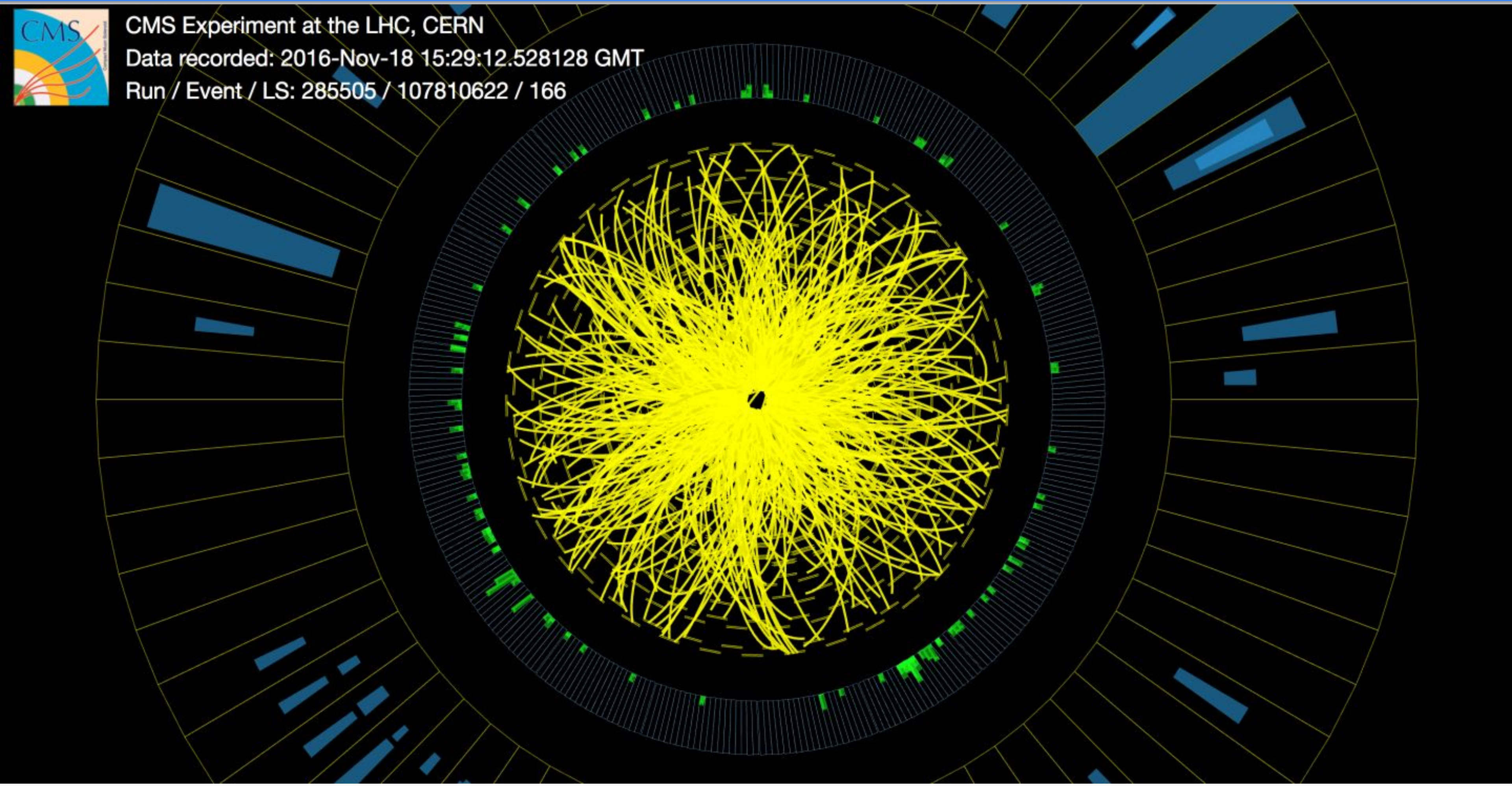
Flow and event-by-event fluctuations in pp, pPb and PbPb collisions at the CMS

Damir Devetak, Vinca Institute of Nuclear Studies

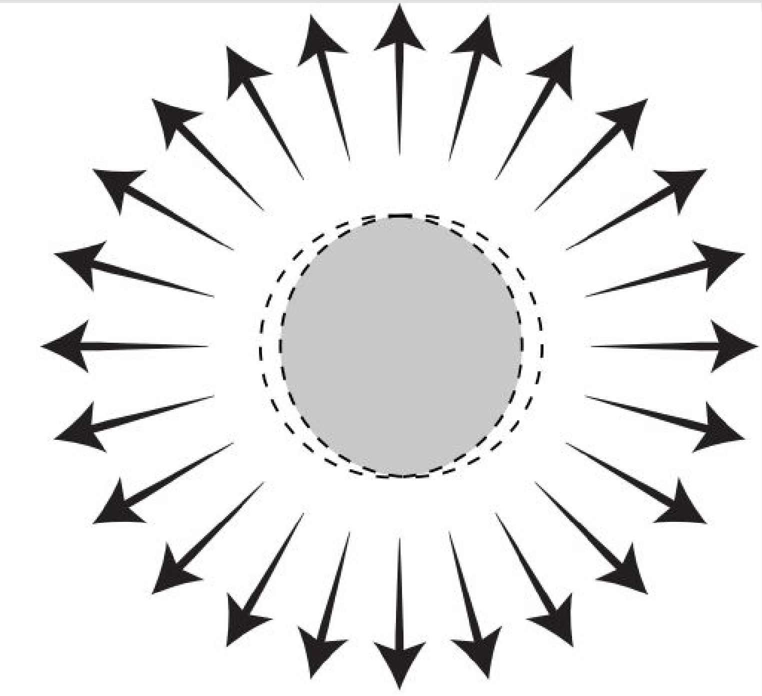
LOW-X, Bari, 2017

Heavy-ion collisions



- ➔ **Charged particle reconstruction**
- ➔ **Information (p_T, Φ, η)**

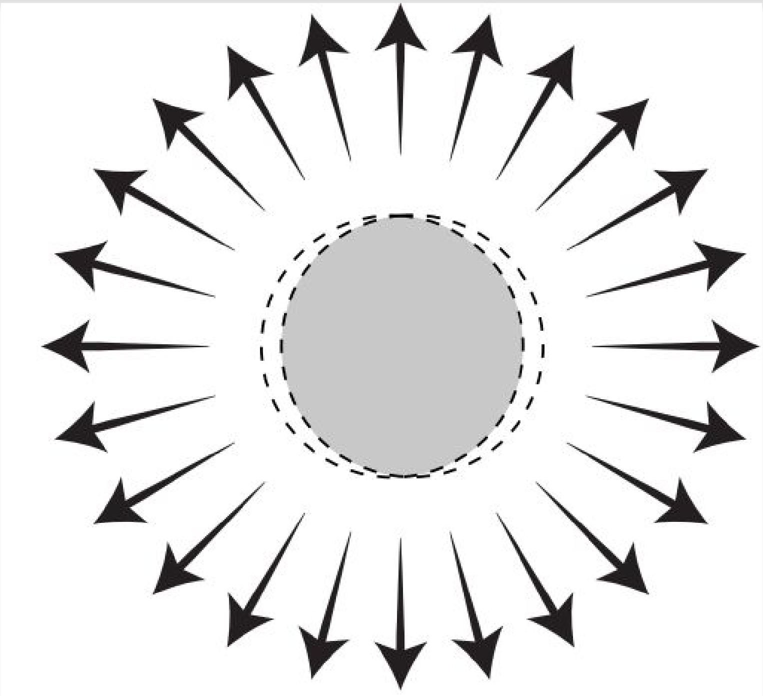
Heavy-ion collisions



Isotropic hadron **emission per-event**

$$\frac{dN}{d\phi} = const$$

Heavy-ion collisions



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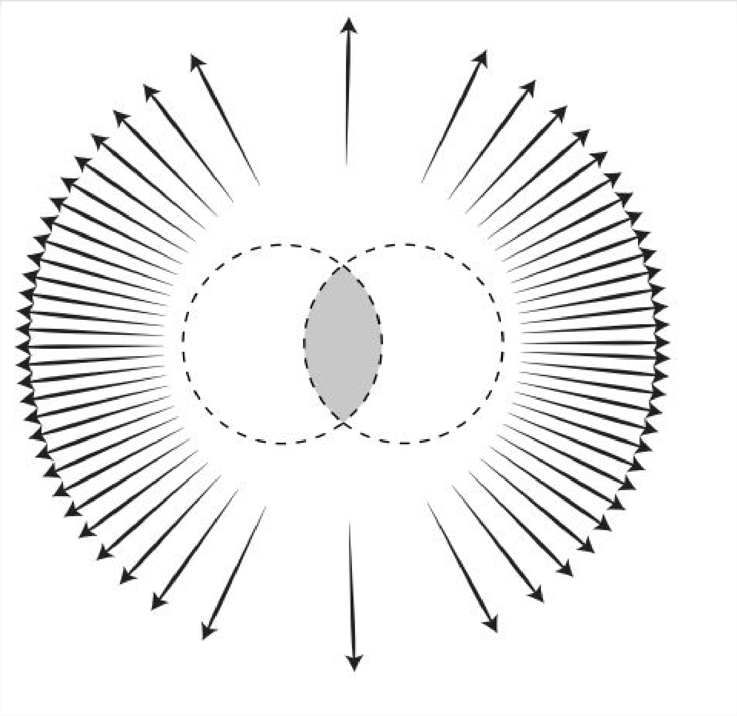
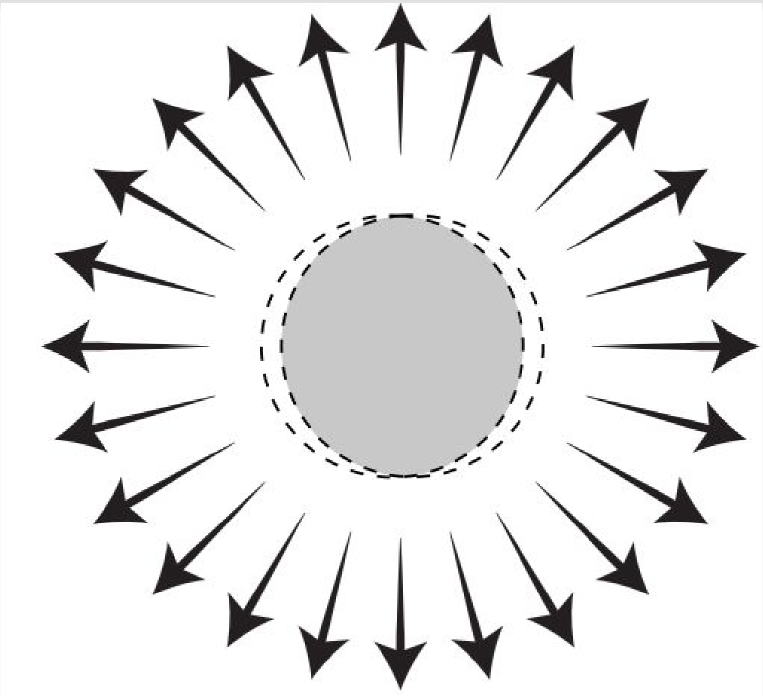
$$\frac{dN}{d\phi} = const$$



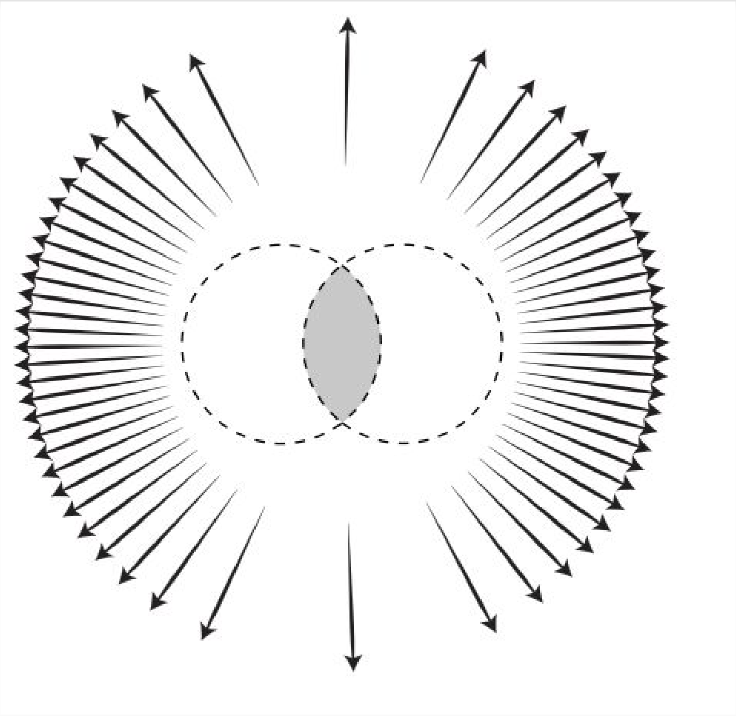
Non-isotropic hadron **emission per-event**

$$\frac{dN}{d\phi} = f(p_T, \eta, C)$$

Heavy-ion collisions



Isotropic hadron
emission per-event



Non-isotropic hadron
emission per-event

$$\frac{dN}{d\phi} \sim 1+2\sum v_n(p_T,\eta)\cos[n(\phi-\Psi_n)]$$

Heavy-ion collisions

$$\frac{dN}{d\phi} \sim 1 + 2 \sum v_n(p_T, \eta) \cos[n(\phi - \Psi_n)]$$

Measurement of the v_n observable

Heavy-ion collisions

$$\frac{dN}{d\phi} \sim 1 + 2\sum v_n(p_T, \eta)\cos[n(\phi - \Psi_n)]$$

Measurement of the v_n observable

What is the best method?

Question of context

Methods:

Event-plane angle

Two-particle correlations

Cumulants n=4,6,8

Lee-Yang Zero

Scalar product

PCA & two-particle correlations

Heavy-ion collisions

$$\frac{dN}{d\phi} \sim 1 + 2\sum v_n(p_T, \eta)\cos[n(\phi - \Psi_n)]$$

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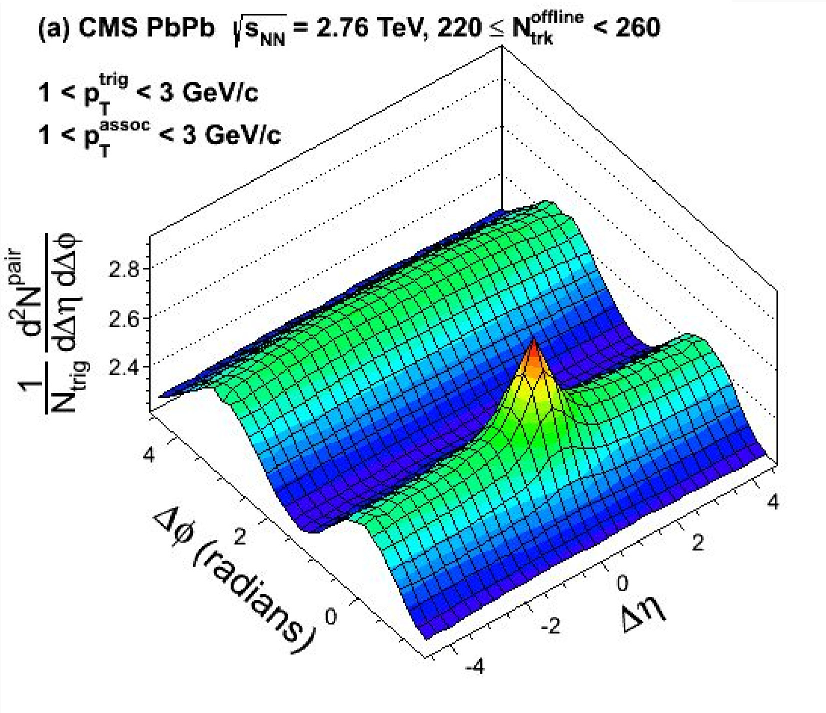


visualization!

Heavy-ion collisions

$$\frac{dN}{d\phi} \sim 1 + 2\sum v_n(p_T, \eta)\cos[n(\phi - \Psi_n)]$$

Methods:

Event-plane angle

Two-particle correlations

Cumulants n=4,6,8

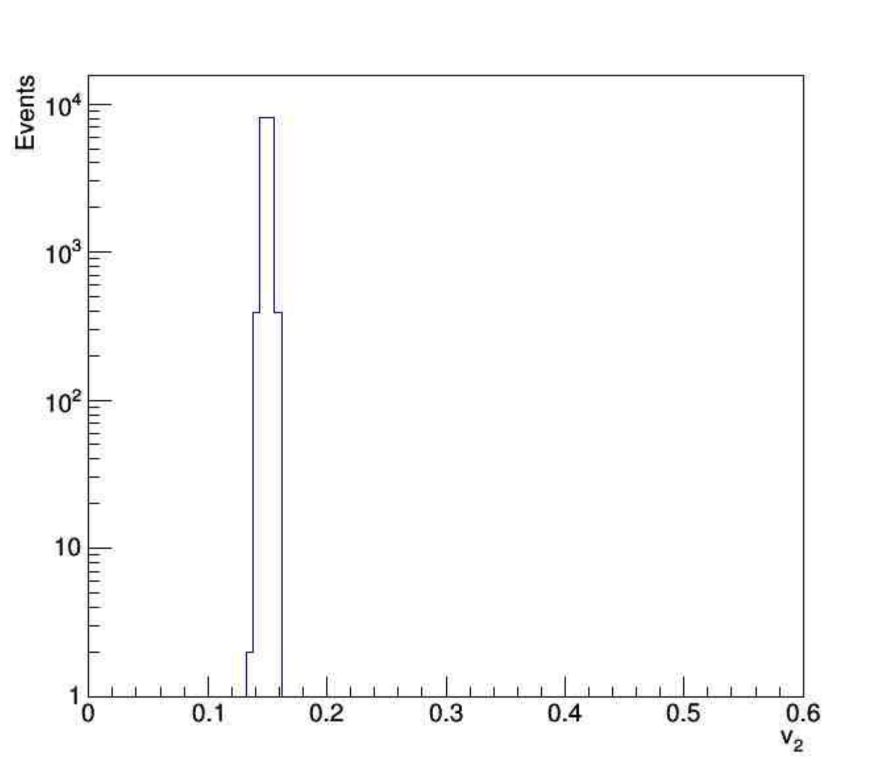
Lee-Yang Zero

Scalar product

PCA & two-particle correlations

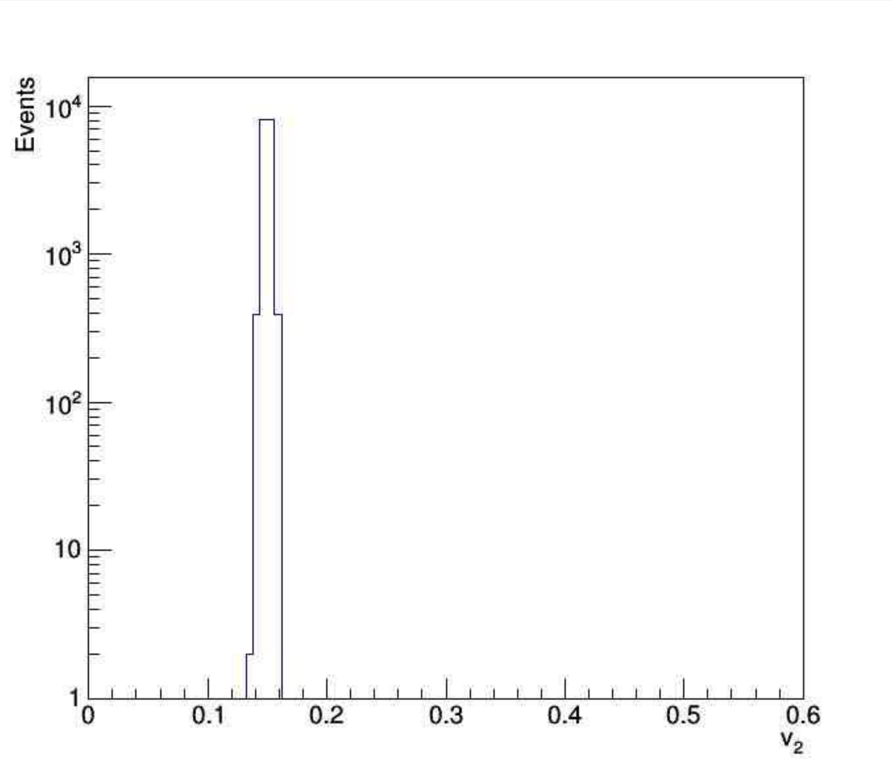
Should extract all non-flow; Not intuitive

Fluctuations of the v_n

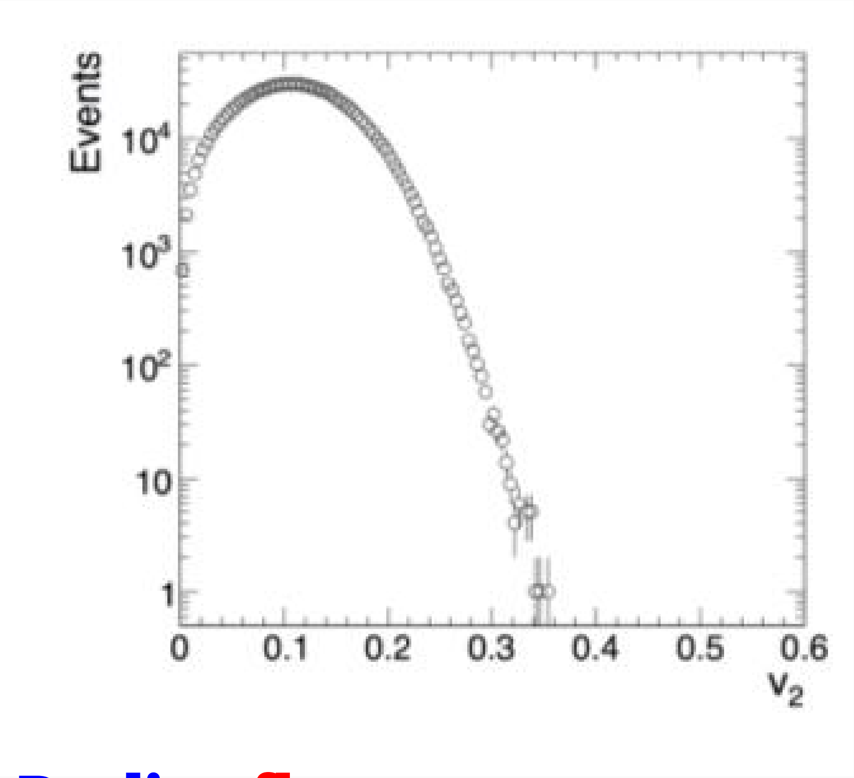


Conjectured: stable

Fluctuations of the v_n

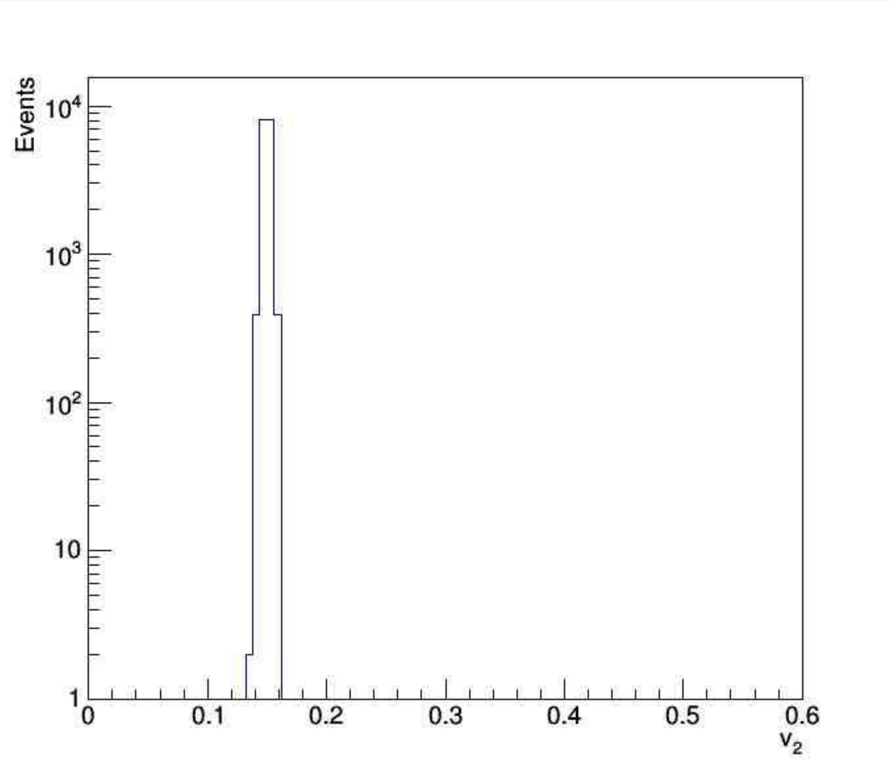


Conjectured: stable

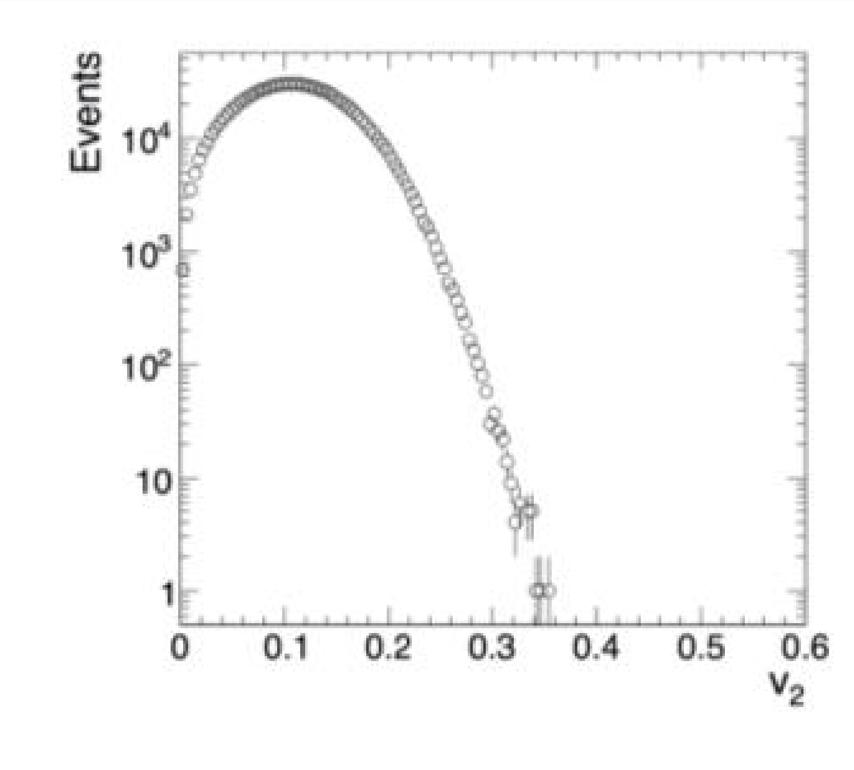


Reality: fluctuates

Fluctuations of the v_n



Conjectured: stable



Reality: fluctuates

- **Not measuring the v_n or the $\langle v_n \rangle$**

Fluctuations of the v_n

- **Measuring cumulants as a function of moments:**

Fluctuations of the v_n

- **Measuring cumulants as a function of moments:**

$$v_n\{2\}=\sqrt{\langle v_n^2\rangle}$$

$$v_n\{4\}=\sqrt[4]{-\langle v_n^4\rangle+2\langle v_n^2\rangle^2}$$

$$v_n\{6\}=\sqrt[6]{(\langle v_n^6\rangle-9\langle v_n^4\rangle\langle v_n^2\rangle+12\langle v_n^2\rangle^3)/4}$$

$$v_n\{8\}=\sqrt[8]{-(\langle v_n^8\rangle-16\langle v_n^6\rangle\langle v_n^2\rangle-18\langle v_n^4\rangle^2+144\langle v_n^4\rangle\langle v_n^2\rangle^2-144\langle v_n^2\rangle^4)/33}$$

Fluctuations of the v_n

- **Measuring cumulants as a function of moments:**

If no fluctuations

$$v_n\{2\} = \sqrt{\langle v_n^2 \rangle} = v_n$$

$$v_n\{4\} = \sqrt[4]{-\langle v_n^4 \rangle + 2\langle v_n^2 \rangle^2} = v_n$$

$$v_n\{6\} = \sqrt[6]{(\langle v_n^6 \rangle - 9\langle v_n^4 \rangle \langle v_n^2 \rangle + 12\langle v_n^2 \rangle^3)/4} = v_n$$

$$v_n\{8\} = \sqrt[8]{-(\langle v_n^8 \rangle - 16\langle v_n^6 \rangle \langle v_n^2 \rangle - 18\langle v_n^4 \rangle^2 + 144\langle v_n^4 \rangle \langle v_n^2 \rangle^2 - 144\langle v_n^2 \rangle^4)/33} = v_n$$

Fluctuations of the v_n

- **Measuring cumulants as a function of moments:**

$$v_n\{2\}=\sqrt{\langle v_n^2\rangle}$$

fluctuations

$$v_n\{4\}=\sqrt[4]{-\langle v_n^4\rangle+2\langle v_n^2\rangle^2}$$

$$v_n\{6\}=\sqrt[6]{(\langle v_n^6\rangle-9\langle v_n^4\rangle\langle v_n^2\rangle+12\langle v_n^2\rangle^3)/4}$$

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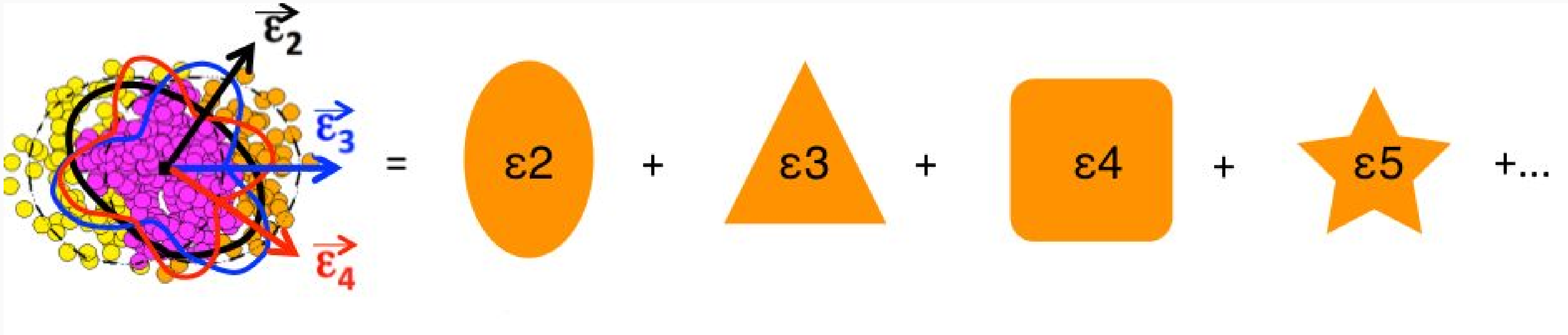
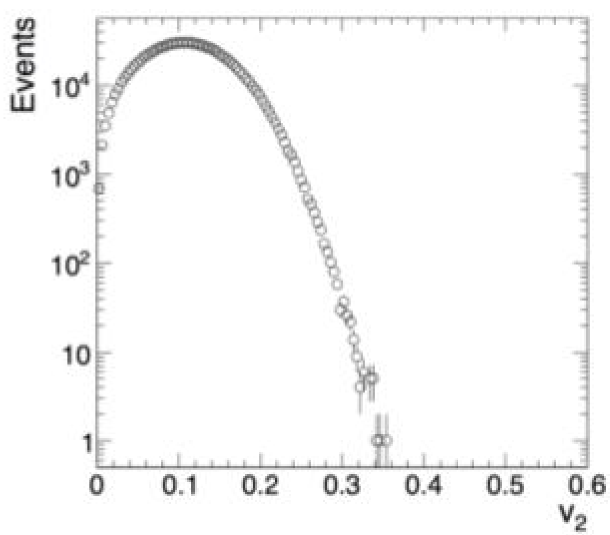
$$v_n\{2\}>v_n\{4\}\approx v_n\{6\}\approx v_n\{8\}$$

Fluctuations of the v_n

★ Fluctuations of the v_n is a response to ε_n fluctuations
★ For **n≤3** linear connection $v_n = k\varepsilon_n$



★ Measurement of $p(v_2)$ with **unfolding**[1]:



★ **Get precise cumulants**
★ $p(\varepsilon_2)$ **inference**

[1] JHEP 1311 (2013) 183.

Fluctuation parametrization

★ Bessel-Gaussian[1]

$$p(\varepsilon_n|\varepsilon_{0,}\delta)=\frac{\varepsilon_n}{\delta^2}exp\left[-\frac{\varepsilon_n^2+\varepsilon_0^2}{2\delta^2}\right]I_0\left(\frac{\varepsilon_n\varepsilon_0}{\delta^2}\right)$$

- $\varepsilon_n\{2\}>\varepsilon_n\{4\}=\varepsilon_n\{6\}=\varepsilon_n\{8\}$

★ Elliptic power law[2]

$$p(\varepsilon_n|\varepsilon_{0,}\alpha)=\frac{2\alpha\varepsilon_n}{\pi}(1-\varepsilon_0^2)^{\alpha+1/2}\int_0^{\pi}\frac{(1-\varepsilon_n^2)^{\alpha-1}d\phi}{(1-\varepsilon_0\varepsilon_n)^{2\alpha+1}}$$

- $\varepsilon_n\{2\}>\varepsilon_n\{4\}>\varepsilon_n\{6\}>\varepsilon_n\{8\}$

$$\upsilon_n\{2\}>\upsilon_n\{4\}\approx\upsilon_n\{6\}\approx\upsilon_n\{8\}$$

[1]Phys.Lett. B659 (2008) 537-541
[2]Phys.Rev. C90 (2014), 024903

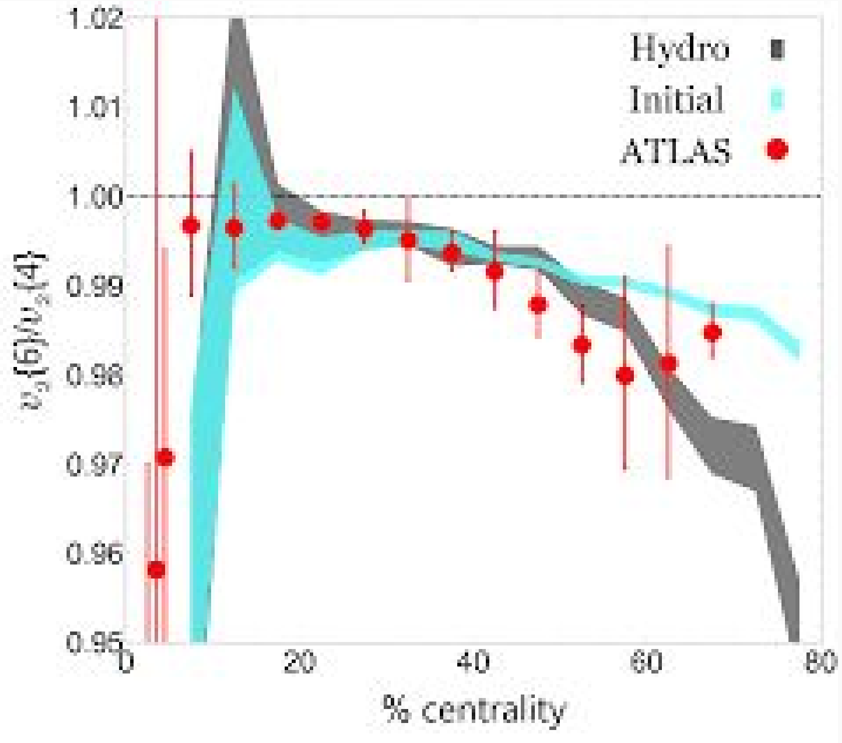
Non-Gaussian Fluctuations

★ Fine splitting observed between $v_2\{4\}$ and $v_2\{6\}$

(Eur.Phys.J. C74 (2014), 3157)

★ From hydrodynamics $v_2\{6\}/v_2\{4\} \approx \varepsilon_2\{6\}/\varepsilon_2\{4\}$

(https://arxiv.org/abs/1608.01823)



Constructing v_n distributions

★ Constructing the $p(v_n)$:

$$\vec{v}_n^{\,obs} = \left(\frac{\sum w_i \cos n\phi_i}{w_i}, \frac{\sum w_i \sin n\phi_i}{w_i} \right) - \langle \vec{v}_n^{\,obs} \rangle$$

$$v_n = \sqrt{v_{n,x}^{obs,2} + v_{n,y}^{obs,2}}$$

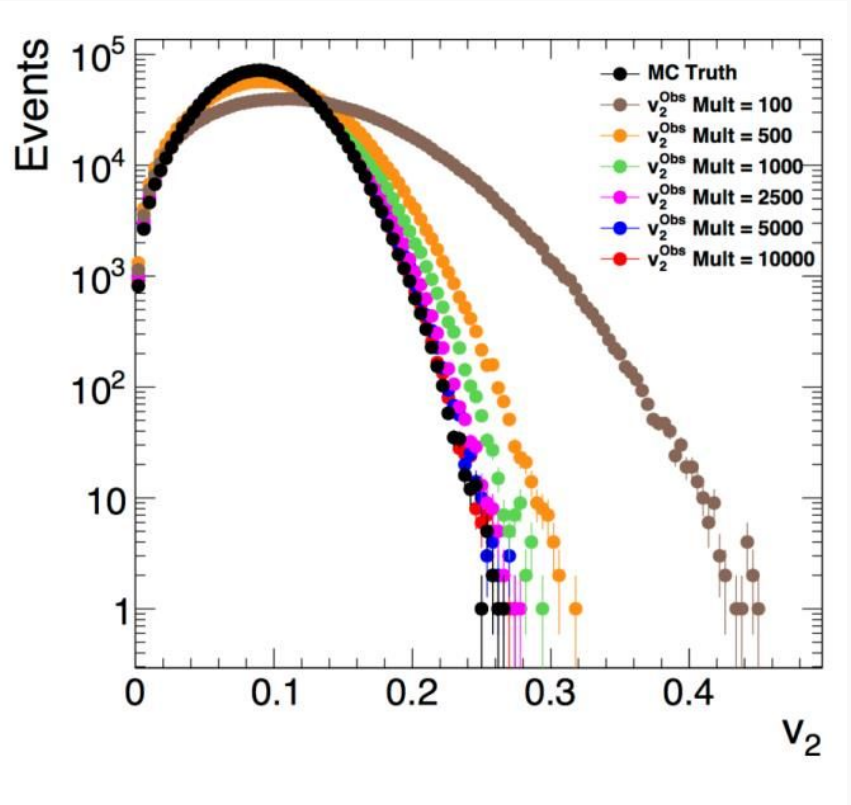
★ Must deal with **statistical resolution.** The $p(v_n^{obs})$ **not the true** $p(v_n)$ for finite N_{tracks}

Smearing effect

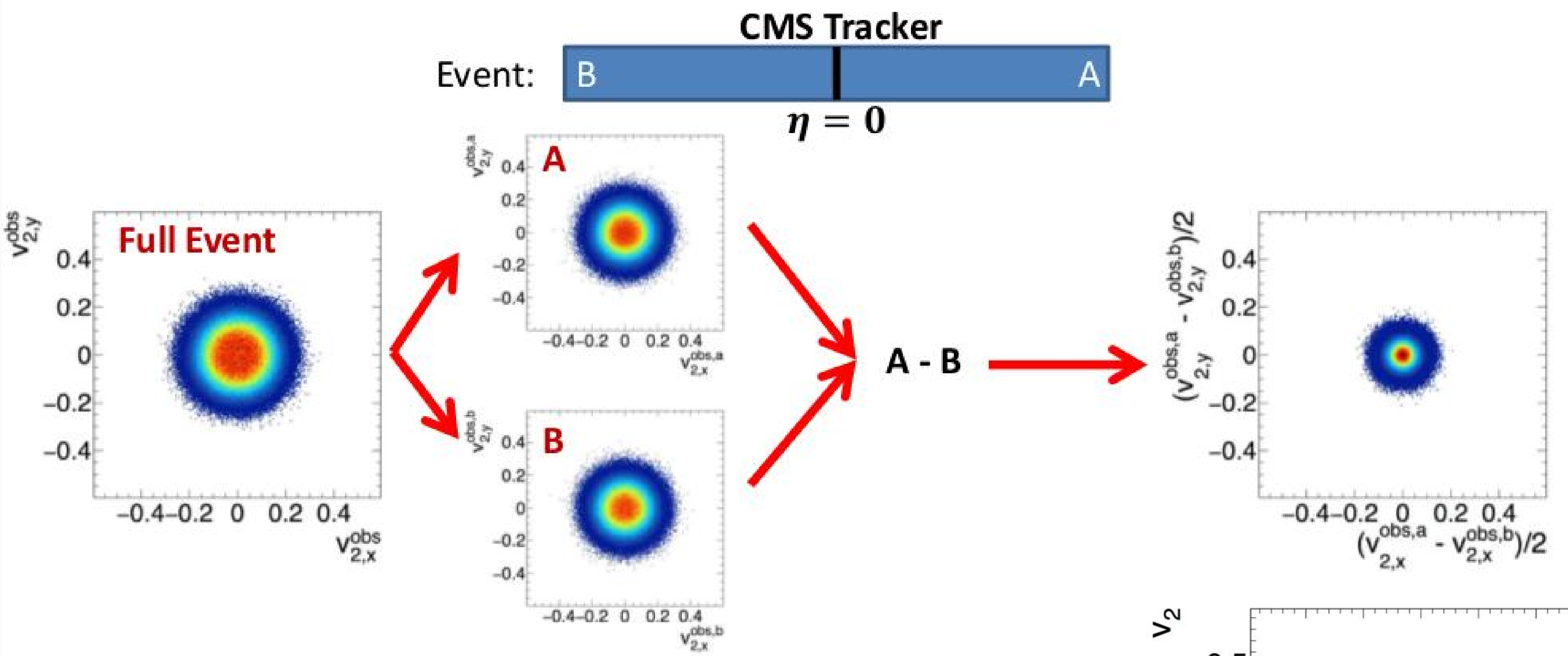
★ **Use unfolding procedure:**

$$p(v_n^{obs} | v_n) \times p(v_n) = p(v_n^{obs})$$

response function



Find response function

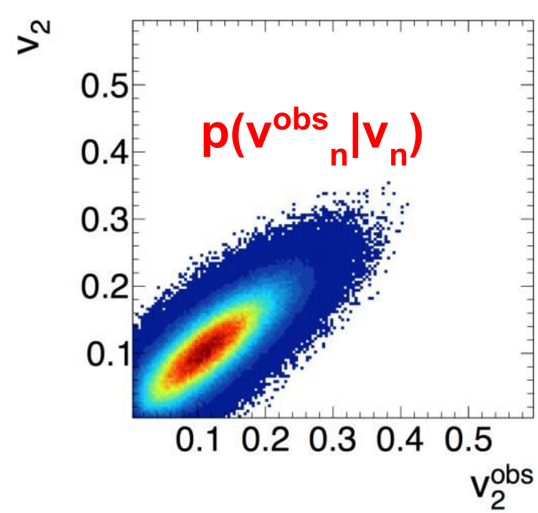


★ Dividing event into two symmetrical subevents

POINT: no flow signal in $p[(\vec{v}_n^{\,obs,a} - \vec{v}_n^{\,obs,b})/2]$

★ Prob. contains only the smearing effect and nonflow

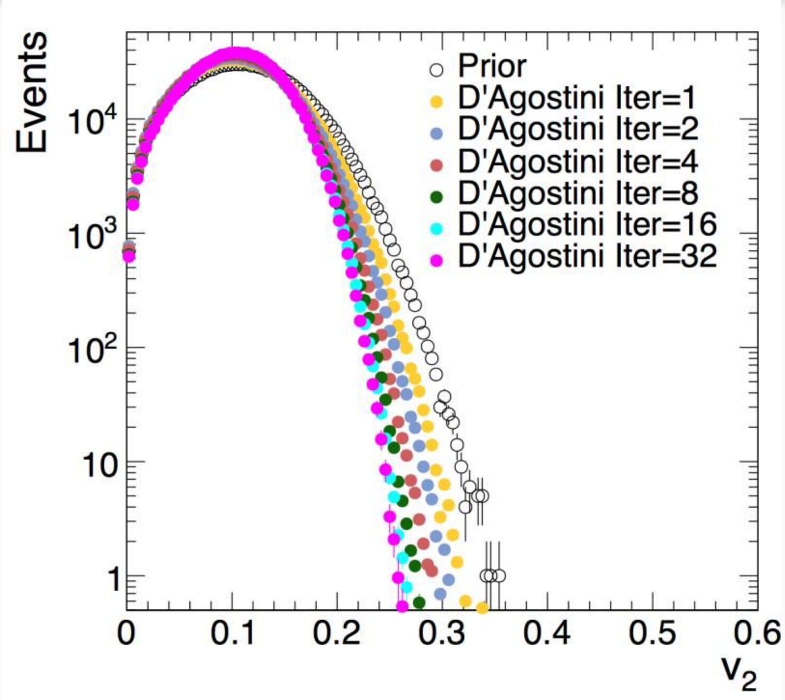
★ Probability difference gives the **response function**

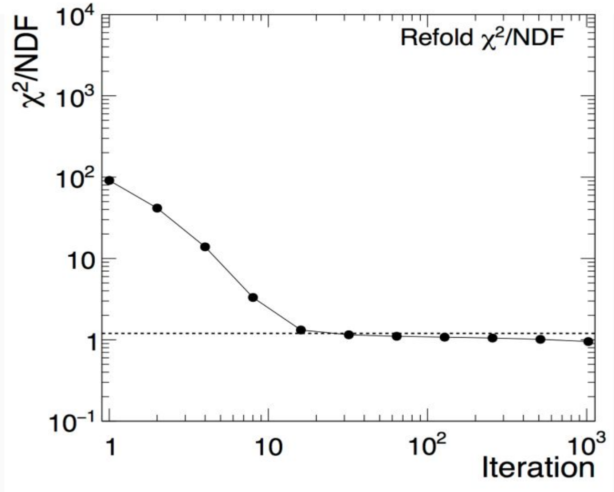


Unfolding method

★ Remove **smearing** using D'Agostino[1] algorithm

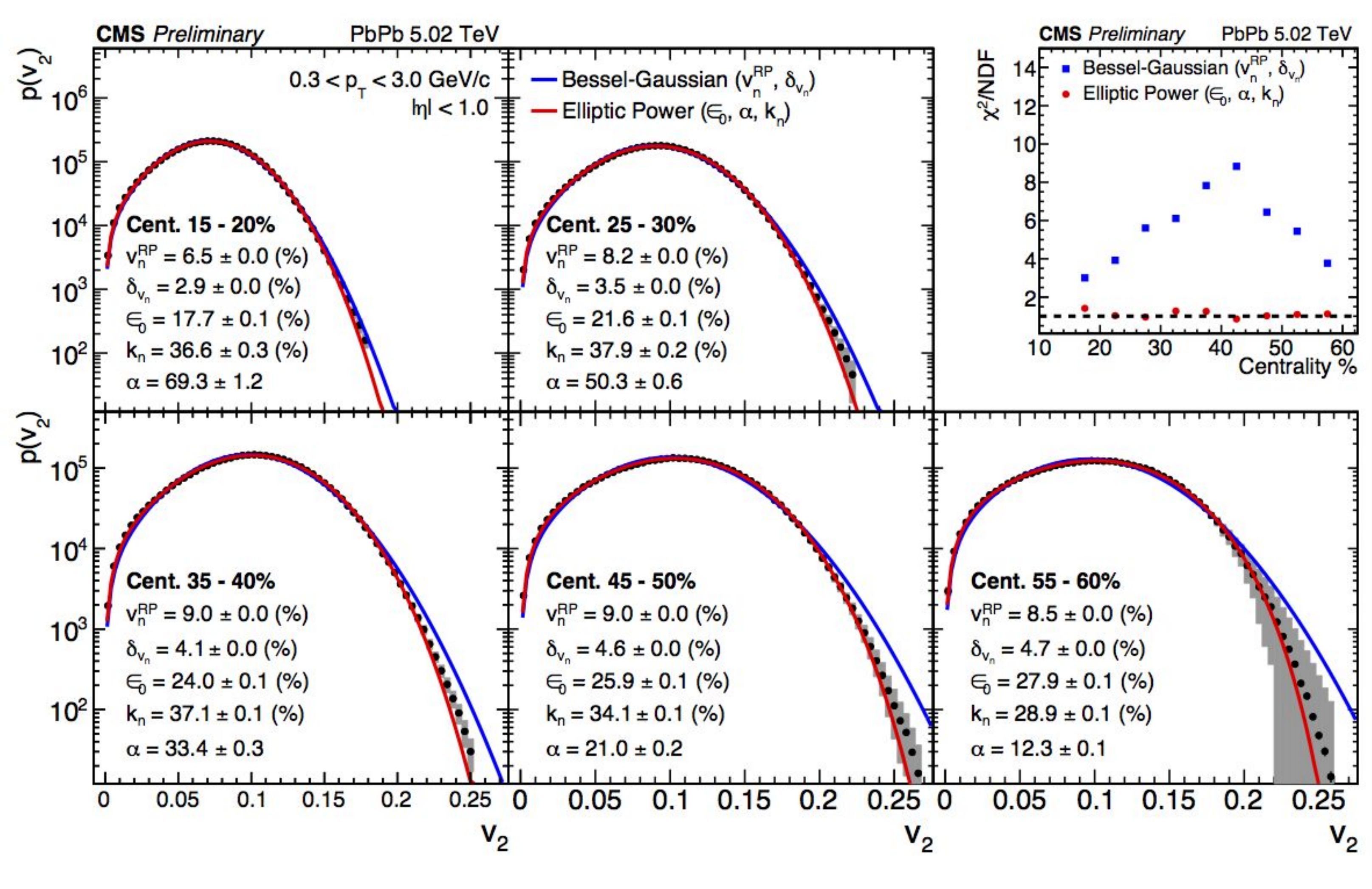
- $\hat{c}_i^{iter+1} = \widehat{M}_{ij}^{iter} e_j$
  - $\widehat{M}_{ij}^{iter} = \frac{A_{ji}\hat{c}_i^{iter}}{\sum_{m,k} A_{mi} A_{jk} \hat{c}_k^{iter}}$
  - $A_{ji} \equiv p(e_j | c_i)$
  - $\hat{c}_i^0 = p(e_j)$
- Regularization necessary
  - Smeared space χ^2/NDF
  - $p(v_n^{obs} | v_n) \times p(v_n)^{iter} = p(v_n^{obs})$





[1]G. D'Agostini, Nucl. Instrum. Meth. A362, 487 (1995)

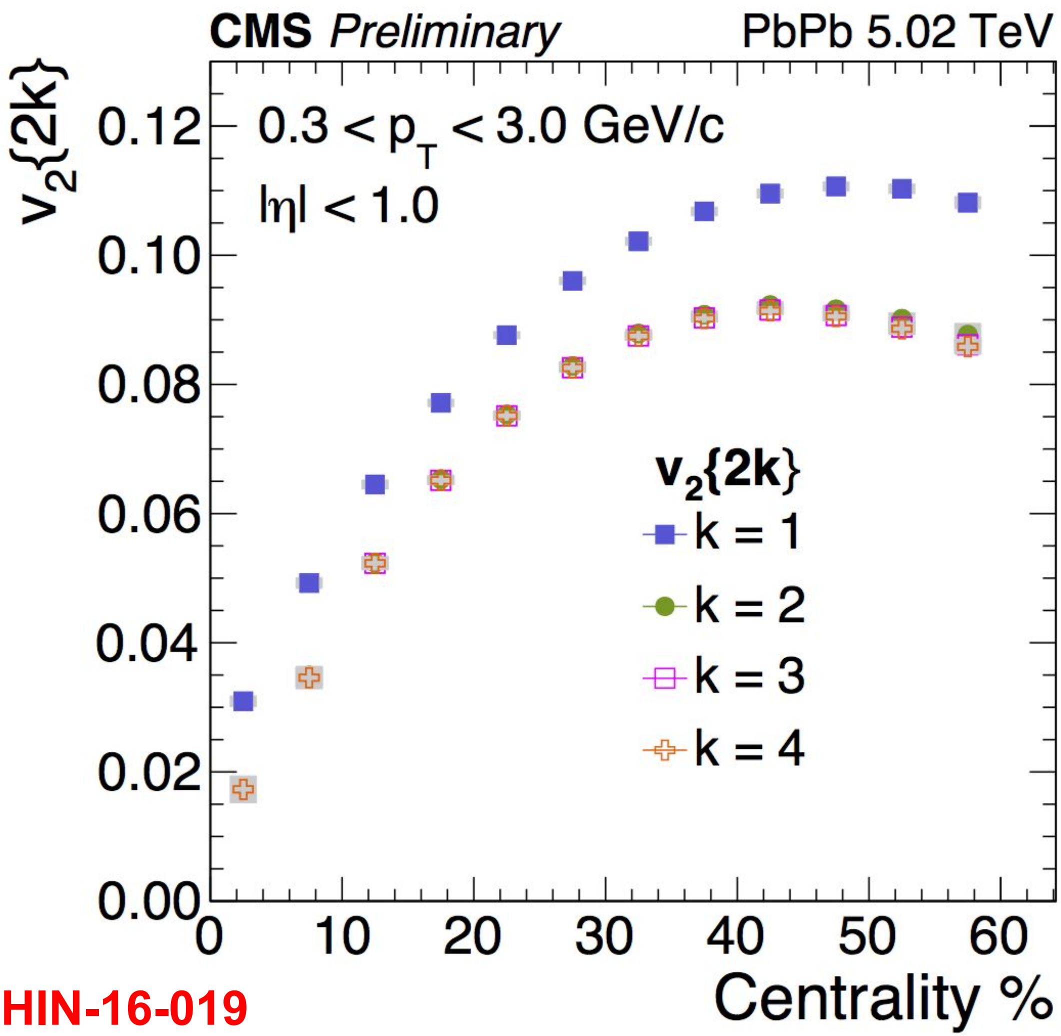
Results: Fitting $p(v_2)$ with Fluctuation Models



HIN-16-019

★ Elliptic power parametrization consistently describes data better than Bessel-Gaussian

Results: cumulants



HIN-16-019

$v_2\{2k\}$=function(**moments**)

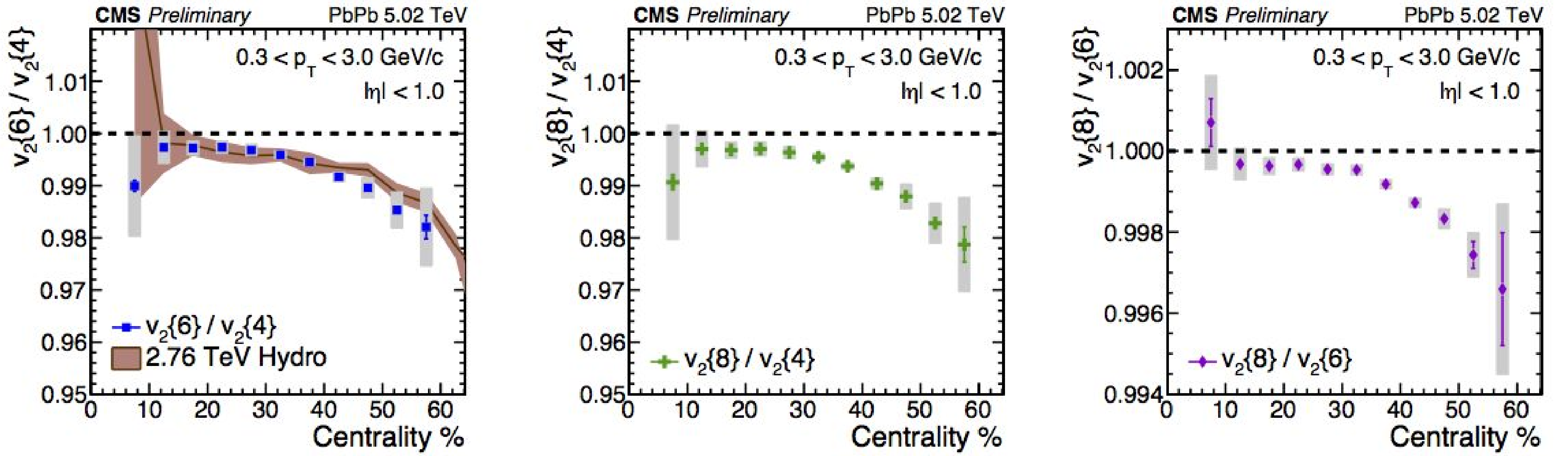
moments:

$$\langle v_n^{2k} \rangle = \int v_n^{2k} p(v_n) dv_n$$

★ **Results show behaviour**

$$v_n\{2\} > v_n\{4\} \approx v_n\{6\} \approx v_n\{8\}$$

Results: Higher-Order Cumulant Ratios



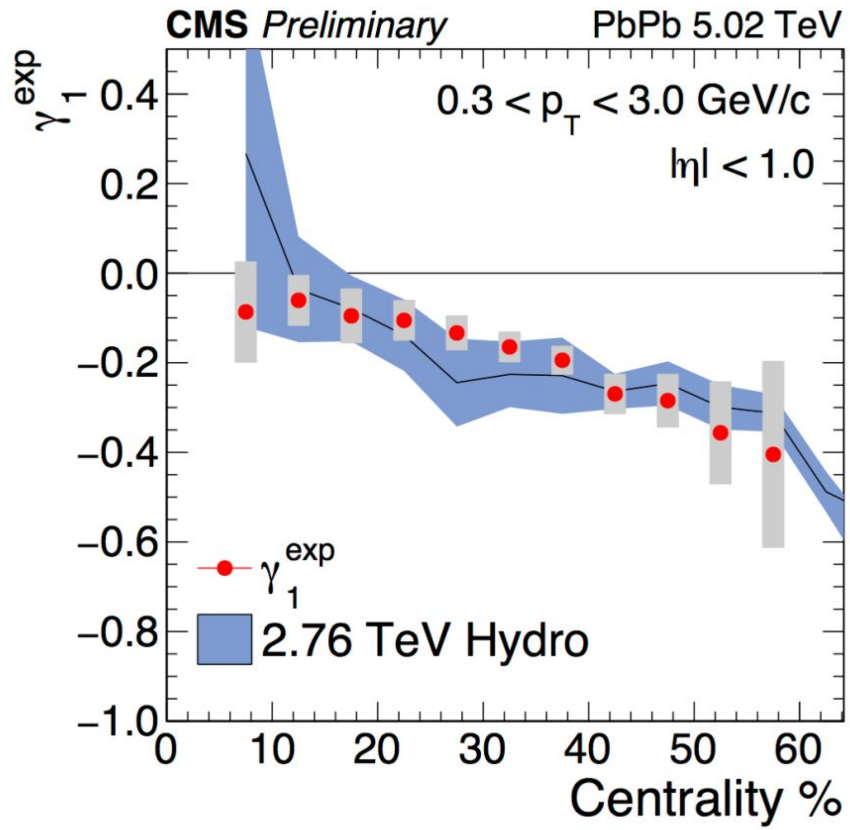
HIN-16-019

★ Fine splitting observed between higher-order cumulants

★ Hydrodynamic predictions[1] for 2.76 TeV consistent with 5.02 TeV measurement

[1]arXiv 1608.01823

Results: Skewness



HIN-16-019

- ★ **New observable for skewness**
- ★ **Hydro prediction** **arXiv 1608.01823** **consistent with data**

$$\gamma_1^{exp} = -6\sqrt{2}\, v_2\{4\}^2 \frac{v_2\{4\} - v_2\{6\}}{\left(v_2\{2\}^2 - v_2\{4\}^2\right)^{3/2}}$$

Correlation between mixed harmonics $\langle v_n \rangle, \langle v_m \rangle$

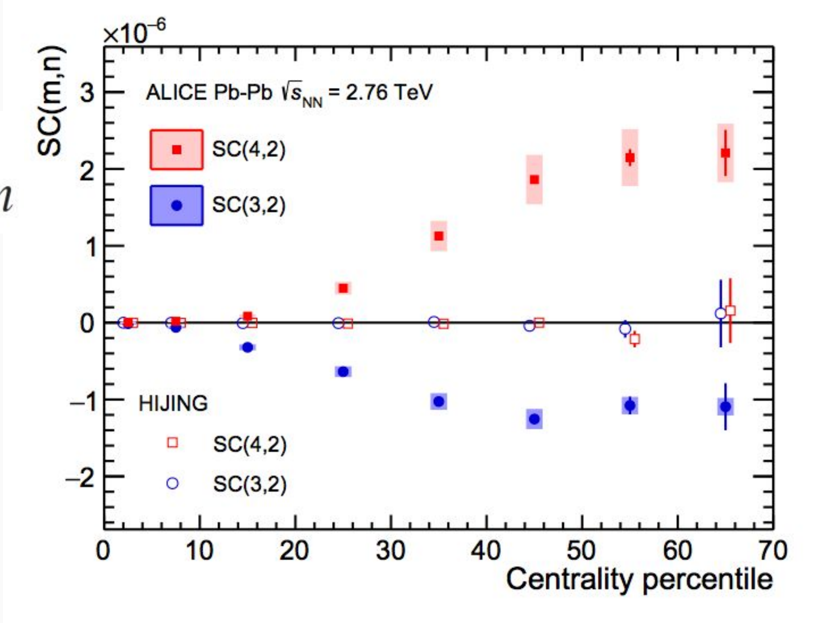
★ Measuring (anti)correlation of **$\langle v_n \rangle, \langle v_m \rangle$** in pp, pPb, PbPb

- Medium response (η/s,...)
- Initial correlations (geometry + fluctuations)

★ **SC(n,m)** observable:

$$SC(n,m) = \langle\langle 4 \rangle\rangle_{n,m} - \langle\langle 2 \rangle\rangle_{n} \cdot \langle\langle 2 \rangle\rangle_{m}$$

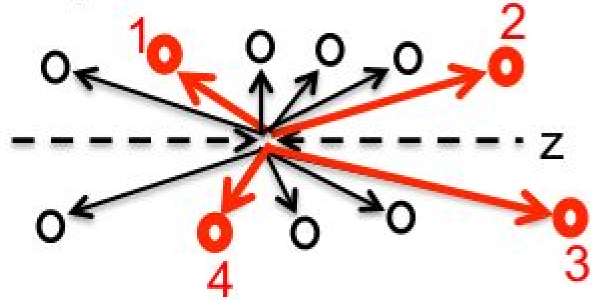
$$SC(n,m) = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle$$



PhysRevLett.117, 182301

Symmetric cumulant

Based on 4-particle cumulant technique



★ **Non--diagonal terms:**

$$SC(n,m) = \langle\langle \cos[n\phi_1 + m\phi_2 - n\phi_3 - m\phi_4] \rangle\rangle$$

★ Using the Q-vector calculation

SC(n,m)>0 correlation
SC(n,m)=0 no correlation
SC(n,m)<0 anti-correlation

combinations:

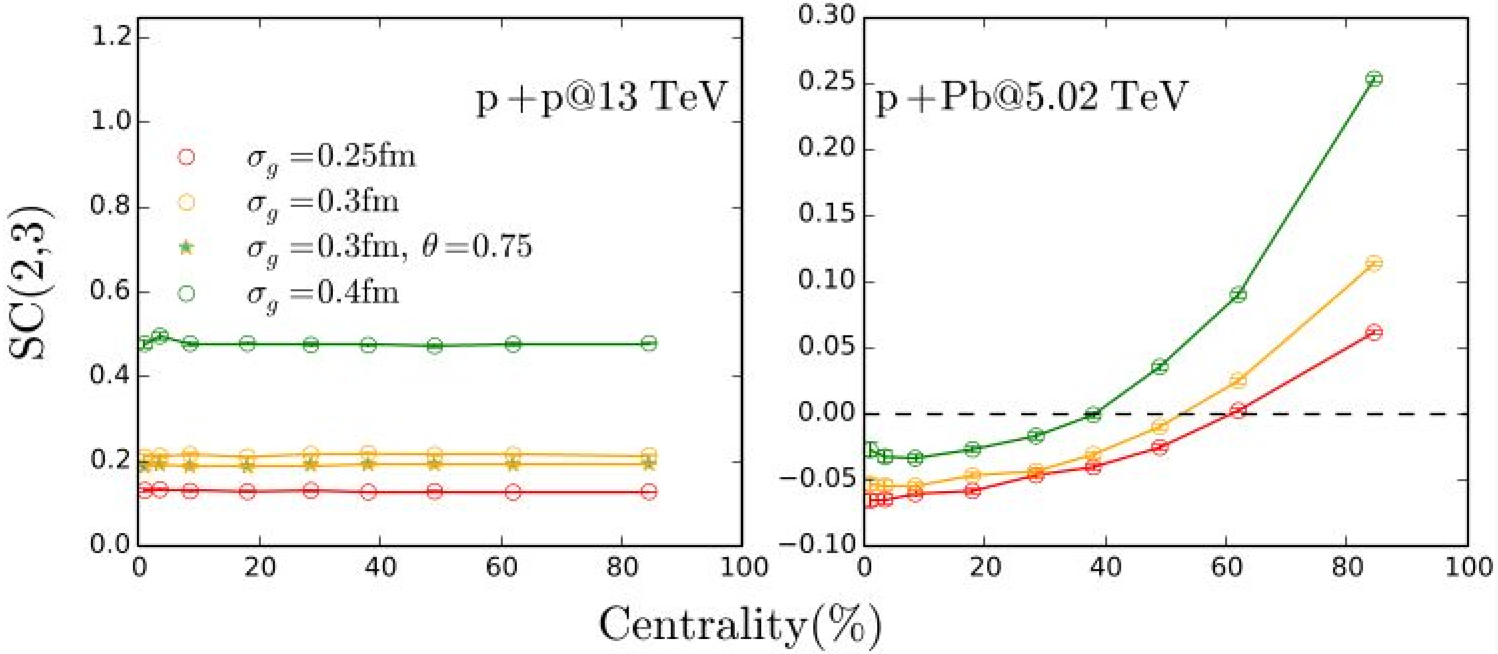
(n,m) = (2,3)
(n,m) = (2,4)

SC in smaller systems

★ **NEW: SC in smaller systems pp and pPb**

- Not measured before

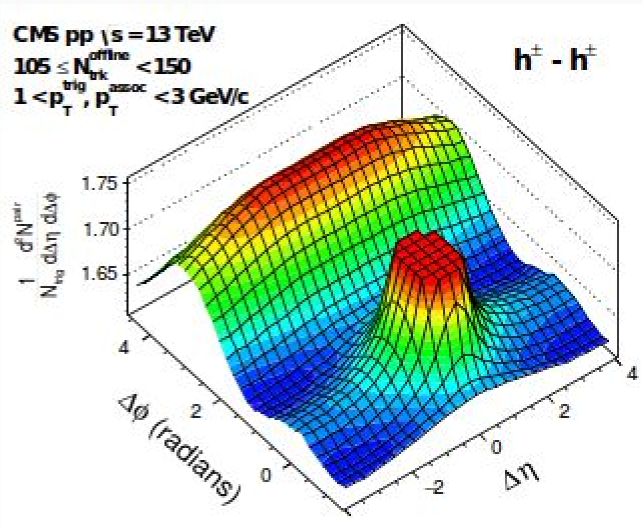
J. Quian, U. Heinz (eccentricity correlation only) **arXiv 1605.09418**



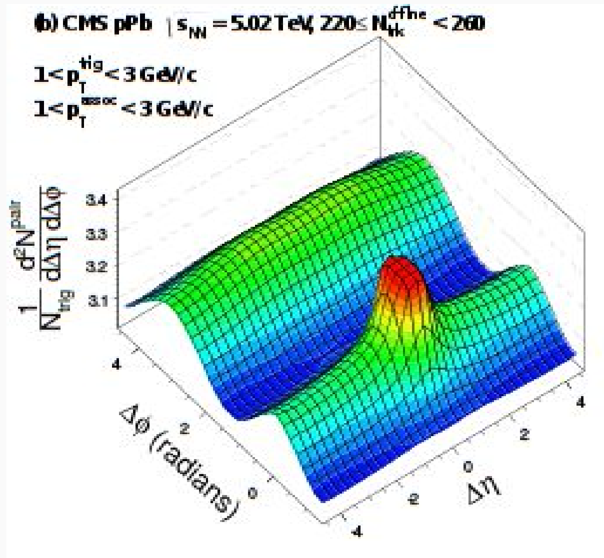
★ **Correlations seen in pp collisions!**

High multiplicity collisions

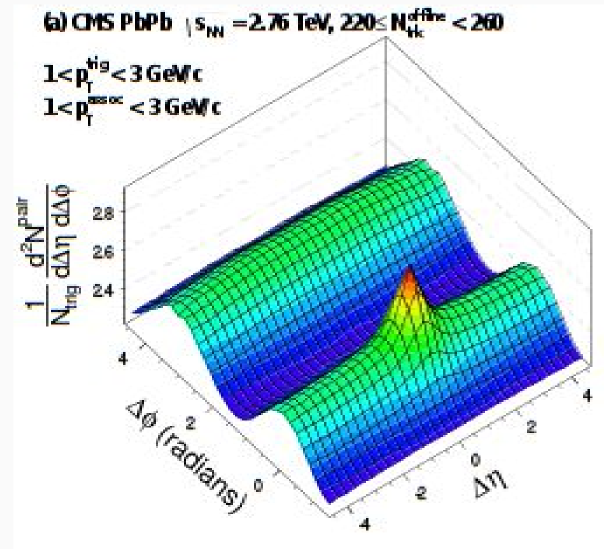
- ★ **Large samples of high-multiplicity events collected for p-p (13 TeV) and p-Pb (5.02 & 8.16 TeV)**



pp



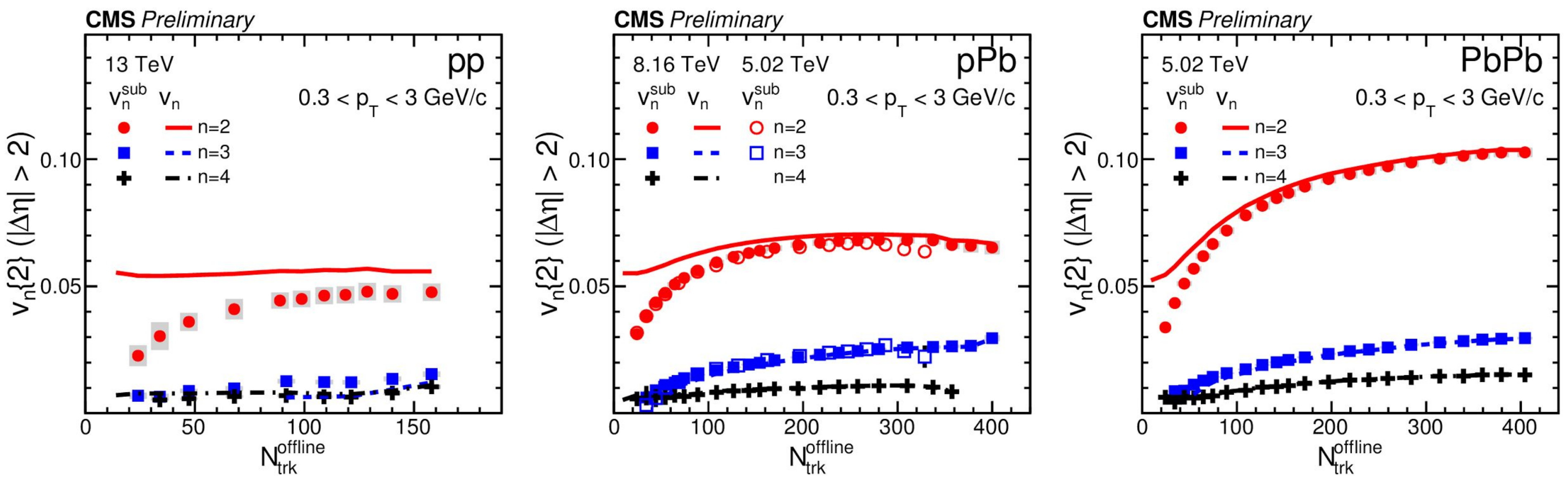
pPb



PbPb

- ★ **Two-particle correlations in all systems**

Results: v_n as function of multiplicity

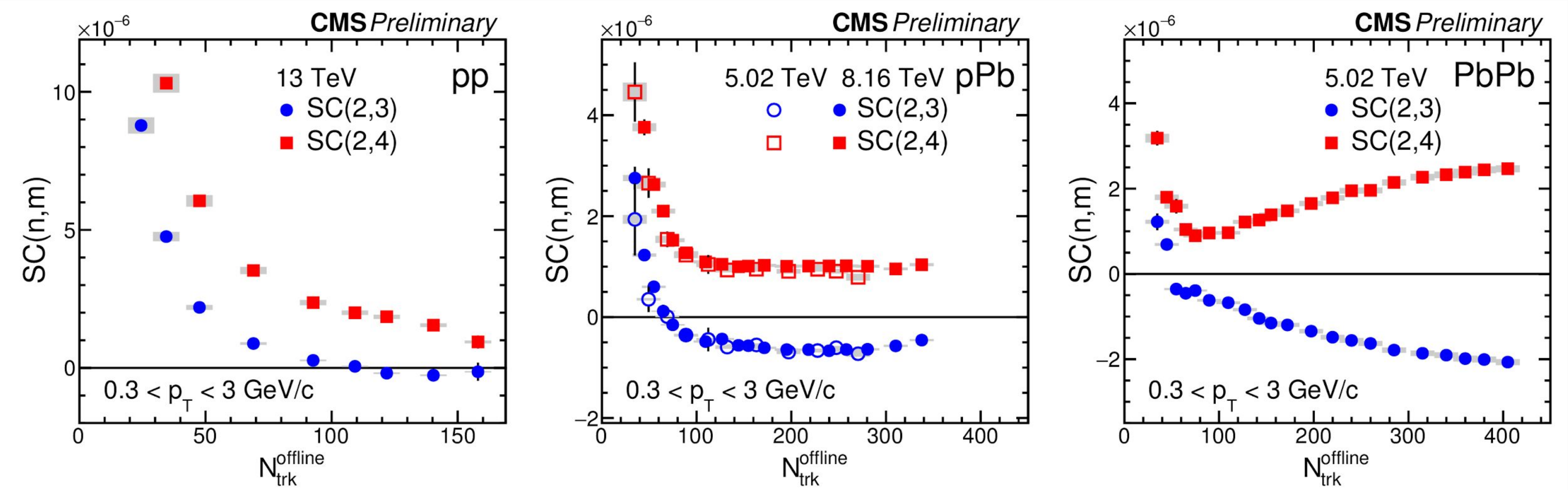


HIN-16-022

★ **Similar pattern** observed across systems for v_n

★ These results used for SC(n,m) normalization

Results: SC as function of multiplicity



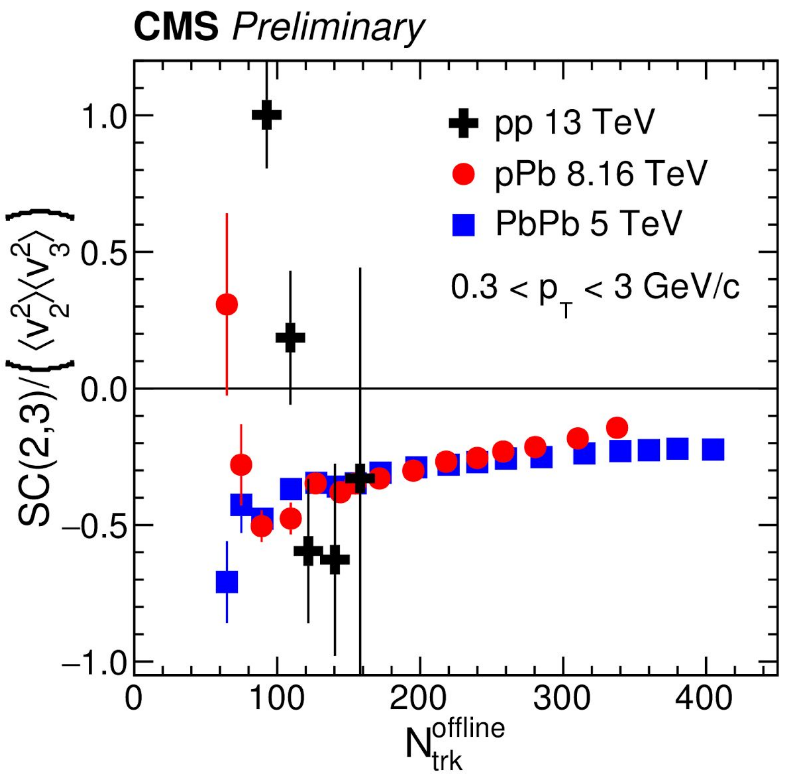
HIN-16-022

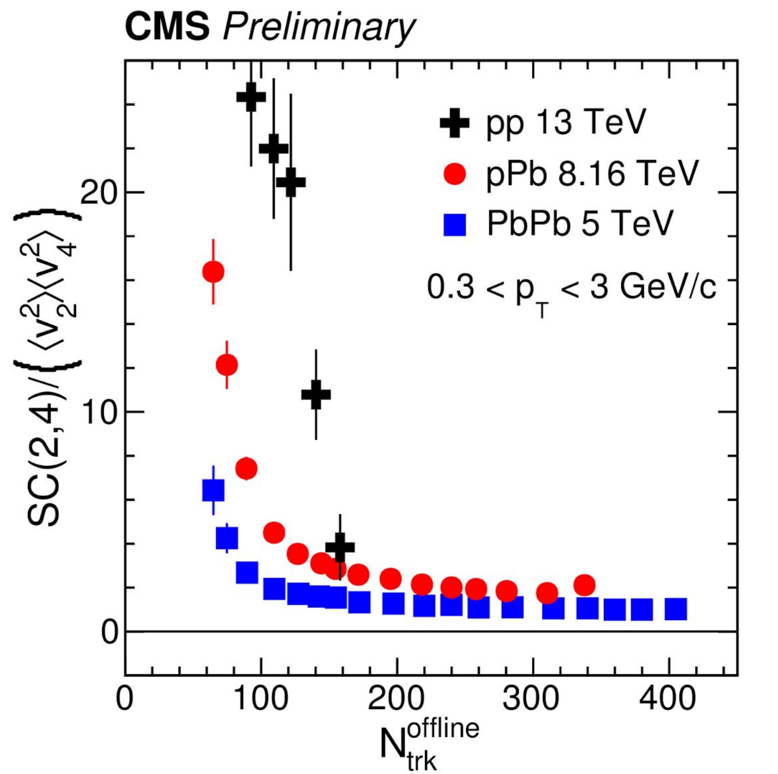
- ★ **Similar pattern** observed across systems for SC
- ★ Need normalization for **apple-apple comparison**

Normalized SC as function of multiplicity

SC normalized by $\langle v_n^2\rangle\langle v_m^2\rangle$

HIN-16-022





(n,m)=(2,3)

- **Similar behaviour pPb and PbPb.**
- **Points to similar IS fluctuations.**

(n,m)=(2,4)

- **Ordering seen: pp>pPb>PbPb**
- **May point to different transport properties**

Summary

★ **New flow results** from CMS for higher energies in **pp, pPb, PbPb**

★ **Fluctuations** essential when dealing with flow harmonics

★ **Measured the $p(v_2)$** which gives cumulants and skewness

★ **Measured the SC(n,m)** cumulant and the corresponding (anti)correlations between fluctuating harmonics