DOGS THAT DO NOT BARK:

RIGHT-HANDED NEUTRINOS IN A SUPERSYMMETRIC WORLD

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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.”

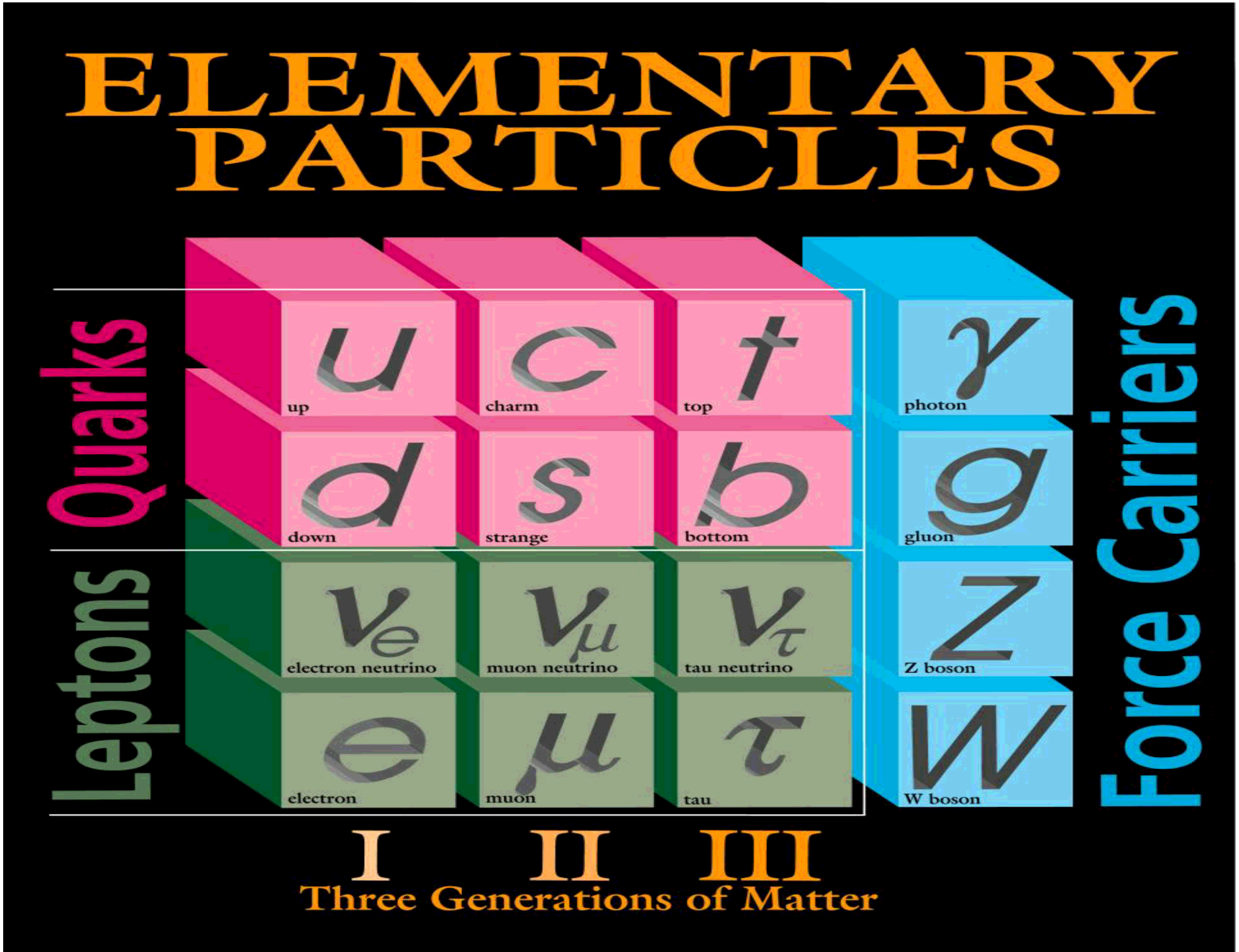
Gregory: ”The dog did nothing in the night-time.”

Holmes: ”That was the curious incident.”

Silver Blaze **in** *The Memoirs of Sherlock Holmes*

by Sir Arthur Conan Doyle

The known elementary particles.....



Fermilab 95-759

The known elementary particles.....

In addition, the 'standard electroweak model' requires the Higgs boson

The left-chiral quarks and leptons are SU(2) doublets, and the right-chiral ones, singlets,

but

no right-handed neutrinos– no neutrino mass

If RH neutrinos (ν_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)**

But in practice....

Neutrinos perhaps have mass and mixing

Evidence from solar, atmospheric and terrestrial

neutrino data + cosmology

$$\Longrightarrow \Delta m^2_{23} \simeq 10^{-3}\, eV^2, \ \Delta m^2_{12} \simeq 10^{-5}\, eV^2$$

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

Individual masses $\lesssim 0.1$ eV

With Higgs doublet(s) only, neutrino mass requires ν_R:

- Just $m_D \bar{\nu_L} \nu_R$ (no lepton number violation) or

- $m_D \bar{\nu_L} \nu_R \; + \; M_R \bar{\nu_R}^c \nu_R$ ($\Delta L = 2$ included)

  $\Longrightarrow \; m_\nu \; = \; m_D^2 / m_R$
  (requires large M_R)

  Depending on the origin of the $\bar{\nu_L} \nu_R$-term, M_R can range from TeV to 10^{14} GeV

At the all-important TeV-scale...

Some new physics is expected

The Higgs mass in the standard model–

subject to large radiative corrections

A cut-off to standard model at $\lesssim$ TeV may

control the damage

A popular solution : supersymmetry (SUSY)

with
$m_{boson} \sim m_{fermion} \lesssim TeV$ so that radiative
corrections beyond TeV cancel

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’) ?

Questions to ask...

Is accelerator phenomenology of SUSY altered by the RH neutrino or its scalar partner?

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Does SUSY with ν_R enable ν-mass and mixing generation mechanisms?

Does the ν_R superfield help us in explaining something more than just neutrino masses?

A right sneutrino and the LHC...

SUSY signals may look different !

Most commonly, the lightest neutralino (χ_1^0) is the lightest SUSY particle (LSP)

Is stable if $R = (-)^{3B+L+2S}$ is conserved, and so better be colourless and neutral

A viable cold dark matter candidate

All SUSY particle production results in decay chains leading to a pair of 'invisible' LSP's

Canonical SUSY signals at the LHC:

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

'jets + missing p_T'

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

'like-sign dileptons (LSD) + jets + missing p_T'

Must χ_1^0 be the LSP?

If the RH neutrino superfield exists, then the $\tilde{\nu}_R$ is an LSP candidate

A right-sneutrino LSP...

More favoured than the $\tilde{\nu}_L$ in a setting where masses evolve from a high scale

Feeble interaction suppresses $\tilde{\nu}_R$ production side by side with low annihilation rate

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)

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

$\sim y_\nu \sim m(Dirac)_\nu$

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

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

The dog that does not bark makes its presence felt!

Things that the ν_R brings into the theory...

- **In the superpotential:**

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

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

y_ν **= 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 ν_R brings into the theory...

- **In the scalar potential,**

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

A_ν is the term driving left-right mixing in the scalar mass matrix

Things that the ν_R brings into the theory...

- **The low-scale sneutrino mass matrix:**

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

$M_{\tilde{L}}$ **= 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 ν_R brings into the theory...

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

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

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 ν_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

The NLSP can be...

$\chi_1^0 \longrightarrow$ **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**

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

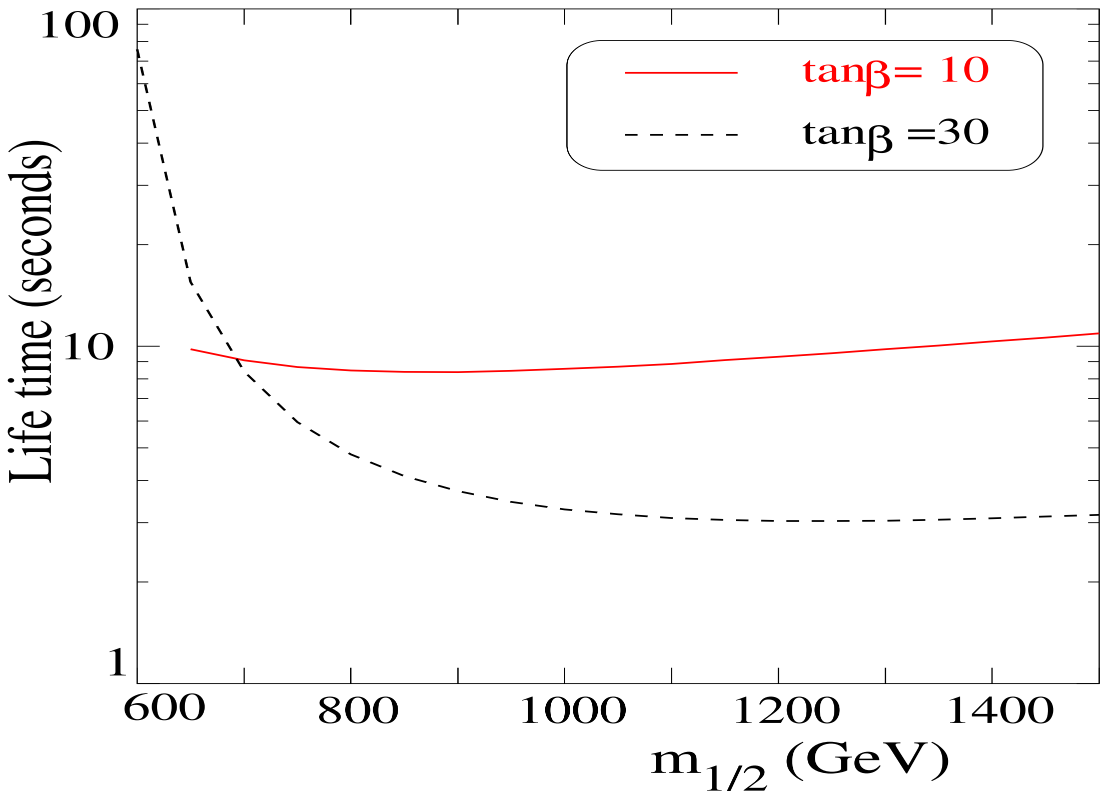
The NLSP can be...

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

$\longrightarrow$ 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



Lifetime of stau NLSP against the universal gaugino mass parameter $m_{1/2}$.

$m_0 = 100$ *GeV,* $A = 100$ *GeV,* $sgn(\mu) = 1$.

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

Supergravity theories with gravitino LSP
J. Feng et al, 2003,2004, J. Ellis et al, 2004,
A. Ibarra + S. Roy, 2006....

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MSSM with stau-neutralino near degeneracy
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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

Jets + two muon-like stau tracks (equivalent of jets + $\not{p}_T$ in MSSM)

Jets + dimuons + two muon-like stau tracks (equivalent of jets + dimuons + $\not{p}_T$ in MSSM)

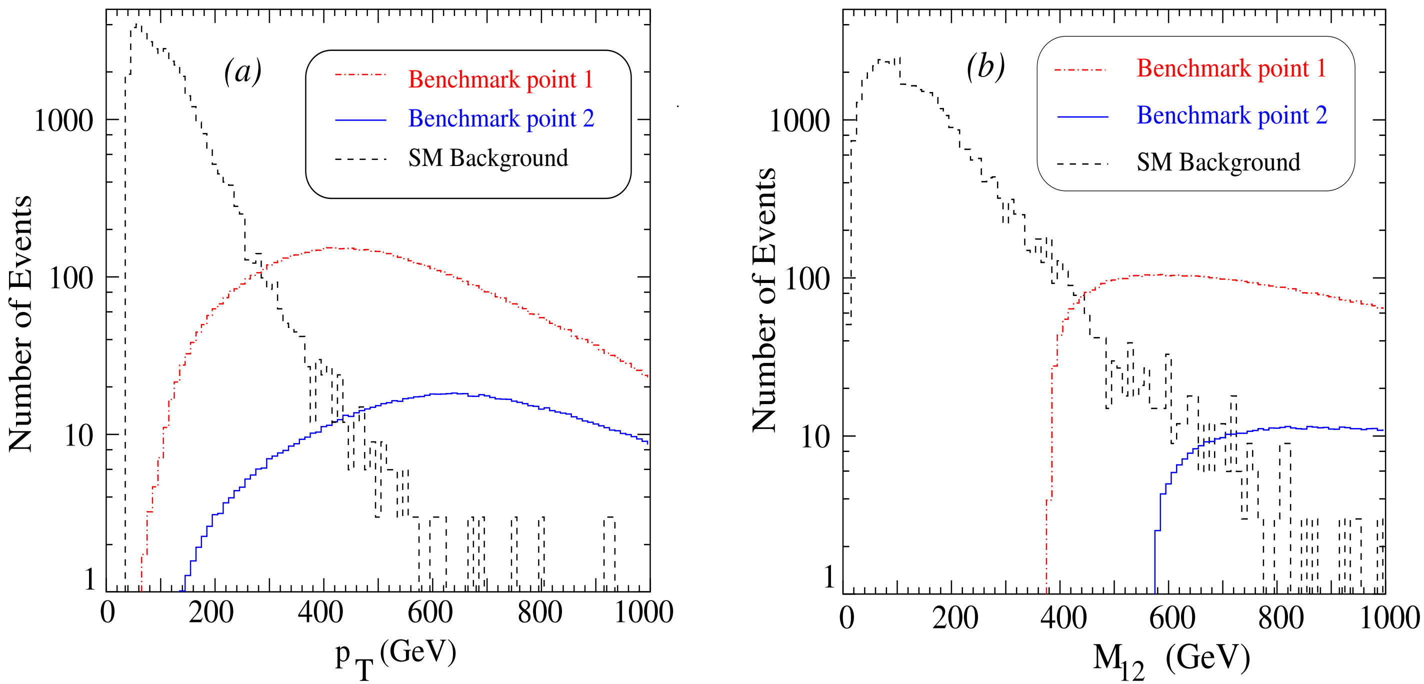
Differentiator: thickness of tracks, time delay, absorption in stoppers ....

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	$m_0 = 100\ GeV,\ m_{1/2} = 600\ GeV$ $A = 100\ GeV,\ sgn(\mu) = +$ $\tan\beta = 30$	$m_0 = 110\ GeV,\ m_{1/2} = 700\ GeV$ $A = 100\ GeV,\ sgn(\mu) = +$ $\tan\beta = 10$
$\|\mu\|$	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
$m_{\tilde{\nu}_{iR}}$	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 stau$_1$ + (≥ 2) hard jets: (a) the transverse momentum distributions for the harder stau$_1$ (b) the invariant mass distribution for the 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.

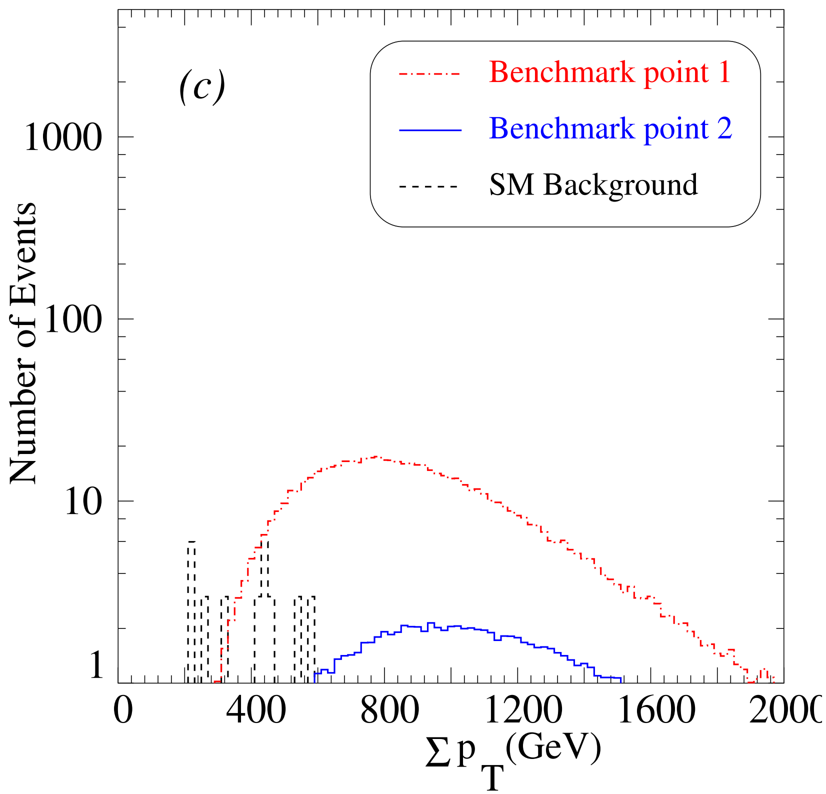
Jets + two tracks: signal vs background

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 = $30\ fb^{-1}$.

Hardness cut on both tracks drastically reduces backgrounds

Jets + two μ's + two tracks:



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

Jets + two μ's + two tracks:

Final States	**Background**	**Benchmark pt. 1(2)**
$2\tilde{\tau}_1$ + 2μ	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	0	553 (89)
($\sum p_T > 600$ GeV)		

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 = $30\ fb^{-1}$.

Finding the answer to a basic question...

SUSY $\Rightarrow$ dark matter candidate if $\Delta L = 1$ (or L-violation by odd units) is forbidden (R-parity conserved)

However, seesaw mechanism (or Majorana neutrino mass) requires $\Delta L = 2$

Can SUSY suggest any underlying principle to justify this?

BM + S. SenGupta + R. Srikanth H., 2006

The proposal...

- Lepton number is a global quantum number shared by the hidden (i.e. SUSY breaking) and observable sectors
- Most SUSY breaking effects come from a chiral superfield $S(L = 0)$
- But there is also a similar superfield $X(L = 1)$
- X is like N_R (RH neutrino that will ultimately have a Majorana mass)

But X does not take part in Yukawa couplings if the superpotential is

$$W = \Lambda^2 S + Y_u^{ij} Q_i U_j^c H_2 + Y_d^{ij} Q_i D_j^c H_1 + Y_e^{ij} L_i E_j^c H_1 + Y_\nu^{ij} L_i N_j^c H_2 + \frac{XX}{2M_P} N_i^c a_{ij} N_j^c, \quad (0)$$

$$\Lambda \simeq \sqrt{(M_P M_{EW})}$$

$\Rightarrow$ **Right-handed ($\Delta L = 2$) neutrino mass** $\sim \frac{(\langle X \rangle)^2}{M_P}$

$\Rightarrow$ **After seesaw mechanism,** $m_\nu \sim 10^{-1}$ **eV if** $\langle X \rangle \sim \Lambda$**,** $m(Dirac)_\nu = O$**(MeV)**

The Kahler potential...

$\mathcal{L} = \int K d^4\theta + (\int W d^2\theta + \text{h.c.}$

$$
\begin{aligned}
K &= K_0(S, S^\dagger, XX^\dagger) + \sum_i K_{\Phi_i}(S, S^\dagger)\Phi_i^\dagger \Phi_i \\
&\quad + \left(K_1(S, S^\dagger) H_1 H_2 + \text{h.c.}\right) .
\end{aligned}
$$

K_0 **is enough to ensure our effects– a near-minimal structure except for a term** $S^\dagger S X^\dagger X$
K_1 **allows the generation of the** μ**(Higgsino mass)-parameter** $\sim \langle F_S \rangle / M_P$

No $\Delta L = 1$ **term (also forbidden by R-symmetry)**
X **and** N **have different R-charges**

The scalar potential

$$V = M_P^4 e^G [M_P^2 G_M K^{M\bar{N}} G_{\bar{N}} - 3]$$

where

$$G = \frac{K}{M_P^2} + \ln \left| \frac{W}{M_P^3} \right|^2$$

$$V_{\rm total} = V_0 + V_1 + V_D$$

$$
\begin{aligned}
V_0 \quad = \quad & e^{K/M_P^2}\Big[K_0^{S\bar{S}}\Lambda^4\left(1+\frac{S\partial_S K_0}{M_P^2}\right)\left(1+\frac{S\partial_S K_0}{M_P^2}\right)^* + \\
& K_0^{X\bar{X}}\Lambda^4\frac{(S\partial_X K_0)(S\partial_X K_0)^*}{M_P^4} - 3\Lambda^4\frac{SS^*}{M_P^2} + \\
& \left(K_0^{X\bar{S}}\Lambda^4\frac{S\partial_X K_0}{M_P^2}\left(1+\frac{S\partial_S K_0}{M_P^2}\right)^* + \text{h.c.}\right)\Big]
\end{aligned}
$$

$$
\begin{aligned}
V_1 \;=\; & e^{K/M_P^2}\left[\left(\frac{\partial W_0}{\partial \Phi_i}\right)^* \frac{\partial W_0}{\partial \Phi_i} + m_0^2(S,S^*)\Phi_i^*\Phi_i \right.\\
& + M_h^2(S,S^*)(H_1^* H_1 + H_2^* H_2) + (-B_\mu(S,S^*)H_1 H_2 \\
& + A_h(S,S^*)(\frac{\partial W_0}{\partial H_1} H_2^* - \frac{\partial W_0}{\partial H_2} H_1^*) + A_2(S,S^*)W_0 \\
& + A_1(S,S^*)\frac{\partial W_0}{\partial \Phi_i}\Phi_i + B_N(S,S^*,X,X^*)\tilde{N}_i^c a_{ij}\tilde{N}_j^c \\
& + \frac{X^* X^*}{M_P}\frac{\partial W_0}{\partial \tilde{N}_i^c} a_{ij}\tilde{N}_j^{c*} + \frac{X X X^* X^*}{2M_P^2} a_{ij} a_{ik} \tilde{N}_j^c \tilde{N}_k^{c*} \\
& \left. + \text{h.c.})\right],
\end{aligned}
$$

With

$\langle S \rangle \simeq M_P$, $\langle F_S \rangle \simeq \Lambda$

$\langle X \rangle \simeq \Lambda$, $\langle F_X \rangle = 0$

$\langle \tilde{N} \rangle \simeq 0$ **(choice of a_{ij} ensures this)**

One has

- **All SUSY-breaking masses $\simeq$ TeV**
- **A vanishing cosmological constant**
- **Lifetime of lightest neutralino $\gtrsim$ age of the universe**

Low-energy SUSY parameters...

Parameter	Source	Order of magnitude
m_0^2	$m_0^2(S, S^*)$ in V_1	TeV^2
A	$A_1(S, S^*),\ A_2(S, S^*)$ in V_1	TeV
B_μ	$B_\mu(S, S^*)$ in V_1	TeV^2
μ	$M_h \sim \frac{F_S}{M_P}$ from K_1	TeV
$m_{1/2}$	$\frac{F_S}{M_P}$ from gauge kinetic terms	TeV

The different parameters of low energy SUSY and their sources.

Summary and Conclusions

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- **They not only provide neutrino masses but also affect the mysteries of the TeV scale in very novel fashions.**
- *These dogs may not bark, but they can bite!*