Pair Production of Squarks In TeV Scale Polarized γp Collisions
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Abstract

The production of squarks in the high energy collisions of the real photons off the protons is discussed. The polarizations of the both photon and proton beams are considered. Although the cross sections for different initial beam polarizations do not differ much, the polarization asymmetry is sensitive to the squark mass. We conclude that the capacity of the future TeV scale γp colliders is quite promising in the search for SUSY particles.

I. INTRODUCTION

In recent years in addition to the well known TeV scale colliders such as pp(pp), ee and e+e− machines the possibilities of the realization of γe, γγ and γp colliders have been proposed and discussed in detail [1]. Here one of the main motivation is to reach the TeV scale at a subprocess level. The collisions of protons from a large hadron machine with electrons from a linac is the most efficient way of achieving TeV scale at a constituent level in ep collisions [2]. A further interesting feature is the possibility of constructing γp colliders on the base of linac-ring ep-machines. This can be realized by using the beam of high energy photons produced by the Compton backscattering of laser photons off a beam of linac electrons. Actually this method was originally proposed to construct γe and γγ colliders on the bases of e+e− linacs [Ginzburg et.al ref.1]. For the physics program at γe and γγ machines see [3,4]. Recently different physics phenomena which can be investigated at γp colliders have been considered in a number of papers [5-7]. It seems that these machines may open new possibilities for the investigations of the Standard Model and beyond it. For a review see [8].

On the other hand among the various extensions beyond the SM the supersymmetry idea seems to be a well-motivated strong candidate to investigate the new physics around TeV scale [9]. In SUSY inspired models the usual particle spectrum is doubled at least; every particle has a superpartner differing in spin by a half unit. Also two Higgs doublets are needed to give mass to both up and down quarks and make the theory anomaly free. It is highly believed that superpartners of the known particles should have masses below 1 TeV in order not to loose the good features of the SUSY. The direct experimental evidence for the sparticles is still lacking and the results of the experiments in the existing colliders indicate that squarks have masses $m_q \geq 100$GeV; consequently higher energy scale should be probed and it is desirable to reach the TeV scale at a constituent level [10,11]. Therefore it might be sensible to say that HERA, LEP, FERMILAB and LHC should be sufficient to check the idea of low energy SUSY, namely the scale between 100 GeV and 1 TeV, however experiments at all possible types of colliding beams would be inevitable to explore the new physics at the TeV scale.

In this paper we will study the pair production of the squarks at TeV scale γp colliders. Several SUSY production processes such as $\gamma p \rightarrow \tilde{q}\tilde{u}X, \gamma p \rightarrow \tilde{w}\tilde{u}X, \gamma p \rightarrow \tilde{q}\tilde{g}X, \gamma p \rightarrow \tilde{q}\tilde{g}X$ (or $\tilde{g}\tilde{g}$) and $\gamma p \rightarrow \tilde{q}\tilde{g}X$ have already been discussed [6]. Also scalar leptoquark productions at TeV energy γp colliders have been investigated [7].
II. PROCESS CROSS SECTION

We consider the minimal supersymmetric extension of the standard model (MSSM) which includes soft breaking terms. Here we have only taken into account the direct interaction of the photons with partons in the proton. The resolved contributions to the SUSY particle productions are relatively small, around 10% which do not affect our estimates for the discovery mass limits of new particles very much [12].

The invariant amplitude for the subprocess $\gamma g \rightarrow \tilde{q}\tilde{q}^*$ proceeds via the t-, u-channel squark exchange and four-point vertex interactions. The polarized differential cross-section of this subprocess can be calculated in terms of the usual Mandelstam variables $s = (p_1 + p_2)^2$, $t = (p_1 - p_3)^2$ and $u = (p_1 - p_4)^2$ as:

$$\frac{d\sigma}{dt} = \left( \frac{d\sigma}{dt} \right)_{n_p} + \xi_\eta \frac{d\sigma}{dt}_{pol}$$

$$\left( \frac{d\sigma}{dt} \right)_{n_p} = \frac{e^2 c_{\tilde{q}}^2 \beta^2}{8 \pi \beta^2} \left[ 1 + \frac{m_{\tilde{q}}^2 (3m_{\tilde{q}}^2 - \hat{s} - \hat{t})}{4(\hat{s} + \hat{t} - m_{\tilde{q}}^2)^2} + \frac{(3m_{\tilde{q}}^2 - \hat{s} + \hat{t})}{4(\hat{s} + \hat{t} - m_{\tilde{q}}^2)} \right]$$

$$+ \frac{m_{\tilde{q}}^2 (m_{\tilde{q}}^2 + \hat{t})}{(m_{\tilde{q}}^2 - \hat{t})^2} + \frac{(5m_{\tilde{q}}^2 + 2\hat{t} - \hat{s})}{4(\hat{s} + \hat{t} - m_{\tilde{q}}^2)} + \frac{(\hat{s} - 2m_{\tilde{q}}^2)(\hat{s} - 4m_{\tilde{q}}^2)}{4(m_{\tilde{q}}^2 - \hat{t})(\hat{s} - m_{\tilde{q}}^2)}$$

$$\left( \frac{d\sigma}{dt} \right)_{pol} = \frac{e^2 c_{\tilde{q}}^2 \beta^2}{16 \pi \beta^2} \left[ \frac{m_{\tilde{q}}^2 (\hat{s} - 2\hat{t}) + m_{\tilde{q}}^2 + \hat{s} + \hat{t} + \hat{t}^2}{(m_{\tilde{q}}^2 - \hat{t})(\hat{s} - m_{\tilde{q}}^2)} \right]$$

Here $c_{\tilde{q}}$ is the squark charge, $g_s = \sqrt{4\pi\alpha_s}$ is the strong coupling constant, $c = \sqrt{4\pi\alpha}$ is the fine structure constant and $\xi_\eta$ are the circular polarization parameters of the photon and gluon respectively. After performing the integration over $t$ one can easily obtain the total cross section for the subprocess $\gamma g \rightarrow \tilde{q}\tilde{q}^*$ as follows:

$$\sigma(\hat{s}, m_{\tilde{q}}, \xi_\eta, \eta) = \sigma_{n_p} + \xi_\eta \sigma_{pol}$$

$$\sigma_{n_p} = \frac{\pi \alpha e_{\tilde{q}}^2 c_{\tilde{q}}^2 \alpha_s}{2\hat{s}} \left[ 2\beta(2 - \beta^2) - (1 - \beta^2)ln \frac{1 + \beta}{1 - \beta} \right]$$

$$\sigma_{pol} = \frac{\pi \alpha e_{\tilde{q}}^2 c_{\tilde{q}}^2 \alpha_s}{2\hat{s}} \left[ 2\beta - 2(1 - \beta^2)ln \frac{1 + \beta}{1 - \beta} \right]$$

where $\beta = (1 - 4m_{\tilde{q}}^2/\hat{s})^{1/2}$.

The above expression in (4) is a cross section for left- squarks or right-squarks only, and a color factor of $C = 1/2$ is already included. In order to obtain the total cross section for the process $\gamma p \rightarrow \tilde{q}\tilde{q}^* X$ one should integrate $\sigma$ over the gluon and photon distributions. For this purpose we make the following change of variables: first expressing $\hat{s}$ as $\hat{s} = x_1 x_2 \hat{s}$ where $\hat{s} = \hat{s}_{\gamma p}, x_1 = E_\gamma / E_p, x_2 = E_p / E_{\gamma}$ and furthermore calling $\tau = x_1 x_2, x_2 = x$ then one obtains $dx_1 dx_2 = dxdx/dx_2$. The limiting values are $x_{1,max} = 0.83$ in order to get rid of the background effects in the Compton backscattering, particularly $e^+ e^-$ pair production in the collision of the laser with the high energy photon in the conversion region, $x_{1,min} = 0, x_{2,max} = 1, x_{2,min} = \hat{s}_{min} / 4m_{\tilde{q}}^2$. Then we can write the total cross section with right circular polarized laser and spin-up proton beam polarized longitudinally as follows:

$$\sigma_{R1} = \int_{x_{min}}^{0.83} dx_1 \int_{f_{x_{min}}^{x_{max}}}^{1} dx_2 \left\{ p \left[ f_{\gamma}^1(x) f_{\gamma_{pol}}^1(x) \sigma(x, m_{\tilde{q}}, 1, -1) + f_{\gamma}^2(x) f_{\gamma_{pol}}^2(x) \sigma(x, m_{\tilde{q}}, 1, 1) \right] + (1 - P) \left[ f_{\gamma}^1(x) f_{\gamma_{pol}}^1(x) \sigma(x, m_{\tilde{q}}, 1, -1) + f_{\gamma}^2(x) f_{\gamma_{pol}}^2(x) \sigma(x, m_{\tilde{q}}, 1, 1) \right] \right\}$$

where the $(\pm 1, \pm 1)$ inside $\sigma$ refers to the values of the Stokes parameters $(\xi_\eta, \eta)$ respectively. Using the Eq.(4) the above expression yields

$$\sigma_{R1} = \int_{4m_{\tilde{q}}^2}^{0.83} dx_1 \int_{f_{x_{min}}^{x_{max}}}^{1} dx_2 \left\{ p \left[ f_{\gamma}^1(x) f_{\gamma_{pol}}^1(x) \sigma_{n_p} + f_{\gamma}^2(x) f_{\gamma_{pol}}^2(x) (-\Delta f_{\gamma_{pol}}^1(x)) \sigma_{pol} \right] + (1 - P) \left[ f_{\gamma}^1(x) f_{\gamma_{pol}}^1(x) \sigma_{n_p} + f_{\gamma}^2(x) f_{\gamma_{pol}}^2(x) (-\Delta f_{\gamma_{pol}}^2(x)) \sigma_{pol} \right] \right\}$$
where $P$ is the polarization percentage of spin-up protons in the beam and for a maximum attainable degree of 70% longitudinal polarization $P = 0.85$. Also $f^u_1$ and $f^d_1$ are the polarized distributions for the photon and gluon inside the proton, respectively. In the numerical calculations we used the unpolarized and difference distributions, $f^u_{\text{unpol}}$ and $\Delta f^u_{\text{pol}}$ taken from [14]:

$$f^u_{\text{unpol}}(x) = \frac{1}{x} \left[ (2.62 + 9.17x)(1 - x)^{0.56} \right]$$  \hspace{1cm} (9)

and

$$\Delta f^u_{\text{pol}} = 16.3001x^{-0.3}(1 - x)^7$$  \hspace{1cm} (10)

Also the energy spectrum of the high energy real photons $f^1_\gamma(y)$ is given as follows [Ginzburg et al. in ref.1]:

$$f^1_\gamma(y) = \frac{2\pi a^2}{\sigma \zeta} \left[ -y + \frac{1}{1 - y} - \frac{4y}{\zeta(1 - y)} + \frac{4y^2}{\zeta^2(1 - y)^2} - \lambda_e \lambda_\gamma \frac{y(2 - y)}{(1 - y)\zeta(1 - y)} \right]$$  \hspace{1cm} (11)

where $\zeta = 4E_w/\omega_0 m^2_1, y = E_\gamma/E_w$. Here $\lambda_e, \lambda_\gamma$ are the linear electron and laser photon helicities respectively and $\sigma$ is the total Compton cross section:

$$\sigma = \sigma^0 + \lambda_e \lambda_\gamma \sigma^1$$  \hspace{1cm} (12)

$$\sigma^0 = \frac{\pi a_0^2}{\sigma m_1^2} \left[ \frac{2 - 8}{\zeta^2} - \frac{16}{\zeta^4} \ln(\zeta + 1) + 1 + \frac{16}{\zeta} - \frac{1}{(\zeta + 1)^2} \right]$$  \hspace{1cm} (13)

$$\sigma^1 = \frac{\pi a^2}{\sigma m_1^2} \left[ \frac{2 + 4}{\zeta} \ln(\zeta + 1) + 1 + \frac{2}{(\zeta + 1)^2} \right]$$  \hspace{1cm} (14)

Here the optimum value of $y_{\text{max}} = 0.83$ corresponds to $\zeta = 4.83$ and $\lambda_e \lambda_\gamma = \pm 1$ correspond to the positive (or negative) laser helicity. To carry out the numerical integration we take $\epsilon_q = 2/3$ hence consider only $u$-type squarks and $\sigma = 0.1$ is taken. The results of the numerical calculations clearly indicate that the process $\gamma p \rightarrow \bar{q} \bar{q}^* X$ has a detectable cross section. In Figs. III(a-c) the dependence on the squark masses is shown for different $\gamma p$ colliders. The relevant parameters of these machines are given in Table 1.

On the other hand observation limit for the new particles is taken to be 100 events per running year (10^7 seconds). This level ofobservability is considered to be satisfactory since the background is expected to be clearer than that encountered in the hadron colliders where 1000 events/year is usually desired due to the strong background processes. Hence taking into account the luminosity values given in Table I [see Aydin et al. in ref.1], one can easily find from the Figs. III(a-c) the upper mass limits for the squarks. These values of discovery limits are also tabulated in Table I. For the $d$-type squarks $(d_L, R, d_L, L, R)$ putting $\epsilon_q = -1/3$, results in the decrease of the cross section by a factor 1/4, but the corresponding upper mass values are approximately some seventy percent of these in the last column of the Table I. Furthermore the mixings among left and right squarks might be taken into consideration. Because their masses are expected to be close to each other, one can assume that $\tilde{q}_L$ and $\tilde{q}_R$ are degenerate in mass which points out that for the $\bar{q} \bar{q}^*$ production one can always consider the sum of the two cross section for $\tilde{q}_L$ and $\tilde{q}_R$ production. Hence if we do this incoherent sum of $\tilde{q}_L$ and $\tilde{q}_R$ and with $m_{\tilde{q}_L} = m_{\tilde{q}_R}$ we must multiply the expression in (4) by an extra factor two, which increases the discovery limits for the squark masses. One additional assumption can be made by assuming five degenerate flavours of $\tilde{q}_L$ and $\tilde{q}_R$, (namely except stop) which multiplies the individual squark pair production cross section, Eq.(3) by about a factor of six and a half. We see that the cross sections for different initial beam polarizations do not differ much which reflects the scalar nature of the squarks.

On the other hand the use of the polarized beams make it possible to look for the polarization asymmetries as a function of the squark masses. In Figs. III(a-c) we have presented the results of the polarization asymmetry using the results of the up and down polarized proton beams. Asymmetry has been defined through the following relation:

$$A_{11} = \frac{\sigma_{11} - \sigma_{\bar{1}\bar{1}}}{\sigma_{11} + \sigma_{\bar{1}\bar{1}}}$$  \hspace{1cm} (15)

As can be seen from the Figures 2(a-c) the asymmetry is sensitive to the squark mass which can be useful for determination of the mass parameter. Furthermore another asymmetry might be defined considering the opposite polarizations of the laser beam. Hence left-right asymmetry defined with respect to the laser beam as

$$A_{L,R} = \frac{\sigma_{11} - \sigma_{\bar{1}\bar{1}}}{\sigma_{11} + \sigma_{\bar{1}\bar{1}}}$$  \hspace{1cm} (16)

The results of the calculations are plotted in Fig. III and a similar behaviour is seen.
One characteristic feature of the R-parity conserving supersymmetric processes is the large missing energy. Usually photino mass is assumed to be less than $m_{\tilde{q}}$. This immediately implies that $\tilde{q} \rightarrow \tilde{q}\tilde{\gamma}$. The decay of the squark into photino is not the only possibility. For squark masses larger than 200-300 GeV and depending on the mass spectrum of the other SUSY particles there exist additional decay modes such as $\tilde{q} \rightarrow \tilde{q}\tilde{\gamma}$, $\tilde{q} \rightarrow \tilde{q}W$, $\tilde{q} \rightarrow \tilde{q}Z$. Branching ratios of these decays depend on the masses of these particles and coupling constants. One possibility of the decay of aino is the decay into a neutrino and a sneutrino. Both particles will not be observed like photinos. Therefore the signature for the process $\gamma p \rightarrow \tilde{q}\tilde{q} X$ will be in general multijets + lepton(s) + large missing energy and missing $p_T$. The definite polarization asymmetries associated with the missing energy and momentum may help in separating these events from the backgrounds.

Actually the production of the squark pairs in $ep \rightarrow \gamma^* g \rightarrow \tilde{q}\tilde{q}$ collisions via the quasi-real photon gluon fusion were studied before [12,13]. However in these studies Weizsacker-Williams approximation has been used for the quasi-real photon distribution $f^\gamma_{Y/e}$. Since the WW-spectrum is much softer than the real $\gamma$ spectrum the discovery mass limits for the squarks in our case turn out to be much higher than the conventional ep-colliders.

Finally our analysis shows that the future pp colliders can have considerable capacities in addition to the well known pp and $e^+e^-$ colliders in the investigation of supersymmetric particles. We see that the range of squark masses that can be explored at various ep-machines (200 GeV - 0.85 TeV) are higher than the corresponding values at standard type ep-colliders (20 GeV - 80 GeV for HERA). Several LHC studies have shown that the reach for squarks will be greater than 1 TeV. But clearer backgrounds in a gamma-proton collider can be considered to be an advantageous feature in extracting supersymmetric signals.

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FIG.1 (a-c) Production cross sections of squark pairs as a function of their masses for various γp colliders. In each figure the polarization states of the beams are indicated as follows: Line: Unpolarized beams, linespoints: right polarized laser, up protons, dots: right polarized laser, down protons.

FIG.2 (a-c) Up-down asymmetry versus squark masses for different γp colliders.

FIG.3. Left-right asymmetry versus squark mass for the HERA+LC γp collider.

TABLE I. Parameters of γp colliders and discovery limits for scalar quarks with $\epsilon_q = 2/3$.

<table>
<thead>
<tr>
<th>Machines</th>
<th>$\sqrt{s_{\gamma p}}$ (TeV)</th>
<th>$\mathcal{L}_{\gamma p}$ (10^{33} cm^{-2}s^{-1})</th>
<th>$m_q$ (TeV) (non-degenerate)</th>
<th>$m_q$ (TeV) (degenerate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERA+LC</td>
<td>1.28</td>
<td>25</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>LHC+TESLA</td>
<td>5.55</td>
<td>500</td>
<td>0.85</td>
<td>1.1</td>
</tr>
<tr>
<td>LHC+e-Linac</td>
<td>3.94</td>
<td>500</td>
<td>0.6</td>
<td>0.7</td>
</tr>
</tbody>
</table>
Fig. 1.a

\( \sqrt{s} = 1.28 \text{ TeV } \text{HERA+LC} \)

\( \sigma (\text{pb}) \)

\( m_t (\text{GeV}) \)

Fig. 1.b

\( \sqrt{s} = 5.55 \text{ TeV } \text{LHC+TESLA} \)

\( \sigma (\text{pb}) \)
Fig. 1.c

\[ \sqrt{s} = 3.04 \text{ TeV LHC+e-Linac} \]

\( \sigma (\text{pb}) \)

Fig. 2.a

\[ \sqrt{s} = 1.28 \text{ TeV HERA+LC} \]

\( A_{\perp 4} \)
Fig. 2.b

\sqrt{s}=5.55 \text{ TeV LHC+TESLA}

Fig. 2.c

\sqrt{s}=3.04 \text{ TeV LHC+e-Linac}
Fig. 3

\[ \sqrt{s} = 1.28 \text{ TeV HERA+LC} \]

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\[ A_{LR} \]

\[ m_{q} \text{(GeV)} \]