SUSY PARTNER SEARCHES AT HERA ENERGIES*

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Supersymmetric (SUSY) particle production at HERA (proton (820 GeV)-electron (30 GeV) collider): (1) $e^- p \rightarrow \tilde{e}^- \tilde{q} X$, (2)$e^- p \rightarrow \tilde{e}^- \tilde{\gamma}$ qXand (3)$e^- p \rightarrow \tilde{\gamma}\tilde{\nu} q X$ are investigated in the framework of the minimal SUSY standard model. Emphasis will be put on how to extract signals by minimizing noises coming from respective background processes. It is also pointed out that the differential left-right asymmetry using longitudinally polarized electron beam gives us useful information on selectrons.

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1. Introduction

Supersymmetry (SUSY) would be one of the promising idea to meet our expectations for "beyond the standard model" [1, 2]. SUSY is a new kind of symmetry which relates bosons and fermions; there is an equal number of bosonic and fermionic degrees of freedom in a multiplet forming one representation of SUSY. If all fundamental symmetries are local gauge symmetries, SUSY is also a local symmetry and it is inevitably led to include the gravity. In the low energy limit, $N = 1$ supergravity grand unified theories (GUT's) are reduced to supersymmetric standard models with soft global SUSY breaking terms [2]. Since the effective SUSY-breaking scale in the low energy supersymmetric standard model would be of order of TeV, the superpartners of quarks and leptons, even if SUSY is broken, may be reached within accelerators which are available presently or in near future. HERA will give us a favourable testing ground for SUSY partner searches.

The purpose of the present talk is to examine a scenario of SUSY unification scheme through phenomenological analysis of SUSY partner production at HERA energies. The main results are based on our present works whose details have been published elsewhere [3].

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Our concern aie SUSY production processes

$$e^-p \to \tilde{e}^-\tilde{q}X, \tag{1.1}$$

$$e^-p \to \tilde{e}^-\tilde{\gamma}\tilde{q}X \tag{1.2}$$

and

$$e^-p \to \tilde{\gamma}\tilde{\nu}qX \tag{1.3}$$

via charged currents as well as neutral currents. They are characterized by a quark jet and missing momentum/energy. In the reactions (1.1) and (1.2) the scattered electron is also helpful to identify the final state.

We concentrate our efforts to minimize noises coming from background processes $e^-p \to e^-qX$ for (1.1) and (1.2) or $e^-p \to \nu qX$ for (1.3) in order to extract signals. We found that the accoplanarity distribution and x (Bjorken variable) distribution play an important role for this purpose. It is also shown that the differential left-right asymmetry $A_{\parallel}(E_{e\perp})$ using longitudinally polarized electron beam serves to determine the mass difference of left- and right-handed selectron. Throughout the analysis we assume the minimal SUSY standard model with two Higgs supermultiplets, SUSY partners of ordinary matter fermions, and gauge bosons.

An emphasis has also been put on a calculational technique which easily enables us to take into account experimental conditions like energy and/or angle cuts in the HERA laboratory frame. Since all calculations have been carried out in the incident electron--quark inside a proton (or electron-proton) centre of mass system, our techniques presenting results explicitly in the HERA laboratory frame will be extremely helpful to experimentalists.

In Sect. 2 brief account of the minimal SUSY standard model is given for later convenience [1]. Sect. 3 is devoted to present main results. We end with some general remarks in Sect. 4.

2. The minimal SUSY standard model

For the self-containedness it would be preferable to summarize the minimum essentials of the minimal SUSY standard model which our calculations recourse to. The model includes the soft SUSY breaking terms which appear as the result of the breakdown of the local SUSY at some higher energy scale. After the spontaneous weak gauge symmetry breaking $SU(2)_L \times U(1)_Y \to U(1)_{em}$ at the weak energy scale, the superpartners of the ordinary matters, gauge and Higgs bosons generally have non-diagonal mass matrices. Particularly, we must seriously consider the gauginos-higgsinos mixing.

The mass terms for the charginos which are the mixed states of the winos and the charged higgsinos are obtained by

$$L^c_{mass} = -\frac{ig}{\sqrt{z}}[\psi^1_H\tilde{W}^+v_1 + \psi^2_{H_2}\tilde{W}^-v_2] + M\tilde{W}^+\tilde{W}^- - \mu\psi^1_{H_1}\psi^2_{H_2} + \text{h.c.} \tag{2.1}$$

Here ψ_{H_1}, ψ_{H_2} are the two SU(2) doublets of two-component spinors of the higgsinos; $\tilde{W}^{\pm}$ are the winos; v_1 and v_2 are the Vacuum Expectation Values (VEVs) of the two scalar Higgs h_1 and h_2, respectively. The mass terms for the neutralinos which are mixed states of the photino, the zino and the neutral higgsinos are expressed as

$$L^N_{\text{mass}} = \frac{ig}{2}(\tilde{W}^3\psi^2_{H_1}v_1 - \tilde{W}^3\psi^1_{H_2}v_2) + \frac{ig'}{2}(\tilde{B}\psi^2_{H_1}v_1 - \tilde{B}\psi^1_{H_2}v_2)$$
$$+\tfrac{1}{2}M\tilde{W}^3\tilde{W}^3 + \tfrac{1}{2}M'\tilde{B}\tilde{B} + \mu\psi^2_{H_1}\psi^1_{H_2} + \text{h.c.} \tag{2.2}$$

In Eqs. (2.1) and (2.2) the soft $SU(2)_L[U(1)_Y]$ gaugino breaking mass $M[M']$ and the Higgs mixing mass μ appear.

The mass matrix for the charginos is obtained from Eq. (2.1) as

$$M_c = \begin{pmatrix} M & \sqrt{2}\, m_W \cos\theta_v \\ \sqrt{2}\, m_W \sin\theta_v & \mu \end{pmatrix} \tag{2.3}$$

with the states

$$\psi^+ = \begin{pmatrix} i\tilde{W}^+ \\ \psi^2_{H_2} \end{pmatrix}, \quad \psi^- = \begin{pmatrix} i\tilde{W}^- \\ \psi^1_{H_1} \end{pmatrix}, \tag{2.4}$$

where $\tan\theta_v = v_1/v_2$. M_c can be analytically diagonalized in terms of the two unitary matrices U, V; $UM_cV^{-1} = M_{\text{cdiag}}$. The mass eigenvalues are

$$M^2_{\tilde{\chi}_{1,2}} = \tfrac{1}{2}\{M^2+\mu^2+2m^2_W$$
$$\pm[(M^2-\mu^2)^2+4m^2_W(m^2_W\cos^2 2\theta_v+M^2+\mu^2+2M\mu\sin 2\theta_v]^{1/2}\}. \tag{2.5}$$

and corresponding mass eigenstates $\tilde{\chi}_{1,2}$ are expressed as follows,

$$\tilde{\chi}_1 = \begin{pmatrix} \chi_1^+ \\ \bar{\chi}_1^- \end{pmatrix}, \quad \tilde{\chi}_2 = \begin{pmatrix} \chi_2^+ \\ \bar{\chi}_2^- \end{pmatrix}. \tag{2.6}$$

where the two-component spinors $\tilde{\chi}^{\pm}_{1,2}$ are defined by

$$\tilde{\chi}_i^+ = V_{ij}\psi_j^+, \quad \tilde{\chi}_i^- = U_{ij}\psi_j^-. \tag{2.7}$$

The mixing matrices U and V are parametrized by mixing angles $\phi_{\pm}$;

$$V = \begin{cases} O_+ \\ \varrho_3 O_- \end{cases}, \tag{2.8}$$

$$U = 0, \quad \text{with} \quad O_{\pm} = \begin{pmatrix} \cos\phi_{\pm} & \sin\phi_{\pm} \\ -\sin\phi_{\pm} & \cos\phi_{\pm} \end{pmatrix} \tag{2.9}$$

where

$$\tan 2\phi_+ = \frac{2\sqrt{2}\, m_W(M\cos\theta_v+\mu\sin\theta_v)}{M^2-\mu^2-2m^2_W\cos 2\theta_v}, \tag{2.10}$$

$$\tan 2\phi_- = \frac{2\sqrt{2}\, m_W(M\sin\theta_v+\mu\cos\theta_v)}{M^2-\mu^2+2m^2_W\cos 2\theta_v}. \tag{2.11}$$

The mass matrix for the neutralinos is obtained from Eq. (2.2) (with $s_W = \sin\theta_W$, $c_W = \cos\theta_W$)

$$M_N = \begin{pmatrix} M'c_W^2+Ms_W^2 & (M-M')s_Wc_W & 0 & 0 \\ (M-M')s_Wc_W & Mc_W^2+M's_W^2 & m_Z & 0 \\ 0 & m_Z & \mu\sin 2\theta_v & \mu\cos 2\theta_v \\ 0 & 0 & \mu\cos 2\theta_v & -\mu\sin 2\theta_v \end{pmatrix} \tag{2.12}$$

with the states

$$\psi_k^0 = (-i\tilde{\gamma}-i\tilde{Z},\ \psi_{H_1}^1\sin\theta_v-\psi_{H_2}^2\cos\theta_v,\ \psi_{H_1}^1\cos\theta_v+\psi_{H_2}^2\sin\theta_v), \tag{2.13}$$

where $\tilde{\gamma}$ and $\tilde{Z}$ are the SUSY partners of the photon and the Z boson, respectively,

$$\tilde{\gamma} = s_W\tilde{W}^3-c_W\tilde{B}, \quad \tilde{Z} = c_W\tilde{W}^3+s_W\tilde{B}. \tag{2.14}$$

We diagonalize M_N numerically by using a real matrix N; $N^TM_NN = \eta M_{\rm Ndiag}$ with $(M_{\rm Ndiag})_k > 0$ $\eta_k = \pm 1$ being the sign of the k-th eigenvalue of $M_{\rm N}$. The two-component neutralinos are defined by

$$\tilde{\chi}_i^0 = N_{ik}\psi_k^0. \tag{2.15}$$

In Eqs. (2.3) and (2.12) independent SUSY parameters are the soft breaking mass $M[M']$, the Higgs mixing mass μ and $\tan\theta_v = v_1/v_2$, the ratio of the two Higgs VEVs. In the GUT (Grand Unified Theories) scenario the two gaugino masses are related to each other by

$$M' = \tfrac{5}{3}\tan^2\theta_W M. \tag{2.16}$$

For simplicity, we assume here that $M \ll \mu$. Then the photino $\tilde{\gamma}$ can be regarded as the mass eigenstate with mass

$$M_{\tilde{\gamma}} = \tfrac{8}{3}\sin^2\theta_W M. \tag{2.17}$$

Then we must fix three independent parameters $M_{\tilde{\gamma}}$, μ and $\tan\theta_v$ to perform the diagonalization.

When the mass eigenstates are obtained we can extract the Feynman rules from the interaction Lagrangian. We list up the interaction Lagrangian needed to calculate the cross sections for our processes in Appendix.

3. *Relevant observables and their characteristic features*

On the basis of minimal SUSY standard model described in the preceding Section we can construct relevant observables to search for SUSY partners by reactions (1.1), (1.2) and (1.3) which are feasible at HERA with a reasonable rate. Amplitudes for subprocesses $M(e^-q)$ contributing to the processes mentioned above can easily be calculated by referring to Figs 1(a)–(h) and the whole amplitudes for electron-proton collisions

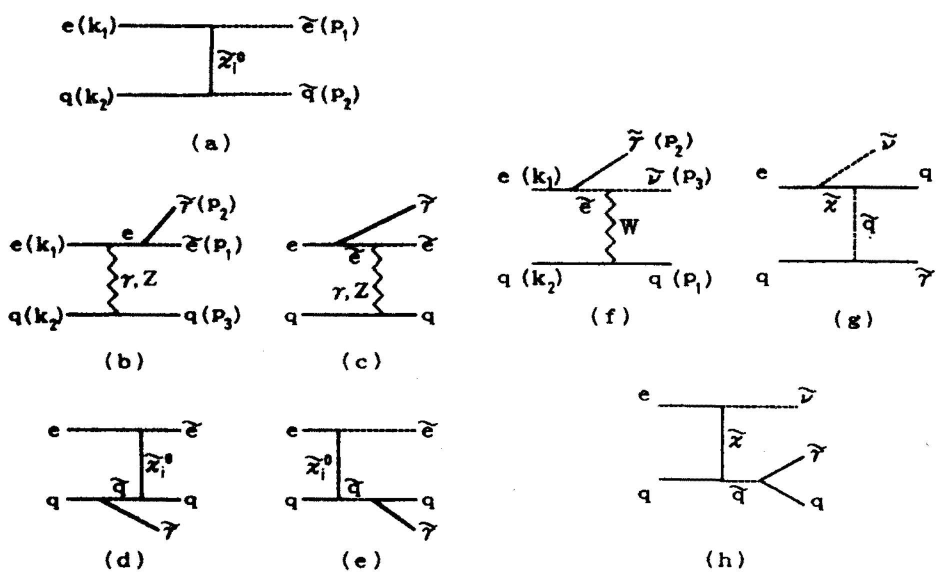

Fig. 1. Feynman diagrams for $e^-q \to \tilde{e}^-\tilde{q}$[(a)], $e^-q \to \tilde{e}\tilde{\gamma}q$ [(b), (c) (d) and [e)] and $e^-q \to \tilde{\gamma}\tilde{\nu}q$ [(f), (g) and (h)]

are obtained by incorporating the quark structure functions with flavour $q_f(x, Q^2)$ in a proton where x and Q^2 denote the momentum fraction carried by quark and the momentum transfer squared, respectively.

3.1. $e^-p \to \tilde{e}^-\tilde{q}X$ and $e^-p \to \tilde{e}^-\tilde{\gamma}qX$

The subprocess Fig. 1(a) contributes to the process $e^-p \to \tilde{e}^-\tilde{q}X$. The polarized differential cross section with initially polarized electrons (left (L) and right (R)) for this process followed by the selectron decay $\tilde{e}^- \to e^-\tilde{\gamma}$ can be written as

$$\frac{d\sigma}{dxdcd\ _e d\cos\theta_e} = \frac{e^4}{8\pi^2}\frac{M_{\tilde{e}}^2}{(M_{\tilde{e}}^2 - M_{\tilde{\gamma}}^2)}\frac{1}{(xs)^{3/2}E_e}\frac{1}{[(c_{\max}-c)(c-c_{\min})]^{1/2}}$$
$$\times \sum_f [q_f(x, Q^2) \overline{\sum_{\text{spin}}} |M(e^-_{\text{L}\atop\text{R}} q \to \tilde{e}^-\tilde{q})|^2 + q_f(x, Q^2) \overline{\sum_{\text{spin}}} |M(e^-_{\text{L}\atop\text{R}} \bar{q} \to \tilde{e}^-\tilde{q}^-)|^2]. \tag{3.1}$$

Here c, E_e, θ_e are cosine of the angle between initial electron and selectron, the final electron energy and electron scattering angle, respectively, s stands for total energy squared of the subprocess. The explicit forms of $M(e^-_{\text{L}\atop\text{R}} q \to \tilde{e}^-\tilde{q})$ are found in Ref. [3]. Concerning the quark structure functions $q_f(x, Q^2)$ we adopted the solution set 1 in Ref. [4].

For later convenience we define the accoplanarity angle ϕ as the angle between the initial electron-final electron plane and the initial electron-final squark plane:

$$\phi = \cos^{-1}\left[\frac{2E_eE_1 - M_{\tilde{e}}^2 + M_{\tilde{\gamma}}^2 - 2E_e p_1 \cos\theta_e \cos\theta}{2p_1E_e \sin\theta_e \sin\theta}\right], \tag{3.2}$$

where $E_1(p_1)$ is the energy (momentum) of the selectron.

For the reaction $e^-p \to \tilde{e}^-\tilde{\gamma}qX$ subprocesses shown in Figs. 1(b)–(e) contribute. However, since we assume that the selectron is heavy enough we can safely disregard contributions from Figs. (d) and (e). Using slightly different variables from (3.1) the polarized differential cross section is expressed as

$$\frac{d\sigma}{dxdc'dE_e'\cos\theta_e' dE_1' d\theta^2} = \frac{4e^6}{\pi^2}\frac{M_{\tilde{e}}^2}{(M_{\tilde{e}}^2 - M_{\tilde{\gamma}}^2}\frac{1}{xsp_1'[(c'_{max}-c')(c'-c'_{min})]^{1/2}}$$

$$\times \sum_f [q_f(x,Q^2)\sum_{\substack{spin\\ R}} |M(e_L^- q \to \tilde{e}^-\tilde{\gamma}q)|^2 + \bar{q}_f(x,Q^2)\sum_{\substack{spin\\ R}} |M(e_L^- q \to \tilde{e}^-\tilde{\gamma}\bar{q})|^2], \qquad (3.3)$$

where $c' = \cos\theta_1'(\cos\theta_e')$ and $E_1'(E_e')$ are cosine of the angle and the energy, respectively, of the selectron (final electron) in the electron-proton center of mass system.

The differential left-right asymmetry defined by

$$A_{\|}(E_{e\perp}) = \frac{\dfrac{d\sigma_R}{dE_{e\perp}} - \dfrac{d\sigma_L}{dE_{e\perp}}}{\dfrac{d\sigma_R}{dE_{e\perp}} + \dfrac{d\sigma_L}{dE_{e\perp}}} \qquad (3.4)$$

serve to determine the mass of the selectron. Here $E_{e\perp} = E_e \sin\theta_e$ is the transverse energy of the final electron.

Fixing the three SUSY parameters $M_{\tilde{\gamma}\mu}$, and $\tan\theta_v$ which appeared in Sect. 2 and diagonalizing the matrix M_N (2.12) we are prepared to compute numerically any desired quantity. Other input standard model parameters are assumed as follows: $\alpha = e^2/4\pi = 1/137$, $\sin^2\theta_W = 0.22$ and $m_Z = 93$ GeV.

(*i*) Total cross section

The total cross section is given by

$$\sigma = \tfrac{1}{2}[\sigma_L + \sigma_R]$$

and numerical integrations have been carried our by using the program package BASES [5]. Due to experimental conditions we imposed such cuts on the electron energy and angle in the HERA laboratory system as $E_e^L > 1$ GeV and $|\cos\theta_e^L| < 0.95$.

For $M_{\tilde{\gamma}} \lesssim 10$ GeV and $M_{\tilde{e}} + M_{\tilde{\gamma}} \lesssim 180$ GeV our results are

$$\sigma(e^-p \to \tilde{e}^-\tilde{q}X) \simeq 0.1\ \text{pb},$$

$$\sigma(e^-p \to \tilde{e}^-\tilde{\gamma}qX) \simeq 0.01\ \text{pb}.$$

On the other hand the background process $e^-p \to e^-qX$ gives us a huge amount of the cross section

$$\sigma_{background}(e^-p \to eqX) \simeq 0.89 \times 10^4\ \text{pb}.$$

As far as the total cross section is concerned we can never see any desired SUSY signal.

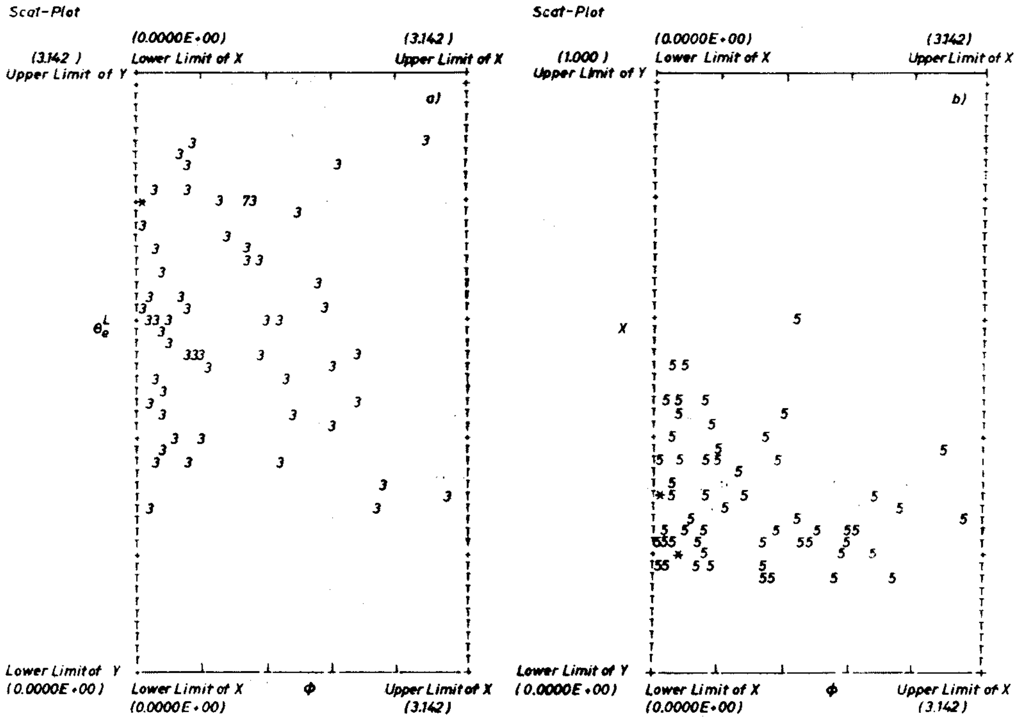

Fig. 2. Scatter plots $\phi-\theta_e^L$ and $\phi-x$ for $e^-p \to \tilde{e}\tilde{p}X$ for SUSY parameters: $M_{\tilde{\gamma}} = 10$ GeV, $\mu = 100$ GeV and $\tan\theta_v = 1$. $M_{\tilde{e}} = 40$ GeV and $M_{\tilde{q}} = 80$ GeV are assumed

(*ii*) Scatter plots $\phi-\theta_e$ and $\phi-x$

Since the final electron appears from the selectron decay accompanied by the missing momentum, the accoplanarity angle ϕ defined by (3.2) distributes widely. Phenomenologically scatter plots $\phi-\theta_e$ and $\phi-x$ are more appropriate than the ϕ distribution itself. We show them in Fig. 2. They are based on 60 events generated by the program package SPRING [5] and the integrated luminosity $L = 100\,\mathrm{pb}^{-1}$ has been assumed for HERA. As seen from Fig. 2 SUSY events are widely spread while the background events are expected to concentrate on the line $\phi = 0$. The accoplanarity would be an appropriate observable to extract SUSY events from their background.

(*iii*) x distribution

If $M_{\tilde{e}}+M_{\tilde{q}} \gtrsim 200$ GeV we have $\sigma(e^-p \to \tilde{e}^-\tilde{q}X) \simeq \sigma(e^-p \to \tilde{e}^-\tilde{\gamma}qX) \simeq 0.01$ pb. So we cannot distinguish these processes only through the magnitude of their total cross section. However, examining the x-distributions for two processes $e^-p \to \tilde{e}^-\tilde{q}X$ and $e^-p \to \tilde{e}^-\tilde{\gamma}qX$ with the same total cross section we can clearly distinguish them as seen from Fig. 3. The different threshold masses $M_{\tilde{e}}+M_{\tilde{q}}$ and $M_{\tilde{e}}+M_{\tilde{\gamma}}$ between these processes are crucial in this respect.

(*iv*) Polarization asymmetry

Figure 4 shows the polarization asymmetry (3.4) plotted against the transverse energy for the process $e^-p \to \tilde{e}^-\tilde{q}X$. We can clearly see that the polarization asymmetry is sensitive

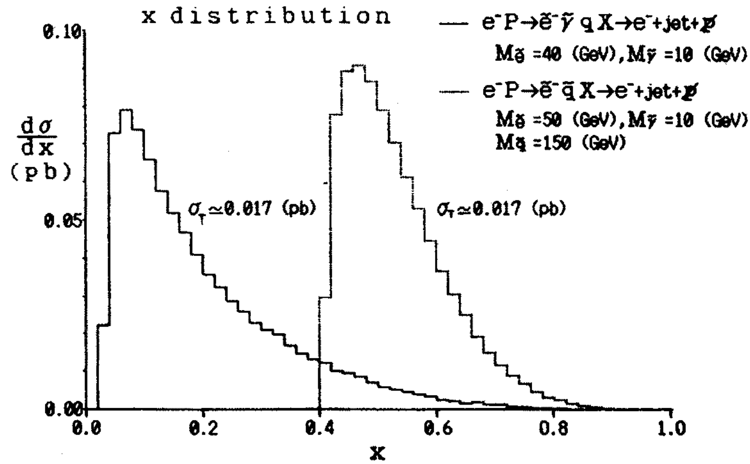

Fig. 3. x distribution $d\sigma/dx$ for (1.1) $e^-p \to \tilde{e}^-\tilde{q}X$ and (1.2) $e^-p \to \tilde{e}^-\tilde{\gamma}X$. Parameters are $M_{\tilde{e}} = 50$ GeV and $M_{\tilde{q}} = 150$ GeV for (1.1) and $M_{\tilde{\gamma}} = 10$ GeV and $M_{\tilde{e}} = 40$ GeV for (1.2). SUSY parameters are $\mu = 100$ GeV and $\tan\theta_v = 1$

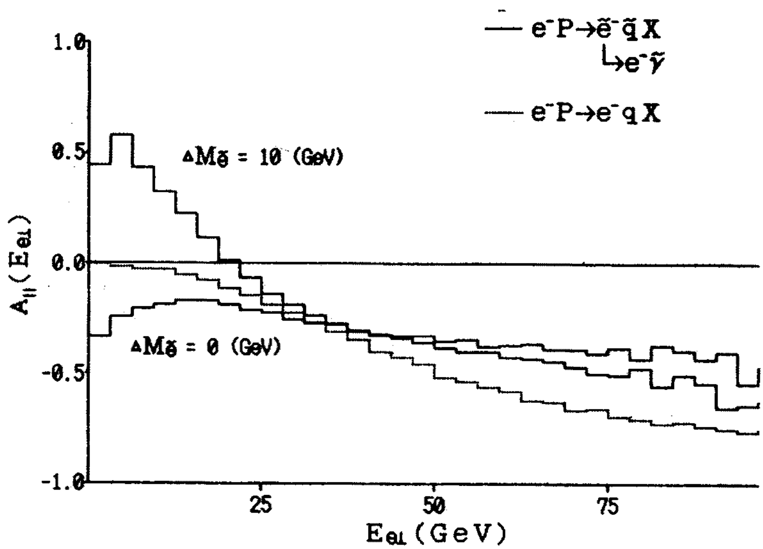

Fig. 4. Differential left-right asymmetry $A_{\parallel}(E_{e\perp})$ for $e^-p \to \tilde{e}^-\tilde{q}X$. Averaged selectron mass $M_{\tilde{e}} = 40$ GeV is commonly adopted. Dotted line is for the background process $e^-p \to eqX$

to the mass difference of left- and right-handed selectron $\Delta M_{\tilde{e}} = M_{\tilde{e}L} - M_{\tilde{e}R}$. In other words, the polarization asymmetry would play an important role to determine the mass difference between the left- and right-handed selectron.

3.2. $e^-p \to \tilde{\gamma}\tilde{\nu}qX$

Subprocesses contributing to the process $e^-p \to \tilde{\gamma}\tilde{\nu}qX$ are shown in Figs. 1 (f), (g) and (h). As before the differential cross section is written in terms of the amplitude squared for subprocesses $M(e^- q_f \to \tilde{\gamma}\tilde{\nu}q_f)$

$$\frac{d\sigma}{dE_q dE_{\tilde{\nu}} d\phi d\cos\theta_q dx} = \sum_f \frac{q_f(x, Q^2)}{(2\pi)^4 8xs} \overline{\sum_{\rm spin}} |M(e^- q_f \to \tilde{\gamma}\tilde{\nu}q_f), \tag{3.5}$$

where E_q, $E_{\tilde{\nu}}$ and ϕ, respectively, denote the energies of the scattered quark and sneutrino, the sneutrino azimuthal angle. θ_q stands for the angle between incident electron momentum and scattered quark one. Although many people discussed this reaction [3] our point of view is to search for SUSY partners through a single quark jet and a large missing energy and to restrict the mass range of sneutrinos and squarks.

(*i*) Total cross section

From a phenomenological point of view, as inputs we choose four parameters, the photino mass $M_{\tilde{\gamma}}$, the light chargino mass $M_{\tilde{\chi}_2}$, the sneutrino mass $M_{\tilde{\nu}}$ and $\tan\theta_v$. By setting experimental conditions to be $5° \leqslant \theta_1^L \leqslant 175°$ and $E_1^L > 1$ GeV numerical integration à la BASES [5] gives us $\sigma \simeq 0.1$ pb for the sneutrino mass $M_{\tilde{\nu}} \leqslant 10$ GeV and the chargino mass $M_{\tilde{\chi}_2} \leqslant 40$ GeV, provided that $M_{\tilde{\gamma}} = 10$ GeV and $\tan\theta_v = 2$.

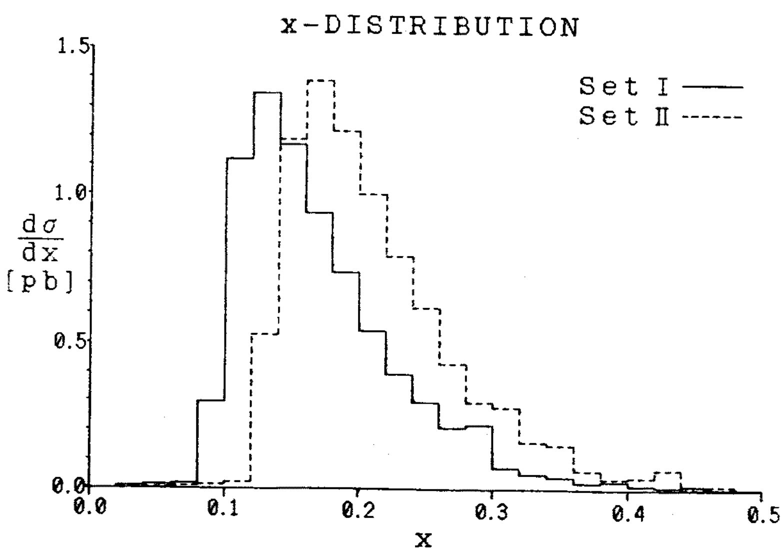

Fig. 5. x distribution $d\sigma/dx$ for $e^-p \to \tilde{\gamma}\tilde{\nu}qX$. Solid curve corresponds to a parameter set $M_{\tilde{\nu}} = 10$ GeV, $M_{\tilde{\gamma}} = 10$ GeV (set I) and $\tan\theta_v = 2$ and dashed line is for a set $M_{\tilde{\nu}} = 40$ GeV, $M_{\tilde{\gamma}} = 10$ GeV and $\tan\theta_v = 1$ (set II)

(*ii*) x distribution

Figure 5 shows the x distribution $d\sigma/dx$ for $e^-p \to \tilde{\gamma}\tilde{\nu}qX$ for different choice of parameters. The distributions are clearly different for different parameters. The large increase of $d\sigma/dx$ for the set I (II) at $x = 0.08$ (0.12) is due to the threshold effect of the real $\tilde{\nu}$-$\tilde{q}$ pair production. In other words the threshold effect sensitively depends on the total mass of the sneutrino and the squark $M_{\tilde{\nu}}+M_{\tilde{q}}$. The x distribution would serve to set limits on $M_{\tilde{\nu}}$ and $M_{\tilde{q}}$.

Since the background process $e^-p \rightarrow \nu qX$ has a peak at $x = 0$ the x distribution $d\sigma/dx$ will distinguish the SUSY production process $e^-p \rightarrow \tilde{\gamma}\tilde{\nu}qX$ from its background.

4. *Concluding remarks*

In the present talk we have presented the SUSY partner production in the framework of the minimal SUSY standard model at HERA energies with longitudinally polarized as well as unpolarized electron beam: $e^-p \rightarrow \tilde{e}^-\tilde{q}X$ (1.1), $e^-p \rightarrow \tilde{e}^-\tilde{\gamma}qX$ (1.2) and $e^-p \rightarrow \tilde{\gamma}\tilde{\nu}qX$ (1.3). These final states are commonly characterized by a single quark jet and missing energy/momentum. We have proposed some relevant quantities to extract signals of SUSY partners from a huge amount of background events. For the integrated luminosity $L \gtrsim 10^2 \sim 10^3\ \mathrm{pb}^{-1}$ our proposal would be expected to be feasible in actual experimental searches.

As for neutral current processes (1.1) and (1.2), the total cross section $\sigma(e^-p \rightarrow \tilde{e}^-\tilde{q}X) \gtrsim 0.1$ pb and $\sigma(e^-p \rightarrow \tilde{e}^-\tilde{\gamma}qX) \simeq 0.01$ pb if $M_{\tilde{\gamma}} \lesssim 10$ GeV and $M_{\tilde{e}^-}+M_{\tilde{q}} \lesssim 150$ GeV. An accoplanarity cut would be efficient to suppress the background process $e^-p \rightarrow e^-qX$. As shown in Fig. 2 the scatter plots $\phi-\theta_e$ and $\phi-x$ have a wide distributions for SUSY partners in contrast to background events which concentrate on $\phi = 0$.

It is our finding that the x distribution $d\sigma/dx$ serves to distinguish the reaction (1.1) from (1.2) and gives us information on the squark masses and neutralino parameters. The left-right polarization asymmetry $A_{\parallel}(E_{e\perp})$ is also appropriate to restrict mass difference of left- and right-handed selectron.

Concerning charged current process (1.3) our calculated total cross section $\sigma(e^-p \rightarrow \tilde{\gamma}\tilde{\nu}qX) \gtrsim 0.1$ pb for $M_{\tilde{\chi}_2} \lesssim 40$ if $M_{\tilde{\nu}} \lesssim 10$ GeV. The background process $e^-p \rightarrow \nu qX$ could be suppressed by cutting small x events in the x distribution $d\sigma/dx$. We also found that the x distribution is advantageous to restrict the mass of sneutrinos and squarks.

Finally we would like to emphasize that the reactions $e^-p \rightarrow \tilde{e}^-\tilde{q}X$, $e^-p \rightarrow \tilde{e}^-\tilde{\gamma}qX$ and $e^-p \rightarrow \tilde{\gamma}\tilde{\nu}qX$ give us a reasonable feasibility to observe SUSY partners at HERA and bring us a new restriction on SUSY parameters. The world first electron-proton collider HERA is an excellent machine producing rich final states which electron-positron colliders will not attain. SUSY partner searches at HERA would meet our expectation in its big energy and a large coverage of accessible kinematic range.

One of us (T. Kobayashi) is grateful to Professor K. Zalewski for his cordial invitation to the XXIX Cracow School of Theoretical Physics, Zakopane and his excellent hospitality extended to him during the stay at Cracow.

APPENDIX

The interaction Lagrangians needed to calculate the cross section for our processes are as follows,

(a) quark-quark-gauge boson

$$L_{qqV} = -\frac{g}{\sqrt{2}}[W_\mu^+ \bar{u}\gamma^\mu P_L d + W_\mu^- \bar{d}\gamma^\mu P_L U] - eA_\mu(e_u\bar{u}\gamma^\mu u + e_d\bar{d}\gamma^\mu d)$$

$$-\frac{g}{c_W} Z_\mu\{\bar{u}\gamma^\mu[(\tfrac{1}{2} - e_u s_W^2)P_L - e_u s_W^2 P_R]u - \bar{d}\gamma^\mu[(\tfrac{1}{2} + e_d s_W^2)P_L + e_d s_W^2 P_R]d\}, \tag{A.1}$$

(a′) lepton-lepton-gauge boson

$$L_{llV} = -\frac{g}{\sqrt{2}}[\bar{\nu}\gamma^\mu P_L e W_\mu^+ + \bar{e}\gamma^\mu P_L \nu W_\mu^-]$$

$$-\frac{g}{2c_W}[\bar{\nu}\gamma^\mu P_L \nu - \bar{e}\gamma^\mu(P_L - 2s_W^2)e]Z_\mu + e\bar{e}\gamma^\mu e A_\mu, \tag{A.2}$$

(b) squark-squark-gauge boson

$$L_{\tilde{q}\tilde{q}V} = -\frac{ig}{\sqrt{2}}[W_\mu^+(\tilde{u}_L^* \overleftrightarrow{\partial^\mu} \tilde{d}_L) + W_\mu^-(\tilde{d}_L^* \overleftrightarrow{\partial^\mu} \tilde{u}_L)]$$

$$-\frac{ig}{c_W} Z_\mu \Sigma_i (T_{3i} - e_i s_W^2)\tilde{q}_i^* \overleftrightarrow{\partial^\mu} \tilde{q}_i - ieA_\mu \Sigma_i e_i \tilde{q}_i^* \overleftrightarrow{\partial^\mu} \tilde{q}_i), \tag{A.3}$$

(b′) slepton-slepton-gauge boson

$$L_{\tilde{l}\tilde{l}V} = -\frac{ig}{\sqrt{2}}[W_\mu^+(\tilde{\nu}_L^* \overleftrightarrow{\partial^\mu} \tilde{e}_L) + W_\mu^-(\tilde{e}_L^* \overleftrightarrow{\partial^\mu} \tilde{\nu}_L)]$$

$$-\frac{ig}{c_W} Z_\mu[\tfrac{1}{2}\tilde{\nu}_L^* \overleftrightarrow{\partial^\mu} \tilde{\nu}_L + (-\tfrac{1}{2} + s_W^2)\tilde{e}_L^* \overleftrightarrow{\partial^\mu} \tilde{e}_L] + ieA_\mu \tilde{e}_L^* \overleftrightarrow{\partial^\mu} \tilde{e}_L), \tag{A.4}$$

(c) quark-squark-chargino

$$L_{l\tilde{l}\chi\pm} = -g[(U_{11}^* \bar{\tilde{\chi}}_1 + U_{21}^* \bar{\tilde{\chi}}_2)P_L U \tilde{d}_L^* + \bar{U} P_R(U_{11}\tilde{\chi}_1 + U_{21}\tilde{\chi}_2)\tilde{d}_L$$

$$+(V_{11}^* \bar{\tilde{\chi}}_1^c + V_{21}^* \bar{\tilde{\chi}}_2)P_L d \tilde{U}_L^* + \bar{d} P_R(V_{11}\tilde{\chi}_1^c + V_{21}\tilde{\chi}_2^c)\tilde{U}_L], \tag{A.5}$$

(c′) lepton-slepton-chargino

$$L_{l\tilde{l}\chi\pm} = -g[(U_{11}^* \bar{\tilde{\chi}}_1 + U_{21}^* \bar{\tilde{\chi}}_2)P_L \nu \tilde{e}_L^* + \bar{\nu} P_R(U_{11}\tilde{\chi}_1 + U_{21}\tilde{\chi}_2)\tilde{e}_L$$

$$+(V_{11}^* \bar{\tilde{\chi}}_1^c + V_{21}^* \bar{\tilde{\chi}}_2)P_L e \tilde{\nu}_L + \bar{e} P_R(V_{11}\tilde{\chi}_1^c + V_{21}\tilde{\chi}_2^c)\tilde{\nu}_L], \tag{A.6}$$

(d) quark-squark-neutralino

$$L_{q\tilde{q}\chi^0} = -\sqrt{2}\sum_i \sum_{j=1}^{4} \bar{q}_i P_R \tilde{\chi}_j^0 \tilde{q}_{jL}\left[\frac{g}{c_W}(T_{3j} - e_i s_W^2)N_{j2} + ee_i N_{j1}\right]$$

$$-\sqrt{2}\sum_i \sum_{j=1}^{4} \bar{q}_i P_L \tilde{\chi}_j^0 \tilde{q}_{iR}\left[\frac{g}{c_W} e_i s_W^2 N_{j2}^* - ee_i N_{j1}^*\right] + \text{h.c.}, \tag{A.7}$$

(d′) lepton-slepton-neutralino

$$L_{l\tilde{l}\chi^0} = -\sqrt{2} \sum_{j=1}^{4} \left\{ \frac{g}{2c_W} \bar{\nu} P_R \tilde{\chi}_j^0 \tilde{\nu}_L N_{j2} - \tfrac{1}{2} \bar{e} P_R \tilde{\chi}_j^0 \tilde{e}_L \left[\frac{g}{c_W} (1 - 2s_W^2) N_{j2} + 2eN_{j1} \right] \right\}$$

$$- \sqrt{2} \sum_{i} \sum_{j=1}^{4} \left\{ \bar{e} P_L \tilde{\chi}_j^0 \tilde{e}_R \left[- \frac{g}{c_W} s_W^2 N_{j2}^* + eN_{j1}^* \right] \right\} + \text{h.c.}, \tag{A.8}$$

where $P_{L,R}$ denote the chiral projection operators $\frac{1}{2}(1 \mp \gamma_5)$.

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