

# Skewness of Event-by-event Elliptic Flow Fluctuations in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with CMS detector

**Nazarova Elizaveta**

(Moscow State University - SINP MSU)  
On behalf of the CMS collaboration  
**CMS-PAS-HIN-16-019**

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Utrecht (Netherlands), 2017**

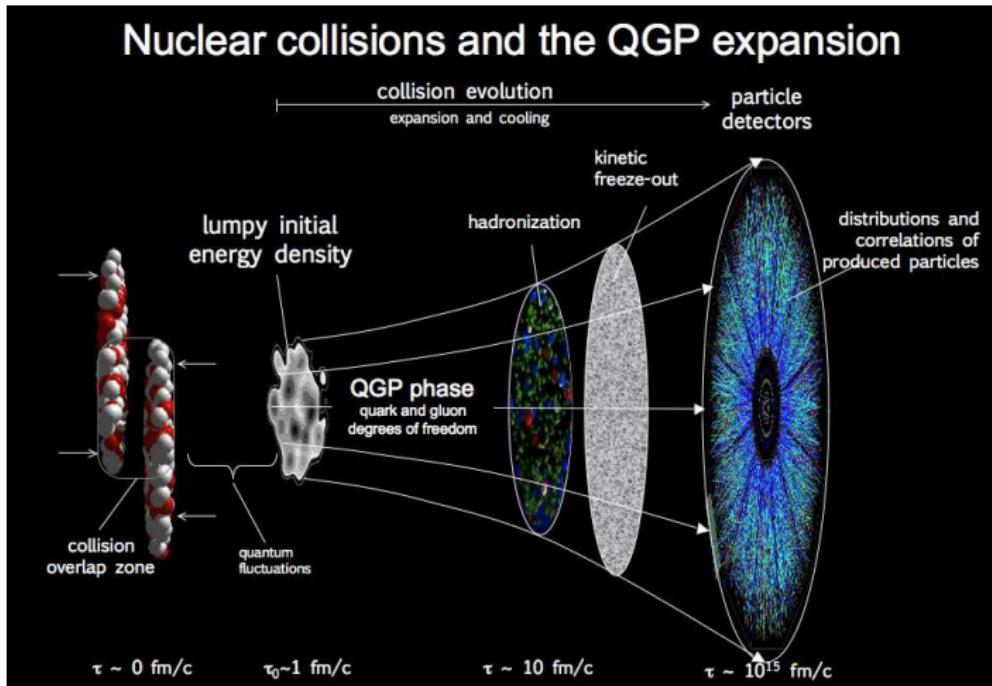


**13.07.2017**



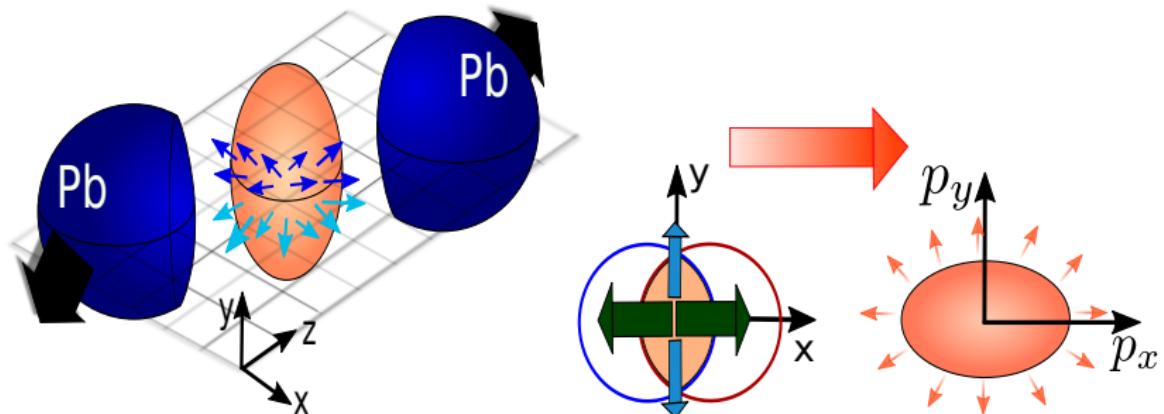
# Introduction: Heavy Ion Collision

P. Sorensen, <http://arxiv.org/abs/arXiv:0905.0174>



# Introduction: Flow

Formation of the overlap region:  
asymmetry in the initial geometry  $\rightarrow$  anisotropy in particle  
momenta distributions (flow)

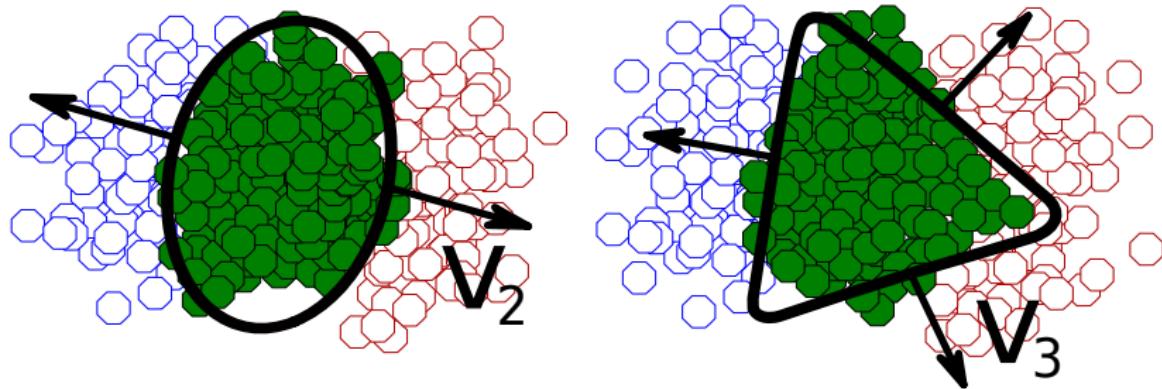


$$\frac{dN}{d\varphi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos(n(\varphi - \Psi_n)) = 1 + 2 \sum_{n=1}^{\infty} (v_{n,x}^{obs} \cos n\varphi + v_{n,y}^{obs} \sin n\varphi)$$

- $v_n$  and  $\varphi$  - magnitude and phase of the  $n^{th}$  - order anisotropy in a given event
- $\Psi_n$  - event plane angle

# Motivation

- Event-by-event (EbyE) analysis ( $v_n \rightarrow p(v_n)$ )
  - Observation of non-zero  $v_3$  at RHIC and LHC<sup>1</sup> ⇒ Participant eccentricity fluctuations ⇒  $v_n$  fluctuates event-by-event



# Motivation

- Event-by-event (EbyE unfolding<sup>2</sup>) analysis ( $v_n \rightarrow p(v_n)$ )
  - Observation of non-zero  $v_3$  at RHIC and LHC  $\implies$  Participant eccentricity fluctuations  $\implies v_n$  fluctuates event-by-event
  - Precise flow fluctuation studies
  - Cumulant extraction using EbyE distributions
  - Estimation of  $p(\varepsilon_n)$

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<sup>2</sup>ATLAS Collaboration, JHEP 1311 (2013) 183

<sup>3</sup>S. A. Voloshin, A. M. Poskanzer, A. Tang and G. Wang, Phys.Lett. B659 (2008) 537-541

<sup>4</sup>CBM Collaboration, Nucl.Phys. A904-905 (2013) 515-518

<sup>5</sup>G. Aad et al., ATLAS Collaboration, Eur.Phys.J. C74 (2014), 3157



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  - Precise flow fluctuation studies
  - Cumulant extraction using EbyE distributions
  - Estimation of  $p(\varepsilon_n)$
- Multi-particle cumulants<sup>3</sup>  $\implies$  moments of  $p(v_n)$ :
  - Observed<sup>4</sup>  $v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$ :
    - Nature of initial state fluctuations is Gaussian
  - Observed splitting<sup>5</sup>  $v_2\{2\} > v_2\{4\} > v_2\{6\} > v_2\{8\}$ :
    - Nature of initial state fluctuations is non-Gaussian

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# Motivation: Cumulant Splitting and Skewness

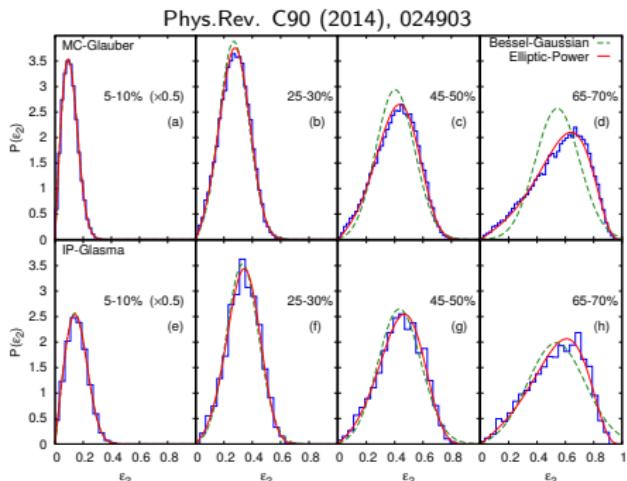
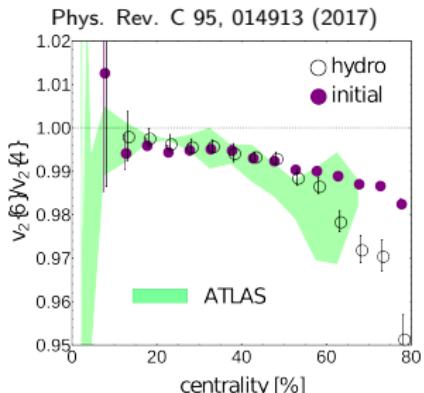
- Splitting of higher-order cumulants

observed<sup>6</sup>

→ evidence of skewness<sup>7</sup> of  $p(\varepsilon_2)$

(hydro calculations show that  
 $v_2\{6\}/v_2\{4\} \approx \varepsilon_2\{6\}/\varepsilon_2\{4\}$ )

→ Suggests that initial state fluctuations  
are non-Gaussian



<sup>6</sup>G. Aad et al., ATLAS Collaboration, Eur.Phys.J. C74 (2014), 3157

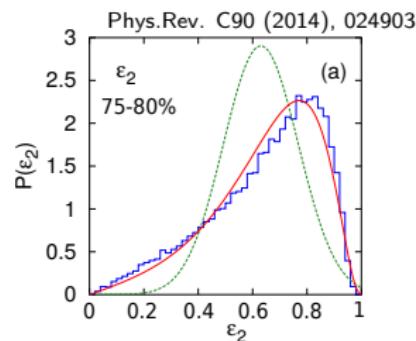
<sup>7</sup>G. Giacalone, L. Yan, J. Noronha-Hostler, J.-Y. Ollitrault, Phys. Rev. C 95, 014913 (2017)

# Motivation: Estimation of $p(\varepsilon_n)$

Two common eccentricity parametrizations:

- Bessel-Gaussian<sup>8</sup> (green line)

$$p(\varepsilon_n | \varepsilon_0, \delta) = \frac{\varepsilon_n}{\delta^2} \text{Exp}\left[-\frac{\varepsilon_n^2 + \varepsilon_0^2}{2\delta}\right] I_0\left(\frac{\varepsilon_n \varepsilon_0}{\delta^2}\right)$$
$$\varepsilon_n\{2\} > \varepsilon_n\{4\} = \varepsilon_n\{6\} = \varepsilon_n\{8\}$$



<sup>8</sup>S. A. Voloshin et al., Phys.Lett. B659 (2008) 537-541

<sup>9</sup>L. Yan, J.-Y. Ollitrault, A. M. Poskanzer, Phys.Rev. C90 (2014), 024903

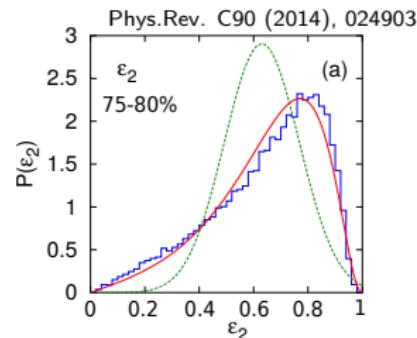
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$$\varepsilon_n\{2\} > \varepsilon_n\{4\} = \varepsilon_n\{6\} = \varepsilon_n\{8\}$$



- Elliptic Power Law<sup>9</sup> (red line)

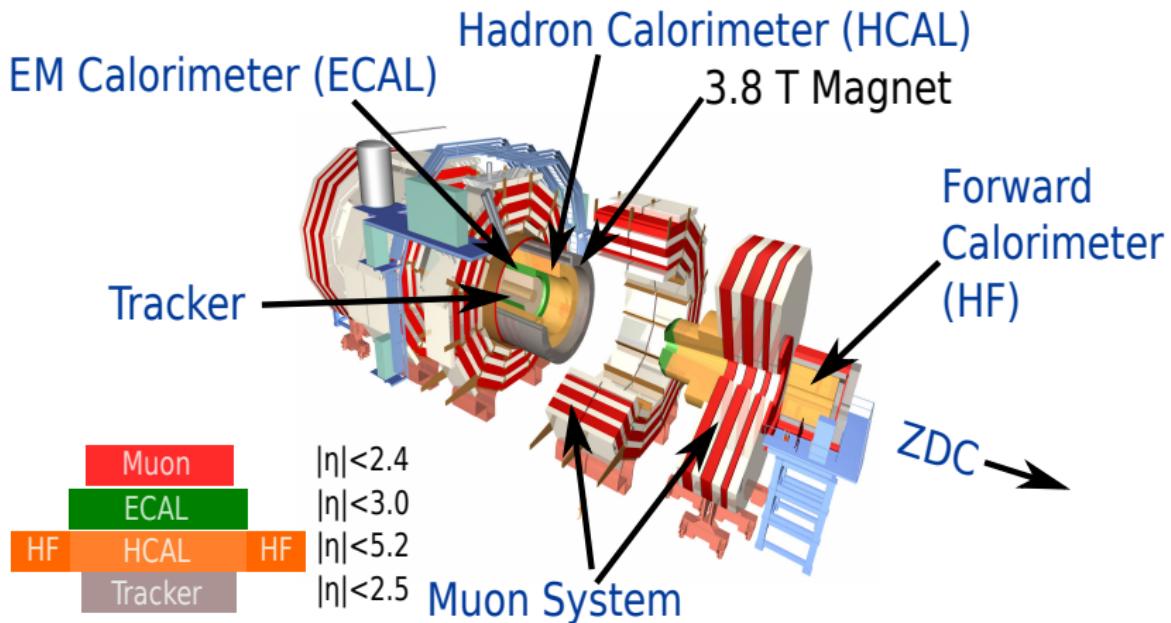
$$p(\varepsilon_n | \varepsilon_0, \alpha) = \frac{2\alpha\varepsilon_n}{\pi} (1 - \varepsilon_0^2)^{\alpha+1/2} \int_0^\pi \frac{(1 - \varepsilon_n^2)^{\alpha-1} d\varphi}{(1 - \varepsilon_0\varepsilon_n \cos \varphi)^{2\alpha+1}}$$

$$|\varepsilon_n| \leq 1, \varepsilon_n\{2\} > \varepsilon_n\{4\} > \varepsilon_n\{6\} > \varepsilon_n\{8\}$$

<sup>8</sup>S. A. Voloshin et al., Phys.Lett. B659 (2008) 537-541

<sup>9</sup>L. Yan, J.-Y. Ollitrault, A. M. Poskanzer, Phys.Rev. C90 (2014), 024903

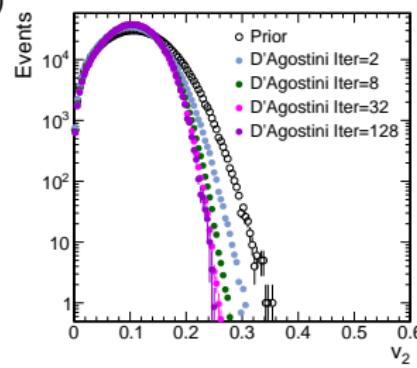
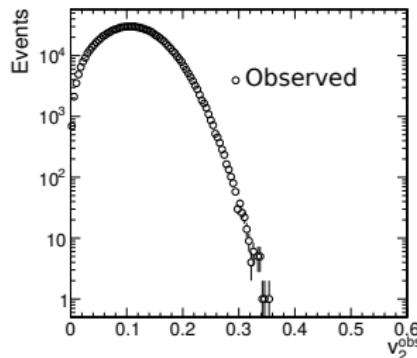
# Analysis: CMS Detector Setup



# Analysis

EbyE  $p(v_n)$  ("true") is smeared:

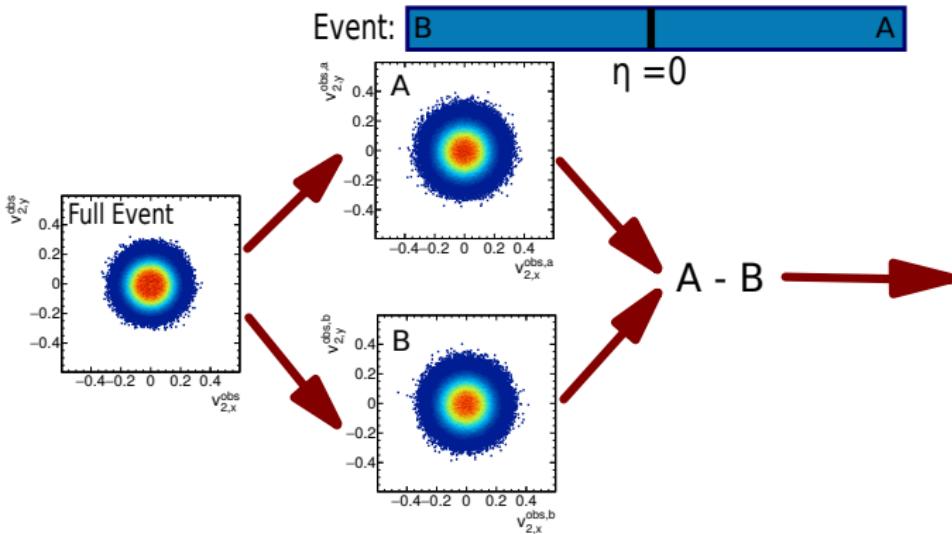
- $p(v_n^{obs}|v_n) \times p(v_n) = p(v_n^{obs})$ 
  - statistical fluctuations (finite number of particles)
  - non-flow correlations (resonance and jet decays)
- Construct  $p(v_n^{obs})$  distribution:
  - $\vec{v}_n^{obs} = \left( \frac{\sum \cos n\varphi_i / \epsilon_i}{\sum 1/\epsilon_i}, \frac{\sum \sin n\varphi_i / \epsilon_i}{\sum 1/\epsilon_i} \right) - \langle \vec{v}_n^{obs} \rangle$
  - Perform D'Agostini Unfolding<sup>10</sup> (using RooUnfold package<sup>11</sup>)



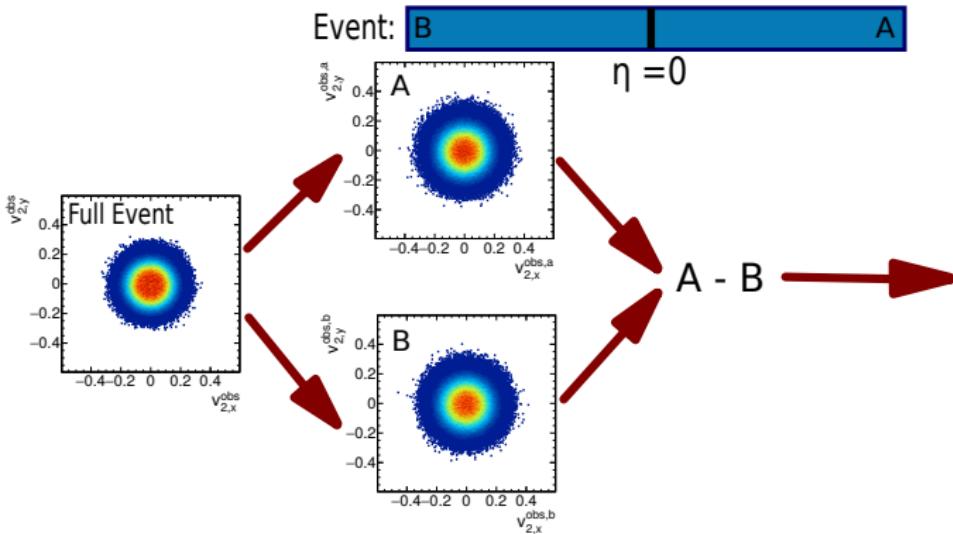
<sup>10</sup>G. D'Agostini, Nucl. Instrum. Meth. A362, 487 (1995)

<sup>11</sup>T. Adye, Proc. of PHYSTAT 2011 Workshop, CERN-2011-006, pp 313-318, 2011

# Analysis: Response Function

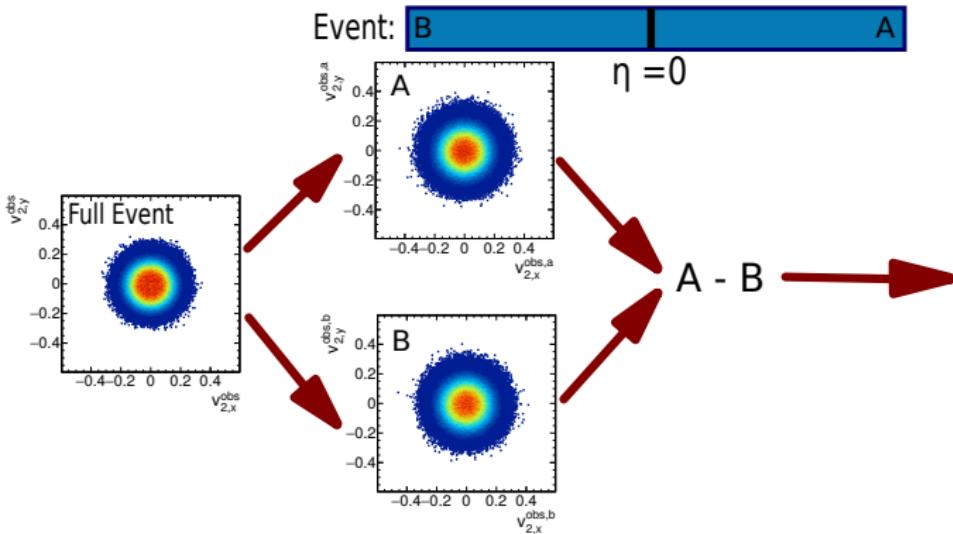


# Analysis: Response Function



- Divide the event into 2 sub-events (2SEs)

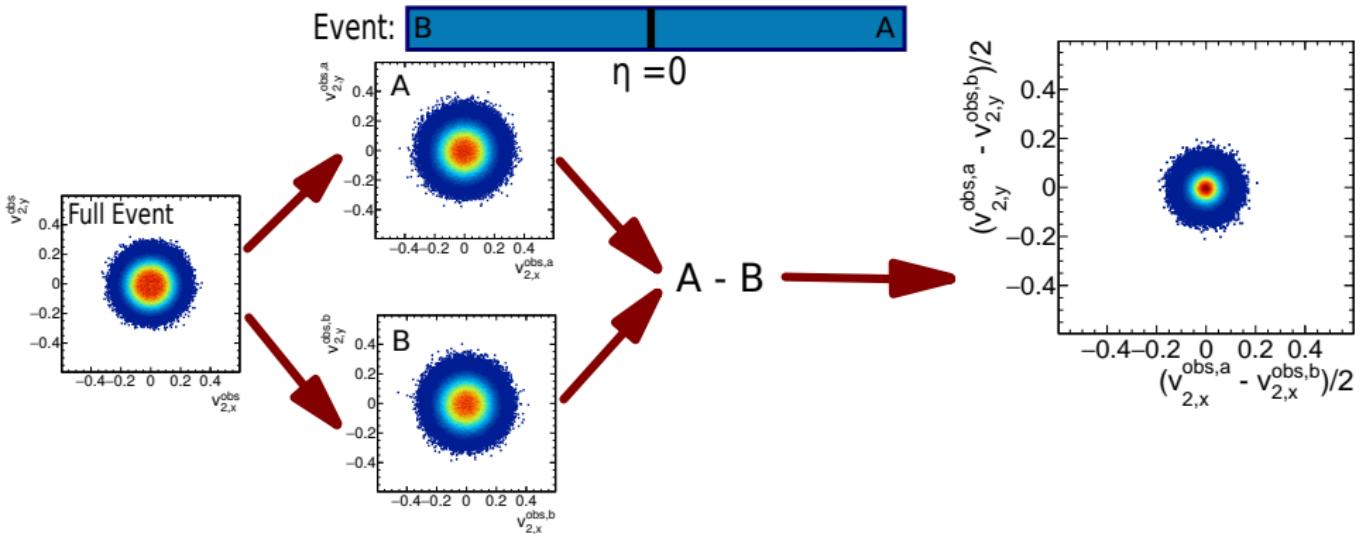
# Analysis: Response Function



- Divide the event into 2 sub-events (2SEs)
- $\ln(\overrightarrow{v}_n^{\text{obs},a} - \overrightarrow{v}_n^{\text{obs},b})/2$  flow signal cancels
  - Remaining effects: statistical and non-flow



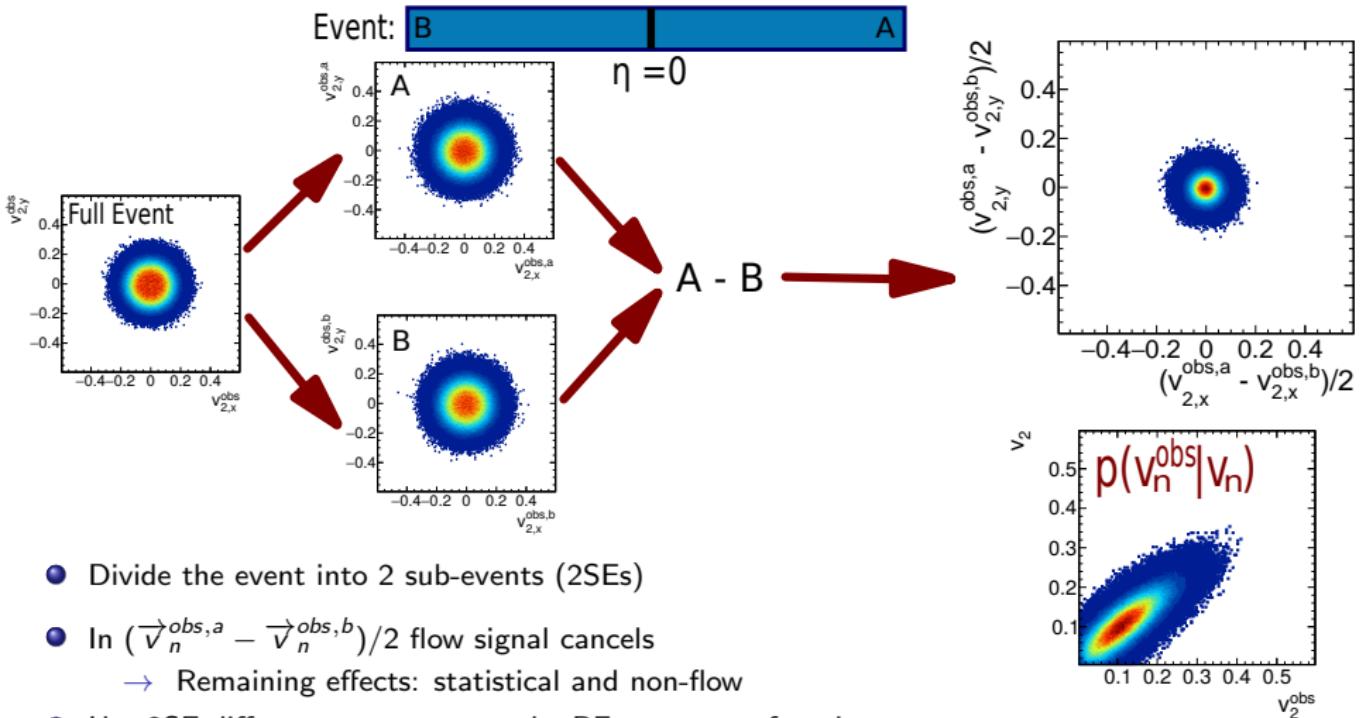
# Analysis: Response Function



- Divide the event into 2 sub-events (2SEs)
- In  $(\vec{v}_n^{\text{obs},\text{a}} - \vec{v}_n^{\text{obs},\text{b}})/2$  flow signal cancels
  - Remaining effects: statistical and non-flow
- Use 2SE difference to construct the RF - response function



# Analysis: Response Function



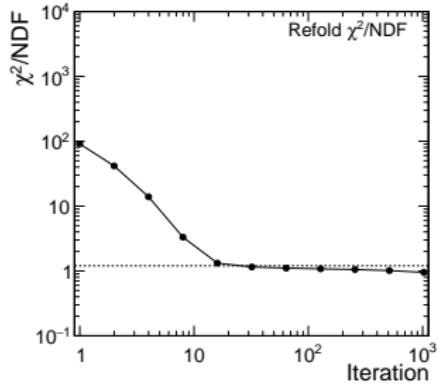
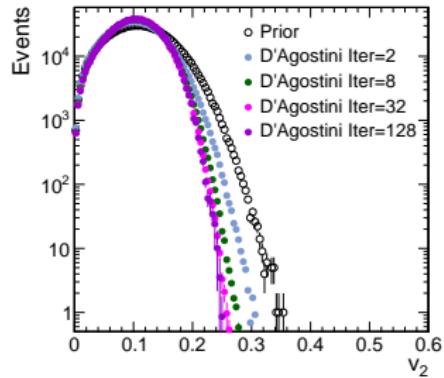
# Analysis: Unfolding regularization

- Iterative unfolding to remove smearing:
  - Unfolding matrix:

$$M_{ij}^{iter} = \frac{A_{ji} c_i^{iter}}{\sum_{m,k} A_{mi} A_{jk} c_k^{iter}},$$

$$\hat{c}^{iter+1} = \hat{M}^{iter} \hat{e}, A_{ji} = p(e_j | c_i)$$

- Regularization to choose "final" distribution:
  - Refolding
  - Cut-off criteria:  $\chi^2/NDF$  (refolded/observed)



# Analysis: Estimation of $p(\varepsilon_n)$

Elliptic Power Law parametrization<sup>12</sup>

$$p(\varepsilon_n | \varepsilon_0, \alpha) = \frac{2\alpha\varepsilon_n}{\pi} (1 - \varepsilon_0^2)^{\alpha+1/2} \int_0^\pi \frac{(1 - \varepsilon_n^2)^{\alpha-1} d\varphi}{(1 - \varepsilon_0\varepsilon_n \cos \varphi)^{2\alpha+1}}, \quad |\varepsilon_n| \leq 1$$

$$\text{If } v_n = k_n * \varepsilon_n \implies p(v_n) = \frac{1}{k_n} p\left(\frac{v_n}{k_n}\right)$$

- $k_n$ 
  - Response coefficient
- $\varepsilon_0$ 
  - ≈ mean reaction plane eccentricity  
(for PbPb collisions)
- $\alpha$ 
  - Describes fluctuations, depends on n



<sup>12</sup>L. Yan, J.-Y. Ollitrault, A. M. Poskanzer, Phys.Rev. C90 (2014), 024903

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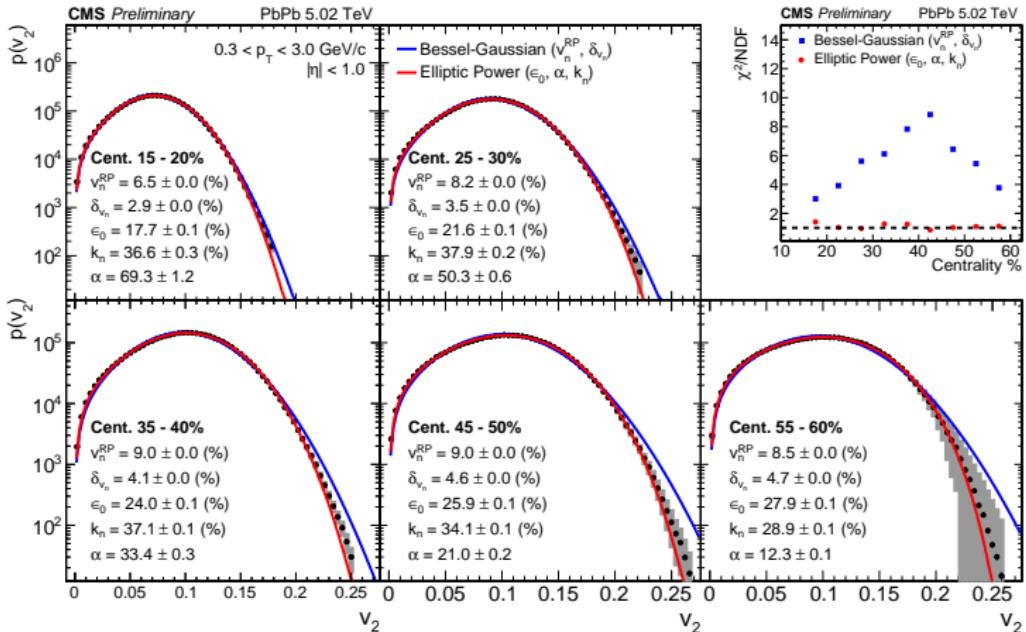
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- $k_n$ 
  - Response coefficient
- $\varepsilon_0$ 
  - ≈ mean reaction plane eccentricity  
(for PbPb collisions)
- $\alpha$ 
  - Describes fluctuations, depends on n
- if  $\varepsilon_0 = 0$ 
  - reduces to Power distribution
- if  $\alpha \gg 1$ 
  - reduces to Gaussian distribution
- in the limit  $\alpha \gg 1$  and  $\varepsilon_0 \ll 1$ 
  - reduces to Bessel-Gaussian distribution



<sup>12</sup>L. Yan, J.-Y. Ollitrault, A. M. Poskanzer, Phys.Rev. C90 (2014), 024903

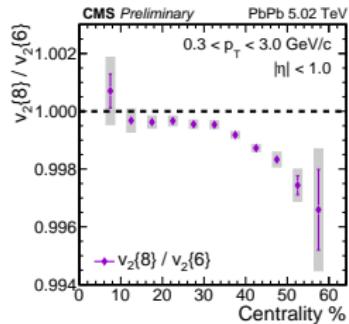
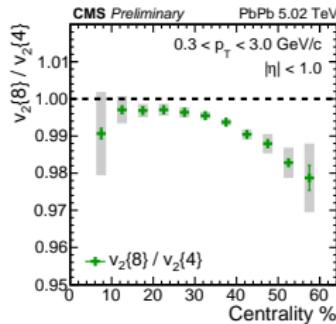
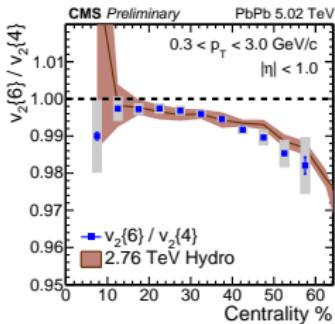
# Results: Fitting EbyE $p(v_n)$



- Elliptic Power Law parametrization describes data better than Bessel-Gaussian
- Allows for extraction of  $p(\epsilon_n)$  without an assumed initial-state model

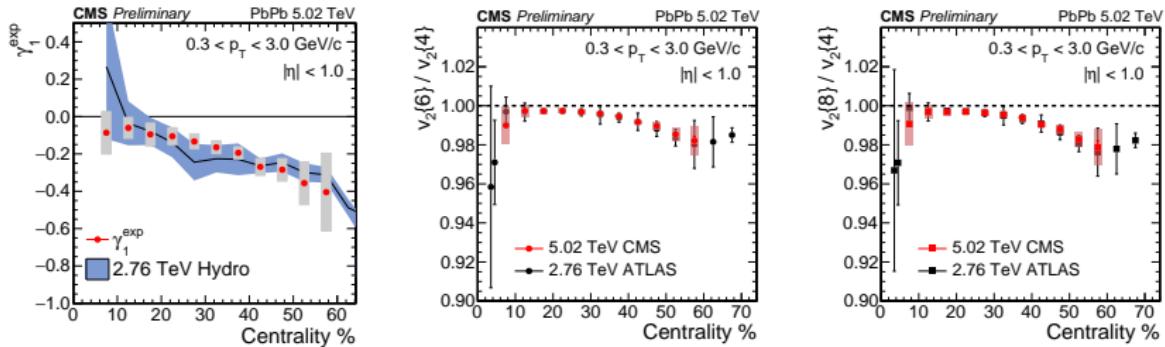


# Results: Cumulant ratios



- Splitting between higher-order cumulants is observed ( $v_2\{4\} > v_2\{6\} > v_2\{8\}$ )
- More pronounced in the peripheral centrality bins
- Consistent with hydrodynamic predictions<sup>13</sup> for 2.76 TeV

# Results: Cumulant ratios and skewness



- Measurements for 2.76 and 5.02 TeV are consistent with each other
  - observables have no strong energy dependence
- Skewness found negative for the whole centrality range



# Conclusion

- Through extracting underlying EbyE  $p(v_n)$  distributions:
  - Splitting of high-order cumulants was observed:  $v_2\{4\} > v_2\{6\} > v_2\{8\}$
  - Negative value of skewness was measured ( $\gamma_1^{\text{exp}}$ )
  - Elliptic Power Law parametrization used to describes distribution of  $p(v_2)$
- Observations suggest non-Gaussian nature of eccentricity fluctuations
- Shows a possibility to extract initial eccentricity and its response coefficient using only  $|\varepsilon_n| \leq 1$  constraint (without an assumed initial-state model)



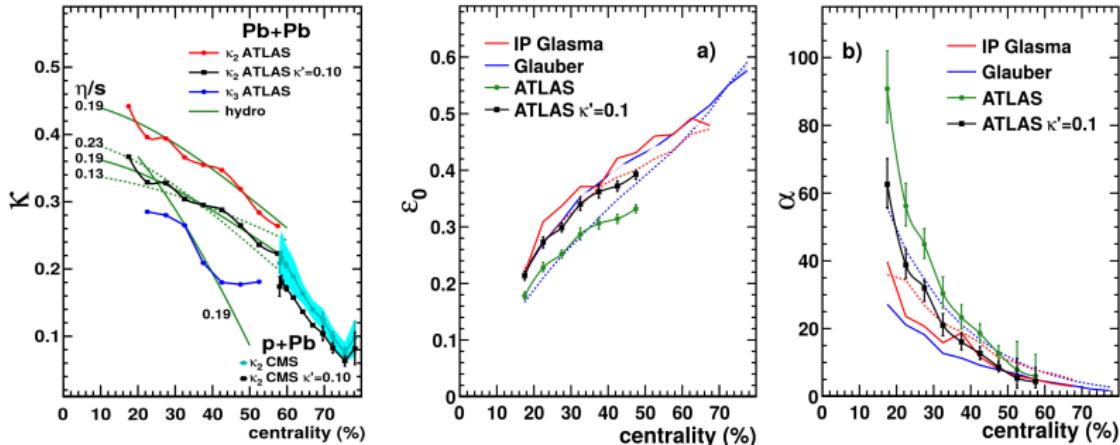
# Conclusion



Thank you for your attention!



# Back-Up: Estimation of $p(\varepsilon_n)$



L. Yan, J.-Y. Ollitrault, A. M. Poskanzer, Physics Letter B 742 (2015) 290



# Motivation: Cumulant Splitting and Skewness

Multi-particle cumulants can be calculated as:<sup>14</sup>

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

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

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

$$v_n\{8\}^8 = -(\langle v_n^8 \rangle - 16\langle v_n^6 \rangle \langle v_n^2 \rangle - 18\langle v_n^4 \rangle^2 +$$

$$144\langle v_n^4 \rangle \langle v_n^2 \rangle^2 - 144\langle v_n^2 \rangle^4)/33$$

Standardized skewness is defined as:  $\gamma_1 \equiv \frac{s_1}{\sigma_x^3}$ .

$$s_1 = \langle (v_x - \bar{v}_2)^3 \rangle, \quad \sigma_y^2 = \langle v_y^2 \rangle$$

$$\sigma_x^2 = \langle (v_x - \bar{v}_2)^2 \rangle = \langle v_x^2 \rangle - \langle v_x \rangle^2$$

$$\bar{v}_2 \equiv \langle v_x \rangle (\langle v_2 \rangle = \sqrt{\langle v_x \rangle^2 + \langle v_y \rangle^2})$$

$$\langle v_x \rangle = \frac{1}{2\pi} \int_0^{2\pi} P(\varphi) \cos(2\varphi) d\varphi$$

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Knowing EbyE distributions, one can measure:  $\langle v_n^{2k} \rangle = \int v_n^{2k} p(v_n) dv_n$ .

Experimentally skewness can be measured using multi-particle cumulants:

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

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<sup>14</sup> usual method uses event-average:  $v_n\{2\} = \sqrt{c_n\{2\}}$ ,  $c_n\{2\} = \langle \langle 2 \rangle \rangle = \langle \langle \cos(\varphi_1 - \varphi_2) \rangle \rangle$

# Back-Up: Data Set and Event Selection

Event Type	Track Collection	Dataset	$N_{events}$
Minimum Bias	HiGeneralAndPixelTracks	/HiMinimumBias2/ HiRun2015-25Aug2016-v1/AOD	100M

**Table:** Data sample for PbPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV

## Event Selection:

- Vertex selection
  - $|v_z| < 15.0$  cm
  - $N_{tracks} > 2$
- $0.3 < p_T < 3.0$  Gev/c
- $|\eta| < 1.0$
- 5%-centrality bins (0 – 60%)

