Remarks on the observation of high multiplicity events at the LHC

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Comments on the observation of high multiplicity events at the LHC

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We analyze the structure of the high multiplicity events observed by the CMS collaboration at the LHC. We argue that the bulk of the observed correlations is due to the production of a pair of jets with $p_t > 15$ GeV/c. We also suggest that high multiplicity events are due to a combination of three effects: high underlying multiplicity for collisions at small impact parameters, upward fluctuations of the gluon density in the colliding protons, and production of hadrons in the fragmentation of dijets. The data analysis is suggested which may clarify the underlying dynamics of the high multiplicity events and probe fluctuations of the gluon field as a function of x.

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I. INTRODUCTION

Recently the CMS collaboration reported the first data on the pp collisions at $\sqrt{s}$= 7 TeV taken with a special high multiplicity (HM) trigger[1]. The trigger selected events with multiplicity $N_{ch} \geq 110$, in the pseudorapidity interval $|\eta| < 2.4$ and $p_t > 0.4$GeV/c. This corresponds to the multiplicities ~ 7 times larger than in the minimal bias inelastic events ($N_{min.bias} \sim 15$). The reported studied the two-particle correlation in pseudorapidity, $\Delta\eta = \eta_1 - \eta_2$, and in the azimuthal angle $\Delta\phi = \phi_1 - \phi_2$. The main focus of the discussion was on the observation of the same side positive correlation (ridge) at $\Delta\phi \sim 0$ in a wide rapidity interval of $2 < |\Delta\eta| < 4$. A similar correlation was observed previously in the heavy ion collisions at RHIC.

The CMS ridge effect was discussed in a number of theoretical papers. However little attention was payed to a number of other remarkable features of the data. The aim of this note is to fill this gap and to suggest possible ways of analyzing the data which may clarify the dynamics of the HM events and provide a tool for studying fluctuations of the nucleon gluon density.

Let us first summarize the basic observations of the CMS study.

- The trigger selects events with average multiplicity which is approximately seven times higher than for the minimum bias inelastic pp collisions. Probability of the selected events is very small,

$$P_{HM} \approx 10^{-5} \div 10^{-6}. \tag{1}$$

- There is a very strong and localized in $\Delta\eta$ positive two-particle correlation for $\Delta\phi \sim 0$ if two particles with $1 < p_t < 3$ GeV/c are selected.
- For the same p_t cut there is a strong positive two-particle correlation for $\Delta\phi \sim \pi$ for a broad range of $\Delta\eta$.
- Total correlated hadron multiplicity of hadrons in the same side $2 < |\Delta\eta| < 4.8$ ridge is ~ 0.04 (0.02) if both selected hadrons have comparable momenta in the range $1 < p_t < 2 (2 < p_t < 3)$ GeV/c (the off-diagonal correlations were not reported yet).

II. ORIGIN OF THE AWAY SIDE RIDGE AND CORRELATIONS IN $\Delta\eta \sim 0, \Delta\phi \sim 0$

The inspection of the correlation plot (Fig. 7 of ref. [1]) indicates that the total excess transverse momentum in the $\Delta\phi \sim \pi$ region is

$$p_t^{balance} \geq \; 15\text{GeV/c}. \tag{2}$$

It is not possible to estimate in the same way the same side correlated transverse momentum since the correlation function for $\Delta\phi = 0$ is off the vertical scale of the plot. However it is clear that the total excess transverse momentum in the $\Delta\eta \sim 0, \Delta\phi \sim 0$ region is comparable to $p_t^{balance}$ (Eq.2).

Thus it appears that the bulk of the observed $\Delta\eta, \Delta\phi$ correlations is due to production of two back to back jets with p_t >15 GeV/c. This would explain both the strong narrow correlation in the towards region and a broad correlation in the away region. The later is due to a broad distribution over x_1, x_2 in the hard parton collisions at typical $x_i \sim 2p_t/\sqrt{s} \sim 5 \cdot 10^{-3}$. A priori this does not exclude a possibility that these jets are softer than the in-vacuum gluon jets observed say in the e^+e^- annihilation due to much higher gluon densities characteristic for these collisions (see discussion below). This may be similar to the softening of the jets observed in the heavy ion collisions. Obviously, a softening of the jets would make it rather difficult to extract jets with such moderate transverse momenta from the data using existing jet finding algorithms.

A natural question here is why $p_t^{balance}$ is so large. Naively the production of jets with smaller p_t produced in the perturbative QCD (pQCD) regime with a higher rate should dominate since the centrality for jets with different p_t is practically the same [2, 3] while the hadron multiplicity in the dijet fragmentation is a rather weak function of p_t. It is possible that a large value of $p_t^{balance}$ is related to the observation of the analysis [3] that p_t at which pQCD starts to dominate grows with $\sqrt{s}$ and may be as large as 8 GeV/c in the generic $\sqrt{s}$= 7 GeV collisions. Though no specific dynamic explanation of this pattern exists so far, it appears likely that the pattern is related to the increase of the gluon density in the pp collisions with increase of $\sqrt{s}$. If so, the effect should be stronger for collisions at small impact parameters which as we argue below dominate the HM collisions since in this case the average gluon densities of the partons involved in the collisions are significantly higher than in generic inelastic collisions.

For the typical $\Delta\eta \sim 2$ we can estimate the invariant mass of the produced dijet system

$$M_{jet_1\,jet_2} = 2p_t \exp(\Delta\eta/2) \sim 100\text{GeV}. \tag{3}$$

The multiplicities of hadrons in the fragmentation of the gluon jets were studied in a number of experimental papers, see [5] and references therein - and found to be in good agreement with the pQCD expectations [4]. Using these data we can estimate that the charge hadron multiplicity in these events due to the gluon dijet fragmentation is ~ 30, and hence gives a substantial ($\sim 25\%$) contribution to the total multiplicity.

Presence of jets with large p_t in the CMS HM events may be of relevance for the interpretation of the same side large $|\Delta\eta|$ ridge. Indeed, pQCD predicts a relatively small suppression of the particle density (integrated over particle energies) emitted in-between jets. The suppression is proportional to $\sqrt{N_c\alpha_s/\pi}$. Also, pQCD leads to the difference between in- and out-of plane emissions (a sort of "string effect"), in favor of in-plane emission - a ridge like structure. The actual numerical value is kinematics and color flow dependent (for extended discussion of the QCD coherence phenomena in the jet production see [4]).

It would be straightforward to find out how important the production of the back to back jets is in the HM events with the data at hand. This would allow also to check how much the pQCD "string effect" contributes to the same side ridge (which constitutes ~ 0.04 charged particle per event for $1 < p_t < 2$ GeV/c). In particular one would be able to test predicted by pQCD dependence of the ridge on the the value of $\eta_1 - \eta_2$. Comparison with the ridge structure in the minimal bias dijet production for $p_t \geq 20 GeV/c$ would be useful as well.

III. DYNAMIC MECHANISMS FOR GENERATING HIGH MULTIPLICITY AND HIGH p_t JETS

It is natural to expect that the average hadron multiplicity should monotonously increase with a decrease of the impact parameter, b. Hence the HM trigger of the CMS should correspond to the collisions at very small b. We can use the analysis of [2] to estimate the probability that an inelastic collision occurs at small impact parameters. We find that the probability for $b < 0.2$ fm is small $\sim 2\%$ but still much larger than P_{hm} (Eq.1).

Let us now estimate the average multiplicity for collisions at $b \sim 0$ for $\sqrt{s} = 7$ TeV. The inclusive dijet trigger selects collisions at a median $b \approx 0.6$ fm [3]. The underlying multiplicity for such collisions is about a factor of two larger than in the minimal bias non-diffractive events, see discussion and references in [3, 6]. So for $b \sim 0$ the enhancement should be somewhat larger.

A rough estimate can be made using information about b-distribution of minimal bias events for which median b is ~ 2 than for the dijet events [3]. Experiments excluded diffractive events when calculating minimal bias hadron multiplicity. The diffractive processes which constitute about 30% of the total inelastic cross section mostly occur at large impact parameters. Taking this into account and comparing the b distribution in non-diffractive minimal bias events and in dijet events one can "subtract" the large b tail of the dijet distribution. As a result we estimate that the average multiplicity for collisions with $b < 0.6 fm$ is about 2.5 times higher than in minimal bias non-diffractive events. One may expect a further increase for $b \sim 0$.

Hence we conclude that a scenario where small P_{hm} is solely due to the small probability of small b collisions and a small probability of selecting dijets with high p_t would lead to a large multiplicity on the scale of

$$N_{ch} = N_{jetjet} + N_{underlying} \geq 70. \tag{4}$$

In this estimate we have assumed for illustration that dijet multiplicity is of the order one. However the obtained N_{ch} is still significantly smaller than the observed one. Thus HM trigger selects the tail of the distribution of the multiplicity for central collisions.

It is natural to expect that to generate a higher multiplicity one needs to take into account fluctuations of the strength of the gluon field on an event by event basis. It was demonstrated in [7] that one can relate the dispersion of the strength of the gluon field at small x to the ratio of inelastic and elastic vector meson production at $t = 0$:

$$\omega_g \equiv \frac{\langle G^2\rangle - \langle G\rangle^2}{\langle G\rangle^2} = \left[\frac{d\sigma^{\gamma_L^* p\to VX}}{dt}\Big/\frac{d\sigma^{\gamma_L^* p\to Vp}}{dt}\right]_{t=0}. \tag{5}$$

A model of global fluctuations was proposed in [7] which allowed the explanation of the magnitude of the experimental ratio in Eq. 5. It took into account the QCD DGLAP evolution of ω_g. For the discussed CMS kinematics the model [7] leads to $\omega_g \sim 0.1$.

We can define the probability for a fluctuation in a nucleon to have the strength of the gluon field $\geq r$ times larger than the gluon parton density which is the average over all configurations in the nucleon as:

$$P(r) = \int d\sigma \frac{G(x,Q^2|\sigma)}{G(x,Q^2)}\theta(G(x,Q^2|\sigma) - rG(x,Q^2)), \tag{6}$$

where σ labels different configurations in nucleons.

Making a simplifying assumption that the distribution over the strength of the gluon field is Gaussian we can estimate

$$P(1.5) \sim 3\%. \tag{7}$$

However it is likely that the probability of the large fluctuations is larger than given by Eq. 7. Indeed the analysis [2] of the data on production of four jets (γ + 3 jets) using information about generalized parton distributions indicates presence of the positive multiparton correlations in nucleons. Such correlations are likely to increase $P(r \geq 1.5)$.

Hence an overall probability for the interaction of two protons to occur at very small impact parameters $b < 0.2$ fm and with *both colliding nucleons* in configurations having gluon density ≥ 1.5 times larger than average, should be $\geq 10^{-5}$ which is comparable to the frequency of the events selected by the HM trigger (Eq. 1). This scenario would yield a larger value of N_{ch} than the estimate of Eq. 4 due to a higher gluon density in the colliding configurations both due to soft and semi-hard interactions. Also it would increase the rate of binary parton collisions per event.

To estimate the rate of dijet production in 2→ 2 collisions we consider first the case of inclusive dijet production. The normalized distribution over b of the inclusive dijet production, $P_2(b)$ was calculated in [2, 3] through the convolution of the generalized gluon parton distributions which are measured in the exclusive hard processes at HERA. For the dipole parameterization of the two gluon form factor ($F_{2g}(t) = (1 - t/m_g^2(x))^{-2}$):

$$P_2(b) = \frac{m_g^2}{12\pi}\left(\frac{m_g b}{2}\right)^2 K_3(m_g b). \tag{8}$$

For the central collisions where $b \sim 0$ it is straightforward to find the ratio of the multiplicities in the $b \sim 0$ collisions and in the minimal bias collisions:

$$R_0 = P_2(0)\sigma_{in}(pp) = \frac{m_g^2}{12\pi}\sigma_{in}(pp). \tag{9}$$

For $x \sim 5 \cdot 10^{-3}$, $M_g^2 \approx 1 GeV^2$, leading to a significant enhancement of the dijet rate $R = 4.6$.

There are two types of fluctuations which modify R - one is fluctuations of $g_N(x, Q^2|\sigma)$, and another is fluctuations of the size of the overlap area, S, of the colliding protons. For example, let us consider a model of a nucleon where the gluon field is mostly in the plane of three valence quarks - "a pancake shape". In this model S for the collisions when the pancakes collide edge on edge is much smaller than in average. If we consider collisions in which the three quarks in each of the nucleons are aligned along the reaction axis S would be even smaller. Since the rate of the jet production is $\propto 1/S$ such collisions would lead to a large enhancement of the jet multiplicity.

Inclusion of the fluctuations would increase R by a factor $r_1 \cdot r_2$:

$$R = R_0 r_1 r_2, \tag{10}$$

suggesting that the enhancement could be as large as 10 for HM events, where

$$r_1 r_2 = \frac{g_N(x_1, Q^2|\sigma) g_{1N}(x_2, Q^2|\sigma)}{g_N(x_1, Q^2) g_{1N}(x_2, Q^2)} \frac{\langle S \rangle}{S} \tag{11}$$

The multiparton 4→ 4 hard collisions occur at even smaller impact parameters than the 2→ 2 hard collisions. Consequently, the enhancement of the four jet production due to the 4→ 4 interactions in HM events as compared to the minimal bias events should be larger than in the 2 → 2 case. We can estimate the enhancement factor in the independent particle approximation using expression for $P_4(b)$ from [2]. Including the effect of fluctuations in the gluon density we find

$$R_{4jet} = \frac{7}{35\pi} m_g^2 \sigma_{in} r_1 r_2 r_3 r_4, \tag{12}$$

which is several times larger than for the two jet case. However the independent parton approximation underestimates the rate of four jet production[2], so the enhancement factor may depend on the mechanism of parton-parton correlations and differ ffrom the square of the enhancement for the dijet production.

IV. TESTING COLOR FLUCTUATION CONJECTURE

Above we have made a conjecture that the HM trigger selects collisions of nucleons in configurations with larger than average gluon density. In other words we suggest that HM and high gluon density fluctuations go hand in hand.

It is rather difficult to check this conjecture using the data analysis procedure of ref. [1] since one could always question whether the HM trigger by itself was selecting events with extra hard collisions.

Here we discuss several possible strategies which address a possible dependence of the gluon fluctuations on x, virtuality of the gluon and overall transverse size of the projectiles. Note here that so far the gluon fluctuations were modeled only in [7]. This model focused on the small x region and led to a decrease of ω_σ with increase of x. In this model significant cancelations are present for the enhancement factor given by Eq. 11 since in this model the upward fluctuation of the gluon field are related to the upward fluctuations of the overall size for configurations. However the model does not include fluctuations of the shape which may not change the gluon densities, for example "pancake" fluctuations discussed in the previoous section. Such effects may lead to significant fluctuations of $g_1 g_2/S$ for a wide range of x.

One option to probe gluon field fluctuations is to look for dijets at the central rapidities in matching back to back narrow cones but to use in the HM trigger only hadrons outside these cones. This way one would be able to determine how much gluon fields in two nucleons are enhanced in the overlapping area as compared to the scenario where no fluctuations are present.

Another option is to consider the multiplicity of the dijet production, N_{2j} in the region $|\eta| > 3.5 \div 3.0$ as a function of the multiplicity at central rapidities,$|\eta| < 2.4 - N_{central}$. The gap between the two regions would minimize the leaking of hadrons from hard collision to the central region. This problem is of importance only if $\eta_1 > 0, \eta_2 < 0$. Both the CMS and the ATLAS can measure jets in this kinematics using forward calorimeter components of their detectors. In this kinematics one would test the fluctuations of gluons either with say $x_1 \sim 10^{-3}$ and $x_2 \gg x_1$ (same side jets) or if $x_1 \sim x_2 > 0.05$ (opposite side jets).

One can expect that $N_{2j} N_{central}$ would grow monotonously with increase of $N_{central}$ due to increase of the centrality of the collisions. There should be a substantial increase of $N_{2j}(N_{central})$ between $N_{central} = N_{min.bias}$ and $N_{central} = 2N_{min.bias}$ corresponding to typical underlying multiplicity for dijet events (which reflects a more central nature of the hard collisions). If the gluon fluctuations would not kick in, N_{2j} would saturate at the value

$$N_{2j} = \lambda N_{2j}(N_{min.bias}), \tag{13}$$

with $\lambda \sim 4$, cf. Eq.9 with a small residual x_i dependence due to the broadening of the transverse distribution of gluons with decrease of x_i [2, 3]

Fluctuations may lead to a continued increase of N_{2j} for $N_{central} \gg 2N_{min.bias}$ due to the fluctuations of the gluon field. The rate of the increase may depend on x_i and p_t of the jets. In particular, in the model of [7] the increase of N_{2j} for $b \sim 0$ events should be weaker for $\eta_1 \sim -\eta_2 \sim 3$ than for $\eta_1 \sim \eta_2 \sim 0$.

In principle, by combining measurements in three discussed kinematic ranges, it may be possible to disentangle the x-dependence of the gluon fluctuations.

V. CONCLUSIONS

In the presented scenario HM events occur when the protons interact at very small impact parameter in special configurations with enhanced gluon field density. Production of two back to back jets with $p_t > 15$ GeV/c in these events is strongly enhanced as compared to the minimal bias events.

To test this hypothesis it is necessary to study the rate of jet production in the HM events in the vicinity of the test particle, and the degree of correlation of such jets with a recoil jet production. Measurement of the ratio of the probability of high p_t jets in the HM at a wide range of rapidities and minimal bias events would be especially revealing and may test the conjecture of the gluon fluctuations in nucleons and study x-dependence of the strength of these fluctuations.

To check the relevance of the pQCD string effect for the explanation of the same side ridge it is necessary to perform a comparison of the HM correlations with the correlations in pp scattering with production of dijets with $p_t \geq 20$ GeV/c. Alternatively the ridge could be due to a selection of rare configurations in the protons of a complicated transverse shape.

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