The $\mu\nu$SSM at the LHC and beyond

Carlos Muñoz

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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 \( \lesssim 140 \text{ GeV} \)
The SUSY standard model with minimal particle content and neutrino masses, contains (at least) the following renormalizable terms:

\[ W = \epsilon_{ab} \left( Y^u_{ij} \hat{H}^b_u \hat{Q}^a_i \hat{\bar{u}}^c_j + Y^d_{ij} \hat{H}^a_d \hat{Q}^b_i \hat{\bar{d}}^c_j + Y^e_{ij} \hat{H}^a_d \hat{L}^b_i \hat{\bar{e}}^c_j + Y^\nu_{ij} \nu^c_j \hat{H}^b_u \hat{\bar{L}}^a_i \right) \]

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, \( Y = -1/2 \)

\[ \lambda''_{i12} \hat{u}^c_i \hat{d}^c_j \hat{d}^c_k + \lambda'_{ijk} \hat{\bar{l}}_i \hat{Q}_j \hat{d}^c_k + \lambda_{ijk} \hat{\bar{l}}_i \hat{\bar{l}}_j \hat{e}^c_k + \lambda_j \nu^c_j \hat{H}_u \hat{\bar{H}}_d + \kappa_{ijk} \nu^c_i \nu^c_j \nu^c_k \]

- By construction, SUSY produces fast proton decay

unless e.g. \( \lambda''_{imk} \lambda'_{1lk} \lesssim 10^{-25} \)

\( \langle \tilde{\nu}_i \rangle \sim \text{TeV} \)

Lopez-Fogliani, C. M., PRL 2006

\[ \mu \nu \text{SSM} \]
To conserve $B$ and $L$ number, one can impose by hand a discrete symmetry (R parity)

Particle $\longrightarrow$ Particle
Sparticle $\longrightarrow$ $-$ Sparticle

i.e. sparticles must appear in pairs

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:

$$\frac{1}{\Lambda}
( k_{ijkl} \hat{Q}_i \hat{Q}_j \hat{Q}_k \hat{L}_l + k'_{ijkl} \hat{u}_i^c \hat{u}_j^c \hat{d}_k^c \hat{e}_l^c ) \quad \Lambda \sim 10^{-19} \text{GeV} \quad \rightarrow \quad k_{112l} \sim 10^{-7}$$
\[ W = \epsilon_{ab} \left( Y^{ij}_{u} \hat{H}^b_u \hat{Q}^a_i \hat{\bar{u}}^c_j + Y^{ij}_{d} \hat{H}^b_d \hat{Q}^b_i \hat{\bar{d}}^c_j + Y^{ij}_{e} \hat{H}^a_d \hat{L}^b_i \hat{\bar{e}}^c_j + Y^{ij}_{\nu} \hat{\nu}^c_j \hat{H}^b_u \hat{\bar{L}}^a_i \right) + \]

\[ \lambda''_{ijk} \hat{u}^c_i \hat{d}^c_j \hat{d}^c_k + \lambda'_{ijk} \hat{\bar{L}}^i \hat{\bar{Q}}^j \hat{d}^c_k + \lambda_{ijk} \hat{\bar{L}}^i \hat{\bar{L}}^j \hat{e}^c_k + \lambda_j \hat{\nu}^c_j \hat{H}^b_u \hat{\bar{H}}^c_d + \kappa_{ijk} \hat{\nu}^c_i \hat{\nu}^c_j \hat{\nu}^c_k \]

But the choice of R-parity is \textit{ad hoc}.

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

\textit{e.g.} \( Z_3 \) Baryon parity forbids only the \textit{B number violating operator}

\[ (\hat{Q}, \hat{\bar{u}}^c, \hat{\bar{d}}^c) \longrightarrow (\hat{Q}, \hat{\bar{u}}^c, \hat{\bar{d}}^c) \]

\[ (\hat{L}, \hat{e}^c, \hat{H}^c_d, \hat{H}^c_u, \hat{\nu}^c) \longrightarrow (\hat{L}, \hat{e}^c, \hat{H}^c_d, \hat{H}^c_u, \hat{\nu}^c) \]

The only “discrete gauge” anomaly free symmetry that also forbids the D=5 operators \( \text{Ibáñez, Ross, 91} \)

\textit{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)

\( \text{Casas, C.M., PLB 1988} \)

\( \text{Font, Ibáñez, Nilles, Quevedo, PLB 1988} \)
**NMSSM limit**

\[ \mathbf{Y_v} \rightarrow 0 \quad \mathbf{\nu^c} \text{ are ordinary singlets with } \langle \tilde{\nu}_i^c \rangle \sim \text{TeV} \]

and R-parity is conserved (in the limit \( \lambda'_{ijk} = \lambda_{ijk} = 0 \))

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

\[ + \lambda'_{ijk} \hat{L}_i^j \hat{Q}_d^k + \lambda_{ijk} \hat{L}_i^j \hat{L}_j^k \hat{e}^c \]

But if \( \mathbf{Y_v} \lesssim 10^{-6} \) of the order of the electron Yukawa

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

\( \text{RPV, which is driven by } \mathbf{Y_v} \lesssim 10^{-6}, \text{ is then small in the } \mu \nu\text{SSM} \)

\[ \text{solves the } \nu \text{ problem: How to accommodate the neutrino data} \]

\[ \text{solves the } \mu \text{ problem: What is the origin of } \mu \ll M_{\text{Planck}} \]

\[ \text{No ad-hoc scales: Only the EW scale generated by soft terms} \]

\( \text{TRpV do not introduce modifications in our analyses of the } \mu \text{ and } \nu \text{ problems (might modify the phenomenology)} \)
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 $\mu \nu$SSM 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:

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

Concerning $\mu\nu$SSM 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 \( \mu \nuSSM \)

**neutrino physics** drives their VEVs to small values

\[ \nu_i \sim Y_\nu \nu_u \lesssim 10^{-6} \times 10^2 = 10^{-4} \text{ GeV} \]

Their masses are essentially determined by the soft masses:

\[ m^2_{\tilde{\nu}_i} = - A_\nu Y_{\nu_i} \nu_u + \ldots \]

\[ m^2_{\tilde{\nu}_i} = \frac{Y_{\nu_i} \nu_u}{\nu_i} \nu_R ( - A_\nu + \ldots ) \]

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

\[ m_{\tilde{\tau}} \sim 100 \text{ GeV} \]
\[ M_{\tilde{\nu}_e, \mu} \sim 1000 \text{ GeV} \]

*e.g. the hierarchy* \( Y_{\nu_3} \sim 10^{-8} - 10^{-7} < Y_{\nu_1,2} \sim 10^{-6} \)

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

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

Carlos Muñoz
UAM & IFT

\[ \mu \nuSSM \]
Bound on the mass of a **tau left sneutrino LSP** from LHC data?

(in the $\mu\nu$SSM)

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

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

Stau is the natural NLSP

Main decay channels are:

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

Decays are controlled by the neutrino seesaw

$$m_{\widetilde{\nu}_\tau} \sim 45 - 100 \text{ GeV} \quad \text{have decay lengths} \quad \sim \text{ mm}$$

**DISPLACED**
There are at present no experimental analyses focused on the $\mu\nu$SSM

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

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

Carlos Muñoz
UAM & IFT

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

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

$\mu\nu$SSM
ATLAS analysis requires high thresholds for lepton momenta. Triggers do not utilize the tracking information:

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

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

To analyze better the events with $\mu\mu/e\mu$ 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: $\text{mu24i}$ (ATLAS collaboration EPJC 75, 2015)

- At least one $\mu$- 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 $\mu$- with $p_T > 26$ GeV allowing the detection of events with ee pairs

$$
\#\text{Dimuons} = \left[ \sigma(pp \rightarrow Z \rightarrow \tilde{\nu}_T \tilde{\nu}_T) \epsilon^Z_{\text{sel}} + \sigma(pp \rightarrow W \rightarrow \tilde{\nu}_T \tilde{\nu}_T) \epsilon^W_{\text{sel}} + \sigma(pp \rightarrow \gamma, Z \rightarrow \tilde{\nu}\tilde{\nu}) \epsilon_{\gamma Z} \right] \times \mathcal{L} \times \left[ \text{BR}(\tilde{\nu}_T \rightarrow \mu\mu) \, \epsilon_{\text{vert}}^{\mu\mu}(cT_R) + \text{BR}(\tilde{\nu}_T \rightarrow \mu\mu) \, \epsilon_{\text{vert}}^{\mu\mu}(cT_L) \right].
$$
Scans using Multinest algorithm as optimizer, searching for points reproducing the current experimental data on:

- **Neutrino physics**
  
  \[
  \sin^2 \theta_{12,13,23} = 0.275-0.35, 0.02045-0.02439, 0.418-0.627 \\
  \Delta m^2_{21,31} = (6.79-8.01) \times 10^{-5}, (2.427-2.625) \times 10^{-3} \text{ eV}^2
  \]

- **Higgs physics** interfaced with HiggsBounds & HiggsSignals

- **Flavor observables**
  
  \(b \rightarrow s\gamma, B \rightarrow \mu\mu, \mu \rightarrow e\gamma, \mu \rightarrow eee\)

  To compute the spectrum and observables SARAH is used to generate a SPheno version of the \(\mu\nu\text{SSM}\)

  Samples of simulated events are generated using MadGraph and PYTHIA
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

$$\Gamma (\tilde{\nu}_\tau \to \tau \ell) \approx \frac{m_{\tilde{\nu}_\tau}}{16\pi} \left( \frac{Y_{\nu_\tau}}{3\lambda} \right)^2.$$
All points (blue&red) fulfill the exp. data with
\[ m_{\tilde{\nu}_\tau} \in (45 - 100) \text{ GeV} \]

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

No points of the $\mu\nu$SSM 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 $\mu\mu$, $\mu e$, $ee$ producing a sufficient number of displaced dilepton events

BRs smaller for $S_2$ because $\lambda$ is larger, $\tan \beta$ smaller, $Y_{\nu_2}$ smaller

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

\[ M_2 \in (169-1431) \text{ GeV} \]
Summarizing:

Red points can be probed at LHC run 3 with:

\[ M_2 = (2g'^2 + g^2)M \]

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

We thus highly motivate both the ATLAS and CMS collaborations to take account of this option of optimizing the triggers seriously.
We have discussed a realistic SUSY model, the $\mu\nu$SSM:

- Solves the $\mu$ problem
- Accommodates easily the $\nu$ 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 multi-Higgses – 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 $\mu\nu$SSM.

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, …