Possible multiparticle ridge-like correlations in very high multiplicity proton–proton collisions

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1. Introduction

An unexpected finding by the CMS Collaboration at the Large Hadron Collider (LHC) is a same-side “ridge” in two-particle correlations produced in very high-multiplicity proton–proton collisions. To be precise, plots of the two-body correlation in relative azimuthal angle \(\delta \phi\), integrated over relative pseudo-rapidity \(\delta \eta\) at a fixed range of transverse momentum \(p_\perp\), exhibit a tendency to peak at \(\delta \phi \approx 0\) [1,2].

Two immediate qualifications are in order: First, there is a much higher ridge near \(\delta \phi \sim \pi\). Secondly, for small pseudo-rapidity difference there is a large peak in the correlation function near \(\delta \phi = 0\). Both of these effects have plausible explanations. The away-side ridge reflects the conservation of transverse momentum: if one particle appears with positive transverse momentum along the \(x\) axis, say, then there must be a particle or particles with negative transverse momentum to balance it. The peak at small \(\delta \phi\) for small \(\delta \eta\) reflects the presence of a jet and/or a resonance which decays to more than one particle near a given \(\eta\) and \(\phi\).

The same-side ridge found by CMS in events with more than 110 particles is statistically significant, but it is not an overwhelming effect. It comes against a background of gradually increasing correlation with increasing \(\delta \phi\). Thus an alternative interpretation could be that, instead of a ridge, the dynamically important phenomenon is actually a dip at a particular small, but nonzero, value of \(\delta \phi\). A number of authors have made comments and suggested explanations for the same-side ridge, including [3–19].

As the authors of the experimental paper have noted, the ridge recalls a similar, more conspicuous, effect seen in nucleus–nucleus collisions. A plausible explanation for the nuclear effect is that when two identical nuclei collide at intermediate-impact-parameter, the region of overlap between the two has an approximately elliptical shape in the plane transverse to the collision axis. Simple hydrodynamics then implies that the expansion along the short axis of the overlap ellipse will be more vigorous than the expansion in the long direction, with equal correlations for \(\delta \phi \approx 0\) and \(\delta \phi \approx \pi\). This effect is amplified by looking at multiparticle correlations which emphasize the second moment of the azimuthal distribution.

Our purpose here is to suggest that a similar ridge effect, albeit with a quite different physical mechanism, may be at work in the high multiplicity \(pp\) collisions. If we think of a proton as three quarks bound by color forces, then a plausible description of the binding involves color flux ‘strings’ or tubes connecting to each quark, and to each other, like the bisectors of a triangle with the quarks at the vertices (“Y” diagrams). The idea of such flux tubes goes back at least to the work of Isgur and Paton [20]. Planar networks of strongly interacting gluons connecting valence quarks are also natural in the higher Fock states of the light-front wave functions of the proton as discussed by Mueller [21]. Such saturating configurations can lead to BFKL phenomena, color-glass models [22], and they could even provide the color-confining potential of valence quarks as seen in the AdS/QCD soft-wall model [23] using light-front holography [24–26]. We also note that “H”-diagrams...
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2. Consequences of the collisions of oriented QCD flux tubes

A linear configuration of the proton has two valence quarks

near one end of a gluon flux tube and a third valence quark at

the other end. We assume that the flux tube has a transverse size

no larger than a few tenths of a Fermi [28]. The probability of

finding such a linear configuration is arguably quite considerable,

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jectation parallel to the lines. The cost in aligning them azimuthally

is reduced to a value in the neighborhood of 1 mb. This is quite

an order of magnitude smaller than the width of a flux tube. To

suming that jets should come from overlap of ‘occupied pixels’ in

the colliding flux tubes, where the pixels have dimensions about

an order of magnitude smaller than the width of a flux tube. To

obtain the assumed total energy one finds only a minority of the

pixels are occupied, and thus the frequency of mini-jet formation

is very low.

While some of this transverse energy can be expected to be in vis-

ible minijets, it is quite possible that at least some subset of these

events are relatively jet-free. We come to this conclusion by as-

suming that jets should come from overlap of ‘occupied pixels’ in

the colliding flux tubes, where the pixels have dimensions about

an order of magnitude smaller than the width of a flux tube. To

obtain the assumed total energy one finds only a minority of the

pixels are occupied, and thus the frequency of mini-jet formation

may be low.

Looking down the beam direction, the generator of particle pro-

duction in the flux tube collisions is an approximate line source,

more extreme in azimuthal asymmetry than the almond–shaped

source region typical of intermediate-impact-parameter heavy-ion

collisions. Therefore, one should expect that this special class of

events has even stronger “ellipticity” effects than in the nuclear

case. In particular, a broader transverse momentum distribution

is to be expected in the azimuthal direction normal to the flux tubes.

Furthermore, this property is expected to be “boost invariant”: If

one were to compare the produced-particle distribution for such an

event at zero rapidity at the LHC with what would be seen at zero

rapidity for a hypothetical asymmetric collider – say 350 TeV

against 35 GeV – the result would be expected to be very similar

because the geometry of the relevant active collision area is essen-

tially the same. Therefore the azimuthal asymmetries seen in

the positive-rapidity half of the detector should be strongly correlated

with those seen in the negative rapidity half of the detector. This

feature is the basic correlation structure of all “ridge” phenomena.

This discussion suggests a flexible search strategy for uncover-

ing not only this phenomenon, but also related effects associated

with the nontrivial impact-plane geometry. For example, one might

begin by restricting attention to the properties of events in the

positive-rapidity half of the detector. After a choice of judicious,

creative cuts and/or event scans, one will hopefully have a sample

of candidate events exhibiting “ridge” effects. For each such event,

one then looks at the data from the other half of the detector. If

the “ridge” effects we have proposed are genuine, they should be

largely reproduced in the other half of the event. In other words,

the correlations should be seen along virtually the entire rapidity

plateau.
In addition to the general strategy described above, we can suggest a more specific test. The key point is that a multiparticle correlation should give a much more conspicuous signal than the two-particle correlation used so far in the experimental analysis, but of course only in that small fraction of the events where the prerequisite conditions of coincidence of narrow strings in the projectile and target are in fact obtained. To be specific, we suggest looking at the following vector \( \vec{V} \), computing its magnitude for each event. If the number of events with large magnitude are greater than expected from chance, one would have powerful evidence for the proposed colliding flux tube mechanism. Define

\[
\vec{V} = \sum_{i=1}^{N} [\cos 2\phi_i \hat{x} + \sin 2\phi_i \hat{y}],
\]

and obtain the distribution of \( \vec{V}^2 \). If the particles were distributed randomly in \( \phi \), then the expectation value of \( \vec{V}^2 \) would be \( N \), where \( N \) is the number of particles in the event in the given region of transverse momentum. The probability of getting a value \( N^2 \) may be estimated by introducing quadrants in the variable \( 2\phi \). Assume each vector can take only the values \( \pm \hat{x} \) or \( \pm \hat{y} \), with each having a probability 1/4. Suppose the first vector is \( +\hat{x} \). Then the chance that the remainder would all be in the same direction would be \((1/4)^{N-1}\). For \( N = 5 \), this would yield a probability 1/256. If, among events in which the ridge was seen, with more than 110 particles per event, and 5 particles separated from each other by about one unit in \( \delta \eta \) in an interval of \( p_T \) between 1 and 2 GeV/c, as many as 2% of the events should show \( \vec{V}^2 \approx 25 \), that could be evidence for the kind of correlation we suggest. This exercise is equivalent to asking the probability — assuming complete randomness in \( \phi \) — that all 5 particles are in either of two opposite octants of \( \phi \). If they were more collimated than that, the probability would be even smaller.

Counting all particles in each event in the specified range of transverse momentum, regardless of rapidity separation, should give a reliable measure of the correlation. Technically, \( \vec{V}^2 \) is just the square of the usual ellipticity variable. An advantage of squaring is that maximal ellipticity events are easy to pick out. Also, it is easier to think about such a scalar variable rather than a vector variable.

At this point let us take a step back to gain perspective on what could cause such phenomena. Obviously projectile and target must overlap in impact parameter to some extent. Dynamics, in the form of the conservation of momentum or of the attraction of outgoing particles to each other, can — as earlier discussed — produce certain correlations, such as the away-side ridge and the clustering of particles with small relative velocity. However, the dynamics cannot explain the long-range (in rapidity) near-side correlations. For this one needs geometry in the transverse plane. We have given a specific example of such a geometry, the presence of parallel overlapping strings with a substantial projection onto the transverse plane. Clearly the overlap mentioned for lower-energy nucleus–nucleus collisions also is an example, even though it involves a very different mechanism.

3. Conclusions

We have suggested that the ridge-like correlation found by the CMS Collaboration [1,2] in high-multiplicity events in \( pp \) collisions at the LHC could be evidence for the collision of aligned high-intensity flux tubes connecting the valence quarks of the colliding protons. A key property is the correlation of ridge events between positive and negative rapidity. Further studies clearly are warranted, including an extended analysis of the CMS data based on the squared correlation vector \( \vec{V}^2 \). If one finds evidence for very strongly aligned “elliptical flow” in \( pp \) collisions, where the formation mechanism for the “ellipse” is in our opinion very different from the geometrical overlap mechanism seen in nucleus–nucleus collisions, then the observation of the “ridge” phenomenon in \( pp \) collisions over a large range of rapidity would be a dramatic demonstration of high-density effects in QCD.

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References