Flow and Correlations in $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb Collisions with ATLAS Detector at the LHC

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Outline

• Harmonic flow \((v_2-v_6)\) measurement
  ➢ Event plane (EP) method
  ➢ Multi-particle cumulants
  ➢ Two-particle (2P) correlations

• Dipolar Flow, \(v_1\)

• Event-by-event \(v_2, v_3\) and \(v_4\) distributions
  ➢ Flow harmonic fluctuations, \(\sigma_n/<v_n>\)

• Reaction plane correlations
Azimuthal Anisotropy of Produced Particles

Strongly interacting QGP

- Pressure gradients lead to azimuthal anisotropy

\[ \frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\phi - \Phi_n)] \]

\[ v_n = \langle \cos[n(\phi - \Phi_n)] \rangle \]

- Initial shape of the interaction region (v_2 - elliptic flow)
- Initial spatial fluctuations of interacting nucleons (higher orders, v_n)
Event Plane Measurement

ATLAS detector

- Pb-Pb 2010 run
  - $\sqrt{s_{\text{NN}}} = 2.76\text{TeV}$
  - $\sim 50 \text{ M MB events}$

Event plane determination is based on $E_T$ measured in FCal $(3.1<|\eta|<4.9)$
Fourier harmonics are measured with charged particles reconstructed in the inner detector:
• $-2.5 < \eta < 2.5$

**ATLAS detector**

**ID tracks (Pixel+SCT)**
• $p_T > 0.5$ GeV

**Pixel tracks**
• $p_T > 0.1$ GeV

**Tracklets (2 pixel hits + vertex)**
• $p_T > 0.03$ GeV (B-off)
Integrated $v_2$ down to very low $p_T$

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- Integrated $v_2$ ($p_T > 30$ MeV) is significantly reduced if compared to CMS results ($p_T > 300$ MeV)

- $v_2(\eta)$ shows weak pseudorapidity dependence but (within systematics) is also consistent with the trend observed by PHOBOS at RHIC
Elliptic Flow in Wide pT Range

Low $p_T$: hydro expansion

Medium $p_T$: coalescence

High $p_T$: jet quenching

• Rapid rise up to $p_T \approx 2 \text{ GeV}$, decrease within 3-8 GeV and weak dependence beyond 8-10 GeV

• $v_2$ shows similar $p_T$-dependence at the LHC and RHIC energy
Cumulant Haronics: $v_2\{2\}$ and $v_2\{4\}$

Elliptic flow harmonics of charged particles were obtained with the cumulant generating function method

- $v_2\{2\}$: consistent between ATLAS, ALICE and CMS
- $v_2\{4\}$: good agreement at low $p_T$, at high $p_T$ CMS obtained stronger flow


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T. Bold, parallel 7D Fri.
Jet $v_2$ at very High $p_T$: 50-200GeV

Azimuthal variation of the jet yield was characterized by the elliptic flow parameter, $v_2^{\text{jet}}$

Insight on the path length dependence of jet quenching in the hot medium
- Centrality dependence observed at lower transverse momenta
- $v_2^{\text{jet}}$ decreases with $p_T$

Aaron R. Angerami, parallel 2B Tue.

ATLAS-CONF-2012-116 $p_T$ [GeV]
Significant $v_2 - v_6$ are measured in broad range of $p_T$, $\eta$ and centrality.

$p_T$ dependence for all measured amplitudes show similar trend.

Stronger centrality dependence of $v_2$ than higher order harmonics.

In most central collisions (0-5%): $v_3$, $v_4$ can be larger than $v_2$.
1-D ($\eta$ projected) correlation function ($|\Delta \eta| > 2$):

$$\frac{dN}{d\Delta \phi} \sim 1 + 2 \sum_n v_{n,n} \cos(n\Delta \phi)$$

$$v_{n,n} = \langle \cos(n\Delta \phi) \rangle$$

$$v_{n,n}^{2P}(p_T^a, p_T^b) \approx v_n^{EP}(p_T^a)v_n^{EP}(p_T^b), n = 2 - 6$$
Decomposition of Two-Particle Correlation Function

Two-particle correlation function structure at low $p_T$ can be explained by flow harmonics $v_2$-$v_6$ and $v_{1,1}$ term.
Dipolar Flow, $v_1$

- $v_{1,1}(p_T^a,p_T^b)$ is consistent with contributions from rapidity-even $v_1$ and global momentum conservation:

$$v_{1,1}^{2P}(p_T^a,p_T^b) \approx v_1(p_T) v_1(p_T) - \frac{p_T^a p_T^b}{M \langle p_T^2 \rangle}$$

- Two-component fit is used to extract $v_1$
  - $v_1$ crosses zero at $p_T \approx 1$ GeV
  - Maximum at $p_T \approx 4-5$ GeV ($\sim v_3$)

J. Jia, parallel 4A Thu.

![Diagram showing $v_1$ fits for different $p_T$ ranges](Fig from P. Stankus)

Measurement of Event-by-Event $v_n$

The azimuthal distribution of charged particles in single event:

$$\frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n^{\text{obs}} \cos n(\phi - \Phi_n)$$

$$= 1 + 2 \sum_{n=1}^{\infty} (v_{n,x}^{\text{obs}} \cos n\phi + v_{n,y}^{\text{obs}} \sin n\phi)$$

$$v_n^{\text{obs}} = \sqrt{(v_{n,x}^{\text{obs}})^2 + (v_{n,y}^{\text{obs}})^2} \rightarrow v_n$$

Due to finite multiplicity, flow vector is smeared randomly around true flow vector $\rightarrow$ corrected by unfolding

J. Jia, parallel 4A Wed.  
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Unfolded $v_2$, $v_3$ and $v_4$ Distributions

- $v_n$ distributions normalized to unity for $n = 2, 3$ and $4$
- Lines represent radial projections of 2D Gaussians, rescaled to $<v_n>$
  - for $v_2$ only in the 0-2% of most central collisions
  - for $v_3$ and $v_4$ over all centralities

Direct measure of flow harmonics fluctuations
$\sigma_2/\langle v_2 \rangle$ shows strong centrality dependence
$\sigma_3/\langle v_3 \rangle$ and $\sigma_4/\langle v_4 \rangle$ are consistent with Gaussian fluctuations
Same relative fluctuations for $0.5 < p_T < 1 \text{GeV}$, $p_T > 0.5 \text{GeV}$ and $p_T > 1 \text{GeV}$

Dotted lines indicate the Gaussian limit: $\frac{\sigma_n}{\langle v_n \rangle} = \sqrt{\frac{4}{\pi}} - 1 \approx 0.523$
Comparison to Glauber and MC-KLN models

Eccentricity distributions from MC Glauber and MC-KLN models

\[ \varepsilon_n = \sqrt{\langle r^n \cos n\phi \rangle^2 + \langle r^n \sin n\phi \rangle^2 \over \langle r^n \rangle} \]

- Both work in 0-1%
- MC-KLN better in 5-10%
- MC Glauber better in 30-50%

\[ \langle \varepsilon_2 \rangle \text{ rescaled to } \langle v_2 \rangle \]

J. Jia, parallel 4A Wed.

ATLAS-CONF-2012-114
Event-by-Event Fluctuations from $v_2\{2\}$ and $v_2\{4\}$

Cumulant method provides a measure of elliptic flow fluctuations

N. Borghini, P.M. Dinh and J.Y. Ollitrault

• Relative flow fluctuations are independent of $p_T$ for 5-10% cent. bin
• For less central collisions $\sigma_{2}/\langle v_2 \rangle$ increases with $p_T$

• $\sigma_{2}/\langle v_2 \rangle$ agrees with the Glauber MC model prediction over a large centrality range but very peripheral collisions


T. Bold, parallel 7D Fri.
The Reaction Plane Correlations

• Study non-linear response of the medium to initial fluctuations.

\[
\frac{dN_{\text{events}}}{d(k(\Phi_n - \Phi_m))} \propto 1 + 2 \sum_{j=1}^{\infty} V_{n,m}^j \cos jk(\Phi_n - \Phi_m)
\]

\[ V_{n,m}^j = \langle \cos jk(\Phi_n - \Phi_m) \rangle \]

k – least common multiple of n & m

• Correlators \( V \) measured with event planes from full \( \eta \)-range of calorimeter \( (-4.8 \text{ to } 4.8) \), corrected for resolution

\[
\left\langle \cos(2\Phi_2 + 3\Phi_3 - 5\Phi_5) \right\rangle
\]

\[
\left\langle \cos(2\Phi_2 - 6\Phi_3 + 4\Phi_4) \right\rangle
\]
Reaction Plane Correlations

- Significant correlations are measured between two and three reaction planes (ATLAS-CONF-2012-049):
  \[ \langle \cos 4(\Phi_2 - \Phi_4) \rangle, \langle \cos 8(\Phi_2 - \Phi_4) \rangle, \langle \cos 12(\Phi_2 - \Phi_4) \rangle, \langle \cos 6(\Phi_3 - \Phi_6) \rangle \]
  \[ \langle \cos 2\Phi_2 + 3\Phi_3 - 5\Phi_5 \rangle, \langle \cos 2\Phi_2 + 4\Phi_4 - 6\Phi_6 \rangle, \langle \cos (-10\Phi_2 + 4\Phi_4 + 6\Phi_6) \rangle \]
  - Correlation is very small but nonzero for \( \langle \cos 6(\Phi_2 - \Phi_3) \rangle \)
  - Correlation is negative for \( \langle \cos (2\Phi_2 - 6\Phi_3 + 4\Phi_4) \rangle \)

- Some correlators in magnitude similar to Glauber model, but not all

- Fluctuations in the initial geometry and dynamical evolution of the medium are important

S. Mohapatra, parallel 7D Fri.
Summary

- ATLAS measured significant flow harmonics of charged particles in Pb-Pb collisions at the LHC energy $\sqrt{S_{\text{NN}}} = 2.76\text{TeV}$ ($v_1$-$v_6$)
- Elliptic flow in broad range of $p_T$ and $\eta$ ($|\eta|<2.5$):
  - Integrated $v_2$ was obtained for $p_T > 0.03$ GeV
  - Cumulant harmonics $v_2\{2\}$ and $v_2\{4\}$ were measured ($0.5 < p_T < 12$ GeV)
  - Jet quenching characterized with $v_2^{\text{jet}}$ for jets at $p_T$ up to 200 GeV
- Higher order flow harmonics and directed flow term ($v_{1,1}$) can explain structures in the two-particle azimuthal correlations
  - Diploar flow, $v_1$, extracted from $v_{1,1}$ term
- Unfolded event–by–event $v_2$, $v_3$ and $v_4$ distributions provide direct information on relative flow fluctuations:
  - $\sigma_2/<v_2>$ shows strong centrality dependence
- Relative fluctuations of elliptic flow from 2- and 4-particle cumulants are consistent with the Glauber MC model
- Mixed reaction plane correlations were obtained
Related Talks:

• Aaron R. Angerami, *Measurements of jet suppression with ATLAS*, parallel 2B Tue.
• Tomasz Bold, *Measurements of flow harmonics with the cumulant method from the ATLAS experiment*, parallel 7D Fri.
• Dominik Derendarz, *Measurement of elliptic and higher-order harmonics at sqrt(s_NN)=2.76TeV Pb-Pb collisions with the ATLAS detector*, parallel 2A Tue.
• Soumya Mohapatra, *Measurement of event plane correlations in Pb-Pb collisions with the ATLAS detector*, parallel 7D Fri.

ATLAS-CONF-2012-049

ATLAS-CONF-2012-114
ATLAS-CONF-2012-116
ATLAS-CONF-2012-117

ATLAS-CONF-2012-118
Backups
Pseudorapidity Dependence of $v_2$

$v_2$ drops by about 5–10% over the range $|\eta|=0\text{–}2.5$

- At RHIC, PHOBOS measured $v_2$ to decrease by $\sim30\%$ within $\eta$ range from 0 to 2.5 ($p_T>0$)
- $v_n$ coefficients are $\sim$boost invariant

D. Derendarz, parallel 2A Tue.
Two-Particle Correlation vs EP Results

Flow harmonics, up to $v_6$, are extracted with 2p correlation method.

Agreements are at 5% level for $v_2$, $v_3$, $v_4$ over a broad centrality range $v_5$ and $v_6$ agree at 10% and 15% level respectively (agreement within the systematic errors for the both methods).
Comparison to $v_n$ from Event Plane Method

\[ \langle v_n \rangle \leq v_{n,EP} \leq \sqrt{\langle v_n \rangle^2 + \sigma_n^2} \]

Dotted lines indicate the Gaussian limit:

\[ \frac{\sqrt{\langle v_n \rangle^2 + \sigma_n^2}}{\langle v_n \rangle} = \frac{2}{\sqrt{\pi}} \approx 1.13 \]
The EbE v2 distributions compared with the eccentricity distributions from two initial geometry models: a Glauber model (red lines) and the MC-KLN model (blue lines).
Figure 3: (left) The distribution of the difference between the per-particle flow vectors of the two half-IDs for events in 20-25% centrality interval. (middle) The projection on to the x-axis overlaid with a fit to a Gaussian. (right) The projection on to the y-axis overlaid with a fit to a Gaussian. The width from the fit, $\delta_{2SE}$, and the quality of the fit, $\chi^2$/DOF are shown.
Higher order event plane correlations in PbPb@LHC

Data: ATLAS Coll., J. Jia et al., Hard Probes 2012

Event-by-event hydrodynamics: Zhi Qiu (VISH2+1, MC-Glauber with $(\eta/s)_{\text{QGP}}=0.08$ and MC-KLN with $(\eta/s)_{\text{QGP}}=0.2$

- VISH2+1 reproduces qualitative features of the centrality dependence of all measured event-plane correlations but is quantitatively off by up to 50%
- Larger $\eta/s$ for MC-KL leads to stronger event-plane correlations (preferred by the data?)