# Measurement of flow harmonics in $\sqrt{s_{NN}} = 2.76\ TeV$ Pb+Pb Collisions with the ATLAS detector

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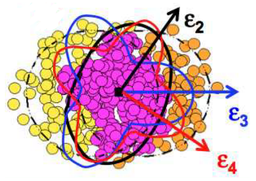
## Motivation



Depiction of the initial geometry of the fireball, showing the various eccentricities

- In heavy ion collisions, a fireball is formed that expandes collectively due to large pressure gradient and low viscosity. The azimuthal distribution of emitted particles reflects the shape initial geometry which fluctuate event by event

$$\frac{dN}{d\phi} \propto (1 + 2\sum_{n=1}^{\infty} v_n \cos(n\phi - n\Psi_{RP,n})) \quad \left(\Psi_{RP,n} \equiv \text{direction of } n^{th} \text{flow}\right)$$

- The correlation with geometry is global correlation, they also contribute to two-particle correlation in the following way

$$\frac{dN_{pairs}}{d\Delta\phi} \propto 1 + 2\sum_{n} v_{n,n}^{a,b} \cos(n\Delta\phi), \text{where } v_{n,n}^{a,b} = v_n^a v_n^b$$

- We can measure $v_n$ from single particle distribution relative to $\Psi_{RP,n}$ ➔ Event-Plane (EP) method,
- We can also measure $v_n$ from pair correlations ➔ Two Particle Correlation (2PC) method

Beside $v_2$, higher order $v_n$ (n>2) carry important information about the medium such as the initial geometry and the viscosity and hence are important observables. e.g. Higher order flow are more sensitive to geometrical fluctuations and viscosity.

We present measurements of $v_2$-$v_6$ using the EP and 2PC methods with the ATLAS detector. We use Forward Calorimeter (FCal, 3.2<|η|<4.9) for centrality and EP measurement, and we use the Inner Detector (ID, full φ coverage and |η|<2.5, corresponding to |Δη| <5.0 for pairs) for charged particles measurements

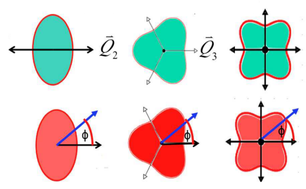
## Event Plane (EP) Analysis

### Reaction plane resolution

- The reaction plane is obtained using the Q-vector method:

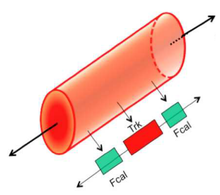
$$Q_{x,n} = \sum_i E_i \cos(n\phi_i)\ ;\ Q_{y,n} = \sum_i E_i \sin(n\phi_i); \Psi_n = \frac{1}{n}\tan^{-1}\left(\frac{Q_{y,n}}{Q_{x,n}}\right)$$

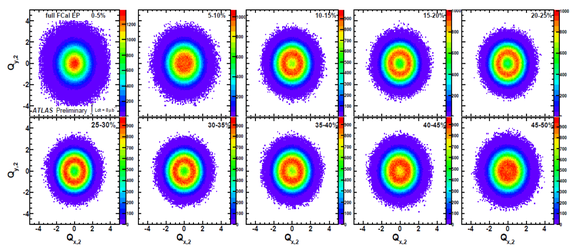
- $E_i$ is the energy deposited in the $i^{th}$ FCal tower having azimuth $\phi_i$.
- In mid-central collisions, the $Q_2$-vector is distributed in a ring like structure indicating the excellent reaction plane resolution of the FCal.
- In central and peripheral collisions and for higher orders, the ring blurs out as the resolution decreases.



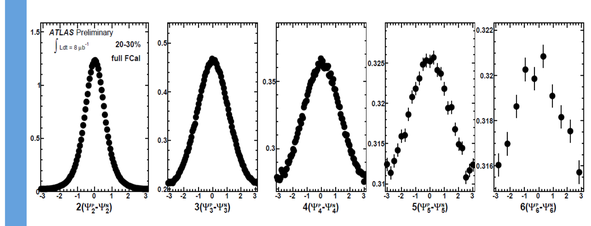
EP is obtained from $E_T$ flow in FCal

- Raw $v_n$ values are obtained by correlating tracks in Inner Detector with EP



Normalized FCal $Q_2$-vector distributions in different Centralities

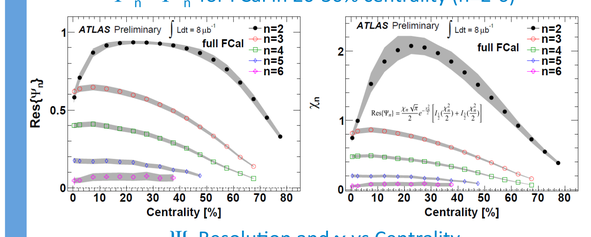


$\Psi^P_n$ - $\Psi^N_n$ for FCal in 20-30% centrality (n=2-6)

- The raw $v_n$ are corrected to account for the FCal reaction-plane resolution:

$$v_n = \frac{v_n^{obs}}{\text{Res}\{\Psi_n\}} = \frac{\langle \cos n(\phi - \Psi_n)\rangle}{\langle \cos n(\Psi_n - \Psi_{RP,n})\rangle}$$

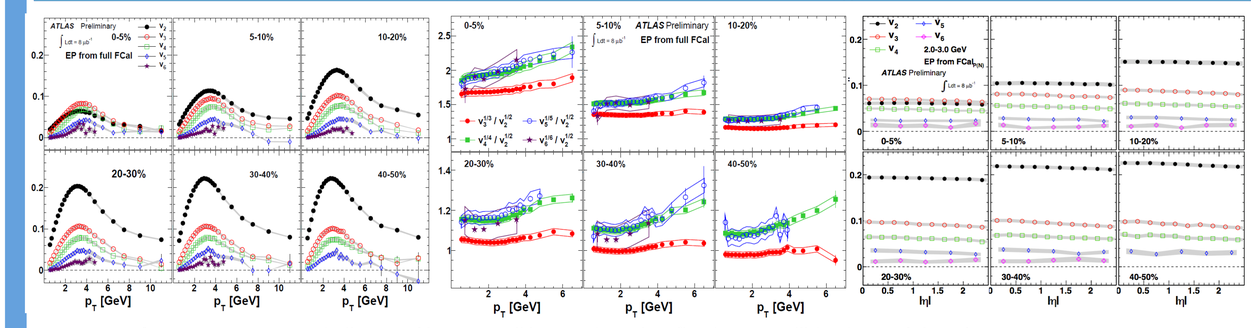
- The resolution is obtained from the two-sub-event method using the distribution of $\Psi_P$-$\Psi_N$ (see figure to the left), where $\Psi_P(\Psi_N)$ are the $n^{th}$ order reaction planes obtained by the Positive (Negative) side of the FCal



$\Psi_n$ Resolution and χ vs Centrality

- Systematic errors on the resolution are obtained by several cross-checks using the three sub-event method, where we correlate the FCal with several other detectors such as the Electromagnetic End-Cap (1.5<|η|<3.2), Electromagnetic Barrel (|η|<1.5), and the Tracking detectors (|η|<2.5)
- In general the resolution for a higher order reaction plane is smaller than that of a lower order plane except in the top 1% most central events where the $\Psi_3$ resolution is higher than the $\Psi_2$ resolution.
- $v_n$ is measured for centrality selections which have good resolution (0-80% for $v_2$, 0-70% for $v_3$ and $v_4$, 0-50% for $v_5$ and 0-40% for $v_6$)

### $p_T$ and η Dependence of $v_n$



- **$p_T$ Dependence:** we see a very similar trend between all harmonics. They first increase till 3-4*GeV* and then decrease.
- In general the higher order harmonic is smaller than a lower order harmonic, except in the most central collisions, where $v_3$ and $v_4$ can be larger than $v_2$ depending on the $p_T$.
- We also observe an interesting (approximate) scaling relation in the $p_T$ dependence between the harmonics. We see that $v_n^{1/n} = k v_2^{1/2}$, where "k" is only weakly dependent on $p_T$.
- **η-Dependence**: for all harmonics, we see only a weak dependence on η (~5% drop). This is important as it is one of the assumptions made when we try to obtain the $v_n$ values from the two-particle correlations.

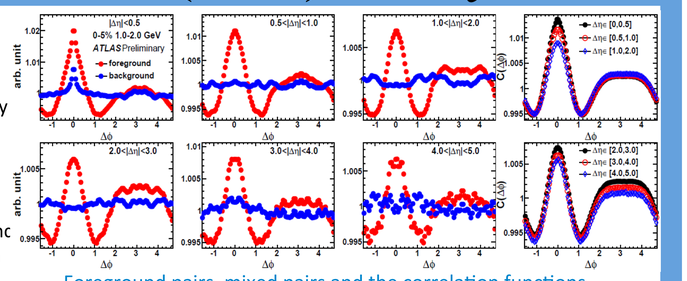
## Two Particle Correlation (2PC) Analysis

### 2PC Method

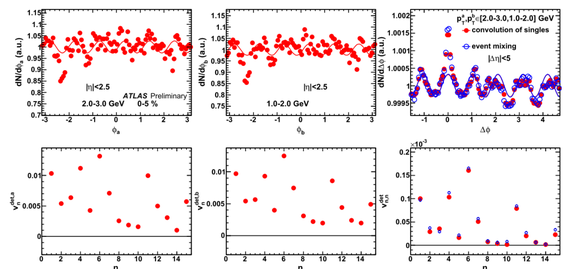
- The correlations are constructed by dividing foreground pairs by mixed background pairs.

$$C(\Delta\phi) = \frac{\text{Foreground Pairs}(\Delta\phi)}{\text{Mixed Pairs}(\Delta\phi)}$$

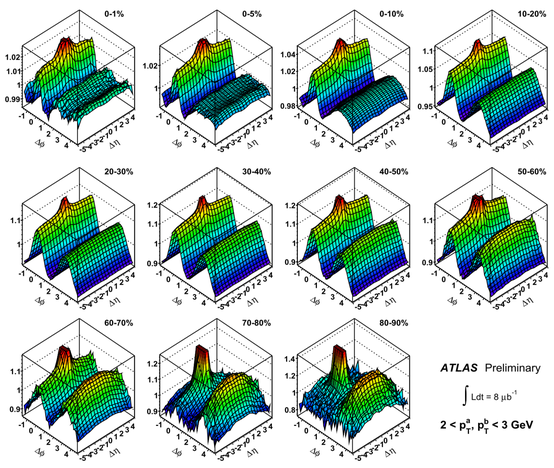
- The mixed background pairs account for detector acceptance and the final correlation contains only physical effects. The figures on the right illustrate this.
- The detector acceptance causes fluctuations ~ 0.001 in the foreground pairs, which mostly cancels out in the ratio.
- This pair acceptance can be calculated analytically by convoluting the two single-particle acceptance functions.
- They are transformed into Fourier space to quantify the influence on the $v_{n,n}$ and $v_n$.
- Such a reconstruction is shown in the figure on the right , both in Δφ and in Fourier space.



Foreground pairs, mixed pairs and the correlation functions



Single particle(and pair) acceptance in φ(Δφ) and Fourier space



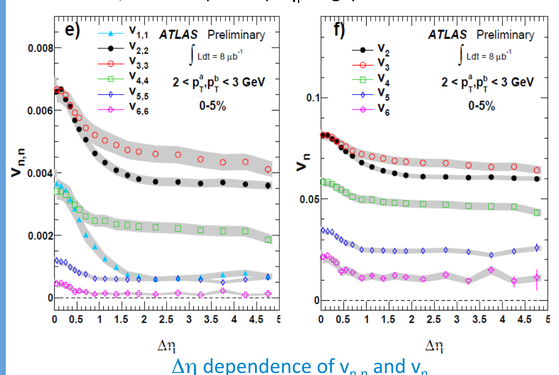
Centrality and Δη dependence of the correlations

### Flow Harmonics From Correlations

- The figures on the right show the steps in obtaining $v_n$
  - a) The 2D correlation function in Δη,Δφ.
  - b) The corresponding 1D correlation function in Δφ for 2<|Δη|<5
  - c) The $v_{n,n}$ obtained using a Discrete Fourier Transformation(DFT)

$$v_{n,n} = \langle \cos(n\Delta\phi)\rangle = \sum_i \cos(n\Delta\phi_i) C(\Delta\phi_i) \Big/ \sum_i C(\Delta\phi_i) \quad \text{n=1-15}$$

  - d) Corresponding $v_n$ values $v_n(p_T^a) = \sqrt{v_{n,n}(p_T^a, p_T^a)}$
- Repeat this procedure in narrow Δη slices to obtain $v_n$ vs Δη.
- The $v_n$ values peak at low Δη, due to jet bias. but are relatively flat afterwards, so we require a |Δη| >2 gap.



Δη dependence of $v_{n,n}$ and $v_n$

### Universality of $v_n$

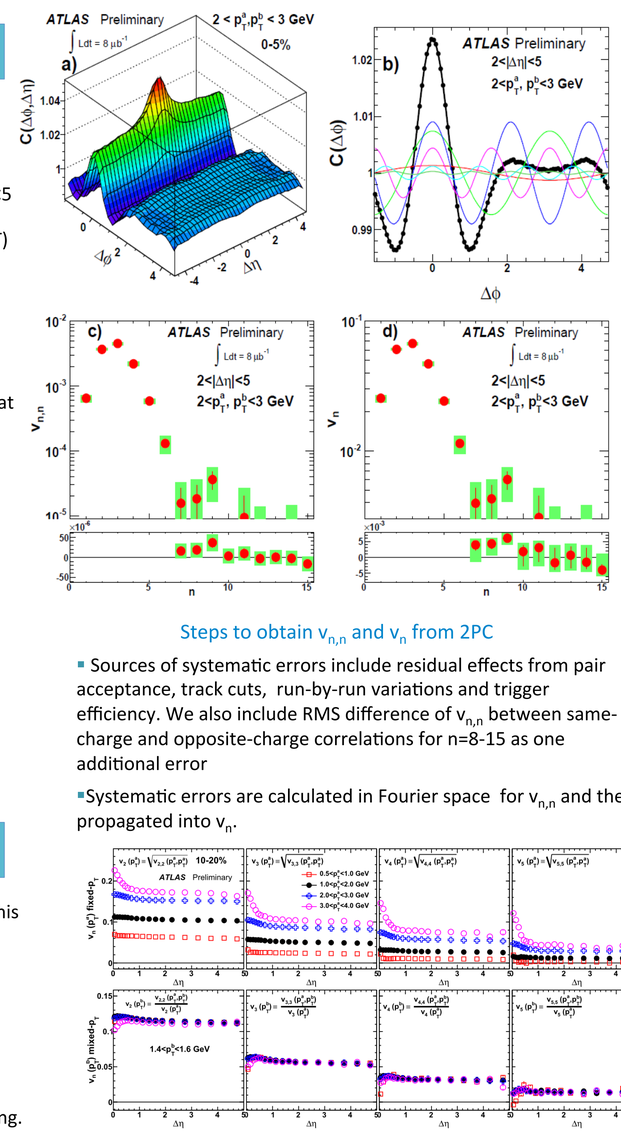
- The $v_n$ of a $p_T$ bin can also be obtained by correlating particles of this bin with particles from a different $p_T$ bin whose $v_n$ we know :

$$v_n^b = v_{n,n}^{a,b} / v_n^a \quad (\text{where } v_n^a = \sqrt{v_{n,n}^{a,a}})$$

- For Δη>1.0, different trigger-partner combinations having very different values of trigger $v_n$ always give same value of the partner (Target) $v_n$.
- For $v_{1,1}$ this factorization does not hold!
- For lower values of Δη, there is inconsistency because of jet-biasing.
- The $v_{n,n}$ is indeed factorizable for n>1.

### Centrality and Δη Dependence

- A near side ridge is seen in central and mid central collisions. Barring the Jet-peak, the ridge has weak Δη dependence.
- An away side double hump structure is seen in the most central events(0-1% and 0-5%) (No flow subtraction), which is also long range in Δη
- The strength of these long range structures increases from central to mid-central events and them diminishes, similar to the flow harmonics. It almost completely vanishes in the 80-90% centrality bin leaving behind the near side peak only. Just like p-p collisions.
- Note: The near side jet peak at (Δη,Δφ) =(0,0) is truncated for better view



Steps to obtain $v_{n,n}$ and $v_n$ from 2PC

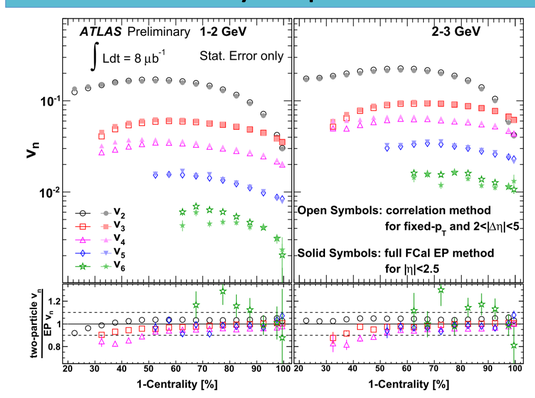
- Sources of systematic errors include residual effects from pair acceptance, track cuts, run-by-run variations and trigger efficiency. We also include RMS difference of $v_{n,n}$ between same-charge and opposite-charge correlations for n=8-15 as one additional error
- Systematic errors are calculated in Fourier space for $v_{n,n}$ and then propagated into $v_n$.



Same value of $v_n$ is obtained independent of the trigger $p_T$

## Comparison Between The Two Methods

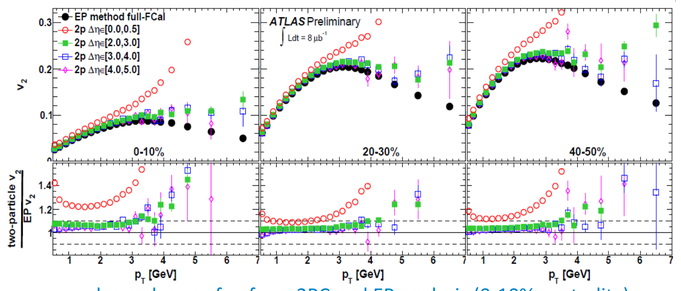
### Centrality Dependence



Centrality dependence of $v_n$ from 2PC and EP analysis

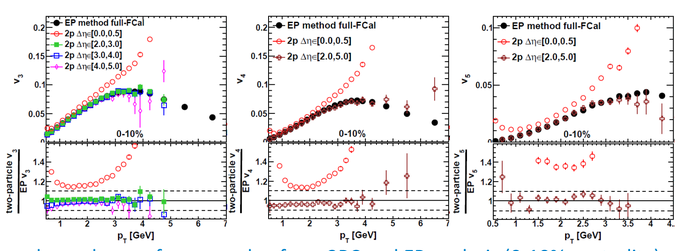
- Good agreement is seen between the $v_n$ obtained from the two methods at low $p_T$
- The agreement worsens for $v_5$ and $v_6$, but still within the systematic errors.
- $v_2$ has a stronger centrality dependence as it is influenced by the elliptical collision geometry which changes with centrality.
- Other harmonics have a weaker centrality dependence as the higher order eccentricities come from fluctuations in the collision geometry and not its average shape.
- It is interesting to note that in the 5% most central collisions, $v_3$ is larger than $v_2$ and it the top 1% most central collisions, even $v_4$ is larger than $v_2$.

### $p_T$ Dependence



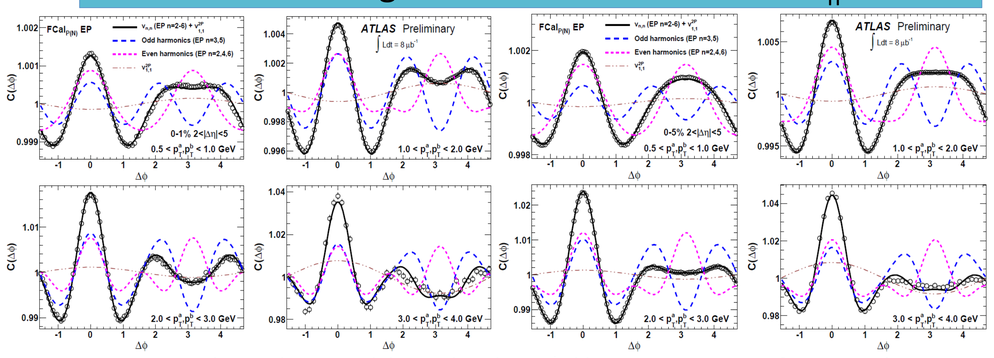
$p_T$ dependence of $v_2$ from 2PC and EP analysis (0-10% centrality)

- The 2PC $v_n$ for |Δη|<0.5 always deviates from the EP results for all $p_T$ and centralities (mainly due to near-side jet). But good agreements are seen for |Δη| >2 at $p_T$<4 GeV.
- However, we start to see deviations for $p_T$>4 GeV even for |Δη|>2 due to increased away-side jet contribution (which swings along Δη).



$p_T$ dependence of $v_3$ , $v_4$ and $v_5$ from 2PC and EP analysis (0-10% centrality)

### Recovering the Correlations From EP $v_n$



Two particle correlations and the predicted even/odd Fourier components from EP analysis

- The consistency between the two methods implies that the structure of the two-particle correlation at large Δη can be largely accounted for by the collective flow. We can check this explicitly by reconstructing the low $p_T$ correlation function at |Δη|>2 from $v_n$ measured by the EP method as

$$C(\Delta\phi) = N_0^{2P}(1 + 2v_{1,1}^{2P}\cos(\Delta\phi) + \sum_{n=2}^{6} v_n^{EP} \times v_n^{EP} \cos(n\Delta\phi))$$

- The pedestal $N_0^{2P}$ and first harmonic $v_{1,1}^{2P}$ are obtained from the correlation analysis
- The correlations are reconstructed well from the EP $v_n$ values. Even the double hump structure on the away side is recovered, suggesting a common physics origin for the near and away-side long range structure
- The away-side structure is clearly due to the interplay of even and odd harmonics, without the requirement for any additional models (such as the "mach cone")

- **In conclusion, we measured $v_2$-$v_6$ by both correlation and event-plane analysis. Significant and consistent $v_2$-$v_6$ were observed by the two methods. We observed that the $v_n$ follow a simple scaling relation: $v_n^{1/n} \propto v_2^{1/2}$. We also concluded that the features in two particle correlations for |Δη|>2 at low and intermediate $p_T$ ($p_T$<4.0*GeV*) can be accounted for by the collective flow of the medium.**