New results on two-particle correlations in proton-proton collisions at 13 TeV from ATLAS at the LHC

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ATLAS measurements of two-particle correlations in $\sqrt{s} = 13$ TeV $pp$ collisions at the LHC are summarized. In high-multiplicity events, long-range rapidity correlation of particles with small azimuthal separation, i.e the “ridge”, is observed with features similar to those seen in measurements of Pb+Pb, $p$+Pb, and lower-energy $pp$ collisions. These results are compatible, within uncertainties, with CMS 7 TeV $pp$ measurements.
1. Introduction

Studies of two-particle correlations in high-multiplicity pp collisions revealed features that are uncannily similar to those observed in heavy-ion collisions [1]. The number of charged-particle pairs produced with small azimuthal-angle separation is enhanced over a wide range of pseudorapidity differences. The cause of this novel phenomenon, known as the “ridge”, remains unknown.

This document summarizes the ATLAS measurement of two-charged-particle correlations in 13 TeV pp collisions at the LHC [2]. This analysis uses 14 nb$^{-1}$ collected during a low-luminosity run (average number of interactions per beam crossing 0.002–0.04) that took place in June 2015.

2. ATLAS detector, efficiencies

Reference [3] describes the ATLAS detector in detail. This measurement used the ATLAS inner detector (ID), minimum-bias trigger scintillators (MBTS), and the trigger and data acquisition systems. The Level-1 trigger (MinBias) requires a signal in at least one MBTS counter; a high-multiplicity trigger (HMT) requires a signal in at least one counter on each side of the MBTS, at least 900 hits in the silicon strip tracker, and at least 60 tracks with $p_T > 0.4$ GeV.

This analysis uses tracks with $p_T > 0.3$ GeV and $|\eta| < 2.5$, reconstructed in the ID and selected as described in Ref. [2]. The pp events used have at least one primary vertex. For events with multiple vertices, only tracks associated with the vertex with the largest $\sum p_T^2$ are used. Here the sum runs over the tracks associated with each vertex. The charged-particle multiplicity, $N_{\text{rec}}^{\text{ch}}$, is defined as the number of tracks with $p_T > 0.4$ GeV associated with the vertex with the largest $\sum p_T^2$. Figure 1 shows the distribution of $N_{\text{rec}}^{\text{ch}}$ and the MinBias and HMT trigger efficiencies.

![Figure 1](image-url)

**Figure 1**: Left: Number of tracks with $p_T > 0.4$ GeV, $N_{\text{rec}}^{\text{ch}}$, in events selected by the MinBias and HMT triggers. Right: MinBias and HMT trigger efficiency as a function of $N_{\text{rec}}^{\text{ch}}$. Figure from Ref. [2].

The MinBias trigger is fully efficient for $N_{\text{rec}}^{\text{ch}} \geq 5$ while the HMT is 90% efficient for $N_{\text{rec}}^{\text{ch}} \geq 60$ and fully efficient for $N_{\text{rec}}^{\text{ch}} \geq 65$. The tracking efficiency, $\varepsilon(p_T, \eta)$, which is evaluated using Monte

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1 ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the center of the LHC ring, and the y-axis points upward. Cylindrical coordinates $(r, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln(\tan(\theta/2))$. Transverse momentum is denoted by $p_T$. 

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Carlo simulation, increases with $p_T$ by less than 6% between 0.3 and 0.6 GeV, and varies only weakly for $p_T > 0.6$ GeV, where it ranges from 88–90% at $\eta = 0$ to 77–80% at $|\eta| = 1.5$ and 68–73% for $|\eta| > 2.0$

3. Two-particle correlation analysis

This analysis follows methods used in previous ATLAS measurements in Pb+Pb and $p+\text{Pb}$ collisions [4, 5, 6]. Two-particle correlations for charged particle pairs with transverse momenta $p_T^a$ and $p_T^b$ are measured as a function of $\Delta \phi = \phi^a - \phi^b$ and $\Delta \eta = \eta^a - \eta^b$, with $|\Delta \eta | \leq 5$, determined by the acceptance of the ID. The correlation function is defined as:

$$C(\Delta \eta, \Delta \phi) = \frac{S(\Delta \eta, \Delta \phi)}{B(\Delta \eta, \Delta \phi)}$$

(3.1)

where $S$ and $B$ are pair distributions constructed with pairs in the same event and in mixed events respectively. Both distributions are corrected for the tracking efficiency of the pair $\varepsilon(p_T^a, \eta^a)\varepsilon(p_T^b, \eta^b)$. Detector acceptance effects largely cancel in the ratio.

Figure 2 shows correlation functions for $N^{\text{rec}}$ intervals 10–30 (left) and $\leq 120$ (right), for track pairs with $0.5 < p_T^a, p_T^b < 5.0$ GeV. Both correlation functions show a prominent peak at $\Delta \eta = \Delta \phi = 0$, and a $\Delta \eta$-dependent enhancement centered at $\Delta \phi = \pi$. These structures arise primarily from jets and dijets respectively. In the high-multiplicity interval, $C(\Delta \eta, \Delta \phi)$ presents a significant enhancement, or "ridge"-like structure, at $\Delta \phi = 0$ that extends over the full $\Delta \eta$ range.

Figure 2: Two-particle correlation functions, $C(\Delta \eta, \Delta \phi)$, measured in events with low (left) and high (right) charged-particle multiplicity, $N^{\text{ch}}$. The plots have been truncated to suppress the peak at $\Delta \eta = \Delta \phi = 0$. In both cases the pairs have $0.5 < p_T^{a,b} < 5.0$ GeV. Figure from Ref. [2].

To focus on the long-range features, one-dimensional correlation functions, $C(\Delta \phi)$, are obtained by integrating the numerator and denominator of Eq. 3.1 over $2 < |\Delta \eta | < 5$. Figure 3 shows the $C(\Delta \phi)$ distribution in different intervals of $N^{\text{ch}}$; all four $C(\Delta \phi)$ distributions show a strong peak centred at $\Delta \phi = \pi$ that arises from the dijets. In the interval $10 < N^{\text{ch}} < 30$ interval, $C(\Delta \phi)$ shows a
minimum at $\Delta \phi = 0$; with increasing $N_{\text{ch}}^{\text{rec}}$, this minimum fills in, and a peak appears and increases in amplitude. A Fourier series with harmonics up to fifth order fits the data well.

Figure 4 shows $C(\Delta \phi)$ measured in the $N_{\text{ch}}^{\text{rec}} > 100$ interval for two ranges of $p_T$: 0.5–1 GeV and 1–2 GeV, with $p_T^b$ allowed to vary over 0.5–5 GeV. The amplitude of the peak at $\Delta \phi = 0$ is larger for the higher $p_T^b$ interval.

Following the ZYAM method [7, 8], the effect of uncorrelated pairs on $C(\Delta \phi)$, which is es-
timated from the constant in the Fourier fit (see Fig. 3), is subtracted; then, the resulting function is normalized to the average number of pairs associated with each particle in the Δφ interval; this defines the “per-trigger-particle yield”, Y(Δφ). The integral of the Y(Δφ) between the two minima near Δφ = 0, which are obtained from the Fourier fit, defines the ridge yield, Y_{int}.

The dominant systematic uncertainties on Y_{int} arise from tracking efficiency (4%), assumptions in the ZYAM procedure (4%) and consistency of the method tested with simulation (4%).

Figure 5 shows the ridge yield as a function of charged-particle multiplicity for same-charge pairs, opposite-charge pairs, and all pairs. In all cases Y_{int} is consistent with zero for N_{rec} < 40 within uncertainties, but increases linearly with N_{rec} for N_{rec} > 40. The results from same-charge pairs and opposite-charge pairs are consistent within statistical uncertainties; this rules out resonances or single jets as possible sources of this phenomenon.

Figure 5: Ridge yield vs charged-particle multiplicity. Results are shown for all pairs, same-charge pairs and opposite-charge pairs. The error bars and shaded bands indicate statistical and systematic uncertainties (for clarity only shown in the all pairs case). Figure from Ref. [2].

Figure 5 shows Y_{int} as a function of p_T for 0.5 < p_T < 5 GeV for three different N_{rec} intervals; in all cases it increases up to p_T < 2.5 GeV and decreases for larger p_T. This behaviour is similar to p+Pb and Pb+Pb measurements [4, 5, 6].

Figure 6: Ridge yield vs p_T measured in different N_{rec} intervals. The error bars and shaded bands indicate statistical and systematic uncertainties. Figure from Ref. [2].

Figure 7 shows a comparison of the measured Y_{int} with CMS 7 TeV pp data [1], which were obtained using similar analysis methods, as a function of N_{rec} and p_T. The differences in analysis
methods are taken into account, as described in Ref. [2]. The measured $Y_{\text{int}}$ at 7 and 13 TeV agree within uncertainties.

![Figure 7](image.jpg)

**Figure 7:** Comparison of the measured $Y_{\text{int}}$ from this analysis to that measured by CMS at 7 TeV [1]. The ATLAS data are plotted at the centres of the corresponding $N_{\text{ch}}$ and $p_{T}^{a,b}$ intervals; CMS data are plotted at the mean values. The bars and shaded bands in ATLAS data represent statistical and systematic uncertainties, respectively; the error bars in the CMS data represent the total uncertainty. Figure from Ref. [2].

### 4. Conclusions

Two-particle correlation functions in high-multiplicity $pp$ collisions at $\sqrt{s} = 13$ TeV show a ridge whose strength increases with charged-particle multiplicity, and has a strong $p_{T}$ dependence. These results are compatible, within uncertainties, with previous CMS 7 TeV $pp$ measurements [1].

### 5. Acknowledgments

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### References


