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Squark-chargino production in polarized gamma-proton collisions at TeV energy scale

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Abstract. – The associated production of squarks and charginos in high-energy collisions of the polarized real photons and protons is discussed. We give the cross-sections for different initial beam polarizations and the polarization asymmetries which can be used to anticipate the masses of squarks and charginos.

Introduction. – Although the Standard Model (SM) of elementary particles has been successful with high precision up to the scale of 100 GeV, there are many theoretical reasons that new physics beyond the SM should exist at TeV scale. Among the models of new physics, the supersymmetry (SUSY) seems to be one of the most promising candidates for TeV scale. A number of TeV energy machines have been proposed or constructing, such as the Large Hadron Collider (LHC), Next Linear e^+e^- Collider (NLC) and Linac-Ring type ep and γp machines. The latter one can be realized by using the beam of high-energy photons produced through the Compton backscattering of laser photons off a TeV energy linear e^- (or e^+) beam. We have already proposed some Linac-Ring–type ep and γp machines [1]. Here we concentrate ourselves only on three of them, *i.e.*, the HERA + LC, LHC + Linac 1 and LHC+TESLA. Their calculated center-of-mass energies and luminosities are given in table I.

A supersymmetric SM has a new spectrum of particles called SUSY particles which are the partners of all the known particles with the spins differing by $\frac{1}{2}$. Some of the SUSY partners are scalar leptons (sleptons, $\tilde{l}$), scalar quarks (squarks, $\tilde{q}$), wino ($\tilde{w}^{\pm}$), Higgsino ($\tilde{H}^{\pm}_{1,2}$) (or mixing of the latter ones, charginos, $\chi^{\pm}_{1,2}$), photino ($\tilde{\gamma}$), zino ($\tilde{z}^0$), Higgsino ($\tilde{H}^0_{1,2}$) (or their mixed states, neutralinos, $\chi^0_{1,2,3,4}$), gluino ($\tilde{g}$) etc. It is commonly believed that these SUSY particles should have masses below 1 TeV. Experiments at the existing colliders have already put the lower mass limits as $m_{\tilde{q}} > 176$ GeV and $m_{\chi^{\pm}} > 99\,\mathrm{GeV}$.

In this paper we study the associated production of the squarks and charginos at TeV energy γp colliders with polarized beams. We have already discussed this process with unpolarized beams [2]. Many other processes such as $\gamma p \to \tilde{q}\tilde{q}^*\mathrm{X}$, $\gamma p \to \tilde{q}\tilde{g}\mathrm{X}$, $\gamma p \to \tilde{q}\tilde{\gamma}$ (or $\tilde{q}\tilde{z}$)X, have already been discussed [3].

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Table I – *Energy and luminosity values of different γp colliders. The discovery mass limits for squarks and winos are given in last three columns for $\lambda_0\lambda_e = +1$ ($\lambda_0\lambda_e = -1$).*

Machines	$\sqrt{s_{ep}}$ (TeV)	$\mathcal{L}_{\gamma p}$ ($10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	$m_{\tilde{q}} = m_{\tilde{w}}$ (TeV)	$m_{\tilde{q}} = 0.25$ $m_{\tilde{w}}$ (TeV)	$m_{\tilde{w}} = 0.10$ $m_{\tilde{q}}$ (TeV)
HERA+LC	1.28	25	0.23(0.25)	0.18(0.23)	0.35(0.40)
LHC+Linac 1	3.04	500	0.65(0.70)	1.00(1.15)	1.33(1.48)
LHC+TESLA	5.55	500	0.95(1.05)	1.55(1.70)	2.15(2.50)

Polarized high-energy gamma beam. – A beam of laser photons ($\omega_0 \approx 1.26\,\mathrm{eV}$, for example) with high intensity, about 10^{20} photons per pulse, is Compton-backscattered off high-energy electrons ($E_e = 250\,\mathrm{GeV}$, for example) from a linear accelerator and turns into hard photons with a conversion coefficient close to unity. The energy of the backscattered photons, E_γ, is restricted by the kinematic condition $y_{\max} = 0.83$ (where $y = E_\gamma/E_e$) in order to get rid of background effects, in particular e^+e^- pair production in the collision of a laser photon with a backscattered photon in the conversion region.

The details of the Compton kinematics and calculations of the cross-section can be found in ref. [4]. The energy spectrum of the high-energy real (backscattered) photons, $f_{\gamma/e}(y)$, is given by

$$f_{\gamma/e}(y) = \frac{1}{D(\kappa)}\left[1 - y + \frac{1}{1-y} - 4r(1-r) - \lambda_e\lambda_0 r\kappa(2r-1)(2-y)\right], \tag{1}$$

where $\kappa = 4E_e\omega_0/m_e^2$ and $r = y/\kappa(1-y)$. Here λ_0 and λ_e are the laser photon and the electron helicities respectively, and $D(\kappa)$ is

$$\begin{aligned} D(\kappa) \;=\; & \left(1 - \frac{4}{\kappa} - \frac{8}{\kappa^2}\right)\ln(1+\kappa) + \frac{1}{2} + \frac{8}{\kappa} - \frac{1}{2(1+\kappa)^2} + \\ & + \lambda_e\lambda_0\left[\left(1 + \frac{2}{\kappa}\right)\ln(1+\kappa) - \frac{5}{2} + \frac{1}{1+\kappa} - \frac{1}{2(1+\kappa)^2}\right]. \end{aligned} \tag{2}$$

In our numerical calculations, we assume $E_e\omega_0 = 0.3\,\mathrm{MeV}^2$ or equivalently $\kappa = 4.8$ which corresponds to the optimum value of $y_{\max} = 0.83$, as mentioned above.

The energy spectrum, $f_{\gamma/e}(y)$, does essentially depend on the value $\lambda_e\lambda_0$. In the case of opposite helicities ($\lambda_e\lambda_0 = -1$) the spectrum has a very sharp peak at the high-energy part of the photons. This allows us to get a highly monochromatic high-energy gamma beam by eliminating the low-energy part of the spectrum [4,5]. On the contrary, for the same helicities ($\lambda_e\lambda_0 = +1$) the spectrum is flat.

The average degree of linear polarization of the photon is proportional to the degree of linear polarization of the laser. In our calculations, we assume that the degree of linear polarization of the laser is zero so that the final photons have only the degree of circular polarization ($\lambda(y) = \langle\xi_2\rangle \neq 0$ and $\langle\xi_1\rangle = \langle\xi_3\rangle = 0$). The circular polarization of the backscattered photon is given as follows:

$$\langle\xi_2\rangle = \lambda(y) = \frac{(1-2r)\left(\dfrac{1}{1-y} + 1 - y\right)\lambda_0 + \lambda_e r\kappa\left(1 + (1-2r)^2(1-y)\right)}{\dfrac{1}{1-y} + 1 - y - 4r(1-r) - \lambda_0\lambda_e r\kappa(2r-1)(2-y)}. \tag{3}$$

For the same initial polarizations ($\lambda_0\lambda_e = +1$), it is seen that $\lambda(y) \approx +1$, as nearly independent of y; while for the case of the opposite polarizations ($\lambda_0\lambda_e = -1$), the curve $\lambda(y)$ smoothly changes from -1 to $+1$ as y increases from zero to 0.83 [4,5].

Polarized cross-sections for the reaction. – The subprocess contributing to our physical process $\gamma p \to \tilde{w}\tilde{q}$X is $\gamma q \to \tilde{w}\tilde{q}$. The invariant amplitude for the specific subprocess $\gamma u \to \tilde{w}^+\tilde{d}$ is the sum of the three terms corresponding to the s-channel u quark exchange, the t-channel $\tilde{w}$ wino exchange and the u-channel $\tilde{d}$ squark exchange interactions:

$$\begin{aligned}
\mathcal{M}_a &= \frac{-iee_q g}{2\hat{s}}\bar{u}(p')(1-\gamma_5)(\not{p}+\not{k})\not{\epsilon}u(p)\,,\\
\mathcal{M}_b &= \frac{-iege_{\tilde{w}}}{2(\hat{t}-m_{\tilde{w}}^2)}\bar{u}(p')\not{\epsilon}(\not{p}-\not{k}+m_{\tilde{w}})(1-\gamma_5)u(p)\,,\\
\mathcal{M}_c &= \frac{-iee_{\tilde{q}} g}{2(\hat{u}-m_{\tilde{q}}^2)}\bar{u}(p')(1-\gamma_5)u(p)(p-p'+k')\cdot\epsilon\,,
\end{aligned} \tag{4}$$

where e_q, $e_{\tilde{q}}$ and $e_{\tilde{w}}$ are the quark, squark and wino charges, and $g = e/\sin\theta_w$ is the weak coupling constant. Note that we ignore the quark masses.

Since we are interested in the polarized cross-section, we use the following density matrices for the initial photon and quark:

$$\begin{aligned}
\rho^{(\gamma)} &= \frac{1}{2}(1+\vec{\xi}\cdot\vec{\sigma})\,,\\
\rho^{(q)} &= u\bar{u} = \not{p}[1+\gamma_5(\lambda_q+\vec{\xi}_\perp\cdot\vec{\gamma}_\perp)]\,,
\end{aligned} \tag{5}$$

where ξ_1, ξ_2 and ξ_3 are Stokes parameters. We take into account only circular polarization for the photon which is defined by ξ_2, as has already been mentioned in the previous section. λ_q stands for the helicity of the parton-quark that is $+1(-1)$ for the spin directions parallel (anti-parallel) to its momentum. The last term in the quark density matrix does not contribute, because after the integration over the azimuthal angle it vanishes.

One can easily obtain the differential cross-section for the subprocess $\gamma u \to \tilde{w}^+\tilde{d}$ as follows:

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}} = \frac{\pi\alpha^2}{\hat{s}^2\sin^2\theta_w}(1+\lambda_q)\left[\frac{\mathrm{d}\hat{\sigma_0}}{\mathrm{d}\hat{t}} + \lambda(y)\frac{\mathrm{d}\hat{\sigma}_1}{\mathrm{d}\hat{t}}\right]. \tag{6}$$

Performing the $\mathrm{d}\hat{t}$ integration from $t_{\min}$ to $t^{\max}$ which are given by

$$t_{\min}^{\max} = \frac{1}{2}(m_{\tilde{w}}^2 + m_{\tilde{q}}^2 - \hat{s})\left[1 \mp \sqrt{1-4m_{\tilde{w}}^2 m_{\tilde{q}}^2/(m_{\tilde{w}}^2+m_{\tilde{q}}^2-\hat{s})^2}\right], \tag{7}$$

we immediately get the total cross-section as

$$\hat{\sigma}(m_{\tilde{w}}, m_{\tilde{q}}, \hat{s}, \lambda(y)) = \frac{\pi\alpha^2}{\hat{s}^2\sin^2\theta_w}(1+\lambda_q)\left[\hat{\sigma_0}(m_{\tilde{w}}, m_{\tilde{q}}, \hat{s}) + \lambda(y)\hat{\sigma_1}(m_{\tilde{w}}, m_{\tilde{q}}, \hat{s})\right]. \tag{8}$$

Note that the cross-sections (eqs. (6) and (8)) are zero for $\lambda_q = -1$ because of the fact that we ignore the quark mass. Integrating the subprocess cross-section $\hat{\sigma}$ over the quark and photon distributions, we obtain the total cross-section for the physical process $\gamma p \to \tilde{w}\tilde{q}$X (the new variables are defined by $\hat{s} \equiv s_{\gamma q} = xys$, $xy = \tau$ and $s \equiv s_{ep}$):

$$\sigma = \int_{(m_{\tilde{w}}+m_{\tilde{q}})^2/s}^{0.83}\mathrm{d}\tau\int_{\tau/0.83}^{1}\frac{\mathrm{d}x}{x}f_{\gamma/e}(\tau/x)f_q(x)\hat{\sigma}(m_{\tilde{w}}, m_{\tilde{q}}, \hat{s}, \lambda(\tau/x))\,, \tag{9}$$

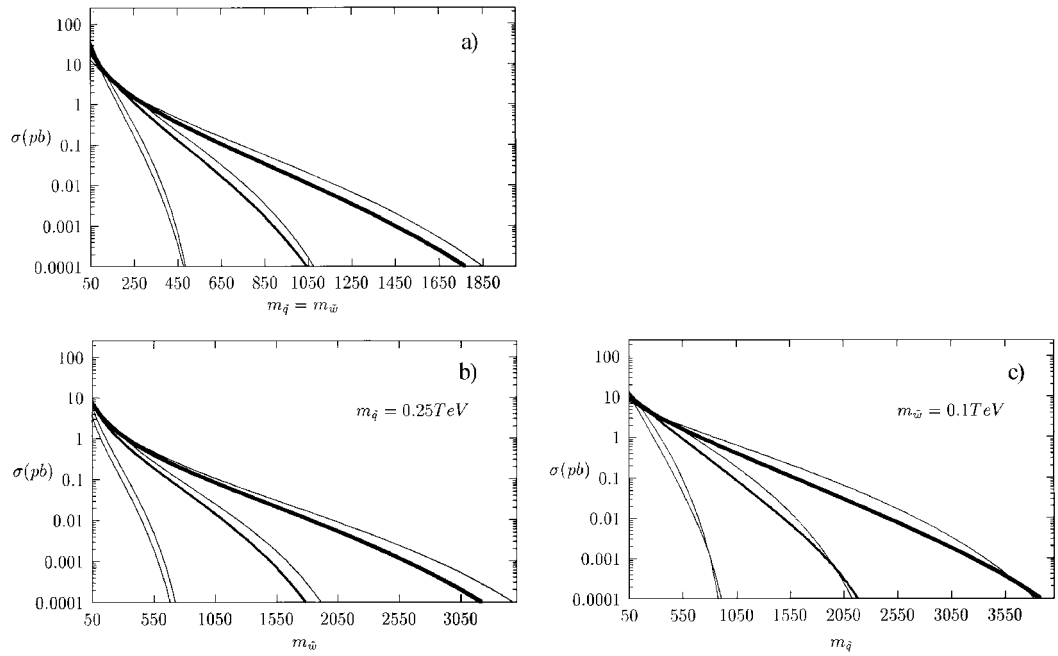


Fig. 1 – Squark-wino production cross-sections as a function of mass. Two thin curves on the left stand for the collider HERA+LC, middle curves for LHC+Linac 1 and two curves on the right for LHC + TESLA. A little bit higher (lower) curve of each twin is for $\lambda_0\lambda_e = -1$ ($\lambda_0\lambda_e = +1$), *i.e.*, σ_- (σ_+).

where the photon distribution function, $f_{\gamma/e}(y)$, is actually the normalized differential cross-section of the Compton backscattering, eq. (1); $f_q(x)$ is the distribution of quarks inside the proton. We set $\lambda_q = +1$ and $f_q(x) \to u^+(x) = \frac{1}{2}(u_{\rm unp} + \Delta u_{\rm pol})$ for the u-type valence quark distribution. In our numerical calculations, we use the distribution functions given in ref. [6] and ref. [7] for the unpolarized and polarized up-quarks, respectively:

$$u_{\rm unp}(x) = 2.751x^{-0.412}(1-x)^{2.69}\,, \tag{10}$$

$$\Delta u_{\rm pol}(x) = 2.132x^{-0.2}(1-x)^{2.40}\,. \tag{11}$$

Performing the integrations in eq. (9) numerically we obtain the total cross-section for the associated wino-squark production. We plot the dependence of the total cross-sections on the masses of the SUSY particles for various proposed γp colliders in figs. 1(a-c) for $\lambda_0\lambda_e = +1$ and -1. By taking 100 events per running year as observation limit for a SUSY particle, one can easily find the upper discovery mass limits from these figures using the luminosities of the proposed γp colliders given in table I. These discovery limits are tabulated in the same table.

Asymmetry. – It may be more interesting to use a polarization asymmetry in determining the masses of SUSY particles. Such an asymmetry can be defined with respect to the product of the polarizations of the laser photon and the electron as follows:

$$A = \frac{\sigma_- - \sigma_+}{\sigma_- + \sigma_+}\,, \tag{12}$$