Collectivity in pA and AA

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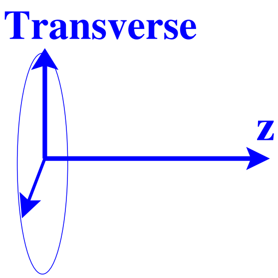
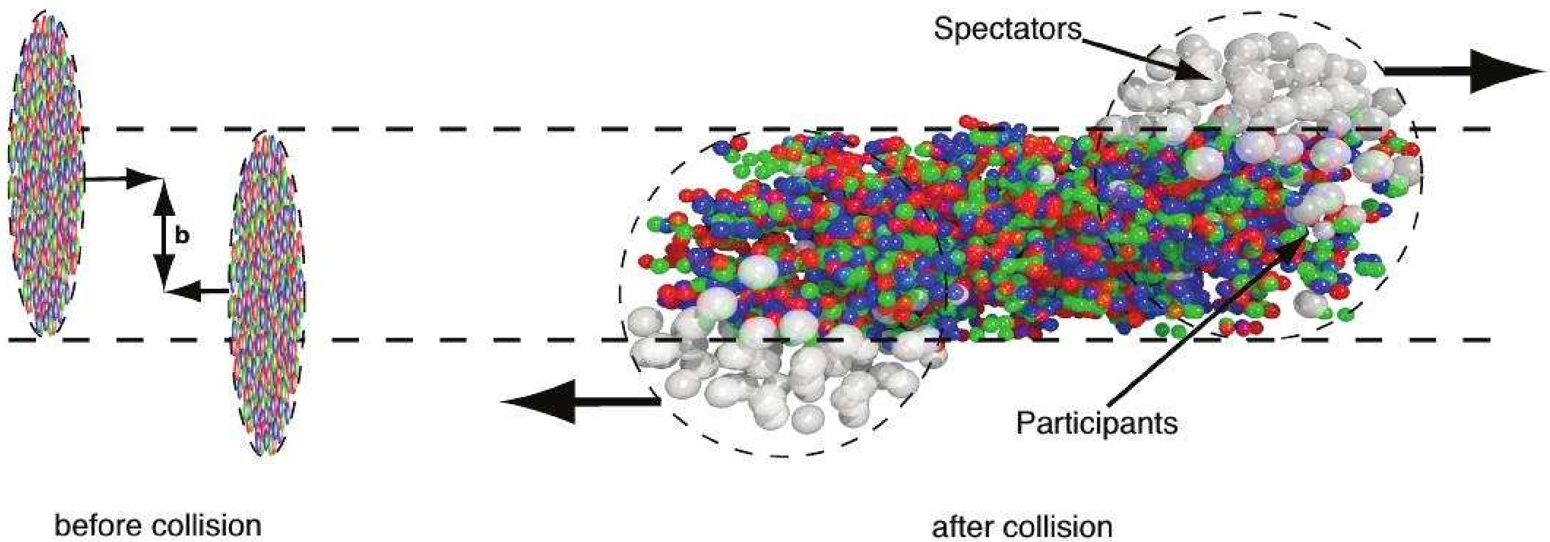
Outline of this talk

- Introduction of heavy-ion collisions – Collective flow
- Model predictions of collective flow fluctuations – hydro. + initial state fluctuations?
- Summary and conclusions.

Large Hadron Collider

One AA collision event





R. Snellings, arXiv:1408.1410

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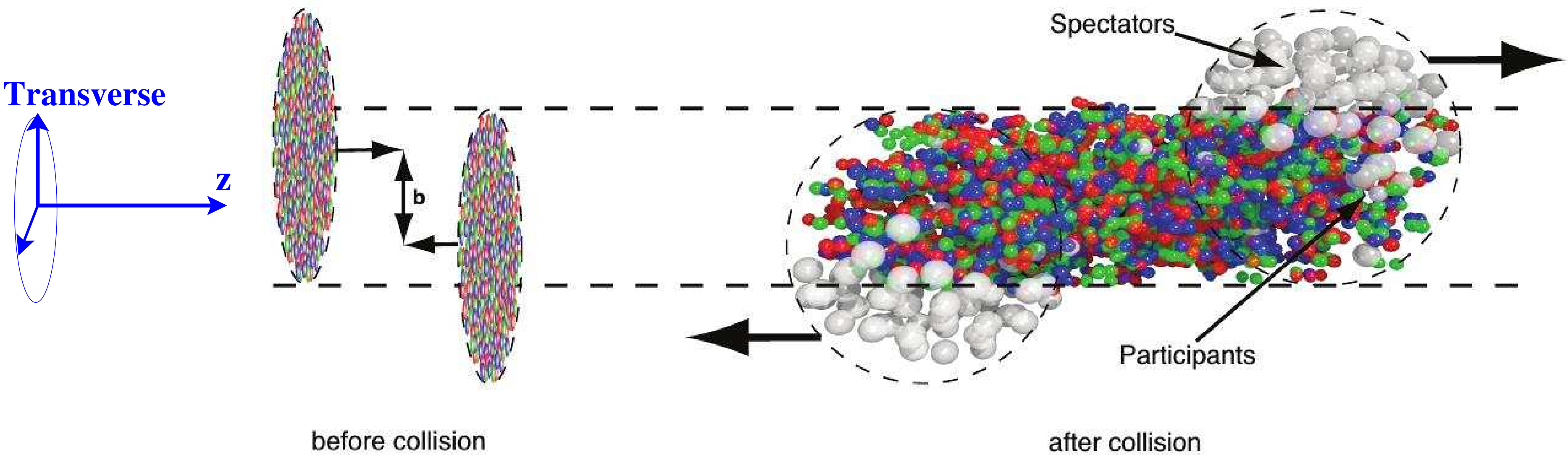

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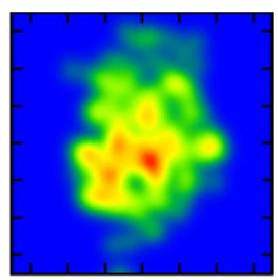
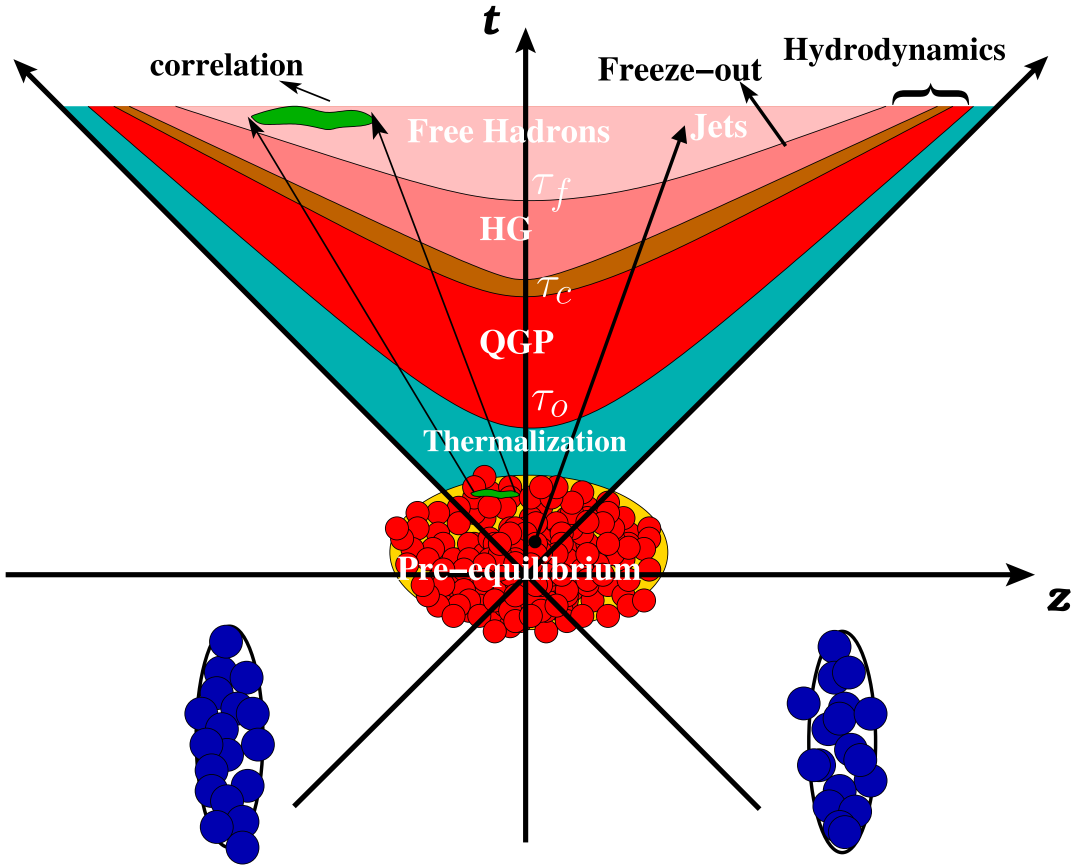
- Initial distribution in the transverse plane:



- Number of participants: multiplicity $\sim$ centrality $\sim$ impact parameter $b \sim N_{\rm track}^{\rm offline}$

Space-time evolution of AA collisions

- Space-time evolution of a heavy-ion collision event with QGP phase

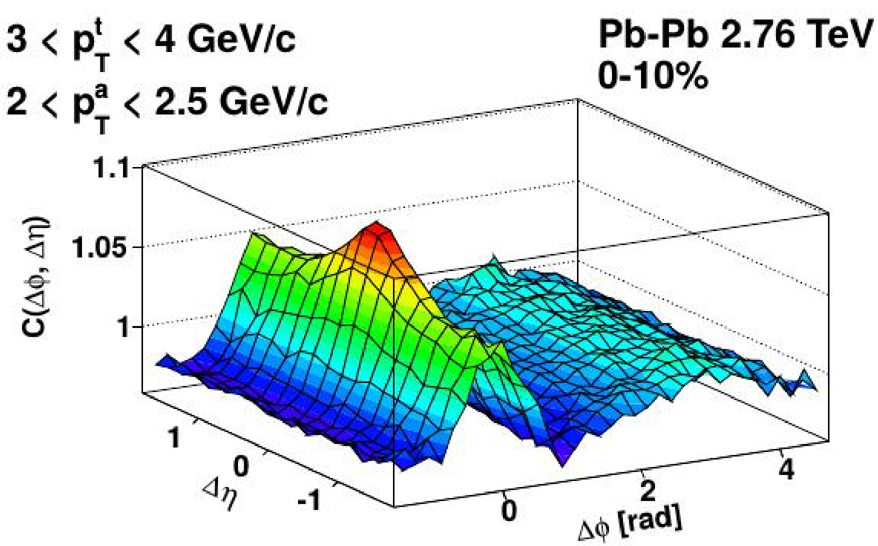


- Nucleus-Nucleus collision → QGP medium → Hadron Gas (HG) → Free Hadrons
- Collective expansion $\Longrightarrow$ correlations in particle spectrum.
- What about pA?

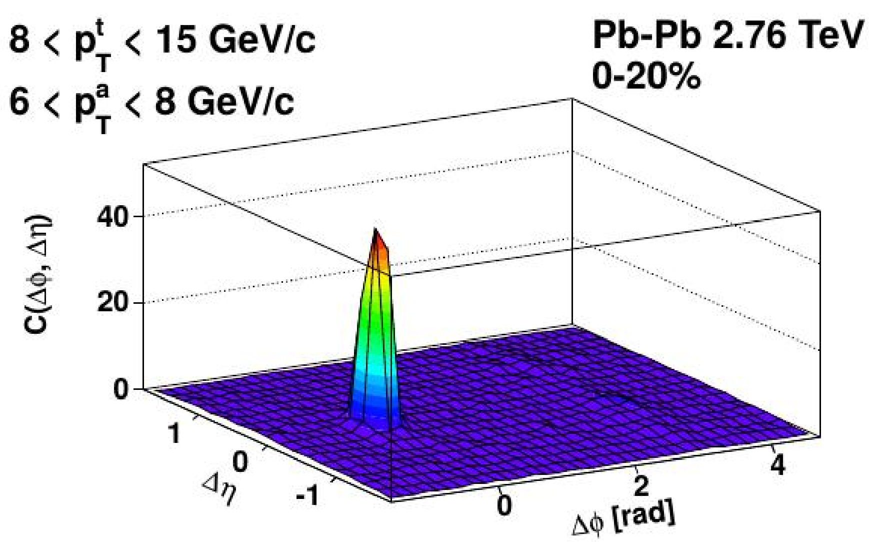
Long range correlations in AA collisions and collective flow

- Two-particle correlations: $(\Delta\phi_p, \Delta\eta)$ *(ALICE Collaboration, PLB 708 (2012) 249-264)*

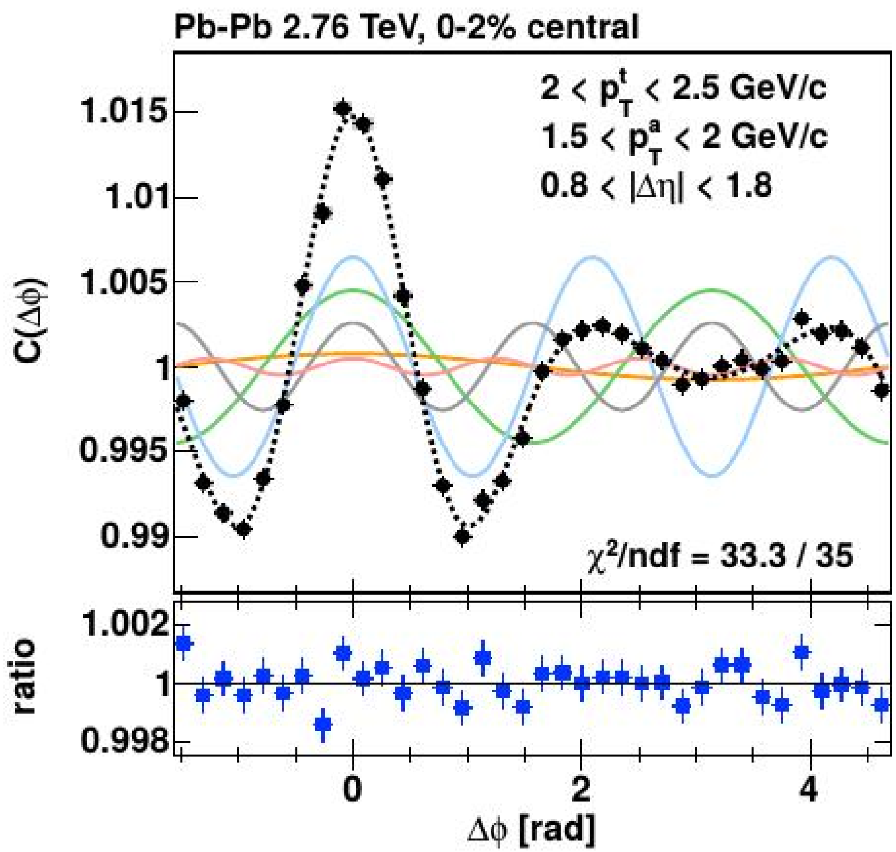
with long-range correlation

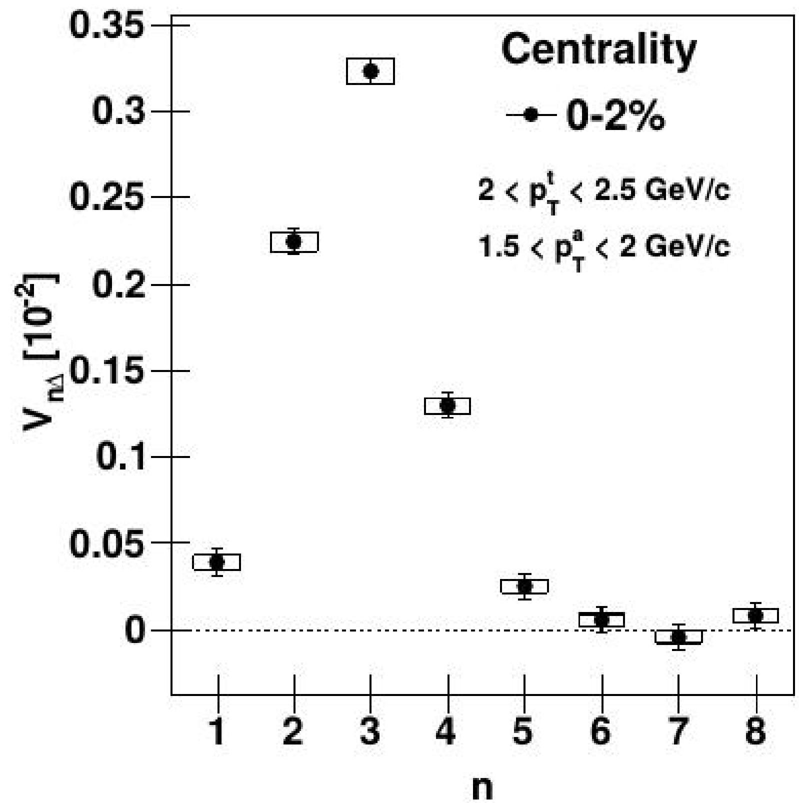


without long-range correlations



- Near-side $(\Delta\phi = 0)$ correlation with large pseudo-rapidity range.

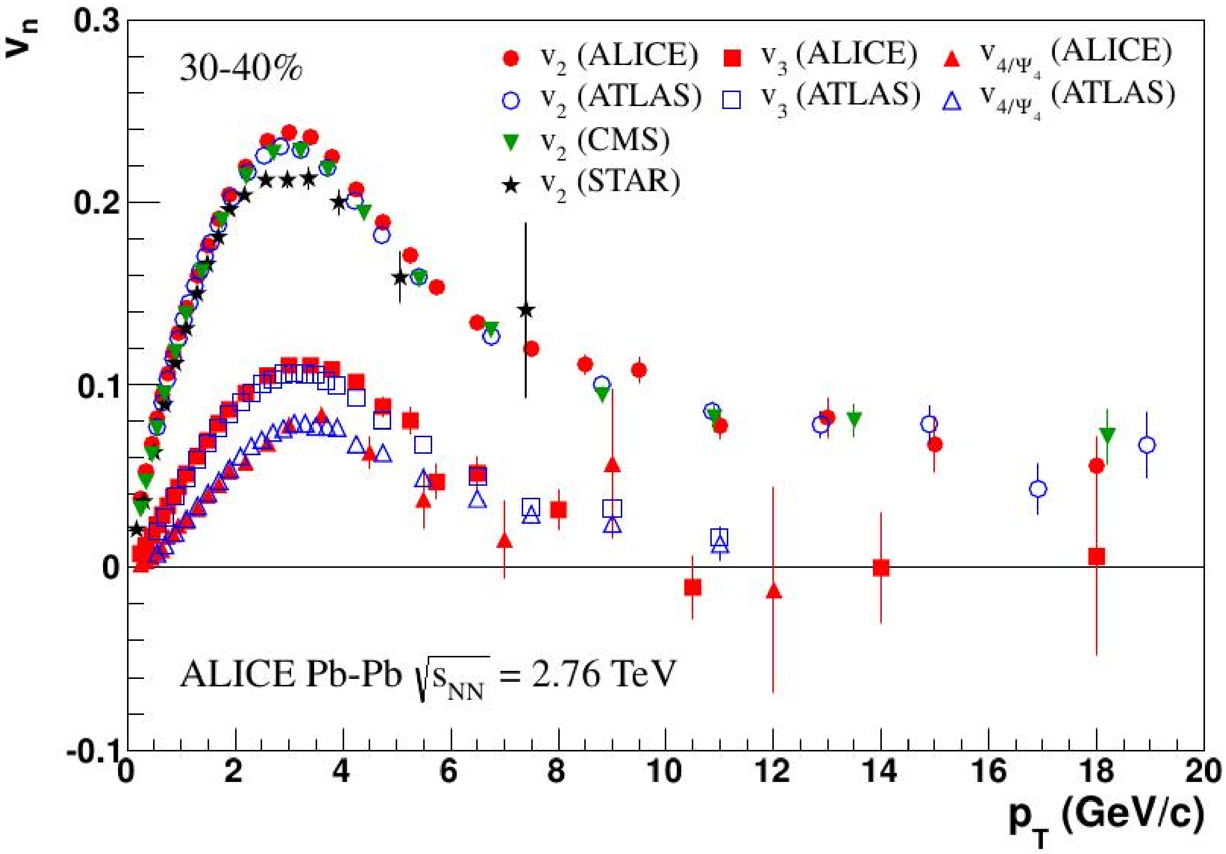




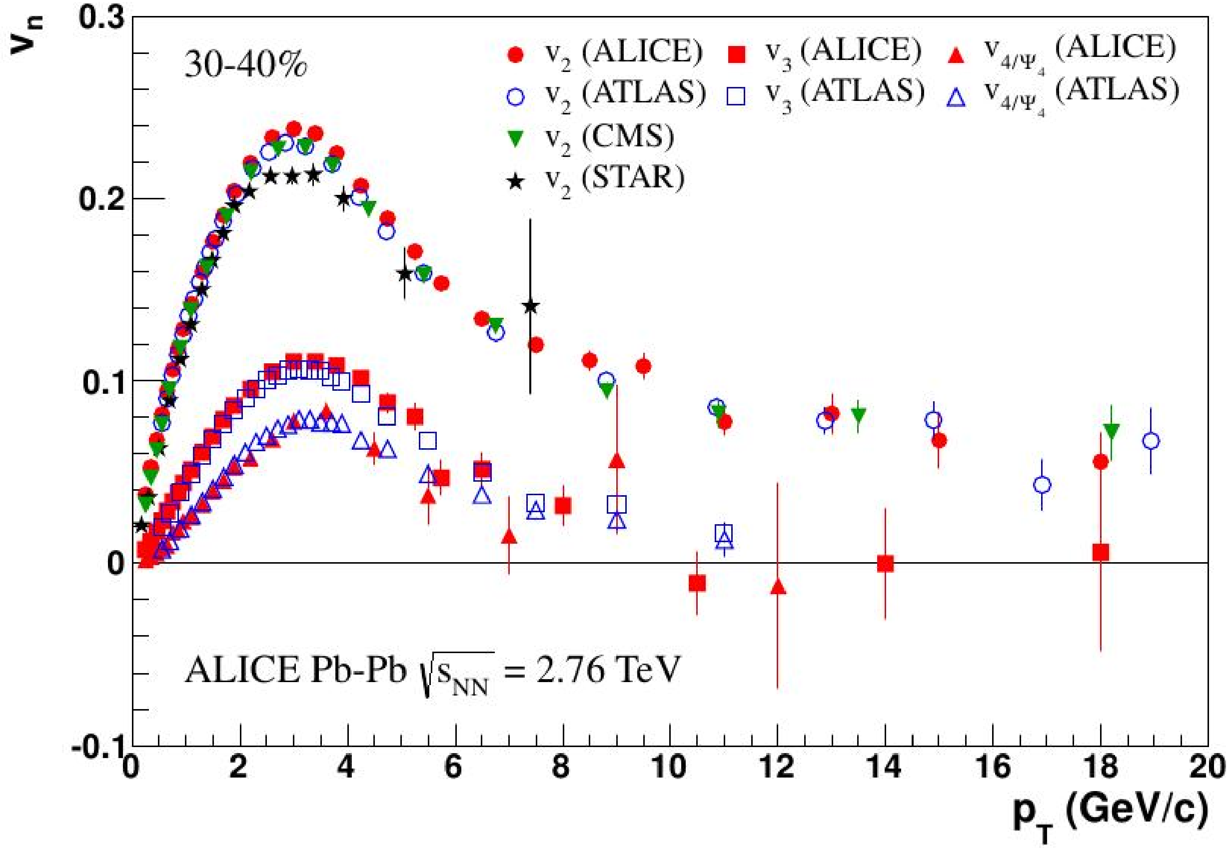
- Particle spectrum Fourier decomposition:

$$\frac{dN}{p_T dp_T d\phi_p dy} = \frac{dN}{2\pi p_T dp_T dy}\left[1 + \sum_{n=1}^{\infty} v_n(\mathrm{y}, p_T) e^{in[\phi_p - \Psi_n(\mathrm{y}, p_T)]} + c.c.\right]$$

- Collective (Harmonic) flow : $V_n = v_n \exp(in\Psi_n)$ vs. (harmonic order n, P_T, etc.)

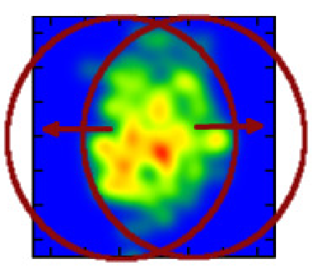


ALICE collaboration, PLB 719(2013)

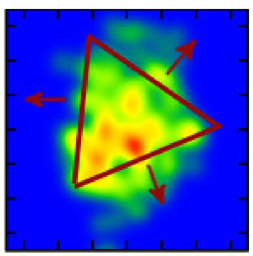


ALICE collaboration, PLB 719(2013)

- Well understood as medium response to initial geometry due to collectivity:



$\epsilon_2, \psi_2 \Rightarrow v_2$

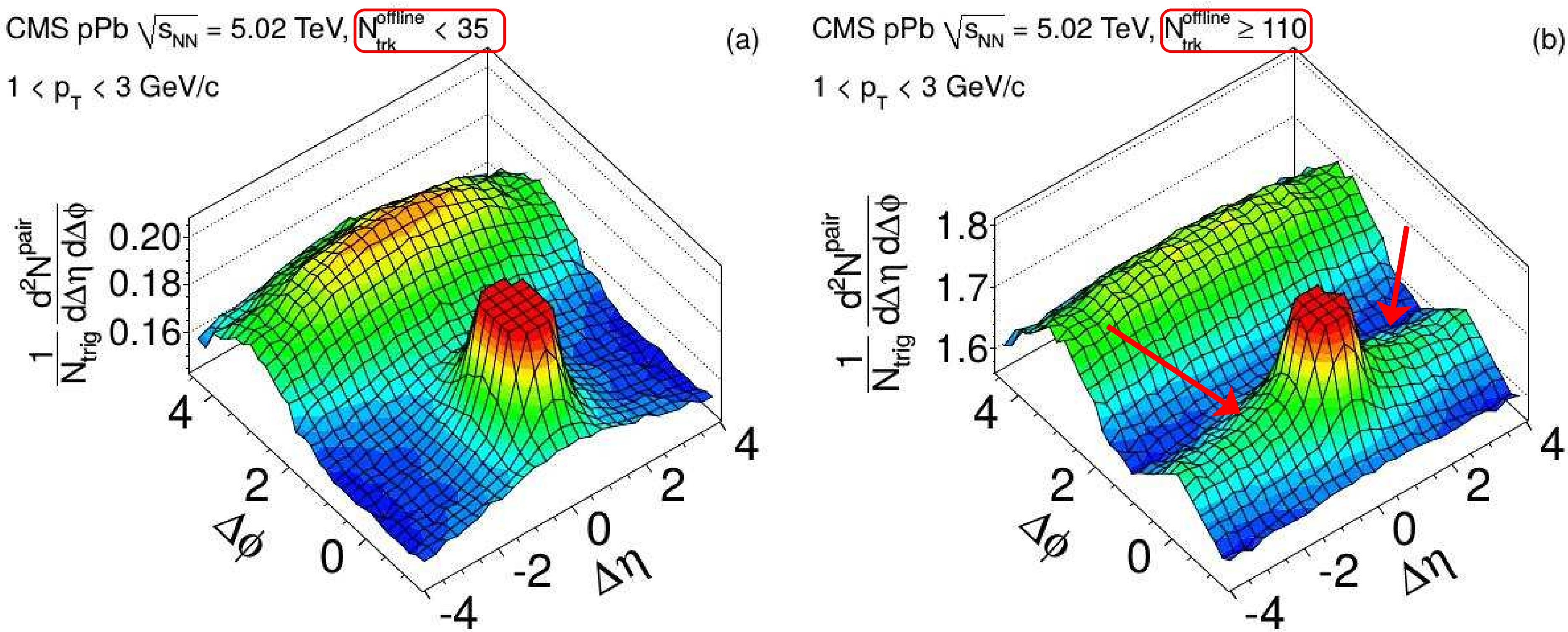


$\epsilon_3, \psi_3 \Rightarrow v_3$

$+(\varepsilon_4, \psi_4) + \ldots$

Collectivity in pA?

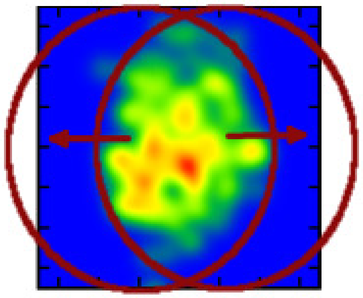
- CMS collaboration : proton-lead with $\sqrt{s} = 5.02$ TeV



(CMS collaboration, PLB718(2013) 795)

Modeling collective flow in the picture of collective expansion

- Characterization of initial state geometry: eccentricity



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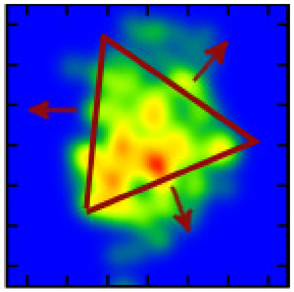

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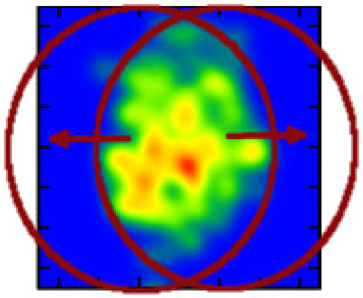

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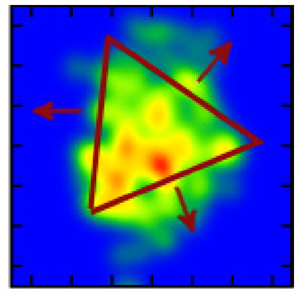

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- Eccentricity: $\varepsilon_n e^{in\psi_n} = -\frac{\{r^n e^{in\phi_r}\}}{\{r^n\}} = \varepsilon_x + i\varepsilon_y$

$$\{\dots\} = \int d^2\vec{x} \dots \rho(\vec{x}). \quad \text{note that } |\varepsilon_n| < 1$$

Modeling collective flow in the picture of collective expansion

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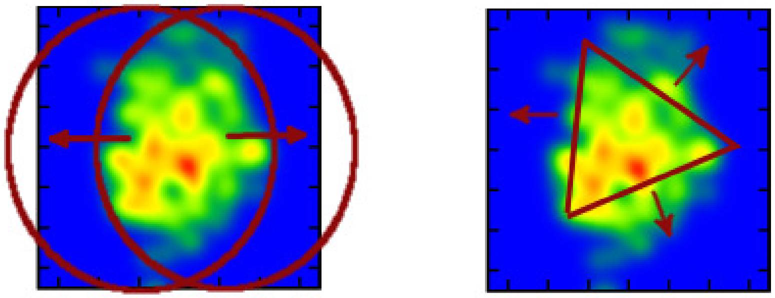

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- Collective flow ($n \leq 3$) from linear response to eccentricity: v_2 and v_3

$$V_n = \underbrace{\kappa_n}_{\text{medium resp.}} \times \varepsilon_n e^{in\psi_n}$$

Modeling collective flow in the picture of collective expansion

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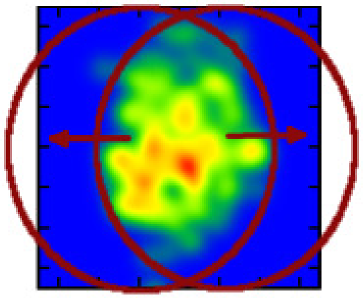

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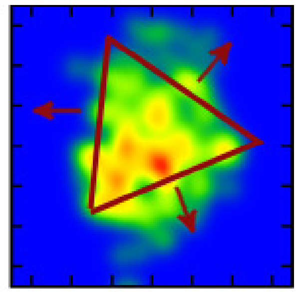

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- Simulation of medium expansion with viscous hydrodynamics $\Rightarrow \kappa_n$.

Fluctuations of ε_n dominate fluctuations of v_n

- Parameterization of initial state eccentricity fluctuations (non-Gaussian):

- **Elliptic Power distribution** : (e.g. assuming N independent point-like sources)

$$P_{\mathrm{EP}}(\varepsilon_x,\varepsilon_y)=\frac{\alpha}{\pi}(1-\varepsilon_0^2)^{\alpha+\frac{1}{2}}\frac{(1-\varepsilon_x^2-\varepsilon_y^2)^{\alpha-1}}{(1-\varepsilon_0\varepsilon_x)^{2\alpha+1}},\qquad \text{with } \varepsilon_x^2+\varepsilon_y^2<1$$

$\alpha \sim N \Rightarrow$ fluctuations, $\quad \varepsilon_0 \Rightarrow$ average RP eccentricity (roughly)

(LY, Jean-Yves Ollitrault and Art Poskanzer)

- **Power distribution** (e.g. ε_3 in AA, ε_n in p-Pb) : fluctuation-driven with $\varepsilon_0=0$

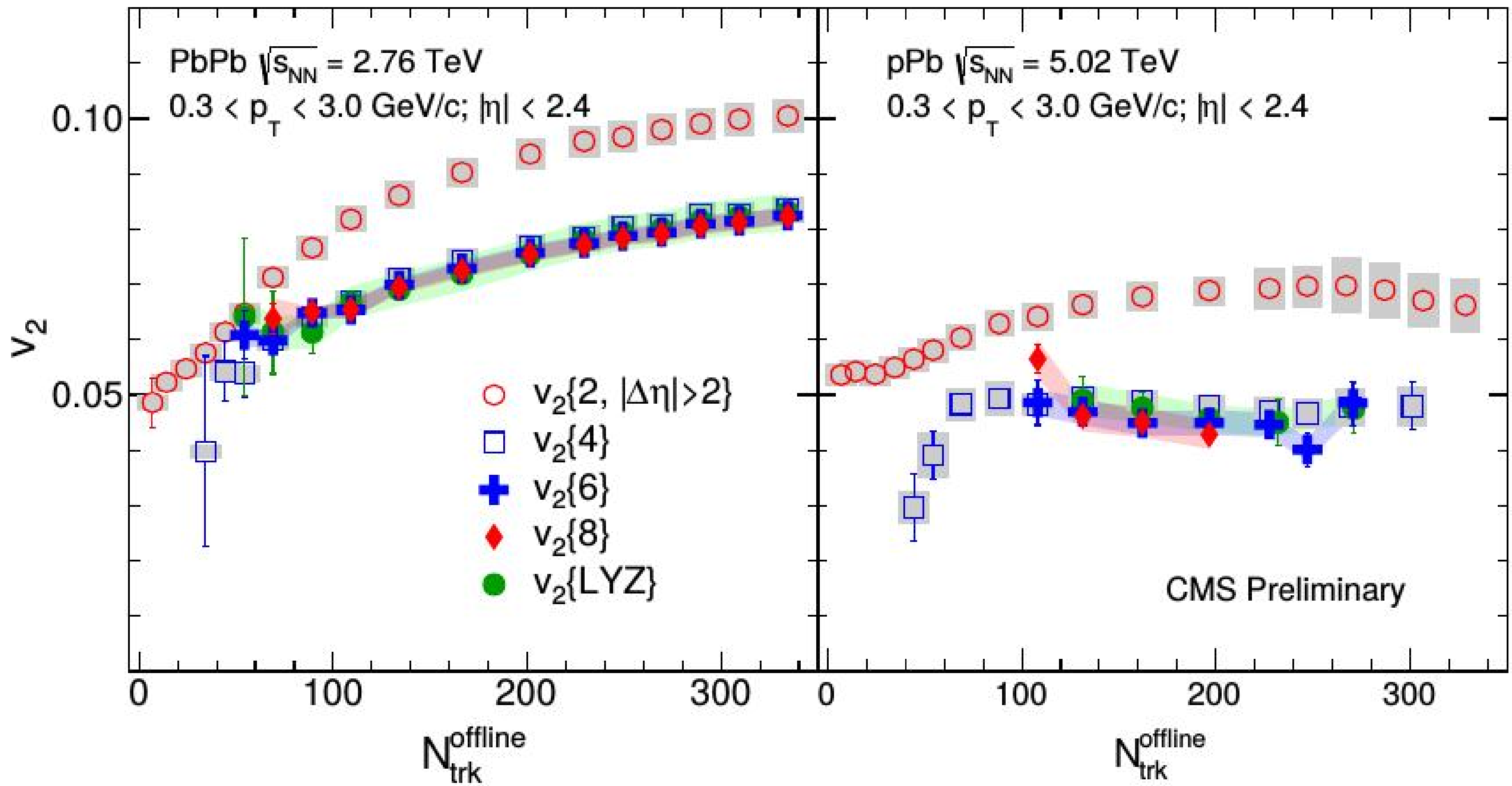
$$P_{\mathrm{Power}}(\varepsilon_x,\varepsilon_y)=\frac{\alpha}{\pi}(1-\varepsilon_x^2-\varepsilon_y^2)^{\alpha-1}\qquad \Leftarrow \qquad P_{\mathrm{EP}}(\varepsilon_0\to 0)$$

(LY, Jean-Yves Ollitrault)

- Scaling by response from hydro. gives rise to fluctuations of collective flow.

Flow fluctuations in pPb

- Cumulants of v_2 from CMS collaboration: multi-particle correlations



CMS collaboration, CMS-PAS-HIN-14-006

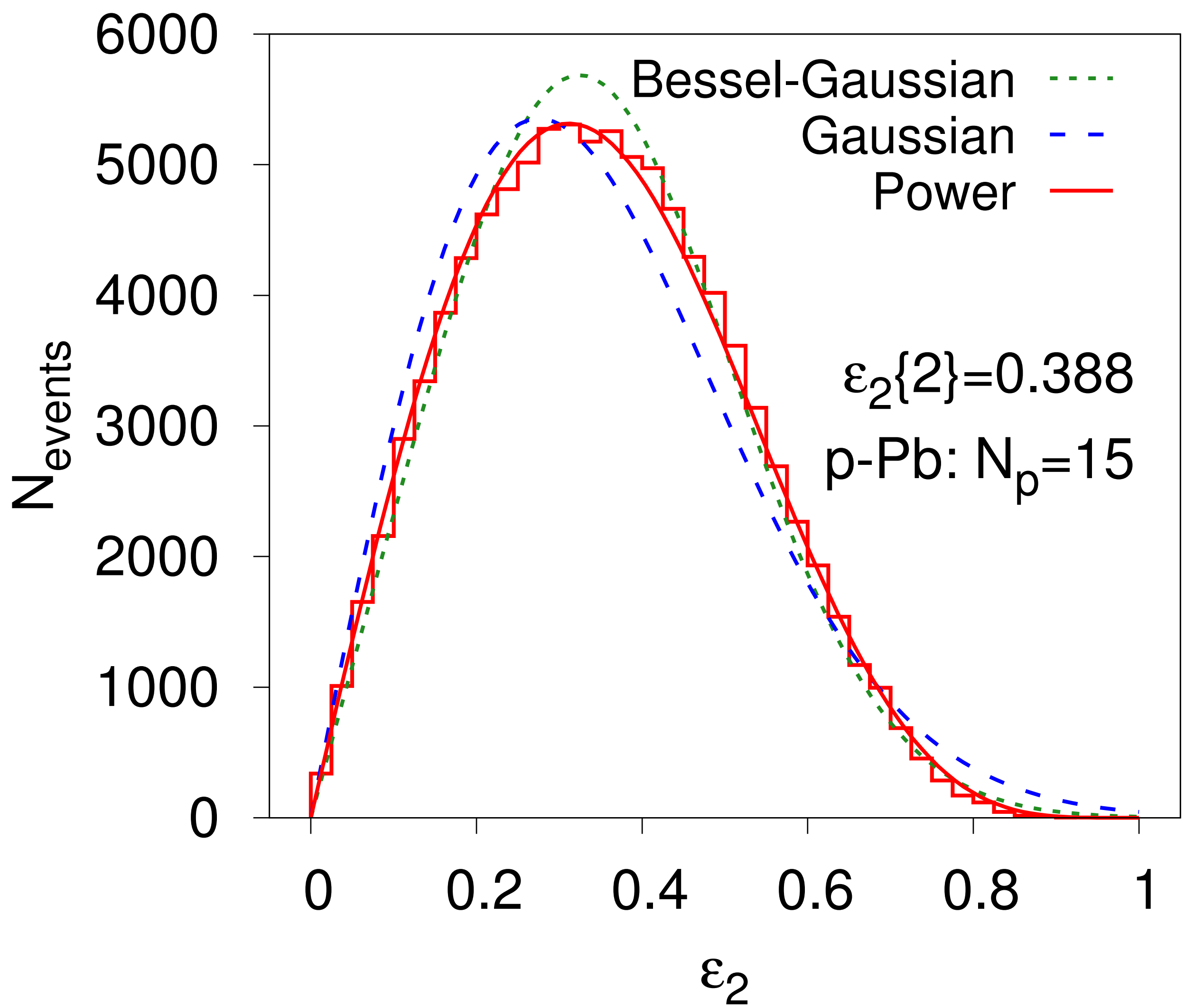
$$v_2\{2\} = \langle |v_2^2| \rangle^{1/2}$$

$$v_2\{4\} = (2\langle |v_2^2| \rangle^2 - \langle |v_2|^4 \rangle)^{1/4}$$

$$\ldots$$

Flow fluctuations in pPb

- Event-by-event dist. of ε_2 in pPb from Monte-Carlo simulations: Power distribution



Flow fluctuations in pPb

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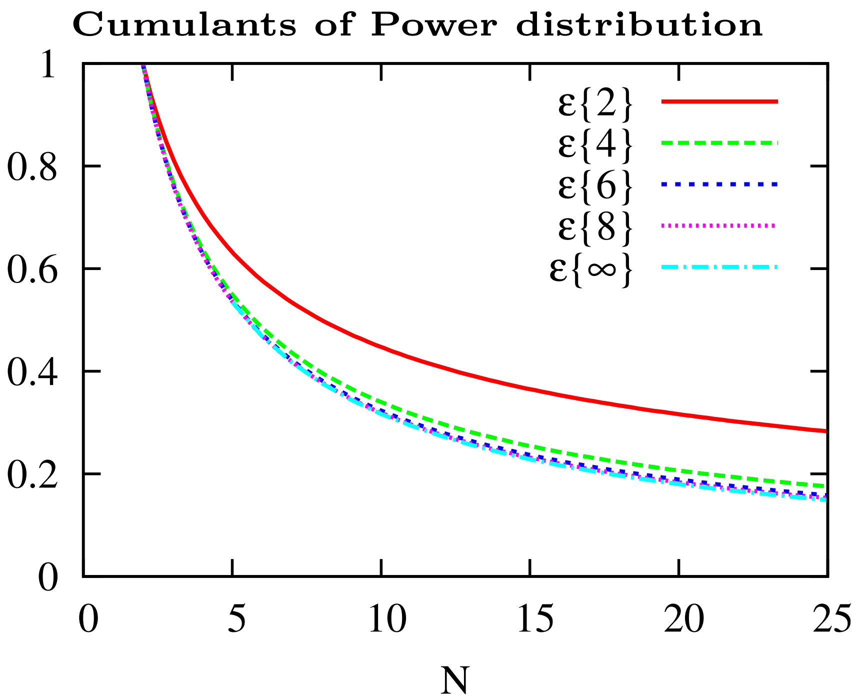

(Seen also in MC-Glauber, Bozek and Broniowski arXiv:1304.3044 and Bzdak et al arXiv:1311.7325)

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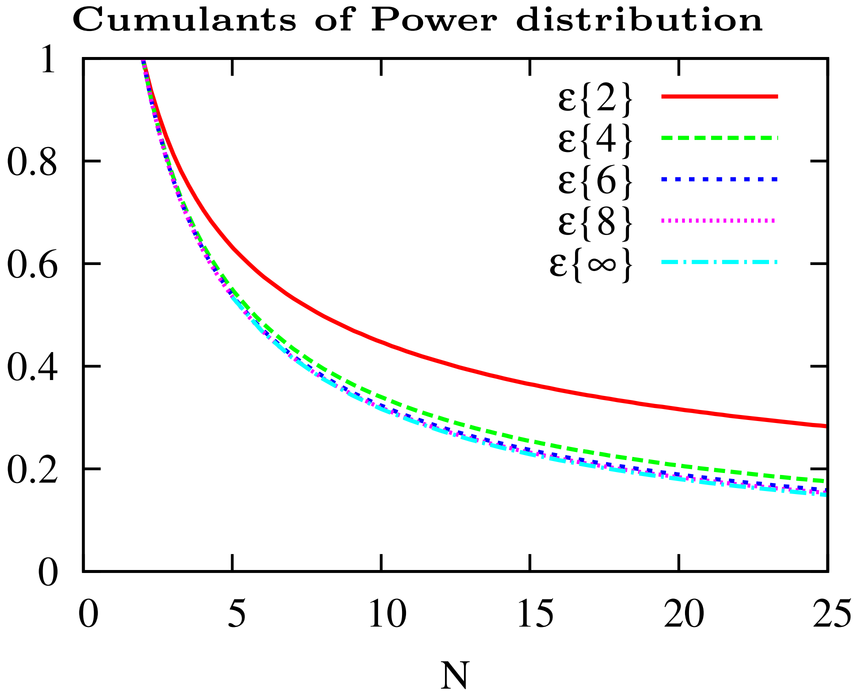

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- Large $v_2\{4\}$ etc. is natural in small system if:.

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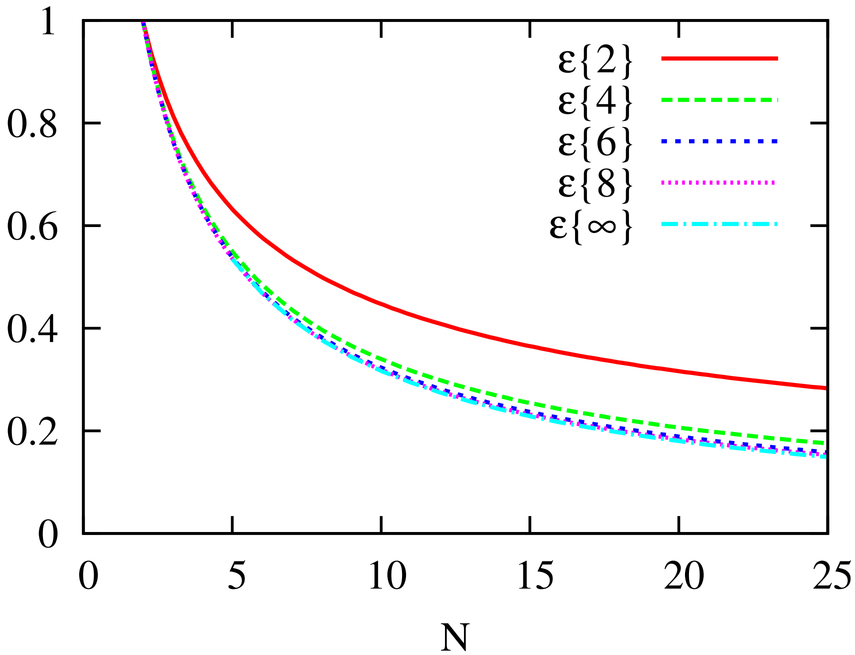
Cumulants of Power distribution



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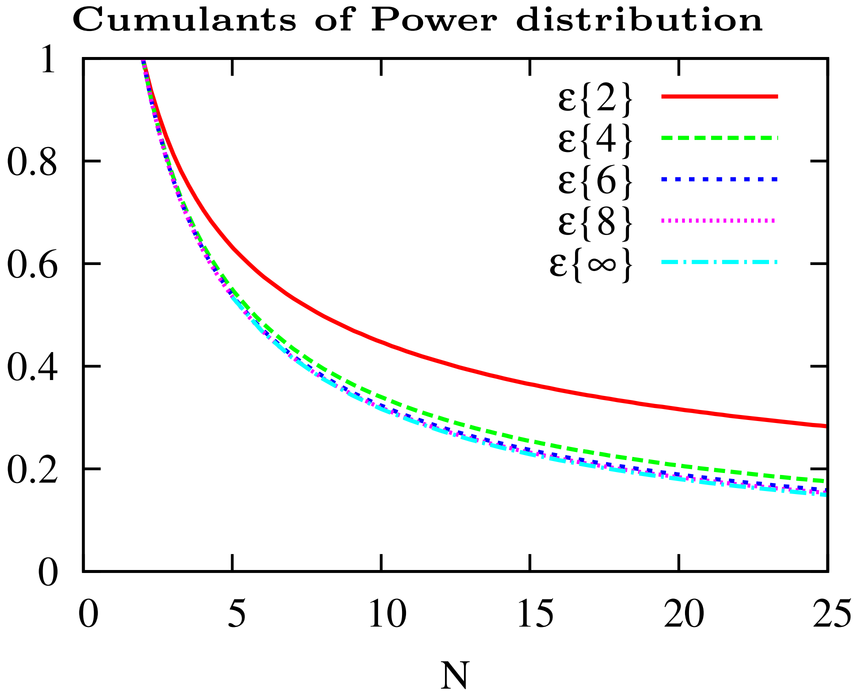

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- Other effects, e.g., coherence of initial fields:

$$0 < v_2\{4\} = v_2\{6\} = v_2\{8\} = \ldots$$

(See for instance, M. Gyulassy et al. arXiv:1405.7825)

Flow fluctuations in pPb

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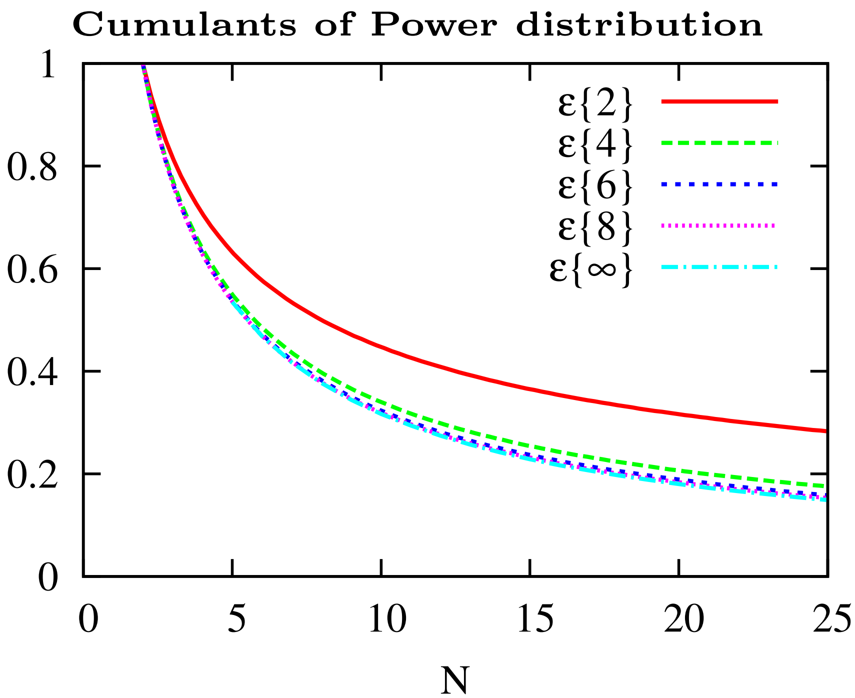

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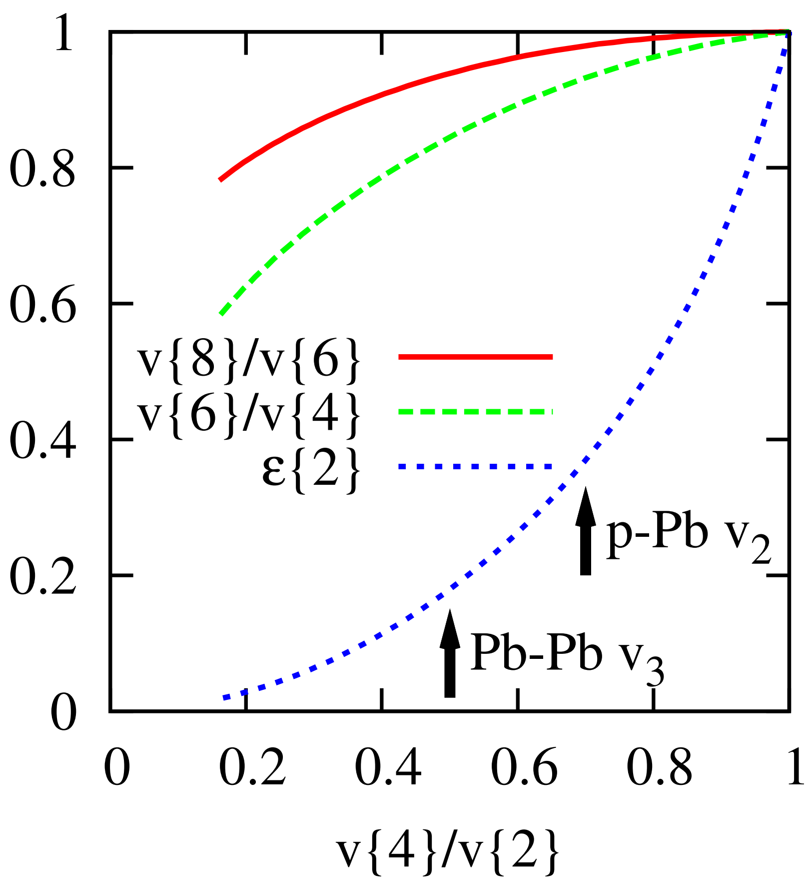
- From Power distribution (hydro.) quantify:

$$0 < v_2\{8\} < v_2\{6\} < v_2\{4\} \dots$$

Analytical relations between cumulants:



Flow fluctuations in pPb

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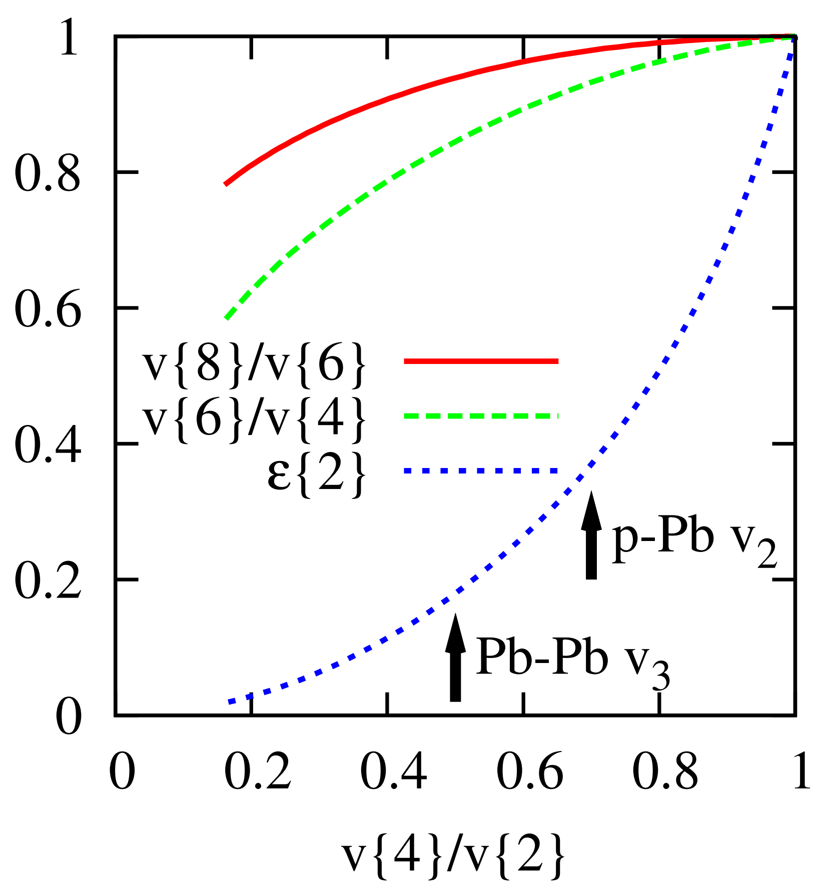

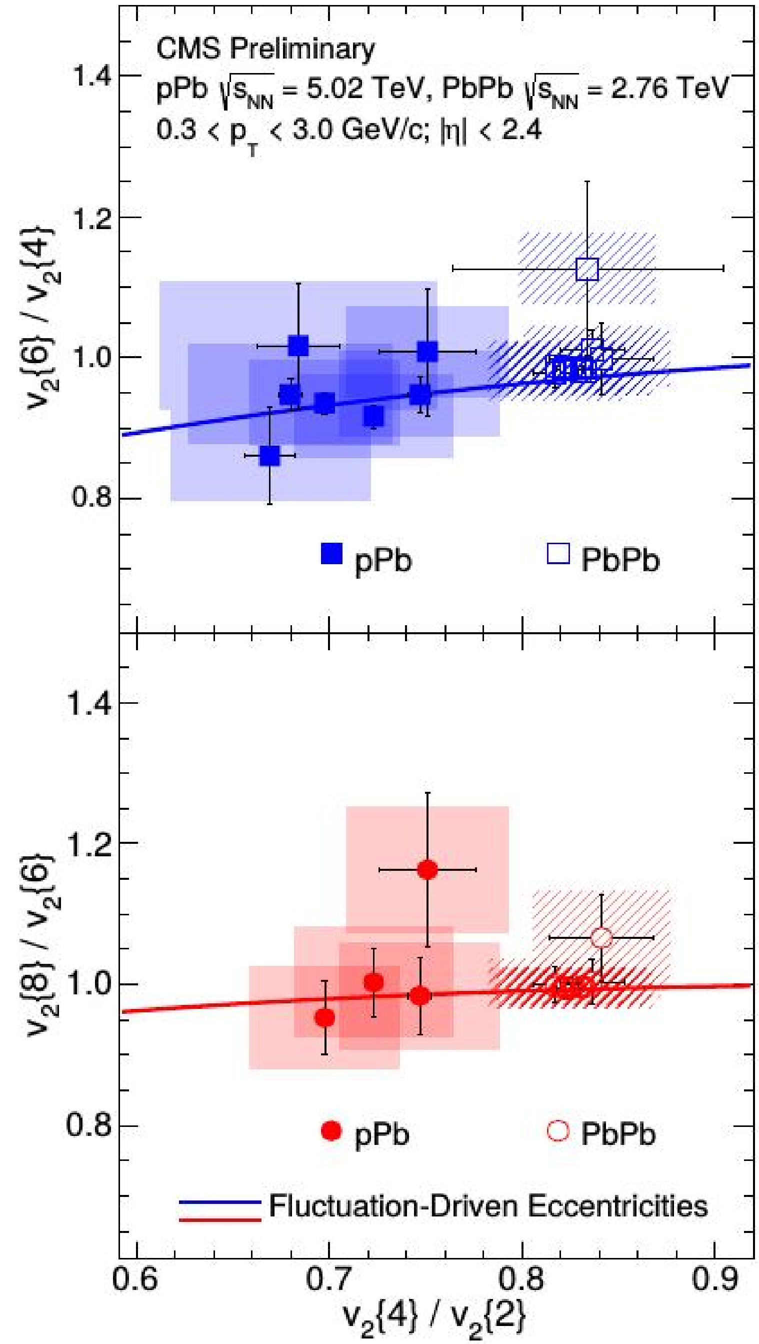

CMS collaboration, CMS-PAS-HIN-14-006

Flow fluctuations in pPb

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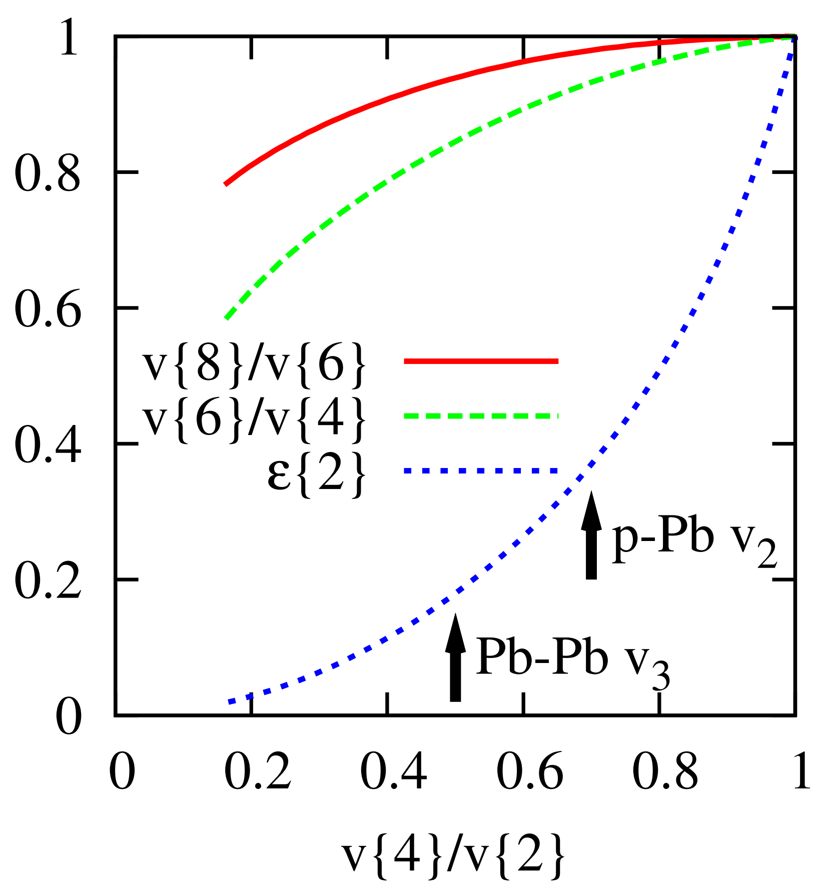
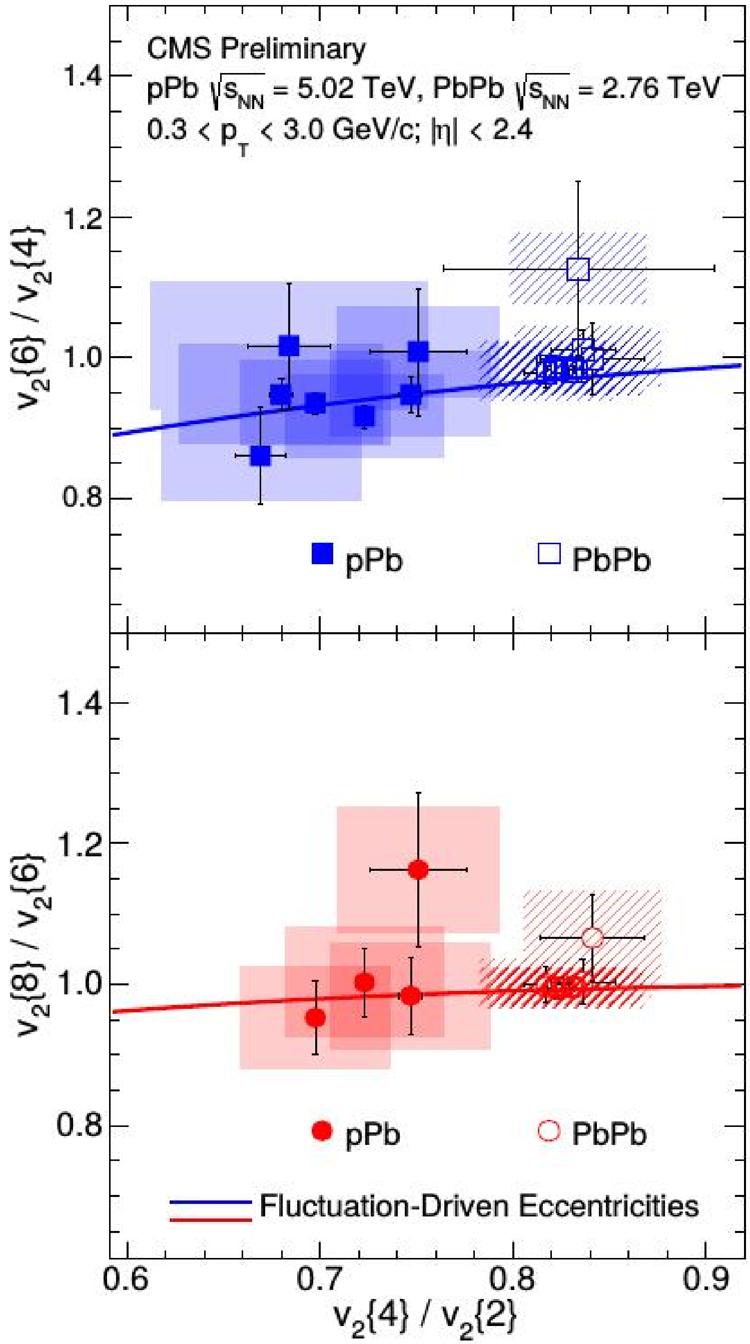


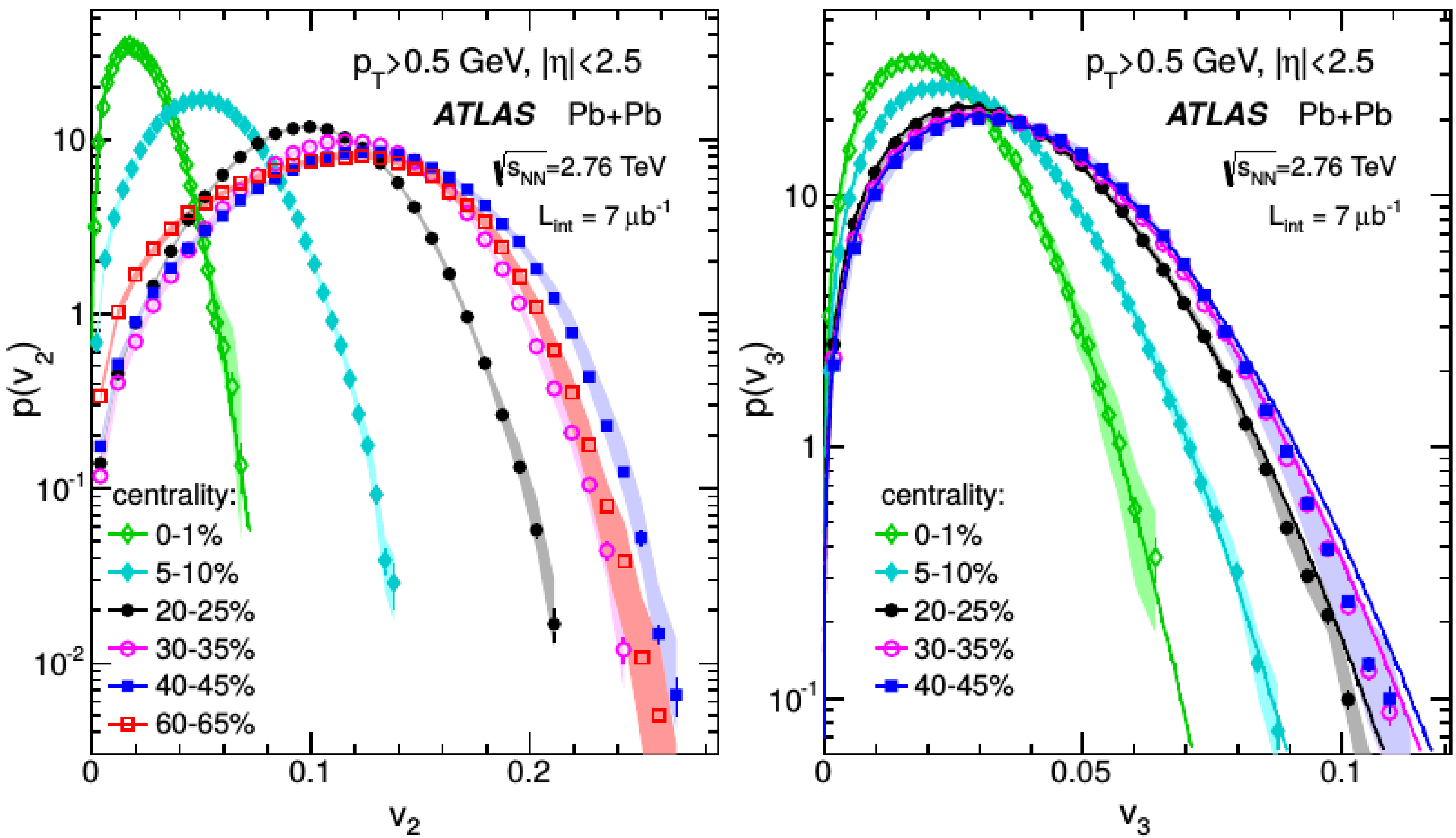


More accurate measurements are necessary.

CMS collaboration, CMS-PAS-HIN-14-006

Flow fluctuations in AA

- Probability distribution of v_2 from ATLAS collaboration:

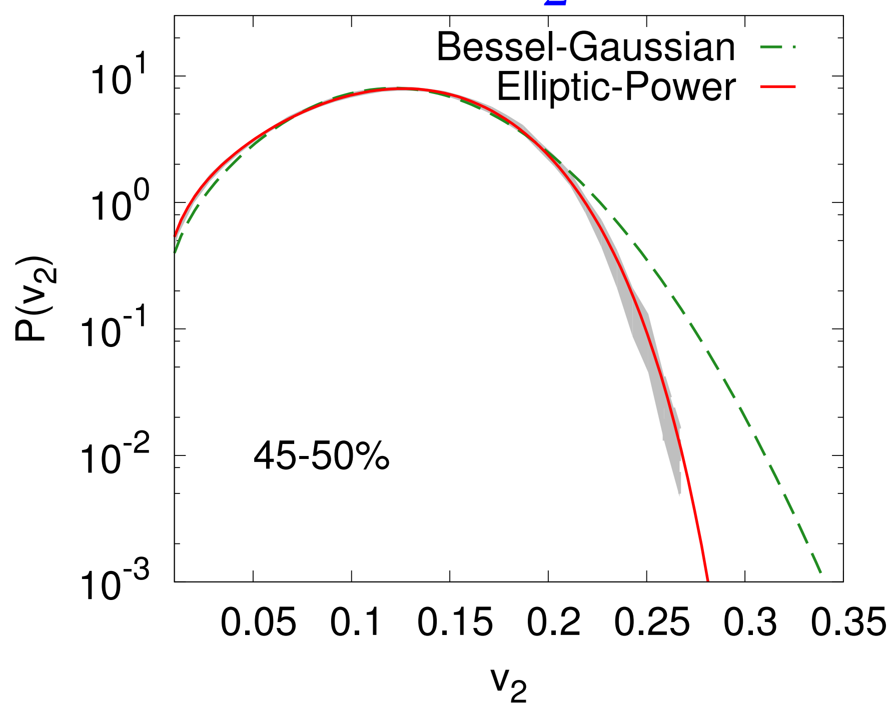


(ATLAS) JHEP 1311(2013)183

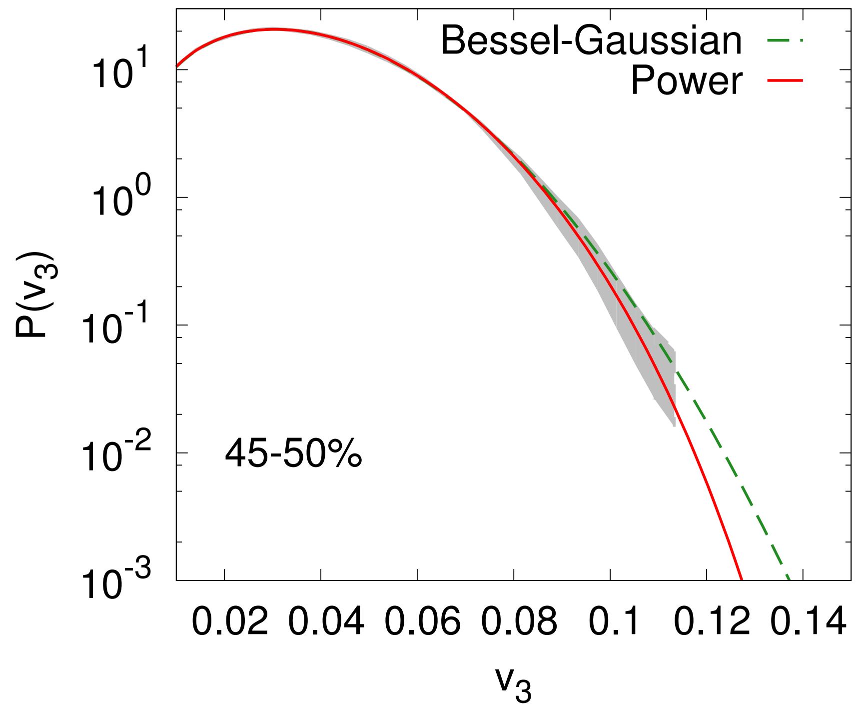
Flow fluctuations in AA

- Rescaled Elliptic Power (or Power) parameterization: ATLAS v_2 and v_3 at 45-50%.

v_2



v_3



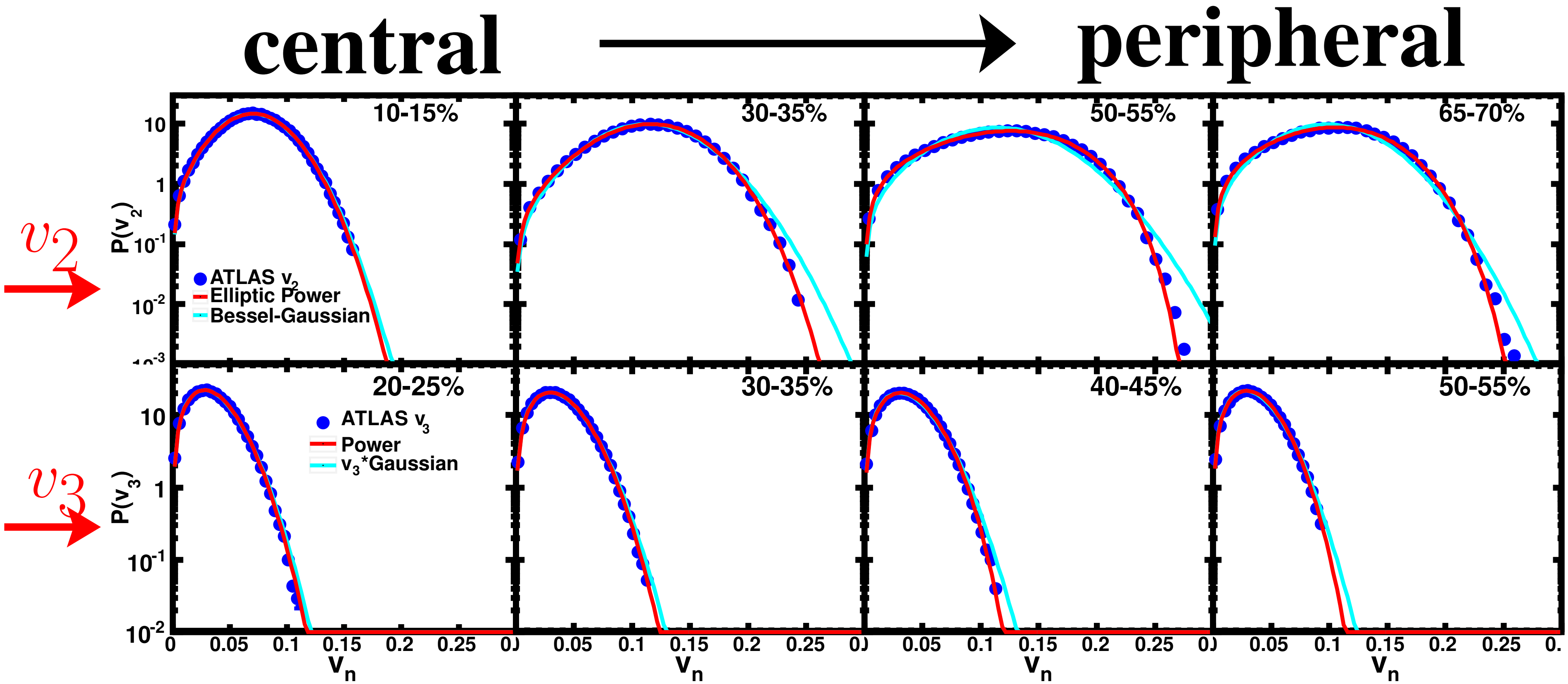
- Distribution of v_n is 'rescaled' Elliptic Power or Power distribution.

$$P(\varepsilon_n)d\varepsilon_n = P(\varepsilon_n(v_n,\kappa_n))\left|\frac{\partial\varepsilon_n}{\partial v_n}\right|dv_n \quad \rightarrow \quad P(v_n/\kappa_n)/\kappa_n dv_n \quad \rightarrow \text{fit } v_n \text{ distribution}$$

$$\rightarrow \quad v_2\{n\} = \kappa_2\varepsilon_2\{n\} \quad \rightarrow \text{solve cumulants}$$

- $\kappa_n \Rightarrow$ flow resp. $\varepsilon_0 \Rightarrow$ average RP eccentricity $\alpha \Rightarrow$ magnitude of fluctuations

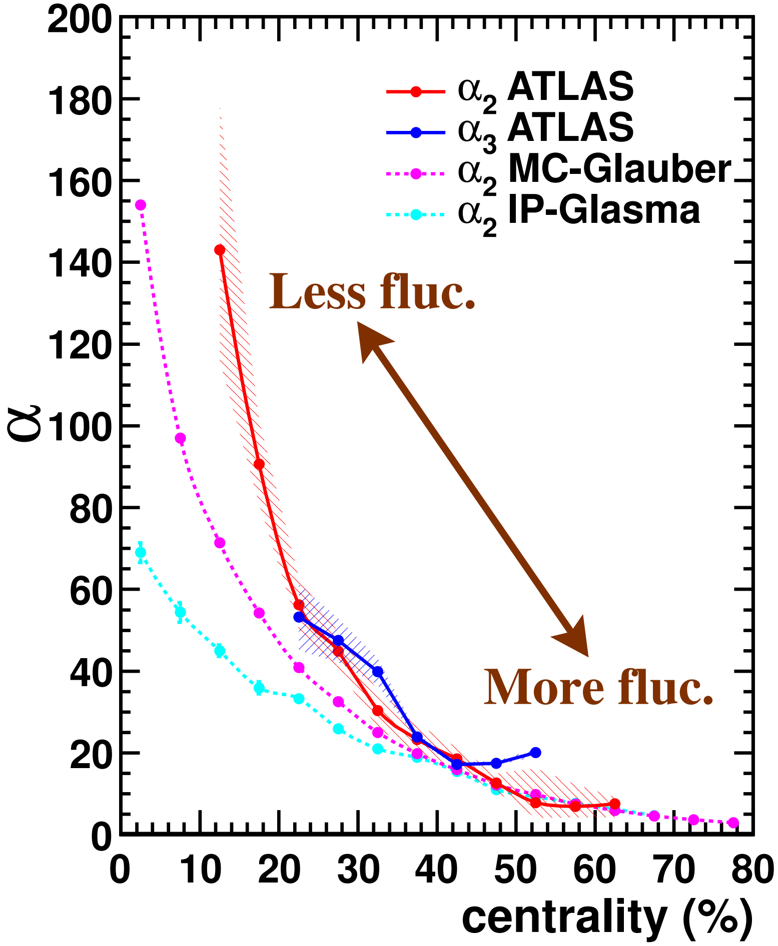
ATLAS EbyE v_n distribution



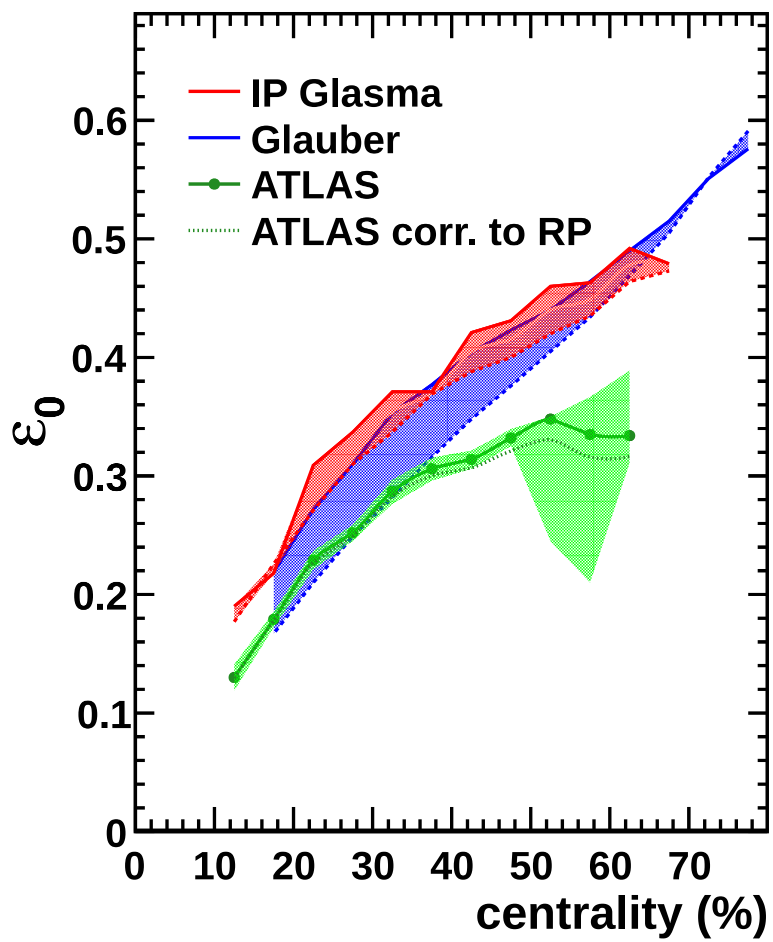
- Improvements with Elliptic Power and Power parameterization w.r.t. non-Gaussianity.

Extract information of initial state from the fit

Fluctuations



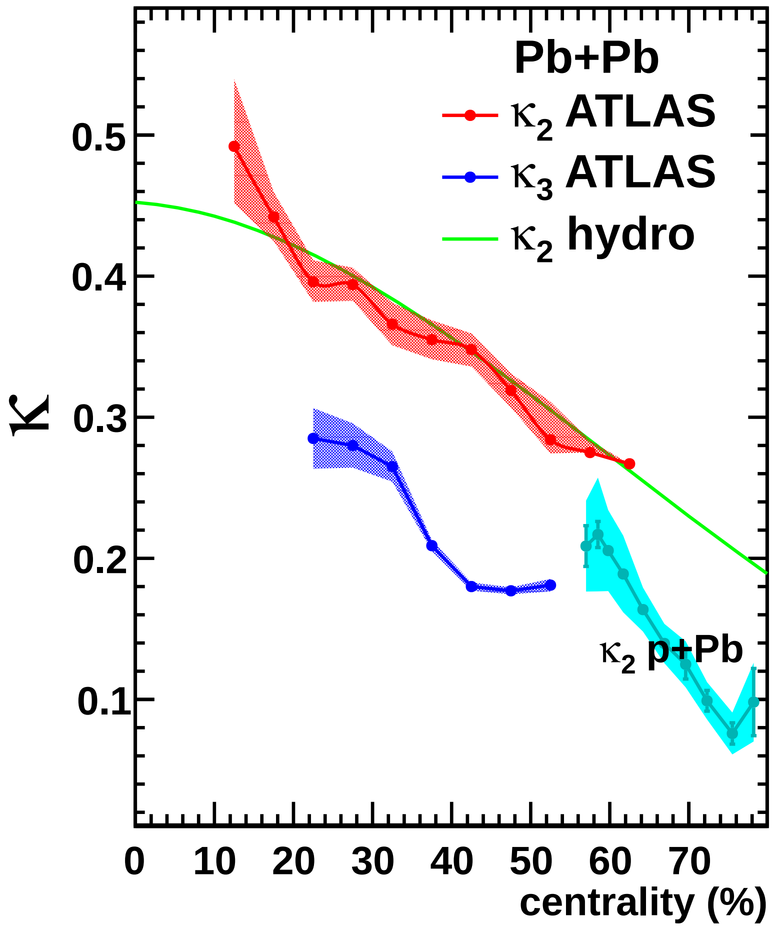
Average RP eccentricity



- Fluctuations become stronger for peripheral collisions.
- Initial shape becomes more elliptic when centrality percentage grows.

κ_n and extracting η/s in hydrodynamic response

- Flow response coefficient $\kappa_n = v_n/\varepsilon_n$ vs centrality



- $\kappa_2 > \kappa_3$.
- κ decreases from central to peripheral.

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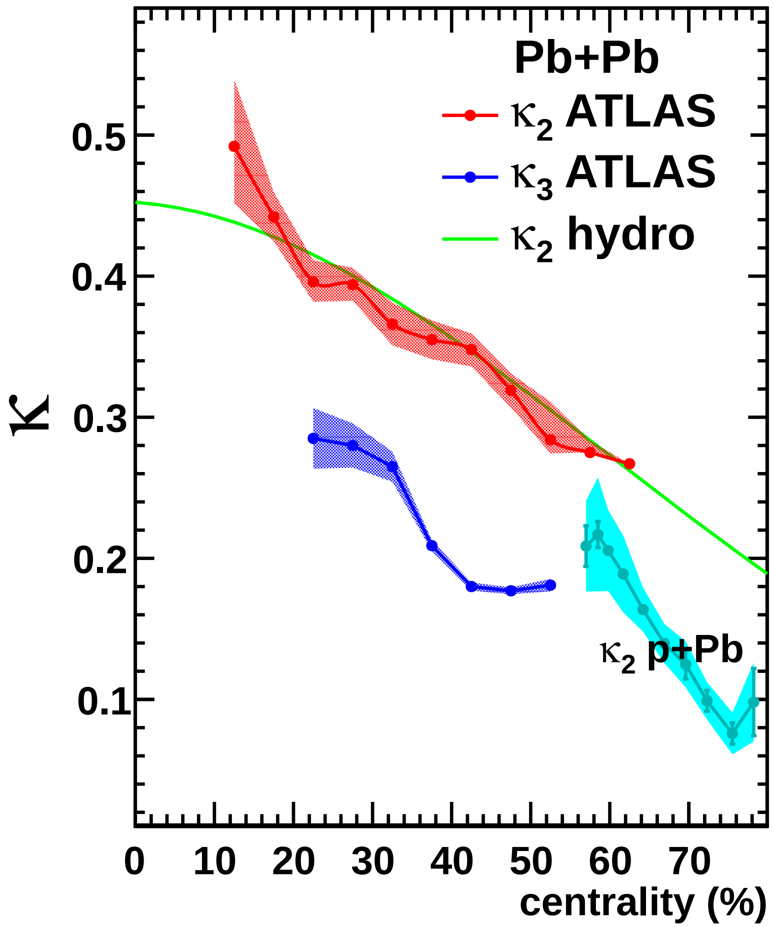

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- κ decreases from central to peripheral.
  - Since η/s determines κ_n
- Fit by hydro.: $\delta\kappa = -\frac{\kappa^{\text{visc.}} - \kappa^{\text{ideal}}}{\eta/s}$

$$\kappa\left(\frac{\eta}{s}\right) = C_0\left[\kappa^{\text{ideal}} - \frac{\eta}{s}\delta\kappa\right],$$

$\kappa^{\text{visc.}}$ and κ^{ideal} are given by hydro.

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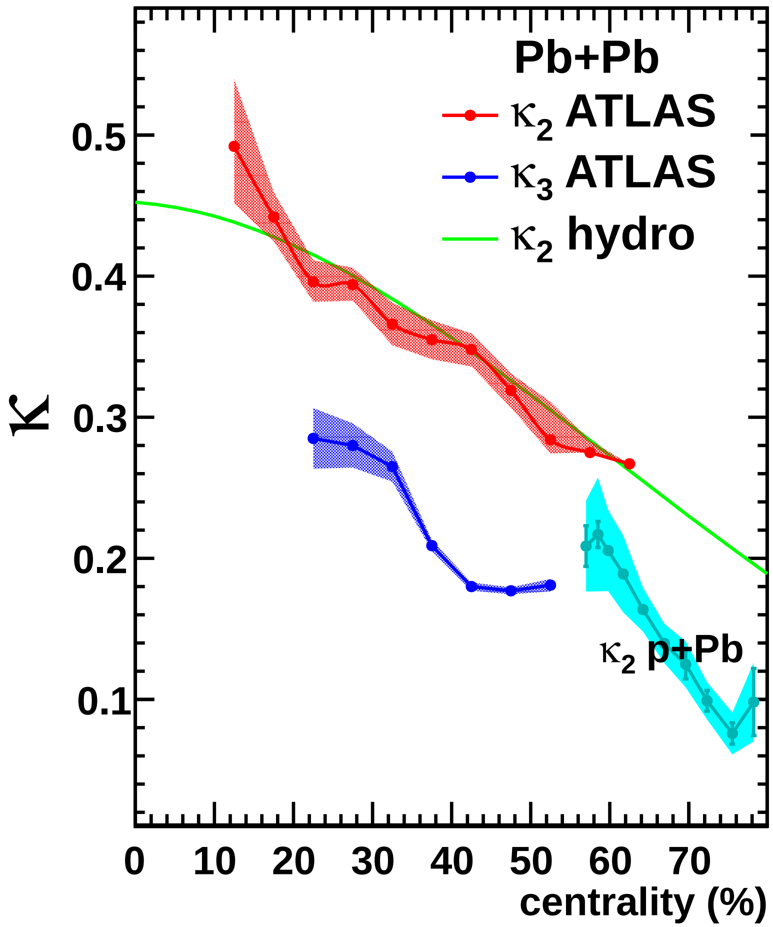

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$$\text{Fit of } v_2 \quad \Rightarrow \quad \frac{\eta}{s} \sim 0.19$$

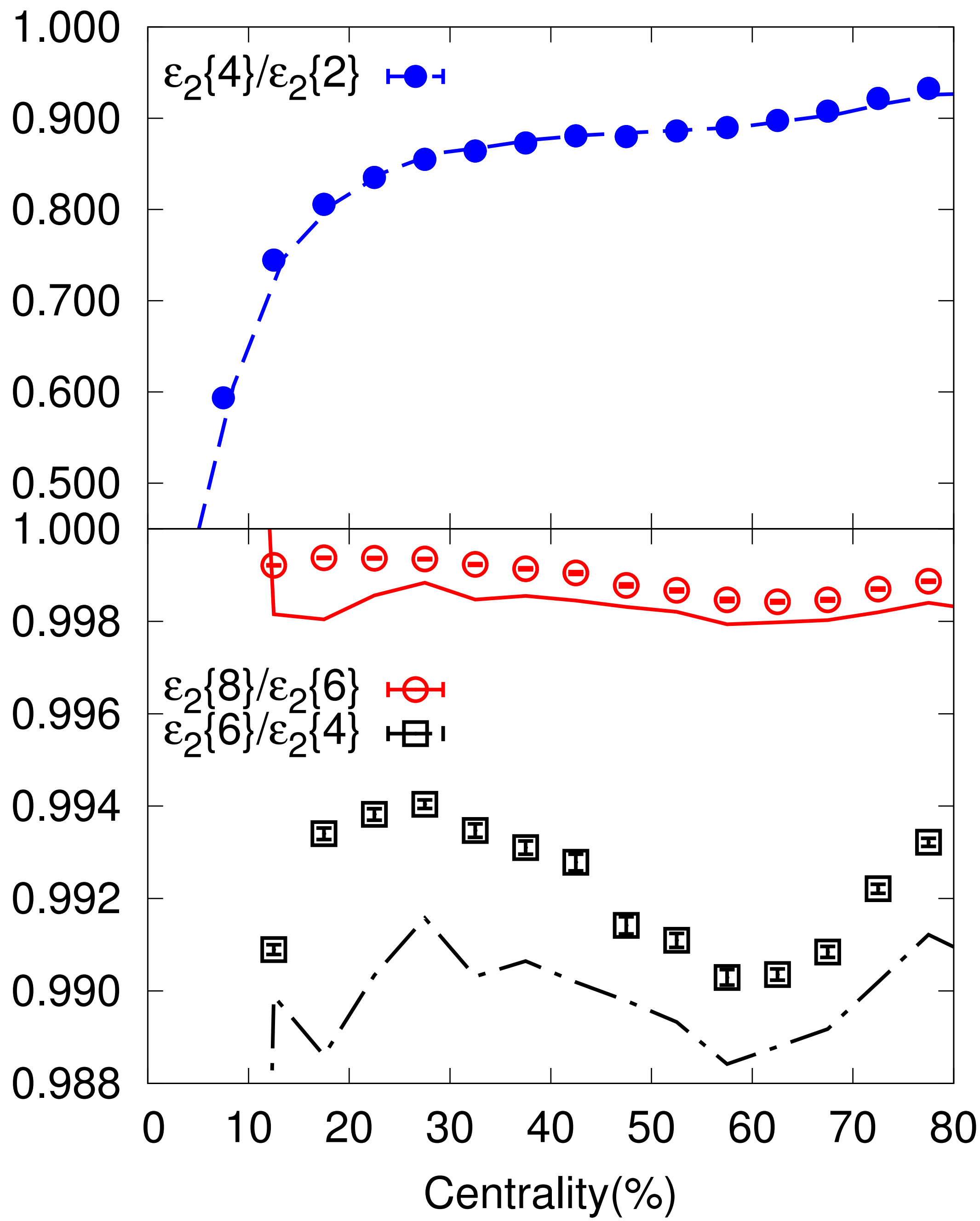
Summary and conclusions

- Collectivity in AA and pA revealed by correlations in the particle spectrum
  1. Long-range correlations observed in AA and high multiplicity pA events.
  2. Collective flow extracted by Fourier decomposition of particle spectrum.
  3. Collectivity in AA is well understood. (hydro. or transport approach)
  4. Correlations in pA is observed, as collectivity?

- Fluctuations of collective flow – more detailed measurement of flow:
  1. Fluctuations in p-Pb: strong indications of collective expansion.
  2. Fluctuations in Pb-Pb: procedure to extract α, ε_0, and κ_2, from fits.

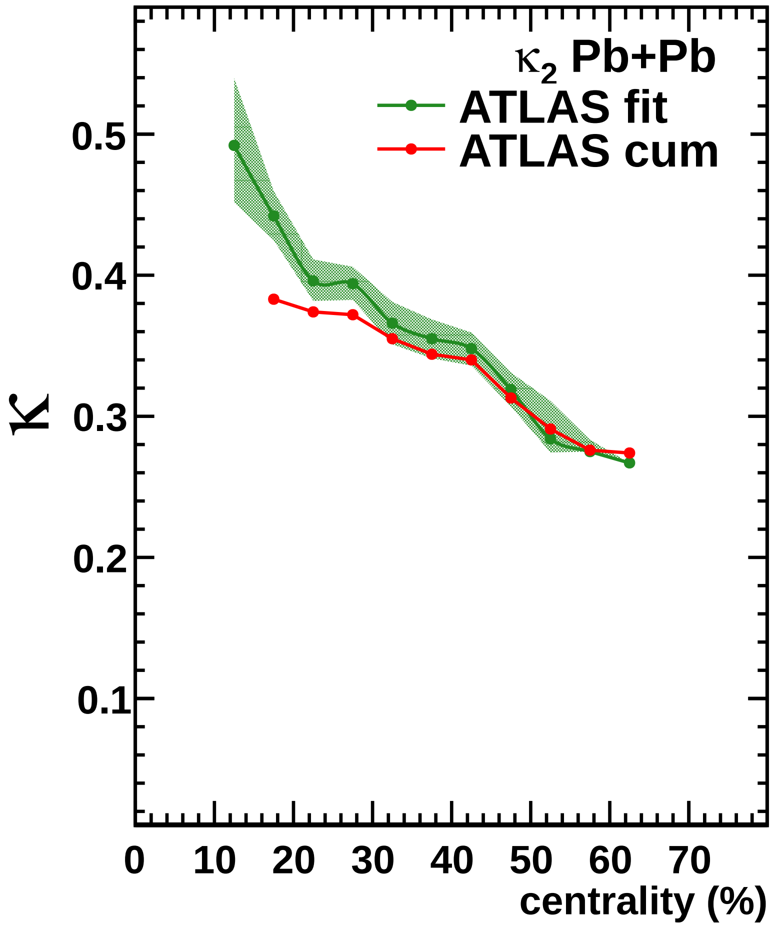
Back-up slides

Cumulants from Elliptic Power

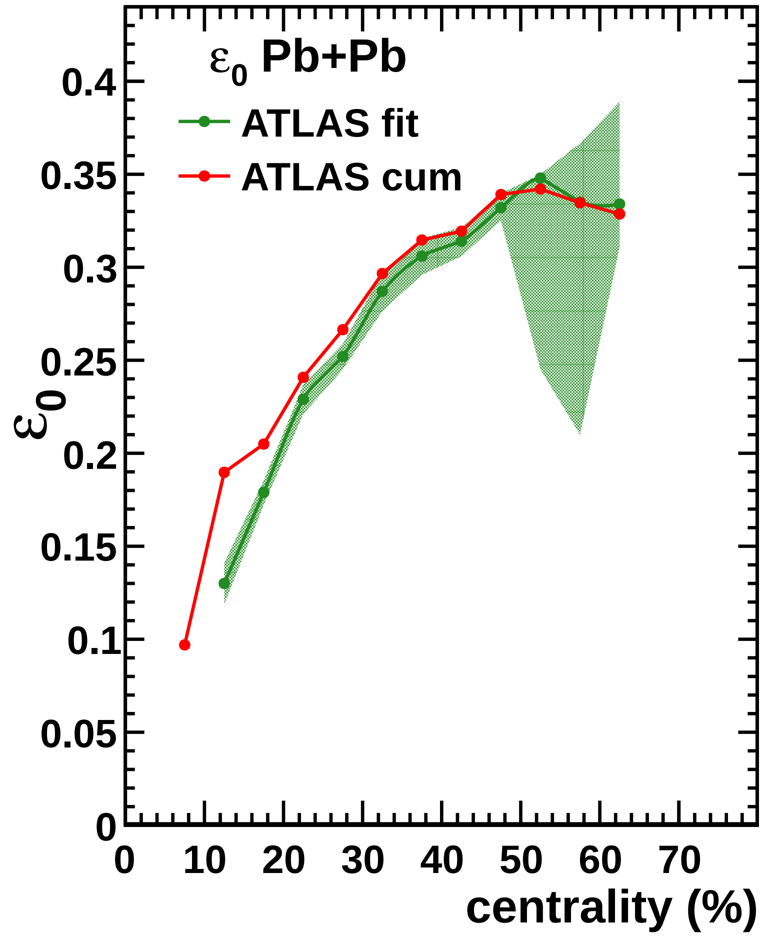


Solving cumulants of v_n

Resp. coefficient



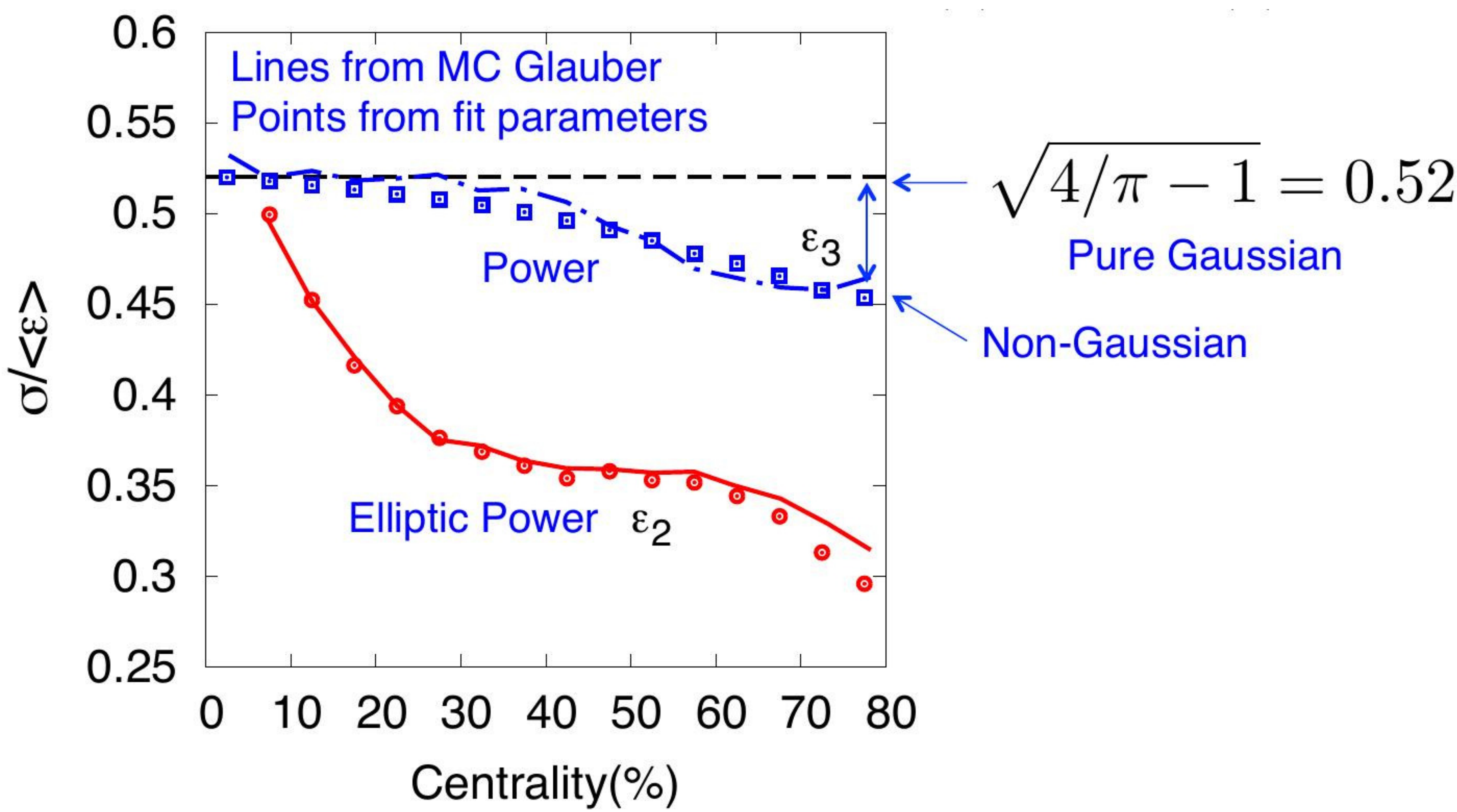
Average RP eccentricity



Some properties – Gaussian limit

- Large system with small mean eccentricity (or $\varepsilon_0 = 0$) and small fluctuations ($\alpha \gg 1$):

$$P_{\mathrm{EP}} \longrightarrow P_{\mathrm{BG}} \quad \text{and} \quad P_{\mathrm{Power}} \longrightarrow P_{\mathrm{Gaussian}}$$



- Remarks :

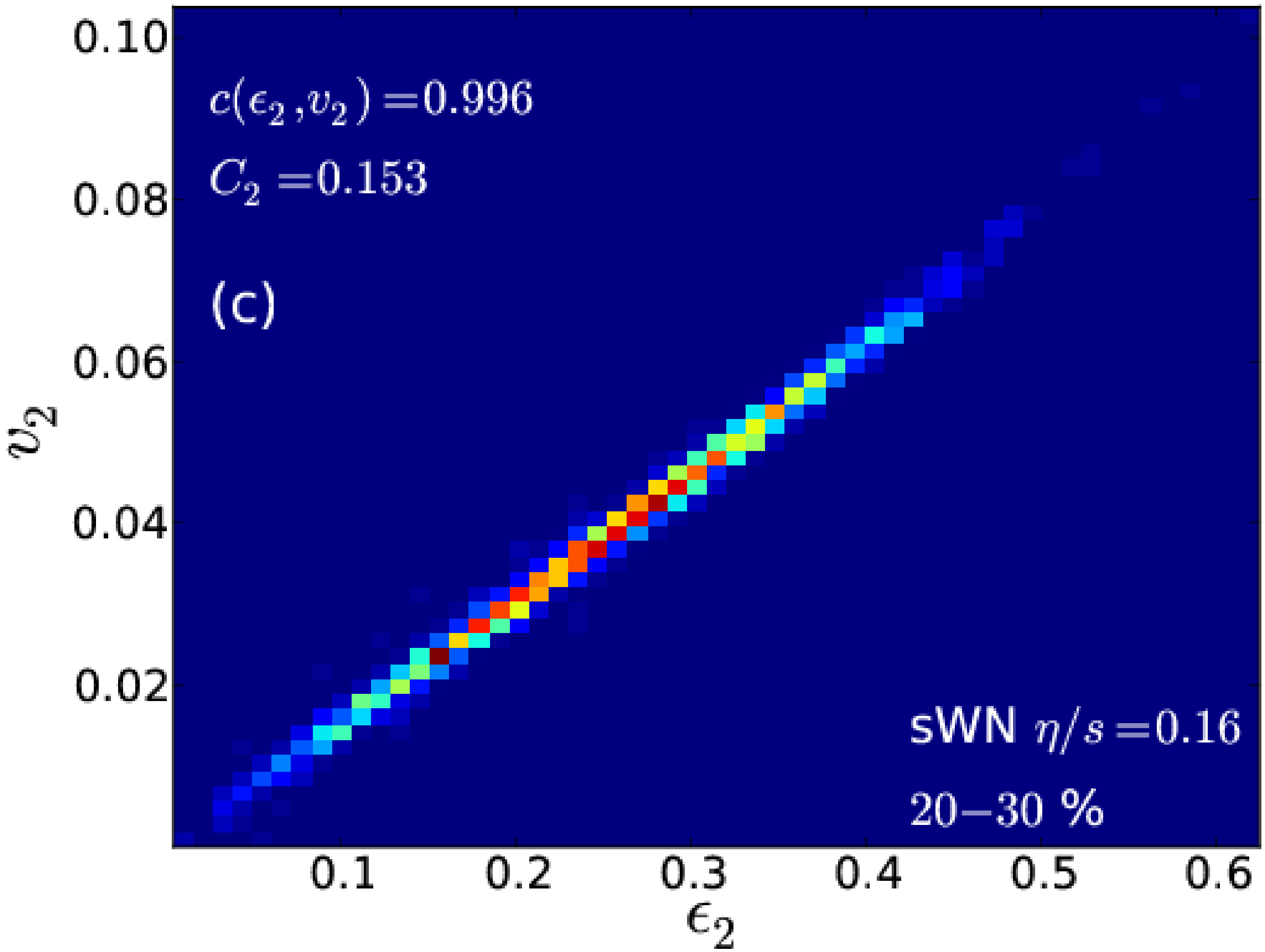
1. Non-Gaussianity is crucial for disentanglement of κ and ε_n.

$$P_{BG}(\varepsilon_n \to \varepsilon_n/\kappa_n) \equiv P_{BG}(\sigma \to \sigma\kappa)$$

2. Generalization accounting for non-linear corrections and fluctuations in flow response.

Linear eccentricity scaling

EbyE dissipative hydro. with shear viscosity = 0.16.



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Goodness of fit