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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- 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

\[
\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos n(\phi - \Phi_n)
\]
The importance of fluctuations

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

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

Four-particle cumulant $\sim \sqrt{(\langle v_2 \rangle^2 - \sigma^2)}$

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

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

Large amount of information regarding the initial geometry and hydrodynamic expansion.
Event by Event flow measurements

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:

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

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

\[
v_n = \sqrt{v_{n,x}^2 + v_{n,y}^2}
\]
Azimuthal distribution in single event

- Ideal detector:

\[
\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} v_n \cos(n\phi - n\Psi) = 1 + \sum_{n=1}^{\infty} \left( v_{n,x} \cos(n\phi) + v_{n,y} \sin(n\phi) \right)
\]

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

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

- Correct for acceptance:

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

\[
v_{n,y} \rightarrow v_{n,y} - v_{n,y}^{\text{det}}
\]
Azimuthal distribution in single event

- **Ideal detector:**

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

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

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

- **Correct for acceptance:**

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

\[
v_{n,y} \rightarrow v_{n,y} - v_{n,y}^{\text{det}}
\]

- **Correct for efficiency by weighting tracks by**

\[
\frac{1}{\varepsilon(\eta, p_T)}
\]
Flow vector distribution & smearing

2D flow vector distribution

\[ v_{n,x} = \langle \cos(n\phi) \rangle, \quad v_{n,y} = \langle \sin(n\phi) \rangle \]
The $v_2^{\text{obs}}$ will differ from the true $v_2$ due to finite multiplicity in the events.
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.
Divide the event into two sub-events with roughly equal number of tracks.

The fluctuation in each sub-event will be \( \sqrt{2} \) 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!

\[ p(\vec{v}_n^{\text{obs}} | \vec{v}_n) \propto e^{-\frac{|\vec{v}_n^{\text{obs}} - \vec{v}_n|^2}{2\delta^2}} \]

\[ \delta = \begin{cases} 
\frac{\delta_{2SE}}{\sqrt{2}} & \text{for half ID} \\
\delta_{2SE} / 2 & \text{for full ID} 
\end{cases} \]

- Response function obtained by integrating out azimuth angle

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

- Use Bayesian unfolding to correct measured \( v_n \) distributions
Basic unfolding performance: $v_2$, 20-25%

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

small improvements for larger $N_{\text{iter}}$.
Despite different initial distribution, all converge for $N_{\text{iter}} = 64$

Wide prior converges from above, narrow prior converges from below.
Main physics result: probability distributions of $v_n$

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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Comparison to Event-plane $v_n$ values
Measuring the hydrodynamic response: $v_2^2$

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

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

Also see Li Yan’s talk in this session
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.
- 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 $N_{\text{iter}} = 8$
small improvements for larger $N_{\text{iter}}$. 
Measuring the hydrodynamic response: $v_3$
Measuring the hydrodynamic response: $v_4^{30}$
EbE distributions

Run 169927
Event 400484
Pb-Pb $\sqrt{s_{NN}}=2.76$ TeV
$\phi > 0.5$ GeV

Run 169927
Event 153906
Pb-Pb $\sqrt{s_{NN}}=2.76$ TeV
$\phi > 0.5$ GeV

Run 169927
Event 153938
Pb-Pb $\sqrt{s_{NN}}=2.76$ TeV
$\phi > 0.5$ GeV

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EbE distributions
Unfolding for Half ID

\[ V_2 \, 20-25\% \]

\[ V_3 \, 20-25\% \]

\[ V_4 \, 20-25\% \]

Events

Unfolded Half-ID

Full-ID Input

Half-ID Input

Full-ID Unfolded

Half-ID Unfolded

\[ N_{\text{int}}=128 \]

\[ p_T>0.5 \text{ GeV} \]

\[ l=0 \text{ as prior} \]
Unfolding implemented using RooUnfold package

- True ("cause" $c$ or $v_n$) vs measured distribution ("effect" $e$ or $v_{n}^{\text{obs}}$)

Denote response function

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

- Unfolding matrix $M$ is determined via iterative procedure

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

- Prior, $c^0$, can be chosen as input $v_{n}^{\text{obs}}$ 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

- $\Psi_n$ is measured here
- $\Psi_m$ is measured here
- Gap

-4.9 < $\eta$ < -0.5  
-0.5 < $\eta$ < 0.5  
0.5 < $\eta$ < 4.9

- Correlations are measured using EM+Forward calorimeters (-4.9 < $\eta$ < -4.9)
- If $\Psi_n$ is measured in negative half (-4.9 < $\eta$ < -0.5), then $\Psi_m$ is measured in positive half of calorimeters (and vice versa).
  - Thus same particles are not used in measuring both $\Psi_n$ and $\Psi_m$.
  - Removes auto-correlation
- There is a $\Delta \eta$ gap of 1 units between the two halves to remove any non-flow correlations
Measuring the three-plane correlations

\[ \Psi_k \]

- 4.8 < \eta < -3.3
- -2.7 < \eta < -0.5
- 0.5 < \eta < 2.7
- 3.3 < \eta < 4.8

- \( \Psi_n \), \( \Psi_m \), and \( \Psi_k \) are measured in different parts of the calorimeter.
  - Thus same particles are not used in measuring any of the \( \Psi \)'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