LLPs from LSPs

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Outline

1. Introduction
2. The 'μ from ν' Supersymmetric Standard Model ($\mu\nu$SSM)
   - Neutrino and left sneutrino sector
   - Higgs physics
3. LLPs from LSPs in the $\mu\nu$SSM
4. Muon (g-2)
5. Conclusions

Introduction

- 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.
- Significant bounds on sparticle masses have been obtained:
  - For strongly interacting sparticles, their masses must be above about 1TeV.
  - For weakly interacting sparticles, the lower bounds are of about 100 GeV, ... in fact bino-like neutralino is basically not constrained due to its small pair production cross section.
- Because of these results, there is a growing interest in searching for displaced signals from LLPs at the LHC
- In the context of the $\mu\nu$SSM, all sparticles are potential candidates for the LSP, i.e. squarks, gluinos, charginos, charged sleptons, sneutrinos, or neutralinos can be the LSP, decaying prompt or with a decay length $\sim$ mm-m.
- Thus, the $\mu\nu$SSM can produce distinctive signals at colliders, e.g. multi-leptons, jets, photons that are verifiable at the LHC or upcoming accelerator experiments, or at non-collider experiments such as neutrino experiments
- In this talk I discuss the some of the LLP scenarios in the $\mu\nu$SSM

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, $\hat{\nu}^c_i$.
- The simplest superpotential of the $\mu\nu$SSM (D. López-Fogliani, C. Muñoz, hep-ph/0508297)

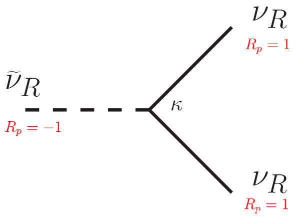
$$W^{\mu\nu\text{SSM}} = \epsilon_{ab}(Y_{u_{ij}} \hat{H}^b_u \hat{Q}^a_i \hat{u}^c_j + Y_{d_{ij}} \hat{H}^a_d \hat{Q}^b_i \hat{d}^c_j + Y_{e_{ij}} \hat{H}^a_d \hat{L}^b_i \hat{e}^c_j)$$

$$+ \epsilon_{ab}(-\lambda_i \hat{\nu}^c_i \hat{H}^a_d \hat{H}^b_u + Y_{\nu_{ij}} \hat{H}^b_u \hat{L}^a_i \hat{\nu}^c_j) + \frac{1}{3}\kappa_{ijk} \hat{\nu}^c_i \hat{\nu}^c_j \hat{\nu}^c_k$$

  - $\lambda_i \hat{\nu}^c_i \hat{H}_u \hat{H}_d \xrightarrow{\text{EWSB}} \mu = \sum \lambda_i \frac{v_{iR}}{\sqrt{2}} \Rightarrow$ μ problem is solved
  - $Y_{\nu_{ij}} \hat{H}_u \hat{L}_i \hat{\nu}^c_j \xrightarrow{\text{EWSB}} m_{\mathcal{D}_{ij}} = Y_{\nu_{ij}} \frac{v_u}{\sqrt{2}}$: Dirac masses
  - $\kappa_{ijk} \hat{\nu}^c_i \hat{\nu}^c_j \hat{\nu}^c_k \xrightarrow{\text{EWSB}} \mathcal{M}_{ij} = 2\kappa_{ijk} \frac{v_{kR}}{\sqrt{2}}$: Majorana masses

  (Dirac and Majorana masses together) $\Rightarrow$ ν problem is solved with an electroweak scale seesaw generated dynamically

- The simultaneous presence of the last three terms explicitly breaks R-parity.
- For $Y_\nu \to 0$, ν^c are ordinary singlets $\Rightarrow$ RPV is driven by Y_ν and since $Y_\nu \lesssim 10^{-6}$, is small in the $\mu\nu$SSM



Consequently:

- 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

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

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

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

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

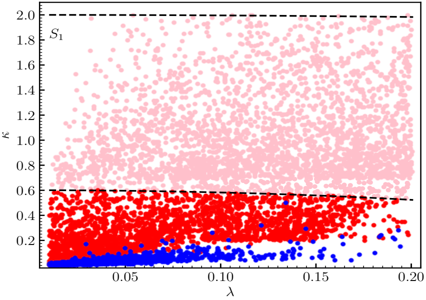
  - e.g. $Y_{\nu_3} \sim 10^{-8} - 10^{-7} < Y_{\nu_{1,2}} \sim 10^{-6} \to m_{\widetilde{\nu}_\tau} \sim 100$ GeV and $m_{\widetilde{\nu}_{e,\mu}} \sim 1000$ GeV

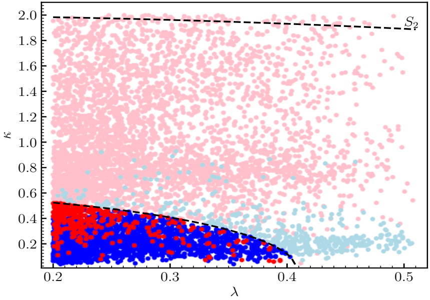
- **Higgs - right sneutrino sector:**
  - Higgs - right sneutrino sector of the $\mu\nu$SSM is somewhat decoupled from neutrino and left sneutrino sector *i.e.* the most relevant parameters for each sector can be decoupled.
  - The model easily explains Higgs data: • Biekötter, Heinemeyer, Muñoz, 1712.07475; • Biekötter, Heinemeyer, Muñoz, 1906.06173 → $\mu\nu$SSM can simultaneously accommodate two excesses measured at LEP and LHC at ~ 96 GeV at the 1σ level. • Kpatcha, López-Fogliani, Muñoz, Ruiz De Austri, 1910.08062 → Scans $0.01 \leq \lambda < 1.2$, $0.01 \leq \kappa < 2$, $1 \leq \tan\beta \leq 40$, $100 \leq v_R/\sqrt{2}(\text{GeV}) \leq 7000$, $0 < T_\lambda(\text{GeV}) \leq 500$, $0 < T_\kappa(\text{GeV}) \leq 500$, $0 < -T_{u_3}(\text{GeV}) \leq 5000$, $200 \leq m_{\widetilde{Q}_{3L}} = m_{\widetilde{u}_{3R}}(\text{GeV}) \leq 2000$

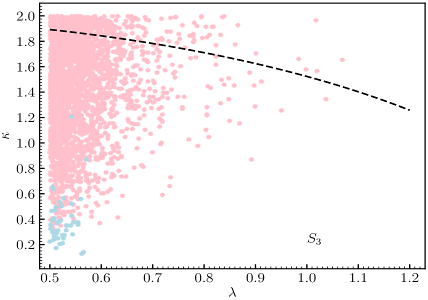
- Viable points in the $\kappa - \lambda$ plane

●, ● $m_{h_i} > m_H = 125$ GeV

●, ● $m_{h_i} < m_H = 125$ GeV







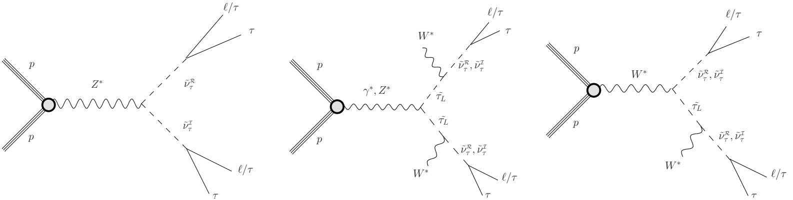
Take home message 1:

1. Higgs sector of the model is very rich, contains many viable solutions with different phenomenological possibilities.
2. Several scalars can be (quasi)degenerated with masses close to 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
- We have analyzed several of them, (some works are in progress) in regions of the parameter space where these LSPs have long decay lengths and therefore are LLPs

- 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

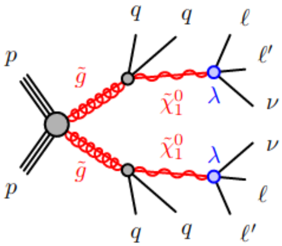
The ATLAS Collaboration

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:

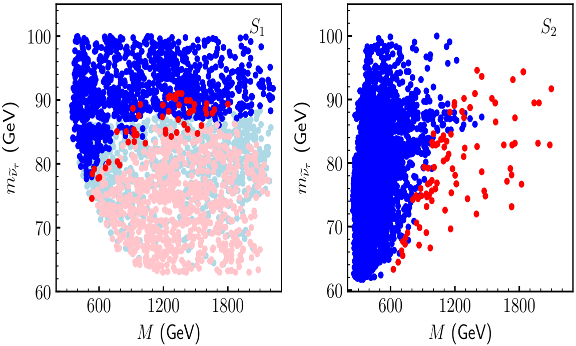


- Also taken into account LEP analysis Eur. Phys. J. **C31** (2003) 1, hep-ex/0210014 to constrain these scenarios

- 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, $g-2$, 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:



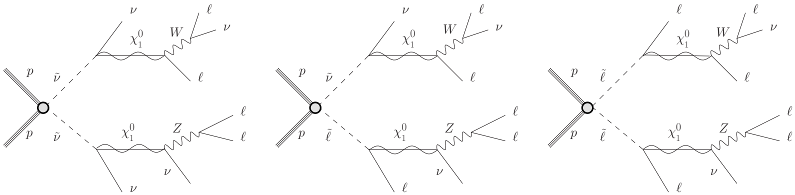
Light-blue, light-red: excluded by LEP.
Blue: cannot be probed at LHC Run 3
Red: can be probed at LHC Run 3

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

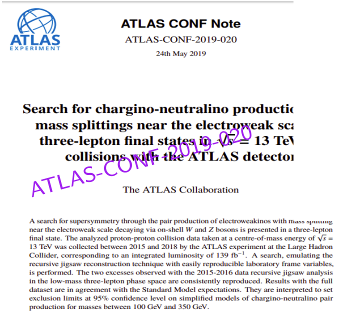
- **Take home message 2:**
  1. It is easy to reproduce neutrino and higgs physics
  2. The extrapolation of the usual bounds on sparticle masses to the $\mu\nu$SSM is not applicable
  3. A $\widetilde{\nu}_\tau$ LLP can be probed at 13-TeV LHC with $\mathcal{L} = 300$ fb^{-1}.

Bino-like LSP (Lara, López-Fogliani, Muñoz, 1810.12455)

- 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.

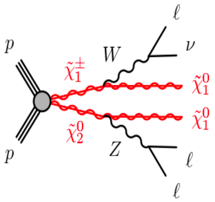

ATLAS CONF Note
ATLAS-CONF-2019-020
24th May 2019

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

ATLAS-CONF-2019-020

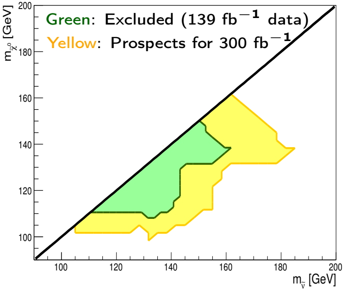
The ATLAS Collaboration

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
- $c\tau_{\text{Bino}} \lesssim 0.2$ mm

Results:

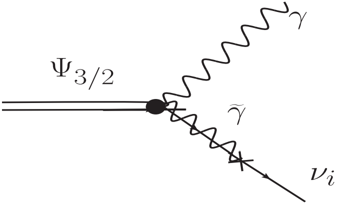


Gravitino LSP

In the $\mu\nu$SSM, the gravitino LSP can be the dark matter candidate and due to the mixing of photino and the left-handed neutrinos, it can decay to $\gamma + \nu$ with lifetime $\gg$ the age of universe.

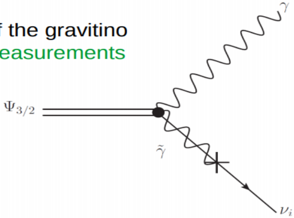
$$\Gamma(\Psi_{3/2} \to \sum_i \gamma\nu) \simeq \frac{1}{32\pi} |U_{\widetilde{\gamma}\nu_i}|^2 \frac{m_{3/2}^3}{M_P^2}$$

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



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

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



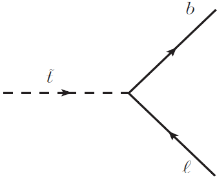
Constraints from *Fermi*-LAT:

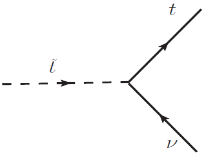
$$m_{3/2} < 17\ \mathrm{GeV}$$

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

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

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





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

- Two main decay modes for stop LSP

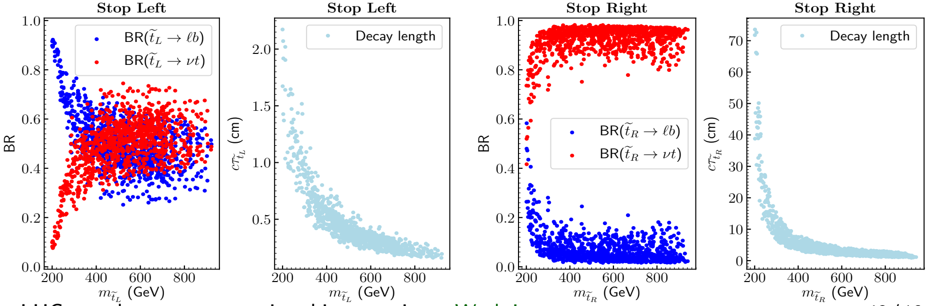
$$\Gamma_{\tilde{t}_L \to \ell_j b} \sim \frac{m_{\tilde{t}}}{16\pi} \left| Y_b \frac{Y_{\nu_j} v_{R_j}}{\mu_{eff}} \right|^2$$

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

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

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

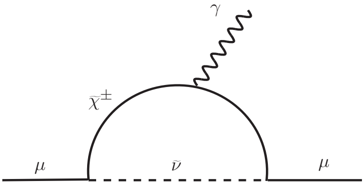
- Cross section similar to MSSM
- Decay length $\sim$ cm - dm
- We imposed: neutrino, higgs physics, $g-2$, flavor observables

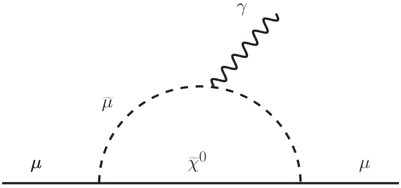


- LHC searches, can constraint this scenario ... Work in progress

Explaining muon $g-2$ data (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.
- The main one loop contributions are

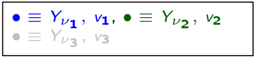


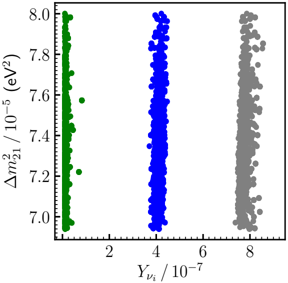


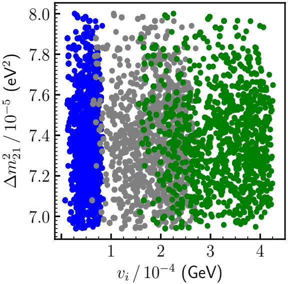
- We exploit the fact that light muon sneutrino & smuon and electroweak gauginos are possible in the $\mu\nu$SSM, to explain the discrepancy.

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

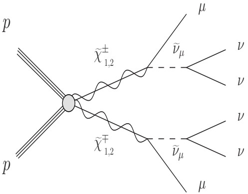
• We imposed: neutrino, higgs physics, $g-2$, flavor observables



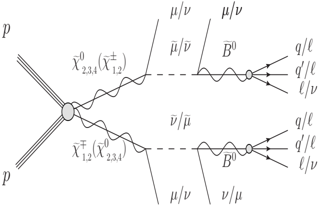




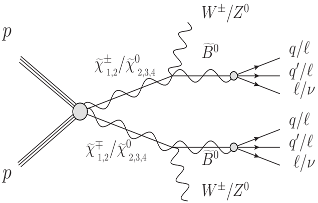
- LHC searches for electroweakinos further constrain the allowed regions of this scenario.



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

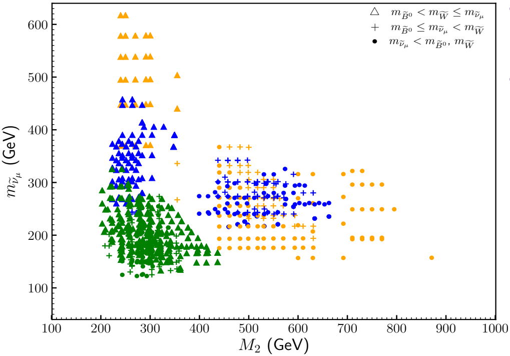


ii) $m_{\widetilde{B}^0} \leq m_{\widetilde{\nu}_\mu} < m_{\widetilde{W}}$



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

- 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 3:**
  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 $\widetilde{\nu}_\mu$, 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 $\mu\nu$SSM has many possible candidates for LSPs and we have analyzed several of them, (some works are in progress) in regions of the parameter space where these LSPs have long decay lengths and therefore are LLPs.
- Studies of these 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}.
- We have also shown that the measurement of the muon $g-2$ can be explained in the $\mu\nu$SSM in the presence of light muon left sneutrino and chargino/neutralino, which are compatible with current LHC searches.

THANK YOU