Minimal flavour seesaw models

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M. B. Gavela, T. Hambye, P. Hernández, D.H., 0906.1461

A short tale: Chiral Pert. Theory

Fundamental Lagrangian

$$\mathscr{L} = \sum_{i=u,d,s} q_{Li} i \not{D} q_{Li} + q_{Ri} i \not{D} q_{Ri} - M_{ij} \bar{q}_i q_j - \frac{1}{2} G_{\mu\nu} G^{\mu\nu}$$

Flavour symmetry: $U(3)_L \times U(3)_R$

$q_{Li} \to L q_{Li}\,, \quad q_{Ri} \to R q_{R_i}\,, \quad M \to L M R^\dagger \qquad L \in U(3)_L\,,\ R \in U(3)_R$

Effective theory (ChPT)

$$\mathscr{L}_{\mathrm{Ch}} = \frac{f^2}{4} \mathrm{Tr}\, \partial \Sigma^\dagger \partial \Sigma - \frac{f^2 \Lambda}{2} \mathrm{Tr}\, M \Sigma\,, \qquad \Sigma \to R \Sigma L^\dagger$$

SPURION PARADIGMA

Flavour symmetry of the SM

Great Big Model of the Whole Universe

(?)

↓

Effective Theory (Standard Model)

$$\mathscr{L}_{SM} = \mathscr{L}_{kin} - V(\text{Higgs}) - Y_d \bar{Q}_u H d_R - Y_u \bar{Q}_u \tilde{H} u_R - \dots$$

Flavour group :

$$G = SU(3)_{Q_L} \times SU(3)_u \times SU(3)_d \times SU(3)_L \times SU(3)_e$$

$$Q_u \rightarrow L_u Q_u \, , \quad d_R \rightarrow R_d d_R \, , \dots \; Y_d \rightarrow L_u Y_u R_d^{\dagger} \, , \dots$$

Flavour symmetry of the SM

Great Big Model of the Whole Universe

Probably also flavour symmetry

$$G = SU(3)_{Q_L} \times SU(3)_u \times SU(3)_d \times SU(3)_L \times SU(3)_e$$

Effective Theory (Standard Model)

$$\mathscr{L}_{SM} = \mathscr{L}_{kin} - V(\text{Higgs}) - Y_d \bar{Q}_u H d_R - Y_u \bar{Q}_u \tilde{H} u_R - \ldots$$

Flavour group :

$$G = SU(3)_{Q_L} \times SU(3)_u \times SU(3)_d \times SU(3)_L \times SU(3)_e$$

$$Q_u \to L_u Q_u \,, \quad d_R \to R_d d_R \,, \ldots \, Y_d \to L_u Y_u R_d^\dagger \,, \ldots$$

Minimal Flavour Violation

Not very useful... unless one can say something more about the fundamental theory.

Assume $\mathscr{L}_{\text{fund.}} = \mathscr{L}(Y_u,\ Y_d,\ \cdots + \text{fields})$.

MINIMAL FLAVOUR VIOLATION

In the low energy Lagrangian (SM) we have

$$\mathscr{L}_{eff} = \sum_i c^i_{d=5}\mathcal{O}^i_{d=5} + c^i_{d=6}\mathcal{O}^i_{d=6} + \dots$$

$$c_{d=5} \equiv c_{d=5}\big(Y_u, Y_d\big)\,, \quad c_{d=6} \equiv c_{d=6}\big(Y_u, Y_d\big)\,, \quad \text{etc}$$

MFV Hypothesis $\equiv$ The Yukawas are the only sources (*irreducible*) of flavour violation.

R. S. Chivukula and H. Georgi, Phys. Lett. B **188**, 99 (1987).

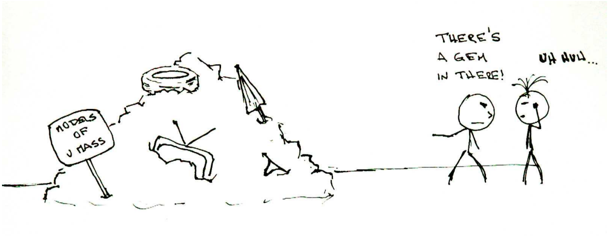
In the case of leptons

In the lepton sector

$$\mathscr{L}_{SM} = \cdots + Y_e \bar{L} \phi e_R + \left(? \right) + \sum_i c^i_{d=5} \mathcal{O}^i_{d=5} + c^i_{d=6} \mathcal{O}^i_{d=6} \cdots$$

$$\text{neutrino mass} \longrightarrow c_{d=5} \equiv c_{d=5}\left(Y_e, ?\right) , \quad c_{d=6} \equiv c_{d=6}\left(Y_e, ?\right) \longleftarrow \text{flavour processes}$$

Need mass for the neutrinos! (Model dependent, Majorana)



V. Cirigliano, B. Grinstein, G. Isidori, M. Wise, hep-ph/0507001.

Requirements for a model of MFV

- Fundamental theory that reduces to the SM.
- Tiny neutrino masses should be deducible. Λ_{LN} Big.
- Rare flavour processes should be measurable. $\Lambda_{fl} \ll \Lambda_{LN}$
- Predictivity. The flavour structure of the coefficients of the $d = 6$ operator should be fixed by that of the $d = 5$ one.

Ex:

$$c_{d=6}^{\alpha\beta} \propto c_{d=5}^{\alpha\beta}\,, \quad c_{d=6}^{\alpha\beta} \propto (c_{d=5}^{\dagger})^{\alpha\sigma} c_{d=5}^{\sigma\beta}\,, \quad \text{any other possibility?}$$

Massive Neutrinos

Massive neutrinos ⇒ NEW PHYSICS!

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino

Detecting Neutrinos

Neutrinos pass through

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Detecting Neutrinos

Neutrinos pass through

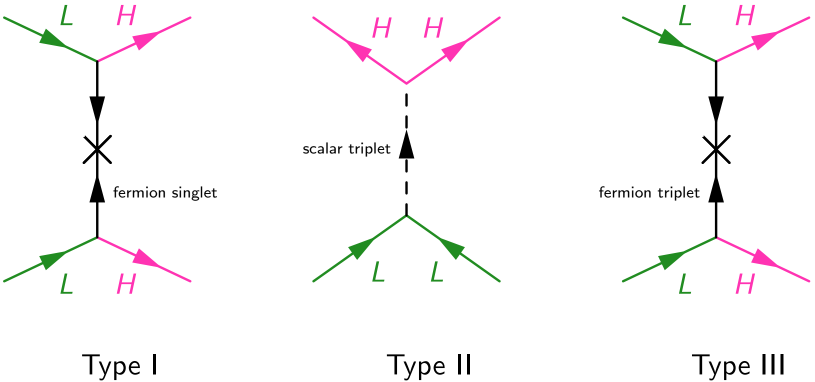
- Dirac Mass. Unnatural particular case of the following.
- Majorana Mass. $\bar{\nu^c}_L \nu_L$. Violates $U(1)_Y$

  Hence Weinberg operator

$$O_W = \frac{c_{d=5}}{\Lambda_{\mathrm{NP}}} \bar{L^c} L H^T H$$

Seesaw Models

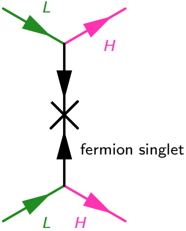
- Three types of models yield the Weinberg operator at tree level



An unsuccessful model

Standard Seesaw (Type I) doesn't work

$$\mathscr{L} = \cdots - Y_N \bar{N} \phi^\dagger L_L - \Lambda_{LN} \bar{N}^c N \dots$$

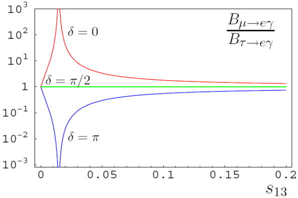


- Neutrino masses: Ok. $M_\nu \propto Y_N^T \frac{1}{\Lambda_{LN}} Y_N$
- Measurable flavour: NOT OK!. $\Lambda_{fl} \equiv \Lambda_{LN}$
- Predictivity: More or less Ok. $c_{d=5} \propto c_{d=6}$ *if no CP*

Scalar mediated seesaw

$$\mathscr{L}_\Delta = \dots + (D_\mu \Delta)^\dagger (D^\mu \Delta) - m_\Delta^2 \Delta^\dagger \Delta + +$$

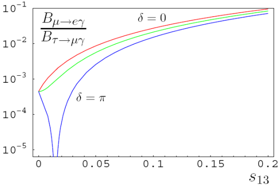
$$+ Y_\Delta^{\alpha\beta} \overline{\widetilde{\ell_{\rm L}}} (\tau \cdot \Delta) \ell_{\rm L} + \mu_\Delta \widetilde{\phi}^\dagger (\tau \cdot \Delta)^\dagger \phi + \dots$$



Yields the *effective coefficients*

$$c_{d=5}^{\alpha\beta} \propto Y_{\Delta\alpha\beta} \frac{\mu_\Delta}{M_\Delta^2} \,,$$

$$c_{d=6}^{\alpha\beta\gamma\delta} \propto \frac{1}{M_\Delta^2} {Y_\Delta}^\dagger_{\alpha\beta} Y_{\Delta\delta\gamma} \,.$$



Hence

$$c_{d=6}^{\alpha\beta\gamma\delta} \propto (c_{d=5}^\dagger)^{\alpha\beta} c_{d=5}^{\gamma\delta}$$

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Leptonic Seesaws I

$$\mathscr{L}_{M_\nu} = \begin{array}{c} \\ \left(\begin{array}{ccc} \bar{L}_i & \bar{N}^c & \bar{N}'^c \\ 0 & Y_N^T\, v & \epsilon\, Y_N'^T\, v \\ Y_N\, v & 0 & \Lambda \\ \epsilon\, Y_N'\, v & \Lambda & 0 \end{array}\right) \end{array} \begin{array}{l} \\ L_i^c \\ N \longleftrightarrow \text{one generation} \\ N' \longleftrightarrow \text{one generation} \end{array}$$

Lepton number violation driven by ϵ

$$c_{\alpha\beta}^{d=5} \equiv \epsilon \left(Y_N'^T \frac{1}{\Lambda} Y_N + Y_N^T \frac{1}{\Lambda} Y_N' \right)_{\alpha\beta}, \qquad c_{\alpha\beta}^{d=6} \equiv \frac{1}{\Lambda^2} \left(Y_N^\dagger Y_N \right)_{\alpha\beta} + o(\epsilon)$$

Leptonic Seesaws I

$$\mathscr{L}_{M_\nu} = \begin{array}{c} \\ \\ \\ \end{array} \begin{array}{ccc} \bar{L}_i & \bar{N}^c & \bar{N}'^c \\ \left(\begin{array}{c} 0 \\ Y_N v \\ \boxed{\epsilon} Y'_N v \end{array}\right. & \begin{array}{c} Y_N^T v \\ 0 \\ \Lambda \end{array} & \left.\begin{array}{c} \boxed{\epsilon} Y_N'^T v \\ \Lambda \\ 0 \end{array}\right) \end{array} \quad \begin{array}{l} \\ L_i^c \\ N \longleftrightarrow \\ N' \longleftrightarrow \end{array} \text{one generation}$$

Lepton number violation driven by ϵ

$$c^{d=5}_{\alpha\beta} \equiv \boxed{\epsilon} \left(Y_N'^T \frac{1}{\Lambda} Y_N + Y_N^T \frac{1}{\Lambda} Y'_N \right)_{\alpha\beta}, \quad c^{d=6}_{\alpha\beta} \equiv \frac{1}{\Lambda^2} \left(Y_N^\dagger Y_N \right)_{\alpha\beta} + \boxed{o(\epsilon)}$$

Leptonic Seesaws I

$$\mathscr{L}_{M_\nu} = \begin{array}{cc} \begin{array}{ccc} \bar{L}_i & \bar{N}^c & \bar{N}'^c \end{array} & \\ \left(\begin{array}{ccc} 0 & Y_N^T v & \boxed{\epsilon} Y_N'^T v \\ Y_N v & 0 & \Lambda \\ \boxed{\epsilon} Y_N' v & \Lambda & 0 \end{array}\right) & \begin{array}{l} L_i^c \\ N \longleftrightarrow \\ N' \longleftrightarrow \end{array} \end{array} \text{one generation}$$

Lepton number violation driven by ϵ

$$c^{d=5}_{\alpha\beta} \equiv \boxed{\epsilon} \left(Y_N'^T \frac{1}{\Lambda} Y_N + Y_N^T \frac{1}{\Lambda} Y_N' \right)_{\alpha\beta}, \qquad c^{d=6}_{\alpha\beta} \equiv \frac{1}{\Lambda^2} \left(Y_N^\dagger Y_N \right)_{\alpha\beta} + \boxed{o(\epsilon)}$$

FUNDAMENTAL

	moduli	phases
Y_N	3	3
Y_N'	3	3
Λ	1	1

vs

LOW ENERGY

- 3 angles and 2 phases in the U_{PMNS}
- 2 masses and 0 phases in M_ν
- 2 overall factors and 5 phases absorbed.

- A normalization factor apart, Yukawas are determined from the U_{PMNS} and neutrino masses!

Leptonic Seesaw II

For both hierarchies

$$Y_N = \frac{y}{\sqrt{2}} \left[f_1 \left(\frac{\Delta m^2_{sol}}{\Delta m^2_{atm}} \right) U^*_{i3} + f_2 \left(\frac{\Delta m^2_{sol}}{\Delta m^2_{atm}} \right) U^*_{i2} \right]$$

- Yukawas are a linear combination of the rows of the PMNS matrix.
- Spectrum determined (modulo normal/inverted hierarchy)

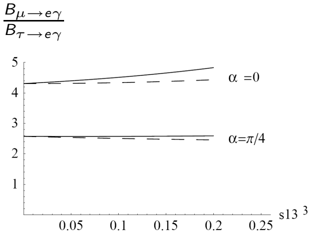
Hence, measuring U_{PMNS}, and ν masses determines EVERYTHING!!

Ex:

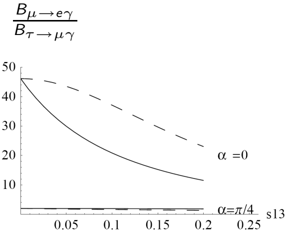
$$B_{\mu\to e\gamma} \propto \left| Y_{N_e} Y_{N_\mu} \right|^2 , \quad |m_{ee}|_{IH} \simeq |s^2_{12} e^{-2i\alpha} - c^2_{12} e^{2i\alpha}|$$

Leptonic Seesaw III

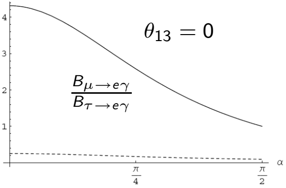
NORMAL HIERARCHY

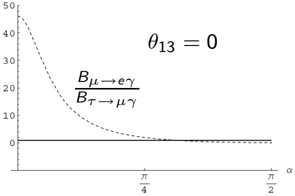


INVERTED HIERARCHY



Strong dependence on the Majorana phase!





Leptonic Seesaw IV

For the mass matrix

$$\mathscr{L}_{M_\nu} = \begin{array}{cc} \begin{array}{ccc} \bar{L}_i & \bar{N}^c & \bar{N}'^c \end{array} & \\ \begin{pmatrix} 0 & Y_N^T v & \epsilon Y_N'^T v \\ Y_N v & \mu' & \Lambda^T \\ \epsilon Y_N' v & \Lambda & \mu \end{pmatrix} & \begin{array}{c} L_i^c \\ N \\ N' \end{array} \end{array} \qquad \begin{array}{c} N \\ N' \end{array} \longleftrightarrow \text{one generation}$$

Redefine

$$\tilde{Y}_N = Y_N' - \frac{\mu}{2\epsilon\Lambda} Y_N$$

to recover previous case. $\tilde{c}_{5,6}(Y', Y) = c_{5,6}(\tilde{Y}, Y)$

- Y_N can still be found using the same algorithm and $c_{d=6}$ is determined from $c_{d=5}$

Conclusions

- Simple seesaw models with at least two separate scales are realizations of the MFV hypothesis in the lepton sector. Ex: Type II Seesaw, Inverse Seesaws, etc.
- Furthermore, a very simple model of realistic neutrino mass generation has been presented within the defined MFV framework. It implements as well several attracting features that include,
  - A separation of the typical scales of flavour and lepton number breaking processes.
  - A full determination of the Yukawa vectors up to overall factors.
  - Only three parameters undetermined by present data, a CP phase, a Majorana phase and θ_{13}