Long-Lived Lightest Supersymmetric Particles (L3SPs) versus LHC and MUON g-2 data

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MultiDark
Multimessenger Approach for Dark Matter Detection

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

- ... and so far this search has been focused mainly on prompt signals with missing energy inspired in R-parity conserving (RPC) models such as the MSSM, where the lightest supersymmetric particle (LSP), the neutralino, is stable

- Significant bounds on Sparticle masses have been obtained:

  - For strongly interacting Sparticles, their masses must be above about 1TeV
  - For weakly interacting Sparticles, their masses must be above about 100 GeV, (apart from a bino-like neutralino which is basically unconstrained due to its small pair production cross section)

- Because of these results, there is a growing interest in searching for displaced signals from Long Lived Particles (LLPs) at the LHC and/or non-minimal models

In this talk I will discuss some of the LLP scenarios in the SUSY μνSSM model

Supersymmetry with right-handed neutrinos

Rigth-handed neutrinos are likely to exist in order to generate neutrino masses

$$W_{\mu\nu SSM} = \epsilon_{ab}\left(Y_u^{ij}\,\hat{H}_u^b\,\hat{Q}_i^a\,\hat{u}_j^c + Y_d^{ij}\,\hat{H}_d^a\,\hat{Q}_i^b\,\hat{d}_j^c + Y_e^{ij}\,\hat{H}_d^a\,\hat{L}_i^b\,\hat{e}_j^c + Y_\nu^{ij}\,\hat{\nu}_j^c\,\hat{H}_u^b\,\hat{L}_i^a\right)$$

$$+\ \lambda_j\,\hat{\nu}_j^c\,\hat{H}_u\,\hat{H}_d + \kappa_{ijk}\,\hat{\nu}_i^c\,\hat{\nu}_j^c\,\hat{\nu}_k^c$$

Lopez-Fogliani, C. M., PRL 2006

No ad-hoc scales: Only the EW scale generated by the soft SUSY-breaking terms

The latter produce $\underbrace{\langle H_u^0\rangle\ ,\ \langle H_d^0\rangle\ ,\ \langle\tilde{\nu}_i^c\rangle \sim \text{TeV}}$

together with $Y_\nu \lesssim Y_e \sim 10^{-6}$, $\kappa \sim 1$ generate a EW scale seesaw

$$m_\nu \sim m_D^2/M_M = (\mathbf{Y}_\nu \langle H_u^0\rangle)^2/\,k\langle\tilde{\nu}_i^c\rangle \sim (10^{-6}\,10^2)^2/10^3 = 10^{-11}\text{ GeV} = 10^{-2}\text{ eV}$$

solving the ν problem: How to accommodate neutrino data

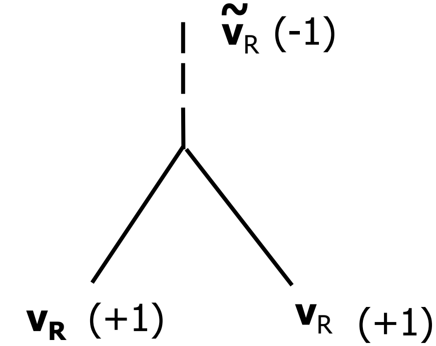
together with $\lambda \sim 1$ generate the μ term, $\mu \sim$ TeV

solving the μ problem: What is the origin of $\mu << M_{Planck}$

$$W_{\mu\nu SSM} = \epsilon_{ab}\left(Y_u^{ij}\,\hat H_u^b\,\hat Q_i^a\,\hat u_j^c + Y_d^{ij}\,\hat H_d^a\,\hat Q_i^b\,\hat d_j^c + Y_e^{ij}\,\hat H_d^a\,\hat L_i^b\,\hat e_j^c + Y_\nu^{ij}\,\hat\nu_j^c\,\hat H_u^b\,\hat L_i^a\right)$$

$$+ \underbrace{\lambda_j\,\hat\nu_j^c\,\hat H_u\,\hat H_d + \kappa_{ijk}\,\hat\nu_i^c\,\hat\nu_j^c\,\hat\nu_k^c}$$

Lopez-Fogliani, C. M., PRL 2006



R-parity is explicitly violated (RPV) by the new terms, implying:

- Sparticles do not appear in pairs, and therefore the LSP decays to SM particles
- All Sparticles are potential LSPs: neutralino, left sneutrino, right slepton, squark, …

If $Y_\nu \longrightarrow 0$, $\hat\nu^c \longrightarrow \hat S$ of the NMSSM where $W = \lambda\,\hat S\,\hat H_u\,\hat H_d + \kappa\,\hat S\,\hat S\,\hat S$ and R-parity is conserved (RPC)

Y_ν are therefore the order parameters determining RPV.
As a consequence, RPV must be small since $Y_\nu \lesssim 10^{-6}$

The smallness of neutrino masses is directly related with the low decay width of the LSP

Thus, the μνSSM can give rise to distinct displaced decays of the LSP producing multi-leptons/jets with small/moderate missing energy from neutrinos

Besides:

- Gravitino is a dark matter candidate with a lifetime longer than the age of the Universe

  K.Y. Choi, D.E. López-Fogliani, C. M., R. Ruiz de Austri, JCAP 2010

- Axino (and multicomponent) dark matter is another possibility

  G. Gomez-Vargas, D.E. López-Fogliani, C. M., A.D. Perez, JCAP 2021, Astropart. Phys. 2021

- Sterile Neutrino is another candidate

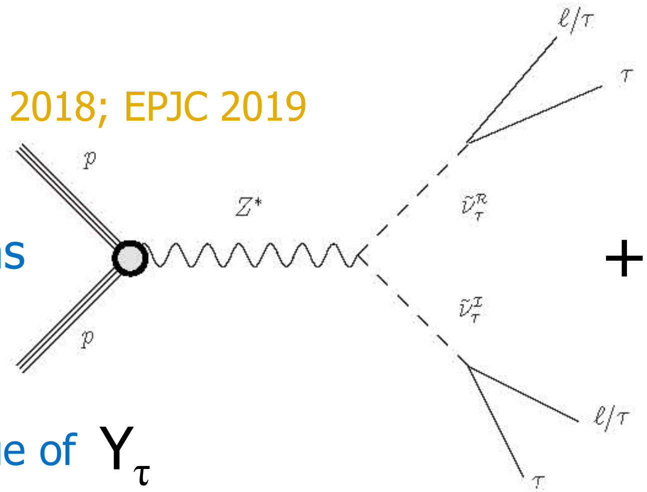
  P. Knees, D.E. López-Fogliani, C. M., 2207.10689

See talk by D.E. López-Fogliani
on Wednesday Sept 28

Bounds on the masses of Left Sneutrino LSPs from LHC data

Ghosh, Lara, Lopez-Fogliani, C. M., Ruiz de Austri, IJMPA 2018

Lara, Lopez-Fogliani, C. M., Nagata, Otono, Ruiz de Austri, PRD 2018; EPJC 2019



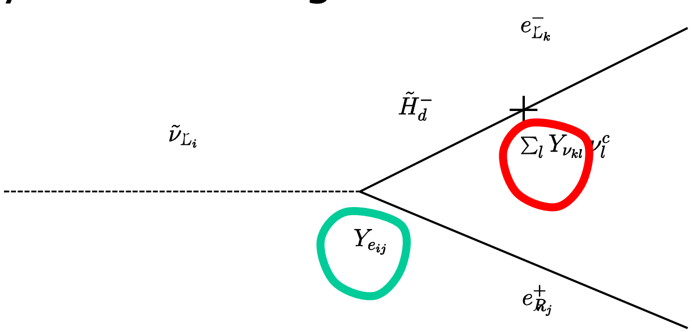
+ ...

$\tilde{\nu}$ LSP directly produced giving rise to multileptons

Left Slepton is the natural NLSP

✦ $\tilde{\nu}_\tau$ LSP particularly interesting because of the large value of Y_τ

A decay channel is e.g:



$$\Gamma\left(\tilde{\nu}_\tau \to \tau \ell\right) \approx \frac{m_{\tilde{\nu}_\tau}}{16\pi}\left(\frac{Y_{\nu_\ell} Y_\tau}{3\lambda}\right)^2 .$$

Decays are controlled by Y_ν, i.e. by the neutrino seesaw

$m_{\tilde{\nu}\tau} \sim 45 - 100$ GeV have decay lengths $\sim$ mm **DISPLACED**

(with the lower limit imposed not to disturb the decay width of the Z)

We recast the result of the ATLAS 8-TeV **dilepton** search to constrain the μνSSM scenario, given their similar topologies

PHYSICAL REVIEW D **92,** 072004 (2015)

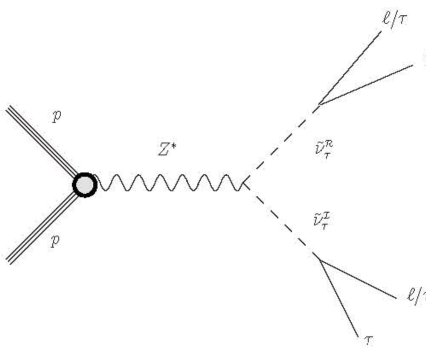
Search for massive, long-lived particles using multitrack displaced vertices or displaced lepton pairs in *pp* collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

G. Aad *et al.*[*]
(ATLAS Collaboration)

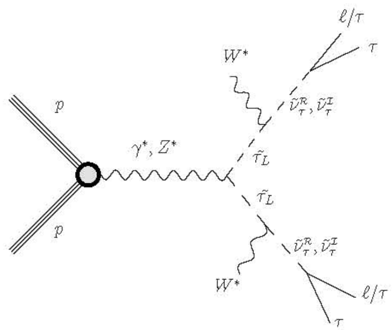
(Received 21 April 2015; revised manuscript received 19 August 2015; published 13 October 2015)

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.

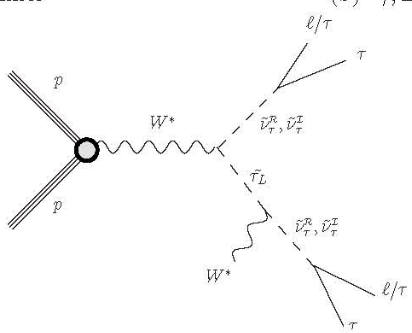
λ LLe



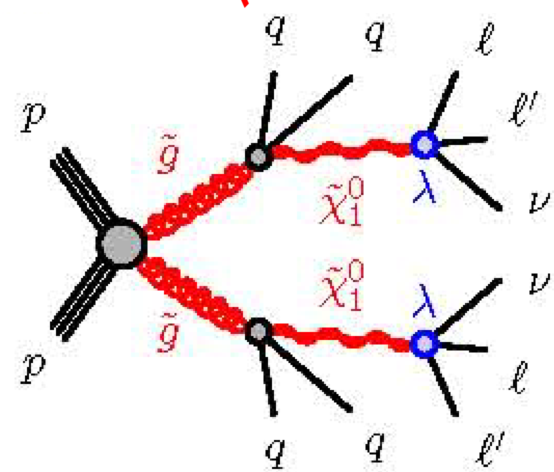
(a) Z channel



(b) γ, Z channels



(c) W channel



The ATLAS displaced-vertex search is sensitive to decay lengths $c\tau \gtrsim$ mm

In these figures, one of the two vertices can also be a two-neutrino vertex

Sampling the model for $m_{\tilde{\nu}\tau} \in (45 - 100)$ GeV

Scan 1 (S_1)	Scan 2 (S_2)
$\tan\beta \in (10, 16)$	$\tan\beta \in (1, 4)$
$Y_{\nu_i} \in (10^{-8}, 10^{-6})$	
$v_i \in (10^{-6}, 10^{-3})$	
$-T_{\nu_3} \in (10^{-6}, 10^{-4})$	
$M_2 \in (150, 2000)$	

We imposed the current experimental data on:

- Neutrino physics

  $\sin^2\theta_{12,\,13,\,23}$ = 0.275-0.35, 0.02045-0.02439, 0.418-0.627

  $\Delta m^2_{21,\,31}$ = (6.79-8.01) 10^{-5} , (2.427-2.625) 10^{-3} eV^2

- Higgs physics (using HiggsBounds & HiggsSignals)

- Flavor observables ($b \to s\gamma$, $B \to \mu\mu$, $\mu \to e\gamma$, $\mu \to eee$)

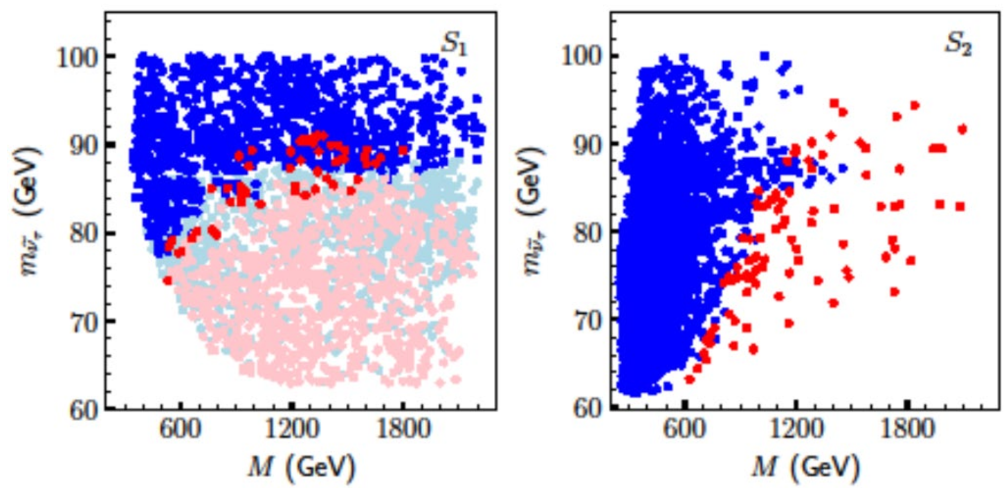
Results

- using the LHC 8-TeV data with 20.3 fb^{-1}: no points can be probed

- with the 13-TeV search with 300 fb^{-1} run 3:

  - Light-blue, light-red: excluded by **LEP**
  - Blue cannot be probed
  - Red can be probed

    (channels μμ, μe, ee producing a sufficient number of displaced dilepton events)



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

$m_{\tilde{\nu}\tau} \sim$ (74-91) GeV (63-95) GeV

Thut, the extrapolation of the usual bounds on Sparticle masses $m_{\tilde{\nu},\tilde{l}} \gtrsim 90$ GeV

to the μνSSM is not adecuate, because the assumption of BR=1 is not applicable

Summary of current bounds on left sneutrino LSP/left slepton masses vs. LHC data

- electron-muon-tau left sneutrinos heavier than about 100 GeV are unsconstrained

- a lower limit of 45 GeV arises for not to disturb the decay width of the Z

- a stronger lower limit of about 61 GeV arises for avoiding the decay of the SM-like Higgs into sneutrino pairs through D-terms

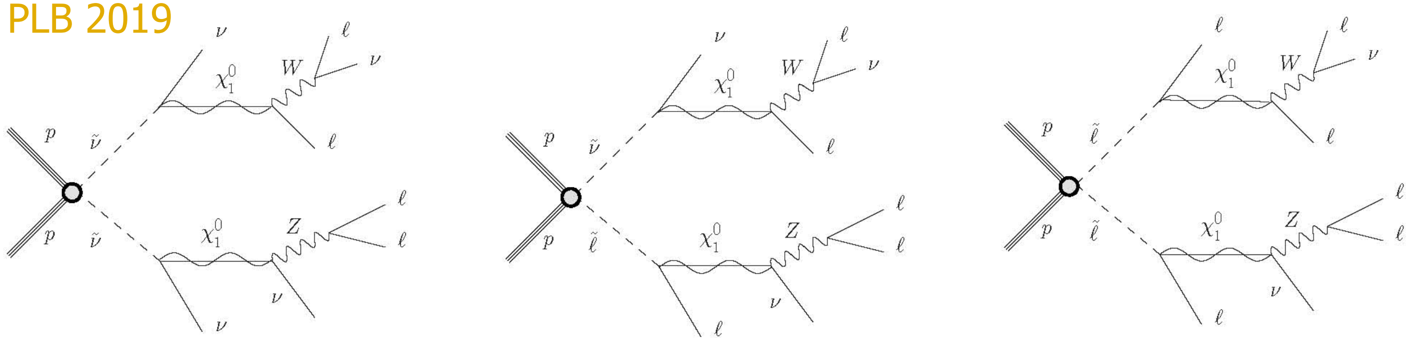
- The same (conservative) lower limit of about 61 GeV can be applied to left sleptons masses since they are a little heavier than left sneutrinos

- for the tau left sneutrino LSP, masses between 61 GeV and 100 GeV can be probed at the LHC run 3 through displaced signals with dileptons

Bound on the mass of a Bino-like neutralino LSP from LHC data

Lara, Lopez-Fogliani, C. M., PLB 2019

A Bino-like LSP in the μνSSM with a Left Sneutrino NLSP



Sneutrino/Slepton pair production followed by the RPV prompt two-body $\underbrace{\text{decay}}_{\text{through the mixing with neutrinos}}$ of a Bino-like LSP (heavier than the Z), producing three light leptons

We recast the result of the ATLAS 13-TeV chargino-neutralino production in compressed spectra in RPC SUSY

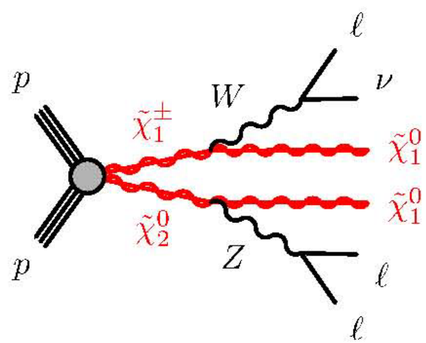
PHYSICAL REVIEW D **101,** 072001 (2020)

Search for chargino-neutralino production with mass splittings near the electroweak scale in three-lepton final states in $\sqrt{s} = 13$ TeV *pp* collisions with the ATLAS detector

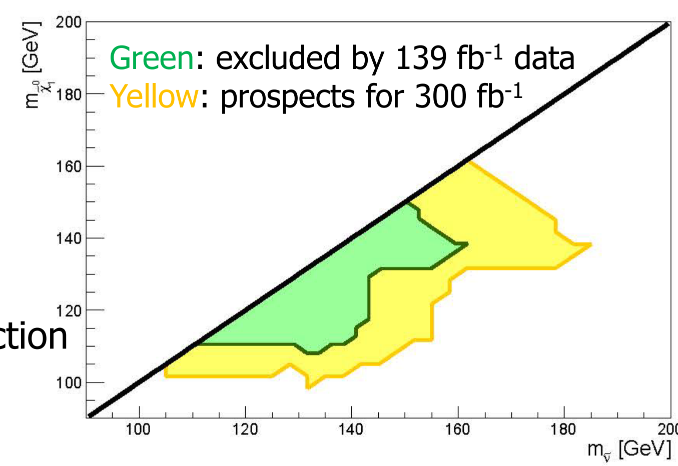
G. Aad *et al.**
(ATLAS Collaboration)

(Received 18 December 2019; accepted 25 February 2020; published 7 April 2020)

A search for supersymmetry through the pair production of electroweakinos with mass splittings near the electroweak scale and decaying via on-shell *W* and *Z* bosons is presented for a three-lepton final state. The analyzed proton-proton collision data taken at a center-of-mass energy of $\sqrt{s} = 13$ TeV were 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 in the 2015–2016 data recursive jigsaw analysis in the low-mass three-lepton phase space are reproduced. Results with the full data set are in agreement with the Standard Model expectations. They are interpreted to set exclusion limits at the 95% confidence level on simplified models of chargino-neutralino pair production for masses up to 345 GeV.

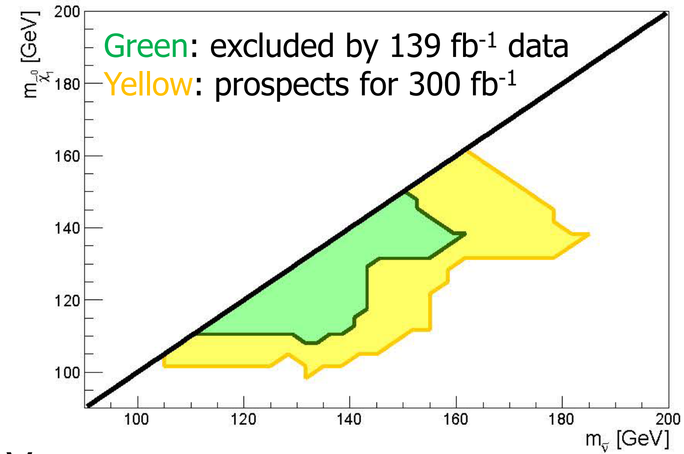


- Wino-like ($\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$) production
- Bino-like ($\tilde{\chi}_1^0$) LSP
- $c\tau_{\text{Bino}} \lesssim 0.2$ mm



Summary of the current bound on the Neutralino LSP mass vs. LHC data

Only the Bino-like neutralino LSP when the Left Sneutrino is the NLSP has been compared with LHC searches with 3 light leptons

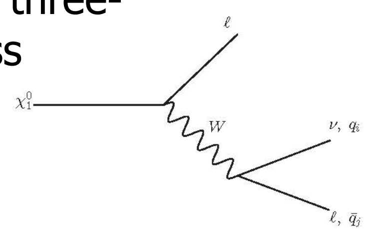


- Only a small región of Bino (Left Sneutrino) masses of about 110-150 (110-160) GeV is excluded using a prompt signal (for Binos heavier than the Z) with three light leptons

- This excluded region can be slightly extended using the LHC run 3 with 300 fb^{-1}:
  Bino (Left Sneutrino) masses between 100-160 (105-185) GeV

❖ We can have signals with 5 or more leptons, and a dedicated experimental analisis might be sensitive in a larger mass region of the μνSSM

❑ These limits can be complemented in the future by searches for displaced three-body decays of the bino-like neutralino when its mass is below the W mass ($c\tau_{\text{Bino}} \sim$ dm - m), leading to leptons and/or quarks final states

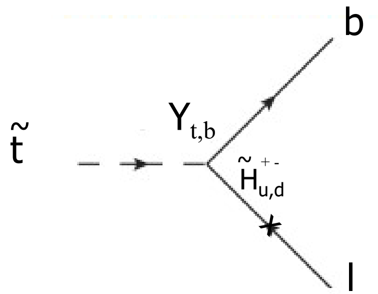


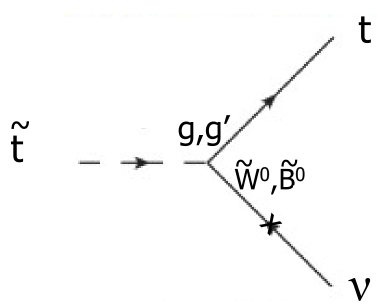
❑ No other scenarios with different compositions for the Neutralino LSP have been compared with LHC data yet, thus to carry out their analyses in the near future is crucial to prove the μνSSM

Bound on the mass of a Stop LSP from LHC data

Kpatcha, Lara, Lopez-Fogliani, C. M., Nagata, Otono, EPJC 2022

Main Stop decay modes:



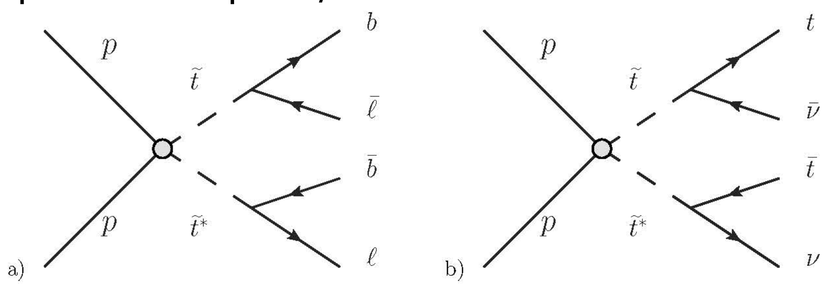


$$\Gamma(\tilde{t}_L \to b\ell_i) \sim \frac{m_{\tilde{t}}}{16\pi}\left(Y_b \frac{\mu_i}{\mu}\right)^2, \quad \sum_i \Gamma(\tilde{t}_L \to t\nu_i) \sim \frac{(m_{\tilde{t}}^2 - m_t^2)^2}{16\pi m_{\tilde{t}}^3}\sum_i \left(\frac{g'}{6}U^V_{i4} + \frac{g}{2}U^V_{i5}\right)^2$$

$$\mu_i = Y_{\nu_i}\frac{v_R}{\sqrt{2}},$$

$$\Gamma(\tilde{t}_R \to b\ell_i) \sim \frac{m_{\tilde{t}}}{16\pi}\left(Y_t \frac{Y_{e_i} v_i}{\sqrt{2}\mu}\right)^2, \quad \sum_i \Gamma(\tilde{t}_R \to t\nu_i) \sim \frac{(m_{\tilde{t}}^2 - m_t^2)^2}{16\pi m_{\tilde{t}}^3}\sum_i \left(\frac{2g'}{3}U^V_{i4}\right)^2,$$

Pair production of stops, decaying with displaced vértices ($c\tau_{\text{Stop}} \sim$ mm - m) to quarks and leptons/neutrinos :



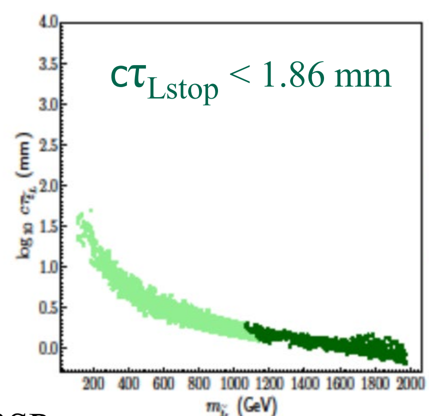
We compare σ_{prod} x BRs with several ATLAS and CMS searches for long-lived particles

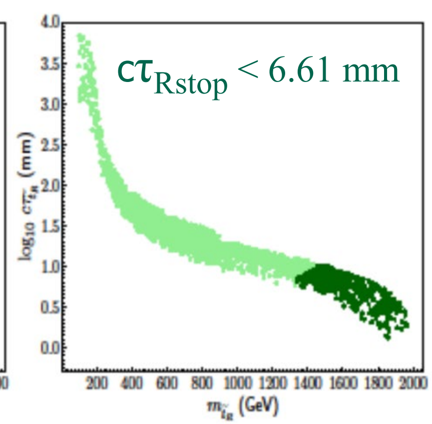
E.g. using TRPV vertices λ' LQd^c

Dark (light) green points allowed (excluded)

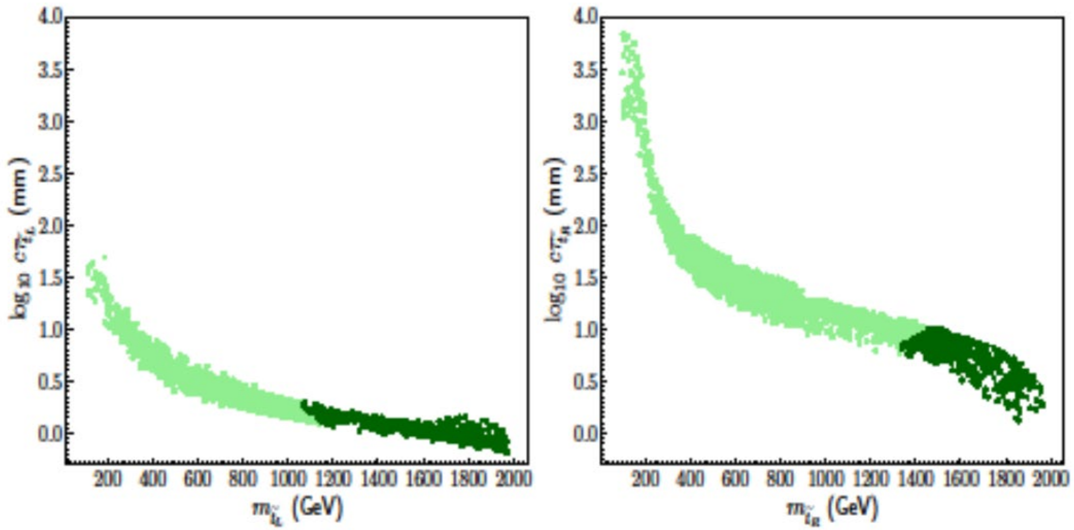
Scan of the parameter space

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





Summary of the current bounds on Stops LSP masses vs. LHC data



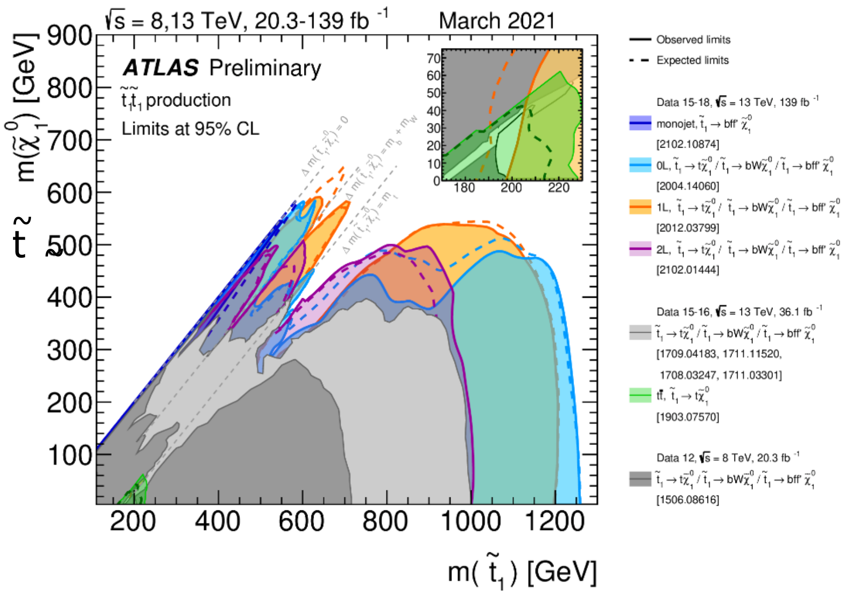
- Our results translate into lower limits on the masses
  - left stop LSP: 1068 GeV
  - right stop LPS: 1341 GeV

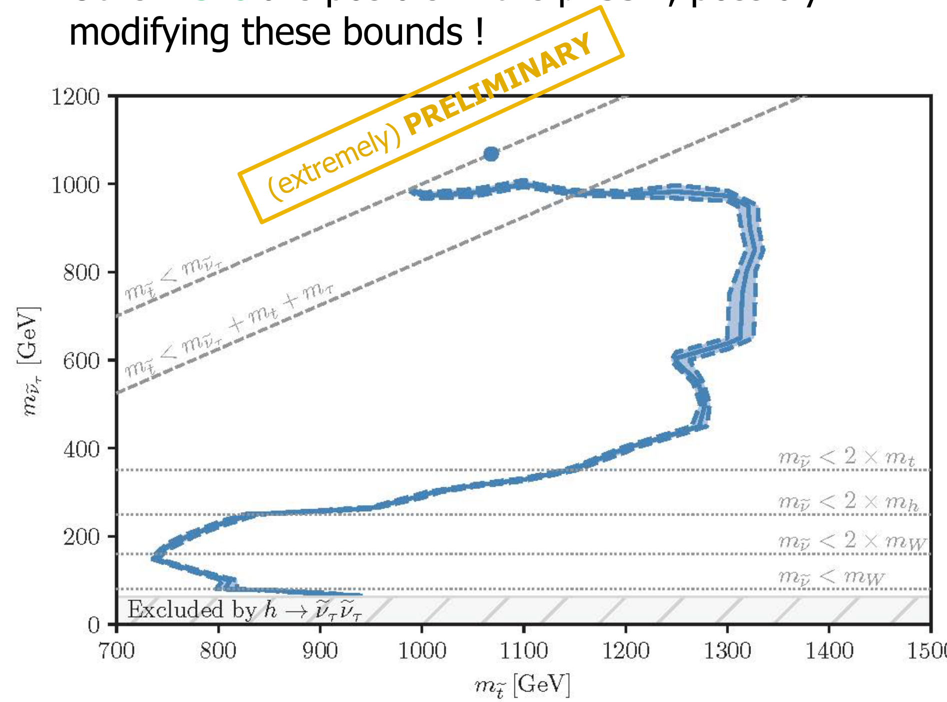
What about the limits for Stop **non**-LSP?

In fact, these would be the adecuate limits to be compared with RPC SUSY models, where the Stop cannot be the LSP

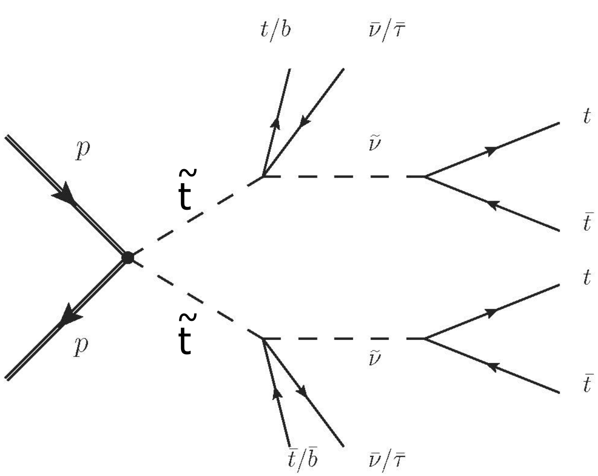
Bounds on Stop NLSP masses in RPC SUSY, where the neutralino is the LSP

Other LSPs are posible in the μνSSM, possibly modifying these bounds !





Kpatcha, Lara, Lopez-Fogliani, C. M., Nagata, Otono, work in progress: In the μνSSM, assuming Left Sneutrino LSP, several signals from pair-production of Stop NLSP are possible, e.g.



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

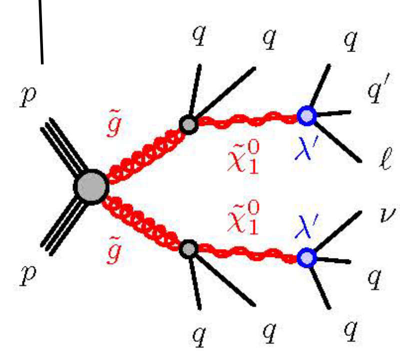
Eur. Phys. J. C 81 (2021) 1023
DOI: 10.1140/epjc/s10052-021-09761-x

CERN-EP-2021-066
30th November 2021

We recast this ATLAS search

Search for R-parity-violating supersymmetry in a final state containing leptons and many jets with the ATLAS experiment using $\sqrt{s}$ = 13 TeV proton–proton collision data

with the result in the μνSSM



lower limit on Stop NLSP mass in TRPV: 1-1.3 TeV, depending on the LSP mass

Conclusions (of this part)

We have discussed a SUSY model with displaced (and prompt) signals, the μνSSM, where the presence of right-handed neutrinos $\hat{\nu}_i^c \, \hat{H}_1^a \hat{H}_2^b$ is decisive in:

- Solving the μ problem
- Accommodating the ν data through a generalized EW seesaw

Because of RPV, the LSP is not stable, and therefore any particle can be the LSP

- LSP lifetime is connected to neutrino physics through neutrino Yukawas
- Novel signals at colliders with multi-lepton/jets final states

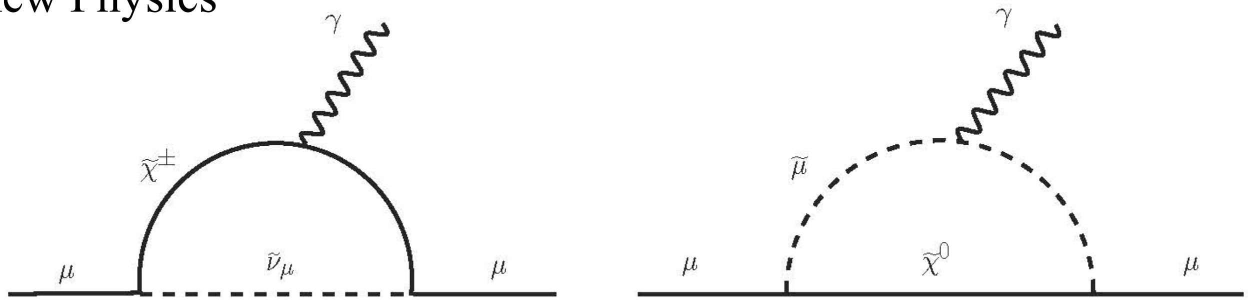
Imposing correct Neutrino and Higgs physics, as well as flavor observables such as B and μ decays, we recast ATLAS and CMS analyses to put bounds on the masses of left sneutrino/slepton LSP, bino LSP, stop LSP/non-LSP

- The lower limits are weaker than those in the MSSM or TRPV

The new MUON g-2 result and the μνSSM

The recent measurement of g-2 in 2021 yields a new deviation of $\Delta a_\mu = (25.1 \pm 5.9) \times 10^{-10}$, corresponding to a 4.2σ discrepancy (*if lattice computations are not considered…*). This could be a signal of new Physics

The main one-loop SUSY contributions are:



To explain this discrepancy, we exploit the fact that light charginos, neutralinos, muon sneutrino and smuon are posible in the μνSSM

Kpatcha, Lara, López-Fogliani, C.M., Nagata, EPJC 2021
Heinemeyer, Kpatcha, Lara, López-Fogliani, C.M., Nagata, EPJC 2021

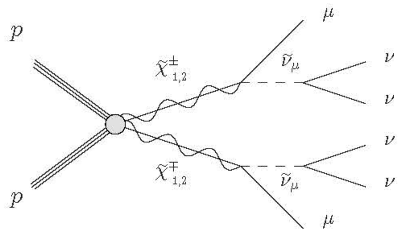
We sample the relevant parameter space reproducing in addition to g-2, Higgs and neutrino data as well as flavor observables such as B and μ decays

The different masses and orderings of the LSPs of the spectra found in our analysis can be classified in 4 cases, and they are further constrained by LHC searches

LHC searches for electroweakinos further constrain the allowed regions of the μνSSM

Some of the processes analyzed are:

$\widetilde{\nu}_\mu$ LSP



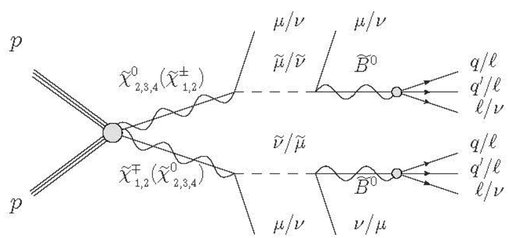
a signal similar to the one expected from a directly produced pair of smuons decaying as $\widetilde{\mu} \to \mu + \widetilde{\chi}^0$ in RPC models. Therefore, they can be compared with the limits obtained by the ATLAS collaboration in the search for sleptons in events with two leptons + MET [35].

1908.08215

Figure 2: Production of a chargino pair, each decaying to a LH muon-sneutrino, which in turn decays to neutrinos, giving rise to the signal 2μ + MET.

$\widetilde{B}^0$ LSP

$m_{\widetilde{B}^0} < m_{\widetilde{\nu}_\mu} < m_{\widetilde{W},\widetilde{H}}$

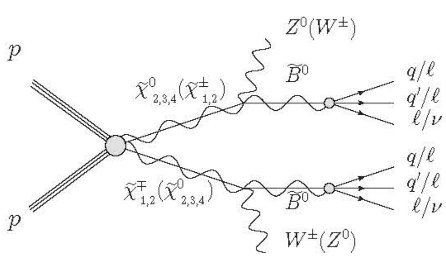


We can apply the limits on LLPs from the ATLAS searches 1504.05162 for decay lengths larger than 1 mm

Figure 3: Production of a chargino pair, chargino-neutralino or a neutralino pair, each decaying to a LH muon-sneutrino or smuon, which in turn decay to a long-lived bino-like neutralino giving rise to a displaced signal.

$\widetilde{B}^0$ LSP

$m_{\widetilde{B}^0} < m_{\widetilde{W},\widetilde{H}} < m_{\widetilde{\nu}_\mu}$

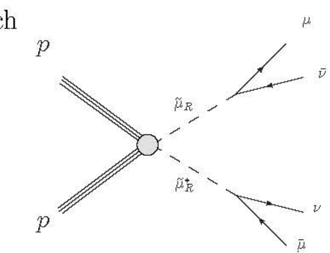


Now, the intermediate decay will mainly produce hadrons

Figure 5: Production of a chargino pair, chargino-neutralino or a neutralino pair, each decaying to a long-lived bino-like neutralino giving rise to a displaced signal.

$\widetilde{\mu}_R$ LSP

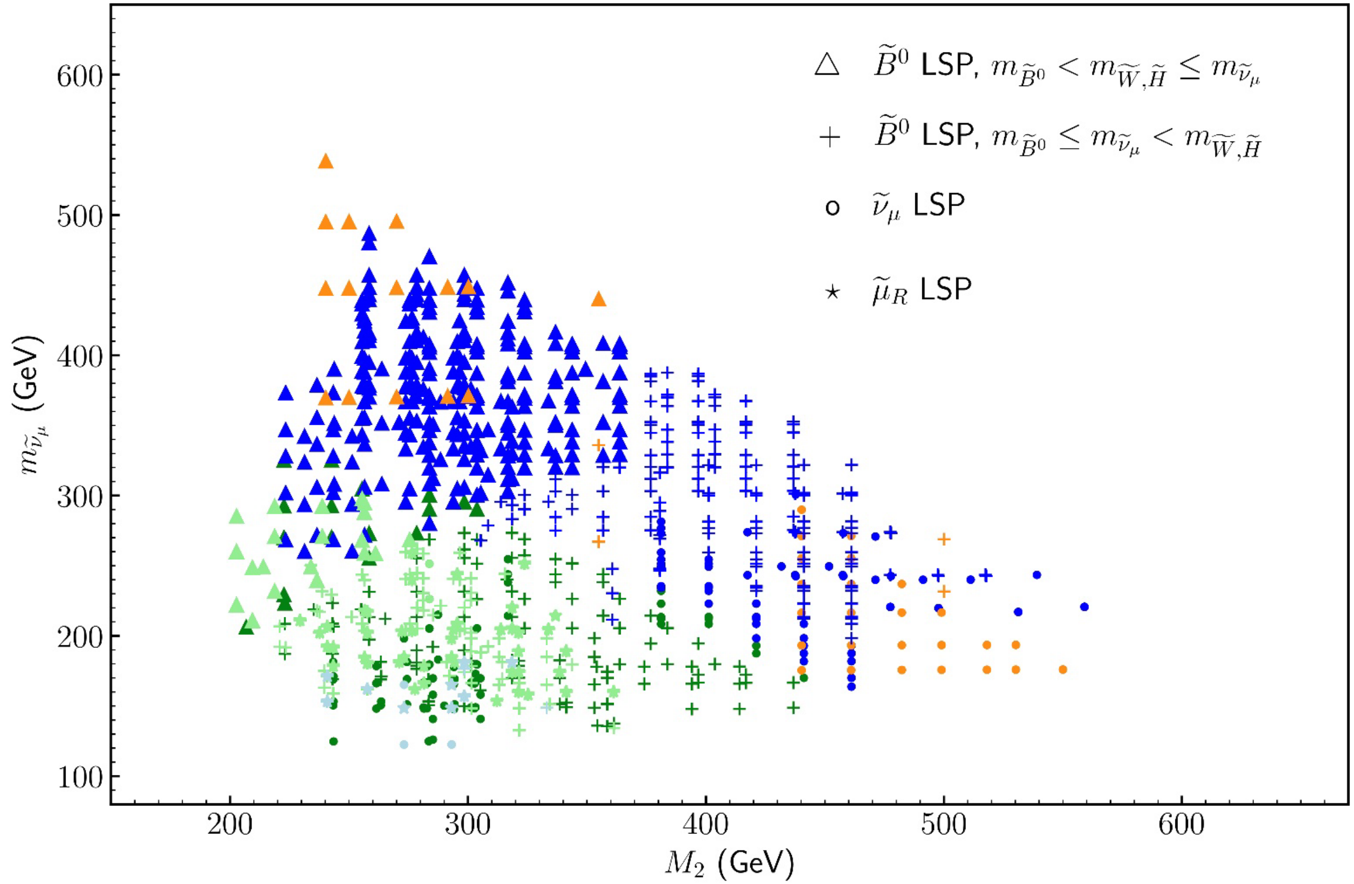
Masses smaller than 96.3 GeV are excluded by LEP



Decay lengths larger than 3mm are constrained by the search for displaced leptons at ATLAS 2011.07812

Figure 6: Production of RH smuon pair, each decaying to a RH muon and neutrino, rise to the signal 2μ + MET.

- Dark-green (1σ) and dark-blue (2σ) points with $m_{\tilde{e}_{2R}}$ =1000 GeV
- Light-green (1σ) and light-blue (2σ) points using $m_{\tilde{e}_{2R}} = 100, 150, 200, 300, 500$ GeV.
- Orange (2σ) points $m_{\tilde{e}_{2R}} = 1500$



We found significant regions compatible with g-2 at the 2σ level and all experimental data

bino-like neutralino masses are in the range 114 GeV $\lesssim m_{\widetilde{B}^0} \lesssim 370$ GeV, wino-like chargino/neutralino masses 200 GeV $\lesssim m_{\widetilde{W}} \lesssim 597$ GeV, and RH smuon masses $106 \lesssim m_{\widetilde{\mu}_R} \lesssim 1387$ GeV. The corresponding LH muon-sneutrino masses are in the range $120 \lesssim m_{\widetilde{\nu}_\mu} \lesssim 540$ GeV.

Concerning the value of μ, we used $\mu \approx 380$ GeV, 800 GeV, corresponding to higgsino-like chargino/neutralino masses in the range 333 GeV $\lesssim m_{\widetilde{H}} \lesssim 878$ GeV.

Conclusions (of the second part)

- The points of the μνSSM compatible with g-2 predict light sleptons and/or gauginos, which can be the prime target for the future (HL-)LHC experiments.
- Those in the 1σ region evade existing searches thanks to
  * Metastability of the bino LSP or right smuon LSP
  * Close mass spectrum in points with left muon-sneutrino LSP
- Displaced-vertex searches in the LHC Run 3 or the HL-LHC offer another promising way to cover large parts of the favored parameter space
  *Bino LSP avoids the current bounds because its decay length is shorter than 1.25 mm
  *right smuon LSP avoids them because its decay length is between 1.5 and 3 mm

To search for these metastable particles efficiently, it is important to optimize the search strategy such that a sub-millimeter displaced vertex and ~ 1 mm displaced lepton tracks can be detected. We encourage the ATLAS and CMS collaborations to consider this optimization seriously

THE END

BACKUP SLIDES

- The points of the μνSSM compatible with g-2 predict light sleptons and/or gauginos, which can be the prime target for the future (HL-)LHC experiments.

- Those in the 1σ region evade existing searches thanks to
  - Metastability of the bino LSP or right smuon LSP
  - Close mass spectrum in points with left muon-sneutrino LSP

- A part of the points will be probed in the future multi-leptón + MET searches at the (HL-) LHC, and the rest may be explored at a larger machine such a 100 TeV hadron collider.

  Sleptons and gauginos are more efficiently probed at lepton colliders through the pair production of these particles

- A discovery of such electroweakly charged states by itself cannot distinguish μνSSM from MSSM. But in the MSSM sleptons lighter than charginos are less favored by the LHC Run 2 results. Furthermore, in the μνSSM, sleptons can even be lighter than bino thanks to the R-parity violation, which is not allowed in the MSSM.

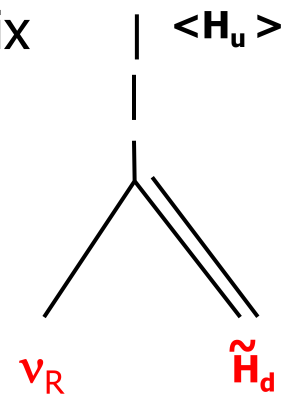
- Displaced-vertex searches in the LHC Run 3 or the HL-LHC offer another promising way to cover large parts of the favored parameter space
  - Bino LSP avoids the current bounds because its decay length is shorter than 1.25 mm
  - RH smuon LSP avoids them because its decay length is between 1.5 and 3 mm

It is possible to improve the sensitivity for a submillimeter decay length; given the extremely low background in these searches, one can relax the requirements on the impact parameter of lepton tracks and the reconstructed position of displaced vertices.
We encourage the ATLAS and CMS collaborations to consider this optimization seriously

μνSSM has *naturally* larger mass matrices than those of the MSSM or NMSSM, because of the new couplings and VEVs:

$\boxed{\langle H_u^0 \rangle = v_u \qquad \langle H_d^0 \rangle = v_d}$ $\quad \langle \tilde\nu_i \rangle = \nu_i \quad \langle \tilde\nu_i^c \rangle = \nu_i^c$

Fields with the same color, electric charge and spin naturally mix



"Neutrinos"

$$\chi^{0T} = (\underbrace{\tilde B^0, \tilde W^0, \tilde H_d, \tilde H_u, \nu_{R_i}}_{\tilde\chi^0_{4,5,6,7,8,9,10}}, \underbrace{\nu_{L_i}}_{\tilde\chi^0_{1,2,3}}),$$

"Leptons"

$$\Psi^{+T} = (\underbrace{-i\tilde\lambda^+, \tilde H_u^+}_{\tilde\chi^+_{1,2}}, e_R^+, \mu_R^+, \tau_R^+)$$

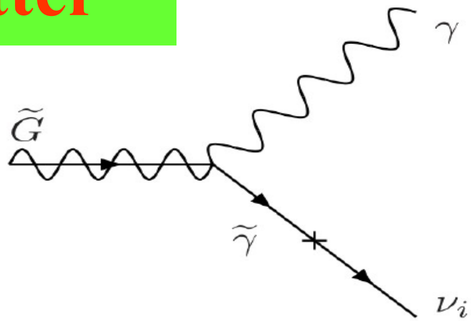
"Scalar and Pseudoscalar Higgses"

$$\mathbf{S}'_\alpha = (\underbrace{h_d, h_u, (\tilde\nu_i^c)^R}_{h_{4,5} \equiv h,\, H\ ,\ h_{1,2,3}}, \underbrace{(\tilde\nu_i)^R}_{h_{6,7,8}}) \qquad \mathbf{P}'_\alpha = (\underbrace{P_d, P_u, (\tilde\nu_i^c)^I}_{P_4 \equiv A\ ,\ P_{1,2,3}}, \underbrace{(\tilde\nu_i)^I}_{P_{5,6,7}})$$

"Charged Higgses"

$$\mathbf{S}'^{+}_\alpha = (\underbrace{H_d^+, H_u^+}_{H^+}, \tilde e_L^+, \tilde\mu_L^+, \tilde\tau_L^+, \tilde e_R^+, \mu_R^+, \tau_R^+),$$

Gravitino as decaying dark matter



The gravitino LSP also decays through the interaction gravitino-photon-photino, due to the photino-neutrino mixing:

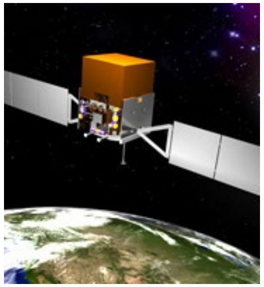
Takayama, Yamaguchi, 2000

$$\Gamma(\psi_{3/2} \to \gamma\nu) = \frac{1}{32\pi}|U_{\tilde{\gamma}\nu}|^2 \frac{m_{3/2}^3}{{M_{\rm P}}^2}$$

Nevertheless, it is supressed both by the Planck mass and the small R-parity violation, thus the lifetime of the gravitino can be longer than the age of the Universe ($\sim 10^{17}$ s)

The photon produces a gamma-ray line at energies equal to **$m_{3/2}/2$**

***Fermi*-LAT** can detect this flux of gamma rays in the halo of the Galaxy



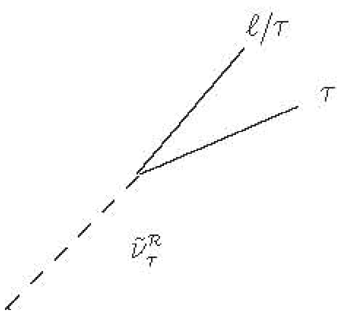
In the $\mu\nu$SSM in order to reproduce neutrino data:

$$10^{-15} \lesssim |U_{\tilde{\gamma}\nu}|^2 \lesssim 5\times 10^{-14}$$

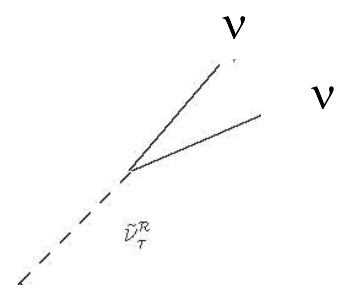
As a consequence, values of the gravitino mass larger than about **10 GeV** are disfavoured by *Fermi* LAT data

Choi, López-Fogliani, C.M., Ruiz de Austri, JCAP 2010
Albert et al., Fermi Collab, JCAP 2014
Gómez-Vargas, López-Fogliani, C.M., Pérez, Ruiz de Austri, JCAP 2017
Gómez-Vargas, López-Fogliani, C.M., Perez, Astropart. Phys. 2021

Because the $\tilde{\nu}_\tau$ in the $\mu\nu$SSM has several relevant decay modes



$\tau\tau,\ \ \tau\mu,\ \ \tau e,\ \ \nu\nu$



the LEP lower bound $m_{\tilde{\nu}\tau} \gtrsim 90$ GeV obtained assuming BR one to leptons via TRPV is not directly applicable in this case

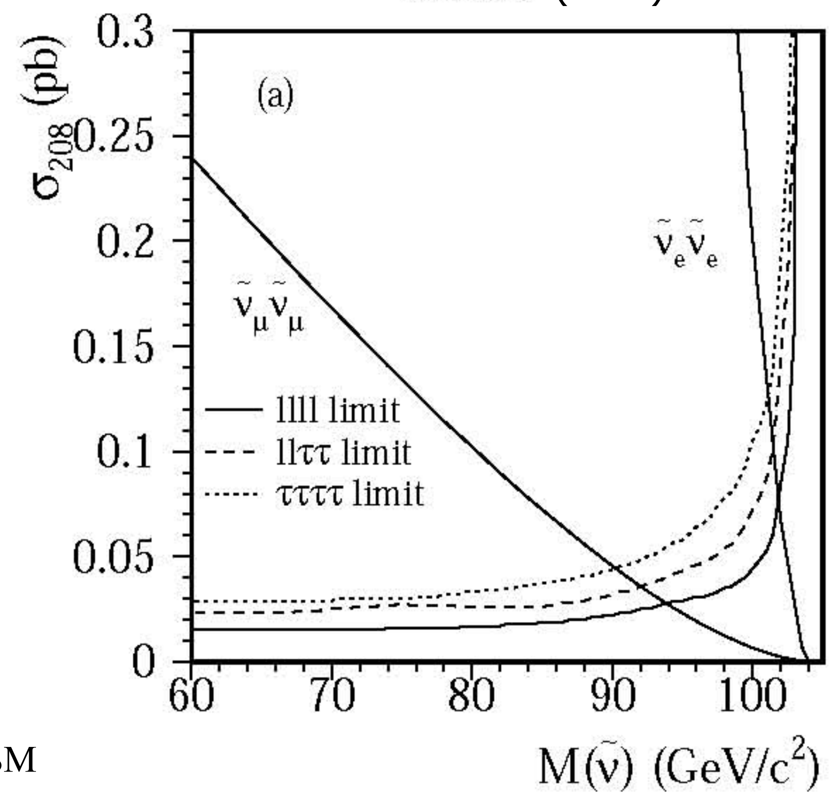
$$\lambda_{133}\hat{L}_2\hat{L}_3\hat{e}^c_3 \longrightarrow$$

$\mu \quad \tilde{\nu}_\tau \quad \tau^c$

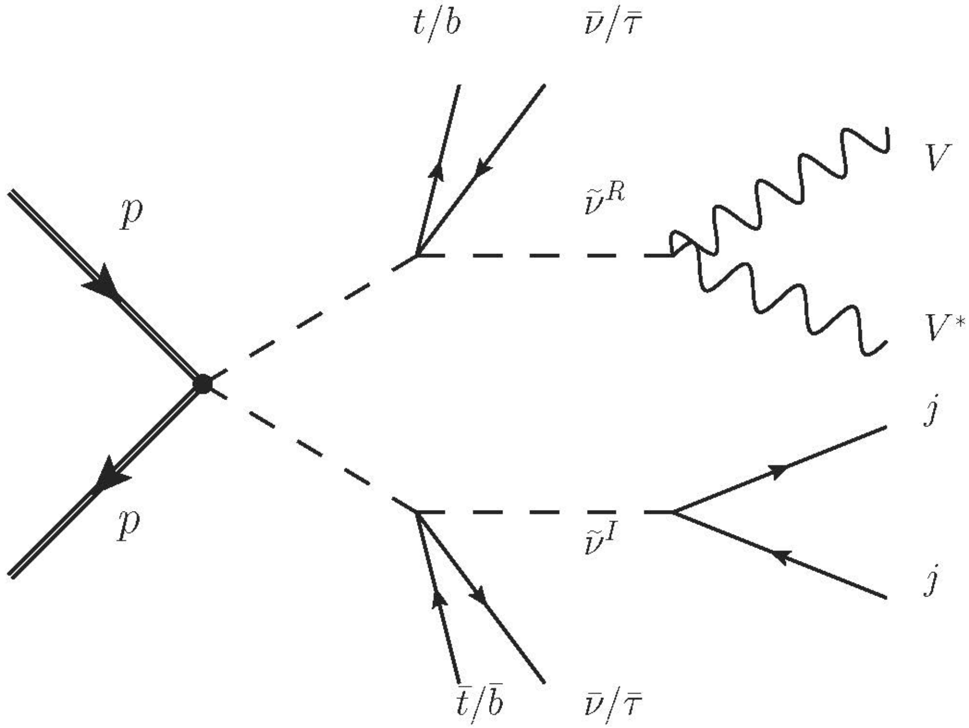
since the upper bound on σ is now supressed by the BRs:

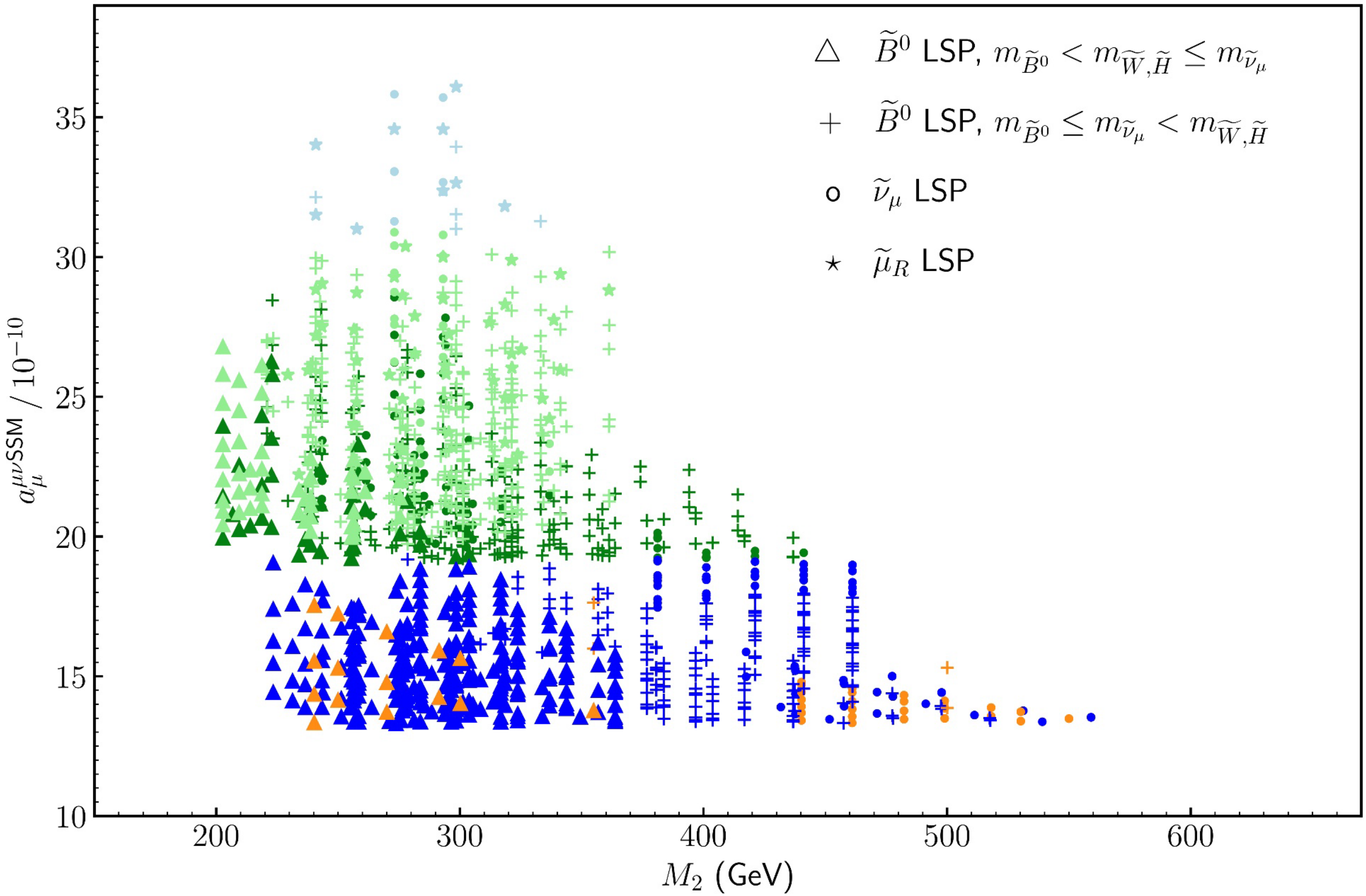
$$\sigma_{208} \ \text{x BR}(\tilde{\nu}_\tau \longrightarrow \tau\mu)^2$$

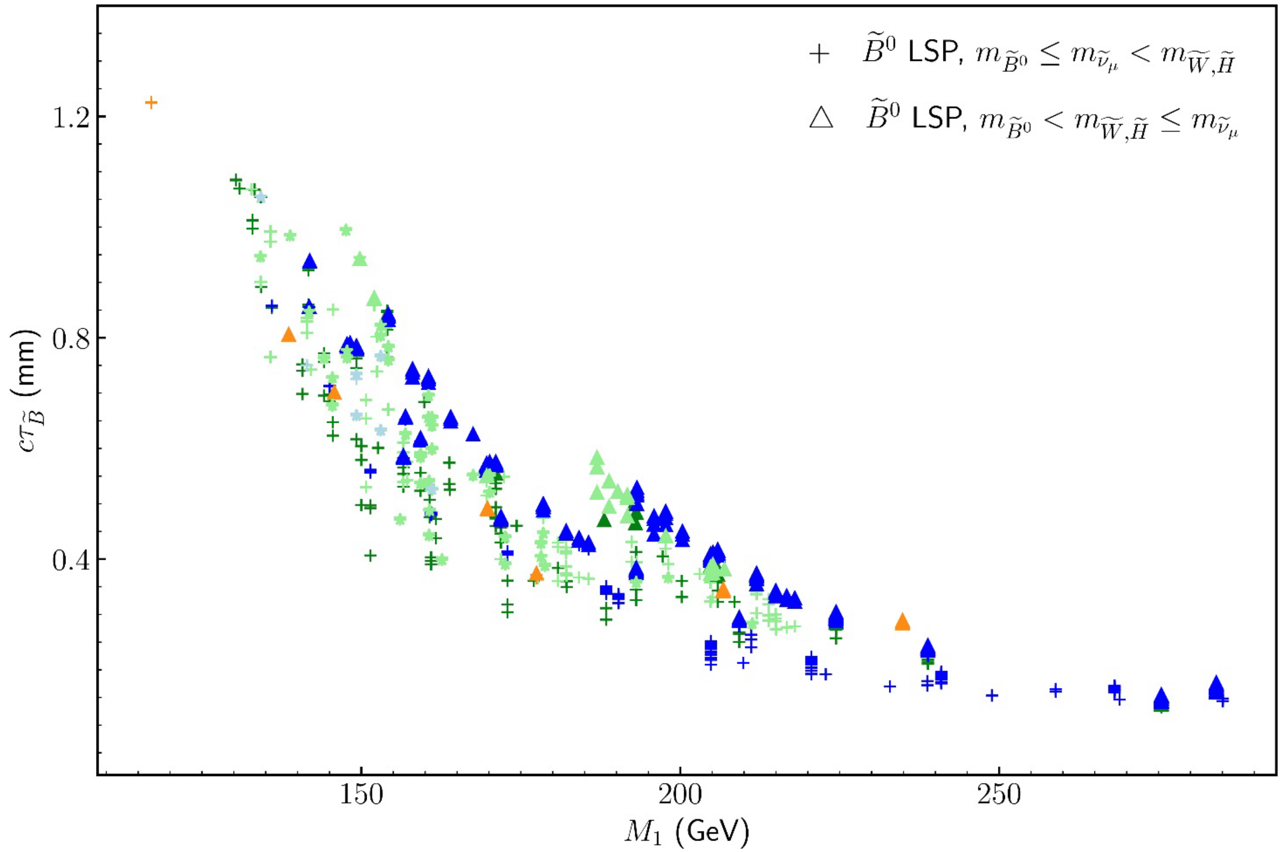
ALEPH (2002)



Stop NLSP with Left Sneutrino LSP




$\widetilde{B}^0$ LSP, $m_{\widetilde{B}^0} < m_{\widetilde{W},\widetilde{H}} \leq m_{\widetilde{\nu}_\mu}$
$\widetilde{B}^0$ LSP, $m_{\widetilde{B}^0} \leq m_{\widetilde{\nu}_\mu} < m_{\widetilde{W},\widetilde{H}}$
$\widetilde{\nu}_\mu$ LSP
$\widetilde{\mu}_R$ LSP
$a_\mu^{\mu\nu\mathrm{SSM}}$ / 10^{-10}
10
15
20
25
30
35
200
300
400
500
600
M_2 (GeV)



Bino LSP points that are unconstrained by LHC searches is because they have 117 GeV $\lesssim M_1 \lesssim$ 285 GeV corresponding to a proper decay length of $\widetilde{B}^0$ LSP in the range 0.1 mm $\lesssim c\tau_{\widetilde{B}^0} \lesssim$ 1.25 mm, as shown in Fig.

Similarly, the light-green and light-blue stars corresponding to points with $\widetilde{\mu}_R$ as the LSP with masses 106 GeV $\lesssim m_{\widetilde{\mu}_R} \lesssim$ 190 GeV, have a decay length in the range 1.5 mm $\lesssim c\tau_{\widetilde{\mu}_R} \lesssim$ 3 mm, avoiding in this way the LEP and LHC constraints