Estimation of single and double diffractive heavy flavor production in hadron-hadron colliders

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Results from a phenomenological analysis for diffractive hadroproduction of heavy flavors at high energies are reported. Diffractive production of charm, bottom, and top are calculated using Regge factorization, taking into account recent experimental determination of the diffractive parton density functions in the Pomeron by the H1 Collaboration at DESY-HERA. In addition, multiple-Pomeron corrections are considered through the rapidity gap survival probability factor. We give numerical predictions for single diffractive as well as double Pomeron exchange cross sections, which agree with the available data for diffractive production of charm and beauty. We make estimates which could be compared to future measurements at the CERN LHC.

I. INTRODUCTION

Diffractive processes in hadron collisions are well described, with respect to the overall cross sections, by Regge theory in terms of the exchange of a Pomeron with vacuum quantum numbers [1]. However, the nature of the Pomeron and its reaction mechanisms are not completely known. A good channel attracting much attention is the use of hard scattering to resolve the quark and gluon content in the Pomeron [2]. Such a parton structure is natural in a modern QCD approach to the strongly interacting Pomeron. The systematic observations of diffractive deep inelastic scattering (DDIS) at HERA have increased the knowledge about the QCD Pomeron, providing us with the diffractive distributions of singlet quarks and gluons in the Pomeron as well as the diffractive structure function [3]. In hadronic collisions, we shall characterize an event as single diffractive if one of the colliding hadrons emits a Pomeron that scatters off the other hadron. A single diffractive reaction would therefore correspond to $h_i + h_j \rightarrow h_i + X$, in which the intact hadron i emits a Pomeron ($h_i \rightarrow h_i + \mathbb{P}$) which interacts with the hadron j ($h_j + \mathbb{P} \rightarrow X$) leading to the referred reaction. Hadron i is detected in the final state with a large longitudinal momentum fraction. Hard diffractive events with a large momentum transfer are also characterized by the absence of hadronic energy in certain angular regions of the final state phase space (rapidity gaps). The events fulfilling the conditions of large rapidity gaps and a highly excited hadron remnant are named single diffractive, in contrast to those in which both colliding hadrons remain intact as they each emit a Pomeron [central diffraction or double Pomeron exchange (DPE) events]. At high energies, there are important contributions from unitarization effects to the single-Pomeron exchange cross section. These absorptive or unitarity corrections cause the suppression of any large rapidity gap process, except elastic scattering. In the black disk limit the absorptive corrections may completely terminate those processes. This partially occurs in (anti)proton-proton collisions, where unitarity is

nearly saturated at small impact parameters [4]. The multiple-Pomeron contributions depend, in general, on the particular hard process and this is called the survival probability factor. At the Tevatron energy, $\sqrt{s} = 1.8$ TeV, the suppression is of order 0.05−0.2 [5−8], whereas for the CERN LHC energy, $\sqrt{s} = 14$ TeV, the suppression appears to be 0.08−0.1 [5,6,8]. These corrections are, therefore, crucial for the reliability of the theoretical predictions for hard diffractive processes.

We present below a calculation for diffractive production of heavy quarks in proton-proton collisions. The motivation is to produce updated theoretical estimations compatible with the scarce accelerator data on single diffractive charm and bottom hadroproduction [9,10] and to obtain reliable predictions to the future measurements at the LHC. These predictions are quite important in the determination of the background processes for diffractive Higgs production and related reactions. The background for the Higgs is a subject of intense debate in the literature and is out of the scope of the present work. Let us illustrate two representative examples: (a) for a low mass Higgs, $M_H \lesssim 150$ GeV, an interesting exclusive channel is the $b\bar{b}$ decay mode $pp \rightarrow p(H \rightarrow b\bar{b})p$ [11]; (b) the inclusive channel $pp \rightarrow (H \rightarrow WW \rightarrow l^+l^- \not{p}_T)X$ [12]. In both cases the heavy quark background contribution is sizable [11,12], namely, the DPE bottom production in (a) and the lepton contribution from heavy quark decays in (b).

For the present purpose we rely on the Regge factorization and the corresponding corrections for multiple-Pomeron scatterings. Factorization for diffractive hard scattering is equivalent to the hard-scattering aspects of the Ingelman and Schlein model [2], where diffractive scattering is attributed to the exchange of a Pomeron, i.e. a colorless object with vacuum quantum numbers. The Pomeron is treated like a real particle. Thus, one considers that a diffractive electron-proton collision is due to an electron-Pomeron collision. Similarly, a diffractive proton-proton collision occurs due to a proton-Pomeron collision. Therefore, the diffractive hard cross sections are

obtained as a product of a hard-scattering coefficient, a known Pomeron-proton coupling, and parton densities in the Pomeron. The parton densities in the Pomeron have been systematically extracted from diffractive DIS measurements. In particular, the quark singlet and gluon content of the Pomeron is obtained from the diffractive structure function $F_2^{D(3)}(x_{\mathbb{P}}, \beta, Q^2)$. Recently, a new analysis of these diffractive parton distributions has been presented [3] by the H1 Collaboration in DESY-HERA.

The paper is organized as follows. In the next section, we present the main formulas to compute the inclusive and diffractive cross sections (single and central diffraction) for heavy flavors hadroproduction. We show the details concerning the parametrization for the diffractive partons distribution in the Pomeron. In addition, we present the theoretical estimations for the rapidity gap survival probability factor. In the last section we present the numerical results, taking properly the experimental cuts, and perform predictions to future measurements in the CERN LHC experiment. The compatibility with data is analyzed and the comparison with other approaches is considered.

II. DIFFRACTIVE HADROPRODUCTION OF HEAVY FLAVORS

Let us start by introducing the main expressions to compute the inclusive and diffractive cross sections for heavy flavor production in hadron colliders. The starting point is the inclusive total cross section for a process in which partons of two hadrons, h_1 and h_2, interact to produce a heavy quark pair, $h_1 + h_2 \rightarrow Q\bar{Q} + X$, at center-of-mass energy $\sqrt{s}$. At leading order (LO) heavy quarks are produced by gg fusion and $q\bar{q}$ annihilation, while at next-to-leading order (NLO), $qg + \bar{q}g$ scattering is also included. At any order, the partonic cross section may be expressed in terms of dimensionless scaling functions $f_{ij}^{(k,l)}$ that depend only on the variable ρ [13],

$$\hat{\sigma}_{ij}(\hat{s}, m_Q^2, \mu_F^2, \mu_R^2) = \frac{\alpha_s^2(\mu_R)}{m_Q^2} \sum_{k=0}^{\infty} [4\pi\alpha_s(\mu_R)]^k$$
$$\times \sum_{l=0}^{k} f_{ij}^{(k,l)}(\rho) \ln^l\left(\frac{\mu_F^2}{m_Q^2}\right), \qquad (1)$$

where $\hat{s}$ is the partonic center of mass, m_Q is the heavy quark mass, μ_R (μ_F) is the renormalization (factorization) scale, and $\rho = \hat{s}/4m_Q^2 - 1$. The cross section is calculated as an expansion in powers of α_s with $k = 0$ corresponding to the Born cross section at order $\mathcal{O}(\alpha_s^2)$. The first correction, $k = 1$, corresponds to the NLO cross section at $\mathcal{O}(\alpha_s^3)$. The total hadronic cross section is obtained by convoluting the total partonic cross section with the parton distribution functions of the initial hadrons,

$$\sigma_{h_1 h_2}(s, m_Q^2) = \sum_{i,j} \int_{\tau}^{1} dx_1 \int_{\tau/x_1}^{1} dx_2 f_i^{h_1}(x_1, \mu_F^2) f_j^{h_2}(x_2, \mu_F^2)$$
$$\times \hat{\sigma}_{ij}(\hat{s}, m_Q^2, \mu_F^2, \mu_R^2), \qquad (2)$$

where the sum $i, j = q, \bar{q}, g$ is over all massless partons, x_1 and x_2 are the hadron momentum fractions carried by the interacting partons, and $\tau = 4m_Q^2/s$. The parton distribution functions, denoted by $f_i^p(x_i, \mu)$, are evaluated at the factorization scale, assumed to be equal to the renormalization scale in our calculations.

For the sake of illustration, we calculate numerically the total inclusive cross sections for heavy flavor pair production using the Martin-Roberts-Stirling-Thorne (MRST) set of partons [14]. The low x region is particularly relevant for $Q\bar{Q}$ production at the LHC as well as at the Tevatron. For charm and bottom production, the gg process becomes dominant and information on the gluon distribution is of particular importance. We compute the cross sections with the following mass and scale parameters: $\mu_c = 2m_c$ (with $m_c = 1.5$ GeV) and $\mu_b = m_b$ (with $m_b = 4.5$ GeV). For the top quark case, we use $\mu_t = m_t$ (where $m_t = 176$ GeV). The present choice for the scales is based on the current phenomenology for heavy quark hadroproduction [15]. The agreement with the total charm cross section data is fairly good. In Figs. 1 and 2 the numerical results (solid curves) are compared to accelerator data of charm and bottom hadroproduction [16], respectively. For the top cross section, we obtain $\sigma_{\text{tot}}(\sqrt{s} = 1.8 \text{ TeV}) = 5$ pb and $\sigma_{\text{tot}}(\sqrt{s} = 14 \text{ TeV}) = 2$ nb. It should be stressed that sizable uncertainties are introduced by changing, for instance, quark masses and/or the renormalization scale. However,
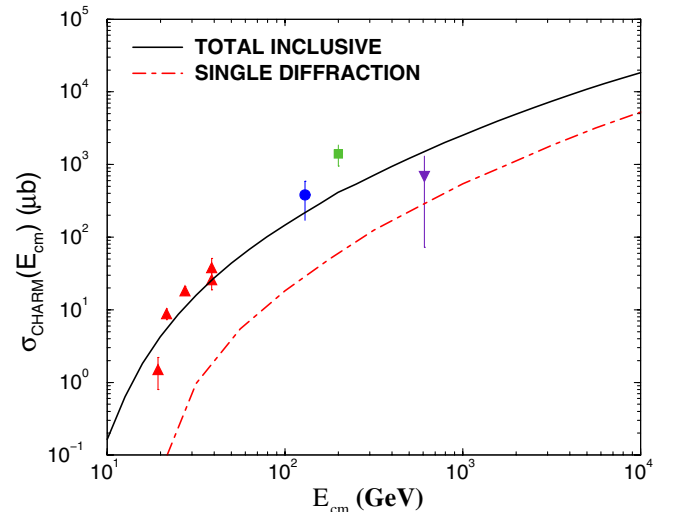

FIG. 1 (color online). Total cross section for inclusive charm hadroproduction (solid line) and the corresponding single diffractive cross section without multiple-Pomeron corrections (dot-dashed line). Available accelerator data are also shown (see text).
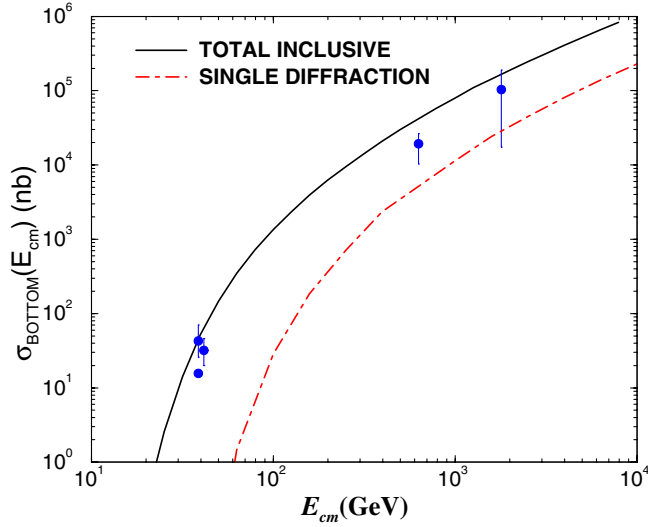
FIG. 2 (color online). Total cross section for inclusive bottom hadroproduction (solid line) and the corresponding single diffractive cross section without multiple-Pomeron corrections (dot-dashed line). Available accelerator data are also shown (see text).

our purpose here is to estimate the diffractive ratios $\sigma^D/\sigma_{\text{tot}}$, which are less sensitive to a particular choice.

For the *hard* diffractive processes we will consider the Ingelman-Schlein (IS) picture [2], where the Pomeron structure (quark and gluon content) is probed. In the case of single diffraction, a Pomeron is emitted by one of the colliding hadrons. That hadron is detected, at least in principle, in the final state and the remaining hadron scatters off the emitted Pomeron. A typical single diffractive reaction is given by $p + p \rightarrow p + Q\bar{Q} + X$. In the IS approach, the single diffractive cross section is assumed to factorize into the total Pomeron-hadron cross section and the Pomeron flux factor [2]. The single diffractive event may then be written as (for equal hadrons)

$$\frac{d\sigma^{\text{SD}}(hh \rightarrow h + Q\bar{Q} + X)}{dx_{\mathbb{P}}^{(i)}d|t_i|} = f_{\mathbb{P}/i}(x_{\mathbb{P}}^{(i)}, |t_i|)$$
$$\times \sigma(\mathbb{P} + h \rightarrow Q\bar{Q} + X),$$

where the Pomeron kinematical variable $x_{\mathbb{P}}$ is defined as $x_{\mathbb{P}}^{(i)} = s_{\mathbb{P}}^{(j)}/s_{ij}$, where $\sqrt{s_{\mathbb{P}}^{(j)}}$ is the center-of-mass energy in the Pomeron-hadron j system and $\sqrt{s_{ij}} = \sqrt{s}$ the center-of-mass energy in the hadron-i hadron-j system. The momentum transfer in the hadron-i vertex is denoted by t_i. A similar factorization can also be applied to the DPE process, where both colliding hadrons can, in principle, be detected in the final state. This diffractive process is also known as central diffraction (CD). Thus, a typical reaction would be $p + p \rightarrow p + p + Q\bar{Q} + X$, and DPE events are thus characterized by two quasielastic hadrons with rapidity gaps between them and the central heavy flavor prod-

ucts. The DPE cross section may then be written as

$$\frac{d\sigma^{\text{DD}}(hh \rightarrow h + h + Q\bar{Q} + X)}{dx_{\mathbb{P}}^{(i)}dx_{\mathbb{P}}^{(j)}d|t_i|d|t_j|}$$
$$= f_{\mathbb{P}/i}(x_{\mathbb{P}}^{(i)}, |t_i|)f_{\mathbb{P}/j}(x_{\mathbb{P}}^{(j)}, |t_j|)\sigma(\mathbb{P} + \mathbb{P} \rightarrow Q\bar{Q} + X).$$

In order to obtain the corresponding expression for diffractive processes, one assumes that one of the hadrons, say, hadron h_1, emits a Pomeron whose partons interact with partons of the hadron h_2. Thus the parton distribution $x_1 f_{i/h_1}(x_1, \mu^2)$ in Eq. (2) is replaced by the convolution between a putative distribution of partons in the Pomeron, $\beta f_{a/\mathbb{P}}(\beta, \mu^2)$, and the "emission rate" of Pomerons by the hadron, $f_{\mathbb{P}/h}(x_{\mathbb{P}}, t)$. The last quantity, $f_{\mathbb{P}/h}(x_{\mathbb{P}}, t)$, is the Pomeron flux factor and its explicit formulation is described in terms of Regge theory. Therefore, we can rewrite the parton distribution as

$$x_1 f_{a/h_1}(x_1, \mu^2) = \int dx_{\mathbb{P}} \int d\beta \int dt f_{\mathbb{P}/h_1}(x_{\mathbb{P}}, t)$$
$$\times \beta f_{a/\mathbb{P}}(\beta, \mu^2)\delta\left(\beta - \frac{x_1}{x_{\mathbb{P}}}\right), \quad (3)$$

and, now defining $\bar{f}(x_{\mathbb{P}}) \equiv \int_{-\infty}^{0} dt f_{\mathbb{P}/h_1}(x_{\mathbb{P}}, t)$, one obtains

$$x_1 f_{a/h_1}(x_1, \mu^2) = \int dx_{\mathbb{P}} \bar{f}(x_{\mathbb{P}}) \frac{x_1}{x_{\mathbb{P}}} f_{a/\mathbb{P}}\left(\frac{x_1}{x_{\mathbb{P}}}, \mu^2\right). \quad (4)$$

Using the substitution given in Eq. (4) we can proceed in writing down the expressions for the single and central (DPE) diffractive cross sections for $Q\bar{Q}$ production using the expression for the total cross section in Eq. (2),

$$\sigma_{h_1 h_2}^{\text{SD}}(s, m_Q^2) = \sum_{i,j=q\bar{q},g} \int_{\tau}^{1} dx_1 \int_{\tau/x_1}^{1} dx_2 \int_{x_1}^{x_{\mathbb{P}}^{\max}} \frac{dx_{\mathbb{P}}^{(1)}}{x_{\mathbb{P}}^{(1)}}$$
$$\times \bar{f}_{\mathbb{P}/h_1}(x_{\mathbb{P}}^{(1)}) f_{i/\mathbb{P}}\left(\frac{x_1}{x_{\mathbb{P}}^{(1)}}, \mu^2\right) f_{j/h_2}(x_2, \mu^2)$$
$$\times \hat{\sigma}_{ij}(\hat{s}, m_Q^2, \mu^2) + (1 \rightleftharpoons 2). \quad (5)$$

A similar expression holds for the DPE process, which reads as

$$\sigma_{h_1 h_2}^{\text{DPE}}(s, m_Q^2) = \sum_{i,j=q\bar{q},g} \int_{\tau}^{1} dx_1 \int_{\tau/x_1}^{1} dx_2 \int_{x_1}^{x_{\mathbb{P}}^{\max}} \frac{dx_{\mathbb{P}}^{(1)}}{x_{\mathbb{P}}^{(1)}}$$
$$\times \int_{x_2}^{x_{\mathbb{P}}^{\max}} \frac{dx_{\mathbb{P}}^{(2)}}{x_{\mathbb{P}}^{(2)}} \bar{f}_{\mathbb{P}/h_1}(x_{\mathbb{P}}^{(1)}) \bar{f}_{\mathbb{P}/h_2}(x_{\mathbb{P}}^{(2)})$$
$$\times f_{i/\mathbb{P}}\left(\frac{x_1}{x_{\mathbb{P}}^{(1)}}, \mu^2\right) f_{j/\mathbb{P}}\left(\frac{x_2}{x_{\mathbb{P}}^{(2)}}, \mu^2\right)$$
$$\times \hat{\sigma}_{ij}(\hat{s}, m_Q^2, \mu^2). \quad (6)$$

Having presented the main expressions for single and central diffraction, in the following subsections we shortly present some details on the Pomeron structure function and Pomeron flux that will be employed in our phenomeno-

logical studies. In addition, an estimation for the multiple-Pomeron corrections is discussed.

A. The Pomeron structure function

In the estimates for the diffractive cross sections, we will consider the diffractive pdf's recently obtained by the H1 Collaboration at DESY-HERA [3]. The Pomeron structure function has been modeled in terms of a light flavor singlet distribution $\Sigma(z)$, consisting of u, d, and s quarks and antiquarks with $u = d = s = \bar{u} = \bar{d} = \bar{s}$, and a gluon distribution $g(z)$. Here, z is the longitudinal momentum fraction of the parton entering the hard subprocess with respect to the diffractive exchange, such that $z = \beta$ for the lowest order quark-parton model process, whereas $0 < \beta < z$ for higher order processes. The Pomeron carries vacuum quantum numbers; thus it is assumed that the Pomeron quark and antiquark distributions are equal and flavor independent: $q_{\mathbb{P}}^f = \bar{q}_{\mathbb{P}}^f = \frac{1}{2N_f}\Sigma_{\mathbb{P}}$, where $\Sigma_{\mathbb{P}}$ is a Pomeron singlet quark distribution and N_f is the number of active flavors. The quark singlet and gluon distributions are parametrized at Q_0^2 with the general form

$$zf_i(z, Q_0^2) = A_i z^{B_i}(1 - z)^{C_i} \exp\left[-\frac{0.01}{(1 - z)}\right] \quad (7)$$

where the last exponential factor ensures that the diffractive pdf's vanish at $z = 1$. For the quark singlet distribution, the data require the inclusion of all three parameters, A_q, B_q, and C_q, in Eq. (7). By comparison, the gluon density is weakly constrained by the data, which is found to be insensitive to the B_g parameter. The gluon density is thus parametrized at Q_0^2 using only the A_g and C_g parameters. With this parametrization, one has the value $Q_0^2 = 1.75$ GeV^2 and it is referred to as the "H1 2006 DPDF Fit A." It is verified that the fit procedure is not sensitive to the gluon pdf and a new adjustment was done with $C_g = 0$. Thus, the gluon density is then a simple constant at the starting scale for evolution, which was chosen to be $Q_0^2 = 2.5$ GeV^2, and it is referred to as the "H1 2006 DPDF Fit B."

Another important element in the calculation is the Pomeron flux factor, introduced in Eq. (3). We take the experimental analysis of the diffractive structure function [3], where the $x_{\mathbb{P}}$ dependence is parametrized using a flux factor motivated by Regge theory, [1],

$$f_{\mathbb{P}/p}(x_{\mathbb{P}}, t) = A_{\mathbb{P}} \cdot \frac{e^{B_{\mathbb{P}}t}}{x_{\mathbb{P}}^{2\alpha_{\mathbb{P}}(t)-1}}, \quad (8)$$

where the Pomeron trajectory is assumed to be linear, $\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}}t$, and the parameters $B_{\mathbb{P}}$ and $\alpha'_{\mathbb{P}}$ and their uncertainties are obtained from fits to H1 FPS data [17]. The normalization parameter $A_{\mathbb{P}}$ is chosen such that $x_{\mathbb{P}} \cdot \int_{t_{\mathrm{cut}}}^{t_{\mathrm{min}}} f_{\mathbb{P}/p}(x_{\mathbb{P}}, t)\mathrm{d}t = 1$ at $x_{\mathbb{P}} = 3 \times 10^{-3}$, where $|t_{\mathrm{min}}| \simeq m_p^2 x_{\mathbb{P}}^2/(1 - x_{\mathbb{P}})$ is the minimum kinematically accessible value of $|t|$, m_p is the proton mass, and $|t_{\mathrm{cut}}| =$

1.0 GeV^2 is the limit of the measurement. The expression in Eq. (8) corresponds to the standard Pomeron flux from Regge phenomenology, based on the Donnachie-Landshoff model [18].

B. Corrections for multiple-Pomeron scattering

In the following analysis we will consider the suppression of the hard diffractive cross section by multiple-Pomeron scattering effects. This is taken into account through a gap survival probability factor. There has been large interest in the probability of rapidity gaps in high energy interactions to survive, as they may be populated by secondary particles generated by rescattering processes. This effect can be described in terms of screening or absorptive corrections [19]. This suppression factor of a hard process accompanied by a rapidity gap not only depends on the probability of the initial state to survive, but is also sensitive to the spatial distribution of partons inside the incoming hadrons, and thus depends on the dynamics of the whole diffractive part of the scattering matrix.

Let us introduce a short discussion on the usual procedure to determine the survival probability factor, estimation of its size, and the uncertainties in its determination. The survival factor of a large rapidity gap (LRG) in a hadronic final state is the probability of a given LRG to not be filled by debris, which originates from the soft rescattering of the spectator partons and/or from the gluon radiation emitted by partons taking part in the hard interaction. Let $\mathcal{A}(s, b)$ be the amplitude of the particular diffractive process of interest, considered in the impact parameter b space. Therefore, the probability that there is no extra inelastic interaction is

$$\langle|S|^2\rangle = \frac{\int d^2b |\mathcal{A}(s, b)|^2 \exp[-\Omega(s, b)]}{\int d^2b |\mathcal{A}(s, b)|^2}, \quad (9)$$

where Ω is the opacity (or optical density) of the interaction. This quantity can be computed using a simple one-channel eikonal model or a more involved multiple-channel model. The opacity $\Omega(s, b)$ reaches a maximum in the center of the proton and becomes small in the periphery. Therefore, the survival factor depends on the spatial distribution of the constituents of the relevant subprocess. For instance, the spatial b distribution of single and double rapidity gap processes is assumed to be controlled by the slope B of the Pomeron-proton vertex, $\beta(t) \propto \exp(-B|t|)$, and the fact that there is no shrinkage coming from the Pomeron amplitude associated with the LRG in hard diffractive subprocesses. In addition, $\exp(-\Omega)$ is the probability that no inelastic soft interaction in the rescattering eikonal chain results in inelasticity of the final state at energy s and impact parameter b.

As the b dependences of single and double-diffractive dissociation amplitudes are distinct, the survival factor is different for each case. The survival factor decreases with

energy due to the growth of the opacity, whereas it increases with the slope B. In order to illustrate the calculation in Eq. (9), let us consider the eikonal model (one channel) and assume a Gaussian b dependence for the scattering amplitude for a hard process, $\mathcal{A}_H(s, b) \propto \exp(-b^2/R_H^2)$, with a constant hard radius R_H. The opacity can be oversimplified in the form $\Omega(s, b) = \frac{\sigma_0 s^\Delta}{\pi R^2(s)} \times \exp[-\frac{b^2}{R^2(s)}]$. Here, $\Delta = \alpha_{\mathbb{P}}(0) - 1$ and the soft slope is $R^2(s) \propto \ln(s)$. In this simple case, Eq. (9) can be analytically evaluated and then give the following: $\langle |S|^2 \rangle = \bar{R}_H \gamma[\bar{R}_H, a(s)]/[a(s)]^{\bar{R}_H}$. We use the notation $\bar{R}_H(s) \equiv \frac{R^2(s)}{R_H^2}$, $a(s) = \sigma_0 s^\Delta$, and $\gamma(a, x)$ is the incomplete Euler gamma function [20]. This rough calculation shows the model dependence on the input values R_H, $R(s)$, and $a(s)$. We refer to Ref. [20] for extensive review on the determination of the LRG survival probability gap factor using the multichannel eikonal models.

Concerning the model dependence, the single-channel eikonal model considers only elastic rescatterings, whereas the multichannel one also takes into account inelastic diffractive intermediate rescatterings. In general, current works in the literature consider a more elaborate two- or three-channel eikonal model. These approaches describe correctly the relevant observables in pp and $p\bar{p}$ collisions as $\sigma_{\text{tot,el}}$, B_{el}, σ_{sd}, and so on [5,6]. The corresponding survival probabilities of single, double, and central channels are not identical because each one has a different hard radius. The available experimental observables which can be compared to the theoretical predictions of the survival probability factor are the hard LRG di-jet data obtained at the Tevatron and HERA [8,20], as well as diffractive hadroproduction of heavy bosons ($W^\pm$ and Z^0) at the Tevatron [21]. Direct information on the survival probability factor is obtained from the diffractive hard jets ratio measured at the Tevatron, where $\frac{\langle |S|^2 \rangle (\sqrt{s}=0.63 \text{ TeV})}{\langle |S|^2 \rangle (\sqrt{s}=1.8 \text{ TeV})} = 2.2 \pm 0.8$. The current theoretical predictions are in agreement with this measurement.

For our purpose, we consider the theoretical estimates from Ref. [8] (labeled KMR), which considers a two-channel eikonal model that embodies pion-loop insertions in the Pomeron trajectory, diffractive dissociation, and rescattering effects. The survival probability is computed for single-, central-, and double-diffractive processes at several energies, assuming that the spatial distribution in impact parameter space is driven by the slope B of the Pomeron-proton vertex. We will consider the results for single diffractive processes with $2B = 5.5 \text{ GeV}^{-2}$ (slope of the electromagnetic proton form factor) and without the N^* excitation, which is relevant to a forward proton spectrometer (FPS) measurement. Thus, we have $\langle |S|^2 \rangle_{\text{KMR}}^{\text{SD}} = 0.15, [0.09]$ and $\langle |S|^2 \rangle_{\text{KMR}}^{\text{DPE}} = 0.08, [0.04]$ for $\sqrt{s} = 1.8$ TeV (Tevatron) [$\sqrt{s} = 14$ TeV (LHC)]. There are similar theoretical estimates, such as the GLM approach [20], which

also consider a multiple-channel eikonal approach. We verify that those results are consistent with each other. We refer to Ref. [20] for a detailed comparison between the two approaches and further discussion on model dependence.

For the sake of illustration, we have adjusted the gap survival probability factor (for single diffraction) as a function of center-of-mass energy using the following functional form, $\langle |S|^2 \rangle^{\text{SD}}(\sqrt{s}) = a/(b + c \ln^d \sqrt{s})$, in the interval $10 \text{ GeV} \leq \sqrt{s} \leq 14$ TeV. This functional form is inspired by the fact that upon reaching the unitarity limit the fraction of diffractive events is expected to vanish as $1/\ln\sqrt{s}$ [22]. For energies lower than $\sqrt{s} \leq 540$ GeV the estimates from Ref. [7] are used. The following parameters are obtained: $a = 2.062$, $b = 4.937$, $c = 4.2 \times 10^{-3}$, and $d = 3.793$. This is useful to obtain the single diffractive cross sections as a function of energy when they are corrected by multiple-Pomeron scattering.

III. RESULTS AND DISCUSSION

In what follows, we present predictions for hard diffractive production of heavy flavors based on the previous discussion. In the numerical calculations, we have used the new H1 parametrizations for the diffractive pdf's [3]. The "H1 2006 DPDF Fit A" is considered, whereas a replacement by "H1 2006 DPDF Fit B" keeps the results unchanged. For the pdf's in the proton we have considered the updated MRST parametrization [14]. In addition, we have used the cut $x_{\mathbb{P}} < 0.1$. The single-Pomeron results, given by Eq. (5), are presented in Figs. 1 and 2 for charm and bottom production (dot-dashed curves). The single diffractive contribution is large, being of order 15%–20% from the total cross section. For the top case, which is not shown in the plots, we get a small cross section. Namely, $\sigma_{t\bar{t}}^{\text{SD}} = 1.5 \times 10^{-3}$ pb at $\sqrt{s} = 1.96$ TeV and $\sigma_{t\bar{t}}^{\text{SD}} = 100$ pb for $\sqrt{s} = 14$ TeV. The cross sections for each heavy flavor rise with energy and differ approximately by a factor proportional to $1/m_Q^2$. The results corrected by unitarity suppression are a factor of about $1/10$ lower than the single-Pomeron ones. In Fig. 3 we present the numerical results for the single diffractive production of charm (long-dashed curve) and bottom (solid curve) considering the suppression factor. We have multiplied Eq. (5) by the energy dependent factor $\langle |S|^2 \rangle^{\text{SD}}(\sqrt{s})$, as discussed in the previous section. Of course, the present curves have to be considered as average results, since the absolute cross sections are sensitive to different choices for the quark masses and renormalization scale.

The results using the multiple-Pomeron correction can be somewhat compared with experimental estimates for the single diffractive cross section. However, data for diffractive production of heavy flavors are scarce. For charm, we quote the most accurate data for production of D^{*-} from the E690 experiment at Fermilab at $\sqrt{s} = 40$ GeV [9].
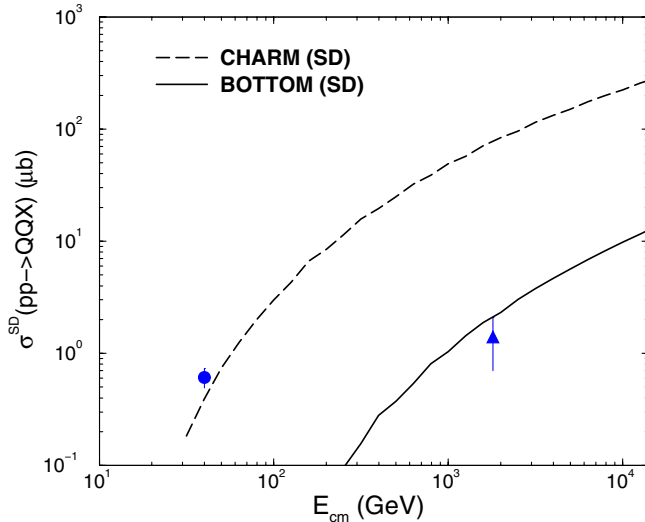
FIG. 3 (color online). Single diffractive cross section for charm and bottom hadroproduction considering multiple-Pomeron corrections as a function of energy. A comparison to experimental data is also shown (see text).

TABLE I. Model predictions for single (SD) and central (DPE) diffractive heavy flavor production at the Tevatron and the LHC. Numbers between parentheses represent the estimates using single-Pomeron exchange.

$\sqrt{s}$	Heavy flavor	R_{SD} (%)	R_{DPE} (%)
1.96 TeV	$c\bar{c}$	3.5 (23.4)	0.08 (1.2)
1.96 TeV	$b\bar{b}$	2.5 (16.9)	0.05 (0.6)
1.96 TeV	$t\bar{t}$	1.5×10^{-3} (0.03)	$\cdots$
14 TeV	$c\bar{c}$	2.8 (30.7)	0.08 (2.0)
14 TeV	$b\bar{b}$	2.1 (23.5)	0.035 (0.9)
14 TeV	$t\bar{t}$	0.4 (4.8)	8×10^{-3} (0.23)

The cross section is $\sigma(pp \rightarrow p[c\bar{c}]X) = 0.61 \pm 0.12(\mathrm{stat}) \pm 0.11(\mathrm{syst})$ μb, which is integrated over $x_F > 0.85$. This data point is represented by the filled circle in Fig. 3. For the bottom case, the estimation $\sigma(pp \rightarrow p[b\bar{b}]X) = 1.4 \pm 0.7$ μb at $\sqrt{s} = 1.8$ TeV is taken from Ref. [23]. This value is obtained using the theoretically predicted inclusive cross section 140 μb and the experimentally measured fraction $R_{b\bar{b}}$ of diffractively produced beauty [10]. This value is represented by the filled triangle in Fig. 3. Our curves reasonably describe these scarce data on diffractive production of heavy flavored hadrons.

Concerning the DPE cross sections, we verify that the single-Pomeron predictions are still large. For instance, using Eq. (6) one has $\sigma_{c\bar{c}}^{\mathrm{DPE}} = 58$ μb and $\sigma_{b\bar{b}}^{\mathrm{DPE}} = 1.2$ μb at $\sqrt{s} = 1.96$ TeV. The top production is suppressed due to the kinematic threshold related to the cutoff in the Pomeron spectrum, $x_{\mathbb{P}} \lesssim 0.1$. This gives little room to observe diffractive top quark events at the Tevatron but is promising for the LHC, where the heavy flavor threshold suppression is less severe. The values reach $\sigma_{c\bar{c}}^{\mathrm{DPE}} = 460$ μb, $\sigma_{b\bar{b}}^{\mathrm{DPE}} = 13$ μb, and $\sigma_{b\bar{b}}^{\mathrm{DPE}} = 5$ pb for $\sqrt{s} = 14$ TeV. The results corrected by the multiple-Pomeron suppression factor are a factor of about 1/100 lower than the single-Pomeron ones.

Let us now compute the diffractive ratios. The single diffractive ratio is defined as $R_{\mathrm{SD}} = \sigma^{\mathrm{SD}}/\sigma_{\mathrm{tot}}$ and the central diffractive ratio by $R_{\mathrm{DPE}} = \sigma^{\mathrm{DPE}}/\sigma_{\mathrm{tot}}$. The results are summarized in Table I, where the diffractive ratios for heavy flavor production are presented for Tevatron and LHC energies. The multiple-Pomeron correction factor is taken from the KMR model. The numbers between parentheses represent the single-Pomeron calculation. Based on these results we verify that the charm and beauty produc-

tion in the single diffractive process could be observable at the Tevatron and the LHC, with a diffractive ratio of order 2%–3%. The top production case is problematic, mostly due to the kinematic threshold. The predictions for central diffractive scattering are still not very promising. However, the study of these events is worthwhile, at least for charm and bottom production. The predictions can be taken as a guide since a more detailed investigation with detector acceptance is deserved. For illustration, in Fig. 4 the energy dependence of the single diffractive ratio for charm and bottom is presented in the interval $0.63 \leq \sqrt{s} \leq 14$ TeV. The ratios decrease in energy due to the gap survival probability factor which behaves as $1/\ln\sqrt{s}$.

Our calculation can be compared to available literature on diffractive heavy flavor production. For instance, in a previous calculation presented in Ref. [24], the author has considered the leading order approximation for the hard scattering and old parametrizations for the Pomeron structure function. Corrections for multiple-Pomeron exchange were not considered. Our results for the absolute cross sections are not comparable but the values for the diffrac-
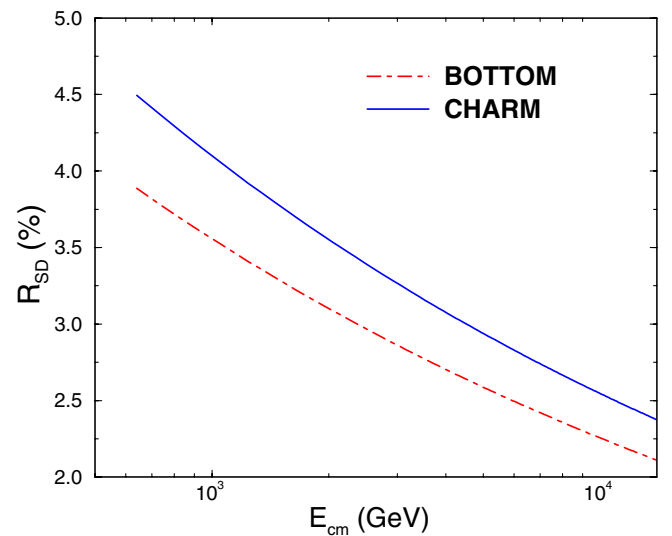

FIG. 4 (color online). The single diffractive ratio, $R_{\mathrm{SD}}(\sqrt{s}, m_Q)$, for charm and bottom hadroproduction considering multiple-Pomeron corrections as a function of energy.

tive ratios for the single-Pomeron case are similar (at least for charm and bottom). The present calculation is in agreement with the recent investigations within the light-cone dipole approach [23]. Our results for the single diffractive production of charm and bottom are similar to those in Ref. [23], including the overall normalization and energy behavior. For the top case, our results seem to be smaller than the dipole calculations.

In summary, we have presented predictions for diffractive heavy flavor production at the Tevatron and the LHC. In calculations we rely on the Regge factorization (single-Pomeron exchange) supplemented by the gap survival probability factor (correction for multiple-Pomeron exchange). For the Pomeron structure function, we take the recent H1 diffractive parton density functions extracted from their measurement of $F_2^{D(3)}$. The results are directly dependent on the quark singlet and gluon content of the Pomeron. We did not observe a large discrepancy in using the different fit procedure for diffractive pdf's. We estimate the multiple interaction corrections by taking the theoretical predictions from a multiple-channel model (KMR),

where the gap factor decreases on energy. That is, $\langle |S|^2 \rangle \simeq$ 15% for Tevatron energies going down to $\langle |S|^2 \rangle \simeq 9\%$ at LHC energy. The consideration of other models for the suppression factor does not introduce dramatic changes. We found that at the Tevatron single and central (DPE) diffractive charm and bottom quark production is observable with a single diffractive ratio $R_{q\bar{q}}^{\mathrm{SD}}$ between 3.5% (charm) and 2.5% (bottom). The DPE cross section for charm and bottom production lies above the total inclusive cross section for the top quark and might also be observable. The diffractive cross sections will be larger by at least 1 order of magnitude at the LHC and also diffractive top quark production could be observable. Therefore, the LHC can be a laboratory for diffractive scattering studies.

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