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THE RIDGE EFFECT AT THE LHC: HIGH DENSITY IN *pp*?*

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The observation of long range near side angular correlation (the so-called *ridge effect*) in *pp* collisions at the LHC is presented. Data on such correlations in heavy ion collisions at RHIC are shown. Previous informations on angular correlations in high energy *pp* collisions are critically reviewed. A spectrum of many recent interpretations concerning the effect is presented.

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1. The LHC data

At the end of 2010 the CMS Collaboration has shown first results on correlations observed in high multiplicity *pp* collisions at 7 TeV (now published as [1]). This observation has spurred quite an interest and thus calls for an in-depth review of relevant physics.

The motivation for such study at LHC came from the observation that the charged particle multiplicity attained in 7 TeV *pp* collisions now approaches the values characteristic for nuclear collisions observed at RHIC at 62 and 200 GeV$/c/N$ (Cu–Cu and Au–Au collisions). Thus, a dedicated high multiplicity trigger was implemented in the two levels of the CMS trigger system. Total data set corresponds to $980\,\mathrm{nb}^{-1}$.

The charged two particle correlation as a function of pseudorapidity $\Delta\eta$ and azimuthal angle $\Delta\varphi$ was defined as follows (signal distribution)

$$S_N(\Delta\eta,\Delta\varphi)=\frac{1}{N(N-1)}\frac{d^2N^{\mathrm{signal}}}{d\Delta\eta\,d\Delta\varphi} \tag{1}$$

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and the background distribution B

$$B_N(\Delta\eta, \Delta\varphi) = \frac{1}{N^2} \frac{d^2 N^{\mathrm{bkg}}}{d\Delta\eta \, d\Delta\varphi} \tag{2}$$

was constructed by randomly selecting two different events and pairing every particle from one event with every particle in the other. The signal to background ratio, denoted R, is defined as

$$R(\Delta\eta, \Delta\varphi) = \left\langle (N-1) \left(\frac{S_N(\Delta\eta, \Delta\varphi)}{B_N(\Delta\eta, \Delta\varphi)} - 1 \right) \right\rangle_N . \tag{3}$$

A study of correlations for different multiplicity selections, and different transverse momentum ranges has revealed a novel structure for multiplicities above 110, and the p_{T} range between 1.0 GeV/c and 3.0 GeV/c. This effect is illustrated in Fig. 1. A clear and significant ridge-like structure is observed at $\Delta\varphi \approx 0$, extending over at least 4 units of pseudorapidity. This feature is not present in low multiplicity events. Two particle correlations were also calculated separately for like-sign and unlike-sign charged pairs. The distributions showed similar behaviour to the all charged data. As a further check, correlation functions were studied for tracks paired with (calorimeter detected) photons, as well as pairs of photons. These distributions showed similar behaviour.

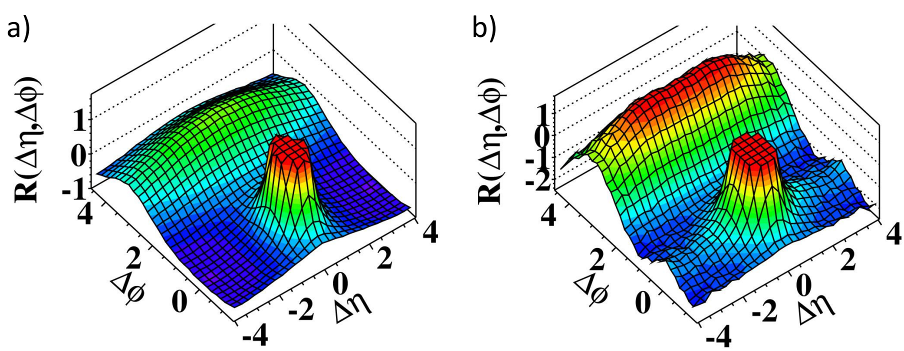


Fig. 1. Two particle correlation function for 7 TeV pp for intermediate p_{T} range, minimum bias events (left) and high multiplicity events (right). The sharp near-side peak from jet correlations is cut-off in order to better illustrate the structure outside that region [1].

Several PYTHIA tunes (and other MC) were also investigated, and no correlation corresponding to the one observed in data was found. The effect is reminiscent of correlations observed in relativistic heavy ion experiments.

2. Some history from heavy ions

Study of two particle correlations in d–Au and Au–Au collisions at RHIC at 200 GeV$/c/N$ were performed in PHOBOS and STAR experiments. Correlations in $\Delta\varphi - \Delta\eta$ were observed for high p_{T} triggers at small angular separation, and ascribed to jet fragmentation. These were not modified in central Au–Au collisions relative to d–Au, which suggested dominant jet fragmentation outside the dense medium. For lower p_{T}, significant near side correlations at large pair separation in $\Delta\eta$ has been observed. At moderately large p_{T} the near side correlation could be factored into a jet-like effect (similar to those observed in pp) and a very much elongated contribution, approximately independent on η — the so-called *ridge effect*. Significantly, ridge properties were similar to bulk particle properties. Figure 2 [2] shows such two particle correlations for central Au–Au and d–Au collisions. Figure 3 [3] shows the *ridge effect* observed in central Au–Au collisions, and, for comparison, a PYTHIA generated correlation for pp collisions.

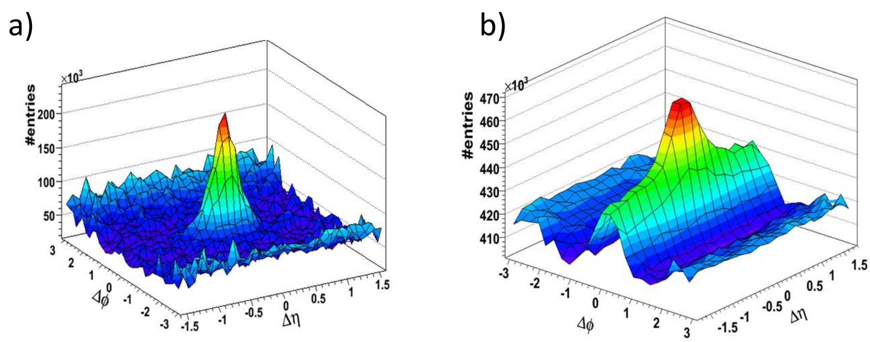
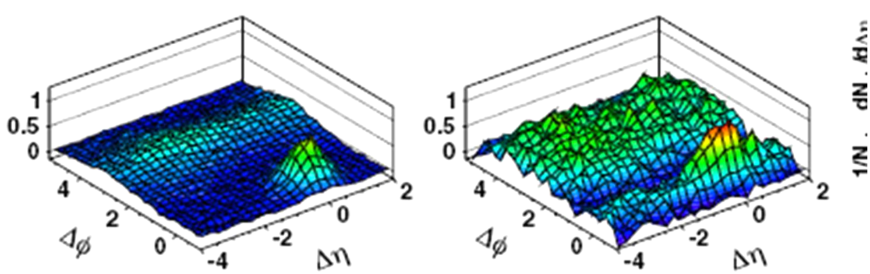


Fig. 2. Two particle correlation function for d–Au (left) and Au–Au central events at 200 GeV$/c/N$ from STAR experiment [2].



(a) $p + p$ PYTHIA (version 6.325) (b) Au+Au 0%–30% (PHOBOS)

Fig. 3. Two particle correlation function for pp event from PYTHIA MC (left) and central Au–Au collisions at 200 GeV$/c/N$ from PHOBOS experiment (right) [3].

The ridge effect is seen to extend over at least 4 units in pseudorapidity, a truly long-range correlation. A study of centrality dependence of the ridge over jet contribution to the effect, displayed in Fig. 4, shows a systematic increase towards the most central sample (highest number of participants).

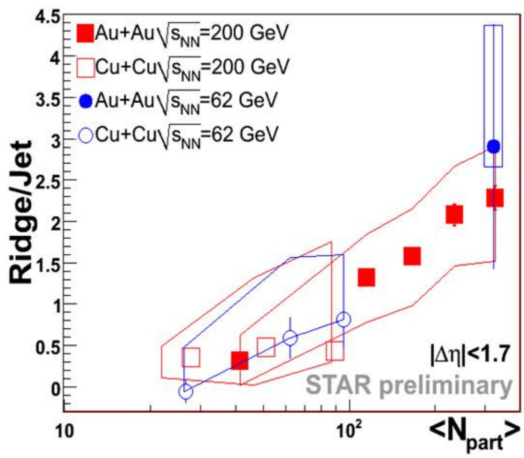


Fig. 4. The Ridge to jet ratio as a function of the number of nucleon participants (centrality measure) from STAR experiment [2].

The RHIC experiments interpretation of the effect, although by no means unique, tended towards ascribing it to the effects in the early stage of the nuclear fireball evolution, such as, for example, colour flux tubes from the coloured glass condensate initial state.

3. First comments and some history from proton–proton

The publication on the long range correlation effect observed in *pp* collisions at 7 TeV at the LHC triggered an immediate activity on the part of several authors. Two days after the CERN seminar showing the effect, Shuryak has published a note on arXiv [4] claiming, that 'perhaps this observation is the first hint for an explosive behaviour in *pp*, which was anticipated for decades'. A week later Dumitru *et al.* [5] have published a paper, arguing that the key features of the LHC result can be understood in the Colour Glass Condensate framework of QCD. We will come back to the subject, but let us first comment on many voices claiming that the observed correlations were, in fact, already known from *pp* data at lower energies.

Two particle correlations were indeed observed in proton–proton/antiproton collisions at the ISR [6] at sqrt(s) 52.6 GeV, in the UA5 experiment [7], at the Tevatron by the E735 experiment [8]. These were not long-range correlations, and have been successfully described within a cluster model, with rather small clusters. Clusters, resonances, string fragmentation effects, Bose–Einstein correlations and the like, are all present in the LHC data, but these effects contribute to short range structure observed, a strong peak superimposed on the wide η ridge. Thus the ridge observed in high multiplicity *pp* collision is a novel phenomenon.

4. Ridge effect in *pp* — attempts at interpretation

There are strong arguments, based on causality, that long range correlations between particles should be formed at early proper times, nearly instantaneously after the collision. They should, therefore, be sensitive to the strong colour fields.

At high energies and/or for large nuclei gluon saturation effects are important. A Colour Glass Condensate effective theory [9] allows for a quantitative comparison of RHIC data and make predictions for LHC *AA* collisions. From there to the *pp* effects there is no fundamental difficulty. The problem is in the saturation scale for *pp*. Here the choice of high multiplicity sample, as performed in the CMS experiment, may allow for selecting the large overlap area of two protons, and presumably, a region of applicability of the formalism of CGC framework of strong longitudinal chromo-electric and chromo-magnetic fields. The authors of [5] have calculated the correlation function similar to that used in the CMS paper, and were able to describe the key features of the *ridge effect* observed.

For completeness, one should mention other attempts at interpreting the *pp* ridge. In particular, Werner *et al.* [10] argue that a hydrodynamical expansion and many flux tubes produced lead in a natural way to the observed effect. This is illustrated in Fig. 5. One should mention that this approach

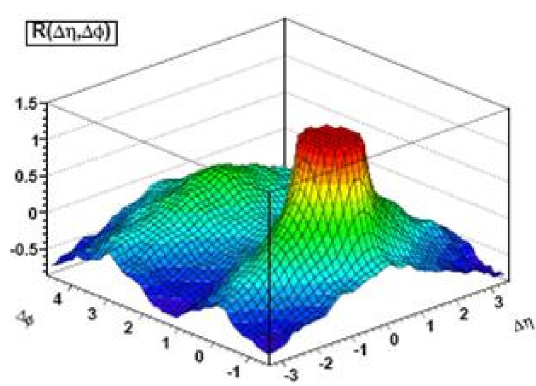


Fig. 5. Two particle correlation function for high multiplicity events in *pp* collisions at 7 TeV, as obtained from a hydrodynamical evolution based on flux tube initial conditions [10].

can also be applied to explain successfully several spectra in Au–Au collisions at RHIC, and fairly well explain the so far published LHC spectra and Bose–Einstein correlations.

Another explanation of the *ridge effect* in high multiplicity *pp* collisions at LHC is offered by Bozek [11], explaining the effect as an elliptic flow manifestation. There is even a comment from the AdS/CFT specialist [12], arguing that long range correlations may appear in modelling of heavy ion and central *pp* collisions by shock waves on the gravity side (although the authors state that calculations appear to be prohibitively complicated to do analytically at the moment).

5. Conclusions

A long range correlation has been observed in high multiplicity *pp* collisions at 7 TeV. This effect resembles the correlation present in Au–Au collisions at 200 GeV$/c/N$.

It is tempting to ascribe this to high density/high energy density phenomena, related to the Quark Gluon Plasma formation.

It would be most interesting to try to eventually observe other high density effects in high multiplicity (presumably — central) *pp* collisions, namely the jet quenching effect. Jet quenching is present in central Pb–Pb collisions at 2.76 TeV$/c/N$, as evidenced by three LHC experiments: ALICE, CMS and ATLAS.

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