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**Associated Gluino-Squark and
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 γp Colliders**

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We discuss the associated productions of gluino-squarks and neutralinos-squarks at the proposed high energy γp colliders. It has been realized that TeV energy γp colliders provide a convenient means for searching for supersymmetry.

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Today, the Standard Model (SM) is accepted as the theory of weak and electromagnetic(referred to as electroweak) phenomena, and strong interactions(QCD). Nearly all available data support the predictions of the SM. However, it is widely thought that the SM is incomplete, connected with the Higgs boson(known as fine-tuning problem). Furthermore, there are other questions to be answered, such as how many fermion generations are there?, why are left-handed fermions in SU(2) doublets and right-handed fermions in SU(2) singlets?, why are some parameters arbitrary? etc. These arguments suggest that it is necessary to look for new physics beyond the SM.

There is a common belief that Supersymmetry (SUSY) is one of the alternative approaches towards the new physics [1–3] . When we consider a supersymmetric extension of the SM, a new spectrum of particles is included in the theory. The new supersymmetric particles are the partners of all the known particles and differ in spin by a half unit. Some of the supersymmetric partners are scalar-leptons ($\tilde{\ell}$), scalar-quarks(squarks, $\tilde{q}$),wino($\tilde{w}$), photino($\tilde{\gamma}$), zino($\tilde{z}$), gluino($\tilde{g}$) etc. There are strong theoretical arguments that the new particles will appear in the range 100 GeV - 1 TeV.

In order to study this energy range in detail future high energy colliders are under construction or being proposed. Since the standard type ep machines like HERA are far from reaching TeV scale at a subprocess level, they are not, in general, expected to be the place of the discovery of supersymmetry. However, colliding of protons from a large hadron machine with electrons from linac is the most proper way of achieving TeV scale at constituent level in ep collisions [4–6]. The further interesting facility is the possibility of constructing γ -proton colliders on the base of Linac-Ring type ep machines [7, 8] and Ref [5]. This is realized by using the beam of high energy photons produced by the Compton backscattering of laser photons off a beam of linac

electrons. This method was originally proposed to construct γe and $\gamma\gamma$ colliders on the bases of e^+e^- linacs [9, 10]. For the physics at $\gamma\gamma$ and γe colliders see Ref [11–16]. In view of new physics, there is much to be learned from γp colliders, considering any specific theory. Earlier studies concerning the physics program for the future γp colliders can be found in [17–22]. Among them, a number of SUSY production processes, $\gamma p \rightarrow \tilde{q}\tilde{u}X$ [21], $\gamma p \rightarrow \tilde{q}\tilde{\bar{q}}X$ [25] and $\gamma p \rightarrow \tilde{w}^+\tilde{w}^-X$ [20] have been discussed recently.

This work deals with the associated production of gluino-squarks and neutralino-squarks to continue the possible searches for SUSY through high energy γp colliders.

When the mass eigenstates have specific couplings the Feynman amplitudes for the subprocesses $\gamma q \rightarrow \tilde{q}\tilde{g}$ and $\gamma q \rightarrow \tilde{q}\tilde{\gamma}$ (or $\tilde{q}\tilde{z}$) can be written as

$$M = M_a + M_b$$

$$M_a = C_{L,R} \bar{u}(p') P_{L,R} \frac{(p+k)_\mu \gamma^\mu}{\hat{s}} \epsilon_\nu \gamma^\nu u(p) \quad (1)$$

$$M_b = C_{L,R} \bar{u}(p') P_{L,R} u(p) \frac{1}{\hat{u} - \tilde{M}_q^2} \epsilon_\mu (2k' - k)^\mu$$

where k , k' , p and p' are the momenta of photon, squark, quark and neutralino(or gluino), and $P_{L,R} = \frac{1}{2}(1 \pm \gamma^5)$. The factors $C_{L,R}$ are given as

$$\begin{aligned} C_L &= C_R = N_c e Q_q g_s & \text{for } \tilde{g} \text{ and } q_{L,R} \\ C_L &= \sqrt{2}(e Q_q)^2 = -C_R & \text{for } \tilde{\gamma} \text{ and } \tilde{q}_{L,R} \\ C_L &= -\frac{\sqrt{2} g e Q_q}{C \cos \theta_w} (T_{3q} - Q_q \sin^2 \theta_w) & \text{for } \tilde{z} \text{ and } \tilde{q}_L \\ C_R &= -\frac{\sqrt{2} g e Q_q^2}{C \cos \theta_w} \sin^2 \theta_w & \text{for } \tilde{z} \text{ and } \tilde{q}_R \end{aligned} \quad (2)$$

where θ_w is the weak mixing angle, Q_q is the electric charge of the quark and N_c is the color factor. $\hat{s} = (k+p)^2$ and $\hat{u} = (k-k')^2$ are Lorentz invariant Mandelstam

variables. After straightforward manipulations the differential cross section for the subprocess takes the form

$$\frac{d\hat{\sigma}}{d\hat{t}} = C \frac{1}{\hat{s}^2} \left\{ \frac{\tilde{M}^2 - \hat{t}}{\hat{s}} + \frac{(\hat{t} + \hat{s})(\hat{t} + \hat{s} - \tilde{M}^2 - 3\tilde{M}_q^2) + \tilde{M}_q^2(\tilde{M}^2 + 2\tilde{M}_q^2)}{(\hat{s} + \hat{t} - \tilde{M}^2)^2} - \frac{2(\hat{t} - \tilde{M}_q^2)(\tilde{M}^2 - \tilde{M}_q^2) + \hat{s}(\hat{s} + \hat{t} - 3\tilde{M}_q^2)}{\hat{s}(\hat{s} + \hat{t} - \tilde{M}^2)} \right\} \quad (3)$$

$$C = \frac{C_{L,R}^2}{32\pi}$$

Here $\tilde{M}$ and $\tilde{M}_q$ stand for the neutralino (or gluino) and squark masses, respectively. It is easy to obtain the total cross section $\hat{\sigma}$ for the subprocess under consideration by integrating over $\hat{t}$ analytically. We need further integration over the quark and the photon distributions in order to have total cross sections for the processes $\gamma p \rightarrow \tilde{q}\tilde{z}(\tilde{q}\tilde{\gamma})X$ and $\gamma p \rightarrow \tilde{q}\tilde{g}X$

$$\sigma = \int_{\tau_{min}}^{0.83} d\tau \int_{\tau/0.83}^1 \frac{dx}{x} f_\gamma\left(\frac{\tau}{x}\right) f_q(x) \hat{\sigma}(\tau s), \quad \tau_{min} = \frac{(\tilde{M} + \tilde{M}_q)^2}{s} \quad (4)$$

where f_γ is the energy spectrum of the backscattered laser photons [10, 14, 15] which is given by

$$f_\gamma(y) = \frac{1}{D(\xi)} \left[1 - y + \frac{1}{(1-y)} - \frac{4y}{\xi(1-y)} + \frac{4y^2}{\xi^2(1-y)^2} \right] \quad (5)$$

$$D(\xi) \simeq 1.84 \quad \text{for } \xi \simeq 4.8$$

and $f_q(x)$ is the quark distribution function which is composed of valence and sea quark distributions in the proton [23].

For numerical results, we assume that u and d-squarks are produced with equal mass. Since final states will include at least a jet resulting from the decay of squark into a quark and a gaugino, the u and d-squark will give the similar jet pattern. Bearing this in mind, we have performed an incoherent sum over u and d-squark in carrying out the numerical integrations.

Dependences of the total cross sections on the masses of the SUSY particles for various proposed γp colliders are shown in Fig. 1, Fig. 2 and Fig. 3.

We take 100 events per working year as the reasonable discovery limit for SUSY particle observations. When using the luminosities given in Table I or Table II one can readily obtain upper limits for SUSY particle masses from the figures. In Table II the places of the mass limits less than 100 GeV are left blank. The gluino-squark case was first discussed for UNK+VLEPP in Ref [17].

The luminosities of proposed colliders in the tables have been taken from Ref [8]. Ten times larger luminosities than those shown in the tables can be possibly achieved by cooling the proton beam [24].

The decay modes of squarks, gluino and neutralinos depend on the mass spectrum and on the coupling constants. Due to the recent calculations on the mass relations and constraints from the top quark mass [26–28], we consider the ordering for the masses of the SUSY particles, starting from the lightest one, as $\tilde{\gamma}$, $\tilde{z}$, $\tilde{w}$, $\tilde{h}$, $\tilde{\ell}$, $\tilde{q}$ and $\tilde{g}$. Then the resulting decay channels will be as follows: The squark will mainly decay into a quark and a photino. There are also possible decays of the squark into a wino or a zino with the less branching ratios. The gluino will decay into a squark and an antiquark. The dominant decay mode of zino will be into the neutrino and sneutrino. Wino will further decay into a neutralino and quark and antiquark. Usually, the photino and the sneutrino are taken as the lightest SUSY particles. Therefore, the signatures for the processes under consideration will be

$$\begin{aligned}\tilde{g}\tilde{q} &\rightarrow 3jets + p_T^{miss} \quad \text{or} \quad multijets + p_T^{miss} \\ \tilde{q}\tilde{\gamma} &\rightarrow jet + p_T^{miss} \quad \text{or} \quad 3jets + p_T^{miss} \\ \tilde{q}\tilde{z} &\rightarrow jet + p_T^{miss} \quad \text{or} \quad 3jets + p_T^{miss}\end{aligned}$$

As to conclude, it is shown that future γp colliders will be one of the considerable

tools in the search for supersymmetry. The possibility of polarized photon and proton beams will be an additional features of these machines.

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FIGURES

FIG. 1. (a-d) Production cross sections for gluino and squarks as a function of their masses for various colliders. In each figure, the upper line corresponds to $\tilde{M}_q = 100$ GeV, the middle line to $\tilde{M}_g = 100$ GeV and the lower line to $\tilde{M}_q = \tilde{M}_g$ cases, respectively.

FIG. 2. (a-d) Production cross sections for photino and squarks as a function of squark masses for various colliders. In each figure $\tilde{M}_\gamma = 50$ GeV and $\tilde{M}_\gamma = 100$ GeV cases have been plotted and the two curves almost coincide.

FIG. 3. (a-d) Production cross sections for zino and squarks as a function of squark masses for various colliders. In each figure $\tilde{M}_z = 100$ GeV, $\tilde{M}_z = 200$ GeV and $\tilde{M}_z = \tilde{M}_q$ cases have been plotted. The lowest curves correspond to the case $\tilde{M}_z = \tilde{M}_q$ and others are still nearly coincident.

TABLES

TABLE I. Parameters of γp colliders and discovery limits for gluino-squark productions.

Machines	$\sqrt{s_{ep}}$ (TeV)	$\mathcal{L}_{\gamma p}$ $10^{31} cm^{-2} s^{-1}$	$\tilde{M}_q = 0.10$ $\tilde{M}_g(\text{TeV})$	$\tilde{M}_g = 0.10$ $\tilde{M}_q(\text{TeV})$	$\tilde{M}_q = \tilde{M}_g$ (TeV)
LHC+TESLA	5.50	50	2.10	0.95	0.75
LHC+Linac1	3.04	50	1.30	0.75	0.55
SSC+NLC	8.94	35	2.65	0.90	0.75
SSC+Linac2	8	80	3.05	1.25	1.02
FNAL+Linac1	1.1	6	0.37	0.25	0.20
HERA+DLC	1.28	2.5	0.32	0.20	0.18
FNAL+NLC	2	2	0.40	0.20	0.18
UNK+VLEPP	3.46	3	0.65	0.27	0.25
LHC+CLIC	7.85	5	1.10	0.35	0.31
SSC+LSC	28.3	20	2.90	0.65	0.60

TABLE II. Parameters of γp colliders and discovery limits for neutralino-squark productions. The upper mass limits in parantheses have been obtained taking the luminosity ten times larger than the ones shown in the third column. $s_{\gamma p}^{max} = 0.83s_{ep}$ and $\mathcal{L}_{\gamma p}$ in $cm^{-2}s^{-1}$.

Machines	$\sqrt{s_{ep}}$ (TeV)	$\mathcal{L}_{\gamma p}$ 10^{31}	$\tilde{M}_\gamma = 0.05$ $\tilde{M}_q(TeV)$	$\tilde{M}_Z = 0.10$ $\tilde{M}_q(TeV)$	$\tilde{M}_Z = \tilde{M}_q$ (TeV)
LHC+TESLA	5.50	50	0.25(0.72)	0.25(0.75)	0.22(0.60)
LHC+Linac1	3.04	50	0.25(0.60)	0.25(0.60)	0.22(0.48)
SSC+NLC	8.94	35	0.17(0.65)	0.18(0.65)	0.17(0.57)
SSC+Linac2	8	80	0.30(0.95)	0.31(0.98)	0.29(0.82)
FNAL+Linac1	1.1	6	- (0.21)	- (0.20)	- (0.17)
HERA+DLC	1.28	2.5	- (0.17)	- (0.15)	- (0.13)
FNAL+NLC	2	2	- (0.15)	- (0.15)	- (0.12)
UNK+VLEPP	3.46	3	- (0.20)	- (0.20)	- (0.17)
LHC+CLIC	7.85	5	- (0.23)	- (0.24)	- (0.22)
SSC+LSC	28.3	20	- (0.35)	- (0.40)	- (0.40)

Fig.1(a)

Fig.1(b)

Fig.1(c)

Fig.1(d)

Fig.2(a)

Fig.2(b)

Fig.2(c)

Fig.2(d)

Fig.3(a)

Fig.3(b)

Fig.3(c)

Fig.3(d)