PhD meeting
Niels Bohr International Academy
May 22nd, 2012

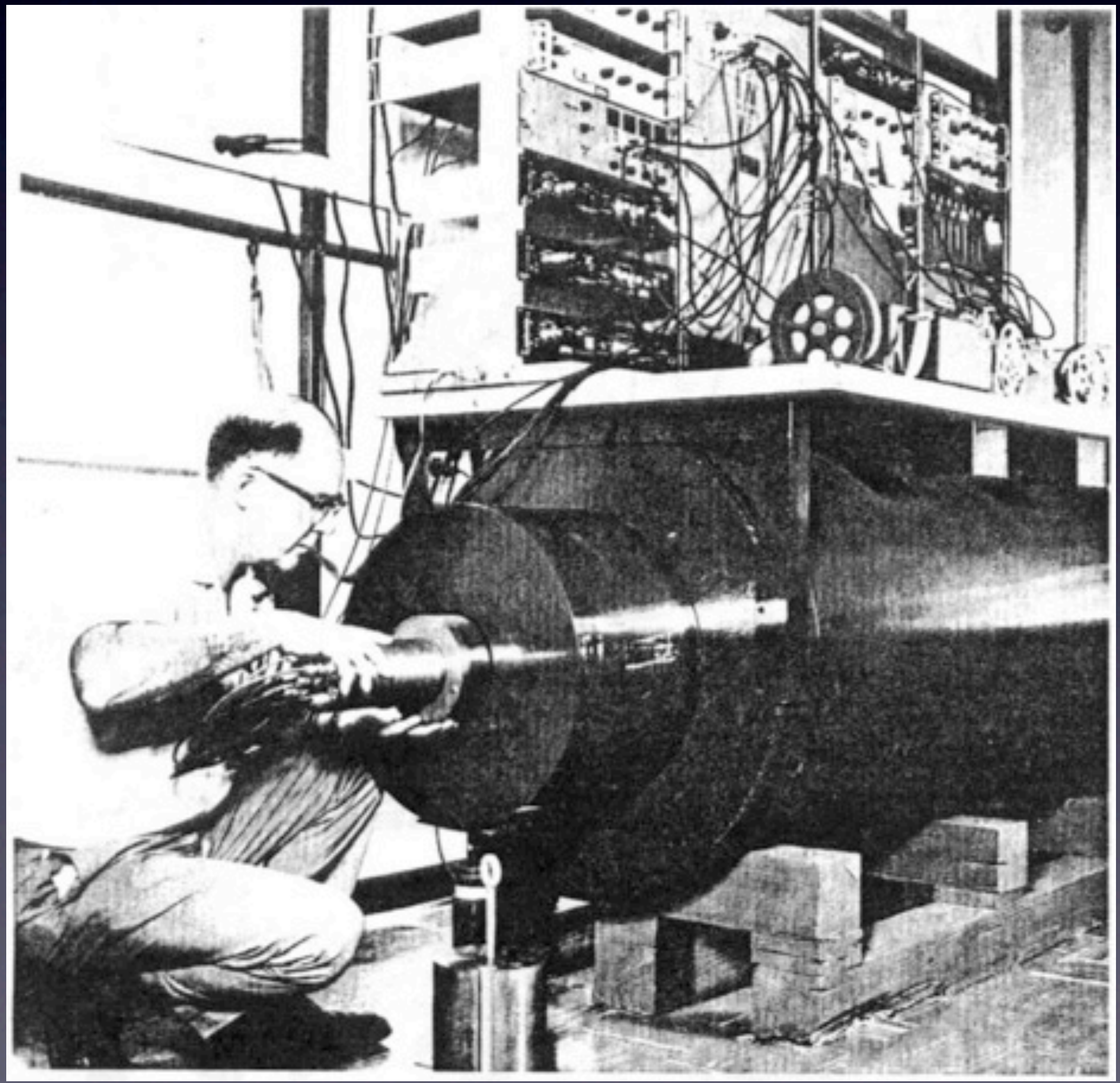
The "New physics" behind neutrino masses

By Christine Hartmann
Advisors: Professor A. Zee,
Professor Poul Henrik Damgaard

The neutrino reveals itself...

Raymond Davies
Homestake Mine experiment, South Dakota in 1960's
Nobel prize in 2002

Wolfgang Pauli
Postulated neutrino in 1930
Nobel prize in 1945



Oscillation probability
-depends on mass differences

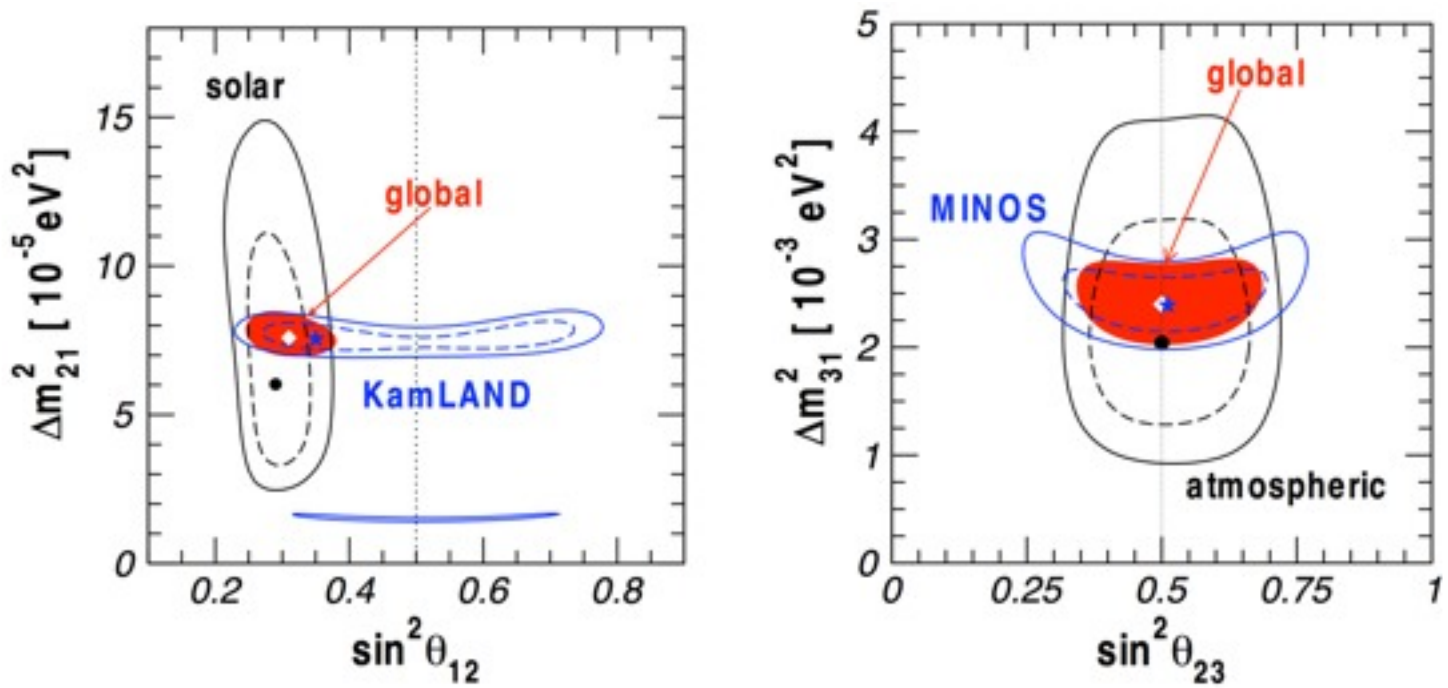
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = V \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha,\beta} - 4 \sum_{j<i=1} \mathrm{Re}[U^*_{\beta j} U_{\alpha j} U_{\beta i} U^*_{\alpha i}] \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) \pm 2 \sum_{j<i=1} \mathrm{Im}[U^*_{\beta j} U_{\alpha j} U_{\beta i} U^*_{\alpha i}] \sin^2\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

Solar and atmospheric neutrino experiment results - only angles and mass squared differences



Parameter	Best fit $\pm 1\sigma$	2 σ	3σ
$\Delta m^2_{12}[10^{-5}eV^2]$	7.62 ± 0.19	7.27-8.01	7.12-8.20
$\lvert\Delta m^2_{32}\rvert[10^{-3}eV^2]$	$2.53^{+0.08}_{-0.10}$ $-(2.40^{+0.10}_{-0.07})$	2.34-2.69 -(2.25-2.59)	2.26-2.77 -(2.15-2.68)
$\sin^2\theta_{12}$	$0.320^{+0.015}_{-0.017}$	0.29-0.35	0.27-0.37
$\sin^2\theta_{23}$	$0.49^{+0.07}_{-0.05}$ $0.53^{+0.05}_{-0.07}$	0.41-0.62 0.42-0.62	0.39-0.64
$\sin^2\theta_{13}$	$0.26^{+0.003}_{-0.004}$ $0.27^{+0.003}_{-0.004}$	0.019-0.033 0.020-0.034	0.015-0.036 0.016-0.037
δ	$(0.83^{+0.54}_{-0.64}\pi$ 0.07π	$0 - 2\pi$	$0 - 2\pi$

Dirac or Majorana?

Dirac: Yukawa type coupling to right-handed neutrinos.

$$\bar{\nu}_R \phi \psi_L + h.c.$$

Majorana: Right-handed neutrino = antiparticle of the left-handed state.

$$\nu_R \rightarrow (\nu_L)^c = C\bar{\nu}_L^T$$

Neutrinos own antiparticles =>

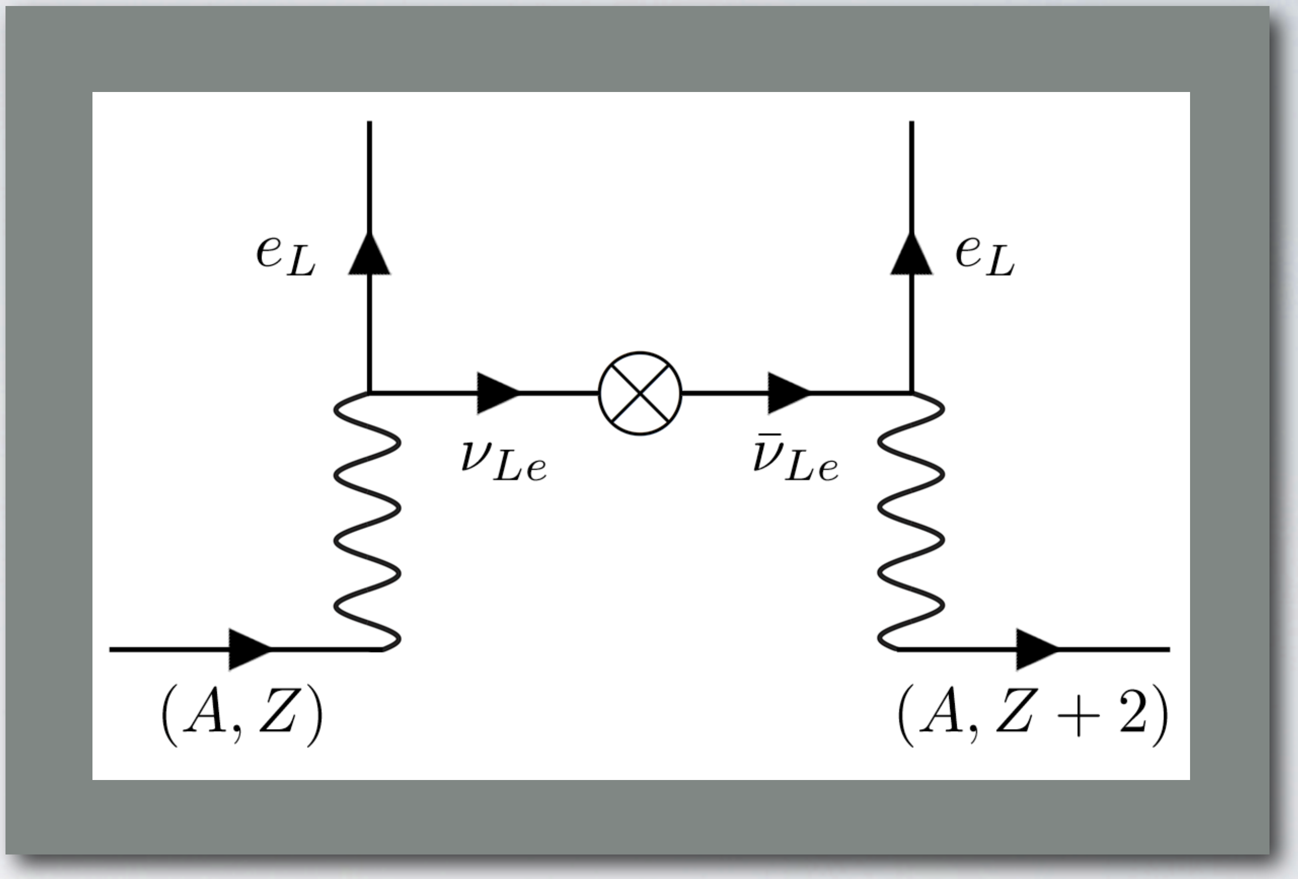
Introduce new non-renormalizable operator.

$$(\phi\tau_2\psi_L)C(\phi\tau_2\psi_L)$$

=> lepton number violation, not forbidden!
Effective field theory - low energy physics, large cut-off scales in denominator, naturally small masses.

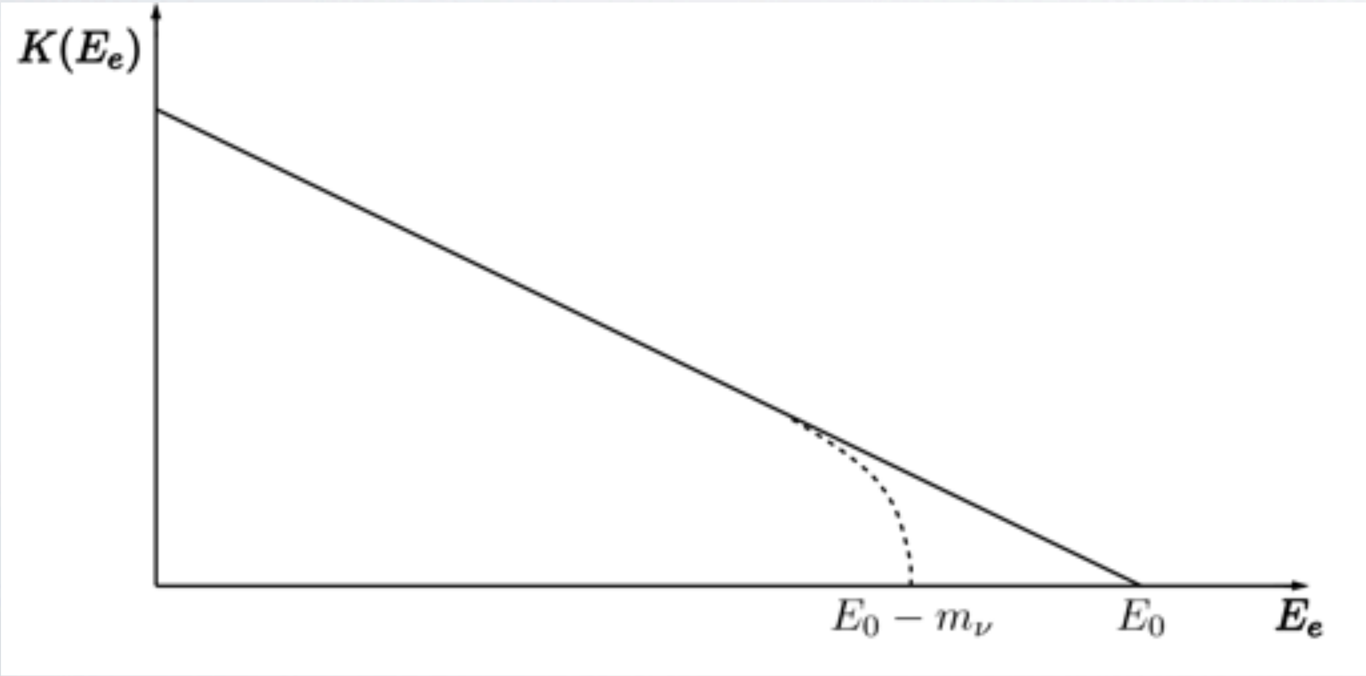
Mass limits from experiments

Neutrinoless double beta decay -Majorana neutrinos



$$|m_{ee}| = |m_1 U_{11}^2 + m_2 U_{12}^2 + m_3 U_{13}^2|$$
$$= \frac{1}{3}|2m_1 + m_2|$$

$$|m_{ee}| \leq 0.38\,\text{eV}$$



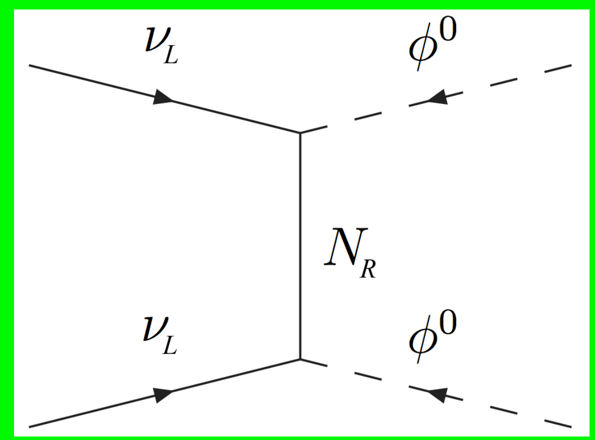
Tritium beta decay - electron spectrum near endpoint

$$m_\beta = (|U_{ei}|^2 m_i^2)^{1/2} \leq 2.2eV$$

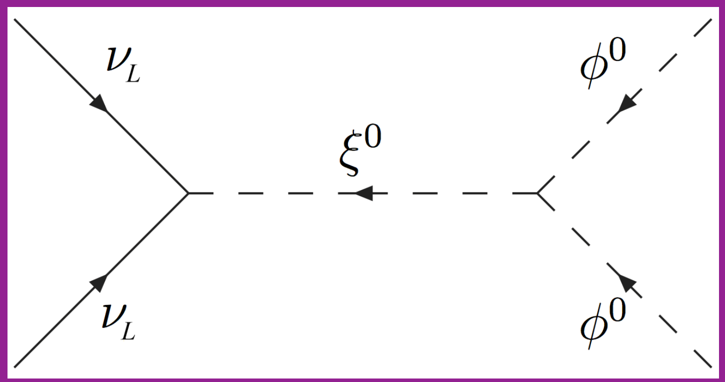
See-saw mechanism

$$\mathcal{O}_5 = \frac{1}{M}(\phi\tau_2\psi)^T C(\phi\tau_2\psi)$$

Type I:



Type II:



Type III: Type I with $N \leftrightarrow \Sigma^0$

Type I see-saw mechanism

$$\boxed{\mathcal{L}^\nu = \bar{\psi}\lambda_\phi \phi N_R + \frac{1}{2} N_R^T C M_R N_R + \text{h.c.}}$$

$$M_D = \lambda_\phi v$$

$$\mathcal{M} \;= \begin{pmatrix} 0 & \lambda_\phi v \\ \lambda_\phi^T v & M_R \end{pmatrix} = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}$$

"See-saw": $\lambda_+ \simeq M_R, \quad \lambda_- \simeq -\dfrac{M_D^2}{M_R}$

$$\boxed{\mathcal{M}_\nu = \; -M_D^T M_R^{-1} M_D}$$

$$\mathcal{L}^\nu = -\psi^T \phi_1^T C(\lambda_\phi \frac{1}{M_R} \lambda_\phi^T) \phi_2 \psi$$

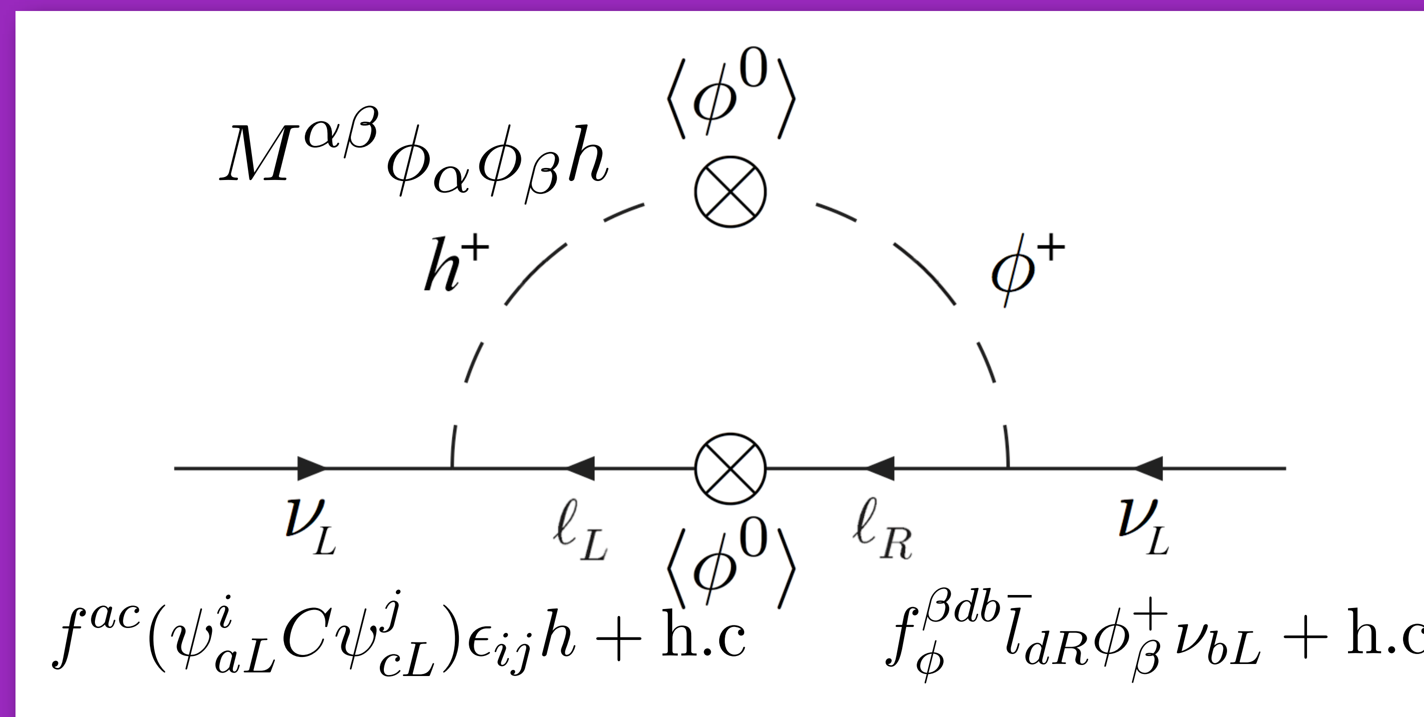
Radiative loop corrections
Zee model

Extra scalar field:

h^+

$$f_\phi^{\beta cd}\bar{l}_{dR}\phi_\beta^0 l_{cL} + \text{h.c}$$

$$m_{cd} = \Sigma_\beta f_\phi^{\beta cd} v_\beta$$



$$M_{ab} = \frac{1}{16\pi^2} f^{ac} m_{cd} f_\phi^{\beta db} v_\alpha M_{\alpha\beta} \frac{1}{m_h^2}\left[\ln\left[\frac{m_{\phi^2}}{m_h^2}\right]\right]$$

How to find the masses?

Need more constraints...

Possible solution: Group theory!

Neutrinos have 3 flavors. Impose finite flavor symmetry with 3 dimensional representations.

Already done, mostly using the tetrahedral group.

My thesis: The Frobenius group

Subgroup of SU(3)

Convenient Irreducible Representations:

$$\mathbf{1} \quad \mathbf{1}' \quad \bar{\mathbf{1}}' \quad \mathbf{3_1} \quad \bar{\mathbf{3}}_\mathbf{1} \quad \mathbf{3_2} \quad \bar{\mathbf{3}}_\mathbf{2}$$

Conclusions

- The neutrino masses have caused a "New physics" problem, where the Standard Model is not a sufficient model.

- Two popular mechanisms have used the Majorana nature of neutrinos to explain the existence of their masses and the small nature.

- Experiments can not predict the absolute masses of the neutrinos. There is still a search for models with enough constraints to predict the masses.

- Using group theory to place enough constraints to predict the masses seems to be a plausible method.