Measurement of the Sensitivity of Two-Particle Correlations in *pp* Collisions to the Presence of Hard Scatterings

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A key open question in the study of multiparticle production in high-energy pp collisions is the relationship between the "ridge"—i.e., the observed azimuthal correlations between particles in the underlying event that extend over all rapidities—and hard or semihard scattering processes. In particular, it is not known whether jets or their soft fragments are correlated with particles in the underlying event. To address this question, two-particle correlations are measured in pp collisions at $\sqrt{s} = 13$ TeV using data collected by the ATLAS experiment at the LHC, with an integrated luminosity of 15.8 pb^{-1}, in two different configurations. In the first case, charged particles associated with jets are excluded from the correlation analysis, while in the second case, correlations are measured between particles within jets and charged particles from the underlying event. Second-order flow coefficients, v_2, are presented as a function of event multiplicity and transverse momentum. These measurements show that excluding particles associated with jets does not affect the measured correlations. Moreover, particles associated with jets do not exhibit any significant azimuthal correlations with the underlying event, ruling out hard processes contributing to the ridge.

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In heavy-ion collisions, two-particle correlations (2PC) in relative azimuthal angle with large pseudorapidity [1] separation show distinct long-range correlations [2–12]. These long-range correlations are a simple manifestation of the single-particle anisotropies, v_n, that originate from the hydrodynamic expansion of the quark-gluon plasma produced in these collisions. The v_n are defined by parametrizing the azimuthal distribution of produced particles as

$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \Psi_n)]\right), \qquad (1)$$

where ϕ is the azimuthal angle of the particle momentum and v_n and Ψ_n are the magnitude and phase of the nth-order anisotropy; see Refs. [4,10] and references therein.

Because of their hydrodynamic origin in nucleus-nucleus (A + A) collisions, such long-range correlations were not expected in smaller colliding systems such as proton-nucleus (p + A) or proton-proton (pp) collisions, where collective phenomena were not commonly expected to develop. However, measurements by CMS showed the presence of such long-range correlations, known as the "ridge," in high-multiplicity pp collisions [13]. Further investigations by ATLAS [9,14,15] have demonstrated that these long-range correlations in pp collisions are produced from single-particle anisotropies similar to those in heavy-ion collisions. These long-range correlations have been interpreted as evidence of collective effects similar to those seen in heavy-ion collisions. However, some authors have proposed that the ridge primarily results from correlated production of partons in the presence of dense gluonic initial states (i.e., the "glasma") [16–20], implying that much of the correlation structure associated with the ridge should be associated with hard- or semihard scattering processes. Previous measurements [21] have shown that the ridge is unmodified in pp collisions producing a Z boson, but no direct measurement in pp collisions of the correlation between jets or their fragments and the underlying event has yet been performed, while such a correlation has been observed in p + Pb collisions [22,23].

This Letter presents 2PC measurements in pp collisions at a center-of-mass energy ($\sqrt{s}$) of 13 TeV, using the ATLAS detector at the LHC. The measurements are performed with two different particle-pair selections. The first case explores correlations between tracks that are not jet constituents, while the second case measures correlations between tracks that are constituents of jets and tracks that are well-separated from jets. Similar measurements in p + Pb collisions have shown significant nonzero v_2 for low [23] and high [22] transverse momentum (p_T) particles generated in hard processes. Correlations are also measured

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in events that are explicitly selected by requiring the presence or absence of low-p_T jets. These measurements can address whether or not the presence of jets affects the ridge, and if the particles from jets exhibit azimuthal correlations with particles from the underlying event and therefore contribute to the ridge.

The measurements presented here are performed using the ATLAS [24] inner detector (ID), minimum-bias trigger scintillators, calorimeters, and the trigger and data acquisition systems [25]. The ID records charged-particle trajectories within the pseudorapidity range $|\eta| < 2.5$ using a combination of silicon pixel detectors including the "insertable B-layer" [26,27], silicon microstrip detectors, and a straw-tube transition radiation tracker, all immersed in a 2 T axial magnetic field [1,28]. The ATLAS calorimeter system consists of a liquid argon (LAr) electromagnetic calorimeter covering $|\eta| < 3.2$, a steel-scintillator sampling hadronic calorimeter covering $|\eta| < 1.7$, a LAr hadronic calorimeter covering $1.5 < |\eta| < 3.2$, and two LAr electromagnetic and hadronic forward calorimeters covering $3.2 < |\eta| < 4.9$. The ATLAS trigger system [29] consists of a Level-1 trigger implemented using a combination of dedicated electronics and programmable logic, and a software-based high-level trigger. An extensive software suite [30] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

The data were collected during Run 2 of the LHC (2015–2018), with an average collision rate per bunch crossing (μ) of less than 3, and an integrated luminosity of 15.8 pb^{-1}. The data used here were recorded using multiple minimum-bias, high-multiplicity, and jet triggers, which are described in Ref. [31]. Additional offline requirements are imposed on the events selected by the triggers. The events are required to have a reconstructed vertex with $|z| < 100$ mm. To suppress events with more than one pp collision in the same bunch crossing, events are required to have only one reconstructed vertex. Pileup events where the vertices from multiple collisions are sufficiently close such that they are reconstructed as a single vertex are not removed by the one vertex requirement. However, such merged events typically have a broader distribution for the longitudinal impact parameter of tracks relative to the vertex ($|z_0 \sin(\theta)|$). Such events are reduced by requiring that the standard deviation of $|z_0 \sin(\theta)|$ for all tracks in an event is less than 0.25 mm.

The reconstruction and performance of tracks and primary vertices in the ID are described in Refs. [32–34]. The specific track selection criteria can be found in Ref. [31]. The track reconstruction efficiencies $\epsilon(p_T, \eta)$ are obtained using Monte Carlo (MC) generated events that are passed through a Geant4 [35] simulation [36] of the ATLAS detector and reconstructed using the procedures applied to the data. The efficiency varies between 69% and 87% as a function of η and p_T.

Jets used in this analysis are reconstructed using the anti-k_t algorithm [37] with a radius parameter of 0.4. The inputs to jet reconstruction are "particle flow objects" as detailed in Ref. [38]. Jets are calibrated to the hadronic scale using scale factors obtained from MC simulations specifically derived for low-μ data. Additional *in situ* corrections [39] are applied, which account for differences in the jet response between the MC samples and data. One issue in this analysis is that the modulation in the soft particles in the event [Eq. (1)] biases the jet p_T in a manner that depends on its orientation relative to the Ψ_n. This affects the measurements of the correlations between jet fragments and the underlying event (UE) particles (discussed in detail below). To mitigate this effect, instead of selecting jets based on their p_T, selections are made on the following groomed quantity:

$$p_T^G = \left| \sum_{\text{constituents}} \boldsymbol{p}_T^{>4\ \text{GeV}} \right|, \tag{2}$$

where the sum runs over all the jet constituents with $p_T > 4$ GeV, which considerably reduces the number of UE particles within the jet, and makes this bias negligible, as shown in Ref. [31].

In previous ATLAS measurements of 2PCs in $p+\mathrm{Pb}$ [40,41] and pp [14,15,21] collisions, events were quantified by $N_{\text{ch}}^{\text{rec}}$: the total number of reconstructed tracks with $p_T > 0.4$ GeV, passing the track selections discussed above. In this analysis, a slight modification is made to ensure that the event activity is not biased by the presence of jets and only reflects the soft multiplicity in the event. The number of constituent tracks in jets with $p_T^G > 15$ GeV is subtracted from the measured multiplicity, and the corrected quantity, $N_{\text{ch}}^{\text{rec,corr}}$, is used to represent the event activity. While counting the constituent tracks of jets, the $p_T > 4$ GeV requirement is not imposed on the tracks. Additionally, this correction is offset by the average number of UE tracks within the jet cone. This offset is estimated by measuring the average number of tracks, as a function of η and ϕ, that are in a $R = 0.4$ cone in events with similar multiplicity and trigger conditions.

In 2PC measurements, the distribution of particle pairs in relative azimuthal angle $\Delta\phi = \phi^a - \phi^b$ are measured. The labels a and b denote the two particles in the pair. In evaluating the correlation functions, the tracks are weighted by the inverse of their reconstruction efficiency, $1/\epsilon(p_T, \eta)$. To suppress short-range correlations, the particles are required to have a pseudorapidity separation of $|\Delta\eta| > 2$. In pp collisions, back-to-back dijets also make a significant contribution to the 2PCs. To remove this contribution, a template-fit method [14,15,21] is employed in which the measured 2PC is described by a fit having two components. The first component accounts for the dijet contribution, $C^{\text{periph}}(\Delta\phi)$, which is measured using low-multiplicity events (called the "peripheral reference"). This analysis

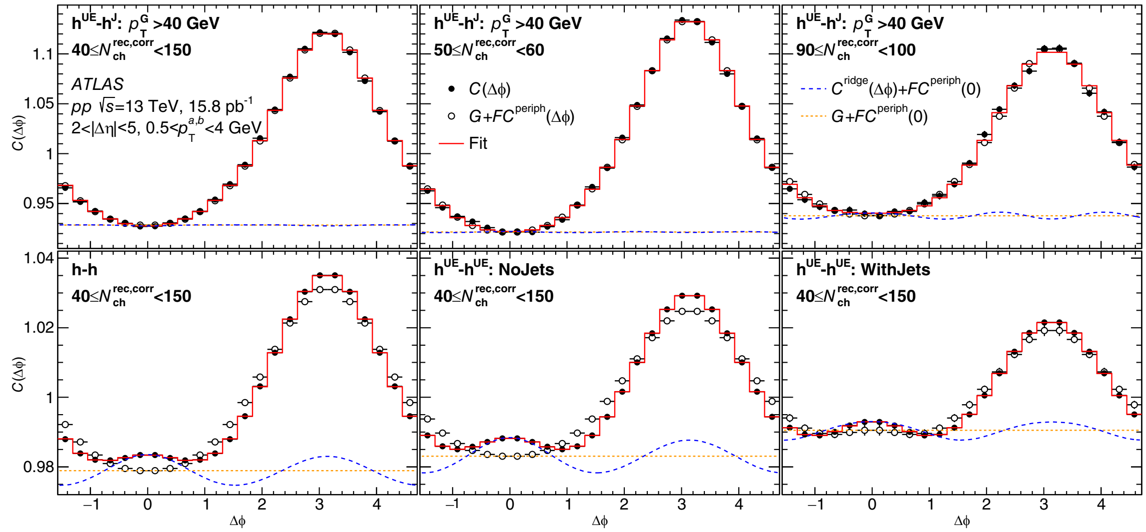

FIG. 1. Template fits to the two-particle correlations in $\Delta\phi$. Events with $10 \leq N_{\mathrm{ch}}^{\mathrm{rec,corr}} < 30$ are used as the peripheral reference. The solid points indicate the measured 2PC, the open circles show the scaled and shifted peripheral reference, and the continuous line shows the fit. The dashed line shows the second-order harmonic component, and the dotted line shows the pedestal of the fit shifted up by $FC^{\mathrm{periph}}(0)$. The top row corresponds to different multiplicity intervals for the $h^{\mathrm{UE}} - h^{J}$ class. The left, center, and right panels in the bottom row correspond to the h-h, $h^{\mathrm{UE}} - h^{\mathrm{UE}}(NoJets)$, and $h^{\mathrm{UE}} - h^{\mathrm{UE}}(WithJets)$ classes, respectively, for the 40–150 multiplicity interval.

uses the $N_{\mathrm{ch}}^{\mathrm{rec,corr}}$ interval of 10–30 to build C^{periph}. The second component accounts for the bulk contribution with a relative harmonic modulation, $C^{\mathrm{ridge}}(\Delta\phi)$. The 2PC can then be described as

$$C(\Delta\phi) = FC^{\mathrm{periph}}(\Delta\phi) + G\left(1 + 2\sum_{n=2} v_{n,n}\cos(n\Delta\phi)\right) \equiv FC^{\mathrm{periph}}(\Delta\phi) + C^{\mathrm{ridge}}(\Delta\phi), \tag{3}$$

where F and $v_{n,n}$ are fit parameters and G is fixed by the requirement that the integrals of the fit and $C(\Delta\phi)$ are equal. The Fourier moments, $v_{n,n}$, obtained from the template fit quantify the strength of the long-range correlation. It is demonstrated in Refs. [14,15] that the $v_{n,n}$ in pp collisions obtained from Eq. (3) factorize as $v_{n,n}(\phi_T^a, \phi_T^b) = v_n(\phi_T^a)v_n(\phi_T^b)$, where v_n is the single particle anisotropy [Eq. (1)]. Thus, $v_n(\phi_T^b)$ is obtained as $v_n(\phi_T^b) = v_{n,n}(\phi_T^a, \phi_T^b)/\sqrt{v_{n,n}(\phi_T^a, \phi_T^a)}$.

The tracks used in this analysis are categorized as follows: those that are separated from all $\phi_T^G > 15$ GeV jets by at least one unit in η [22] and having $0.5 < p_T < 4$ GeV are considered to be UE tracks (h^{UE}); tracks that are included as particle-flow constituents of jets having $p_T^G > 40$ GeV (called "trigger jets" henceforth) are considered to be jet constituents (h^J). Five classes of correlations are studied in this Letter: (1) standard 2PC [14,15] without applying any rejection of tracks around jets; (2) 2PC where both tracks are h^{UE}—about 14% of h-h 2PC pairs are removed by the above-mentioned rejection; (3) 2PC using events with no jets with $p_T^G > 15$ GeV; (4) 2PC using events with at least one jet with $p_T^G > 15$ GeV; (5) 2PC performed between h^{UE} and h^J. These five classes are referred to as h-h, $h^{\mathrm{UE}} - h^{\mathrm{UE}}(AllEvents)$, $h^{\mathrm{UE}} - h^{\mathrm{UE}}(NoJets)$, $h^{\mathrm{UE}} - h^{\mathrm{UE}}(WithJets)$, and $h^{\mathrm{UE}} - h^J$, respectively, in the text below.

These classes are not mutually exclusive. Specifically, the $h^{\mathrm{UE}} - h^{\mathrm{UE}}(NoJets)$ and $h^{\mathrm{UE}} - h^{\mathrm{UE}}(WithJets)$ classes add up to the $h^{\mathrm{UE}} - h^{\mathrm{UE}}(AllEvents)$ class. The $h^{\mathrm{UE}} - h^J$ class has no overlapping particle-pairs with the ones in the $h^{\mathrm{UE}} - h^{\mathrm{UE}}(AllEvents)$, $h^{\mathrm{UE}} - h^{\mathrm{UE}}(NoJets)$, and $h^{\mathrm{UE}} - h^{\mathrm{UE}}(WithJets)$ classes. The h-h class is identical to the measurements performed in the previous ATLAS publications [14,15], and is used as a reference with which other classes are compared.

For the $h^{\mathrm{UE}} - h^J$ case, additional requirements are imposed on the trigger jets to avoid distortions of the 2PC. They must have no other jet with $p_T^G > 15$ GeV within $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 1$ and they must have a balancing jet with $p_T^G > 15$ GeV and with $|\Delta\phi| > 5\pi/6$. The first requirement removes distortions of the 2PC at smaller $\Delta\phi$ while the second requirement ensures that fragments of the balancing jet are excluded from h^{UE}.

It may happen that some constituents of jets originate in the UE, leading to a contribution of combinatorial pairs in the 2PC. These combinatorial pairs, by construction, have the same correlation as those where both the tracks are from the UE. The contribution of such pairs is removed by the following technique. For each event that contributes to the $h^{\mathrm{UE}} - h^J$ correlation, a separate 2PC is made using another event with similar vertex position and multiplicity. In this event, one track is picked from an η-ϕ region that is

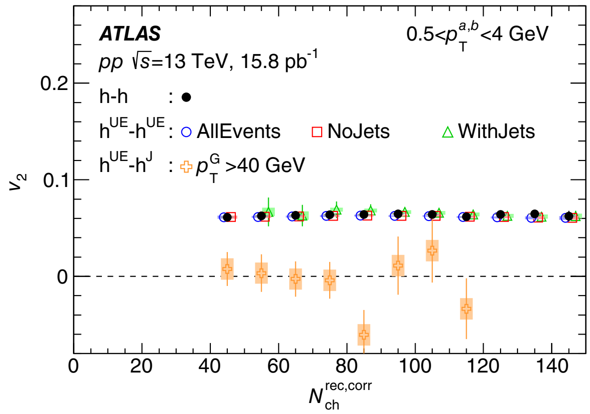

FIG. 2. The multiplicity dependence of v_2 for $2 < |\Delta\eta| < 5$. Events with $10 \leq N_{\mathrm{ch}}^{\mathrm{rec,corr}} < 30$ are used as the peripheral reference. Jets with $p_T^G > 15$ GeV are used to classify the $h^{\mathrm{UE}} - h^{\mathrm{UE}}(NoJets)$ and $h^{\mathrm{UE}} - h^{\mathrm{UE}}(WithJets)$ samples. The data point for the $h^{\mathrm{UE}} - h^{\mathrm{UE}}(WithJets)$ case has a particularly large statistical uncertainty in the 40–50 multiplicity interval and is not shown. The data points for the $h^{\mathrm{UE}} - h^{\mathrm{UE}}(AllEvents)$, $h^{\mathrm{UE}} - h^{\mathrm{UE}}(NoJets)$, and $h^{\mathrm{UE}} - h^{\mathrm{UE}}(WithJets)$ samples are slightly shifted along the x axis for clarity. The error bars and bands correspond to statistical and systematic uncertainties, respectively.

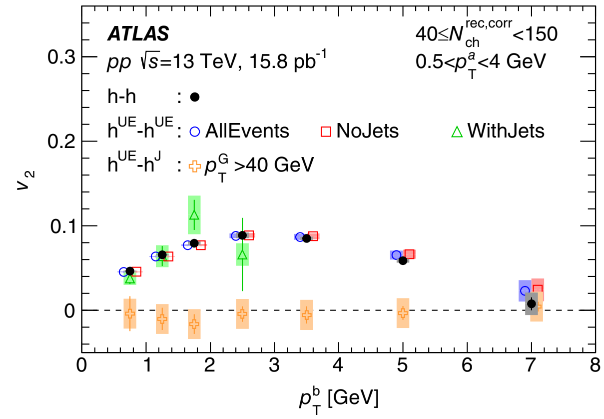

FIG. 3. The p_T^b dependence of the v_2 obtained for the 40–150 multiplicity interval for $2 < |\Delta\eta| < 5$. Events with $10 \leq N_{\mathrm{ch}}^{\mathrm{rec,corr}} < 30$ are used as the peripheral reference. Jets with $p_T^G > 15$ GeV are used to classify the $h^{\mathrm{UE}} - h^{\mathrm{UE}}(NoJets)$ and $h^{\mathrm{UE}} - h^{\mathrm{UE}}(WithJets)$ samples. The data points for the h-h sample are drawn at the nominal values while the data points for the $h^{\mathrm{UE}} - h^{\mathrm{UE}}(AllEvents)$, $h^{\mathrm{UE}} - h^{\mathrm{UE}}(NoJets)$, and the highest p_T^b point of $h^{\mathrm{UE}} - h^J$ samples are shifted slightly for clarity. The error bars and bands correspond to statistical and systematic uncertainties, respectively.

within $R = 0.4$ cone of the jet axis and the other track is picked from the same η range as in the $h^{\mathrm{UE}} - h^J$ event. This combinatorial 2PC is then subtracted from the $h^{\mathrm{UE}} - h^J$ 2PC.

Statistical uncertainties in the measured 2PCs are evaluated using a bootstrapping procedure previously used in Ref. [42]. Systematic uncertainties in the v_2 measurements are estimated by varying different aspects of the analysis. For the template-fit procedure, the $N_{\mathrm{ch}}^{\mathrm{rec,corr}}$ multiplicity range for the peripheral reference selection was varied from the nominal 10–30 to 10–40 and 20–40 [31] and the change in the v_2 values is included as a systematic uncertainty. For the multiplicity dependence, this uncertainty for the v_2 is 0.01 (absolute) for the $h^{\mathrm{UE}} - h^J$ class and is typically within 2% for the other classes. This uncertainty is fully correlated across all multiplicity intervals and is the dominant uncertainty for the $h^{\mathrm{UE}} - h^J$ class. Uncertainties in the tracking efficiency are propagated into the measured v_2. This uncertainty on the v_2 is less than 0.5%, and is estimated by varying the efficiency up and down within its uncertainties ($\sim \pm 3\%$) [43], and re-evaluating the v_2. The systematic uncertainty due to nonprimary tracks is estimated by varying the selection criteria for transverse and longitudinal impact parameters, resulting in a 0.5% change in v_2. The 2PC analyses often use event mixing [4,10] to estimate and correct the 2PCs for the detector's pair acceptance. This correction is quite small, and the full effect of the correction is included as a systematic uncertainty. As discussed previously, the events used in this analysis are required to have the standard deviation of $|z_0 \sin(\theta)|$ for the tracks in an event to be smaller than 0.25 mm, to reduce pileup. Conservatively, the entire effect of this selection, which varies with multiplicity but is typically within 1%, is taken to be a systematic uncertainty associated with pileup effects.

Figure 1 compares the 2PCs for all classes, except the $h^{\mathrm{UE}} - h^{\mathrm{UE}}(AllEvents)$ class. The figure also shows the template fits including the components of the fits. In general, the template fits describe the 2PCs quite well. A near-side ridge is visible for the h-h, $h^{\mathrm{UE}} - h^{\mathrm{UE}}(WithJets)$, and $h^{\mathrm{UE}} - h^{\mathrm{UE}}(NoJets)$ cases, while the $C^{\mathrm{periph}}(\Delta\phi)$ appears to describe the full distribution in the $h^{\mathrm{UE}} - h^J$ case.

Figure 2 shows the multiplicity dependence of the v_2 for all five 2PC classes. The v_2 values for the h-h case vary weakly with multiplicity, as previously reported in Refs. [14,15]. The v_2 values in the $h^{\mathrm{UE}} - h^{\mathrm{UE}}(AllEvents)$, $h^{\mathrm{UE}} - h^{\mathrm{UE}}(NoJets)$, and $h^{\mathrm{UE}} - h^{\mathrm{UE}}(WithJets)$ cases, are all consistent with the h-h result. This demonstrates that removing tracks associated with jets does not impact the long-range UE correlations, and nor does the presence (or absence) of jets in an event. Within uncertainties, the v_2 values in the $h^{\mathrm{UE}} - h^J$ case are consistent with zero. The mean v_2 for the $h^{\mathrm{UE}} - h^J$ correlations over the 40–150 multiplicity range is $-0.009 \pm 0.010(\mathrm{statistical}) \pm 0.014(\mathrm{systematic})$. This indicates that particles produced in hard scattering processes (with $p_T^G > 40$ GeV) do not contribute significantly to the long-range correlation observed in pp collisions. Figure 3 shows the p_T dependence of the v_2. The differential $v_2(p_T)$ values in the $h^{\mathrm{UE}} - h^{\mathrm{UE}}(AllEvents)$, $h^{\mathrm{UE}} - h^{\mathrm{UE}}(NoJets)$, and $h^{\mathrm{UE}} - h^{\mathrm{UE}}(WithJets)$ cases are found to be consistent with the

h-h case. Again, within uncertainties, the $h^{\mathrm{UE}} - h^J$ v_2 values are consistent with zero, across the entire measured p_T range. The findings drawn from the p_T dependence are consistent with those from the multiplicity dependence, and similarly demonstrate that the presence or absence of jets has no influence on the flow of the UE and that there are no correlations between jet fragments and the UE. The features of the v_2 values discussed above do not show any systematic variation with the jet selections—for example, the p_T^G thresholds used in the analysis, as discussed in Ref. [31].

In conclusion, this Letter studies long-range 2PCs in pp collisions when rejecting tracks in the vicinity of jets, and the correlations between jet constituent tracks and tracks from the UE. The 2PCs are analyzed using a template-fit procedure, previously developed by ATLAS [15], which extracts second-order Fourier coefficients (v_2) of the anisotropy. These results demonstrate that the magnitude of the v_2 is not affected when removing tracks associated with jets, or by the presence or absence of jets in the event. The v_2 measured with correlations between jet constituents with $p_T < 8$ GeV and UE tracks are consistent with zero within uncertainties. These features are observed both in the v_2 multiplicity and p_T dependence.

The observation that fragments of high-p_T jets in pp collisions do not have measurable long-range azimuthal correlations with the UE and that the production of Z bosons [21] or jets does not significantly influence the long-range correlations between UE particles, suggest a complete "factorization" between hard-scattering processes and the physics responsible for the ridge. Further studies are needed to extend this measurement to higher p_T to compare with previous measurements in $p+\mathrm{Pb}$ collisions [22] where such factorization is broken. This Letter provides important insights into the origin of the long-range correlations observed in pp collisions and offers new fundamental input to theoretical models.

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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, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

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