Charged Hadron Azimuthal Anisotropy ($v_2$) in $\sqrt{s_{NN}} = 2.76$ TeV PbPb collisions from CMS

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for the CMS Collaboration
Motivation

- **Goal:** To explore hydrodynamic flow at the LHC energy by measuring azimuthal anisotropy as a function of transverse momentum, pseudorapidity and centrality in a broad kinematic range:
  - $0.3 < p_T < 12.0$ GeV/c
  - $|\eta| < 2.4$
  - 12 centrality classes in the range 0-80%

- **Four Methods:**
  - Event Plane
  - Cumulant 2\textsuperscript{nd} order
  - Cumulant 4\textsuperscript{th} order
  - Lee-Yang Zeros
  
  each has a different sensitivity to non-flow!
CMS Detector

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

- **Event selection:**
  - Minimum bias event selection: double coincidence of either the Beam Scintillation Counters (BSC) or Forward Hadronic calorimeters (HF)
  - Additional off-line selection (removal of beam gas, beam scraping, etc.)
  - Vertex position: $|z| < 10\text{cm}$

- **Total number of events after applying cuts $\sim 2.3\text{M}$**
Centrality Determination

• Based on the total sum of the transverse energy in HF

- 12 centrality classes: 0-80%

![Graph showing centrality classes and sum of transverse energy](image-url)
Track Reconstruction

- High $p_T$ tracks ($>0.9$ GeV/c) were reconstructed using both the silicon strip and pixel detectors.

- A second tracking iteration used only the pixel detector to produce “pixel-only” tracks with $p_T$ down to 0.2 GeV/c.

- The two iterations were merged, using only “full” tracks with a $p_T$ above 1.5 GeV/c, and using “pixel-only” tracks below 1.8 GeV/c.

**Absolute Efficiency**

- $|\eta| < 0.8$
- $2.0 < |\eta| < 2.4$

**Fake Rate**

- $|\eta| < 0.8$
- $2.0 < |\eta| < 2.4$

**$p_T$ Resolution**

- $|\eta| < 0.8$
- $2.0 < |\eta| < 2.4$
Methods

- **Event Plane Method:**
  - 3-subevent method is used to calculate resolution corrections based on pseudorapidity ($-2 \leq \eta < -1$), ($-0.75 < \eta \leq 0.75$), ($1 \leq \eta < 2$)
  - $\Delta \eta > 1$ pseudorapidity separation between event plane and $v_2$ tracks
  - flattening of the event planes (Fourier expansion)
  - high $p_T$ limit of 3.0 GeV/c on the tracks to determine event planes

- **Cumulant 2nd and 4th Order Method:**
  - auto-correlations are avoided by removing the particles that are used for determining differential flow from the integral flow
  - fixed multiplicity in each centrality class

- **Lee-Yang Zeros Method:**
  - sum and product generating functions were used
\( v_2(p_T) \) as a function of centrality

Several trends can be observed:
- \( v_2 \) increases from central to peripheral collisions up to 50% centrality.
- \( v_2 \) peaks at around 3 GeV/c.
- The different methods show differences consistent with the expected sensitivity to non-flow effects.
Good agreement between CMS and ALICE, with the CMS $v_2(p_T)$ measurement extended from $p_T \sim 5$ GeV/c to $p_T \sim 10$ GeV/c.
$v_2(p_T)$ Comparison with PHENIX

At low $p_T (< 2\text{GeV/c})$ measurements at the LHC energy are found to be only slightly larger than those obtained at RHIC. This increase is within the systematic uncertainties.

Flow is maximum around 40-50% centrality, consistent with RHIC results.
Integrated $v_2$ vs centrality

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

Error bars are statistical errors. Shaded boxes represent systematic errors.
Collision Energy Dependence

The logarithmic scaling of $v_2$ with $\sqrt{s_{NN}}$ persists to LHC energies.

CMS Preliminary Stat. Uncertainties
Mid-Central

CMS: 20-30%, $v_2\{LYZ\}$, extrapolated to $p_t=0$
Participant Eccentricity Dependence

Collective flow is driven by the initial asymmetry in the participant overlap zone and subsequent hydrodynamic expansion of the reaction system.

\[ v_2 \text{ rises up to } \varepsilon_{\text{part}} \approx 0.4. \]  

The subsequent decrease may indicate lack of equilibration.

\[ \varepsilon_{\text{part}} = \sqrt{\left(\sigma_y^2 - \sigma_x^2\right)^2 + 4\sigma_{xy}^2} \]

\[ \sigma_y^2 + \sigma_x^2 \]

Centrality (%) 0 10 20 30 40 50 60 70 80 90

\( v_2 \) rises up to \( \varepsilon_{\text{part}} \approx 0.4 \). The subsequent decrease may indicate lack of equilibration.
-15 to 40% increase is seen from RHIC to LHC
-the increase is most pronounced for central events
-$v_2/\varepsilon_{\text{part}}$ scales with the transverse particle density
Integrated $v_2$ (all methods) as a function of pseudorapidity

Clearly shows the separation of methods.
Stronger pseudorapidity dependence is observed for the most peripheral collisions.
Conclusions

We have presented detailed measurements of $v_2$ for $\sqrt{s_{NN}} = 2.76$ TeV PbPb collisions with good statistics and large pseudorapidity coverage.

$v_2(p_T)$ at mid-rapidity for $p_T < 2$ GeV/c is similar to that measured at the highest RHIC energy.

The integral $v_2$ value is strongest at midrapidity. A stronger rapidity dependence is observed for the most peripheral collisions.

The evolution of $v_2$ with centrality and eccentricity indicates that in more peripheral collisions (>40-50%) the system may not be completely equilibrated.

These data provide the basis for future detailed comparisons to models.
Higher Harmonics?

Julia Velkovska
Plenary
“Flow Measurements from CMS”
Tuesday 24 May 2011

Michael Issah
Poster Session I
Tuesday 24 May 2011 17:20
Board # 31
BACKUP
Systematic Studies

• Systematic studies common to all methods include:
  – Particle composition
  – Centrality determination and trigger efficiency
  – Track kinematic cuts
  – Fake track contribution to integral $v_2$
  – Uncertainty in efficiency corrections

• EP specific systematic checks:
  – Different track $p_T$ cuts when calculating Event Plane angles
  – Acceptance
  – Flattening check
  – Subevent pseudorapidity gap
  – Flattening parameters as a function of vertex

• Cumulant specific systematic checks:
  – Numeric stability with respect to $r_0$ parameter

• LYZ specific systematic checks:
  – Multiplicity fluctuations
**Systematic Uncertainties**

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 $0.3 < p_T < 3.0$ 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>$</td>
<td>\eta</td>
<td>$ All</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>
</tr>
<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>
</tr>
</tbody>
</table>
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>
- Event plane angles are defined in three pseudorapidity regions (\(-2 \leq \eta < -1, \ |\eta| \leq 0.75, 1 \leq \eta < 2\))

\[
\Psi'_n = \frac{1}{n} \tan^{-1} \left( \frac{\sum_i w_i \sin (n \varphi_i)}{\sum_i w_i \cos (n \varphi_i)} \right)
\]

- Event plane flattening (21st order)

\[
\Psi_2 = \Psi'_2 \left( 1 + \sum_j^{j_{\text{max}}} \frac{1}{j} \left( - \langle \sin (2j \Psi'_2) \rangle \cos (2j \Psi_2) + \langle \cos (2j \Psi'_2) \rangle \sin (2j \Psi_2) \right) \right)
\]

- 3-subevent method is used to calculate resolution corrections:

\[
R_A = \sqrt{\frac{\langle \cos (n (\Psi_n^A - \Psi_n^B)) \rangle \langle \cos (n (\Psi_n^A - \Psi_n^C)) \rangle}{\langle \cos (n (\Psi_n^B - \Psi_n^C)) \rangle}}
\]

- Extracted \(v_2\) signal is corrected for resolution:

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

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

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

integrated flow

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

differential flow

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

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

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

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

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

\[
G_n = \prod_{i=1}^{M} \left(1 + \frac{2x \cos(n\phi_i) + 2y \sin(n\phi_i)}{M}\right) \quad D_{p/n} = \frac{\langle e^{ip\psi} G_n(z) \rangle}{\langle G_n(z) \rangle}
\]
For each centrality, define the complex-valued generating function:

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

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:

\[ v_{2m}^\theta (\eta, p_T) = V_2^\theta \frac{J_1(j_{01})}{J_m(j_{01})} \Re \left( \frac{\langle \cos[2m(\phi_j - \theta)]e^{ir_0^\theta Q_2^\theta} \rangle}{i^{m-1} \langle Q_2^\theta e^{ir_0^\theta Q_2^\theta} \rangle} \right) \]

\( J_m \) is Bessel function of the first kind \( m=1 \) for \( v_2 \)

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

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