PHENIX results on the Run-16 d+Au beam energy scan

Ron Belmont
For the PHENIX Collaboration
University of Colorado Boulder

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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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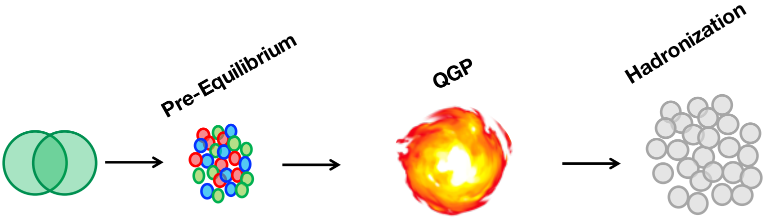
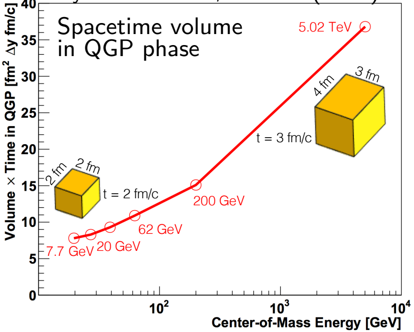
- Early 2010s—QGP in d+Au!
- Mid 2010s and now-ish—QGP in high multiplicity p+p? QGP in mid-multiplicity p+p?? QGP in d+Au even at low energies???

"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

Testing hydro by controlling system size



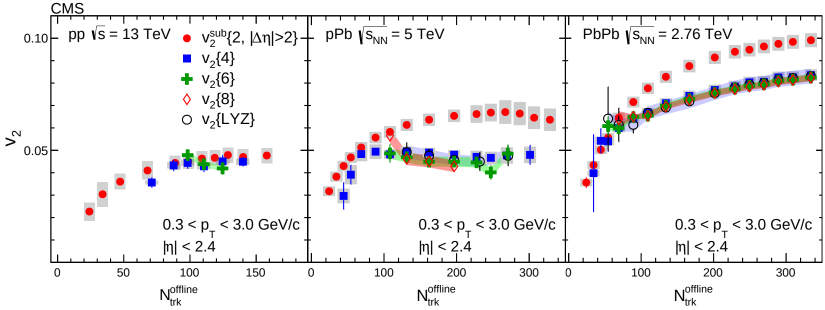
J.D. Orjuela Koop et al
Phys. Rev. C 93, 044910 (2016)



- 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

Multiparticle correlations in small systems

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



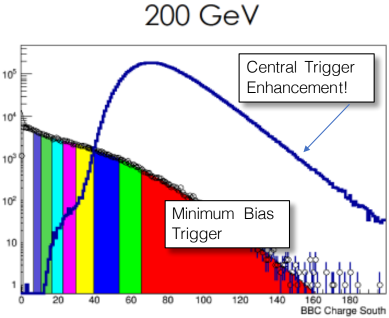
- Multiparticle correlations: a strong case for collectivity in small systems
- Gaussian fluctuations:

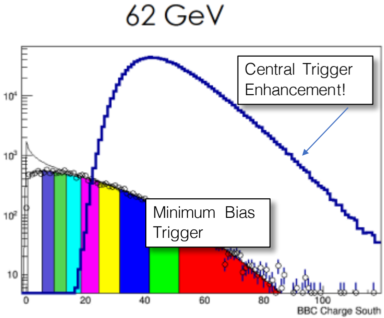
$$v_2\{2\} = \sqrt{v_2^2 + \sigma^2 + \delta} \qquad \delta \text{ non-flow, } \sigma \text{ variance}$$

$$v_2\{2, |\Delta\eta| > 2\} = \sqrt{v_2^2 + \sigma^2} \qquad \text{eta gap removes some non-flow}$$

$$v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx \sqrt{v_2^2 - \sigma^2} \qquad \text{higher orders remove non-flow}$$

- Can multiparticle correlations be measured in small systems at RHIC?

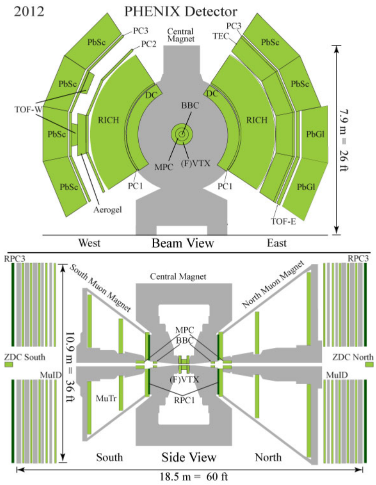




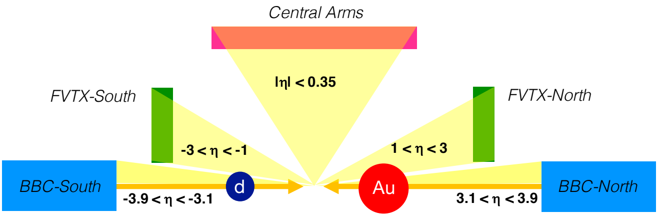
d+Au collision energy	total events analyzed	central events analyzed
200 GeV	636 million	585 million
62.4 GeV	131 million	76 million
39 GeV	137 million	49 million
19.6 GeV	15 million	3 million

PHENIX

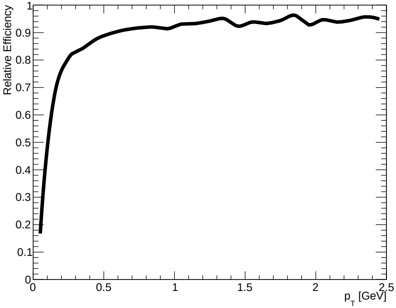
- Central arms (CNT) cover $|\eta| < 0.35$, tracking, momentum determination, PID, etc.
- Forward vertex detector (FVTX) covers $1 < |\eta| < 3$, tracking only (no momentum vector information)
- Beam beam counters (BBC): centrality and vertex determination
- BBC and FVTX used for triggering
- BBC south and FVTX south used for event plane determination for Run16 flow analysis (south = backward)
- CNT, FVTXS, BBCS used for event plane resolution



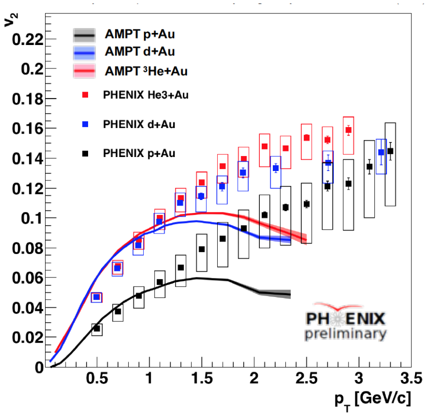
The PHENIX forward vertex detector



- FVTX: forward vertex detector —silicon strip technology
- Very precise vertex/DCA determination
- No momentum determination, p_T dependent efficiency — measured v_2 roughly 18% higher than true



A Multi-Phase Transport model

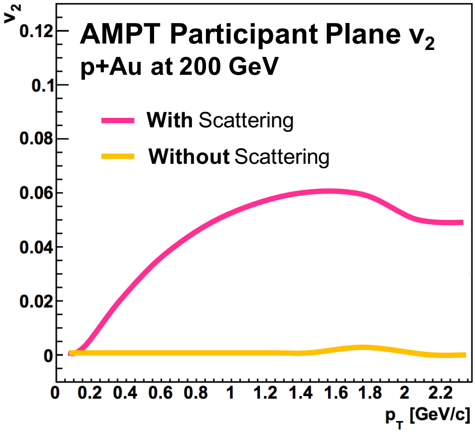


AMPT basic features

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

- AMPT has significant success in describing flow-like signatures (for low p_T and p_T-integrated)
- AMPT produces final state particles over the full available phasespace —possible to perform exact same analysis on data and model

AMPT with no scattering

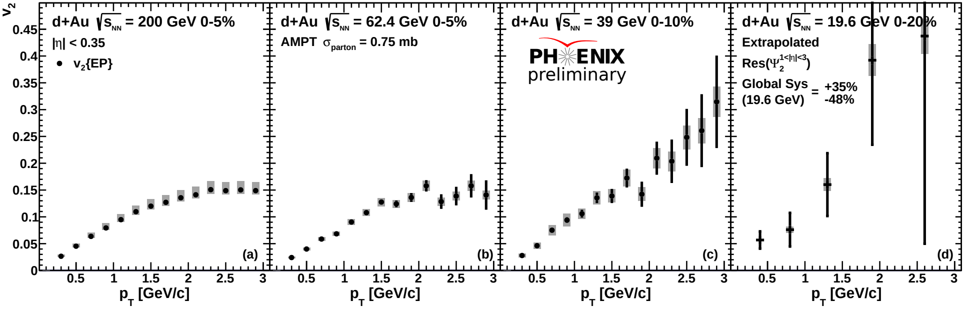


- Turn off scattering in AMPT—remove all correlations with initial geometry $\sigma_{parton} = 0$ and $\sigma_{hadron} = 0$
- Participant plane v_2 goes to zero
- Other sources of correlation remain—non-flow

Intermission

Event plane results

v_2 vs p_T, comparisons to AMPT



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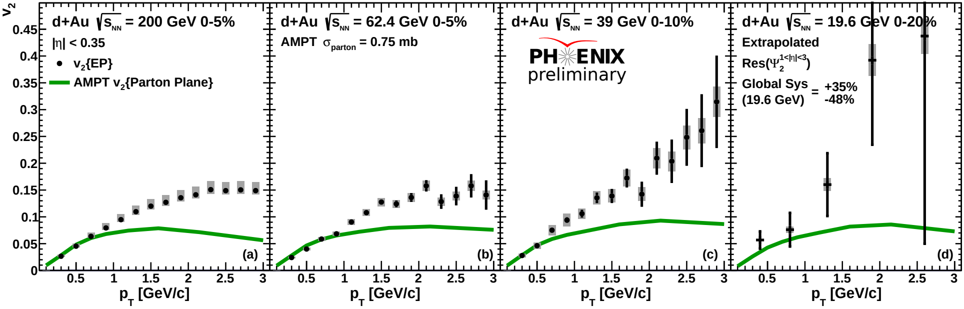

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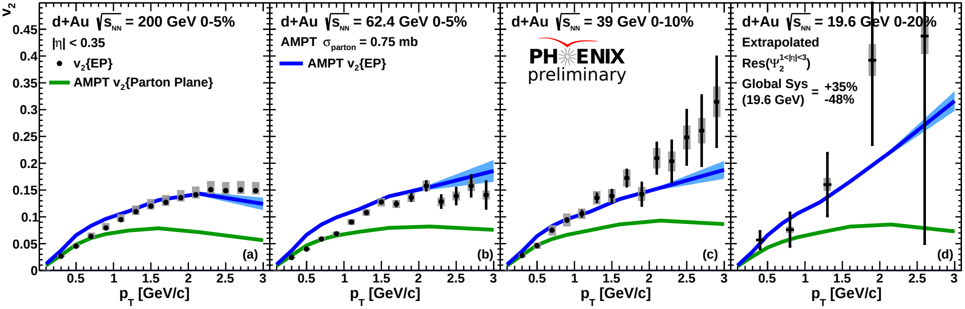

- Event plane v_2 vs p_T measured for all energies
- AMPT flow only (parton plane) shows good agreement at low p_T
- AMPT flow+non-flow (event plane) shows reasonable agreement for all p_T

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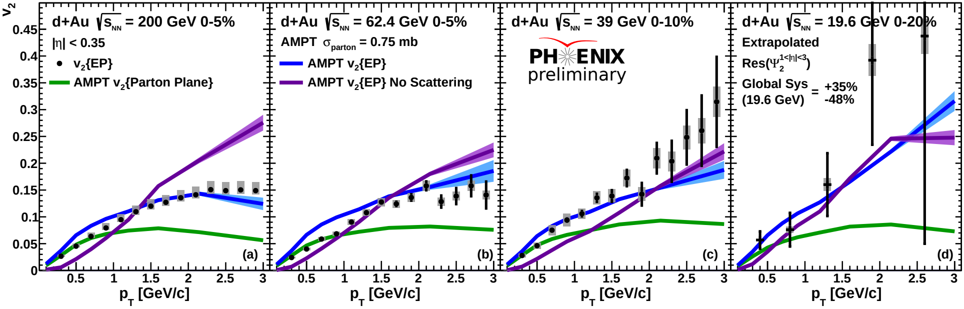

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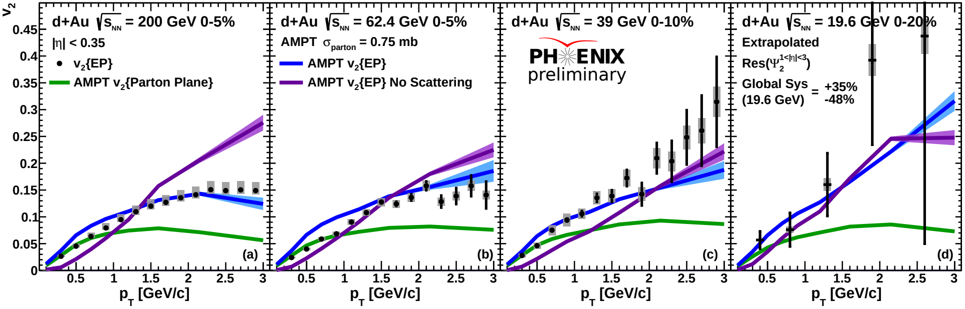

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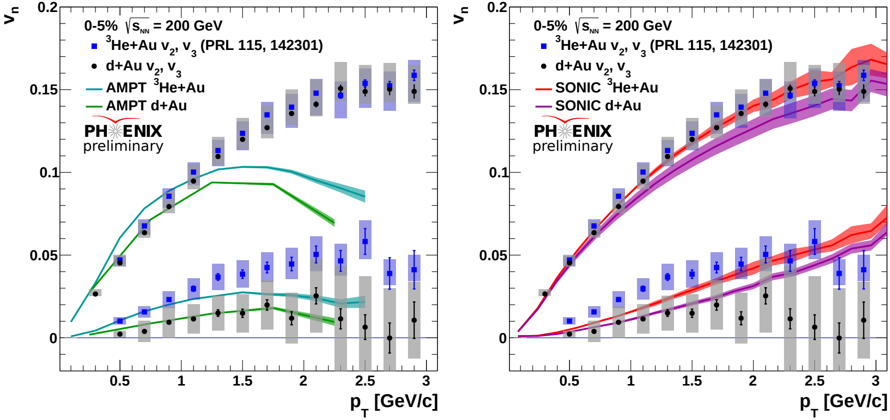
- **Important**: non-flow is **not additive**

v_3 vs p_T—a further test of geometry engineering



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- Excellent further confirmation that geometry engineering works

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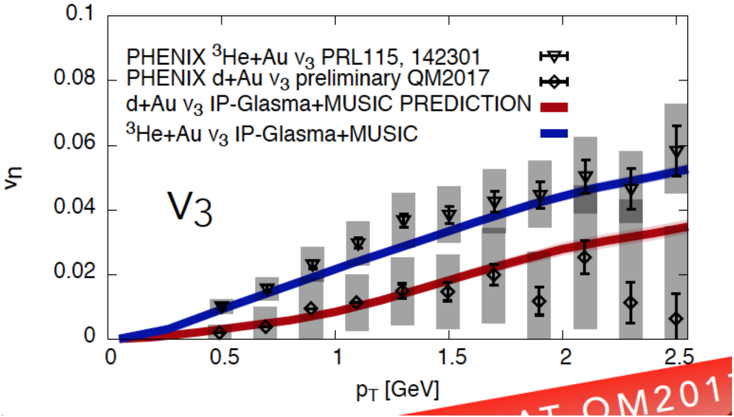


- v_3 is non-zero and lower in d+Au compared to ^{3}He+Au
- Excellent further confirmation that geometry engineering works
- New hydro prediction from Björn shows excellent agreement with data

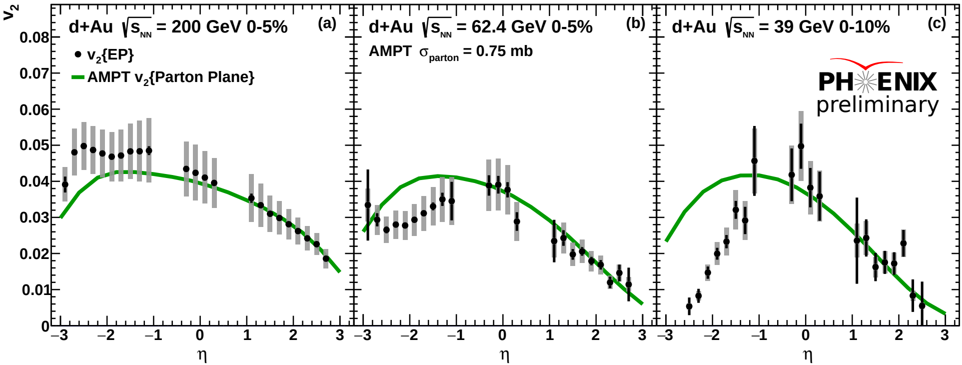
Intermission

- Positive v_2 vs p_T observed at all energies
- Hydro theory describes 200 GeV and 62.4 GeV with flow only while 39 and 19.6 GeV must have some significant non-flow
- AMPT suggests flow dominates at low p_T, mix of flow+non-flow at mid and high p_T, and the non-flow is non-additive
- v_3 vs p_T results in d/^{3}He+Au confirm geometry engineering, excellent agreement with hydro

Intermission

v_2 vs η

v_2 vs η, comparison with AMPT



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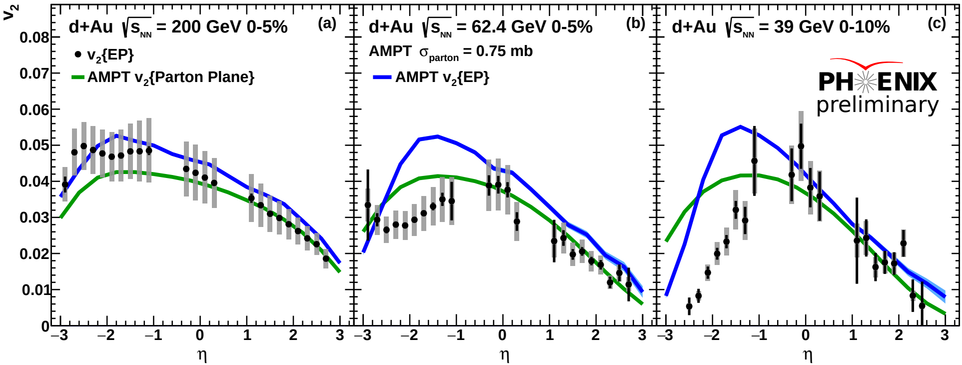

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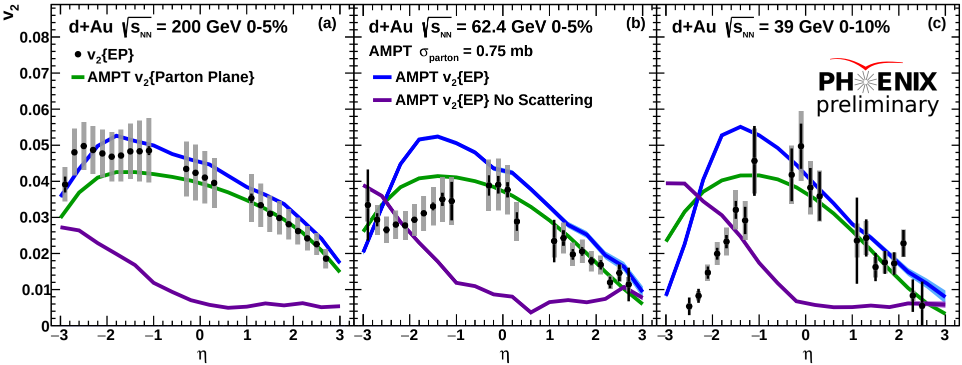

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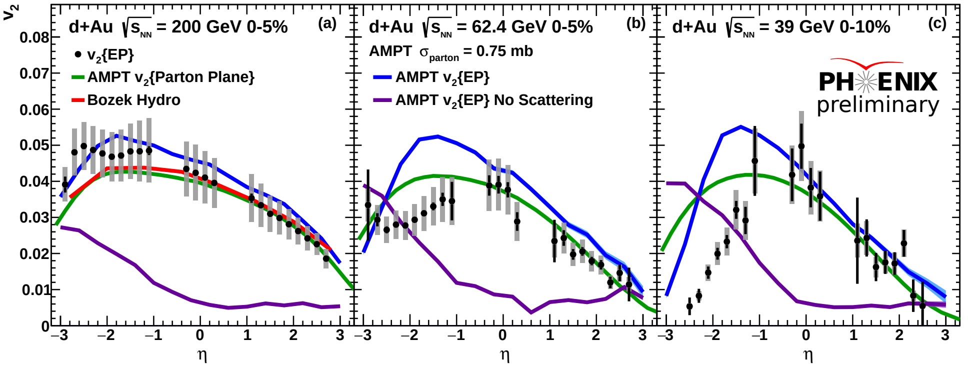

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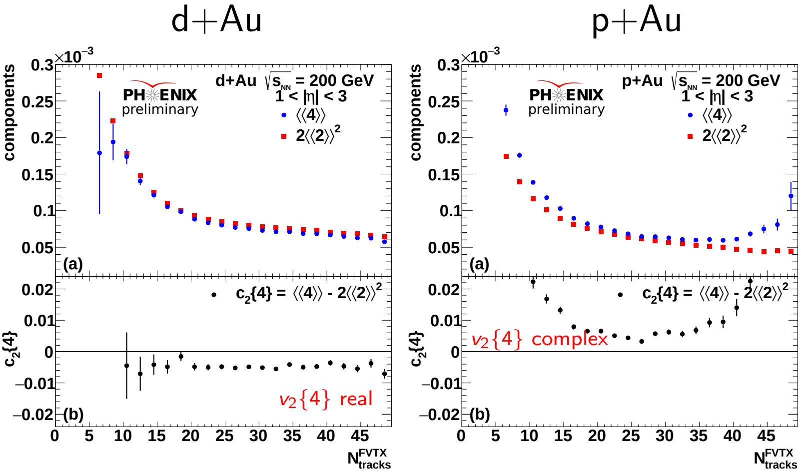
- AMPT flow+non-flow shows striking anti-correlation at backward rapidity
- AMPT non-flow only shows nothing at mid and forward, large v_2 at backward rapidity near the detector (*highly* non-additive)
- Hydro theory at 200 GeV very similarly to AMPT and data

- More hydro theory calculations for η dependence would be very helpful
- The data shows large forward/backward asymmetry that decreases with energy, but is that what's really happening?
- AMPT flow only shows forward/backward asymmetry at all energies
- AMPT flow+non-flow shows strong anticorrelation between flow and non-flow at backward rapidity that brings v_2 backward down significantly
- The non-flow is *highly* non-additive

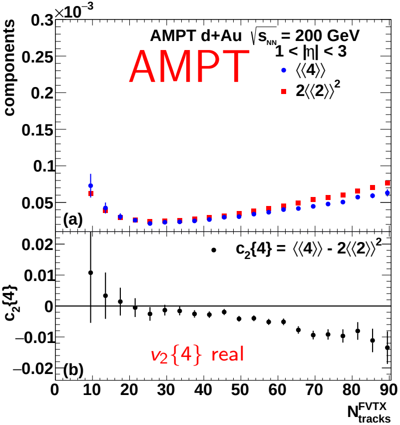
Intermission

Multiparticle correlations

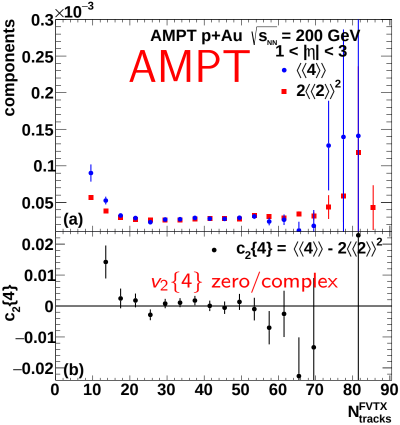


- Real $v_2\{4\}$ in d+Au, complex $v_2\{4\}$ in p+Au
- Fluctuations could dominate in the p+Au ($v_2\{4\} \approx \sqrt{v_2^2 - \sigma^2}$)

d+Au



p+Au



- AMPT similar to data—real $v_2\{4\}$ in d+Au, complex $v_2\{4\}$ in p+Au
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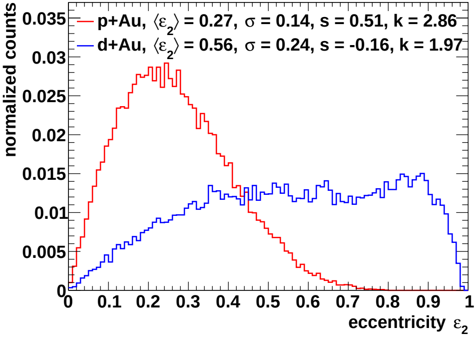
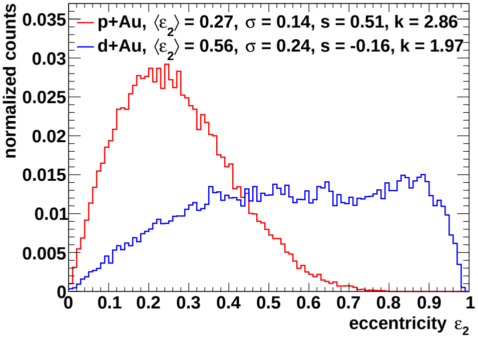


	p+Au	d+Au
$\langle\varepsilon_2\{2\}\rangle$	0.303	0.610
$\langle\varepsilon_2\rangle$	0.270	0.560
$\langle\varepsilon_2\{4\}\rangle$ Approx.	0.232	0.505
$\langle\varepsilon_2\{4\}\rangle$ Exact	0.166	0.508

- Eccentricity cumulants: $\varepsilon_2\{2\} = (\langle\varepsilon_2^2\rangle)^{1/2}$, $\varepsilon_2\{4\} = (-(\langle\varepsilon_2^4\rangle - 2\langle\varepsilon_2^2\rangle^2))^{1/4}$
- We don't have the v_n distribution but in the hydro limit $v_n \propto \varepsilon_n$
- Gaussian? No. Small relative variance? No.
- $\varepsilon_2\{4\} = \sqrt{\varepsilon_2^2 - \sigma^2}$ doesn't apply!

Eccentricity distributions and cumulants



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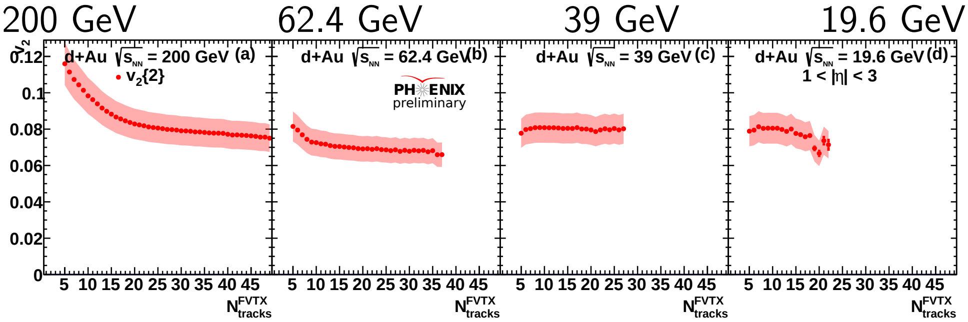
$$\varepsilon_2\{4\} = (\varepsilon_2^4 - 2\varepsilon_2^2\sigma^2 - 4\varepsilon_2 s\sigma^3 - (k-2)\sigma^4)^{1/4}$$

- the variance brings $\varepsilon_2\{4\}$ down
- 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 $= 3$
- Some math details in the backups

$v_2\{2\}$ and $v_2\{4\}$ in the d+Au beam energy scan



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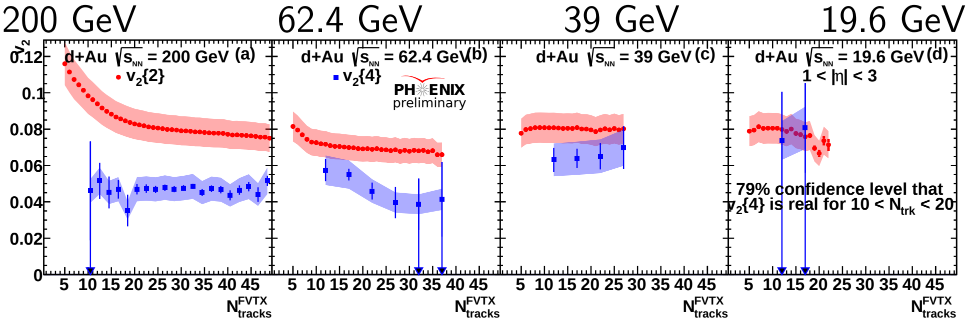
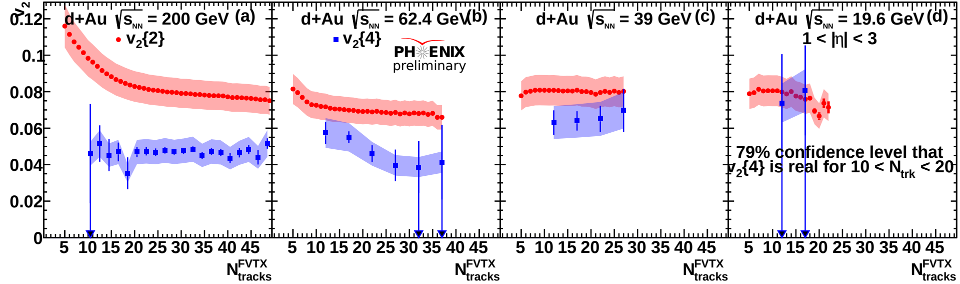
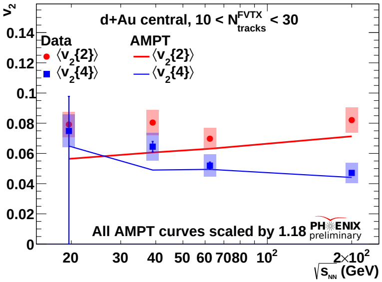


- $v_2\{2\}$ relatively constant with N_{tracks}^{FVTX} and collision energy
- Observation of real $v_2\{4\}$ in d+Au at all energies!
- Strong (?) evidence for collectivity

$v_2\{2\}$ and $v_2\{4\}$ in the d+Au beam energy scan

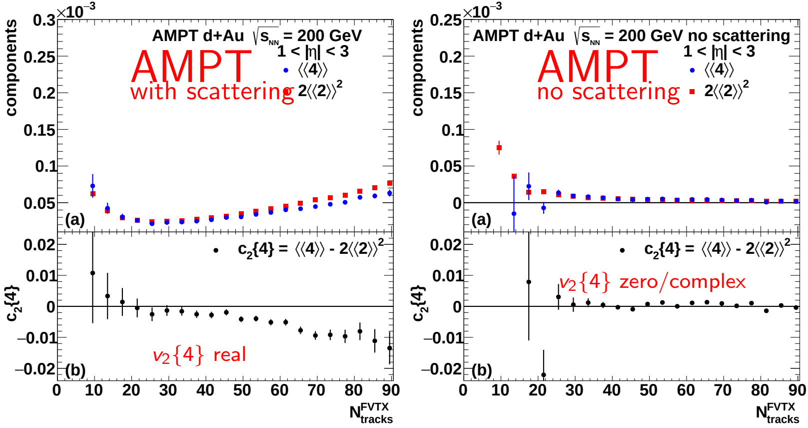
200 GeV 62.4 GeV 39 GeV 19.6 GeV





- Select $10 < N_{tracks}^{FVTX} < 30$, integrate
- Trend of $v_2\{2\}$ and $v_2\{4\}$ merging as $\sqrt{s_{NN}}$ is lowered
- AMPT sees the same trend

AMPT with no scattering



- Turn off scattering in AMPT—remove all correlations with initial geometry
- Components show different trend but are still non-zero
- But $v_2\{4\}$ goes from real to $\sim$zero—connection between real $v_2\{4\}$ and geometry in d+Au

Final thoughts

- Positive v_2 vs p_T observed from 200 GeV all the way down to 19.6 GeV
  - 200 and 62.4 GeV can be described either with flow only or with flow+non-flow
  - 39 and 19.6 GeV require significant non-flow in any scenario
- Positive v_3 vs p_T observed in 200 GeV
  - Lower than v_3 in ^{3}He+Au as expected from initial geometry —geometry engineering works
- Positive v_2 vs η observed from 200 GeV down to 39 GeV
  - 200 GeV can be described as flow only for almost all η
  - Lower energies can be described as flow only for mid and forward rapidity
  - Lower energies show possible flow/non-flow anti-correlation at backward rapidity—this can obscure what is likely a strong forward/backward asymmetry at all energies
- Real valued $v_2\{4\}$ observed from 200 GeV all the way down to 19.6 GeV
  - Multiparticle correlations generally held as best evidence for collectivity
  - There is still the risk of some non-flow contribution to $v_2\{4\}$
  - It's very important to understand the details of the fluctuations

Additional Material

Clearly, "fluctuations" are doing a lot of work for us. What do we mean, and how well do we understand them?

- We always say $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx \sqrt{v_2^2 - \sigma^2}$

Cumulants: a closer inspection

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- Is that really true?

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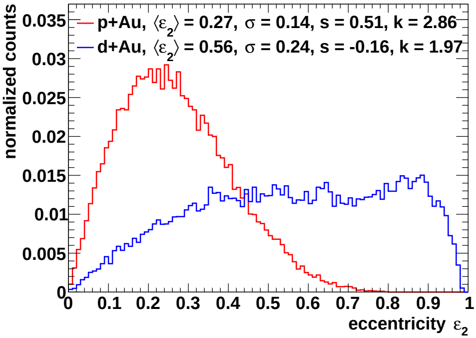
  - Small relative variance, $\sigma/v_n \ll 1$
- Are these assumptions valid? Let's have a look...

Eccentricity distributions and cumulants



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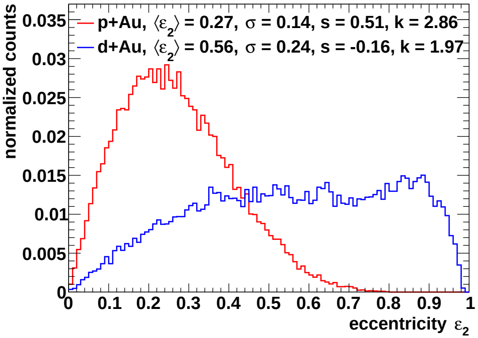

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- Eccentricity cumulants: $\varepsilon_2\{2\} = (\langle\varepsilon_2^2\rangle)^{1/2}$, $\varepsilon_2\{4\} = (-(\langle\varepsilon_2^4\rangle - 2\langle\varepsilon_2^2\rangle^2))^{1/4}$
- We don't have the v_n distribution but in the hydro limit $v_n \propto \varepsilon_n$
- Gaussian? No. Small relative variance? No.

Back to basics (a brief excursions)

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 excursions)

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)

$$\begin{aligned}
\mu_n &= \sum_{k=1}^{n} B_{n,k}(\kappa_1, ..., \kappa_{n-k+1}) \quad (= B_n(\kappa_1, ..., \kappa_{n-k+1})) \\
\kappa_n &= \sum_{k=1}^{n} (-1)^{k-1} (k-1)! B_{n,k}(\mu_1, ..., \mu_{n-k+1}),
\end{aligned}$$

Back to basics (a brief excursions)

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 excursions)

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

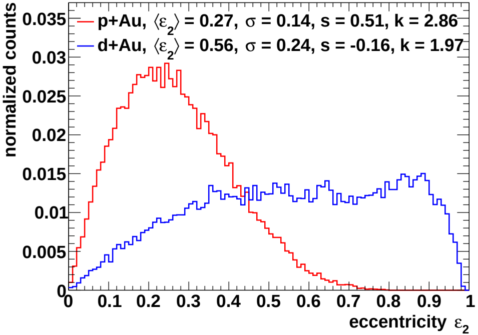
$$\begin{aligned} \Big(\langle v_n^4\rangle &= v_n^4 + 6v_n^2\sigma^2 + 3\sigma^4 + 4v_n\kappa_3 + \kappa_4\Big) \\ -\Big(2\langle v_n^2\rangle^2 &= 2v_n^4 + 4v_n^2\sigma^2 + 2\sigma^4\Big) \\ &\rightarrow \\ \langle v_n^4\rangle - 2\langle v_n^2\rangle^2 &= -v_n^4 + 2v_n^2\sigma^2 + \sigma^4 + 4v_n\kappa_3 + \kappa_4 \end{aligned}$$

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

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

So the correct form is actually much more complicated than we tend to think...

Eccentricity distributions and cumulants

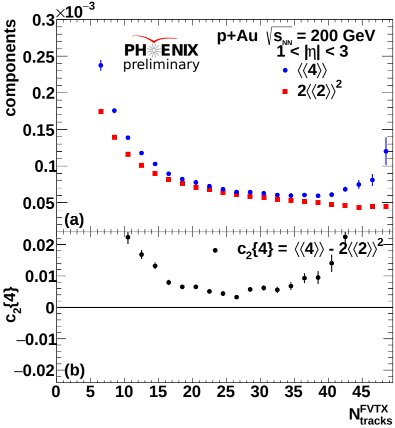


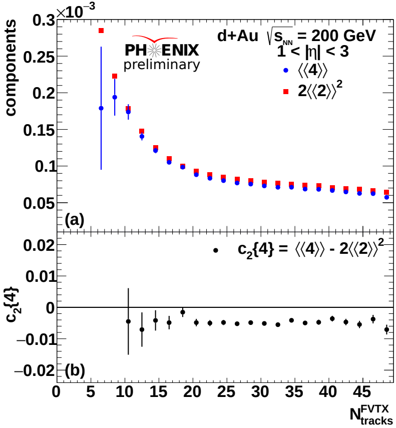
	p+Au	d+Au
$\langle\varepsilon_2\{2\}\rangle$	0.303	0.610
$\langle\varepsilon_2\rangle$	0.270	0.560
$\langle\varepsilon_2\{4\}\rangle$ Approx.	0.232	0.505
$\langle\varepsilon_2\{4\}\rangle$ Exact	0.166	0.508

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

- the variance brings $\varepsilon_2\{4\}$ down
- 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

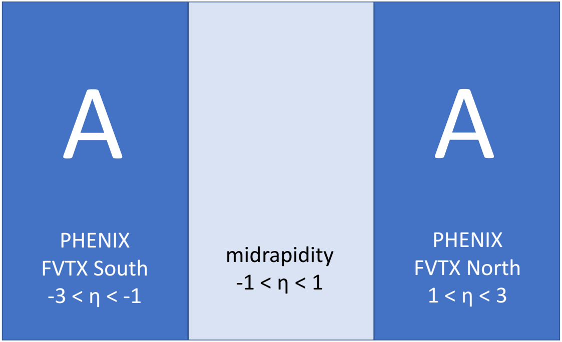




$$v_2\{4\} = (v_2^4 - 2v_2^2\sigma^2 - 4v_2 s\sigma^3 - (k-2)\sigma^4)^{1/4}$$

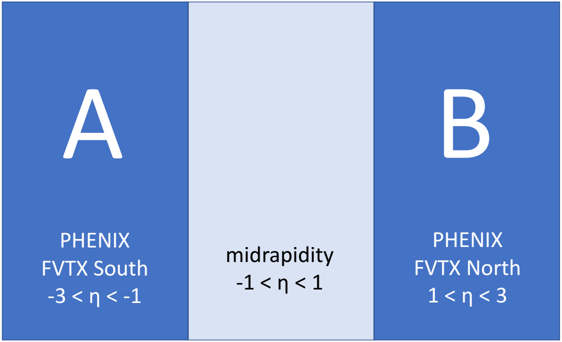
- Eccentricity fluctuations alone go a long way towards explaining this
- Additional fluctuations in the (imperfect) translation of ε_2 to v_2?

How to apply an eta gap in the FVTX?



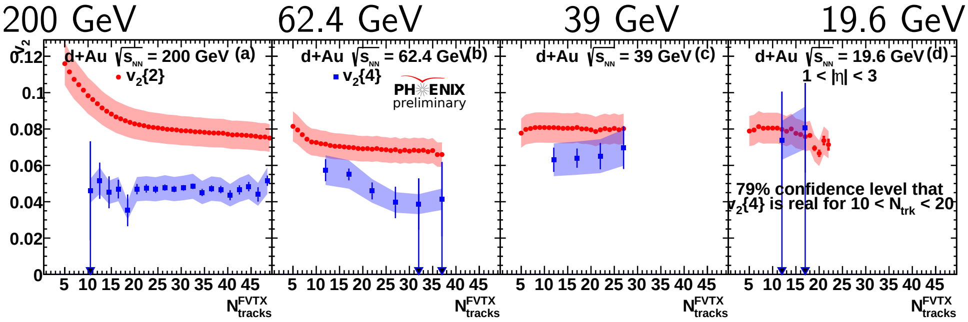
- $v_2\{2\}$ and $v_2\{4\}$—use tracks anywhere in the FVTX

How to apply an eta gap in the FVTX?

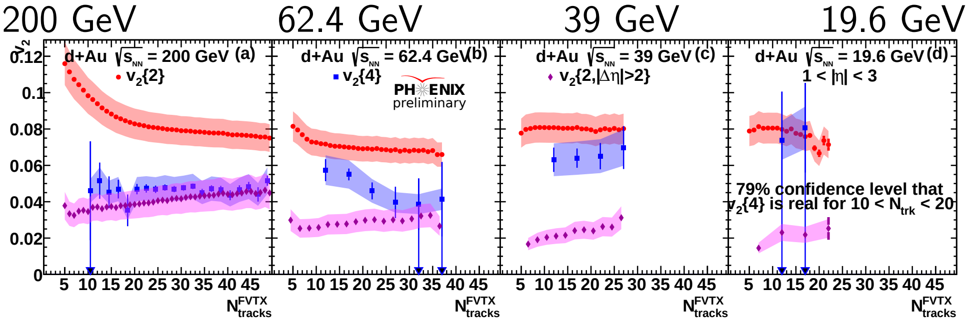


- $v_2\{2\}$ and $v_2\{4\}$—use tracks anywhere in the FVTX
- $v_2\{2, |\Delta\eta| > 2\}$—require one track in south (backward rapidity) and one in north (forward)

Can we apply an eta gap to get a better handle on the non-flow?



- $v_2\{2\}$ and $v_2\{4\}$ vs N_{tracks}^{FVTX}, all tracks anywhere in FVTX



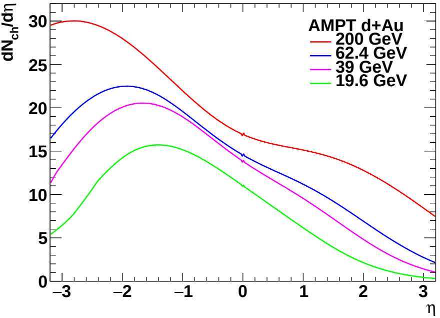
- $v_2\{2\}$ and $v_2\{4\}$ vs N^{FVTX}_{tracks}, all tracks anywhere in FVTX
- $v_2\{2,|\Delta\eta|>2\}$ vs N^{FVTX}_{tracks}, one track backward, the other forward

$$v_2\{2,|\Delta\eta|>2\} = \sqrt{v_2^2+\sigma^2} \qquad v_2\{2\} = \sqrt{v_2^2+\sigma^2+\delta}$$

$$v_2\{4\} \approx \sqrt{v_2^2-\sigma^2}$$

- Hard to understand this result based on fluctuations
- The eta gap reduces the non-flow, but what else does it do?

What can AMPT tell us about asymmetric collisions?



- Asymmetric collision systems have:
  —asymmetric $dN_{ch}/d\eta$
  —asymmetric v_2 vs η
- The FVTX combined is weighted by $dN_{ch}/d\eta$ towards backward rapidity, where v_2 is also higher—the effect is more pronounced at lower energies
- The FVTX two subevent is equally weighted between forward and back: $\sqrt{v_2^B v_2^F}$

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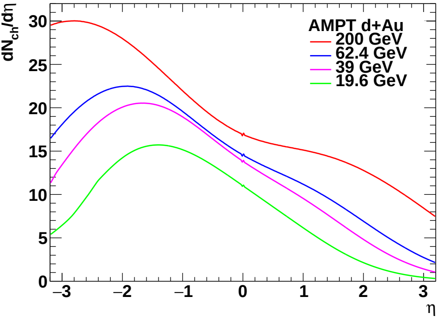

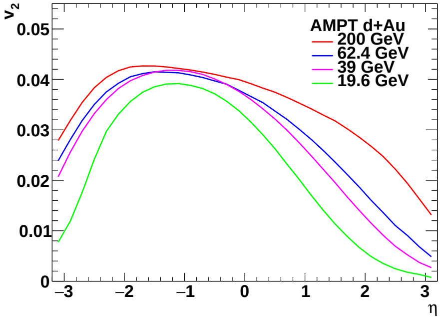

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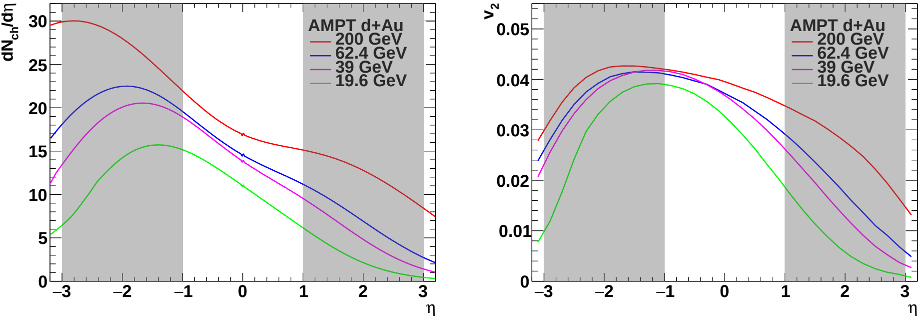

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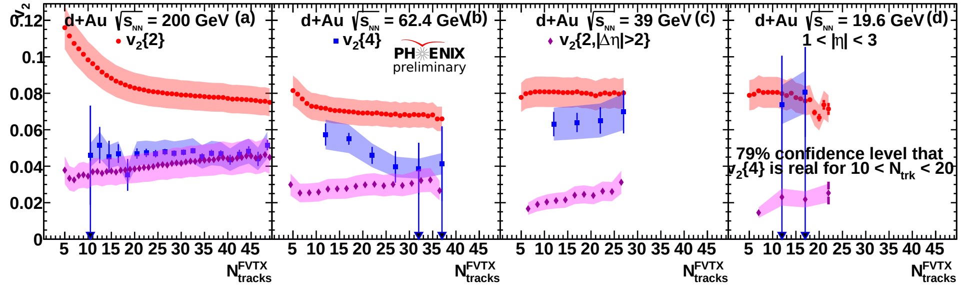
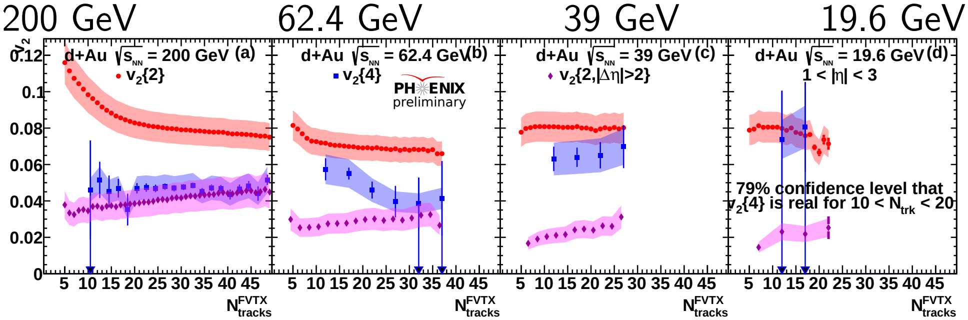
Understanding $v_2\{2\}$, $v_2\{4\}$, and $v_2\{2, |\Delta\eta| > 2\}$

200 GeV 62.4 GeV 39 GeV 19.6 GeV



- $v_2\{2\}$ and $v_2\{4\}$ vs N^{FVTX}_{tracks}—weighted average of v_2^B and v_2^F
- $v_2\{2, |\Delta\eta| > 2\}$ vs N^{FVTX}_{tracks}—fixed, equal weighting $\sqrt{v_2^B v_2^F}$
- $dN_{ch}/d\eta$ and v_2 vs η alone may explain these results

Understanding $v_2\{2\}$, $v_2\{4\}$, and $v_2\{2, |\Delta\eta| > 2\}$



- $v_2\{2\}$ and $v_2\{4\}$ vs N_{tracks}^{FVTX}—weighted average of v_2^B and v_2^F
- $v_2\{2, |\Delta\eta| > 2\}$ vs N_{tracks}^{FVTX}—fixed, equal weighting $\sqrt{v_2^B v_2^F}$
- $dN_{ch}/d\eta$ and v_2 vs η alone may explain these results
- There may be additional effects like event plane decorrelation, e.g. $v_2\{2, |\Delta\eta| > 2\} = \sqrt{v_2^B v_2^F \cos(2(\psi_2^B - \psi_2^F))}$