Tr. J. of Physics
22 (1998) , 733 – 739.

International Workshop on Linac-Ring
Type ep and γp Colliders

Heavy Quark Production at γp Colliders

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Abstract

Heavy quark pair production at γp colliders is discussed. It is shown that the numbers of $t\bar{t}$ 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 $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV [1, 2]. The latest combined value for the top quark mass is $m_t = 175 \mp 6$ GeV [3].

In $p\bar{p}$ 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 γp 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 $p\bar{p}$ collisions.

In this work, we show the capabilities of γp colliders [4, 5, 6, 7, 8], as complementary machines, via the production of heavy quarks. First, we estimate the numbers of $t\bar{t}$ pairs which will be produced at future γp 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 $\gamma g \to q\bar{q}$. The Feynman amplitudes consist of two well-known diagrams and it is easy to obtain the differential cross section [13]:

$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{2\pi\alpha_{em}\alpha_s Q^2 C}{\hat{s}}\Bigg[\frac{4m^2\hat{s}}{(\hat{t}-m^2)(\hat{u}-m^2)} + \frac{\hat{u}-m^2}{(\hat{t}-m^2)} + \frac{\hat{t}-m^2}{(\hat{u}-m^2)} - \frac{4m^4\hat{s}^2}{(\hat{t}-m^2)^2(\hat{u}-m^2)^2}\Bigg] \tag{1}$$

where $\hat{s} = (p_\gamma + p_g)^2, \hat{t} = (p_\gamma - p_q)^2, \hat{u} = (p_q - p_g)^2$ are Lorentz invariant Mandelstam variables; p_γ, p_g, p_q and m denote photon, gluon, quark momenta and quark mass, respectively. α_{em} is the fine structure constant and α_s is the strong coupling constant. Q is the charge of heavy quarks, and the color factor C is 1/2.

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

$$\hat{\sigma} = \frac{\pi \alpha_{em} \alpha_s Q^2}{\hat{s}(1+\beta^2)} \left[2\beta(\beta^4 - \beta^2 - 2) + (\beta^6 + \beta^4 - 3\beta^2 - 3) \ln\left(\frac{1-\beta}{1+\beta} \right) \right] \tag{2}$$

where $\beta = \sqrt{1 - 4m^2/\hat{s}}$. 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 $\gamma p \to \bar{q}qX$:

$$\sigma = \int_{\tau_{min}}^{0.83} d\tau \int_{\tau/0.83}^{1} \frac{dx}{x} f_\gamma\left(\frac{\tau}{x}\right) G(x, Q_0^2) \hat{\sigma}(\tau s) \tag{3}$$

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]

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

with $\xi = 4.8$ and $D(\xi) = 1.84$. Gluon distribution function in the proton $G(x, Q_0^2)$, where $Q_0^2 = \hat{s}/2$, has been chosen as follows [15]

$$G(x, Q_0^2) = \frac{1}{x} 0.77 x^{-0.3} (1-x)^{5.3} (1 + 5.2x) \tag{5}$$

and different parametrizations were proposed by [16].

$$G(x, Q_0^2) = \frac{1}{x}(0.444 x^{-1/2} - 1.886) \quad and \tag{6}$$

$$G(x, Q_0^2) = 25.56 x^{-1/2} \qquad x < 0.01 \tag{7}$$

$$G(x, Q_0^2) = \frac{1}{x}(2.62 + 9.17x)(1-x)^{5.90} \qquad x > 0.01 \tag{8}$$

Gluon density in the proton can be measured at HERA down to the values of x of the order of 10^{-4}. However, γp 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 $\gamma p \to b\bar{b}X$. 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 γp collisions, $\hat{\sigma}(\hat{s})$ has a maximum value when $\hat{s} = xys \simeq 7m_q^2$. We can obtain the x values down to $10^{-5} - 10^{-6}$ depending on the center of mass energy of the γp 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 $x(\simeq 10^{-5})$.

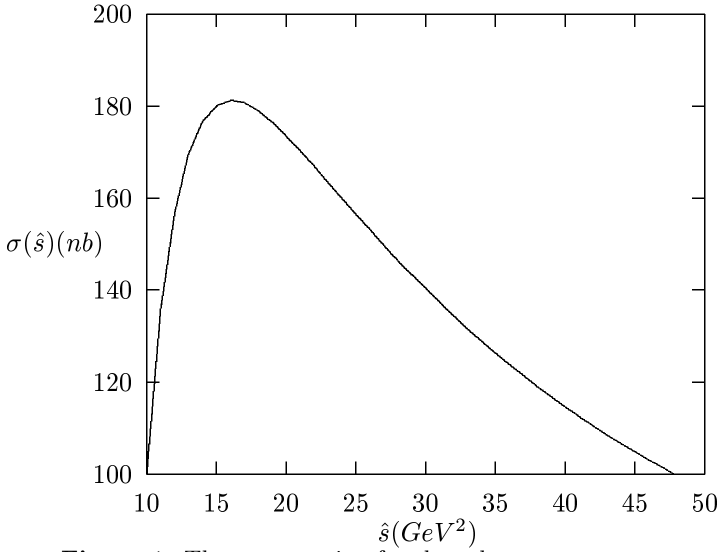


Figure 1. The cross section for the subprocess $\gamma g \to c\bar{c}$.

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 γp 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 α_s^2 in the total cross section are smaller than 10 percent 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 percent for large values of heavy quark masses [17].

Table 1. Parameters of γp 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 γp 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 γp 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 γp colliders.

Machines	$N_{t\bar{t}}$	$m_{d_4,D}(TeV)$	$m_{u_4}(TeV)$
HERA+LC	270	0.16	0.21
LHC+Linac1	25000	0.48	0.60
LHC+TESLA	50000	0.68	0.90

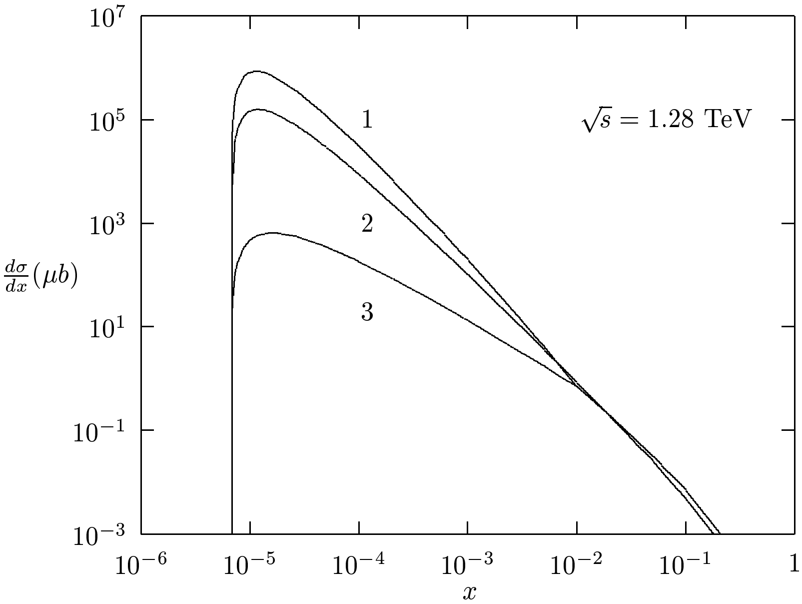
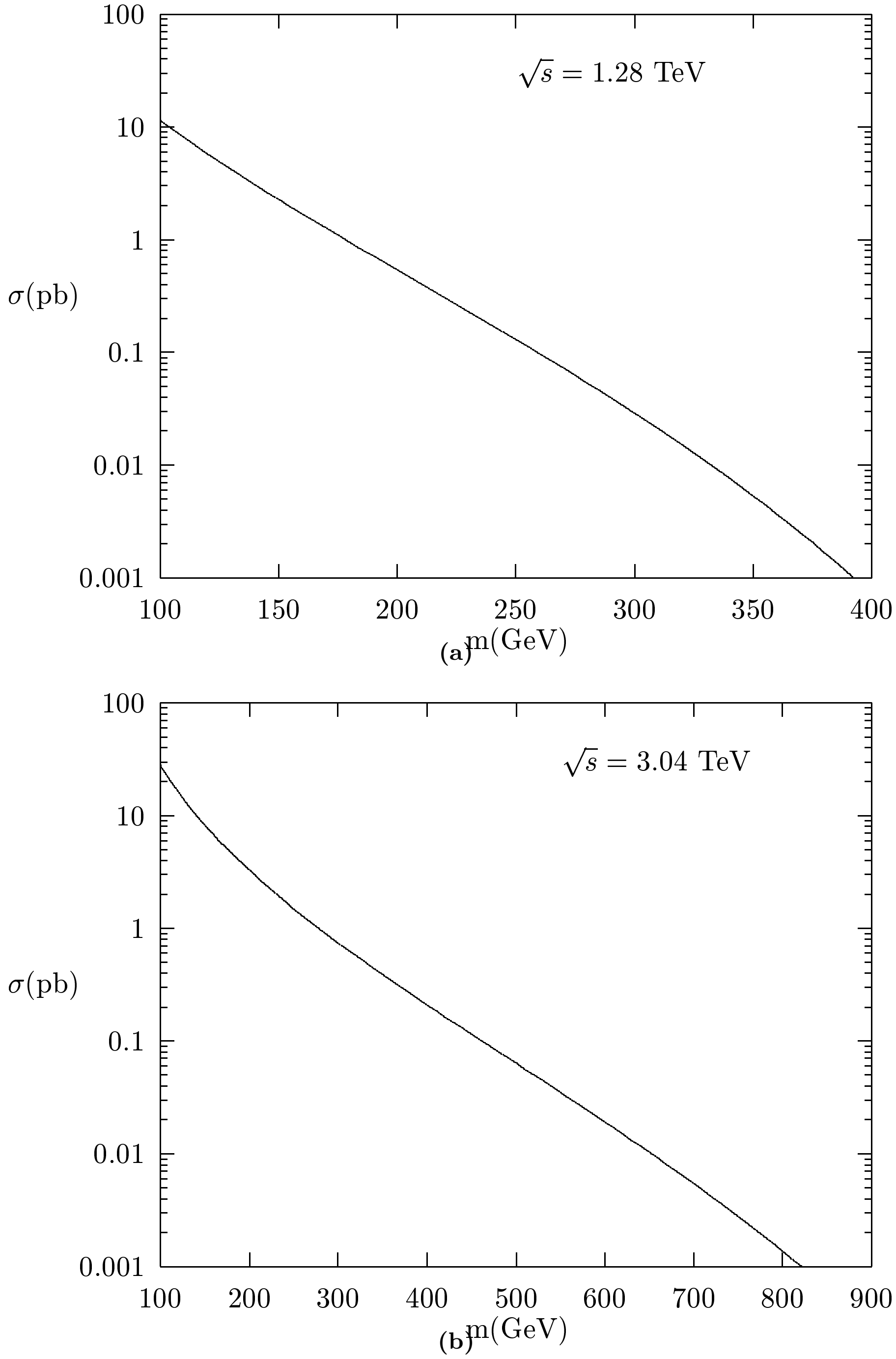


Figure 2. The differential cross section $d\sigma/dx$ for the process $\gamma p \to c\bar{c}X$. Curves 1, 2 and 3 correspond to different parametrizations of gluon distributions defined in the text.

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 $d_4 \to t + W$. Then, if $m_{u_4} > m_{d_4} + m_W$, the dominant decay mode will be $u_4 \to d_4 + W$. 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.



100
10
1
0.1
0.01
0.001
σ(pb)
$\sqrt{s} = 1.28$ TeV
100
150
200
250
300
350
400
m(GeV)
(a)
100
10
1
0.1
0.01
0.001
σ(pb)
$\sqrt{s} = 3.04$ TeV
100
200
300
400
500
600
700
800
900
m(GeV)
(b)

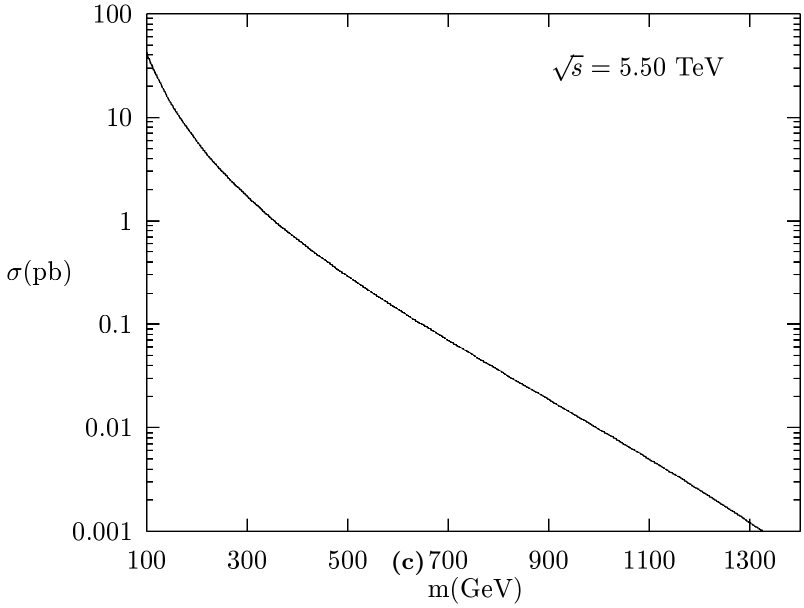


Figure 3. (a,b,c). Total cross sections for pair production of quarks (Q=2/3) as a function of their masses for proposed γp colliders.

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 $m_D > 130GeV$. We can find the Branching Ratios BR$(D \rightarrow uW) \sim 0.6$ and 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, γp-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.

We would like to express our gratitude to S. Sultansoy for useful discussions and crucial remarks.

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