The μνSSM at the LHC and beyond

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MultiDark
Multimessenger Approach for Dark Matter Detection

Opportunities at future high energy colliders
Madrid, 2019, 11 June-5 July

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

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

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

$\lambda'_{ijk}\ \lambda_{ijk}$ <<

unless $\lambda''_{11k}\ \lambda'_{11k} \lesssim 10^{-26}$

Lopez-Fogliani, C. M., PRL 2006

μνSSM

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

$$+$$

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

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

Particle ⟶ Particle
Sparticle ⟶ — Sparticle

i.e. sparticles must appear in pairs

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

$$(\hat Q, \hat u^c, \hat d^c, \hat L, \hat e^c, \hat\nu_k^c) \longrightarrow -(\hat Q, \hat u^c, \hat d^c, \hat L, \hat e^c, \hat\nu_k^c)$$

$$(\hat H_d, \hat H_u) \longrightarrow (\hat H_d, \hat H_u)$$

Notice that this (conservative) approach forbids all these (renormalizable) couplings

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

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

$$\frac{1}{\Lambda}\left(k_{ijkl}\,\hat Q_i\hat Q_j\,\hat Q_k\hat L_l + k'_{ijk}\,\hat u^c_i\hat u^c_j\hat d^c_k\,\hat e^c_l\right), \quad \Lambda \sim 10^{-19}\,\mathrm{GeV} \;➡\; k_{112l} \lesssim 10^{-7}$$

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

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

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

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

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

The only discrete *gauge* symmetry that also forbids the D=5 n.r. proton decay operators

Ibáñez, Ross, 1991, 92

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)*

NMSSM limit

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

spontaneous **BRpV**

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

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

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

EW scale seesaw

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

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 $\mu << M_{\mathrm{Planck}}$

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

Who gives more for less ?

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

LH neutrinos

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

This generalized seesaw
implies 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 gauginos

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

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

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 in the **μνSSM**

K.Y. Choi, D.E. López-Fogliani, C. M., R. Ruiz de Austri, JCAP 03 (2010) 028

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

D.J.H. Chung, A.J. Long, PRD 81 (2010) 123531

Concerning μνSSM LHC phenomenology:

- 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 displaced vertices, multi-lepton/jets final states, multiHiggses

Talk by Thomas:
Accommodate excesses at LEP and LHC at 96 GeV reproducing also neutrino physics

T. Biekotter, S. Heinemeyer, C.M., 1906.06173

The left sneutrinos are special in the μνSSM

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

because of their minimization condition

$$V_{\text{soft}} = m_{H_d}^2 H_d^0 H_d^{0*} + m_{H_u}^2 H_u^0 H_u^{0*} + \underline{m_{\tilde{L}_{ij}}^2 \tilde{\nu}_i \tilde{\nu}_j^*} + m_{\tilde{\nu}_{ij}^c}^2 \tilde{\nu}_i^c \tilde{\nu}_j^{c*}$$
$$+ \left(\underline{a_{\nu_{ij}} H_u^0 \tilde{\nu}_i \tilde{\nu}_j^c} - a_{\lambda_i} \tilde{\nu}_i^c H_d^0 H_u^0 + \frac{1}{3} a_{\kappa_{ijk}} \tilde{\nu}_i^c \tilde{\nu}_j^c \tilde{\nu}_k^c + \text{c.c.} \right) , \qquad a_{\nu_{ij}} \equiv (A_\nu Y_\nu)_{ij},\ a_{\lambda_i} \equiv (A_\lambda \lambda)_i,\ a_{\kappa_{ijk}} \equiv (A_\kappa \kappa)_{ijk},$$

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

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

- Their masses are essentially determined by the soft masses:

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

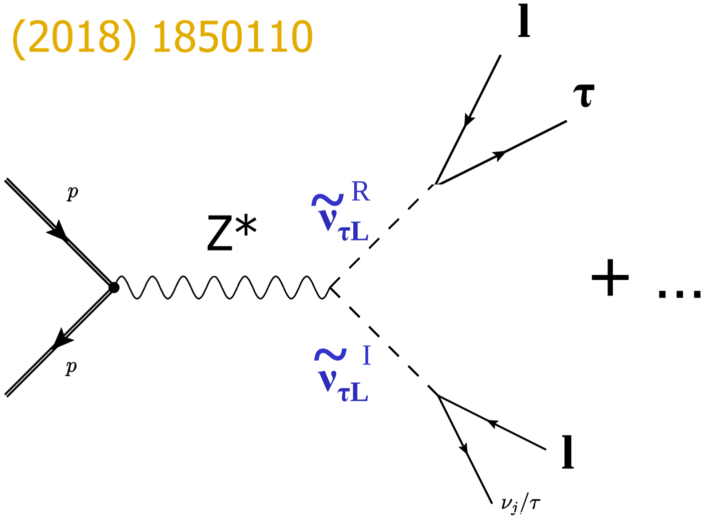
neutrino physics drives their masses, thus we expect some generation to be light

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

$\tilde{\nu}_\tau$ LSP specially interesting because Y_τ is large implying large BRs

Are there experimental bounds on the mass of a tau left sneutrino LSP ?

Ghosh, Lara, Lopez-Fogliani, C. M., Ruiz de Austri, IJMPA 33 (2018) 1850110

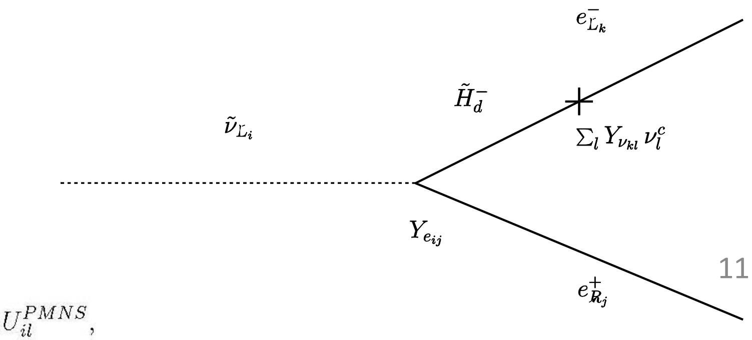


$\tilde{\nu}_\tau$ LSP directly produced
giving rise to multileptons

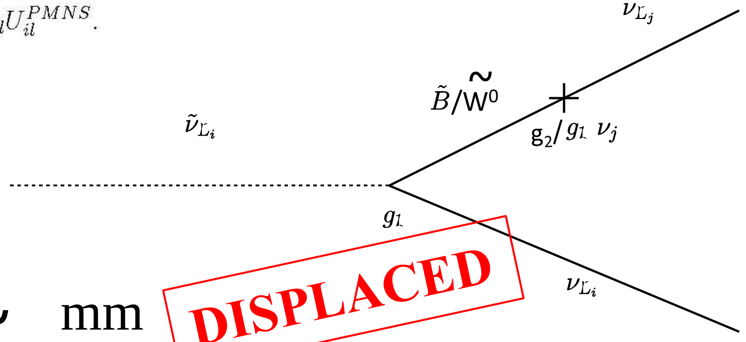
Stau is the natural NLSP

Main decay channels are:

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



$$\sum_i \Gamma(\widetilde{\nu}_\tau \to \nu_\tau \nu_i) \approx \frac{m_{\widetilde{\nu}_\tau}}{16\pi} \sum_i \left| \frac{g'}{2} U^V_{i4} - \frac{g}{2} U^V_{i5} \right|^2 , \qquad U^V_{i4} \approx \frac{-g'}{\sqrt{2} M_1} \sum_l v_l U^{PMNS}_{il} , \quad U^V_{i5} \approx \frac{g}{\sqrt{2} M_2} \sum_l v_l U^{PMNS}_{il} .$$



Decays are controlled by the neutrino seesaw

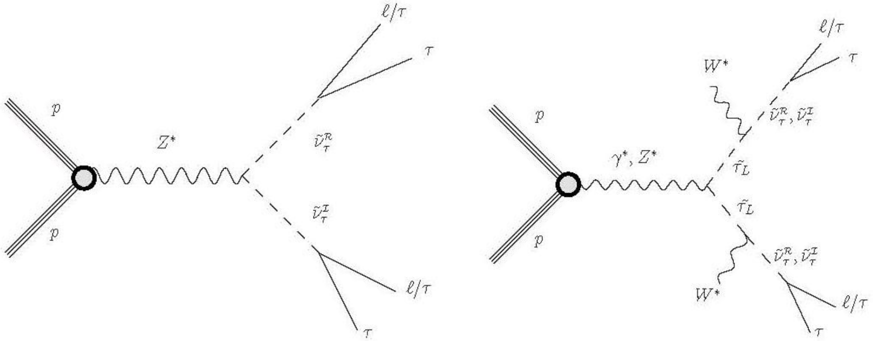
$m_{\tilde{\nu}_\tau} \sim$ 45 – 100 GeV have decay lengths ~ mm

DISPLACED

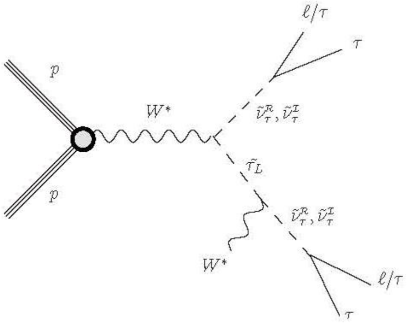
There are at present no experimental analyses focused on the μνSSM

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

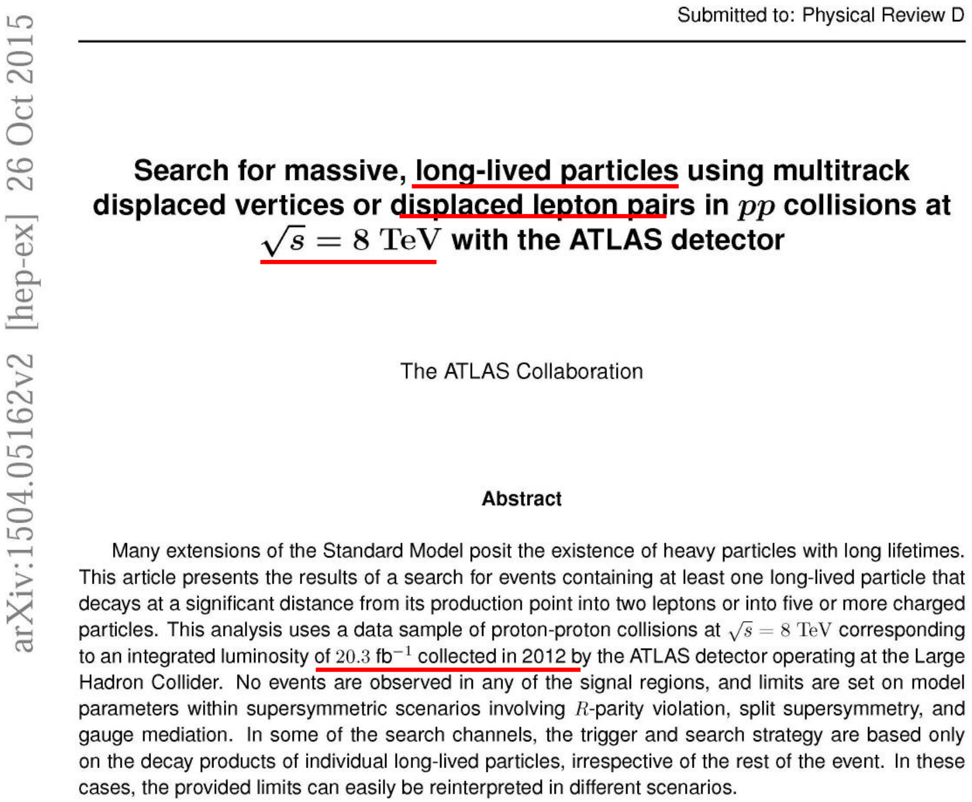
Lara, Lopez-Fogliani, C. M., Nagata, Otono, Ruiz de Austri, PRD 98 (2018) 075004



(a) Z channel (b) γ, Z channels



(c) W channel



Submitted to: Physical Review D

arXiv:1504.05162v2 [hep-ex] 26 Oct 2015

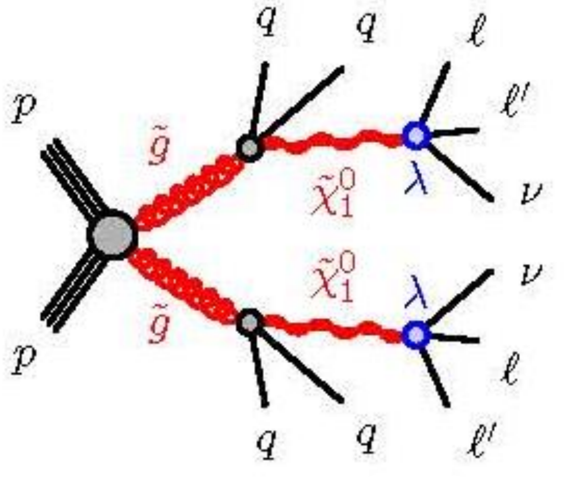
Search for massive, long-lived particles using multitrack displaced vertices or displaced lepton pairs in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

The ATLAS Collaboration

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.

The ATLAS displaced-vertex search is sensitive to $c\tau \gtrsim \mathrm{mm}$



Their limits can be translated into a vertex-level 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

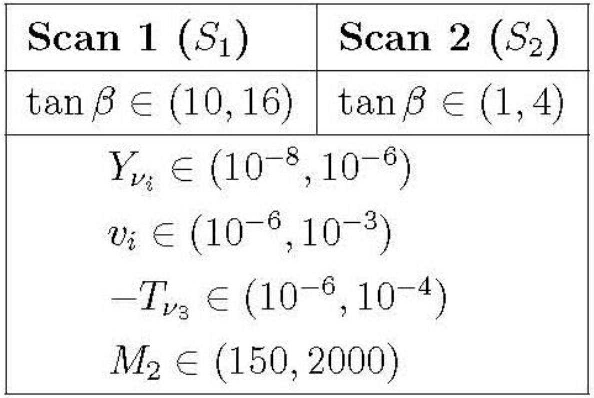
To study the prospects for the 13-TeV searches we also considered an optimization (ATLAS collaboration EPJC 77, 2017)

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

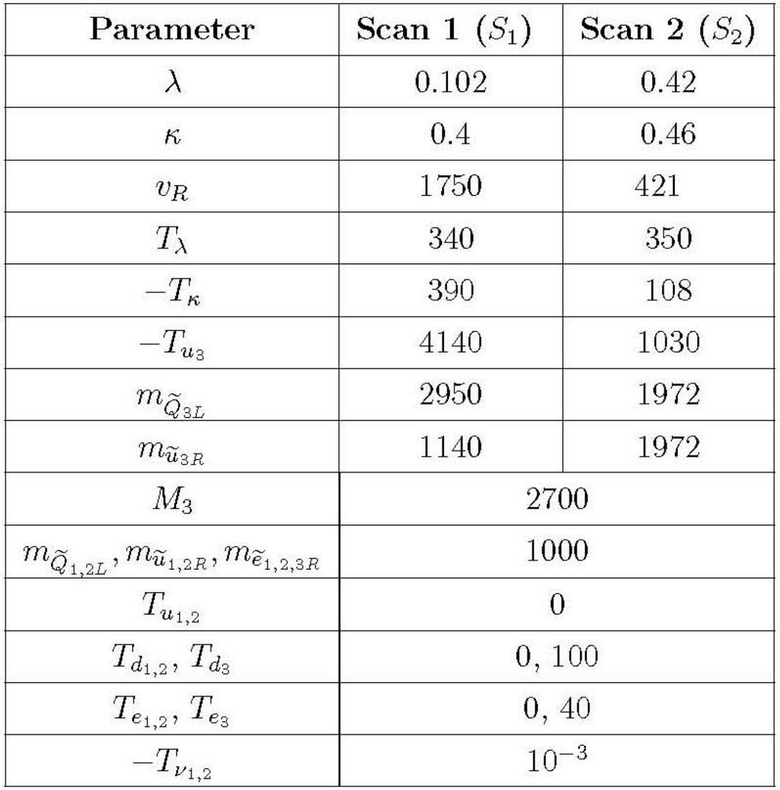
allowing the detection of events with ee pairs

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

Kpatcha, Lara, Lopez-Fogliani, C. M., Nagata, Otono, Ruiz de Austri, tomorrow in arXiv



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



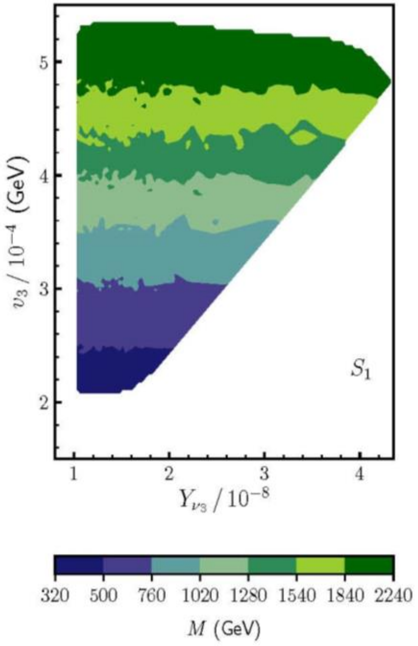
Parameter	**Scan 1 (S_1)**	**Scan 2 (S_2)**
λ	0.102	0.42
κ	0.4	0.46
v_R	1750	421
T_λ	340	350
$-T_\kappa$	390	108
$-T_{u_3}$	4140	1030
$m_{\widetilde{Q}_{3L}}$	2950	1972
$m_{\widetilde{u}_{3R}}$	1140	1972
M_3	2700	
$m_{\widetilde{Q}_{1,2L}}, m_{\widetilde{u}_{1,2R}}, m_{\widetilde{e}_{1,2,3R}}$	1000	
$T_{u_{1,2}}$	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}	

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

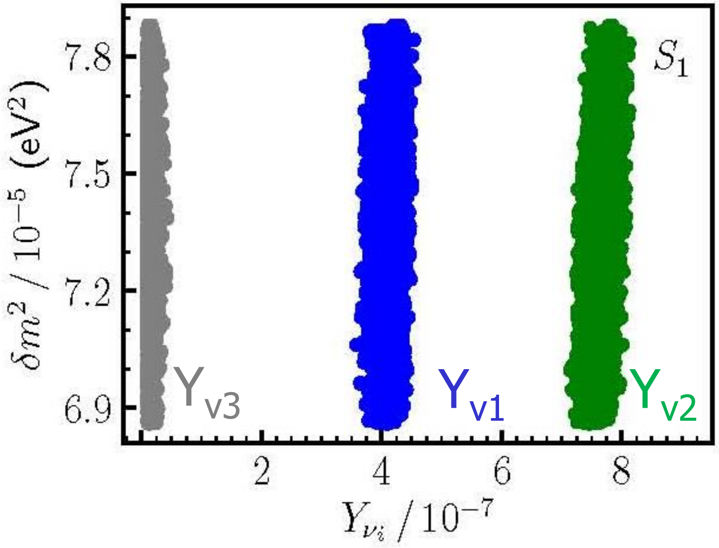
- Neutrino physics
- Higgs physics
- Flavor observables
  (b → sγ, B → μμ, μ → eγ, μ → eee)

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

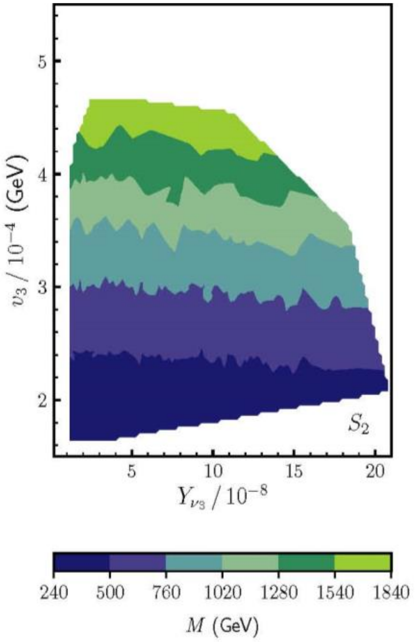
Samples of simulated events are generated using MadGraph and PYTHIA

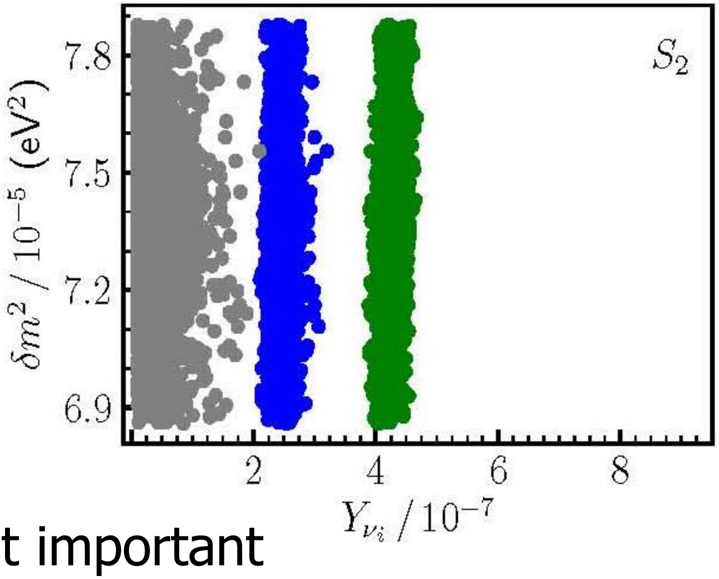


A tau sneutrino LSP implies that the tau neutrino Yukawa is the smallest



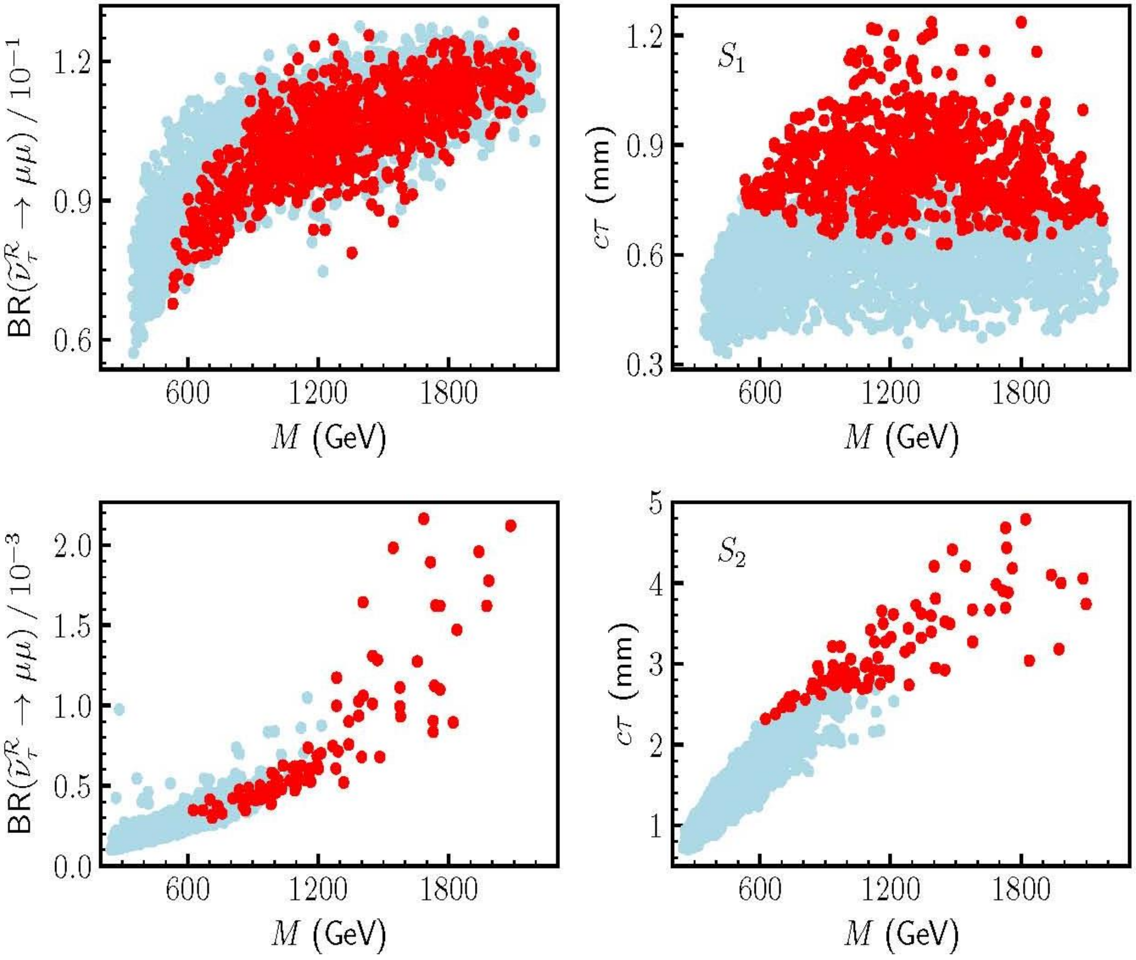
driving neutrino physics to dictate that muon neutrino Yukawa is the largest



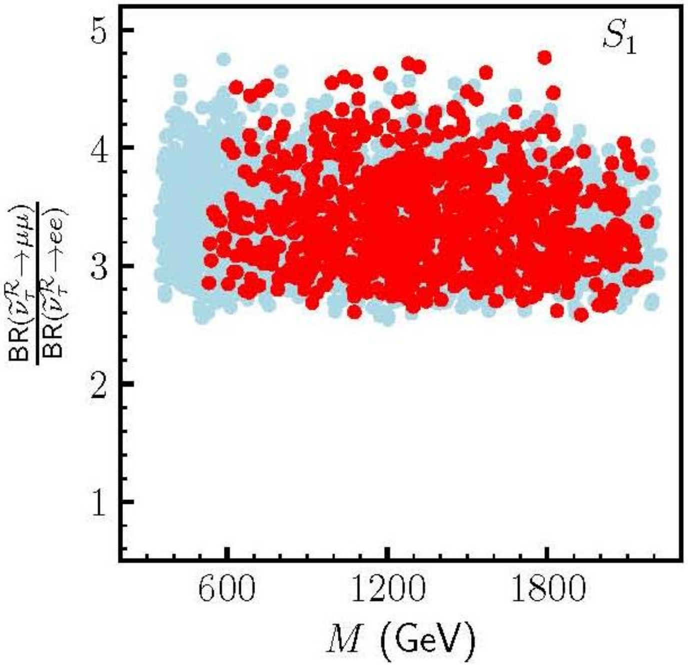


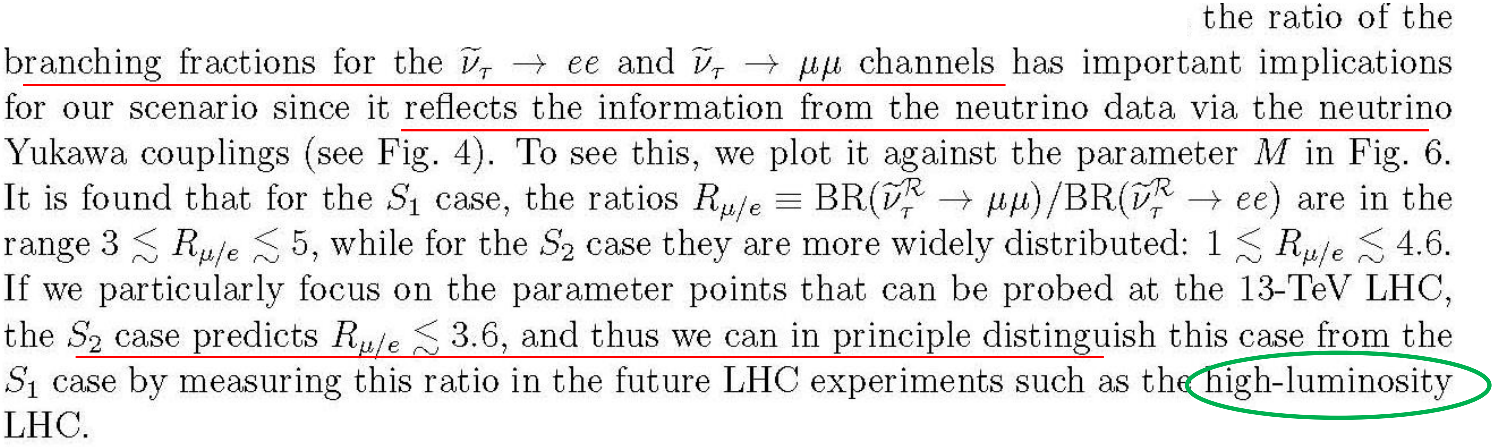
As a consequence the most important contribution to the dilepton BRs comes from the channel sneutrino to tau muon

Although no points of the μνSSM can be probed using the 8-TeV data with 20.3 fb^{-1} , the prospects for the 13-TeV search with 300 fb^{-1} *run 3*:



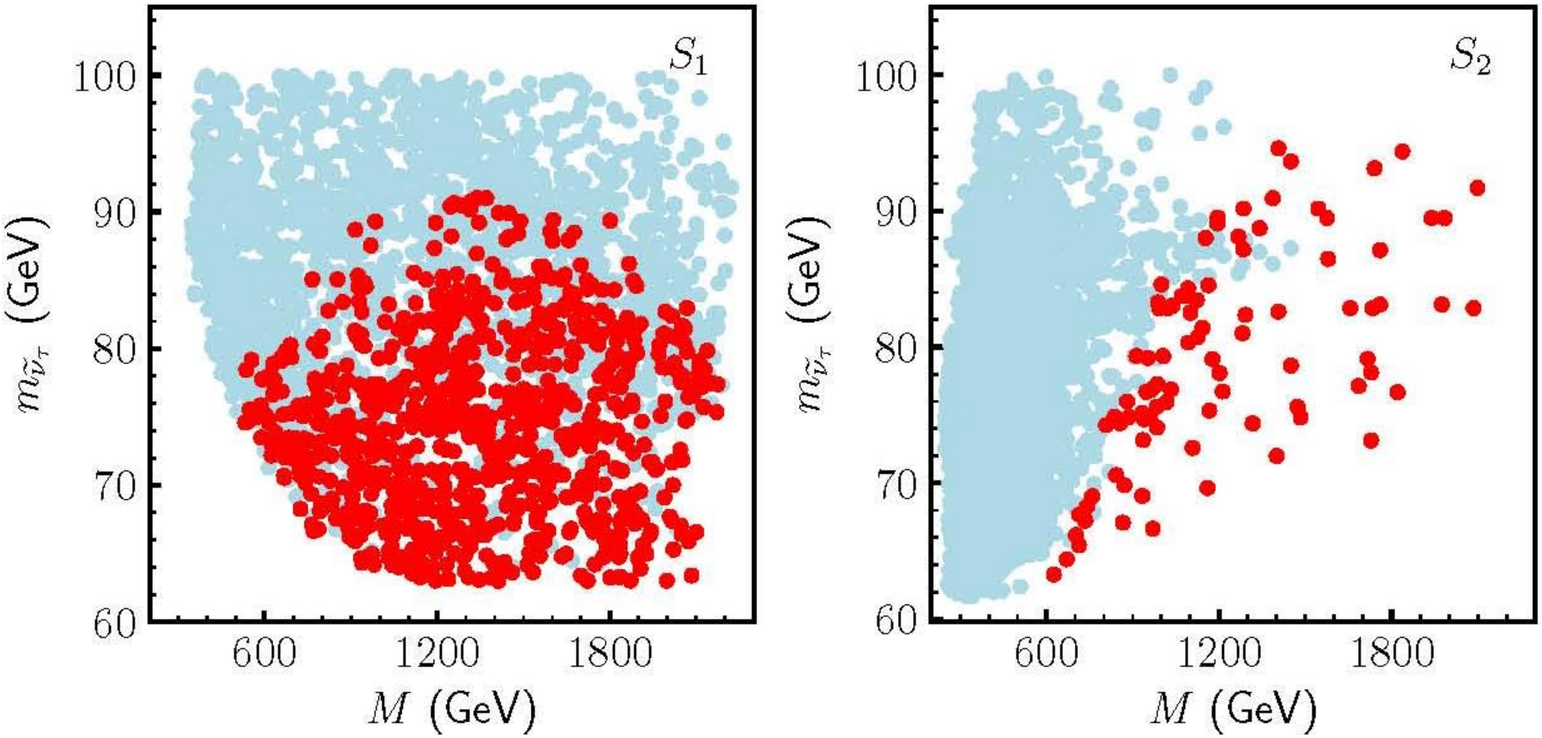
Red points can be probed (channels μμ, μe, ee)





the ratio of the branching fractions for the $\widetilde{\nu}_\tau \to ee$ and $\widetilde{\nu}_\tau \to \mu\mu$ channels has important implications for our scenario since it reflects the information from the neutrino data via the neutrino Yukawa couplings (see Fig. 4). To see this, we plot it against the parameter M in Fig. 6. It is found that for the S_1 case, the ratios $R_{\mu/e} \equiv \mathrm{BR}(\widetilde{\nu}_\tau^{\mathcal{R}} \to \mu\mu)/\mathrm{BR}(\widetilde{\nu}_\tau^{\mathcal{R}} \to ee)$ are in the range $3 \lesssim R_{\mu/e} \lesssim 5$, while for the S_2 case they are more widely distributed: $1 \lesssim R_{\mu/e} \lesssim 4.6$. If we particularly focus on the parameter points that can be probed at the 13-TeV LHC, the S_2 case predicts $R_{\mu/e} \lesssim 3.6$, and thus we can in principle distinguish this case from the S_1 case by measuring this ratio in the future LHC experiments such as the high-luminosity LHC.

Summarizing:



Sneutrino masses	63-91 GeV	63-95 GeV
Gaugino parameter M	530-2175 GeV	625-2100 GeV

can be probed at LHC run 3

Conclusions

It's too early to declare SUSY dead

I 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
- 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

But not constrained at the LHC yet !

THE END