Collective phenomena in $pp$ collisions at CMS

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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, $N_{\text{trk}}^{\text{offline}} \geq 110$

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

(c) PbPb $\sqrt{s_{NN}} = 2.76$ TeV, $220 < N_{\text{trk}}^{\text{offline}} \leq 260$

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Long-range “ridge” in pPb

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

Diagram: CMS Preliminary

(a) pp $\sqrt{s} = 13$ TeV, $N_{\text{trk}}^{\text{offline}} \geq 105$

(b) $1.0 < p_T < 2.0$ GeV/c

$2.0 < |\Delta \eta| < 4.0$

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

- No collision energy dependence
- CGC overshoots at high multiplicity
- Hydro calculations?

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

- What about $v_2$, $v_3$ in pp?
- Particle species dependence?
- Is it collective?
Probing phenomena in pPb collisions with identified parameters at CMS

- In pA, hydro calculation limited by proton shape

- pp collision provides exclusive probe of proton shape fluctuation at very short time scale!

B. Schenke

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\( v_n \) 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:

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

- CMS pp $\sqrt{s} = 7$ TeV
- $|\Delta \eta| > 2$
- $0.3 < p_T < 3$ GeV/c
- PYTHIA6

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

- CMS pp $s = 7$ TeV, $|\Delta \eta| > 2$
- $0.3 < p_T < 3$ GeV/c

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

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

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

![Graph showing correlation between h^+ and h^-](image)
Correction for jet contribution

- Correlation between away and near-side jet contribution

![Graph showing corrections for jet contribution](image-url)

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)

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

- Bias to more jet contribution when selecting high multiplicity

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

- 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

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

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

\( (110 \leq N < 150) - (10 \leq N < 20) \times \left( \frac{Y_{\text{high}}}{Y_{\text{low}}} \right) \)

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

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

Preliminary

\( V_{n\Delta} \) 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**

- $v_2(p\bar{p}) \approx 4\%$ at high multiplicity
- $v_2(p\bar{p}) < v_2(pPb) < v_2(PbPb)$
Probing (novel long range correlation phenomena) in PpB (collisions with identified particles at CMS)

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v₃ vs. multiplicity

v₃(pp) ≈ 1.2% at high multiplicity

Trend of deviation from v₃(pPb) & v₃(PbPb) at high multiplicity
- $v_3(pp) \approx 1.2\%$ at high multiplicity
- Trend of deviation from $v_3(pPb)$ & $v_3(PbPb)$ at high multiplicity
- More constraints on the proton shape
\[ V^0 \text{ correlation} \]

- Topological \( V^0 \) reconstruction
  - \( K^0_S \rightarrow \pi^+\pi^- \)
  - \( \Lambda \rightarrow p^+\pi^- \)

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

\( \Delta \phi \) (radians)

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

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

- 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
### 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

#### (a)

- $0.0 \leq p_T \leq 2.0$ GeV/c
- $1.0 < p_T < 2.0$ GeV/c
- $2.0 < |\Delta \eta| < 4.0$

#### (b)

- $0 < p_T \leq 5$ GeV/c
- $5 < p_T \leq 10$ GeV/c
- $10 < p_T \leq 15$ GeV/c

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**Graph Details**

- **Associated yield / (GeV/c)**
- **$p_T$ (GeV/c)**
- **$N_{\text{trk}}^{\text{offline}}$**
Validation of subtraction in data

- 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

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

For purely jet correlation, \( V_{\text{sub}}^{n\Delta} \times N_{\text{assoc}}^{\text{high}} = 0 \) expected, which requires

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

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

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

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

0.3 < \( p_T \) < 3 GeV/c

\[ Y_{\text{jet}} \]

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

0.3 < \( p_T \) < 3 GeV/c
Validation of Subtraction in MC

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

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

$0.3 < p_T < 3$ GeV/c

Preliminary
Validation of Subtraction in MC

PYTHIA8 pp 7TeV
\(0.3 < p_T^{\text{ass,trg}} < 3 \text{ GeV}\)
\(|\Delta \eta| > 2\)
GEN

\[V_{2\Delta}\]

\(\frac{0.010}{0.005}\)

\(\frac{0.005}{0.000}\)

\(N_{\text{offline}}^{N_{\text{track}}^< 10}\)
\(N_{\text{offline}}^{N_{\text{track}}^< 20}\)
\(N_{\text{offline}}^{N_{\text{track}}^< 30}\)
\(N_{\text{offline}}^{N_{\text{track}}^< 40}\)

No subtraction
Subtraction 10 < \(N_{\text{track}}\) < 20
Subtraction 20 < \(N_{\text{track}}\) < 30
Subtraction 30 < \(N_{\text{track}}\) < 40
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 < $p_T^{trg}$ < 9 GeV/c
0.3 < $p_T^{assoc}$ < 3 GeV/c
|$\Delta \eta$| > 2

$\frac{1}{N_{trg}} \frac{dN^\text{pair}}{d\Delta \phi} - C_{ZYM}$

Preliminary

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

$\frac{1}{N_{trg}} \frac{dN^\text{pair}}{d\Delta \phi} - C_{ZYM}$

Preliminary

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No bias on jet distribution in $\Delta\eta$

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

$V_{\text{sub}2}$

$|\Delta\eta|$
Test of Subtraction in data

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

$V_2(\Omega)$ vs $N_{\text{offline\_trk}}$

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

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

$|\Delta \eta| > 2$

- No sub.
- $10 \leq N_{\text{trk}} < 20$ sub.

$0.3 < p_T < 3$ GeV

Preliminary

$N_{\text{off}} \text{line}_{\text{trk}}$
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, $h^+ - h^-$
- $K^0_S$ as trigger, charge hadron as associated, $K^0_S - h^-$
- $\Lambda$ as trigger, charge hadron as associated, $\Lambda - h^+$

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

$110 \leq N^{\text{offline}}_{\text{trk}} < 150$

$1 < P_T^{\text{trg}}, P_T^{\text{assoc}} < 3$ GeV/c
Probing novel long range correlation phenomena in $pp$ (collisions with identified particles at CMS).

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$\nu_n$ extraction

CMS $pp$ $\sqrt{s_{NN}} = 7$ TeV

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

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

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

Preliminary

Fourier fits

$\Delta/\bar{\Delta}$-$h^\pm$

$K^0_s$-$h^\pm$

$h^\pm$-$h^\pm$
Correction for jet contribution

CMS pp $\sqrt{s_{NN}} = 7$ TeV

$1 < p_T < 3$ GeV/c

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

Preliminary
No mass dependence of $v_2$ from jet correlation at low multiplicity

- Mass ordering in low $p_T$ region at high multiplicity
CMS pp $\sqrt{s} = 7$ TeV

$110 \leq N_{\text{off}}^{\text{trk}} < 150$

Preliminary

$|\Delta \eta| > 2$

Polynomial fits to $K_S^0$

Data/Fit

$V_2^{\text{sub}(2)}/n_q$

$K^0_S$

$\Lambda/\bar{\Lambda}$

$K^0_S$

$KE_T/n_q$ (GeV)
Two particle correlation function after low multiplicity subtraction