Neutrinos as drivers of decaying gravitino DM and novel LHC signals

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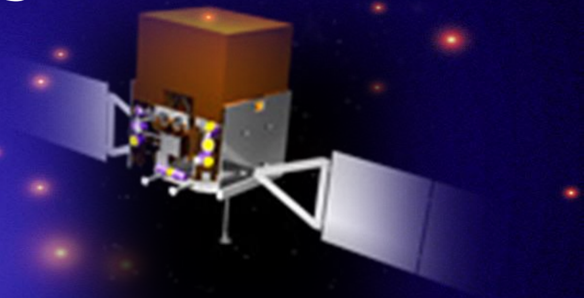
MultiDark
Multimessenger Approach for Dark Matter Detection



4th IBS-MultiDark-IPPP workshop, Daejeon, Oct 7-11, 2019

The fact that the Higgs is:

-an elementary scalar

-with a mass of 125 GeV

puts support on the idea of SUSY…

since (at least) a scalar particle exists,…, it produces the hierarchy problem, …., SUSY solves it and predicts a SM-like Higgs with a mass $\lesssim$ 140 GeV

The fact that neutrinos are:

-massive

-with masses $\lesssim$ eV

puts support on the idea of RH neutrinos…

since neutrinos are very light,…, they produce the ν problem (how to accommodate neutrino data), ….,
RH neutrinos + seesaw helps to solve it

RH neutrinos $Y_\nu^{ij}\,\hat{H}_{\_}\,\hat{L}_i^a\,\hat{\nu}_j^c$

$m_D = Y_\nu \langle H\rangle \lesssim 10^{-13}\,10^2\ \text{GeV} = 10^{-11}\ \text{GeV} = 10^{-2}\ \text{eV}$

+

seesaw to avoid a large hierarchy in Yukawa couplings $Y_\nu \lesssim 10^{-13}$

$\mathcal{M}_{ij}\ \nu_i^c \nu_j^c$

$$\begin{bmatrix} 0 & m_D \\ m_D & \mathcal{M} \end{bmatrix} \Rightarrow \begin{cases} m_\nu \sim m_D^2/\mathcal{M} = (Y_\nu \langle H\rangle)^2/\mathcal{M} \\ M_\nu \sim \mathcal{M} \end{cases}$$

if $Y_\nu \lesssim 10^{-6}$ of the order of the electron Yukawa *and* $\mathcal{M} \sim 10^3$

EW scale seesaw $m_\nu \lesssim (10^{-6}\,10^2)^2/10^3 = 10^{-11}$ GeV

We can accommodate both solutions

SUSY and RH neutrinos (+ seesaw) in the same model

$$W = Y_\nu^{ij} \hat{\nu}_j^c \hat{H}_u \hat{L}_i + K_{ijk} \hat{\nu}_i^c \hat{\nu}_j^c \hat{\nu}_k^c$$

$\mathcal{M}_{ij}$

Majorana masses when $\langle \tilde{\nu}_i^c \rangle$ ~ TeV

Because the new couplings modify **V**

But since H_d and L have the same SM quantum numbers, Y=-1/2

$$+ \lambda_i \hat{\nu}_i^c \hat{H}_u \hat{H}_d$$

μ-term

with the extra bonus of

solving the μ problem:
What is the origin of μ << M_{planck} ?

No ad-hoc scales in the model:
Only the EW scale generated by soft terms

Lopez-Fogliani, C. M., PRL 2006

μνSSM

λ_i drive the mixing of H_u and H_d with RH sneutrinos

- Novel signals with multi-Higgses

For a recent work, see:
Biekotter, Heinemeyer, C. M., 1906.06173

Neutrino Yukawas drive RPV ; since $Y_\nu \lesssim 10^{-6}$, RPV is small

- Novel signals with: displaced vertices, multi-leptons,multi-jets

which seems good in view of the current experimental bounds on RPC models, based on missing energy

Because of the (new) neutrino Yukawa couplings, in addition to

$<H_u^0>$, $<H_d^0>$, $\langle\tilde{\nu}_i^c\rangle$ ~ TeV

also the LH sneutrinos get VEVs $\langle\tilde{\nu}_i\rangle$ $\quad \nu_i \sim Y_\nu v_u \lesssim 10^{-6}\, 10^2\, \text{GeV} = 10^{-4}$ GeV

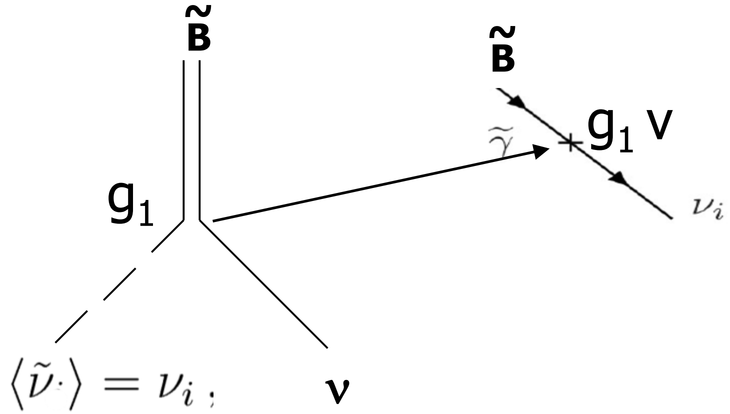
Neutrino Yukawas drive small LH sneutrino VEVs

(unlike RH sneutrino VEVs, whose driving forces are λ, k ~ 1)

because of their minimization condition $V_{\text{soft}} = m_{H_d}^2 H_d^0 H_d^{0*} + m_{H_u}^2 H_u^0 H_u^{0*} + m_{\tilde{L}_{ij}}^2 \tilde{\nu}_i \tilde{\nu}_j^* + m_{\tilde{\nu}_{ij}^c}^2 \tilde{\nu}_i^c \tilde{\nu}_j^{c*} + A_\nu Y_\nu H_u^0 \tilde{\nu}_i \tilde{\nu}_j^c + \ldots$

which implies $m^2_{\tilde{L}i}\, \nu_i = - A_\nu\, v_R\, Y_{\nu i}\, v_u + \ldots \longrightarrow \nu_i \sim Y_\nu v_u$

Generalized EW scale seesaw



Because of RPV, fields with the same quantum numbers mix

Mixing of LH neutrinos with neutralinos and RH neutrinos

Mixing of neutralinos with RH neutrinos

$$\begin{bmatrix} 0_{3x3} & m \\ m^T & \mathcal{M} \end{bmatrix}_{10x10}$$

producing that neutrino masses and mixing angles can easily be fitted to experimental data (even with flavour diagonal neutrino Yukawas)

Mixing of LH neutrinos with RH neutrinos and Higgsinos: 'ν_R-Higgsino seesaw'

Mixing of LH neutrinos with gauginos: 'Gaugino seesaw'

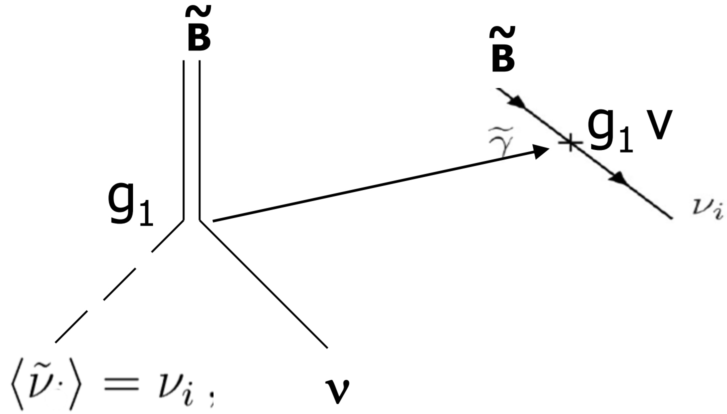
$$(m_{\nu_L})_{ij} \simeq \frac{Y_{\nu_i} Y_{\nu_j} v_u^2}{6\kappa \, v_R}(1-3\delta_{ij}) - \frac{v_i \, v_j}{2M}$$

$M = M_1 M_2 / (g'^2 M_2 + g^2 M_1)$

Both terms are of similar order

In a sense, this gives a *natural* answer to why the mixing angles are so different in the quark vs. lepton sector: because no generalized seesaw exists for the quarks

Generalized EW scale seesaw



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xing of LH neutrinos with I neutrinos and Higgsinos: -Higgsino seesaw'

$$(m_{\nu_L})_{ij} \simeq \frac{m_D^2}{\mathcal{M}} (1 - 3\delta_{ij}) - \frac{v_i\, v_j}{2M}$$

Mixing of LH neutrinos with gauginos: 'Gaugino seesaw'

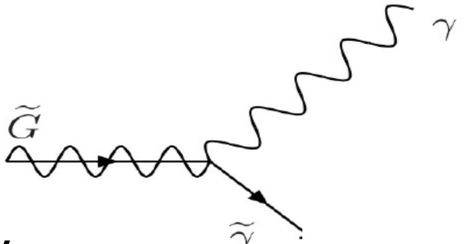
$M=M_1M_2 / (g'^2M_2 + g^2M_1)$

Both terms are of the same order

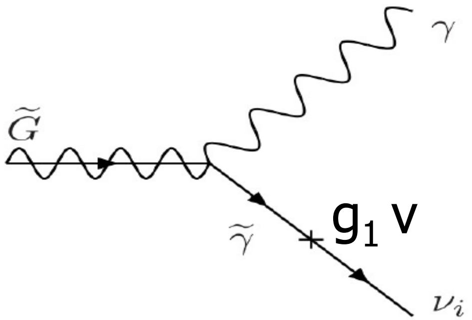
In a sense, this gives a *natural* answer to why the mixing angles are so different in the quark vs. lepton sector: because no generalized seesaw exists for the quarks

Neutrino Yukawas drive gravitino LSP as a DM candidate

If gravitino is not the LSP, it decays to the LSP through gravitational interactions



If gravitino is the LSP, it also decays due to RPV



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

but the decay width is supressed both by the Planck mass and the RPV:

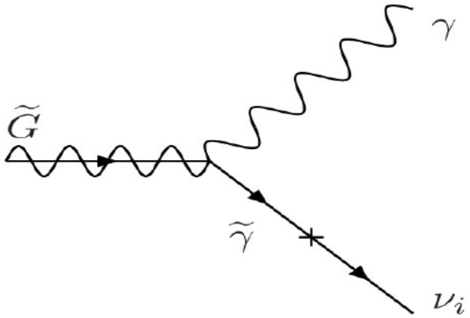
$$\left| U_{\tilde{\gamma}\nu} \right|^2 \sim | g_1 \nu/M_1 |^2 \sim 10^{-14} - 10^{-15}$$

since $\nu \sim \mathbf{10^{-4}}$ GeV because of the small neutrino Yukawa $\mathbf{Y}_\nu \sim 10^{-6}$

Thus the lifetime is longer than the age of the Universe ($\sim 10^{\mathbf{17}}$ s), and the gravitino can be a good DM candidate

$$\tau_{3/2} = \Gamma^{-1}(\tilde{G} \to \gamma\nu) \simeq 8.3 \times 10^{26} \,\text{sec} \times \left(\frac{m_{3/2}}{1\text{GeV}}\right)^{-3} \left(\frac{|U_{\gamma\nu}|^2}{7 \times 10^{-13}}\right)^{-1}$$

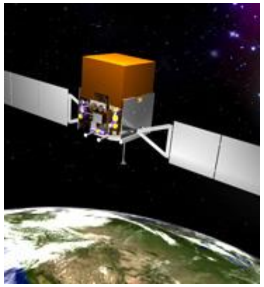
Gravitino as decaying DM



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

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

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

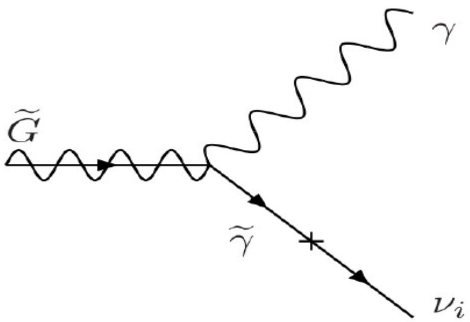


In the $\mu\nu$SSM in order to reproduce neutrino data (masses and mixing angles): $10^{-15} \lesssim |U_{\tilde{\gamma}\nu}|^2 \lesssim 5\times10^{-14}$

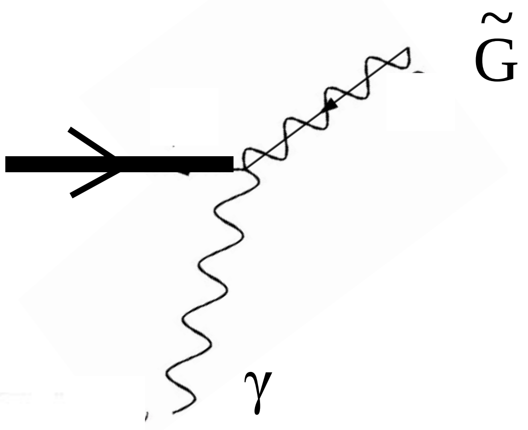
As a consequence, values of the gravitino mass larger than about **10 GeV** are disfavoured by *Fermi* LAT data

Ki-Young Choi, López-Fogliani, C.M., Ruiz de Austri, JCAP 2010
Albert, Gómez-Vargas, Grefe, C.M., Weniger et al., Fermi Collab, JCAP 2014
Gómez-Vargas, López-Fogliani, C.M., Pérez, Ruiz de Austri, JCAP 2017

Gravitino DM alters collider signals?



e.g. neutralino NLSP



$$c\,\tau^{3/2}_{\tilde{\chi}^0_4} \sim 80\ \text{km}\ \left(\frac{m_{3/2}}{10\ \text{keV}}\right)^2 \left(\frac{m_{\tilde{\chi}^0_4}}{50\ \text{GeV}}\right)^{-5} .$$

For gravitinos heavier than 10 keV, the decay width of neutralino into gravitino and photon is much smaller than the RPV decay widths into SM particles (decay lengths ~ mm)

Collider signals are not altered,
effectively a NLSP behaves like a LSP decaying through RPV channels

Concerning μνSSM LHC phenomenology:

Scan 1 (S_1)	Scan 2 (S_2)	Scan 3 (S_3)
$0.01 \leq \lambda < 0.2$	$0.2 \leq \lambda < 0.5$	$0.5 \leq \lambda < 1.2$
$0.01 \leq \kappa \leq 2$		
$1 \leq \tan\beta \leq 40$		
$100 \leq v_R/\sqrt{2} \leq 7000$		
$0 < T_\lambda \leq 500$		
$0 < -T_\kappa \leq 500$		
$0 < -T_{u_3} \leq 5000$		
$200 \leq m_{\widetilde{Q}_{3L}} = m_{\widetilde{u}_{3R}} \leq 2000$		

Scans using Multinest algorithm as optimizer, searching for points reproducing the current experimental data on:

- Higgs physics
  interfaced with HiggsBounds & HiggsSignals

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

Scan 1 (S_1)	Scan 2 (S_2)	Scan 3 (S_3)
$m_{\widetilde{Q}_{1,2L}} = m_{\widetilde{u}_{1,2R}} = m_{\widetilde{d}_{1,2,3R}} = m_{\widetilde{e}_{1,2,3R}} = 1000$		
$T_{u_{1,2}} = T_{d_{1,2}} = T_{e_{1,2}} = 0,\ T_{e_3} = 40,\ T_{d_3} = 100$		
$-T_{\nu_{1,2}} = 10^{-3},\ -T_{\nu_3} = 3 \times 10^{-4}$		
$M_1 = \frac{M_2}{2} = \frac{M_3}{3} = 900$		
$Y_{\nu_1} = 2 \times 10^{-7},\ Y_{\nu_2} = 4 \times 10^{-7},\ Y_{\nu_3} = 0.5 \times 10^{-7}$		
$v_{1L} = 1.5 \times 10^{-4},\ v_{2L} = 4 \times 10^{-4},\ v_{3L} = 5.5 \times 10^{-4}$		

To compute the spectrum and observables SARAH is used to generate a SPheno version of the μνSSM

Kpatcha, Lopez-Fogliani, C. M., Ruiz de Austri, IN PREPARATION

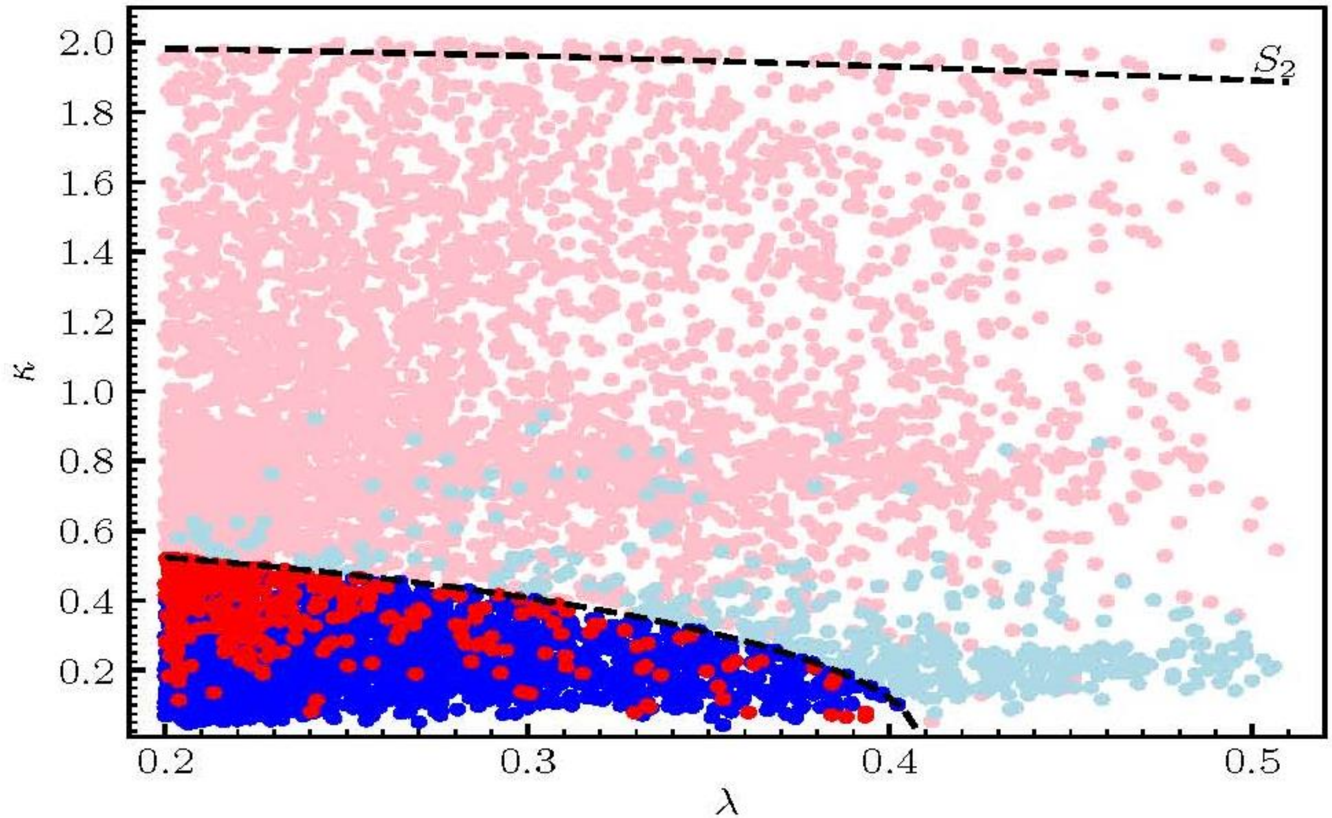


Figure 8: Viable points of the parameter space for S_2 in the $\kappa - \lambda$ plane. The red and light-red (blue and light-blue) colours represent cases where the SM-like Higgs is (is not) the lightest scalar. All red and blue points below the lower black dashed line fulfill the perturbativity condition up to GUT scale of Eq. (24). Light-red and light-blue points below the upper black dashed line fulfill the perturbativity condition up to 10 TeV of Eq. (25).

Armed with these results, we can study now detection of LSPs at the LHC

- Any particle can be the LSP, since the LSP decays to SM particles

stau, squark, neutralino,..., sneutrino

The left sneutrinos are special in the μνSSM because of their couplings:

$$Y_\nu^{ij} \hat{\nu}_j^c \hat{H}_u \hat{L}_i$$

- Their masses are essentially determined by the soft masses (which in turn are determined by the minimization conditions):

$$m^2_{\tilde{\nu}_i} = \frac{Y_{\nu i} v_u}{v_i} v_R (- A_\nu + \dots)$$

The hierarchy of neutrino Yukawas makes natural to expect some generation to be light

e.g. the hierarchy $Y_{\nu 3} \sim 10^{-8} - 10^{-7} < Y_{\nu 1,2} \sim 10^{-6}$ ⟶ $m_{\tilde{\nu}_\tau} \sim 100$ GeV, $M_{\tilde{\nu}_{e,\mu}} \sim 1000$ GeV

We have normal ordering with the gaugino seesaw as the dominant one for the third family

$\tilde{\nu}_\tau$ LSP specially interesting because Y_τ is large implying large BRs for its decay to leptons

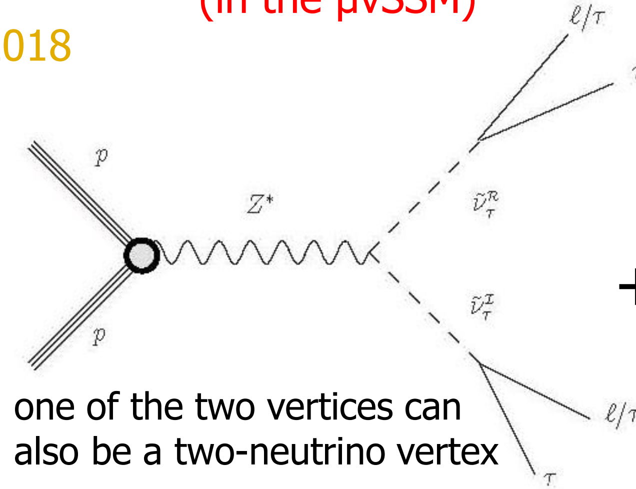
Bound on the mass of a tau left sneutrino LSP from LHC data ?

(in the μνSSM)

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

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

Stau is the natural NLSP



(a) Z channel

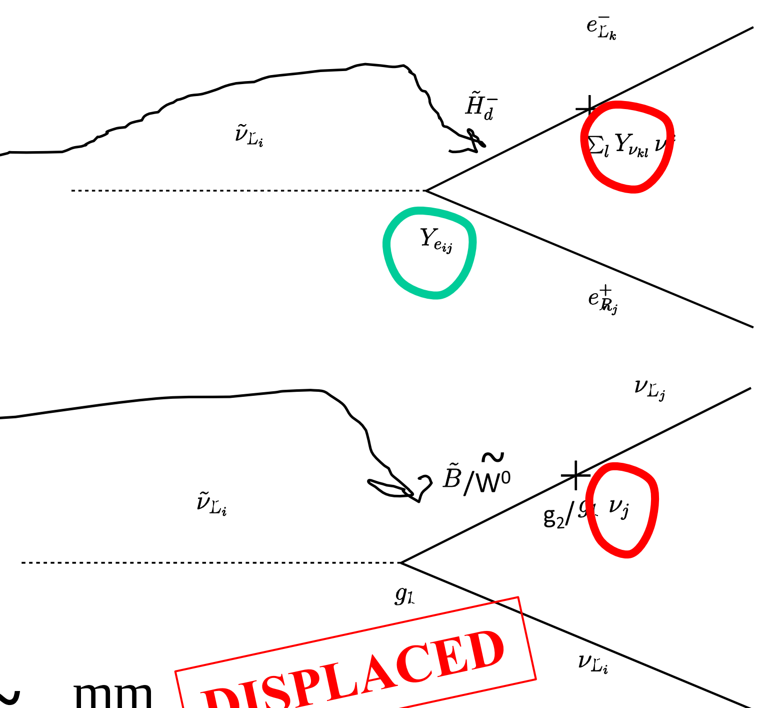
+ ...

one of the two vertices can also be a two-neutrino vertex

Main decay channels are:

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

$$\sum_i \Gamma(\tilde{\nu}_\tau \to \nu_\tau \nu_i) \approx \frac{m_{\tilde{\nu}_\tau}}{16\pi}\frac{1}{2M^2}\sum_i v_i^2,$$



Neutrino Yukawas drive the LSP decays

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

DISPLACED

There are at present no experimental analyses focused on the μνSSM

We recast the result of the ATLAS 8-TeV **dilepton** search to constrain our scenario

Lara, Lopez-Fogliani, C. M., Nagata, Otono, Ruiz de Austri, PRD 98 (2018) 075004

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

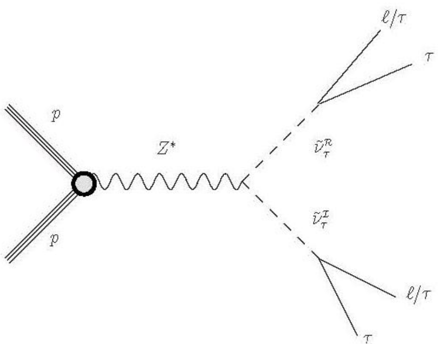
Search for massive, long-lived particles using multitrack displaced vertices or displaced lepton pairs in *pp* collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

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

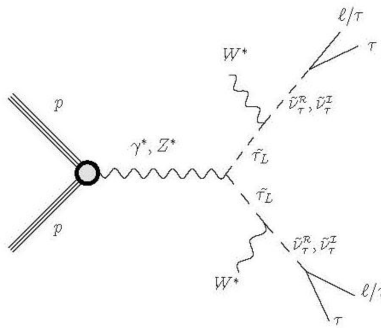
(Received 21 April 2015; revised manuscript received 19 August 2015; published 13 October 2015)

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.

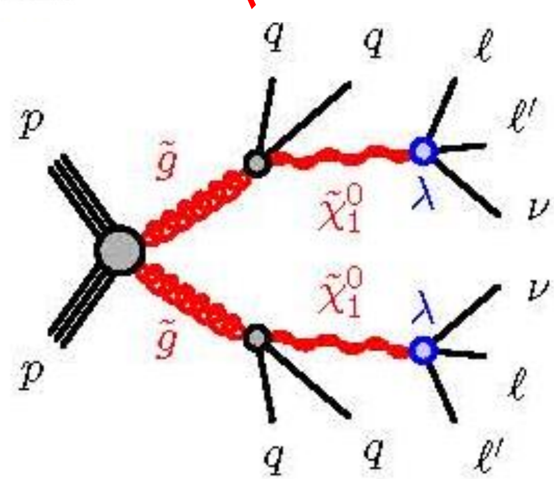
λLLe^c



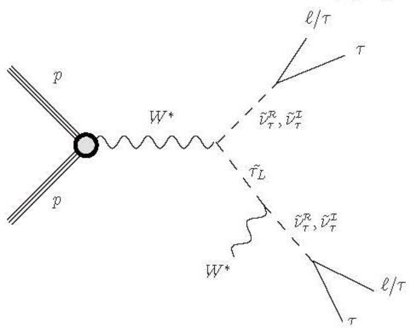
(a) Z channel



(b) γ, Z channels



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



(c) W channel

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

Their limits can be translated into a vertex-level efficiency: Larger $c\tau$ better efficiency

Kpatcha, Lara, Lopez-Fogliani, C. M., Nagata, Otono, Ruiz de Austri, 1907.02092

$m_{\tilde{\nu}_\tau} \in (45 - 100)$ GeV

Scan 1 (S_1)	Scan 2 (S_2)
$\tan\beta \in (10, 16)$	$\tan\beta \in (1, 4)$
$Y_{\nu_i} \in (10^{-8}, 10^{-6})$	
$v_i \in (10^{-6}, 10^{-3})$	
$-T_{\nu_3} \in (10^{-6}, 10^{-4})$	
$M_2 \in (150, 2000)$ = $2\, M_1$	

Parameter	Scan 1 (S_1)	Scan 2 (S_2)
λ	0.102	0.42
κ	0.4	0.46
v_R	1750	421
T_λ	340	350
$-T_\kappa$	390	108
$-T_{u_3}$	4140	1030
$m_{\tilde{Q}_{3L}}$	2950	1972
$m_{\tilde{u}_{3R}}$	1140	1972
M_3	2700	
$m_{\tilde{Q}_{1,2L}}, m_{\tilde{u}_{1,2R}}, m_{\tilde{e}_{1,2,3R}}$	1000	
$T_{u_{1,2}}$	0	
$T_{d_{1,2}}, T_{d_3}$	0, 100	
$T_{e_{1,2}}, T_{e_3}$	0, 40	
$-T_{\nu_{1,2}}$	10^{-3}	

Scans using Multinest algorithm as optimizer, searching for points reproducing the current experimental data on:

- Higgs physics
  interfaced with HiggsBounds & HiggsSignals

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

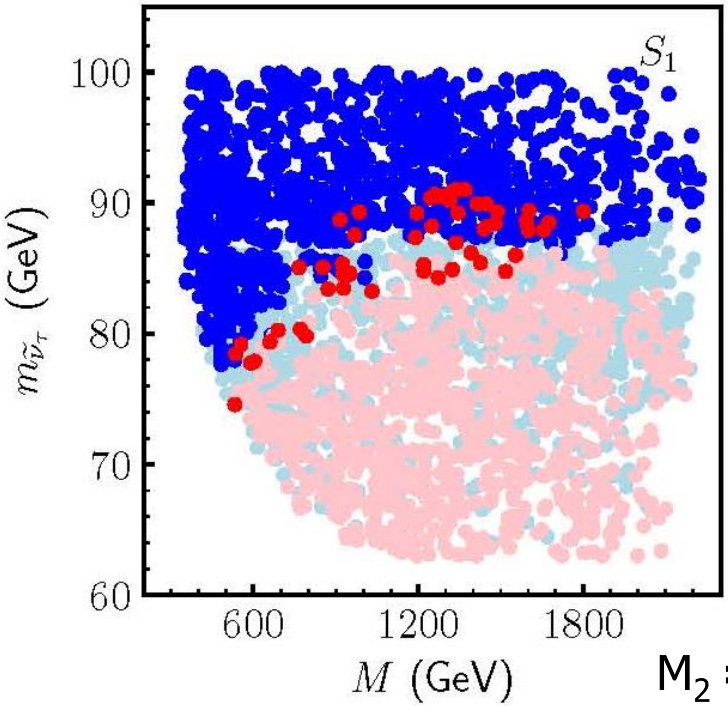
- Neutrino physics

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

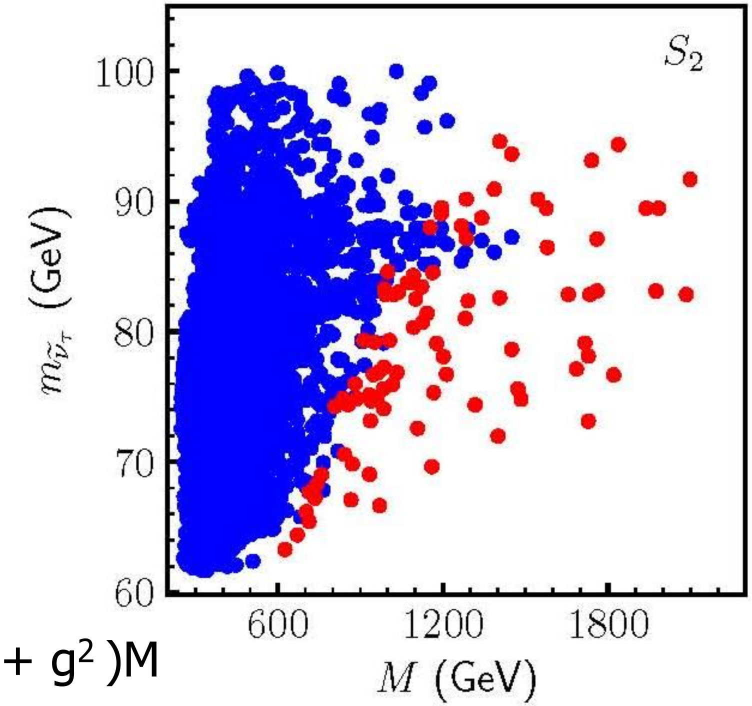
$\Delta m^2_{21,\,31}$ = (6.79-8.01) 10^{-5}, (2.427-2.625) 10^{-3} eV^2

To compute the spectrum and observables SARAH is used to generate a SPheno version of the μνSSM

Samples of simulated events are generated using MadGraph and PYTHIA



$M_2 = (2g'^2 + g^2)M$



All points (blue & red) fulfill the experimental data with $m_{\tilde{\nu}\tau} \in (45 - 100)$ GeV

Light-red points in S_1 are already excluded by the LEP bound on LH sneutrino masses

Blue points cannot be probed
channels μμ, μe, ee not producing a sufficient number of displaced dileptons

Red points can be probed in the 13 TeV search with 300 fb^{-1} *run 3:*

		S_1	S_2
$m_{\tilde{\nu}\tau}$	$\in$	(74-91) GeV	(63-95) GeV
M_2	$\in$	(363-1483) GeV	(427-1431) GeV

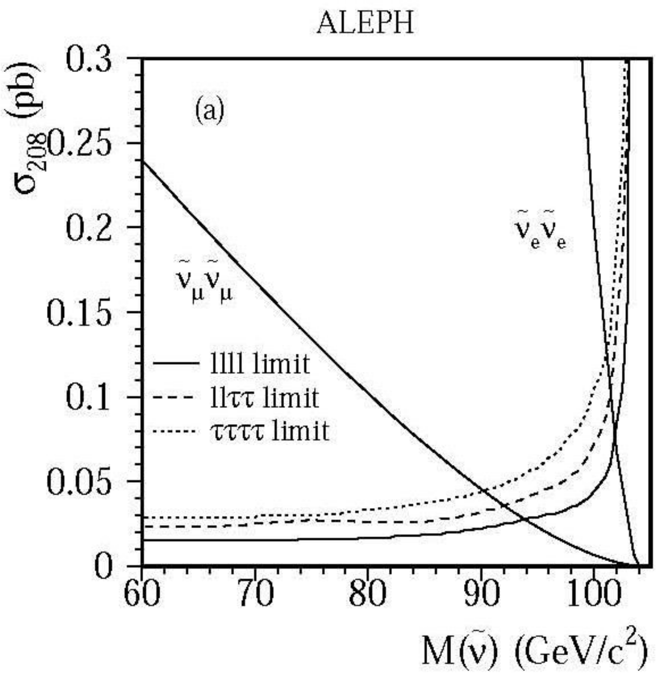


Figure 6: (a) The 95% C.L. cross-section upper limits for sneutrinos decaying directly via a dominant $LL\bar{E}$ operator. The three curves correspond to different possible final states, with $\ell = e$ or μ, due to the specific choice of sneutrino flavour and λ_{ijk}. The MSSM cross section for pair production of muon and electron sneutrinos are superimposed; the tau sneutrinos have the same cross section as the muon type. The 95% C.L. limits in the $(m_\chi, m_{\tilde{\nu}})$ plane for $\tilde{\nu}_e$ (b) and for

Assuming BR=1 implies a lower bound of 90 GeV for sneutrino LSP in this RPV model

To recast this result we have to multiply this cross section by BR ($\tilde{\nu}_\tau \longrightarrow \tau\mu)^2$
lowering the bound to 74 GeV for S_1 and no bound for S_2 in the μνSSM

This shows that the extrapolation of the usual bounds on sparticle masses to the μνSSM is not applicable

Conclusions

The introduction of neutrino Yukawas in SUSY drives naturally RPV

$$W = Y_\nu^{ij} \hat{\nu}^c_j \hat{H}_u \hat{L}_i \longrightarrow \kappa_{ijk} \hat{\nu}^c_i \hat{\nu}^c_j \hat{\nu}^c_k + \lambda_i \hat{\nu}^c_i \hat{H}_u \hat{H}_d$$

solving the μ and ν problems   μνSSM

Neutrino Yukawas drive gravitino LSP as a decaying DM candidate

THE END

Neutrino Yukawas drive the LSP decays

Concrete novel signals at colliders with multiHiggses displaced/prompt vertices, multi-lepton/jets final states

Be careful: the extrapolation of the usual bounds on sparticle masses to the μνSSM is not applicable… it's too early to declare SUSY dead

For the near future, it would be interesting to analyze whether we can recast LHC analyses *run 2* to put bounds on the masses of other possible LSPs like stop, gluino, RH stau,…