THE RIDGE EFFECT FROM p–p TO Pb–Pb (AND BACK)*

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The long-range near-side correlation investigated in heavy-ion collisions at RHIC has turned up, unexpectedly, in high-multiplicity pp collisions studied by the CMS experiment at the LHC. This effect in now also observed in Pb–Pb collisions. A spectrum of many recent interpretations concerning the effect is presented.

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1. Introduction and some history from heavy ions

A study of correlations in particle production at high energy — be it elementary or nuclear collisions — may shed light on the mechanism of such processes, and thus is being extensively pursued in several experiments. The charged two-particle correlation as a function of pseudorapidity $\Delta\eta$ and azimuthal angle $\Delta\varphi$ can be defined as follows

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

and the background distribution B

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

is 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

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

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Studies of long range two-particle correlations in d–Au and Au–Au collisions at RHIC at a center-of-mass energy of 200 GeV were performed in PHOBOS [1] and STAR [2] experiments. Correlations in $\Delta\varphi$–$\Delta\eta$ were observed for high p_{T} 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 correlation 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 p–p) and a very much elongated contribution, approximately independent on η — the so-called Ridge Effect. Significantly, properties of particles contributing to the ridge were similar to bulk particle properties. Fig. 1 [2] shows such two particle correlations for central Au–Au and d–Au collisions. A study of centrality dependence of the ridge yield shows a systematic increase towards the most central sample (highest number of participants).

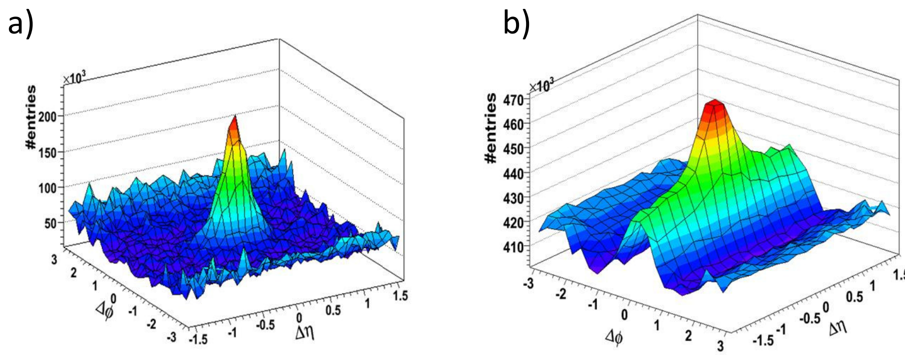

Fig. 1. Two particle correlation function for d–Au (left) and Au–Au (right) central events at $\sqrt{s_{NN}} = 200$ GeV from STAR experiment [2].

The interpretation of the RHIC experiment 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.

2. Correlations in high multiplicity p–p collisions at the LHC

At LHC the charged-particle multiplicity attained in 7 TeV p–p collisions now approaches the values characteristic for nuclear collisions observed at RHIC at $\sqrt{s_{NN}} = 62$ GeV and 200 GeV (Cu–Cu and Au–Au collisions). Thus it is tempting to look for effects related to such high multiplicities. A dedicated high multiplicity trigger was implemented in the two levels of the CMS trigger system. At the end of 2010 the CMS Collaboration has shown first results on correlations observed in high multiplicity p–p collisions at 7 TeV (now published as [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 $p_{\rm T}$ range between 1.0 GeV/c and 3.0 GeV/c. This effect is illustrated in Fig. 2.

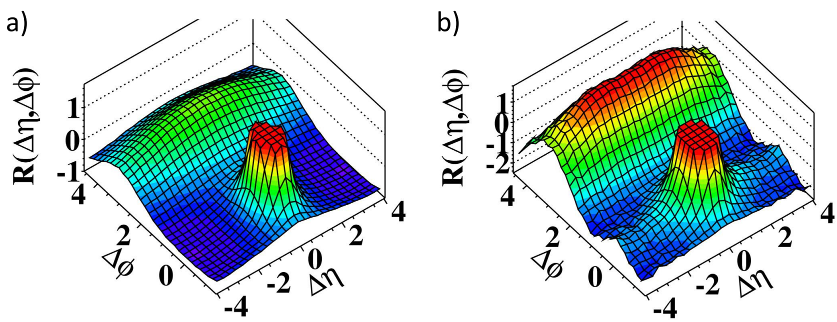

Fig. 2. Two particle correlation function for 7 TeV p–p for intermediate $p_{\rm T}$ range, minimum bias events (left) and high multiplicity events (right). The sharp near-side peak from jet correlations is cut off in order to better illustrate the structure outside that region [3].

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.

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

Updated studies of this effect in p–p as a function of particle transverse momentum, rapidity and event characteristics were shown at the Quark Matter 2011 Conference [4]. Fig. 3 shows the results based on larger statistics from 1.78 pb^{-1} sample. The per trigger particle associated yield distribution in high multiplicity ($N > 110$) p–p collisions at $\sqrt{s} = 7$ TeV with trigger particles with $2 < p_{\rm T}^{\rm trig} < 3$ GeV/c and associated particles with $1 < p_{\rm T}^{\rm assoc} < 2$ GeV/c presented in Fig. 4 (left) clearly shows a ridge-like structure at $\Delta\varphi \approx 0$ extending to large $\Delta\eta$, as previously observed. The right-hand side of the figure demonstrates that at higher $p_{\rm T}^{\rm trig}$ the ridge disappears.

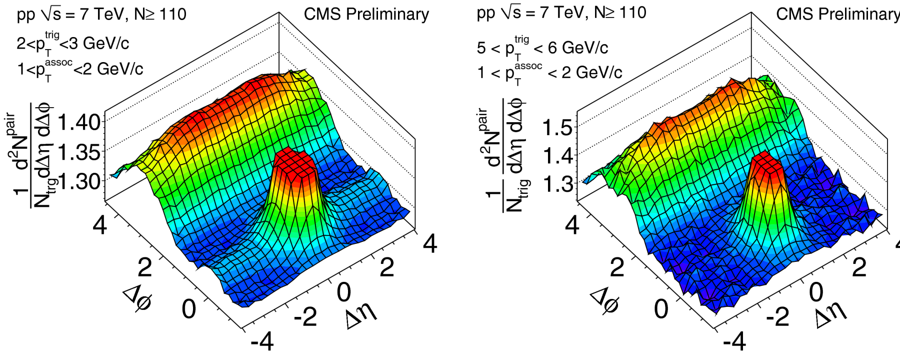

Fig. 3. Two-dimensional (2D) per-trigger-particle associated yield of charged hadrons as a function of $\Delta\eta$ and $\Delta\varphi$ with jet peak cutoff for better demonstration of the ridge from high-multiplicity ($N \geq 110$) p–p collisions at $\sqrt{s} = 7$ TeV, for $2 < p_{\rm T}^{\rm trig} < 3$ GeV$/c$ and $1 < p_{\rm T}^{\rm assoc} < 2$ GeV$/c$ (left), and $5 < p_{\rm T}^{\rm trig} < 6$ GeV$/c$ and $1 < p_{\rm T}^{\rm assoc} < 2$ GeV$/c$ (right) [4].

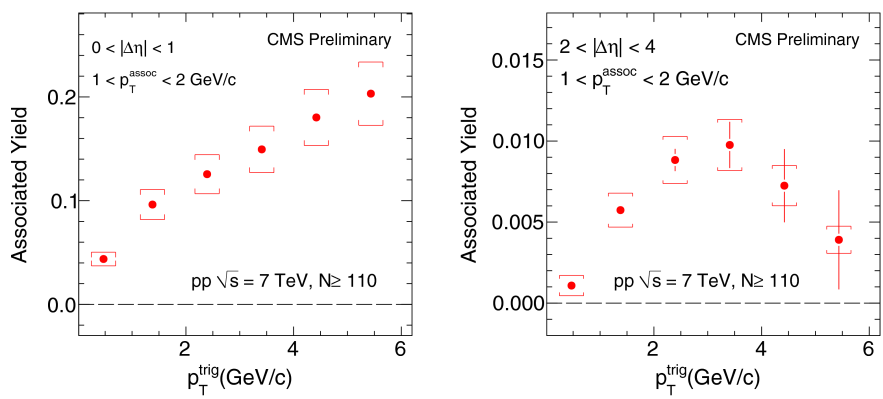

Fig. 4. Integrated near-side associated yields for the short-range jet region ($0 < |\Delta\eta| < 1$) and the long-range ridge region ($2 < |\Delta\eta| < 4$), with $1 < p_{\rm T}^{\rm assoc} < 2$ GeV$/c$, above the minimum level found by the ZYAM procedure [5], as a function of $p_{\rm T}^{\rm trig}$ for $N \geq 110$ of p–p collisions at $\sqrt{s} = 7$ TeV. The statistical uncertainties are shown as bars, while the brackets denote the systematic uncertainties [4].

A study of transverse momentum of the trigger particle dependence of the correlation has revealed several observations (Fig. 4).

For the near side (small $\Delta\varphi$ region) the associated yield for the short-range jet region increases with $p_{\rm T}^{\rm trig}$, as expected due to the increasing contribution from high $p_{\rm T}$ jets. The ridge yield first increases up to $p_{\rm T}^{\rm trig}$ around 2–3 GeV$/c$ and then decreases for higher $p_{\rm T}$.

The observation of the Ridge Effect for high multiplicity p–p collisions has spurred quite an interest, and several theoretical predictions and postdictions appeared.

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 [6] allows for a quantitative comparison of RHIC data and makes predictions for LHC AA collisions. From there to the p–p effects there is no fundamental difficulty. The problem is in the saturation scale for p–p. 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 [7] 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 p–p ridge. In particular, Werner *et al.* [8] argue that a hydrodynamical expansion and many flux tubes produced lead in a natural way to the observed effect.

Another explanation of the Ridge Effect in high multiplicity p–p collisions at LHC is offered by Bozek [9], explaining the effect as an elliptic flow manifestation.

3. The Pb–Pb results

At the QM2011 Conference, the CMS experiment has shown results on dihadron correlations in 2.76 TeV Pb–Pb collisions [4]. Here again, as illustrated in Fig. 5, a very clear and significant ridge-like structure is observed for central Pb–Pb samples. A study of trigger transverse momentum dependence of the ridge structure shows similar behaviour as that in high multiplicity p–p collisions.

The long range correlations can clearly relate to the effects of hydrodynamical flow. Thus a Fourier decomposition technique has been applied. The $\Delta\varphi$ projected distribution has been decomposed into Fourier series, with the following expression

$$\frac{1}{N_{\rm trig}}\frac{dN^{\rm pair}}{d\Delta\varphi} = \frac{N_{\rm assoc}}{2\pi}\left\{1+\sum_{n=1}^{\infty} 2V_{n\Delta}\cos(n\Delta\varphi)\right\}, \tag{4}$$

where $N^{\rm assoc}$ represents the total number of dihadron pairs per trigger particle for a given $\Delta\eta$ range and $p_{\rm T}^{\rm trig}$, $p_{\rm T}^{\rm assoc}$ bin. First five Fourier coefficients

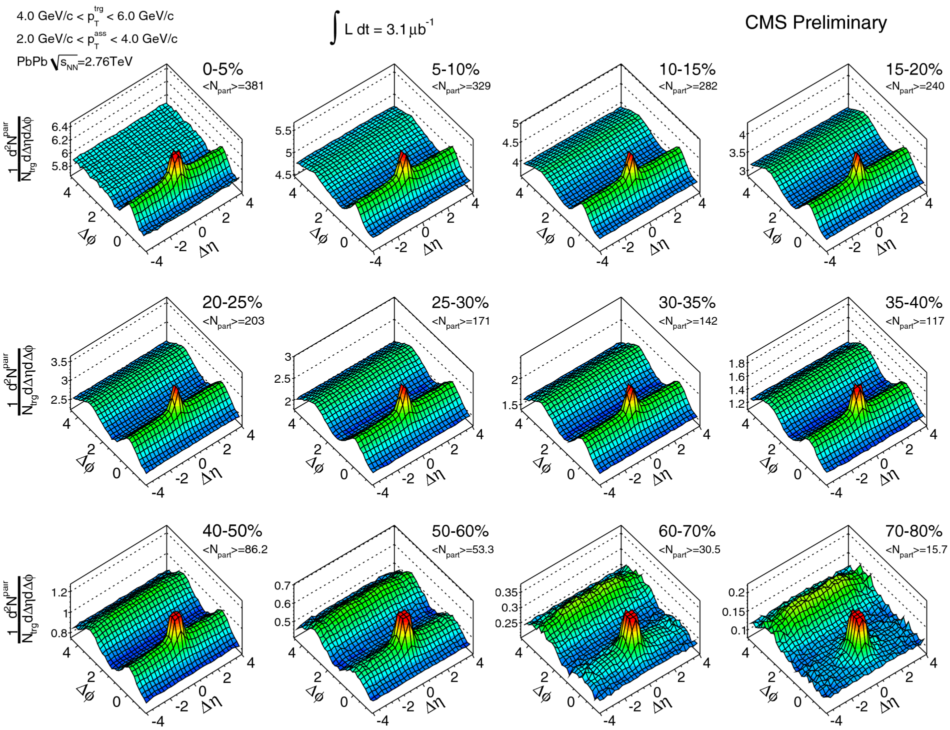

Fig. 5. Two-dimensional (2D) per-trigger-particle associated yield of charged hadrons as a function of $\Delta\eta$ and $\Delta\varphi$ for $4 < p_{\rm T}^{\rm trig} < 6$ GeV/c and $2 < p_{\rm T}^{\rm assoc} < 4$ GeV/c in 12 centrality classes of Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The centrality labelling is such that 0–5% is the most central 5% of Pb–Pb collisions [4].

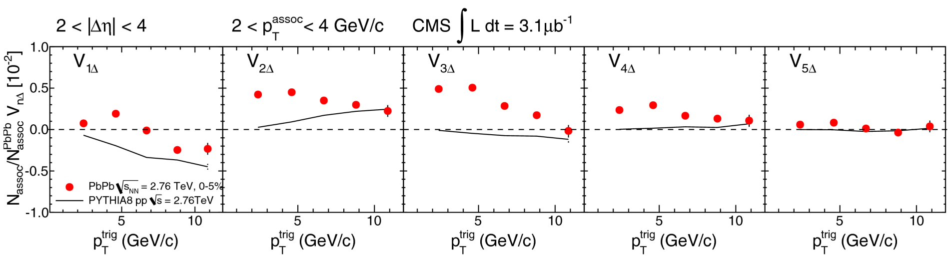

Fig. 6. Fourier coefficients, $V_{1\Delta}$, $V_{2\Delta}$, $V_{3\Delta}$, $V_{4\Delta}$ and $V_{5\Delta}$, extracted as functions of $p_{\rm T}^{\rm trig}$ for $2 < p_{\rm T}^{\rm assoc} < 4$ GeV/c for the 0–5% most central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The error bars represent statistical uncertainties only. The solid lines show the predictions from the PYTHIA8 simulation of p–p collisions at $\sqrt{s} = 2.76$ TeV [4].

determined from the fit for the most central Pb–Pb collisions are shown in Fig. 6 as a function of $p_{\rm T}^{\rm trig}$. For symmetric nuclei, the azimuthal distribution of the participant nucleons should contain only even terms. In the case of significant event-by-event fluctuations in the positions of the individual nucleons, odd terms can appear in the participant distribution, and, via hydrodynamic expansion, lead to higher-order harmonics in the momentum distributions of the emitted particles. Fig. 6 clearly demonstrates the importance of odd terms in dihadron correlations.

The flow harmonics extracted from long-range azimuthal dihadron correlations have been studied for different centrality selections, as illustrated in Fig. 7. The v_2^f term depends strongly on the centrality (as characterized by the number of participant nucleons), and the higher-order terms are only weakly dependent on the centrality of the collision. Higher order terms are particularly interesting, as — presumably — they are sensitive both to the initial geometry fluctuations and to the medium properties, such as the viscosity, as argued in [10]. Moreover, if the azimuthal dihadron correlations result from single particle anisotropy, related to collective hydrodynamic expansion [11], the Fourier components of the decomposition of the two-particle correlation, should be given by the product of the single particle coefficients. The experimental check of such factorization could throw light on the question of the origin of the Ridge Effect: is it a reflection of the single particle anisotropies — or there are more physics factors behind it. This factorization study will be a subject of the forthcoming CMS publication on correlations in Pb–Pb.

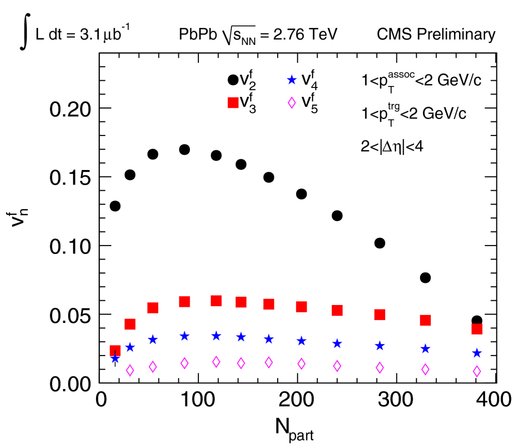

Fig. 7. The flow harmonics v_2^f, v_3^f, v_4^f and v_5^f extracted from the long-range ($2 < |\Delta\eta| < 4$) azimuthal dihadron correlations for $1 < p_{\rm T}^{\rm trig} < 2$ GeV/c and $1 < p_{\rm T}^{\rm assoc} < 2$ GeV/c as a function of the number of participating nucleons ($N_{\rm part}$) in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [4].

In view of the above experimental observations, it is very tempting to ask, whether the Ridge Effect observed in high multiplicity p–p collisions can also be analysed/described in terms of Fourier decomposition and what it would tell us about the nature and origin of observed correlations.

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