The μνSSM at the LHC and beyond

Carlos Muñoz

Instituto de Física Teórica
UAM-CSIC
Madrid, Spain

Departamento de
Física Teórica

MultiDark
Multimessenger Approach
for Dark Matter Detection

15th DSU, Buenos Aires, July 15-19, 2019

The fact that the Higgs is:

-an elementary scalar

-with a mass of 125 GeV

puts support on the idea of SUSY…

Since scalar particles exist,…, they produce the hierarchy problem, …., SUSY solves it and predicts the Higgs with a mass $\lesssim$ 140 GeV

The SUSY standard model with minimal particle content and neutrino masses, contains (at least) the following renormalizable terms:

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

where we kill the bilinear terms with a discrete Z_3 symmetry (like the one imposed in the NMSSM)

Actually, this is the case of the low-energy limit of string constructions, where only trilinear couplings are present: we are left with an accidental Z_3 symmetry

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

$$\lambda''_{ijk}\hat{u}^c_i\hat{d}^c_j\hat{d}^c_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{d}^c_k + \lambda_{ijk}\hat{L}_i\hat{L}_j\hat{e}^c_k + \boxed{\lambda_j\,\hat{\nu}^c_j}\,\hat{H}_u\,\hat{H}_d + \boxed{\kappa_{ijk}\hat{\nu}^c_i}\,\hat{\nu}^c_j\,\hat{\nu}^c_k$$

μ-term

Majorana masses

- **By construction, SUSY produces fast proton decay**

e.g. $\lambda'_{i12}\,\lambda_{i12} \lesssim 10^{-9}$

unless e.g. $\lambda''_{imk}\,\lambda'_{11k} \lesssim 10^{-25}$

when $\langle\tilde{\nu}^c_i\rangle$ ~ TeV

Lopez-Fogliani, C. M., PRL 2006

μνSSM

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

$$+\ \underbrace{\lambda''_{ijk}\,\xcancel{\hat{u}^c_i\,\hat{d}^c_j\,\hat{d}^c_k} + \lambda'_{ijk}\,\xcancel{\hat{L}_i\,\hat{Q}_j\,\hat{d}^c_k} + \lambda_{ijk}\,\xcancel{\hat{L}_i\,\hat{L}_j\,\hat{e}^c_k}} + \lambda_j\,\xcancel{\hat{\nu}^c_j\,\hat{H}_u}\,\hat{H}_d + \kappa_{ijk}\,\xcancel{\hat{\nu}^c_i\,\hat{\nu}^c_j\,\hat{\nu}^c_k}$$

To conserve **B** and **L** number, one can impose by hand a discrete symmetry (**R parity**)

$$\text{Particle} \longrightarrow \text{Particle}$$
$$\text{Sparticle} \longrightarrow -\ \text{Sparticle}$$

i.e. sparticles must appear in pairs

equivalent to Z_2 matter parity, where in the superpotential is imposed the symmetry:

$$(\hat{Q},\ \hat{u}^c,\ \hat{d}^c,\ \hat{L},\ \hat{e}^c,\ \hat{\nu}^c) \longrightarrow -(\hat{Q},\ \hat{u}^c,\ \hat{d}^c,\ \hat{L},\ \hat{e}^c,\ \hat{\nu}^c)$$
$$(\hat{H}_d,\ \hat{H}_u) \longrightarrow (\hat{H}_d,\ \hat{H}_u)$$

This conservative approach (**RPC**) forbids all these couplings

May be is too much… the terms with neutrinos are harmless for proton decay

Besides, D=5 (n.r.) proton-decay operators are not forbidden by R parity:

$$\frac{1}{\Lambda}\left(k_{ijkl}\,\hat{Q}_i\hat{Q}_j\,\hat{Q}_k\hat{L}_l + k'_{ijkl}\,\hat{u}^c_i\hat{u}^c_j\hat{d}^c_k\,\hat{e}^c_l\right),\quad \Lambda \sim 10^{-19}\,\text{GeV} \Rightarrow k_{112l} \lesssim 10^{-7}$$

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

$$\xcancel{\lambda''_{ijk}\,\hat{u}^c_i\,\hat{d}^c_j\,\hat{d}^c_k} + \lambda'_{ijk}\,\hat{L}_i\,\hat{Q}_j\,\hat{d}^c_k + \lambda_{ijk}\,\hat{L}_i\,\hat{L}_j\,\hat{e}^c_k + \lambda_j\,\hat{\nu}^c_j\,\hat{H}_u\,\hat{H}_d + \kappa_{ijk}\,\hat{\nu}^c_i\,\hat{\nu}^c_j\,\hat{\nu}^c_k$$

But the choice of R-parity is *ad hoc.*

There are other discrete symmetries that forbid some of these terms, but others are allowed

e.g. Z_3 Baryon parity forbids only the B number violating operator

$$(\hat{Q}, \hat{u}^c, \hat{d}^c) \longrightarrow -(\hat{Q}, \hat{u}^c, \hat{d}^c)$$

$$(\hat{L}, \hat{e}^c, \hat{H}_d, \hat{H}_u, \hat{\nu}^c) \longrightarrow (\hat{L}, \hat{e}^c, \hat{H}_d, \hat{H}_u, \hat{\nu}^c)$$

The only "discrete *gauge"* anomaly free symmetry that also forbids the D=5 operators Ibáñez, Ross, 91

Also stringy selection rules. E.g. in the heterotic string:

- *particles are attached to different sectors in the compact space*
- *or they have U(1) charges (with the extra U(1)s broken by a FI D-term)*

Casas, C.M., PLB 1988
Font, Ibáñez, Nilles, Quevedo, PLB 1988

NMSSM limit

$Y_\nu \longrightarrow 0$ ν^c are ordinary singlets with $\langle \tilde{\nu}^c_i \rangle$ ~ TeV
and R-parity is conserved (in the limit $\lambda'_{ijk}=\lambda_{ijk}=0$)

spontaneous **BRpV**

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

$$+\ \lambda'_{ijk}\hat L_i\hat Q_j\hat d^c_k + \lambda_{ijk}\,\hat L_i\,\hat L_j\,\hat e^c_k + \boxed{\lambda_j\,\hat\nu^c_j}\,\hat H_u\,\hat H_d + \boxed{\kappa_{ijk}\hat\nu^c_i}\,\hat\nu^c_j\,\hat\nu^c_k$$

But if $Y_\nu \lesssim 10^{-6}$ of the order of the electron Yukawa

EW scale seesaw

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

RPV, which is driven by $Y_\nu \lesssim 10^{-6}$, is then small in the **μνSSM**

solves the ν problem: How to accommodate the neutrino data

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

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

TRpV do not introduce modifications in our analyses of the μ and ν problems (might modify the phenomenology)

solves the ν problem: How to accommodate the neutrino data

In addition to $\langle H_u^0 \rangle$, $\langle H_d^0 \rangle$, $\langle \tilde{\nu}_i^c \rangle$ the left sneutrinos also get VEVs $\boxed{\langle \tilde{\nu}_i \rangle}$

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

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

and the EW scale seesaw induces small values: $v_i \sim Y_\nu\, v_u \lesssim 10^{-6}\, 10^2 = \boxed{10^{-4}\,\text{GeV}}$

neutrino physics drives their VEVs

Because of RPV, fields with the same quantum numbers mix

RH neutrinos
neutralinos

LH neutrinos

This is a generalized seesaw:

$$\mathcal{M}_n = \begin{pmatrix} M & m \\ m^T & 0_{3\times 3} \end{pmatrix};$$

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

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

Mixing of LH neutrinos with gauginos: 'Gaugino seesaw'

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

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

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

Besides, concerning μνSSM cosmology:

Gravitino is a dark matter candidate

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

Axino dark matter is also possible:
G. Gomez-Vargas, D.E. López-Fogliani, C. M., A.D. Perez, in preparation

EW phase transition is sufficiently strongly first order to realize electroweak baryogenesis

D.J.H. Chung, A.J. Long, PRD 2010

Concerning μνSSM LHC phenomenology, because of RPV:

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

  stau, squark, neutralino,…, sneutrino

- There is no missing energy as a special signal

  which in view of the current experimental bounds on RPC models…

- Novel signals with multiHiggses (H_u, H_d, sneutrinos)
  displaced vertices,
  multi-lepton final states,
  multi-jet final states

The left sneutrinos are special in the μνSSM

- neutrino physics drives their VEVs to small values

$$\nu_i \sim Y_\nu \nu_u \lesssim 10^{-6}\, 10^{2} = 10^{-4} \text{ GeV}$$

- Their masses are essentially determined by the soft masses:

$$m^2_{\tilde{L}_i} \nu_i = - A_\nu \nu_R Y_{\nu i} \nu_u + \dots$$

$$m^2_{\tilde{\nu}_i} = \frac{Y_{\nu i} \nu_u}{\nu_i} \nu_R (- A_\nu + \dots)$$

neutrino physics drives their masses, thus we expect some generation to be light

e.g. the hierarchy $Y_{\nu 3} \sim 10^{-8} - 10^{-7} < Y_{\nu 1,2} \sim 10^{-6} \longrightarrow \left\{ \begin{array}{l} m_{\tilde{\nu}_\tau} \sim 100 \text{ GeV} \\ M_{\tilde{\nu}_{e,\mu}} \sim 1000 \text{ GeV} \end{array} \right.$

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

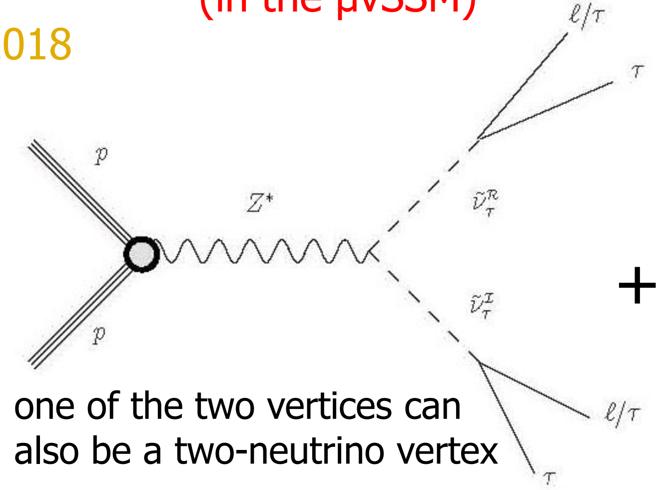
Bound on the mass of a tau left sneutrino LSP from LHC data ?

(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



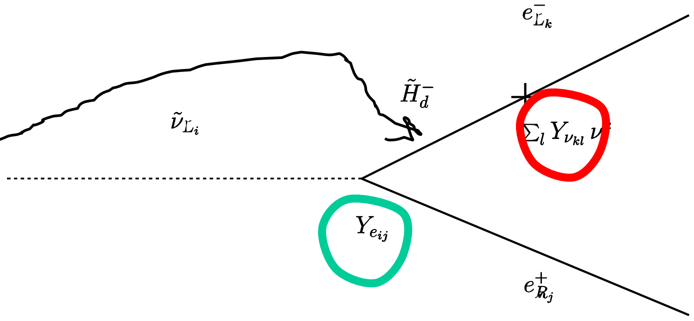
one of the two vertices can
also be a two-neutrino vertex

(a) Z channel

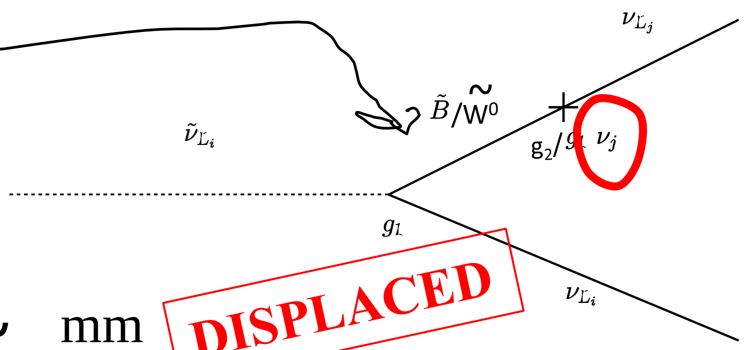
+ ...

Main decay channels are:

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



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



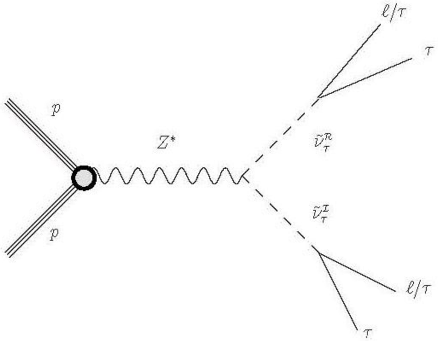
Decays are controlled by the neutrino seesaw

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

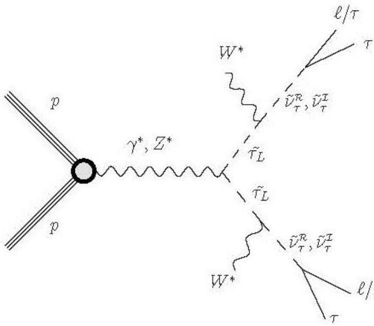
There are at present no experimental analyses focused on the μνSSM

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

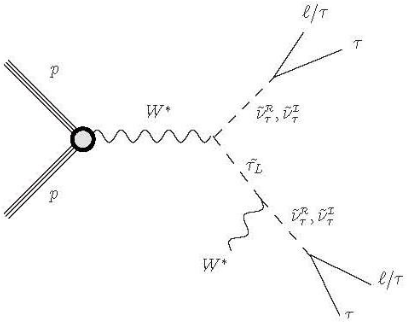


(a) Z channel

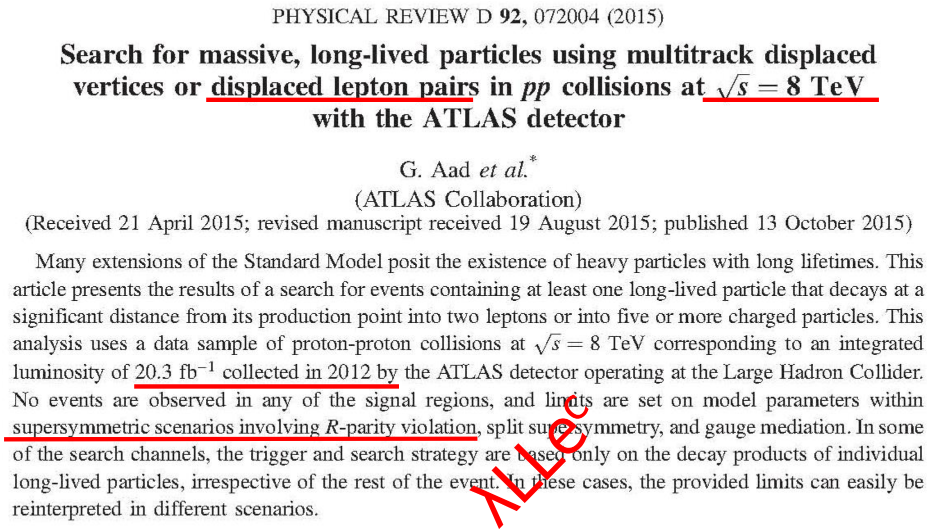


(b) γ, Z channels

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



(c) W channel



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

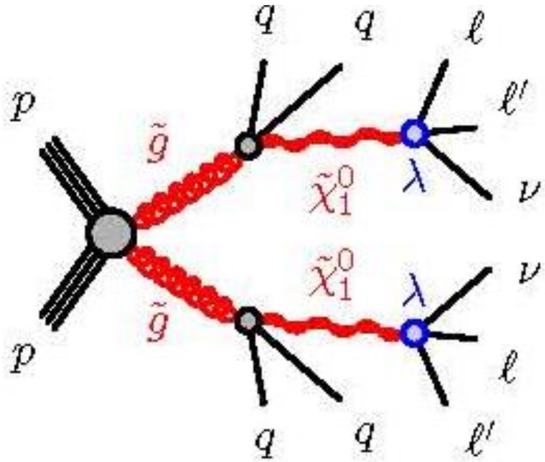
G. Aad *et al.**

(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.

$\lambda L L e^c$



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

ATLAS analysis requires high thresholds for lepton momenta.
Triggers do not utilize the tracking information:

- One μ- with $p_T > 50$ GeV, one e- with $p_T > 120$ GeV
  or two e- with $p_T > 40$ GeV each

But $m_{\tilde{\nu}_\tau} < 100$ GeV and low boosted → decay products with momenta of a few tens of GeV

To analyze better the events with μμ/eμ pairs for the 8-TeV searches, we proposed an optimization of the trigger requirements by means of a high level trigger that exploits tracker information: mu24i (ATLAS collaboration EPJC 75, 2015)

- At least one μ- with $p_T > 24$ GeV

To study the prospects for the 13-TeV searches we also considered an optimization (ATLAS collaboration EPJC 77, 2017)

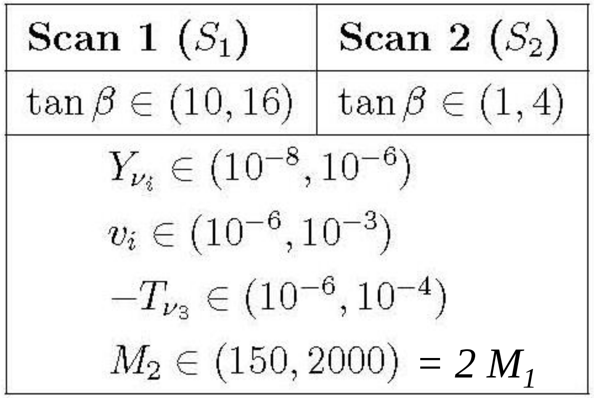
- At least one e- or μ- with $p_T > 26$ GeV

allowing the detection of events with ee pairs

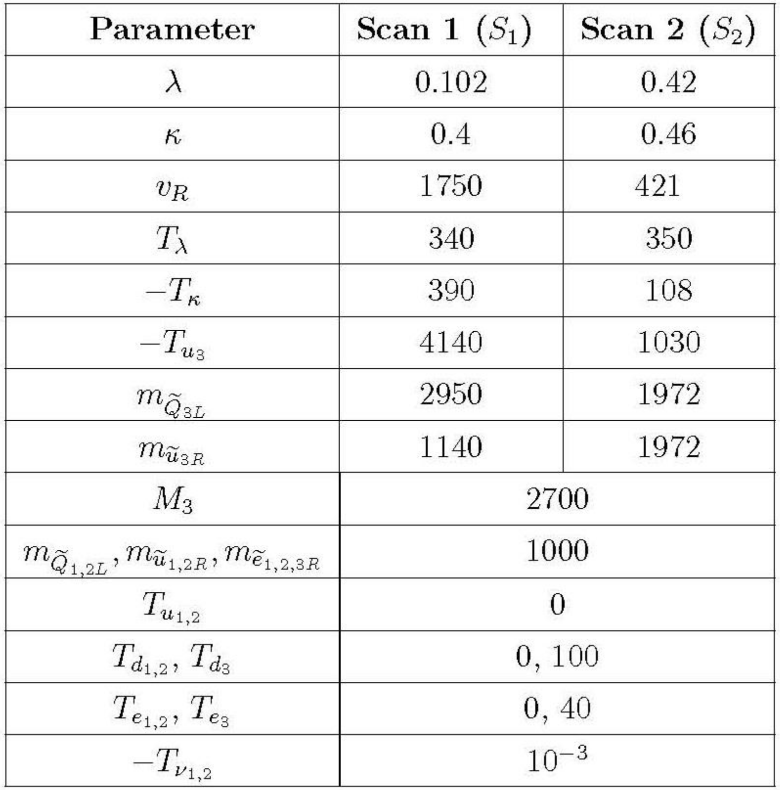
$$\begin{aligned}\#\mathrm{Dimuons} = &\left[\sigma(pp \to Z \to \widetilde{\nu}_\tau \widetilde{\nu}_\tau)\epsilon^{Z}_{\mathrm{sel}} + \sigma(pp \to W \to \widetilde{\nu}_\tau \widetilde{\tau})\epsilon^{W}_{\mathrm{sel}} + \sigma(pp \to \gamma, Z \to \widetilde{\tau}\widetilde{\tau})\epsilon^{\gamma,Z}_{\mathrm{sel}}\right] \\ &\times \mathcal{L} \times \left[\mathrm{BR}(\widetilde{\nu}^{\mathcal{R}}_\tau \to \mu\mu)\ \epsilon^{\mu\mu}_{\mathrm{vert}}(c\tau^{\mathcal{R}}) + \mathrm{BR}(\widetilde{\nu}^{\mathcal{I}}_\tau \to \mu\mu)\ \epsilon^{\mu\mu}_{\mathrm{vert}}(c\tau^{\mathcal{I}})\right],\end{aligned}$$

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
$m_{\widetilde{Q}_{3L}}$	2950	1972
$m_{\widetilde{u}_{3R}}$	1140	1972
M_3	2700	
$m_{\widetilde{Q}_{1,2L}}, m_{\widetilde{u}_{1,2R}}, m_{\widetilde{e}_{1,2,3R}}$	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:

- 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

  interfaced with HiggsBounds & HiggsSignals

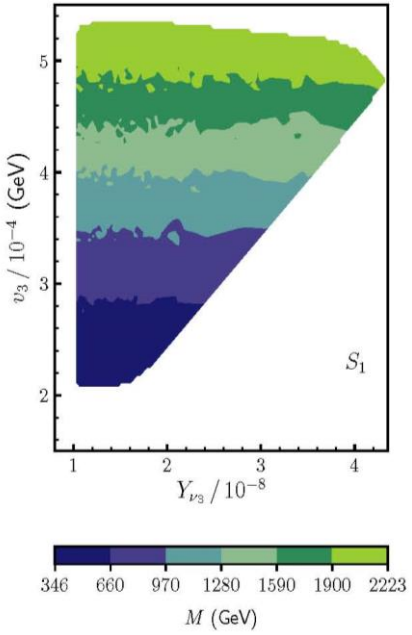
- Flavor observables

  (b → sγ, B → μμ, μ → eγ, μ → eee)

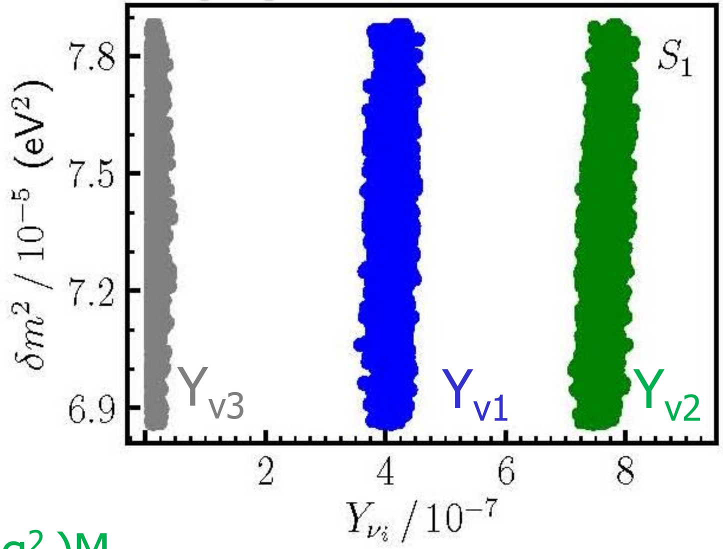
To compute the spectrum and observables SARAH is used to generate a SPheno version of the μνSSM

Samples of simulated events are generated using MadGraph and PYTHIA

Constraints from neutrino/sneutrino physics



A tau sneutrino LSP $\lesssim$ 100 GeV implies that the tau neutrino Yukawa is the smallest

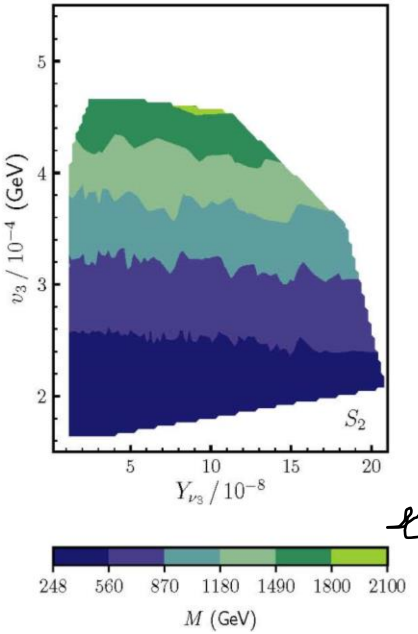


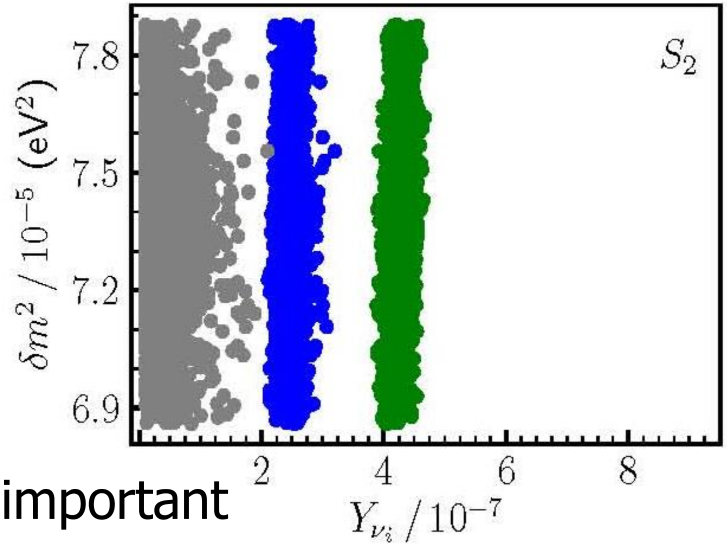
driving neutrino physics to dictate:

the range of $M_2 = (2g'^2 + g^2)M$

(S_1) 236-1514 GeV

(S_2) 169-1431 GeV





and that the muon neutrino Yukawa is the largest

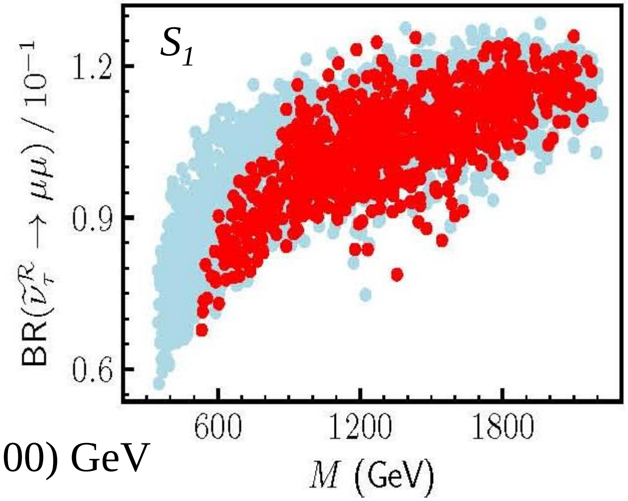
As a consequence the most important contribution to the dilepton BRs comes from the channel sneutrino to tau muon

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

Constraints from LHC searches

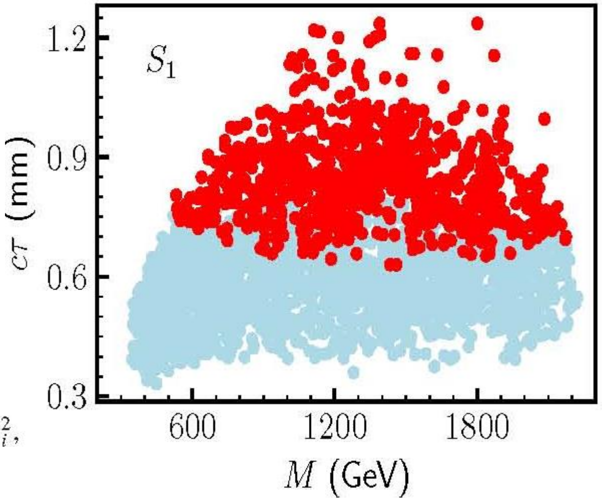
All points (blue&red) fulfill the exp. data with

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



Dilepton BRs increase with larger M, since decay width to neutrinos decreases

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



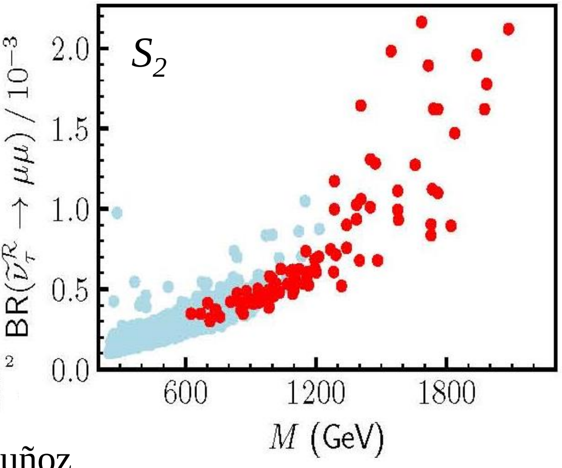
$M_2 = (2g'^2 + g^2)M \in (236\text{-}1514)$ GeV to fulfill neutrino physics

No points of the μνSSM can be probed using the 8-TeV data with 20.3 fb^{-1}

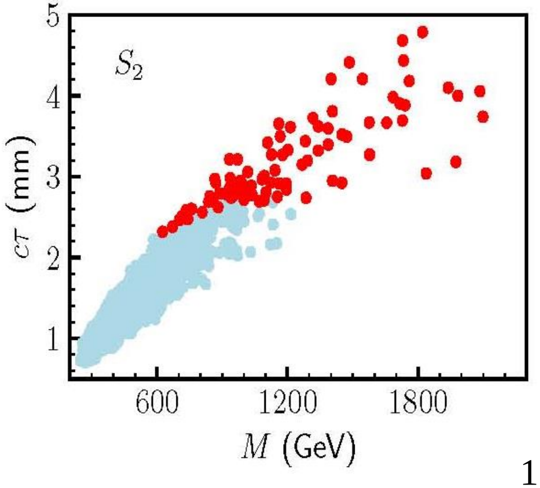
Red points can be probed in the 13 TeV search with 300 fb^{-1} *run 3:*
channels μμ, μe, ee producing a sufficient number of displaced dilepton events

BRs smaller for S_2 because λ is larger, tan β smaller, $Y_{\nu 2}$ smaller

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

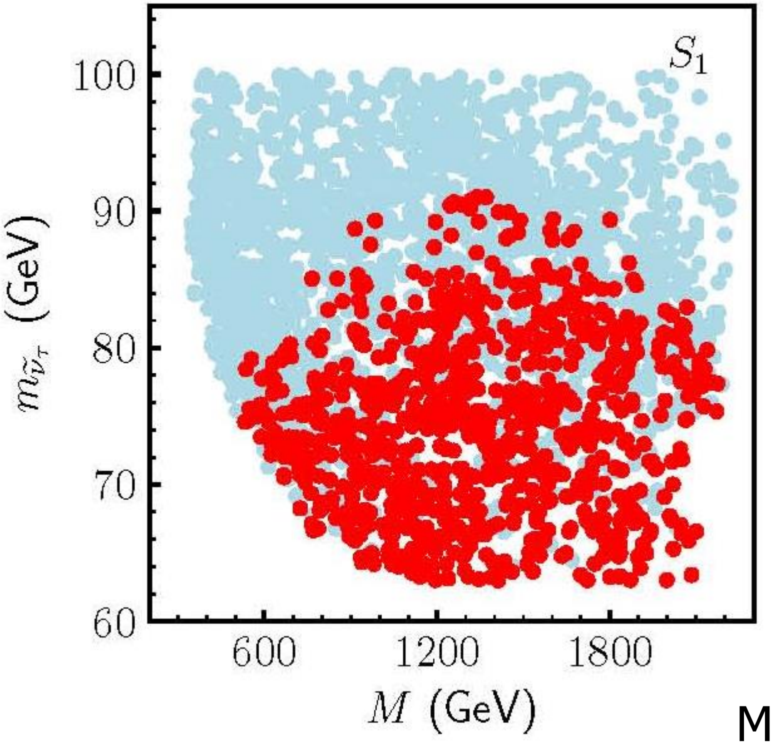


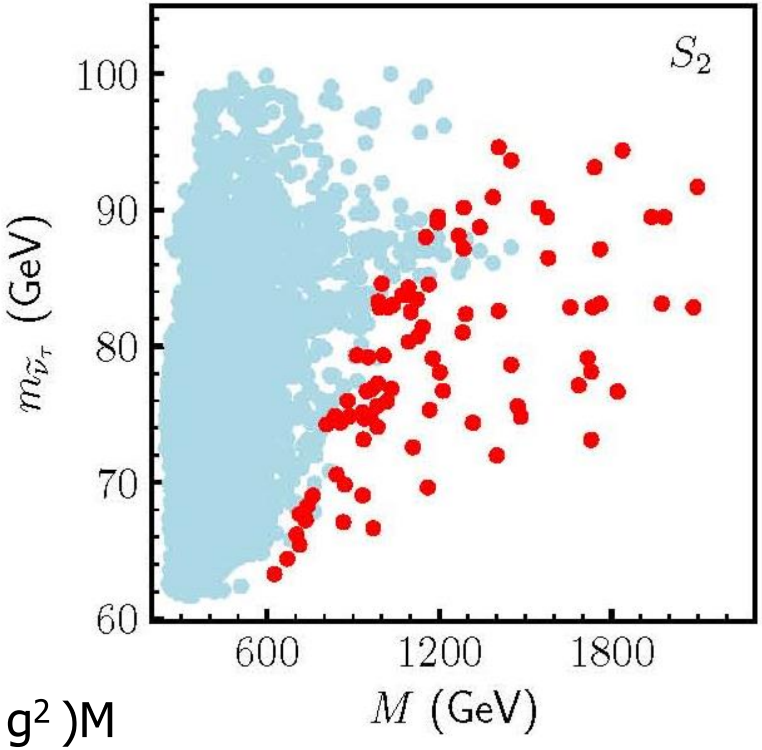
Still a significant number of red points because of the larger decay lengths, implying larger vertex-level efficiency



$M_2 \in (169\text{-}1431)$ GeV

Summarizing:





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

Red points can be probed at LHC run 3 with:

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

We thus highly motivate both the ATLAS and CMS collaborations to take account of this option of optimizing the triggers seriously

Conclusions

It's too early to declare SUSY dead

We have discussed a realistic SUSY model, the μν**SSM**

$\hat{\nu}_i^c \, \hat{H}_1^a \hat{H}_2^b$

- Solves the **μ** problem
- Accommodates easily the **ν** data through a generalized EW seesaw
- Does not introduce any new particle apart from RH neutrinos
- Everything occurs at the electroweak scale
- The gravitino can be a candidate for dark matter
- Electroweak baryogenesis is possible
- Concrete novel signals at colliders with multiHiggses displaced/prompt vertices, multi-lepton/jets final states
- LSP lifetime is connected to neutrino physics

However, there is still a lack of LHC bounds on the masses of the sparticles in the μνSSM

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

THE END