High parton densities and striking final states at the LHC

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Recent data from HERA show that the proton's quark and gluon distributions grow fairly rapidly with decreasing x-values for a fixed value of Q^2. This means that the number of partons, quarks and gluons, in the wavefunction of a high energy proton becomes large at very small values of x. Present indications are that $xG(x, Q^2)$, the number gluons per unit rapidity and having spatial transverse size $\Delta x_\perp \approx 1/Q$, may be between 20 and 30 at moderate Q^2 and at the smallest x-values available at HERA. It is widely believed that parton densities cannot grow indefinitely at small x, but that "parton saturation" will cause number densities to become constant or, perhaps, grow slowly as x becomes extremely small. Exactly how parton saturation comes about, and its relationship to unitarity, is currently under vigorous study by theorists working in QCD.

Why this is such an exciting question is not hard to see. Gluons having longitudinal momentum fraction x and transverse size $\Delta x_\perp \propto 1/Q$ give a contribution to the typical QCD field strength in the light cone wavefunction of the proton of size

$$\Delta x_\perp^2 \bar{F}_{\mu\nu}^2 \propto xG(x, Q^2). \tag{1}$$

Thus when $xG(x, Q^2)$ becomes as large as $[Q^2\alpha_s(Q^2)]^{-1}$ typical field strengths will reach values of $\bar{F}_{\mu\nu} \propto 1/g_s(Q)$. At such values perturbation theory ceases to be reliable and a new nonperturbative regime of QCD is reached. This is a regime where α_s is small, and so the usual nonperturbative order parameters and condensates of QCD are unimportant, but because field strengths are so large interactions are highly nonlinear. Although parton number densities at HERA and Fermilab energies are large they do not appear to be large enough to reach a truly high density regime where perturbation theory breaks down while α_s is still small. Deep inelastic scattering on nuclei at HERA may allow one to reach saturation in the $Q^2 \approx 1 - 2GeV^2$ region[1] but studies of very high density partonic systems where α_s is clearly small can only be done at LHC.

From the discussion given above it would seem that the physics we are considering here may be closely related to that of relativistic heavy ion collisions where one also focuses on high density partonic systems. Indeed the very early stages of a heavy ion collision deal with exactly the same QCD phenomena of high field strengths and saturation. Estimates[2] for LHC suggest that the high field strength regime can be reached for gluons at a scale of $Q^2 \approx 5GeV^2$ during the very early stages of a heavy ion collision. (A crude estimate of the momentum where saturation becomes important is given in Eq.3.15 of Ref.3 as $Q^2 = \frac{9}{16}\pi\alpha N_c \frac{AxG}{R^2}$ with A the atomic number and R the radius of the nuclei in a head-on collision.) Then after a short time kinetic equilibration takes place and field strengths are lowered to their equilibrium value of $\bar{F}_{\mu\nu} \propto \frac{1}{\sqrt{g_s(T)}}$.

Typical proton-proton collisions at LHC will not produce parton densities as high as those at the early stages of heavy ion collisions at LHC, however, proton-proton collisions have several advantages. (i) Hadronic and jet signals are much easier to study in a proton-proton collision than in a heavy ion collision especially if one is trying to extract information from the very earliest stages of the heavy ion collision. (ii) In a proton-proton collision fluctuations far from the average occur often enough to be measureable and thus a quite high density partonic system may be produced for moderate values of Q^2.

This leads us to the essential topic of this section, that of high multiplicity, and high parton density, fluctuations in proton-proton collisions at LHC. One expects BFKL contributions to semihard collision, producing jets of about 5 GeV transvere momentum, to occur with a cross section of about a millibarn at LHC energies. This "one hard pomeron" contribution has an energy dependence which grows like $e^{(\alpha_P-1)Y}$ with $\alpha_P - 1 = \frac{4\alpha_s N_c}{\pi}\ell n2 \approx 1/2$ in leading logarithmic approximation. Correspondingly we expect about $(\alpha_P - 1)$ semihard jets to be produced per unit rapidity. Thus although gluon distributions are quite large in the LHC energy region not many of these gluons are freed in a typical collision.

However, parton fluctuations are very large in the proton, and there is a significant cross section for having a multiplicity of semihard jets k times (with k large) that of a typical semihard collision. Such events come from a

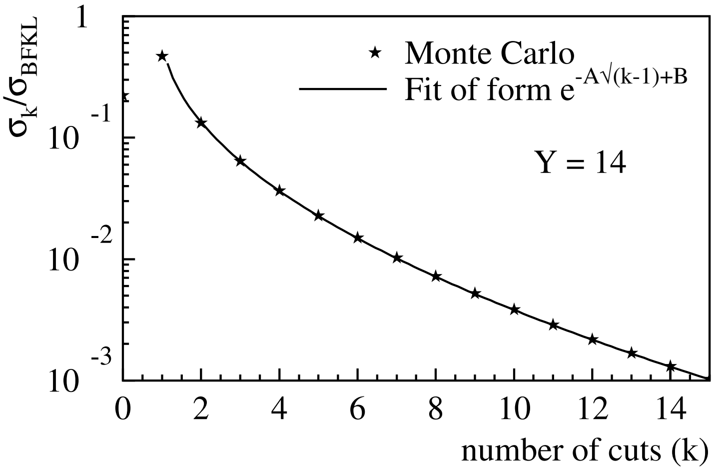

Figure 1: Cross section for different numbers of cut pomerons, together with a fit of the form Eq. (2).

$k-(cut)$ pomeron contribution and have recently been evaluated analytically in a simple model and numerically in QCD.[4] For all k

$$\frac{\sigma_k}{\sigma_{BFKL}} = e^{-A\sqrt{k-1}\,+B}, \tag{2}$$

with A and B constant, gives a good fit to Monte Carlo data coming from the dipole formulation of BFKL dynamics. (The $e^{A\sqrt{k}}$ behavior, for large k, comes naturally in the parton picture)[4] σ_k is the cross section for k cut pomerons while σ_{BFKL} is the total BFKL contribution to semihard scattering. Numerical results are shown in Fig.1 for BFKL dynamics extending over 14 units of rapidity and for transverse momenta of the produced jets corresponding to $\alpha_s = 0.18$. From the figure one can see that it may be possible to go out to $k = 10$ or more, and still have a significant cross section.

Recalling that the number of jets produced per unit rapidity is $(\alpha_P - 1)\cdot k \approx \frac{1}{2}k$, such events would be fairly striking. Over a few units of rapidity there would be, for $k = 10$, about 5 jets per unit rapidity. For jets having $k_\perp$ on the order of 5 GeV this should be right around the saturation regime where one can expect the jets to interact strongly. (It is also where our present ability to calculate in perturbation theory breaks down so that one should regard (2), which comes from perturbation theory, only as an estimate when k is as large as 10.)

Besides having a lot of jets in a few units of rapidity what other signals might one expect from this high field strength "hot spot"? One can expect a significant amount of charm and bottom quark production along with the gluon jets with bottom production perhaps only mildly suppressed compared to charm. In principle, one could also expect helicity conservation for light quarks to break down due to the axial anomaly since instanton contributions can become important as soon as field strengths become large. It is not clear, however, whether there is any experimental way to measure this chiral symmetry-breaking. This is clearly an important challenge. This is a subject still in its infancy and one can expect new ideas and signals to come about in the course of the theoretical development of the subject, a development which is receiving impetus also from the importance of understanding the earliest stages of heavy ion collisions.[5]

References

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