Top-squark mixing effects in the supersymmetric electroweak corrections to top-quark production at the Fermilab Tevatron

Jin Min Yang

*China Center of Advanced Science and Technology (World Laboratory), P.O. Box 8730, Beijing 100080, People's Republic of China and Department of Physics, Henan Normal University, Xinxiang, Henan 453002, People's Republic of China**

Chong Sheng Li

China Center of Advanced Science and Technology (World Laboratory), P.O. Box 8730, Beijing 100080, People's Republic of China and Department of Physics, Peking University, Beijing 100871, People's Republic of China

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Taking into account the mixing effects between left- and right-handed top squarks, we calculate the genuine supersymmetric electroweak correction to top-quark production at the Fermilab Tevatron in the minimal supersymmetric model. The analytic expressions of the corrections to both the parton level cross section and the total hadronic cross section are presented. Some numerical examples are also given to show the size of the corrections. [S0556-2821(96)02019-X]

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I. INTRODUCTION

The top quark has been discovered by the Collider Detector at Fermilab (CDF) and D0 Collaborations at the Fermilab Tevatron [1]. The mass and production cross section are found to be $176\pm 8(\mathrm{stat})\pm 10(\mathrm{syst})[199^{+19}_{-21}(\mathrm{stat})\pm 22(\mathrm{syst})]$ GeV and $6.8^{+3.6}_{-2.4}(6.4\pm 2.2)$ Pb by CDF [D0] Collaboration. The comparison of the theoretical calculation of the top-quark production cross section with experimental results is necessary in the test of the mechanism by which top quarks are produced. Within the framework of the standard model (SM) the next-to-leading-order calculation for the QCD processes was completed several years ago [2]. Recent works [3] has extended those results with the inclusion of the exact order α_s^3 corrected cross section and the resummation of the leading soft gluon corrections in all orders of perturbation theory. The cross section was predicted to be $\sigma_{t\bar{t}}(m_t=176\ \mathrm{GeV})=4.79^{+0.67}_{-0.41}$ Pb [3]. The latest results given by Berger and Contopanagos [4] was $\sigma_{t\bar{t}}(m_t=175\ \mathrm{GeV})=5.52^{+0.07}_{-0.45}$ Pb. The one-loop electroweak corrections to the cross section were found to be only a few percent [5]. Therefore, the results of theoretical prediction in the SM are almost consistent with the experimental results within the region of the errors.

Since the corrections to top quark production cross section above 20% are potentially observable at the Fermilab Tevatron, it is tempting to calculate the radiative corrections arising from the new physics beyond the SM. In the minimal supersymmetric model (MSSM), the Yukawa correction [6] and supersymmetric QCD correction as well as the top-squark mixing effects in supersymmetric QCD correction [7] were calculated. The genuine supersymmetric electroweak corrections of order $\alpha m_t^2/m_W^2$ which arise from loops of chargino, neutralino, and squark, have also been calculated by us in Ref. [8] and its erratum [9], where we neglected the mixings between left- and right-handed squarks and assumed the mass degeneracy for all squarks. In such a simple case, the analytic results were quite simple and the numerical size of the corrections could not reach the observable level for squark mass heavier than 100 GeV. However, due to the possible significant mixing effects between left- and right-handed top squarks, which is suggested by low-energy supergravity models, and is completely general [10], the mass splitting between the two mass eigenstates of top squark may be quite large. The supersymmetric electroweak corrections may be sensitive to top squark mixing effects.

In this paper, taking into account the mixing effects between left- and right-handed top squarks, we present the genuine supersymmetric electroweak correction to top-quark production at the Fermilab Tevatron in the minimal supersymmetric model. In Sec. II, we briefly overview top-squark mixing. In Sec. III, we give the analytic expressions of the corrections to both the parton level cross section and the total hadronic cross section. In Sec. IV we present some numerical examples to show the size of the corrections.

II. TOP-SQUARK MIXING

The mass matrix of top squarks takes the form [10]

$$-L_m=(\tilde{t}_L^*\tilde{t}_R^*)\begin{pmatrix} m^2_{\tilde{t}_L} & m_t M_{LR} \\ m_t M_{LR} & m^2_{\tilde{t}_R}\end{pmatrix}\begin{pmatrix}\tilde{t}_L \\ \tilde{t}_R\end{pmatrix},$$

$$m^2_{\tilde{t}_L}=M^2_{\tilde{t}_L}+m_t^2+\cos(2\beta)\left(\tfrac{1}{2}-\tfrac{2}{3}\sin^2\theta_W\right)M_Z^2,$$

$$m^2_{\tilde{t}_R}=M^2_{\tilde{t}_R}+m_t^2+\tfrac{2}{3}\cos(2\beta)\sin^2\theta_W M_Z^2,$$

$$M_{LR}=\mu\cot\beta+A_t\widetilde{M}, \tag{1}$$

where $M^2_{\tilde{t}_L},M^2_{\tilde{t}_R}$ are the soft supersymmetry- (SUSY-) breaking mass terms for left- and right-handed top squarks,

*Mailing address.

μ is the coefficient of the H_1H_2 mixing term in the superpotential, $A_t\widetilde{M}$ is the coefficient of the dimension-three trilinear soft SUSY-breaking term $\widetilde{t}_L\widetilde{t}_R H_2$, and $\tan\beta = v_2/v_1$ is the ratio of the vacuum expectation values of the two Higgs doublets.

The mass eigenstates of top squark are obtained by

$$\begin{pmatrix}\widetilde{t}_1\\ \widetilde{t}_2\end{pmatrix} = R\begin{pmatrix}\widetilde{t}_L\\ \widetilde{t}_R\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\widetilde{t}_L\\ \widetilde{t}_R\end{pmatrix} \tag{2}$$

and the masses of $\widetilde{t}_{1,2}$ are given by

$$RM^2_{\widetilde{t}}R^T = \begin{pmatrix} m^2_{\widetilde{t}_1} & 0\\ 0 & m^2_{\widetilde{t}_2}\end{pmatrix}. \tag{3}$$

The expressions of θ and $m^2_{\widetilde{t}_{1,2}}$ are given by

$$\tan 2\theta = \frac{2M_{LR}m_t}{m^2_{\widetilde{t}_L} - m^2_{\widetilde{t}_R}}, \tag{4}$$

$$m^2_{\widetilde{t}_{1,2}} = \frac{1}{2}\left[m^2_{\widetilde{t}_L} + m^2_{\widetilde{t}_R} \mp \sqrt{(m^2_{\widetilde{t}_L} - m^2_{\widetilde{t}_R})^2 + 4M^2_{LR}m^2_t}\right]. \tag{5}$$

For sbottoms, since we neglect the mixing between left- and right-handed sbottoms, we have

$$m^2_{\widetilde{b}_{1,2}} = m^2_{\widetilde{b}_{L,R}} = m^2_b + M^2_{\widetilde{b}_{L,R}} \pm \cos(2\beta)(T^3_{L,R} - Q_b\sin^2\theta_W)M^2_Z, \tag{6}$$

where $T^3_{L,R} = -\frac{1}{2}$, 0 and $Q_b = -\frac{1}{3}$. $M_{\widetilde{b}_{L,R}}$ are the soft SUSY-breaking mass terms for left- and right-handed sbottoms.

III. ANALYTICAL EXPRESSION OF THE CORRECTION

At the Fermilab Tevatron, the top quark is dominantly produced via quark-antiquark annihilation [11]. The genuine supersymmetric electroweak correction of order $\alpha m_t^2/m_W^2$ to the amplitude is contained in the correction to the vertex of top-quark color current. The relevant Feynman diagrams are shown in Fig. 1 in Ref. [7]. The Feynman rules can be found in Ref. [12]. In our calculation, we use dimensional regularization to regulate all the ultraviolet divergences in the virtual loop corrections and we adopt the on-mass-shell renormalization scheme [13]. The renormalized amplitude for $q\bar{q}\to t\bar{t}$ can be written as

$$M_{\rm ren} = M_0 + \delta M, \tag{7}$$

where M_0 is the amplitude at the tree-level and δM is the correction to the amplitude, which are given by

$$\begin{aligned}M_0 = {}& \overline{v(p_2)}(-ig_sT^A\gamma^\nu)u(p_1)\frac{-ig_{\mu\nu}}{\hat{s}}\overline{u(p_3)}\\ &\times(-ig_sT^A\gamma^\mu)v(p_4),\end{aligned} \tag{8}$$

$$\delta M = \overline{v(p_2)}(-ig_sT^A\gamma^\nu)u(p_1)\frac{-ig_{\mu\nu}}{\hat{s}}\overline{u(p_3)}\,\delta\Lambda^\mu v(p_4). \tag{9}$$

Here, p_1,p_2 denote the momenta of the incoming partons, and p_3,p_4 are used for outgoing t quark and its antiparticle. $\hat{s}$ is center-of-mass energy of parton level process. $\delta\Lambda^\mu$ stand for the genuine supersymmetric electroweak corrections to the vertex of top-quark color current, which are given by

$$\begin{aligned}\delta\Lambda^\mu = {}& -ig_sT^A\frac{g^2m_t^2}{32\pi^2m_W^2\sin^2\beta}[\gamma^\mu F_1 + \gamma^\mu\gamma_5F_2 + k^\mu F_3\\ &+ k^\mu\gamma_5F_4 + ik_\nu\sigma^{\mu\nu}F_5 + ik_\nu\sigma^{\mu\nu}\gamma_5F_6],\end{aligned} \tag{10}$$

where $\sigma^{\mu\nu} = (i/2)[\gamma^\mu,\gamma^\nu]$ and the form factor F_i are obtained by

$$F_i = F_i^c + F_i^n, \tag{11}$$

where F_i^c and F_i^n arise from chargino and neutralino diagrams, respectively. F_i^c are given as

$$\begin{aligned}F_1^c = {}& \sum_{j=1,2}V_{j2}V^*_{j2}[c_{24} + m_t^2(c_{11}+c_{21}) + (\tfrac{1}{2}B_1 + m_t^2B_1')\\ &\times(m_t,\widetilde{M}_j,m_{\widetilde{b}})],\end{aligned} \tag{12}$$

$$F_2^c = \sum_{j=1,2}V_{j2}V^*_{j2}[c_{24} + \tfrac{1}{2}B_1(m_t,\widetilde{M}_j,m_{\widetilde{b}})], \tag{13}$$

$$F_3^c = \tfrac{1}{2}m_t\sum_{j=1,2}V_{j2}V^*_{j2}(c_{21} - 2c_{23}), \tag{14}$$

$$F_4^c = \tfrac{1}{2}m_t\sum_{j=1,2}V_{j2}V^*_{j2}(c_{21} + 4c_{22} - 4c_{23}), \tag{15}$$

$$F_5^c = -\tfrac{1}{2}m_t\sum_{j=1,2}V_{j2}V^*_{j2}(c_{11} + c_{21}), \tag{16}$$

$$F_6^c = -\tfrac{1}{2}m_t\sum_{j=1,2}V_{j2}V^*_{j2}(c_{11} + c_{21} - 2c_{12} - 2c_{23}), \tag{17}$$

where the functions $c_{ij}(-p_3,p_3+p_4,\widetilde{M}_j,m_{\widetilde{b}},m_{\widetilde{b}})$ and B_1 are the three-point and two-point Feynman integrals [14]. The chargino masses $\widetilde{M}_j$ and matrix elements V_{ij} depend on parameters $M,\mu,\tan\beta$, whose expressions can be found in Ref. [12]. $B'_{0,1}$ are defined by

$$B'_{0,1}(m,m_1,m_2) = \left.\frac{\partial B_{0,1}(p,m_1,m_2)}{\partial p^2}\right|_{p^2=m^2}, \tag{18}$$

F_i^n are obtained by

$$F_i^n = F_i^{\widetilde{t}_1} + F_i^{\widetilde{t}_2} + F_i^s \quad (\text{for } i=1,2), \tag{19}$$

$$F_i^n = F_i^{\widetilde{t}_1} + F_i^{\widetilde{t}_2} \quad (\text{for i}=3,4,5,6), \tag{20}$$

F_1^s and F_2^s are given by

$$F_1^s=\sum_{j=1}^{4}\{\tfrac{1}{2}N_{j4}N_{j4}^*[B_1(m_t,\widetilde{M}_{0j},m_{\tilde{t}_1})+B_1(m_t,\widetilde{M}_{0j},m_{\tilde{t}_2})]+m_t^2N_{j4}N_{j4}^*[B_1'(m_t,\widetilde{M}_{0j},m_{\tilde{t}_1})+B_1'(m_t,\widetilde{M}_{0j},m_{\tilde{t}_2})]$$

$$+m_t\widetilde{M}_{0j}N_{j4}N_{j4}\sin(2\theta)[B_0'(m_t,\widetilde{M}_{0j},m_{\tilde{t}_2})-B_0'(m_t,\widetilde{M}_{0j},m_{\tilde{t}_1})]\},\qquad(21)$$

$$F_2^s=\sum_{j=1}^{4}\tfrac{1}{2}N_{j4}N_{j4}^*\cos(2\theta)[B_1(m_t,\widetilde{M}_{0j},m_{\tilde{t}_1})-B_1(m_t,\widetilde{M}_{0j},m_{\tilde{t}_2})],\qquad(22)$$

$F_i^{\tilde{t}_1}$ are given by

$$F_1^{\tilde{t}_1}=\sum_{j=1}^{4}\{N_{j4}N_{j4}^*[c_{24}+m_t^2(c_{11}+c_{21})]-\sin(2\theta)N_{j4}N_{j4}m_t\widetilde{M}_{0j}(c_0+c_{11})\},\qquad(23)$$

$$F_2^{\tilde{t}_1}=\sum_{j=1}^{4}N_{j4}N_{j4}^*c_{24}\cos(2\theta),\qquad(24)$$

$$F_3^{\tilde{t}_1}=\sum_{j=1}^{4}[\tfrac{1}{2}m_tN_{j4}N_{j4}^*(c_{21}-2c_{23})+\tfrac{1}{2}\sin(2\theta)N_{j4}N_{j4}\widetilde{M}_{0j}(2c_{12}-c_{11})],\qquad(25)$$

$$F_4^{\tilde{t}_1}=\tfrac{1}{2}\cos(2\theta)m_t\sum_{j=1}^{4}N_{j4}N_{j4}^*(c_{21}+4c_{22}-4c_{23}),\qquad(26)$$

$$F_5^{\tilde{t}_1}=\sum_{j=1}^{4}[-\tfrac{1}{2}m_tN_{j4}N_{j4}^*(c_{11}+c_{21})+\tfrac{1}{2}\sin(2\theta)N_{j4}N_{j4}\widetilde{M}_{0j}(c_0+c_{11})],\qquad(27)$$

$$F_6^{\tilde{t}_1}=-\tfrac{1}{2}\cos(2\theta)m_t\sum_{j=1}^{4}N_{j4}N_{j4}^*(c_{11}-2c_{12}+c_{21}-2c_{23}),\qquad(28)$$

where $c_{ij}(-p_3,p_3+p_4,\widetilde{M}_{0j},m_{\tilde{t}_1},m_{\tilde{t}_1})$ are the three-point Feynman integrals [14]. The neutralino masses $\widetilde{M}_{0j}$ and matrix elements N_{ij} are obtained by diagonalizing the matrix Y [12]. Giving the values for the parameters $M,M',\mu,\tan\beta$, the matrix N and N_D can be obtained numerically. Here, the parameters M,M' are the masses of gauginos corresponding to SU(2) and U(1), respectively. With the grand unification assumption, i.e., SU(2)×U(1) is embedded in a grand unified theory, we have the relation $M'=(5/3)(g'^2/g^2)M$. $F_i^{\tilde{t}_2}$ are given by

$$F_i^{\tilde{t}_2}=F_i^{\tilde{t}_1}|_{\sin(2\theta)\to-\sin(2\theta),\cos(2\theta)\to-\cos(2\theta),m_{\tilde{t}_1}\to m_{\tilde{t}_2}}.\qquad(29)$$

The renormalized cross section for parton level process $q\bar{q}\to t\bar{t}$ is given by

$$\hat{\sigma}(\hat{s})=\hat{\sigma}^0+\Delta\hat{\sigma},\qquad(30)$$

with

$$\hat{\sigma}^0=\frac{8\pi\alpha_s^2}{27\hat{s}^2}\beta_t(\hat{s}+2m_t^2),\qquad(31)$$

$$\Delta\hat{\sigma}=\frac{8\pi\alpha_s^2}{9\hat{s}^3}\beta_t\frac{g^2m_t^2}{32\pi^2m_W^2\sin^2\beta}[\tfrac{2}{3}F_1\hat{s}(\hat{s}+2m_t^2)+2F_5m_t\hat{s}^2],\qquad(32)$$

where $\beta_t=\sqrt{1-4m_t^2/\hat{s}}$.

The hadronic cross section is obtained by convoluting the subprocess cross section $\hat{\sigma}_{ij}$ of partons i,j with parton distribution functions $f_i^A(x_1,Q),f_j^B(x_2,Q)$, which is given by

$$\sigma(S)=\sum_{i,j}\int_{\tau_0}^{1}\frac{d\tau}{\tau}\left(\frac{1}{S}\frac{dL_{ij}}{d\tau}\right)(\hat{s}\hat{\sigma}_{ij}),\qquad(33)$$

with

$$\frac{dL_{ij}}{d\tau}=\int_{\tau}^{1}\frac{dx_1}{x_1}[f_i^A(x_1,Q)f_j^B(\tau/x_1,Q)+(A\leftrightarrow B)].\qquad(34)$$

In the above the sum runs over all incoming partons carrying a fraction of the proton and antiproton momenta $(p_{1,2}=x_{1,2}P_{1,2})$, $\sqrt{S}=1.8$ TeV is the center-of-mass energy of Fermilab Tevatron, $\tau=x_1x_2$, and $\tau_0=4m_t^2/S$. As in Ref. [3], we do not distinguish the factorization scale Q and the renormalization scale μ and take both as the top-quark mass. In order to compare our results with the Yukawa corrections

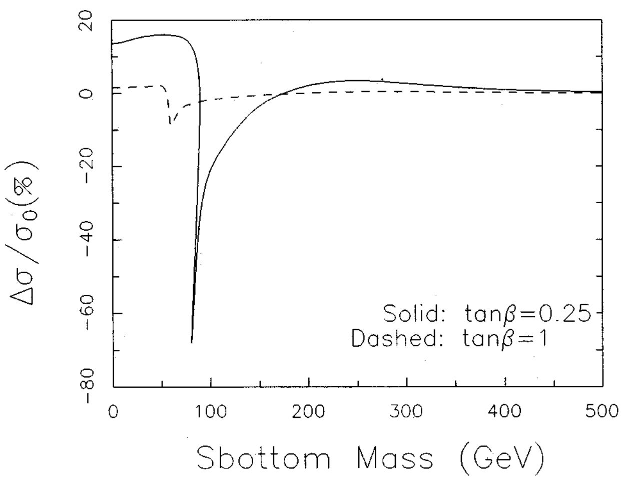

FIG. 1. The plot of relative correction to the hadronic cross section vs sbottom mass, where $M_{LR}=1.5m_{\tilde{b}}$.

in Ref. [6], we use the same parton distribution function as in Ref. [6], i.e., the Morfin-Tung leading-order parton distribution function [15].

IV. NUMERICAL EXAMPLES AND DISCUSSION

In the numerical examples presented in Figs. 1–3, we fixed $M=200$ GeV, $\mu=-100$ GeV, and used the relation $M'=\frac{5}{3}(g'^2/g^2)M$ to fix M'. Also, we assumed $M_{\tilde{t}_R}=M_{\tilde{t}_L}=M_{\tilde{b}_L}$ which depend on sbottom mass $m_{\tilde{b}}\equiv m_{\tilde{b}_1}$ as in Eq. (6). For $\tan\beta$ and the mixing parameter M_{LR}, we restrict them to the range $\tan\beta>0.25$ [6], $M_{LR}\leqslant 3m_{\tilde{b}_1}$ [16]. Other input parameters are $m_Z=91.188$ GeV, $\alpha_{\rm em}=1/128.8$, and $G_F=1.166372\times 10^{-5}$ $(\text{GeV})^{-2}$. m_W is determined through [17]

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}\frac{1}{1-\Delta r}, \tag{35}$$

where, to order $O(\alpha m_t^2/m_W^2)$, Δr is given by [18]

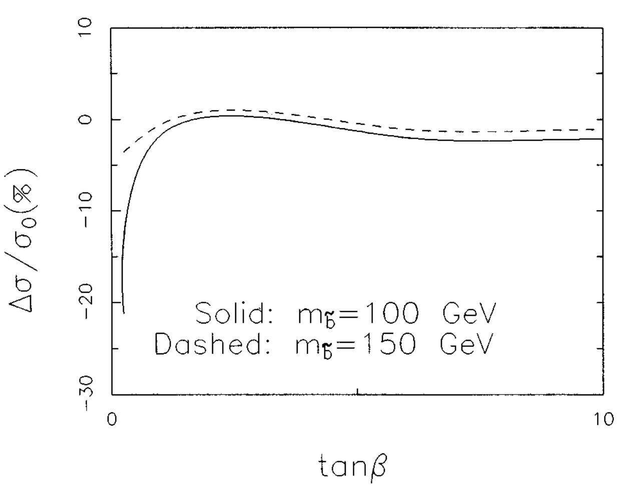

FIG. 2. The plot of relative correction to the hadronic cross section vs $\tan\beta$, where $M_{LR}=1.5m_{\tilde{b}}$.

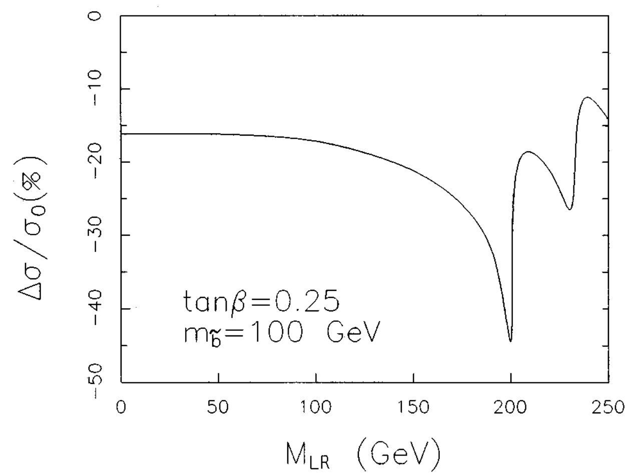

FIG. 3. The plot of the relative correction to the hadronic cross section vs the top-squark mixing parameter M_{LR}.

$$\Delta r\sim-\frac{\alpha N_C c_W^2 m_t^2}{16\pi^2 s_W^4 m_W^2}. \tag{36}$$

The relative correction to the hadronic cross section as a function of sbottom mass is presented in Fig. 1 for $\tan\beta=0.25$ and $\tan\beta=1$, respectively. Since the correction is proportional to $1/\sin^2\beta$, the size of correction for $\tan\beta=0.25$ is much larger than the corresponding correction size for $\tan\beta=1$. In the range $m_{\tilde{b}}<150$ GeV, the correction is very sensitive to sbottom mass. The correction can be either negative or positive, depending on sbottom mass. For $m_{\tilde{b}}>200$ GeV, the correction drops to about zero size, showing the decoupling behavior of MSSM. Each plot in Fig. 1 has a sharp dip, which occurs at the threshold point $m_t=m_{\tilde{b}}+\tilde{M}_j$. The chargino masses $\tilde{M}_{1,2}=(230,100)$ GeV for $\tan\beta=0.25$ and $\tilde{M}_{1,2}=(220,120)$ GeV for $\tan\beta=1$, thus the threshold point locates at $m_{\tilde{b}}=76$ GeV for $\tan\beta=0.25$ and $m_{\tilde{b}}=56$ GeV for $\tan\beta=1$.

Figure 2 shows the dependence of the relative correction to the hadronic cross section on the value of $\tan\beta$ for sbottom mass $m_{\tilde{b}}=100$ GeV and 150 GeV, respectively. The correction is very sensitive to $\tan\beta$ in the range $\tan\beta<1$. When $\tan\beta\ll 1$, the correction size gets very large since it is proportional to $1/\sin^2\beta$.

Figure 3 is the plot of the relative correction to the hadronic cross section versus the top-squark mixing parameter M_{LR}. The corresponding neutralino masses in this figure are (122, 115, 77, 229) GeV and chargino masses are (230, 100) GeV. The starting point $M_{LR}=0$ corresponds to no-mixing case, at which top-squark masses $m_{\tilde{t}_{1,2}}=m_{\tilde{t}_{L,R}}=(213,\ 216)$ GeV and the mixing angle $\theta=0$. As M_{LR} increases, the mass splitting between two top-squarks increases. At $M_{LR}=200$ GeV, top-squark masses $m_{\tilde{t}_{1,2}}=(103,\ 285)$ GeV and the mixing angle $\theta=0.775$. The two sharp dips in the plot correspond to two threshold points at about $M_{LR}=200$ GeV and 230 GeV, at which $m_t=m_{\tilde{t}_1}+\tilde{M}_{0j}$.

So, from Figs. 1–3 we found that only for $\tan\beta<1$ and $m_{\tilde{b}}<150$ GeV the correction size may exceed 20%. For $\tan\beta\geqslant 1$ or $m_{\tilde{b}}>150$ the correction size can only reach a few percent. In Ref. [6], the Yukawa correction from the SUSY Higgs sector to the hadronic cross section was found to be very small for $\tan\beta = 1$, on the order of one percent, and only for minimum value $\tan\beta = 0.25$ the correction can be above 10% but never exceeds 20%. Therefore, the genuine supersymmetric electroweak corrections are comparable to the Yukawa correction from the SUSY Higgs sector.

In conclusion, we presented the analytical expression for the genuine supersymmetric electroweak corrections of order $\alpha m_t^2/m_W^2$ to top-quark pair production at the Fermilab Tevatron with the consideration of top-squark mixing. Numerical examples showed that only for $\tan\beta < 1$ and $m_{\tilde{b}} < 150$ GeV the correction can exceed 20%. In the most favorable case, these supersymmetric corrections, combined with Yukawa corrections of the Higgs sector and also SUSY QCD correction, are potentially observable at Fermilab Tevatron and could be used to place restrictions on MSSM.

Note added. After we finished this paper, we saw a similar report (hep-ph/9605419) by J. Kim J. Lopez, D. Nanopoulos, and R. Rangarajan, [Report No. hep-ph/9605419 (unpublished)] which has some overlap with this work. As pointed out in their paper, their results are in agreement with ours.

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