Three Body Decays of $\tilde{\chi}_1^0$ in $R_p$ violating models with dominant $\lambda$ and $\lambda'$ couplings.

Rohini M. Godbole

(CERN, Geneva)

Plan :

1. $R_p$ violation in SUSY: why consider it and a few relevant facts.
2. Effects of $R_p$ at colliders.
3. Three body decays of $\tilde{\chi}_1^0$ via $R_p$
   - Couplings we consider
   - Why these particular ones?
4. Results
5. Conclusions

(hep-ph/ 0108244)

In collaboration with F. Borzumati, J.L. Kneur and F. Takayama.
Three body decays of $\tilde{\chi}_0$ in $R_p$ violating models with dominant $\lambda$ and $\lambda'$ couplings.

**Introduction**

$R_p$ violation in SUSY:

- No deep theoretical reason for its conservation 😄
- Actually $B, L$ symmetries of the SM but NOT of the MSSM
- Supersymmetry and Gauge Invariance allow $R_p$ terms in the Superpotential

$$W_{R_p} = \frac{1}{2} \lambda_{ijk} L_i L_j E^c_k + \chi_{ijk} L_i Q_j D^c_k + \frac{1}{2} \lambda'_{ijk} U^c_i D^c_j D^c_k + \kappa_i L_i H_2,$$

(1)

$L_i, Q_i$: doublet Lepton, Quark superfields, $E_i, U_i, D_i$ the singlet Lepton and Quark superfields.

- $\nu$ masses can be generated in an economical way without introducing any new fields. 😄
- Tree level via the Bilinear $\kappa_i$,
- Quantum one or two loop level via the Trilinears $\lambda, \lambda'$,
- Kamioka, SNO $\rightarrow$ Unambiguous proof of $\nu$ masses.
- Enough freedom to generate the mass patterns required by all the data.
Three body decays of $\tilde{\chi}_0^1$ in $R_p$ violating models with dominant $\lambda$ and $\lambda'$ couplings.

Introduction

• No DM candidate, as the $\tilde{\chi}_1^0$ not stable, 😞
• Proton will decay very rapidly for TeV scale SUSY breaking. 😊
• Can be cured by adopting $B$ conservation $\lambda'' = 0$. This choice preferred if we don’t want $R_p$ terms to wash out baryogenesis.
• Unified string theories actually prefer models with $B$ conservation and $R_p$ violation. 😊


These models treat the Lepton and the Quark fields differently and have two discrete symmetries. $B$ conservation and $R_p$ eliminates not just the dimension 4 operators for proton decay BUT also dimension 5.

• All this makes $R_p$ theoretically interesting
• A large no. 48 Yukawa type couplings. No theoretical indications about their sizes. 😊
• Many of the unknown couplings constrained by low energy processes, e.g. Proton Decay, $\mu$ decay, cosmological arguments, e.g. the baryogenesis. 😊

CERN, Geneva

Rohini Godbole
Introduction

▷ A host of references!!

Host of constraints on $\lambda, \lambda'$

Majority of these come from virtual effects caused by sparticle exchanges via $R_p$ interactions (loops).

- Constraints get less severe for $\lambda, \lambda'$ with increasing number of third generation indices.
- Virtual effects depend on sparticle masses.
- Sometimes can also depend on a lot of other details of the SUSY model e.g. the L-R mixing in the sfermion sector etc.
- The $L$ violating couplings can be constrained severely particularly by $\nu$ masses. Constraints quite model dependent.

Important to study the effects of the same $R_p$ couplings in collider environment, which can help clarify model building.
Three body decays of $\tilde{\chi}_0^0$ in $R_p$ violating models with dominant $\lambda$ and $\lambda'$ couplings.

$R_p$ violation at the colliders.

Effects of $R_p$ violation at Colliders:

- Depend on the size of the coupling.

  - $LSP$ no longer stable. It need not even be $\tilde{\chi}_1^0$. If ANY $R_p$ coupling is $> 10^{-6}$ it WILL decay within the detector

  S. Dawson, NPB 261 (1985) 297.

  - We take $\tilde{\chi}_1^0$ to be the LSP. The decays can and will give rise to strikingly different final states.


  $\tilde{\chi}_1^0 \rightarrow f \bar{f}_1 f_2$ (more on these decays later). For masses of $\tilde{\chi}_1^0, \tilde{\chi}_1^\pm$ of interest at LHC, NLC, even a $t$ in the final state will be allowed.

  - For larger $R_p$ couplings more things can happen

    - Decays of particles and sparticles other than the $LSP$ via $R_p$ interactions


    $\tilde{t} \rightarrow b \bar{l}, t \rightarrow b \bar{l}$

    - Some more on the particle decays later.
- Virtual effects of sparticle exchange on tree level processes. \[ pp \rightarrow \mu^+ \mu^- \]


\[ pp \rightarrow t\bar{t} \]


\( R_p \) contribution to \( t\bar{t} \) produces a polarisation asymmetry bet. \( t \) and \( \bar{t} \).
Three body decays of $\tilde{\chi}_0^0$ in $R_p$ violating models with dominant $\lambda$ and $\lambda'$ couplings.

- Resonant or nonresonant production of a single sparticle via the $R_p$ couplings


For example, $pp \rightarrow t\bar{b}\tilde{\tau}$ via $\lambda'_{333}$. Similar to $H^-$ produced via $\bar{t}bH^-$ coupling.

- Even for $m_{\tilde{t}} > m_t$ rates appreciable for $\lambda'_{333}$ as small as 0.05.
- $\tilde{\tau}$ so produced will have both $R_p$ and $RPC$ decays. $RPC$ decays will produce $\tilde{\chi}_1^0$.
- Some of these decays can fake the charged Higgs signal.
- A comprehensive study requires full analysis of the three body decays of the $\tilde{\chi}_1^0, \tilde{\chi}_1^\pm$. 

CERN, Geneva

Rohini Godbole
Three body $R_p$ decays of $\tilde{\chi}_1^0$.

- $\lambda$ with more than one third generation index not constrained too much by collider experiments.
- Models for $\nu$ masses on the other hand can constrain these.
- Probes of the $L$ violating $\lambda, \lambda'$ couplings at the colliders that involve studying the physics of the third generation $t, b$ and $\tau$ will certainly provide important inputs to model building when taken in conjunction with $\nu$ mass issue.
- Third generation sfermions likely to give rise to larger virtual effects as they are expected to be lighter.
- For $\tilde{\chi}_1^0, \tilde{\chi}_1^+$ with masses of interest at the $LHC, NLC$, final states with third generation fermions including $t$ are possible.
- One needs a study of the $R_p$ decays of $\tilde{\chi}_1^0, \tilde{\chi}_1^+$ retaining effects of the mass of the third generation fermions, for $L$ violating coupling.
- Formulae had been derived including the mass effects by Dreiner et al, JHEP 0004 (2000) 008. Our formulae, in the limit of real L-R sfermion mass term, agree with theirs. Their analysis focuses on the effects of the $B$ violating couplings.
Three body decays of $\tilde{\chi}_1^0$ in $R_p$ violating models with dominant $\lambda$ and $\lambda'$ couplings.

- What has been done by us?
  - Calculated 3 body $R_p$ decays of the $\tilde{\chi}_1^0$ with dominant $\lambda, \lambda'$ couplings involving at least two three generation indices.
  - Kept the mass effects of the third generation fermions and the sfermion L-R mixing terms complex.
  - Analysed numerically for cases with unified/ununified gaugino masses, including effect of subdominant $\lambda, \lambda'$.
  - Our code can be used to implement three body decays of the lightest neutralino with one dominant $R_p$ and $L$ violating coupling. Generalisation to more than one subdominant couplings is easy.
  - Analysed decays into purely third generation final state fermions including $t$. 

CERN, Geneva

Rohini Godbole
Three body $\mathcal{R}_p$ decays of $\tilde{\chi}^0_1$.

$\lambda'_{333}$

Decays of the $\tilde{\tau}$:

$R_p$ conserving decay:

$\tilde{\tau} \rightarrow \tau \tilde{\chi}^0_1$, $\tilde{\tau} \rightarrow \nu_\tau \tilde{\chi}^-_1$, $m_t > m_{\tilde{\tau}}$

$\mathcal{R}_p$ decay:

$\tilde{\tau} \rightarrow b \bar{t}$

$m_t < m_{\tilde{\tau}}$.

If the $\mathcal{R}_p$ coupling is sizable the net final state produced decided by relative branching ratios of $\tilde{\chi}^0_1, \tilde{\chi}^+_1$ into different channels.

Production of $\tilde{\tau}$ through $\mathcal{R}_p$ couplings and its decay via the same will give rise to

$pp \rightarrow t \bar{b} \tilde{\tau} X \rightarrow t \bar{b} t b X$

* The same final state as the $H^\pm$.

$RPC$ decays of the $\tilde{\tau}$ and $\mathcal{R}_p$ decays of the $\tilde{\chi}^0_1$ can also produce

$pp \rightarrow t \bar{b} \tilde{\tau} X \rightarrow (2t)(2b)(2\tau)X$

$\rightarrow t b (2\bar{b}) \tau \nu_\tau X$

e tc.

* Characteristic $L$ violating decays of $\tilde{\chi}^0_1$: like sign fermion pairs.
### Results.

**$\chi'_{333}$ Domination:**

- Decays of the $\tilde{\chi}^0_1$
  - $\tilde{\chi}^0_1 \rightarrow b\bar{b}\nu_{\tau}$  
    \[ m_{\tilde{\chi}^0_1} < m_t \text{ MASSLESS} \]
  - $\tilde{\chi}^0_1 \rightarrow b\bar{t}\nu_{\tau} + \text{C.C.}$  
    \[ m_{\tilde{\chi}^0_1} > m_t \text{ MASSIVE} \]
  - For a Wino like $\tilde{\chi}^0_1$, in the absence of the L-R mixing the second diagram with a $\tilde{b}_R$ exchange will not contribute.
  - A substantial gaugino/higgsino mixing causes an increase in the width into massive mode for low $\tan\beta$ and into massless mode for large $\tan\beta$.
  - In the results we present widths of the charge conjugate modes $t\bar{b}\nu_{\tau}$ and $t\bar{b}\bar{\nu}_{\tau}$ is given separately.
Three body decays of $\tilde{\chi}_1^0$ in $R_p$ violating models with dominant $\lambda$ and $\lambda'$ couplings.

Results.

---

Wino like $\tilde{\chi}_1^0$  Solid line $\tilde{\chi}_1^0$ Bino like.

Left panel: no L-R mixing in the Squark sector.

Right Panel: Moderate left right entries. $A_t - \mu \cot \beta = 150$ GeV, $A_b - \mu \tan \beta = 2000$.

$M_\star$ is a squark mass scale. $\frac{M_{\tilde{\chi}_1^0}}{\tilde{\chi}_1^0} = 600$ GeV.

▶ The massless mode is the larger one, but massive mode is not negligible either.

▶ Enhancement of the widths by an order of magnitude for $\tilde{\chi}_1^0 \sim \tilde{W}$.

▶ With moderate L-R squark mixing, even for $\tilde{\chi}_1^0 \sim \tilde{W}$, the $\tilde{b}$ mediated diagram contributes to massive mode. Smaller $\tilde{t}_1, \tilde{b}_1$, masses enhance the width for the massive mode for a $\tilde{B}$ like $\tilde{\chi}_1^0$. 

CERN, Geneva

Rohini Godbole
Three body decays of $\tilde{\chi}_0^0$ in $R_p$ violating models with dominant $\lambda$ and $\lambda'$ couplings.

**Results.**

- **Dependence on $\tan \beta$.**

\begin{align*}
\bar{b}b\nu_\tau \text{ decay width : solid line} & \quad \bar{t}b\nu \text{ width : dashed line.}
\end{align*}

Left panel: $\tan \beta = 3$, Trilinear soft terms = 350 GeV

Right Panel: $\tan \beta = 30$, Trilinear soft terms = 150 GeV.

$M_*^*$ is the squark mass scale. $M_{\tilde{B}}$, slepton mass and $\mu = 600$ GeV.

- The massive mode is larger at lower $\tan \beta$ and the massless one for the higher values.

- With $\lambda'_{333}$ dominant, the massive decay has a large width for low $\tan \beta$ and large higgsino-gaugino mixing. Otherwise the massless mode is larger, though the massive mode is nonnegligible.
**Results.**

- Dependence on $\lambda'_{333}$ value.

\[ \Gamma(b\bar{b}\nu_\tau, t\bar{b}\tau) \]

$\bar{b}b\nu_\tau$ decay width: solid line; $t\bar{b}\nu$ width: long dashed line.

All the other parameters same as in the earlier case.

In the resonant sfermion region very little dependence on $\lambda'_{333}$ and otherwise scales down simply like $\lambda'^2_{333}$. 
Results.

- Comparable $\lambda$ and $\lambda'$ couplings.

$\bar{b}b\nu_{\tau}$ decay width: solid line; $t\bar{b}\tau$ width: long dashed line.
$\tau\bar{\tau}\nu_{\mu}$ decay width: small dashed line; $\mu\bar{\tau}\nu_{\tau}$ width: dotted line.

Left panel: Widths, Right Panel: B.R., No L-R mixing, $\mu = 500$ GeV, $\tan\beta = 3$, Bino mass = 500 GeV.

▷ All the widths are not too dissimilar
▷ B.R. into a final state with $t$ is not too small.
Conclusions.

- Important to have a collider probe of the $R_p$, $\lambda$ and $\lambda'$ couplings with more than one third generation index.

- Single charged slepton production via the $R_p$ coupling $\lambda'_{i33}$ can produce final states which can be confused with the $H^{\pm}$ signal.

- Even for smaller but dominant $R_p$, $\lambda$ and $\lambda'$ couplings with more than one third generation index, the three body $R_p$ decays of $\tilde{\chi}_1^0$, $\tilde{\chi}_1^+$ can have important phenomenological consequences for new particle searches at the future colliders.

- If the $\tilde{\chi}_1^0$ is ‘Wino’ like its decay widths increases by over an order of magnitude.

- If the $\tilde{\chi}_1^0$ is lighter than the $t$, its $R_p$ decays will be dominantly into massless fermions: $b\bar{b}\nu_\tau$ for dominant $\lambda'_{333}$ coupling, $c\bar{b}\tau$, $s\bar{b}\nu_\tau$ and the charge conjugate modes $\bar{c}b\bar{\tau}$, $\bar{s}b\bar{\nu}_\tau$ for dominant $\lambda'_{323}$, whereas for $\lambda_{233}$ it is $\bar{\mu}\tau\nu_\tau$ and $\mu\bar{\tau}\bar{\nu}_\tau$.

- For a $\tilde{\chi}_1^0$ heavier than the $t$ the massive decay modes can become competitive for large L-R sfermion mass term and /or for substantial mixing in the higgsino/gaugino sector, at not too large tan $\beta$.

- All the $R_p$ decays of the $\tilde{\chi}_1^0$ produce final states with like sign dileptons as the telltale signature of the $L$ violation, as long as the final state $t$ decays hadronically.