Hydrodynamic flow in Pb+Pb collisions observed via azimuthal angle correlations of charged hadrons

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CMS Collaboration

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Physics Motivation

Measure the Anisotropic Asymmetry to Address:

- EoS and Viscosity of the Medium
- Opacity of the Medium (via high-p\textsubscript{T} anisotropy)
- Role of Fluctuations and Initial State

Difficulties from Complications:

- Non-Flow Correlations: Jets, Resonance Decays, ...
- Initial State Fluctuations

Addressed by Multiple Methods and Higher-Order Harmonics:

- use different methods with different sensitivities to non-flow
- \(v_3, v_5\) dominated by fluctuations
- \(v_2, v_4, v_6\) from hydrodynamic flow and fluctuations
- higher harmonics probe different length scales
The CMS Detector

- Silicon Pixel and Strip Detectors
- 3.8 T Magnet
- Minimum Bias Trigger and Centrality Determination
- BSC and HF Detectors
- Tracking and Event Plane Reconstruction
- ECAL
- HCAL
- Muon Detectors
Tracking Reconstruction in Heavy Ions

- High $p_T$ tracks (>1.5 GeV/c) reconstructed from silicon strip and pixel detectors.
- Low $p_T$ tracks (0.3-1.8 GeV/c) reconstructed from only the pixel detector.
- Collections merged and cleaned for duplicates.
Four Methods Used for Extracting $v_2$ Signal

**Event Plane**
- based on particle correlations with the event plane
- gives an estimate of the reaction plane
- requires corrections for the detector acceptance

**2nd Order Cumulant**
- based on 2-particle correlations

**4th Order Cumulant**
- based on 4-particle correlations
- removes lower order non-flow effects

**Lee-Yang Zeros**
- based on all particle correlations in each event
- removes non-flow effects

Higher order harmonics up to $v_6$ were measured using select methods:

n = 2  n = 3  n = 4  n = 5  n = 6
$v_2(p_T)$ as a Function of Centrality

- $v_2$ increases from central to peripheral up to 50% centrality.
- $v_2$ peaks at around 3 GeV/c.
- method differences consistent with expected sensitivity to non-flow
$v_2(p_T)$ Comparison to Other Experiments

n = 2

CMS Preliminary PbPb $\sqrt{s_{NN}} = 2.76$ TeV
40-50% Centrality Stat. Uncertainties

ALICE Collaboration,

PHENIX AuAu $\sqrt{s_{NN}} = 200$ GeV

CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV

PHENIX Collaboration,

ALICE Collaboration,
$v_2(p_T)$ Data and AMPT Comparison

The relationship between methods is well described by AMPT.

Fluctuations are important!
Integrated $v_2$ versus Centrality

CMS Preliminary PbPb $\sqrt{s_{NN}} = 2.76$ TeV

- Maximal flow at 40-50% centrality

- Method Differences: as expected due to non-flow and fluctuations
Integrated $v_2$ as a Function of Pseudorapidity

- Weak $\eta$-dependence, stronger for most peripheral collisions (EP and $v_2\{2\}$)

- May constrain descriptions of the longitudinal dynamics
$v_3(p_T)$ as a Function of Centrality

- Sizable signal; weak centrality dependence for integrated $v_2$
- $v_3$ at mid-rapidity driven by fluctuations
$v_4(p_T)$ as a Function of Centrality

CMS-PAS HIN-11-005

- LYZ, $v_4\{3\}$ and $v_4\{5\}$ – consistent results

n = 4
$v_5(p_T)$ as a Function of Centrality

- $v_5$ rises quadratically with $p_T$ in contrast with other flow harmonics.
$v_4(p_T)$ and $v_6(p_T)$ as a Function of Centrality

- $v_6$(LYZ) is small but finite: reaches 2% in mid-central collisions
The Full Harmonic Spectrum

- $v_n$ vs $N_{\text{part}}$ shows different trends:
  - even harmonics have similar centrality dependence:
    - decreasing $\to 0$ with increasing $N_{\text{part}}$
  - $v_3$ has weak centrality dependence, finite for central collisions

CMS-PAS
HIN-11-005

0.3 < $p_T$ < 3.0 GeV/c
$|n| < 0.8$

PbPb $\sqrt{s_{\text{NN}}} = 2.76$ TeV
CMS Preliminary
Conclusions

- Detailed Measurements of $v_n$ in PbPb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - Good statistics and pseudorapidity Coverage

- $v_2(pt)$: maximum at 3 GeV/c then decreases
  - still finite at 10 GeV/c

- Integral $v_2$ is strongest at midrapidity; slowly decreases at forward rapidity

- $v_2$ comparable to RHIC measurements at $\sqrt{s_{NN}} = 200$ GeV
  - similar $p_T$ dependence
  - small increase in integral $v_2$

- $v_3$ is sizable and almost independent of centrality
  - expected by fluctuations

- $v_5$ and $v_6$ are finite
Physics Analysis Summaries

These preliminary results are published and available publicly on the CERN Document Server.

Elliptic Flow Results:


Higher-Order Flow Results:

Backup
Anisotropic Flow

Schematic of a heavy ion collision:

\[ \phi - \Psi_r \]

impact parameter

Analogous system: A strongly-interacting degenerate fermi gas of atoms.


Initial State Position Anisotropy

Final State Momentum Anisotropy

Measuring the \( v_2 \) coefficient can constrain hydrodynamic and transport properties of the hot and dense medium produced in the collision.

\[ E \frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_t dp_t dy} \left( 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_r)) \right) \]

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

Second Fourier coefficient \( n=2 \) quantifies the particle emission "in-plane" versus "out-of plane"
LHC: 2010 Heavy Ion Run

Data taking without magnetic field
CMS Detector Profile
Event Selection and Centrality Determination

Minimum Bias trigger based on double-coincidence of either the beam scintillation counters (BSC) or forward hadronic calorimeters (HF).

Additional offline event selection used to remove electromagnetic ultra-peripheral collisions, beam gas, beam scraping, and other non-collision events.

Centrality was determined using the total energy in both HF calorimeters, dividing events into 40 categories. These were divided into 12 larger bins for this analysis:

- 0-5%
- 5-10%
- 10-15%
- 15-20%
- 20-25%
- 25-30%
- 30-35%
- 35-40%
- 40-50%
- 50-60%
- 60-70%
- 70-80%
Details of the Event Plane Method

- Uses 3-subevent event plane resolution correction.


- Standard flattening procedure to remove azimuthal detector asymmetries (21st order Fourier decomposition)


1. Event Plane is Determined from the Azimuthal Correlations themselves:

\[ \Psi_n = \left( \tan^{-1} \frac{\sum_i w_i \sin(n\phi_i)}{\sum_i w_i \cos(n\phi_i)} \right) / n \]

2. Resolution correction factor is determined by splitting particles into three sub-events based on pseudorapidity:

\[ R_A = \sqrt{\frac{\langle \cos(n(\Psi^A_n - \Psi^B_n)) \rangle \langle \cos(n(\Psi^A_n - \Psi^C_n)) \rangle}{\langle \cos(n(\Psi^B_n - \Psi^C_n)) \rangle}} \]

3. Extracted \( v_2 \) signal is corrected for the resolution:

\[ v_n(EP) = \frac{v_n^{obs}(EP)}{R} = \frac{\langle \cos n(\varphi - \Psi_n) \rangle}{\langle \cos n(\Psi_n - \Psi_R) \rangle} \]
Details of the Cumulant Method

- Since all particles are correlated to the reaction plane, they are also indirectly correlated with each other.

\[ < v_n >^2 = < \cos[n(\phi_i - \phi_j)] > \]
\[ v_n(p_T) = \frac{< \cos[n(\phi_i - \phi_j)] >}{< v_n >} \]

integrated flow       differential flow

- **2-particle correlations** can be expressed in terms of flow and non-flow components:

\[ \langle e^{i\Delta(\phi_1-\phi_2)} \rangle_m = v_n^2 + \langle e^{i\Delta(\phi_1-\phi_2)} \rangle_c \]  

- **4-particle correlation** can be decomposed in the similar way:

\[ v_n^4 \quad 2 < e^{i\Delta(\phi_1-\phi_2)} >_c^2 \quad O(\frac{1}{N^3}) \]

- Integral and differential flow signals are obtained by using generating functions:

\[ G_n = \prod_{i=1}^{M} \left( 1 + \frac{2x \cos(n\phi_i) + 2y \sin(n\phi_i)}{M} \right) \]
\[ D_{p/n} = \frac{\langle e^{ip\psi}G_n(z) \rangle}{\langle G_n(z) \rangle} \]
Details of the Lee-Yang Zeros Method

For each centrality, define the complex-valued generating function:

\[ G_2^\theta (ir) \equiv \left\langle e^{irQ_2^\theta} \right\rangle = \frac{1}{N_{\text{evt}} \text{ events}} \sum e^{irQ_j^\theta} \]

with

\[ Q_2^\theta = \sum_{j=1}^{M} w_j \cos(2(\phi_j - \theta)) \]

weight: \( w_j \), \( \theta \) : fixed angle

Then **Integrated flow is**:

\[ V_2^\theta = j_{01} / r_0^\theta \]

\( r_0^\theta \) is first minimum of \( |G_2^\theta (ir)| \), \( j_{01} \) : 2.405

Then **Differential flow is**:

\[ v_{2m}^\theta (\eta, p_T) = V_2^\theta \frac{J_1(j_{01})}{J_m(j_{01})} \text{Re} \left( \left\langle \frac{\cos[2m(\phi_j - \theta)]e^{ir_0^\theta Q_j^\theta}}{i^{m-1} Q_j^\theta e^{ir_0^\theta Q_j^\theta}} \right\rangle \right) \]

The method:

- less biased by non-flow correlations than other methods.
- less biased by autocorrelations.
- less biased by detector asymmetry.

Another generating function(Product) can be used in LYZ. It gives the same results for \( v_2 \)

J_m is Bessel function of the first kind

m=1 for \( v_2 \)
Integrated $v_2$ Comparison to ALICE

Good agreement between CMS and ALICE other than the most peripheral collisions.

Error bars are statistical errors. Shaded boxes represent systematic errors.

Systematic Studies

Systematic Studies Common to all Methods Include:

- Particle composition (pion/kaon/proton ratio)
- Centrality determination and trigger efficiency
- Tracking kinematic cuts
- Fake track contribution to elliptic flow
- Uncertainty in efficiency corrections

Systematic Studies for the Event Plane Method Include:

- Tracking transverse momentum cut for calculating the event plane angle
- Detector acceptance
- Flattening check
- Subevent pseudorapidity gap
- Flattening parameters as a function of the vertex position
### Event Selection Summary

Table 1: The effects of various cuts on the data sample. % values are always with respect to the line above (the cuts are applied in sequence).

<table>
<thead>
<tr>
<th>Cut</th>
<th>events remaining</th>
<th>% of events remaining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Physics events</td>
<td>4604505</td>
<td>100.00</td>
</tr>
<tr>
<td>HLT_HIMinBiasHfOrBSC_Core trigger</td>
<td>2889239</td>
<td>62.75</td>
</tr>
<tr>
<td>no BSC halo</td>
<td>2857150</td>
<td>98.89</td>
</tr>
<tr>
<td>HF offline coincidence</td>
<td>2762005</td>
<td>96.67</td>
</tr>
<tr>
<td>reconstructed vertex</td>
<td>2686247</td>
<td>97.26</td>
</tr>
<tr>
<td>Beam-gas removal</td>
<td>2682361</td>
<td>99.86</td>
</tr>
<tr>
<td>ECAL cleaning</td>
<td>2673123</td>
<td>99.66</td>
</tr>
<tr>
<td>HCAL cleaning</td>
<td>2672977</td>
<td>99.99</td>
</tr>
<tr>
<td>vertex position</td>
<td>2316724</td>
<td>86.67</td>
</tr>
</tbody>
</table>
Table 2: Systematic uncertainties in the measurement of $v_2(p_T)$ for $|\eta| < 0.8$ with the event plane method.

<table>
<thead>
<tr>
<th>Source</th>
<th>Centrality</th>
<th>00-10%</th>
<th>10-20%</th>
<th>20-30%</th>
<th>30-40%</th>
<th>40-80%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle composition</td>
<td>All</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Centrality determination</td>
<td>All</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Track $p_T$ cuts in EP</td>
<td>All</td>
<td>1.0%</td>
<td>1.0%</td>
<td>1.0%</td>
<td>1.0%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Acceptance</td>
<td>All</td>
<td>&lt; 2%</td>
<td>&lt; 1%</td>
<td>&lt; 0.8%</td>
<td>&lt; 0.5%</td>
<td>&lt; 0.5%</td>
</tr>
<tr>
<td>Track kinematic cuts</td>
<td>[0.3; 1.0]</td>
<td>7.0%</td>
<td>3.0%</td>
<td>2.0%</td>
<td>&lt; 1.0%</td>
<td>&lt; 1.0%</td>
</tr>
<tr>
<td></td>
<td>[1.0; 2.0]</td>
<td>4.0%</td>
<td>2.0%</td>
<td>&lt; 1.0%</td>
<td>&lt; 1.0%</td>
<td>&lt; 1.0%</td>
</tr>
<tr>
<td></td>
<td>[2.0; 12.0]</td>
<td>2.0%</td>
<td>&lt; 1.0%</td>
<td>&lt; 1.0%</td>
<td>&lt; 1.0%</td>
<td>&lt; 1.0%</td>
</tr>
<tr>
<td>Total</td>
<td>[0.3; 1.0]</td>
<td>7.4%</td>
<td>3.5%</td>
<td>2.6%</td>
<td>1.9%</td>
<td>1.9%</td>
</tr>
<tr>
<td></td>
<td>[1.0; 2.0]</td>
<td>4.7%</td>
<td>2.7%</td>
<td>2.0</td>
<td>1.9%</td>
<td>1.9%</td>
</tr>
<tr>
<td></td>
<td>[2.0; 12.0]</td>
<td>3.2%</td>
<td>2.1%</td>
<td>2.0%</td>
<td>1.9%</td>
<td>1.9%</td>
</tr>
</tbody>
</table>
### Systematic Uncertainties

Table 3: Systematic uncertainties in the measurement of $v_2(\eta)$ for $0.3 < p_T < 3.0\text{GeV}/c$ with the event plane method.

<table>
<thead>
<tr>
<th>Source</th>
<th>Centrality</th>
<th>00-10%</th>
<th>10-20%</th>
<th>20-30%</th>
<th>30-40%</th>
<th>40-80%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle composition</td>
<td>All</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Centrality determination</td>
<td>All</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Acceptance</td>
<td>All</td>
<td>&lt; 2%</td>
<td>&lt; 1%</td>
<td>&lt; 0.8%</td>
<td>&lt; 0.5%</td>
<td>&lt; 0.5%</td>
</tr>
<tr>
<td>Efficiency corrections</td>
<td>[0.0; 0.8]</td>
<td>&lt; 1.0%</td>
<td>&lt; 1.0%</td>
<td>&lt; 1.0%</td>
<td>&lt; 1.0%</td>
<td>&lt; 1.0%</td>
</tr>
<tr>
<td></td>
<td>[0.8; 1.6]</td>
<td>1.0%</td>
<td>&lt; 1.0%</td>
<td>&lt; 1.0%</td>
<td>&lt; 1.0%</td>
<td>&lt; 1.0%</td>
</tr>
<tr>
<td></td>
<td>[1.6; 2.4]</td>
<td>5.0%</td>
<td>2.0%</td>
<td>1.0%</td>
<td>1.0%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Fake track $v_2$</td>
<td>All</td>
<td>0.8%</td>
<td>0.6%</td>
<td>0.4%</td>
<td>0.4%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Track $p_T$ cuts in EP</td>
<td>All</td>
<td>1.0%</td>
<td>1.0%</td>
<td>1.0%</td>
<td>1.0%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Track kinematic cuts</td>
<td>All</td>
<td>&lt; 3.0%</td>
<td>&lt; 2.5%</td>
<td>&lt; 1.6%</td>
<td>&lt; 1.0%</td>
<td>&lt; 1.0%</td>
</tr>
<tr>
<td>Total</td>
<td>[0.0; 0.8]</td>
<td>4.2%</td>
<td>3.4%</td>
<td>2.8%</td>
<td>2.4%</td>
<td>2.3%</td>
</tr>
<tr>
<td></td>
<td>[0.8; 1.6]</td>
<td>4.2%</td>
<td>3.4%</td>
<td>2.8%</td>
<td>2.4%</td>
<td>2.3%</td>
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<tr>
<td></td>
<td>[1.6; 2.4]</td>
<td>8.1%</td>
<td>4.2%</td>
<td>2.8%</td>
<td>2.4%</td>
<td>2.3%</td>
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</tbody>
</table>