$\tilde{t}\bar{\tilde{t}}$ Bound State Production at Multi-TeV Hadron Colliders

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Within the scenario in which one of the scalar partners of the top quark is lighter than the top quark itself, we calculate the cross sections of $\tilde{t}\bar{\tilde{t}}$ bound state $\tilde{\eta}_t(0^{++})$ production in multi-TeV pp collisions. Although the present Fermilab Tevatron cannot find such a bound state because of too small cross sections, future colliders might catch the first evidence of supersymmetry by detecting it.

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One of the most fantastic ideas to go beyond the standard model is supersymmetry (SUSY), which solves the hierarchy problem and is the only known way to unify all interactions of fundamental particles. Recently, it has caused new interest through the observations that, with a not so large SUSY breaking scale (~ 1 TeV), the minimal supersymmetric extension of the standard model is consistent with grand unification with a rather large unification scale of around 10^{16} GeV, and hence is compatible with the proton lifetime [1]. However, these observations are due to very indirect arguments. A direct way to confirm the realization of SUSY is to discover the supersymmetric particles.

SUSY predicts, as a consequence of a fermion-boson symmetry, the presence of supersymmetric partners to all ordinary particles. A lot of work has been done so far experimentally and theoretically to search for SUSY particles. Various mass limits for supersymmetric partners have been given: For example, $m_{\tilde{q}} > 106$ GeV for scalar quarks and $m_{\tilde{g}} > 106$ GeV for gluinos based on the minimal SUSY model [2]. These bounds come from the assumption that all scalar quarks with both chiralities, except for $\tilde{t}_R$ and $\tilde{t}_L$, are degenerate in mass. This assumption seems to be necessary for the first two generations because of stringent bounds on flavor-changing neutral currents and parity violations [3]. However, for the third generation partners there is, *a priori*, no such severe requirement of degeneracy. With a scalar quark mass matrix including very heavy quarks, the SUSY models do not in general exclude the possibility that one of the scalar partners of the heavy quark is lighter than the other partner and even lighter than the heavy quark itself [4]. If this scenario really works, we can expect to find new phenomena which have not yet taken place in low energy physics. So far there have been several papers discussing the physical implications of this scenario [5]. Here we discuss another possibility of the SUSY search by concentrating on the production of the bound state of scalar top quarks at supercolliders.

Recently, the Collider Detector at Fermilab (CDF) Collaboration has increased the lower bound of the top quark mass to $m_t \geq 91$ GeV [6], which is already larger than the W mass. Furthermore, the electroweak high-precision measurements allow us to estimate the top quark mass as $m_t = 125$ to 144 ± 30 GeV, $m_t < 181$ GeV (95% C.L.) [7]. Therefore, we can expect the top quark to have a good chance of realizing the above-mentioned scenario, $m_{\tilde{t}} < m_t$, where $m_{\tilde{t}}$ represents the mass of the lighter scalar partner.

In this paper, we play the game in this scenario and concentrate on how to find the scalar top partner $\tilde{t}$. (We call the lighter scalar partner $\tilde{t}$ hereafter.) In the next-generation multi-TeV colliders, we will have copious production of not only top quarks but also $\tilde{t}$'s. Looking back upon the past, new flavor's degrees of freedom have often been discovered in their hidden form such as quarkonia ($c\bar{c}, b\bar{b}$), which have a long lifetime and hence sharp resonance peaks. If a single decay of $\tilde{t}$ is kinematically suppressed or its decay width is not so large, the bound states of $\tilde{t}$ are also expected to exist and might be found as resonances. If this is the case, the first evidence of SUSY might be caught by detecting the production of the $\tilde{t}\bar{\tilde{t}}$ bound state. Although in the present scenario a $\tilde{t}$ cannot decay into a top quark t kinematically, it could decay, in general, into lighter quarks like $\tilde{t} \to b\tilde{W}$, $\tilde{t} \to c\tilde{\gamma}$, etc., depending on the mass of decay particles. If these processes are suppressed by phase-space constraints and/or small intergeneration mixings, a $\tilde{t}$ has a long lifetime and a rather long-lived $\tilde{t}\bar{\tilde{t}}$ state is expected to exist with small width [case (a)]: Typically $\Gamma_{\rm tot}(\tilde{\eta}_t(0^{++})) \simeq 2.1$-$4.3$ MeV for $m_{\tilde{t}} = 110$-150 GeV. On the other hand, if the $\tilde{t} \to b\tilde{W}$ is kinematically allowed, then the $\tilde{\eta}_t$ decay width becomes larger [case (b)]: As a typical example, $\Gamma_{\rm tot}(\tilde{\eta}_t(0^{++})) \simeq 30$-$400$ MeV for $m_{\tilde{t}} = 110$-150 GeV and $m_{\tilde{W}} = 100$ GeV by assuming $V_{i1} = 1/\sqrt{2}$, where V_{i1} is the matrix element diagonalizing the chargino-Higgsino mass matrix [8]. The analysis of case (b) is consistent with that of Bigi, Fadin, and Khoze [9] who

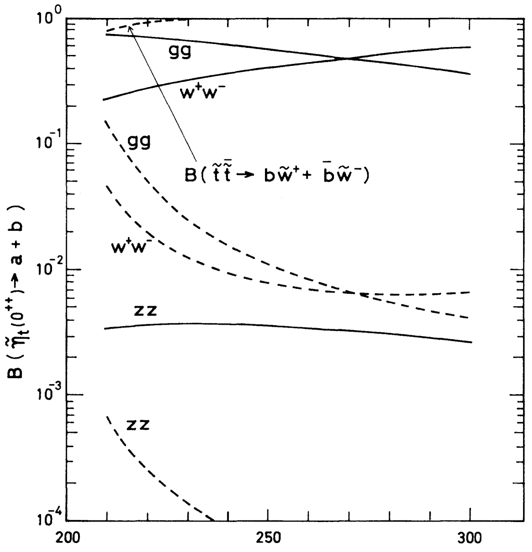

FIG. 1. $M_{\tilde\eta_t}$ dependence of branching ratios of $\tilde\eta_t(0^{++})$. Solid [dashed] lines represent case (a) [case (b)].

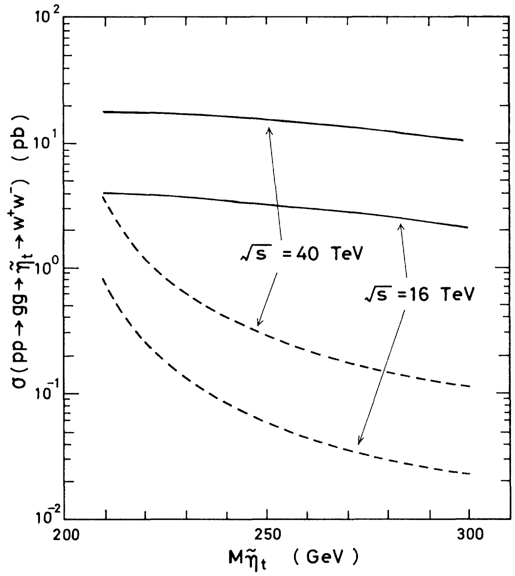

FIG. 2. $M_{\tilde\eta_t}$ dependence of $\sigma(pp\to gg\to\tilde\eta_t\to W^+W^-)$ with $m_t=150$ GeV at $\sqrt{s}=16$ and 40 TeV. Solid [dashed] lines represent case (a) [case (b)].

have also discussed, but differently, $\tilde\eta_t$ production with large widths.

Let us concentrate on the production of the S-wave $\tilde\eta_t(0^{++})$ in high energy pp collisions. We confine the discussion to the minimal supersymmetric model (MSSM). The dominant production process is gluon-gluon fusion because of the predominantly large gluon luminosity in multi-TeV energy regions. The production rate through the process $pp\to gg\to\tilde\eta_t$ is calculated by [10]

$$\sigma(pp\to gg\to\tilde\eta_t)=\int dM^2\frac{\pi^2\tau}{8M^3_{\tilde\eta_t}}\Gamma(\tilde\eta_t\to gg)R(\tau,Q^2)\frac{1}{\pi}\times\frac{M_{\tilde\eta_t}\Gamma_{\rm tot}(\tilde\eta_t)}{(M^2-M^2_{\tilde\eta_t})^2+M^2_{\tilde\eta_t}\Gamma^2_{\rm tot}(\tilde\eta_t)}\,,\qquad(1)$$

where $Q^2=M^2_{\tilde\eta_t}/4$ and $\tau=M^2_{\tilde\eta_t}/s$ with incident energy $\sqrt{s}$. $R(\tau,Q^2)$ is given as

$$R(\tau,Q^2)=\int_\tau^1\frac{dx}{x}g(x,Q^2)g(\tau/x,Q^2)\,,\qquad(2)$$

where we take the gluon distribution functions $g(x,Q^2)$ of the Duke-Owens parametrization (set 1) [11]. Although use of the Breit-Wigner formula in Eq. (1) might be misleading in the large width case where the bound states cannot be separately resolved [12,13], we believe that our analysis here is still reasonable as the first approximation since the decay width [here, at most 400 MeV even for case (b)] remains smaller than the splitting (typically, $\alpha_s^2 m_{\tilde t}\simeq 1$ GeV in the present case). By assuming typically $m_{\tilde t}$ to be larger than m_W and m_Z, the decay processes considered here are $\tilde\eta_t\to W^+W^-$, ZZ, gg, $\gamma\gamma$, $Z\gamma$, and $q\bar q$ [14]. All these decay widths are proportional to the wave function at the origin of $\tilde\eta_t$ which is estimated as $|\Psi(0)|^2=(\alpha_s M_{\tilde\eta_t}/3)^3/\pi$, by assuming a Coulomb-type potential via gluon exchange. In the present work, α_s is estimated to be $\alpha_s=4\pi/[7\ln(m^2_{\tilde t}/\Lambda^2)]$ with $\Lambda=0.12$ GeV and the scalar bottom mass is assumed tentatively as $m_{\tilde b}=m_{\tilde t}+180$ GeV. Branching ratios of $\tilde\eta_t\to gg$, W^+W^-, and ZZ are calculated for both cases (a) and (b) and presented in Fig. 1. While $B(\tilde\eta_t\to W^+W^-)$ is considerably larger for case (a), it is significantly small for case (b) owing to the large contribution of $\tilde t\to b+\tilde W$. Calculated cross sections for the process $pp\to gg\to\tilde\eta_t\to W^+W^-$ are shown in Fig. 2. The invariant mass distributions for the final W^+W^- system are calculated for $m_{\tilde t}=130$, 140, and 150 GeV for the typical example of $m_t=150$ GeV and presented in Fig. 3 for $\sqrt{s}=40$ TeV, where the detector resolution ($=1$ GeV) is taken into account for case (a). In case (b) the resonance becomes broader owing to $\tilde t\to b+\tilde W$. In this figure, the invariant mass distribution for toponium $\eta_t(0^{-+})$ productions is also presented: The large width for η_t productions is mainly due to the single top decay width $\Gamma(\eta_t(0^{-+})\to\bar t bW^+$ or $t\bar bW^-)$ [15]. (Note that finding η_t, in practice, might be difficult for a very heavy top quark with its large width [16].)

Now, how can one identify the signals of $\tilde\eta_t\to W^+W^-$? The background comes from QCD hard 2-gluon productions leading to back-to-back 2 jets+2 jets events and QCD WW productions leading to 2 jets/$l\bar\nu+\bar l\nu$. Since the 4-jet cross section is much larger than that of the signals, we cannot find the signals in these

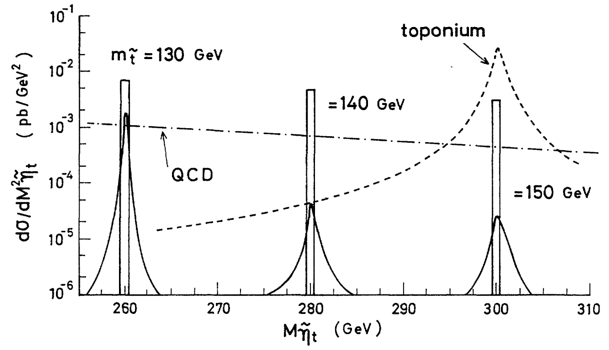

FIG. 3. $\tilde{\eta}_t$ mass dependence of the production cross section for $pp \to gg \to \tilde{\eta}_t \to W^+W^-$ for $m_{\tilde{t}}=130$, 140, and 150 GeV with $m_t=150$ GeV at $\sqrt{s}=40$ TeV. The rectangle represents case (a) where the detector resolution ($=1$ GeV) is taken into account. The broader resonance represents case (b). The dashed line shows η_t resonance coming from $pp \to gg \to \eta_t \to W^+W^-$ with $m_t=150$ GeV. The dot-dashed line denotes the QCD background for $pp \to W^+W^-$.

events. One possibility is to find the events of $l\bar{\nu}+\bar{l}\nu$ and/or 2 jets$+l\bar{\nu}$, though it might be rather difficult to reconstruct the W momentum correctly from the events with missing energy. The background cross section, $pp \to W^+W^-$+anything, has been calculated by many people [17]. Here we present it in Fig. 3, where we see some excess due to $\tilde{\eta}_t$ productions over the background in some kinematical region of $m_{\tilde{t}}$. In practice, whether η_t production can be observed in experiment depends on its width and the detector resolution. Although in the case with large widths and poor resolution limits we expect not sharp resonance peaks but an overall enhancement of the WW production cross section, the present calculation suggests that this enhancement could be observable for rather smaller $m_{\tilde{t}}$. Now, it is interesting to examine the prediction of the present scenario in the current Fermilab Tevatron experiment. However, unfortunately the Tevatron cannot find such a bound state since the cross section for $\tilde{\eta}_t$ productions is too small, i.e., $\sim 7.1\times 10^{-4}$ pb [case (a)] and $\sim 1.1\times 10^{-5}$ pb [case (b)] for WW channels at $\sqrt{s}=1$ TeV with $m_{\tilde{t}}=130$ GeV.

So far we have neglected the Higgs-boson interactions, which means that we have assumed the Higgs boson to be too heavy to be produced from $\tilde{\eta}_t$ decays. If the Higgs boson is lighter than $\tilde{t}$, say about 100 GeV, then we must take the Higgs-boson interactions into account. (MSSM has two neutral scalar Higgs bosons. Here we assume only the lighter one H is around 100 GeV.) For very heavy quark bound states, the Higgs-boson exchange can dominate over the gluon exchange and its interesting physics implications have been discussed in the literature [18].

Here we focus only on what physical effects will be induced to $\tilde{\eta}_t$ productions by switching on the Higgs-boson interactions. The coupling constant between $\tilde{t}$ and Higgs bosons contains the term proportional to the top quark mass together with Higgs boson's mixing angles and it has room to be large for some kinematical regions. In these regions the Higgs-boson interactions can enhance the $\tilde{\eta}_t$ wave functions at the origin and hence increase the cross sections for $\tilde{\eta}_t$ productions. In addition, the branching ratios of $\tilde{\eta}_t$ decays are altered: By assuming $m_H=100$ GeV, $m_{\tilde{t}}=130$ GeV, and $m_t=150$ GeV, those of $\tilde{\eta}_t \to HH$, W^+W^-, ZZ, and gg turn out to be 0.598 (0.038), 0.257 (0.016), 0.013 (0.001), and 0.131 (0.008) for case (a) (case (b)), respectively. Calculated cross sections for $pp \to gg \to \tilde{\eta}_t \to HH$ are presented in Fig. 4, where the ratio of two vacuum expectation values is assumed to be $\tan\beta \equiv v_2/v_1 = m_t/m_b$ and the mixing angle between two neutral Higgs bosons to be $\alpha=\pi/2$, as a typical example. A large number of events for two Higgs productions can be obtained: For example, $\sim 2.0\times 10^5$ events [case (a)], $\sim 1.3\times 10^4$ events [case (b)] for $M_{\tilde{\eta}_t}=260$ GeV with $m_t=150$ GeV if the integrated luminosity $\mathcal{L}=10^{40}$ cm^2. Since the 4-jet QCD cross section is again much larger than that of the signals, $\tilde{\eta}_t \to HH$, one should identify the signals by detecting final states with back-to-back two τ pairs and/or 2 jets$+\tau\bar{\tau}$. Then the QCD background is $pp \to ZZ$ alone. Its cross section is around 15 pb for $M_{ZZ}=260$ GeV at $\sqrt{s}=40$ TeV [17], which lies between case (a) and case (b). However, smaller values of $\tan\beta$ and m_H increase the signal's cross section even more. Moreover, there is no background from $\eta_t(0^{-+})$ decays because $\eta_t(0^{-+}) \to HH$ is forbidden by parity conservation. Therefore, the process pp

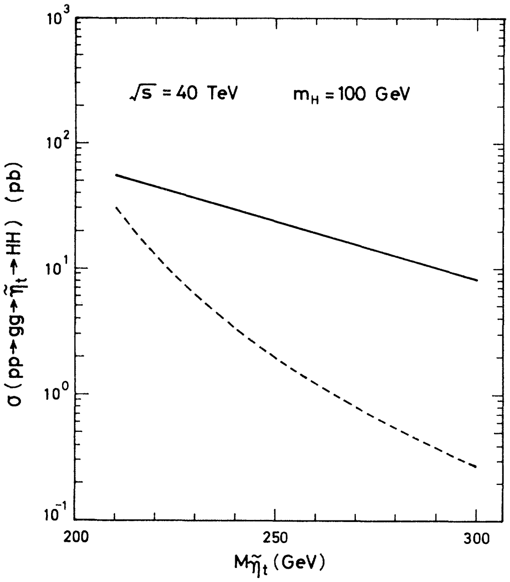

FIG. 4. $M_{\tilde{\eta}_t}$ dependence of $\sigma(pp \to gg \to \tilde{\eta}_t \to HH)$ for $m_t=150$ GeV, and $m_H=100$ GeV at $\sqrt{s}=40$ TeV. Solid [dashed] line represents case (a) [case (b)].

$\rightarrow gg \rightarrow \tilde{\eta}_t \rightarrow HH$ is quite promising if m_H lies in adequate regions.

The present analysis suggests that one might have a good chance to catch evidence of SUSY by detecting $\tilde{\eta}_t$ production at supercolliders if the present scenario really works. One could find the $\tilde{\eta}_t(0^{++})$ resonance together with the $\eta_t(0^{-+})$ resonance in WW channels (in practice, there might be two possible enhancements of the WW production cross sections due to the $\tilde{\eta}_t$ and η_t productions) or identify the $\tilde{\eta}_t(0^{++})$ production with its subsequent decay $\tilde{\eta}_t \rightarrow HH$. Conversely, if one could never find such $\tilde{\eta}_t$ production experimentally, it might be suggested that the present scenario does not work even for the top flavor.

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