PHENIX results on multiparticle correlations in small systems

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For the PHENIX Collabotation

Quark Matter XXVI
Chicago, IL
7 February 2017

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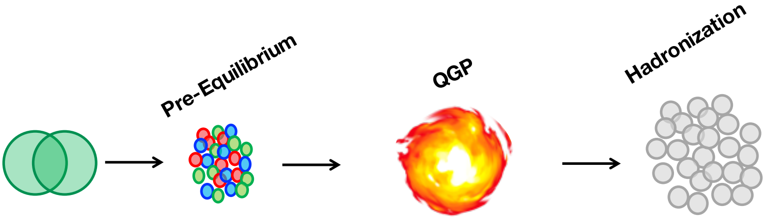
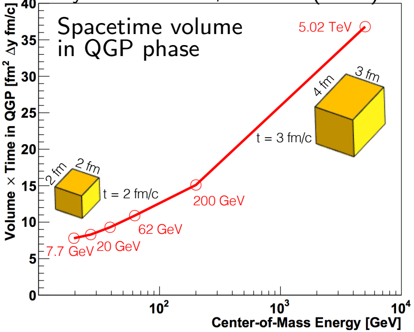
Testing hydro by controlling system size



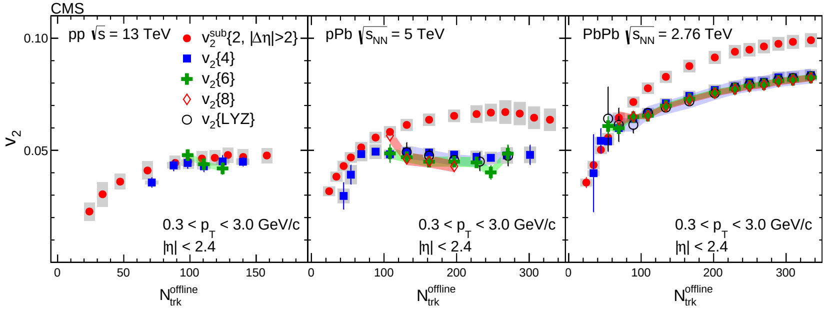
J.D. Orjuela Koop et al
Phys. Rev. C 93, 044910 (2016)



- 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:

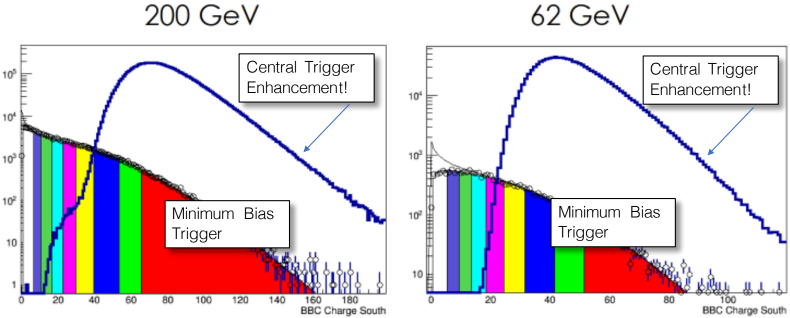
$$v_2\{2\} = \sqrt{v_2^2 + \sigma^2 + \delta} \qquad \delta \text{ non-flow, } \sigma \text{ variance}$$

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

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

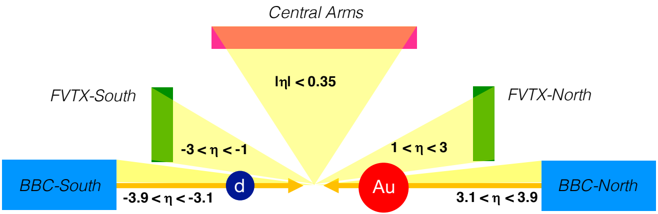
- Can multiparticle correlations be measured in small systems at RHIC?

2016 d+Au beam energy scan in PHENIX

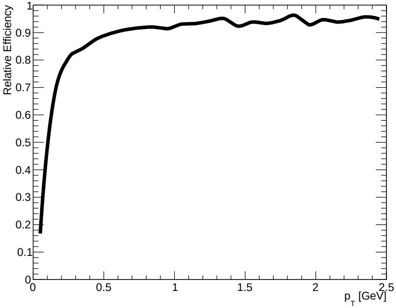


d+Au collision energy	total events analyzed	central events analyzed
200 GeV	636 million	585 million
62.4 GeV	131 million	76 million
39 GeV	137 million	49 million
19.6 GeV	15 million	3 million

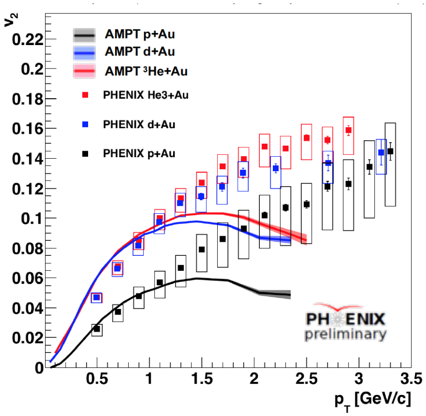
The PHENIX forward vertex detector



- 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

Experimental method and details

Definition of Q-vectors

$$Q_{n,x} = \sum_{i=1}^{M} \cos n\phi_i = \Re\mathfrak{e}\, Q_n, \quad Q_{n,y} = \sum_{i=1}^{M} \sin n\phi_i = \Im\mathfrak{m}\, Q_n$$

Calculation of correlators

$$\langle 2 \rangle = \frac{Q_n Q_n^* - M}{M(M-1)}$$

$$\langle 4 \rangle = \frac{|Q_n|^4 + |Q_{2n}|^2 - 2\Re\mathfrak{e}\left[Q_{2n} Q_n^* Q_n^*\right]}{M(M-1)(M-2)(M-3)} - 2\,\frac{2(M-2)\,|Q_n|^2 - M(M-3)}{M(M-1)(M-2)(M-3)}.$$

Calculation of cumulants

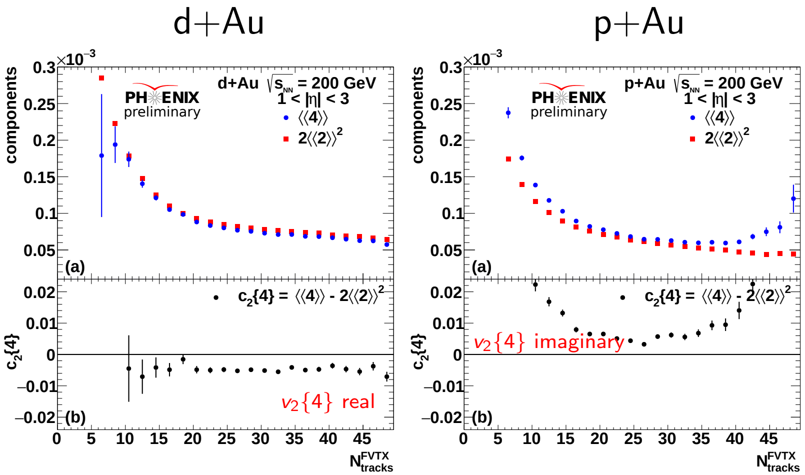
$$c_n\{2\} = \langle\langle 2 \rangle\rangle$$

$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2\langle\langle 2 \rangle\rangle^2$$

Determination of harmonic coefficients

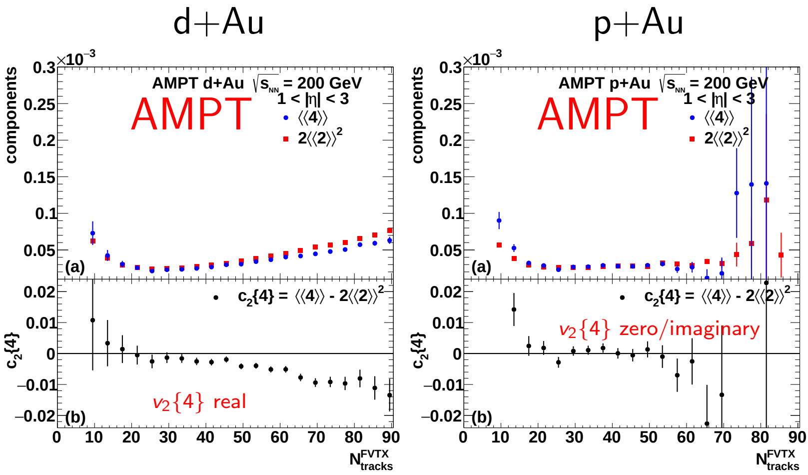
$$v_n\{2\} = \sqrt{c_n\{2\}}$$

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$



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

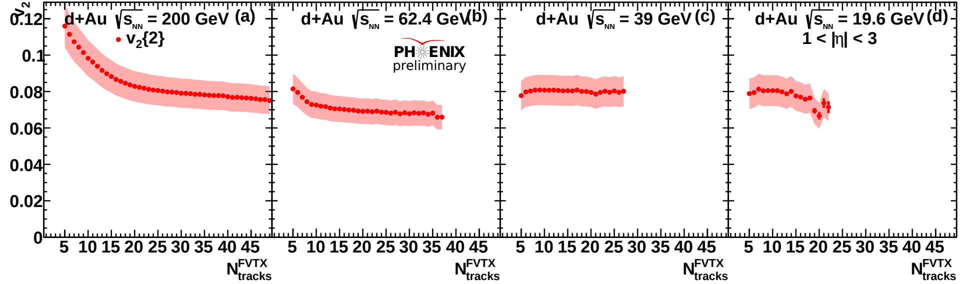
Components and cumulants in p+Au and d+Au in AMPT



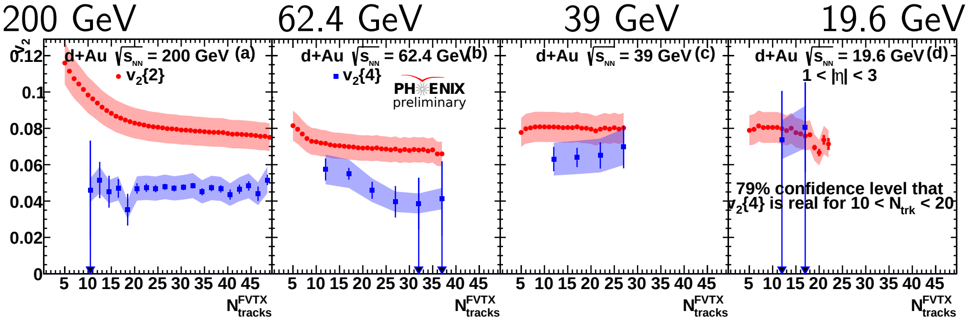
- AMPT similar to data—real $v_2\{4\}$ in d+Au, imaginary $v_2\{4\}$ in p+Au
- Fluctuations could dominate in the p+Au ($v_2\{4\} = \sqrt{v_2^2 - \sigma^2}$)

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

200 GeV 62.4 GeV 39 GeV 19.6 GeV



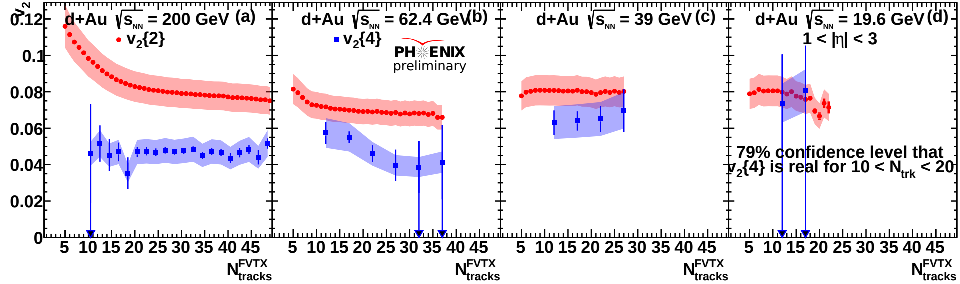
- $v_2\{2\}$ relatively constant with N_{tracks}^{FVTX} and collision energy



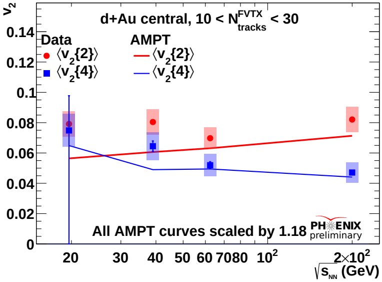
- $v_2\{2\}$ relatively constant with N^{FVTX}_{tracks} and collision energy
- **Observation of real $v_2\{4\}$ in d+Au at all energies!!!**
- **Strong evidence for collectivity**

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

200 GeV | 62.4 GeV | 39 GeV | 19.6 GeV



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

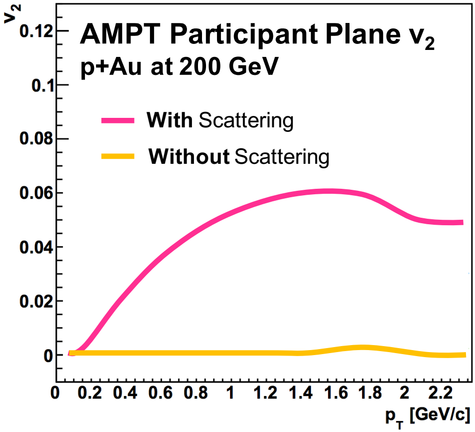


Intermission

The story so far:

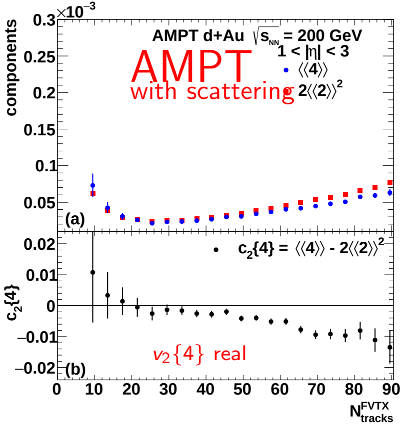
- Real $v_2\{4\}$ in d+Au collisions at all energies!
- Imaginary $v_2\{4\}$ in p+Au at 200 GeV, maybe fluctuations dominate? Good reason to believe collectivity/flow in p+Au as well
- Is real-valued $v_2\{4\}$ really a good measure for collectivity?
- Good news: we can turn the knobs in AMPT to see if we can draw a clear connection between $v_2\{4\}$ and initial geometry in d+Au

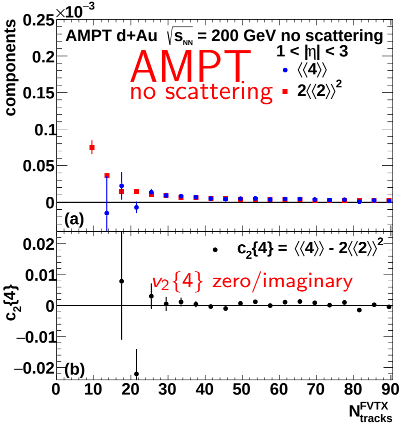
AMPT with no scattering



- 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

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 ∼zero—connection between real $v_2\{4\}$ and geometry in d+Au

Intermission

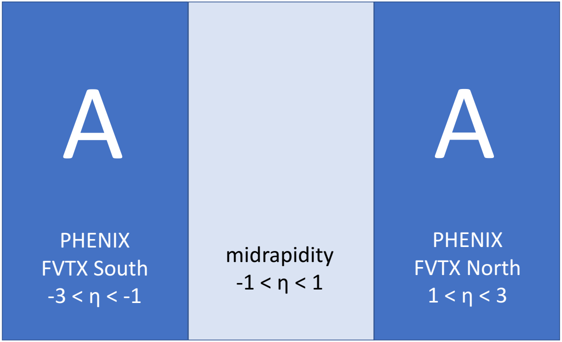
The story so far:

- Real $v_2\{4\}$ in d+Au collisions at all energies!
- Clear connection between real $v_2\{4\}$ and initial geometry—strong evidence for collective behavior

What about the non-flow?

- We've shown $v_2\{2\}$ but potentially significant non-flow
- We assume $v_2\{4\}$ removes all the non-flow, but are we sure?
- Try to apply an eta gap on the 2-particle ($v_2\{2, |\Delta\eta| > 2\}$) to get a better handle on non-flow

How to apply an eta gap in the FVTX?



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

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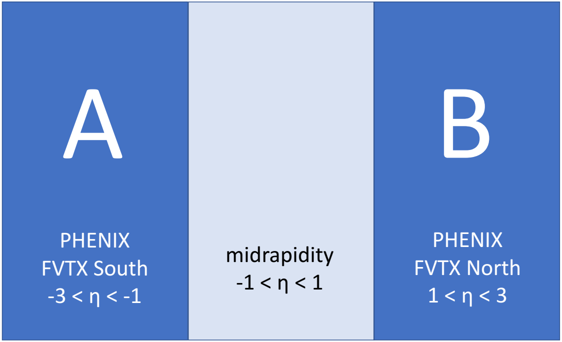
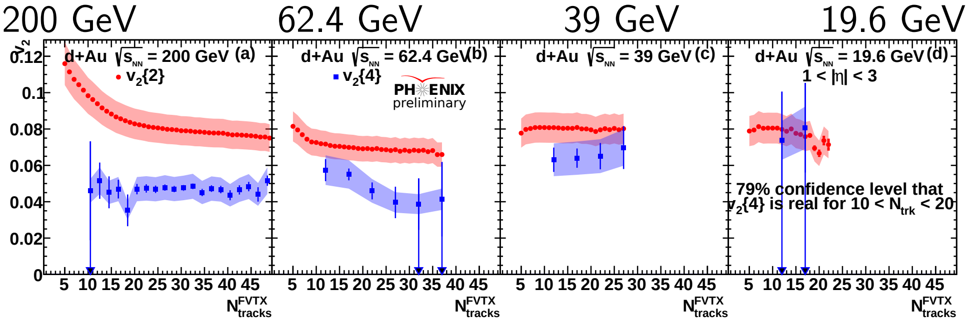


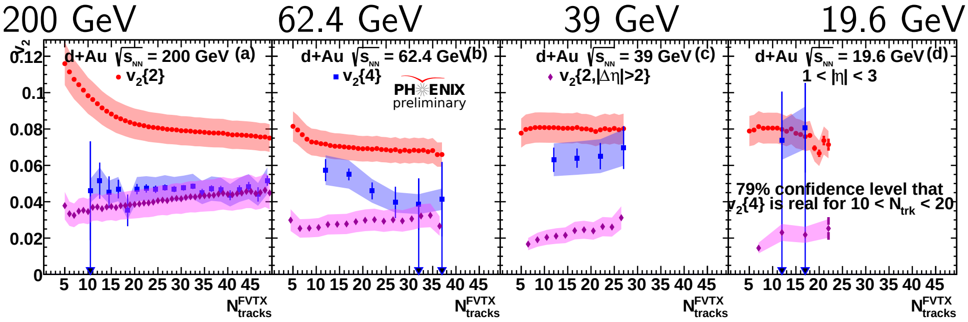
- $v_2\{2\}$ and $v_2\{4\}$—use tracks anywhere in the FVTX
- $v_2\{2, |\Delta\eta| > 2\}$—require one track in south (backward rapidity) and one in north (forward)

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



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

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



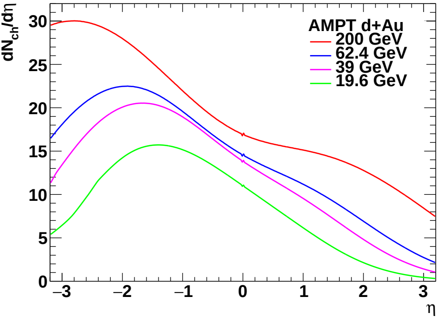
- $v_2\{2\}$ and $v_2\{4\}$ vs N_{tracks}^{FVTX}, all tracks anywhere in FVTX
- $v_2\{2, |\Delta\eta| > 2\}$ vs N_{tracks}^{FVTX}, one track backward, the other forward

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

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

- 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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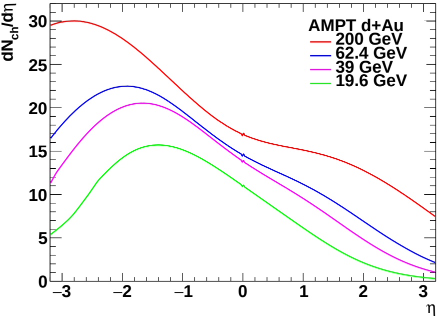

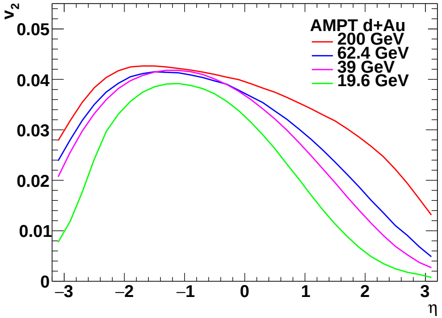

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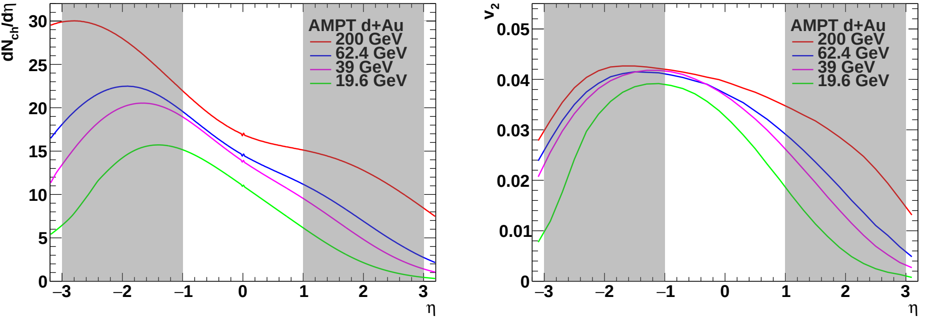

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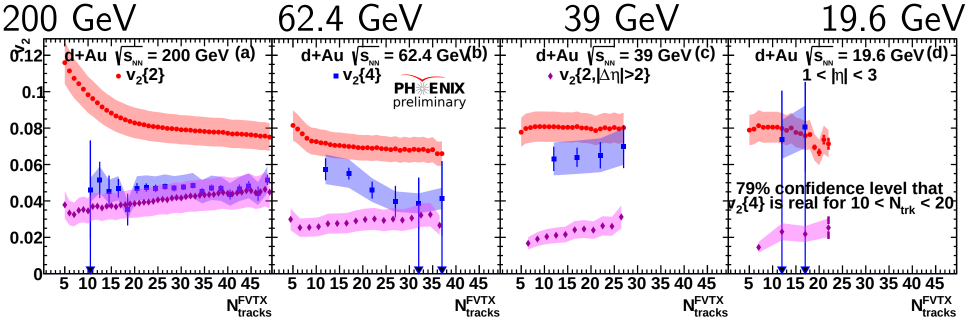
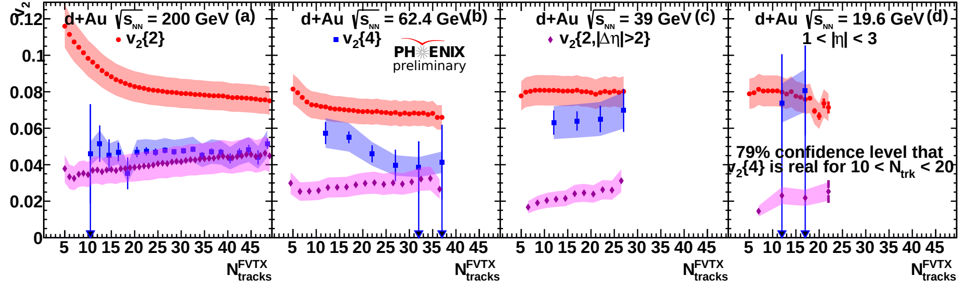
Understanding $v_2\{2\}$, $v_2\{4\}$, and $v_2\{2, |\Delta\eta| > 2\}$



- $v_2\{2\}$ 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

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_{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. $v_2\{2, |\Delta\eta| > 2\} = \sqrt{v_2^B v_2^F \cos(2(\psi_2^B - \psi_2^F))}$

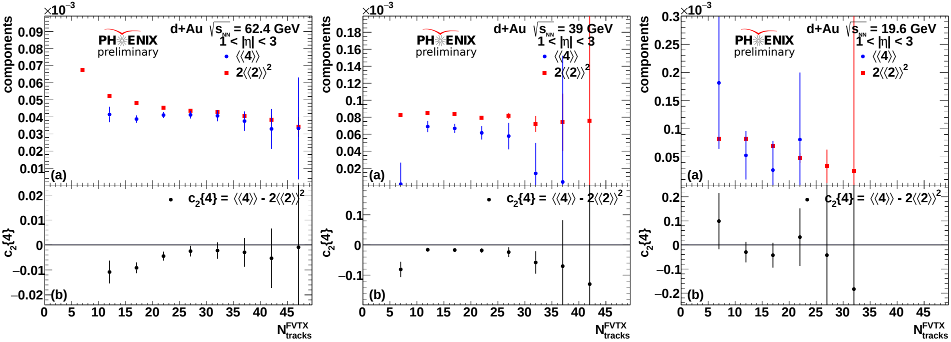
Summary and Outlook

- **Observation of real-valued $v_2\{4\}$ in d+Au collisions at 200, 62.4, 39, and 19.6 GeV from the 2016 d+Au beam energy scan**
  - **Connection between real-valued $v_2\{4\}$ and initial geometry established**
  - **Strong evidence for collectivity**
- $v_2\{4\}$ observed to be everywhere imaginary in p+Au collisions at 200 GeV
  - Could be dominance of fluctuations ($\sigma/v_2 > 1$)
  - Good reason to believe collectivity exists in p+Au (many PHENIX measurements on the topic)
  - Contrast with p+Pb at 5.02 TeV—what happens in between RHIC and LHC energies?
- The trend of $v_2\{2\}$, $v_2\{2, |\Delta\eta| > 2\}$, and $v_2\{4\}$ with collision energy is consistent with expectations based on $dN_{ch}/d\eta$ and v_2 vs η
  - AMPT shows similar trends
  - Additional effects may be at play—event plane decorrelation?
- Additional measurements are possible and potentially very valuable
  - We plan to explore $v_2\{6\}$ in d+Au
  - It may be possible to look at $v_3\{4\}$ in ^{3}He+Au

Additional Material

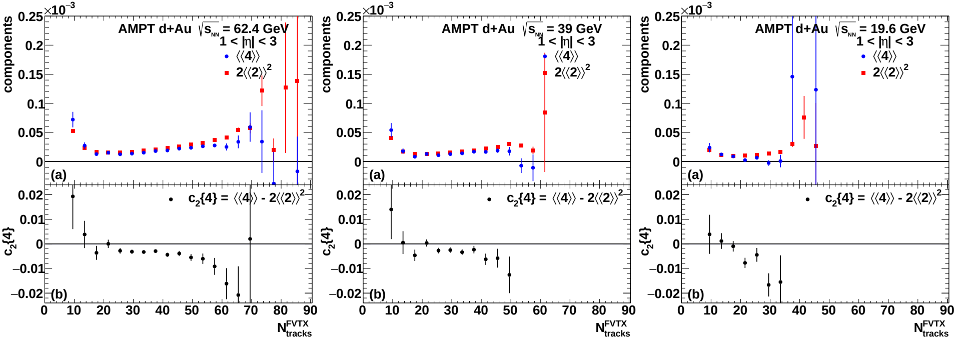
Утро в сосновом лесу

Утро в сосновом лесу



- components, d+Au lower energies, data

Results



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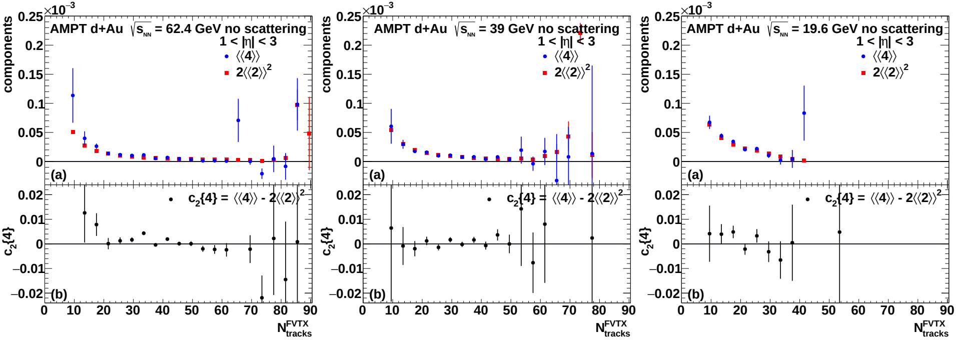
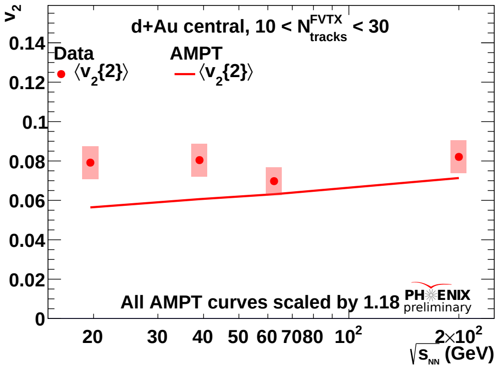


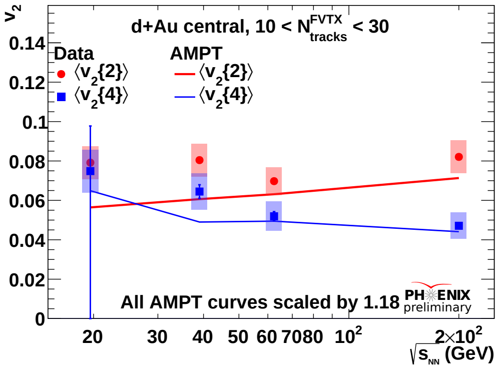
- components, d+Au lower energies, AMPT no scattering

Results



- v_2 in d+Au at all energies

Results



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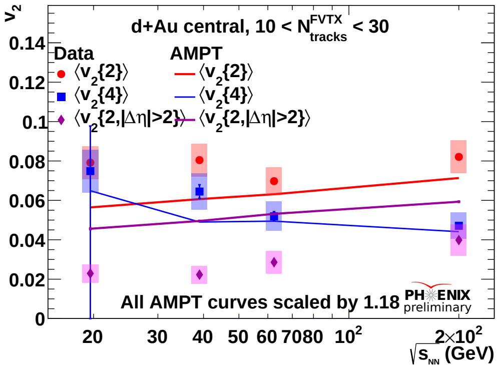

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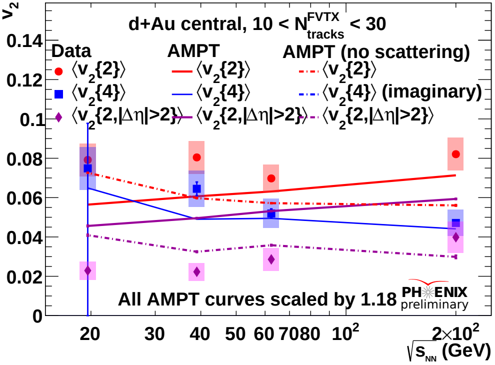

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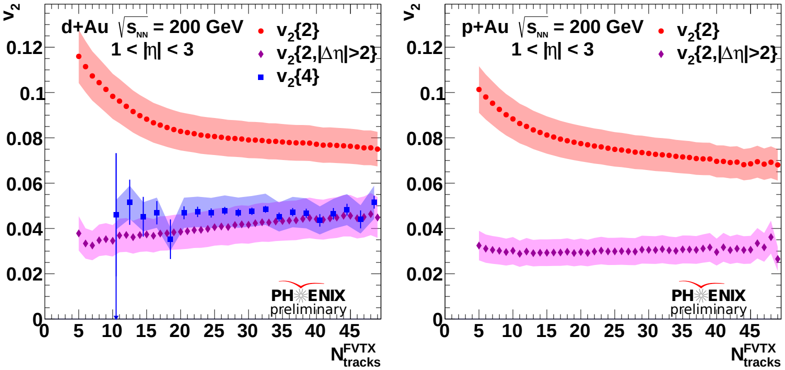

- d+Au at 200 GeV on the left, p+Au at 200 GeV on right
- $v_2\{2\}$ and $v_2\{2, |\Delta\eta| > 2\}$ lower for p+Au, as expected from geometry