# Ultra-relativistic $^3$He-Au collisions

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Heavy-ion seminar
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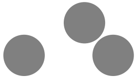
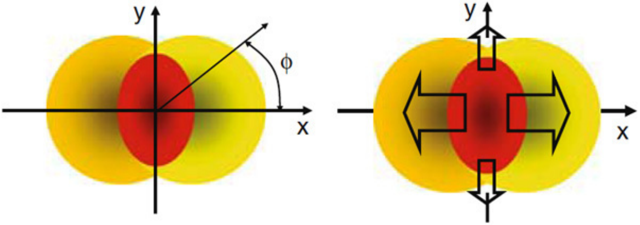
$^3$He 

[research with **Piotr Bożek**]

# Flow

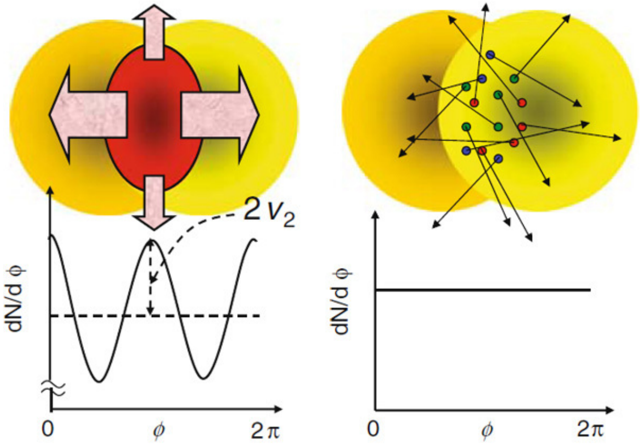
# Phenomenon of flow

How do we know that quark-gluon plasma is formed?




"Initial shape – final flow" transmutation detectable in the asymmetry of the momentum distribution of detected particles – follows from collectivity

# Elliptic flow from collectivity

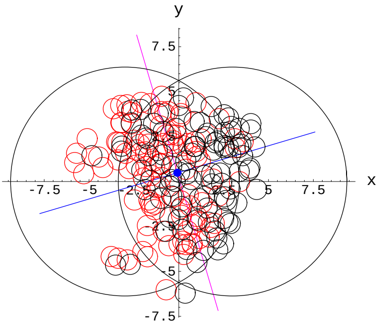



[ALICE]

$$dN/d\phi = A\left(1 + 2\sum_n v_n \cos[n(\phi - \Psi_n)]\right)$$

# Harmonic flow from shape+fluctuations

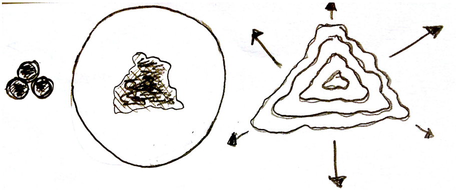
Wounded nucleons – experienced at least one inelastic collision [Białas, Błeszyński & Czyż]




- Initial fireball is asymmetric in the transverse plane from
  1) geometry 2) fluctuations
- collectivity! – **flow generated**
- Strong elliptic flow, triangular flow (in Au+Au entirely from **fluctuations**), higher-order harmonic flow

# Throwing triangles against a wall

asymmetry of shape → asymmetry of initial fireball →
→ hydro or transport → collective harmonic flow

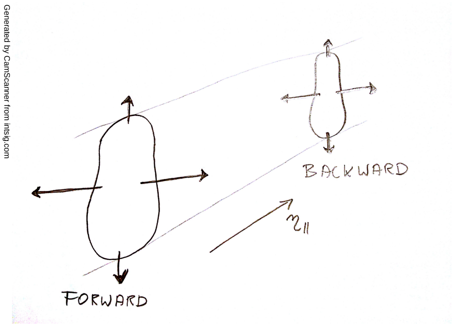


nuclear triangular geometry → fireball triangular geometry → triangular flow

Generated by CamScanner from intsig.com

Triangles: $^{3}$He-Au at RHIC [PHENIX]
Our proposal for $^{12}$C as a tool to detect $\alpha$ structure

# Factorization of the transverse and longitudinal distributions

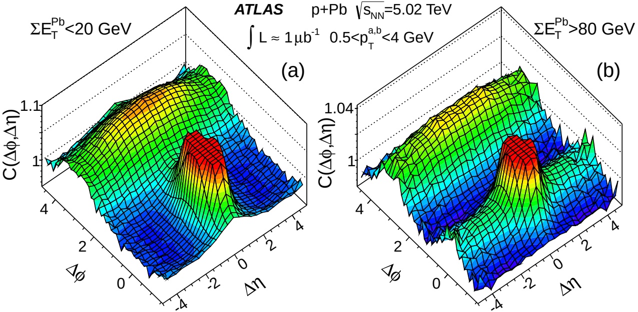


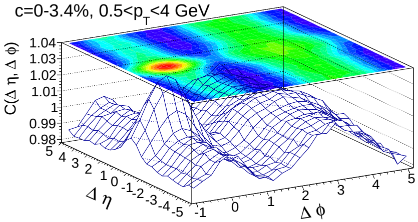

alignment of F and B event planes (can be checked experimentally)

collimation of flow at distant longitudinal separations $\to$ ridges!

# Surfers - the near-side ridge

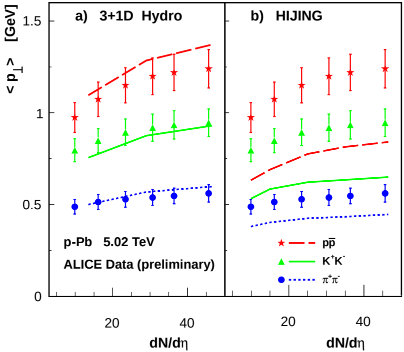
# Ridge in p-Pb: ATLAS vs 3+1D hydro

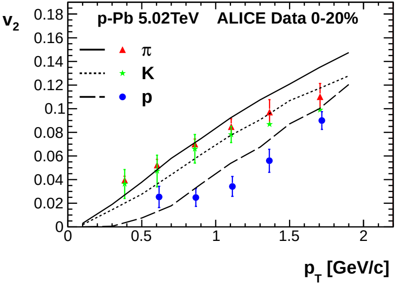



[another approach: CGC-based calculation by Dusling & Venugopalan]

# Mass ordering in p-Pb from flow




$< p_T >_\pi = 0.48$ GeV, $< p_T >_K = 0.72$ GeV, $< p_T >_p = 0.99$ GeV

$(|\eta| < 2.4)$

[more details in Bożek, WB, & Torrieri, PRL 111 (2013) 172303]

# Eccentricity parameters (event-by-event)

We will need quantitative measures of deformation
Eccentricity parameters $\epsilon_n$ (Fourier analysis)

$$\epsilon_n e^{i\Psi_n} = \frac{\sum_j \rho_j^n e^{in\phi_j}}{\sum_j \rho_j^n}$$

describe the shape of each event ($j$ labels the initial sources in the event in the transverse plane, $n$=rank)
$n = 2$ – ellipticity, $n = 3$ – triangularity, ...

Two components:

- intrinsic shape
- from fluctuations

# Hydro without hydro

**We have to a very good approximation linear response**

$$v_n = \kappa_n \epsilon_n, \quad n = 2, 3, \dots$$

($\kappa_n$ depends on multiplicity, energy, hydro parameters)

Cumulant moments: $\epsilon_n\{2\}^2 = \langle \epsilon_n^2 \rangle, \ \epsilon_n\{4\}^4 = 2\langle \epsilon_n^2 \rangle - \langle \epsilon_n^4 \rangle$

**Ratio's insensitive to response:**

$$\frac{\sigma(v_n)}{\langle v_n \rangle} = \frac{\sigma(\epsilon_n)}{\langle \epsilon_n \rangle}$$

$$\frac{v_n\{m\}}{v_n\{2\}} = \frac{\epsilon_n\{m\}}{\epsilon_n\{2\}}, \quad m = 4, 6, \dots$$

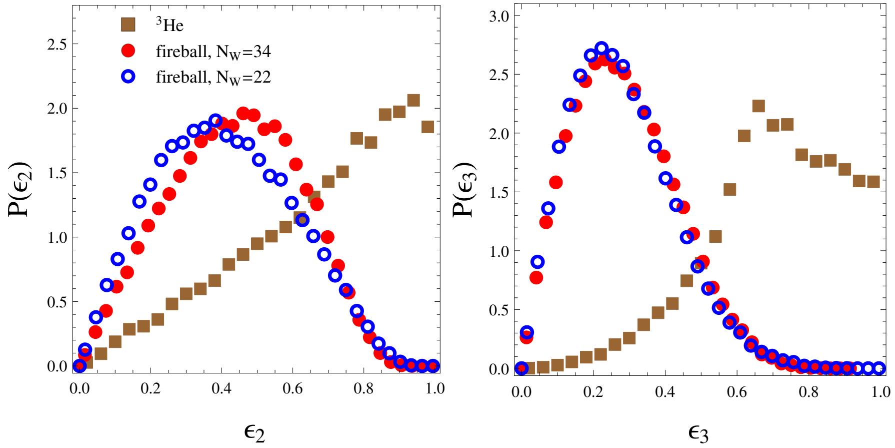
(infer limited info on flow from just the eccentricities, no hydro!)

[see, e.g., Bzdak, Bożek & McLerran, NPA 927 (2014) 15]

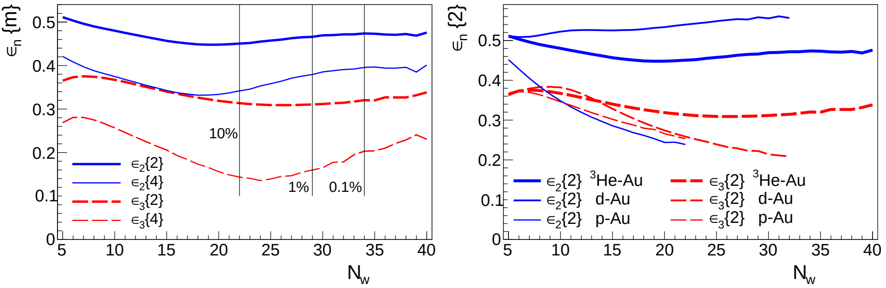
# $^3$He-Au

[more details in Bożek & WB, PLB 739 (2014) 308 and arXiv:1503.00468]

# Eccentricities of $^3$He and fireball



# Predictions based on eccentricities



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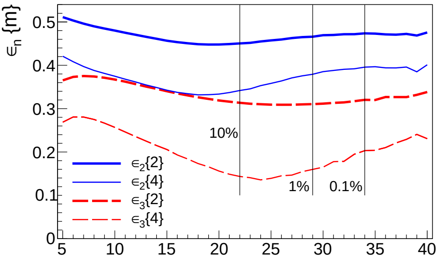
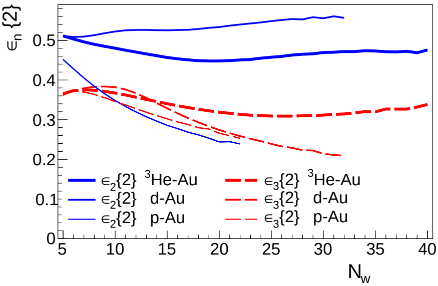
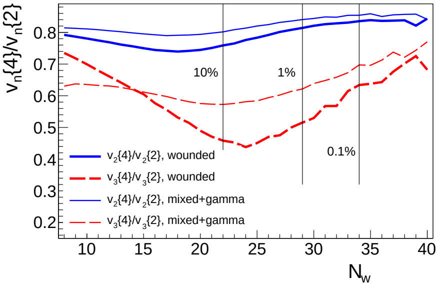
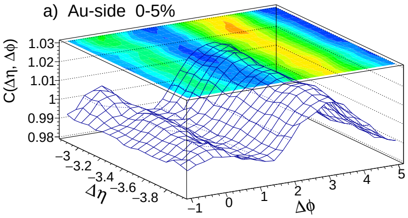


# Ridges in $^3$He-Au



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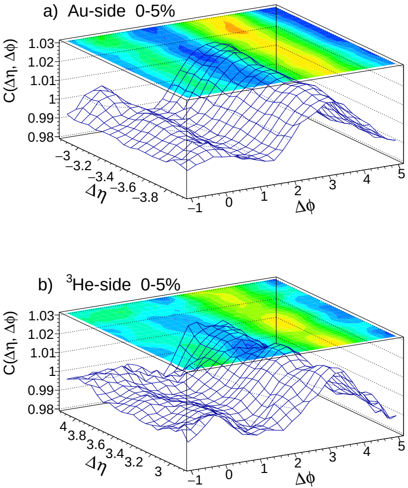
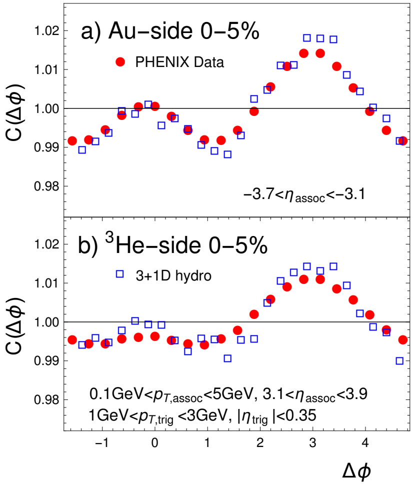
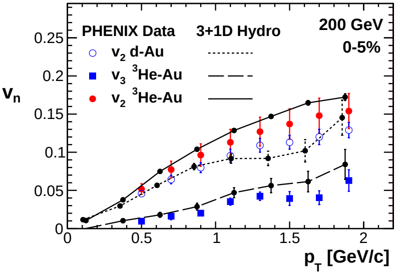


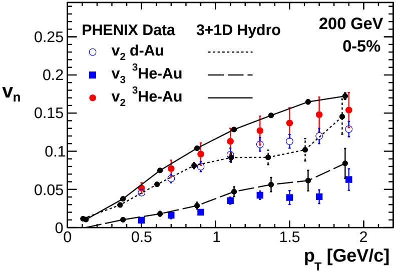



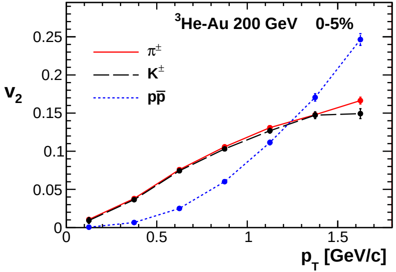

(seen on both pseudorapidity sides)

# Flow in $^3$He-Au



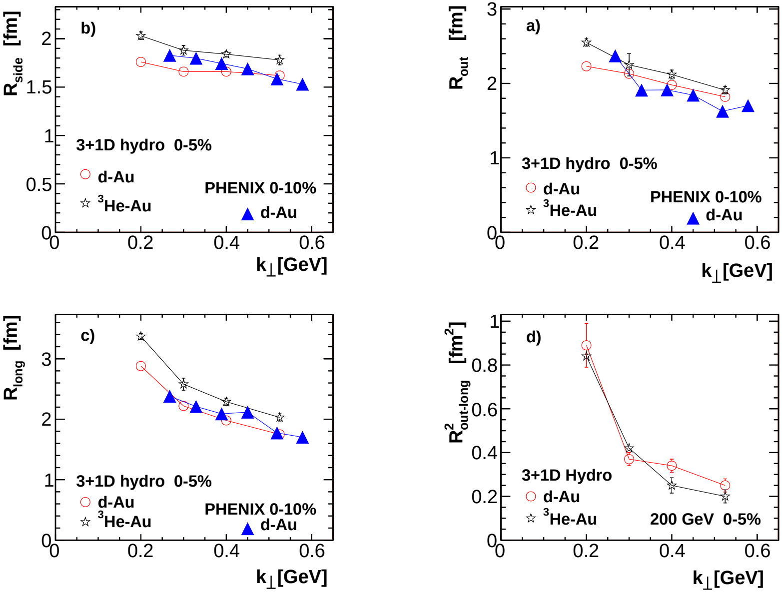
# Flow in $^3$He-Au




(mass ordering visible)

# Femtoscopy in $^3$He-Au (HBT correlation radii



# Conclusions

# Conclusions

- Small systems look very collective (p-Pb, d-Au, $^3$He-Au): The near-side ridge, flow, mass orderings, $k_T$-dependence of the HBT radii
- Good quantitative agreement of 3+1D hydro event-by-event hydro with the preliminary PHENIX data on $^3$He-Au (no "retuning", same parameters as for other systems: Glauber model for the initial condition, shear and bulk viscosity, initial time, statistical hadronization at $T_f = 150$ MeV)