Supersymmetry @ Low energy scales

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Contents

Introduction

- It has been established that there is strong evidence in favour of neutrino masses

- This is an indication of physics beyond the SM

- The most popular candidate for physics beyond the SM within the TeV scale is SUSY

- Question: Could SUSY also be responsible for neutrino masses ?

- It might also end up predicting specific experimental signals at high energy colliders

Introduction

Some of the ways in which SUSY can be of special significance to neutrino masses

- SUSY can provide new scales. Open up additional possibilities in the neutrino sector – helpful in explaning mass hierarchies

- Extended sparticle spectrum in SUSY can lead to mechanisms for mass generation, for example, through additional radiative effects

- Possibility of low-energy lepton number violation inbuilt in certain types of SUSY theories might lead to generation of Majorana masses

Neutrinos

- Experimental results on neutrinos $\Longrightarrow$ non-zero neutrino masses and mixing angles
- The data can be explained well with
  - $7.09 \times 10^{-5}\mathrm{eV}^2 \leq \Delta m^2_{21} \leq 8.19 \times 10^{-5}\mathrm{eV}^2,$
  - $2.14 \times 10^{-3}\mathrm{eV}^2 \leq \Delta m^2_{31} \leq 2.76 \times 10^{-3}\mathrm{eV}^2,$
  - $0.27 \leq \sin^2\theta_{12} \leq 0.36, \;\; 0.39 \leq \sin^2\theta_{23} \leq 0.64,$
  - $0.001 \leq \sin^2\theta_{13} \leq 0.035,$ $\Delta m^2_{ij} \equiv m^2_i - m^2_j$
- One needs to go to a theory beyond the SM
- SUSY predicts new particles at the TeV scale
- Tempting to see whether TeV scale SUSY can explain the observed pattern of neutrino masses and mixing

Neutrinos in SUSY

- In the MSSM, neutrinos are exactly massless

- Consider supersymmetric extension of an extended SM that contains Majorana neutrino masses

- In such models, the lepton number violation can generate interesting phenomena in the sector of supersymmetric leptons

- The effect of ΔL =2 operators is to introduce a mass splitting and mixing into the sneutrino-antisneutrino system

- Or ΔL = 1 operators (R-parity violating SUSY)

- LSP decays – intresting phenomenology at the LHC

Dirac masses – conserved lepton number

A term in the superpotential $W = Y_\nu \hat{L}\hat{\nu}^c H_u$

$$\Longrightarrow m_\nu \sim Y_\nu \langle H_u \rangle$$

$m_\nu \sim 5 \times 10^{-2}$ eV $\Longrightarrow Y_\nu \sim 10^{-13}$ – very small

Small Y_ν from F-term SUSY breaking

Consider the operator: $\frac{1}{M^2} X^\dagger \hat{L}\hat{\nu}^c H_u$

$X \rightarrow$ hidden sector field

$$W = \frac{\langle F_X \rangle}{M^2} \hat{L}\hat{\nu}^c H_u \Longrightarrow Y_\nu \sim \frac{\langle F_X \rangle}{M^2} = \frac{\tilde{m}}{M}$$

$\tilde{m} \equiv \frac{F_X}{M} \rightarrow$ soft susy breaking mass parameter $\sim \mathcal{O}$ (TeV)

Neutrino mixing can be explained by assuming some flavor structure of Y_ν

Arkani-Hamed, Hall, Murayama, Smith, Weiner (2001); A. de Gouvea (2016)

ΔL=2 terms – Majorana masses

- If there is lepton number violation at a high scale M, it is possible to have ΔL = 2 neutrino mass terms via the dimension-5 operator

$$\mathcal{L}_5 = \frac{\lambda}{M} LLHH$$

Gives neutrino masses on the order of v^2/M

S. Weinberg, PRL **43**, 1566 (1979)

ΔL=2 Majorana masses – seesaw mechanism

- In the context of MSSM, supplement $\hat{\nu}_i$ (contained in $SU(2)_L$ doublet $\hat{L}_i$) with gauge singlet $\hat{\nu}^c_i$

$$\delta W = Y^{ij}_\nu \hat{H}_u \hat{L}_i \hat{\nu}^c_j + m^{ij}_M \hat{\nu}^c_i \hat{\nu}^c_j$$

- couplings Y_ν determine the Dirac masses for the neutrinos – $m_D \ll m_M$
- $m_M \rightarrow$ Majorana masses
- light neutrino masses $m_\nu \sim \frac{m^2_D}{m_M}$

$$Y_\nu \sim \mathcal{O}(1),\ m_M \sim 10^{15}\ \text{GeV} \Longrightarrow m_\nu \sim 10^{-2}\ \text{eV}$$

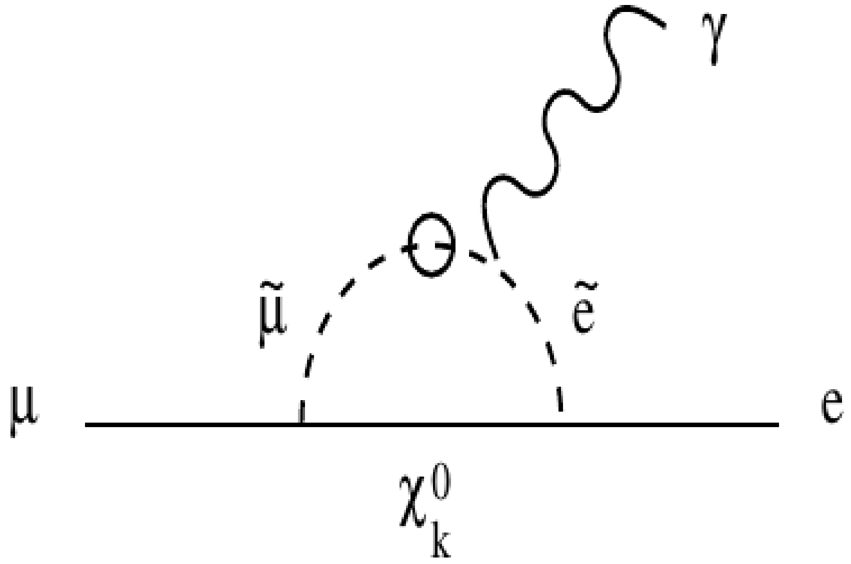
- Very interesting possibility in the context of the attempts to connect the SM with GUTS with $M_{GUT} \sim 10^{15}$ GeV

Charged lepton flavor violation in SUSY seesaw model

- Flavor changing right-handed neutrino Yukawa coupling

$\Longrightarrow$ Non-vanishing LFV slepton masses by radiative correction.

F. Borzumati and A. Masiero (1986)



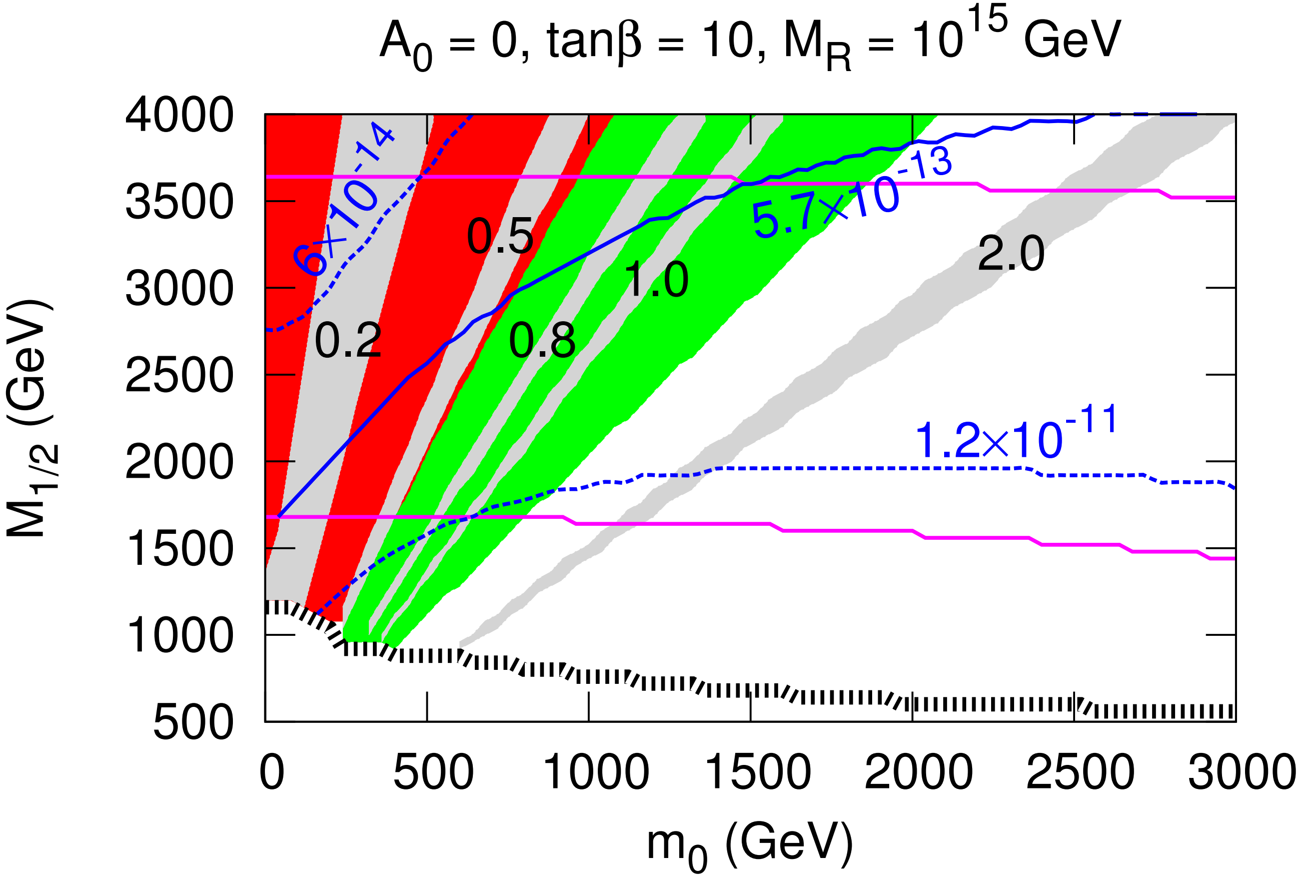
$\Longrightarrow$ LFV: $\tau \to \mu\gamma$, $\mu \to e\gamma$, ...may be detected in future

Slepton flavor mixing can be probed through $\tilde{l}_i \to l_j \chi^0_1$ decays

Abada et al. (2012), Ibarra, Roy (2007)

Charged lepton flavor violation in SUSY seesaw model

BR($\mu \to e\gamma$) $< 5.7 \times 10^{-13}$, BR($\tau \to \mu\gamma$) $< 4.4 \times 10^{-8}$,
BR($\tau \to e\gamma$) $< 3.3 \times 10^{-8}$. /



A.J.R Figueiredo, A.M. Teixeira, 1309.7951

Sneutrino mixing phenomena

- The effect of ΔL =2 operators is to introduce a mass splitting and mixing into the sneutrino-antisneutrino system

- Neutrino mass and sneutrino mass splitting are related as a consequence of the LNV interactions and SUSY breaking Grossman, Haber (1997); Hirsch *et al*, (1997)

Consider MSSM + one $\hat{\nu}^c$

$$\delta W = Y_\nu \hat{H}_u \hat{L} \hat{\nu}^c + \frac{1}{2} M \hat{\nu}^c \hat{\nu}^c - \mu \hat{H}_u \hat{H}_d$$

$$m_\nu \approx \frac{m_D^2}{M}$$

Grossman and Haber, PRL 79, 3438 (1997)
Davidson and King, PLB 445, (1998)191

Sneutrino mixing phenomena

$$V_{soft} = m^2_{\tilde{L}} \tilde{\nu}^* \tilde{\nu} + m^2_{\tilde{\nu}^c} \tilde{\nu}^{c*} \tilde{\nu}^c + (Y_\nu A_\nu H_u^0 \tilde{\nu} \tilde{\nu}^c + M B_N \tilde{\nu}^c \tilde{\nu}^c + H.c.)$$

- Define $\tilde{\nu} = (\tilde{\nu}_1 + i\tilde{\nu}_2)/\sqrt{2}$ and $\tilde{\nu}^c = (\tilde{\nu}^c_1 + i\tilde{\nu}^c_2)/\sqrt{2}$
- Two light sneutrino mass eigenstates $\tilde{\nu}_1$ and $\tilde{\nu}_2$ are split

$$\frac{\Delta m_{\tilde{\nu}}}{m_\nu} \approx \frac{2(A_\nu - \mu \cot\beta - B_N)}{m_{\tilde{\nu}}} \qquad [m_{\tilde{\nu}} \equiv \tfrac{1}{2}(m_{\tilde{\nu}_1} + m_{\tilde{\nu}_2})]$$

Assume μ, A_ν, and $m_{\tilde{\nu}}$ are all $\sim$ 100 GeV

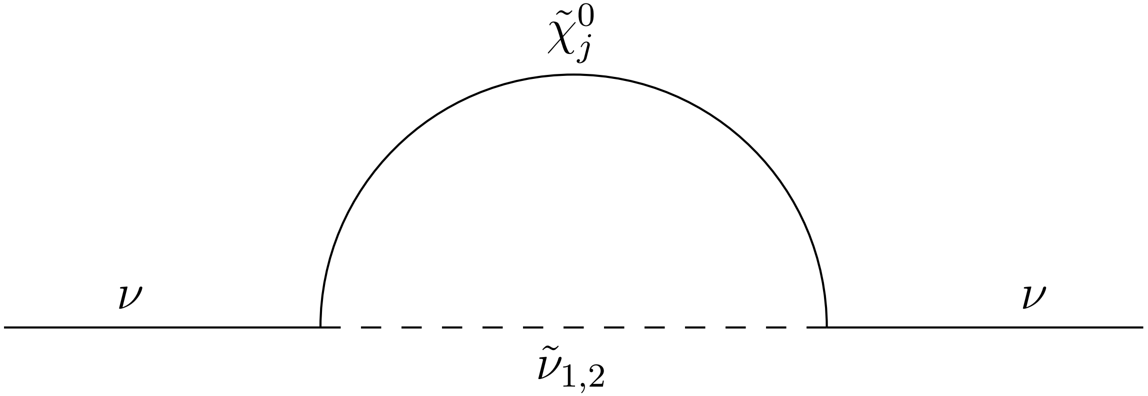
If $B_N \sim \mathcal{O}(m_Z)$, then $\frac{\Delta m_{\tilde{\nu}}}{m_\nu} \sim \mathcal{O}(1)$
If $B_N \gg m_Z$, sneutrino mass splitting is significantly enhanced.

Grossman and Haber, PRL 79, 3438 (1997)
Davidson and King, PLB 445, (1998)191

Loop effects

One-loop contribution to the neutrino mass due to sneutrino mass splitting

Grossman, Haber (1997); Hirsch *et al*, (1997)



Loop contribution $m_\nu^{(1)} \approx 10^{-3} \Delta m_{\tilde{\nu}}$

If $\Delta m_{\tilde{\nu}}/(m_\nu)^0 \gtrsim 10^3$, one-loop correction to the neutrino mass cannot be neglected

Loop effects

Assuming no unnatural cancellation

$$m_\nu = (m_\nu)^0 + (m_\nu)^1$$

Radiative corrections to $m_\nu \Longrightarrow \Delta m_{\tilde{\nu}}/m_\nu \lesssim \mathcal{O}(10^3)$

$$m_\nu \sim 0.1 \text{ eV} \Longrightarrow \Delta m_{\tilde{\nu}} \lesssim 0.1 \text{ keV}$$

Sneutrino-antisneutrino oscillation

- $\Delta m_{\tilde{\nu}}$ induces sneutrino-antisneutrino oscillation
- lepton number can be tagged by the charge of the final state lepton

Similar behaviour in the flavor oscillation of B^0–$\bar{B}^0$ system

At t = 0

$$|\tilde{\nu}\rangle = \frac{1}{\sqrt{2}}[|\tilde{\nu}_1\rangle + i|\tilde{\nu}_2\rangle]$$

The state at time t is

$$|\tilde{\nu}(t)\rangle = \frac{1}{\sqrt{2}}[e^{-i(m_1 - i\Gamma_{\tilde{\nu}}/2)t}|\tilde{\nu}_1\rangle + ie^{-i(m_2 - i\Gamma_{\tilde{\nu}}/2)t}|\tilde{\nu}_2\rangle]$$

Oscillation Probability Contd.

Probability of finding a “wrong-sign charged lepton”

$$P(\tilde{\nu} \to \ell^+) = \frac{x_{\tilde{\nu}}^2}{2(1+x_{\tilde{\nu}}^2)} \times B(\tilde{\nu}^* \to \ell^+)$$

$$P_{\tilde{\nu}\to\tilde{\nu}^*} = \frac{x_{\tilde{\nu}}^2}{2(1+x_{\tilde{\nu}}^2)} \qquad x_{\tilde{\nu}} \equiv \frac{\Delta m_{\tilde{\nu}}}{\Gamma_{\tilde{\nu}}}$$

$$x_{\tilde{\nu}} \sim 1 \Longrightarrow \Gamma_{\tilde{\nu}} \sim 0.1 \text{ keV}$$

Two-body decays – $\tilde{\nu} \to \nu\tilde{\chi}^0$ and/or $\tilde{\nu} \to \ell^-\tilde{\chi}^+$

Three-body decays – $\tilde{\nu} \to \ell^-\tilde{\tau}_1^+\nu_\tau$ and $\tilde{\nu} \to \nu\tilde{\tau}_1^\pm\tau^\mp$

$$m_{\tilde{\tau}_1} < m_{\tilde{\nu}} < m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_1^\pm}$$

Lepton charge asymmetry

- Number of negatively charged leptons (N_{l^-}) is proportional to $P(\tilde{\nu} \to \tilde{\nu})$
- Number of positively charged leptons (N_{l^+}) is proportional to $P(\tilde{\nu} \to \tilde{\nu}^*)$

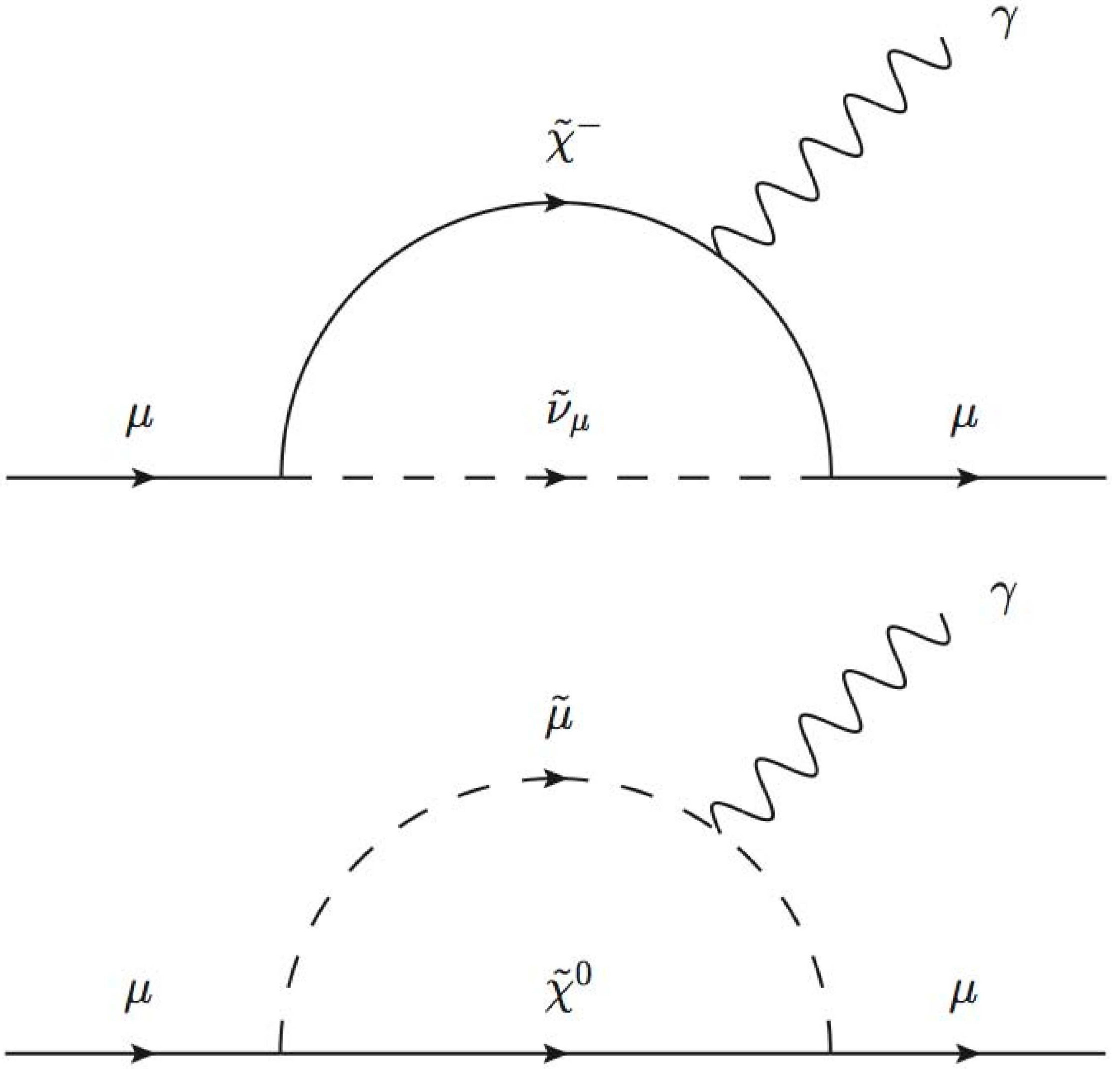
$$A_{asym} \equiv \frac{N_{l^-} - N_{l^+}}{N_{l^-} + N_{l^+}}$$

- At the LHC one can study this asymmetry through $pp \longrightarrow \tilde{\nu}_\tau \tilde{\tau}_1^+$

$$A_{asym} = P_{\tilde{\nu}_\tau \to \tilde{\nu}_\tau^*} - P_{\tilde{\nu}_\tau \to \tilde{\nu}_\tau}$$

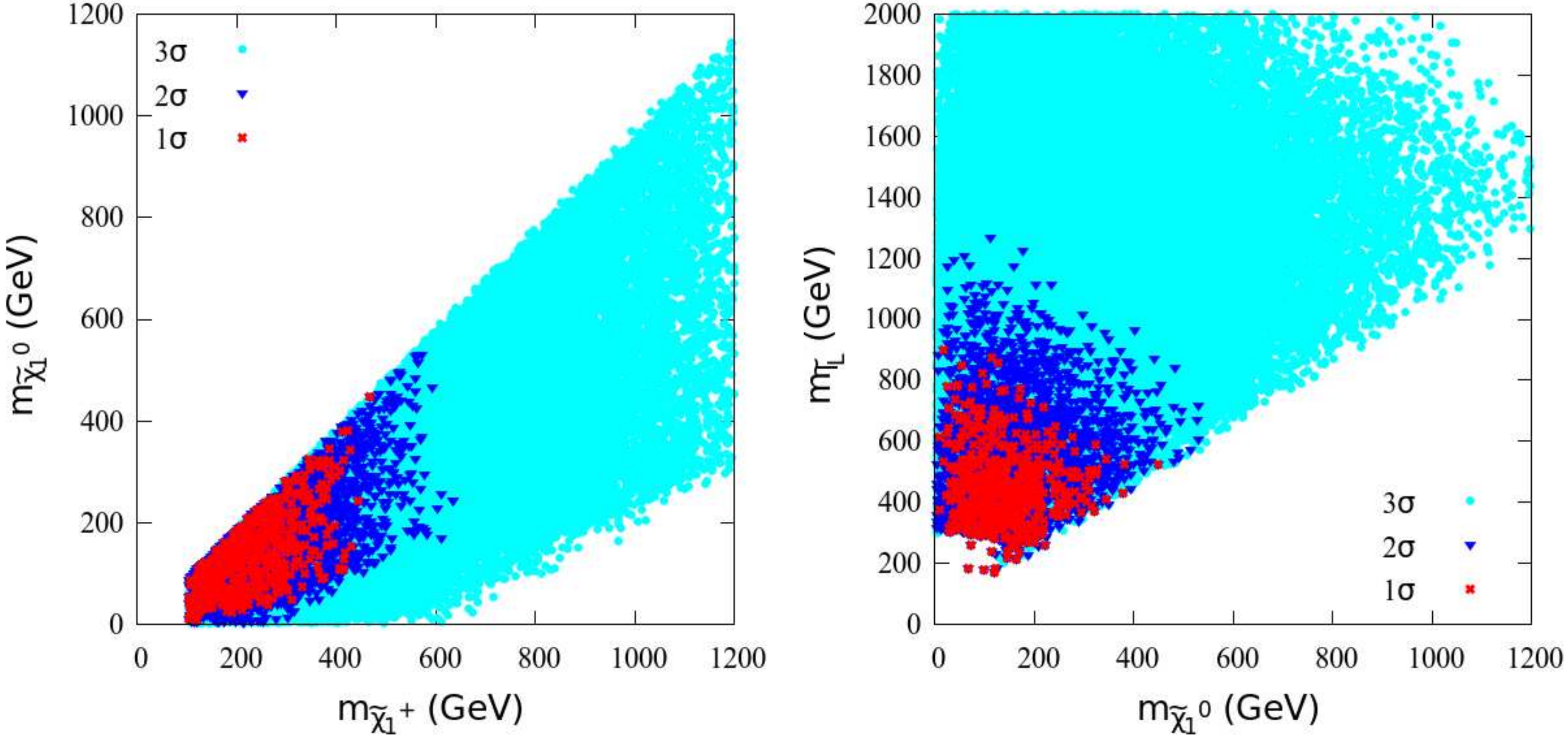
Elsayed et al. (2013)
Dedes, Haber, Rosiek(2008)
Ghosh, Honkavaara, Huitu, Roy (2008), (2010)

Muon $(g-2)$ and SUSY



Muon $(g-2)$ and SUSY

$$\Delta a_\mu = (29.3 \pm 9.0) \times 10^{-10}$$



A. Choudhury, S. Mondal, 1603.05502

For a more recent analysis, see, A. Kobakhidze, M. Talia, L. Wu, 1608.03641

MSSM with R-parity violation (ΔL =1)

- Neutrino masses in MSSM with RPV have been widely studied

$$R = (-1)^{3B+L+2s}$$

- $W = \epsilon_{ij}[-\mu_\alpha \hat{L}^i_\alpha \hat{H}^j_U + \frac{1}{2}\lambda_{\alpha\beta m}\hat{L}^i_\alpha \hat{L}^j_\beta \hat{E}_m + \lambda'_{\alpha nm}\hat{L}^i_\alpha \hat{Q}^j_n \hat{D}_m - h_{nm}\hat{H}^i_U \hat{Q}^j_n \hat{U}_m]$,

- It is not possible to distinguish between $\hat{H}_D$ and $\hat{L}_m$ $(m = 1, 2, 3)$

- Four supermultiplets by one symbol $\hat{L}_\alpha$ $(\alpha = 0, 1, 2, 3)$, with $\hat{L}_0 \equiv \hat{H}_D$

- $V_{\rm soft} = (M^2_{\widetilde{L}})_{\alpha\beta}\,\widetilde{L}^{i*}_\alpha \widetilde{L}^i_\beta - (\epsilon_{ij}B_\alpha \tilde{L}^i_\alpha H^j_U + {\rm h.c.}) + \epsilon_{ij}[\frac{1}{2}A_{\alpha\beta m}\widetilde{L}^i_\alpha \widetilde{L}^j_\beta \widetilde{E}_m + A'_{\alpha nm}\widetilde{L}^i_\alpha \widetilde{Q}^j_n \widetilde{D}_m + {\rm h.c.}]$

Hall, Suzuki (1984)

I.H. Lee (1984)

Neutrino masses

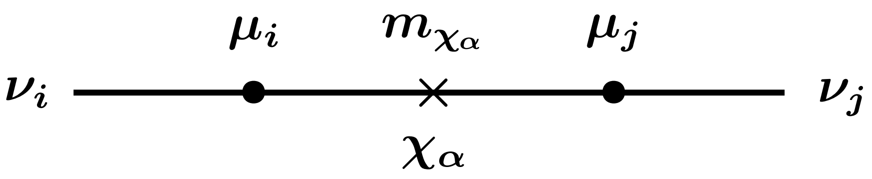
- we will work in a specific basis in the space spanned by $\hat{L}_\alpha$ such that $v_m = 0$ and $v_0 = v_d$

  Tree level ($\mu\mu$) masses
- Neutralino and neutrino mixing

  In the basis $\{\widetilde{B}, \widetilde{W}^3, \widetilde{H}_U, \nu_\beta\}$

$$\begin{pmatrix}
M_1 & 0 & m_Z s_W v_u/v & -m_Z s_W v_d/v & 0 & 0 & 0 \\
0 & M_2 & -m_Z c_W v_u/v & m_Z c_W v_d/v & 0 & 0 & 0 \\
m_Z s_W v_u/v & -m_Z c_W v_u/v & 0 & \mu & \mu_1 & \mu_2 & \mu_3 \\
-m_Z s_W v_d/v & m_Z c_W v_d/v & \mu & 0 & 0 & 0 & 0 \\
0 & 0 & \mu_1 & 0 & 0 & 0 & 0 \\
0 & 0 & \mu_2 & 0 & 0 & 0 & 0 \\
0 & 0 & \mu_3 & 0 & 0 & 0 & 0
\end{pmatrix}$$

Tree level ($\mu\mu$) masses



$$[m_\nu]_{ij}^{(\mu\mu)} = X_T \mu_i \mu_j$$

$$X_T = \frac{m_Z^2 m_{\tilde{\gamma}} \cos^2\beta}{\mu(m_Z^2 m_{\tilde{\gamma}} \sin 2\beta - M_1 M_2 \mu)} \sim \frac{\cos^2\beta}{\tilde{m}}$$

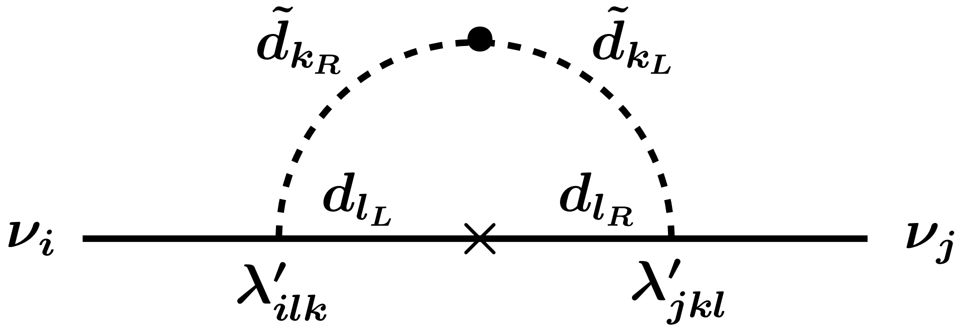
- The tree level neutrino masses are the eigenvalues of $[m_\nu]_{ij}^{(\mu\mu)}$

$$m_3^{(T)} = X_T(\mu_1^2 + \mu_2^2 + \mu_3^2)\,, \qquad m_1^{(T)} = m_2^{(T)} = 0$$

at the tree level only one neutrino is massive. Its mass is proportional to the RPV parameter $\sum \mu_i^2$ and to $\cos^2\beta$.

Grossman, Rakshit (2004)
Valle et al (1997)
Mukhopadhyaya, Roy (1997)

Trilinear ($\lambda'\lambda'$ and $\lambda\lambda$) loops

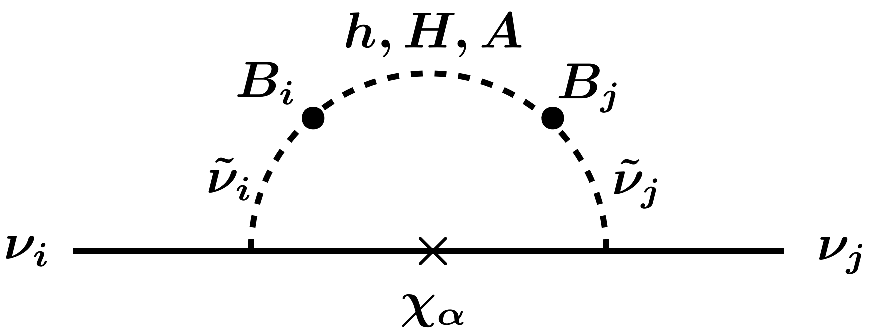


$$[m_\nu]_{ij}^{(\lambda'\lambda')} \approx \sum_{l,k} \frac{3}{8\pi^2} \lambda'_{ilk}\, \lambda'_{jkl}\, \frac{m_{d_l}\, \Delta m^2_{\tilde{d}_k}}{m^2_{\tilde{d}_k}}$$

$$\sim \sum_{l,k} \frac{3}{8\pi^2} \lambda'_{ilk} \lambda'_{jkl} \frac{m_{d_l} m_{d_k}}{\tilde{m}}$$

- trilinear loop-generated masses are suppressed by the RPV couplings λ'^2 [λ^2]
- by a loop factor
- by two down-type quark [charged lepton] masses

Bilinear (BB) loop induced masses



- Two insertions of RPV B_i parameters
- sneutrino splitting induced masses

Assuming that all the masses are of the order of the weak scale

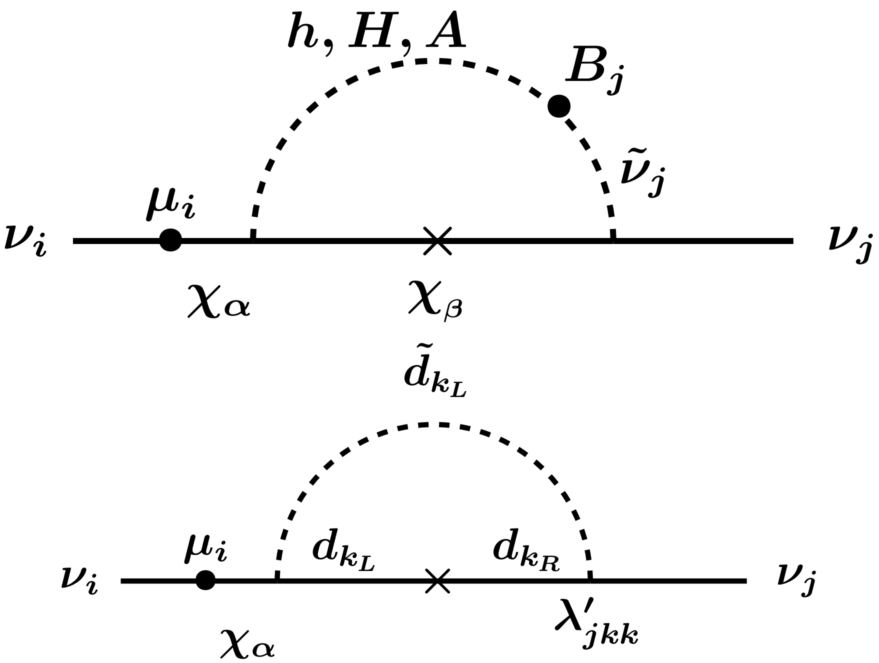
$$[m_\nu]_{ij}^{(BB)} \sim \frac{g^2}{64\pi^2 \cos^2\beta} \frac{B_i B_j}{\tilde{m}^3}$$

- One non-vanishing eigenvalue

- In general B_α is not proportional to μ_α

- one neutrino mass eigenstate acquires mass at tree level, and the other from bilinear loops

Other loops



- Contributions to the neutrino masses are subleading

Decays of the LSP

- LSP decays because of the RPV
- $\tilde{\chi}_1^0$–$W^{\pm}$–$l_i^{\mp}$, $\tilde{\chi}_1^0$–ν_i–Z possible
- Possible decay modes are $\tilde{\chi}_1^0 \to W^{\pm} + l^{\mp}$ and $\tilde{\chi}_1^0 \to Z + \nu_i$
- One can find various correlations of these decay branching ratios with the neutrino data
- Measurable decay length ($\sim$ mm) of the LSP is another important consequence

Mukhopadhyaya, Roy, Vissani (1998)
Choi, Chun, Kang, Lee (1999)
Romao, Diaz, Hirsch, Porod, Valle (2000)
Porod, Hirsch, Romao, Valle (2001)

Decays of the LSP

- Neutrino masses and mixings as well as LSP decay properties are determined by the same interactions

- Connections between high energy LSP physics at the LHC and neutrino oscillation physics

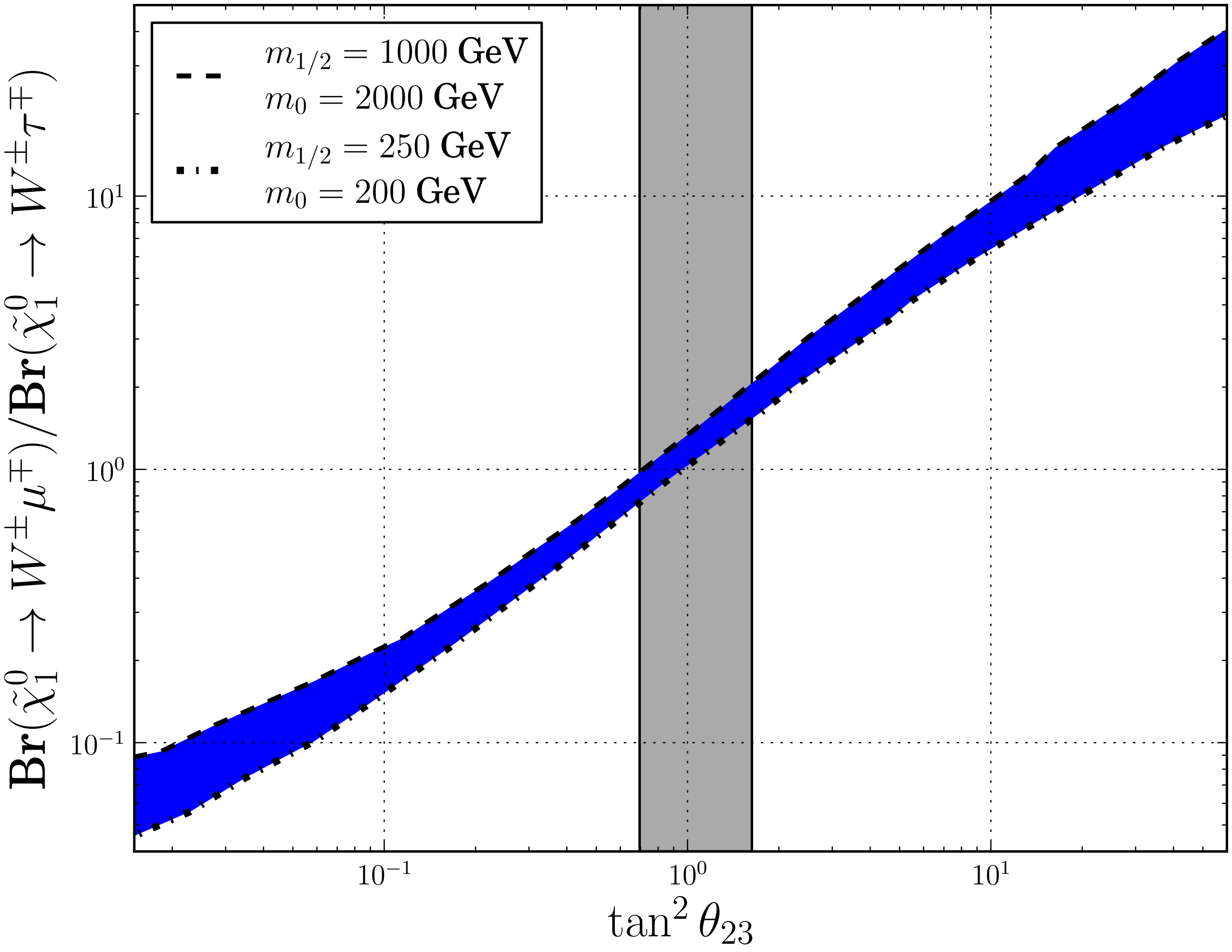
- For instance, the ratio between charged current decays

$$\frac{\text{Br}(\tilde{\chi}_1^0 \rightarrow W^{\pm}\mu^{\mp})}{\text{Br}(\tilde{\chi}_1^0 \rightarrow W^{\pm}\tau^{\mp})} \sim \tan^2\theta_{23}$$

Various collider studies (multileptons, OSD, SSD)

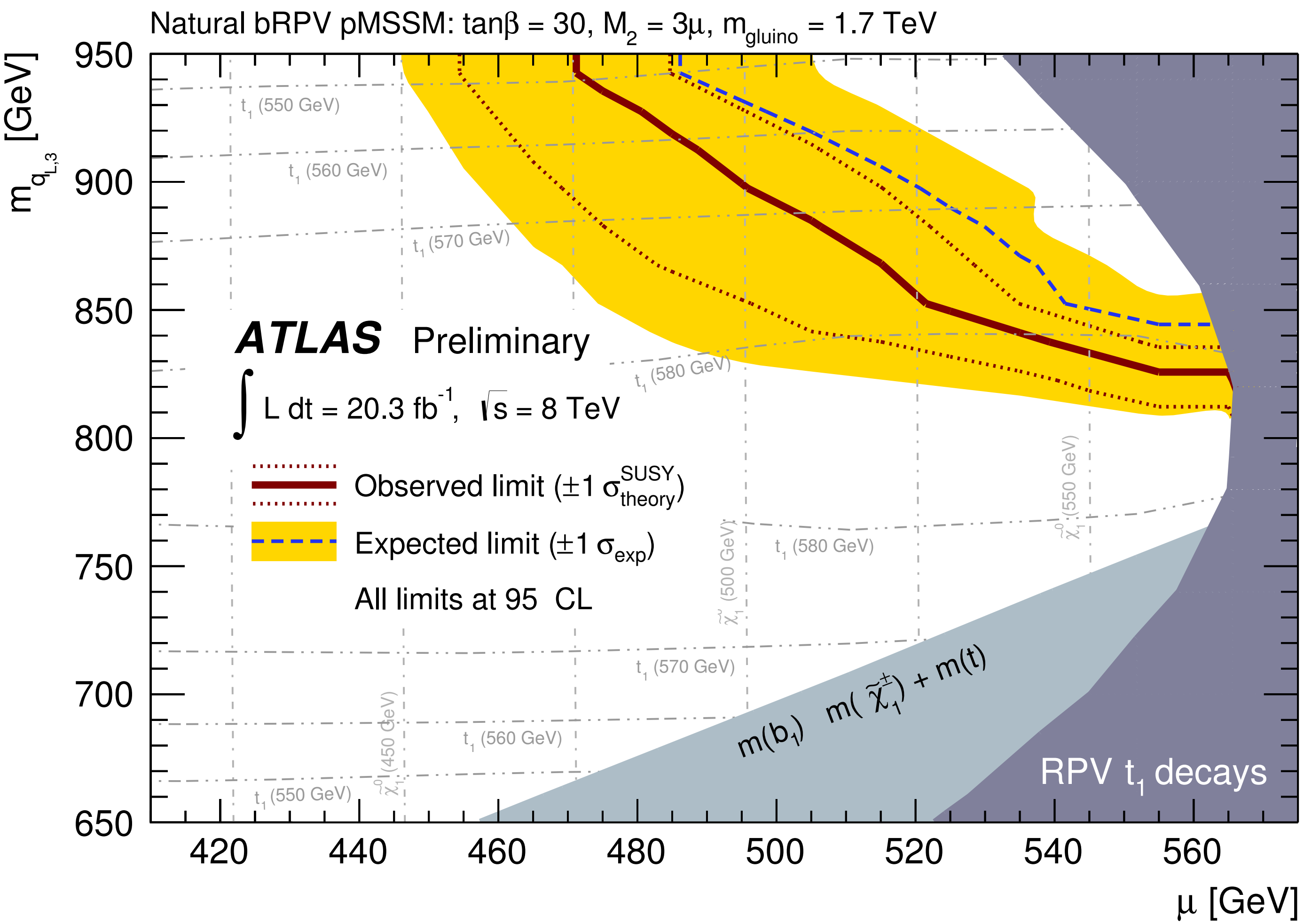
V. Mitsou, arXiv:1510.02660
F. de Campos *et al.* arXiv:1206.3605
Datta, Mukhopadhyaya, Vissani (2000)

LSP decays and atmospheric angle



F. de Campos *et al.* arXiv:1206.3605

Constraints from ATLAS



V. Mitsou, arXiv:1510.02660

μ-problem

- SUSY has been plagued by the so-called "μ-problem".

$$W = \mu \hat{H}_1 \hat{H}_2 + \ldots$$

- EWSB requires μ to be roughly of the order of a few hundreds of GeV

$$\frac{1}{2} m_Z^2 = \frac{m_{H_1}^2 - m_{H_2}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

- $\Longrightarrow \mu \sim$ soft scalar masses

- μ respects SUSY – no obvious reason why it should be of the same order as SUSY breaking soft masses

$\mu\nu$**SSM**

- A class of models introduces gauge singlet neutrino superfields $\hat{\nu}_i^c$ to the solve the μ problem

D.E. López-Fogliani and C. Munõz, PRL 97, 041801 (2006)

- Generate small active neutrino masses through the terms in the superpotential involving the neutrino Yukawa coupling

- VEVs of the singlet sneutrinos induce Majorana mass terms of themselves at the TeV scale

- $Y_\nu \sim 10^{-6}$ to generate the correct mass scale of the light neutrinos

$\mu\nu$SSM

- Explain the experimental data on neutrinos

- Neutrino masses have two contributions： seesaw mechanism + neutrino-neutralino mixing

- Neutrino data and the solution to the μ problem can be accommodated with the same set of gauge singlet superfields

D.E. López-Fogliani and C. Munõz, PRL 97, 041801 (2006)
P. Ghosh, S. Roy (2009)

The model and its minima

Superpotential

$$W = \epsilon_{ab}(Y_u^{ij}\hat{H}_2^b\hat{Q}_i^a\hat{u}_j^c + Y_d^{ij}\hat{H}_1^a\hat{Q}_i^b\hat{d}_j^c + Y_e^{ij}\hat{H}_1^a\hat{L}_i^b\hat{e}_j^c) +$$
$$Y_\nu^{ij}\hat{H}_2^b\hat{L}_i^a\hat{\nu}_j^c - \epsilon_{ab}\lambda^i\hat{\nu}_i^c\hat{H}_1^a\hat{H}_2^b + \frac{1}{3}\kappa^{ijk}\hat{\nu}_i^c\hat{\nu}_j^c\hat{\nu}_k^c$$

- Note that the usual bilinear μ term is absent from the superpotential

- If the scalar potential of the model is such that non-zero VEVs of the scalar components ($\tilde{\nu}_i^c$) are induced, an effective $\mu\hat{H}_1^a\hat{H}_2^b$ is generated with $\mu \equiv \lambda^i\langle\tilde{\nu}_i^c\rangle$

- It is usually expected that the VEVs of $\tilde{\nu}_i^c$ are at the EW scale $\Longrightarrow \mu \sim$ EW scale

Neutral Fermions

- Fermionic partners of $\tilde{\nu}_i^c$ and $\tilde{\nu}_i$ mix with $\tilde{H}_{1,2}$
- Similarly $\tilde{W}_3$, $\tilde{B}$ mix with the neutrinos due to the sneutrino VEVs
- In the basis $\Psi_m \equiv \left(\tilde{B}^0, \tilde{W}_3^0, \tilde{H}_1^0, \tilde{H}_2^0, \nu_e^c, \nu_\mu^c, \nu_\tau^c, \nu_e, \nu_\mu, \nu_\tau\right)$ the neutral fermion mass term in the Lagrangian is of the form $\mathcal{L}_{neutral}^{mass} \equiv -\frac{1}{2}\Psi_m^T \mathcal{M}_n \Psi_m + \text{H.c.}$ where

$$\mathcal{M}_n = \begin{pmatrix} M_{7\times7} & m_{7\times3}^T \\ m_{3\times7} & 0_{3\times3} \end{pmatrix}$$

10×10 matrix

Neutrino mass

Neutralino mass matrix

$$\mathcal{M}_n = \begin{pmatrix} M_{7\times 7} & m^T_{7\times 3} \\ m_{3\times 7} & 0_{3\times 3} \end{pmatrix}$$

- It has a seesaw structure

- The effective 3×3 light neutrino mass matrix is given by

$$m^{neutrino}_{3\times 3} = -m_{3\times 7} M^{-1}_{7\times 7} m^T_{7\times 3}$$

P. Ghosh et al. (2014)
J. Fidalgo et al (2009)
N. Escudero et al (2008)
P. Dey et al (2010)

LSP decays and correlation with neutrino data

LSP will decay

In the neutral fermion sector there are seven heavy states
Four states are simlar to the MSSM neutralinos

Remaining three are mainly singlet states

The lightest one depends on a number of unknown parameters

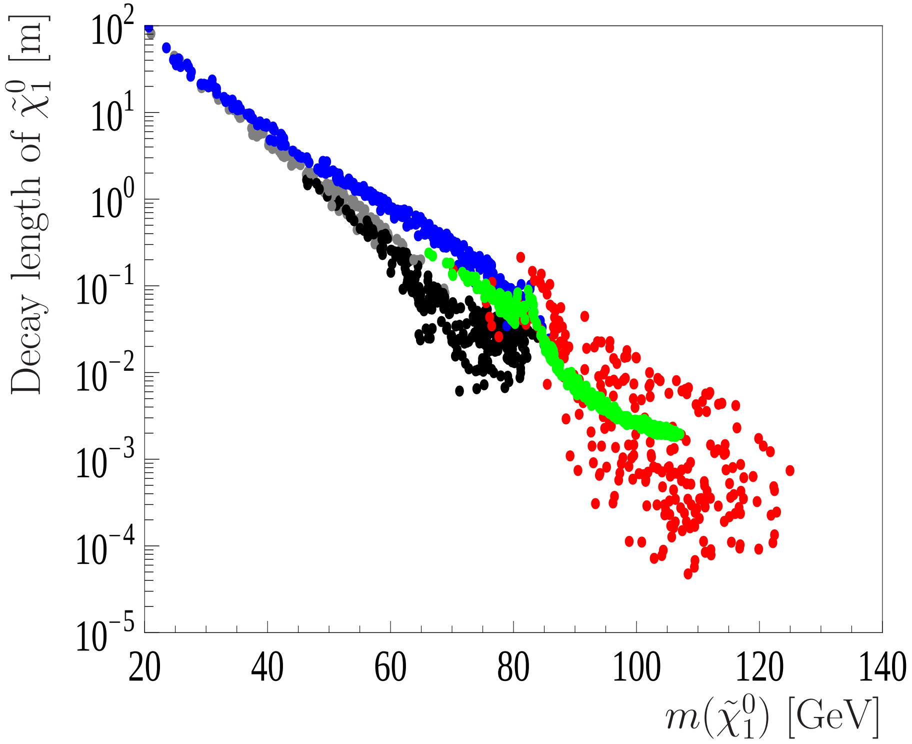
- $\tilde{\chi}_1^0$–$W^\pm$–$l_i^\mp$, $\tilde{\chi}_1^0$–ν_i–Z possible

Possible decay modes are $\tilde{\chi}_1^0 \rightarrow W^\pm + l^\mp$ and $\tilde{\chi}_1^0 \rightarrow Z + \nu_i$
One can find various correlations of these decay branching ratios with the neutrino data

P. Ghosh, S. Roy (2009)
A. Bartl, M. Hirsch, A. Vicente, S. Liebler, W. Porod (2009)

LHC phenomenology of $\mu\nu$SSM

- Since light singlino-like (ν^c) neutralinos may exist, rather long decay lengths are posible



Bartl, Hirsch, Liebler, Porod, Vicente (2009)

- A pair of such LSP can couple to a Higgs boson created via gluon fusion

Axino dark matter in SUSY

- Supersymmetric extension of the SM that incorporate the axion solution to the strong CP problem necessarily contain also the axino

- The axino, stable or almost stable on cosmological time scales

- Well motivated dark matter candidate :

- Axinos differ from WIMPs –

  - ⋆ Exceedingly weakly interacting (EWIMPs)

  - ⋆ Different cosmological properties

  - ⋆ Different ways of testing them in experiment

Introducing Axinos

- An inevitable prediction of combining axions and SUSY is the existence of Axino

- Experimental confirmation of axino existence – validate two theoretical hypotheses designd to solve

    - $\star$ the strong CP problem by a very light axion
    - $\star$ the gauge hierarchy problem by SUSY

- Axinos possess some distinctive properties - lead to important cosmological implications

- Mass of the axino is generically not of the order of the SUSY breaking scale – can be much lower

Makes the axino an intriguing candidate for the LSP and dark matter

Axino mass

- Most important axino parameter in cosmology – $m_{\tilde{a}}$
- Saxion mass is set by M_{SUSY}

The axino mass is strongly model dependent

Tamvakis and Wyler pointed out that

$$m_{\tilde{a}} \sim \mathcal{O}(M_{SUSY}^2/f_a)$$

at tree level in the spontaneously broken global SUSY

- In the literature a whole range of axino mass was considered – can be much smaller or much larger than M_{SUSY}

- In cosmological studies – treats axino mass as a free parameter and axino interactions from $U(1)_{PQ}$ symmetry

Axinos in cosmology

- Depending on axino mass and production mechanism, cosmic axinos may fall into one or more than one population of relics

Treat axino mass as a free parameter ranging from eV to multi-TeV scales

- Two generic ways of producing relic axinos in the early universe

$\star$ Thermal production from scatterings and decays of particles in thermal equilibrium

$\star$ Non-thermal production from the decays of heavier particles after their frezeout

Thermal Production

Primordial axinos decouple from thermal equilibrium at the temperature

$$T_{dec} = 10^{11}\ \mathrm{GeV} \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^2 \left(\frac{0.1}{\alpha_s}\right)^3$$

- Overclose the universe unless $m_{\tilde{a}} \lesssim$ 2 keV

In inflationary cosmology, population of primordial axinos is strongly diluted by cosmic inflation

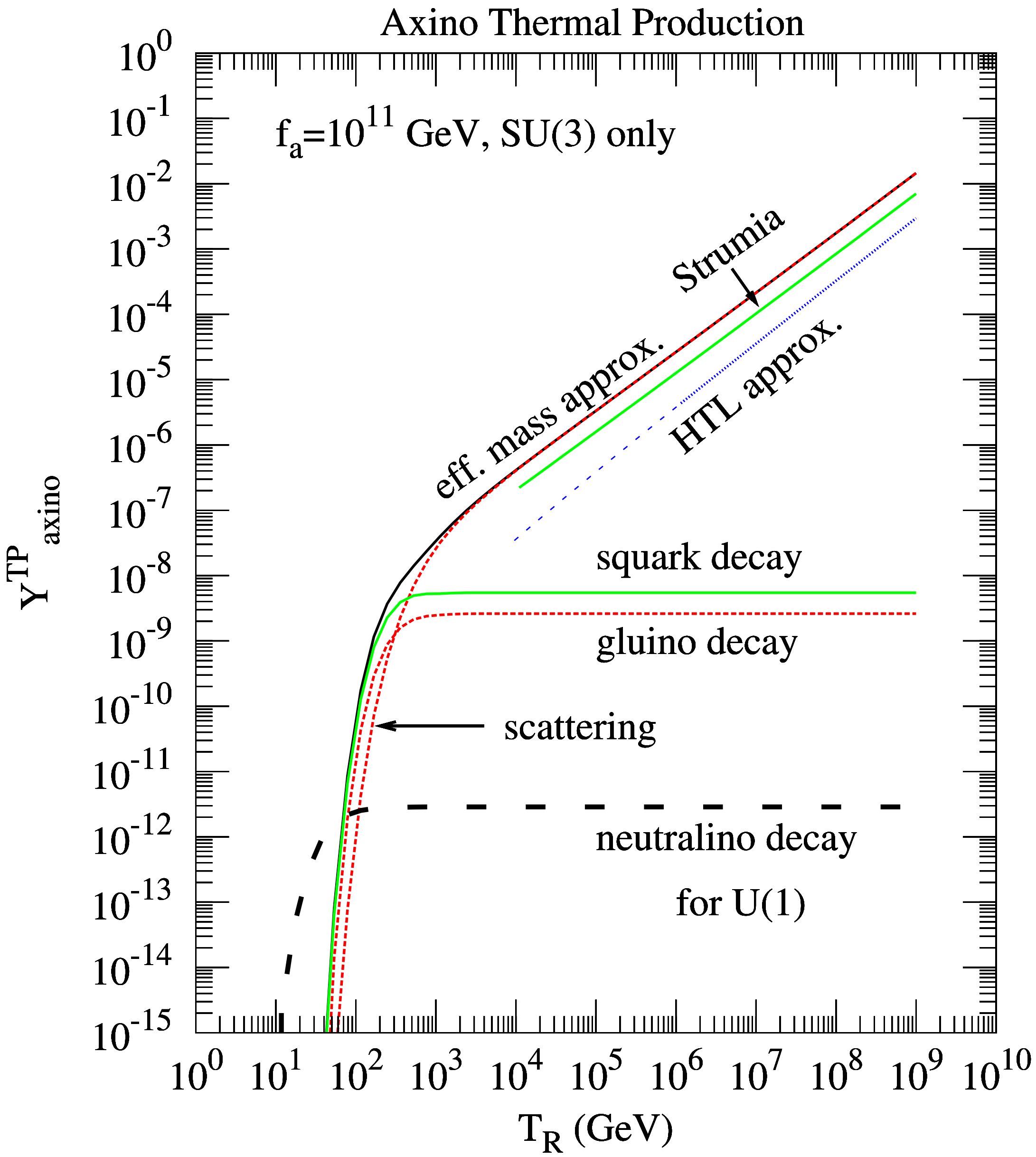
However, axinos are re-generated during reheating

- Axinos can be produced from scattering in thermal plasma

- No. density $\propto T_R \Rightarrow$ keV mass upper bound is relaxed

K.-Y. Choi, J.E. Kim, L. Roszkowski, arXiv:1307.3330

$$Y^{TP}_{\tilde{a}} \equiv n_{\tilde{a}}/s$$



Non-thermal Production

- Axinos can be produced from out-of-equilibrium decays of heavier non-thermal particles

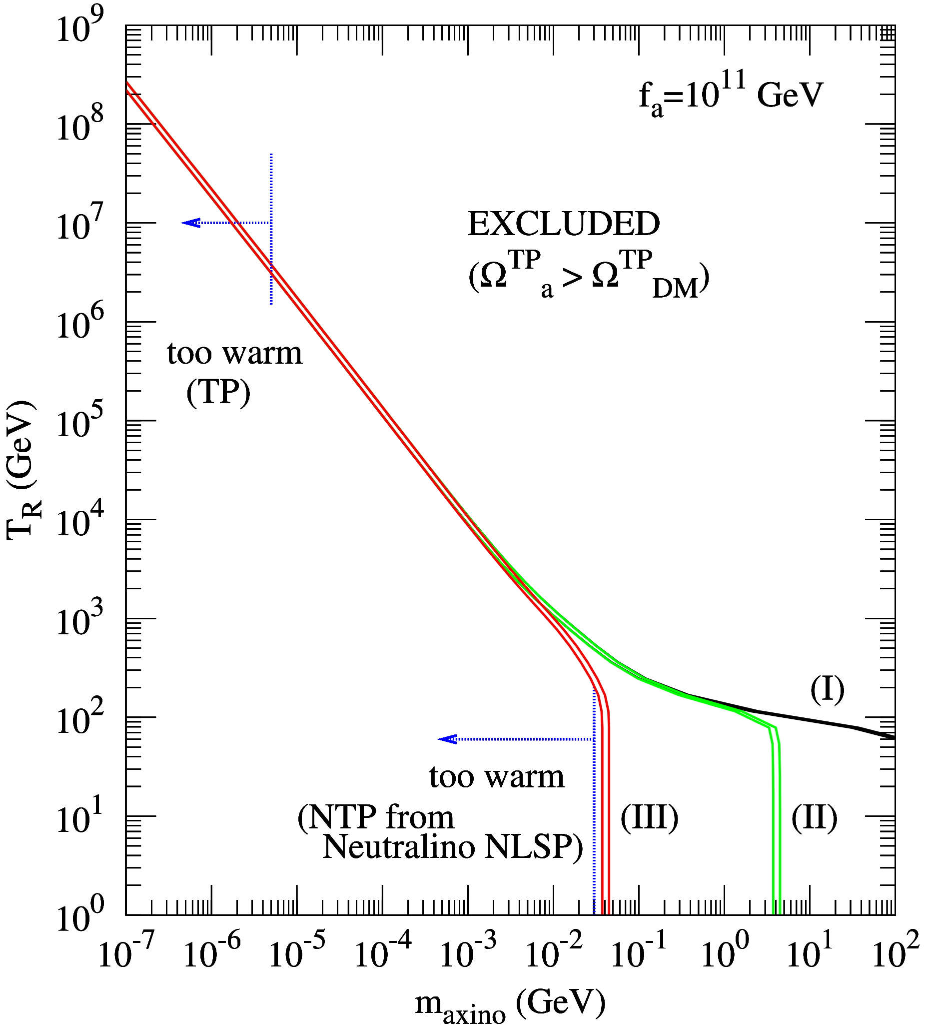
- Axino abundance is independent of T_R and its relic number density depends on the number density and the decay modes of the decaying mother particles

- Particularly interesting case is axino production from the NLSP

- The non-thermal production of axinos from the NLSP decay is given by

$$\Omega_{\tilde{a}}^{\mathrm{NTP}} = \frac{m_{\tilde{a}}}{m_{\mathrm{NLSP}}}\Omega_{\mathrm{NLSP}} \simeq 2.7 \times 10^{10}\Big(\frac{m_{\tilde{a}}}{100\,\mathrm{GeV}}\Big)Y_{\mathrm{NLSP}}$$

T_R vs $m_{\tilde{a}}$ with both TP and NTP



K.-Y. Choi, J.E. Kim, L. Roszkowski, arXiv:1307.3330

Axino as WDM

Rajagopal, Turner and Wilczek obtained

$m_{\tilde{a}} <$ 2 keV for axinos to be WDM

in the absence of a subsequent period of inflation

- This bound can be relaxed if the reheating temperature T_R after inflation is much lower than the PQ symmetry breaking scale, f_a

- In this case the primordial population of WDM axinos is diluted away and WDM axinos are subsequently regenerated after the reheating phase

Axino as CDM

- For CDM axinos, relatively low T_R are preferred

- Therefore, axino is a good candidate for DM in models of thermal inflation which takes places at a late time and naturally predicts a low reheating temperature

- Scenarios with a mixed axion-axino population of CDM have also been considered

Axino DM and RPV

- Axino is good DM candidate even if R-parity is not exactly conserved

$$\tau > 4.3 \times 10^{17} \text{ s}$$

Consider bilinear R-parity breaking

$$W_{\not{R}} = \epsilon_i L_i H_u$$

$$\mathcal{L}_{soft\not{R}} = B_i L_i H_u$$

Presence of these bilinear terms leads the axino to decay into a photon and a neutrino

$$\Gamma(\tilde{a} \to \gamma \nu_i) = \frac{1}{128\pi^3} |U_{\tilde{\gamma}\tilde{Z}}|^2 \frac{m_{\tilde{a}}^3}{f_a^2} C^2_{a\gamma\gamma} \alpha^2_{em} \xi_i^2 ,$$

where $\xi_i = \langle \tilde{\nu}_i \rangle / v$ and v = 174 GeV

$$U_{\tilde{\gamma}\tilde{Z}} = M_Z \sum_\alpha \frac{N_{\tilde{Z}\alpha} N^*_{\tilde{\gamma}\alpha}}{m_{\tilde{\chi}\alpha}}$$

Axino DM and RPV

$$\tau(\tilde{a} \to \gamma\nu_i) = 3 \times 10^{35} s \left(\frac{\xi_i|U_{\tilde{\gamma}\tilde{Z}}|}{10^{-7}}\right)^{-2} \left(\frac{m_{\tilde{a}}}{5\ \mathrm{keV}}\right)^{-3} \left(\frac{f_a}{10^{11}\ \mathrm{GeV}}\right)^{2}$$

The X-ray flux from the dark matter halos can be calculated for a given galaxy knowing its luminosity distance and the dark matter distribution

One can constrain the axino mass by looking at the flux of X-ray photons

S.P. Liew (2014)
K-Y. Choi, O. Seto, (2014)
P. Dey, B. Mukhopadhyaya, S. Roy, S.K. Vempati (2012)

Conclusions

- Massive neutrinos suggest physics beyond the SM
- Various options in the context of SUSY
- Gauge singlet neutrinos, seesaw mechanism, MSSM with RPV, TeV scale seesaw etc
- The decays of the LSP can show some correlations with the neutrino data
- Signals of sneutrino oscillation
- LHC data will restrict large portion of the parameter space
- Axino is an intriguing candidate for DM in SUSY with the axion solution of the strong CP problem
- In RPV MSSM, decaying Axinos can be DM and can produce X-ray photon lines which can be detected.