Elliptic Flow Fluctuations in PbPb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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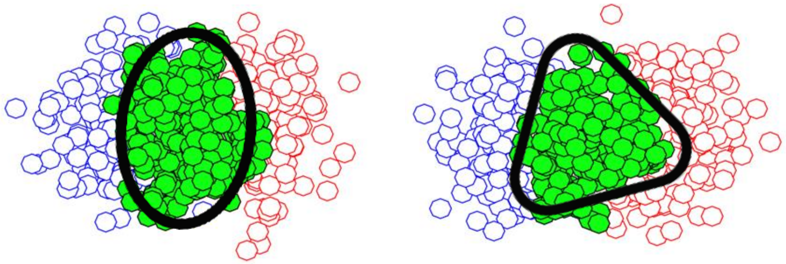
(University of Kansas)
On behalf of the CMS collaboration

Quark Matter 2017, Chicago
8 February 2017

A Bit of History

- Observation of non-zero v_3 at RHIC and LHC[1]
  - Participant eccentricity fluctuations: $v_n \rightarrow p(v_n)$



[1]Phys.Rev. C81 (2010) 054905

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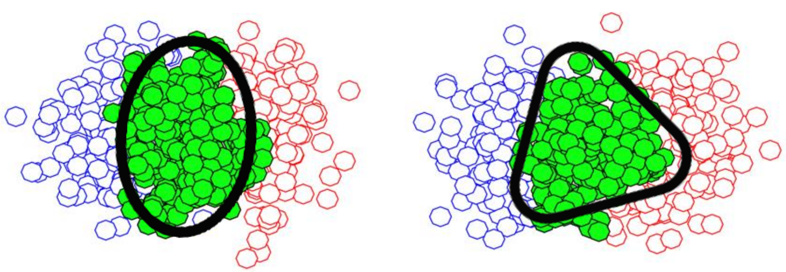
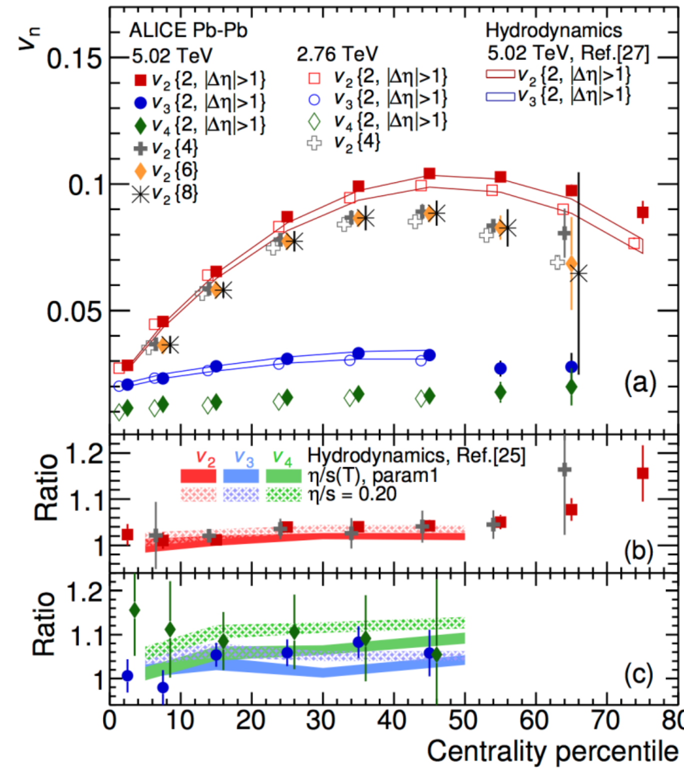


Phys.Rev.Lett. 116 (2016) 132302



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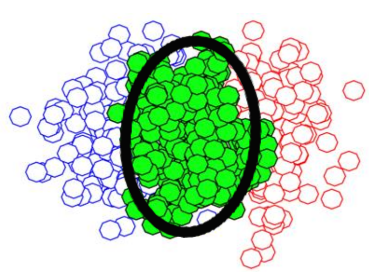
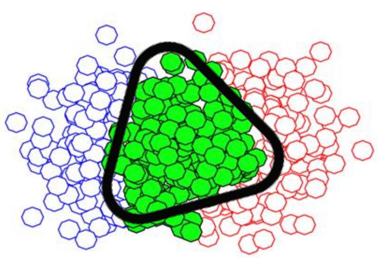
  - Participant eccentricity fluctuations: $v_n \rightarrow p(v_n)$
- Multi-particle cumulants[2] probe the moments of $p(v_n)$
- Measurement of $p(v_n)$ using unfolding[3]
  - Allows for precision fluctuation studies
    - Obtain all moments of $p(v_n)$
    - Precise cumulants
    - $p(\varepsilon_n)$ inference





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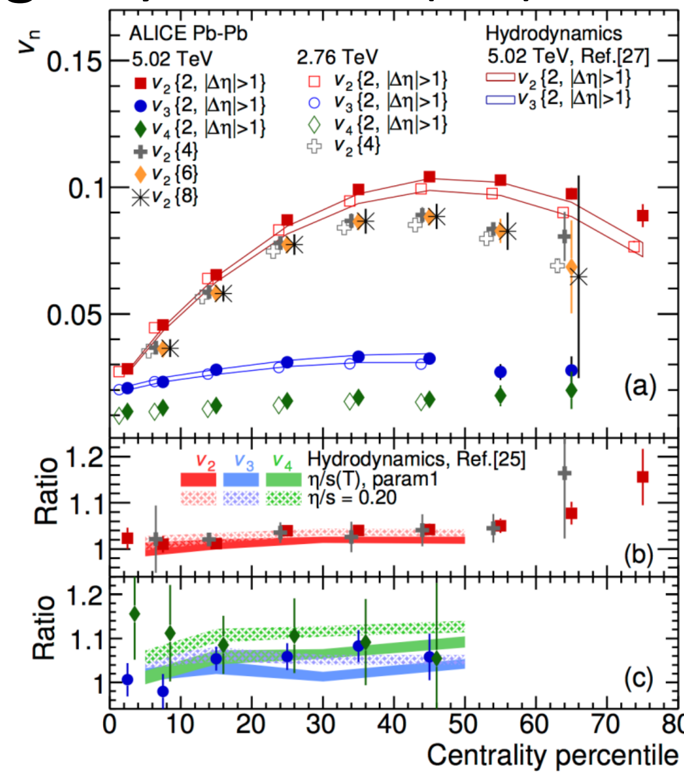

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[3]JHEP 1311 (2013) 183

Fluctuation Parametrization

- Prevailing eccentricity fluctuation models
  - Bessel-Gaussian[1]

$$p(\varepsilon_n|\varepsilon_0,\delta) = \frac{\varepsilon_n}{\delta^2}\,\mathrm{Exp}\left[-\frac{\varepsilon_n^2+\varepsilon_0^2}{2\delta^2}\right] I_0\left(\frac{\varepsilon_n\varepsilon_0}{\delta^2}\right), \qquad \varepsilon_n \in \mathbb{R}$$

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

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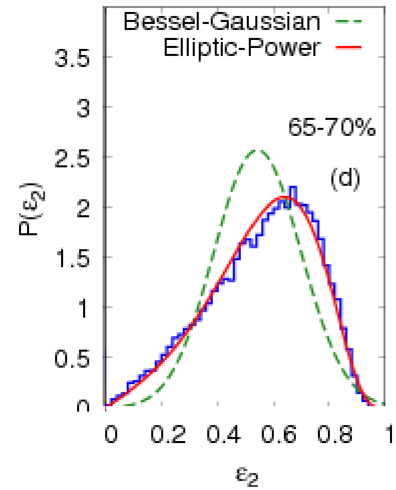
  - $\varepsilon_n\{2\} > \varepsilon_n\{4\} = \varepsilon_n\{6\} = \varepsilon_n\{8\}$
  - Elliptic power law[2]

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

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



Phys.Rev. C90 (2014), 024903

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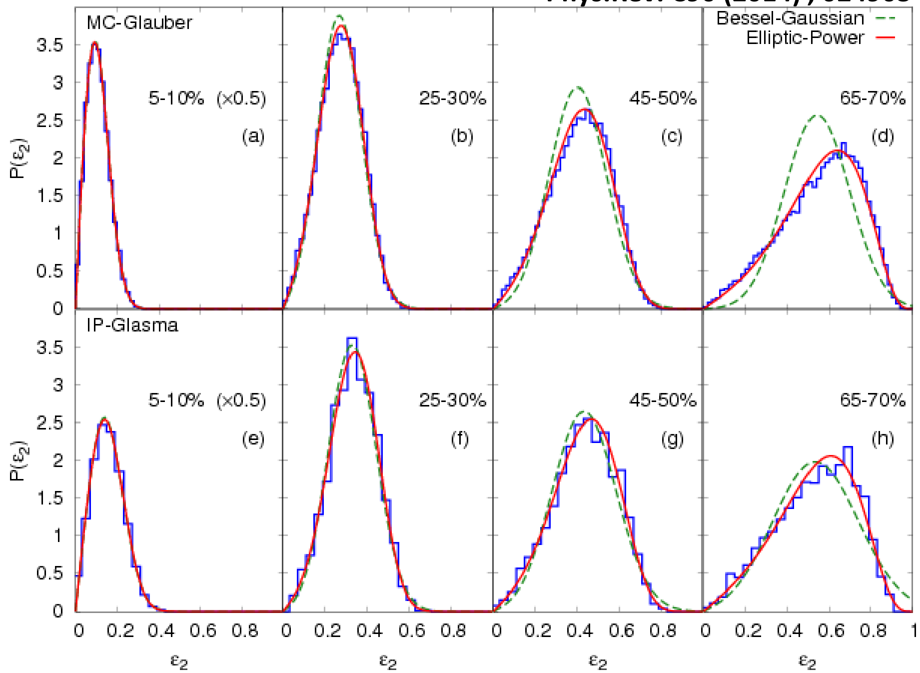
Non-Gaussian Fluctuations

- Fine splitting observed[1] between $v_2\{4\}$ and $v_2\{6\}$
  - Consequence of $p(\varepsilon_2)$ being skewed with respect to the reaction plane[2]

Phys.Rev. C90 (2014) , 024903



[1]Eur.Phys.J. C74 (2014), 3157

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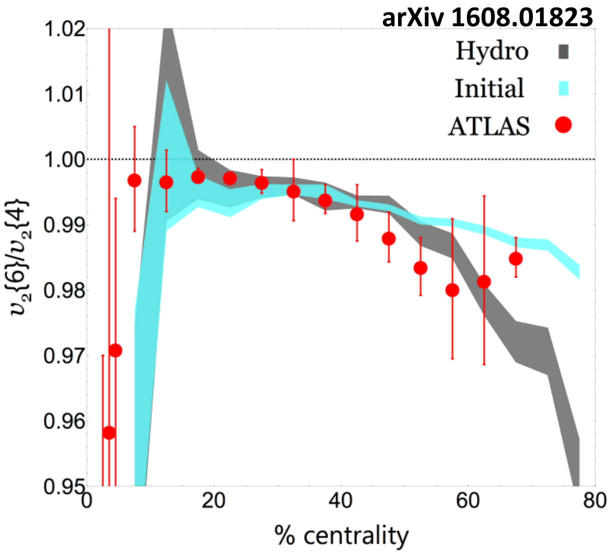
Non-Gaussian Fluctuations

- Fine splitting observed[1] between $v_2\{4\}$ and $v_2\{6\}$
  - Consequence of $p(\varepsilon_2)$ being skewed with respect to the reaction plane[2]
- Hydrodynamic calculations[2] show that $v_2\{6\}/v_2\{4\} \approx \varepsilon_2\{6\}/\varepsilon_2\{4\}$
  - Observable helps to constrain initial stages of the QGP



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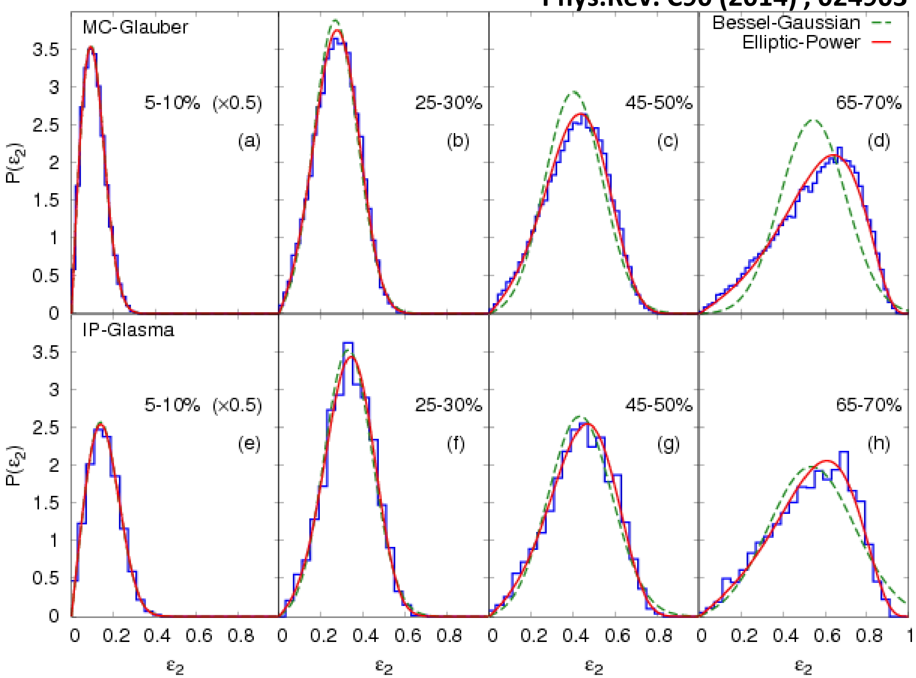

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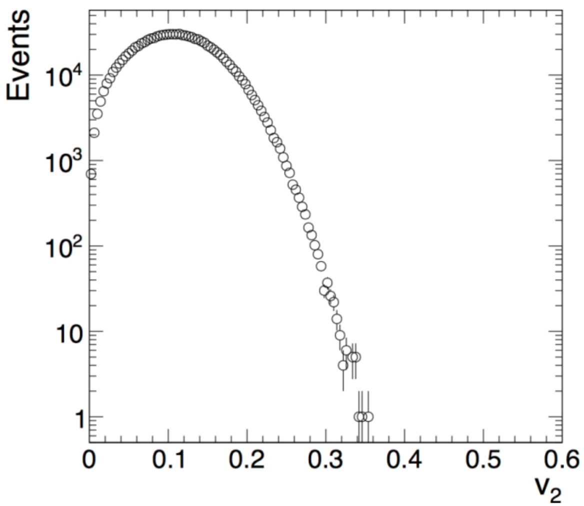
Observed Flow Harmonic Distributions

- Construct an event-by-event $p(v_n^{obs})$:
  - $\vec{v}_n^{obs} = \left(\frac{\sum \cos n\phi_i/\varepsilon_i}{\sum 1/\varepsilon_i}, \frac{\sum \sin n\phi_i/\varepsilon_i}{\sum 1/\varepsilon_i}\right) - \langle \vec{v}_n^{obs} \rangle$



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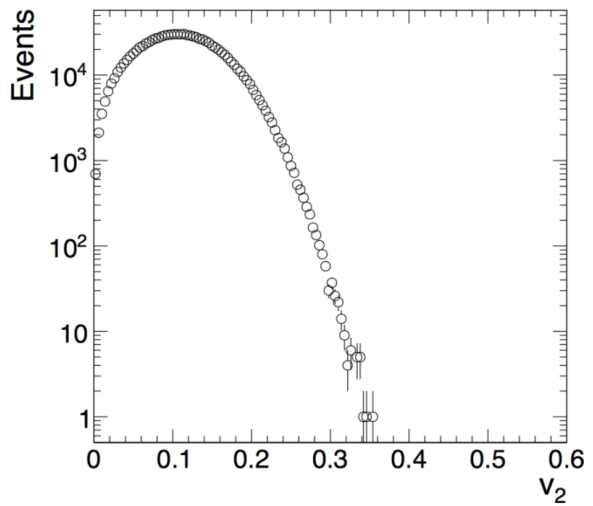

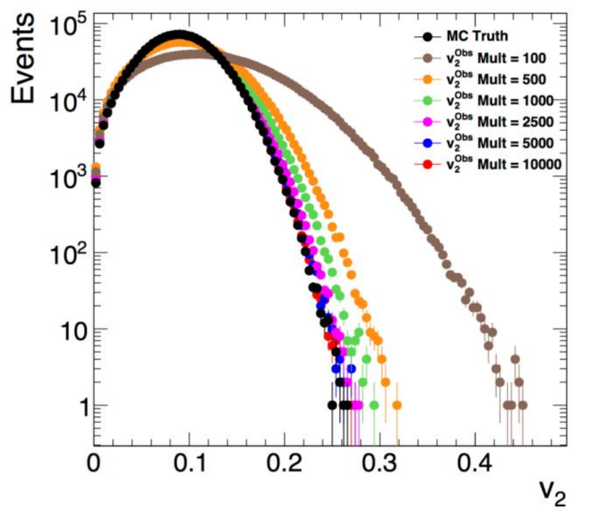

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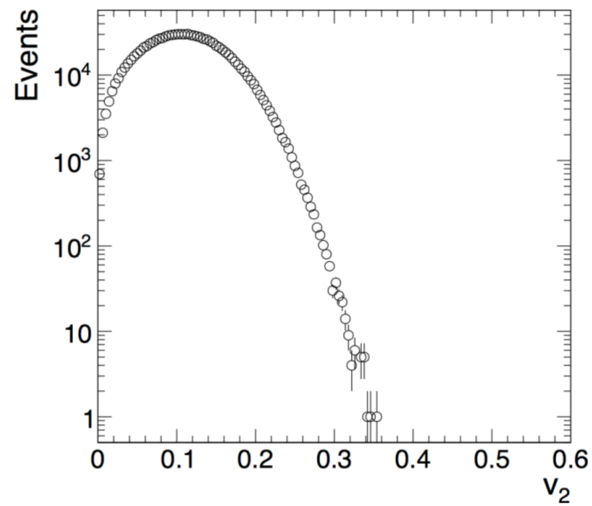
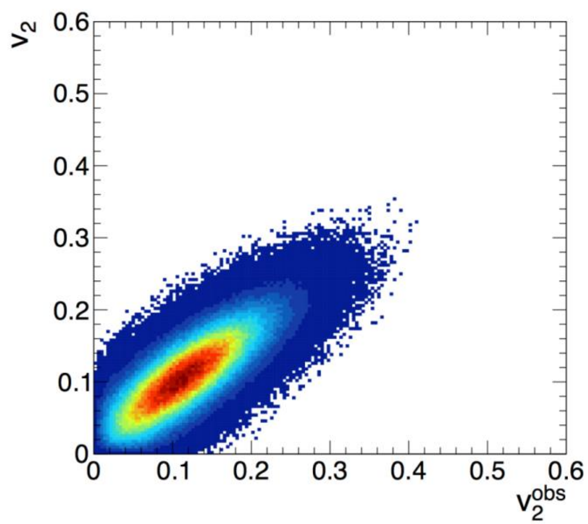
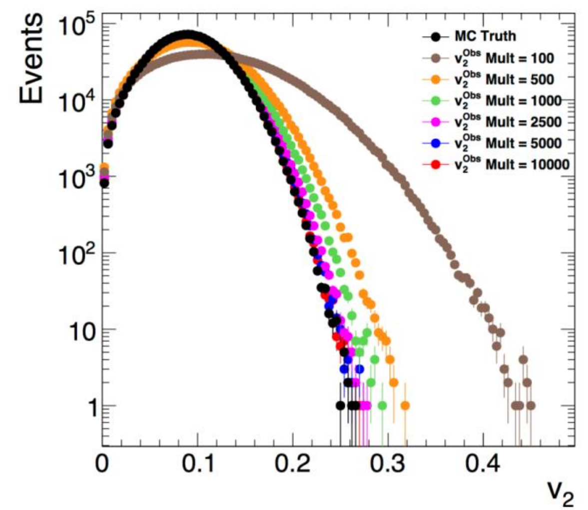
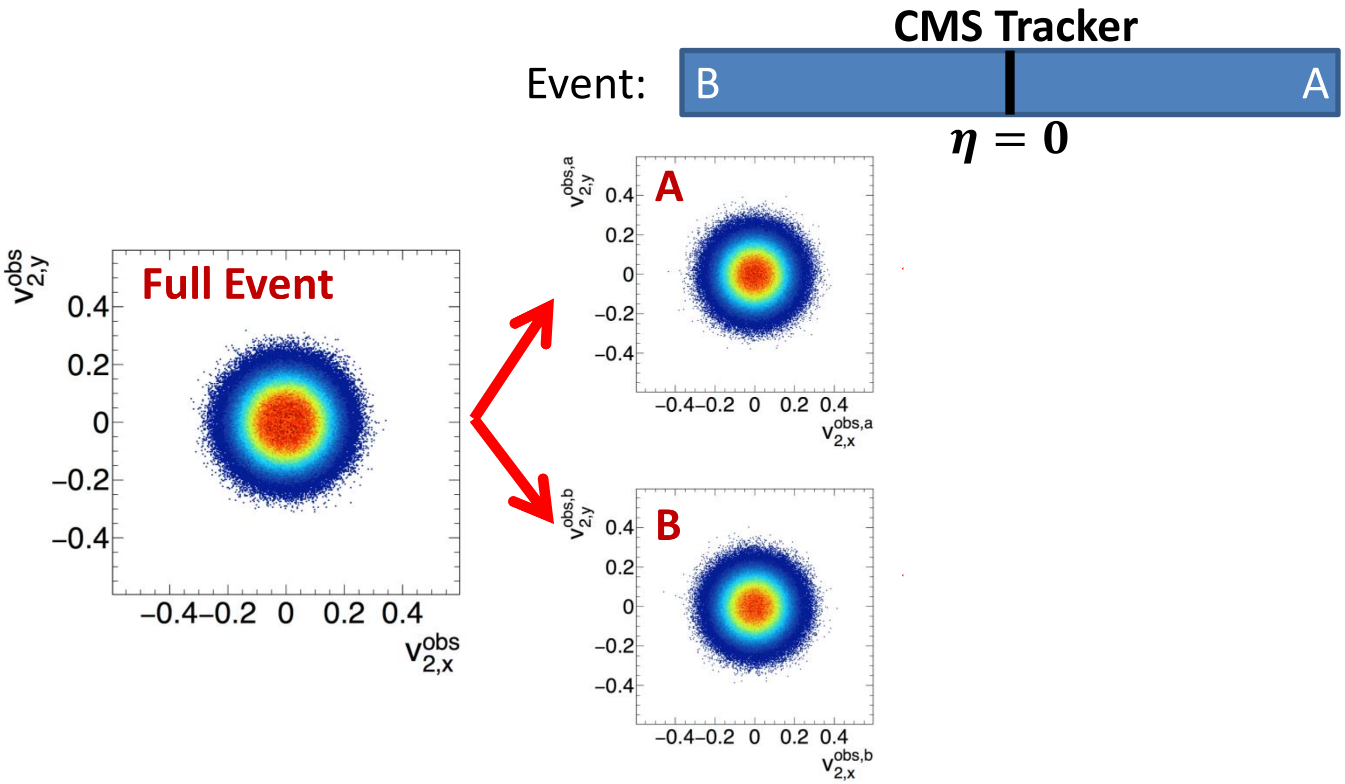
- Must account for statistical resolution
  - Quantified by a response function
    - $p(v_n^{obs}|v_n) \times p(v_n) = p(v_n^{obs})$
  - Use unfolding







Building the Response Function



- Divide event into two, symmetric subevents

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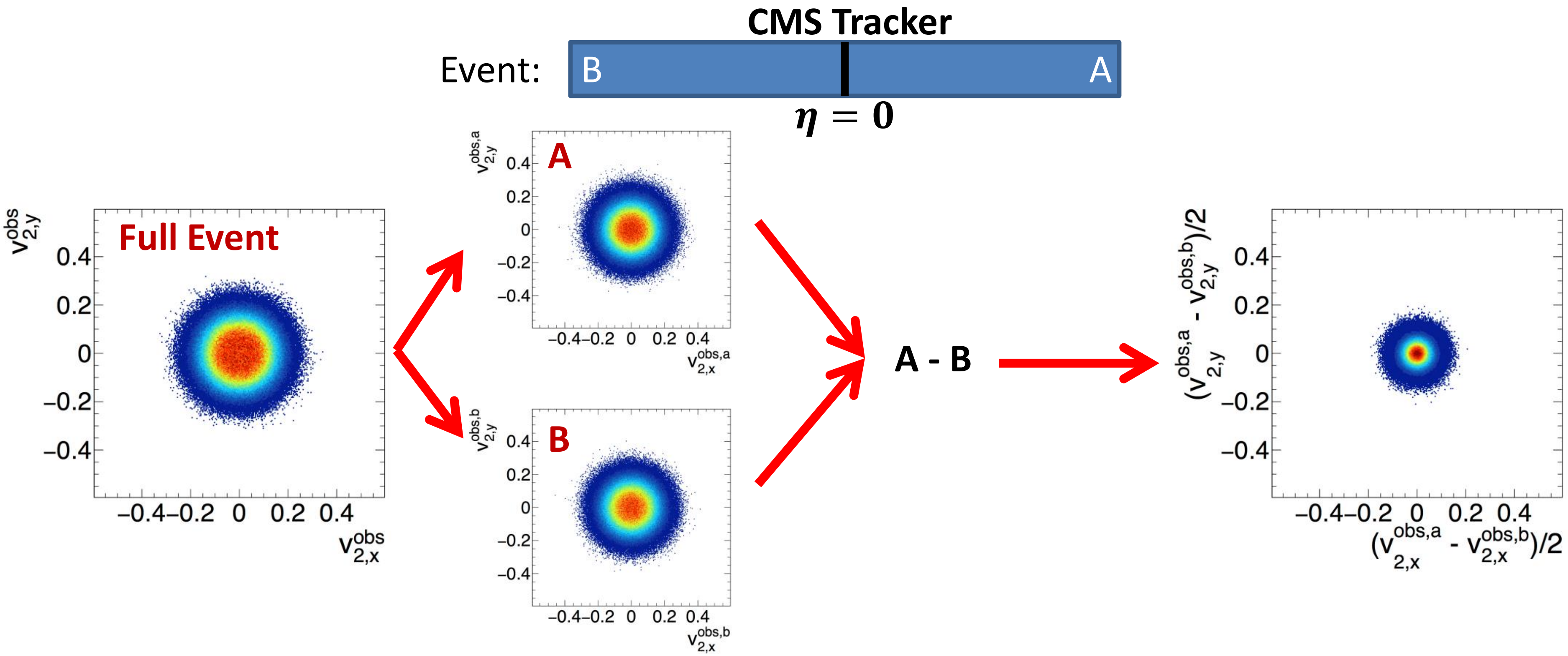

- Divide event into two, symmetric subevents
- Physical flow signal cancels in distribution of $(\vec{v}_n^{\,obs,a} - \vec{v}_n^{\,obs,b})/2$
    - Remaining effects are those from statistical smearing and non-flow

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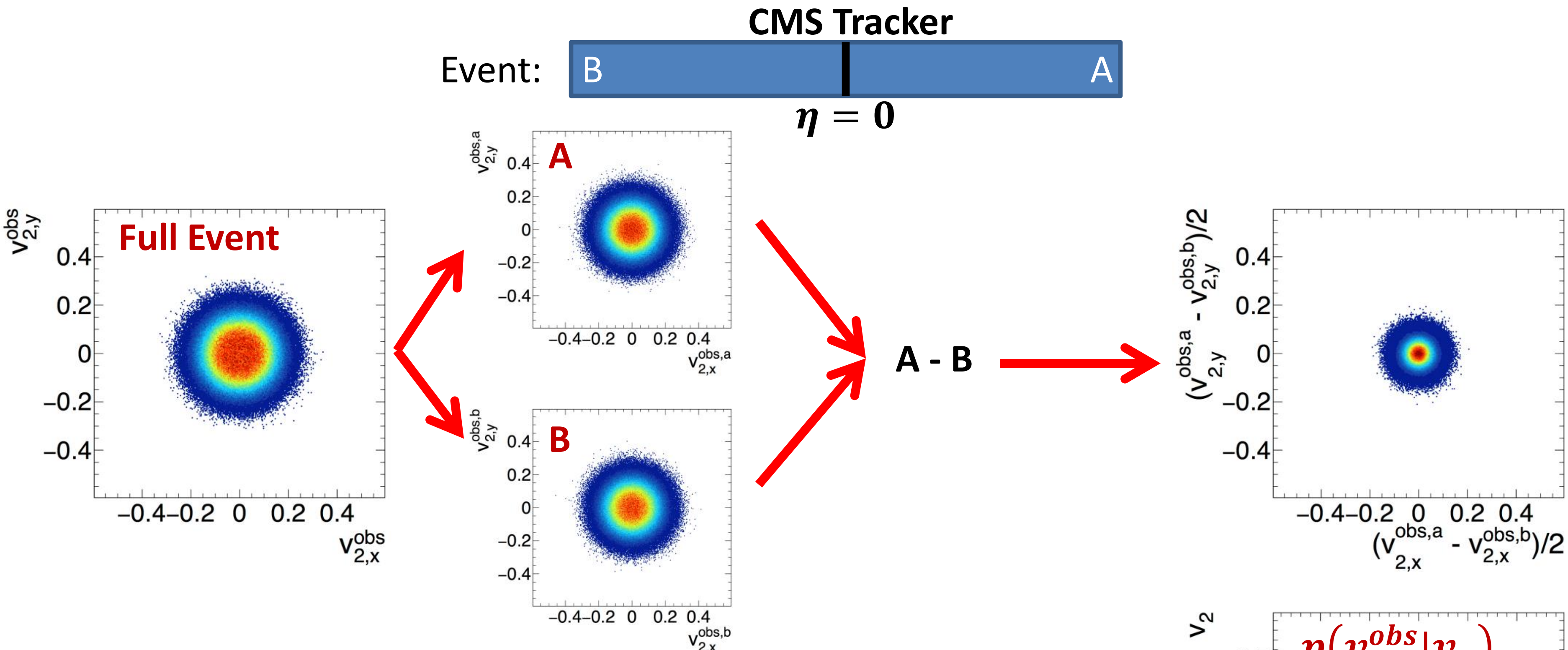

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- Physical flow signal cancels in distribution of $(\vec{v}_n^{\,obs,a} - \vec{v}_n^{\,obs,b})/2$
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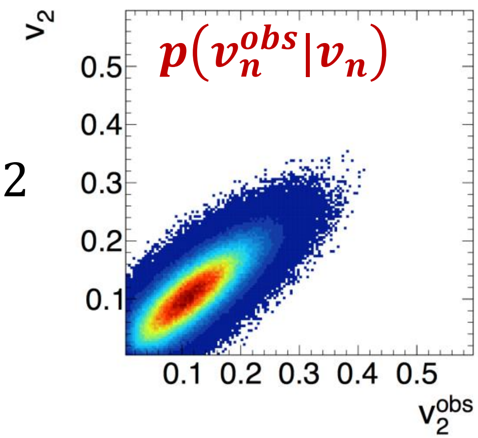
- Subevent difference distribution is used to build the response function



Unfolding

- Iteratively remove smearing using D'Agostini iteration unfolding[1]
  - $\hat{c}_i^{iter+1} = \widehat{M}_{ij}^{iter} e_j$
    - $\widehat{M}_{ij}^{iter} = \frac{A_{ji}\hat{c}_i^{iter}}{\sum_{m,k} A_{mi}A_{jk}\hat{c}_k^{iter}}$
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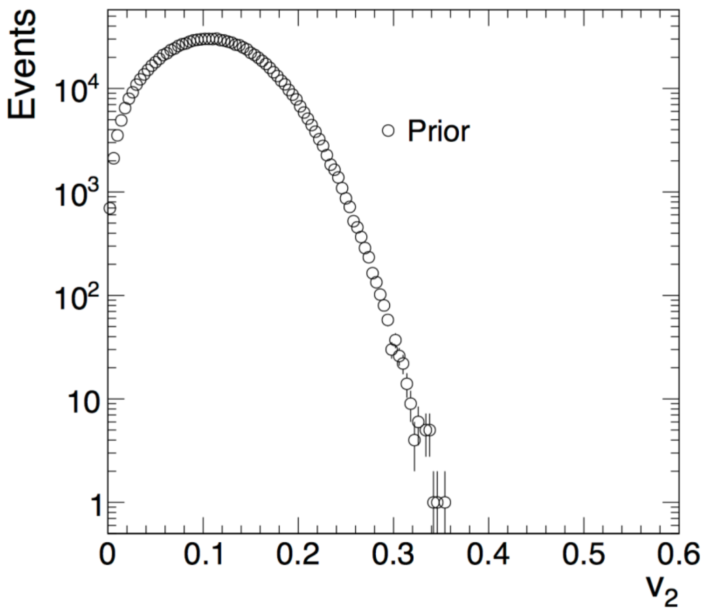

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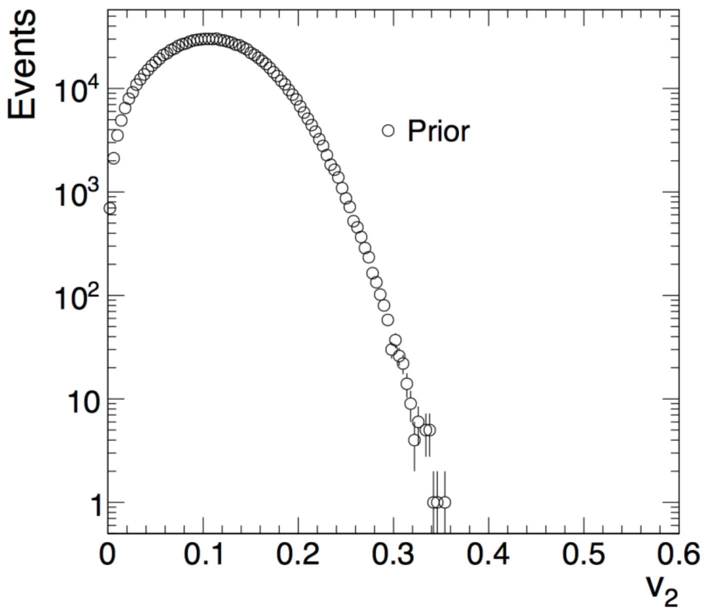
  - Regularization necessary
    - Smeared space χ^2/NDF
    - $p(v_n^{obs} | v_n) \times p(v_n)^{iter} = p(v_n^{obs})$



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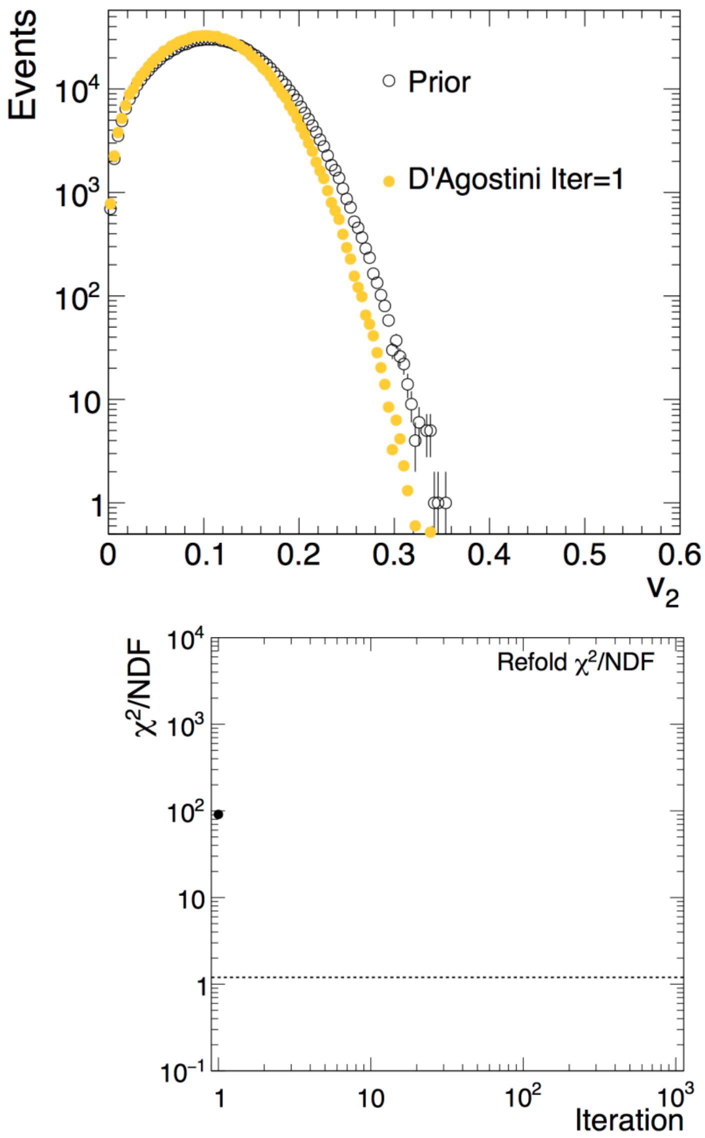

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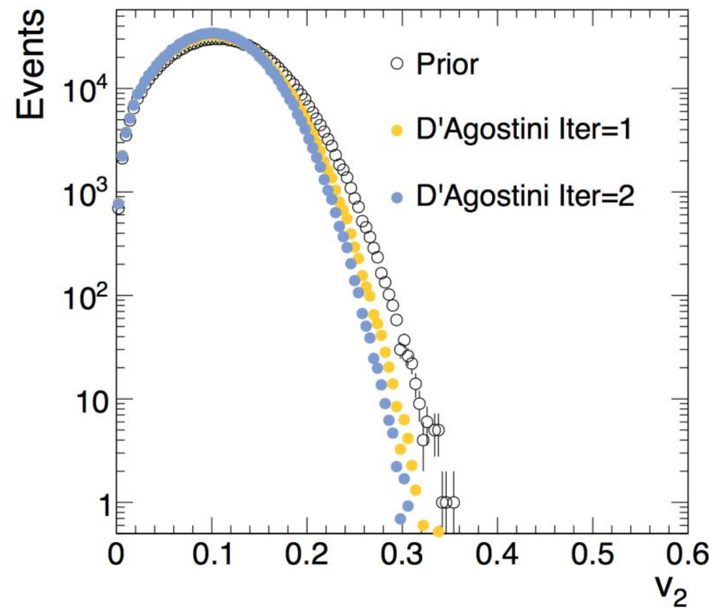

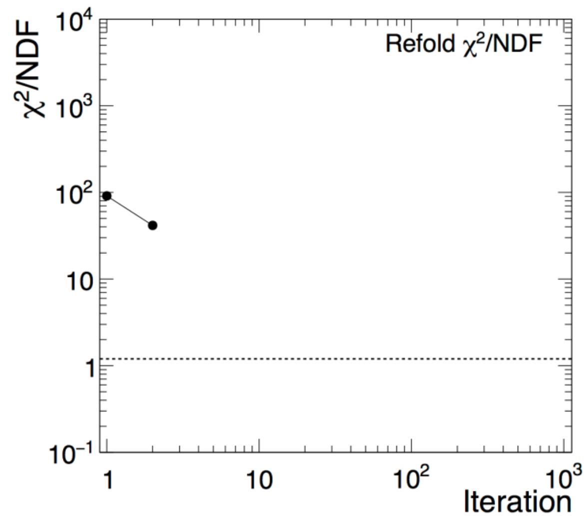

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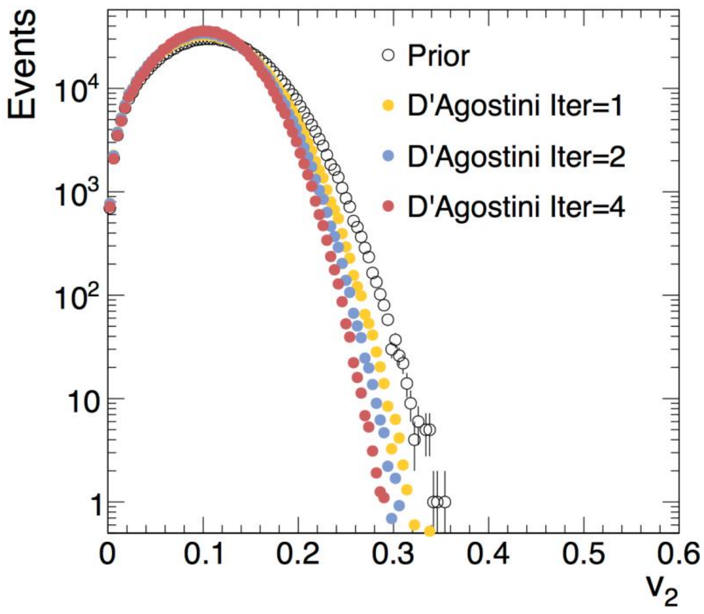

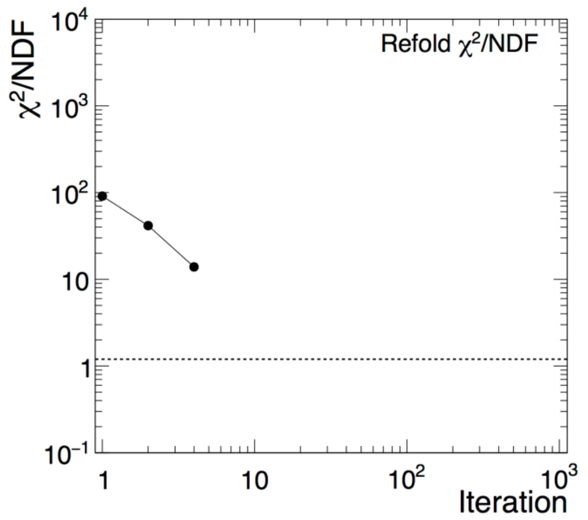

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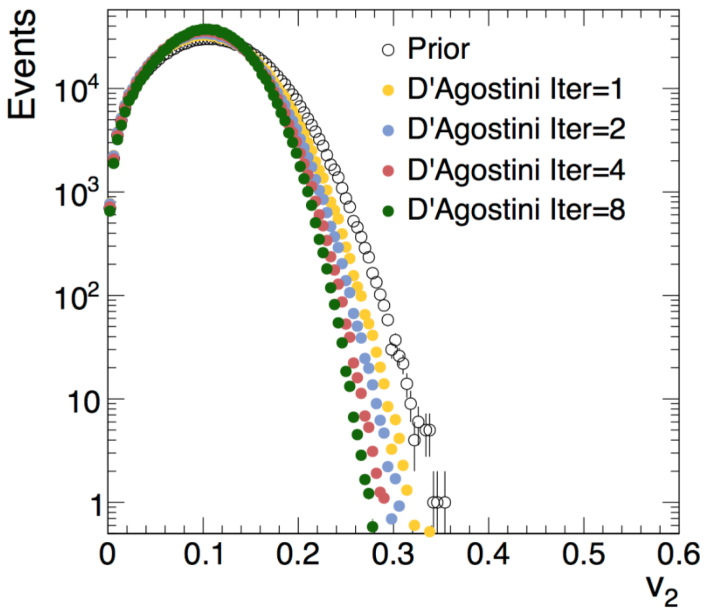

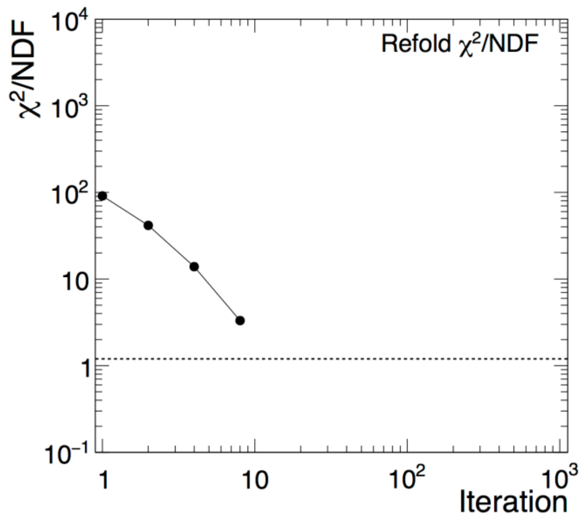

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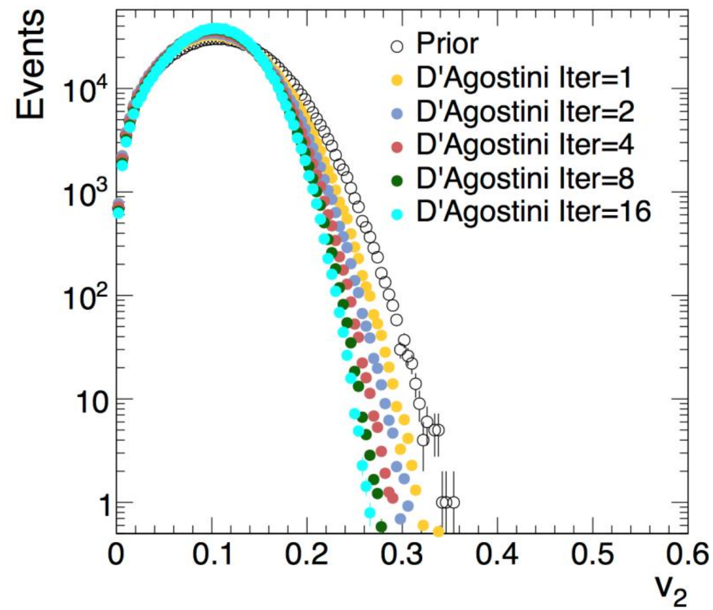

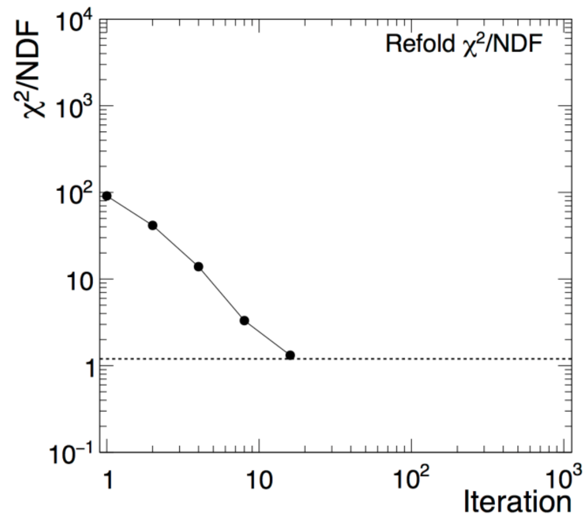

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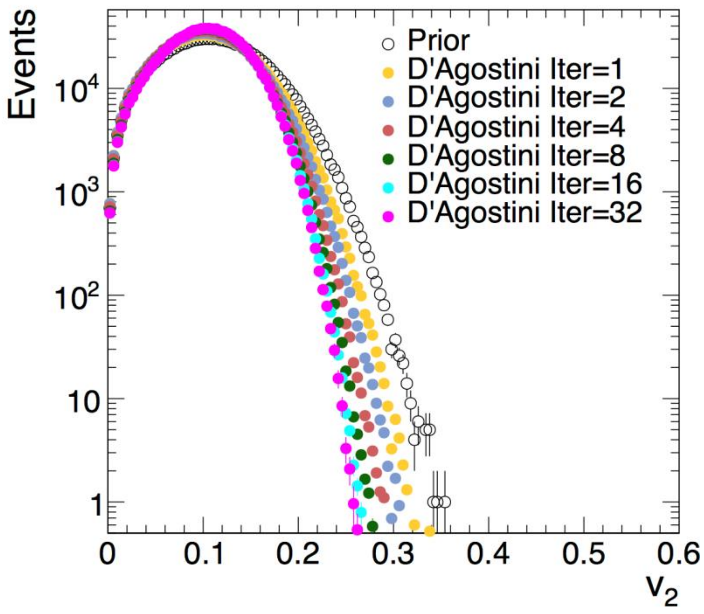

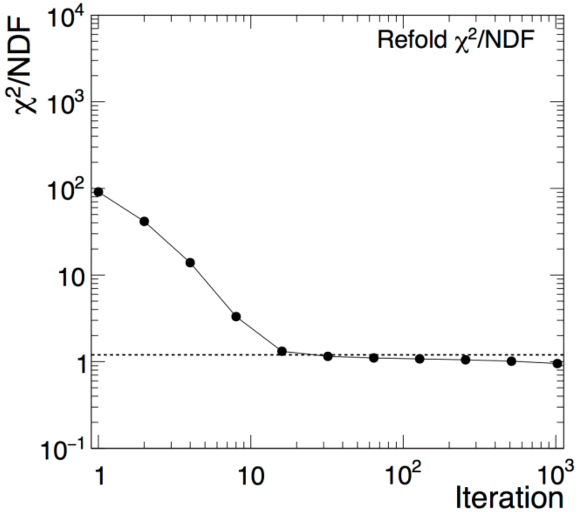

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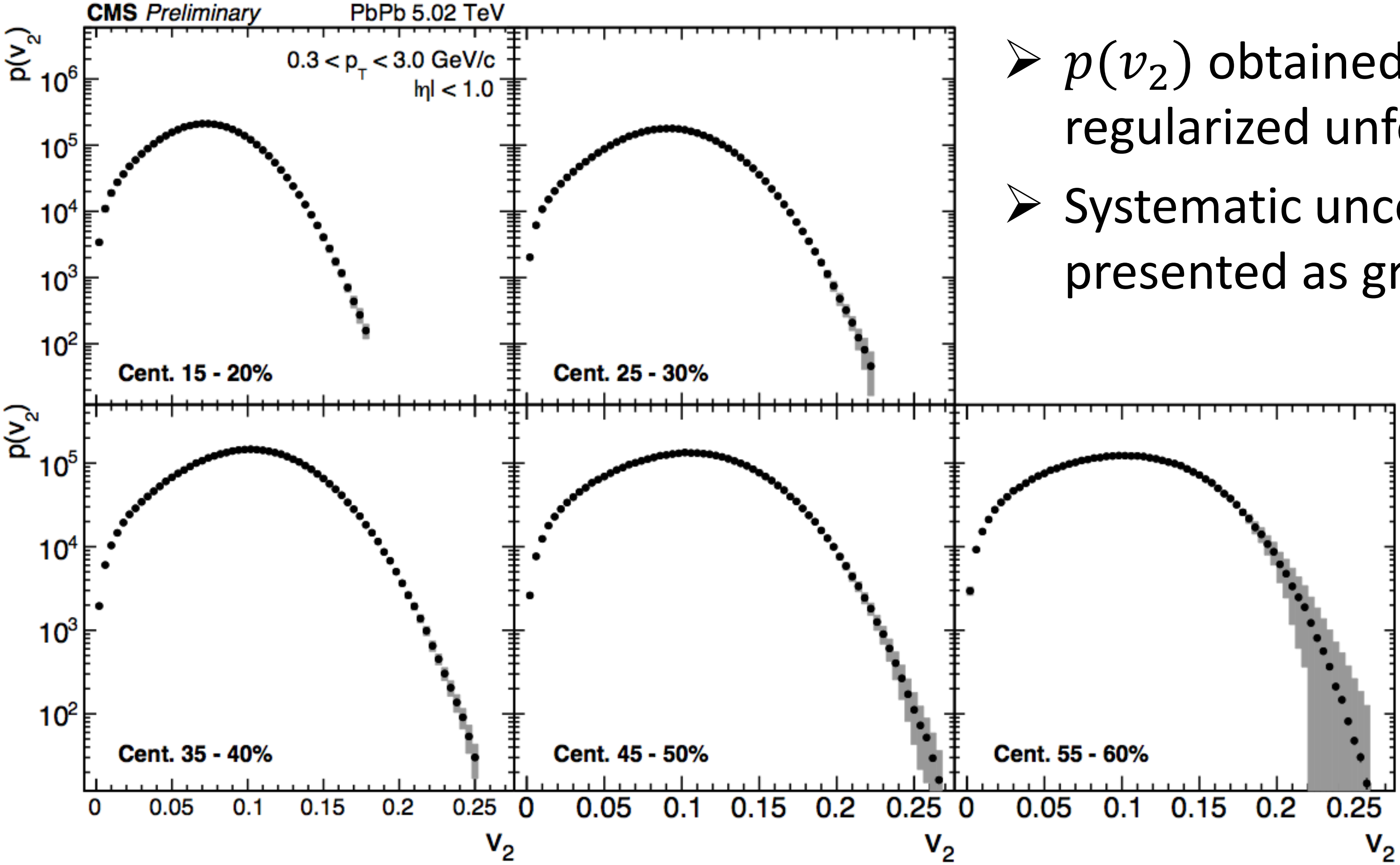
Results: $p(v_2)$ Distributions



- $p(v_2)$ obtained from regularized unfolding
- Systematic uncertainties presented as gray bands

Fluctuation Parametrization

- Elliptic power law parametrization:

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

$$p(v_n) = \frac{1}{k_n}p\left(\frac{v_n}{k_n}\right)$$

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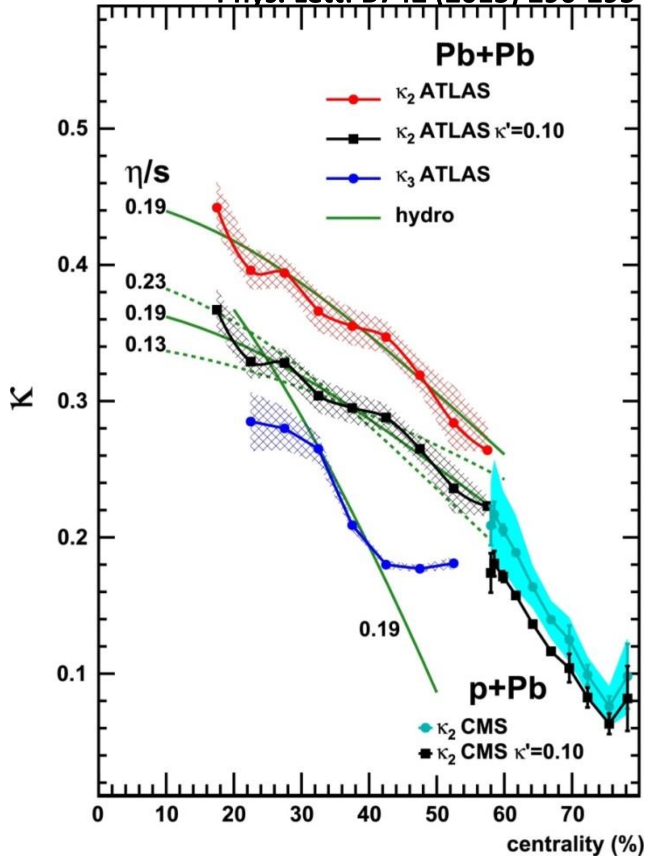
- k_n
  - Response coefficient
  - Factorizes when fluctuations are non-Gaussian

Phys. Lett. B742 (2015) 290-295



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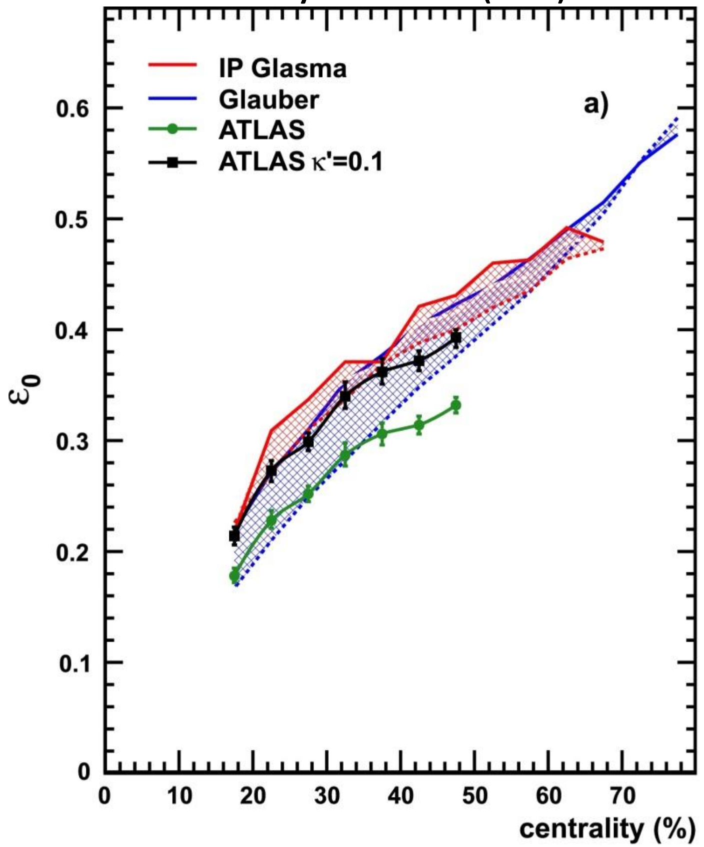

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  - Approximately equal to the mean reaction plane eccentricity

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- k_n
  - Response coefficient
  - Factorizes when fluctuations are non-Gaussian
- ε_0
  - Approximately equal to the mean reaction plane eccentricity
- α
  - Describes fluctuations magnitude

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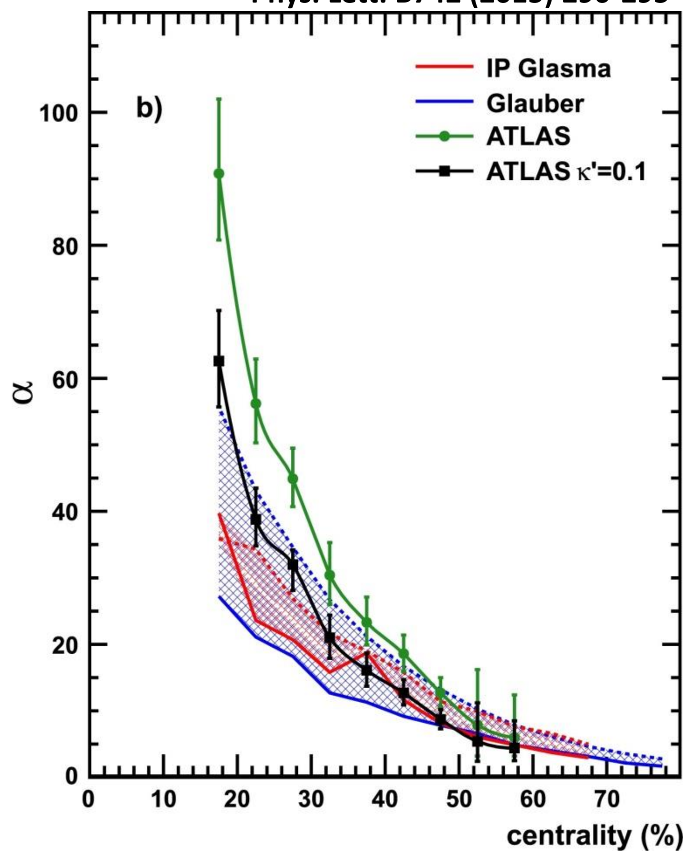
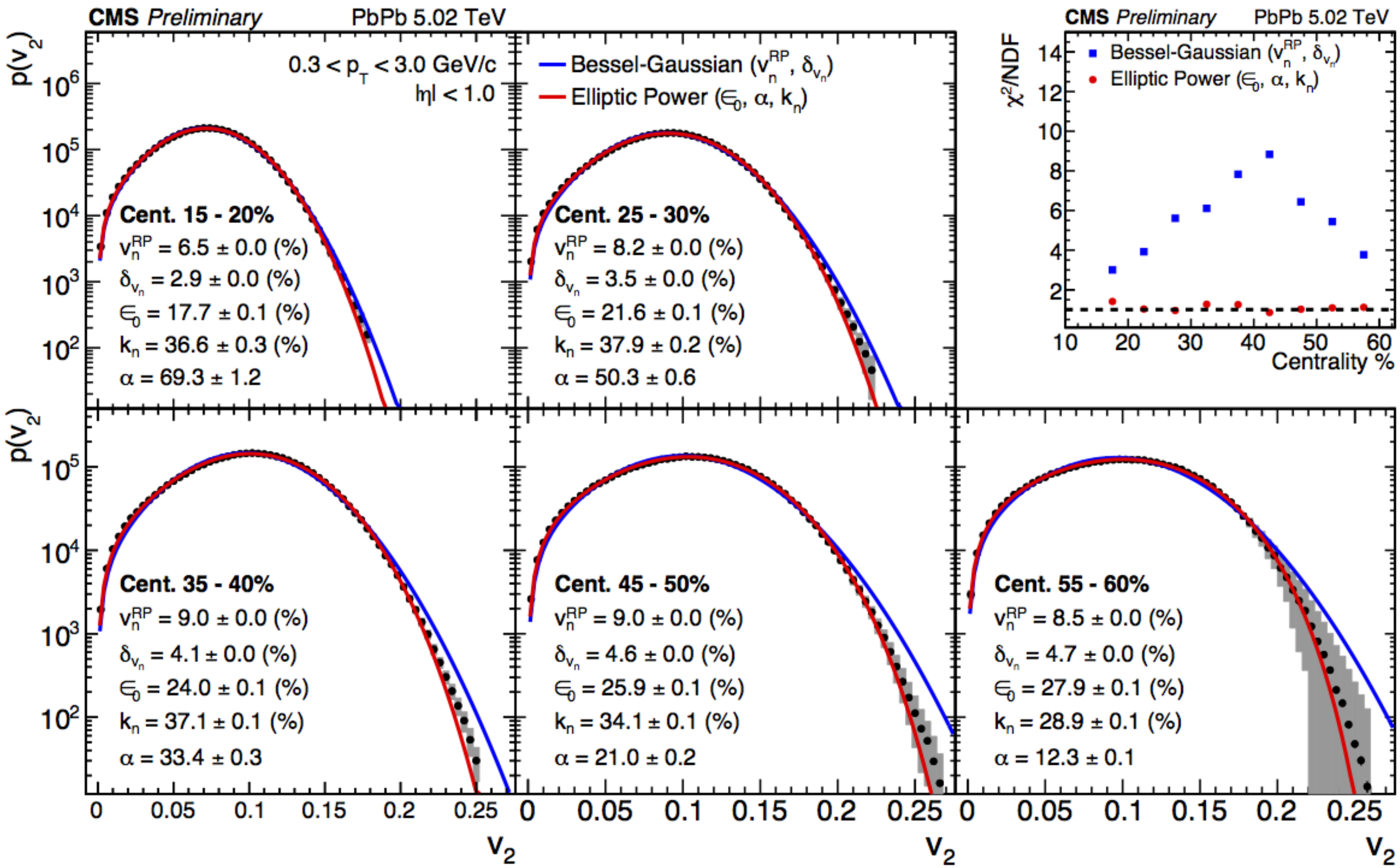
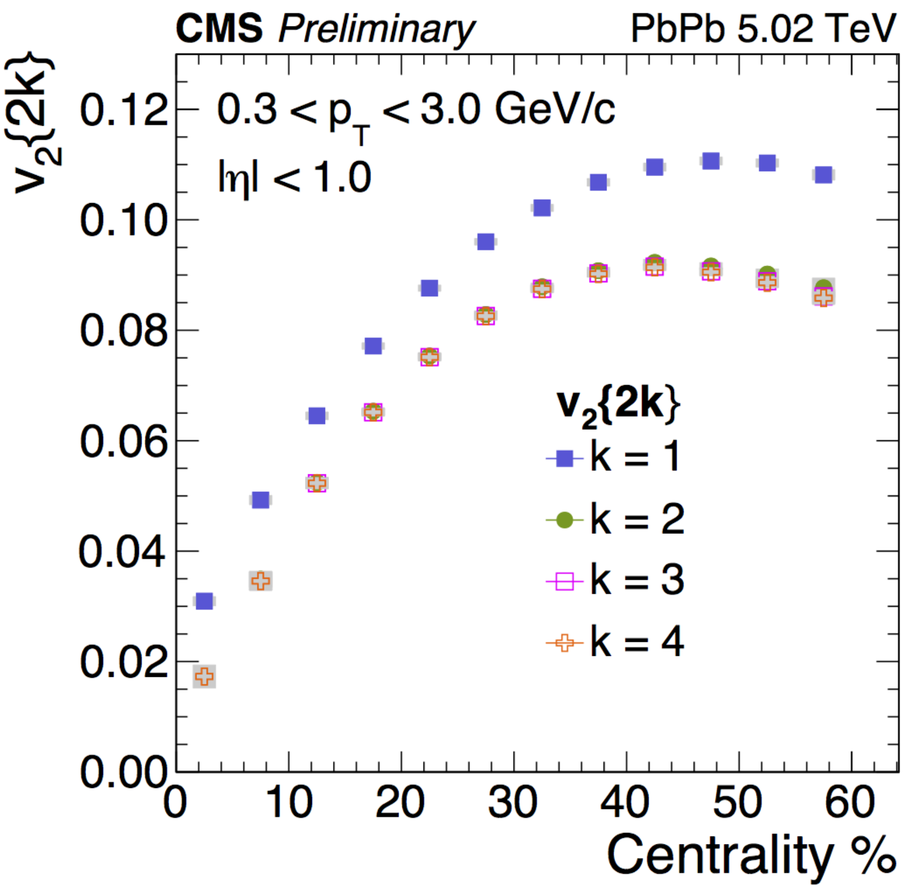


Results: Fitting $p(v_2)$ with Fluctuation Models



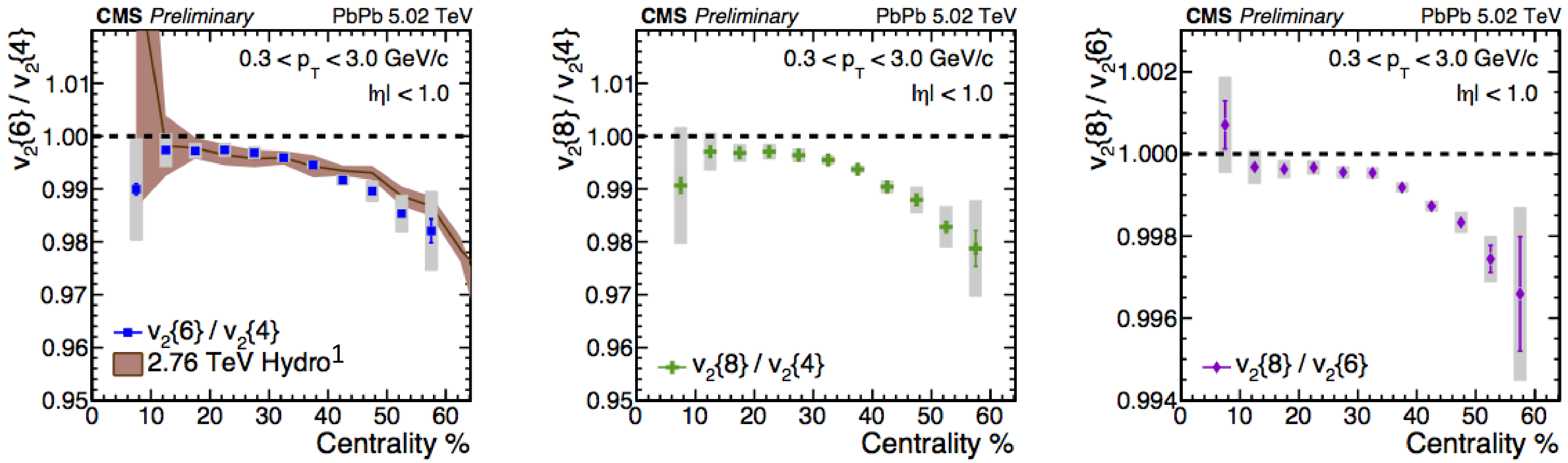
- Elliptic power parametrization consistently describes data better than Bessel-Gaussian
- Elliptic power fit allows for extraction k_n without an assumed initial-state model

Results: Cumulants



- Exhibits the expected $v_2\{2\} > v_2\{4\} \approx v_2\,\{6\} \approx v_2\,\{8\}$ behavior
- Statistical uncertainties obtained using Jackknife resampling
- Splitting of the higher-order cumulants more pronounced in peripheral events

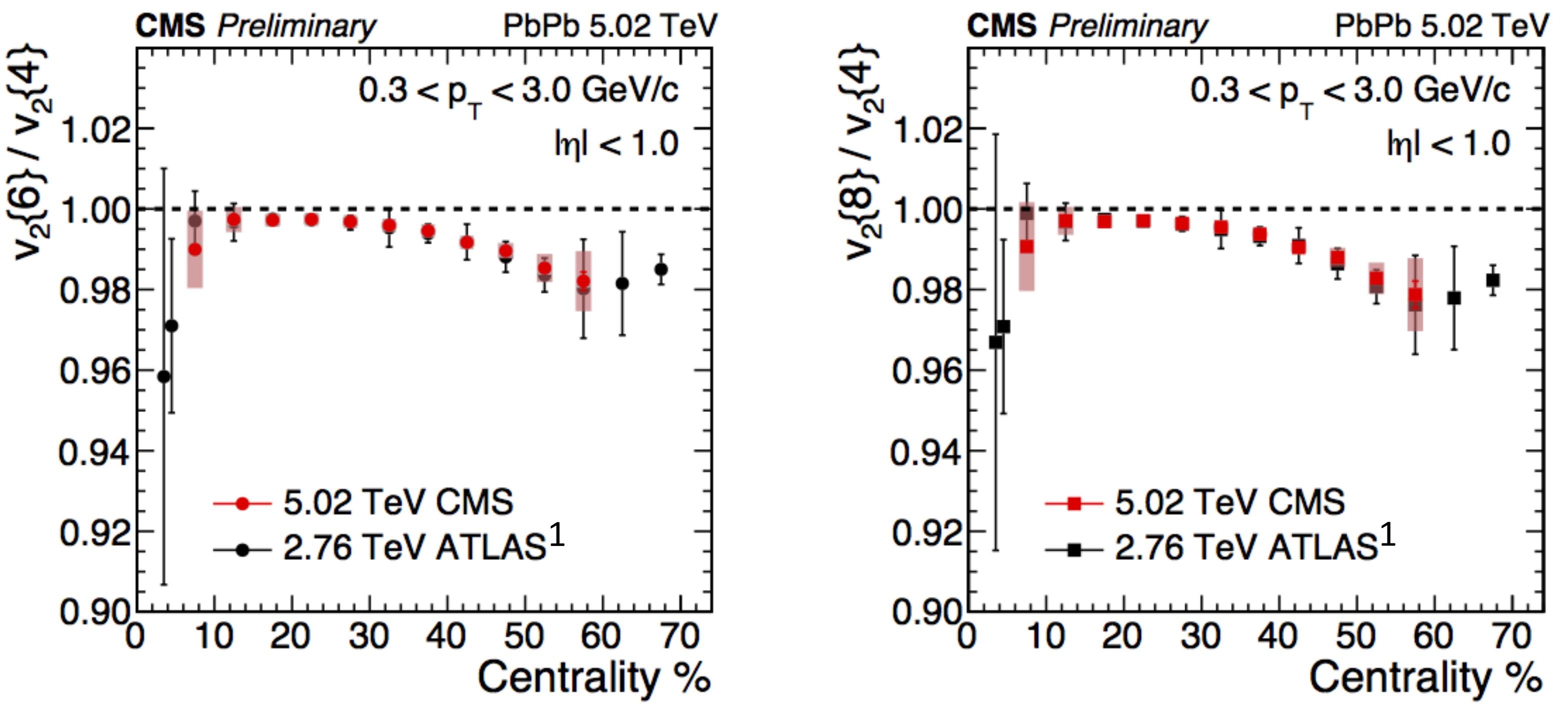
Results: Higher-Order Cumulant Ratios



- Fine-level splitting observed between higher-order cumulants
  - $v_2\{4\} > v_2\{6\} > v_2\{8\}$
- Hydrodynamic predictions[1] for 2.76 TeV consistent with 5.02 TeV measurement

[1]arXiv 1608.01823

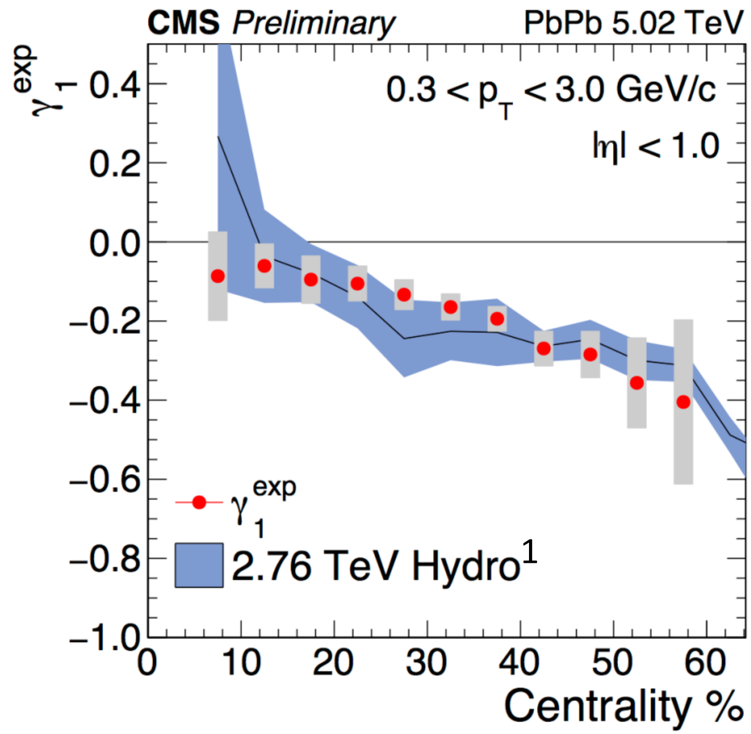
Results: Compare to Other Measurements



- ➢ Higher-order cumulant ratios consistent between 2.76 and 5.02 TeV measurements
- ➢ Suggests no strong energy dependence between 2.76 and 5.02 TeV

[1]Eur. Phys. J. C74 (2014), 3157

Results: Skewness



- $\gamma_1^{exp} = -6\sqrt{2}v_2\{4\}^2 \frac{v_2\{4\}-v_2\{6\}}{(v_2\{2\}^2-v_2\{4\}^2)^{3/2}} \approx \frac{\left\langle \left(v_2^{RP}-\langle v_2^{RP}\rangle\right)^3\right\rangle}{\left(\sqrt{\left\langle \left(v_2^{RP}\right)^2\right\rangle-\langle v_2^{RP}\rangle^2}\right)^3}$
- Hydrodynamic predictions[1] for 2.76 TeV consistent with 5.02 TeV measurement

[1]arXiv 1608.01823

Summary

- By measuring $p(v_2)$ we have observed
  - $v_2\{4\} > v_2\{6\} > v_2\{8\}$
  - Skewness is negative
  - $p(v_2)$ described well by the elliptic power law parametrization
    - Allows for extraction of initial anisotropy and response coefficient without an assumed model of initial state
    - Bessel-Gaussian fails because it does not incorporate $|\varepsilon_n| \leq 1$ constraint