Flow fluctuations versus Initial state fluctuations

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Outline

- Selected experimental results on flow fluctuations.
- Are flow fluctuations simply related to initial state fluctuations?
- Recent progress since IS2013

Anisotropic flow

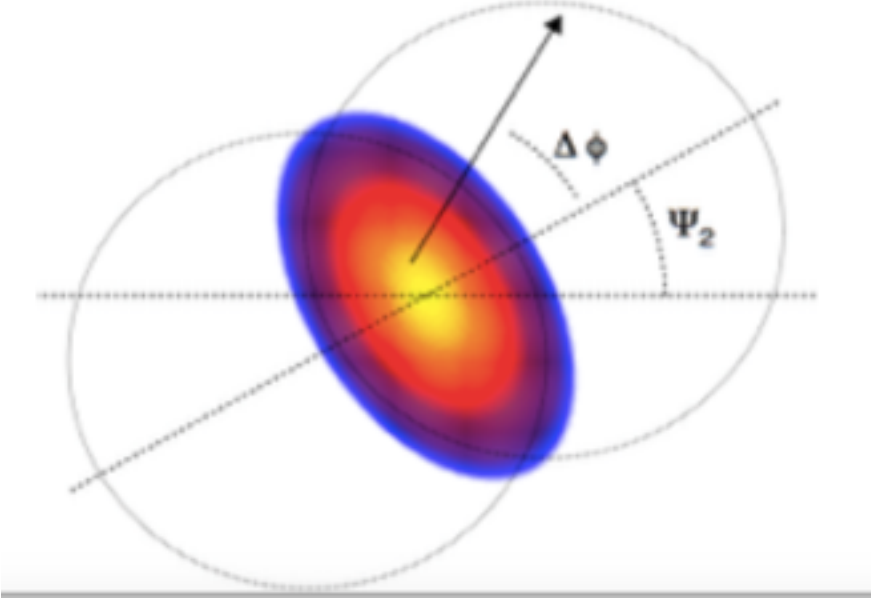
- Particles are emitted independently, with a *probability distribution* that is not isotropic in azimuthal angle

$$P(\phi)= \sum_n V_n \exp(-in\phi)$$

- $v_n \equiv |V_n| \equiv$ anisotropic flow
  $v_2 \equiv$ elliptic flow
  $v_3 \equiv$ triangular flow…

Flow fluctuations

- V_n fluctuates event to event.
- V_2 in nucleus-nucleus:
  mean V_2 *from geometry*
  + *fluctuations*
- V_3 in nucleus-nucleus,
  V_2 in proton-nucleus:
  just fluctuations



Alver et al nucl-ex/0610037

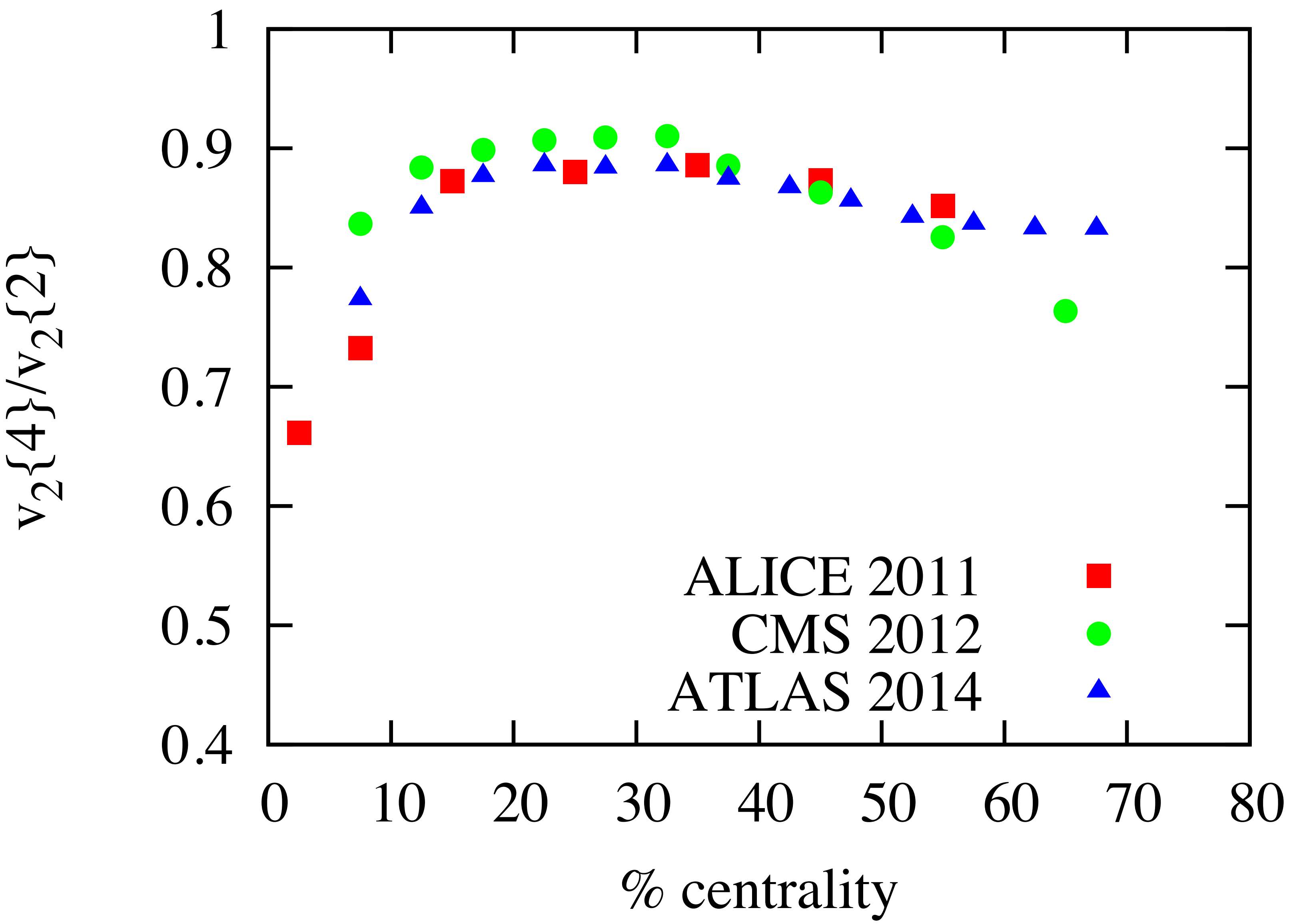
Alver Roland 1003.0194

Moments and cumulants

- $v\{2\} \equiv (\langle v^2 \rangle)^{1/2}$
- $v\{4\} \equiv (2\langle v^2 \rangle^2 - \langle v^4 \rangle)^{1/4}$
- $v\{6\} \equiv ((\langle v^6 \rangle - 9\langle v^4 \rangle \langle v^2 \rangle + 12\langle v^2 \rangle^3)/4)^{1/6}$
- If v does not fluctuate, $v\{2\}=v\{4\}=v\{6\}=v$
- In general $v\{4\}<v\{2\}$
- Event-plane method: $\langle v \rangle < v\{EP\} < v\{2\}$

Alver et al 0711.3724

v_2 fluctuations in Pb-Pb



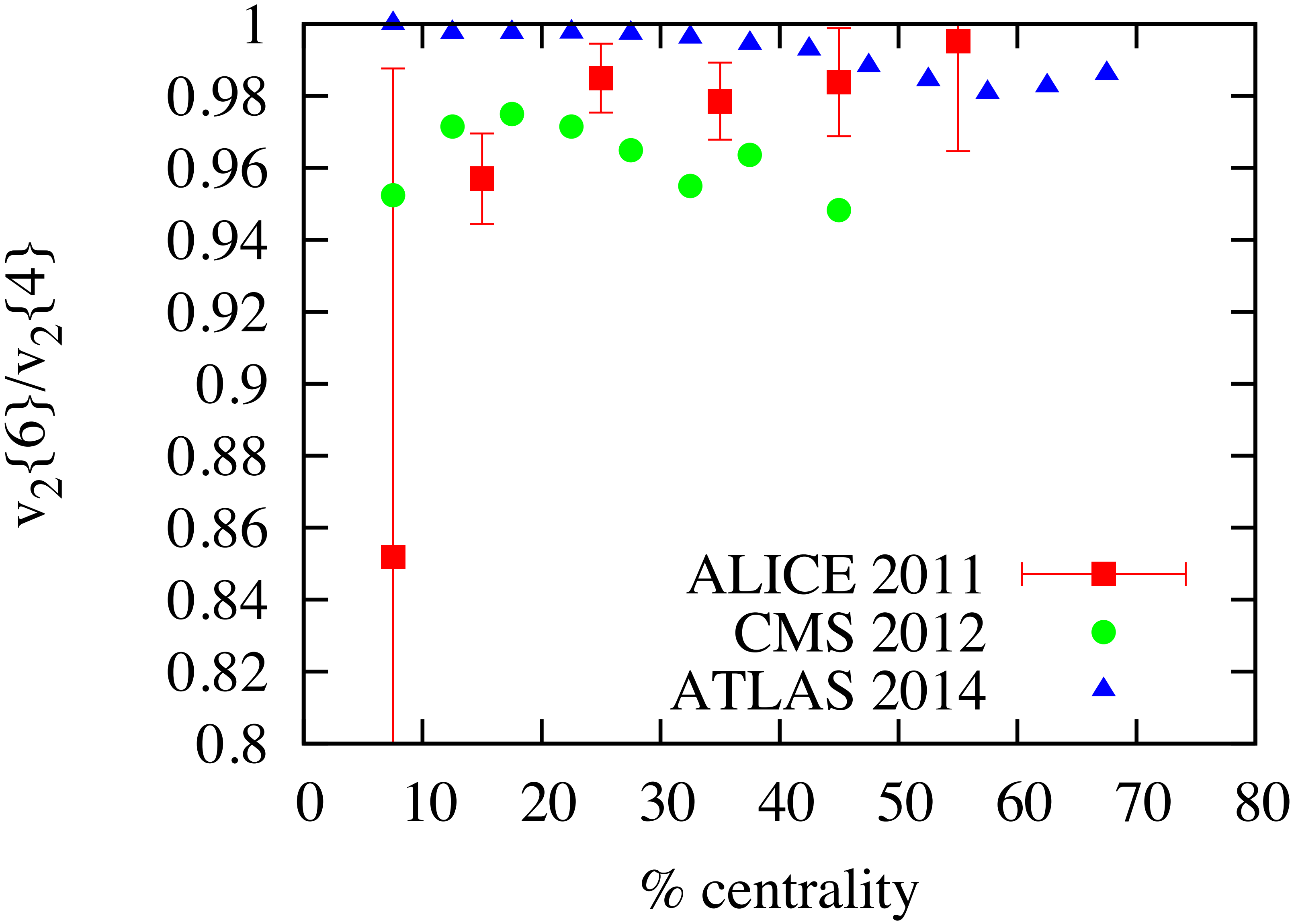
For CMS, I use $v_2\{EP\}$ as an approximation for $v_2\{2\}$: probably explains the small discrepancy

Gaussian fluctuations?

Voloshin et al. 0708.0800

- Gaussian (aka Bessel-Gaussian) flow fluctuations:
- V_2 in nucleus-nucleus:
  $v_2\{4\}=v_2\{6\}=v_2\{LYZ\}=v_2$ in reaction plane
- V_3 in nucleus-nucleus: $v_3\{4\}=0$
  V_2 in proton-nucleus: $v_2\{4\}=0$

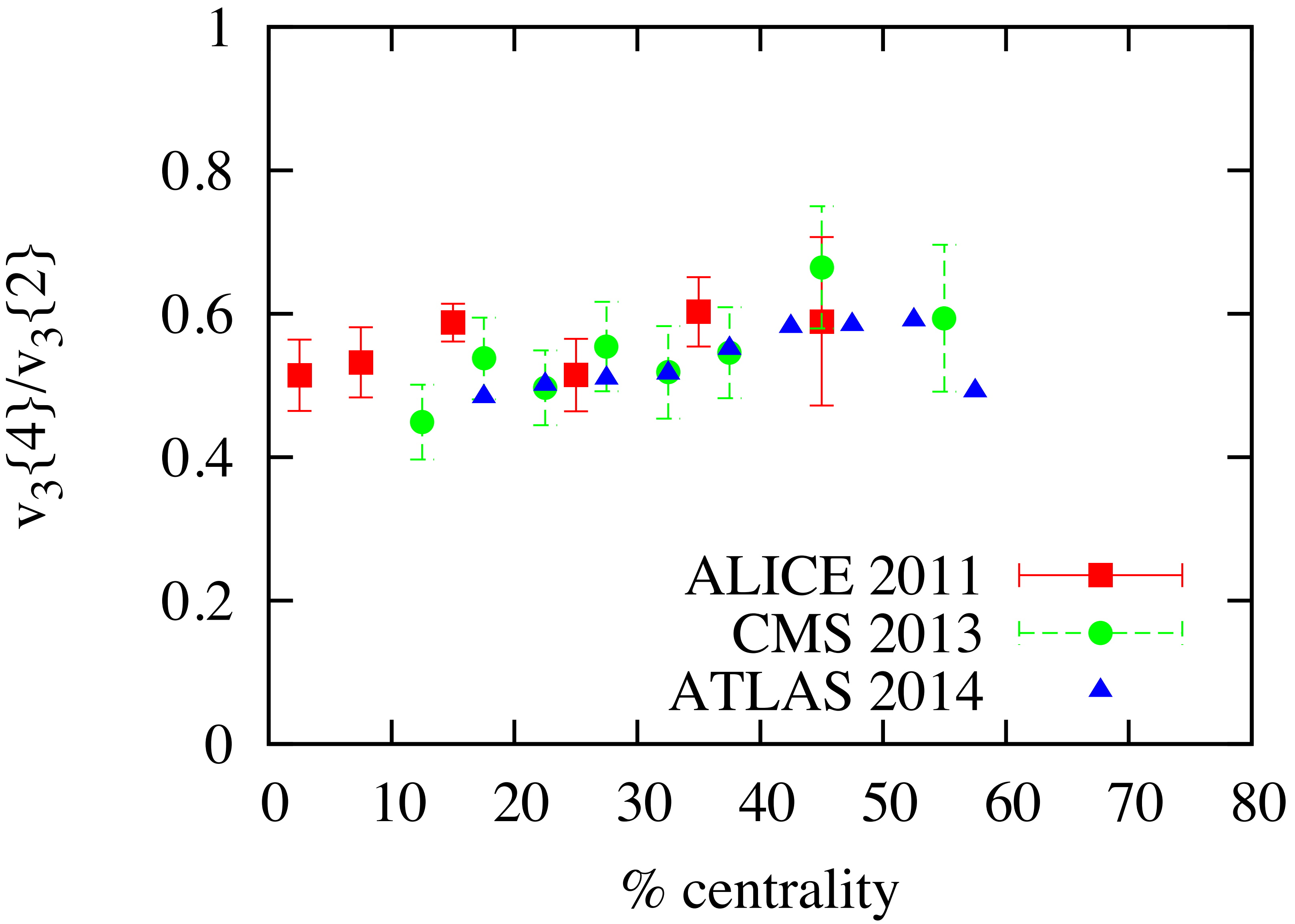
Are v_2 fluctuations Gaussian?



For ALICE and CMS, I assumed $v_2\{6\}=v_2\{LYZ\}$: Probably not good.

Small non-Gaussianities seen by ATLAS. Larger for smaller systems.

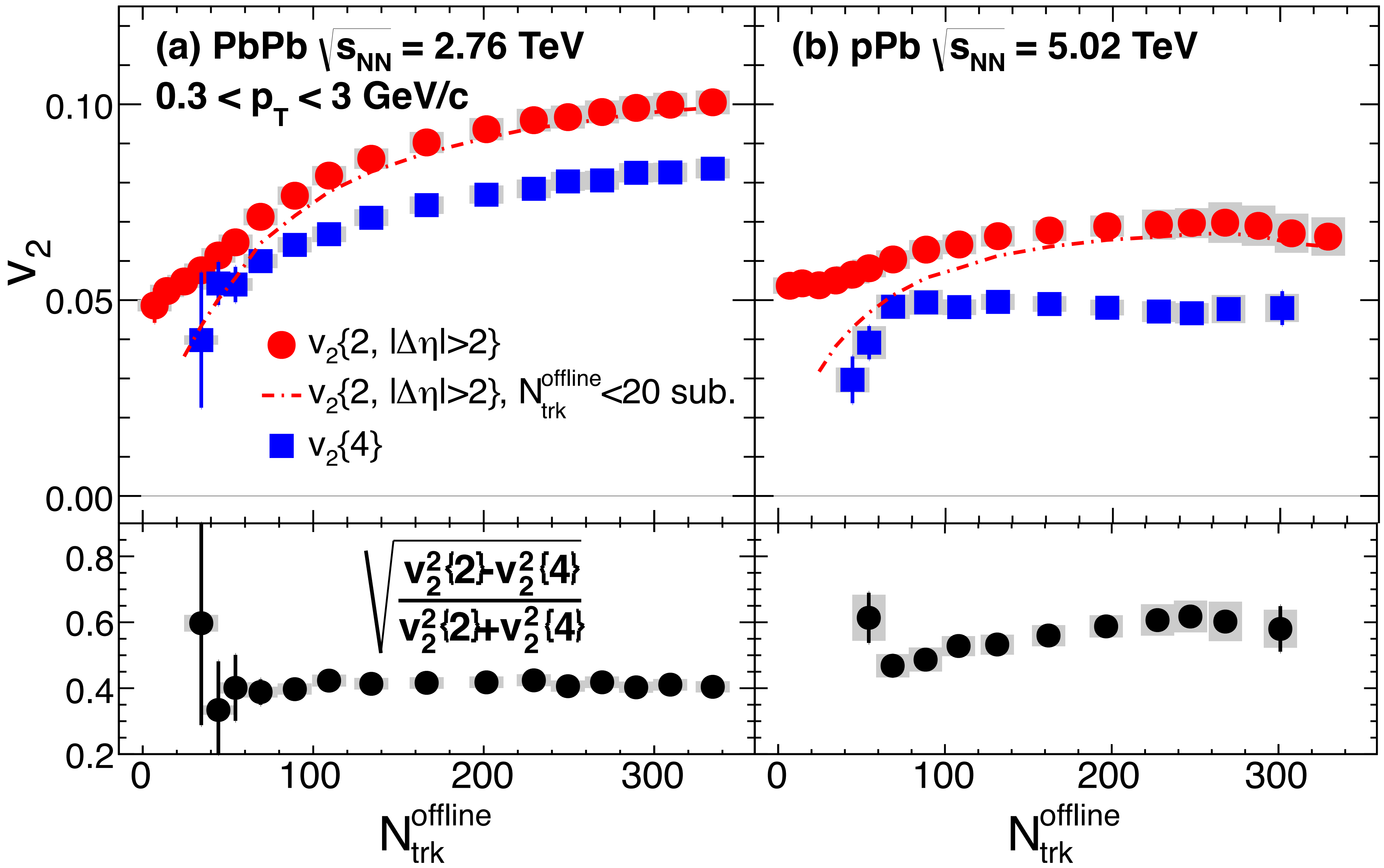
Are v_3 fluctuations Gaussian?



All 3 experiments see $v_3\{4\} \neq 0$:
non-Gaussian fluctuations clearly seen

v_2 fluctuations in p-Pb collisions

CMS 1305.0609



Large $v_2\{4\}$: large non-Gaussianities

From initial state fluctuations to flow fluctuations

- Take a Monte-Carlo model of initial conditions
- Evolve using relativistic hydrodynamics
- Compute particle distribution
- Average over events

Paatelainen et al

Schenke et al

Bozek et al

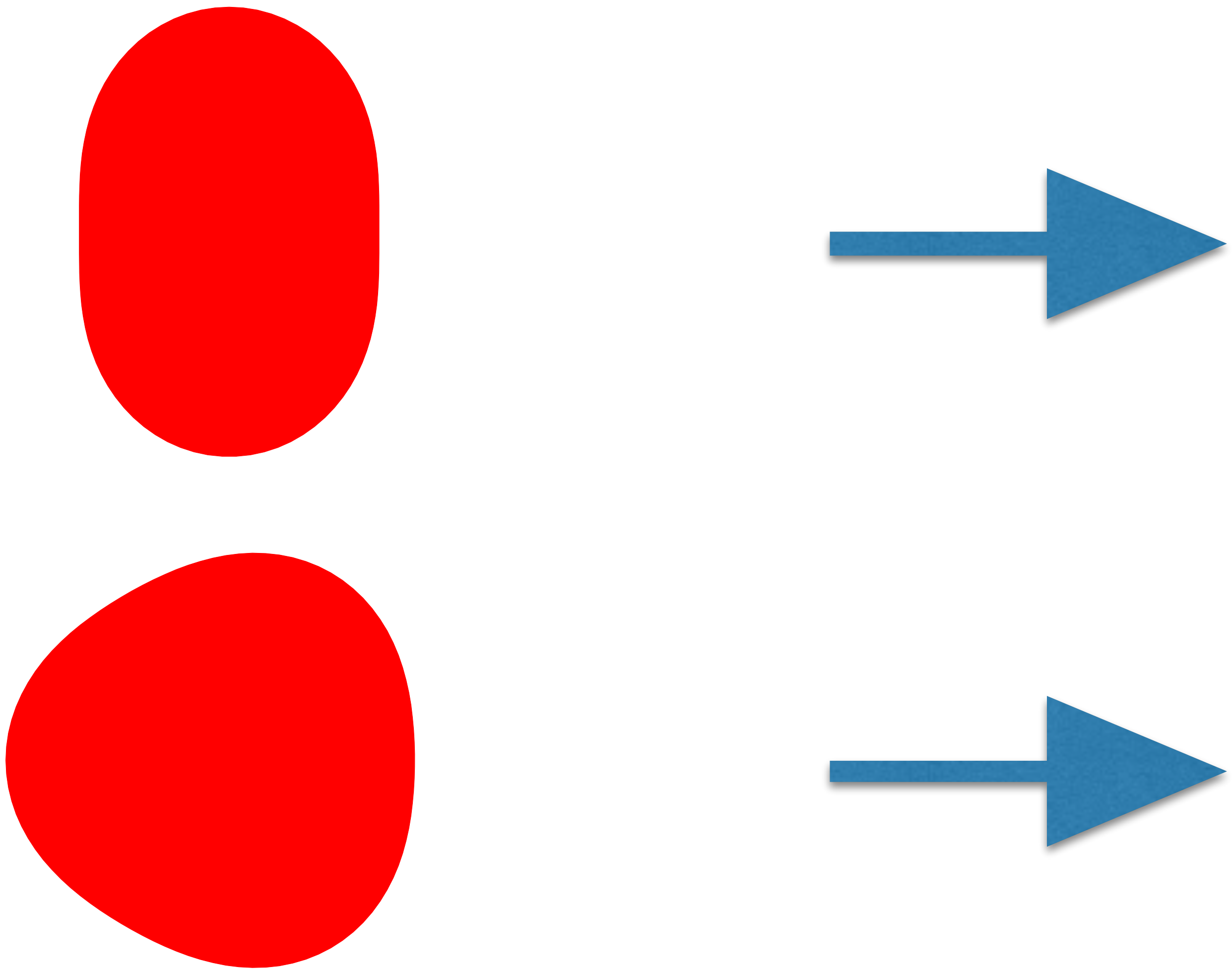
Werner et al

The origin of anisotropic flow

Initial transverse density profile

Expansion

Final distribution

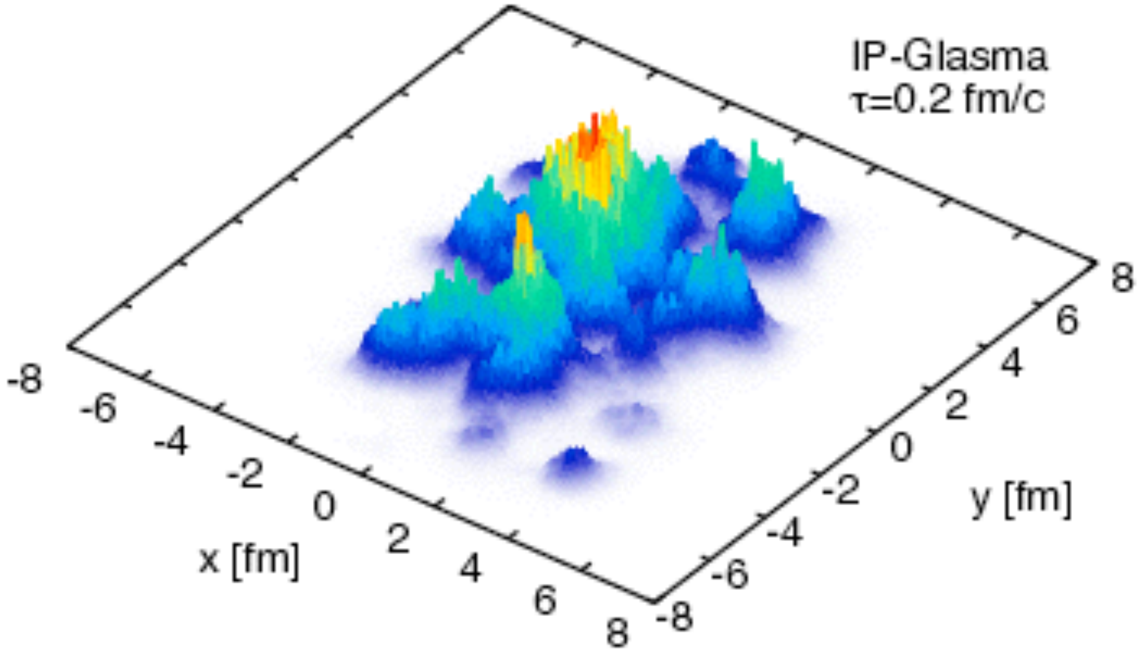


Elliptic flow v_2

Triangular flow v_3

Initial anisotropies

= Fourier decomposition of the initial density profile $\rho(x,y)$



Schenke Tribedy Venugopalan 1202.6646

$$\varepsilon_n \equiv \frac{\left| \int r^n e^{in\phi} \rho(r,\phi) r dr d\phi \right|}{\int r^n \rho(r,\phi) r dr d\phi}$$

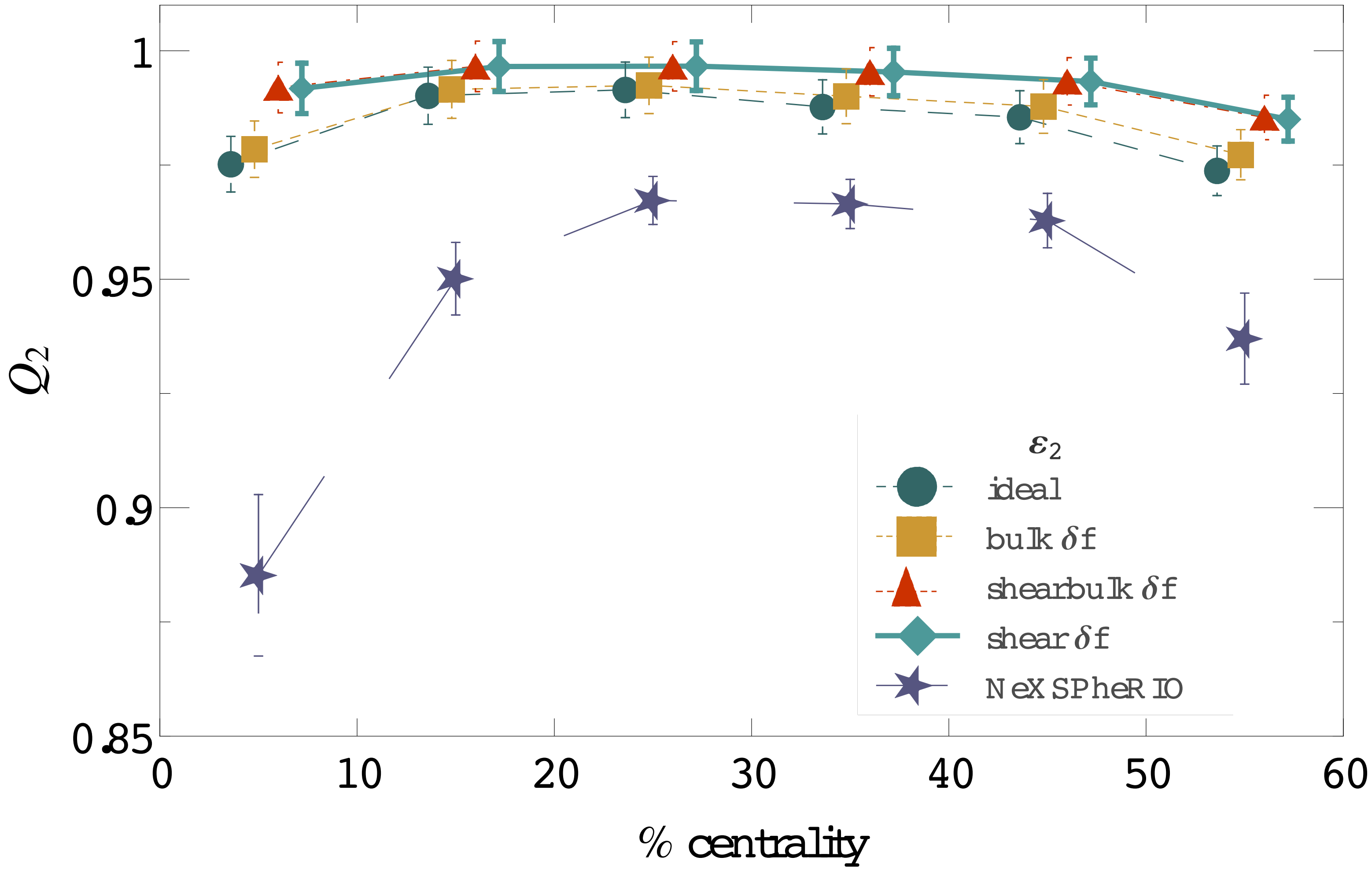
$\varepsilon_2 \equiv$ initial eccentricity

$\varepsilon_3 \equiv$ initial triangularity

$|\varepsilon_n| < 1$ by definition

v_2 is strongly correlated with ε_2

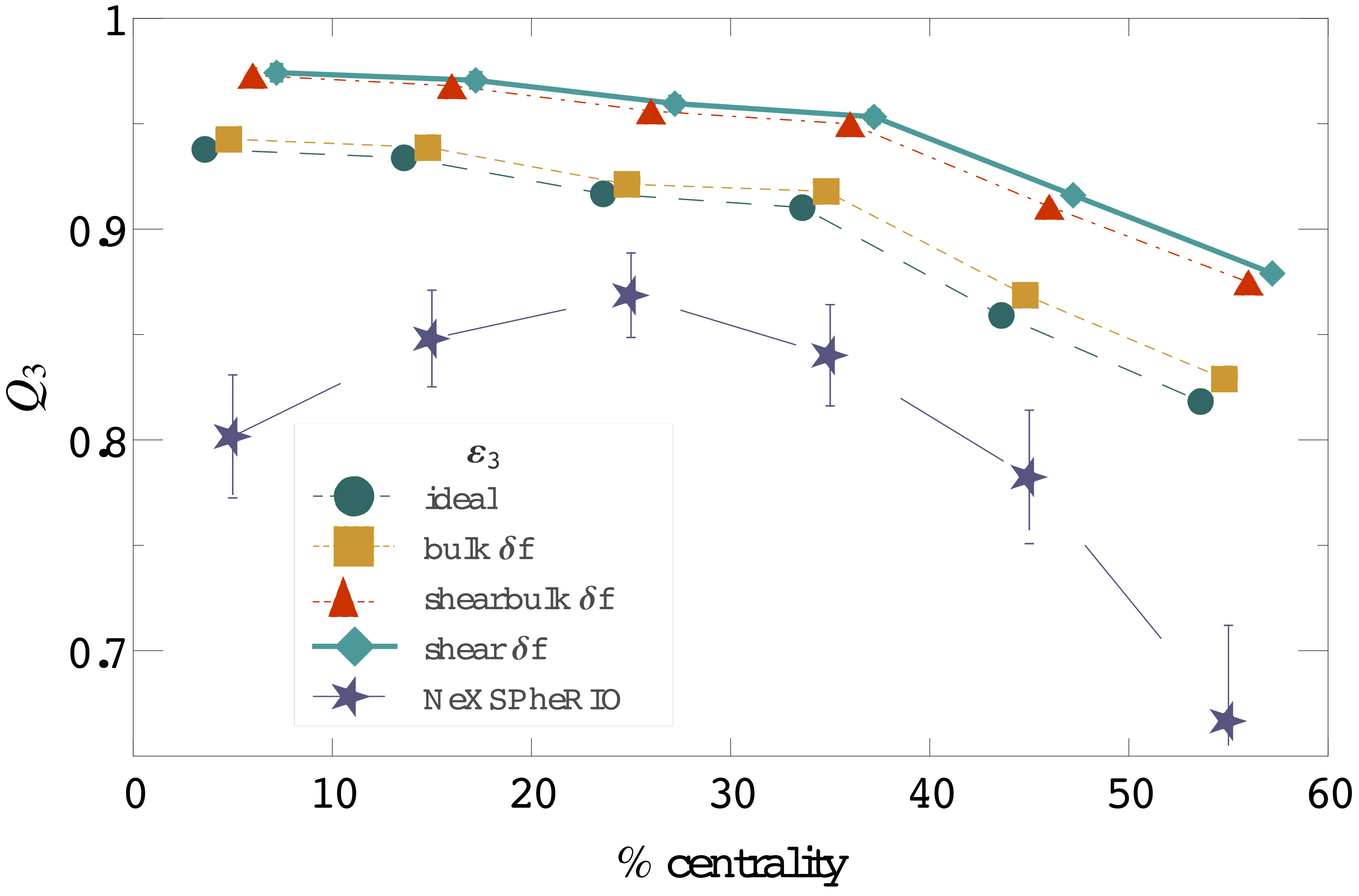
linear (Pearson) correlation coefficient in event-by-event viscous hydro



Gardim Noronha-Hostler Luzum Grassi 1411.2574

v_3 is strongly correlated with ε_3

linear (Pearson) correlation coefficient in event-by-event viscous hydro



Gardim Noronha-Hostler Luzum Grassi 1411.2574

Flow as linear response

$$v_2 \approx \kappa_2\ \varepsilon_2$$

$$v_3 \approx \kappa_3\ \varepsilon_3$$

response coefficients

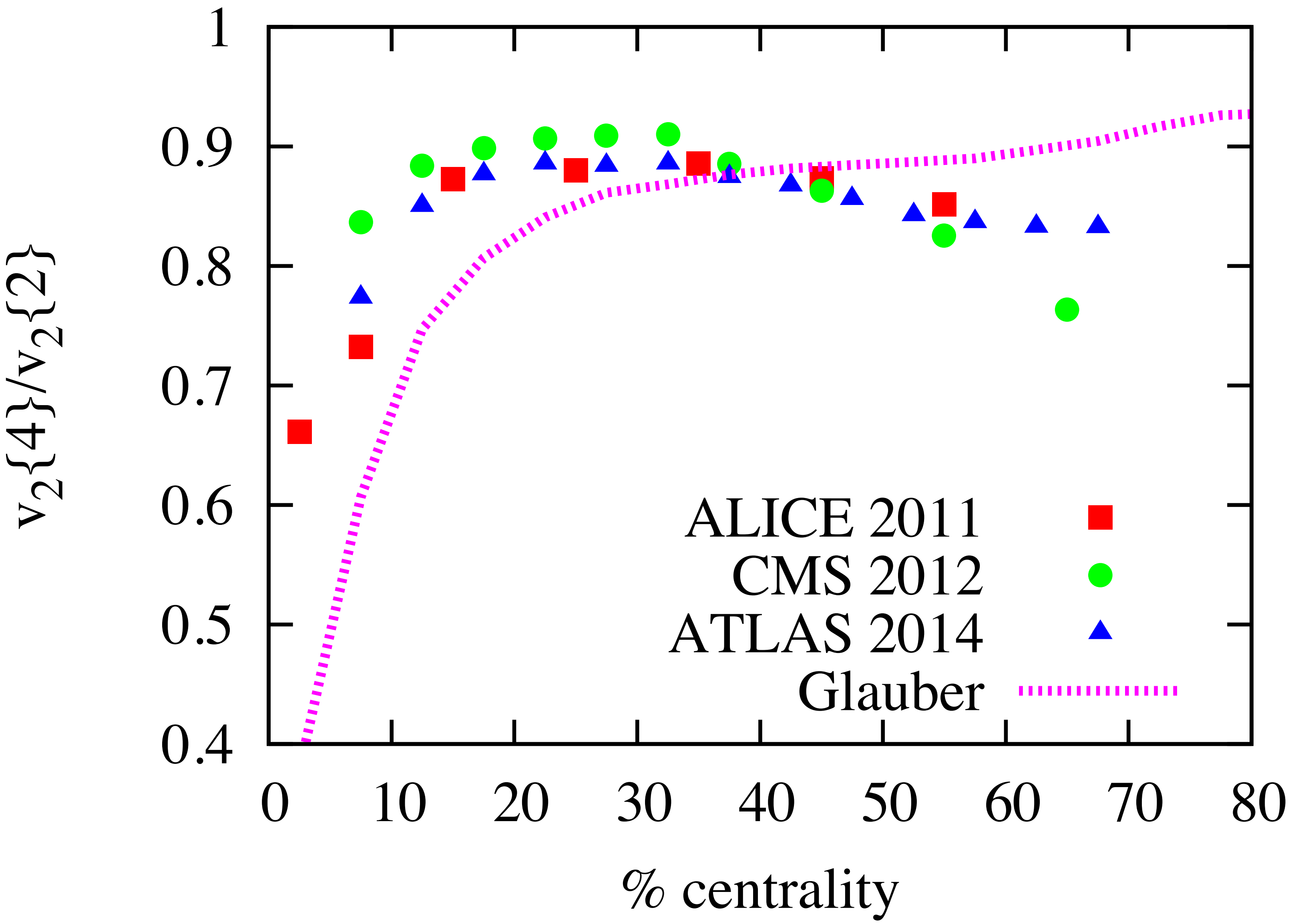
fluctuate event to event.

depend on system and centrality, not on details of initial conditions

v_n fluctuations are due to ε_n fluctuations

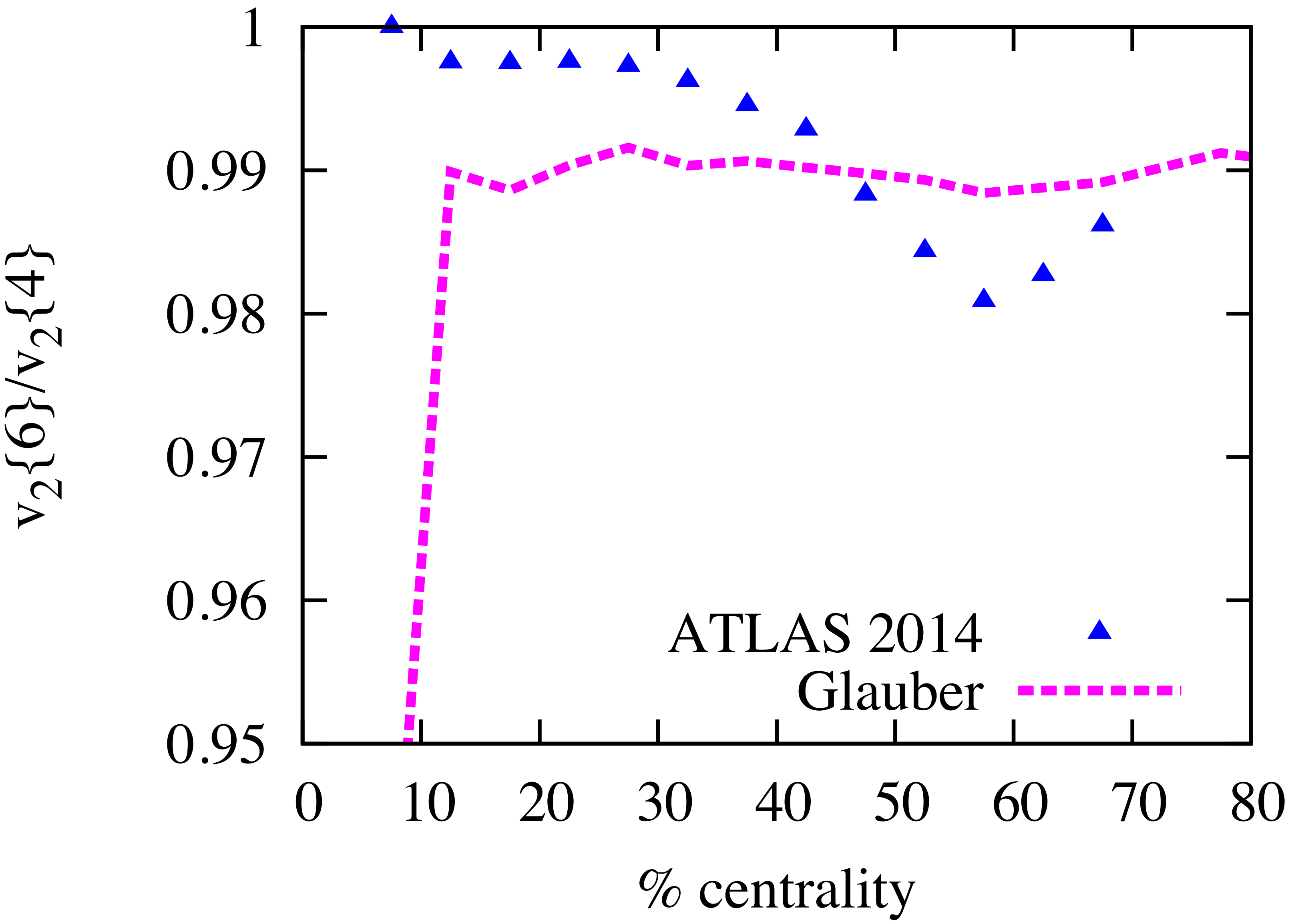
$$v_n\{4\}/v_n\{2\} = \varepsilon_n\{4\}/\varepsilon_n\{2\}$$

v_2 fluctuations vs ε_2 fluctuations



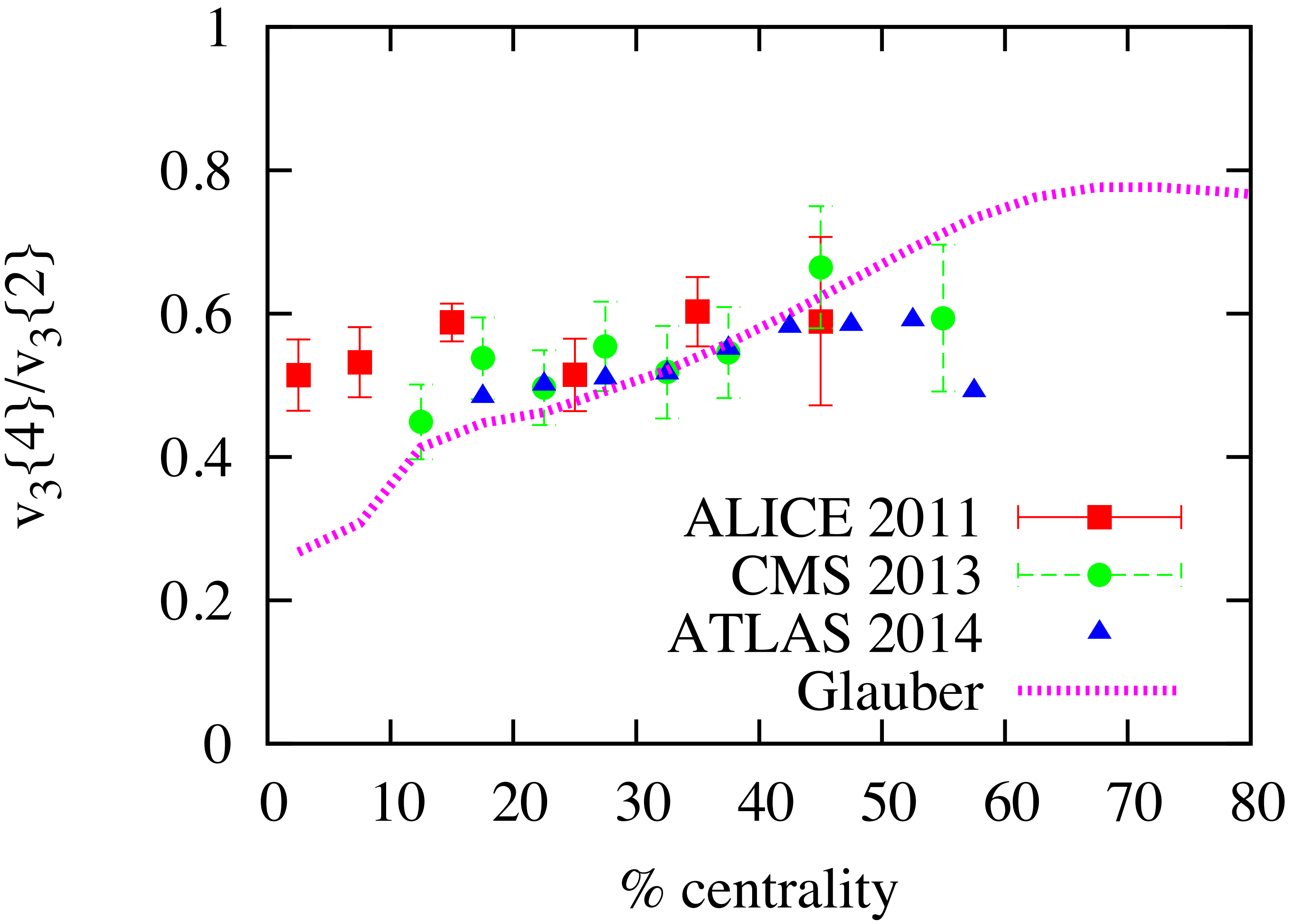
ε_2 fluctuations from Glauber: in the ballpark

v_2 fluctuations vs ε_2 fluctuations



Non-Gaussianities from Glauber: in the ballpark

v_3 fluctuations vs ε_3 fluctuations



Non-Gaussianities from Glauber: in the ballpark

A discussion at IS2013

- Non-Gaussian flow fluctuations are seen both in Pb-Pb (v_3) and in pPb (v_2)
- Similar non-Gaussianities are seen in initial state models
- Do we understand their origin?

Alver et al. 0711.3724

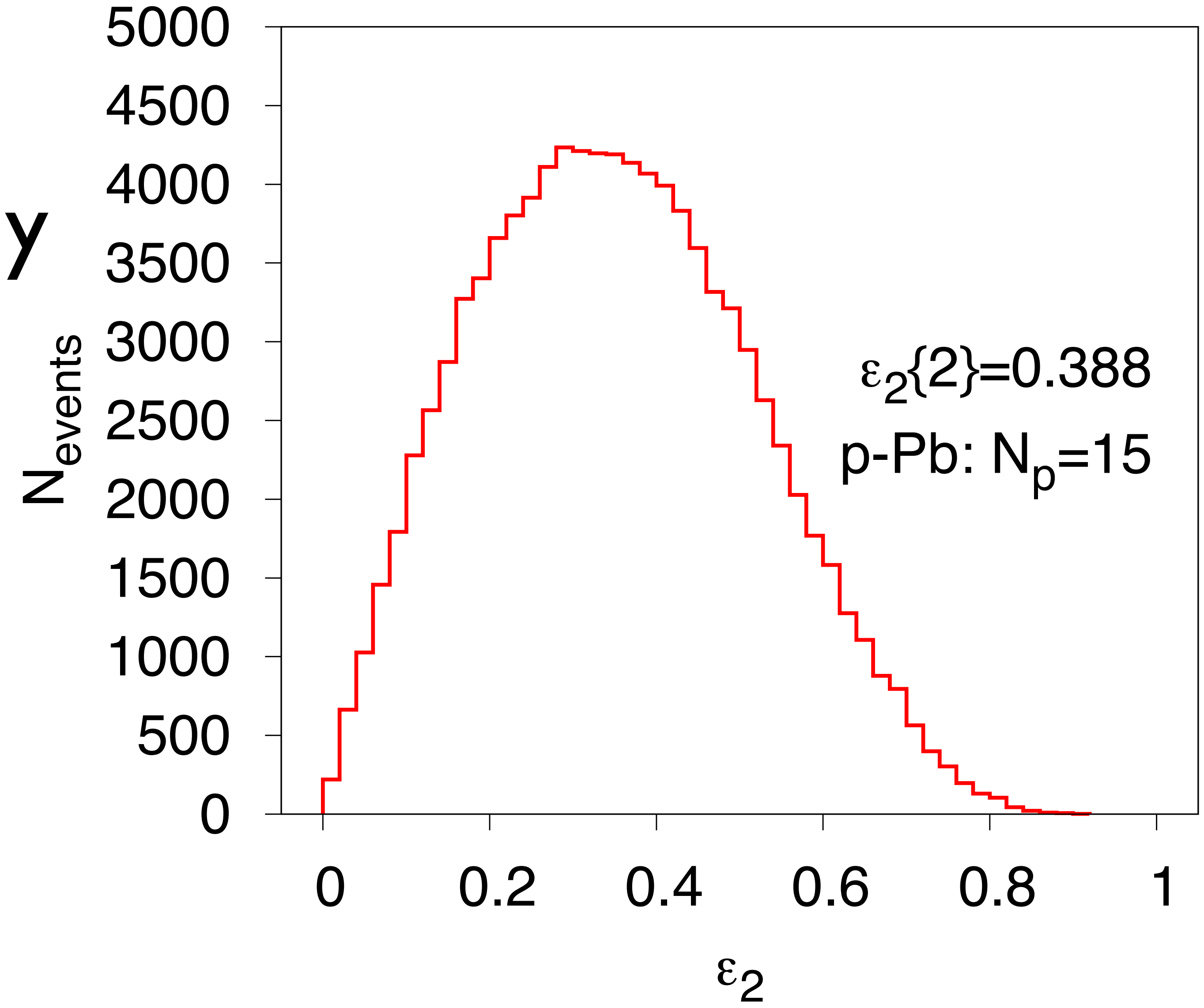
Bhalerao Luzum JYO 1107.5485

Distribution of initial anisotropy

Central p+Pb collision:
ε_2 from fluctuations only

small system:
large fluctuations &
anisotropies

Monte-Carlo Glauber simulation



Is there a simple law that describes this distribution?

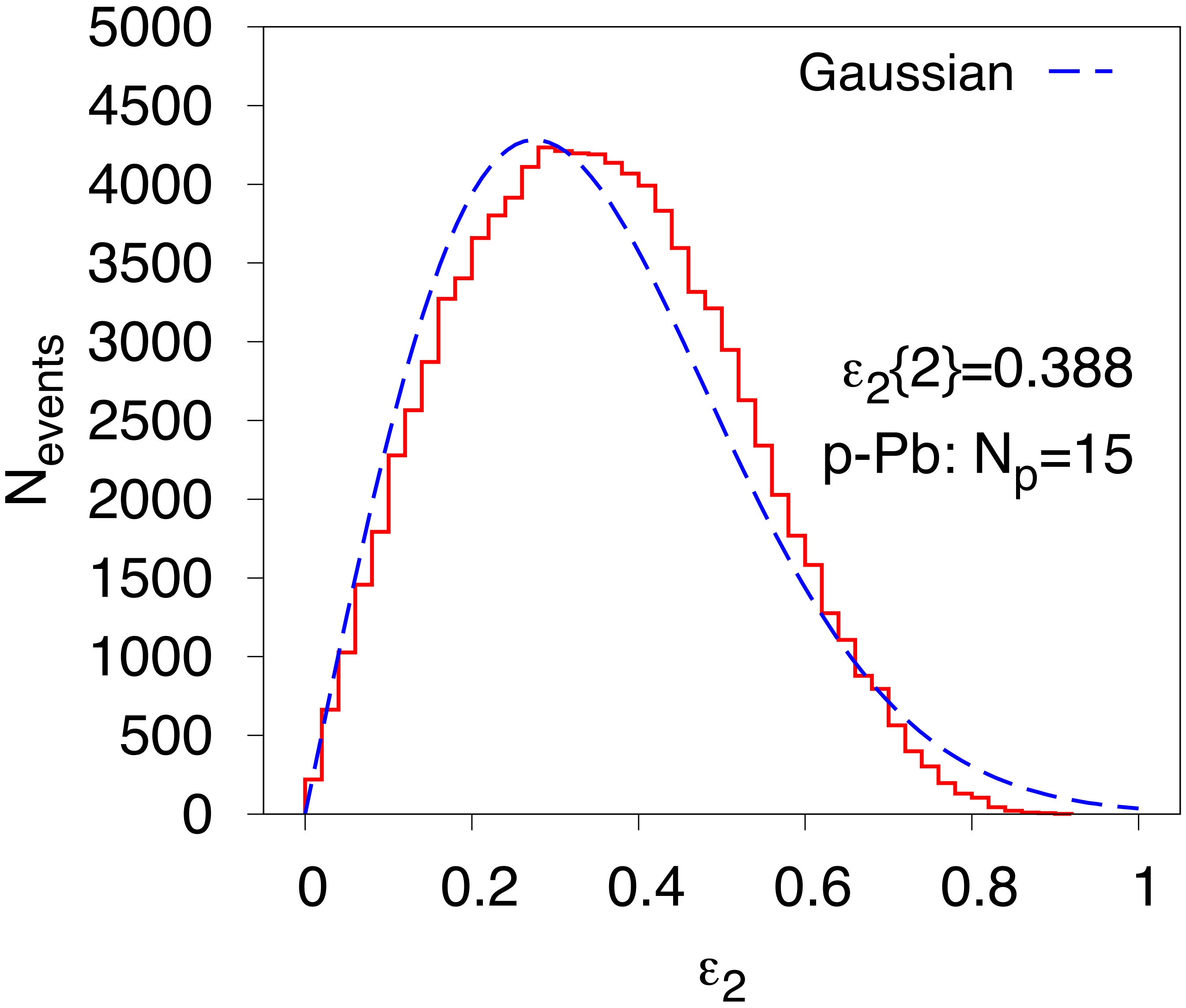
Gaussian?

Central limit theorem

$P(\varepsilon_2) = 2(\varepsilon_2/\sigma^2)\exp(-\varepsilon_2^2/\sigma^2)$

Not a good fit.

Does not implement the condition $\varepsilon_2 < 1$



New "*Power*" distribution

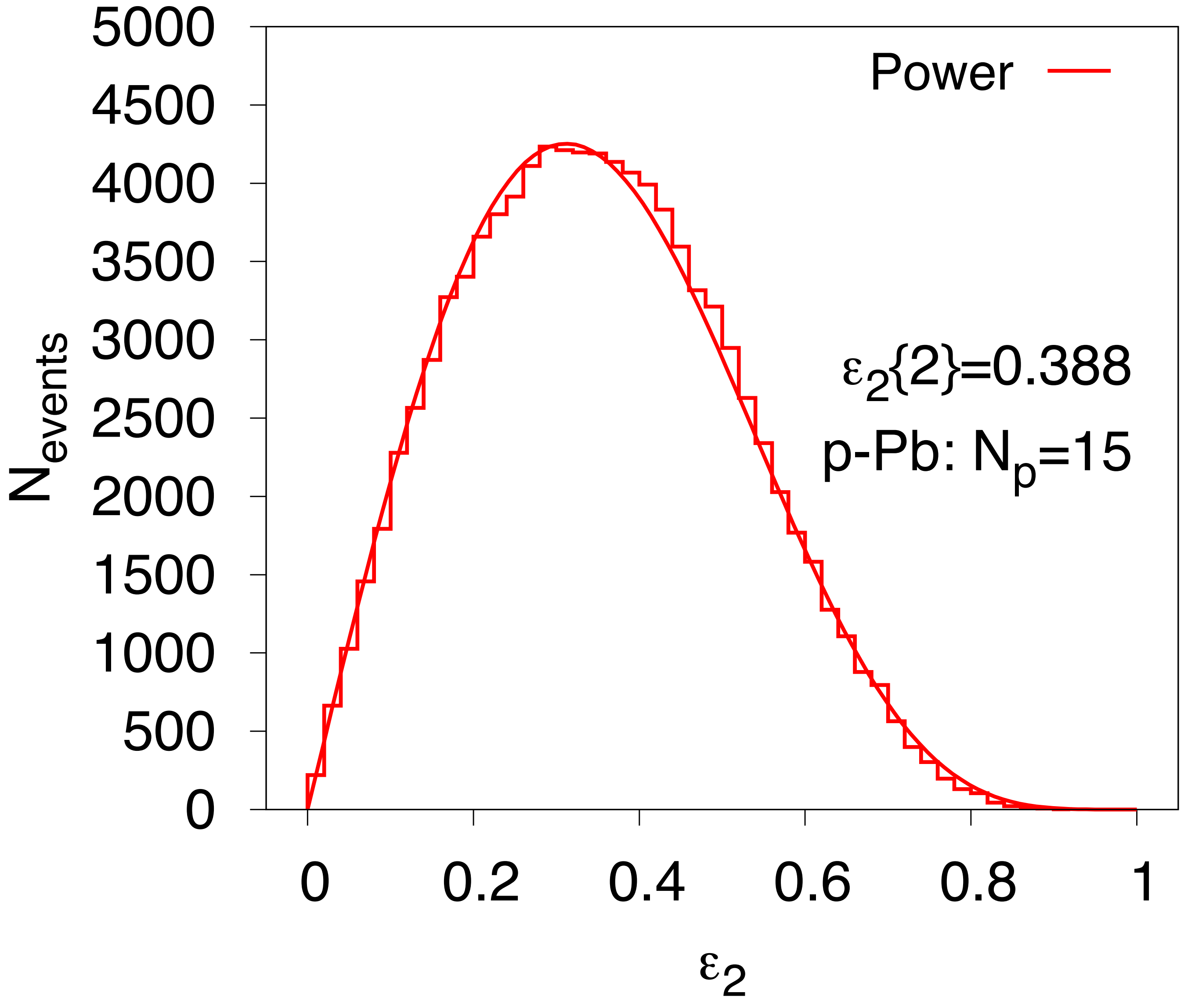
$P(\varepsilon_2) = 2\alpha\varepsilon_2(1-\varepsilon_2^2)^{\alpha-1}$

Equivalent to Gaussian for $\alpha \gg 1$

Naturally implements the condition $\varepsilon_2 < 1$.

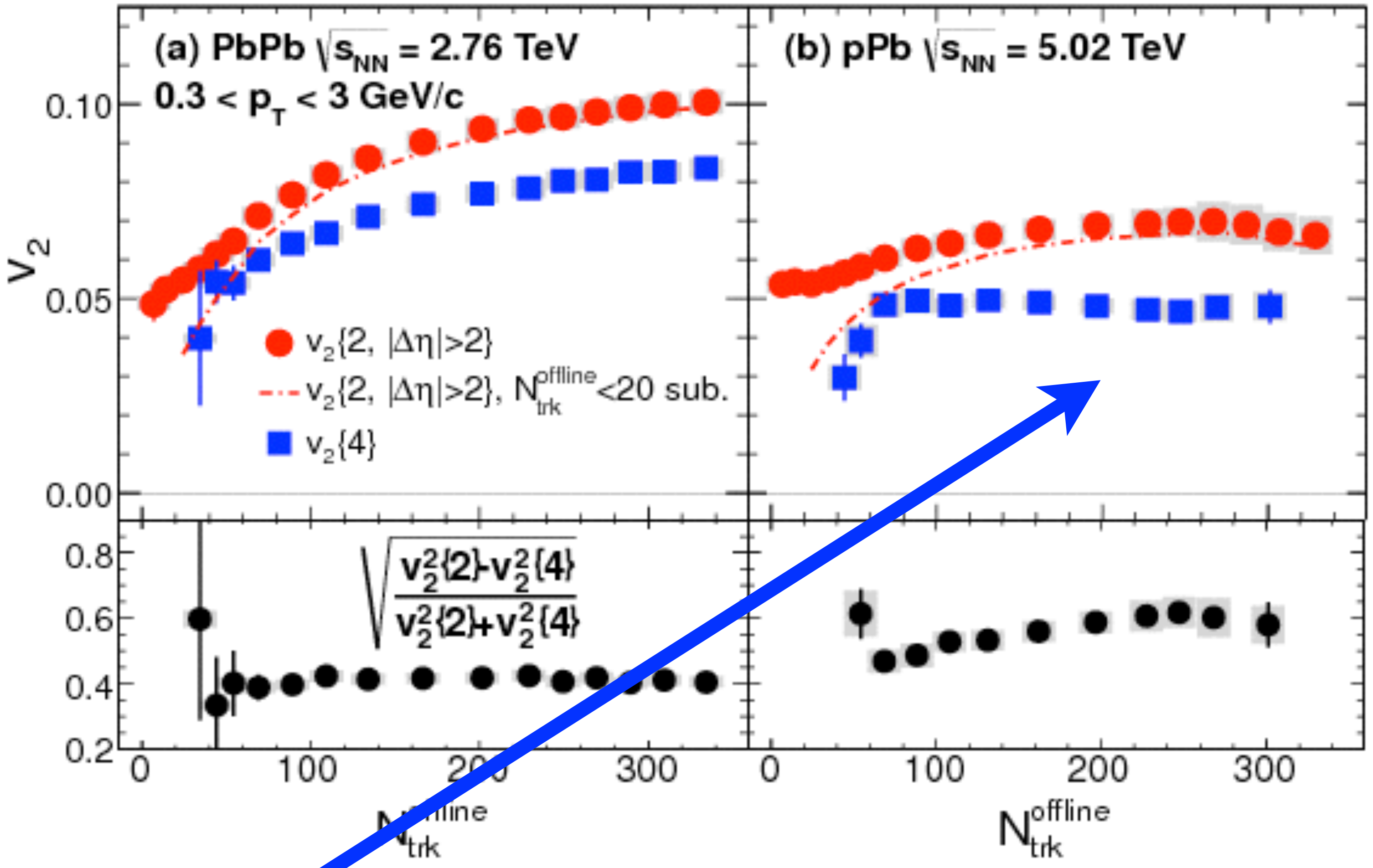
Predicts $\varepsilon_2\{4\} > 0$

Li Yan, JYO, PRL 112 (2014) 082301



Much better fit to Monte-Carlo results!

Natural explanation for $v_2\{4\}$ in pPb



CMS 1305.0609

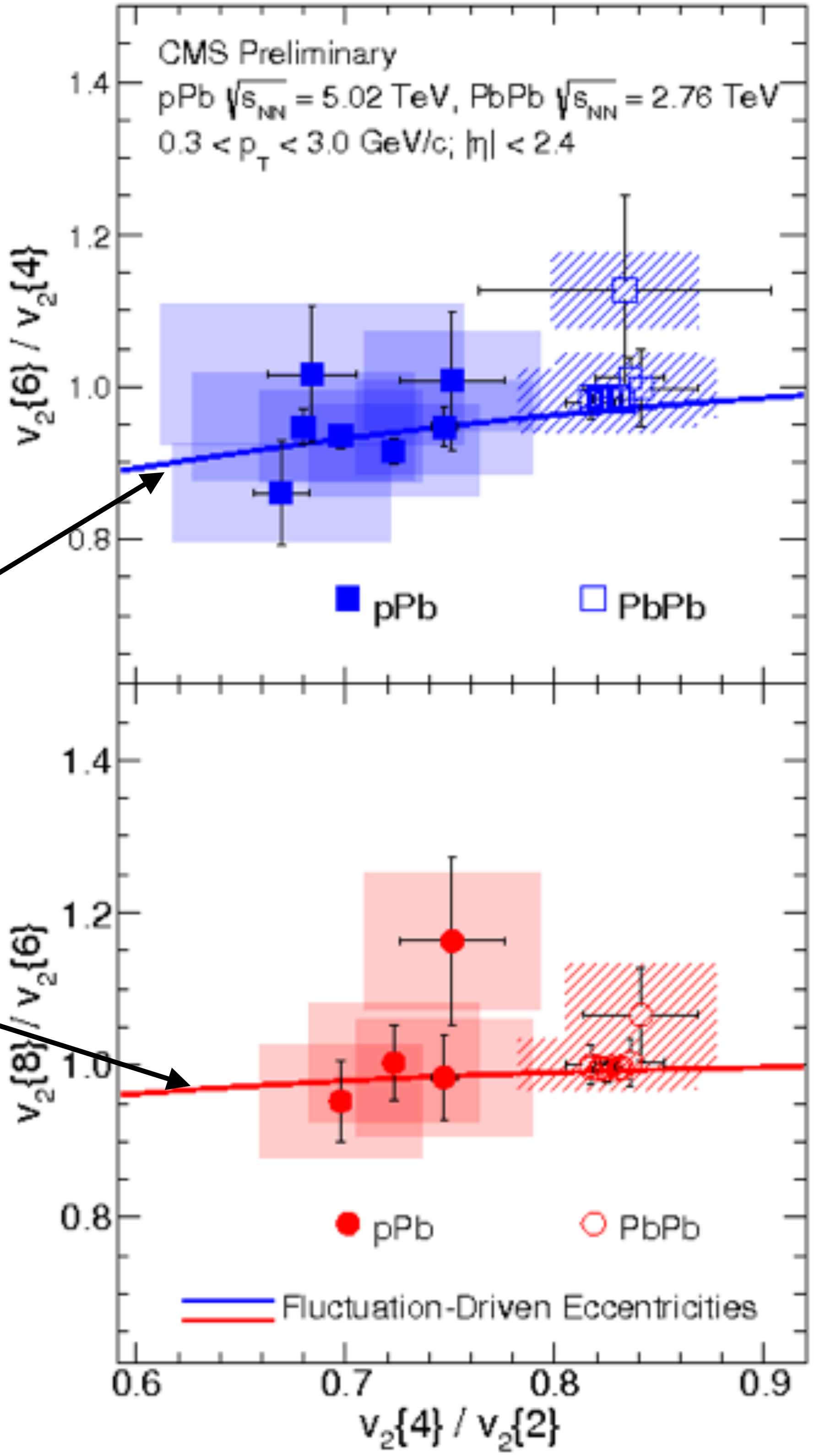
Small system: large fluctuations: large $v_2\{4\}/v_2\{2\}$

Predictions: higher-order cumulants

- Using as input the experimentally measured ratio $v_2\{4\}/v_2\{2\}$

- Quantitative prediction for higher-order cumulants $v_2\{6\}$ and $v_2\{8\}$

- New CMS data (QM2014) in good agreement with our prediction



Conclusions

- Direct evidence from experimental data that anisotropic flow in p-Pb and Pb-Pb collisions is driven by large anisotropies in the initial state: the statistics of ε_n *hits the boundary* $\varepsilon_n < 1$
- The statistics of large fluctuations is not described by the central limit theorem but nevertheless universal to a good approximation.
- Flow fluctuations reflect to a large extent fluctuations in initial anisotropies. Corrections to this picture?

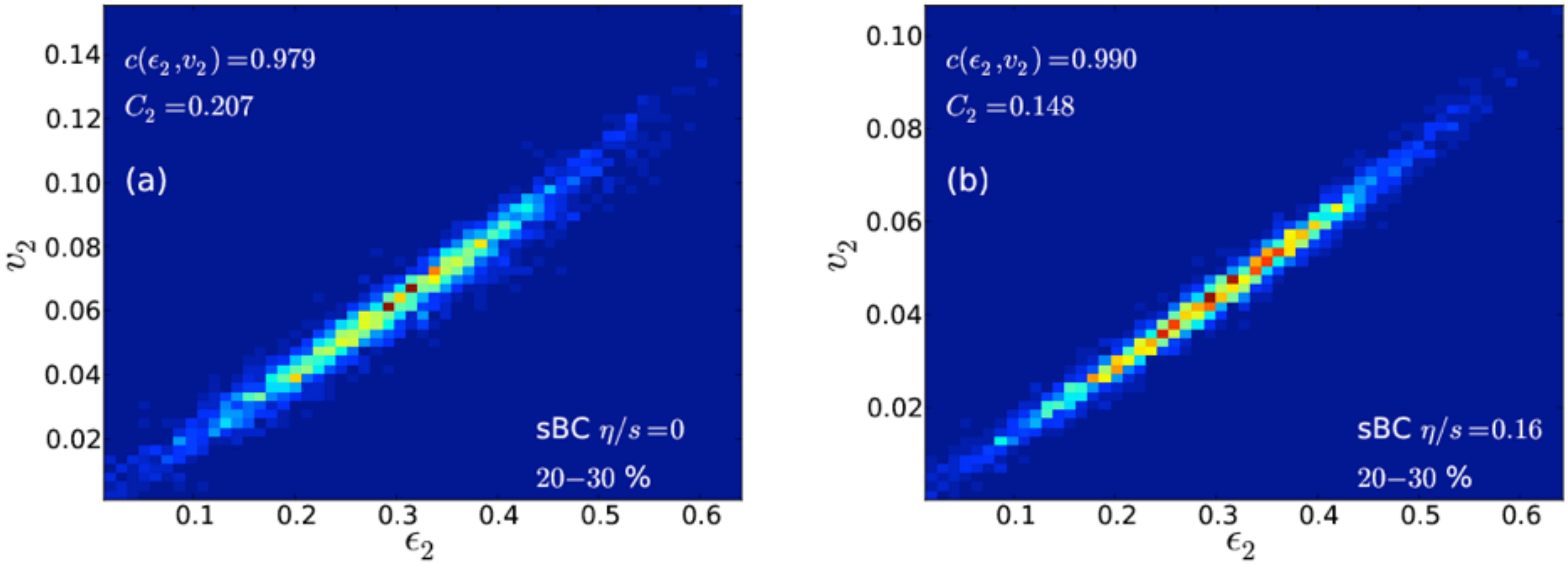
More in the next talk by Art Poskanzer

Perspectives

- Experiments: explore flow fluctuations through the double-differential structure of pair correlations *Talks by Wei Li, Rajeev Bhalerao*
- Hydro: do we understand the response to initial fluctuations beyond simple eccentricity scaling? *More in the next talk by Art Poskanzer*
- Initial state: understand on general grounds the initial anisotropies and their statistical properties. *Talk by Jean-Paul Blaizot*

Backup

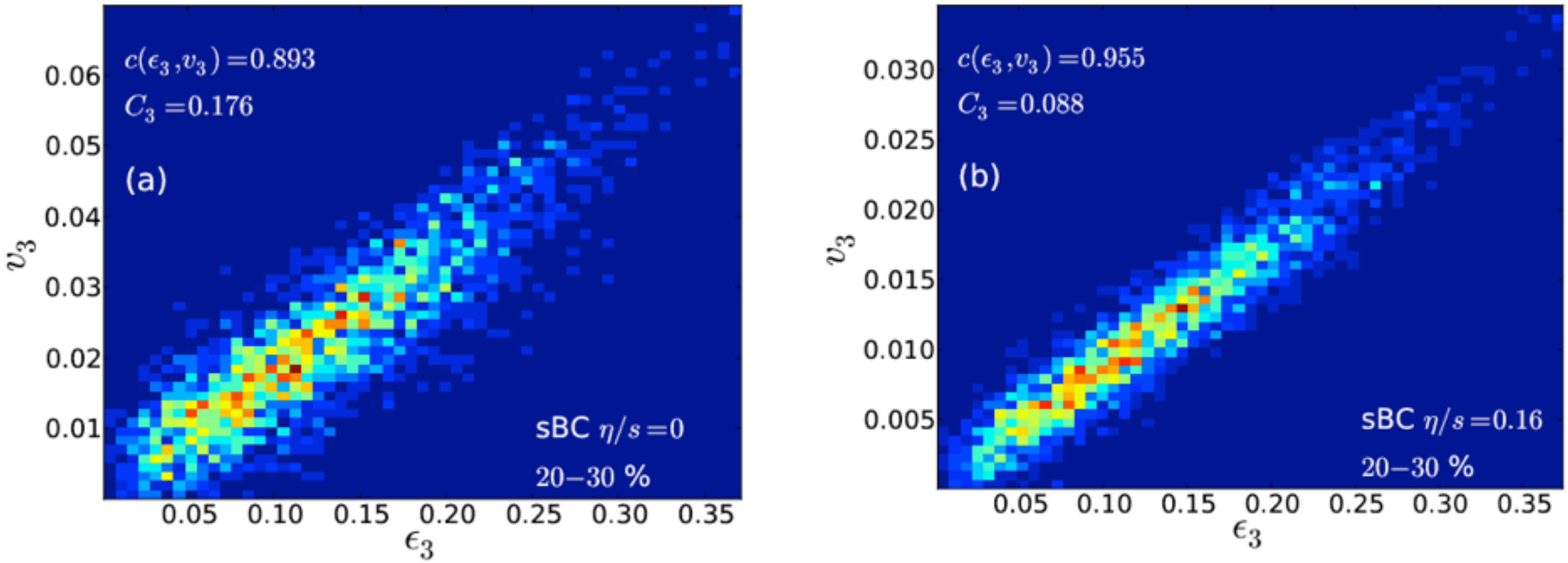
Elliptic flow v_2 versus initial eccentricity ε_2



Niemi Denicol Holopainen Huovinen 1212.1008

Each point=different initial density profile.
v_2 is almost perfectly linear in ε_2

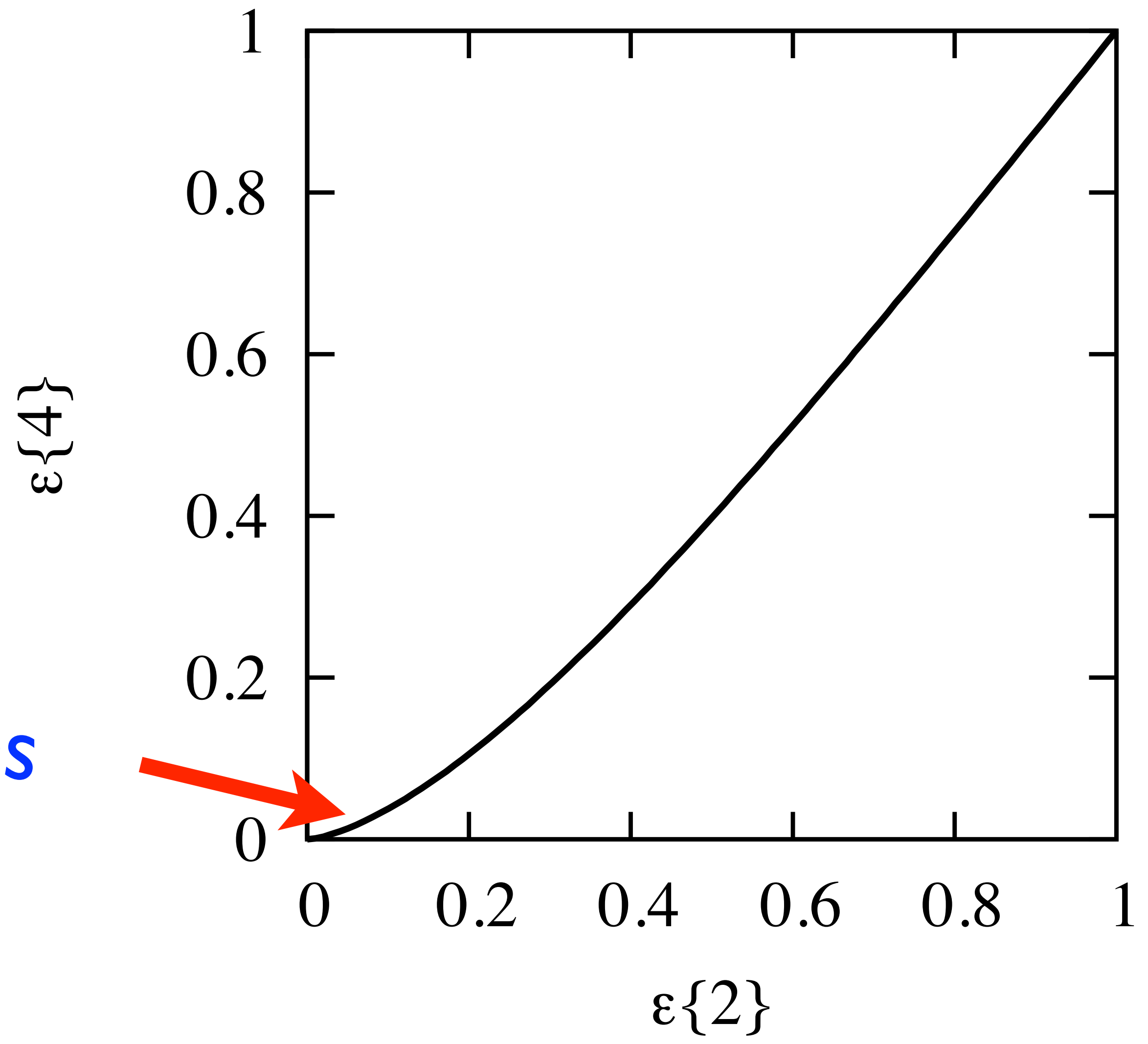
Triangular flow v_3 versus initial triangularity ε_3



Niemi Denicol Holopainen Huovinen 1212.1008

v_3 is also strongly correlated with ε_3

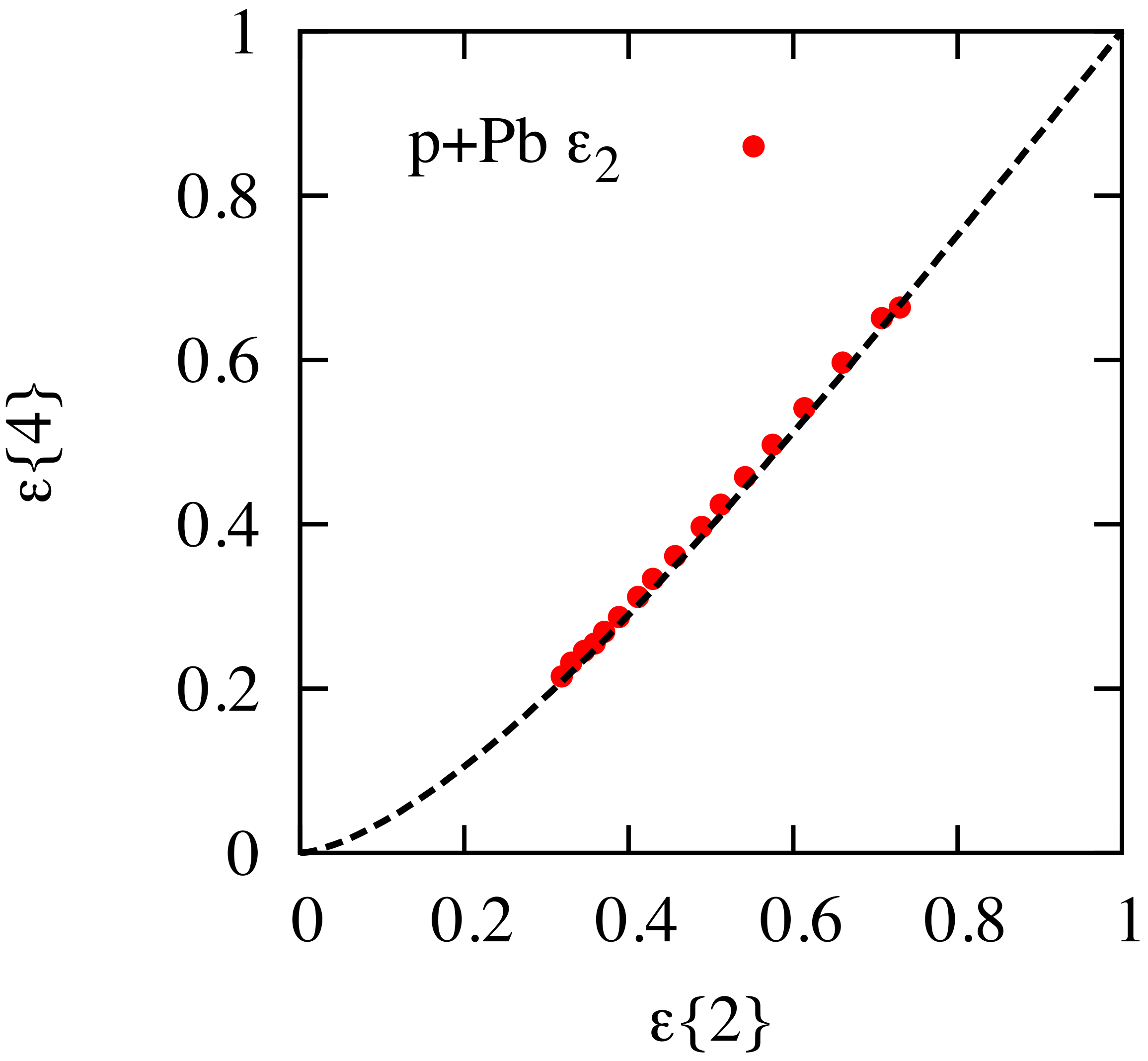
Natural explanation for $\varepsilon_2\{4\}$ in pPb



Central limit:
large system,
small fluctuations
ε{2}<< 1 and
ε{4}<< ε{2}

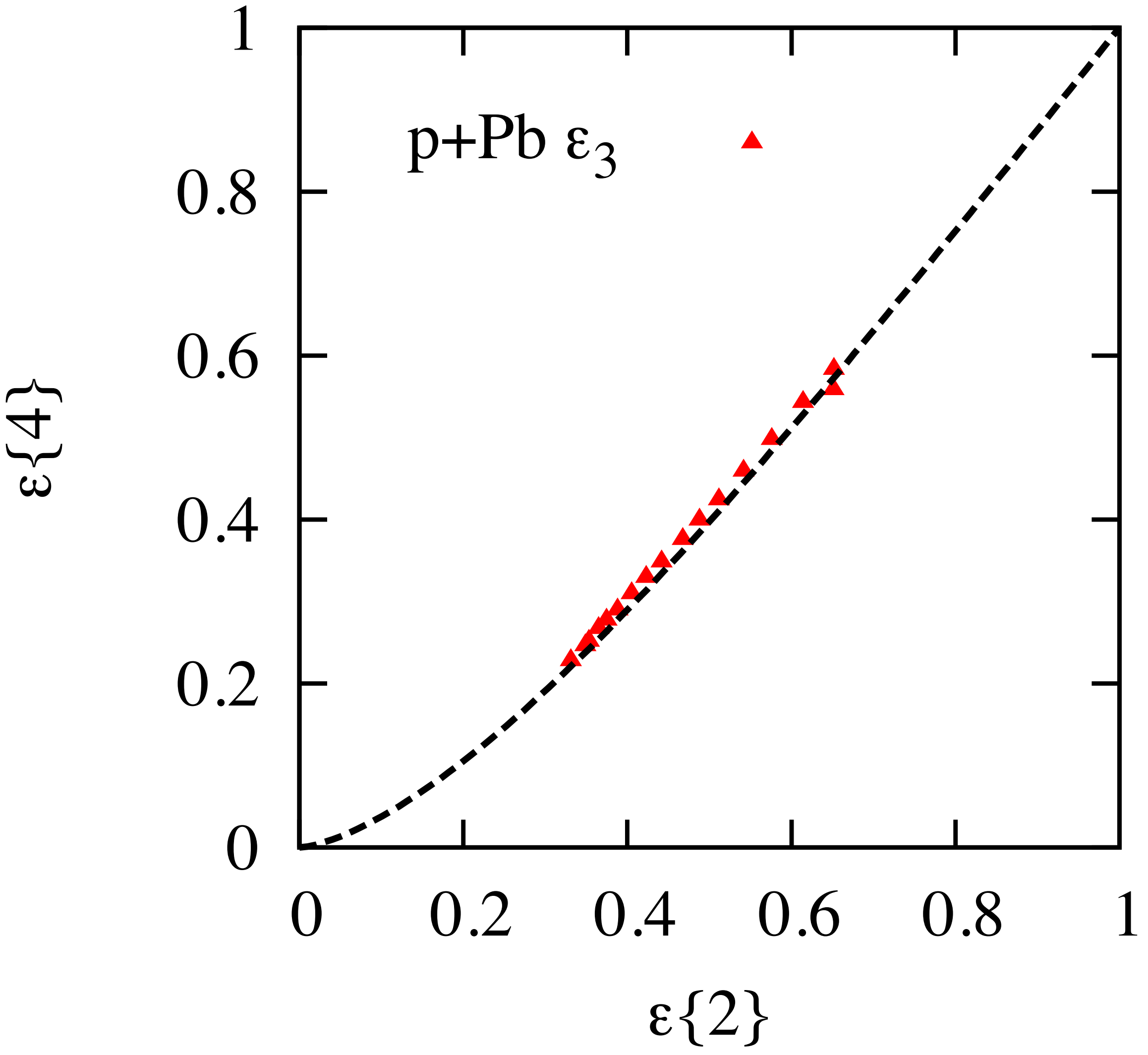
Prediction of the *power* distribution

Testing universality with cumulants



Each point: different number of hit nucleons in target

Testing universality with cumulants



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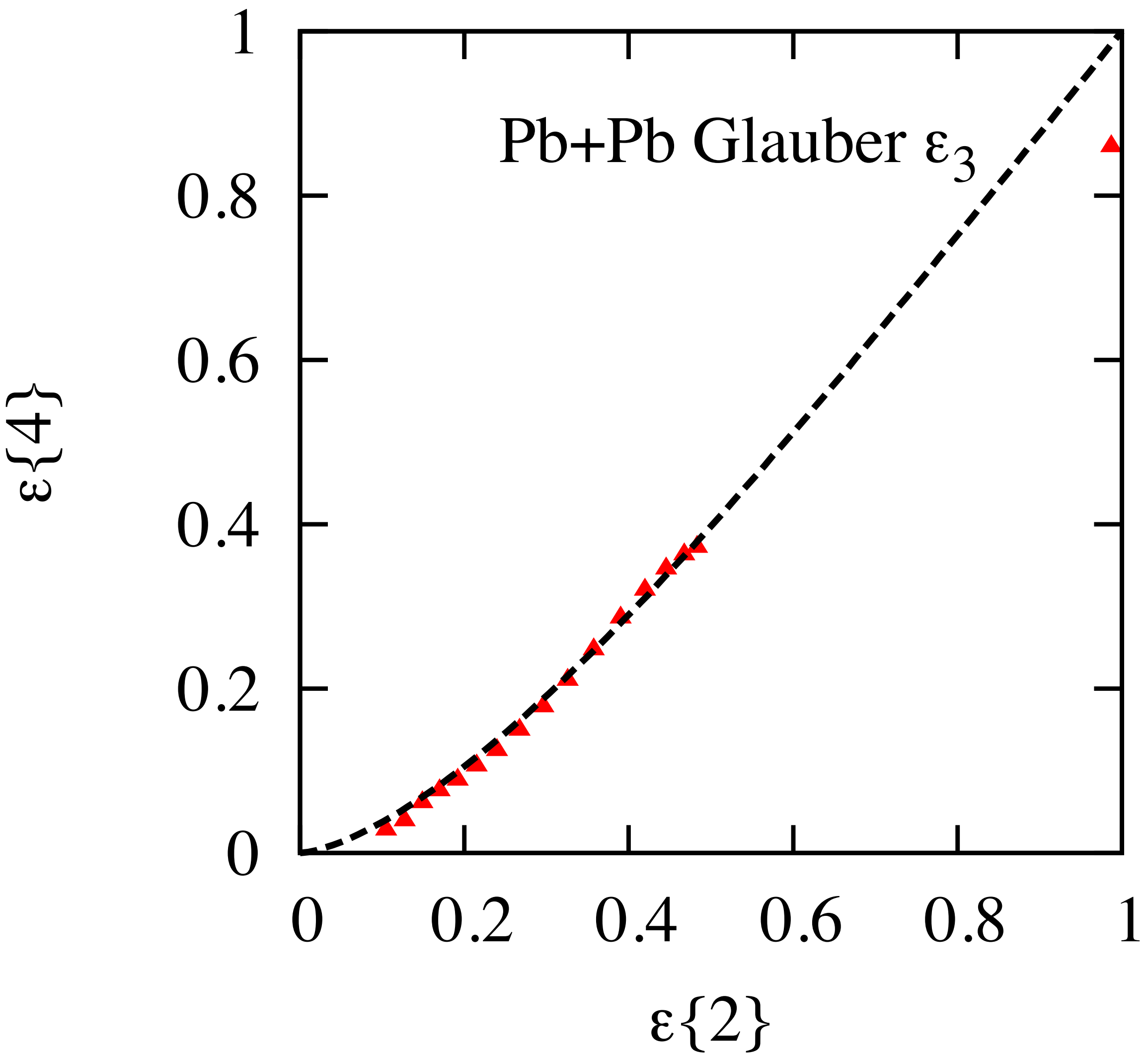
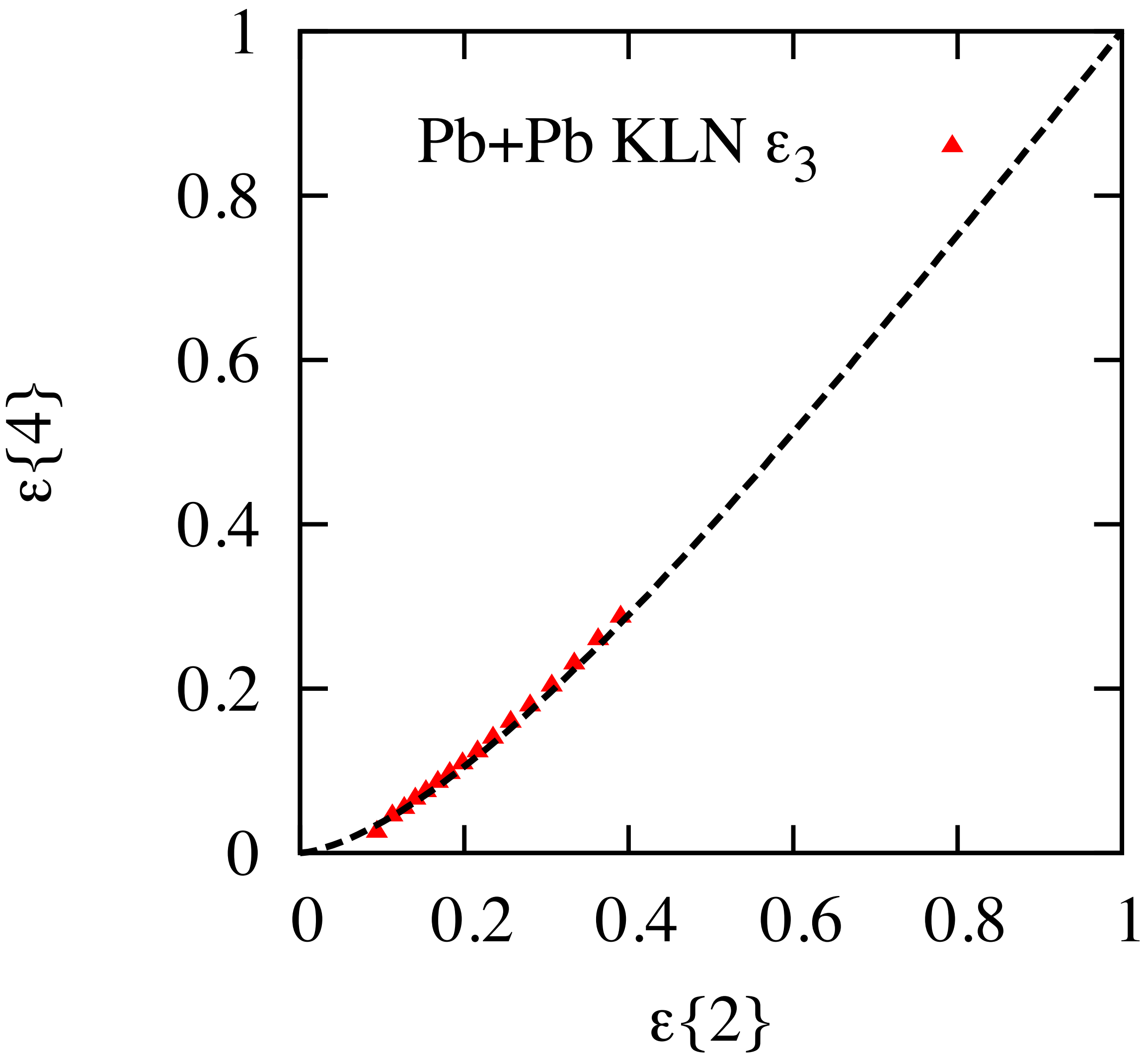


Each point: different centrality

Pb-Pb: Larger system: smaller anisotropies

Testing universality with cumulants



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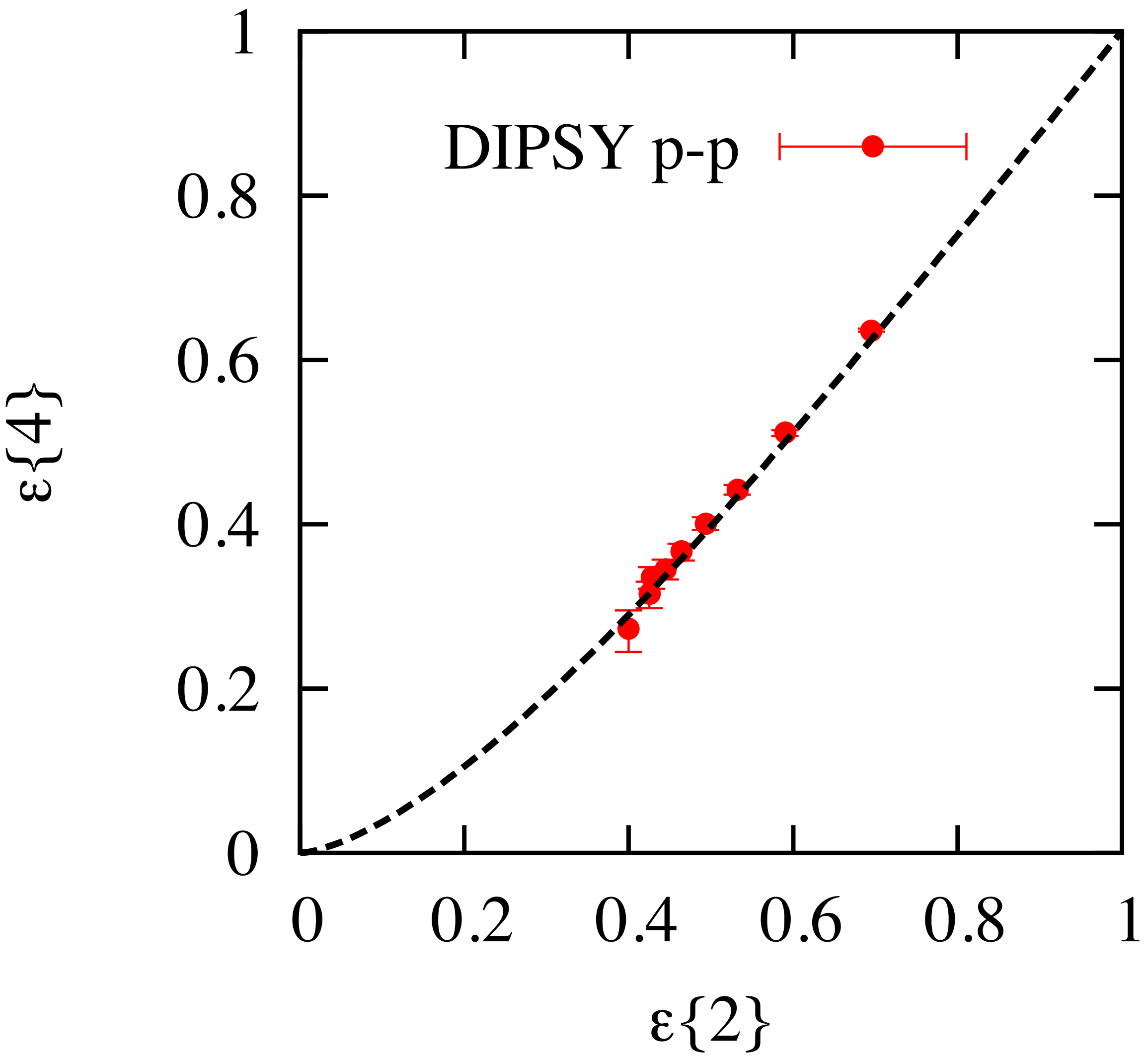
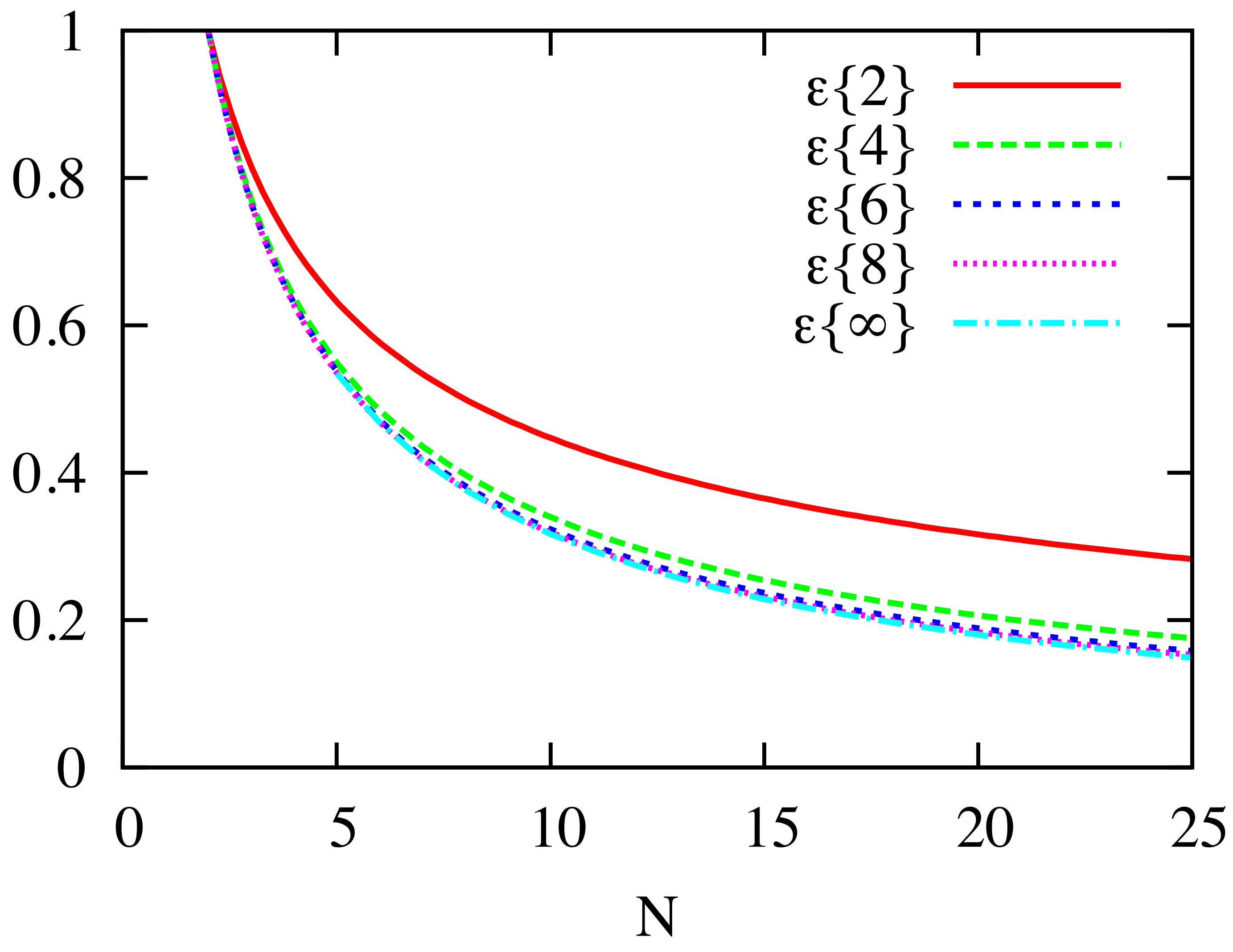


data from Avsar Flensburg Hatta JYO Ueda 1009.5643

Each point: different parton multiplicity

Higher-order cumulants

(predicted by the power distribution)



ε{n} quickly converges as order n increases