An Overview of Neutrino Physics

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Lecture 3: Outline

- Absolute Neutrino Mass
- Origin of Seesaw
- Three Types of Seesaw
- Seesaw at LHC
- Neutrinoless Double Beta decay

Absolute Neutrino Masses

- Tritium β-deay

  $m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$

  Present bound:

  $m_\beta < 2.3$ eV (95% C.L.) (Mainz, Troisk)

- Neutrinoless double beta decay

  $m_{\beta\beta} = \mid c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \mid$

  Present bound:

  $m_{\beta\beta} < 0.25 - 0.52$ (GERDA),

  $m_{\beta\beta} < 0.11 - 0.25$ (Xe)

  Nuclear Matrix Element Uncertainty

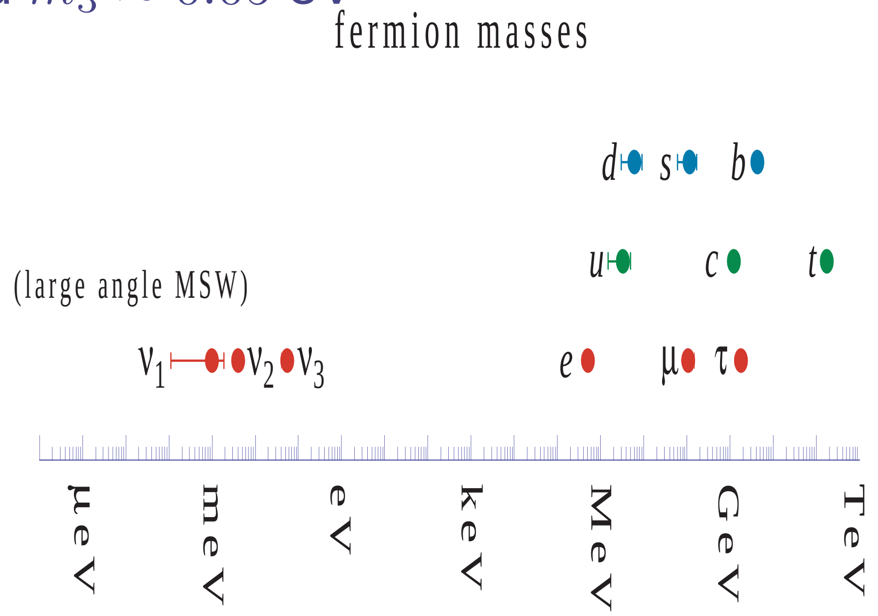
- Cosmology

  $m_{cosmo} = \Sigma m_i$

  Varies from $\approx$ 0.2 - 1 eV depending on the data set used

Neutrino Masses

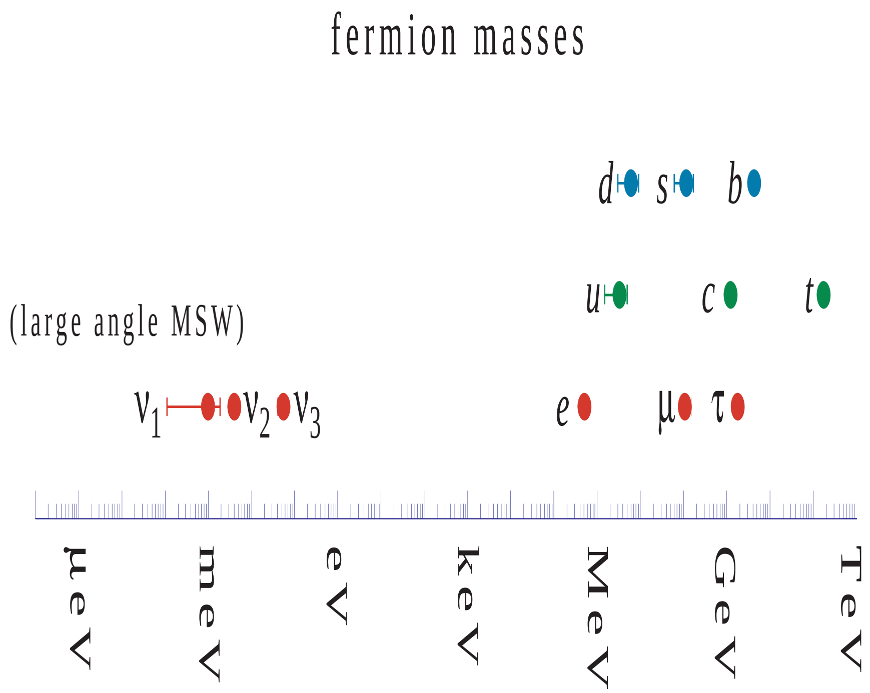
- For normal hierarchy:
  $m_1 \approx 0$, $m_2 \approx 0.009$ eV and $m_3 \approx 0.05$ eV



- Neutrino masses much smaller than quark and charged lepton masses
- Hierarchy of neutrino masses not strong : $m_3/m_2 \leq 6$
- completely different from quark sector
- Inverted hierarchy and quasidegeneracy has no analogue in quark sector

Models for Neutrino Mass: Key Issues

- Why neutrino masses are much smaller than quark and lepton masses



- Most natrural way for generating small neutrino masses is the Seesaw Mechanism

Models for Neutrino Mixing: Key Issues

- Why two large and one small mixing angle unlike in quark sector where all mixing angles are small
- Close to Tri-bimaximal form

$$U_{TBM} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}} \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix} \mathrm{diag}(e^{i\alpha_1/2}, e^{i\alpha_2/2}, e^{i\alpha_3/2}) \ ,$$

Harrison, Perkins and Scott

- $\sin^2\theta_{23} = 0.5$, $\sin^2\theta_{12} = 0.33$, $\sin^2\theta_{13} = 0$
- Flavour symmetry S_3, A_4, $\mu - \tau$ symmetry ...
- Current data $\Rightarrow \sin^2\theta_{23} = 0.5$, $\sin^2\theta_{12} = 0.33$, $\sin^2\theta_{13} = 0.1 \rightarrow$ Perturbed Tri-Bimaximal Form
- Renormalization group effects...

Why neutrino masses are small

- Is the smallness of neutrino mass related to some new physics at high scale $\longrightarrow$ seeaw mechanism
- $\mathcal{M} = m_D^T M_R^{-1} m_D$; $\quad m_D \sim v Y_\nu$
- $m_\nu \sim 0.05$ eV for $M_R = 10^{16}$ GeV, $m_D \sim 100$ GeV, $Y_\nu \sim 1$

Higher Dimensional Operators

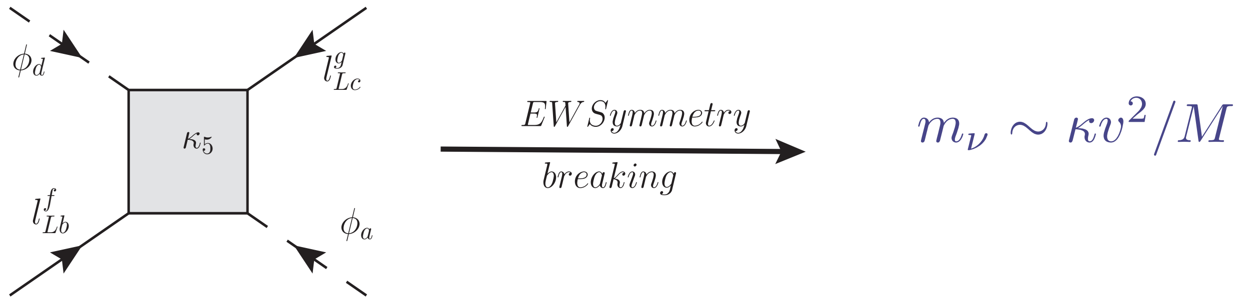
- SM is an effective field theory and one can add non-renormalizable operaotors:

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{eff}^{d=5} + \mathcal{L}_{eff}^{d=6} + \cdots\,, \quad \text{with} \quad \mathcal{L}_{eff}^{d} \propto \frac{1}{\Lambda_{\mathcal{NP}}^{d-4}}\,\mathcal{O}^d\,.$$

- They parameterize the effects of the high energy degrees of freedom on the low energy theory order by order
- The operator coefficients are weighted by inverse powers of the scale of new physics $\Lambda_{\rm NP}$

The Dimension 5 Operator

- Dimension 5 only 1 operator
- $\mathcal{L} = c_5 LLHH$ $\quad c_5 = \kappa/M \quad$ Weinberg, 1979
- After EWSB $L_{eff}^{d=5} \to m_\nu \sim \kappa v^2/M$
- Can be small if scale of new physics is high
- Lepton number violation $\Longrightarrow$ Neutrinos are Majorana particles
- Correct neutrino mass $\Longrightarrow M \sim 10^{15}$ GeV
- Can the new physics be GUT ?

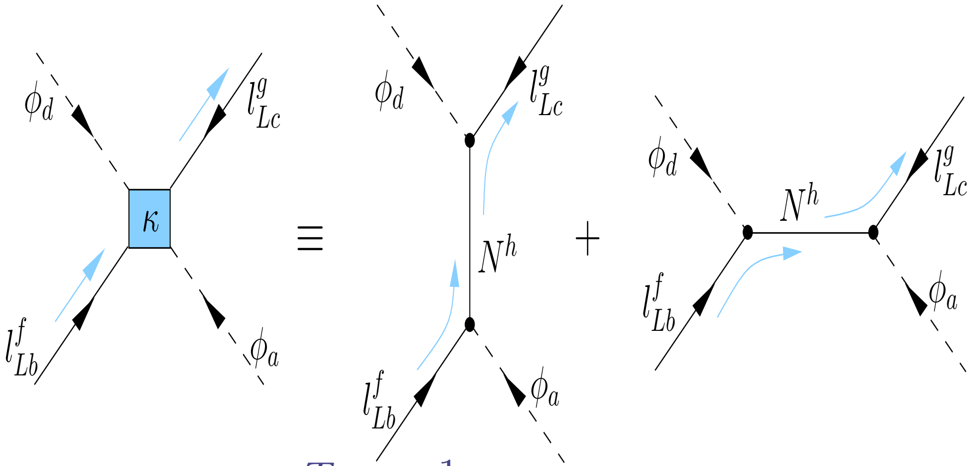


How can one generate the Dimension 5 operataor ?

- $\mathcal{L}_{eff} = \kappa LL\phi\phi$
- Three ways to form a gauge singlet with the SM doublets l and ϕ such that neutrino mass can be generated
  - Type-I : L and ϕ form a singlet [$2 \times 2 = 3 \oplus 1$]
    $\longrightarrow$ Mediated by heavy singlet Fermions
  - Type-II: L and L (and ϕ and ϕ) form a triplet [$3 \times 3 = 5 \oplus 3 \oplus 1$]
    $\longrightarrow$ Mediated by heavy $SU(2)$ triplet Higgs
  - Type-III: L and ϕ form a triplet [$3 \times 3 = 5 \oplus 3 \oplus 1$]
    $\longrightarrow$ Mediated by $SU(2)$ heavy triplet fermions
- Mediated by $\longrightarrow$ tree level exchange at a high scale $\sim$ heavy particle mass
- L-L and $\phi - \phi$ forming singlets does not give neutrino mass term

Type-I seesaw

- $\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + (Y_\nu)\overline{N_R}\,\tilde{\phi}^\dagger l_L \; + \; \frac{1}{2}\overline{N_R{}^c}(M_R)_{ij}N_R \; + \; \mathrm{h.c}$



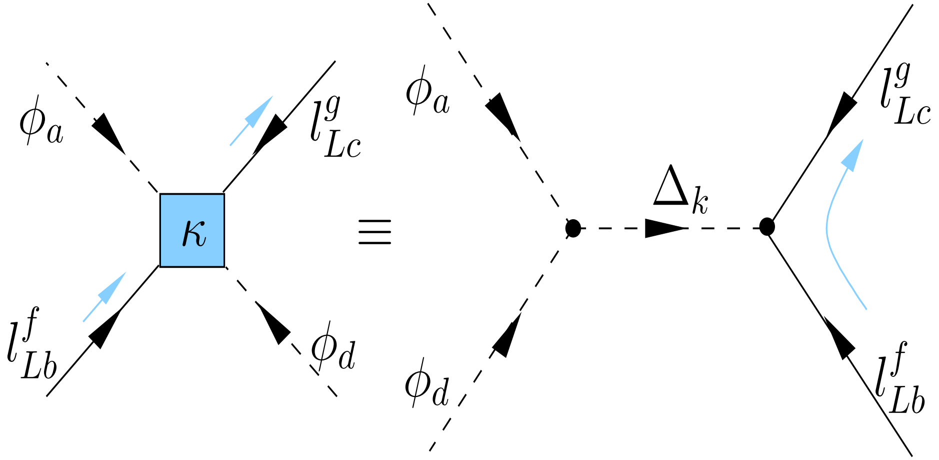
$\kappa = Y_\nu^T M_R^{-1} Y_\nu$ (at M_R) $\quad m_\nu = \kappa v^2$

Minkowski 77, Yanagida 79, Glashow 79, Gell Mann,Rammond, Slansky 79, Mohapatra, Sen janovic 80

- $M_\nu = m_D^T M_R^{-1} m_D$, $m_D = vY_\nu$
- Fits naturally into SO(10) GUTS : $N_R \in \underline{16}$ of SO(10)
- Left-Right Symmetric Models
- Seesaw Scale $\sim M_R \sim 10^{15}$ GeV
- Cannot be tested directly
- Possibilites for TeV scale type-I seesaw ?

Type-II seesaw

- $\mathcal{L} \subset \mathcal{L}_{SM} + f_L LL\Delta + {M_\Delta}^2 \Delta^\dagger \Delta + \mu \Delta^\dagger \phi\phi$



$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^- & -\Delta^+/\sqrt{2} \end{pmatrix}$$

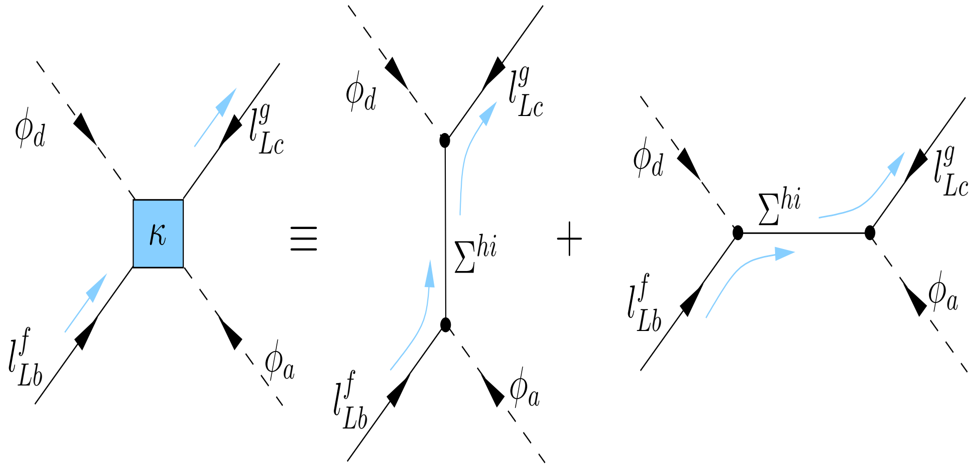
$\kappa = f_L \frac{\mu}{{M_\Delta}^2} \qquad m_\nu = \kappa v^2$

Magg, Wetterich 80; Schechter, Valle 80 Lazarides, Shafi, Wetterich81, Mohapatra Senjanovic 81; Gelmini, Roncadelli 81

- $M_L = f_L \frac{\mu v^2}{{M_\Delta}^2}$
- Fits naturally into $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ and SO(10) GUTS
- Also possible to have $M_\Delta \sim$ TeV, with small μf_L
- Can be probed at LHC

Type-III seesaw

- $\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \bar{l}\sqrt{2}Y_\Sigma^\dagger \Sigma \widetilde{\phi} - \phi^T \varepsilon^T \overline{\Sigma}\sqrt{2}Y_\Sigma l + \frac{1}{2}[\overline{\Sigma} M \Sigma^C]$



$$\Sigma_R = \begin{pmatrix} \Sigma_R^0/\sqrt{2} & \Sigma_R^+ \\ \Sigma_R^- & -\Sigma_R^0/\sqrt{2} \end{pmatrix}$$

SU(2) triplet, Y=0

$$\kappa = Y_\Sigma^T M_R^{-1} Y_\Sigma$$

Foot,Lew,He, Joshi 89

- Fits naturally into the 24 dimensional representation of SU(5)
  $24 \in (1,1,0) + (1,3,0)$
- Gauge coupling unification in SU(5) for $M_\Sigma \sim$ TeV for $M_{GUT} \sim 10^{16}$ GeV
- Can generate neutrino mass through type-I + type-III seesaw
- Can be probed at LHC

Prediction of low energy observables

- Consider type-I seesaw
- The Majorana mass matrix at seesaw scale $M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^{\mathrm{T}} & M_R \end{pmatrix}$.
- The light neutrino mass matrix after the seesaw diagonalization assuming $M_R \gg m_D$ is given by $\mathcal{M} = -m_D^T M_R^{-1} m_D$
- The neutrino mixing matrix is obtained as $V_\nu^{\mathrm{T}} \mathcal{M} V_\nu = \mathrm{diag}(m_1, m_2, m_3)$
- In a basis where the charged lepton mass matrix is diagonal $U_{PMNS} = V_\nu$
- For 3 N_Rs:

  No. of free parameters in m_D = 18 -3 = 15

  No. of free parameters in M_R = 12 -3 = 9

  Total no. of free parameters = 24
- Number of Low energy parameters = 9
- What is the minimal number of N_R's required ?

Minimal Sessaw Model

$$\mathcal{M} = -m_D^T M_R^{-1} m_D$$

- If we have only one N_R at high scale $\longrightarrow$ $\mathcal{M}$ has two zero eigenvalues
- With 2 N_Rs there is only one massless state $\longrightarrow$ can be consistent with the low energy data
- $m_D \to 3 \times 2;\ M_R^{-1} = 2 \times 2$
- Number of free parameters: $m_D \to 9; M_R^{-1} \to 4$
- Reduction in number of free parameters
- Low scale parameter : 9

Barbieri, Hambye, Romanino 03; Ibarra, Ross 04; Guo,Xing,Zhou 2007; Chang, Kang,Siyeon, 04

Reconstructing the Sessaw

$$\mathcal{M} = -m_D^T M_R^{-1} m_D$$

- We do not know m_D
- We do not know M_R
- Less number of low energy parameters
- Need assumptions about m_D, M_R
- Using GUT motivated forms of m_D ($m_D \sim m_{up}$)
- Conventional seesaw gives small mixing
- Combination of type-I and type-II seesaw to generate large mixing

Lindner,Rodejohann, 07

Reconstructing the Sessaw

- In a basis where M_R and m_l are diagonal

$$-m_D\, M_R^{-1}\, m_D^T = U\, m_\nu^{\rm diag}\, U^T$$

$$\boxed{m_D = i\, U\, \sqrt{m_\nu^{\rm diag}}\; R\, \sqrt{M_R}}$$

Casas, Ibarra (2001)

- R orthogonal
- m_ν, U, M_R known
- Still many possibilities for m_D

Texture zeros

- Texture zero $\rightarrow$ very small entries in neutrino mass matrices
- Can be due to flavour symmetries
- Initially applied to quark sector

  Fritzsch, 78; Giudice, 92; Rammond, Roberts, Ross, 93; Branco, Silva-Marcos94....
- Texture zeros in M_ν, m_D, M_R

  Frampton, Glashow, Marfatia, Xing,Desai,Roy,Vaucher, Merle,Rodejohann,Leontaris, Lola,Scheich,Vergados, Barr, Dorsner,Kageyama,Kaneko,Shimoyama,Tanimoto,Yanagida,Barbieri, Hambye,Romanino,Hagedorn,Watanabe,Yoshioka, Guo, Xing,Zhou,

Implications of Seesaw

- Neutrinos are Majorana Particles. $\Longrightarrow$ Neutrinoless double beta decay
- Heavy mediators can decay to lepton, Higgs and and their antiparticles $\rightarrow$ leptogenesis $\rightarrow$ Baryon assymetry of the Universe
- Can Seesaw be tested at LHC ?
- If new physics scale is $\sim 10^{15}$ GeV then no connection can be made to LHC $\rightarrow$ TeV scale seesaw
- If $M_R \sim$ TeV , $m_D/M_R \sim 10^{-1} \Longrightarrow$ large light-heavy mixing
- Lepton Flavour Violation e.g $\mu \rightarrow e\gamma$ through light-heavy mixing
- Di-lepton signal at LHC
- Vacuum stability bound on the Higgs
- TeV Seesaw Model – Inverse Seesaw, Higher-dimensional operators with enlarged particle contents, specific textures...

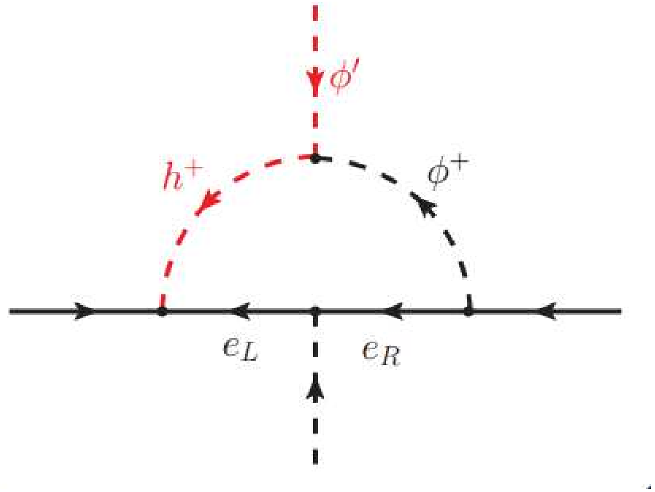
Seesaw at LHC ?

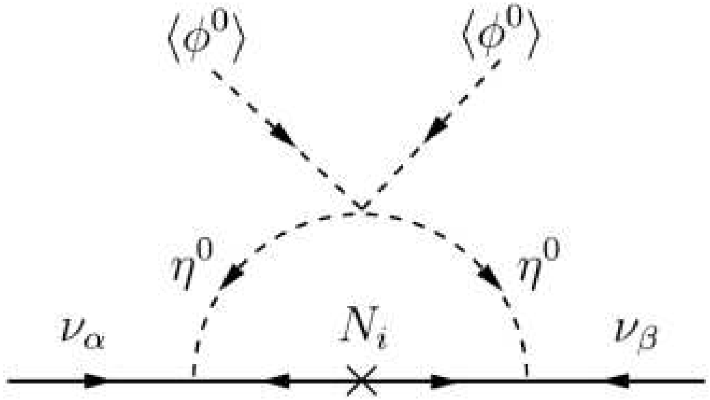
- $m_\nu = m_D^2/M; \quad m_D \sim Y_\nu v$
- $m_\nu \sim 0.01$ eV for $M = 10^{16}$ GeV, $m_D \sim 100$ GeV, $Y_\nu \sim 1$
- If $M \sim$ 1000 GeV then we need $Y_\nu \sim 10^{-6}$ for $m_\nu \sim 0.1$ eV
- So $Y_\nu \sim Y_e$
- More natural ?
- Seesaw scale $\sim$ TeV $\Longrightarrow$ can be probed at LHC (?)
- Small Y_ν is a problem
- Exception Left-Right symmetric models with W_R at TeV scale... can give rise to additional processes

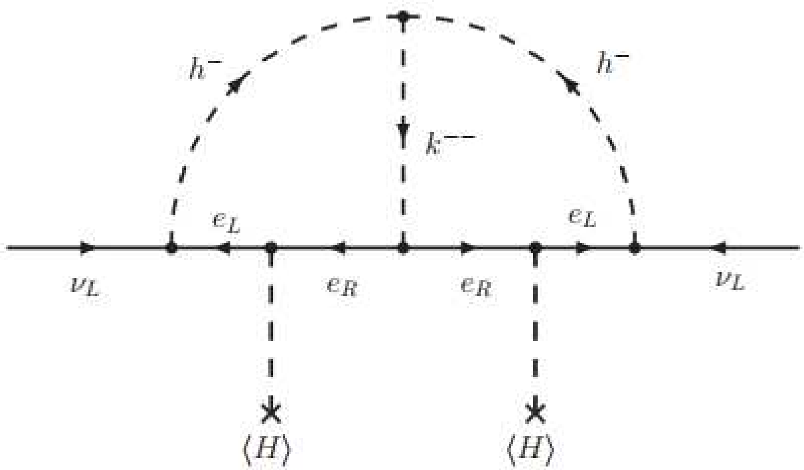
Is Seesaw the only option ?

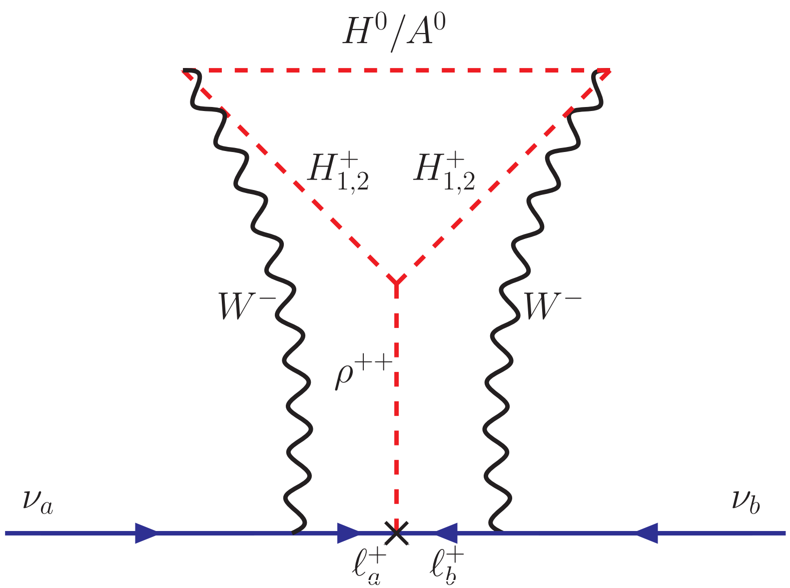
- An alternative to Seesaw is the radiative neutrino mass models where neutrino mass is absent and tree level but can arise at the loop level
- The smallness of neutrino mass is explaned by loop supressions
- New Physics scale close to TeV $\rightarrow$ LHC, LFV procceses
- Also higher dimensional (> 5) models with enlarged particle contents
- Mass Generation : Seesaw + radiative
- Rich Phenomenology

Radiative Generation of Neutrino Mass









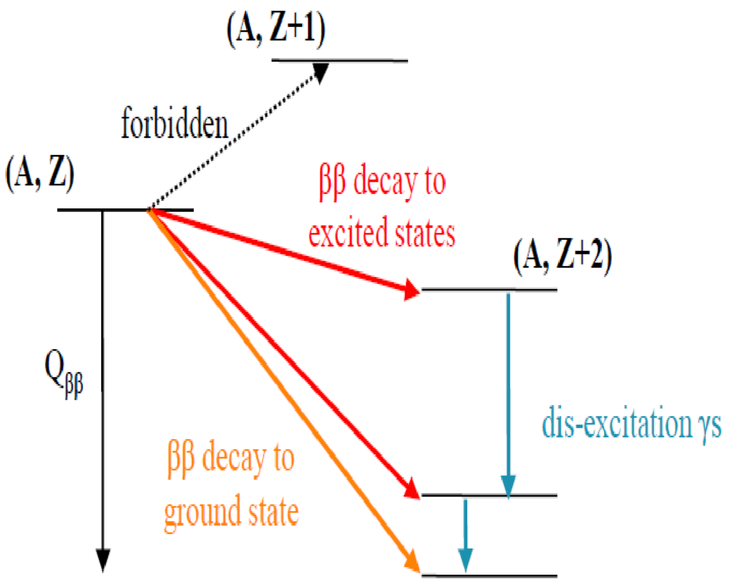
- Zee model, Ma model, Zee-Babu model, Cocktail model

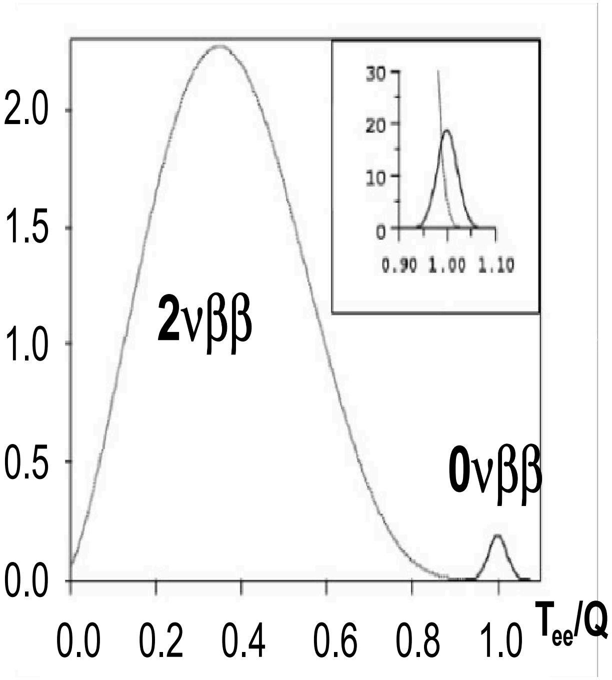
Neutrinoless Double Beta decay

- Neutrinoless double β decay $(A, Z) \to (A, Z + 2) + 2e^-$
- Possible in principle for even-even nuclei for which usual β-decay is energetically forbidden if Lepton number is violated
- 35 nuclei can undergo $0\nu\beta\beta$
- $2\nu\beta\beta$ has been observed
- $0\nu\beta\beta$ implies lepton number violation.. $\Longrightarrow$ particles are their own anti-particles..
- Can establish Majorana Nature of the Neutrino

$0\nu\beta\beta$: Experimental Signature

- $(A, Z) \rightarrow (A, Z+2) + 2e^-$
- Minimum information : spectrum of the energy sum of the two electrons
- Exhibits a peak at Q over the $2\nu\beta\beta$ tail





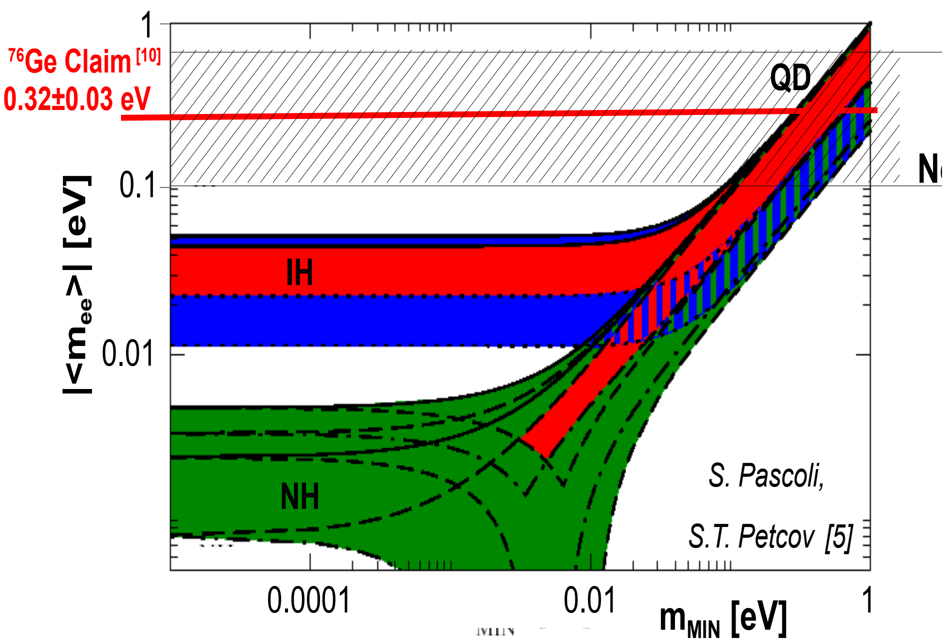
- Additional signatures: Angular correlation between the two electrons, track and event topology, daughter nuclear species..

$0\nu\beta\beta$: Experimental Bounds

- Positive claim by part of HM group:
  $T^{0\nu}_{1/2} = 2.23^{+0.44}_{-0.31} \times 10^{25}$ yr at 68% CL using ^{76}Ge

  H. V. Klapdor-Kleingrothaus *et al.* Phys. Lett. B **586**, 198 (2004).

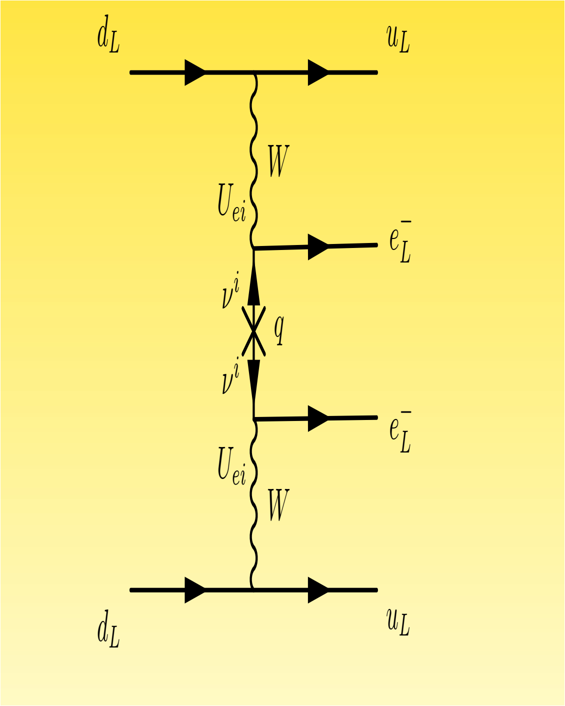
- $\frac{1}{T^{0\nu}_{1/2}} = G|\mathcal{M}_\nu|^2 \left|\frac{m^\nu_{ee}}{m_e}\right|^2 \rightarrow m^\nu_{ee}$ can be extracted
- Depending on the NME used: $m^\nu_{ee} = 0.21 - 0.58$ eV



- $\Longrightarrow$ neutrinos are quasi-degenerate
- Many new experiments were planned to test this..

Half Life for Neutrinoless Double Beta decay

- $(A, Z) \to (A, Z+2) + 2e^-$
- Standard Picture: $0\nu\beta\beta$ mediated by the light neutrinos



- The half-life for $0\nu\beta\beta$,

$$\frac{1}{T_{1/2}^{0\nu}} = G|\mathcal{M}_\nu|^2 \left|\frac{m_{ee}^\nu}{m_e}\right|^2 ,$$

- $G \to$ contains the phase space factors (calculable)
- $\mathcal{M}_\nu$ is the nuclear matrix element (complicated).
- $|m_\nu^{ee}| = |U_{ei}^2\, m_i| \to$ the effective mass, (interesting)

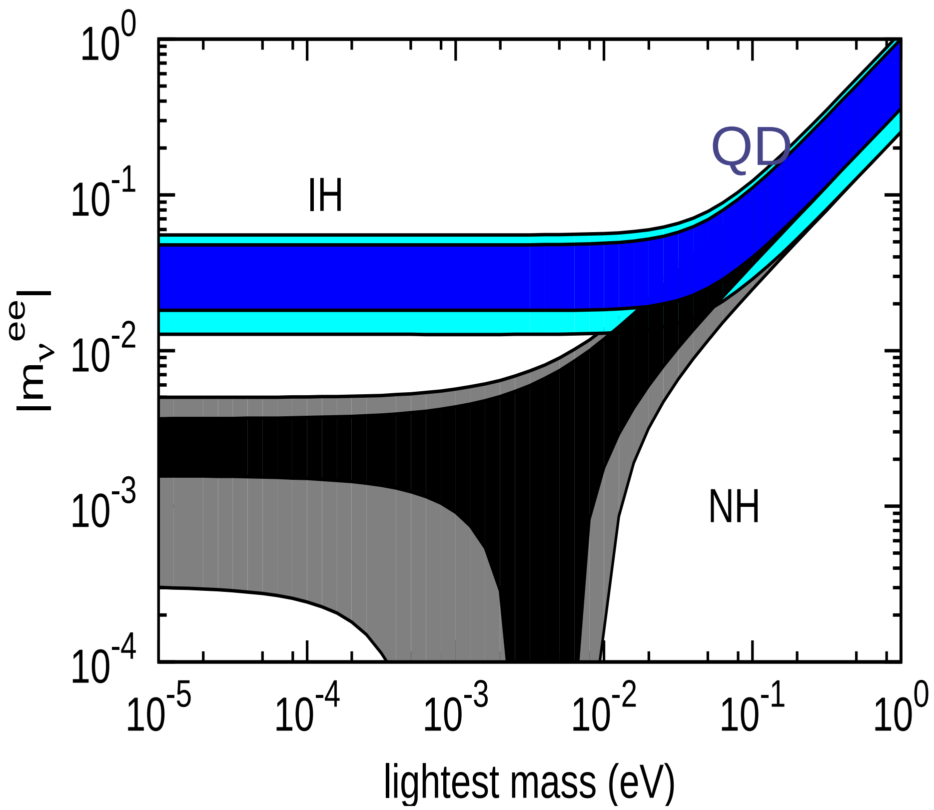
- Additional diagrams possible in Seesaw models

The effective mass

$$|m_\nu^{ee}| = |m_1 U_{e1}^2 + m_2 U_{e2}^2 e^{2i\alpha_1} + m_3 U_{e3}^2 e^{2i\alpha_2}|$$

- ν Mass Spectrum • Absolute ν Mass Scale • CP phases

- Depends on 7 out of 9 parameters of neutrino mass matrix



NH: $m_1 << m_2 << m_3$

IH: $m_3 << m_1 \approx m_2$

QD: $m_1 \approx m_2 \approx m_3$

$0\nu\beta\beta$: Recent Results

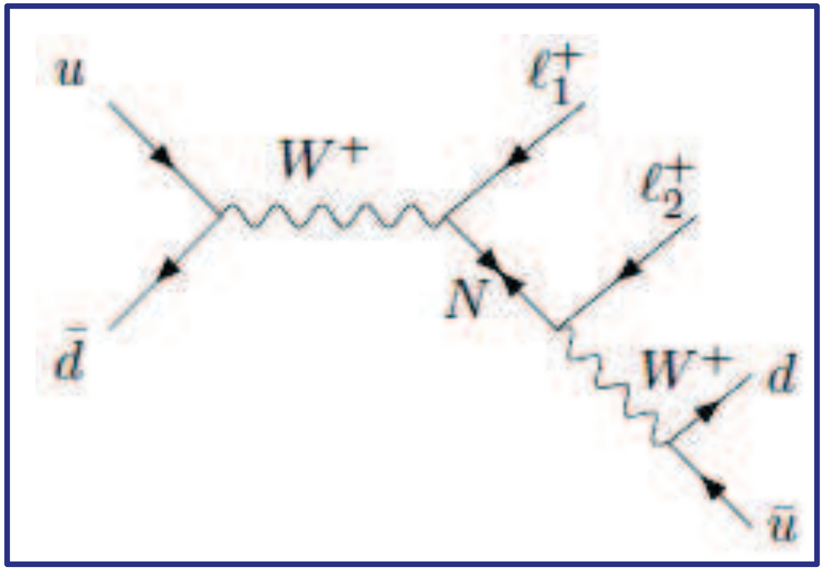
- New results from experiments using ^{136}Xe
- $T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr at 90% CL (KamLAND-ZEN) (2013)
- $T^{0\nu}_{1/2} > 1.6 \times 10^{25}$ yr at 90% C.L. (EXO) (2012)
- $T^{0\nu}_{1/2} > 3.4 \times 10^{25}$ yr at 90% CL (Combined, 2013)
- Recent results from GERDA : $T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) > 2.1 \times 10^{25}$ yr at 90% CL
- GERDA + IGEX + HM : $T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) > 3.0 \times 10^{25}$ yr at 90% CL
- Can be translated into lower bound on m^{ν}_{ee}
- Depends on NME

$0\nu\beta\beta$: Experimental Bounds

NME	Limit on m_{ee}^{ν} (eV)				
	^{76}Ge			^{136}Xe	
	GERDA	comb	KK	KLZ	comb
EDF(U)	0.32	0.27	0.27-0.35	0.15	0.11
ISM(U)	0.52	0.44	0.44-0.58	0.28	0.21
IBM-2	0.27	0.23	0.23-0.30	0.19	0.14
pnQRPA	0.28	0.24	0.24-0.31	0.20	0.15
SRQRPA-B	0.25	0.21	0.21-0.28	0.18	0.14
SRQRPA-A	0.31	0.26	0.26-0.34	0.27	0.20
QRPA-B	0.26	0.22	0.22-0.29	0.25	0.19
QRPA-A [?]	0.28	0.24	0.24-0.31	0.29	0.21
SkM-HFB-QRPA [?]	0.29	0.24	0.24-0.32	0.33	0.25

- GERDA and KK barely consistent
- Inconsistent with combined KLZ+EXO limit for most NME's

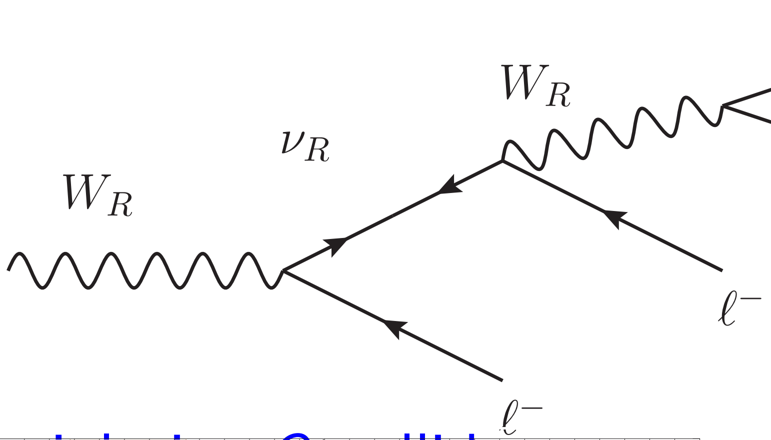
Can Maorana Nature be tested at Colliders ?



- Same sign di-leptons + jet
- Controlled by light-heavy mixing

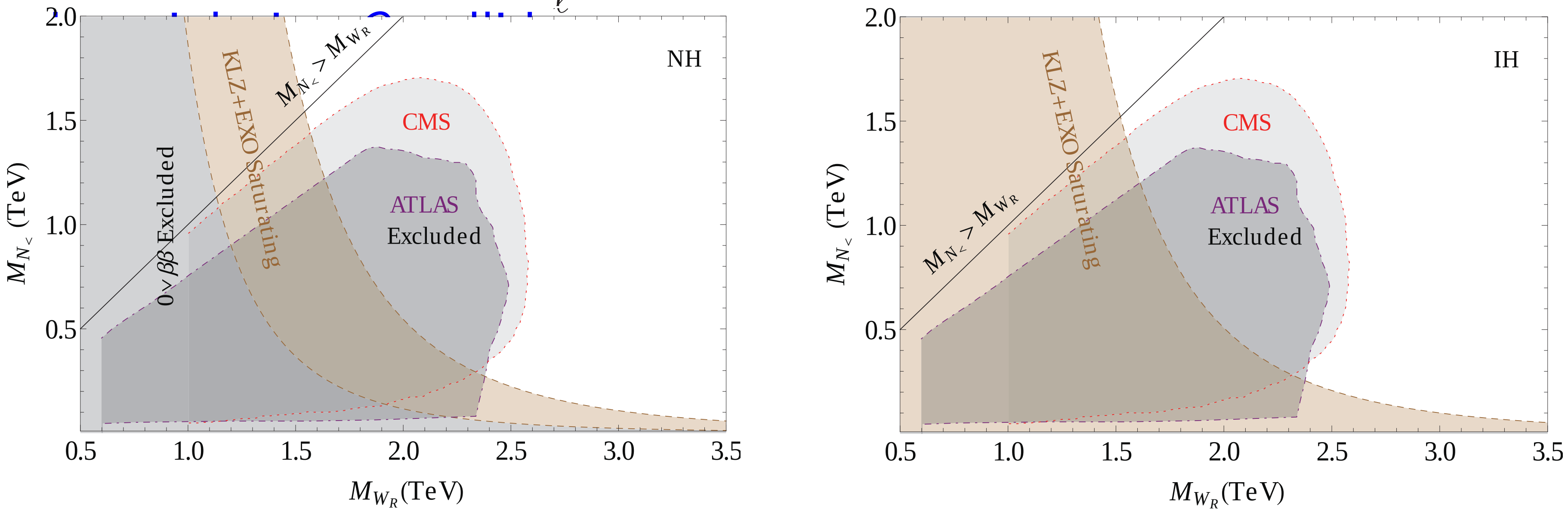
Can Maorana Nature be tested at Colliders ?

- Left-Right Symmetric Models: $SU(2)_R \times SU(2)_L \times U(1)_{B-L}$



- Same sign di-leptons + jet , Golden Channel

[Keung Senjanovic '83]



- Complimentary constraints for NH

Dev, S.G, Mitra, Rodejohann,2013

Finally ...

Thank You to the team SANGAM @ HRI