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SATURATION EFFECTS IN FINAL STATES DUE TO CCFM EQUATION WITH ABSORPTIVE BOUNDARY*

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We apply the absorptive boundary prescription to include saturation effects in the CCFM evolution equation. We are in particular interested in saturation effects in exclusive processes which can be studied using the Monte Carlo event generator CASCADE. We calculate the cross section for three-jet production and the distribution of charged hadrons.

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1. Introduction

At the dawn of LHC it is desirable to have tools which could be safely used to evolve colliding protons to any point of available in collision phase space. It is also desirable to have a formulation within the Monte Carlo framework because this allows to study complete events. At present, there are two main approaches within perturbative QCD which can be applied to describe the evolution of the parton densities: collinear factorisation with integrated parton densities and the DGLAP evolution equations and k_{T} factorisation with an unintegrated gluon density and the BFKL evolution equation [1]. These two approaches resume different perturbative series and are valid in different kinematic regimes of the longitudinal momentum fraction carried by the partons. However, they tend to merge at higher orders meaning that one is a source of subleading corrections for the other. The economic way to combine information from both of them is to use the CCFM approach [2] which interpolates between the DGLAP and BFKL approaches and which has the advantage of being applicable to Monte Carlo simulations of final states. However, if one wants to study physics at largest energies

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available at LHC one has to go beyond DGLAP, CCFM or BFKL because all these equations were derived in an approximation of dilute partonic system where partons do not overlap or, to put it differently, do not recombine. Because of this, those equations cannot be safely extrapolated towards high energies, as this is in a conflict with unitarity requirements. To account for dense partonic systems one has to introduce a mechanism which allows partons to recombine. There are various ways to approach this problem [3], here we are interested in the one which can be directly formulated within the $k_{\rm T}$ factorisation approach [4]. In this approach, one can formulate a momentum space version [5] of the Balitsky–Kovchegov equation [6] which sums up a large part of important terms for saturation and which is a nonlinear extension of the BFKL equation. As it is a nonlinear equation it is quite cumbersome, but one can avoid complications coming from nonlinearity by applying absorptive boundary conditions [7], which mimics the nonlinear term in the BK equation. Here, in order to have a description of exclusive processes and to account for saturation effects, we use the CCFM evolution equation together with an absorptive boundary [8] (see also [9] for a similar approach) implemented in the CASCADE Monte Carlo event generator [10].

Th outline of this presentation is the following. In Sec. 2 we show a description of F_2 data using the CCFM equation. In Sec. 3 we describe a way to incorporate saturation effects. Finally, in Sec. 4 we show results for angular distribution of three jets and the distribution of charged particles.

2. CCFM evolution equation and F_2

The CCFM evolution equation is a linear evolution equation which sums up a cascade of gluons under the assumption that gluons are strongly ordered in an angle of emission. This can be schematically written as:

$$xA(x,k_{\rm T}^2,q^2) = xA_0(x,k_{\rm T}^2,q^2) + K \otimes xA(x,k_{\rm T}^2,q^2)\,,$$

where x is the longitudinal momentum fraction of the proton carried by the gluon, $k_{\rm T}$ is its transverse momentum and q is a factorisation scale. The initial gluon distribution equals:

$$xA_0(x,k_{\rm T},\mu^2) = Nx^{Bg}(1-x)^4 \exp\left[(k-\mu)^2/\sigma^2\right]\,,$$

where the parameters above are to be determined by a fit to data. At present, we keep parameters μ and σ fixed and fit N and Bg. Using the $k_{\rm T}$ factorisation theorem, the gluon density coming from the CCFM equation can be applied to calculate F_2 and compare it with measurements. In the $k_{\rm T}$ factorisation approach the observables are calculated via the convolution

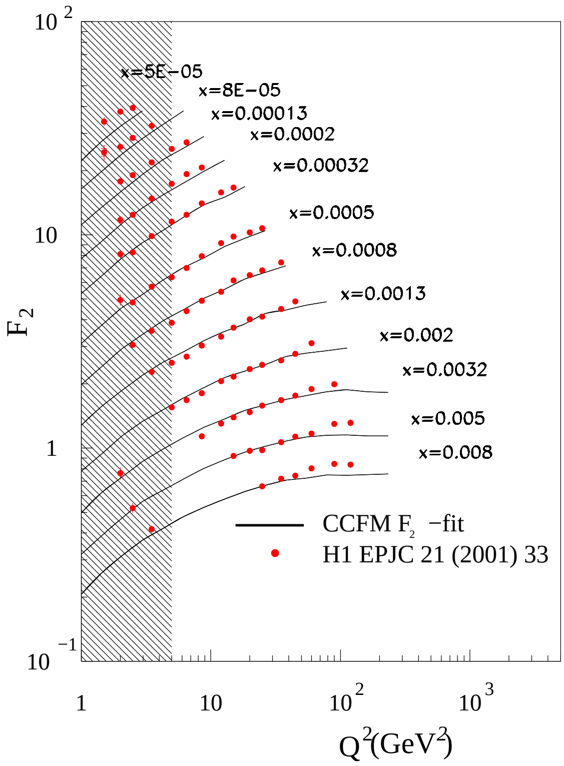


Fig. 1. F_2 description of HERA data with CCFM evolution equation.

of an off-shell hard matrix element with the gluon density. The appropriate formula for F_2 reads in schematic form:

$$F_2\left(x, Q^2\right) = \Phi\left(x, k_T^2, q^2(Q^2)\right) \otimes xA\left(x, k_T^2, q^2\left(Q^2\right)\right) ,$$

where the convolution symbol stands for the integration over longitudinal and transversal momenta. From Fig. 1 we see agreement with F_2 measurements. We should however note that for processes in the forward region at the LHC we will probe the gluon density at smaller x than at HERA and unitarity corrections could be visible.

The CCFM equation predicts that the gluon density behaves like:

$$A(x, k^2, \mu^2) \sim x^{-\beta}$$

for small x with $\beta > 0$. This power like behaviour is in conflict with unitarity bounds. As it has been already stated, the way to introduce a part of the unitarity corrections is to introduce nonlinear terms to the BFKL or CCFM evolution equation. The nonlinearity gives rise to the so called energy dependent saturation scale below which the gluon density is suppressed. Following

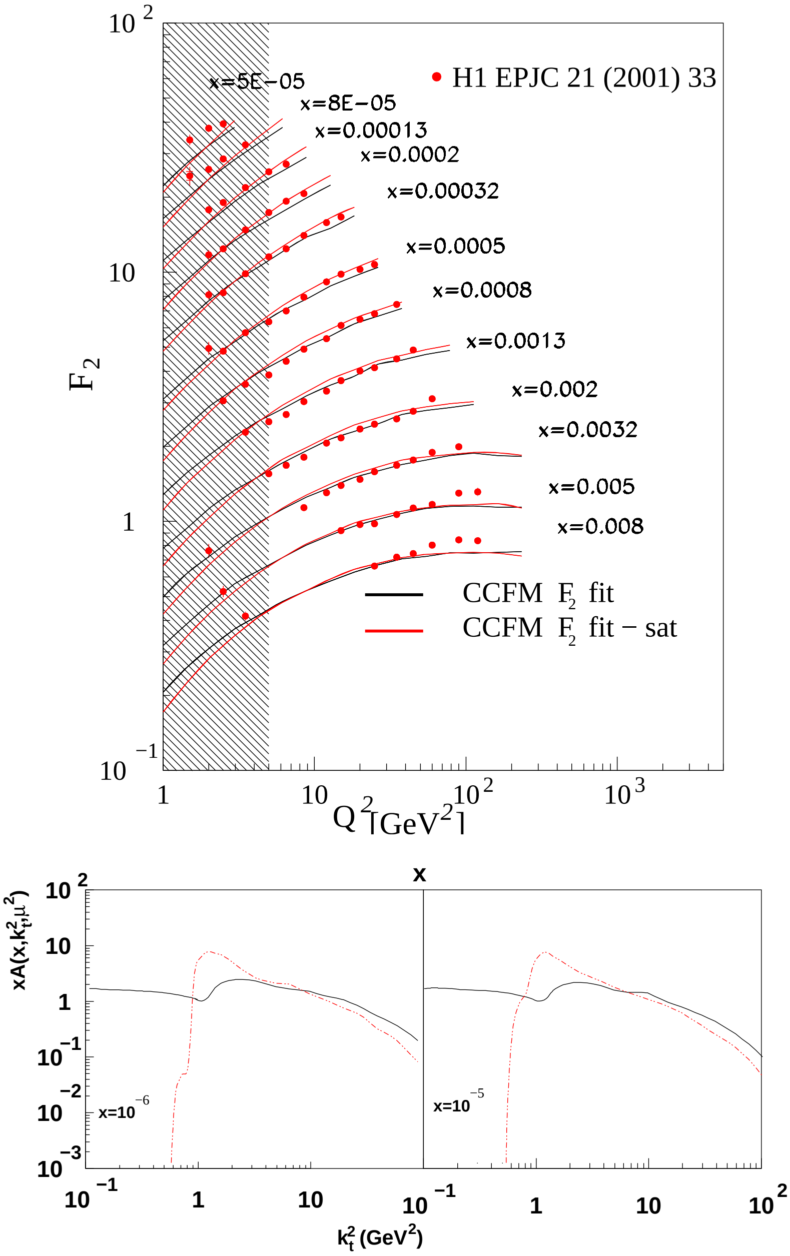


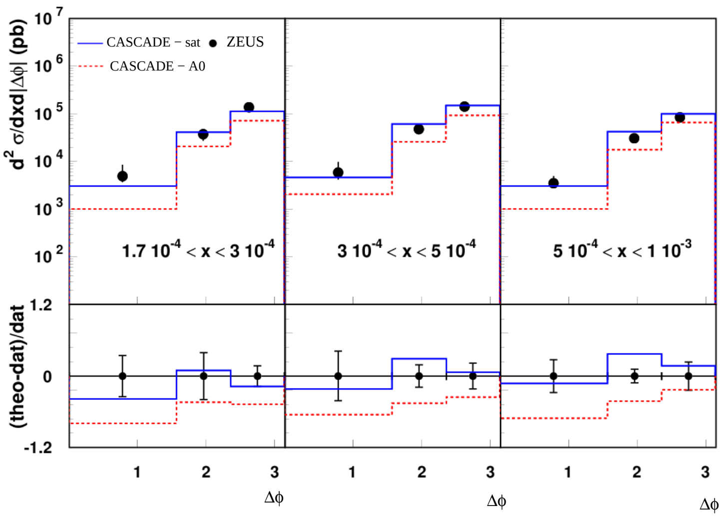
Fig. 2. (Up) F_2 calculated using CCFM with saturation compared to CCFM and to the data. (Down) Comparison of gluon density obtained from CCFM with saturation to gluon density from CCFM as a function of k_{T}^2 for $x = 10^{-5}$, $x = 10^{-6}$.

an idea of Mueller and Triantafyllopoulos, we model the saturation effects by introducing an absorptive boundary which mimics the nonlinear term. In the original approach it was required that the BFKL amplitude should be equal to unity for a certain combination of k_{T}^2 and x. Here we introduce the energy dependent cutoff on transverse gluon momenta which acts as an absorptive boundary and slows down the rate of growth of the gluon density. As a prescription for the cutoff we use the GBW [11] saturation scale $k_{\mathrm{sat}} = k_0(x_0/x)^{\lambda/2}$ with parameters x_0, k_0, λ to be determined by a fit. We are aware of the fact that this approach has obvious limitations since the saturation line is not impact parameter dependent and is not affected by the evolution. However, it provides an energy dependent cutoff which is easy to be implemented in a Monte Carlo program, and therefore, we consider it as a reasonable starting point for future investigations.

We applied our prescription to calculate the F_2 structure function and we obtained good descriptions of HERA data, both in scenario with and without saturation, see Fig. 2. However, the gluon densities which are used in the calculation of the F_2 structure function have very different shape and they may have impact on exclusive observables even in HERA range.

3. Impact of saturation on exclusive observables

Using the gluon density determined by a fit to F_2 data we may now go on to investigate the impact of saturation on exclusive observables. As a first exclusive observable we choose the differential cross section for three jet events in DIS [12]. Here we are interested in the dependence of the cross section on the azimuthal angle $\Delta\phi$ between the two hardest jets. This calculation is motivated by the fact that the produced hard jets are directly sensitive to the momentum of the incoming gluon and therefore are sensitive to the gluon k_{T} spectrum. In the results we see a clear difference between the approach which includes saturation and the one which does not include it. The description with saturation is closer to the data, suggesting the need for saturation effects. Another observable we choose is the p_{T} spectrum of produced charged particles in DIS [13]. We compare our calculation with a calculation based on the CCFM and on DGLAP evolution equations. In Fig. 3 we see that the CCFM with saturation describes data better then the other approaches. CCFM overestimates the cross-section for very low x data while DGLAP underestimates it. This is easy to explain since in CCFM one can get large contributions from larger momenta in the chain due to the lack of ordering in k_{T} while in DGLAP large k_{T}'s in the chain are suppressed. On the other hand, CCFM with saturation becomes ordered for small x both in k_{T} and rapidity, and therefore it interpolates between them.



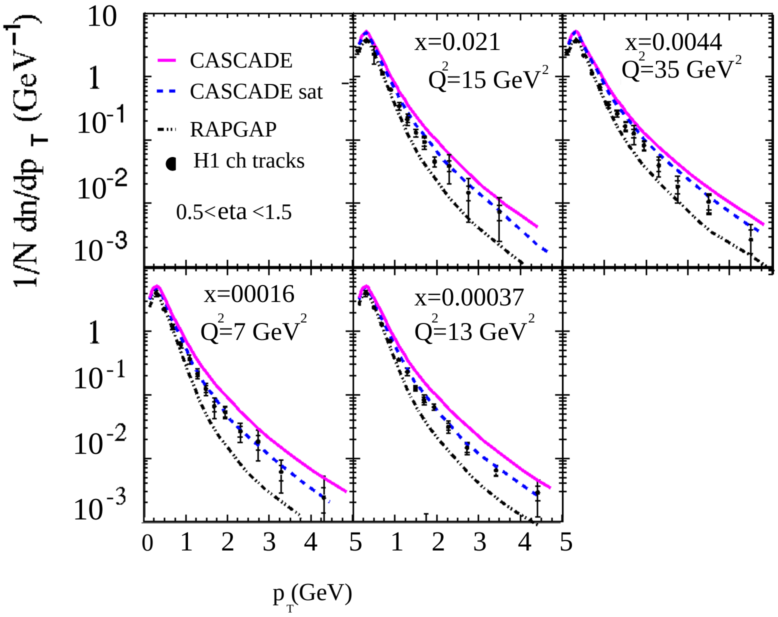


Fig. 3. (Up) Differential cross section for three jet event from CCFM with saturation boundary (solid lines) and from CCFM without saturation (dotted lines). The ratio shows the theory prediction minus the data divided by the data (down). Distribution of charged hadrons calculated within CCFM without saturation (continuous lines), CCFM with saturation (dashed lines) and DGLAP (dotted lines).

4. Conclusions

In this contribution we studied saturation effects in exclusive observables using a Monte Carlo event generator. Including saturation effects we obtained a reasonably good description of DIS data for the $\Delta\phi$ distribution of jets and $p_{\rm T}$ spectrum of produced charged hadrons, see Fig. 3. We compared the predictions with saturation to ones which do not include it. We clearly see that the approach based on saturation gives a better description of the considered observables.

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