Fluctuations of the nucleon transverse parton densities and inelastic collisions at the LHC

Mark Strikman

Penn State Univeristy, University Park, PA 16802, USA

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We consider constraints on modeling of inelastic collisions at the LHC which follow from the studies of the transverse structure of nucleon, fluctuations of the strength of the gluon field at small x and the rate of the multiparton interactions at the Tevatron. Effects due to proximity to the black disk regime are discussed. We also suggest that gluon fluctuations are maybe responsible for a number of the features of the high multiplicity events studied by CMS

1 Introduction

Modeling of the inelastic collisions at the LHC has two principal goals. One is to ensure a good description of the underlying events for the processes used to look for new particles. Another is to learn about working of QCD at ultrahigh energies. In the first case one can use a wider range of the input parameters allowing them to be outside the range dictated by the other data, ignoring effects of high gluon densities which start to be important at the LHC energies. However this way one can easily overlook emergence of new QCD phenomena.

In this talk I will focus on several challenges for building realistic description of inelastic *pp* collisions: including realistic transverse parton distributions in modeling *pp* collisions, including parton - parton correlations to describe multiparton interactions with realistic single parton transverse densities, realistic modeling of effects of black disk regime (BDR) at moderate transverse momenta both in the central and forward region, probing BDR at forward rapidities, modeling effects of diffraction for inelastic collisions.

2 Impact parameter distributions of the hard inelastic collisions

Most of the current Monte Carlo approaches model *pp* collisions using the impact parameter representation. This is a natural framework for description of the complete picture of the high energy interaction since in high–energy *pp* scattering angular momentum conservation implies that the impact parameter b becomes a good quantum number. Hence it is natural to consider amplitudes and cross sections in the impact parameter representation.

The QCD factorization theorem for hard exclusive processes [1] allows to determine in a model independent way the small x generalized diagonal parton distribution (GPD), $g(x, t|Q^2)$, where the momentum transfer to the nucleon is in the transverse direction, with $t = -\mathbf{\Delta}_\perp^2$ (we follow the notation of Refs. [2, 3]). This function reduces to the usual gluon density in the nucleon in the limit of zero momentum transfer, $g(x, t = 0|Q^2) = g(x|Q^2)$. Its two-dimensional Fourier transform

$$g(x, \rho|Q^2) \;\equiv\; \int \frac{d^2\Delta_\perp}{(2\pi)^2}\, e^{i(\boldsymbol{\Delta}_\perp \boldsymbol{\rho})}\, g(x, t = -\boldsymbol{\Delta}_\perp^2|Q^2) \tag{1}$$

describes the one–body density of gluons with given x in transverse space, with $\rho \equiv |\boldsymbol{\rho}|$ measuring the distance from the transverse center–of–momentum of the nucleon, and is normalized such that $\int d^2\rho\, g(x, \rho|Q^2) \;=\; g(x|Q^2)$. It is convenient to separate the information on the total density of gluons from their spatial distribution and parametrize the GPD in the form

$$g(x, t|Q^2) \;=\; g(x|Q^2)\, F_g(x, t|Q^2), \tag{2}$$

where the latter function satisfies $F_g(x, t = 0|Q^2) = 1$ and is known as the two–gluon form factor of the nucleon. Its Fourier transform describes the normalized spatial distribution of gluons with given x,

$$F_g(x, \rho|Q^2) \;\equiv\; \int \frac{d^2\Delta_\perp}{(2\pi)^2}\, e^{i(\boldsymbol{\Delta}_\perp \boldsymbol{\rho})}\, F_g(x, t = -\boldsymbol{\Delta}_\perp^2|Q^2), \tag{3}$$

with $\int d^2\rho\, F_g(x, \rho|Q^2) = 1$ for any x.

The QCD factorization theorem predicts that the t-dependence of the vector meson (VM) production should be a universal function of t for fixed x (up to small DGLAP evolution effects). Indeed the t-slope of the J/ψ production is practically Q^2 independent, while the t-slope of the production of light vector mesons approaches that of J/ψ for large Q^2.

The t–dependence of the measured differential cross sections of exclusive processes at $|t| < 1\,\mathrm{GeV}^2$ is commonly described either by an exponential, or by a dipole form inspired by analogy with the nucleon elastic form factors. Correspondingly, we consider here two parametrizations of the two–gluon form factor:

$$F_g(x, t|Q^2) \;=\; \left\{ \begin{array}{l} \exp(B_g t/2), \\ \\ (1 - t/m_g^2)^{-2}, \end{array} \right. \tag{4}$$

where the parameters B_g and m_g are functions of x and Q^2. The two parametrizations give very similar results if the functions are matched at $|t| = 0.5\,\mathrm{GeV}^2$, where they are best constrained by present data (see Fig. 3 of Ref. [4]); this corresponds to [3]

$$B_g \;=\; 3.24/m_g^2. \tag{5}$$

The analysis of the HERA exclusive data leads to

$$B_g(x) = B_{g0} \;+\; 2\alpha_g' \;\ln(x_0/x), \tag{6}$$

where $x_0 = 0.0012, B_{g0} = 4.1\ ({}^{+0.3}_{-0.5})\ \mathrm{GeV}^{-2}, \alpha_g' = 0.140\ ({}^{+0.08}_{-0.08})\ \mathrm{GeV}^{-2}$ for $Q_0^2 \sim 3\ \mathrm{GeV}^2$. For fixed x, $B_g(x, Q^2)$ slowly decreases with increase of Q^2 due to the DGLAP evolution [2]. The uncertainties in parentheses represent a rough estimate based on the range of values spanned by the H1 and ZEUS fits, with statistical and systematic uncertainties added linearly.

The probability distribution of pp impact parameters in events with a given hard process, $P_2(x_1, x_2, b|Q^2)$, is given by the ratio of the cross section at given b and the cross section integrated over b. As a result

$$P_2(x_1, x_2, b|Q^2) \equiv \int d^2\rho_1 \int d^2\rho_2 \, \delta^{(2)}(\boldsymbol{b} - \boldsymbol{\rho}_1 + \boldsymbol{\rho}_2) F_g(x_1, \rho_1|Q^2) \, F_g(x_2, \rho_2|Q^2) \, . \tag{7}$$

This distribution represents an essential tool for phenomenological studies of the underlying event in pp collisions [2, 3].

For the two parametrizations of Eq. (4), Eq. (7) leads to (for $x \equiv x_1 = x_2$)

$$P_2(x, b|Q^2) \; = \; \begin{cases} (4\pi B_g)^{-1} \, \exp[-b^2/(4B_g)], \\ [m_g^2/(12\pi)] \, (m_g b/2)^3 \, K_3(m_g b), \end{cases} \tag{8}$$

where the parameters B_g and m_g are taken at the appropriate values of x and Q^2.

Comment: The popular Monte Carlo approaches to modeling pp collisions at the collider energies – PYTHIA[5] and HERWIG[6] – use x-independent transverse distributions of partons. In PYTHIA it is given by the sum of two exponentials. This distribution is roughly equivalent to the dipole parametrization with $m^2 \approx 2$ GeV^2 [7] which is hardly consistent with the data on J/ψ exclusive photo-production. For smaller x the difference is even larger since the transverse size increases with decrease of x – see Eq. 6. In HERWIG the dipole fit is used with m_g treated as a free parameter which is allowed to vary in a broad interval. Using parametrizations of the transverse distribution with $m_g^2 s \sim 2\text{GeV}^2$ leads to a much more narrow area in the impact parameter for events collisions with a dijet trigger – a factor of two for $x \sim 10^{-2}$ and at least of three for $x \leq 10^{-3}$. Such strong localization of the hard interactions in b strongly suppresses probability of the hard collisions at large impact parameters, leaving a much larger phase space for soft collisions. It also masks problems with s-channel unitarity for large $b \sim 1.5$ fm [8].

Comparison of Eq. (8) with the b dependence of the generic inelastic collisions [2, 3] leads to conclusion that there are two distinctive classes of collisions at the LHC – large b collisions with a modest dijet activity and the central events with enhanced dijet activity. Also the QCD analysis of [2, 3] has demonstrated that in the kinematics available at the LHC the distribution over b of inclusive dijet production changes very little with the variation of x's of the colliding partons and with p_T of the produced jets. This leads to the expectation of the universal structure of the underlying events [3]. Indeed ATLAS and CMS report that for sufficiently high p_T of the leading particle (≥ 6 - 8 GeV/c for $\sqrt{s} = 7$ TeV) the away multiplicity $|\Delta\phi| > 120^o$ practically does not depend on p_T. Note however that a more accurate study of the universality and possible difference between two gluon jets and $q\bar{q}$ trigger would require introducing a tighter cut on $\Delta\phi$ or subtracting the jet fragmentation contribution by fitting $\Delta\phi$ dependence of the underlying multiplicity.

Many further tests of the discussed picture which were suggested in Ref. [3] will be feasible in a near future. They include (i) Check that the transverse multiplicity does not depend on rapidities of the jets, (ii) Study of the multiplicity at $y < 0$ for events with jets at $y_1 \sim y_2 \sim 2$. This would allow to check that the transverse multiplicity is universal and that multiplicity in the away and towards regions are similar to the transverse multiplicity for $y \leq 0$. (iii) Studying whether transverse multiplicity is the same for quark and gluon induced jets. Since the gluon radiation for production of $W^{\pm}, Z$ is smaller than for gluon dijets, a subtraction of the radiation effect mentioned below is very important for such a comparison.

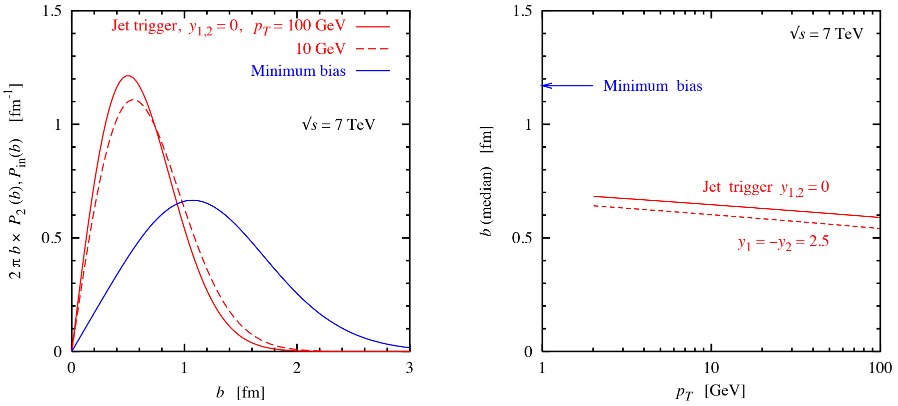

Figure 1: (a) Impact parameter distributions of inelastic pp collisions at $\sqrt{s} = 7\,\text{TeV}$. *Solid (dashed) line:* Distribution of events with a dijet trigger at zero rapidity, $y_{1,2} = 0$, for $p_T = 100\,(10)\,\text{GeV}$ cf. Eq. (8). *Dotted line:* Distribution of minimum–bias inelastic events. (b) Dependence of median b on p_T for different rapidities of the dijets.

It is also worth noting that in the experimental comparisons of transverse multiplicity in the events with dijet trigger and generic inelastic events the diffractive events are often removed from the comparison. There is a strong evidence for suppression of the dijet production in the diffractive events confirming generic expectation that high energy inelastic diffraction is predominantly a large b phenomenon. Hence removing diffractive events reduces the difference between median b's of two classes of the events. Therefore a strong increase of the transverse multiplicity occurs over somewhat smaller range of impact parameters than indicated by Fig. 1.

3 Correlations of partons and multiparton interactions

Measurements of multiparton interactions provide a unique opportunity to study parton - parton correlations in nucleons. Multiparton interactions were observed in a number of experiments at the Tevatron. The first results from the ATLAS experiment were reported at this meeting.

If we parameterize $4 \to 4$ cross section as

$$\frac{d\sigma(4 \to 4)}{d\Omega_1 d\Omega_2} = \frac{1}{S} \frac{d\sigma(2 \to 2)}{d\Omega_1} \frac{d\sigma(2 \to 2)}{d\Omega_2} \tag{9}$$

where Ω_i is the phase volume for production of a pair of jets, the Tevatron data indicate $S \sim 15$ mb. Similar S (which is often denoted as σ_{eff} or πR^2_{int}) was reported by ATLAS at this meeting.

In the independent particle approximation which is used in all Monte Carlo models with multiparton interactions, the two-parton GPD is equal to the product of single particle GPDs discussed in section 2. Using parametrization of Eq. (8) one finds [2, 9]

$$\frac{1}{S} = \int \frac{d^2\Delta}{(2\pi)^2} F_g^4(\Delta) = \frac{m_g^2}{28\pi}, \tag{10}$$

which leads to approximately a factor of two smaller cross section than the one observed at the Tevatron: $S \approx 34$ mb. This clearly shows that significant *positive* correlations should be present between partons for x's $\sim$ few 10^{-2} probed experimentally.

There are a priori two possibilities: (a) correlations induced via pQCD evolution which correspond to $3 \to 4$ processes [9], (b) non-perturbative correlations at the resolution scale of $Q_0^2 \sim 1$ GeV^2.

The analysis of [10, 11] indicates that $3 \to 4$ processes play a minor role in the Tevatron kinematics and do not allow to solve this discrepancy. Hence the only viable option seems to be presence of non-perturbative correlations. In principle they could be due to transverse or longitudinal correlations or a mix. Our studies indicate that for small x the enhancement of the cross section results from comparable contributions of the transverse and longitudinal correlations [11]. A model independent measurement of the longitudinal correlations will be possible in the pA collisions [12].

Hence in modeling inelastic collisions at the LHC one is faced with a choice between two options: ignoring information about transverse distribution of partons from hard exclusive processes and fixing it to describe four jet event – this solution is implemented in the standard versions of PYTHIA – or introducing parton-parton correlations in generating configurations for MCs, – so far not implemented in any MCs.

4 Fluctuations of the gluon field and high multiplicity events at LHC

Strength of the gluon field should depend on the size of the quark configurations. For example, the gluon field in the small configurations should be strongly screened – the gluon density much smaller than average.

The variance of the gluon strength at small x can be extracted from the comparison of the diffractive processes: $\gamma_L^* + p \to V + X$ and $\gamma_L^* + p \to V + p$ [13]:

$$\omega_g \equiv \frac{\langle G^2\rangle - \langle G\rangle^2}{\langle G\rangle^2} = \frac{d\sigma_{\gamma^*+p\to VM+X}}{dt} \Bigg/ \frac{d\sigma_{\gamma^*+p\to VM+p}}{dt}\Bigg|_{t=0}. \tag{11}$$

The HERA data indicate that for $Q^2 \sim 3$ GeV^2 and $x \sim 10^{-3}$, $\omega_g \sim 0.15 \div 0.2$ which is rather close to the value for the analogous ratio for the soft diffraction which measures fluctuations of overall strength of the *soft* hadronic interactions.

How can one probe the gluon fluctuations in pp collisions? Let us consider multiplicity of an inclusive hard process – dijet,... as a function of some cuts – for example overall hadron multiplicity, M (trigger), and build the ratio

$$R = \frac{M(trigger)}{M(minimum - bias)}. \tag{12}$$

If there are no fluctuations of the parton densities, the maximal value of R is reached if the trigger selects collisions at small impact parameters $b \sim 0$. Using Eq. (8) we find [14]

$$R = P_2(0)\sigma_{in}(pp) = \frac{m_g^2}{12\pi}\sigma_{in}(pp) \approx 4.5. \tag{13}$$

A larger enhancement of R could arise only from the fluctuations of the gluon density per unit area.

The first measurement which appears to be relevant for addressing the question of fluctuations was reported by ALICE [15]. The multiplicity of J/ψ was studied as a function of the multiplicity in the central detector, namely $dN^R_{ch}/d\eta = dN_{ch}/d\eta_{\eta=0}/\left\langle dN_{ch}/d\eta_{\eta=0}\right\rangle$, for $dN^R_{ch}/d\eta \leq 5$. It was found that R increases with increase of $dN^R_{ch}/d\eta$ reaching values ≈ 5 for $dN^R_{ch}/d\eta \sim 4$. This number is close to what we estimated above. Any further increase of R would require presence of the fluctuations in transverse gluon density. An enhancement above the geometric $b = 0$ effect is given by the factor

$$R_{fl} = \frac{g_N(x_1, Q^2|n) g_N(x_2, Q^2|n)}{g_N(x_1, Q^2) g_N(x_2, Q^2)} \frac{\langle S\rangle}{S}. \tag{14}$$

Here n labels configurations selected by the trigger, and S is the area of the transverse overlap. In principle R_{fl} could reach very large values. For example, if we consider a collision of two protons in cigar shape configurations with the same gluon density for different orientations of the protons, the enhancement would be proportional to the ratio of the principal axes of the ellipsoid. Another mechanism for the enhancement of R_{fl} is the presence of the dispersion in the gluon density with $\omega_g \sim 0.15 \div 0.2$, Eq. (11), which leads to a few percent probability for the gluon field to be a factor 1.5 larger than average.

These observations are maybe of relevance for the discussion of the high multiplicity (HM) events studied by the CMS [16]. In the analysis very rare events were selected which have the overall multiplicity for $|\eta| < 2.4$ of at least a factor of ≥ 7 larger than the minimum–bias events. Probability of such events is very small: $P_{HM} \approx 10^{-5} \div 10^{-6}$. The two-particle correlations were measured as a function of the distance in the pseudorapidity - $\Delta\eta$ and the azimuthal angle - $\Delta\phi$. Three types of correlations were observed : (a) very strong local correlation for $\Delta\eta \sim 0, \Delta\phi \sim 0$, (b) strong correlation for $\Delta\phi \sim \pi$ for a wide range of $\Delta\eta$, (c) a weak correlation for $2 < |\Delta\eta| < 4.8, \Delta\phi \sim 0$ – so called ridge.

The first question to address is how to get such a large multiplicity. It is pretty obvious that such events should originate from very central collisions. Based on our knowledge of $P_2(b)$ we find that the probability of the collisions at b < 0.2 fm is ∼2%. Using information about dispersion of fluctuations of the gluon fields we estimate the probability of fluctuation where **both** nucleons have $g > 1.5 g_N(x)$ is $\geq 10^{-3}$. So a natural guess is that the CMS trigger selected central collisions with enhanced gluon fields in both nucleons. This should result in a much higher rate of jet production per event. Indeed inspection of the HM data indicates presence of a large total excess transverse momentum in the $\Delta\phi \sim \pi$ region. Presumably it is due to production of two back to back jets with the trigger jet generating the narrow same side correlation. Qualitatively, a large probability of the dijets is maybe due to the combination of centrality and the gluon density fluctuation. A quantitative analysis of the excess transverse momenta in the same side and away side regions is badly needed.

Note also that the increase of the multiplicity due to selection of $b \sim 0$ and selection of $b \sim 0$ and enhanced dijet production is not sufficient to generate a factor of 7 increase in the multiplicity - without of the gluon density fluctuations these two effects typically lead to $N_{ch} \sim 70$. The $g > g_N(x)$ gluon fluctuations would naturally lead to a further increase of N_{ch}.

The same side ridge could originate from the QCD string effect [17]. This could be tested by studying collisions with production of dijets with $p_T \sim 15$ GeV/c without HM trigger. Alternative mechanism would be fluctuations of the transverse shape of the colliding nucleons plus presence of the absorptive effects for $p_t \leq 3$ GeV/c. Such a scenario appears quite natural for the high density mechanism we discuss here.

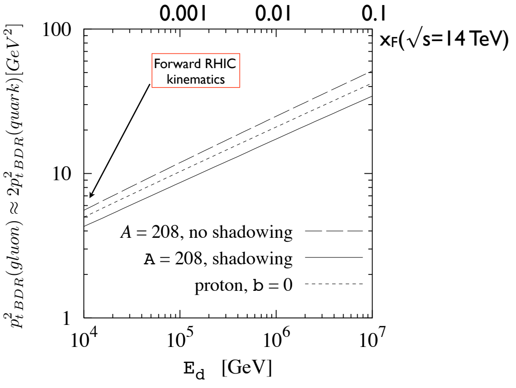

Figure 2: The p_T range where interaction is close to the BDR for the interaction of $q\bar{q}$ and color octet dipoles plotted as a function of the energy of the dipole and of x of the interacting parton for pp interactions at $\sqrt{s} = 14$TeV.

5 Onset of nonlinear regime and suppression of minijets in *pp* collisions

One of the important observations of the MC models is that to reproduce the data one needs to suppress production of minijets. PYTHIA [5] introduces the energy dependent suppression factor

$$R(p_T) = p_T^4/(p_T^2 + p_0^2(s))^2, \tag{15}$$

with $p_0(\sqrt{s} = 7 \text{ TeV}) \approx 3$ GeV/c, corresponding to $R(p_T = 4 \text{ GeV/c}) = 0.4$. In HERWIG [6] a cutoff of similar magnitude is introduced of the form $\theta(p_T - p_0'(s))$. (Need for a cutoff of similar magnitude can be derived also by considering requirements imposed by the condition that probability of the pp collision at a given impact parameter (as determined from the data on elastic scattering) should be larger than the probability of processes with jet production. One can see that the main minijet contribution to the cross section for $\sqrt{s}$= 7 TeV originates from $x_i \sim 2p_T/\sqrt{s} \geq 10^{-3}$ and virtualities $Q^2 \geq 10$ GeV^2. This is where kinematics describes well DIS scattering. So cutoff is not connected to the taming of the parton distributions at small x. This is consistent with the studies of the elastic small dipole − nucleon interaction which indicate that for this kinematics partial waves of the scattering amplitude are far from the limit of complete absorption (Black Disk Regime - BDR) even for small b, for a review see [2]. The results of this analysis for $b = 0$ are presented in Fig.2. However interaction of the colliding partons with the rest of the nucleon corresponds to much larger invariant energies and hence smaller x. This is because a parton in the nucleon with a given x_1 resolves the gluons in the second nucleon with x_2 down to $4p_T^2/x_1 s$. For example, taking $x \sim 10^{-2}$, $\sqrt{s}$=14 TeV and $\sim p_T^2 = 4$ GeV^2 we find $x_2(min) = 10^{-4}$. For these x interaction is much closer to BDR, see Fig.2. Hence it appears that BDR for gluons is present in the kinematics relevant for the presence of effective cutoff for the minijet production via interactions with the "spectator" partons. How to implement this effect in the MCs remains an open question. In any case, such a procedure has to overcome an important deficiency of the current procedure – suppression of the interaction of leading partons with media which allows a parton with large x_F to propagate through the center of the nucleon without interaction at relatively small virtualities. Such a scenario clearly contradicts the pattern of strong suppression of the leading particle production expected in the BDR. These expectations are consistent with the regularities of the leading pion production in the central deuteron-gold collisions at RHIC where local nuclear gluon density is comparable to that at the average impact parameters in *pp* collisions at the LHC, see [18] for the recent summary.

6 Conclusions

It is important to start developing models of inelastic *pp* collisions which satisfy constraints on the transverse distributions of partons from the hard exclusive processes, as well as from the measurements of MPI. This would require introducing significant correlations in the generalized double parton distributions. Effects of the BDR dynamics should be also taken into account.

It is important to perform dedicated analyses of the data to test transverse geometry of the *pp* collisions and to understand better dependence of the diffractive collisions on impact parameter. A number of the processes can be used to probe color fluctuations effects in *pp* collisions with a hard trigger. Critical tests of the underlying dynamics and in particular effects of proximity to the BDR could be performed studying hadron production in the fragmentation region and the long range correlations between hadron production in the forward and central regions.

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