LLPs from LSPs and the Muon g-2

ESSODJOLO KPATCHA

Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

Universidad Autónoma de Madrid

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- The search for low-energy SUSY is one of the main goals of the LHC

  ... and so far this search has been focused mainly on scenarios, with prompt signals & simplified assumptions, inspired by *R*-parity conserving models, e.g. Minimal Supersymmetric Standard Model

  - significant bounds on sparticle masses have been obtained.

- Because of this, there has been a growing interest in:

  - more complex scenarios such as displaced signals, and/or
  - non minimal models.

- I discuss some scenarios of the long-lived particles in the context of *R*-parity violating SUSY model, the 'μ-from-ν' Supersymmetric Standard Model

Outline:

1. Introduce the $\mu\nu$SSM.
2. Phenomenology of some candidates for lightest supersymmetric particles.
3. How some of the LSPs can contribute to explain the muon g-2 data.
4. Conclusions

The $\mu\nu$SSM

- The superfield content of the $\mu\nu$SSM is the same as that of the MSSM + 3 families of right-handed neutrino superfields, $\hat{\nu}_i^c$.

- The simplest superpotential of the $\mu\nu$SSM [López-Fogliani, Muñoz, hep-ph/0508297]

$$W = \varepsilon_{ab}\left(Y_{u_{ij}}\hat{H}_u^b\hat{Q}_i^a\hat{u}_j^c + Y_{d_{ij}}\hat{H}_d^a\hat{Q}_i^b\hat{d}_j^c + Y_{e_{ij}}\hat{H}_d^a\hat{L}_i^b\hat{e}_j^c\right) + \varepsilon_{ab}\left(-\overbrace{\lambda_i\hat{\nu}_i^c}^{\mu_{eff}}\hat{H}_d^a\hat{H}_u^b + \overbrace{Y_{\nu_{ij}}\hat{H}_u^b\hat{L}_i^a\hat{\nu}_j^c\right) + \frac{1}{3}\kappa_{ijk}\hat{\nu}_i^c\hat{\nu}_j^c\hat{\nu}_k^c}^{\text{neutrino physics}}$$

- The simultaneous presence of the last three terms explicitly breaks R-parity.

  ► RPV is driven by Y_ν, and since $Y_\nu \lesssim 10^{-6}$, is very small

  ► Particle spectrum is enhanced, any particle can be the LSP,

  ► Expect novel signals with prompt & displaced vertices and/or multi-lepton & multi-jets final state

- With a generalized seesaw, all light neutrinos get masses and mixing at tree level

$$(m_\nu)_{ij} \approx \frac{m_{\mathscr{D}_i} m_{\mathscr{D}_j}}{3\mathscr{M}}(1-3\delta_{ij}) - \frac{v_{iL}v_{jL}}{4M}, \quad m_{\mathscr{D}_i} = \frac{Y_{\nu_i} v_u}{\sqrt{2}}, \mathscr{M} = 2\frac{\kappa v_R}{\sqrt{2}}, \frac{1}{M} = \frac{g'^2}{M_1} + \frac{g^2}{M_2}$$

- Left sneutrinos are special... their masses are determined by the soft masses and driven by neutrino physics.

$$m^2_{\widetilde{\nu}_i} \approx \frac{Y_{\nu_i} v_u}{v_i}\frac{v_R}{\sqrt{2}}\left[\frac{-T_{\nu_i}}{Y_{\nu_i}} + \frac{v_R}{\sqrt{2}}\left(-\kappa + \frac{3\lambda}{\tan\beta}\right)\right]; \quad Y_{\nu_3} \sim 10^{-8} < Y_{\nu_{1,2}} \sim 10^{-6} \rightarrow m_{\widetilde{\nu}_\tau} \sim 100 \text{ GeV}$$

- The model easily explains Higgs data [EK, López-Fogliani, Muñoz, Ruiz De Austri, 1910.08062]

► also can simultaneously accommodate the two excesses measured at LEP and LHC at $\sim$ 96 GeV [Biekötter, Heinemeyer, Muñoz, 1712.07475, 1906.06173].

► Higgs sector is very rich, contains many viable solutions with different phenomenological possibilities:

e.g. several scalars with (quasi)degenerated masses $\sim$ 125 GeV can have their signal rates superimposed to the resonance observed at LHC.

LSPs in the $\mu\nu$SSM

- $\mu\nu$SSM has many possible candidates for LSPs
- Several of them have been analyzed, e.g.
  - Bino-like LSP [Lara, López-Fogliani, Muñoz, 1810.12455]
  - Stops LSP
  - Left sneutrinos LSP

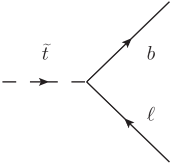
Stops LSPs [EK, Lara, Lõpez-Fogliani, Muñoz, Nagata, Otono, 2111.13212]

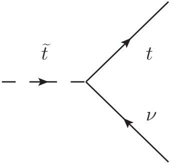
- The tree-level mass matrix in $(\widetilde{t}_L, \widetilde{t}_R)$ basis reads:

$$m_{\widetilde{t}}^2 = \begin{pmatrix} m_t^2 + m_{\widetilde{Q}_{3L}}^2 + \Delta\widetilde{u}_L & m_t X_t \\ m_t X_t & m_t^2 + m_{\widetilde{u}_{3R}}^2 + \Delta\widetilde{u}_R \end{pmatrix}, \quad \text{where } X_t = \left(\frac{T_{u_3}}{Y_{u_3}} - \frac{\mu}{\tan\beta}\right)$$

X_t is the left-right stop mixing, m_t is the top quark mass, and $\Delta\widetilde{u}_{L,R}$ are the D-term contributions.

$\rightarrow$ the most relevant parameters for stops masses are: $m_{\widetilde{Q}_{3L}}$, $m_{\widetilde{u}_{3R}}$, T_{u_3}





- Scan of the parameter space

Scan 1	Scan 2
$m_{\widetilde{Q}_{3L}} \in (200, 1200)$	$m_{\widetilde{u}_{3R}} \in (200, 1200)$
$-T_{u_3} \in (0, 2000)$	
$Y_{\nu_1} \in (10^{-8}, 10^{-6})$	
$v_{1,2} \in (10^{-5}, 10^{-3})$	
$M_1 \in (1500, 2500)$	
$T_\lambda \in (0.5, 2000)$	
$\lambda \in (0.3, 0.7)$	
$\tan\beta \in (1, 20)$	

- Main decay modes

$$\Gamma(\widetilde{t}_L \to b\ell_i) \sim \frac{m_{\widetilde{t}}}{16\pi}\left(Y_b \frac{Y_{\nu_i} v_R}{\sqrt{2}\mu}\right)^2$$

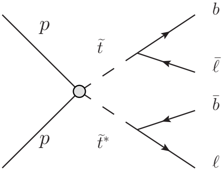
$$\Gamma(\widetilde{t}_R \to b\ell_i) \sim \frac{m_{\widetilde{t}}}{16\pi}\left(Y_t \frac{Y_{e_i} v_i}{\sqrt{2}\mu}\right)^2$$

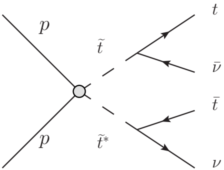
$$\Gamma(\widetilde{t}_L \to t\nu) \sim \frac{(m_{\widetilde{t}}^2 - m_t^2)^2}{16\pi m_{\widetilde{t}}^3} \sum_i \left(\frac{g'}{6} U^V_{i4} + \frac{g}{2} U^V_{i5}\right)^2$$

$$\Gamma(\widetilde{t}_R \to t\nu) \sim \frac{(m_{\widetilde{t}}^2 - m_t^2)^2}{16\pi m_{\widetilde{t}}^3} \sum_i \left(\frac{2g'}{3} U^V_{i4}\right)^2$$

- Constraints: neutrino, higgs physics, g-2, flavor observables
- Decay length $\sim$ mm - m
- Cross section similar to MSSM

- LHC searches put limit on stops mass



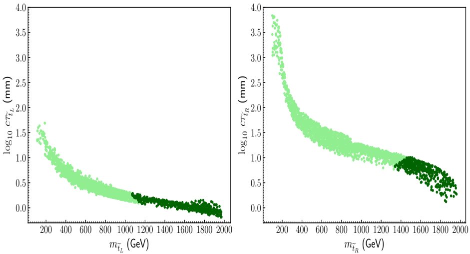


• We compare $\sigma_{\text{prod}} \times$BRs with LHC searches

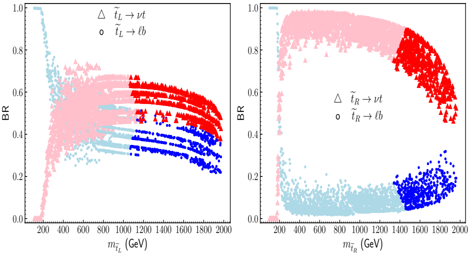
→ Depending on the decay length of $\tilde{t}_L$ and $\tilde{t}_R$, we apply different LHC searches:

Results: dark colored points are allowed, while light ones are excluded.

Stop decay length vs. mass



Stop decay branching fractions vs. mass



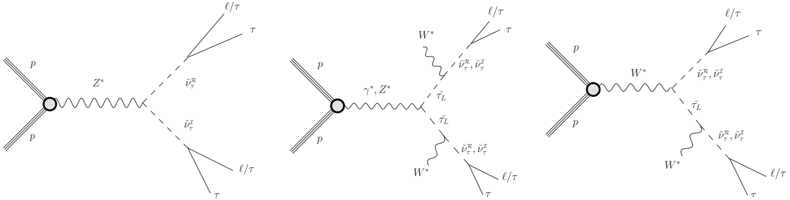
Key message 1:

The limit on stops mass

- right stop LSP $m_{\tilde{t}_R} > 1341$ GeV
- left stop LSP $m_{\tilde{t}_L} > 1068$ GeV
- We expect that more parameter points will be explored at the HL-LHC

$\widetilde{\nu}_\tau$ LSP [EK, Lara, López-Fogliani, Muñoz, Nagata, Otono, Ruiz de Austri, 1907.02092]

- Production and decay of $\widetilde{\nu}_\tau$ LSP in the $\mu\nu$SSM



- We recast the result of the ATLAS search for displaced dileptonour scenario

Search for massive, long-lived particles using multitrack displaced vertices or displaced lepton pairs in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

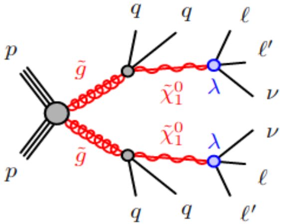
Phys. Rev. D92 (2015) 072004

The ATLAS Collaboration

Abstract

Many extensions of the Standard Model posit the existence of heavy particles with long lifetimes. This article presents the results of a search for events containing at least one long-lived particle that decays at a significant distance from its production point into two leptons or into five or more charged particles. This analysis uses a data sample of proton-proton collisions at $\sqrt{s} = 8$ TeV corresponding to an integrated luminosity of 20.3 fb^{-1} collected in 2012 by the ATLAS detector operating at the Large Hadron Collider. No events are observed in any of the signal regions, and limits are set on model parameters within supersymmetric scenarios involving R-parity violation, split supersymmetry, and gauge mediation. In some of the search channels, the trigger and search strategy are based only on the decay products of individual long-lived particles, irrespective of the rest of the event. In these cases, the provided limits can easily be reinterpreted in different scenarios.

- Topology:



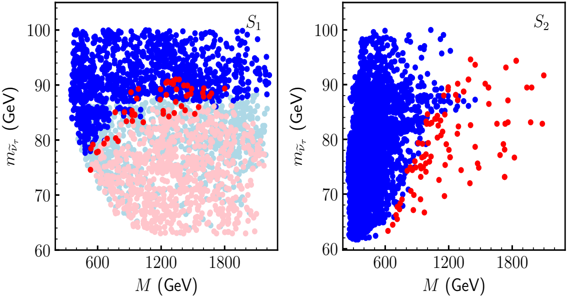
- We also considered LEP bound on left sneutrino masses [hep-ex/0210014] to constrain this scenario

- Sampling the model for $\widetilde{\nu}_\tau$ LSP with $m_{\widetilde{\nu}_\tau} \in (45, 100)$ GeV, and impose neutrino & higgs physics, $c\tau$ > 0.1 mm, muon g-2, flavor observables.

Scan S_1	**Scan S_2**
$\tan\beta \in (10, 16)$	$(1, 4)$
$Y_{\nu_i} \in (10^{-8}, 10^{-6})$	
$v_i \in (10^{-6}, 10^{-3})$	
$-T_{\nu_3} \in (10^{-6}, 10^{-4})$	
$M_2 \in (150, 2000)$	

- Light colored points are excluded by LEP
- Dark blue cannot be probed at run 3 of the LHC

Results: Tau sneutrino mass vs. gaugino mass parameter



- Dark red can be probed at run 3 of the LHC:
- S1: $m_{\widetilde{\nu}_\tau} \in$ 74 - 91 GeV, $M \in$ 532 - 1801 GeV
- S2: $m_{\widetilde{\nu}_\tau} \in$ 63 - 95 GeV, $M \in$ 625 - 2100 GeV

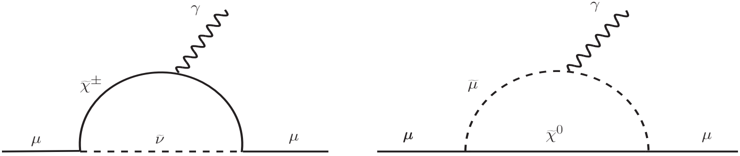
- **Key message 2:**
  - The extrapolation of the usual bounds on sparticles is not applicable
  - A $\widetilde{\nu}_\tau$ LLP can be probed at 13 TeV LHC with $\mathscr{L} = 300$ fb^{-1}

Explaining the muon g-2 data

1. [EK, Lara, Lopez-Fogliani, Muñoz, Nagata; 1912.04163]
2. [Heinemeyer, EK, Lara, Lopez-Fogliani, Muñoz, Nagata; 2104.03294]

Explaining the muon g-2 data

- The new measurement of $\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (25.1 \pm 5.9) \times 10^{-10}$ by MUON G-2 collaboration represents 4.2σ discrepancy from the SM, and could be a sign of new physics.
- In SUSY models, the main one loop contributions are:

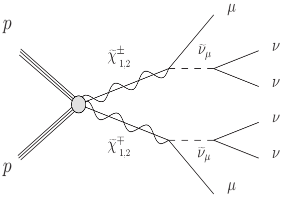


$\rightarrow$ Light $\widetilde{\nu}_\mu$, $\widetilde{\mu}$, $\widetilde{B}$ and $\widetilde{W}$ are possible in the model $\Rightarrow$ can explain Δa_μ?

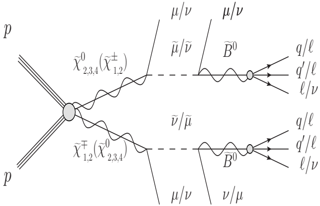
- Scan parameters:

Scan
$\tan\beta \in (10, 16)$
$Y_{\nu_i} \in (10^{-8}, 10^{-6})$
$v_i \in (10^{-6}, 10^{-3})$
$-T_{\nu_2} \in (10^{-6}, 4 \times 10^{-4})$
$M_2 \in (150, 1000)$

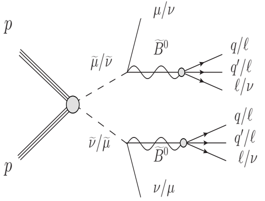
- LHC searches further constrain the allowed regions



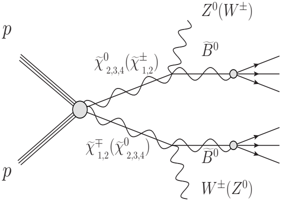
i) $m_{\widetilde{\nu}_\mu} < m_{\widetilde{B}^0} < m_{\widetilde{W}}$



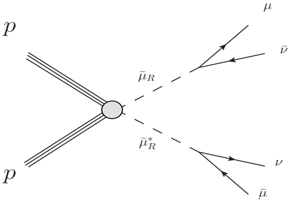
ii) $m_{\widetilde{B}^0} \leq m_{\widetilde{\nu}_\mu} < m_{\widetilde{W}}$



iii) $m_{\widetilde{B}^0} \leq m_{\widetilde{\nu}_\mu} < m_{\widetilde{W}}$

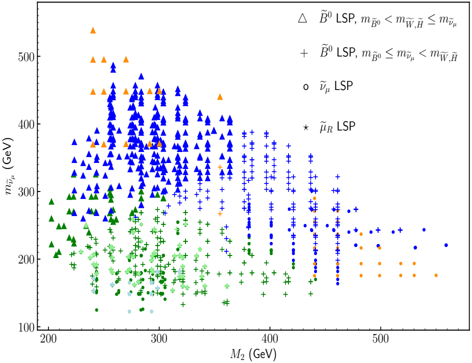


iv) $m_{\widetilde{B}^0} < m_{\widetilde{W}} \leq m_{\widetilde{\nu}_\mu}$



v) $\widetilde{\mu}_R$ LSP

- **Results:** Important regions of the parameter space reproduces Δa_μ, neutrino and higgs physics, and LHC searches.



- Blue, Yellow: 2σ of Δa_μ
  Green: 1σ of Δa_μ

Key message 3:

- Multi-lepton/jets + MET searches can probe the model.
- The predictions can be used for pinning down the mass of $\widetilde{\nu}_\mu$, and for narrowing down the mass scale for electroweakinos.

Conclusions

Conclusions

- The $\mu\nu$SSM is a very attractive model to
  - simultaneously reproduce the correct neutrino and higgs physics,
  - produce novel signals at colliders with prompt & displaced vertices, multi-higgses, multi-lepton, and multi-jet final states.
- The model has many possible viable candidates for LSP that are LLPs that can be probed at 13 TeV LHC and HL-LHC.
  - the extrapolation of the usual bounds on sparticle masses to the $\mu\nu$SSM is not applicable, offering a way to relax tensions with experimental data.
- The muon g-2 data can be reproduced, thanks to the possibility of having light muon sneutrinos and charginos, neutralinos that are still compatible with current LHC limits.

So, it's still too early to give up on SUSY !

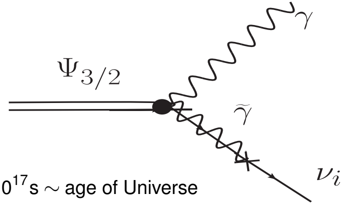
Thank you for your attention !

Dark matter candidates

- **Gravitino:** (Refs: Ki-Young, López-Fogliani, Muñoz, Ruiz de Austri, arXiv:0906.3681; Gómez -Vargas, López-Fogliani, Muñoz, Pérez, Ruiz de Austri, arXiv:1110.3305)

  Due to the mixing of photino and the left-handed neutrinos, $\Psi_{3/2}$ decays into $\gamma\nu$

$$\Gamma(\Psi_{3/2} \to \sum_i \gamma\nu) \simeq \frac{1}{32\pi}|U_{\tilde{\gamma}\nu_i}|^2 \frac{m_{3/2}^3}{M_P^2}$$



$$\tau_{3/2} \simeq 3.8 \times 10^{27}\ \text{s} \left(\frac{|U_{\tilde{\gamma}\nu_i}|^2}{10^{-16}}\right)^{-1} \left(\frac{m_{3/2}}{10\ \text{GeV}}\right)^{-3} \gg 10^{17}\text{s} \sim \text{age of Universe}$$

  ► Monochromatic photons produced in the decay of gravitino can be probed in the indirect detection of DM through gamma-ray measurements

  $\to$ Fermi-LAT constraints: $m_{3/2} < 17$ GeV, $\tau_{3/2} > 4 \times 10^{25}$ s

- **Axino** (Ref: Gómez-Vargas, López-Fogliani, Muñoz, Perez, arXiv:1911.03191)

  The axino LSP can be a decaying DM candidate in a similar way to the gravitino,

  ► Small RPV, and Peccei-Quinn scale suppress the decay rate, $\to c\tau \gg$ age of the Universe, but producing a signal with a gamma-ray line.

  ► Fermi-LAT constraints $m_{\text{axino}} < 3$ GeV.

- **Multicomponent DM made of gravitino and axino** (Ref: Gómez-Vargas, López-Fogliani, Muñoz, Perez, arXiv:1911.03191 & arXiv:1911.08550)

  Axino is the LSP, and gravitino Next-to-LSP, (or vice versa) can contribute to the relic density.
  ► There is a parameter region where a mixture of both sparticles can be obtained, with a double-line signal arising as a smoking gun.

- **Right-handed neutrinos** (Ref.: Knees, López-Fogliani, Muñoz, *et al.*, in preparation)

  RH neutrinos can behave as sterile neutrinos and be candidates for DM. But for that to work, some of them must have small couplings in such a way that they obtain keV masses, and lifetimes long enough to be candidates for DM.