Hydrodynamics and RHIC Data

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The Internet
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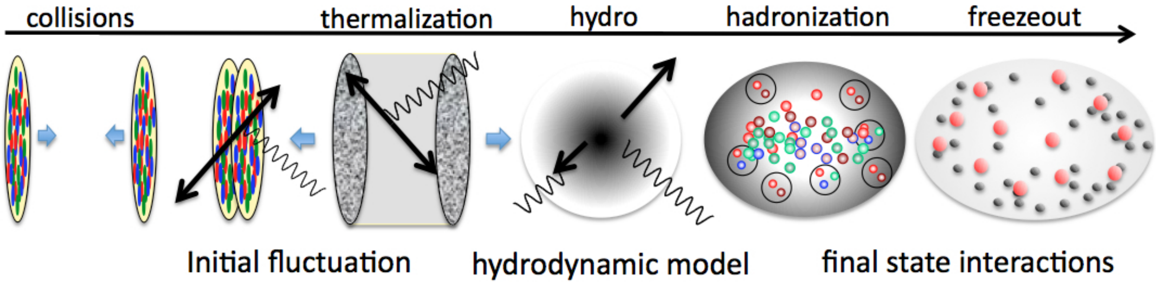
Quick outline

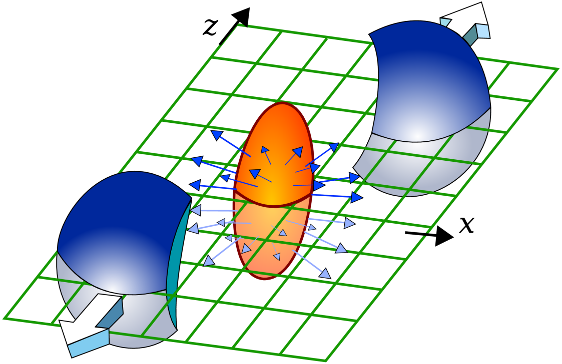
- Brief overview of the standard model of heavy ion collisions (the hydro paradigm)
- Small systems beam energy scan
- Small systems geometry scan
- A quick look outside RHIC

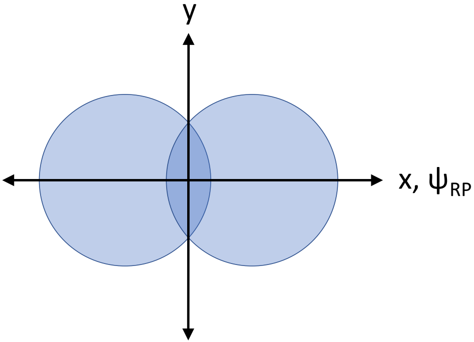
Standard model of heavy ion physics



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

Azimuthal anisotropy measurements

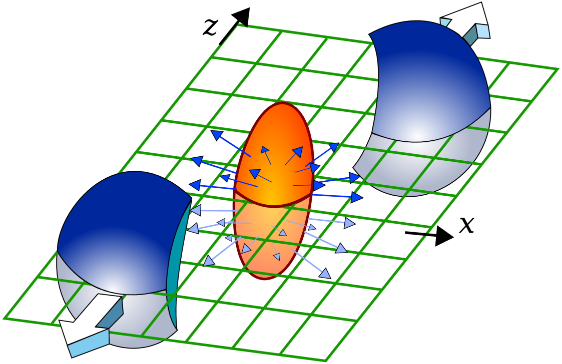


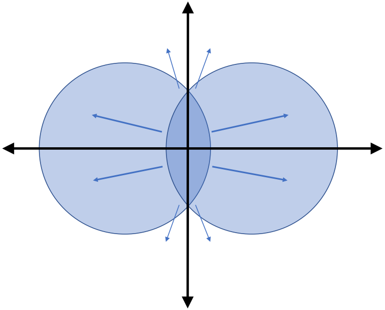


$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos n\varphi \qquad v_n = \langle \cos n\varphi \rangle \qquad \varepsilon_n = \frac{\sqrt{\langle r^n \cos n\varphi \rangle + \langle r^n \sin n\varphi \rangle}}{\langle r^n \rangle}$$

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

Azimuthal anisotropy measurements





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

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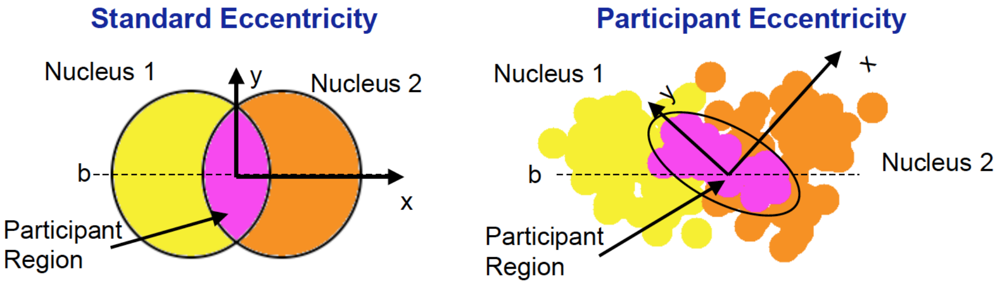
Important discovery in 2005

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



A nucleus isn't just a sphere

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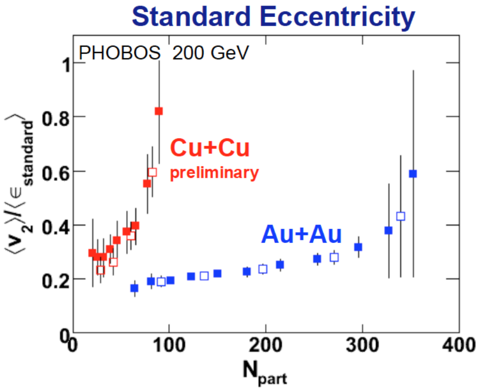

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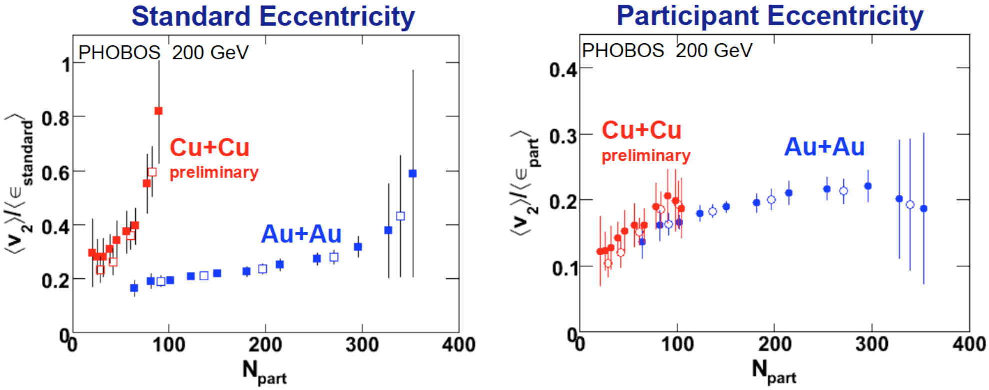


A nucleus isn't just a sphere

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

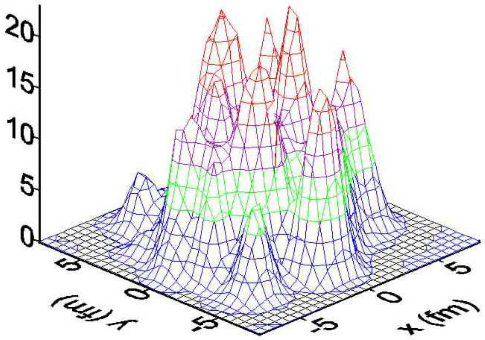
R.Andrade[1], F.Grassi[1], Y.Hama[1], T.Kodama[2], O.Socolowski Jr.[3], and B.Tavares[2]

[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

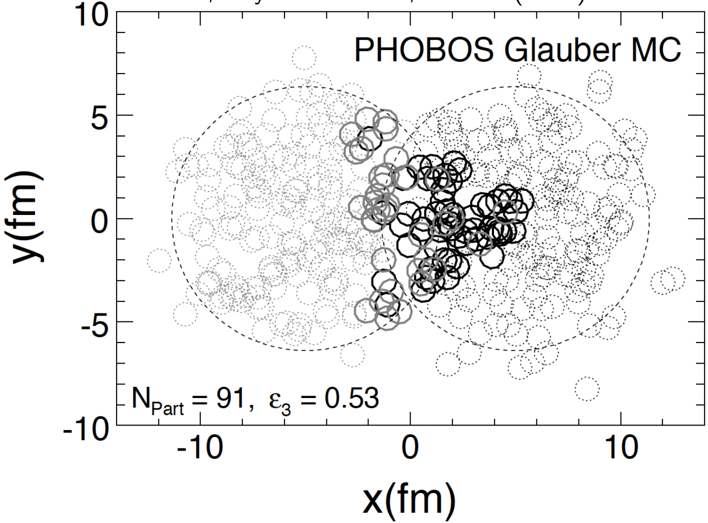
Received 1 January 2004



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

Important discovery in 2010

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



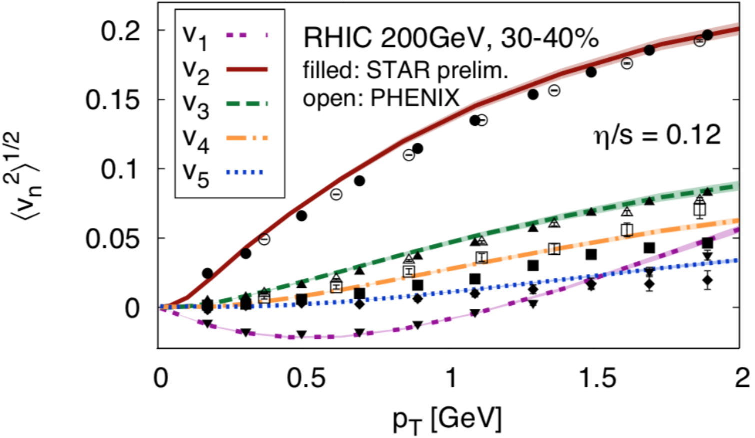
Nucleon fluctuations can produce non-zero ε_n for odd n

Symmetry planes ψ_n can be different for different harmonics

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

Data and theory for v_n

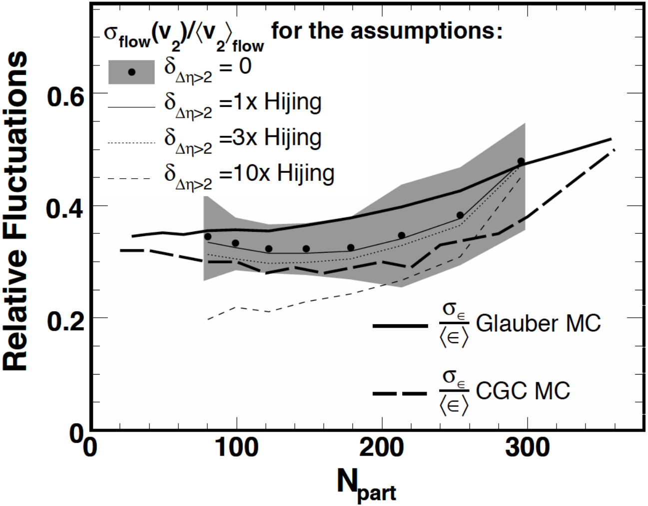
Gale et al, Phys. Rev. Lett. 110, 012302 (2013)



$$\frac{dN}{d\varphi} \propto 2v_1 \cos\varphi + 2v_2 \cos 2\varphi + 2v_3 \cos 3\varphi + 2v_4 \cos 4\varphi + 2v_5 \cos 5\varphi$$

Fluctuations in large systems

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



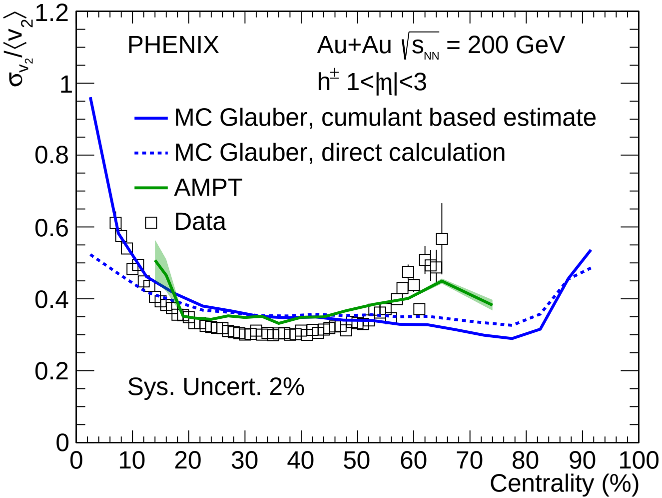
Fluctuations should also be translated, so measure $\sigma_{v_2}/\langle v_2\rangle$

$|\eta| < 1$

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

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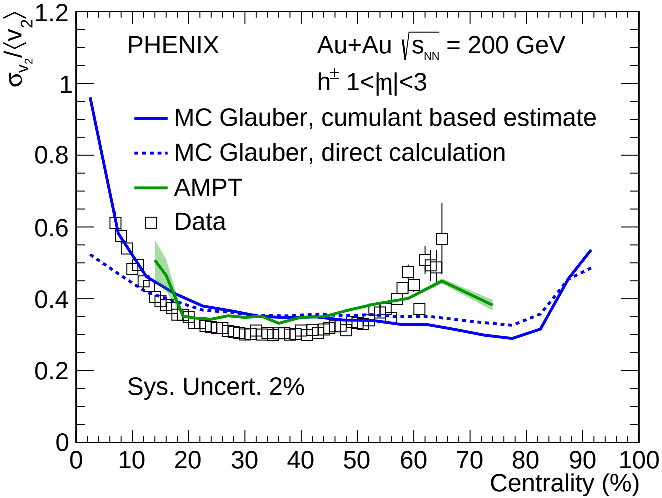

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$1 < |\eta| < 3$

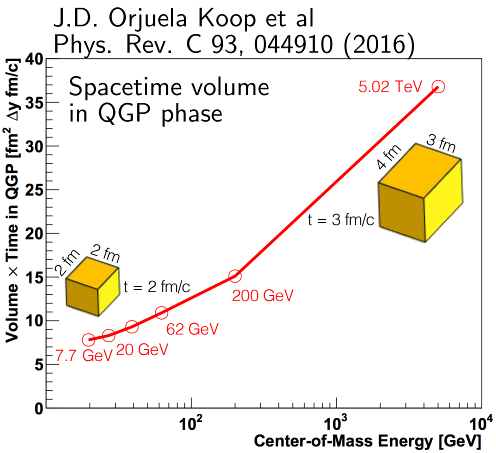
Central: breakdown of small-variance limit (assumed in data and solid line)

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

Intermission

Small systems beam energy scan

Testing hydro by controlling system size and life time

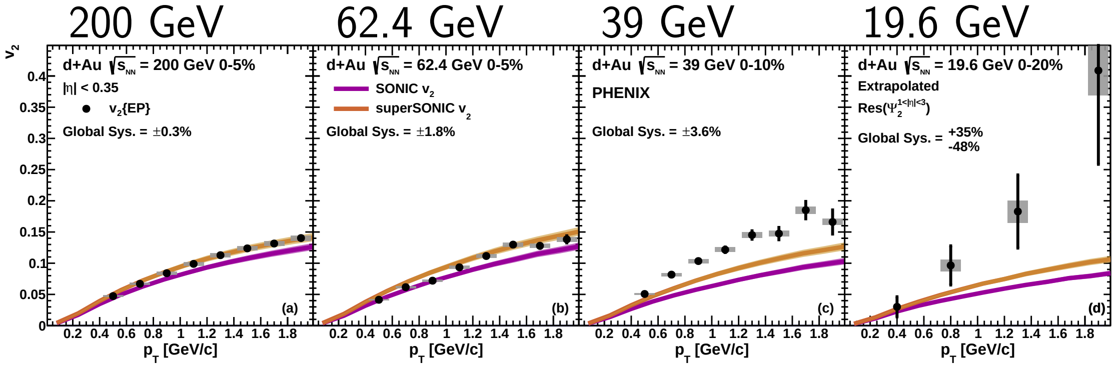


Geometry in d+Au collisions dominated by deuteron shape, thus largely independent of collision energy

Spacetime volume of system in QGP phase decreases with decreasing collision energy

d+Au beam energy scan

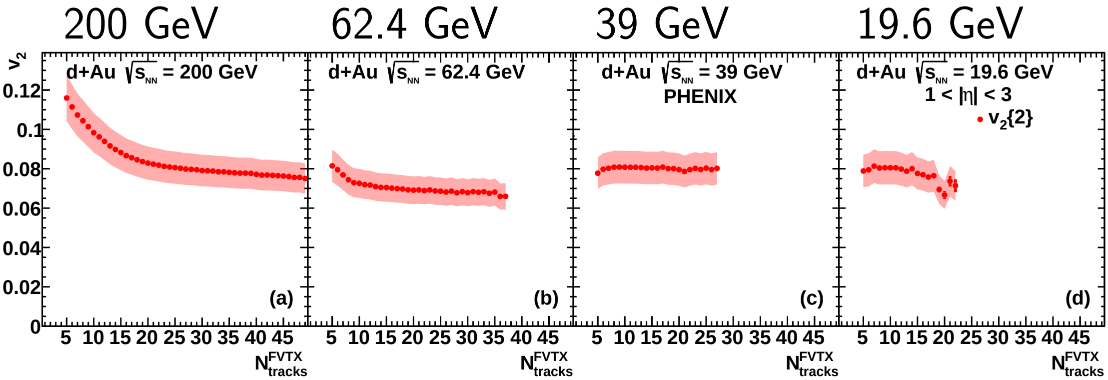
PHENIX, Phys. Rev. C 96, 064905 (2017)



- Hydro theory agrees with higher energies very well, underpredicts lower energies
- Likely need different EOS for lower energies; influence of conserved charges likely more important at lower energies (see e.g. M. Martinez et al, arXiv:1911.10272, 1911.12454)
- Nonflow likelier to be an issue due to lower multiplicity at lower energies

d+Au beam energy scan

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



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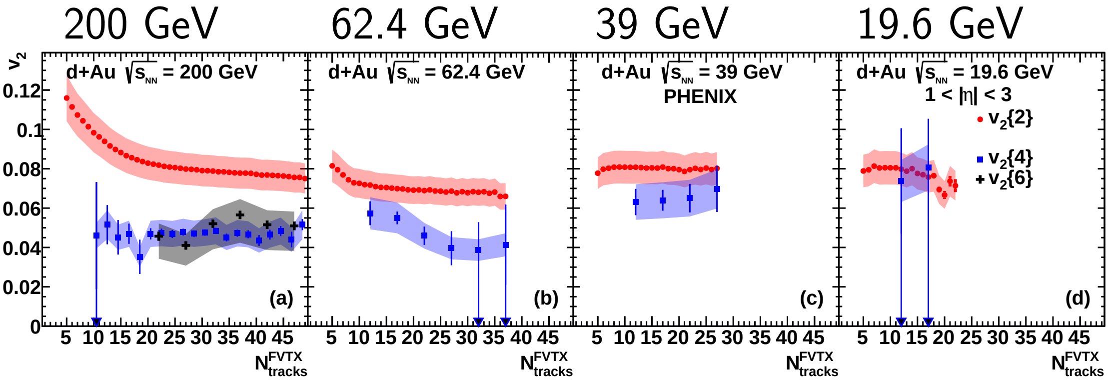

- Measurement of $v_2\{6\}$ in d+Au at 200 GeV and $v_2\{4\}$ in d+Au at all energies

d+Au beam energy scan

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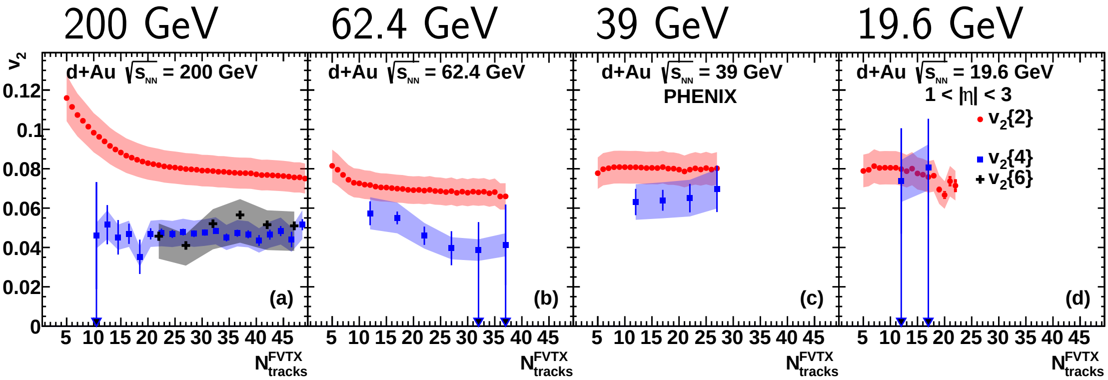
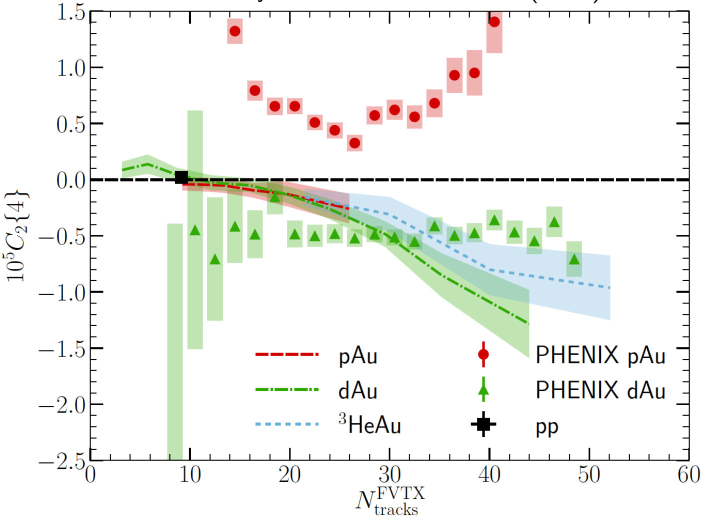


- Measurement of $v_2\{6\}$ in d+Au at 200 GeV and $v_2\{4\}$ in d+Au at all energies
- Multiparticle correlations can be a good indicator of collectivity, but beware caveats

Cumulants in p+Au and d+Au at 200 GeV

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



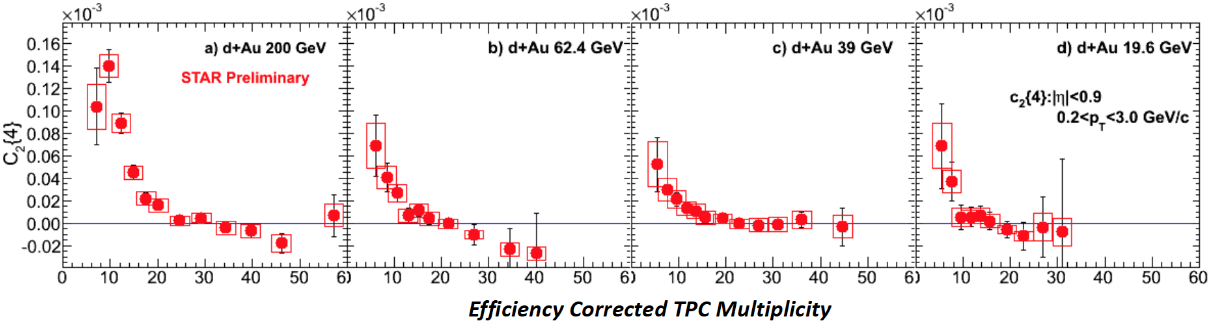
Cumulants are computationally expensive in hydro theory, so not as well-studied

This particular calculation doesn't show the strong geometry dependence seen in the data

Important to note this is 2+1D hydro, so the kinematics can't match the data

d+Au beam energy scan

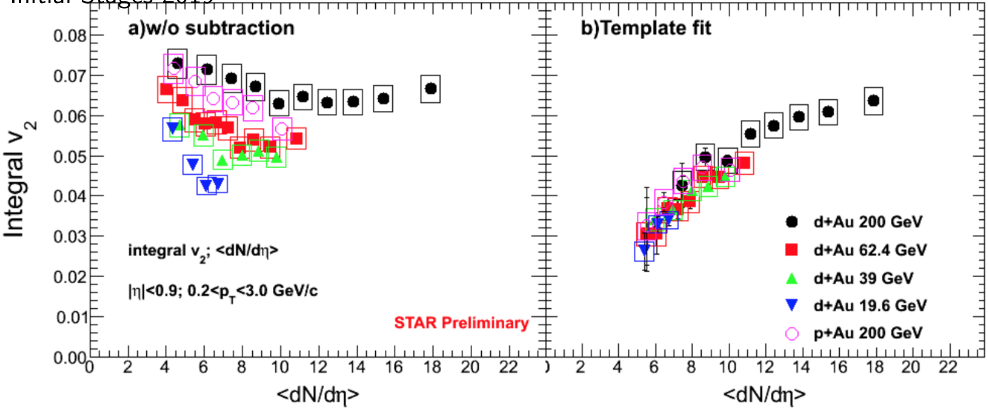
STAR, Initial Stages 2019



- STAR sees negative $c_2\{4\}$ in d+Au, qualitatively consistent with PHENIX
- The differences in kinematics between the two experiments are important

d+Au beam energy scan

STAR, Initial Stages 2019



- STAR $v_2\{2\}$ qualitatively like PHENIX (important: different kinematics)

d+Au beam energy scan

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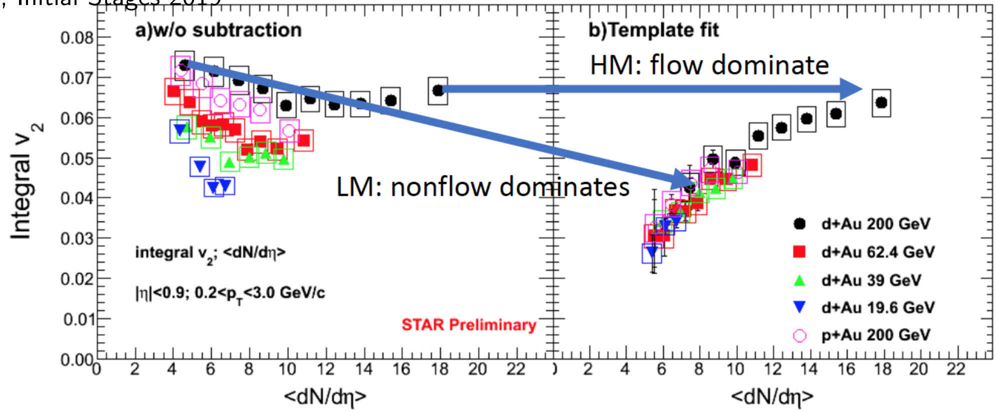

- STAR $v_2\{2\}$ qualitatively like PHENIX (important: different kinematics)
- High multiplicity dominated by collective flow

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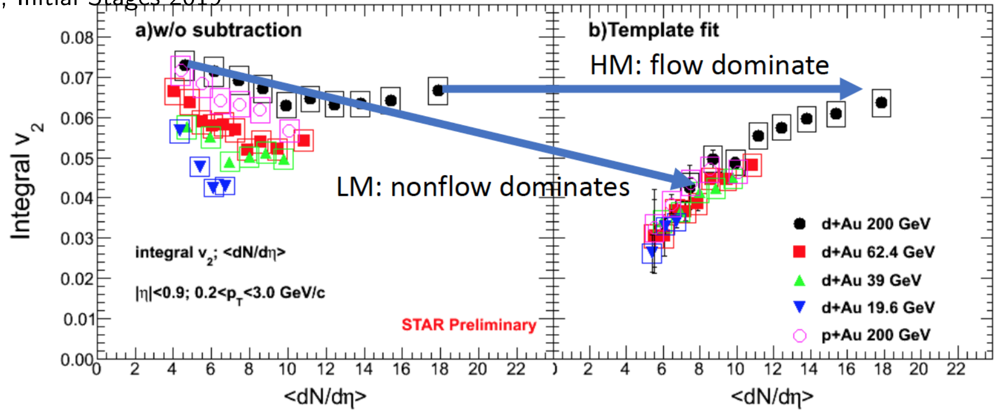

- STAR $v_2\{2\}$ qualitatively like PHENIX (important: different kinematics)
- High multiplicity dominated by collective flow
- One needs to be careful about assumptions in nonflow subtraction methods
  —See S. Lim et al, Phys. Rev. C 100, 024908 (2019)

Intermission

Small systems geometry scan

Testing hydro by controlling system geometry

PHYSICAL REVIEW LETTERS

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

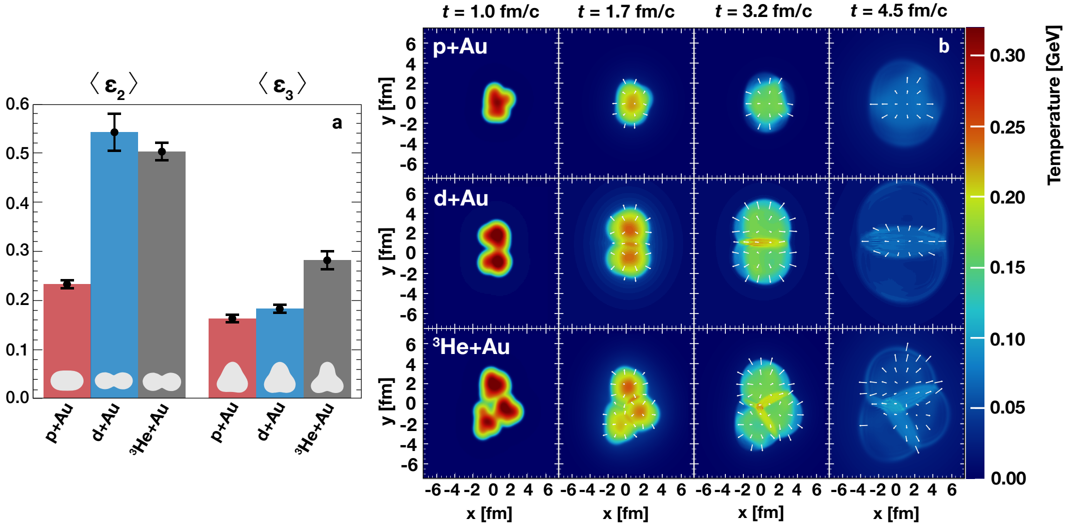
J. L. Nagle, A. Adare, S. Beckman, T. Koblesky, J. Orjuela Koop, D. McGlinchey, P. Romatschke, J. Carlson, J. E. Lynn, and M. McCumber

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

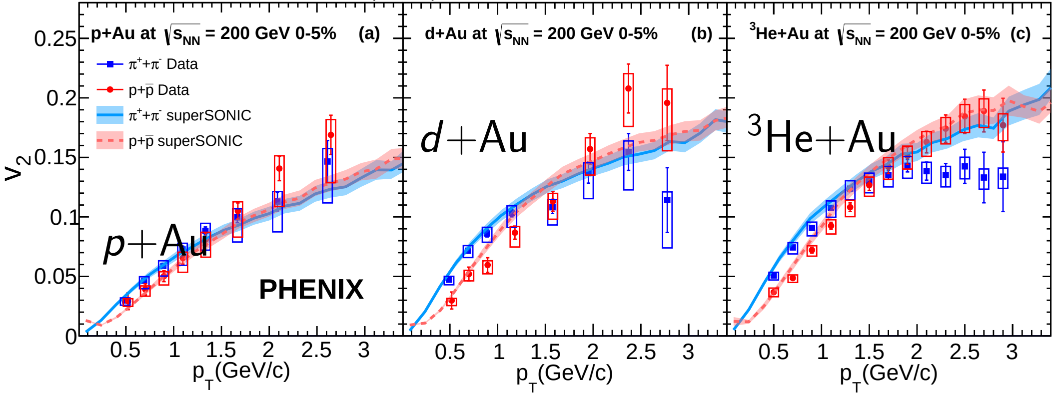
Testing hydro by controlling system geometry

PHENIX, Nat. Phys. 15, 214–220 (2019)



Small systems geometry scan

PHENIX, Phys. Rev. C 97, 064904 (2018)



- Identified particle v_2 vs p_T in p+Au, d+Au, and ^{3}He+Au
  —Low p_T mass ordering well-described by hydro
  —Hydro doesn't have enough splitting at mid-p_T (hadronization by Cooper-Frye)

Small systems geometry scan

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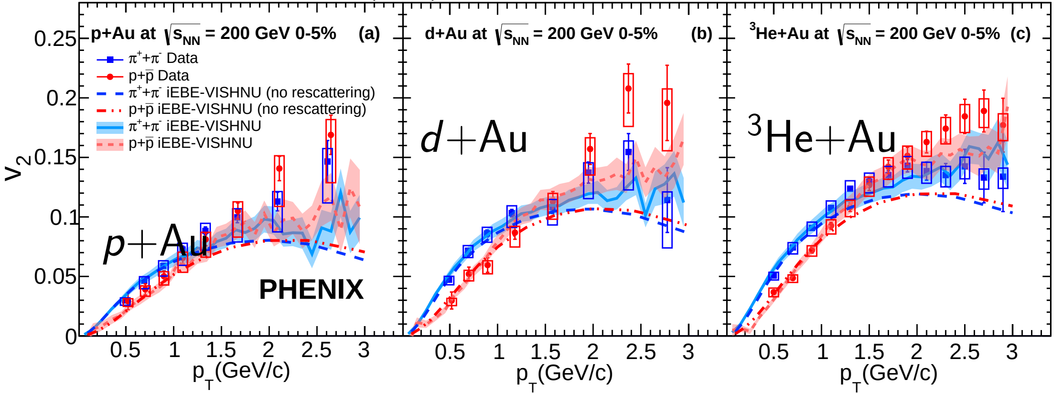

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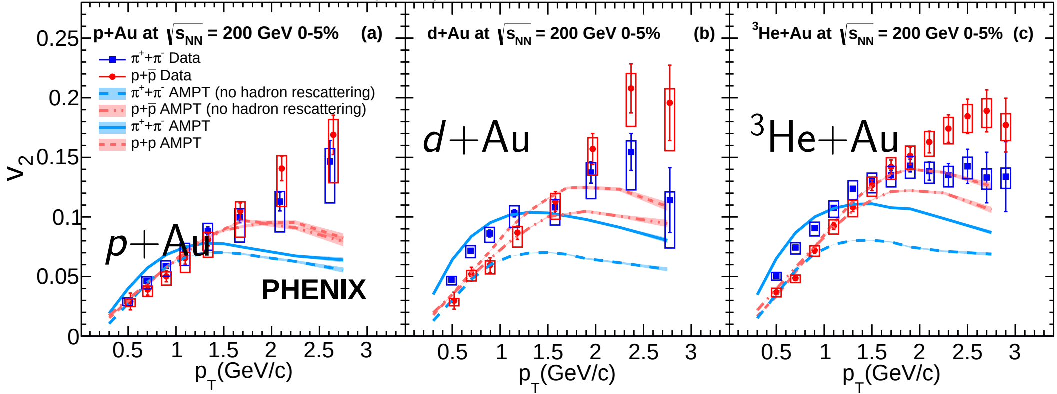

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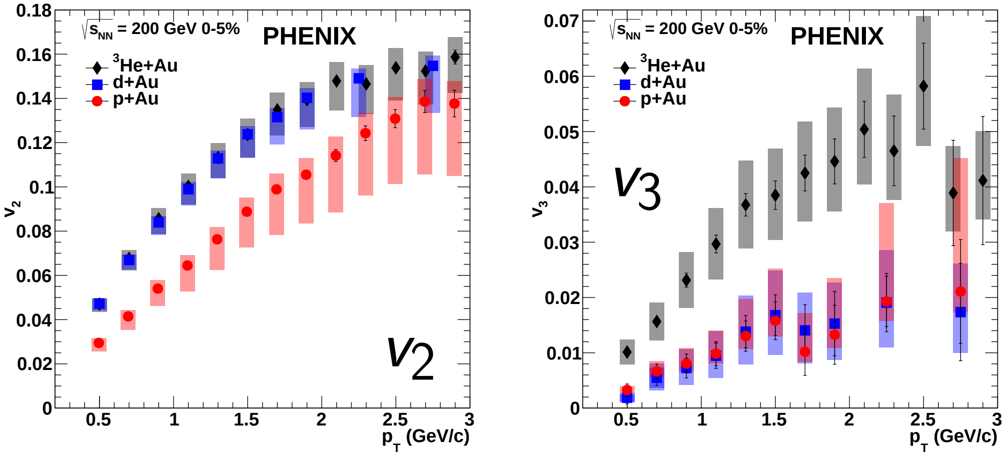
  —Low p_T mass ordering well-described by hydro
  —Hydro doesn't have enough splitting at mid-p_T (hadronization by Cooper-Frye)
- AMPT gets mid-p_T separation because of the more realistic hadronization (coalescence)

Testing hydro by controlling system geometry

PHENIX, Nat. Phys. 15, 214–220 (2019)



- 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

Testing hydro by controlling system geometry

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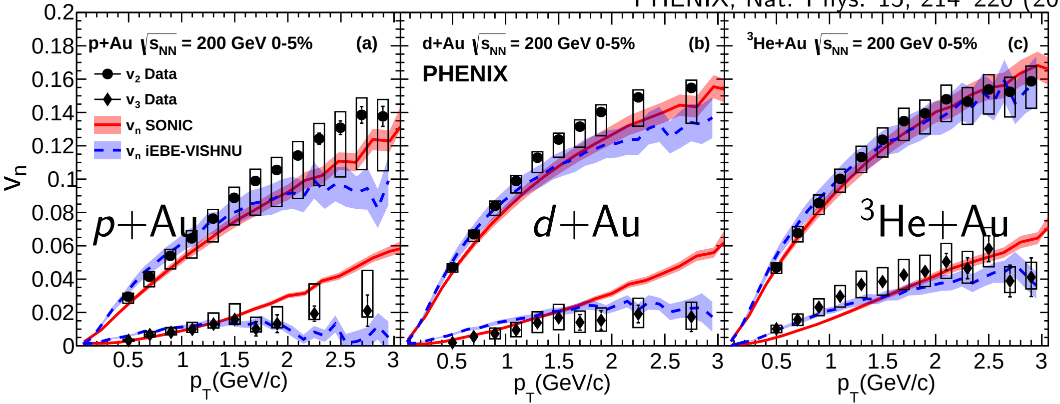

- v_2 and v_3 vs p_T predicted or described very well by hydrodynamics in all three systems
  —All predicted (except v_2 in d+Au) in J.L. Nagle et al, PRL 113, 112301 (2014)
  —v_3 in p+Au and d+Au predicted in C. Shen et al, PRC 95, 014906 (2017)

Testing hydro by controlling system geometry

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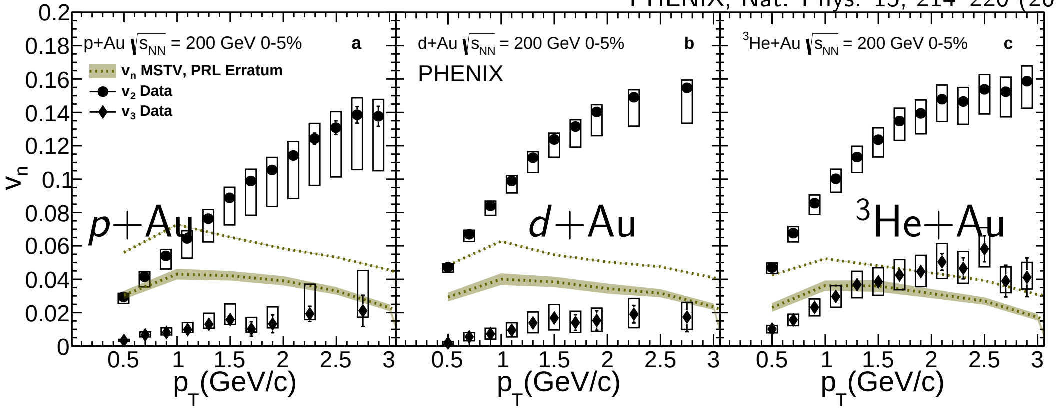
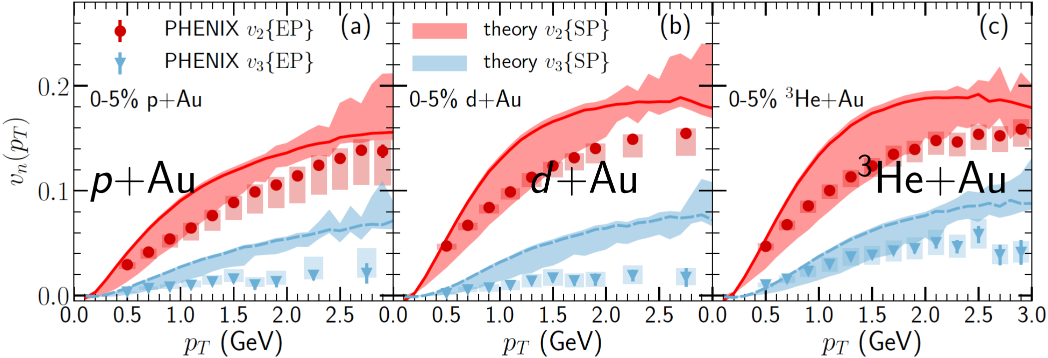


- Initial state effects alone do not describe the data
  —Phys. Rev. Lett. 123, 039901 (Erratum) (2019)

Testing hydro by controlling system geometry

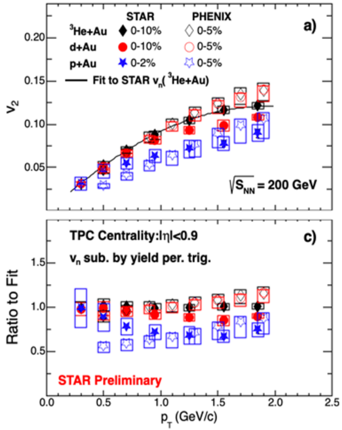
PHENIX, Nat. Phys. 15, 214–220 (2019)



- Important to include initial state effects
  —B. Schenke et al, Phys. Lett. B 803, 135322 (2020)

Comparisons with STAR

STAR, Quark Matter 2019



Good agreement between STAR and PHENIX for v_2

Comparisons with STAR

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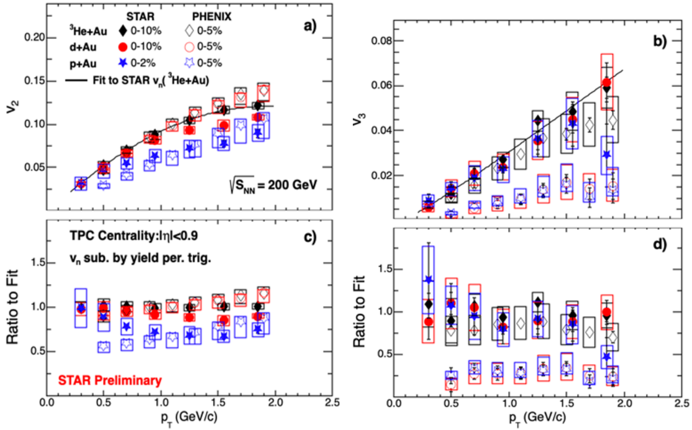
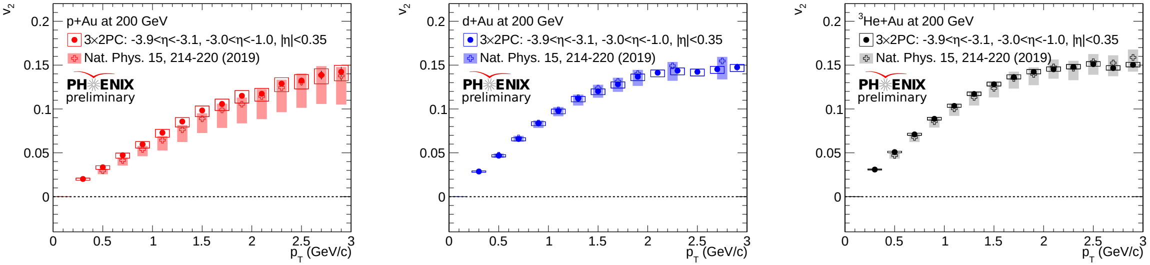


Good agreement between STAR and PHENIX for v_2

Large discrepancy between STAR and PHENIX for v_3

PHENIX data update



- 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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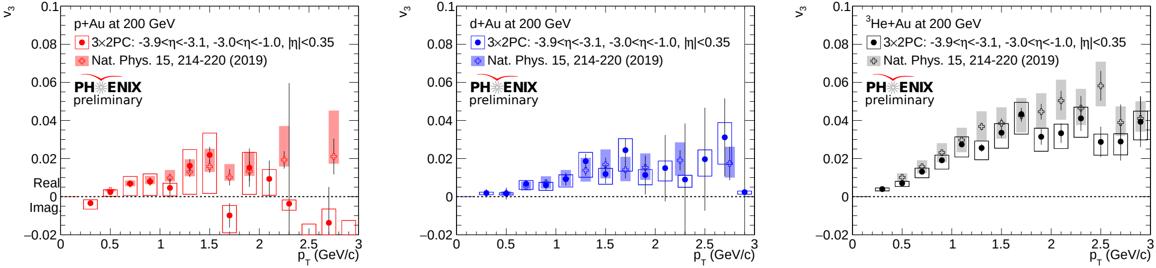

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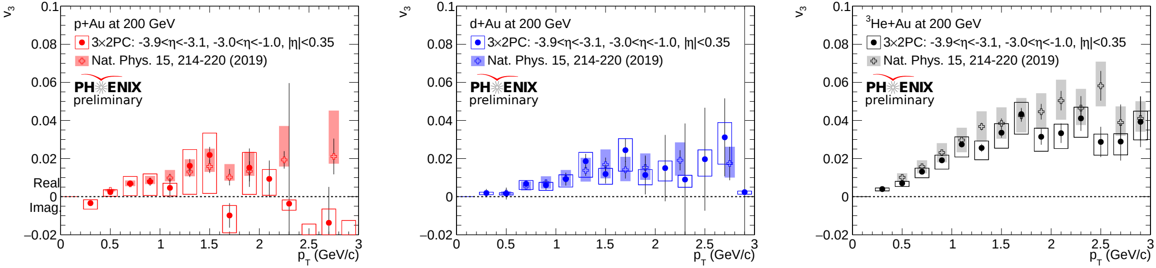

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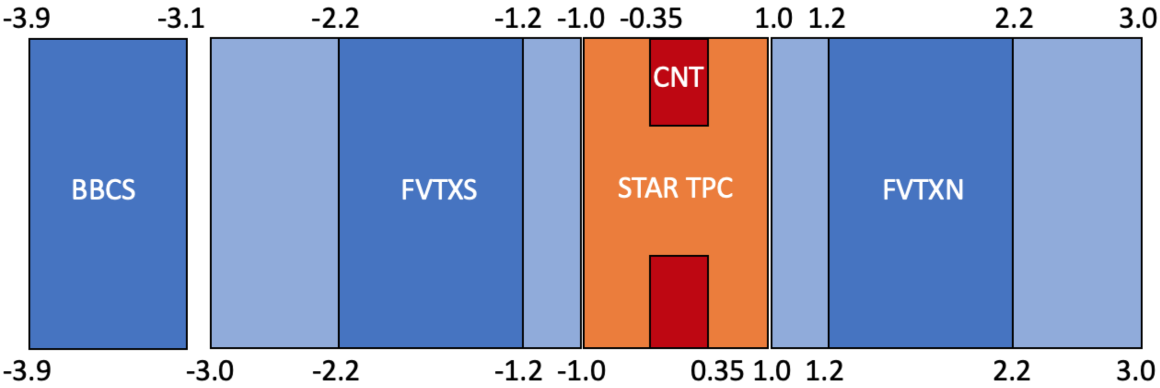
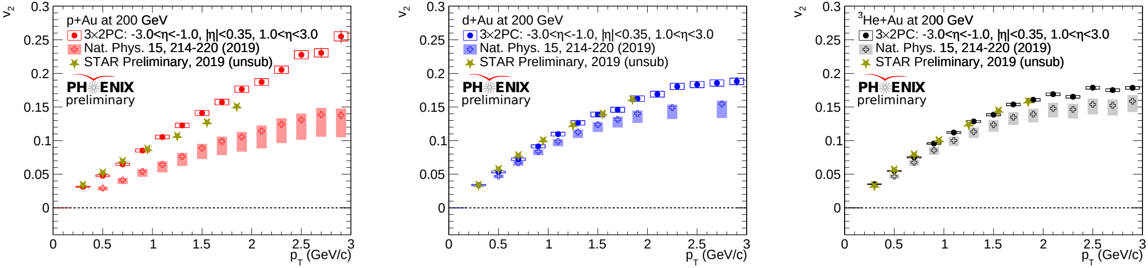
- All new analysis using two-particle correlations with event mixing instead of event plane method
  —Completely new and separate code base
  —Very different sensitivity to key experimental effects (beam position, detector alignment)
- It's essential to understand the two experiments have very different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



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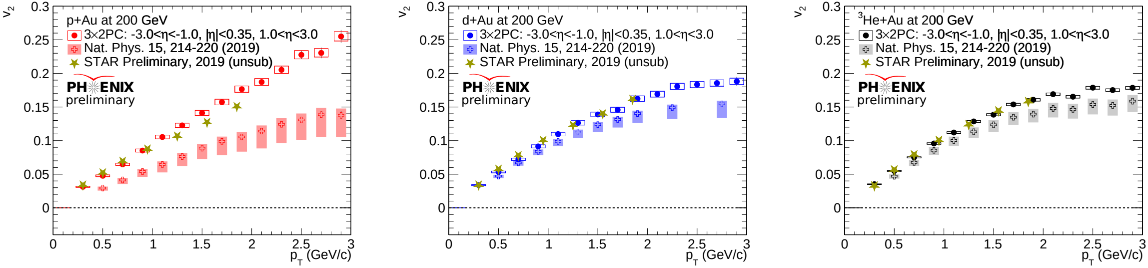

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  —Similar physics for the two different pseudorapidity acceptances

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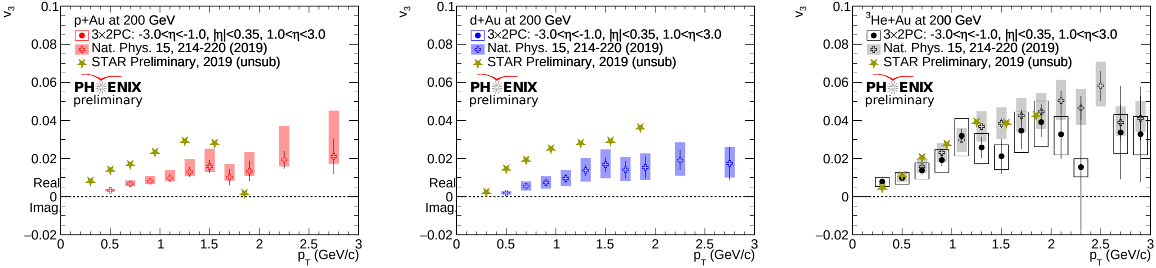

- Good agreement with STAR for v_2
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- Strikingly different results for v_3
  —Rather different physics for the two different pseudorapidity acceptances
  —Decorrelation effects much stronger for v_3 than v_2

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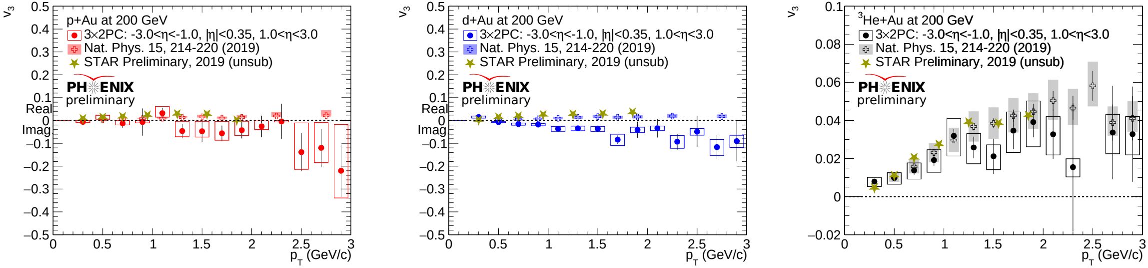

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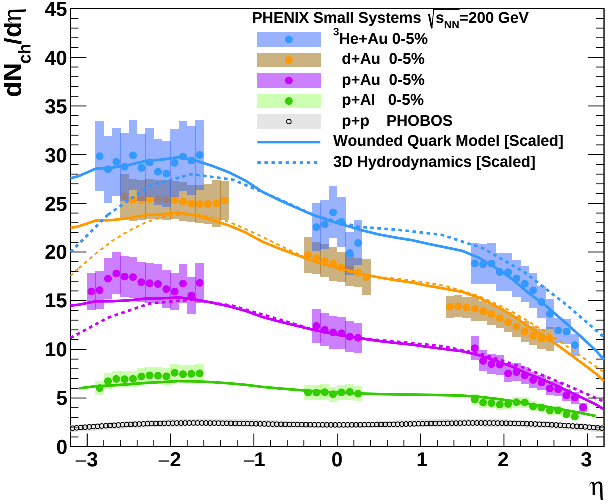
Longitudinal dynamics in small systems

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



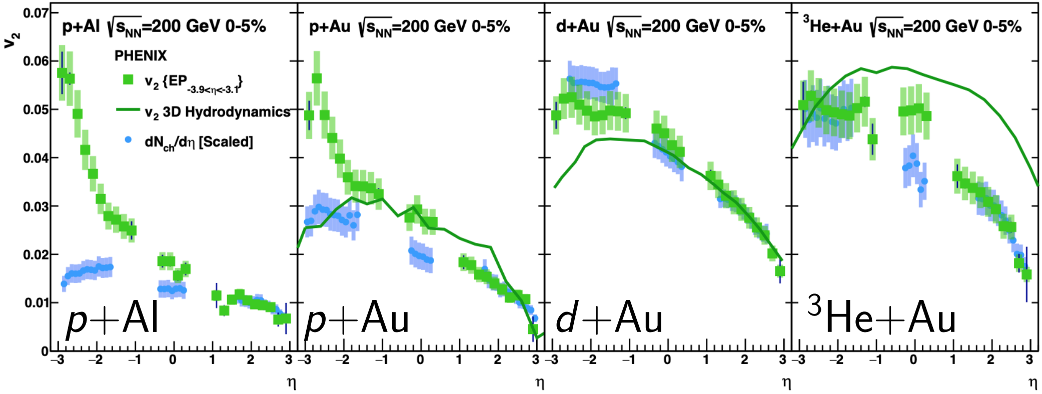
p+Al, p+Au, d+Au, ^{3}He+Au

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))

Longitudinal dynamics in small systems

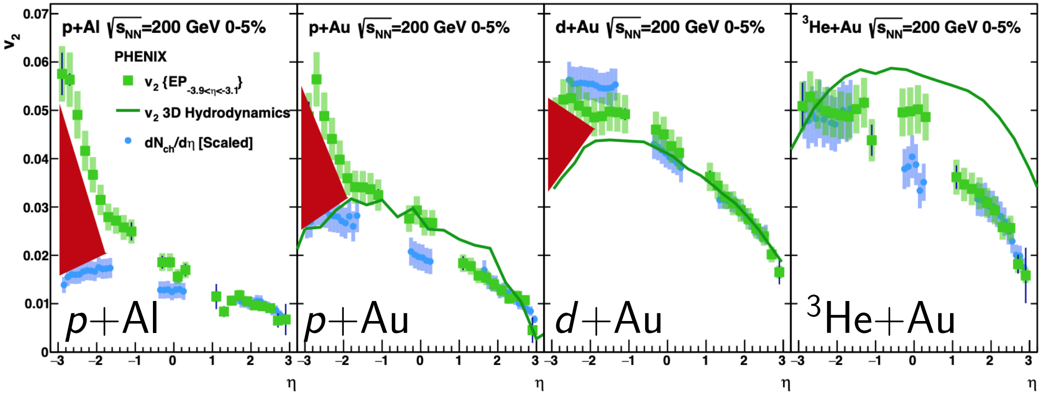
Phys. Rev. Lett. 121, 222301 (2018)



- 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))

Longitudinal dynamics in small systems

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



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

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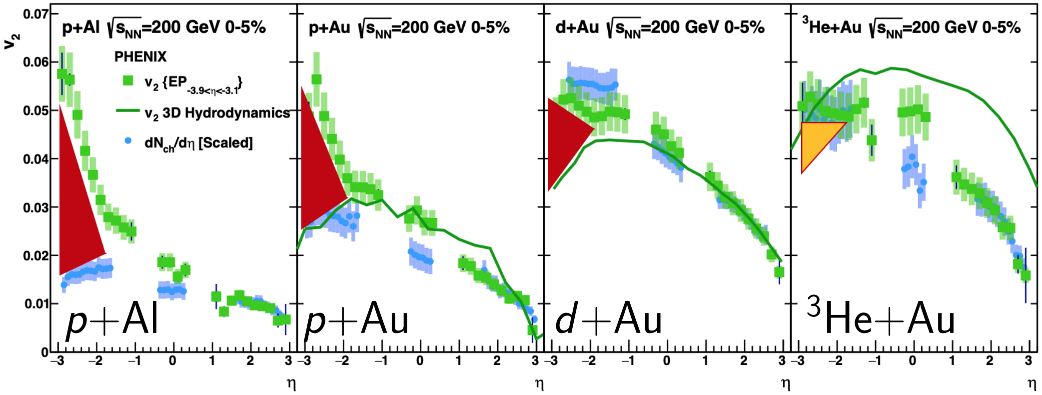

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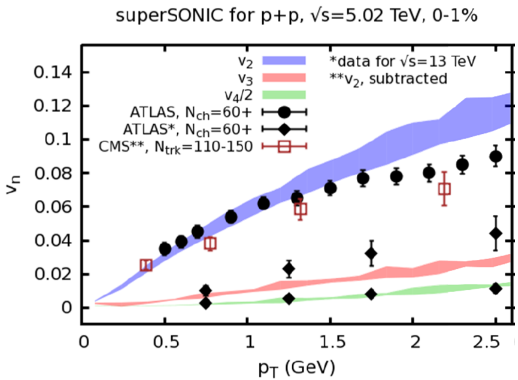
Intermission

A quick look elsewhere

$p+p$ collisions at the LHC

Weller & Romatschke, PLB 774, 351 (2017)



- Hydro does a good job of $v_n\{2\}$...

$p+p$ collisions at the LHC

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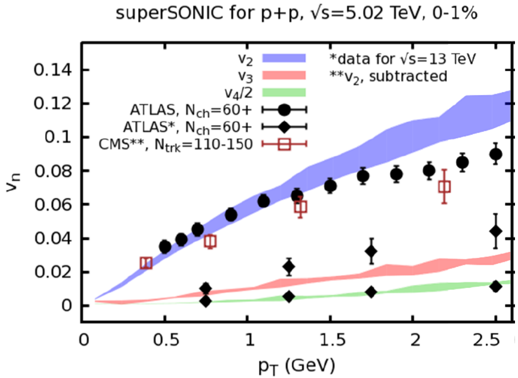
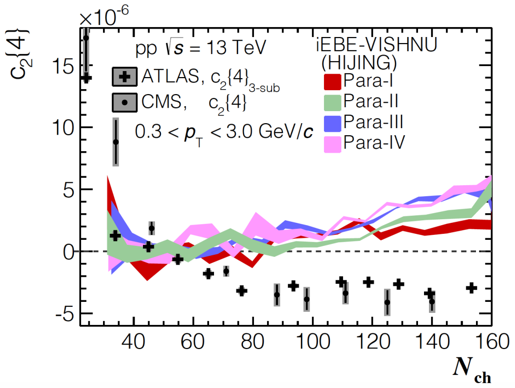


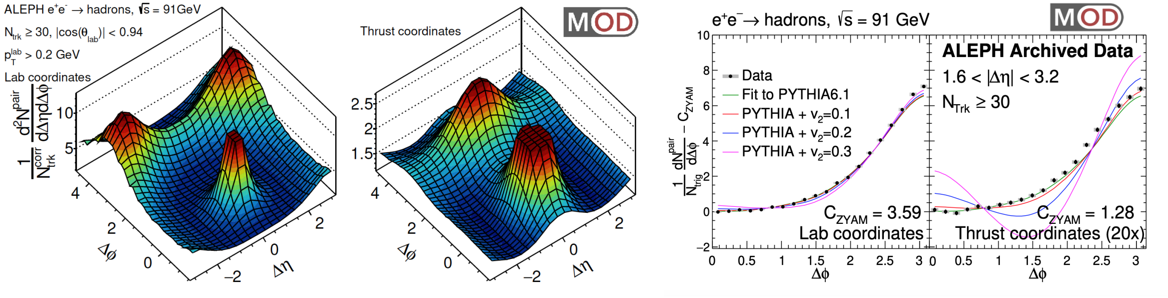
W. Zhao et al, PLB 780, 495 (2018)



- Hydro does a good job of $v_n\{2\}$...
- ...but hydro cannot even get the correct sign of $c_2\{4\}$

Extremely small systems at LEP

Badea et al, Phys. Rev. Lett. 123, 212002 (2019)



- No apparent collectivity in ALEPH $e^{+}+e^{-}$ data
- Suggested based on hydro considerations—P. Romatschke, Eur. Phys. J. C 77, 21 (2017)
- Not expected in AMPT—J.L. Nagle et al, Phys. Rev. C 97, 024909 (2018)
- Not expected based on strangeness saturation—P. Castorina et al, Eur. Phys. J. A 57, 111 (2021)

Brief summary and outlook

- Long term understanding of collective and hydrodynamical behavior in large systems
- Geometry and fluctuations play essential roles in observables
- Many successful predictions for both the small systems beam energy scan and the small systems geometry scan from hydrodynamics
  —Pushing the envelope for regimes of applicability of hydro
  —Driving theoretical developments in hydro
- Some notable challenges
  —Small systems cumulants (including long-known sign issue in p+p at LHC)
  —Longitudinal dynamics (STAR-PHENIX geometry scan, $dN_{ch}/d\eta$, $v_2(\eta)$,...)
  —Need for more realistic hadronization