Measurement of event-by event v_n in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV with the ATLAS detector

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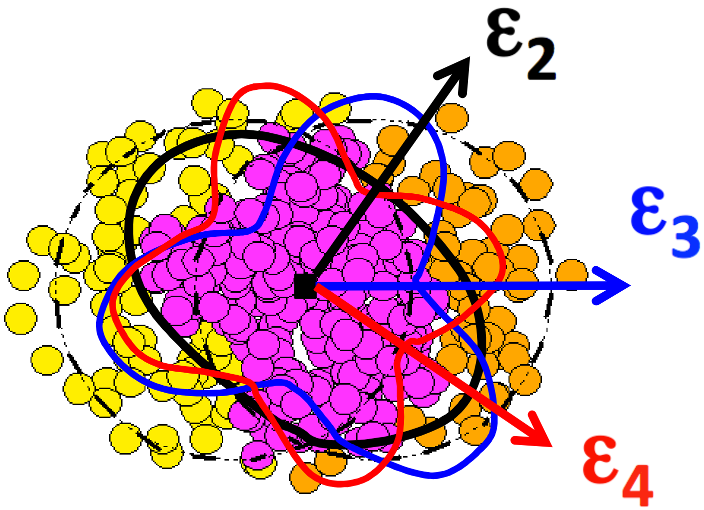
for the **ATLAS** Collaboration

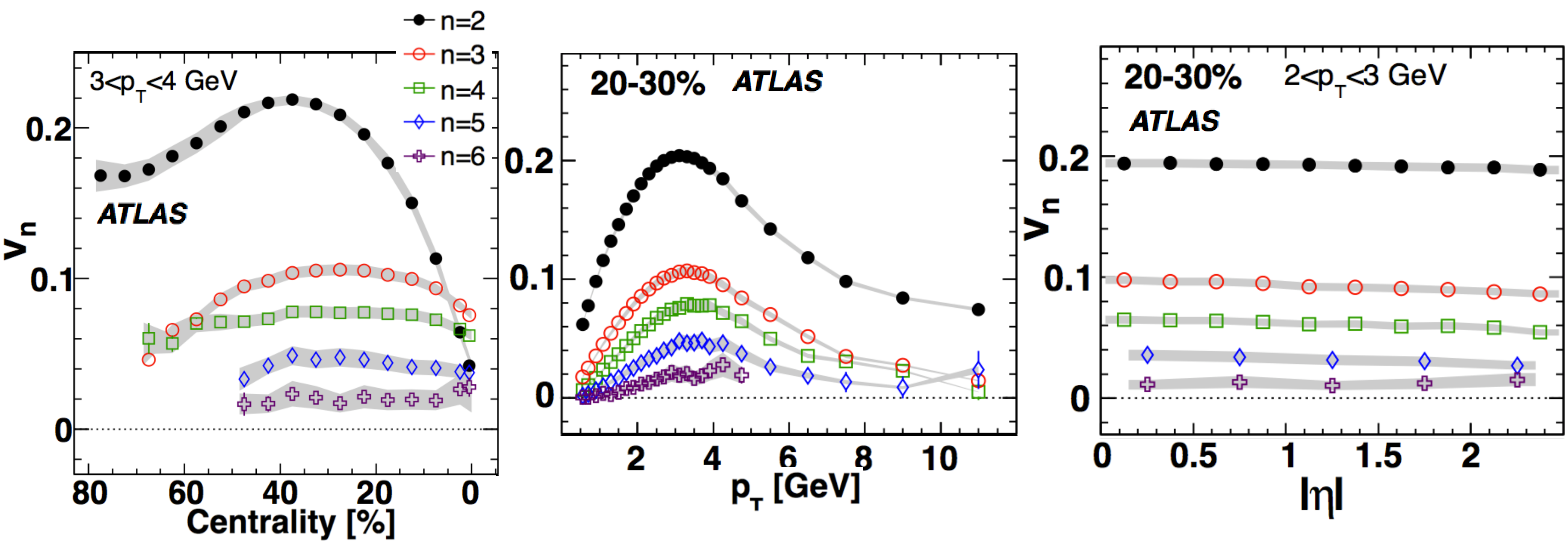
- Event by event measurement of v_n distributions: ATLAS-CONF-2012-114
- ATLAS event-Plane Correlation Note: ATLAS-CONF-2012-049

Hot Quarks 2012
14-21 October 2012

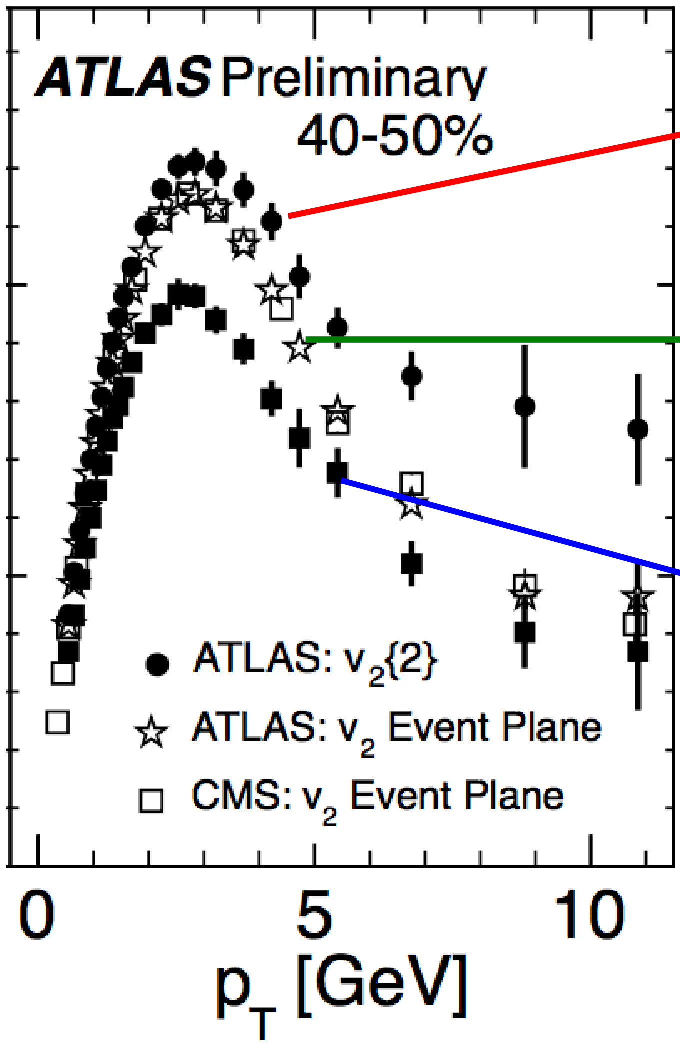
Flow harmonics



$$\frac{dN}{d\phi} \propto 1 + \sum_n 2\mathrm{v}_n \cos n(\phi - \Phi_n)$$



The importance of fluctuations



Two-particle cumulant ~ $\sqrt{\langle v_2\rangle^2+\sigma^2}$

EP Method in between $\langle v_2\rangle$ and $\sqrt{\langle v_2\rangle^2+\sigma^2}$

Four-particle cumulant ~ $\sqrt{\langle v_2\rangle^2-\sigma^2}$

Measuring the full distribution of EbE v_n distribution completely supercedes these measurements.

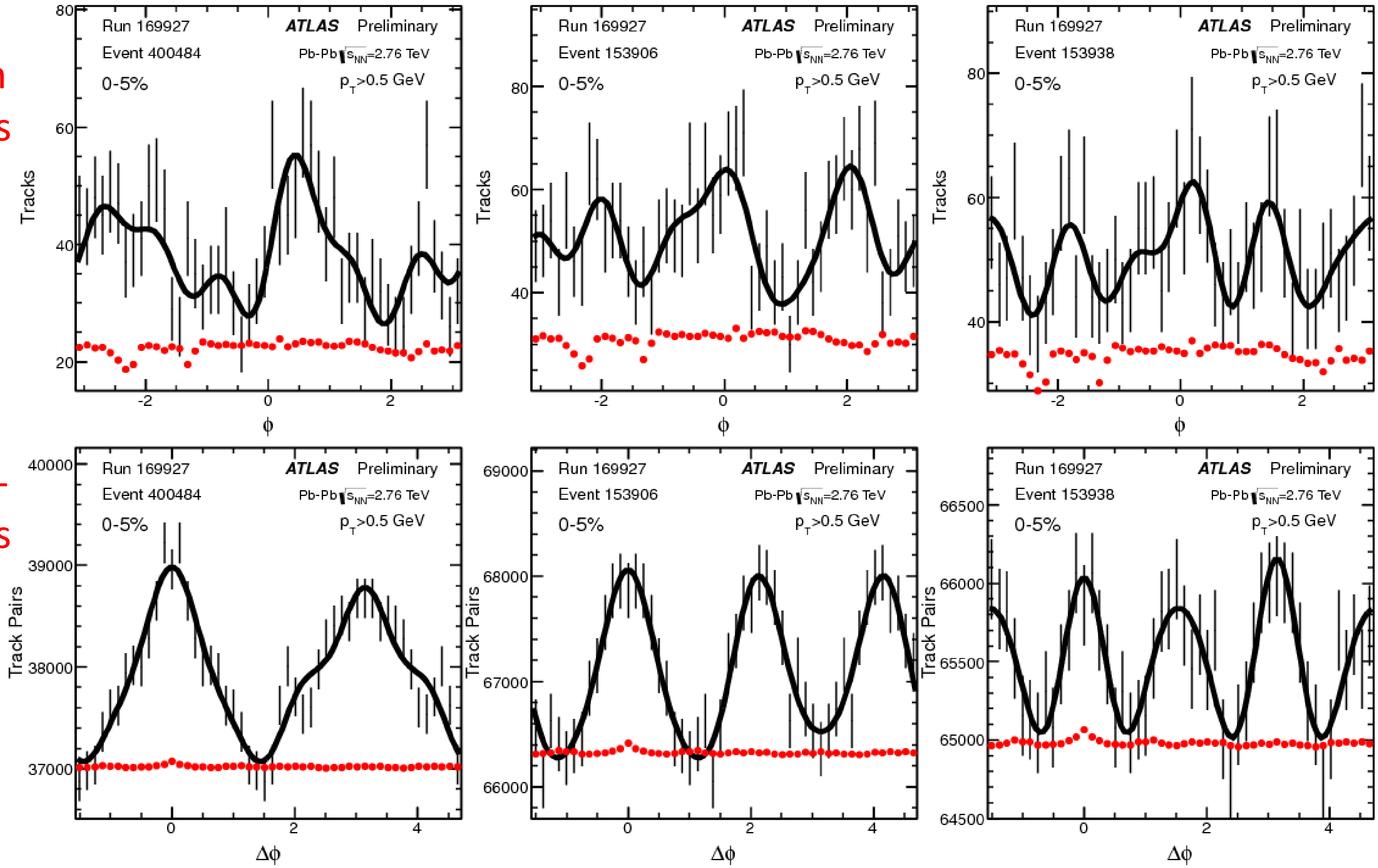
Not only do we get the $\langle v_n\rangle$ and σ but also the full shape of the distribution.

Large amount of information regarding the initial geometry and hydrodynamic expansion.

Event by Event flow measurements

Track distribution in three central events

Corresponding two-particle correlations



The large acceptance of the ATLAS detector and large multiplicity at LHC makes EbE v_n measurements possible for the first time.

Azimuthal distribution in single event

- Ideal detector:

$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1} v_n \cos(n\phi - n\Psi_n) = 1 + \sum_{n=1} \left(v_{n,x} \cos(n\phi) + v_{n,y} \sin(n\phi) \right)$$

$$v_{n,x} = \langle \cos(n\phi) \rangle, \quad v_{n,y} = \langle \sin(n\phi) \rangle$$

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

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- Correct for acceptance:

$$v_{n,x} \rightarrow v_{n,x} - v_{n,x}^{\text{det}}$$

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- Correct for acceptance:

$$v_{n,x} \rightarrow v_{n,x} - v_{n,x}^{\det}$$

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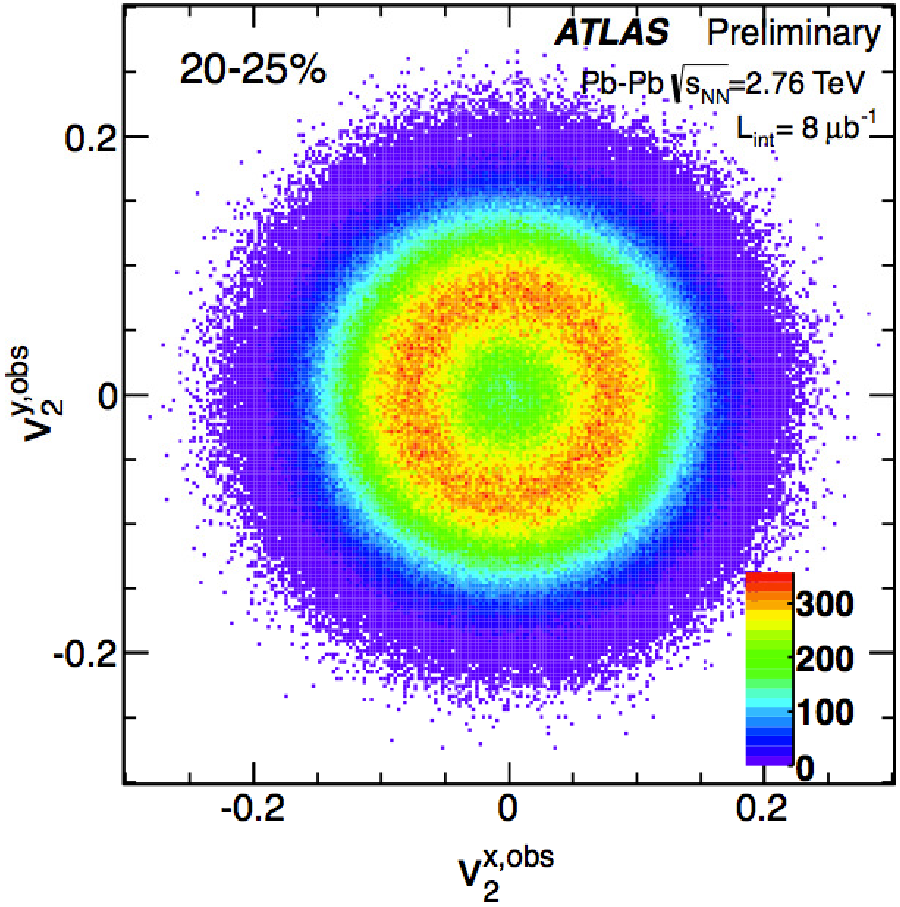
- Correct for efficiency by weighting tracks by $\frac{1}{\varepsilon(\eta, \mathrm{p_T})}$

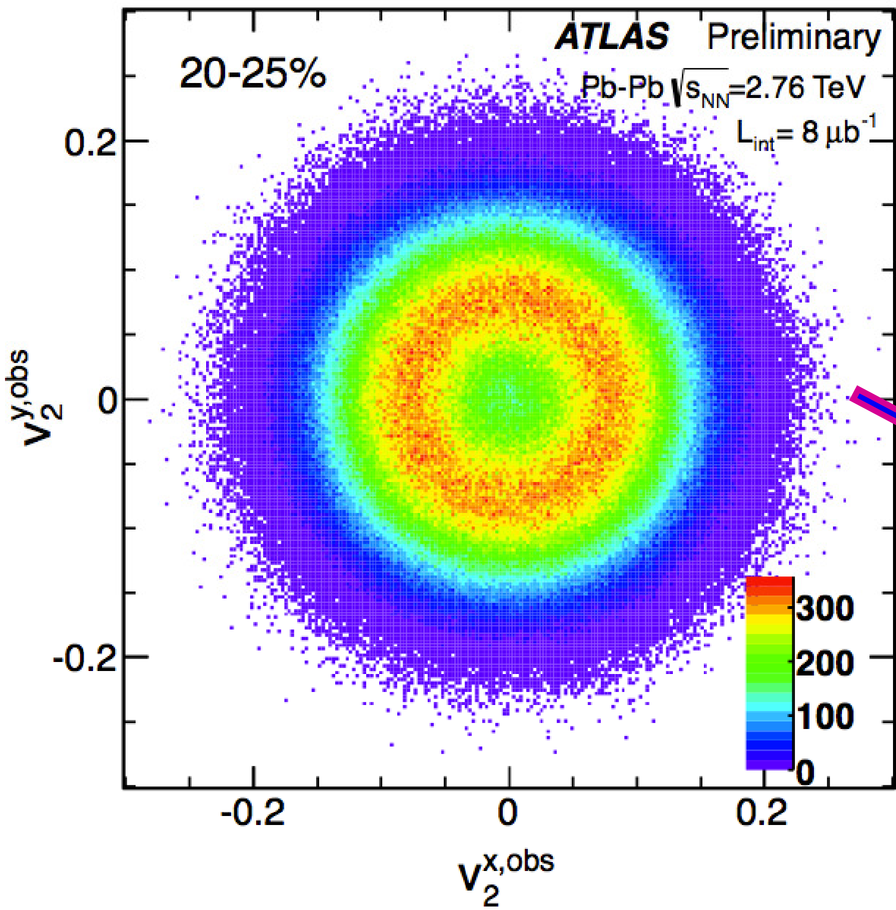
Flow vector distribution & smearing



2D flow vector distribution

$$v_{n,x} = \langle \cos(n\phi) \rangle, \quad v_{n,y} = \langle \sin(n\phi) \rangle$$

Flow vector distribution & smearing



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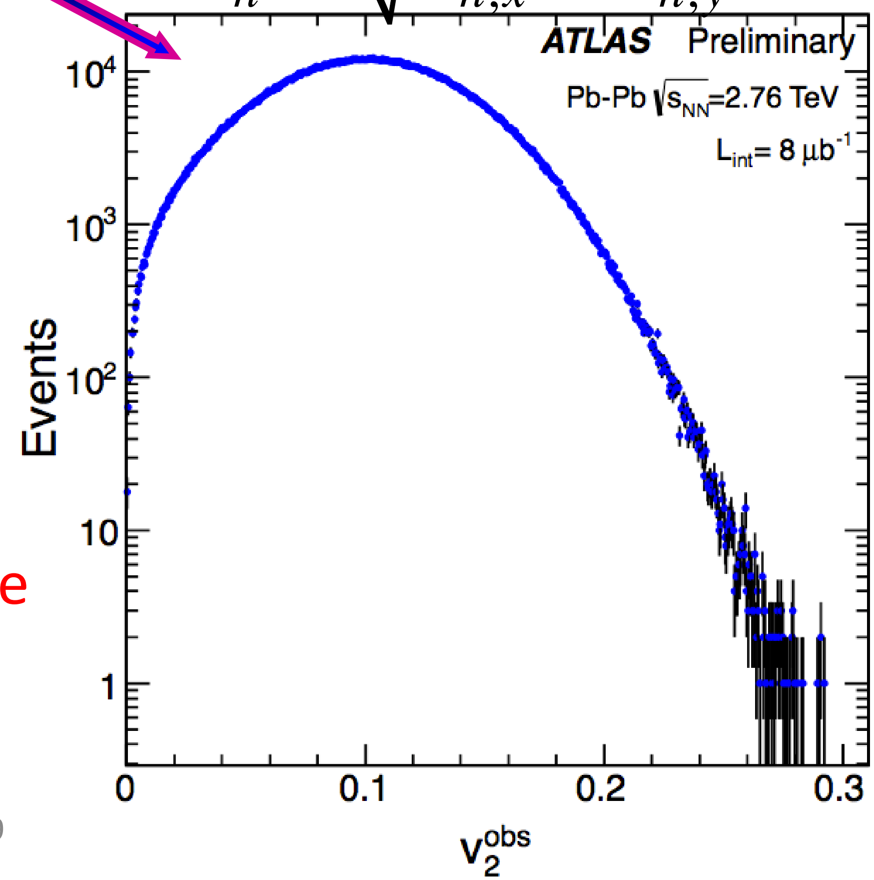
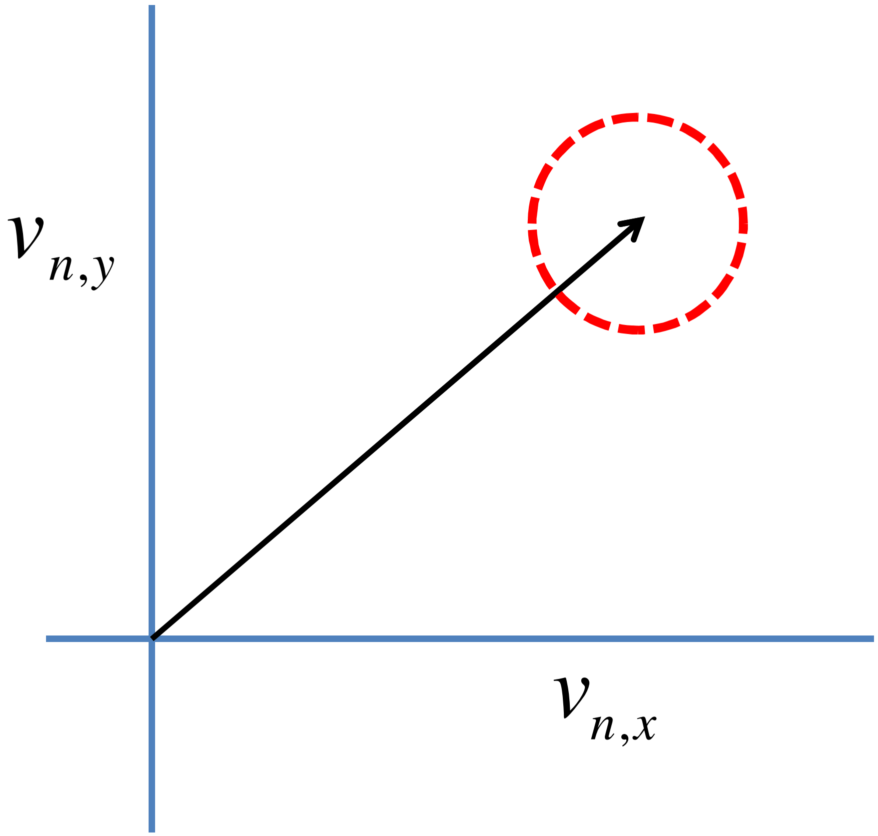


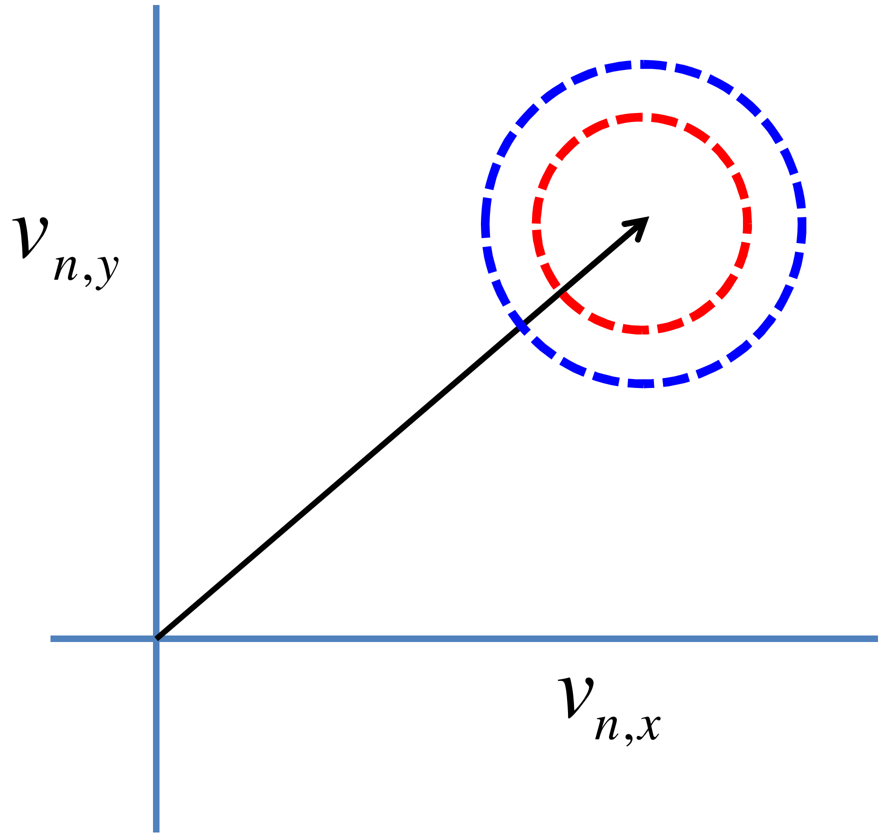
The v_2^{obs} will differ from the true v_2 due to finite multiplicity in the events

Determining response function



- The measured v_n vector will fluctuate about the true vector due to finite number of tracks
- The fluctuation will be a 2D Gaussian
- Response function will be known if the width of the Gaussian fluctuation can be determined

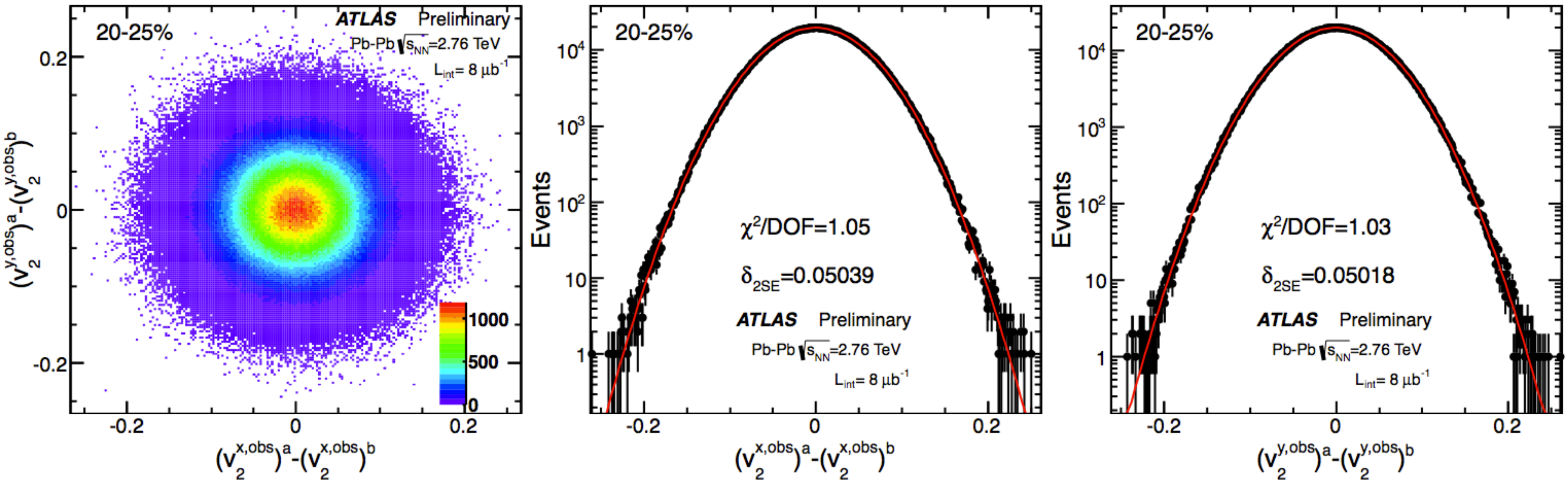
Determining response function



- Divide the event into two sub-events with roughly equal number of tracks
- The fluctuation in each sub-event will be √2 times larger than the full event
- If we take difference between the flow vectors for the two sub-events, the signal will cancel and we will get the size of the fluctuation

Determining response function

- Estimated by the correlation between "**symmetric**" subevents



- 2D response function is a 2D Gaussian!

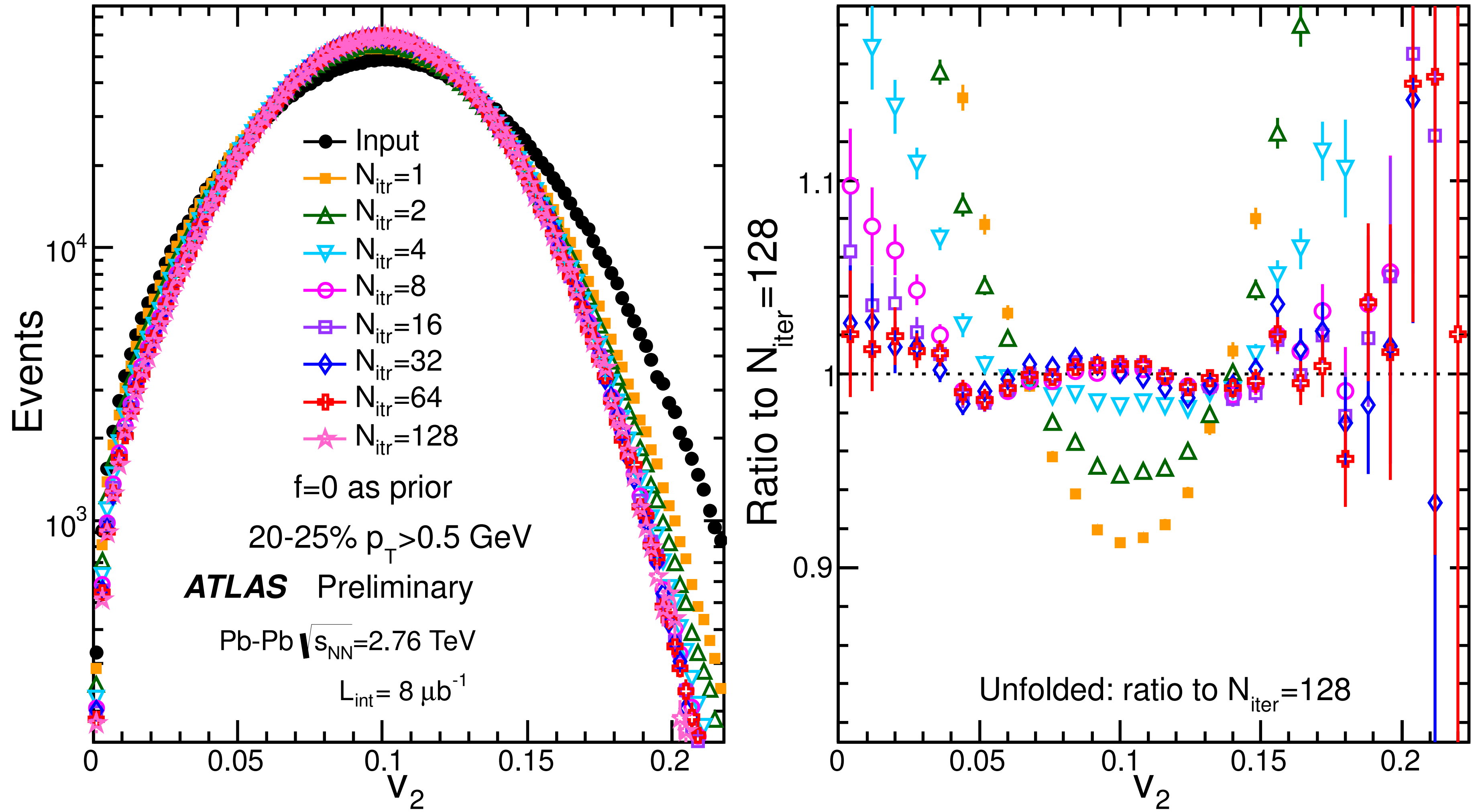
$$p(\vec{v}_n^{\rm obs}|\vec{v}_n) \propto e^{-\frac{|\vec{v}_n^{\rm obs}-\vec{v}_n|^2}{2\delta^2}} \quad \delta = \begin{cases} \delta_{\rm 2SE}/\sqrt{2} & \text{for half ID} \\ \delta_{\rm 2SE}/2 & \text{for full ID} \end{cases}$$

- Response function obtained by integrating out azimuth angle

$$p(v_n^{\rm obs}|v_n) \propto v_n^{\rm obs} e^{-\frac{(v_n^{\rm obs})^2+v_n^2}{2\delta^2}} I_0\left(\frac{v_n^{\rm obs} v_n}{\delta^2}\right)$$

- Use Bayesian unfolding to correct measured v_n distributions

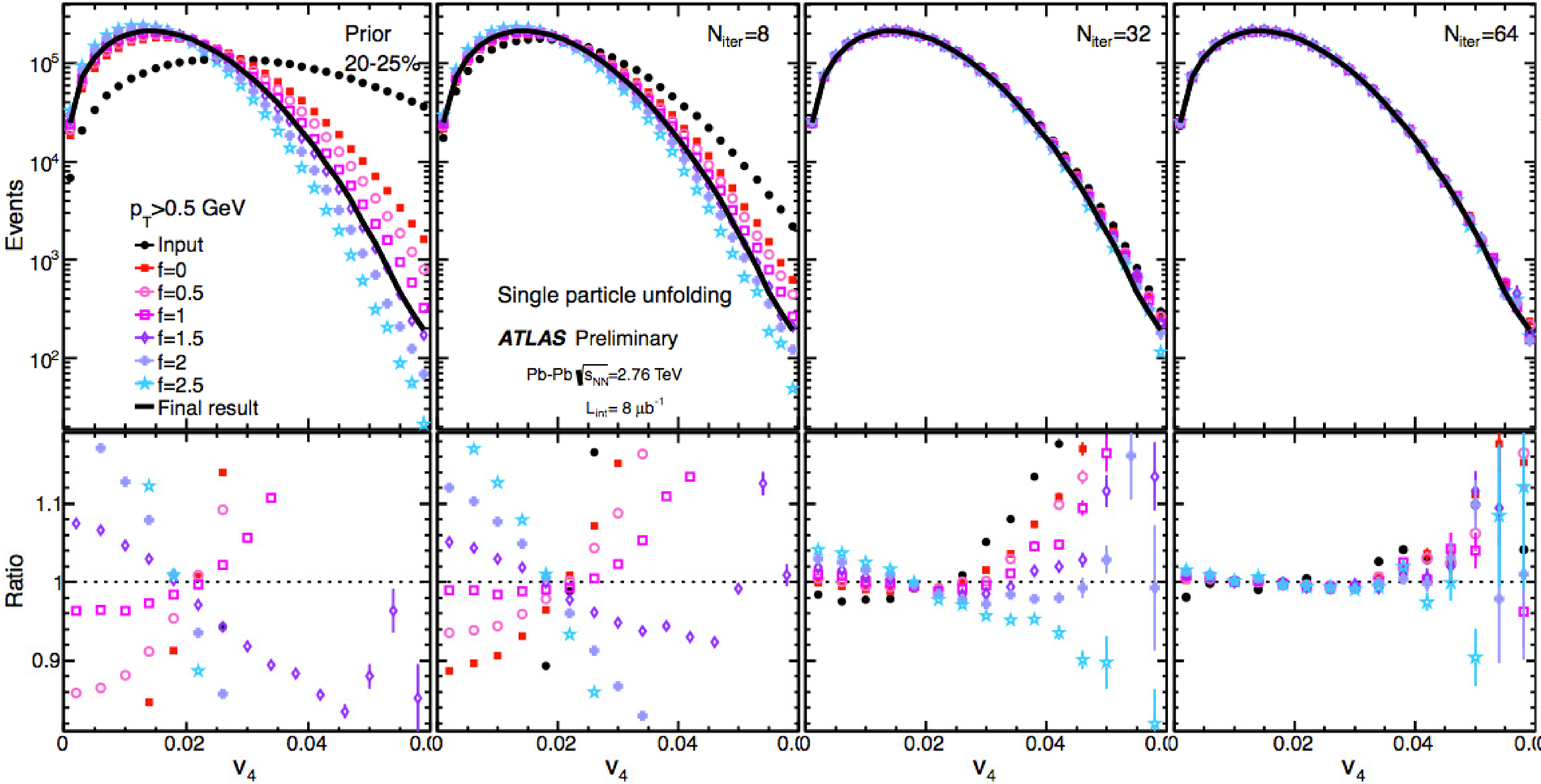
Basic unfolding performance: v_2, 20-25% [13]



v_2 converges within a few % for N_{iter}=8

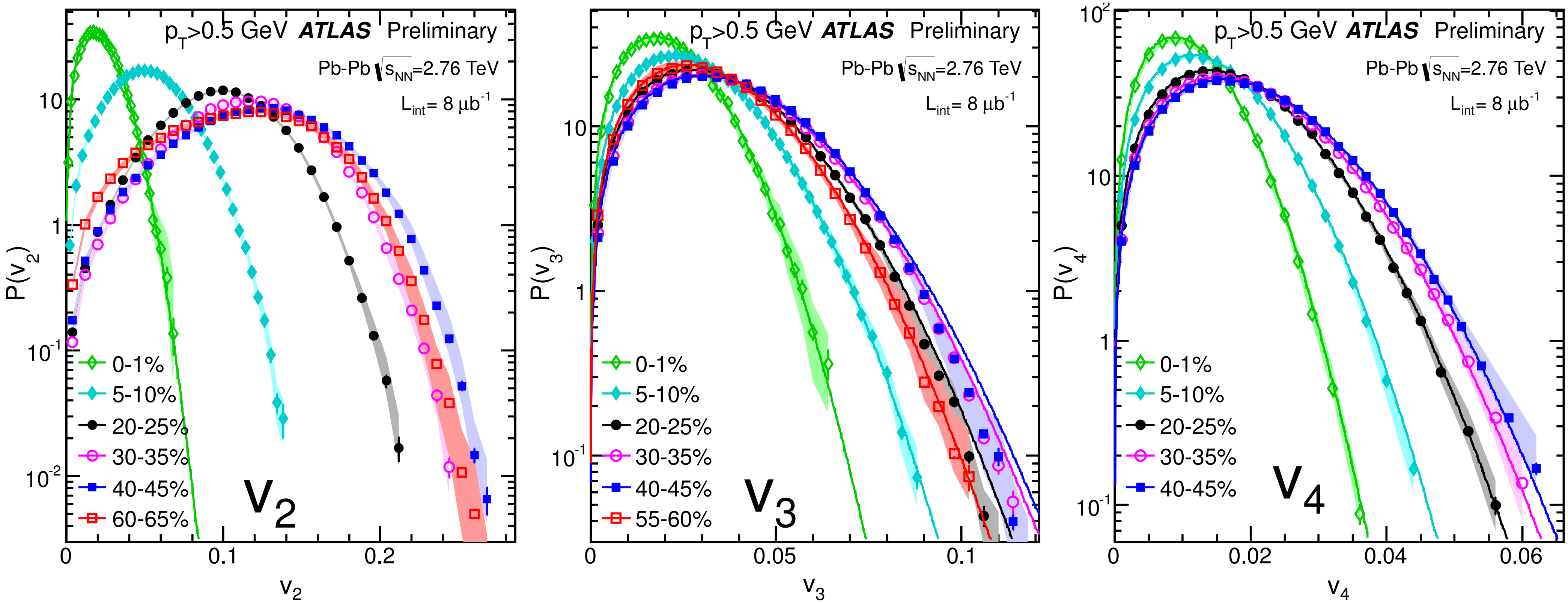
small improvements for larger N_{iter}.

Dependence on prior: v_4 20-25%



- Despite different initial distribution, all converge for N_{iter}=64
- Wide prior converges from above, narrow prior converges from below.

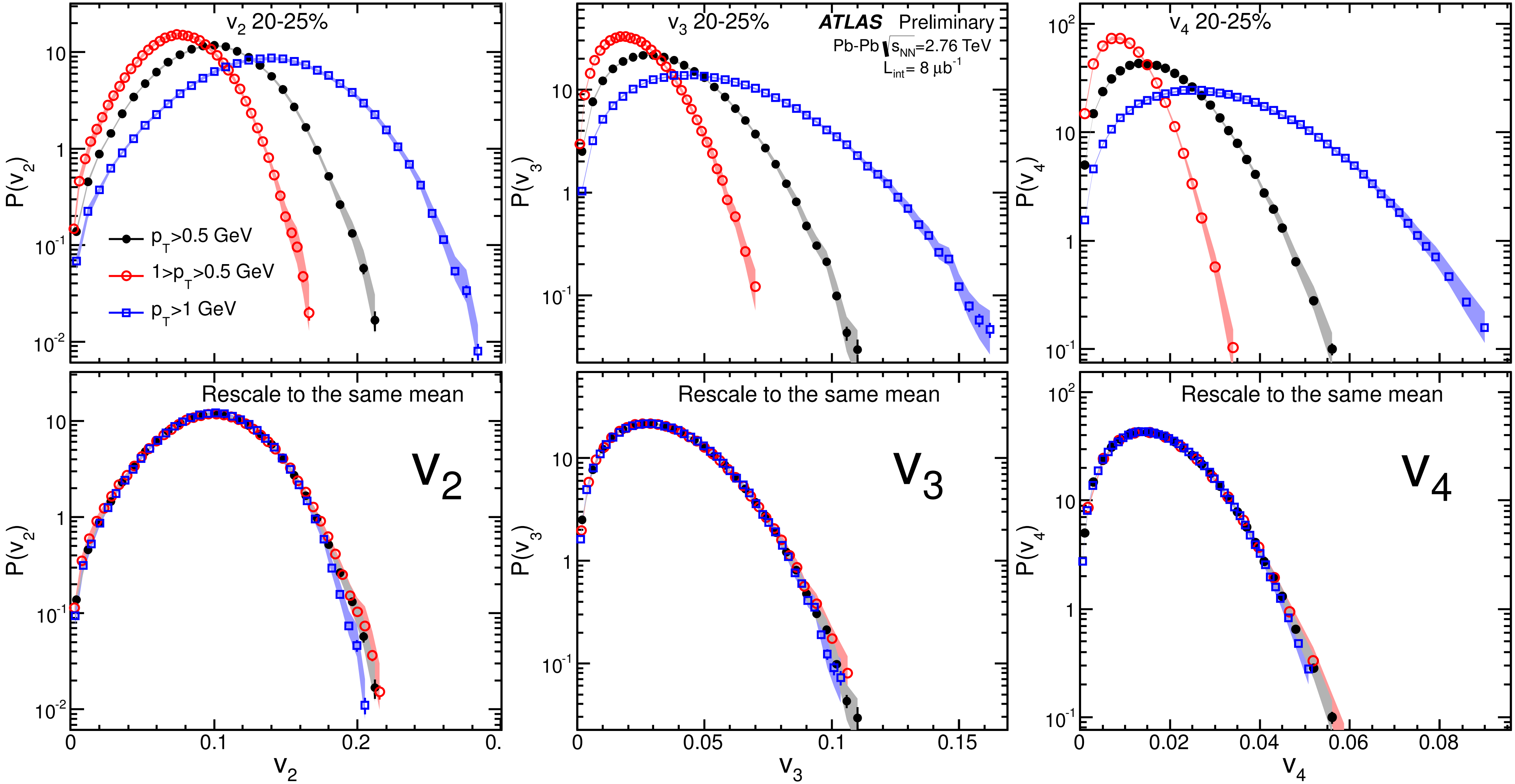
v_2-v_4 probability distributions



Main physics result: probability distributions of EbE v_n

for gaussian distributions: $p(v_n) = \frac{v_n}{\sigma} e^{-v_n^2/2\sigma^2}$, $\sigma = \sqrt{\frac{2}{\pi}} \langle v_n \rangle$

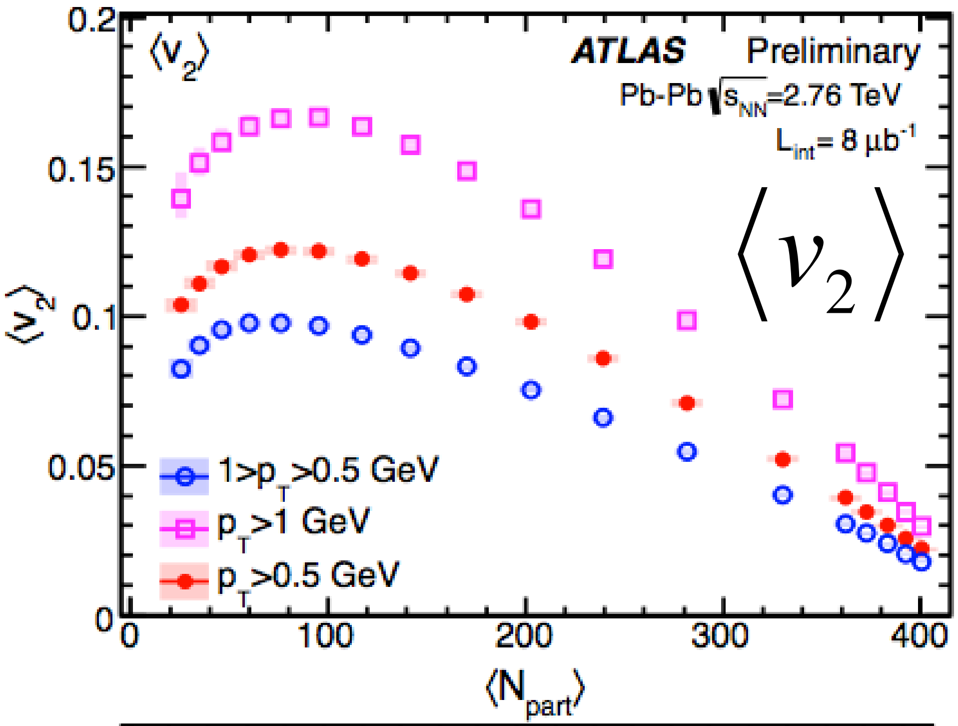
Unfolding in different p_T ranges: 20-25%

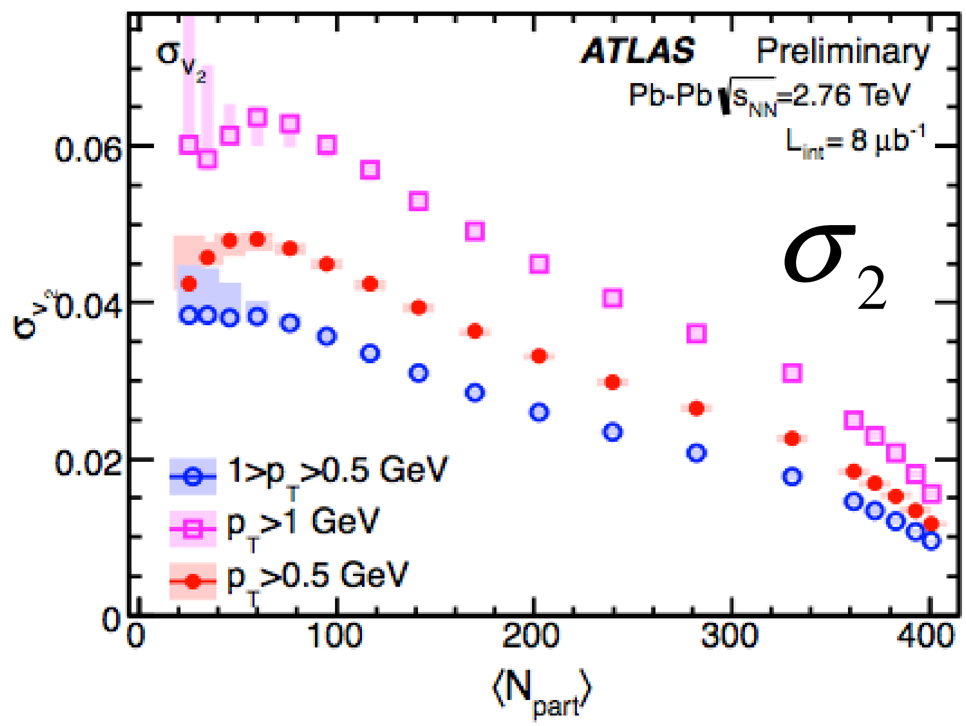


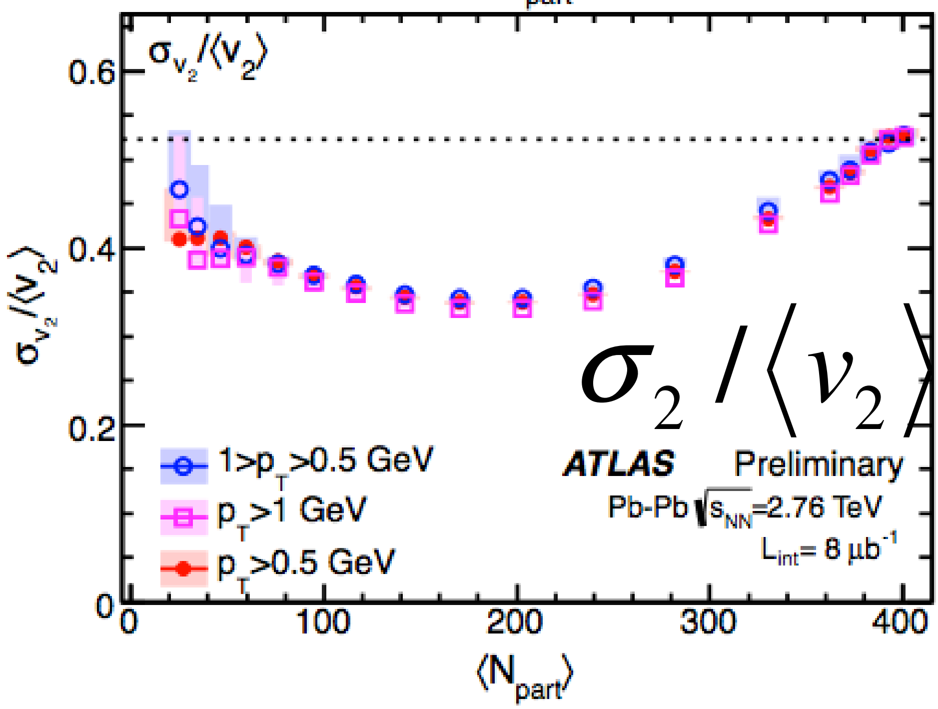
Distributions for higher p_T bin is broader, but they all have ~same reduced shape

Hydrodynamic response ~ independent of p_T.

Comparison to Event-plane v_n values







for gaussian fluctuations : $\sigma_n / \langle v_n \rangle \approx 0.523$

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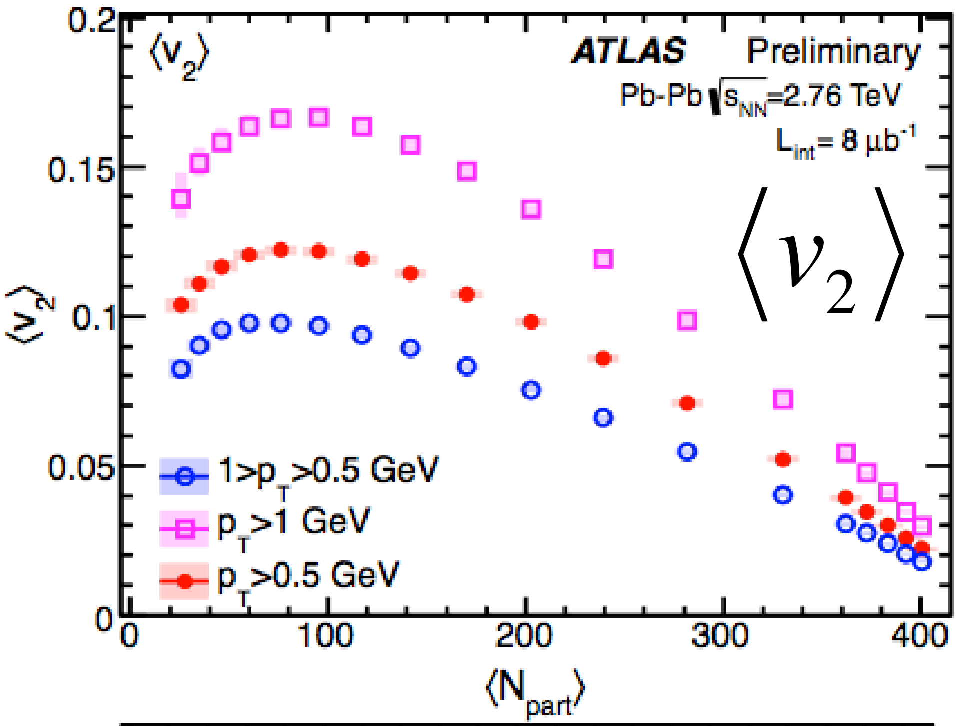

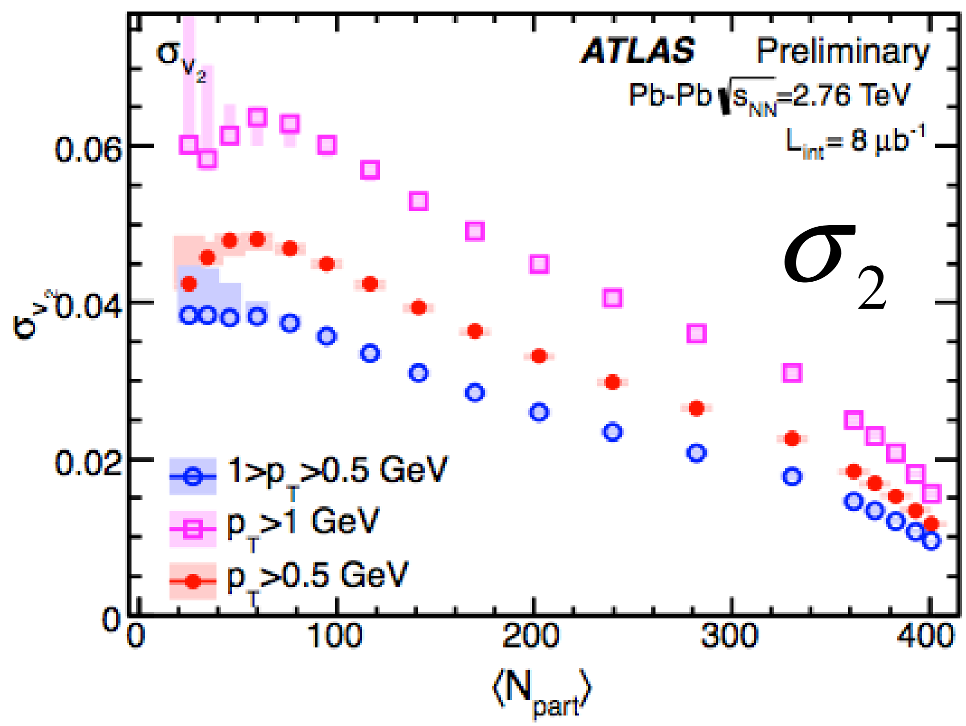

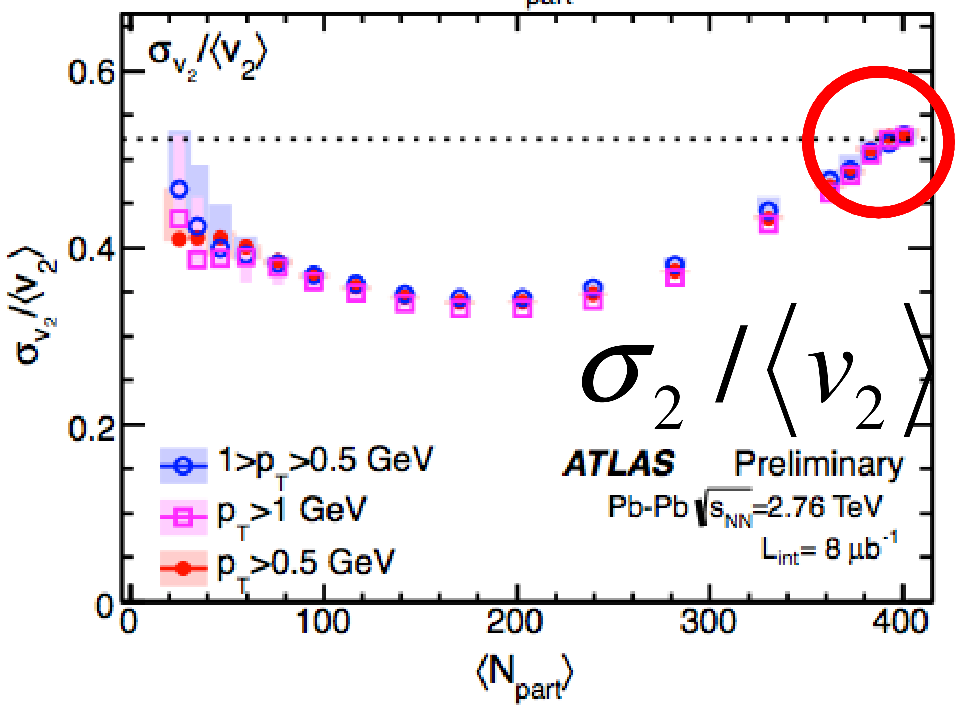

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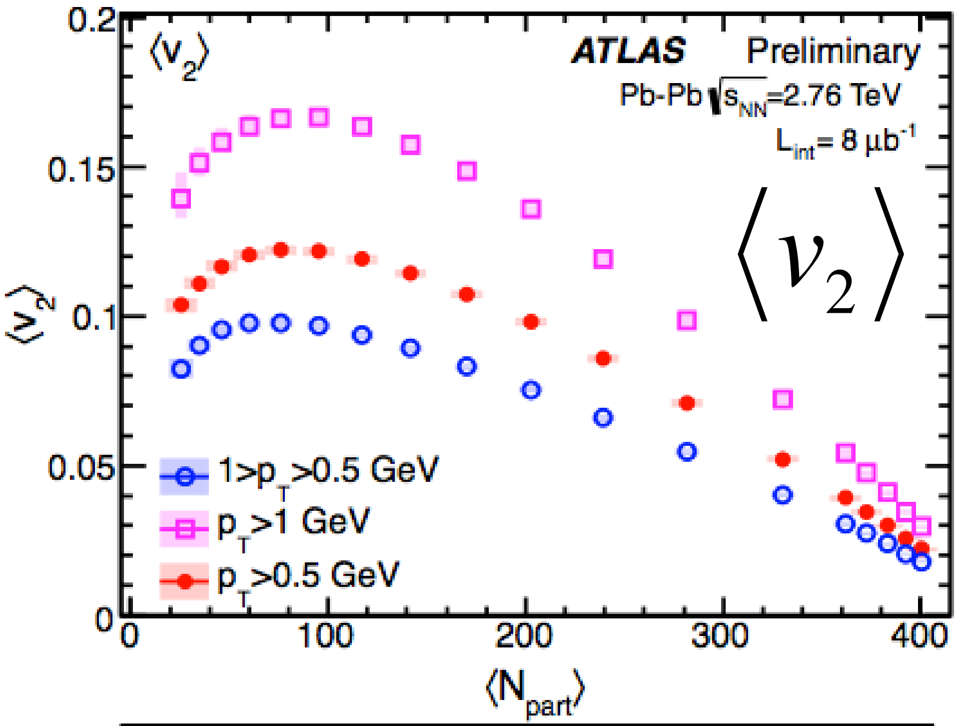

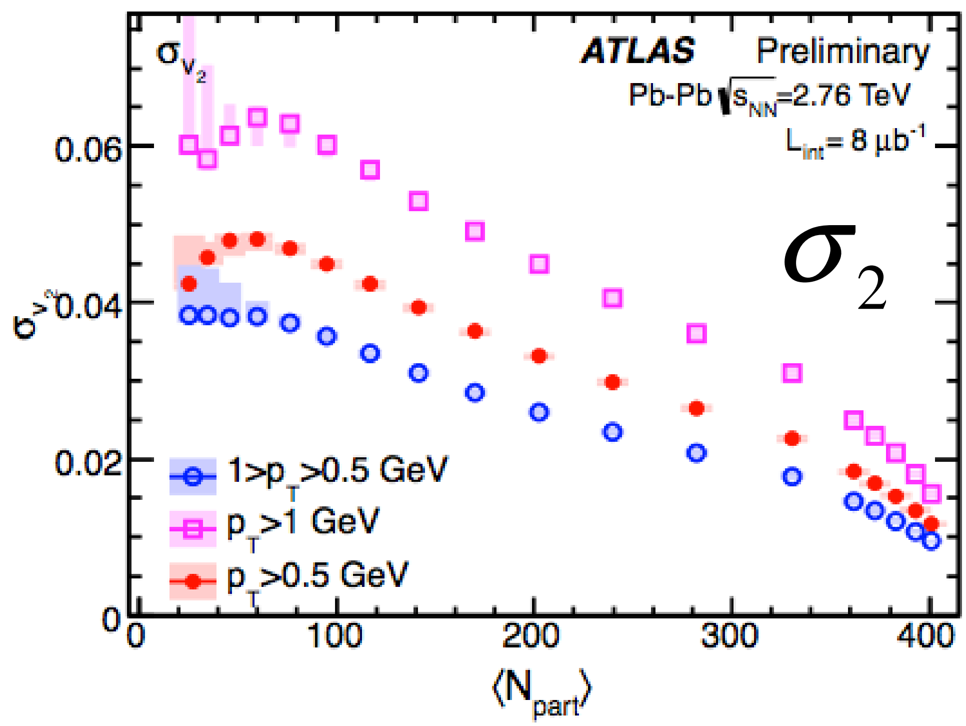

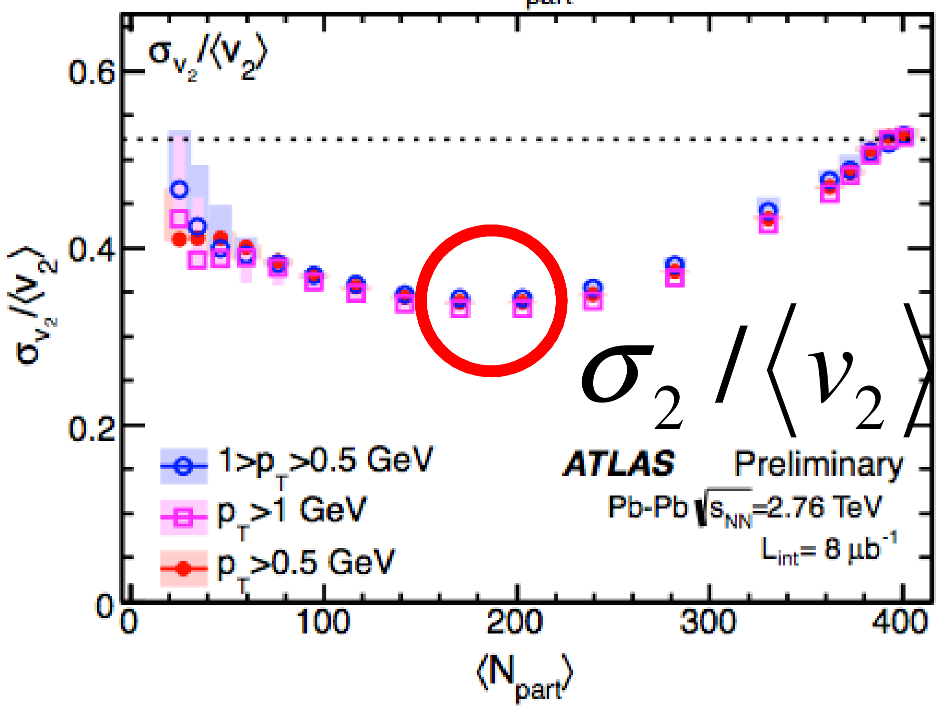

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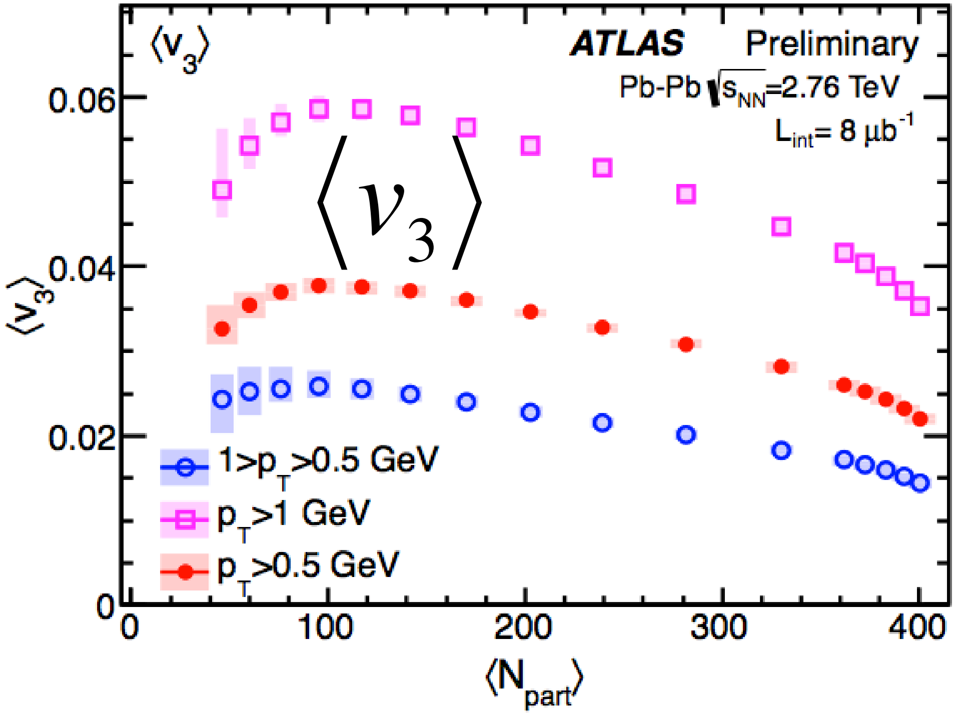

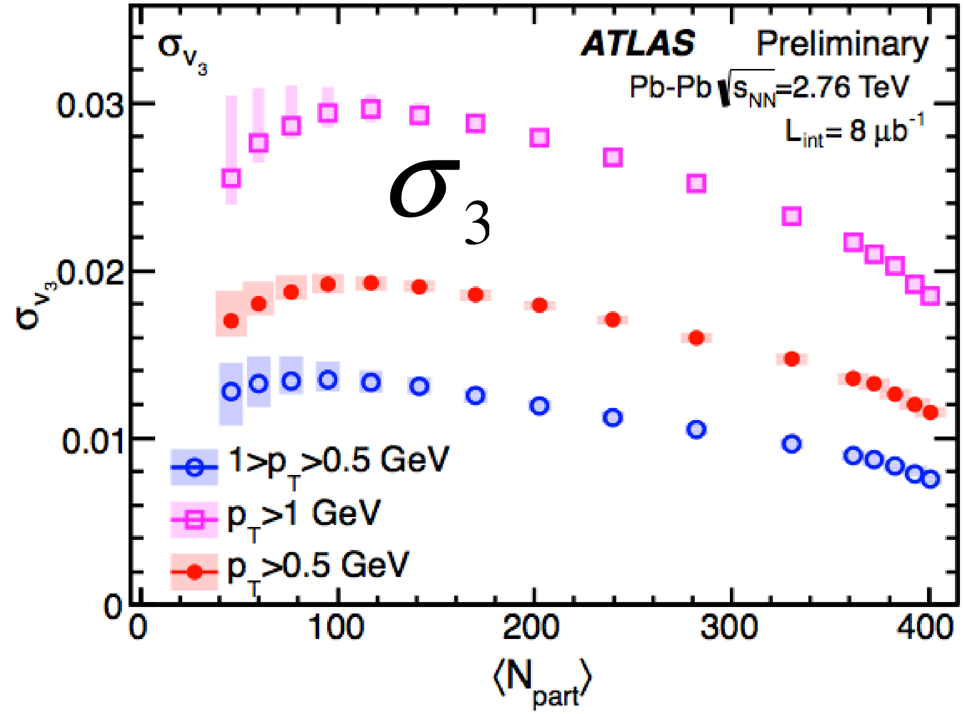

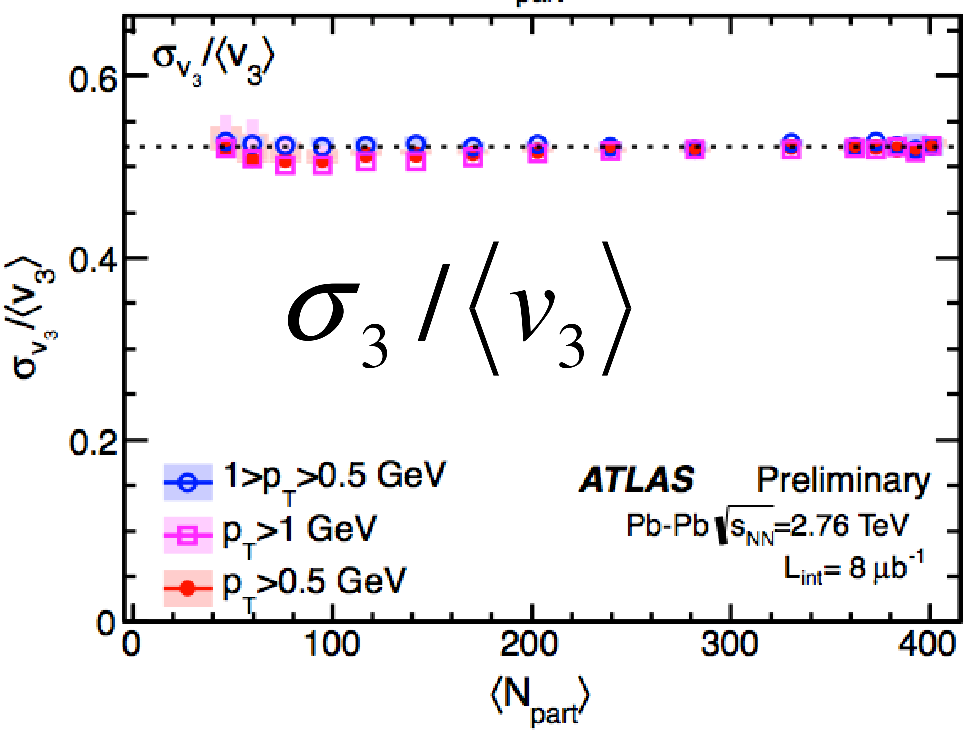

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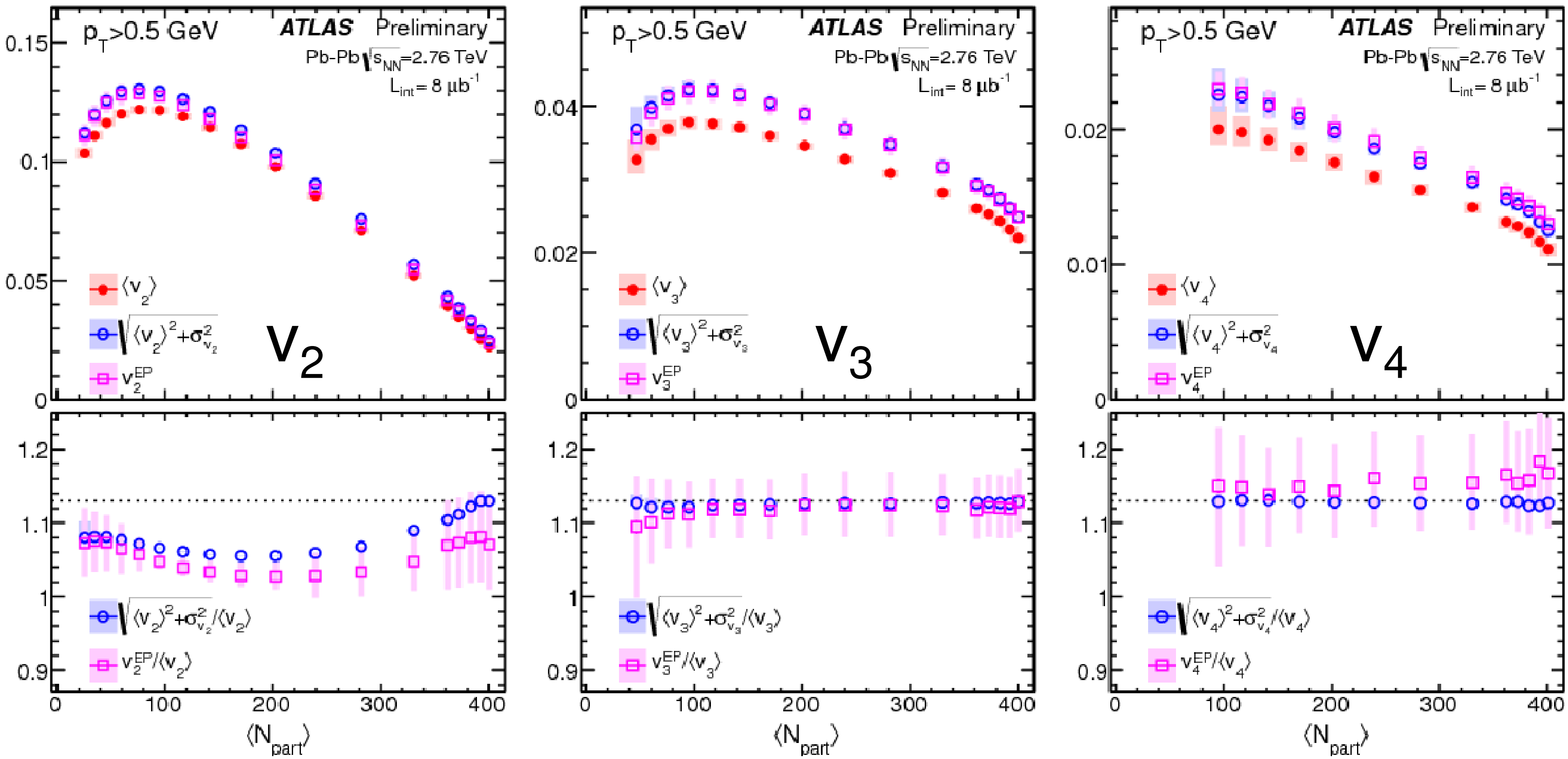
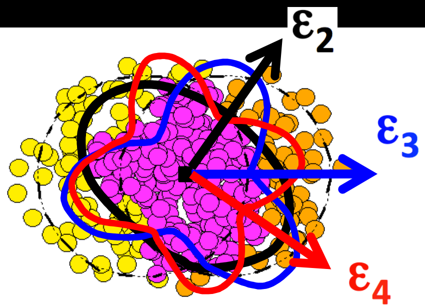
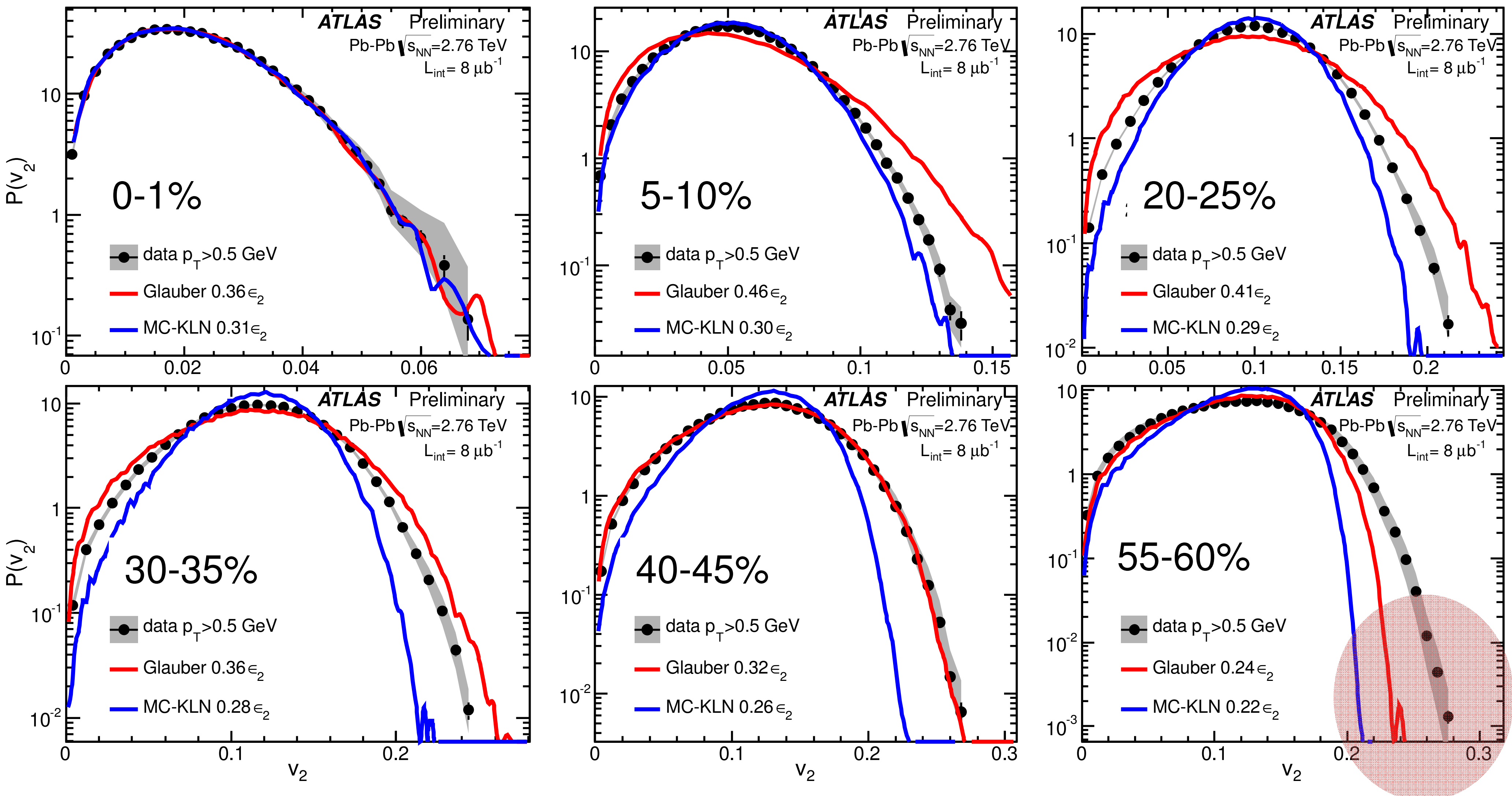


Measuring the hydrodynamic response: v_2



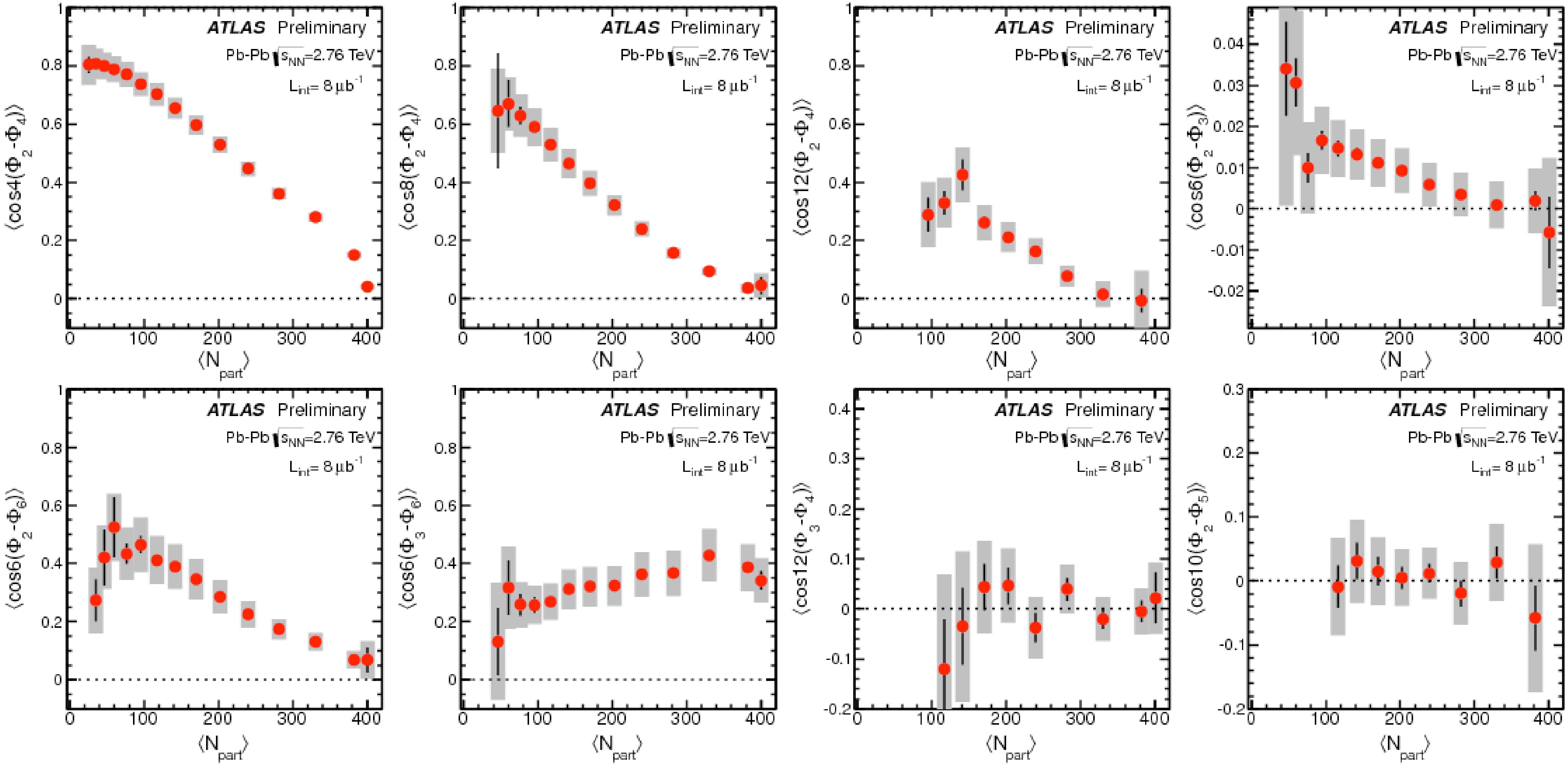
$$v_n \propto \epsilon_n = \frac{\sqrt{\langle r^n \cos n\phi\rangle^2 + \langle r^n \sin n\phi\rangle^2}}{\langle r^n\rangle}$$

For Glauber and CGC mckln



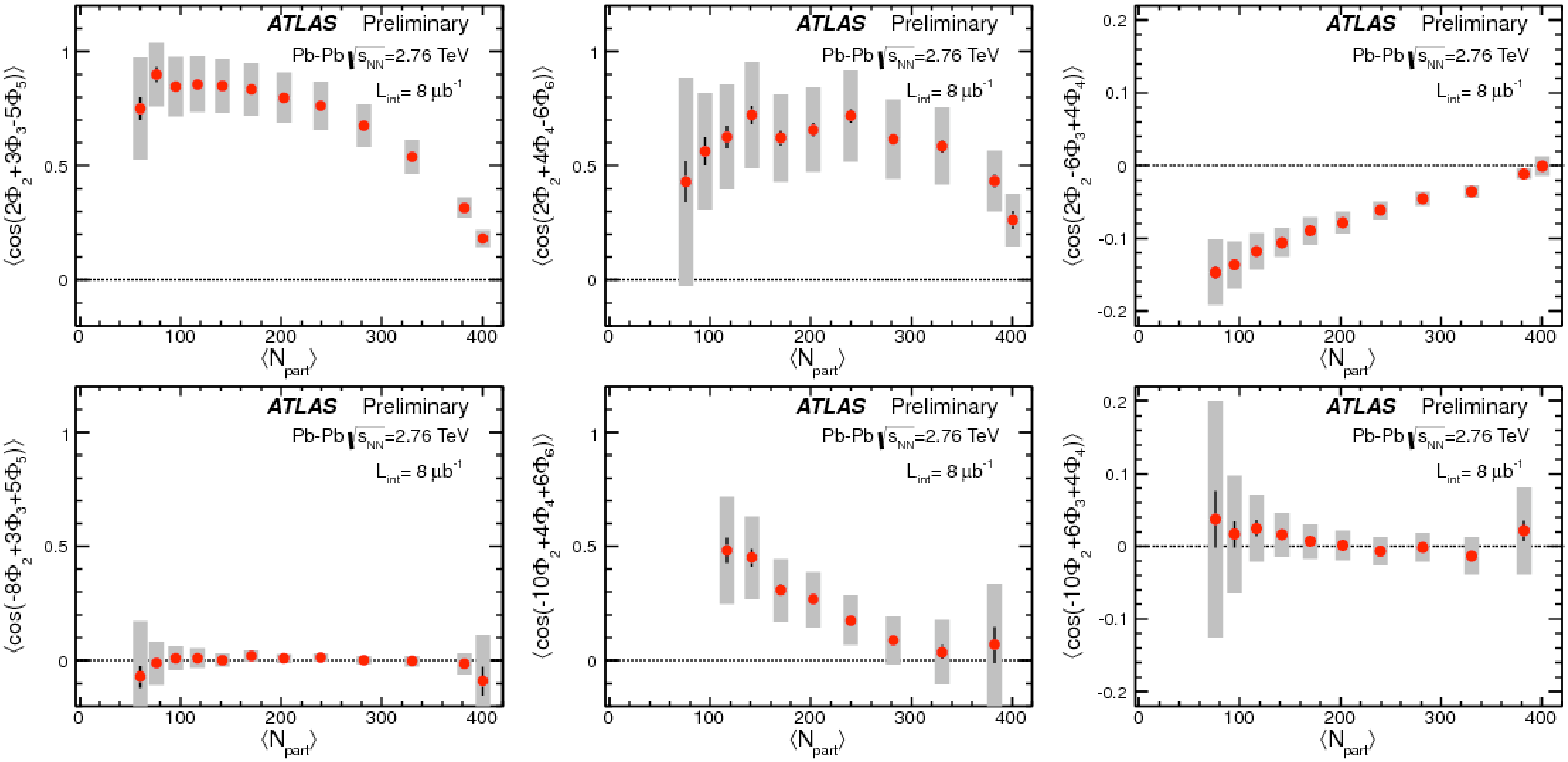
Both models fail describing $p(v_2)$ across the full centrality range

Two-plane correlations



Also see Li Yan's talk in this session

Three-plane correlations



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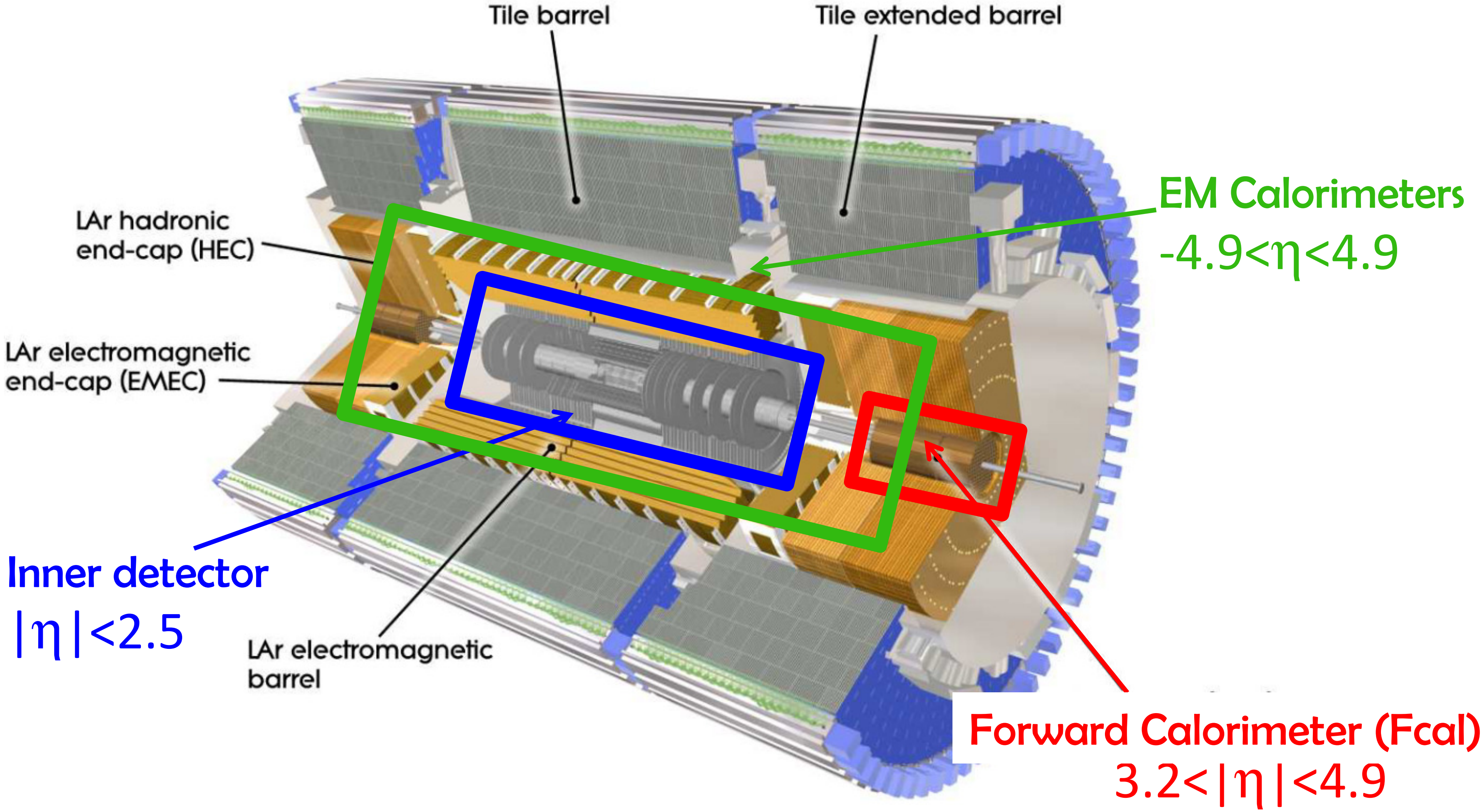
Summary

- Measured event-by-event probability distribution of v_2-v_4 in various centrality bins.
- The v_2 distribution is radial projection of 2D Gaussian in most central events.
  - But significant deviation is seen for >5%
- For v_3, v_4 the distributions are consistent with 2D Gaussian for all centralities
- The reduced shape of v_n distributions has no p_T dependence → hydro response independent of p_T
- $p(v_2)$ is inconsistent with $p(\varepsilon_2)$ from Glauber &MC-KLN model.
- Also measured a large set of two and three-plane correlations
- Both measurements are the first of their kind.
  - Provide direct constraints on the hydrodynamic response to initial geometry fluctuations.

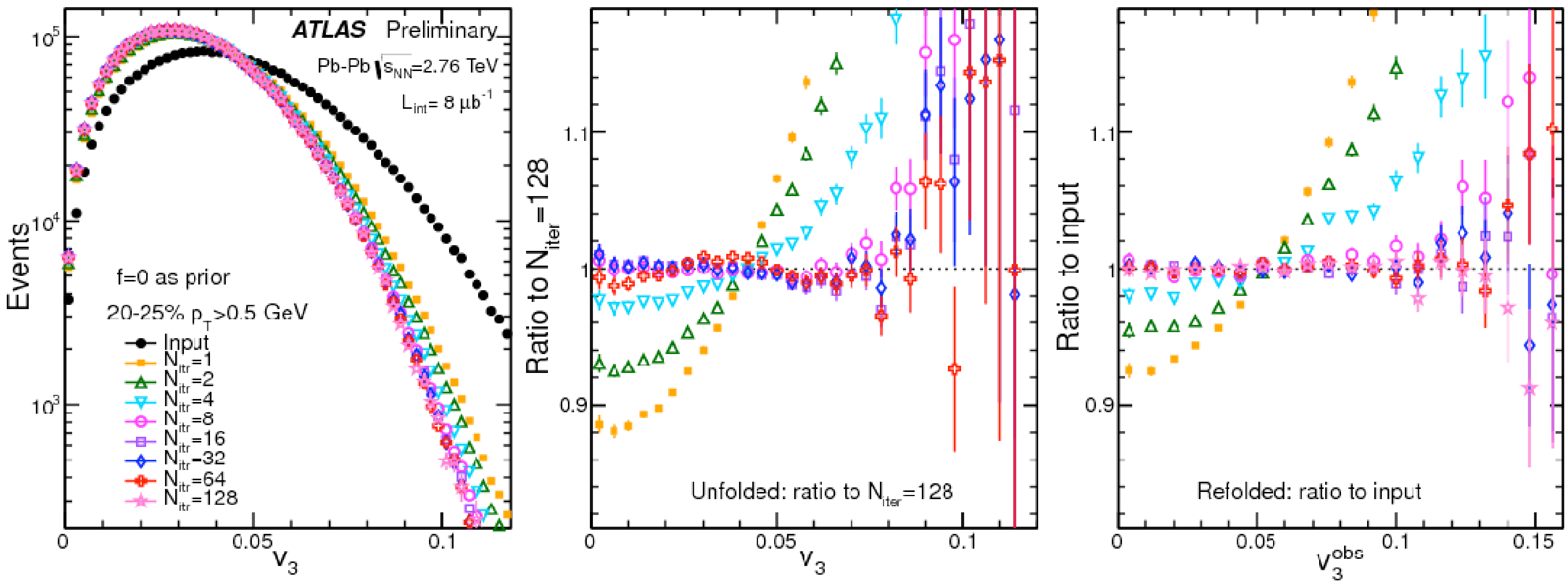
BACKUP SLIDES

ATLAS Detector



- Tracking coverage : $|\eta|<2.5$
- FCal coverage : $3.2<|\eta|<4.9$ (used to determine Event Planes)
- For reaction plane correlations use entire EM calorimeters ($-4.9 <\eta< 4.9$)

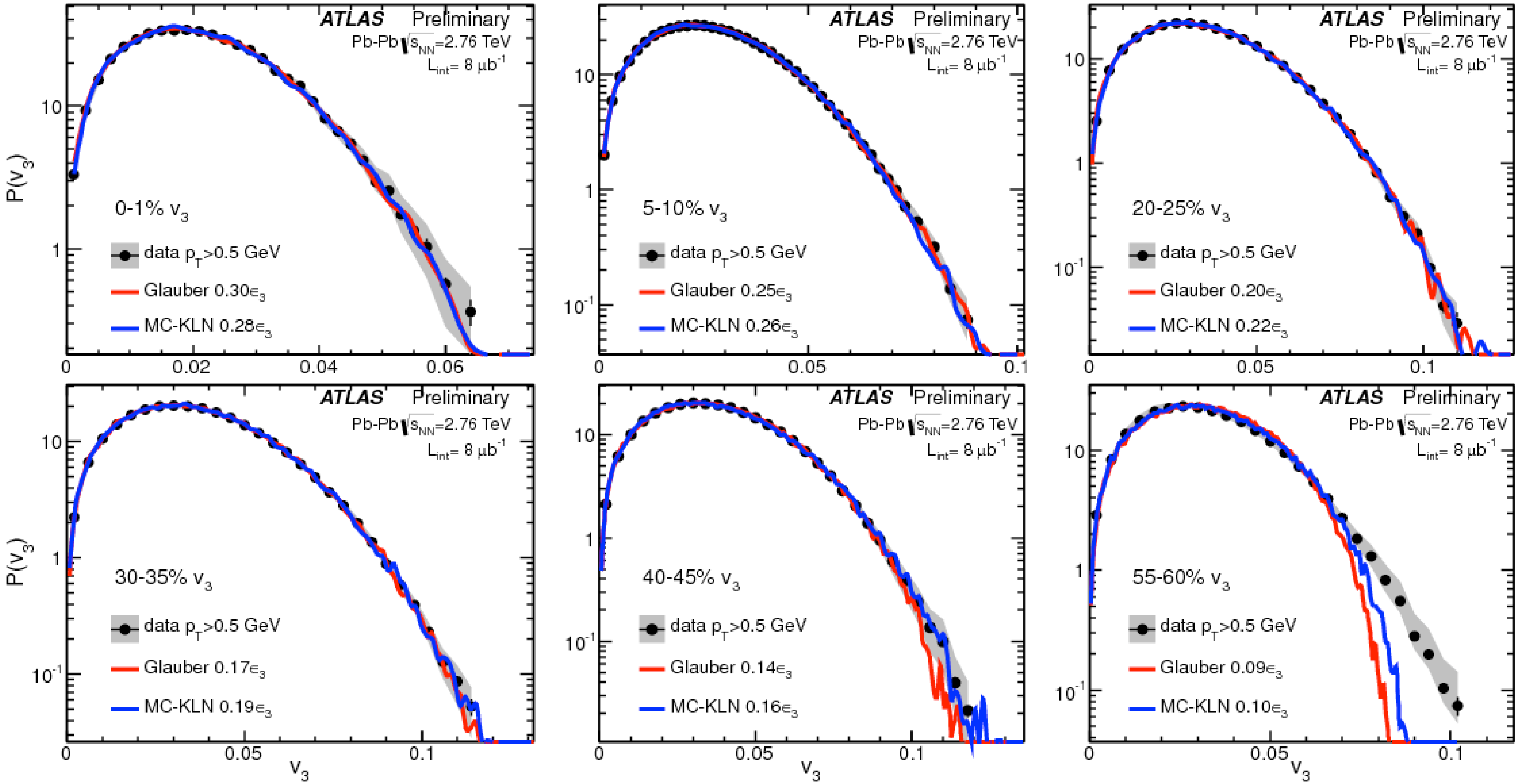
Basic unfolding performance: v_2, 20-25%



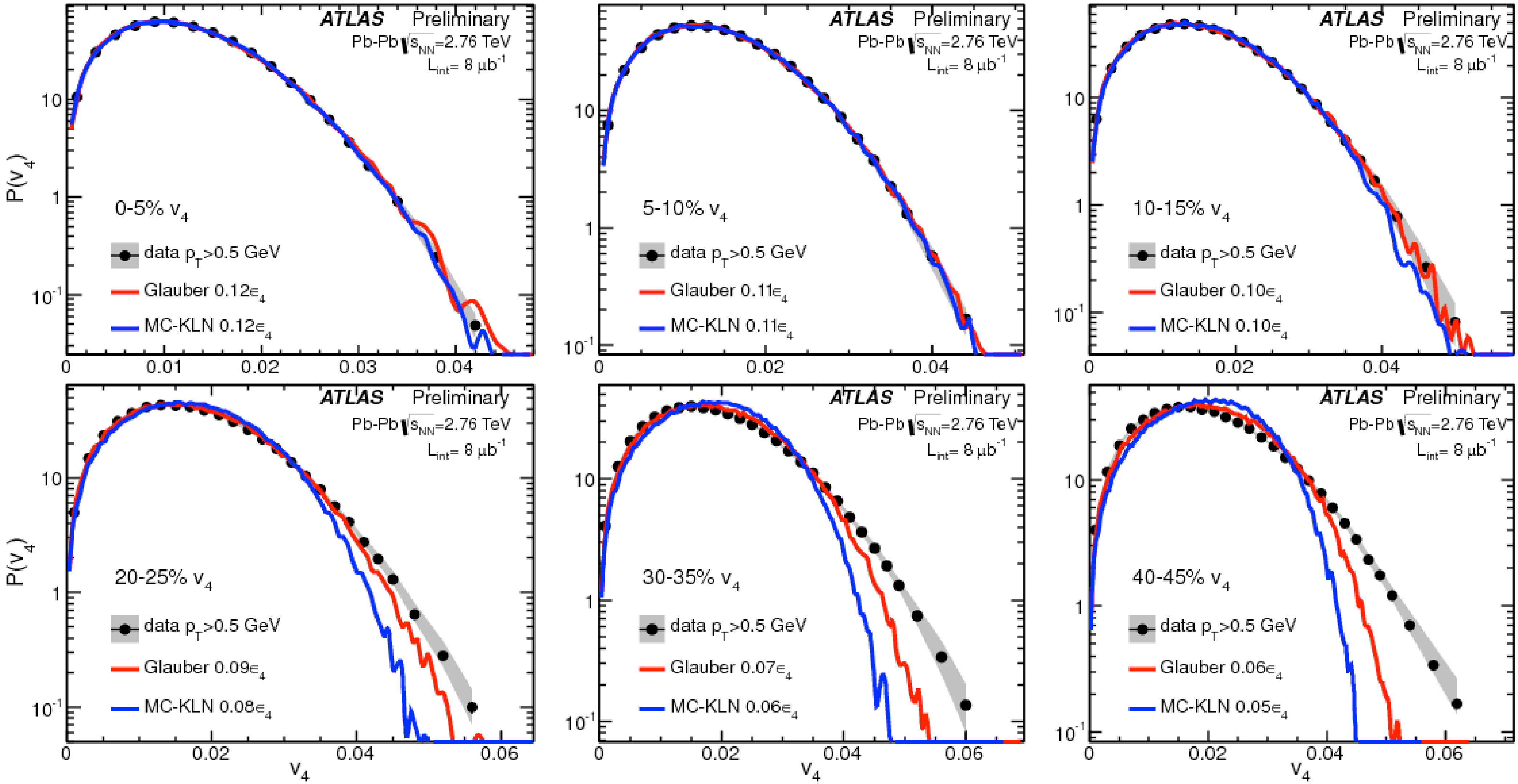
v_2 converges within a few % for N_{iter}=8

small improvements for larger N_{iter}.

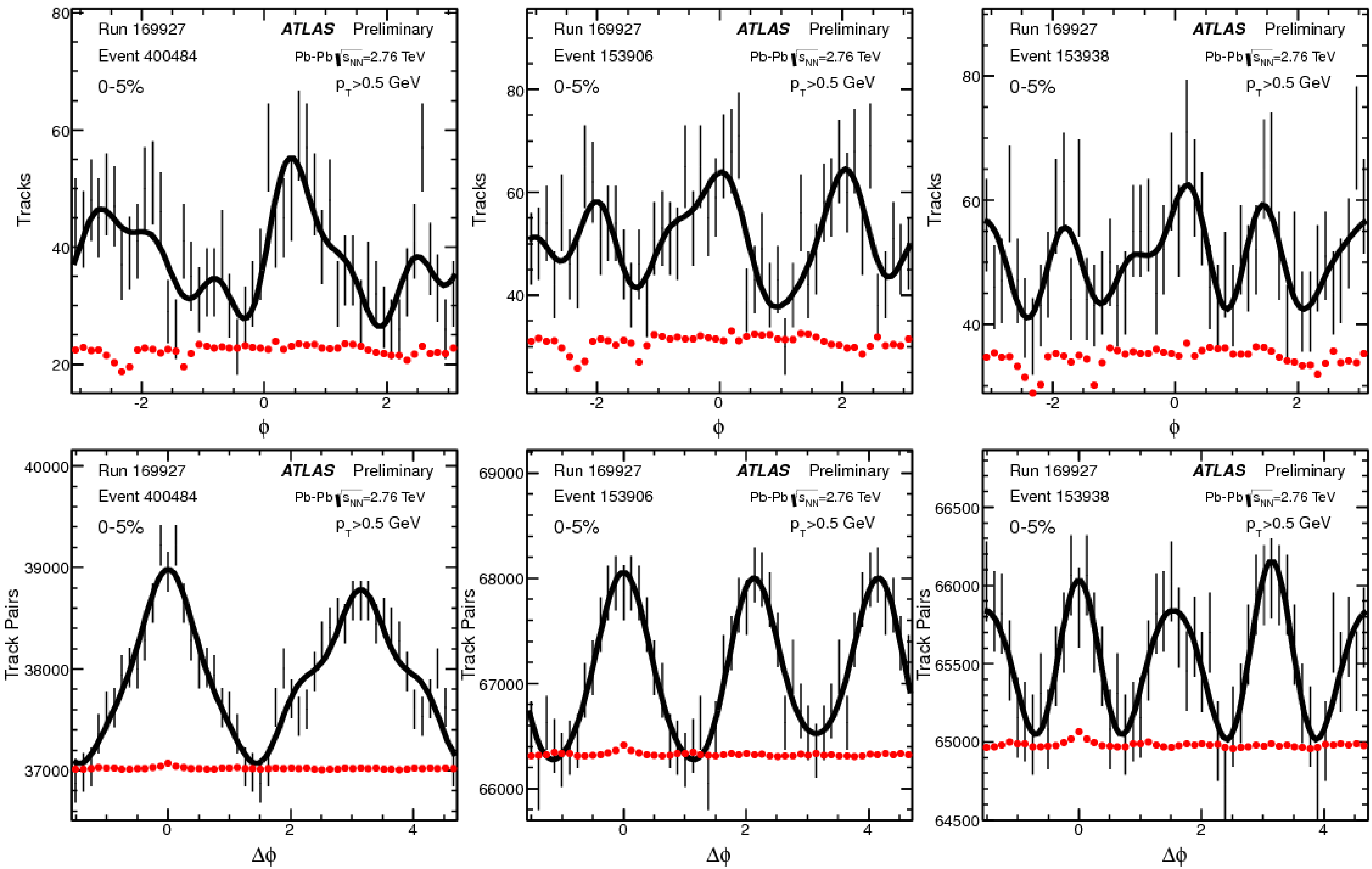
Measuring the hydrodynamic response: v_3 [29]



Measuring the hydrodynamic response: v_4 [30]



EbE distributions



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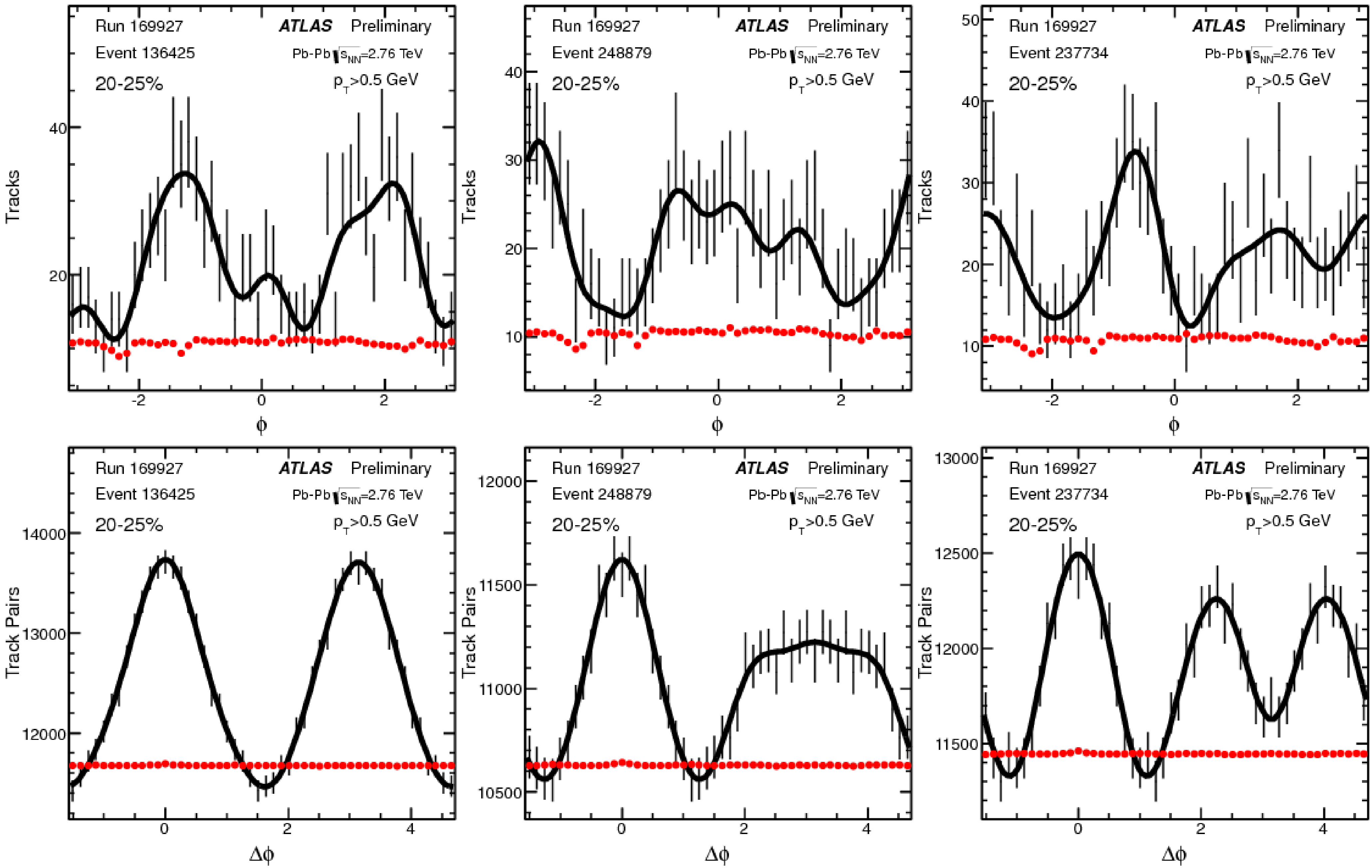
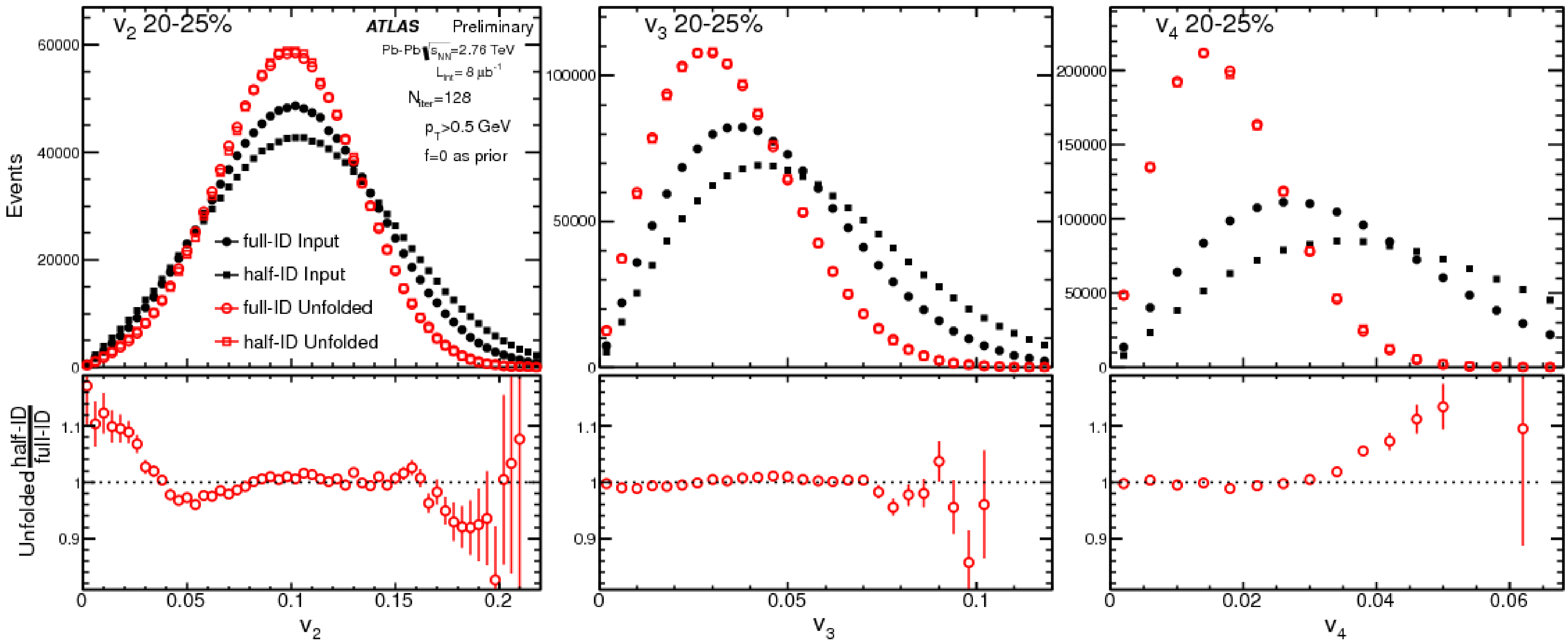


Unfolding for Half ID



Bayesian unfolding

- Unfolding implemented using RooUnfold package
  - True ("cause" c or v_n) vs measured distribution ("effect" e or v_n^{obs})

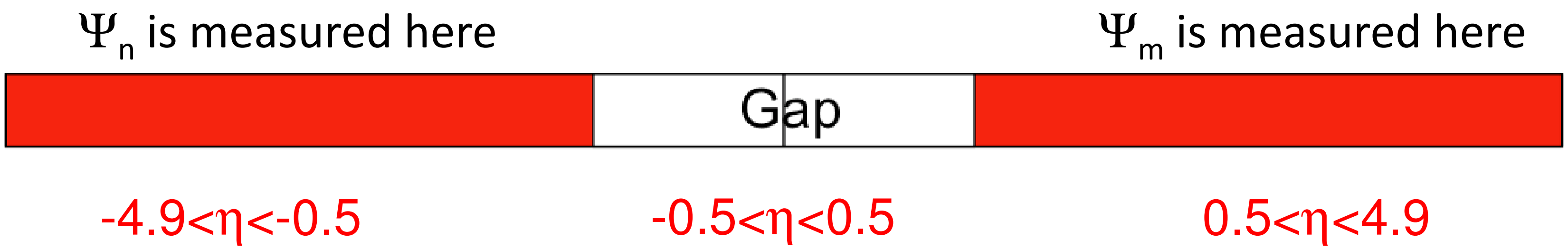
    Denote response function $A_{ji} = p(e_j|c_i)$

  - Unfolding matrix M is determined via iterative procedure

$$\hat{c}^{\text{iter}+1} = \hat{M}^{\text{iter}} e, \quad \hat{M}_{ij}^{\text{iter}} = \frac{A_{ji}\hat{c}_i^{\text{iter}}}{\sum_{m,k} A_{mi} A_{jk} \hat{c}_k^{\text{iter}}}$$

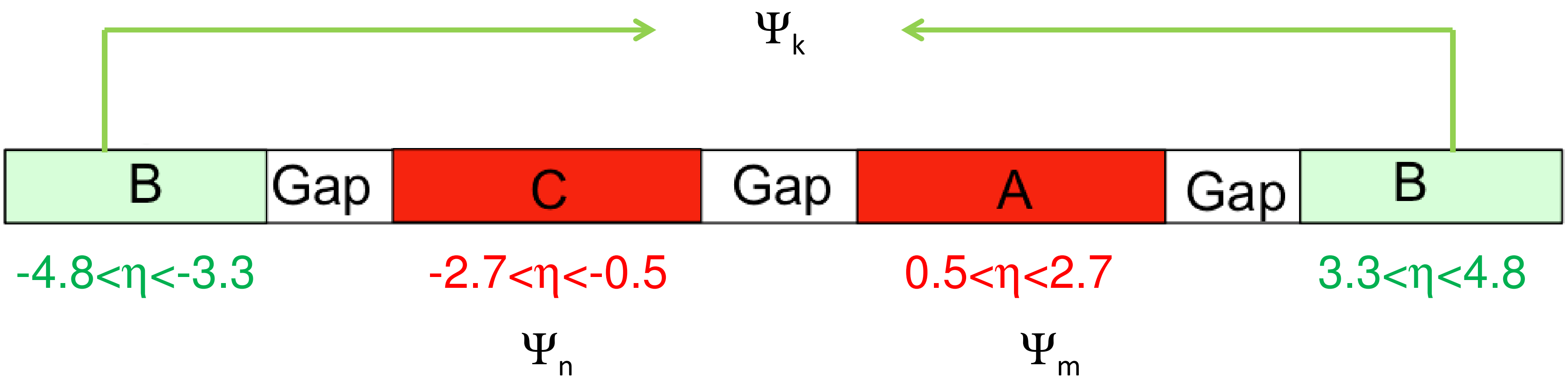
  - Prior, c^0, can be chosen as input v_n^{obs} distribution or it can be chosen to be closer to the truth by a simple rescaling according to the EP v_n

Measuring the two-plane correlations



- Correlations are measured using EM+Forward calorimerers (-4.9<η<-4.9)
- If Ψ_n is measured in negative half (-4.9<η<-0.5), then Ψ_m is measured in positive half of calorimeters (and vice versa).
  - Thus same particles are not used in measuring both Ψ_n and Ψ_m.
  - Removes auto-correlation
- There is a Δη gap of 1 units between the two halves to remove any non-flow correlations

Measuring the three-plane correlations



- Ψ_n ,Ψ_m and Ψ_k are measured in different parts of the calorimeter.
  - Thus same particles are not used in measuring any of the Ψ's.
  - Thus there is no auto-correlation
- There is a $\Delta\eta$ gap between any two of the detectors
- Event mixing is used to remove detector effects