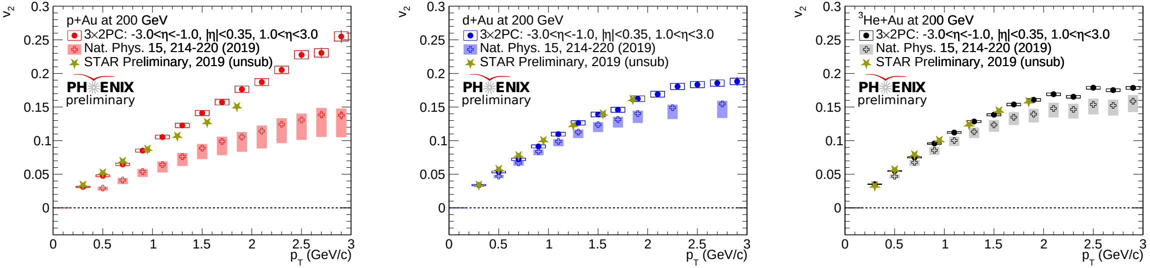
More STAR and PHENIX data comparisons

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



More STAR and PHENIX data comparisons

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

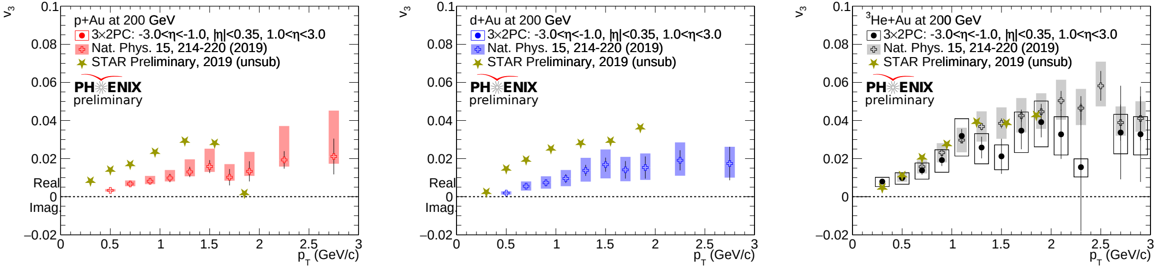


Good agreement with STAR for v_2

—Similar physics for the two different pseudorapidity acceptances

More STAR and PHENIX data comparisons

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



Good agreement with STAR for v_2

—Similar physics for the two different pseudorapidity acceptances

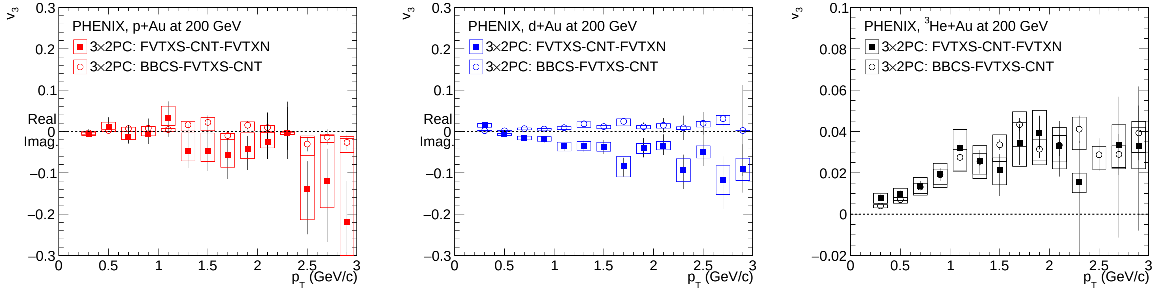
Strikingly different results for v_3

—Rather different physics for the two different pseudorapidity acceptances

—Longitudinal effects much stronger for v_3 than v_2

More STAR and PHENIX data comparisons

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



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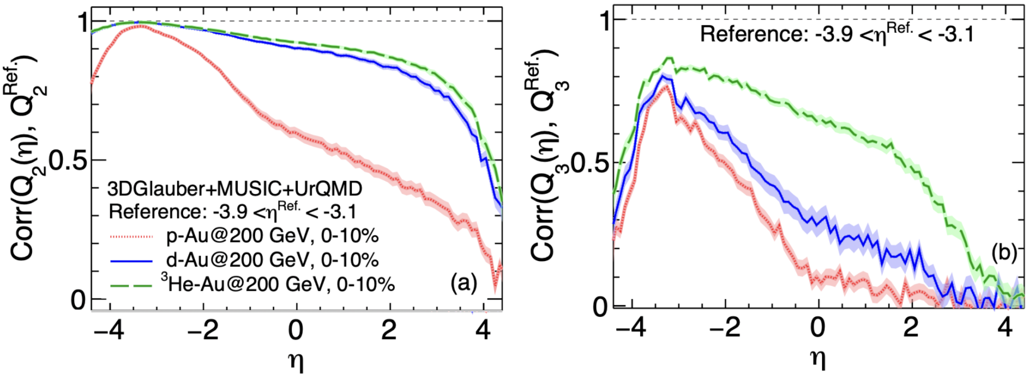
Pseudorapidity dependence in small systems

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

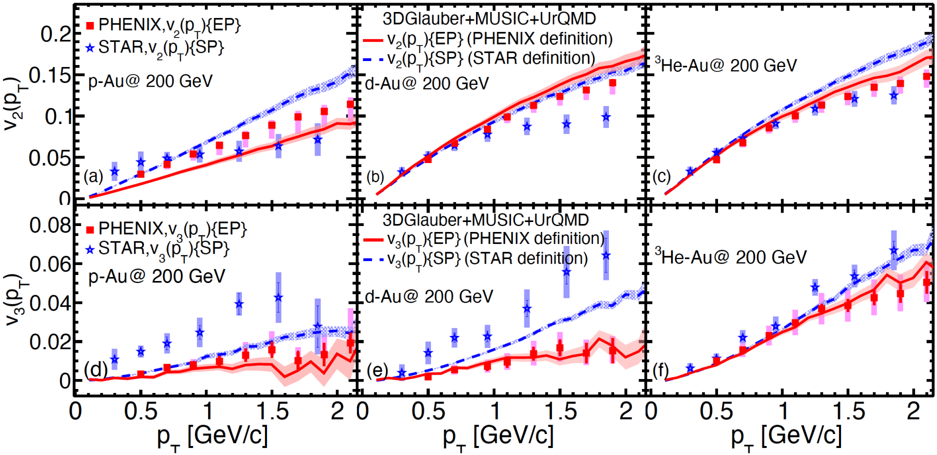


Flow vectors become decorrelated with increasing pseudorapidity separation
—The effect is much stronger for v_3 than for v_2

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...

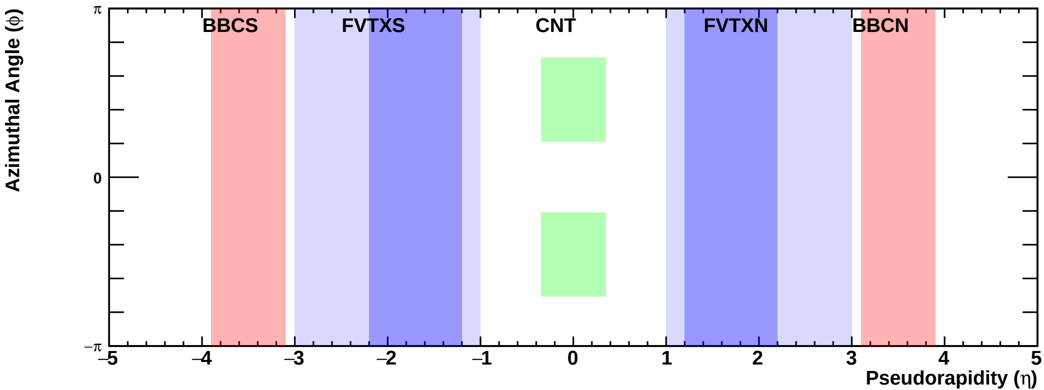
Pseudorapidity dependence in small systems

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



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

Opportunity for sPHENIX

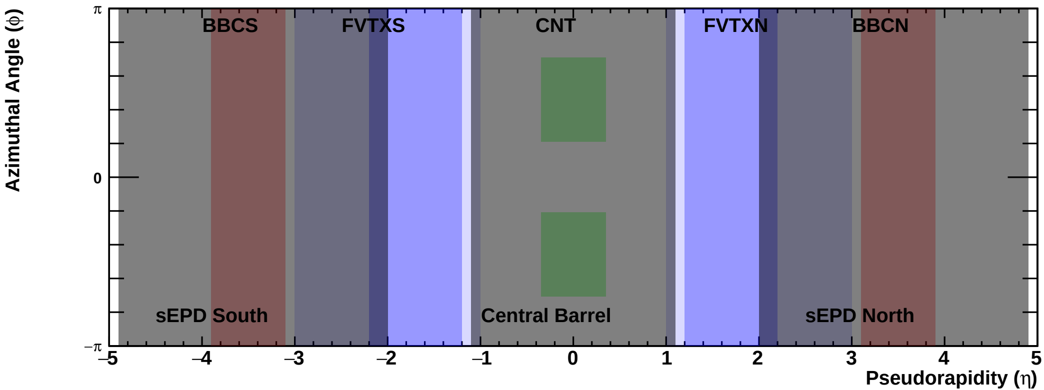


Thanks to large acceptance and high data rate, sPHENIX can make a major contribution

The central barrel can match the STAR measurement

The sEPD can extend the PHENIX measurement to even larger pseudorapidity separation

Opportunity for sPHENIX



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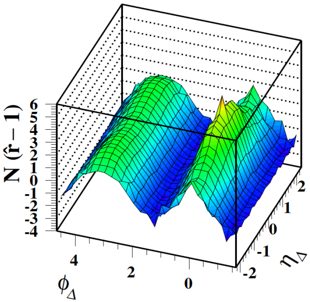
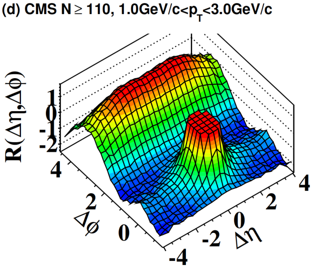
The central barrel can match the STAR measurement

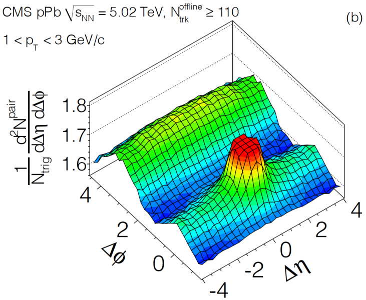
The sEPD can extend the PHENIX measurement to even larger pseudorapidity separation

The ridge is a signature of flow

STAR, PRC 73, 064907 (2006) CMS, JHEP 1009, 091 (2010) CMS, PLB 718, 795 (2013)





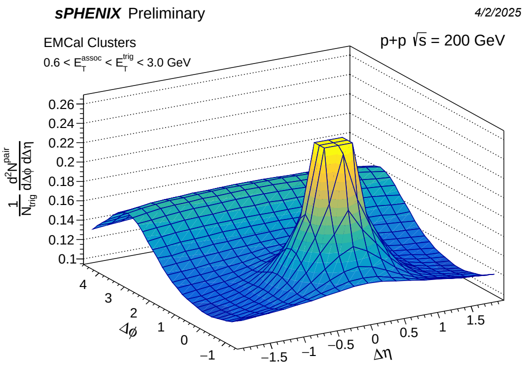


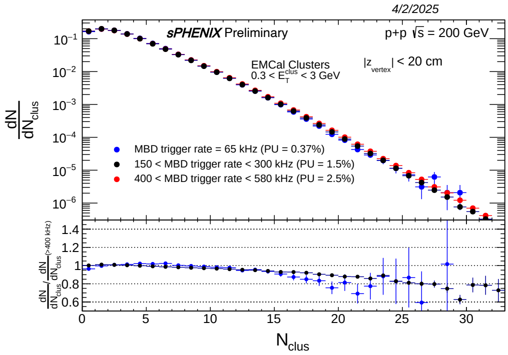
Extended structure away from near-side jet peak interpreted as collective effect due to presence of QGP

- Discovered by STAR in Au+Au in 2004 (PRC 73, 064907 (2006) and PRL 95, 152301 (2005))
- Realized by STAR to be flow in 2009 (PRL 105, 022301 (2010))
- First found in small systems by CMS (JHEP 1009, 091 (2010) and PLB 718, 795 (2013))

The ridge is a signature of flow

sPHENIX performance plots



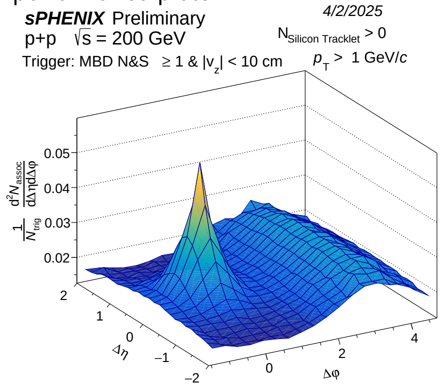


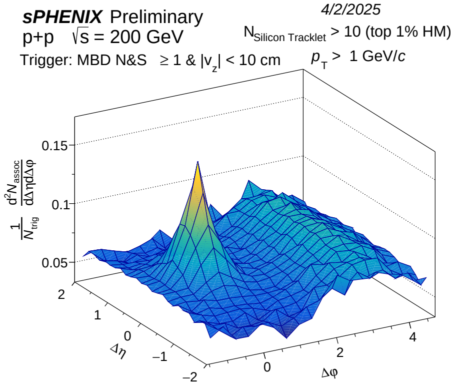
Is there a p+p ridge at RHIC? The hunt is on!

The current analysis uses about 1% at most of the total data, using the full dataset acquired via streaming readout will allow further study of high-multiplicity events

The ridge is a signature of flow

sPHENIX performance plots





Is there a p+p ridge at RHIC? The hunt is on!

The current analysis uses about 1% at most of the total data, using the full dataset acquired via streaming readout will allow further study of high-multiplicity events

Summary and Outlook

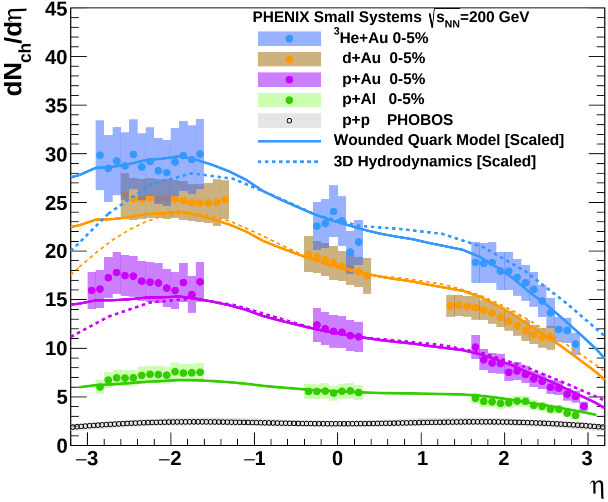
- Lots of exciting opportunities for very interesting flow measurements with sPHENIX!
- While flow measurements are a bonus rather than the core sPHENIX science mission, the PAC24 report clearly highlights the potential opportunities for new flow measurements
  - "The PAC recommends a Au+Au run in which sPHENIX collects at least 7/nb of data as the highest priority for Run 25."
    —This corresponds to about 50 billion events
  - "The PAC has received beam use requests for running pp, p+Au, and O+O collision systems. The PAC sees all three of these proposed runs as fully aligned with RHIC's core scientific mission, and in fact as key elements of completing that mission. Each of these three proposed runs is necessary to address central open RHIC Science questions in a decisive way."
    —More p+p needed for Upsilon program
    —Exciting prospects for more small systems measurements

Intermission

Additional Information

Pseudorapidity dependence in small systems

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



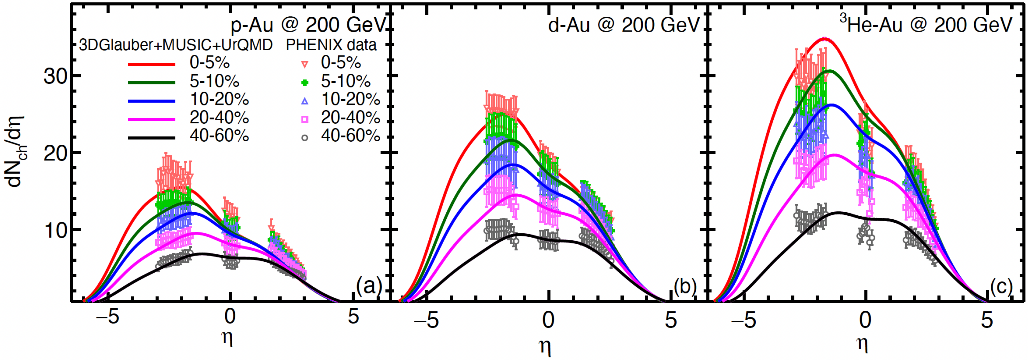
p+Al, p+Au, d+Au, ^{3}He+Au

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



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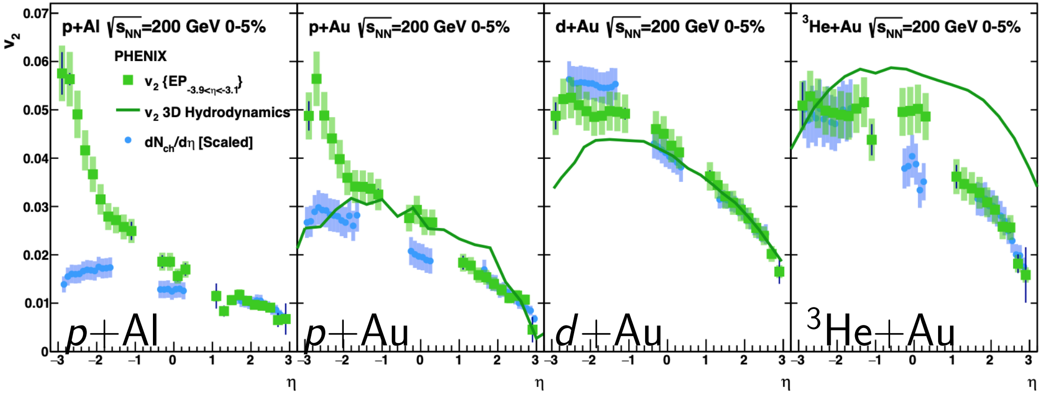

v_2 vs η in p+Al, p+Au, d+Au, and ^{3}He+Au

Good agreement with 3D hydro for p+Au and d+Au (Bozek et al, PLB 739, 308 (2014))

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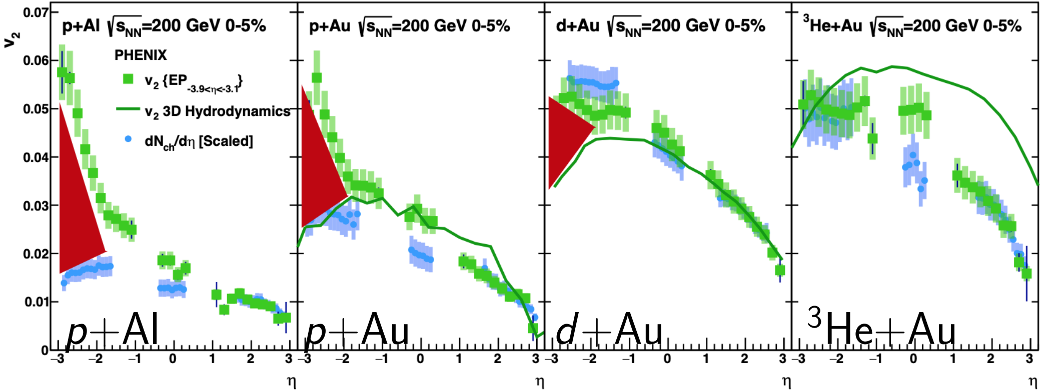
PHENIX, Phys. Rev. Lett. 121, 222301 (2018)



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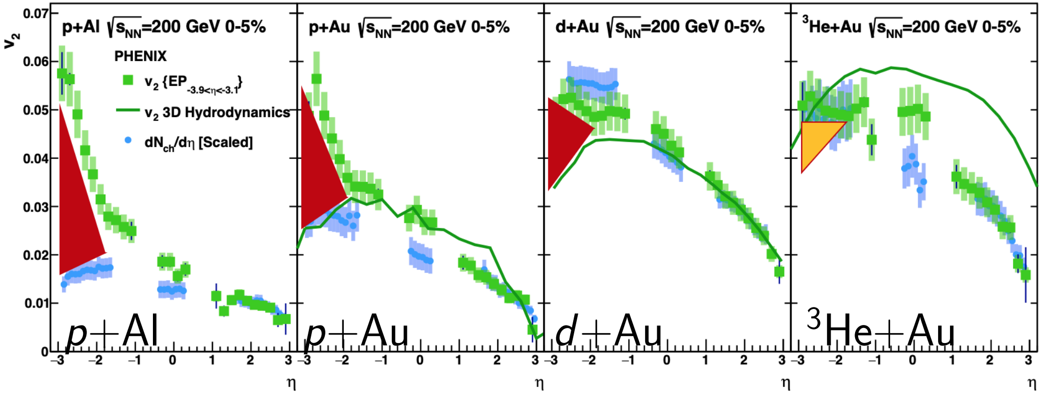
Prevalence of nonflow near the EP detector $(-3.9 < \eta < -3.1)$

Pseudorapidity dependence in small systems

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



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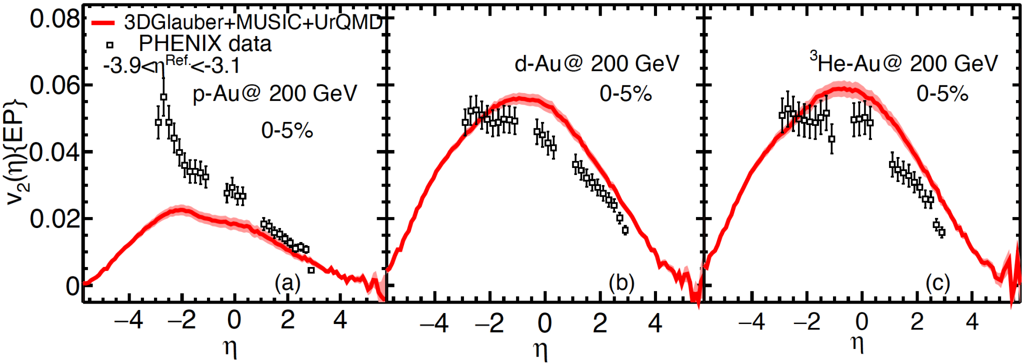

Good agreement with 3D hydro for $v_2(\eta)$ in p+Au, p+Au, ^{3}He+Au

Small systems geometry scan

PHYSICAL REVIEW LETTERS

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Exploiting Intrinsic Triangular Geometry in Relativistic $^{3}\mathbf{He}+\mathbf{Au}$ 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

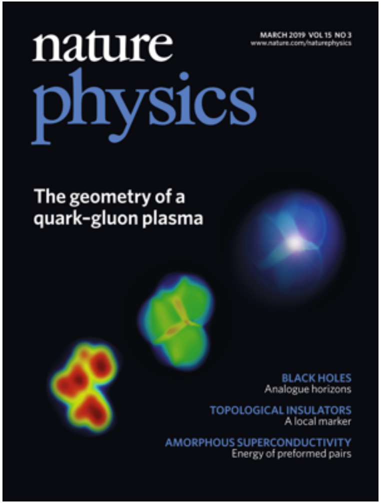
nature physics

Letter | Published: 10 December 2018

Creation of quark–gluon plasma droplets with three distinct geometries

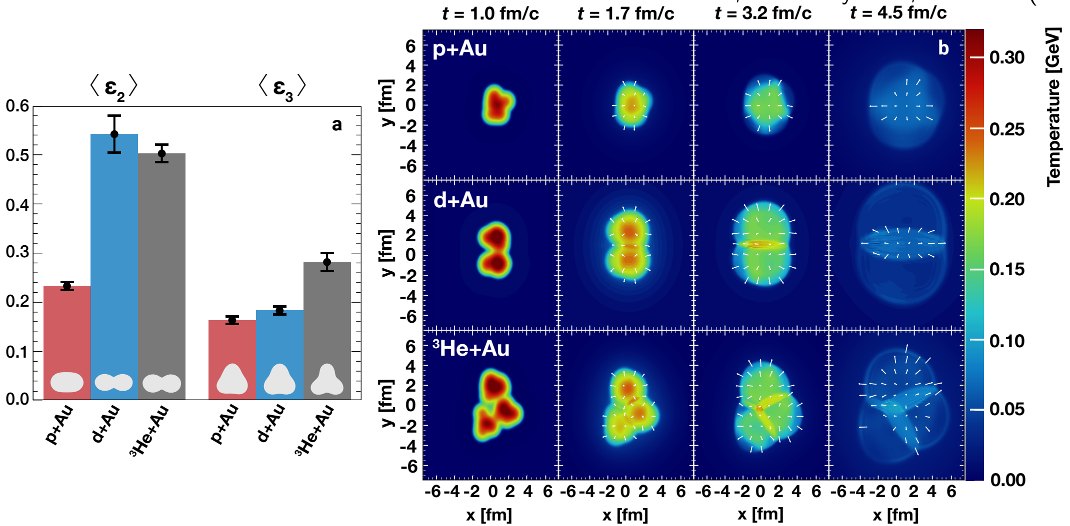
PHENIX Collaboration

Nature Physics **15**, 214–220(2019) | Cite this article



Small systems geometry scan

PHENIX, Nat. Phys. 15, 214–220 (2019)



Small systems geometry scan

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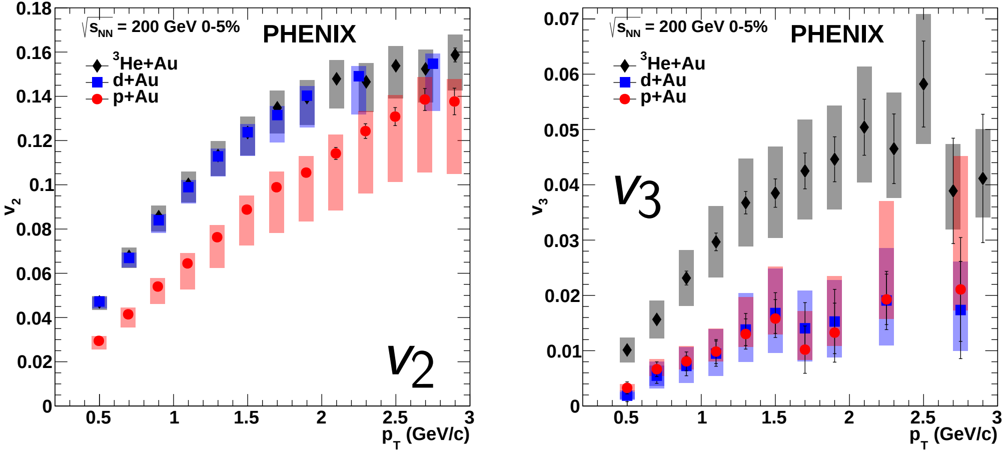
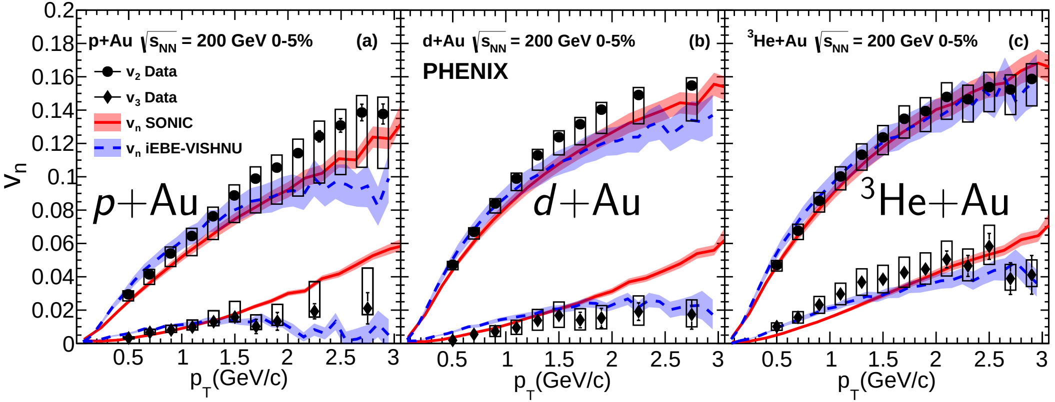


v_2 and v_3 ordering matches ε_2 and ε_3 ordering in all three systems

—Collective motion of system translates the initial geometry into the final state

Small systems geometry scan

PHENIX, Nat. Phys. 15, 214–220 (2019)



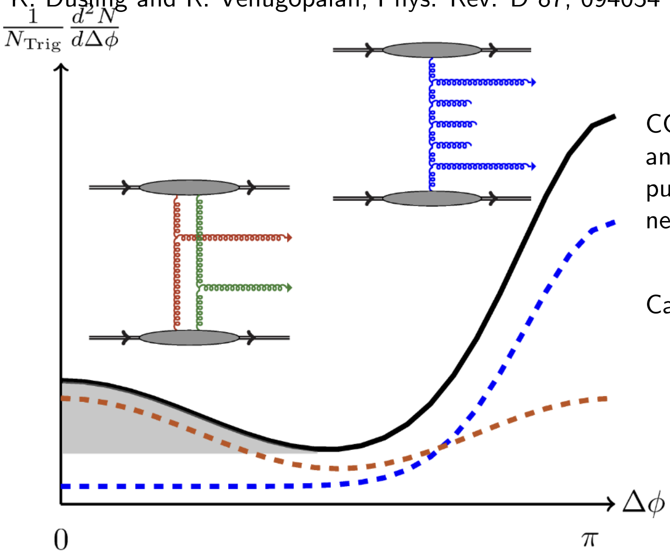
v_2 and v_3 vs p_T predicted or described very well by hydrodynamics in all three systems

—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)

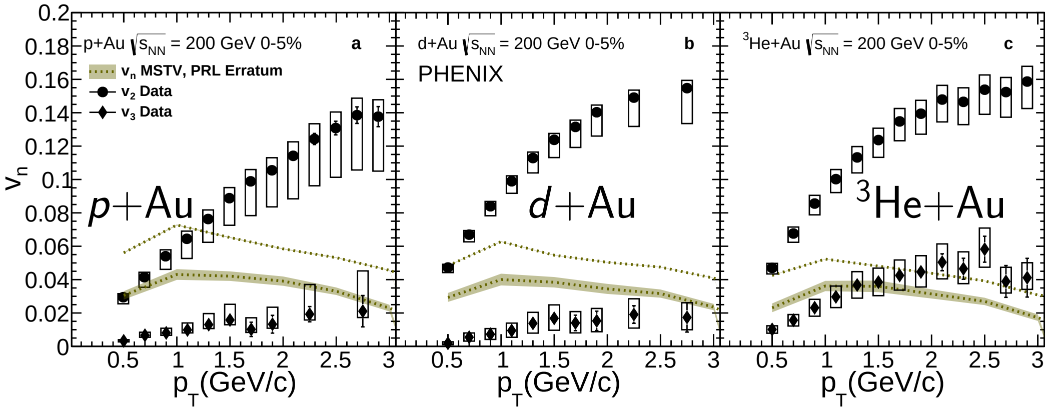


CGC framework: glasma diagrams produce angular correlations like the ridge and v_n purely from initial state correlations, with no need for final state interactions (hydro)

Can they explain the data?

Initial state effects cannot explain the data

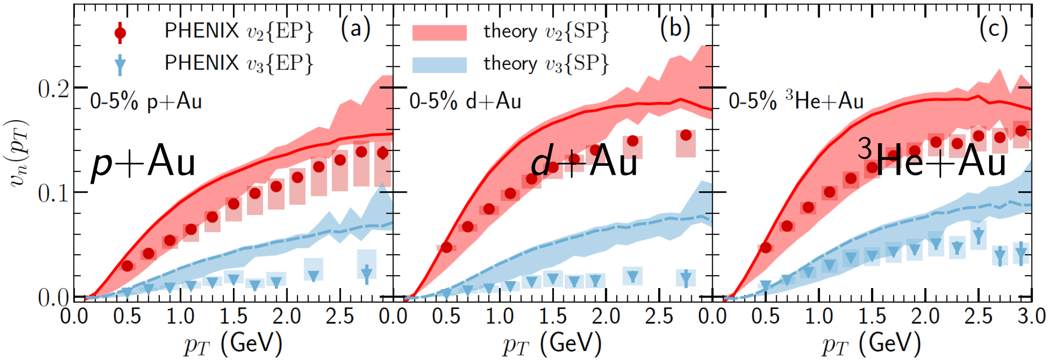
PHENIX, Nat. Phys. 15, 214–220 (2019)



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

How important are initial state effects?

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

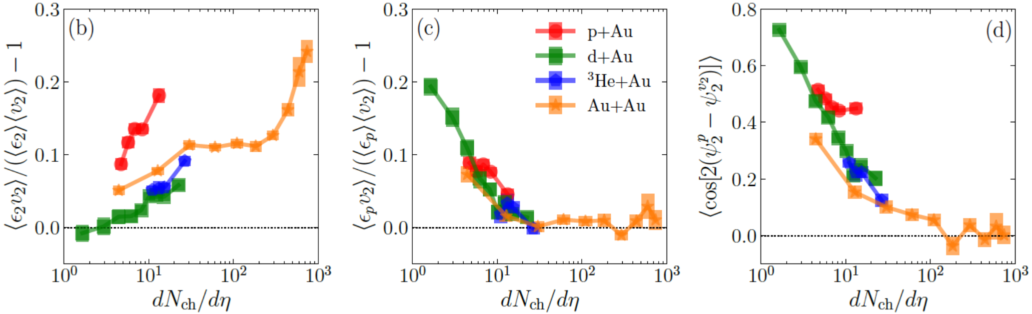


Initial state effects important for theory, but make little contribution for central collisions

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)

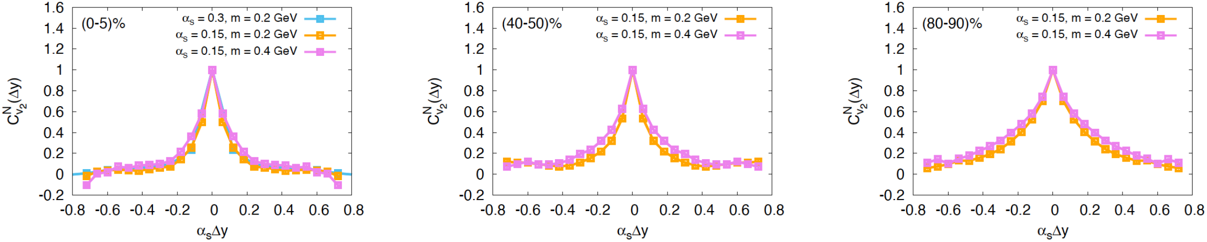


For central p+Au, modest correlation between ε_p and v_2

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)

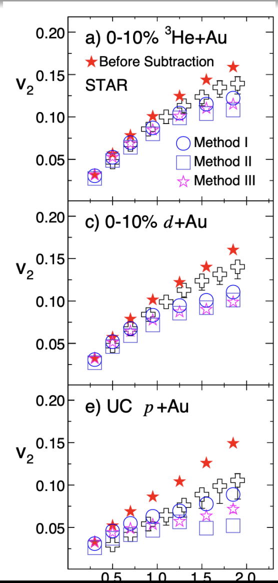


The CGC/Glasma correlations appear to be too narrow in (pseudo)rapidity to have any significant impact on the data

—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

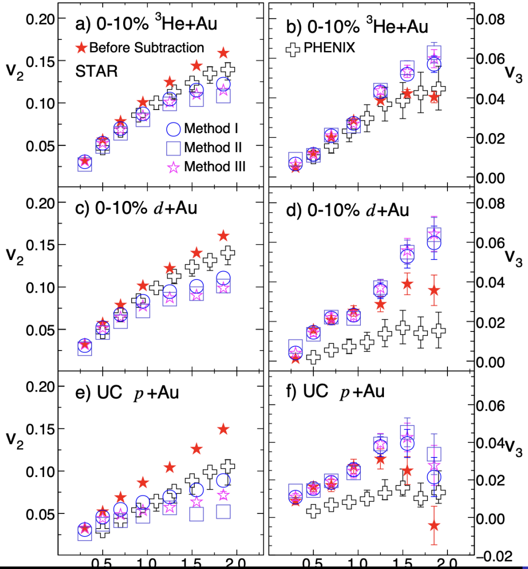
Comparisons with STAR



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

Good agreement between STAR and PHENIX for v_2

Comparisons with STAR



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

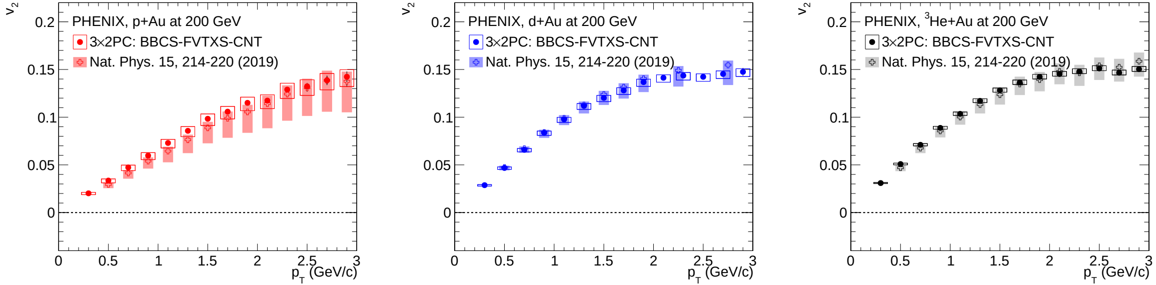
Good agreement between STAR and PHENIX for v_2

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)

PHENIX data update

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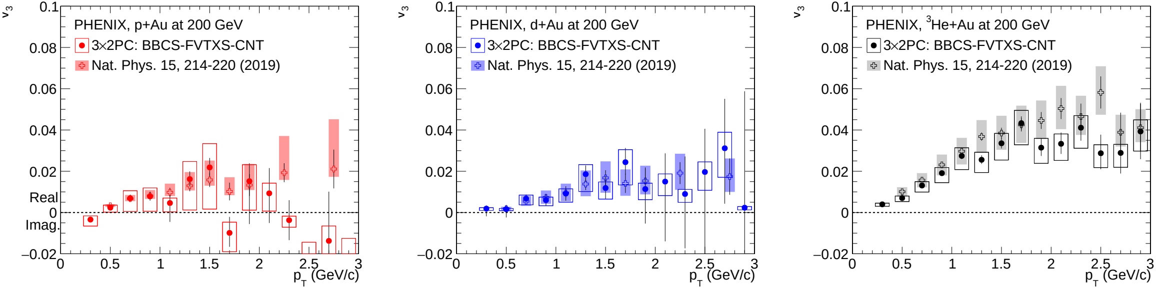

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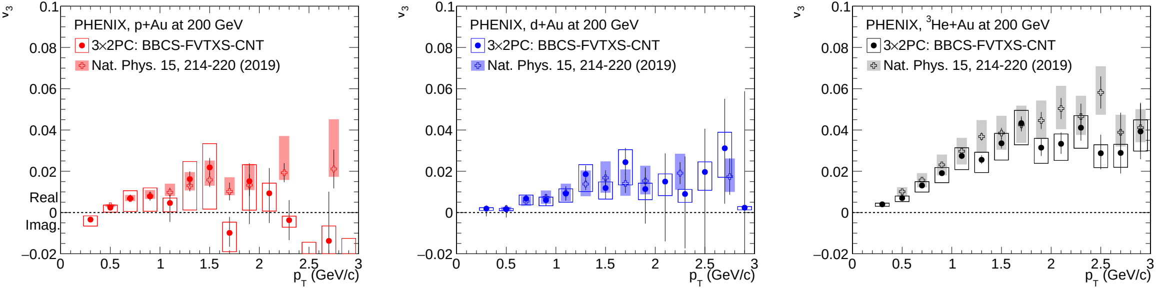

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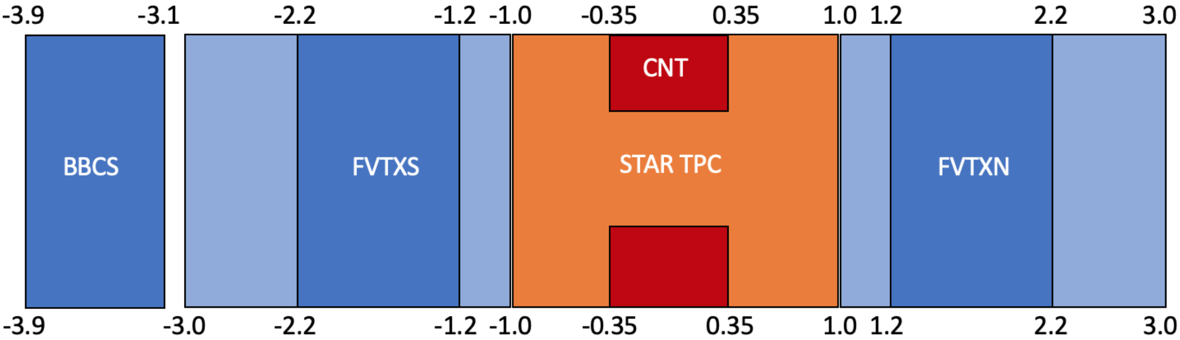
All new analysis using two-particle correlations with event mixing instead of event plane method
—Completely new and separate code base
—Very different sensitivity to key experimental effects (beam position, detector alignment)

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

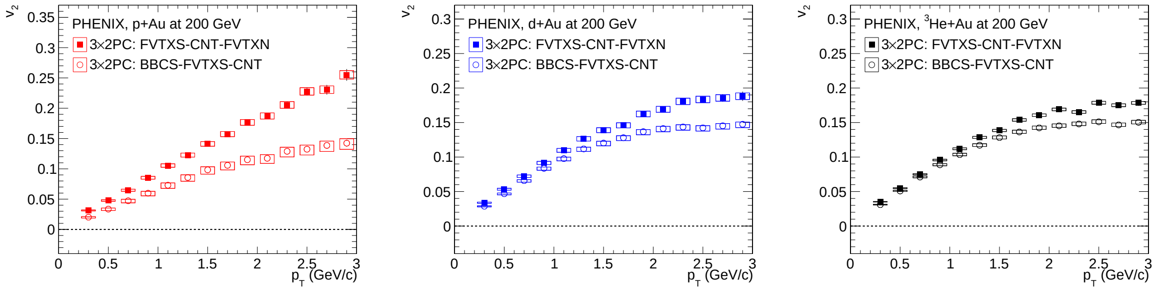


The PHENIX Nature Physics paper uses the BBCS-FVTXS-CNT detector combination
—This is very different from the STAR analysis (TPC only)

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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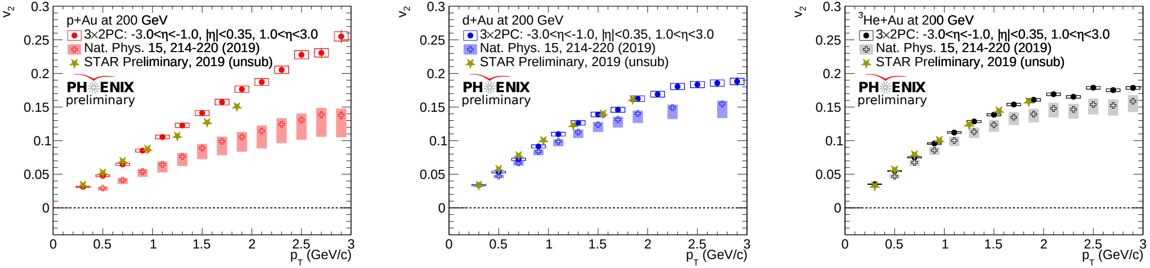

Good agreement with STAR for v_2

—Similar physics for the two different pseudorapidity acceptances

More STAR and PHENIX data comparisons

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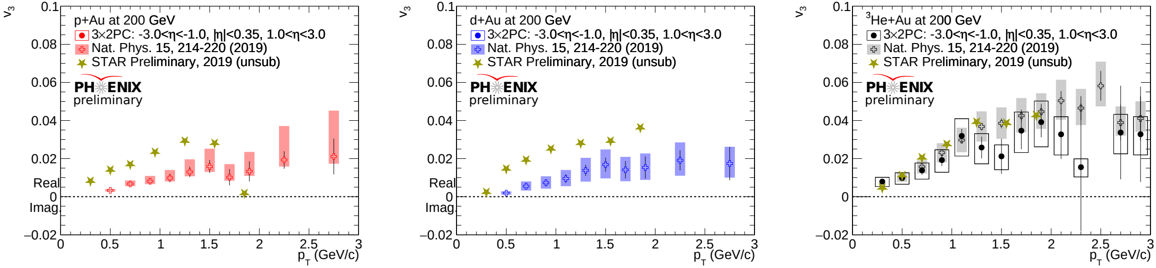


Good agreement with STAR for v_2

—Similar physics for the two different pseudorapidity acceptances

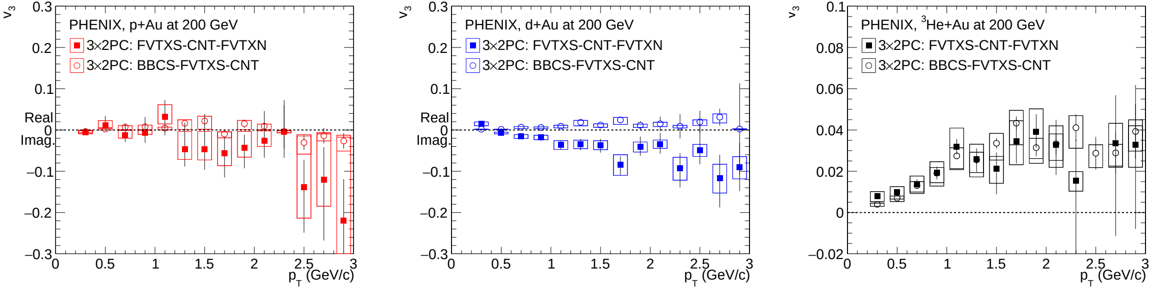
Strikingly different results for v_3

—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

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



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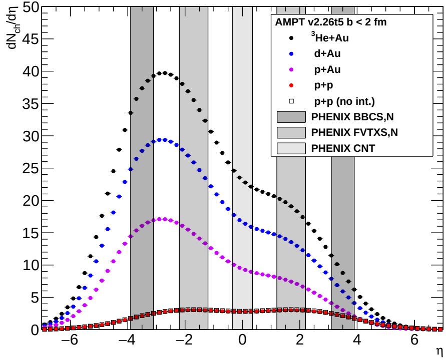
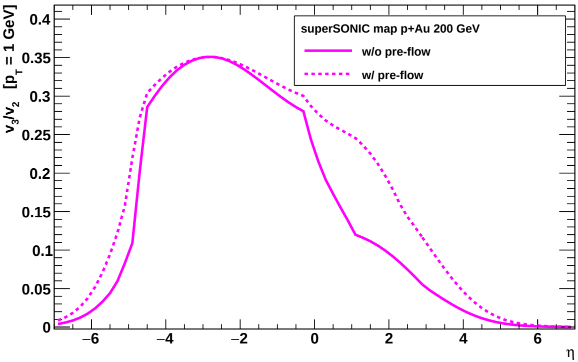
Pseudorapidity dependence in small systems

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



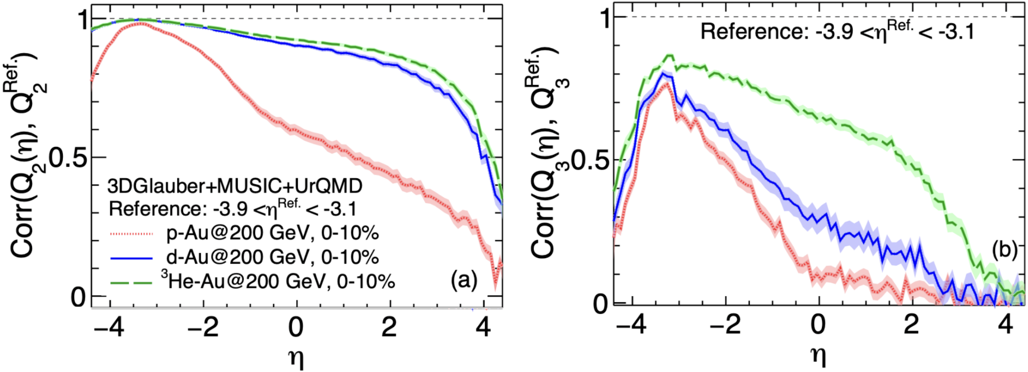


$dN_{ch}/d\eta$ from AMPT, $v_3(\eta)$ from (super)SONIC

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)

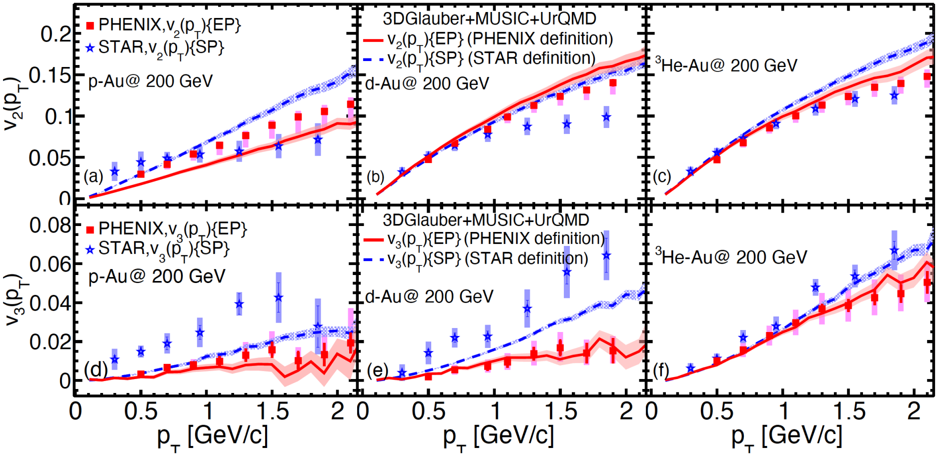


Flow vectors become decorrelated with increasing pseudorapidity separation
—The effect is much stronger for v_3 than for v_2

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...

Pseudorapidity dependence in small systems

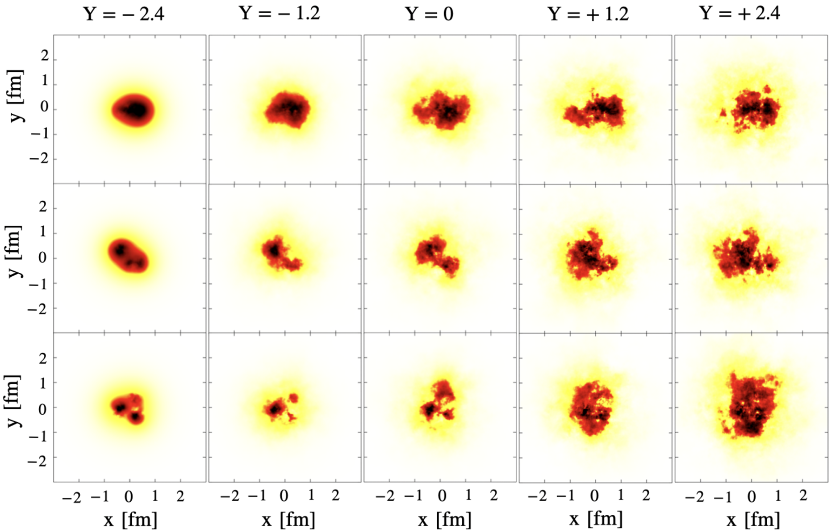
W. Zhao et al, Phys. Rev. C 107, 014904 (2023)



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

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)

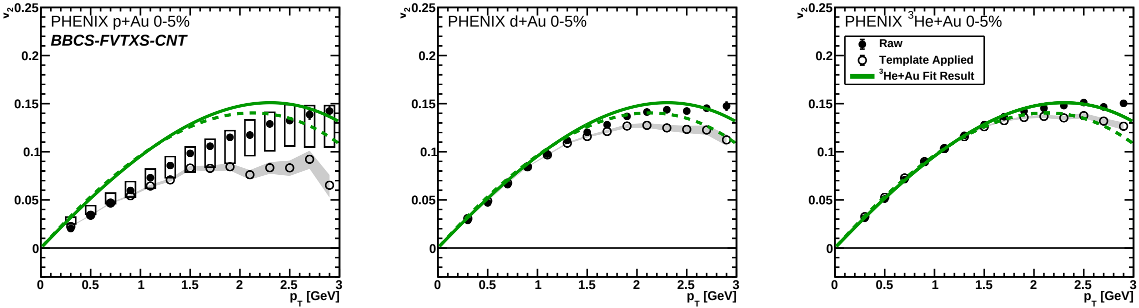
https://arxiv.org/abs/2107.07287

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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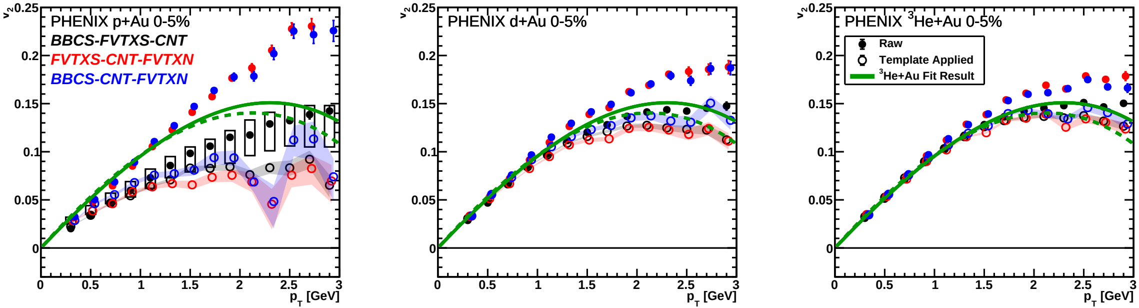


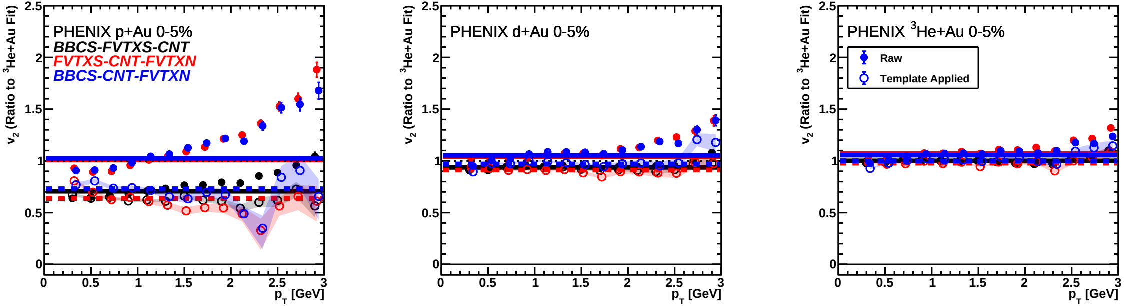
The BBCS-FVTXS-CNT combination minimizes non-flow, so subtraction doesn't make too much difference

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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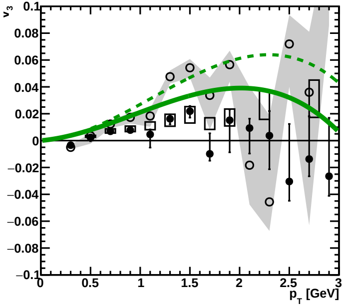

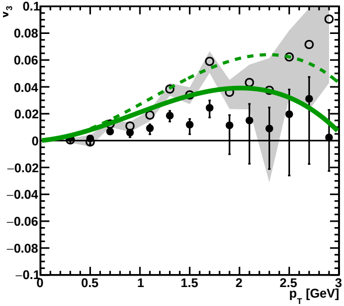

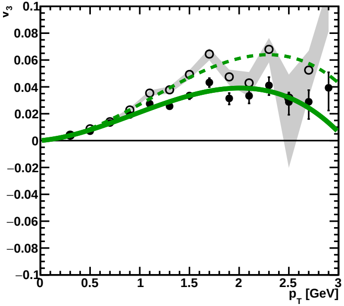

There's a larger relative change for v_3 compared to v_2, but the smaller value of v_3 makes the non-flow subtraction more sensitive to non-closure

Additional non-flow studies using published data tables

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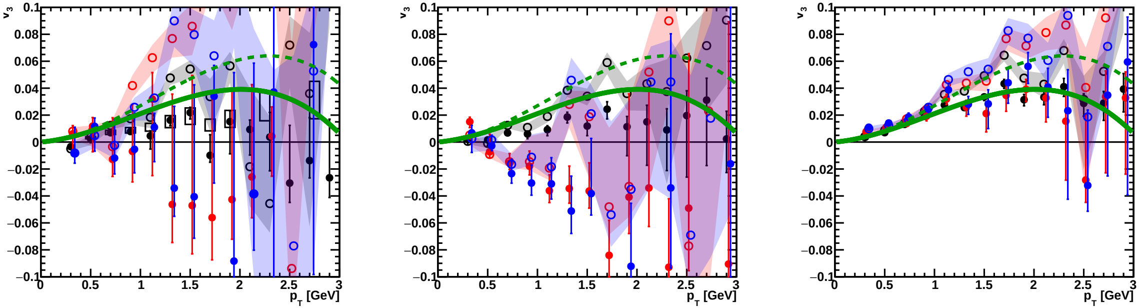

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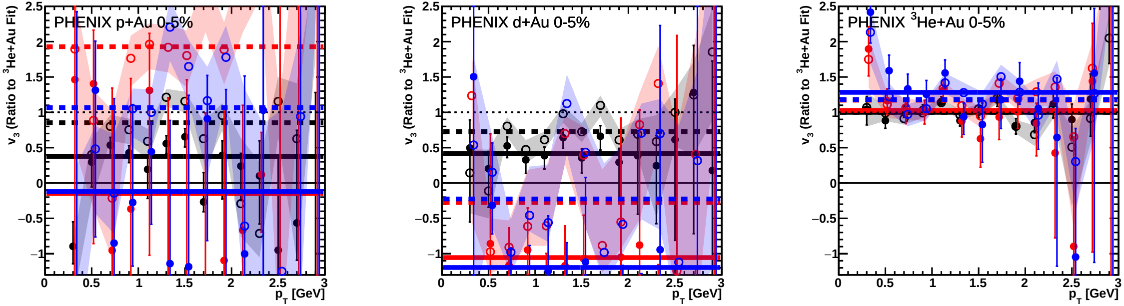
For the combinations with more non-flow, where the v_3 is imaginary in p+Au and d+Au, the non-flow subtraction is completely uncontrolled

Additional non-flow studies using published data tables

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



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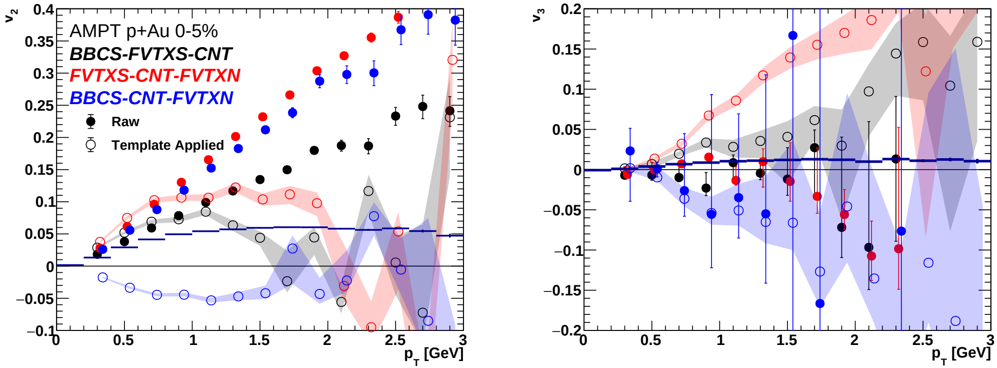
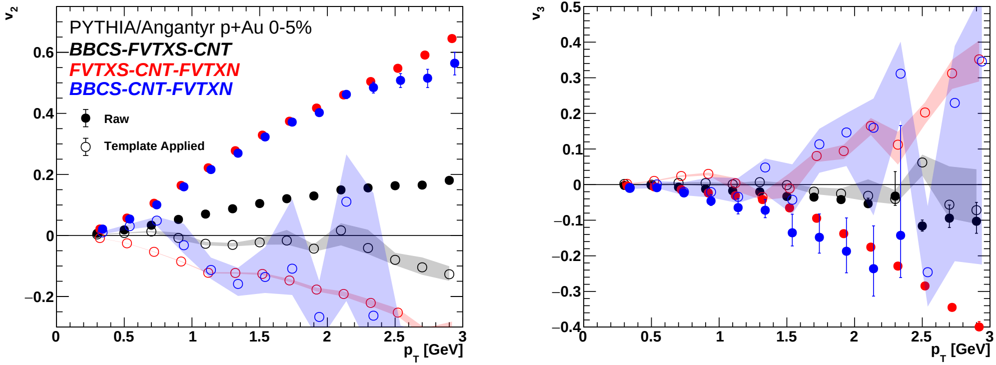


Closure is considerably violated in AMPT

Additional non-flow studies using published data tables

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



Closure is considerably violated in AMPT and PYTHIA/Angantyr

Additional non-flow studies using published data tables

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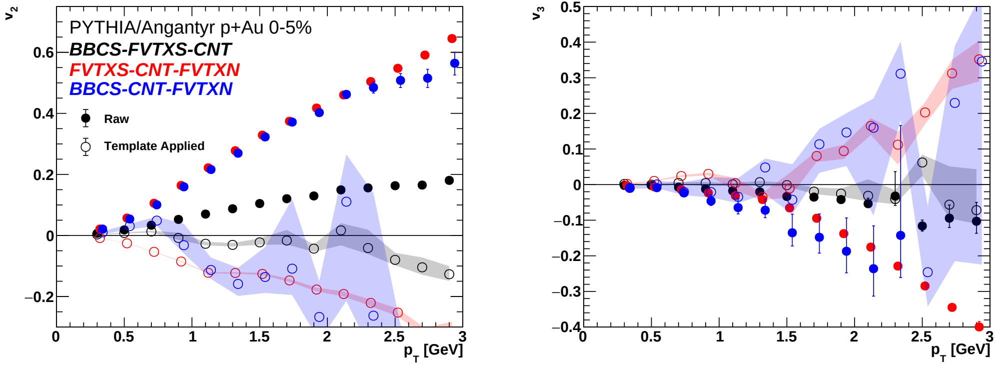

Closure is considerably violated in AMPT and PYTHIA/Angantyr

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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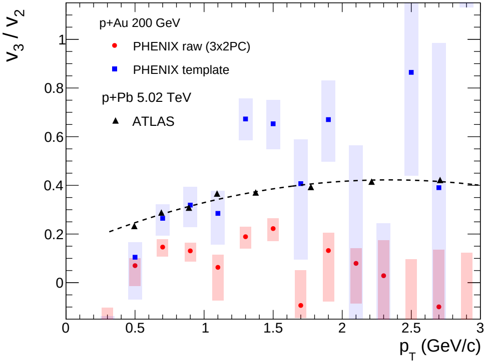
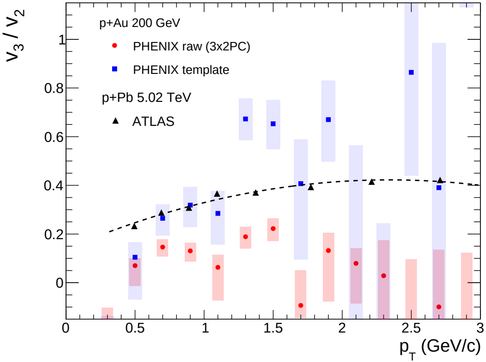
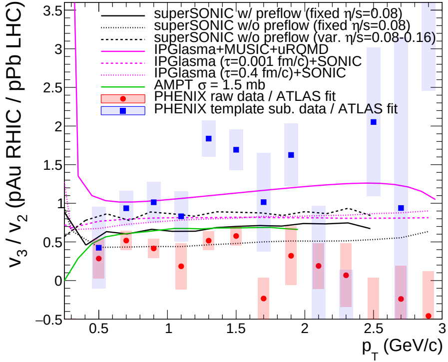


The standard PHENIX v_3/v_2 is lower than the ATLAS, while the non-flow corrected is above

Additional non-flow studies using published data tables

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





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