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Measurement of long-range correlations in Z-tagged pp events with ATLAS

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Measurements of azimuthal correlations between two particles separated in pseudorapidity have shown striking similarities between results obtained in pp, p+A and A+A collision systems. In pp collisions, unlike in p+A and A+A, the strength of the correlations, quantified by the anisotropy parameter v_2, shows little dependence on the observed charged-particle multiplicity. Recent theoretical models suggest that this can result from an intrinsically weaker correlation between the charged-particle multiplicity and the impact parameter of the pp collision. An independent handle on the impact parameter dependence can be obtained by requiring the presence of a hard-scattering process in the collision. In this report, the measurement of two-particle correlations in pp collisions containing a Z boson identified in dimuon decay channel is presented. The analysis uses ATLAS data recorded with nominal pp luminosity, with a high pileup. A novel procedure was developed to correct the two-particle correlation function for the contribution of tracks arising from pileup . The multiplicity dependence of the charged-particle v_2 measured in Z-tagged events at the energy $\sqrt{s}$= 8 TeV is compared to the v_2 measured in inclusive collisions. They are found to be of a similar magnitude.

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1. Introduction

The azimuthal anisotropy measured in small collision systems is currently under thorough experimental and theoretical debate [1]. One of the surprising results obtained in pp collisions is that the second-order flow harmonics, v_2, is independent of the event activity, as expressed by the charged particle multiplicity [2, 3, 4]. In a recent publication [5], it was noticed that fluctuations in the internal structure of the nucleon could contribute to this independence, despite a possible strong correlation between v_2 and the collision impact parameter, b. On the other hand, it is expected that selecting events containing a hard process should restrict the range of b and as a consequence limit the strong correlations between v_2 and b. Therefore, a measurement of azimuthal anisotropy in pp interactions containing Z bosons (Z-tagged events) [6], characterised by the momentum transfer $Q^2 \approx (80\text{ GeV})^2$, was performed using the data collected by the ATLAS detector [7].

The azimuthal anisotropy analysis is performed using the two-particle correlation method in pp interactions at the energy $\sqrt{s} = 8$ TeV, recorded in 2012 and corresponding to the total integrated luminosity of 19.4 fb^{-1}. The dataset was collected under conditions of high instantaneous luminosity, for which the average number of collisions per bunch crossing is $\mu \approx 20$. The multiple, simultaneous interactions (pileup) in pp events contaminate the measurement of the two-particle correlations (2PC) in the pp collisions containing the Z boson. To correct for this effect, a novel procedure is developed, which removes the pileup contribution on a statistical basis. The procedure is briefly described in the next Section.

2. The pileup correction

In the analysis presented in Ref. [6], events with the presence of a Z boson candidate reconstructed in the dimuon channel of an invariant mass between 80 GeV and 100 GeV are considered. The flow harmonics measurement uses charged-particle tracks reconstructed in the Inner Detector (ID) with a standard procedure [8], excluding the two muon tracks from the Z decay. The ID tracks in a pp interaction containing the Z boson (*Direct events*) are called *Direct tracks*. It is required that the distance of closest approach of a direct track to the beam line in the transverse plane, d_0, and in the longitudinal direction z_0 satisfy: $|d_0| < 1.5$ mm and $|\omega| < 0.75$ mm, where $\omega = (z_0 - z_{\text{vtx}})\sin\theta$. The z_{vtx} is the longitudinal coordinate of the Z-tagged collision vertex and θ is the polar angle of the track. As a result of these requirements, the direct tracks not only contain the tracks from the pp collision containing the Z boson (*Signal tracks*) but also contain significant fraction of *Background* (pileup) tracks from other interactions at the same bunch-crossing. To correct for the pileup, an event sample, called *Mixed*, is constructed out of Z boson tagged events. In the procedure it is required that the longitudinal distance between the z_{vtx} positions of direct events and events used, along with the direct event, to build the mixed event sample is $|\Delta z_{xvt}| > 15$ mm. Additionally, both events are required to have μ within the same integer count and be taken during the same beam fill of the LHC to assure the same detector configuration in both events. Furthermore, to accommodate differences in z_{vtx} distributions among different beam fills, the reduced values of μ and z_{vtx} are used: $\overline{\mu} = \mu/2\pi\text{RMS}(z_{\text{vtx}})$, $\overline{z}_{\text{vtx}} = (z - \langle z_{\text{vtx}}\rangle)/\text{RMS}(z_{\text{vtx}})$. To suppress statistical fluctuations, 20 mixed events are produced for each direct event. All the selection requirements assure that mixed events well reproduce the background component in direct events. As such, the mixed event track

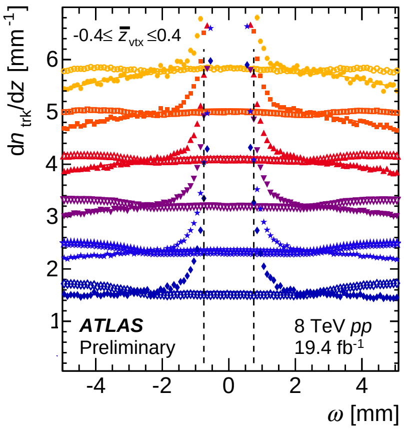

Figure 1: The number of tracks per mm as a function of ω for direct events (solid markers) and mixed events (open markers). The different marker colours correspond to increasing values of reduced $\overline{\mu}$ from 0.06 for the bottom to 0.27 for the top distributions. The vertical dashed lines show the acceptance window $|\omega| < 0.75$ mm [6].

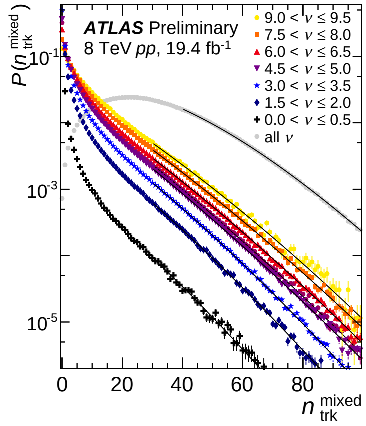

Figure 2: Probability distributions for the number of $n_{\rm trk}^{\rm mixed}$. The different coloured markers correspond to different values of ν. The grey distributions indicate the ν-averaged $n_{\rm trk}^{\rm direct}$ distribution, shown for comparison. The curves represent fits to data points [6].

multiplicity, $n_{\rm trk}^{\rm mixed}$, can be used to correct the multiplicity of direct tracks, $n_{\rm trk}^{\rm direct}$, to obtain the number of signal tracks, $n_{\rm trk}^{\rm signal}$ = $n_{\rm trk}^{\rm direct}$ -$n_{\rm trk}^{\rm mixed}$.

Figure 1 shows the average track density in direct and mixed events for different $\overline{\mu}$ values for -0.4 $\leq \overline{z} \leq$ 0.4. In all distributions belonging to direct events the signal tracks form the peak at origin (truncated) and the background tracks form a distribution under and outside the peak. The average number of mixed tracks under the peak in the acceptance window $|\omega| < 0.75$ mm, ν, represents the contribution of background tracks estimated with the mixed events. The full probability distributions of $n_{\rm trk}^{\rm mixed}$ for different ν are shown in Fig. 2. For a comparison, the $n_{\rm trk}^{\rm direct}$ probability distribution, averaged over the sample, is also shown. Figure 2 indicates that the background tracks significantly affect direct distributions. This is directly illustrated in Fig. 3, where examples of probability distributions of the $n_{\rm trk}^{\rm signal}$ contributing to fixed number of direct tracks are shown for $n_{\rm trk}^{\rm direct}$ = 30, 60, and 90 at the high pileup conditions $\nu \approx 9$. Boxes shown in the plot are centered horizontally at the mean values of $n_{\rm trk}^{\rm signal}$ and have width equal to 2×RMS of a corresponding

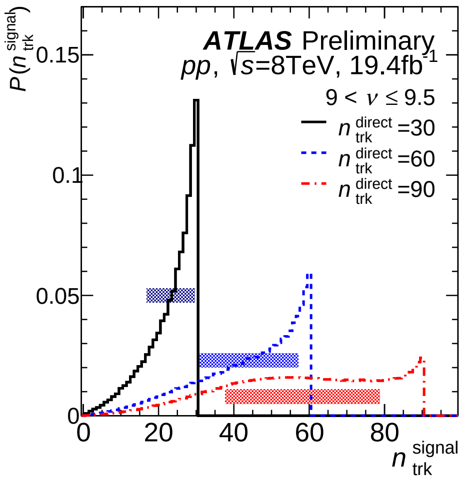

Figure 3: The probability distribution of signal tracks contributing to an event with 30, 60 and 90 (black, blue and red) direct tracks. Boxes denote the horizontal range equal to the mean ± RMS value for the histograms. The distributions are shown for $9 < \nu \leq 9.5$ [6].

distribution. As one can see, the signal track contributions to direct tracks populate a wide range indicating a presence of a significant fraction of background tracks in $n_{\mathrm{trk}}^{\mathrm{direct}}$. For the large values of $n_{\mathrm{trk}}^{\mathrm{direct}}$ the distributions even develop a second maximum as shown with the red histogram. The following analysis is restricted to $\nu < 7.5$ range, since beyond that value the pileup is too large to reliably correct the two particle correlations.

In pp interactions the flow harmonics are obtained with the two-particle correlation function measured in the relative pseudorapidity ($\Delta\eta$) and azimuthal angle ($\Delta\phi$) of two charged particles with transverse momenta p_{T}^{a} and p_{T}^{b}. To suppress the non-flow correlations due to jet production, momentum conservation, resonance decays or Bose-Einstein correlations, the 2PC are measured for particles forming a pair that have the large pseudorapidity separation, $|\Delta\eta| > 2$. Additionally, using a template fitting method [3, 4], the 2PC function is separated into two components: a per-trigger scaled yield for low-multiplicity interactions, describing the remaining back-to-back jet correlations, and a long-range $\Delta\phi$-modulated term, representing flow-like component. The fitted azimuthal modulation amplitude $2\mathrm{v}_{2,2}$ was found to factorize into a product of single particle flow harmonics $2\mathrm{v}_2 \cdot \mathrm{v}_2$, hence the second order Fourier harmonics are obtained from the formula: $\mathrm{v}_2 = \sqrt{\mathrm{v}_{2,2}}$.

To calculate the 2PC for signal tracks, the contribution of the pileup, estimated by mixed event precedure, has to be removed from direct track 2PC. One can write:

$$(\text{signal} \times \text{signal}) = (\text{direct} \times \text{direct}) - (\text{mixed} \times \text{mixed}) - 2(\text{direct}) \times (\text{mixed}) - (\text{mixed}) \times (\text{mixed}),$$

where brackets $(\cdots \times \ldots)$ or $(\ldots) \times (\ldots)$ denote the 2PC constructed between tracks in the same event or in two different events, respectively. The correction terms are calculated in small bins of ν, for each number of $n_{\mathrm{trk}}^{\mathrm{direct}}$ and for all combinations of $n_{\mathrm{trk}}^{\mathrm{mixed}} < n_{\mathrm{trk}}^{\mathrm{direct}}$. Then, using distributions like those shown in Fig. 3 as weighting factors, the background is removed from the (direct $\times$ direct) term according to the above equation. Finally, the results measured in different ν conditions are averaged and grouped into wider $n_{\mathrm{trk}}^{\mathrm{signal}}$ bins.

3. Results

The final result for v_2 in the 8 TeV pp Z-tagged event sample, measured with the 2PC method, is presented in Fig. 4 as a function of $n_{\mathrm{trk}}^{\mathrm{signal}}$. The pileup corrected 2PC are measured in a large range of track multiplicities, up to $n_{\mathrm{trk}}^{\mathrm{signal}} = 100$ and over the 0.5–5 GeV p_{T} range. The left panel compares the final v_2 for Z-tagged events to the v_2 obtained with the template fitting method in 5 TeV and 13 TeV inclusive pp collisions [3]. The right panel shows the ratio of the v_2 in the 8 TeV pp Z-tagged events to the v_2 in 13 TeV inclusive pp collisions. The Z-tagged v_2 values show a weak dependence on the multiplicity, similar to the results obtained with the inclusive samples, and are consistent with the inclusive measurements, within 1–2σ systematic uncertainty.

4. Summary

In this analysis, the two-particle correlations in $\sqrt{s}$= 8 TeV pp collisions containing a Z boson are studied. The dataset corresponds to an integrated luminosity of 19.4 fb^{-1}. The correlations are studied using a template fitting method that separates the long-range correlation from the dijet contribution. Due to the high luminosity conditions, a significant contribution to the 2PC from tracks

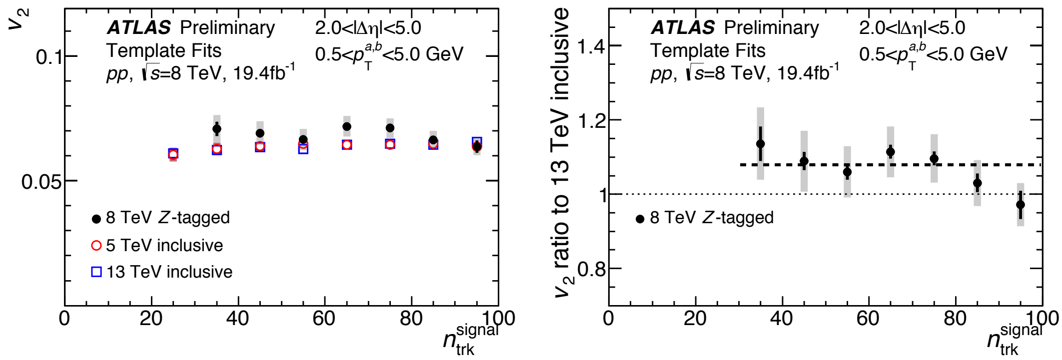

Figure 4: Left panel: the pileup corrected v_2 values obtained from the template fits as a function of $n_{\rm trk}^{\rm signal}$. For comparison, the v_2 values obtained in 5 and 13 TeV inclusive pp data are also shown. The error bars and shaded bands indicate statistical and systematic uncertainties, respectively. Right panel: the ratio of the v_2 in 8 TeV Z-tagged event sample to the v_2 in inclusive 13 TeV pp collisions as a function of $n_{\rm trk}^{\rm signal}$. The horizontal dotted line indicates unity and is intended to guide the eye. Results are plotted for $0.5 < p_{\rm T}^{\rm a,b} < 5$ GeV [6].

due to the pileup interactions is observed and contaminates the measured correlations. A novel pileup removal method is developed to remove the background contribution. The second order Fourier coefficient, v_2, is extracted and its multiplicity dependence is compared to that observed in inclusive pp collisions. The corrected v_2 shows a weak dependence on the event multiplicity, similar to that observed in inclusive pp collisions. The magnitude of the observed v_2 is found to be consistent with that observed in inclusive pp collisions. The measurement demonstrates that in pp collisions, the long-range correlation involving soft particles is not significantly modified by a hard-scattering process and should help to better understand the mechanism behind the origin of the long-range correlations observed in small collision systems.

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