Signals for Scalar Top Quark at $ep$ Collider HERA

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In the framework of the minimal supersymmetric standard model (MSSM) and the R-parity breaking model (RBM), we investigate production processes of the scalar top (stop) at HERA energies. These models are characterized by the possible existence of the light stop whose mass is lighter than those of the top quark and the other squarks. It is shown that in the MSSM the stop pair production via boson-gluon fusion gives a sizeable cross section and the most serious background $ep \rightarrow e\bar{c}cX$ could be suppressed by appropriate kinematical cuts. We also show that in the RBM the stop is singly produced in the neutral current processes and we have a clear signal as a sharp peak in the Bjorken parameter $x$ distribution of the scattered electron.

1. INTRODUCTION

The standard model (SM) of strong and electroweak interactions describes amazingly well particle physics phenomena up to the electroweak breaking scale. Particularly, the agreement between theory and experiment in the LEP experiments was so impressive. Nevertheless, we know that the SM could not be the ultimate theory of everything, so long as there are a large number of free parameters, the arbitrariness of particle masses and mixing angles,
and the lack of any explanation for the replication of generations and so on. Still there is no experimental sign of new physics beyond the SM.

Various theoretical attempts are open to go beyond the SM. Among them the supersymmetry (SUSY) [1] seems to provide us an elegant and reasonable approach to meet the expectation, provided that the SUSY breaking scale is $O(1\text{TeV})$. In the framework of SUSY, every boson (fermion) is accompanied by a fermionic (bosonic) partner with equal mass and coupling. The requirement of equal mass is relaxed by the broken SUSY either spontaneously or explicitly through introducing soft SUSY breaking terms like gaugino mass terms, scalar mass terms or trilinear couplings of scalar particles. Still, there is no experimental evidence for SUSY partners of any of the known particles, and only some limits on their masses are given [2]. The theoretical expectation for SUSY, however, is getting stronger than ever. The analysis of the running coupling constant by SUSY GUTs recently done seems to encourage people who believe in SUSY [3].

The purpose of the present paper is to focus our attention on the scalar top quark ($\tilde{t}_1$) and investigate its production mechanisms and decay properties in the framework of the minimal supersymmetric model (MSSM) and the R-parity breaking model (RBM) [4]. We calculate cross sections together with detectable signals expected to observe at HERA, the world first electron-proton collider. Contrary to predicted high mass of the top quark, which is not discovered yet, the stop mass could be lower than that of the top quark in a model [5]. The expected mass of the stop is clearly within the reach of HERA. This is one of our strong motivation of the present work. Higher energies available than LEP and cleaner events than hadron colliders are another reason which has driven us to HERA. Particularly, the stop could be singly produced in $ep$ collisions in the RBM [6,7,8] because of the existence of the electron-quark-squark couplings. Clearly HERA is the best machine to search for the stop in such models, because we expect the remarkable peak structure in the Bjorken parameter $x$ distribution. The theoretical prediction of the discovery limit of the stop depends upon various model parameters as well as the energy and luminosity of HERA. We search for a possible experimental signal observable in $ep$ collisions.
The present paper is organized as follows. After the model building of the stop in Sec.II we discuss the stop production in MSSM in Sec.III. Section IV is devoted to the resonance production of the stop by invoking the R-parity breaking. Finally, in Sec.V we give concluding remarks.

II. MODEL BUILDING

In the framework of the supersymmetric standard model, scalar fermion mass matrices are expressed by

\[ M_\tilde{f}^2 = \begin{pmatrix} m_{\tilde{f}_L} & a_f m_f \\ a_f m_f & m_{\tilde{f}_R} \end{pmatrix}, \] (1)

where \( m_{\tilde{f}_{L,R}} \) and \( a_f \) are the SUSY mass parameters and \( m_f \) denote the ordinary fermion masses. We can see from Eq. (1) that for the sleptons and the squarks except for the stops, the left and right handed sfermions are mass eigenstates in good approximation owing to small fermion masses in the off-diagonal elements of the mass matrices. On the other hand, the large mixing between the left and right handed stops will be expected from the large top-quark mass \[5\], and the mass eigenstates are expressed by

\[ \begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} \tilde{t}_L \cos \theta_t - \tilde{t}_R \sin \theta_t \\ \tilde{t}_L \sin \theta_t + \tilde{t}_R \cos \theta_t \end{pmatrix}, \] (2)

where \( \theta_t \) denotes the mixing angle of stops:

\[ \sin 2\theta_t = \frac{2a_t m_t}{\sqrt{(m_{\tilde{t}_L}^2 - m_{\tilde{t}_R}^2)^2 + 4a_t^2 m_t^2}}, \] (3a)

\[ \cos 2\theta_t = \frac{m_{\tilde{t}_L}^2 - m_{\tilde{t}_R}^2}{\sqrt{(m_{\tilde{t}_L}^2 - m_{\tilde{t}_R}^2)^2 + 4a_t^2 m_t^2}}. \] (3b)

We can easily calculate the mass eigenvalues of the stops as

\[ m_{\tilde{t}_1, \tilde{t}_2}^2 = \frac{1}{2} \left[ m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 \mp \left( (m_{\tilde{t}_L}^2 - m_{\tilde{t}_R}^2)^2 + (2a_t m_t)^2 \right)^{1/2} \right]. \] (4)

The SUSY mass parameters \( m_{\tilde{t}_{L,R}} \) and \( a_t \) are parametrized in the following way \[9\]:
\[ m_{\tilde{t}_L}^2 = M_{\tilde{t}_L}^2 + m_Z^2 \cos 2\beta \left( \frac{1}{2} - \frac{2}{3} \sin^2 \theta_W \right) + m_t^2, \]  
\[ m_{\tilde{t}_R}^2 = M_{\tilde{t}_R}^2 + \frac{2}{3} m_Z^2 \cos 2\beta \sin^2 \theta_W + m_t^2, \]  
\[ a_t = -(A_t + \mu \cot \beta), \]

where \( M_{\tilde{t}_L,R}, \tan \beta, \mu \) and \( A_t \) denote the soft-breaking scalar masses, the ratio of two Higgs vacuum expectation values (= \( v_2/v_1 \)), the Higgs mass parameter and the trilinear coupling constant, respectively. In Fig. 1 we show contours of the various lighter stop masses \( m_{\tilde{t}_1} \) in \((A_t, M_{\tilde{t}})\) plane for given values of \((m_t, \mu, \tan \beta)\), where we take \( M_{\tilde{t}_L} = M_{\tilde{t}_R} = M_{\tilde{t}} \). We find that if SUSY mass parameters and the top mass are the same or of the same order of magnitude, the cancellation could occur in the expression for the lighter stop mass Eq. (4). So we get one light stop \( \tilde{t}_1 \) lighter than the top as well as the other squarks for a wide range of the SUSY parameters.

After the mass diagonalization we can obtain the interaction Lagrangian in terms of the mass eigenstate \( \tilde{t}_1 \). In Fig. 2 we show the Feynman rules for the lighter stop \( \tilde{t}_1 \) couplings to the gauge bosons \( \gamma, Z \) and \( g \). While the stop couplings to the gluon and photon do not depend on the mixing angle \( \theta_t \), the \( Z \)-boson coupling depends sensitively on \( \theta_t \). More specifically, it is proportional to \( C_{\tilde{t}_1} \equiv \frac{2}{3} \sin^2 \theta_W - \frac{1}{2} \cos^2 \theta_t \). Note that for a special value of \( \theta_t \sim 0.983 \), the \( Z \)-boson coupling completely vanishes \([10]\).

III. STOP PRODUCTION IN MSSM

In the MSSM the light stop \( \tilde{t}_1 \) will be produced in pair via boson-gluon fusion \([11]\):

\[ e^\pm p \to e^\pm \tilde{t}_1 \tilde{t}_1^* X. \]  

Feynman diagrams for the sub-processes are depicted in Fig. 3. Referring to Fig. 3 we find that the \( \gamma - g \) contribution to the sub-processes is much larger than that of \( Z - g \) \([11]\). Since the \( \gamma - g \) contribution does not depend on the stop mixing angle \( \theta_t \), the total cross section is not sensitive to \( \theta_t \), but only depends on the stop mass \( m_{\tilde{t}_1} \). Owing to the photon dominance, we can use the Weizsäcker-Williams approximation (WWA) ;
\[
\frac{d\sigma}{dz} = \int dy P(y) \int d\eta G(\eta, \hat{s}') \frac{d\hat{\sigma}}{dz},
\]

where \(y = (p \cdot q)/(p \cdot \ell_e)\) and \(z = (p \cdot p_f)/(p \cdot q)\) with the variables defined in Fig. 3. The WWA factorizes the cross section of the process (8) into the probability for emitting photon from lepton;

\[
P(y) = \frac{\alpha^2}{2\pi} \frac{1 + (1 - y)^2}{y} \log \frac{Q_{\text{max}}^2}{Q_{\text{min}}^2},
\]

the boson-gluon fusion cross section involving the real photon

\[
\frac{d\hat{\sigma}}{dz} = \frac{4}{9} \frac{\pi \alpha_s s'}{s' z^2 (1 - z)^2} \left[ 2m_{\tilde{t}_1}^2 - 2m_{\tilde{t}_1}^2 s' z (1 - z) + s' z^2 (1 - z)^2 \right]
\]

and the gluon distribution function \(G(\eta, \hat{s}')\), where \(\eta\) denotes the momentum fraction of the gluon in the proton and \(\hat{s}' = y \eta s\). The numerical integration has been performed by using the program package BASES. We have the total cross sections: 2.4pb for \(m_{\tilde{t}_1} = 30\text{GeV}\), 0.5pb for \(m_{\tilde{t}_1} = 40\text{GeV}\), \(5 \times 10^{-2}\text{pb}\) for \(m_{\tilde{t}_1} = 60\text{GeV}\) and \(8 \times 10^{-3}\text{pb}\) for \(m_{\tilde{t}_1} = 70\text{GeV}\).

Now, what is the experimental signature? How to suppress its background? Actually, the stop can decay into the various final states:

\[
\tilde{t}_1 \rightarrow t \tilde{Z}_1 \quad \text{(12a)}
\]

\[
\rightarrow b \tilde{W}_1 \quad \text{(12b)}
\]

\[
\rightarrow b \ell \tilde{\nu} \quad \text{(12c)}
\]

\[
\rightarrow b \nu \tilde{\ell} \quad \text{(12d)}
\]

\[
\rightarrow b W \tilde{Z}_1 \quad \text{(12e)}
\]

\[
\rightarrow b \ell \nu \tilde{Z}_1 \quad \text{(12f)}
\]

\[
\rightarrow c \tilde{Z}_1, \quad \text{(12g)}
\]

where \(\tilde{Z}_1, \tilde{W}_1, \tilde{\nu}\) and \(\tilde{\ell}\), respectively, denote the lightest neutralino, the lighter chargino, the sneutrino and the slepton. If we consider the light stop with mass lighter than 40GeV, the first five decay modes (12a) to (12e) are kinematically forbidden due to the lower mass
bounds for respective particles; $m_t > 90\text{GeV}$, $m_{\tilde{Z}_1} > 20\text{GeV}$, $m_{\tilde{\nu}_1} > 45\text{GeV}$, $m_{\tilde{l}} > 45\text{GeV}$, and $m_{\tilde{\nu}} > 40\text{GeV}$ [2]. So there left (12f) and (12g). The one-loop mode $\tilde{t}_1 \rightarrow c \tilde{Z}_1$ (12g) dominates over the four-body mode $\tilde{t}_1 \rightarrow b \ell \nu \tilde{Z}_1$ (12f), because of the large logarithmic factor $\ln(M_{\text{planck}}/m_W)$ appearing in (12g) [3]. So we can conclude that such light stop will decay into the charm quark jet plus the missing momentum taken away by the neutralino with almost 100% branching ratio.

Naively, it will be expected that TEVATRON and/or LEP can set severe bounds on the stop mass through the processes; $gg \rightarrow \tilde{t}_1 \tilde{t}_1^* \rightarrow c\bar{c} \tilde{Z}_1 \tilde{Z}_1$ (TEVATRON) and/or $Z \rightarrow \tilde{t}_1 \tilde{t}_1^*$ (LEP). However, the situation is not so obvious. Baer et al. [14] have performed the analyses of the experimental data of 4pb$^{-1}$ integrated luminosity TEVATRON running, and have obtained the results that the stop could easily be escaped the detection if $m_{\tilde{Z}_1} > \sim 10\text{GeV}$. Such large neutralino mass could make the charm quark jets softer. Consequently the stop production cross section plotted against the missing transverse energy becomes smaller than the present upper bounds, where we impose cuts on the missing transverse energy. Moreover, we find that LEP cannot exclude the light stop for appropriate mixing angle $\theta_t$. In Fig. 4 we show the stop mass dependence of the decay width $\Gamma(Z \rightarrow \tilde{t}_1 \tilde{t}_1^*)$. The horizontal line corresponds to the present upper bound for $\Delta \Gamma_Z$ at LEP [15]. We can find that the stop with mass $m_{\tilde{t}_1} \sim 20\text{GeV}$ has not been excluded if the mixing angle $\theta_t$ is larger than about 0.6. The origin of such sensitivity of $\Gamma(Z \rightarrow \tilde{t}_1 \tilde{t}_1^*)$ has already been discussed in the previous section. Recently DELPHI has performed the analyses on the direct search for the stop through $e^+ e^- \rightarrow \tilde{t}_1 \tilde{t}_1^*$ and also studied $\Delta \Gamma_Z$ [15]. The result is still negative. According to their analyses we have the excluded region in ($\theta_t$, $m_{\tilde{t}_1}$) plane shown in Fig. 5. In the same figure we show the excluded region at TRISTAN assuming massless photino [16]. In this figure we also show the typical searchable regions at HERA. We can clearly see that HERA would cover the window near $\theta_t \simeq 1$ in LEP region. The upper bound at HERA goes upward for large integrated luminosity and efficient background suppression.

For the light stop ($m_{\tilde{t}_1} \sim 40\text{GeV}$) production at HERA, the event signature is $e\ell \tilde{c}X$ with
large missing momentum due to unseen neutralinos. The most serious background process comes from the direct charm pair production \( ep \rightarrow e\overline{c}X \) via boson-gluon fusion process whose total cross section is about 1 \( \mu b \) without any cuts. In order to suppress this background we find the following kinematical cuts to be efficient; 1) the lower transverse momentum \( P^T_{D,\overline{D}} \) cuts for both \( D \) and \( \overline{D} \) mesons in laboratory (LAB) system, 2) the upper momentum transfer squared \( Q^2 \) cut and 3) the lower missing transverse momentum \( \slashed{P}_T \) cut in LAB system 4) the acoplanarity angle \( \phi_{(D-\overline{D})} \) cut, \( \phi_{(D-\overline{D})} \) being the angle between the \( D \)-proton and \( \overline{D} \)-proton planes in the boson-proton center of mass system. 5) the polar angle \( \theta_{D,\overline{D}} \) cuts, \( \theta_{D,\overline{D}} \) being the polar angle of \( D \) or \( \overline{D} \) with respect to the initial proton axis in LAB system. In Fig. 6 we show the acoplanarity angle distribution for the stop production followed by the decay \( \tilde{t}_1 \rightarrow c\tilde{Z}_1 \rightarrow (D\)-meson) plus missing momentum and those for the background with cuts mentioned above. These events in Fig 6 were generated in the kinematical regions; 
\[ 5 < Q^2 < 100 \text{(GeV/c)}^2, \quad 10^{-3} < x < 1, \quad 0.1 < |\sin \theta_{D,\overline{D}}| \quad \text{and} \quad \slashed{P}_T > 5 \text{GeV/c} \]
by making use of the generator AROMA \([17]\) with JETSET \([18]\). Here we took \( m_{\tilde{t}_1} = 30 \text{GeV}, \quad m_{\tilde{Z}_1} = 18 \text{GeV} \) and the integrated luminosity \( L = 50 \text{pb}^{-1} \). We see that the \( D \)-meson jets with \( \cos \phi_{(D-\overline{D})} > 0 \) can be used to separate the stop production from its background coming from boson-gluon fusion process.

**IV. STOP RESONANCES IN RBM**

In the RBM there could exist the exotic Yukawa couplings of the stop \( \tilde{t}_1 \), which violate the R-parity defined by \((-)^{3B+L+2S}\). Here \( L, \ B \) and \( S \) denote the lepton number, baryon number and spin, respectively. The R-parity breaking (RB) couplings in the supersymmetric models \([4]\) are required in order to explain the cosmic baryon number violation, the origin of the masses and the magnetic moments of neutrinos and some interesting rare processes in terms of the lepton and/or baryon number violation. Here we take a coupling of the stop \( \tilde{t}_1 \):

\[
\mathcal{L}_{int} = \lambda'_{131} \cos \theta_t (\tilde{t}_1 \bar{d} P_L e + \tilde{t}_1^* \bar{e} P_R d) \tag{13}
\]
originated from the RB superpotential $W = \lambda'_{ijk} L_i Q_j \bar{D}_k$, where $i \sim k$ are generation indeces and $L$, $Q$ and $\bar{D}$ denote the chiral superfields. The couplings generated from the superpotential are most suitable for the $ep$ collider experiments at HERA because the squarks will be produced in the $s$-channel in $e\bar{q}$ sub-processes. Here we consider the coupling (13), which generates the $s$-channel stop $\tilde{t}_1$ production in the neutral current (NC) process $[6]$:

$$e^\pm p \rightarrow (\tilde{t}_1 X) \rightarrow e^\pm qX$$

(14)

and the relevant Feynman diagrams are depicted in Fig. 7. The production of squarks in the first and second generation at HERA has been discussed in Ref. [7,8].

We calculate the inclusive differential cross section for the NC processes $e^\pm p \rightarrow e^\pm qX$ with polarized $e^\pm$ beams:

$$\frac{d\sigma}{dx dQ^2} = 2\frac{\alpha^2}{x^2 s^2} \sum_q \left[ q(x, Q^2) \sum_i T_i(e^\pm_{L,R} q) + \bar{q}(x, Q^2) \sum_i T_i(e^\pm_{L,R} \bar{q}) \right],$$

(15)

where $x$ and $Q^2$ denote the Bjorken scaling parameter and the four momentum transfer squared, respectively, and $q(x, Q^2)$ are the quark distribution functions [12] in the nucleon. The analytic expression for the coefficients $T_i(e^\pm_{L,R} q)$ is presented in the Appendix. The cross section depends sensitively on the decay width of the stop. In this calculation we assume $\text{BR}(\tilde{t}_1 \rightarrow ed) \simeq 100\%$, i.e.,

$$\Gamma_{\tilde{t}_1} = \frac{\alpha}{4} F_{RB}(\tilde{t}_1) m_{\tilde{t}_1},$$

(16)

where the coupling strength $F_{RB}(\tilde{t}_1)$ is defined as

$$F_{RB}(\tilde{t}_1) = \frac{\lambda'_{31}^2 \cos^2 \theta_t}{4\pi \alpha}.$$

(17)

This situation corresponds to the case of $m_{\tilde{t}_1} < m_t + m_{\tilde{Z}_1}$, $m_b + m_{\tilde{W}_1}$. While for $m_{\tilde{t}_1} > m_t + m_{\tilde{Z}_1}$ or $m_b + m_{\tilde{W}_1}$ $\text{BR}(\tilde{t}_1 \rightarrow ed)$ will compete with $\text{BR}(\tilde{t}_1 \rightarrow t\tilde{Z}_1)$ or $\text{BR}(\tilde{t}_1 \rightarrow b\tilde{W}_1)$. The analyses for such case will be presented elsewhere [19].

We expect a clear signal of the stop as a sharp peak in the Bjorken parameter $x$ distribution. The peak point corresponds to $x = m^2_{\tilde{t}_1}/s$. In Fig. 8 we show the $x$ distributions
at fixed $Q^2$. As clearly seen from Fig. 8, the lower $Q^2$ cuts would be very efficient for suppression of the SM background, since the $s$-channel stop contribution is independent of $Q^2$.

In Fig. 8 we take the beam to be $e^-$. The event rates depend on not only the RB coupling strength $\lambda'_{131}$ but also the kind of beam. This is shown in Fig. 9, where we fixed $x = 0.2$ at the peak value. It is found that the $e^+$ beam is more efficient than the $e^-$ one to separate the stop signal from the SM background. This can easily be understood from the structure of the coupling. While the $e^-$ collides only with sea $\bar{d}$-quarks in the proton, the $e^+$ collides with valence $d$-quarks. The difference of the structure function of the proton is naturally reflected in the cross sections. We also note that the polarized $e^-_L$ and $e^+_R$ beams could be advantageous to suppress the SM background. In Fig. 10 we show the $y (= Q^2/sx)$ dependence of the asymmetries defined as

$$ C_R \equiv \frac{d\sigma(e^+_R)/dx dy - d\sigma(e^-_L)/dx dy}{d\sigma(e^+_L)/dx dy + d\sigma(e^-_R)/dx dy} \quad (18) $$

and

$$ A_{e^-} \equiv \frac{d\sigma(e^-_L)/dx dy - d\sigma(e^-_R)/dx dy}{d\sigma(e^-_L)/dx dy + d\sigma(e^-_R)/dx dy}. \quad (19) $$

We find that the polarized $e^\pm$ beams will be effective to identify the stop signal. Next we show in Fig. 11 the searchable parameter region at HERA in $(\lambda'_{131}, m_{\tilde{t}_1})$ plane. The shaded-region is experimentally excluded through the atomic parity violation experiments [4]. The area inside the solid contour represents the region accessible at HERA for the production of more than ten signal events above the SM background with $Q^2>10^3$ (GeV/c)$^2$ in 100pb$^{-1}$ running. HERA will open up a large window as for the existence of the stop with RB coupling at mass up to 200 (270) GeV at the coupling of $\lambda'_{131} \approx 0.1$ with $e^-$ ($e^+$) beams.

It is well known that the similar $x$ peak could be expected in the leptoquark production at HERA [20]. We should point out that the stop with the RB couplings could be discriminated from most of the leptoquarks by its distinctive properties; 1) the $x$ peak originated from the stop would exist only in the NC (not exist in the CC) process because there is no RB
stop couplings to the neutrinos, 2) the $e^+$ beams are more favorable than the $e^-$ beams as mentioned above. One of the leptoquarks $\tilde{S}_{1/2}$ with the charge $Q = -2/3$ will give same signature with the RB stop, if the stop has $\text{BR} (\tilde{t}_1 \rightarrow ed) \simeq 100\%$. Again we note that this situation corresponds to the case of $m_{\tilde{t}_i} < m_t + m_{\tilde{Z}_1}$, $m_b + m_{\tilde{W}_1}$. While for $m_{\tilde{t}_i} > m_t + m_{\tilde{Z}_1}$ or $m_b + m_{\tilde{W}_1}$ BR$(\tilde{t}_1 \rightarrow t\tilde{Z}_1)$ or BR$(\tilde{t}_1 \rightarrow b\tilde{W}_1)$ will compete with BR$(\tilde{t}_1 \rightarrow ed)$ and the stop could be discriminated from the leptoquark $\tilde{S}_{1/2}$ with the charge $Q = -2/3$ \footnote{19}.

\section*{V. CONCLUDING REMARKS}

We have investigated various production processes of the stop at HERA energies in the framework of the MSSM and the RBM. For the stop with $m_{\tilde{t}_i} \lesssim 50\,\text{GeV}$ appropriate kinematical cuts will enable us to see signals well above the background. The stop produced via R-breaking interactions shows a sharp peak in the $x$ distribution due to its $s$-channel resonance.

The discovery of the stop would reveal us simultaneously the existence of the top flavor and the supersymmetry. This is a really big impact to the present day particle physics. HERA would be the ideal machine for our stop searches because it is $ep$ collider with just suitable energy range for our purpose.

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\section*{APPENDIX A}

The analytic expression for the cross section Eq.\,(15) is given as follows.

$$
\frac{d\sigma}{dx dQ^2}[e_{L,R}^-] = \frac{2\pi\alpha^2}{x^2 s^2} \left[ \sum_{i=1}^2 T_u^i [e_{L,R}^-](x, Q^2) u(x, Q^2) + \sum_{i=1}^2 \bar{T}_u^i [e_{L,R}^-](x, Q^2) \bar{u}(x, Q^2) \right] 
+ \sum_{i=1}^4 T_d^i [e_{L,R}^-](x, Q^2) d(x, Q^2) + \sum_{i=1}^4 \bar{T}_d^i [e_{L,R}^-](x, Q^2) \bar{d}(x, Q^2) \right],
$$

where
\[ T_1^u[e_L] = \frac{(Q^2 - sx)^2}{Q^4} (e^e e^u + \frac{Q^2}{Q^2 + m_Z^2} A_L^e A_R^u)^2, \]
\[ T_1^u[e_R] = \frac{(Q^2 - sx)^2}{Q^4} (e^e e^u + \frac{Q^2}{Q^2 + m_Z^2} A_L^e A_R^u)^2, \]
\[ T_2^u[e_L] = \frac{s^2 x^2}{Q^4} (e^e e^u + \frac{Q^2}{Q^2 + m_Z^2} A_R^e A_L^u)^2, \]
\[ T_2^u[e_R] = \frac{s^2 x^2}{Q^4} (e^e e^u + \frac{Q^2}{Q^2 + m_Z^2} A_R^e A_L^u)^2, \]
\[ \bar{T}_1^u[e_L] = \frac{s^2 x^2}{Q^4} (e^e e^u + \frac{Q^2}{Q^2 + m_Z^2} A_R^e A_L^u)^2, \]
\[ \bar{T}_1^u[e_R] = \frac{s^2 x^2}{Q^4} (e^e e^u + \frac{Q^2}{Q^2 + m_Z^2} A_R^e A_L^u)^2, \]
\[ \bar{T}_2^u[e_L] = \frac{(Q^2 - sx)^2}{Q^4} (e^e e^u + \frac{Q^2}{Q^2 + m_Z^2} A_R^e A_L^u)^2, \]
\[ \bar{T}_2^u[e_R] = \frac{(Q^2 - sx)^2}{Q^4} (e^e e^u + \frac{Q^2}{Q^2 + m_Z^2} A_R^e A_L^u)^2, \]
\[ T_1^{d}[e_{L,R}] = T_1^u[e_{L,R}] \big|_{u \rightarrow d}, \quad T_2^{d}[e_{L,R}] = T_2^u[e_{L,R}] \big|_{u \rightarrow d}, \]
\[ T_3^{d}[e_{L}] = -F_{RB}(\tilde{t}_1) \frac{(Q^2 - sx)^2}{Q^2(Q^2 - sx - m_{Z}^2)} (e^e e^d + \frac{Q^2}{Q^2 + m_Z^2} A_L^e A_R^d), \]
\[ T_3^{d}[e_{R}] = 0, \quad (A13) \]
\[ T_4^{d}[e_{L}] = \frac{1}{4} F_{RB}(\tilde{t}_1) \frac{(Q^2 - sx)^2}{Q^2(Q^2 - sx - m_{Z}^2)^2}, \quad (A14) \]
\[ T_4^{d}[e_{R}] = 0, \quad (A15) \]
\[ \bar{T}_1^{d}[e_{L,R}] = \bar{T}_1^u[e_{L,R}] \big|_{u \rightarrow d}, \quad \bar{T}_2^{d}[e_{L,R}] = \bar{T}_2^u[e_{L,R}] \big|_{u \rightarrow d}, \]
\[ \bar{T}_3^{d}[e_{L}] = -F_{RB}(\tilde{t}_1) \frac{s^2 x^2(s x - m_{Z}^2)}{Q^2((s x - m_{Z}^2)^2 + m_{Z}^2 \Gamma_{t_1}^2)} (e^e e^d + \frac{Q^2}{Q^2 + m_Z^2} A_L^e A_R^d), \]
\[ \bar{T}_3^{d}[e_{R}] = 0, \quad (A17) \]
\[ \bar{T}_4^{d}[e_{L}] = \frac{1}{4} F_{RB}(\tilde{t}_1) \frac{s^2 x^2}{(s x - m_{Z}^2)^2 + m_{Z}^2 \Gamma_{t_1}^2}, \quad (A19) \]
\[ \bar{T}_4^{d}[e_{R}] = 0, \quad (A20) \]

for $e^-$ beams. The formula for $e^+$ beams can be obtained by the following replacement in the above formula for the $e^-$ beams:

$$e_{L,R}^- \rightarrow e_{R,L}^+$$

$$q \rightarrow \bar{q}$$

(A21)

(A22)
\( \bar{q} \rightarrow q \) \hspace{1cm} (A23)

Here, \( e^f \) denote the electromagnetic charge of matter fermion \( f \), and

\[
A_L^f \equiv -\frac{T_3^f - e^f \sin^2 \theta_W}{\cos \theta_W \sin \theta_W}, \quad (A24)
\]

\[
A_R^f \equiv e^f \tan \theta_W, \quad (A25)
\]

where \( T_3^f \) are the third component of isospin and \( \theta_W \) is the Weinberg angle.
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FIGURES

FIG. 1. Contour of lighter stop mass $m_{\tilde{t}_1}$ (GeV) in $(A_t, M_{\tilde{t}})$ plane. We take $M_{\tilde{t}_L} = M_{\tilde{t}_R} = M_{\tilde{t}}$ and $(m_t$(GeV), $\mu$(GeV), $\tan\beta$) = (150, -300, 2) for (a) and (150, -300, 12) for (b).

FIG. 2. Feynman rules for the lighter stop $\tilde{t}_1$ couplings to $g$, $\gamma$ and $Z$.

FIG. 3. Feynman diagrams for sub-process $e^\pm g \rightarrow e^\pm \tilde{t}_1 \tilde{t}_1^*$

FIG. 4. $m_{\tilde{t}_1}$ dependence of decay width $\Gamma(Z \rightarrow \tilde{t}_1 \tilde{t}_1^*)$. The horizontal line corresponds to the present upper bound for $\Delta \Gamma_Z$ at LEP.

FIG. 5. Excluded parameter region in $(\theta_t, m_{\tilde{t}_1})$ by LEP and searchable region at HERA. Region under the dotted line corresponds to excluded region at TRISTAN assuming massless photino, which is valid for $m_{\tilde{t}_1} - m_\gamma > 8$GeV.

FIG. 6. Acoplanarity distribution. Kinematical cuts are $P_{T,D,D}^T > 2$GeV/c and $5$GeV/c, $5 < Q^2 < 100$(GeV/c)$^2$, $P_T > 5$GeV/c and $|\sin \theta_{D,D}| > 0.1$.

FIG. 7. Feynman diagrams for sub-process $e^\pm q \rightarrow e^\pm q$.

FIG. 8. $x$ distribution at fixed $Q^2$. Adopted parameters are $m_{\tilde{t}_1} = 200$GeV, $\lambda'_{131} = 0.25$ and $\theta_t = 0.0$.

FIG. 9. $y$ distribution at fixed $x$ using the electron and the positron. $x$ is fixed at 0.2. Adopted parameters are $m_{\tilde{t}_1} = 140$GeV and $\theta_t = \pi/4$.

FIG. 10. $y$ distribution at fixed $x$ of differential asymmetries $C_R(a)$ and $A_e^-(b)$. $x$ is fixed at 0.2. Adopted parameters are $m_{\tilde{t}_1} = 140$GeV and $\theta_t = 0$.

FIG. 11. Searchable parameter region at HERA in $(\lambda'_{131}, m_{\tilde{t}_1})$. Kinematic cut is $Q^2 > 10^3$(GeV/c)$^2$. 

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