Searching for collectivity and testing the limits of hydrodynamics: small systems at RHIC

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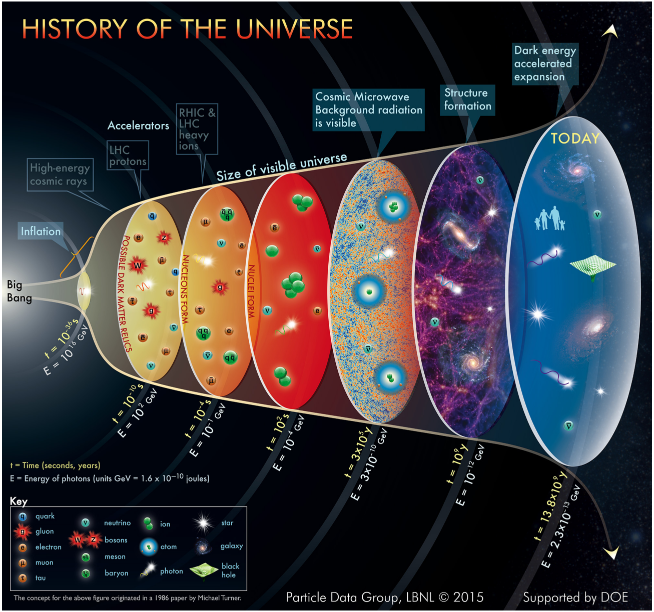
Утро в сосновом лесу

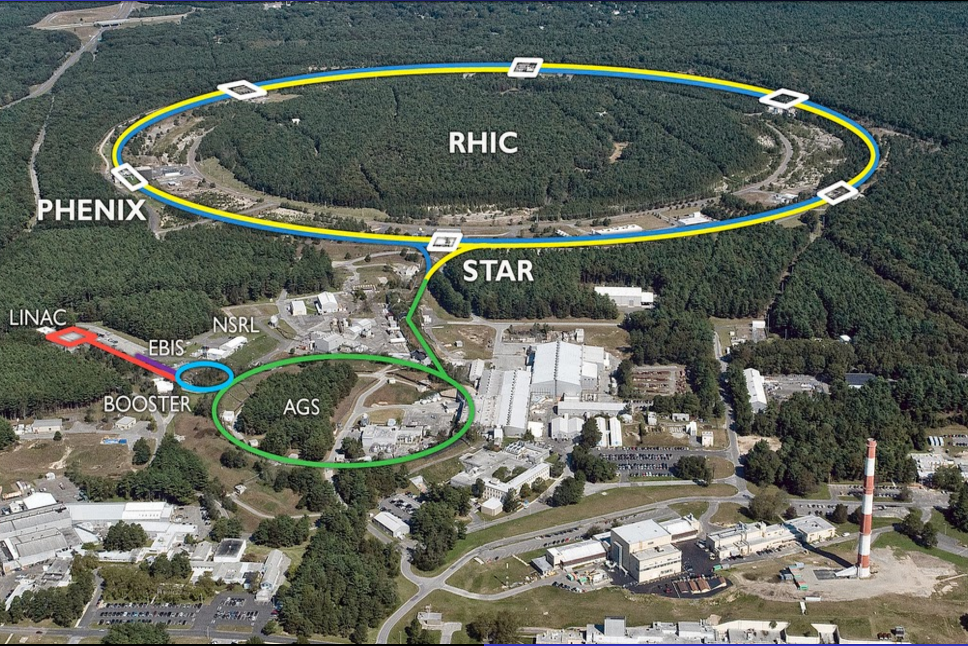
Утро в сосновом лесу

The history of the universe



- The QGP is a system of approximately free quarks and gluons
- The early universe (few microseconds) was a QGP
- We can recreate the QGP in the lab in collisions of heavy nuclei at relativistic speeds
- Goal: study the properties of the QGP

The Relativistic Heavy Ion Collider



The Relativistic Heavy Ion Collider

- RHIC is the only polarized proton collider in the world
- RHIC is one of two heavy ion colliders, the other being the LHC
- RHIC is a dedicated ion collider and is designed to collide many different species of ions at many different energies—vastly more flexible than the LHC

Collision Species	Collision Energies (GeV)
p↑+p↑	510, 500, 200, 62.4
p+Al	200
p+Au	200
d+Au	200, 62.4, 39, 19.6
^{3}He+Au	200
Cu+Cu	200, 62.4, 22.5
Cu+Au	200
Au+Au	200, 130, 62.4, 56, 39, 27, 19.6, 15, 11.5, 7.7, 5, ...
U+U	193

And lots more to come!

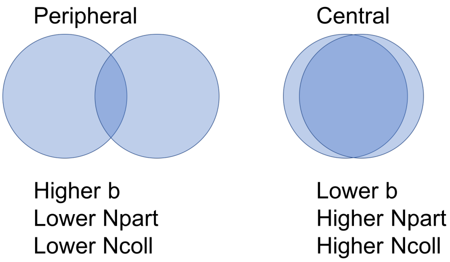
Outline

- A few basic things about heavy ions
  —Centrality
  —Anisotropic flow
  —Quark number scaling
  —Baryon enhancement
- Small systems
  —Geometry scan
  —d+Au beam energy scan
- The future and final thoughts

Centrality

Centrality

- Need to characterize the overlap of the two nuclei
- b (impact parameter)—separation between the centers of the two nuclei
- N_{part}—number of nucleons in the overlap region
- N_{coll}—number of nucleon-nucleon collisions



Centrality	$\langle N_{coll} \rangle$	$\langle N_{part} \rangle$
Au+Au		
0-10%	960.2 $\pm$ 96.1	325.8 $\pm$ 3.8
10-20%	609.5 $\pm$ 59.8	236.1 $\pm$ 5.5
20-40%	300.8 $\pm$ 29.6	141.5 $\pm$ 5.8
40-60%	94.2 $\pm$ 12.0	61.6 $\pm$ 5.1
60-92%	14.8 $\pm$ 3.0	14.7 $\pm$ 2.9
d+Au		
0-20%	15.1 $\pm$ 1.0	15.3 $\pm$ 0.8
20-40%	10.2 $\pm$ 0.7	11.1 $\pm$ 0.6
0-100%	7.6 $\pm$ 0.4	8.5 $\pm$ 0.4
40-60%	6.6 $\pm$ 0.4	7.8 $\pm$ 0.4
60-88%	3.1 $\pm$ 0.2	4.3 $\pm$ 0.2
p+p	$\equiv 1$	$\equiv 2$

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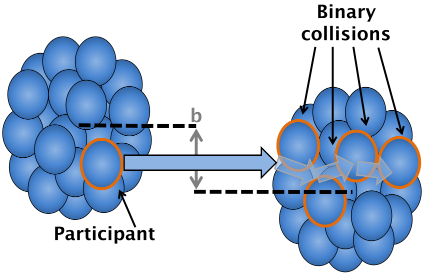

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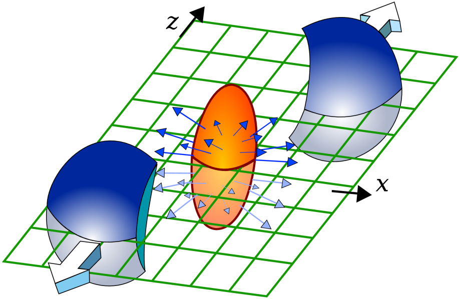
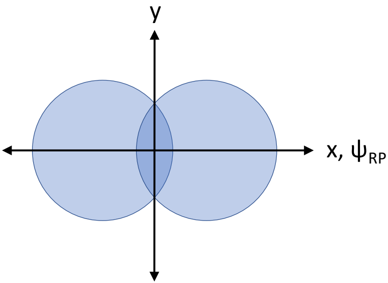
p+p	≡ 1	≡ 2

Intermission

Azimuthal anistropy

Azimuthal anisotropy measurements

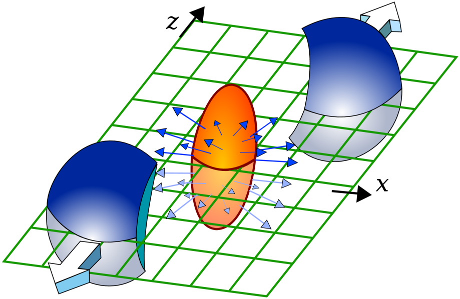


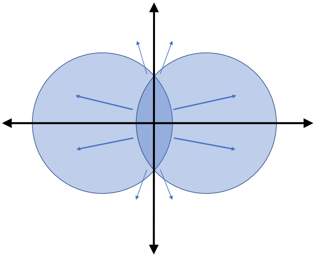


$$\frac{dN}{d\varphi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos n\varphi \qquad v_n = \langle \cos n\varphi \rangle \qquad \varepsilon_n = \frac{\sqrt{\langle r^2 \cos n\varphi\rangle + \langle r^2 \sin n\varphi\rangle}}{\langle r^2 \rangle}$$

- Roughly constant pressure → larger pressure gradient "in plane" → **azimuthal anisotropy**—characterize with Fourier series
- Hydrodynamics translates initial shape (ε_n) into final state distribution (v_n)
- Overlap shape is approximately elliptical, so expect v_2 to be the largest

Azimuthal anisotropy measurements





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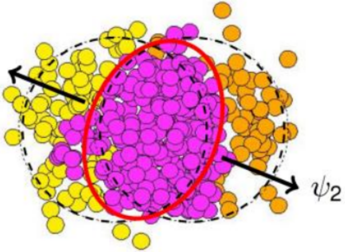
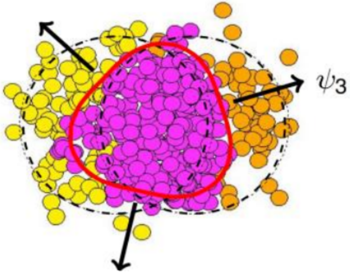
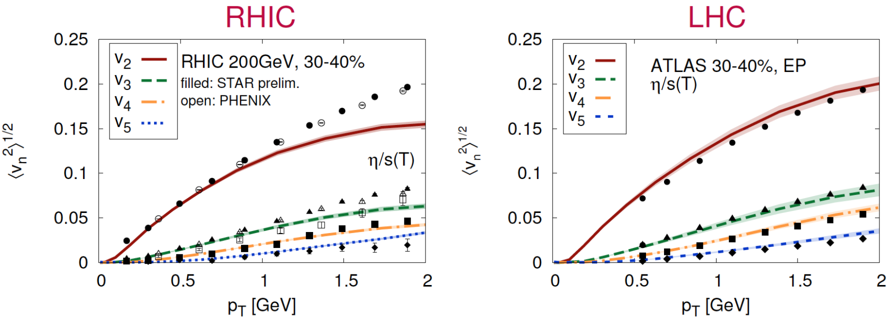




- A nucleus isn't actually just a sphere
- Fluctuations in nucleon position can lead to interesting shapes
- Symmetry planes can be different for different harmonics

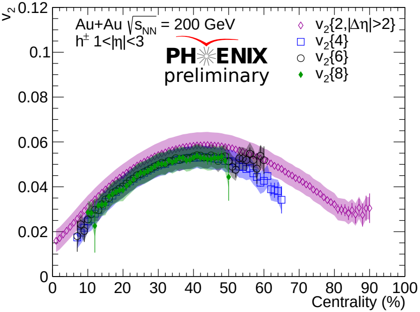
Data and theory for v_n

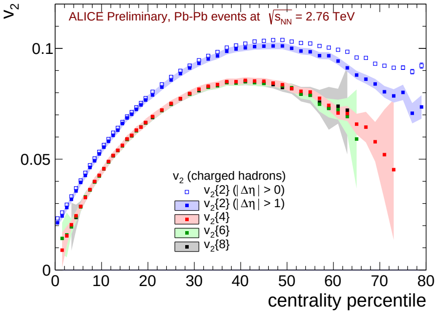
Gale et al, Phys. Rev. Lett. 110, 012302 (2013)



- Note that v_2 is the largest, as expected (elliptic shape→elliptic flow)
- Way, way, too much data to show, but here's one example
- The hydrodynamics theory describes the data for many v_n very well

Multiparticle measurements





- Multiparticle correlations: can use 2, 4, 6, 8, ... particles to measure v_n
- Insights into fluctuations

  —2 is above, 4,6,8 consistent → Gaussian-ish fluctuations
- Multiparticle correlations offer favorable combinatorics

  —Dilution factor $\equiv \left\lfloor \frac{N}{k} \right\rfloor / \binom{N}{k} \approx (k-1)!/N^{k-1}$

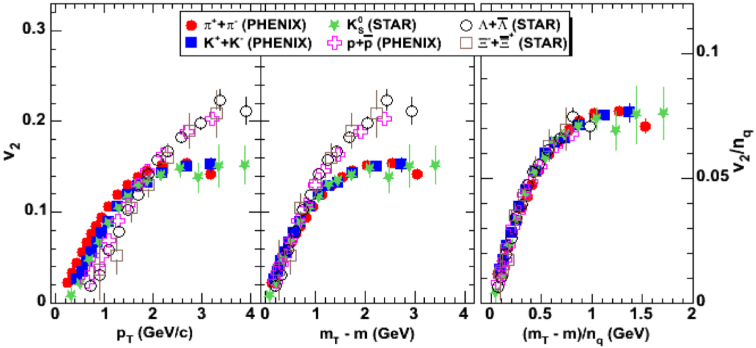
  —Efficiently suppress few-particle correlations

Intermission

Quark number scaling

Constituent quark scaling of elliptic flow

PHENIX, Phys. Rev. Lett. 90, 162301 (2007)



In recombination model, estimate of hadron v_2 is

$$v_2^{(M)}(P) = v_2^q(xP) + v_2^q((1-x)P) \qquad \approx 2v_2^q(P/2)$$
$$v_2^{(B)}(P) = v_2^q(xP) + v_2^q(x'P) + v_2^q((1-x-x')P) \qquad \approx 3v_2^q(P/3)$$

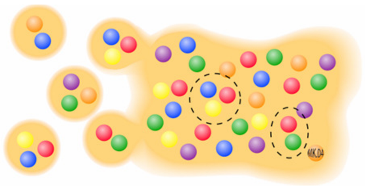
Hence constituent quark scaling

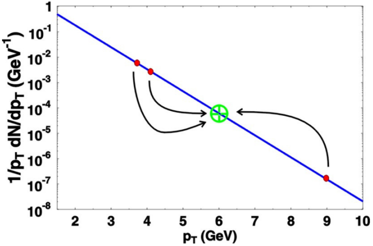
Intermission

Baryon enhancement
OR
My PhD thesis in four slides

Particle production by recombination

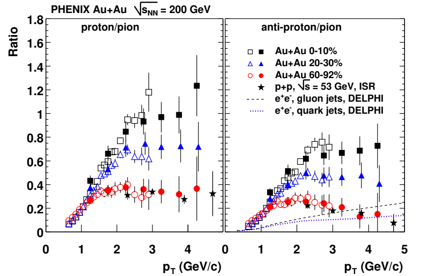
- Partons close together in phase space can coalesce into bound states
- The QGP is a system of thermalized partons—lots of partons near each other
- $P < p$ for fragmentation because $P = zp$ and $P > p$ for recombination because $xP = p$
- To make a 6 GeV hadron:
  —fragmentation: 1 parton, > 6 GeV
  —reco meson: 2 partons, ≈ 3 GeV
  —reco baryon: 3 partons, ≈ 2 GeV



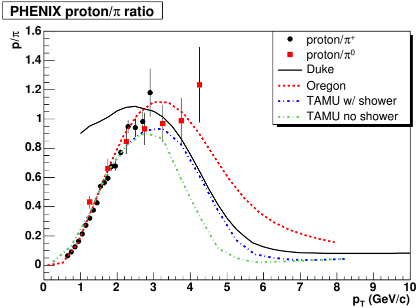


Baryon enhancement in Au+Au

PHENIX, Phys. Rev. Lett. 91, 172301 (2003)



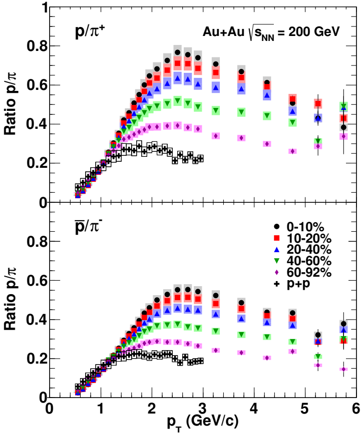
PHENIX, Nucl. Phys. A757, 184-283 (2005)



- Baryon production significantly enhanced relative to meson production —Larger system has more enhancement
- Hadronization by parton recombination explains this enhancement

p/π ratios, revisited

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



- Strong centrality dependence of p/π ratios in Au+Au collisions, as before

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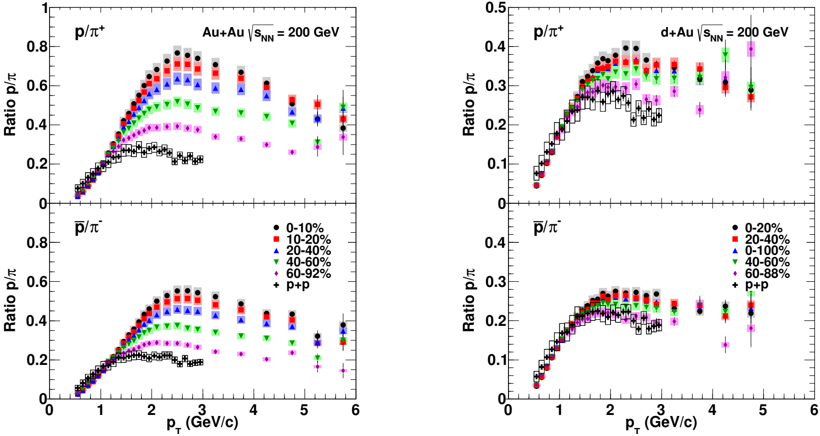

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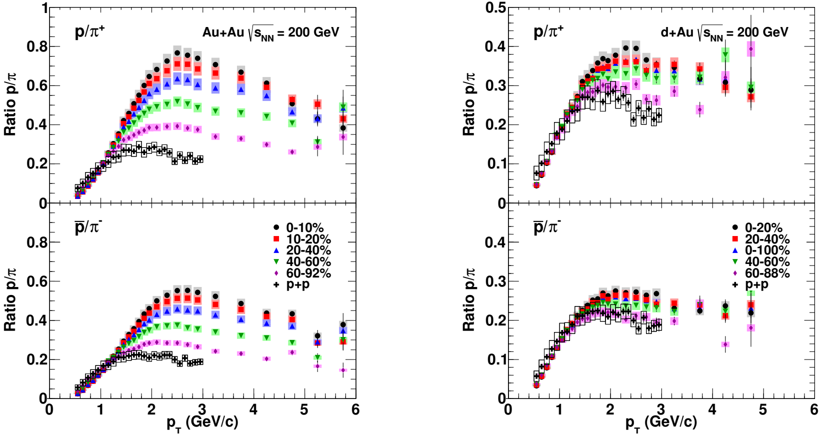
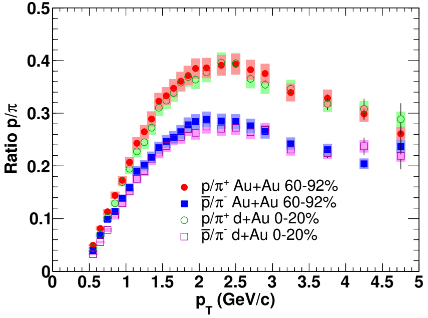


- Strong centrality dependence of p/π ratios in Au+Au collisions, as before
- Strong centrality dependence of p/π ratios in d+Au collisions as well
- How to understand? Recombination?
  —See Hwa and Yang, Phys. Rev. Lett. 93, 082302 (2004)

Comparison of peripheral Au+Au to central d+Au

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



- Identical p/π ratios

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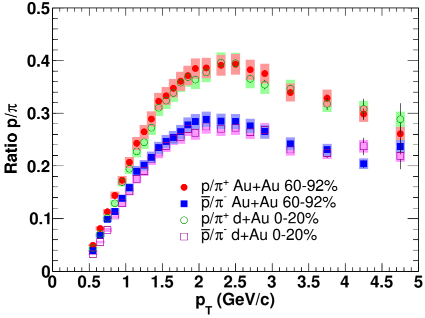

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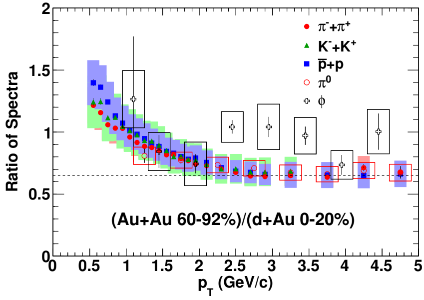

- Identical p/π ratios
- Universal curve for ratio of spectra

Comparison of peripheral Au+Au to central d+Au

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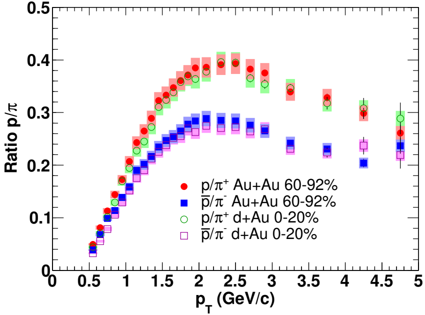

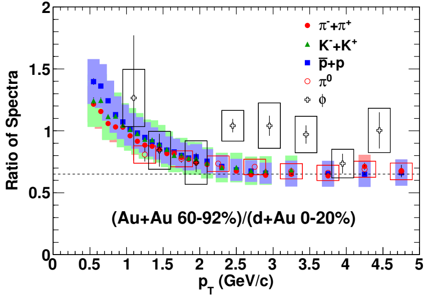

- Identical p/π ratios
- Universal curve for ratio of spectra
- **Striking similarities between peripheral Au+Au and central d+Au —Why?**

Intermission

Small systems

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

Media Attention

Physics World, September 22, 2017 (clickable link)
Phys.org, September 18, 2017 (clickable link)

Home » Physics » General Physics » September 18, 2017

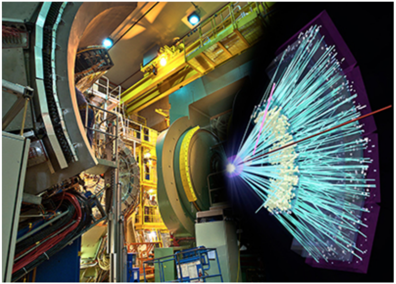
Possible evidence for small, short-lived drops of early universe quark-gluon plasma

September 18, 2017 by Karen Mcnulty Walsh

"To distinguish color glass condensate from QGP, we need more detailed theoretical descriptions of what these things look like," Belmont said.

Collider serves up drop of primordial soup

Sep 22, 2017



Tiny drop: PHENIX and reconstructed particle tracks from a QGP

PHENIX colleague Ron Belmont of the University of Colorado says it is still possible that the elliptical emission they have observed is due not to the formation of tiny QGPs but instead down to nuclear properties prior to collision. When accelerated close to light speed, time slows down for the heavy nuclei, which means, according to quantum chromodynamics, that they appear as a dense wall of gluons. The fact that these condensates are thicker in the centre of the nuclei might explain why particles generated in the collisions are not emitted in random directions, he says.

Testing the hydro QGP picture in small systems

This is important, so let's do it right

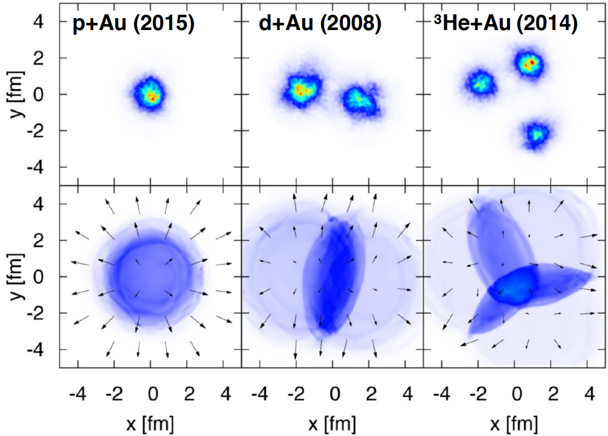
- Vary the geometry
  —Recall that hydro translates ε_n to v_n
- Fix the geometry, vary the size and lifetime

Intermission

Small systems geometry scan

Testing hydro by controlling system geometry

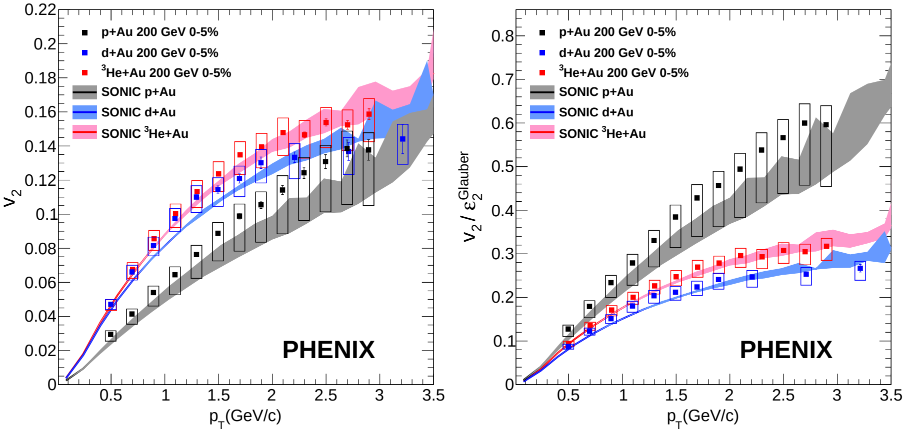
$\varepsilon_2 = 0.24$	$\varepsilon_2 = 0.57$	$\varepsilon_2 = 0.48$
$\varepsilon_3 = 0.16$	$\varepsilon_3 = 0.17$	$\varepsilon_3 = 0.23$



- Hydrodynamics translates initial geometry into final state
- Test hydro hypothesis by varying initial state

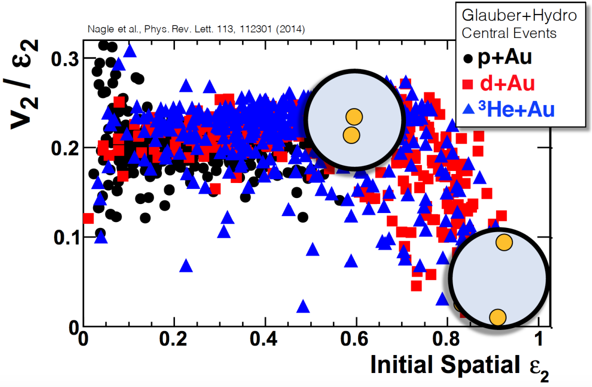
$\varepsilon_2^{\text{p+Au}} < \varepsilon_2^{\text{d+Au}} \approx \varepsilon_2^{\text{3He+Au}}$ $\quad \varepsilon_3^{\text{p+Au}} \approx \varepsilon_3^{\text{d+Au}} < \varepsilon_3^{\text{3He+Au}}$

PHENIX, Phys. Rev. C 95, 034910 (2017)



- Hydro theory describes the data extremely well
- Imperfect scaling with ε_2 captured by hydro
  —Disconnected hot spots

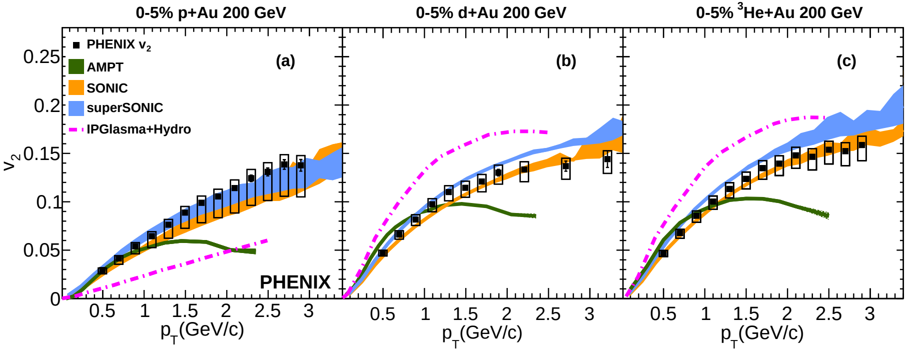
J.L. Nagle et al, Phys. Rev. Lett. 113, 112301 (2014)



- v_2/ε_2 relationship breaks for very large ε_2
- The hydro hotspots are so far apart that they never connect —Efficiency to translate ε_2 into v_2 goes down

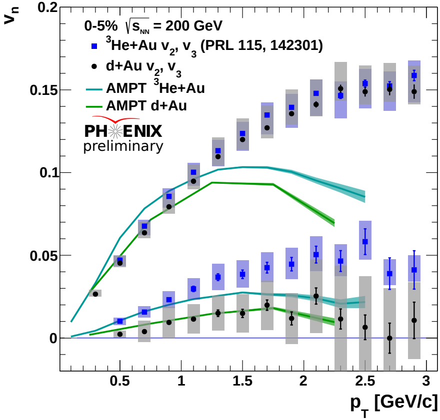
v_2 vs p_T in the geometry scan

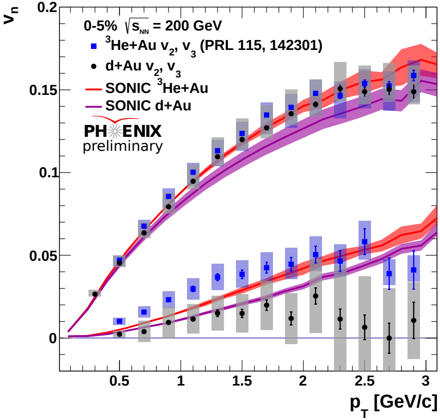
PHENIX, Phys. Rev. C 95, 034910 (2017)



- Hydro theory describes the data extremely well
- IPGlasma+Hydro calculation is an older version with too-round protons—more on that later

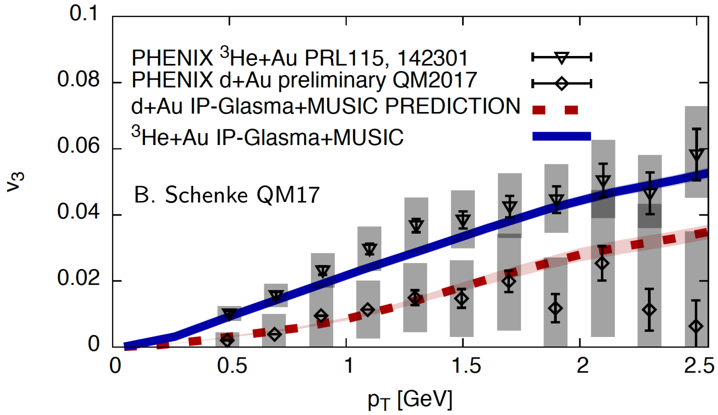
v_3 vs p_T in the geometry scan





- v_3 is non-zero and lower in d+Au compared to ^{3}He+Au
- Excellent further confirmation that geometry engineering works
- Hydro predictions show excellent agreement with data

v_3 vs p_T in the geometry scan



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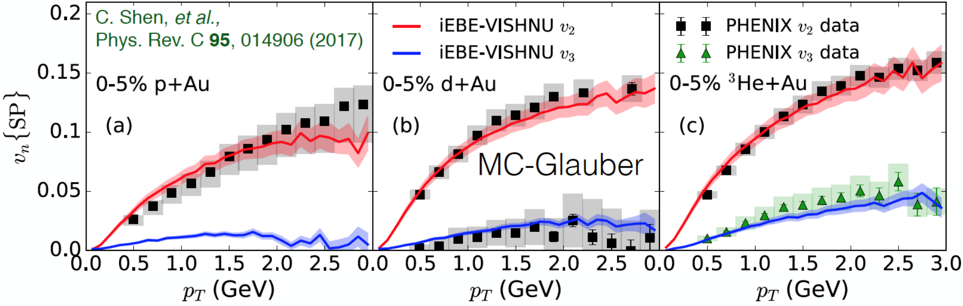


- v_3 is non-zero and lower in d+Au compared to ^{3}He+Au
- Excellent further confirmation that geometry engineering works
- Hydro predictions show excellent agreement with data
- v_3 in p+Au is in the works, anticipate showing at QM18 this summer

Quick recap of small systems geometry scan

Second harmonic

- Geometries: $\varepsilon_2^{\text{p+Au}} < \varepsilon_2^{\text{d+Au}} \approx \varepsilon_2^{\text{3He+Au}}$
- Observables: $v_2^{\text{p+Au}} < v_2^{\text{d+Au}} \approx v_2^{\text{3He+Au}}$

Third harmonic

- Geometries: $\varepsilon_3^{\text{p+Au}} \approx \varepsilon_3^{\text{d+Au}} < \varepsilon_3^{\text{3He+Au}}$
- Observables: $v_3^{\text{p+Au}} \stackrel{?}{\approx} v_3^{\text{d+Au}} < v_3^{\text{3He+Au}}$

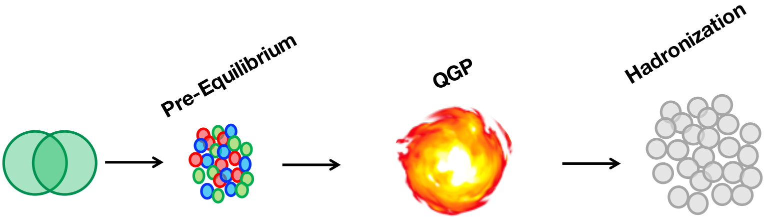
What's next?

- v_3 in p+Au coming soon!
- Friendly request to CGC folks: more calculations!

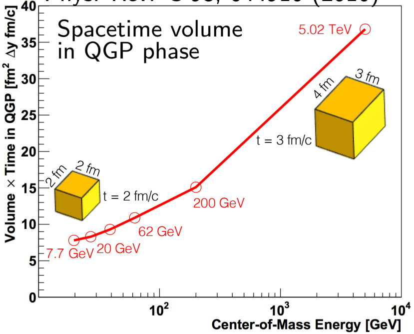
Intermission

Small systems beam energy scan

Testing hydro by controlling system size and life time

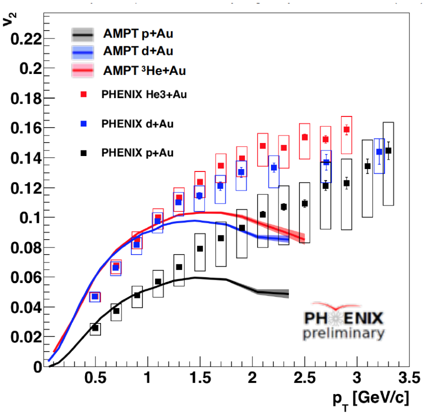


J.D. Orjuela Koop et al
Phys. Rev. C 93, 044910 (2016)



- 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

A Multi-Phase Transport model



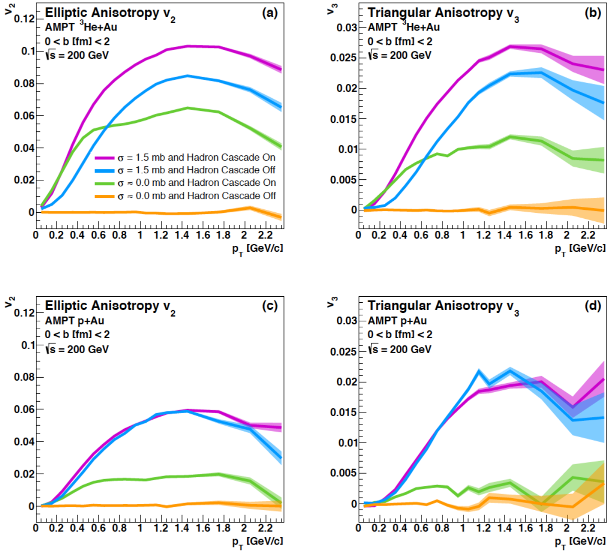
AMPT basic features

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

- AMPT has significant success in describing flow-like signatures
- AMPT is not hydro, but it is *collective*
  —translation of initial geometry to final state distributions
- AMPT produces final state particles over the full available phasespace
  —possible to perform exact same analysis on data and model

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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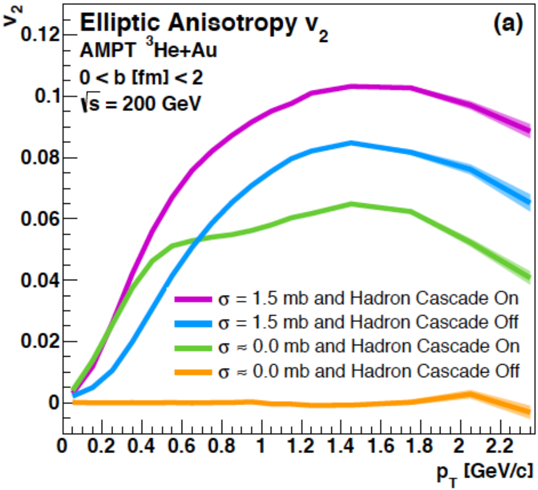

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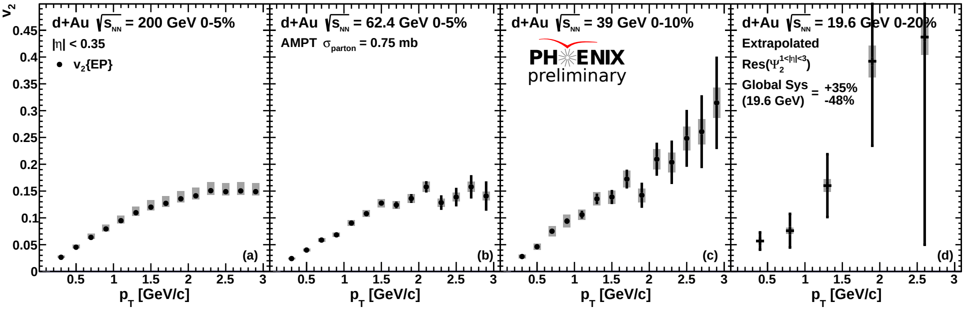
v_2 vs p_T, comparisons to AMPT

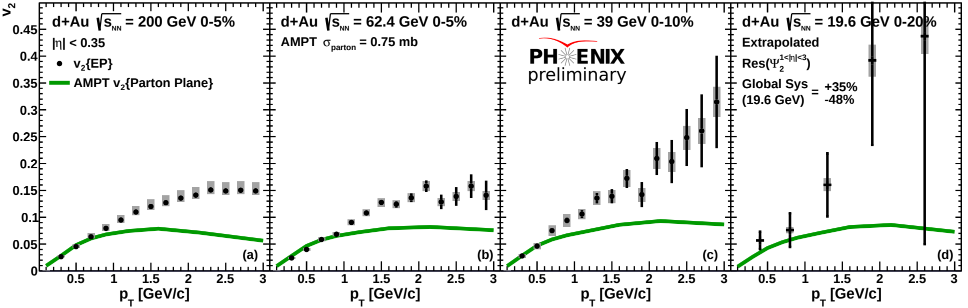
PHENIX, Phys. Rev. C 96, 064905 (2017)



- Event plane v_2 vs p_T measured for all energies

v_2 vs p_T, comparisons to AMPT

PHENIX, Phys. Rev. C 96, 064905 (2017)



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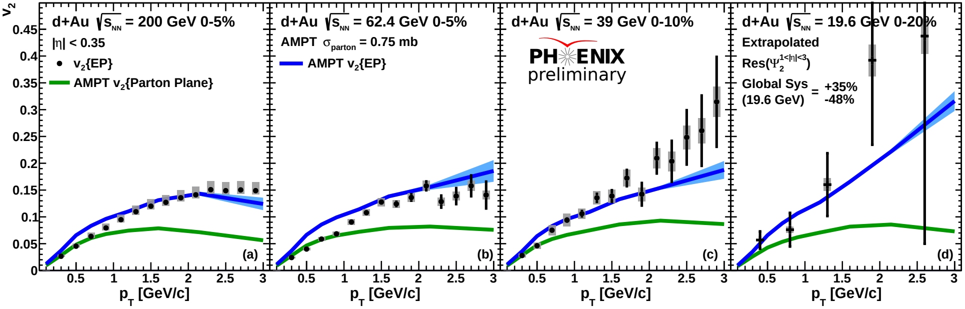

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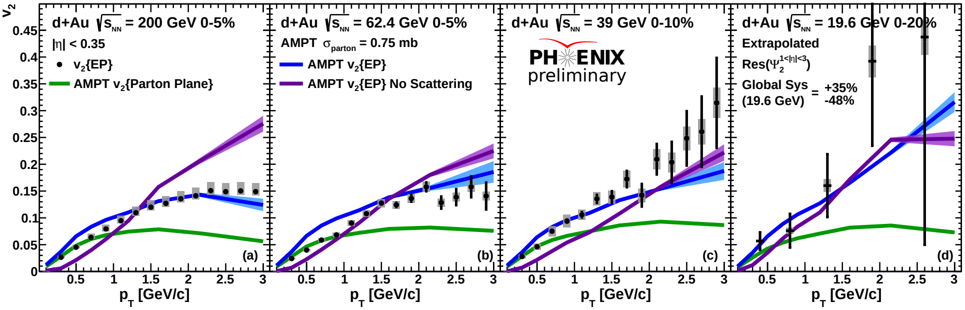
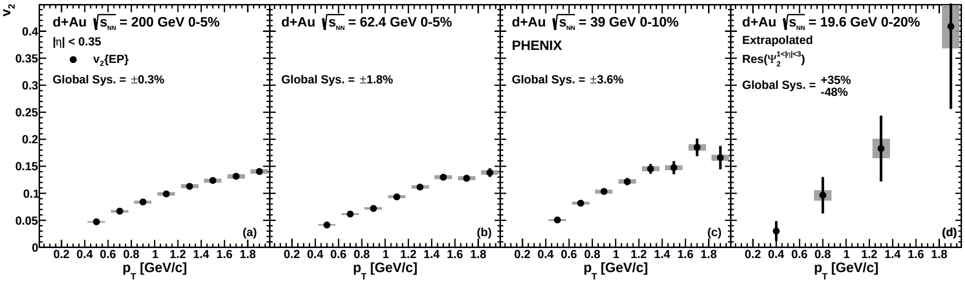


- Event plane v_2 vs p_T measured for all energies
- AMPT flow only shows good agreement at low p_T
- AMPT flow+non-flow shows reasonable agreement for all p_T
- AMPT non-flow only far under-predicts for low p_T, too high for high p_T

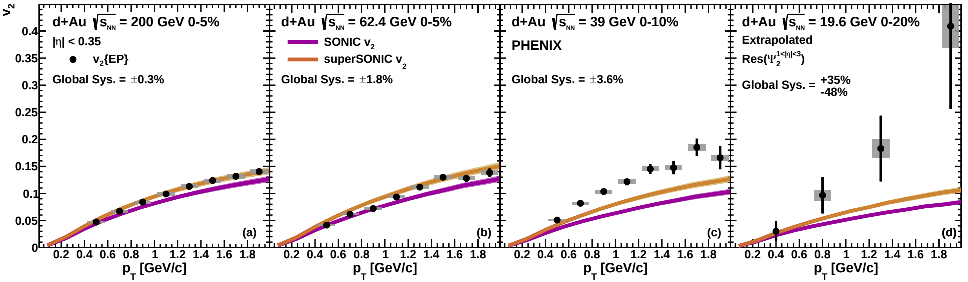
PHENIX, Phys. Rev. C 96, 064905 (2017)



- Event plane v_2 vs p_T measured for all energies

v_2 vs p_T, comparisons to theory

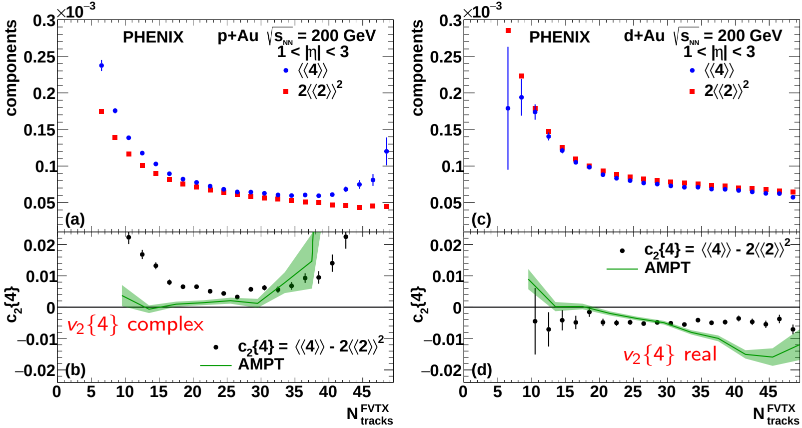
PHENIX, Phys. Rev. C 96, 064905 (2017)



- Event plane v_2 vs p_T measured for all energies
- Hydro theory agrees with higher energies very well, far underpredicts lower energies—lots of non-flow at lower energies

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

PHENIX, Phys. Rev. Lett. (in press)



- Positive $c_2\{4\}$ doesn't mean absence of collectivity (other p+Au results)
- Negative $c_2\{4\}$ doesn't mean collectivity, could be CGC (Mace, Dusling, Skokov, Venugopalan, others)
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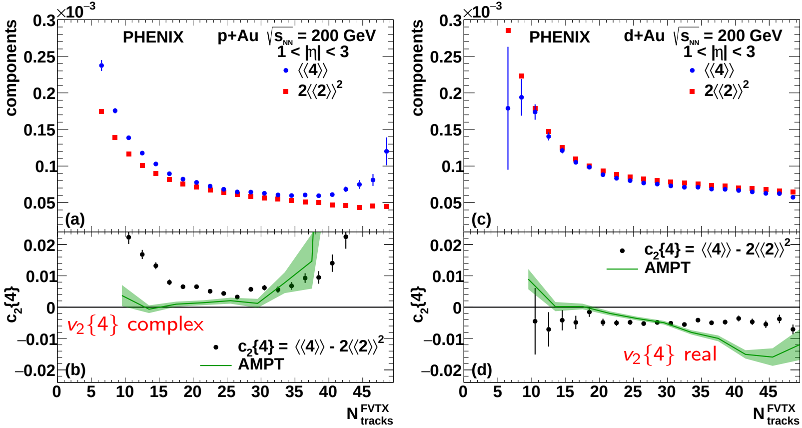

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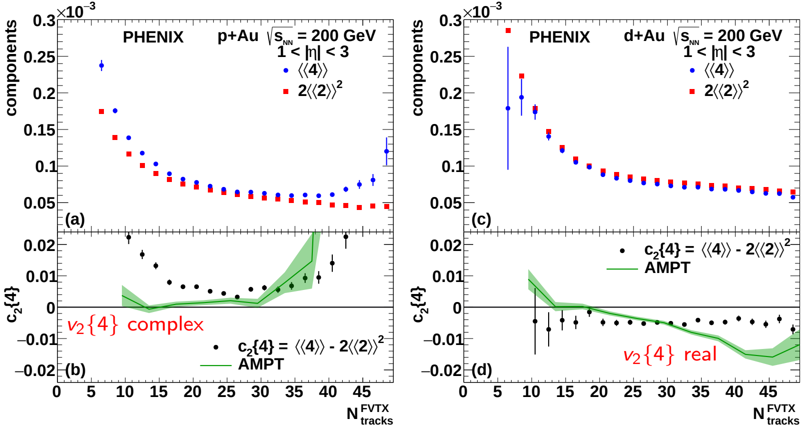

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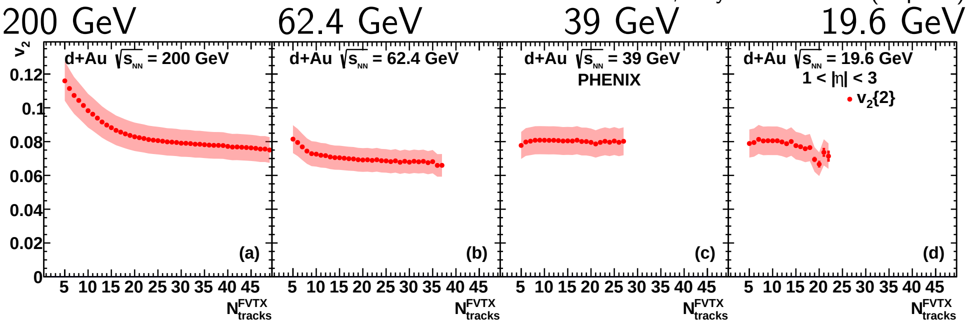
- AMPT shows similar trends as data, fluctuations could dominate in the p+Au
- Is the sign of $c_2\{4\}$ a good indicator of collectivity? No.

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

PHENIX, Phys. Rev. Lett. (in press)



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

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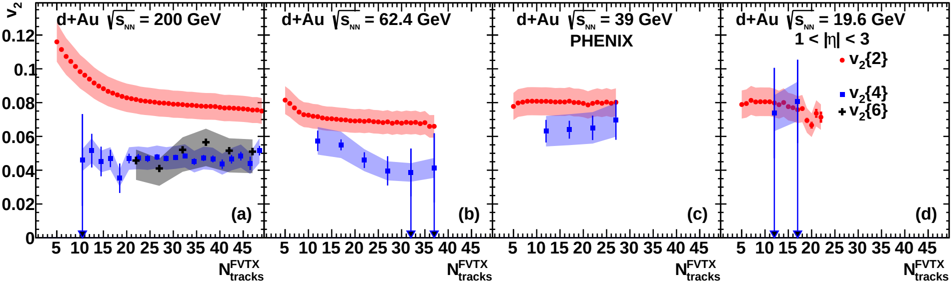
PHENIX, Phys. Rev. Lett. (in press)

200 GeV 62.4 GeV 39 GeV 19.6 GeV



- $v_2\{2\}$ relatively constant with N_{tracks}^{FVTX} and collision energy
- Measurement of $v_2\{4\}$ in d+Au at all energies
- Measurement of $v_2\{6\}$ in d+Au at 200 GeV

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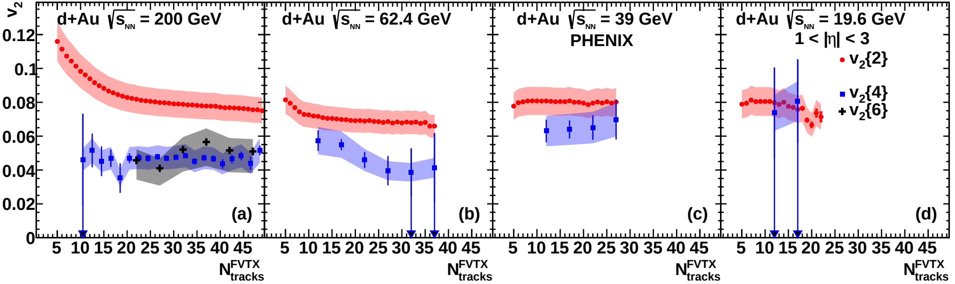

- $v_2\{2\}$ relatively constant with N_{tracks}^{FVTX} and collision energy
- Measurement of $v_2\{4\}$ in d+Au at all energies
- Measurement of $v_2\{6\}$ in d+Au at 200 GeV
- $v_2\{4\}$ increases and approaches $v_2\{2\}$
  (19.6 GeV looks a bit like CMS p+p...)

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

PHENIX, Phys. Rev. Lett. (in press)

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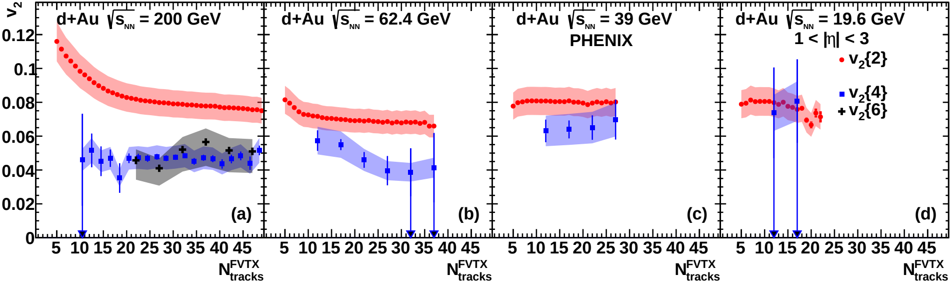
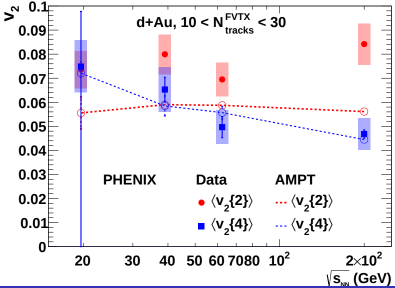
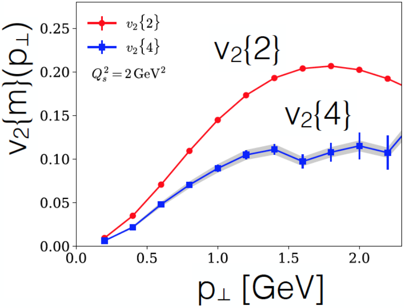
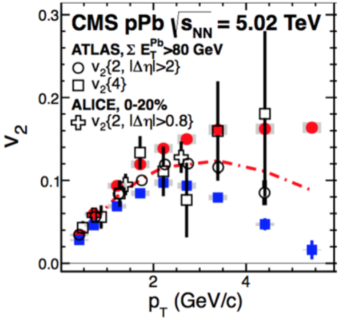


- Select $10 < N^{FVTX}_{tracks} < 30$, integrate
- AMPT sees similar trend
- Fluctuations?



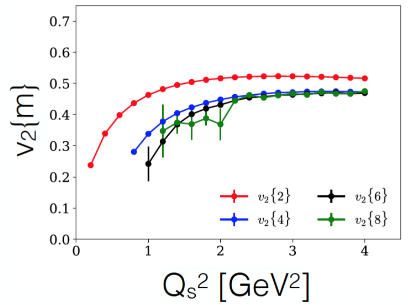
Mark Mace, Initial Stages 2017





- Dusling, Mace, Venugopalan arXiv:1705.00745 and arXiv:1706.06260
- Striking similarity between CGC inspired calculations and LHC data
- Caveats: p+A only, Q_s doesn't directly map to collision energy/multiplicity
- Challenge and opportunity: p/d/^{3}He+Au

CGC inspired calculations of multiparticle correlations



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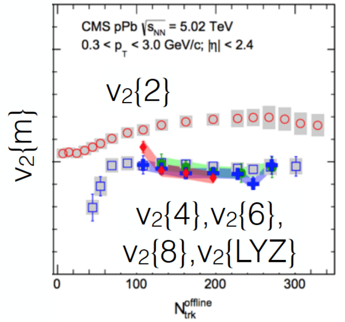

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- Challenge and opportunity: p/d/^{3}He+Au

- Good agreement with hydro at 200 GeV and 62.4 GeV, bad agreement at 39 and 19.6 GeV
- Good agreement with AMPT at all 4 energies
- Real $v_2\{4\}$ in d+Au collisions at all energies
- Complex $v_2\{4\}$ in p+Au at 200 GeV, maybe fluctuations dominate? Other measurements suggest collectivity/flow in p+Au as well
- On the other hand, is real-valued $v_2\{4\}$ really a good measure for collectivity? No.
- What about CGC? Good success in p+Pb, what about p/d/^{3}He+Au?

Intermission

The future

The 2015 Long Range Plan for Nuclear Science

Recommendation I: The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.
—CEBAF, FRIB, Symmetries & Neutrinos, **RHIC** (BES II & **sPHENIX**)

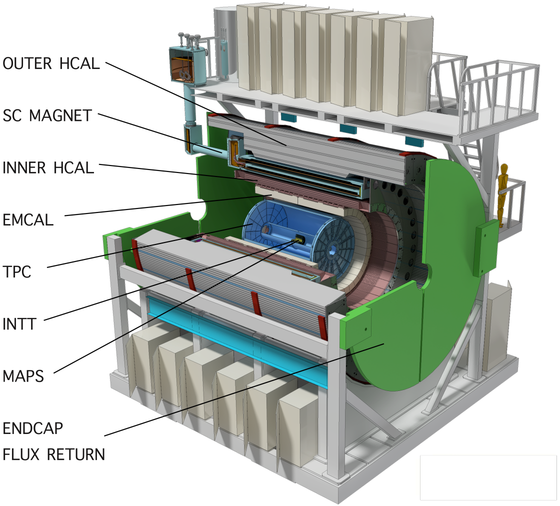
Recommendation II: We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

Recommendation III: We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

Recommendation IV: We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.

sPHENIX

From the LRP: **[The goal is to] probe the inner workings of QGP by resolving its properties at shorter and shorter length scales.... essential to this goal... is a state-of-the-art jet detector at RHIC, called sPHENIX.**



sPHENIX: timeline

• (Final?) Calorimetry beam test	February 20–March 27, 2018
• Director's Review	March 6–8, 2018
• Order for Outer HCal steel	March 2018
• DOE OPA CD-1/CD-3a Review	May 8–10, 2018
• Authorization for CD-1/-CD-3a	July 2018
• DOE OPA CD-2/CD-3b Review	May 2019
• Authorization for CD-2/-CD-ba	July 2019
• Fabrication orders	August 2019
• Installation begins	April 2021
• Installation complete	July 2022
• Initial commissioning complete	September 2022
• First collisions	January 2023

sPHENIX: beam tests

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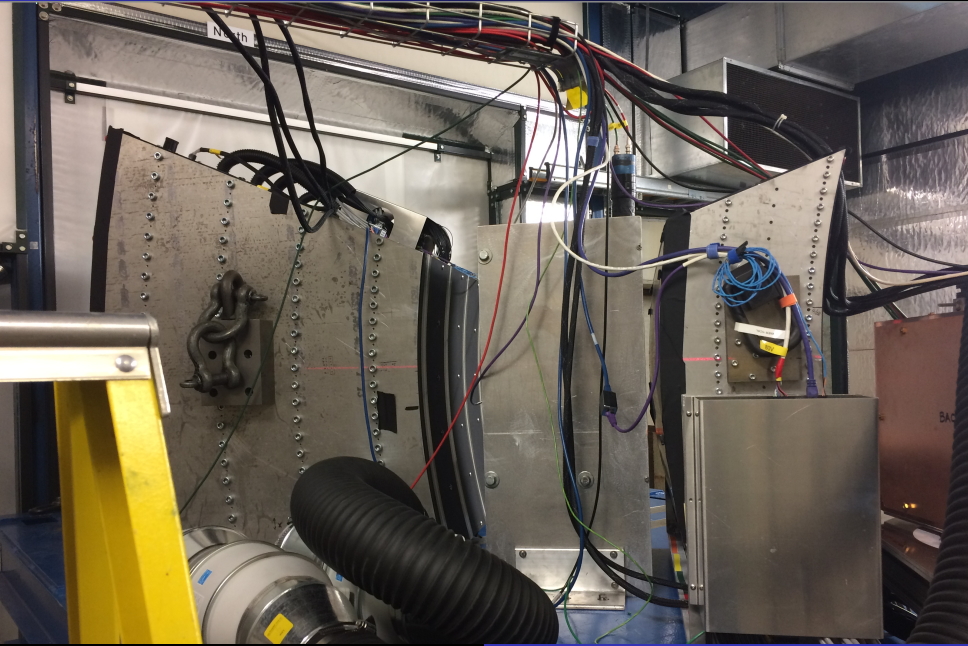

sPHENIX: beam tests

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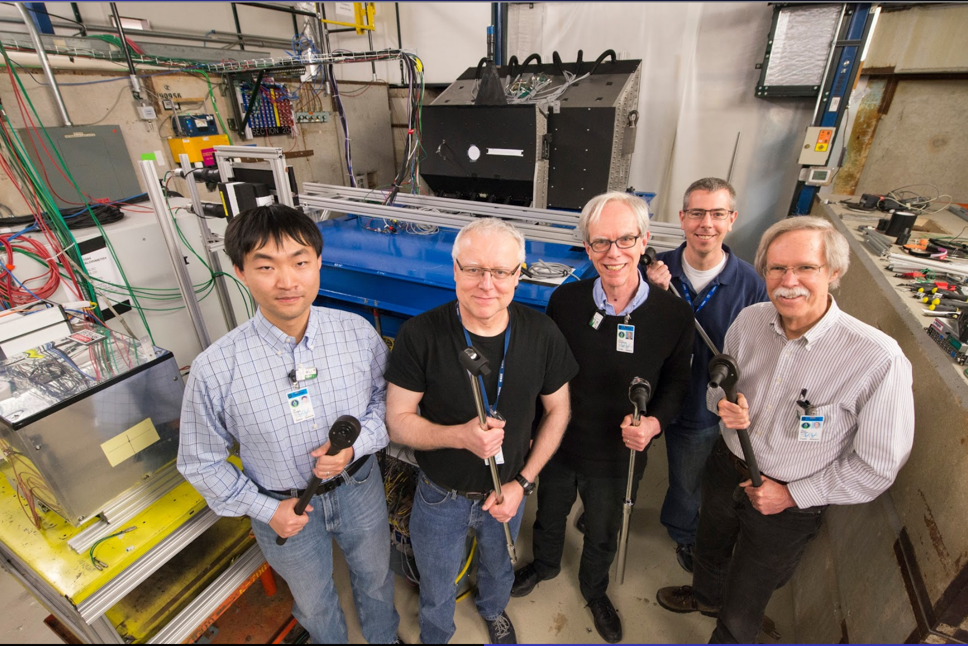
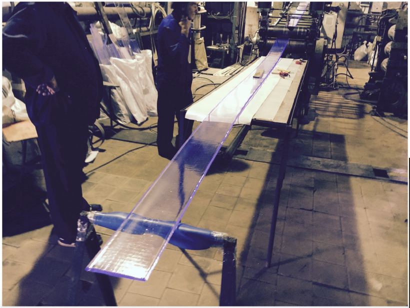
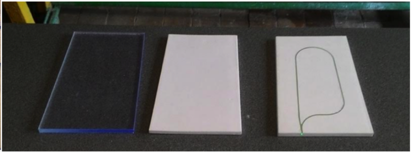
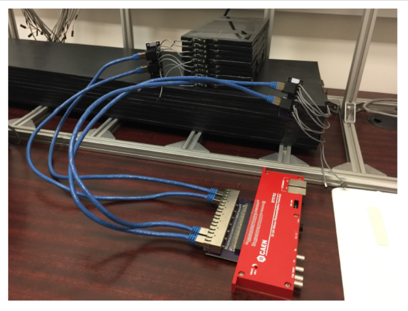
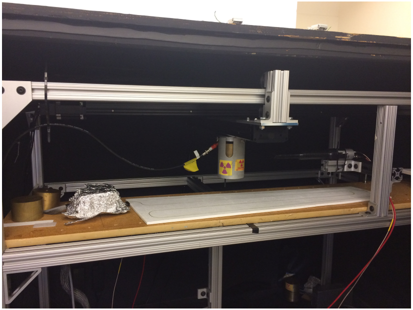


sPHENIX: HCal tiles





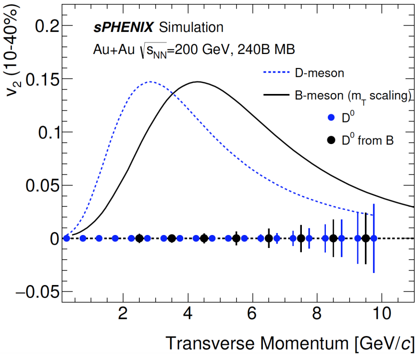




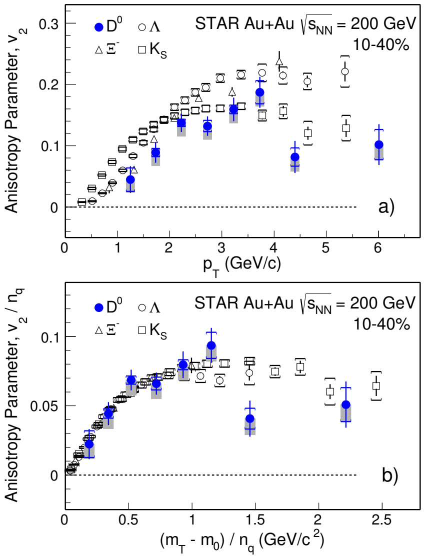
sPHENIX: jets: hybrid approach?

sPHENIX: heavy flavor!

sPHENIX: heavy flavor!



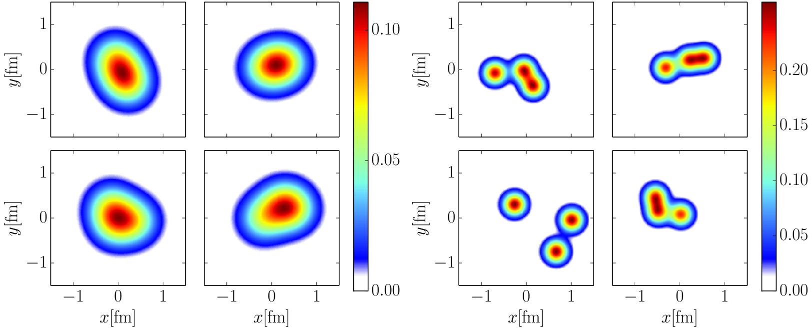
STAR, Phys. Rev. Lett. 118, 212301 (2017)



- Charm flows like light quarks
- Heavy flavor flow is an outstanding problem
- Measurements of D-meson (and B-meson) flow in sPHENIX will yield key insights

Proton shape at the EIC

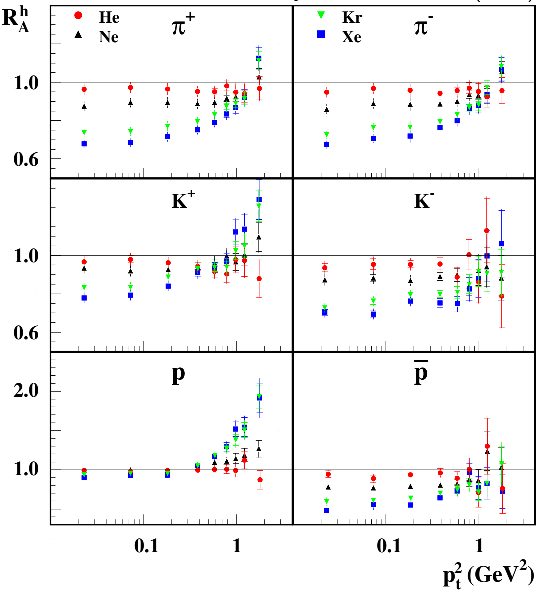
Mäntysaari and Schenke, PRL 117 052301 (2016) and PRD 94 034042 (2016)



- IPGlasma+Hydro can be improved with realistic proton shape
- Study exclusive vector meson production (diffractive DIS)
  —Coherent: average shape; incoherent: shape fluctuations
- "A future electron ion collider has the potential to provide much more precise data in a wider kinematical range"

Hadronization at the EIC

HERMES, Phys. Lett. B 780, 1 (2007)



- Hadronization is modified in e+A collisions relative to e+p
- Connection to modification observed in small/large heavy ion collisions?
- Study hadronization at the EIC!

Final thoughts

- Lots of interesting observables in small systems
- All the data measured so far supports the collective/hydro picture
- Is the CGC ruled out? No! Plenty of room for new advances there
- Lots of exciting things to do in the future
- It's a great time for nuclear physics

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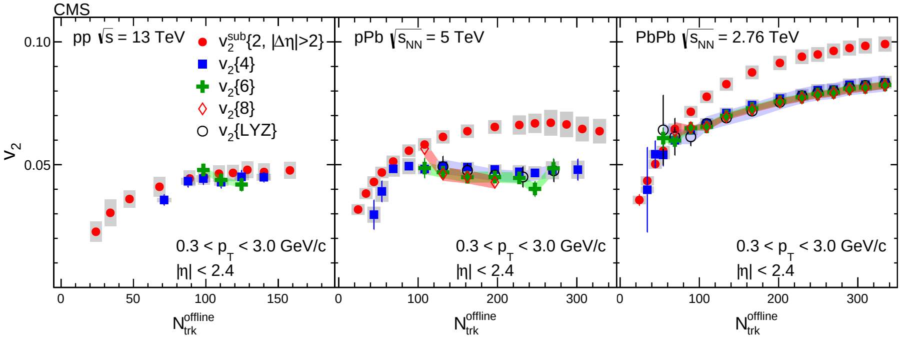
"The optimist regards the future as uncertain." —Eugene Wigner

Additional Material

Multiparticle correlations in small systems

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



- Multiparticle correlations: a strong case for collectivity
- Influence of fluctuations:

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

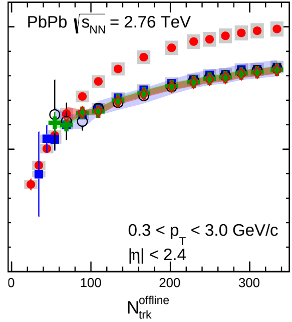
$$v_2\{2, |\Delta\eta| > 2\} = \sqrt{v_2^2 + \sigma^2} \qquad \text{eta gap removes some non-flow}$$

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

- Significant and well-known success in Au+Au and Pb+Pb

Multiparticle correlations in small systems

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



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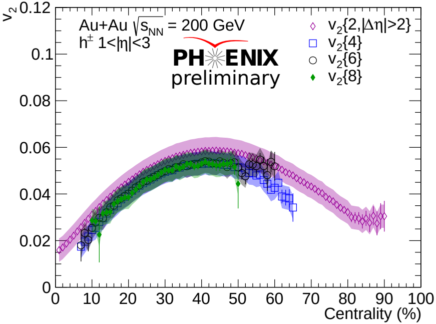

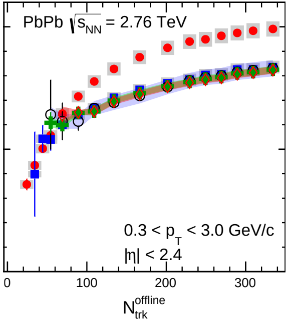

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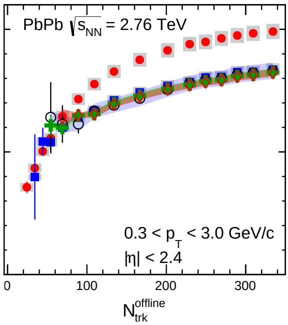

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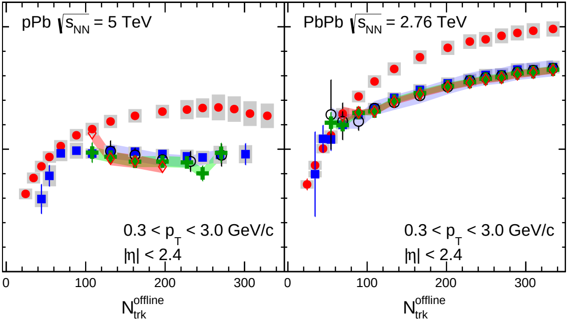

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- p+Pb remarkably similar to Pb+Pb

Multiparticle correlations in small systems

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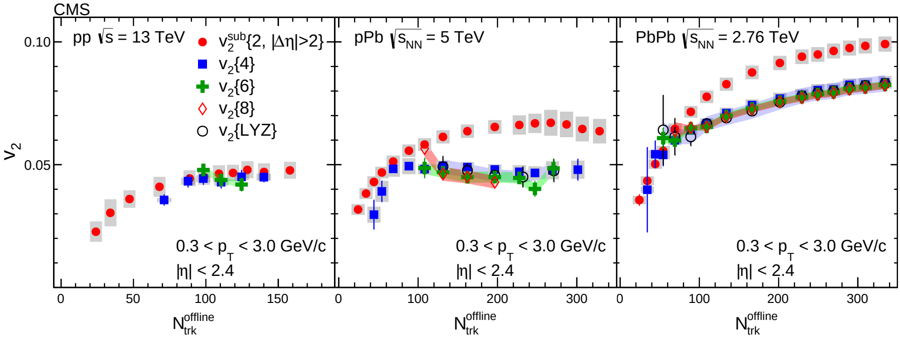

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- $\sigma = 0$ in p+p? Need to understand the fluctuations better

Multiparticle correlations in small systems

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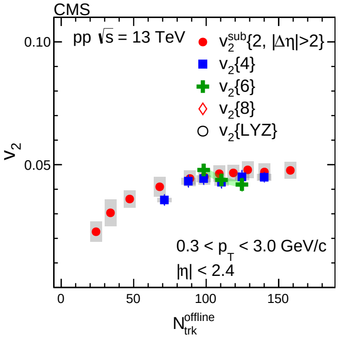

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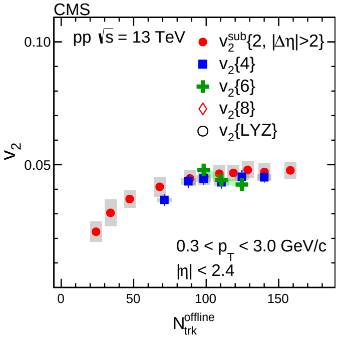
$$v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx \sqrt{v_2^2 - \sigma^2} \qquad \text{higher orders remove non-flow}$$

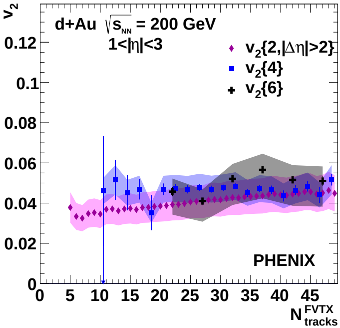
- $\sigma = 0$ in p+p? Need to understand the fluctuations better

Multiparticle correlations in small systems

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



PHENIX, Phys. Rev. Lett. (in press)



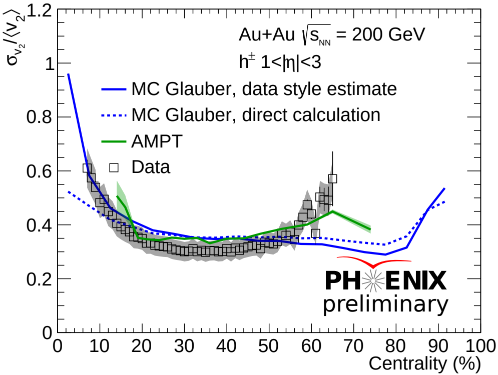
- Multiparticle correlations: a strong case for collectivity
- Influence of fluctuations:

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

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

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

- $\sigma = 0$ in p+p and d+Au? Need to understand the fluctuations better



Not a new idea, but:

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

- Standard picture of fluctuations works well for most centralities in Au+Au
- Up-tick in peripheral can be explained by non-linearity in hydro response (e.g. J. Noronha-Hostler et al Phys. Rev. C 93, 014909 (2016))
- We'll keep coming back to fluctuations...

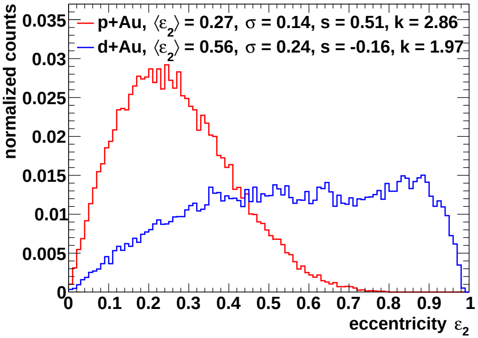
Intermission

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

Cumulants: a closer inspection

- We always say $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx \sqrt{v_2^2 - \sigma^2}$
- Is that really true? Not necessarily!
- Two assumptions are required to get there:
  - Gaussian fluctuations
  - Small relative variance, $\sigma/v_n \ll 1$
- Are these assumptions valid? Let's have a look...

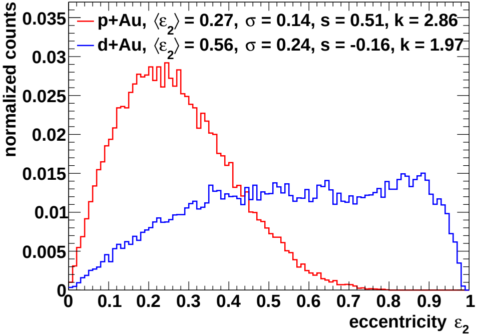
Eccentricity distributions and cumulants



	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

- 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 $v_n \propto \varepsilon_n$

Eccentricity distributions and cumulants



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- 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 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)

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

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

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

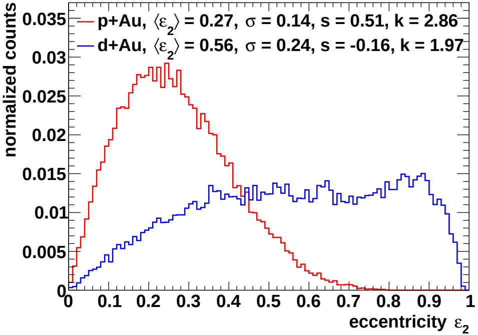
$$\left(\langle v_n^4\rangle = v_n^4 + 6v_n^2\sigma^2 + 3\sigma^4 + 4v_n\kappa_3 + \kappa_4\right)$$
$$-\left(2\langle v_n^2\rangle^2 = 2v_n^4 + 4v_n^2\sigma^2 + 2\sigma^4\right)$$
$$\rightarrow$$
$$\langle v_n^4\rangle - 2\langle v_n^2\rangle^2 = -v_n^4 + 2v_n^2\sigma^2 + \sigma^4 + 4v_n\kappa_3 + \kappa_4$$

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

Eccentricity distributions and cumulants

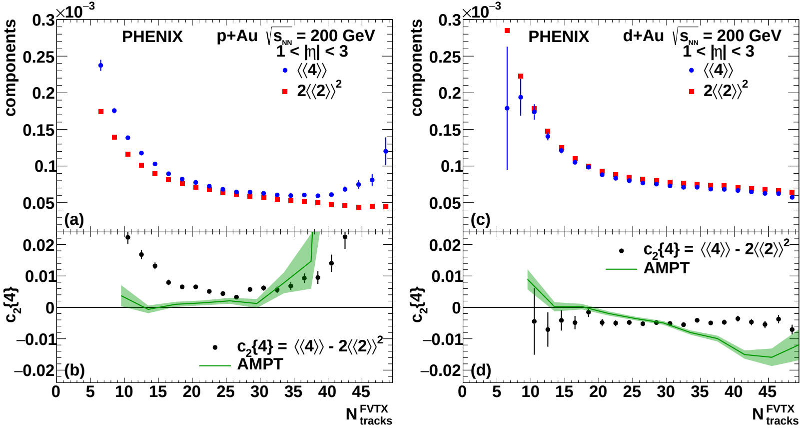


	p+Au	d+Au
ε_2^4	0.00531	0.0983
$2\varepsilon_2^2\sigma^2$	0.00277	0.0370
$4\varepsilon_2 s\sigma^3$	0.00147	-0.0053
$(k-2)\sigma^4$	0.00031	-0.0001

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

- the variance brings $\varepsilon_2\{4\}$ down (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 $= 3$

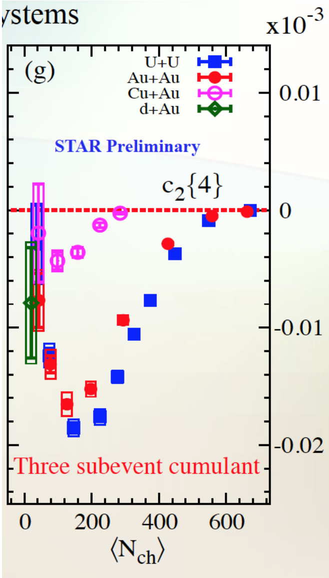
Eccentricity distributions and cumulants



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

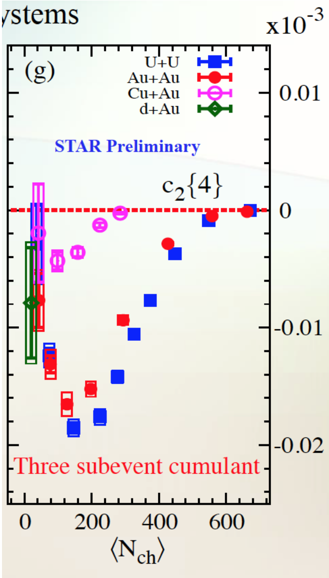
- Eccentricity fluctuations alone go a long way towards explaining this
- Additional fluctuations in the (imperfect) translation of ε_2 to v_2?

STAR cumulant results



- Three subevent $c_2\{4\}$
- No p+Au point, but d+Au point is $\approx -8 \times 10^{-6}$
- $v_2\{4\} \approx 0.05$, in good agreement with PHENIX

STAR cumulant results



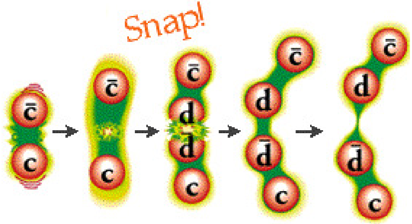
- Three subevent $c_2\{4\}$
- No p+Au point, but d+Au point is $\approx -8 \times 10^{-6}$
- $v_2\{4\} \approx 0.05$, in good agreement with PHENIX
- (Almost too good?)

Particle production by fragmentation

- Pair creation through stretching and breaking of gluon flux tubes

$$V(r) = -C_F \frac{\alpha_s}{r} + kr$$

- Fragmentation function $D_{c \to h}(z)$—probability that parton c fragments into hadron h with fraction z of the parton momentum

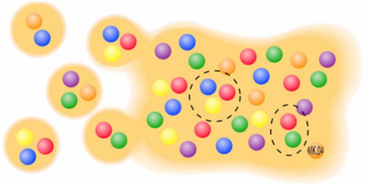


$$E\frac{d^3N_h}{dP^3} = \frac{1}{\pi}\sum_{abcd}\iiint dz dx_a dx_b f_a(x_a) f_b(x_b) \frac{d\sigma}{d\hat{t}}(ab \to cd) D_{c\to h}(z)/z$$

$$E\frac{d^3N_h}{dP^3} = \int d\Sigma \frac{P \cdot u}{(2\pi)^3} \sum_c \int dz\ z^{-3} w_c(P/z)\ D_{c\to h}(z)$$

Particle production by recombination

- Partons close together in phase space can coalesce into bound states
- The QGP is a system of thermalized partons—lots of partons near each other
- Each parton has a fraction x of the total momentum of the produced hadron



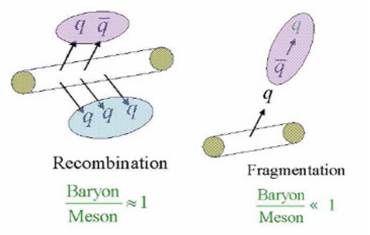
$$E\frac{d^3N^{(Meson)}}{dP^3} = \int d\Sigma \frac{P\cdot u}{(2\pi)^3} \sum_{\alpha\beta} \int dx\; w_\alpha(xP)\bar{w}_\beta((1-x)P)\; |\phi^{(M)}_{\alpha\beta}(x)|^2$$

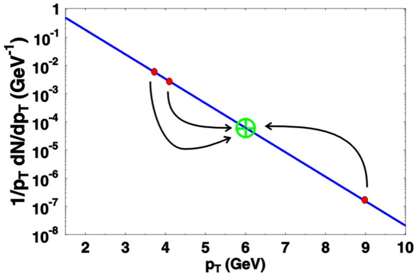
$$E\frac{d^3N^{(Baryon)}}{dP^3} = \int d\Sigma \frac{P\cdot u}{(2\pi)^3} \sum_{\alpha\beta\gamma} \iint dxdx'\; w_\alpha(xP)w_\beta(x'P)w_\gamma((1-x-x')P)\; |\phi^{(B)}_{\alpha\beta\gamma}(x,x')|^2$$

Fragmentation and recombination

P—hadron momentum
p—parton momentum

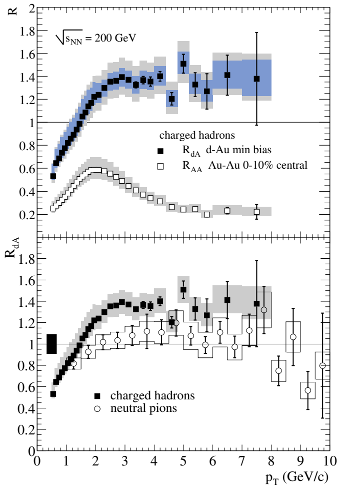
- $P < p$ for fragmentation because $P = zp$ and $P > p$ for recombination because $xP = p$
- To make a 6 GeV/c hadron by fragmentation, need one parton with >6 GeV/c
- To make a 6 GeV/c meson by recombination, need two partons with ≈3 GeV/c
- To make a 6 GeV/c baryon by recombination, need three partons with ≈2 GeV/c





Physics motivation: cold nuclear matter effects

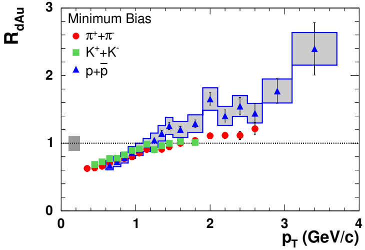
- In addition to effects from the QGP, there are initial state effects caused by the cold nuclear matter
- Some models proposed particle suppression at RHIC could be from initial state effects, but the data show Cronin enhancement
- Cronin enhancement: enhancement of particle yield at intermediate p_T in p+A collisions relative to p+p
- Unidentified hadrons show greater enhancement than neutral pions...



PHENIX, Phys. Rev. Lett. 91, 072303 (2003)

Physics motivation: cold nuclear matter effects

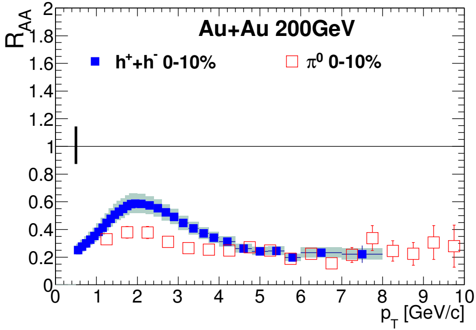
- Strong particle species dependence for Cronin enhancement
- Most models of the Cronin enhancement rely on initial state effects like multiple parton rescatterings—no particle species dependence
- Recombination model applied to d+Au uses final state effect in cold nuclear matter, greater Cronin enhancement for baryons than for mesons—discussed in Phys. Rev. Lett. 93, 082302 (2004)
  by R.C. Hwa and C.B. Yang
- Soft partons at low x can take place of thermal partons in hot nuclear matter, so recombination may make sense here

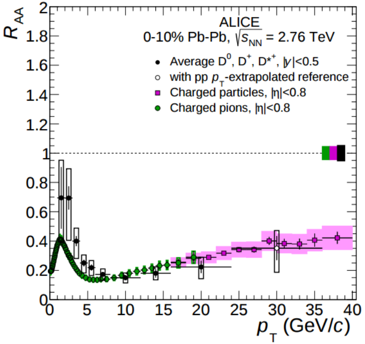


PHENIX, Phys. Rev. C91, 024904 (2006)

Suppression of high energy particles

PHENIX, Phys. Rev. C 69, 034910 (2004)



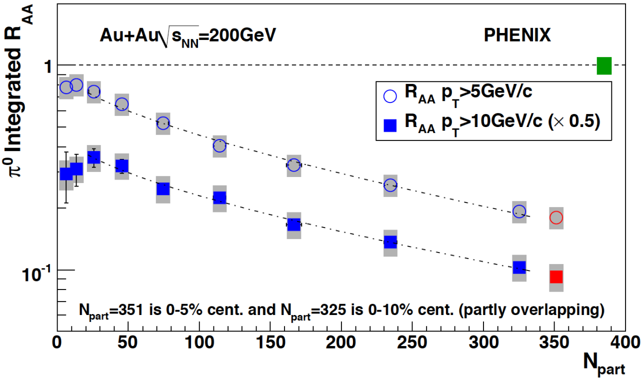


$$R_{AA} = \frac{N^{A+A}_{particles}}{N^{p+p}_{particles} \times N_{coll}}$$

$R_{AA} < 1$ means particles are suppressed

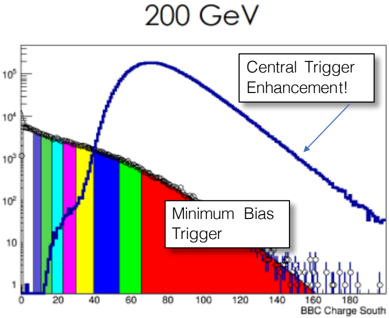
Suppression of high energy particles

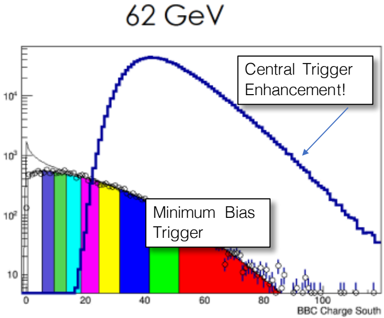
PHENIX, Phys.Rev.Lett. 101, 232301 (2008)



- R_{AA} decreases (more suppression) with increasing N_{part} (bigger system)
- More medium → more stuff in the way → more suppresssion
- System size/geometry important aspect of suppression

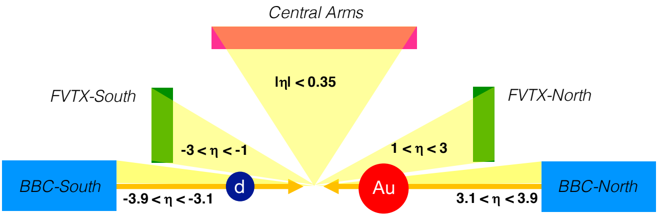
2016 d+Au beam energy scan in PHENIX



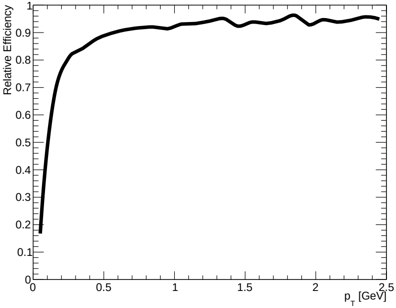


d+Au collision energy	total events analyzed	central events analyzed
200 GeV	636 million	585 million
62.4 GeV	131 million	76 million
39 GeV	137 million	49 million
19.6 GeV	15 million	3 million

The PHENIX forward vertex detector

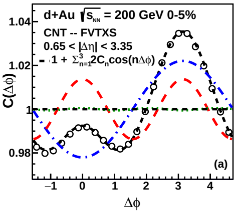


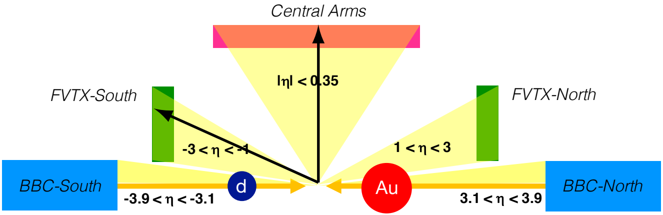
- FVTX: forward vertex detector —silicon strip technology
- Very precise vertex/DCA determination
- No momentum determination, p_T dependent efficiency — measured v_2 roughly 18% higher than true



Two particle correlations

PHENIX, Phys. Rev. C 96, 064905 (2017)

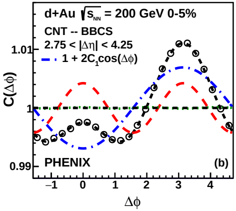


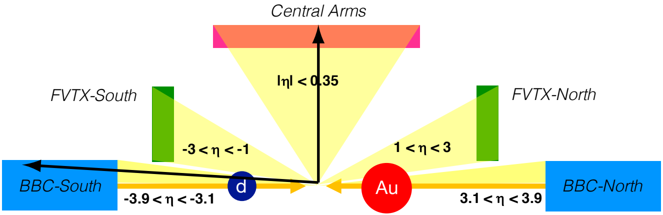


- $0.65 < |\Delta\eta| < 3.35$

Two particle correlations

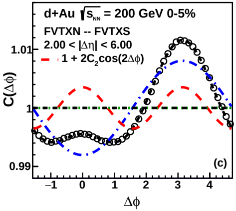
PHENIX, Phys. Rev. C 96, 064905 (2017)

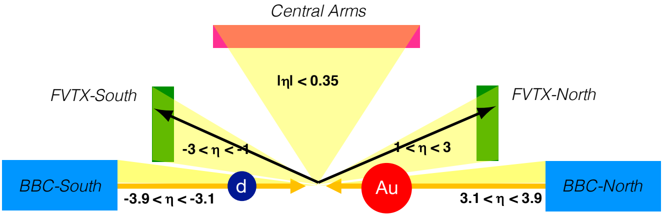




- $2.75 < |\Delta\eta| < 4.25$

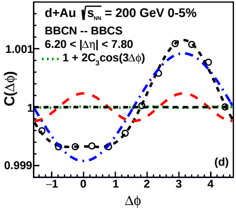
PHENIX, Phys. Rev. C 96, 064905 (2017)

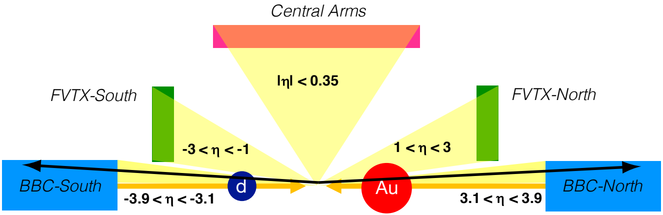




- $2.0 < |\Delta\eta| < 6.0$

PHENIX, Phys. Rev. C 96, 064905 (2017)

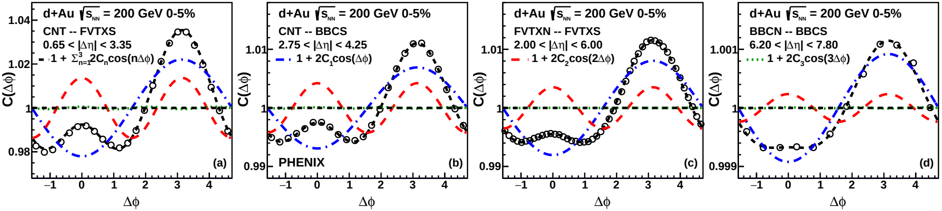


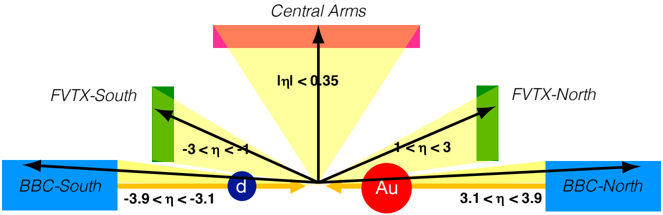


- $6.2 < |\Delta\eta| < 7.8$

Two particle correlations

PHENIX, Phys. Rev. C 96, 064905 (2017)





- $0.65 < |\Delta\eta| < 7.8$
- Wide range of pseudorapidity separation has potential to provide significant leverage to disentangle various flow and non-flow effects
- Ridge observed for $|\Delta\eta| > 6.2$—long range indeed!

Definition of Q-vectors

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

Calculation of event plane

$$n\psi_n = \arctan \frac{Q_{n,y}}{Q_{n,x}}$$

Calculation of harmonic coefficients v_n

$$v_n = \langle \cos(n(\phi - \psi_n)) \rangle / R(\psi_n)$$

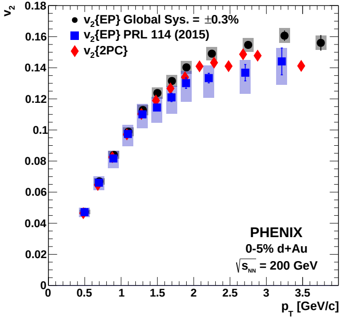
Determination of event plane resolutions

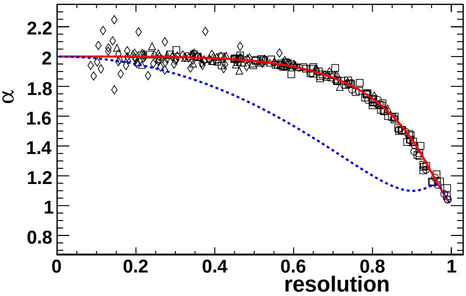
$$R(\psi_n^A) = \sqrt{\frac{\langle \cos(n(\psi_n^A - \psi_n^B)) \rangle \langle \cos(n(\psi_n^A - \psi_n^C)) \rangle}{\langle \cos(n(\psi_n^B - \psi_n^C)) \rangle}}$$

(CNT, FVTXS, BBCS used for event plane resolution)

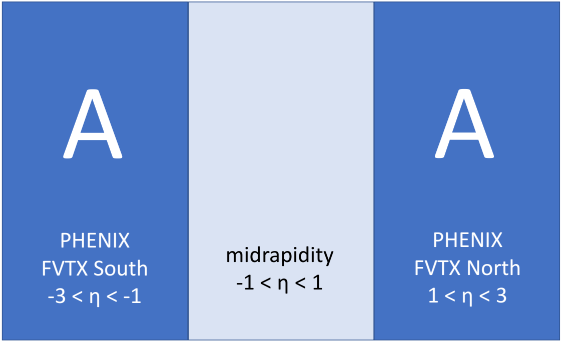
v_2 vs p_T 200 GeV method comparison

PHENIX, Phys. Rev. C 96, 064905 (2017) J.Y. Ollitrault et al Phys Rev C 80, 014904 (2009)



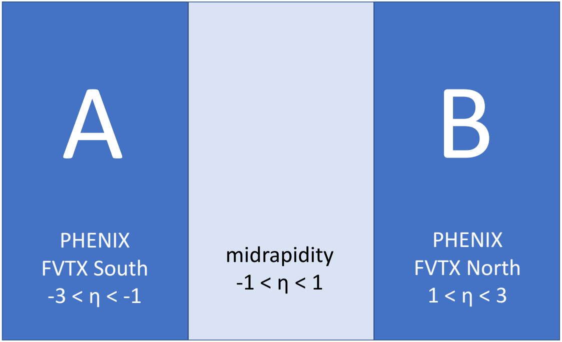


- Important to remember that $v_n\{\text{EP}\}$ is an estimator of $\langle v_n^\alpha \rangle^{1/\alpha}$
- High multiplicity $\rightarrow$ high resolution $\rightarrow \alpha = 1$
- Low multiplicity $\rightarrow$ low resolution $\rightarrow \alpha = 2$
- For all RHIC small systems results, $\alpha = 2$
  —same dependence on fluctuations as two-particle methods



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

How to apply an eta gap in the FVTX?

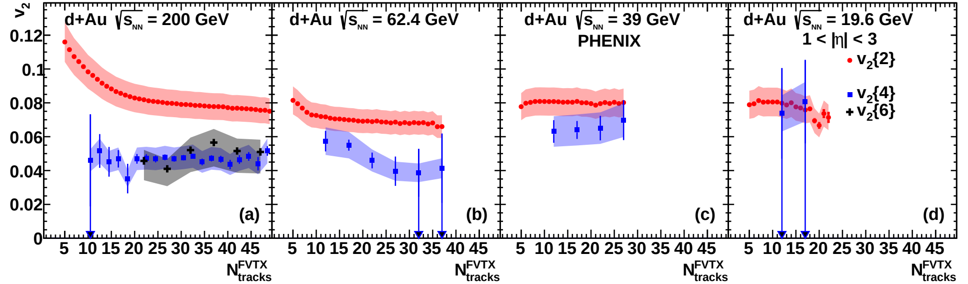


- $v_2\{2\}$ and $v_2\{4\}$—use tracks anywhere in the FVTX
- $v_2\{2, |\Delta\eta| > 2\}$—require one track in south (backward rapidity) and one in north (forward)

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

PHENIX, Phys. Rev. Lett. (in press)

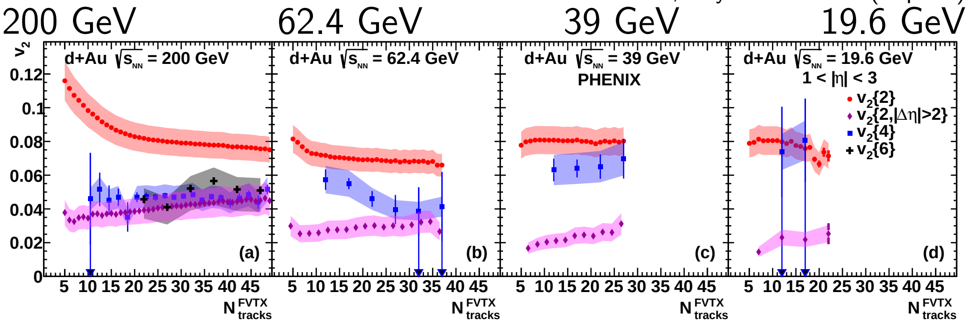
200 GeV 62.4 GeV 39 GeV 19.6 GeV



- $v_2\{2\}$ 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?

PHENIX, Phys. Rev. Lett. (in press)



- $v_2\{2\}$ 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

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

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

- How to understand this?

Understanding two-particle estimates of v_2 when using subevents

- $dN_{ch}/d\eta$ and v_2 are larger at backward rapidity, so $v_2\{2\}$ and $v_2\{4\}$ are weighted towards backward
- $v_2\{2, |\Delta\eta| > 2\}$ is weighted equally between forward and backward as $\sqrt{v_2^B v_2^F}$
- $v_2^B > v_2^F$, so $v_2^2 > v_2^B v_2^F$

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- The fluctuations are not actually the variance but rather the covariance ς_{BF}
- $\sqrt{v_2^2 + \sigma^2} \rightarrow \sqrt{v_2^B v_2^F + \varsigma_{BF}}$
- Correlation strength between forward and backward $|\varsigma_{BF}| \leq \sigma_B\sigma_F$—fluctuations can contribute less than expected

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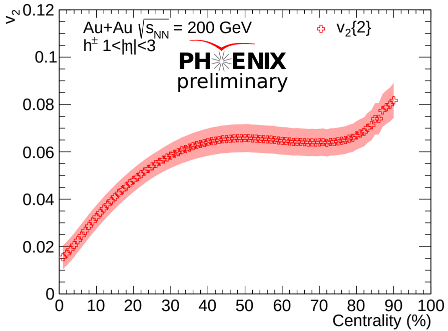
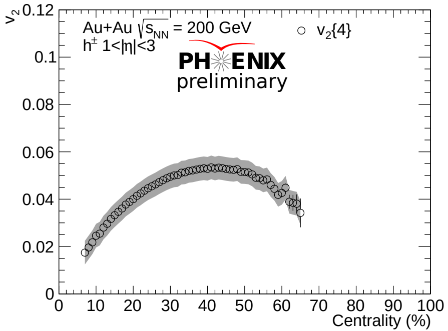
- Correlation strength between forward and backward $|\varsigma_{BF}| \leq \sigma_B \sigma_F$—fluctuations can contribute less than expected
- Event plane decorrelation small in Au+Au but could be larger in d+Au
- But that's already encoded in the v_2 vs η measurement discussed earlier

Understanding two-particle estimates of v_2 when using subevents





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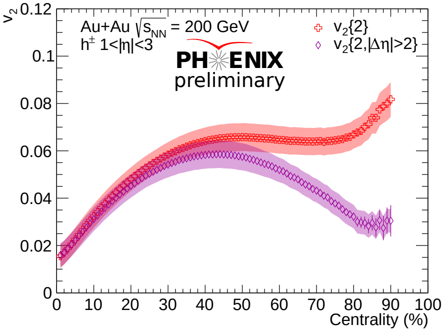
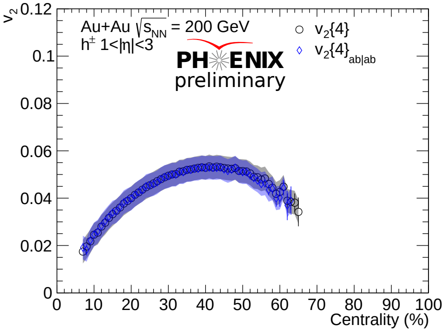
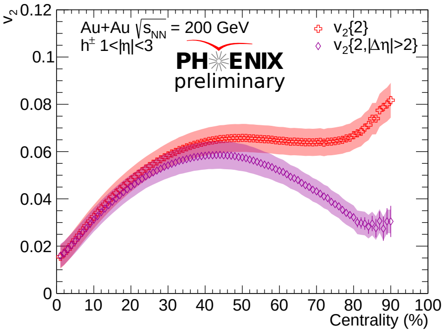
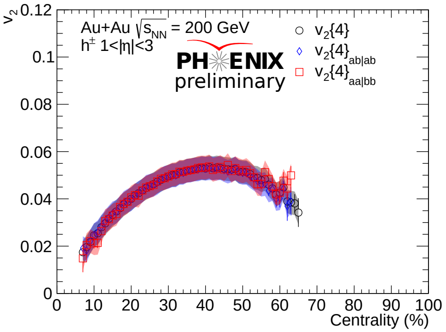




Understanding two-particle estimates of v_2 when using subevents

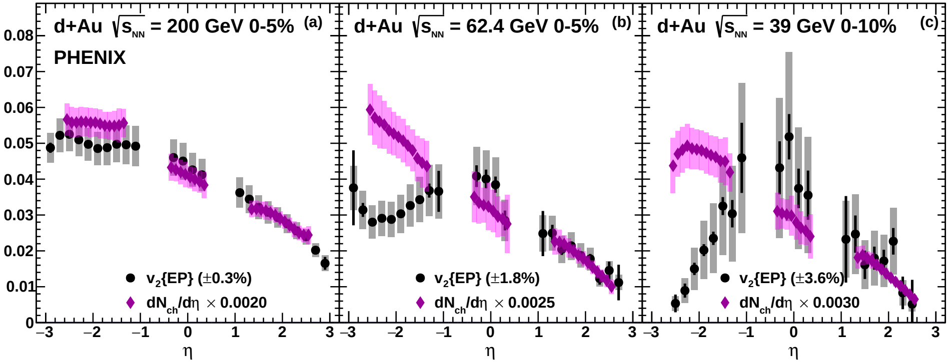




- Two-particle correlation without eta gap has significant non-flow
- Can't disentangle flow/non-flow/decorrelation effects (by looking at this plot)
- Four particle correlation with and without subevents is identical
- Non-flow and decorrelations don't affect four-particle results in Au+Au
- Decorrelation effects present but small (few %) in Au+Au

v_2 and $dN_{ch}/d\eta$ vs η

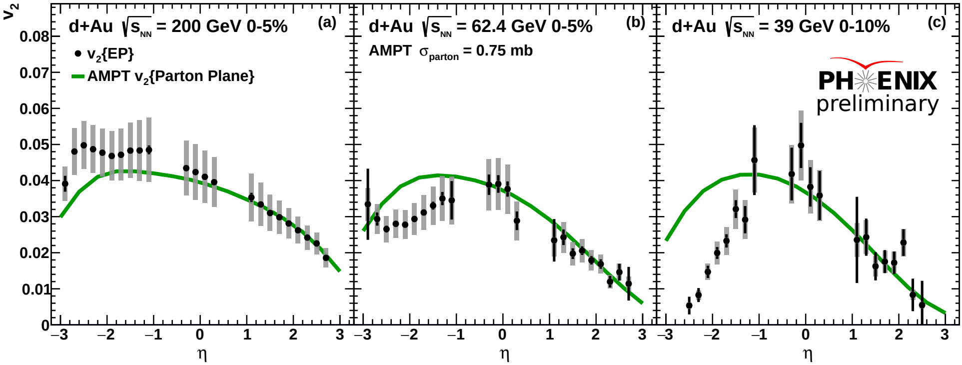
PHENIX, Phys. Rev. C 96, 064905 (2017)



- BBC south ($-3.9 < \eta < -3.1$) used to estimate the event plane
- 200 GeV shows strong forward/backward asymmetry in v_2 and $dN_{ch}/d\eta$ (both much larger at backward)
- Asymmetry is large for $dN_{ch}/d\eta$ at all energies, where as v_2 asymmetry seems to decrease with decreasing energy

v_2 vs η, comparison with AMPT

PHENIX, Phys. Rev. C 96, 064905 (2017)



- AMPT flow only agrees with mid and forward rapidity very well, but shows higher v_2 at backward for lower energies

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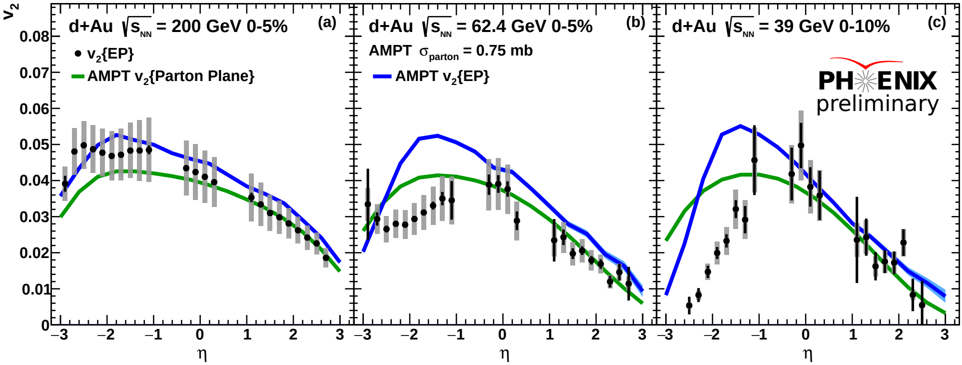
PHENIX, Phys. Rev. C 96, 064905 (2017)



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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

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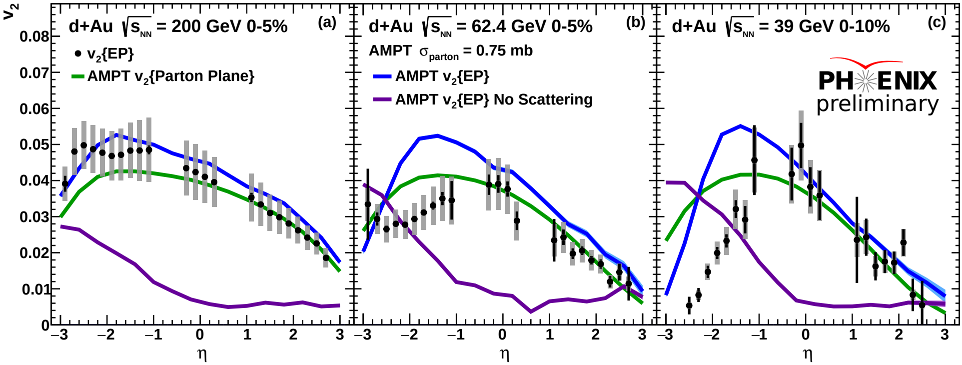
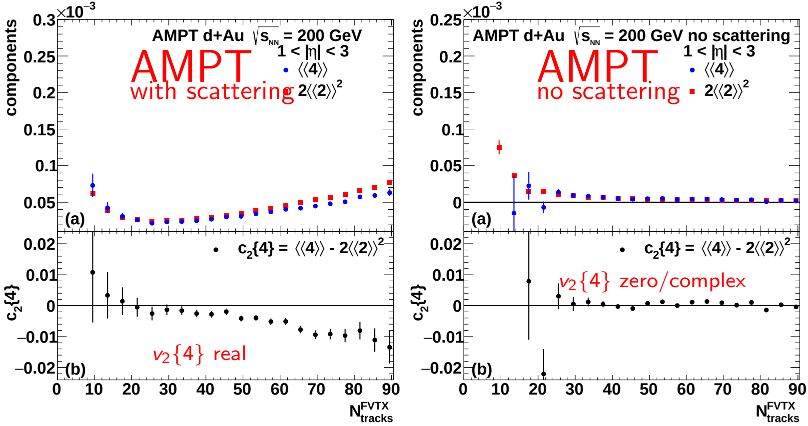


- AMPT flow only agrees with mid and forward rapidity very well, but shows higher v_2 at backward for lower energies
- AMPT flow+non-flow is very similar at mid and forward
- AMPT flow+non-flow shows striking anti-correlation at backward rapidity
- AMPT non-flow only shows nothing at mid and forward, large v_2 at backward rapidity near the detector

- 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
- **Flow and non-flow are non-additive**

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 *but not in p+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 in d+Au
- Geometry plays an important role
- The sign of $c_2\{4\}$ is *not* a good indicator of collectivity

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

Experimental method and details

Definition of Q-vectors is the same as before

Two particle correlator:

$$\begin{aligned}\langle 2\rangle &= \langle\cos(n(\phi_1-\phi_2))\rangle \quad (= v_n^2)\\ &= \frac{Q_nQ_n^*-M}{M(M-1)}\end{aligned}$$

Four particle correlator:

$$\begin{aligned}\langle 4\rangle &= \langle\cos(n(\phi_1+\phi_2-\phi_3-\phi_4))\rangle \quad (= v_n^4)\\ &= \frac{|Q_n|^4+|Q_{2n}|^2-2\mathfrak{Re}\left[Q_{2n}Q_n^*Q_n^*\right]}{M(M-1)(M-2)(M-3)} - 2\,\frac{2(M-2)\,|Q_n|^2-M(M-3)}{M(M-1)(M-2)(M-3)}.\end{aligned}$$

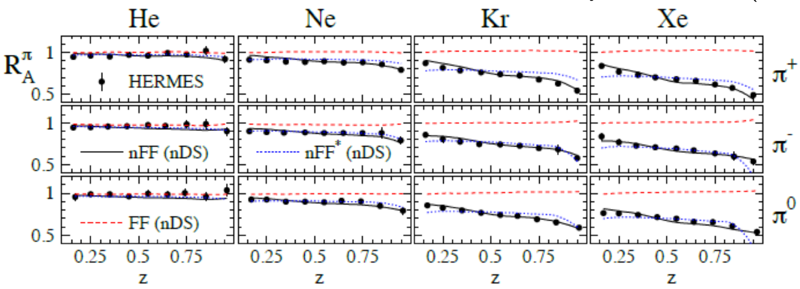
Calculation of cumulants and harmonic coefficients

$$\begin{aligned} c_n\{2\} &= \langle\langle 2\rangle\rangle & &= \langle v_n^2\rangle & v_n\{2\} &= \sqrt{c_n\{2\}}\\ c_n\{4\} &= \langle\langle 4\rangle\rangle - 2\langle\langle 2\rangle\rangle^2 & &= \langle v_n^4\rangle - 2\langle v_n^2\rangle^2 & v_n\{4\} &= \sqrt[4]{-c_n\{4\}}\end{aligned}$$

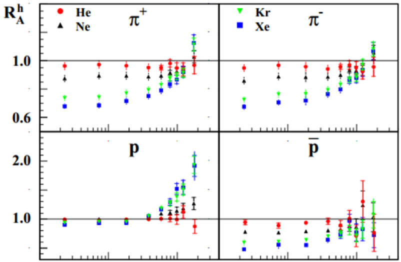
(FVTXN and FVTXS used for multiparticle calculations)

Hadronization at the EIC

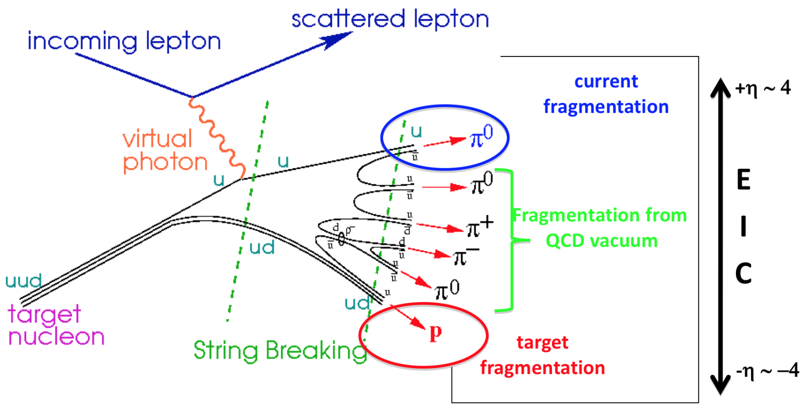
HERMES, Eur. Phys. J. A 47, 113 (2011)



HERMES, Phys. Lett. B 780, 1 (2007)



- Hadronization is modified in e+A collisions relative to e+p
- Connection to modification observed in small/large heavy ion collisions?
- Study hadronization at the EIC!


scattered lepton
incoming lepton
virtual photon
u
u
ud
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target nucleon
String Breaking
ud
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π^0
π^0
π^+
π^-
π^0
p
current fragmentation
Fragmentation from QCD vacuum
target fragmentation
$+\eta \sim 4$
E
I
C
$-\eta \sim -4$