Measurements of flow and correlation phenomena in pp, pPb and PbPb collisions at CMS

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SPRACE – UNESP
For the CMS Collaboration
Where do we stand?

- Azimuthal correlations and collective flow
  - In AA collisions at RHIC: signature of the QGP as a nearly perfect liquid
  - In pA collisions at LHC: collectivity evidence discovered more recently
  - In pp collisions at LHC: what do we know so far?

- This talk highlights
  - Recent results on azimuthal anisotropy up to $p_T \approx 100 \text{ GeV/c}$
    - Flow harmonics $v_n$ with high $p_T$ tracks in PbPb collisions – path lengths of the energy loss
  - Ridge phenomena in pp collisions at 13 TeV
    - $v_2$ and $v_3$ flow harmonics measured
    - $v_2\{4\}$ and $v_2\{6\}$ flow cumulants: investigating collectivity
CMS Detector

EM Calorimeter (ECAL)
Tracker (Pixels and Strips)
Muon System
Hadron Calorimeter (HCAL)
Beam Scintillator Counters (BSC)
Forward Hadron Calorimeter (HF)

|η| < 2.4
|η| < 5.2
|η| < 3.0
|η| < 2.5

\[ \eta = - \ln(\tan(\theta/2)) \]

| |ΔΦ| \leq 2\pi |
Flow in high energy collisions

- Hydrodynamical picture of eccentricities (fluctuating initial conditions) and the corresponding flow single particle Fourier harmonics

- Azimuthal dependence of particle yield: Fourier harmonic expansion

\[
E \frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left( \sum_{n=1}^{\infty} 2 v_n \cos[n(\phi - \Psi_{n,EP})] \right)
\]
Flow in high energy collisions

- Hydrodynamical picture of eccentricities (fluctuating initial conditions) and the corresponding flow single particle Fourier harmonics

<table>
<thead>
<tr>
<th>低 pT</th>
<th>中间 pT</th>
<th>高 pT</th>
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<tr>
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Hydrodynamic flow (asymmetry, pressure gradients & spatial anisotropies)

Soft-hard interplay (hadrons from thermal quarks + jet fragments)

Path-length dependent energy loss

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Flow methods: Q-vectors, SP and $v_2\{m\}$

- Scalar Product (Event Plane) Method

Mathematical expression:

$$Q_n = \sum_j^M \omega_j e^{i n \phi_j}$$

Scalar Product (Event Plane) Method Resolution:

$$v_n(SP) = \frac{\langle Q_n \cdot Q_n^* \rangle}{\sqrt{\langle Q_n \cdot Q_n^* \rangle \langle Q_{nA} \cdot Q_{nA}^* \rangle \langle Q_{nB} \cdot Q_{nB}^* \rangle}}$$
Flow methods: Q-vectors, SP and $v_2\{m\}$

- Scalar Product (Event Plane) Method

$Q_n = \sum_j^M \omega_j e^{in\phi_j}$

$v_n(\text{SP}) = \frac{\langle Q_n \cdot Q^*_n \rangle}{\sqrt{\langle Q_n \cdot Q^*_n \rangle \langle Q^*_n \cdot Q^*_n \rangle}}$

- Particle cumulants

- $m$-particle correlations in $v_n\{m\}$
  (illustration for $m=4 \rightarrow v_n\{4\}$)

$<2> = <e^{in(\phi_1-\phi_2)}> 
<4> = <e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}> 
\eta = 2.4$

$c_n\{4\} = <4> - 2 \times <2>^2 
\eta = -2.4$

$v_n\{4\} = \frac{4}{\sqrt{-c_n\{4\}}} 
\eta = 2.4$

Suppresses 2-particle correlations

Includes all 4-particle correlations
High-$p_T$ $v_2$ and $v_3$ in PbPb collisions at 5.02 TeV

- $v_n$ harmonics from Scalar Product method

- $v_2$ rises up to $p_T \approx 3$ GeV/c then falls; $v_2 > 0$ up to $p_T \approx 100$ GeV/c
- $v_2$ increases from central to peripheral collisions; similar $p_T$ behavior
- $v_3$ shows similar behavior as $v_2$, but is centrality independent at low $p_T$
- $v_3$ are non-zero up to $p_T \approx 20$ GeV/c (in all centrality ranges)
High-\(p_T\) results for Scalar Product and Cumulants

- \(v_2\{SP\}\) and \(v_2\{4\}, v_2\{6\}, v_2\{8\}\) in six centrality classes

- \(p_T < 3 \text{ GeV/c} : v_2\{SP\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \rightarrow \) consistent with hydrodynamics
- \(p_T > 10 \text{ GeV/c} : v_2\{SP\} \approx v_2\{m\} \rightarrow \) collective anisotropy till high \(p_T\) (jet quenching?)
- anisotropies at low and high \(p_T\) \rightarrow likely related to IS anisotropy and EbyE fluctuations
- challenge to theoretical models
Ridge observed in Run-I in pp, pPb and PbPb

\[ p \rightarrow \bullet \leftarrow p \]

\[ \text{Pb} \rightarrow \text{Pb} \]

\[ \text{CMS } \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}, 220 \leq N_{\text{off}}^{\text{trk}} \leq 260 \]

\[ 1 < p_T^{\text{trig}} < 3 \text{ GeV/c} \]
\[ 1 < p_T^{\text{assoc}} < 3 \text{ GeV/c} \]

\[ \frac{1}{N_{\text{trig}}} \frac{\partial^2 N}{\partial \Delta \eta \partial \Delta \phi} \]

\[ R(\Delta \eta, \Delta \phi) \]

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\[ 1 < p_T^{\text{assoc}} < 3 \text{ GeV/c} \]
Dihadron correlations technique – I

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

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

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

Event 1

Same event pairs

Mixed event pairs

Ratio:

Associated hadron yield per trigger

CMS pPb \( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}, N_{\text{h}} \geq 110 \)
\( 1 < p_T < 3 \text{ GeV/c} \)
Dihadron correlations technique – II

- For quantifying the ridge: average the 2D two-particle correlation function over \(|\Delta \eta| > 2\) (avoid jet contamination)

- \(V_{n\Delta}\) extracted using Fourier fit

\[
\frac{1}{N_{\text{trig}}} \frac{dN^{\text{pair}}}{d\Delta \phi} = \frac{N_{\text{assoc}}}{2\pi} \left\{ 1 + \sum_n 2V_{n\Delta} \cos(n\Delta \phi) \right\}
\]

- Single \(v_n\) computed by

\[
V_{n\Delta}(p_T^a, p_T^b) = v_n(p_T^a) \times v_n(p_T^b)
\]

\[
v_n\{2, |\Delta \eta| > 2\}(p_T) = \frac{V_{n\Delta}(p_T^\text{ref}, p_T^\text{ref})}{V_{n\Delta}(p_T, p_T^\text{ref})}
\]
Dihadron correlations-III: subtraction

- Low multiplicity subtraction applied on $V_{n\Delta}$
  - Remove jet correlation contribution
    - bottom plot used to estimate jet correlation part
  - Assume jet-induced correlations invariant with multiplicity
  - $v_2(N_{\text{trk}}^{\text{offline}} < 20) = 0$, by construction

\[
V_{n\Delta}^{\text{sub}} = V_{n\Delta} - \left(10 < N_{\text{trk}}^{\text{offline}} < 20\right) \frac{N_{\text{assoc}}^{(10 < N_{\text{trk}}^{\text{offline}} < 20)}}{N_{\text{assoc}}} \times \frac{Y_{\text{jet}}^{(10 < N_{\text{trk}}^{\text{offline}} < 20)}}{Y_{\text{jet}}}
\]
Ridge scrutinized in pPb collisions

- Higher harmonics: $v_3$ results in pPb very similar to $v_3$ in PbPb

**PLB 724 (2013) 213**

![Graph showing $v_3$ results in pPb and PbPb](image)

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Ridge scrutinized in pPb collisions

- Higher harmonics: $v_3$ results in pPb very similar to $v_3$ in PbPb

- Strong signal of collectivity in pPb, similar to PbPb
  - $v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\infty\}$

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Ridge scrutinized in pPb collisions

- Higher harmonics: $v_3$ results in pPb very similar to $v_3$ in PbPb
- Strong signal of collectivity in pPb, similar to PbPb
  - $v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\infty\}$
- Clear mass ordering from ID particles ($V^0$'s)
  - radial flow

**PLB 724 (2013) 213**

**PRL 115 (2015) 012301**

**PLB 742 (2015) 200**

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Ridge scrutinized in pPb collisions

- Higher harmonics: $v_3$ results in pPb very similar to $v_3$ in PbPb

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- In summary, in pPb: collective effects observed!

- Possible origins:
  - IS interactions (e.g., CGC)
  - IS geometry & fluctuations + FS interactions (hydrodyn.)
Ridge for $h^± h^±$, $K^0_s h^±$, $\Lambda/\Lambda h^±$ in HM pp collisions

- Dihadron correlations
  - $h^± h^±$ hadrons (top)
  - $K^0_s h^±$ (middle)
  - $\Lambda/\Lambda h^±$ (bottom)

- (left) low multiplicity $10 \leq N_{trk}^{\text{offline}} \leq 20$
  range: no near-side ridge

- (right) high multiplicity $105 \leq N_{trk}^{\text{offline}} \leq 150$
  range: long-structure near $\Delta\phi=0$

arXiv:1606.06198

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$v_2^{\text{sub}\{2\}}$ and $v_3^{\text{sub}\{2\}}$ extracted from $V_{2\Delta}, V_{3\Delta}$

- $v_2^{\text{sub}\{2\}}$ (elliptic) and $v_3^{\text{sub}\{2\}}$ (triangular) flow harmonics vs. $N_{\text{trk}}^{\text{offline}}$
  - for $h^\pm h^\mp$ in pp collisions at $\sqrt{s}=13, 7, 5$ TeV (earlier results from pPb and PbPb added)
    - weak or almost no energy dependence in $v_2^{\text{sub}\{2\}}$
    - $v_2^{\text{sub}\{2\}} \rightarrow$ similar pattern as in pPb: grows with $N_{\text{trk}}^{\text{offline}}$ and then flattens
    - $v_3^{\text{sub}\{2\}} \rightarrow$ very similar to $v_3^{\text{sub}\{2\}}$ in pPb and PbPb collisions; increase at a lower rate

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- $v_2^{\text{sub}\{2\}}$ versus $p_T$ before and after applying jet corrections

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arXiv:1606.06198
$v_2$ for $h^\pm$, $K^0_s$ and $\bar{\Lambda}/\Lambda$ as trigger particles

- no clear mass-ordering for low $N_{\text{trk}}^{\text{offline}}$
- high multiplicity $N_{\text{trk}}^{\text{offline}}$ range: mass-ordering observed (radial flow)
- $v_2^{\text{sub}{2}}$ increase with $p_T$ (up to 2-3 GeV/c) then decrease
- particle mass ordering: $K^0_s$ higher than $\Lambda/\bar{\Lambda}$ at low $p_T$ then reverse at high $p_T$

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arXiv:1606.06198
Evidence of collectivity in pp collisions at 13 TeV

- Similar to the observations in pPb and PbPb collisions, except $v_2\{2\}$
  - smaller $v_2\{2\}/v_2\{4\}$ → fewer fluctuating sources in the IS in pp collisions? [PRL 112 (2014) 082301]

- Higher-order cumulant analysis in pp: $v_2\{2\} \approx v_2\{4\} \approx v_2\{6\}$ → collectivity in pp collisions!

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CMS

**pp $\sqrt{s} = 13$ TeV**

$0.3 < p_T < 3.0$ GeV/$c$

$|\eta| < 2.4$

- $v_2^{sub}\{2, |\Delta\eta| > 2\}$
- $v_2\{4\}$
- $v_2\{6\}$
- $v_2\{8\}$
- $v_2\{LYZ\}$

**PbPb $\sqrt{s_{NN}} = 5$ TeV**

$0.3 < p_T < 3.0$ GeV/$c$

$|\eta| < 2.4$

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

$0.3 < p_T < 3.0$ GeV/$c$

$|\eta| < 2.4$

Offline tracks $N_{trk}$

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Summary and Conclusions

– Azimuthal anisotropy in PbPb collisions up to $p_T \approx 100$ GeV
  - $p_T < 3 \text{ GeV/c}: v_2^{\text{SP}} > v_2^4 \approx v_2^6 \approx v_2^8 \rightarrow$ consistent with hydrodynamics
  - $p_T > 10 \text{ GeV/c}: v_2^{\text{SP}} \approx v_2^4 \approx v_2^6 \approx v_2^8 \rightarrow$ collective anisotropy till high $p_T$: path lengths of the in-medium jet energy loss
  - $v_2$ results at low and high $p_T \rightarrow$ IS anisotropy and EbyE fluctuations
  - challenge to theoretical models

– Ridge phenomena in pp collisions at 13 TeV
  - $v_2^2$ and $v_3^2$ flow harmonics for $\sqrt{s} = 5, 7$ and 13 TeV
    - very similar to pPb and PbPb cases, but with smaller intensity
    - nearly energy independent
  - mass-ordering observed in $v_2^2$ of $h^\pm, K^0_s$ and $\bar{\Lambda}/\Lambda$
  - cumulant results: $v_2^4 \approx v_2^6 \rightarrow$ collectivity in pp collisions!
  - additional challenge to theoretical models!
Azimuthal correlations ($v_2$): low $p_T$ vs. high $p_T$

- Exploring connection of low $p_T$ (hydro dominated) with high $p_T$ (jet quenching dominated) with $v_2$ data

- $v_2$ in three $p_T$ ranges vs. low $p_T$ ($1 < p_T < 1.25$ GeV/c) for all centralities
  - 0-20% divided in four bins of 5% bin width; above 20%, bin width of 10%
- Strong correlation of low and high $p_T$ values in full centrality range
- Indication that initial geometry and its fluctuations may be responsible
Two-particle Fourier coefficients vs. multiplicity

- $V_{2\Delta}$ and $V_{3\Delta}$ before and after jet correction procedure compared to PYTHIA 8 tune CUETO8M1 MC results (back-to-back jets only)
  - before subtraction: $V_{2\Delta}$ flat in $N_{\text{off trk}}$ and $V_{3\Delta} < 0$ from PYTHIA (b-to-b jets, $\Delta \phi \approx 0$)
  - after subtraction: $V_{2\Delta}$ grows w/ $N_{\text{off trk}}$ and flattens; $V_{3\Delta} > 0$ in full $N_{\text{off trk}}$
Mass-ordering in $v_2^{\text{sub}\{2\}}$ of $h^\pm$, $K^0_s$ and $\bar{\Lambda}/\Lambda$

- After subtracting jet contributions (top)
  - $v_2^{\text{sub}\{2\}}$ increase with $p_T$ (up to 2-3 GeV/c) then decrease
  - particle mass ordering: $K^0_s$ higher than $\bar{\Lambda}/\Lambda$ at low $p_T$ then reverse at high $p_T$

- Scaling with number of constituent quarks
  - $v_2^{\text{sub}\{2\}}/n_q$ vs. $KE_T/n_q$ (trans. kin. energy/quark)
  - dashed curve: polynomial fit to $K^0_s$ data
  - ratio of $v_2^{\text{sub}\{2\}}/n_q$ results for $K^0_s$ and $\bar{\Lambda}/\Lambda$ particles divided by this polynomial fit
    - approximate scaling for $KE_T/n_q > 0.2$ GeV
Comparing $v_2\{m\}$ for different systems

- Comparison between $v_2\{2\}$, $v_2\{4\}$ and $v_2\{6\}$ in p-p and p-Pb:
  - $v_2\{2\}/v_2\{4\}$ (p-p) ≤ $v_2\{2\}/v_2\{4\}$ (p-Pb) → related to IS fluctuations

- One possible explanation: PRL 112 (2014) 082301
  - smaller $v_2\{2\}/v_2\{4\}$ → Less IS fluctuating sources

- Still true before subtraction → Upper limit