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Probing top quark decay into light stop in the supersymmetric standard model at the upgraded Tevatron

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ABSTRACT

We investigate the possibility of observing the exotic decay mode of the top quark into the lightest stop ($\tilde{t}_1$) and neutralino ($\tilde{\chi}_1^0$) in the minimal supersymmetric standard model with R-parity at the upgraded Tevatron. First we determine the allowed range for the branching fraction $B(t \to \tilde{t}_1 \tilde{\chi}_1^0)$ in the region of parameter space allowed by the R_b data and the CDF $ee\gamma\gamma + \not{E}_T$ event, and then consider all possible backgrounds and investigate the possibility of observing this final state at the Tevatron. We find that this final state is unobservable at Run 1. However, Run 2 can provide significant information on this new decay mode of the top quark: either discover it, or establish a strong constraint on the masses of $\tilde{t}_1$ and $\tilde{\chi}_1^0$ given approximately by $M_{\tilde{\chi}_1^0} > M_{\tilde{t}_1} - 6$ GeV.

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1. Introduction

Because of its large mass, the top quark has the potential to be a sensitive probe for new physics. In strongly interacting theories, such as top condensation and extended technicolor, the top quark plays an essential role in the electroweak symmetry breaking and in the understanding of flavor physics. In weakly interacting theories, such as supersymmetry (SUSY) [1], the heavy top quark provides a solution to the electroweak symmetry breaking and makes it possible that the top quark may decay into its lightest superpartner [2] ($\tilde{t}_1$) plus the lightest neutralino ($\tilde{\chi}_1^0$). Assuming that $\tilde{t}_1$ decays dominantly into $c\tilde{\chi}_1^0$, this SUSY decay mode of the top quark will give rise to a new final state in $t\bar{t}$ production at the Fermilab Tevatron, $t\bar{t} \to Wbc\tilde{\chi}_1^0\tilde{\chi}_1^0$.

A careful study of this final state is well motivated since the presently allowed parameter space [3][4] of the minimal supersymmetric standard model (MSSM), implied by the $ee\gamma\gamma+\not{E}_T$ event at CDF [5] and the LEP R_b data , will allow the top quark to have this new decay mode $t \to \tilde{t}_1\tilde{\chi}_1^0$. It is also implied in this scenario that $M_{\tilde{t}_1} < M_{\tilde{\chi}_1^\pm}$ [3,4], where $\tilde{\chi}_1^\pm$ is the lightest chargino, so the decay $\tilde{t}_1 \to b\tilde{\chi}_1^+$ is not allowed. In the case that the $\tilde{t}_1$ is lighter than the next-to-lightest neutralino $\tilde{\chi}_2^0$, $\tilde{l}^\pm$ and $\tilde{\nu}$, the dominant decay of $\tilde{t}_1$ is $\tilde{t}_1 \to c\tilde{\chi}_1^0$ via one loop processes [6], with a branching fraction of almost 100% [3]. Therefore searching for this final state may be a powerful tool for probing SUSY at FNAL.

The possibility for detecting the $Wbc\tilde{\chi}_1^0\tilde{\chi}_1^0$ final state in $t\bar{t}$ production was first discussed in Ref. [7] where the focus was mainly on the background $t\bar{t} \to W^-W^+b\bar{b}$. In this article, in the framework of the MSSM with the lightest neutralino being the LSP, we will present a detailed analysis including all the possible backgrounds. In particular, we first determine the allowed range for $B(t \to \tilde{t}_1\tilde{\chi}_1^0)$ in the region of parameter space allowed by the R_b data and the $ee\gamma\gamma+\not{E}_T$ event at CDF, and then show what additional constraints can be imposed on the allowed parameter space if this final state is not observed at the Tevatron. We find a lower bound of 0.07 for $B(t \to \tilde{t}_1\tilde{\chi}_1^0)$ in the presently allowed parameter space [3][4], and, as a result, we find that Run 2 can either discover this new decay mode or provide an additional strong constraint given approximately by $M_{\tilde{\chi}_1^0} > M_{\tilde{t}_1} - 6$ GeV. However, our results show that even if $B(t \to \tilde{t}_1\tilde{\chi}_1^0)$ is as large as 0.5, it is unobservable at Run 1.

This paper is organized as follows. In Sec. 2 we examine the range of values for $B(t \to \tilde{t}_1\tilde{\chi}_1^0)$ in the region of parameter space allowed by the R_b data and the $ee\gamma\gamma+\not{E}_T$ event.

[2] Electroweak baryogenesis in SUSY requires a light stop to have a strong first order phase transition [2].
[3] The four-body decay mode $\tilde{t}_1 \to b\tilde{\chi}_1^0 f_1\bar{f}_2$ is kinematically suppressed by both $\tilde{\chi}_1^\pm-$ and $W^\pm-$ propagators and thus its partial width is negligibly small.

In Sec. 3 we examine all possible backgrounds and investigate the possibility of observing $t\bar{t} \to Wbc\tilde{\chi}_1^0\tilde{\chi}_1^0$ at the Tevatron. And finally in Sec. 4 we present a summary.

2. Bounds for $B(t \to \tilde{t}_1\tilde{\chi}_1^0)$

It was found that in order to explain all of the presently available low energy data the lightest mass eigenstate ($\tilde{t}_1$) of the stop squarks is likely to be the right-stop ($\tilde{t}_R$) with mass of the order of M_W [4]. So we assume $\tilde{t}_1 = \tilde{t}_R$ in our analyses. The interaction Lagrangian of top (t), stop($\tilde{t}_1$) and neutralino ($\tilde{\chi}_1^0$) is given by [8]

$$\mathcal{L}_{t\tilde{t}_1\tilde{\chi}_1^0} = -\sqrt{2}\bar{t}(AP_L + BP_R)\tilde{\chi}_1^0\tilde{t}_1 + H.c., \tag{1}$$

where $P_{L,R} = (1 \mp \gamma_5)/2$ and

$$A = -\frac{2}{3}e(N_{11}C_W + N_{12}S_W) + \frac{2}{3}\frac{gS_W^2}{C_W}(N_{12}C_W - N_{11}S_W), \tag{2}$$

$$B = -\frac{gM_tN_{14}}{2M_W \sin\beta}. \tag{3}$$

Here $S_W \equiv \sin\theta_W, C_W \equiv \cos\theta_W$, and N_{ij} are the elements of the 4×4 matrix N which diagonalizes the neutralino mass matrix [1]. The decay $t \to \tilde{t}_1\tilde{\chi}_1^0$ has been calculated to one-loop level in Refs. [9] and [10]. Here we neglect the loop corrections, which are only on the order of 10%; the partial width is given at tree level by

$$\begin{aligned}\Gamma(t \to \tilde{t}_1\tilde{\chi}_1^0) \;=\; & \frac{1}{16\pi M_t^3}\lambda^{1/2}(M_t^2, M_{\tilde{\chi}_1^0}^2, M_{\tilde{t}_1}^2)\left[(|A|^2 + |B|^2)(M_t^2 + M_{\tilde{\chi}_1^0}^2 - M_{\tilde{t}_1}^2)\right. \\ & \left. +4Re(A^*B)M_tM_{\tilde{\chi}_1^0}\right], \end{aligned}\tag{4}$$

where $\lambda(x,y,z) = (x-y-z)^2 - 4yz$.

The parameters involved in $\Gamma(t \to \tilde{t}_1\tilde{\chi}_1^0)$ are:

$$M_{\tilde{t}_1}, M_2, M_1, \mu, \tan\beta, \tag{5}$$

where M_2 and M_1 are gaugino masses corresponding to $SU(2)$ and $U(1)$, μ is the coefficient of the H_1H_2 mixing term in the superpotential, and $\tan\beta = v_2/v_1$ is the ratio of the vacuum expectation values of the two Higgs doublets. If the $ee\gamma\gamma + \not{E}_T$ event is due to $\tilde{e}_L$ pair production (depending on the scenario, the selectrons decay into either $e\tilde{\chi}_2^0$ or $e\tilde{\chi}_1^0$, followed by $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \gamma$ or $\tilde{\chi}_1^0 \to \tilde{G}\gamma$, respectively, where $\tilde{G}$ is the gravitino), the region of the parameter space allowed by both the $ee\gamma\gamma + \not{E}_T$ event and the R_b data are given as [3]

$$\begin{aligned} 50 \le M_1 \le 92 \text{ GeV}, &\quad 50 \le M_2 \le 105 \text{ GeV}, \\ 0.75 \le M_2/M_1 \le 1.6, &\quad -65 \le \mu \le -35 \text{ GeV}, \\ 0.5 \le |\mu|/M_1 \le 0.95, &\quad 1 \le \tan\beta \le 3, \\ 33 \le M_{\tilde{\chi}_1^0} \le 55 \text{ GeV}, &\quad 45 \le M_{\tilde{t}_1} \le 80 \text{ GeV}. \end{aligned} \tag{6}$$

If the $ee\gamma\gamma + \not{E}_T$ event is due to $\tilde{e}_R$ pair production, the allowed region is [3]

$$\begin{aligned} 60 \le M_1 \le 85 \text{ GeV}, &\quad 40 \le M_2 \le 85 \text{ GeV}, \\ 0.6 \le M_2/M_1 \le 1.15, &\quad -60 \le \mu \le -35 \text{ GeV}, \\ 0.5 \le |\mu|/M_1 \le 0.8, &\quad 1 \le \tan\beta \le 2.2, \\ 32 \le M_{\tilde{\chi}_1^0} \le 50 \text{ GeV}, &\quad 45 \le M_{\tilde{t}_1} \le 80 \text{ GeV}. \end{aligned} \tag{7}$$

In the region of Eq.(6) we obtain

$$0.07 \le B(t \to \tilde{t}_1 \tilde{\chi}_1^0) \le 0.50, \tag{8}$$

and in the region of Eq.(7),

$$0.10 \le B(t \to \tilde{t}_1 \tilde{\chi}_1^0) \le 0.50. \tag{9}$$

So, if the $ee\gamma\gamma + \not{E}_T$ event is explained by the MSSM with the lightest neutralino being the LSP, the exotic decay $t \to \tilde{t}_1 \tilde{\chi}_1^0$ must occur at a branching ratio larger than 0.07.

Upper bounds for this exotic decay of the top quark can also be derived from the available data at FNAL. Currently, the FNAL top quark pair production counting rate is interpreted as a measurement of $\sigma(t\bar{t}) \times B^2(t \to bW)$. Since the final states $t\bar{t} \to Wb\bar{c}\tilde{\chi}_1^0\tilde{\chi}_1^0$ and $t\bar{t} \to c\tilde{\chi}_1^0\tilde{\chi}_1^0\bar{c}\tilde{\chi}_1^0\tilde{\chi}_1^0$ do not have enough leptons or jets to be included in the dileptonic, leptonic or hadronic event samples, they are invisible to the current counting experiments at FNAL. So the quantity $[1 - B(t \to \tilde{t}_1\tilde{\chi}_1^0)]^2$, which gives the fraction of events in which both the t and $\bar{t}$ decay normally [4], should lie within the measured range of $\sigma[t\bar{t}]_{\rm exp}/\sigma[t\bar{t}]_{\rm QCD}$. Note that in our analyses we neglected the SUSY effects [13][14] in $t\bar{t}$ production and thus the theoretical value of $\sigma[t\bar{t}]$ is given by the SM value $\sigma[t\bar{t}]_{\rm QCD}$. The production cross section measured by

[4] Here we assume that the only exotic decay mode of top quark in R-parity conserving MSSM is $t \to \tilde{t}_1\tilde{\chi}_1^0$. If charged Higgs is light enough, $t \to H^+ b$ is also possible; its phenomenological implications at Tevatron have been studied [11]. The FCNC decays $t \to cZ, c\gamma, cg, ch$ are negligibly small in R-parity conserving MSSM [12].