The initial state and early time dynamics in heavy-ion collisions

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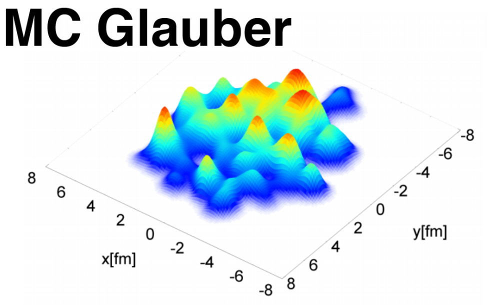
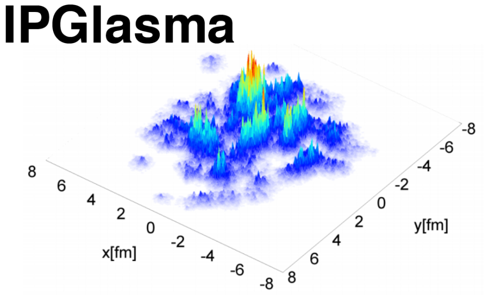
What do we mean by the initial state and early time dynamics?

What is the initial state?

- Size: how big is the overlap?
- Shape: what does the overlap look like?

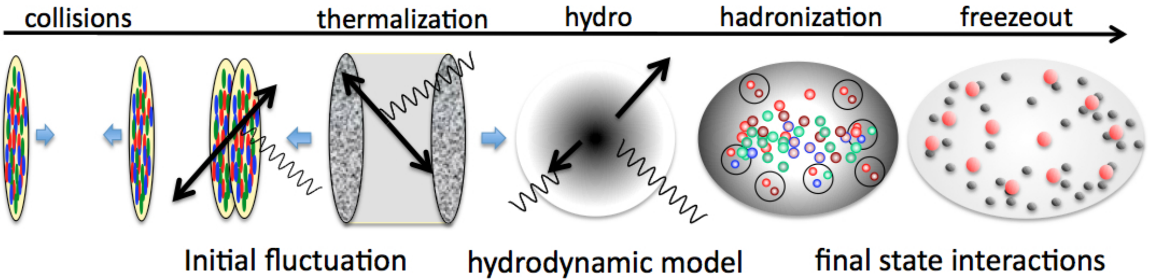




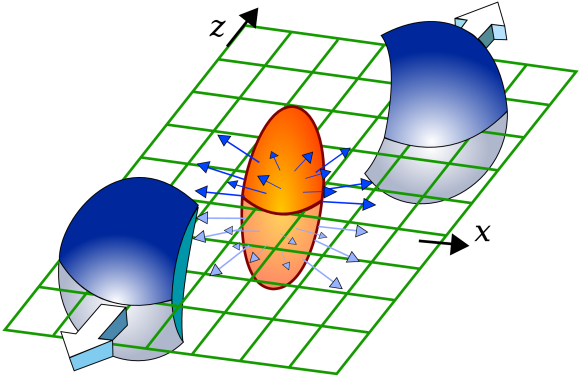
What are early time dynamics?

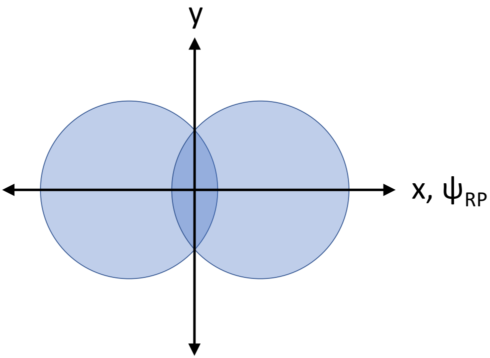
- How does the system evolve given the initial conditions?

Standard model of heavy ion physics



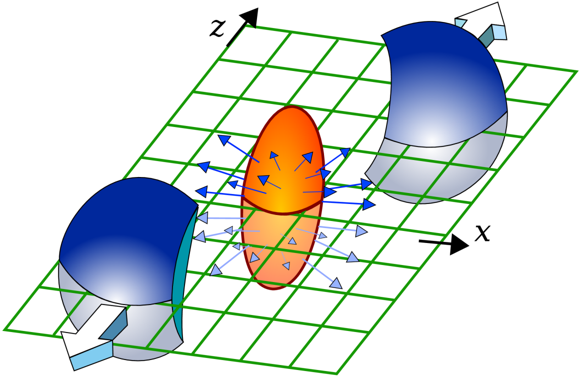
Phase	Initial state & early times?
Initial overlap	Yes
Pre-equilibrium	Yes
QGP in hydro evolution	Yes
Hadronization	No
Hadron gas phase	No
Freezeout and final state	No

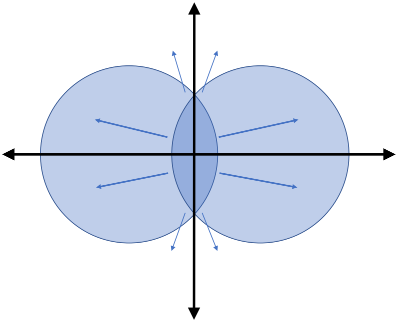




$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos n\varphi \qquad v_n = \langle \cos n\varphi \rangle \qquad \varepsilon_n = \frac{\sqrt{\langle r^2 \cos n\varphi \rangle + \langle r^2 \sin n\varphi \rangle}}{\langle r^2 \rangle}$$

- Hydrodynamics translates initial shape (ε_n) into final state distribution (v_n)
- Overlap shape approximately elliptical, expect v_2 to be the largest
- $\varphi = \phi_{lab} - \psi_{RP}$





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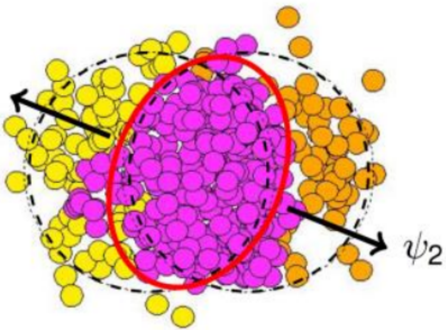
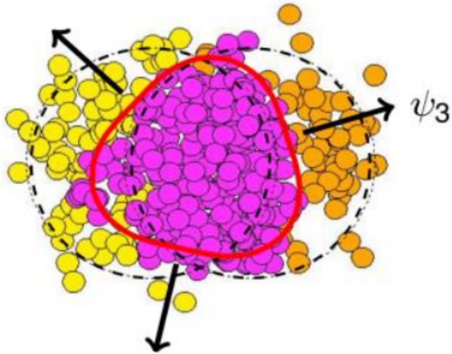
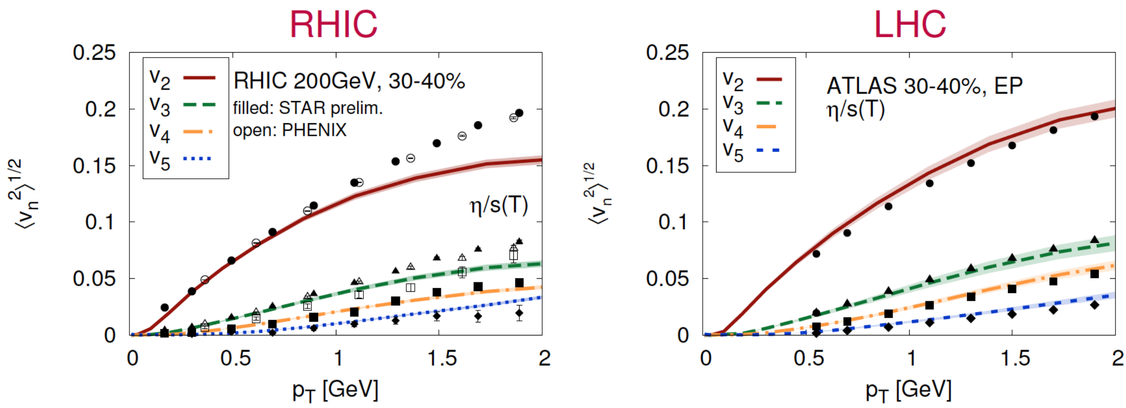




- Symmetry planes ψ_n can be different for different harmonics
- $\varphi = \phi_{lab} - \psi_n$

Data and theory for v_n

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



$$\frac{dN}{d\varphi} \propto 2v_2 \cos 2\varphi + 2v_3 \cos 3\varphi + 2v_4 \cos 4\varphi + 2v_5 \cos 5\varphi$$

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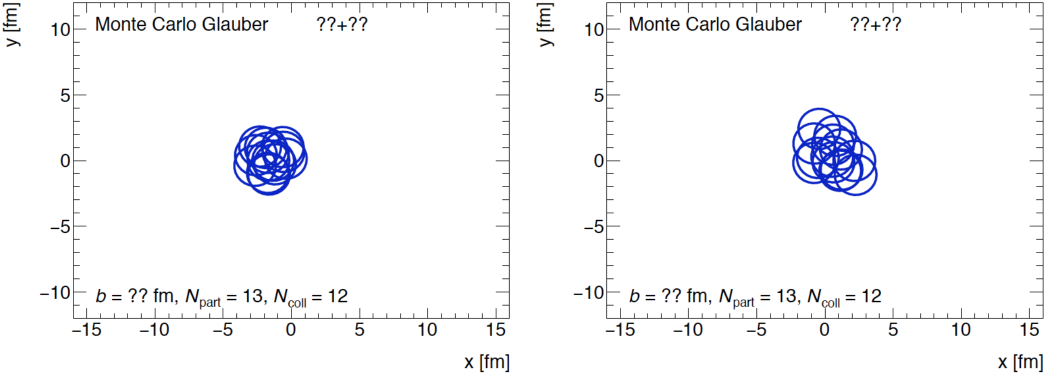
"Twenty years ago, the challenge in heavy ion physics was to find the QGP. Now, the challenge is to not find it." —Jürgen Schukraft, QM17

Which is which?

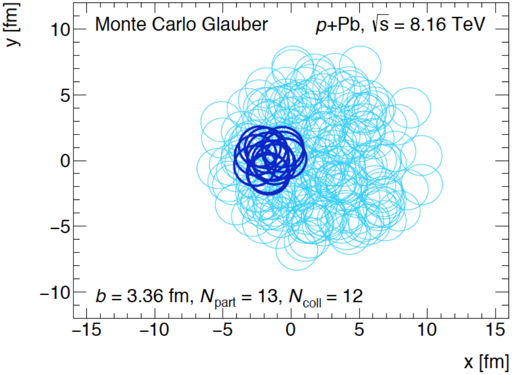
Figures courtesy D. V. Perepelitsa

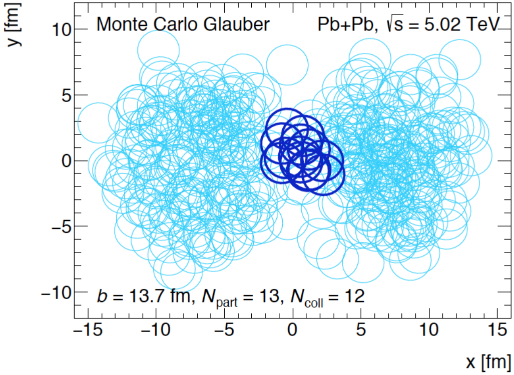


...maybe we shouldn't be so surprised?

Which is which?

Figures courtesy D. V. Perepelitsa





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

Testing the hydro QGP picture in small systems

Two key ideas (several years of RHIC operations)

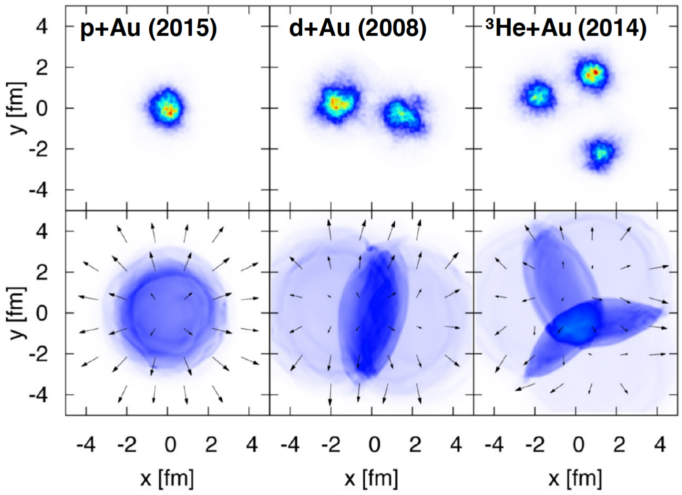
- Vary the geometry (different collision species), fix size and lifetime (same collision energy)
- Fix the geometry (same collision species), vary the size and lifetime (different collision energy)

Small systems geometry scan

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

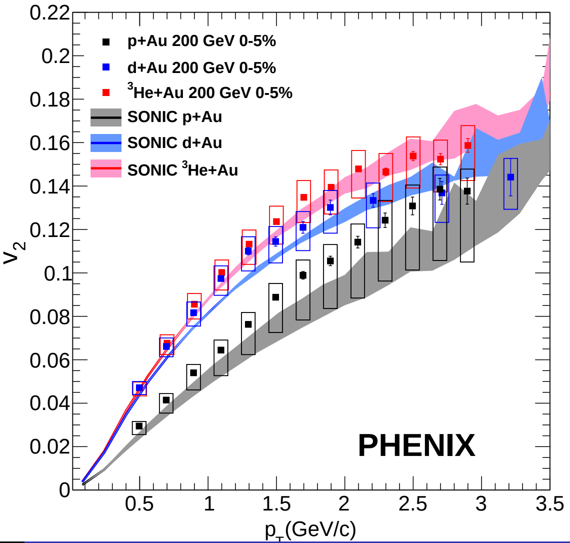
	ε_2	ε_3
p+Au	0.24	0.16
d+Au	0.57	0.17
^{3}He+Au	0.48	0.23

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

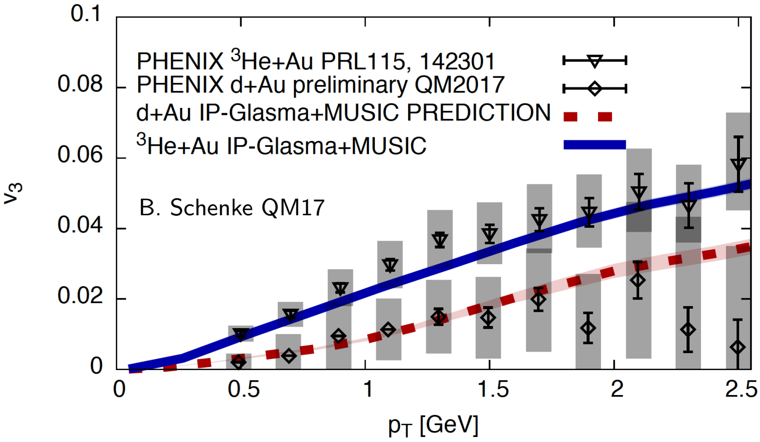


PHENIX, Phys. Rev. C 95, 034910 (2017)

- v_2 ordering as expected from ε_2 ordering
- Hydro theory fits data perfectly

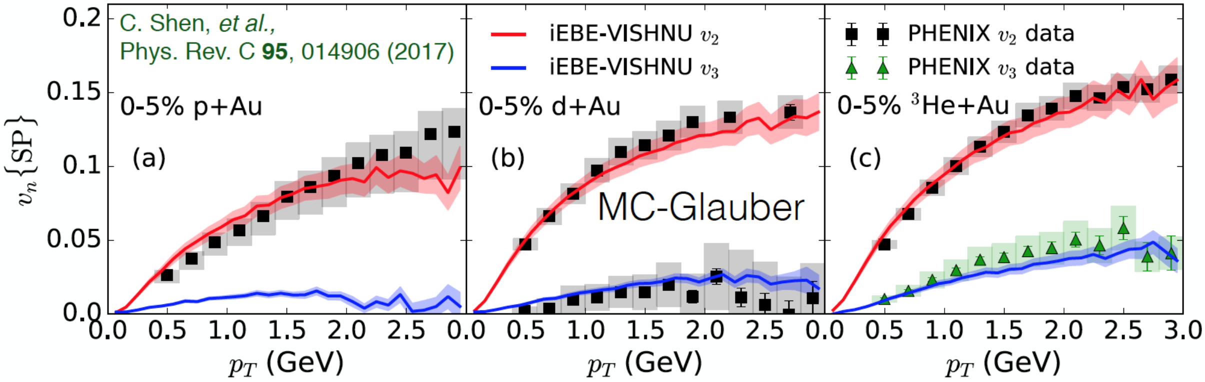


v_3 vs p_T in the geometry scan



- v_3 in d+Au less than v_3 in ^{3}He+Au as expected from ε_3
- Excellent agreement between theory and experiment

v_2 and v_3 vs p_T in the geometry scan



- v_2 and v_3 follow pattern of ε_2 and ε_3
- Last piece of puzzle: v_3 in p+Au is in the works

Quick recap of small systems geometry scan

Second harmonic

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

Third harmonic

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

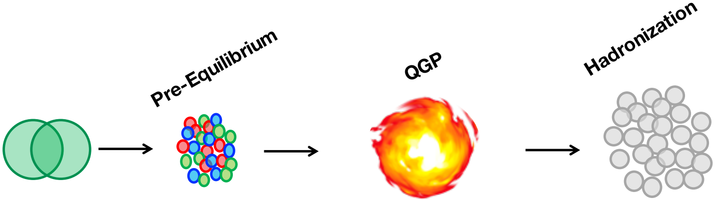
What's next?

- v_3 in p+Au coming soon!
- Alternate explanations? Need more theory calculations!

Intermission

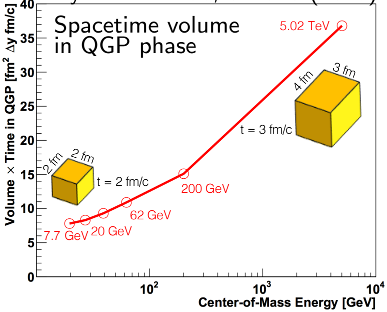
Small systems beam energy scan

Testing hydro by controlling system size and life time

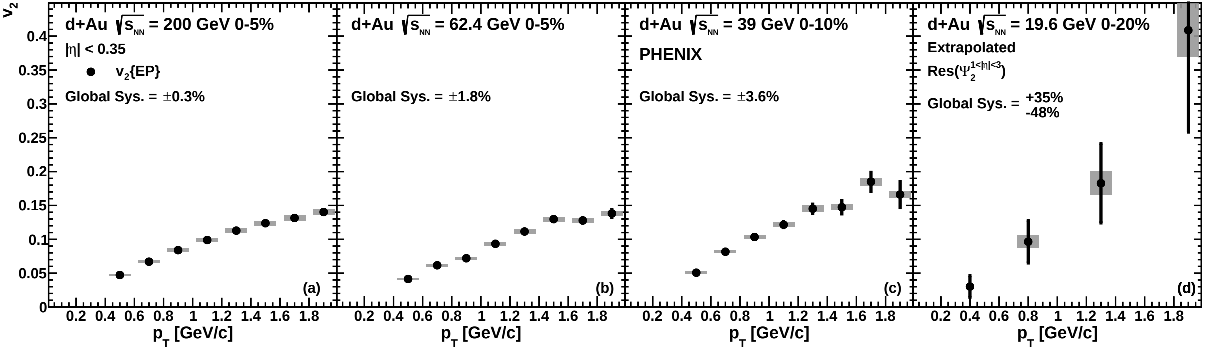


- Standard picture for A+A: QGP in hydro evolution
- What about small systems? And lower energies?
- Use collisions species and energy to control system size, test limits of hydro applicability

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



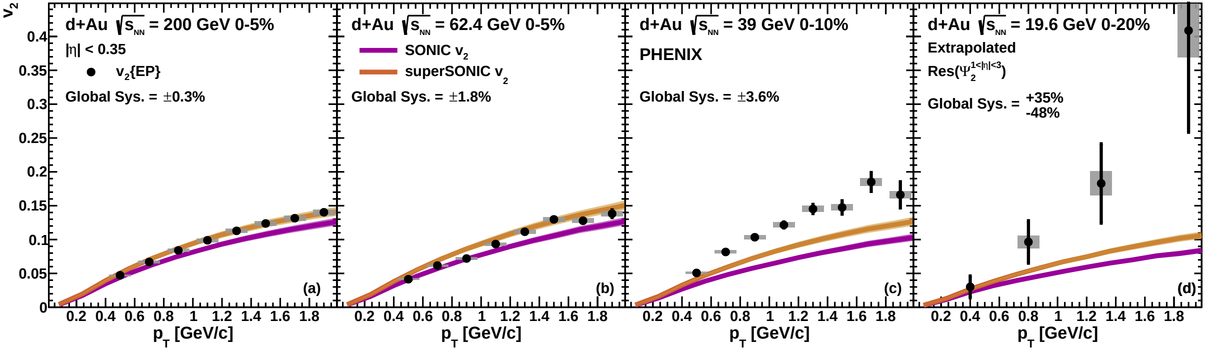
PHENIX, Phys. Rev. C 96, 064905 (2017)



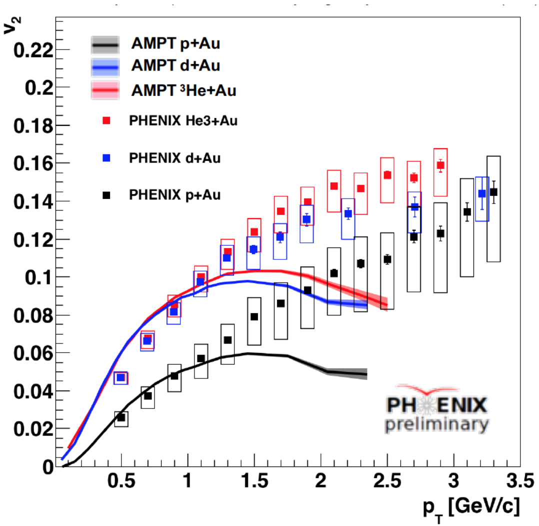
- Event plane v_2 vs p_T measured for all energies

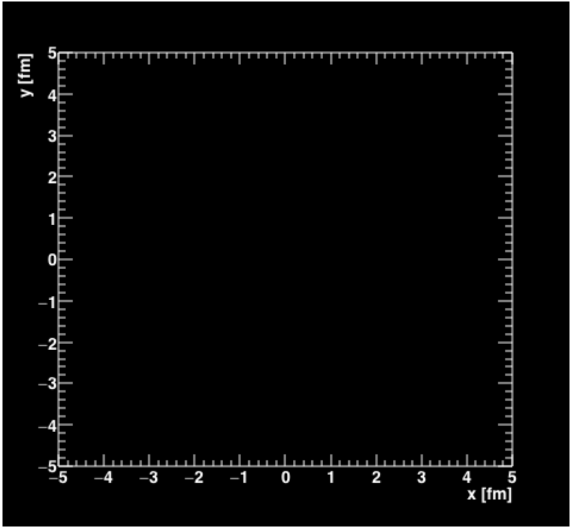
v_2 vs p_T, comparisons to theory

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



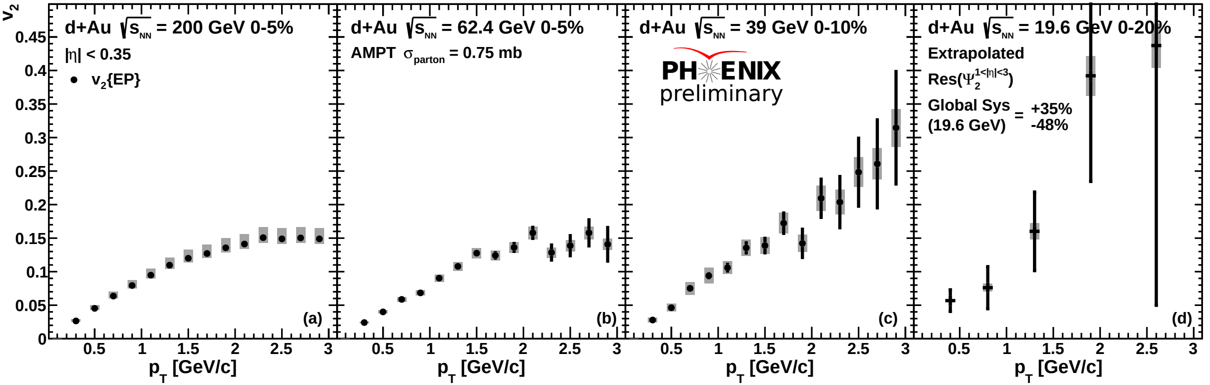
- Event plane v_2 vs p_T measured for all energies
- Hydro theory agrees with higher energies very well, far underpredicts lower energies—lots of non-flow at lower energies


v2
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.5
1
1.5
2
2.5
3
3.5
pT [GeV/c]
AMPT p+Au
AMPT d+Au
AMPT 3He+Au
PHENIX He3+Au
PHENIX d+Au
PHENIX p+Au
PHENIX
preliminary


y [fm]
x [fm]
5
4
3
2
1
0
−1
−2
−3
−4
−5

v_2 vs p_T, comparisons to AMPT

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



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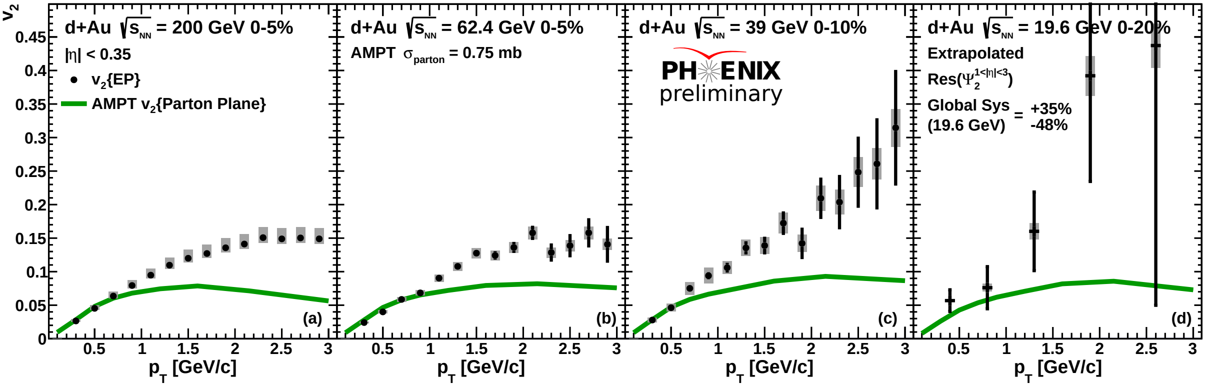

- AMPT flow only shows good agreement at low p_T and all energies

v_2 vs p_T, comparisons to AMPT

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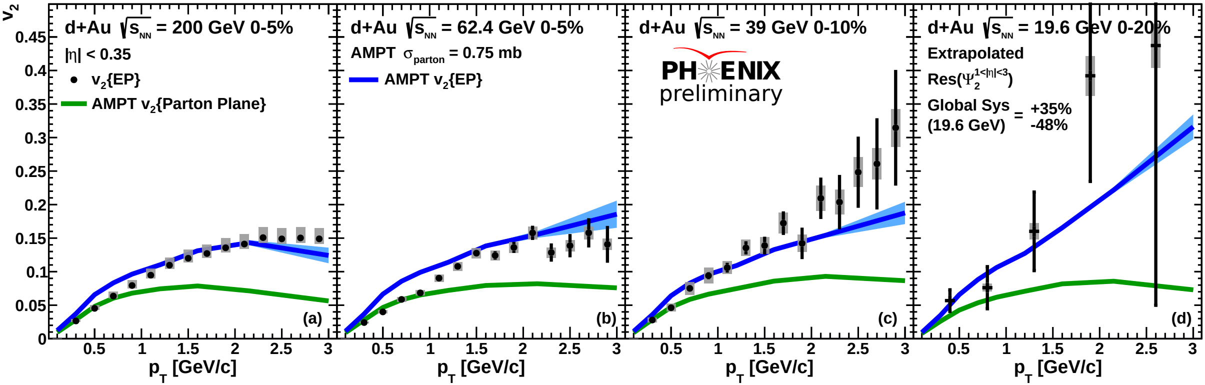
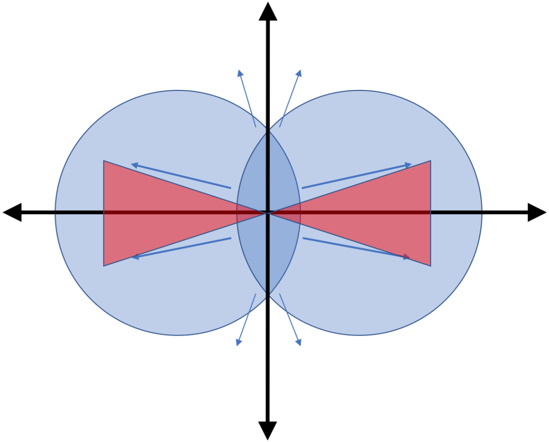


- AMPT flow only shows good agreement at low p_T and all energies
- AMPT flow+non-flow shows reasonable agreement for all p_T and all energies

flow and nonflow

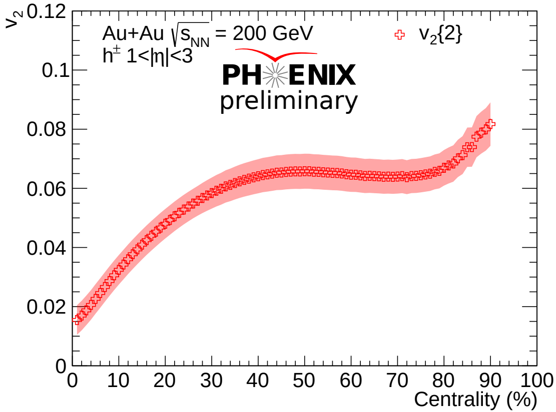


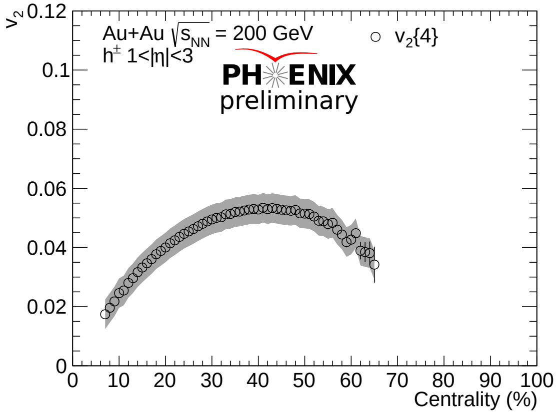
$$v_n = \langle \cos(n(\phi_{\text{some particle}} - \psi_n)) \rangle$$
$$v_n^2 = \langle \cos(n(\phi_{\text{some particle}} - \phi_{\text{some other particle}})) \rangle$$

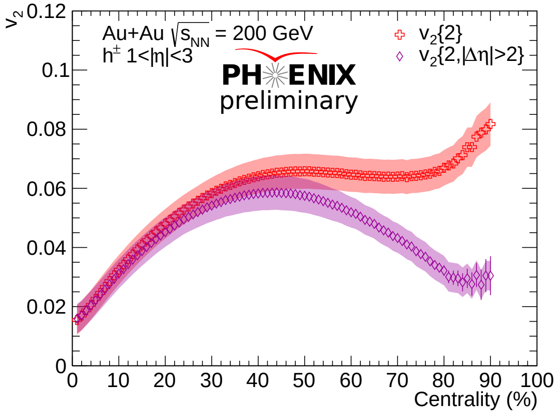
- How to deal with "fake flow"?
  —Kinematics
  —Combinatorics

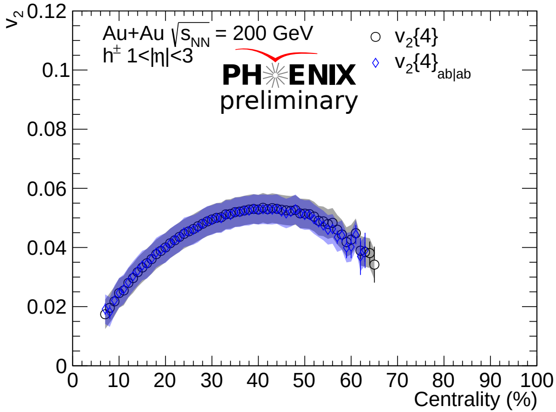
$$v_n^2 = \langle \cos(n(\phi_a - \phi_b)) \rangle$$
$$v_n^4 = \langle \cos(n(\phi_a + \phi_b - \phi_c - \phi_d)) \rangle$$
$$v_n^6 = \langle \cos(n(\phi_a + \phi_b + \phi_c - \phi_d - \phi_e - \phi_f)) \rangle$$
$$v_n^8 = \ldots$$

Nonflow approaches in AuAu



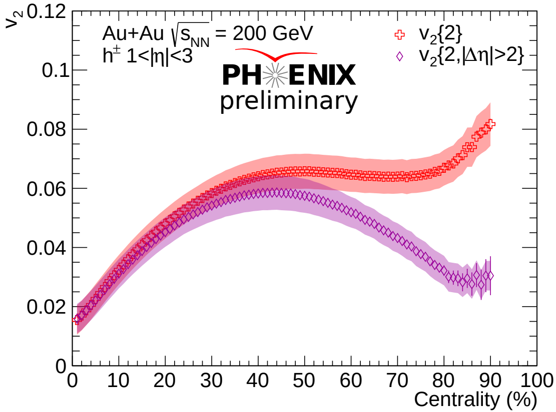


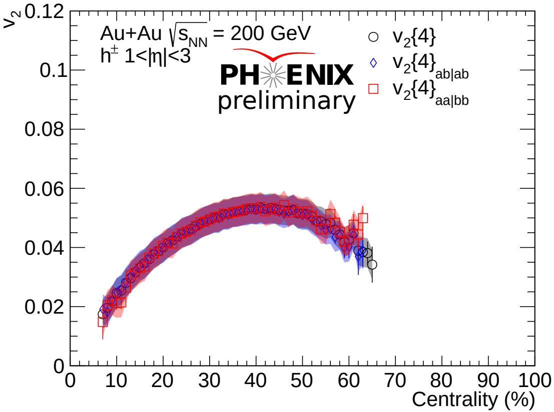




- Large pseudorapidity separation
  —Big difference for 2-particle (good)
  —No difference for 4-particle (good)

Nonflow approaches in AuAu





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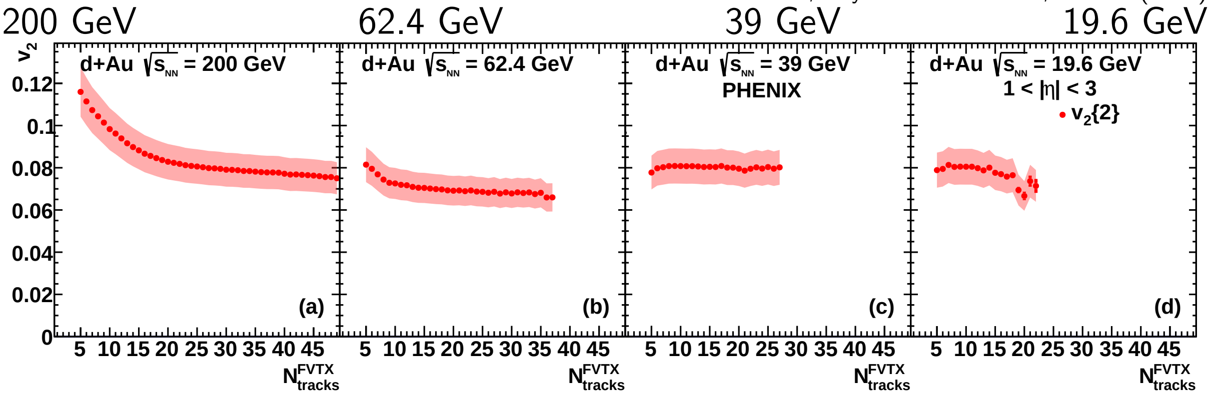
Multi-particle v_2 in the d+Au beam energy scan

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



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

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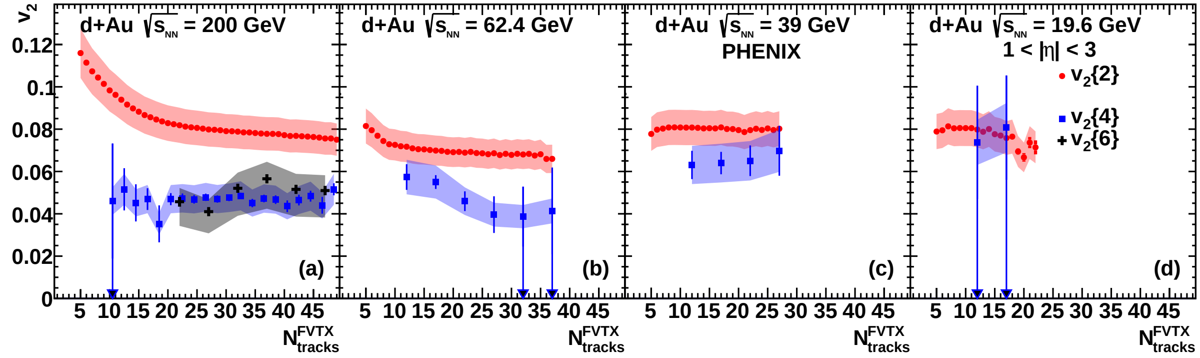
PHENIX, Phys. Rev. Lett. 120, 062302 (2018)

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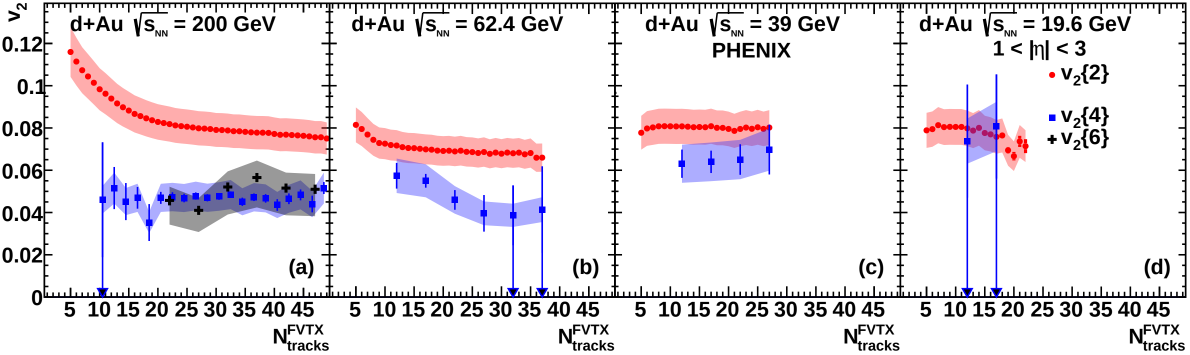
PHENIX, Phys. Rev. Lett. 120, 062302 (2018)

200 GeV | 62.4 GeV | 39 GeV | 19.6 GeV

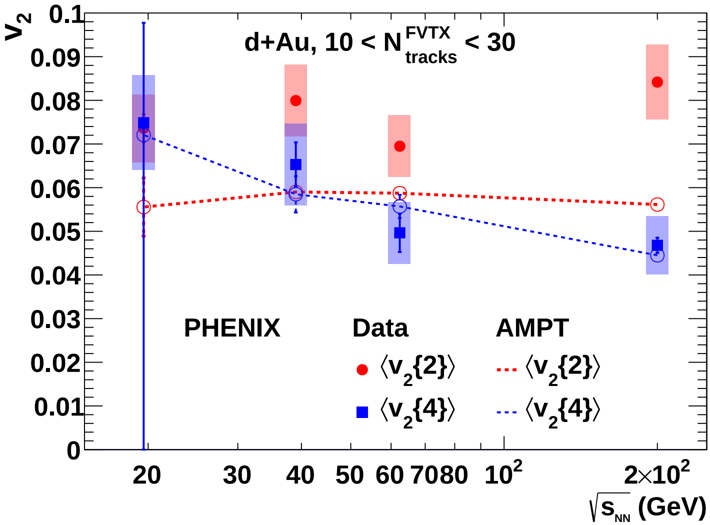


- $v_2\{2\}$ relatively constant with N_{tracks}^{FVTX} and collision energy
- Measurement of $v_2\{4\}$ in d+Au at all energies
- Measurement of $v_2\{6\}$ in d+Au at 200 GeV
- $v_2\{4\}$ increases and approaches $v_2\{2\}$

Multi-particle v_2 in the d+Au beam energy scan

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

- Select $10 < N_{tracks}^{FVTX} < 30$, integrate
- AMPT sees similar trend
- Fluctuations?
  - Not Bessel-Gaussian
  - Not small-variance limit
  - Need to understand fluctuations better

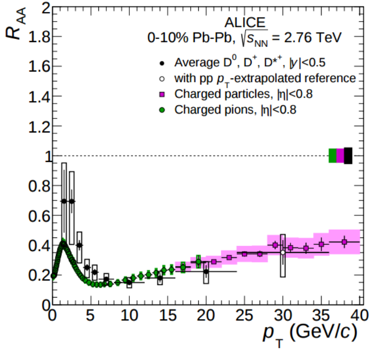


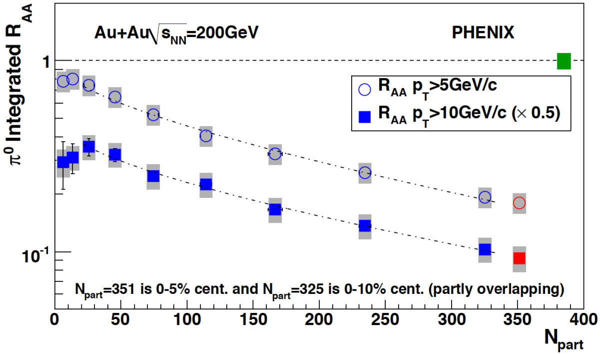
Quick recap of small systems beam energy scan

- Good agreement with hydro at 200 GeV and 62.4 GeV, bad agreement at 39 and 19.6 GeV —Nonflow
- Good agreement with AMPT at all 4 energies
- Measured $v_2\{6\}$ at 200 GeV
- Measured $v_2\{4\}$ at all 4 energies energies
- Need to understand the fluctuations better

Hard scattering as understood by a flow person
(Caveat emptor)

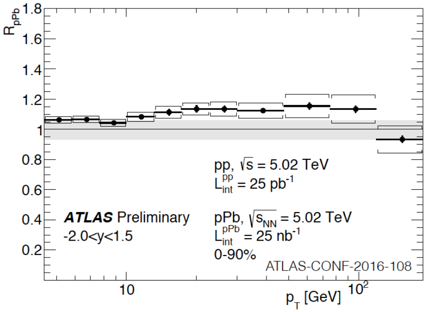
- Hard scattering means large momentum transfer Q^2 between partons
- Leads to final state particle with large p_T
- Probe small distance scales $x \approx 1/Q$
  (e.g. 2 GeV $\leftrightarrow$ 0.1 fm)
- Probe early times because scatterings occur during nuclear crossing $\tau = 2R/\gamma$
  (e.g. $\tau = 0.13$ fm for Au+Au at 200 GeV)

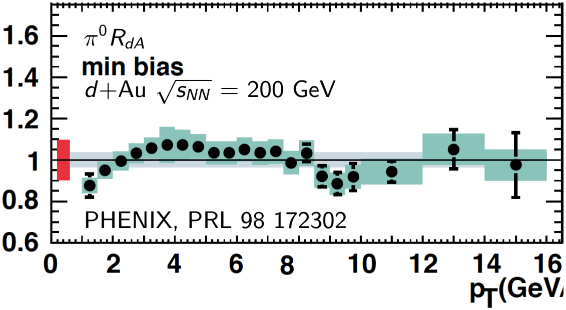




- $R_{AA} = \frac{N^{A+A}_{particles}}{N^{p+p}_{particles} \times N_{coll}}$
- $R_{AA} < 1$ means particles are suppressed
- Bigger system: more suppression
- Suppression even in peripheral (small-ish)

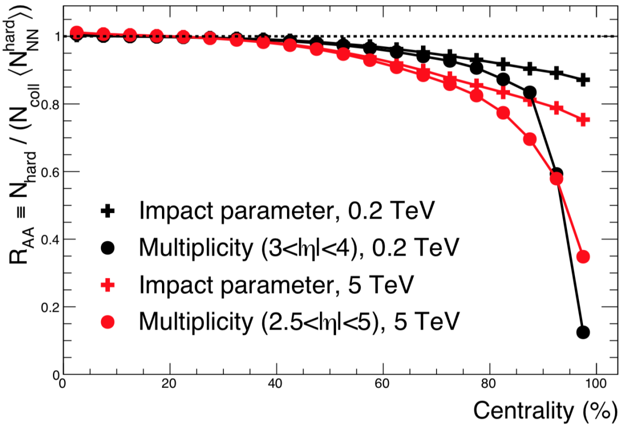
Hard scattering in small systems





- $R_{p/dA} = \dfrac{N^{p/d+A}_{particles}}{N^{p+p}_{particles} \times N_{coll}}$
- $R_{p/dA} \approx 1$ means no modification
- Only showing minimum bias...
- Similar system size as peripheral Au+Au but no suppression?

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



Suppression in peripheral A+A could be entirely due to bias effects

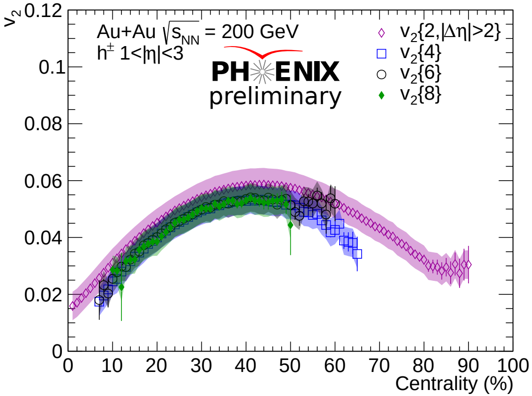
- More multi-parton interactions at small b, fewer at large b
- Correlation between centrality selection criterion (e.g. event multiplicity) and hard process rate (i.e. presence of high p_T particle)
- End result for both is same: more hard collisions in "central" vs "peripheral"

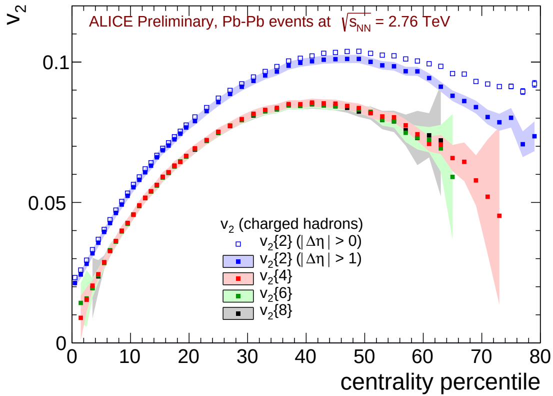
Summary

- The initial state seems to be well-described by MC Glauber and IP-Glasma
- The early time dynamics appear to be well-described by hydrodynamics
- System energy dependence shows intriguing results
- Collision geometry dependence agrees extremely well with hydro
  —Room for alternate explanations? Yes! Need more theory predictions
- Hard processes occur during early times and probe small distances
  —QGP microscope
- Small systems exhibit collectivity but not high p_T particle suppression
  —We used to claim that small systems are too small, but peripheral A+A is also small...
  —Apparent peripheral suppression may be misleading, bias effects can be significant...

Additional Material

Multi-particle correlations: combinatorics and fluctuations





- Favorable combinatorics—dilution factor $\equiv \left\lfloor \frac{N}{k} \right\rfloor / \binom{N}{k} \approx (k-1)!/N^{k-1}$
- Insights into fluctuations: "cumulant" $v_n\{k\}$ mixes different moments of v_n

$$v_n\{2\} = (v_n^2 + \sigma^2)^{1/2}, \quad v_n\{4\} \approx v_n\{6\} \approx v_n\{8\} \approx (v_n^2 - \sigma^2)^{1/2}$$

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)

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

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

Back to basics (a brief 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)

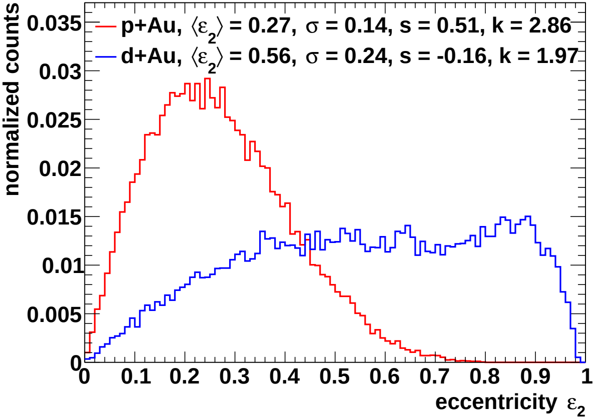
Subbing in $x = v_n$, $\kappa_2 = \sigma^2$, we find

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

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...

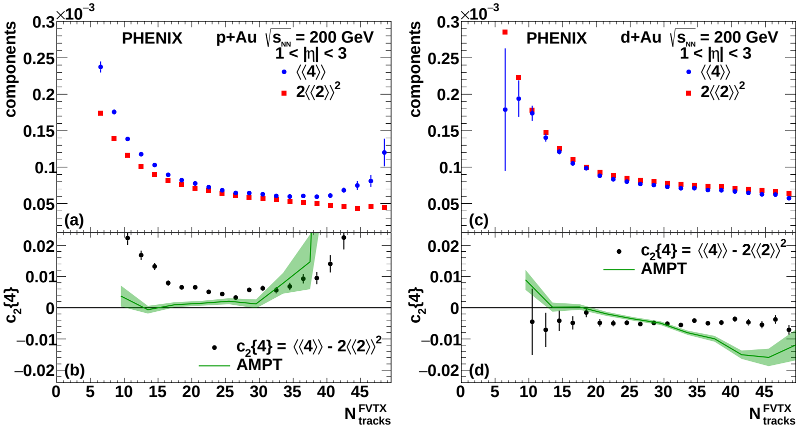


	p+Au	d+Au
ε_2^4	0.00531	0.0983
$2\varepsilon_2^2\sigma^2$	0.00277	0.0370
$4\varepsilon_2 s\sigma^3$	0.00147	-0.0053
$(k-2)\sigma^4$	0.00031	-0.0001

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

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

Eccentricity distributions and cumulants

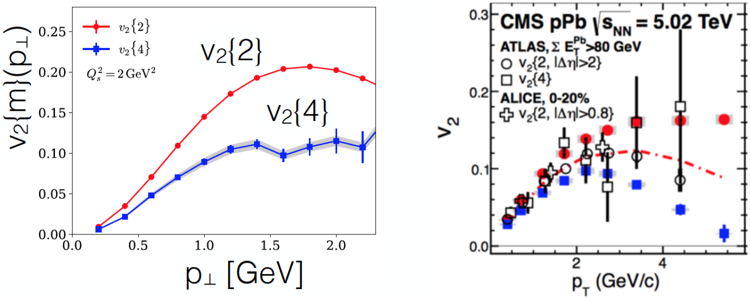


$$v_2\{4\} = (v_2^4 - 2v_2^2\sigma^2 - 4v_2 s\sigma^3 - (k-2)\sigma^4)^{1/4}$$

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

CGC inspired calculations of multiparticle correlations

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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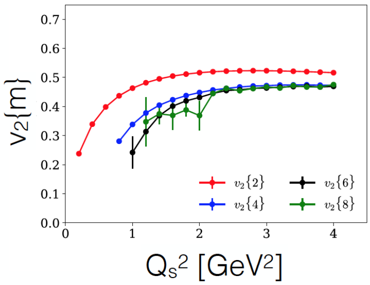

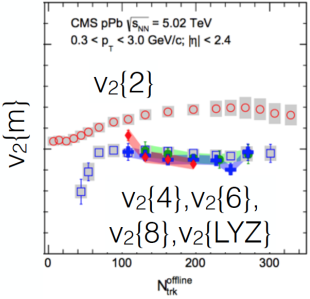

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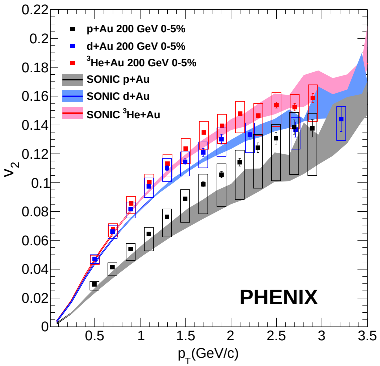
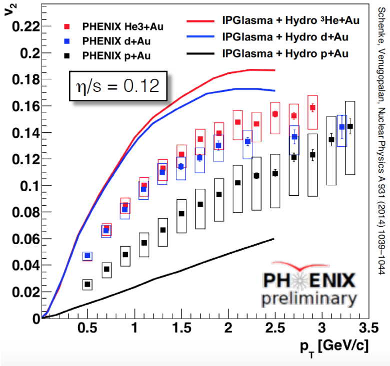
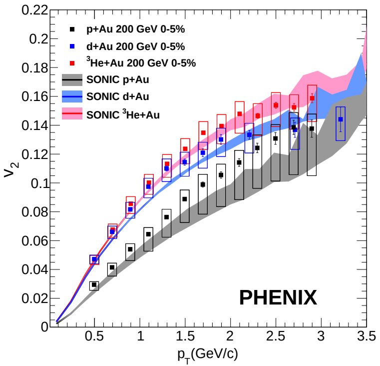
MC Glauber vs IP-Glasma

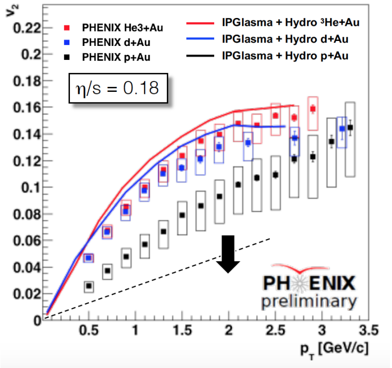




- Glauber left, IP-Glasma right

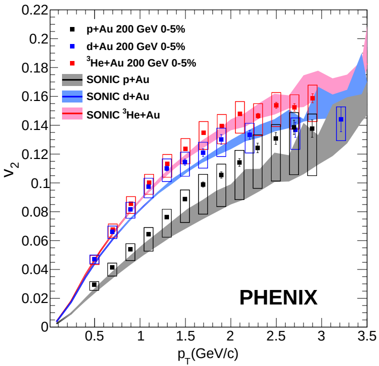
MC Glauber vs IP-Glasma

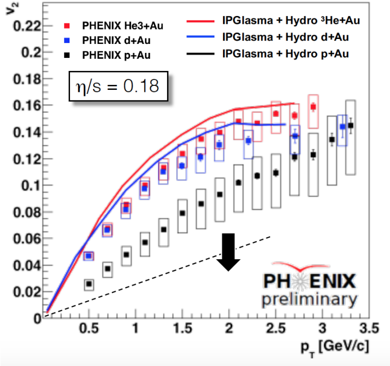




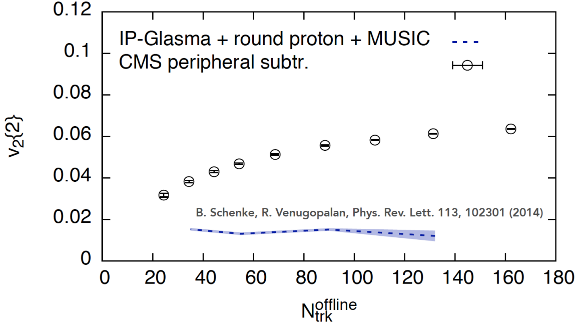
- Glauber left, IP-Glasma right
- Can tune parameters to match d/^{3}He+Au but can't get all three

MC Glauber vs IP-Glasma

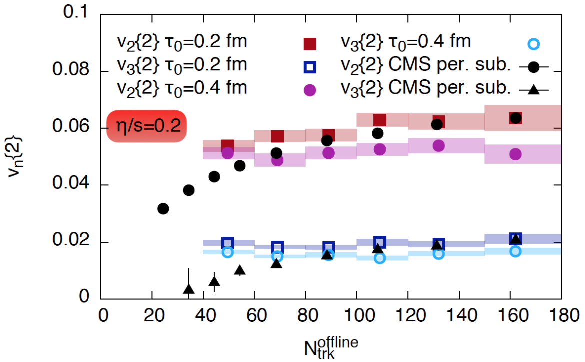




- Glauber left, IP-Glasma right
- Can tune parameters to match d/^{3}He+Au but can't get all three
- Known issue in IP-Glasma of too-circular protons



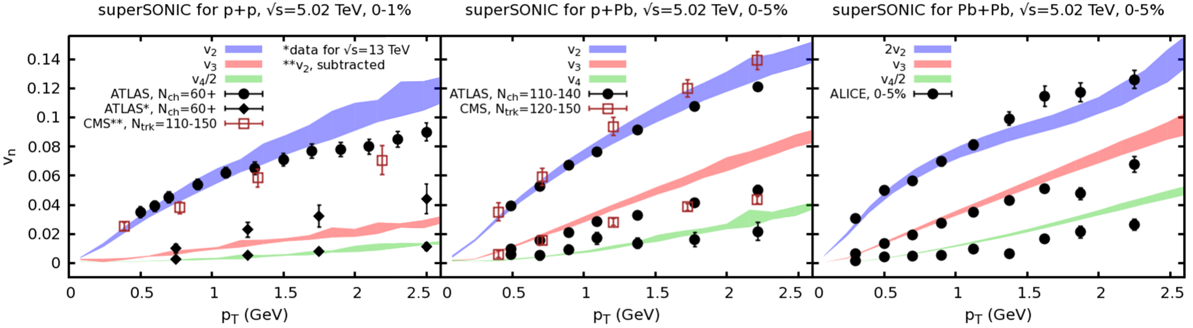
H. Mäntysaari et al, Phys. Lett. B 772, 681 (2017)



- Round protons on left—spectacular failure
- Realistic proton shape (and fluctuations) on right—dramatically better

One fluid to rule them all

R. Weller and P. Romatschke, Phys. Lett. B 774, 351 (2017)



- MC Glauber initial conditions
- NB: single set of fluid parameters for all systems