Measurement of harmonic flow from heavy ion collisions in ATLAS

R. Debbe BNL for the ATLAS Collaboration

Based on 1203.3087 <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HION-2011-01/>

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Outline

Physics of flow and techniques.

Physics of higher harmonics.

The ATLAS detector.

Results from Event Plane (EP) and Two particle correlation (2PC) methods.

Summary.

Physics of flow and Measurement Techniques.

Initial fluctuations in the nucleon configuration determine the hydrodynamic flow of the system formed in Pb+Pb collisions.

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

The flow of that system is studied with azimuthal distributions of charged particles. Two methods are used:

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

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

The resulting distributions from both methods are expressed as a Fourier series.

Initial spatial anisotropy in Pb+Pb translates into pressure gradients. The physics of acoustic waves in a dissipative medium can be used to study the expanding QCD system.

Relations among the different measured flow harmonics may be used to extract the specific shear viscosity η/s of the newly formed system.

The ATLAS detector

Charged particle tracking with the Inner Detector: $|\eta| < 2.5$
FCal coverage: $3.3 < |\eta| < 4.8$ (used to determine Event Planes).

Event Plane method

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

← Use ID tracking

← Use Fcal energy deposition

The angle Ψ_n defining the reaction plane for each harmonic is extracted from energy deposited in the FCal:

$$\tan(n\Psi_n) = \frac{\sum_i E_{\text{T}}^i \sin(n\Phi_i)}{\sum_i E_{\text{T}}^i \cos(n\Phi_i)}$$

where the sums and index i refer to Fcal cells.

The distribution of azimuthal angle w.r.t. the event plane angle Ψ_n is constructed. Final results are corrected for the “resolution” to find the event plane.

Results from EP

The second harmonic v_2 (“elliptic flow”) is the only one that shows pronounced centrality dependence (size and shape of initial state).

Higher harmonics show a weaker centrality dependence and are present even at the most central events.

In the most central collisions and for intermediate values of p_T , v_3 is the dominant correlation.

All harmonics show the same behavior as when extracted from different bins of transverse momentum; They all increase in value to a maximum at $\sim 3\text{-}4$ GeV/c and then drop into a long tail at high p_T . The ordering of the harmonics by magnitude is the same at all centralities except at the very central events.

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Scaling between v_n

Excluding the most central events, higher harmonics scale with v_2 ;

$$v_n^{1/n} = k v_2^{1/2}$$

This flat p_T dependence may reinforce the acoustic nature of the expansion and provide access to the eccentricities at the time of the collision.

Centrality dependence

The scaling of the higher harmonics present a clear common centrality dependence at all values of p_T ; flat up to mid-central collisions followed by strong rise towards central events.

Similar behavior seen at RHIC for $n=4$

PHENIX Collaboration, Phys. Rev. Lett. 105, 062301 (2010).

Rapidity dependance

The pseudo-rapidity dependence of the flow harmonics is small and appears to be more pronounced in the most peripheral events. Similar behavior is seen at other p_T bins.

Energy dependence of the flow

X. Gong QM2011

Compared to RHIC measurements, the increase of the collision energy by ~ 1 order of magnitude does not substantially change the magnitude of the flow.

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Two Particle η and ϕ correlations

$$C(\Delta\phi, \Delta\eta) = \frac{S(\Delta\phi, \Delta\eta)}{B(\Delta\phi, \Delta\eta)}$$

The $(\Delta\phi, \Delta\eta)$ dist. of pairs is built in p_T ranges and centralities, then normalized by similar dist. from mixed events to account for background.

Jet-like correlations are always seen in near side $\Delta\phi \sim 0$

The ridge extends to all values in $\Delta\eta$, disappears in peripheral events.

Away-side evolves from two humps to jet-like structure.

Obtaining harmonics from correlations

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

- The 2D correlation function in $\Delta\eta, \Delta\phi$.
- The corresponding 1D correlation function in $\Delta\phi$ for $2 < |\Delta\eta| < 5$ (the $|\Delta\eta|$ cut removes near side jet)
- The $v_{n,n}$ obtained using a Discrete Fourier Transformation (DFT)
- Corresponding v_n values

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

Bands indicate systematic errors

v_n in $\Delta\eta$ slices is extracted from the 2D correlations.

A cut of $|\Delta\eta| > 2$ eliminates jet-like correlation on the $\Delta\phi \sim 0$ side.

Extracted values of the $v_{n,n}$ in two p_T bins as function of the centrality of the events.

Low p_T bin, driven by flow

Higher p_T bins show more of jet type correlations; odd harmonics become negative.

The Power Spectrum

The resulting values for the harmonic coefficients v_n are shown function of n for four p_T ranges. The higher harmonics are shown with a linear scale.

The variation of the magnitude for each harmonic may be related to viscosity of the medium; viscous systems are more dissipative for higher harmonics.

Comparison of both methods

The harmonic coefficients obtained with both methods agree well.

Open symbols:
fixed p_T 2PC

Error bars show statistical errors.

Reproducing 2PC from EP

$$C(\Delta\phi) = \underbrace{b^{2P}}_{\text{From 2PC method}} (1 + \underbrace{2v_{1,1}^{2P}}_{\text{From EP method}} \cos \Delta\phi + 2 \sum_{n=2}^6 \underbrace{v_n^{EP}}_{\text{From EP method}} \underbrace{v_n^{EP}}_{\text{From EP method}} \cos n\Delta\phi)$$

Slices of the 2PC 2D correlation can be reproduced within ~5% using coefficients extracted with the EP method. Near and away side structures are well described in four p_T ranges.

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Summary

- The ATLAS Collaboration has measured the flow present in Pb+Pb collisions at 2.76 TeV.
- Two methods were used to analyze the measurements in a Fourier decomposition.
- The magnitude and nature of the flow at LHC appears as very similar as that measured at RHIC.
- The results are consistent with an acoustic expansion of the opaque and low viscosity system formed in heavy ion collisions at LHC.
- Features of the 2PC like the ridge and double humps in the away side are accounted by the interplay of even and odd harmonics.