Polarization Effects in Scalar Lepton Production at High Energy $\gamma\gamma$ Colliders

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Abstract: We investigate the charged scalar lepton production processes $\gamma\gamma \rightarrow \tilde{\ell}^+\tilde{\ell}^-$ at high energy $\gamma\gamma$ colliders in the framework of the minimal supersymmetric standard model (MSSM). Here the high energy $\gamma$ beams are obtained by the backward Compton scattering of the laser flush by the electron in the basic linear TeV $ee$ colliders. We consider the polarization of the laser photons as well as the electron beams. Appropriate beam polarization could be effective to enhance the cross section and to extract the signal from the dominant background $\gamma\gamma \rightarrow W^+W^-$. 

In addition to well-known types of "TeV" colliders such as $pp$, $ep$ and linear $e^+e^-$ colliders, the possibilities for realization of the $e\gamma$ and $\gamma\gamma$ colliders have been discussed in detail by Ginzburg et al. [1]. Here the high energy photon beams will be obtained by the backward Compton scattering of the laser flush by one of electron beam in the basic linear $ee$ colliders. Recently, the physics potential at those colliders has been analyzed energetically from both the theoretical [2] and experimental [3] point of view. In fact such colliders will provide us with a powerful machinery for investigating the standard model (SM) through a direct proof of the gauge vertices [4], unraveling the hadronic content of the photon [5] and searching for the neutral Higgs boson [6]. The $e\gamma$ and $\gamma\gamma$ colliders are also suited for searching for some exotic particles predicted by the models beyond the standard model, such as supersymmetric partners [7, 8, 9, 10], excited fermions [11, 12] and the leptoquarks [13].

In this paper we investigate the charged scalar lepton (slepton) production at the $\gamma\gamma$ colliders. The sparticle production at the $\gamma\gamma$ colliders, including the slepton production, has already been discussed in Ref.[8, 9]. In those papers, however, the initial beam polarization has not been concerned. Here we focus our attention to the physical consequence of the initial beam polarization at the $\gamma\gamma$ colliders in the slepton production.

The polarized cross sections for the sub-processes $\gamma\gamma \rightarrow X$ are expressed as

$$d\hat{\sigma}(\xi_2(z_1), \xi_2(z_2)) = \frac{1}{4} \left[ (1 + \xi_2(z_1)) (1 + \xi_2(z_2)) d\hat{\sigma}[\gamma^+\gamma^+] + (1 - \xi_2(z_1)) (1 - \xi_2(z_2)) d\hat{\sigma}[\gamma^-\gamma^-] + (1 - \xi_2(z_1)) (1 + \xi_2(z_2)) d\hat{\sigma}[\gamma^-\gamma^+] + (1 - \xi_2(z_1)) (1 - \xi_2(z_2)) d\hat{\sigma}[\gamma^+\gamma^-] \right],$$

(1)
where $\xi_2(z_i)$ denote the Stokes parameters of the circular polarized $\gamma$ beams. Note that there are no terms proportional to $\xi_1$ and $\xi_3$ because we have assumed that the initial laser lights are circularly polarized and thus the secondary gamma beams are also circularly polarized ($\xi_1 = \xi_3 = 0$).

The each polarized cross sections in Eq.(1) for the slepton pair production $\gamma\gamma \rightarrow \tilde{\ell}^+\tilde{\ell}^-$ are given by

$$
\frac{d\hat{\sigma}}{d\cos\theta}[\gamma\gamma \rightarrow \tilde{\ell}^+\tilde{\ell}^-] = \frac{2\pi\alpha^2}{s(1 - \hat{\beta}^2\cos^2\theta)^2}\hat{\beta}(1 - \hat{\beta}^2)^2
$$

$$
\frac{d\hat{\sigma}}{d\cos\theta}[\gamma\gamma \rightarrow \tilde{\ell}^+\tilde{\ell}^-] = \frac{2\pi\alpha^2}{s(1 - \hat{\beta}^2\cos^2\theta)^2}\hat{\beta}(1 - \cos^2\theta)^2, \quad (2)
$$

where $s \equiv s_{\gamma\gamma}$ and $\hat{\beta} \equiv \sqrt{1 - 4m_{\ell}^2/s}$. The total cross sections are given by

$$
\hat{\sigma}[\gamma\gamma \rightarrow \tilde{\ell}^+\tilde{\ell}^-] = \frac{2\pi\alpha^2}{s}\hat{\beta}(1 - \hat{\beta}^2)\left[1 + \frac{1 - \hat{\beta}^2}{2\hat{\beta}}\ln\frac{1 + \hat{\beta}^2}{1 - \hat{\beta}^2}\right]
$$

$$
\hat{\sigma}[\gamma\gamma \rightarrow \tilde{\ell}^+\tilde{\ell}^-] = \frac{2\pi\alpha^2}{s}\hat{\beta}\left[3 - \hat{\beta}^2 + \frac{1}{2\hat{\beta}}(-3 + 2\hat{\beta}^2 + \hat{\beta}^4)\ln\frac{1 + \hat{\beta}^2}{1 - \hat{\beta}^2}\right]. \quad (3)
$$

Since our processes are pure SUSY QED processes, we can express cross sections for all charged sleptons $\tilde{\ell} = (\tilde{e}_{L,R}, \tilde{\mu}_{L,R}, \tilde{\tau}_{1,2})$ by the formulae Eqs.(2) and (3). Moreover, multiplying the factor $\epsilon_q^4C$ ($\epsilon_q$ and $C = 3$ respectively denote the electric charge and the color degree of freedom), we can use the formulae Eqs.(2) and (3) for the squark $\tilde{q} = (\tilde{u}_{L,R}, \tilde{d}_{L,R}, \cdots, \tilde{t}_{1,2})$ pair production. For completeness, we also give the formula for the sub-process cross section of $\gamma\gamma \rightarrow W^+W^-$, which will be needed in the discussion of background suppression;

$$
\frac{d\hat{\sigma}}{d\cos\theta}[\gamma\gamma \rightarrow W^+W^-] = \frac{2\pi\alpha^2}{s(1 - \hat{\beta}^2\cos^2\theta)^2}\hat{\beta}'(3 + 10\hat{\beta}'^2 + 3\hat{\beta}'^4)
$$

$$
\frac{d\hat{\sigma}}{d\cos\theta}[\gamma\gamma \rightarrow W^+W^-] = \frac{2\pi\alpha^2}{s(1 - \hat{\beta}^2\cos^2\theta)^2}\hat{\beta}'\left[16 - 16\hat{\beta}'^2 + 3\hat{\beta}'^4 + 2\hat{\beta}'^2(8 - 3\hat{\beta}'^2)\cos^2\theta + 3\hat{\beta}'^4\cos^4\theta\right], \quad (4)
$$

where $\hat{\beta}' \equiv \sqrt{1 - 4m_W^2/s}$. Our results Eq.(4) are in agreement with the ones of Ginzburg et al. [4].

If the incident gamma beams were monochromatic, the formulae (1),(2),(3) and (4) would give just the cross sections. However, since each gamma is the secondary beam, the experimental cross sections are obtained by folding the sub-process cross sections $d\hat{\sigma}$ (2) and (4) with the energy spectra $D_{\gamma/e}$ of the high energy photons generated by the backward Compton scattering of the laser light ;

$$
d\sigma = \int_0^{z_1^{\text{max}}} dz_1 \int_0^{z_2^{\text{max}}} dz_2 D_{\gamma/e}(z_1)D_{\gamma/e}(z_2) d\hat{\sigma}(z_1z_2s_{ee} - 4m_{\ell}^2). \quad (5)
$$

Here $z_i$ ($i = 1, 2$) denotes the energy fraction of each high energy gamma beam ; $z_i = E_{\gamma_i}/E_e$. Note that the upper limit of $z_i$ is determined by the kinematics of the backward-Compton scattering, i.e., $z_i \lesssim 0.83$. If $z_i$ becomes larger than this value the back-scattered
and laser photon have enough energy to produce the $e^+e^-$ pair, and in turn the conversion efficiency drops considerably. In the following we take $z_i^{\text{max}} = 0.83$. The maximum value of the total energies of $\gamma\gamma$ sub-processes corresponds to about 80% of $\sqrt{s}$ of the basic $ee$ colliders,

$$\sqrt{s_{\gamma\gamma}} < \sqrt{z_1^{\text{max}} z_2^{\text{max}} s_{ee}} \approx 0.8\sqrt{s_{ee}}. \quad (6)$$

Both $D_{\gamma/e}$ and $\xi_2$ are functions of $z_i$ and depend on $\lambda_i$, the mean helicity of electron to be scattered off by the laser photon, and $P_i^c$, that of the laser photon:

$$D_{\gamma/e}(z_i) = D_{\gamma/e}(z_i; \lambda_i P_i^c) \quad \xi_2(z_i) = \xi_2(z_i; \lambda_i, P_i^c). \quad (7)$$

It should be mentioned that $D_{\gamma/e}(z_i)$ depend only on the value $\lambda_i P_i^c$. By polarizing the $e$ beams and the laser photons, we can obtain monochromatic and polarized gamma beams. For example, if we set $\lambda_{1,2} = +1/2$ and $P_{1,2}^c = -1$ we can get not only highly monochromatic energy spectra but also the highly polarized initial gamma beams with the Stokes parameters $\xi_2(z_{1,2}) \approx +1$ at $z_{1,2} \approx z_{1,2}^{\text{max}}$.

In Fig. 1 we show the slepton mass dependence of the polarized cross sections for the sub-processes Eq. (3), where we take $\sqrt{s} = \sqrt{s_{\gamma\gamma}} = 1\text{TeV}$. It is found that a choice of polarization $(\xi_2(z_1), \xi_2(z_2)) = (+, \pm)$ enhances the cross sections for the sleptons with masses close to the threshold values, because those polarized cross sections have the $s$-wave contribution (see Eqs.(2) and (3)). We can conclude that in order to get large cross sections for the sleptons with large masses $m_{\tilde{\ell}} \approx \sqrt{s}/2$, the polarized photon beams with $(\xi_2(z_1), \xi_2(z_2)) = (+, \pm)$ would be efficient. On the other hand, if the total energy $\sqrt{s}$ was large enough $\sqrt{s} \gg 2m_{\tilde{\ell}}$, $(\xi_2(z_1), \xi_2(z_2)) = (\pm, \mp)$ would be useful.

Next we show the numerical results for the experimental cross sections Eq. (3). The slepton mass dependence of the polarized cross sections is shown in Fig. 2, where we set $\sqrt{s_{ee}} = 1\text{TeV}$. For comparison, we also plotted the total cross sections for $e^+e^- \rightarrow \tilde{e}_R \tilde{\ell}^c$ and $e^+e^- \rightarrow \tilde{\mu}_R \tilde{\mu}_R$, where we take the lightest neutralino mass as $m_{\tilde{\ell}_1} = m_{\tilde{\mu}_B} = 50\text{GeV}$. The cross section for the electront production at $e^+e^-$ colliders are larger than the $\gamma\gamma$ one, because there exist the $t$-channel neutralino contributions. On the other hand, the $\gamma\gamma$ cross section will be much larger than $e^+e^-$ one for 2nd (and 3rd) generation sleptons if $\sqrt{s}$ is large compared with the mass threshold. This is originated from the $s$-wave contribution in Eqs.(2) and (3). In particular, the beam polarization $\lambda_{1,2} = +1/2$ and $P_{1,2}^c = -1$ will significantly enhance the cross section. This is because the polarization brings us highly monochromatic energy spectra and the highly polarized initial photon beams $(\xi_2(z_1), \xi_2(z_2)) \approx (+, +)$ at $z_{1,2} \approx z_{1,2}^{\text{max}}$. Such photon polarization enhances the sub-process cross sections for the sleptons with the masses $m_{\tilde{\ell}} \approx \sqrt{s_{\text{max}}}/2 \approx 0.4\sqrt{s}$. Note that we can get the same enhanced cross sections when we choose $\lambda_{1,2} = -1/2$ and $P_{1,2}^c = +1$.

Now we should discuss the signatures of the processes and the background suppression. Here we pay attention to the right-handed sleptons $\tilde{\ell}_R$ production, because this mass eigenstate is lighter than the left-handed one in most of the supergravity GUTs. It is expected that the signature of this process will be rather simple because $\tilde{\ell}_R$ decays dominantly into $\ell\tilde{Z}_1$, where $\tilde{Z}_1$ denotes the lightest neutralino. For the left-handed slepton production, which has more complicated decay pattern, we refer to Ref. 8. Since
we can legitimately assume $\tilde{Z}_1$ as the lightest SUSY particle (LSP), the signature of our process will be the charged lepton pair plus large missing energies taken away by the LSP. The most serious SM background is $\gamma\gamma \rightarrow W^+W^- \rightarrow (\ell^+\nu)(\ell^-\bar{\nu})$ \cite{10}. We have already given the formula Eq.(4) for the sub-process $\gamma\gamma \rightarrow W^+W^-$ cross section. At the TeV energy colliders, a charged lepton coming from the $W$-boson decay will be emitted into almost same direction with that of the parent $W$. Consequently, a cut on the acoplanarity $\phi_{acop}$ of the charged lepton pair will be effective to suppress the $WW$ background.

In Fig. 3 we show the Monte-Carlo event generation for the signal and the background processes in the transverse energy $E_T^{\ell}$ (a) and the missing transverse energy $E_{T}^{miss}$ (b) distributions, where we impose a cut on the acoplanarity, $\phi_{acop} > 40^\circ$. Here we take $\sqrt{s} = \sqrt{s_{ee}} = 1$TeV, $m_{\tilde{\ell}_R} = 350$GeV, $m_{\tilde{Z}_1} = 50$GeV, $(\lambda_{1,2}, P_{1,2}^c) = (+1/2, -1)$ and the luminosity $L = 25$fb$^{-1}$. It is found that a lower cut on $E_T^{\ell}$ or $E_{T}^{miss}$ will be useful for more suppression of the background. The slepton mass dependence of the total cross section, after imposing cuts on the missing transverse energy $E_{T}^{miss} > 150$GeV as well as on the acoplanarity $\phi_{acop} > 40^\circ$, is shown in Fig. 4, where we take the neutralino mass as $m_{\tilde{Z}_1} = 50$GeV [150GeV] in (a) [(b)]. The horizontal lines correspond to the $WW$ background cross section after imposing the cuts. We should be noted that the background cross section is almost unaffected by the initial beam polarization. We see that if we take the polarization $(\lambda_{1,2}, P_{1,2}^c) = (+1/2, -1)$, the signal cross sections dominate over the background one for the masses near the kinematical limit $m_{\tilde{\ell}_R} \lesssim 0.4\sqrt{s}$. Note that this is almost independent on the neutralino mass. On the other hand, the cross sections drops significantly for large neutralino and slepton masses if the initial beams were not polarized.

We have investigated the charged slepton production at $\gamma\gamma$ colliders and focused our attention to the physical consequence of the initial beam polarization. It has been shown that appropriate beam polarization could be useful to enhance the cross sections for the sleptons with the masses $m_{\tilde{\ell}} \lesssim 0.4\sqrt{s}$. We have explicitly shown that the most serious $WW$ background can be suppressed by the cuts on the acoplanarity and the missing transverse energy as well as the choice of polarization. For the slepton in 2nd (and 3rd) generation the $\gamma\gamma$ cross section can be larger than $e^+e^-$ one if we take appropriate initial beam polarization and the large total energies $\sqrt{s} \sim 2.5m_{\tilde{\ell}}$. This property is originated from the $s$-wave contribution in the scalar pair production cross section. This could enable us to see, moreover, the squarkonium (especially the stoponium) production in the $\gamma\gamma$ colliders, which could not be seen in the $e^+e^-$ colliders \cite{10, 15}. Another good property of the processes is the simple dependence on the arbitrary SUSY parameters, i.e., the cross sections depend only on the final sfermion masses. This could be useful to check the universality of masses of sleptons and squarks in the 1st and 2nd generation.

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References

[1] I. F. Ginzburg, G. L. Kotkin, V. G. Serbo and V. I. Telnov, *Nucl. Instrum. Methods*, 205 (1983) 47 ; I. F. Ginzburg, G. L. Kotkin, S. L. Panfil, V. G. Serbo and V. I. Telnov, *Nucl. Instrum. Methods*, 219 (1984) 5
[2] S. Brodsky, Plenary talk at the 2nd International Workshop on Physics and Experiments at Linear $e^+e^-$ Colliders, (Waikoloa, Hawaii, 26-30, April, 1993)

[3] D. Borden, Plenary talk at the 2nd International Workshop on Physics and Experiments at Linear $e^+e^-$ Colliders, (Waikoloa, Hawaii, 26-30, April, 1993)

[4] I. F. Ginzburg, G. L. Kotkin, S. L. Panfil and V. G. Serbo, Nucl. Phys. B228 (1983) 285; A. Grau and J. A. Grijóls, Nucl. Phys. B233 (1984) 375; P. Kalyniak, G. Couture and S. Godfrey, Proc. of the XII Warsaw Symposium on Elementary Particle Physics, ed. by Z. Ajduk et al., (World Scientific, 1990) p.595; S. Y. Choi and F. Schrempp, Phys. Lett. B272 (1991) 149; Proc. of the Workshop on $e^+e^-$ Collisions at 500GeV: The Physics Potential, ed. by P. M. Zerwas, DESY 92-123B (1992) p.793; K. Cheung, preprint, NUHEP-TH-92-24 (1992); G. Bélanger and F. Boudjema, Proc. of the Workshop on $e^+e^-$ Collisions at 500GeV: The Physics Potential, ed. by P. M. Zerwas, DESY 92-123B (1992) p.783

[5] R. Najima, Proc. of the 3rd Meeting on Physics at TeV Energy Scale, ed. by K. Hidaka et al., KEK Report 90-9 (1990) p.112; I. F. Ginzburg, Novosibirsk preprint, 28 (182) (1990); E. E. Boos and G. V. Jikia, Phys. Lett. B275 (1992) 164; E. Boos, M. Dubinin, V. Ilyin, A. Pukhov, G. Jikia and S. Sultanov, Phys. Lett. B273 (1991) 173; K. Hagiwara, I. Watanabe and P. M. Zerwas, Phys. Lett. B278 (1992) 187; F Richard, Proc. of the Workshop on $e^+e^-$ Collisions at 500GeV: The Physics Potential, ed. by P. M. Zerwas, DESY 92-123B (1992) p.883; K. Cheung, preprints, NUHEP-TH-92-21 (1992); NUHEP-TH-93-3 (1993); D. Bowser-Chao and K. Cheung, preprint, NUHEP-TH-92-29 (1993); K Melnikov and O. Yakovlev, preprint, BUDKERINF 93-4 (1993)

[6] M. Drees and R. M. Godbole, Proc. of the Workshop on $e^+e^-$ Collisions at 500GeV: The Physics Potential, ed. by P. M. Zerwas, DESY 92-123B (1992) p.863; O. J. P. Éboli et al., Phys. Lett. B301 (1993) 115

[7] A. Goto and T. Kon, Europhys. Lett. 13 (1992) 211; 14 (1991) 281; A. Goto and T. Kon, Europhys. Lett. 19 (1992) 575; T. Kon and A. Goto, Phys. Lett. B295 (1992) 324 H. König and K. A. Peterson, Phys. Lett. B294 (1992) 110; F. Cuypers, G. J. van Oldenborgh and R. Rückl, Nucl. Phys. B383 (1992) 45; preprint CERN-TH-6742/92 (1992)

[8] A. Goto and T. Kon, Europhys. Lett. 13 (1990) 211; 14 (1991) 281;

[9] F. Cuypers, G. J. van Oldenborgh and R. Rückl, preprint CERN-TH-6742/92 (1992)

[10] T. Kon, Talks at the 4th Workshop on JLC, (KEK, 15–16, March, 1993) and the 2nd International Workshop on Physics and Experiments at Linear $e^+e^-$ Colliders, (Waikoloa, Hawaii, 26-30, April, 1993); Seikei Univ. preprint, ITP-SU-93/02 (1993)

[11] I. F. Ginzburg and D. Yu. Ivanov, Phys. Lett. B276 (1992) 214

[12] T. Kon, I. Ito and Y. Chikashige, Phys. Lett. B287 (1992) 277

[13] O. J. P. Éboli et al., preprint, IFT-P.014/93

[14] A. Bartl, W. Majerotto and B. Mösslacher, Proc. of the Workshop on $e^+e^-$ Collisions at 500GeV: The Physics Potential, ed. by P. M. Zerwas, DESY 92-123B (1992) p.641
[15] T. Kon, in preparation
Figure Captions

Figure 1: Scalar lepton mass dependence of total cross sections for each photon polarization ($\xi_2(z_1), \xi_2(z_2)$). We take $\sqrt{s_{\gamma\gamma}} = 1$TeV.

Figure 2: Scalar lepton mass dependence of total cross sections for each initial beam polarization ($\lambda_1, P_{c1}^\perp$) and ($\lambda_2, P_{c2}^\perp$). We take $\sqrt{s_{\ell\ell}} = 1$TeV.

Figure 3: Monte-Carlo event generation for $\gamma\gamma \rightarrow \tilde{\ell}^- \tilde{\ell}^+$ and $\gamma\gamma \rightarrow W^+W^-$ with cut $\phi_{\text{acop}} > 40^\circ$. We take $\sqrt{s_{\ell\ell}} = 1$TeV, $m_{\tilde{\ell}_R} = 350$GeV, $m_{\tilde{Z}_1} = 50$GeV, ($\lambda_{1,2}, P_{c1,2}^\perp$) = (+1/2, -1) and the luminosity $L = 25$fb$^{-1}$.

Figure 4: Scalar lepton mass dependence of total cross sections with cuts $E_{T}^{\text{miss}} > 150$GeV and $\phi_{\text{acop}} > 40^\circ$. We take $\sqrt{s_{\ell\ell}} = 1$TeV and $m_{\tilde{Z}_1} = 50$GeV for (a) and 150GeV for (b). Horizontal lines correspond to $WW$ background cross section after imposing the cuts.