

# Saturation effects in final states due to CCFM with absorptive boundary

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## Abstract

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

## 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 formulation within Monte Carlo framework because this allows to study complete events (see also contribution of E. Avsar to ISMD 08). At present there are two main approaches within pQCD which can be applied to describe evolution of the parton densities: collinear factorisation with integrated parton densities, with DGLAP as the master equation and  $k_T$  factorisation with unintegrated gluon density with BFKL as the master equation [1]. These two approaches resum different perturbative series and are valid in different 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 [2] approach which interpolates between DGLAP and BFKL and which has the advantage of being applicable to Monte Carlo simulation of final states. However, if one wants to study physics at largest energies 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 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  $k_T$  factorisation approach [4]. In this approach one can formulate momentum space version [5] of the Balitsky-Kovchegov equation [6] which sums up 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 description of exclusive processes and account for saturation effects we use CCFM evolution equation together with absorptive boundary implemented in CASCADE Monte Carlo event generator [8].

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In section one we show description of  $F_2$  data using CCFM equation. In section two we describe way to incorporate saturation effects. In section three we show results for angular distribution of three jets and 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:  $x A(x, k_T^2, q^2) = x A_0(x, k_T^2, q^2) + K \otimes x A(x, k_T^2, q^2)$  where  $x$  is the longitudinal momentum fraction of the proton carried by the gluon,  $k_T$  is its transverse momentum and  $q$  is a factorisation scale. The initial gluon's distribution  $x A_0(x, k_T, \mu^2) = N x^{Bg} (1-x)^4 \exp[-(k-\mu)^2/\sigma^2]$  parameters are to be determined by fit to data. At present we keep parameters  $\mu$  and  $\sigma$  fixed and fit  $N$  and  $Bg$ . Using  $k_T$  factorisation theorem gluon density coming from the CCFM equation can be applied to calculate  $F_2$  and compare with measurements. In the  $k_T$  factorisation approach the observables are calculated via convolution of an off-shell hard matrix element with gluon density. The appropriate formula in schematic form for  $F_2$  reads:  $F_2(x, Q^2) = \Phi(x, k_T^2, Q^2) \otimes x A(x, k_T^2, q^2(Q^2))$  where the convolution symbol stands for integration in longitudinal and transversal momenta. From Fig. 1 we see agreement with  $F_2$  measurements. We should however note that at the LHC for processes in the forward region we will probe the gluon density at smaller  $x$  than at HERA and unitarity corrections could be visible.

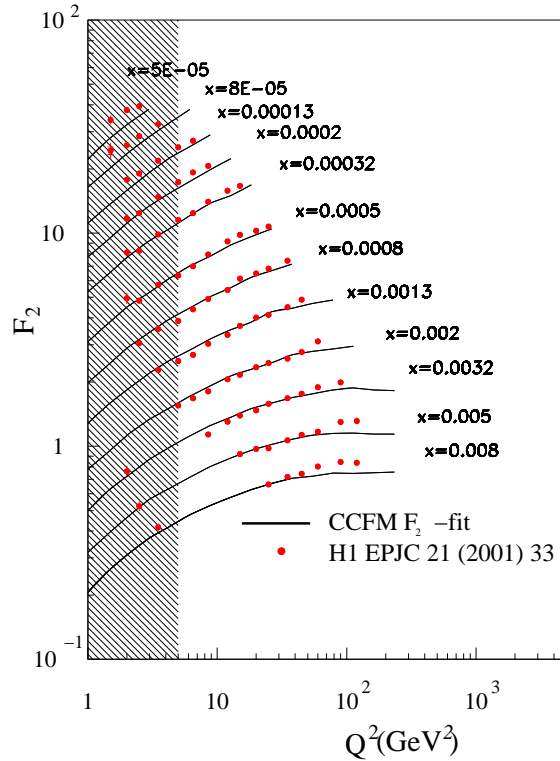


Fig. 1:  $F_2$  description of HERA data with CCFM evolution equation

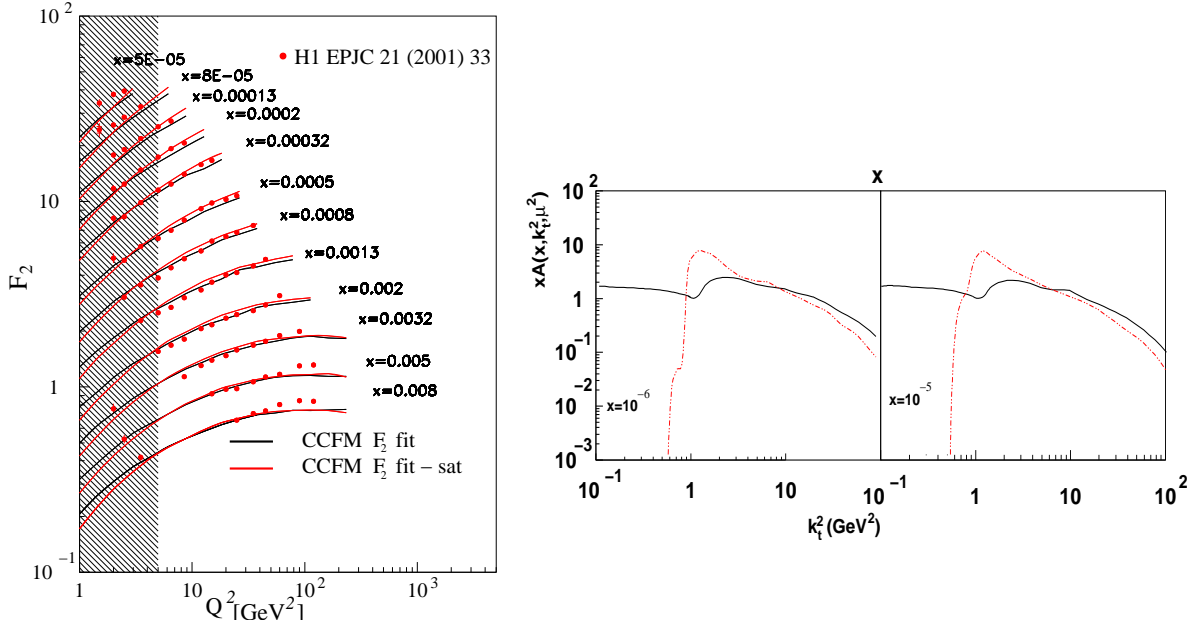


Fig. 2: (left)  $F_2$  calculated using CCFM with saturation compared to CCFM and to the data. (right) Comparison of gluon density obtained from CCFM with saturation to gluon density from CCFM as a function of  $k_T^2$  for  $x = 10^{-5}$ ,  $x = 10^{-6}$

### 3 $F_2$ from CCFM with saturation

The CCFM equation predicts the gluon density which behaves like  $A(x, k^2, \mu^2) \sim x^\beta$  and this power like behaviour is in conflict with unitarity bounds. As it has been already stated the way to introduce part of 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 gluon density is suppressed. Following an idea of A. Mueller and D. 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 absorptive boundary and slows down the rate of growth of the gluon density. As a prescription for the cutoff we use the GBW [9] saturation scale  $k_{sat} = k_0(x_0/x)^{\lambda/2}$  with parameters  $x_0, k_0, \lambda$  to be determined by 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 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 calculation of the  $F_2$  structure function have very different shape and they may have impact on exclusive observables even in HERA range.

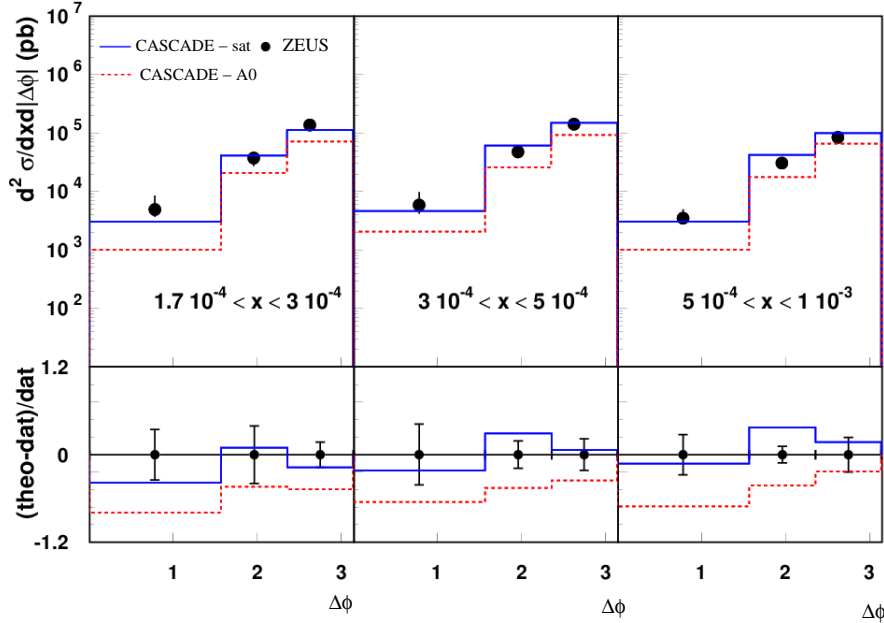


Fig. 3: (up) Differential cross section for three jet event calculated within CCFM with saturation boundary (blue line) compared to CCFM without saturation (red line). (down) Ratio between theory prediction minus data divided by data

#### 4 Impact of saturation on exclusive observables

Using the gluon density determined by 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 [10]. 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 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 data suggesting the need for saturation effects. Another observable we choose is the  $p_T$  spectrum of produced charged particles in DIS [11]. We compare our calculation with calculation based on CCFM and on DGLAP evolution equations. From the plots Fig. 4 we see that the CCFM with saturation describes data better than the other approaches. CCFM overestimates the cross-section for very low  $x$  data while DGLAP underestimates it. This is easy to explain, in CCFM one can get large contributions from larger momenta in the chain due to lack of ordering in  $k_T$  while in DGLAP large  $k_T$  in the chain is suppressed. On the other hand CCFM with saturation becomes ordered for small  $x$  both in  $k_T$  and rapidity and therefore interpolates between these two.

#### 5 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  $\Delta\phi$  distribution of jets Fig. 3 and  $p_T$  spectrum of produced charged hadrons Fig. 4. We compared prediction based on an approach with saturation to one which does not include

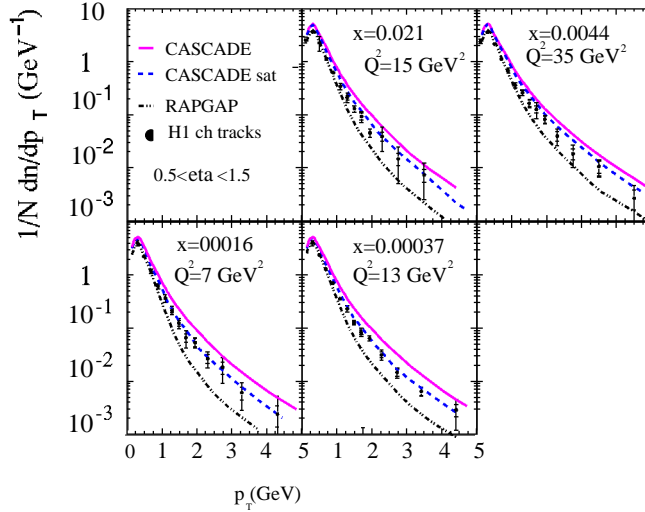


Fig. 4: Differential cross section for transverse momentum distribution of charged hadrons calculated within CCFM (violet continuous line), CCFM with saturation (dashed blue line) and DGLAP (dotted black line)

it, and we clearly see that the approach based on saturation gives a better description of the measurements.

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