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Search for SUSY with R-parity violation at γp and γe colliders

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Abstract

We present an outlook for possible R_p violating SUSY search at γp and γe colliders. Single production of third generation slepton/sneutrino through the λ'_{ijk} couplings at a γp collider is investigated and compared with the results of resonant sfermion productions at the existing colliders. Also single sneutrino production at a future γe collider through the $\lambda_{[ij]k}$ couplings is discussed. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Among the various extensions beyond the Standard Model (SM), supersymmetry (SUSY) appears to be a well-motivated strong option to investigate the physics at TeV scale. In the past most discussions of SUSY phenomenology assumed R-parity (R_p) conservation [1]. R-parity is defined by

$$R_p = (-1)^{3B+L+2S}, \tag{1}$$

where S is the spin, B is the baryon-number and L is the lepton-number of the particle. Hence under this discrete symmetry SM particles are even while their superpartners are odd. This implies that SUSY particles are pair produced, every SUSY particle decays into another one and that there is lightest supersymmetric particle (LSP) which is stable. Actually conservation of R-parity is put by purpose to ensure that the minimal supersymmetric extension of the standard model (MSSM) retain the symmetries of the SM, where in particular baryon and lepton quantum numbers are conserved separately [2].

In the usual formulation the MSSM is defined by the superpotential

$$\begin{aligned} W_R = {} & Y^u_{ij} Q_i \cdot H_u U_j + Y^d_{ij} Q_i \cdot H_d \overline{D}_j \\ & + Y^e_{ij} L_i \cdot H_d \overline{E}_j + \mu H_u \cdot H_d, \end{aligned} \tag{2}$$

which respects the multiplicative R-parity defined above. However there is no deep theoretical justification for imposing R_p conservation, since gauge and Lorentz invariances allow for the following additional terms in the superpotential

$$\begin{aligned} W_{\not R_p} = {} & \frac{1}{2}\lambda_{[ij]k} L_i \cdot L_j \overline{E}_k + \lambda'_{ijk} L_i \cdot Q_j \overline{D}_k \\ & + \frac{1}{2}\lambda''_{i[jk]} \overline{U}_i \overline{D}_j \overline{D}_k + \epsilon_i L_i \cdot H_u, \end{aligned} \tag{3}$$

which explicitly break it. The MSSM with R_p conservation has been extensively studied and direct searches for superpartners at the existing colliders are still continuing [3]. On the other hand R_p violation leads to a different phenomenology and recently the interest in the $\not R_p$ models has been motivated by the observation

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of a number of events at high Q^2 at HERA. Also in R_p-violating models neutrinos acquire masses and can mix; therefore it is a good candidate to explain the neutrino oscillations observed in Super-Kamiokande [4]. Terms with the lepton number violating Yukawa couplings λ'_{ijk} make the ep collider HERA especially promising for the resonant production of squarks, and possible explanations of these high Q^2 events within the framework of R-parity violating supersymmetry have been discussed in the literature [5]. Although further data taken by the H1 and ZEUS collaborations failed to produce any further "excess" events with high-Q^2 a rich phenomenology of $\not{R}_p$ emerged for HERA. Also formation of s-channel slepton and squark resonances at LEP2 and TEVATRON at current energies is an exciting possibility in $\not{R}_p$-SUSY searches [6].

On the other hand in recent years in addition to the existing colliders the possibilities of the realization of γe, $\gamma\gamma$ and γp colliders have been proposed and discussed in detail [7]. Colliding the beam of high energy photons produced by Compton backscattering of laser photons off linac electrons with the beam of a proton ring is the idea leading to TeV scale γp colliders. Physics program of the photon colliders are studied in [8]. Also search for SUSY in polarized γp collisions have been investigated in [9].

In searching the superpartners squarks might be too heavy to be produced at HERA, LEP or TEVATRON, but sleptons are generally expected to be lighter than squarks so single slepton production would be interesting. Also pair production of sleptons via R_p conserving mechanisms might be closed kinematically. The s-channel slepton resonance production via $\not{R}_p$ interactions in e^+e^- collisions through $e^+e^- \to \tilde\nu \to l^+l^-$, and in $p\bar p$ collisions through $p\bar p \to \tilde\nu \to l^+l^-$, $p\bar p \to \tilde l^+ \to l^+\nu$ have been examined in the literature [10]. In e^+p collisions at HERA squark resonance productions via $e^+d^k_R \to \tilde u^j_L$ ($\tilde u^j = \tilde u, \tilde c, \tilde t$), $e^+\bar u^j_L \to \bar{\tilde d}^k{}_R$, ($\tilde d^k = \tilde d, \tilde s, \tilde b$) have been investigated in [11].

Although HERA, LEP, FERMILAB and LHC should be sufficient to check the low energy SUSY however experiments at all possible types of colliding beams would be inevitable to explore the new physics around the TeV scale, and hence future γe and γp colliders might play a complementary role to the existing facilities. In this Letter we mainly focus on the single stau and sneutrino productions at photon–proton and photon–electron collisions as an alternative to the above-mentioned s-channel resonance production.

2. Selectron (stau) production at gamma–proton colliders

In four-component Dirac notation the R_p violating Lagrangian generated by $W_{\not{R}_p}$ is

$$\begin{aligned}\mathcal{L}_{\not{R}_p} = \lambda_{[ij]k}\big[&\tilde\nu_{iL}\bar e_{kR}e_{jL} + \tilde e_{jL}\bar e_{kR}\nu_{iL}\\ &+ \tilde e^\star_{kR}\overline{(\nu_{iL})^C}e_{jL} - \tilde\nu_{jL}\bar e_{kR}e_{iL}\\ &- \tilde e_{iL}\bar e_{kR}\nu_{jL} + \tilde e^\star_{kR}\overline{(\nu_{jL})^C}e_{iL}\big]\\ + \lambda'_{ijk}\big[&\tilde\nu_{iL}\bar d_{kR}d_{jL} + \tilde d_{jL}\bar d_{kR}\nu_{iL}\\ &+ \tilde d^\star_{kR}\overline{(\nu_{iL})^C}d_{jL} - \tilde e_{iL}\bar d_{kR}u_{jL}\\ &- \tilde u_{jL}\bar d_{kR}e_{jL} - \tilde d^\star_{kR}\overline{(e_{iL})^C}u_{jL}\big]\\ + \lambda''_{i[jk]}\epsilon_{\alpha\beta\gamma}\big[&\tilde u^\star_{iR\alpha}\bar d_{kR\beta}d^C_{jR\gamma} + \tilde d_{jR\beta}\bar e_{kR\gamma}u^C_{iR\alpha}\\ &+ \tilde d^\star_{kR\gamma}\overline{(u_{iR\alpha})^C}d_{jR\beta}\big] + \text{h.c.},\end{aligned} \tag{4}$$

where i, j, k are the generation indices. In photon–proton collisions a single slepton or a single squark production is possible. Let us take first as an example, the single charged slepton production, $\gamma p \to \tilde e^j_L X$. One of the relevant subprocesses, $\gamma u \to \tilde e^j_L d^k_R$, proceeds via the s-channel u-quark, t-channel slepton and u-channel d-quark exchanges. The invariant amplitude in four-component Dirac notation (which could be written equally in two-component Weyl language) is

$$M = N_c g_e \lambda' \epsilon_\mu(k)\bar u(p')Q^\mu u(p), \tag{5}$$

$$Q^\mu = \frac{1}{2}(1-\gamma_5)\left[\frac{\not{k}+\not{p}}{\hat s - m_u^2}\gamma^\mu + \frac{(p-p'+k')^\mu}{\hat t - m_{\tilde e}{}^2} + \gamma^\mu\frac{\not{p}'-\not{k}}{\hat u - m_d^2}\right], \tag{6}$$

where $g_e = \sqrt{4\pi\alpha}$, $\epsilon_\mu(k)$ is the photon polarisation and k, p, k' and p' are the four momenta of the photon, quark in the proton, slepton and outgoing quark, respectively. The differential cross-section for the subprocess is given by

$$\frac{d\hat\sigma}{d\hat t} = \frac{1}{16\pi\hat s^2}M^2 \tag{7}$$

and after performing the integration over $\hat{t}$ one can easily obtain the total cross-section for the subprocess $\gamma u \to \tilde{e}_L^j d_R^k$. In order to obtain the total cross-section for the process $\gamma p \to \tilde{e}_L^i d_R^k X$ one should integrate $\hat{\sigma}$ over the quark and photon distributions. For this purpose we make the following change of variables: first expressing $\hat{s}$ as $\hat{s} = x_1 x_2 s$ where $\hat{s} = s_{\gamma q}$, $s = s_{ep}$, $x_1 = E_\gamma / E_e$, $x_2 = E_q / E_p$ and furthermore calling $\tau = x_1 x_2$, $x_2 = x$ then one obtains $dx_1\, dx_2 = dx\, d\tau / x$. 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, $x_{1,\min} = 0$, $x_{2,\max} = 1$, $x_{2,\min} = \tau/0.83$, $\hat{s}_{\min} = m_{\tilde{e}}^2 + m_d^2 + m_{\tilde{e}} m_d$. Then we can write the total cross-section as:

$$\sigma = \int\limits_{m_{\tilde{e}}^2 + m_d^2 + m_{\tilde{e}} m_d / s}^{0.83} d\tau \int\limits_{\tau/0.83}^{1} dx \frac{1}{x} f_\gamma\left(\frac{\tau}{x}\right) f_q(x) \times \hat{\sigma}(\tau s, m_{\tilde{e}}), \tag{8}$$

where $f_q(x)$ is the distribution of up-quarks inside the proton [12]

$$f_q(x) = 2.751 x^{-0.412} (1 - x)^{2.69} \tag{9}$$

and $f_\gamma(y)$ is the energy spectrum of the high energy real photons (Ginzburg et al. in Ref. [7])

$$f_\gamma(y) = \frac{1}{D(\kappa)} \left[1 - y - \frac{1}{1 - y} - \frac{4y}{\kappa(1 - y)} + \frac{4y^2}{\kappa^2 (1 - y)^2} \right] \tag{10}$$

with $y = E_\gamma / E_e, \kappa \cong 4.8$, $D(\kappa) \cong 1.84$, and $y_{\max} \cong 0.83$. Q^2 independent proton structure function used above is satisfactory for the present analysis.

Since the third generation sfermions are usually expected to be lightest we consider λ'_{31k} couplings hence look for the production of $\tilde{\tau}$. Taking $\lambda'_{311} = 0.11 \times m_{\tilde{d}}/100\,\text{GeV}$ as given in the literature the results of the numerical integration for $\gamma p \to \tilde{\tau}_L d_R X$ is plotted in Fig. 1.

Similarly the d-quark inside the proton permits the production $\gamma p \to \tilde{\tau}_L u_R X$ through again the λ'_{311} coupling which contributes roughly half of the u-quark contribution and leads to the same signature. As can be seen from the figure the total cross-section for a $\tilde{\tau}$ mass of 300 GeV is about 0.1 pb. Hence around 100 events per running year can be seen at HERA + LC up to $\tilde{\tau}$ masses of 300 GeV. For comparison we note that for the resonant production of squarks of masses up to 200 GeV at the HERA the total cross-section is 0.1–1 pb (see E. Perez et al. in Ref [10]). On the other hand, if one uses the Weizsacker–Williams approximations for the quasi-real photon distribution at the HERA machine a similar process is possible but with an almost hundred times smaller cross-section since WW-spectrum is much softer than the real γ-spectrum. Clearly for the HERA machine resonant production of the sparticles in R-parity violating MSSM is the dominant process.

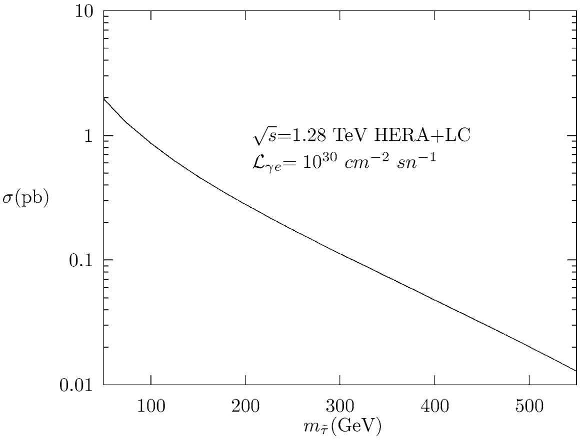

Fig. 1. Production cross-section of stau as a function of its mass for HERA + LC γp collider.

Signature In models with R-parity violation the LSP is unstable, which leads to signatures which differ strongly from the characteristic missing energy signals in usual MSSM. In our case the produced slepton ($\tilde{\tau}$) will decay either by direct $\not{R}_p$ couplings as $\tilde{e}_L^i \to e_R^j + \nu_k$ (through λ_{ijk}) or $d_R^j + u_L^k$ (through λ'_{ijk}) leading to the signals 1 lepton + 1 jet + $\not{E}_T$ or 3 jets; or by cascading through MSSM to the LSP which in turn decays via $\not{R}_p$: $\tilde{e}_L^i \to e_L^i + \tilde{\chi}_1^o$, $\tilde{\chi}_1^o \to \ell^+ \ell^- \nu$ or $q' \bar{q} \ell$ leading to the signals 3 leptons + 1jet + $\not{E}_T$ or 2 leptons + 3 jets. These LSP decays depend on couplings λ' but also on the supersymmetry parameters M_2, μ and $\tan\beta$ (see E. Perez et al. in Ref. [10]). In the special cases involving only the operators $L_i Q_j \overline{D}_j$ the LSP can also dominantly decay via the radiative process $\tilde{\chi}_1^o \to \gamma + \nu$ [13]. Another possibility within the MSSM is first decaying to a chargino by $\tilde{e}_L^i \to \nu_i + \tilde{\chi}_1^\pm$ and then followed by the chargino decay through $\tilde{\chi}_1^\pm \to \ell^\pm q\bar{q}$ or $\nu q\bar{q}'$ leading to the signals 1 lepton + 3 jets + $\not{E}_T$ or 3 jets + $\not{E}_T$. One has also the decay $\tilde{\chi}_1^\pm \to W^\pm \tilde{Z}^o$ leading to multijets + leptons + $\not{E}_T$. The $\not{R}_p$ decays of $\tilde{\chi}_1^\pm$ dominate over MSSM decays as long as λ' is not too small (e.g., around 0.1). On the other hand the above $\not{R}_p$ decays of the produced slepton have the following partial decay widths:

$$\Gamma_{\tilde{e}_L^i \to e_R^j + \nu_k} = \frac{m_{\tilde{e}} (\lambda_{131})^2}{16\pi}, \tag{11}$$

$$\Gamma_{\tilde{e}_L^i \to d_R^j + u_L^k} = \frac{m_{\tilde{e}} (\lambda'_{311})^2}{16\pi}. \tag{12}$$

Therefore since $(\lambda'_{311})^2 \gg (\lambda_{131})^2$, $\tilde{\tau}_L \to d_R + u_L$ is the main $\not{R}_p$ decay leading to 3 jets.

3. Single sneutrino production at gamma–proton colliders

$\not{R}_p$ Yukawa couplings λ'_{ijk} offer also the opportunity to produce single sneutrino in gamma–proton collisions. The relevant subprocess $\gamma d \to \tilde{\nu}_L^i d_R^k$, proceeds via the d-quark exchange in s- and t-channels. The invariant amplitude is given as in Eq. (5), with Q^μ as,

$$Q^\mu = \frac{1}{2}(1-\gamma_5)\left[\frac{\not{k}+\not{p}}{\hat{s}-m_d^2} + \frac{\not{p}'-\not{k}}{\hat{t}-m_d^2}\right]\gamma^\mu. \tag{13}$$

Since in the t-channel instead of a heavy sparticle a d-quark is exchanged the cross-section for sneutrino production becomes considerably bigger than the slepton case. The details of the calculation for the total cross-section is similar to the one in the previous process. Taking $\lambda'_{311} = 0.11 \times m_{\tilde{d}}/100$ GeV and the simplistic Q^2 independent distribution of down-quarks inside the proton as [11]

$$f_q(x) = 0.67x^{-0.6}\left(1-x^{1.5}\right)^{4.5} \tag{14}$$

the results of the numerical integration for $\gamma p \to \tilde{\nu}_{\tau L} d_R X$ is plotted in Fig. 2. Hence around 100 events per running year can be seen at HERA + LC up to $\tilde{\nu}_\tau$ masses of 175 GeV. For single sneutrino production at LEP and hadron colliders see [6,10] and [14].

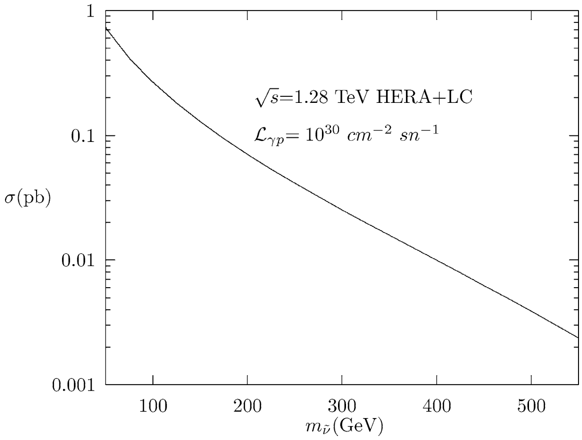

Fig. 2. Production cross-section of sneutrino as a function of its mass for HERA + LC γp collider.

Signature The produced sneutrino can directly decay to the ordinary particles through $\tilde{\nu} \to \ell^+\ell^-$ via $LL\overline{E}$ interactions or to $\tilde{\nu} \to q\bar{q}'$ via λ'_{ijk} couplings. Assuming dominant λ'_{ijk} coupling constants then the principal $\not{R}_p$ decay signature is *three jets*. On the other hand sneutrinos may have gauge decays, $\tilde{\nu}_i \to \chi^\pm \ell_i$ also. The produced chargino can decay into a neutralino which has further possible $\not{R}_p$ decay modes noted in the previous section leading to *three jets* + *three* (*two*) *leptons* + missing energy.

4. Single sneutrino production at electron–photon colliders

$\not{R}_p$ Yukawa couplings $\lambda_{[ij]k}$ (i.e., fourth term in Eq. (4)) offer the opportunity to produce sneutrinos in photon–electron collisions. One of the the relevant subprocess $\gamma e \to \tilde{\nu}_{\tau L} \mu_R$, proceeds via electron (left-handed) exchange in s-channel and muon (right-handed) exchange in t-channel. The invariant amplitude in two-component MSSM language is given as

$$M = g_e \lambda \epsilon_\mu(k) \psi_+(p') Q^\mu \psi_-(p), \tag{15}$$

$$Q^\mu = \left[\frac{(k+p)_\nu}{\hat{s}-m_e^2}\sigma^\nu \bar{\sigma}^\mu + \frac{(p'-k)_\nu}{\hat{t}-m_\mu{}^2}\sigma^\nu \bar{\sigma}^\mu\right], \tag{16}$$

where $\psi_+(p')$ $(\psi_-(p))$ is the Weyl spinor for the right-handed muon (left-handed electron) and $\lambda_{132} = 0.06$ (present upper bound) for this particular process. The total cross section for the above γe process may be written as

$$\hat{\sigma}(\hat{s}, \gamma e) = \int_{t_{\min}}^{t_{\max}} \frac{1}{16\pi \hat{s}^2} M^2 \, d\hat{t}, \tag{17}$$

where

$$t_{\max/\min} = \left(\frac{m_{\tilde{\nu}}^2 - m_{\mu}^2}{2\sqrt{s}}\right)^2 - \left\{\frac{\sqrt{s}}{2} \mp \left[\frac{(s + m_{\mu}^2 - m_{\tilde{\nu}}^2)^2}{4s} - m_{\mu}^2\right]^{1/2}\right\}^2. \tag{18}$$

The total cross-section for $e^+e^- \to e\mu\tilde{\nu_\tau}$ is given by

$$\sigma\left(s, e^+e^-\right) = 2 \int_{m_{\tilde{\tau}}^2/s}^{0.83} f_{\gamma/e}(y) \hat{\sigma}(ys, m_{\tilde{\nu}}) \, dy, \tag{19}$$

where $f_{\gamma/e}$ is the distribution of high energy real photons at a given fraction $y = E_\gamma / E_e$. The factor two is due to the antisneutrino coming from the charge conjugate diagrams. The results of numerical integration for $e^+e^- \to e\mu\tilde{\nu}_\tau$ is plotted in Fig. 3 for a linear collider with center-of-mass energy of 500 GeV. As can be seen from the figure around *one thousand* events per running year can be observed up to $\tilde{\nu}_\tau$ masses of 200 GeV. On the other hand using the Weizsacker–Williams approximation for the photon flux the same process can also be studied at the ordinary modes of LEP2 and NLC. The relevant calculations are completely similar to the above analysis, the only difference is in taking the upper limit of the integral as unity in the Eq. (19) and the insertion of the WW-distribution, which is given by

$$f_{\gamma/e}(y) = \frac{\alpha}{2\pi}\left[\frac{1 + (1-y)^2}{y} \ln \frac{Q_{\max}^2}{Q_{\min}^2} - 2m_e^2\left(\frac{1}{Q_{\min}^2} - \frac{1}{Q_{\max}^2}\right)\right]. \tag{20}$$

The results of the numerical integration for the total cross-section at a center of mass energy of 500 GeV is shown in Fig. 4 as a function of the sneutrino mass. The total cross-section is approximately a hundred times smaller than the value obtained at the γe collider mode of NLC, and consequently the discovery mass reach for $\tilde{\nu}_\tau$ is less than 100 GeV. This process has been investigated previously in [15] for the ordinary modes of LEP2 and NLC using WW-photons, where they also presented a detailed background analysis. Their numerical results concerning the total cross-section are higher than ours, which might be due to a much smaller cut-off used as the lower limit in Eq. (19), but it affects the results severely.

In this Letter we have first investigated single slepton and sneutrino productions at TeV scale γp colliders considering R-parity violating $LQ\overline{D}$ interactions. Also sneutrino production through $LL\overline{E}$ interactions at γe mode of the NLC colliders has been discussed. For comparison, it is shown that for $\tilde{\nu}_\tau$ production the

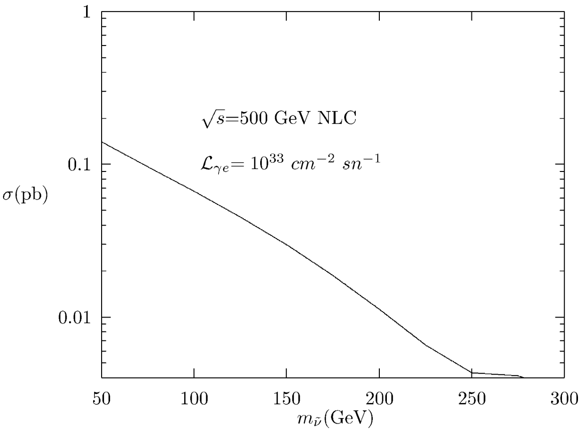

Fig. 3. Production cross-section of sneutrino as a function of its mass for HERA + LC γp collider.

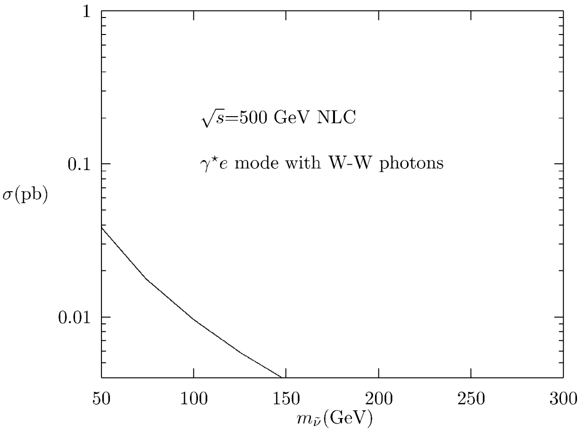

Fig. 4. Production cross-section of sneutrino as a function of its mass for NLC ordinary mode with WW-photons.

γe collider mode of a future NLC gives much higher values of the total cross-section than the normal operation mode through soft WW-photons. The production cross-sections are functions of only sparticle mass and $\not{R}_p$ coupling constants, and lead to detectable signals. Polarizations of the initial photon beam [8], which can be accomplished relatively easily, constitute additional advantages. Our results show that γe and γp colliders can play complementary role in searching for supersymmetry in the future.

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