Anisotropy harmonics from long-range correlations in high multiplicity pp collisions

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For the CMS Collaboration

Quark Matter Conference, Kobe – September 29 (2015)
Long-range “ridges” at LHC

- The “ridge” seen in all systems at the LHC!
  - Hydrodynamic flow origin in PbPb collision.
  - What about small systems?

(a) $pp \sqrt{s} = 7$ TeV, $N^{\text{offline}}_{\text{trk}} \geq 110$

(b) $p\text{Pb} \sqrt{s_{\text{NN}}} = 5.02$ TeV, $220 < N^{\text{offline}}_{\text{trk}} \leq 260$

(c) $p\text{Pb} \sqrt{s_{\text{NN}}} = 2.76$ TeV, $220 < N^{\text{offline}}_{\text{trk}} \leq 260$

1 $< p_T < 3$ GeV/c

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Long-range “ridge” in pPb

- Collectivity!
- Mass ordering!
- “Radial flow”!

CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $220 < N_{\text{trk}}^{\text{offline}} < 260$

$1 < p_T < 3$ GeV/c

CMS Preliminary

$|y_{\text{cm}}| < 1.0$

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

$0.3 < p_T < 3.0$ GeV/c; $|\eta| < 2.4$

$2 < \Delta \phi \{2, 4, 6, 8, \text{LYZ} \}$

$0.05 < v_2 < 0.10$

CMS PbPb

$0.3 < p_T = 2.76$ TeV

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

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

(0.006-0.06%)

CMS pp $\sqrt{s} = 7$ TeV, $L_{\text{int}} = 5$ pb$^{-1}$

CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $L_{\text{int}} = 35$ nb$^{-1}$

CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV, $L_{\text{int}} = 2.3$ mb$^{-1}$

HIN-PAS-15-006

Talk by Hong Ni

Poster by Z. Tu (#0214)

9/28/15

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Long-range “ridge” in pp

Collectivity in even smaller system?
Hydro flow at the smallest scale?
Other contenders? E.g. Color Glass Condensate glasma
Long-range “ridge” in pp

No collision energy dependence

CMS Preliminary

- pp $\sqrt{s} = 13$ TeV, $N_{\text{trk}}^{\text{offline}} \geq 105$
- pp $\sqrt{s} = 7$ TeV, $N_{\text{trk}}^{\text{offline}} \geq 110$

(a) $1.0 < p_T < 2.0$ GeV/c
(b) $2.0 < |\Delta \eta| < 4.0$

FSQ-PAS-15-002
Long-range “ridge” in pp

What about \( v_2 \), \( v_3 \) in pp?

Particle species dependence?

Is it collectivity?

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Probing (novel long range correlation phenomena in \( pPb \) collisions (with identified parameters at CMS)

*Zhenyu Chen (Rice University)* for the CMS Collaboration

Hot Quarks Workshop 2014

19/28/15

Zhenyu Chen

- Quark Matter 2015, Kobe, Japan

- In pA, hydro calculation limited by proton shape

![Graph showing proton shape fluctuation](image)

- pp collision provides exclusive probe of proton shape fluctuation at very short time scale!
\( v_n \) extraction

- Two particle correlation functions projected in ridge range (\(|\Delta \eta| > 2\)), fit by Fourier decomposition to get \( V_{n\Delta} \):

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

- Assume factorization:

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

\( \text{CMS pp} \sqrt{s_{NN}} = 7 \text{ TeV} \)

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

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

Long range (\(|\Delta \eta| > 2\))

Preliminary

110 \leq N < 150

Fourier fits
$V_{2\Delta}$ vs. multiplicity

- Data & MC difference → contribution other than jet correlation
\( V_{2\Delta}, V_{3\Delta} \) vs. multiplicity

- Data & MC difference \( \rightarrow \) contribution other than jet correlation
**V_{2\Delta}, V_{3\Delta} vs. multiplicity**

- Data & MC difference → contribution other than jet correlation
- Positive $V_{3\Delta}$ → brand new phenomena!
Correction for jet contribution

- Back-to-back jet correlation on the away side

![Graph showing correlation between h^±-h^± with Fourier fits and CMS pp data with S_{NN} = 7 TeV.](image)
Correlation between away and near-side jet contribution

CMS pp, \( \sqrt{s_{NN}} = 7 \text{ TeV} \)
- \( 1 < p_{T}^{\text{trig}} < 3 \text{ GeV/c} \)
- \( 1 < p_{T}^{\text{assoc}} < 3 \text{ GeV/c} \)
Long range (|\( \Delta \eta \)| > 2)

Preliminary

\( 110 \leq N < 150 \)
\( 10 \leq N < 20 \)

Fourier fits

\[ \frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta \phi} - C_{\text{ZYAM}} \]

Short range (|\( \Delta \eta \)| < 1) minus
Long range (|\( \Delta \eta \)| > 2)

\[ \frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta \phi} - C_{\text{ZYAM}} \]
**Correction for jet contribution**

- Bias to more jet contribution when selecting high multiplicity

![Graph showing comparison of jet contributions](image)

- Calibrating the bias by near-side jet yield $Y_{\text{jet}}$

  low multiplicity subtraction to remove jet contribution:

$$V_{n\Delta}^{\text{sub}} \times N_{\text{assoc}}^{\text{high}} = V_{n\Delta}^{\text{high}} \times N_{\text{assoc}}^{\text{high}} - V_{n\Delta}^{\text{low}} \times N_{\text{assoc}}^{\text{low}} \times \frac{Y_{\text{jet}}^{\text{high}}}{Y_{\text{jet}}^{\text{low}}}$$
After low multiplicity subtraction

- CMS pp \( \sqrt{s_{NN}} = 7 \) TeV
- \( 110 \leq N < 150 \) - \( 10 \leq N < 20 \) \( \times (Y^{\text{high}}_\text{jet} / Y^{\text{low}}_\text{jet}) \)
- \( 1 < p_T < 3 \) GeV/c
- Long range \( |\Delta \eta| > 2 \)
- Preliminary

\[
V_{n\Delta} \text{ after subtraction:} \\
V_{1\Delta}^{\text{sub}} \approx 0.0003 \\
V_{2\Delta}^{\text{sub}} \approx 0.0042 \\
V_{3\Delta}^{\text{sub}} \approx 0.0008
\]

“Double ridge” structure similar to pPb and PbPb
$V_{2\Delta}, V_{3\Delta}$ vs. multiplicity

- $V_{2\Delta}, V_{3\Delta}$ become relative constant at high multiplicity
- Low multiplicity subtraction works well for jet correlation (MC)
$v_2$ vs. multiplicity

- $v_2(pp) \approx 4\%$ at high multiplicity
- $v_2(pp) < v_2(pPb) < v_2(PbPb)$

CMS Preliminary

- $pPb \sqrt{s_{_{NN}}} = 5.02$ TeV
- PbPb $\sqrt{s_{_{NN}}} = 2.76$ TeV

$|\Delta \eta| > 2$

$0.3 < p_T < 3$ GeV/c

$N_{\text{trk}}$ offline

$N_{\text{trk}}$ offline

$N_{\text{trk}}$ offline
\( v_3 \) vs. multiplicity

- \( v_3(pp) \approx 1.2\% \) at high multiplicity
- Trend of deviation from \( v_3(pPb) \) & \( v_3(PbPb) \) at high multiplicity
**v₃ vs. multiplicity**

- \( v₃(pp) \approx 1.2\% \) at high multiplicity
- Trend of deviation from \( v₃(pPb) \) & \( v₃(PbPb) \) at high multiplicity
- More constraints on the proton shape
$
\mathbf{V^0 \text{ correlation}}$

- **Topological $V^0$ reconstruction**
  - $K^0_s \rightarrow \pi^+\pi^-$
  - $\Lambda \rightarrow p^+\pi^-$

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**Similar correlation as charge hadron**

$\mathbf{K^0_s - h^\pm}$

$\mathbf{\Lambda/\bar{\Lambda} - h^\pm}$
No mass dependence of $v_2$ from jet correlation at low multiplicity

Mass ordering in low $p_T$ region at high multiplicity
4-particle correlation: collectivity?

- Q-cumulant 4-particle correlation
  \[
  \langle \langle 4 \rangle \rangle \equiv \left\langle e^{i n (\phi_1 + \phi_2 - \phi_3 - \phi_4)} \right\rangle
  \]
  
  \[
  c_n \{4\} = \langle \langle 4 \rangle \rangle - 2 \cdot \langle \langle 2 \rangle \rangle^2
  \]
  
  related to \( v_2 \) as
  
  \[
  v_2 \{4\}^4 = -c_2 \{4\}
  \]

- \( c_2 \{4\} \) decrease with multiplicity, same behavior as in pPb
4-particle correlation: collectivity?

- **Q-cumulant 4-particle correlation**
  \[ \langle \langle 4 \rangle \rangle \equiv \left< e^{i n (\phi_1 + \phi_2 - \phi_3 - \phi_4)} \right> \]
  
  \[ c_n \{ 4 \} = \langle \langle 4 \rangle \rangle - 2 \cdot \langle \langle 2 \rangle \rangle^2 \]
  
  related to \( v_2 \) as

  \[ v_2 \{ 4 \}^4 = -c_2 \{ 4 \} \]

- **\( c_2 \{ 4 \} \) decrease with multiplicity, same behavior as in pPb**

- **Indication of negative \( c_2 \{ 4 \} \) at high multiplicity, stay tuned!**
Summary

Presented the second-order ($v_2$) and third-order ($v_3$) anisotropy of charge hadron, $K^0_S$ and $\Lambda$ for high multiplicity pp collisions

- Multiplicity dependent (charge hadron)
  - overall $v_2(pp) < v_2(pPb) < v_2(PbPb)$
  - $v_3(pp)$ deviates from $v_3(pPb \& PbPb)$ at high multiplicity

- Transverse momentum dependent (PID)
  - Mass ordering clearly observed in low $p_T$ region
Back up
- **2010 pp, 6.2 pb⁻¹**
- **Triggers**
  - High Multiplicity Trigger
  - Minimum Bias Trigger

| N_{trk}^{\text{offline}} (|\eta|<2.4, p_T>0.4 GeV/c) | HLT efficiency |
|-----------------|-----------------|
| 0               | 0.0             |
| 50              | 0.5             |
| 100             | 1.0             |
| 150             | 1.0             |

![Graphs of High Multiplicity Trigger and Minimum Bias Trigger](image)
Probing (novel long, range correlation phenomena in PbPb (collisions (with identified particles at CMS (Zhenyu Chen (Rice University) for the CMS Collaboration l Hot Quarks Workshop 2014 l

19/28/15

Zhenyu Chen
Quark Matter 2015, Kobe, Japan

CMS Preliminary

- pp $\sqrt{s} = 13$ TeV, $N_{\text{trk}}^\text{offline} \geq 105$
- pp $\sqrt{s} = 7$ TeV, $N_{\text{trk}}^\text{offline} \geq 110$
- Glasma+BFKL, $N_{\text{trk}}^\text{offline} \approx 100$, 13 TeV
- Glasma+BFKL, $N_{\text{trk}}^\text{offline} \approx 100$, 7 TeV

Associated yield / (GeV/c)

0.04
0.02
0.00

$p_T$ (GeV/c)

0
2
4
50
100
150

$N_{\text{trk}}^\text{offline}$

1.0 < $p_T$ < 2.0 GeV/c
2.0 < $|\Delta \eta|$ < 4.0

(b)
Systematic studies considering: from low to high multiplicity
- Potential de-correlation between near and away side jet contribution
- Potential change of jet distribution in $\Delta \eta$ and $\Delta \phi$

One overall test: cut leading particle $p_T$

Subtraction robust against potential bias on jet mechanism
The subtraction procedure to remove jet contribution

\[ V_{n\Delta}^{\text{sub}} \times N_{\text{assoc}}^{\text{high}} = V_{n\Delta}^{\text{high}} \times N_{\text{assoc}}^{\text{high}} - V_{n\Delta}^{\text{low}} \times N_{\text{assoc}}^{\text{low}} \times \frac{\gamma_{\text{high}}^{\text{jet}}}{\gamma_{\text{low}}^{\text{jet}}} \]

For purely jet correlation

\[ V_{n\Delta}^{\text{sub}} \times N_{\text{assoc}}^{\text{high}} = 0 \text{ expected,} \]

which requires

\[ V_{n\Delta}^{\text{high}} \times N_{\text{assoc}}^{\text{high}} = V_{n\Delta}^{\text{low}} \times N_{\text{assoc}}^{\text{low}} \times \frac{\gamma_{\text{high}}^{\text{jet}}}{\gamma_{\text{low}}^{\text{jet}}} \]

\[ \frac{V_{n\Delta}^{\text{high}} \times N_{\text{assoc}}^{\text{high}}}{\gamma_{\text{high}}^{\text{jet}}} = \frac{V_{n\Delta}^{\text{low}} \times N_{\text{assoc}}^{\text{low}}}{\gamma_{\text{low}}^{\text{jet}}} \]
Validation of Subtraction in MC

![Graph 1](#)

- CMS pp $\sqrt{s_{NN}} = 7$ TeV
- PYTHIA6 TuneZ2 pp 7 TeV
- PYTHIA8 Tune4C pp 7 TeV

$0.3 < p_T < 3$ GeV/c

![Graph 2](#)

- CMS pp $\sqrt{s_{NN}} = 7$ TeV
- PYTHIA6 TuneZ2 pp 7 TeV
- PYTHIA8 Tune4C pp 7 TeV

$0.3 < p_T < 3$ GeV/c
Validation of Subtraction in MC

\[ \frac{N_{\text{assoc}} \times V_{2\Delta}}{Y_{\text{jet}}} \]

- CMS pp $\sqrt{s_{NN}} = 7$ TeV
- PYTHIA6 TuneZ2 pp 7 TeV
- PYTHIA8 Tune4C pp 7 TeV

0.3 < $p_T$ < 3 GeV/c

N_{\text{offline}}^{\text{trk}}
Validation of Subtraction in MC

PYTHIA8 pp 7TeV
0.3 < p_{\text{ass,trg}}^{T} < 3 \text{ GeV}
|\Delta \eta| > 2

No subtraction
Subtraction 10 < N_{\text{trk}}^{\text{offline}} < 20
Subtraction 20 < N_{\text{trk}}^{\text{offline}} < 30
Subtraction 30 < N_{\text{trk}}^{\text{offline}} < 40

V_{2\Delta}

 offline

GEN

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Potential de-correlation between near and away side jet contribution

- Jet yield used in subtraction estimated by long-range ($|\Delta\eta|>2$) away side ($|\Delta\phi|>2\pi/3$) yield minus near side yield ($|\Delta\phi|<\pi/3$).

- Systematic uncertainty assigned.
No bias on jet distribution in $\Delta \phi$

CMS pp $\sqrt{s} = 7$ TeV

$6 < p_T^{\text{trg}} < 9$ GeV/c

$0.3 < p_T^{\text{assoc}} < 3$ GeV/c

$|\Delta \eta| > 2$

$110 \leq N_{\text{trg}}^{\text{offline}} < 150$

$(10 \leq N_{\text{trk}}^{\text{offline}} < 20) \times (Y_{\text{jet}}^{\text{high}}/Y_{\text{jet}}^{\text{low}})$

$0.3 < p_T^{\text{trg}} < 3$ GeV/c

$0.3 < p_T^{\text{assoc}} < 3$ GeV/c

$|\Delta \eta| > 2$

$110 \leq N_{\text{trg}}^{\text{offline}} < 150$

$(10 \leq N_{\text{trk}}^{\text{offline}} < 20) \times (Y_{\text{jet}}^{\text{high}}/Y_{\text{jet}}^{\text{low}})$
No bias on jet distribution in $\Delta \eta$

CMS pp $\sqrt{s} = 7$ TeV
$0.3 < p_T < 3$ GeV/c

$V^2_{\text{sub}2}$ vs $|\Delta \eta|$ for different $N_{\text{trk}}$ bins. Preliminary results.
Test of Subtraction in data

CMS pp $\sqrt{s} = 7$ TeV
$0.3 < p_T < 3$ GeV
$|\Delta \eta| > 2$

$V_2\{\Omega\}$

$N_{\text{offline}}^{\text{trk}}$

Preliminary

- 10 ≤ $N_{\text{offline}}^{\text{trk}}$ < 20 Sub.
- 10 ≤ $N_{\text{offline}}^{\text{trk}}$ < 15 Sub.
- 15 ≤ $N_{\text{offline}}^{\text{trk}}$ < 20 Sub.
- 20 ≤ $N_{\text{offline}}^{\text{trk}}$ < 25 Sub.
- 25 ≤ $N_{\text{offline}}^{\text{trk}}$ < 30 Sub.
- 30 ≤ $N_{\text{offline}}^{\text{trk}}$ < 40 Sub.
V_{1\Delta} in data & MC

Preliminary

CMS pp $\sqrt{s} = 7$ TeV

$|\Delta \eta| > 2$

$0.3 < p_T < 3$ GeV

$N_{\text{trk}}^{\text{offline}}$

$10 \leq N_{\text{trk}} < 20$ sub.

PYTHIA6 No sub.  
PYTHIA6 $10 \leq N_{\text{trk}} < 20$ sub.
Two particle correlation function

- Clear ridge at high multiplicity
- No ridge at low multiplicity
Two particle correlation function

- Two particle correlation constructed for:
  - Charge hadron as both trigger and associated, $h^\pm - h^\pm$
  - $K^0_S$ as trigger, charge hadron as associated, $K^0_S - h^\pm$
  - $\Lambda$ as trigger, charge hadron as associated, $\Lambda - h^\pm$
Probing (novel long range correlation phenomena in PbPb collisions with identified particles at CMS)

Zhenyu Chen (Rice University) for the CMS Collaboration

Hot Quarks Workshop 2014

\[ \text{CMS pp } \sqrt{s_{NN}} = 7 \text{ TeV} \]

- Preliminary
- Fourier fits

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

Long range (|\Delta\eta| > 2)

Preliminary

\[ \frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta\phi} - C_{ZYM} \]

\[ \pm \theta \]

Short range (|\Delta\eta| \leq 1)
minus
Long range (|\Delta\eta| > 2)

\[ \text{CMS pp } \sqrt{s_{NN}} = 7 \text{ TeV} \]

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

Long range (|\Delta\eta| > 2)

Preliminary

\[ \frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta\phi} - C_{ZYM} \]

\[ \pm \theta \]

Short range (|\Delta\eta| \leq 1)
minus
Long range (|\Delta\eta| > 2)

\[ \text{CMS pp } \sqrt{s_{NN}} = 7 \text{ TeV} \]

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

Long range (|\Delta\eta| > 2)

Preliminary

\[ \frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta\phi} - C_{ZYM} \]

\[ \pm \theta \]

Short range (|\Delta\eta| \leq 1)
minus
Long range (|\Delta\eta| > 2)

\[ \text{CMS pp } \sqrt{s_{NN}} = 7 \text{ TeV} \]

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

Long range (|\Delta\eta| > 2)

Preliminary

\[ \frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta\phi} - C_{ZYM} \]

\[ \pm \theta \]

Short range (|\Delta\eta| \leq 1)
minus
Long range (|\Delta\eta| > 2)
Correction for jet contribution

\[ \frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta\phi} = \text{C}_{\text{ZYAM}} \]

CMS pp \( \sqrt{s_{NN}} = 7 \) TeV

(110 \leq N < 150) - (10 \leq N < 20) \times (Y_{\text{jet}}^{\text{high}} / Y_{\text{jet}}^{\text{low}})

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

Long range (|\Delta\eta| > 2)

Preliminary

- \( h^+ - h^+ \)
- \( K^0_S - h^+ \)
- \( \Lambda / \bar{\Lambda} - h^+ \)
No mass dependence of $v_2$ from jet correlation at low multiplicity

Mass ordering in low $p_T$ region at high multiplicity
NCQ scaling in pp

CMS pp \( \sqrt{s} = 7 \text{ TeV} \)

110 \( \leq N_{\text{trk}}^{\text{offline}} \) < 150

Preliminary

\(|\Delta \eta| > 2\)

Data/Fit

Polynomial fits to \( K^0_S \)
Two particle correlation function after low multiplicity subtraction

CMS pp $\sqrt{s} = 7$ TeV Preliminary
(110\leq N_{\text{trk}}^{\text{offline}} < 150) minus
(10\leq N < 20) \times Y_{\text{jet}}^{\text{high}} / Y_{\text{jet}}^{\text{low}}
1<p_T<3\text{GeV/c}

PYTHIA6 TuneZ2 pp 7 TeV
(90\leq N_{\text{trk}}^{\text{offline}} < 110) minus
(10\leq N < 20) \times Y_{\text{jet}}^{\text{high}} / Y_{\text{jet}}^{\text{low}}
1<p_T<3\text{GeV/c}