Flow harmonics in Pb+Pb collisions at energy of $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector

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• Integrated elliptic flow with the event plane method
  – Data collected with the solenoid off allows to include particles with very low $p_T$ into the measurement
  – Elliptic flow $\sqrt{s_{NN}}$ scaling

• Measurement of $v_n$ harmonics with multiparticle cumulants
  – Differential $v_2$ measured with 2,4,6 and 8 particle correlation
  – Higher order harmonics $v_3$ and $v_4$ measured with 4 particle cumulants
  – Relative fluctuations of $v_2$, $v_3$ and $v_4$ harmonics
Motivation

- Study collision energy dependence of elliptic flow at forward rapidity observed by PHOBOS – is it valid at the LHC energy?

- Higher order harmonics arise due to event-by-event fluctuations in the initial geometry

- Cumulants technique allows for measurement of the $v_n$ fluctuations

\[ \eta' = \eta - y_{\text{beam}} \]
Event plane method

- Event plane angle $\Psi_n$ and its resolution estimated using FCal ($3.2 < |\eta| < 4.8$)

\[
\Psi_n = \frac{1}{n} \tan^{-1} \left( \frac{\sum E_{i}^{\text{towers}} w_i \sin(n \phi_i)}{\sum E_{i}^{\text{towers}} w_i \cos(n \phi_i)} \right)
\]

\[
R = \sqrt{\langle \cos[2(\Psi_2^N - \Psi_2^P)] \rangle}
\]
Event plane method

- Event plane correlated with ID tracks ($|\eta|<2.5$)
  \[ v_n = \left\langle \cos \left( n \left( \phi_i^{P,N} - \Psi_n^{N,P} \right) \right) \right\rangle / R \]

- Sub-event technique used to maximize pseudorapidity separation between track and EP detectors ($\eta - \text{gap} > 3.2$)

- Integrated $v_n$ obtained from differential $v_n(p_T, \eta)$ corrected for efficiency and fake rate
  \[ v_n^{\text{integral}} = \sum_k \sum_i N_{ik}^c \frac{v_{nik}}{\sum_k \sum_i N_{ik}^c} \]
  \[ N_{ik}^c = N_{ik} \left( 1 - f_{ik} \right) / \epsilon_{ik} \]
Three tracking techniques used to minimize the low $p_T$ iteration limit ($p_{T,0}$)
- IDT – default tracking $p_T > 0.5$ GeV
- PXT – low $p_T$ tracking $p_T > 0.1$ GeV
- TKT – field off data, $p_T > 0.07$ GeV (estimated with MC)

Consistent result with tracking techniques for matching $p_{T,0}$
- $0.5$ GeV IDT and PXT
- $0.07 – 0.1$ GeV TKT and PXT
• Trend observed at RHIC appears to be followed up at the LHC energies

• The ATLAS and CMS results agree within their uncertainties.
Cumulant method

- Multi-particle (2k) cumulants are insensitive to lower order correlations (< 2k) – non flow eliminated by construction
- Generating function is used to obtain 2k-particle correlation and cumulants
- Cumulants give estimate of relative fluctuations:

\[
F(v_n) = \sqrt{\frac{v_n\{2\}^2 - v_n\{4\}^2}{v_n\{2\}^2 + v_n\{4\}^2}}
\]

- To lower the influence of non-flow effects in estimation of relative fluctuations \(v_n\{EP\}\) is used instead of \(v_n\{2\}\)

- Particles of Interest (POI): \(0.5 < p_T < 20 \text{ GeV}, |\eta|<2.5\)
- Reference Particles (RP): \(0.5 < p_T < 5 \text{ GeV}, |\eta|<2.5\)
Transverse momentum dependence of $v_2$

- $v_2\{2\}$ shows a strong flow signal at high $p_T$ (jet-like correlations)
- Strong reduction of $v_2$ by using more than 2 particle correlations

$$v_n\{2\} > v_n\{EP\} > v_n\{4\}$$

$$v_n\{4\} \approx v_n\{6\} \approx v_n\{8\}$$
Transverse momentum dependence of $v_3$ and $v_4$

- Significant values of $v_3\{4\}$ and $v_4\{4\}$ calculated
- $v_{3,4}\{4\} < v_{3,4}\{2\}$ - expected from fluctuations and suppression of non-flow effects
Event by event flow harmonics

- $p(v_n)$ probability distributions

- Relative widths provides direct constraints on the hydrodynamic response to initial geometry fluctuations
- Can be obtained and compared with the cumulant approach
Centrality dependence of $v_n$ harmonics

- Comparison of $v_n\{2,4\}$ with $v_n\{EP\}$ and $v_n\{EbyE\}$ (mean of $p(v_n)$ distribution)

- $v_n\{2\} > v_n\{EP\} > v_n\{EbyE\} > v_n\{4\}$

- Difference between $v_n\{2\}$ and $v_n\{4\}$ more pronounced for $n = 3,4$
Cumulants vs event-by-event $v_n$

- Cumulants of $p(v_n)$ distributions ($v_n^{\text{calc}\{\text{EbyE}\}}$) are in excellent agreement with directly measured cumulants.

- Residual differences between $v_n\{4\}$, $v_n\{6\}$ an $v_n\{8\}$ – reproduced by EbyE cumulants.
Elliptic flow fluctuations $p_T$ dependence

- Event plane $v_2\{EP\}$ method used instead of $v_2\{2\}$ to lower the contribution of non-flow effects
- Only 2-5% bin shows significant $p_T$ dependence
Fluctuations of $v_n <N_{\text{part}}>$ dependence

- Strong dependence of $F(v_2)$ on centrality with a minimum at $<N_{\text{part}}>$ ≈ 200
- Large triangular and quadrangular harmonic fluctuations are measured
- Weak dependence of $F(v_3), F(v_4)$ on centrality
- Good agreement cumulant results with EbyE calculations
- ATLAS results are consistent with the CMS estimate of $v_3$ relative fluctuations
- Both models fail to reproduce the relative fluctuations
Conclusions

- Measurement of centrality dependence of integrated elliptic flow with the variation of the low p$_T$ integration limit has been presented
- The results are strong thanks to the three complementary methods
- Pseudorapidity dependence of integrated v$_2$ compatible with extended longitudinal scaling

- Reduction of harmonics observed when calculated with higher order cumulants
  - $v_n\{2\} > v_n\{EP\} > v_2\{EbyE\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$
  - $v_3\{2\} \gg v_3\{4\}$
  - $v_4\{2\} \gg v_4\{4\}$

- Relative fluctuations of $v_n$ (for $n=2,3,4$)
  - Strong centrality dependence for elliptic flow
  - Large values and weak N$_\text{part}$ dependence of fluctuations for $n=3,4$ indicate large fluctuation in the shape of the initial geometry
  - Both Glauber and KLN-MC models did not reproduce these fluctuations in the full centrality range
Backup
Cumulants vs event-by-event $v_n$

ATLAS Preliminary
Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV
$L_{\text{int}} = 7 \mu b^{-1}$ $|n| < 2.5$
$0.5 < p_T < 20$ GeV

$V_2$ $v_2^{(2)}$ $v_2^{\text{calc}}(2,\text{EbyE})$

$V_2$ $v_2^{(4)}$ $v_2^{\text{calc}}(4,\text{EbyE})$

$V_2$ $v_2^{(6)}$ $v_2^{\text{calc}}(6,\text{EbyE})$

$V_2$ $v_2^{(8)}$ $v_2^{\text{calc}}(8,\text{EbyE})$

ratio

$\langle N_{\text{part}} \rangle$

ratio

$\langle N_{\text{part}} \rangle$
Pseudorapidity dependence of $v_2$

- $v_2^{(2)}$ shows a strong flow signal at high $p_T$ (jet-like correlations)
- Strong reduction of $v_2$ by using more than 2 particle correlations

$v_n^{(2)} > v_n^{(EP)} > v_n^{(4)}$

$v_n^{(4)} \approx v_n^{(6)} \approx v_n^{(8)}$
Pseudorapidity dependence of $v_3$ and $v_4$

- Significant values of $v_3\{4\}$ and $v_4\{4\}$ calculated

- $v_{3,4}\{4\} < v_{3,4}\{2\}$ - expected from fluctuations and suppression of non-flow effects
How to reach particles with very low $p_T$

- Three tracking techniques explored
  - Pixel tracklets (TKT) – built from 2 hits in the first two layers of pixel detector and the vertex position
    - Method used on the data recorded with solenoid field switched off
    - Fully efficient for particles with $p_T > 0.1 \text{GeV}$ (estimated with MC)
    - The price to pay is no $p_T$ measurement
  - Pixel tracks (PXT) – built from the information in the pixel detector only (typically 3 hits at the midrapidity)
    - Applied to data with magnetic field on
    - Minimum reconstructed $p_T = 0.1 \text{ GeV}$
    - The drawback of using only the information from pixel detector is high fake rate and lower $p_T$ resolution
    - PXT are used as a link between results obtained with TKT in field off data and the fully efficient IDT reconstructed with the presence of magnetic field
  - Inner detector tracks (IDT) – default track reconstruction algorithm using information from the entire ATLAS inner detector
    - Minimum reconstructed $p_T = 0.5 \text{ GeV}$
Pixel tracklets (TKT) performance

- Minimum reconstructed $p_T \approx 0.07$ GeV (point where efficiency reach 50%)
- Efficiency stable with $p_T$ above 0.1 GeV and no significant variation with centrality
- Fake rate affecting only the most central collisions for the low $p_T$ and high $\eta$
- Correction for the final $v_2$ measurement
- Fake flow removal

![Graphs showing efficiency and ratio with $p_T$ and $\eta$]
Pixel tracks (PXT) performance

- Minimum reconstructed $p_T = 0.1$ GeV
- Efficiency dependent on $p_T$, especially in low $p_T$ region
- Strong centrality dependence of efficiency
- Significant fake rate in low $p_T$ region
- Corrections for the final $v_2$ measurement
  - Efficiency parametrization as a function of local density around reconstructed track
  - Fake flow removal
  - Correcting for limited $p_T$ resolution
Inner detector tracks (IDT) performance

- Minimum reconstructed $p_T = 0.5$ GeV
- Efficiency stable with $p_T$ and no significant variation with centrality
- Fake rate affecting only most central collisions for the low $p_T$ and high $\eta$
- Correction for the final $v_2$ measurement
  - Fake flow removal
Systematic uncertainties

- Significant improvement with respect to the preliminary result
- Dominant sources of uncertainty
  - in central collisions - presence of fake tracks
  - uncertainty in the centrality bins definition
Pseudorapidity dependence of integrated $v_2$

- Weak pseudorapidity dependence is observed, regardless of minimum $p_T$ integration threshold used.
- Consistent result with three tracking techniques for matching $p_{T,0}$:
  - $0.5$ GeV IDT and PXT
  - $0.07 - 0.1$ GeV TKT and PXT
• Agreement with the CMS when the integration threshold tuned to match each others (0.3 GeV)

• ALICE result with matching $p_T$ range slightly higher – due to differences in event plane and tow-particle correlation methods