Small systems in heavy ion collisions

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JETSCAPE Workshop
The Internet
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A brief history of heavy ion physics

- 1973—Formulation of QCD
- 1974—MIT bag model of hadrons
- 1975—Collins and Perry show existence of QCD plasma
- 1979—Shuryak coins "QGP" and proposes use of heavy ion collisions
- 1980s and 1990s—AGS and SPS... QGP at SPS!
- Early 2000s—QGP at RHIC! No QGP at SPS? d+Au as control.
- Mid-late 2000s—Detailed, quantitative studies of strongly coupled QGP. d+Au as control.
- 2010—Ridge in high multiplicity p+p (LHC)! Probably CGC!
- Early 2010s—QGP in p+Pb!
- Early 2010s—QGP in d+Au!
- Mid 2010s and now-ish—QGP in high multiplicity p+p? QGP in mid-multiplicity p+p?? QGP in d+Au even at low energies???

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- 1980s and 1990s—AGS and SPS... QGP at SPS!
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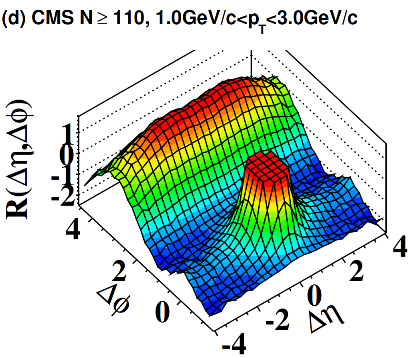
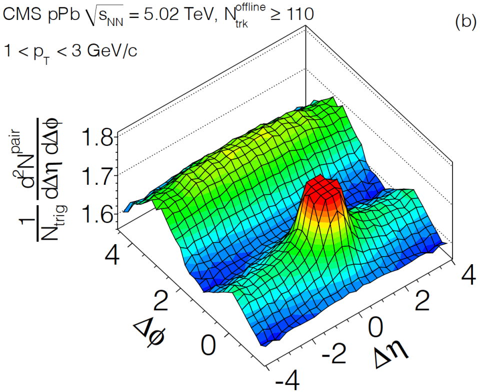
"Twenty years ago, the challenge in heavy ion physics was to find the QGP. Now, the challenge is to not find it." —Jürgen Schukraft, QM17

The ridge in small systems at the LHC

JHEP 1009, 091 (2010)



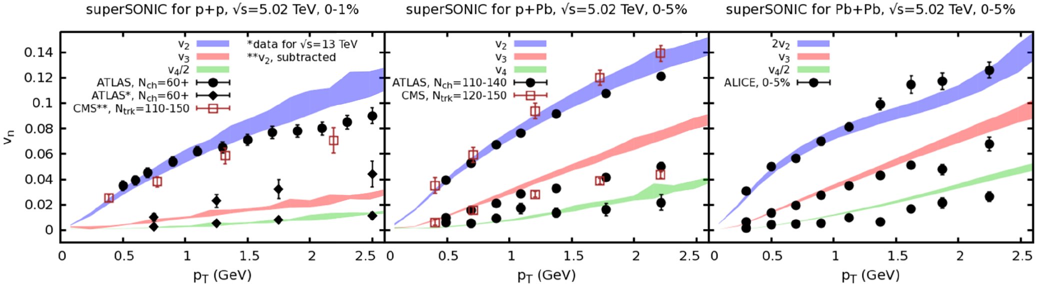
Phys. Lett. B 718, 795 (2013)



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

Flow in small systems at the LHC

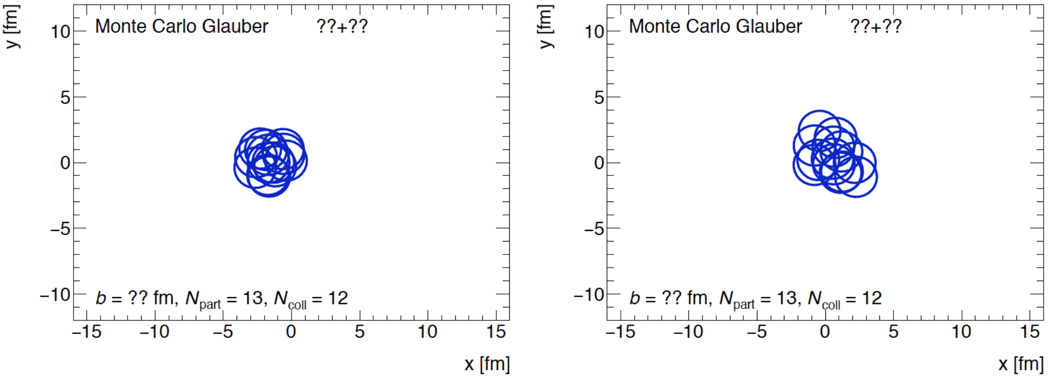
Weller & Romatschke, Phys. Lett. B 774, 351 (2017)



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

Which is which?

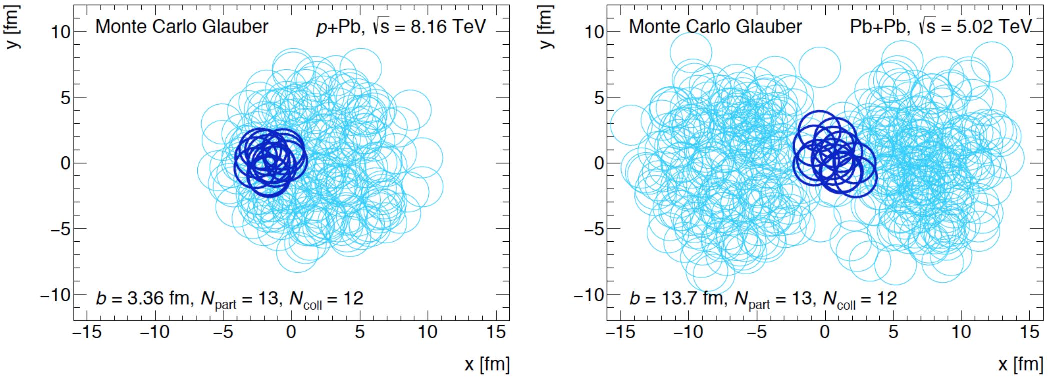
Figures courtesy D.V. Perepelitsa



...maybe we shouldn't be so surprised?

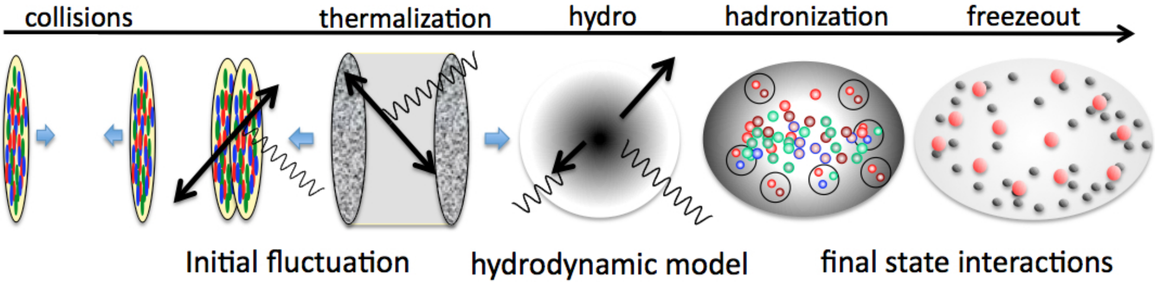
Which is which?

Figures courtesy D.V. Perepelitsa



...maybe we shouldn't be so surprised?

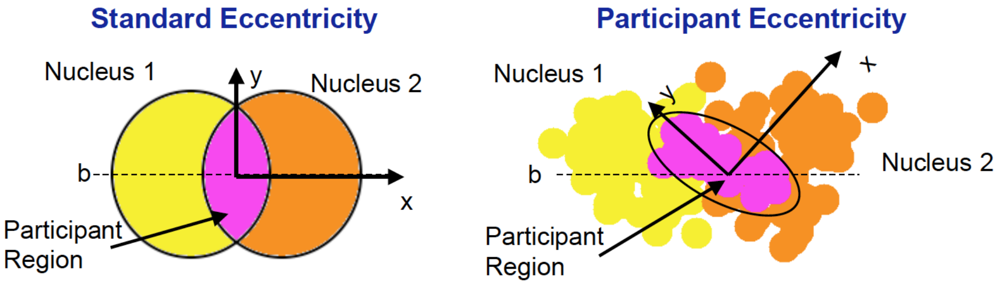
Standard model of heavy ion physics



Based on developments in hydro theory over the last few years, we should replace "thermalization" with "hydrodynamization"
(or "pseudo-thermalization" per M. Strickland, WWND20)

Important discovery in 2005

G. Roland, PHOBOS Plenary, Quark Matter 2005



A nucleus isn't just a sphere
Optical Glauber → Monte Carlo Glauber

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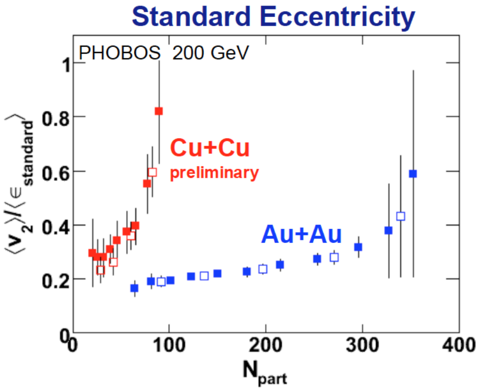

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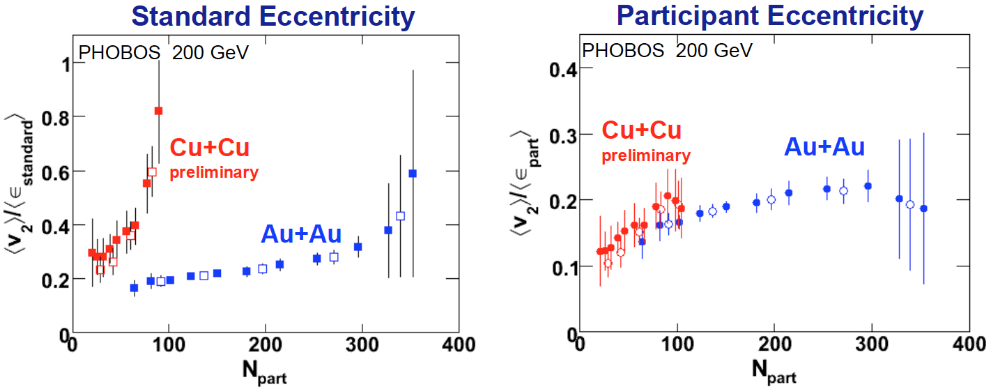


A nucleus isn't just a sphere
Optical Glauber → Monte Carlo Glauber

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

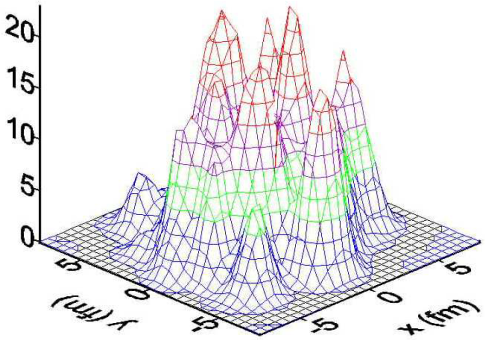
R.Andrade[1], F.Grassi[1], Y.Hama[1], T.Kodama[2], O.Socolowski Jr.[3], and B.Tavares[2]

[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

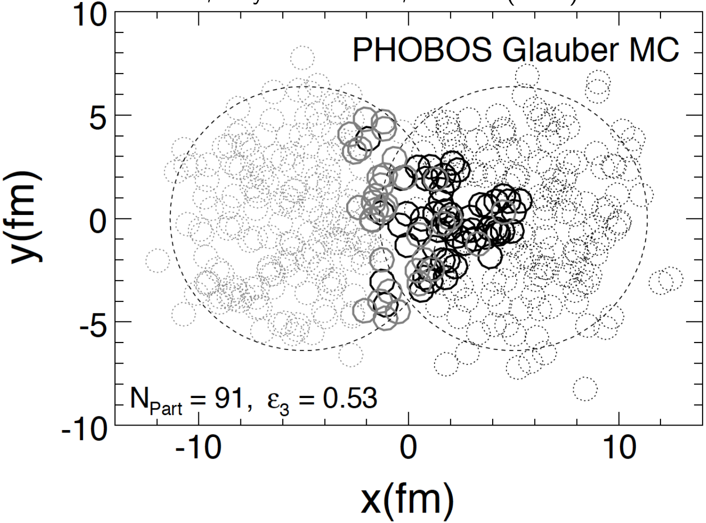
Received 1 January 2004



Worth noting that lumpy initial conditions were predicted as early as 2004

Important discovery in 2010

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



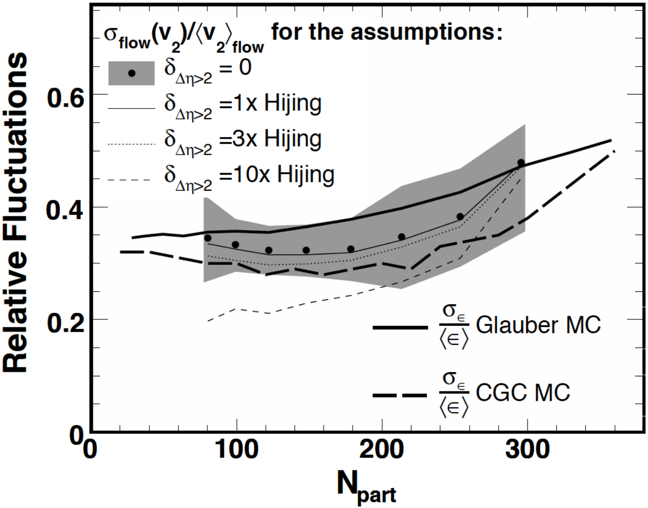
Nucleon fluctuations can produce non-zero ε_n for odd n

Symmetry planes ψ_n can be different for different harmonics

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

Fluctuations in large systems

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



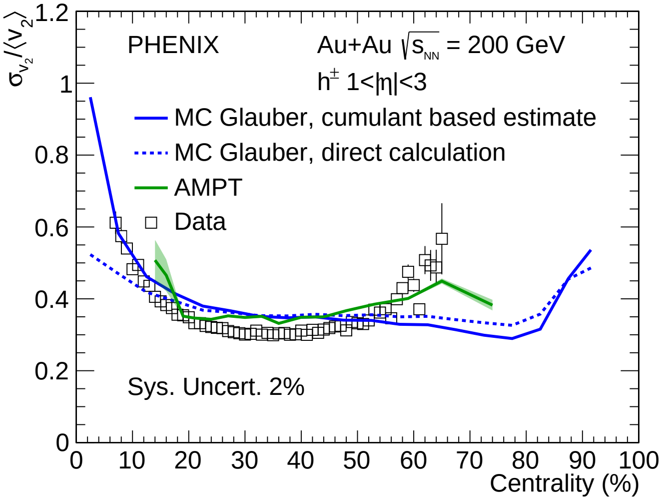
Fluctuations should also be translated, so measure $\sigma_{v_2}/\langle v_2 \rangle$

$|\eta| < 1$

Generally good agreement with models of initial geometry

Fluctuations in large systems

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



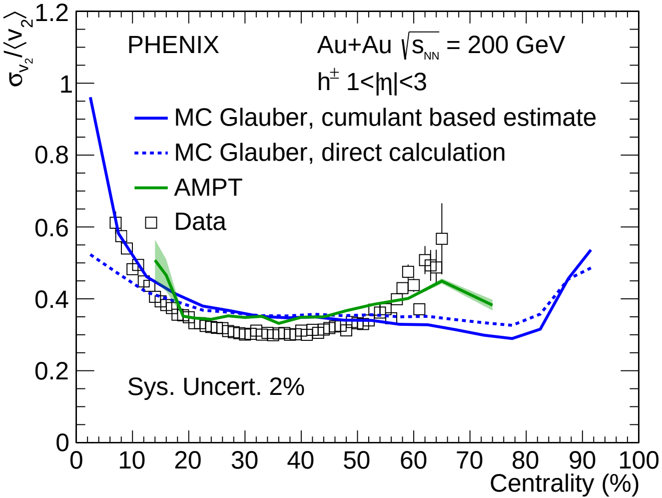
Fluctuations should also be translated, so measure $\sigma_{v_2}/\langle v_2 \rangle$

$1 < |\eta| < 3$

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

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

Intermission

Small systems geometry scan

Given what we know, can we use geometry to understand small systems?

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

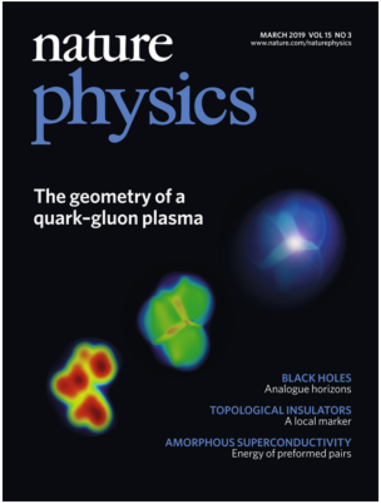
nature physics

Letter | Published: 10 December 2018

Creation of quark–gluon plasma droplets with three distinct geometries

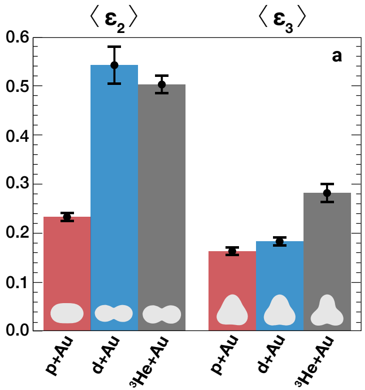
PHENIX Collaboration

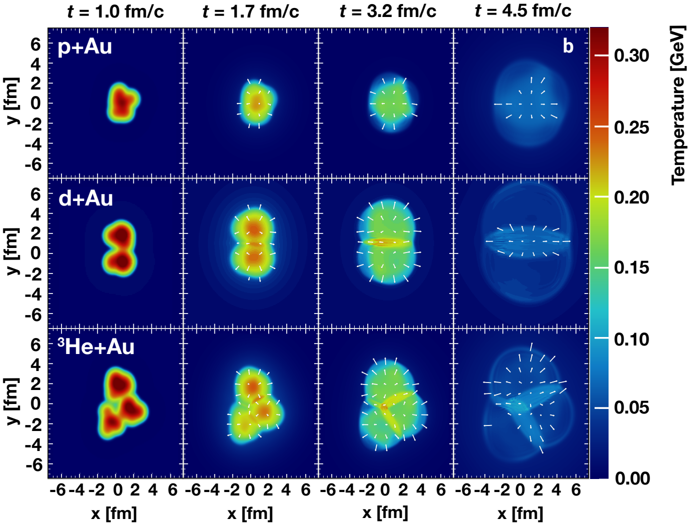
Nature Physics **15**, 214–220(2019) | Cite this article



Testing hydro by controlling system geometry

Nature Physics 15, 214–220 (2019)





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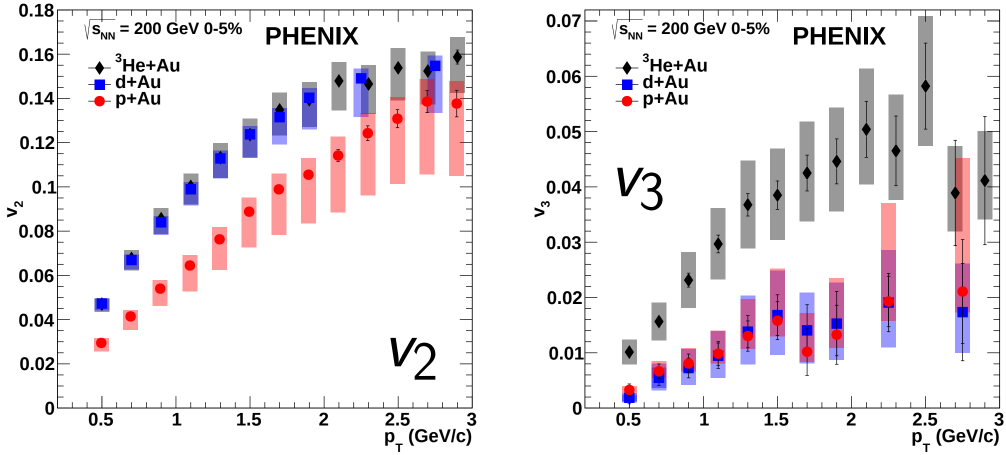
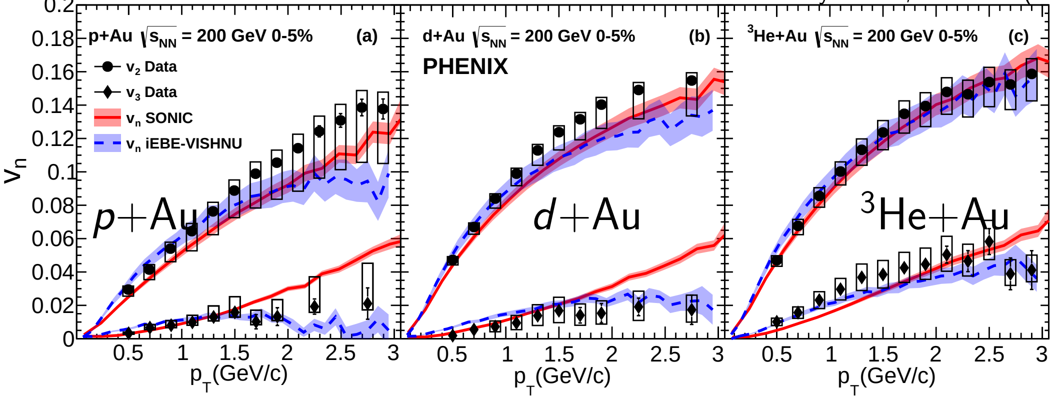


- v_2 and v_3 ordering matches ε_2 and ε_3 ordering in all three systems

—Regardless of mechanism, the correlation is geometrical and thus collective

Testing hydro by controlling system geometry

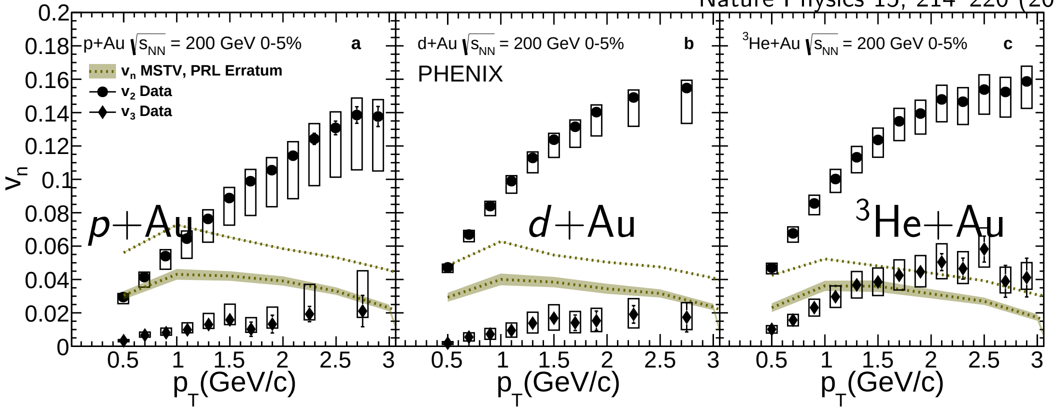
Nature Physics 15, 214–220 (2019)



- 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)

Testing hydro by controlling system geometry

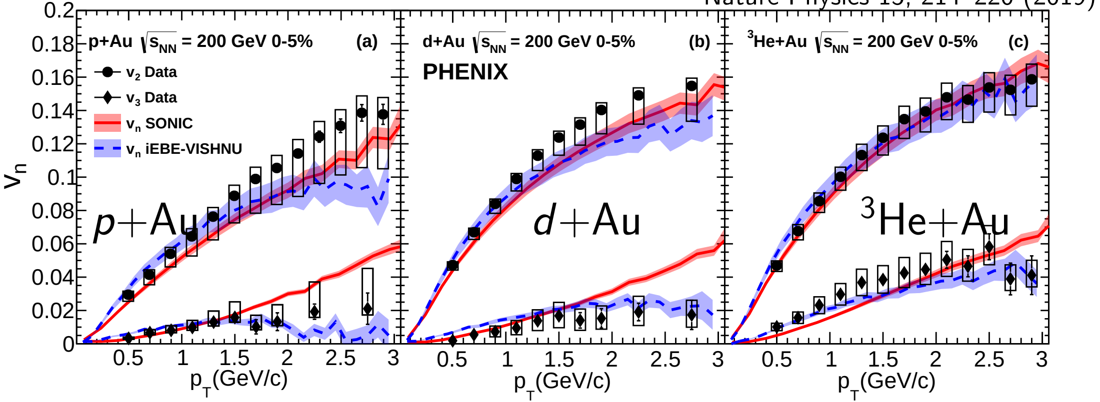
Nature Physics 15, 214–220 (2019)



- v_2 and v_3 vs p_T predicted or described very well by hydrodynamics in all three systems
- Initial state models do not reproduce the data
  —Phys. Rev. Lett. 123, 039901 (Erratum) (2019)

Testing hydro by controlling system geometry

Nature Physics 15, 214–220 (2019)



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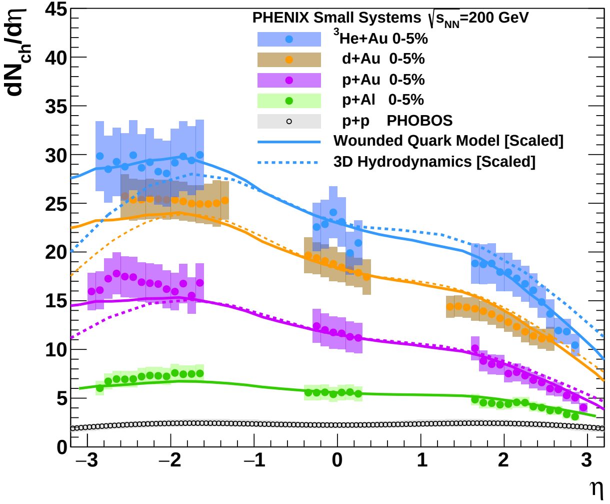
Longitudinal dynamics in small systems

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



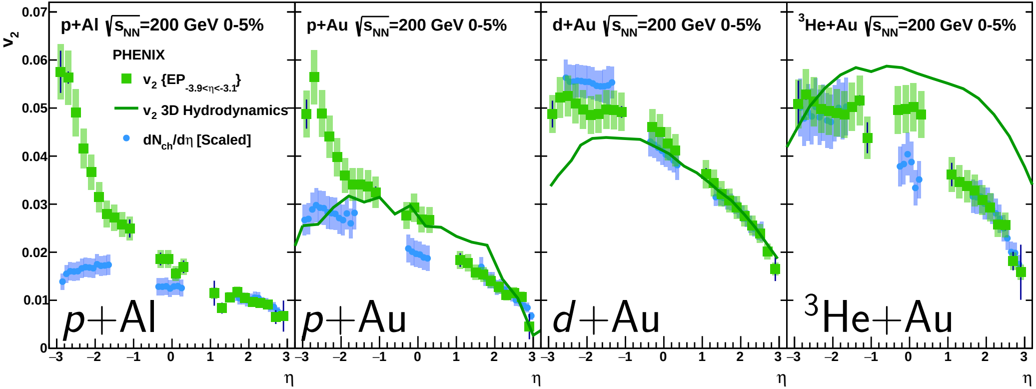
p+Al, p+Au, d+Au, ^{3}He+Au

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)

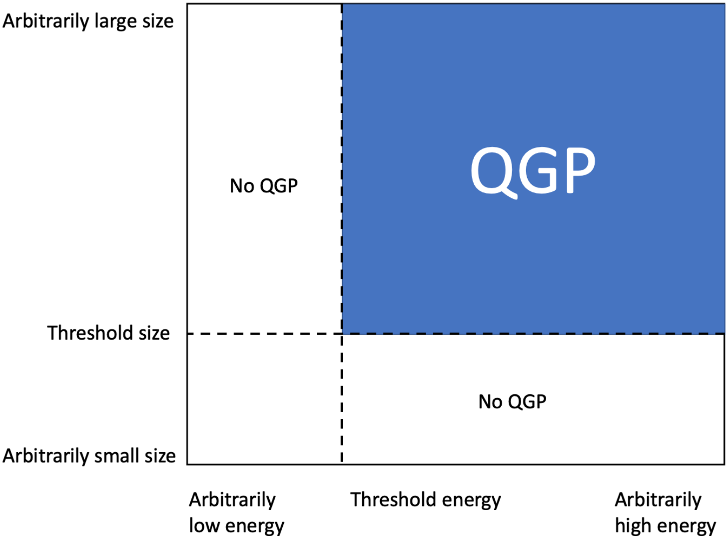


- v_2 vs η in p+Al, p+Au, d+Au, and ^{3}He+Au
- Good agreement with 3D hydro for p+Au and d+Au (Bozek et al, PLB 739, 308 (2014))
- Prevalence of non-flow near the EP detector, decreases with increasing system size/multiplicity

Intermission

Can we turn the QGP off?

Let's have a look at *extremely* small systems



Extremely small systems in hydro theory

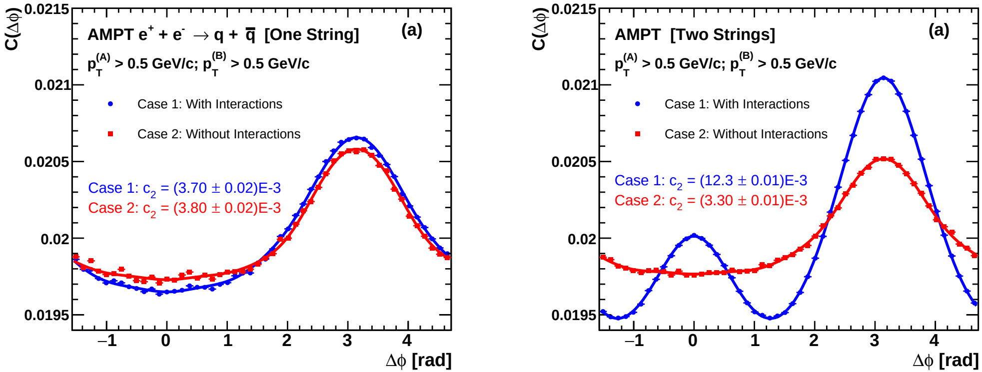
P. Romatschke, Eur. Phys. J. C 77, 21 (2017)

"I predict the breakdown of hydrodynamics at momenta of order seven times the temperature, corresponding to a smallest possible QCD liquid drop size of 0.15 fm."

"In view of the 'QGP drop size lower bound' of 0.15 fm, it is maybe not surprising that the matter created in $p+p$ collisions would behave hydrodynamically. At this scale, however, $p+p$ collisions may not be the ultimate drop size test. QCD-QED couplings allow fluctuations of electrons to e.g. quark pairs, thus opening up the possibility of local energy deposition reminiscent of $p+p$ collisions occurring in $e^{+}+e^{-}$ collisions (cf. Refs. [70–72]). Data on $e^{+}+e^{-}$ collisions taken at e.g. LEP should be re-analyzed with modern tools in order to find (or rule out) hydrodynamic behavior in these systems."

Extremely small systems in AMPT

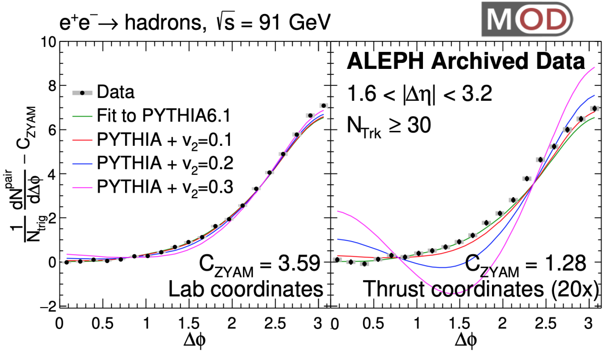
J.L. Nagle et al, Phys. Rev. C 97, 024909 (2018)



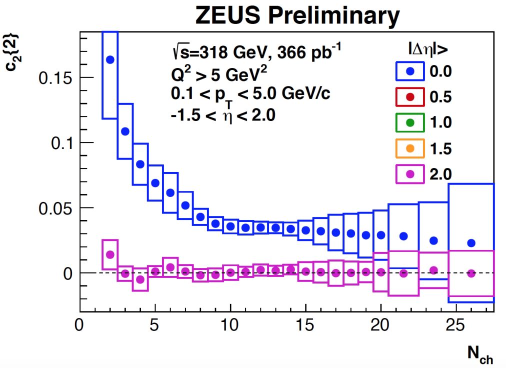
- A single color string ($e^+ + e^-$ collisions) shows no sign of collectivity
- Two color strings shows collectivity
  —Small systems like $p/d/^3$He+Au have more

Extremely small systems at LEP and HERA

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

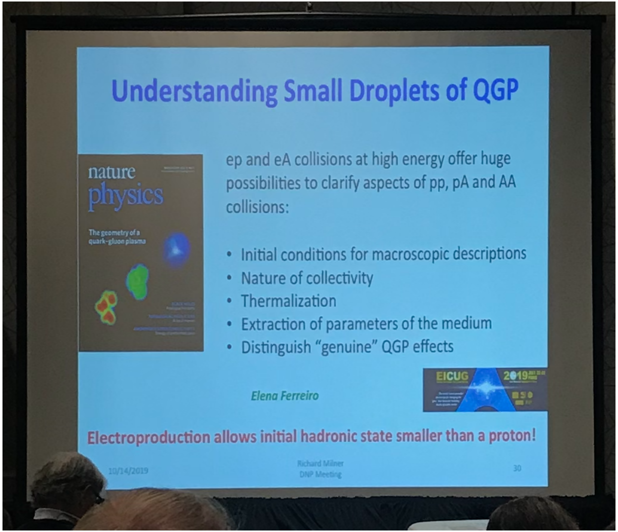


J. Onderwaater, Quark Matter 18



- No ridge in ALEPH $e^+ + e^-$ data
- c_2 with eta gap is zero in ZEUS $e+p$ data
- No apparent collectivity in leptonic collisions
  —More analysis is essential to better understand the data

Extremely small systems at the EIC



Considerable interest in the EIC community to use the EIC to explore this physics

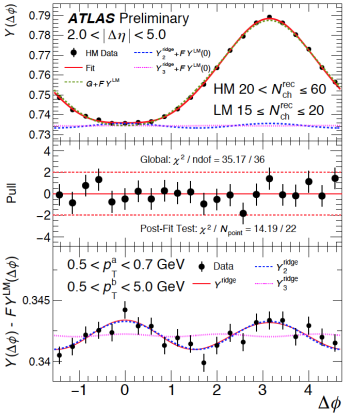
Richard Milner, Fall DNP 2019

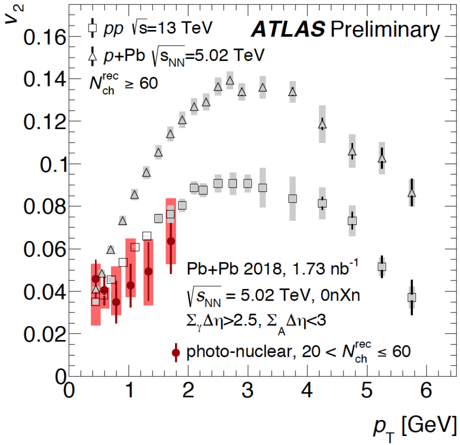
Elena Ferreiro, EICUG 2019 (Paris)

Flow in small systems at the LHC

D.V. Perepelitsa, ISMD 2019

ATLAS-CONF-2019-022





- Observation of collectivity in γ+Pb collisions
- Photon fluctuates into a vector meson (e.g. ρ)

Review of the story so far

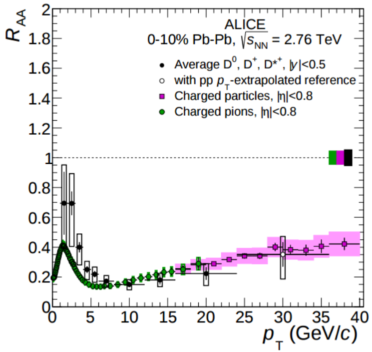
- Observation of collectivity in p+p, p+Pb, and all large systems at the LHC
  —Hydrodynamics describes a very wide array of observables
- Observation of collectivity in p+Au, d+Au, ^{3}He+Au, and all large systems at RHIC
  —Hydrodynamics successfully predicted the outcome of the small systems geometry scan
- Apparent *absence* of collectivity in e^++e^- and e+p collisions
  —Highlights importance of high quality archival data
  —Highlights major opportunities for further study in e+p and e+A collisions (e.g. EIC)
- Observation of collectivity in γ+Pb at the LHC
  —Major additional motivation for further study at EIC

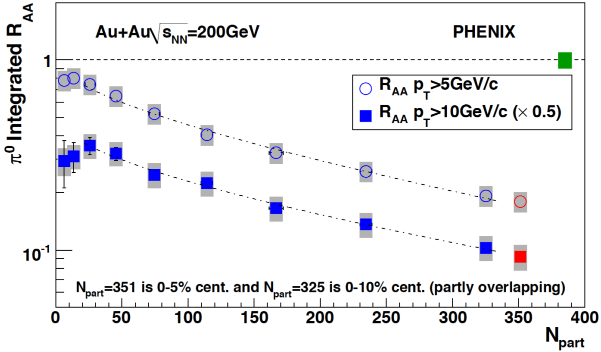
Intermission

Hard scattering as understood by a flow person
(Caveat emptor)

- Hard scattering means large momentum transfer Q^2 between partons
- Leads to final state particles with large p_T
- Probe small distance scales $d \approx 1/Q$
  (e.g. 20 GeV $\leftrightarrow$ 0.01 fm)
- Probe early times because scatterings occur during nuclear crossing $\tau = 2R/\gamma$
  (e.g. $\tau = 0.13$ fm for Au+Au at 200 GeV)

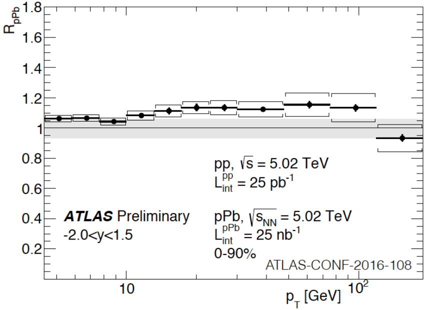
Hard scattering in large systems

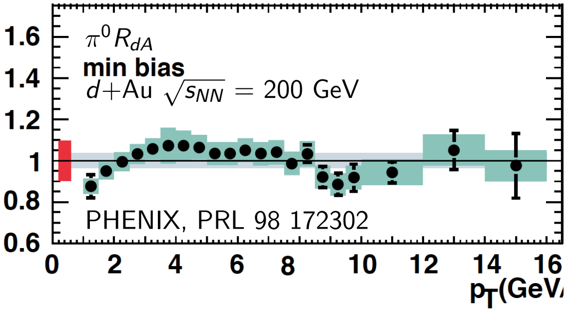




- $R_{AA} = \frac{N^{A+A}_{particles}}{N^{p+p}_{particles} \times N_{coll}}$
- $R_{AA} < 1$ means particles are suppressed
- Bigger system: more suppression
- *Apparent* suppression even in peripheral (small system size)

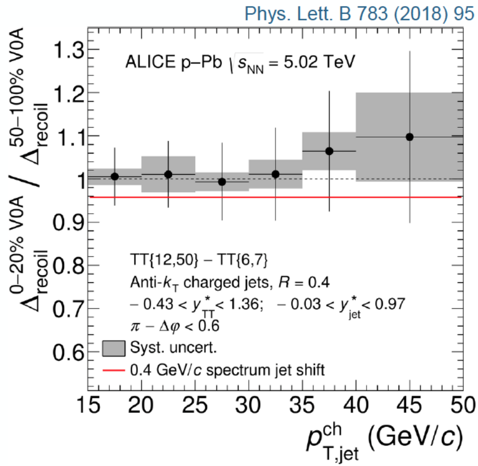
Hard scattering in small systems

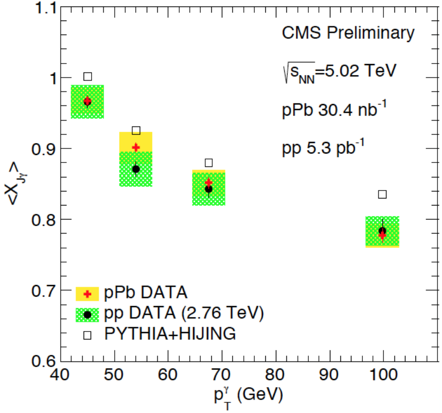




- $R_{p/dA} = \frac{N^{p/d+A}_{particles}}{N^{p+p}_{particles} \times N_{coll}}$
- $R_{p/dA} \approx 1$ means no modification
- Only showing minimum bias...
- Similar system size as peripheral Au+Au but no suppression?

Hard scattering in small systems

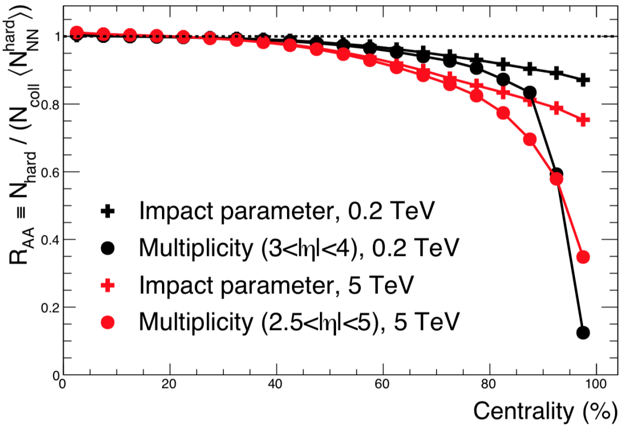




- Need more sophisticated tools to study energy loss (obvious benefit in large systems as well)
- Hadron-jet and photon-jets correlation shows no modification in small systems at LHC

Selection bias

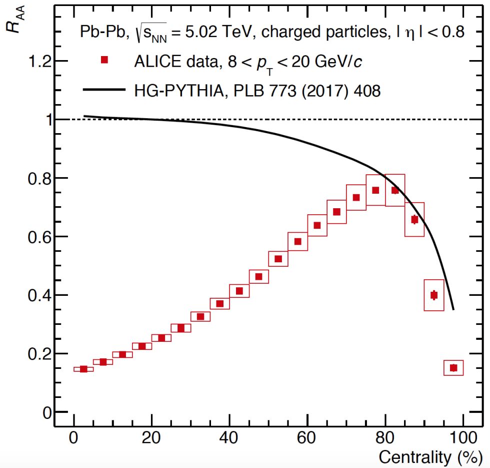
C. Loizides and A. Morsch, Phys. Lett. B 773, 408 (2017)



Suppression in peripheral A+A could be entirely due to bias effects

- More multi-parton interactions at small *b*, fewer at large *b*
- Correlation between centrality selection criterion (e.g. event multiplicity) and hard process rate (i.e. presence of high p_T particle)
- End result for both is same: more hard collisions in "central" vs "peripheral"

Selection bias



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Review of the story on hard probes

Large systems

- Long standing observation of particle suppression in large systems
- Major strides in observables, moving away from simple single particle R_{AA} and towards sophisticated correlation measurements with jets
- Do not yet have quantitative knowledge of transport parameters in large systems
- Quantitative understanding of these parameters and the underlying microphysics is a key motivation for sPHENIX

Review of the story on hard probes

Small systems

- Observation of *absence* of particle suppression in small systems *despite strong evidence for QGP formation*
- Major issue? Apparent similarities between central small systems and peripheral large systems
- Perceived presence of particle suppression in peripheral A+A collisions may be an event selection artifact, not a physics effect
- Where in system size is the onset of suppression?
  —Strong motivation for intermediate system size scan like O+O, Ar+Ar, etc

Final thoughts

- QGP is created in small and large systems
- What are the conditions under which QGP formation is possible?
- Where in system size is the onset of particle suppression?

Final thoughts

- QGP is created in small and large systems
- What are the conditions under which QGP formation is possible?
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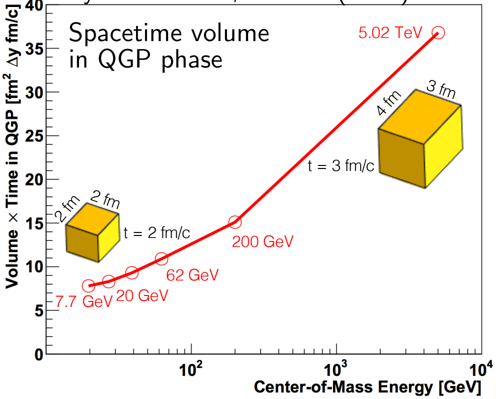
"The optimist regards the future as uncertain."—Eugene Wigner

Extra material

Testing hydro by controlling system size and life time

J.D. Orjuela Koop et al
Phys. Rev. C 93, 044910 (2016)

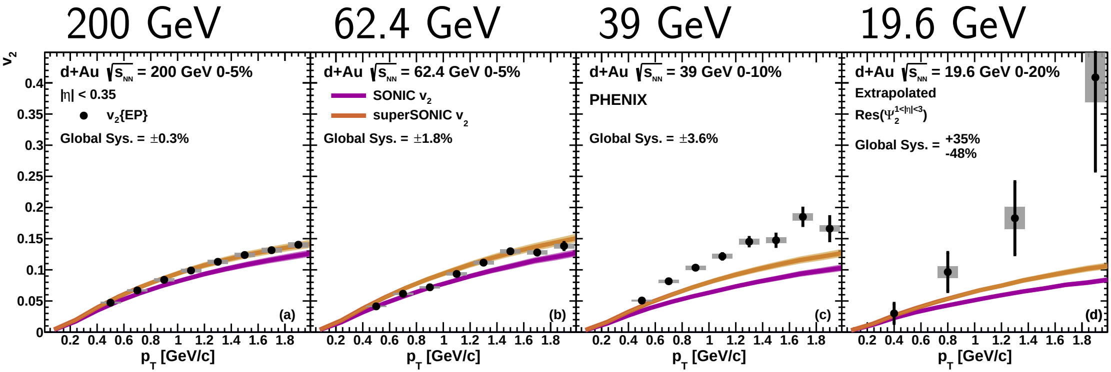


Geometry in d+Au collisions dominated by deuteron shape, thus largely independent of collision energy

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

d+Au beam energy scan

Phys. Rev. C 96, 064905 (2017)

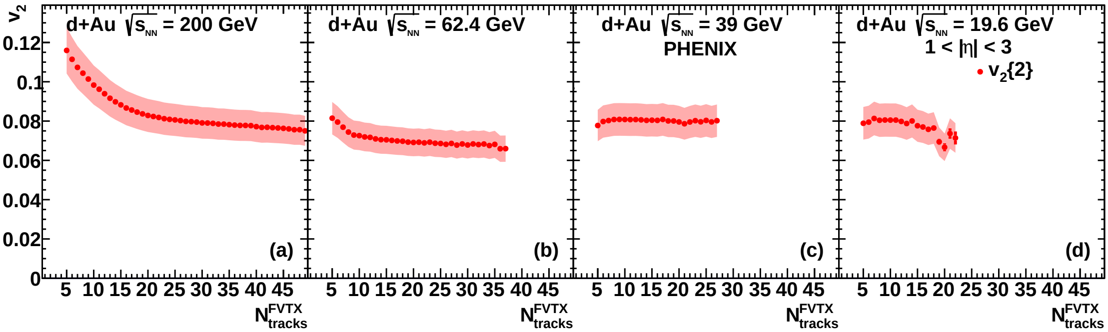


- Hydro theory agrees with higher energies very well, underpredicts lower energies
  —Breakdown of hydro?
  —Predominance of other correlations?

d+Au beam energy scan

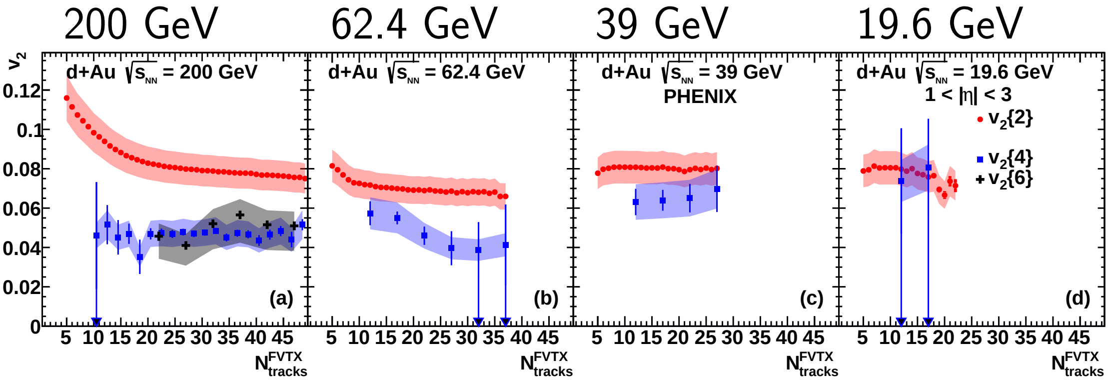
Phys. Rev. Lett. 120, 062302 (2018)

200 GeV | 62.4 GeV | 39 GeV | 19.6 GeV



d+Au beam energy scan

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



- 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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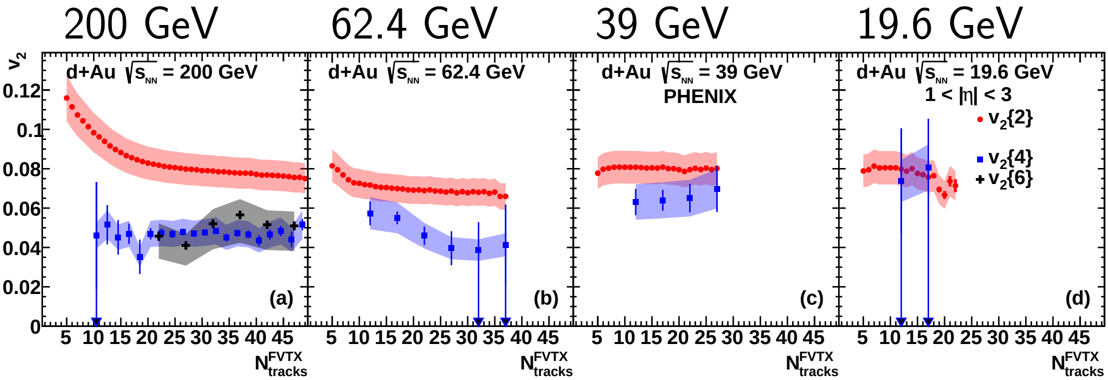


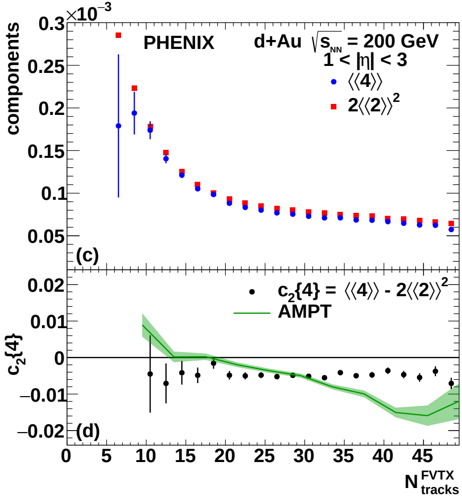
- Measurement of $v_2\{6\}$ in d+Au at 200 GeV and $v_2\{4\}$ in d+Au at all energies
- Multiparticle correlations can be a good indicator of collectivity

Components and cumulants in p+Au and d+Au at 200 GeV

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

$$v_2\{4\} = (-c_2\{4\})^{1/4}$$

Negative $c_2\{4\}$ means real $v_2\{4\}$



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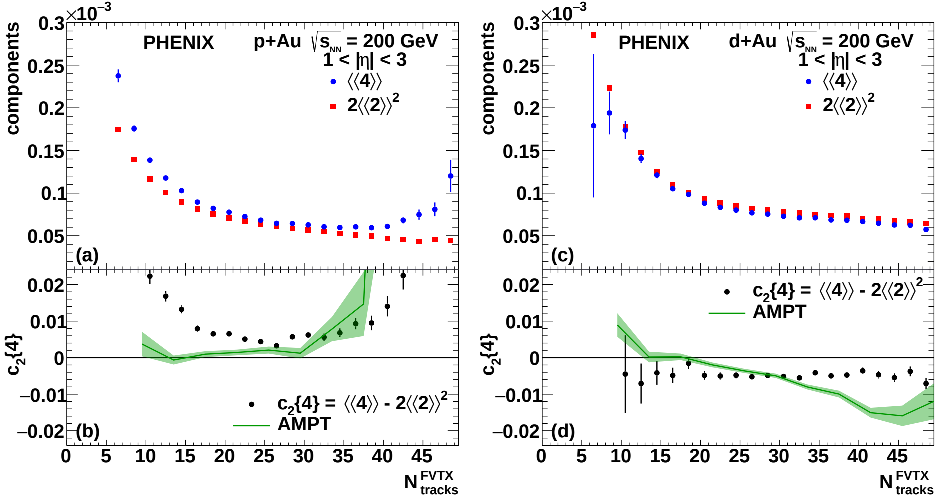

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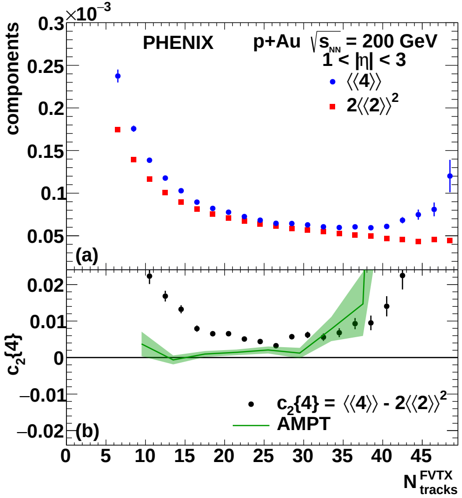
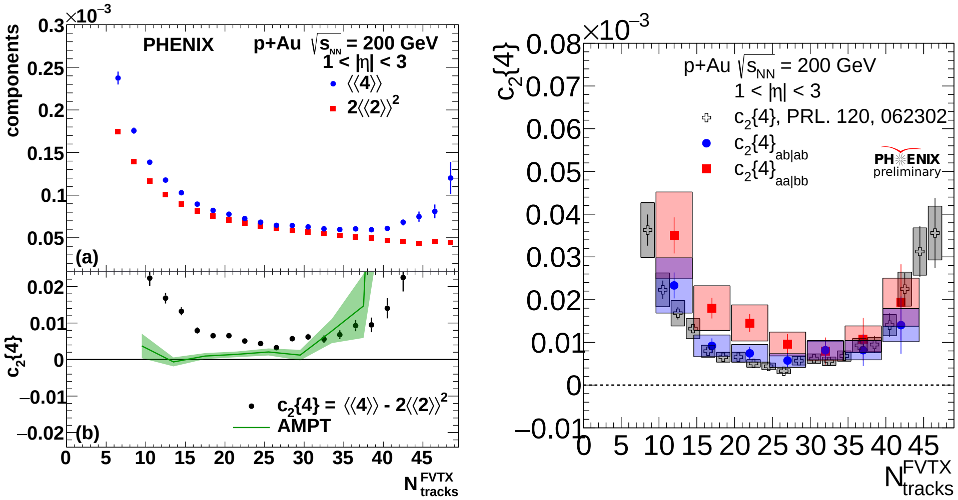


$c_2\{4\}$ is positive in p+Au

Can we blame this on nonflow?

Components and cumulants in p+Au and d+Au at 200 GeV

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

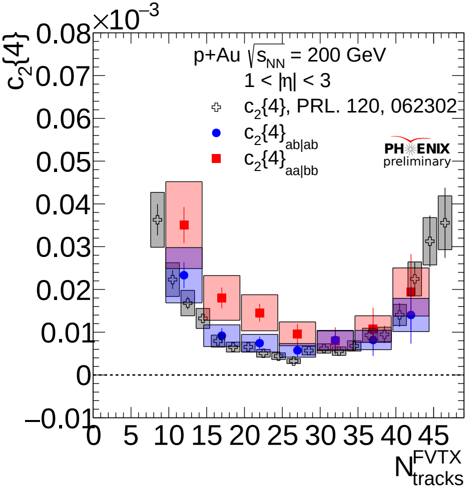


Components and cumulants in p+Au and d+Au at 200 GeV

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

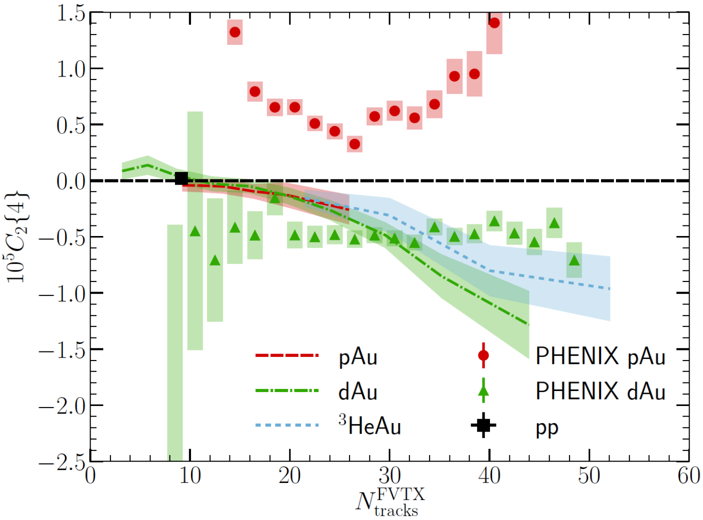
Use of subevents further suppresses nonflow

Positive $c_2\{4\}$ in p+Au doesn't seem to be related to nonflow



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

C. Shen et al, arXiv:1908.06212



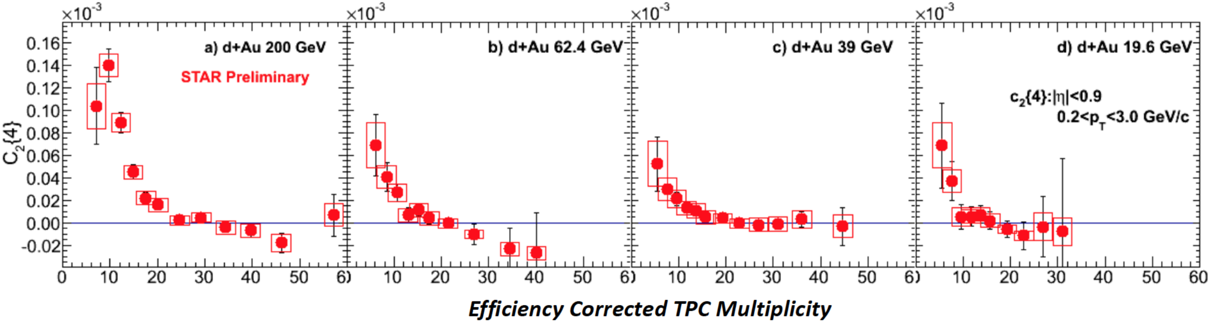
Cumulants are computationally expensive in hydro theory, so not as well-studied

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

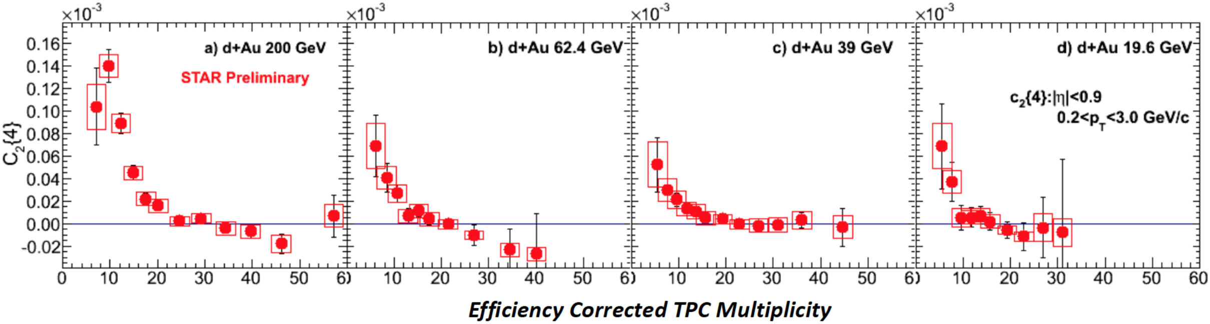
S. Huang, Initial Stages 2019



- 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

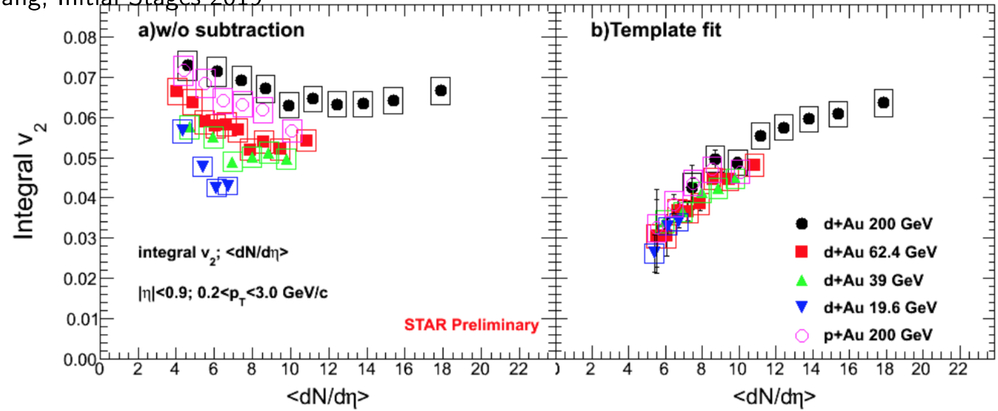
S. Huang, Initial Stages 2019



- STAR sees negative $c_2\{4\}$ in d+Au, qualitatively consistent with PHENIX
- The differences in kinematics between the two experiments are important
- In fact, the STAR kinematics are better suited to comparison to 2+1D hydro —Unfortunately, the statistical precision is limited

d+Au beam energy scan

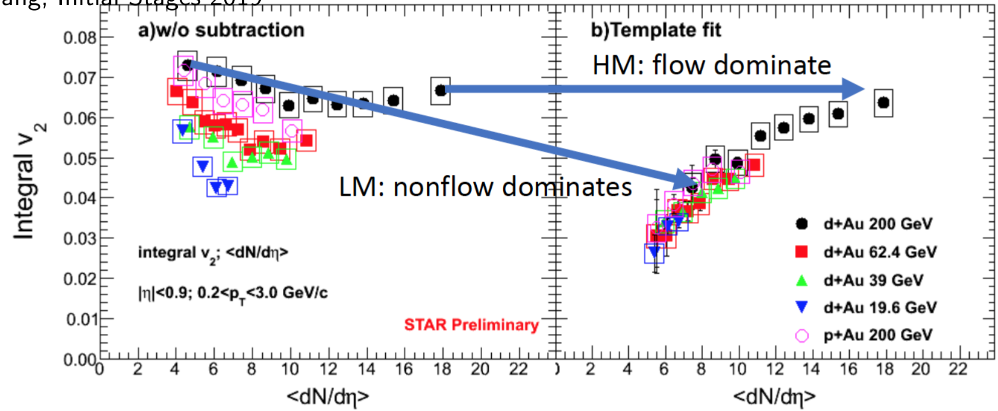
S. Huang, Initial Stages 2019



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

d+Au beam energy scan

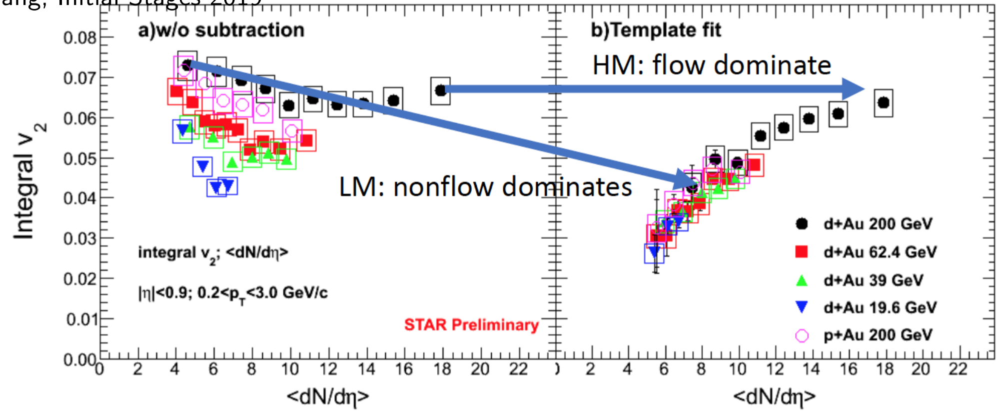
S. Huang, Initial Stages 2019



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

d+Au beam energy scan

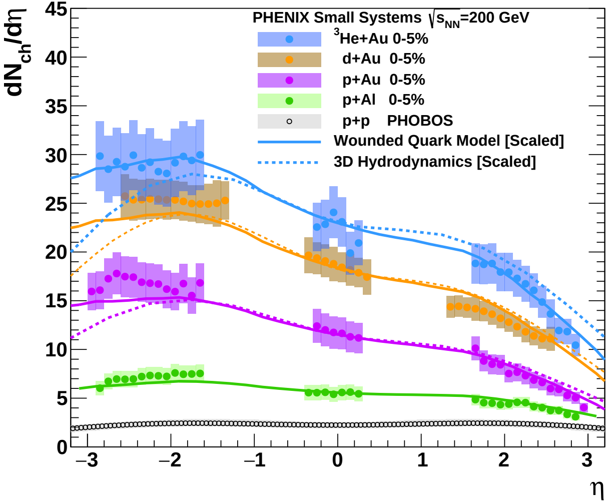
S. Huang, Initial Stages 2019



- 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)

Longitudinal dynamics in small systems

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



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

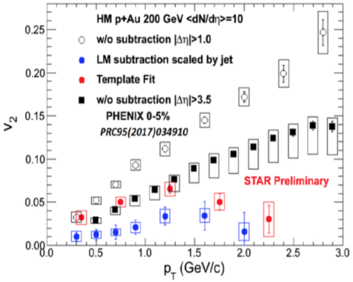
Good agreement with wounded quark model

Good agreement with 3D hydro

Comparisons with STAR

STAR Preliminary v_2 #1, QM 2018 (Venice)

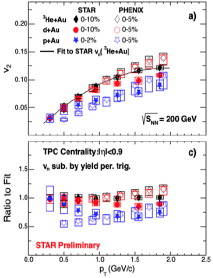
https://indico.cern.ch/event/656452/contributions/2869833/



STAR states that PHENIX result is “wrong” and has substantial non-flow not accounted for in uncertainties.

STAR Preliminary v_2 #2, QM 2019 (Wuhan)

https://indico.cern.ch/event/792436/contributions/3535629/



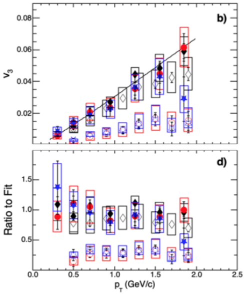
STAR states

“The STAR and PHENIX measurements for $v_2\{2\}$ are in reasonable agreement for all systems”

NO EXPLANATION FOR WHAT CHANGED!

STAR New Preliminary v_3, QM 2019 (Wuhan)

https://indico.cern.ch/event/792436/contributions/3535629/



STAR states

“The STAR and PHENIX $v_3\{2\}$ measurements for p/d+Au differ by more than a factor of 3”

Comparisons with STAR

PHENIX takes the issue seriously, so we are doing our due diligence!

The published small systems results use the event plane method, where the resolution nominally follows $R(\chi) = \frac{\sqrt{\pi}}{2}\chi e^{-\frac{\chi^2}{2}} \left(I_0(\frac{\chi^2}{2}) + I_1(\frac{\chi^2}{2}) \right)$
In small systems we're in the limiting case where $\chi \ll 1$ so $R \propto \chi$ (note that $\chi = v_n\sqrt{N_{ch}}$).

The set of PHENIX event plane resolutions do not follow the expected pattern.

The origin of this effect appears to be the beam and angle offset relative to the detector and an additional offset of the PHENIX central carriage (all of these things vary between operational periods). The effect is qualitatively reproduced in toy simulation studies that utilize the full analysis procedure.

The three-subevent 2-particle correlation method uses event mixing, which appears to correct these effects quite well. Checks with the 3x2PC method show no such bias as seen in EP method for all systems, and all of these checks agree with published EP results within uncertainties.

Further checks on going as part of due diligence!