Search for supersymmetric mesinos near production threshold in terms of superflavor symmetry *

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Abstract: Supersymmetry (SUSY) may be one of the most favored extensions of the Standard Model (SM), but so far at the LHC no evidence of SUSY particles has been observed. An obvious question is whether they have already emerged but escaped our detection, or whether they do not exist at all. We propose that the future ILC may provide sufficient energy and luminosity to produce SUSY particles as long as they are not too heavy. Superflavor symmetry associates production rates of SUSY mesinos with those of regular mesons, because both contain a heavy constituent and a light one. In this work, we estimate the production rate of SUSY mesinos near their production threshold and compare it with $\mathrm{B\bar{B}}$ production. Our analysis indicates that if SUSY mesinos with masses below $\sqrt{s}/2$ ($\sqrt{s}$ is the ILC energy) exist, they could be observed at the future ILC or even the proposed CEPC in China.

Key words: SUSY, ILC, superflavor symmetry, mesino

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1 Introduction

As is well known, one of the most important goals of high energy physics research is to look for new physics beyond the Standard Model (BSM). Supersymmetry (SUSY) may be the most favorable extension of the Standard Model (SM) because it can reasonably explain the naturalness problem of the Higgs and provide a dark matter candidate. Moreover, its existence makes the strong, electromagnetic and weak interactions merge into one point at the grand unification scale [1]. However, so far, no SUSY particles have ever been observed at the Tevatron or LHC. One may wonder if the SUSY model is wrong or should be radically modified. Of course, there is one more possibility, which is that the SUSY particles have indeed been produced, but have not been identified, being buried in the messy background at hadron colliders. Some authors, for example the authors of [2–5], have noticed this possibility and have tried to reanalyze the LHC data and indicate the probability of misidentifying the SUSY particles.

In the minimal supersymmetric standard model (MSSM) and the modified SUSY models, the scalar top quark has two mass eigenstates, $\tilde{\mathrm{t}}_1$ and $\tilde{\mathrm{t}}_2$, and the lighter one ($\tilde{\mathrm{t}}_1$) is assumed to be the lightest squark. Generally, it is believed that the lightest supersymmetric particle (LSP) is the colorless neutralino $\tilde{\chi}_1^0$. The present results of the CMS and ATLAS Collaborations in searches for the scalar top quark can be found in Refs. [6, 7], and it is noted that there is still the possibility of a stop with a mass of a few hundreds of GeV, e.g. there are windows: $m(\tilde{\mathrm{t}}_1)>200$ GeV with $m(\tilde{\mathrm{t}}_1)-m(\tilde{\chi}_1^0)<m(\mathrm{W})$, and a heavier stop as $m(\mathrm{W})<m(\tilde{\mathrm{t}}_1)-m(\tilde{\chi}_1^0)<m(\mathrm{t})$. The literature suggests that considering the 125 GeV Higgs boson observed at LHC, a sub-TeV stop could be allowed by the data [8, 9].

It is also widely recognized that a hadron collider is a machine for discovery, whereas an electron-positron collider is for precise measurement and unambiguous confirmation of discoveries. As long as the SUSY theory or its modified versions are valid and the stop mass is within the energy ranges of LHC and ILC, stop pairs should be produced at those machines. At the hadron colliders, the signals of the produced SUSY particles might be buried in the messy background, so one may turn to the electron-positron collider to search for evidence of their existence.

In the literature, it is suggested that the squark $\tilde{\mathrm{t}}_1$ is the next-to-lightest supersymmetric particle (NLSP). If the mass of $\tilde{\mathrm{t}}_1$ is not far away from that of the LSP,

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its lifetime could be longer than $1/\Lambda_{\rm QCD}$ [10–15], and it can attract a SM quark(anti-quark) to form a color singlet SUSY hadron [15–19]: the production of mesinos. The decay width of $\tilde{\rm t}_1$ has been calculated by several authors and it is found that it could hadronize before decaying [20, 21]. For SUSY mesinos consisting of $\tilde{\rm t}_1$ and a heavy anti-quark $\bar{\rm Q}$(Q=c, b), the fragmentation functions are calculable through perturbative QCD, and they have been studied by Chang et al. [22]. In their scheme, to reliably determine the initial conditions for the evolution differential equation, the SM quark must be heavy so that perturbative QCD can apply. Obviously, the production rate for such processes is much suppressed, whereas if the SM constituent quark is light (u, d, s), the production rate might be greatly enhanced. Unfortunately, however, non-perturbative QCD effects would then be dominant, so the perturbative computation becomes unreliable. An alternative method for evaluating the production rate of such mesinos is needed.

In this work, we focus on the production rate of a SUSY mesino which consists of a heavy scalar quark and a light SM antiquark at $\rm e^+e^-$ colliders. The production rates of a pair of SUSY squark-anti-squarks at electron-positron colliders have been well calculated at the tree-level and loop-level (see, e.g. [20, 23, 24]), thus the key point is how to calculate the hadronic matrix elements, which are fully governed by non-perturbative QCD. Obviously, to directly evaluate the relevant hadronic matrix elements one needs to invoke concrete models. The production of a B-meson, which has a similar structure to a mesino, has been well measured near its threshold by the CLEO [25], Belle [26], and BaBar [27] collaborations. Therefore, the production rates of B-mesons and SUSY mesinos which may be obtained at ILC near their thresholds can be naturally associated by means of the superflavor symmetry [28] via sharing the same Isgur-Wise function. For the meson case the heavy constituent is a heavy quark(anti-quark) of a color-triplet(anti-triplet) fermion b($\bar{\rm b}$) or c($\bar{\rm c}$), whereas for the SUSY mesino case the heavy constituent is a color-triplet(anti-triplet) scalar.

In the ILC technical design report (volume II) [29], the stop-quark $\tilde{\rm t}_1$ is expected to be found as long as $m_{\tilde{\rm t}_1} \leqslant \sqrt{s}/2$. In its early stage, the ILC will be running at $\sqrt{s} = 500$ GeV with luminosity 500 fb^{-1}. At this stage, the $\tilde{\rm t}_1$ mass could be determined to 1 GeV and even 0.5 GeV accuracy [29, 30]. Its center of mass energy will then be upgraded to 1 TeV with luminosity 1000 fb^{-1}. At that energy scale, a SUSY particle with mass less than 0.5 TeV could be found, and if considering possible R-violation, even heavier SUSY particles might be observed.

This work is organized as follows: in Section 2, we formulate the cross sections for productions of SUSY mesino $\tilde{\rm X}$ and heavy SM meson B in terms of superflavor symmetry. In Section 3, we present our numerical results along with all input parameters, and we especially show that mesino production could be associated with B-meson production at B-factories. The last section is devoted to our conclusion and some discussions.

2 Superflavor symmetry and SUSY mesino production

2.1 Superflavor symmetry and its application

Let us first have a brief review of superflavor symmetry, and then focus on its application. Georgi and Wise extended the scenarios of heavy quark spin and flavor symmetry and introduced superflavor symmetry [28]. Superflavor symmetry relates the processes involving a heavy meson made of a heavy quark $\rm h_v^+$ and a light anti-quark to a heavy fermion (mesino) made of a color triplet scalar χ_v (here we suppose it to be a squark) and a light color-anti-triplet anti-quark. The Lagrangian of the heavy triplets with velocity v is [28]

$$\mathscr{L}_v=\frac{1}{2}{\rm i}(\bar{h}_v^+ v_\mu \overleftrightarrow{D}^\mu h_v^+ + 2m_\chi \chi_v^\dagger v_\mu \overleftrightarrow{D}^\mu \chi_v). \tag{1}$$

Putting $\rm h_v^+$ and χ_v together into a 5-column vector with a given velocity v, one has

$$\Psi_v=\begin{pmatrix} h_v^+ \\ \chi_v \end{pmatrix}. \tag{2}$$

Here one can write the wavefunctions of the meson and mesino consisting of $\rm h_v$ and χ_v as

$$\Psi_{\rm H}(v)=\begin{pmatrix} \sqrt{m_{\rm h}}\gamma_5\frac{1}{2}(1-\not{v}) \\ 0 \end{pmatrix} \tag{3}$$

and

$$\Psi_{\rm X}(v)=\begin{pmatrix} 0 \\ \dfrac{u^{\rm T}C}{\sqrt{2m_\chi}} \end{pmatrix}, \tag{4}$$

where C is the charge conjugation operator and u is the spinor wave function of the χ bound state.

In the heavy quark effective theory (HQET) [31–33], for the transition of $\rm b \to c$, gluons (or photons) are exchanged at the t-channel and the hadronic transition matrix element can be described by a unique Isgur-Wise function $\xi(\omega)$ where $\omega = v\cdot v'$ is the recoil variable and v, v' are the four-velocities of the initial and final heavy hadrons. For the production process, the gluon, photon or $\rm Z_0$ (see in the following) is exchanged at the s-channel and the kinematic region is different as $v \to -v$ [34]. We need to generalize the Isgur-Wise function to the kinematic region of production, and some discussion about this situation was given in Ref. [34].

From the matrix elements of meson and mesino given by Georgi and Wise [28], the corresponding forms at pair production are

$$\langle H(v')\bar{H}(v)|J'^{\mu}|0\rangle=\langle H(v')\bar{H}(v)|\bar{h}\gamma^{\mu}h|0\rangle$$
$$=\xi(-v\cdot v')m_h(v'-v)^{\mu}, \tag{5}$$
$$\langle X(v')\bar{X}(v)|J^{\mu}|0\rangle=\langle X(v')\bar{X}(v)|\mathrm{i}\chi^{\dagger}\overleftrightarrow{\partial}^{\mu}\chi|0\rangle$$
$$=\xi(-v\cdot v')\frac{1}{2}(v'-v)^{\mu}\bar{u}'v, \tag{6}$$

where $\xi(-v\cdot v')$ is the Isgur-Wise function, and $\xi(1)=1$ at zero recoil point is the normalization condition.

It is natural to apply superflavor symmetry to SUSY hadron production. In the heavy flavor mass limit, in high energy collisions, $\mathrm{b\bar{b}}$ or stop pairs are produced, and then b and $\mathrm{\bar{b}}$ or $\tilde{\mathrm{t}}_1$ and $\bar{\tilde{\mathrm{t}}}_1$ hadronize into bound states by attracting antiquarks(quarks) from the vacuum. The two different processes ($\mathrm{b}\to$hadron and $\tilde{\mathrm{t}}_1\to$ SUSY hadron) are naturally associated by superflavor symmetry. Obviously, a heavy quark fragmenting into a double heavy flavor meson (for example $\mathrm{b}\to\bar{\mathrm{B}}_{\mathrm{c}}(\mathrm{b\bar{c}})$) is more suppressed compared with a single heavy meson (for example $\mathrm{b}\to\bar{\mathrm{B}}_{\mathrm{d}}(\mathrm{b\bar{d}})$) by a factor of $10^{-4}\sim10^{-3}$ [35–40]. The case of SUSY hadron production is similar, i.e. production of mesino $\tilde{\mathrm{t}}_1\bar{\mathrm{b}}(\bar{\mathrm{c}})$ is more suppressed than $\tilde{\mathrm{t}}_1\bar{\mathrm{q}}$(q=u, d, s).

A theoretical estimate shows that so-called stoponium can be formed, and the binding energy is about 1–3 GeV [41], which is much smaller than the mass of the stop and does not affect the phase space of the production.

Next we calculate the production rate of $\mathrm{e^+e^-}\to\tilde{\mathrm{X}}\bar{\tilde{\mathrm{X}}}$ near its threshold at ILC, whose low background makes it more advantageous than hadron colliders.

2.2 Estimating the SUSY mesino production rate

We now calculate the production rates of the mesino and B-meson near their thresholds in the same theoretical framework.

Below we will derive the transition amplitudes and cross sections for the processes $\mathrm{e^+e^-}$ to $\mathrm{B\bar{B}}$ and $\tilde{\mathrm{X}}\bar{\tilde{\mathrm{X}}}$, where B and $\tilde{\mathrm{X}}$ denote the meson and mesino respectively. For the process $\mathrm{e^+e^-}\to\mathrm{B\bar{B}}$ at B factories, the collision energy $\sqrt{s}$ is much less than the mass of the $\mathrm{Z_0}$, thus the $\mathrm{Z_0}$ contribution can be safely ignored. By contrast, since in the process $\mathrm{e^+e^-}\to\tilde{\mathrm{X}}\bar{\tilde{\mathrm{X}}}$, $\sqrt{s}$ is larger than the mass of the $\mathrm{Z_0}$, the $\mathrm{Z_0}$ contribution must be included. The differential cross section for the B-meson is

$$\mathrm{d}\sigma(\mathrm{B\bar{B}}) = \frac{1}{8s_1}\sum_{s_{\mathrm{i}},s_{\mathrm{f}}}\Big|\frac{-\mathrm{i}}{3}e\langle B\bar{B}|\bar{b}\gamma^{\mu}b|0\rangle \times\frac{1}{s_1}\langle0|\bar{e}(-\mathrm{i}e)\gamma_{\mu}e|\mathrm{e^+e^-}\rangle\Big|^2\mathrm{d}\tilde{v}, \tag{7}$$

where only the photon contribution is taken into account, and for the mesino it is

$$\mathrm{d}\sigma(\tilde{\mathrm{X}}\bar{\tilde{\mathrm{X}}}) = \frac{1}{8s_2}\sum_{s_{\mathrm{i}},s_{\mathrm{f}}}\Big|\frac{2\mathrm{i}}{3}e\langle\tilde{X}\bar{\tilde{X}}|\tilde{t}_1^{\dagger}\overleftrightarrow{\partial}^{\mu}\tilde{t}_1|0\rangle \times\frac{1}{s_2}\langle0|\bar{e}(-\mathrm{i}e)\gamma_{\mu}e|\mathrm{e^+e^-}\rangle+g_{\mathrm{tz}}\langle\tilde{X}\bar{\tilde{X}}|\tilde{t}_1^{\dagger}\overleftrightarrow{\partial}^{\mu}\tilde{t}_1|0\rangle \times\frac{1}{s_2-m_{\mathrm{Z}}^2}\langle0|\bar{e}\gamma_{\mu}g_{\mathrm{ez}}e|\mathrm{e^+e^-}\rangle\Big|^2\mathrm{d}\tilde{v}, \tag{8}$$

where

$$g_{\mathrm{tz}}=\frac{\mathrm{i}e}{\sin\theta_{\mathrm{w}}\cos\theta_{\mathrm{w}}}\left(\frac{1}{2}\cos^2\theta_{\mathrm{t}}-\frac{2}{3}\sin^2\theta_{\mathrm{w}}\right)$$

is the coupling constant between the stop and $\mathrm{Z_0}$ boson, θ_{t} in g_{tz} is the stop mixing angle [10], θ_{w} is the Weinberg angle,

$$g_{\mathrm{ez}}=\frac{-\mathrm{i}e}{\sin\theta_{\mathrm{w}}\cos\theta_{\mathrm{w}}}\left(\frac{1-\gamma_5}{4}-\sin^2\theta_{\mathrm{w}}\right)$$

is the coupling constant between electron and $\mathrm{Z_0}$ boson, $\sqrt{s_1}$ is the center of mass energy of the B factory and $\sqrt{s_2}$ is the center of mass energy of the ILC. Here s_{i} is the spin projections of the electron and positron in the initial state and s_{f} is the spin projections of the produced B mesons or SUSY mesinos in the final state, with $\mathrm{d}\tilde{v}$ being the corresponding final state phase space.

Figure 1 and Fig. 2 show the leading order Feynman diagrams for the processes $\mathrm{e^+e^-}\to\mathrm{B\bar{B}}$ and $\mathrm{e^+e^-}\to\tilde{\mathrm{X}}\bar{\tilde{\mathrm{X}}}$ respectively. The transition amplitudes for mesons are

$$\mathrm{i}\mathcal{M}_{\mathrm{B}}=\xi(-\omega)\left(-\mathrm{i}\frac{1}{3}e(p_2-p_1)_{\mu}\right)\frac{-\mathrm{i}}{s_1}\bar{v}(k_2)(-\mathrm{i}e\gamma^{\mu})u(k_1), \tag{9}$$

and for mesinos are

$$\mathrm{i}\mathcal{M}_{\tilde{\mathrm{X}}} = \xi(-\omega)[\bar{u}(p_2)\mathrm{i}\frac{2}{3}e\frac{(p_2-p_1)_{\mu}}{2m_{\tilde{\mathrm{t}}_1}}v(p_1) \times\frac{-\mathrm{i}}{s_2}\bar{v}(k_2)(-\mathrm{i}e\gamma^{\mu})u(k_1) +\bar{u}(p_2)g_{\mathrm{tz}}\frac{(p_2-p_1)_{\mu}}{2m_{\tilde{\mathrm{t}}_1}}v(p_1) \times\frac{-\mathrm{i}}{s_2-m_{\mathrm{Z}}^2}\bar{v}(k_2)\gamma_{\mu}g_{\mathrm{ez}}u(k_1)]. \tag{10}$$

Here $\omega=v\cdot v'=\frac{s}{2m^2}-1$, k_1 and k_2 are the momenta of the incoming electron and positron, and p_1 and p_2 are the momenta of the outgoing anti-hadron and hadron. It is noted that the hadronic matrix elements are determined according to the superflavor symmetry as shown in Eqs. (5) and (6). Thus we obtain the cross section for pair production as

$$\sigma = \frac{1}{2s}\int\frac{\mathrm{d}^3p_1}{(2\pi)^3}\frac{1}{2E_1}\frac{\mathrm{d}^3p_2}{(2\pi)^3}\frac{1}{2E_2} \times(2\pi)^4\delta^4(p_1+p_2-k_1-k_2)\frac{1}{4}\sum_{\mathrm{spin}}|\mathcal{M}|^2. \tag{11}$$

The final expression includes the Isgur-Wise function $|\xi(-\omega)|^2$, which determines the hadronic matrix elements and manifests the non-perturbative QCD effects in the hadronization. As mentioned above, we cannot use the data to fix the parameters, so generally we will obtain the values of the Isgur-Wise function for certain ω by employing some phenomenological models.

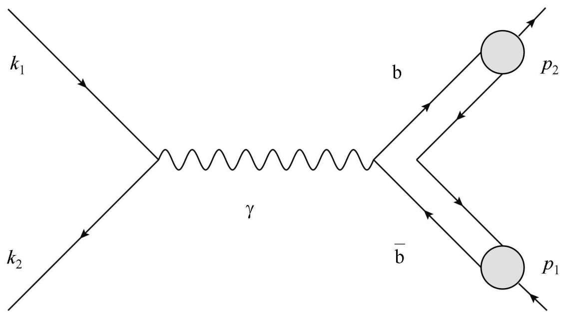

Fig. 1. The process of $e^+e^-\to B\bar{B}$.

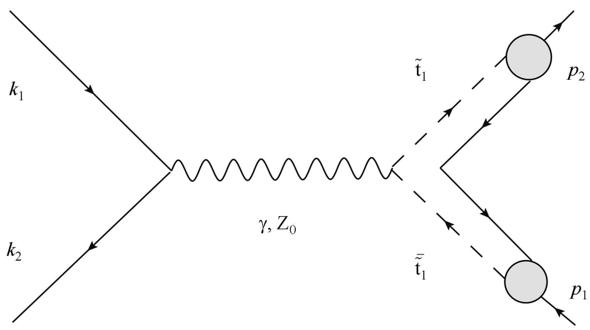

Fig. 2. The process of $e^+e^-\to\tilde{X}\bar{\tilde{X}}$.

3 Numerical analysis

So far, the collider experiments including the Tevatron and LHC have not yet set stringent constraints on $m_{\tilde{t}_1}$ [42, 43], and we assume $m_{\tilde{t}_1}$ varying from 200 GeV to 500 GeV.

In our numerical calculation, $m_B=5.3$ GeV, $m_{\tilde{t}_1}=$ 210–250 GeV is taken for $\sqrt{s}=500$ GeV and $m_{\tilde{t}_1}$=420–500 GeV for $\sqrt{s}$=1 TeV respectively. The running Weinberg angle $\sin^2\theta_w$ is taken as $\sin^2\theta_w=0.2398$ for $\sqrt{s}=500$ GeV and $\sin^2\theta_w=0.2444$ for $\sqrt{s}=1$ TeV, α_e is approximately equal to $\alpha_e(m_Z)=1/128.78$, the range of mixing angle θ_t is uncertain and generally can span in a rather wide range of 0–π. Following Ref. [10], in our computation we take a few special values of $\cos^2\theta_t$ as 0, 1/2 and 1. Our results obviously depend on the concrete value of $|\xi(-\omega)|^2$. We need to extrapolate $\xi(\omega)$ from a transition region into the annihilation region as $\omega\to-\omega$, and we can write the Isgur-Wise function as

$$\xi(-\omega)=1-\rho^2(|\omega|-1)+c(|\omega|-1)^2+\cdots, \tag{12}$$

where the parameters ρ and c are calculated in lattice QCD [44].

Many authors have calculated the numerical value $\xi(\omega)$ in different ways [45–49]. In their works, $\xi(\omega)<1$ when $\omega>1$, and all of their results show that $\xi(1.2)\approx0.8$, $\xi(1.4)\approx0.65$, $\xi(1.6)\approx0.55$ and $\xi(1.8)\approx0.5$ for the processes $B\to D$ [45–49]. A brief discussion about the numerical value of the $|\xi(-\omega)|^2$ will be given in the next section. In Tables 1 and 2, we list the production rates of the SUSY mesinos for various ω-values.

In Tables 1 and 2 we show the numerical values of the cross sections in the range of $m_{\tilde{t}_1}$=250–210 GeV and $m_{\tilde{t}_1}$=500–420 GeV corresponding to ω varying from 1 to 1.83 at the center of mass energy $\sqrt{s}=500$ GeV and $\sqrt{s}=1$ TeV respectively. Table 3 gives the results of $\sigma(e^+e^-\to B\bar{B})$ with the same ω values as those in Tables 1, 2.

Table 1. The cross sections of $\sigma(e^+e^-\to\tilde{X}\bar{\tilde{X}})$ with the center of mass energy $\sqrt{s}$=500 GeV.

ω	1.00	1.17	1.36	1.58	1.83
$m_{\tilde{t}_1}$/GeV	250	240	230	220	210
$\sigma^{\text{expected}}(e^+e^-\to\tilde{X}\bar{\tilde{X}})$/fb ($\cos^2\theta_t$=0)	0	0.34	1.33	2.73	4.77
$\sigma^{\text{expected}}(e^+e^-\to\tilde{X}\bar{\tilde{X}})$/fb ($\cos^2\theta_t$=1/2)	0	0.33	1.28	2.64	4.61
$\sigma^{\text{expected}}(e^+e^-\to\tilde{X}\bar{\tilde{X}})$/fb ($\cos^2\theta_t$=1)	0	0.50	1.93	3.97	6.94

Table 2. The cross section of $\sigma(e^+e^-\to\tilde{X}\bar{\tilde{X}})$ with the center of mass energy $\sqrt{s}$=1 TeV.

ω	1.00	1.17	1.36	1.58	1.83
$m_{\tilde{t}_1}$/GeV	500	480	460	440	420
$\sigma^{\text{expected}}(e^+e^-\to\tilde{X}\bar{\tilde{X}})$/fb ($\cos^2\theta_t$=0)	0	0.08	0.34	0.69	1.21
$\sigma^{\text{expected}}(e^+e^-\to\tilde{X}\bar{\tilde{X}})$/fb ($\cos^2\theta_t$=1/2)	0	0.08	0.32	0.65	1.14
$\sigma^{\text{expected}}(e^+e^-\to\tilde{X}\bar{\tilde{X}})$/fb ($\cos^2\theta_t$=1)	0	0.12	0.46	0.95	1.66

In Tables 4 and 5 we also list the cross sections of the process $e^+e^-\to\tilde{t}_1\bar{\tilde{t}}_1$ with $m_{\tilde{t}_1}$ varying in the ranges 250–210 GeV and 500–420 GeV. The authors of Ref. [20] calculated the cross section and gave its dependence on the CM energy of the ILC, while assuming $m_{\tilde{t}_1}$ to be 200 GeV and 420 GeV respectively. Our results are generally consistent with theirs. From the data above we can find that the ratio of a scalar top quark pair transiting into a SUSY mesino pair is about 10%–20%.

Table 3. The cross section of $\sigma(e^+e^-\to B\bar{B})$ for the CM energy $\sqrt{s}$ of the B-factories.

ω	1.00	1.17	1.36	1.58	1.83
$\sqrt{s}$/GeV	10.60	11.04	11.52	12.04	12.62
$\sigma(e^+e^-\to B\bar{B})$/pb	0	0.94	1.58	1.84	2.06

Table 4. The cross section of $\sigma(e^+e^-\to\tilde{t}_1\bar{\tilde{t}}_1)$ with the center of mass energy $\sqrt{s}$=500 GeV.

ω	1.00	1.17	1.36	1.58	1.83
$m_{\tilde{t}_1}$/GeV	250	240	230	220	210
$\sigma^{\rm theor}(e^+e^-\to\tilde{t}_1\bar{\tilde{t}}_1)$/fb ($\cos^2\theta_t=0$)	0	3.14	8.62	15.34	22.86
$\sigma^{\rm theor}(e^+e^-\to\tilde{t}_1\bar{\tilde{t}}_1)$/fb ($\cos^2\theta_t=1/2$)	0	3.04	8.33	14.84	22.12
$\sigma^{\rm theor}(e^+e^-\to\tilde{t}_1\bar{\tilde{t}}_1)$/fb ($\cos^2\theta_t=1$)	0	4.57	12.54	22.32	33.28

Table 5. The cross section of $\sigma(e^+e^-\to\tilde{t}_1\bar{\tilde{t}}_1)$ with the center of mass energy $\sqrt{s}$=1 TeV.

ω	1.00	1.17	1.36	1.58	1.83
$m_{\tilde{t}_1}$/GeV	500	480	460	440	420
$\sigma^{\rm theor}(e^+e^-\to\tilde{t}_1\bar{\tilde{t}}_1)$/fb($\cos^2\theta_t=0$)	0	0.79	2.18	3.87	5.77
$\sigma^{\rm theor}(e^+e^-\to\tilde{t}_1\bar{\tilde{t}}_1)$/fb ($\cos^2\theta_t=1/2$)	0	0.75	2.06	3.67	5.47
$\sigma^{\rm theor}(e^+e^-\to\tilde{t}_1\bar{\tilde{t}}_1)$/fb ($\cos^2\theta_t=1$)	0	1.09	2.99	5.32	7.94

4 Discussion and conclusions

With the help of superflavor symmetry, we evaluate the production rate of stop-mesino pairs and $B\bar{B}$ near their thresholds within the same theoretical framework. Thus the production rate of the SUSY mesino pair near its production threshold at the future ILC can be compared with the B-meson pair production rate at the B-factories. However, so far the experimental measurement of the continuum contribution to $B\bar{B}$ at the B-factories is not available because it is buried in large background corresponding to various resonances, so extraction of the continuum contribution is almost impossible.

Let us discuss it more explicitly. We intend to use the superflavor symmetry where the non-perturbative QCD effects are included in a unique Isgur-Wise function $\xi(|\omega|)$ to analyze the mesino production directly. Meanwhile in the same scheme, we also calculate the production rate of $B\bar{B}$ near its production threshold where the obtained rate is nothing but the continuum contribution to the process $e^+e^-\to B\bar{B}$; this is a by-product of this research. In other words, in the heavy flavor mass limit, the QCD contribution in heavy flavor hadron production is independent of the heavy flavor's mass and spin. When we adopt superflavor symmetry to estimate the production rate of SUSY mesinos, the B-meson production rate near its production threshold can be obtained simultaneously. Indeed, if there are data available for the $B\bar{B}$ production rate near the threshold, namely the rate directly coming from $e^+e^-\to B\bar{B}$, we can use the experimentally measured value to estimate the production rate of mesinos.

Indeed, we wish to use the data of the B-factory to predict the production rates as

$$\frac{\sigma^{\rm theor}(e^+e^-\to\tilde{X}\bar{\tilde{X}})}{\sigma(e^+e^-\to\tilde{X}\bar{\tilde{X}})}\sim\frac{\sigma^{\rm theor}(e^+e^-\to B\bar{B})}{\sigma^{\rm exp}(e^+e^-\to B\bar{B})}, \tag{13}$$

where the superscript "theor" means the theoretically predicted value, $\sigma^{\rm exp}(e^+e^-\to B\bar{B})$ is the measured value at B-factories and $\sigma(e^+e^-\to\tilde{X}\bar{\tilde{X}})$ is what we expect. The ratio of

$$\frac{\sigma^{\rm theor}(e^+e^-\to\tilde{X}\bar{\tilde{X}})}{\sigma^{\rm theor}(e^+e^-\to B\bar{B})}$$

can be obtained in terms of the superflavor symmetry, so that one can eventually obtain $\sigma(e^+e^-\to\tilde{X}\bar{\tilde{X}})$. In fact, by the superflavor symmetry we can relate the matrix element $\langle\tilde{X}\bar{\tilde{X}}|J^\mu|0\rangle$ to the matrix element $\langle B\bar{B}|J'^\mu|0\rangle$, where J^μ and J'^μ are vector currents corresponding to squark-anti-sqaurk and quark-anti-quark productions respectively.

Unfortunately, all the available data about B-meson productions are not exactly what we need, because they are from $e^+e^-\to\Upsilon(4s)/\Upsilon(5s)/\Upsilon(6s)\to B\bar{B}$, namely via the Υ resonances. Instead, we need data on the direct production of $e^+e^-\to B\bar{B}$, i.e the contribution of the continuum of the spectrum near the threshold. The total spectrum on R_b (defined as $R_b(s)=\sigma_b(s)/\sigma^0_{\mu\mu}(s)$)

provided by experimentalists [27], which is close to 0.3, cannot be used either[1)]. Indeed, we expect and hope that our experimental colleagues can figure out an elegant way to extract the continuum contribution from the data or directly measure it in the future (we believe that they will be able to do it!); then we will obtain more accurate numerical results of the mesino production rate near threshold, since in that case the theoretical uncertainties brought up by dealing with the non-perturbative QCD effects would be greatly reduced.

Therefore, even though the idea of directly using the data of $B\bar{B}$ production is suggestive, it is not practical at present. All we can do is to theoretically calculate the production rates for both $e^+e^- \to B\bar{B}$ and $e^+e^- \to \tilde{X}\bar{\tilde{X}}$. A by-product is that through the calculation, one can obtain the contribution of the continuum to the production of $e^+e^- \to B\bar{B}$, which is also needed by experimentalists. Once we observe the production of mesinos at e^+e^- colliders, the information can be applied to super B-factories and super charm-tau factories.

From Refs. [45–49] we can find that $\xi(\omega)$ decreases as ω increases, so when ω increases, the value of $|\xi(\omega)|^2$ is smaller than 1. Therefore, the real production rate of the mesino pair is slightly less than the value we list in Tables 1 and 2. On the other hand, the heavy quark/squark pair captures a light quark pair from a vacuum to form a meson/mesino pair. This means that as the velocity of the heavy quark/squark pair increases, the probability of capturing a light quark pair from the vacuum decreases.

The ILC is proposed to begin running in 10 years' time. Its early stage is designed to run at a center of mass energy of $\sqrt{s}$=500 GeV with yearly integrated luminosity 500 fb^{-1}, then the energy will be upgraded to 1 TeV with the integrated luminosity 1000 fb^{-1} [29]. In Table 6 and Table 7 we list the numbers of SUSY stop mesino pairs generated per year at ILC for $\sqrt{s}$=500 GeV and $\sqrt{s}$=1 TeV respectively.

Table 6. Number of events predicted in ILC with center of mass energy $\sqrt{s}$=500 GeV and yearly integrated luminosity 500 fb^{-1}.

ω	1.00	1.17	1.36	1.58	1.83
$m_{\tilde{t}_1}$/GeV	250	240	230	220	210
events	0	170	665	1365	2385
events	0	165	640	1320	2305
events	0	250	965	1985	3470

Even when we take the detection efficiency into account, there should still be a sufficiently large number of events to be observed.

Following suggestions given in the literature, we consider the scalar top quark $\tilde{t}_1$ as the NLSP, thus the mesino which consists of $\tilde{t}_1$ and a SM anti-quark has very distinctive characteristics. It is a fermion of baryon number zero, so it is completely different from the SM baryons. Moreover, as R-parity is conserved, the main decay mode of the stop is $\tilde{t}_1 \to \tilde{\chi}_1^0+$ SM quark (+others) where $\tilde{\chi}_1^0$ is the lightest SUSY particle (LSP): the neutralino. If the mass splitting between stop and neutralino is sufficiently small, the decay channel $\tilde{t}_1 \to \tilde{\chi}_1^0$+b+W$^{(*)}$ is restricted by the final state phase space. Another probable channel would be $\tilde{t}_1 \to \tilde{\chi}_1^0$+c(u), which occurs via loops, so it is suppressed. The main decay mode of the mesino is via the process where $\tilde{t}_1$ transits to $\tilde{\chi}_1^0$ by radiating a SM quark which later combines with the constituent anti-quark (as a spectator) in the mesino to constitute a SM meson (either pseudoscalar or vector). Thus the observable process is that of a fermion of $B=0$ transition to a SM meson plus missing energy. This signal is very clean and unique, so that from such a signal, one can immediately identify the SUSY mesino. Since the stop mesino can be charged ($\tilde{t}_1+\bar{d}$(or $\bar{s}$)), one would not miss its trajectory.

Table 7. Number of events predicted in ILC with center of mass energy $\sqrt{s}$=1 TeV and yearly integrated luminosity 1000 fb^{-1}.

ω	1.00	1.17	1.36	1.58	1.83
$m_{\tilde{t}_1}$/GeV	500	480	460	440	420
events	0	80	340	690	1210
events	0	80	320	650	1140
events	0	120	460	950	1660

Therefore we expect a stop mesino with a relatively long lifetime to be detected at the facilities which will be available in the near future. The authors of Ref. [41] also suggest that stoponium may be observed via its decay products $\gamma\gamma$ and ZZ at LHC in the following 14 TeV running. They should definitely be more easily observed at the ILC due to its clean background.

Our numerical computations depend on the Isgur-Wise function which manifests the non-perturbative QCD effects. Since the function is phenomenologically introduced it brings uncertainties into our numerical results. We expect that if the continuum contribution to $e^+e^- \to B\bar{B}$ could be extracted from the data or directly experimentally measured, we would be able to greatly reduce the theoretical uncertainties and help to draw a more definite conclusion.

It is also noted that the updated SUSY hadron search results given by the CMS [50] and ATLAS [51] Collaborations indicate that SUSY hadron lifetimes should be

1) For this point, we thank Dr. C. Z. Yuan of IHEP who told us that there are no such data about the continuum of the spectra available, and also that there is not an appropriate way to extract the continuum contribution from the data so far.

shorter than the μ's if they exist with sub-TeV masses. Indeed, if their lifetimes are too short, it is disadvantageous for their detection, but there is still a possibility of the direct detection of stop mesinos. We lay hope on the next run of LHC, which may provide information about the SUSY particles, and look forward to the future ILC, where the SUSY particles can be better identified. Moreover, the proposed CEPC (Circular Electron-Positron Collider) and the tera Z-factory in China could also be used in the search for mesinos.

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