Initial deformation of a QGP droplet from collisions with polarized deuterons

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Excited QCD 19, Schladming, 30.01-3.02,19

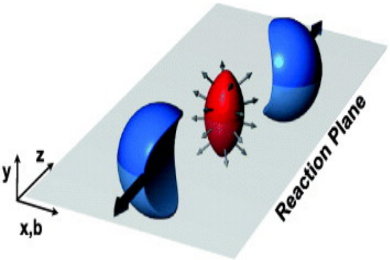
details: Piotr Bożek and WB: PRL 121 (2018) 202301 [arXiv:1808.09840]

2015/19/B/ST2/00937
NATIONAL SCIENCE CENTRE POLAND

Collectivity

Collective response to initial geometry

asymmetry in the transverse plane (Glauber model, KLN model, IP-Glasma)



[Snellings 2011]

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

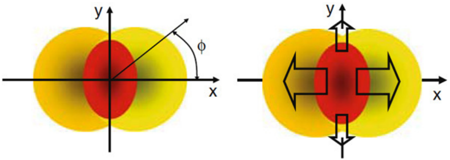
elliptic flow: $\frac{dN}{d\phi} \propto 1 + 2v_2 \cos(2\phi)$

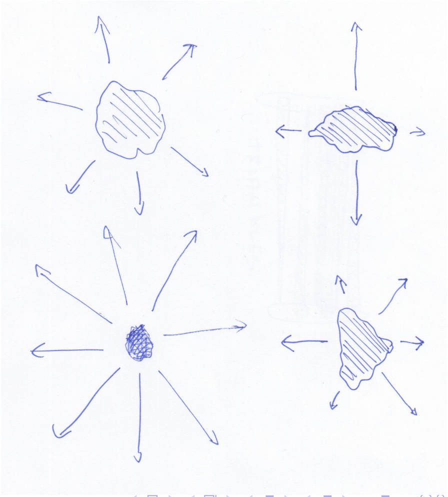
$\epsilon_2 + \text{hydro response} \to v_2$ [Ollitrault 1992]
larger gradient and stronger flow in-plane $\to v_2 > 0$
event plane (reaction plane) must be reconstructed in each event

Shape-flow transmutation

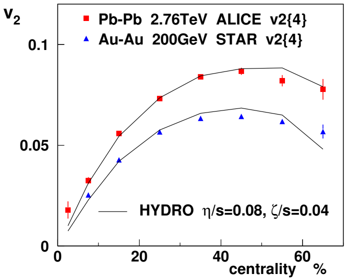
[Ollitrault '92 ... Miller, Snellings, 2001 ...]

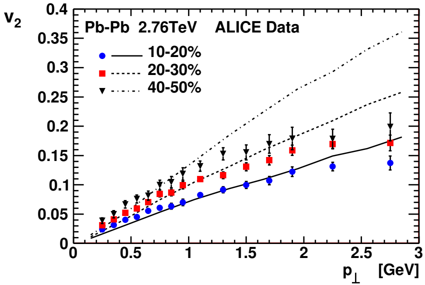
Collective response to geometry and fluctuations
many particles, final/intermediate-state interactions, generation of flow





Collective flow observed in A+A collisions



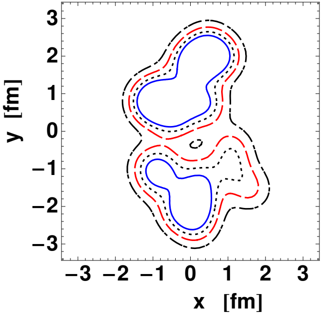


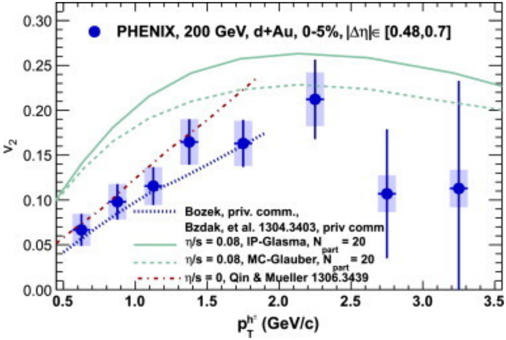
initial shape asymmetry transformed into flow asymmetry
strong indication of collective behavior in A+A collisions

Small systems

d+A

"small" systems [Bożek 2011]



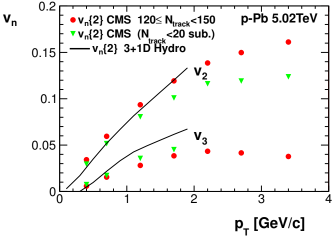


large deformation in $d \to$ large eccentricity of geometry

$\to$ large elliptic flow

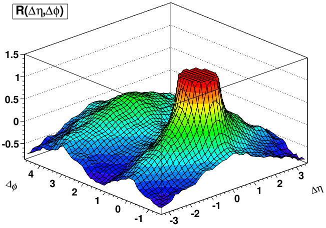
Elliptic and triangular flow in p-Pb

Hydro consistent with data



PB, WB, Torrieri 2013, Qin, Müller 2013, Bzdak et al. 2013, I. Kozlov et al. 2014, . . .

Hydro generates the ridge



[Werner, Karpenko, Pierog 2011]

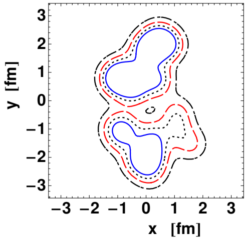
- v_2, v_3 consistent with hydro

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

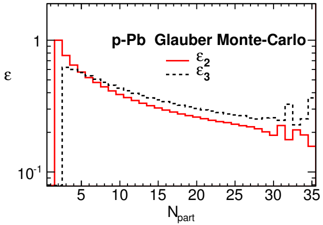
Geometry control in small systems

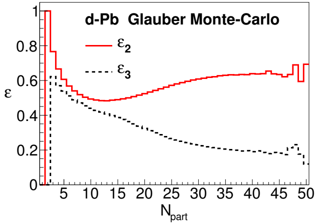
deuteron:

intrinsic deformation > fluctuations



proton:

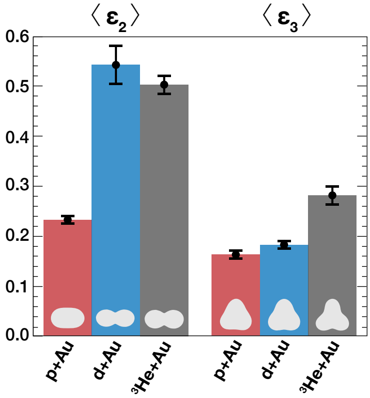


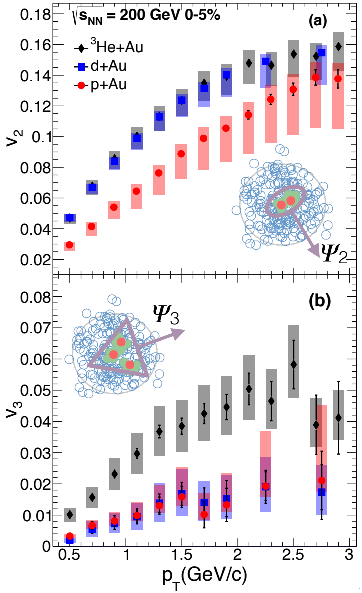


large eccentricity - large flow component — $v_2(dA) > v_2(pA)$

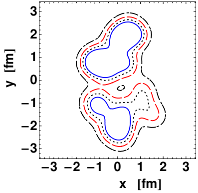
Flow hierarchy in small systems

[PHENIX, 2018]





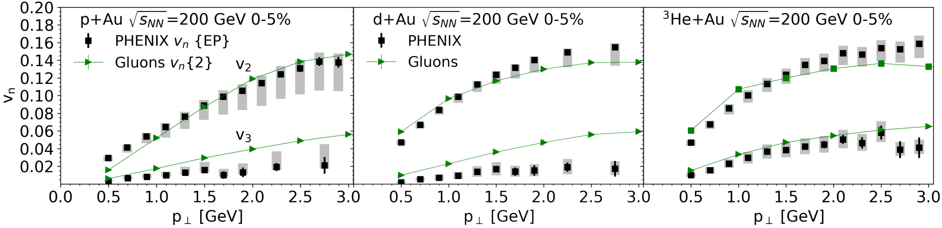
Color Glass Condensate



independent sources in d+A $\rightarrow$
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 2018]

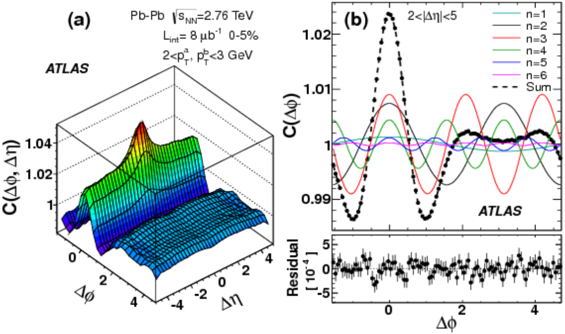


Questioned in [Nagle, Zajc 2018] $\rightarrow$ controversy

Flow observation

two-particle correlations in relative azimuthal angle

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

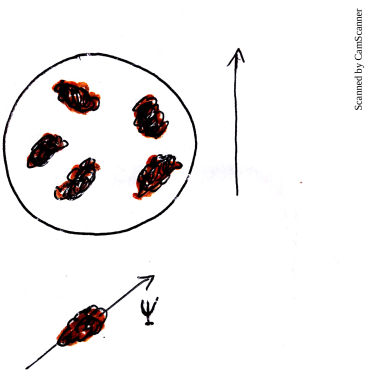


non-flow (e.g. initial state) correlations important at low multiplicity!

Correlation measurements

No control/knowledge of the orientation

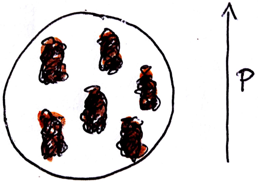
[a few d+A collisions overlaid on the same plot]



$$\frac{dN}{d\phi_1 d\phi_2} \propto 1 + 2v_2^2\{2\}\cos\left[2(\phi_1 - \phi_2)\right] + \dots$$

Proposed one-body measurement $v_2\{\Phi_P\}$

Scanned by CamScanner



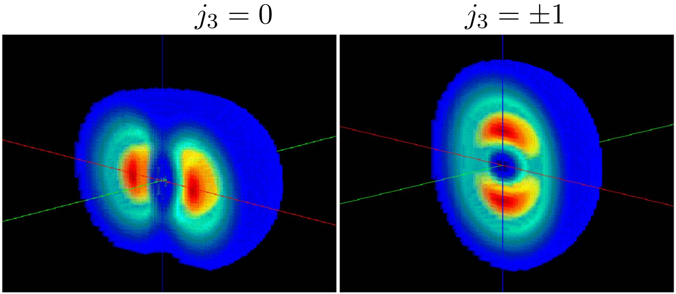
$$\frac{dN}{d\phi} \propto 1 + 2v_2\{\Phi_P\}\cos\left[2(\phi - \Phi_P)\right] + \ldots$$

Advantageous from the experimental point of view

CGC would produce no signal!

Polarized deuteron

Deuteron



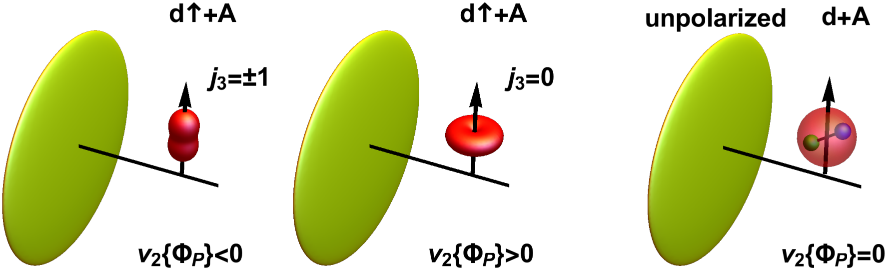
[Garcon, Van Orden 2001]

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

${}^{2S+1}L_j$ notation

Polarized d+A collisions

Motivation: collectivity vs CGC dispute [PB, WB, PRL 121 (2018) 202301]



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 $|LL_3\rangle|SS_3\rangle$,

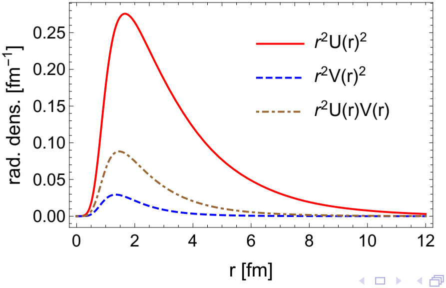
$$|\Psi(r;1)\rangle = U(r)|00\rangle|11\rangle + V(r)\left[\sqrt{\tfrac{3}{5}}|22\rangle|1\,{-1}\rangle - \sqrt{\tfrac{3}{10}}|21\rangle|10\rangle + \sqrt{\tfrac{1}{10}}|20\rangle|11\rangle\right]$$

$$\ldots$$

Orthonormality of the spin parts yields

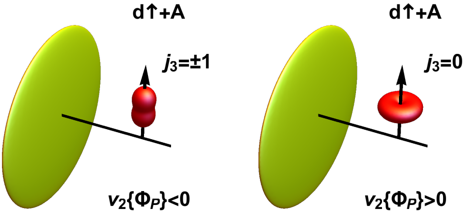
$$|\Psi(r,\theta,\phi;\pm 1)|^2 = \tfrac{1}{16\pi}\left[4U(r)^2 - 2\sqrt{2}\left(1-3\cos^2\theta\right)U(r)V(r) + \left(5-3\cos^2\theta\right)V(r)^2\right]$$

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



Reid'93

Ellipticity of $|\Psi|^2$ with respect to a fixed polarization axis

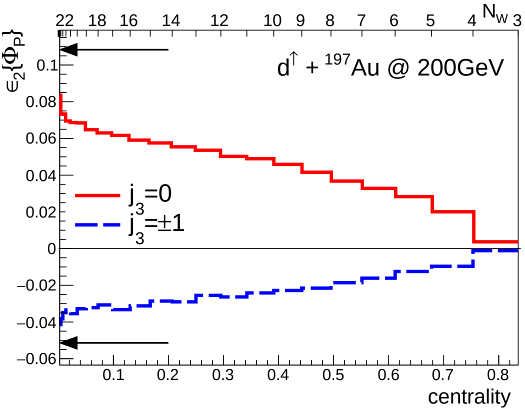


$$\epsilon_2^{|\Psi|^2_{j_3=0}}\{\Phi_P\} = \frac{\int d^3r\, r^2\{\frac{2\sqrt{2}}{5}U(r)V(r) - \frac{1}{5}V(r)^2\}}{\int d^3r\, r^2\{\frac{2}{3}U(r)^2 - \frac{2\sqrt{2}}{15}U(r)V(r) + \frac{11}{15}V(r)^2\}} \simeq 0.11$$

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

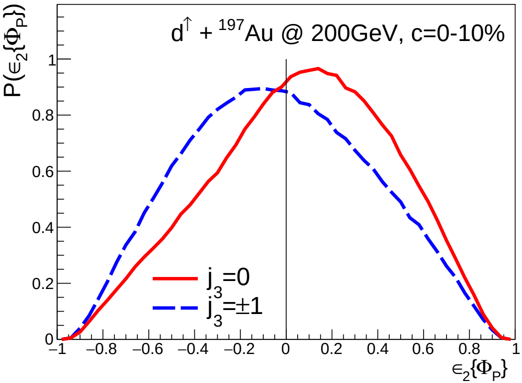
Ellipticity of the fireball relative to polarization axis

Glauber Monte Carlo `GLISSANDO`

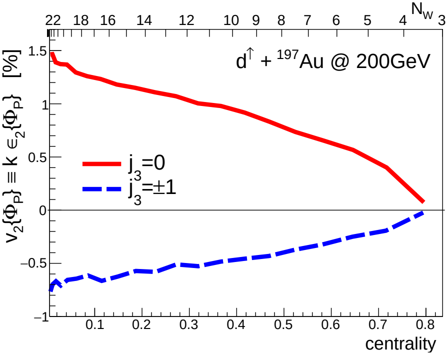


$\sim$30% reduction from $\epsilon_2^{|\Psi|^2}$ (arrows) (nucleons from Au)

Distribution of the ellipticity of the fireball (most central)



Predictions



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

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

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

Quadrupole moment

Estimate of $\epsilon_2\{\Phi_P\}$ to Q_2

Quadrupole moment:

$$Q_2 = \left\langle r^2 \sqrt{\frac{16\pi}{5}} Y_{20}(\Omega) \right\rangle = \langle 3z^2 - r^2 \rangle$$

$$\epsilon_2\{\Phi_P\} \simeq -\frac{3Q_2}{4Z\langle r^2\rangle_{\rm ch} + Q_2}$$

(with the approx. that neutrons follow protons)

Wigner-Eckart theorem ($\hat{Q}_2$ is a rank-2 tensor):

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

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

Estimates based on nuclear data

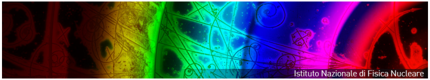
	j	j_3	$\langle r^2\rangle_{\rm ch}^{1/2}$ [fm]	Q_2 [fm^2]	$\epsilon_2^{\lvert\Psi\rvert^2}\{\Phi_P\}$ [%]
d	1	± 1	2.1414(25)	0.2860(15)	~ -5
		0		$\times(-2)$	~ 10
^{7}Li	$\frac{3}{2}$	$\pm\frac{3}{2}$	2.4	~ -4	~ 15
		$\pm\frac{1}{2}$		$\times(-1)$	~ -15
^{9}Be	$\frac{3}{2}$	$\pm\frac{3}{2}$	2.5	~ -5	~ -15
		$\pm\frac{1}{2}$		$\times(-1)$	~ 15
^{10}B	3	± 3	2.5	~ 8.5	~ -20

Experimental prospects

Experimental prospects

"Easy" flow measurement (one-body), but one needs a polarized target...

SMOG@LHCb



Internal gas target experiments at the LHC

V.Carassiti[1], G.Ciullo[1], P. Di Nezza[2], P.Lenisa[1], L.Pappalardo[1], E.Steffens[3]

[1] University of Ferrara and INFN, [2] INFN - Laboratori Nazionali di Frascati, [3] University of Erlangen

In collaboration with:
R.Engels (fz-juelich), J.Depner (Erlangen), K.Grigoryev (fz-juelich), E.Maurice (CNRS/IN2P3, Orsay), A.Nass (fz-juelich), F.Rathmann (fz-juelich), D.Reggiani (PSI-Zurich), A.Vasilyev (Gatchina),

12/09/18

- Elliptic flow in ultra-relativistic collisions with polarised deuterons

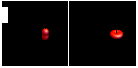
pol

arXiv:1808.09840

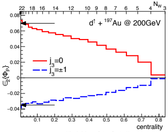
Ridge and flow measurements, connected to collectivity phenomena, are among the most interesting results achieved in the last years in the QGP physics.

We can put this in connection with spin clarifying the nature of dynamics in small systems

its experimental confirmation would prove the presence of the shape-flow transmutation mechanism, typical of hydrodynamic expansion, or rescattering in the later stages of the fireball evolution



ultra-relativistic d+A collision, where the deuteron is polarised along the axis ΦP perpendicular to the beam



Ellipticities of the fireball

A polarised D-beam at BNL will not come in a near future

A polarised target at LHC can easily provide Pb $D^{\uparrow}$ collisions

Experimental prospects

“Easy” flow measurement (one-body), but one needs a polarized target...

AFTER@LHC

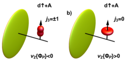
Plans for future fixed target experiments at the LHC

Cynthia Hadjidakis
IPN Orsay, Paris-Sud/Paris-Saclay University, France

Town meeting: Relativistic Heavy Ion Physics
CERN
24 October, 2018

Other opportunities: collective-like effects in Pb-D$^{\uparrow}$

– Intrinsic deformation of polarized (transversally) deuteron → non-zero v_2 in case of collective dynamics (hydro, transport models) wrt transverse target polarisation axis in Pb+D$^{\uparrow}$ for charged particles
– No azimuthal asymmetries expected from the correlation from gluon dynamics (CGC model): powerful probe to discriminate among models



P. Bozek and W. Broniowski. arXiv:1808.09840

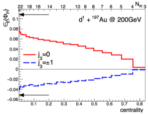
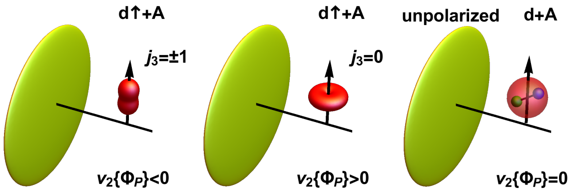


FIG. 3. Ellipticities of the fireball formed in polarized d+Au collisions at the energy of $\sqrt{s_{NN}} = 200$ GeV. The lower coordinate axis shows the centrality as defined via the produced entropy S. The top coordinate axis shows the corresponding number of the wounded nucleons. The arrows indicate the ellipticities of the modulus squared of the deuteron wave function of Eq. (8).

Conclusions

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 $j \geq 1$