Displaced Vertices and long-lived charged particles in the NMSSM with Right-Handed Sneutrino

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MultiDark Multimessenger Approach for Dark Matter Detection

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In collaboration with David G. Cerdeño and Osamu Seto, based on JHEP 1405 (2014) 035 (arXiv: 1311.7260)

MSSM: μ Problem

$$W_{\text{MSSM}} \supset -\mu H_1 \cdot H_2$$

After REWSB takes place μ has to be of the order of the EW scale

$\rightarrow \mu$ Problem *Kim, Nilles '84*

Solution

Introduction of a singlet S

$$W_{\text{NMSSM}} \supset -\lambda S H_1 \cdot H_2 + \frac{1}{3}\kappa S^3$$

After REWSB takes place S acquires a vev v_s and originates $\mu = \lambda v_s$ that is of the order of the EW scale.

Higgs mass in the NMSSM

$$m_h^{2,tree} = m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta,$$

New contribution at the tree-level Higgs mass, so no large loop corrections are needed. Same case as adding triplets. *See Garcia-Pepin's, Nardini's and di Chiara's talks.*

Right-Handed (S)Neutrinos in the NMSSM

Superpotential

Introduction of a supermultiplet N

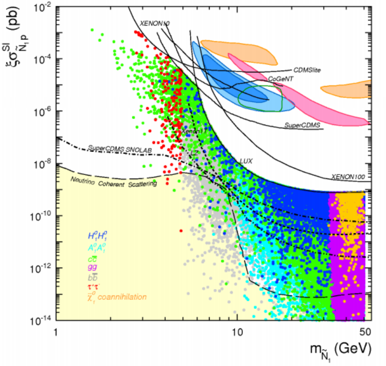
Kitano,Oda '00, Garbrecht, Pallis, Pilaftsis '06 Cerdeno, Munoz, Seto '08 Cerdeno, Seto '09

$$W = W_{\text{NMSSM}} + \lambda_N SNN + y_N L \cdot H_2 N$$

- RH sneutrino: Good dark matter candidate
- RH neutrino: Interesting phenomenology. Low scale see-saw, displaced vertices, long-lived NLSP.

Parameters

5 new parameters: $m_{\tilde{N}}$, λ_N, y_N, A_{λ_N}, A_{y_N}



Sneutrino Dark Matter

- Good Dark Matter candidate
- It is widely extended in the $(\sigma^{SI}_{\tilde{N}p}, m_{\tilde{N}})$ plane.
- It can explain the little excess in gamma rays coming from the Galactic Centre.

Cerdeno, Seto '08
Cerdeno, Seto'09
Cerdeno, Peiro, Seto'11
Cerdeno, Peiro, Robles'14

Neutrino Masses

Mass Matrix

After REWSB takes place the term $\lambda_N SNN$ originates a Majorana mass for N, $M_N = 2\lambda_N v_s$. This term and $y_N L \cdot H_2 N$ provide a neutrino mass matrix:

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & \mathbf{y}_N v_2 \\ \mathbf{y}_N^T v_2 & 2\lambda_N v_s \end{pmatrix}$$

See-saw

In order to obtain a see-saw mechanism we assume $y_N v_2 \ll \lambda_N v_s$, so the masses of the physical states are

$$m_{\nu_1} = \frac{(y_N v_2)^2}{2\lambda_N v_s} \qquad m_{\nu_2} = 2\lambda_N v_s$$

Neutrino Yukawa Coupling

To reproduce the tiny neutrino masses $y_N \sim \mathcal{O}(10^{-6})$

Neutrino Mixing

Mixing of states

We can write the physical states as a function of the gauge states

$$\nu_i = N^{\nu}_{iL}\nu_L + N^{\nu}_{iR}N$$

Neglecting terms of the order $\mathcal{O}(y_N^2)$ and beyond

$$\nu_1 = \nu_L + N^{\nu}_{1R}N, \quad \nu_2 = N^{\nu}_{2L}\nu_L + N$$

$$N^{\nu}_{1R} = -N^{\nu}_{2L} = \frac{y_N v_2}{2\lambda_N v_s}$$

Heavy Neutrino Decay

There exists a mixing that makes the heavy neutrino decay.

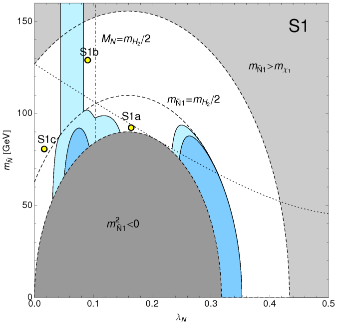
Displaced Vertices: Benchmark points

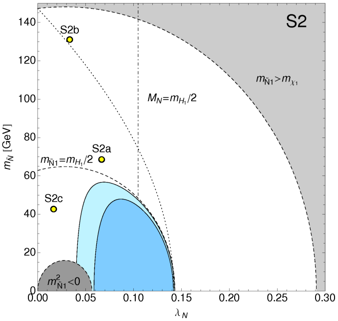
	S1	S2	S3
$\tan\beta$	2.0	2.5	2.7
(M_1, M_2, M_3)	(500, 650,1950) GeV	(300, 600, 1800) GeV	(345, 575, 2500) GeV
μ	152 GeV	180 GeV	595 GeV
(λ, κ)	(0.50, 0.27)	(0.60, 0.40)	(0.58, 0.34)
(A_λ, A_κ)	(283, -220) GeV	(265, -50) GeV	(1189, -225) GeV
$m_{H_1^0}$	99.5 GeV	125.7 GeV	125.8 GeV
$m_{H_2^0}$	125.8 GeV	225.7 GeV	656.9 GeV

Squarks around 2 TeV

Spectrum computed by `NMSSMTools` $\to$ Loop corrections, low energy observables, LEP constraints...

Displaced Vertices: Benchmark points

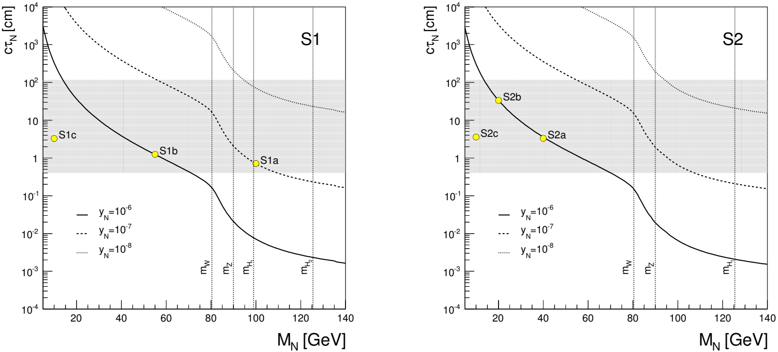




S1a: $m_{\tilde{N}_1}$=20 GeV, $M_N = 100$ GeV
S1b: $m_{\tilde{N}_1}$=100 GeV, $M_N = 55$ GeV
S1c: $m_{\tilde{N}_1}$=70 GeV, $M_N = 10$ GeV

S2a: $m_{\tilde{N}_1}$=40 GeV, $M_N = 40$ GeV
S2b: $m_{\tilde{N}_1}$=20 GeV, $M_N = 20$ GeV
S2c: $m_{\tilde{N}_1}$=10 GeV, $M_N = 10$ GeV

Displaced Vertices: RH Neutrino decays



Displaced Vertices: Signatures at the LHC

Process	Signature
$N \to W^{\pm} l_i^{\mp} \to \nu_j l_j^{\pm} l_i^{\mp}$	$2\ell(+\not{E}_T)$
$\to q\bar{q}' l_i^{\mp}$	ℓjj
$N \to Z\nu_i \to \nu_i l_j^{\pm} l_j^{\mp}$	$2\ell(+\not{E}_T)$
$\to \nu_i q\bar{q}$	$2j(+\not{E}_T)$
$N \to H_i^0 \nu_i \to \nu_i l_j^{\pm} l_j^{\mp}$	$2\ell(+\not{E}_T)$
$\to \nu_i q\bar{q}$	$2j(+\not{E}_T)$
$\to \nu_i \gamma\gamma$	$2\gamma(+\not{E}_T)$

Caution

$\not{E}_T$ is not a good variable for displaced vertices

Information about the mass

m_{jjl}^{inv} from the same displaced vertex $\to$ Peak mass around M_N

m_{ll}^{inv} from the same displaced vertex $\to$ Endpoint variable:

- If $M_N < m_{W,Z}$: $\boxed{(m_{ll}^{inv})^2 \simeq m_N^2}$
- If $M_N > m_{W,Z}$: $\boxed{(m_{ll}^{inv})^2 = m_N^2 - m_{W,Z}^2}$

MC Event Simulation

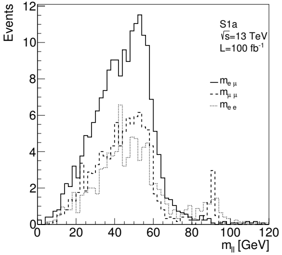
We simulate events with `CalcHEP 3.4`.
We simulate detector effects

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E/\text{GeV}}} \oplus b$$

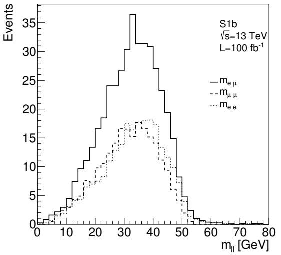
Cuts

- 10 mm $< c\tau < 100$ mm
- Electrons $p_T > 10$ GeV and $|\eta_e| < 2.5$
- Muons $p_T > 6$ GeV and $|\eta_\mu| < 2.5$
- Jet $p_T > 15$ GeV and $|\eta_j| < 2.5$
- Isolated object $\Delta R > 0.4$ ($\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$)

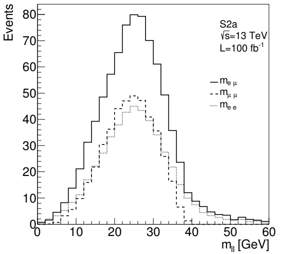
Displaced Vertices: Signatures at the LHC



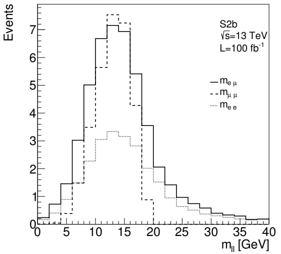
$M_N = 100$ GeV



$M_N = 55$ GeV

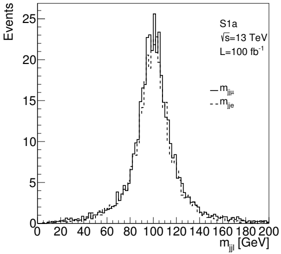


$M_N = 40$ GeV

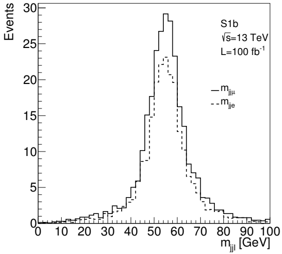


$M_N = 20$ GeV

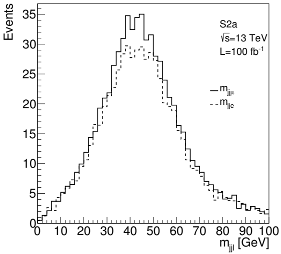
Displaced Vertices: Signals at the LHC



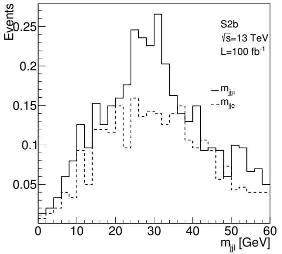
$M_N = 100$ GeV



$M_N = 55$ GeV

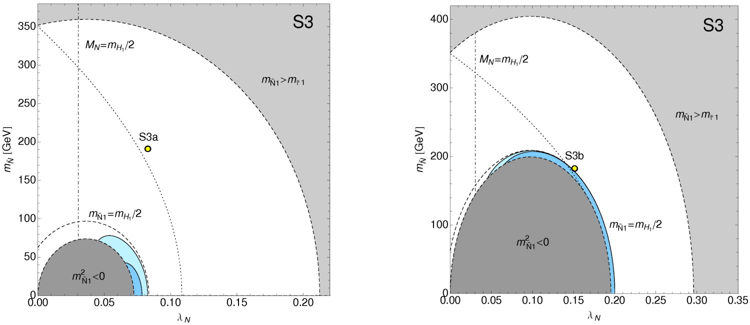


$M_N = 40$ GeV



$M_N = 20$ GeV

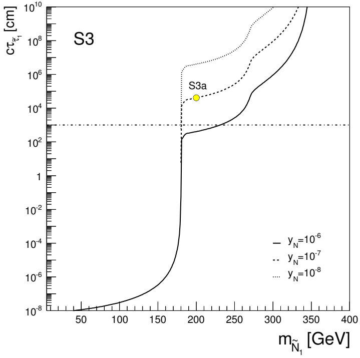
Long-lived charged particles: Benchmark Points

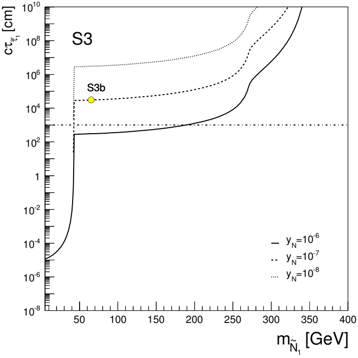


LHC long-lived staus

LHC constraints the mass of the long-lived staus to be greater than $m_{\tilde{\tau}_1} = 342$ GeV

Long-lived charged particles: Signals at the LHC





Cuts

- 2 staus that scape the detector ($c\tau > 10$ m)
- $\beta(\equiv v/c) < 0.95$
- $p_T > 50$ GeV and $|\eta| < 2.5$

$\sqrt{s} = 13$ TeV and $\mathcal{L} = 100$ fb^{-1}

S3a: 30.3 events
S3b: 28.9 events

Conclusions

- We introduce two singlet superfields to solve the μ problem (S) and the neutrino mass problem (N).
- The introduction of the singlet S adds tree-level contribution to the Higgs mass.
- The introduction of the singlet N adds RH-sneutrinos and RH-neutrinos.
- RH-sneutrinos are well DM candidates.
- RH-neutrinos could produce displaced vertices and the stau to be long-lived.
- Specific signatures at the LHC that are interesting to look for.

Thank you for your attention!