Droplets of quark gluon plasma: small systems at RHIC

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A brief history of heavy ion physics

- 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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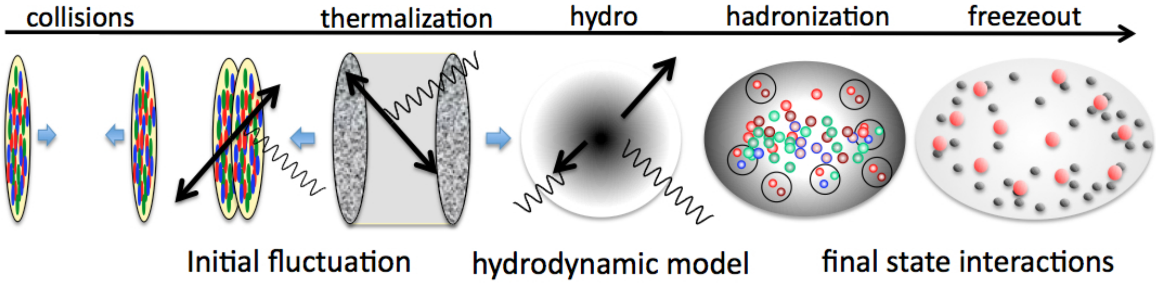
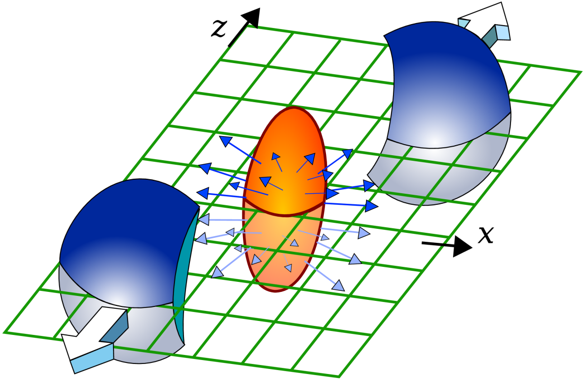
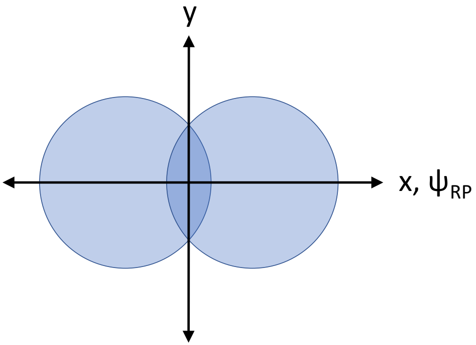
"Twenty years ago, the challenge in heavy ion physics was to find the QGP. Now, the challenge is to not find it." —Jürgen Schukraft, QM17

Standard model of heavy ion physics



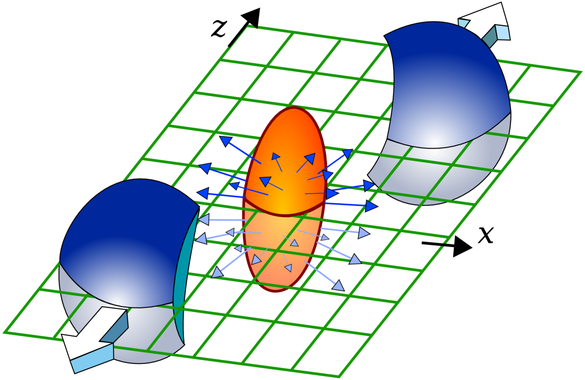
Azimuthal anisotropy measurements

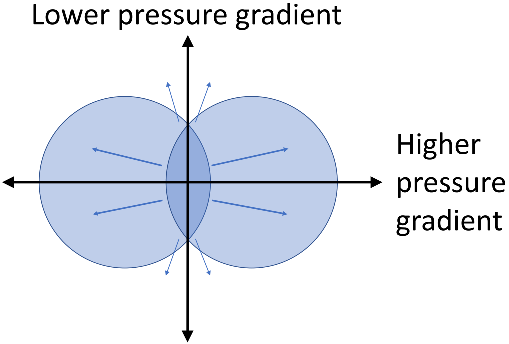




$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos n\varphi \qquad v_n = \langle \cos n\varphi \rangle \qquad \varepsilon_n = \frac{\sqrt{\langle r^2 \cos n\varphi \rangle + \langle r^2 \sin n\varphi \rangle}}{\langle r^2 \rangle}$$

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





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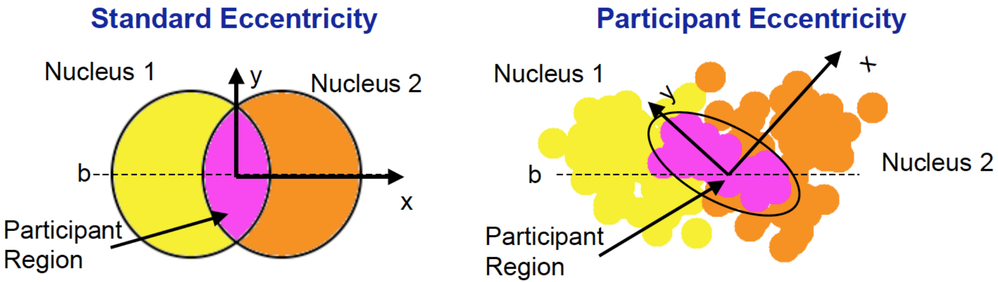
Important discovery in 2005

G. Roland, PHOBOS Plenary, Quark Matter 2005



A nucleus isn't just a sphere

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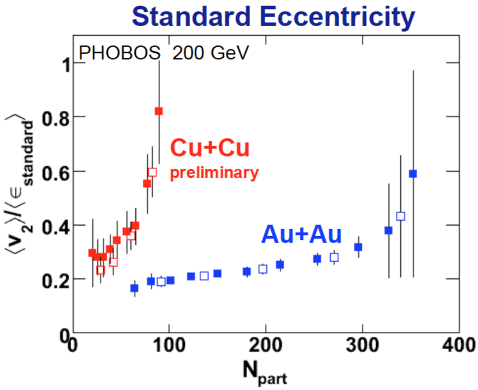

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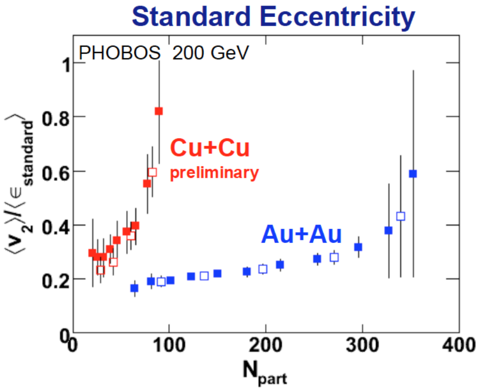
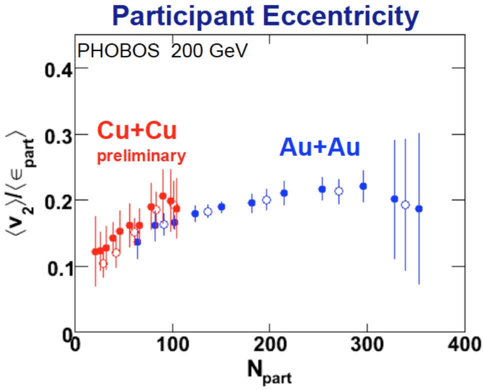
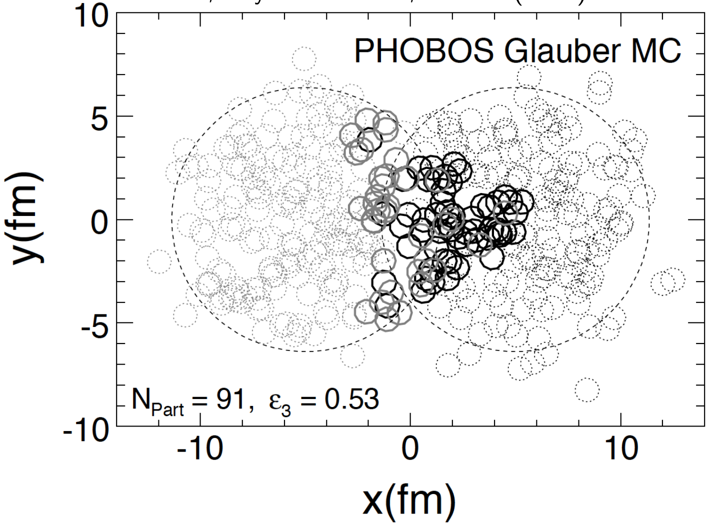




A nucleus isn't just a sphere

Important discovery in 2010

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



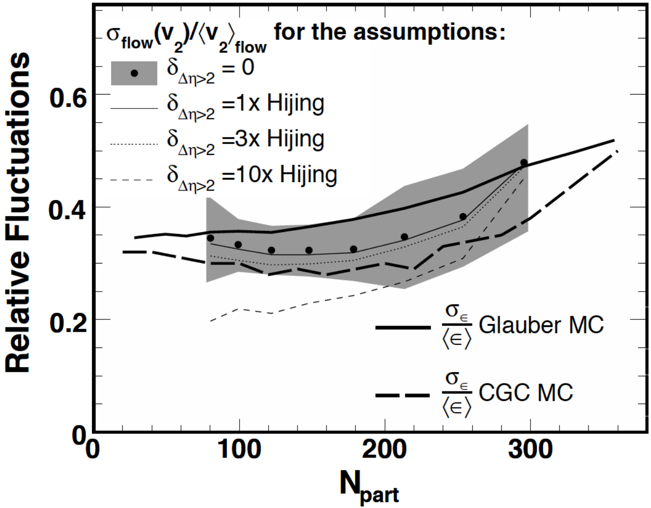
Nucleon fluctuations can produce non-zero ε_n for odd n

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)



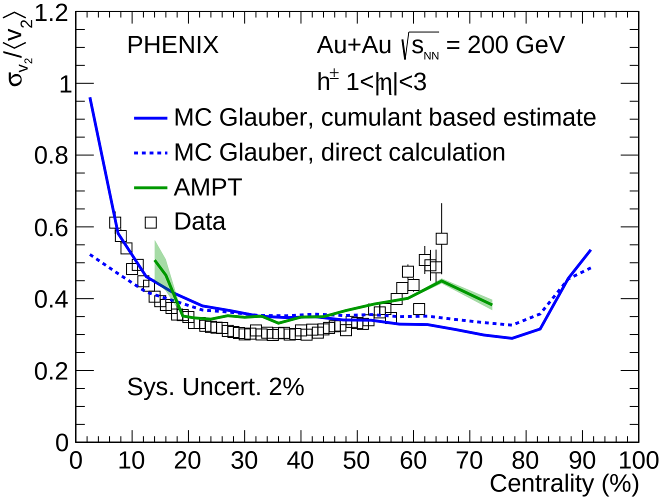
Fluctuations should also be translated, so measure $\sigma_{v_2}/\langle v_2\rangle$

$|\eta| < 1$

Generally good agreement with models of initial geometry

Fluctuations in large systems

PHENIX, arXiv:1804.10024 (accepted by Phys. Rev. C)



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

$1 < |\eta| < 3$

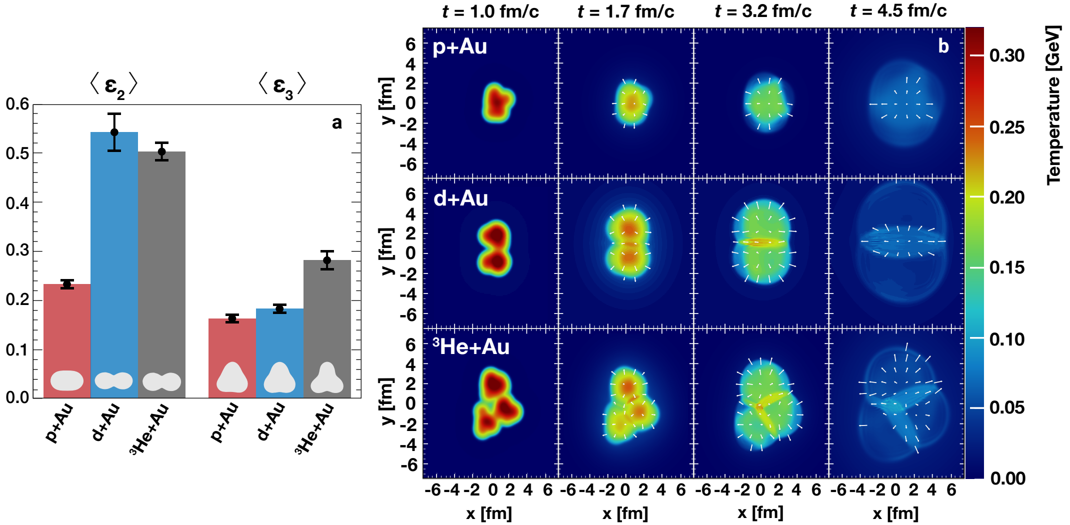
Generally good agreement with models of initial geometry

Intermission

Intermission

Testing hydro by controlling system geometry

Nature Physics 15, 214–220 (2019)



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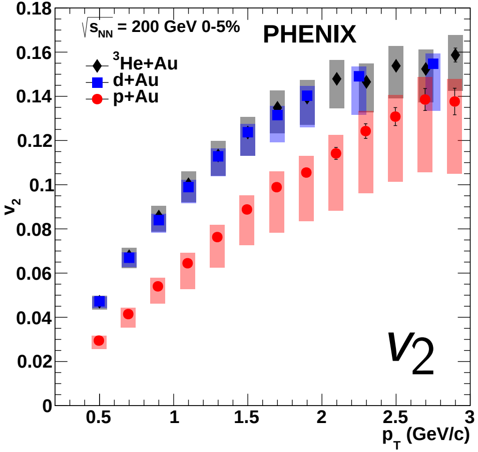
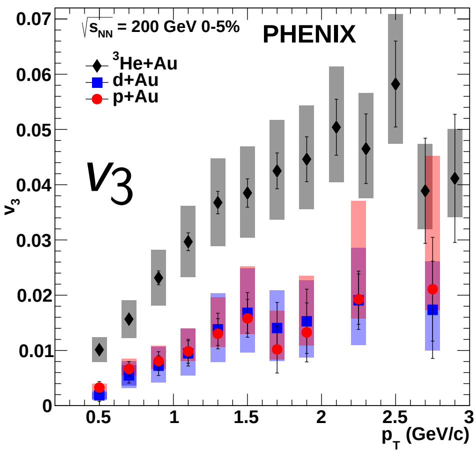
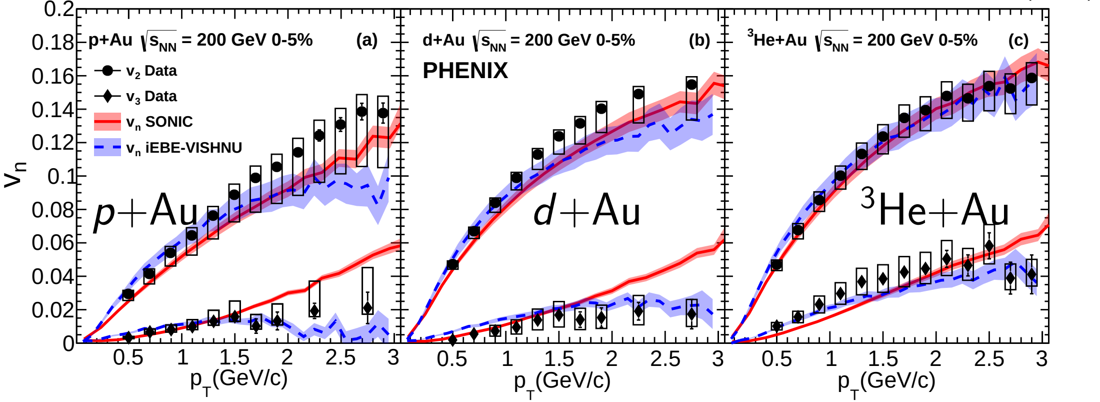




- v_2 and v_3 ordering matches ε_2 and ε_3 ordering in all three systems

Testing hydro by controlling system geometry

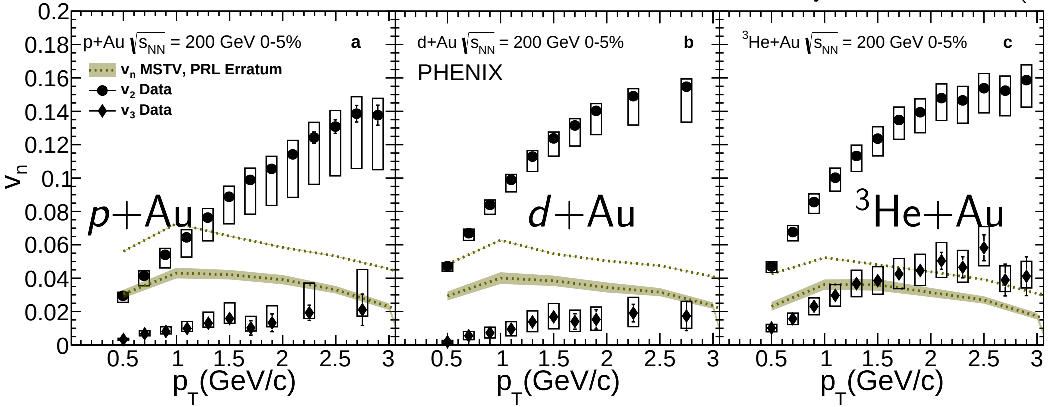
Nature Physics 15, 214–220 (2019)



- v_2 and v_3 vs p_T described very well by hydro in all three systems

Testing hydro by controlling system geometry

Nature Physics 15, 214–220 (2019)



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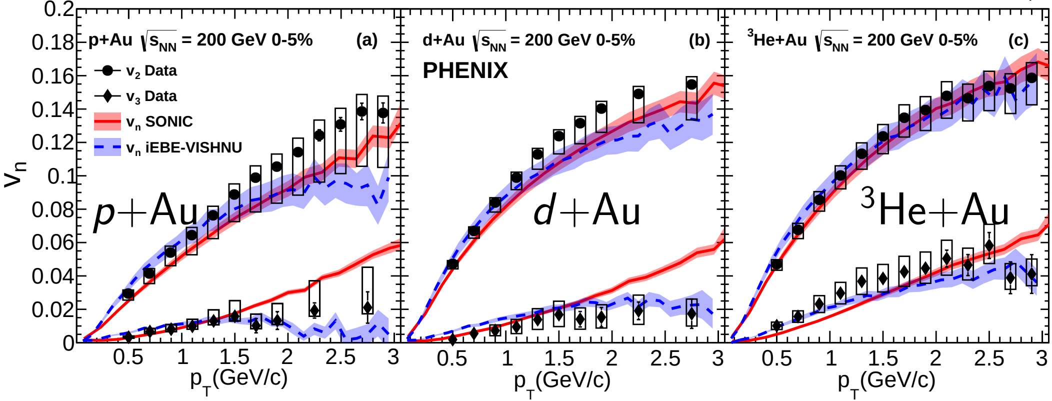

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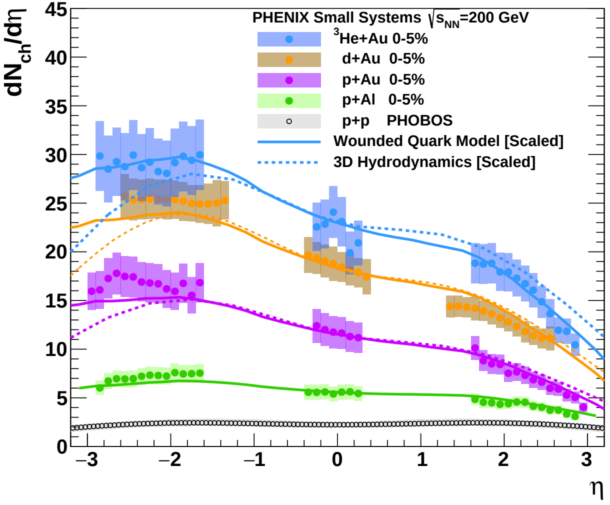
Longitudinal dynamics in small systems

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



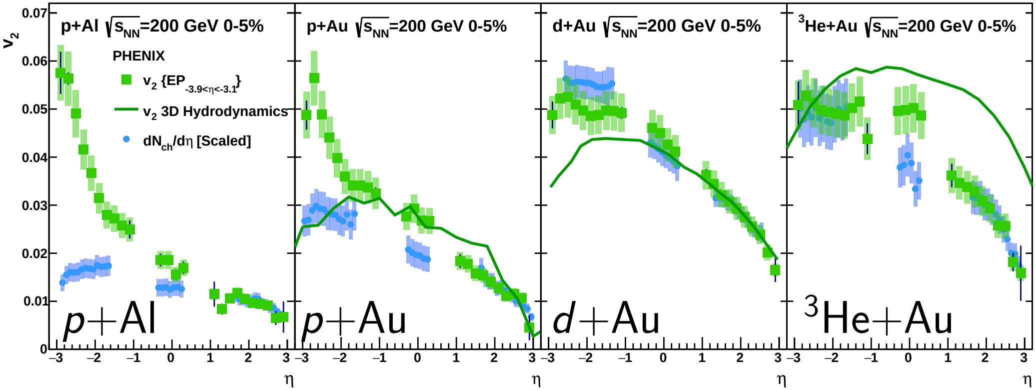
p+Al, p+Au, d+Au, ^{3}He+Au

Good agreement with wounded quark model

Good agreement with 3D hydro

Longitudinal dynamics in small systems

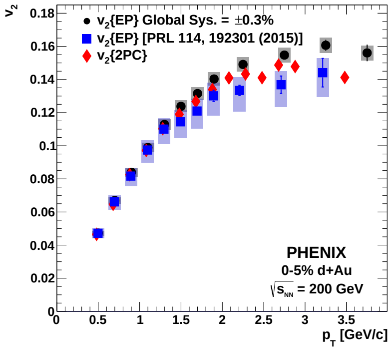
Phys. Rev. Lett. 121, 222301 (2018)



- 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
- Prevalence of non-flow near the EP detector, decreases with increasing system size/multiplicity

Nonflow in small systems

Phys. Rev. C 96, 064905 (2017)



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

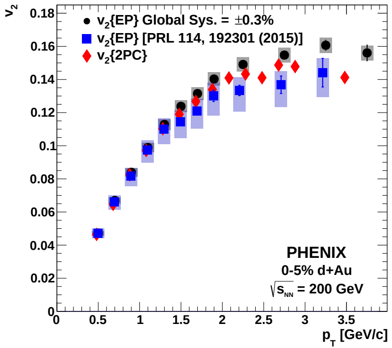
MPC EP: $2.75 < \Delta\eta < 4.05$

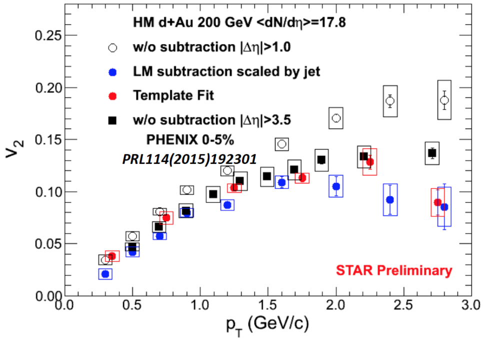
2PC: 3-sub event method with BBC, FVTX, CA

- Nonflow is kinematically suppressed in PHENIX

Nonflow in small systems

Phys. Rev. C 96, 064905 (2017) | S. Huang, Quark Matter 2018

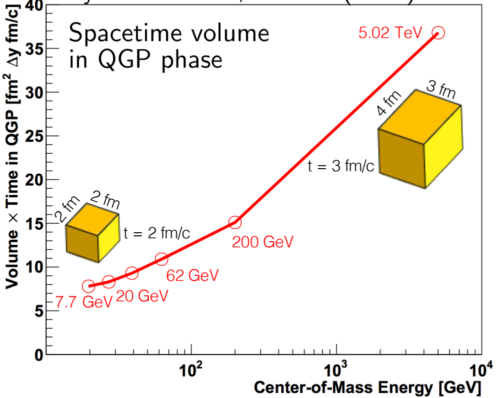




- Nonflow is kinematically suppressed in PHENIX
- STAR measurement uses kinematic range with more nonflow
  —Subtracted result matches PHENIX
- For highest p_T points, oversubtraction is an issue
  —See S. Lim et al, Phys. Rev. C 100, 024908 (2019)

Testing hydro by controlling system size and life time

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

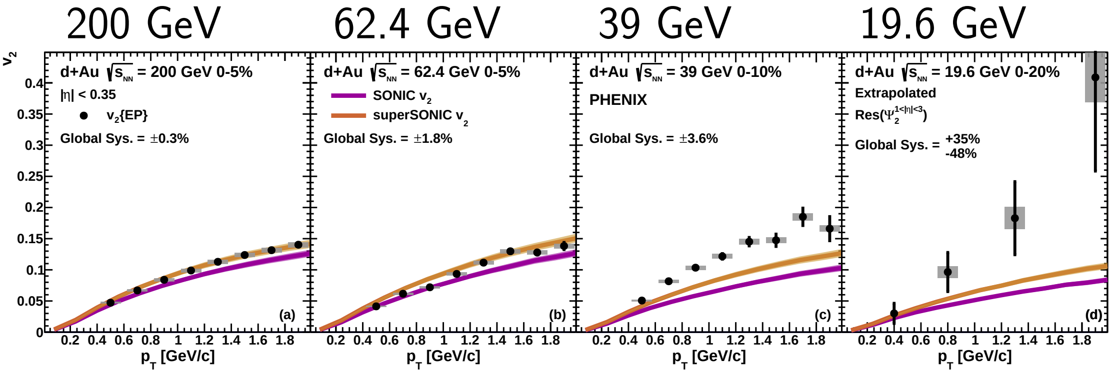


Geometry in d+Au collisions dominated by deuteron shape, thus largely independent of collision energy

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

d+Au beam energy scan

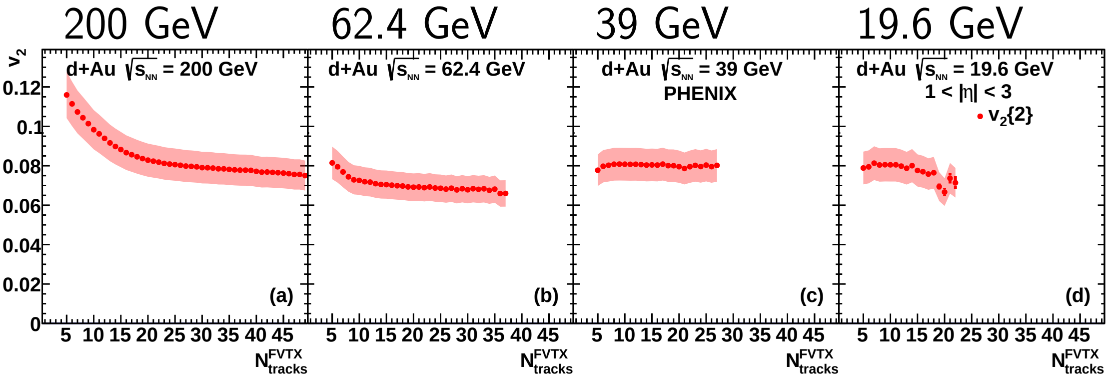
Phys. Rev. C 96, 064905 (2017)



- 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)



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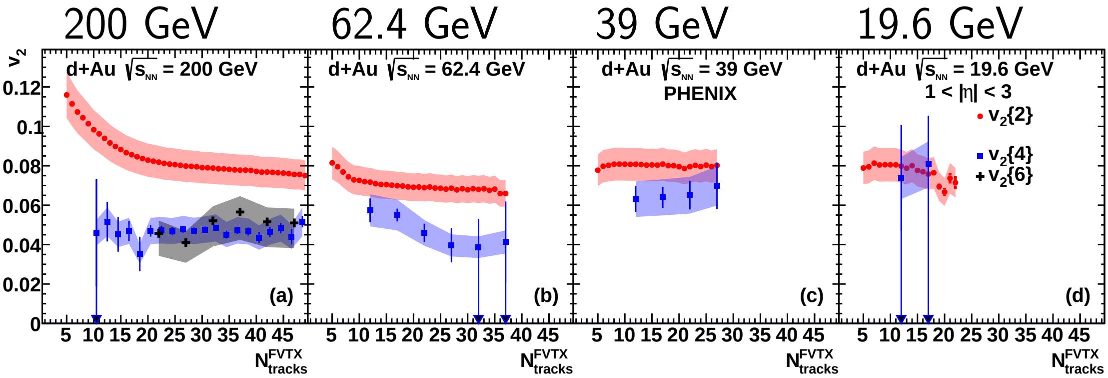

- Measurement of $v_2\{6\}$ in d+Au at 200 GeV and $v_2\{4\}$ in d+Au at all energies

d+Au beam energy scan

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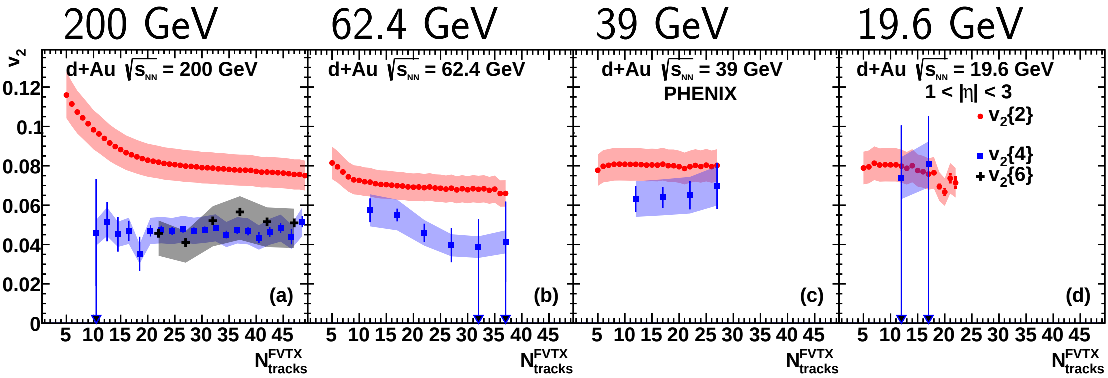


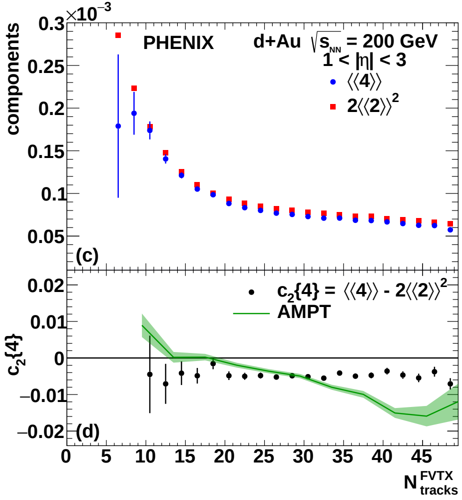
- Measurement of $v_2\{6\}$ in d+Au at 200 GeV and $v_2\{4\}$ in d+Au at all energies
- Multiparticle correlations can be a good indicator of collectivity

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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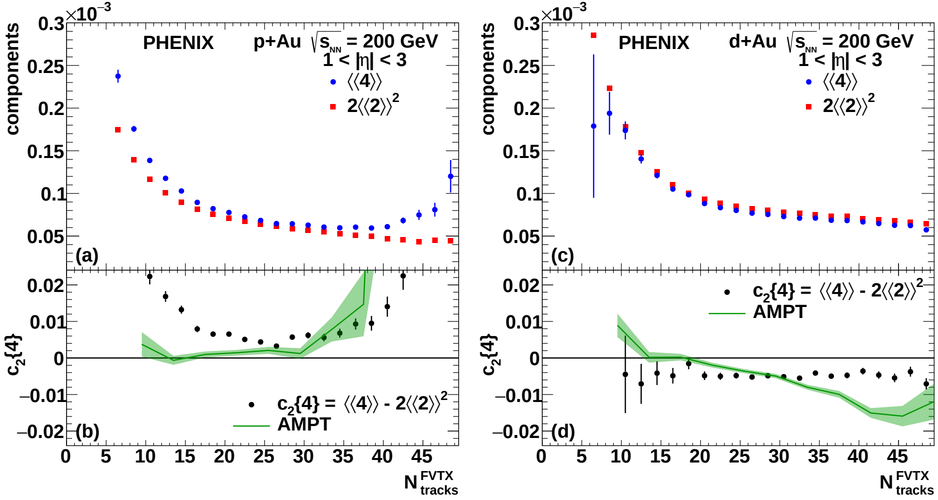

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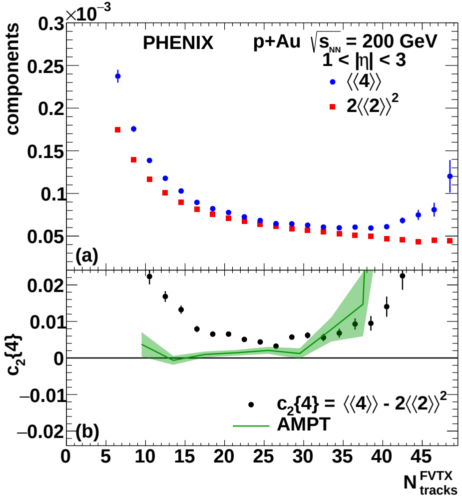

$c_2\{4\}$ is positive in p+Au

Can we blame this on nonflow?

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

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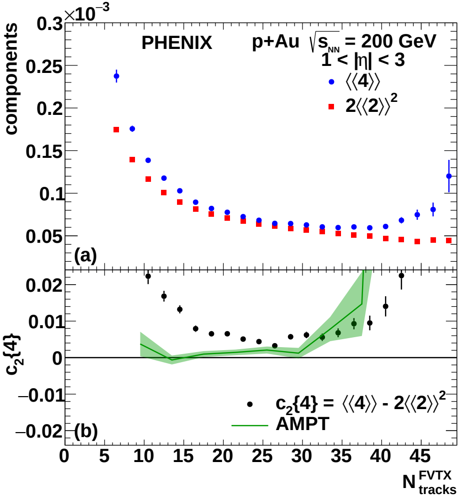
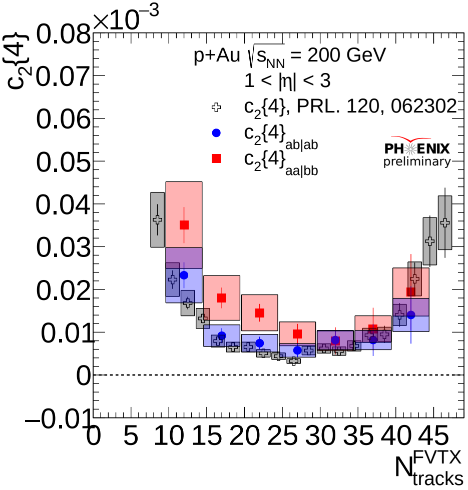
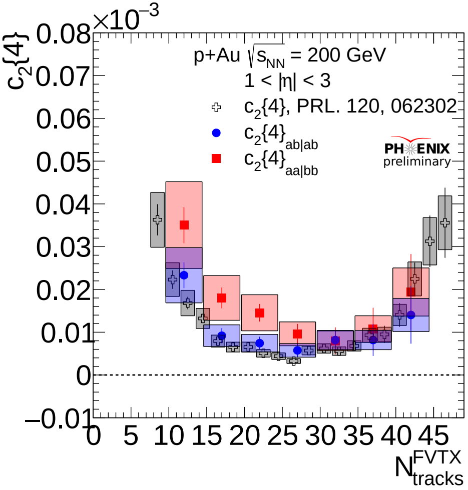




Phys. Rev. Lett. 120, 062302 (2018)

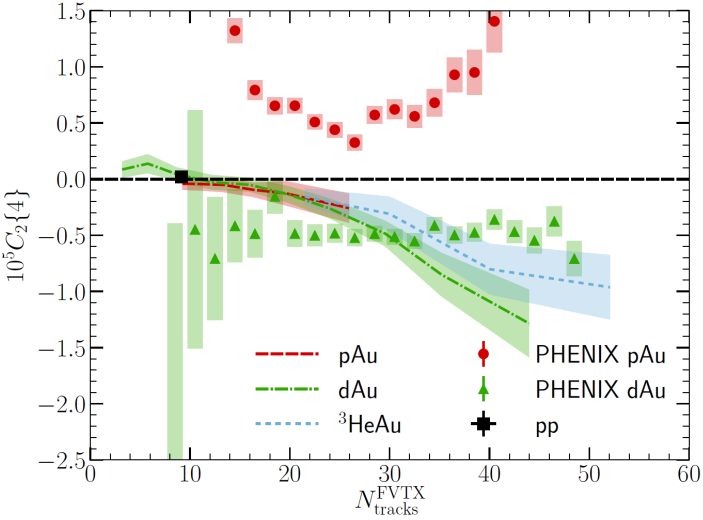
Use of subevents further suppresses nonflow

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



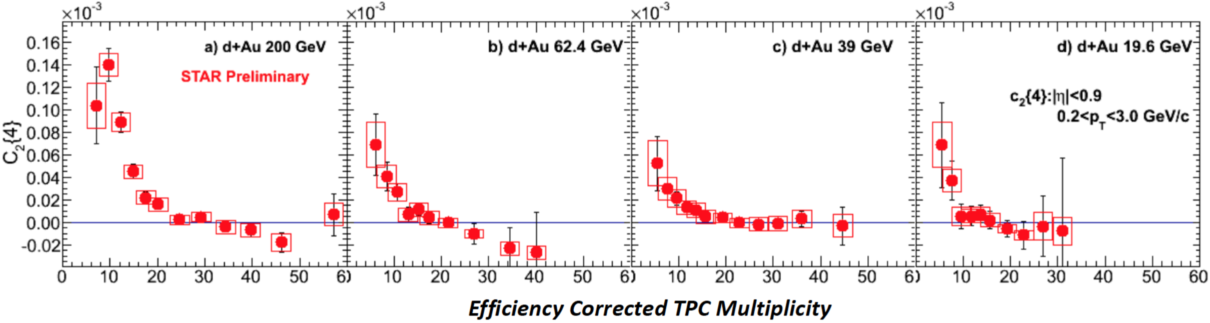
Cumulants are computationally expensive in hydro theory, so not as well-studied

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

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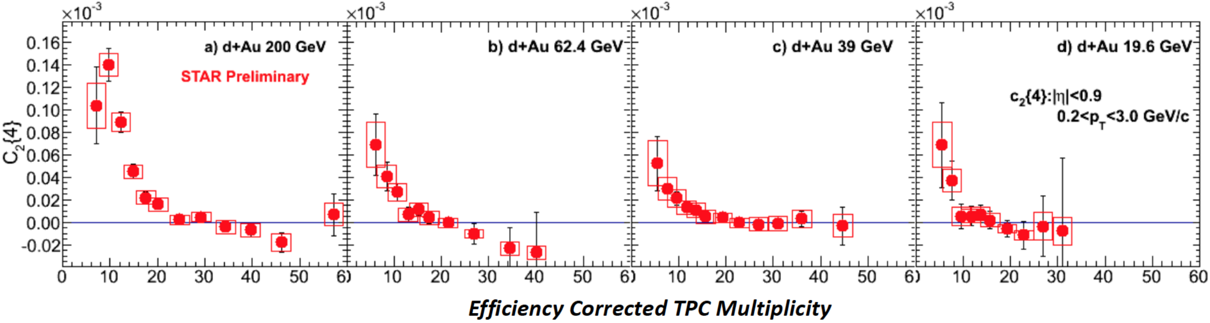
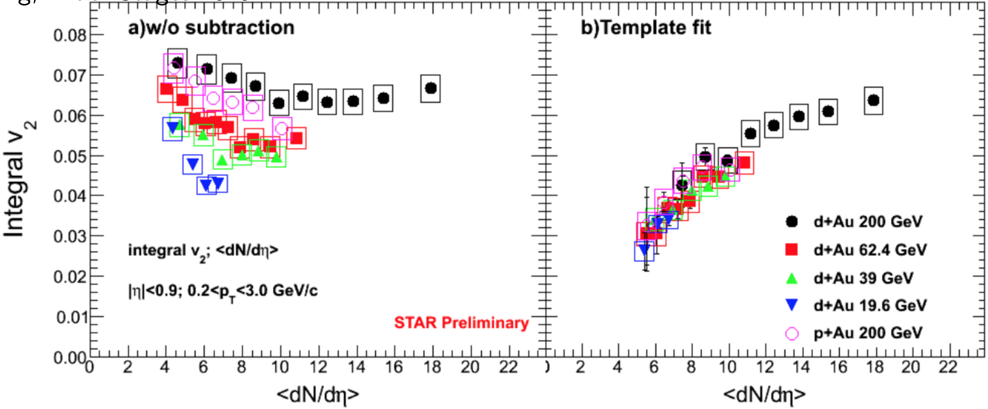


- STAR sees negative $c_2\{4\}$ in d+Au, qualitatively consistent with PHENIX
- The differences in kinematics between the two experiments are important
- In fact, the STAR kinematics are better suited to comparison to 2+1D hydro
  —Unfortunately, the statistical precision is limited

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

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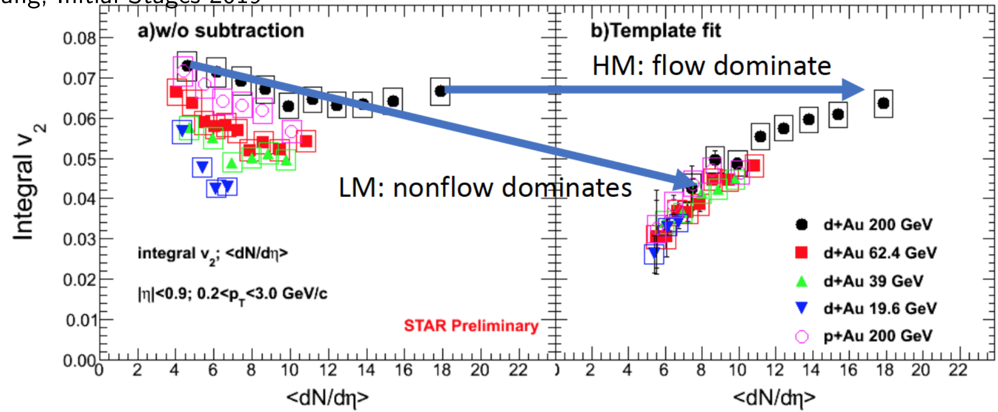

- STAR $v_2\{2\}$ qualitatively like PHENIX (important: different kinematics)
- High multiplicity dominated by collective flow

d+Au beam energy scan

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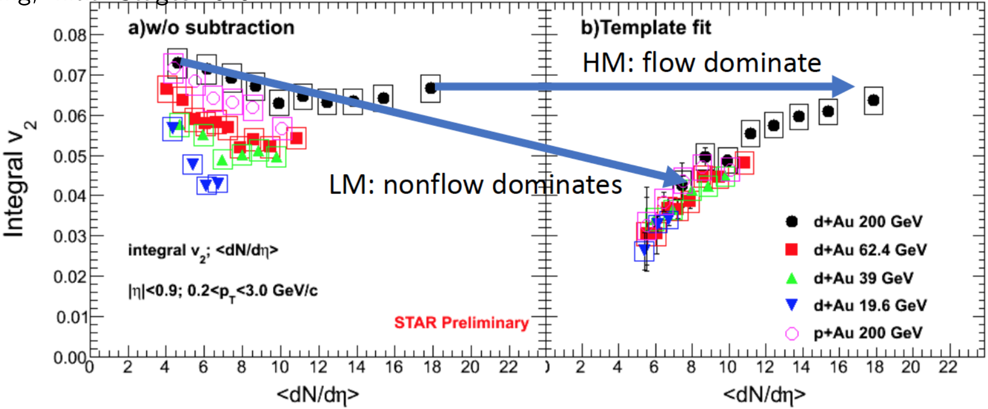
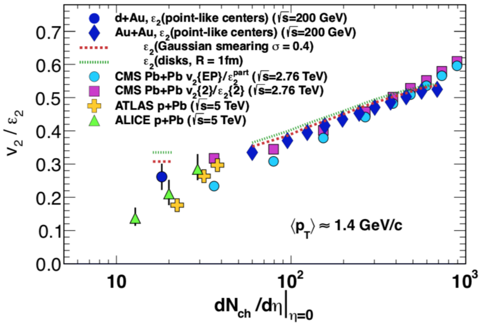


- STAR $v_2\{2\}$ qualitatively like PHENIX (important: different kinematics)
- High multiplicity dominated by collective flow
- One needs to be careful about assumptions in nonflow subtraction methods —See S. Lim et al, Phys. Rev. C 100, 024908 (2019)

From small systems to large

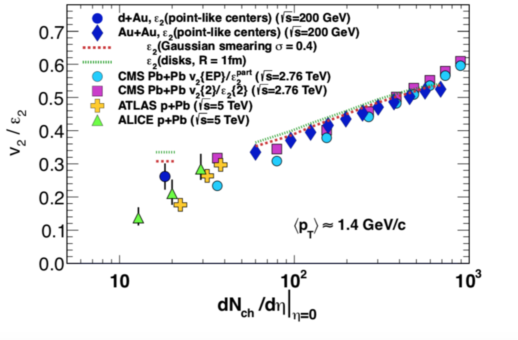
PHENIX, PRL 111 212301 (2013)



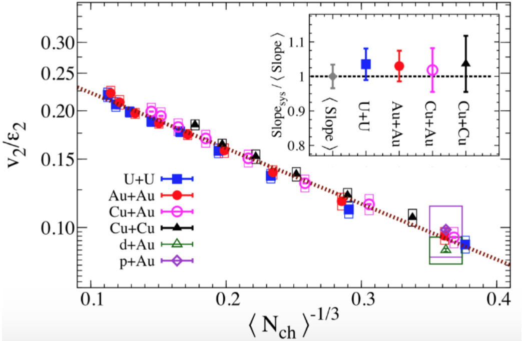
- Simultaneous scaling of eccentricity and size/multiplicity

From small systems to large

PHENIX, PRL 111 212301 (2013)



STAR, PRL 122 172301 (2019)



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From small systems to large

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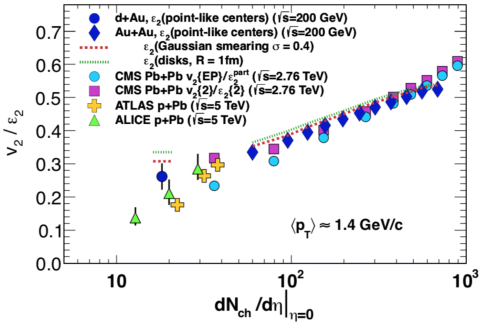

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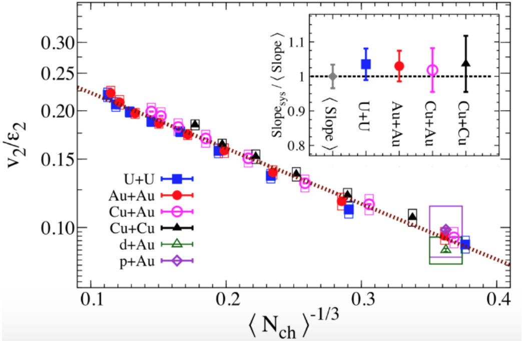

- Simultaneous scaling of eccentricity and size/multiplicity
- All systems follow the same trend

From small systems to large

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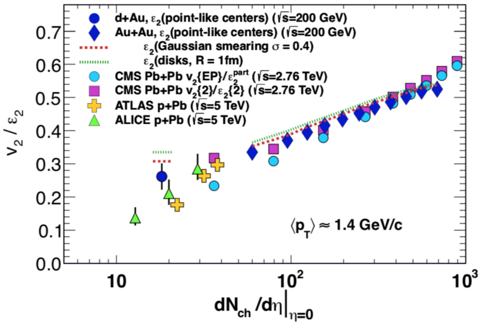

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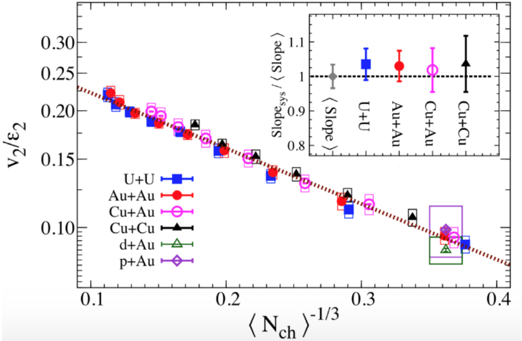


- Simultaneous scaling of eccentricity and size/multiplicity
- All systems follow the same trend
- Worth noting the hydro feelings don't like these kinds of simplistic scalings
  —The dynamics are complicated, these scalings assume linear hydro, etc

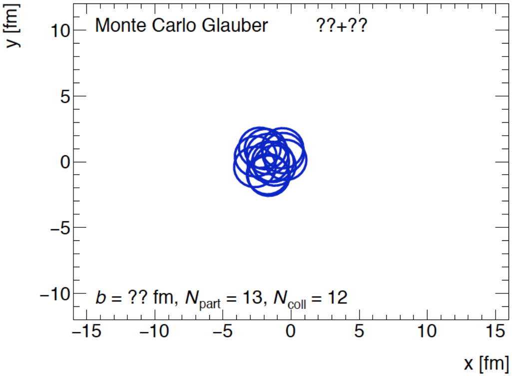
Summary

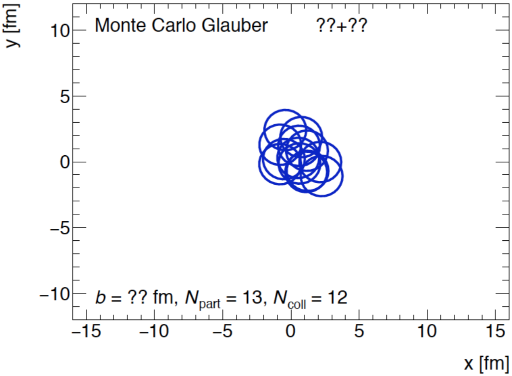
- Hydrodynamics translates initial geometrical shape into final state azimuthal anisotropies
- Evidence of this translation is seen in small and large systems
- The v_2 and v_3 in p+Au, d+Au, and ^{3}He+Au qualitatively follow the geometrical ordering of the initial state
- The v_2 and v_3 in p+Au, d+Au, 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

Which is which?

Figures courtesy D. V. Perepelitsa

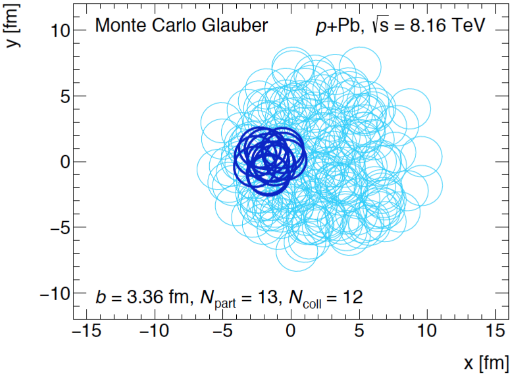


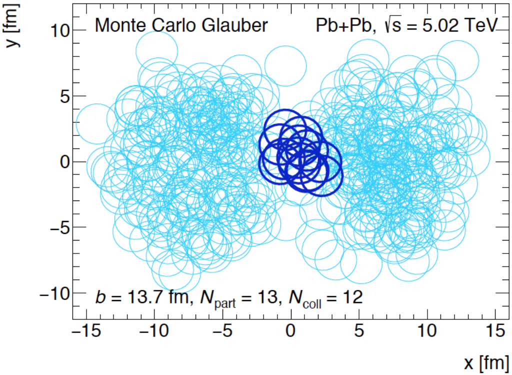


...maybe we shouldn't be so surprised?

Which is which?

Figures courtesy D. V. Perepelitsa





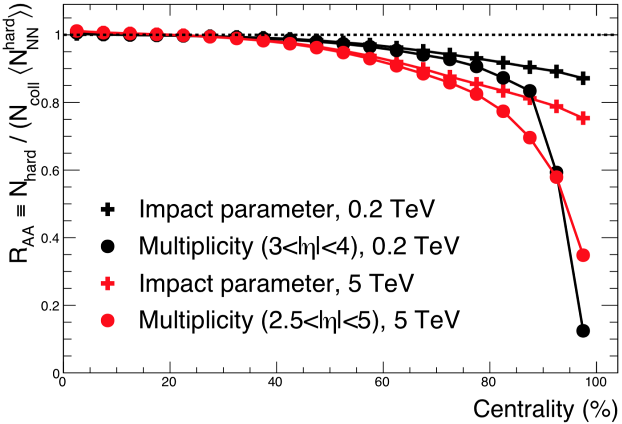
...maybe we shouldn't be so surprised?

Main point of controversy: absence of particle suppression

- A wide variety of hard scattering measurements suggest QGP formation in $A+A$ collisions
  —Single particle measurements
  —Hadron-hadron correlations
  —Jet-hadron correlations
  —Jet-jet correlations
  —Photon-hadron correlations
  —Photon-jet correlations
- These effects *appear* to be present in all centralities
- These effects are not present in small systems

Selection bias

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



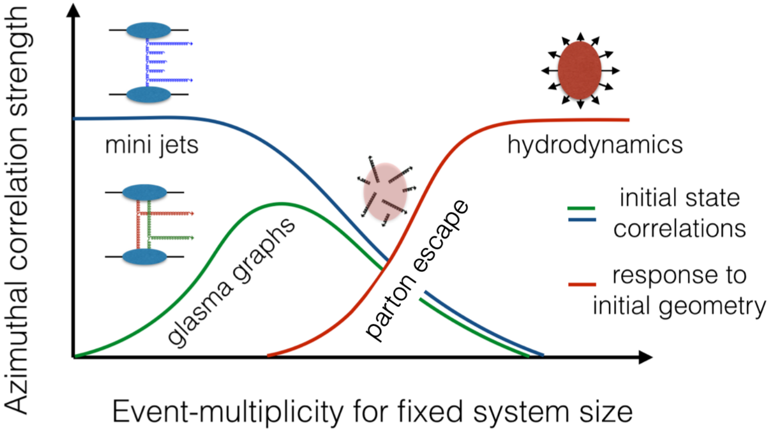
Apparent suppression in peripheral A+A is probably due to event selection bias effects

- 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"

Competing theories

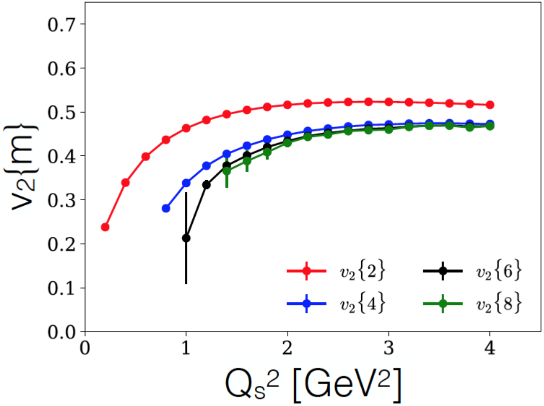
Where are we?

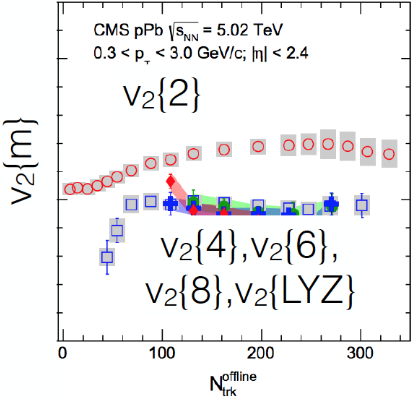
Figure: S. Schlitching, QM2015.



CGC results on cumulants

Phys. Rev. Lett. 120, 042002 (2018)

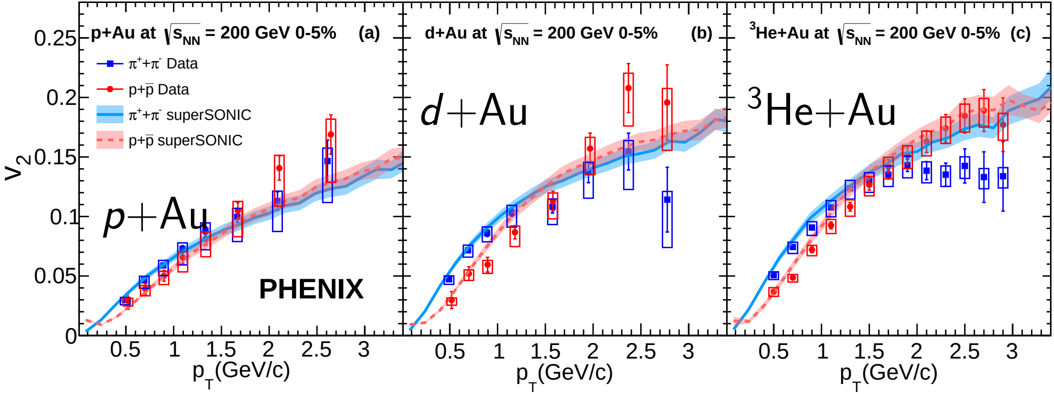




- Abelian calculations ($N_c = 1$) can produce correct ordering of $v_2\{2\}$, $v_2\{4\}$, $v_2\{6\}$, $v_2\{8\}$
- Problem: QCD is non-Abelian ($N_c = 3$)
- In full calculation, higher cumulants are N_c^2-suppressed, so the ordering fails to match data

Small systems geometry scan

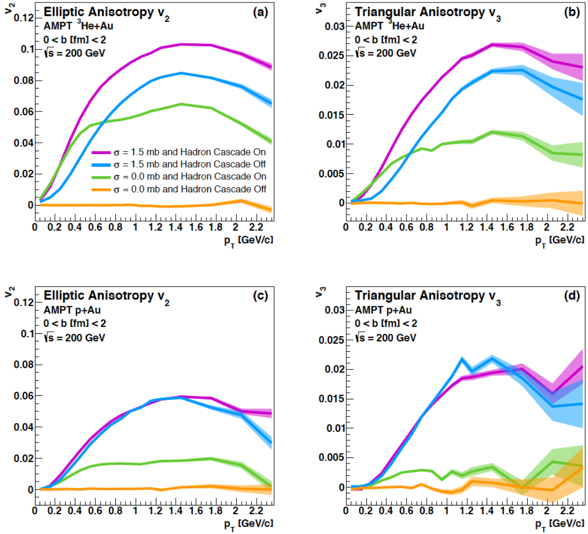
Phys. Rev. C 97, 064904 (2018)



- Identified particle v_2 vs p_T in p+Au, d+Au, and ^{3}He+Au
  —Mass ordering well-described by hydro

AMPT with no scattering

J.D. Orjuela Koop et al Phys. Rev. C 92, 054903 (2015)



- Turn off scattering in AMPT—remove all correlations with initial geometry $\sigma_{parton} = 0$ and $\sigma_{hadron} = 0$
- Participant plane v_2 goes to zero
- Other sources of correlation remain—non-flow

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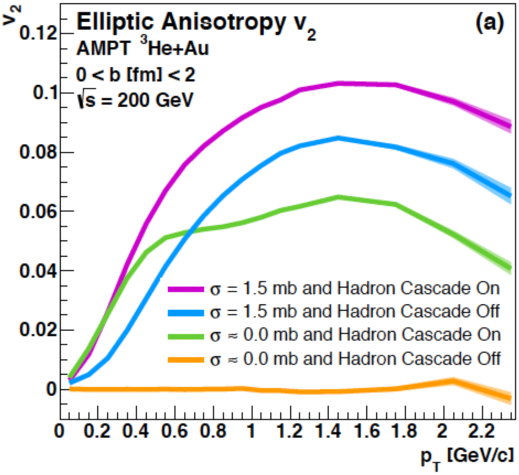

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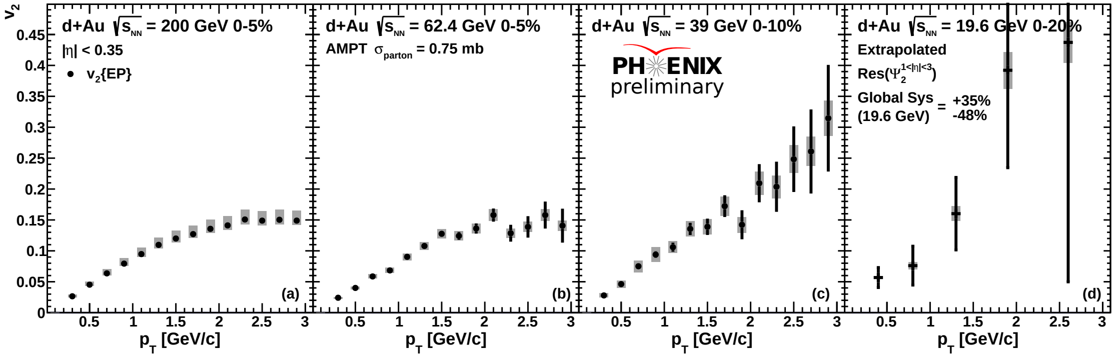
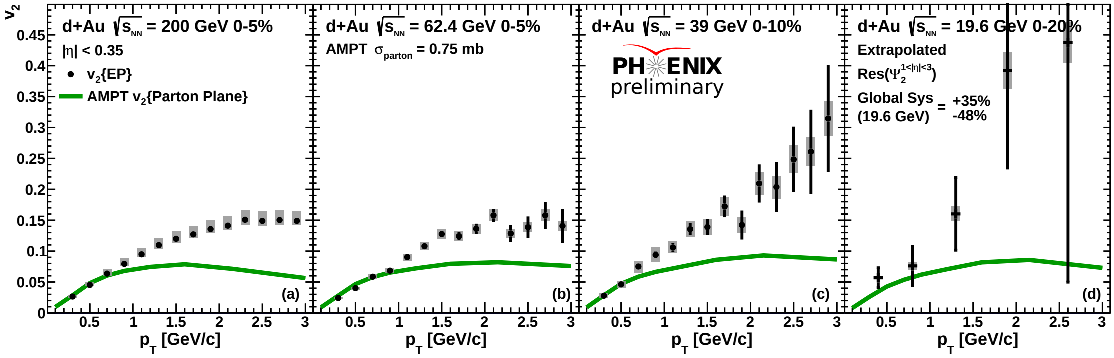
v_2 vs p_T, comparisons to AMPT

Phys. Rev. C 96, 064905 (2017)



v_2 vs p_T, comparisons to AMPT

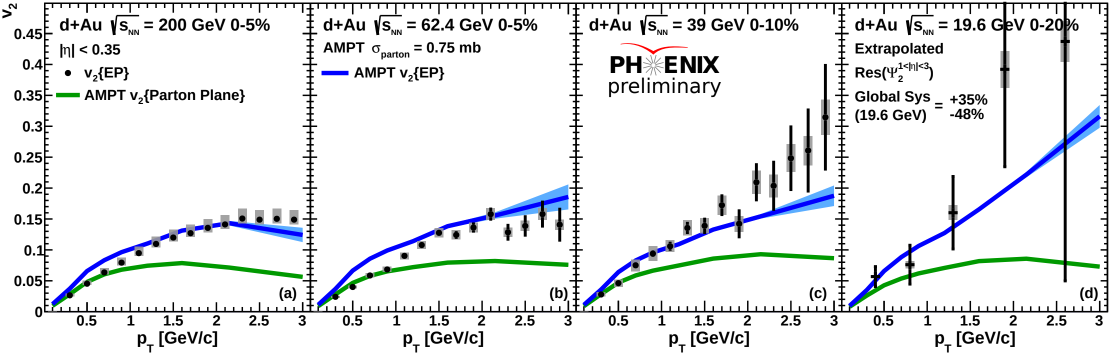
Phys. Rev. C 96, 064905 (2017)



- AMPT flow only shows good agreement at low p_T and all energies

v_2 vs p_T, comparisons to AMPT

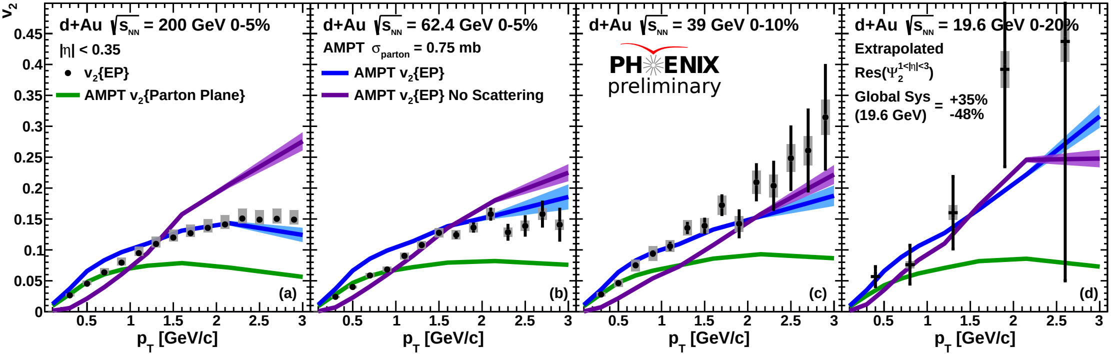
Phys. Rev. C 96, 064905 (2017)



- AMPT flow only shows good agreement at low p_T and all energies
- AMPT flow+non-flow shows reasonable agreement for all p_T and all energies

v_2 vs p_T, comparisons to AMPT

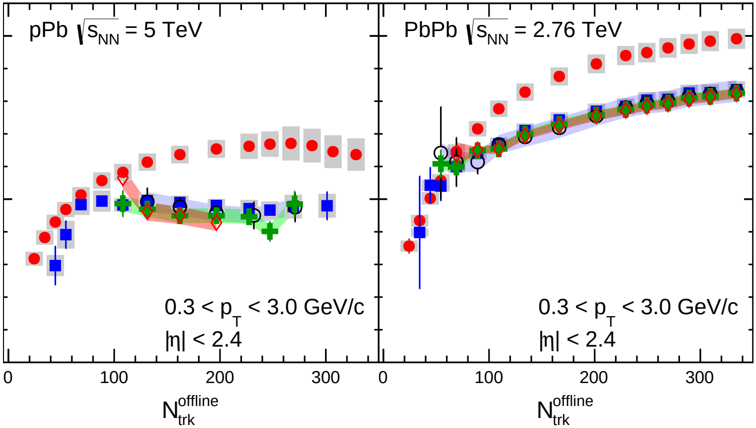
Phys. Rev. C 96, 064905 (2017)



- AMPT flow only shows good agreement at low p_T and all energies
- AMPT flow+non-flow shows reasonable agreement for all p_T and all energies
- AMPT non-flow only far under-predicts for low p_T, too high for high p_T

Multiparticle correlations in large and small systems

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

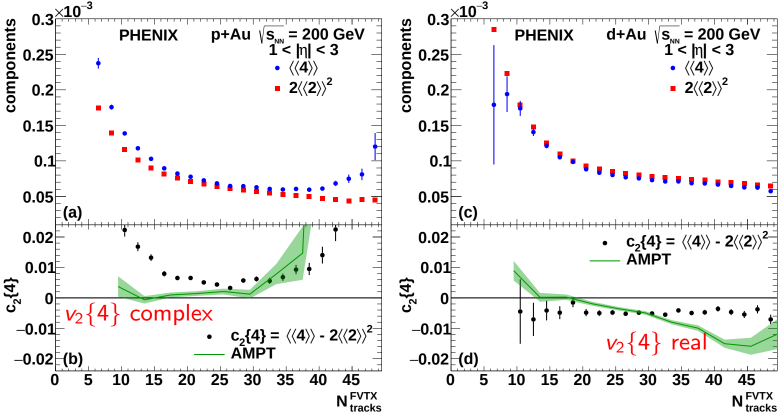


$$v_n^2\{2\} = \langle v_n \rangle^2 + \sigma^2$$
$$v_n^2\{4,6,8\} \approx \langle v_n \rangle^2 - \sigma^2$$

- Multiparticle correlations reflect global correlation from geometry in Pb+Pb, Au+Au, Cu+Cu, etc
- The p+Pb has a remarkably similar pattern as the Pb+Pb

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

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



- Is the sign of $c_2\{4\}$ a good indicator of collectivity? No.
- Fluctuations could dominate in the p+Au...

Back to basics (a brief excursion)

The (raw) moments of a probability distribution function $f(x)$:

$$\mu_n = \langle x^n \rangle \equiv \int_{-\infty}^{+\infty} x^n f(x) dx$$

The moment generating function:

$$M_x(t) \equiv \langle e^{tx} \rangle = \int_{-\infty}^{+\infty} e^{tx} f(x) dx = \int_{-\infty}^{+\infty} \sum_{n=0}^{\infty} \frac{t^n}{n!} x^n f(x) dx = \sum_{n=0}^{\infty} \mu_n \frac{t^n}{n!}$$

Moments from the generating function:

$$\mu_n = \left. \frac{d^n M_x(t)}{dt^n} \right|_{t=0}$$

Key point: the moment generating function uniquely describe $f(x)$

Back to basics (a brief excursion)

Can also uniquely describe $f(x)$ with the cumulant generating function:

$$K_x(t) \equiv \ln M_x(t) = \sum_{n=0}^{\infty} \kappa_n \frac{t^n}{n!}$$

Cumulants from the generating function:

$$\kappa_n = \left. \frac{d^n K_x(t)}{dt^n} \right|_{t=0}$$

Since $K_x(t) = \ln M_x(t)$, $M_x(t) = \exp(K_x(t))$, so

$$\mu_n = \left. \frac{d^n \exp(K_x(t))}{dt^n} \right|_{t=0}, \quad \kappa_n = \left. \frac{d^n \ln M_x(t)}{dt^n} \right|_{t=0}$$

End result: (details left as an exercise for the interested reader)

$$\mu_n = \sum_{k=1}^{n} B_{n,k}(\kappa_1, ..., \kappa_{n-k+1}) \qquad = B_n(\kappa_1, ..., \kappa_{n-k+1})$$

$$\kappa_n = \sum_{k=1}^{n} (-1)^{k-1}(k-1)! B_{n,k}(\mu_1, ..., \mu_{n-k+1}) \quad = L_n(\kappa_1, ..., \kappa_{n-k+1})$$

Back to basics (a brief excursion)

Evaluating the Bell polynomials gives

$$\begin{aligned}
\langle x \rangle &= \kappa_1 \\
\langle x^2 \rangle &= \kappa_2 + \kappa_1^2 \\
\langle x^3 \rangle &= \kappa_3 + 3\kappa_1\kappa_2 + \kappa_1^3 \\
\langle x^4 \rangle &= \kappa_4 + 4\kappa_1\kappa_3 + 3\kappa_2^2 + 6\kappa_1^2\kappa_2 + \kappa_1^4
\end{aligned}$$

One can tell by inspection (or derive explicitly) that κ_1 is the mean, κ_2 is the variance, etc.

Back to basics (a brief excursion)

Subbing in $x = v_n$, $\kappa_2 = \sigma^2$, we find

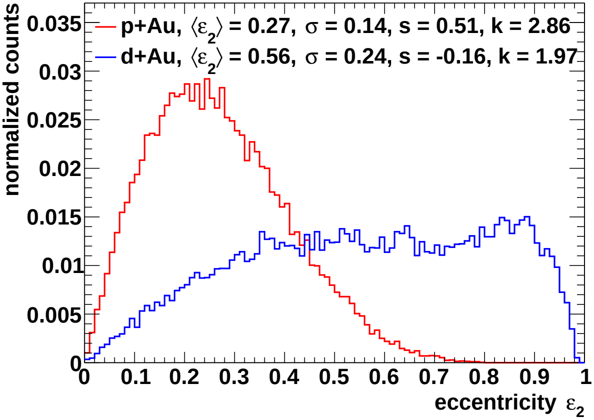
$$\left(\langle v_n^4\rangle = v_n^4 + 6v_n^2\sigma^2 + 3\sigma^4 + 4v_n\kappa_3 + \kappa_4\right)$$
$$-\left(2\langle v_n^2\rangle^2 = 2v_n^4 + 4v_n^2\sigma^2 + 2\sigma^4\right)$$
$$\rightarrow$$
$$\langle v_n^4\rangle - 2\langle v_n^2\rangle^2 = -v_n^4 + 2v_n^2\sigma^2 + \sigma^4 + 4v_n\kappa_3 + \kappa_4$$

Skewness s: $\kappa_3 = s\sigma^3$
Kurtosis k: $\kappa_4 = (k-3)\sigma^4$

$$v_n\{2\} = (v_n^2 + \sigma^2)^{1/2}$$
$$v_n\{4\} = (v_n^4 - 2v_n^2\sigma^2 - 4v_n s\sigma^3 - (k-2)\sigma^4)^{1/4}$$

So the fully general form is a bit more complicated than we tend to think...

Eccentricity distributions and cumulants

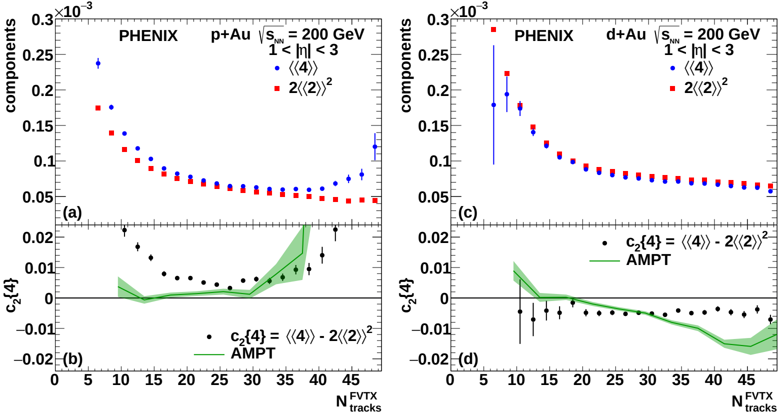


$$\varepsilon_2\{4\} = (\varepsilon_2^4 - 2\varepsilon_2^2\sigma^2 - 4\varepsilon_2 s\sigma^3 - (k-2)\sigma^4)^{1/4}$$

	p+Au	d+Au
ε_2^4	0.00531	0.0983
$2\varepsilon_2^2\sigma^2$	0.00277	0.0370
$4\varepsilon_2 s\sigma^3$	0.00147	-0.0053
$(k-2)\sigma^4$	0.00031	-0.0001

- the variance brings $\varepsilon_2\{4\}$ down (this term gives the usual $\sqrt{v_2^2 - \sigma^2}$)
- positive skew brings $\varepsilon_2\{4\}$ further down, negative skew brings it back up
- kurtosis > 2 brings $\varepsilon_2\{4\}$ further down, kurtosis < 2 brings it back up
  —recall Gaussian has kurtosis $= 3$

Eccentricity distributions and cumulants



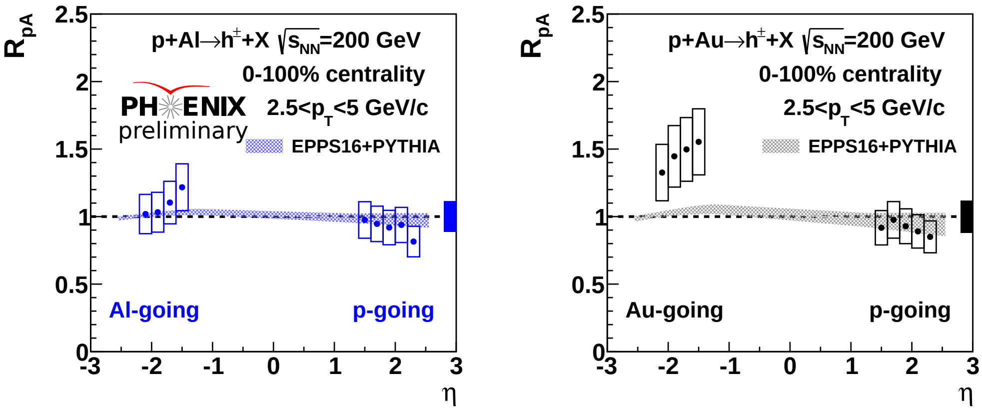
$$v_2\{4\} = (v_2^4 - 2v_2^2\sigma^2 - 4v_2 s\sigma^3 - (k-2)\sigma^4)^{1/4}$$

- Eccentricity fluctuations alone go a long way towards explaining this
- Additional fluctuations in the (imperfect) translation of ε_2 to v_2?

Intermission

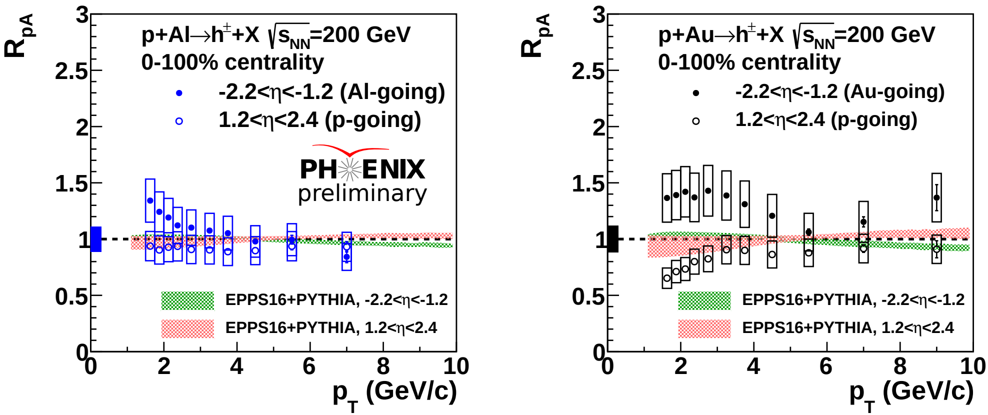
Particle production in small systems

Small systems nuclear modification



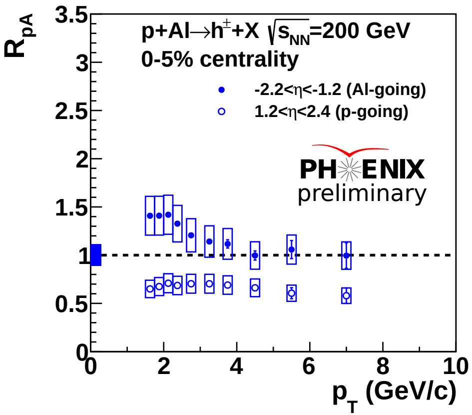
- Forward modification consistent with nPDF effects (EPPS16)

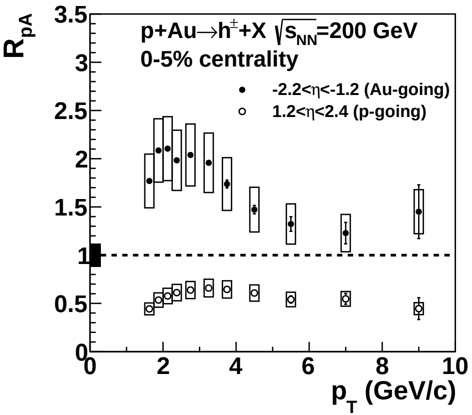
Small systems nuclear modification



- High-p_T modification consistent with nPDF effects (EPPS16)

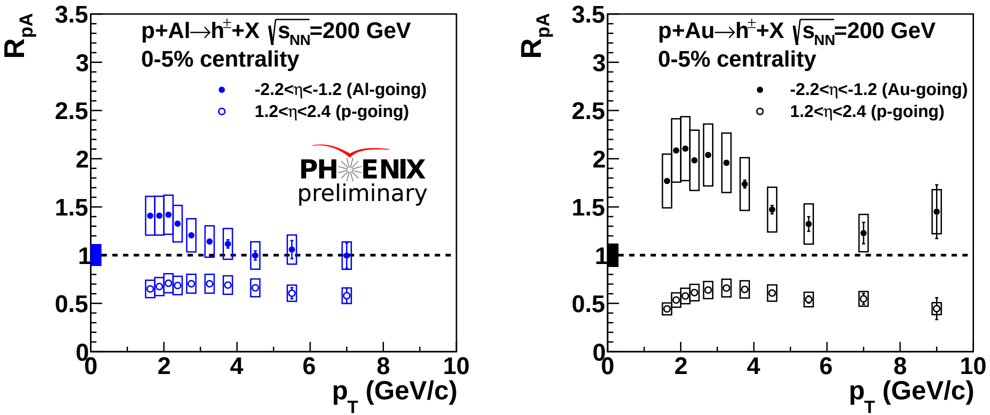
Small systems nuclear modification





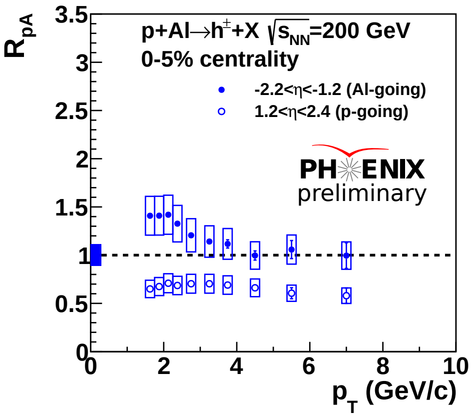
- Stronger effects in central collisions

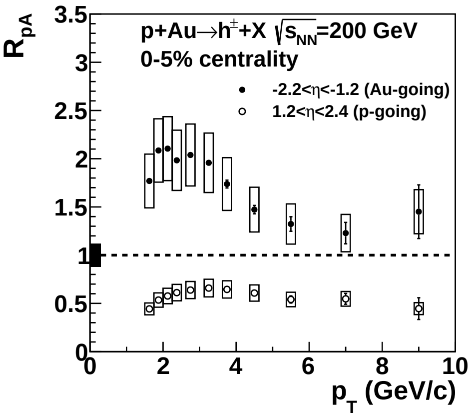
Small systems nuclear modification



- Strong enhancement for backward at intermediate p_T—why?

Small systems nuclear modification

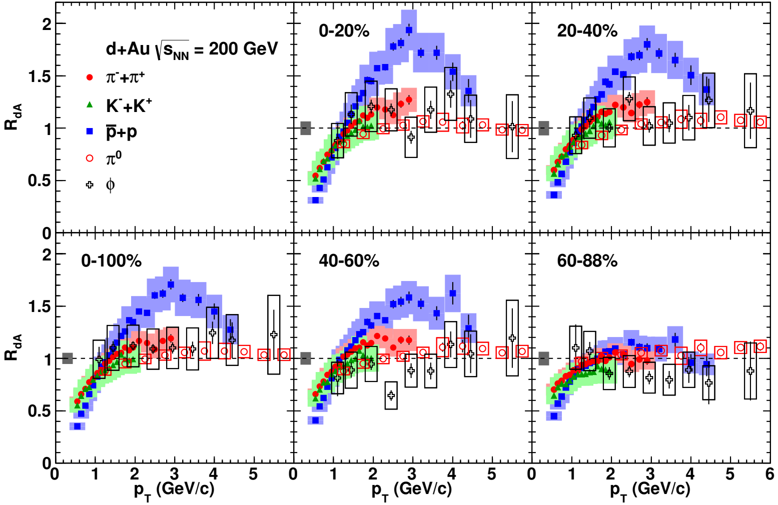




- Strong enhancement for backward at intermediate p_T—why?
- Don't forget: particle species dependence of Cronin! There must be final state effect(s)...

Particle species dependence of "Cronin enhancement"

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

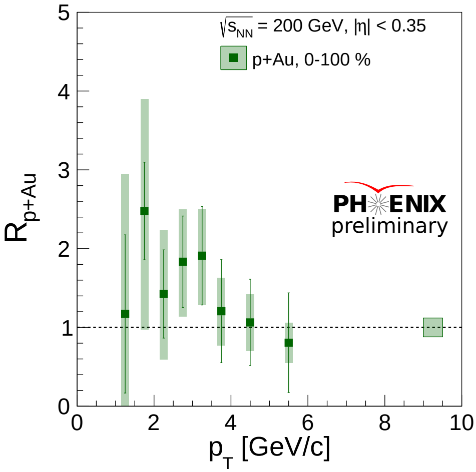


π^+, π^-, π^0,
K^+, K^-,
p, $\bar{p}$,
ϕ

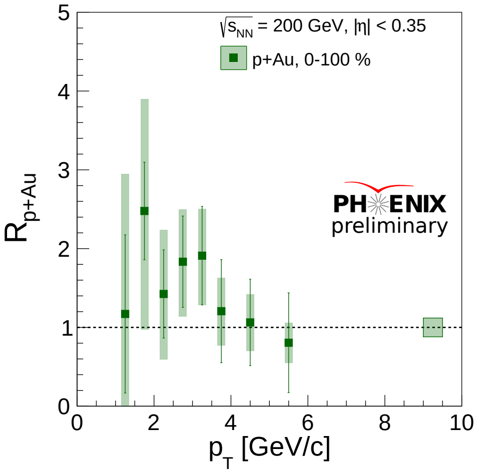
Protons much more strongly modified than pions

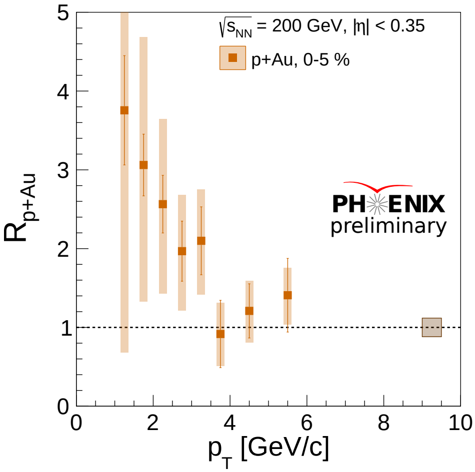
ϕ mesons similar to pions

Photons in small systems



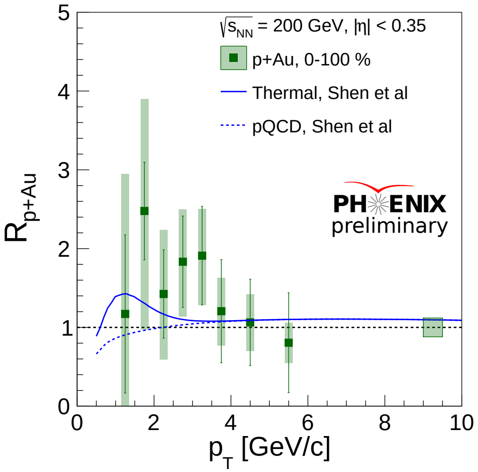
Photons in small systems

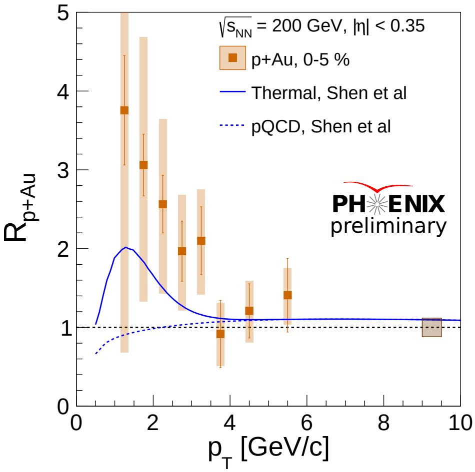




- Thermal photons in p+Au?

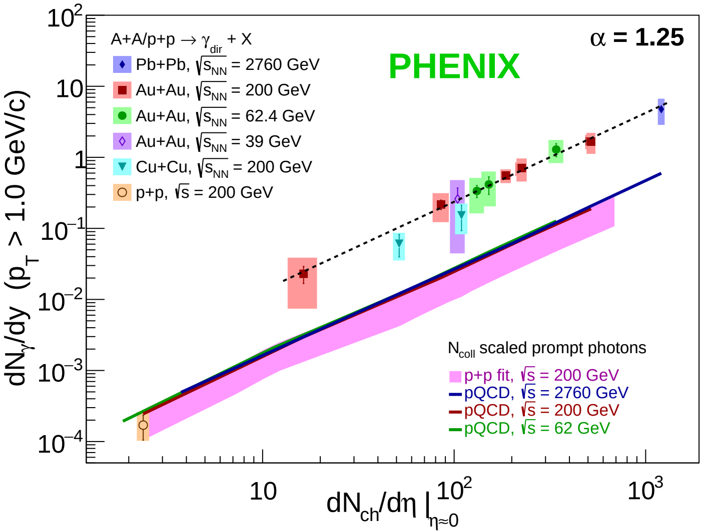
Photons in small systems





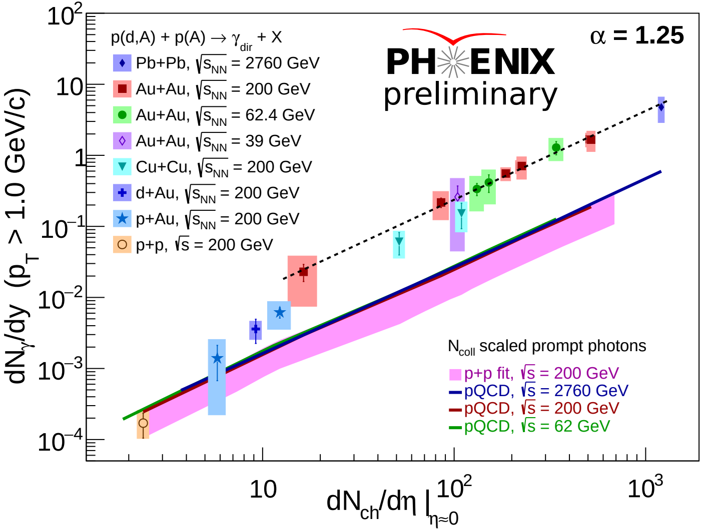
- Thermal photons in p+Au? Theory from Phys. Rev. C 95, 014906 (2017)

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