Search for electroweak superpartners in events with multi-leptons.

based on I.L, D. E. Lopez-Fogliani, C. Munoz (1810.xxxxx)

Iñaki Lara Pérez

Universidad Autónoma de Madrid
Instituto de Física Teórica

CPAN days - Salamanca

The $\mu\nu SSM$

Supersymetric Standard Model +Three right handed neutrino superfields:

$$W = W_{MSSM_{\mu=0}} \underbrace{+ Y_\nu^{ij} \hat{H}_u^b \hat{L}_i^a \hat{\nu}_j^c - \epsilon_{ab} \lambda_i \hat{\nu}_i^c \hat{H}_d^a \hat{H}_u^b + \frac{1}{3} \kappa^{ijk} \hat{\nu}_i^c \hat{\nu}_j^c \hat{\nu}_k^c}_{\mu\nu SSM}.$$

After EWSB v_d, v_u, v_{iR} and v_{iL} acquire vevs:

- ⋆ Coupling to Higgs superfields ⇒ Effective μ-term $\mu^{eff} = \lambda_i v_{iR}$
- ⋆ Coupling to Left handed lepton superfields ⇒ Dirac mass for neutrinos $\left(m_D^{eff}\right)_{ij} = \frac{1}{\sqrt{2}} Y_{\nu_{ij}} v_2$
- ⋆ Majorana mass for right handed neutrinos $\left(M_M^{eff}\right)_{ij} = \sqrt{2} \kappa_{ijk} v_{jR}$

These couplings breaks R-parity explicitly ⇒ LSP unstable. (When $Y_\nu^{ij} \to 0$ is restored.)
Neutrino mass ⇒ Electroweak scale Type-I seesaw with $Y_{\nu_{ij}} \sim 10^{-6}$.

$$m_\nu = \frac{1}{4 M_{\text{eff}}} \sum_i \left[v_i^2 + v_d \left(\frac{2 v_i Y_{\nu_i}}{\lambda} + \frac{v_d Y_{\nu_i}^2}{\lambda^2} \right) \right], with \frac{1}{M} \approx \frac{g'^2}{M_1} + \frac{g^2}{M_2}. \qquad (1)$$

Bino-Like Neutralino phenomenology

- Tree-level mass is approximately the bino soft mass (M_1).
- Production crossection of a Bino-dominated neutralino pair is very small. If squarks not light.
- If $\tilde{\chi}^0$ is the LSP, it decays to SM particles through Y_ν / v_l suppresed channels.

Assuming $\lambda \sim \kappa \sim 0{,}2$ and masses above 125 GeV, the dominant decay channels:

$$\Gamma\left(\tilde{\chi}^0 \to \ell W\right) \approx \frac{g_2^2 m_{\tilde{\chi}^0}}{16\pi}\left(1-\frac{m_W^2}{m_{\tilde{\chi}^0}^2}\right)^2\left(1+\frac{m_{\tilde{\chi}^0}^2}{2m_W^2}\right)\left|U^V_{\tilde{B}\nu_i}\right|.$$

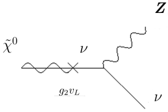
$$\Gamma\left(\tilde{\chi}^0 \to \nu Z\right) \approx \frac{g_2^2 m_{\tilde{\chi}^0}}{16\pi\cos^2\theta_W}\left(1-\frac{m_Z^2}{m_{\tilde{\chi}^0}^2}\right)^2\left(1+\frac{m_{\tilde{\chi}^0}^2}{2m_Z^2}\right)\left|U^V_{\tilde{B}\nu_i}\right|.$$

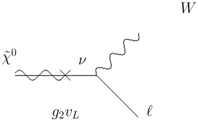
$$\Gamma\left(\tilde{\chi}^0 \to \nu h\right) \approx \frac{g_1^2 m_{\tilde{\chi}^0}}{64\pi}\sqrt{1-\left(\frac{m_h}{m_{\tilde{\chi}^0}}\right)^2}\left|Z^H_{\tilde{\nu}h}\right|.$$

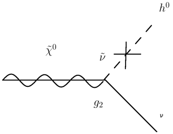
Bino-Like Neutralino phenomenology

Mixings between SM particles and sparticles proportional to Y_ν/v_{Li}.$\rightarrow$ Can be approximated using mass-insertion aproximation.

- $U^V_{\tilde{B}\nu_i} \sim \frac{g_1 v_{Li}}{M_1}$
- $Z^H_{\tilde{\nu}h} \sim \frac{m^2_{H_u^{\mathcal{R}}\tilde{\nu}_i^{\mathcal{R}}}}{m^2_{\tilde{\nu}_i}}$







If $m_{\tilde{\nu}} \sim m_h$ the mixing can be enhanced!

Low bino soft mass enhance decays to gauge bosons of the bino-like neutralino.

Total Width $\sim 10^{-12}$ GeV $\rightarrow$ $c\tau$ 0,1 mm

If $m^0_{\tilde{\chi}} \lesssim m_W$ three-body decays through off-shell gauge bosons dominate decays.$\rightarrow$ DISPLACED VERTICES.

Small number of neutralino pairs expected to be directly produced at LHC.$\rightarrow$ Neutralinos can be produced in the decay of heavier SUSY particles.

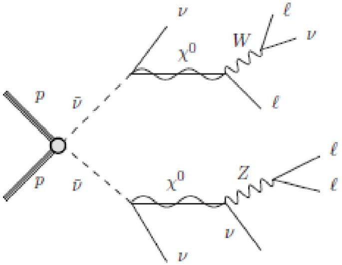
Light Sneurinos and Sleptons can be a source of neutralino pairs.
Crossections of the order 300fb if $m_{\tilde{\nu}} \sim 100$ GeV.
Tree-level mass is approximately:

$$m^2_{\widetilde{\nu}^{\mathcal{I}}_i \widetilde{\nu}^{\mathcal{I}}_i} \approx \frac{Y_\nu v_u}{v_{iL}} v_R \left(-A_\nu - \kappa v_R + \frac{\lambda v_R}{\tan\beta} \right),$$

CP-odd/even degenerate, and Sleptons slightly more massive $-m_W^2 \cos 2\beta$.
$A_\nu \sim 100$ GeV predicts $m_{\tilde{\nu}} \sim 100$ GeV.
Sparticle RPC decays dominate always over RPV due to small RPV in the $\mu\nu SSM$.

$$\tilde{\nu} \rightarrow \tilde{\chi}^0 \nu \qquad \& \qquad \tilde{\ell} \rightarrow \tilde{\chi}^0 \ell$$

Pair production of sneutrinos/sleptons decaying to a neutralino LSP lead to events with multiple leptons in final state.



Sneutrino/Slepton crossection drop fast (200 GeV slepton $\rightarrow\sim$ 20fb).
Neutralino mass has to be above m_W to decay promptly.$\Rightarrow$ In the region of the parameter space accesible with LHC searches for electroweak partners in events with multiple propmt leptons the neutralino-sneutrino/slepton system is quite compressed.

Alternative: Use ATLAS searches for compressed chargino-neutralino system on RPC MSSM.

CERN-EP-2018-113 $\rightarrow$ Events with two or three leptons originated from gauge bosons + Use of "Jigsaw Reconstruction Techniques" to separate from backgrounds. Use the SR designed for compressed spectra ($S\ell3$_ISR. and $S\ell2$_ISR.).
Same selection requirements aplied to:

- Sneutrino/Slepton production as NLSP. Bino-like neutralino LSP
- Three families of sleptons degenerated.
- $m_{\tilde{\chi}^0} \lesssim m_{\tilde{\nu}} \in (100, 200)$ GeV.

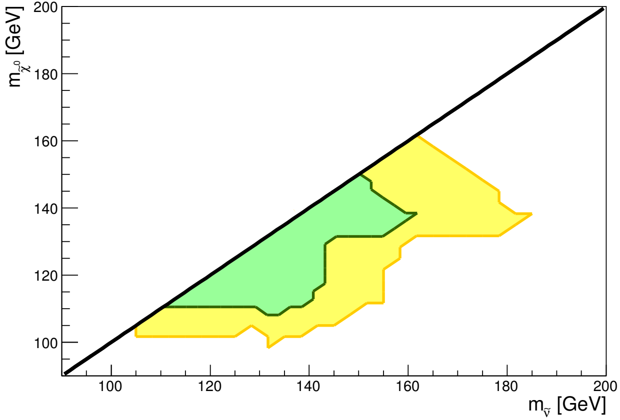
Events generated using `MadGraph5_aMC@NLO v2.6.3.2` at LO + crossection at NLO+NLL using `Resummino v2.01`. Events pased to `PYTHIA v8.201` for showering and hadronization and `DELPHES v3.3.3` for detector simulation.

Maximum Yield is obtained around $m_{\tilde{\chi}^0} \in (110, 120)$ and $m_{\tilde{\nu}} \in (120, 140)$, with a number of events expected in Sℓ3_ISR of ~ 5.

$m_{\tilde{\chi}^0}$	120.2	$m_{\tilde{\nu}}$	125.2	$m_{\tilde{\ell}_L}$	145.1
BR($\tilde{l}_{Li} \to l_i \tilde{\chi}^0$)	1	BR($\tilde{\nu}_i \to \nu \tilde{\chi}^0$)	1	BR($\tilde{\chi}^0 \to e/\mu W$)	$3{,}5 \times 10^{-1}$
BR($\tilde{\chi}^0 \to \tau W$)	$2{,}9 \times 10^{-2}$	BR($\tilde{\chi}^0 \to \nu Z$)	$2{,}4 \times 10^{-1}$	$\Gamma_{\tilde{\chi}^0}$	$1{,}28 \times 10^{-12}$
$\sigma(pp \to \tilde{\nu}\tilde{\nu})$	143.75	$\sigma(pp \to \tilde{\nu}\tilde{\ell}_L)$	276.32	$\sigma(pp \to \tilde{\ell}_L\tilde{\ell}_L)$	80.94

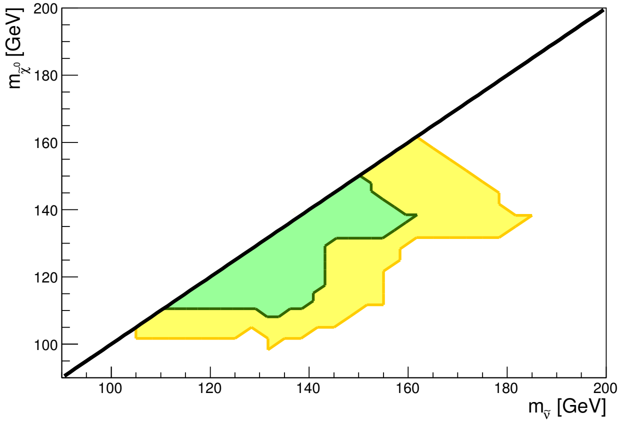
The number of events expeced is below the expected ($S^{95}_{exp}= 6{,}9^{+3{,}1}_{-2{,}2}$) limit for all points. Moreover, the observed limit ($S^{95}_{obs}= 15{,}3$) is significanlty larger than the expected due to $\sim$ 3 sigma local excess.

Assuming the excess will disapear with more luminosity, we scale the expected limits to calculate prospect limits on the sneutrino-neutralino pair:



Green region correspond to 100fb^{-1} and yellow area to 300fb^{-1}.
Potential exclusion up to 160 GeV for 100fb^{-1} and 185 GeV for 300fb^{-1}.

Limits could be complemented with other multilepton searches.



- Searches for displaced multileptons for $m_{\tilde{\chi}^0} < m_W$
- Searches for more than three leptons and moderate MET in region $m_{\tilde{\chi}^0} \ll m_{\tilde{\nu}}$

Conclusions.

- Bino-like neutralino LPS in the $\mu\nu SSM$ with masses above m_W decay mainly involving gauge bosons, with prompt decays.
- Small pair-production crossection makes direct production searches unpromising.
- Production through the decay of light sneutrinos/sleptons can yield a measurable number of multileptons events.
- Recasting of searches for electroweak superpartners in compressed scenarios can be used to test the sneutrino/slepton-neutralino system.$\rightarrow$ No limits form current analysis.
- Future updates with 100fb^{-1} and 300fb^{-1} could put bounds to sneutrino mass.
- Complementary searches with displaced multilepton events to cover low neutralino mass.

Thank you for your time!

SUSY with broken R-parity

R-parity is proposed to protect proton from fast decay. $\Rightarrow$ Implies stable LSP and Missing transverse momentum signal at LHC.

$\star$ There are dimension-five operators permited by R-parity which lead to proton decay:

$$\mathcal{O}_5 = \frac{\bar{u}\bar{u}\bar{d}e}{M}$$
$$\mathcal{O}_5 = \frac{QQQL}{M}$$

$\star$ There are alternatives to R-parity to prevent the proton to decay, such as *Proton Hexality* (equivalent at tree level to R-parity) or *Barion Triality* (Allows only for $\not{L}$). L.E. Ibáñez and G. Ross, Nucl. Phys. B 368, 3 (1992).H.K. Dreiner, C. Luhn and M. Thormeier, Phys. Rev. D 73, 075007 (2006)

R-parity violation is motivated in models explaining neutrino physics such as BRpV or $\mu\nu SSM$. Signatures at colliders are completely different.

The $\mu\nu SSM$ Lagrangian

$$W = W_{MSSM_{\mu=0}} \underbrace{+ Y_\nu^{ij} \hat{H}_u^b \hat{L}_i^a \hat{\nu}_j^c - \epsilon_{ab} \lambda_i \hat{\nu}_i^c \hat{H}_d^a \hat{H}_u^b + \frac{1}{3} \kappa^{ijk} \hat{\nu}_i^c \hat{\nu}_j^c \hat{\nu}_k^c .}_{\mu\nu MSSM}$$

⋆ In the limit $Y_\nu^{ij} \to 0$, R-parity is restored.
⋆ We assume a soft-breaking sector with a structure inspired by SUGRA models with diagonal Kähler metric:

$$T_{\lambda_i} = A_{\lambda_i} \lambda_i ; T_{\kappa_{ijk}} = A_{\kappa_{ijk}} \kappa_{ijk} ; T_\nu^{ij} = A_\nu Y_\nu^{ij}$$
$$T_u^{ij} = A_u Y_u^{ij}; \quad T_d^{ij} = A_d Y_d^{ij}; \quad T_e^{ij} = A_e Y_e^{ij}$$

We also assume no intergenerational mixing in the trilinear terms, neither in the squared sfermion mass matrices.

Scalar potential

The scalar potential receives contributions from F-terms, D-Terms and soft terms, mixing all neutral scalar states:

$$V^{(0)} = V_{soft} + V_D + V_F$$

With the choice of CP conservation, one can define the neutral scalars as:

$$H_1^0 = \frac{1}{\sqrt{2}}(\phi_1 + v_1 + i\sigma_1)$$

$$H_2^0 = \frac{1}{\sqrt{2}}(\phi_2 + v_2 + i\sigma_2)$$

$$\widetilde{\nu}_{iR} = \frac{1}{\sqrt{2}}(\phi_{iR} + v_{IR} + i\sigma_{iR})$$

$$\widetilde{\nu}_{iL} = \frac{1}{\sqrt{2}}(\phi_{iL} + v_{IL} + i\sigma_{iL})$$

After EWSB,all of them can develop real VEVs

$$\langle H_1 \rangle = \frac{v_1}{\sqrt{2}}, \langle H_2 \rangle = \frac{v_2}{\sqrt{2}}, \langle \widetilde{\nu}_{iR} \rangle = \frac{v_{iR}}{\sqrt{2}}, \langle \widetilde{\nu}_{iL} \rangle = \frac{v_{iL}}{\sqrt{2}}$$

However spontaneus CP violation is possible with all parameters real.

J.Fidalgo, D.López-Fogliani, C.Muñoz, R.R.de Austri JHEP 08 (2009) 105

Minimization equations

$$m^2_{H_d} = -\frac{1}{4} G^2 \left(v_{iL} v_{iL} + v_d^2 - v_u^2 \right) - \lambda_i \lambda_j v_{iR} v_{jR} - \lambda_i \lambda_i v_u^2$$
$$+ v_{iR} \tan\beta \left(T_{\lambda_i} + \lambda_j \kappa_{ijk} v_{kR} \right) + Y_{\nu_{ij}} \frac{v_{iL}}{v_d} \left(\lambda_k v_{kR} v_{jR} + \lambda_j v_u^2 \right) - \frac{1}{v_d} V^{(n)}_{v_d} , \quad (2)$$

$$m^2_{H_u} = \frac{1}{4} G^2 \left(v_{iL} v_{iL} + v_d^2 - v_u^2 \right) - \lambda_i \lambda_j v_{iR} v_{jR} - \lambda_j \lambda_j v_d^2$$
$$+ 2\lambda_j Y_{\nu_{ij}} v_{iL} v_d - Y_{\nu_{ij}} Y_{\nu_{ik}} v_{kR} v_{jR} - Y_{\nu_{ij}} Y_{\nu_{kj}} v_{iL} v_{kL}$$
$$+ v_{iR} \frac{1}{\tan\beta} \left(T_{\lambda_i} + \lambda_j \kappa_{ijk} v_{kR} \right) - \frac{v_{iL}}{v_u} \left(T_{\nu_{ij}} v_{jR} + Y_{\nu_{ij}} \kappa_{ljk} v_{lR} v_{kR} \right) - \frac{1}{v_u} V^{(n)}_{v_u} , \quad (3)$$

$$m^2_{\widetilde{\nu}^c_{ij}} v_{jR} = -T_{\nu_{ji}} v_{jL} v_u + T_{\lambda_i} v_u v_d - T_{\kappa_{ijk}} v_{jR} v_{kR} - \lambda_i \lambda_j \left(v_u^2 + v_d^2 \right) v_{jR} + 2\lambda_j \kappa_{ijk} v_d v_u v_{kR}$$
$$- 2\kappa_{lim} \kappa_{ljk} v_{mR} v_{jR} v_{kR} + Y_{\nu_{ji}} \lambda_k v_{jL} v_{kR} v_d + Y_{\nu_{kj}} \lambda_i v_d v_{kL} v_{jR} - 2 Y_{\nu_{jk}} \kappa_{ikl} v_u v_{jL} v_{lR}$$
$$- Y_{\nu_{ji}} Y_{\nu_{lk}} v_{jL} v_{\nu_l} v_{kR} - Y_{\nu_{ki}} Y_{\nu_{kj}} v_u^2 v_{jR} - V^{(n)}_{v_{iR}} , \quad (4)$$

$$m^2_{\widetilde{L}_{ij}} v_{jL} = -\frac{1}{4} G^2 \left(v_{jL} v_{jL} + v_d^2 - v_u^2 \right) v_{iL} - T_{\nu_{ij}} v_u v_{jR} + Y_{\nu_{ij}} \lambda_k v_d v_{jR} v_{kR} + Y_{\nu_{ij}} \lambda_j v_u^2 v_d$$
$$- Y_{\nu_{il}} \kappa_{ljk} v_u v_{jR} v_{kR} - Y_{\nu_{ij}} Y_{\nu_{lk}} v_{\nu_l} v_{jR} v_{kR} - Y_{\nu_{ik}} Y_{\nu_{jk}} v_u^2 v_{jR} - V^{(n)}_{v_{iL}} . \quad (5)$$

One can see that the vevs v_{iR} are naturally around M_{SUSY}. While from Eq.4, when $Y^{ij}_{\nu} \to 0$ then $v_{iL} \to 0$, and we can estimate $v_{iL} \sim Y^{ii}_{\nu} v_2$.

The $\mu\nu SSM$ seesaw .

$$\mathcal{M}_n = \begin{pmatrix} M & m \\ m^T & 0_{3\times 3} \end{pmatrix}, \qquad \begin{array}{l} M \to M_1, M_2, \lambda_i v_{iR}, \sqrt{2}\kappa_{ijk} v_{jR} \sim \mathcal{O}(M_{SUSY}) \\ m \sim Y_\nu^{ii} v_u \end{array}$$

At first approximation $m_{eff} = -m^T \cdot M^{-1} \cdot m$ and one can diagonalize as $U_{MNS}^T m_{eff} U_{MNS} = diag(m_1, m_2, m_3)$. Approximately:

$$(m_{eff\,|\,real})_{ij} \simeq \frac{v_u^2}{6\kappa v_R} Y_{\nu_i} Y_{\nu_j} \left(1 - 3\,\delta_{ij}\right) - \frac{1}{2M_{eff}} \left[v_{iL} v_{jL} + \frac{v_d \left(Y_{\nu_i}\nu_j + Y_{\nu_j}\nu_i\right)}{3\lambda} + \frac{Y_{\nu_i} Y_{\nu_j} v_d^2}{9\lambda^2} \right] ,$$

In the limit of heavy gauginos $M \to \infty$:

$$(m_{eff\,|\,real})_{ij} \simeq \frac{v_u^2}{6\,\kappa v_R} Y_{\nu_i} Y_{\nu_j} \left(1 - 3\,\delta_{ij}\right).$$

In the limit of heavy singlinos $v_{iR} \to \infty$ and large $\tan\beta$:

$$(m_{eff\,|\,real})_{ij} \simeq -\frac{v_{iL} v_{jL}}{2M}.$$

⋆ Is possible to reproduce neutrino physics with diagonal Yukawa couplings.

Constraints on trilinear+bilinear

After EWSB effective terms are generated:

Trilinear terms

- $\lambda_{ijk} \sim Y_{\nu_{ii}} \kappa \frac{m_{l_{jk}}}{v} \frac{(1-\delta_{ij})\delta_{jk}}{\sqrt{1+\tan^2\beta}} \lesssim 2 \times 10^{-10}$ for $j = k = 3$
- $\lambda'_{ijk} \sim Y_{\nu_{ii}} \kappa \frac{m_{d_{jk}}}{v} \frac{\delta_{jk}}{\sqrt{1+\tan^2\beta}} \lesssim 2 \times 10^{-10}$ for $j = k = 3$

Bilinear

- $\epsilon_i^{eff} \sim Y_{\nu_{ij}} v_{jR} \lesssim 2 \times 10^{-3}$ GeV for $i = j = 3$

Experimental constraints form Cosmology, Colliders and Flavour physics are:

- *R-parity* $\lesssim \mathcal{O}(10^{-20}) \Rightarrow$ DM candidate.
- $\mathcal{O}(10^{-20}) \lesssim$ *R-parity* $\lesssim \mathcal{O}(10^{-12}) \Rightarrow$ Ruled out (Interference with Big-bang nucleosynthesis).
- $\mathcal{O}(10^{-12}) \lesssim$ *R-parity* $\lesssim \mathcal{O}(10^{-9}) \Rightarrow$ Decay outside detector (E_T^{miss}).

Stringest constraints (with $m_Soft \sim 1$TeV) over:

- $|\lambda^*_{ij2}\lambda_{ij1}| \lesssim 8.2\times10^{-5}$ [$\mu \to e\gamma$].
- $|\lambda^*_{i12}\lambda_{i11}| \lesssim 6.6\times10^{-7}$ [$\mu \to 3e$].
- $|\lambda^*_{i12}\lambda'_{i12}| \lesssim 6\times10^{-9}$ [$K_L \to e\mu$].
- $|\lambda'^*_{i21}\lambda'_{i12}| \lesssim 4.5\times10^{-9}$ [$K\bar{K}$].
- $|\lambda'^*_{i31}\lambda'_{i13}| \lesssim 3.3\times10^{-8}$ [$B\bar{B}$].
- $|\lambda'^*_{ij1}\lambda'_{2j2}| \lesssim 3\times10^{-7}$ [$K_L \to e\mu$].

Z_3 Symmetric superpotential

⋆ If a discrete Z_3 symmetry is imposed to the superpotential, to avoid dimensionful parameters ⇒ After EWSB Domain walls are generated which can dominate the energy density of the universe, producing large anisotropies on the CMB

⋆ If Z_3 is an accidental symmetry ⇒ Nonrenormalizable interactions lift the degeneracy between vacua

⋆ If the right handed neutrino superfields couple in the most general way to heavy fields ⇒Radiative corrections can induce very large terms in the effective action linear in $\hat{\nu}_R$

⋆ Impose R-symmetries in the nonrenormalizable lagrangian to allow only non-dangerous higher dimension terms

J. R. Ellis, K. Enqvist, D. V. Nanopoulos, K. A. Olive, M. Quiros and F. Zwirner,Phys. Lett. B176 (1986) 403.
B. Ray and G. Senjanovic, Phys. Rev. D49 (1994)2729.
S. A. Abel, S. Sarkar and P. L. White, Nucl. Phys. B454 (1995) 663.
S. A. Abel, Nucl. Phys. B480 (1996) 55.
C. Panagiotakopoulos and K. Tamvakis, Phys. Lett. B446 (1999) 224

LFV

$\star$ Same QFV contraints as to the NMSSM apply to the $\mu\nu SSM$.
$\star$ The $\mu\nu SSM$ superpotential includes terms which break explicitly Lepton number conservation. $\Rightarrow$ Small violation:

- BR$(\mu \to e\gamma)_{\mu\nu SSM}$ =3.96$\times10^{-26}$ « BR$(\mu \to e\gamma)_{exp}$ <5.7$\times10^{-13}$
- BR$(\tau \to e\gamma)_{\mu\nu SSM}$ =2.23$\times10^{-28}$ « BR$(\tau \to e\gamma)_{exp}$ <3.3$\times10^{-8}$
- BR$(\tau \to \mu\gamma)_{\mu\nu SSM}$ =2.22$\times10^{-28}$ « BR$(\tau \to \mu\gamma)_{exp}$ <4.4$\times10^{-8}$
- BR$(\mu \to eee)_{\mu\nu SSM}$=1.0$\times10^{-26}$ « BR$(\mu \to eee)_{exp}$ <1.0$\times10^{-12}$
- BR$(\tau \to e\mu\mu)_{\mu\nu SSM}$=1.341$\times10^{-28}$« BR$(\tau \to e\mu\mu)_{exp}$ <4.4$\times10^{-8}$
- Limits on $\mu \to e$ conversion: $\mu\nu SSM \sim 10^{-26}$ « Exp Limits $\lesssim 10^{-11}$