Top Squark Mixing Effects in Supersymmetric Electroweak Corrections to Top Quark Production at the Tevatron (Postprint)

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Abstract

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Full Text

Preamble

HNU-ITP-96-1: Top-squark mixing effects in the supersymmetric electroweak corrections to top quark production at the Tevatron

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Abstract

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1. Introduction

The top quark has been discovered by the CDF and D0 collaborations at the Tevatron [?]. The measured mass and production cross section are approximately 176 GeV and 6.8 pb, respectively. The comparison of theoretical calculations of the top quark production cross section with experimental results is essential for testing the production mechanism. Within the Standard Model (SM), the next-to-leading-order calculation for the QCD processes was completed several years ago [?]. Recent works [?] have extended these results with the inclusion of the exact order α_s^3 corrected cross section and the resummation of the leading soft gluon corrections to all orders in perturbation theory. The cross section was predicted to be $\sigma_{t\bar{t}}(m_t = 176\text{ GeV}) = 4.79^{+0.67}_{-0.45}$ pb [?]. The latest results given by Berger [?] were $\sigma_{t\bar{t}}(m_t = 175\text{ GeV}) = 5.52^{+0.07}_{-0.41}$ pb. The one-loop electroweak corrections to the cross section were found to be only a few percent [?]. Therefore, the theoretical predictions in the SM are almost consistent with the experimental results within the error margins.

Since corrections to the top quark production cross section exceeding 20% are potentially observable at the Tevatron, it is worthwhile to calculate the radiative corrections arising from new physics beyond the SM. In the minimal supersymmetric model (MSSM), the Yukawa correction and supersymmetric QCD correction were calculated in Refs. [?, ?]. These corrections cannot reach the observable level for experimentally allowed parameter values. The genuine supersymmetric electroweak corrections of order $\alpha m_t^2/m_W^2$, which arise from loops of charginos, neutralinos, and squarks, have also been calculated by us in Ref. [?] and its erratum [?], where we neglected the mixings between left- and right-handed squarks and assumed 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 masses 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 but is completely general [?], the mass splitting between the two mass eigenstates of the 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 Tevatron in the minimal supersymmetric model. In Sec. 2, we briefly review top-squark mixing. In Sec. 3, we give the analytic expressions of the corrections to both the parton level cross section and the total hadronic cross section. In Sec. 4, we present some numerical examples to show the size of the corrections.

2. Top-squark mixing

The mass matrix of top-squarks takes the form [**?**]:

$$\mathcal{L}_m = (\tilde{t}_L^* \ \tilde{t}_R^*) \begin{pmatrix} m_{\tilde{t}_L}^2 & m_t M_{LR} \\ m_t M_{LR} & m_{\tilde{t}_R}^2 \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

where

$$m_{\tilde{t}_L}^2 = M_{\tilde{t}_L}^2 + m_t^2 + \cos(2\beta)\left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right) M_Z^2$$

$$m_{\tilde{t}_R}^2 = M_{\tilde{t}_R}^2 + m_t^2 + \frac{2}{3}\cos(2\beta)\sin^2\theta_W M_Z^2$$

$$M_{LR} = \mu \cot\beta + A_t$$

Here, $M_{\tilde{t}_L}$ and $M_{\tilde{t}_R}$ are the soft SUSY-breaking mass terms for left- and right-handed top-squarks, μ is the coefficient of the $H_1 H_2$ mixing term in the superpotential, A_t is the coefficient of the dimension-three trilinear soft SUSY-breaking term $\tilde{t}_L \tilde{t}_R H_2$, 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:

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

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

$$m_{\tilde{t}_{1,2}}^2 = \frac{1}{2}\left[m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 \mp \sqrt{(m_{\tilde{t}_L}^2 - m_{\tilde{t}_R}^2)^2 + 4M_{LR}^2 m_t^2}\right]$$

The expressions for θ and $m_{\tilde{t}_{1,2}}$ are given by:

$$\tan 2\theta = \frac{2M_{LR} m_t}{m_{\tilde{t}_L}^2 - m_{\tilde{t}_R}^2}$$

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

$$m_{\tilde{b}_{1,2}}^2 = M_{\tilde{b}_{L,R}}^2 + m_b^2 + \cos(2\beta)(T_{L,R}^3 - Q_b \sin^2\theta_W) M_Z^2$$

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

3. Analytical expression of the correction

At the Tevatron, the top quark is dominantly produced via quark-antiquark annihilation [?]. 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 the top-quark color current. The relevant Feynman diagrams are shown in Fig. 1 of Ref. [?]. The Feynman rules can be found in Ref. [?].

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 [?]. The renormalized amplitude for $t\bar{t}$ production can be written as:

$$\mathcal{M}_{\rm ren} = \mathcal{M}_0 + \delta\mathcal{M}$$

where $\mathcal{M}_0$ is the amplitude at tree-level and $\delta\mathcal{M}$ is the correction to the amplitude, which are given by:

$$\mathcal{M}_0 = \bar{v}(p_2)\left(-ig_s T^A\gamma^\nu\right)u(p_1)\frac{-ig_{\nu\mu}}{\hat{s}}\bar{u}(p_3)\left(-ig_s T^A\gamma^\mu\right)v(p_4)$$

$$\delta\mathcal{M} = \bar{v}(p_2)\left(-ig_s T^A\gamma^\nu\right)u(p_1)\frac{-ig_{\nu\mu}}{\hat{s}}\bar{u}(p_3)\delta\Lambda^\mu v(p_4)$$

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

$$\delta\Lambda^\mu = \frac{-ig_s T^A}{32\pi^2 m_W^2\sin^2\beta}\left[\gamma^\mu F_1 + \gamma^\mu\gamma_5 F_2 + k^\mu F_3 + k^\mu\gamma_5 F_4 + ik_\nu\sigma^{\mu\nu}F_5 + ik_\nu\sigma^{\mu\nu}\gamma_5 F_6\right]$$

where $\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$ and the form factors F_i are obtained by:

$$F_i = F_i^c + F_i^n$$

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

$$F_1^c = \sum_{j=1,2}|V_{j2}|^2\left[c_{24} + m_t^2(c_{11}+c_{21}) + (B_1 + m_t^2 B_1')(m_t, \tilde{M}_j, m_{\tilde{b}})\right]$$

$$F_2^c = \sum_{j=1,2}|V_{j2}|^2(c_{21} - 2c_{23})$$

$$F_3^c = \sum_{j=1,2} |V_{j2}|^2 B_1(m_t, \tilde{M}_j, m_{\tilde{b}})$$

$$F_4^c = \sum_{j=1,2} |V_{j2}|^2 (c_{21} + 4c_{22} - 4c_{23})$$

$$F_5^c = \sum_{j=1,2} |V_{j2}|^2 (c_{11} + c_{21})$$

$$F_6^c = \sum_{j=1,2} |V_{j2}|^2 (c_{11} + c_{21} - 2c_{12} - 2c_{23})$$

where the functions $c_{ij}(p_3, p_3 + p_4, \tilde{M}_j, m_{\tilde{b}}, m_{\tilde{b}})$ and B_1 are the 3-point and 2-point Feynman integrals [**?**]. The chargino masses $\tilde{M}_j$ and matrix elements V_{ij} depend on parameters $M, \mu, \tan\beta$, whose expressions can be found in Ref. [**?**]. $B'_{0,1}$ are defined as:

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

The F_i^n are obtained by:

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

$$F_i^n = F_i^{\tilde{t}_1} - F_i^{\tilde{t}_2} \quad (\text{for } i = 3, 4, 5, 6)$$

$F_i^{\tilde{t}_1}$ and $F_i^{\tilde{t}_2}$ are given by:

$$F_1^{\tilde{t}_1} = \sum_{j=1}^{4} |N_{j4}|^2 \left[B_1(m_t, \tilde{M}_j^0, m_{\tilde{t}_1}) + B_1(m_t, \tilde{M}_j^0, m_{\tilde{t}_2})\right] + m_t \tilde{M}_j^0 N_{j4}^2 \sin(2\theta) \left[B'_1(m_t, \tilde{M}_j^0, m_{\tilde{t}_1}) + B'_1(m_t, \tilde{M}_j^0, m_{\tilde{t}_2}\right.$$

$$F_2^{\tilde{t}_1} = \sum_{j=1}^{4} |N_{j4}|^2 \cos(2\theta) \left[B_1(m_t, \tilde{M}_j^0, m_{\tilde{t}_1}) - B_1(m_t, \tilde{M}_j^0, m_{\tilde{t}_2})\right]$$

$$F_3^{\tilde{t}_1} = \sum_{j=1}^{4} |N_{j4}|^2 \left[c_{24} + m_t^2(c_{11} + c_{21})\right] + \sin(2\theta) N_{j4}^2 m_t \tilde{M}_j^0 (c_0 + c_{11})$$

$$F_4^{\tilde{t}_1} = \sum_{j=1}^{4} |N_{j4}|^2 c_{24} \cos(2\theta)$$

$$F_5^{\tilde{t}_1} = \sum_{j=1}^{4} \left[m_t |N_{j4}|^2 (c_{21} - 2c_{23}) + \sin(2\theta) N_{j4}^2 \tilde{M}_j^0 (2c_{12} - c_{21}) \right]$$

$$F_6^{\tilde{t}_1} = \sum_{j=1}^{4} \left[\cos(2\theta) m_t |N_{j4}|^2 (c_{21} + 4c_{22} - 4c_{23}) \right]$$

where $c_{ij}(p_3, p_3 + p_4, \tilde{M}_j^0, m_{\tilde{t}_1}, m_{\tilde{t}_1})$ are the 3-point Feynman integrals [**?**]. The neutralino masses $\tilde{M}_j^0$ and matrix elements N_{ij} are obtained by diagonalizing the matrix Y [**?**]. Given the values for the parameters $M, M', \mu, \tan\beta$, the matrix N 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(5) embedding where SU(2) and U(1) are embedded in a grand unified theory, we have the relation $M' = \frac{5}{3}\frac{g_1^2}{g_2^2} M$.

$F_i^{\tilde{t}_2}$ are given by:

$$F_i^{\tilde{t}_2} = F_i^{\tilde{t}_1} \text{ with } \sin(2\theta) \to -\sin(2\theta), \cos(2\theta) \to -\cos(2\theta), m_{\tilde{t}_1} \to m_{\tilde{t}_2}$$

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

$$\hat{\sigma}(\hat{s}) = \hat{\sigma}_0 + \Delta\hat{\sigma}$$

where

$$\hat{\sigma}_0 = \frac{2\pi\alpha_s^2}{27\hat{s}^2} \beta_t (\hat{s} + 2m_t^2)$$

and

$$\Delta\hat{\sigma} = \frac{2\pi\alpha_s^2}{9\hat{s}^3\beta_t} \frac{\alpha_{em}}{32\pi^2 m_W^2 \sin^2\beta} \left[F_1 \hat{s}(\hat{s} + 2m_t^2) + 2F_5 m_t \hat{s}^2 \right]$$

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 $f_i^A(x_1, Q)$, $f_j^B(x_2, Q)$:

$$\sigma(S) = \sum_{i,j} \int_{\tau_0}^{1} d\tau \int_{\tau}^{1} \frac{dx_1}{x_1} \left[\hat{s}\hat{\sigma}_{ij}\right] f_i^A(x_1, Q) f_j^B(\tau/x_1, Q) + (A \leftrightarrow B)$$

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 the Tevatron, $\tau = x_1 x_2$ and $\tau_0 = 4m_t^2/S$. As in Ref. [?], 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 in Ref. [?], we use the same parton distribution function as in Ref. [?], i.e., the Morfin-Tung leading-order parton distribution function [?].

4. 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 $M' = \frac{5}{3}\frac{g_1^2}{g_2^2}M$ to fix M'. Also we assumed $M_{\tilde{t}_R} = m_{\tilde{b}_1}$ as in Eq. (6). For $\tan\beta$ and the mixing parameter M_{LR}, we restrict them to the range $\tan\beta \geq 0.25$ and $M_{LR} \leq 3m_{\tilde{b}_1}$ [?]. Other input parameters are $m_Z = 91.188$ GeV, $\alpha_{em} = 1/128.8$, and $G_F = 1.166 \times 10^{-5}$ (GeV)$^{-2}$. m_W is determined through [?]:

$$m_W^2 = \frac{m_Z^2}{2}\left[1 + \sqrt{1 - \frac{4\pi\alpha_{em}}{\sqrt{2}G_F m_Z^2}(1 + \Delta r)}\right]$$

where, to order $\mathcal{O}(\alpha m_t^2/m_W^2)$, Δr is given by [?]:

$$\Delta r = \frac{3\alpha_{em}}{16\pi \sin^2\theta_W}\frac{m_t^2}{m_W^2}$$

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 the correction for $\tan\beta = 0.25$ is much larger than the corresponding size for $\tan\beta = 1$. In the range $m_{\tilde{b}} < 150$ GeV, the correction is very sensitive to the sbottom mass. The correction can be either negative or positive, depending on the sbottom mass. For $m_{\tilde{b}} > 200$ GeV, the correction drops to approximately zero, showing the decoupling behavior of the 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 are $\tilde{M}_{1,2} = (230, 100)$ GeV for $\tan\beta = 0.25$ and $\tilde{M}_{1,2} = (220, 120)$ GeV for $\tan\beta = 1$, thus the threshold point is located at $m_{\tilde{b}} = 76$ GeV for $\tan\beta = 0.25$ and $m_{\tilde{b}} = 56$ GeV for $\tan\beta = 1$.

Fig. 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 becomes very large since it is proportional to $1/\sin^2\beta$.

Fig. 3 is a 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 the no-mixing case, at which the top-squark masses are $m_{\tilde{t}_{1,2}} = m_{\tilde{t}_{L,R}} = (213, 216)$ GeV and the mixing angle $\theta = 0$. As M_{LR} increases, the mass splitting between the two top-squarks increases. At $M_{LR} = 200$ GeV, the top-squark masses are $m_{\tilde{t}_{1,2}} = (103, 285)$ 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 $m_t = m_{\tilde{t}_1} + \tilde{M}^0_j$.

From Figs. 1-3 we find that only for $\tan\beta < 1$ and $m_{\tilde{b}} < 150$ GeV can the correction size exceed 20%. For $\tan\beta \geq 1$ or $m_{\tilde{b}} > 150$ GeV, the correction size can only reach a few percent. In Ref. [**?**], 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 a percent, and only for the minimum value $\tan\beta = 0.25$ could the correction exceed 10% but never reach 20%. Therefore, the genuine supersymmetric electroweak corrections are comparable to the Yukawa correction from the SUSY Higgs sector.

In conclusion, we have presented the analytical expression for the genuine supersymmetric electroweak corrections to top quark production at the Tevatron, taking into account the mixing effects between left- and right-handed top-squarks. The numerical results show that these corrections can be significant for certain parameter ranges and should be considered in precision studies of top quark physics.

Note: Figure translations are in progress. See original paper for figures.