Droplets of quark gluon plasma: PHENIX results on small systems at RHIC

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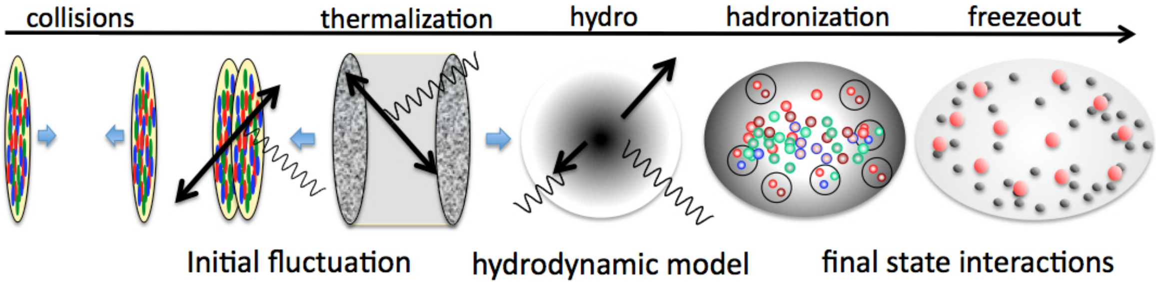
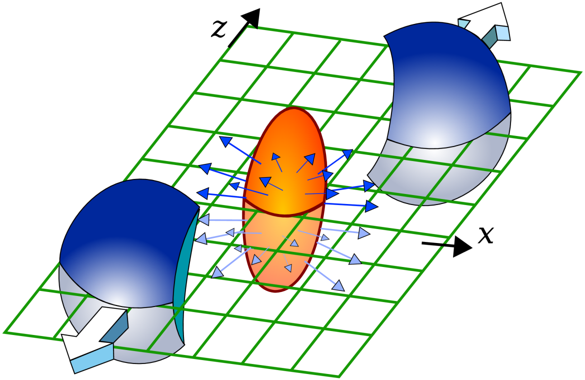
Winter Workshop on Nuclear Dynamics
Puerto Vallarta, Jalisco, Mexico
2 March 2020

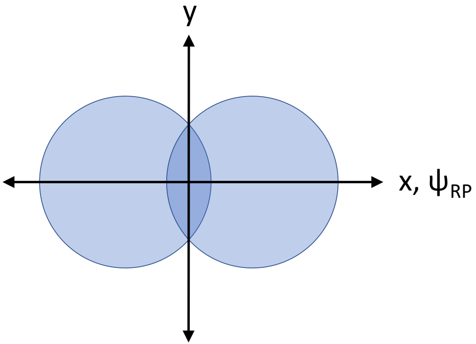
Standard model of heavy ion physics



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

Azimuthal anisotropy measurements

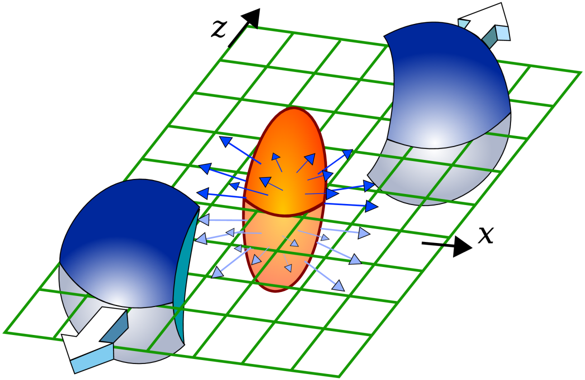


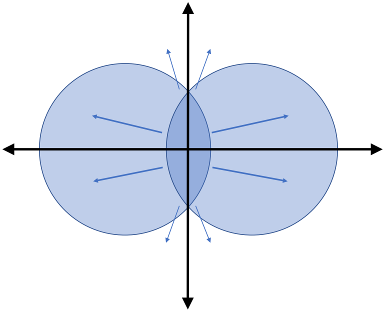


$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos n\varphi \qquad v_n = \langle \cos n\varphi \rangle \qquad \varepsilon_n = \frac{\sqrt{\langle r^n \cos n\varphi \rangle + \langle r^n \sin n\varphi \rangle}}{\langle r^n \rangle}$$

- Hydrodynamics translates initial shape (ε_n) into final state distribution (v_n)

Azimuthal anisotropy measurements



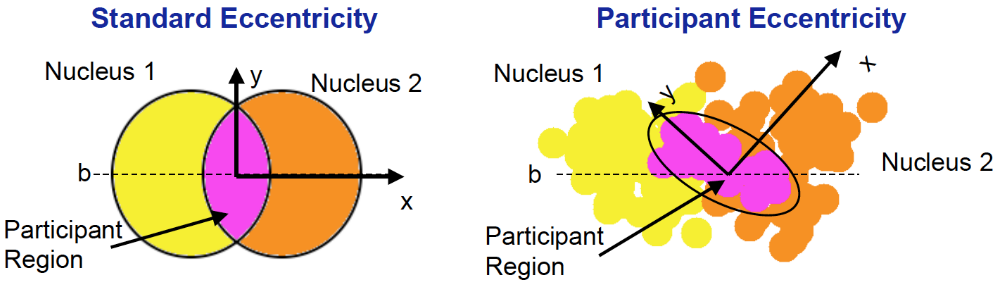


$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos n\varphi \qquad v_n = \langle \cos n\varphi \rangle \qquad \varepsilon_n = \frac{\sqrt{\langle r^n \cos n\varphi \rangle + \langle r^n \sin n\varphi \rangle}}{\langle r^n \rangle}$$

- Hydrodynamics translates initial shape (ε_n) into final state distribution (v_n)

Important discovery in 2005

G. Roland, PHOBOS Plenary, Quark Matter 2005



A nucleus isn't just a sphere

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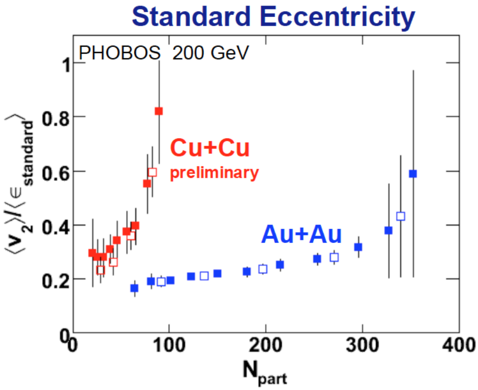

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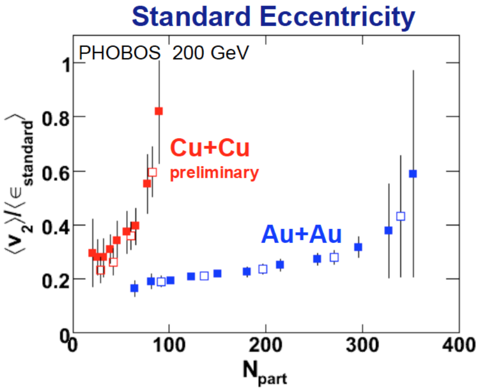
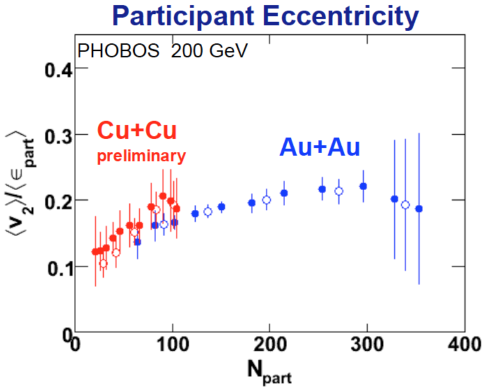
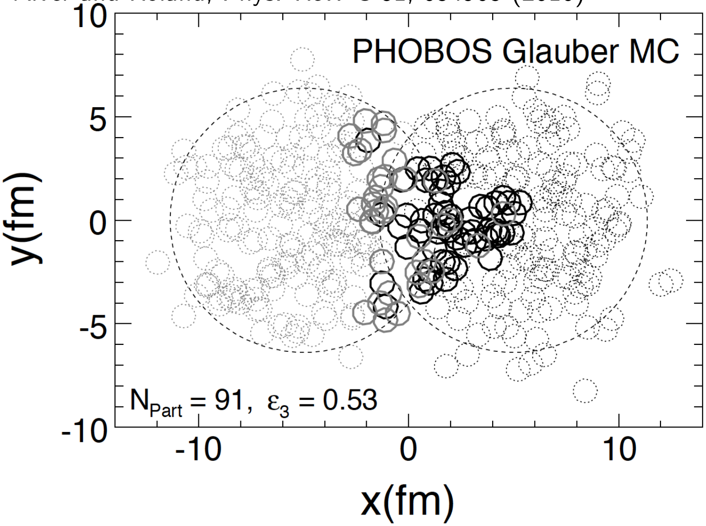




A nucleus isn't just a sphere

Important discovery in 2010

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



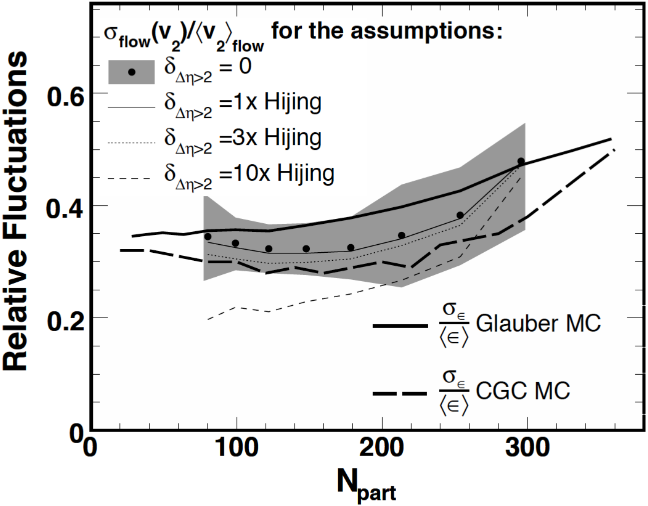
Nucleon fluctuations can produce non-zero ε_n for odd n

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)



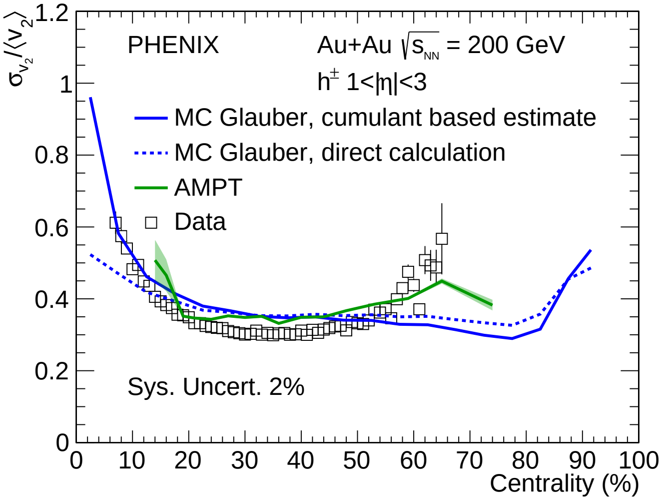
Fluctuations should also be translated, so measure $\sigma_{v_2}/\langle v_2 \rangle$

$|\eta| < 1$

Generally good agreement with models of initial geometry

Fluctuations in large systems

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



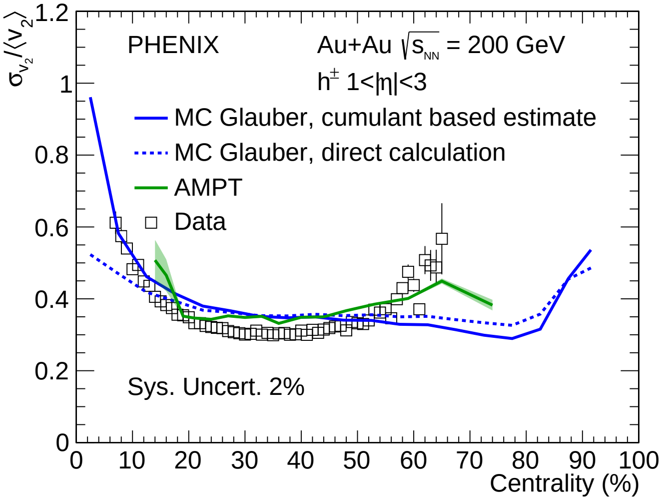
Fluctuations should also be translated, so measure $\sigma_{v_2}/\langle v_2\rangle$

$1 < |\eta| < 3$

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

Intermission

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

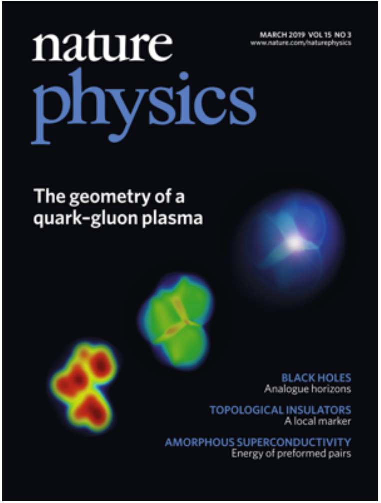
nature physics

Letter | Published: 10 December 2018

Creation of quark–gluon plasma droplets with three distinct geometries

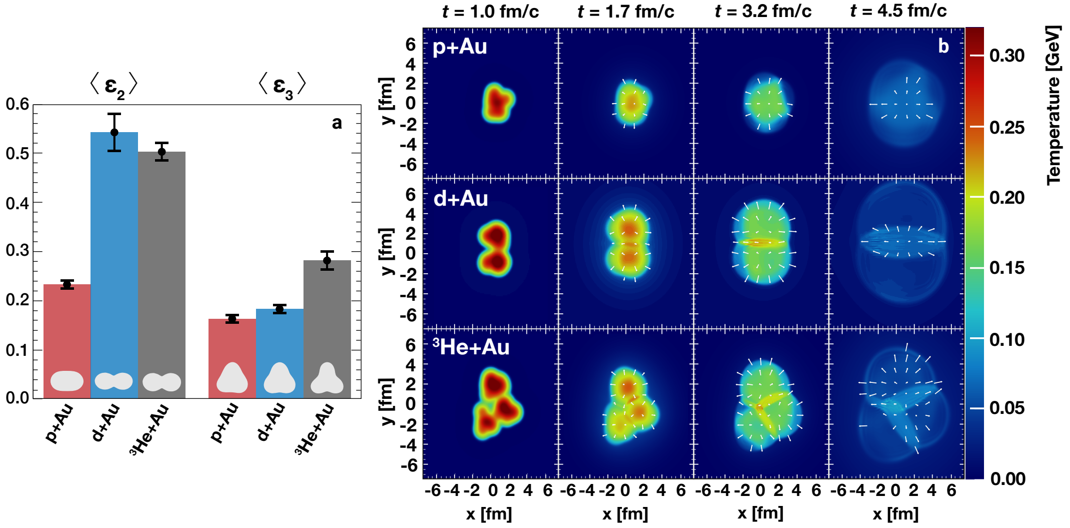
PHENIX Collaboration

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



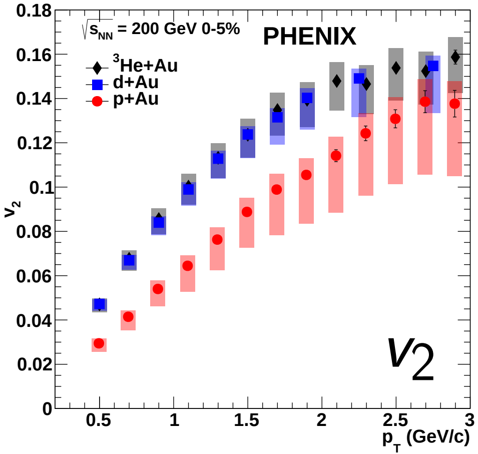
Testing hydro by controlling system geometry

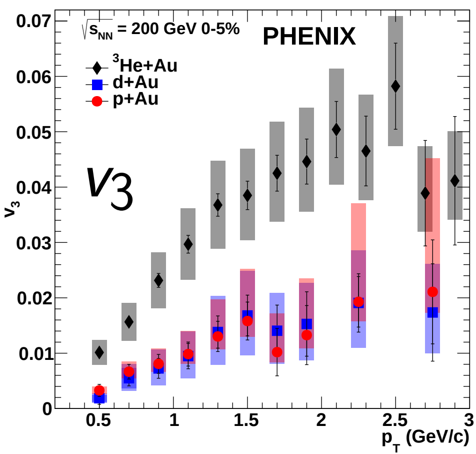
Nature Physics 15, 214–220 (2019)



Testing hydro by controlling system geometry

Nature Physics 15, 214–220 (2019)

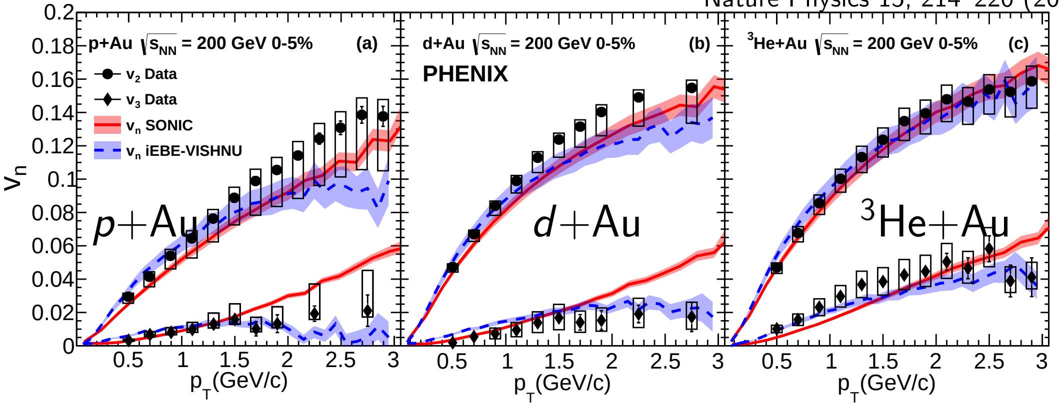




- v_2 and v_3 ordering matches ε_2 and ε_3 ordering in all three systems
  —Regardless of mechanism, the correlation is geometrical and thus collective

Testing hydro by controlling system geometry

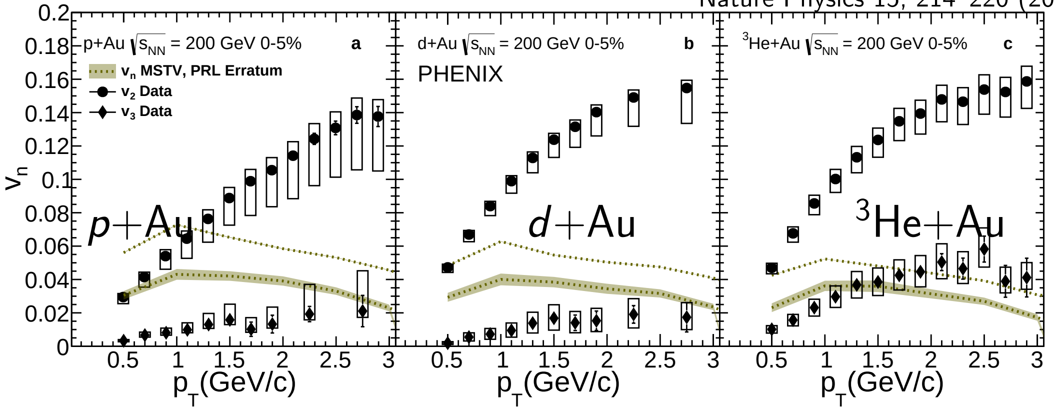
Nature Physics 15, 214–220 (2019)



- 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

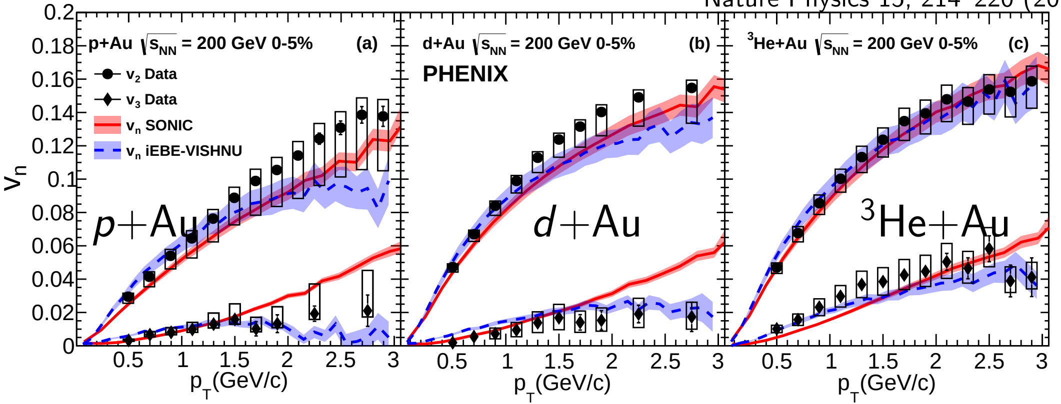
Nature Physics 15, 214–220 (2019)



- 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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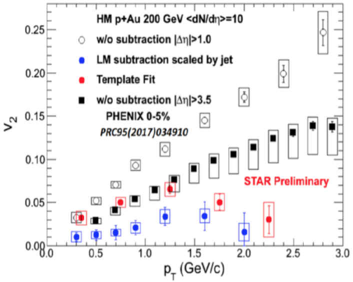
Comparisons with STAR

STAR Preliminary v_2 #1, QM 2018 (Venice)

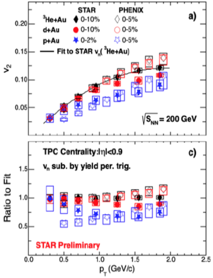
https://indico.cern.ch/event/656452/contributions/2869833/



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/



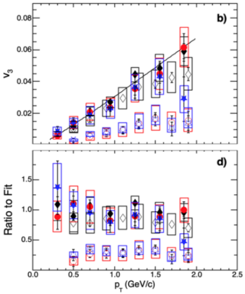
STAR states

"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.

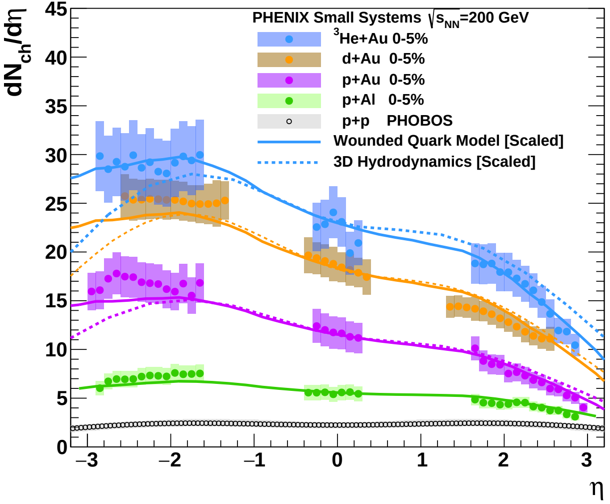
The origin of this effect appears to be the beam and angle offset relative to the detector and an additional offset of the PHENIX central carriage (all of these things vary between operational periods). The effect is qualitatively reproduced in toy simulation studies that utilize the full analysis procedure.

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!

Longitudinal dynamics in small systems

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



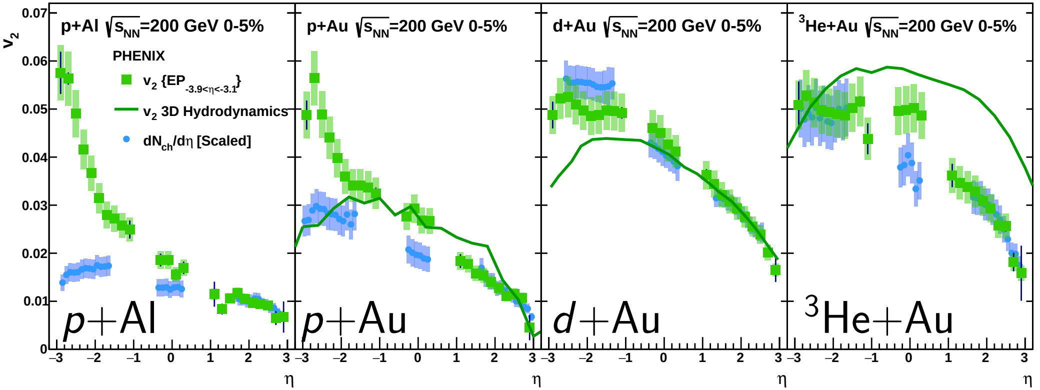
p+Al, *p*+Au, *d*+Au, ^{3}He+Au

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)



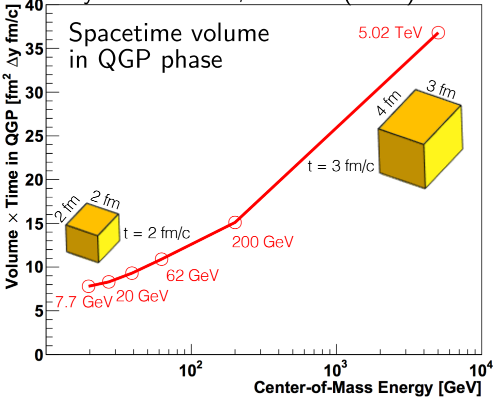
- v_2 vs η in p+Al, p+Au, d+Au, and ^{3}He+Au
- Good agreement with 3D hydro for p+Au and d+Au (Bozek et al, PLB 739, 308 (2014))
- Prevalence of non-flow near the EP detector, decreases with increasing system size/multiplicity

Intermission

Intermission

Testing hydro by controlling system size and life time

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

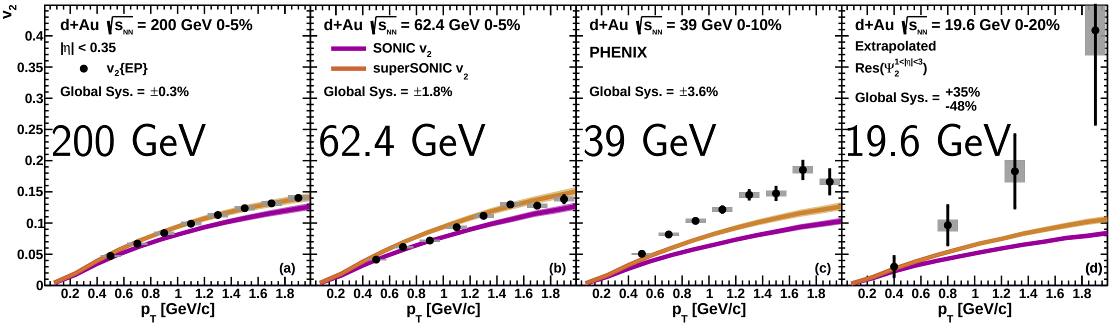


Geometry in d+Au collisions dominated by deuteron shape, thus largely independent of collision energy

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

d+Au beam energy scan

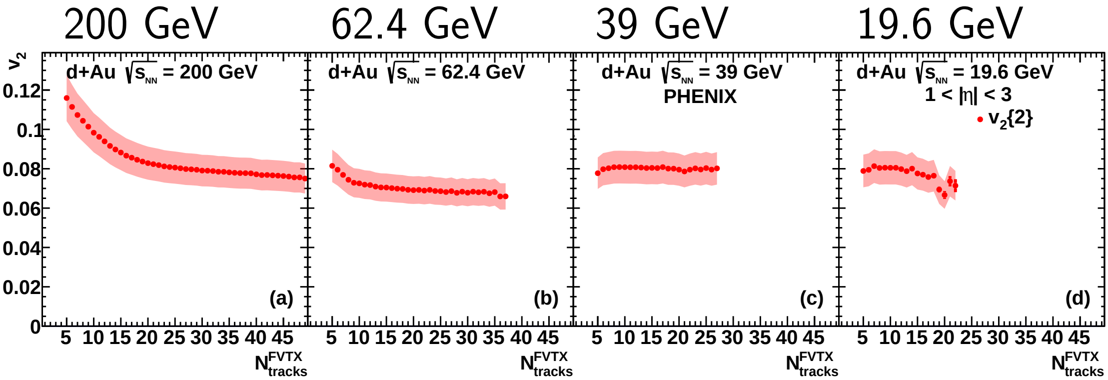
Phys. Rev. C 96, 064905 (2017)



- Hydro theory agrees with higher energies very well, underpredicts lower energies
- 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

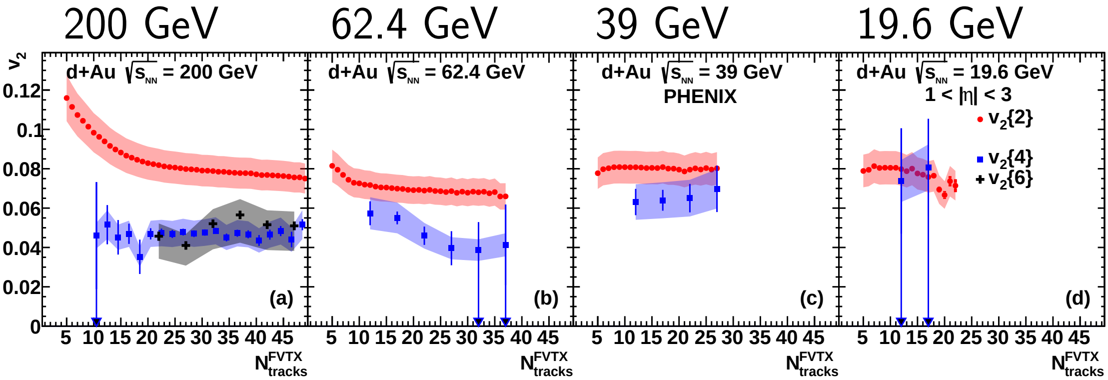
d+Au beam energy scan

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



d+Au beam energy scan

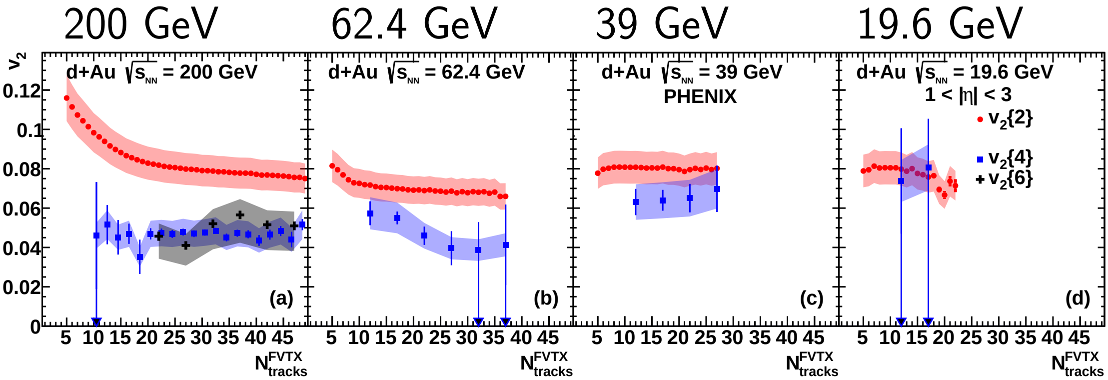
Phys. Rev. Lett. 120, 062302 (2018)



- 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

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



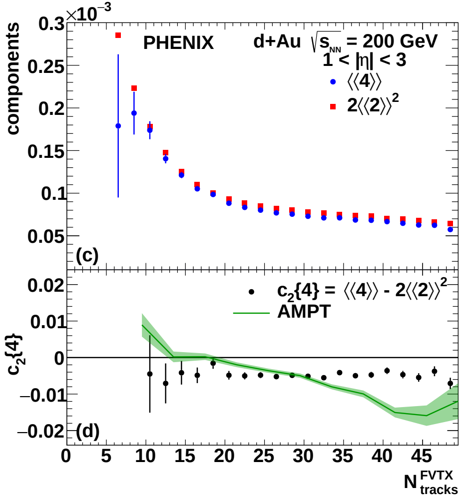
- Measurement of $v_2\{6\}$ in d+Au at 200 GeV and $v_2\{4\}$ in d+Au at all energies
- Multiparticle correlations can be a good indicator of collectivity

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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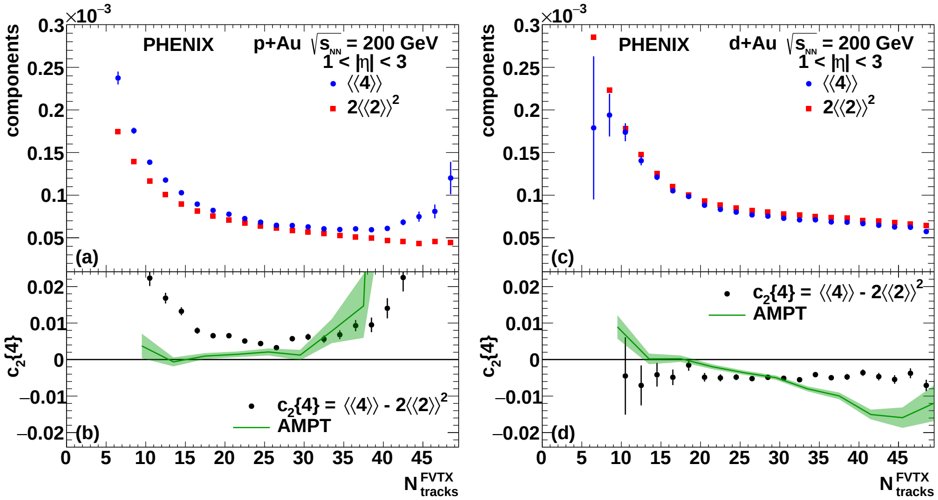

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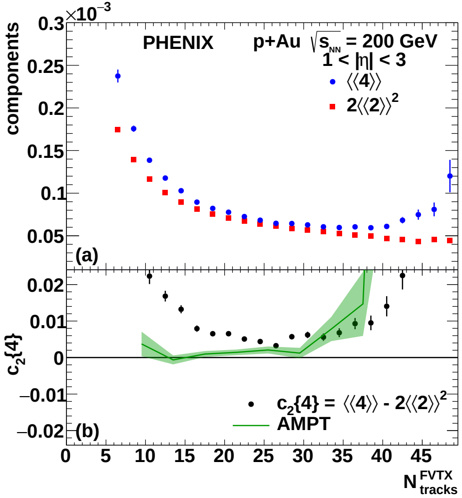
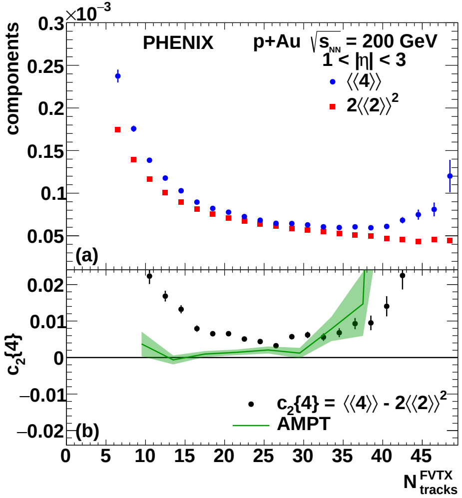


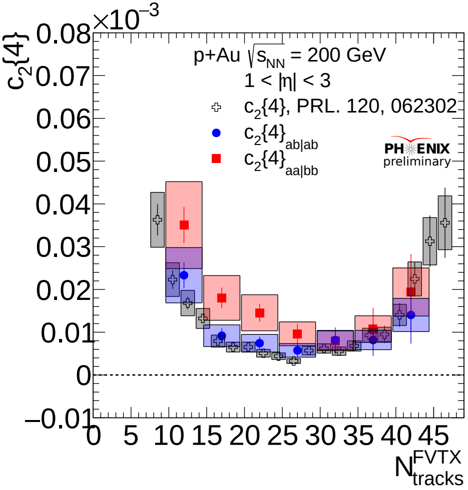
$c_2\{4\}$ is positive in p+Au

Can we blame this on nonflow?

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

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

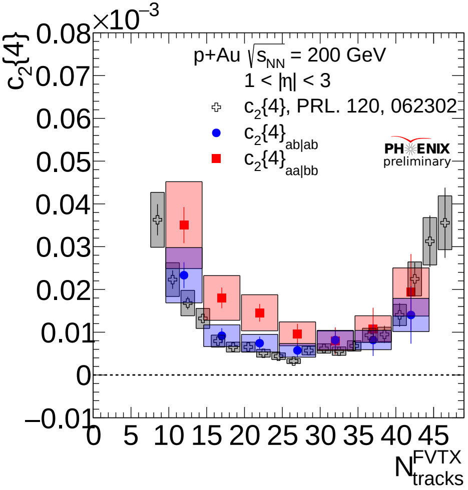




Components and cumulants in p+Au and d+Au at 200 GeV

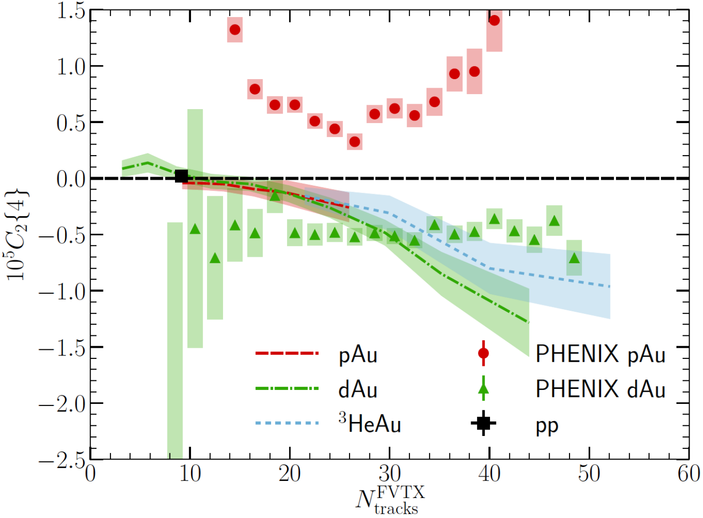
Use of subevents further suppresses nonflow

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

B. Schenke 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

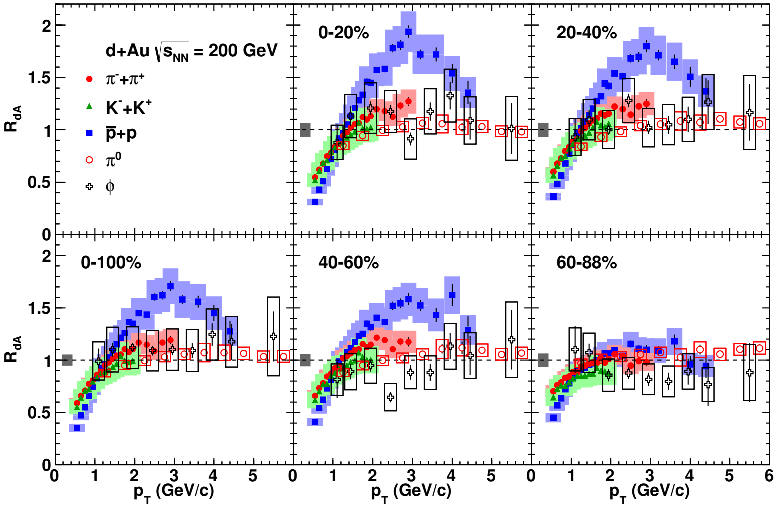
Summary

- Collective motion translates initial geometrical shape into final state azimuthal anisotropies
- Evidence of this translation is seen in small and large systems
- The v_2 and v_3 in p+Au, d+Au, and ^{3}He+Au qualitatively follow the geometrical ordering of the initial state
- The v_2 and v_3 in p+Au, d+Au, and ^{3}He+Au quantitatively agree with multiple hydrodynamical calculations
- A variety of collective signatures are seen in the d+Au beam energy scan
  —v_2 vs p_T agrees with hydro at the higher two energies
  —Observation of multiparticle correlations at all energies

Extra material

Particle species dependence of "Cronin enhancement"

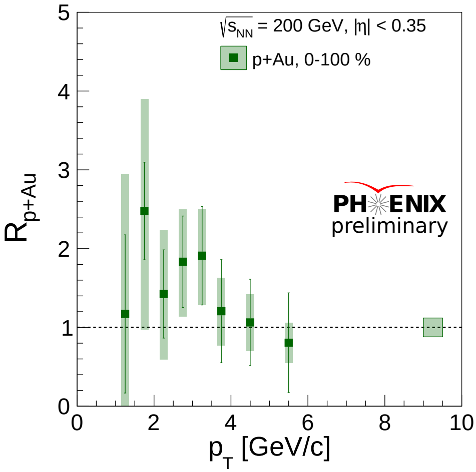
PHENIX, Phys. Rev. C 88, 024906 (2013)



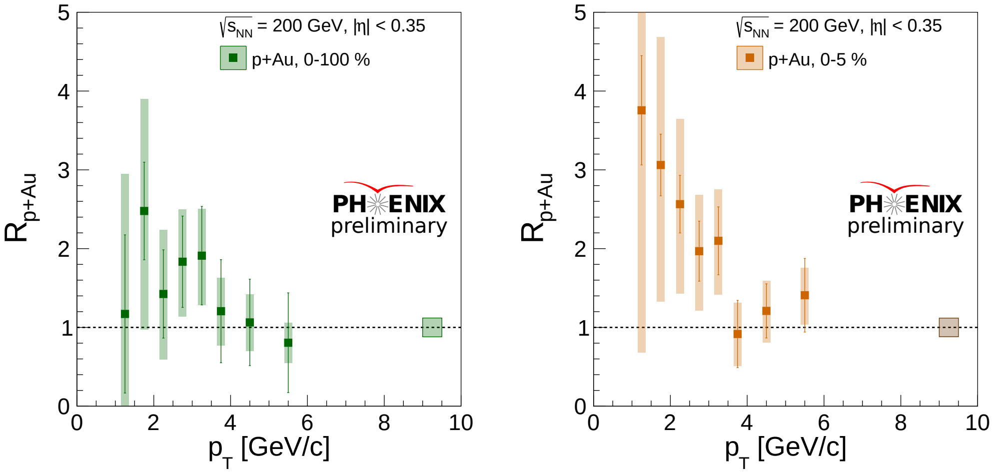
π^+, π^-, π^0,
K^+, K^-,
p, $\bar{p}$,
ϕ

Protons much more strongly modified than pions
ϕ mesons similar to pions

Photons in small systems

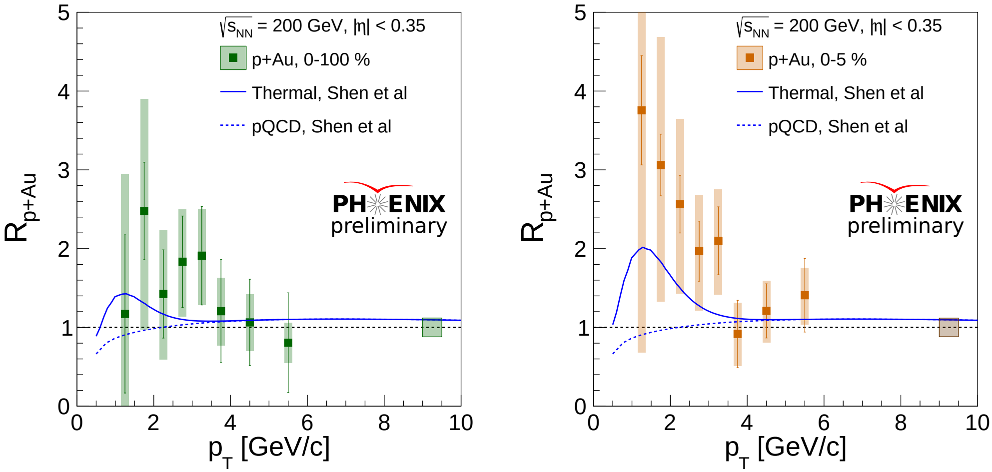


Photons in small systems



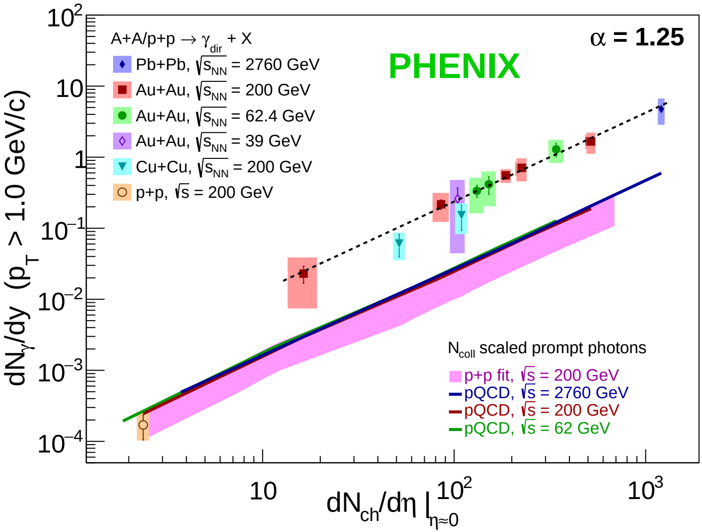
- Thermal(-ish) photons in p+Au?

Photons in small systems



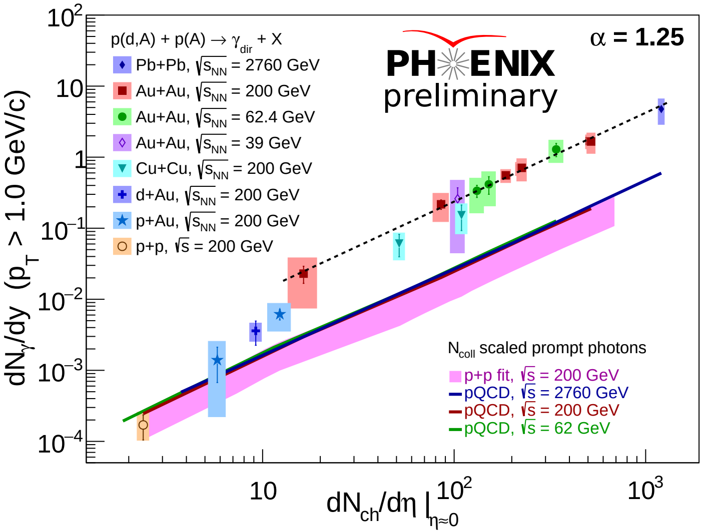
- Thermal(-ish) photons in p+Au? Theory from Phys. Rev. C 95, 014906 (2017)

Photon yields



Common scaling for Au+Au and Pb+Pb at different energies; very different from N_{coll}-scaled $p+p$

Photon yields

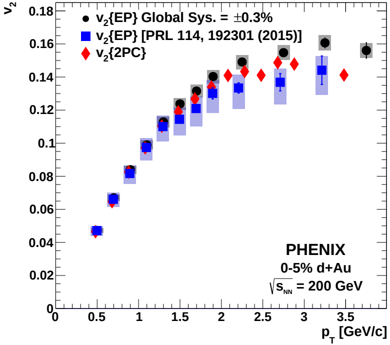


Common scaling for Au+Au and Pb+Pb at different energies; very different from N_{coll}-scaled $p+p$

p+Au and d+Au in between

Comparisons with STAR

Phys. Rev. C 96, 064905 (2017)



FVTX EP: $0.65 < \Delta\eta < 3.35$

MPC EP: $2.75 < \Delta\eta < 4.05$

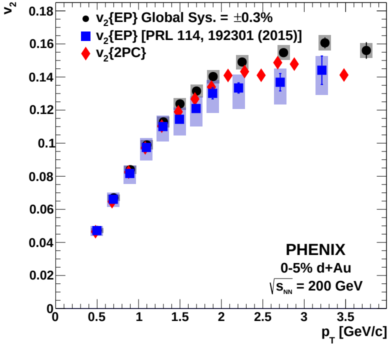
2PC: 3-sub event method with BBC, FVTX, CA

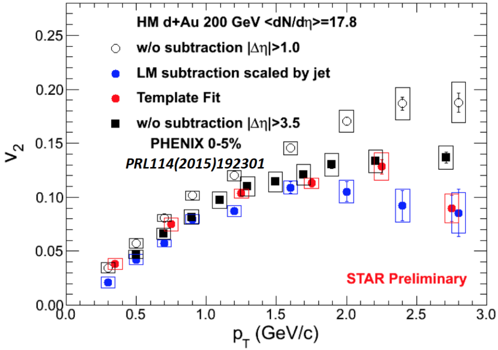
- Nonflow is kinematically suppressed in PHENIX

Comparisons with STAR

Phys. Rev. C 96, 064905 (2017)

S. Huang, Quark Matter 2018

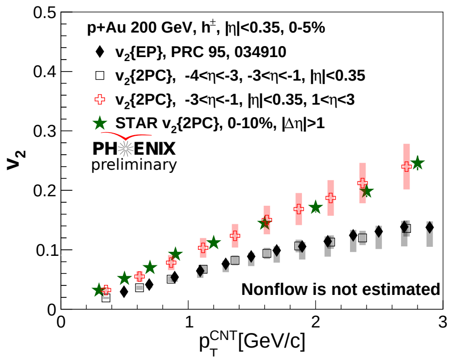


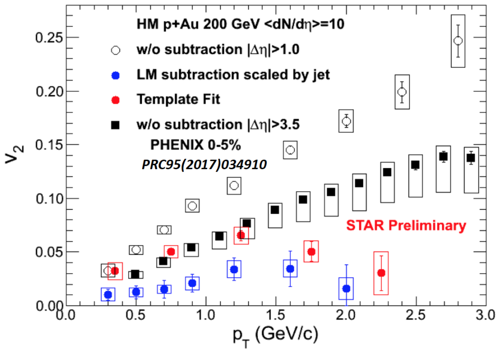


- Nonflow is kinematically suppressed in PHENIX
- STAR measurement uses kinematic range with more nonflow
  —Subtracted result matches PHENIX
- For highest p_T points, oversubtraction is an issue
  —See S. Lim et al, Phys. Rev. C 100, 024908 (2019)

Comparisons with STAR

S. Huang, Quark Matter 2018





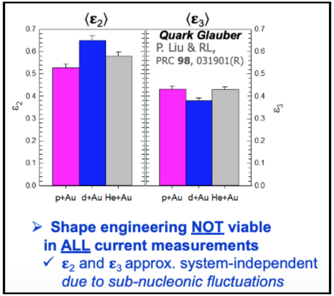
- Nonflow is kinematically suppressed in PHENIX
- We can also choose a different set of detectors to better (NOT exactly) match the STAR acceptance
  —Good agreement with STAR unsubtracted results in this configuration (more nonflow)

Initial eccentricities

Initial Geometry Models

System	Nagle Nucleons w/o NBD fluctuations	Welsh Nucleons w/ NBD fluctuations	Welsh Quarks w/ NBD and Gluon fluctuations	STAR QM19 No Details
ε_2 p+Au	0.23	0.32	0.38	0.52
ε_2 d+Au	0.54	0.48	0.51	0.65
ε_2 ^{3}He+Au	0.50	0.50	0.52	0.58
ε_3 p+Au	0.16	0.24	0.30	0.43
ε_3 d+Au	0.18	0.28	0.31	0.38
ε_3 ^{3}He+Au	0.28	0.32	0.35	0.43

STAR QM19
No mention of p+Au, d+Au, 3He+Au in the PRC reference given!



- Nagle et al: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.113.112301
- Welsh et al: https://journals.aps.org/prc/abstract/10.1103/PhysRevC.94.024919
- STAR QM19: https://indico.cern.ch/event/792436/contributions/3535629/

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  —Note: no mention of small systems in the PRC reference listed