Energy independent scaling of the ridge and final state description of high multiplicity $p + p$ collisions at $\sqrt{s} = 7$ and 13 TeV

Debojit Sarkar*

Variable Energy Cyclotron Centre, HBNI, 1/AF-Bidhannagar, Kolkata 700064, India
and Laboratori Nazionali di Frascati, INFN, Frascati 00044, Italy

(Received 28 July 2017; published 28 February 2018)

An energy independent scaling of the near-side ridge yield at a given multiplicity has been observed by the ATLAS and the CMS collaborations in $p + p$ collisions at $\sqrt{s} = 7$ and 13 TeV. Such a striking feature of the data can be successfully explained by approaches based on initial state momentum space correlation generated due to gluon saturation. In this paper, we try to examine if such a scaling is also an inherent feature of the approaches that employ strong final state interaction in $p + p$ collisions. We find that hydrodynamical modeling of $p + p$ collisions using EPOS 3 shows a violation of such scaling. The current study can, therefore, provide important new insights on the origin of long-range azimuthal correlations in high multiplicity $p + p$ collisions at the LHC energies.

DOI: 10.1103/PhysRevD.97.034036

I. INTRODUCTION

The long-range ridgelike structure of the azimuthal correlations as observed in the high multiplicity $p + p$ [1,2] and $p + A$ collisions [3,4] at the LHC energies shows striking similarity with similar measurements in heavy ion collisions. In heavy ion collisions [5–8] such long-range correlations are attributed to hydrodynamical response of a strongly interacting system to the initial spatial anisotropy. However, the origin of such correlations in small collision systems is debated to be either driven by hydrodynamic response of initial state geometry [9–13] or due to intrinsic momentum space correlations among the initially produced patrons [14–17]. Assuming the applicability of hydrodynamics [18–21] one can explain several experimental observations in high multiplicity $p + p$ and $p + \text{Pb}$ collisions at LHC energies [9–11,13]. For example, simulations based on EPOS 3 which includes event by event 3 + 1 D hydrodynamic evolution can provide a good explanation of the energy dependence of $dN_{ch}/d\eta$ in $p + p$ collisions [12], ridge [10,11], mass ordering of the elliptic flow coefficients (v_2) of identified particles [11], hardening of spectra with multiplicity and the trend of baryon to meson enhancement at the intermediate transverse momentum (p_T) in $p + p$ and $p + \text{Pb}$ collisions at the LHC energies [13,22–25]. Also, the hydrodynamical approach implemented inside

EPOS 3 can consistently explain the multiplicity dependence of v_2 in heavy ion collisions as well as in small collision systems [26,27]—providing a unified description of the reaction dynamics for different collision systems at the LHC energies [26]. Alternative approaches based on purely initial state models and percolation of strings along with quenching of the partons can also explain several qualitative and quantitative features of the ridgelike correlations over a wide range of systems and energies [28–38]. Models such as CGC+PYTHIA [15] have demonstrated that initial state correlations in momentum space generated as a consequence of gluon saturation can survive fragmentation and explain the mass ordering of flow harmonics, mean transverse momentum ($\langle p_T \rangle$) in high multiplicity $p + p$ collisions at the LHC energy.

By far, no experimental observable has been able to convincingly discriminate the two scenarios. Therefore, the debate, on whether collective behaviors observed in high multiplicity $p + p$ collisions are purely initial state effects driven by gluon saturation [15] or a hydrodynamic response to initial geometry [9,10], is still on. In this work we study one particular aspect of the ridgelike correlations that might shed some light into such debate and elucidate the origin of long-range correlations in small collision systems.

The ATLAS and the CMS collaborations have demonstrated an interesting energy independent scaling of the near-side ridgelike correlations when plotted against the produced charged particle multiplicity in $p + p$ collisions at $\sqrt{s} = 7$ and 13 TeV [39,40]. In other words, the strength of the near-side ridge depends only on the produced multiplicity and not on collision energy. This scaling has been shown to be a natural consequence of the multiparticle

*debojit03564@gmail.com

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](#). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

production in the regime of gluon saturation [16]. In a CGC based calculation, in high energy $p + p$ collisions, the saturation scale determines both the multiplicity and the near-side correlated ridge yield and also their energy dependence [16]. Therefore, fixing the multiplicity also fixes the ridge yield and one obtains a universal scaling curve between ridge yield and multiplicity at different energies as shown in Ref. [16]. By far, such scaling has not been explored using an approach that employs strong final state interaction. In this paper, we therefore explore such scaling using the hydrodynamical framework as implemented in EPOS 3. Any indication of a possible violation in the energy independent scaling of ridge yield in EPOS 3 will provide important insight about the origin of the ridgelike structure in high multiplicity $p + p$ collisions.

The goal of this work is to qualitatively investigate the experimentally observed energy independent scaling of ridge yield in the hydrodynamical framework rather than quantitatively explain the data. The paper is organized as follows. In the next section, we give a brief description of the EPOS 3 event generator. The construction of the correlation function and the method of extraction of the ridge yield are discussed in Sec. III. The discussions on the results and a summary are provided in the final section.

II. EPOS 3 MODEL

The EPOS 3 model includes a $3 + 1$ D hydrodynamical simulation with flux tube initial conditions [10,13,41–44]. For a detailed description of EPOS 3 we refer the reader to Refs. [10,11,13,45]. The initial state dynamics used in this model is based on “Parton based Gribov Regge Theory” [45]. After multiple initial state scatterings, a partonic system is produced that consists of longitudinal color flux tubes or strings (known as “pomeron”) [10] of small transverse size (radius ≈ 0.2 fm) which are extended up to many units of space-time rapidity η_s . The multiplicity of an event is proportional to the number of initially produced pomerons (flux tubes/strings). They carry transverse momentum of the hard scattered partons in the transverse direction. Depending on the energy of the string segments and local string density, the high density area forms a “core” and the low density area form a “corona” region [42]. In a typical low-multiplicity $p + p$ collisions, one expects the formation of a corona dominated system in which the hadrons are produced via string fragmentation (Schwinger mechanism) [11,41]. But, in high multiplicity $p + p$ collisions, due to the large number of initial parton-parton scatterings, the string density becomes high enough that the strings cannot decay independently [10]. Instead, one switches to a final state description in which the energy density and the flow velocity are estimated from the four-momenta of the infinitesimal string segments and used as the initial condition for the final hydrodynamic evolution [10]. In EPOS 3, only the core region (dominant in high multiplicity events) undergoes hydrodynamic evolution

[11] and finally hadrons are produced from such a region via Cooper-Frye prescription.

The ridgelike structure in the high multiplicity $p + p$ collisions in EPOS 3 is generated in the following way. After multiple parton-parton scatterings in the initial state, the transverse positions (spatial) of the flux tubes are generated randomly and overlapping of these flux tubes generates the high density core region. The fluctuations in the transverse positions of the overlapping flux tubes may lead to an eccentric (dominantly elliptic) shape of the core region and the hydrodynamic response to such eccentricity eventually leads to a $\cos(2\Delta\phi)$ modulation in the azimuthal correlation function [11]. The longitudinal invariance of the initial state of EPOS 3 is responsible for the long-range ridgelike structure of such an azimuthal correlation. EPOS 3 also generates dijet correlations through the corona region. The strings in the corona hadronize by Schwinger’s mechanism and constitute the jet part of the produced system. This model has successfully explained several qualitative and quantitative features of the ridgelike structures observed in high multiplicity $p + p$ [10] and $p + \text{Pb}$ [11] collisions at the LHC energies. In this paper, we will use EPOS 3 to study the two particle correlation and investigate the experimentally observed energy independent scaling of ridge yields [16,39,40] in $p + p$ collisions at $\sqrt{s} = 7$ and 13 TeV.

III. ANALYSIS METHOD

In the present analysis, the correlation function is obtained among two sets of particles classified as *trigger* and *associated*. The p_T range of trigger and associated particles is $0.5 < p_T < 4.0$ GeV/c and the correlation function has been constructed with a p_T ordering ($p_T^{\text{Assoc}} < p_T^{\text{Trigger}}$). The pseudorapidity of the particles is restricted within $-2.4 < \eta < 2.4$ and the reason for such a choice is motivated by the CMS acceptance [39]. A two-dimensional (2D) correlation function is obtained as a function of relative azimuthal angle $\Delta\phi = \phi_{\text{trigger}} - \phi_{\text{associated}}$ and relative pseudorapidity $\Delta\eta = \eta_{\text{trigger}} - \eta_{\text{associated}}$. The same event correlation function is defined as $\frac{dN_{\text{same}}}{N_{\text{trigger}} d\Delta\eta d\Delta\phi}$, where N_{same} is the number of particles associated to triggers particles (N_{trigger}) that are taken from the same event. To correct for pair acceptance the same event correlation function is divided by the mixed event correlation function $\alpha \frac{dN_{\text{mixed}}}{d\Delta\eta d\Delta\phi}$. The mixed event correlation function is constructed by correlating the trigger particles in one event with the associated particles from other events within the same multiplicity class. The factor α is used to normalize the mixed event to make it unity for pairs where both particles go into approximately the same direction ($|\Delta\eta| \approx 0$, $|\Delta\phi| \approx 0$) [43,44].

In this analysis, the correlation functions are constructed in six multiplicity classes defined by the number of particles (N_{ch}) produced within $|\eta| < 2.4$ and

FIG. 1. Two particle $\Delta\eta - \Delta\phi$ correlation function as obtained from EPOS 3 in $p + p$ collisions for $N_{ch} > 120$ at (a) $\sqrt{s} = 7$ TeV and (b) $\sqrt{s} = 13$ TeV.

FIG. 2. The comparison of the ZYAM subtracted $\Delta\phi$ projection of the long-range ($2.0 < |\Delta\eta| < 4.0$) near-side ($|\Delta\phi| < \pi/2$) correlation function in $p + p$ collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 13$ TeV.

$p_T > 0.4$ GeV/c [39]. The 2D correlation functions with ($N_{ch} > 120$) in pp collisions at 7 and 13 TeV are shown in Fig. 1. The particles from jet fragmentation are expected to be confined in a small angular region ($|\Delta\eta| \approx 0$, $|\Delta\phi| \approx 0$), so the ridge is estimated from the $\Delta\phi$ projection over the range ($2.0 < |\Delta\eta| < 4.0$). The pedestal is determined from the $\Delta\phi$ projection with the zero yield at minimum (ZYAM) assumption [44,46] and subtracted from the correlation function. The ZYAM subtracted $\Delta\phi$ projection of the near-side ($|\Delta\phi| < \pi/2$) ridge estimated from the $2.0 < |\Delta\eta| < 4.0$ is shown in Fig. 2. The near-side ridge yield is estimated by integrating the $\Delta\phi$ projection in the range $|\Delta\phi| < \pi/2$ [44].

IV. RESULTS AND DISCUSSION

Aforementioned, in current work we restrict ourselves to only qualitative comparisons of the dihadron correlations with the experimental data [39,40]. In Fig. 1 the 2D $\Delta\eta - \Delta\phi$ correlation functions estimated from EPOS 3 in the highest multiplicity class ($N_{ch} > 120$) of $p + p$ collisions at $\sqrt{s} = 7$ and 13 TeV are shown. The long-range ridge structure along with the jet peak is observed in both cases similar to the experimental data. For the purpose of this work, we concentrate only on the long range ($2.0 < |\Delta\eta| < 4.0$) of the near-side ($|\Delta\phi| < \pi/2$) ridge component of the correlation function and therefore make a $\Delta\phi$ projection over the range $2.0 < |\Delta\eta| < 4.0$ as shown in Fig. 2. The strength of the ridge in $p + p$ collisions at 13 TeV is found to be stronger compared to that of $p + p$ collisions at 7 TeV. So, Fig. 2 indicates that at a fixed multiplicity, the anisotropy in the azimuthal distribution of particles is higher at higher collision energies.

In order to better demonstrate this effect, we integrate the ZYAM subtracted long-range ($2.0 < |\Delta\eta| < 4.0$) correlation function over the range ($|\Delta\phi| < \pi/2$) to extract the near-side ridge yield for different multiplicity bins. Figure 3 shows the multiplicity evolution of the near-side ridge yield in EPOS 3 for $p + p$ collisions at both energies for $0.5 < (p_{T,Trig}, p_{T,Assoc}) < 4.0$ GeV/c. At lower multiplicities ($N_{ch} < 85$), the ridge yield is found to be approximately energy independent. However, at higher multiplicities, a strong energy dependence of the ridge yield is observed as highlighted in Fig. 4. The ridge yield in $p + p$ collisions at 13 TeV is found to be consistently higher compared to the $p + p$ collisions at 7 TeV for $N_{ch} > 85$. In other words, we do not see any energy independent scaling of ridge yield with multiplicity in EPOS 3 as observed by the ATLAS and the CMS collaborations [39,40]. Such scaling has been observed to hold in the LHC data even for multiplicity classes that correspond to 10 times the mean multiplicity [39,40]. A possible reason for this scaling violation in higher multiplicity classes ($N_{ch} > 85$) of EPOS 3 can be understood as follows. At higher multiplicity classes, the core which originates due to the overlapping of the flux tubes constitutes the dominant part of the system [44,47]. It is

FIG. 3. Multiplicity dependence of the near-side ($|\Delta\phi| < \pi/2$) ridge ($2.0 < |\Delta\eta| < 4.0$) yield (ZYAM subtracted) as estimated from EPOS 3 in $p + p$ collisions at $\sqrt{s} = 7 \text{ TeV}$ and $\sqrt{s} = 13 \text{ TeV}$.

therefore expected that the final state effects possibly lead to the observed scaling violation. As discussed previously, in EPOS 3, the anisotropy in the azimuthal distribution of the final state particles originates from the hydrodynamic response to the initial anisotropy (eccentricity) of the transverse energy density profile of the core region [10]. Such eccentricity is generated from the statistical fluctuations in the transverse positions of the initially produced flux tubes, an approach similar to the one discussed in [48]. The produced multiplicity of the final state particles, on the other hand, does not depend on the details of such fluctuations. Therefore, nothing prevents the initial eccentricity and final multiplicity to have different energy dependence. One, therefore, does not expect the strength of ridge, driven by initial eccentricity, to be independent of energy at a fixed multiplicity.

Now, the scaling violation appears to be prominent only in the core dominated higher multiplicity classes. In EPOS 3, the multiplicity (or the energy) per individual flux tube increases with $\sqrt{s}$. Due to higher initial energy density at higher collision energies, a smaller overlapping region (core) can contribute to the same multiplicity originating from a larger overlap region in lower energy collisions. The initial transverse energy density is expected to be more anisotropic in the case of less overlap between the flux tubes compared to the case where overlap is more [49]. As a result, at a fixed multiplicity, higher eccentricity, i.e. a stronger ridge is expected in higher collision energies compared to the lower collision energy case.

In summary, the observation of long-range ridgelike correlations in $p + p$ collisions has been a topic of great interest in recent times. Several features of the ridgelike correlations have been both qualitatively and quantitatively

FIG. 4. Multiplicity dependence of the near-side ($|\Delta\phi| < \pi/2$) ridge ($2.0 < |\Delta\eta| < 4.0$) yield (ZYAM subtracted) as estimated from EPOS 3 in high multiplicity ($N_{ch} > 85$) $p + p$ collisions at $\sqrt{s} = 7 \text{ TeV}$ and $\sqrt{s} = 13 \text{ TeV}$.

explained by approaches that are based on both initial state effects due to gluon saturation and final state effects like hydrodynamic evolution in the presence initial spatial anisotropy. In this work, we investigate a very specific experimental observation which indicates that the strength of the near-side ridge yield follows an energy independent scaling when plotted against the multiplicity of produced particles in $p + p$ collisions at the LHC energies [39,40]. Such energy independent scaling of ridge yield at the LHC has been explained from an approach based on gluon saturation in which the multiparticle production is determined from a single saturation scale [16,39,40]. In this work we demonstrate that the approaches based on strong final state effects do not show such scaling. We argue that such violation of energy independent scaling constrains the interpretations of long-range correlation in high multiplicity $p + p$ collisions based on final state effects at the LHC energies. More specifically, to observe an energy independent scaling of the ridge with multiplicity in final state approach, one needs to incorporate additional constraints such as energy independent scaling of initial eccentricity with produced multiplicity.

ACKNOWLEDGMENTS

I acknowledge fruitful discussions and suggestions from Prithwish Tribedy on this manuscript. I also thank Subhasis Chattopadhyay for his help and support throughout this work. I thank Klaus Werner for allowing me to use EPOS 3 for this study. Thanks to the VECC grid computing team for their constant effort to keep the facility running and helping in EPOS data generation and data analysis.

- [1] CMS Collaboration, *Phys. Lett. B* **718**, 795 (2013).
- [2] CMS Collaboration, *Phys. Lett. B* **765**, 193 (2017).
- [3] B. Abelev *et al.* (ALICE Collaboration), *Phys. Lett. B* **719**, 29 (2013).
- [4] B. Abelev *et al.* (ALICE Collaboration), *Phys. Lett. B* **726**, 164 (2013).
- [5] R. Bala, I. Bautista, J. Bielcikova, and A. Ortiz, *Int. J. Mod. Phys. E* **25**, 1642006 (2016).
- [6] B. Abelev *et al.* (ALICE Collaboration), *Phys. Rev. Lett.* **736**, 196 (2014).
- [7] S. S. Adler *et al.* (PHENIX Collaboration), *Phys. Rev. C* **69**, 034909 (2004).
- [8] B. Abelev *et al.* (ALICE Collaboration), *Phys. Lett. B* **736**, 196 (2014).
- [9] P. Bozek, W. Broniowski, and G. Torrieri, *Phys. Rev. Lett.* **111**, 172303 (2013).
- [10] K. Werner, Iu. Karpenko, and T. Pierog, *Phys. Rev. Lett.* **106**, 122004 (2011).
- [11] K. Werner, M. Bleicher, B. Guiot, Iu. Karpenko, and T. Pierog, *Phys. Rev. Lett.* **112**, 232301 (2014).
- [12] W. Lukas *et al.* (ATLAS Collaboration), Report No. ATL-PHYS-PROC-2016-086.
- [13] K. Werner, B. Guiot, Iu. Karpenko, and T. Pierog, *Phys. Rev. C* **89**, 064903 (2014).
- [14] K. Dusling and R. Venugopalan, *Phys. Rev. D* **87**, 094034 (2013).
- [15] B. Schenke, S. Schlichting, P. Tribedy, and R. Venugopalan, *Phys. Rev. Lett.* **117**, 162301 (2016).
- [16] K. Dusling, P. Tribedy, and R. Venugopalan, *Phys. Rev. D* **93**, 014034 (2016).
- [17] A. H. Rezaeian, *Phys. Lett. B* **727**, 218 (2013).
- [18] E. Shuryak and I. Zahed, *Phys. Rev. C* **88**, 044915 (2013).
- [19] P. Ghosh, S. Muhuri, J. K. Nayak, and R. Varma, *J. Phys. G* **41**, 035106 (2014).
- [20] S. K. Prasad, V. Roy, S. Chattopadhyay, and A. K. Chaudhuri, *Phys. Rev. C* **82**, 024909 (2010).
- [21] D. d'Enterria, G. Kh. Eyyubova, V. L. Korotkikh, I. P. Lokhtin, S. V. Petrushanko, L. I. Sarycheva, and A. M. Snigirev, *Eur. Phys. J. C* **66**, 173 (2010).
- [22] B. Abelev *et al.* (ALICE Collaboration), *Phys. Lett. B* **760**, 720 (2016).
- [23] B. Abelev *et al.* (ALICE Collaboration), *Phys. Lett. B* **728**, 25 (2014).
- [24] R. D. De Souza *et al.* (ALICE Collaboration), Identified particle production in pp collisions at 7 and 13 TeV measured with ALICE, <https://indico.cern.ch/event/403913/contributions/2142003/>.
- [25] B. Abelev *et al.* (ALICE Collaboration), *Phys. Lett. B* **727**, 371 (2013).
- [26] K. Werner, *J. Phys. Conf. Ser.* **636**, 012006 (2015).
- [27] K. Werner, B. Guiot, Iu. Karpenko, M. Bleicher, T. Pierog, and S. Porteboeuf-Houssais, *J. Phys. Conf. Ser.* **422**, 012001 (2013).
- [28] J. P. Blaizot, F. Gelis, and R. Venugopalan, *Nucl. Phys.* **A743**, 13 (2004).
- [29] A. Krasnitz and R. Venugopalan, *Nucl. Phys.* **B557**, 237 (1999).
- [30] A. Dumitru, K. Dusling, F. Gelis, J. Jalilian-Marian, T. Lappi, and R. Venugopalan, *Phys. Lett. B* **697**, 21 (2011).
- [31] K. Dusling and R. Venugopalan, *Phys. Rev. Lett.* **108**, 262001 (2012).
- [32] K. Dusling and R. Venugopalan, *Phys. Rev. D* **87**, 094034 (2013).
- [33] A. Dumitru, L. McLerran, and V. Skokov, *Phys. Lett. B* **743**, 134 (2015).
- [34] B. Schenke, S. Schlichting, and R. Venugopalan, *Phys. Lett. B* **747**, 76 (2015).
- [35] T. Lappi, B. Schenke, S. Schlichting, and R. Venugopalan, *J. High Energy Phys.* **01** (2016) 061.
- [36] K. Dusling, M. Mace, and R. Venugopalan, *Phys. Rev. Lett.* **120**, 042002 (2018).
- [37] S. Schlichting and P. Tribedy, *Adv. High Energy Phys.* **2016**, 1 (2016).
- [38] C. Andrés, A. Moscoso, and C. Pajares, *Phys. Rev. C* **90**, 054902 (2014).
- [39] CMS Collaboration, *Phys. Rev. Lett.* **116**, 172302 (2016).
- [40] ATLAS Collaboration, Report No. ATLAS-CONF-2015-027, 2015.
- [41] K. Werner, Iu. Karpenko, T. Pierog, M. Bleicher, and K. Mikhailov, *Phys. Rev. C* **82**, 044904 (2010).
- [42] K. Werner, *Phys. Rev. Lett.* **98**, 152301 (2007).
- [43] D. Sarkar, S. Choudhury, and S. Chattopadhyay, *Phys. Lett. B* **760**, 763 (2016).
- [44] D. Sarkar and S. Chattopadhyay, *Phys. Rev. C* **95**, 044906 (2017).
- [45] H. J. Drescher, M. Hladik, S. Ostapchenko, T. Pierog, and K. Werner, *Phys. Rep.* **350**, 93 (2001).
- [46] K. Aamodt *et al.* (ALICE Collaboration), *Phys. Rev. Lett.* **108**, 092301 (2012).
- [47] A. Ortiz, G. Bencedi, and H. Bello, *J. Phys. G* **44**, 065001 (2017).
- [48] J. Casalderrey-Solana and U. A. Wiedemann, *Phys. Rev. Lett.* **104**, 102301 (2010).
- [49] P. Bozek, *Acta Phys. Pol. B* **41**, 837 (2010).