Observation of long-range elliptic anisotropies in $\sqrt{s} = 13$ and 2.76 TeV $pp$ collisions with the ATLAS detector

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Abstract

ATLAS has measured two-particle angular correlations in $\sqrt{s} = 13$ and 2.76 TeV $pp$ collisions at the LHC. The well-known "ridge" is observed in high-multiplicity events. Per-trigger-particle yields, $Y(\Delta\phi)$, are found to be consistent with a linear combination of the per-trigger-yield measured with $<20$ reconstructed tracks, and a constant combinatoric contribution modulated by $\cos(2\Delta\phi)$. The fitted Fourier coefficient $v_2$, exhibits factorization, suggesting that the ridge results from per-event $\cos(2\phi)$ modulation of the single-particle distribution with Fourier coefficient $v_2$. They are found to be weakly dependent on multiplicity and to have a $p_T$ dependence similar to that measured in $p+Pb$ and $Pb+Pb$ collisions. The $v_2$ values in the 13 and 2.76 TeV are consistent within uncertainties. These results suggest that the ridge in $pp$ collisions arises from the same or similar underlying physics as observed in $p+Pb$ collisions, and that the dynamics responsible for the ridge has no strong $\sqrt{s}$ dependence.

Keywords: Hadron-Hadron Scattering, Particle Correlations

1. Introduction

Measurement of two-particle angular correlations in Pb+Pb collisions [1] at the LHC showed an enhancement of particle pairs at small relative azimuthal-angle, $\Delta\phi$, that extends over a wide range of pseudorapidity differences, $\Delta\eta$, which is often referred to as "ridge". The ridge has also been observed in $p+Pb$ [2] and high-multiplicity $pp$ [3]. The ridge in $p+Pb$ has been found to result from a global sinusoidal modulation of the per-event single-particle azimuthal-angle distributions [4, 5]. While many theoretical interpretation of the ridge, including those based on hydrodynamics [6, 7], saturation [8, 9], or other mechanisms [10], have been, or could be applied to $pp$ and $p+Pb$, it has not been demonstrated that the ridge in $pp$ results from single-particle azimuthal anisotropies. Testing whether ridge in $pp$ and $p+Pb$ arise from the same underlying features of single-particle distributions may provide insights into the physics responsible for the phenomena. Separately, a study of the $\sqrt{s}$ dependence of the ridge in $pp$ collisions may help distinguish competing between theories.

2. Analysis Details

This analysis uses 14 nb$^{-1}$ of 13 TeV and 4.0 pb$^{-1}$ 2.76 TeV data collected by ATLAS during Run 2 and Run 1, using ATLAS inner detector ($|\eta| < 2.5$), minimum-bias trigger scintillators and forward calorimeter [11]. To enhance the statistics for high-multiplicity events, high-multiplicity triggers (HMT) are applied...
and they are only used where their multiplicity selection is more than 90% efficient. The measured charge-particle multiplicity, \( N_{\text{ch}}^{\text{rec}} \), is defined as the number of tracks having \( p_T > 0.4 \text{ GeV} \) and associated with the primary vertex.

The two particle angular correlation function is defined in previous ATLAS measurements [1]. The long-range component of the correlation function \( Y(\Delta \phi) \), per-trigger-particle yields, is defined as:

\[
Y(\Delta \phi) = \left( \frac{\int B(\Delta \phi) d\Delta \phi}{N^0 \int d\Delta \phi} \right) C(\Delta \phi)
\]

(1)

where \( N^0 \) denotes the trigger particles and \( C(\Delta \phi) \) is obtained by integrating the numerator and denominator of \( C(\Delta \eta, \Delta \phi) \) over \( 2 < |\Delta \eta| < 5 \). The per-trigger-particle yield shows a substantial “pedestal” of uncorrected pairs. A standard approach for estimating the level of the combinatoric background is the Zero-Yield At Minimum (ZYAM) procedure, which underestimates the yield associated with the sinusoidal modulation of the pair distribution.

For better estimation of ridge yield associated with the harmonic modulation of the pair distribution, \( Y^{\text{cent}}(\Delta \phi) \) from “central” collisions could be decomposed into a superposition of a “peripheral” \( Y^{\text{periph}}(\Delta \phi) \) scaled up by a multiplicative factor \( F \) and ridge yield \( Y^{\text{ridge}}(\Delta \phi) \):

\[
Y^{\text{cent}} = F Y^{\text{periph}} + Y^{\text{ridge}}
\]

(2)

where factor \( F \) could be determined by scaling jet-yield in the near-side, as described in ATLAS previous \( p+\text{Pb} \) ridge analysis [5]. In this analysis, \( F \) value is instead determined by a template fitting method as described below, which gives consistent \( F \) values with previous jet-yield scaling method. Both methods assume that the shape of away-side jet is independent of multiplicity.

To be more specific, the peripheral per-trigger-particle yield \( Y^{\text{periph}} \) is decomposed as:

\[
Y^{\text{periph}} = N_0^{\text{periph}} + N_0^{\text{periph}} v_{n,n}^{\text{periph}} \cos(n\Delta \phi) + Y^{\text{periph}}_{\text{jet}}
\]

(3)

where first term \( N_0^{\text{periph}} \) represents uncorrelated pairs, or the pedestal, which could be either included or excluded in the template-fitting. Second term is the ridge yield in peripheral collisions, with \( v_{n,n} \) as one of the fit coefficients. Expand \( Y^{\text{cent}} \) in the same way as Eq. 3 and denote \( F N_0^{\text{periph}} / N_0^{\text{cent}} \) as \( \alpha \), the “measured” long-range correlation \( v_{n,n}^{\text{ridge}} \) is:

\[
v_{n,n}^{\text{ridge}} = \frac{v_{n,n}^{\text{periph}} - \alpha v_{n,n}^{\text{periph}}}{1 - \alpha}
\]

(Include pedestal)

(4)

\[
v_{n,n}^{\text{ridge}} = \frac{v_{n,n}^{\text{periph}}}{1 - \alpha}
\]

(Exclude pedestal)

(5)

Fig. 1. Left panel: The \( N_{\text{rec}}^{\text{ch}} \) dependence of \( v_2 \) in 13 TeV data for \( 0.5 < p_T < 5.0 \text{ GeV} \) for three different choices of the peripheral multiplicity interval, \( N_{\text{ch}}^{\text{periph}} \). Right panel: Similar plot but with the pedestal, \( Y^{\text{periph}}(0) \), subtracted from \( Y^{\text{periph}}(\Delta \phi) \) when performing the template fits. Taken from Ref. [12].
where $v_{\text{cent}}$ and $v_{\text{periph}}$ are the “true” long-range correlations in central and peripheral collisions respectively.

Whether including the pedestal or not only change ridge yield by a scale factor $1 - \alpha$. If correct $v_{\text{cent}}$ has a weak multiplicity dependence, the measured $v_{\text{ridge}}$ will recover the correct $v_{\text{cent}}$ when the pedestal is included. In this analysis, including the pedestal is the default method.

To test the sensitivity of the results due to the dijet shape changes, the analysis was repeated using $N_{\text{ch}}^{\text{rec}} < 5$, $N_{\text{ch}}^{\text{rec}} < 10$ and $10 \leq N_{\text{ch}}^{\text{rec}} < 20$ intervals to form $Y_{\text{periph}}$. The calculated $v_2$ values (will be introduced later, for now it could be treated as the ridge yield) are shown in Fig.1: when the pedestal is included, three different peripheral references give consistent results, meaning the measurements using template-fitting are stable regardless of the choice of peripheral references.

3. Results and Discussions

![ATLAS](13 TeV)

Fig. 2. Two-particle correlation functions, $C(\Delta \eta, \Delta \phi)$, in 13 TeV $pp$ collisions in $10 \leq N_{\text{ch}}^{\text{rec}} < 30$ (left) and $N_{\text{ch}}^{\text{rec}} \geq 120$ (right). The distributions have been truncated to suppress the peak at $\Delta \eta = \Delta \phi = 0$. Taken from Ref [12].

Examples of correlation functions in the 13 TeV data are shown in Fig. 2 for $10 \leq N_{\text{ch}}^{\text{rec}} < 30$ (left) and $N_{\text{ch}}^{\text{rec}} \geq 120$ (right), respectively. The strong peak at $\Delta \eta = \Delta \phi = 0$ arises primarily from jets and the enhancement extending over a wide $\Delta \eta$ range centered at $\Delta \phi = \pi$ results primarily from dijets. In low-multiplicity, the long-range correlation shape is concaved-up on near-side, while in high-multiplicity, a ridge begins to develop as an enhancement extending over the wide $\Delta \eta$ range.

![ATLAS](13 TeV)

Fig. 3. Per-trigger-particle yields, $Y(\Delta \phi)$, with different components of the template for two $N_{\text{ch}}^{\text{rec}}$ intervals $40 - 50$ (left) and $\geq 120$ (right). The scaled $Y_{\text{periph}}$ shifted up by $G$ are shown with open points; the $Y_{\text{periph}}(\Delta \phi)$ functions shifted up by $F Y_{\text{periph}}(0)$ are shown with the dashed lines; and the full fit function is shown by the solid curve. Taken from Ref [12].

The results of the template-fitting are shown in Fig. 3 for two $N_{\text{ch}}^{\text{rec}}$ intervals in 13 TeV $pp$ collisions. The template-fitting simultaneously describes the ridge, which arises from an interplay of the concave $Y_{\text{periph}}$
and the cosine function, the height of the peak in the $Y(\Delta \phi)$ at $\Delta \phi \sim \pi$, and the narrowing of the peak which results from a negative contribution of the $2v_{2,2} \cos(2\Delta \phi)$ term in the region near $\Delta \phi = \pi/2$.

![Graph showing correlation functions](image)

Fig. 4. Measured $v_{2,2}$ (top) and $v_2$ (middle) values versus $N_{ch}^{rec}$ for different $p_T^{ch}$ intervals for 2.76 (left) and 13 TeV (right) data. Measured $v_2$ values versus $p_T^{ch}$ (bottom) for 13 and 2.76 TeV data for the $50 \leq N_{ch}^{rec} < 60$ interval (left) and for three $N_{ch}^{rec}$ intervals in the 13 TeV data (right). Taken from Ref [12].

If the two-particle angular correlation arises from modulation of single-particle $\phi$ distribution, then $v_{2,2}$ should factorized such that $v_{2,2}(p_T^1, p_T^2) = v_2(p_T^1) v_2(p_T^2)$, where $v_2$ is the $\cos(2\phi)$ Fourier coefficient of the single-particle anisotropy. In other words, if factorization holds, the $v_2(p_T)$ should be independent of $p_T$, which is tested in Fig. 4 (top and middle): the three sets of $v_2$ values agree within uncertainties, indicating that $v_{2,2}$ factorizes.

As shown in Fig. 4, the measured $v_2$ have a very weak dependence of $N_{ch}^{rec}$ and are consistent between two energies within uncertainties. The $p_T$ dependence of $v_2$ (bottom left) is similar for both energies to that previously measured in $p+$Pb and Pb+Pb collisions: it increases with $p_T$ at low $p_T$, reaches maximum between 2 and 3 GeV, and then decreases at higher $p_T$.

4. Summary

We present two-particle correlations in $\sqrt{s} = 13$ and 2.76 TeV $pp$ collisions. The correlation functions show a ridge whose strength increases with multiplicity. A new template fitting procedure shows that the per-trigger-particle yields for $|\Delta \eta| > 2$ are well described by a superposition of the scaled yields measured in a low-multiplicity and a constant modulated by $\cos(2\Delta \phi)$. The extracted Fourier coefficients $v_{2,2}$ exhibit factorization and $v_2$ of the single-particle modulation are $N_{ch}^{rec}$-independent and agree between 2.76 and 13 TeV within uncertainties. They follow a $p_T$ trend similar to that observed in $p+$Pb and Pb+Pb collisions. These results suggest that the ridges in $pp$ and $p+$Pb collisions arise from a similar physical mechanism which does not have a strong $\sqrt{s}$ dependence.
References