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Neutrino Oscillations in Split Supersymmetry

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Neutrino Oscillations

The neutrino mass matrix is diagonalized by the rotation matrix V_{PMNS}, such that the mass eigenstates evolve in time as

$$\psi_i = \sum_j e^{-iE_j t} \, V_{PMNS}^{ij} \, \psi_j$$

Calculating transition probabilities in the ultra-relativistic limit, where

$$E_i \approx |\vec{p}| + \frac{m_i^2}{2|\vec{p}|}$$

leads to results like (in the two neutrino approximation)

$$P_{\nu_i \to \nu_j} = \sin^2(2\theta) \sin^2\left(1.27 \frac{\Delta m^2 L}{E}\right)$$

where θ is the mixing angle.

Three Neutrinos

A general 3×3 neutrino mass matrix is diagonalized by a Pontecorvo-Maki-Nakagawa-Sakata matrix of the type

$$V_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- θ_{23}: atmospheric angle
- θ_{13}: reactor angle
- θ_{12}: solar angle
- Δm^2_{23}: atmospheric mass squared difference
- Δm^2_{12}: solar mass squared difference

Experimental Constraints

Experimental results are consistent with the following values of the mixing angles and masses:

$$
\begin{aligned}
0.52 < \; & \tan^2\theta_{23} < 2.1 \\
& \tan^2\theta_{13} < 0.049 \\
0.30 < \; & \tan^2\theta_{12} < 0.61 \\
1.4\times 10^{-3} < \; & \Delta m^2_{23} < 3.3\times 10^{-3} \quad \mathrm{eV}^2 \\
7.2\times 10^{-5} < \; & \Delta m^2_{12} < 9.1\times 10^{-5} \quad \mathrm{eV}^2 \\
& m_{ee} < 0.84 \quad \mathrm{eV}
\end{aligned}
$$

There is no direct measurement of the scale of neutrino masses.

From Table 1 (3 σ values) hep-ph/0405172, M. Maltoni, T. Schwetz, M. Tortola, J. W. F. Valle

Bilinear R-Parity Violation

R-Parity and Lepton Number are violated by bilinear terms in the superpotential.

The three parameters $\epsilon_1, \epsilon_2, \epsilon_3$ have units of mass:

$$W = W_{MSSM} + \epsilon_i \widehat{L}_i \widehat{H}_u$$

These terms induce sneutrino vacuum expectation values $< \tilde{\nu}_i >= v_i$, which contribute to the gauge boson masses (although in a negligible amount):

$$v_u^2 + v_d^2 + v_1^2 + v_2^2 + v_3^3 = v^2 \sim (246\,\mathrm{GeV})^2$$

In the soft supersymmetry breaking potential the following terms are added:

$$V^{soft} = V_{MSSM}^{soft} + B_i \epsilon_i \widetilde{L}_i H_u$$

Neutralinos and Neutrinos

In basis the $(\psi^0)^T = (-i\lambda', -i\lambda^3, \widetilde{H}_1^1, \widetilde{H}_2^2, \nu_e, \nu_\mu, \nu_\tau)$ the neutralino/neutrino mass matrix is

$$\mathbf{M}_N = \begin{bmatrix} M_1 & 0 & -\frac{1}{2}g'v_d & \frac{1}{2}g'v_u & -\frac{1}{2}g'v_1 & -\frac{1}{2}g'v_2 & -\frac{1}{2}g'v_3 \\ 0 & M_2 & \frac{1}{2}gv_d & -\frac{1}{2}gv_u & \frac{1}{2}gv_1 & \frac{1}{2}gv_2 & \frac{1}{2}gv_3 \\ -\frac{1}{2}g'v_d & \frac{1}{2}gv_d & 0 & -\mu & 0 & 0 & 0 \\ \frac{1}{2}g'v_u & -\frac{1}{2}gv_u & -\mu & 0 & \epsilon_1 & \epsilon_2 & \epsilon_3 \\ -\frac{1}{2}g'v_1 & \frac{1}{2}gv_1 & 0 & \epsilon_1 & 0 & 0 & 0 \\ -\frac{1}{2}g'v_2 & \frac{1}{2}gv_2 & 0 & \epsilon_2 & 0 & 0 & 0 \\ -\frac{1}{2}g'v_3 & \frac{1}{2}gv_3 & 0 & \epsilon_3 & 0 & 0 & 0 \end{bmatrix}$$

and a neutrino 3×3 mass matrix is induced.

Low Energy See-Saw

Low energy see-saw mechanism with three neutrinos

$$\mathbf{M}_N = \begin{bmatrix} \mathcal{M}_{\chi^0} & m^T \\ m & 0 \end{bmatrix} \Longrightarrow m_{eff} = -m \cdot \mathcal{M}_{\chi^0}^{-1} \cdot m^T$$

defining $\Lambda_i = \mu v_i + \epsilon_i v_d$, the effective mass matrix is

$$m_{eff} = \frac{M_1 g^2 + M_2 g'^2}{4\, det(\mathcal{M}_{\chi^0})} \begin{bmatrix} \Lambda_1^2 & \Lambda_1\Lambda_2 & \Lambda_1\Lambda_3 \\ \Lambda_1\Lambda_2 & \Lambda_2^2 & \Lambda_2\Lambda_3 \\ \Lambda_1\Lambda_3 & \Lambda_2\Lambda_3 & \Lambda_3^2 \end{bmatrix} \sim A^{(0)}\Lambda_i\Lambda_j$$

and only one neutrino acquire mass at tree level

$$m_{\nu_3} = Tr(m_{eff}) = \frac{M_1 g^2 + M_2 g'^2}{4\, det(\mathcal{M}_{\chi^0})} |\vec{\Lambda}|^2$$

Neutrino Angles at Tree Level

The diagonalization $V_\nu^T m_{eff} V_\nu = \mathrm{diag}(0,0,m_\nu)$ is performed with two rotations:

$$V_\nu = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & -\sin\theta_{23} \\ 0 & \sin\theta_{23} & \cos\theta_{23} \end{bmatrix} \times \begin{bmatrix} \cos\theta_{13} & 0 & -\sin\theta_{13} \\ 0 & 1 & 0 \\ \sin\theta_{13} & 0 & \cos\theta_{13} \end{bmatrix}$$

The atmospheric angle θ_{23} and the reactor angle θ_{13} are simple functions of the Λ_i

$$\tan\theta_{23} = -\frac{\Lambda_2}{\Lambda_3} \qquad \tan\theta_{13} = -\frac{\Lambda_1}{\sqrt{\Lambda_2^2+\Lambda_3^2}}$$

and the solar angle is undefined at tree level.

Effect of loops

The neutrino mass matrix at tree level has the form,

$$M_{ij}^{\nu(0)} = A^{(0)} \Lambda_i \Lambda_j$$

and at one loop,

$$M_{ij}^{\nu} = A \Lambda_i \Lambda_j + B(\Lambda_i \epsilon_j + \Lambda_j \epsilon_i) + C \epsilon_i \epsilon_j$$

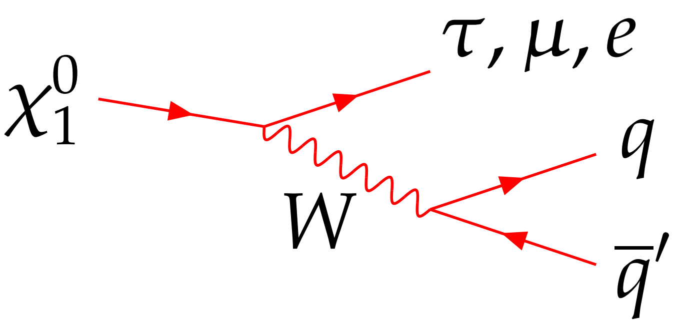
For each individual loop we have,

- Z, W, $\tilde{t}$: $\sim A \Lambda_i \Lambda_j$
- χ^+, χ^0, $\tilde{b}$: $\sim A \Lambda_i \Lambda_j + B(\Lambda_i \epsilon_j + \Lambda_j \epsilon_i) + C \epsilon_i \epsilon_j$

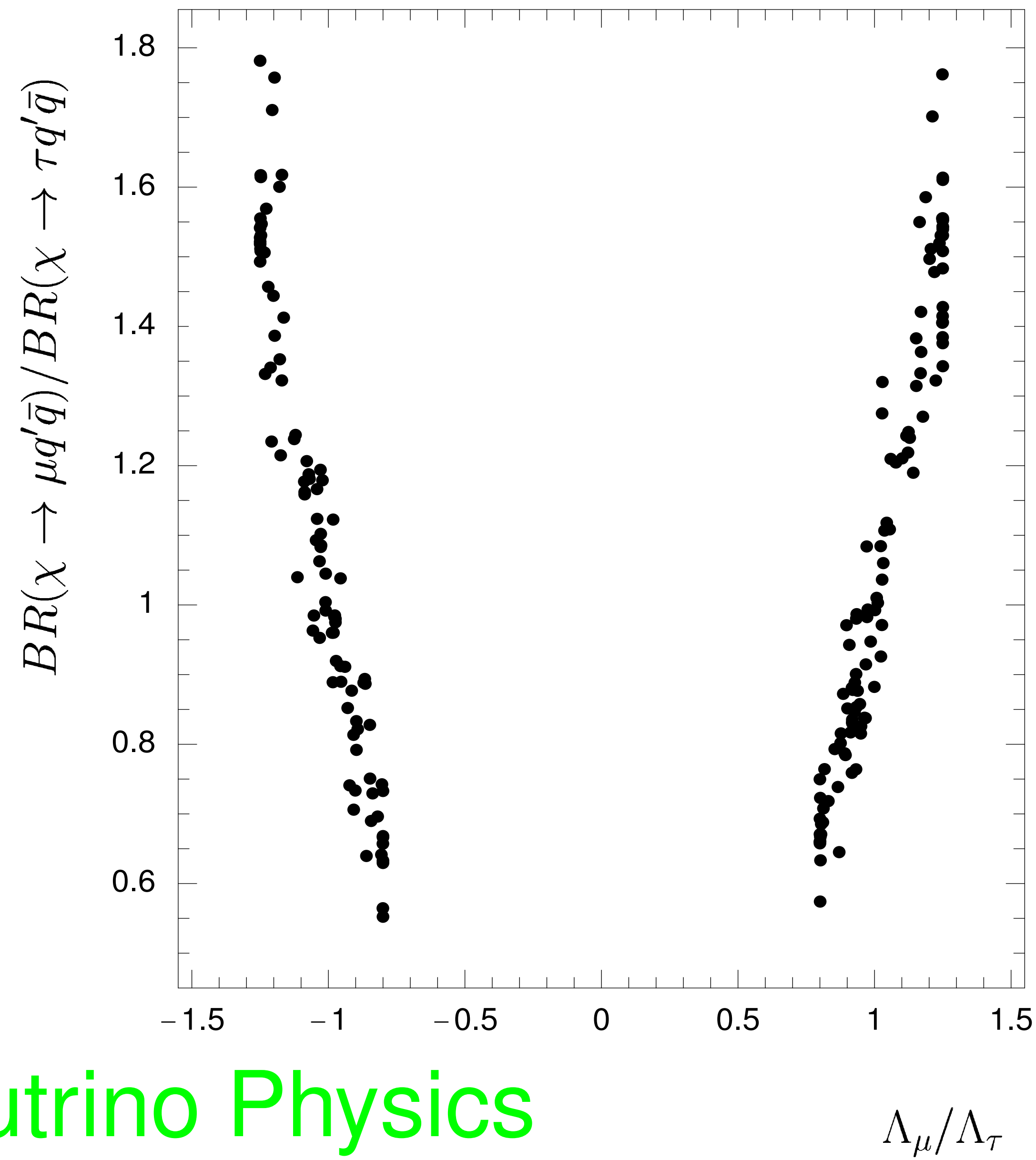
The first three loops renormalize the atmospheric mass. The second three loops break the symmetry, inducing a solar mass.

Neutralino Decays

In the presence of BRpV a neutralino LSP is not stable:



Ratios of BR are closely related to the Λ_i parameters.



Collider Physics $\Leftrightarrow$ Neutrino Physics

Split Supersymmetry

Based on work by,

M.A. Díaz, Pavel Fileviez-Perez, and Clemencia Mora

hep-ph/0605285

Split Susy, Rp Conserved

All scalars except for one neutral Higgs doublet H are heavy, with a mass of the order of $\widetilde{m}$. The higgsino mass and the Higgs-higgsino-gaugino vertices in the supersymmetric lagrangian valid above $\widetilde{m}$ are,

$$\mathcal{L}_{susy} = \mu \widetilde{H}_u^T i\sigma_2 \widetilde{H}_d - \frac{H_u^\dagger}{\sqrt{2}} \left(g\sigma^a \widetilde{W}^a + g' \widetilde{B} \right) \widetilde{H}_u - \frac{H_d^\dagger}{\sqrt{2}} \left(g\sigma^a \widetilde{W}^a + g' \widetilde{B} \right) \widetilde{H}_d$$

The fine-tuned light Higgs doublet $H = -c_\beta i\sigma_2 H_d^* + s_\beta H_u$, and the equivalent couplings in the effective lagrangian below $\widetilde{m}$ are given by,

$$\mathcal{L}_{split} = -\frac{H^\dagger}{\sqrt{2}} \left(\tilde{g}_u \sigma^a \widetilde{W}^a + \tilde{g}'_u \widetilde{B} \right) \widetilde{H}_u - \frac{H^T i\sigma_2}{\sqrt{2}} \left(-\tilde{g}_d \sigma^a \widetilde{W}^a + \tilde{g}'_d \widetilde{B} \right) \widetilde{H}_d$$

with the following matching conditions at the scale $\widetilde{m}$:

$$\tilde{g}_u(\widetilde{m}) = g(\widetilde{m}) \sin\beta(\widetilde{m}) \qquad \tilde{g}_d(\widetilde{m}) = g(\widetilde{m}) \cos\beta(\widetilde{m})$$
$$\tilde{g}'_u(\widetilde{m}) = g'(\widetilde{m}) \sin\beta(\widetilde{m}) \qquad \tilde{g}'_d(\widetilde{m}) = g'(\widetilde{m}) \cos\beta(\widetilde{m})$$

Running

The couplings $\tilde{g}_u$, $\tilde{g}_d$, $\tilde{g}'_u$, and $\tilde{g}'_d$, run with their own RGE [Giudice, Romanino, $Nucl.Phys.B$**699**, 65 (2004)]. In particular we have,

$$\begin{aligned} \frac{\tilde{g}_u}{\tilde{g}_d}(m_W) &\approx \tan\beta(\tilde{m})\left\{1+\frac{\cos(2\beta)}{64\pi^2}(7g^2-3g'^2)\Big|_{\tilde{m}}\ln\frac{\tilde{m}}{m_W}\right\} \equiv \tan\beta \\ \frac{\tilde{g}'_u}{\tilde{g}'_d}(m_W) &\approx \tan\beta(\tilde{m})\left\{1-\frac{\cos(2\beta)}{64\pi^2}(9g^2+3g'^2)\Big|_{\tilde{m}}\ln\frac{\tilde{m}}{m_W}\right\} \equiv \tan'\beta \end{aligned}$$

Definition: $\tilde{g}^2 \equiv \tilde{g}_u^2(m_W)+\tilde{g}_d^2(m_W)$, $\tilde{g}'^2 \equiv \tilde{g}'^2_u(m_W)+\tilde{g}'^2_d(m_W)$.

In this case, the neutralino mass matrix loops like

$$\mathbf{M}_{\chi^0} = \begin{bmatrix} M_1 & 0 & -\frac{1}{2}\tilde{g}'c'_\beta v & \frac{1}{2}\tilde{g}'s'_\beta v \\ 0 & M_2 & \frac{1}{2}\tilde{g}c_\beta v & -\frac{1}{2}\tilde{g}s_\beta v \\ -\frac{1}{2}\tilde{g}'c'_\beta v & \frac{1}{2}\tilde{g}c_\beta v & 0 & -\mu \\ \frac{1}{2}\tilde{g}'s'_\beta v & -\frac{1}{2}\tilde{g}s_\beta v & -\mu & 0 \end{bmatrix}$$

Split Susy, Rp Violated

The higgsino-lepton mixing and the Lepton-slepton-gaugino vertex in the supersymmetric lagrangian valid above $\widetilde{m}$ are,

$$\mathcal{L}_{susy} = \epsilon_i \widetilde{H}_u^T i\sigma_2 L_i - \frac{L_i^\dagger}{\sqrt{2}} \left(g\sigma^a \widetilde{W}^a + g' \widetilde{B} \right) \widetilde{L}_i$$

Since the sleptons and the Higgs bosons mix, this time the fine-tuned light Higgs is equal to

$$H = -c_\beta i\sigma_2 H_d^* + s_\beta H_u - s_i i\sigma_2 \widetilde{L}_i^*$$

and the equivalent couplings in the effective lagrangian below $\widetilde{m}$ are given by,

$$\mathcal{L}_{split} = -\frac{a_i}{\sqrt{2}} H^T i\sigma_2 \left(-\tilde{g}_d \sigma^a \widetilde{W}^a + \tilde{g}'_d \widetilde{B} \right) L_i$$

with the following matching conditions at the scale $\widetilde{m}$:

$$a_i(\widetilde{m})\tilde{g}_d(\widetilde{m}) = g(\widetilde{m}) s_i(\widetilde{m}) \qquad a_i(\widetilde{m})\tilde{g}'_d(\widetilde{m}) = g'(\widetilde{m}) s_i(\widetilde{m})$$

where the s_i are the Higgs-slepton mixing angles.

S.S. Low Energy See-Saw

In Split Susy the low energy see-saw mechanism is similar to the MSSM:

$$\mathbf{M}_N = \begin{bmatrix} \mathcal{M}_{\chi^0} & m^T \\ m & 0 \end{bmatrix} \Longrightarrow m_{eff} = -m \cdot \mathcal{M}_{\chi^0}^{-1} \cdot m^T$$

but the mixing looks like,

$$m = \begin{bmatrix} -\frac{1}{2}\tilde{g}' c'_\beta a_1 v & \frac{1}{2}\tilde{g} c_\beta a_1 v & 0 & \epsilon_1 \\ -\frac{1}{2}\tilde{g}' c'_\beta a_2 v & \frac{1}{2}\tilde{g} c_\beta a_2 v & 0 & \epsilon_2 \\ -\frac{1}{2}\tilde{g}' c'_\beta a_3 v & \frac{1}{2}\tilde{g} c_\beta a_3 v & 0 & \epsilon_3 \end{bmatrix}$$

If we define $\lambda_i = a_i \mu + \epsilon_i$, which are related to the MSSM-BRpV parameters by $\Lambda_i = \lambda_i v_d$, the effective neutrino mass matrix is given by

$$m_{eff} = \frac{M_1 \tilde{g}^2 c_\beta^2 + M_2 \tilde{g}'^2 c'^2_\beta}{4\, det(\mathcal{M}_{\chi^0})} v^2 \begin{bmatrix} \lambda_1^2 & \lambda_1\lambda_2 & \lambda_1\lambda_3 \\ \lambda_1\lambda_2 & \lambda_2^2 & \lambda_2\lambda_3 \\ \lambda_1\lambda_3 & \lambda_2\lambda_3 & \lambda_3^2 \end{bmatrix} \sim A^{(0)} \lambda_i \lambda_j$$

and again only one neutrino acquire mass at tree level.

S.S. Tree Level Results

The diagonalization $V_\nu^T m_{eff} V_\nu = \mathrm{diag}(0,0,m_\nu)$ is performed with two rotations:

$$V_\nu = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & -\sin\theta_{23} \\ 0 & \sin\theta_{23} & \cos\theta_{23} \end{bmatrix} \times \begin{bmatrix} \cos\theta_{13} & 0 & -\sin\theta_{13} \\ 0 & 1 & 0 \\ \sin\theta_{13} & 0 & \cos\theta_{13} \end{bmatrix}$$

with the atmospheric angle θ_{23} and the reactor angle θ_{13} satisfying

$$\tan\theta_{23} = -\frac{\lambda_2}{\lambda_3} \qquad \tan\theta_{13} = -\frac{\lambda_1}{\sqrt{\lambda_2^2 + \lambda_3^2}}$$

and the solar angle is undefined at tree level. The tree level mass for the only massive neutrino is:

$$m_{\nu_3} = Tr(m_{eff}) = \frac{M_1 \tilde{g}^2 c_\beta^2 + M_2 \tilde{g}'^2 c_\beta'^2}{4\,det(\mathcal{M}_{\chi^0})}\, v^2 |\vec{\lambda}|^2$$

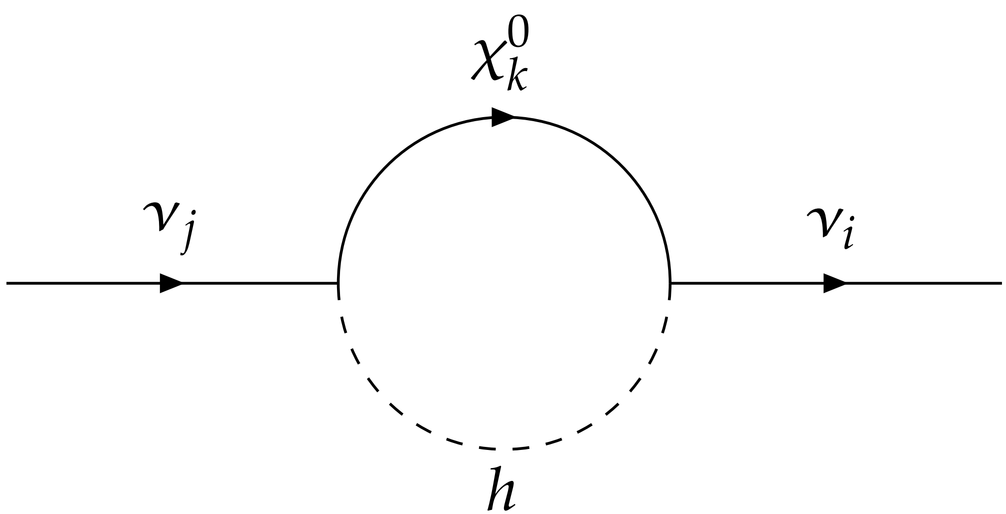
Higgs boson loop

The Higgs boson contribution to the mass matrix is,

$$\Delta M_\nu^{ij} = \Delta\widetilde{\Pi}^h_{ij}(0) = -\frac{1}{16\pi^2}\sum_k G^h_{ijk}\, m_k\, B_0(0; m_k^2, m_h^2)$$

The loop can be represented by the diagram

$$\Delta\widetilde{\Pi}^h_{ij}(0) =$$



This diagram has the form,

$$\Delta\widetilde{\Pi}^h_{ij}(0) = A\Lambda_i\Lambda_j + B(\Lambda_i\epsilon_j + \Lambda_j\epsilon_i) + C\epsilon_i\epsilon_j$$

generating a solar neutrino mass. To this diagram we need to add the Goldstone boson contribution, which tends to cancel the Higgs contribution but not enough to spoil the solution [See Davidson & Losada, Haber & Grossman].

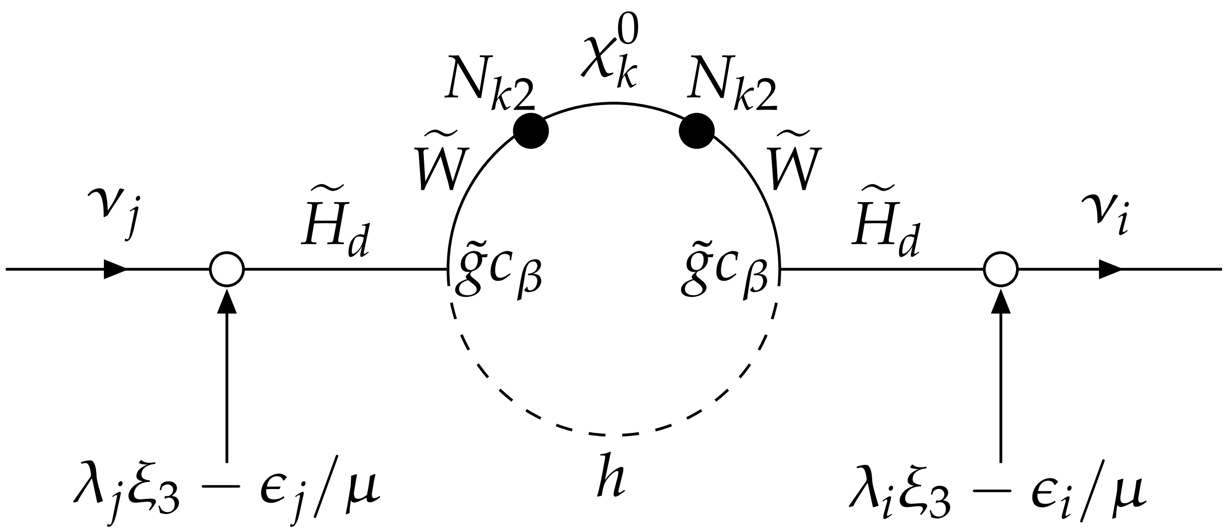
Higgs boson loop in detail

The Higgs boson loop in detail is,

$$\Delta\widetilde{\Pi}^h_{ij}(0) = -\frac{1}{64\pi^2}\sum_k (E_k\lambda_i + F_k\epsilon_i)(E_k\lambda_j + F_k\epsilon_j)\, m_k\, B_0(0; m_k^2, m_h^2)$$

and part of it can be represented by the diagram

$$\Delta\widetilde{\Pi}^h_{ij}(0) =$$



with,

$$\begin{aligned} E_k &= -(\tilde{g}s_\beta N_{k2} - \tilde{g}' s'_\beta N_{k1})\xi_4 - N_{k4}(\tilde{g}s_\beta\, \xi_2 - \tilde{g}' s'_\beta\, \xi_1) \\ &\quad + (\tilde{g}c_\beta N_{k2} - \tilde{g}' c'_\beta N_{k1})\xi_3 + N_{k3}(\tilde{g}c_\beta\, \xi_2 - \tilde{g}' c'_\beta\, \xi_1) \\ F_k &= -\frac{1}{\mu}(\tilde{g}c_\beta N_{k2} - \tilde{g}' c'_\beta N_{k1}) \end{aligned}$$

A Split Susy Solution

The chosen Split Supersymmetry benchmark is:

$$M_1 = 50\,\mathrm{GeV}\,, \qquad \mu = 200\,\mathrm{GeV}\,,$$
$$M_2 = 300\,\mathrm{GeV}\,, \qquad m_h = 120\,\mathrm{GeV}\,,$$
$$\tan\beta = 50\,,$$

and the BRpV solution is characterized by,

$$\epsilon_1 = -0.107\,\mathrm{GeV}\,, \qquad \lambda_1 = 0.0001\,\mathrm{GeV}\,,$$
$$\epsilon_2 = -0.001\,\mathrm{GeV}\,, \qquad \lambda_2 = 0.031\,\mathrm{GeV}\,,$$
$$\epsilon_3 = 0.217\,\mathrm{GeV}\,, \qquad \lambda_3 = -0.036\,\mathrm{GeV}\,.$$

The values of the neutrino observables in this scenario are,

$$\Delta m^2_{\mathrm{atm}} = 2.3\times 10^{-3}\,\mathrm{eV}^2\,, \qquad \tan^2\theta_{\mathrm{atm}} = 1.22\,,$$
$$\Delta m^2_{\mathrm{sol}} = 8.4\times 10^{-5}\,\mathrm{eV}^2\,, \qquad \tan^2\theta_{\mathrm{sol}} = 0.56\,,$$
$$m_{ee} = 0.0037\,\mathrm{eV}\,, \qquad \tan^2\theta_{13} = 0.0083\,,$$

within experimental bounds.

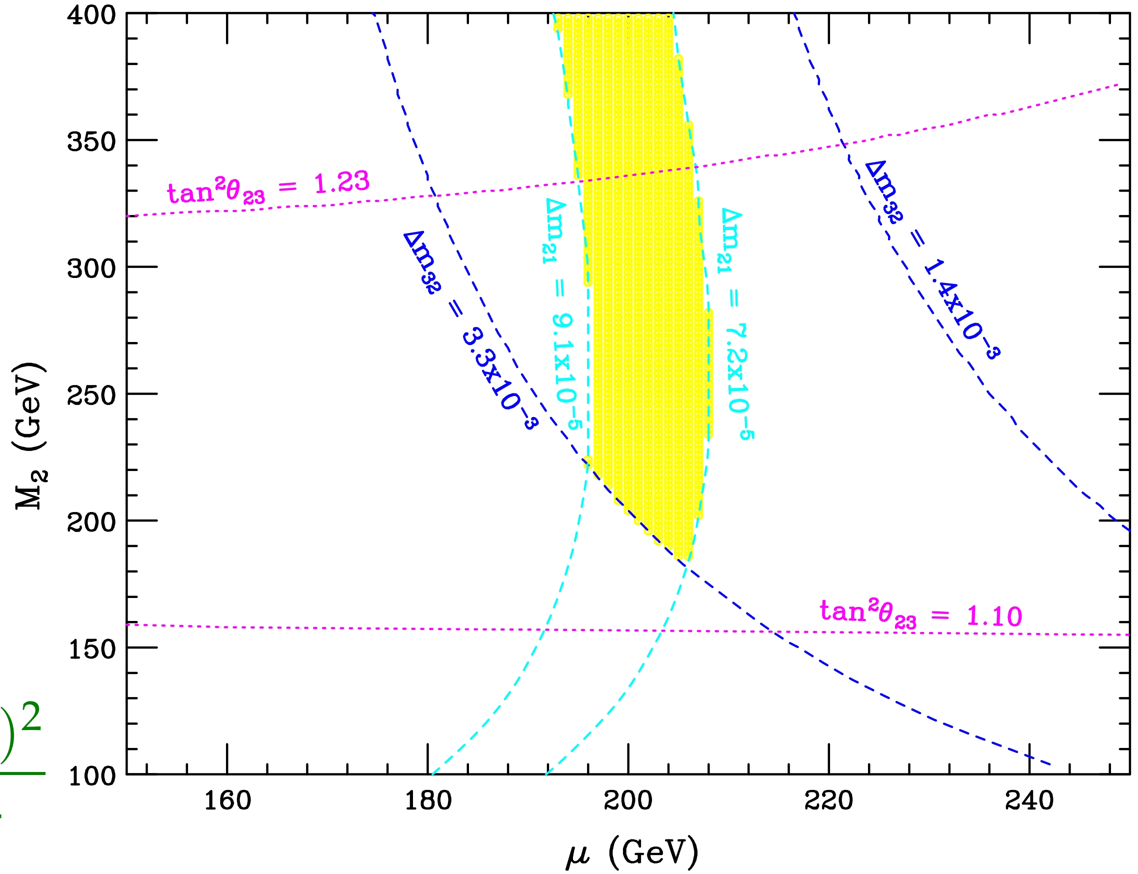
Gaugino-Higgsino mass plane

BRpV and Split Susy parameters are fixed to the benchmark values, except M_2 and μ, which are varied.

Perturbative expressions for the neutrino masses are,

$$m_{\nu_2} = C\frac{|\vec{\lambda}\times(\vec{\epsilon}\times\vec{\lambda})|^2}{|\vec{\lambda}|^4}$$

$$m_{\nu_3} = A|\vec{\lambda}|^2 + 2B(\vec{\epsilon}\cdot\vec{\lambda}) + C\frac{(\vec{\epsilon}\cdot\vec{\lambda})^2}{|\vec{\lambda}|^2}$$



with $A = -620$ GeV, $B = -0.95$ GeV, $C = 0.25$ GeV, and

$$M_\nu^{eff} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & A\lambda_2^2 & A\lambda_2\lambda_3 \\ 0 & A\lambda_2\lambda_3 & A\lambda_3^2 \end{bmatrix} + \begin{bmatrix} 0 & B\epsilon_1\lambda_2 & B\epsilon_1\lambda_3 \\ B\epsilon_1\lambda_2 & 0 & B\epsilon_3\lambda_2 \\ B\epsilon_1\lambda_3 & B\epsilon_3\lambda_2 & 2B\epsilon_3\lambda_3 \end{bmatrix} + \begin{bmatrix} C\epsilon_1^2 & 0 & C\epsilon_1\epsilon_3 \\ 0 & 0 & 0 \\ C\epsilon_1\epsilon_3 & 0 & C\epsilon_3^2 \end{bmatrix}$$

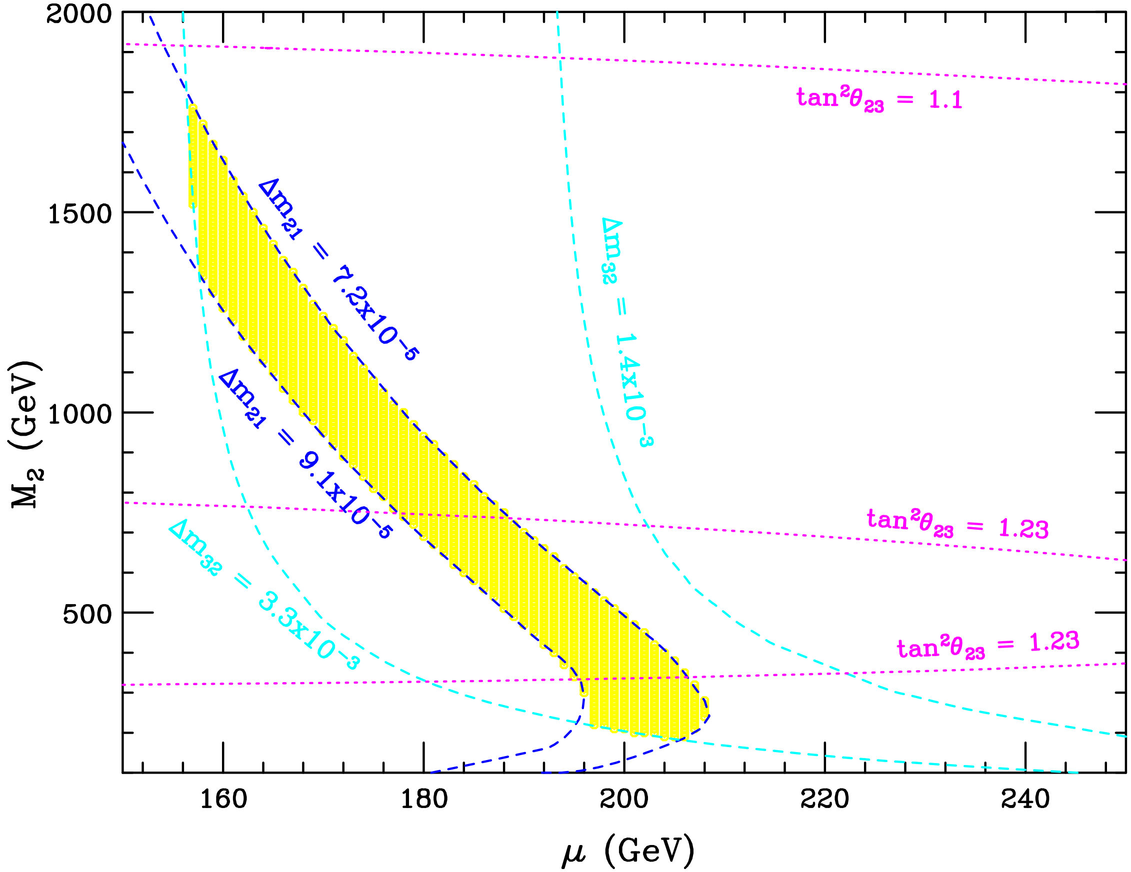
Gaugino-Higgsino mass plane

The eigenvectors at tree level are,

$$\vec{v}_1 = \frac{\vec{\epsilon}\times\vec{\lambda}}{|\vec{\epsilon}\times\vec{\lambda}|}$$

$$\vec{v}_2 = \frac{\vec{\lambda}\times(\vec{\epsilon}\times\vec{\lambda})}{|\vec{\lambda}\times(\vec{\epsilon}\times\vec{\lambda})|}$$

$$\vec{v}_3 = \frac{\vec{\lambda}}{|\vec{\lambda}|}$$



The rotation matrix is,

$$V_{PMNS} = \left(\begin{array}{c|c|c} v_{11} & v_{21} & v_{31} \\ v_{12} & v_{22} & v_{32} \\ v_{13} & v_{23} & v_{33} \end{array}\right) = \left(\begin{array}{c|c|c} c_{13}c_{12} & c_{13}s_{12} & s_{13} \\ -s_{23}s_{13}s_{12} & -s_{23}s_{13}s_{12}+c_{23}c_{12} & s_{23}c_{13} \\ -c_{23}s_{13}c_{12} & -c_{23}s_{13}s_{12}-s_{23}c_{12} & c_{23}c_{13} \end{array}\right)$$

from where the atmospheric, solar, and reactor angles can be obtained.

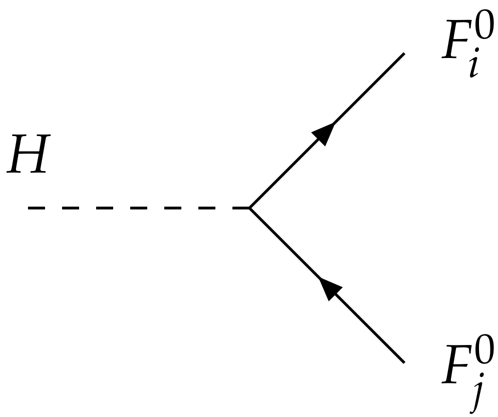
Conclusions

- Supersymmetry with Bilinear R-Parity Violation provides a framework for neutrino masses and mixing angles compatible with experiments.
- In Split Supersymmetry with BRpV the Higgs boson forms the only and crucial loop, and trilinear RpV couplings are essentially irrelevant.
- Neutrino parameters can be extracted from collider physics, specially from neutralino decays.

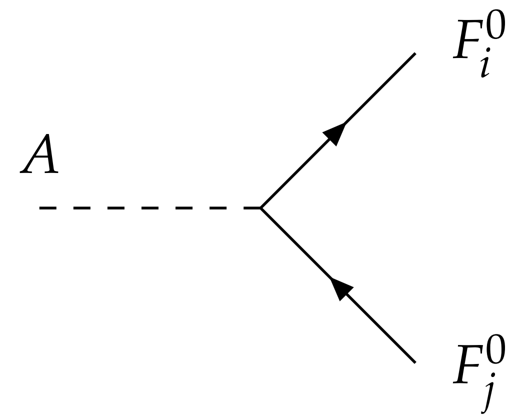
Effect of the Decoupling

For simplicity, we assume all sneutrinos very heavy and neglect the running from $\widetilde{m}$.

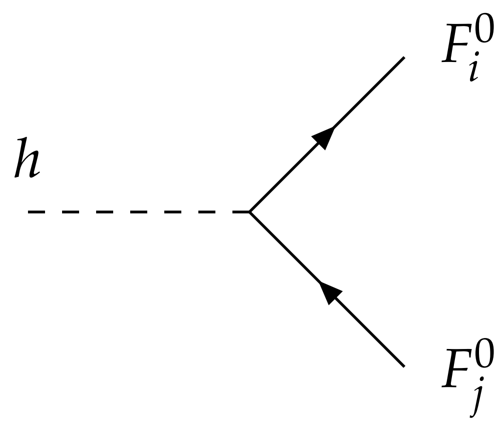
The CP-even and CP-odd Higgs loops depend on the couplings:



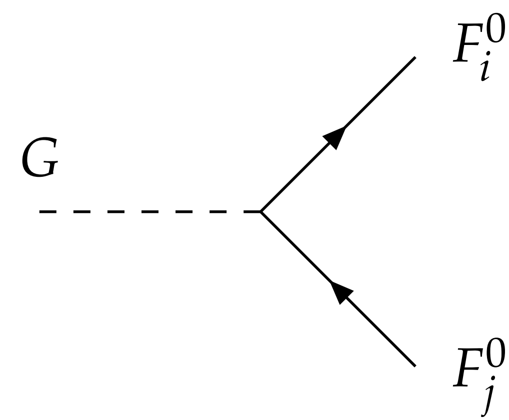
$$= i\,O_{ij}^{nnH} = -i\,(Q_{ij}^{nn} c_\alpha - S_{ij}^{nn} s_\alpha)$$



$$= O_{ij}^{nnA}\gamma_5 = (Q_{ij}^{nn} s_\beta - S_{ij}^{nn} c_\beta)\gamma_5$$



$$= i\,O_{ij}^{nnh} = i\,(Q_{ij}^{nn} s_\alpha + S_{ij}^{nn} c_\alpha)$$



$$= O_{ij}^{nnG}\gamma_5 = -(Q_{ij}^{nn} c_\beta + S_{ij}^{nn} s_\beta)\gamma_5$$

Effect of the Decoupling

The loops involving the k^{th} neutralino contribute with

$$\Delta\Pi^0_{ij} = -\frac{m_{\chi^0_k}}{16\pi^2}\Big[O^{\nu\chi H}_{ik}O^{\nu\chi H}_{jk}B_0^{0kH} + O^{\nu\chi h}_{ik}O^{\nu\chi h}_{jk}B_0^{0kh} - O^{\nu\chi A}_{ik}O^{\nu\chi A}_{jk}B_0^{0kA} - O^{\nu\chi G}_{ik}O^{\nu\chi G}_{jk}B_0^{0kG}\Big]$$

and in the limit of degenerate scalars and pseudoscalars:

$$O^{\nu\chi H}_{ik}O^{\nu\chi H}_{jk} + O^{\nu\chi h}_{ik}O^{\nu\chi h}_{jk} - O^{\nu\chi A}_{ik}O^{\nu\chi A}_{jk} - O^{\nu\chi G}_{ik}O^{\nu\chi G}_{jk} = 0$$

obtaining a cancellation between scalars and pseudoscalars. In Split Susy H and A are decoupled, with $s_\alpha = -c_\beta$ and $c_\alpha = -s_\beta$. The contribution to the neutrino mass matrix is,

$$\Delta\Pi^0_{ij} = -\frac{m_{\chi^0_k}}{16\pi^2}\left[O^{\nu\chi h}_{ik}O^{\nu\chi h}_{jk}B_0^{0kh} - O^{\nu\chi G}_{ik}O^{\nu\chi G}_{jk}B_0^{0kG}\right]$$

and in the limit of degenerate scalars and pseudoscalars:

$$O^{\nu\chi h}_{ik}O^{\nu\chi h}_{jk} - O^{\nu\chi G}_{ik}O^{\nu\chi G}_{jk} = -2s_\beta c_\beta(Q^{\nu\chi}_{ik}S^{\nu\chi}_{jk} + Q^{\nu\chi}_{jk}S^{\nu\chi}_{ik})$$

and the cancellation is incomplete.

Sugra: Three Neutrinos

Based on work by,

M.A. Díaz, Clemencia Mora, and Alfonso Zerwekh

Eur.Phys.J.C44,277(2005)

Sugra Parameters at the GUT Scale

Sugra is characterized by the following parameters, all defined at the GUT scale, except for $\tan\beta$ which is defined at the SUSY scale:

- m_0: Universal scalar mass.
- $M_{1/2}$: Universal gaugino mass.
- $\tan\beta$: Ratio between vev's.
- A_0: Common trilinear coupling.
- $\mathrm{sign}(\mu)$: Sign of higgsino mass.

In BRpV we add ϵ_i and Λ_i as input at the SUSY scale.

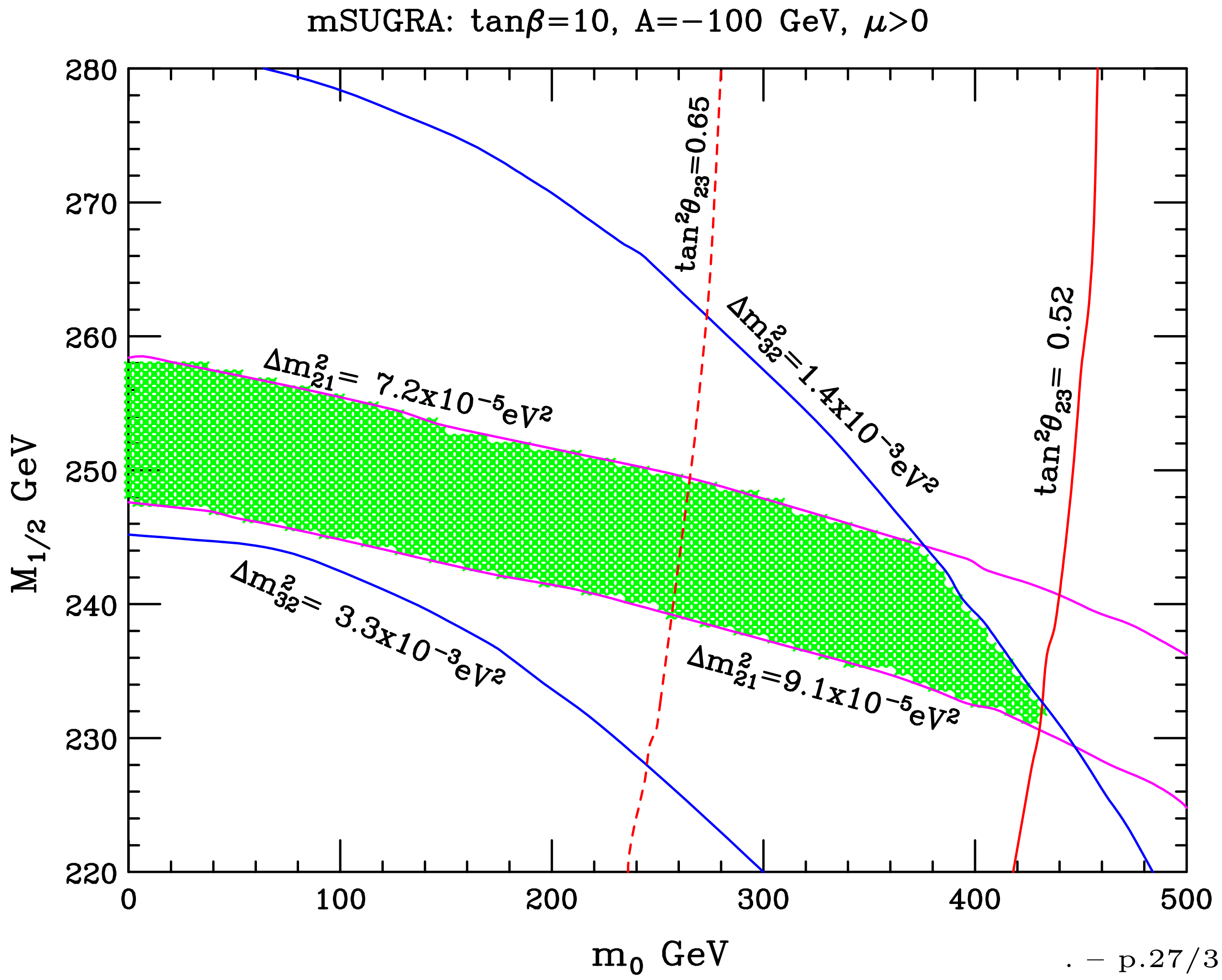
Neutrinos in Supergravity

Solutions to neutrino physics in a Sugra model with universal soft terms at the GUT scale, except for ϵ_i and $B_i (\Rightarrow \Lambda_i)$, which are free at the weak scale.

Input:

$$\epsilon_1 = -0.0004\,\text{GeV}$$
$$\epsilon_2 = 0.052\,\text{GeV}$$
$$\epsilon_3 = 0.051\,\text{GeV}$$

$$\Lambda_1 = 0.022\,\text{GeV}^2$$
$$\Lambda_2 = 0.0003\,\text{GeV}^2$$
$$\Lambda_3 = 0.039\,\text{GeV}^2$$



Sugra: scan on neutrino parameters

For a fixed sugra point in parameter space, ϵ_i and Λ_i are randomly varied, accepting solutions with good masses and mixing angles.

Spectrum:

$m(\chi_1^0) = 99\,\text{GeV}$

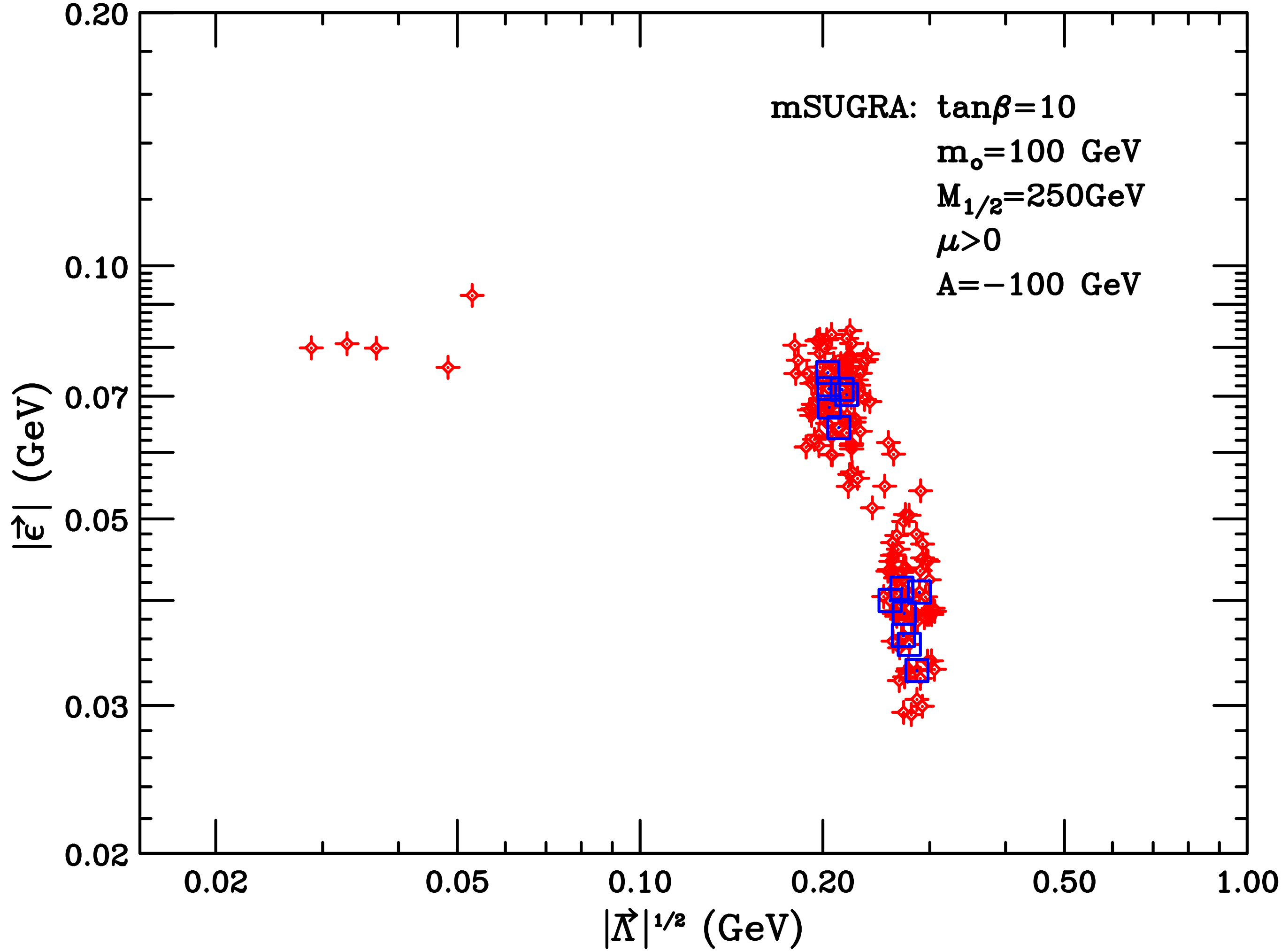
$m(\chi_1^\pm) = 175\,\text{GeV}$

$m(\tilde{t}_1) = 376\,\text{GeV}$

$m(\tilde{b}_1) = 492\,\text{GeV}$

$m(h) = 111\,\text{GeV}$

$m(H^\pm) = 408\,\text{GeV}$



Sugra scenario predictions

Sugra benchmark predicts,

$$\Delta m^2_{\rm atm} = 2.7 \times 10^{-3}\,{\rm eV}^2\,, \qquad \tan^2\theta_{\rm atm} = 0.72\,,$$
$$\Delta m^2_{\rm sol} = 8.1 \times 10^{-5}\,{\rm eV}^2\,, \qquad \tan^2\theta_{\rm sol} = 0.55\,,$$
$$m_{ee} = 0.0036\,{\rm eV}\,, \qquad \tan^2\theta_{13} = 0.0058\,,$$

within experimental bounds.

Atmospheric Mass

The atmospheric mass can be approximated as

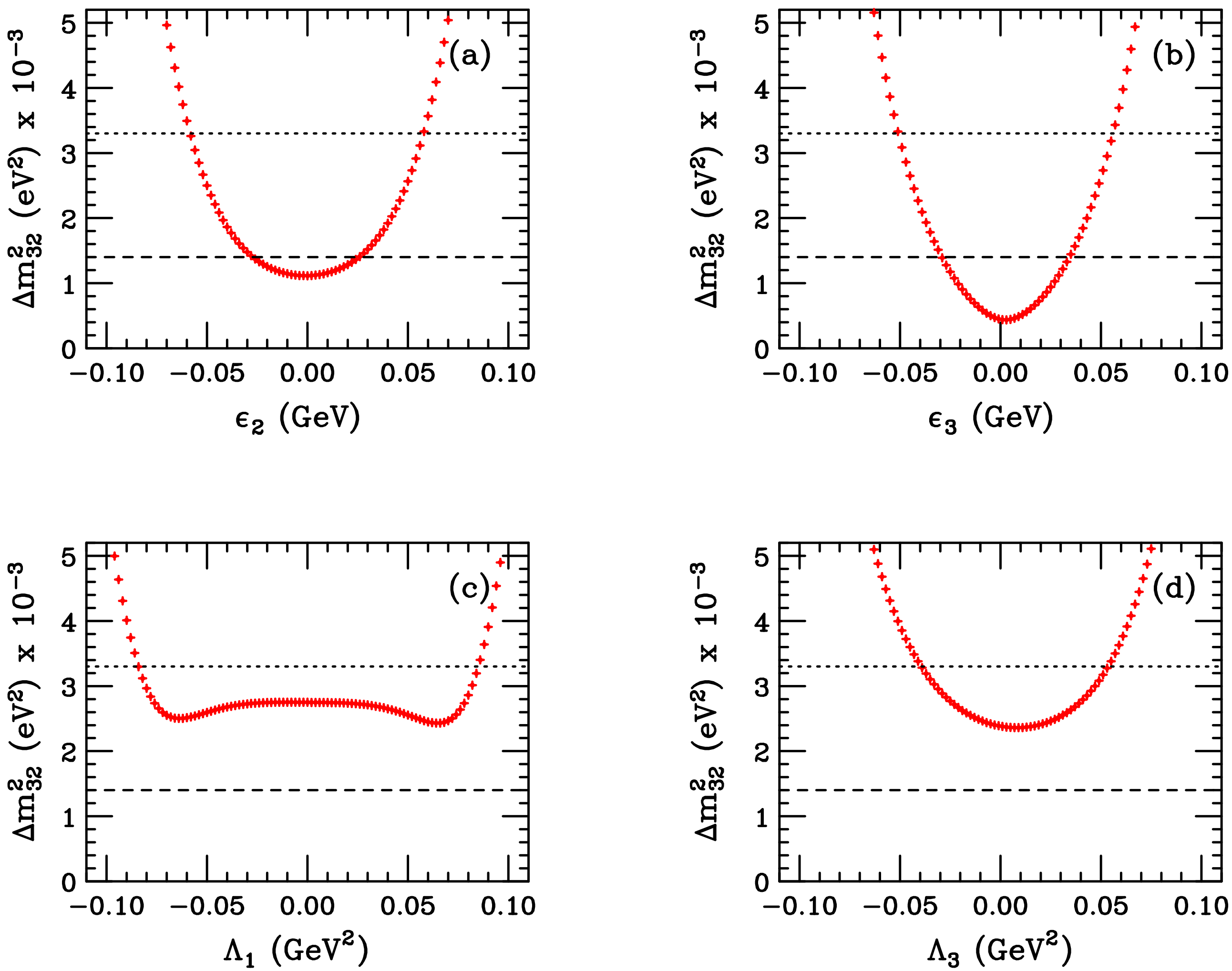
$$\Delta m^2_{32} \approx \frac{3}{2}\sqrt{5}(A\Lambda_3^2 + C\epsilon_3^2)C\epsilon_2^2$$

explaining the quadratic dependence of Δm^2_{32} on ϵ_2, ϵ_3, and Λ_3, and the mild dependence on Λ_1.

$A \approx 8$ eV/GeV^4

$B \approx -1$ eV/GeV^3

$C \approx 9$ eV/GeV^2



Atmospheric Angle

The atmospheric angle can be approximated as

$$\tan 2\theta_{23} \approx \frac{2C\epsilon_2\epsilon_3}{A\Lambda_3^2 + C(\epsilon_3^2 - \epsilon_2^2)} \left[\neq \tan 2\theta_{23}^{(0)} = \frac{2\Lambda_2\Lambda_3}{\Lambda_3^2 - \Lambda_2^2} \right]$$

If $\epsilon_2 \to 0$ then $\tan^2\theta_{23} \to 0$, as seen in frame (a).

If $\epsilon_3 \to 0$ then $\tan^2\theta_{23} \to \pi/2$, as seen in frame (b).