PROCEEDINGS OF SCIENCE

Single-diffractive production of heavy mesons in pp collisions

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In this proceeding we present our theoretical results for the single-diffractive production of open heavy flavor mesons in pp collisions. We estimate that this mechanism constitutes 0.5-2 per cent of the inclusive production of the same mesons in Tevatron and LHC kinematics. In Tevatron kinematics the theoretical expectations are in reasonable agreement with the available experimental data. In LHC kinematics the predicted cross-sections are sufficiently large and could be accessed experimentally. We also analyze the dependence of the cross-sections on multiplicity of co-produced hadrons, and find that it should be significantly lower than that of inclusive production of the same heavy mesons. If confirmed experimentally, this result would corroborate that multiplicity enhancement seen in inclusive production of different quarkonia states is related to multipomeron contributions, rather than other mechanisms.

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1. Introduction

In high energy pp and pA collisions, up to twenty percent of all the events might be of diffractive origin [1]. Since the early days of Quantum Chromodynamics (QCD), such events have been considered as a complementary source of information about the dynamics of strong interactions. The diffractive events are characterized by the presence of large rapidity gaps between different groups of hadrons in the final state. In QCD, such gaps are explained by the exchange of the color neutral pomerons in the t-channel. The partonic structure of pomerons does not depend on the process in which they participate, something that has been understood in detail in the context of BFKL. For this reason, the cross-sections of the diffractive processes frequently permit a straightforward factorization into independent (and relatively simple) parts, related only by the exchange of pomerons. While the cleanest channel for the analysis of diffractive processes is electroproduction, there are also numerous theoretical studies of diffractive hadroproduction. Experimentally some of these channels have been studied at the Tevatron and the LHC [1–4], and might be complemented by further studies in the nearest future [5].

In this proceeding we present the results for single-diffractive heavy meson production, $pp \to p + M X$, where M is an open heavy flavor meson. This process presents special interest, since it could help to understand the contribution of multipomeron mechanisms to heavy quark production in general. While conventionally it is assumed that for heavy quarks the multipomeron mechanisms are suppressed compared to the dominant two-gluon fusion (see [6] for overview), recent studies of the multiplicity dependence of heavy quarkonia are at tension with this assumption [7–11] and potentially could signal a sizable contribution of multipomeron mechanisms [12, 13]. The single diffractive production gives the possibility to resolve this ambiguity, since at the partonic level its cross-section is dominated by the three-pomeron fusion alone, and has a structure similar to that of the three-pomeron correction in the inclusive channel. The fact that it includes only one cut pomeron significantly simplifies the theoretical analysis and reduces the number of possible production mechanisms. The feasibility of experimental study for such process has been discussed in [5], and potentially it could be measured during the High Luminosity Run at the LHC.

This proceeding is structured as follows. In Section 2 we present the main theoretical results for the cross-section of the single-diffractive open heavy meson production, and compare the theoretical expectations with available experimental data. In Section 3 we discuss extension of our approach for high-multiplicity events, predictions and compare them with multiplicity dependence of *inclusive* production.

2. Single diffractive Production of heavy flavors

The production cross-section of the heavy meson M might be related to that of the heavy quarks of flavor i by a mere convolution with the corresponding fragmentation function D_i. For this reason in what follows we will focus on the evaluation of the heavy flavor production cross-section $d\sigma_{\bar{Q}_i Q_i}$ via a single diffractive mechanism. For heavy flavors the evaluations might be performed perturbatively in the heavy quark mass limit. However, for single-diffractive channel these evaluations might be complemented by the so-called rapidity gap survival factors, which in essence describe the probability that the rapidity gap between partons will not be filled with debris of the secondary processes. The evaluation of these factors for single-diffractive channels is straightforward and follows the general framework developed in [15].

In LHC kinematics the typical light-cone momentum fractions $x_{1,2}$ carried by gluons are very small, and for this reason for the evaluation of $d\sigma_{\bar{Q}_iQ_i}$ it is appropriate to use the color dipole framework (also known as CGC/Sat) [17–19]. The single diffractive cross-section $d\sigma_{\bar{Q}_iQ_i}$ in this approach is given by [16]

$$\frac{d\sigma_{\bar{Q}_iQ_i}\left(y,\,\sqrt{s}\right)}{dy\,d^2p_T} = \int d^2k_T x_1\, g\left(x_1,\,\boldsymbol{p}_T-\boldsymbol{k}_T\right)\int_0^1 dz\int_0^1 dz'\int\frac{d^2r_1}{4\pi}\int\frac{d^2r_2}{4\pi} \times e^{i(\boldsymbol{r}_1-\boldsymbol{r}_2)\cdot\boldsymbol{k}_T}\,\Psi^{\dagger}_{\bar{Q}Q}\left(r_2,\,z,\,p_T\right)\Psi_{\bar{Q}Q}\left(r_1,\,z,\,p_T\right)N_M^{(\mathrm{SD})}\left(x_2;\,\vec{r}_1,\,\vec{r}_2\right) \tag{1}$$

where $(y,\ p_T)$ are the rapidity and transverse momentum of the heavy quark in the target rest frame, $\boldsymbol{r}_1$ and $\boldsymbol{r}_2$ stand for the transverse separation of the quark and antiquark in the amplitude and its conjugate, z is the fraction of the incoming gluon's light-cone momentum carried by a quark, and $\boldsymbol{k}_T$ is the transverse momentum of the heavy quark with respect to incoming gluon. The variables $x_{1,2}$ are defined as $x_{1,2}=e^{\pm y^*}\sqrt{m_M^2+\langle p_{\perp M}^2\rangle}/\sqrt{s}$. The notation $g\left(x_1,\ \boldsymbol{p}_T\right)$ is used for the unintegrated gluon PDF; $\Psi_{g\to\bar{Q}Q}(r,\,z)$ is the light-cone wave function of the $\bar{Q}Q$ pair. The amplitude N_M^{SD} for the case of the single-diffractive production was evaluated in [16], and is given by

$$N_M^{(\mathrm{SD})}\left(x,\,z,\,\vec{\boldsymbol{r}}_1,\,\vec{\boldsymbol{r}}_2\right)\approx\int d^2\boldsymbol{b}\prod_{k=1,2}\left[\mathcal{N}_+\left(x,\,z,\,\boldsymbol{r}_k,\,\boldsymbol{b}\right)\left(\frac{N_c}{4}\right)+\mathcal{N}\left(x,\,\boldsymbol{r}_k,\,\boldsymbol{b}\right)\left(\frac{N_c^2-4}{4N_c}+\frac{1}{6}\right)\right] \tag{2}$$

$$\mathcal{N}_+\left(x,\,z,\,\boldsymbol{r},\,\boldsymbol{b}\right)\equiv 2\mathcal{N}\left(x,\,z\boldsymbol{r},\,\boldsymbol{b}\right)+2\mathcal{N}\left(x,\,\bar{z}\boldsymbol{r},\,\boldsymbol{b}\right)-\frac{1}{2}\mathcal{N}\left(x,\,\boldsymbol{r},\,\boldsymbol{b}\right), \tag{3}$$

where $\mathcal{N}\left(x,\,\boldsymbol{r},\,\boldsymbol{b}\right)$ is the phenomenological impact parameter ($\boldsymbol{b}$)-dependent color singlet dipole cross-section (in what follows we will use for the latter the phenomenological parametrization from [20]). The structure of (2) demonstrates that the single-diffractive mechanism is a higher twist ($\sim\mathcal{O}\left(r^2\right)$) contribution compared to the inclusive production, and thus should have stronger suppression at large p_T. In this approach the gluon uPDF $x\,g\left(x,\,k^2\right)$ can be related to the dipole scattering amplitude $\mathcal{N}\left(x,\,\boldsymbol{r}\right)=\int d^2b\,\mathcal{N}\left(x,\,\boldsymbol{r},\,\boldsymbol{b}\right)$, as was discussed in [21, 22], so the single diffractive cross-section might be expressed only in terms of the color dipole amplitude.

While the single-diffractive production has been experimentally studied quite extensively, the production of heavy mesons in such events was done only in one experimental study by the CDF collaboration [2]. This study established that the ratio of diffractive and inclusive cross-sections of B-mesons, $R_{\bar{b}b}^{(\mathrm{diff.})}=\sigma_{B^+}^{\mathrm{diff}}(s)/\sigma_{B^+}^{\mathrm{incl}}(s)$ equals $R_{\bar{b}b}^{(\mathrm{diff.})}(\sqrt{s}=1.8\,\mathrm{TeV})\approx(0.62\pm0.19\pm0.16)\,\%$. The theoretical expectations for this ratio at different energies are presented in Table 1. We can see that for the kinematics of CDF the theoretical expectation agrees fairly well with experimental data. This ratio has a mild dependence on energy, and in LHC kinematics has approximately the same magnitude. Theoretically, the smallness of the ratio is largely due to the gap survival factors mentioned earlier, as well as an additional suppression by the factor $\sim\left(\Lambda_{\mathrm{QCD}}/m_Q\right)^2$, since it is a higher twist contribution compared to the inclusive channel. While both single diffractive and inclusive production cross-sections increase as a function of energy, their ratio slightly *decreases* due to stronger suppression by the gap survival factor in single-diffractive cross-section.

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$\sqrt{s}$	$R_{\bar{c}c}^{(\text{diff})}$	$R_{\bar{b}b}^{(\text{diff})}$	$R_{J/\psi}^{(\text{diff})}$
1.8 TeV	2.20 %	0.40 %	0.57%
7 TeV	1.87 %	0.33 %	0.45%
13 TeV	1.59 %	0.30 %	0.40%

Table 1: The ratio of single diffractive and inclusive productions cross-sections for different energies. The second and the third columns correspond to the c- and b-quarks ($R_{\bar{c}c}^{(\text{diff})}$ and $R_{\bar{b}b}^{(\text{diff.})}$ respectively), whereas the last column $R_{J/\psi}^{(\text{diff})}$ is for the non-prompt J/ψ production.

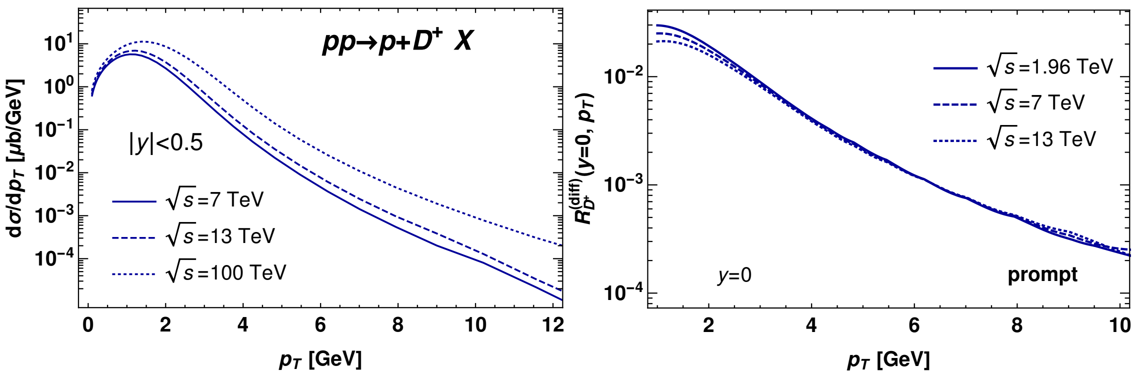

Figure 1: Left: The cross-section $d\sigma/dp_T$ of single diffractive production of D^+-mesons for several energies ($\sqrt{s}$) in the kinematics of the ongoing and forthcoming experiments. Integration over the rapidity bin $|y| < 0.5$ is implied. Right plot: The ratio of single diffractive to inclusive production cross-sections $d^2\sigma/dy\, dp_T$.

In the left panel of the Figure 1 we show the theoretical predictions for the single-diffractive cross-sections of D-mesons. We can see that numerically it is quite sizable and might be measured with reasonable precision. In the right panel of the Figure 1 we show the ratio of the single-diffractive to inclusive cross-sections. As discussed earlier, the smallness of the ratio is largely due to the gap survival factors which contribute only in single-diffractive channel. The large p_T-suppression is a mere consequence of the fact that single-diffractive production is a higher twist effect. For the sake of definiteness we considered in both panels of Figure 1 the production of D^+ mesons; for other D-mesons the p_T-dependence has a very similar shape, although the cross-section might vary numerically by a factor of two due to the difference in fragmentation functions. However, in the ratio of single diffractive to inclusive cross-sections this difference largely cancels, so the ratio is almost the same for all D-mesons. A more detailed comparison for separated contributions of prompt and nonprompt mechanisms, as well as similar analysis for B-mesons and non-prompt J/ψ mesons might be found in [16].

3. Multiplicity dependence

Recently several experimental studies [7–11] found an abnormally rapid dependence on multiplicity of charged particles co-produced in inclusive heavy flavor production. This result reinvigorated the interest in the theoretical understanding of the multiplicity enhancement mechanisms, and several independent mechanisms have been suggested for its explanation. In order to understand the underlying mechanism, it is important to complement existing data with multiplicity dependencies in other channels. The single-diffractive production from this point presents a lot of interest, because the existence of rapidity gap in final state reduces the number of possible mechanisms and simplifies its consideration. The extension of these experimental measurements to single diffractive channel is also quite straightforward. Traditionally the multiplicity dependence is presented for a self-normalized double ratio

$$\frac{dN_M/dy}{\langle dN_M/dy\rangle}=\frac{d\sigma_M\left(y,\,\eta,\,\sqrt{s},\,n\right)/dy}{d\sigma_M\left(y,\,\eta,\,\sqrt{s},\,\langle n\rangle=1\right)/dy}\Bigg/\frac{d\sigma_{\rm ch}\left(\eta,\,\sqrt{s},\,Q^2,\,n\right)/d\eta}{d\sigma_{\rm ch}\left(\eta,\,\sqrt{s},\,Q^2,\,\langle n\rangle=1\right)/d\eta} \tag{4}$$

where $\langle N_{\rm ch}\rangle = \Delta\eta\, dN_{\rm ch}/d\eta$ is the average number of particles detected in a given pseudorapidity window $(\eta-\Delta\eta/2,\ \eta+\Delta\eta/2)$, $n = N_{\rm ch}/\langle N_{\rm ch}\rangle$ is the relative enhancement of the number of charged particles in the same pseudorapidity window, $d\sigma_M(y,\,\sqrt{s},\,n)$ is the production cross-sections for heavy meson M with rapidity y and $N_{\rm ch} = n\,\langle N_{\rm ch}\rangle$ charged particles in the pseudorapidity window $(\eta-\Delta\eta/2,\ \eta+\Delta\eta/2)$, whereas $d\sigma_{\rm ch}(y,\,\sqrt{s},\,n)$ is the production cross-sections for $N_{\rm ch} = n\,\langle N_{\rm ch}\rangle$ charged particles in the same pseudorapidity window.

In the color dipole approach, the events with enhanced multiplicity $n \gtrsim 1$ technically can be described modifying the dipole amplitude of cut pomerons, which might contribute to enhancement in a given rapidity window. For the single-diffractive cross-section (1) this implies a modification of the gluon density in $g(x, k_\perp)$. For moderate values of $n \lesssim 10$ the modification of the dipole amplitude reduces to rescaling of the saturation scale Q_s^2 as $Q_s^2\,(x,\,b;\,n) \;=\; n\,Q^2\,(x,\,b)$ [14]. In Figure 2 we show the multiplicity dependence of the ratio (4). At very small n, when saturation effects are small, the size of the dipole is controlled by the mass of heavy quark $\sim 1/m_Q$, and in view of the small-r asymptotic behavior of the dipole amplitude $N\,(y,\,\boldsymbol{r},\,n)$, translates into a simple $\sim n^\gamma$ dependence, where $\gamma \approx 0.63 - 0.76$ is a numerical parameter. As we can see from the same Figure 2, this behavior is different from *inclusive* production. If confirmed experimentally, this result would corroborate that multiplicity enhancement in inclusive channels is due to multipomeron contributions, thus potentially ruling out alternative explanations.

We expect that suggested processes might be studied by the CMS (see their recent feasibility study in [5]), ALICE and STAR collaborations.

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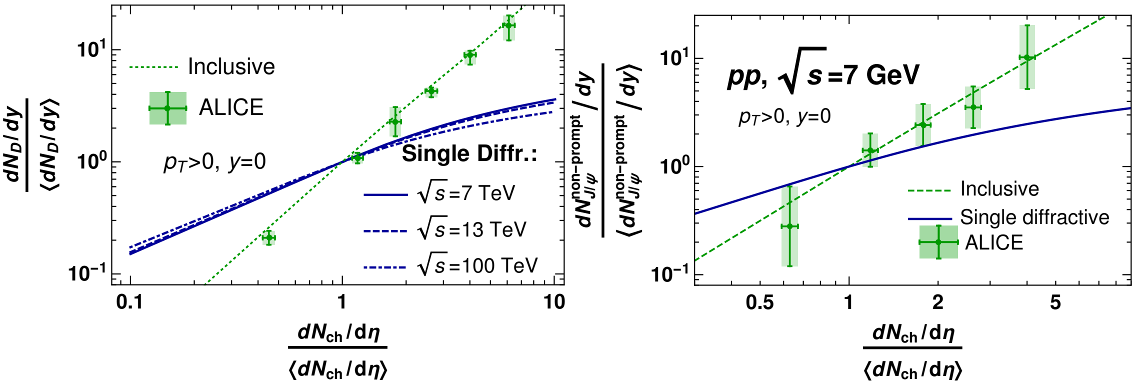

Figure 2: Multiplicity dependence of the p_T-integrated production cross-sections. Left and right panels correspond to D-mesons and nonprompt J/ψ mesons respectively. The predictions for the single diffractive mechanism are given by solid blue curves (the same for all mesons, see the text for explanation). We also added for comparison the data for inclusive production: theoretical expectations from [23] and experimental points from ALICE [7] .

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