Collective flow and charged hadron correlations in 2.76 TeV PbPb collisions at CMS

Sandra S. Padula

for the CMS collaboration
Origin of azimuthal correlations

- Smooth IC
  - odd harmonics = 0 (by symmetry)
- Fluctuations in IC
  → give rise to odd harmonics ≠ 0

Elliptic flow

\[
\frac{dN}{d\phi} \sim 1 + 2v_2 \cos 2(\phi - \psi_2) + 2v_3 \cos 3(\phi - \psi_3) + \ldots
\]

Triangular flow

Smooth Initial Conditions

Fluctuations in IC
Azimuthal correlations investigated in CMS

Hydrodynamic flow driven by asymmetric pressure gradients & spatial anisotropies
Soft-hard interplay (hadrons from thermal quarks + jet fragmentation)
Path-length dependent energy loss

low $p_T$
intermediate $p_T$
high $p_T$

$p_T$ (GeV/c)
Highlights

• Measuring azimuthal anisotropy of charged particles:
  – Physics motivation:
    • EoS, opacity, and viscosity of the medium
    • Initial conditions and the role of fluctuations
  – Elliptic anisotropy at lower $p_T \rightarrow$ different methods
    • Event Plane
    • Cumulants
      – Two-particle: $v_2\{2\}$
      – Four-particle: $v_2\{4\}$
    • Lee-Yang Zeros
  – Elliptic anisotropy at high $p_T$ (Event Plane)
  – Dihadron correlations
    • Investigate anisotropies of higher order Fourier harmonics

• Summary
The CMS Detector includes:

- EM Calorimeter (ECAL)
- Hadron Calorimeter (HCAL)
- Beam Scintillator Counters (BSC)
- Forward Calorimeter (HF) (2.9<|η|<5.0)

**Tracker**
- (Pixels and Strips)

- Muon System

Very large coverage

( |Δφ| ≤ 2π, |Δη| < 5 )

η=0

η=2.5

η=-ln[tan(θ/2)]

θ

ζ

y

x

φ

z

Sandria S. Padula

ICHEP 2012 - Melbourne
Four methods: EP, $v_2\{2\}$, $v_2\{4\}$, LYZ

**Event Plane**

\[ v_2\{EP\} = \langle \cos \left[ 2(\phi - \psi_{EP}) \right] \rangle / R \]

**Need to correct for $\psi_{EP}$ resolution (R)**

- \( \eta = -5 \)
- \( \eta = -3 \)
- \( \eta = -2.4 \)
- \( \eta = 2.4 \)
- \( \eta = 0 \)
- \( \eta = 3 \)
- \( \eta = 5 \)

**Two-particle Cumulant**

\[ v_2\{2\} = \sqrt{\langle \cos \left[ 2(\phi_1 - \phi_2) \right] \rangle} \]

**Consider all two-particle correlations**

**Four-particle Cumulant**

\[ v_2\{4\} = (2\langle \cos[2(\phi_1 - \phi_2)] \rangle)^2 - \langle \cos(\phi_1 + \phi_2 - \phi_3 - \phi_4) \rangle )^{1/4} \]

**Consider all four-particle correlations**

**Lee-Yang Zeros**

**Consider all particle correlations (not all shown)**
Di-hadron correlations (5th method)

Signal

\[ S(\Delta \eta, \Delta \phi) = \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{same}}}{d \Delta \eta \, d \Delta \phi} \]

Particle 1: trigger
Particle 2: associated

Background distribution:

\[ B(\Delta \eta, \Delta \phi) = \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{mix}}}{d \Delta \eta \, d \Delta \phi} \]

Di-hadron correlations (5th method)

\[ \Delta \eta = \eta_{\text{assoc}} - \eta_{\text{trig}} \]
\[ \Delta \phi = \phi_{\text{assoc}} - \phi_{\text{trig}} \]

Associated hadron yield per trigger:

\[ \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{pair}}}{d \Delta \eta \, d \Delta \phi} = B(0, 0) \times \frac{S(\Delta \eta, \Delta \phi)}{B(\Delta \eta, \Delta \phi)} \]

1st analysis: PbPb@ \( \sqrt{s_{NN}} = 2.76 \text{ GeV} \):
0-5% most central coll. \( \Rightarrow \) JHEP07, 076 (2011)

40-50%

\[ 3 < p_{T_{\text{trig}}} < 3.5 \text{ GeV}/c \]
\[ 1 < p_{T_{\text{assoc}}} < 1.5 \text{ GeV}/c \]

Fourier analysis of $\Delta \phi$ correlations

Fourier decomposition: fitting the 1D $\Delta \phi$-projected distribution for $1 < |\Delta \eta| < 4$ as

$$\frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta \phi} = \frac{N_{\text{assoc}}}{2\pi} \left\{ 1 + \sum_{n=1}^{N_{\text{max}}} 2V_{n\Delta} \cos(n\Delta \phi) \right\} \quad (N_{\text{max}} = 5)$$

Flow driven correlations:

$$V_{n\Delta}(p_T^{\text{trig}}, p_T^{\text{assoc}}) = v_n(p_T^{\text{trig}}) \times v_n(p_T^{\text{assoc}})$$

Complementary to standard flow methods (i.e., EP, cumulants, LYZ)
$v_2(p_T)$: results for the 4 first methods

All methods:

- $v_2(p_T)$ grows up to 40-50%, then decreases

- Behavior with $p_T$: rise up to $p_T \sim 3\text{GeV/c}$, then gradually decreases (except $v_2\{2\}$ above 50%)

arXiv:1204.1409
Integrated $v_2$ scaled by eccentricity

Participant Eccentricity

$\epsilon_{\text{part}} \equiv \frac{\sqrt{(\sigma_{y'}^2 - \sigma_{x'}^2)^2 + 4\sigma_{x'y'}^2}}{\sigma_{y'}^2 + \sigma_{x'}^2}$

Cumulant Moments

$\epsilon \{2\}^2 \equiv \langle \epsilon_{\text{part}}^2 \rangle$

$v_2 \{2\} = \frac{v_2 \{4\}}{\epsilon \{4\}} \sim \frac{v_2 \{\text{EP} \}}{\epsilon_{\text{part}}}$

Differences between the methods → well described by Glauber model eccentricities for 15-40% centrality

$v_2 / \epsilon$ scales with the charged-particle rapidity density & is in good agreement with PHOBOS

Comparison with PHOBOS/RHIC

arXiv:1204.1409
$v_2(p_T)$: comparison with ALICE & low energies

- (1) CMS & ALICE for $v_2\{2\}$ and $v_2\{4\}$ $\rightarrow$ good agreement within uncertainties

- (2) Qualitative $\sqrt{s_{NN}}$ dependence of integrated $v_2$ [4.7 GeV (AGS) - 2.76 TeV (LHC)]: 20-30% log increase with $\sqrt{s_{NN}}$ from RHIC@200GeV to LHC@2.76 GeV
$v_2(p_T)$ extended to high $p_T$ & versus $N_{part}$ (EP)

- First precise measurements of $v_2(p_T)$ up to $p_T \sim 60$ GeV/c (comparison with ATLAS)
- $v_2$ gradually decreases above $p_T=10$ GeV/c; remains $\neq 0$ up to very high $p_T$

$arXiv: 1204.1850$
2nd-5th order single-particle azimuthal harmonics

- Assuming factorization, i.e.,
  \[ v_n(p_T^{\text{trig}}) = \frac{V_{n\Delta}(p_T^{\text{trig}}, p_T^{\text{low}})}{v_n(p_T^{\text{low}})}, \text{ where } v_n(p_T^{\text{low}}) = \sqrt{V_{n\Delta}(p_T^{\text{low}}, p_T^{\text{low}})} \]

- Non-zero \( v_3 \) and \( v_5 \) reflect fluctuations in IC
- For most peripheral (> 30%) \( \rightarrow \) \( v_3 \)-\( v_5 \) truncated due to statistical limitations

(🌟 included for completeness)
$v_2(p_T)$ at LHC with 4+1 complementary methods

$v_2(p_T)$ at LHC behaves similarly as at RHIC

Dihadron higher order $v_n \rightarrow$ new insight in IC, etc.

First $v_2$ measurements at 20 $< p_T \leq$ 60 GeV/c

High-$p_T$ $v_2$ results $\rightarrow$ constraints on energy loss models
» Centrality dependence of the harmonics, \( v_2 \) to \( v_5 \) \( \rightarrow \) 3 \( p_T^{\text{trig}} \) ranges:

- Strong \( v_2 \) dependence on centrality (not significant for \( v_3-v_5 \))
  - Expected from both hydrodynamic flow phenomena (lower-\( p_T \)) & path-length dependence of the parton energy-loss (higher \( p_T \))
  - \( v_2 \) sensitive to the lenticular shape (larger for peripheral coll.) of initial collision region; \( v_3-v_5 \) mostly driven by fluctuations in IC
$v_2$ from Di-hadron Correlations

$v_2(p_T)$ from dihadron correlation method (derived using fixed $1 < p_T^{assoc} < 1.5$ GeV/c) agrees well with EP method.
Two-dimensional (2D) per-trigger-particle associated yield of charged hadrons as a function of $|\Delta_{1}\eta|$ and $|\Delta_{1}\phi|$ for $3 < p_{\text{trig}} < 3.5 \text{ GeV/c}$ and $1 < p_{\text{assoc}} < 1.5 \text{ GeV/c}$, for the five central ranges of PbPb collisions at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$. The near-side peak is truncated in the two most peripheral distributions to better display the surrounding structure.

The analysis is performed in twelve centrality classes of PbPb collisions ranging from the most central 0–5% to the most peripheral 70–80%. Within each centrality range, the yield described in Eq. (1) is calculated in 0.5 cm wide bins of the vertex position ($z_{\text{vtx}}$) along the beam direction and then averaged over the range $|z_{\text{vtx}}| < 15 \text{ cm}$.

When filling the signal and background distributions, each pair is weighted by the product of correction factors for the two particles. These factors are the inverse of an efficiency that is a function of each particle's pseudorapidity and transverse momentum, $\varepsilon_{\text{trk}}(\eta, p_{\text{T}}) = A(\eta, p_{\text{T}})E(\eta, p_{\text{T}})^{-1} - F(\eta, p_{\text{T}})$, where $A(\eta, p_{\text{T}})$ is the geometrical acceptance, $E(\eta, p_{\text{T}})$ is the reconstruction efficiency, and $F(\eta, p_{\text{T}})$ is the fraction of misidentified tracks. The effect of this weighting factor only changes the overall scale but not the shape of the associated yield distribution, which is determined by the signal-to-background ratio.

As described in Ref. [1], the track-weighting procedure is tested using MC events generated with HYDJET [39] (version 1.6) propagated through a full detector simulation. The tracking efficiencies themselves are checked using simulated tracks embedded into actual data events. Systematic uncertainties due to variations of the track reconstruction efficiency as a function of vertex location and also the procedure used to generate the background events are evaluated. The individual contributions are added in quadrature to find the final systematic uncertainties of 7.3–7.6%.

The two-dimensional (2D) per-trigger-particle associated yield distribution of charged hadrons as a function of $|\Delta_{1}\eta|$ and $|\Delta_{1}\phi|$ is measured for each $p_{\text{trig}}$ and $p_{\text{assoc}}$ interval, and in different centrality classes of PbPb collisions. An examination of the $v_2$ not prominent.
Dihadron correlations @ high $p_T$

- First observation of long range near-side (\(\Delta \phi \sim 0\)) structure for $p_T^{\text{trig}} > 20$ GeV/c
$v_2(\eta)$ and centrality of integrated $v_2$

- $v_2(\eta)$ is larger at mid-rapidity
- constant or decreases very slowly at larger values of $|\eta|$

- integrated $v_2$ vs. centrality for $|\eta| < 0.8$: increase from central to peripheral collisions (max. ~ 40–50%)
Near-side peak ($\Delta \phi \approx 0$): mostly jet fragmentation

Away-side region ($\Delta \phi \approx \pi$): nearly flat (weakly dependent in $\Delta \eta$)

pp data at 2.76 GeV: similar structure to 70-80% peripheral PbPb

Strength of 2 regions $\to$ quantified by integrating over 2 ranges wrt $\Delta \phi_{\text{min}} \approx 1.18$
Integrated associated yields

- Near-side peak: increases by 1.7 from 70-80% to 0-5% [in (I)]; but only 1.3 in (IV) (at RHIC almost no centrality dependence)
- Away-side: yield decrease with centrality (negative for most central)
- On both near and away sides → yield in PbPb matches that in pp for the most peripheral events.
Centralities of the 1D $\Delta\phi$ distribution

- Averaging the 2D ($\Delta\eta, \Delta\phi$) in limited region in $\Delta\eta$

\[
\frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta\phi} = \frac{1}{(\Delta\eta_{\text{max}} - \Delta\eta_{\text{min}})} \int_{\Delta\eta_{\text{min}}}^{\Delta\eta_{\text{max}}} \frac{1}{N_{\text{trig}}} \frac{d^2N_{\text{pair}}}{d\Delta\eta d\Delta\phi} d\Delta\eta
\]

Short-range:

$0 < |\Delta\eta| < 1$

Long-range:

$2 < |\Delta\eta| < 4$
Dihadron correlations and single-particle anisotropies

- Factorization: valid up to $p_T^{assoc} \sim 3.5$ GeV/c & $p_T^{assoc} \sim 8$ GeV/c

- For 0-5% events → complex situation: factorization does not apply and other mechanisms must be at action, perhaps a complicated interplay of different particle production mechanisms between low-pT (hydrodynamic flow) and high-pT (dijet production) particles.