Collectivity in Small Systems: Experiment

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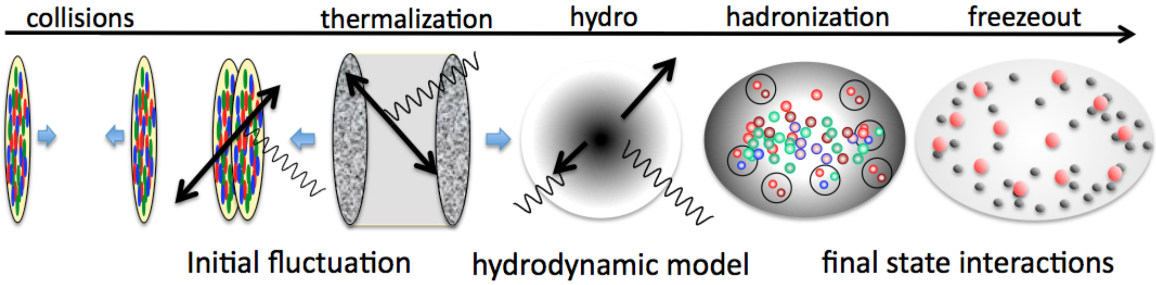
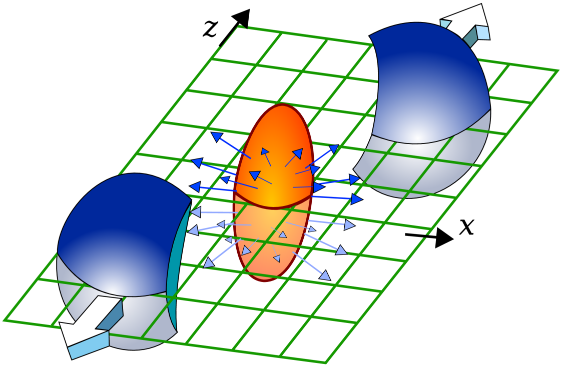
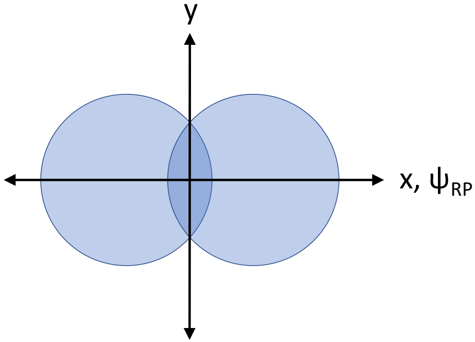
Standard model of heavy ion physics



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

Azimuthal anisotropy measurements

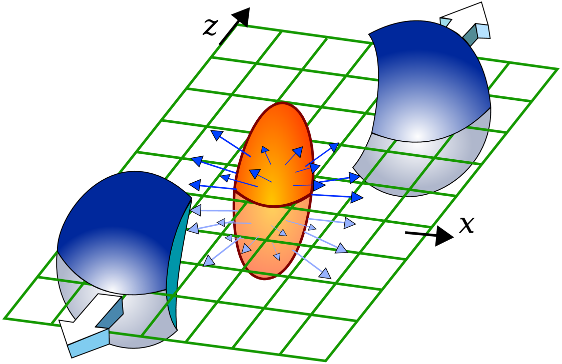


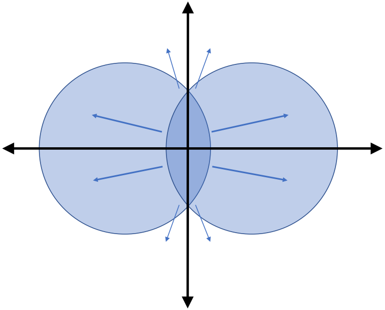


$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos n\varphi \qquad v_n = \langle \cos n\varphi \rangle \qquad \varepsilon_n = \frac{\sqrt{\langle r^n \cos n\varphi \rangle + \langle r^n \sin n\varphi \rangle}}{\langle r^n \rangle}$$

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

Azimuthal anisotropy measurements





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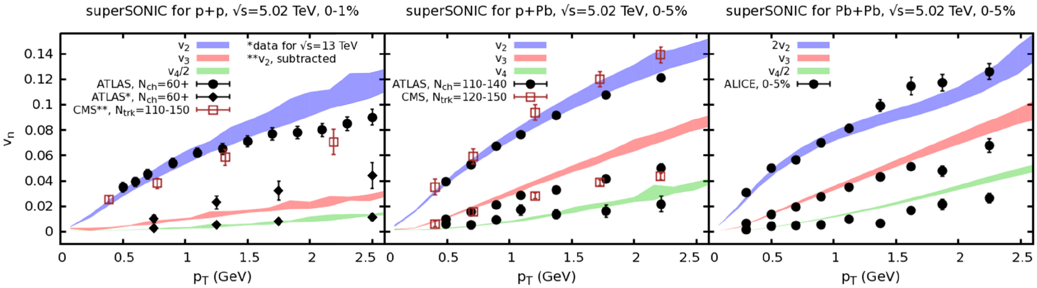
Azimuthal anisotropy measurements

Weller & Romatschke, Phys. Lett. B 774, 351 (2017)

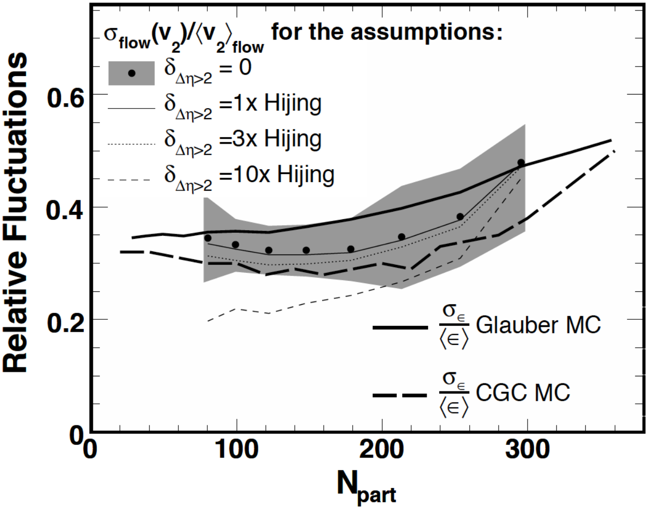


- Hydrodynamics provides simultaneous description of v_2, v_3, v_4 in p+p, p+Pb, Pb+Pb

$$\frac{dN}{d\varphi} \propto \cdots + 2v_2 \cos 2\varphi + 2v_3 \cos 3\varphi + 2v_4 \cos 4\varphi + \ldots$$

Fluctuations in large systems

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



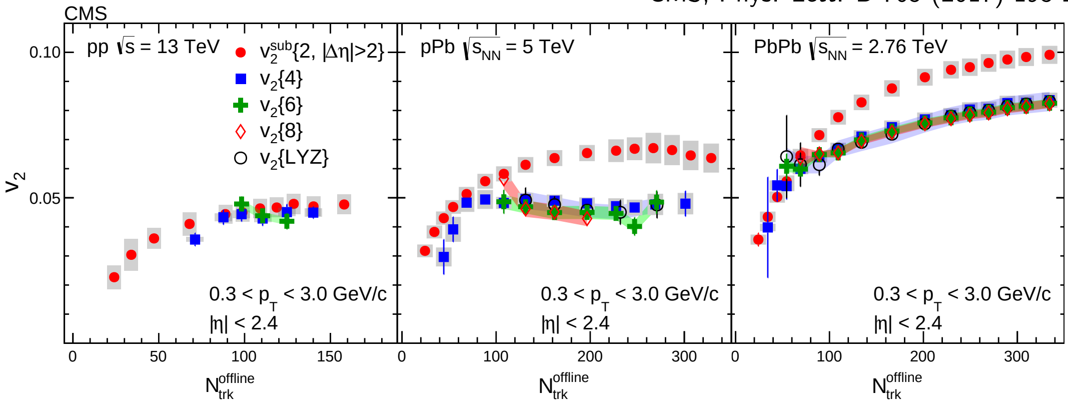
Fluctuations should also be translated, so measure $\sigma_{v_2}/\langle v_2\rangle$

$|\eta| < 1$

Generally good agreement with models of initial geometry

Multiparticle Correlations

CMS, Phys. Lett. B 765 (2017) 193-220

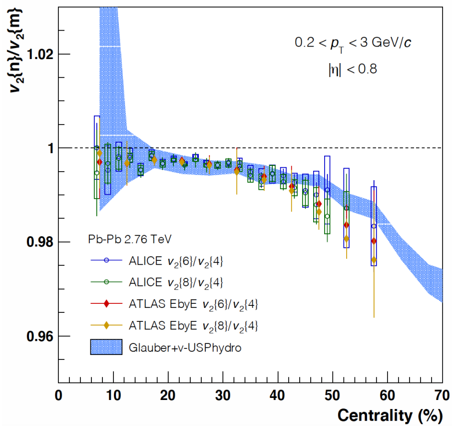


- Fluctuations are very important and manifest in multiparticle correlations

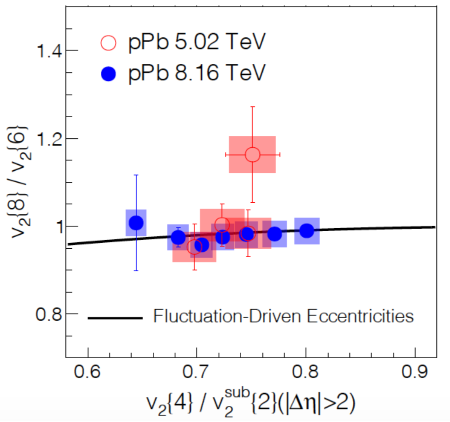
$$v_2\{2, |\Delta\eta| > 2\} = \sqrt{v_2^2 + \sigma^2},\ v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx \sqrt{v_2^2 - \sigma^2}$$

Multiparticle Correlations

ALICE, JHEP 1807, 103 (2018)



CMS, Phys. Rev. C 101, 014912 (2020)

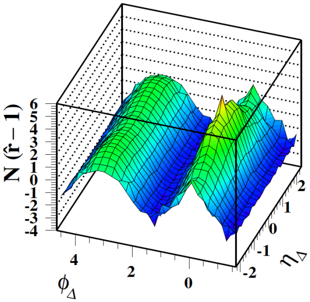


Ratios $(v_n\{j\}/v_n\{k\}) \rightarrow$ insights into fluctuations via probability dist $P(v_n)$

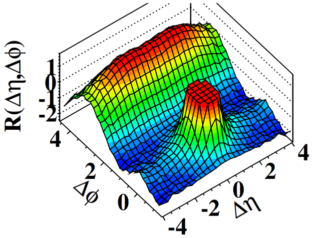
p+Pb data exhibit expected patterns based on geometry

The ridge is a signature of flow

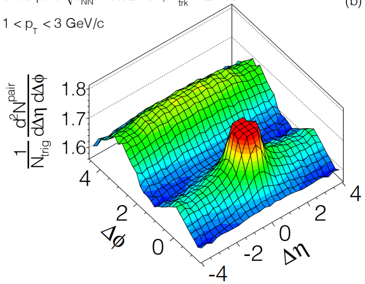
STAR, PRC 73, 064907 (2006)



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

- First 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))

Testing hydro by controlling system geometry

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

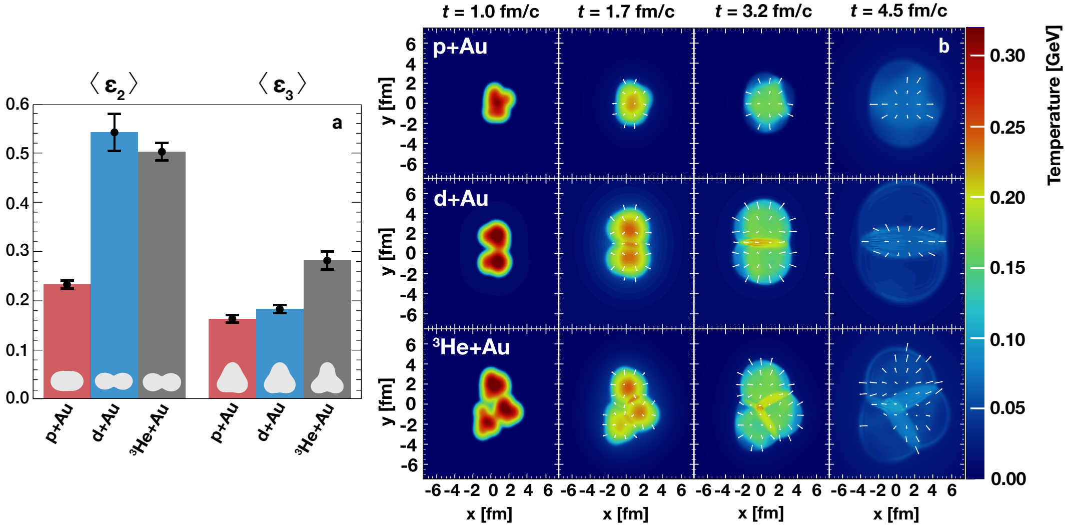
J. L. Nagle, A. Adare, S. Beckman, T. Koblesky, J. Orjuela Koop, D. McGlinchey, P. Romatschke, J. Carlson, J. E. Lynn, and M. McCumber

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)



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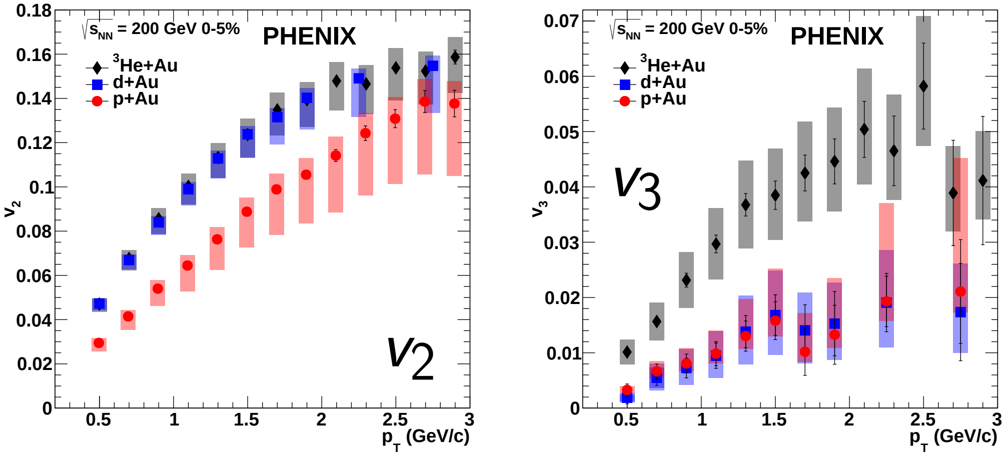
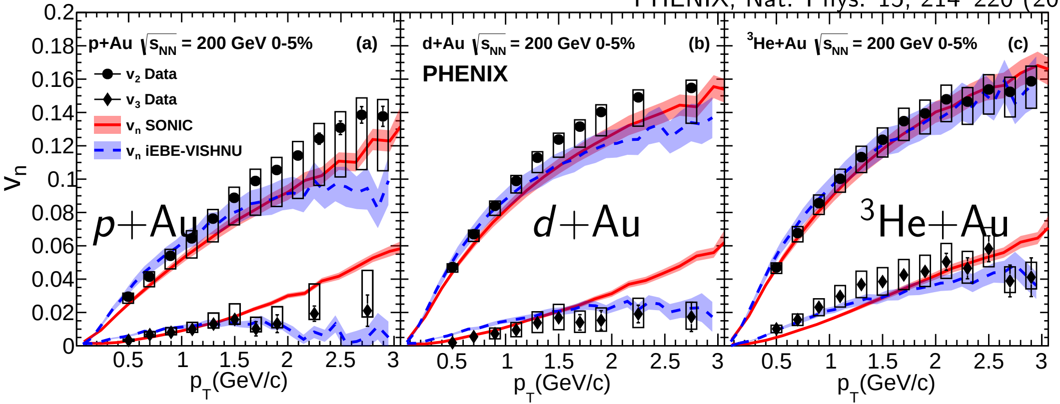


- v_2 and v_3 ordering matches ε_2 and ε_3 ordering in all three systems
  —Collective motion of system translates the initial geometry into the final state

Testing hydro by controlling system geometry

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)

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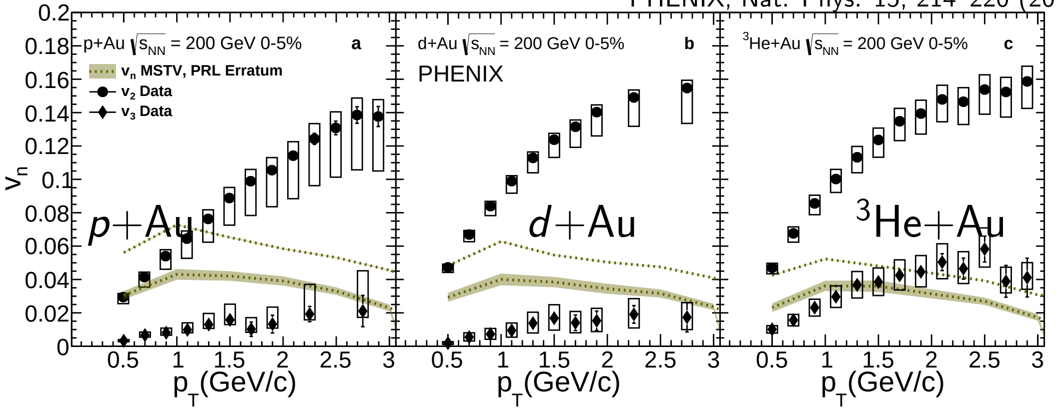
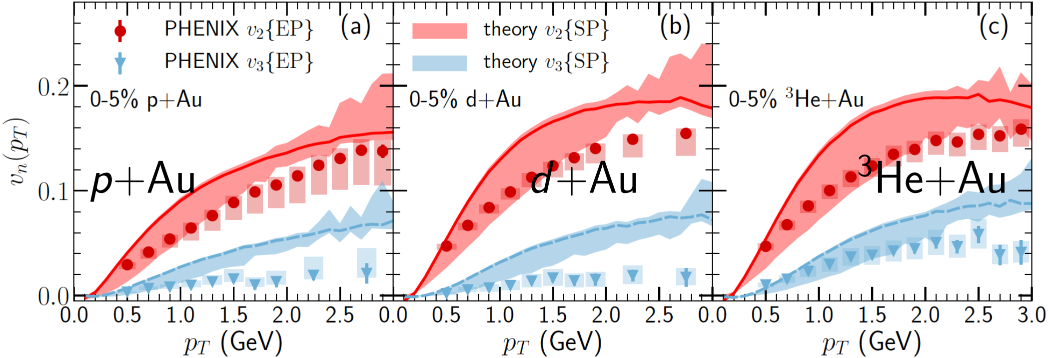


- Initial state effects alone do not describe the data
  —Phys. Rev. Lett. 123, 039901 (Erratum) (2019)

Testing hydro by controlling system geometry

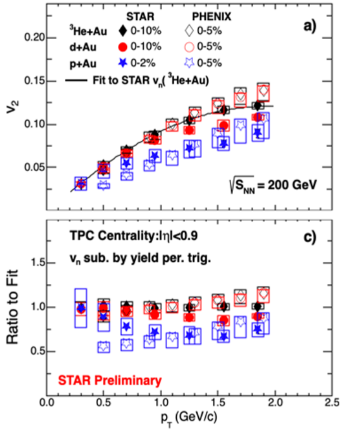
PHENIX, Nat. Phys. 15, 214–220 (2019)



- 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

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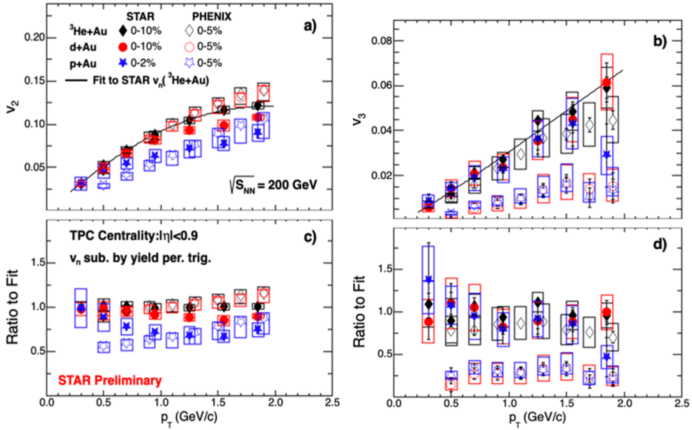

Good agreement between STAR and PHENIX for v_2

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
- Observed bias in event plane resolutions caused by beam offset, beam angle, detector alignment
  —This effect carefully studied systematically
  —Extracted coefficients in new analysis do not show any bias
- Measurement error ruled out

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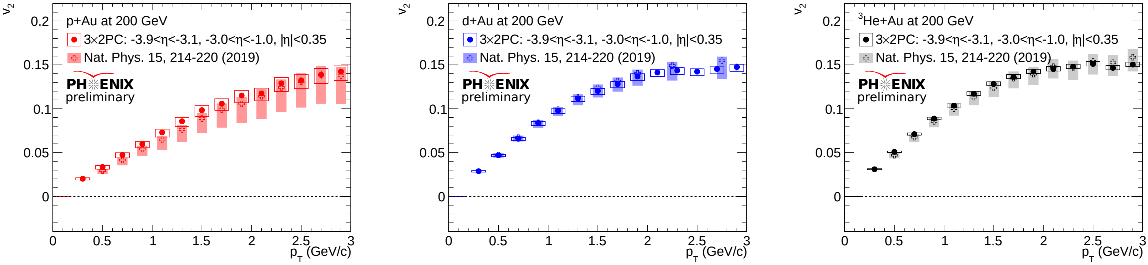

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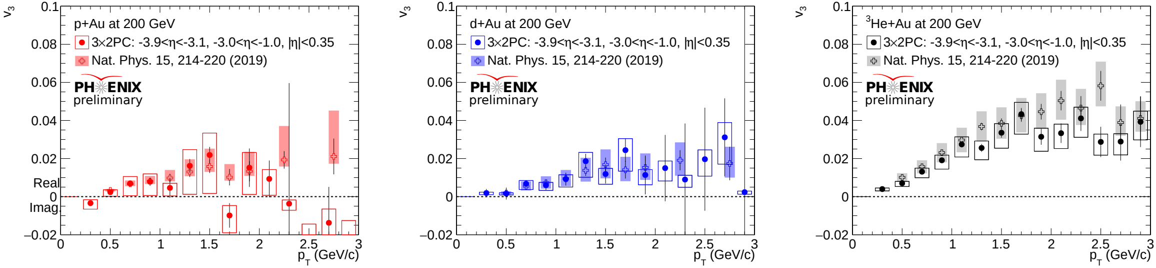

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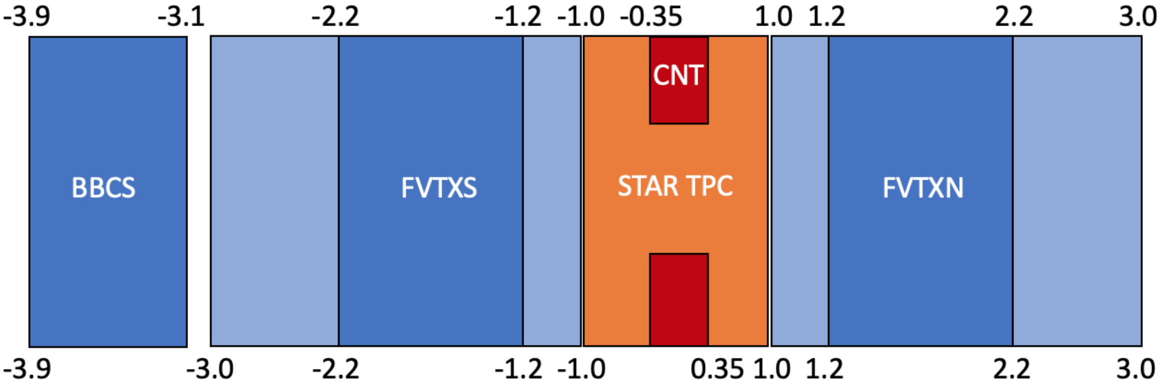
STAR and PHENIX detector comparison



- The 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

- STAR not showing new results on this topic for IS21, but has verified their QM19 results —Both experiments' results confirmed, so differences need to be understood in terms of physics

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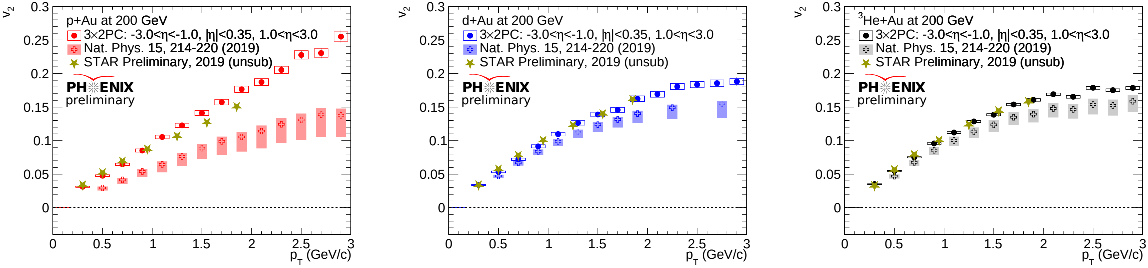

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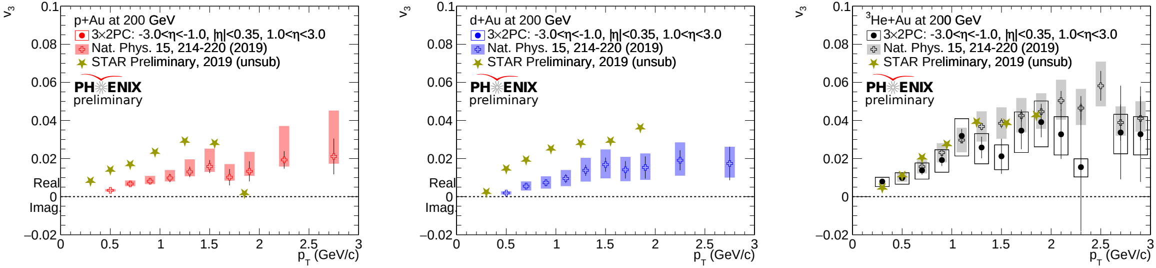

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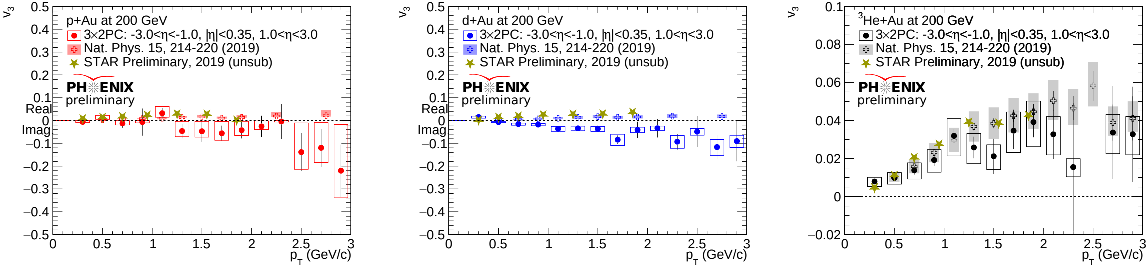
  —Decorrelation effects much stronger for v_3 than v_2 (cf Qipeng's talk right before this one)

More STAR and PHENIX data comparisons



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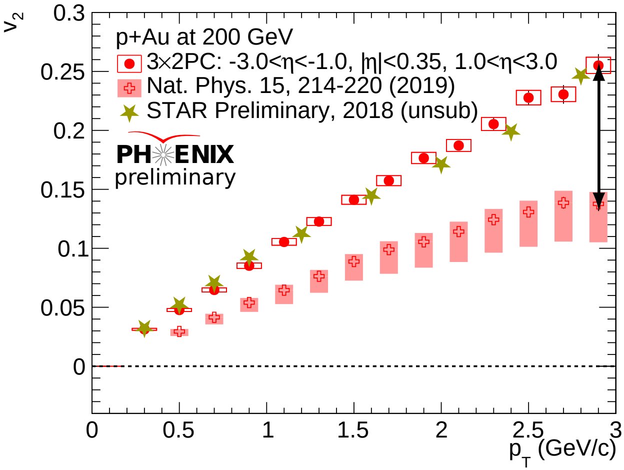
Understanding the nonflow contribution: v_2 in p+Au as a case study



- 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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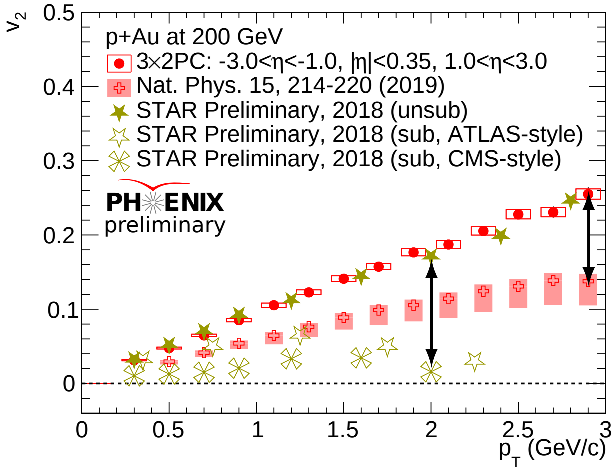

- The large difference between the PHENIX published and STAR preliminary in this case is nonflow
- PHENIX suppresses nonflow via kinematic selection
- STAR applies non-flow subtraction procedure
- One needs to be careful about the risk of over-subtraction methods—S. Lim et al, Phys. Rev. C 100, 024908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

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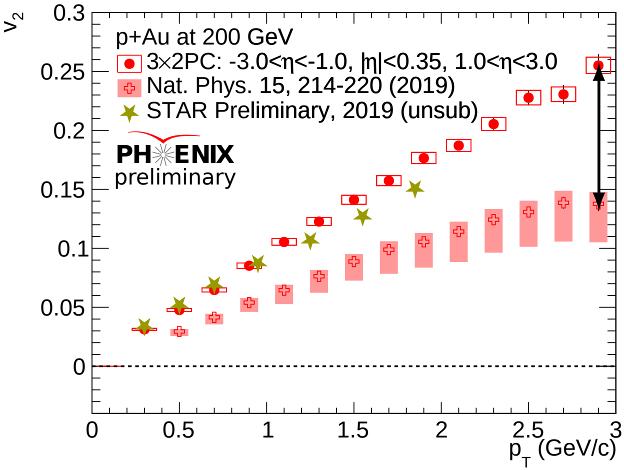

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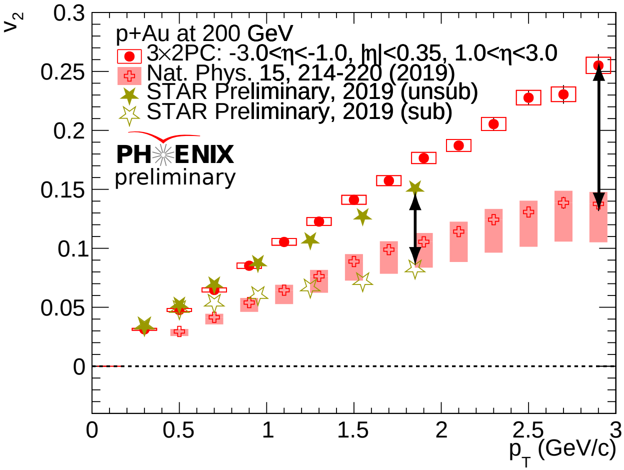


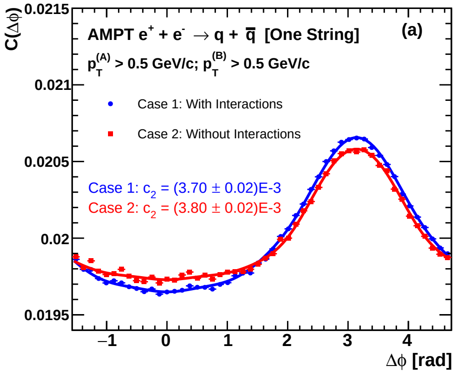
- The large difference between the PHENIX published and STAR preliminary in this case is nonflow
- PHENIX suppresses nonflow via kinematic selection
- STAR applies non-flow subtraction procedure
- Considerable improvement in nonflow subtraction in STAR 2019 preliminary, reasonable agreement with PHENIX

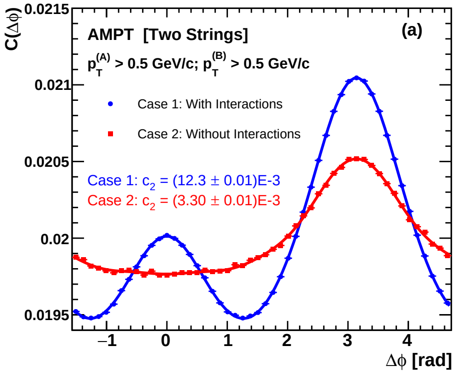
Intermission

How about *extremely* small systems?

Extremely small systems in AMPT

J.L. Nagle et al, Phys. Rev. C 97, 024909 (2018)

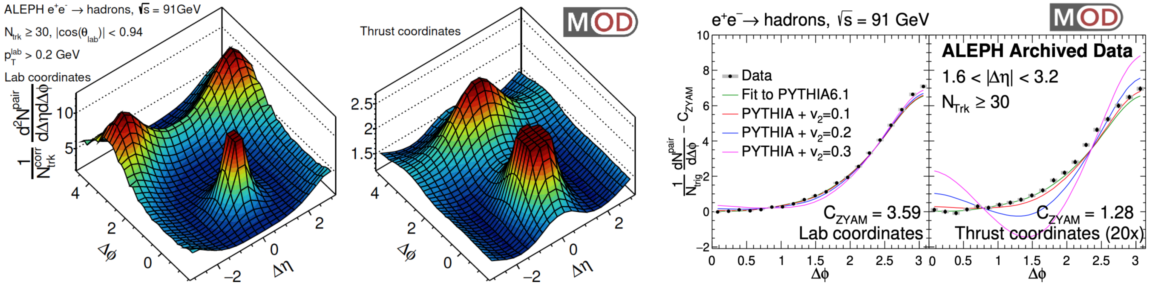




- A single color string ($e^+ + e^-$ collisions) shows no sign of collectivity
- Two color strings shows collectivity
  —In AMPT, $p+p$ has two strings and $p/d/^3$He+Au have more

Extremely small systems at LEP

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

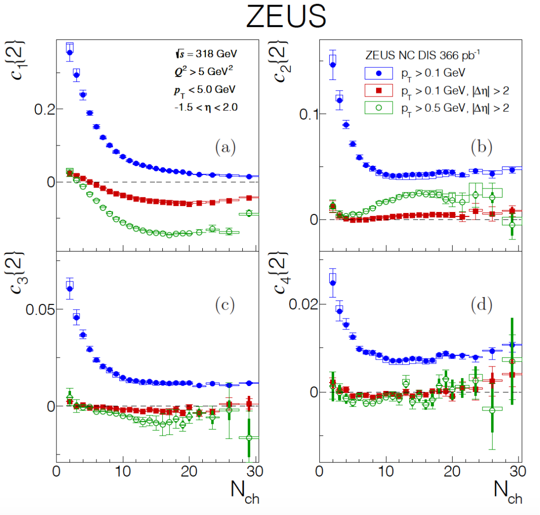


No apparent collectivity in ALEPH $e^{+}+e^{-}$ data

- Brought up as a possibility in e.g. P. Romatschke, Eur. Phys. J. C 77, 21 (2017)
- Not expected in parton escape picture (see previous slide)
- Not expected (below $\sqrt{s} \approx 7$ TeV) in e.g. P. Castorina et al, arXiv:2011.06966

Extremely small systems at HERA and the EIC

Abt et al, JHEP 04, 070 (2020)



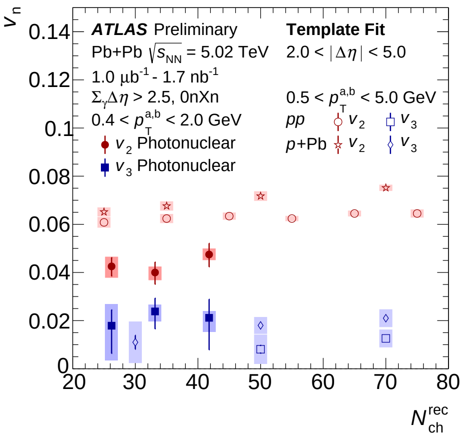
"The correlations observed here do not indicate the kind of collective behaviour recently observed at the highest RHIC and LHC energies in high-multiplicity hadronic collisions."

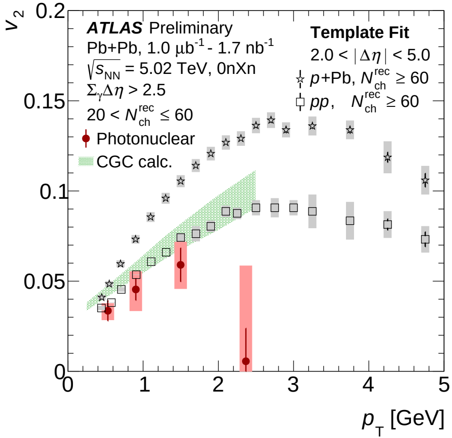
No collectivity in e+p collisions at HERA $\rightarrow$
Not likely to find collectivity in e+p collisions at EIC
But what about e+A collisions?

Considerable interest in this topic within EIC community (see talks by R. Milner, E. Ferreiro, others...)

Extremely small systems at the LHC

ATLAS Preliminary, B. Seidlitz (this conference)





- Observation of collectivity in photonuclear collisions
- Collective picture: photon fluctuates into a vector meson (e.g. ρ), not so different from p+Pb
- Initial state picture: CGC calculation in good agreement, further investigation needed

Brief summary and outlook

- Long term understanding of collective and hydrodynamical behavior of heavy ion data
- Geometry and fluctuations play essential roles in observables
- PHENIX results on small systems geometry scan fully confirmed
  —Apparent STAR-PHENIX discrepancy must be understood in terms of physics
  —Better understanding of longitudinal dynamics is essential
- Apparent (near-) universality of collectivity in hadronic collisions
  —Collectivity observed in photonuclear collisions (which may be purely hadronic)
- Apparent absence of collectivity in leptonic and semi-leptonic collisions
- Possibility for future observation of collectivity in (semi-) leptonic collisions?
  —Both interest and opportunity in $e+A$ collisions at the EIC
  —Far-future $e^{+}+e^{-}$ colliders *might* reach necessary conditions for collectivity

Extra material