Ultra-relativistic light-heavy nuclear collisions and collectivity

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[research with Piotr Bożek, Enrique Ruiz Arriola, Maciej Rybczyński]
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

\[ dN/d\phi = A \left( 1 + 2 \sum_n v_n \cos[n(\phi - \Psi_n)] \right) \]
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 $\rightarrow$ asymmetry of initial fireball $\rightarrow$
$\rightarrow$ hydro or transport $\rightarrow$ collective harmonic flow

nuclear triangular geometry $\rightarrow$ fireball triangular geometry $\rightarrow$ triangular flow

Triangles: $^3$He-Au at RHIC [PHENIX]
Our proposal for $^{12}$C as a tool to detect $\alpha$ structure
alignment of F and B event planes (can be checked experimentally)

collimation of flow at distant longitudinal separations $\rightarrow$ ridges!
Surfers - the near-side ridge
Ridge in p-Pb: ATLAS vs 3+1D hydro

\[ \Sigma E_T^{Pb} < 20 \text{ GeV} \]

\[ \int L \approx 1 \mu b^{-1} \quad 0.5 < p_T^{a,b} < 4 \text{ GeV} \]

\[ \Sigma E_T^{Pb} > 80 \text{ GeV} \]

[another approach: CGC-based calculation by Dusling & Venugopalan]
Mass ordering in p-Pb from flow

\[ \langle p_T \rangle_{\pi} = 0.48 \text{ GeV}, \quad \langle p_T \rangle_K = 0.72 \text{ GeV}, \quad \langle p_T \rangle_p = 0.99 \text{ GeV} \]

\(|\eta| < 2.4\)

[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

\[ v_n = \kappa_n \epsilon_n, \quad n = 2, 3, \ldots \]

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

Cumulant moments:

\[ \epsilon_n \{2\}^2 = \langle \epsilon_n^2 \rangle, \quad \epsilon_n \{4\}^4 = 2 \langle \epsilon_n^2 \rangle - \langle \epsilon_n^4 \rangle \]

Ratio's insensitive to response:

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

\[ \frac{v_n \{m\}}{v_n \{2\}} = \frac{\epsilon_n \{m\}}{\epsilon_n \{2\}}, \quad m = 4, 6, \ldots \]

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

[see, e.g., Bzdak, Bożek & McLerran, NPA 927 (2014) 15]
$^3\text{He-Au}$

[more details in Bożek & WB, PLB 739 (2014) 308 and arXiv:1503.00468]
Ridges in $^3$He-Au

a) Au-side 0-5%

$C(\Delta \eta, \Delta \phi)$

b) $^3$He-side 0-5%

$C(\Delta \eta, \Delta \phi)$

seen on both pseudorapidity sides
Ridges in $^3$He-Au

(a) Au-side 0-5%

(b) $^3$He-side 0-5%

(seen on both pseudorapidity sides)

PHENIX Data

3+1D hydro

WB (IFJ PAN & UJK)

light-heavy
eQCD15
Flow in $^3$He-Au

PHENIX Data 3+1D Hydro 200 GeV 0-5% $d$-$Au$ $v_2$ $v_3$ $^3$He-$Au$ $v_2$ $^3$He-$Au$

$[\text{GeV/c}] T_p$

(light-heavy)

WB (IFJ PAN & UJK) eQCD15 15 / 22
Flow in $^3$He-Au

PHENIX Data 3+1D Hydro 200 GeV 0-5%

$^3$He-Au 200 GeV 0-5%

(mass ordering visible)
Femtoscopy in $^3$He-Au (HBT correlation radii)

- **b)** 
  - $R_{\text{side}}$ vs. $k_\perp$ [GeV] for $^3$He-Au 0-5%.
  - Data points: PHENIX 0-10%.
  - Symbols: ○ d-Au, ★ $^3$He-Au, ▲ d-Au.

- **a)**
  - $R_{\text{out}}$ vs. $k_\perp$ [GeV] for $^3$He-Au 0-5%.
  - Data points: PHENIX 0-10%.
  - Symbols: ○ d-Au, ★ $^3$He-Au, ▲ d-Au.

- **c)**
  - $R_{\text{long}}$ vs. $k_\perp$ [GeV] for $^3$He-Au 0-5%.
  - Data points: PHENIX 0-10%.
  - Symbols: ○ d-Au, ★ $^3$He-Au, ▲ d-Au.

- **d)**
  - $R_{\text{out-long}}^2$ vs. $k_\perp$ [GeV] for 200 GeV 0-5%.
  - Data points: PHENIX 0-10%.
  - Symbols: ○ d-Au, ★ $^3$He-Au, ▲ d-Au.
$^{12}\text{C-A}$

[more details in WB & Ruiz Arriola, PRL 112 (2014) 112501
Piotr Bożek, WB, Ruiz Arriola & Rybczyński, PRC 90 (2014) 064902]
Geometry vs multiplicity correlations in $^{12}\text{C}-\text{Pb}$

Two extreme cases of angular orientation
cluster plane parallel or perpendicular to the transverse plane:

- **flat-on**
  - higher multiplicity
  - higher triangularity
  - lower ellipticity

- **sidewise**
  - lower multiplicity
  - lower triangularity
  - higher ellipticity
Clusters: **(qualitative signal!)**

When $N_w \uparrow$ then $\langle \epsilon_3 \rangle \uparrow$ and $\langle \epsilon_2 \rangle \downarrow$

and $\langle \sigma(\epsilon_3)/\epsilon_3 \rangle \downarrow$, $\langle \sigma(\epsilon_2)/\epsilon_2 \rangle \uparrow$

No clusters:

similar behavior for $n = 2$ and $n = 3$
Ratios of cumulant moments

\[ v_n(4)/v_n(2) \text{ (wounded)} \]

- \( n=2, \text{ BEC} \)
- \( n=3, \text{ BEC} \)
- \( n=2, \text{ VMC} \)
- \( n=3, \text{ VMC} \)

10% 1% 0.1%
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)
- Studies of $^{12}$C-A collisions would open a completely new window of studying low-energy nuclear structure (ground state with $\alpha$ particles) with ultra-relativistic collisions. Can do hydro without hydro by taking ratios of moments