Tau Physics at SuperB Factory

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Tau physics and Lepton Flavour Violation

- Neutrino oscillation signatures suggest that Lepton Flavour Violating (LFV) decays will occur.
- B factories are an excellent place to study this by examining τ-decays.
- Can differentiate between various extensions of the Standard Model.
- Consider two models: MSSM+ν_R and $\not{L}$-MSSM .

MSSM$+\nu_R$

- Experiments suggest that neutrinos have a small, non-zero mass.
- The simplest way to extend the MSSM to incorporate this is by introducing a leptonic $SU(2)_L \times U(1)_Y$ singlet field, ν_R, to the Lagrangian
- Mixing between left- and right-handed interaction states, results in a Majorana neutrino with a 'see-saw' suppressed mass.

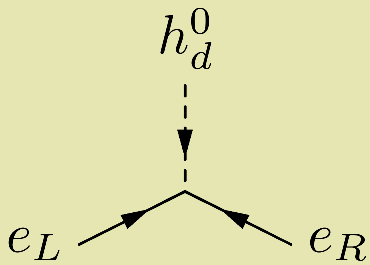
$$\Delta\mathcal{L} = -H_u \nu_R Y_\nu L - \frac{1}{2}\nu_R M_R \nu_R$$

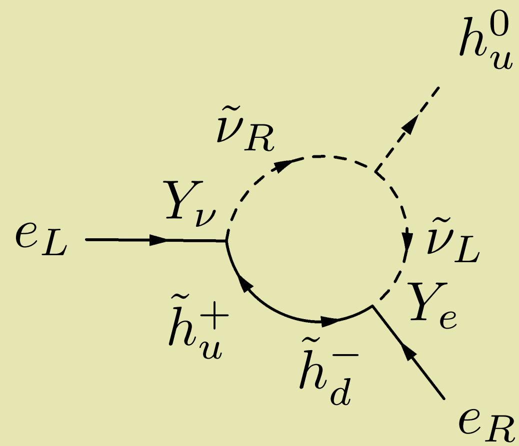
where $H_u = (h_u^+, h_u^0)$ and $L = (\nu_L, e_L)$

Gell-Mann, Ramond, Slansky; Yanagida '79

Non-holomorphic mass terms for charged leptons

- At loop level, extra mass terms at generated



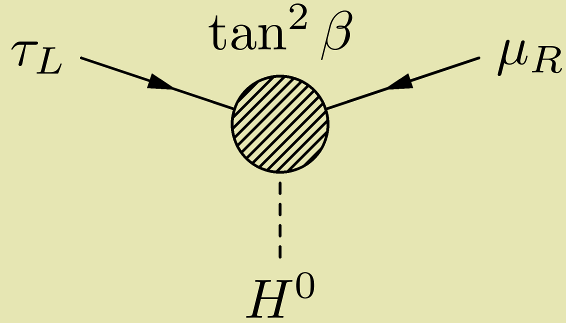


$$-\mathcal{L}_{\text{eff}} = e_R v_d Y_e e_L + e_R v_d Y_e[\varepsilon_1 + \varepsilon_2 Y_\nu^\dagger Y_\nu] e_L \tan\beta$$

- Cannot simultaneously diagonalise terms, giving rise to non-diagonal neutral Higgs interaction.

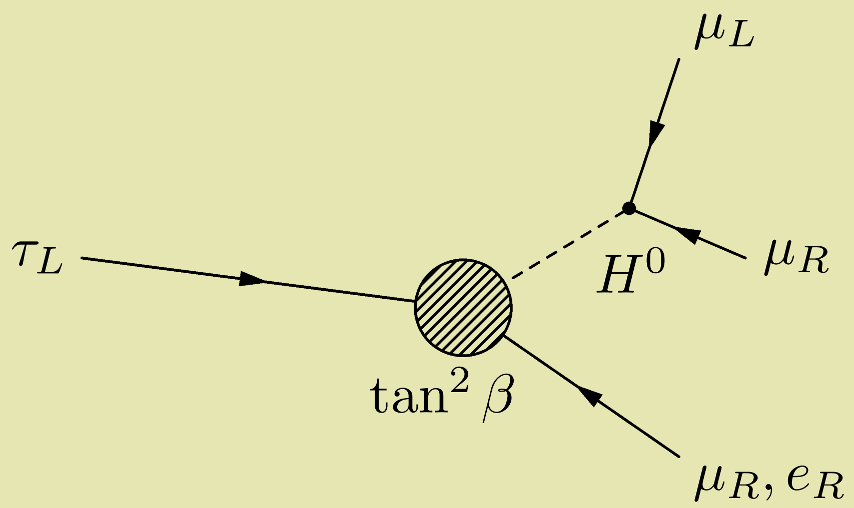
Babu, Kolda '99

- Effective Higgs vertex proportional to $\tan^2\beta$.



Babu, Kolda '99

Application 1: $\tau \to 3\mu, e\mu\mu$



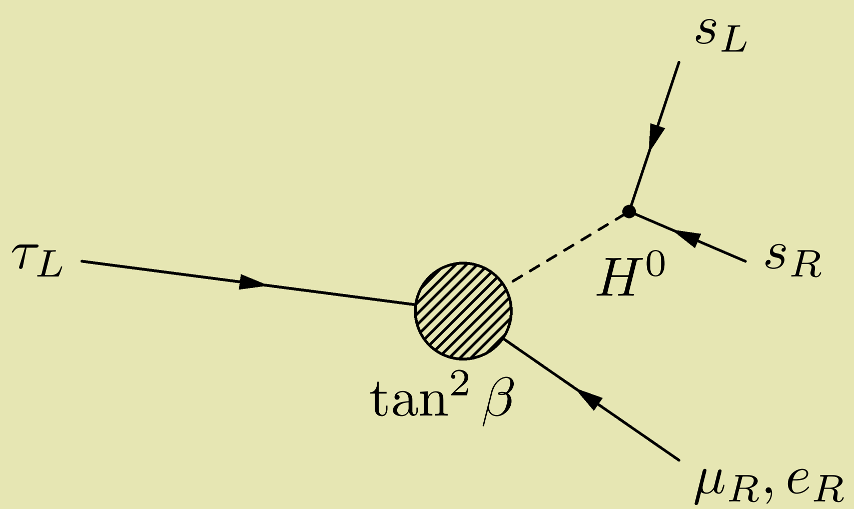
$$\mathcal{B}(\tau \to 3\mu)^{\rm Higgs} \simeq 1.6 \times 10^{-8} \left(\frac{\tan\beta}{60}\right)^6 \left(\frac{100{\rm GeV}}{M_{H_3}}\right)^4$$

$$\mathcal{B}(\tau \to 3\mu)^{\gamma} \simeq 3.0 \times 10^{-6} \left(\frac{\tan\beta}{60}\right)^2 \left(\frac{100{\rm GeV}}{M_{\rm SUSY}}\right)^4$$

If $M_H \ll M_{\rm SUSY} \simeq 1{\rm TeV}$ then the Higgs mediated diagram dominates.

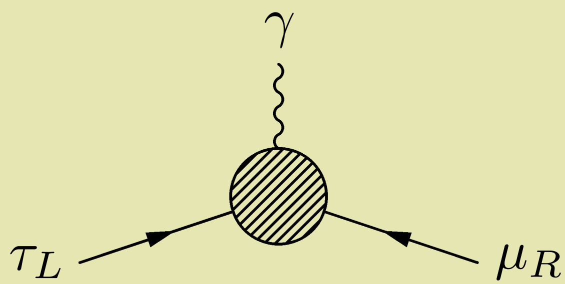
Dedes, Ellis, Raidal '02; Babu, Kolda '02

Application 2: $\tau \to \mu\eta$



$$\mathcal{B}(\tau \to \mu\eta)^{\text{Higgs}} = 8.4 \times \mathcal{B}(\tau \to 3\mu)^{\text{Higgs}}$$

$\tau \to \mu\gamma$



$$\mathcal{B}(\tau \to \mu\gamma) \simeq 1.3 \times 10^{-3} \left(\frac{\tan\beta}{60}\right)^2 \left(\frac{100\mathsf{GeV}}{M_{\mathsf{SUSY}}}\right)^4$$

Hisano, Moroi, Tobe, Yamaguchi '95

Bounds

$$\mathcal{B}(\tau \to \mu\gamma) < 6.8 \times 10^{-8}$$ BaBar (hep-ex/0502032)

$$\mathcal{B}(\tau \to \mu\eta) < 1.5 \times 10^{-7}$$ Belle (hep-ex/0503041)

- Higgs mediated LFV processes are indirectly contrained by the limits on the processes $l \to l'\gamma$ and $B_s^0 \to \mu\mu$.
- After applying constraints, the following bounds are produced.

$$\mathcal{B}(\tau \to 3\mu, e\mu\mu) \lesssim 4 \times 10^{-10}$$
$$\mathcal{B}(\tau \to \mu\eta) \lesssim 3 \times 10^{-9}$$

Dedes, Ellis, Raidal '02

See-saw MSSM conclusions

- Higgs boson mediated LFV processes are enhanced by powers of $\tan\beta$ and are orders of magnitude larger that the Standard Model predictions.

- $\tau \rightarrow \mu\gamma$ is currently the only LFV decay which can saturate the experimental bound.

- LFV modes such as $\tau \rightarrow 3\mu, e\mu\mu$ and $\tau \rightarrow \mu\eta$ turn out to be small, with $\mathcal{B} \sim 10^{-10} - 10^{-9}$ when current experimental constraints are imposed.

Lepton number violating MSSM

- The most general supersymmetric extension of the standard model, with minimal particle content contains terms which violate either lepton number or baryon number.

- The presence of both lepton number and baryon number violation leads to fast proton decay.

- To avoid this, we impose a discrete symmetry when constructing the Lagrangian.

- Two discrete symmetries are preferred: R-parity and $\mathcal{Z}_3$, which leaves just lepton number violating terms.

- $\not{L}$-MSSM gives rise to 'see-saw' suppressed neutrino masses, where gauginos and higgsinos provide the heavy mass scale.

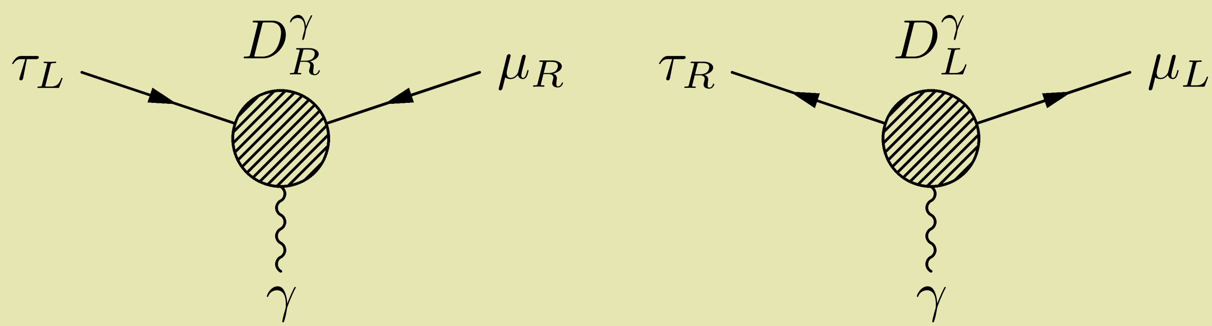
Ibanez, Ross '94; Joshipura, Nowakowski '95

Effective Operators

- LFV events can be derived in terms of effective operators, in a model independent manner.

- Leading contributions to the effective operators arise from $d = 6$, $SU(2)_L \times U(1)_Y$ invriant operators.

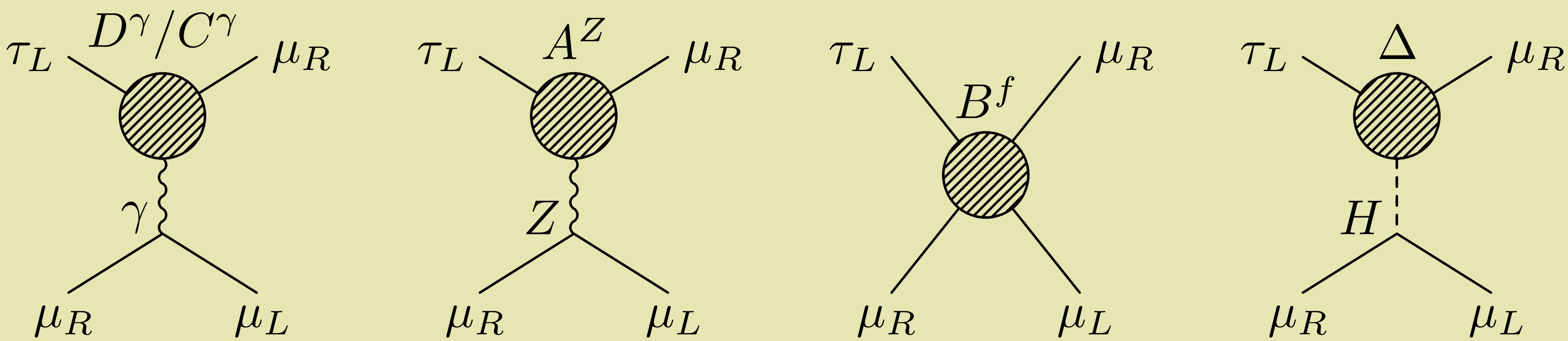
- For example, the $\tau - \mu - \gamma$ vertex, with an on-shell photon, arises from the following terms in the effective Lagrangian.



$$\mathcal{L}_{\rm eff} = e m_\tau \left[i D_L^\gamma \bar{\mu_L} \bar{\sigma}^{\mu\nu} \bar{\tau_R} + i D_R^\gamma \mu_R \sigma^{\mu\nu} \tau_L + \text{H.c.} \right] F_{\mu\nu}$$

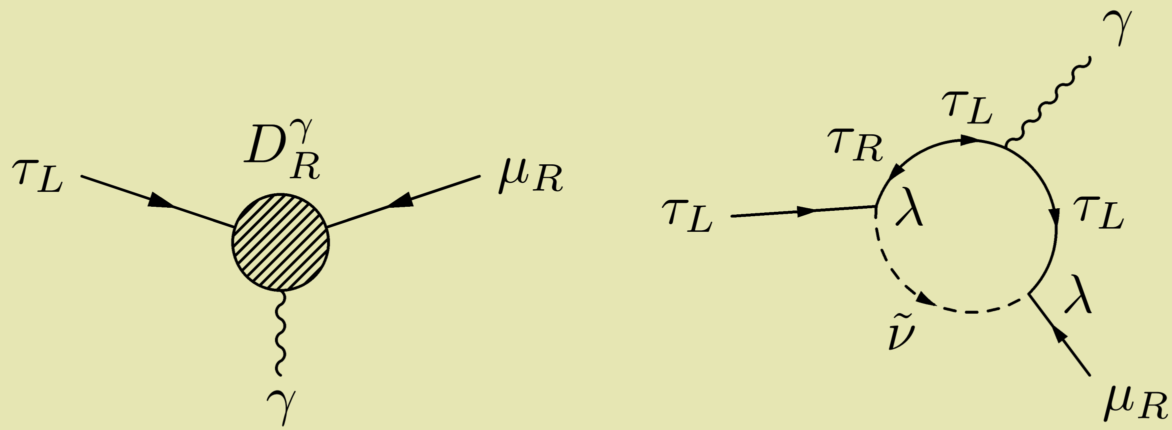
Brignole, Rossi '04

$\tau \to 3\mu$



$$\mathcal{B}(\tau \to 3\mu) = \mathcal{F}\left(C^\gamma, D^\gamma, A^Z, B^f, \Delta\right)\mathcal{B}(\tau \to \mu\bar{\nu}_\mu\nu_\tau)$$

$\tau \to \mu\gamma$



$$\mathcal{B}(\tau \to \mu\gamma) = \frac{48\pi^3\alpha}{G_F^2}\left[|D_L^\gamma|^2 + |D_R^\gamma|^2\right]\mathcal{B}(\tau \to \mu\bar{\nu}_\mu\nu_\tau)$$

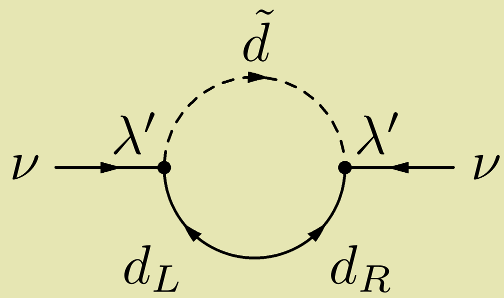
Neutrino masses in $\not{L}$-MSSM

- In the tree-level $\not{L}$-MSSM we obtain one massive, see-saw suppressed neutrino and two massless neutrinos.

- Loop corrections lift the degeneracy between the two massless neutrinos.

- The neutrino masses, and hence mass squared differences, are dependent on the values of lepton number violating couplings.

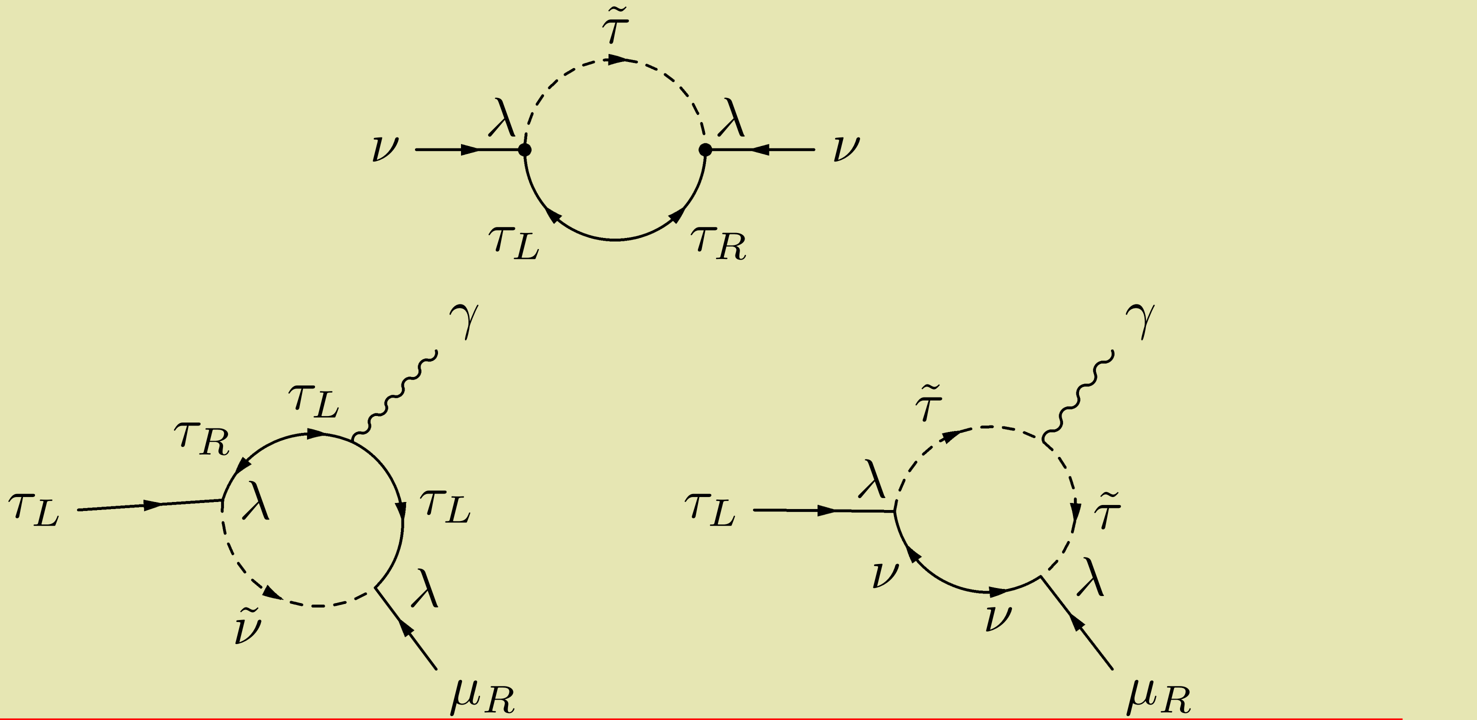
- Values for lepton violating couplings exist which reproduce experimental results for mass squared differences and mixing angles.



Dedes, SR, Rosiek '06

Interplay between τ-decay and neutrino masses

- The lepton number violating couplings which give rise to the mass squared differences observed in neutrino experiments will be correlated with the branching ratios for τ-decays.



Summary and Conclusions

- τ-decays at B-factories will provide useful information in determining the phenomenology of physics beyond the Standard Model.
- The see-saw MSSM is well studied; predictions for, and relations between, branching ratios exist in the literature.
- The $\not{L}$-MSSM will provide different experimental signatures making it possible to discern the various models.
- We intend to study $\not{L}$-MSSM lepton flavour violating events further, including LFV events which may occur at tree level, such as neutrinoless double beta decay or μ-e conversion in the nucleus.
- It will be possible to correlate experimental results from neutrino physics with LFV experiments.

A supersymmetric standard model

Find the most general Lagrangian which is

- invariant under Lorentz, $SU(3)_C \times SU(2)_L \times U(1)_Y$
  and supersymmetry transformations; renormalizable
- minimal in particle content

Neither lepton number (L) nor baryon number (B) are conserved
Two options:

- constrain lagrangian parameters
- impose a further discrete symmetry when constructing the lagrangian

Superpotential

Lagrangian contains terms of the form

$$\text{Yukawa Terms:} -\frac{1}{2}\frac{\partial^2 \mathcal{W}}{\partial\varphi_i \partial\varphi_j}\psi_i\psi_j - \text{H.c.}$$

$$\text{F-terms:} -\sum_i \left|\frac{\partial \mathcal{W}}{\partial\varphi_i}\right|^2$$

where the most general superpotential is given by

$$\mathcal{W} = Y_E L H_1 E + Y_D H_1 Q D^c + Y_U Q H_2 U^c - \mu H_1 H_2$$

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$$+\frac{1}{2}\lambda L L E^c + \lambda' L Q D^c - \kappa L H_2$$

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$$+\frac{1}{2}\lambda L L E^c + \lambda' L Q D^c - \kappa L H_2$$

$$+\frac{1}{2}\lambda'' U^c D^c D^c$$

R-parity

Under R-parity

- Standard model particles (including scalar Higgs bosons) are even
- corresonding superpartners are odd

If R-parity is imposed when constructing the Lagrangian

- Terms in the Lagrangian which violate either L or B are excluded
- The lightest supersymmetric particle (LSP) is stable
- Sneutrino fields do not acquire a non-zero vacuum expectation values; R-parity is not violated spontaneously

R-parity conserving minimal supersymmetric standard model (Rpc-MSSM)

Neutral scalar particle content

- neutral, complex scalar components of two higgs chiral supermultiplets, h_2^0 and h_1^0
- neutral, complex scalar components of lepton supermultiplets, $\tilde{\nu}_{Li}$

If R_P conservation is imposed on the Lagrangian there are no bilinear terms which cause mixing between fields with different R_P.

No mixing between Higgs bosons and sneutrinos.

The neutral scalars decouple into CP-even and CP-odd real scalar eigenstates
The Higgs bosons

$$\{h_2^0, h_1^0\} \longrightarrow \{h^0, H^0, A^0, G^0\}$$

and the sneutrinos

$$\tilde{\nu}_{Li} \longrightarrow \{\tilde{\nu}_{+\,i}, \tilde{\nu}_{-\,i}\}$$

The scalar potential can be minisimised to obtain values for the vacuum expectation values (vevs) of h_2^0 and h_1^0.

R-parity violating minimal supersymmetric standard model (Rpv-MSSM)

Without imposing the conservation of R-parity on the Lagrangian, bilinear terms exist between (and hence, mixing occurs between)

- charged gauginos, charged higgsinos and charged leptons
- neutral gauginos, neutral higgsinos and neutrinos
- Higgs bosons, sneutrinos
- . . .

giving rise to some attractive features.
The mixing between neutrinos and neutral gauginos/higgsinos produces one tree-level, 'see-saw' suppressed, neutrino mass.

B. C. Allanach, A. Dedes and H. K. Dreiner, Phys. Rev. D **69**, 115002 (2004)

Neutrino-neutralino mass matrix

$$\mathcal{L} \supset -\frac{1}{2}\begin{pmatrix} -i\tilde{B}^0 & -i\tilde{W}^0 & \tilde{h}_2^0 & \tilde{h}_1^0 & \nu_i \end{pmatrix} \mathcal{M}_\mathcal{N} \begin{pmatrix} -i\tilde{B}^0 \\ -i\tilde{W}^0 \\ \tilde{h}_2^0 \\ \tilde{h}_1^0 \\ \nu_i \end{pmatrix}$$

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$$\mathcal{M}_{\mathcal{N}} = \begin{pmatrix} M_1 & 0 & gv_u/\sqrt{2} & -gv_d/\sqrt{2} & -gv_j/\sqrt{2} \\ 0 & M_2 & -g_2v_u/\sqrt{2} & g_2v_d/\sqrt{2} & g_2v_j/\sqrt{2} \\ gv_u/\sqrt{2} & -g_2v_u/\sqrt{2} & 0 & \mu & \kappa_j \\ -gv_d/\sqrt{2} & g_2v_d/\sqrt{2} & \mu & 0 & 0_j \\ -gv_i/\sqrt{2} & g_2v_i/\sqrt{2} & \kappa_i & 0_i & 0_{ij} \end{pmatrix}$$

$$\langle h_2^0 \rangle = v_u \quad \langle h_1^0 \rangle = v_d \quad \langle \tilde{\nu}_{Li} \rangle = v_i$$

$$\mathcal{M}_{\mathcal{N}} = \begin{pmatrix} M_1 & 0 & gv_u/\sqrt{2} & -gv_d/\sqrt{2} & -gv_j/\sqrt{2} \\ 0 & M_2 & -g_2 v_u/\sqrt{2} & g_2 v_d/\sqrt{2} & g_2 v_j/\sqrt{2} \\ gv_u/\sqrt{2} & -g_2 v_u/\sqrt{2} & 0 & \mu & \kappa_j \\ -gv_d/\sqrt{2} & g_2 v_d/\sqrt{2} & \mu & 0 & 0_j \\ -gv_i/\sqrt{2} & g_2 v_i/\sqrt{2} & \kappa_i & 0_i & 0_{ij} \end{pmatrix}$$

A. S. Joshipura and M. Nowakowski, Phys. Rev. D **51**, 2421 (1995)
M. Nowakowski and A. Pilaftsis, Nucl. Phys. B **461**, 19 (1996)

$$
\mathcal{M}_{\mathcal{N}} = \left(\begin{array}{cccc|c} M_1 & 0 & g v_u/\sqrt{2} & -g v_d/\sqrt{2} & -g v_j/\sqrt{2} \\ 0 & M_2 & -g_2 v_u/\sqrt{2} & g_2 v_d/\sqrt{2} & g_2 v_j/\sqrt{2} \\ g v_u/\sqrt{2} & -g_2 v_u/\sqrt{2} & 0 & \mu & \kappa_j \\ -g v_d/\sqrt{2} & g_2 v_d/\sqrt{2} & \mu & 0 & 0_j \\ \hline -g v_i/\sqrt{2} & g_2 v_i/\sqrt{2} & \kappa_i & 0_i & 0_{ij} \end{array} \right)
$$

$$
\mathcal{M}_{\mathcal{N}} = \left(\begin{array}{cc} M_{\tilde{\chi}\,4\times 4} & m_{4\times 3} \\ m^T_{3\times 4} & 0_{3\times 3} \end{array} \right)
$$

Suggestive of the seesaw mechanism

4 eigenvalues $\sim M_{\tilde{\chi}}$ 3 eigenvalues $\sim \frac{mm^T}{M_{\tilde{\chi}}}$

$$\mathcal{M}_{\mathcal{N}} = \left(\begin{array}{ccc|cc} M_1 & 0 & g v_u/\sqrt{2} & -g v_d/\sqrt{2} & -g v_j/\sqrt{2} \\ 0 & M_2 & -g_2 v_u/\sqrt{2} & g_2 v_d/\sqrt{2} & g_2 v_j/\sqrt{2} \\ g v_u/\sqrt{2} & -g_2 v_u/\sqrt{2} & 0 & \mu & \kappa_j \\ -g v_d/\sqrt{2} & g_2 v_d/\sqrt{2} & \mu & 0 & 0_j \\ \hline -g v_i/\sqrt{2} & g_2 v_i/\sqrt{2} & \kappa_i & 0_i & 0_{ij} \end{array} \right)$$

$$\mathcal{M}_{\mathcal{N}} = \left(\begin{array}{cc} N_{4\times 3} & n_{4\times 4} \\ n'_{3\times 3} & 0_{3\times 4} \end{array} \right)$$

The mass^2 given by eigenvalues of $\mathcal{M}_{\mathcal{N}}^{\dagger}\mathcal{M}_{\mathcal{N}}$

$$n = \begin{pmatrix} -gv_d/\sqrt{2} & -gv_1/\sqrt{2} & -gv_2/\sqrt{2} & -gv_3/\sqrt{2} \\ g_2v_d/\sqrt{2} & g_2v_1/\sqrt{2} & g_2v_2/\sqrt{2} & g_2v_3/\sqrt{2} \\ \mu & \kappa_1 & \kappa_2 & \kappa_3 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

n has 3 linearly dependant rows, giving two zero eigenvalues with corresponding eigenvectors $\vec{e}_{1,2}$

$$\mathcal{M}_{\mathcal{N}}\vec{q}_i = \begin{pmatrix} N_{4\times 3} & n_{4\times 4} \\ n'_{3\times 3} & 0_{3\times 4} \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 0 \\ \vdots \\ \vdots \\ \vec{e}_i \\ \vdots \end{pmatrix} = \begin{pmatrix} \vdots \\ \vdots \\ \lambda_i \vec{e}_i \\ \vdots \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$\vec{q}_{1,2}$ are zero eigenvectors of the full matrix.

The neutral scalar bosons all mix

$$\{h_2^0, h_1^0, \tilde{\nu}_{Li}\} \longrightarrow \{h^0, H^0, A^0, G^0, \tilde{\nu}_{+\,i}, \tilde{\nu}_{-\,i}\}$$

In general

- 10×10 mixing matrix of real, scalar fields.
- Solve minimisation conditions to find 5 complex vevs.
- Not clear which phases can be rotated away and which are physical; explicit CP-violation?
- Not clear if vevs are real; spontaneous CP-violation?

Vanishing sneutrino vev basis

Notice that if R_P is not imposed, h_1^0 and $\tilde{\nu}_{Li}$ carry the same quantum numbers, even before symmetry breaking.
Define $\tilde{\nu}_{L\alpha} = (h_1^0, \tilde{\nu}_{Li}) \qquad \mu_\alpha = (\mu, \kappa_i)$
Solving the minimisation conditions defines a direction in this $(h_1^0, \tilde{\nu}_{Li})$ space.
In the interaction basis, we are free to define any direction in $(h_1^0, \tilde{\nu}_{Li})$ to be the Higgs.
Had the basis been rotated such that the Higgs points in this direction, a basis would have been chosen such that the sneutrino vevs are zero.

M. Bisset, O. C. W. Kong, C. Macesanu and L. H. Orr, Phys. Lett. B **430**, 274 (1998)
Y. Grossman and H. E. Haber, Phys. Rev. D **59**, 093008 (1999)