Tuning the shape of the fireball with heavy-ion collisions on polarized deutrons

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AGH

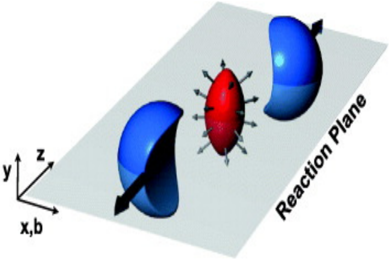
work with Wojciech Broniowski PRL 121 (2018) 202301 [arXiv:1808.09840]

NCN : 2015/17/B/ST2/00101

Collectivity - Collective response to initial geometry asymmetry in the transverse plane at finite impact parameter

Glauber model, KLN model, IP-Glasma

eccentricity - $\epsilon_2 = -\frac{\int dxdy(x^2-y^2)\rho(x,y)}{\int dxdy(x^2+y^2)\rho(x,y)}$



Snellings 2011

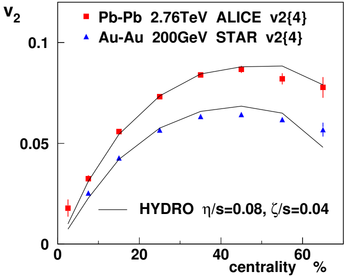
larger gradient and stronger flow in-plane - $v_2 > 0$ - **elliptic flow**

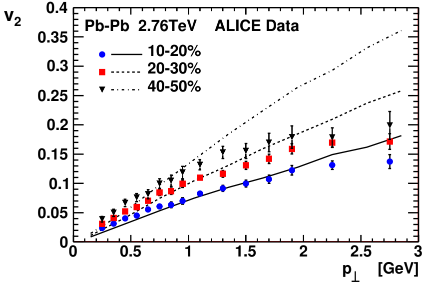
$$\frac{dN}{d\phi} \propto 1 + 2v_2 cos(2\phi)$$

$\epsilon_2 + \mathrm{HYDRO\ RESPONSE} \longrightarrow \mathrm{v}_2$ (Ollitrault 1992)

Event Plane (Reaction plane) must be reconstructed in each event

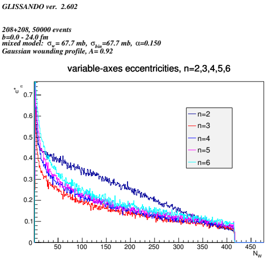
Collective flow observed in A+A collisions





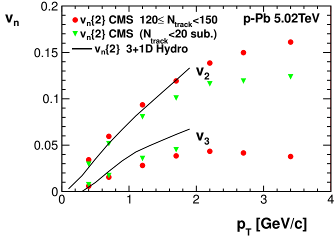
initial shape asymmetry transformed into flow asymmetry

strong indication of collective behavior in A+A collisions



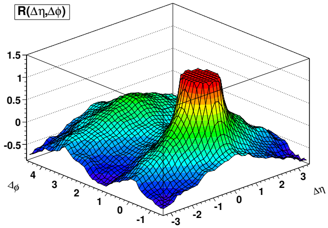
Small systems - Elliptic and triangular flow in p-Pb

Hydro consistent with data



PB, W.Broniowski, G. Torrieri arXiv:1306.5442; G.Y. Qin, B. Müller 1306.3439; I. Kozlov et al. 1405.3976; A. Bzdak et al. 1304.34003, . . .

Hydro generates the ridge



Werner, Karpenko, Pierog, 1011.0375

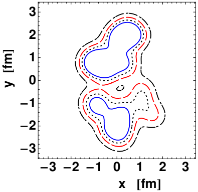
- v_2, v_3 consistent with hydro

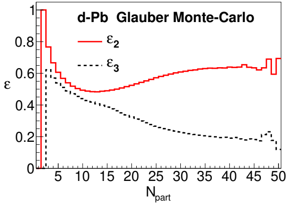
$v_{2,3}$ - hydro response to initial deformation !

Geometry control in small systems – use deformed projectile

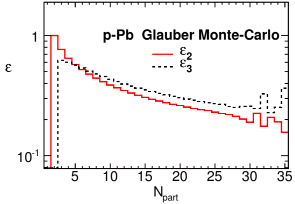
deuteron projectile

intrinsic deformation dominates over fluctuations





proton projectile

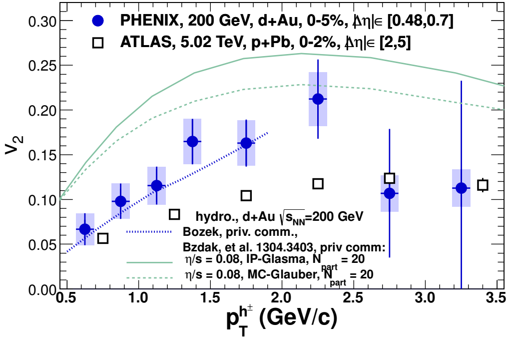


large eccentricity - large flow component — $v_2(dA) > v_2(pA)$

Controled initial conditions in small systems

(PB 1112.0915)

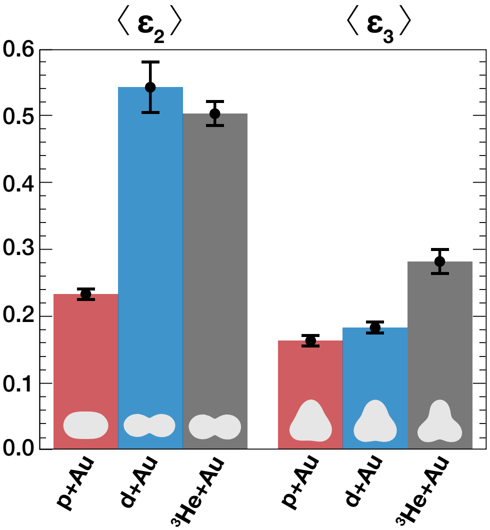
Elliptic and triangular flow in d-Au

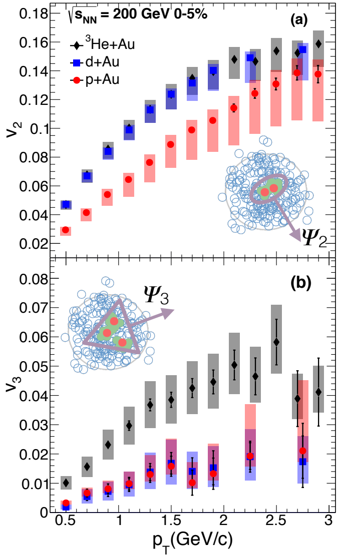


Predictions for d+A qualitatively and **quantitatively** confirmed by experiment

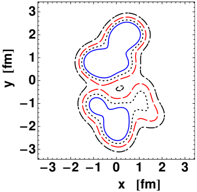
Flow hierarchy in small systems

[PHENIX, arXiv:1805.02973]



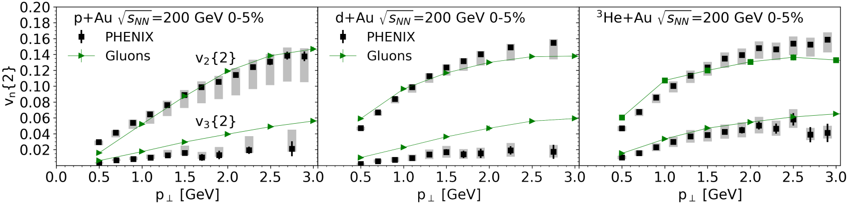


Color Glass Condensate



independent sources in d+A.
v_2 in d+A would be smaller than in p+A,
contrary to experiment.

MSTV: high multiplicity events have larger saturation scales and specific orientation of the deuteron, with one nucleon behind the other
[Mace, Skokov, Tribedy, Venugopalan, PRL 121 (2018) 052301 (1805.09342)]

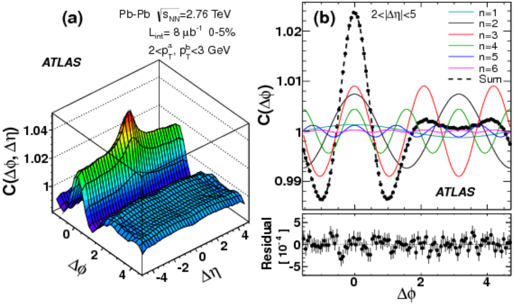


Questioned in [Nagle, Zajc, arXiv:1808.01276] → controversy

Flow observation - two-particle correlations in relative azimuthal angle

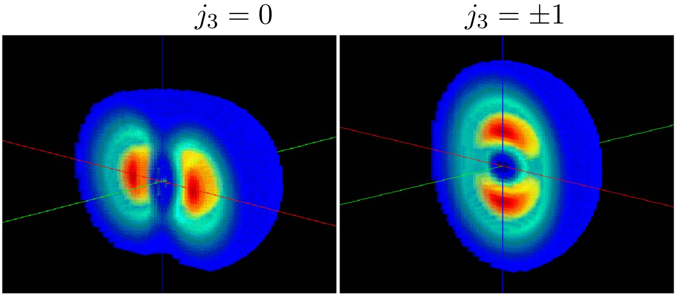
$$C(\Delta\phi) \propto \int d\phi_1 d\phi_2 \delta(\phi_1 + \Delta\phi - \phi_2) \frac{dN}{d\phi_1 d\phi_2}$$
$$\propto 1 + 2v_1^2 \cos(\Delta\phi) + 2v_2^2 \cos(2\Delta\phi) + 2v_3^2 \cos(3\Delta\phi) + \dots$$

cummulant method



non-flow (e.g. initial state) correlations important at low multiplicity !

Deuteron



Garcon, Van Orden : arXiV: nucl-th/0102049

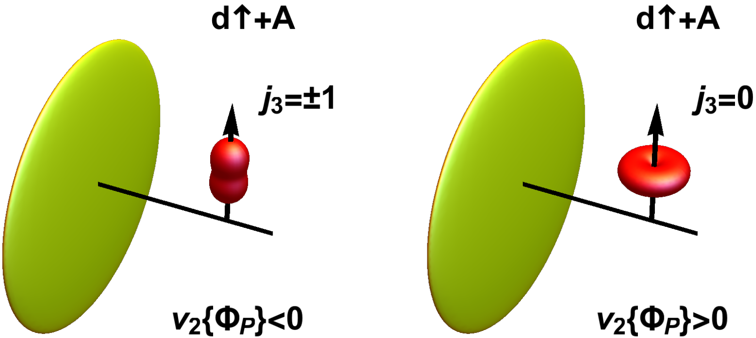
- $J^P = 1^+$, can be polarized
- predominantly $^3S_1$-wave
- small ($\sim 5\%$) $^3D_1$-wave admixture (deformed)

$^{2S+1}L_j$ notation

Collision with a polarized deuteron

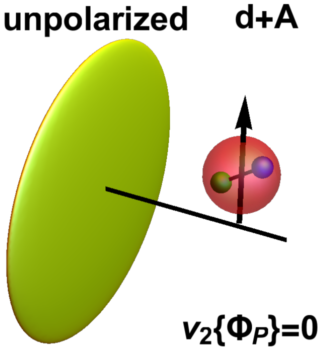
Motivation: collectivity vs CGC dispute

PB, W. Broniowski PRL 121 (2018) 202301



Collision with a polarized deuteron

Motivation: collectivity vs CGC dispute



Wave function

$$|\Psi(r;j_3)\rangle = U(r)|j=1,j_3,L=0,S=1\rangle + V(r)|j=1,j_3,L=2,S=1\rangle$$

Explicitly, with the Clebsch-Gordan decomposition onto states $|LL_3\rangle|SS_3\rangle$,

$$|\Psi(r;1)\rangle = U(r)|00\rangle|11\rangle + V(r)\left[\sqrt{\tfrac{3}{5}}|22\rangle|1\,{-1}\rangle - \sqrt{\tfrac{3}{10}}|21\rangle|10\rangle + \sqrt{\tfrac{1}{10}}|20\rangle|11\rangle\right]$$

$$\dots$$

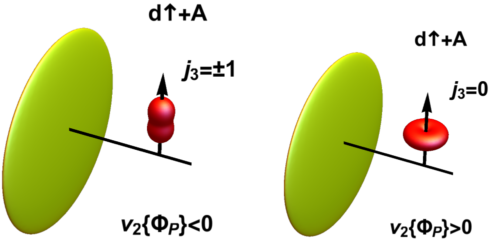
Orthonormality of the spin parts yields

$$|\Psi(r,\theta,\phi;\pm1)|^2 = \tfrac{1}{16\pi}\left[4U(r)^2 - 2\sqrt{2}\left(1-3\cos^2\theta\right)U(r)V(r) + \left(5-3\cos^2\theta\right)V(r)^2\right]$$

$$|\Psi(r,\theta,\phi;0)|^2 = \tfrac{1}{8\pi}\left[2U(r)^2 + 2\sqrt{2}\left(1-3\cos^2\theta\right)U(r)V(r) + \left(1+3\cos^2\theta\right)V(r)^2\right]$$

...the $U(r)V(r)$ terms are not so small!

Eccentricity with respect to a fixed axis at Φ_P

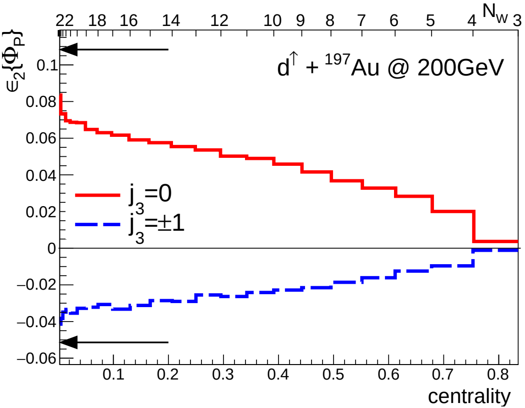


$$\epsilon_2^{|\Psi|^2_{j_3=0}}\{\Phi_P\} = \frac{\int d^3r\, r^2 \{\frac{2\sqrt{2}}{5}U(r)V(r) - \frac{1}{5}V(r)^2\}}{\int d^3r\, r^2\{\frac{2}{3}U(r)^2 - \frac{2\sqrt{2}}{15}U(r)V(r) + \frac{11}{15}V(r)^2\}} \simeq 0.11$$

$$\epsilon_2^{|\Psi|^2_{j_3=\pm 1}}\{\Phi_P\} \simeq -0.47\epsilon_2^{|\Psi|^2_{j_3=0}}\{\Phi_P\} \simeq -0.05$$

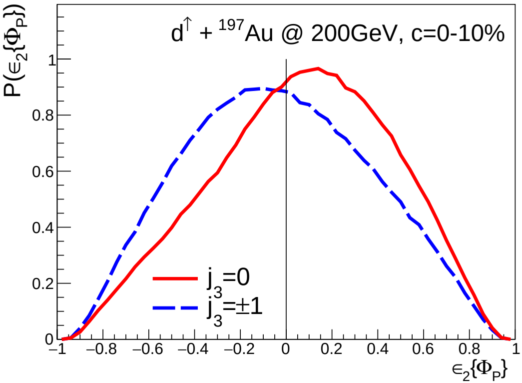
Ellipticity of the fireball relative to polarization axis

Monte Carlo Glauber model d+Au



$\sim$30% reduction compared to $\epsilon_2^{|\Psi|^2}$ (nucleons from Au)

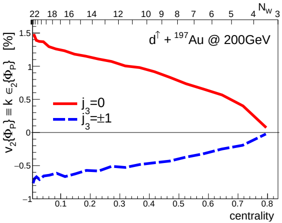
Distribution of the ellipticity of the fireball (most central)



PREDICTIONS - v_2 relative to polarization axis

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos\left[2(\phi - \Phi_P)\right]$$

$$v_2 \simeq k\epsilon_2, \quad k \sim 0.2$$



For $j = 1$ nuclei, the *tensor polarization* is

$$P_{zz} = n(1) + n(-1) - 2n(0)$$

$$v_2\{\Phi_P\} \simeq k\, \epsilon_2^{j_3=\pm 1}\{\Phi_P\} P_{zz}$$

$$-0.5\% \lesssim v_2\{\Phi_P\} \lesssim 1\%$$

One-particle distribution - can be measured precisely !

Fixed target experiments - easier to polarize

Relation of $\epsilon_2\{\Phi_P\}$ to quadrupole moment Q_2

Quadrupole moment:

$$Q_2 = \left\langle r^2 \sqrt{\frac{16\pi}{5}} Y_{20}(\Omega) \right\rangle = 2\langle z^2 - x^2 \rangle$$

$$\epsilon_2\{\Phi_P\} \equiv -\frac{\langle z^2 - x^2 \rangle}{\langle z^2 + x^2 \rangle} = -\frac{\langle z^2 - x^2 \rangle}{\langle \frac{2}{3}(z^2 + 2x^2) + \frac{1}{3}(z^2 - x^2) \rangle} = -\frac{3Q_2}{4\langle r^2 \rangle + Q_2}$$

Wigner-Eckart theorem (Q_2 is a rank-2 tensor):

$$\langle j j_3 | \hat{Q}_{20} | j j_3 \rangle = \langle j j_3 2 0 | j j_3 \rangle \langle j || \hat{Q}_2 || j \rangle$$

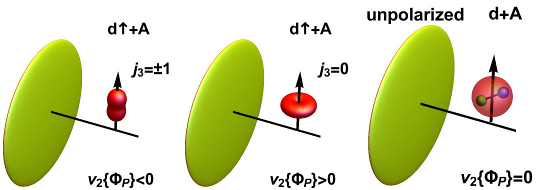
The lowest possible j is 1 (no effect for ^{3}He or tritium, $j = \frac{1}{2}$)

Ellipticity estimates based on nuclear data

	j	j_3	$\langle r^2\rangle^{1/2}$ [fm]	Q_2 [fm^2]	$\epsilon_2^{\|\Psi\|^2}\{\Phi_P\}$ [%]
d	1	± 1	2.14	0.28	~ -5
		0		$\times(-2)$	~ 10
^{7}Li	$\frac{3}{2}$	$\pm\frac{3}{2}$	2.4	~ -4	~ 60
		$\pm\frac{1}{2}$		$\times(-1)$	~ -40
^{9}Be	$\frac{3}{2}$	$\pm\frac{3}{2}$	2.5	~ -5	~ -50
		$\pm\frac{1}{2}$		$\times(-1)$	~ 75

Conclusions

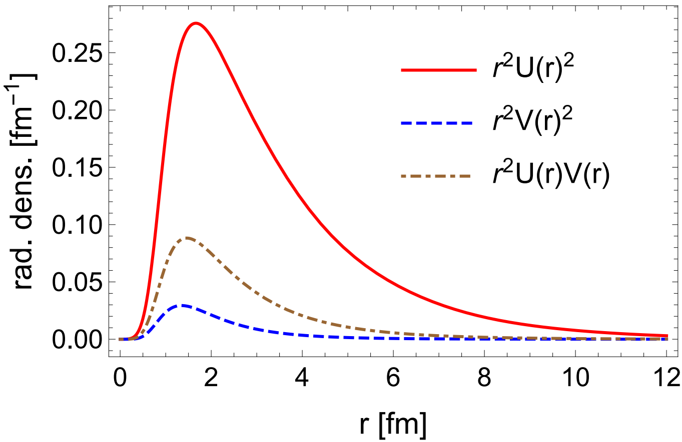
- **collisions with polarized deuterons**
  -new observable sensitive to collectivity



- Other opportunities:

  1. Hard probes (jets, photons, heavy flavor mesons) relative to Φ_P
  2. Interferometry correlations relative to Φ_P
  3. Other polarized (small) nuclei with $j \geq 1$

Reid 93


0.25
0.20
0.15
0.10
0.05
0.00
rad. dens. [fm^{-1}]
0
2
4
6
8
10
12
r [fm]
$r^2U(r)^2$
$r^2V(r)^2$
$r^2U(r)V(r)$