Observation of Long-Range, Near-Side Angular Correlations in Proton-Proton Collisions at the LHC

The CMS Collaboration

I. 2-Particle correlation functions

II. Minimum bias results

III. High multiplicity results

IV. Cross-checks

Gunther Roland/MIT

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Angular Correlation Functions

I. Definition

Correlation Functions:

II. Anatomy
Correlation Function Definition

Signal distribution:

\[ S_N(\Delta \eta, \Delta \varphi) = \frac{1}{N(N-1)} d^2 N_{\text{signal}} \]

Background distribution:

\[ B_N(\Delta \eta, \Delta \varphi) = \frac{1}{N^2} d^2 N_{\text{bkg}} \]

\[ R(\Delta \eta, \Delta \varphi) = \left( N - 1 \right) \left( \frac{S_N(\Delta \eta, \Delta \varphi)}{B_N(\Delta \eta, \Delta \varphi)} - 1 \right) \]

\[ \Delta \eta = \eta_1 - \eta_2 \]
\[ \Delta \varphi = \varphi_1 - \varphi_2 \]

CMS pp 7TeV

p_T-inclusive two-particle angular correlations in min bias collisions
Angular Correlation Functions

CMS 7TeV pp min bias
Angular Correlation Functions

Short-range correlations ($\Delta \eta < 2$):
- Resonances
- String fragmentation
- "Clusters"

CMS 7TeV pp min bias

Lower $p_T$ "clusters"

Higher $p_T$ "clusters"

Short-range correlations ($\Delta \eta < 2$):
- Resonances
- String fragmentation
- "Clusters"
Angular Correlation Functions

“Away-side” ($\Delta \phi \sim \pi$) jet correlations: Correlation of particles between back-to-back jets

“Near-side” ($\Delta \phi \sim 0$) jet peak: Correlation of particles within a single jet

CMS 7TeV pp min bias
Momentum conservation:

\[ \sim -\cos(\Delta \phi) \]

Bose-Einstein correlations:

\[ (\Delta \phi, \Delta \eta) \sim (0,0) \]

CMS 7TeV pp min bias
Angular Correlation Functions

“Away-side” \((\Delta \phi \sim \pi)\) jet correlations:
Correlation of particles between back-to-back jets

Bose-Einstein correlations:
\((\Delta \phi, \Delta \eta) \sim (0,0)\)

Momentum conservation:
\(\sim -\cos(\Delta \phi)\)

“Near-side” \((\Delta \phi \sim 0)\) jet peak:
Correlation of particles within a single jet

Short-range correlations \((\Delta \eta < 2)\):
Resonances, string fragmentation, “clusters”
Correlations in Min Bias pp

CMS pp Data

Pythia D6T
PYTHIA describes the energy dependence
Matches cluster width $\delta$ in data
Underestimates the cluster size $K_{\text{eff}}$
High Multiplicity Events
High Multiplicity Events

Dedicated trigger needed to record highest multiplicities

Level-1:
Require $E_T > 60$ GeV in calorimeters

High-Level trigger:
Count number of tracks with $p_T > 0.4$ GeV/c, $|\eta| < 2$, within $dz < 0.12$cm of a **single** vertex with $z < 10$cm
High Multiplicity Trigger

Two different HLT thresholds:
\( N_{\text{online}} > 70 \) and \( N_{\text{online}} > 85 \)

HLT85 trigger range un-prescaled for full 980nb\(^{-1}\)

Multiplicity binning uses \( p_T > 0.4 \) GeV/c, \(|\Delta\eta| < 2.4\)

<table>
<thead>
<tr>
<th>Multiplicity bin (( N_{\text{offline}}^{\text{trk}} ))</th>
<th>Event Count</th>
<th>( \langle N_{\text{offline}}^{\text{trk}} \rangle )</th>
</tr>
</thead>
<tbody>
<tr>
<td>MinBias</td>
<td>21.43M</td>
<td>15.9</td>
</tr>
<tr>
<td>( N_{\text{offline}}^{\text{trk}} &lt; 35 )</td>
<td>19.36M</td>
<td>13.0</td>
</tr>
<tr>
<td>35 \leq N_{\text{offline}}^{\text{trk}} &lt; 90</td>
<td>2.02M</td>
<td>45.3</td>
</tr>
<tr>
<td>90 \leq N_{\text{offline}}^{\text{trk}} &lt; 110</td>
<td>302.5k</td>
<td>96.6</td>
</tr>
<tr>
<td>( N_{\text{offline}}^{\text{trk}} \geq 110 )</td>
<td>354.0k</td>
<td>117.8</td>
</tr>
</tbody>
</table>

Out of \( 5\times10^{10} \) collisions
Vertex selections:
- OfflinePrimaryVertices
- NDOF>4
- |vz|<10cm

Event-selection and analysis done with tracks pointing to primary vertex with O (100µm) resolution

Track quality selections:
- highPurity bit
- $\frac{dxy/\sigma(dxy)}{}<3$ & $\frac{dz/\sigma(dz)}{}<3$, relative to primary vertex
- $\frac{\sigma(p_T)}{p_T}<0.1$

Main corrections:
- Tracking/acceptance efficiency, fake rate
- HLT triggering efficiency - data driven
Results

Inclusive \( p_T \)

MinBias

(high multiplicity (\( N > 110 \))

Jet peak/away-side correlations enhanced in high multiplicity events

Abundant jet production in high multiplicity sample

(a) MinBias, \( p_T > 0.1 \text{GeV/c} \)

(c) \( N > 110, p_T > 0.1 \text{GeV/c} \)
Inclusive $p_T$

MinBias

Cut off peak at $(0,0)$:
Shows structure of away-side ridge (back-to-back jets)
Small change for large $\delta\eta$ around $\delta\phi \sim 0$?
Results

Intermediate $p_T$: 1-3 GeV/c

MinBias

(b) MinBias, $1.0 \text{GeV/c} < p_T < 3.0 \text{GeV/c}$

high multiplicity ($N > 110$)

(d) $N > 110$, $1.0 \text{GeV/c} < p_T < 3.0 \text{GeV/c}$

Pronounced structure at large $\delta \eta$ around $\delta \phi \sim 0$!
No $\delta\phi \sim 0$ structure in PYTHIA 8 at large $\delta\eta$
Same for Herwig++, madgraph, PYTHIA6
“Ridge” maximal for highest multiplicity and $1 < p_T < 3$ GeV/c
Zero Yield At Minimum (ZYAM)

Associated yield: correlated multiplicity per particle

- **Data**
- **PYTHIA8**

- \( N > 110 \)
- \( 2.0 < |\Delta \eta| < 4.8 \)
- \( 1 \text{GeV/c} < p_T < 2 \text{GeV/c} \)

Minimum of \( R \)

Associated yield grows with increasing multiplicity
Like-Sign vs Unlike-Sign

No dependence on relative charge sign
Systematic Uncertainties

- Statistical uncertainty negligibly small
- However, the signal is subtle and unexpected
- Estimate systematic uncertainties
- Is there a way to fake the signal *qualitatively*?
Systematic Uncertainties

+ bugs?

Analysis code
  + efficiency, fakes

Reconstruction
  + trigger efficiency, bias

Trigger
  + detector noise, acceptance, efficiency

Detector
  + pile-up, beam backgrounds

CMS Event
  Physics

Test the complete chain with data-driven checks!
Analysis Code

Ridge is seen with three independent analysis codes

Independent code
Same definition of $R$
Same input file (skim)

Control analysis I

Control analysis II

| $N > 100$
| $1 < p_T < 3$GeV/c
| $|\Delta \eta| > 2$

Independent code
Different definition of $R$
Different input file (skim)
Reconstruction Code

(Largely) independent code
Independent detectors
Also: Variation of tracking + vertexing parameters
Ridge is seen using min bias trigger + offline selection

No trigger bias seen from comparison of trigger paths
Detector

Pair multiplicity distribution for $|\Delta \eta|>2$ and $|\Delta \phi|<1$

- Ridge is not caused by rare events with large # of pairs

Constrain one track to one $\phi$ octant

Data

$R(\Delta \Phi)$

- $0<\phi_1<\pi/4$
- $\pi/4<\phi_1<\pi/2$
- $\pi/2<\phi_1<3\pi/4$
- $3\pi/4<\phi_1<\pi$
- $-\pi/4<\phi_1<0$
- $-\pi/2<\phi_1<-\pi/4$
- $-3\pi/4<\phi_1<-\pi/2$
- $-\pi<\phi_1<-3\pi/4$

Ridge is $\phi$ symmetric
Ridge region shows no structure in $\eta_1$ vs $\eta_2$
Event Backgrounds

Select higher fraction of possible beam-gas or beam-scraping events

Reject beam background by veto on fraction of low quality tracks

Ridge region shows no sensitivity to beam background

Note: Analysis is done on HighPurity tracks
Event Backgrounds

Correlate tracks from high multiplicity vertex with tracks from different collision (vertex) in same bunch crossing

\[ N > 110 \]
\[ 1.0 \text{GeV/c} < p_T < 3.0 \text{GeV/c} \]

No background or noise effects seen in cross-collision correlations
Event Pileup

Compare different run periods
(fraction of pileup varies by x4-5)

Change in pileup fraction by factor 2-4
has almost no effect on ridge signal

CMS preliminary

Compare different vertex regions
(fraction of pile-up $\sim dN/dvtx_z$)

CMS preliminary
Pileup effects are suppressed due to excellent resolution
Track counting done with $\sigma_{dz}$, $\sigma_{dxy}$ of $O(100\mu m)$
Final Test: ECAL photons

Use ECAL “photon” signal
Mostly single photons from $\pi^0$'s
No efficiency, and $p_T$, $\phi$ smearing corrections

Track-photon correlations

Note: photons reconstructed using “particle flow” event reconstruction technique
Final Test: ECAL photons

Use ECAL “photon” signal
Mostly single photons from $\pi^0$'s
No efficiency, and $p_T$, $\phi$ smearing corrections

Photon-photon correlations
Qualitative confirmation
Independent detector, independent reconstruction
Systematic Uncertainties

Each step tested with data-based checks

No indication of effect that would fake ridge signal (irrespective of magnitude)

<table>
<thead>
<tr>
<th>Sources</th>
<th>Syst. on ridge yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pileup</td>
<td>15%</td>
</tr>
<tr>
<td>HLT efficiency</td>
<td>4-5%</td>
</tr>
<tr>
<td>Tracking</td>
<td>1-2%</td>
</tr>
<tr>
<td>ZYAM</td>
<td>0.0025</td>
</tr>
</tbody>
</table>

Conservative estimates of uncertainties on ridge associated yield
Summary

• Study of short-range and long-range angular correlations in pp collisions with CMS at LHC

• Observation of long-range, near-side correlations in high multiplicity events
  – Signal grows with event multiplicity
  – Effect is maximal in the $1 < p_T < 3$ GeV/c range

• Long-range, near-side correlation is not seen in low multiplicity events and generators, but resembles effects seen in heavy-ion collisions at high energies

• This is a subtle effect in a complex environment – careful work is needed to establish physical origin