Small systems: some recent results

Ron Belmont
University of North Carolina Greensboro

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Outline

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

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

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

Intermission

Particle production in small systems

Nuclear modification factor

We want to know if nuclear collisions are a simple superposition of nucleon-nucleon collisions, or if something special is happening

Nuclear modification factor for A+B collisions

$$R_{AB} = \frac{\text{Yield in A+B collisions}}{\text{Appropriate scaling} \times \text{Yield in p+p collisions}}$$

What's the appropriate scaling? We call it N_{coll}, the number of binary nucleon-nucelon collisions

$R_{AB} = 1$ means no modification

$R_{AB} > 1$ means enhancement

$R_{AB} < 1$ means suppression

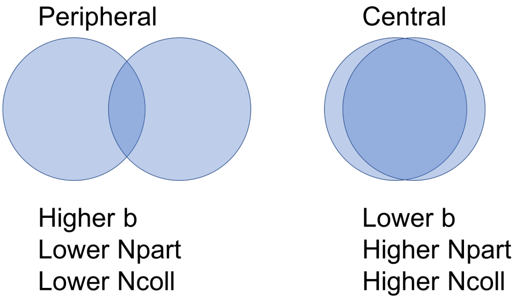
Centrality

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	$\langle N_{\mathrm{part}} \rangle$	$\langle N_{\mathrm{coll}} \rangle$
Pb+Pb		
0-5%	382.7 ± 5.1	1685 ± 190
5-10%	329.7 ± 4.6	1316 ± 140
10-20%	260.5 ± 4.4	921 ± 96
20-30%	186.4 ± 3.9	556 ± 55
30-40%	128.9 ± 3.3	320 ± 32
40-50%	85.0 ± 2.6	171 ± 16
50-60%	52.8 ± 2.0	84.3 ± 7
60-70%	30.0 ± 1.3	37.9 ± 3
70-80%	15.8 ± 0.6	15.6 ± 1
p+p	$\equiv 2$	$\equiv 1$

Centrality

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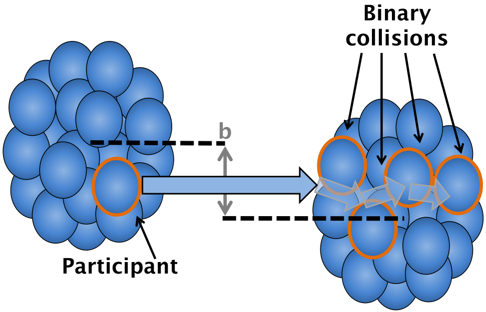

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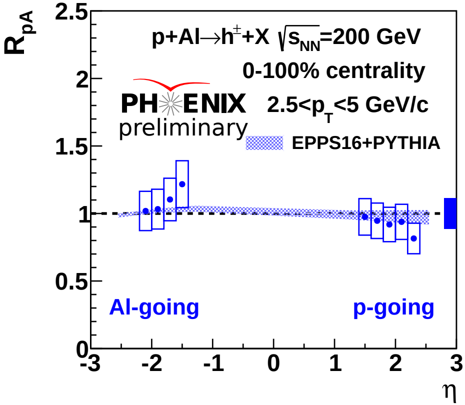
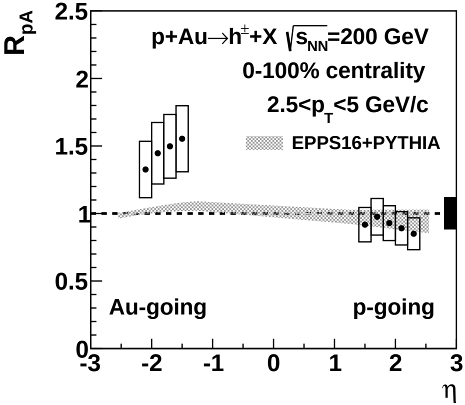
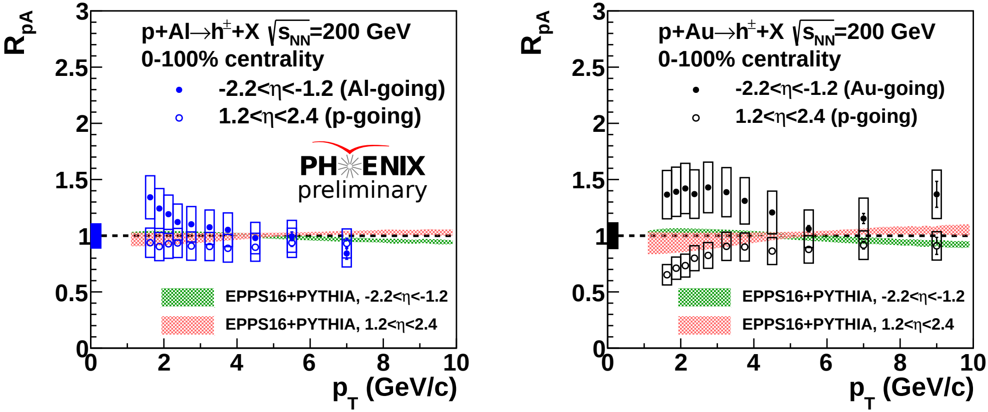
p+p	≡ 2	≡ 1

Small systems nuclear modification



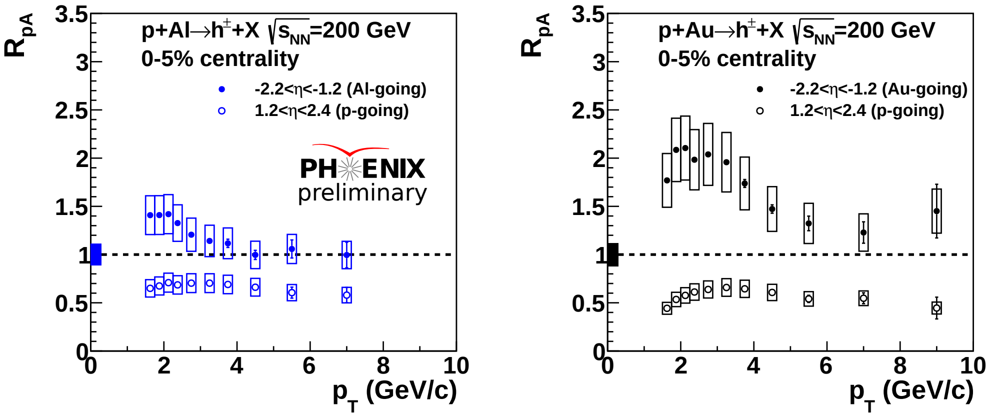


Forward modification consistent with nPDF effects (EPPS16)



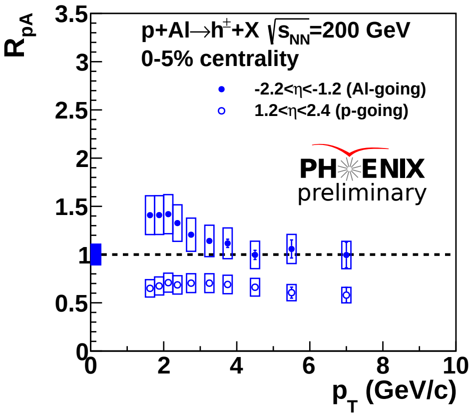
High-p_T modification consistent with nPDF effects (EPPS16)

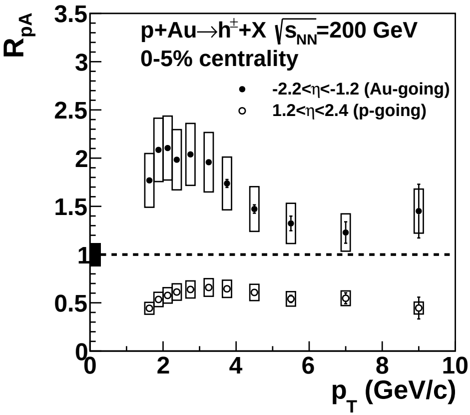
Small systems nuclear modification



Stronger effects in central collisions

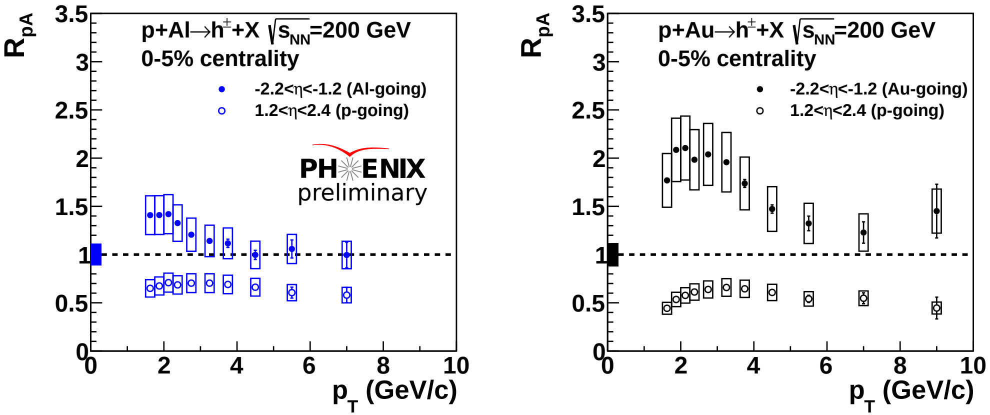
Small systems nuclear modification





Strong enhancement for backward at intermediate p_T—why?

Small systems nuclear modification

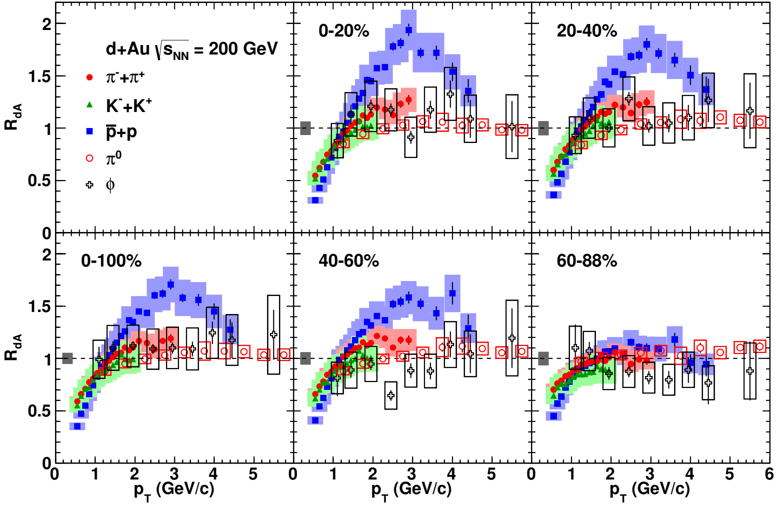


Strong enhancement for backward at intermediate p_T—why?

Don't forget: particle species dependence of Cronin! There must be final state effect(s)...

Particle species dependence of "Cronin enhancement"

Phys. Rev. C 88, 024906 (2013)



π^+, π^-, π^0,

K^+, K^-,

p, $\bar{p}$,

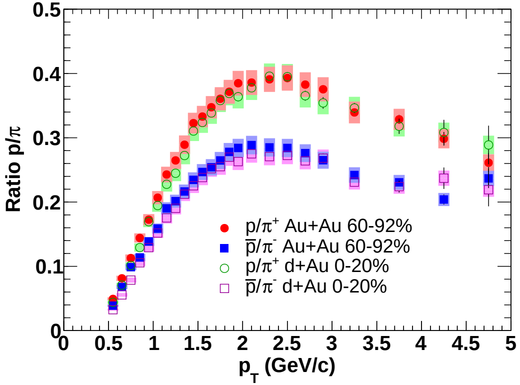
ϕ

Protons much more strongly modified than pions

ϕ mesons are heavier than protons

Comparison of peripheral Au+Au to central d+Au

Phys. Rev. C 88, 024906 (2013)



Identical p/π ratios

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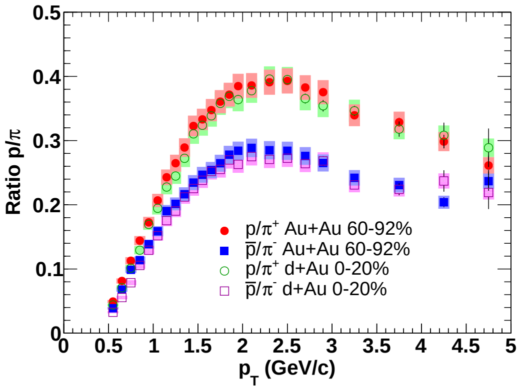

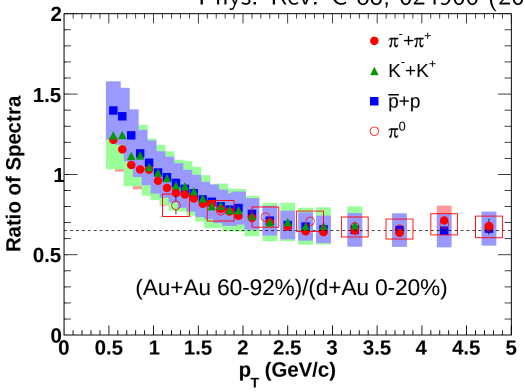

Identical p/π ratios

Universal curve for ratio of spectra

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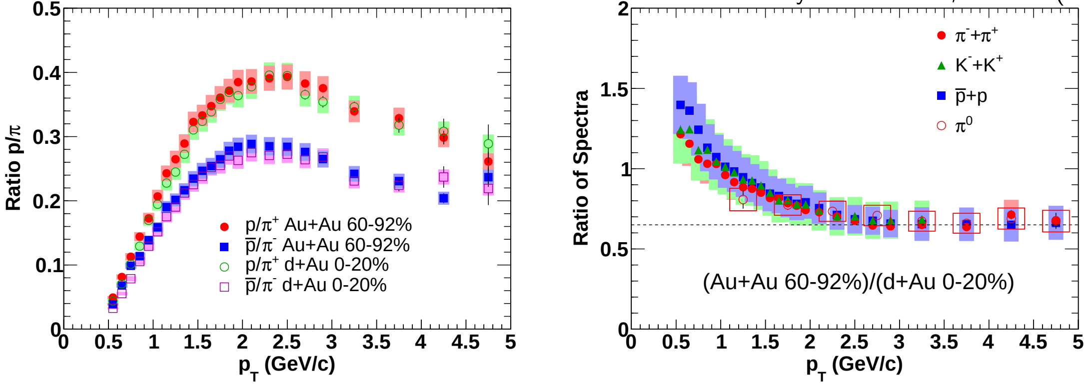
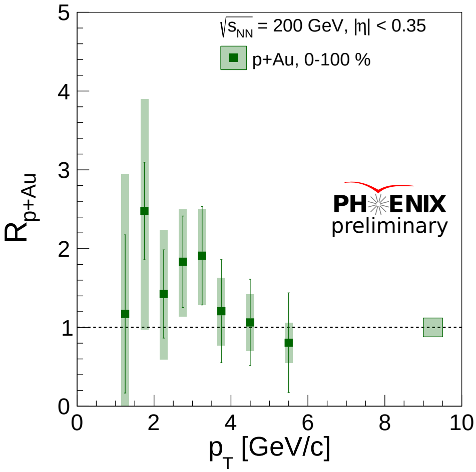


Identical p/π ratios

Universal curve for ratio of spectra

(Ask me about the baryon anomaly if you'd like to know more...)

Photons in small systems



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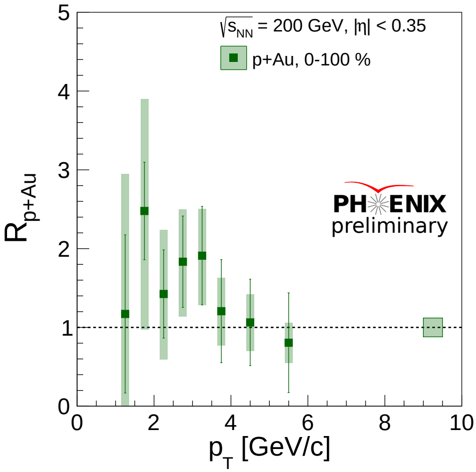
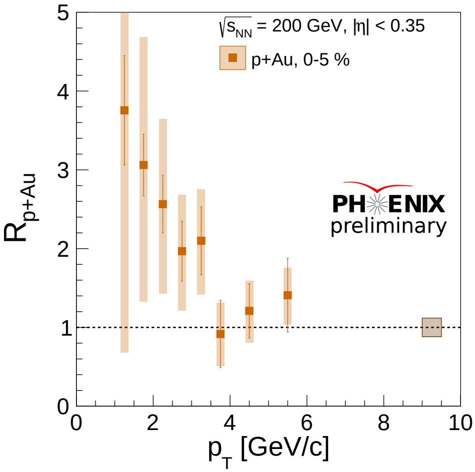
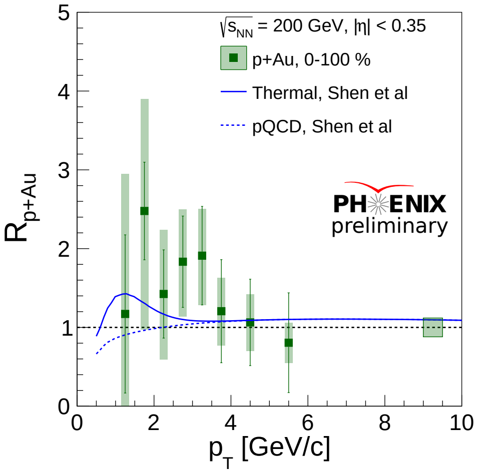
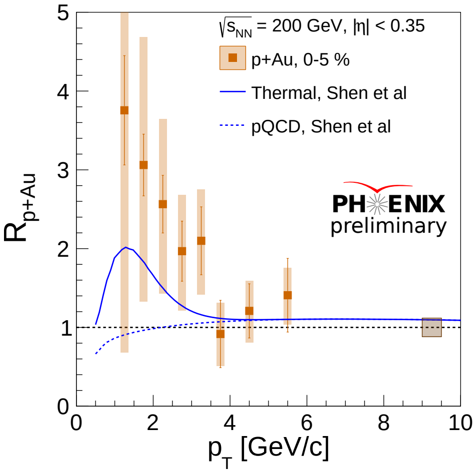




Thermal photons in p+Au?

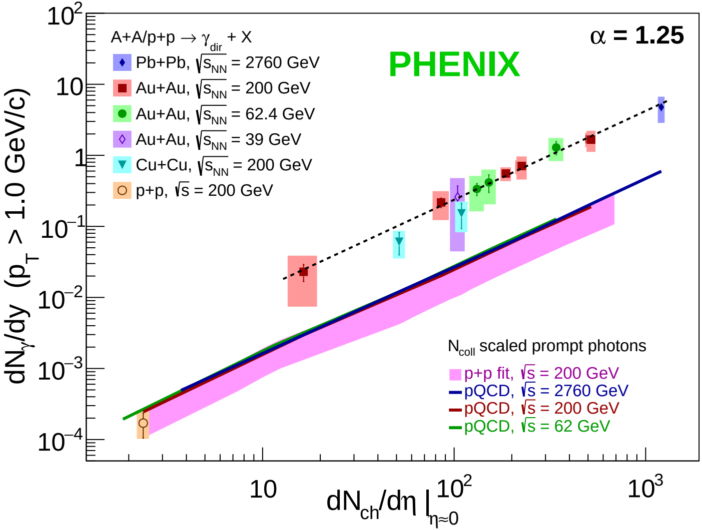
Photons in small systems





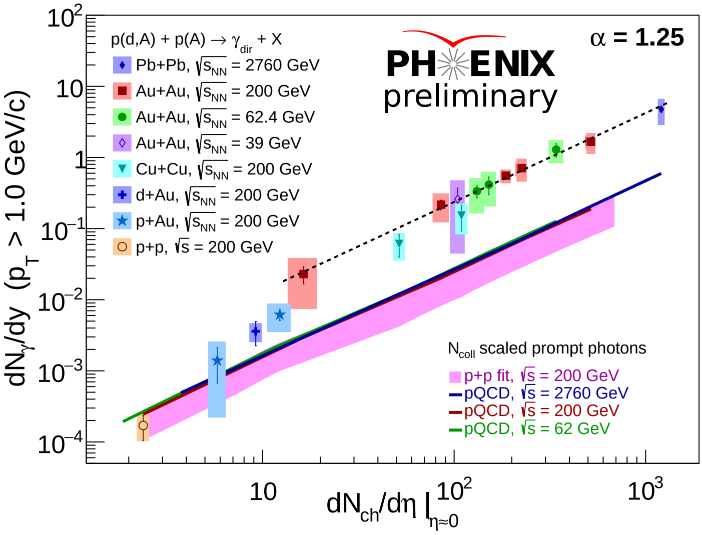
Thermal photons in $p+$Au? Theory from Phys. Rev. C 95, 014906 (2017)

Photon yields



Common scaling for Au+Au and Pb+Pb at different energies; very different from N_{coll}-scaled $p+p$

Photon yields



Common scaling for Au+Au and Pb+Pb at different energies; very different from N_{coll}-scaled p+p

p+Au and d+Au in between

Brief summary: particle production in small systems

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

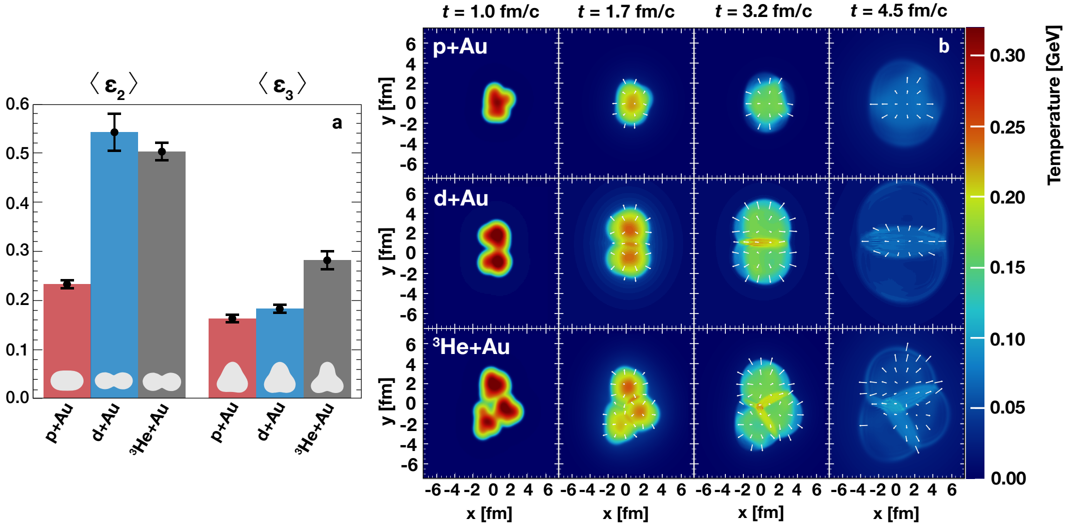
Nuclear modification strongly dependent on particle species
—Must be final state effect(s)
—Hadronization, radial flow, etc...

Intermission

Small systems geometry scan

Testing hydro by controlling system geometry

arXiv:1805.02973, in press (Nature Physics)



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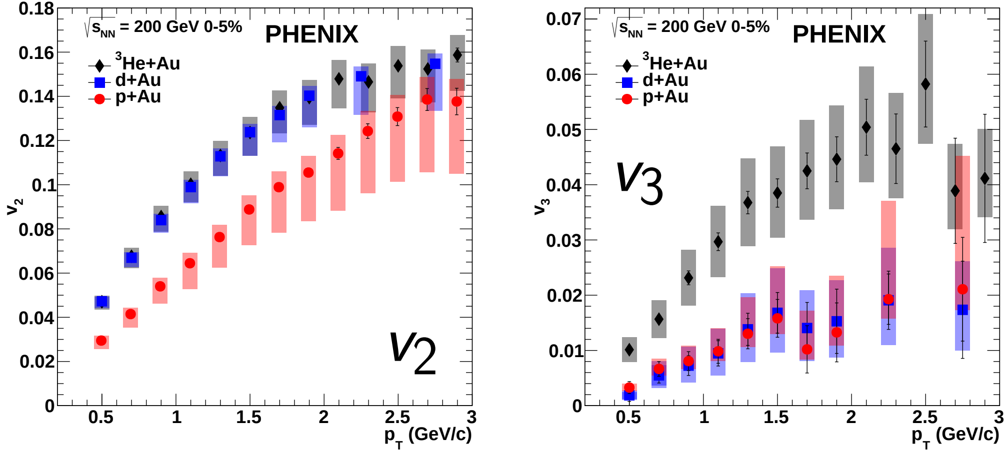
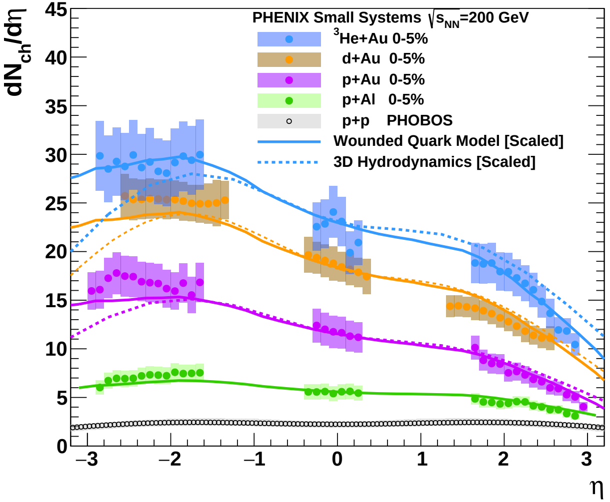


v_2 and v_3 ordering matches ε_2 and ε_3 ordering in all three systems

Longitudinal dynamics in small systems

Phys. Rev. Lett. 121, 222301 (2018)



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

Good agreement with wounded quark model

Good agreement with 3D hydro

Longitudinal dynamics in small systems

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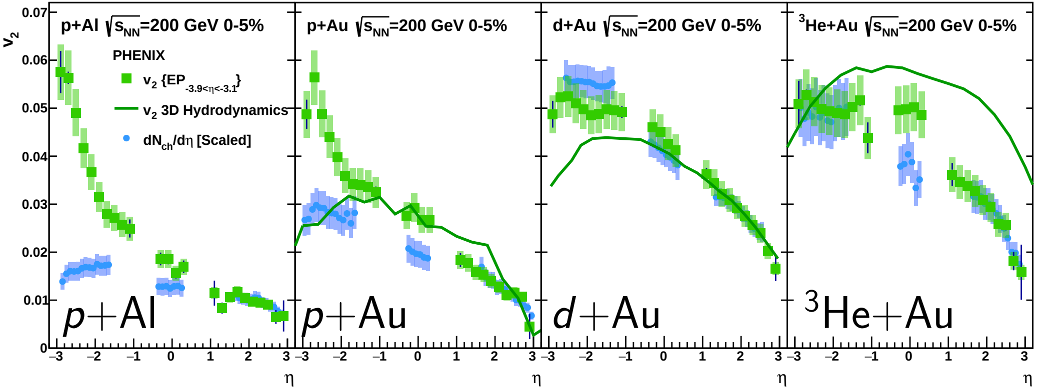


v_2 vs η in p+Al, p+Au, d+Au, and ^{3}He+Au

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

Brief summary: small systems geometry scan

Comprehensive set of measurements for longitudinal dynamics

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

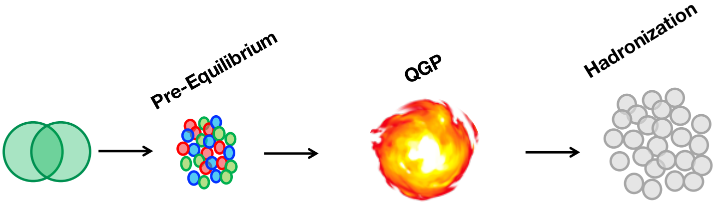
v_2 and v_3 in p+Au, d+Au, ^{3}He+Au are well-described by hydro theory
—Strongest evidence to date for QGP formation in small systems

Comprehensive set of measurements of longitudinal dynamics
—More 3d hydro calculations needed

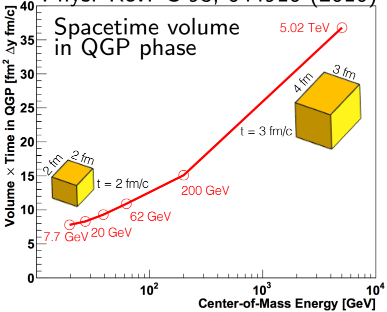
Intermission

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)



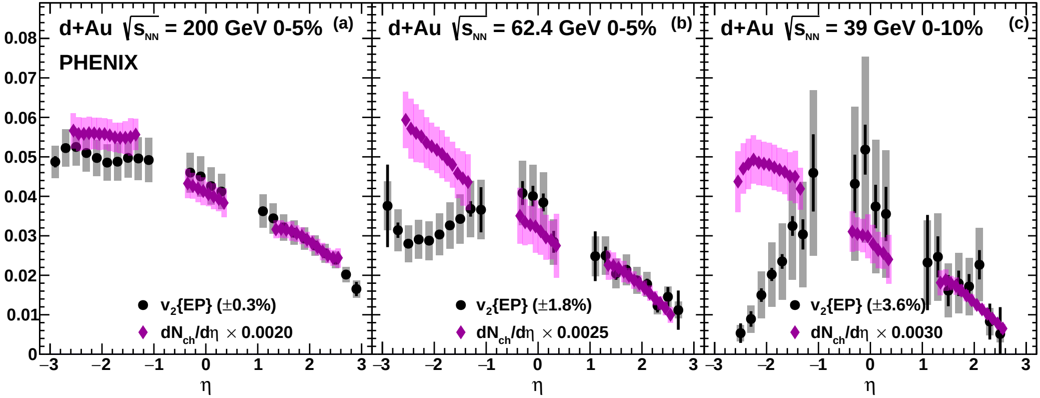
Standard picture for A+A:
QGP in hydro evolution

What about small systems?
And lower energies?

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

Longitudinal dynamics in the small systems beam energy scan

Phys. Rev. C 96, 064905 (2017)



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

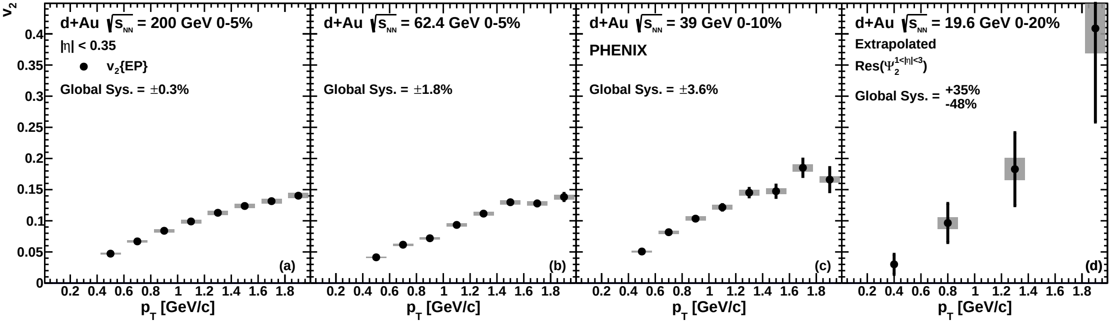
200 GeV shows strong forward/backward asymmetry in v_2 and $dN_{ch}/d\eta$

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

v_2 in the d+Au beam energy scan

Phys. Rev. C 96, 064905 (2017)

200 GeV | 62.4 GeV | 39 GeV | 19.6 GeV



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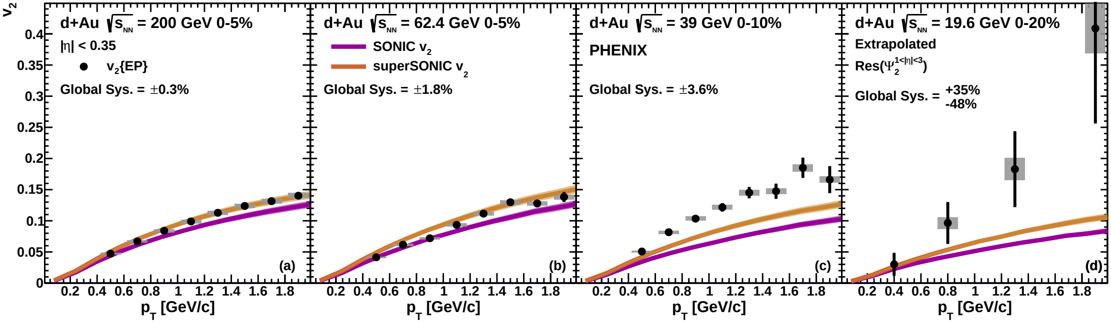
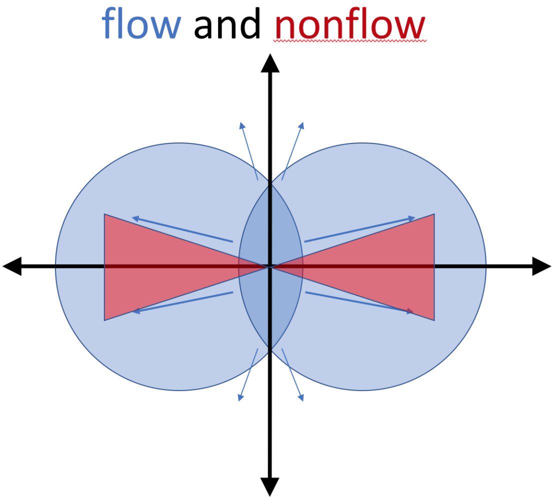


Recall that yesterday I said this breakdown might be blamed on "non-flow"

Non-flow reduction approaches



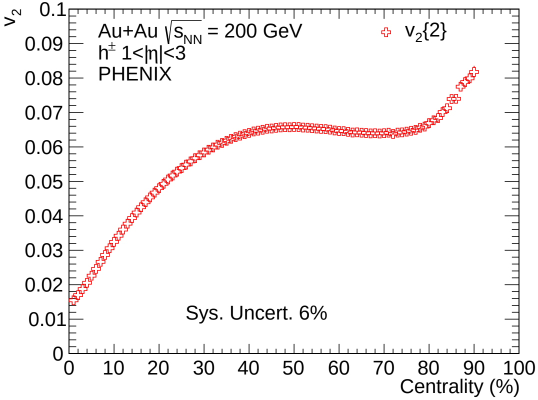
$$v_n = \langle \cos(n(\phi_{\text{some particle}} - \psi_n)) \rangle$$
$$v_n^2 = \langle \cos(n(\phi_{\text{some particle}} - \phi_{\text{some other particle}})) \rangle$$

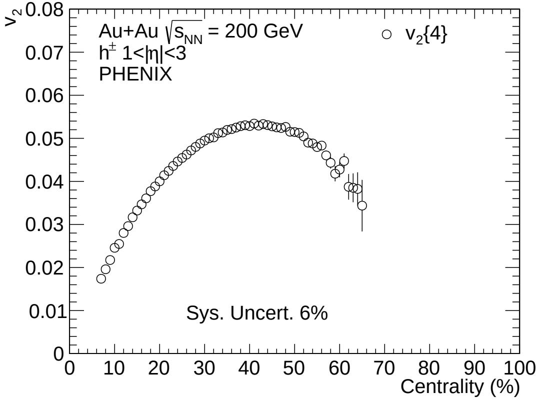
How to deal with "fake flow"?
—Kinematics
—Combinatorics

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

Nonflow approaches in AuAu

arXiv:1804.10024 (accepted by Phys. Rev. C)





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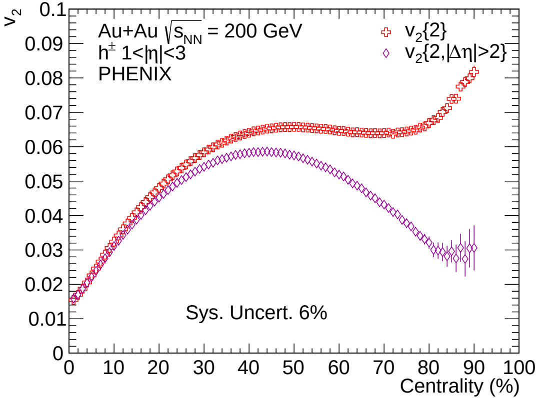

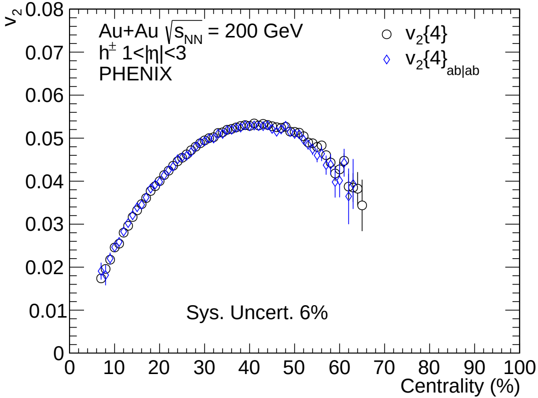

Large pseudorapidity separation

—Big difference for 2-particle (good)

—No difference for 4-particle (good)

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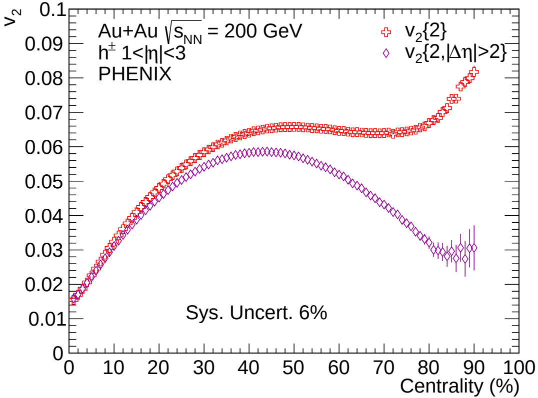

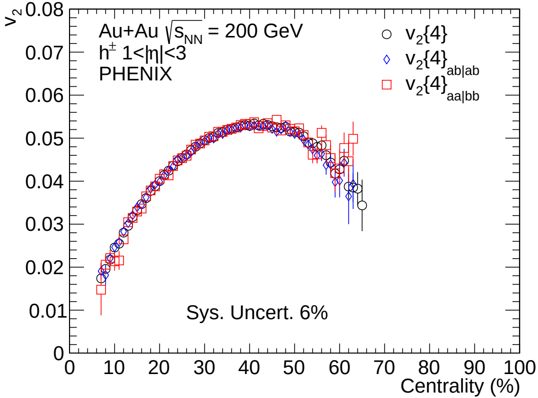

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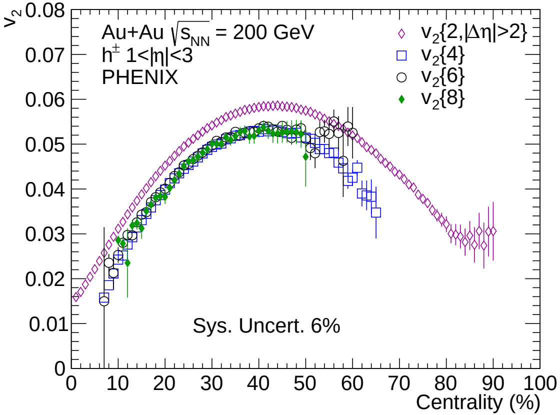


Favorable combinatorics

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

—Efficiently suppress few-particle correlations

Insights into fluctuations: “cumulant” $v_n\{k\}$ mixes different moments of v_n

—If Gaussian-ish fluctuations:

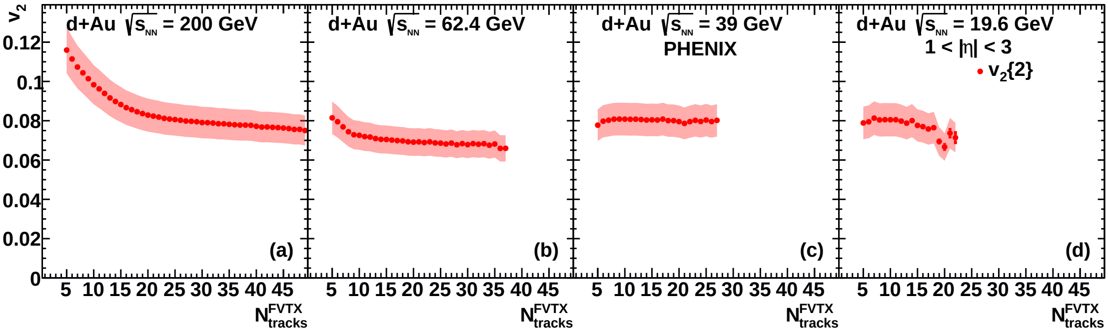
$$v_n\{2\} = (v_n^2 + \sigma^2)^{1/2}$$

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

d+Au beam energy scan

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

200 GeV   62.4 GeV   39 GeV   19.6 GeV



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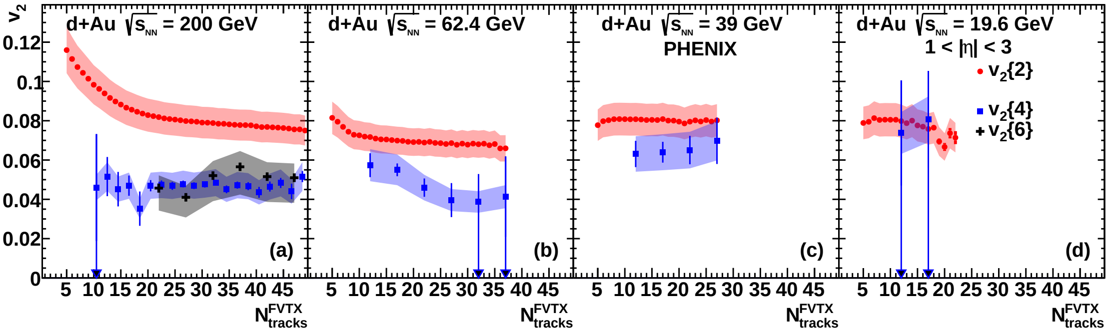


Measurement of $v_2\{6\}$ in d+Au at 200 GeV and $v_2\{4\}$ in d+Au at all energies

d+Au beam energy scan

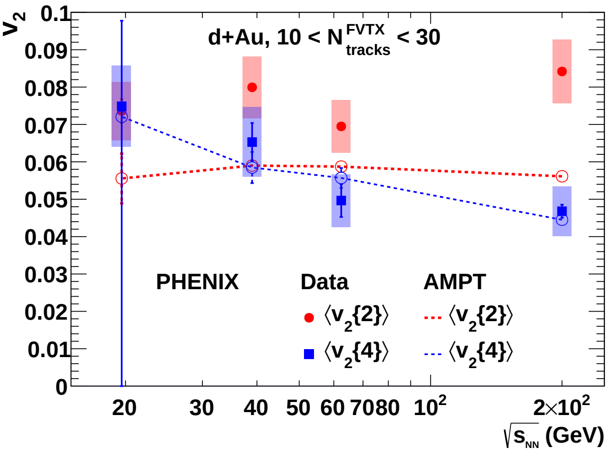
Phys. Rev. Lett. 120, 062302 (2018)

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

AMPT sees similar trend

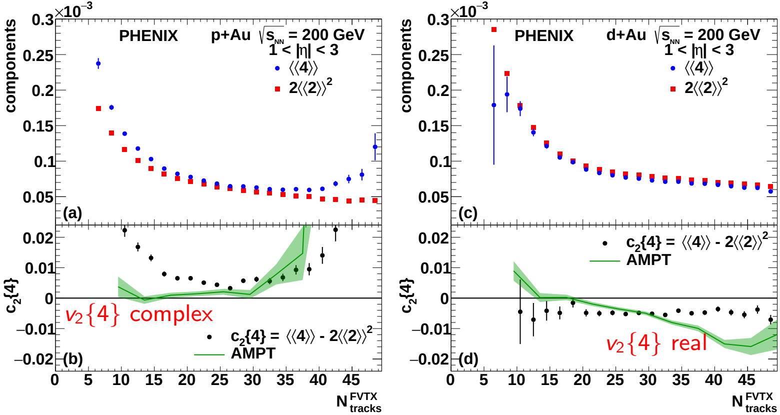
Fluctuations?

- $\langle v_n^2 \rangle \pm \sigma^2$ seems to completely fail here...



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

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



Fluctuations very different in p+Au compared to d+Au?

Back to basics (a brief excursion)

The (raw) moments of a probability distribution function $f(x)$:

$$\mu_n = \langle x^n \rangle \equiv \int_{-\infty}^{+\infty} x^n f(x) dx$$

The moment generating function:

$$M_x(t) \equiv \langle e^{tx} \rangle = \int_{-\infty}^{+\infty} e^{tx} f(x) dx = \int_{-\infty}^{+\infty} \sum_{n=0}^{\infty} \frac{t^n}{n!} x^n f(x) dx = \sum_{n=0}^{\infty} \mu_n \frac{t^n}{n!}$$

Moments from the generating function:

$$\mu_n = \left. \frac{d^n M_x(t)}{dt^n} \right|_{t=0}$$

Key point: the moment generating function uniquely describe $f(x)$

Back to basics (a brief excursion)

Can also uniquely describe $f(x)$ with the cumulant generating function:

$$K_x(t) \equiv \ln M_x(t) = \sum_{n=0}^{\infty} \kappa_n \frac{t^n}{n!}$$

Cumulants from the generating function:

$$\kappa_n = \left. \frac{d^n K_x(t)}{dt^n} \right|_{t=0}$$

Since $K_x(t) = \ln M_x(t)$, $M_x(t) = \exp(K_x(t))$, so

$$\mu_n = \left. \frac{d^n \exp(K_x(t))}{dt^n} \right|_{t=0}, \quad \kappa_n = \left. \frac{d^n \ln M_x(t)}{dt^n} \right|_{t=0}$$

End result: (details left as an exercise for the interested reader)

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

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

Back to basics (a brief excursion)

Evaluating the Bell polynomials gives

$$\begin{aligned}
\langle x \rangle &= \kappa_1 \\
\langle x^2 \rangle &= \kappa_2 + \kappa_1^2 \\
\langle x^3 \rangle &= \kappa_3 + 3\kappa_1\kappa_2 + \kappa_1^3 \\
\langle x^4 \rangle &= \kappa_4 + 4\kappa_1\kappa_3 + 3\kappa_2^2 + 6\kappa_1^2\kappa_2 + \kappa_1^4
\end{aligned}$$

One can tell by inspection (or derive explicitly) that κ_1 is the mean, κ_2 is the variance, etc.

Back to basics (a brief excursion)

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

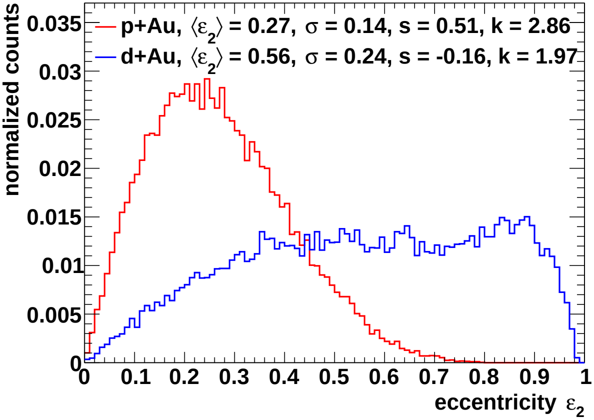
$$\left(\langle v_n^4\rangle = v_n^4 + 6v_n^2\sigma^2 + 3\sigma^4 + 4v_n\kappa_3 + \kappa_4\right)$$
$$-\left(2\langle v_n^2\rangle^2 = 2v_n^4 + 4v_n^2\sigma^2 + 2\sigma^4\right)$$
$$\rightarrow$$
$$\langle v_n^4\rangle - 2\langle v_n^2\rangle^2 = -v_n^4 + 2v_n^2\sigma^2 + \sigma^4 + 4v_n\kappa_3 + \kappa_4$$

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

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

So the fully general form is a bit more complicated than we tend to think...

Eccentricity distributions and cumulants



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

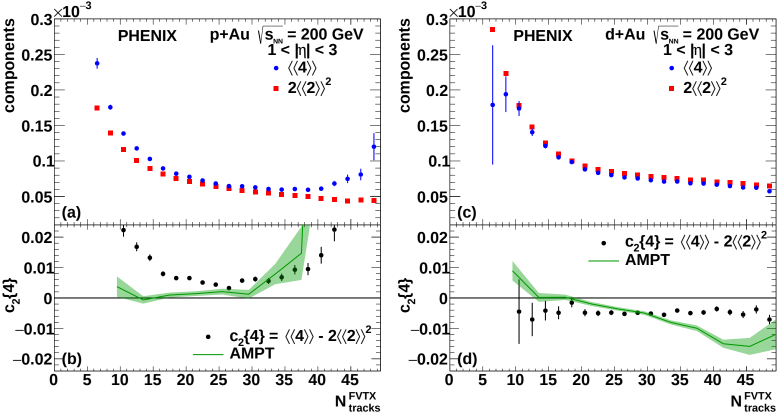
	p+Au	d+Au
ε_2^4	0.00531	0.0983
$2\varepsilon_2^2\sigma^2$	0.00277	0.0370
$4\varepsilon_2 s\sigma^3$	0.00147	-0.0053
$(k-2)\sigma^4$	0.00031	-0.0001

the variance brings $\varepsilon_2\{4\}$ down (this term gives the usual $\sqrt{v_2^2 - \sigma^2}$)

positive skew brings $\varepsilon_2\{4\}$ further down, negative skew brings it back up

kurtosis > 2 brings $\varepsilon_2\{4\}$ further down, kurtosis < 2 brings it back up
—recall Gaussian has kurtosis $= 3$

Eccentricity distributions and cumulants



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

Eccentricity fluctuations alone go a long way towards explaining this

Additional fluctuations in the (imperfect) translation of ε_2 to v_2?

Brief summary: small systems beam energy scan

Measurement of v_2 vs p_T for d+Au at 200, 62.4, 39, and 19.6 GeV
—Hydro describes higher two energies well, misses lower two energies

Measurement of v_2 vs η for d+Au at 200, 62.4, and 39 GeV
—Hydro theory at lower energies would be very useful

Measurement of $v_2\{6\}$ at 200 GeV and $v_2\{4\}$ at all four energies
—Nonflow should be combinatorially suppressed
—Important to take the highly non-trivial fluctuations seriously


"And now for something completely different."
Monty Python

Learning goals for CME

Helicity is the projection of the spin along the trajectory

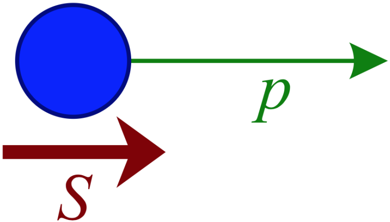
Chirality is kind of like helicity, but more fundamental

Parity (P) in 3 dimensions is the inversion of all spatial coordinates

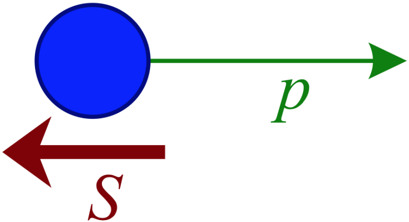
Charge-parity (CP) is parity and flipping the charges

We can study fundamental symmetries of QCD with heavy ion physics by searching for P- and CP-violation

Right-handed:



Left-handed:



Helicity is $\vec{s} \cdot \vec{p}$

—Right-handed: spin along momentum

—Left-handed: spin opposite to momentum

Chirality is an internal quantum number

—Same as helicity for massless particles

—Evolves with time for massive particles (Higgs)

Chirality

Helicity and chirality are P-odd, meaning they change sign under parity transformation

Any state can be written as the sum of the left and right components, i.e. $\psi = \psi_R + \psi_L$

A vector quantity is the sum of the chiral quantities, e.g. $J^\mu_V = J^\mu_R + J^\mu_L$

An axial quantity is the difference of the chiral quantities, e.g. $J^\mu_A = J^\mu_R - J^\mu_L$

Symmetry groups can also be represented this way, $G_R \times G_L = G_V \times G_A$

Chirality

Chiral symmetry and breaking

In general, there are three categories of symmetry breaking
–explicit: not actually present in the Lagrangian
–sponteous: present in the Lagrangian but lost in the equations of motion
–anomalous: present in the classical theory but lost in quantization

Chiral symmetry summary:

Symmetry	Status	Meaning or effect
$SU(N_f)_V$	Approximate	flavor symmetry, pseudo-Goldstone bosons
$SU(N_f)_A$	Spontaneously broken	98% of nucleon mass
$U(1)_V$	Exact	baryon conservation
$U(1)_A$	Anomalously broken	chiral anomaly

C, P, T, and CPT

C is charge conjugation
—Flip the sign of the charges

P is parity inversion
—Flip the spatial coordinates

T is time reversal
—Flip the time coordinate

CPT is do all three of these at the same time
—CPT theorem: any Lorentz invariant QFT is CPT invariant
—C, P, T can be broken alone or in pairs as long as CPT is preserved

Parity

What is parity?

In 3 space dimensions, parity is the simultaneous inversion of all three dimensions

$$P\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix}$$

Scalar quantities (e.g. mass, charge) are P-even

Vector quantities (e.g. momentum, electric field) are P-odd

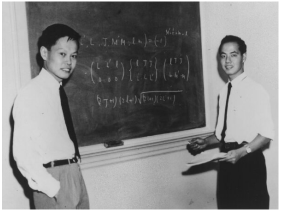
Pseudo-vector quantities (e.g. angular momentum, magnetic field) are P-even
$\vec{L} = \vec{r} \times \vec{p} \quad \rightarrow \quad \vec{L} = -\vec{r} \times -\vec{p}$

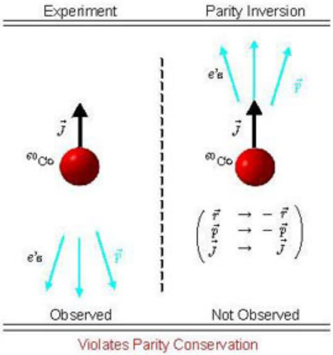
Parity was long believed to be conserved in all laws of physics

However...

P-violation in weak interactions

Proposed by T.D. Lee and C.N. Yang, Phys. Rev. 104, 254 (1956)
Discovered by C.S. Wu et. al., Phys. Rev. 105, 1314 (1957)





Electron emission from $^{60}\mathrm{Co} \to {}^{60}\mathrm{Ni} + e + \overline{\nu}_e$ was found to be anti-parallel to the nuclear spin—parity violation
Pauli was shocked and insisted the experiments be repeated

P- and CP-violation in strong interactions

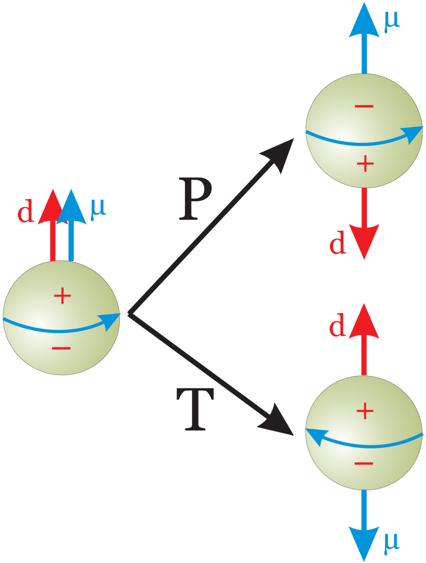
A non-zero neutron electric dipole moment (nEDM) violates parity

A non-zero nEDM also violates time reversal, by CPT theorem T-violation implies CP-violation

Measurements consistent with zero, strict upper limits (2.9×10^{-26} e-cm)

The observed absence is surprising because of "natural" CP-violating terms in the QCD Lagrangian

$$\mathcal{L} = -\frac{1}{4}F^{a}_{\mu\nu}F^{\mu\nu}_{a} - \frac{\theta g^2}{32\pi^2}F^{a}_{\mu\nu}\tilde{F}^{\mu\nu}_{a} + \overline{\psi}(i\not{D} - me^{i\theta\gamma_5})\psi$$



Topological charge and the QCD vacuum

Chern-Simons Current:

$$K^\mu = \frac{g^2}{32\pi^2}\varepsilon^{\mu\nu\alpha\beta}\left(A^a_\nu F^a_{\alpha\beta} - \frac{g}{3} f_{abc} A^a_\nu A^b_\alpha A^c_\beta\right)$$

Chern-Simons Number:

$$N_{CS} = \int d^3x\, K^0 \in \mathbb{Z}$$

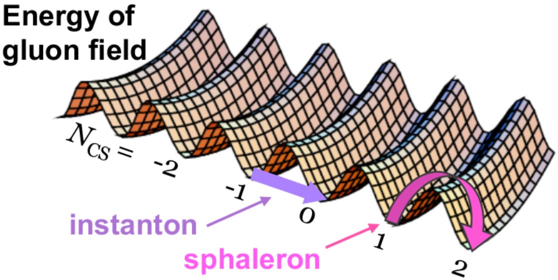
$U(1)_A$ anomaly:

$$\partial_\mu J^\mu_A = -\frac{g^2}{32\pi^2} F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a$$

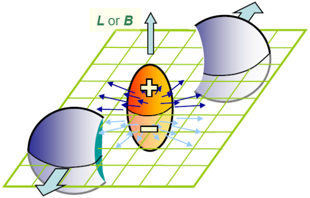
Topological charge:

$$\Delta N_{CS} = Q_w = \frac{g^2}{32\pi^2}\int d^4x\, F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a \in \mathbb{Z}$$

(Transitions are instantons and sphalerons)



The magnetic field in heavy ion collisions

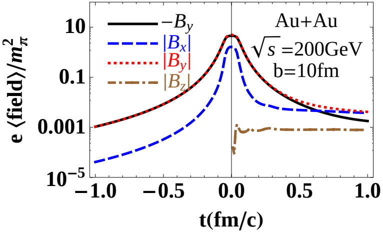


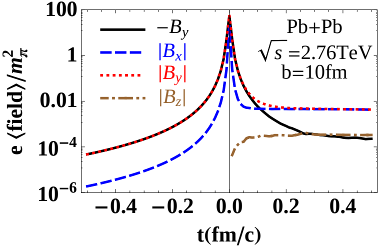
The spectating protons are just moving charged particles, so they make a B-field

The peak strength strength is roughly $10^{14\text{-}16}$ T—largest magnetic field in the known universe!

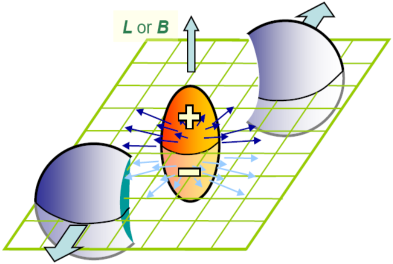
The spectators nominally define both the magnetic field and the geometry, so $\psi_B \approx \psi_{RP}$

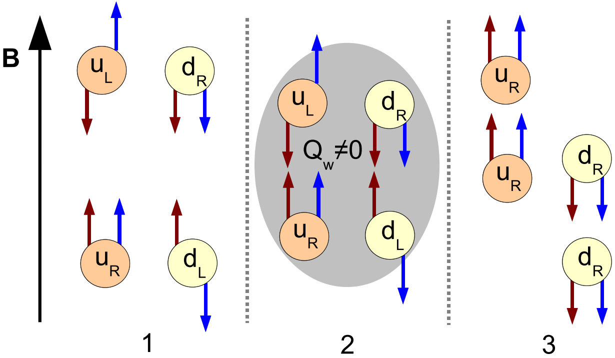
W.-T. Deng and X.-G. Huang
Phys. Rev. C 85, 044907 (2012)





The Chiral Magnetic Effect





Chiral imbalance induced by quantum anomaly
Alignment of spins by external magnetic field induces electric current of chiral quarks

$$\vec{J}_V = \frac{e^2}{2\pi^2}\mu_A \vec{B}$$

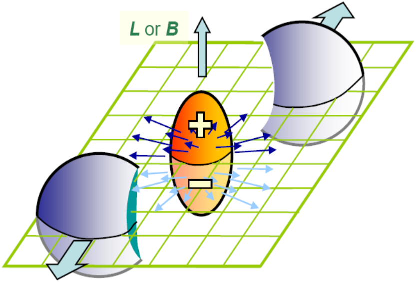
$\vec{J}$: P-odd, C-odd, CP-even

$\vec{B}$: P-even, C-odd, CP-odd

The CME correlator

The Fourier expansion from before but now including P-odd sine terms

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty}[v_n \cos n\varphi + a_n \sin n\varphi] \qquad a_n = \langle \sin n\varphi \rangle$$



Normally we ignore sine terms, but now we need them

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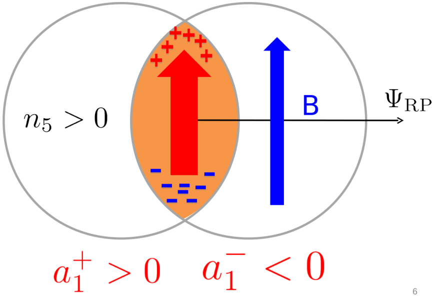

Normally we ignore sine terms, but now we need them

Positive particles go above the reaction plane $a_1^+ > 0$

Negative particles go below the reaction plane $a_1^- < 0$

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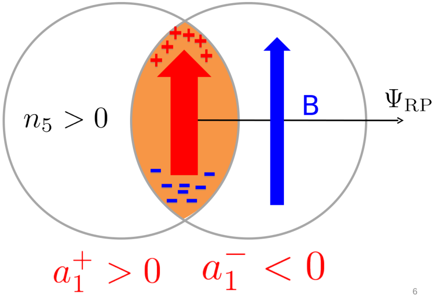

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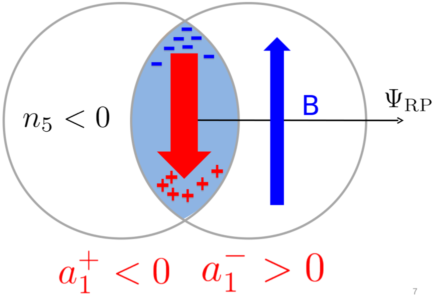

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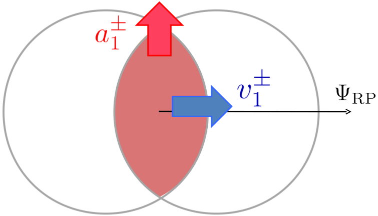
However...

Q_w fluctuates about $\langle Q_w \rangle = 0$, so $\langle a_1^\pm \rangle = 0$

The CME correlator

What to do? Measure 2 particle correlation with respect to the reaction plane (Voloshin, Phys. Rev. C 70 057901 (2004))

$$\begin{aligned}\langle \cos(\phi_a + \phi_b - 2\psi_{RP}) \rangle &= \langle \cos\varphi_a \cos\varphi_b \rangle - \langle \sin\varphi_a \sin\varphi_b \rangle \\ &= [\langle v_{1,a} v_{1,b} \rangle + B_{in}] - [\langle a_{1,a} a_{1,b} \rangle + B_{out}]\end{aligned}$$



Same sign $\langle a_1^{\pm} a_1^{\pm} \rangle > 0$

Opposite sign $\langle a_1^{\pm} a_1^{\mp} \rangle < 0$

Directed flow is rapidity-odd, $\langle v_1 v_1 \rangle \approx 0$

Optimistically, $\langle \cos(\phi_a + \phi_b - 2\psi_{RP}) \rangle = -\langle a_{1,a} a_{1,b} \rangle$

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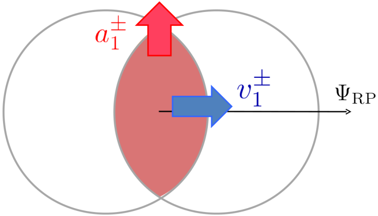

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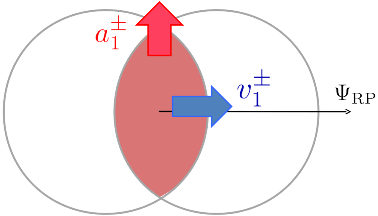

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Optimistically, $\langle \cos(\phi_a + \phi_b - 2\psi_{RP}) \rangle = -\langle a_{1,a} a_{1,b} \rangle$

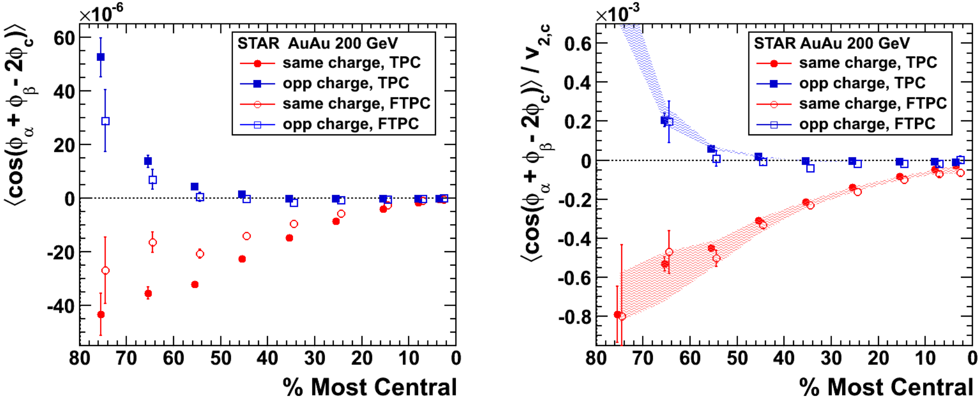
However...

RP dependent backgrounds remain

If dipole fluctuations, $\langle v_1 v_1 \rangle \neq 0$

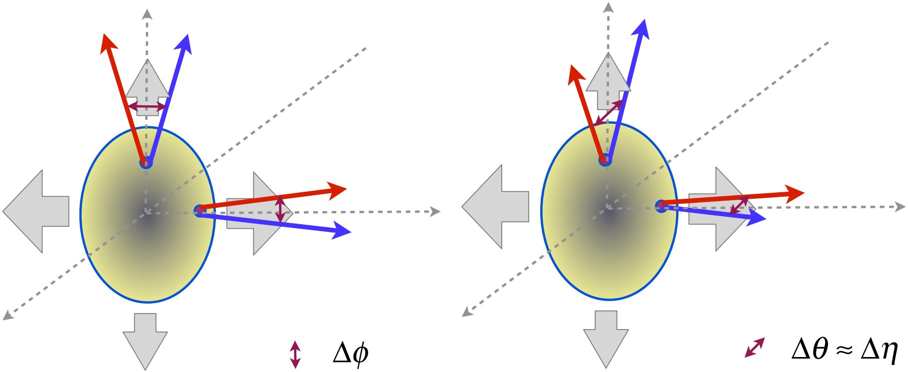
The first CME results (STAR)

STAR, Phys. Rev. C 81, 054908 (2010)



Strong negative correlation for same sign, consistent with CME expectation
No correlation of opposite sign

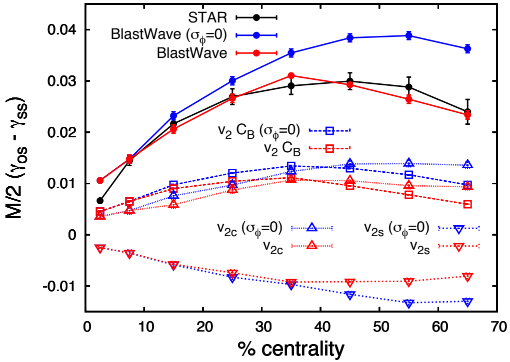
Backgrounds

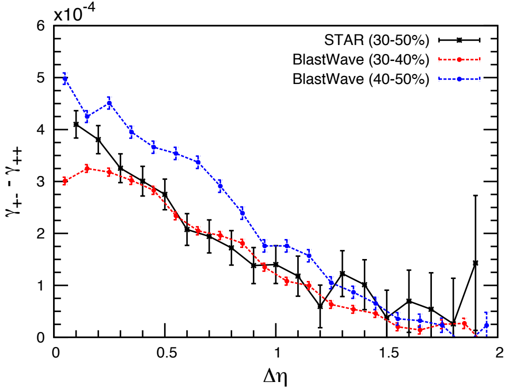


LCC: local charge conservation—charges are created in $\pm$ pairs at a single space-time point
Angle between pairs is collimated by the radial+anisotropic flow background
Simple and intuitive mechanism for generating charge-dependent angular correlations

Backgrounds

S. Schlichting and S. Pratt, Phys. Rev. C 83 014913 (2011)



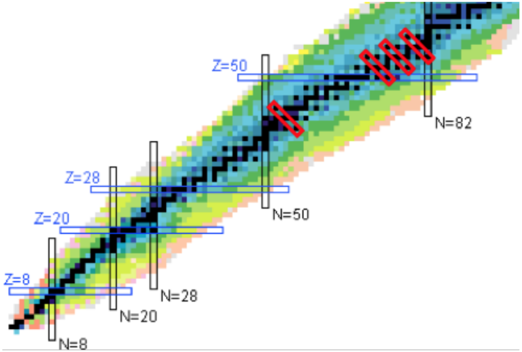


Construct a simple model of LCC+flow using the Blastwave model
Results show very good agreement with STAR CME correlator results (OS-SS)
However, the absence of OS correlation and the strong SS correlation is not explained in this (simple) model

Isobaric collisions

Why isobars?

- Different Z means different B-field (change signal)
- Same A means same multiplicity (fix background)
- Similar shape means similar v_2 (fix background)



Requirements $\Delta Z = 4$ and non-zero abundance

Low Z nucl	High Z nucl	B^2 ratio
$^{96}_{40}$Zr	$^{96}_{44}$Ru	1.21
$^{124}_{50}$Sn	$^{124}_{54}$Xe	1.17
$^{130}_{52}$Te	$^{130}_{56}$Ba	1.16
$^{136}_{54}$Xe	$^{136}_{58}$Ce	1.15

- Lighter pairs offer higher B^2 ratio (good)
- Heavier pairs offer higher multiplicity

Isobaric collisions

Nuclear structure is more important than previously thought in heavy ions

- Most nuclei are not spherical, and the deviations from sphericity can vary widely
- Ellipticity shape parameter β_2 affects the initial eccentricity ε_2 in heavy ion collisions and therefore the measured v_2
- Recent STAR results: v_2 much higher in ultra-central U+U compared to ultra-central Au+Au
- Deformation may also affect B-field

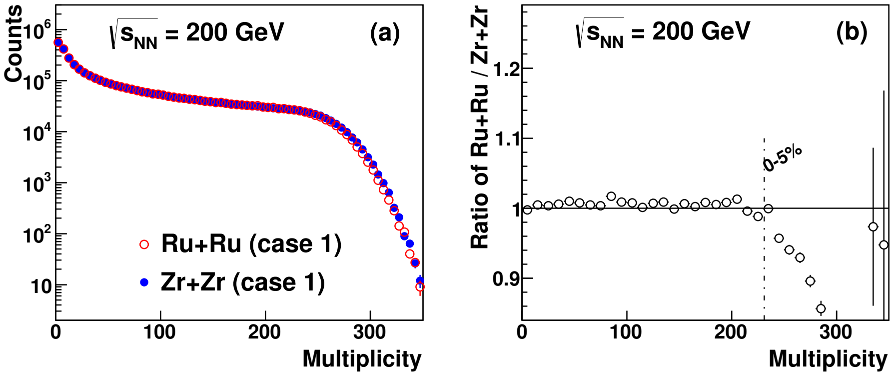
Possible problem: Zr/Ru are not spherical, may not have the same shape, shape parameters not especially well-known

- Case 1: $\beta_2[^{96}_{40}\mathrm{Zr}] = 0.080$, $\beta_2[^{96}_{44}\mathrm{Ru}] = 0.158$
- Case 2: $\beta_2[^{96}_{40}\mathrm{Zr}] = 0.217$, $\beta_2[^{96}_{44}\mathrm{Ru}] = 0.053$

Opportunity: measure v_2 in ultra-central Zr+Zr and Ru+Ru to determine relative β_2

Isobaric collisions

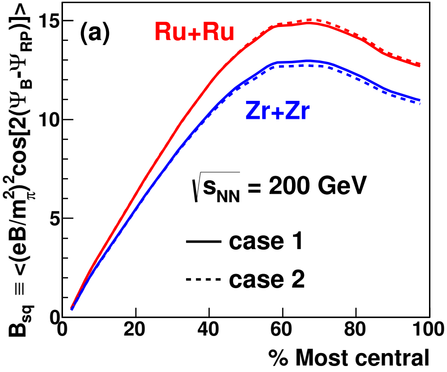
CME Task Force Report, arXiv:1608.00982

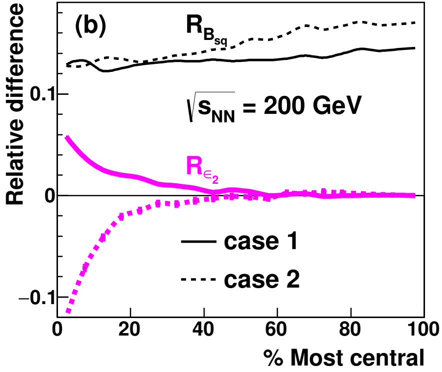


Possible problem: Zr/Ru are not spherical, may not have the same shape
Solution: for the most part this doesn't actually matter
Solution 1: Multiplicities are identical except for very central

Isobaric collisions

CME Task Force Report, arXiv:1608.00982

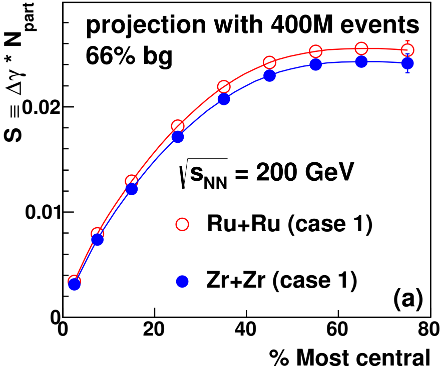


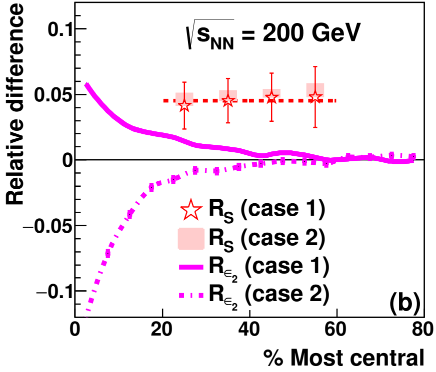


Possible problem: Zr/Ru are not spherical, may not have the same shape
Solution: for the most part this doesn't actually matter
Solution 2: B-field and eccentricity aren't so different

Isobaric collisions

CME Task Force Report, arXiv:1608.00982





Possible problem: Zr/Ru are not spherical, may not have the same shape
Solution: for the most part this doesn't actually matter
Solution 3: Expected signal difference stronger than differences in ε_2

Brief summary

Topological transitions in the QCD vacuum lead to P- and CP-violating effects

Such effects may be measurable in heavy ion physics

The measurements so far indicate significant background contamination

Isobaric collisions from 2018 will hopefully shed light on the issue

Final thoughts

Collisions of large nuclei create the quark gluon plasma, a state of matter that existed in the early universe

Collisions of small+large and small+small nuclei also appear to create the QGP, or at least something very similar to the matter created in collisions of large nuclei

Collisions of large nuclei create the largest magnetic field in the known universe

We hope to test fundamental symmetries of QCD using heavy ion physics

Final thoughts

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Collisions of large nuclei create the largest magnetic field in the known universe

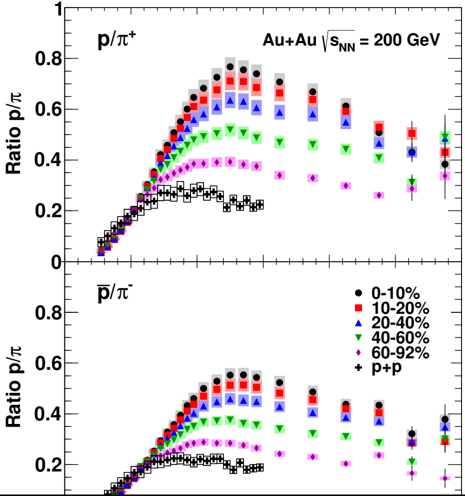
We hope to test fundamental symmetries of QCD using heavy ion physics

Thanks!

Additional material

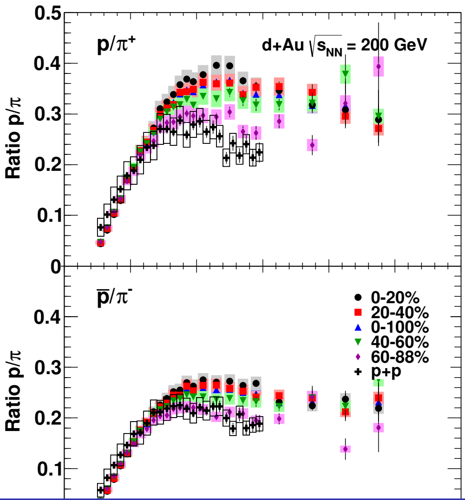
p/π ratios, revisited

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



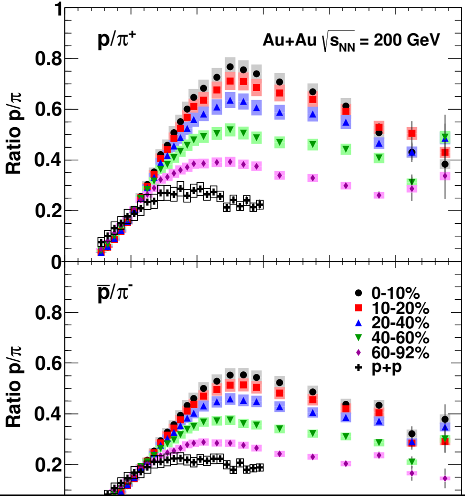
p/π ratios, revisited

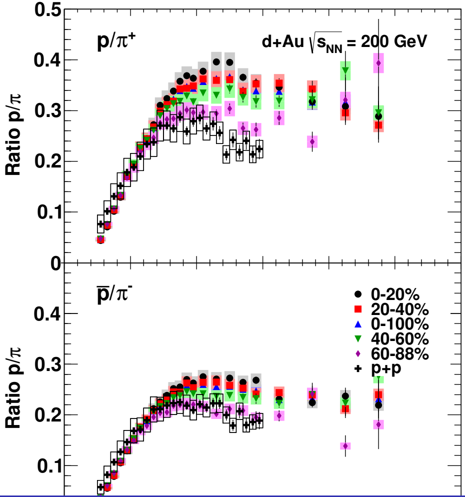
PHENIX, Phys. Rev. C 88, 024906 (2013)



p/π ratios, revisited

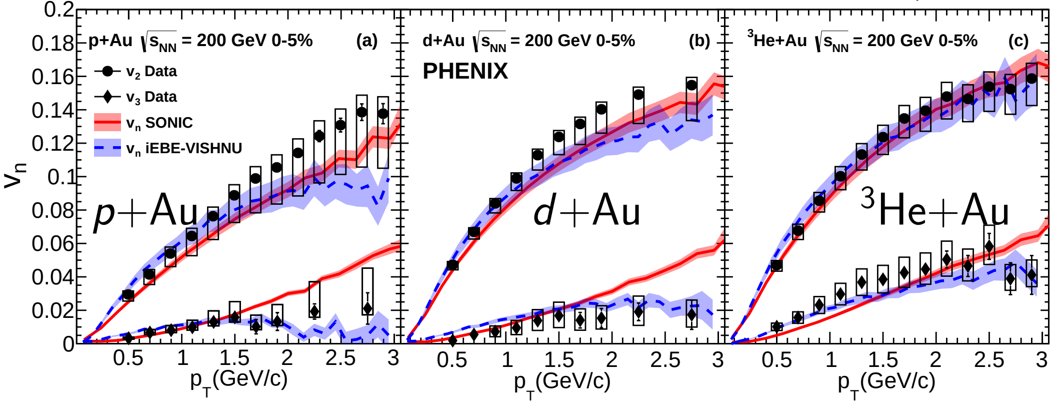
PHENIX, Phys. Rev. C 88, 024906 (2013)





Testing hydro by controlling system geometry

arXiv:1805.02973, in press (Nature Physics)

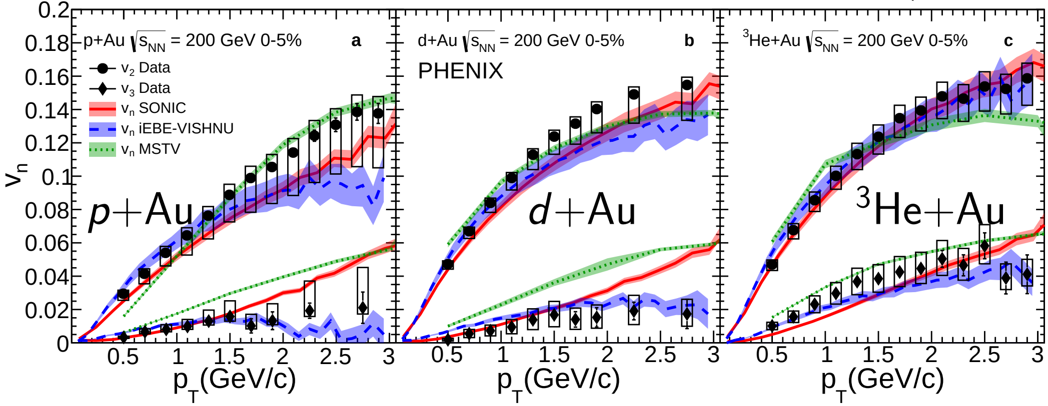


v_2 and v_3 vs p_T described very well by hydro in all three systems

—Strongly suggests QGP droplets in hydro evolution

Testing hydro by controlling system geometry

arXiv:1805.02973, in press (Nature Physics)



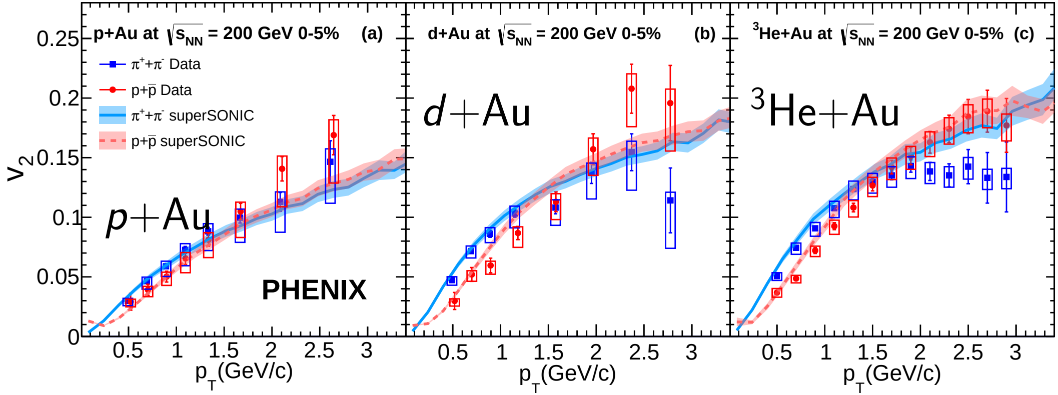
v_2 and v_3 vs p_T described very well by hydro in all three systems

—Strongly suggests QGP droplets in hydro evolution

Initial state model does good job for v_2 but misses strong geometry dependence of v_3

Small systems geometry scan

Phys. Rev. C 97, 064904 (2018)

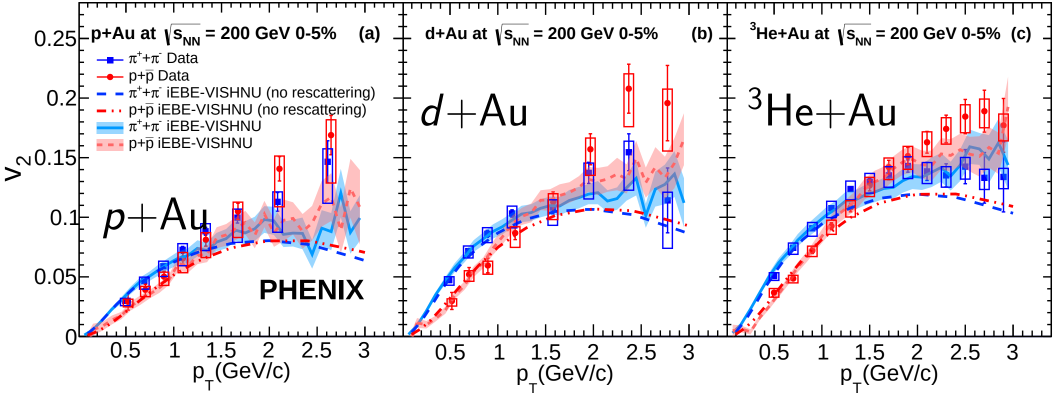


Identified particle v_2 vs p_T in p+Au, d+Au, and ^{3}He+Au

—Mass ordering well-described by hydro

Small systems geometry scan

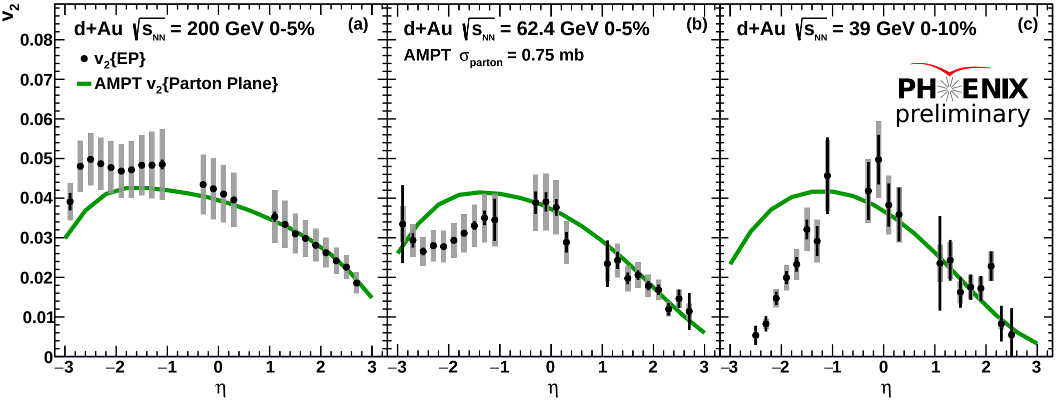
Phys. Rev. C 97, 064904 (2018)



Identified particle v_2 vs p_T in p+Au, d+Au, and ^{3}He+Au
—Mass ordering well-described by hydro

v_2 vs η, comparison with AMPT

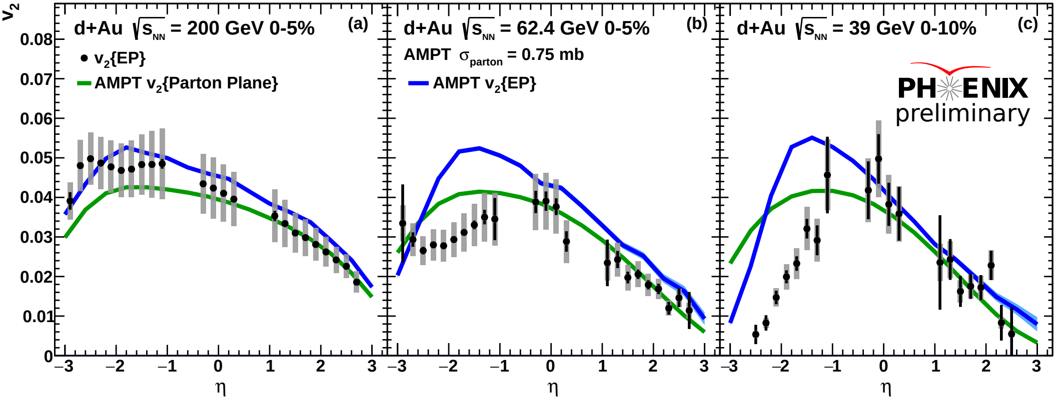
Phys. Rev. C 96, 064905 (2017)



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

v_2 vs η, comparison with AMPT

Phys. Rev. C 96, 064905 (2017)



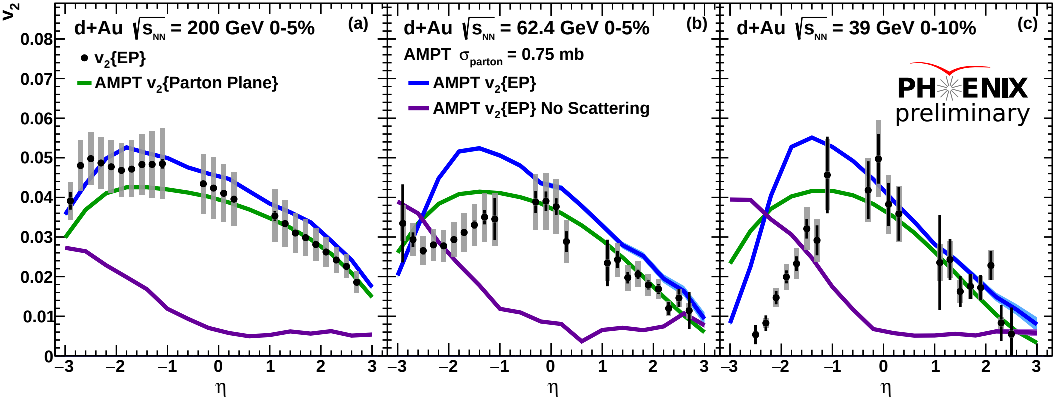
AMPT flow only agrees with mid and forward rapidity very well, misses backward rapidity

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

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

v_2 vs η, comparison with AMPT

Phys. Rev. C 96, 064905 (2017)



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

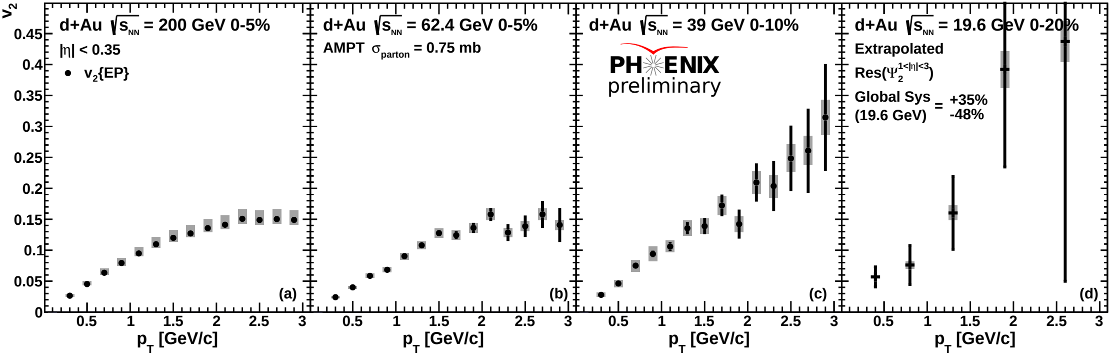
AMPT flow+non-flow is very similar at mid and forward

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

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

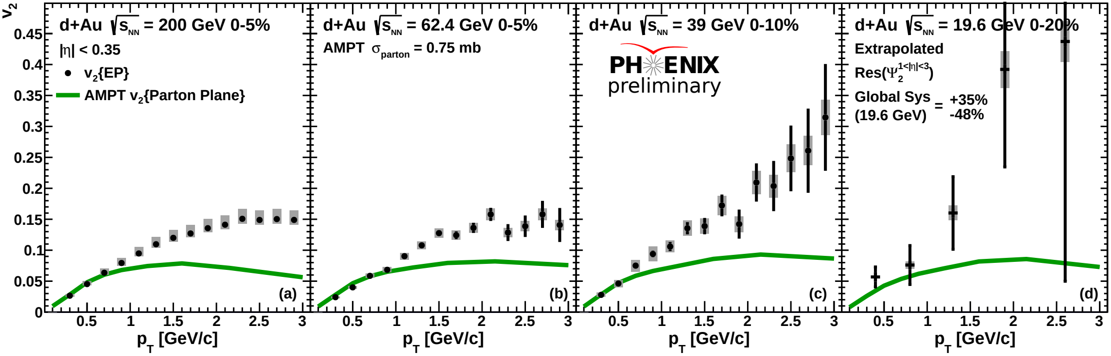
v_2 vs p_T, comparisons to AMPT

Phys. Rev. C 96, 064905 (2017)



v_2 vs p_T, comparisons to AMPT

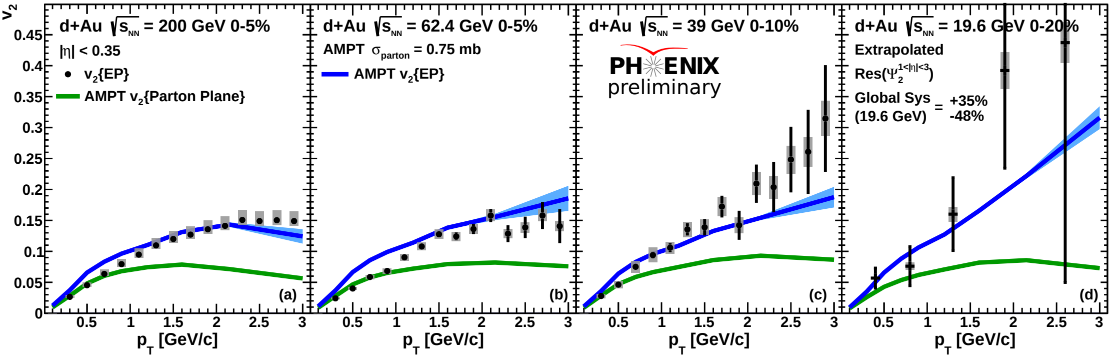
Phys. Rev. C 96, 064905 (2017)



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

v_2 vs p_T, comparisons to AMPT

Phys. Rev. C 96, 064905 (2017)



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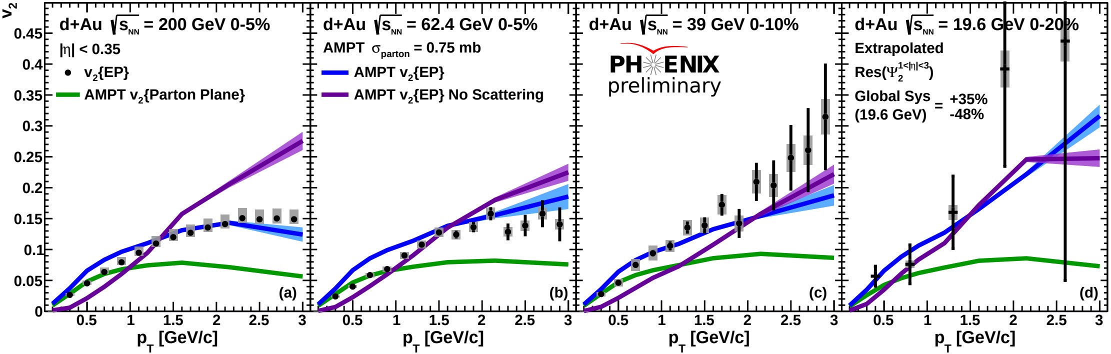
AMPT flow+non-flow shows reasonable agreement for all p_T and all energies

v_2 vs p_T, comparisons to AMPT

Phys. Rev. C 96, 064905 (2017)



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

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

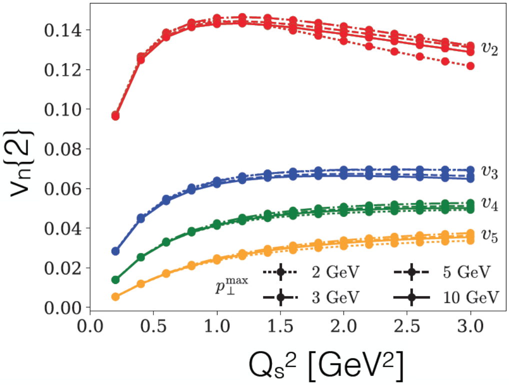
AMPT non-flow only far under-predicts for low p_T, too high for high p_T

Intermission

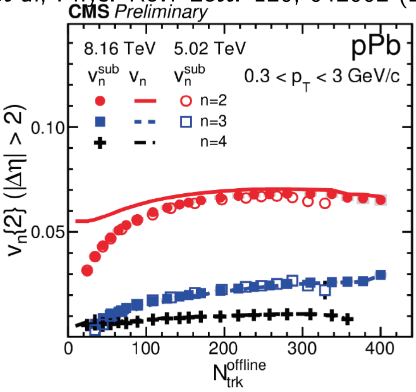
The CGC strikes back?

CGC results on small systems

K. Dusling et al, Phys. Rev. Lett. 120, 042002 (2018)



Dusling, MM, Venugopalan PRL 120 (2018)



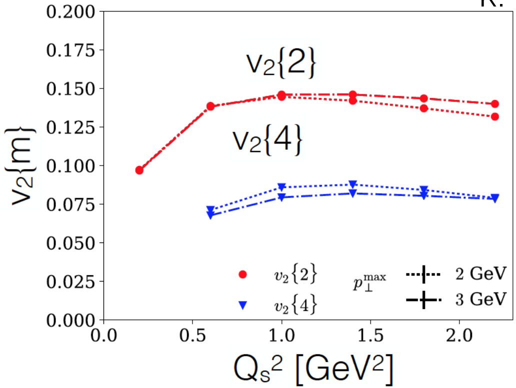
CMS-PAS-HIN-16-022

Can qualitatively reproduce harmonic ordering

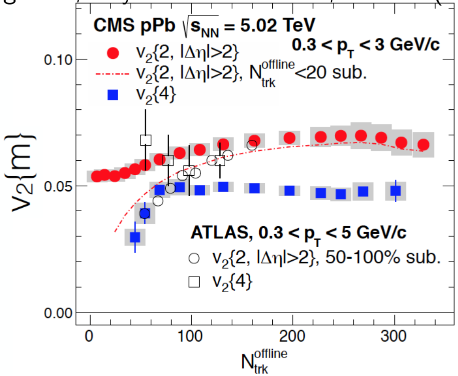
Off from data by a factor of 2 to 3

CGC results on small systems

K. Dusling et al, Phys. Rev. Lett. 120, 042002 (2018)



Dusling, MM, Venugopalan PRL 120 (2018)



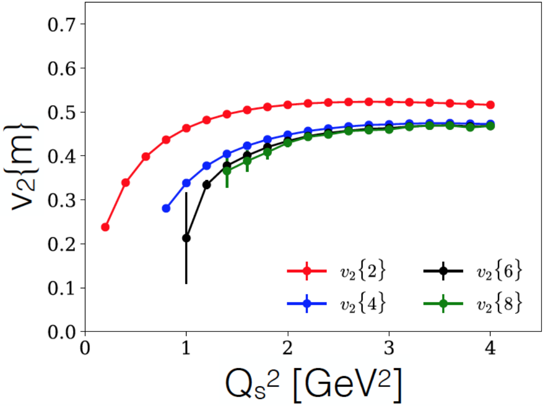
CMS PLB 724 (2013) 213

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

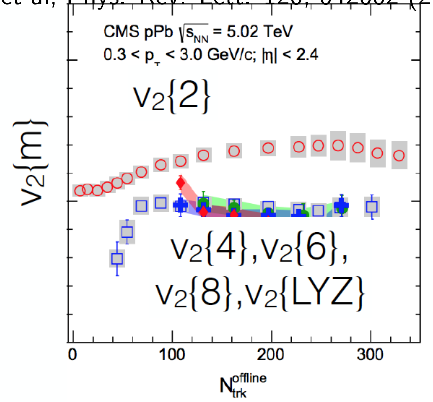
Disagreement with data by a factor of 2, but qualitative features match

CGC results on small systems

K. Dusling et al, Phys. Rev. Lett. 120, 042002 (2018)



Dusling, MM, Venugopalan PRL 120 (2018)



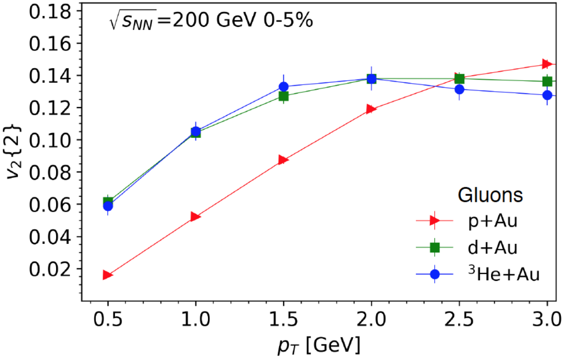
CMS PRL 115 (2015) 012301

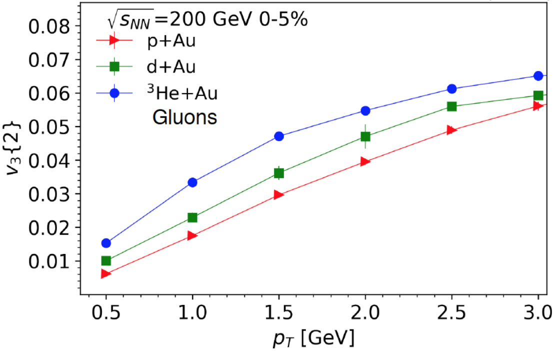
Abelian calculations can produce $v_2\{2\}$, $v_2\{4\}$, $v_2\{6\}$, $v_2\{8\}$

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

CGC results on small systems

M. Mace et al, Phys. Rev. Lett. 121, 052301 (2018)

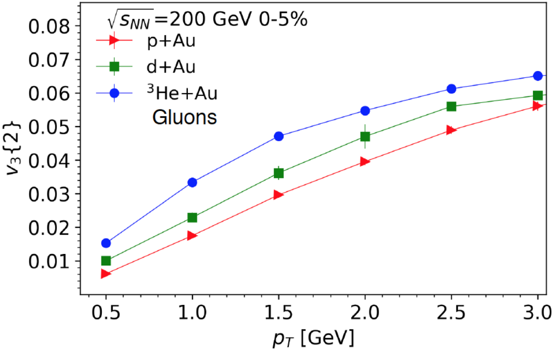


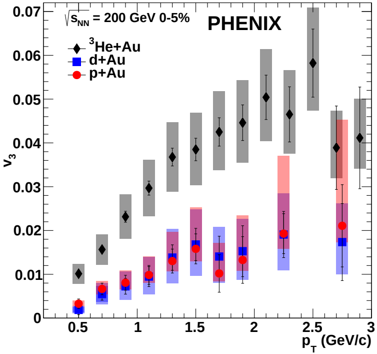


New (and somewhat controversial): v_2 and v_3 for small systems

CGC results on small systems

M. Mace et al, Phys. Rev. Lett. 121, 052301 (2018)





New (and somewhat controversial): v_2 and v_3 for small systems

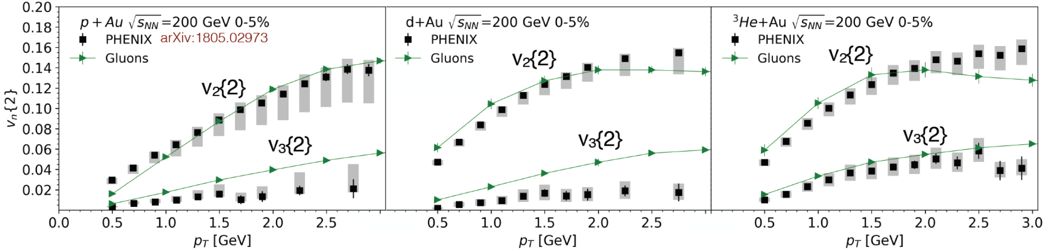
v_3 ordering is wrong

—CGC: p+Au $<$ d+Au $<$ ^{3}He+Au

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

CGC results on small systems

M. Mace et al, Phys. Rev. Lett. 121, 052301 (2018)



v_2 qualitatively right, quantitatively iffy

v_3 qualitatively iffy

Brief summary: the CGC strikes back?

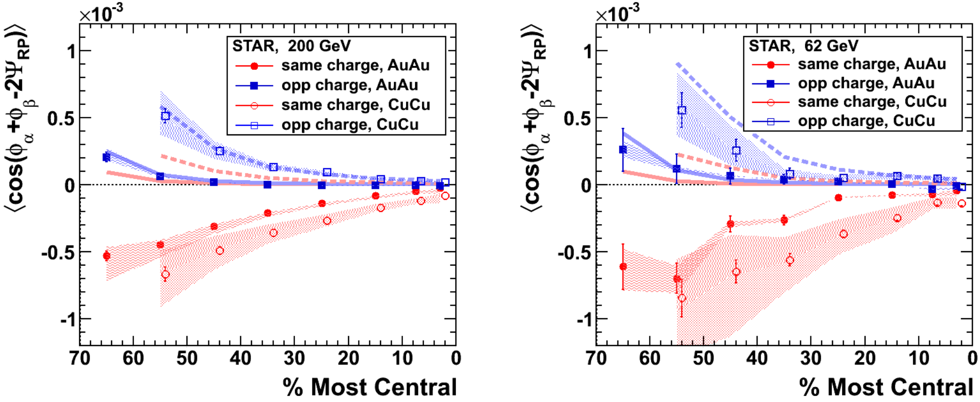
CGC calculations now in some quantitative with RHIC data, but that means the LHC data needs to be revisited

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

v_n and multiplicity distribution may provide additional discriminating power

The first CME results (STAR)

STAR, Phys. Rev. C 81, 054908 (2010)



Strong negative correlation for same sign in both Au+Au and Cu+Cu

Positive correlation of opposite sign for Cu+Cu

—Maybe the medium is small enough to preserve the correlation?