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## Long range correlations and their event scale dependence in high multiplicity pp collisions at $\sqrt{s} = 13$ TeV

### Abstract

The observed azimuthal modulations of long-range correlations in pseudorapidity in small systems like pp or p-Pb collisions show strikingly similar features to those seen in heavy ion collisions. Many theoretical approaches to interpreting this effect have been developed. However, it is still unclear whether these long-range correlations are due to final or initial state effects. To further investigate these effects, we studied long-range correlations as a function of transverse momentum in very high multiplicity pp collisions at  $\sqrt{s} = 13$  TeV, collected with the high multiplicity event trigger during 2016 and 2017 with ALICE. In this talk, we present the near-side per-trigger yield at large pseudorapidity separation (ridge yield) as a function of transverse momentum in pp collisions at  $\sqrt{s} = 13$  TeV. The results are compared to previous measurements from CMS experiments. In addition, we present the ridge yield in events where harder fragmentation processes are present, to explore possible physical origins of long-range correlations.

## 1 Introduction

Strong collectivity observed in the azimuthal correlations of particles emitted over a wide pseudorapidity range, in high-energy nucleus-nucleus collisions at RHIC [1–4] and LHC [5–7], has indicated the formation of a strongly interacting quark gluon plasma (QGP) matter, which exhibits hydrodynamic behavior (see the reviews [8–10]). The recent efforts are nowadays focused on constraining the transport properties of the QGP in hydrodynamic models [11–13] along with few advanced experimental efforts [14–17]. In recent years similar long-range collective azimuthal correlations are also observed for small systems with high final-state particle multiplicity such as proton-proton (pp) [18–21] proton-nucleus (pA) [22–25], and lighter nucleus-nucleus systems [26, 27], revealing strong indications for collective flow with hydrodynamic characteristics even in small systems, though the volume and lifetime of the medium produced are expected to be small.

Measurements of two-particle angular correlations are typically performed in terms of two dimensional  $\Delta\eta - \Delta\phi$  correlation functions, where  $\eta$  is the pseudorapidity and  $\phi$  is the azimuthal angle. Long-range structure of two-particle correlation functions is of particular interest in studies of possible novel collective effects, where the effects of known sources such as resonance decays and fragmentation of high-momentum partons are known to be small. In most Monte Carlo (MC) event generators for proton-proton (pp) collisions, the typical sources of such long-range correlations are momentum conservation and away-side ( $\Delta\phi \approx \pi$ ) jet correlations. The enhancement in the associated yield of two-particle correlations at small relative azimuthal angle ( $\Delta\phi$ ) that extends over a long-range of relative pseudorapidity ( $\Delta\eta$ ), is dubbed “ridge” due to its shape in  $\Delta\eta - \Delta\phi$  plot. The shape of these  $\Delta\phi$  correlations can be studied via a Fourier decomposition [28, 29]. The second and third order terms are the dominant harmonic coefficients  $v_n$ . The  $v_n$  coefficients can be related to the collision geometry and density fluctuations of the colliding nuclei [30–32] and to the transport properties of the QGP in relativistic viscous hydrodynamic models [11–13, 33, 34].

The ridge structures in high-multiplicity pp and pPb events have been attributed to mechanisms that involve initial-state effects, such as gluon saturation [35, 36] and colour connections [37, 38] forming along the longitudinal direction and final-state effects, such as parton-induced interactions [39], and collective effects due to a hydrodynamic behaviour of the produced particles arising in a high-density system possibly formed in these collisions [40, 41]. Hybrid models which implement both effects are generally used in hydrodynamic simulations [42, 43]. The importance of the proton shape and its fluctuations to model the small system was recognized in [43]. The hydrodynamics itself might not be the only mechanism of the observed collectivity was acknowledged in [44]. The influence and interplay of initial state and final state effects are recently studied carefully for the first time in [45], pointing out that the details of the initial state are crucially important for the quantitative description of observables in small systems [46]. The attempts to describe the collective effects systematically from the small to large systems are being made both for experiments [21] and theory side [45]. However, a quantitative description of the full set of experimental data has not yet been achieved. The summary of various explanations for the observed correlations in these small systems are summarized in [47–49].

Furthermore, if collectivity in small systems is due to final state interactions, it should be possible to measure its effect on jets. Proving the presence of jet quenching will be another crucial milestone to demonstrate the existence of the final-state effect in high multiplicity pp collisions. The most of observables for the jet quenching in pp and pPb collisions didn’t show any clear evidences so far [50–53]. The difficulties are attributed to an ambiguous reference since the hard probes themselves are also enhanced by requiring high multiplicity in the event [51, 54].

The ATLAS experiment has recently shown that the ridge remains in events tagged with a Z-boson [55], possibly with an accompanying jet. The impact parameter dependence on di-jet or multi-jet production in pp collisions was studied in [56]. The microscopic model for collectivity, based on interacting string

implemented in the PYTHIA8 Monte Carlo event generator so called “shoving model” [57], can qualitatively reproduce the CMS near-side ridge yield [20] and ATLAS Z-tagged ridge. This challenges the hydrodynamic picture and predicts modifications to jet fragmentation properties [58].

To further investigate these effects, we studied long-range correlations as a function of transverse momentum in very high multiplicity pp collisions at  $\sqrt{s} = 13$  TeV, collected with the high multiplicity event trigger during 2016 and 2017 with ALICE. In this article, we present the near-side per-trigger yield at large pseudorapidity separation as a function of transverse momentum. The results are compared to previous measurements from CMS experiments. In addition, we present the ridge yield in events where harder fragmentation processes are present, to explore possible physical origins of long-range correlations. The experimental setup and measurements are described in Sec. 2. In Sec. ?? we present the analysis methods. The sources of systematic uncertainties are explained in Sec. 4. The results of the measurements are presented in Sec. 5. In Sec. 6 we present comparisons to model calculations. Finally, Sec. 7 summarizes our new results.

## 2 Experimental setup

Delivery of protons with world-highest energy by LHC at CERN makes it possible to generate various phenomena from their collisions. Recent center-of-mass energy of colliding two protons is increased up to  $\sqrt{s} = 13$  TeV during LHC Run2 period. Among data from proton-proton collisions at 13 TeV, This paper describes analysis results obtained by using 2016 to 2018 data sets. The full description of ALICE detector in the LHC Run 2 can be found in Refs. [59, 60]. The present analysis mainly uses V0 [61], ITS (Inner Tracking System) [62] and TPC (Time Projection Chamber) [63] detectors.

The V0 detector consists of two rings, V0-A and V0-C, each made of 32 scintillator tiles, covering the full azimuthal angle within  $2.8 < \eta < 5.1$  and  $-3.7 < \eta < -1.7$ , respectively. The V0 provides trigger and estimation of event multiplicity. A sample of events including higher numbers of produced particles is obtained with a high multiplicity trigger, which is achieved by requiring higher amplitude of V0 Detector.

The responsibility of reconstruction of charged track is up to the ITS and the TPC. The ITS is composed of three subsystems, Silicon Pixel Detector (SPD), Silicon Drift Detector (SDD) and Silicon Strip Detector (SSD). The ITS has an acceptance up to  $|\eta| < 1.95$  for single charged track reconstruction. The TPC, which is working inside solenoidal magnetic field of 0.5 T, has an acceptance up to  $|\eta| < 0.9$  for charged tracks reaching the outer radius of the TPC. The tracking of charged-particles is done with the combination of the ITS and the TPC, which enable the reconstruction of tracks down to 0.2 GeV/c with  $\sim 75\%$  efficiency.

The multiplicity class used in the present analysis is top 0-0.1%, which denotes the most particle-abundant events including  $\sim 31$  charged particles in the mid-rapidity region ( $|\eta| < 0.5$ ). This analysis uses charged particles, whose reconstructed transverse momenta are larger than 0.2 GeV/c in a fiducial region as  $|\eta| < 0.9$ .

## 3 Analysis Procedure

The two-particle correlation between trigger particle and associated particle is measured as function of relative pseudo rapidity ( $\Delta\eta$ ) and azimuthal angle ( $\Delta\phi$ ). The following equation expresses the correlation as associated yield per trigger particle as function of  $\Delta\eta$  and  $\Delta\phi$  with a given transverse momentum ( $p_{T,\text{trig}}$ ,  $p_{T,\text{assoc}}$ ) of trigger particle and associated particle with the notation of  $p_{T,\text{trig}} > p_{T,\text{assoc}}$ .

$$\frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{pair}}}{d\Delta\eta d\Delta\phi} = B(0,0) \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}, \quad (1)$$

where the  $N_{\text{trig}}$  is the number of trigger particles in the corresponding event class. The signal distribution  $S(\Delta\eta, \Delta\phi)$  is constructed using two-particle correlation in the same event and the background distribution  $B(\Delta\eta, \Delta\phi)$  is constructed using two-particle correlation in mixed 10 events having the same primary vertex and belonging to the same multiplicity class.

The quantitative study of ridge is done with  $\Delta\phi$  distribution at large  $\Delta\eta$  to achieve direct comparison of ridges between different event classes and transverse momentum intervals. The large  $\Delta\eta$  range is defined as  $1.6 < |\Delta\eta| < 1.8$ , which allows non-flow effects, mainly coming from the jet, not to contribute to the  $\Delta\phi$  distribution.

$$\frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta\phi} = \int_{|\Delta\eta| > 1.6} d\Delta\eta \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{pair}}}{d\Delta\eta d\Delta\phi} \quad (2)$$

The baseline of the correlations is subtracted by implementing Zero-Yield-At-Minimum (ZYAM) procedure. The minimum yield ( $C_{\text{ZYAM}}$ ) at the minimum  $\Delta\phi$  ( $\Delta\phi_{\text{min}}$ ) of the  $\Delta\phi$  distribution are obtained from the function, which fits the  $\Delta\phi$  distribution with Fourier series up to the third harmonic. Subtracting  $C_{\text{ZYAM}}$  from the  $\Delta\phi$  distribution makes the yield at  $\Delta\phi_{\text{min}}$  zero in order to take into consideration the major combinatorial correlations to be rejected. The associated yield of the ridge ( $Y^{\text{assoc}}$ ) is obtained by integrating the near-side peak of the  $\Delta\phi$  distribution over  $|\Delta\phi| < |\Delta\phi_{\text{min}}|$  after ZYAM.

$$Y^{\text{assoc}} = \int_{|\Delta\phi| < |\Delta\phi_{\text{min}}|} d\Delta\phi \frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta\phi} \quad (3)$$

The ridge yield is further studied with various event selections regarding hard processes. The event selection is applied by requiring minimum transverse momentum of leading track or jet reconstructed in the mid-rapidity, where the leading track is accepted within  $|\Delta\eta| < 0.9$  and reconstructed jet, which are made with anti- $k_T$  algorithm with cone radius as 0.4, is accepted within  $|\Delta\eta| < 0.4$ . The high  $p_T$  track and jet mostly generated from the hard scatterings in the initial collisions of hadrons so that tagging of events with transverse momentum of leading track or jet allows us to access to the high momentum transfer.

Monte Carlo simulation with PYTHIA8 event generator and with particle transport through the detector using GEANT simulation has been used to estimate the charged single particle efficiency and the contamination from the non-primary particle. The corrections have been tested by comparing the distributions, which are constructed with generated true particles and reconstructed particles with detector responses. The several percentage of non-closure has been considered into systematic uncertainty.

## 4 Systematic Uncertainty

The background distribution is constructed using several events having same primary vertex. The effect of construction of background distribution is estimated by varying the primary vertex interval from 2 cm to 1 cm. The estimated effect is 6-10%.

The  $\Delta\eta$  projection range for construction of long-range  $\Delta\phi$  is sensitive to contamination of non-flow effect. The effect of  $\Delta\eta$  projection range is estimated by varying the projection range. The estimated effect is 10-15% for  $p_T > 1.0$  GeV/c and 20% for  $0.5 < p_T < 1.0$  GeV/c.

The M.C. closure test for efficiency correction results in  $\sim 4\%$  discrepancy. The discrepancy is considered into systematic uncertainty.

The effect of primary vertex selection along the beam axis is estimated by varying the selection range of primary vertex from  $|z_{\text{vtx}}| < 8$  cm to  $|z_{\text{vtx}}| < 6$  cm. The estimated effect is  $\sim 4\%$ . The effect of rejection of pile-up events. is estimated by varying the methodology of pile-up rejection. The estimated effect is  $\sim 4\%$ . The effect of track selection is estimated by varying a few selection criteria included in track selection. The estimated effect is  $\sim 5\%$ .

**Table 1:** Summary of the systematic uncertainties. See text for details.

Source	Uncertainty
Event mixing	6-10%
$\Delta\eta$ projection range	10-15%
M.C. closure	4%
Primary vertex	4%
Pileup Cut	4%
Track selection	5%
Total	14-20%

## 5 Results

The two-dimensional associated yield per trigger particle is shown in Figure 1 for pairs of trigger particle and associated particle with  $1.0 < p_{T,\text{assoc}} < p_{T,\text{trig}} < 2.0$  GeV/c in pp collisions at  $\sqrt{s} = 13$  TeV in the 0-0.1% (left), 5-20% (middle) and 20-100% (right) multiplicity class estimated by V0 detector, which covers forward rapidity region. The ridge is clearly seen in high multiplicity class unlike in lower multiplicity classes.

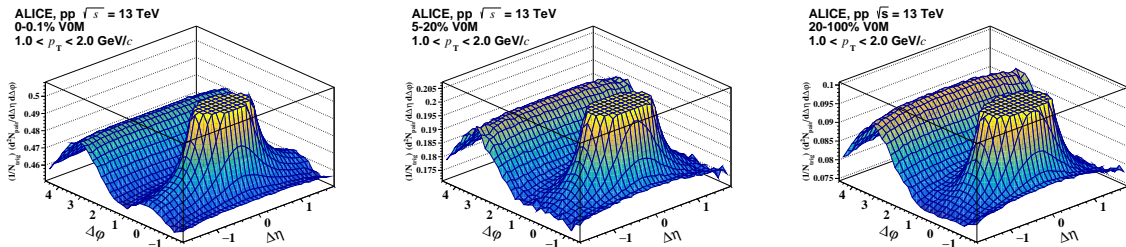
The one-dimensional  $\Delta\phi$  distribution is shown in Figure 2 for pairs of particles with various  $p_T$  intervals in very high multiplicity class. The associated yield per trigger particle is compared with CMS results. The near-side peak is highest in the  $1.0 < p_T < 2.0$  interval and gradually decreases with increasing  $p_T$ .

The spectra of the ridge yield is shown in Figure 3 in very high multiplicity class and compared with CMS results. The estimator of particle multiplicity of ALICE is done with forward subsystem(V0), whereas that of CMS is done by mid-rapidity particles meeting with the condition of  $|\eta| < 2.4$  and  $p_T > 0.4$  GeV/c. Dedicated comparison is conducted and the difference of particle multiplicity is estimated to be about 20%. Taking into account the difference in acceptance of charged tracks and comparable definition of multiplicity,, the measurements are can be considered comparable with each other.

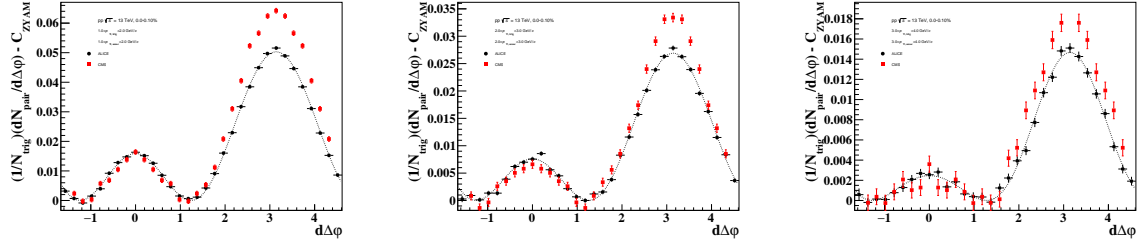
To further understand the behavior of the ridge in events including hard processes, the two-dimensional associated yield per trigger particle is measured with the leading track selection as shown in Figure 4. The ridge is still visible in the events where  $p_T^{\text{Lead}} > 7$  GeV/c, which means that the ridge co-exists with hard-scattering in pp collisions.

The one-dimensional  $\Delta\phi$  distribution with the leading track selection is shown in Figure 5. The near-side yield doesn't change with respect to the leading track requirements within the uncertainties, whereas the away-side peak increases as the leading track requirement gets stronger, presumably because of the increase of the recoil jet yield.

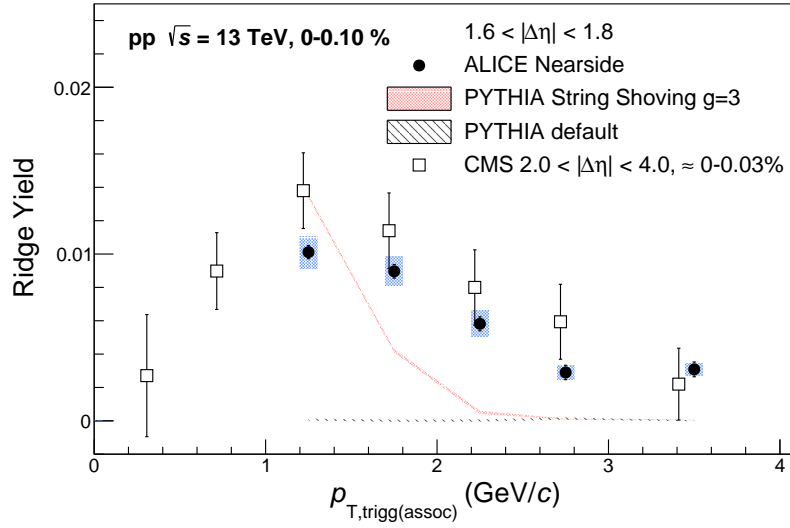
The ridge yield is inspected as a function of the leading track selection in Figure 6. As seen in the



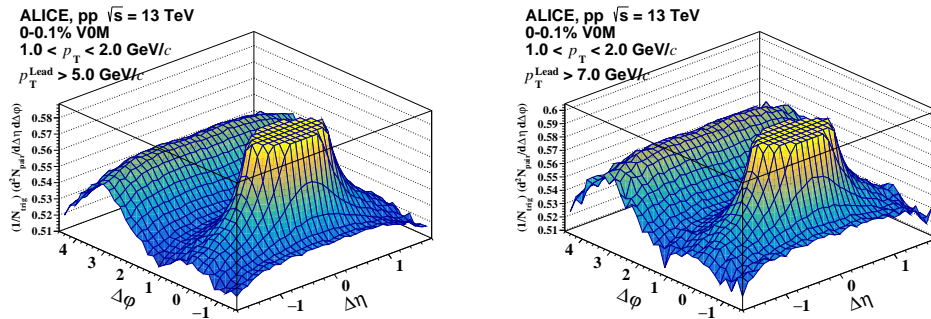
**Fig. 1:** Two-dimensional associated yield per trigger particle as function of  $\Delta\eta$  and  $\Delta\phi$  in 0-0.1% (left), 5-20% (middle) and 20-100% (right) multiplicity class. The interval of transverse momentum of trigger particle and associated particle is  $1.0 < p_T < 2.0$  GeV/c.



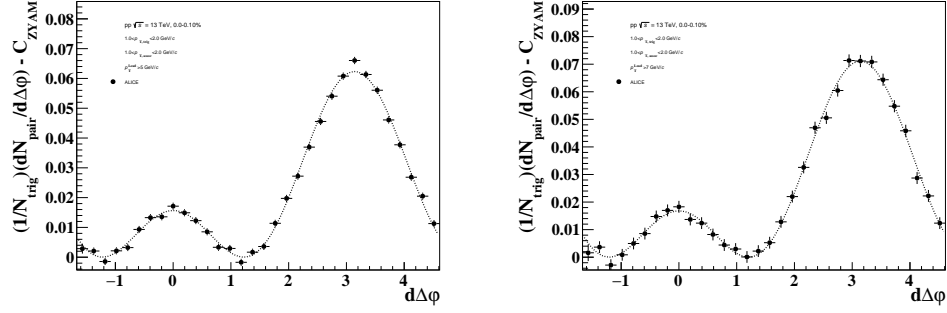
**Fig. 2:** One-dimensional  $\Delta\phi$  distribution in the large  $\Delta\eta$  with various transverse momentum intervals. Interval of transverse momentum of trigger particle and associated particle is  $1.0 < p_T < 2.0$  GeV/c (left),  $2.0 < p_T < 3.0$  GeV/c (middle) and  $3.0 < p_T < 4.0$  GeV/c (right), respectively.



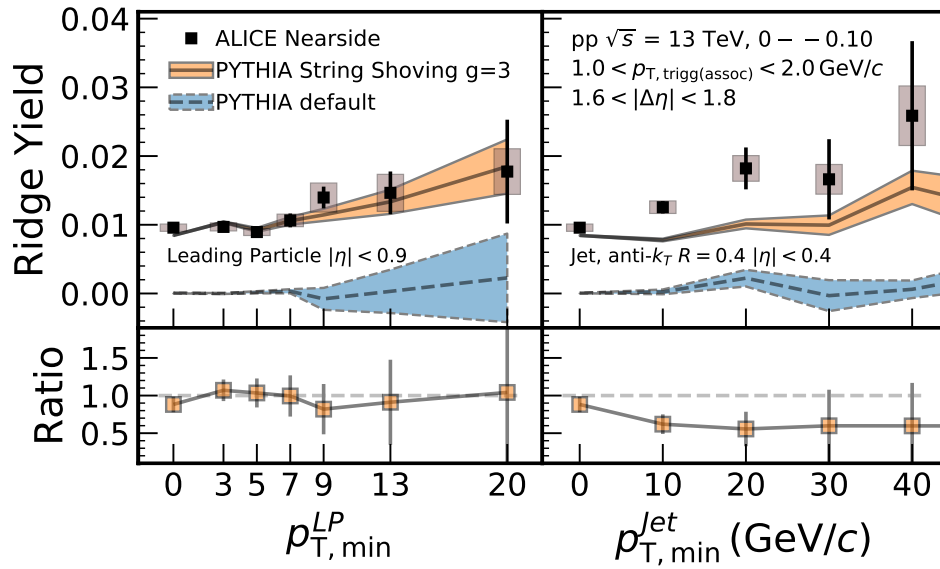
**Fig. 3:** (color online) The spectra of ridge yield as function of transverse momentum. The spectrum is compared with CMS result [? ].



**Fig. 4:** Two-dimensional associated yield per trigger particle as function of  $\Delta\eta$  and  $\Delta\phi$  in top 0-0.1% multiplicity class. The interval of transverse momentum of trigger particle and associated particle is  $1.0 < p_T < 2.0$  GeV/c for the plots. Threshold for leading track selection is 5 GeV/c (left) and 7 GeV/c (right), respectively.



**Fig. 5:** One-dimensional  $\Delta\phi$  distribution in the large  $\Delta\eta$  with various leading track selection thresholds. Interval of transverse momentum of trigger particle and associated particle is  $1.0 < p_T < 2.0$  GeV/c. Threshold for leading track selection is 5 GeV/c (left) and 7 GeV/c (right) respectively.



**Fig. 6:** The ridge yield spectrum with respect to the leading particle and jet selections. The ridge yields are identical within uncertainties.

previous plots, the ridge yield does not depend on the selection, which indicates that the ridge is not affected significantly by the hardness of the events.

## 6 Model Comparison

## 7 Conclusions

Two-particle angular correlations in large  $|\Delta\eta|$  has been measured in very high multiplicity events in pp collisions at  $\sqrt{s} = 13$  TeV with ALICE. The measured associated yield is found to be consistent with the previous results from CMS experiment. The ridge yield, for the first time, has been observed in events including hard processes. Furthermore, it is found to be independent of the hardness of the events. This observation is important for the study of the origins of the ridge in small collision systems.



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