Supersymmetry with right-handed neutrinos and the LHC

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The LHC...

The first real chance to look for new physics at the TeV scale

Supersymmetry (SUSY) — a common target, because

- For low-scale physics, EW scale is stabilised
- For high-scale physics, hints of GUT, SUGRA, strings, . ..??
- A dark matter candidate is suggested

Most important: unbiased prediction and analysis of data
The Minimal SUSY Standard Model (MSSM)

\[ R = (-)^{(3B+L+2S)} \text{ conserved} \Rightarrow \text{the LSP is a dark matter candidate} \]

The lightest neutralino as the LSP is favoured the most

\[ \Rightarrow \text{Signals with large missing } E_T \]

The ‘canonical SUSY signals’
The MSSM and its searches...

Commonly assume that
no right-handed neutrinos $\Rightarrow$ no neutrino mass

A harmless assumption *prima facie*, since
If RH neutrinos ($\nu_R$) exist, they are completely sterile, except for the interaction $\sim y_\nu \bar{\nu}_L \nu_R H$

$y_\nu \sim m^\nu_{Dirac}$ (H = Higgs doublet)

Only $m^\nu_{Dirac}$ possible if there is no $\Delta L$
In practice....

Neutrinos seem to have mass and mixing

With Higgs doublet(s) only, neutrino mass usually requires $\nu_R$ for conserved $\Delta L$

The right-chiral sneutrino can be the LSP

Interaction with matter suppressed–direct dark matter search limits evaded

**Bottomline:** A $\tilde{\nu}_R$-type LSP with mass $\sim 100$ GeV is consistent

In mSUGRA + right (s)neutrinos..

With high-scale SUSY breaking generating $M_{\tilde{\nu}_R}$,

$$\frac{dM_{\tilde{\nu}_R}^2}{dt} = \frac{2}{16\pi^2} y_{\nu}^2 A_{\nu}^2$$

Extremely small Yukawa couplings

$\Rightarrow$ $M_{\tilde{\nu}_R}$ nearly frozen at the high-scale value $m_0$

Other sfermion masses are pushed up at the electroweak scale

$\Rightarrow$ A right-chiral sneutrino for every family is at the bottom of the spectrum
Things that the $\nu_R$ brings into the theory...

• In the superpotential:

$$W^R_{\nu} = y_\nu H_u L \nu^c_R$$

$$m_\nu = y_\nu \langle H^0_u \rangle = y_\nu v \sin \beta$$

$y_\nu =$ Yukawa coupling, $L = (l, \nu_L)$

$\hat{H}_u =$ Higgs superfield giving mass to the $T_3 = +1/2$ fermions

$$\tan \beta = v_u / v_d$$
Things that the $\nu_R$ brings into the theory...

● In the scalar potential,

$$-\mathcal{L}_{soft} \sim M_{\tilde{\nu}_R}^2 |\tilde{\nu}_R|^2 + (y_\nu A_\nu H_u \tilde{L}\tilde{\nu}_R^c + h.c.)$$

$A_\nu$ is the term driving left-right mixing in the scalar mass matrix
Things that the $\nu_R$ brings into the theory...

- The low-scale sneutrino mass matrix:

$$m_{\tilde{\nu}}^2 = \begin{pmatrix}
M_{\tilde{\nu}L}^2 + \frac{1}{2} m_Z^2 \cos 2\beta & y_{\nu} v (A_{\nu} \sin \beta - \mu \cos \beta) \\
y_{\nu} v (A_{\nu} \sin \beta - \mu \cos \beta) & M_{\tilde{\nu}R}^2
\end{pmatrix}$$

$M_{\tilde{\nu}L} = $ soft mass for the left-handed sleptons
$M_{\tilde{\nu}R} = $ soft mass for the right-handed sneutrino

In general, $M_{\tilde{\nu}L} \neq M_{\tilde{\nu}R}$ because of different evolution patterns + D-term contribution for the former.

Physical states: $\tilde{\nu}_1$ (lighter), $\tilde{\nu}_2$ (heavier)
Things that the $\nu_R$ brings into the theory...

The LSP state(s) = $\tilde{\nu}_1$

Dominantly $\tilde{\nu}_R$, with admixture of $\tilde{\nu}_L \sim y_\nu$

All decay widths into $\tilde{\nu}_1$ is $\sim y_\nu^2$

Extremely suppressed– decay takes place outside detector

Within the detector, all decays lead to the NLSP
The NLSP controls collider phenomenology

For a charged NLSP (e.g. $\tilde{\tau}_1$), one sees stable tracks
The NLSP can be...

\( \tilde{\tau}_1 \) (the lighter stau, dominated by \( \tilde{\tau}_R \)):

→ allowed over a large region

A charged track can be seen in the muon chamber—kinematically differentiable


\( \tilde{t}_1 \) (the lighter stop): not only tracks,
but also gluino reconstruction possible

A long-lived stau NLSP can occur in...

Supergravity theories with gravitino LSP
A. Ibarra, S. Roy (2006)....
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(co-annihilation region)
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Supergravity with $\tilde{\nu}_R$ LSP

When the $\tilde{\tau}_1$ is the NLSP...

SUSY cascades can end in $\chi^0_{(1,2)}$-pairs, with

$$\chi^0_{(1,2)} \longrightarrow \tau \tilde{\tau}_1$$

If $\tau, \tilde{\tau}_1$ are reconstructed, one can reconstruct neutralino mass peaks

A unique feature of the quasi-stable charged NLSP scenario — a legacy of right-handed $\nu$’s in SUSY

The principal issues involved...

- Identifying the appropriate final state
- Event selection criteria
- Full reconstruction of the $\tilde{\tau}$’s
- Full knowledge of $\tilde{\tau}$ momentum + energy (with mass $a$ priori unknown)
- Finding the right $\tau - \tilde{\tau}$ pairs out of $\tau \tau \tilde{\tau} \tilde{\tau}$: reducing combinatorial backgrounds
Broad features of the procedure

- **Final state:**
  \[2\tau_j + 2\bar{\tau}(charged - tracks) + \not{E}_T + X\]
  \(\tau_j\): jet out of one-prong tau decay
  \(X\) includes all other jets

- **Tau-identification:** \(p_T > 50\) GeV,
  Efficiency = 50%, jet rejection factor \(\sim 1/20\)

- **\(\tau\) reconstruction done in the collinear approximation**
  (both jet and \(\nu\) in the direction of \(\tau\))
  \(\bar{p}_j = x_{1,2}\bar{p}_\tau\) for each \(\tau\),
  \(x_{1,2}\) solved from information on
  the two components of \(\not{p}_T\)

\[\not{p}_T = -p_T^{visible} : p_T^{visible} = p_T^{(j/l/\gamma)} + p_T^{(soft/unclustered)}\]

(finite resolution effects included)
Separating $\tilde{\tau}$-tracks from muons....

Solution: $p_T$-cut on each track + a cut on $\sum |p_T|$
Full reconstruction of the $\tilde{\tau}$-....

Requires the knowledge of $m_{\tilde{\tau}}$-....

$$\sqrt{m^2_{\tilde{\tau}} + |p_{\tilde{\tau}}|^2 E_{\tilde{\tau}}} - \sqrt{m^2_{\tilde{\tau}} + |p_{\tilde{\tau}}|^2 E_{\tilde{\tau}}} = p_{\tilde{\tau}} \cdot p_{\tilde{\tau}} - p_{\tilde{\tau}} \cdot p_{\tilde{\tau}}$$

Strategy: identify the right pair for each event

with any ‘seed’ $m_{\tilde{\tau}}$

Demand the two pairs to have least $m_{inv}$, differing by $\leq 50$ GeV

Then solve the equation for $m_{\tilde{\tau}}$ event by event

The peak gives the real $m_{\tilde{\tau}}$
Full reconstruction of the $\tilde{\tau}$-...
Neutralino reconstruction....

For each event, using the reconstructed \( \tilde{\tau} \) mass, keep the \( \tau \tilde{\tau} \) peak pairs with lesser (\( \leq 50 \text{GeV} \)) separation.
Neutralino reconstruction...

\[ m_{\tilde{\chi}^0_1} = 248 \text{ GeV} \]
\[ m_{\tilde{\chi}^0_2} = 469 \text{ GeV} \]

\[ M_{\tilde{\tau}\tilde{\tau}} \text{ in GeV} \]

No. of Events

\[ \tilde{\tau} \text{-NLSP mass} = 189 \text{ GeV} \]
Neutralino reconstruction....

\[ m_{\tilde{\chi}_0^1} = 129 \text{ GeV} \]
\[ m_{\tilde{\chi}_0^2} = 241 \text{ GeV} \]

- \( \tilde{\tau} \)-NLSP mass = 106 GeV
Neutralino reconstruction....

\[ m_{\tilde{\chi}_0^1} = 129 \text{ GeV} \]
\[ m_{\tilde{\chi}_0^2} = 240 \text{ GeV} \]

\[ M_{\tilde{\tau}} \text{ in GeV} \]

No. of Events

\[ \tilde{\tau} \text{-NLSP mass } = 124 \text{ GeV} \]
Neutralino reconstruction....

- $\chi_2^0$-peaks difficult to obtain when its production rates in cascades are low

- $\chi_1^0$ peaks get lost when $m_{\chi_1^0}$, $m_{\bar{\tau}}$ are close:
  - $\tau$’s become soft

- Both the $\chi_1^0$ and $\chi_2^0$ peaks seen when none of the above situations applies
The region in the $m_0 - M_{1/2}$ plane, where it is possible to reconstruct at least one of the neutralinos at the LHC, with $\tan\beta = 30$ and $A_0 = 100$.

Blue: at least 100 events in the vicinity of the peak.
Green: at least 50 events in the vicinity of the peak.
Summary and conclusions

- mSUGRA + right-neutrino superfield can often lead to $\tilde{\nu}_R$-LSP + $\tilde{\tau}$-NLSP

- $\tilde{\tau}$-NLSP $\Rightarrow$ charged tracks: distinguishable through kinematic cuts

- $m_{\tilde{\tau}}$ can be reconstructed as a peak

- At least one of the two lightest neutralinos can be fully reconstructed over a large region of the parameter space.