High-$p_T$ $v_n$ Harmonics in PbPb Collisions at 5.02 TeV

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Fourier harmonics $v_n$

$$\frac{dN(p_T)}{d\phi} \propto 1 + \sum 2v_n(p_T)\cos[n(\phi - \Psi_n)]$$
Motivation

- Fourier harmonics $v_n$
  \[
  \frac{dN(p_T)}{d\phi} \propto 1 + \sum 2v_n(p_T)\cos[n(\phi - \Psi_n)]
  \]

- Low $p_T$
  - Collectivity, hydrodynamics
  - Geometry($v_2$) + fluctuations ($v_3,4,...$)
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➢ Low $p_T$
  - Collectivity, hydrodynamics
  - Geometry($v_2$) + fluctuations ($v_3,4...$)

➢ High $p_T$
  - Path length dep. energy loss

\[ \sum \]
Motivation

- Fourier harmonics $v_n$
  \[ \frac{dN(p_T)}{d\phi} \propto 1 + \sum 2 v_n(p_T) \cos[n(\phi - \Psi_n)] \]

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  - Path length dep. energy loss
  - $R_{AA}(p_T)$: average energy loss

\[\sum_{n=0}^{\infty} \frac{1}{n+1} \frac{dN}{dp_T} \propto \frac{1}{(\ln p_T)^{1+\Delta}}\]

\begin{align*}
  &\sum_{n=0}^{\infty} \frac{1}{n+1} \frac{dN}{dp_T} \\
  &\propto \frac{1}{(\ln p_T)^{1+\Delta}}
\end{align*}

\[PRL \ 116 \ (2016) \ 132302\]
Motivation

- Measurement of high $p_T$ $v_n$
  - Complementary to $R_{AA}(p_T, \phi)$
  - Initial state + energy loss
- **2015 PbPb run at LHC**
  - $\sqrt{s_{NN}} = 5.02$ TeV, 404 $\mu$b$^{-1}$
  - MinimumBias ($p_T < 14$ GeV/c)

- **High $p_T$ track trigger**
  - $|\eta| < 1.0$, $14.0 < p_T < 100$ GeV/c
Scalar Product

\[ Q_n = \sum_j w_j e^{i n \phi_j} \]

Sum over tracks (tracker), or towers (HF)
Scalar Product

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Sum over tracks (tracker), or towers (HF)

\[ v_n \{\text{SP}\} = \frac{\langle Q_n \cdot Q_{nA}^* \rangle}{R} \]

- Large \( \eta \) gap applied (\(|\Delta \eta|>3.0\))

Tracker

HF-

-5 \( <\eta< -3 \)

HF+

3 \( <\eta< 5 \)

\( Q_{nA} \)

\( Q_n \)

HF- – HF+

\( -1 \quad 0 \quad 1 \)
Scalar Product

\[ Q_n = \sum_j w_j e^{i \phi_j} \]

Sum over tracks (tracker), or towers (HF)

\[ v_n \{\text{SP}\} = \frac{\langle Q_n \cdot Q_{nA}^* \rangle}{\sqrt{\langle Q_{nA} \cdot Q_{nB}^* \rangle \langle Q_{nA} \cdot Q_{nC}^* \rangle}} \]

\[ \sqrt{\langle Q_{nB} \cdot Q_{nC}^* \rangle} \]

- Large \( \eta \) gap applied (\(|\Delta\eta| > 3.0\))
- \( v_n \{\text{SP}\} \), non-ambiguous measure of RMS \( v_n \)
Results – $v_2\{SP\}$ high $p_T$

- FIRST time measure of $v_2\{SP\}$ up to 100 GeV/c
- $v_2\{SP\}$ remains positive at very high $p_T$
Low $p_T v_2$ increase from most-central to mid-central, then decrease

$v_2$ increase with $p_T$, peaked $\sim 3$ GeV/c, decrease while increasing $p_T$
Results – $v_2\{\text{SP}\}$

CMS Preliminary

PbPb $\sqrt{s_{\text{NN}}} = 5.02$ TeV

CMS-PAS-HIN-15-014

30 – 50%

$R_{AA}$

$25.8 \, \text{pb}^{-1} (5.02 \, \text{TeV pp}) + 404 \, \mu \text{b}^{-1} (5.02 \, \text{TeV PbPb})$

CMS

Preliminary

$T_{AA}$ and lumi. uncertainty

$|\eta|<1$

CMS-PAS-HIN-15-015
Results – $v_2\{SP\}$

At high $p_T$, less suppressed, more isotropic (less $v_2$)
Results – $v_3\{SP\}$ high $p_T$

- FIRST time measure of $v_3\{SP\}$ up to 100 GeV/c
- Consistent with 0 for $p_T > 30$ GeV/c

CMS Preliminary

PbPb $\sqrt{s_{NN}} = 5.02$ TeV

CMS-PAS-HIN-15-014
Results – $v_3\{SP\}$ low $p_T$

- FIRST time measure of $v_3\{SP\}$ up to 100 GeV/c
- Consistent with 0 for $p_T > 30$ GeV/c
- Little centrality dependence for $v_3$
Results – $v_3\{SP\}$ low $p_T$

- FIRST time measure of $v_3\{SP\}$ up to 100 GeV/c
- Consistent with 0 for $p_T > 30$ GeV/c
- Little centrality dependence for $v_3$

Multi-particle or few particle?
Cumulant

- Reference: $|\eta| < 2.4, 1 < p_T < 5 \text{ GeV/c}$

\[
\nu_n \{4\} = \sqrt[4]{-c_n \{4\}}
\]

\[
\nu_n \{6\} = \sqrt[6]{c_n \{6\}} / 4
\]

\[
\nu_n \{8\} = \sqrt[8]{-c_n \{8\}} / 33
\]

- 4-, 6-, 8-particle Q-Cumulant

[A. Bilandzic et.al., PRC 83 (2011) 044913]
• Reference: $|\eta| < 2.4$, $1 < p_T < 5$ GeV/c

• Particle of interest (POI): $|\eta| < 1.0$

\[
v_n\{4\}(p_T) = -d_n\{4\}/(-c_n\{4\})^{3/4}
\]
\[
v_n\{6\}(p_T) = \frac{d_n\{6\}}{4}/\left(\frac{c_n\{6\}}{4}\right)^{5/6}
\]
\[
v_n\{8\}(p_T) = \frac{-d_n\{8\}}{33}/\left(\frac{-c_n\{8\}}{33}\right)^{7/8}
\]

$d_n\{m\}$: 1 particle from POI within given $p_T$ range, $m-1$ particles from Ref.
• Reference: $|\eta| < 2.4$, $1 < p_T < 5$ GeV/c
• Particle of interest (POI): $|\eta| < 1.0$
• Multi-particle cumulant $v_n\{m\}$
  – Suppress correlations with few particle ($<m$)
Results – $v_2\{4,6,8\}$

- FIRST time measure multi-particle $v_2\{4,6,8\}$ up to 100 GeV/c
- Multi-particle $v_2\{4,6,8\}$ seems converge with $v_2\{SP\}$ at high $p_T$
- Multi-particle nature of high $p_T$ particles – Initial state effect
Results – $v_2\{4,6,8\}$

- Low $p_T$, $v_2\{SP\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$
- Expected in hydrodynamics
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Results – $v_2\{4,6,8\}$

- Low $p_T$, $v_2\{\text{SP}\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$
- Expected in hydrodynamics
Results – $v_2\{$high$\}$ vs $v_2\{$low$\}$
Results – $v_2\{\text{high}\}$ vs $v_2\{\text{low}\}$

- High $p_T$ $v_2$ strongly correlated with low $p_T$ $v_2$
- Suggestion of initial state effect
Results – $v_2\{\text{high}\}$ vs $v_2\{\text{low}\}$

- High $p_T$ $v_2$ strongly correlated with low $p_T$ $v_2$
- Suggestion of initial state effect
- Slope decrease while increasing $p_T$
Results – Compare to Models

- CUJET3.0 fails over full \( p_T \) and centrality dependence
  - JHEP 02 (2016) 169
- SHEE with linear energy loss has good agreement
  - arXiv:1609.05171
Summary

- $v_2\{\text{SP}\}$, $v_3\{\text{SP}\}$ and $v_2\{4,6,8\}$ up to 100 GeV/c
- Non-zero $v_2$ observed at very high $p_T$
- $v_2\{4,6,8\}$ show multi-particle nature at high $p_T$
- $v_3\{\text{SP}\}$ is consistent with zero for $p_T > 30$ GeV/c
- Strongly correlated high $p_T$ $v_2$ and low $p_T$ $v_2$
Backup
CMS Preliminary
PbPb $\sqrt{s_{NN}} = 5.02$ TeV

ALICE, $|\eta| < 0.8$
- $v_2\{2\}, |\Delta \eta| > 1$
- $v_3\{2\}, |\Delta \eta| > 1$
- $v_2\{4\}$

CMS, $|\eta| < 1.0$
- $v_2\{2\}, |\Delta \eta| > 3$
- $v_3\{2\}, |\Delta \eta| > 3$
- $v_2\{4\}$

0-5%

30-40%

10-20%

20-30%
