Measurement of elliptic and higher-order harmonics at 2.76 TeV Pb+Pb collisions with the ATLAS detector.

Dominik Derendarz
for the ATLAS Collaboration
Institute of Nuclear Physics PAN, Kraków, Poland
Why azimuthal anisotropy in AA is interesting?

• **Signature of strongly interacting QGP**

• **Sensitive to**
  
  – Initial shape of the interaction region ($v_2$)
  
  – Initial spatial fluctuations of nucleons (higher orders)
    
    Related to ridge, Mach cone.

• **Mechanism of particle production**
  
  – Low $p_T$ (< ~2GeV): hydro expansion (perfect liquid)
    
    (Nucl. Phys. A Volume 757)
  
  – Medium $p_T$ (~2-6 GeV): coalescence models
    
  
  – High $p_T$: constrain on jet quenching models
Pressure gradients lead to azimuthal anisotropy

\[
\frac{dN}{d(\phi - \Psi_n)} = N_0 \left( 1 + 2v_1 \cos(\phi - \Psi_1) + 2v_2 \cos(2(\phi - \Psi_2)) + 2v_3 \cos(3(\phi - \Psi_3)) + \ldots \right)
\]

**Directed flow**  
**Elliptic flow**  
**Triangular flow**

Fourier harmonics  
\[ \nu_n = \langle \cos(n(\Phi - \Psi)) \rangle \]
ATLAS detector

Centrality determination

- Energy deposited in entire FCal is used for **centrality determination**
- Event plane is measured based on energy deposition in the first sampling layer of FCal
- Fourier harmonics are reconstructed in inner detector from charged particle tracks:
  - $p_T > 0.5$ GeV
  - $|\eta| < 2.5$
• Energy deposited in entire FCal is used for centrality determination
• Event plane is measured based on energy deposition in the first sampling layer of FCal
• Fourier harmonics are reconstructed in inner detector from charged particle tracks:
  • $p_T > 0.5$ GeV
  • $|\eta| < 2.5$
Event plane determination

- Reaction plane ($\Psi_{RP}$) is approximated by event plane ($\Psi_{n}^{EP}$) measured in FCal:

$$\Psi_{n}^{EP} = \frac{1}{n} \tan^{-1} \left( \frac{\sum E_{T,i}^{tower} w_i \sin(n\phi_i)}{\sum E_{T,i}^{tower} w_i \cos(n\phi_i)} \right)$$

- The event plane resolution correction factor $R$ is obtained using two-sub event and various tree-subevent method

- Significant resolution for harmonics $n=2$ – 6

- Resolution corrected harmonics:

$$v_n = \langle \cos(n(\Phi - \Psi_n)) \rangle / R$$
$p_T$ dependence of the $v_2$ of charged particles

- All centrality intervals shows:
  - Rapid rise in $v_2(p_T)$ up to $p_T \sim 3$ GeV
  - Decrease out to 7-8 GeV
  - Weak $p_T$-dependence above 9-10 GeV

- The strongest elliptic flow at LHC is observed in centralities 30-50%

Comparison with ALICE and RHIC experiments

- All data sets are quite consistent for both low and high $p_T$
No substantial $\eta$ dependence for any $p_T$ or centrality interval is observed.

Different than PHOBOS measurements at RHIC in which $v_2$ decreases by $\sim$30% within the same $\eta$ range (PHOBOS Phys. Rev. C72 (2005) 051901)
Higher order flow harmonics

- The $p_T$-dependence of $v_2$-$v_6$ for several centrality selections

- Similar $p_T$-dependence for all harmonics

- $v_n$ generally decreases for larger $n$, except in the most central events:
  - $v_3$ dominates in $p_T$ range $\sim 2$-7 GeV
  - $v_4 > v_2$ in $p_T$ range $\sim 3$-5 GeV
Higher order harmonics scaling

- Hydrodynamics model suggests scaling $v_4 \sim v_2^2$ (PHENIX PRL 105, 062301 (2010))

- The $p_T$-dependence of the $v_n^{1/n}/v_2^{1/2}$ ($n=3-6$) ratio for several centrality selections

- Weak $p_T$-dependence of the ratio except 5% most central events

- Ratio for $n=3$ systematically lower than for $n=4, 5$
The two-particle correlation function: 

\[ C(\Delta \phi, \Delta \eta) = \frac{N_s(\Delta \phi, \Delta \eta)}{N_m(\Delta \phi, \Delta \eta)} \]

- \( N_s \) – same event pairs
- \( N_m \) – mixed event pairs
Two-particle correlation method

The two-particle correlation function: \( C(\Delta \phi, \Delta \eta) = \frac{N_s(\Delta \phi, \Delta \eta)}{N_m(\Delta \phi, \Delta \eta)} \)

- \( N_s \) – same event pairs
- \( N_m \) – mixed event pairs

\[
\frac{dN}{d\Delta \phi} \propto 1 + 2 \sum_n v_{n,n} \cos(n \Delta \phi)
\]

Projected onto \( \Delta \phi \)

1D correlation function
The two-particle correlation function:

\[ C(\Delta \phi, \Delta \eta) = \frac{N_s(\Delta \phi, \Delta \eta)}{N_m(\Delta \phi, \Delta \eta)} \]

\[ v_{n,n} = \sum_m \cos(n \Delta \phi_m) C(\Delta \phi_m) \]

\[ v_{n,n} = \langle \cos(n \Delta \phi) \rangle = \frac{\sum_m \cos(n \Delta \phi_m) C(\Delta \phi_m)}{\sum_m C(\Delta \phi_m)} \]

Projected onto \(\Delta \phi\):

1D correlation function

\[ \frac{dN}{d\Delta \phi} \propto 1 + 2 \sum_n v_{n,n} \cos(n \Delta \phi) \]

\(v_{n,n}\) are calculated via Discrete Fourier Transform (DFT):

\(N_s\) – same event pairs
\(N_m\) – mixed event pairs
Two-particle correlation method

The two-particle correlation function:

$$C(\Delta \phi, \Delta \eta) = \frac{N_s(\Delta \phi, \Delta \eta)}{N_m(\Delta \phi, \Delta \eta)}$$

$N_s$ – same event pairs

$N_m$ – mixed event pairs

Projected onto $\Delta \phi$

1D correlation function

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

$v_{n,n}$ are calculated via Discrete Fourier Transform (DFT):

$$v_{n,n} = \langle \cos(n \Delta \phi) \rangle = \frac{\sum m \cos(n \Delta \phi_m) C(\Delta \phi_m)}{\sum m C(\Delta \phi_m)}$$

It is expected that for flow modulations:

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

And for "fixed-pT" correlations:

$$V_n = \sqrt{v_{n,n}}$$
Good agreement between both methods in the selected kinematical range (p_T 1-3 GeV, 2<|η|<5)
Two particle correlation vs EP results

\[ C(\Delta \Phi) = b^{2\text{PC}} (1 + 2v_{1,1}^{2\text{PC}} \cos \Delta \Phi + 2 \sum_{n=2}^{6} v_n^{\text{EP},a} v_n^{\text{EP},b} \cos n \Delta \Phi) \]

- \( b^{2\text{PC}} \): average of the correlation function
- \( v_{1,1}^{2\text{PC}} \): first harmonic from the 2PC analysis
- Other \( v_n \) components measured with the event plane method
- Correlation function reproduced very well

More details on \( v_1 \):
J. Jia talk 15 Aug 11:20 AM
Session: Parallel 4A
Summary

- ATLAS measured $v_2$ and higher order flow harmonics up to $v_6$ in wide $p_T$, $\eta$ and centrality range

- $v_n(p_T)$ shows the same trends
  - rise up to $\sim 3$ GeV
  - decrease within 3-8 GeV
  - varies weakly out to 20 GeV

- $v_n(\eta)$ remains approximately constant

- $v_3$ is dominating in the most central collisions

- $v_n$’s follow approximate scaling relation $v_n^{1/n} \propto v_2^{1/2}$

- Good agreement between event plane and two particle correlation results for $v_n$