Measurement of elliptic and higher order flow at $\sqrt{s_{NN}} = 2.76\, TeV$ Pb+Pb Collisions with the ATLAS detector

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Introduction and Motivation

- Initial spatial fluctuations of nucleons lead to higher moments of deformations in the fireball, each with its own orientation.
- The spatial anisotropy is transferred to momentum space by collective flow.

\[
\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle + \langle r^n \sin n\phi \rangle}{\langle r^n \rangle}} \\
\tan(n\Psi_n) = \frac{\langle r^n \sin n\phi \rangle}{\langle r^n \cos n\phi \rangle}
\]

Singles: \[
\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos n(\phi - \Psi_n) \quad \text{EP method}
\]

Pairs: \[
\frac{dN}{d\Delta\phi} \propto 1 + \sum_n 2v_n^a v_n^b \cos(n\Delta\phi) \quad \text{2PC method}
\]

- The harmonics \( v_n \) carry information about the medium: initial geometry, \( \eta/s \)
- Understanding of higher order \( v_n \) can shed light on the physics origin of “ridge” and “cone” seen in 2P correlations.
• Tracking coverage : $|\eta|<2.5$
• FCal coverage : $3.3<|\eta|<4.8$ (used to determine Event Planes)
\[ v_n = \frac{v_{n}^{\text{obs}}}{\text{Res}\{\Psi_n\}} = \frac{\langle \cos n (\phi - \Psi_n) \rangle}{\langle \cos n (\Psi_n - \Psi_{\text{RP},n}) \rangle} \]
• 5% Centrality bins + 0-1% centrality bin

• $v_2$ has a stronger centrality dependence.

• Other $v_n$ are flatter.

• In most central collisions, $v_3, v_4$ can be larger than $v_2$ at high enough $p_T$.
• Similar trend across all harmonics (increase till 3-4GeV then decrease)
• In most central collisions (0-5%): $v_3, v_4$ can be larger than $v_2$. 
Observe scaling: $v_n^{1/n} = k v_2^{1/2}$, where “k” is only weakly dependent on $p_T$.

R. Lacey et al. (http://arxiv.org/abs/1105.3782)
\( v_n \) from RHIC to LHC

From Xiaoyang Gong
Quark Matter 2011 Talk

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\[ \eta \text{ Dependence of } v_n \]

- Weak dependence on \( \eta \) (\( \sim 5\% \) drop within acceptance)

- For Correlations:
  \[ v_{n,n}^{a,b} = v_n^a \times v_n^b \]

relation is true only if the \( \eta \) dependence is weak
Two Particle $\Delta \eta - \Delta \phi$ correlations

Near-side jet peak is always visible

Ridge seen in central and mid-central collisions, weak $\eta$ dependence

Ridge strength first increases then decreases with centrality

Away side has double hump structure in most central events

Peripheral events have jet related peaks only

Peripheral events have near side peak truncated

**ATLAS** Preliminary

$\int L dt = 8 \mu b^{-1}$

$2 < p_T^a, p_T^b < 3 GeV$
Obtaining harmonics from correlations

a) The 2D correlation function in $\Delta \eta, \Delta \phi$.

b) The corresponding 1D correlation function in $\Delta \phi$ for $2 < |\Delta \eta| < 5$ (the $|\Delta \eta|$ cut removes near side jet)

c) The $v_{n,n}$ obtained using a Discrete Fourier Transformation (DFT)

d) Corresponding $v_n$ values

$$v_n \left(p_T^a\right) = \sqrt{v_{n,n} \left(p_T^a, p_T^a\right)}$$

 Bands indicate systematic errors
\( \Delta \eta \) dependence of \( v_n \)

- Repeat procedure in narrow \( \Delta \eta \) slices to obtain \( v_n \) vs \( \Delta \eta \).

- \( v_n \) values peak at low \( \Delta \eta \), due to jet bias.

- Relatively flat afterwards, so we require a \(|\Delta \eta| > 2\) gap (to remove near-side jet).

Bands indicate systematic errors
Universality of $v_n$

- $v_{n,n}$ is expected to factorize into single $v_n$ for flow
  $$v_{n,n}(p_T^a, p_T^b) = v_n(p_T^a) v_n(p_T^b)$$

- Obtain $v_n$ using “fixed $p_T$” correlations
  $$v_n(p_T^a) = \sqrt{v_{n,n}(p_T^a, p_T^a)}$$

- Cross-check via “mixed-$p_T$” correlation
  $$v_n(p_T^b) = \frac{v_{n,n}(p_T^a, p_T^b)}{v_n(p_T^a)}$$

- Indeed, $v_{n,n}$ factorizes! (above certain $\Delta \eta$)
Comparison between the two methods

Centrality Dependence

\[ \int L dt = 8 \, \mu b^{-1} \quad \text{Stat. Error only} \]

\( V_n \)

Open Symbols: correlation method for fixed-\( p_T \) and \( 2 < |\Delta \eta| < 5 \)

Solid Symbols: full FCal EP method for \( |\eta| < 2.5 \)

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The 2PC $v_n$ for $|\Delta \eta|<0.5$ deviates from the EP results (for all $p_T$).

Good agreement seen for $|\Delta \eta|>2$ at $p_T<4$ GeV.

See deviations for $p_T>4$ GeV even for $|\Delta \eta|>2$ due to increased away-side jet contribution (which swings along $\Delta \eta$).
We see similar trend as $v_2$
Recovering the correlations from EP $v_n$

\[ C(\Delta \phi) = b_{2P}^2 (1 + 2v_{1,1}^{2P} \cos \Delta \phi + 2 \sum_{n=2}^{6} v_n^{EP} v_n^{EP} \cos n\Delta \phi) \]

- Chose $v_{1,1}$ and normalization to be same as original correlation function, but all other harmonics are from EP analysis.
- Correlation function is well reproduced, ridge and cone are recovered!
- Common physics origin for the near and away-side long range structures.
Summary

•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.
  – Measured in phase space much larger than at RHIC.
  – Each $v_n$ can act as independent cross-check for $\eta/s$.

•Noted that $v_2$ doesn’t change drastically from RHIC to LHC

•Observed that the $v_n$ follow a simple scaling relation: $v_n^{1/n} \propto v_2^{1/2}$.

•Concluded that the features in two particle correlations for $|\Delta \eta|>2$ at low and intermediate $p_T$ ($p_T<4.0GeV$) can be accounted for by the collective flow of the medium.
  – Double hump and ridge arise due to interplay of even and odd harmonics

For more results see:

• ATLAS $v_n$ analysis note: http://cdsweb.cern.ch/record/1352458
• ATLAS HI public results page:
  • https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavylonsPublicResults
BACKUP SLIDES
Breakdown of $v_{1,1}$ scaling

- Left panel: $v_1(p_T^a)$ vs $\Delta \eta$ for four fixed-$p_T$ correlations.
  - We see that $v_{1,1}(p_T^a)$ can become negative showing eta dependence of $v_1$

- Right panel: $v_1(p_T^b)$ vs for target $p_T$ in (1.4,1.6) GeV
  - We see that $v_1(p_T^b)$ depends on $p_T^a$ showing the breakdown of the scaling relation
Universality of $v_n$

$\frac{v_2 (p_T^b)}{v_2 (p_T^a)} = \sqrt{\frac{p_T^b}{p_T^a}}$

$\frac{v_3 (p_T^b)}{v_3 (p_T^a)} = \sqrt{\frac{p_T^b}{p_T^a}}$

$\frac{v_4 (p_T^b)}{v_4 (p_T^a)} = \sqrt{\frac{p_T^b}{p_T^a}}$

$\frac{v_5 (p_T^b)}{v_5 (p_T^a)} = \sqrt{\frac{p_T^b}{p_T^a}}$

$\frac{v_6 (p_T^b)}{v_6 (p_T^a)} = \sqrt{\frac{p_T^b}{p_T^a}}$

$1.4 < p_T^b < 1.6$ GeV

$0.5 < p_T^a < 1.0$ GeV

$1.0 < p_T^a < 2.0$ GeV

$2.0 < p_T^a < 3.0$ GeV

$3.0 < p_T^a < 4.0$ GeV
Comparison to RHIC

- Similar magnitude and $p_T$ dependence in overlapping $p_T$ range

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$v_2$ out to 20GeV

- Charged hadrons, $p_T=0.5$-20 GeV, mid-rapidity, $|\eta|<1$
$p_T$ evolution of $\Delta \phi$ correlations

- $p_T$ evolution of two-particle $\Delta \phi$ correlations for 0-10% centrality selection, with a large rapidity gap ($|\Delta \eta| > 2$) to suppress the near-side jets and select only the long range components.
$v_{n,n}$ and $v_n$ vs $\Delta \eta$ for other centralities

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$\int Ldt = 8 \mu b^{-1}$

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$p_T$ Dependence of $v_3$ (2PC)
$\pt$ Dependence of $v_4$ (2PC)

- **EP method** full-FCal
- $2p$ $\Delta \eta \in [0.0, 0.5]$
- $2p$ $\Delta \eta \in [2.0, 5.0]$

**ATLAS Preliminary**

LDt $= 8 \mu b^{-1}$

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$p_T$ Dependence of $v_5$ (2PC)
• The EP is determined with the Q-vector method using flow in FCal

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

• In mid-central collisions, the $Q_2$ vector is distributed in a ring-like structure indicating the excellent ability of the FCal in determining the reaction plane

• In Central and mid-central collisions and for higher harmonics, the ring blurs out
The correlations are constructed by dividing foreground pairs by mixed background pairs.

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

- Mixed background pairs account for detector acceptance. Final correlation contains only physical effects.
- The detector acceptance causes fluctuations \(~ 0.001\) in the foreground pairs, which mostly cancels out in the ratio.
Recovering 0-1% correlation

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Recovering 0-5% correlation

- $0.5 < p_{T}^1 p_{T}^2 < 1.0$ GeV
- $2.0 < p_{T}^1 p_{T}^2 < 3.0$ GeV
- $3.0 < p_{T}^1 p_{T}^2 < 4.0$ GeV

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