Hydro in small systems:
How small can a QGP be?

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Outline

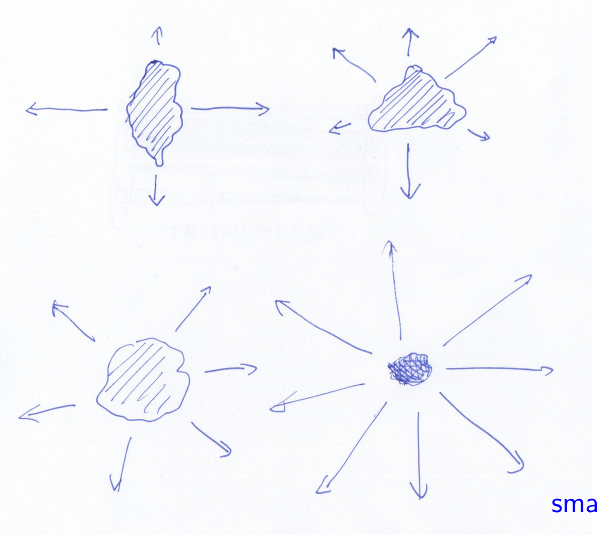
- More remarks on light-heavy collisions

    • see Monday talks by Schlichting, Mohapatra, Collab. reviews, parallel sessions

- Collisions with polarized light targets
- Collisions with light clustered nuclei

Remarks

Shape – flow transmutation

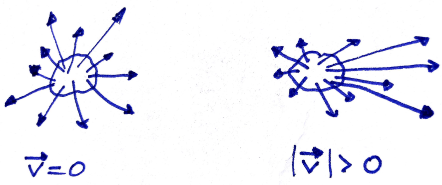


smaller $\rightarrow$ faster

Any (copious) rescattering will do (hydro, transport)!

Collimation from the Doppler effect

- Emission from a fast moving element of fluid
- Collimation of hadrons (increasing with mass)



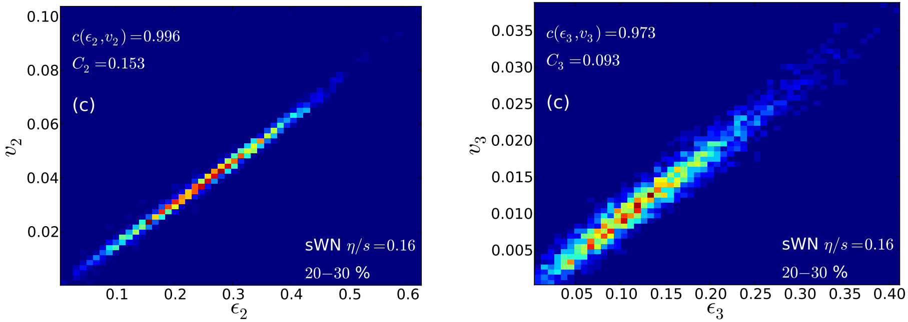
Multi-particle correlations in the azimuth are used in the cumulant or other methods to extract the flow coefficients with reduced the non-flow contamination (from jets, resonance decays, ...)

[Borghini, Ollitrault 2001]

Hydro without hydro

Approximately $v_n = \kappa_n \epsilon_n$, $(n = 2, 3)$

- κ_n depend on the collision energy, multiplicity, viscosity ...



Au+Au@200 GeV [Niemi, Denicol, Holopainen, Huovinen 2012]

- cf. talk by Behera on Tuesday

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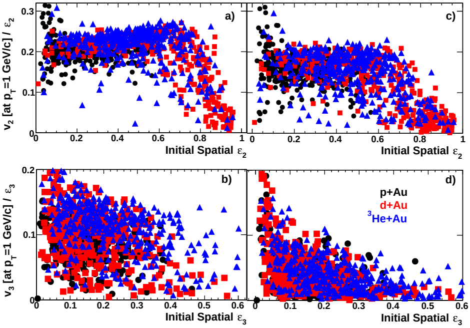


$T_f = 150$ MeV (left) and 170 MeV (right) [Nagle, Adare, Beckman, Koblesky, Orjuela Koop, McGlinchey, Romatschke, Carlson, Lynn, McCumber, PRL 113 (2014) 112301]

- cf. talk by Behera on Tuesday

Hydro without hydro

Approximately $v_n = \kappa_n \epsilon_n$, $(n = 2, 3)$

- κ_n depend on the collision energy, multiplicity, viscosity ...

Allows us to construct response-independent coefficients, e.g.,

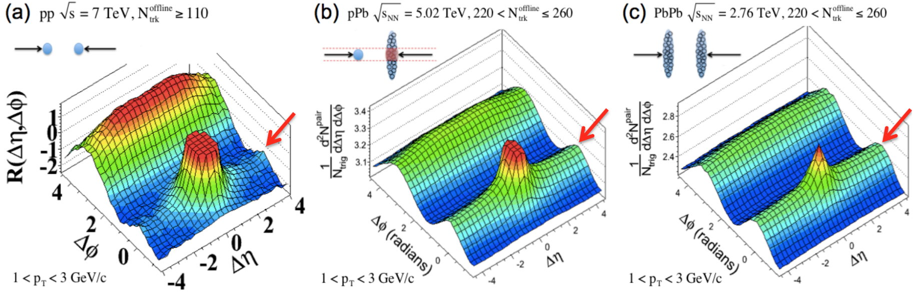
$$v_n\{4\}/v_n\{2\} \simeq \epsilon_n\{4\}/\epsilon_n\{2\}$$

which probe the geometry-fluctuation interplay
(more geometry $\rightarrow v_n\{4\}/v_n\{2\}$ goes up)

[Bożek WB, Ruiz Arriola, Rybczyński, 2014,
Giacalone, Noronha-Hostler, Ollitrault, 2017]

- cf. talk by Behera on Tuesday

Ridge

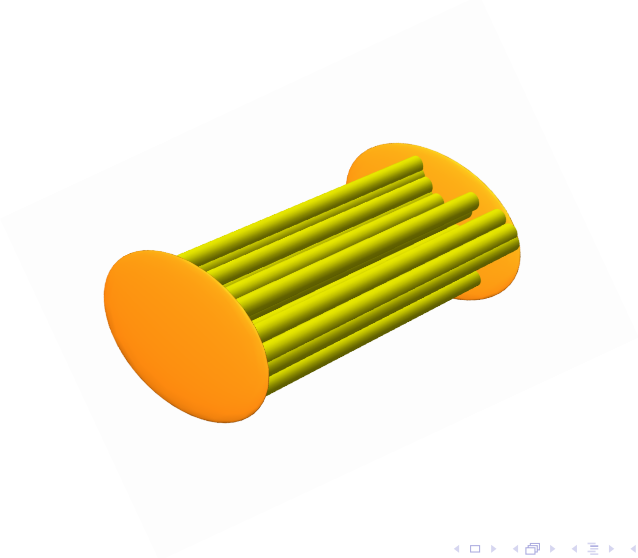


Together with the transverse-longitudinal factorization, the near-side ridge indicates collectivity

understanding of the ridges $\rightarrow$

Factorization of the transverse and longitudinal distributions

left-moving participants   strings   right-moving participants



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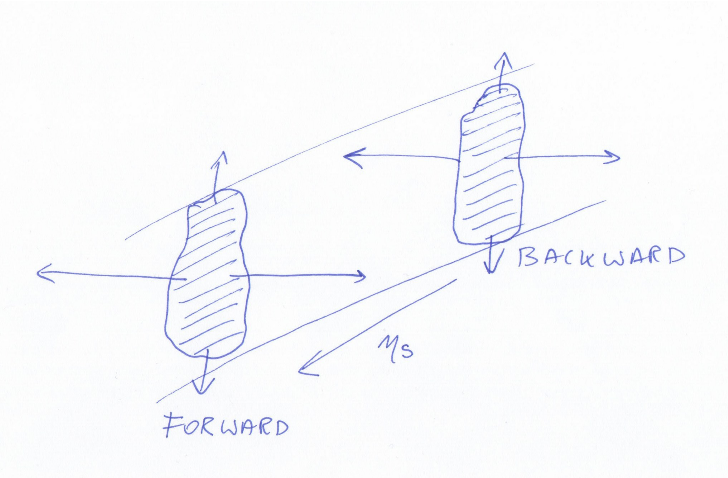


Approximate (up to fluctuations) alignment of F and B event planes

Collimation of flow at very distant longitudinal separations → ridges!

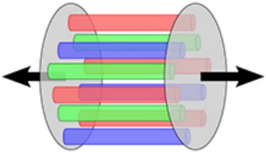
Surfers - the near-side ridge

Collimated even if separated by a mile!

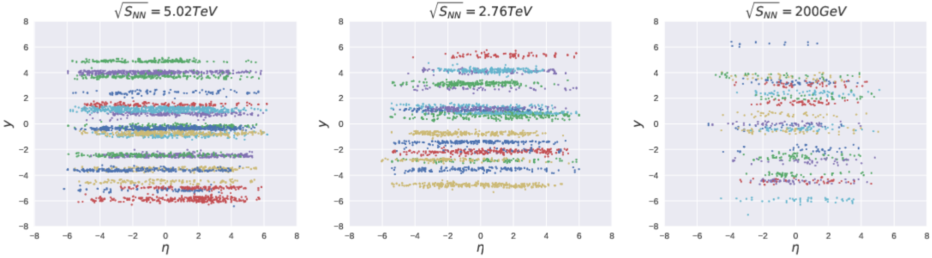
Something had to create the wave!

Realizations

Glasma tubes:



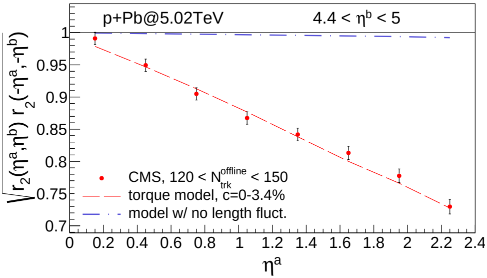
AMPT (HIJING, Lund model) [Wu et al. 2018]:



string breaking crucial →

Torque (decorrelation) in p-Pb

- String breaking essential to describe torque in p-Pb



- cf. Huang on Monday, Bożek and Qin on Tuesday

Not covered at IS19: longitudinal fluctuations

a_{nm} coefficients

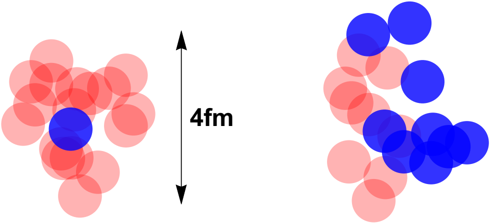
[Bzdak, Teaney, 2012, Jia, Radhakrishnan, Zhou, 2016, Monnai, Schenke, PLB 752 (2016) 317, PB, WB, Olszewski, Phys.Rev. C92 (2015) 054913, ATLAS]

p-A, how small?

Initial fireball in p-Pb vs Pb-Pb

Sample transverse-plane configuration of centers of the participant nucleons in a p+Pb collision from `GLISSANDO`
5% of collisions have more than 18 participants, rms ~ 1.5 fm – quite large!

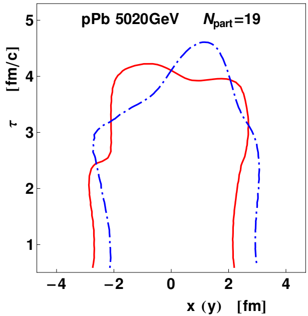
p-Pb@5.02 TeV, N_W=18 Pb-Pb@2.76 TeV, N_W=18



Size reflects the NN inelasticity profile
Most central values of N_w in p-Pb would fall into the 60-70% or 70-80% centrality class in Pb+Pb
Pb+Pb: c=60-70% $\equiv 22 \leq N_w \leq 40$, c=70-80% $\equiv 11 \leq N_w \leq 21$

Hydro evolution of the p-Pb fireball

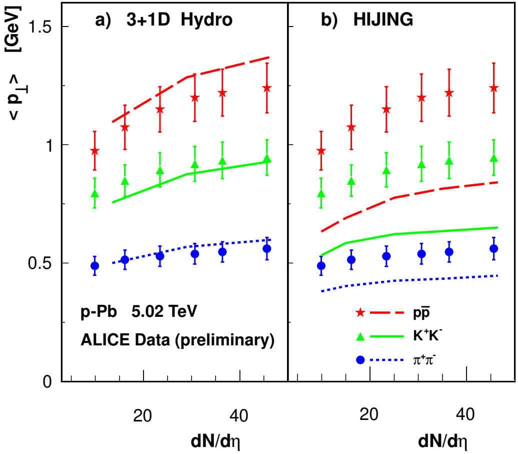
Not so small!



isotherms at freeze-out $T_f = 150$ MeV
(for two sections in the transverse plane)

- evolution lasts about 4 fm/c – shorter but more rapid than in Pb+Pb
- strong gradients $\rightarrow$ essential role of viscosity

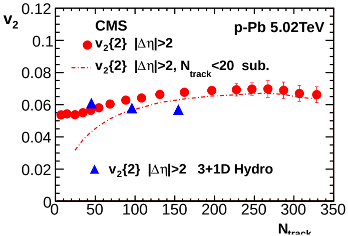
Mass hierarchy in p-A

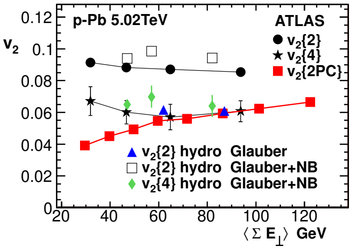


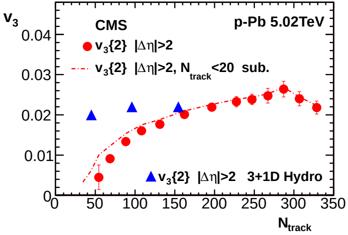
[PB, WB, Torrieri, PRL 111 (2013) 172303]

Harmonic flow in p-A

- see experimental talks!

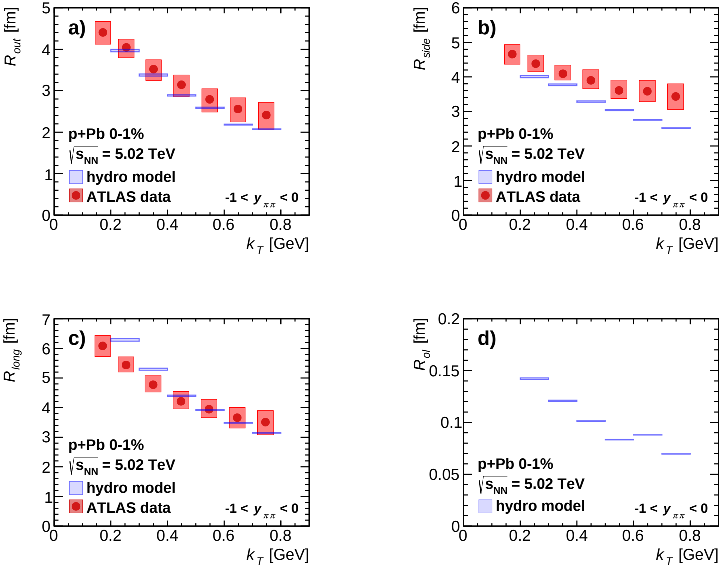






[PB, WB, PRC 88 (2013) 014903]

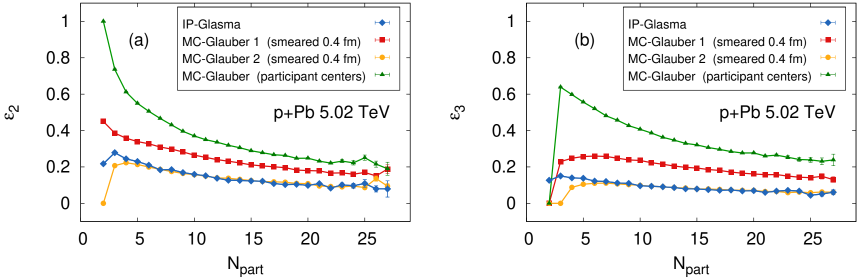
Interferometry



[PB, Bysiak, 2017]

IP-Plasma vs Glauber

Can we distinguish approaches by the initial condition?



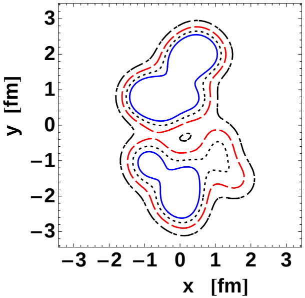
[Bzdak, Schenke, Tribedy, Venugopalan, Phys.Rev. C87 (2013) 064906]

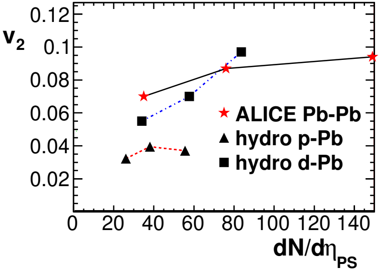
d-A, ^{3}He-Au

[pioneered by Bożek 2012]

intrinsic dumbbell shape with large deformation: rms $\simeq 2$ fm

initial entropy density in a d-Pb collision with $N_{\text{part}} = 24$





Resulting large elliptic flow confirmed with the later RHIC analysis
(geometry + fluctuations)

d-A

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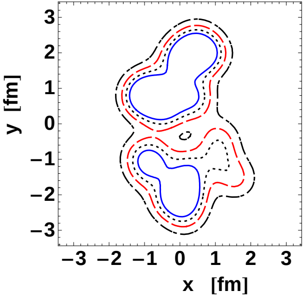

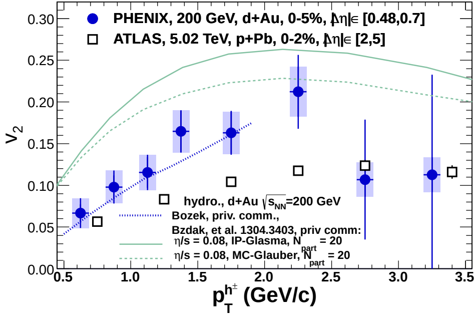

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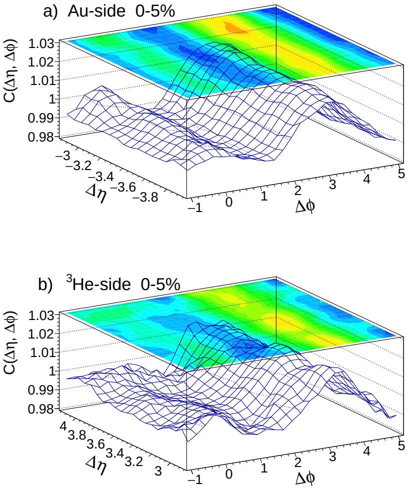
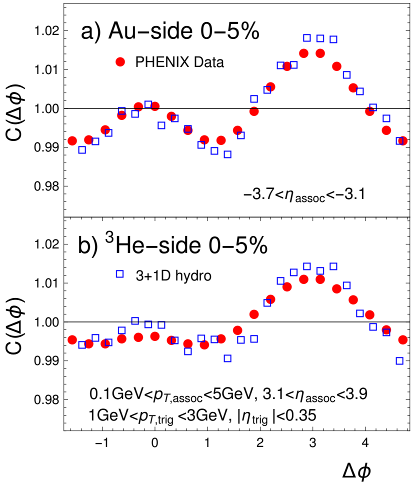
(geometry + fluctuations)

Ridge in ^{3}He-Au at RHIC



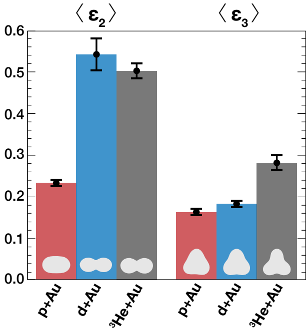


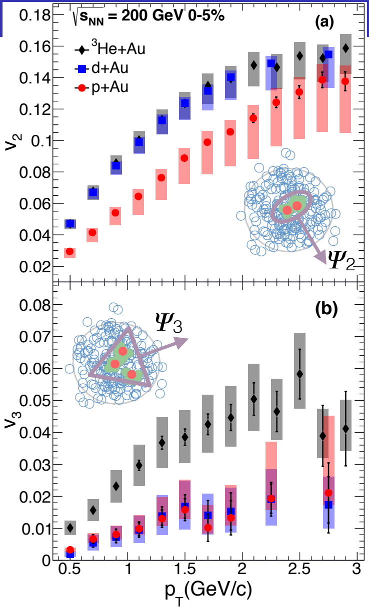
(seen on both pseudorapidity sides)

[PB, WB 2015]

Flow hierarchy in small systems

[PHENIX, 2018]

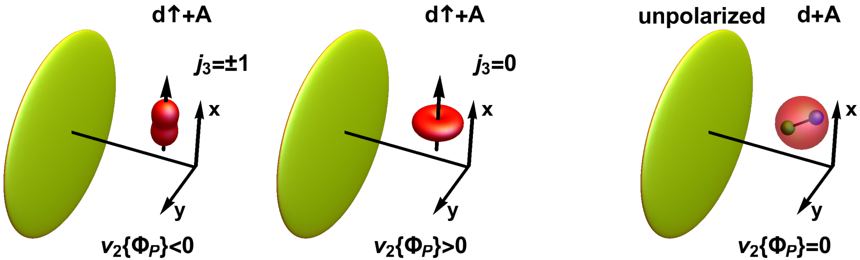




- see talks by Mace, Zajc, poster by Nagle

Controlling the geometry:
A – polarized d collisions

Polarized d+A collisions

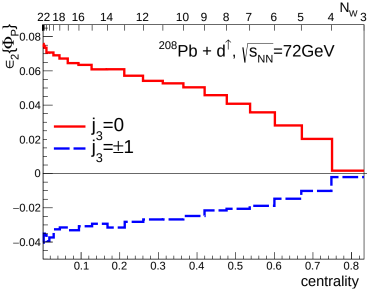


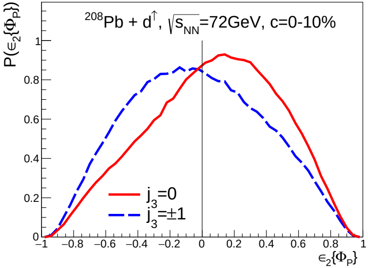
Admixture of the D-wave allows us to control the geometry! Small but measurable effect

[PB, WB, PRL 121 (2018) 202301]

Ellipticity of the fireball relative to polarization axis

GLISSANDO:



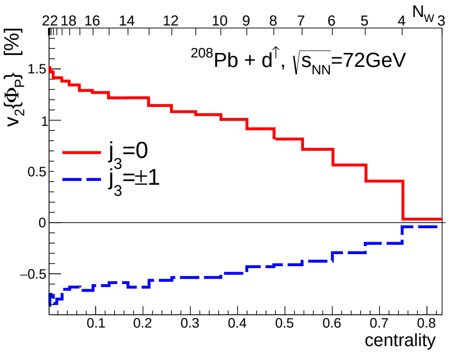


Predictions

one-body (!)

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

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



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

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

$$v_2\{\Phi_P\} \simeq k\, \epsilon_2^{j_3=\pm 1}\{\Phi_P\} P_{zz}, \quad -1.5 \le P_{zz} \le 0.7$$

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

One-particle distribution – can be measured precisely! Random fluctuations cancel

Single spin asymmetry $\sim \sin(\phi - \Phi_P)$ innocuous

Prospects at fixed target experiments

NA61@SPS, AFTER@LHC – difficulty in injecting a polarized gas target into the Pb beam

- see talks by Schmidt, Di Nezza

2.76A TeV Pb beam on a fixed target $\to \sqrt{s_{NN}} = 72$ GeV, at LHCb $-2.3 < \eta_{\rm CM} < 0.7$

[C. Barschel, Ph.D. thesis, (2014)
R. Aaij et al. (LHCb), JINST 9, P12005 (2014), arXiv:1410.0149]

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

Quadrupole moment:

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

$$\epsilon_2\{\Phi_P\} \sim -\frac{3Q_2}{4Z\langle r^2 \rangle}$$

(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	$\langle r^2\rangle_{ch}^{1/2}$ [fm]	Q_2 [fm^2]	$-\frac{3Q_2}{4Z\langle r^2\rangle}$ [%]
d	1	± 1	2.1421(88)	0.2860(15)	-5.6
		0		$\times(-2)$	$\times(-2)$
^{7}Li	$\frac{3}{2}$	$\pm\frac{3}{2}$	2.444(42)	$-4.03(4)$	19
		$\pm\frac{1}{2}$		$\times(-1)$	$\times(-1)$
^{9}Be	$\frac{3}{2}$	$\pm\frac{3}{2}$	2.519(12)	$5.29(4)$	-17
		$\pm\frac{1}{2}$		$\times(-1)$	$\times(-1)$
^{10}B	± 3	± 3	2.428(50)	$8.47(6)$	-25
		± 2		$\times 0$	0
		± 1		$\times(-3/5)$	$\times(-3/5)$
		0		$\times(-4/5)$	$\times(-4/5)$

$$v_2\{\Phi_P\} \simeq -k\frac{3Q_2}{4Z(\langle r^2\rangle + \frac{3}{2}\langle b^2\rangle)}\frac{3j_3^2 - j(j+1)}{j(2j-1)}P$$

Light clustered nuclei

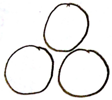
^{12}C-A – role of α clusters

"Futurology" from [WB, Ruiz Arriola, PRL 112 (2014) 112501]
Nuclear structure from ultra-relativistic collisions!

Probe to what degree ^{12}C is made of three α's

Specific features of the ^{12}C collisions with a "wall" of Pb or Au:

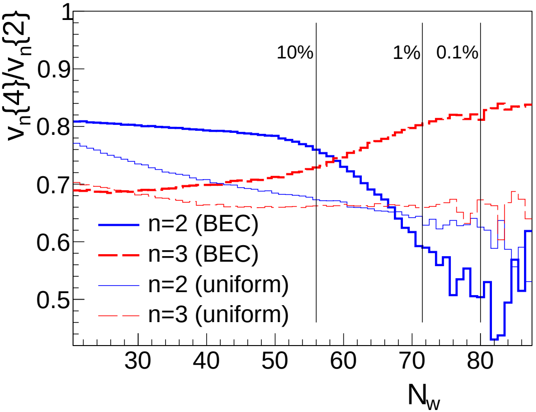
The cluster plane parallel or perpendicular to the transverse plane:



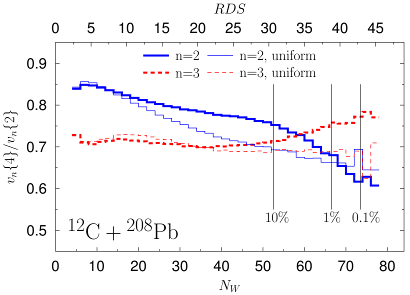
higher multiplicity	lower multiplicity
higher triangularity	lower triangularity
lower ellipticity	higher ellipticity

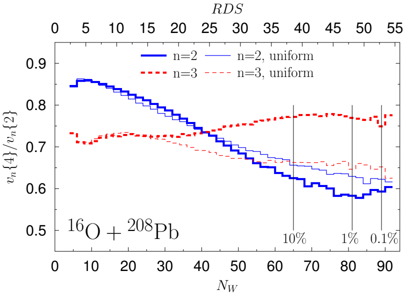
^{12}C - ^{197}Au, $\sqrt{s_{NN}} = 200$ GeV

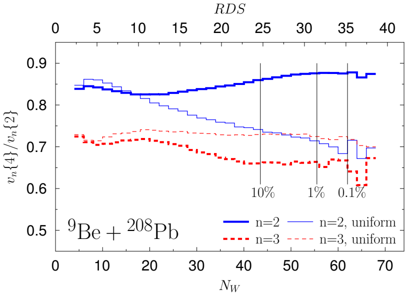
[PB, WB, Ruiz Arriola, Rybczyński. PRC90 (2014) no.6, 064902]
$\rightarrow$ effects of geometric arrangement for most central
$v_n\{4\}/v_n\{2\}$ a good response-invariant probe (recall $v_n \simeq \kappa\epsilon_n$, $n = 2, 3$))
[see also Giacalone, Noronha-Hostler, Ollitrault, PRC95 (2017) 054910]



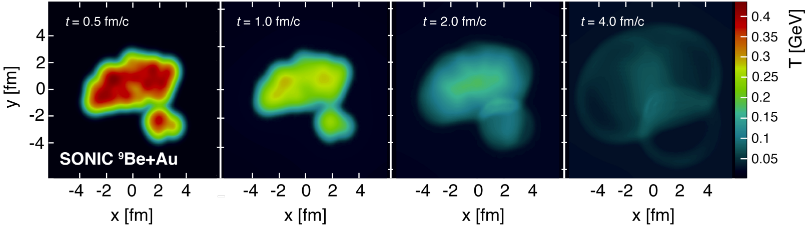
light - ^{208}Pb, $\sqrt{s_{NN}} = 17$ GeV (SPS)







Idea picked up in [Lim, Carlson, Loizides, Lonardoni, Lynn, Nagle, Orjuela Koop, Ouellette, PRC 99 (2019) 044904] with exp. prospects



two α clusters and the neutron

Summary

Summary

- Shape-flow transmutation in small systems
- Much to see in longitudinal fluctuations
- Polarized deuteron - controlled geometry
- Clustered small nuclei - insight into nuclear structure from harmonic flow

Loizides at QM2015

Observable or effect	PbPb	pPb (at high mult.)	pp (at high mult.)
Low p_T spectra ("radial flow")	yes	yes	yes
Intermed. p_T ("recombination")	yes	yes	yes
Particle ratios Statistical model	GC level $\gamma_s^{GC} = 1$, 10–30%	GC level except Ω $\gamma_s^{GC} \approx 1$, 20–40%	GC level except Ω $\gamma_s^{C} < 1$, 20–40% [2]
HBT radii ($R(k_T)$, $R(\sqrt[3]{N_{ch}})$)	$R_{out}/R_{side} \approx 1$ [3]	$R_{out}/R_{side} \lesssim 1$	$R_{out}/R_{side} \lesssim 1$
Azimuthal anisotropy (v_n) (from two part. correlations)	$v_1 - v_7$	$v_1 - v_5$	v_2, v_3
Characteristic mass dependence	v_2, v_3 [4]	v_2, v_3	v_2
Directed flow (from spectators)	yes	no	no
Higher order cumulants (mainly $v_2\{n\}, n \geq 4$)	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6$" [5]
Weak η dependence	yes	yes	not measured
Factorization breaking	yes ($n = 2, 3$)	yes ($n = 2, 3$)	not measured
Event-by-event v_n distributions	$n = 2 - 4$	not measured	not measured
Event plane and v_n correlations	yes	not measured	not measured
Direct photons at low p_T	yes	not measured	not measured [6]
Jet quenching	yes	not observed [7]	not measured [8]
Heavy flavor anisotropy	yes	hint [9]	not measured