



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 multi-particle production in high-energy pp collisions is the relationship between the “ridge” – observed azimuthal correlations between particles in the underlying event that extend over all rapidities – and hard or semi-hard 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.

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 (QGP) produced in these collisions. The v_n are defined by parameterizing the azimuthal distribution of produced particles as:

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

where ϕ is the azimuthal angle of the particle momentum and v_n and Ψ_n are the magnitude and phase of the n^{th} -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 is primarily composed of hard partons scattering off of a dense gluonic state [16–20], implying that much of the correlation structure associated with the ridge should be associated with hard- or semi-hard 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 non-zero v_2 for low [23] and high [22] transverse momentum (p_T) particles generated in hard processes. Correlations are also measured 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 (MBTS), 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” (IBL) [26, 27], silicon microstrip detectors (SCT), and a straw-tube transition radiation tracker (TRT), 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 (FCal) covering $3.2 < |\eta| < 4.9$. The ATLAS trigger system [29] consists of a Level-1 (L1) trigger implemented using a combination of dedicated electronics and programmable logic, and a software-based high-level trigger

(HLT). 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 $|z| < 100 \text{ mm}$. 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:

$$p_T^G = \left| \sum_{\text{constituents}} p_T^{> 4 \text{ GeV}} \right|, \quad (2)$$

where the sum runs over all the jet constituents with $p_T > 4 \text{ GeV}$, 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 $p+\text{Pb}$ [40, 41] and pp [14, 15, 21] collisions, events were quantified by $N_{\text{ch}}^{\text{rec}}$: the total number of reconstructed tracks with $p_T > 0.4 \text{ GeV}$, 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 $p_T^G > 15 \text{ GeV}$ 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 $p_T > 4 \text{ GeV}$ 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 uses the $N_{\text{ch}}^{\text{rec,corr}}$ interval of 10–30 to build C^{periph} . The second component accounts for the bulk contribution with a relative harmonic modulation, $C^{\text{ridge}}(\Delta\phi)$. The 2PC can then be described as:

$$\begin{aligned} C(\Delta\phi) &= FC^{\text{periph}}(\Delta\phi) + G \left(1 + 2 \sum_{n=2} v_{n,n} \cos(n\Delta\phi) \right) \\ &\equiv FC^{\text{periph}}(\Delta\phi) + C^{\text{ridge}}(\Delta\phi), \end{aligned} \quad (3)$$

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 $v_{n,n}(p_T^a, p_T^b) = v_n(p_T^a) v_n(p_T^b)$, where v_n is the single particle anisotropy (Eq. (1)). Thus, $v_n(p_T^b)$ is obtained as $v_n(p_T^b) = v_{n,n}(p_T^a, p_T^b) / \sqrt{v_{n,n}(p_T^a, p_T^a)}$.

This Letter studies how the presence of a hard-scattering affects the structure of the long-range correlation of UE particles (quantified by the v_n), and also investigates whether tracks that are constituents of jets (jet-fragment) exhibit any azimuthal correlation with the UE. To get an unbiased set of UE tracks for the correlation analysis, the UE tracks used in the 2PC are required to be separated from all $p_T^G > 15$ GeV jets in the event by at least one unit in η . These tracks are referred as h^{UE} in this study. This approach has previously been used in studies of p +Pb collisions [22]. Subsequently, correlations are studied between particle-pairs where both particles are from the UE, or pairs where one particle is from the UE and the other particle is a jet constituent (h^J). Five classes of correlations are studied in this Letter:

- h - h : Standard 2PC [14, 15] without applying any rejection of tracks around jets.
- $h^{UE} - h^{UE}(\text{AllEvents})$: 2PC where both tracks are h^{UE} . About 14% of h - h 2PC pairs are removed by the abovementioned rejection.
- $h^{UE} - h^{UE}(\text{NoJets})$: 2PC using events with no jets with $p_T^G > 15$ GeV.
- $h^{UE} - h^{UE}(\text{WithJets})$: 2PC using events with at least one jet with $p_T^G > 15$ GeV.
- $h^{UE} - h^J$: 2PC performed between h^{UE} and h^J (for jets with $p_T^G > 40$ GeV).

These classes are not mutually exclusive. Specifically, the $h^{UE} - h^{UE}(\text{NoJets})$ and $h^{UE} - h^{UE}(\text{WithJets})$ classes add up to the $h^{UE} - h^{UE}(\text{AllEvents})$ class. The $h^{UE} - h^J$ class has no overlapping particle-pairs with the ones in the $h^{UE} - h^{UE}(\text{AllEvents})$, $h^{UE} - h^{UE}(\text{NoJets})$, and $h^{UE} - h^{UE}(\text{WithJets})$ 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. The $h^{UE} - h^{UE}(\text{AllEvents})$ class is used to study the effect of removing jets-associated tracks from the long-range correlations. The $h^{UE} - h^{UE}(\text{WithJets})$ and $h^{UE} - h^{UE}(\text{NoJets})$ classes contrast how the presence or absence of jets in an event affect the 2PC, even when the tracks associated with the jets are not used in the 2PC. Finally, the $h^{UE} - h^J$ class is used to study whether the jet-fragments also exhibit long-range correlations with the UE. To measure the $h^{UE} - h^J$ correlations, one of the tracks in the 2PC is selected from the constituents of a $p_T^G > 40$ GeV jet, while the other is an UE track. To prevent any possible biases to the shape of the 2PC from split

and nearby jets, an isolation requirement is imposed that no jets with $p_T^G > 15$ GeV are present within a $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ of one unit from the $p_T^G > 40$ GeV jet. Since jets usually occur in pairs, a matched recoil jet with $p_T^G > 15$ GeV is required to be present in the event located at $|\Delta\phi| > 5\pi/6$ from the first jet. The requirement of a matched recoil jet ensures that all the h^{UE} used in the 2PC are also separated from the recoil jet. This consequently reduces possible biases from dijet pairs to the $h^{UE} - h^J$ 2PC. The $h^{UE} - h^J$ 2PC requires some additional steps in the construction of the correlation functions. 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 $h^{UE} - h^J$ 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 within $R = 0.4$ cone of the jet-axis and the other track is picked from the same η range as in the $h^{UE} - h^J$ event. This combinatorial 2PC is then subtracted from the $h^{UE} - h^J$ 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 $N_{ch}^{rec,corr}$ 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 $h^{UE} - h^J$ 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 $h^{UE} - h^J$ 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 non-primary 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 $h^{UE} - h^{UE}(AllEvents)$ 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 , $h^{UE} - h^{UE}(WithJets)$ and $h^{UE} - h^{UE}(NoJets)$ cases, while the $C^{periph}(\Delta\phi)$ appears to describe the full distribution in the $h^{UE} - h^J$ 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 $h^{UE} - h^{UE}(AllEvents)$, $h^{UE} - h^{UE}(NoJets)$, and $h^{UE} - h^{UE}(WithJets)$ 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 $h^{UE} - h^J$ case are consistent with zero. The mean v_2 for the $h^{UE} - h^J$ correlations over the 40–150 multiplicity range is $-0.009 \pm 0.010(\text{statistical}) \pm 0.014(\text{systematic})$. 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 $h^{UE} - h^{UE}(AllEvents)$, $h^{UE} - h^{UE}(NoJets)$ and $h^{UE} - h^{UE}(WithJets)$ cases are found to be consistent with the h - h case. Again, within uncertainties, the $h^{UE} - h^J$ v_2 values are consistent with zero,

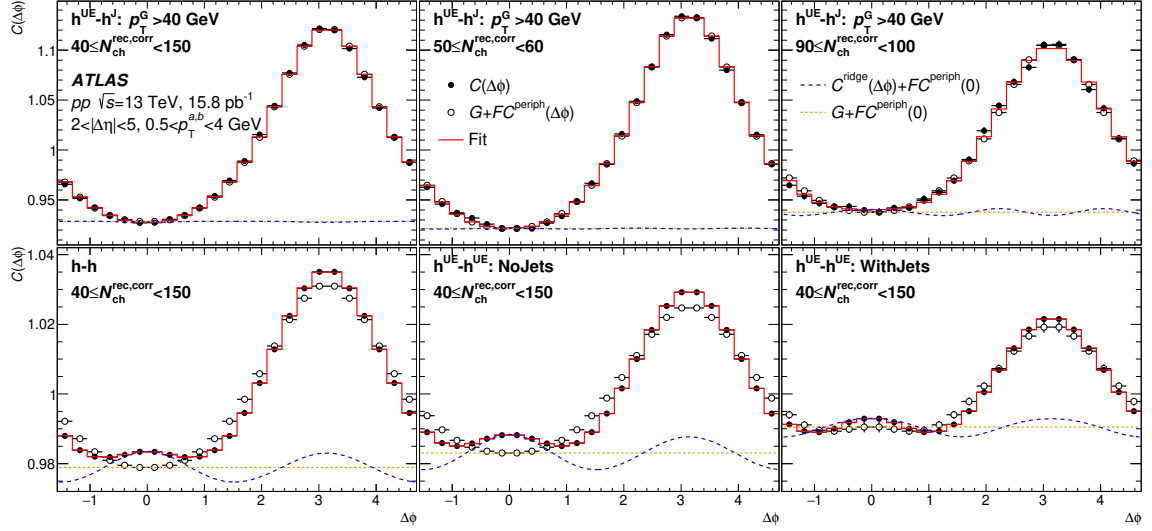


Figure 1: Template-fits to the two-particle correlations in $\Delta\phi$. Events with $10 \leq N_{\text{ch}}^{\text{rec,corr}} < 30$ are used as the peripheral reference. The solid points indicate the measured 2PC, the open circles show the scaled and shifted peripheral reference, and the continuous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

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 [31].

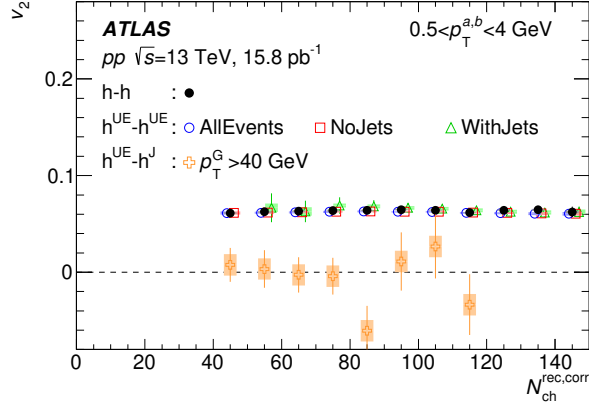


Figure 2: The multiplicity dependence of v_2 for $2 < |\Delta\eta| < 5$. Events with $10 \leq N_{\text{ch}}^{\text{rec,corr}} < 30$ are used as the peripheral reference. Jets with $p_{\text{T}}^{\text{G}} > 15$ GeV are used to classify the $h^{\text{UE}} - h^{\text{UE}}(\text{NoJets})$ and $h^{\text{UE}}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

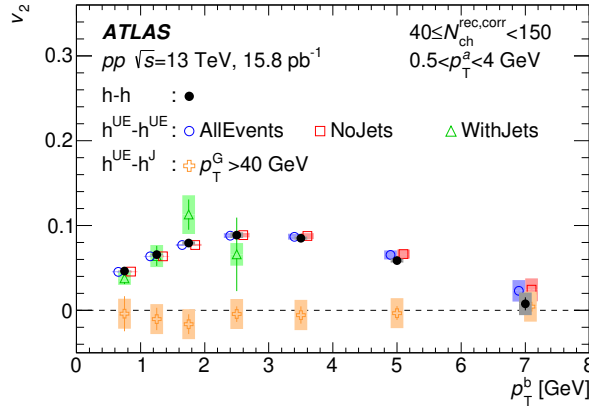


Figure 3: The p_{T}^{b} dependence of the v_2 obtained for the 40–150 multiplicity interval for $2 < |\Delta\eta| < 5$. Events with $10 \leq N_{\text{ch}}^{\text{rec,corr}} < 30$ are used as the peripheral reference. Jets with $p_{\text{T}}^{\text{G}} > 15$ GeV are used to classify the $h^{\text{UE}}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

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 $p_{\text{T}} < 8$ 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 +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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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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Appendix

A Supplemental Material Allowed by Journal to Accompany Online Version of Paper

A.1 Detailed trigger description

Multiple triggers were used to record the data and can broadly be classified into three categories. The first category of triggers selects a set of minimum-bias events through a L1 trigger that requires a signal in at least one MBTS counter, and a second trigger that requires at least one reconstructed track with $p_T > 0.2$ GeV at the HLT. The second category is a set of high-multiplicity triggers that apply a L1 requirement on either the transverse energy (E_T) in the calorimeters or a hit in at least one MBTS counter on each side, and an HLT requirement on the multiplicity of HLT-reconstructed tracks with $p_T > 0.4$ GeV that is associated with the reconstructed vertex with the highest multiplicity in the event. The third is a set of triggers that enhance the rate of jets. These include a set of triggers that require a jet at L1 and at the HLT, and another set of triggers that require a minimum threshold on the total E_T in the calorimeter at L1.

A.2 Detailed track selection criteria

The criteria used to select tracks include the requirements of $p_T > 0.4$ GeV and $|\eta| < 2.5$, a hit in the IBL or a hit in the pixel layer next to the IBL, and a minimum of six hits in the SCT. Additionally, the transverse impact parameter of the track relative to the average beam position, and the longitudinal impact parameter of the track relative to the vertex are both required to be less than 1.5 mm. To remove tracks with mis-measured p_T due to interactions with the material or other effects, the track-fit χ^2 probability is required to be larger than 0.01 for tracks having $p_T > 10$ GeV.

A.3 Multiplicity distributions

Figure 4 shows the distribution of $N_{\text{ch}}^{\text{rec,corr}}$ for the events in the h - h , $h^{\text{UE}}-h^{\text{UE}}$ (*AllEvents*), $h^{\text{UE}}-h^{\text{UE}}$ (*NoJets*), $h^{\text{UE}}-h^{\text{UE}}$ (*WithJets*), and $h^{\text{UE}}-h^J$ cases. The default peripheral reference in the template-fits is constructed using the events in the 10–30 multiplicity interval. The average minimum-bias multiplicity of reconstructed charged-particle tracks in 13 TeV pp collisions in ATLAS is ~ 20 , and the default range for the peripheral reference is taken to be a ± 10 window around this mean value. Alternative peripheral references built from the 10–40 and 20–40 multiplicity intervals are used to evaluate systematic uncertainties, where the lower and upper multiplicity ranges are increased by 10 from the default interval. The 0–10 multiplicity interval, is excluded from the peripheral references as 1) the $h^{\text{UE}}-h^{\text{UE}}$ (*WithJets*) and $h^{\text{UE}}-h^J$ cases have very few events at these low multiplicities, and 2) such low multiplicity are likely to contain a significant contribution from diffractive events.

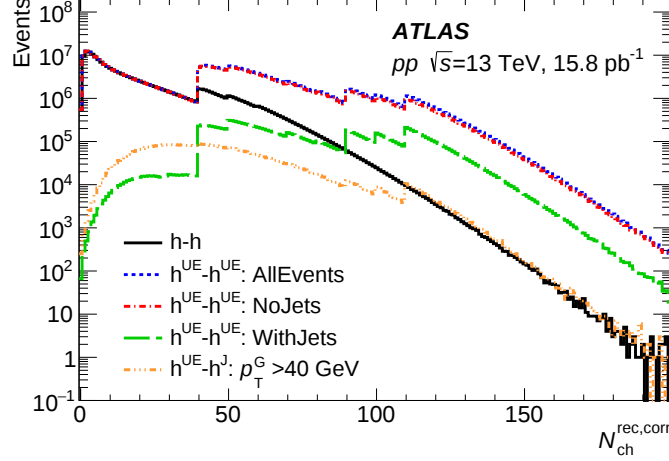


Figure 4: The distribution of $N_{\text{ch}}^{\text{rec,corr}}$ for the $\sqrt{s} = 13$ TeV pp data used in this analysis. The different lines denote the h - h , $h^{\text{UE}} - h^{\text{UE}}(\text{AllEvents})$, $h^{\text{UE}} - h^{\text{UE}}(\text{NoJets})$, $h^{\text{UE}} - h^{\text{UE}}(\text{WithJets})$, and $h^{\text{UE}} - h^{\text{J}}$ cases. The discontinuities in the distributions correspond to different high-multiplicity trigger thresholds.

A.4 PYTHIA 8 Embedding

This section motivates the choice of the 4 GeV requirement used in Eq. (2) to remove the bias from the UE modulation on the jet selection. The effect of UE modulation on the jet selection is estimated by a toy PYTHIA 8 embedding study. The PYTHIA 8 events are simulated using the Monash 2013 tune with multi-parton interaction off and initial-state radiation on. Jet reconstruction is performed on these generated events, using the anti- k_{T} clustering algorithm with a radius parameter of 0.4. The jets thus produced are called *generated-jets* hereafter. The generated events are filtered by requiring the events to have a generated-jet with p_{T} greater than 15 GeV and a balanced generated-jet with $p_{\text{T}} > 10$ GeV and $|\Delta\phi| > 5\pi/6$ relative to the first jet. The generated (stable¹) particles are embedded onto minimum bias data events. After the embedding, jets are reconstructed using the embedded particles and the original particle flow objects [38] present in the data-event, using the anti- k_{T} clustering algorithm with a radius parameter of 0.4. These jets are called *embedded-jets* hereafter. Similar jet clustering is also done using only the particle flow objects in the minimum-bias data used in the embedding study. These jets are called *data-jets* hereafter.

The embedded-jets are required to match a generated-jet with $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.1$. The embedded-jets are also required to be separated from data-jets by $\Delta R > 0.8$. The p_{T} of the embedded-jets is always larger than the p_{T} of the matched generated-jet as the particle flow objects in the data always push up the p_{T} . The issue of concern for this analysis is that this increase in the p_{T} is dependent on the azimuthal angle that the jet makes with the second-order event-plane, due to the modulation in the UE. To visualize the bias from the UE modulation, the difference between the azimuthal angle of the embedded-jet, ϕ^{jet} , and the second-order event plane angle, Ψ_2^{Data} , is plotted in Figure 5. The Ψ_2 angle is calculated using particles from the data events only, excluding particles within one unit in η around any data-jets with p_{T} greater than 15 GeV. Since PYTHIA 8 events are uncorrelated with the data event onto which they are embedded, the distribution of $\phi^{\text{jet}} - \Psi_2^{\text{Data}}$ is, by construction, constant for the generated-jets. However, for the embedded-jets the corresponding distribution is modulated, as shown in Figure 5.

¹ The generated particles that are not decayed further by PYTHIA 8 are called stable here.

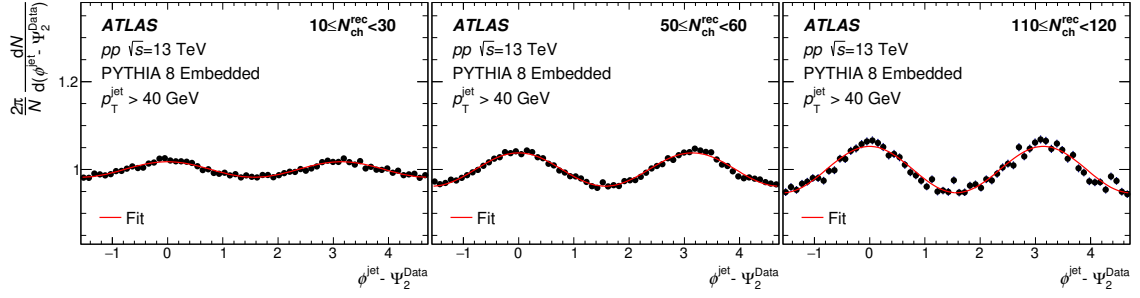


Figure 5: The distribution of $\phi^{\text{jet}} - \Psi_2^{\text{Data}}$ for the embedded jets. The continuous line indicates a Fourier fit to the distribution that includes a 2nd order modulation. The different panels correspond to different multiplicity intervals.

Since the modulation effects are dominated by low p_T particles, grooming the jets to remove soft particles can remove the UE bias. A groomed jet p_T definition is proposed here, by summing the p_T of jet constituents with p_T greater than a particular threshold X :

$$p_T^G = \left| \sum p_T > X \text{ GeV} \right|, \quad (4)$$

Figure 6 shows the $\phi^{\text{jet}} - \Psi_2^{\text{Data}}$ using different values of the threshold X in Eq. (4). The modulation in the distribution systematically decreases with increasing X , and is nearly gone for $X = 4$ GeV.

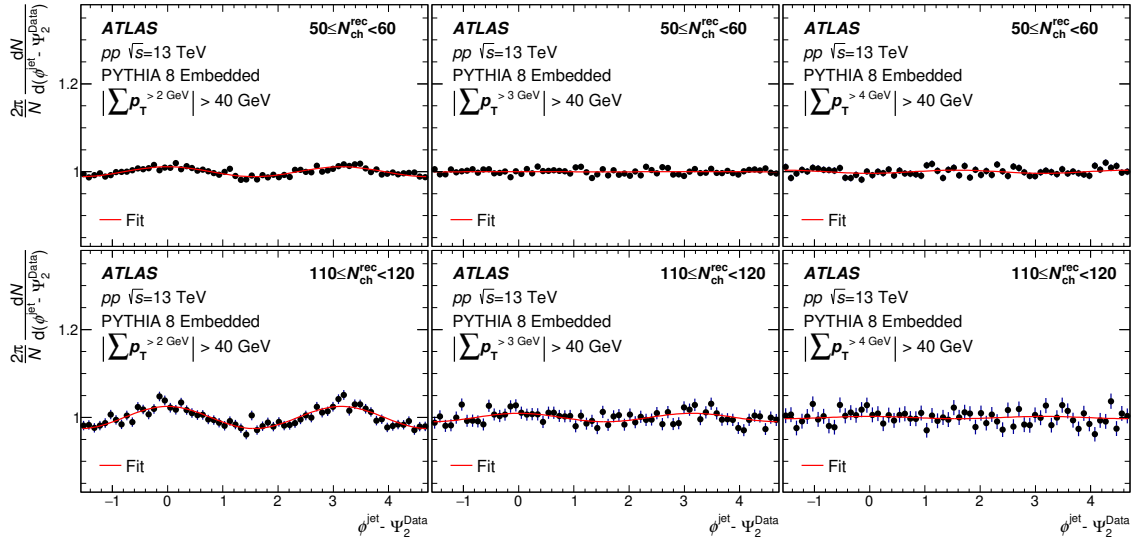


Figure 6: The distribution of $\phi^{\text{jet}} - \Psi_2^{\text{Data}}$ for the embedded jets. The continuous line indicates a Fourier fit to the distribution that includes a 2nd order modulation. From left to right, the three panels in each row correspond to increasing thresholds X (in Eq. (4)) of 2 GeV, 3 GeV, and 4 GeV. The top (bottom) row corresponds to the 50–60 (110–120) multiplicity interval.

A.5 Cross checks on jet selections used in the analysis

This section discusses several checks that are made to test the sensitivity of the results on the jet selections used in the analysis.

- The sensitivity of the $h^{UE} - h^J$ v_2 measurements to the p_T^G selection is evaluated by varying the p_T^G selection threshold from the nominal value of 40 GeV to 35 GeV and 50 GeV.
- The sensitivity of the v_2 to the p_T threshold applied on the jet constituents in Eq. (2) is checked by raising it from its default value of 4 GeV to 4.5 GeV.
- The sensitivity of results to the choice of the jet p_T^G used to isolate the h^{UE} tracks is investigated by increasing the threshold from its nominal value of 15 GeV to 20 GeV.
- As stated in the Letter as isolation requirement is imposed on the $p_T^G > 40$ GeV jets in the $h^{UE} - h^J$ correlations. This isolation requirement requires that there are no $p_T^G > 15$ GeV jets within $\Delta R = 1$ of the $p_T^G > 40$ GeV jets used in the $h^{UE} - h^J$ correlation analysis. As a cross-check the measurements are repeated with this isolation requirement removed.

For all these cases no significant variation is observed in the measurements, and the results with these variations are consistent with the nominal ones within the quoted systematic and statistical uncertainties.

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