Novel signals from novel R-parity violation

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MultiDark
Multimessenger Approach for Dark Matter Detection

Searches for long-lived particles at the LHC: Workshop of the LHC LLP Community

CERN, April 24-26, 2017

Summary of Works and ideas in collaboration with

Daniel E. López-Fogliani
Roberto Ruiz de Austri
Pradipta Ghosh
Iñaki Lara
Vasiliki Mitsou

based on the model $\mu\nu$SSM hep-ph/0508297, PRL (2006)

The fact that the Higgs is:

-likely an elementary scalar
-with a mass of ~125 GeV

puts support on the idea of SUSY…

scalar particles exist,…, they produce the hierarchy problem, …., SUSY predicts the Higgs with a mass $\lesssim$ 140 GeV

- The simplest interpretation of SUSY is to assume R-parity conservation:
  - Particles and sparticles are not mixed
  - the LSP is stable producing missing energy at colliders

- However, novel signals with missing energy have not been discovered yet

- If R-parity is violated (RPV), SUSY particles can decay to standard model particles, and the bounds become significantly weaker

Supersymmetry with right-handed neutrinos

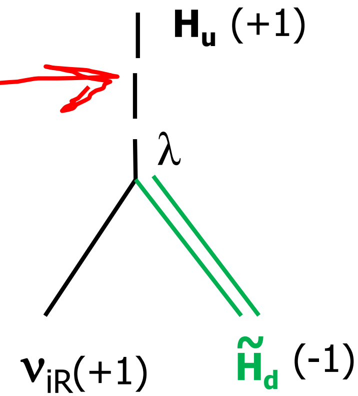
Rigth-handed neutrinos are likely to exist in order to generate neutrino masses $Y^{\nu}_{ij}\, H_u\, L_i\, \nu^c_j$

$$L_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, \quad \begin{matrix} e^c_i \\ \nu^c_i \end{matrix}, \quad Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \quad \begin{matrix} d^c_i \\ u^c_i \end{matrix}$$

$$H_d = \begin{pmatrix} H^0_d \\ H^-_d \end{pmatrix}, \quad H_u = \begin{pmatrix} H^+_u \\ H^0_u \end{pmatrix}$$

R-parity is naturally violated:

$$W = Y^e_{ij}\, H_d\, L_i\, e^c_j + Y^d_{ij}\, H_d\, Q_i\, d^c_j - Y^u_{ij}\, H_u\, Q_i\, u^c_j - Y^{\nu}_{ij}\, H_u\, L_i\, \nu^c_j$$
$$+ \lambda_{ijk}\, L_i\, L_j\, e^c_k + \lambda'_{ijk}\, L_i\, Q_j\, d^c_k + \frac{1}{3}\kappa_{ijk}\, \nu^c_i \nu^c_j\, \nu^c_k + \lambda_i\, H_u\, H_d\, \nu^c_i\, .$$



* Only one scale in the model: the soft SUSY-breaking scale ~ TeV

* The VEVs of the right sneutrinos generate:

- an effective μ-term **solving the μ problem**
- effective Majorana masses for neutrinos **solving the ν problem** (how to accommodate neutrino data)

  electroweak-scale seesaw with $Y_\nu \lesssim 10^{-6}$ ← like the electron Yukawa
- an effective bilinear term

μνSSM Lopez-Fogliani, C. M., PRL 2006

A simple re-interpretation of the spectrum

neutrinos/leptons	neutral Higgs

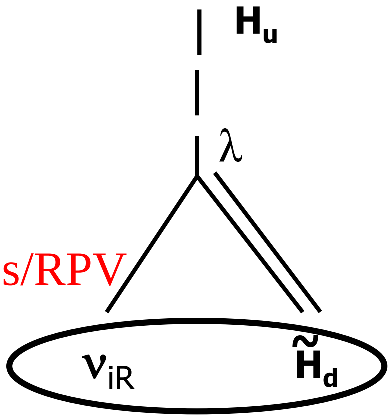
exist in Nature (SM)

SUSY predicts

neutrinos/leptons	neutral/charged Higgsinos
+	+
sneutrinos/sleptons	neutral/charged Higgses

SUSY with neutrinos/RPV

neutrinos/leptons	neutral/charged Higgsinos	are mixed
+	+	
sneutrinos/sleptons	neutral/charged Higgses	are mixed



There are only neutrinos/leptons (and quarks) and their scalar partners

$$L_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, \quad \begin{matrix} e_i^c \\ \nu_i^c \end{matrix}, \quad Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \quad \begin{matrix} d_i^c \\ u_i^c \end{matrix} \quad \longrightarrow \quad L_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, \quad \begin{matrix} e_i^c \\ \nu_i^c \end{matrix}, \quad Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix}, \quad \begin{matrix} d_i^c \\ u_i^c \end{matrix}$$

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \quad H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$$

Higgses are vector-like leptons of a fourth family

$$\longrightarrow \quad L_4 = \begin{pmatrix} \nu_4 \\ e_4 \end{pmatrix}, \quad L_4^c = \begin{pmatrix} e_4^c \\ \nu_4^c \end{pmatrix} \quad Q_4 = \begin{pmatrix} u_4 \\ d_4 \end{pmatrix}, \quad Q_4^c = \begin{pmatrix} d_4^c \\ u_4^c \end{pmatrix}$$

Proposal of new (vector-like) quarks

Heavier quarks and leptons will decay to the lightest ones

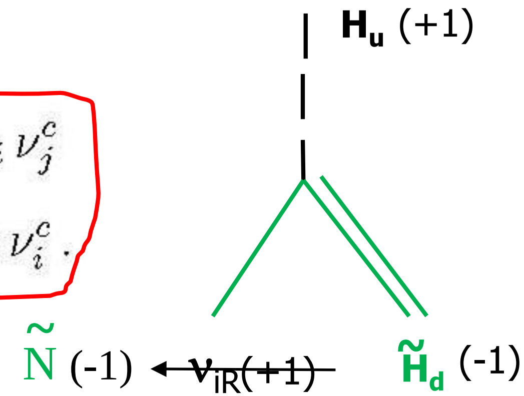
In this framework, the first scalar particle discovered at the LHC is a sneutrino belonging to a 4th-family vector-like doublet representation

Phenomenology of displaced vertices at the LHC

It is related to neutrino physics:

* $\mathbf{Y}_\nu \longrightarrow 0$, R-parity is recovered

$$W = Y^e_{ij}\, H_d\, L_i\, e^c_j + Y^d_{ij}\, H_d\, Q_i\, d^c_j - Y^u_{ij}\, H_u\, Q_i\, u^c_j - Y^\nu_{ij}\, H_u\, L_i\, \nu^c_j + \frac{1}{3}\kappa_{ijk}\, \nu^c_i\, \nu^c_j\, \nu^c_k + \lambda_i\, H_u\, H_d\, \nu^c_i \, .$$



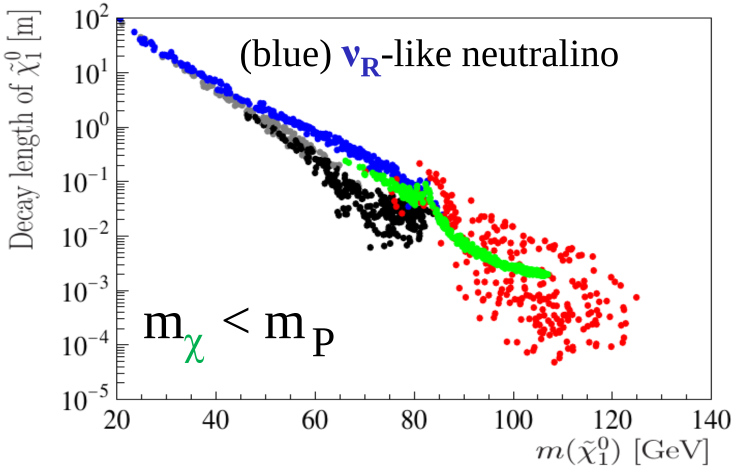
* But $\mathbf{Y}_\nu \lesssim 10^{-6}$, implying that there is a relevant area of the parameter space producing displaced vertices

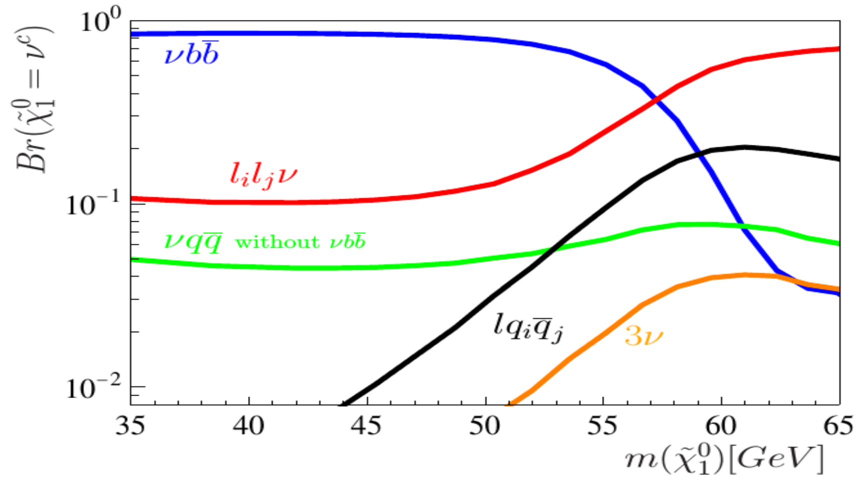
Since the 'LSP' is no longer stable, all particles are potential LSPs:
neutralino, sneutrino, stau, squark, chargino

Neutralino LSP

$Y_\nu \sim 10^{-6}$ ⟶ $m_\chi \sim 20 - 120$ GeV have decay lengths ~ m – 1 mm

Bartl, Hirsch, Vicente, Liebler, Porod, JHEP 2009



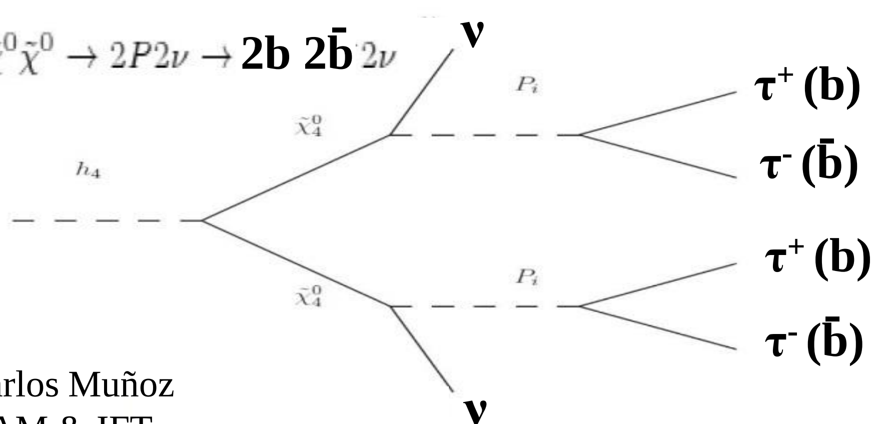


Example: Displaced neutralino from SM-like Higgs

Fidalgo, Lopez-Fogliani, C.M., Ruiz de Austri, JHEP 2011
Ghosh, Lopez-Fogliani, Mitsou, C.M., Ruiz de Austri, PRD 2013

$h_4 \to \tilde{\chi}^0\tilde{\chi}^0 \to 2P2\nu \to 2\tau^+2\tau^-2\nu$

$h_4 \to \tilde{\chi}^0\tilde{\chi}^0 \to 2P2\nu \to 2b\,2\bar{b}\,2\nu$



$(2m_\tau < m_P < 2m_b)$ multileptons

$(2m_b < m_P)$ multijets

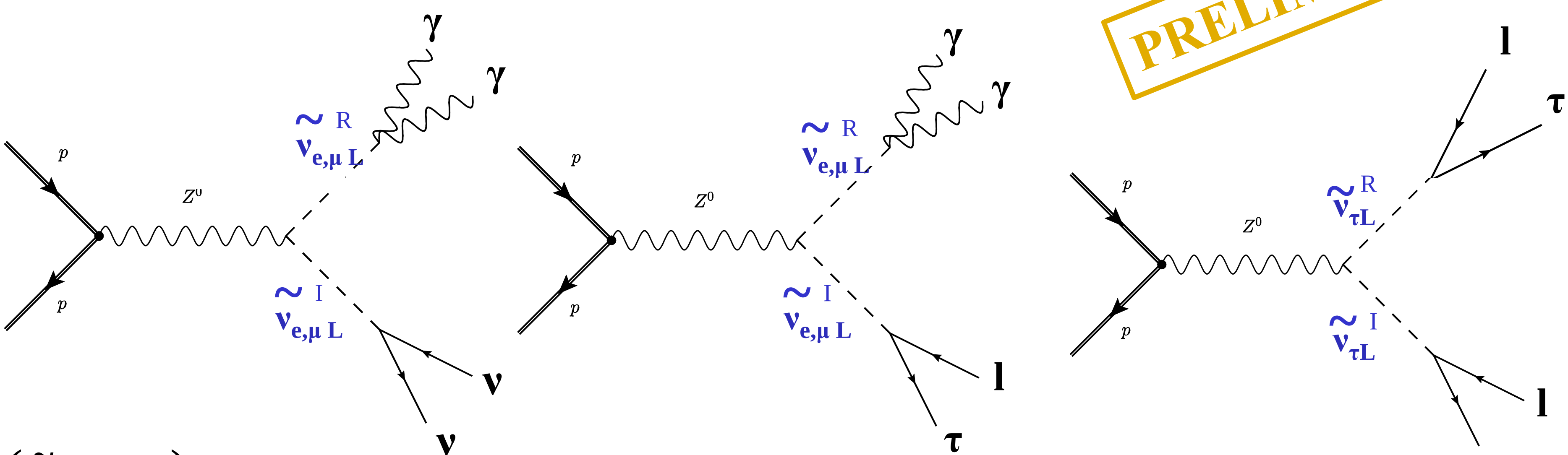
$Br(\tilde{\chi}_4^0 \to \sum_{i=1}^3 \nu_i \tau^+\tau^-) \approx 99\%$ (b $\bar{b}$) $Br(h_4 \to \tilde{\chi}_4^0\tilde{\chi}_4^0) \approx 1\%$

Left Sneutrino LSP

Ghosh, Lara, Lopez-Fogliani, C.M., Ruiz de Austri, in preparation

$\mathbf{Y}_\nu \sim 10^{-6}$ ⟶ $m_{\tilde{\nu}_L} \sim 45 - 100$ GeV have decay lengths ~ mm

PRELIMINAR



$(\tilde{\nu}_{e,\mu}$ LSP$)$ diphoton + missing energy

$(\tilde{\nu}_{\tau}$ LSP$)$ diphoton + leptons

$(\tilde{\nu}_{\tau}$ LSP$)$ multileptons

13 TeV
$\mathcal{L}$=20 fb^{-1} ⟶ $\sigma_t \times \mathcal{L} \sim 10$ ~ 2 ~ 1200

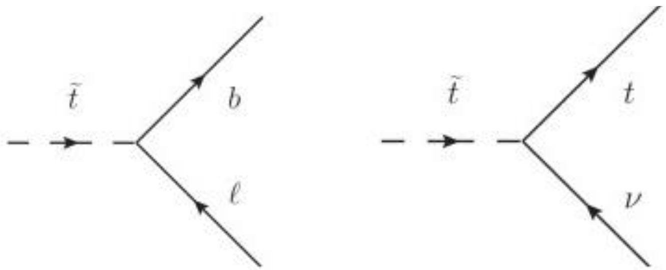
$\mathbf{Y_\nu} \sim 10^{-6}$

Stop LSP

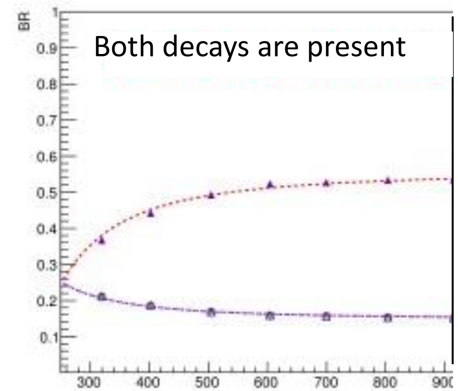
PRELIMINAR

Two dominant decay channels

$\tilde{t}_R$ *Decay to top and neutrino dominant, BR~1*



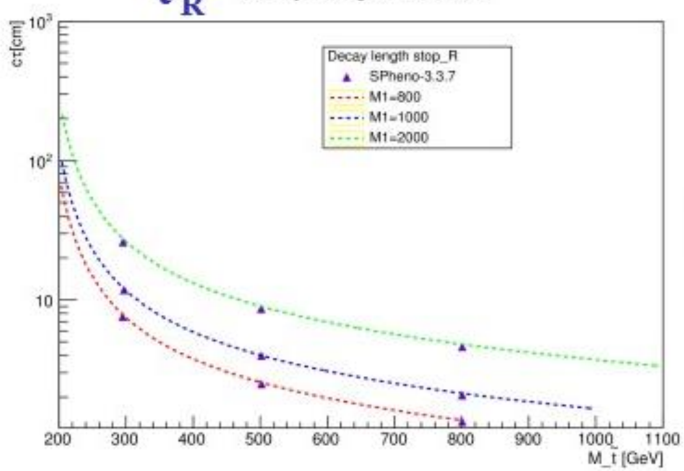
$\tilde{t}_L$



$$\Gamma_{\tilde{t}\to\nu_i t} \sim \frac{|M_{\tilde{t}}^2 - M_t^2|^2}{16\pi M_{\tilde{t}}^3}\left[|\frac{2g_1^2}{\sqrt{3}}\frac{v_{\nu_i}}{M_1}Z^U_{1,6}|^2 + |\frac{1}{2}Z^U_{1,3}(\frac{g_1^2 v_{\nu_i}}{\sqrt{3}M_2} - \frac{\sqrt{3}g_2^2 v_{\nu_i}}{M_1})|^2\right]$$

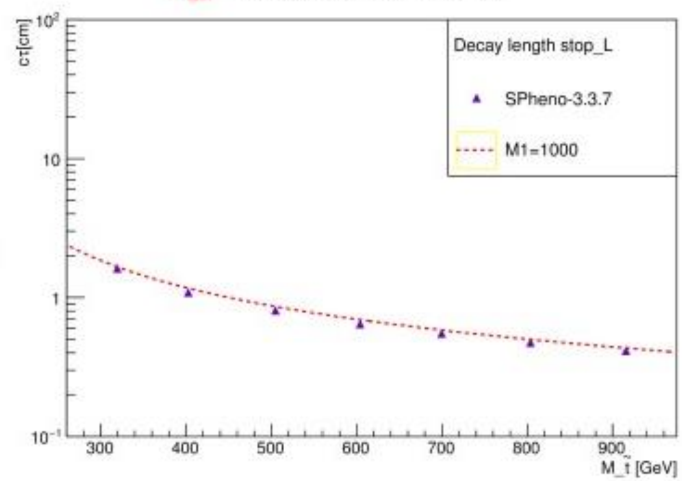
$$\Gamma_{\tilde{t}\to\ell_j b} \sim \frac{M_{\tilde{t}}}{16\pi}[|Y_{d,33}Z^U_{1,3}\frac{Y_{\nu_{jj}}v_{\nu_j^c}}{\lambda_i v_{\nu_i^c}}|^2 + |Z^U_{1,6}\frac{Y_e v_{\nu_j}}{\lambda_i v_{\nu_i^c}}|^2]$$

$\tilde{t}_R$ Decay Lenght vs Mass



Decay length ~ cm

$\tilde{t}_L$ Decay Lenght vs Mass



Cross section similar to MSSM

Conclusions

SUSY with right-handed neutrinos naturally produces R-parity violation

- Interesting theoretical advantages:

  - **solves the μ problem**
  - **solves the ν problem**
  - **reinterpretion of the Higgs(es) as a "4th family" of lepton superfields**

- Interesting LHC phenomenology:

  - Novel signals with displaced vertices,
    multilepton final states,
    multijets
    diphoton + leptons
    diphoton + missing energy
    ...