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Diffractive exclusive production of heavy quark pairs at high energy proton-proton collisions

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We discuss exclusive double diffractive (EDD) production of heavy quark - heavy antiquark pairs at high energies. Differential distributions for $c\bar{c}$ at $\sqrt{s}$ = 1.96 GeV and for $b\bar{b}$ at $\sqrt{s}$ = 14 TeV are shown and discussed. Irreducible leading-order $b\bar{b}$ background to Higgs production is calculated in several kinematical variables. The signal-to-background ratio is shown and several improvements are suggested.

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1. Introduction

There is recently a growing theoretical interest in studying exclusive processes. Exclusive production of the Higgs boson is a flag process of special interest and importance. Only a few processes have been measured so far at the Tevatron (see [1] and references therein). Khoze, Martin and Ryskin developed an approach in the language of off-diagonal unintegrated gluon distributions. This approach was applied to exclusive production of Higgs boson [2]. In our recent paper we applied the formalism to exclusive production of $c\bar{c}$ quarks. Quite large cross sections have been found [3].

The cross section for the Standard Model Higgs production is of the order of 1 fb for M_H = 120 GeV [2]. The dominant $b\bar{b}$ decay channel is therefore preferential from the point of view of statistics. The $b\bar{b}$ exclusive production was estimated only at higher order [4]. It was argued that the leading-order contribution is rather small using a so-called J_z = 0 rule [4]. Here we show a quantitative calculation which goes beyond this simple rule. In our calculation we include exact matrix element for massive quarks and the $2 \to 4$ phase space. This fully four-body calculation allows to impose cuts on any kinematical variable one wish to select. Different types of backgrounds to Higgs production were studied before e.g. in Ref.[5].

2. Formalism

2.1 The amplitude for $pp \to ppQ\bar{Q}$

Let us concentrate on the simplest case of the production of $q\bar{q}$ pair in the color singlet state.

In analogy to the Khoze-Martin-Ryskin approach (KMR) [2] for Higgs boson production, we write the amplitude of the exclusive diffractive $q\bar{q}$ pair production $pp \to p(q\bar{q})p$ in the color singlet state as

$$\mathscr{M}^{pp\to ppq\bar{q}}_{\lambda_q\lambda_{\bar{q}}}(p_1',p_2',k_1,k_2) = s\cdot\pi^2\frac{1}{2}\frac{\delta_{c_1c_2}}{N_c^2-1}\Im\int d^2q_{0,t}\,V^{c_1c_2}_{\lambda_q\lambda_{\bar{q}}}(q_1,q_2,k_1,k_2)$$
$$\frac{f^{\rm off}_{g,1}(x_1,x_1',q_{0,t}^2,q_{1,t}^2,t_1)\;f^{\rm off}_{g,2}(x_2,x_2',q_{0,t}^2,q_{2,t}^2,t_2)}{q_{0,t}^2\,q_{1,t}^2\,q_{2,t}^2}\,, \qquad (2.1)$$

where λ_q, $\lambda_{\bar{q}}$ are helicities of heavy q and $\bar{q}$, respectively. Above $f_1^{\rm off}$ and $f_2^{\rm off}$ are the off-diagonal unintegrated gluon distributions in nucleon 1 and 2, respectively.

The longitudinal momentum fractions of active gluons are calculated based on kinematical variables of outgoing quark and antiquark: $x_1 = \frac{m_{3,t}}{\sqrt{s}}\exp(+y_3)+\frac{m_{4,t}}{\sqrt{s}}\exp(+y_4)$ and $x_2 = \frac{m_{3,t}}{\sqrt{s}}\exp(-y_3)+\frac{m_{4,t}}{\sqrt{s}}\exp(-y_4)$, where $m_{3,t}$ and $m_{4,t}$ are transverse masses of the quark and antiquark, respectively, and y_3 and y_4 are corresponding rapidities.

The bare amplitude above is subjected to absorption corrections. The absorption corrections are taken here in a simple multiplicative form.

2.2 $gg \to Q\bar{Q}$ vertex

Let us consider the subprocess amplitude for the $q\bar{q}$ pair production via off-shell gluon-gluon fusion. The color singlet $q\bar{q}$ pair production amplitude can be written as

$$V^{c_1c_2}_{\lambda_q\lambda_{\bar{q}}}(q_1,q_2,k_1,k_2) \equiv n^+_\mu n^-_\nu V^{c_1c_2,\mu\nu}_{\lambda_q\lambda_{\bar{q}}}(q_1,q_2,k_1,k_2), \qquad (2.2)$$

The tensorial part of the amplitude reads:

$$V^{\mu\nu}_{\lambda_q\lambda_{\bar q}}(q_1,q_2,k_1,k_2) = g_s^2\,\bar u_{\lambda_q}(k_1)\left(\gamma^\nu \frac{\hat q_1-\hat k_1-m}{(q_1-k_1)^2-m^2}\gamma^\mu - \gamma^\mu \frac{\hat q_1-\hat k_2+m}{(q_1-k_2)^2-m^2}\gamma^\nu\right)v_{\lambda_{\bar q}}(k_2). \tag{2.3}$$

The coupling constants $g_s^2 \to g_s(\mu_{r,1}^2)g_s(\mu_{r,2}^2)$. In the present calculation we take the renormalization scale to be $\mu_{r,1}^2 = \mu_{r,2}^2 = M_{q\bar q}^2/4$ or $M_{q\bar q}^2$. The exact matrix element is calculated numerically.

2.3 Off-diagonal unintegrated gluon distributions

In the KMR approach the off-diagonal parton distributions (i=1,2) are calculated as

$$\begin{aligned} f_i^{\mathrm{KMR}}(x_i,Q_{i,t}^2,\mu^2,t_i) &= R_g \frac{d[g(x_i,k_t^2)S_{1/2}(k_t^2,\mu^2)]}{d\log k_t^2}|_{k_t^2=Q_{it}^2}\,F(t_i) \\ &\approx R_g \frac{dg(x_i,k_t^2)}{d\log k_t^2}|_{k_t^2=Q_{i,t}^2}\,S_{1/2}(Q_{i,t}^2,\mu^2)\,F(t_i)\,, \end{aligned} \tag{2.4}$$

where $S_{1/2}(q_t^2,\mu^2)$ is a Sudakov-like form factor. It is reasonable to take a running (factorization) scale as: $\mu_1^2 = \mu_2^2 = M_{q\bar q}^2/4$ or $M_{q\bar q}^2$.

R_g can be estimated in the case of off-diagonal collinear PDFs when $x' \ll x$ and $xg = x^{-\lambda}(1-x)^n$ as $R_g = \frac{2^{2\lambda+3}}{\sqrt{\pi}}\frac{\Gamma(\lambda+5/2)}{\Gamma(\lambda+4)}$. Typically $R_g \sim 1.3$ – 1.4 at the Tevatron energy. The off-diagonal form factors are parametrized here as $F(t) = \exp(B_{\mathrm{off}}t)$ with B_{off} = 2 GeV^{-2}. We take $Q_{1,t}^2 = \min\left(q_{0,t}^2, q_{1,t}^2\right)$ and $Q_{2,t}^2 = \min\left(q_{0,t}^2, q_{2,t}^2\right)$. In evaluating f_1 and f_2 It was proposed [2] to express the $S_{1/2}$ in Eq. (2.4) through the standard Sudakov form factors as:

$$S_{1/2}(q_t^2,\mu^2) = \sqrt{T_g(q_t^2,\mu^2)}\,. \tag{2.5}$$

3. Results

3.1 $pp \to pp c\bar c$

In our calculation of $c\bar c$ we have fixed the scale of the Sudakov form factor to be $\mu = M_{c\bar c}/2$. Such a choice of the scale leads to a strong damping of the cases with large rapidity gaps between q and $\bar q$.

In the left panel of Fig. 1 we show distribution in rapidity. The results obtained with the KMR method are shown together with inclusive gluon-gluon contribution. The effect of absorption leads to a damping of the cross section by an energy-dependent factor. For the Tevatron this factor is about 0.1. If the extra factor is taken into account the EDD contribution is of the order of 1% of the inclusive cross section.

In the right panel of Fig. 1 we show the differential cross section in transverse momentum of the charm quark. Compared to the inclusive case, the exclusive contribution falls significantly faster than in the inclusive case.

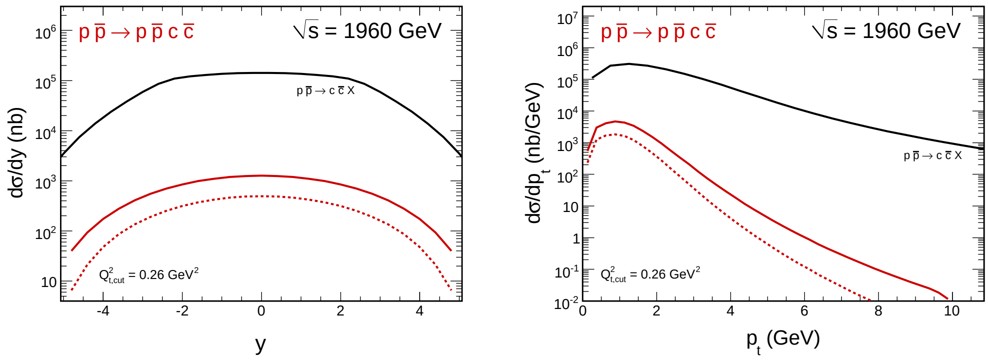

Figure 1: Rapidity distribution of c or $\bar{c}$ (left) and transverse momentum distribution of c or $\bar{c}$ (right). The top curve is for inclusive production in the k_t-factorization approach with the Kwieciński UGDF and $\mu^2 = 4m_c^2$, while the two lower lines are for the EDD mechanism for the KMR UGDF with leading-order GDF [11]. The solid line is calculated from the exact formula and the dashed line for the simplified formula (when only derivative of GDF is taken). Absorption effects were included approximately by multiplying the cross section by S_G = 0.1.

3.2 $pp \to ppb\bar{b}$

In parallel to the exclusive $b\bar{b}$ production, we calculate the differential cross sections for exclusive Higgs boson production. Compared to the standard KMR approach here we calculate the amplitude with the hard subprocess $g^*g^* \to H$ taking into account off-shellness of the active gluons. The details of the off-shell matrix element can be found in Ref. [6]. In contrast to the exclusive χ_c production [7] the off-shell effects for $g^*g^* \to H$ give only a few percents.

The same unintegrated gluon distributions are used for the Higgs and continuum $b\bar{b}$ production. In the case of exclusive Higgs production we calculate the four-dimensional distribution in the standard kinematical variables: y, t_1, t_2 and ϕ. Assuming the full coverage for outgoing protons we construct the two-dimensional distributions $d\sigma/dyd^2p_t$ in Higgs rapidity and transverse momentum. The distribution is used then in a simple Monte Carlo code which includes the Higgs boson decay into the $b\bar{b}$ channel. It is checked whether b and $\bar{b}$ enter into the pseudorapidity region spanned by the detector.

We have done calculations with different collinear gluon distributions: GRV [11], CTEQ [12], GJR [13] and MSTW [14]. The integrated double-diffractive $b\bar{b}$ contribution calculated seems bigger than the contribution of the exclusive photoproduction of $b\bar{b}$ estimated in [15]. While the $\gamma\gamma$ contribution is rather small, it is significant compared to the double-diffractive component at large $M_{b\bar{b}} > 100$ GeV. This can be understood by a damping of the double diffractive component at large $M_{b\bar{b}}$ by the Sudakov form factor [2, 3].

In the left panel of Fig.2 we show the double diffractive contribution for a selected (CTEQ6 [12]) GDF and the contribution from the decay of the Higgs boson including decay width calculated as in Ref. [16], see the sharp peak at $M_{b\bar{b}}$ = 120 GeV. The cross section for the Higgs production, including absorption effects with $S_G = 0.03$ is less than 1 fb. The result shown in Fig.2 includes also BR($H \to b\bar{b}$) $\approx$ 0.8 and the rapidity restrictions. The second much broader peak corresponds to the exclusive production of the Z^0 boson with the cross section calculated as in Ref. [17]. The

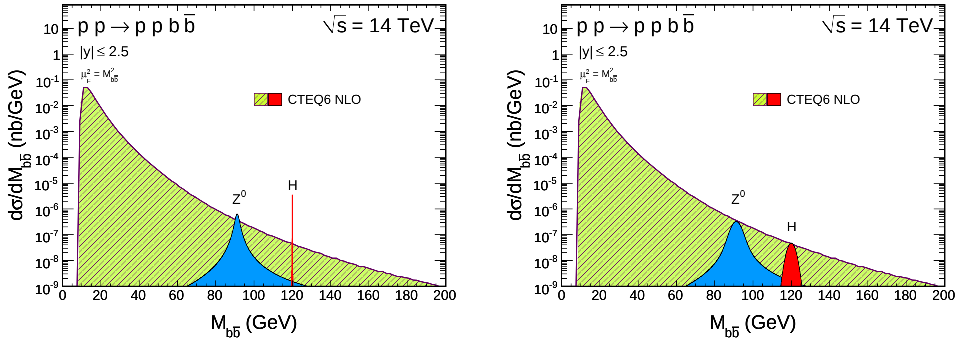

Figure 2: The $b\bar{b}$ invariant mass distribution for $\sqrt{s}$ = 14 TeV and for b and $\bar{b}$ jets in the rapidity interval $-2.5 < y < 2.5$ corresponding to the ATLAS detector. The absorption effects for the Higgs boson and the background were taken into account by multiplying by $S_G = 0.03$. The left panel shows purely theoretical predictions, while the right panel includes experimental resolution.

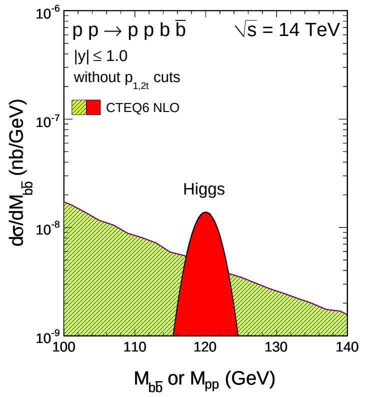

Figure 3: The $b\bar{b}$ invariant mass distribution for $\sqrt{s}$ = 14 TeV for a limited range of b and $\bar{b}$ rapidities: $-1 < y < 1$.

exclusive cross section for $\sqrt{s}$ = 14 TeV is 16.61 fb including absorption and branching fraction $\mathrm{BR}(Z^0 \to b\bar{b}) \approx 0.15$. In contrast to the Higgs case the absorption effects for the Z^0 production are much smaller [17]. The sharp peak corresponding to the Higgs boson clearly sticks above the background.

In reality the situation is, however, much worse as both protons and in particular b and $\bar{b}$ jets are measured with a certain precision which leads to a smearing in $M_{b\bar{b}}$. Experimentally instead of $M_{b\bar{b}}$ one will measure rather two-proton missing mass (M_{pp}). The experimental effects are included in the simplest way by a convolution of the theoretical distributions with the Gaussian smearing function with σ = 2 GeV [18, 19] which is determined mainly by the precision of measuring forward protons. In the right panel we show the two-proton missing mass distribution when the smearing is included. Now the bump corresponding to the Higgs boson is below the $b\bar{b}$ background. With the experimental resolution assumed above the identification of the Standard Model Higgs seems rather difficult.

Can the situation be improved by imposing further cuts? In Fig. 3 (left panel) we show the result for a more limited range of b and $\bar{b}$ rapidity, i.e. not making use of the whole coverage of the main LHC detectors. Here we omit the Z^0 contribution and concentrate solely on the Higgs signal. Now the signal-to-background ratio is somewhat improved. Similar improvements of the signal-to-background ratio can be obtained by imposing cuts on jet transverse momenta [9].

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References

[1] M.G. Albrow, T.D. Coughlin and J.R. Forshaw, Arxiv.1006.1289.

[2] V. A. Khoze, A. D. Martin and M. G. Ryskin, Phys. Lett. B **401**, 330 (1997);
A. B. Kaidalov, V. A. Khoze, A. D. Martin and M. G. Ryskin, Eur. Phys. J. C **33**, 261 (2004).

[3] R. Maciuła, R. Pasechnik and A. Szczurek, Phys. Lett. B **685**, 165 (2010).

[4] V. A. Khoze, M. G. Ryskin and A. D. Martin, Eur. Phys. J. C **64**, 361 (2009).

[5] M. Chaichian, P. Hoyer, K. Huitu, V.A. Khoze and A.D. Pilkington, JHEP 0905 (2009) 011.

[6] R. S. Pasechnik, O. V. Teryaev and A. Szczurek, Eur. Phys. J. C **47**, 429 (2006).

[7] R. S. Pasechnik, A. Szczurek and O. V. Teryaev, Phys. Rev. D **78**, 014007 (2008);
R. S. Pasechnik, A. Szczurek and O. V. Teryaev, Phys. Lett. B **680**, 62 (2009);
R. S. Pasechnik, A. Szczurek and O. V. Teryaev, Phys. Rev. D **81**, 034024 (2010).

[8] R. Maciuła, R.S. Pasechnik and A. Szczurek, arXiv:1006.3007 (hep-ph).

[9] R. Maciuła, R.S. Pasechnik and A. Szczurek, a work in preparation.

[10] T.D. Coughlin and J.R. Forshaw, JHEP 1001, 121 (2010).

[11] M. Glück, E. Reya and A. Vogt, Z. Phys. **C67**, 433 (1995).

[12] J. Pumplin et al., JHEP 0207, 012 (2002).

[13] M. Glück, D. Jimenez-Delgado, E. Reya, Eur. Phys. J. **C53**, 355 (2008).

[14] A.D. Martin et al., Eur. Phys. J. **C63**, 189 (2009).

[15] V.P. Goncalves and M.V.T. Machado, Phys. Rev. **D75**, 031502(R) (2007).

[16] G. Passarino, Nucl. Phys. B **488**, 3 (1997).

[17] A. Cisek, W. Schäfer and A. Szczurek, Phys. Rev. **D80** 074013 (2009).

[18] A. Pilkington, private communication.

[19] Ch. Royon, private communication.