Heavy Quark Production at $\gamma p$ Colliders

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Abstract

Heavy quark pair production at $\gamma p$ colliders is discussed. It is shown that the numbers of $tt$ pairs are sufficiently large for investigation of the top quark properties in detail.

Recently, the CDF and D0 Collaborations have reported the discovery of the top quark in $pp$ collisions at $\sqrt{s} = 1.8$ TeV [1, 2]. The latest combined value for the top quark mass is $m_t = 175 \pm 6$ GeV [3].

In $pp$ collisions the top quarks are expected to be produced in pairs by both gluon-gluon fusion and $q\bar{q}$ annihilation. For a heavy quark mass greater than 100 GeV, $q\bar{q}$ annihilation is expected to be the dominant production source at Fermilab energies. However, in $\gamma p$ collisions the gamma-gluon fusion will be the dominant production mode for heavy quark pair production with an expected background less than that of the $pp$ collisions.

In this work, we show the capabilities of $\gamma p$ colliders [4, 5, 6, 7, 8], as complementary machines, via the production of heavy quarks. First, we estimate the numbers of $tt$ pairs which will be produced at future $\gamma p$ colliders. Then, we obtain upper mass limits for new heavy quarks, fourth SM family $u_4$ and $d_4$ quarks predicted by the democratic mass matrix (DMM) approach [9] and isosinglet $D$ quarks predicted by $E_6$ model [10, 11, 12]. Finally, we discuss the signatures for new heavy quark production.

The quark-antiquark pairs will be produced through the subprocess $\gamma g \rightarrow q\bar{q}$. The Feynman amplitudes consist of two well-known diagrams and it is easy to obtain the differential cross section [13]:

$$\frac{d\sigma}{dt} = \frac{2\pi\alpha_{em}\alpha_s Q^2 C}{\hat{s}} \left[ \frac{4m^2\hat{s}}{(l-m^2)(\hat{u}-m^2)} + \frac{\hat{u}-m^2}{(l-m^2)} + \frac{\hat{l}-m^2}{(\hat{u}-m^2)} - \frac{4m^4\hat{s}^2}{(l-m^2)^2(\hat{u}-m^2)^2} \right] \tag{1}$$
where \( s = (p_\gamma + p_g)^2, \tilde{t} = (p_\gamma - p_q)^2, \tilde{u} = (p_q - p_g)^2 \) are Lorentz invariant Mandelstam variables; \( p_\gamma, p_g, p_q \) and \( m \) denote photon, gluon, quark momenta and quark mass, respectively. \( \alpha_{em} \) is the fine structure constant and \( \alpha_s \) is the strong coupling constant. \( Q \) is the charge of heavy quarks, and the color factor \( C \) is \( 1/2 \).

The integration over \( \tilde{t} \) can be carried out analytically to get the cross section for the subprocess \( \gamma g \to q\bar{q} \)

\[
\hat{\sigma} = \frac{\pi\alpha_{em}\alpha_s Q^2}{s(1 + \beta^2)} \left[ 2\beta(\beta^2 - 1) + (\beta^4 + 3\beta^2 - 3) \ln(\frac{1}{1 + \beta}) \right]
\]

where \( \beta = \sqrt{1 - 4m^2/s} \). Further integration over gluon distributions in proton and energy spectrum of photon should be performed to obtain the total cross section for the heavy quark pair production through the process \( \gamma p \to q\bar{q}X \):

\[
\sigma = \int_{\tau_{min}}^{0.83} d\tau \int_{\tau/0.83}^{1} \frac{dx}{x} f_\gamma(\tau) G(x, Q^2_0)\hat{\sigma}(\tau s)
\]

where \( \tau_{min} = 4m^2/s \) and \( \hat{s} = \tau s \). The energy spectrum of high energy photons obtained through the Compton backscattering of laser photons on high energy electron beam has the form [14]

\[
f_\gamma(y) = \frac{1}{D(\xi)} \left[ 1 - y + \frac{1}{1 - y} - \frac{4y}{\xi(1 - y)} + \frac{4y^2}{\xi^2(1 - y)^2} \right],
\]

with \( \xi = 4.8 \) and \( D(\xi) = 1.84 \). Gluon distribution function in the proton \( G(x, Q^2_0) \), where \( Q^2_0 = \hat{s}/2 \), has been chosen as follows [15]

\[
G(x, Q^2_0) = \frac{1}{x} 0.77x^{-0.3}(1 - x)^{5.3}(1 + 5.2x)
\]

and different parametrizations were proposed by [16].

\[
G(x, Q^2_0) = \frac{1}{x} (0.444x^{-1/2} - 1.886) \quad \text{and}
\]

\[
G(x, Q^2_0) = 25.56x^{-1/2} \quad x < 0.01
\]

\[
G(x, Q^2_0) = \frac{1}{x} (2.62 + 9.17x)(1 - x)^{5.90} \quad x > 0.01
\]

Gluon density in the proton can be measured at HERA down to the values of \( x \) of the order of \( 10^{-4} \). However, \( \gamma p \) colliders will give the opportunity to investigate gluon distributions at extremely small \( x \) by means of the process \( \gamma p \to c\bar{c}X \) and \( \gamma p \to bbX \).

The cross section \( \hat{\sigma}(\hat{s}) \) for the charm quark pair production as a function of \( \hat{s} \) is plotted in Fig.1. As it can be seen from this figure, in \( \gamma p \) collisions, \( \hat{\sigma}(\hat{s}) \) has a maximum value when \( \hat{s} = xys \approx 7m_c^2 \). We can obtain the \( x \) values down to \( 10^{-5} - 10^{-6} \) depending on the center of mass energy of the \( \gamma p \) colliders. As an illustration, \( c\bar{c} \) pair production
differential cross section, $d\sigma/dx$, for the HERA+LC proposal is given in Fig. 2. One can see from this figure the parametrizations of three kind (Eq. 5, 6 and 7 correspond to the curves 2, 3 and 1, respectively) lead to drastically different behaviours at small $x$. Then, the main part of the $c\bar{c}$ pairs will be produced at extremely small $x(\simeq 10^{-5})$.

![Figure 1. The cross section for the subprocess $\gamma g \rightarrow c\bar{c}$.](image)

For the heavy quark pair production, the total cross sections versus the heavy quark mass are plotted in Figures 3 a,b,c for HERA+LC, LHC+Linac1 and LHC+TESLA $\gamma p$ colliders in the case of $Q=2/3$. The cross sections for heavy quark production with charge $Q = -1/3$ decrease by a factor of $1/4$. Contributions of terms with $\alpha_s^2$ in the total cross section are smaller than $10\%$ for $m_q > 100$ GeV and we neglect it at this stage. Then, the contribution from "resolved" photons can be also neglected, because it is expected to contribute about $1\%$ for large values of heavy quark masses [17].

| Table 1. Parameters of $\gamma p$ colliders. $s_{\gamma p}^{max} = 0.83 s_{ep}$. |
|---------------------------------|---|---|---|---|
| Machines | $E_p$ (TeV) | $E_e$ (TeV) | $\sqrt{s_{ep}}$ (TeV) | $\mathcal{L}_{\gamma p}(10^{30})$ cm$^{-2}$s$^{-1}$ |
| HERA+LC | 0.82 | 0.50 | 1.28 | 25 |
| LHC+Linac1 | 7.50 | 0.30 | 3.04 | 500 |
| LHC+TESLA | 7.50 | 1.00 | 5.50 | 500 |

The numbers of $t\bar{t}$ pairs which will be produced at different $\gamma p$ machines can be easily obtained from Figure 3 by using luminosities given in Table 1. The results are presented in Table 2 for $m_t = 175$ GeV. These numbers are sufficiently large for investigation of the top quark properties in detail. In Table 2, we also give the observable upper mass limits.
for new heavy quarks. Here we take 100 events per year as the discovery limit for new heavy quarks at $\gamma p$ colliders. This value is quite reasonable due to clearer background compared to hadron colliders. The upper mass limits for new heavy quarks at these machines are comparable with those at the future $pp$ and $\gamma\gamma$ colliders [18, 19].

**Table 2.** Numbers of $t\bar{t}$ pairs ($m_t = 175$ GeV) per year and upper mass limits for new heavy quarks at $\gamma p$ colliders.

<table>
<thead>
<tr>
<th>Machines</th>
<th>$N_{t\bar{t}}$</th>
<th>$m_{d_4, D}(TeV)$</th>
<th>$m_{u_4}(TeV)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERA+LC</td>
<td>270</td>
<td>0.16</td>
<td>0.21</td>
</tr>
<tr>
<td>LHC+Linac1</td>
<td>25000</td>
<td>0.48</td>
<td>0.60</td>
</tr>
<tr>
<td>LHC+TESLA</td>
<td>50000</td>
<td>0.68</td>
<td>0.90</td>
</tr>
</tbody>
</table>

**Figure 2.** The differential cross section $d\sigma/dx$ for the process $\gamma p \rightarrow c\bar{c}X$. Curves 1, 2 and 3 correspond to different parametrizations of gluon distributions defined in the text.

Signatures for the production of new heavy quarks will depend on their masses and mixings. Note that the lightest of $u_4$ and $d_4$ will decay only due to mixing with the first three family quarks. When the mixing between the fourth and the third family quarks is dominant: if $m_{u_4} > m_{d_4}$, the dominant decay mode for $d_4$ will be $d_4 \rightarrow t + W$. Then, if $m_{u_4} > m_{d_4} + m_W$, the dominant decay mode will be $u_4 \rightarrow d_4 + W$. In this case, signatures for $u_4$ and $d_4$ search are similar (may be a little complicated) to those for $t$-quark. Pair production of $d_4$ quarks will appear in the detector as two high energy $b$ jets associated with a $W^+W^-$ pair.
$\sqrt{s} = 1.28 \text{ TeV}$

![Graph of $\sigma(\text{pb})$ vs. $p_T$ for $\sqrt{s} = 1.28 \text{ TeV}$](image)

$\sqrt{s} = 3.04 \text{ TeV}$

![Graph of $\sigma(\text{pb})$ vs. $p_T$ for $\sqrt{s} = 3.04 \text{ TeV}$](image)
A different situation takes place for the $D$-quark decays because flavor changing neutral currents appear. Indeed, the $D$-quark will decay due to mixings with usual down-type quarks. Notice that experimental lower limit for the $D$-quark mass is the same as for the $t$-quark, namely $m_D > 130\text{GeV}$. We can find the Branching Ratios $\text{BR}(D \rightarrow uW) \sim 0.6$ and $\text{BR}(D \rightarrow dZ) \sim 0.4$ [20]. Therefore, the essential part of $D$-decays will be induced by flavor changing neutral currents. In particular, $D \rightarrow d\ell^+\ell^-(\ell = e, \mu, \tau)$ decay channels occur with probability more than 1%.

In conclusion, $\gamma p$-colliders will give the opportunities to investigate the properties of the top quark and search for new heavy quarks. These machines have an additional advantage in analysing gluon distributions in the proton.

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**References**


