Signatures of hydrodynamic behavior in small collision systems

by
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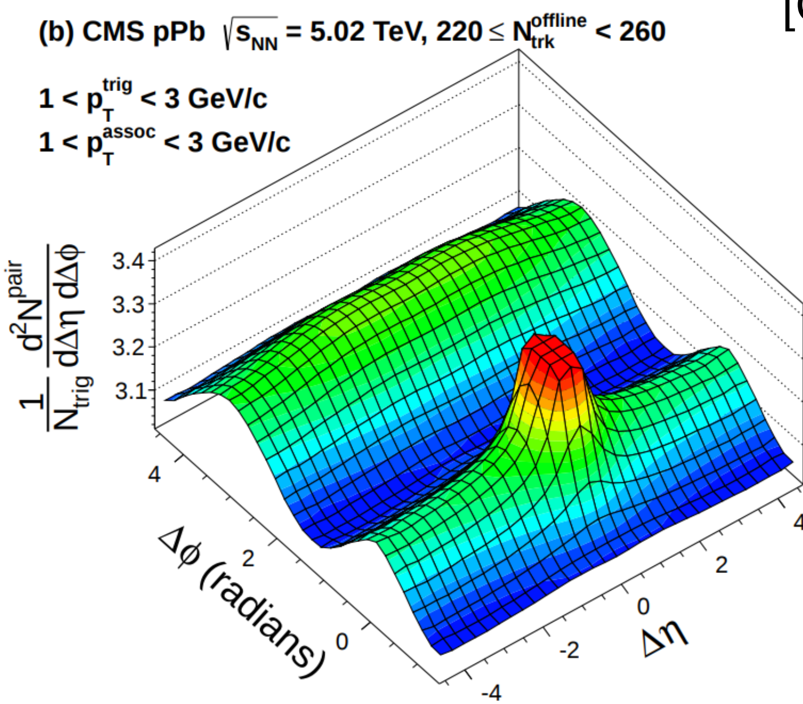
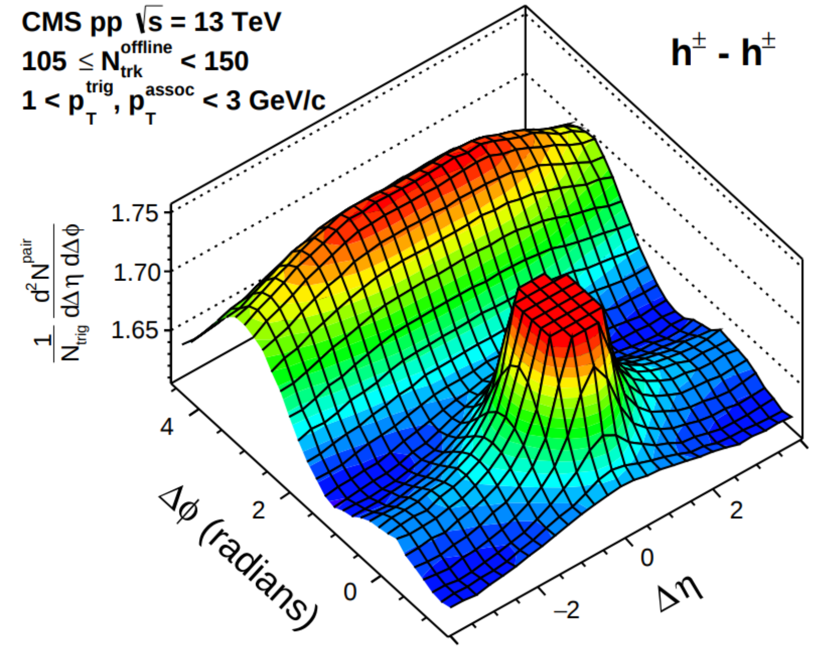
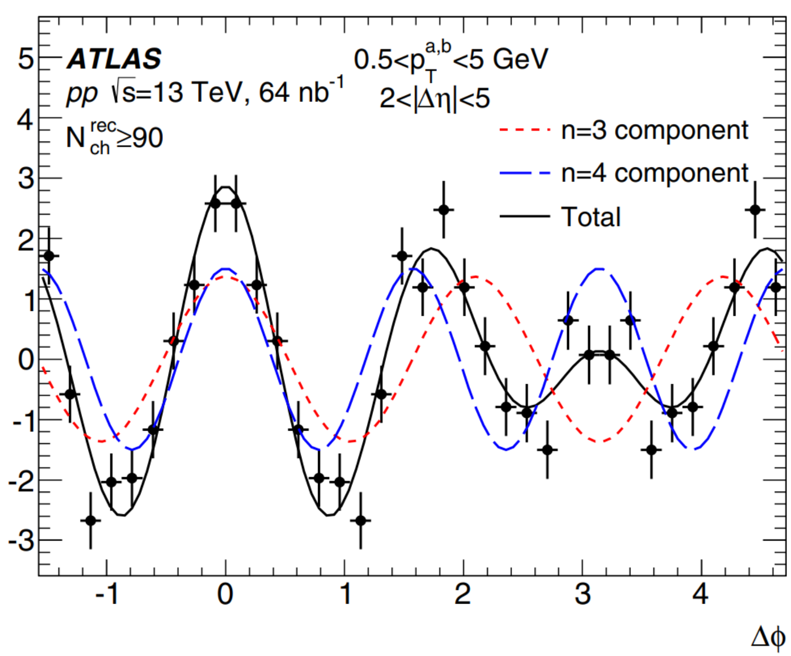
Typical signatures of final-state collectivity observed in small systems
(also p+Au and d+Au).

[CMS Collaboration, **arXiv 1305:0609** and **1606:06198**]







[ATLAS Collaboration, **arXiv 1609:06213**]

Natural explanation in the hydrodynamic framework of heavy-ion collisions.

- understanding long-range anisotropy: feature #1

Particles are emitted independently at the freeze-out surface.

$$\left\langle \left\langle e^{in\left(\phi^{(1)}-\phi^{(2)}\right)} \right\rangle \right\rangle \stackrel{\text{(flow)}}{=} \boxed{\left\langle \left\langle e^{in\phi^{(1)}} \right\rangle \left\langle e^{-in\phi^{(2)}} \right\rangle \right\rangle} = \left\langle v_n^{(1)} v_n^{(2)} e^{in(\Psi_n^{(1)}-\Psi_n^{(2)})} \right\rangle$$

$$c_2\{2\}$$

$$\frac{2\pi}{N_{\text{pairs}}} \left\langle \frac{dN_{\text{pairs}}}{d\Delta\phi} \right\rangle \stackrel{\text{(flow)}}{=} 1 + \sum_{n=1}^{\infty} 2 \boxed{\left\langle v_n^{(1)} v_n^{(2)} \right\rangle} \cos n(\Delta\phi)$$

[Luzum, **arXiv 1107:0592**]

Doing so, all the correlations surviving after averaging over events are due to genuine **collective** effects.

Corrections to this picture are ‘nonflow’ (typically killed off by rapidity gaps, though we have to assume that the momentum densities do not depend on rapidity).

- understanding long-range anisotropy: feature #2

The hydro evolution converts spatial anisotropies into momentum anisotropies. Initial anisotropies quantified by ε_n .

[Teaney and Yan, **arXiv 1010:1876**]

For n=2,3 hydro shows:

$$v_n = k_n \varepsilon_n$$

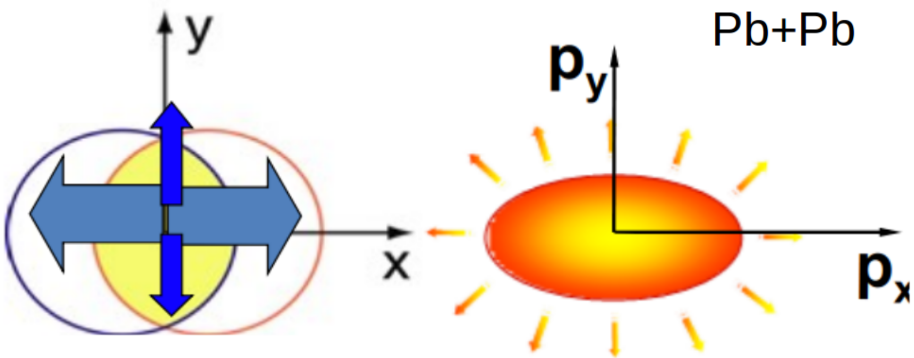
In practice, then, an elliptic anisotropy yields elliptic flow, a triangular anisotropy yields triangular flow...

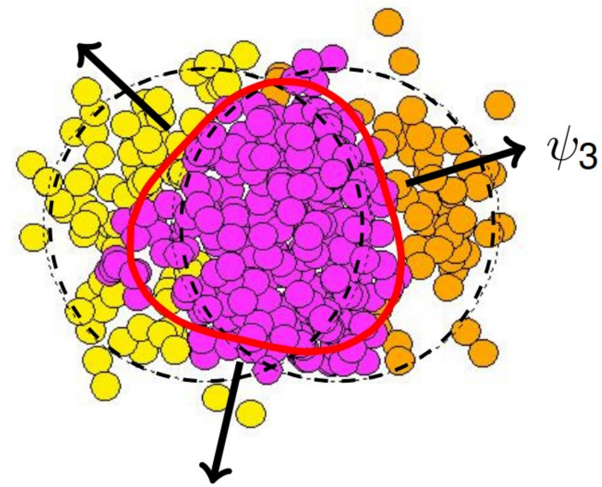
Important: any observable which is insensitive to the scaling constant is a direct probe of the initial state, e.g., ratios of cumulants. [Bhalerao, Luzum, Ollitrault, **arXiv 1104:4740**]

$$\frac{v_n\{\mu\}}{v_n\{\nu\}} = \frac{\varepsilon_n\{\mu\}}{\varepsilon_n\{\nu\}}$$

- understanding long-range anisotropy: feature #2

In AA collisions:





- V2 simply given by nonzero impact parameter (intrinsic almond geometry).
- V3, and V2 at b=0 from fluctuations (mainly participant nucleons).

In pA (and pp) collisions:

-V2 and V3 have the same origin, just fluctuations. No intrinsic geometry.
- in p+p and some models of p+A, need sub-nucleonic structures.

[Welsh, Singer, Heinz, **arXiv 1605:09418**]
[Mantisaari, Schenke, Shen, Tribedy, **arXiv 1705:03177**]
[Zhao, Zhou, Xu, Deng, Song, **arXiv 1801:00271**]

The previous features allow to make generic, model-independent predictions for several observables. But in small systems one comment is in order.

Going 'backwards':

Final-state v_n ⇒ Initial-state ε_n ⇒ initial density fluctuations ⇒ stronger gradients

Navier-Stokes:

$$\rho\left(\frac{\partial\vec{v}}{\partial t}+\vec{v}\cdot\vec{\nabla}\vec{v}\right)=-\vec{\nabla}P+\boxed{\eta\nabla^2\vec{v}}$$

⇒ **Larger viscous corrections!!**

How far can we go before hydro breaks down?
New questions triggered by collectivity in small systems.

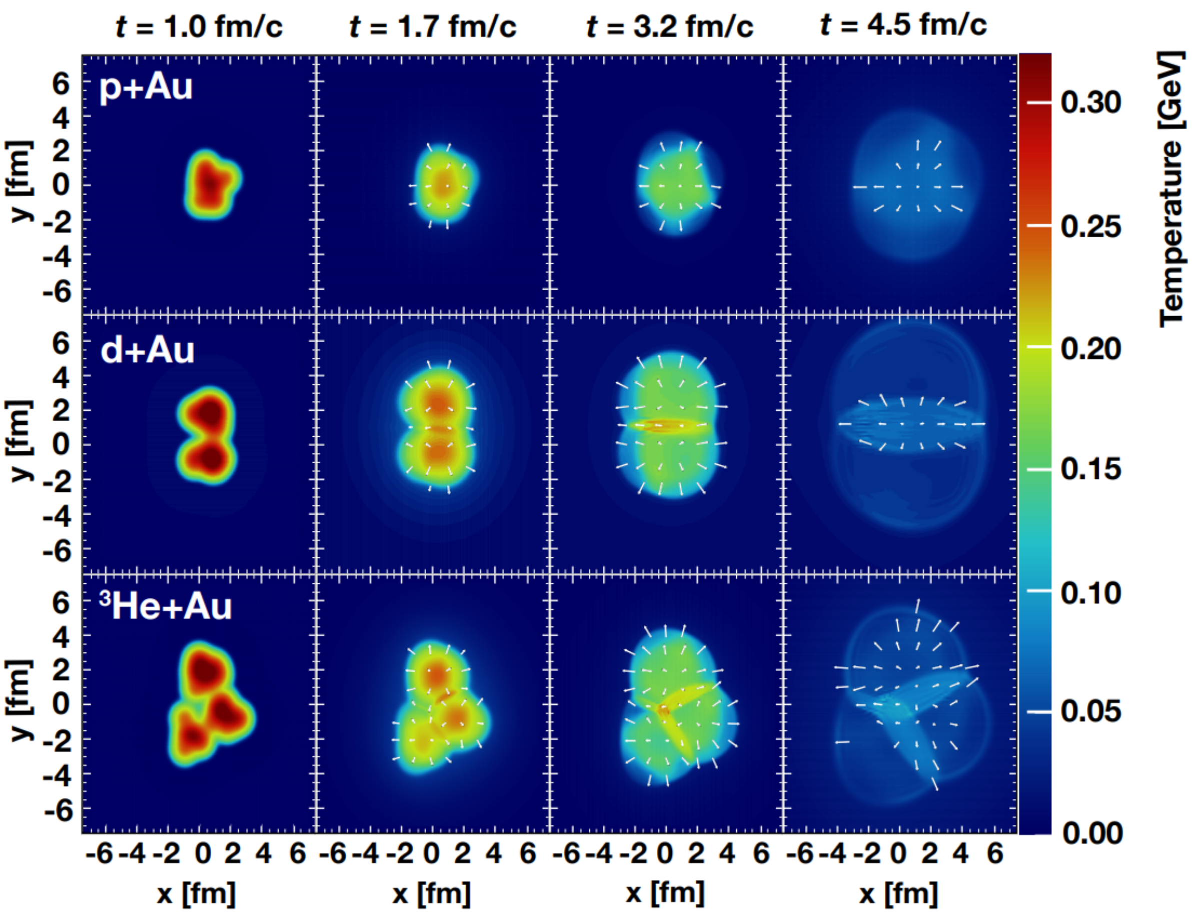
[more insight in Ryan Weller's talk]

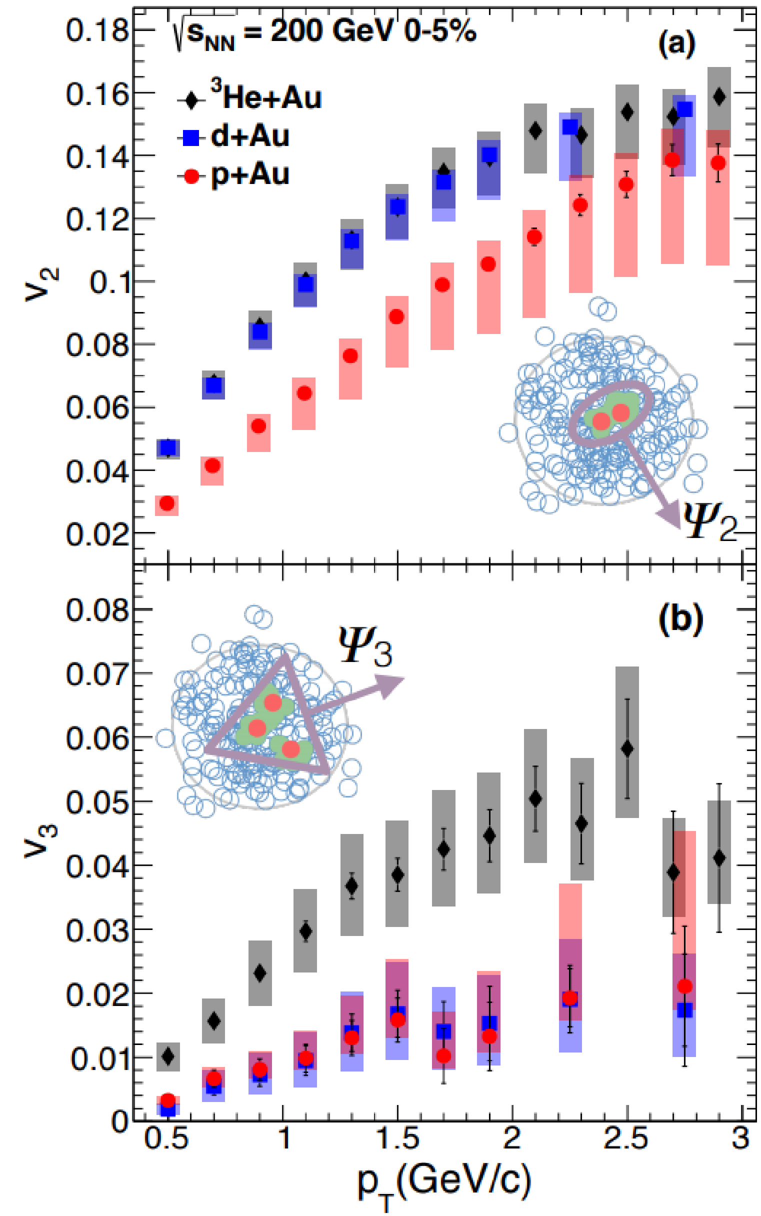
In the following, I assume hydro applies.

--> My goal is to show that we can understand nontrivial details of the measured observables in pA collisions:
rms anisotropies and **cumulants of flow fluctuations**.

The obvious prediction for rms anisotropies...

[PHENIX collaboration, arXiv 1805:02973]





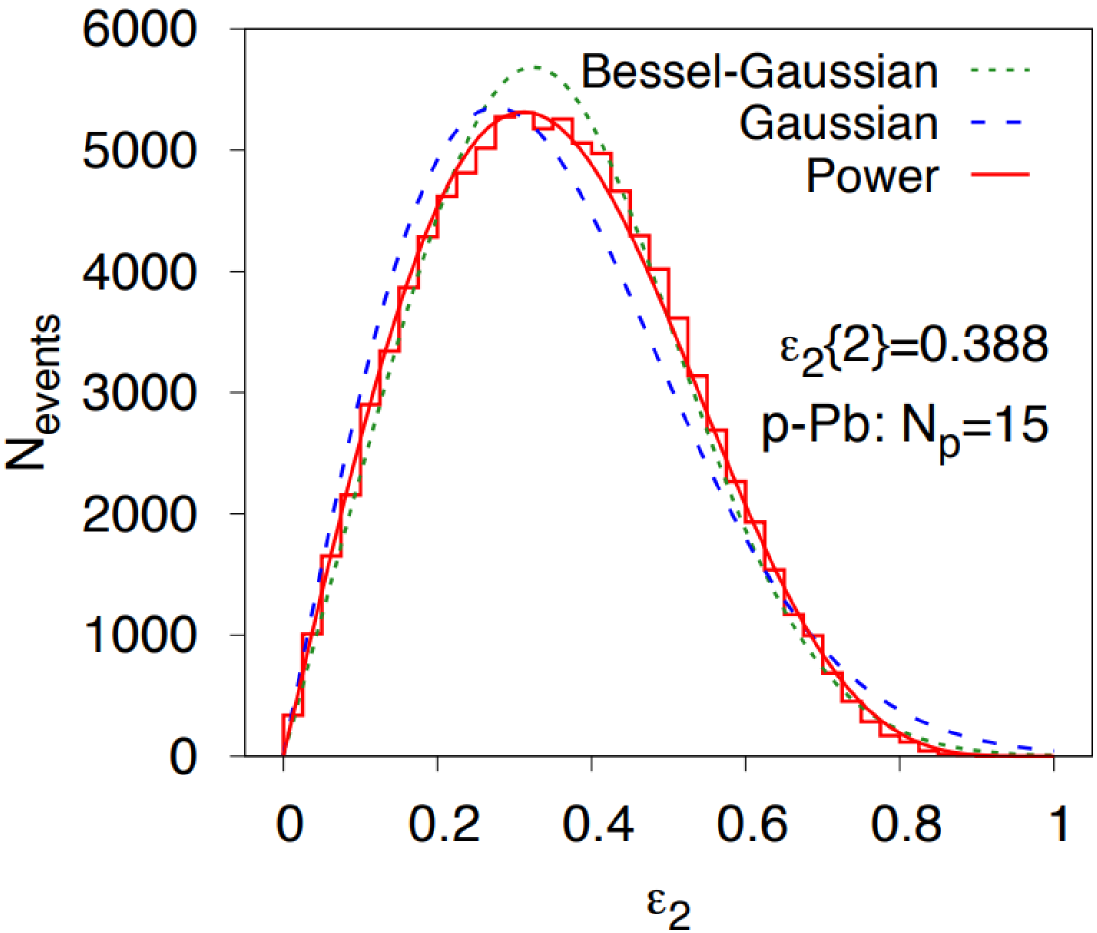
...all the expected trends are observed!
(they are highly nontrivial)

Easy. Let us move to something more involved. What about non-Gaussianities?

[Yan and Ollitrault, **arXiv 1312:6555**]

Power distribution: an "*almost*" exact result for the distribution of the eccentricity

$$P(\varepsilon) = 2\alpha\varepsilon(1-\varepsilon^2)^{\alpha-1}$$



- for anisotropies without preferred directions (fluctuations only).

- Non-Gaussianity generated through the bound eps <1.

- the parameter alpha fixes the width.

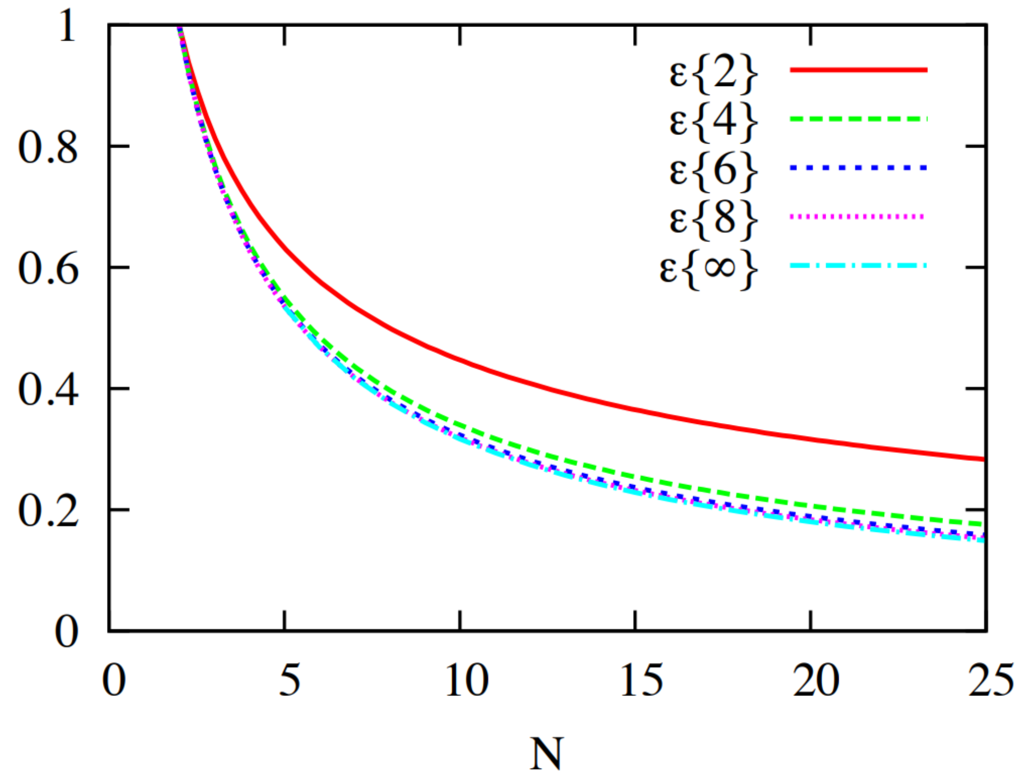
Properties:

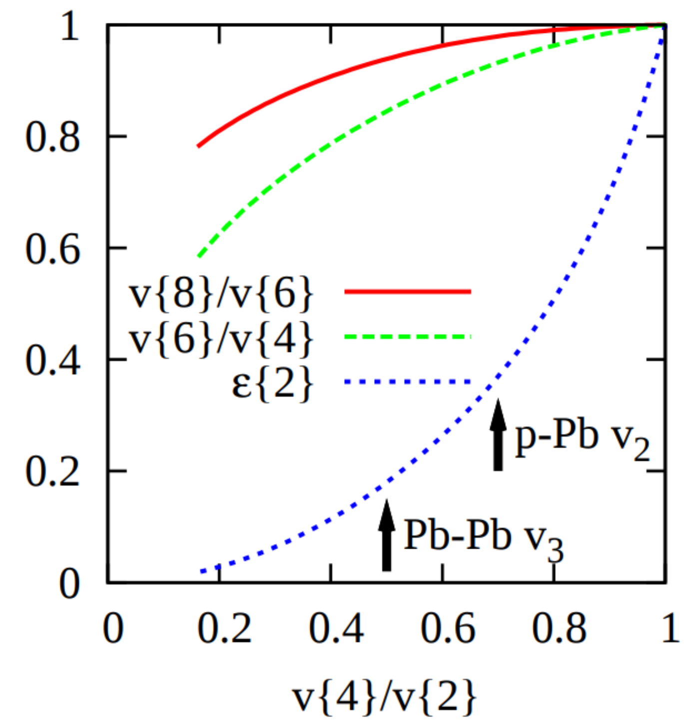
- it fixes the 'side' of the non-Gaussianity: all cumulants are positive (c{4}=-v{4}^4 < 0)

- higher orders are pretty much degenerate, i.e., the infamous v{2} > v{4} ~ v{6} ~ v{8} ...

- but more remarkably: it provides universal predictions for higher-order ratios as function of v{4}/v{2}=e{4}/e{2}.

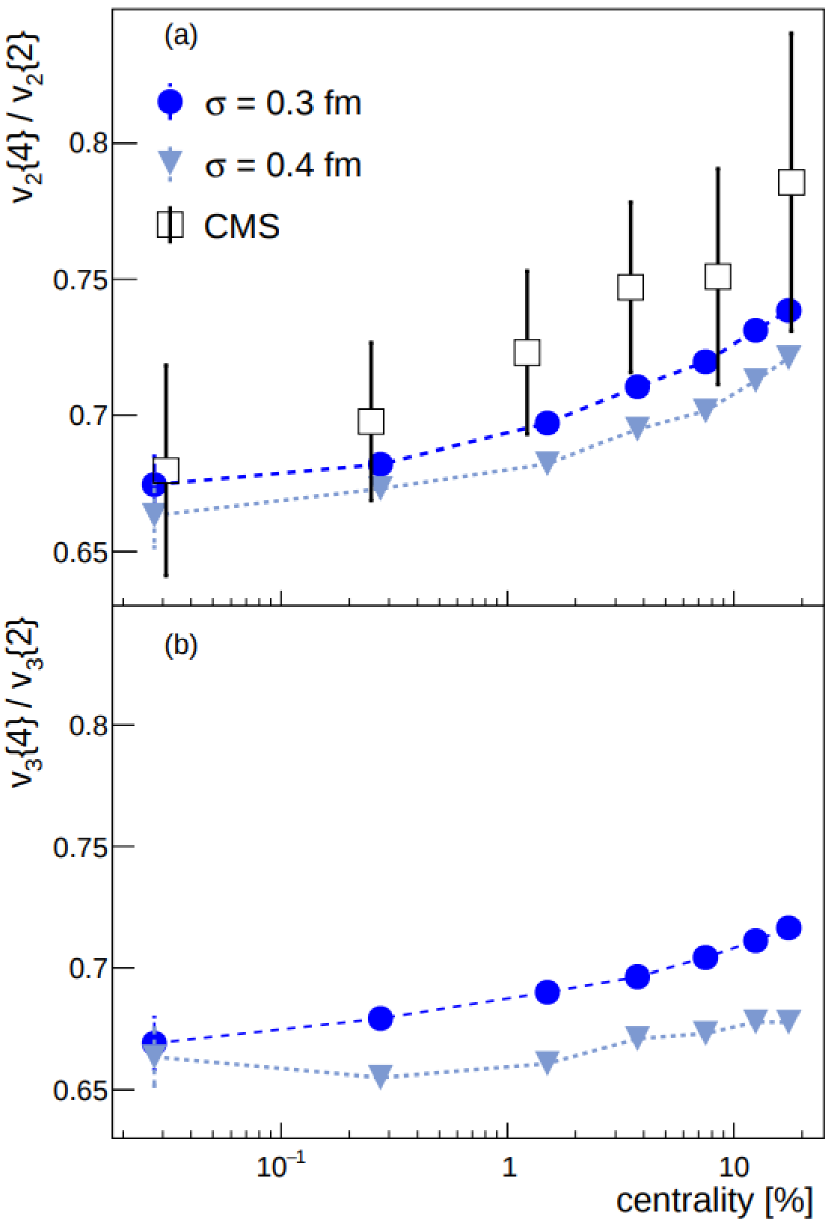
No Glauber. No models.
<u>Just universal lines!!!!</u>

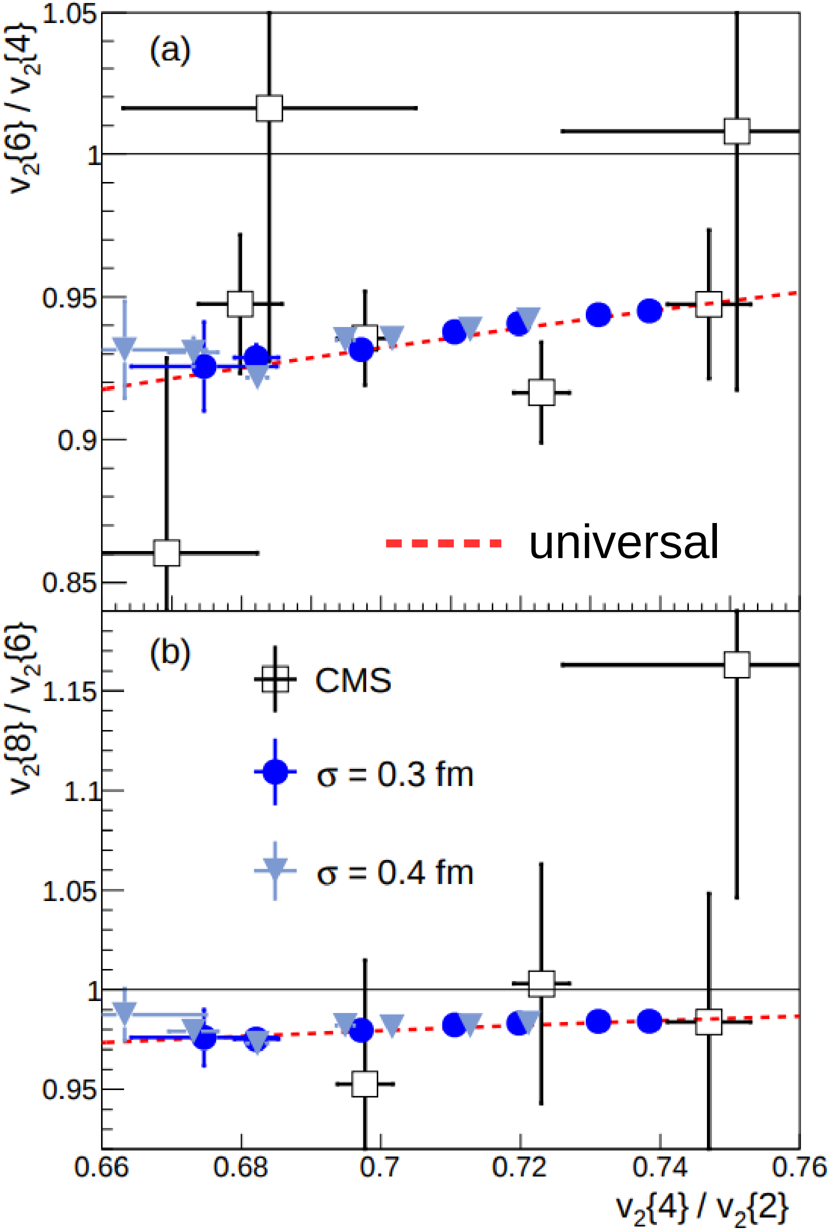




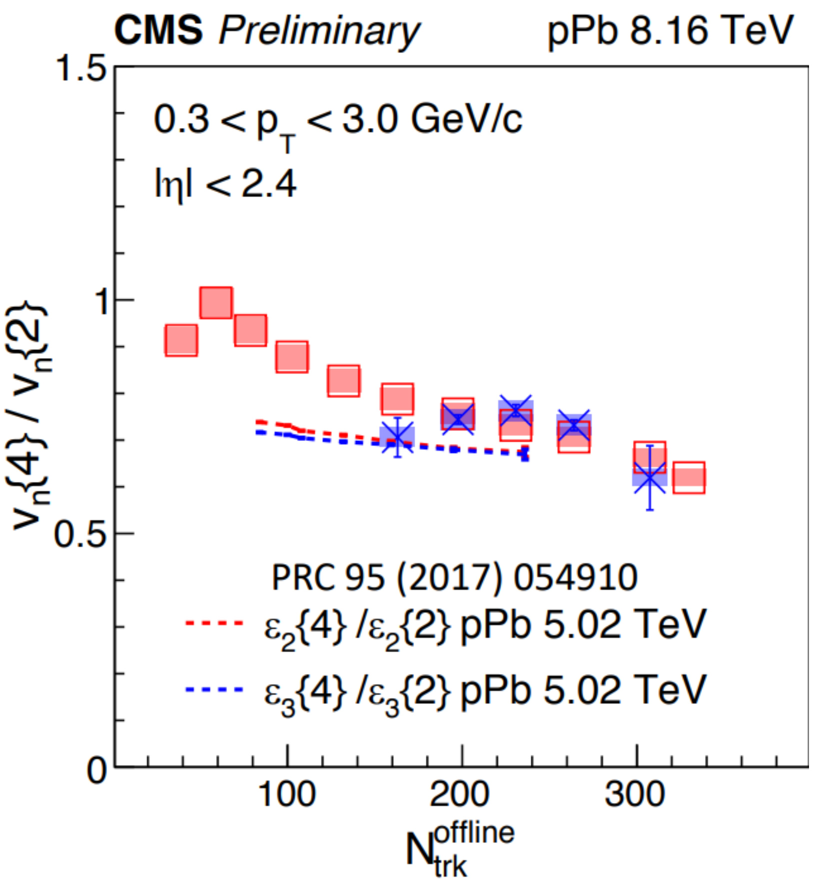
MC Glauber calculations + 5 TeV data

[Giacalone, Noronha-Hostler, Ollitrault, **arXiv 1702:01730**]
+
[CMS Collaboration, **arXiv 1502:05382**]

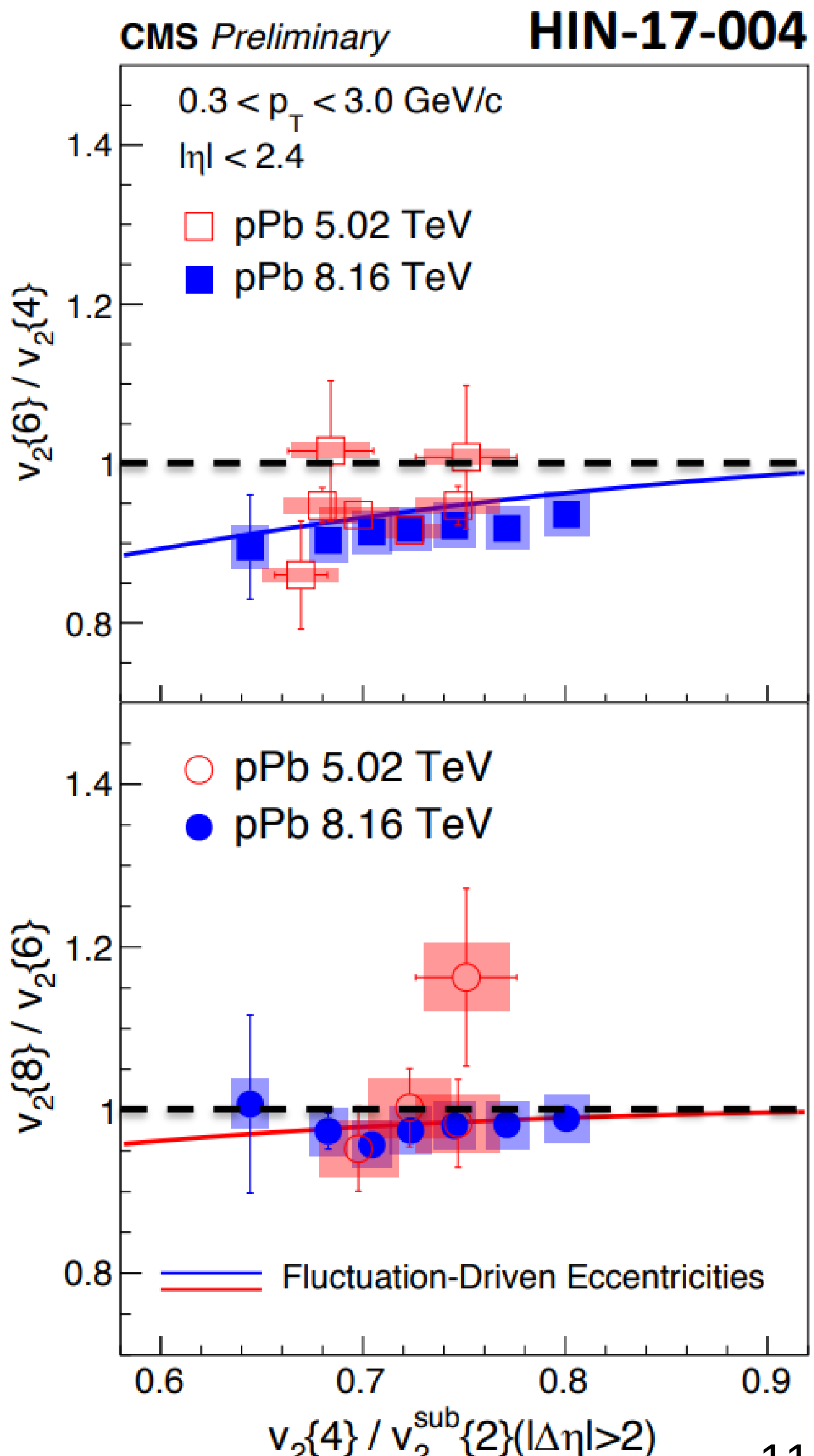




NEW data !!! (preliminary)

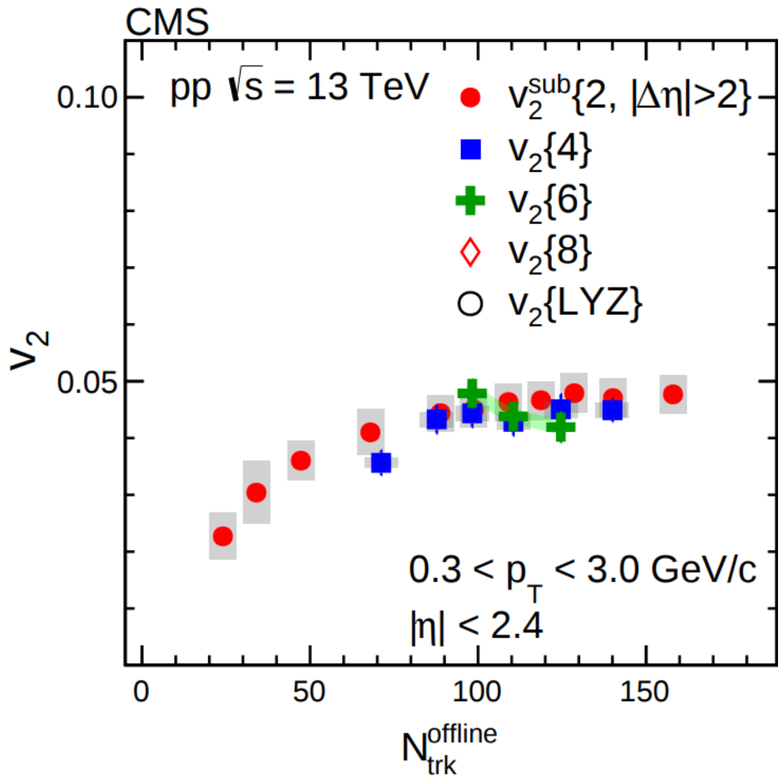


[QM18 talk by Quan Wang]



Breakthrough results about collectivity in small systems.

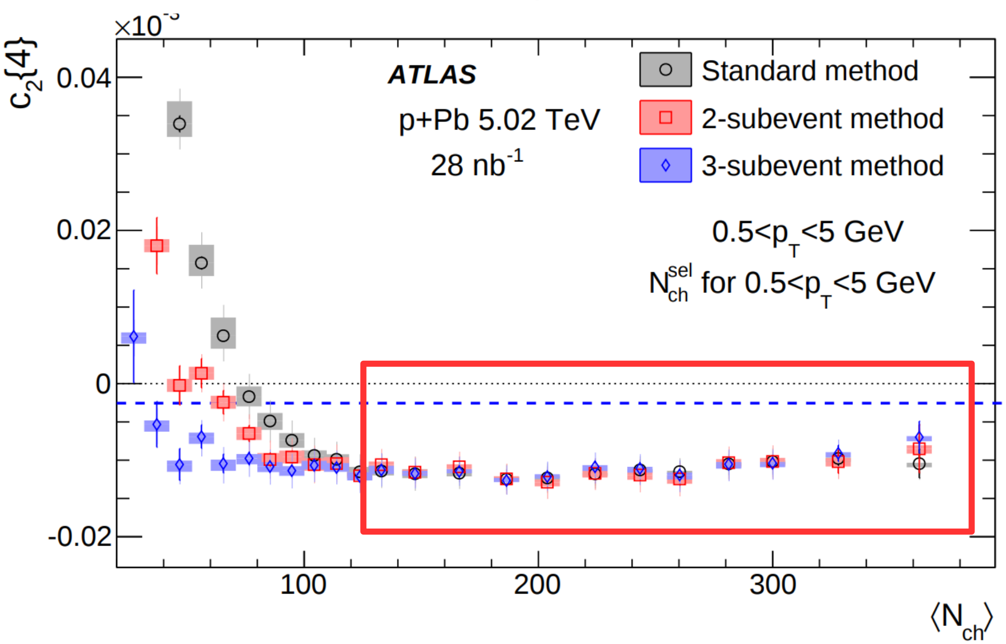
A word about p+p and nonflow.

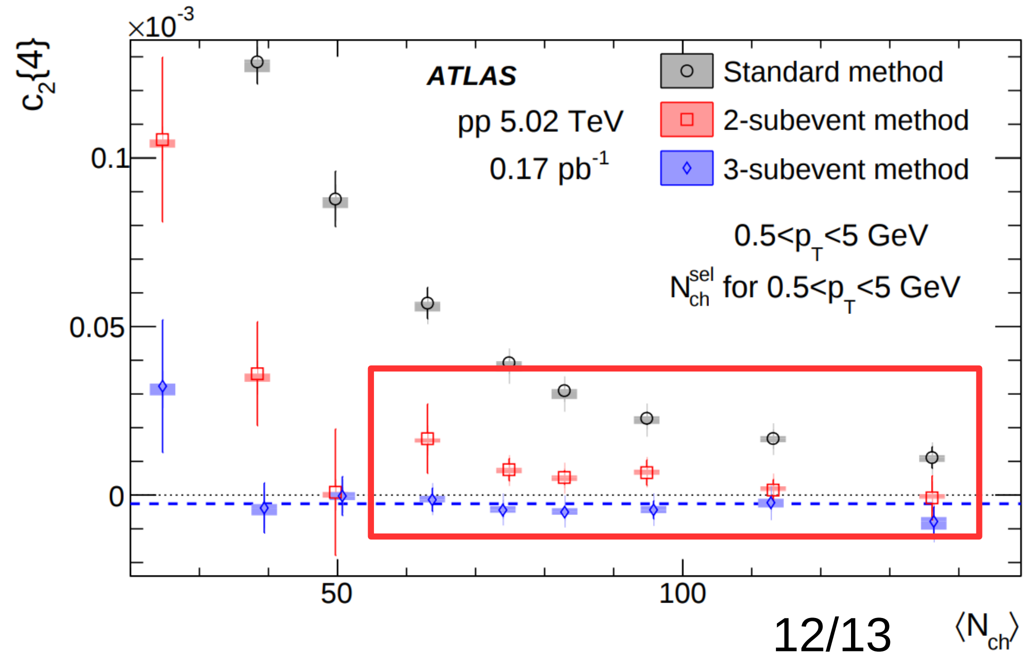


CMS measured v{2}~v{4} in p+p, not predicted by hydrodynamics!
[CMS Collaboration, **arXiv 1606:06198**]

ATLAS solved the issue applying subevents to remove nonflow in the 4-particle correlation.
[ATLAS Collaboration, **arXiv 1708:06198**]

Results rather unchanged in p+Pb, but in p+p they depend dramatically on the method..





- Conclusive remarks.
- Assuming hydro, the simple paradigm “response to geometry + independent particle emission” explains all data on flow in pA collisions with ridicolous precision: Experiments have essentially proven that the system is a fluid in p+A collisions.
- Still, not the end of the story: **i)** jet quenching is not observed in p+Pb collisions; **ii)** models where the momentum anisotropy is entirely due to initial state correlations (within CGC framework [Dusling, Mace, Venugopalan, **arXiv 1706:06260**]) present naturally the same behaviors as the hydrodynamic framework. Not clear where the truth lies/what the level of separation between the two approaches is.
- In p+p collisions, we are very far from clear signatures of genuine hydro: nonflow dominates even the 4-particle correlators. One would need v{6} or v{8} with sub-event methods, which is very demanding in terms of statistics, and is not even clear how many sub-events would be needed.
- Observables beyond rms anisotropies and cumulants will soon provide more insight (symmetric cumulants, plane correlators).
- Thank you all!

BACKUP

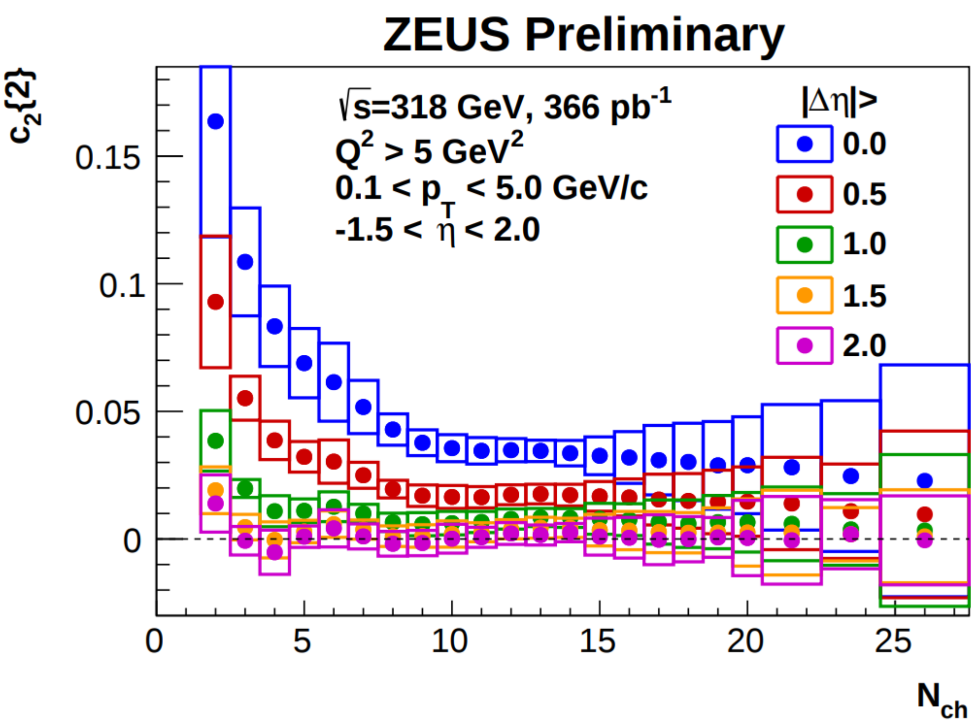
Cumulants in general.

$$v_n\{2\}^2 = \langle v_n^2 \rangle$$
$$v_n\{4\}^4 = 2\langle v_n^2 \rangle^2 - \langle v_n^4 \rangle$$
$$v_n\{6\}^6 = \frac{1}{4}\left[\langle v_n^6 \rangle - 9\langle v_n^2 \rangle\langle v_n^4 \rangle + 12\langle v_n^2 \rangle^3\right]$$
$$v_n\{8\}^8 = \frac{1}{33}\left[144\langle v_n^2 \rangle^4 - 144\langle v_n^2 \rangle^2\langle v_n^4 \rangle + 18\langle v_n^4 \rangle^2 + 16\langle v_n^2 \rangle\langle v_n^6 \rangle - \langle v_n^8 \rangle\right]$$

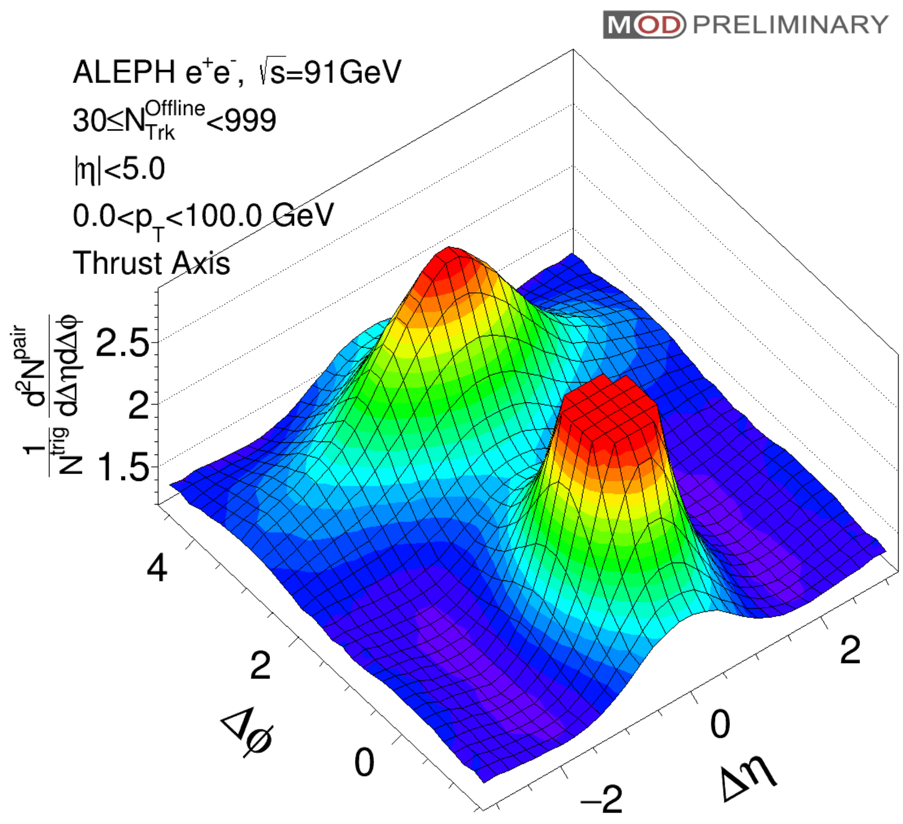
Application to power and Bessel-Gaussian distributions:

	Gauss	BG	Power
$\varepsilon\{2\}$	σ	$\sqrt{\sigma^2 + \bar{\varepsilon}^2}$	$\frac{1}{\sqrt{1+\alpha}}$
$\varepsilon\{4\}$	0	$\bar{\varepsilon}$	$\left[\frac{2}{(1+\alpha)^2(2+\alpha)}\right]^{1/4}$
$\varepsilon\{6\}$	0	$\bar{\varepsilon}$	$\left[\frac{6}{(1+\alpha)^3(2+\alpha)(3+\alpha)}\right]^{1/6}$
$\varepsilon\{8\}$	0	$\bar{\varepsilon}$	$\left[\frac{48\left(1+\frac{5\alpha}{11}\right)}{(1+\alpha)^4(2+\alpha)^2(3+\alpha)(4+\alpha)}\right]^{1/8}$

Going to even smaller systems..



[QM18 talk by Jacobus Onderwaater]



[QM18 talk by Yen-Jie Lee]

No evidence of collective flow.