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Implications of the HERA Events for the R-Parity Breaking SUSY Signals at Tevatron

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Abstract

The favoured R-parity violating SUSY scenarios for the anomalous HERA events correspond to top and charm squark production via the λ'_{131} and λ'_{121} couplings. In both cases the corresponding electronic branching fractions of the squarks are expected to be $\ll 1$. Consequently the canonical leptoquark signature is incapable of probing these scenarios at the Tevatron collider over most of the MSSM parameter space. We suggest alternative signatures for probing them at Tevatron, which seem to be viable over the entire range of MSSM parameters.

1. The Anomalous HERA Events :

The H1 and ZEUS experiments have reported some anomalous high- Q^2 events from the HERA e^+p collider, which could be suggestive of new physics beyond the Standard Model (SM). The H1 experiment has reportedly seen 12 neutral-current events, $e^+p \rightarrow e^+qX$, at $Q^2 > 15,000 \text{ GeV}^2$ against the SM prediction of 5 [1]; while ZEUS has reported 5 events at $Q^2 > 20,000 \text{ GeV}^2$ against the prediction of 2 [2]. Moreover the excess of 7 events observed by H1 seem to cluster around a common e^+q mass of

$$M \simeq 200 \text{ GeV}, \quad (1)$$

which is not inconsistent with those of the ZEUS events [3]. Taken together, they represent an excess of 10 events, with a common mass range of 200–220 GeV. They are based on the 1994–'96 data, corresponding to a combined luminosity of 34 pb^{-1} for the two experiments, while the reported detection efficiency for each experiment is about 80%. This corresponds to a cross-section of

$$\sigma \simeq 0.4 \text{ pb} \quad (2)$$

for these anomalous events.

These events have aroused a good deal of excitement in high energy physics in the past few months; and several possible mechanisms of new physics have been suggested [4-10]. It should be noted of course that the statistical significance of the signal is about 3σ for each experiment, which is by no means conclusive. The ongoing experiments at HERA are expected to double the data sample in another year. While very welcome, this may not be sufficient to settle the issue conclusively. It is imperative therefore to see if the contending new physics mechanisms can be tested at other colliders — in particular at Tevatron, which has a considerable energy reach to probe these mechanisms.

The new physics mechanisms suggested are mainly of two types — (i) a contact interaction term corresponding e.g. to a heavy Z' exchange [6,8,9], and (ii) the production and decay of a generic leptoquark, i.e. a hypothetical particle coupling to the e^+q channel [4-8]. The first interpretation seems to be disfavoured on several grounds. The size of the contact interaction term required is at best marginally compatible with the upper limits from LEP and Tevatron colliders. Moreover it favours the standard e^+q mass distribution,

$M = \sqrt{s \cdot x}$, as given by the x distribution of the quark, instead of its clustering at a high value of M . For the same reason, the M integrated cross-section is expected to go down at large Q^2 . Instead, the clustering in M and the flat distribution over a very large range of Q^2 observed in the data clearly favour the formation and decay of a generic leptoquark in the e^+q channel.

Thus, it is natural to ask whether some of the extensions of the SM can naturally account for such a leptoquark. The leptons and quarks are unified in GUT, which naturally predict leptoquark states both as gauge (vector) bosons and Higgs scalars [10, 11]. However, the exchange of these objects in GUT generally leads to lepton and baryon number violating interactions, and in particular to proton decay. Thus the stability of proton implies these objects to be very heavy ($M > 10^{15}$ GeV), which puts them far beyond the reach of present or foreseeable future machines. While there are examples of GUT models like E_6 , having leptoquarks without baryon number violating couplings [10], there is no natural reason to expect them to be as light as a few hundred GeV.

A more plausible candidate for a generic leptoquark in the mass range of a few hundred GeV is the scalar superpartner of quark (squark) in the R-parity violating SUSY model [12, 13]. In this case they can have lepton and baryon number violating Yukawa couplings and mediate proton decay as well. Unlike the gauge couplings, however, these Yukawa couplings are not constrained by any symmetry consideration. Therefore one can assume a finite value for the lepton number violating coupling while setting the baryon number violating ones to zero. The former ensures squark coupling to the e^+q channel while the latter prevents proton decay. Thus in the R-parity violating SUSY model the squark can masquerade as a leptoquark and naturally account for the anomalous HERA events. Indeed these squarks are by far the most promising new physics candidates for the HERA events; and as such they have attracted a good deal of attention in the current literature on this subject [4-7]. The purpose of this work is to identify the most plausible R-parity violating SUSY scenarios for the anomalous HERA events and study the corresponding signals for the Tevatron collider.

2. R-Parity Breaking SUSY Scenarios :

We shall consider the minimal supersymmetric extension of the standard model (MSSM) with explicit R-parity breaking [13]. The latter arises from the following Yukawa interaction terms in the Lagrangian:

$$L = \lambda_{ijk} l_i \tilde{l}_j \bar{e}_k + \lambda'_{ijk} l_i \tilde{q}_j \bar{d}_k + \lambda''_{ijk} \bar{d}_i \tilde{d}_j \bar{u}_k, \quad (3)$$

plus analogous terms from the permutation of the tilde, denoting the scalar superpartner. Here l and \bar{e} (q and \bar{u} , \bar{d}) are the left-handed lepton doublet and antilepton singlet (quark doublet and antiquark singlet) fields; and i, j, k are the generation indices. The terms relevant for the HERA events are

$$\lambda'_{ijk} (l_i \tilde{q}_j \bar{d}_k + l_i q_j \tilde{d}_k) + h.c. \quad (4)$$

It is customary to assume a hierarchical structure for these Yukawa couplings in analogy with the standard Yukawa couplings of the quarks and leptons. The squark formation and decay processes corresponding to different choices of the leading λ' coupling of eq.(4) are shown in Table - I. Only the 1st row corresponds to squark formation from a valence quark, while all other cases are from sea quarks. Knowing these quark fluxes one can easily calculate the cross-section for these processes at HERA for a given $\lambda' \sqrt{B}$, where B denotes the squark branching fraction into the shown channel. The 2nd column shows the sizes of corresponding $\lambda' \sqrt{B}$, required to explain the cross-section (2) of the HERA events [5,6]. While the required size of the quantity is small for the valence quark case (1st row), it is larger by an order of magnitude in the other cases. Note that for the last two rows there is an equal probability of \tilde{d}_j decay into the neutrino channel, i.e. $B \leq 1/2$.

The last column shows the upper limits on these R violating couplings from other processes. The λ'_{111} limit comes from neutrinoless double beta decay [14], $\lambda'_{112,113}$ limits from charge current universality [15], $\lambda'_{121,131}$ limits from atomic parity violation [16], $\lambda'_{122,133}$ limits from ν_e mass [17], λ'_{123} limit from forward-backward asymmetry [15], and λ'_{132} from Z-decay [18]. All but the last of these limits are taken from the recent compilation of ref.[5]. They are all 1σ limits.

More recently a precise measurement of atomic parity violation in $^{55}\text{Ce}_{133}$ has been reported[19]. The measured value of the weak charge is $Q^{ex}_W = -72.11 \pm 0.27 \pm 0.89$, where the 2nd error is theoretical. This is in remarkable agreement with the SM value of $Q^{SM}_W \simeq -72.9$ [20]. From

$$Q_W = -2[C_{1u}(2Z + N) + C_{1d}(Z + 2N)], \quad (5)$$

$$\Delta C_{1d} = \frac{\lambda'_{1j1}{}^2 \sqrt{2}}{8M_{q_j}^2 G_F} \quad (6)$$

it is clear that R-violating SUSY contribution can only add to the magnitude of Q_{W}^{SM} . Consequently a 1σ bound would imply a very severe restriction on the λ'_{1j1} coupling. But such a bound would not be justified since the data point is roughly 1σ below the magnitude of SM. Therefore we have estimated the 2σ bound, where the experimental and the theoretical errors of Q_{W}^{ex} have been added linearly. The resulting bound for a 200 GeV squark, $\lambda'_{1j1} < 0.10$, is shown in the bracket in Table - I. This bound is consistent with the one obtain in ref.[21].

Comparing the 2nd and 3rd columns of this Table, we see that the required coupling is reasonably small compared to its upper limit for the charm and top squark productions from a valence quark, i.e.

$$e^+d \rightarrow \tilde{c}_L \rightarrow e^+d, \quad (7)$$

$$e^+d \rightarrow \tilde{t}_L \rightarrow e^+d, \quad (8)$$

where the subscript L denotes left chirality. Moreover, the inclusion of NLO correction in eq.(7) and (8) is expected to reduce the required value of $\lambda'_{1j1}\sqrt{B}$ further by $\sim 30\%$ [22]. Therefore we shall concentrate on these two cases, in studying the R violating SUSY signal at the Tevatron. There is only one other case, where the required $\lambda'\sqrt{B}$ is compatible with the upper limit on λ' . This corresponds to top squark production from the strange quark sea,

$$e^+s \rightarrow \tilde{t}_L \rightarrow e^+s. \quad (9)$$

This case has been recently studied in [18], where it was shown to give a consistent solution to the HERA anomaly over a limited range of the MSSM parameter space. We shall discuss this possibility while studying the top squark production scenarios of eq.(8) at the Tevatron collider.

A brief discussion of the squark branching fraction B is in order. Under the assumption of hierarchical λ' couplings, there is only one dominant R violating channel in a given scenario. The corresponding decay width of squark is

$$\Gamma_{\mathcal{R}} = \frac{1}{16\pi} \lambda'^2 M. \quad (10)$$

In addition the squark has R conserving decays into chargino and neutralino channels. The corresponding decay width Γ_R will be a function of the MSSM parameters, but independent of λ' . Thus

$$B = \frac{\Gamma_R}{\Gamma_R + \Gamma_R}. \quad (11)$$

Note that the product $\lambda'\sqrt{B}$ is constrained by the cross-section of the HERA events, as shown in the second column of Table-I. This can be used to eliminate λ' from eqs.(10,11), so that in any given scenario the branching fraction B is a unique function of the MSSM parameters. Thus

$$B = \frac{\sqrt{1 + 4\Gamma_R/\Gamma_R^c} - 1}{2\Gamma_R/\Gamma_R^c}, \quad (12)$$

where

$$\Gamma_R^c = \frac{1}{16\pi} (.04)^2 M \quad (13)$$

for the favoured scenarios of eqs.(7,8). As we shall see below, in these cases one gets a $B \ll 1$ over a large part of the MSSM parameter space. The signal for charm and top squark production at Tevatron will depend sensitively on this branching fraction. Note that for the scenario of eq.(9) one has to replace the factor .04 by 0.3 in eq.(13). Consequently the branching fraction B remains of the order 1 throughout the allowed MSSM parameter space in this scenario.

Let us conclude this section with a brief discussion of the MSSM parameters, relevant for our analysis [23]. We shall assume a common gaugino and a common sfermion mass at the unification scale. Consequently the masses of the SU(3), SU(2) and U(1) gauginos (\tilde{g} , \tilde{W} and \tilde{B}) at the electroweak scale are related via their gauge couplings, i.e.

$$\begin{aligned} M_3 &= (g_s^2/g^2) M_2 \simeq 3.3M_2, \\ M_1 &= (5g^2/3g^2) M_2 \simeq 0.5M_2. \end{aligned} \quad (14)$$

Thus there is only one independent gaugino mass M_2 . Of course the electroweak gauginos, \tilde{W} and \tilde{B} , will mix with the higgsinos, resulting in the physical chargino ($\tilde{W}_{1,2}$) and neutralino (\tilde{Z}_{1-4}) states. Their masses and

compositions will depend on two more parameters - the higgsino mass parameter (μ) and the ratio of the two higgs vacuum expectation values ($\tan \beta$). Finally, the right and left handed squarks of the first two generations are expected to have roughly degenerate masses and so also the sleptons. These two masses are related via the renormalisation group equations which imply [12]

$$M_{\tilde{q}}^2 \simeq M_{\tilde{t}}^2 + 0.85M_3^2. \quad (15)$$

After QCD correction the physical (pole) mass of the gluino is [24]

$$M_{\tilde{g}} = (1 + 4.2\alpha_s/\pi) M_3 = 1.15M_3 \lesssim M_{\tilde{q}}. \quad (16)$$

Because of the large top quark mass, the top squarks are expected to have lower masses, with the hierarchy [25]

$$M_{\tilde{t}_R} < M_{\tilde{t}_L} < M_{\tilde{q}}. \quad (17)$$

Moreover the large top quark mass also implies large mixing between \tilde{t}_L and \tilde{t}_R . This can further reduce the mass of the lighter physical state

$$\tilde{t}_1 = \tilde{t}_L \cos \theta + \tilde{t}_R \sin \theta. \quad (18)$$

It also implies that \tilde{t}_1 has significant left and right handed components. Thus it is a natural candidate for the anomalous HERA events. Indeed the possibility of this top squark production has been suggested for several years as a promising R-parity violating SUSY signal at HERA [25]. Therefore, we shall first investigate the implications of this scenario for the Tevatron collider. It should be noted that in this case the λ' should be replaced by $\lambda' \cos \theta$ in the second column of Table - I as well as in eq.(10). However the eqs.(12,13) remain unchanged.

3. The Top Squark (Stop) Scenario at Tevatron :

The dominant mechanism for stop production at Tevatron are the leading order QCD processes of quark-antiquark and gluon-gluon fusion [26]

$$\bar{q}q \rightarrow \tilde{t}_1 \tilde{t}_1^* \quad , \quad gg \rightarrow \tilde{t}_1 \tilde{t}_1^*. \quad (19)$$

The R violating Yukawa coupling has negligible contribution to the production cross section and hence it is not considered here. Indeed the above

production processes hold equally well for leptoquark production. It was recently shown in [27] that these LO processes, combined with the LO structure functions, reproduce the NLO cross-section to within 15%. But combining them with the NLO structure functions underestimates the cross-section by a factor of 1.5 - 2. Therefore we shall use the LO structure functions CTEQ 3L [28] in our analysis with the standard choice of the QCD scale Q equal to the squark mass. We have checked that one gets essentially identical results with the GRV 94 LO [29] structure functions. The structure functions are used via the PDFLIB version 6.06 [30].

Because of the large top mass, $m_t \simeq 175$ GeV, the stop decay into the neutralino states can only proceed through higher order processes,

$$\tilde{t}_1 \rightarrow c\tilde{Z}_1 \text{ and } \tilde{t}_1 \rightarrow b\bar{q}q'\tilde{Z}_1, \quad (20)$$

as long as

$$M_{\tilde{t}_1} \leq M_{\tilde{W}_1}. \quad (21)$$

The corresponding decay widths are negligibly small [31] compared to the R violating decay width (13). Therefore, the dominant decay mode in this case is the R violating decay

$$\tilde{t}_1 \rightarrow e^+d. \quad (22)$$

On the other hand the R conserving decay

$$\tilde{t}_1 \rightarrow b\tilde{W}_i \quad (23)$$

will dominate, when kinematically allowed. The corresponding decay width is given by [25]

$$\begin{aligned} \Gamma(\tilde{t}_1 \rightarrow b\tilde{W}_i) &= \frac{g^2}{16\pi} M_{\tilde{t}_1} (1 - M_{\tilde{W}_i}^2/M_{\tilde{t}_1}^2)^2 (A_L^2 + A_R^2) \\ A_R &= -\frac{m_b U_{i2} \cos \theta}{\sqrt{2} M_W \cos \beta}, \quad A_L = V_{i1}^* \cos \theta + \frac{m_t V_{i2}^* \sin \theta}{\sqrt{2} M_W \sin \beta}, \end{aligned} \quad (24)$$

where U, V are the chargino mixing matrices and we have neglected the b mass in the phase space factor.

Fig.1 shows the resulting branching fraction for the R violating decay (22) over the relevant MSSM parameter space for $M_{\tilde{t}_1} = 200$ GeV. The contours for the lighter chargino mass $M_{\tilde{W}_1} = 85$ GeV and 180 GeV are also shown in

this figure. The former represents the limit of chargino mass which can be probed at LEP-II, although it has not been done so far for the R violating SUSY model. We see that the branching fraction for the direct leptonic decay (22) is $B \leq 0.2$ for a large part of the parameter space corresponding to $M_{\tilde{W}_1} < 180$ GeV (going up to $M_{\tilde{W}_1} < 200$ GeV for a 220 GeV stop). It should be noted that it corresponds to the most favoured region of the MSSM parameter space in terms of the naturalness criterion [32]. Thus the type of the stop signal at Tevatron will be sensitive to the choice of MSSM parameters. Let us analyse them case by case.

(A) **Direct Leptonic Decays** : This corresponds to the direct leptonic decays (22) of the stop pair, resulting in a pair of hard and isolated e^+e^- along with a pair of jets. Both the production and decay processes are identical to the leptoquark case recently investigated by the CDF and DØ collaborations [33,34], except that in this case there can be no decay into the neutrino channel. Using a parton level Monte Carlo simulation we have estimated the signal cross-section following the CDF cuts [33]:

- (i) E_{Te1} and $E_{Te2} > 25$ GeV, $|\eta_{e1}|$ or $|\eta_{e2}| < 1$, isolation ($E_T^{Ac} < 0.1E_{Te}$) ;
- (ii) $E_{Tj1} > 30$ GeV, $E_{Tj2} > 15$ GeV, $|\eta_{j1,j2}| < 2.5$, cone size $R_j = 0.7$;
- (iii) $M_{ee} \neq 76 - 106$ GeV;
- (iv) $E_{Te1} + E_{Te2} > 70$ GeV, $E_{Tj1} + E_{Tj2} > 70$ GeV.

This is supplemented by the identification efficiency of 0.77 for the electron pair along with an azimuthal efficiency factor of 0.75 (corresponding to 85% azimuthal coverage for each electron). We have checked that the acceptance factor after each set of cuts agrees quite well with the CDF result.

Fig.2 shows the signal cross-sections before and after the above mentioned cuts against the stop mass. The right hand scale shows the number of events for the integrated luminosity of 110 pb^{-1} corresponding to the CDF data [33]. After these cuts there are 3 remaining events in this data against a SM background of similar size. The corresponding 95% CL limit of ~ 8 events implies a stop mass limit of ~ 200 GeV. One can eliminate the background by suitable cuts on the ej invariant masses, which can not be implemented however in our parton level MC simulations. The CDF group has achieved this while retaining 2/3rd of the signal by requiring the two ej invariant

masses to match within 20% and their average value to agree with the leptoquark (stop) mass within a 3σ resolution error. This is illustrated by the dotted line in Fig.2, which is obtained by multiplying the long dashed line by $2/3$ over the appropriate mass range. The corresponding 95% CL limits of 3 events gives a better mass bound of $M > 210$ GeV. It may be added here that the $D\emptyset$ group has been able to eliminate the background while retaining 80% of the signal via a hardness cut

$$H_T = E_{Te1} + E_{Te2} + E_{Tj1} + E_{Tj2} > 350 \text{ GeV}. \quad (25)$$

Combining this with an optimized set of kinematic cuts and a higher integrated luminosity of 123 pb^{-1} they have reported a higher mass limit of $M > 225$ GeV [34].

Thus the CDF and $D\emptyset$ leptoquark limits would rule out the stop scenario if the direct leptonic decays are dominant, i.e. $M_{\tilde{W}_1} \geq M_{\tilde{t}_1}$. It may be noted here that the alternative scenario of eq. (9) corresponds to $B > 0.5$, which may be already incompatible with the combined CDF and $D\emptyset$ data. However the favoured scenario (8) implies $B \leq 0.2$ over a large part of the MSSM parameter space corresponding to $M_{\tilde{W}_1} < 180$ GeV (Fig.1). This means a reduction of the dilepton signal cross-section by a factor of at least 25. Evidently the present data sample of CDF and $D\emptyset$ is in no position to probe a signal of this size. One expects a 20 fold increase in the integrated luminosity to 2 fb^{-1} during the next (Main Injector(MI)) run of Tevatron. Moreover the increase of the CM energy from 1.8 to 2 TeV corresponds to a 50% increase in the cross-section. Thus one expects a 30 fold increase in the signal size during the MI run, which can probe the stop signal down to $B = 0.2$. Nonetheless there is a significant range of MSSM parameters, corresponding to $B < 0.2$, which will not be accessible to the dilepton signal during the MI run. With a further increase of luminosity to 20 fb^{-1} at TeV33 it may be possible to probe the entire MSSM parameter space for the stop scenario via the dilepton channel. Nonetheless it is important to see if one can do better via the other decay modes of stop.

(B) **Mixed Mode** : A more favourable signature for stop pair production in the low B ($\lesssim 0.2$) region is provided by the mixed mode, corresponding to direct leptonic decay (22) of one stop, while the other undergoes cascade decay

$$\tilde{t}_1 \rightarrow b\tilde{W}_1, \tilde{W}_1 \rightarrow q'\tilde{q}\tilde{Z}_1, \tilde{Z}_1 \xrightarrow{\lambda'_{131}} \bar{b}\bar{v}d + h.c. \quad (26)$$

Note that the R violating decay of the lightest superparticle (LSP) in this case is restricted to the neutrino channel due to the large top mass. Thus the final state will consist of a very hard e^\pm , a large number of jets including a pair of b , and a modest amount of missing p_T carried by the neutrino. We have estimated the signal cross-section for the following set of cuts:

- (i) $p_T^e > 40$ GeV, $|\eta_e| < 1$, isolation ($E_T^{AC} < 0.1p_T^e$);
- (ii) $n_j \geq 3$ with $E_T^j > 15$ GeV, $|\eta_j| < 2.5$, cone size $R_j = 0.7$;
- (iii) $M_T(e, E_T) \neq 50 - 110$ GeV
- (iv) $\geq 1b$ -jet with $E_T^b > 20$ GeV and $|\eta_b| < 2$.

The 3rd cut is designed to reduce W decay background. We assume electron identification and b -tagging efficiencies of

$$\varepsilon_{e-id} = 0.8 \quad \varepsilon_b = 0.3. \quad (27)$$

With the above acceptance cuts and b -tagging, the dominant SM background is expected to come from $\bar{t}t$ production. Fig.3 shows the signal cross-section for a 200 GeV stop along with the $\bar{t}t$ background at $\sqrt{s} = 2$ TeV. The MSSM parameters used are

$$M_2 = 150\text{GeV}, \mu = -400\text{GeV}, \tan\beta = 2 \Rightarrow M_{\tilde{W}_1} = 158\text{GeV}, M_{\tilde{Z}_1} = 77\text{GeV}; \quad (28)$$

but the signal cross-section is insensitive to these parameters. The signal shows a much harder electron p_T distribution than the $\bar{t}t$ background. Besides one can exploit the clustering of invariant mass of the electron with the hardest jet at $M \simeq 200\text{GeV}$, to distinguish the signal from the background. Thus it seems feasible to separate the signal from the background while retaining the bulk of the signal size.

The size of the signal cross-section in Fig.3 is about 50 fb, corresponding to ~ 100 events at the MI run. But it is yet to be multiplied by the branching factor $\simeq 2B$. The smallest branching fraction over the allowed MSSM parameter space (Fig.1) is $B \simeq 7\%$. Hence this signature should be able to probe the stop signal at the MI run over the full parameter space of MSSM. An interesting feature of this signal is that the b -jet pair will contain unlike as well as like sign b 's with equal probability, though it may be hard to test it experimentally.

(C) **Cascade Decays** : The largest event rate for $B \leq 0.2$ corresponds to the cascade decay (26) of each of the stop pair. The resulting final state consists of 4 b -quarks and a missing p_T carried by the neutrinos; but the latter is severely degraded compared to the R conserving case. Consequently the process suffers from a large background from $\bar{t}t$ as well as $\bar{b}b$ production. The leptonic decay of one of the charginos ($\tilde{W}_1 \rightarrow l\nu\tilde{Z}_1$) will give a lepton (e, μ) 40% of the time; but its detectibility will depend on the chargino-neutralino mass difference. In any case the $\bar{t}t$ background remains and is 30–40 times larger at the level of the raw cross-section. Therefore one would need tripple b tag to separate this signal from the background. We have estimated the signal cross-section for the two channels with the following cuts:

- (I) $p_T^b > 40$ GeV, $n_b \geq 3$ with $E_T^b > 20$ GeV, $|\eta_b| < 2$;
- (II) $p_T^l > 15$ GeV, $|\eta_l| < 1$, $E_T^{AC} < 0.1p_T^l$, $p_T^b > 20$ GeV, $n_b \geq 3$ with $E_T^b > 20$ GeV, $|\eta_b| < 2$;

assuming a b -tagging efficiency $\epsilon_b = 0.3$. Table-II shows the cross-sections for these two channels for a stop mass of 200 GeV and a CM energy of 2 TeV. The cross-sections are shown for several values of the M_2 and μ parameters with $\tan\beta = 2$. The cross-sections are similar in size at $\tan\beta = 10$ as well. The first two rows correspond to the gaugino dominated region ($M_2 \ll |\mu|$), characterised by $M_{\tilde{Z}_1} \simeq M_{\tilde{W}_1}/2$. The last two rows correspond to the higgsino dominated region ($|\mu| \ll M_2$), characterised by $M_{\tilde{Z}_1} \simeq M_{\tilde{W}_1}$. The first case implies harder lepton p_T but relatively soft missing- p_T , compared to the second. Consequently the missing- p_T signal goes up while the leptonic signal goes down as we go from the gaugino region to the higgsino one. Notwithstanding this complementarity, however, the absolute size of the signal is too small to provide a viable signature for an integrated luminosity of $2fb^{-1}$. In short, we found no viable signature for detecting stop pair production, when both of them undergo cascade decay via (26).

Note that the above conclusion is based on the current b tagging efficiency of 30%. An increase of this efficiency to 50%, as envisaged for the Main Injector run, will result in a 4-5 times increase in the signal cross-section. This could make it viable over a large range of MSSM parameters.

4. The Charm Squark (Scharm!) Scenario at Tevatron :

In this case one expects 8 species of roughly degenerate squarks along with a gluino of comparable or smaller mass. Only one of them, the left handed charm squark \tilde{c}_L , has the R violating decay mode as required to explain the HERA anomaly

$$\tilde{c}_L \rightarrow e^+ d. \quad (29)$$

In order to estimate its branching fraction B , let us note that the width for the largest R conserving decays into the \tilde{W} dominated chargino and neutralino states are

$$\begin{aligned} \Gamma(\tilde{c}_L \rightarrow s \tilde{W}_i) &= \frac{g^2}{16\pi} M_{\tilde{c}} (1 - M_{\tilde{W}_i}^2/M_{\tilde{c}}^2)^2 V_{i1}^2, \\ \Gamma(\tilde{c}_L \rightarrow c \tilde{Z}_i) &= \frac{g^2}{32\pi} M_{\tilde{c}} (1 - M_{\tilde{Z}_i}^2/M_{\tilde{c}}^2)^2 N_{i2}^2. \end{aligned} \quad (30)$$

The masses and compositions of these states correspond to

$$M_{\tilde{W}_i, \tilde{Z}_i} \simeq M_2 \leq \frac{1}{3} M_{\tilde{c}} \quad \text{and} \quad V_{i1}, N_{i2} \simeq 1. \quad (31)$$

Combining these with eqs.(12,13) one sees that the branching fraction for the R violating decay (29) is

$$B \lesssim 1/20. \quad (32)$$

Therefore the direct leptonic decay channel (29) will not give a viable SUSY signature in this case. Instead one has to consider the cascade decay of the squarks and gluinos into the LSP. Fortunately the R violating decay of the LSP into e^\pm ,

$$\tilde{Z}_1 \xrightarrow{\lambda'_{121}} \bar{c} e^+ d (\bar{s} \bar{v} d) + h.c. \quad (33)$$

provides a distinctive like sign dilepton (LSD) signature in this case. Using this signature one can test this R violating SUSY scenario over most of the MSSM parameter space even with the present Tevatron data.

In this case one has to consider a host of production processes [26]

$$q\bar{q}(gg) \rightarrow \tilde{q}\tilde{q}, q\bar{q}(gg) \rightarrow \tilde{g}\tilde{g}, qg(\bar{q}g) \rightarrow \tilde{q}\tilde{g}(\tilde{q}\tilde{g}). \quad (34)$$

For $M_{\tilde{q}} < M_{\tilde{g}}$, the cascade decay proceeds via the electroweak decays of squarks. Over most of the parameter space of interest the \tilde{W}_1 and \tilde{Z}_2 states

are dominated by the \tilde{W} component while the \tilde{Z}_1 is dominated by \tilde{B} . Thus the dominant decay modes of the left-handed squark are

$$\tilde{q}_L \rightarrow q'\tilde{W}_1, q\tilde{Z}_2(\tilde{W}_1 \rightarrow q\bar{q}'\tilde{Z}_1, \tilde{Z}_2 \rightarrow q\bar{q}\tilde{Z}_1), \quad (35)$$

while the right-handed squark decays directly into the LSP,

$$\tilde{q}_R \rightarrow q\tilde{Z}_1. \quad (36)$$

For $M_{\tilde{g}} < M_{\tilde{q}}$, the cascade decay proceeds via the 3-body decays of gluino, i.e.

$$\tilde{g} \rightarrow q\bar{q}'\tilde{W}_1(50\%), q\bar{q}\tilde{Z}_2(30\%), q\bar{q}\tilde{Z}_1(20\%), \quad (37)$$

where the approximate branching fractions are indicated in the bracket [35]. Finally the produced pair of LSP undergo the R violating decay (33).

Thanks to the Majorana nature of the LSP (\tilde{Z}_1), the final state di-electron have equal probability of having unlike and like signs. The latter constitutes a viable signature due to the low SM background in this channel. Indeed the LSD signature for R violating SUSY model has been considered in [35,36] for a variety of the λ and λ' couplings. We shall concentrate here on λ'_{121} as the leading R violating Yukawa coupling, as suggested by the charm squark scenario. We have estimated the LSD cross-section for the following kinematic cuts:

$$p_T^l > 15\text{GeV}, |\eta_l| < 1, \text{ Isolation } (E_T^{AC} < 5\text{GeV}) . \quad (38)$$

The SM background for these cuts has been estimated to be only 2.4 fb at the CM energy of 1.8 TeV, coming mainly from WZ and $t\bar{t}$ channels[36].

Fig.4 shows the LSD signal cross-section at a CM energy of 1.8 TeV for different choices of the MSSM parameters. In each case the signal is shown for a common squark mass $M_{\tilde{q}} = 210$ GeV, with $M_{\tilde{g}} = 150\text{--}240$ GeV. The upper limit of $M_{\tilde{g}}$ is suggested by eqs.(15,16)[37]. The contributions from the three final states of eq.(34) to the signal are shown separately. They include the contributions from the small leptonic components in $\tilde{W}_1, \tilde{Z}_2 \rightarrow \tilde{Z}_1$ decays. But the bulk of the contribution corresponds to the dielectron coming from the LSP decays. We have not included any efficiency factor for electron identification. But it is clear from this figure that, even after making allowance for the identification efficiency, one expects to see at least half a dozen like sign dielectron events with the present Tevatron luminosity of 110pb^{-1} . We conclude this section with the hope that this data will be

analysed soon to probe the R violating SUSY model, and in particular to test the charm squark scenario for the anomalous HERA events. Indeed it should be possible to do this with the dilepton data even without charge identification, where one can control the SM background by choosing suitable kinematic cuts.

5. Summary :

The two favoured scenarios for the anomalous HERA events in the R-parity violating SUSY model are the production of top and charm squarks off the valence d quark via the Yukawa couplings λ'_{131} and λ'_{121} respectively. We have studied the prospects of testing these scenarios at the Tevatron collider assuming MSSM with common superparticle masses at the unification scale. In this case the size of the required λ' coupling and the corresponding decay branching fraction B can be independently estimated as functions of the MSSM parameters. We find $B \ll 1$ for the charm squark, while the same is also true for the stop over a large range of the MSSM parameters. Consequently the canonical leptoquark signature of dilepton plus dijets is of limited value in probing these scenarios at Tevatron. We suggest alternative signatures, which seem to be viable over the entire parameter space of interest. We have also considered the alternative scenario for stop production from a strange quark via the λ'_{132} coupling. In this case $\lambda' > 1/2$; and this scenario may be already in conflict with the combined Tevatron data via the leptoquark signature.

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Table–I: Different squark formation and decay processes are shown along with the size of the corresponding R violating Yukawa couplings, required to explain the HERA events. The last column shows the upper limits on these couplings from other processes.

Process	Reqd. $\lambda'\sqrt{B}$	λ' limit ($M_{\tilde{q}} \simeq 200$ GeV)
$e^+d \rightarrow \tilde{u}_j \rightarrow e^+d$	0.04	$\lambda'_{111} < .004, \lambda'_{121,131} < .13(.10)$
$e^+s \rightarrow \tilde{u}_j \rightarrow e^+s$	0.3	$\lambda'_{112} < .06, \lambda'_{122} < .09, \lambda'_{132} < 0.6$
$e^+b \rightarrow \tilde{u}_j \rightarrow e^+b$	0.6	$\lambda'_{113} < .06, \lambda'_{123} < .55, \lambda'_{133} < .003$
$e^+\bar{u} \rightarrow \tilde{d}_k \rightarrow e^+\bar{u}$	0.3	$\lambda'_{111} < .004, \lambda'_{112,113} < .06$
$e^+\bar{c} \rightarrow \tilde{d}_k \rightarrow e^+\bar{c}$	0.4	$\lambda'_{121} < .13, \lambda'_{122} < .09, \lambda'_{123} < .55$

Table–II: Stop cross-section in the cascade decay channels with and without a lepton for $M_{\tilde{t}_1} = 200$ GeV, $\sqrt{s} = 2$ TeV and the cuts described in the Text. The results are shown for several gaugino and higgsino mass parameters with $\tan\beta = 2$.

M_2 (GeV)	μ (GeV)	$M_{\tilde{W}_1}$ (GeV)	$M_{\tilde{z}_1}$ (GeV)	$\sigma(fb)$ (I) $p_{T+} \geq 3b$ (II) $l + p_{T+} \geq 3b$
150	-400	158	77	3.3 2
100	-800	105	51	2 1.4
100	-100	101	51	3 1.5
200	-100	112	89	6 1.2
300	-100	111	95	8 0.8

Figure Captions

- Fig.1 : The stop branching fraction(eq.11) is shown as a contour plot in the M_2, μ plane for the stop mass $M_{\tilde{t}_1} = 200\text{GeV}$, $\tan\beta = 2$ and (a) $\theta_{\tilde{t}} = 0^\circ$ (b) $\theta_{\tilde{t}} = -45^\circ$. Contours for the lighter chargino mass of 180GeV(solid line) and 85GeV(dotted line) are shown.
- Fig.2 : The stop pair-production cross section(No. of events for 110 pb^{-1} luminosity) shown against the stop mass at the Tevatron collider energy of 1.8 TeV. The solid line corresponds to the raw cross section, while the long and short dashed lines correspond to the dielectron+dijet cross sections following the CDF cuts as described in the text.
- Fig.3 : The signal cross section(solid line) corresponding to the mixed mode(B) is shown for stop mass of 200 GeV along with the $t\bar{t}$ background(dashed line) against the p_T of the electron at 2 TeV. The MSSM parameters are $M_2 = 150\text{GeV}$, $\mu = -400\text{GeV}$, and $\tan\beta = 2$.
- Fig.4 : The gluino-gluino(solid line), squark-antisquark(short dashed) and squark-gluino(long dashed) contributions to LSD cross section shown as a function of gluino mass for $(\mu, \tan\beta) =$ (a) -100 GeV, 2 (b) -300 GeV, 2 (c)-300 GeV, 10.

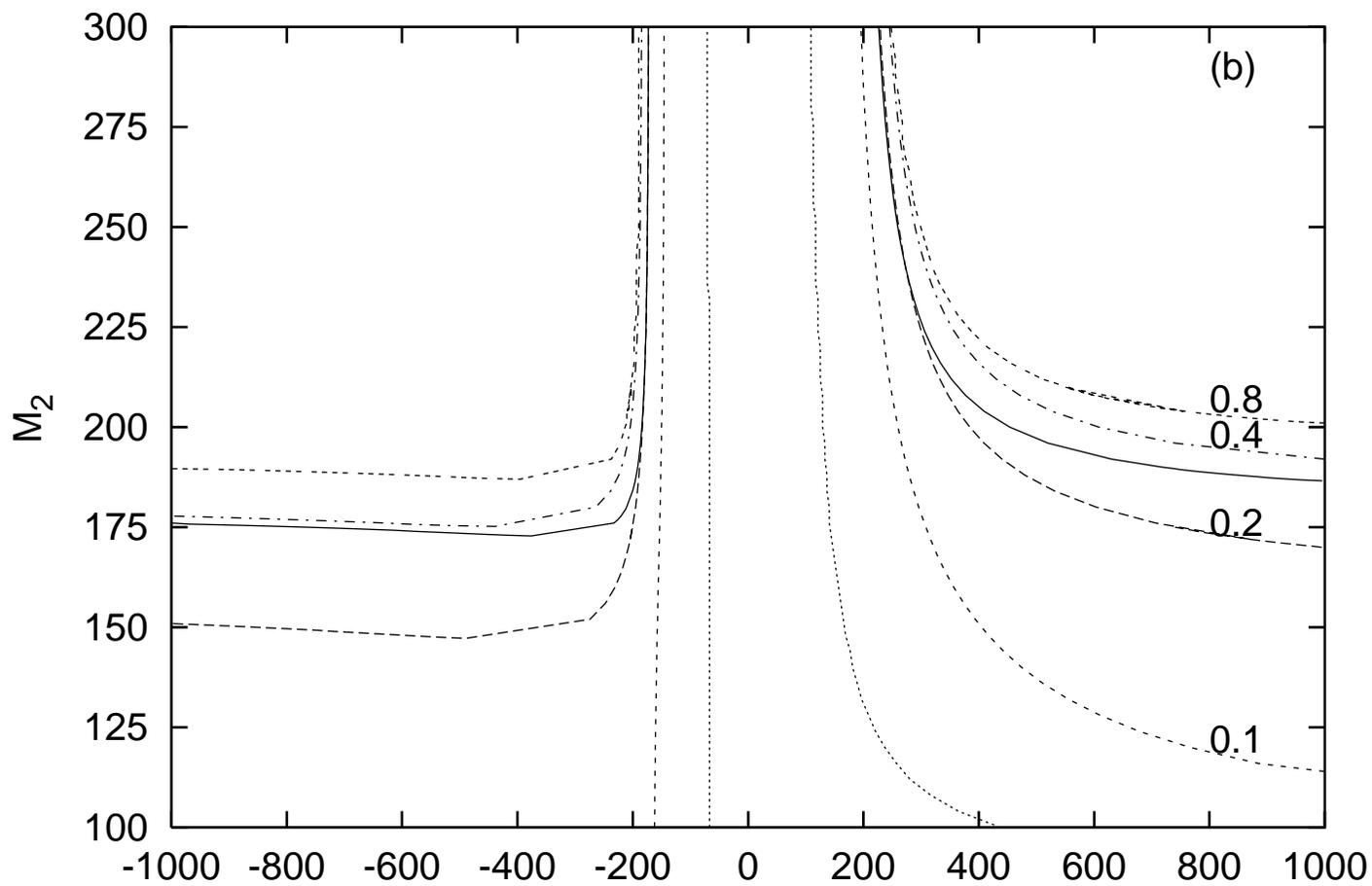
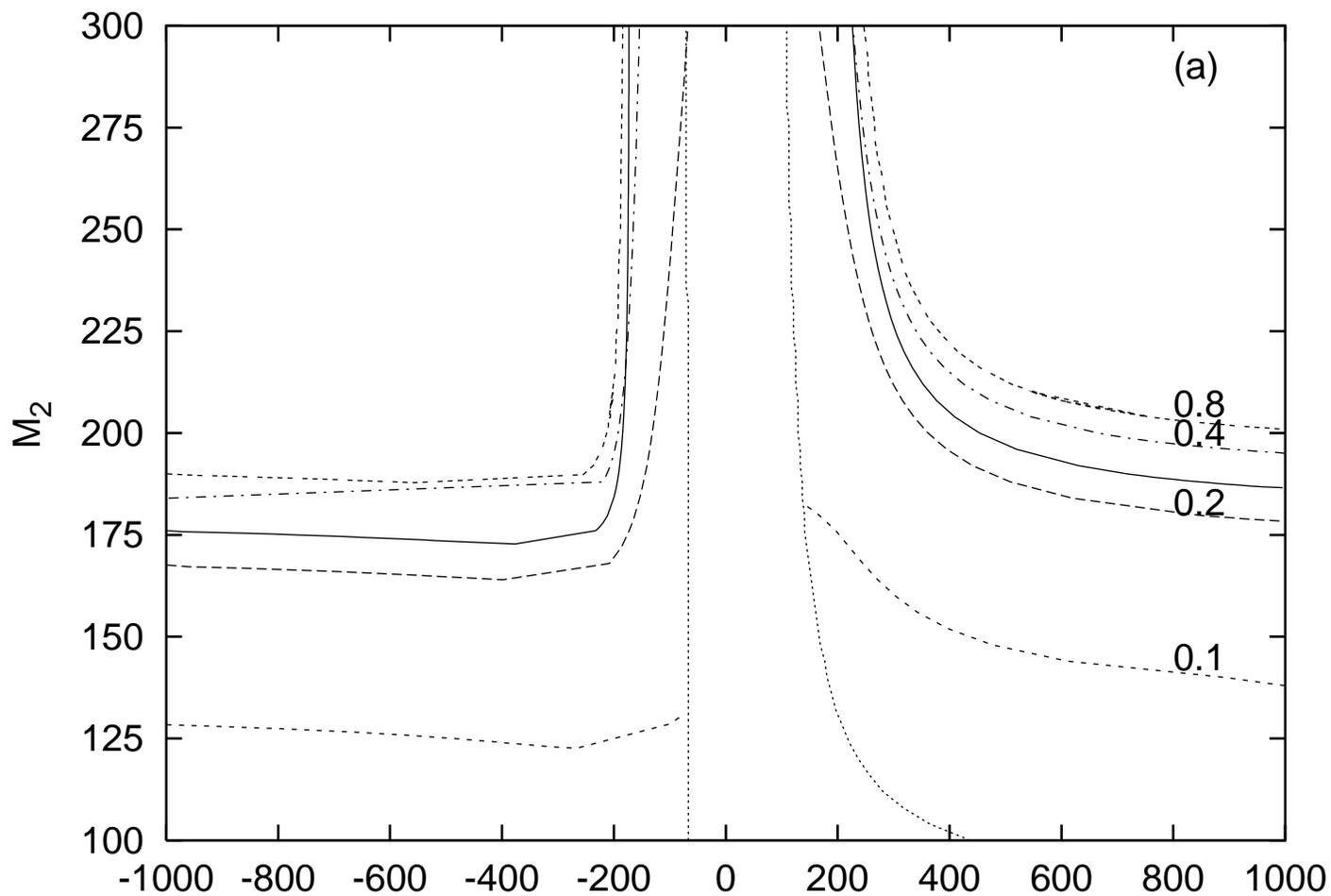


Fig.1

μ

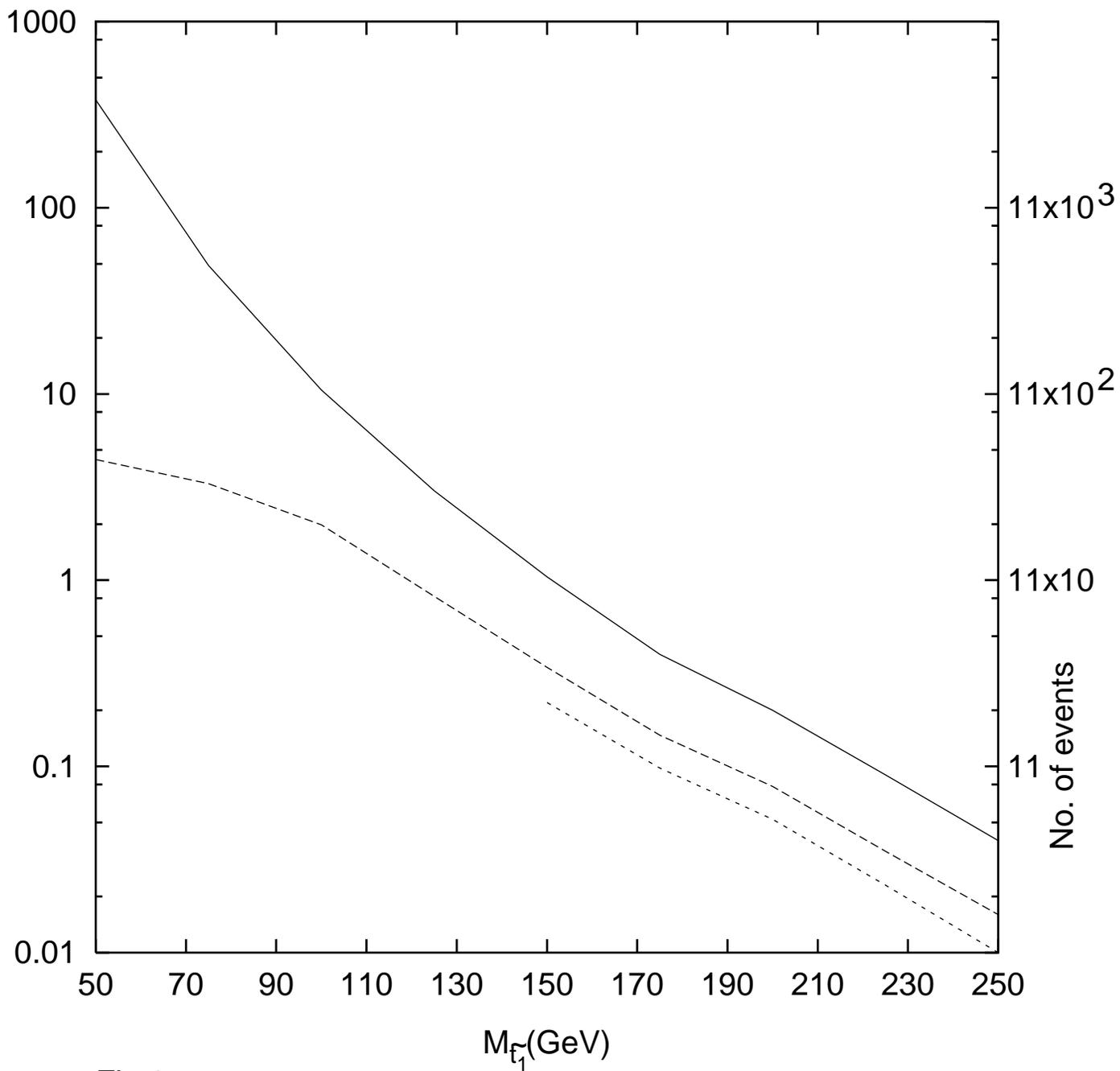


Fig.2

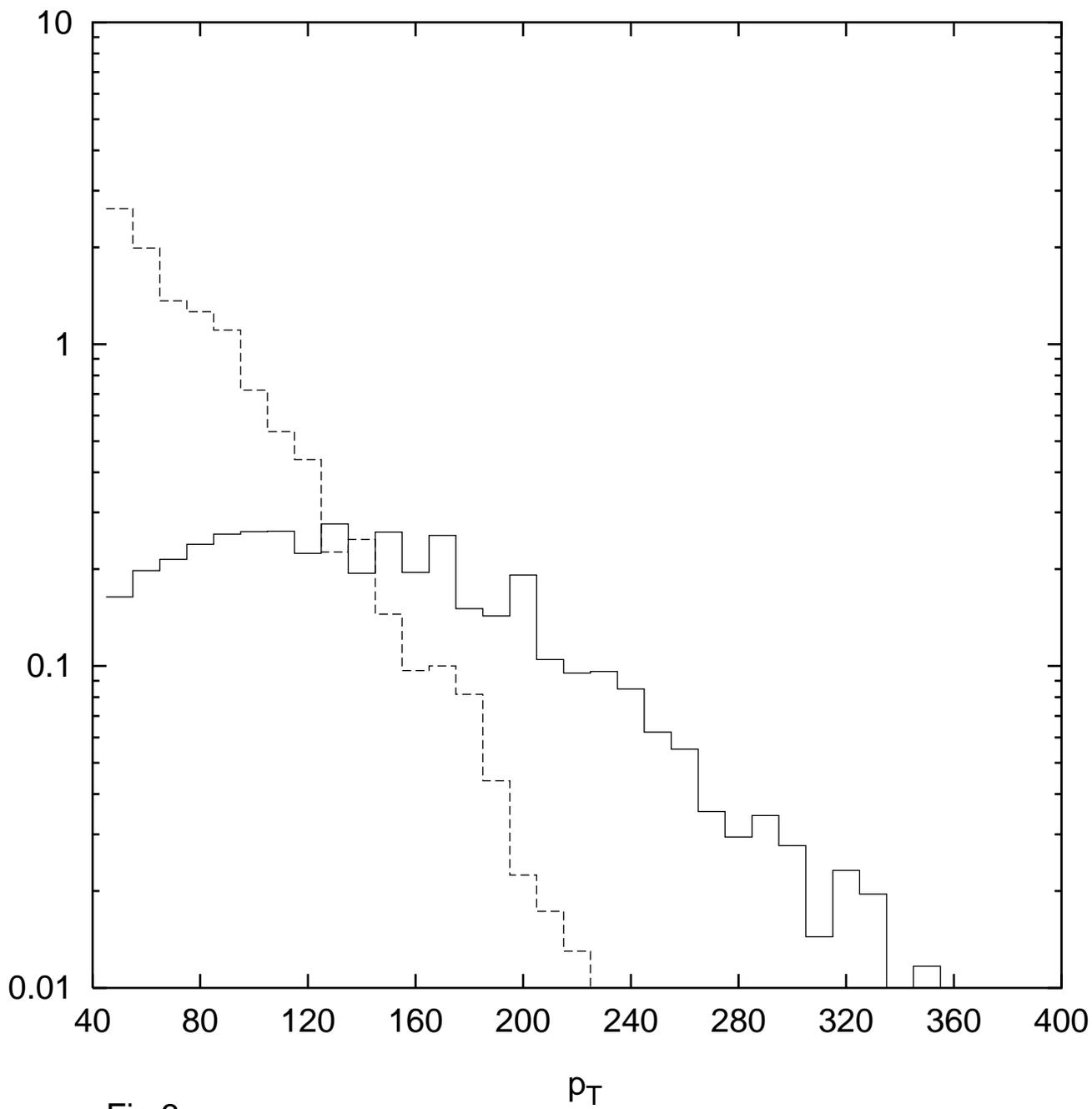


Fig.3

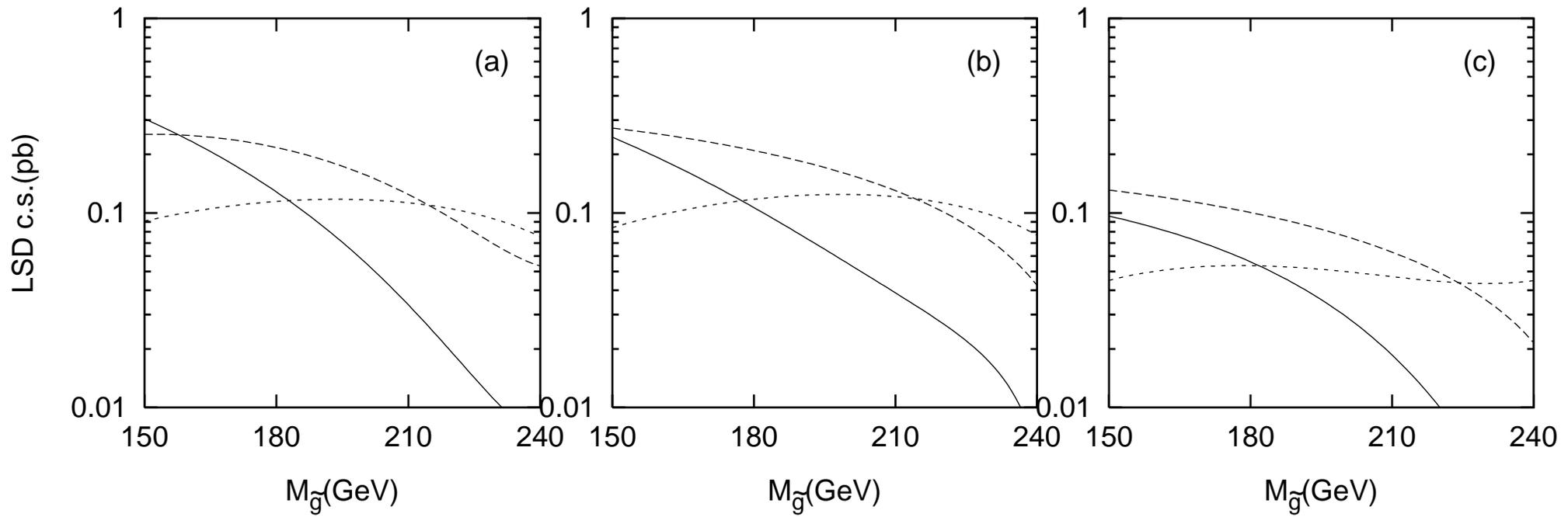


Fig.4