Resonant sneutrino production at Tevatron Run II

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Abstract

We consider the single chargino production at Tevatron $p\bar{p} \to \tilde{\nu}_i \to \tilde{\chi}^{\pm}_1 l^{\mp}_i$ as induced by the resonant sneutrino production via a dominant R-parity violating coupling of type $\lambda'_{ijk} L_i Q_j D^c_k$. Within a supergravity model, we study the three leptons final state. The comparison with the expected background demonstrate that this signature allows to extend the sensitivity on the supersymmetric mass spectrum beyond the present LEP limits and to probe the relevant R-parity violating coupling down to values one order of magnitude smaller than the most stringent low energy indirect bounds. The trilepton signal offers also the opportunity to reconstruct the neutralino mass in a model independent way with good accuracy.

In the minimal supersymmetric standard model (MSSM), the supersymmetric (SUSY) particles must be produced in pairs. In contrast, the single superpartner production which benefits from a larger phase space is allowed in the R-parity violating ($\not{R}_p$) extension of the MSSM. In particular the SUSY particle resonant production can reach high cross-sections either at leptonic [1] or hadronic colliders [2], even taking into account the strongest low-energy bounds on $\not{R}_p$ coupling constants [3]. Hadronic colliders provide an additional advantage in that they allow to probe a wide mass range of the new resonant particle, due to the continuous energy distribution of the colliding partons. Furthermore, since the resonant production has a cross-section which is proportional to the relevant coupling squared, this could allow an easier determination of the $\not{R}_p$ coupling than pair production reaction. Indeed in the latter case, the sensitivity on the $\not{R}_p$ coupling is mainly provided by the displaced vertex analysis for the Lightest Supersymmetric Particle (LSP) decay, which is difficult experimentally especially at hadronic colliders.

The SUSY particle produced at the resonance mainly decays through R-parity conserving interactions into the LSP, via cascade decays. In the case of a dominant $\lambda''_{ijk} U^c_i D^c_j D^c_k$ coupling, the decay of the LSP leads to multi-jets final states, wich have an high QCD background at hadronic colliders. Besides, at hadronic colliders, the $\lambda_{ijk} L_i L_j E^c_k$ couplings do not contribute

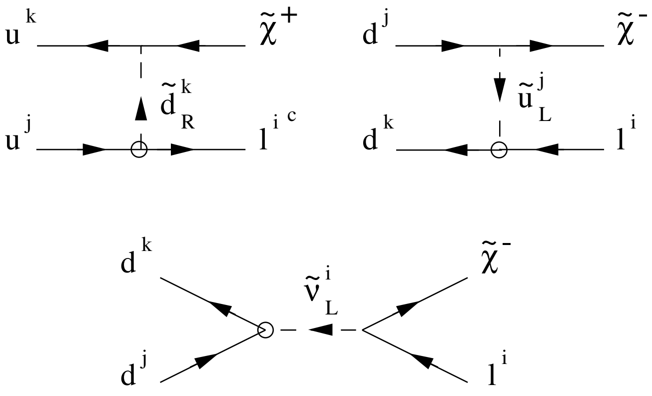

Figure 1: Feynman diagrams for the single chargino production at Tevatron via the λ'_{ijk} coupling (symbolised by a circle in the figure). The arrows denote flow of the particle momentum.

to resonant production. In this letter, we thus assume a dominant $\lambda'_{ijk} L_i Q_j D^c_k$ coupling which initiates the resonant sneutrino production $\bar{d}_j d_k \to \tilde{\nu}_i$ and hence the single chargino production at Tevatron through $p\bar{p} \to \tilde{\nu}_i \to \tilde{\chi}^{\pm}_1 l^{\mp}_i$. We focus on the three leptons signature associated with the cascade decay $\tilde{\chi}^{\pm}_1 \to \tilde{\chi}^0_1 l^{\pm}_p \nu_p$, $\tilde{\chi}^0_1 \to l^+_i \bar{u}_j d_k\ + c.c.$, assuming the $\tilde{\chi}^0_1$ to be the LSP. The main motivation rests on the possibility to reduce the background. This is similar in spirit to a recent study [4] of the like sign dilepton signature from the single neutralino production at Tevatron via the resonant charged slepton production.

We concentrate on the λ'_{211} coupling. The associated hard scattering processes, $d\bar{d} \to \tilde{\nu}_\mu \to \tilde{\chi}^{\pm}_1 \mu^{\mp}$, $d\bar{d} \to \tilde{\chi}^{\pm}_1 \mu^{\mp}$ and $u\bar{u} \to \tilde{\chi}^{\pm}_1 \mu^{\mp}$ (see Fig.1), involve first generation quarks for the initial partons. The indirect constraint on this coupling is $\lambda'_{211} < 0.09(\tilde{m}/100GeV)$ [3]. While λ'_{111} is disfavored due to severe constraints [3], the case of a dominant λ'_{311} could also be of interest.

Our framework is the so-called minimal supergravity model (mSUGRA), in which the absolute value of the Higgsino mixing parameter $|\mu|$ is determined by the radiative electroweak symmetry breaking condition. We restrict to the infrared fixed point region for the top quark Yukawa coupling, in which $\tan\beta$ is fixed [5]. We shall present results for the low solution $\tan\beta \simeq 1.5$ and for $sign(\mu) = -1$, $A = 0$. In fact the cross-section for the single chargino production depends smoothly on the μ, A and $\tan\beta$ parameters. The cross-section can reach values of order a few picobarns. For instance, choosing the mSUGRA point, $M_2(m_Z) = 200GeV$, $m_0 = 200GeV$, and taking $\lambda'_{211} = 0.09$ we find using CTEQ4 [6] parametrization for the parton densities a cross-section of $\sigma(p\bar{p} \to \tilde{\chi}^{\pm}_1 \mu^{\mp}) = 1.45pb$ at a center of mass energy $\sqrt{s} = 2TeV$. Choosing other parametrizations does not change significantly the results since mainly intermediate Bjorken x partons are involved in the studied process. The cross-section depends mainly on the $m_{1/2}$ (or equivalently M_2) and m_0 soft SUSY breaking parameters. As M_2 increases, the chargino mass increases reducing the single chargino production rate. At high values of m_0, the sneutrino mass is enhanced so that the resonant sneutrino production is reduced. This leads to a decrease of the single chargino production rate since the t and u channels contributions are small compared to the resonant sneutrino contribution. Finally, for values of $m_{\tilde{\nu}_\mu}$ (which is related to m_0) approaching $m_{\tilde{\chi}^{\pm}_1}$ (which is related to M_2), a reduction of the chargino production is caused by the decrease of the phase space factor associated to the decay $\tilde{\nu}_\mu \to \chi^{\pm}_1 \mu^{\mp}$.

The single chargino production cross-section must be multiplied by the leptonic decays branching fractions which are $B(\tilde{\chi}^{\pm}_1 \rightarrow \tilde{\chi}^0_1 l^{\pm}_p \nu_p) = 33\%$ (summed over the three leptons species) and $B(\tilde{\chi}^0_1 \rightarrow \mu u d) = 55\%$, for the point chosen above of the mSUGRA parameter space. The leptonic decay of the chargino is typically of order 30% for $m_{\tilde{l}}, m_{\tilde{q}}, m_{\tilde{\chi}^0_2} > m_{\tilde{\chi}^{\pm}_1}$, and is smaller than the hadronic decay $\tilde{\chi}^{\pm}_1 \rightarrow \tilde{\chi}^0_1 \bar{q}_p q'_p$ because of the color factor. When $\tilde{\chi}^0_1$ is the LSP, it decays via λ'_{211} either as $\tilde{\chi}^0_1 \rightarrow \mu u d$ or as $\tilde{\chi}^0_1 \rightarrow \nu_\mu d d$, with branching ratios $B(\tilde{\chi}^0_1 \rightarrow \mu u d)$ ranging between $\sim 40\%$ and $\sim 70\%$.

The backgrounds for the three leptons signature at Tevatron are: (1) The top quark pair production followed by the top decays $t \rightarrow bW$ where one of the charged leptons is generated in b-quark decay. (2) The $W^{\pm} Z^0$ and $Z^0 Z^0$ productions followed by leptonic decays of the gauge bosons. It has been pointed out recently [7, 8] that non negligible contributions can occur through virtual gauge boson, as for example the $W^* Z^*$ or $W \gamma^*$ productions. However, these contributions lead at most to one hard jet in the final state in contrast with the signal and have not been simulated. (3) Standard Model productions as for instance the $Wt\bar{t}$ production. These backgrounds have been estimated in [9] to be negligible at $\sqrt{s} = 2TeV$. We have checked that the Zb production gives a negligible contribution to the 3 leptons signature. (4) The fake backgrounds as, $p\bar{p} \rightarrow Z + X$, $Drell-Yan + X$, $b\bar{b}b$, where X and b-quarks fake a charged lepton. Monte Carlo simulations using simplified detector simulation cannot give a reliable estimate of this background. (5) The supersymmetric background generated by the superpartner pair production. This background is characterised by two cascade decays ending each with the decay of the LSP as $\tilde{\chi}^0_1 \rightarrow \mu u d$ via the λ'_{211} coupling, and thus is suppressed compared to the signal due to the additional branching fraction factors. Moreover the SUSY background incurs a larger phase space suppression. In particular its main contribution, namely the squark and gluino pair productions, is largely suppressed for large $\tilde{q}$ and $\tilde{g}$ masses [10]. Although a detailed estimation has not been performed we expect that this background can be further reduced by analysis cuts, since at least four jets are expected in the final state and leptons should appear less isolated than in the signal.

We have simulated the single chargino production $p\bar{p} \rightarrow \tilde{\chi}^{\pm}_1 \mu^{\mp}$ with a modified version of the SUSYGEN event generator [11] and the Standard Model background ($W^{\pm}\ Z^0$, $Z^0\ Z^0$ and $t\bar{t}$ productions) with the PYTHIA event generator [12]. Both SUSYGEN and PYTHIA have been interfaced with the SHW detector simulation package [13], which mimics an average of the CDF and D0 Run II detector performance.

The following cuts aimed at enhancing the signal-to-background ratio have been applied. First, we have selected the events with at least three charged leptons ($e^{\pm}$ or $\mu^{\pm}$) with energies greater than $10GeV$ for the softer of them and $20GeV$ for the two others, namely, $N_l \geq 3$ $[l = e, \mu]$ with $E_{min}(l) > 10GeV$, $E_{med}(l) > 20GeV$ and $E_{max}(l) > 20GeV$. In addition, since our final state is $3l + 2jets + \not{E}$ we have required that the minimum number of jets should be equal to two, where the jets have an energy higher than $10GeV$, namely, $N_j \geq 2$ with $E_j > 10GeV$. This selection criteria suppresses the background from the gauge bosons production which generates at most one hard jet. Note that these events requiring high energy charged leptons and jets are easily triggered at Tevatron. In order to eliminate poorly isolated leptons originating from the decays of hadrons (as in the $t\bar{t}$ production), we have imposed the isolation cut $\Delta R = \sqrt{\delta\phi^2 + \delta\theta^2} > 0.4$, where ϕ is the azimuthal angle and θ the polar angle, between the 3 most energetic charged leptons and the 2 hardest jets. We have also demanded that $\delta\phi > 70°$ between the leading charged lepton and the 2 hardest jets. With the cuts described above and for an integrated luminosity of $\mathcal{L} = 1fb^{-1}$ at $\sqrt{s} = 2TeV$ for Tevatron Run II, the $Z^0 Z^0$, $W^{\pm} Z^0$, $t\bar{t}$ productions lead to $0.22, 0.28, 1.1$ events respectively.

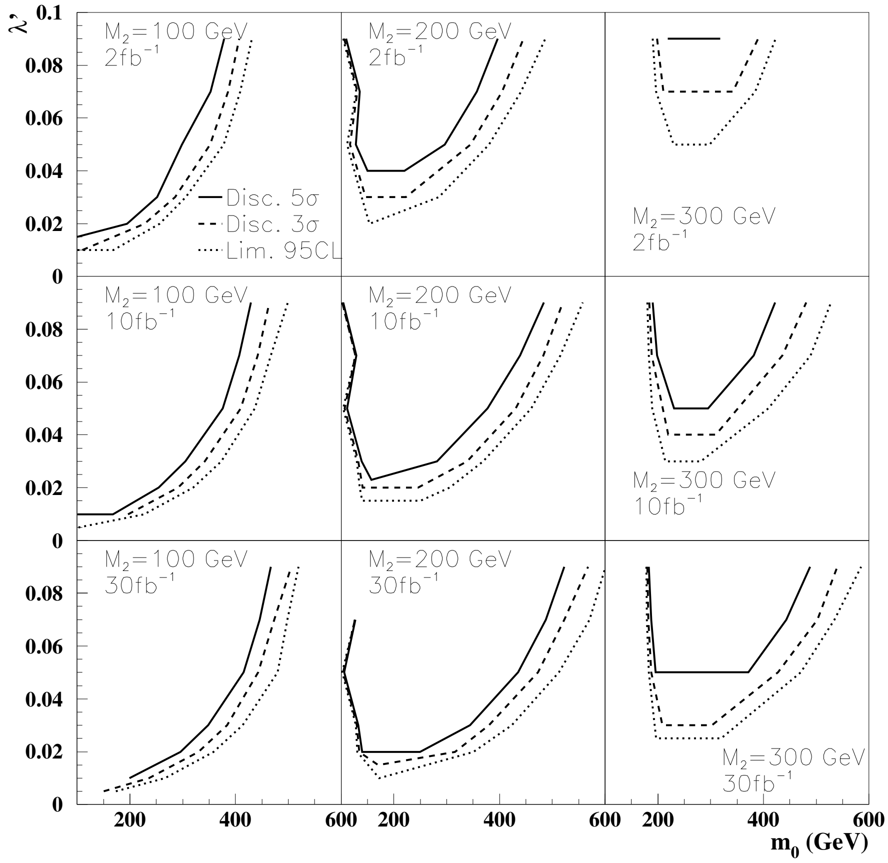

Figure 2: Discovery contours at 5σ (full line), 3σ (dashed line) and limit at 95% $C.L.$ (dotted line) presented in the plane λ'_{211} versus the m_0 parameter, for different values of M_2 and of luminosity.

In Fig.2, we present the 3σ and 5σ discovery contours and the limits at 95% confidence level in the λ'_{211}-m_0 plane, using a set of values for M_2 and the luminosity. For a given value of M_2, we note that the sensitivity on the λ'_{211} coupling decreases at high and low values of m_0. At high values of m_0, the sneutrino mass is enhanced inducing a decrease of the sneutrino production cross-section. At low values of m_0, the sneutrino mass decreases leading to a reduction of the phase space factor for the decay $\tilde{\nu}_\mu \to \tilde{\chi}^\pm_1 \mu^\mp$ which follows the resonant sneutrino production. Similarly, we note the decrease of the sensitivity on the λ'_{211} coupling when M_2 increases for a fixed value of m_0. This is due to the increase of the chargino mass which results also in a smaller phase space factor for the sneutrino decay.

In Fig.3, the discovery potential is shown in the plane m_0 versus $m_{1/2}$, for different values of λ'_{211} and of luminosity. For the same reasons as above, we observe a reduction of the sensitivity on λ'_{211} when m_0 (respectively, $m_{1/2}$ or equivalently M_2) increases for a fixed value of $m_{1/2}$ (respectively m_0).

An important improvement with respect to the limits derived recently from LEP data [14] can already be obtained within the first year of Run II at Tevatron ($\mathcal{L} = 1 fb^{-1}$). Even Run

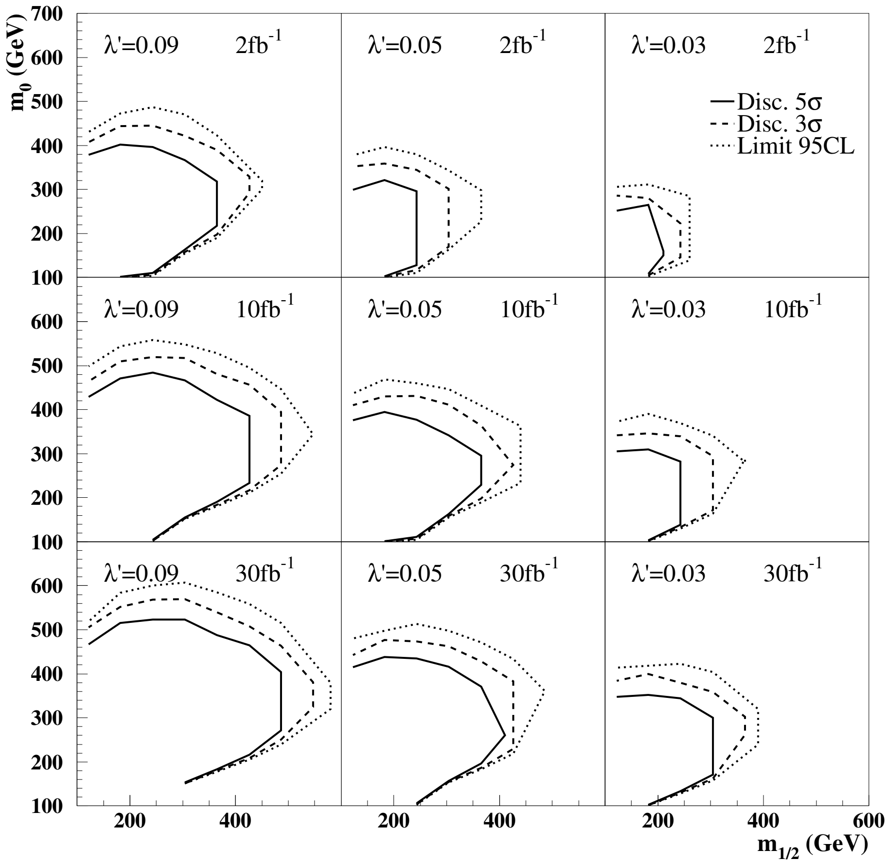

Figure 3: Discovery contours at 5σ (full line), 3σ (dashed line) and limit at 95% $C.L.$ (dotted line) presented in the plane m_0 versus $m_{1/2}$, for different values of λ'_{211} and of luminosity.

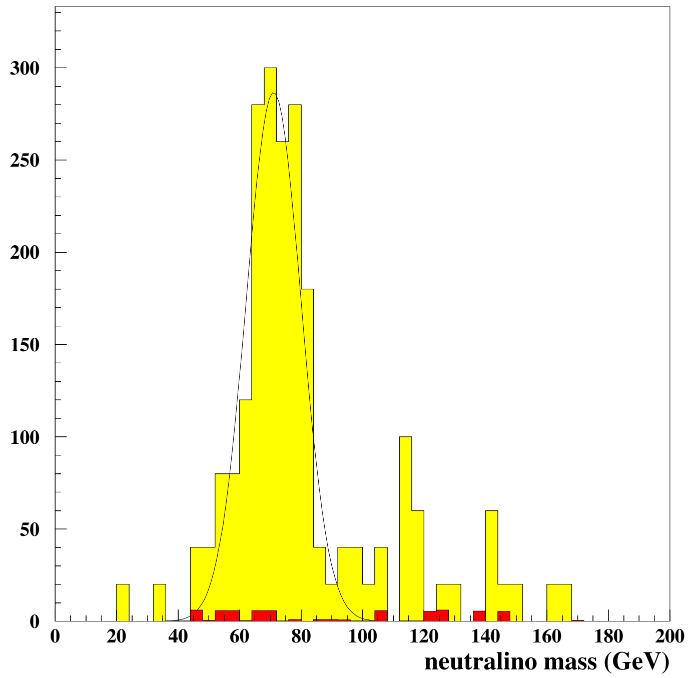

Figure 4: Distribution for the invariant mass of the 2 jets and the lower energy muon in the $e\mu\mu$ events, for a luminosity of $\mathcal{L} = 30 fb^{-1}$. The sum of the WZ, ZZ and $t\bar{t}$ backgrounds is in black and the signal is grey. The mSUGRA point taken for this figure is, $m_0 = 200GeV$, $M_2 = 150GeV$ ($m_{\tilde{\chi}_1^0} = 77GeV$), and the $\not R_p$ coupling is $\lambda'_{211} = 0.09$.

I data could probably lead to new limits on the supersymmetric parameters. The strongest bounds on the supersymmetric masses obtained at LEP in an $R\!\!\!/_p$ model with non-vanishing λ' Yukawa coupling are $m_{\tilde{\chi}_1^\pm} > 94GeV$, $m_{\tilde{\chi}_1^0} > 30GeV$, $m_{\tilde{l}} > 81GeV$ [14]. Note that for the minimum values of m_0 and $m_{1/2}$ spanned by the parameter space described in Fig.2 and Fig.3, namely $m_0 = 100GeV$ and $M_2 = 100GeV$, the spectrum is $m_{\tilde{\chi}_1^\pm} = 113GeV$, $m_{\tilde{\chi}_1^0} = 54GeV$, $m_{\tilde{\nu}_L} = 127GeV$, $m_{\tilde{l}_L} = 137GeV$, $m_{\tilde{l}_R} = 114GeV$, so that we are well above these limits. Since both the scalar and gaugino masses increase with m_0 and $m_{1/2}$, the parameter space described in these figures lies outside the present forbidden range, in the considered framework.
With the luminosity of $\mathcal{L} = 30fb^{-1}$ expected at the end of the Run II, $m_{1/2}$ values up to $550GeV$ ($350GeV$) corresponding to a chargino mass of about $m_{\tilde{\chi}_1^\pm} \approx 500GeV$ ($300GeV$) can be probed if the λ'_{211} coupling is 0.09 (0.03). The sensitivity on m_0 reaches $600GeV$ ($400GeV$), which corresponds to a sneutrino mass of about $m_{\tilde{\nu}_\mu} \approx 600GeV$ ($450GeV$), for a value of the λ'_{211} coupling equal to 0.09 (0.03). Couplings down to a value of 0.005 can also be tested at Tevatron Run II, in the promising scenario where $m_0 = 200GeV$ and $M_2 = 100GeV$, namely, $m_{\tilde{\chi}_1^\pm} \approx 100GeV$ and $m_{\tilde{\nu}_\mu} \approx 200GeV$.

Let us make a few remarks on the model dependence of our results. First, as we have discussed above, the sensitivity reaches depend on the SUSY parameters mainly through the supersymmetric mass spectrum. Secondly, in the major part of the mSUGRA parameter space, the LSP is the $\tilde{\chi}_1^0$. Besides, in the mSUGRA model, the mass difference between $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ is large enough not to induce a dominant $R\!\!\!/_p$ decay for the chargino. Notice also that we have chosen the scenario of low $\tan\beta$. For high $\tan\beta$, due to the slepton mixing in the third generation, the $\tilde{\tau}$ slepton mass can be reduced down to $\sim m_{\tilde{\chi}_1^\pm}$ so that the branching ratio of the $\tilde{\chi}_1^\pm$ decay into tau-leptons $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \tau_p^\pm \nu_\tau$ increases and exceeds that into e and μ leptons, leading to a decrease of the efficiency after cuts. For example, the efficiency at the mSUGRA point $m_0 = 200GeV$, $M_2 = 150GeV$, $sign(\mu) = -1$, $A = 0$, is 4.93% for $\tan\beta = 1.5$ and 1.21% for $\tan\beta = 50$. However, for still decreasing $\tilde{\tau}$ mass, $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \tau_p^\pm \nu_\tau$ starts to dominate over the hadronic mode so that the efficiency loss is compensated by the leptonic decays of the τ, and the branching of the $\chi_1^\pm$ into e and μ leptons can even increase up to 34%. For instance, the efficiency for $m_0 = 300GeV$, $M_2 = 300GeV$, $sign(\mu) = -1$, $A = 0$, is 5% for the 2 values $\tan\beta = 1.5$ and $\tan\beta = 50$.

Another particularly interesting aspect of our signal is the possibility of a $\tilde{\chi}_1^0$ neutralino mass reconstruction in a model independent way. As a matter of fact, the invariant mass distribution of the charged lepton and the 2 jets coming from the neutralino decay $\tilde{\chi}_1^0 \to \mu u d$ allows to perform a clear neutralino mass reconstruction. The 2 jets found in these events are generated in the $\tilde{\chi}_1^0$ decay. In order to select the requisite charged lepton, we concentrate on the $e\mu\mu$ events. In those events, we know that for a relatively important value of the mass difference, $m_{\tilde{\nu}_\mu} - m_{\tilde{\chi}_1^\pm}$, the leading muon comes from the decay, $\tilde{\nu}_\mu \to \tilde{\chi}_1^\pm \mu^\mp$, and the other one from the neutralino decay (the electron is generated in the decay $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 e^\pm \nu_e$). In Fig.4, we present the invariant mass distribution of the lepton and 2 jets selected through this method. The average reconstructed $\tilde{\chi}_1^0$ mass is about $71 \pm 9GeV$ to be compared with the generated mass of $\tilde{\chi}_1^0$ $m = 77GeV$. In a more detailed analysis of this signal [15, 16], the neutralino mass can be reconstructed with higher precision using for e.g. constrained fit algorithms. This mass reconstruction is performed easily in contrast with the pair production analysis in $R\!\!\!/_p$ scenarios [17] which suffers an higher combinatorial background. Moreover, a reconstruction of the chargino and sneutrino masses is also possible. This invariant mass distribution would also allow to discriminate between the signal and the SUSY background.

As a conclusion, we have presented a new possibility of studying resonant sneutrino productions in $R\!\!\!/_p$ models at Tevatron. Results (see also [16]) lead to a sensitivity on the λ'_{211} coupling, on the sneutrino and chargino masses well beyond the present limits. Besides, a model-independent reconstruction of the neutralino mass can be performed easily with great accuracy. Our work leads to the interesting conclusion that the three leptons signature considered as a 'gold plated' channel for the discovery of supersymmetry at hadronic colliders [7, 8, 9], is also particularly attractive in an R-parity violation context.

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