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

A. Szczurek

Institute of Nuclear Physics PAN, ul. Radzikowskiego 152, Kraków, Poland and University of Rzeszów, ul. Refjana 16a, Rzeszów, Poland

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We discuss exclusive double diffractive (EDD) production of Higgs boson and 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 $bb$ background to Higgs production is calculated in several kinematical variables. The signal-to-background ratio is shown and several improvements are suggested by imposing cuts on $b$ ($\bar{b}$) transverse momenta and rapidities.

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I. INTRODUCTION

Exclusive production of the Higgs boson can be an alternative to the present studies of Higgs in inclusive processes. There is recently a growing theoretical interest in studying exclusive processes. Only a few processes have been measured so far, mostly 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 papers we applied the same formalism to exclusive production of $c\bar{c}$ and $b\bar{b}$ quarks. Quite large cross sections have been found [3,4].

The cross section for the Standard Model Higgs production is of the order of 1 fb for light Higgs [2]. The dominant $b\bar{b}$ decay channel is therefore preferential from the point of view of statistics. It was argued that the leading-order contribution is rather small using a so-called $J_z = 0$ rule. 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 $2 \rightarrow 4$ phase space. This fully four-body calculation allows to impose cuts on kinematical variables. Different types of backgrounds to Higgs production were studied before e.g. in Ref. [6].

II. FORMALISM

Let us concentrate on the simplest case of the production of $q\bar{q}$ pair in the color singlet state. Color octet state would demand an emission of an extra gluon which considerably complicates the calculations. We do not consider the $q\bar{q}g$ contribution as it is higher order compared to the one considered here.

We write the amplitude of the exclusive diffractive $q\bar{q}$ pair production $pp \rightarrow p(q\bar{q})p$ in the color singlet state as

$$\mathcal{M}^{pp \rightarrow ppq\bar{q}}(p_1', p_2', k_1, k_2) = s \cdot \pi^2 \frac{\delta_{2\perp}}{2 \sqrt{s}} \int d^2q_{01} V_{\lambda_1\lambda_q}^{c1c2}(q_1, q_2, k_1, k_2) f_{1\perp}^c(x_1, x'_1, q_{\perp01}^2, q_{\perp1}^2, k_{\perp1}^2) f_{2\perp}^c(x_2, x'_2, q_{\perp02}^2, q_{\perp2}^2, k_{\perp2}^2),$$

where $\lambda_q$, $\lambda_q$ are helicities of heavy $q$ and $\bar{q}$, respectively. Above $f_{1\perp}^c$ and $f_{2\perp}^c$ 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: $x_1 = \frac{m_q}{s} \exp(+y_3) + \frac{m_{\bar{q}}}{s} \exp(+y_4)$ and $x_2 = -\frac{m_q}{s} \exp(-y_3) + \frac{m_{\bar{q}}}{s} \exp(-y_4)$, where $m_{3,4}$ and $m_{4,4}$ 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.

Let us consider the subprocess amplitude for the $q\bar{q}$ pair production via off-shell gluon-gluon fusion. The vertex factor $V_{\lambda_1\lambda_q}^{c1c2} = V_{\lambda_1\lambda_q}^{c1c2}(q_1, q_2, k_1, k_2)$ in expression (2.1) is the production amplitude of a pair of massive quark $q$ and antiquark $\bar{q}$ with helicities $\lambda_q$, $\bar{\lambda}_q$ and momenta $k_1$, $k_2$, respectively. The color singlet $q\bar{q}$ pair production amplitude can be written as

$$V_{\lambda_1\lambda_q}^{c1c2}(q_1, q_2, k_1, k_2) = n_\mu n'_\nu V_{\lambda_1\lambda_q}^{c1c2;\mu\nu}(q_1, q_2, k_1, k_2),$$

The tensorial part of the amplitude reads:

$$V_{\lambda_1\lambda_q}^{\mu\nu}(q_1, q_2, k_1, k_2) = g_s^2 \tilde{u}_{\lambda_q}(k_1) \gamma^\mu \frac{k_{\perp1} - m_q}{(q_1 - k_1)^2 - m_q^2} \gamma^\nu \frac{-m_{\bar{q}}}{(q_2 - k_2)^2 - m_{\bar{q}}^2} \tilde{u}_{\lambda_q}(k_2).$$

The coupling constants $g_s^2 = g_s^2(M_{q\bar{q}}^2/4)g_s^2(M_{q\bar{q}}^2/4)$. In the present calculation we take the renormalization scale to be $\mu_{R,1}^2 = \mu_{R,2}^2 = M_{q\bar{q}}^2$ or $M_{q\bar{q}}^2$. The exact matrix element is calculated numerically. Analytical formulae are shown explicitly in [3].
The off-diagonal parton distributions \((i=1,2)\) are calculated as
\[
\begin{align*}
 f_i^{\text{KMR}}(x_i, Q_i^2, \mu_r^2, t_i) &= \\
 &= R_f \left. \frac{d\sigma(q_i^2, k_i^2)}{d\log k_i^2} \right|_{k_i^2=Q_i^2} F(t_i) \tag{2.3}
\end{align*}
\]
where \(S_{1/2}(q_i^2, \mu_r^2)\) is a Sudakov-like form factor relevant for the case under consideration. It is reasonable to take \(\mu_r^2 = \mu_s^2 = M_{qg}/4\) or \(M_{qg}^2\).

The factor \(R_f\) here cannot be calculated from first principles in the most general case of off-diagonal UGDFs. It can be estimated in the case of off-diagonal collinear PDFs when \(x' \ll x\) and \(xg = x^{-\lambda}(1-x)^n\). Then \(R_f = \frac{2^{\lambda+3} \Gamma(\lambda+5/2)}{\Gamma(\lambda+4)}\). Typically \(R_f \sim 1.3 - 1.4\) at the Tevatron energy. The off-diagonal form factors are parametrized here as \(F(t) = \exp(B_{\text{off}} t)\). In practical calculations we take \(B_{\text{off}} = 2\ \text{GeV}^{-2}\). In the original KMR approach the following prescription for the effective transverse momentum is taken: \(Q_i^2 = \min \left(\frac{Q_i^2}{\lambda}, q_i^2\right)\) and \(Q_i^2, t = \min (q_i^2, q_i^2, t_i)\). In evaluating \(f_1\) and \(f_2\) needed for calculating the amplitude \((2.1)\) we use different collinear distributions. It was proposed \([2]\) to express the \(S_{1/2}\) form factors in Eq. \((2.3)\) through the standard Sudakov form factors as:
\[
S_{1/2}(q_i^2, \mu_r^2) = \sqrt{T_f(q_i^2, \mu_r^2)} \tag{2.4}
\]

The cross section for the four-body reaction is calculated as
\[
d\sigma = \frac{1}{2} |M_{2\to 4}|^2 \frac{(2\pi)^4 \delta^4(p_a + p_b - p_1 - p_2 - p_3 - p_4)}{(2\pi)^3 d^3 p_2 (2\pi)^3 d^3 p_3 (2\pi)^3 d^3 p_4 (2\pi)^2 d^2 p_1} \tag{2.5}
\]
The details how to conveniently reduce the number of kinematical integration variables are given elsewhere.

### III. RESULTS

#### A. \(pp \to pp\tilde{c}\)

Let us proceed now with the presentation of differential distributions of charm quarks produced in the EDD mechanism. In this case 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. \ref{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 dominant gluon-gluon fusion contribution.

The corresponding rapidity-integrated cross section at \(\sqrt{s} = 1960\ \text{GeV}\) is: 6.6 \(\mu\)b for the exact formula, 2.4 \(\mu\)b for the simplified formula (see Eq. \((2.3)\)). For comparison the inclusive cross section (gluon-gluon component only) is 807 \(\mu\)b.

#### B. \(pp \to pp\bar{b}\)

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. \([7]\). In contrast to the exclusive \(\chi_c\) production \([8]\), due to a large factorization scale \(\sim M_H\) the off-shell effects for \(g^* g^* \to H\) give only a few percents.

The same unintegrated gluon distributions based on the collinear 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 \(\phi\). Assuming the full coverage for outgoing protons we construct the two-dimensional distributions \(d\sigma/dy d^2p_t\) in

\ref{fig:1}

**FIG. 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 \([3]\) while the two lower lines are for the EDD mechanism with leading-order collinear gluon distribution \([10]\). The solid line is calculated from the exact formula and the dashed line for the simplified formula \([4]\). An extra cut on the momenta in the loop \(Q_{t,cut}^2 = 0.26\ \text{GeV}^2\) was imposed. Absorption effects were included by multiplying the cross section by the gap survival factor \(S_G = 0.1\).

In the right panel of Fig. \ref{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 with transverse momentum than in the inclusive case.
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 subsequently whether $b$ and $\bar{b}$ enter into the pseudorapidity region spanned by the central detector.

In Fig. 2 we show the most essential distribution in the invariant mass of the centrally produced $b\bar{b}$ pair, which is also being the missing mass of the two outgoing protons.

In this calculation we have taken into account typical detector limitations in rapidity $-2.5 < y_b, y_{\bar{b}} < 2.5$. We show results with different collinear gluon distributions from the literature: GRV [10], CTEQ [11], GJR [12] and MSTW [13]. The results obtained with radiatively generated gluon distributions (GRV, GJR) allow to use low values of $Q_t = q_0 t, q_{1t}, q_{2t}$ whereas for other gluon distributions an upper cut on $Q_t$ is necessary. The lowest curve in Fig 2 represents the $\gamma\gamma$ contribution [4]. While the integrated over phase space $\gamma\gamma$ contribution is rather small, it is significant compared to the double-diffractive component at large $M_{b\bar{b}} > 100$ GeV.

The absorption for the $H$ boson clearly sticks above the continuum has maxima far above the background. In the above calculations we have assumed an ideal measurement.

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 automatically 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 $G(M) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(M-M_0)^2}{2\sigma^2}\right)$ with $\sigma = 2$ GeV 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 clearly sticks above the background. With the experimental resolution assumed above the identification of the Standard Model Higgs seems rather difficult. The situation for some scenarios beyond the Standard Model may be better.

Can the situation be improved by imposing further cuts? In Fig. 4 we show the distribution for the EDD background in $y_b$ and $y_{\bar{b}}$. In contrast to the Higgs the cross section for the $b\bar{b}$ continuum has maxima far
from the diagonal. This can be used to impose cuts on quark/antiquark rapidities. In Fig. 4 (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. This would be obviously at the expense of a deteriorated statistics. Similar improvements of the signal-to-background ratio can be obtained by imposing cuts on jet transverse momenta. Detailed studies of the role of cuts is discussed in [5].

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