Two- and four-particle correlations in pPb collisions from CMS

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for the CMS Collaboration
Can you guess: PbPb, pPb or pp?
Motivation

High-multiplicity pp collisions at $\sqrt{s} = 7$ TeV

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pPb collisions could be even more violent!

- 418 charged particles detected!
We study 2-particle correlations
To find ....ridges everywhere ...

(a) \( p \rightarrow p \rightarrow N_{\text{trk}}^{\text{offline}} \geq 110 \)

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

(b) \( \text{Pb} \rightarrow \text{Pb} \rightarrow 35-40\% \)

\[ N_{\text{trig}} \frac{d^2 N_{\text{pair}}}{d\Delta \phi d\Delta n} \]

CMS pPb \( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}, N_{\text{trk}}^{\text{offline}} \geq 110 \)

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

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2013 pPb data: match the multiplicity in PbPb

- Extend the multiplicity range in pPb
- Study Fourier harmonics
- 4-particle correlations
- Revisit PbPb
Questions to address

• What is the origin of the ridge in small systems?
  – Collective flow?
  – Quantum interference of gluons (CGC)?
  – … or something else?

• What are the initial state fluctuations?

• Methods:
  – Compare 2- and 4-particle correlations in different collision systems
  – Study high-order harmonics
  – multiplicity dependence
EXPERIMENTAL DETAILS
Data sets and triggers

- Start with a L1 trigger “seed”: total transverse energy > 20,40 GeV
- 4 High-Multiplicity HLT trigger thresholds based on tracking
- Each recorded 20 M events in 3 weeks run
- pPb integrated luminosity: 31nb⁻¹
- PbPb data from 2011: 50-100% , 2.3 μb⁻¹ reanalyzed
2-particle correlations

Signal pair distribution:

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

Background pair distribution:

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

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

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

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

(b) CMS pPb \(|S_{NN}| = 5.02 \text{ TeV}, 220 < n_{\text{trig}} < 260\)

1 \(< p_T^{\text{trig}} < 3 \text{ GeV}/c\)

1 \(< p_T^{\text{assoc}} < 3 \text{ GeV}/c\)

Event 1:

Event 2:
Collective effects: decompose in Fourier components

Jet-like correlations

Long and short range correlations
Fourier decomposition

Assuming factorization:

\[ V_n \{2, |\Delta \eta| > 2\} (p_T) = \frac{V_{n\Delta} (p_T^\text{ref} \cdot p_T^\text{ref})}{\sqrt{V_{n\Delta} (p_T^\text{ref} \cdot p_T^\text{ref})}} \]

Fourier decomposition:

\[ \frac{dN_{\text{pair}}}{d\Delta \phi} \sim 1 + 2 \sum_{n=1} V_{n\Delta} \cos(n \Delta \phi) \]

Take low reference \( p_T \) bin (0.3-3 GeV/c)
pPb: Subtraction of peripheral correlations

- Away-side:
  - non-flow correlations

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

- Subtract peripheral

\[N_{\text{trk}}^{\text{offline}} < 20\]

  - to get \(v_2, v_3\)

\[V_{n\Delta} (\text{cent}) - V_{n\Delta} (\text{peri}) \times \frac{N_{\text{assoc}} (\text{peri})}{N_{\text{assoc}} (\text{cent})} \times \frac{Y_{\text{jet}} (\text{cent})}{Y_{\text{jet}} (\text{peri})}\]

Account for the fact that jet correlation increases with multiplicity

Note: Results are obtained with or without peripheral subtraction

Test in HIJING
multi-particle correlations

Four particle correlations (Q-cumulant method):

\[ c_n\{4\} = \left\langle \langle 4 \rangle \right\rangle - 2 \cdot \left\langle \langle 2 \rangle \right\rangle^2 \]
Effect of multiplicity fluctuations on $c_2\{4\}$

Turn-on of the signal in data

Narrow bins + averaging: $c_2\{4\} > 0$

Wide bins: “generate” $v_2$ in HIJING
RESULTS
Long range 1 D correlation functions

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The ridge yield in different systems

Similar $p_T$ dependence in PbPb and pPb

Turn on around $N_{\text{trk}} \sim 50$

Independent of system size

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$1 < p_T^{\text{trig}} < 2 \text{ GeV/c}$

$1 < p_T^{\text{assoc}} < 2 \text{ GeV/c}$
**p_T dependence of \( v_n \): PbPb vs pPb**

Dashed-dotted curves
N<20 subtracted
Important for high-p_T

Remarkable similarity in PbPb and pPb for same multiplicity
v_2\{4\} turn-on around N_{trk} \sim 50; weak multiplicity dependence
Multiplicity dependence of $v_2$

Larger fluctuation in pPb

\begin{align*}
    v_n \{2\} &= \sqrt{\langle v_2 \rangle^2 + \sigma_{v_n}^2} \\
    v_n \{4\} &= \sqrt{\langle v_2 \rangle^2 - \sigma_{v_n}^2} \\
    \frac{\sigma_{v_n}}{v_n} &= \sqrt{\frac{v_n^2 \{2\} - v_n^2 \{4\}}{v_n^2 \{2\} + v_n^2 \{4\}}} \\
\end{align*}
Multiplicity dependence of $v_3$

- Independent of system size
- Does not extrapolate to 0

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$0.3 < p_T < 3$ GeV/c

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

$\sqrt{s_{NN}} = 5.02$ TeV
Other hints of collective effects?

Inverse slope of $m_T$ distributions, $T_{\text{slope}}$:

$$\frac{1}{m_T} \frac{dN}{dm_T} \sim \exp\left(-\frac{m_T}{T_{\text{slope}}}\right)$$

Inverse slope increases with particle mass and with multiplicity. Reminiscent of radial flow.
Conclusions

- CMS has measured elliptic and triangular flow coefficients in pPb and PbPb collisions.
- Similar $p_T$ and multiplicity dependence in different systems; $v_3$ is identical in pPb and PbPb.
- Four-particle correlations indicate a turn-on of multi-particle dynamics at $\sim N_{trk} \sim 50$.
- The ridge becomes apparent at the same multiplicity independent of system size.
  - Are we probing the limits of hydrodynamics?
- Hints of multiplicity dependent radial expansion.
- pPb provides a testing ground for our “reference” ideas.
$v_2/\epsilon_2$ vs $dN_{ch}/d\eta |_{\eta=0}$

- pPb $\sqrt{s_{NN}} = 5.02$ TeV, $v_2$ \{2, |$\Delta\eta|>2\}/\epsilon_2$ \{2\} (70-100\% sub.)
- PbPb $\sqrt{s_{NN}} = 2.76$ TeV, $v_2$ \{2, |$\Delta\eta|>2\}/\epsilon_2$ \{2\} (70-100\% sub.), reanalyzed
- PbPb $\sqrt{s_{NN}} = 2.76$ TeV, $v_2$ \{EP\}/\epsilon_2$ \{2\}, published

$0.3 < p_T < 3$ GeV/c

CMS Preliminary
<table>
<thead>
<tr>
<th>$N_{\text{trk}}$ bin</th>
<th>PbPb data</th>
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<th>pPb data</th>
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<tbody>
<tr>
<td></td>
<td>$\langle C_{\text{trk}} \rangle$</td>
<td>$\langle N_{\text{trk}}^{\text{offline}} \rangle$</td>
<td>$\langle N_{\text{trk}}^{\text{corrected}} \rangle$</td>
<td>Fraction</td>
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<td>$[0, \infty)$</td>
<td>92±4</td>
<td>10</td>
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<td>$[40, 50)$</td>
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<td>68±3</td>
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<td>$[50, 60)$</td>
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<td>$[120, 150)$</td>
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<td>$[150, 185)$</td>
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<td>$[260, 300)$</td>
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<td>$[300, 350)$</td>
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<td>$1 \times 10^{-7}$</td>
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</table>
CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV

120 ≤ $N_{\text{trk}}^{\text{offline}}$ < 150

150 ≤ $N_{\text{trk}}^{\text{offline}}$ < 185

185 ≤ $N_{\text{trk}}^{\text{offline}}$ < 220

220 ≤ $N_{\text{trk}}^{\text{offline}}$ < 260

CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV

ALICE, 0-20%

v$_3$[2, $|\Delta \eta| > 0.8$]

v$_3$[2, $|\Delta \eta| > 2$], $N_{\text{trk}}^{\text{offline}} < 20$ sub.