Muon g-2, Dark Matter, and Long-lived Particles at the LHC

Dr. Essodjolo KPATCHA

Instituto de Física Teórica UAM-CSIC

Universidad Autónoma de Madrid

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Outline

1. The 'μ from ν' Supersymmetric Standard Model ($\mu\nu$SSM)
2. LLPs from LSPs in the $\mu\nu$SSM
3. Explaining the muon g-2 data

- 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 prompt signals with MET inspired in RPC models, such as the MSSM... $\rightarrow$ significant bounds on sparticle masses have been obtained.

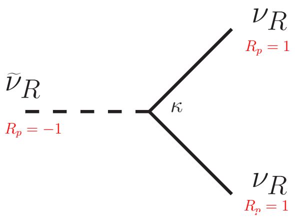
- Because of these results, there is a growing interest in displaced signals from long lived particles (LLPs).

- In this talk I discuss the some scenarios of the LLPs from the lightest supersymetric particles (LSP) in the context of the $\mu\nu$SSM:
  - phenomenology at the LHC
  - possible candidates for dark matter (DM)
  - how such LSPs can can contribute to explain the muon g-2 data.

- 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)

$$W^{\mu\nu\mathrm{SSM}} = \epsilon_{ab}(Y_{u_{ij}} \hat{H}_u^b \hat{Q}_i^a \hat{u}_j^c + Y_{d_{ij}} \hat{H}_d^a \hat{Q}_i^b \hat{d}_j^c + Y_{e_{ij}} \hat{H}_d^a \hat{L}_i^b \hat{e}_j^c)$$
$$+ \epsilon_{ab}(-\lambda_i \hat{\nu}_i^c \hat{H}_d^a \hat{H}_u^b + Y_{\nu_{ij}} \hat{H}_u^b \hat{L}_i^a \hat{\nu}_j^c) + \frac{1}{3} \kappa_{ijk} \hat{\nu}_i^c \hat{\nu}_j^c \hat{\nu}_k^c$$

- The simultaneous presence of the last three terms explicitly breaks R-parity.
  $\rightarrow$ RPV is driven by Y_ν, and since $Y_\nu \lesssim 10^{-6}$, is small in the $\mu\nu$SSM



Consequences of RPV:

- Fields with same quantum numbers are mixed.
- Any particle can be the LSP and such LSP is not stable.
- Novel signals with multi-Higgses, displaced vertices, multi-lepton, multi-jets final states are expected.

- **Neutrino - left sneutrino sector**
  - With a generalized seesaw, all light neutrinos get masses at tree level

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

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

$$m^2_{\widetilde{\nu}_i} \approx \frac{Y_{\nu_i} v_u}{v_i} \frac{v_R}{\sqrt{2}} \left[\frac{-T_{\nu_i}}{Y_{\nu_i}} + \frac{v_R}{\sqrt{2}} \left(-\kappa + \frac{3\lambda}{\tan\beta} \right) \right]$$

  - e.g. $Y_{\nu_3} \sim 10^{-8} - 10^{-7} < Y_{\nu_{1,2}} \sim 10^{-6} \to m_{\widetilde{\nu}_\tau} \sim 100$ GeV and $m_{\widetilde{\nu}_{e,\mu}} \sim 1000$ GeV

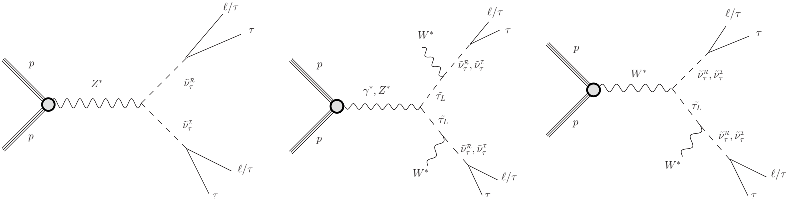
- **Higgs - right sneutrino sector:**
  - The model easily explains Higgs data → Kpatcha, López-Fogliani, Muñoz, Ruiz De Austri, 1910.08062;
    and also can simultaneously accommodate the two excesses measured at LEP and LHC at ∼ 96 GeV → Biekötter, Heinemeyer, Muñoz, 1712.07475, 1906.06173.
  - Higgs sector of the model is very rich, contains many viable solutions with different phenomenological possibilities.

    e.g. several scalars can be (quasi)degenerated with masses ∼ 125 GeV, and thus can have their signal rates superimposed to the scalar 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 (also some works are in progress)

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



- We recast the result of the ATLAS search for displaced dilepton to constrain our 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

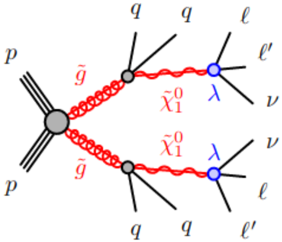
The ATLAS Collaboration

Phys. Rev. D92 (2015) 072004

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:



- Also taken into account LEP analysis (hep-ex/0210014) to constrain this scenario

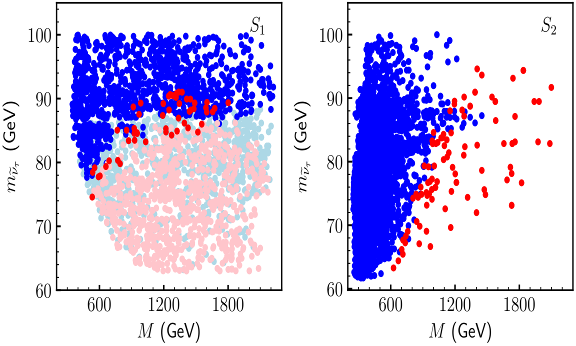
- Sampling the model for $\widetilde{\nu}_\tau$ LSP with $m_{\widetilde{\nu}_\tau} \in (45, 100)$ GeV. (Kpatcha, Lara, López-Fogliani, Muñoz, Nagata, Otono, Ruiz de Austri, 1907.02092)
- We imposed: neutrino, higgs physics, decay length > 0.1 mm, muon g-2, flavor observables

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

Results:

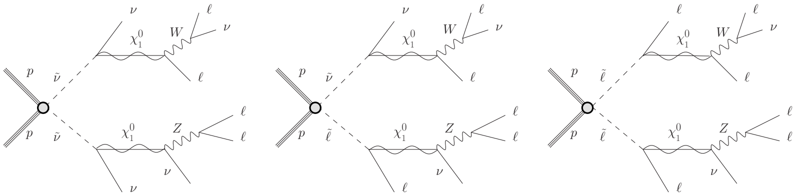
Light-blue, light-red: excluded by LEP.
Blue: cannot be probed at LHC Run 3
Red: can be probed at LHC Run 3

- $c\tau_{\widetilde{\nu}_\tau} \sim 0.1 - 5$ mm

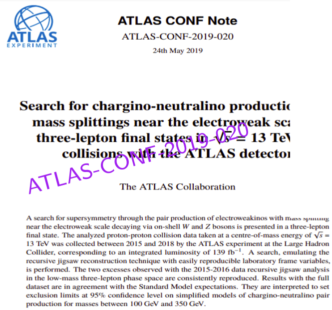


- **Take home message**
  1. It is easy to reproduce neutrino and higgs physics
  2. The extrapolation of the usual bounds on sparticle masses to the $\mu\nu$SSM is not applicable
  3. A $\widetilde{\nu}_\tau$ LLP can be probed at 13-TeV LHC with $\mathcal{L} = 300$ fb^{-1}.

- Production and decay of Bino-like LSP in the $\mu\nu$SSM



- ATLAS searches can be used to test this Bino-like LSP, signal with 3 leptons + MET.



ATLAS CONF Note

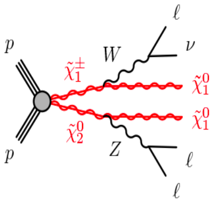
ATLAS-CONF-2019-020

24th May 2019

Search for chargino-neutralino producti[...] mass splittings near the electroweak sc[...] three-lepton final states in $\sqrt{s}$ = 13 Te[...] collisions with the ATLAS detector

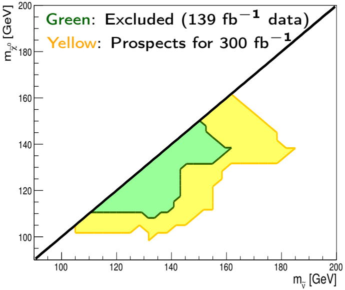
The ATLAS Collaboration

A search for supersymmetry through the pair production of electroweakinos with mass splitting near the electroweak scale decaying via on-shell W and Z bosons is presented in a three-lepton final state. The analyzed proton-proton collision data taken at a centre-of-mass energy of $\sqrt{s}$ = 13 TeV was collected between 2015 and 2018 by the ATLAS experiment at the Large Hadron Collider, corresponding to an integrated luminosity of 139 fb^{-1}. A search, emulating the recursive jigsaw reconstruction technique with easily reproducible laboratory frame variables, is performed. The two excesses observed with the 2015-2016 data recursive jigsaw analysis in the low-mass three-lepton phase space are consistently reproduced. Results with the full dataset are in agreement with the Standard Model expectations. They are interpreted to set exclusion limits at 95% confidence level on simplified models of chargino-neutralino pair production for masses between 100 GeV and 350 GeV.

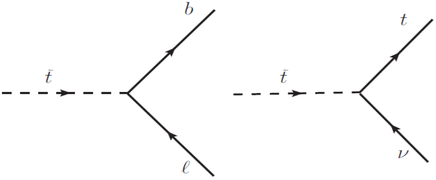


- Wino-like ($\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$) production
- Bino-like ($\tilde{\chi}_1^0$) LSP
- $c\tau_{\rm Bino} \lesssim 0.2$ mm

Results:



Stops LSPs (Kpatcha, Lara, López-Fogliani, Muñoz, Nagata, Otono, Ruiz de Austri, In Preparation)



- Two main decay modes for stop LSP

$$\Gamma_{\tilde{t}_L \to \ell_j b} \sim \frac{m_{\tilde{t}}}{16\pi} \left| Y_b \frac{Y_{\nu_j} v_{R_j}}{\mu_{eff}} \right|^2$$

$$\Gamma_{\tilde{t}_L \to \nu_j t} \sim \frac{|m_{\tilde{t}}^2 - m_t^2|^2 v_i^2}{64\pi m_{\tilde{t}}^3} \left| \frac{g_1^2}{6M_1} + \frac{g_2^2}{M_2} \right|^2$$

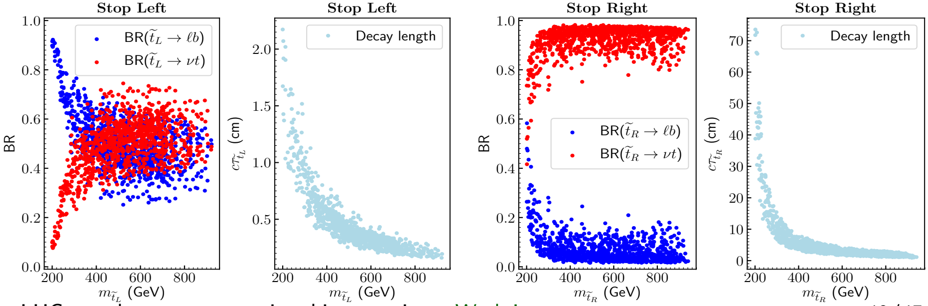
$$\Gamma_{\tilde{t}_R \to \ell_j b} \sim \frac{m_{\tilde{t}}}{16\pi} \left| Y_b \frac{Y_{e_j} v_j}{\mu_{eff}} \right|^2$$

$$\Gamma_{\tilde{t}_R \to \nu_j t} \sim \frac{|m_{\tilde{t}}^2 - m_t^2|^2 v_i^2}{16\pi m_{\tilde{t}}^3} \left| \frac{2g_1^2}{3M_1} \right|^2$$

- Cross section similar to MSSM
- Decay length $\sim$ cm - dm

Input parameters
$200 \leq M_{\tilde{U}_3}, M_{\tilde{Q}_3}$ (GeV) ≤ 1200
$0 \leq -T_{u_{33}}$ (GeV) ≤ 2000
$0.5 \leq T_\lambda$ (GeV) ≤ 2000
$0.3 \leq \lambda \leq 0.7$
$1 \leq \tan\beta \leq 20$
$1500 \leq M_1$ (GeV) ≤ 2500
$10^{-5} \leq v_1, v_2$ (GeV) $\leq 10^{-3}$
$10^{-8} \leq Y_{\nu_{11}} \leq 10^{-6}$

- We imposed: neutrino, higgs physics, $g-2$, flavor observables

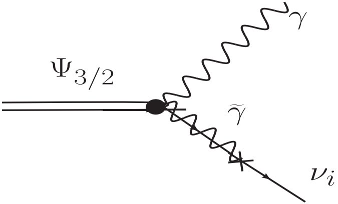


- LHC searches, can constraint this scenario ... Work in progress

- **Gravitino** (Ki-Young Choi, López-Fogliani, Muñoz, Ruiz de Austri, JCAP 2010 JCAP 2010; Gómez -Vargas, López-Fogliani, Muñoz, Pérez, Ruiz de Austri, JCAP 2017)
  The Gravitino LSP can be the dark matter candidate and due to the mixing of photino and the left-handed neutrinos, with lifetime greater than the age of universe.

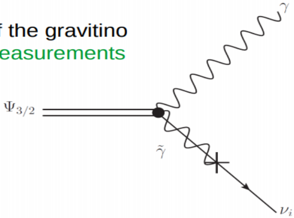
$$\Gamma(\Psi_{3/2} \to \sum_i \gamma\nu) \simeq \frac{1}{32\pi} |U_{\tilde{\gamma}\nu_i}|^2 \frac{m_{3/2}^3}{M_P^2}$$

$$|U_{\tilde{\gamma}\nu}|^2 \sim |g_1 v_i / M_1|^2 \sim 10^{-14}\text{-}\ 10^{-15}$$



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

Monochromatic photons produced in the decay of the gravitino
⇒ Indirect detection of DM through gamma-ray measurements



Constraints from *Fermi*-LAT:

$$m_{3/2} < 17\ \text{GeV}$$

$$\tau_{3/2} > 4 \times 10^{25}\ \text{s}$$

Gómez-Vargas, López-Fogliani, Muñoz, Perez, Ruiz de Austri JCAP (2017)

- **Axino** (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, allowing to have lifetimes greater than the age of the Universe, but producing a signal with a gamma-ray line.
  ▶ The Fermi-LAT constraints impose that axino masses must be smaller than about 3 GeV.
  ▶ Axino DM can be explored in future gamma-ray missions such as the proposed e-ASTROGAM (masses $\sim$ 2 MeV - 3 GeV, and lifetimes $\sim 2.10^{26} - 8.10^{30} s$)

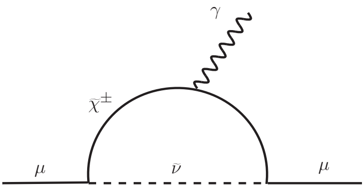
- **Multicomponent DM made of gravitino and axino** (Gómez-Vargas, López-Fogliani, Muñoz, Perez, arXiv:1911.03191 and arXiv:1911.08550)
  If axino is the LSP, and gravitino Next-to-LSP, (or vice versa), both can contribute to the relic density.
  ▶ There is a parameter region where a mixture of both sparticles can be obtained, with a double-line signal arising as a smoking gun.

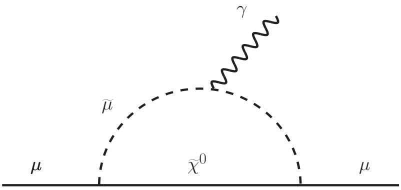
- **Right-handed neutrinos** (Knees, López-Fogliani, Muñoz, *et al.*, in preparation)
  RH neutrinos can behave as sterile neutrinos and be candidates for DM. But for that to work, some of they must have small couplings in such a way that they obtain keV masses, and lifetimes long enough to be candidates for DM.

Take home message:
The $\mu\nu$SSM is an appealing scenario for solving the DM problem, with different interesting potential candidates.

Muon g-2 (Kpatcha, Lara, López-Fogliani, Muñoz, Nagata, 1912.04163)

- The measurement of $\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (26.8 \pm 6.3 \pm 4.3) \times 10^{-10}$ represents 3.5σ discrepancy and this could be a sign of new physics beyond the SM.
- In SUSY models, the main one loop contributions are



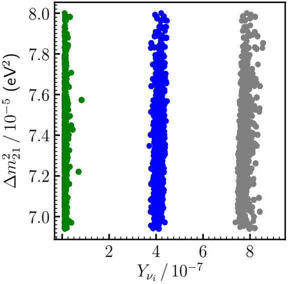


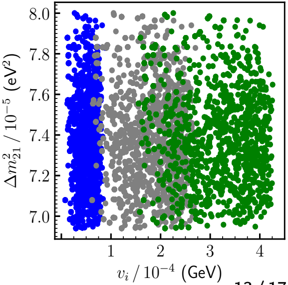
- We exploit the fact that light muon sneutrino & smuon and electroweak gauginos are possible in the $\mu\nu$SSM, to explain the discrepancy.

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

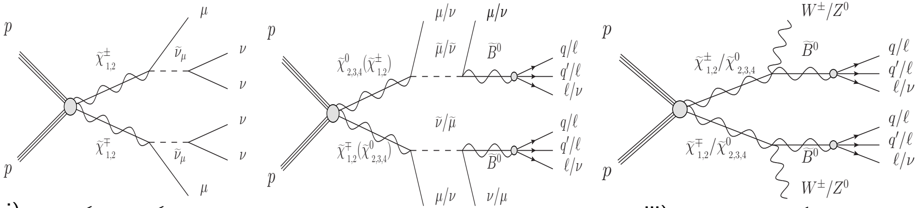
• We imposed: neutrino, higgs physics, $g-2$, flavor observables

• $\equiv Y_{\nu_1}$, v_1, • $\equiv Y_{\nu_2}$, v_2
• $\equiv Y_{\nu_3}$, v_3



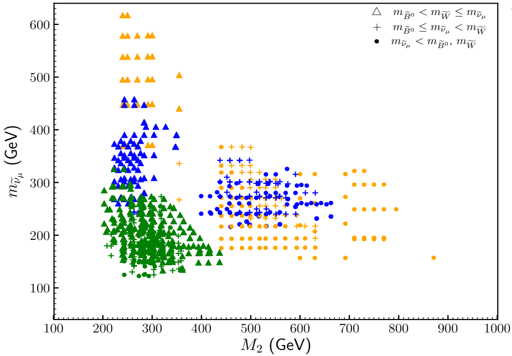


- LHC searches for electroweakinos further constrain the allowed regions of this scenario.



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

- Important regions of the parameter space reproduces Δa_μ, neutrino and higgs physics, and LHC searches, (Kpatcha Lara, López-Fogliani, Muñoz, Nagata, 1912.04163)



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

Take home message:

1. Multi-lepton + MET searches can probe the model.
2. Th prediction of the $\mu\nu$SSM can be used to pinning down the mass of $\tilde{\nu}_\mu$, and to narrow down the mass scale for a potential discovery of electroweakinos

Conclusions

- The $\mu\nu$SSM is a very attractive SUSY model that, in addition to simultaneously reproducing correct neutrino and higgs physics, can also produce novel signals at colliders with multi-Higgses, prompt/displaced vertices, multi-lepton/jet final states.

- Also, 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 model has many possible candidates for LLPs, and the studies of some of them LLPs (e.g. $\widetilde{\nu}_{\tau,\mu}$, Bino, Wino, Stop), shown that important regions can be probed at 13-TeV LHC with $\mathcal{L} = 300$ fb^{-1}.

- The $\mu\nu$SSM is an appealing scenario for solving the DM problem, with different interesting potential candidates (e.g. Gravitino, axino, RH neutrinos).

- The measurement of the muon $g-2$ can be explained, thanks to the possibility of having light muon sneutrinos and chargino-neutralino that are still compatible with current LHC limits.

THANK YOU