Flow in small systems: a few recent results

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Утро в сосновом лесу

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A very brief history of recent heavy ion physics

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

Outline

Particle production in small systems
—Final state effects are observed
—Photon modification consistent with QGP formation

Small systems geometry scan
—Observation that correlations are geometrical in origin
—Data well-reproduced by hydro

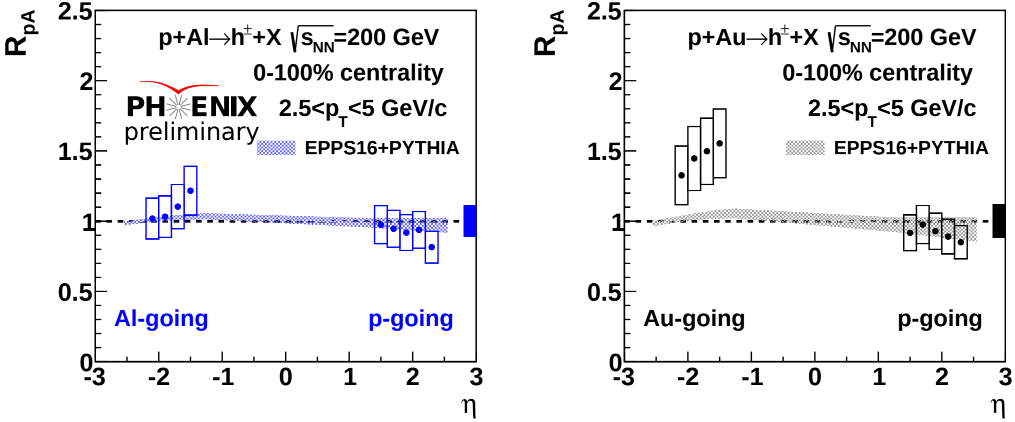
Small systems energy scan
—Similar correlations for all energies
—Non-trivial fluctuations

Alternate viewpoints
—The CGC strikes back?

Intermission

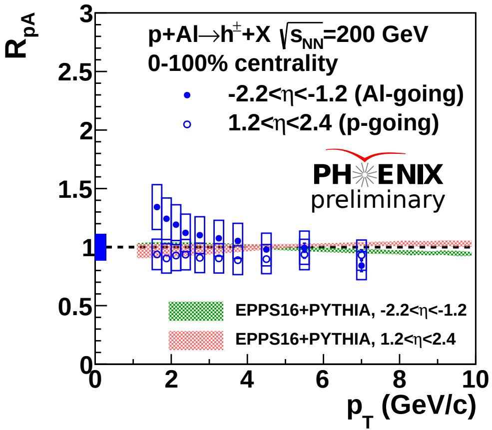
Particle production in small systems

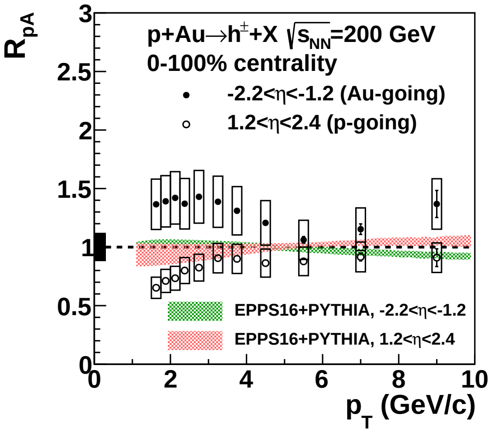
Small systems nuclear modification



Forward modification consistent with nPDF effects (EPPS16)

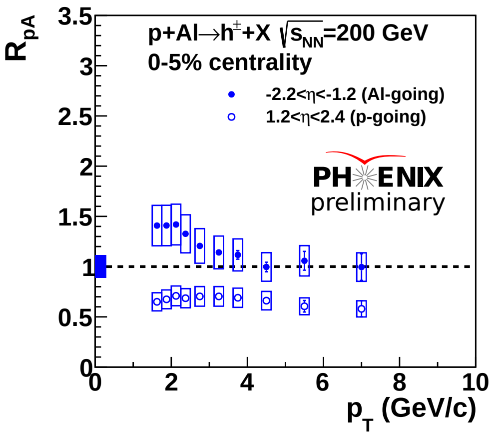
Small systems nuclear modification

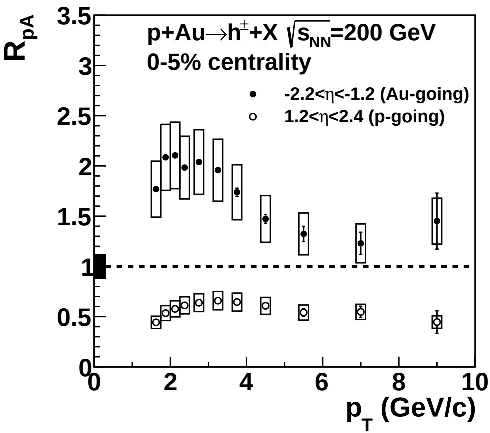




High-p_T modification consistent with nPDF effects (EPPS16)

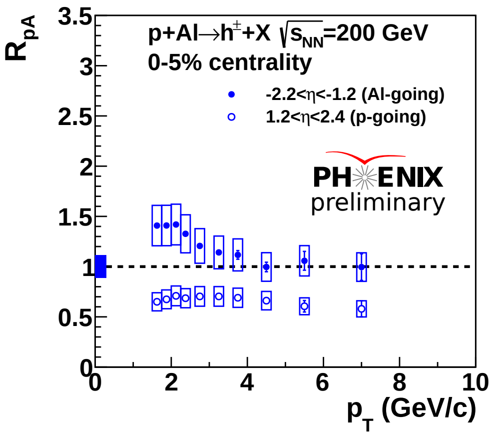
Small systems nuclear modification

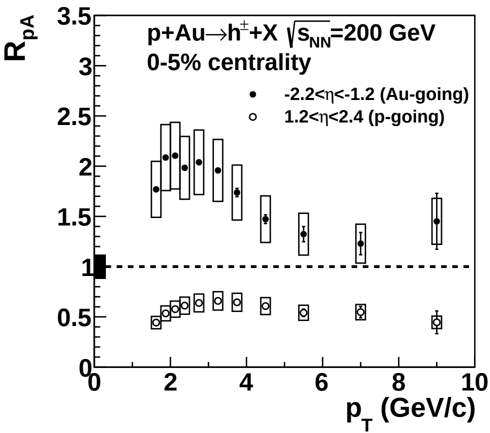




Stronger effects in central collisions

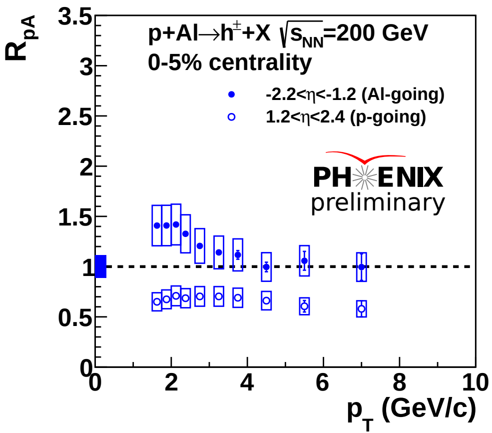
Small systems nuclear modification

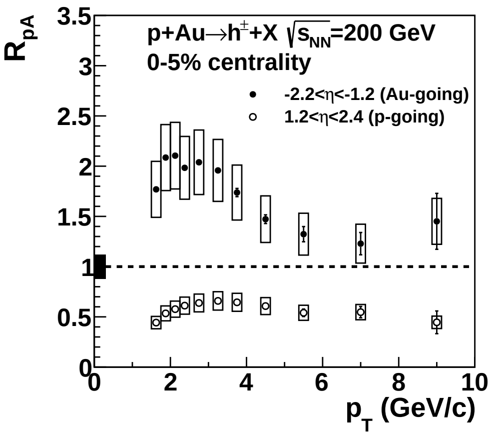




Strong enhancement for backward at intermediate p_T—why?

Small systems nuclear modification



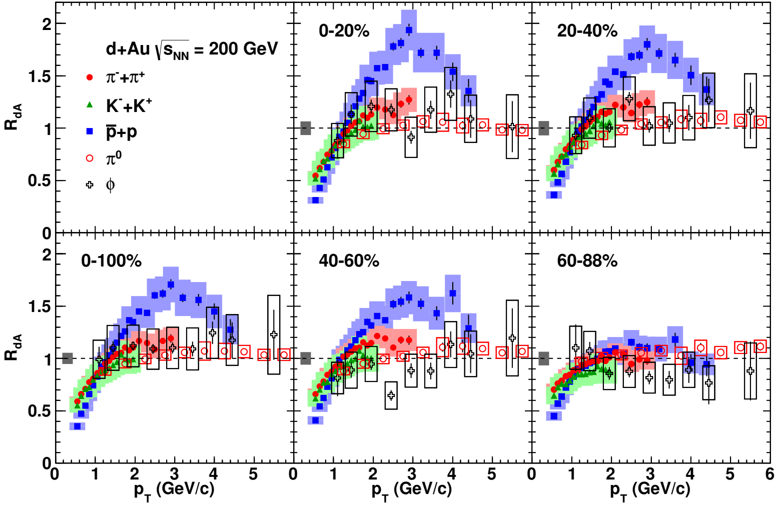


Strong enhancement for backward at intermediate p_T—why?

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^-,

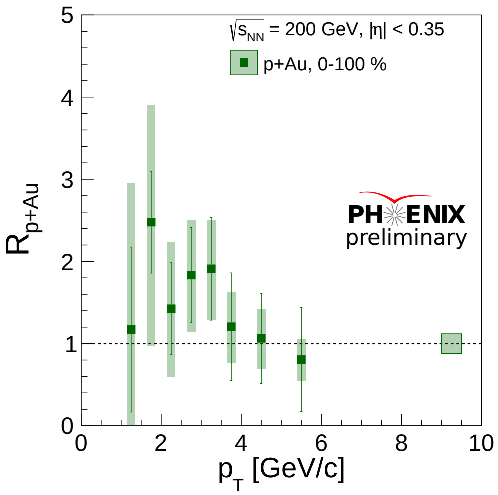
p, $\bar{p}$,

ϕ

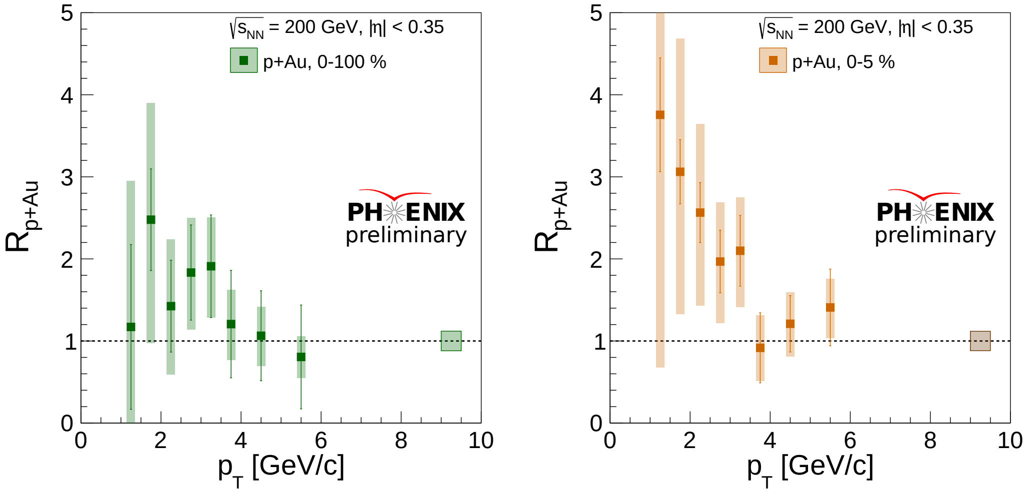
Protons much more strongly modified than pions

ϕ mesons confusing as always...

Photons in small systems

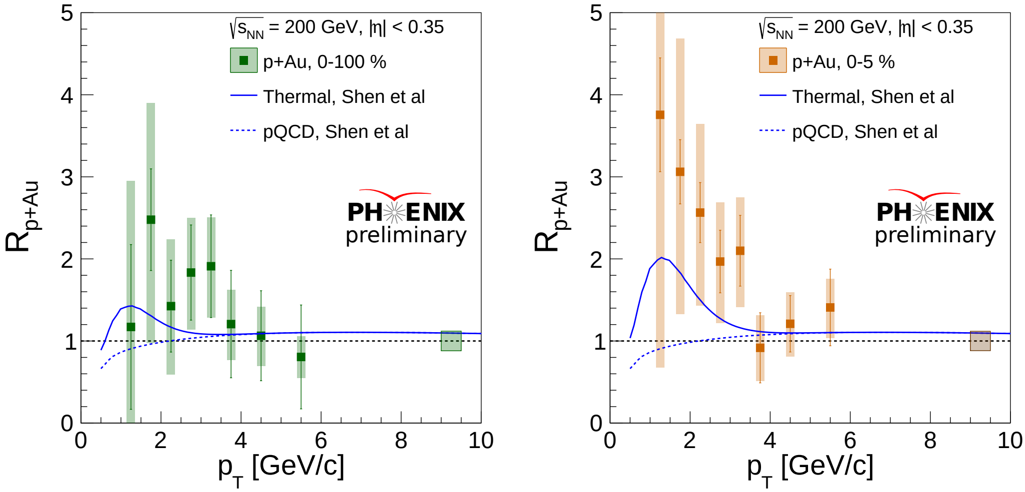


Photons in small systems



Thermal photons in p+Au?

Photons in small systems



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

Brief summary: particle production in small systems

Strong modifications at forward & backward rapidities
—Not nPDF effects alone
—Additional initial state effects possible (e.g. the usual multiple scattering)

Nuclear modification strongly dependent on particle species
—Must be final state effect(s)
—Hadronization, radial flow, etc...

Intermission

Small systems geometry scan

Testing hydro by controlling system geometry

arXiv:1805.02973, submitted to Nature Physics

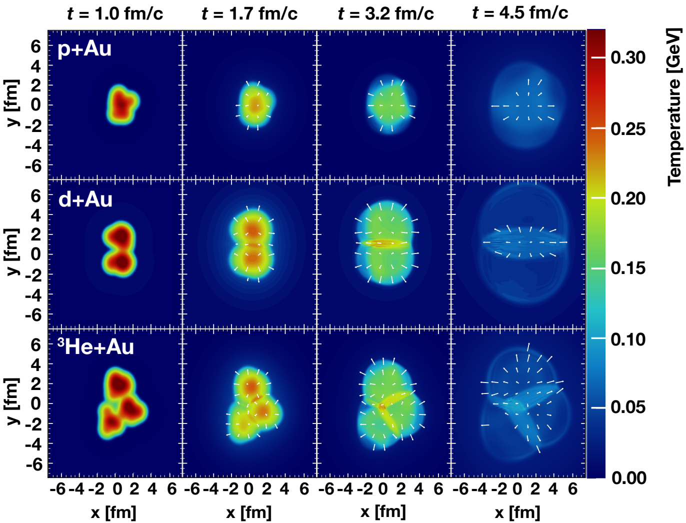
Hydrodynamics translates initial geometry into final state

Test hydro hypothesis by varying initial state

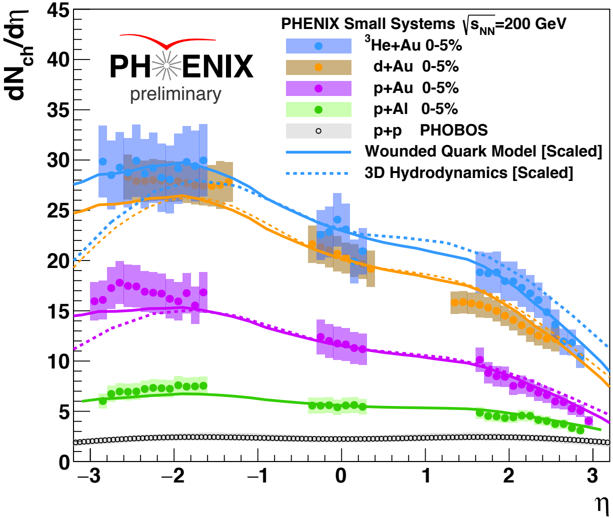
	ε_2	ε_3
p+Au	0.24	0.16
d+Au	0.57	0.17
^{3}He+Au	0.48	0.23

$$\varepsilon_2^{p+Au} < \varepsilon_2^{d+Au} \approx \varepsilon_2^{3He+Au}$$

$$\varepsilon_3^{p+Au} \approx \varepsilon_3^{d+Au} < \varepsilon_3^{3He+Au}$$



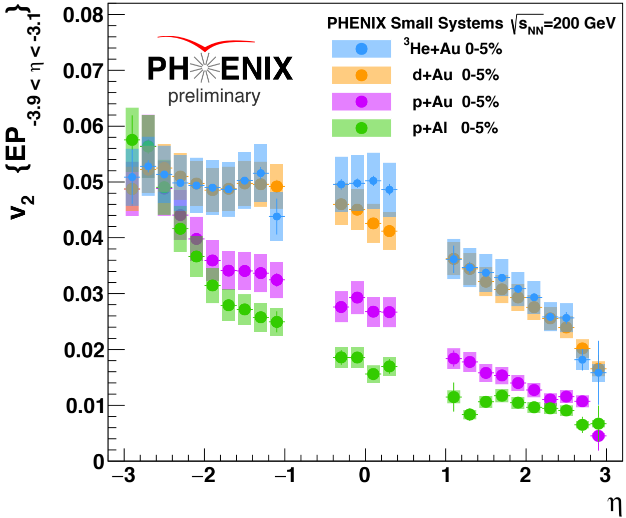
Longitudinal dynamics in small systems



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

Good agreement with wounded quark model

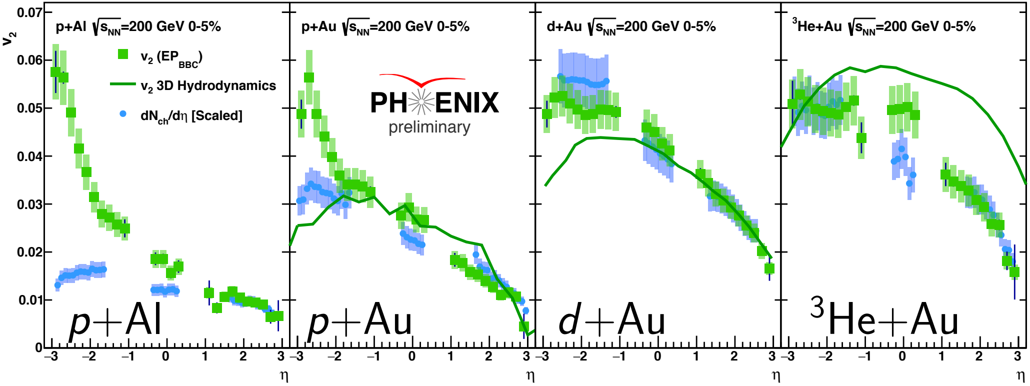
Good agreement with 3D hydro



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

Also have v_2 vs η

Longitudinal dynamics in small systems

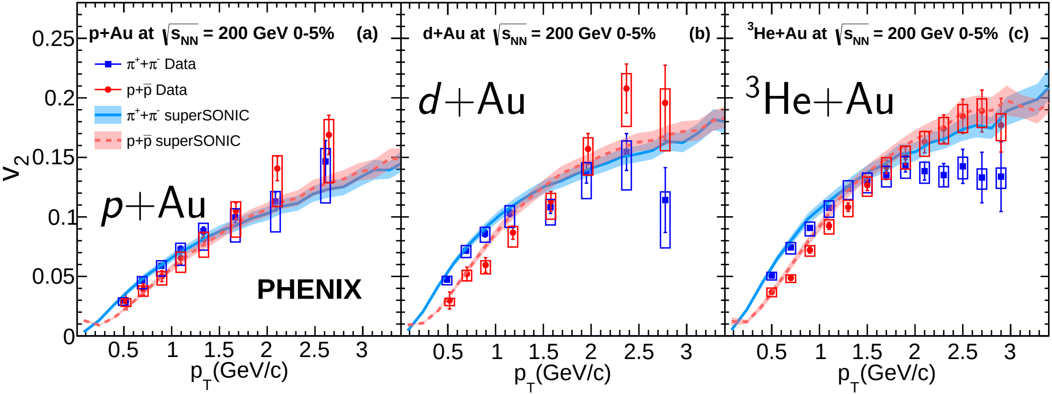


Good agreement with 3D hydro for p+Au and d+Au

Apparent scaling between v_2 and $dN_{\mathrm{ch}}/d\eta$—coincidence?

Small systems geometry scan

arXiv:1710.09736, accepted by Phys. Rev. C



Identified particle v_2 vs p_T in p+Au, d+Au, and ^{3}He+Au

—Mass ordering well-described by hydro

Small systems geometry scan

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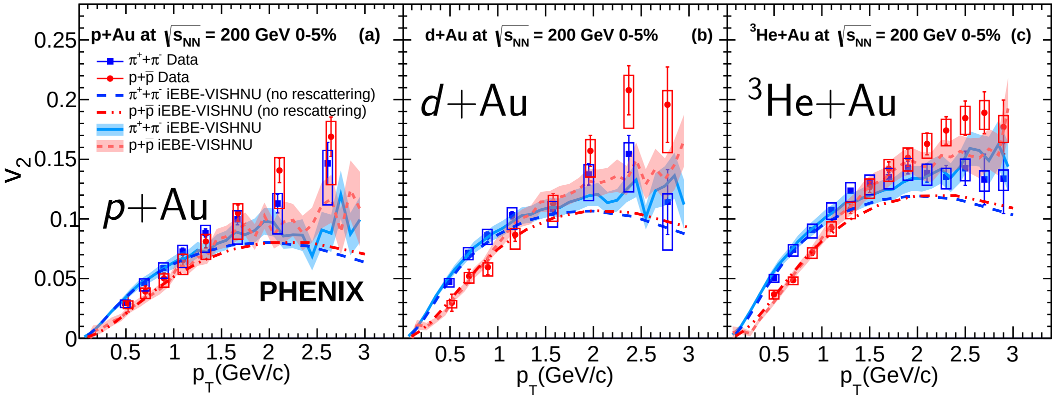

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Testing hydro by controlling system geometry

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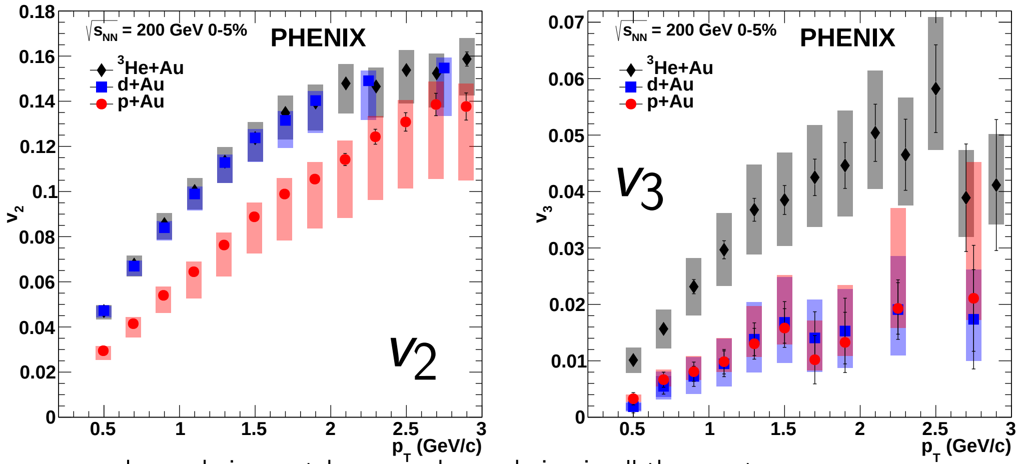

v_2 and v_3 ordering matches ε_2 and ε_3 ordering in all three systems
—Regardless of mechanism, the correlation is geometrical

Testing hydro by controlling system geometry

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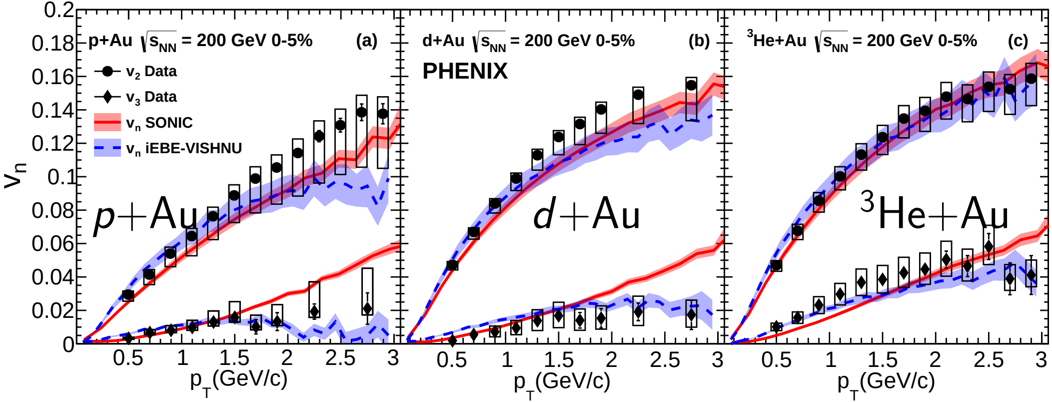


v_2 and v_3 vs p_T described very well by hydro in all three systems

—Strongly suggests QGP droplets in hydro evolution

Brief summary: particle production in small systems

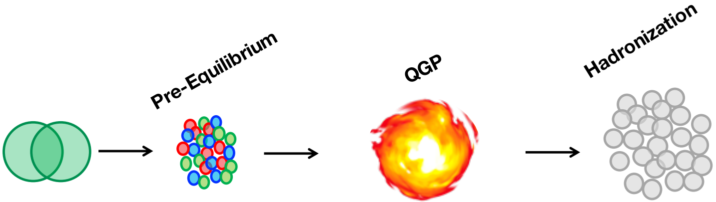
Comprehensive set of measurements for longitudinal dynamics

v_2 and v_3 match ε_2 and ε_3 ordering in p+Au, d+Au, ^{3}He+Au
—Correlation is definitively geometrical in origin

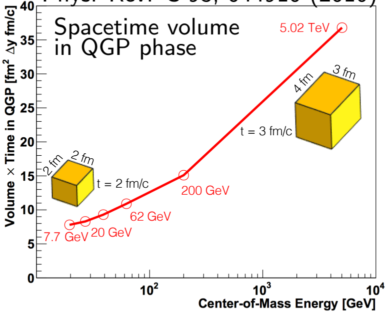
v_2 and v_3 in p+Au, d+Au, ^{3}He+Au are well-described by hydro theory
—Strongest evidence to date for QGP formation in small systems

Intermission

Small systems beam energy scan



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



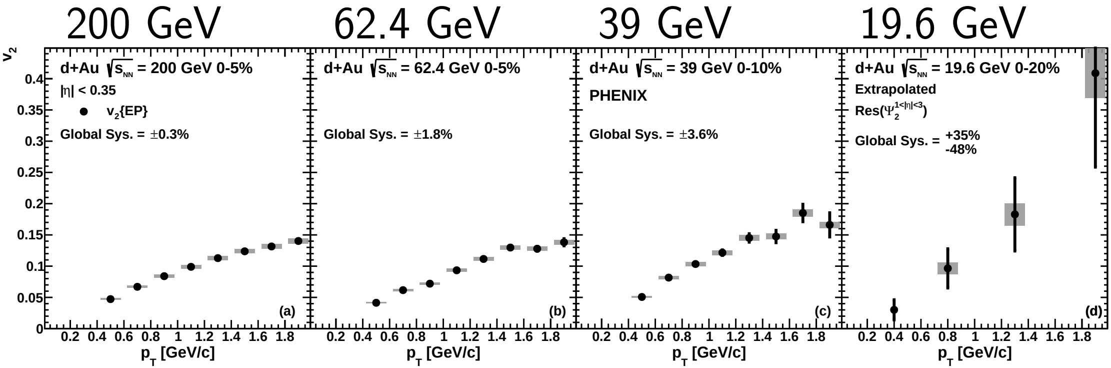
Standard picture for A+A:
QGP in hydro evolution

What about small systems?
And lower energies?

Use collisions species and energy to control system size, test limits of hydro applicability

d+Au beam energy scan

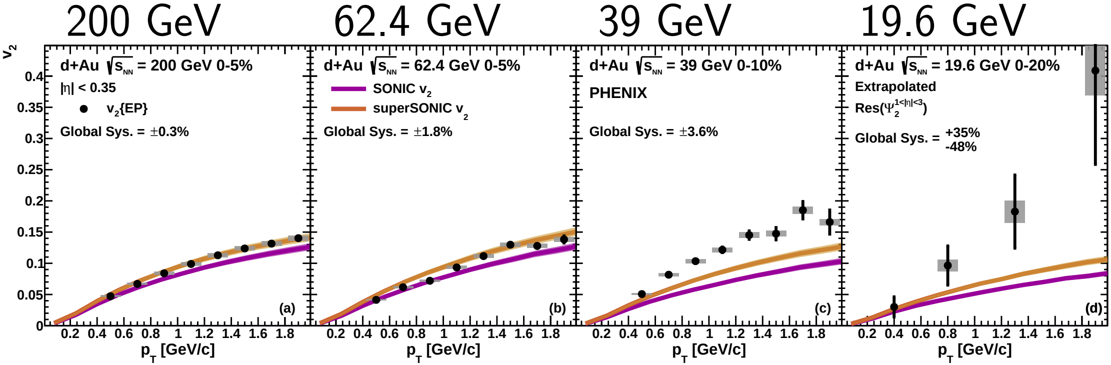
Phys. Rev. C 96, 064905 (2017)



Event plane v_2 vs p_T measured for all energies

d+Au beam energy scan

Phys. Rev. C 96, 064905 (2017)

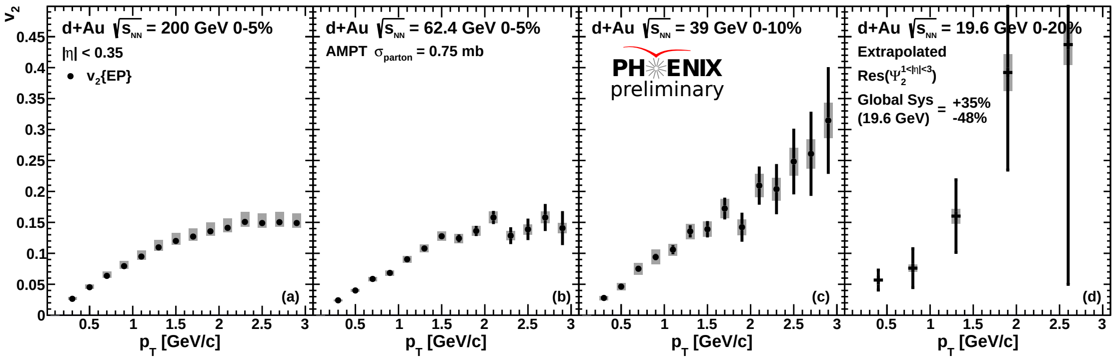


Event plane v_2 vs p_T measured for all energies

Hydro theory agrees with higher energies very well, underpredicts lower energies—nonflow?

v_2 vs p_T, comparisons to AMPT

Phys. Rev. C 96, 064905 (2017)



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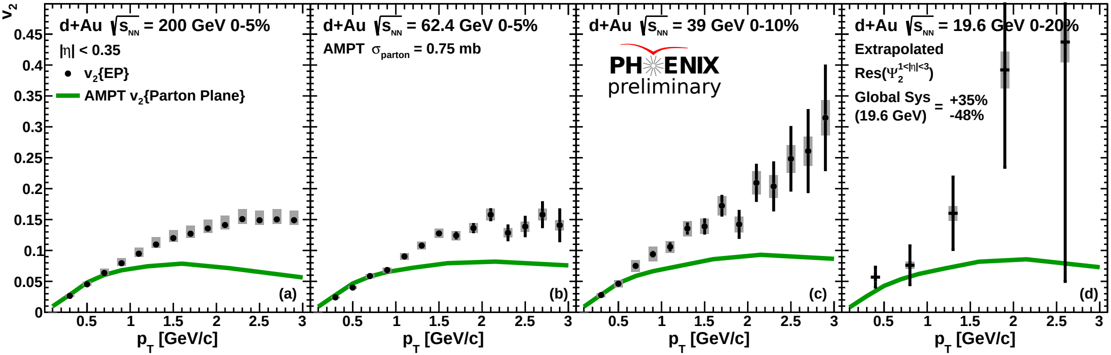

AMPT flow only shows good agreement at low p_T and all energies

v_2 vs p_T, comparisons to AMPT

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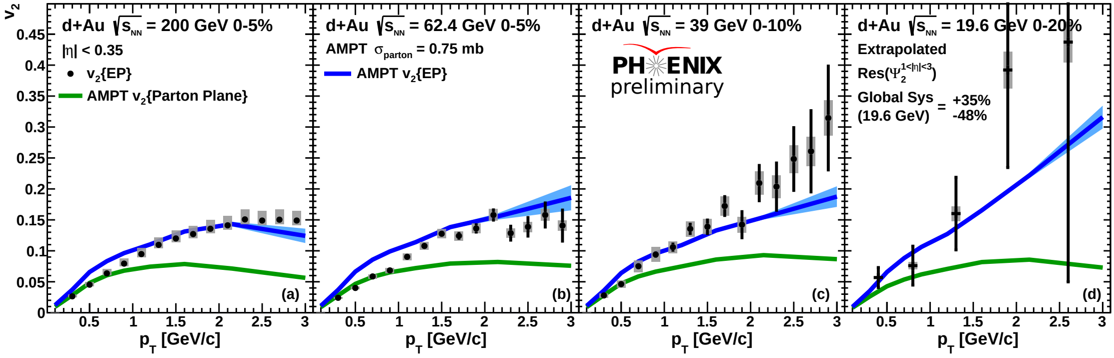

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AMPT flow+non-flow shows reasonable agreement for all p_T and all energies

v_2 vs p_T, comparisons to AMPT

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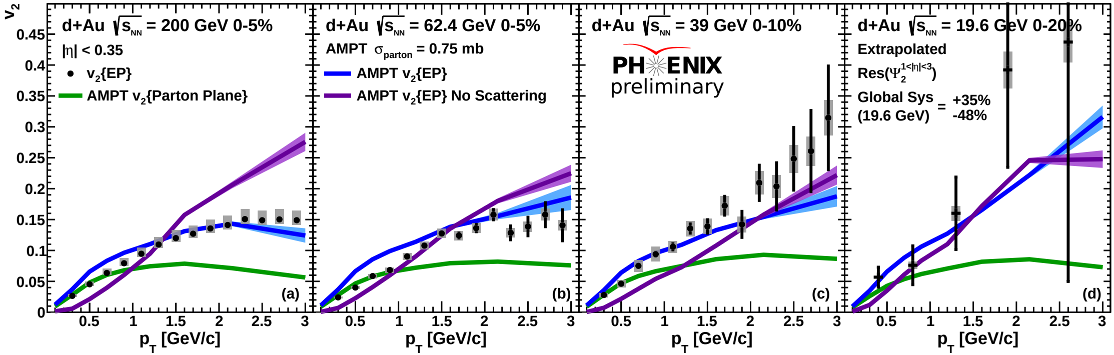


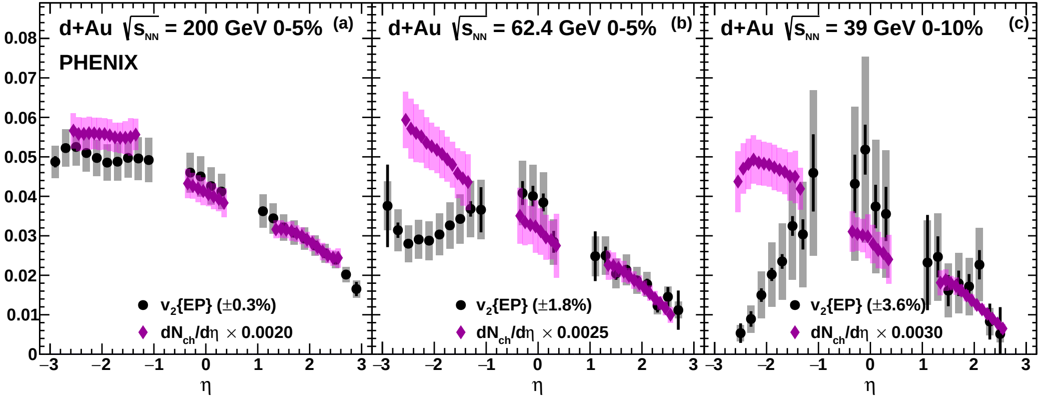
AMPT flow only shows good agreement at low p_T and all energies

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

v_2 and $dN_{ch}/d\eta$ vs η

Phys. Rev. C 96, 064905 (2017)



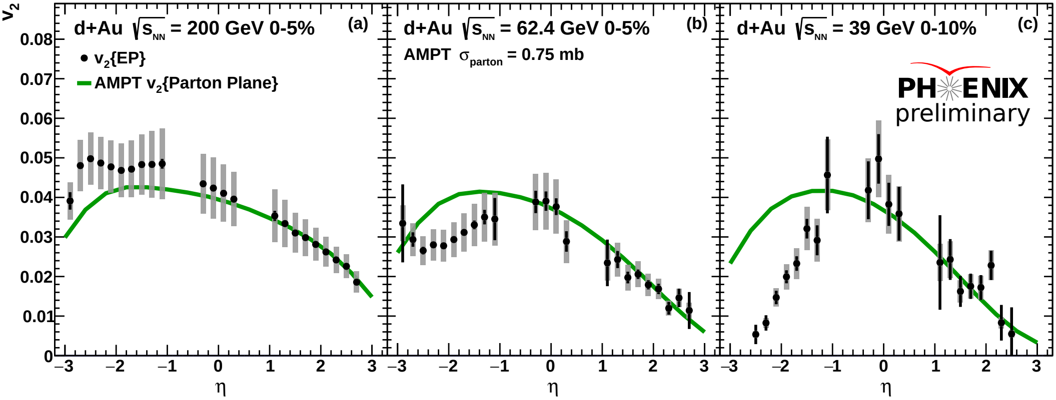
BBC south ($-3.9 < \eta < -3.1$) used to estimate the event plane

200 GeV shows strong forward/backward asymmetry in v_2 and $dN_{ch}/d\eta$

Asymmetry is large for $dN_{ch}/d\eta$ at all energies, but not for v_2

v_2 vs η, comparison with AMPT

Phys. Rev. C 96, 064905 (2017)



AMPT flow only agrees with mid and forward rapidity very well, misses backward rapidity

v_2 vs η, comparison with AMPT

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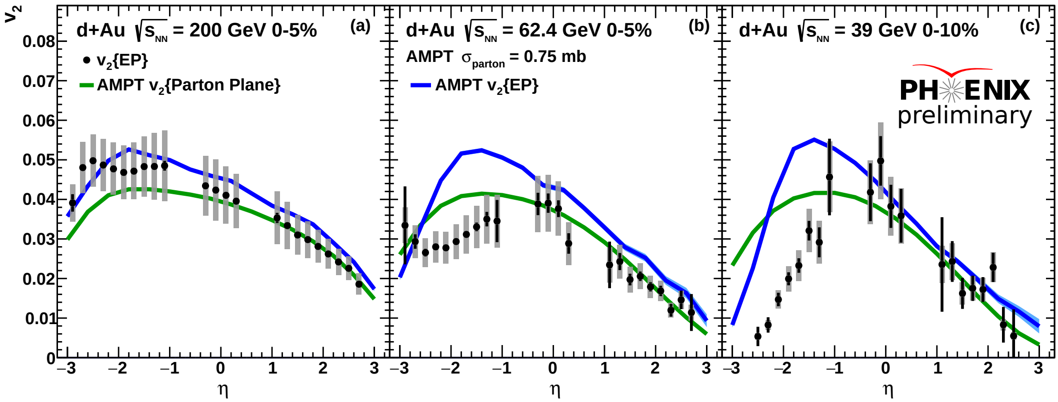

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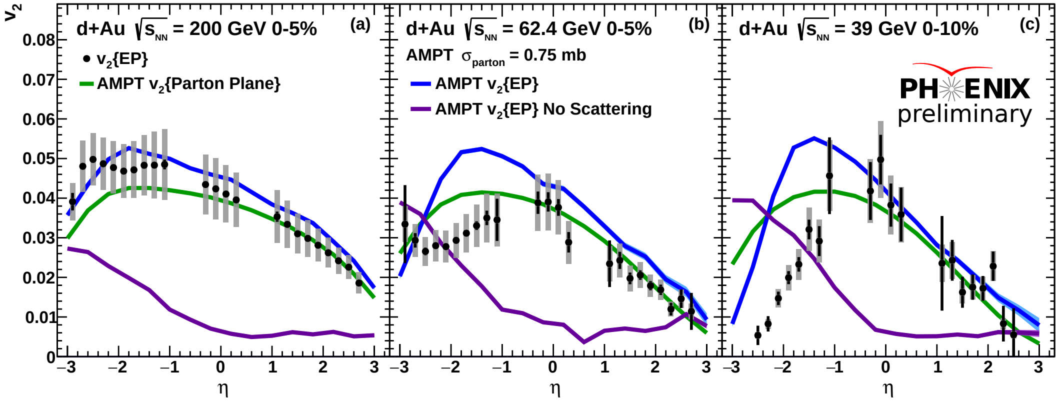
AMPT flow+non-flow is very similar at mid and forward

AMPT flow+non-flow shows striking anti-correlation at backward rapidity

v_2 vs η, comparison with AMPT

Phys. Rev. C 96, 064905 (2017)



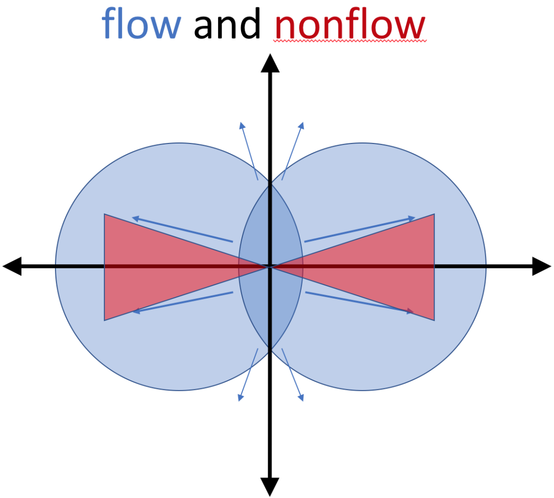
AMPT flow only agrees with mid and forward rapidity very well, misses backward rapidity

AMPT flow+non-flow is very similar at mid and forward

AMPT flow+non-flow shows striking anti-correlation at backward rapidity

AMPT non-flow only shows nothing at mid and forward, large v_2 at backward rapidity near the

Multi-particle correlations



$$v_n = \langle \cos(n(\phi_{\text{some particle}} - \psi_n)) \rangle$$

$$v_n^2 = \langle \cos(n(\phi_{\text{some particle}} - \phi_{\text{some other particle}})) \rangle$$

How to deal with "fake flow"?
—Kinematics
—Combinatorics

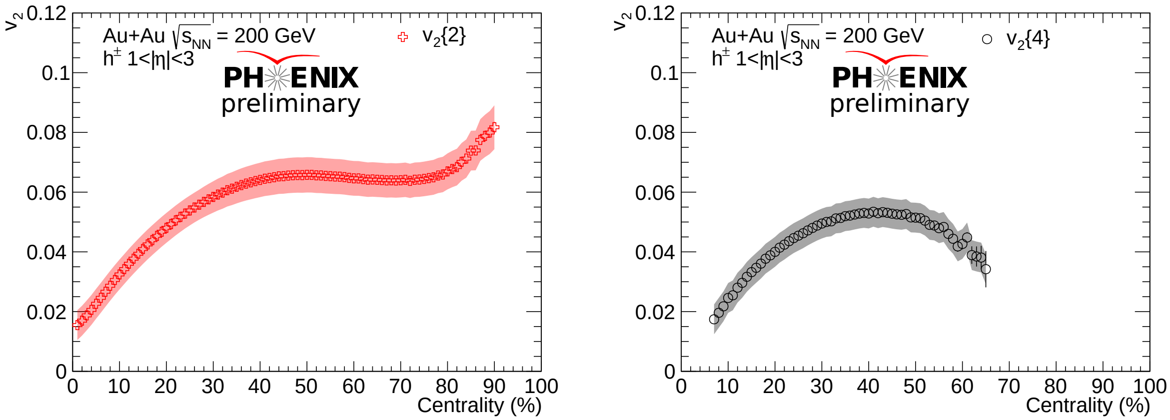
$$v_n^2 = \langle \cos(n(\phi_a - \phi_b)) \rangle$$

$$v_n^4 = \langle \cos(n(\phi_a + \phi_b - \phi_c - \phi_d)) \rangle$$

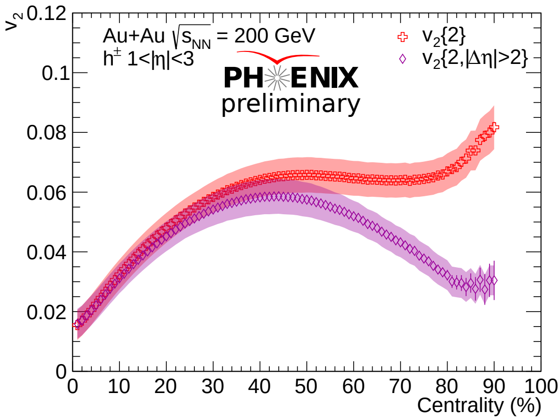
$$v_n^6 = \langle \cos(n(\phi_a + \phi_b + \phi_c - \phi_d - \phi_e - \phi_f)) \rangle$$

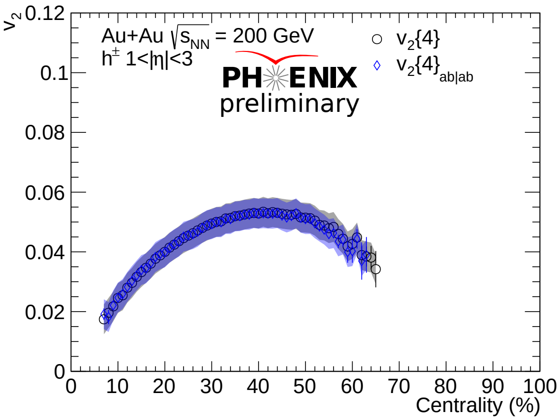
$$v_n^8 = \ldots$$

Nonflow approaches in AuAu



Nonflow approaches in AuAu



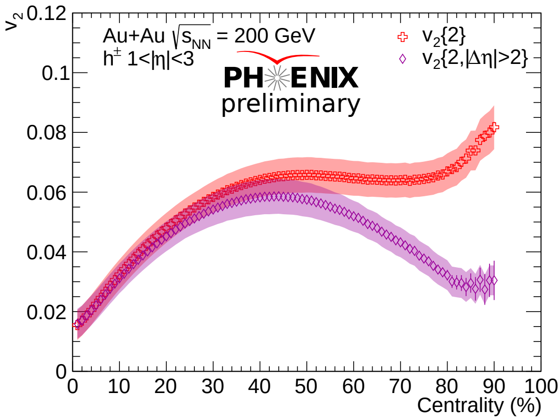


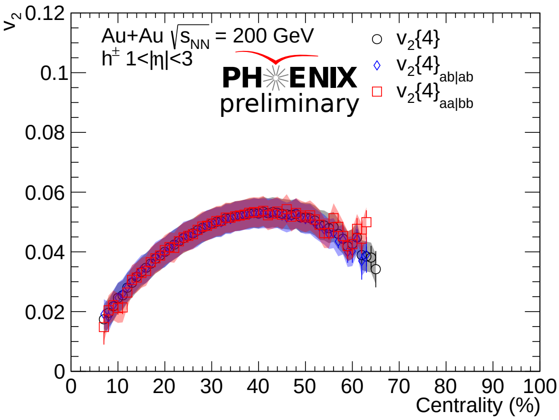
Large pseudorapidity separation

—Big difference for 2-particle (good)

—No difference for 4-particle (good)

Nonflow approaches in AuAu



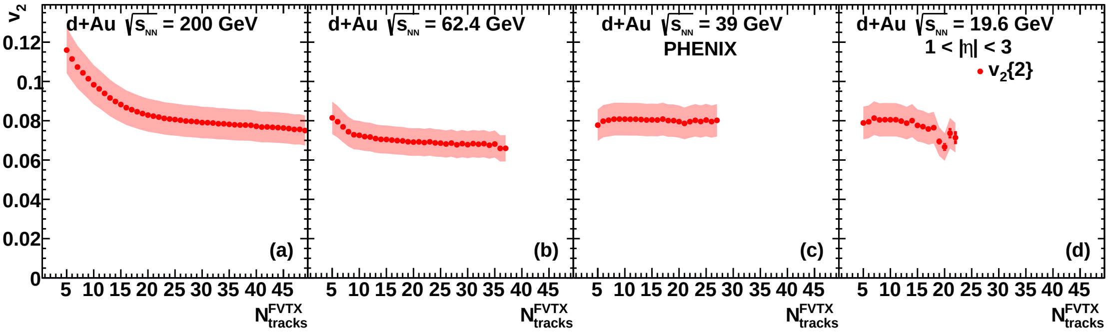


Large pseudorapidity separation
—Big difference for 2-particle (good)
—No difference for 4-particle (good)

d+Au beam energy scan

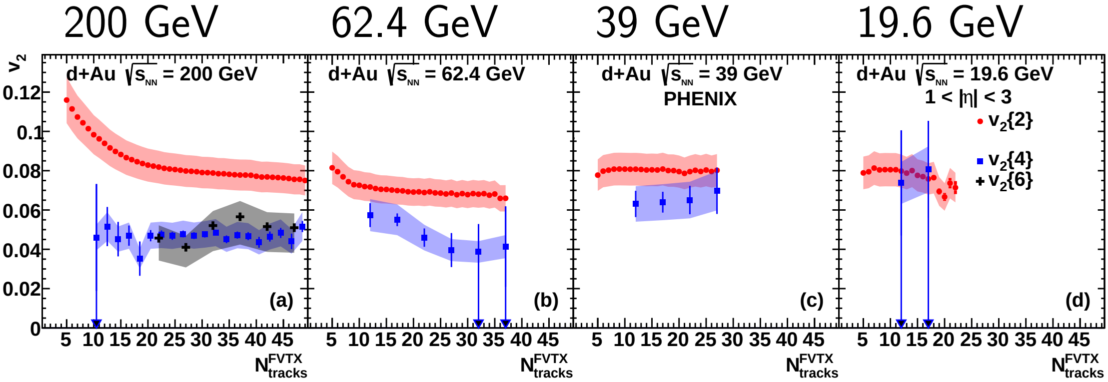
Phys. Rev. Lett. 120, 062302 (2018)

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

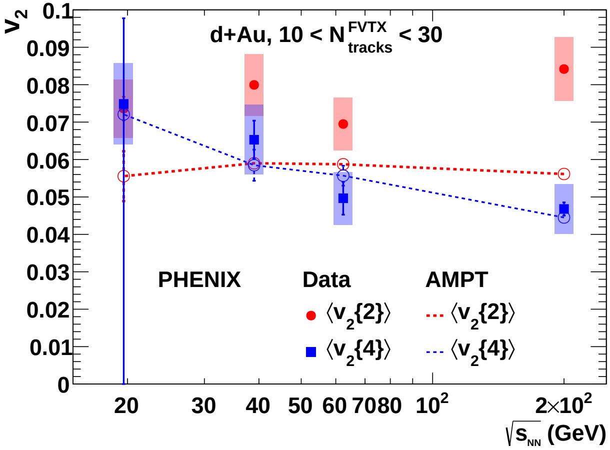
Phys. Rev. Lett. 120, 062302 (2018)

Select $10 < N^{\mathrm{FVTX}}_{\mathrm{tracks}} < 30$, integrate

AMPT sees similar trend

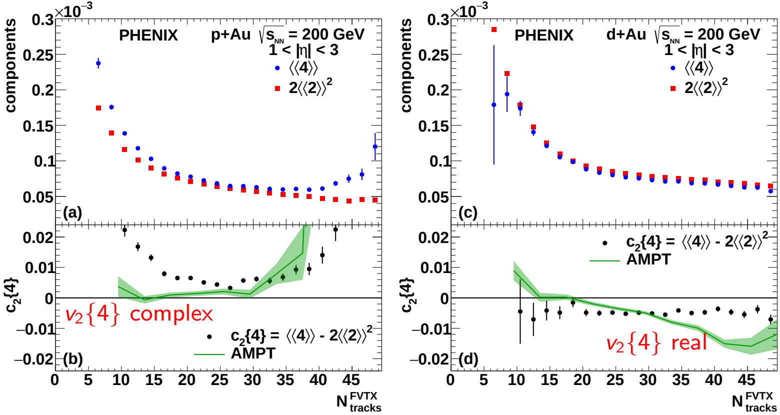
Fluctuations?

- Not Bessel-Gaussian
- Not small-variance limit
- Need to understand fluctuations better



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)

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

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

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

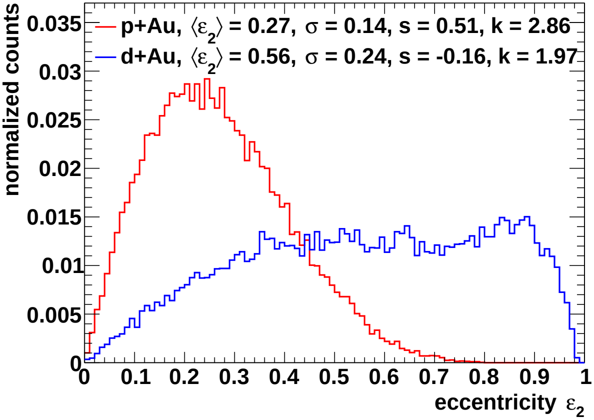
$$\left(\langle v_n^4 \rangle = v_n^4 + 6v_n^2\sigma^2 + 3\sigma^4 + 4v_n\kappa_3 + \kappa_4\right)$$
$$-\left(2\langle v_n^2 \rangle^2 = 2v_n^4 + 4v_n^2\sigma^2 + 2\sigma^4\right)$$
$$\rightarrow$$
$$\langle v_n^4 \rangle - 2\langle v_n^2 \rangle^2 = -v_n^4 + 2v_n^2\sigma^2 + \sigma^4 + 4v_n\kappa_3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

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



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

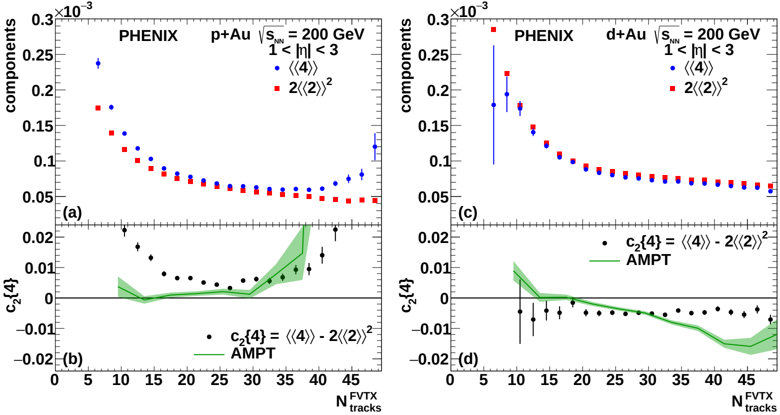
	p+Au	d+Au
ε_2^4	0.00531	0.0983
$2\varepsilon_2^2\sigma^2$	0.00277	0.0370
$4\varepsilon_2 s\sigma^3$	0.00147	-0.0053
$(k-2)\sigma^4$	0.00031	-0.0001

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?

Brief summary: small systems beam energy scan

Measurement of v_2 vs p_T for d+Au at 200, 62.4, 39, and 19.6 GeV
—Hydro describes higher two energies well, misses lower two energies
—AMPT describes all data well with mix of flow and nonflow

Measurement of v_2 vs η for d+Au at 200, 62.4, and 39 GeV
—Hydro theory at lower energies would be very useful
—Interesting anticorrelation between flow and nonflow at backward rapidity

Measurement of $v_2\{6\}$ at 200 GeV and $v_2\{4\}$ at all four energies
—Nonflow should be combinatorially suppressed
—Highly non-trivial fluctuations

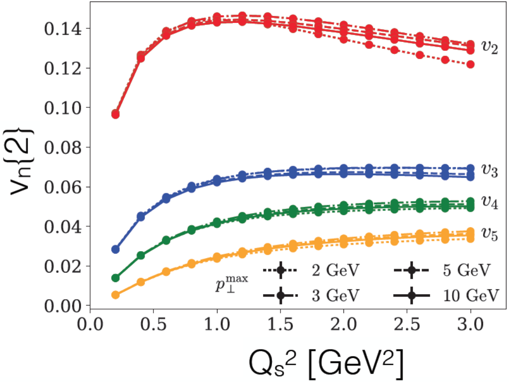
Intermission

The CGC strikes back?

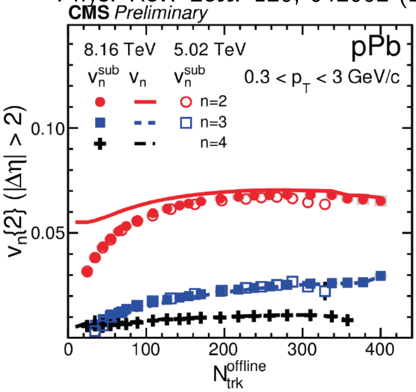
CGC results on small systems

Mark Mace, QM18

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



Dusling, MM, Venugopalan PRL 120 (2018)



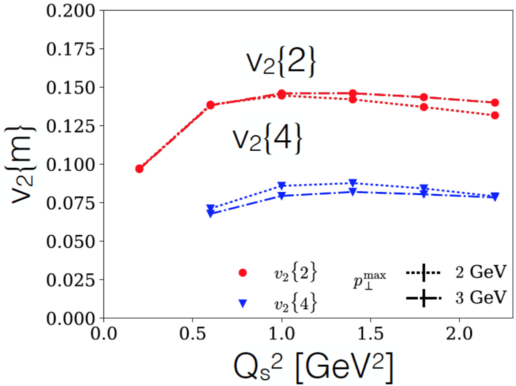
CMS-PAS-HIN-16-022

Can qualitatively reproduce harmonic ordering

Off from data by a factor of 2 to 3

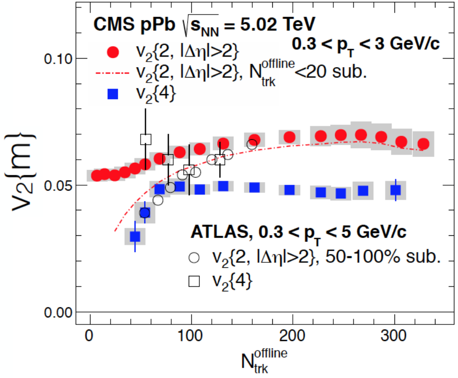
CGC results on small systems

Mark Mace, QM18



Dusling, MM, Venugopalan PRL 120 (2018)

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



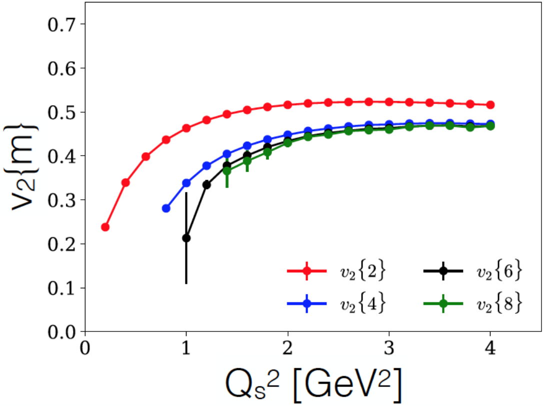
CMS PLB 724 (2013) 213

Can reproduce $v_2\{2\}$ and $v_2\{4\}$

Disagreement with data by a factor of 2, but qualitative features match

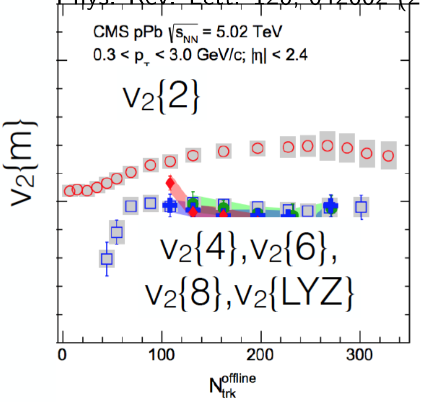
CGC results on small systems

Mark Mace, QM18



Dusling, MM, Venugopalan PRL 120 (2018)

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



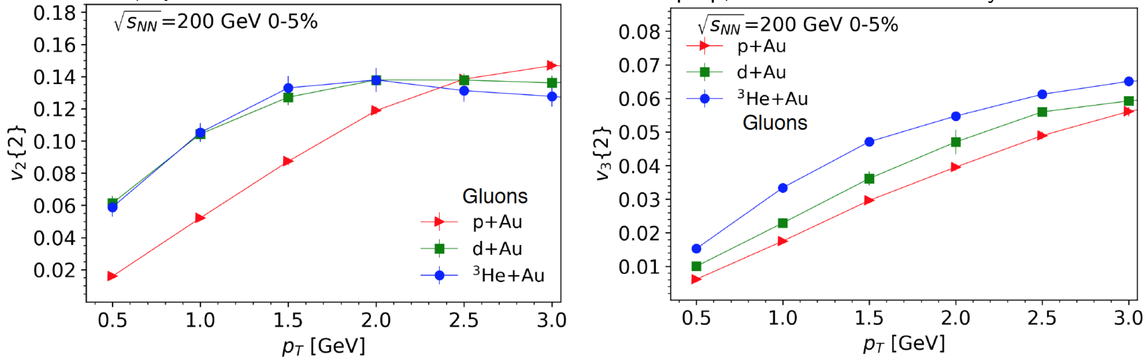
CMS PRL 115 (2015) 012301

Abelian calculations can produce $v_2\{2\}$, $v_2\{4\}$, $v_2\{6\}$, $v_2\{8\}$

Disagreement with data by factor of 5, but qualitative features match

CGC results on small systems

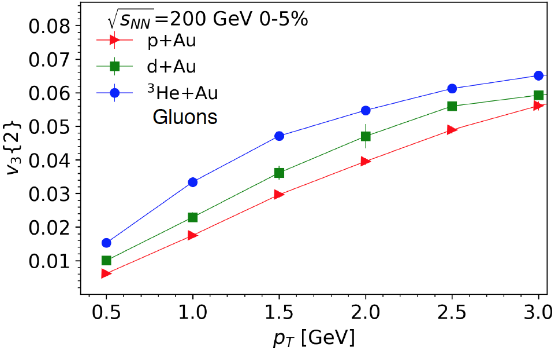
Mark Mace, QM18 in prep, to be submitted to Phys. Rev. Lett.



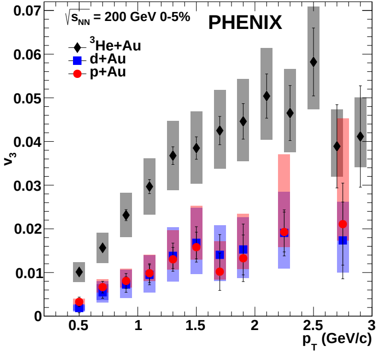
New for QM18: v_2 and v_3 for small systems

CGC results on small systems

Mark Mace, QM18



in prep, to be submitted to Phys. Rev. Lett.



New for QM18: v_2 and v_3 for small systems

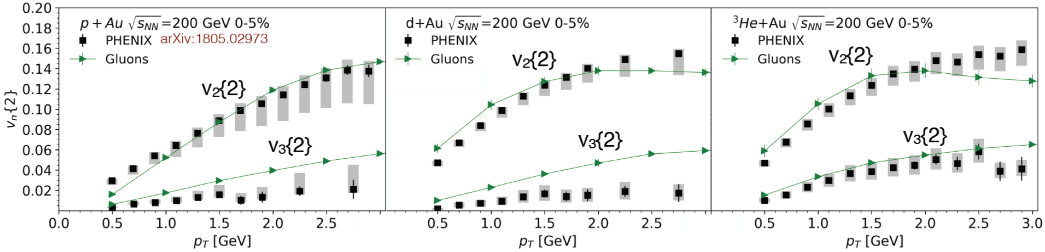
v_3 ordering is not quite right

—CGC: p+Au $<$ d+Au $<$ ^{3}He+Au

—Data: p+Au $\approx$ d+Au $<$ ^{3}He+Au

CGC results on small systems

Mark Mace, QM18 — in prep, to be submitted to Phys. Rev. Lett.



Description of data now *quantitative* rather than *qualitative*

Hopefully coming soon: which set of refinements made this possible?

Brief summary: the CGC strikes back?

CGC calculations now in some quantitative with RHIC data, but that means the LHC data needs to be revisited

Unclear which further theoretical refinements may be possible (not long ago it was assumed that odd harmonics were all zero)

v_n and multiplicity distribution may provide additional discriminating power

Final thoughts

Initial and final state effects are clear in the data
—*Which* final state effects is perhaps not so clear

Low-p_T photon enhancement observed in p+Au
—Consistent with EM radiation from QGP
—Other explanations possible?

Wealth of data from small systems beam energy and geometry scans
—Higher energies described by hydro, all energies described by AMPT
—All geometries described by hydro, also somewhat described by CGC

Final thoughts

Initial and final state effects are clear in the data
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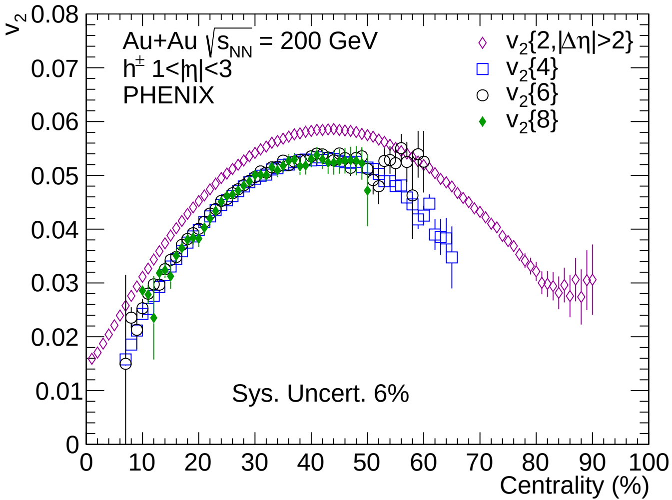
"The optimist regards the future as uncertain."—Eugene Wigner

Intermission

Additional material

Collectivity in large systems

arXiv:1804.10024 (submitted to Phys Rev C)



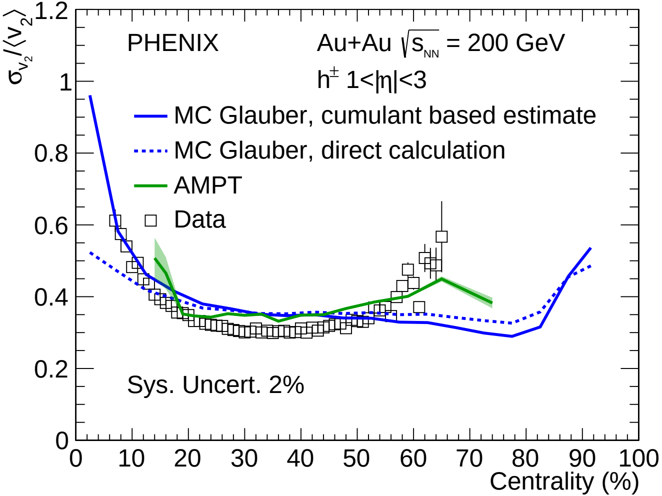
$$1 < |\eta| < 3$$

$v_2\{2\}$, $v_2\{4\}$, $v_2\{6\}$,

$v_2\{8\}$

Collectivity in large systems

arXiv:1804.10024 (submitted to Phys Rev C)



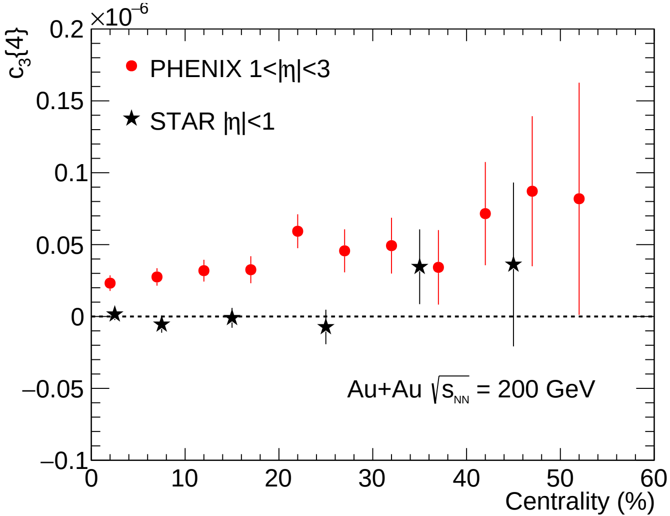
$$1 < |\eta| < 3$$

$$\sigma_{v_2}/\langle v_2 \rangle$$

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))

arXiv:1804.10024 (submitted to Phys Rev C)

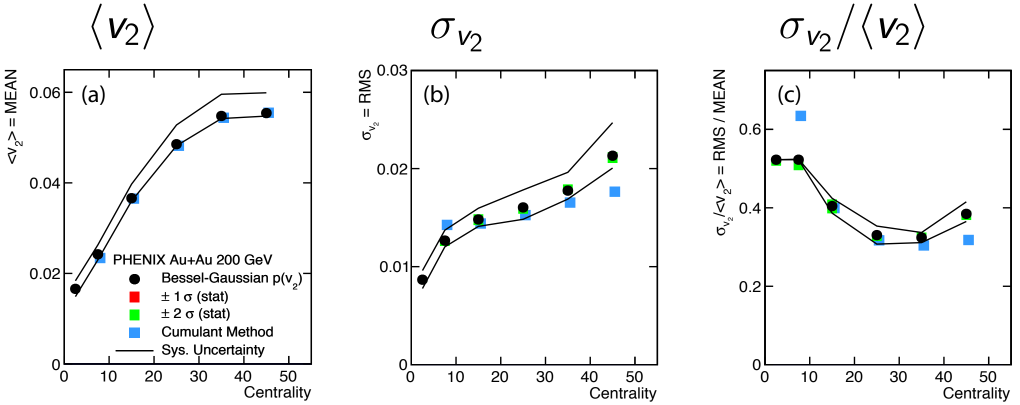


$1 < |\eta| < 3$

Cannot extract

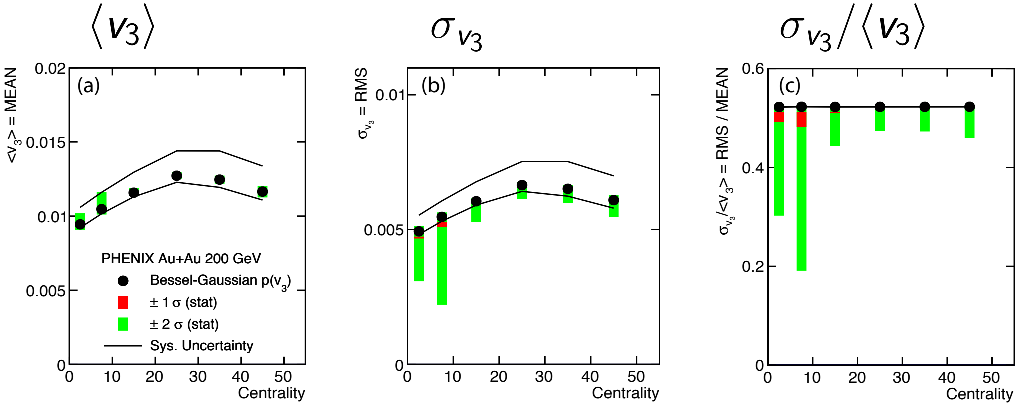
$\sigma_{v_3}/\langle v_3\rangle$

arXiv:1804.10024 (submitted to Phys Rev C)

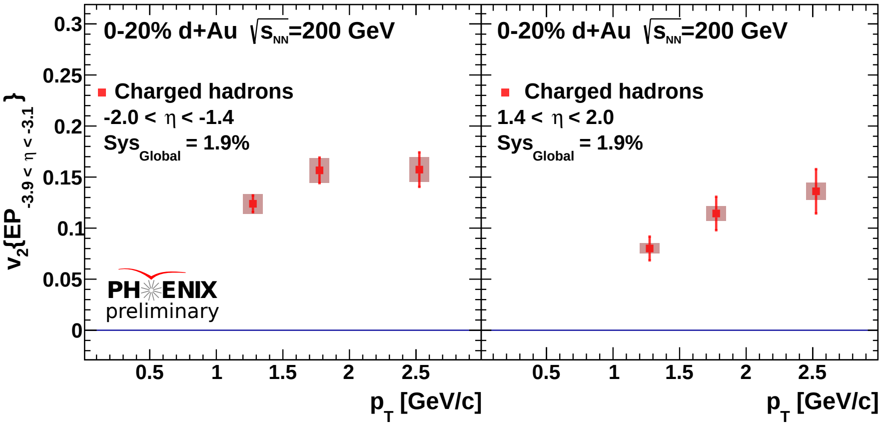


Can extract $\langle v_2 \rangle$ and σ_{v_2} separately using forward-fold

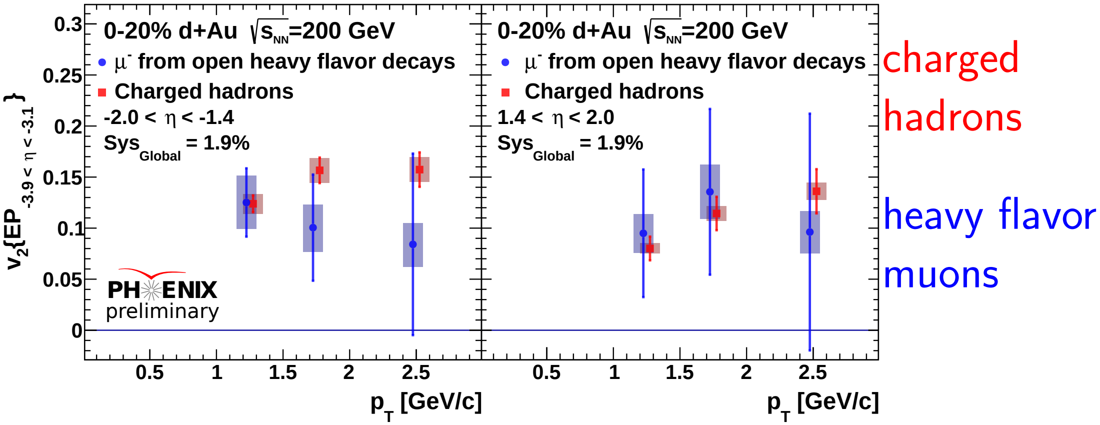
arXiv:1804.10024 (submitted to Phys Rev C)



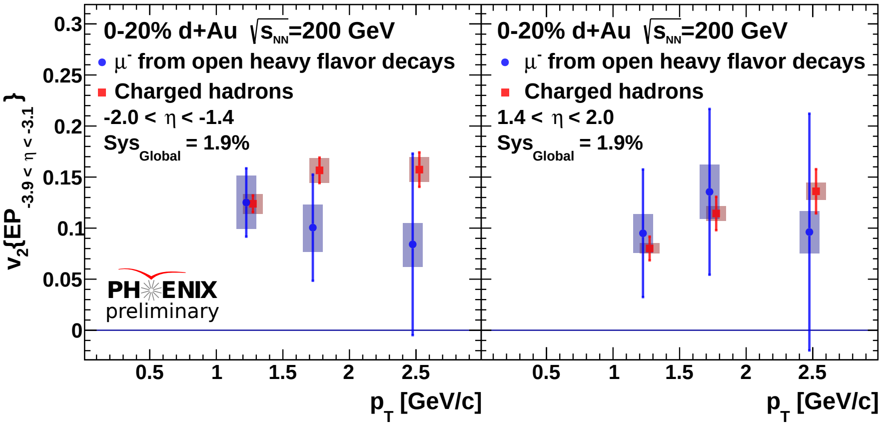
Can extract $\langle v_3 \rangle$ and σ_{v_3} separately using forward-fold



charged hadrons



Nonzero v_2 for heavy flavor in d+Au



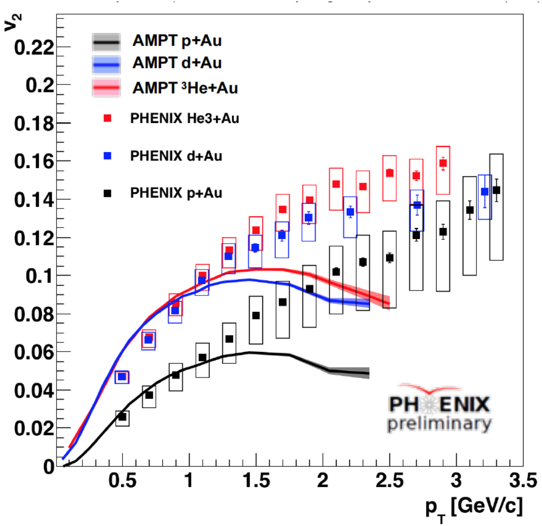
charged hadrons

heavy flavor muons

Nonzero v_2 for heavy flavor in d+Au

3.22σ, 2.16σ for $v_2 > 0$ at backward, forward (99.9%, 98.5% one-sided)

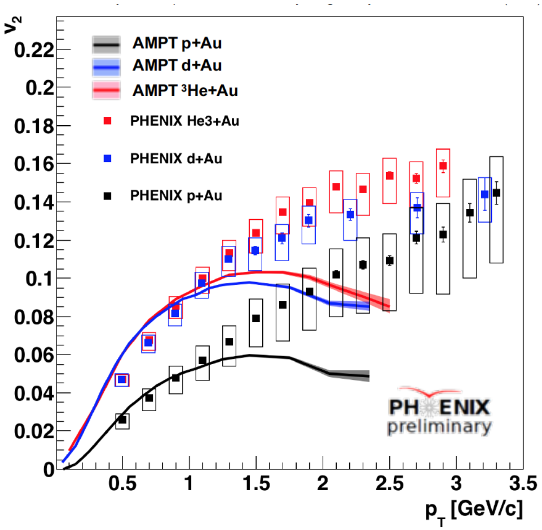
AMPT



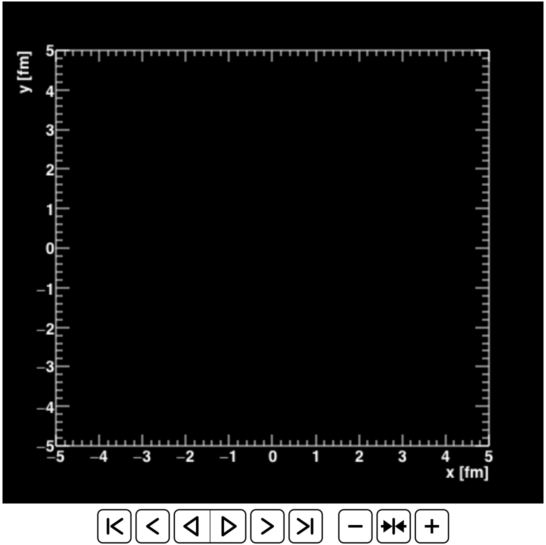
AMPT basic features

Initial conditions	HIJING
Particle production	String melting
Pre-equilibrium	None
Expansion	Parton scattering (tunable)
Hadronization	Spatial coalescence
Final stage	Hadron cascade (tunable)

AMPT



v_2
AMPT p+Au
AMPT d+Au
AMPT ³He+Au
PHENIX He3+Au
PHENIX d+Au
PHENIX p+Au
PHENIX
preliminary
p_T [GeV/c]



y [fm]
x [fm]