Ultra-relativistic light-heavy nuclear collisions and collectivity

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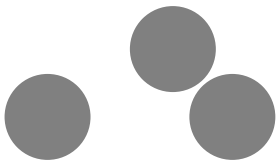
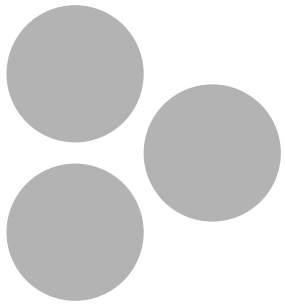
^{3}He 

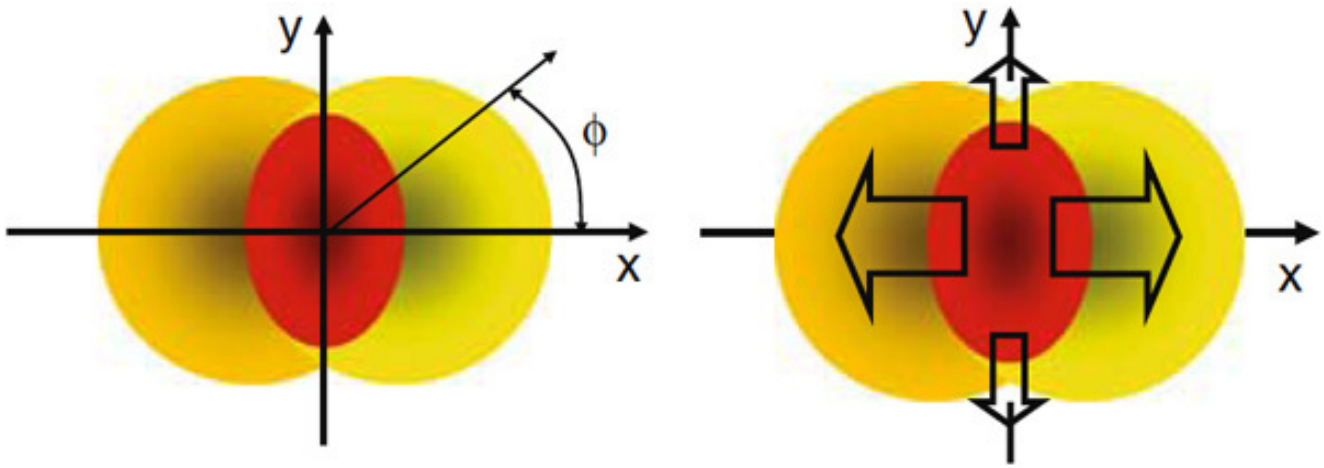
^{12}C 

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

Flow

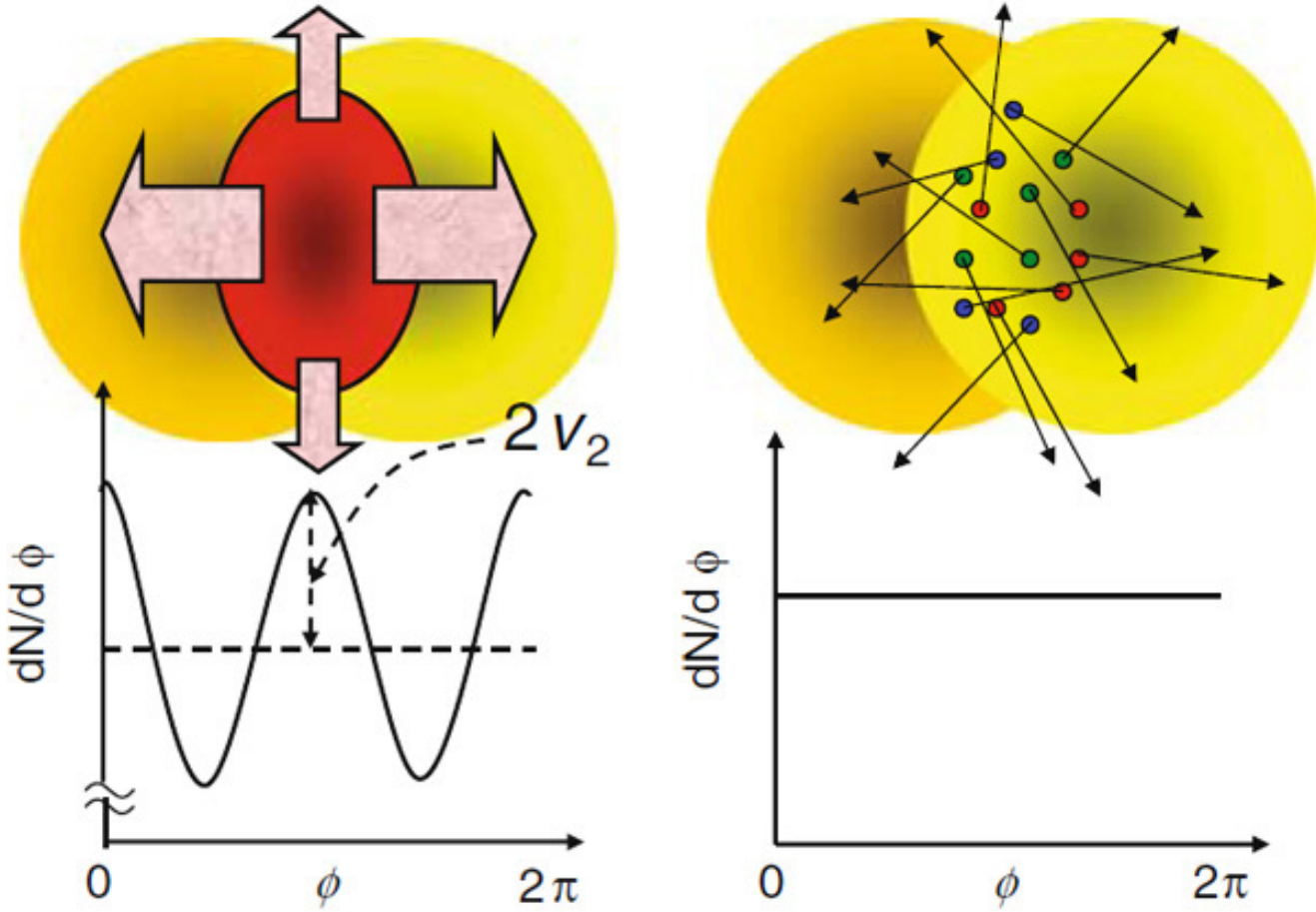
Phenomenon of flow

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

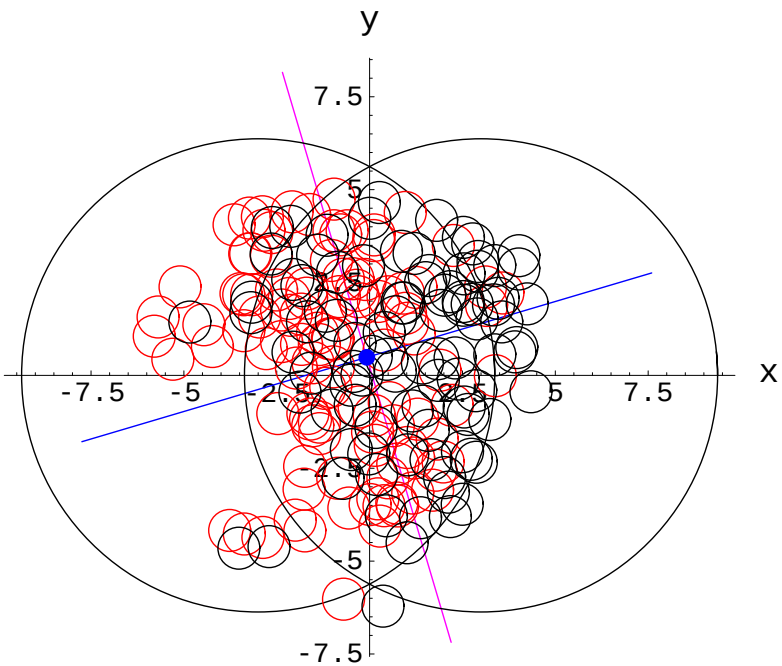


[ALICE]

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

Harmonic flow from shape+fluctuations

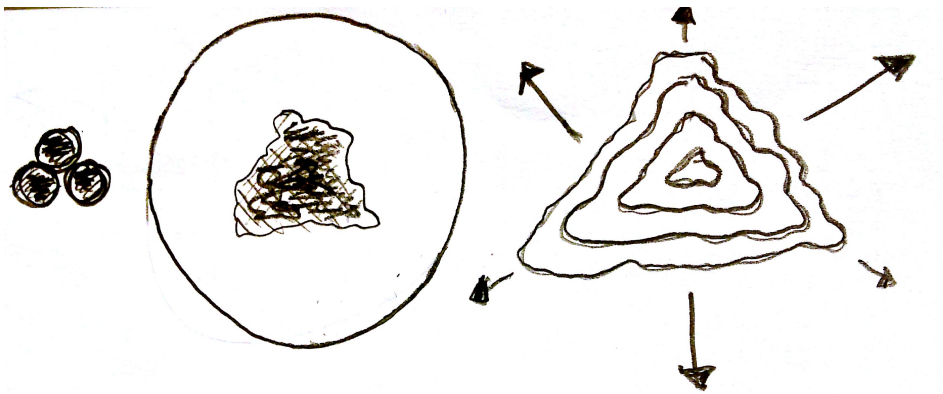
Wounded nucleons – experienced at least one inelastic collision
[Białas, Błeszyński & Czyż]



- 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

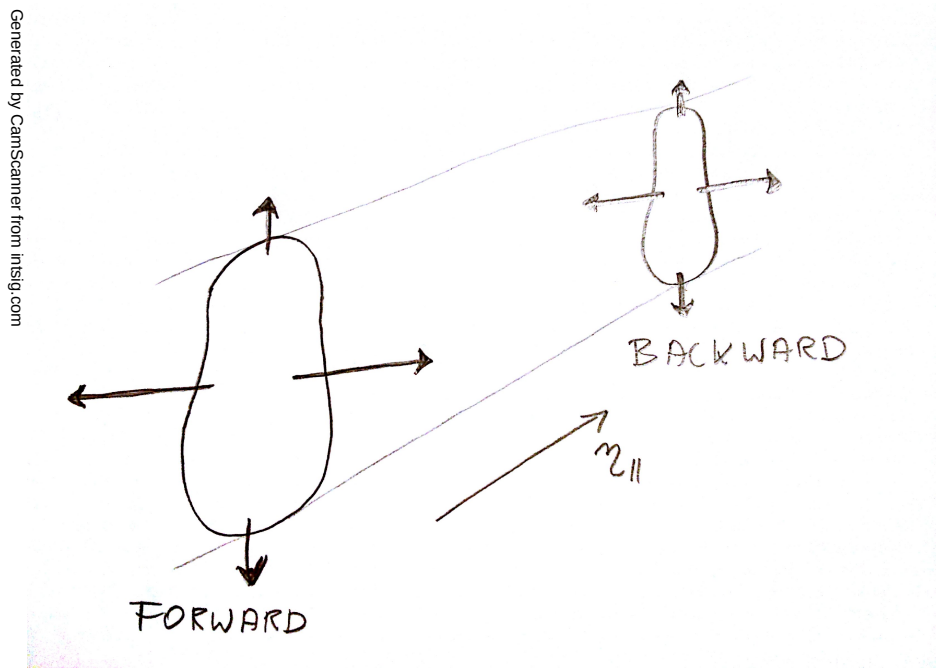
asymmetry of shape $\rightarrow$ asymmetry of initial fireball $\rightarrow$
$\rightarrow$ hydro or transport $\rightarrow$ collective harmonic flow



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 α structure

Factorization of the transverse and longitudinal distributions

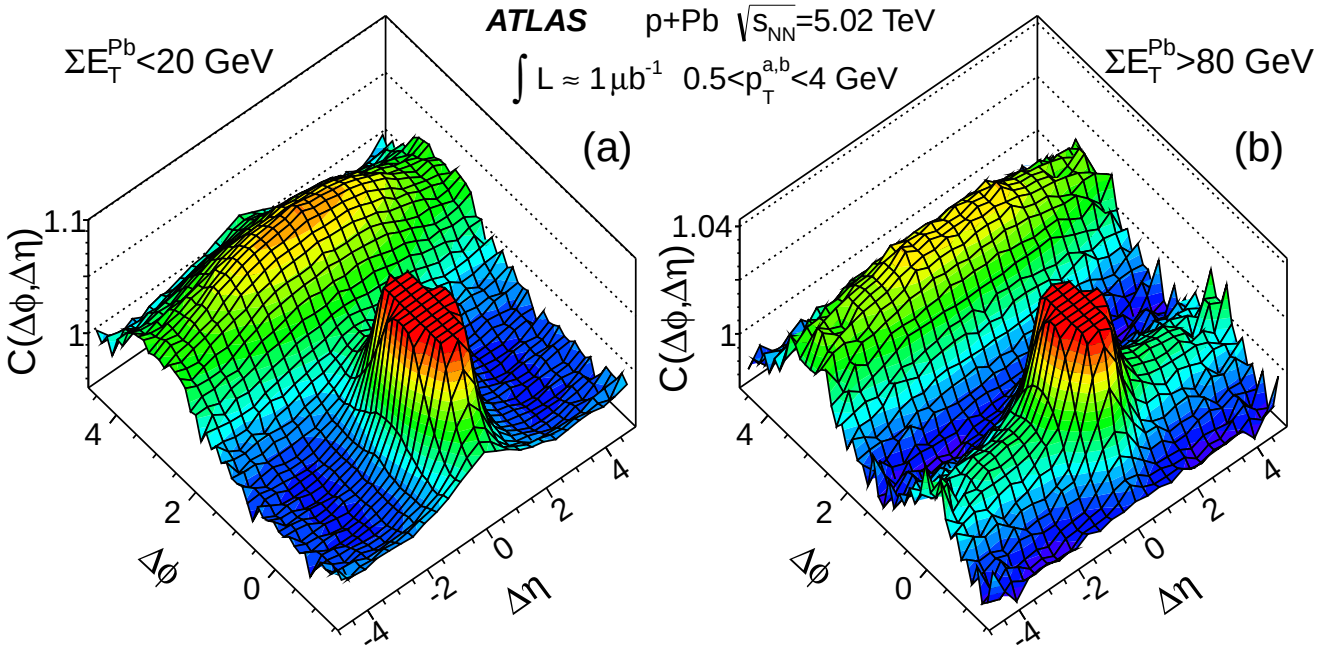


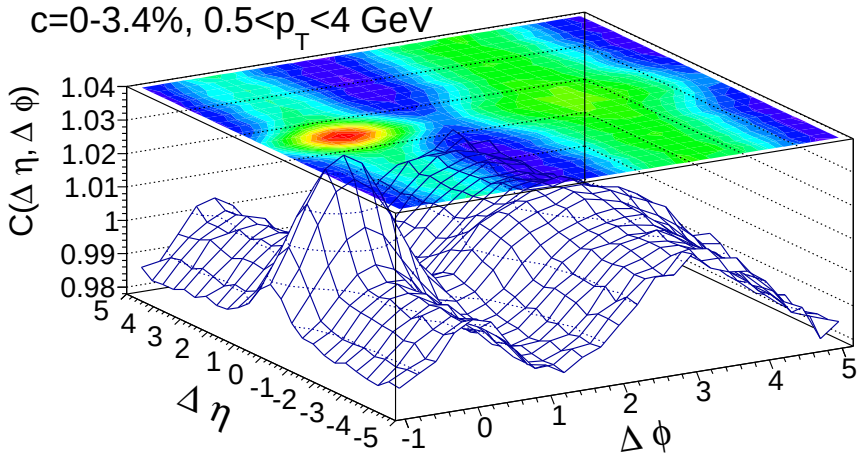
alignment of F and B event planes (can be checked experimentally)

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

Surfers - the near-side ridge

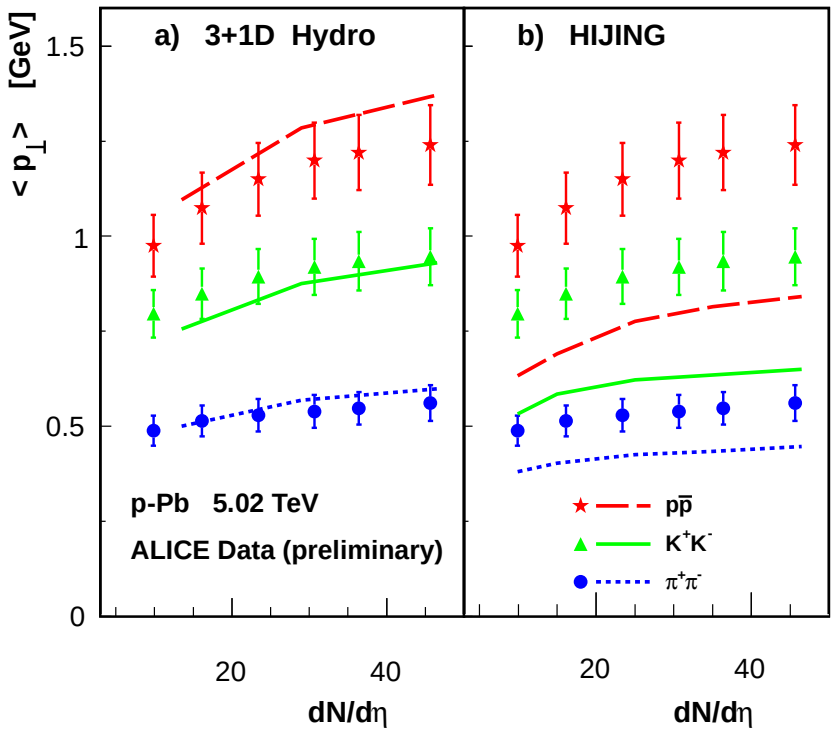
Ridge in p-Pb: ATLAS vs 3+1D hydro

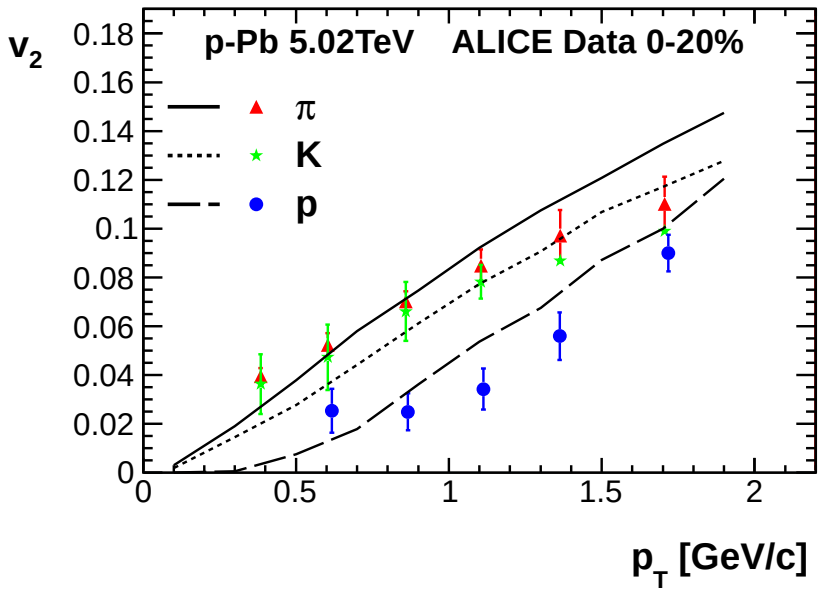




[another approach: CGC-based calculation by Dusling & Venugopalan]

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 ϵ_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

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

(κ_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:

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

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

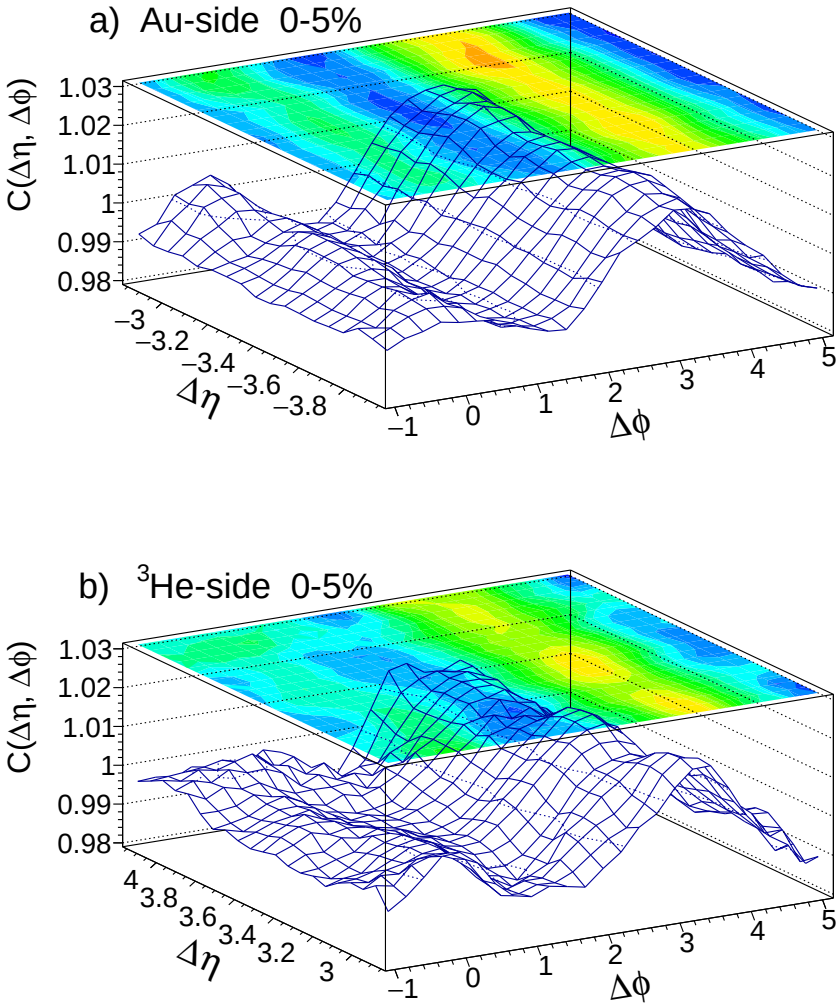
(infer limited info on flow from just the eccentricities, no hydro!)

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

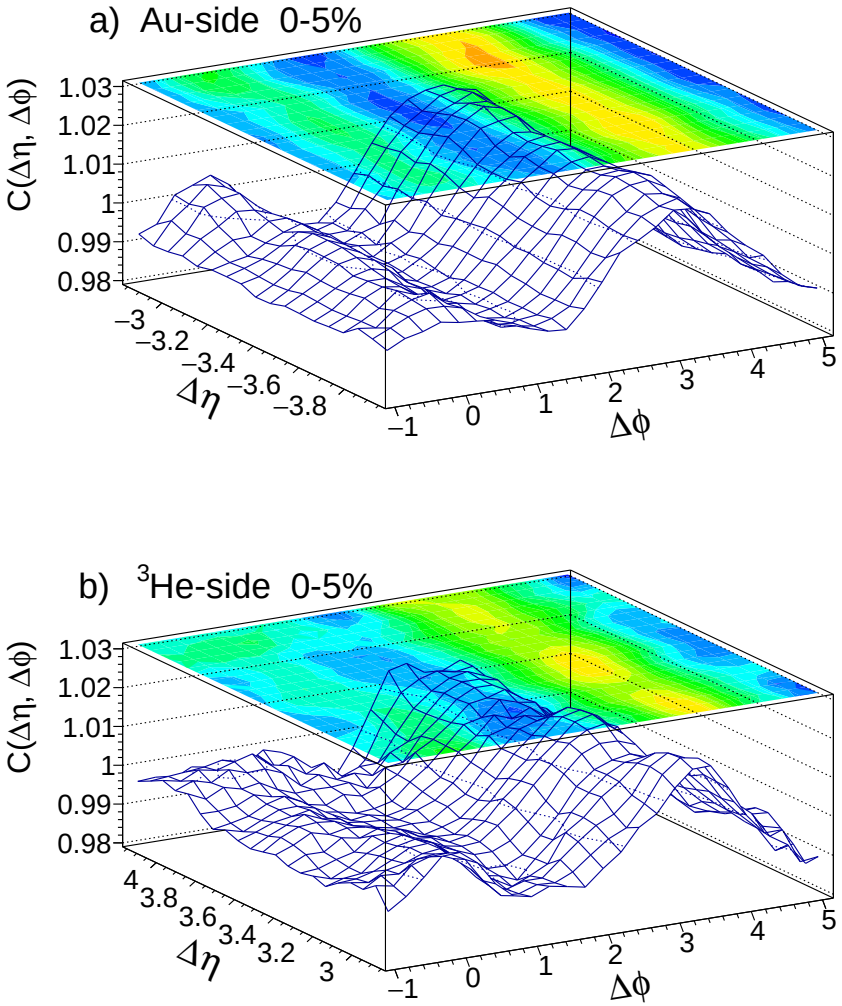
^{3}He-Au

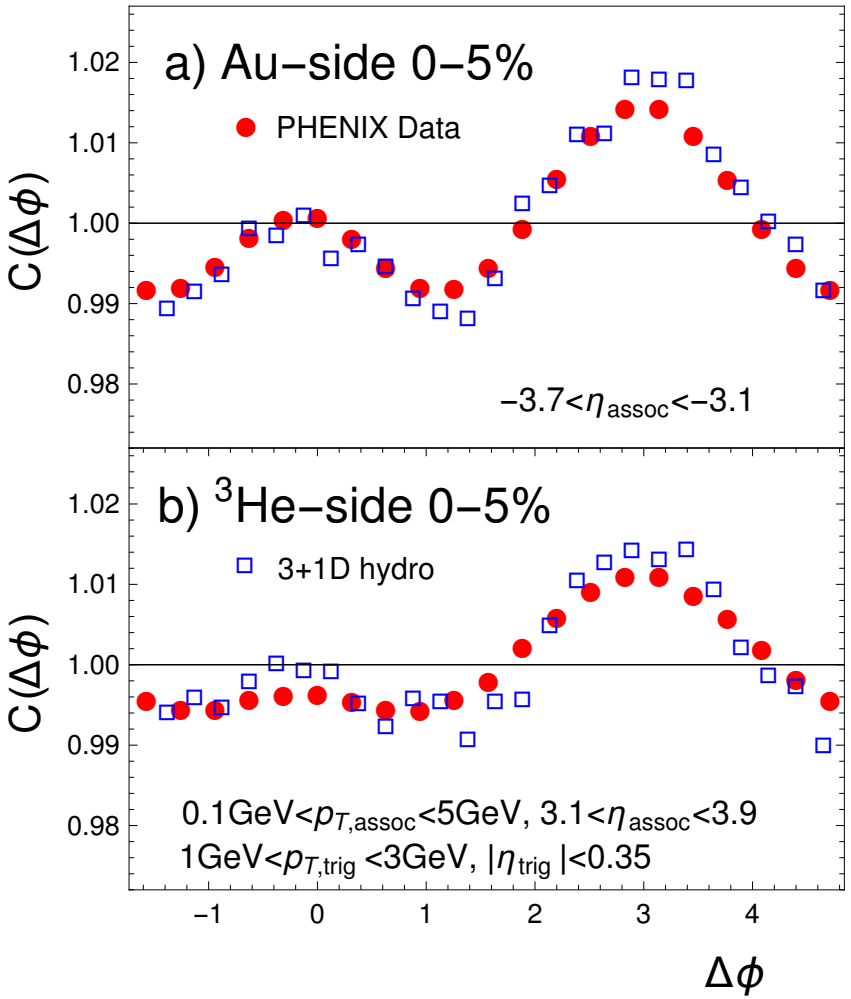
[more details in Bożek & WB, PLB 739 (2014) 308 and arXiv:1503.00468]

Ridges in ^{3}He-Au



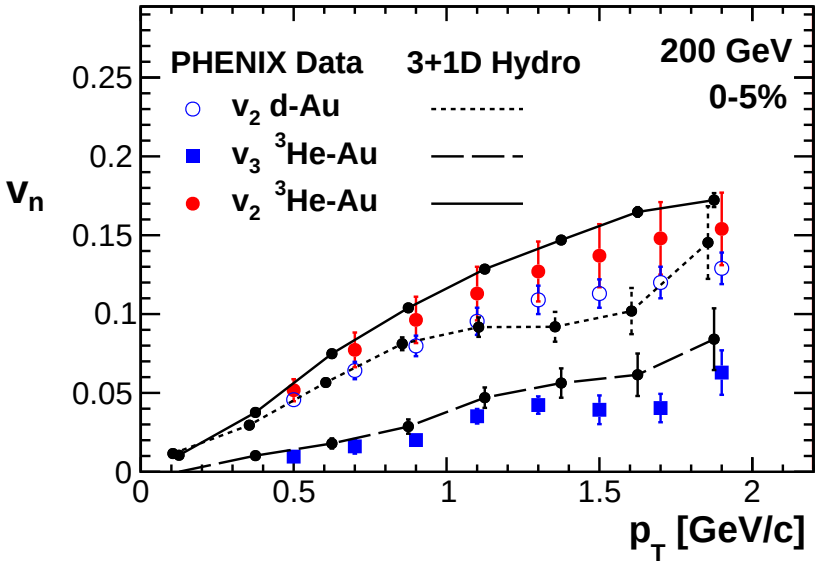
Ridges in ^{3}He-Au



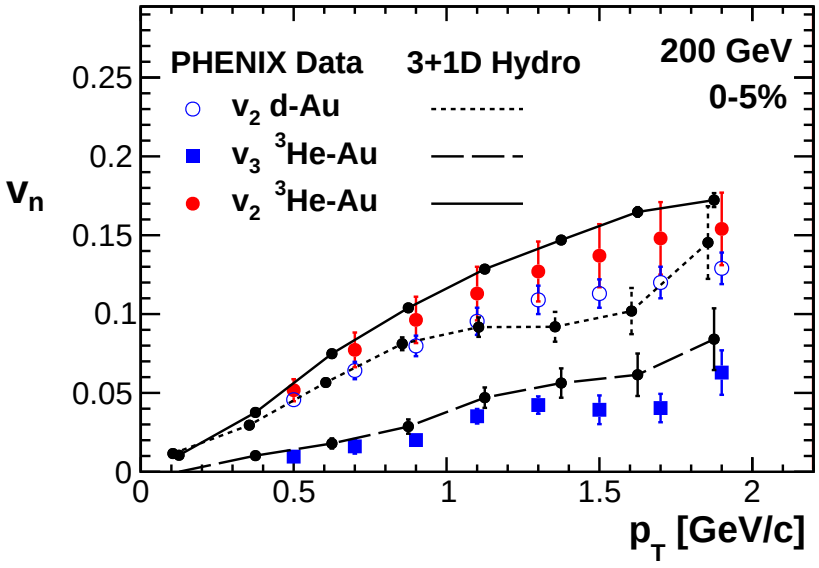


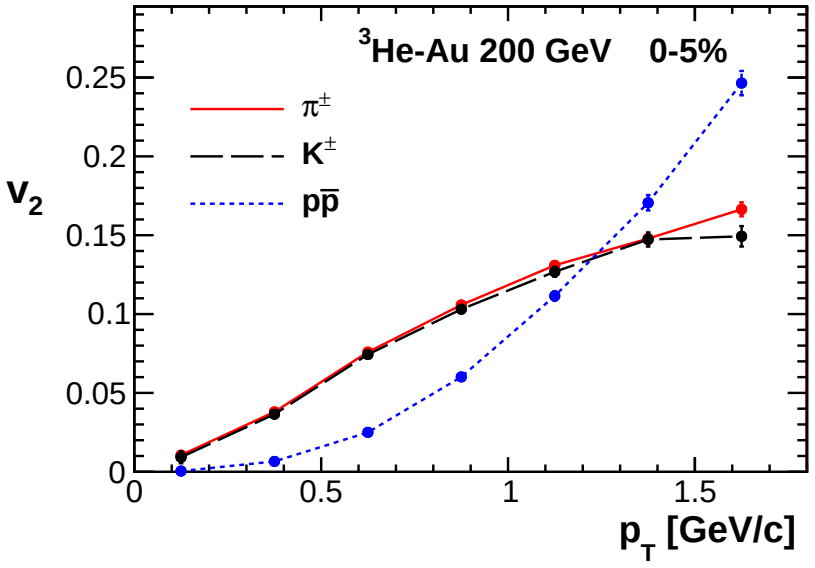
(seen on both pseudorapidity sides)

Flow in ^{3}He-Au



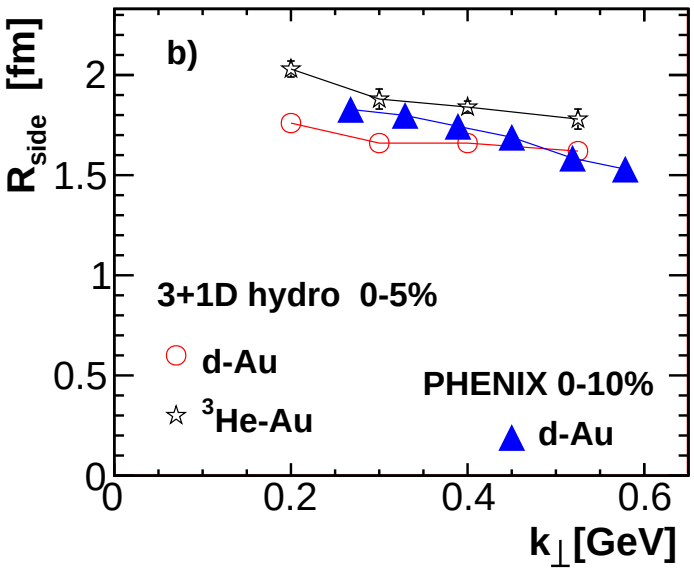
Flow in ^{3}He-Au

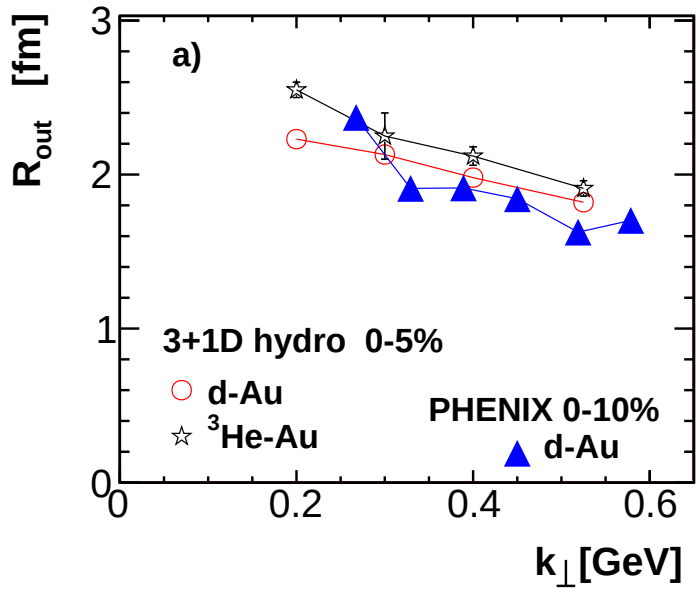


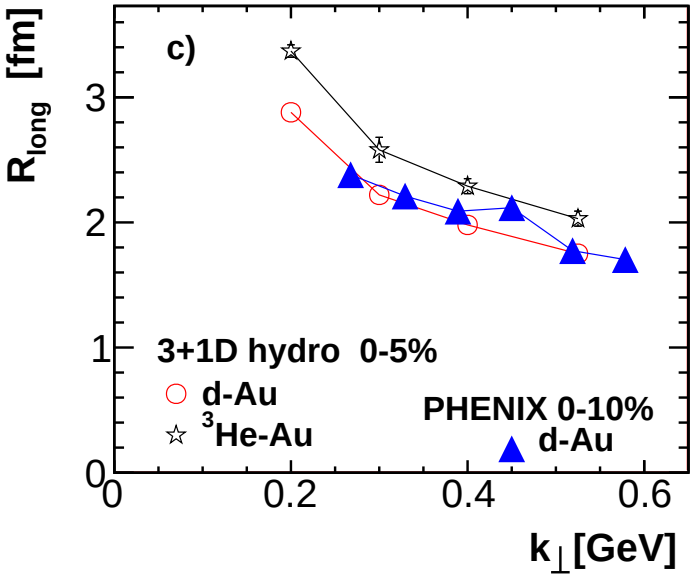


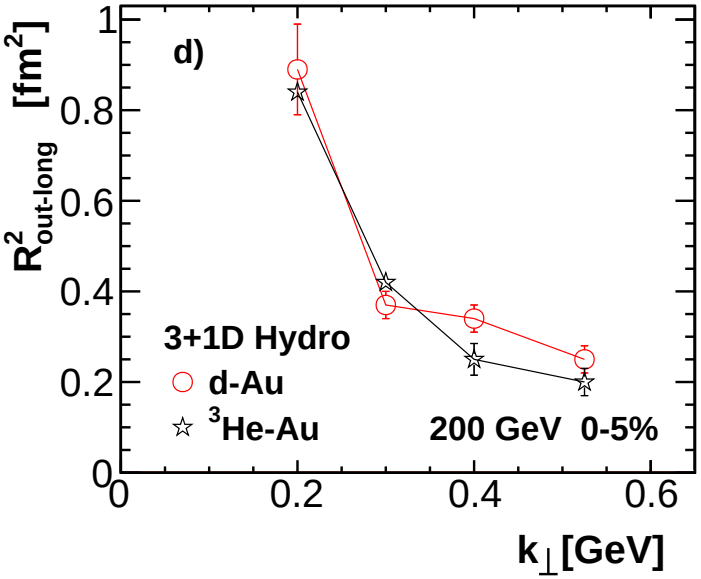
(mass ordering visible)

Femtoscopy in ^{3}He-Au (HBT correlation radii









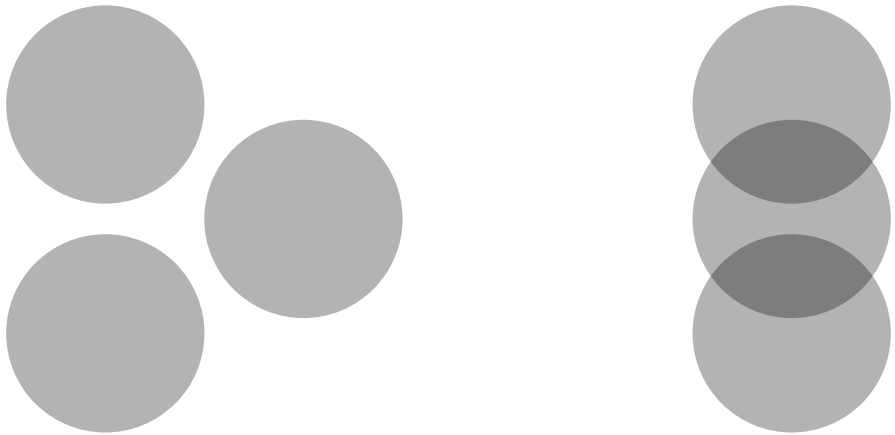
^{12}C-A

[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}C-Pb

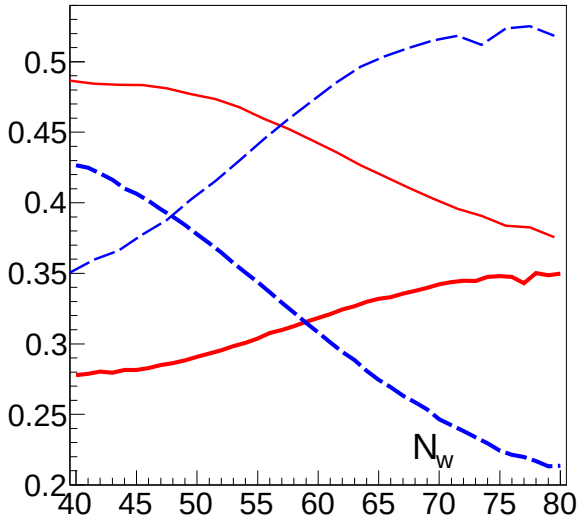
Two extreme cases of angular orientation

cluster plane parallel or perpendicular to the transverse plane:

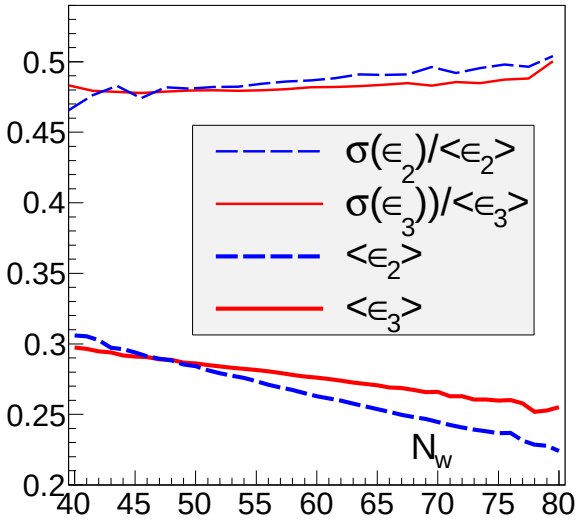


flat-on	sidewise
higher multiplicity	lower multiplicity
higher triangularity	lower triangularity
lower ellipticity	higher ellipticity

Ellipticity and triangularity vs multiplicity



clustered



unclustered

Clusters: (qualitative signal!)

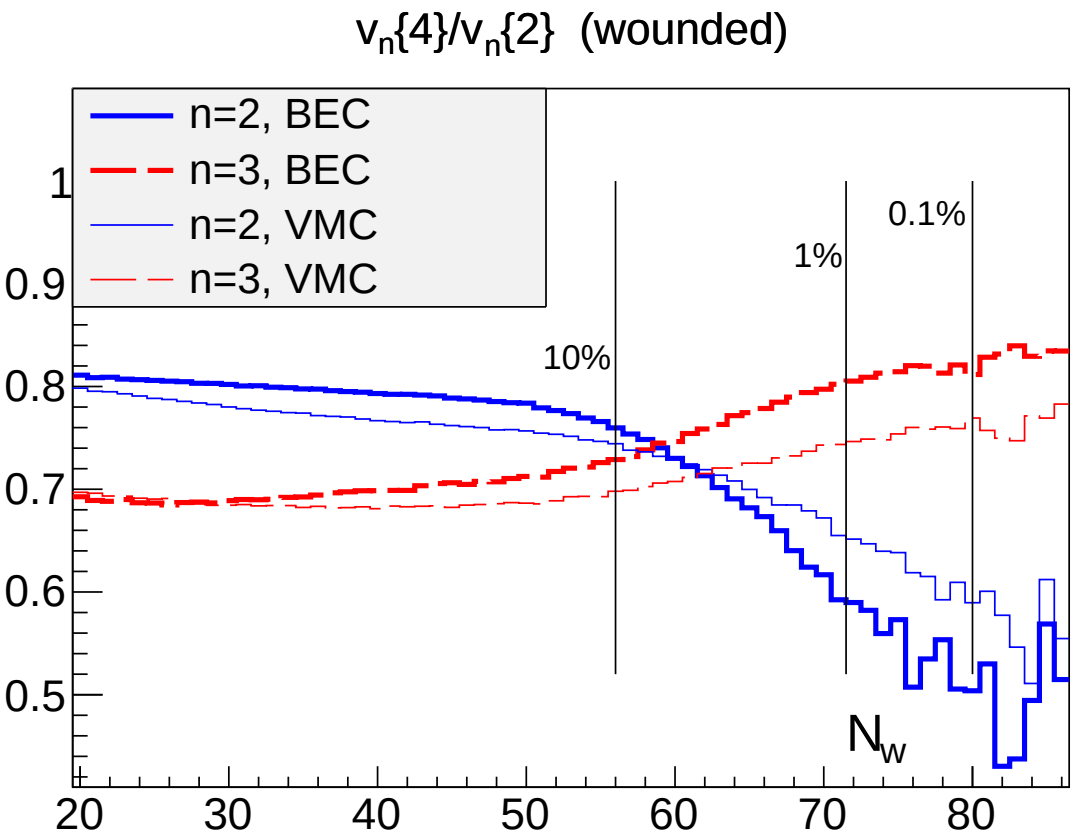
When $N_w \nearrow$ then $\langle\epsilon_3\rangle \nearrow$ and $\langle\epsilon_2\rangle \searrow$

and $\langle\sigma(\epsilon_3)/\epsilon_3\rangle \searrow$, $\langle\sigma(\epsilon_2)/\epsilon_2\rangle \nearrow$

No clusters:

similar behavior for $n = 2$ and $n = 3$

Ratios of cumulant moments



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 α particles) with ultra-relativistic collisions. Can do hydro without hydro by taking ratios of moments