Heavy quark photoproduction in \( pp \) coherent interactions at LHC

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In this work we analyse the possibility of constraining the QCD dynamics at high energies studying the heavy quark photoproduction at LHC in coherent interactions. The rapidity distribution and total cross section for charm and bottom production are estimated using three different phenomenological saturation models which successfully describe the HERA data. Our results indicate that the experimental study of the inclusive heavy quark photoproduction can be very useful to discriminate between the classical and quantum versions of the Color Glass Condensate (CGC) formalism.

1. INTRODUCTION

The cross sections for heavy quark production in hadron-hadron and lepton-hadron collisions at high energies are strongly dependent on the behavior of the gluon distribution, which is determined by the underlying QCD dynamics. Theoretically, at high energies the QCD evolution leads to a system with high gluon density, characterized by the limitation of the maximum phase-space parton density that can be reached in the hadron wave function (parton saturation). The transition is specified by a typical scale, which is energy dependent and is called the saturation scale. Signals of parton saturation have already been observed both in ep deep inelastic scattering at HERA and in deuteron-gold collisions at RHIC. However, the observation of this new regime still needs confirmation and so there is an active search for new experimental signatures. In this contribution we study the inclusive and diffractive photoproduction of heavy quarks in coherent proton-proton collisions considering three phenomenological models based on the Color Glass Condensate formalism, which describe quite well the current experimental HERA data for inclusive and exclusive observables (For a detailed discussion see Ref. [1]).

In hadron-hadron colliders, the relativistic protons give rise to strong electromagnetic fields, which can interact with each other. Namely, quasi-real photons scatter off protons at very high energies in the current hadron colliders [2]. Our main motivation comes from the fact that in coherent interactions at Tevatron and LHC the photon reaches energies higher than those currently accessible at DESY - HERA. The heavy quark photoproduction cross section in a proton-proton collision is given by,

\[
\sigma(p + p \rightarrow p + Q\bar{Q} + Y) = 2 \int_0^\infty \frac{dN_\gamma(\omega)}{d\omega} \times \sigma_{\gamma p \rightarrow Q\bar{Q} Y} \left(W_{\gamma p}^2 = 2 \omega \sqrt{S_{NN}}\right) d\omega, \tag{1}
\]

where \( \omega \) is the photon energy in the center-of-mass frame (c.m.s.), \( W_{\gamma p} \) is the c.m.s. photon-proton energy and \( \sqrt{S_{NN}} \) denotes the proton-proton c.m.s. energy. The final state \( Y \) can be a hadronic state generated by the fragmentation of one of the colliding protons (inclusive production) or a proton (diffractive production).

2. PHOTOPRODUCTION OF HEAVY QUARKS

In the color dipole approach the inclusive and diffractive heavy quark photoproduction cross
section are given by \[ \sigma_{\text{tot}} = 2 \int d^2 b \langle N(x, r, b) \rangle \] (2)

and
\[ \sigma_{\text{tot}}^D = \int d^2 b \langle N^2(x, r, b) \rangle . \] (3)

where
\[ \langle (...) \rangle = \int d^2 r \int dz |\Psi_\gamma(r, z)|^2 (...) \] (4)

In these equations the variable \( r \) defines the relative transverse separation of the pair (dipole), \( z(1-z) \) is the longitudinal momentum fractions of the quark (antiquark) and the function \( \Psi_\gamma \) is the light-cone wave function for transversely polarized photons, which depends in our case of the charge and mass of the heavy quark. The function \( N(x, r, b) \) is the forward dipole-target scattering amplitude for a dipole with size \( r \) and impact parameter \( b \) which encodes all the information about the hadronic scattering, and thus about the non-linear and quantum effects in the hadron wave function \[ \langle \rangle \]. During the last years an intense activity in the area resulted in sophisticated models for the dipole-proton scattering amplitude, which have strong theoretical constraints and which are able to describe the HERA and/or RHIC data. In what follows we will use three distinct phenomenological saturation models based on the Color Glass Condensate formalism which describe quite well the more recent HERA data: the IIM \[ \text{I} \], the bCGC \[ \text{b} \] and the IP-SA T \[ \text{IP} \] models. In the bCGC model, which is the quantum version of the CGC formalism, the dipole-proton scattering amplitude is given by
\[ \mathcal{N}^{\text{bCGC}} = \begin{cases} N_0 \left( \frac{Q_s}{2} \right)^2 \left( \gamma_s + \ln \left( \frac{Q_s}{2} \right) \right) \frac{r Q_s}{2} \leq 2 \\ 1 - \exp[-A \ln^2(B r Q_s)] \quad r Q_s > 2 \end{cases} \]

with
\[ Q_s = \left( \frac{x_0}{x} \right)^\frac{1}{2} \left[ \exp \left( -\frac{b^2}{2B_{\text{CGC}}} \right) \right] \frac{1}{\sqrt{x}} . \] (5)

Furthermore, we will use in our calculations the scattering amplitude scattering proposed in Ref. \[ \text{[8]} \], denoted IP-SAT, which is given by
\[ \mathcal{N}^{\text{IP-SAT}}(x, r, b) = 1 - S(x, r, b) , \] (6)

where
\[ S = \exp \left( -\frac{\pi^2}{2N_e} r^2 \alpha_s \frac{\mu^2}{2} x g(x) \right) T(b) , \] (7)

the scale \( \mu^2 \) is related to the dipole size \( r \) by \( \mu^2 = 4/r^2 + \mu_0^2 \) and the gluon density is evolved from a scale \( \mu_0^2 \) up to \( \mu^2 \) using LO DGLAP evolution without quarks assuming that the initial gluon density is given by \( x g(x, \mu_0^2) = A_g x^{-\lambda_g} (1-x)^{5.6} \). The values of the parameters \( \mu_0^2 \), \( A_g \) and \( \lambda_g \) are determined from a fit to \( F_2 \) data. Moreover, it is assumed that the proton shape function \( T(b) \) has a Gaussian form, \( T(b) = \frac{1}{\sqrt{2\pi B_G}} \exp[-(b^2/2B_G)] \), with \( B_G \) being a free parameter which is fixed by the fit to the differential cross sections for exclusive vector meson production. The parameter set used in our calculations is the one presented in the first line of Table III of \[ \text{[8]} \]: \( \mu_0^2 = 1.17 \text{ GeV}^2 \), \( A_g = 2.55 \), \( \lambda_g = 0.020 \) and \( B_G = 4 \text{ GeV}^{-2} \). The previous expression for the forward scattering amplitude can be obtained to leading logarithmic accuracy in the classical effective theory of the Color Glass Condensate formalism. Moreover, it is applicable when the leading logarithms in \( Q^2 \) dominate the leading logarithms in \( 1/x \), with the small \( r \) limit being described by the linear DGLAP evolution at small-\( x \). In contrast, the bCGC model for \( N \) captures the basic properties of the quantum evolution in the CGC formalism, describing both the bremsstrahlung limit of linear small-\( x \) evolution (BFKL equation) as well nonlinear renormalization group at high parton densities (very small-\( x \)). Consequently, the IP-SAT model can be considered a phenomenological model for the classical version of the CGC, while the bCGC for the quantum limit. It is important to emphasize that both models provide excellent fits to a wide range of HERA data for \( x \leq 0.01 \). Therefore, the study of observables which are strongly dependent on \( N \) is very important to constrain the underlying QCD dynamics at high energies. In what follows we consider these two models as input in our calculations of the inclusive and diffractive heavy quark photoproduction in coherent \( pp \) interactions at LHC energies.
3. RESULTS

The distribution on rapidity $y$ of the produced open heavy quark state can be directly computed using its relation with the photon energy $\omega$, i.e., $y \propto \ln \frac{\omega}{m_Q}$. A reflection around $y = 0$ takes into account the interchange between the proton emitting the photon and the target proton. Explicitly, the rapidity distribution is written down as,

$$\frac{d\sigma}{dy}[pp \rightarrow pQQY] = \omega \frac{dN_\gamma(\omega)}{d\omega} \sigma_{pp \rightarrow QQY},$$

where $Y$ is a hadronic final state $X$ produced by proton fragmentation in the inclusive case and $Y = p$ for diffractive production.

The resulting rapidity distributions for inclusive and diffractive heavy quark photoproduction at LHC energies coming out of the distinct phenomenological models considered in previous section are depicted in Figs. 1 and 2, respectively. For the inclusive case (Fig. 1), the IIM and bCGC predictions are very similar. In contrast, these predictions are distinct in the diffractive case (Fig. 2), with the bCGC prediction being larger than IIM one at mid-rapidity. On the other hand, the IP-SAT prediction is larger than these predictions by a factor 2 (3) in the charm (bottom) case. We can consider the IIM and bCGC predictions as lower bounds for the coherent production of heavy quarks at LHC. Our results indicate that the experimental study of the inclusive heavy quark photoproduction can be very useful to discriminate between the classical and quantum versions of the CGC formalism. It also is true in the diffractive case, where the different models can be discriminated more easily.

The results for the integrated cross section considering the distinct phenomenological models are presented in Table 1 for the inclusive and diffractive charm and bottom pair production at LHC. The IP-SAT model gives the largest rates among the approaches studied, followed by the bCGC and IIM models with almost identical predictions. Therefore, these reactions can have high rates at the LHC kinematical regime. The cross sections for diffractive production are approximately two orders of magnitude smaller than the inclusive case, but due the clear experimental signature of this process (two rapidity gaps), its experimental analysis still is feasible.

4. CONCLUSIONS

In summary, we have computed the cross sections for inclusive and diffractive photoproduction of heavy quarks in $pp$ collisions at LHC energies. This has been performed using modern phenomenological models based on the Color Glass Condensate formalism, which describe quite well the inclusive and exclusive observables measured in $ep$ collisions at HERA. The obtained values are shown to be sizeable at Tevatron and are increas-
Figure 2. The rapidity distribution for the diffractive charm (upper panel) and bottom (lower panel) photoproduction on \( pp \) reactions at LHC energy \( \sqrt{S_{NN}} = 14 \text{ TeV} \). Different curves correspond to distinct phenomenological models.

The feasibility of detection of these reactions is encouraging, since their experimental signature should be sufficiently clear. Furthermore, they enable to constrain the underlying QCD dynamics at high energies, which is fundamental to predict the observables which will be measured in central hadron-hadron collisions at LHC \[9\].

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| QQ | HIM | bCGC | IP-SAT |
|----|-----|------|--------|
| \( c\bar{c} \) (incl.) | 3821 nb | 3662 nb | 7542 nb |
| \( c\bar{c} \) (diff.) | 165 nb | 161 nb | 532 nb |
| \( b\bar{b} \) (incl.) | 51 nb | 51 nb | 158 nb |
| \( b\bar{b} \) (diff.) | 0.32 nb | 0.52 nb | 3 nb |

Table 1
The integrated cross section for the inclusive and diffractive photoproduction of heavy quarks in \( pp \) collisions at LHC energies.