SIGNATURES OF VIRTUAL LSPs AT THE TEVATRON

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ABSTRACT

Relatively light sneutrinos which are experimentally allowed and are not theoretically disfavoured may significantly affect the currently popular search strategies for supersymmetric particles by decaying dominantly into an invisible channel. In certain cases the second lightest neutralino may also decay invisibly leading to two extra carriers of missing energy (in addition to the lightest supersymmetric particle (LSP) ) - the virtual LSPs (VLSPs). The lighter charginos which would be produced in pairs with reasonably large cross-sections at TEVATRON energies, decay dominantly into the hadronically quiet lepton + sneutrino ( / E_T ) modes with large branching ratios leading to interesting unlike sign dilepton events which are not swamped by the standard model background. The kinematical cuts required to eliminate the backgrounds from WW, Drell-Yan and τ pair production are discussed in detail. With 100 pb^{-1} luminosity 10 - 35 background free events can be found in a large region of the SUSY parameter space.

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I. INTRODUCTION.

Supersymmetry (SUSY) [1] provides an elegant solution of the notorious fine-tuning problem [2] which arises in the standard model (SM). Moreover, this solution works only if the supersymmetric partners of the known particles have masses $\sim 1$ TeV. The lower end of this interesting mass spectrum is already accessible to some of the ongoing accelerators like the Fermilab Tevatron or LEP–100 at CERN. The planned accelerators like the LEP–200 or the LHC at CERN can probe even higher mass scales. The search for supersymmetry (SUSY) is, therefore, a high priority programme.

The strategy for hunting SUSY particles hinges on one crucial assumption: there is a single, stable (by virtue of a conserved quantum number (R-parity)), weakly interacting particle, the so-called lightest supersymmetric particle (LSP). This particle if produced easily escapes detection. It is further assumed that as a result of the above conservation law all other superparticles eventually decay into the LSP. The LSP alone carries missing transverse energy ($\not{E}_T$) which is traditionally regarded as the most distinctive signature of SUSY particles.

The minimal supersymmetric extension of the standard model (MSSM) contains four spin 1/2 neutral particles. These particles are the super–partners of the photon, the $Z$ boson and the two neutral Higgs bosons. Linear combinations of these four states, the four neutralinos ($\tilde{N}_i$, i=1-4), are the physical states. In the currently favoured models, the lightest among them ($\tilde{N}_1$) is assumed to be the LSP [1].

Recently it has been emphasised[2, 3] that there may exist SUSY particles which, though unstable, decay dominantly into invisible channels. This occurs if the sneutrinos ($\tilde{\nu}$) (the super–partners of the neutrinos), though heavier than the LSP, are
lighter than the lighter chargino ($\tilde{\chi}_2$) and the second lightest neutralino ($\tilde{N}_2$) and are much lighter than all other SUSY particles. As a consequence, the **invisible two-body decay mode** $\tilde{\nu} \rightarrow \nu \tilde{N}_1$ opens up and completely dominates over others, being the only kinematically allowed two-body decay of the sneutrinos. The other necessary condition for this scheme to work is that the $\tilde{N}_1$ has a substantial Zino component. This, however, is almost always the case as long as the gluino (the super–partner of the gluon) has a mass ($m_{\tilde{g}}$) in the range interesting for the SUSY searches at the Tevatron [4]. Moreover, in such cases the $\tilde{N}_2$ which also has a dominant Zino component, decays primarily through the process $\tilde{N}_2 \rightarrow \nu \bar{\nu}$. These two particles ($\tilde{N}_2$ and $\tilde{\nu}$) decaying primarily into invisible channels, hereafter called **virtual LSP (VLSP)**’s, may act as additional sources of $\not{E}_T$ and can significantly affect the strategies for SUSY search[2].

Another important consequence of relatively light sneutrinos is that $\tilde{\chi}_2$ decays leptonically with a branching ratio (BR) $\approx 1$. This occurs via the mode $\tilde{\chi}_2 \rightarrow l \tilde{\nu}$ which is its only kinematically allowed two body decay. In the following this decay will play a crucial role, with $l = e$ or $\mu$.

So far the SUSY search programmes at hadron colliders [4] are primarily based on the production of the strongly interacting particles – the squarks and the gluinos – and their subsequent decays. The impact of the VLSPs on these searches were considered in [2]. However as the luminosity accumulates at the Tevatron, processes with lower cross-sections may also become relevant in the SUSY hunt programme [4, 5]. Virtual LSP’s can significantly affect these search strategies as well. For example, in the conventional SUSY scenarios the process [3, 4] $p \bar{p} \rightarrow \tilde{\chi}_2 \tilde{N}_2 \rightarrow 3l + \not{E}_T$ can probe SUSY parameter ranges which are competitive with the reach of LEP-II [3]. In models with virtual LSP’s, thanks to the decay $\tilde{N}_2 \rightarrow \nu \bar{\nu}$, the final state for the above process may consist only
of a single lepton (from $\tilde{\chi}_2 \rightarrow l\tilde{\nu}$) + $\not{E}_T$. This will obviously be overwhelmed by the backgrounds from $W \rightarrow l\nu$.

The presence of virtual LSP’s can, however, strengthen the hadronically quiet 2+$\not{E}_T$ signal coming from $\tilde{\chi}_2$-pair production followed by the decay $\tilde{\chi}_2 \rightarrow l\tilde{\nu}$, where $l = e$ or $\mu$. In the conventional scenario this signal cannot compete with the background, e.g. , from $WW$ production. The cross-section for the latter process is about 10$pb$, while the $\tilde{\chi}_2\tilde{\chi}_2$ production cross-section is only $\sim 1 pb$. Since similar BR’s are involved in the signal and the background, the signal does not seem to be promising. If, on the other hand, virtual LSP’s are present, the situation changes drastically since $B(\tilde{\chi}_2 \rightarrow l\tilde{\nu}) \approx 2/3$, which is significantly larger than $B(W \rightarrow l\nu)$, where $l = e$ or $\mu$. The signal cross-section is then estimated to be 4/9$pb$, while the background cross-section is approximately 2/5$pb$. In this paper we analyse this hadronically quiet unlike sign dilepton signal more quantitatively. We note that the sneutrinos being massive, the lepton spectrum in the decay is expected to be softer than that of the leptons from $W$ decays. Exploiting this fact we can eliminate the lepton background coming from $W-W$ pair production by imposing suitable kinematical cuts.

The other important backgrounds that we have considered are the 1) Drell- Yan pair production of $\tau^+ - \tau^-$ and their subsequent leptonic decays, 2) $p\overline{p} \rightarrow Z-Z$ with one $Z$ decaying into an invisible mode and the other decaying leptonically, 3) $p\overline{p} \rightarrow W-W$, one $W$ decays leptonically into a stable lepton ($e$ or $\mu$), while the other decays into a $\tau$ and a neutrino; the $\tau$ subsequently decays leptonically. All these backgrounds and their removal are discussed in detail in the next section, where we also present our results systematically.
II. Results and Discussions.

We have generated the $\tilde{\chi}_2 - \tilde{\chi}_2$ events by a parton level Monte-Carlo programme using the EHLQ-2 parton density functions. The formula for chargino pair production cross-section is given, e.g., in [8]. The chargino pair production cross-section, thus computed, matches well with the cross-sections given by others [6]. Our choices of the SUSY parameters are consistent with the constraints from LEP 100 [10].

Our signal for the chargino pair production is hadronically quiet opposite sign dilepton events ($e$ or $\mu$). We show in the fig. 1 the $P_T$ distribution of leptons (without any kinematic cuts) arising from the decays of W’s and charginos. We see that the leptons from W decay peak around 35 GeV as expected, whereas the leptons from the chargino decay are considerably softer because this decay is associated with a heavy sneutrino. We finally note that if events are selected with both the leptons having $P_T < 25$ GeV the background is removed almost completely, without affecting signal very much.

Drell-Yan $e^+ - e^-$ and $\mu^+ - \mu^-$ events are expected to be back to back in the transverse plane and can be easily eliminated. However, $\tau^+ - \tau^-$ events with both the $\tau$’s decaying leptonically constitute a more serious background. These leptons essentially move along the $\tau$ direction as a result of high boost. So these leptons will also be nearly back to back in the transverse plane. Following the CDF collaboration we have introduced an upper cut of 160° on $\phi$, the azimuthal angle between the leptons in the transverse plane. Low $P_T$ background leptons, however, survive this cut. We show in fig. 2 the $P_T$ distribution of leptons from the background and the signal with the cut on the azimuthal angle as discussed above. The distribution clearly shows that the Drell-Yan leptons which survive this cut have $P_T$ peaking at low values. A cut of $P_T > 10$ Gev
eliminates the remaining background.

In summary we demand that both the leptons should have $P_T$ within a window of $10\,\text{GeV} < P_T < 25\,\text{GeV}$ and the azimuthal angle between the leptons <160°. The requirement that both the leptons fall within the $P_T$ window, very efficiently reduces the background.

We have also considered the $\not{E}_T$ distributions of chargino pair events and WW events with the above $\phi$ and $\not{E}_T$ cut. Both the signal and the background have large $\not{E}_T$. It turns out that the conventional $P_T$ cut is not particularly efficient in this case.

We have also introduced CDF type cut [12] on the invariant mass of the lepton pair used in the context of the search for hadronically quiet trilepton events and have required $80\,\text{GeV} < M_{ll} < 100\,\text{GeV}$. We have used the isolation cut between the two leptons similar to that used by the CDF group [12]. We require the isolation $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$ between the leptons to be greater than 0.4. Apart from these cuts we have taken care of the CDF detector acceptance for electrons and muons by introducing different pseudorapidity cuts as described in [12].

With all these cuts we have no background events from ZZ production, with one Z decaying invisibly and the other leptonically or from WW production, with one W going to $e$ or $\mu$ and the other going to $\tau$ which then decays leptonically.

We now discuss the signal events which survive all these cuts. We have calculated the signal cross-section with different values of $m_{\tilde{g}}$ and the $\mu$ parameter for two values of $\tan \beta$ (=2 and 10). All through we have taken $m_{\tilde{q}} = m_{\tilde{g}} + 125\,\text{GeV}$. Table I shows the number of events surviving all cuts with an integrated luminosity of 100 $\text{pb}^{-1}$ for $\tan \beta = 2$ and Table II shows the same for $\tan \beta = 10$. For each set of parameters lighter chargino mass $m_{\tilde{\chi}^\pm_2}$ has also been shown. We have taken the sneutrino mass to be 60
GeV. The numbers of ee, e-µ and µ - µ events are quoted differently since the detector acceptances are different for e and µ. It is expected that with the main injector upgrade at the Tevatron the integrated luminosity would be as high as 1000pb⁻¹ by the end of this century [13]. It is quite clear from the numbers given in the tables that should this happen, SUSY search following the strategy chalked out in the paper will be even more attractive.

We see that even for low gluino mass, \( m_\tilde{g} = 150 \text{ GeV} \), which is outside the domain of search via the like sign dilepton mode in this scenario \([2]\) we expect about 22 events for \( \mu = -100 \text{ GeV} \) and 8 events for \( \mu = -200 \text{ GeV} \).

For a higher gluino mass (\( m_\tilde{g} = 300 \text{ GeV} \)), which is likely to be beyond the reach of the Tevatron by direct search following any conventional search strategy, we still find about 10 - 35 background free events with \( \mu \) positive and \( \tan \beta = 2 \). For \( \tan \beta = 10 \) only \( \mu = 200 - 300 \text{ GeV} \) gives the above number of background free events.

It is obvious that the lepton \( P_\tau \) spectrum from charginos sensitively depends on the mass difference between the chargino and the sneutrino. For low mass difference the spectrum becomes too soft to be distinguishable from the Drell-Yan \( \tau^+ - \tau^- \) background. Again a large mass difference makes the lepton spectrum too hard to be distinguishable from the WW background. In the fig. 3 we show for the purpose of illustration a plot of the number of surviving signal events with 100 pb⁻¹ luminosity as a function of the sneutrino mass for a fixed mass of the chargino (=82 GeV). We see there is an optimal mass difference between the chargino and the sneutrino where these cuts are most efficient. Thus for any mass of the chargino we can actually probe the mass of the sneutrino in a certain range.

In this paper the masses of the of the SUSY particles were treated as free phenomeno-
logical parameters. It has, however, already been argued that [2], the VLSP scenario can be accommodated in models based on $N = 1$ Supergravity with common scalar and gaugino masses at a high scale[1]. For further details see [14].

III. Conclusions

In conclusion we wish to reiterate that in the presence of the VLSP’s the hadronically quiet di- and tri-lepton events switch their roles. As pointed out in ref 2, the later signal which is at the focus of current interests [5, 6, 12] may be completely wiped out, while the former looks indeed promising. In this paper we have quantified this claim of ref 2 by calculating the signal at Tevatron energies. We have also shown that the Standard Model background can be eliminated by a judicious combination of kinematical cuts. For a wide range of the SUSY parameter space 10-35 background free events are estimated on the basis of an integrated luminosity of $100 \text{ pb}^{-1}$. With the enhancement of the integrated luminosity due to a possible upgradation of the main injector at the Tevatron, searches in this channel seems to be even more promising.

At Tevatron energies the mass of chargino and sneutrino that can be probed by this method is limited by the available energy. The strategy outlined in this paper can be extended in a straightforward way to LHC energies where higher chargino and sneutrino masses can be probed. At LEP II SUSY signals for chargino masses in the range 80 - 90 GeV can also be looked for via the hadronically quiet unlike sign dilepton events. The elimination of the backgrounds will however be much easier due to the characteristically cleaner environment of a $e^+ - e^-$ machine.

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References

[1] For reviews see, for example, H.P. Nilles, Phys. Rep. 110, 1 (1984); P. Nath, R. Arnowitt and A. Chamseddine, Applied N = 1 Supergravity, ICTP Series in Theo. Phys., Vol I, World Scientific (1984); H. Haber and G. Kane, Phys. Rep. 117, 75 (1985); S. P. Misra, Introduction to Supersymmetry and Supergravity, Wiley Eastern, New Delhi (1992).

[2] A. Datta, B. Mukhopadhyaya and M. Guchhait, PREPRINT MRI - PHY-11/93, submitted for publication.

[3] Some aspects of VLSPs in the context of SUSY searches at hadron colliders have been considered by H. Baer, C. Kao and X. Tata, Phys. Rev. D48, R2978 (1993); M. Barnett, J. Gunion and H. Haber, LBL preprint LBL-34106 (1993).

[4] CDF collaboration, F. Abe et al., Phys. Rev. Lett. 69, 3439 (1992).

[5] R. Arnowitt and P. Nath, Mod. Phys. Lett. A2, 331 (1987).

[6] H. Baer and X. Tata, Phys. Rev. D47, 2739 (1993).

[7] See, for example, V. Barger and R. Phillips, Collider Physics (Addison-wesley, 1987).
[8] E.Eichten et al, Rev.Mod. Phys. **56**, 579(1984).

[9] V.Barger et al, Phys.Lett. **131 B**, 372(1983).

[10] H. Baer, M Drees, X. Tata, Phys. Rev. D**41**, 3414(1990); G. Bhattacharyya, A. Datta, S. N. Ganguli and A. Raychaudhuri, Phys. Rev. Lett. **64**, 2870(1990); A. Datta, M. Guchhait and A. Raychaudhuri, Z. Phys. C**54**, 513 (1992). J. Ellis, G. Ridolfi and F. Zwirner, Phys. Lett. B**237**, 923(1990); M. Davier in Proc. Joint International Lepton-Photon and Europhysics Conference in High Energy Physics, Geneva, 1992 (eds. S. Hegarty et al., World Scientific, 1992) p151.

[11] CDF collaboration, F. Abe et al., Phys.Rev.D **45**, 3921(1992).

[12] CDF collaboration, Fermilab–conf–93/213–E CDF.

[13] See, for example, J. Huth (CDF collaboration) in Proc. XXVI International Conference on High Energy Physics, Dallas, 1992 (ed J. R. Stanford, AIP Conference Proceedings no. 272) p1273.

[14] A.Datta, M.Drees and M.Guchait ,paper submitted to the XXVII International Conf on High Energy Physics, Glasgow,1994,Contribution Code: gls 0712 and Dortmund University pre-print (in preparation).
FIGURE CAPTIONS

1) $P_T$ distribution of leptons with no kinematical cuts. Continuous curve: leptons from chargino decay. Dashed curve: leptons from W decay. SUSY parameters: $m_{\tilde{g}} = 200$ GeV, $\tan\beta = 2$, $\mu = -200$ GeV, $m_{\tilde{\chi}_2^\pm} = 82$ GeV, $m_{\tilde{\nu}} = 60$ GeV.

2) $P_T$ distribution of leptons with $\phi < 160^\circ$ and other cuts (but no cut on $P_T$). Continuous curve: leptons from chargino. Dashed curve: leptons from Drell-Yan $\tau - \tau$ pair production followed by leptonic decays of $\tau$’s. SUSY parameters: same as in figure 1.

3) Variation of the number of signal events surviving all cuts in $100 \, pb^{-1}$ integrated luminosity as a function of the sneutrino mass. SUSY parameters: $m_{\tilde{g}} = 200$ GeV, $\tan\beta = 2$, $\mu = -200$ GeV, $m_{\tilde{\chi}_2^\pm} = 82$ GeV.
Table 1: Number of dilepton events: $\tan \beta = 2.0$, All masses in GeV.

| $m_{\tilde{g}}$ | $\mu$ | $m_{\tilde{\chi}^0_2}$ | ee | $\mu\mu$ | e-$\mu$ | Total no of events |
|-----------------|-------|------------------------|----|---------|---------|-------------------|
| 150             | -100  | 71.6                   | 8  | 4       | 10      | 22                |
| ,,              | -200  | 67.5                   | 3  | 1       | 4       | 8                 |
| 200             | -200  | 82.5                   | 9  | 4       | 11      | 24                |
| ,,              | -400  | 77                     | 13 | 6       | 17      | 36                |
| 250             | -100  | 92.7                   | 2  | 1       | 2       | 5                 |
| ,,              | -300  | 95.2                   | 2  | 1       | 2       | 5                 |
| ,,              | 500   | 70.7                   | 8  | 4       | 11      | 23                |
| ,,              | 700   | 74.7                   | 13 | 6       | 17      | 36                |
| ,,              | 300   | 75.5                   | 13 | 6       | 17      | 36                |
| ,,              | 500   | 86.8                   | 7  | 2       | 8       | 17                |
| ,,              | 700   | 91.1                   | 4  | 1       | 4       | 9                 |
Table 2: Number of dilepton events : $\tan \beta = 10.0$, All masses in GeV.

| $m_{\tilde{g}}$ | $\mu$ | $m_{\tilde{\chi}_2^0}$ | ee | $\mu\mu$ | e-$\mu$ | Total no of events |
|-----------------|-------|--------------------------|----|-----------|---------|--------------------|
| 200             | -300  | 66.3                     | 1  | 1         | 2       | 4                  |
| 250             | -400  | 83.2                     | 10 | 2         | 4       | 16                 |
| "               | 300   | 73.2                     | 11 | 5         | 15      | 31                 |
| "               | -200  | 67.5                     | 10 | 3         | 3       | 16                 |
| 300             | -400  | 99.2                     | 2  | 0         | 1       | 3                  |
| "               | 200   | 78.3                     | 12 | 5         | 14      | 31                 |
| "               | 300   | 88.4                     | 4  | 2         | 3       | 9                  |
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