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Top squark mass: current limits revisited and new limits from Tevatron Run-I

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Abstract

Analyzing the $\ell + n$-jets $+ \not{E}_T$ (where $n \geqslant 2$) data from Run-I of the Tevatron using the Bayesian technique, we obtain model independent limits on the product $\mathrm{BR}(\tilde{t}_1 \to be^+\nu_e\tilde{\chi}_1^0) \times \mathrm{BR}(\tilde{t}_1^* \to \bar{b}q\bar{q}'\tilde{\chi}_1^0)$ for different values of the lighter top squark ($\tilde{t}_1$) mass and the lightest supersymmetric particle ($\tilde{\chi}_1^0$) mass. The signal events have been simulated by interfacing the 4-body decay of $\tilde{t}_1$ at the parton level with the event generator PYTHIA. These limits have been translated into exclusion plots in the $m_{\tilde{t}_1}$–$m_{\tilde{\chi}_1^0}$ plane, which also turn out to be fairly model independent for fixed values of the BR of the competing loop decay mode $\tilde{t}_1 \to c\tilde{\chi}_1^0$. Assuming the loop decay BR to be negligible and using the leading order cross section for $\tilde{t}_1\tilde{t}_1^*$ pair production, we obtain conservatively $m_{\tilde{t}_1} \geqslant 77.0$ (74.5) GeV for $m_{\tilde{\chi}_1^0} = 5$ (15) GeV, while for $\mathrm{BR}(\tilde{t}_1 \to c\tilde{\chi}_1^0) = 20\%$, the corresponding limits are $m_{\tilde{t}_1} \geqslant 68.0$ (65.0) GeV. Using the larger next to leading order cross section stronger limits are obtained. For example, if $\mathrm{BR}(\tilde{t}_1 \to c\tilde{\chi}_1^0) = 20\%$, $m_{\tilde{t}_1} \geqslant 73.0$ (72.7) GeV for $m_{\tilde{\chi}_1^0} = 5$ (15) GeV. Our limits nicely complement the ALEPH bounds which get weaker for low $m_{\tilde{\chi}_1^0}$.

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The minimal supersymmetric standard model (MSSM) [1] is a well motivated extension of the Standard Model (SM), but there is no evidence of it as well as it has not been ruled out by the electroweak precision measurements at LEP [2]. Unfortunately, we are not equipped with any theoretical guideline about the range of superparticle masses since the exact SUSY breaking mechanism is unknown yet, although several interesting suggestions exist [1]. From unsuccessful searches at LEP [3] and Tevatron Run-I [4,5] some

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experimental lower bounds on superparticle masses exist.

The second phase of experiments at the Tevatron, the Run-II, is in progress. It is expected that an integrated luminosity of at least 2 fb^{-1} per experiment at 2 TeV center of mass energy will be accumulated. This is about ten times larger than the acquired luminosity in Run-I with center of mass energy 1.8 TeV.

However, in view of the existing limits on the masses of the strongly interacting sparticles (squarks and gluinos) [4,5] and the rather marginal increase in the center of mass energy, most of the unexplored parameter space in this sector is likely to be beyond the kinematic reach of Run-II as well. Since this is the only currently available machine for direct SUSY searches until the LHC starts, it is important to identify the sparticles with reasonable production cross sections which may be within the striking range of the Tevatron.

The lighter top squark mass eigenstate $\tilde{t}_1$ could be an interesting possibility. This is because the large top quark mass induces a large mixing term in the top squark mass matrix [6]. When the matrix is diagonalized, one of the mass eigenvalues may turn out to be rather small over a large region of the MSSM parameter space. In fact, it is quite conceivable that $\tilde{t}_1$ is the next lightest supersymmetric particle (NLSP), the lightest neutralino $\tilde{\chi}_1^0$ being the lightest supersymmetric particle (LSP) by assumption in most R-parity (R_p) conserving models.

Since the $\tilde{t}_1$ could be the only strongly interacting sparticle within the kinematic range of Run-II, it is important to carefully plan the strategy for searching it. The existing limits on $m_{\tilde{t}_1}$ may provide important guidelines for this plan. In the first part of this Letter we shall critically re-examine the existing limits. Since we do not want to commit ourselves to any specific SUSY breaking mechanism we shall discuss only the limits which are valid in the most general R_p conserving MSSM. In the second part of this Letter we shall derive some new limits using Run-I data.

The collider signatures, however, crucially depend on whether the top squark is the NLSP or not. In this Letter we shall be mainly concerned with the scenarios with a top squark NLSP with $m_{\tilde{t}_1}$ below the top quark mass. It is further assumed that all three body decays like $\tilde{t}_1 \to bW\tilde{\chi}_1^0$, where $\tilde{\chi}_1^0$ is the only superparticle in the final state, are kinematically forbidden. In this case the only allowed decay modes in the R_p conserving MSSM are the following:

(i) The flavour changing loop decay into a charm quark and the LSP, $\tilde{t}_1 \to c\tilde{\chi}_1^0$, [7];
(ii) The 4-body decay into a b quark, the LSP and two approximately massless fermions, $\tilde{t}_1 \to b\tilde{\chi}_1^0 f\bar{f}'$, where $f\bar{f}' = q\bar{q}'$ or $l\bar{\nu}_l$ ($\ell = e, \mu$) [8].

We note in passing that if $m_W + m_{\tilde{\chi}_1^0} \lesssim m_{\tilde{t}_1} \lesssim m_b + m_W + m_{\tilde{\chi}_1^0}$, then the decay $\tilde{t}_1 \to qW\tilde{\chi}_1^0$, where $q = d$ or s, can occur in principle. Of course the BR of this mode could be suppressed by a mixing angle expected to be very small if the quark and the squark mass matrices are aligned. The magnitude of this parameter, however, is very much model dependent and the possibility that this mode may compete with the decays (i) and (ii) also having small widths, cannot be apriorily ruled out. The resulting signal consisting of W + light hadrons + $\not{E}_T$ may be difficult to detect, especially so if $m_{\tilde{\chi}_1^0}$ and consequently the $\not{E}_T$ is small. To the best of our knowledge this signal has not been studied so far. This decay mode, which could be a test of alignment of the quark and squark mass matrices, is not of particular interest for this Letter since Run-I data is sensitive to $m_{\tilde{t}_1} \lesssim m_W$ only.

Until very recently most of the limits on the top squark NLSP, derived from unsuccessful searches at LEP and Tevatron, were based on the assumption that the former decay occur with 100% branching ratio (BR). Moreover these limits have additional dependence on SUSY parameters in the following way.

At hadron colliders the leading order (LO) cross section for pair production of top squarks depends on $m_{\tilde{t}_1}$ only since it is a pure QCD process [9]. The dependence on other SUSY parameters, e.g., the gluino mass $m_{\tilde{g}}$, the masses of the other squarks, the mixing angle $\cos\theta_{\tilde{t}}$ (where $\theta_{\tilde{t}}$ is the mixing angle in top squark sector), etc., arise only through the next to leading order (NLO) corrections, which yield somewhat larger cross sections [10]. The efficiency of the kinematical cuts required to isolate the top squark signal from the SM background, on the other hand, strongly depends on the lightest neutralino mass $m_{\tilde{\chi}_1^0}$. The existing conservative limits from Tevatron based on the LO cross section [11,12] and the assumption of 100% BR's of the loop decay, are presented

as exclusion plots in the $m_{\tilde{t}_1}$–$m_{\tilde{\chi}_1^0}$ plane (see [11, Fig. (2)]). The most stringent bound, from Tevatron experiments, puts a lower limit of $m_{\tilde{t}_1} \geqslant 119$ GeV for $m_{\tilde{\chi}_1^0} = 40$ GeV. This limit becomes considerably weaker for higher value of $m_{\tilde{\chi}_1^0}$, e.g, $m_{\tilde{t}_1} \geqslant 102$ GeV for $m_{\tilde{\chi}_1^0} = 50$ GeV [11]. Thus, even if we temporarily set aside the questionable assumption of 100% BR's for the loop decay, the existing limits from Tevatron on $m_{\tilde{t}_1}$ could be rather weak for relatively large $\tilde{\chi}_1^0$ mass.

Using the model dependent assumption of the complete dominance of the loop decay limits on $m_{\tilde{t}_1}$ have also been obtained at LEP [13]. At e^+e^- colliders the electroweak $\tilde{t}_1\tilde{t}_1^*$ production cross section has an additional dependence on the $\theta_{\tilde{t}}$. The cross section is maximum for $\theta_{\tilde{t}} = 0^\circ$ while it is minimum for $\theta_{\tilde{t}} = 56^\circ$, when $\tilde{t}_1$ decouples from the Z. For larger values of $\theta_{\tilde{t}}$ the cross section is essentially the same as that for $\theta_{\tilde{t}} = 56^\circ$ [14], particularly so for relatively high $m_{\tilde{t}_1}$ kinematically accessible to LEP. This behavior of the cross section ensures that the limits corresponding to $\theta_{\tilde{t}} = 56^\circ$ are valid to a very good approximation for higher values of $\theta_{\tilde{t}}$. The efficiency of the kinematical cuts also depends on $m_{\tilde{\chi}_1^0}$ although the dependence is somewhat different from that in the case of Tevatron data. For $\theta_{\tilde{t}} \gtrsim 56^\circ$ and $m_{\tilde{t}_1} \gtrsim 78.0$ GeV, no exclusion is possible for low $m_{\tilde{\chi}_1^0}$, although for higher $m_{\tilde{\chi}_1^0}$ better limits are obtained even if $m_{\tilde{\chi}_1^0} \approx m_{\tilde{t}_1}$ (see [15, Fig. 2(a)]). It should be emphasized that it is precisely for these low $m_{\tilde{\chi}_1^0}$ the CDF limits using the same assumption of the dominance of the loop decay are more stringent and limits extending beyond the kinematical reach of LEP are obtained. Thus the limits from LEP and Tevatron complement each other.

It has been known for some time that in a wide region of the MSSM parameter space the BR's of the 4-body decay can be substantial and may even dominate over the loop decay. The dependence of the 4-body decay rate on SUSY parameters has been studied in great detail both in the MSSM and the minimal supergravity (mSUGRA) [8,16]. Especially for large values of $\theta_{\tilde{t}}$ and small values of $\tan\beta$ this mode can be the dominant one. Thus the limits discussed above may require significant revision. The dependence on other MSSM parameters will be reviewed later and some new points will be discussed.

Very recently both ALEPH [15] and D0 Collaborations [17] have analyzed, respectively, LEP and Tevatron data using special assumptions for the 4-body decay. D0 has obtained cross section limits as a function of $m_{\tilde{t}_1}$ assuming 100% BR's for the leptonic 4-body decay [17]. This assumption, however, is unrealistic. As has already been noted this BR's does not exceed the 20% level considering both the e and μ modes [16].

For the first time the ALEPH Collaboration has analyzed the data taking into account both the competing decay modes. One set of realistic limits have been obtained by assuming that the 4-body decay overwhelms the loop decay and the relative BR's of the 4-body leptonic and hadronic decays of $\tilde{t}_1$ closely follow that of the W^* (see [15, Fig. 3(a)]). The exclusion plot in the $m_{\tilde{t}_1}$–$m_{\tilde{\chi}_1^0}$ plane shows that for low $m_{\tilde{\chi}_1^0}$, $m_{\tilde{t}_1} > 78.0$ (84.0) GeV is allowed for $\theta_{\tilde{t}} = 56^\circ$ (0°).

Another set of limits has been obtained by varying both the loop decay and the 4-body semileptonic decay BR's as free parameters. They have then checked whether a particular $m_{\tilde{t}_1}$ can be excluded via any one of the two competing decay modes. As already discussed, these limits also depend on $m_{\tilde{\chi}_1^0}$ and $\theta_{\tilde{t}}$. Unfortunately the numerical values of the semileptonic 4-body decay BR's used in deriving the limits are not always realistic. For example, the absolute lower limit of $m_{\tilde{t}_1} > 63.0$ GeV at 95% confidence level has been obtained for the loop decay BR's = 22%, the semileptonic 4-body BR's = 55%, $\Delta M = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} = 5$ GeV and $\theta_{\tilde{t}} = 56^\circ$. The assumed semileptonic 4-body BR's, however, is unrealistic. We have checked that for $m_{\tilde{t}_1}$ within the kinematic reach of LEP the hadronic 4-body BR's is much larger than the semileptonic one over the entire MSSM parameter space. Higher values of $m_{\tilde{t}_1}$ are excluded for lower values of $m_{\tilde{\chi}_1^0}$ (see Ref. [15, Fig. 4(a) and (b)]). For example, fixing the loop decay BR's at 22% the strongest limit $m_{\tilde{t}_1} \gtrsim 95.0$ GeV is obtained for $\Delta M = 25$ GeV. However, for still larger values of ΔM, the limits get weaker as can be seen from the limit $m_{\tilde{t}_1} \gtrsim 89.0$ GeV for $\Delta M = 45$ GeV. No limit for still higher values of ΔM has been presented. In summary the ALEPH limits become weaker for $\theta_{\tilde{t}} \gtrsim 56^\circ$ and relatively low $m_{\tilde{\chi}_1^0}$.

The purpose of this Letter is to show that precisely in these regions of the MSSM parameter space, the data from Tevatron Run-I [18] already gives al-

most model independent, stronger limits inspite of the rather modest integrated luminosity. The conservative limits using the LO production cross section can be further improved if somewhat larger NLO cross sections are employed. For most of the parameter space $\sigma_{\rm NLO}(p\bar{p} \to \tilde{t}_1\tilde{t}_1^*)$ is 30% higher than the $\sigma_{\rm LO}(p\bar{p} \to \tilde{t}_1\tilde{t}_1^*)$ [10]. More importantly, this analysis outlines a strategy using which the Run-II search at slightly higher production cross section and much higher integrated luminosity can spectacularly enrich the information about the top squark NLSP in a fairly model independent way.

We looked into the existing CDF and D0 data and tried to identify the one which can be best utilized to constrain the 4-body decay modes of $\tilde{t}_1$. In principle the classic jets + missing E_T ($\not\!\!E_T$) data [4] used for squark–gluino searches can be used to constrain the 4-body decay of the top squark in the all hadronic mode which has the largest BR's. Unfortunately the stiff $\not\!\!E_T$ cut used to extract the existing data suitable for heavy superparticle searches give rather poor selection efficiency for the light $\tilde{t}_1$ accessible at Tevatron Run-I. We, therefore, analyzed the CDF data [18] used for a different search channel, $\tilde{t}_1 \to b\ell^+\tilde{\nu}_\ell$, leading to the signal $\ell + n$-jets + $\not\!\!E_T$, where $n \geqslant 2$. The same signal also arises from the 4-body decay of top squark when one $\tilde{t}_1$ decays leptonically and the other decays hadronically. Our analysis, however, will be handicapped due to the rather modest branching ratio of the semileptonic mode and the kinematical cuts optimized for a different decay channel. Nevertheless some useful conclusions emerge.

The 4-body decay has been simulated at the parton level using CTEQ4M parton distribution function [19], where one of the $\tilde{t}_1$ decays leptonically while the other decays hadronically:[1]

$$p\bar{p} \to \tilde{t}_1\tilde{t}_1^* \to b\bar{\ell}\nu_\ell\tilde{\chi}_1^0\bar{b}q\bar{q}'\tilde{\chi}_1^0 \quad (\ell = e \text{ or } \mu).$$

PYTHIA is then used for hadronization of the partons from $\tilde{t}_1$ decays. The final state particles have been passed through a toy detector simulation (using tools in PYTHIA) which mimics the effect of the CDF detector. The events are characterized by considerable $\not\!\!E_T$, due to the $\tilde{\chi}_1^0$, more than one energetic jets, displaced secondary vertices due to the b-quark jets and an isolated high p_T lepton from the top squark decay. Jet reconstruction, tagging of b-jets and lepton (e, μ) identification have been done following the CDF analysis using the same parameters and efficiencies. In particular, efficiency for tagging individual b-jets has been assumed to be 0.24 [20].

The important event selection criteria following CDF are as follows:

1. Considerable $\not\!\!E_T$ due to the two $\tilde{\chi}_1^0$'s and a ν from the decays of $\tilde{t}_1\tilde{t}_1^*$: $\not\!\!E_T \geqslant 25$ GeV.
2. At least 2 jets where the jets are reconstructed within $|\eta| \leqslant 2.4$ with cone algorithm ($\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.7$): $E_T^{\rm jet,1} > 12$ GeV and $E_T^{\rm jet,2} > 8$ GeV, where the jets are ordered in descending $\not\!\!E_T$.
3. At least one isolated lepton: electrons with $E_T > 10$ GeV and $|\eta_e| < 1.1$ and muons $p_T > 10$ GeV and $|\eta_\mu| < 0.6$ are selected.
4. Events with opposite sign di-lepton were removed to reduce Drell–Yan background.
5. At least one secondary vertex tagged jet from one of the b-jets.

To test the reliability of our simulation and analysis, $t\bar{t}$ events generated by PYTHIA have been passed through the same simulation and analysis chain. The number of $t\bar{t}$ events passing our selection is 17.38 which compares favourably with the number of $t\bar{t}$ events passing CDF selection, i.e., 17.8 ± 4.5 [18]. This validates the simulation and analysis chain used for deriving the new limits. Evidently the efficiency increases with increasing $m_{\tilde{t}_1}$ and for the same $m_{\tilde{t}_1}$ increases with decreasing $m_{\tilde{\chi}_1^0}$, (see Fig. 1). Thus limits better than that obtained by the ALEPH Collaboration [15] for low $m_{\tilde{\chi}_1^0}$ is expected.

From 88 pb^{-1} data a total of 87.3 ± 8.8 background events (N_b) were expected from SM processes. Significant contributions come from the W + jets, where W decays leptonically, $t\bar{t}$, $b\bar{b}$, $t\bar{b}$, $Z + n$-jets, where $n \geqslant 2$ and fake lepton events. Number of data events ($N_{\rm data}$) passing the selection is 81 (see Ref. [18]).

Since no excess over the expected SM background is observed in the data, 95% CL upper limits on the product of the branching ratios = BR($\tilde{t}_1 \to be^+\nu_e\tilde{\chi}_1^0$) × BR($\tilde{t}_1^* \to \bar{b}q\bar{q}'\tilde{\chi}_1^0$) = BR($\tilde{t}_1 \to$

[1] Charge conjugate interactions have been assumed unless otherwise stated.

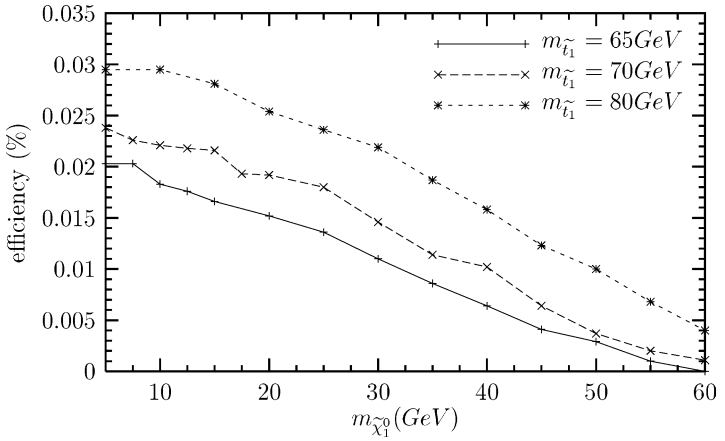

Fig. 1. Selection efficiency of the signal plotted as a function of $m_{\tilde{\chi}_1^0}$ for different values of the top squark mass ($m_{\tilde{t}_1}$).

$b\mu^+\nu_\mu\tilde{\chi}_1^0) \times \mathrm{BR}(\tilde{t}_1^* \to \bar{b}q\bar{q}'\tilde{\chi}_1^0)$, where q and q' correspond to all flavours kinematically allowed, are obtained for different values of $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$. Hereafter this product of branching ratios will be denoted by PBR. For determining the 95% CL limits, posterior probability distributions for each $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$ were obtained using the Bayesian technique [21] assuming the following: error on the luminosity ± 4 pb^{-1}, error on the total expected number of SM background events ± 8.8 (taken from Ref. [18]) and $\pm 10\%$ error on the estimated acceptance of the signal events. We have not taken into account the error in the cross section due to the uncertainties in the choice of the parton distribution functions, but we have checked that even if we take into account this uncertainty no appreciable change in the limits occur. For each value of the PBR 1000 Monte Carlo experiments were performed to determine the corresponding probability.

Upper limits on the PBR have been calculated using $\sigma(p\bar{p} \to \tilde{t}_1\tilde{t}_1^*)$ both in the LO and NLO approximation. These limits are shown in Fig. 2. For any given combination of $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$ the limits obtained by using the relatively low LO production cross section are weaker as expected. We shall follow the prescription of Ref. [10] and estimate the possible impact of the NLO cross section on our limits by using the LO cross sections scaled by a factor of 1.3 as an input to the limit calculation. The resulting stronger limits are presented in Fig. 2. We have concentrated on low values of $m_{\tilde{\chi}_1^0}$ because in this region of the parameter space our analyses lead to limits better than those obtained by ALEPH [15].

The regions of the MSSM parameter space, where the theoretical expectation of the PBR is above the 95% CL upper limit are excluded by this analysis. We shall now show that a significant region of the MSSM parameter space which was not excluded by the previous analyses are excluded in a fairly model independent way.

In Fig. 3, we plotted the PBR as a function of the loop decay BR for $m_{\tilde{t}_1} = 75$ GeV. The two BR's in the product are calculated by randomly varying all other MSSM parameters, taking into account the direct limits from LEP and Tevatron [3,12,13]. In particular the following ranges have been considered: the common slepton mass $m_{\tilde{l}_L} = m_{\tilde{l}_R} =$ [120–500] GeV, the common mass for the squarks $m_{\tilde{q}_L} = m_{\tilde{q}_R} =$ [300–800] GeV, $\cos\theta_{\tilde{t}} =$ [0.01–0.90] ($\theta_{\tilde{t}} =$ [89.43°–25.84°]), the trilinear soft breaking term in the b sector $A_b =$ [150–750] GeV, the trilinear soft breaking term in the τ sector $A_\tau =$ [150–350] GeV, the U(1) gaugino mass $M_1 =$ [5–50] GeV, the SU(2) gaugino mass $M_2 =$ [110–300] GeV, the higgsino mass parameter $\mu =$ [50–500] GeV, the ratio of the vacuum expectation values of the two neutral Higgs fields $\tan\beta =$ [5–50] and the pseudoscalar Higgs boson mass $M_A =$ [300–900] GeV. It should be noted that we have not invoked the model dependent assumption of gaugino mass unification. On the other hand, the common mass for the first two generations

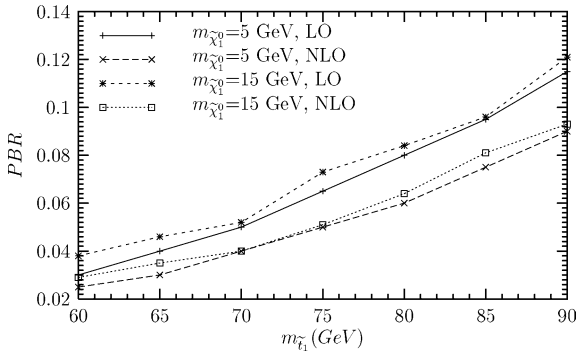

Fig. 2. The upper limit on the product of branching ratios (PBR, see text) as a function of $m_{\tilde{t}_1}$ for different values of $m_{\tilde{\chi}_1^0}$. Limits for both leading order (LO) and next to leading order (NLO) $\tilde{t}_1\tilde{t}_1^*$ production cross section are presented.

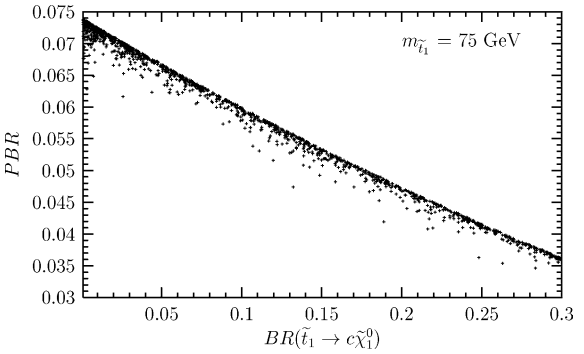

Fig. 3. The PBR as a function of BR($\tilde{t}_1 \to c\tilde{\chi}_1^0$) for $m_{\tilde{t}_1} = 75$ GeV. The modest spread in PBR for a fixed BR($\tilde{t}_1 \to c\tilde{\chi}_1^0$) is due to the variation of the MSSM parameters (see text).

of squarks as suggested by the absence of flavour changing neutral currents has been used. We have also checked that the PBR remain almost unchanged if we consider the range $\mu = [(-500)–(-50)]$ GeV. Hence, the figure is drawn only for positive μ.

A cursory look into the Feynman diagrams [8] for each of the 4-body decay mode of $\tilde{t}_1$ would suggest that the theoretical prediction of the above product depends on many free parameters. An important result of this Letter is to establish that inspite of this apparent model dependence, a fairly model independent approach for extracting the limits is possible. For a fixed BR($\tilde{t}_1 \to c\tilde{\chi}_1^0$), the PBR lies in a rather narrow range even if all model parameters are arbitrarily varied. This is not difficult to understand. For top squark masses sensitive to the data we are examining and chargino and slepton masses above the current LEP limits, both the semileptonic and the hadronic 4-body BR's follow the corresponding W^* BR in most cases. For a given loop decay BR's, the overall 4-body BR's is fixed. Now the PBR lies in a narrow range even if the MSSM parameters are widely varied subject to the above constraints. We have found the same behaviour of the PBR for other value of $m_{\tilde{t}_1}$ relevant for our analysis ($65.0 \lesssim m_{\tilde{t}_1} \lesssim 85.0$ GeV).

Some numerical examples are given below. When the loop decay BR is negligible ($\lesssim 0.5\%$), the theoretical PBR lies between 0.069–0.073. This range reflects the uncertainty in the MSSM parameters, $\cos\theta_{\tilde{t}}$ being the most important one among them. In this particular case if $0.01 < \cos\theta_{\tilde{t}} < 0.18$ ($89.43^\circ > \theta_{\tilde{t}} > 79.63^\circ$), the BR of the loop decay is negligible. For LSP mass 5 (15) GeV the limit is $m_{\tilde{t}_1} > 76.5$–77.5 GeV (74.0–75.0 GeV) if the limiting PBR (see Fig. 2) corresponding to the LO production cross section is used. For the purpose of quoting limits we shall use the central value of each range.

Using the NLO cross section as discussed above the corresponding limits become stronger: 83.0–84.2 GeV (81.5–82.5 GeV) for $m_{\tilde{\chi}_1^0} = 5$ (15) GeV. Thus most of the narrow region of the parameter space corresponding to large $\theta_{\tilde{t}}$ and low $m_{\tilde{\chi}_1^0}$ allowed by the ALEPH analysis (see Ref. [15, Fig. 3(a)]), is disallowed by Run-I data if the NLO cross section is used.

If on the other hand, the loop BR's is fixed at 20%, for LSP mass 5 (15) GeV, the limit is $m_{\tilde{t}_1} > 67.5$–68.5 GeV (64.2–66.1 GeV) using the LO cross section. Stronger limits 72.5–73.5 GeV (72.2–73.2 GeV) emerge corresponding to the NLO cross section. This should be compared with Fig. 4(b) of Ref. [15].

Assuming that the loop decay BR's is negligible and fixing the PBR at 0.073, a number motivated by Fig. 3, we present the constraints in the $m_{\tilde{t}_1}$–$m_{\tilde{\chi}_1^0}$ plane in Fig. 4. This may be compared with the limits in Fig. 3(a) of [15]. Although the improvement using the leading order cross section is rather modest, the NLO cross section leads to significant improvement in the large $\theta_{\tilde{t}}$ and small $m_{\tilde{\chi}_1^0}$ scenario. Our results, therefore, nicely complements the ALEPH limits.

Some comments on the importance of the parameter $\cos\theta_{\tilde{t}}$ are now in order. It has already been noted in Ref. [8] that the parameter ϵ, as defined in [7], plays a crucial role in the loop decay. By adjusting various

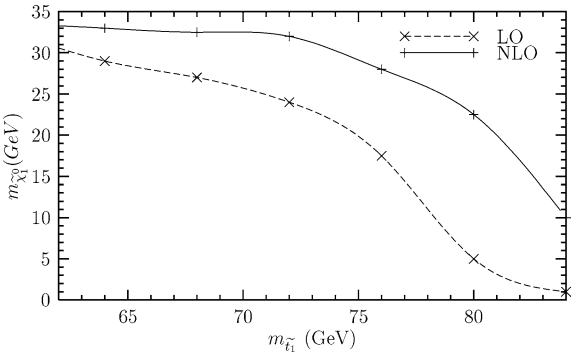

Fig. 4. The excluded region in the $m_{\tilde{t}_1}$–$m_{\tilde{\chi}_1^0}$ plane from Tevatron Run-I assuming the BR($\tilde{t}_1 \to c\tilde{\chi}_1^0$) to be negligible. The regions below the dotted (solid) lines are excluded using the LO (NLO) production cross sections.

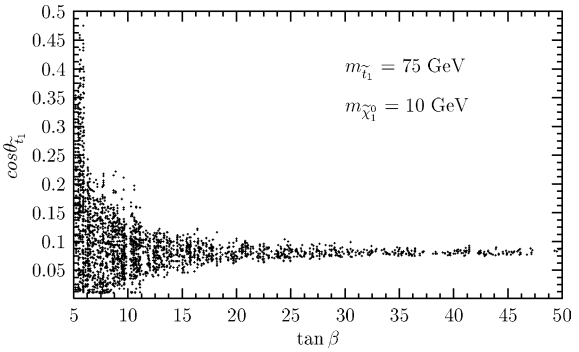

Fig. 5. The excluded regions in the $\tan\beta$–$\cos\theta_{\tilde{t}}$ plane for $m_{\tilde{t}_1} = 75$ GeV and $m_{\tilde{\chi}_1^0} = 10$ GeV. The dots represent excluded points where the PBR exceeds its upper limit for this combination of $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$. M_1, M_2 and μ are varied such that the $m_{\tilde{\chi}_1^0}$ is fixed. The other MSSM parameters, which affects the result mildly (see text) are $m_{\tilde{l}_L} = m_{\tilde{l}_R} = 300$ GeV, $m_{\tilde{q}_L} = m_{\tilde{q}_R} = 500$ GeV, $A_b = 300$ GeV, $A_\tau = 200$ GeV, $M_A = 300$ GeV.

SUSY parameters the magnitude of ϵ can be suitably reduced leading to a vanishingly small loop decay BR. In some regions of the parameter space this may require a fair amount of fine-tuning. This is illustrated in Fig. 5 in the $\cos\theta_{\tilde{t}}$–$\tan\beta$ plane for $m_{\tilde{t}_1} = 75$ GeV and $m_{\tilde{\chi}_1^0} = 10$ GeV, where the dots correspond to the PBR greater than or equal to its limiting value. The parameters M_1, M_2 and μ have been varied such that the $m_{\tilde{\chi}_1^0}$ is fixed. The choice of the other MSSM parameters are given in the figure caption. It is seen that for large $\tan\beta$ the PBR is sensitive to the data for a very narrow range of $\cos\theta_{\tilde{t}}$ values, where as for small $\tan\beta$ this happens for a much larger range of $\cos\theta_{\tilde{t}}$. The dominance of the 4-body is, therefore, more probable at small $\tan\beta$. For example in Fig. 5, the PBR is greater than or equal to its limiting value for $0.07 < \cos\theta_{\tilde{t}} < 0.1$ ($85.98 > \theta_{\tilde{t}} > 84.26°$) and $\tan\beta = 45$. Even if all MSSM parameters are randomly varied keeping $m_{\tilde{t}_1}$ and $\tan\beta$ fixed, the above range marginally changes to $0.01 < \cos\theta_{\tilde{t}} < 0.1$ ($89.43 > \theta_{\tilde{t}} > 84.26°$). On the other hand for $\tan\beta = 5$ the range for the above set of MSSM parameters is $0.01 < \cos\theta_{\tilde{t}} < 0.35$ ($89.43 > \theta_{\tilde{t}} > 69.51°$), see Fig. 5. These features have been noted for all $m_{\tilde{t}_1}$ sensitive to the data we are using.

This Letter sketches a fairly model independent strategy for top squark search including its 4-body decays. This approach can be easily extended to analyses using Run-II data. There are reasons to be optimistic about the prospect of $\tilde{t}_1$ search via the 4-body decay channels at Tevatron Run-II. Firstly the $\tilde{t}_1\tilde{t}_1^*$ production cross section at $\sqrt{s} = 2$ TeV will be slightly higher and the total integrated luminosity much larger. Moreover kinematical cuts can be specially designed for the 4-body decay channel. For example, jets + $\not\!\!E_T$ data at a relatively low $\not\!\!E_T$ will improve the search prospect via the hadronic decay mode of both the top squarks, which has the largest BR's. Instead of using a very stiff $\not\!\!E_T$ cut, the background can be suppressed by efficient b-tagging and utilizing the large number of jets in the signal. With good τ detection efficiency 4-body final states with τ-leptons may also lead to further improvements.

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