Ridge Formation Induced by Jets in pp Collisions at 7 TeV

Rudolph C. Hwa[1] and C. B. Yang[1,2]
[1] *Institute of Theoretical Science and Department of Physics University of Oregon, Eugene, OR 97403-5203, USA*
[2] *Institute of Particle Physics, Hua-Zhong Normal University, Wuhan 430079, P. R. China*

(Dated: November 4, 2010)

An interpretation of the ridge phenomenon found in pp collisions at 7 TeV is given in terms of enhancement of soft partons due to energy loss of semihard jets. A description of ridge formation in nuclear collisions can directly be extended to pp collisions, since hydrodynamics is not used, and azimuthal anisotropy is generated by semihard scattering. Both the p_T and multiplicity dependencies are well reproduced. Some suggestions are made about other observables.

PACS numbers: 13.85.Ni, 25.75.Gz

The observation of ridge structure in two-particle correlation in pp collisions at 7 TeV by the CMS Collaboration at LHC [1] has opened up the question of whether it has a similar origin as that already found at RHIC in Au-Au collisions at 0.2 TeV [2–6]. A great deal is known about the ridge in heavy-ion collisions, since various experiments have studied two-particle (with or without trigger) and three-particle correlations. The dominant theme is that the ridge exhibits the effect of high or intermediate-p_T jets on a dense medium. If the phenomenon seen at LHC reveals similar features upon further investigation, it would imply that soft partons of high density can be created in pp collisions and can affect the passage of hard partons through them. If not, a new mechanism needs to be found. Various theoretical speculations have been advanced with varying degrees of attention to the specifics of the CMS data [7–10]. In this article we propose a model that is an extension of our past interpretation of the ridge phenomena in the RHIC data, but is particularly suitable for pp collisions at LHC, since the dynamical origin is jet production rather than hydrodynamics. We have a simple formula that can reproduce the CMS data quantitatively with the use of two parameters that can clearly describe the physics involved.

The most direct approach to the study of ridges is to consider only events selected by triggers with $p_T^{\rm trig}$ in an intermediate p_T range, as first reported by Putschke [3, 11]. The dependence of the ridge yield on centrality in nuclear collisions indicates that the ridge is formed when there is a jet in a dense medium. Having an exponential behavior in $p_T^{\rm assoc}$ at values less than $p_T^{\rm trig}$ suggests that the ridge particles are related to the soft partons, but they have an inverse slope larger than that of the inclusive distribution, implying an enhancement effect of the jet [3, 12]. If triggers are not used as in autocorrelation, minijets are seen and ridges are also observed at $|\Delta\eta| > 1$ in central collisions [2, 6]. For pp collisions at LHC we cannot presume the existence of a dense medium of partons, which is a possibility we leave open. However, we can and shall assume that ridge formation is due to high- or intermediate-p_T jets, whether or not the jets are detected by triggers. Thus if an event has no hard or semihard scattering, there is no ridge in the two-particle correlation, by assumption. Our goal is to study the properties of correlation between soft particles generated by semihard jets. It should be noted that there are models in which the ridge phenomenon can occur without jets, such as in Refs. [8, 10, 13–15].

At RHIC dihadron correlations in the azimuthal angles at midrapidity have been studied in detail; in particular, the dependence on the trigger angle relative to the reaction plane reveals features that are important about ridge formation [16–18]. Any model on the origin of ridges at $|\Delta\eta| > 1$ should contain properties that are consistent with the azimuthal behavior at $|\Delta\eta| < 1$. The latter is described in a model (CEM) in which a Gaussian width ($\sigma \sim 0.34$) limits the extent of the angular correlation between the trigger and local flow direction [19]. The implication is that in triggered events the ridge particles are formed from soft partons that are transversely correlated to the semihard partons even after the jet component is subtracted out. Such a correlation between soft and semihard partons can be the source of azimuthal anisotropy in single-particle inclusive distribution without triggers [20]. This soft-semihard correlation in the transverse plane at midrapidity can be extended to $|\Delta\eta| > 1$, and will form the core idea in our model to describe the CMS data.

It is important to distinguish the jet and ridge components among the hadrons associated with a semihard or hard parton that generates a trigger particle. The jet component reveals the effect of the medium on the hadronization of the semihard parton (**TS** component in the recombination model [21]), while the ridge component manifests the effect of the semihard parton on the hadronization of the medium (**TT** recombination). The soft partons in the medium are referred to as thermal (**T**) partons in heavy-ion collisions. The inverse slope of the exponential dependence on the transverse momentum k_T is changed from T to T' due to the enhancement of the thermal motion of the soft partons caused by the energy loss of the semihard parton that passes through the medium in the vicinity [12, 20]. That is what we mean by soft-semihard correlation, even in pp collisions where the notion of thermal partons may be questionable. It is known empirically that there exists an exponential peak at small p_T at LHC [22–24]; that is sufficient for us to refer to the underlying partons as soft, the recombination of which gives the low-p_T hadrons.

An issue to discuss is about longitudinal correlation, which has been the concern of most theoretical studies. At $|\eta| < 2.4$ and $p_T < 4$ GeV/c, the hadron p_L is less than 22 GeV/c, so Feynman x_F is $< 6.3\times10^{-3}$ at $\sqrt{s} = 7$ TeV, and the corresponding partons that recombine have even lower x values. Those are soft wee partons deep in the sea, whose correlations can be strongly influenced by fluctuations. We shall assume that there is no dynamical longitudinal correlation among partons in the $|\eta| < 2.4$ region, although indirect correlation can exist up to the observed $|\Delta\eta| < 4.8$ due to transverse correlation induced by jets. The absence of direct longitudinal correlation has been considered before in the study of triggered ridge and found to be successful in reproducing the correlation in $\Delta\eta$ observed by PHOBOS at RHIC [4, 25].

Having given the introductory remarks above, we can now be more specific in what we mean by transverse correlation. Suppose that a semihard scattering occurs in a pp collision at 7 TeV and sends a parton to the $\eta \approx 0$ region with a parton momentum k_T in the 5-10 GeV/c range, which we shall regard as intermediate at LHC. Whatever the medium effect on it may be, it can lead to a cluster of hadrons with limited range in η and ϕ [1]. It cannot directly cause the production of an associated particle at $\eta = 2.4$ since the p_L of that particle can exceed 20 GeV/c, hence forbidden by energy conservation. Any particle produced outside the jet peak carries longitudinal momentum that is driven by the initial partons (right- or left-movers) of the incident protons. In the conventional parton model it is assumed that there are no significant longitudinal constraints on those initial partons [26, 27]. We add, however, that their transverse momentum distribution can be affected by the semihard scattering before they recede from one another. At early time the right- and left-movers need not be arranged as in Hubble expansion, i.e., a right-moving parton may be located on the left side of the region of uncertainty, and vice-versa; hence, those initial partons can be sensitive the passage of the semi-hard parton across their ways. The quantum fluctuations that generate the transverse k_T distribution of the forward (or backward) moving partons may be enhanced by the energy loss of the semihard parton. More specifically, let $\exp(-k_T/T)$ represent the distribution in the absence of semihard scattering; then our assertion is that the distribution changes to $\exp(-k_T/T')$ with $T' > T$ in the presence of semihard scattering, provided that the affected partons are in the vicinity of the semihard parton trajectory in the transverse plane, i.e., on the near side. Furthermore, such a change occurs for all partons independent of their longitudinal momenta up to $x \sim 10^{-2}$, say. This is in essence the physical input of our model. Note that although there is no explicit longitudinal correlation, a hadron detected at $\eta = 2.4$ and another one at $\eta = -2.4$ can both have $\exp(-p_T/T')$, where recombination leads from the parton k_T to the hadron p_T with the same T' [21], which is higher than T for both particles without the semihard jet. Details about recombination are less important here in the narrative than the physical problem. We see that jet can induce what appears like longitudinal correlation with $\Delta\eta = 4.8$, but in reality it is the transverse correlation due to $T \to T'$ at all η that leads to the ridge phenomenon. We stress that this is not the usual notion of transverse correlation where particles with different p_T but with nearly the same η are correlated as in a jet. The transverse correlation that we consider here is among particles at different η, at least one of which is outside the jet region. For a visual analogy it may be helpful to recall the adage that rising tide raises all boats — even though, we add, there are no intrinsic horizontal correlations among the boats.

Let the single-particle distribution be $\rho(p_T, \eta) = dN/p_T d\eta dp_T$, which will be abbreviated by $\rho_1(i)$ for the ith particle, so that two-particle distribution is denoted by $\rho_2(1, 2)$. Define two-particle correlation by $C_2(1, 2) = \rho_2(1, 2) - \rho_1(1)\rho_1(2)$. The measure for ridge used by CMS is

$$\mathcal{R}_{\rm CMS}(1, 2) = NC_2(1, 2)/\rho_1(1)\rho_1(2), \qquad (1)$$

where N is the number of charged particles in a multiplicity bin. In more detail the quantities in Eq. (1) are averaged over bins of p_T, so Ref. [1] exhibits

$$\mathcal{R}_{\rm CMS}(p_T, \Delta\eta, \Delta\phi) = N \frac{\prod_{i=1,2}\left[\int_{[p_T]} dp_{Ti} p_{Ti}\right] C_2(1, 2)}{\prod_{i=1,2}\left[\int_{[p_T]} dp_{Ti} p_{Ti} \rho_1(i)\right]} \qquad (2)$$

where $[p_T]$ denotes the range of integration from $p_T - 0.5$ to $p_T + 0.5$ (GeV/c). A ridge then appears in the 2D $\Delta\eta$-$\Delta\phi$ distribution where $\Delta\eta = \eta_1 - \eta_2$ and $\Delta\phi = \phi_1 - \phi_2$. A projection of it onto $\Delta\phi$ is done by integrating $|\Delta\eta|$ over the range 2.0 to 4.8. The associated yield in the ridge is then determined by integrating over a range of $\Delta\phi$ around 0 where $\mathcal{R}_{\rm CMS}$ is above its minimum, i.e.,

$$Y_R(p_T, N) = \int_R d\Delta\phi \int_{\pm 2}^{\pm 4.8} d\Delta\eta \; \mathcal{R}_{\rm CMS}(p_T, \Delta\eta, \Delta\phi). \qquad (3)$$

This measure of the ridge yield is given for 4 bins of p_T and N each [1]. The data points are shown in Fig. 1.

What is remarkable about the data is that Y_R is very small for both $0.1 < p_T < 1$ and $3 < p_T < 4$ GeV/c, but jumps up by nearly an order of magnitude in the $1 < p_T < 2$ GeV/c bin. It is very unusual in high-energy physics where the p_T behavior is so drastically different on the two sides of 1 GeV/c. The increase of Y_R with N is not surprising, especially if one has in mind that jets are connected with the ridge phenomenon.

Our explanation of the p_T and N dependencies of Y_R is very simple. As discussed earlier, transverse correlation due to semihard jets is the origin, $\Delta\eta$ correlation being only a by-product. Semihard partons change the soft

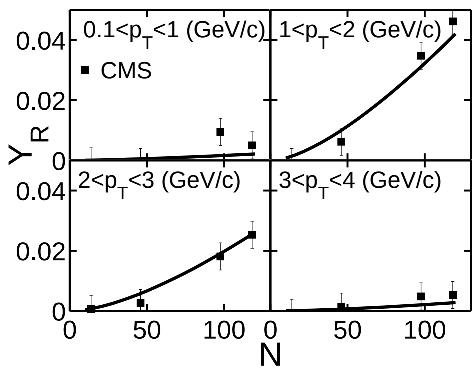

FIG. 1: Ridge yield vs multiplicity N for 4 bins of p_T. Data are from Ref. [1], and lines are from model calculation.

parton distribution by an enhancement of T, resulting in a difference that is identified as the ridge distribution

$$R(p_T) = R_0(e^{-E_T/T'} - e^{-E_T/T}), \tag{4}$$

where $E_T = m_T - m_h$ and $m_T = (p_T^2 + m_h^2)^{1/2}$. We change from p_T to $E_T(p_T)$ in the exponent, a generalization that allows proton production to be describable in the same framework. Eq. (4) was introduced previously in Refs. [20, 28] for the description of ridges in nuclear collisions. In fact, the dip of $R(p_T)$ at small p_T was a prediction in Ref. [20]. We simply adopt the same form for pp collision here. The difference $\Delta T = T' - T$ is a measure of the magnitude of the influence by semihard scattering and will naturally be related to the multiplicity N. Our hypothesis in this work is that $C_2(1,2)$ is proportional to $R(1)R(2)$, so that our model expression for Eqs. (2) and (3) is

$$Y_R(p_T, N) = cN \prod_{i=1}^{2} \left[\frac{\int_{[p_T]} dp_{Ti} p_{Ti} R(p_{Ti}, N)}{\int_{[p_T]} dp_{Ti} p_{Ti} \rho_1(p_{Ti})} \right], \tag{5}$$

where c is an adjustable parameter that depends on the experiment. In writing $C_2(1,2) = cR(1)R(2)$ without reference to η_1 and η_2, we are assuming that there is no longitudinal correlation between 1 and 2; yet $C_2(1,2)$ is non-zero due to the semihard jets at any $\eta_{\rm jet}$ that generate the η-independent ridge. The two particles at η_1 and η_2, most likely on the two sides of $\eta_{\rm jet}$, appear correlated because their p_T distributions are both enhanced by the jet. $R(1)$ and $R(2)$ are independent responses, so they enter into $C_2(1,2)$ as factorized products.

The single-particle distribution for $|\eta| < 2.4$ at 7 TeV is given by CMS in the Tsallis parametrization [23]

$$\rho_1(p_T) = \rho_0(1 + \frac{E_T}{nT_0})^{-n} \tag{6}$$

with $T_0 = 0.145$ GeV/c and $n = 6.6$. The average p_T found from the above fit is $\langle p_T \rangle = 0.545$ GeV/c.

We use Eq. (6) in (5) and fit the data in Fig. 1 with two parameters (apart from normalization), which we choose to be T and β, where

$$\frac{\Delta T}{T} = \beta \ln N, \qquad \Delta T = T' - T. \tag{7}$$

This dependence on N is reasonable, since at higher N there is higher probability for jet production and hence larger ΔT, which is in the exponent in Eq. (4). The result of the fit is shown by the solid lines in Fig. 1 for

$$T = 0.294 \text{ GeV} \qquad \text{and} \qquad \beta = 0.0175. \tag{8}$$

Evidently, our model reproduces the data very well for all p_T and N bins. $Y_R(p_T, N)$ is small at small p_T because $R(p_T)$ in Eq. (4) is suppressed as $p_T \to 0$. The reason for that is discussed below. $Y_R(p_T, N)$ is also small at large p_T; that is due both to the exponential suppression of $R(p_T)$ and the power-law decrease of $\rho_1(p_T)$ at high p_T. The increase with N that is most pronounced in the $1 < p_T < 2$ GeV/c bin, where $R(p_T)$ is maximum, is clearly due to the enhancement of T when jet production is more likely in accordance to Eq. (7). At $N = 100$, $\Delta T/T$ is about 8%, which is slightly lower than that observed in nuclear collisions at RHIC where $T = 355 \pm 6$ MeV/c and $T' = 416 \pm 22$ MeV/c for $4 < p_T^{\rm trig} < 6$ GeV/c [3].

The reason why $R(p_T)$ must vanish as $p_T \to 0$ is related to azimuthal anisotropy in nuclear collisions. We have advocated the view that the ridge component before being averaged over ϕ contains all the ϕ dependence of the inclusive distribution [20, 29]. In that approach we have shown without using hydrodynamics that elliptic flow (v_2) can be reproduced at all centralities, provided that $R(p_T) \to 0$ at vanishing p_T because $v_2(p_T) \to 0$. Since the azimuthal behavior is determined primarily by the initial geometry of the collision system [20, 28, 29], such an approach may well be applicable to pp collisions, for which the validity of hydrodynamics used for nuclear collisions is doubtful. The origin of the ϕ dependence in the geometrical approach is the anisotropy of semihard emission when the initial configuration is almond-shaped. It may not be unreasonable to consider the initial configuration in pp collisions also, when the impact parameter is non-zero. The radial dependence of parton densities at low x in a proton will become a relevant subject to investigate if significant ϕ anisotropy is found in pp collisions at various multiplicity N.

The Tsallis distribution in Eq. (6) has the property of a power-law behavior at large p_T, but an exponential behavior, $\exp(-E_T/T_0)$, at low p_T. It is then of interest to note the difference between the values of T_0 and T, the latter being twice larger than the former. It may appear as being inconsistent; however, the average $\langle p_T \rangle$ of $\exp(-E_T/T)$ is 0.6 GeV/c, only 10% higher than that for Eq. (6). Thus different parametrizations of the E_T distribution give essentially the same physical quantity. Eq. (6) is a fit of the CMS data [23] that emphasizes the p_T^{-n} behavior at high p_T, while Eq. (4) is a theoretical model of the ridge distribution at low p_T.

We have given an interpretation of the ridge phenomenon in pp collisions in terms of soft partons on which very little is known. By drawing on what we do know about the soft partons in nuclear collisions, we are led to the implication that a dense medium can be created even in *pp* collisions at 7 TeV and that (a) the medium can be responsive to semihard jets, (b) there can be azimuthal anisotropy, (c) the p_T spectrum in the ridge is harder than that of the inclusive, and (d) that hadronization is by recombination. None of the above rely on the validity of hydrodynamics for *pp* collisions, or the existence of intrinsic long-range longitudinal correlation, and all of them can be checked by further experimental measurements. The last item cannot be checked directly, but one of its consequences is that the p/π ratio can be large, which is a property of all recombination/coalescence models [31]. We expect the p/π ratio in the ridge to increase with p_T at low p_T in *pp* collisions at 7 TeV. The rate of that increase depends on the soft parton density, which we estimate from the CMS data [23] to be such as to allow the ratio to reach 0.5 at $3 < p_T < 5$ GeV/c before decreasing due to shower partons. A ratio larger than 0.2 cannot be explained by fragmentation. Thus the experimental determination of the p/π ratio in the ridge will be very interesting and should provide further insight on the structure and origin of the ridge.

Our model for the ridge is that it is a response to semihard partons, which can be detected as jets if specifically looked for. Yet in our description of the ridge distribution in Eq. (4), we have not defined precisely what a jet is. Semihard scattering cannot be reliably calculated in pQCD and can be pervasive in nuclear collisions at RHIC or *pp* collisions at LHC. Our model at this stage does not require precise formulation of semihard scattering. To describe ridge formation as being induced by jets is sufficient to convey the physical idea that is distinctly different from long-range rapidity correlation without jets.

The basic issue raised by the observation of the ridge by CMS is whether a system of high density soft partons can be created in *pp* collisions. The system may be too small for the applicability of hydrodynamics, but azimuthal anisotropy can nevertheless exist for small systems in non-central collisions, so consequences on ϕ asymmetry should be measurable, as the ridge structure on the near side demonstrates. Our consideration of ridge formation as being generated by semihard jets applies to both hadronic and nuclear collisions. Thus we go further to suggest that even in single-particle distribution in *pp* collisions at LHC there may exist a ridge component that contains all the ϕ dependence, as found in heavy-ion collisions [20, 28]. A more direct test of our model is to check whether the inverse slope of the exponential peak increases with N as found in Eqs. (7) and (8), the details of which may depend on the separation of the π and p components.

This work was supported in part, by the U. S. Department of Energy under Grant No. DE-FG02-96ER40972 and by the National Natural Science Foundation of China under Grant No. 10775057 and 11075061.

[1] CMS Collaboration, J. High Energy Physics (to be published), arXiv:1009.4122.
[2] J. Adams *et al.*, (STAR Collaboration), Phys. Rev. C **73**, 064907 (2006).
[3] B. I. Abelev *et al.*, (STAR Collaboration), Phys. Rev. C **80**, 064912 (2009).
[4] B. Aver *et al.*, (PHOBOS Collaboration), Phys. Rev. Lett. **104**, 062301 (2010).
[5] B. I. Abelev *et al.*, (STAR Collaboration), Phys. Rev. Lett. **105**, 022301 (2010).
[6] M. Daugherity (for STAR Collaboration), J. Phys. G: Nucl. Part. Phys. **35**, 104090 (2008).
[7] E. Shuryak, arXiv:1009.4635.
[8] S. M. Troshin and N. E. Tyurin, arXiv:1009.5229.
[9] A. Dumitru *et al.*, arXiv:1009.5295.
[10] P. Bozek, arXiv:1010.0405.
[11] J. Putschke, J. Phys. G: Nucl. Part. Phys. **34**, S679 (2007).
[12] R. C. Hwa, in *Quark-Gluon Plasma 4*, edited by R. C. Hwa and X. N. Wang (World Scientific, Singapore, 2010).
[13] S. Gavin, L. McLerran, and G. Moschelli, Phys. Rev. C **79**, 051902 (2009).
[14] A. Dumitru *et al.*, Nucl. Phys. A **810**, 91 (2008).
[15] K. Dusling *et al.*, Nucl. Phys. A **836**, 159 (2010).
[16] A. Feng (for STAR Collaboration), J. Phys. G: Nucl. Part. Phys. **35**, 104082 (2008).
[17] D. Netrakanti (for STAR Collaboration), Nucl. Phys. A **830**, 681c (2009).
[18] M. M. Aggarwal *et al.*, (STAR Collaboration), arXiv:1004.2377.
[19] C. B. Chiu and R. C. Hwa, Phys. Rev. C **79**, 034901 (2009).
[20] C. B. Chiu, R. C. Hwa and C. B. Yang, Phys. Rev. C **78**, 044903 (2008).
[21] R. C. Hwa and C. B. Yang, Phys. Rev. C **70**, 024905 (2004).
[22] G. Aad *et al.*, (ATLAS Collaboration), Phys. Lett. B **688**, 21 (2010).
[23] V. Khachatryan *et al.*, (CMS Collaboration), Phys. Rev. Lett. **105**, 022002 (2010).
[24] K. Aamodt *et al.*, (ALICE Collaboration), Phys. Lett. B **693**, 53 (2010).
[25] R. C. Hwa, talk given at INT Workshop, May, 2010; C. B. Chiu and R. C. Hwa (to appear).
[26] R. P. Feynman, *Photon-Hadron Interaction* (Benjamin Press, Reading, MA, 1972).
[27] J. D. Bjorken, SLAC Summer School, SLAC-167 vol. I (1973) (unpublished).
[28] R. C. Hwa and L. Zhu, Phys. Rev. C **81**, 034904 (2010).
[29] R. C. Hwa, Phys. Lett. B **666**, 228 (2008).
[30] K. P. Das and R. C. Hwa, Phys. Lett. **68**B, 459 (1977).
[31] R. C. Hwa and C. B. Yang, Phys. Rev. C **67**, 034902 (2003); V. Greco, C. M. and P. Lévai, Phys. Rev. Lett. **90**, 202302 (2003); R. J. Fries, B. Müller, C. Nonaka, and S. A. Bass, Phys. Rev. Lett. **90**, 202303 (2003).