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# **RIGHT-HANDED NEUTRINOS IN A SUPERSYMMETRIC WORLD**

***SOME IMPLICATIONS FOR THE LHC***

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# The LHC....

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

**Supersymmetry (SUSY) — a common target, since**

- **For low-scale physics, EW scale is stabilised**
- **For high-scale physics, hints of Guts, strings, SUGRA ..??..**

**Most important: unbiased prediction and analysis of data**

# The MSSM and its searches...

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**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  $\sim y_\nu \bar{\nu}_L \nu_R H$**

*$y_\nu \sim m_{Dirac}^\nu$*  **(H = Higgs doublet)**

**Only  $m_{Dirac}^\nu$  possible if there is no  $\Delta L$  (even)**

## But in practice....

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Neutrinos perhaps have mass and mixing

Evidence from solar, atmospheric and terrestrial neutrino data + cosmology

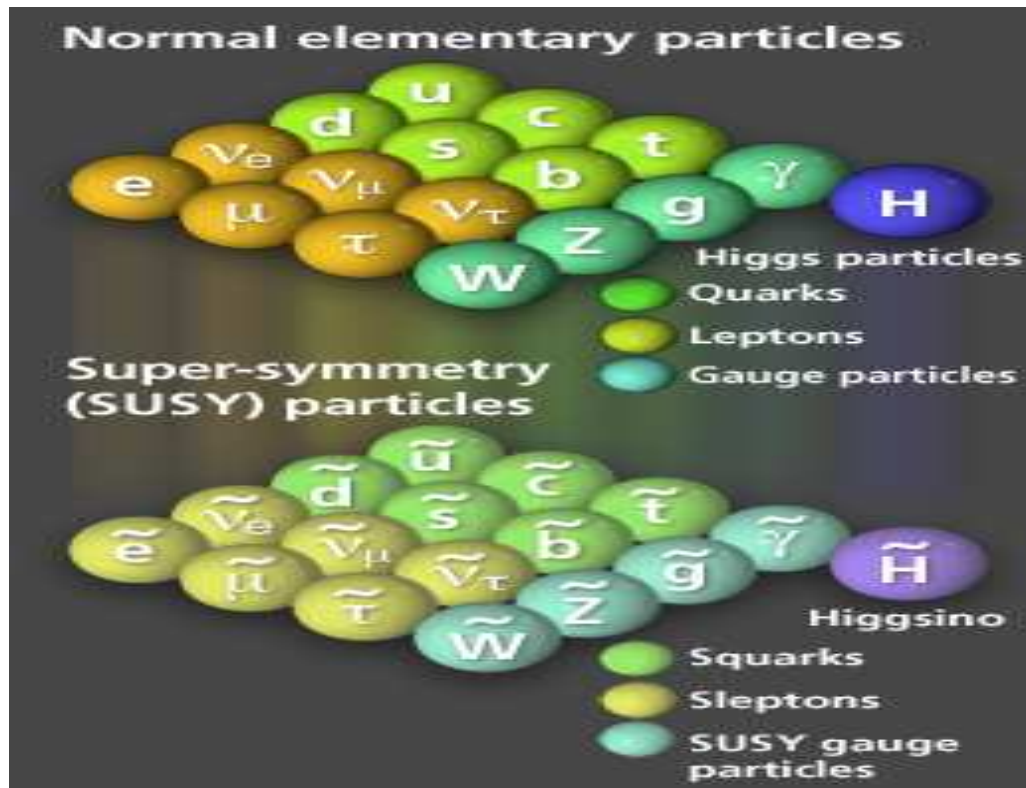
$$\implies \Delta m_{23}^2 \simeq 10^{-3} \text{ eV}^2, \Delta m_{12}^2 \simeq 10^{-5} \text{ eV}^2$$

$$\theta_{23} \simeq 45^\circ, \theta_{12} \simeq 35^\circ, \theta_{13} \lesssim 12^\circ$$

**Individual masses**  $\lesssim 0.1 \text{ eV}$

With Higgs doublet(s) only, neutrino mass usually requires  $\nu_R$ , especially for  $\Delta L \neq 1$

# In the minimal SUSY model, too...



**No  $\Delta L = 1$**

**The lightest SUSY particle is stable**

**A dark matter candidate**

**Usually the lightest 'neutralino'**

# Canonical SUSY signals at the LHC...

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With

$$\chi_1^0 = (\dots)\tilde{B} + (\dots)\tilde{W}_3 + (\dots)\tilde{H}_1^0 + (\dots)\tilde{H}_1^0$$

$$pp \longrightarrow \tilde{g}\tilde{g}(\tilde{q}\tilde{q}^*)(\tilde{q}\tilde{q}) \longrightarrow (\text{anti})\text{quarks} + \chi_1^0\chi_1^0$$

‘jets + missing  $p_T$ ’

$$pp \longrightarrow \tilde{g}\tilde{g} \longrightarrow \chi_1^\pm\chi_1^\pm \dots \longrightarrow (\text{anti})\text{quarks} + l^\pm l^\pm \chi_1^0\chi_1^0$$

‘like-sign dileptons (LSD) + jets + missing  $p_T$ ’

**Must  $\chi_1^0$  be the LSP?**

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## SUSY and right-handed neutrinos:

- Both are ‘perhaps necessary’
- Does it make any serious difference to have SUSY with right-chiral neutrino superfields (i.e. RH neutrinos as well as corresponding spin-zero ‘sneutrinos’) ?

# A right-sneutrino LSP...

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**More favoured than the  $\tilde{\nu}_L$  in a setting**

**where masses evolve from a high scale  
Interaction with matter suppressed– direct dark  
matter search limits evaded**

**Bottomline: A  $\tilde{\nu}_R$ -type LSP in the mass range**

**$O(100)$  GeV is consistent**

**Consequence in accelerator experiments: decay  
chains lead to different final states**

# New signals at the LHC (no L-violation)

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The LSP (dominantly a  $\tilde{\nu}_R$ ) couples to all other SUSY particles with a strength

$$\sim y_\nu \sim m(\text{Dirac})_\nu$$

**SUSY particle production**

$\Rightarrow$  **cascades into the next-to-lightest SUSY particle (NLSP)**

$\Rightarrow$  **Very slow decay of the NLSP to the LSP**

# New signals at the LHC

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The LSP only is cosmologically stable, but the NLSP (maybe charged) appears stable in the collider detectors

The signal of the 'stable' NLSP can be *not* missing- $p_T$  *but* charged tracks

# Things that the $\nu_R$ brings into the theory...

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- In the superpotential:

$$W_\nu^R = y_\nu H_u L \nu_R^c$$

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

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

$\hat{H}_u$  = 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...

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- In the scalar potential,

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

$A_\nu$  is the term driving left-right mixing in the scalar mass matrix

# Things that the $\nu_R$ brings into the theory...

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- The low-scale sneutrino mass matrix:

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

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

$M_{\tilde{\nu}_R}$  = soft mass for the right-handed sneutrino

In general,  $M_{\tilde{L}} \neq M_{\tilde{\nu}_R}$  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...

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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 jacked 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...

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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

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*Gregory (Scotland Yard detective): "Is there any other point to which you would wish to draw my attention?"*

*Holmes: "To the curious incident of the dog in the night-time."*

*Gregory: "The dog did nothing in the night-time."*

*Holmes: "That was the curious incident."*

*Silver Blaze in The Memoirs of Sherlock Holmes*

*by Sir Arthur Conan Doyle*

# The NLSP can be...

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$\chi_1^0 \longrightarrow$  **No difference in collider signal**

$\chi_1^\pm, \tilde{\nu}_L \longrightarrow$  **Difficult to accommodate in most models**

$\tilde{t}_1$  (the lighter stop)  $\longrightarrow$  **interesting signal,**

**in a certain region of the parameter space**  
**Studied earlier for cases where the stop decays**  
**within the detector**

A. de Gouvea + S. Gopalakrishna + W. Porod, 2006

# The NLSP can be...

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$\tilde{\tau}_1$  (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**

**S. K. Gupta + BM + S K Rai, PRD, 2007**

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

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Supergravity theories with gravitino LSP

J. Feng et al, 2003,2004, J. Ellis et al, 2004,

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**MSSM with stau-neutralino near degeneracy**

**(co-annihilation region)**

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2006....

**Supergravity with  $\tilde{\nu}_R$  LSP**

T. Ashaka + K. Ishiwata + T. Moroi, 2006, S. K. Gupta + BM + S. K.  
Rai, 2007

# Two types of signals

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Jets + two muon-like stau tracks (equivalent of jets +  $\cancel{p}_T$  in MSSM)

Jets + dimuons + two muon-like stau tracks (equivalent of jets + dimuons +  $\cancel{p}_T$  in MSSM)

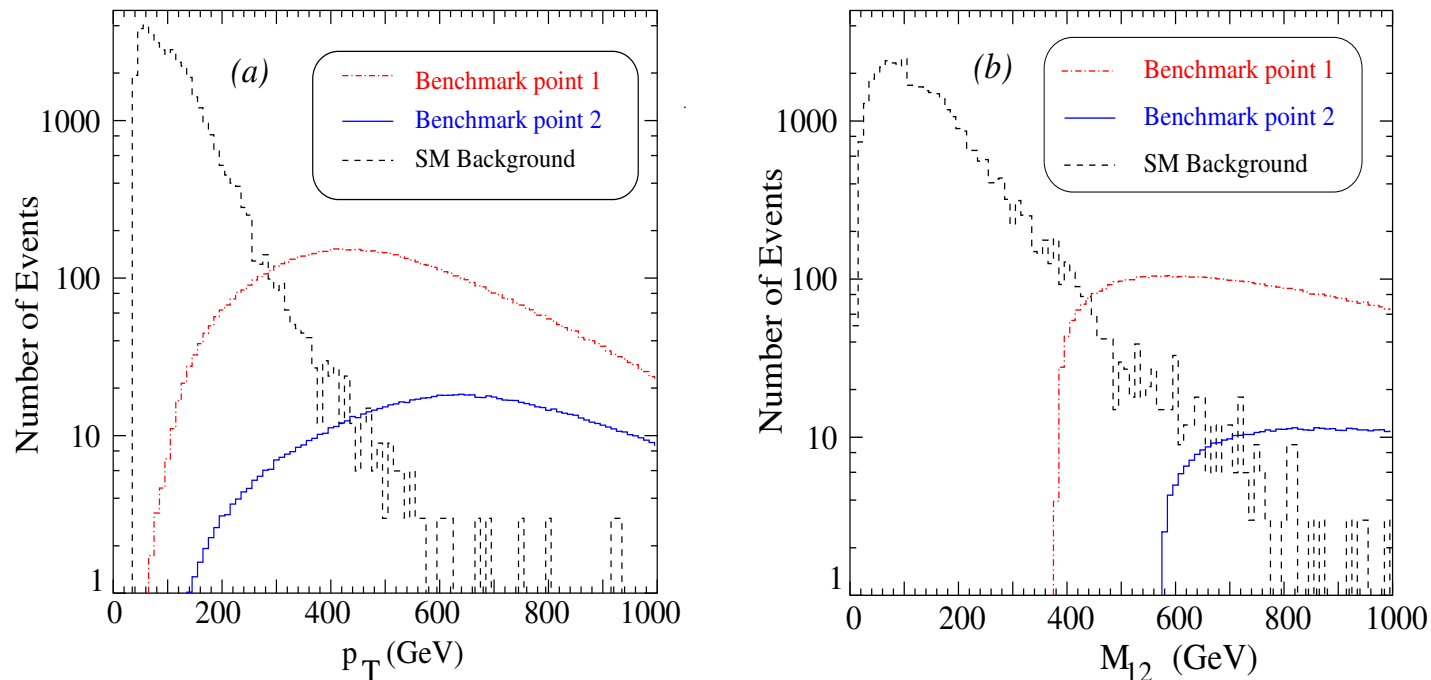
Differentiator: thickness of tracks, time delay, absorption in stoppers ....

**Observation: Kinematic separation of muonic and stable stau tracks is possible at the LHC**

# Benchmark points in a SUGRA setting...

Parameter	Benchmark point 1	Benchmark point 2
mSUGRA input	$m_0 = 100 \text{ GeV}, m_{1/2} = 600 \text{ GeV}$ $A = 100 \text{ GeV}, \text{sgn}(\mu) = +$ $\tan \beta = 30$	$m_0 = 110 \text{ GeV}, m_{1/2} = 700 \text{ GeV}$ $A = 100 \text{ GeV}, \text{sgn}(\mu) = +$ $\tan \beta = 10$
$ \mu $	694	810
$m_{\tilde{e}_L}, m_{\tilde{\mu}_L}$	420	486
$m_{\tilde{e}_R}, m_{\tilde{\mu}_R}$	251	289
$m_{\tilde{\nu}_{eL}}, m_{\tilde{\nu}_{\mu L}}$	412	479
$m_{\tilde{\nu}_{\tau L}}$	403	478
$m_{\tilde{\nu}_{sR}}$	100	110
$m_{\tilde{\tau}_1}$	187	281
$m_{\tilde{\tau}_2}$	422	486
$m_{\chi_1^0}$	243	285
$m_{\chi_2^0}$	469	551
$m_{\chi_3^0}$	700	815
$m_{\chi_4^0}$	713	829
$m_{\chi_1^\pm}$	470	552
$m_{\chi_2^\pm}$	713	829
$m_{\tilde{g}}$	1366	1574
$m_{\tilde{u}_L}, m_{\tilde{c}_L}$	1237	1424
$m_{\tilde{u}_R}, m_{\tilde{c}_R}$	1193	1373
$m_{\tilde{d}_L}, m_{\tilde{s}_L}$	1239	1426
$m_{\tilde{d}_R}, m_{\tilde{s}_R}$	1189	1367
$m_{\tilde{t}_1}$	984	1137
$m_{\tilde{t}_2}$	1176	1365
$m_{\tilde{b}_1}$	1123	1330
$m_{\tilde{b}_2}$	1161	1358
$m_{h^0}$	118	118
$m_{H^0}$	712	941
$m_{A^0}$	707	935
$m_{H^\pm}$	717	944

# Jets + two tracks: signal vs background



*Kinematic distributions for the signal  $2 \text{ stau}_1 + (\geq 2) \text{ hard jets}$ : (a) the transverse momentum distributions for the harder  $\text{stau}_1$  (b) the invariant mass distribution for the  $\text{stau}_1$  pair. The dash-dot-dash (red) histograms are for benchmark point 1 and the solid (blue) histogram for benchmark point 2. The dashed histograms show the corresponding SM background.*

# Jets + two tracks: signal vs background

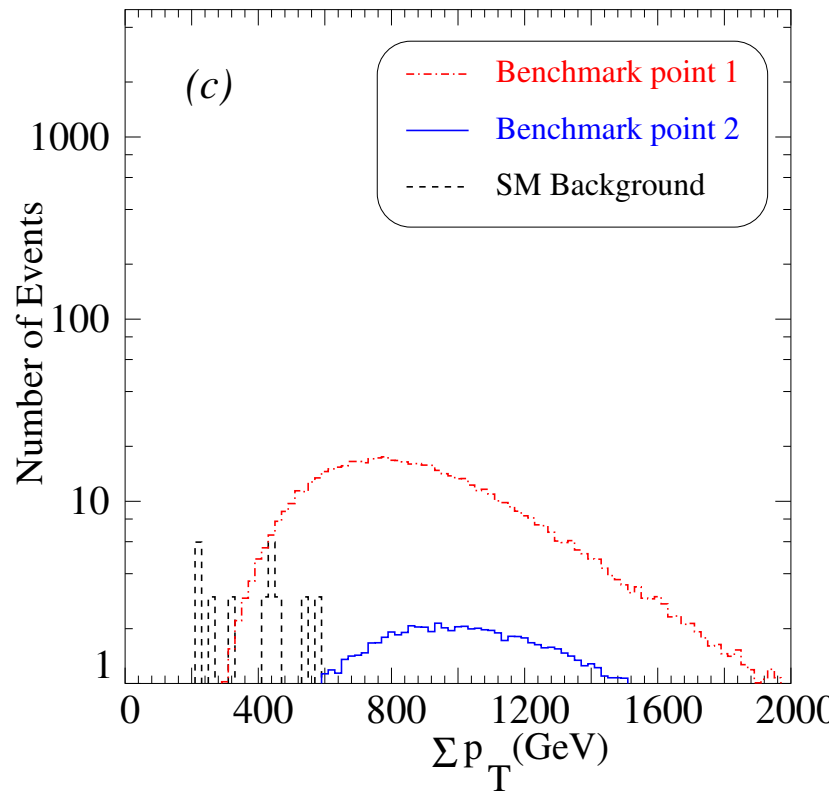
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Cuts	Background	Benchmark point 1(2)
Basic	39617	8337 (1278)
Basic + $p_T > 350$ GeV	5	2587 (737)

*The expected number of events for the signal and background with the cuts imposed. Integrated luminosity =  $30 \text{ fb}^{-1}$ .*

Hardness cut on both tracks drastically reduces backgrounds

# Jets + two $\mu$ 's + two tracks:



*Distributions in the scalar sum of  $p_T$ 's of all tracks in the muon chamber.*

## Jets + two $\mu$ 's + two tracks:

Final States	Background	Benchmark pt. 1(2)
$2\tilde{\tau}_1 + 2\mu$	83	689 (103)
$2\tilde{\tau}_1 + 2\mu + (\geq 2)$ hard jets	29	686 (103)
$2\tilde{\tau}_1 + 2\mu + (\geq 2)$ hard jets ( $\sum p_T > 600$ GeV)	0	553 (89)

*The expected number of events for the signal and background with the different cuts imposed on the selection of events.  $\sum p_T$  corresponds to the scalar sum of the individual transverse momenta of the charged tracks in the muon chamber. Integrated luminosity =  $30 \text{ fb}^{-1}$ .*

# The case of a stop NLSP...

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D. Choudhury + S. K. Gupta + BM, in preparation

**One requires non-universal scalar masses**

**The 'light stop' can decay as**

$$\tilde{t}_1 \longrightarrow b\tilde{\nu}_{\tau R}\tau^+$$

**or leptons of the first two generations**

**Decay length  $\simeq 10^5 - 10^8$  m for**

**(right) sneutrino LSP mass  $\simeq 150 - 200$  GeV**

# Signals of stop-pairs...

$$pp \longrightarrow \tilde{t}_1 \tilde{t}_1^*$$

## Two tracks in the muon chamber

Cuts	SBP1	SBP2	BKG	
$p_{T_{\tilde{t}_1}} > 25 \text{ GeV},  \eta_{\tilde{t}_1}  < 2.5$ and $\Delta R_{\tilde{t}_1 \tilde{t}_1} > 0.2$	754645	158638	19814927	
$p_{T_{\tilde{t}_1}} > 200 \text{ GeV}$	236873	77428	3106	
$m_{\tilde{t}_1 \tilde{t}_1} > 1400 \text{ GeV}$	6180	4324	0	

*Efficiency of cuts on signal 1 at the LHC. The integrated luminosity assumed to be  $30 \text{ fb}^{-1}$ . stop NLSP mass = 240, 330 in the two cases.*

# Gluino signals...

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$$pp \longrightarrow \tilde{g}\tilde{g} \longrightarrow t\tilde{t}_1^*\bar{t}\tilde{t}_1$$

With  $\int L dt = 300 \text{ fb}^{-1}$ ,

**One can distinguish the stop track from stau tracks**

**With one top decaying hadronically, the gluino can be reconstructed**

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## Conclusions

- *SUSY spectra with right-sneutrino LSP are phenomenologically viable*
- *Allowed in a SUGRA setting*
- *LHC signals can be completely new*
- *Stau and stop NLSP scenarios have distinct signatures*
- *Direct mass reconstruction for the gluino is possible*