ATLAS flow measurements

Jiangyong Jia for the ATLAS Collaboration

HPT2012   Oct 21th- Oct 24th

Simplified

Φ

Realistic

Φ_4

Φ_2

Φ_3

pressure
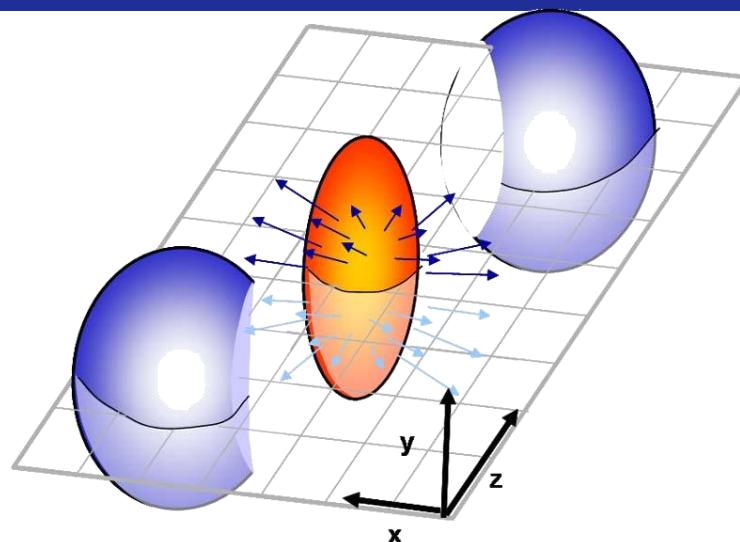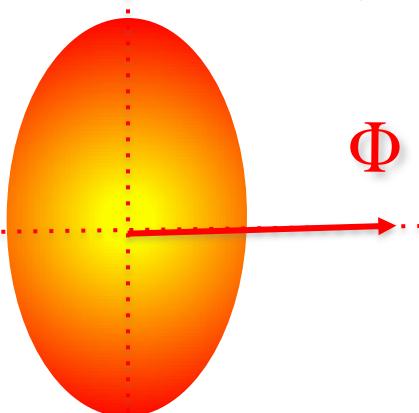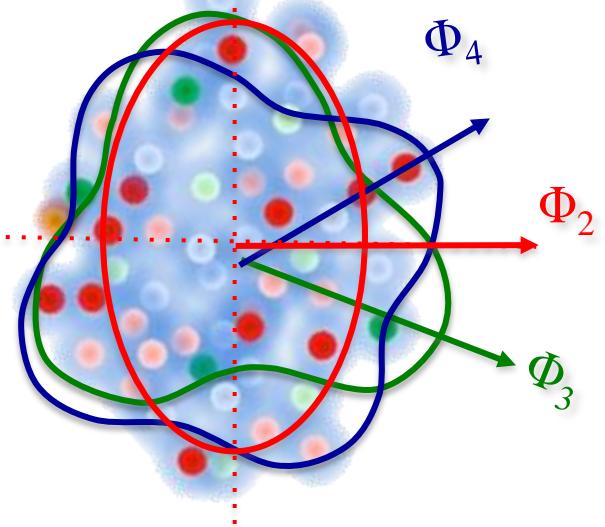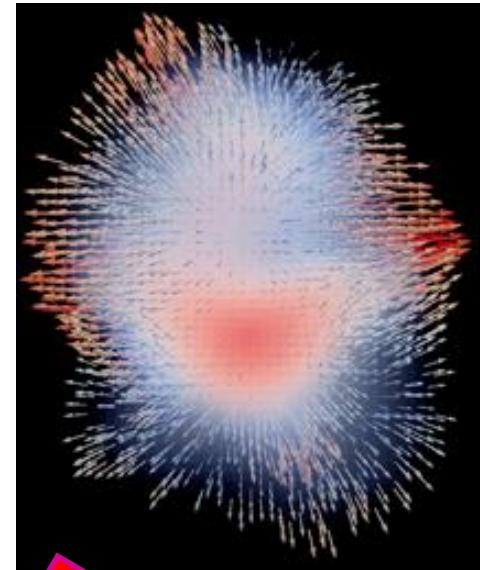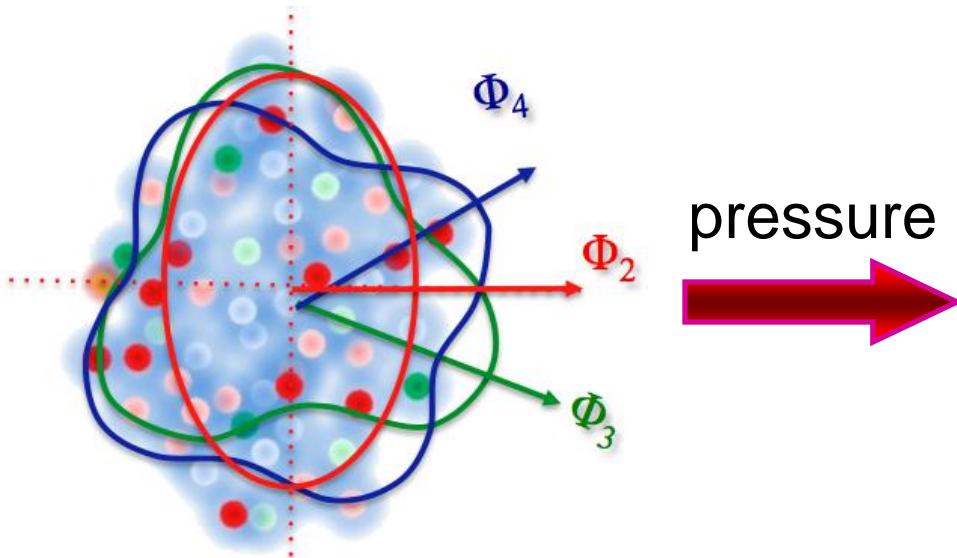
by MADAI.us

Single particle distribution

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n} v_{n} \cos n\left(\phi - \Phi_{n}\right)$$

Pair distribution

$$\frac{dN}{d\,\Delta\phi} = \left[\frac{dN}{d\,\phi_{a}} * \frac{dN}{d\,\phi_{b}}\right] \propto 1 + \sum_{n} 2 v_{n}^{a} v_{n}^{b} \cos\left(n \Delta \phi\right)$$

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos n\left(\phi - \Phi_n\right)$$

- Significant fluctuations, factor of ~ 2 in central events
- Can not be explained by detector effects (red histogram)

Fluctuation event by event

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos n(\phi - \Phi_n)$$
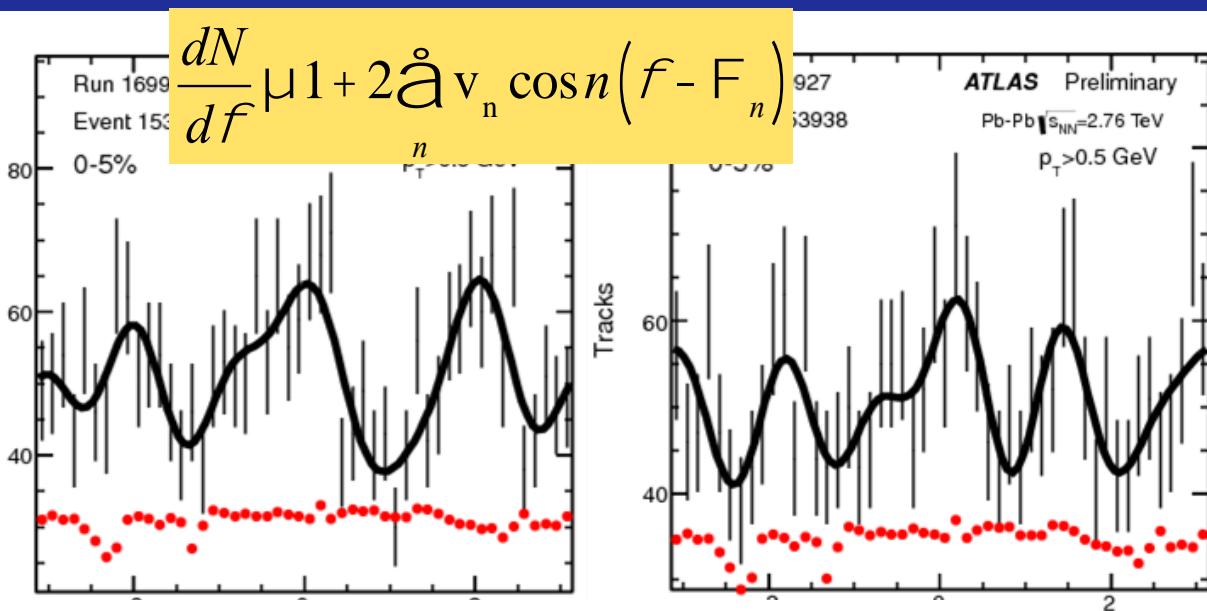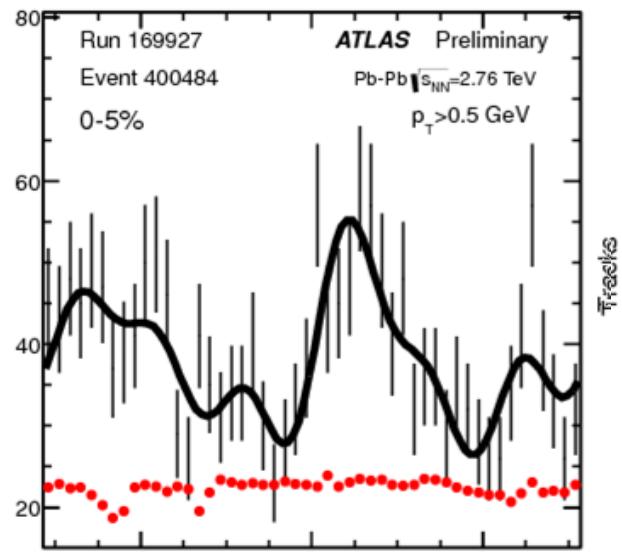
Rich event-by-event patterns for v_n and Φ_n!
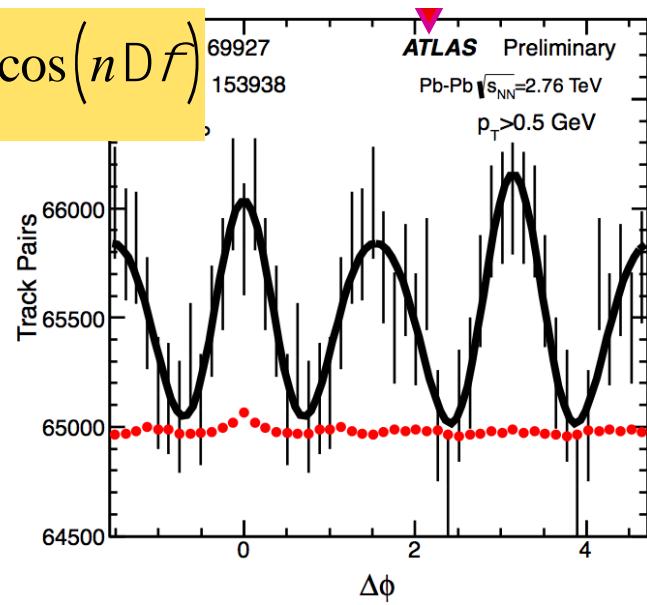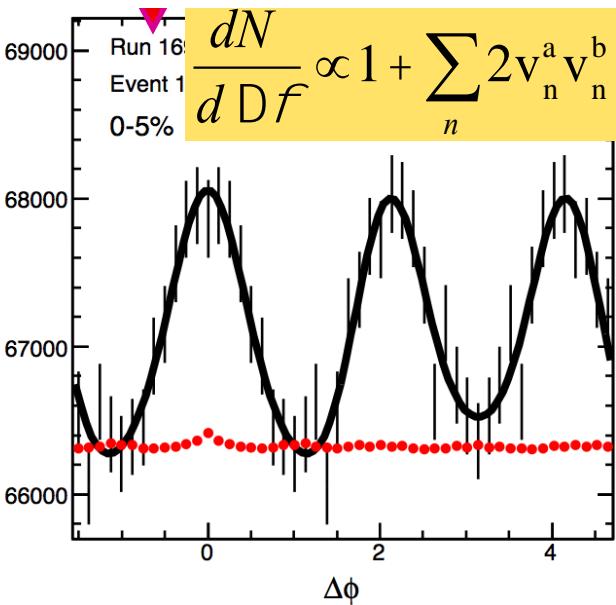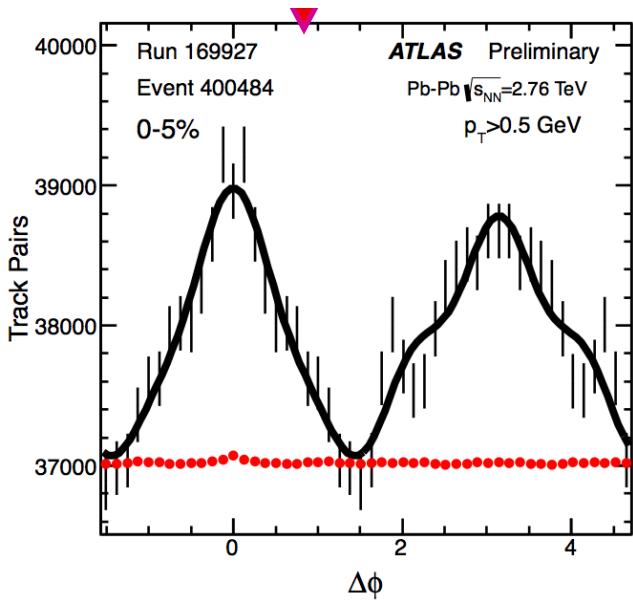
$$\frac{dN}{d\Delta\phi} \propto 1 + \sum_n 2 v_n^a v_n^b \cos(n\Delta\phi)$$

Flow observables
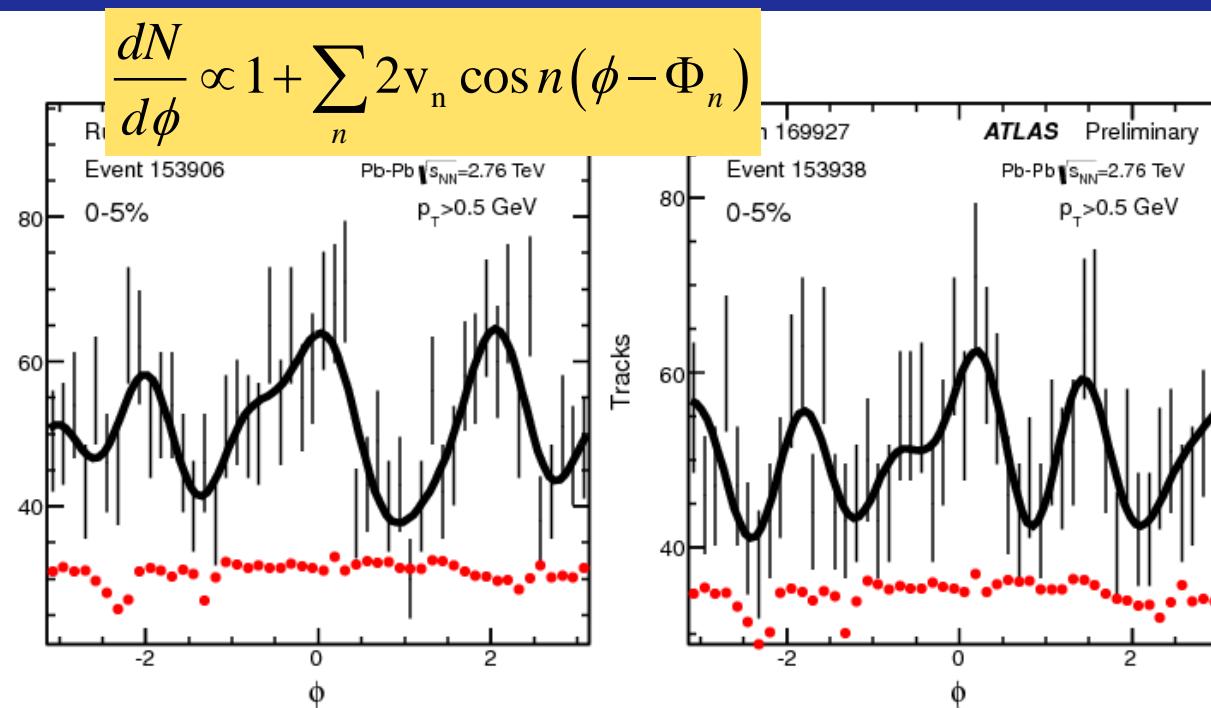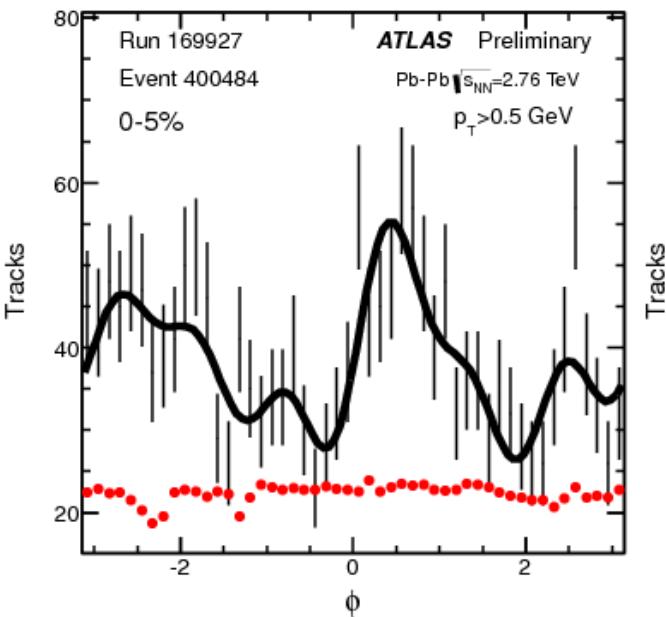
$$\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos n(\phi - \Phi_n)$$

- Mean values of $v_n(p_T, \eta, cent)$.   PhysRevC.86.014907
- Event by event v_n distributions.   ATLAS-CONF-2012-114
- Correlations between flow phases Φ_n. ATLAS-CONF-2012-49

- Probes into dynamical expansion of the matter
- Sensitive to the initial density distribution/fluctuations
- Extraction of the matter properties in more details

Tile barrel

Tile extended barrel

LAr hadronic
end-cap (HEC)

LAr electromagnetic
end-cap (EMEC)

EM Calorimeters
$-4.9 < \eta < 4.9$

Inner detector
$|\eta| < 2.5$

LAr electromagnetic
barrel

Forward Calorimeter (FCal)
$3.2 < |\eta| < 4.9$
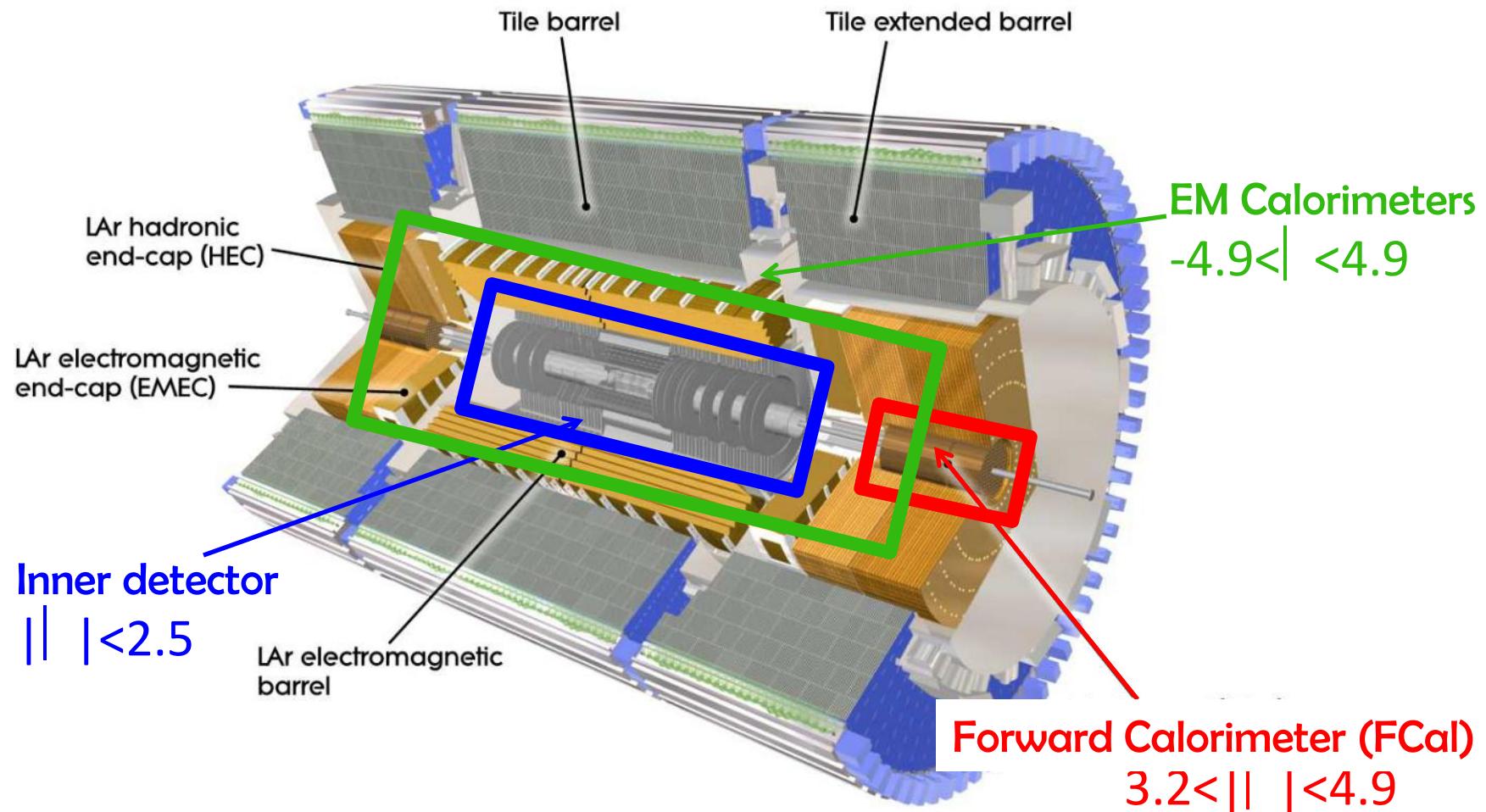
- Tracking $|\eta| < 2.5$ → for v_n measurement
- E_T in forward calorimeter $3.2 < |\eta| < 4.9$ → event plane
- Event plane correlations use entire calorimeter $-4.9 < \eta < 4.9$

Averaged flow: v_n(cent,p_T,η)

Phys. Rev. C 86,
014907 (2012)
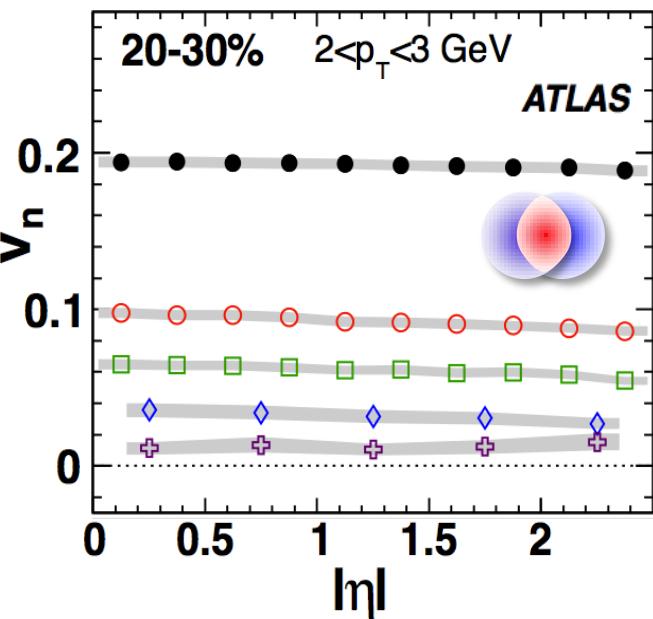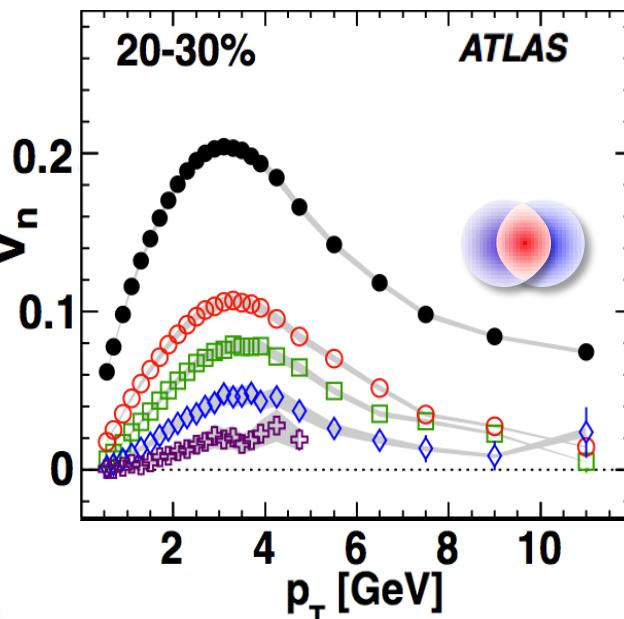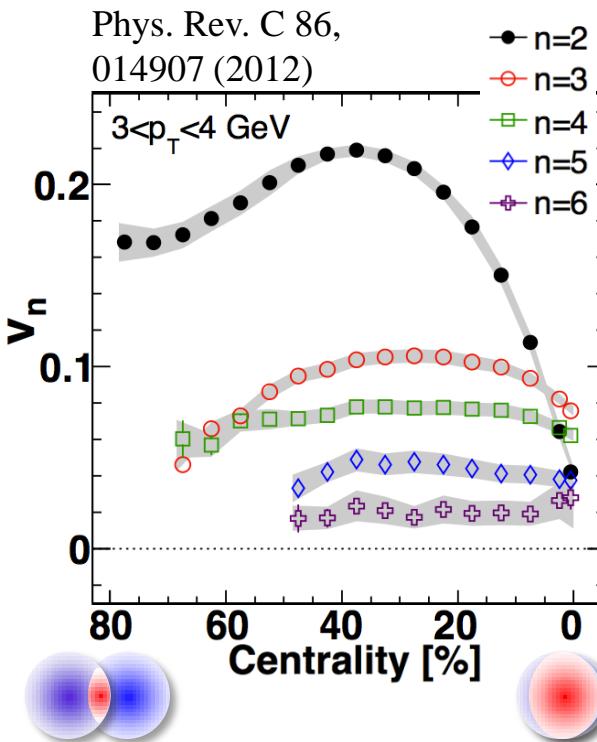
■ **Features of Fourier coefficients**

  ■ v_n coefficients rise and fall with centrality.

  ■ v_n coefficients rise and fall with p_T.

  ■ v_n coefficients are ~boost invariant.

Flow correlations are long range!

(a) ATLAS — 2-3 GeV — Phys. Rev. C 86, 014907 (2012) — $C(\Delta\phi, \Delta\eta)$, $|\Delta\eta|>2$, $\Delta\phi$, $\Delta\eta$

(b) Pb-Pb $\sqrt{s_{NN}}=2.76$ TeV, $L_{int}= 8 \, \mu b^{-1}$ 0-5%, $2<p_T^a$, $p_T^b<3$ GeV, $2<|\Delta\eta|<5$, ATLAS — $C(\Delta\phi)$, Residual [$\times 10^{-4}$], $\Delta\phi$
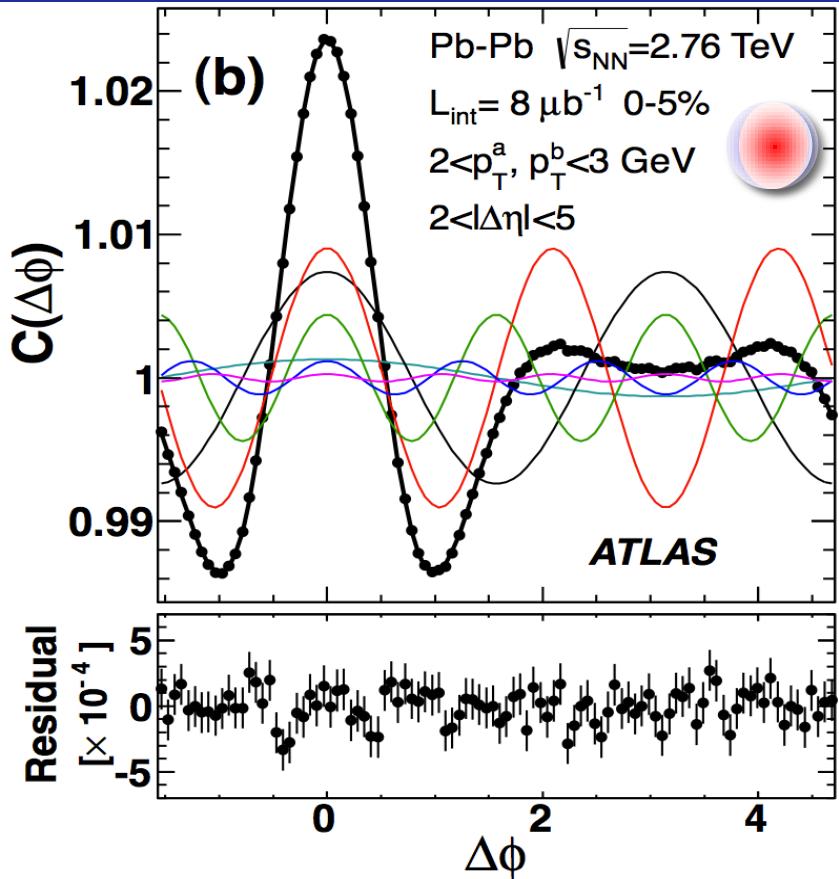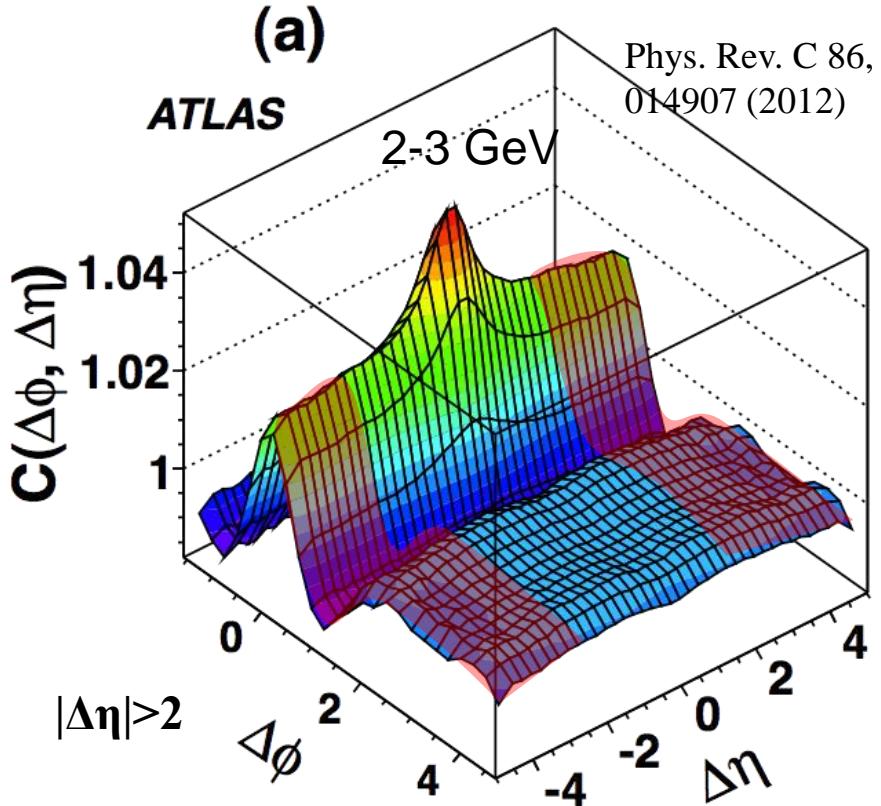
- Long range structures ("ridge") described by harmonics $v_{1,1}$-$v_{6,6}$

$$\frac{dN}{d\,\Delta\phi} \propto 1 + \sum_n 2v_{n,n}\left(p_T^a, p_T^b\right)\cos\left(n\Delta\phi\right) \quad v_{n,n}\left(\mathbf{p_T^a}, \mathbf{p_T^b}\right) = v_n\left(\mathbf{p_T^a}\right)v_n\left(\mathbf{p_T^b}\right) + \mathbf{non\text{-}flow}$$

# Factorization of $v_{n,n}$ to v_n as a function of $\Delta\eta$

$$v_{n,n}\left(p_T^a, p_T^b\right) = v_n\left(p_T^a\right)\boxed{v_n\left(p_T^b\right)} + \textbf{non - flow}$$
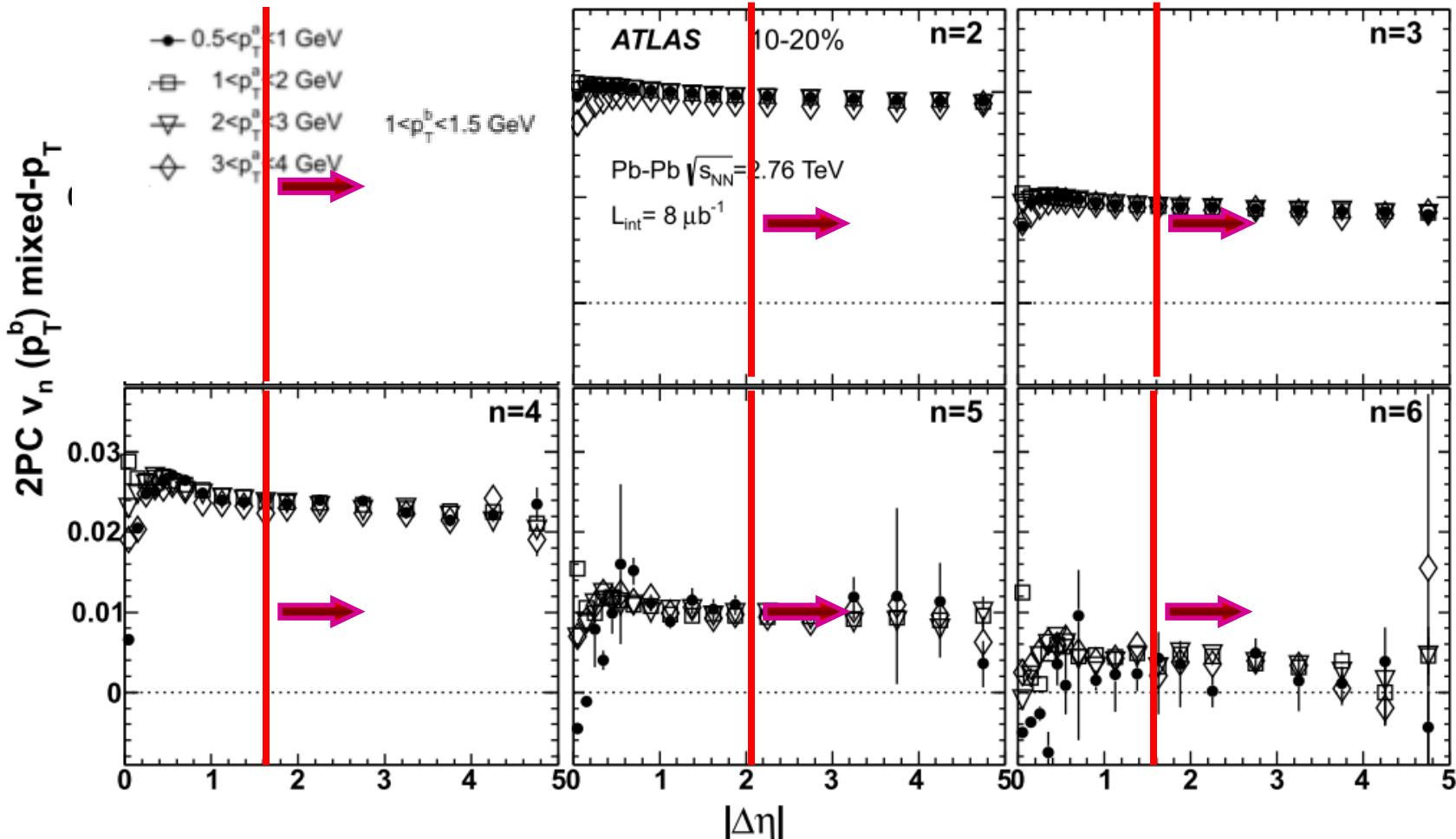
- Factorization works well for n=2-6, weak $\Delta\eta$ dependence
- Break down of $v_{1,1}$ is due to global momentum conservation

Directed (odd component) flow vanishes at η=0
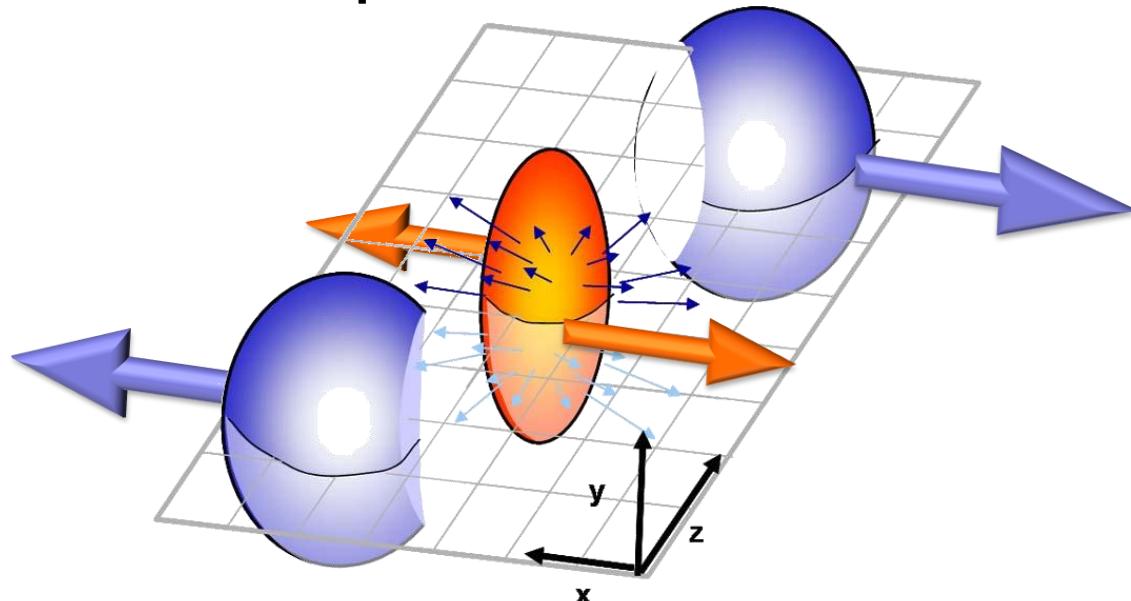
Dipolar (even component) flow ~boost invariant in η
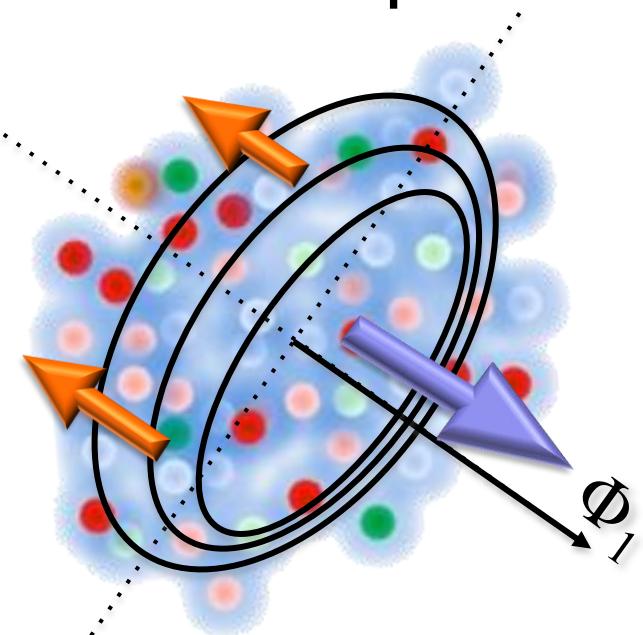
But also include non-flow effects: Momentum of individual particle must be balanced by others:

$$v_{1,1}\left(p_T^a, p_T^a\right) = v_1\left(p_T^a\right)v_1\left(p_T^b\right) + \textbf{non-flow} = -\frac{p_T^a \cdot p_T^b}{M\left\langle p_T^2\right\rangle}$$

Behaviors of $v_{1,1}(p_T^a, p_T^b)$
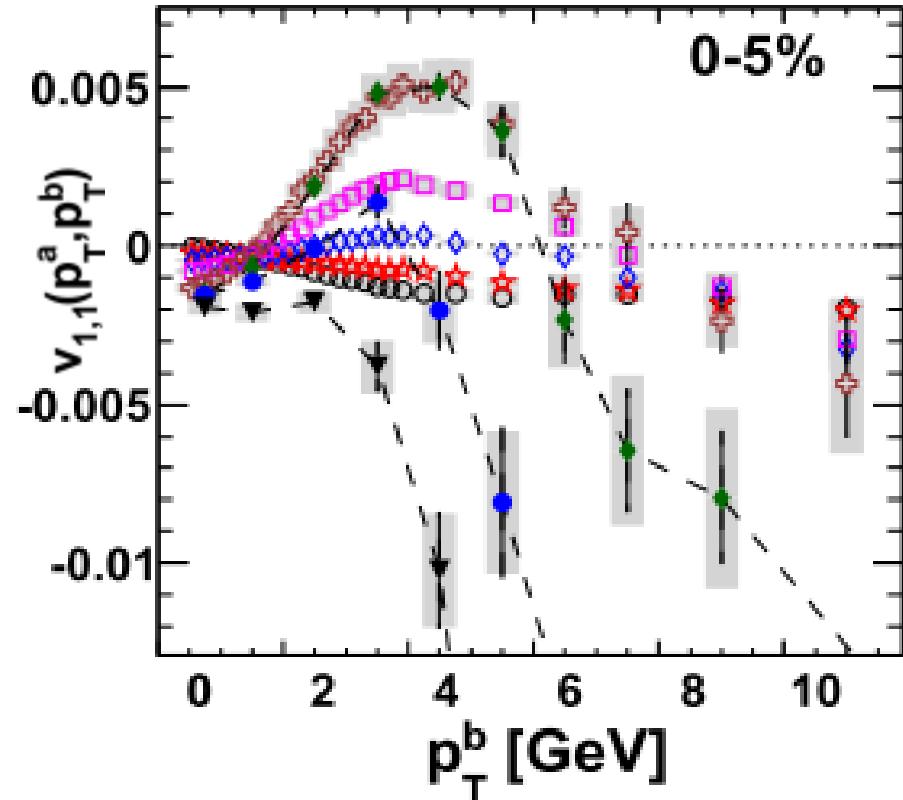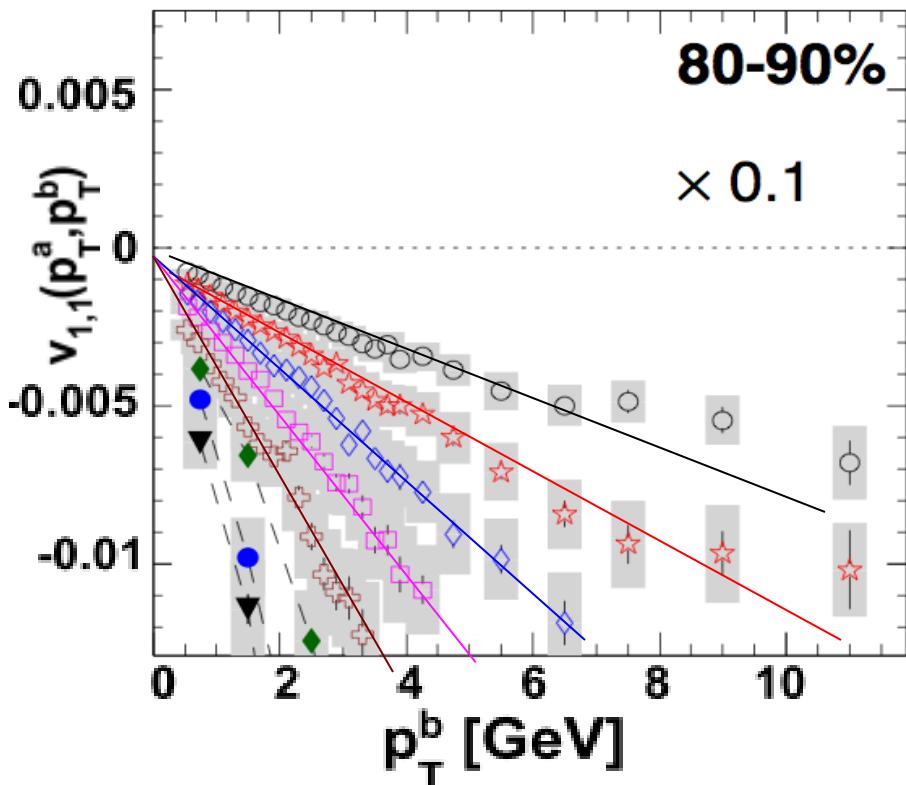
Well described by $\quad -\dfrac{p_T^a \times p_T^b}{M\left\langle p_T^2 \right\rangle}$

$$v_{1,1}(p_T^a, p_T^b) \overset{?}{=} v_1(p_T^a)v_1(p_T^b) - \frac{p_T^a \times p_T^b}{M\left\langle p_T^2 \right\rangle}$$

Extracting the │ -even v_1 (p_T)
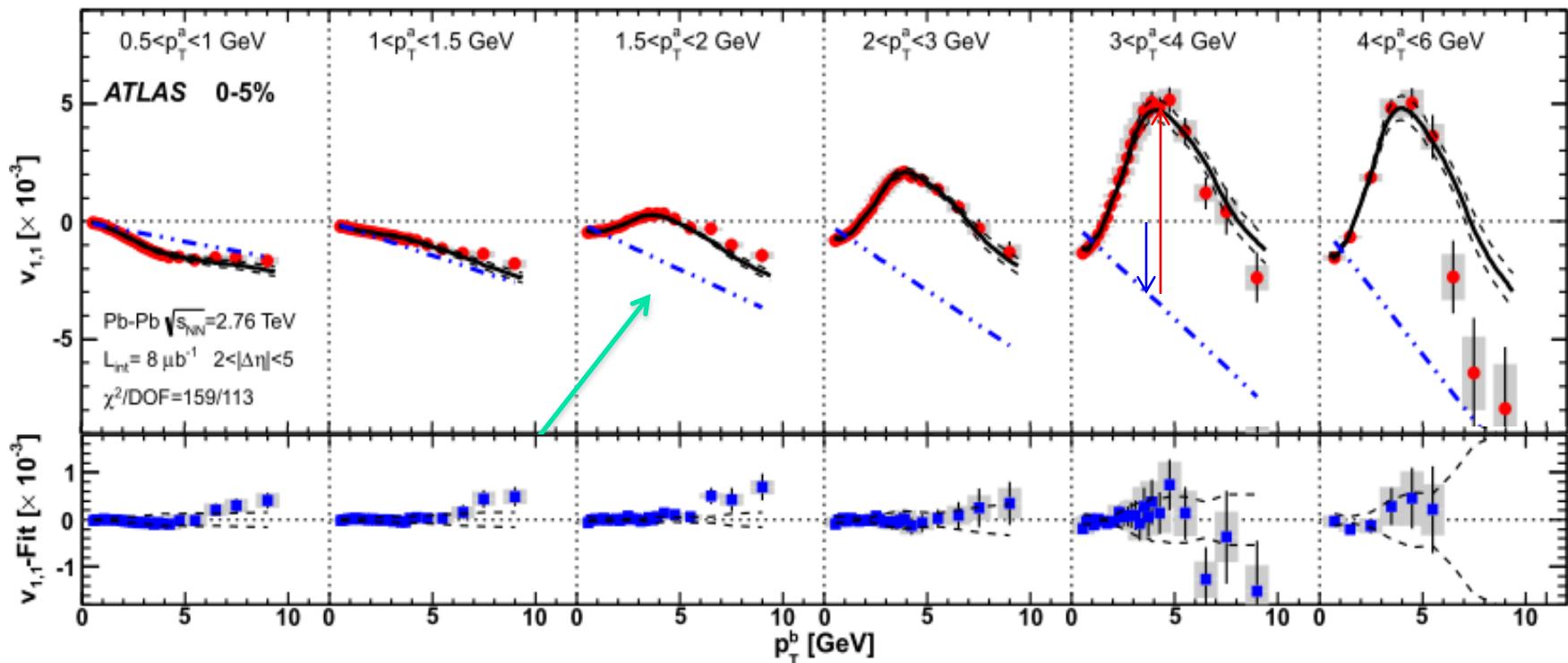
$$v_{1,1}(p_T^a, p_T^b) = v_1^{\mathrm{Fit}}(p_T^a)v_1^{\mathrm{Fit}}(p_T^b) - cp_T^a p_T^b$$

Excellent Fit!
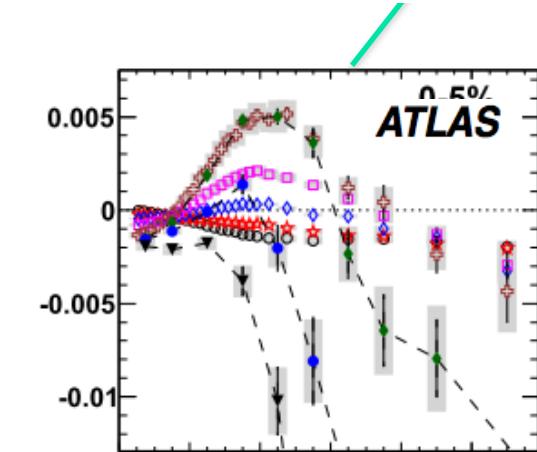
Red Points: $v_{1,1}$ data

Black line : Fit to functional form

Blue line: momentum conservation component

Extracted dipolar flow

Phys. Rev. C 86, 014907 (2012)
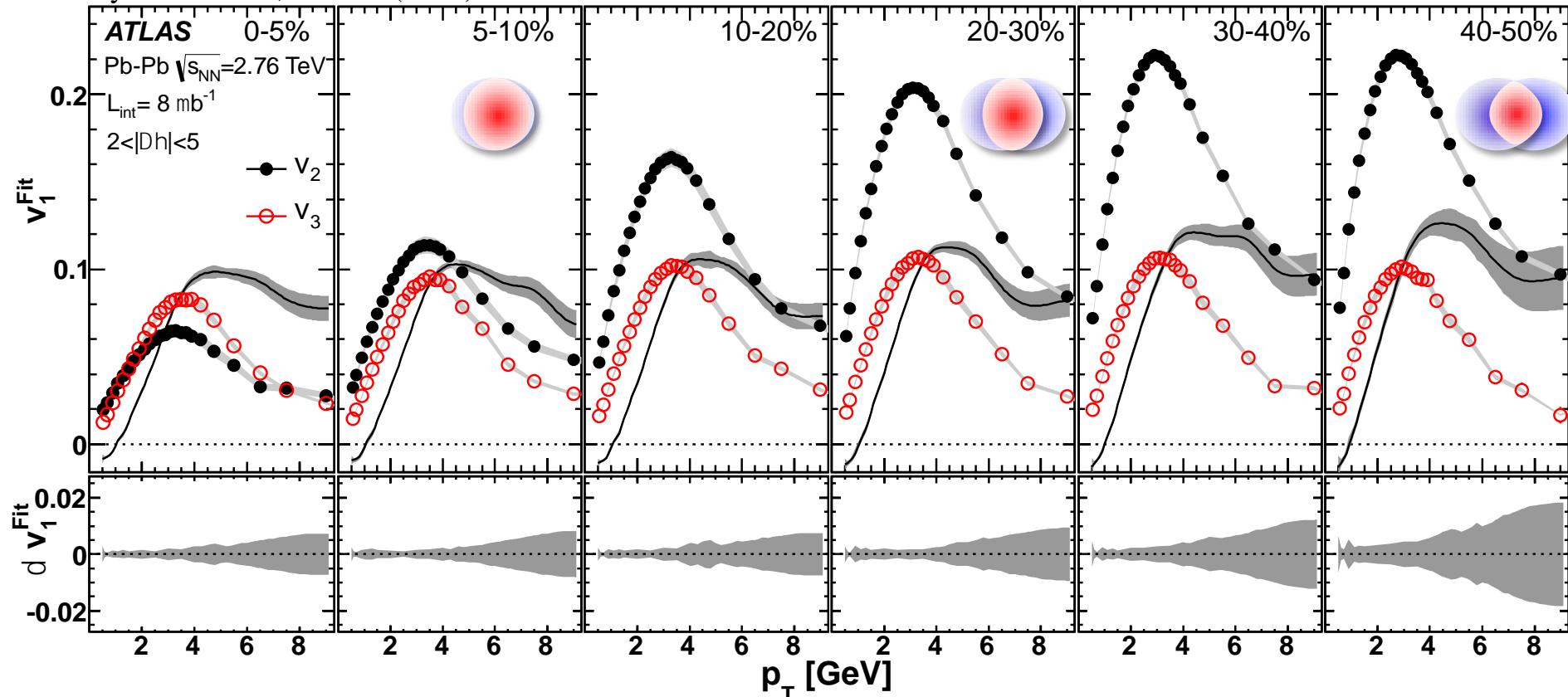
- Negative for $p_T < 1.0$ GeV → expected from hydro calculations
- Similar magnitudes as v_3 but much larger at high p_T
  - Large high p_T v_1 expected from L-dependence of energy loss

1203.3265

$v_{1,1}$ component shown by brown dashed lines

Most of $v_{1,1}$ is due to momentum conservation

Most of $v_{1,1}$ is due to dipolar flow
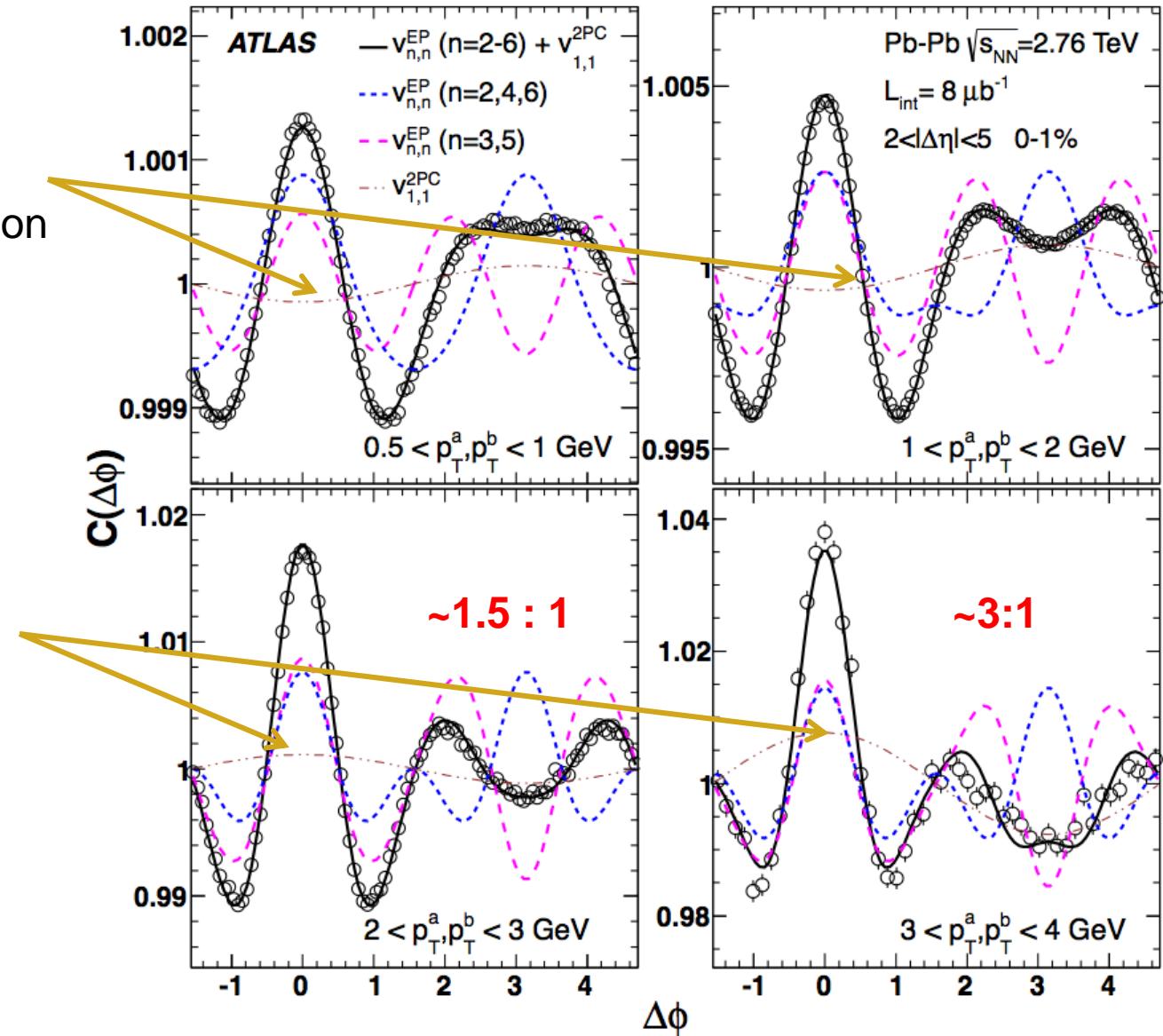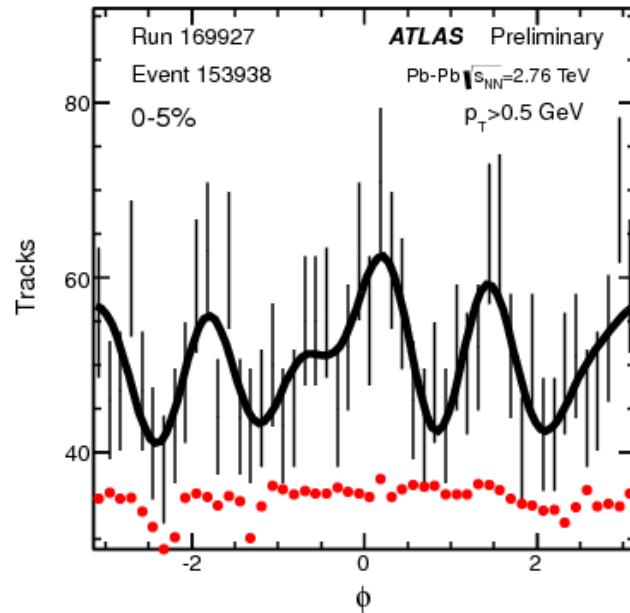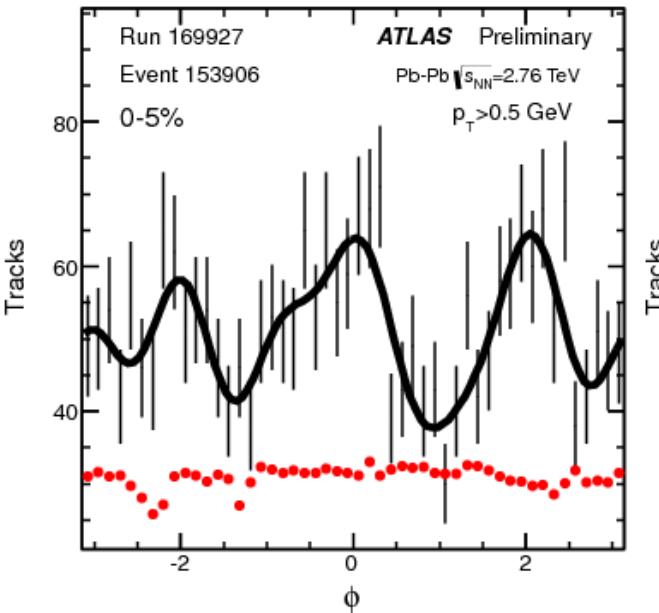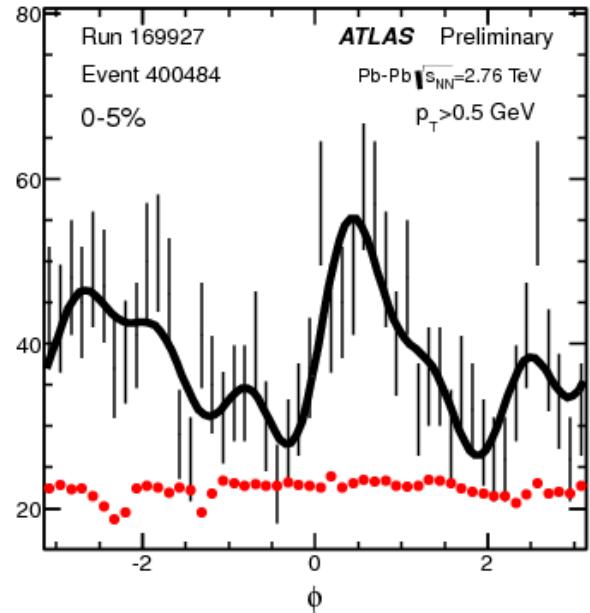
~1.5 : 1

~3:1

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

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Flow vector and smearing

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_n \left[v_{n,x}^{obs}\cos(n\varphi) + v_{n,y}^{obs}\sin(n\varphi) \right]$$

$$\vec{v}_n^{\,obs} = (v_{n,x}^{obs}, v_{n,y}^{obs}) = \vec{v}_n^{\,true} + \vec{p}_n^{\,smear}$$
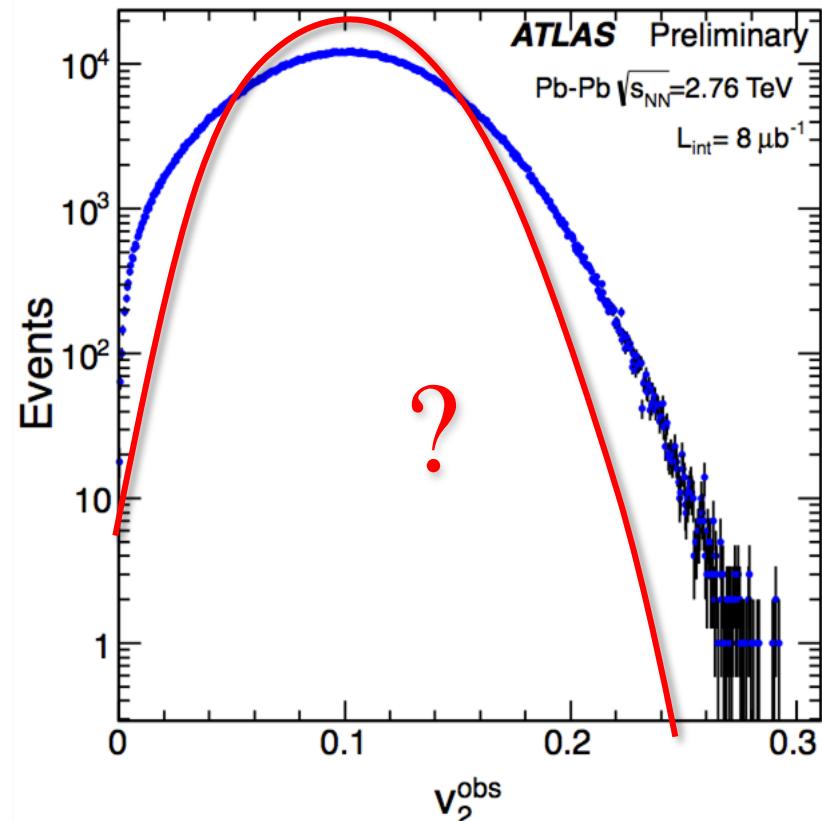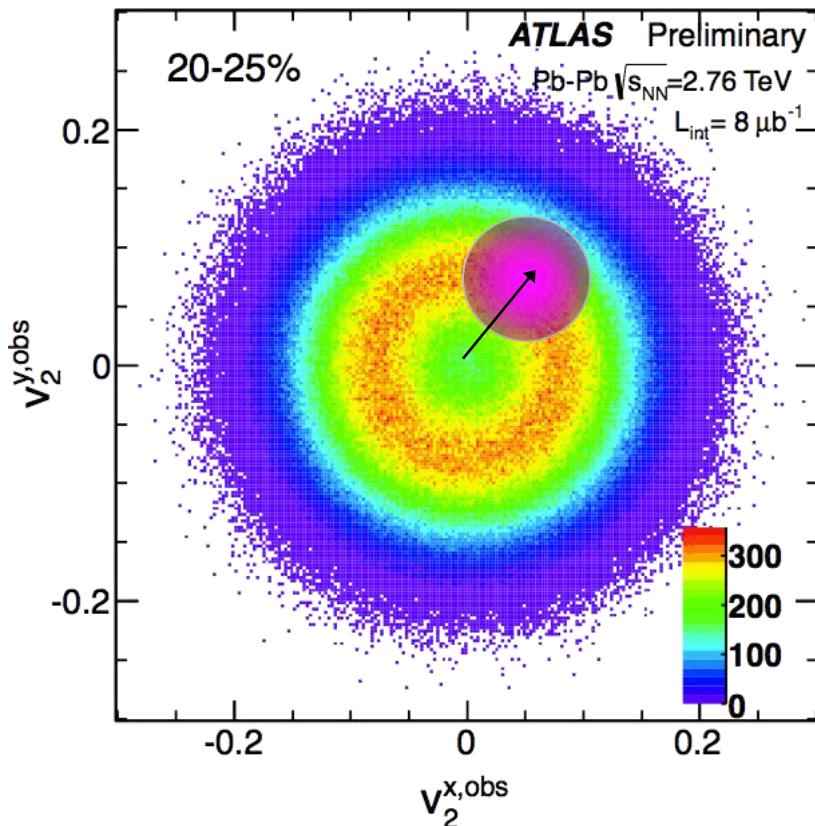
The key of unfolding is response function: $p(v_n^{obs}|v_n)$
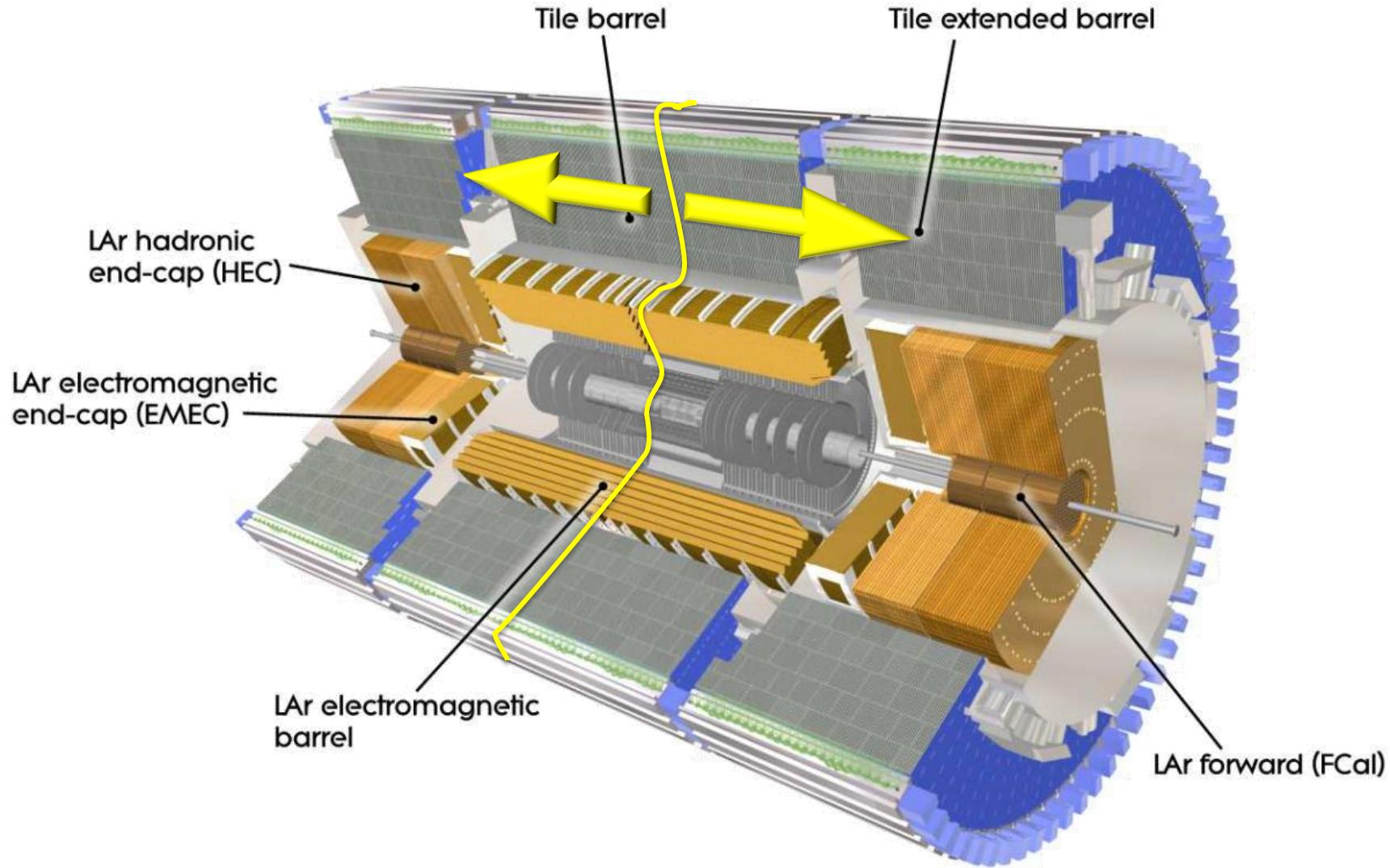
Sub-event "A" – Sub-event "C" = { **Signal:** cancelled
Fluctuations: √2 larger
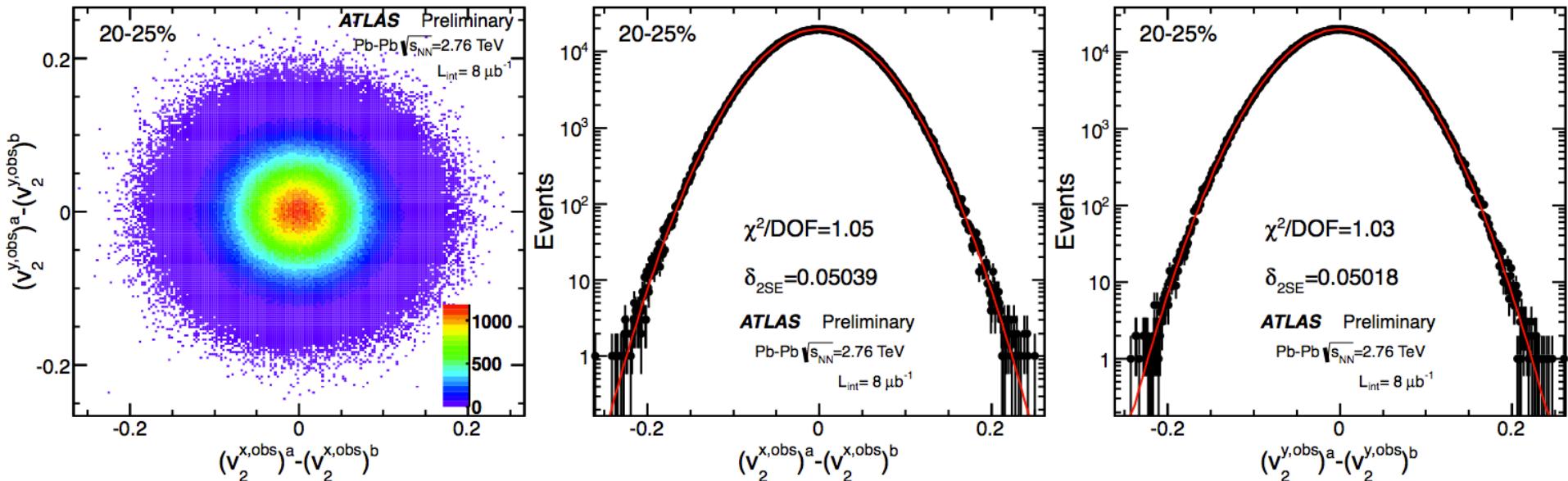
2D response function is a 2D Gaussian

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

1D response function obtained by integrating out azimuth angle

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

Data driven method
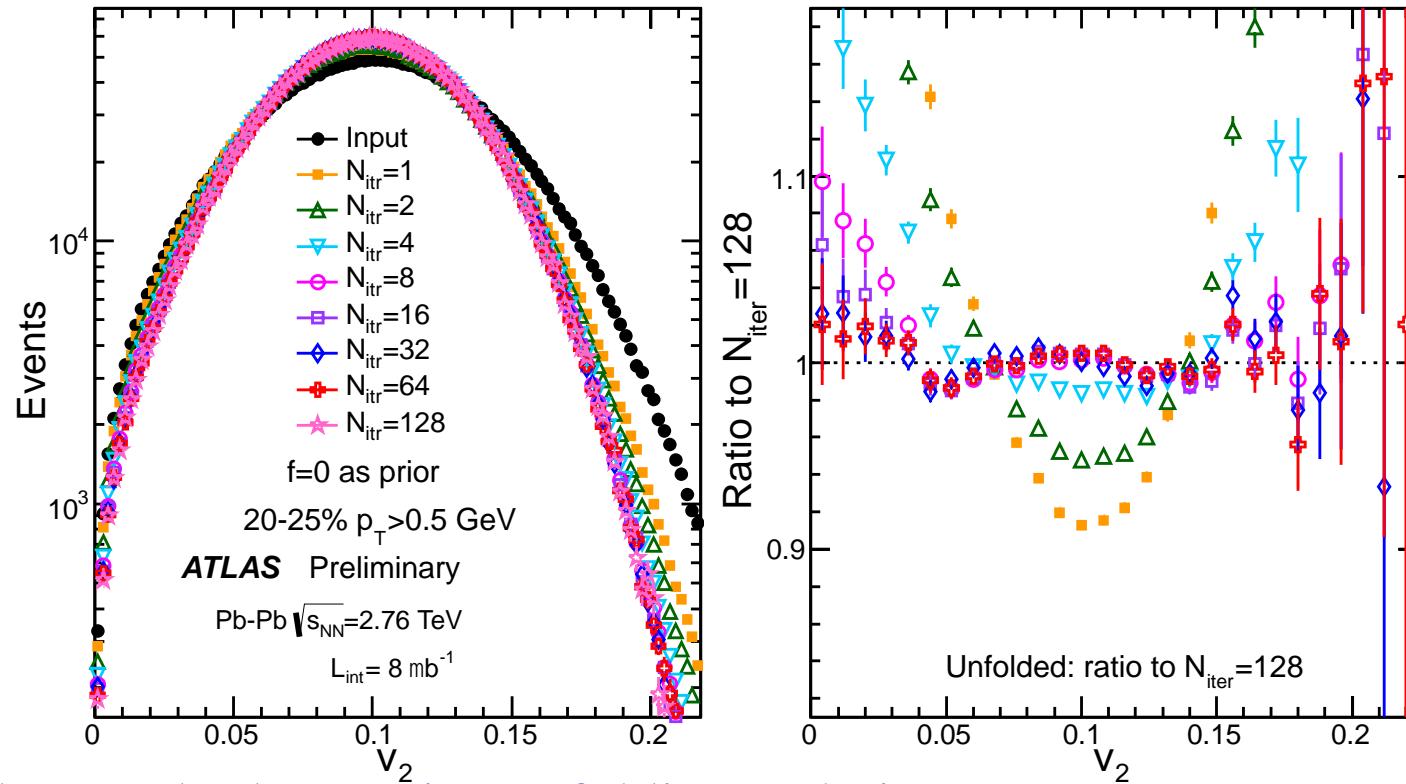
- Use the standard Bayesian unfolding technique

- Converges within a few % for $N_{iter}=8$, small improvements for larger N_{iter}.

- Many cross checks show good consistency
    - Unfolding with different initial distributions   Details in ATLAS-CONF-2012-114
    - Unfolding using tracks in a smaller detector
    - Unfolding directly on the EbE two-particle correlation.

Flow probability distributions
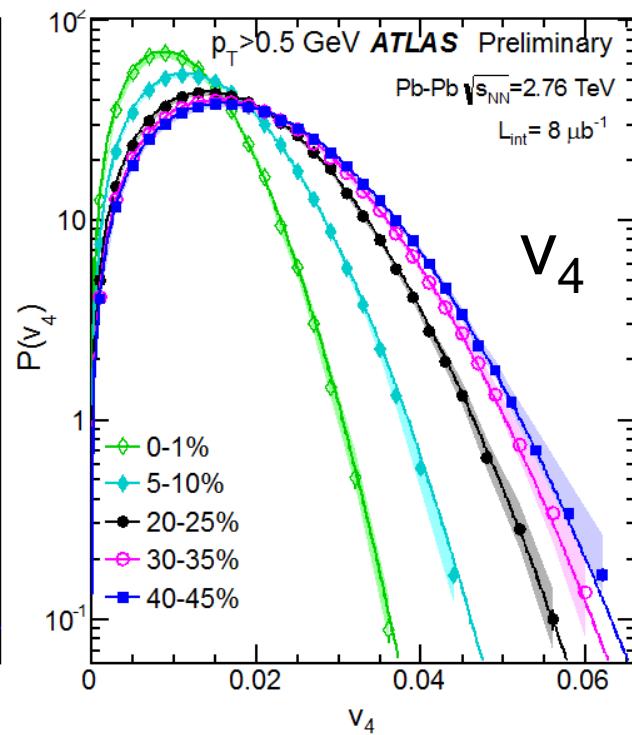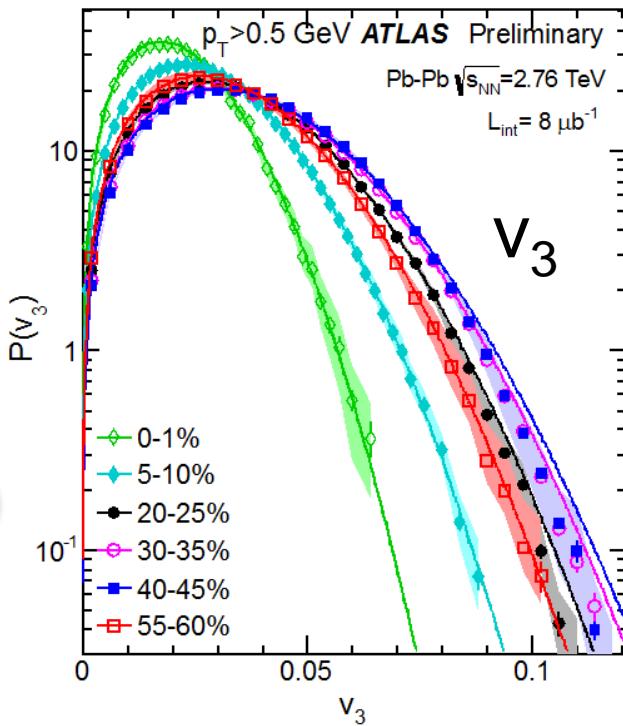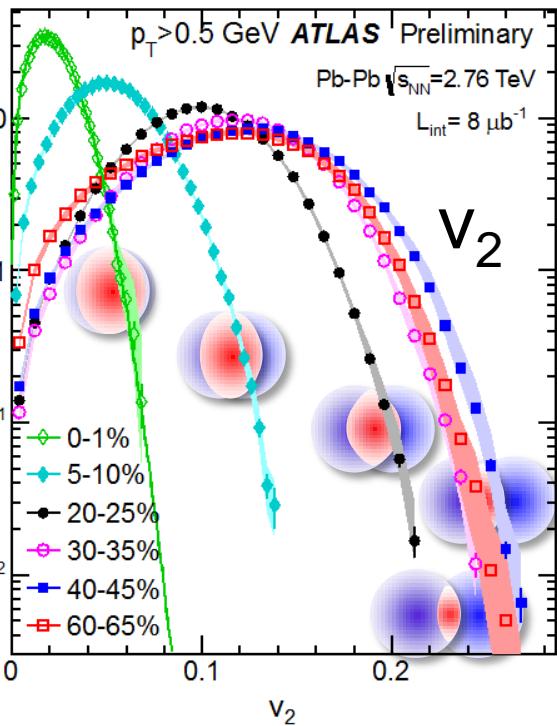
- v_n distributions corrected for detector effect and finite multiplicity
- v_2 in central, and v_3 v_4 in all centrality are described by a radial

  Gaussian function: $P(v_n) = \dfrac{v_n}{\sigma^2} e^{-\frac{v_n^2}{2\sigma^2}}$ →driven by Gaussian fluctuation

$$\frac{\sigma_{v_n}}{\langle v_n \rangle} = \sqrt{\frac{4}{\pi} - 1} = 0.523 \qquad \sqrt{\langle v_n^2 \rangle} = \frac{2}{\sqrt{\pi}} \langle v_n \rangle = 1.13 \langle v_n \rangle$$

p_T-scaling of the probability distribution
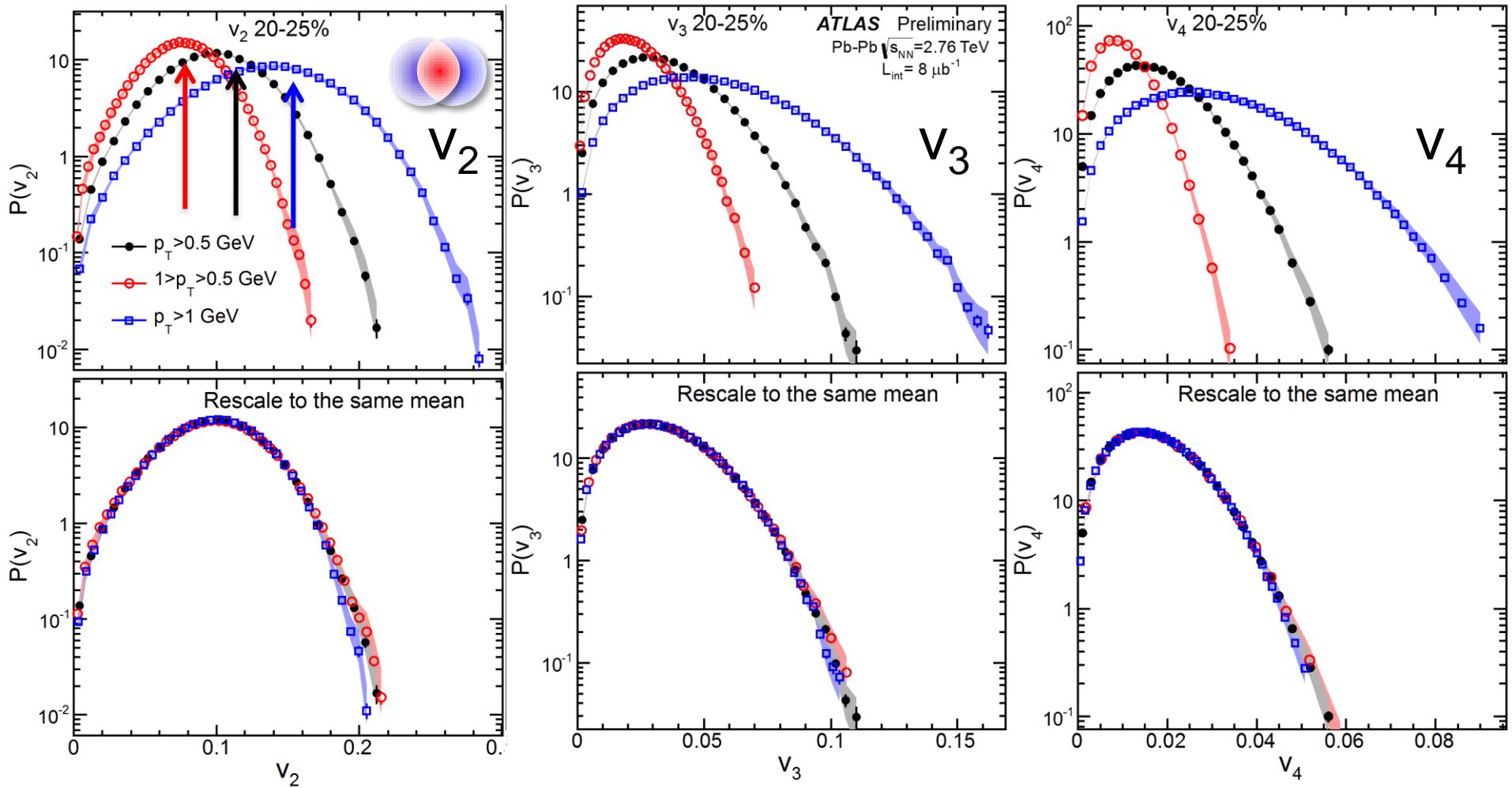
All p_T bins have similar shape, hold for all n.

Hydrodynamic response ~ independent of p_T.

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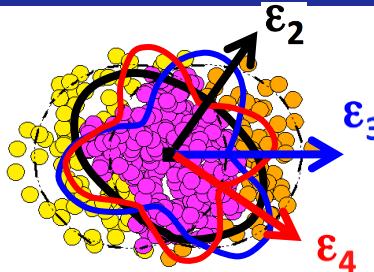
$$v_n \propto \epsilon_n = \frac{\sqrt{\langle r^n \cos n\phi \rangle^2 + \langle r^n \sin n\phi \rangle^2}}{\langle r^n \rangle}$$

Glauber and CGC mckln

Rescale ϵ_n distribution to the mean of data
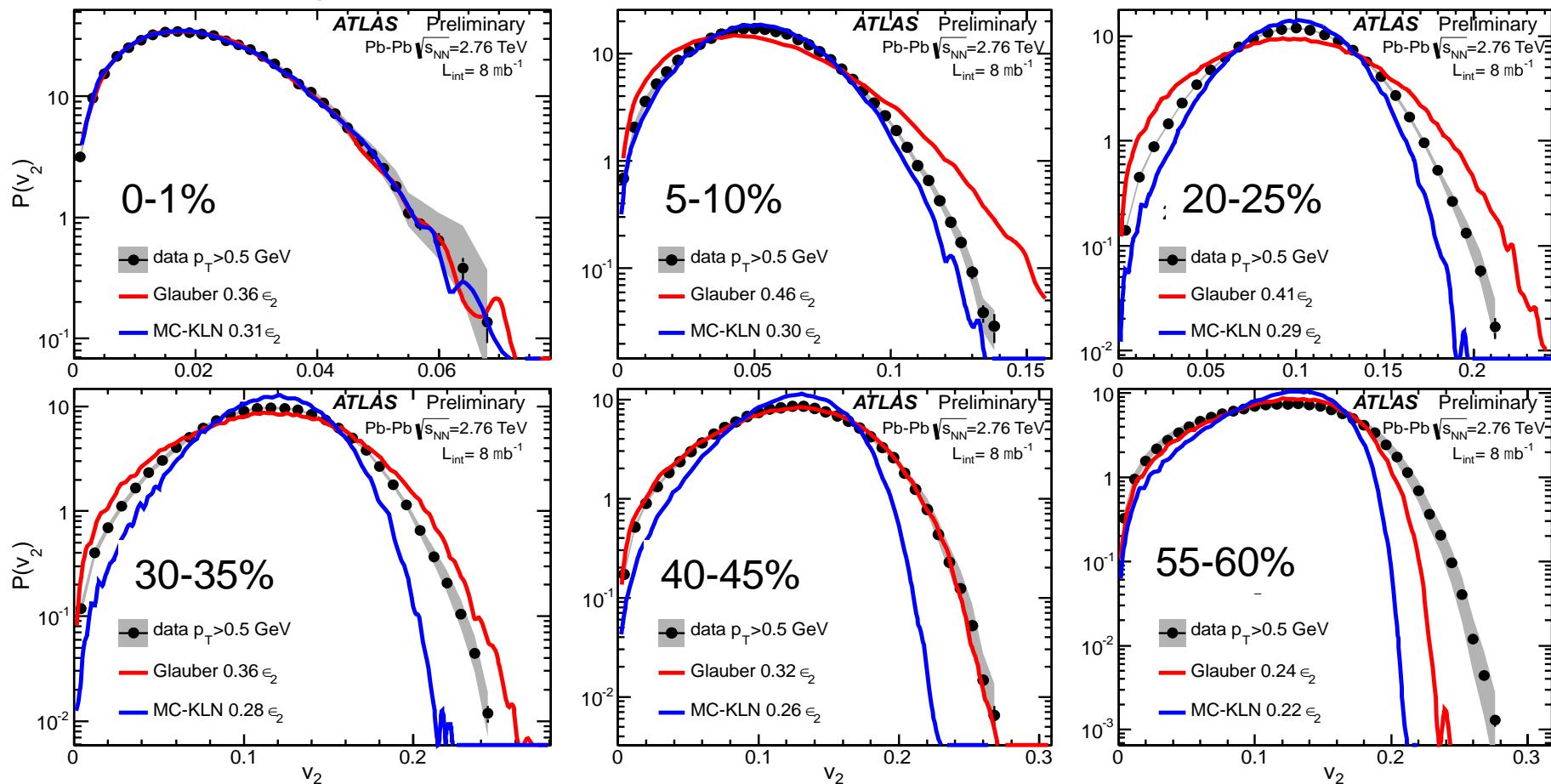
Both models fail describing $p(v_2)$ across the full centrality range

$$\frac{\sigma_{v_n}}{\langle v_n \rangle} = \sqrt{\frac{4}{\pi} - 1} = 0.523$$

Gaussian limit

- **Direct precision measurement of the relative fluctuations**
  - Consistent with but more precise than those obtained indirectly from cummulant method

$$\frac{\sigma_2}{<v_2>} \approx \sqrt{\frac{v_2\{2\}^2 - v_2\{4\}^2}{v_2\{2\}^2 + v_2\{4\}^2}}$$

- Expectations: $\langle v_n \rangle \leq v_n^{\mathrm{EP}} \leq \sqrt{\langle v_n^2 \rangle} = \sqrt{\langle v_n \rangle^2 + \sigma_{v_n}^2}$. **Verified!!**

◯ $\sqrt{v_n^2} / \langle v_n \rangle$

□ $v_n^{\mathrm{EP}}/\langle v_n \rangle$

ATLAS EP $v_n \approx \sqrt{v_n^2}$ within few %
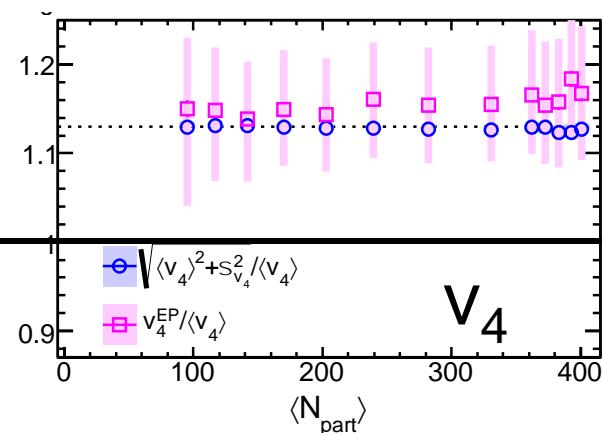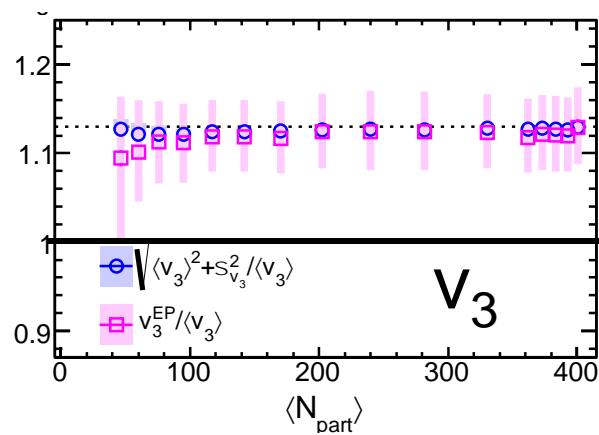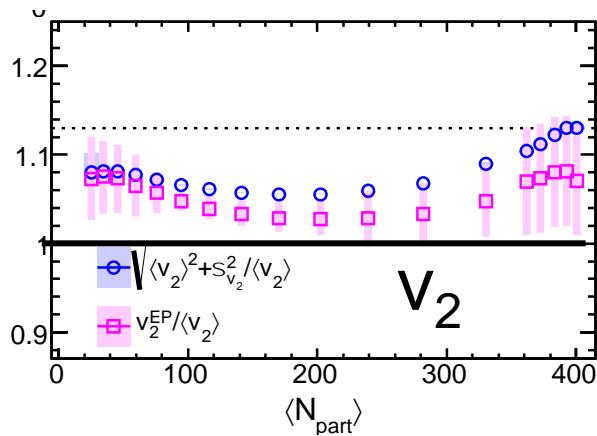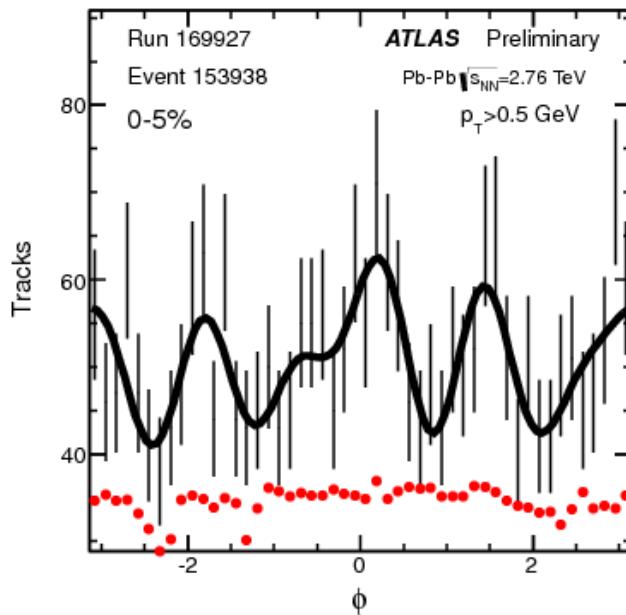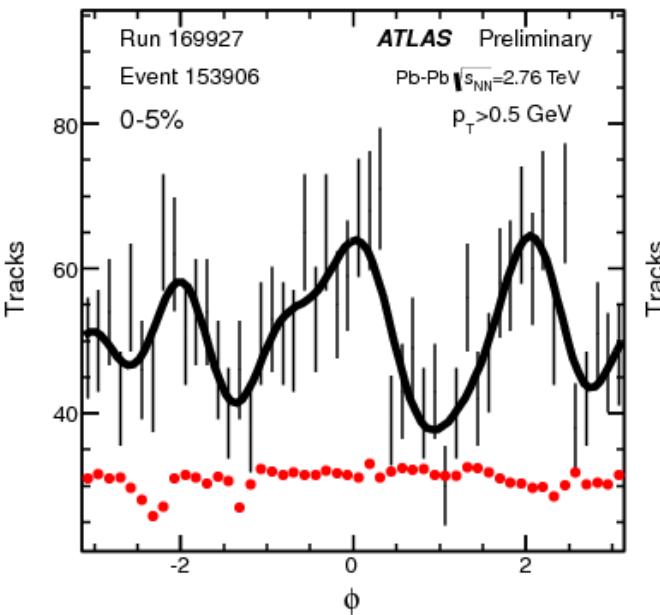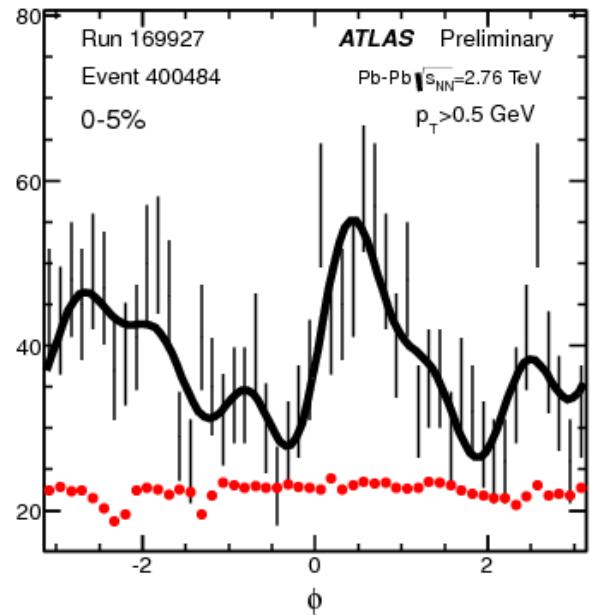
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- Correlation can exist in the initial geometry and also generated during hydro evolution

- The correlation can be quantify via a set of simple correlators

arXiv:1205.3585
arXiv:1203.5095

$$\frac{dN_{events}}{d\left(k(\Phi_n - \Phi_m)\right)} = 1 + 2\sum_{j=1}^{\infty} V_{n,m}^{\,j} \cos\left(jk(\Phi_n - \Phi_m)\right)$$

$$V_{n,m}^{\,j} = \left\langle \cos\left(jk(\Phi_n - \Phi_m)\right)\right\rangle$$
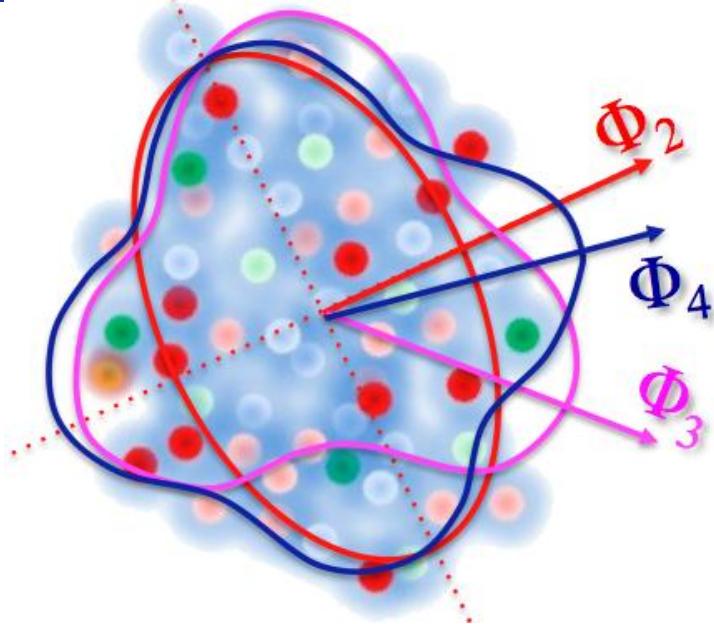
- Measured quantify need to be corrected by resolution

$$\left\langle \cos\left(jk(\Phi_n - \Phi_m)\right)\right\rangle = \frac{\left\langle \cos\left(jk(\Psi_n - \Psi_m)\right)\right\rangle}{\mathrm{Res}(jk\Psi_n)\mathrm{Res}(jk\Psi_m)}$$

$$\Phi_n = True, \quad \Psi_n = Measured$$

- This can be generalized into multi-plane correlations

$$\left\langle \cos\left(c_1\Phi_1 + 2c_2\Phi_2 ... lc_l\Phi_l\right)\right\rangle \quad c_1 + 2c_2 + ...lc_l = 0$$
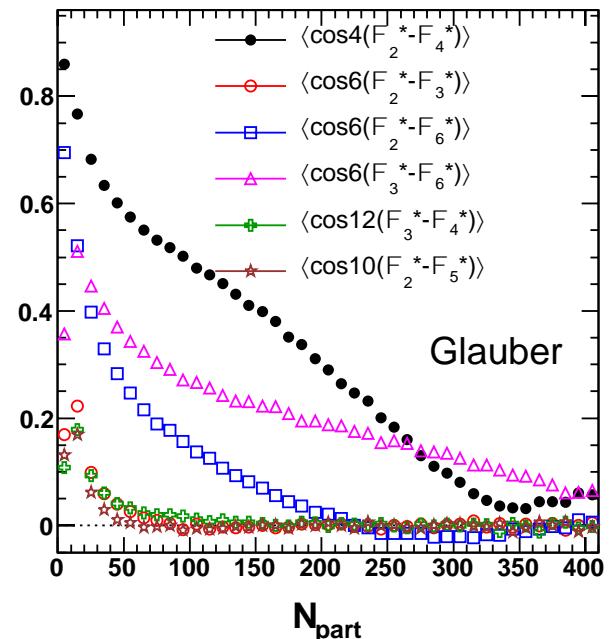
A list of measured correlators

- List of two-plane correlators

$$\langle \cos 4(\Phi_2 - \Phi_4) \rangle$$
$$\langle \cos 8(\Phi_2 - \Phi_4) \rangle$$
$$\langle \cos 12(\Phi_2 - \Phi_4) \rangle$$
$$\langle \cos 6(\Phi_2 - \Phi_3) \rangle$$
$$\langle \cos 6(\Phi_2 - \Phi_6) \rangle$$
$$\langle \cos 6(\Phi_3 - \Phi_6) \rangle$$
$$\langle \cos 12(\Phi_3 - \Phi_4) \rangle$$
$$\langle \cos 10(\Phi_2 - \Phi_5) \rangle$$

- List of three-plane correlators

"2-3-5"
$$\langle \cos(2\Phi_2 + 3\Phi_3 - 5\Phi_5) \rangle$$
$$\langle \cos(-8\Phi_2 + 3\Phi_3 + 5\Phi_5) \rangle$$

"2-4-6"
$$\langle \cos(2\Phi_2 + 4\Phi_4 - 6\Phi_6) \rangle$$
$$\langle \cos(-10\Phi_2 + 4\Phi_4 + 6\Phi_6) \rangle$$

"2-3-4"
$$\langle \cos(2\Phi_2 - 6\Phi_3 + 4\Phi_4) \rangle$$
$$\langle \cos(-10\Phi_2 + 6\Phi_3 + 4\Phi_4) \rangle$$

$$2\Phi_2 + 4\Phi_4 - 6\Phi_6 \;=\; 4(\Phi_4 - \Phi_2) - 6(\Phi_6 - \Phi_2)$$
$$-10\Phi_2 + 4\Phi_4 + 6\Phi_6 \;=\; 4(\Phi_4 - \Phi_2) + 6(\Phi_6 - \Phi_2)$$

Reflects correlation of two Φ_n relative to the third

Two-plane correlations

$\left\langle \cos(1 \times 4(\Phi_2 - \Phi_4)) \right\rangle$ $\left\langle \cos(2 \times 4(\Phi_2 - \Phi_4)) \right\rangle$ $\left\langle \cos(3 \times 4(\Phi_2 - \Phi_4)) \right\rangle$
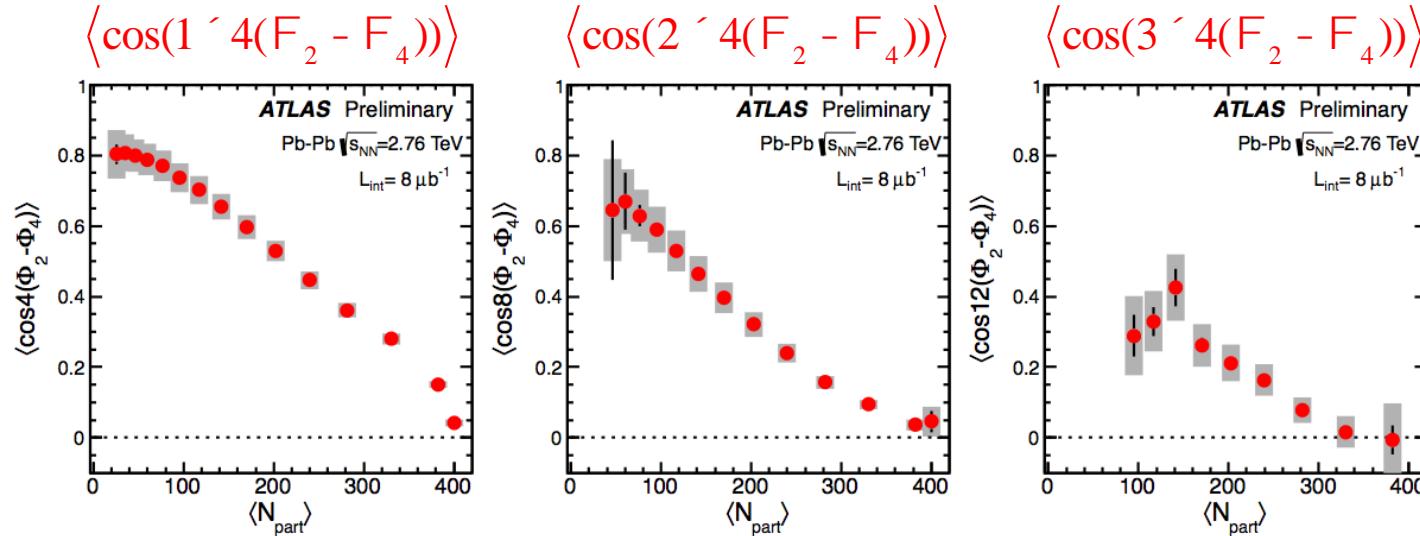
$$v_6 e^{-i\,6\Upsilon_6} = \text{geometry} + v_2 v_2 v_2 e^{-i\,6\Upsilon_2} + v_3 v_3 e^{-i\,6\Upsilon_3} + ...$$

Teany & Yan

Rich centrality dependence patterns

Three-plane correlations

"2-3-5" correlation
$$\langle \cos(2\Phi_2 + 3\Phi_3 - 5\Phi_5)\rangle$$
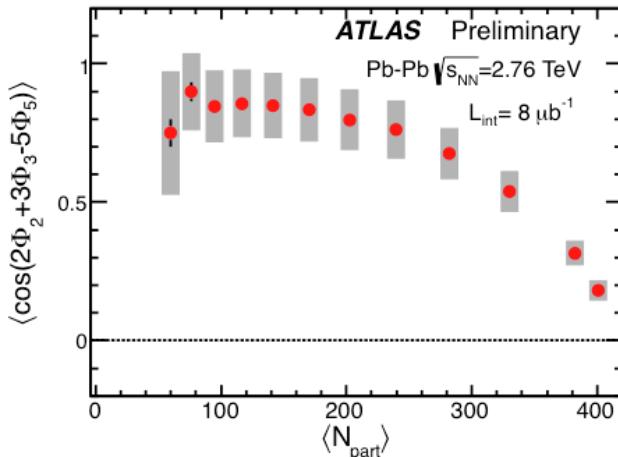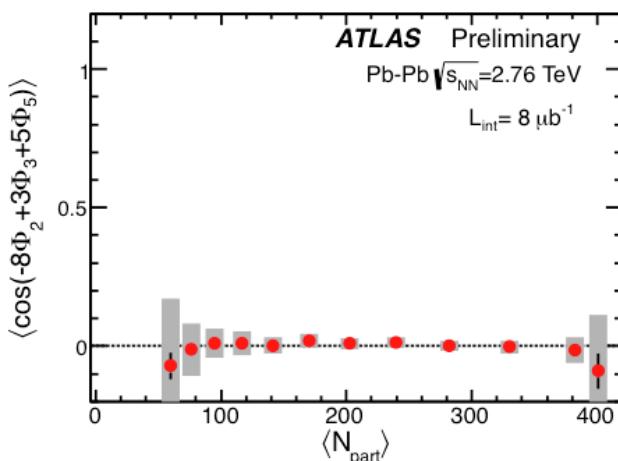
"2-4-6" correlation
$$\langle \cos(2\Phi_2 + 4\Phi_4 - 6\Phi_6)\rangle$$
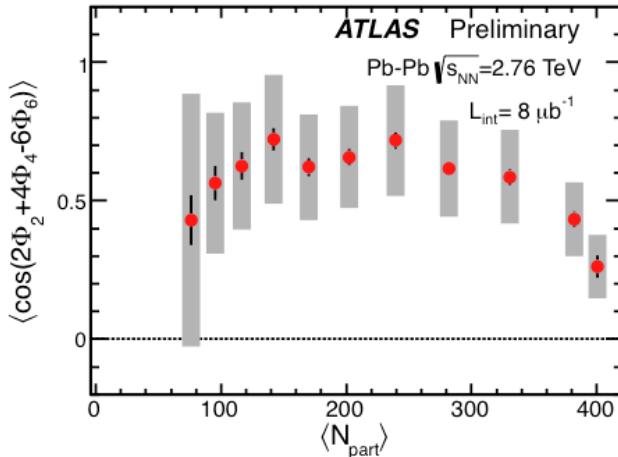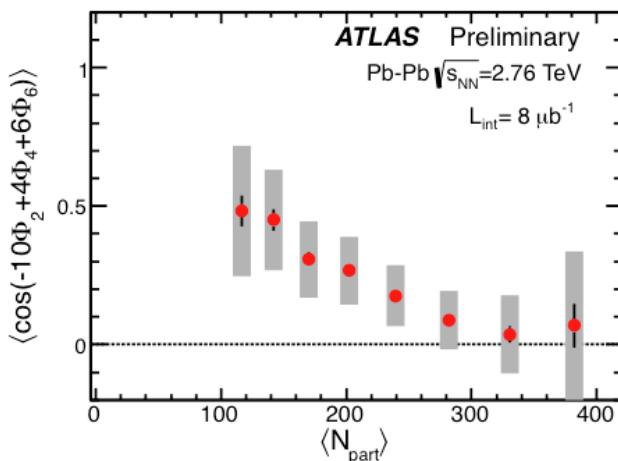
"2-3-4" correlation
$$\langle \cos(2\Phi_2 - 6\Phi_3 + 4\Phi_4)\rangle$$

$$\langle \cos(-8\Phi_2 + 3\Phi_3 + 5\Phi_5)\rangle$$

$$\langle \cos(-10\Phi_2 + 4\Phi_4 + 6\Phi_6)\rangle$$
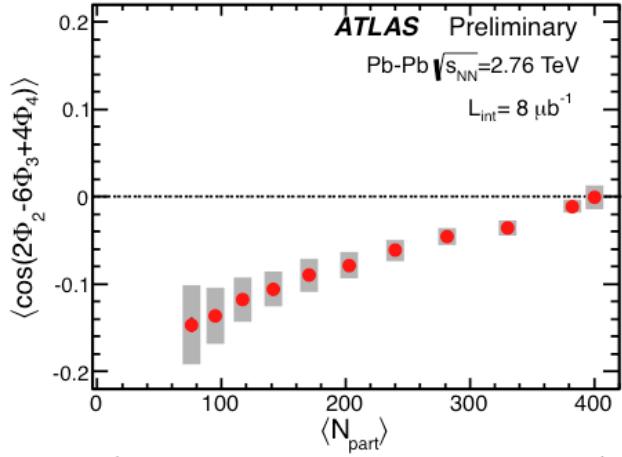
$$\langle \cos(-10\Phi_2 + 6\Phi_3 + 4\Phi_4)\rangle$$
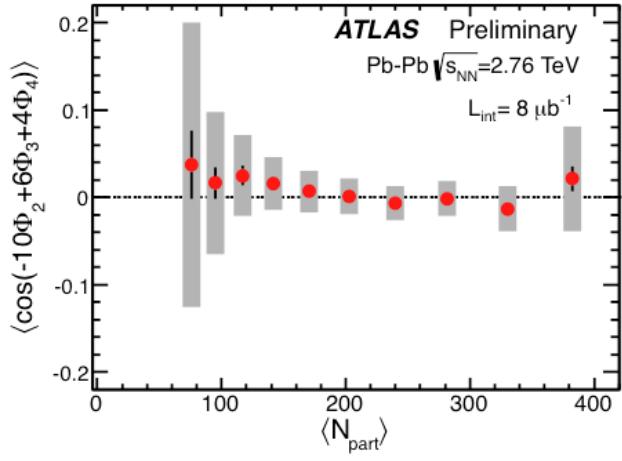
Rich centrality dependence patterns

Compare with EbE hydro calculation: 2-plane

Initial geometry + hydrodynamic

● ATLAS data

— MC-Glb., $\eta/s = 0.08$

- - - MC-KLN, $\eta/s = 0.2$

Zhe & Heinz

geometry only

— MC-Glb.

- - - MC-KLN.

$\langle\cos(4(\Psi_2-\Psi_4))\rangle$ $\langle\cos(8(\Psi_2-\Psi_4))\rangle$ $\langle\cos(12(\Psi_2-\Psi_4))\rangle$ $\langle\cos(6(\Psi_2-\Psi_3))\rangle$

$\langle\cos(4(\Phi_2-\Phi_4))\rangle$ $\langle\cos(8(\Phi_2-\Phi_4))\rangle$ $\langle\cos(12(\Phi_2-\Phi_4))\rangle$ $\langle\cos(6(\Phi_2-\Phi_3))\rangle$

N_{part}

EbE hydro qualitatively reproduce features in the data

Initial geometry
+ hydrodynamic

● ATLAS data

── MC-Glb., $\eta/s = 0.08$

─ ─ MC-KLN, $\eta/s = 0.2$

Zhe & Heinz

geometry only

── MC-Glb.

─ ─ MC-KLN.

$\langle \cos(2\Psi_2 + 3\Psi_3 - 5\Psi_5) \rangle$

$\langle \cos(2\Psi_2 + 4\Psi_4 - 6\Psi_6) \rangle$

$\langle \cos(2\Psi_2 - 6\Psi_3 + 4\Psi_4) \rangle$

$\langle \cos(2\Phi_2 + 3\Phi_3 - 5\Phi_5) \rangle$

$\langle \cos(2\Phi_2 + 4\Phi_4 - 6\Phi_6) \rangle$

$\langle \cos(2\Phi_2 - 6\Phi_3 + 4\Phi_4) \rangle$

N_{part}
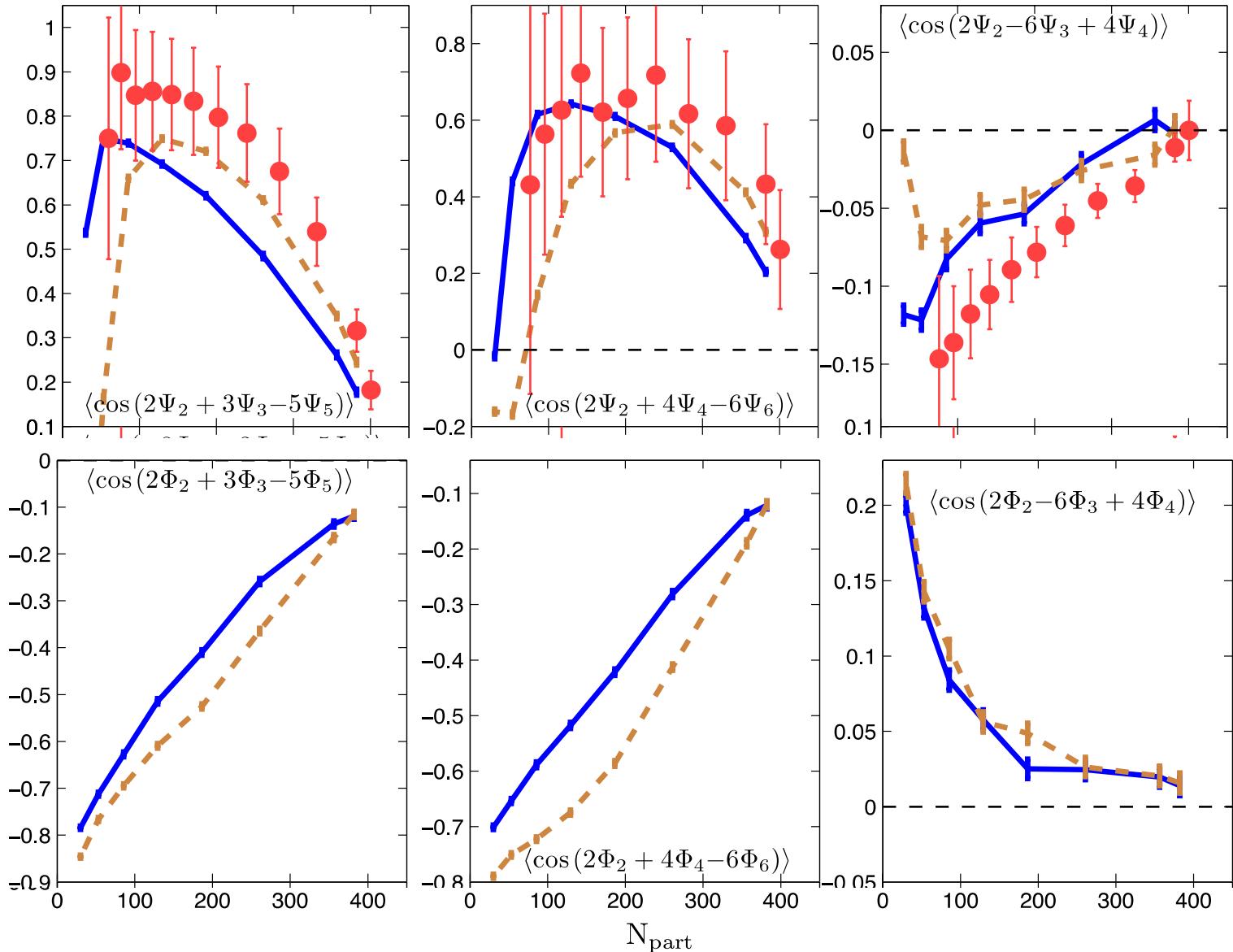
EbE hydro qualitatively reproduce features in the data

- Detailed differential measurement of $v_n(p_T, \eta, \text{centrality})$ for n=1-6

  - Factorization of $v_{n,n}$ to v_n works well for n=2-6, but breaks for n=1
  - dipolar flow v_1 extracted from $v_{1,1}$ via a two component fit.
    - v_1 magnitude comparable to v_3, indicating significant dipole deformation in the initial state. High p_T v_1 may reflect L dependence of energy loss

- Event-by-event probability distribution of v_2-v_4

  - Consistent with Gaussian fluctuation for v_2 in central and v_3, v_4 in all centralities
  - The shape has no p_T dependence→hydro response independent of p_T
  - Glauber &MC-KLN model fails to describe the shape for all centralies.
  - Event plane v_n ~ RMS v_n for n=3-4, but is in between RMS and mean for n=2

- Many correlations between two and three event planes

  - Some correlations qualitatively similar to Glauber model, many are not
  - Provides new constraints for initial geometry as well as hydro models

Qiu and Heinz, arXiv:1208.1200 Teaney and Yan, arXiv:1206.1905

Dependence on prior: v_4 20-25%
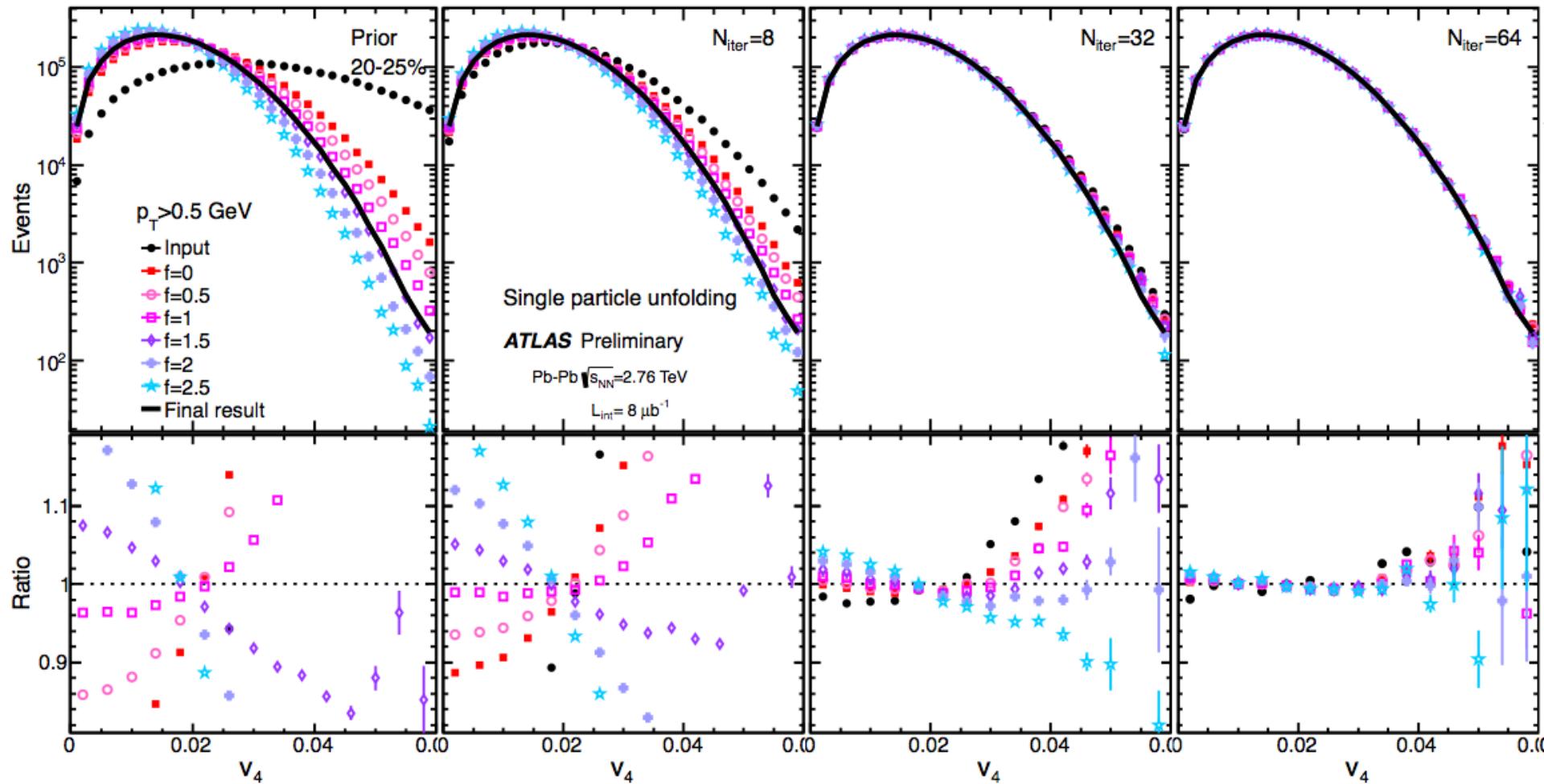
- Despite different initial distribution, all converged for N_{iter}=64
- Wide prior converges from above, narrow prior converges from below! Provide constrains on the residual non-convergence

Compare to unfolding for half-ID: 20-25%

- Agrees within a few % in most cases, but can be larger in the tails, which mainly reflects the non-convergence of half-ID (since width of its response function is √2 wider)
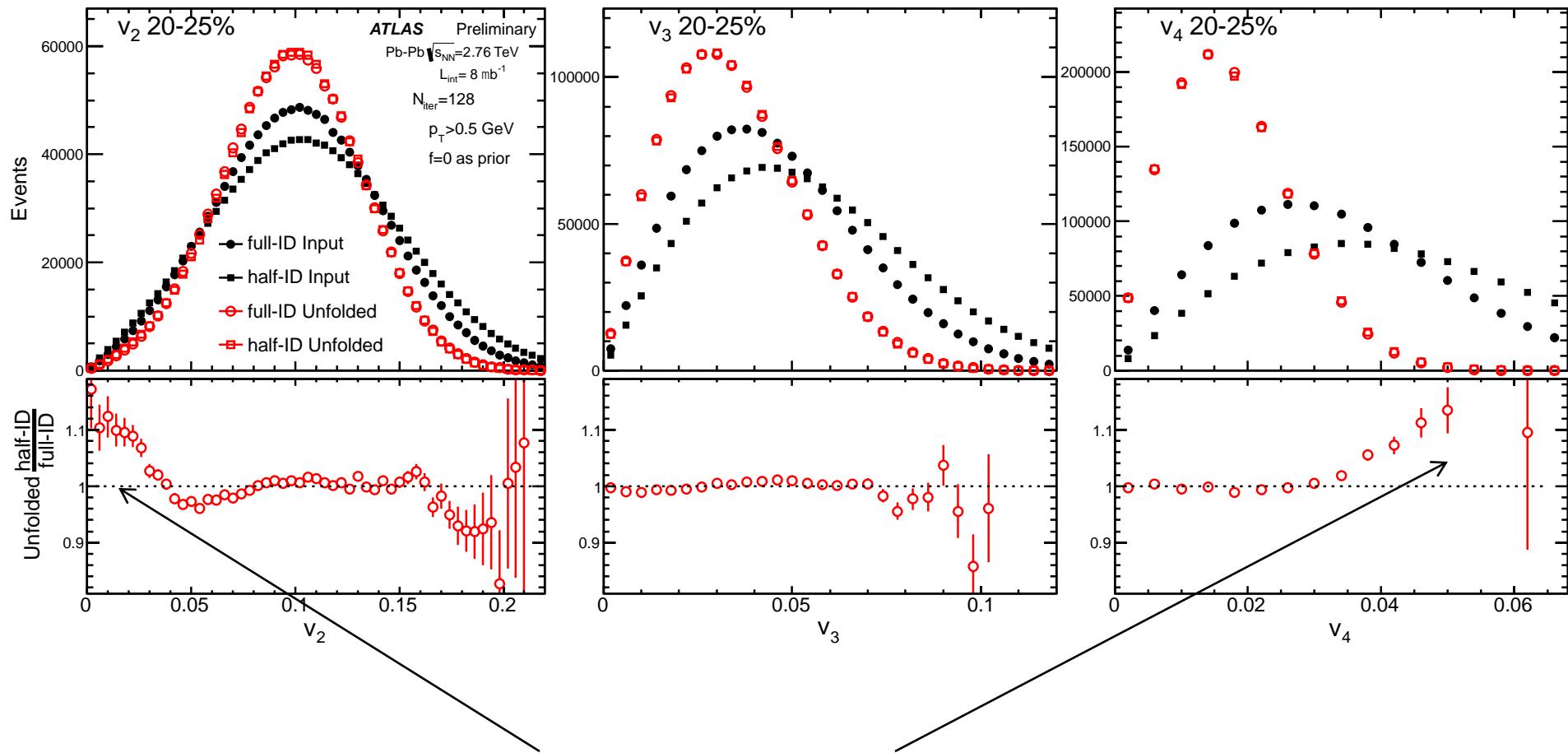


Residual non-convergence of half-ID
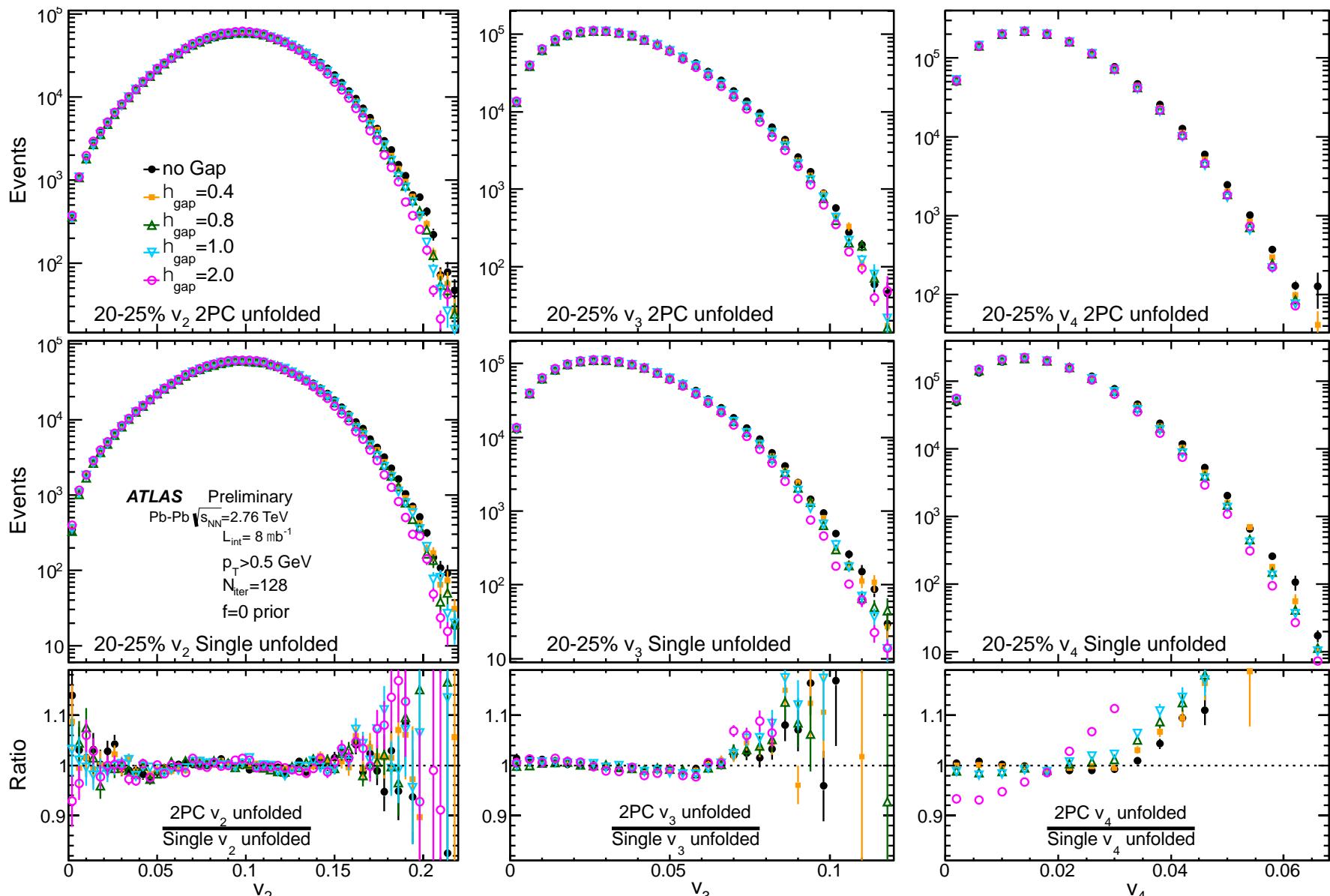
Figure 21: The unfolded distributions from 2PC method (top row), single particle method (middle row) and the ratios between the two (bottom row) for different values of η_{gap} in the 20-25% centrality interval and for $n = 2$ (left column), $n = 3$ (middle column) and $n = 4$ (right column).
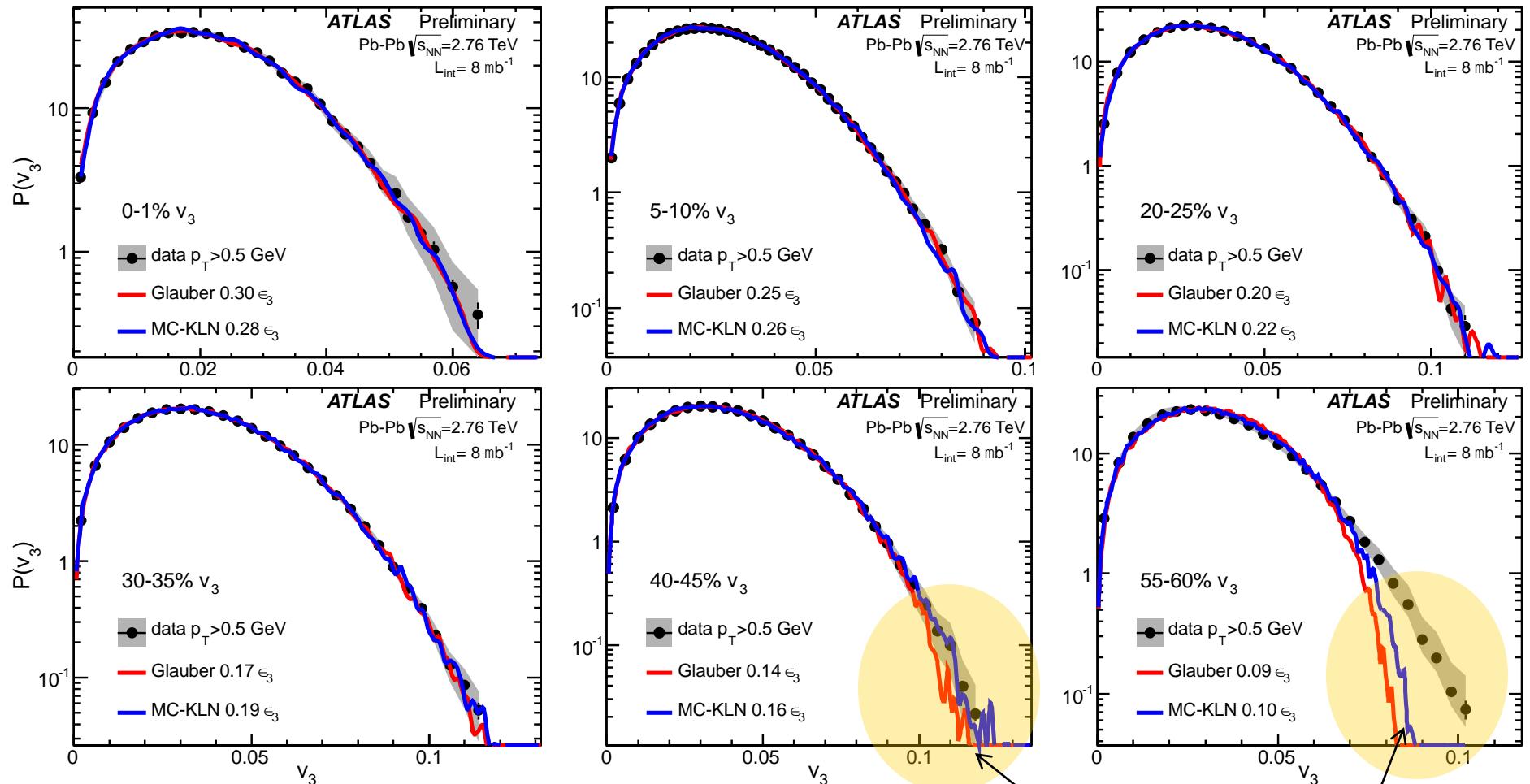
- Good agreement except in peripheral collisions, but this could be trivial, since all Gaussian functions have same reduced shape.
- Similar observation for v$_4$

Non-linear responses

Non-linear responses