The inverse seesaw family: Dirac & Majorana

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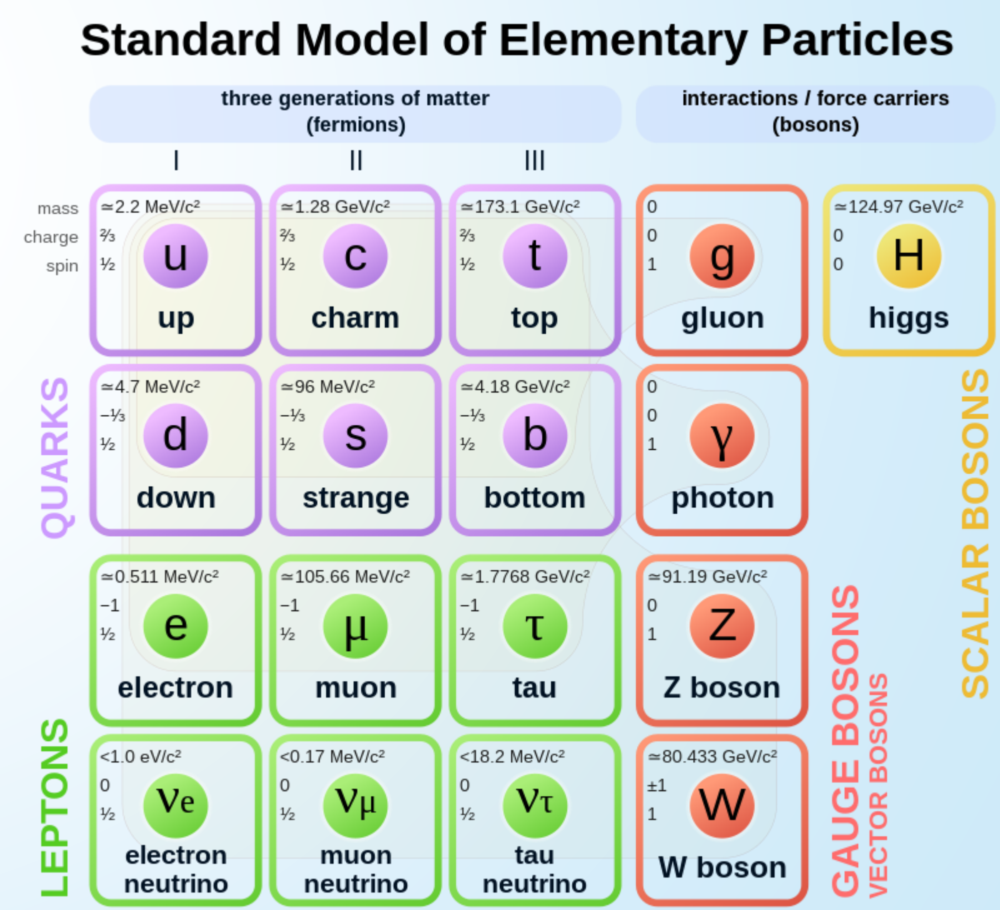
The Standard Model and its drawbacks

- The SM is one of the most precise theories of history.
- Yet we have very well stablished observational proof of its incompleteness:
  - **Neutrino masses.**
  - Dark matter.
  - Matter-anti matter asymmetry.

  - Anomalies? B anomalies, g-2

~~Xenon 1T~~, CDF-II mW, short baseline neutrino oscillations…

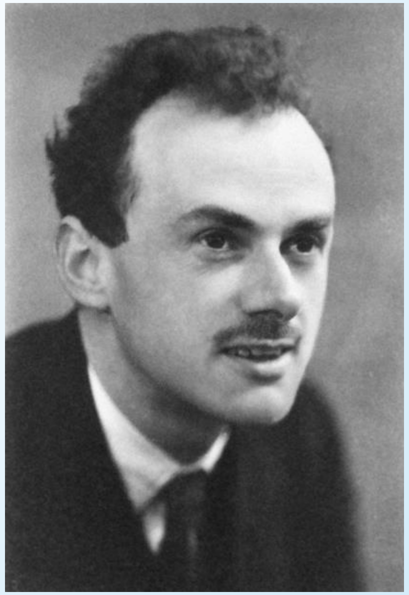


Neutrino masses

- SM predicts massless neutrinos due to no ν_R.
- An extension of the SM accounting for neutrino masses must answer two additional questions.
  - Neutrino nature: Dirac/Majorana.
  - Smallness of neutrino mass.

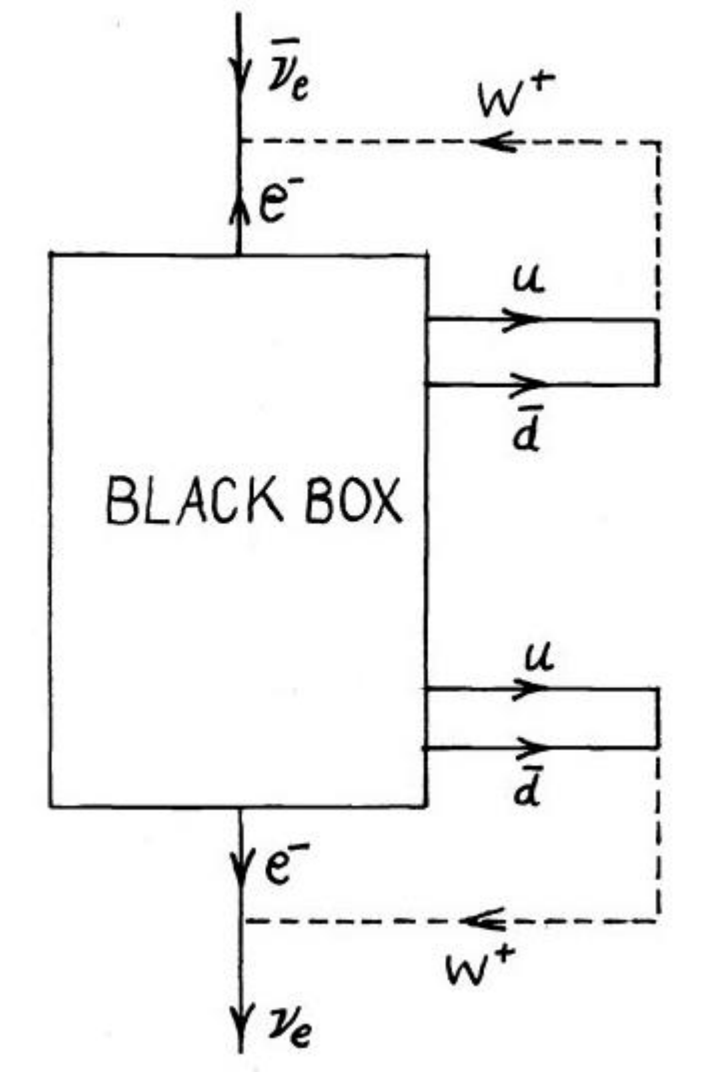
Neutrino nature

- All charged fermions are Dirac particles. What about neutrinos?
- Deeply intertwined with the mass generation and lepton number.
  - Dirac neutrinos need a protecting symmetry.



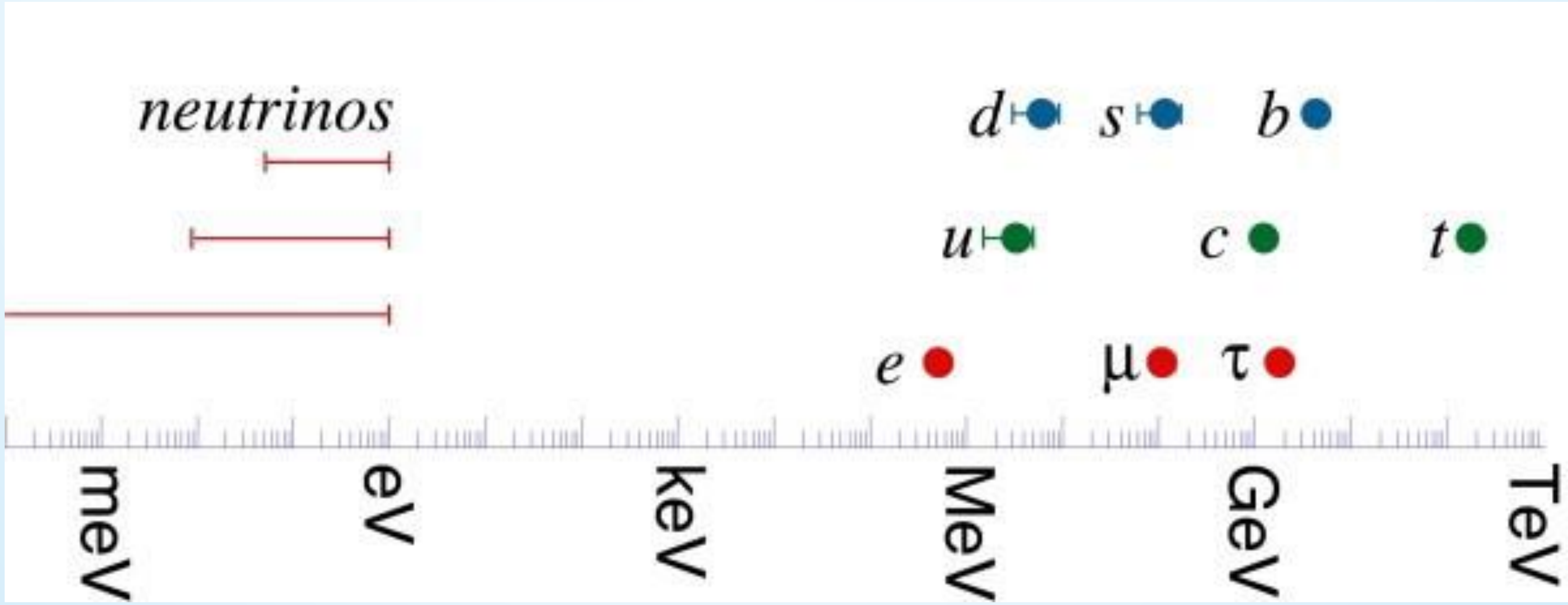
Neutrino nature

- Multiple examples of well motivated models for both cases.
- Confusion theorem: difference $\propto m_\nu$ (Kayser, Gibrat-Debu and F. Perrier 1989)
- Our best chance may be to detect $\nu 0ee$ (Schechter-Valle 1982)



Smallness of neutrino mass

- Charged lepton masses are hierarchichal respect one another (part of the flavour problem).
  - $m_t / m_e \approx 10^5$
- But neutrinos are *much* lighter $m_e / m_\nu > 10^6$



Smallness of neutrino mass

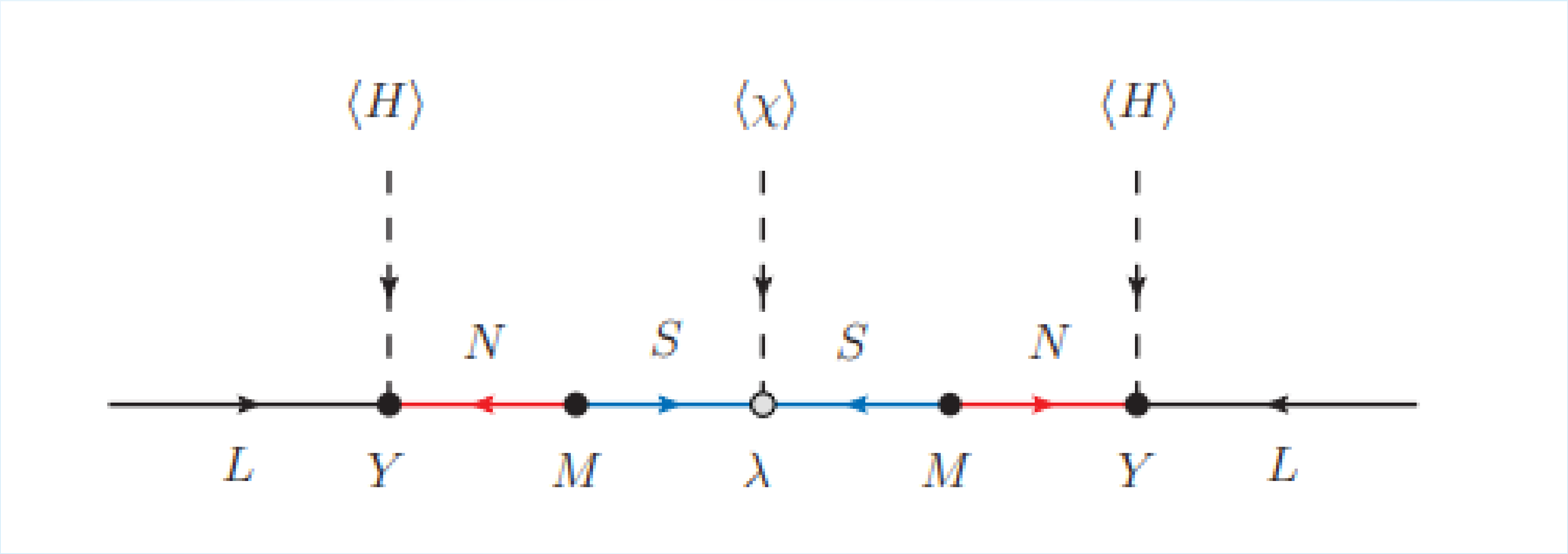
- The following ‘smallness mechanisms’ are used in the literature:
  - Seesaw mechanisms: $m_\nu \propto {}^1/_\Lambda, \quad \Lambda \gg \Lambda_{EW}$.
  - Loop suppression: ${}^1/_{(4\pi)^2}$ per loop.
  - **Naturalness mechanisms**: symmetry protects smallness of a parameter μ ‘a la ‘t Hooft’ (‘t Hooft 1980). $m_\nu \propto \mu$.
  - Combinations of the above.

Inverse seesaw mechanism

- Requirements in order to have an inverse seesaw mechanism
  - Presence of a symmetry-breaking parameter μ. In the limit $\mu \to 0$ we recover a bigger symmetry. Could be explicit or **spontaneous** breaking. There could be multiple μ_i.
  - $m_\nu \propto \mu_i$.
  - Extended fermion sector.
- Nice features: low scale models and rich pheno! E.g. collider signatures, $\mu^- \to e^-\gamma \ldots$

Vanilla inverse seesaw

- Mohapatra, Valle 1986.
- The protecting symmetry is Lepton number.
- Spontaneous breaking version: the vev of a singlet χ breaks L in two units, i.e. $U(1)_L \xrightarrow{\langle 0|\chi|0\rangle} Z_2$.



Vanilla inverse seesaw

- Mohapatra, Valle 1986.
- Interesting pheno: Majoron, light scalar, cLFV…

$$\mathcal{L}_m = \begin{pmatrix} \bar{\nu}^c & \bar{N}^c & \bar{S}^c \end{pmatrix} \begin{pmatrix} 0 & Y v & 0 \\ Y^T v & \mu' & M^T \\ 0 & M & \mu \end{pmatrix} \begin{pmatrix} \nu \\ N \\ S \end{pmatrix}$$

$$m_\nu = -Y^2 \frac{v^2 \mu}{M^2}$$

Fields	$SU(2)_L \otimes U(1)_Y$	$U(1)_{B-L} \to \mathbb{Z}_2$	Fields	$SU(2)_L \otimes U(1)_Y$	$U(1)_{B-L} \to \mathbb{Z}_2$
L	$(\mathbf{2}, -1/2)$	$-1 \to -1$			
N	$(\mathbf{1}, 0)$	$1 \to -1$	S	$(\mathbf{1}, 0)$	$-1 \to -1$
H	$(\mathbf{2}, 1/2)$	$0 \to 1$	χ	$(\mathbf{1}, 0)$	$2 \to 1$

Simplest Dirac inverse seesaw

- We now build the analogous Dirac version.
- We choose the 445 B-L as protecting symmetry (Montero, Pleitez 2009; Ma, Srivastava 2015)
  - SM leptons ~ -1.
  - SM quarks $\sim {}^1/_3$.
  - $(\nu_{R1}, \nu_{R2}, \nu_{R3}) \sim (-4, -4, 5)$.
  - New fermions beyond SM come as VL pairs.

445 B-L solution

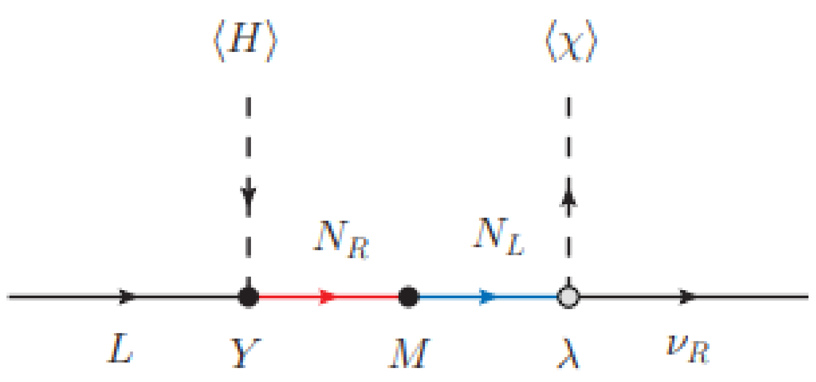
- Properties of the 445 solution:
  - It is anomaly free. Can be gauged (removes the Diracon, Z' pheno).
  - Leads to massless neutrinos if exact, Dirac neutrinos if broken in three units $U(1)_{B-L} \to Z_3$. Forbids Majorana terms.
  - Can stabilize DM on its own (Bonilla, SCC, Cepedello, Peinado, Srivastava 2018).
  - In our inverse seesaw setup protects smallness of neutrino mass.

Simplest Dirac inverse seesaw

- Similar particle content as the Majorana inverse seesaw

$$\mathcal{M} = \begin{pmatrix} 0 & Y v \\ \mu & M \end{pmatrix}$$

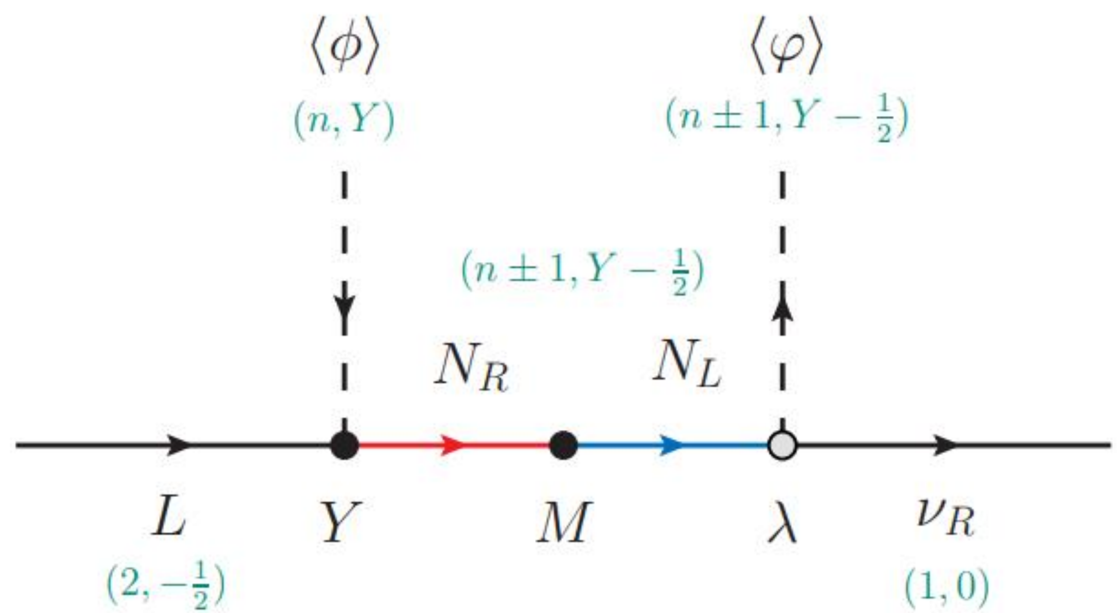
$$m_\nu = Y\, v\, \frac{\mu}{M}$$

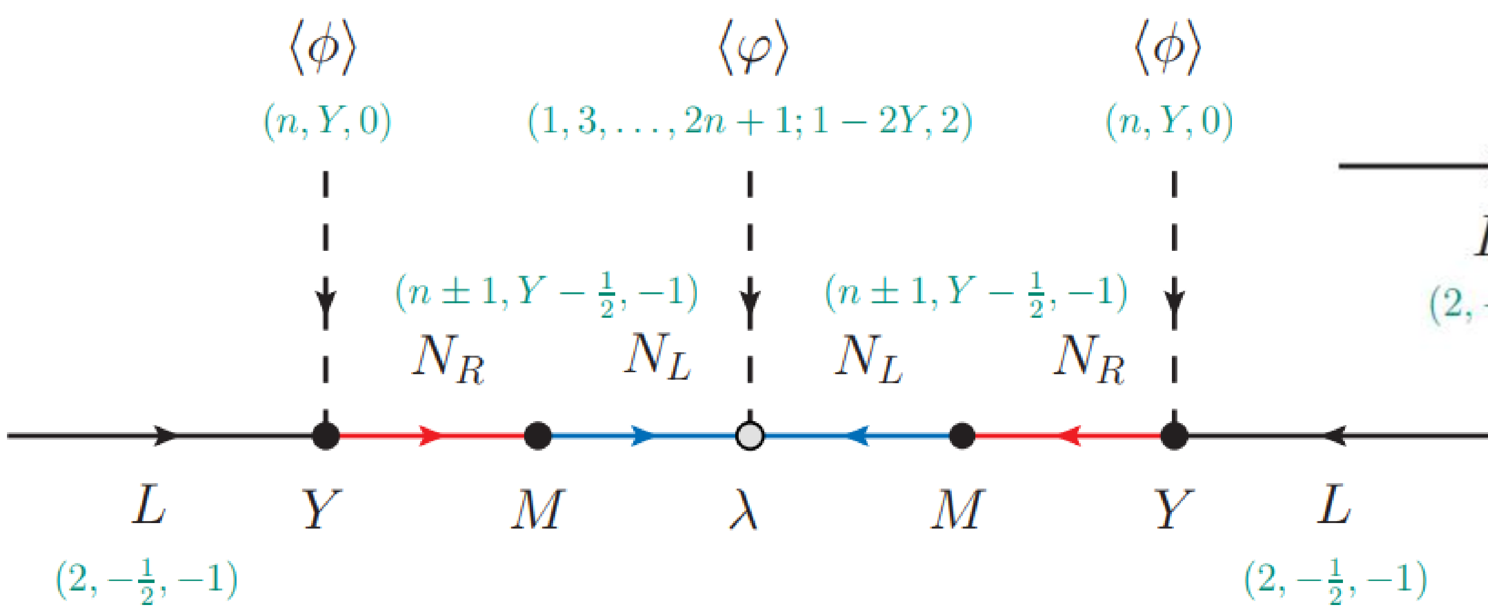


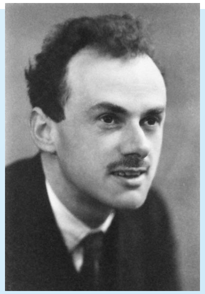
	Fields	$SU(2)_L \otimes U(1)_Y$	$U(1)_{B-L} \to \mathbb{Z}_3$	Fields	$SU(2)_L \otimes U(1)_Y$	$U(1)_{B-L} \to \mathbb{Z}_3$
Fermions	L_i	$(\mathbf{2}, -1/2)$	$-1 \to \omega^2$	ν_R	$(\mathbf{1}, 0)$	$(-4, -4, 5) \to \omega^2$
	N_L	$(\mathbf{1}, 0)$	$-1 \to \omega^2$	N_R	$(\mathbf{1}, 0)$	$-1 \to \omega^2$
Scalars	H	$(\mathbf{2}, 1/2)$	$0 \to \omega^0$	χ	$(\mathbf{1}, 0)$	$3 \to \omega^0$

Generalizations

- We can increase the SU(2) multiplicity.
- Richer collider signatures.

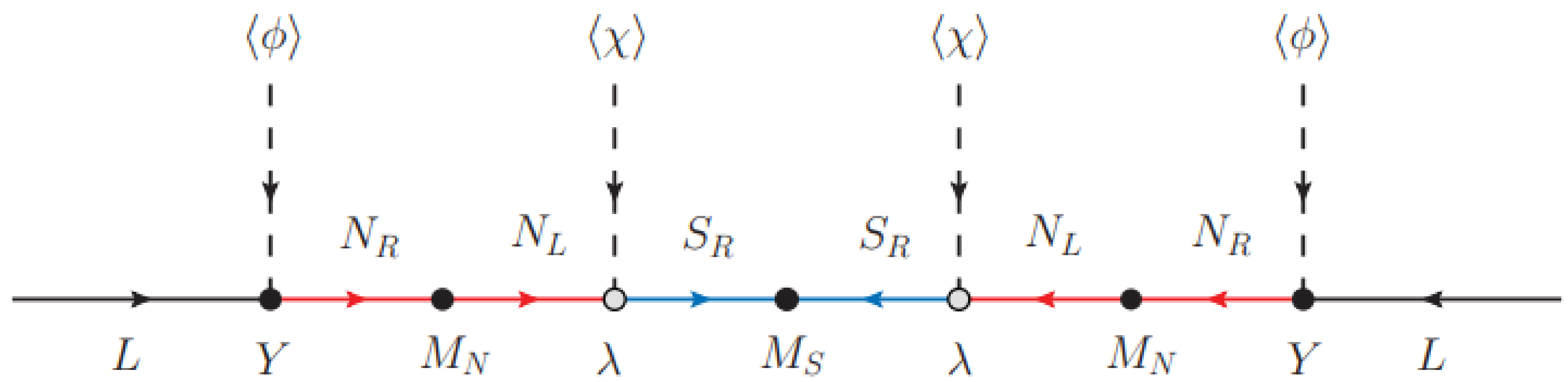






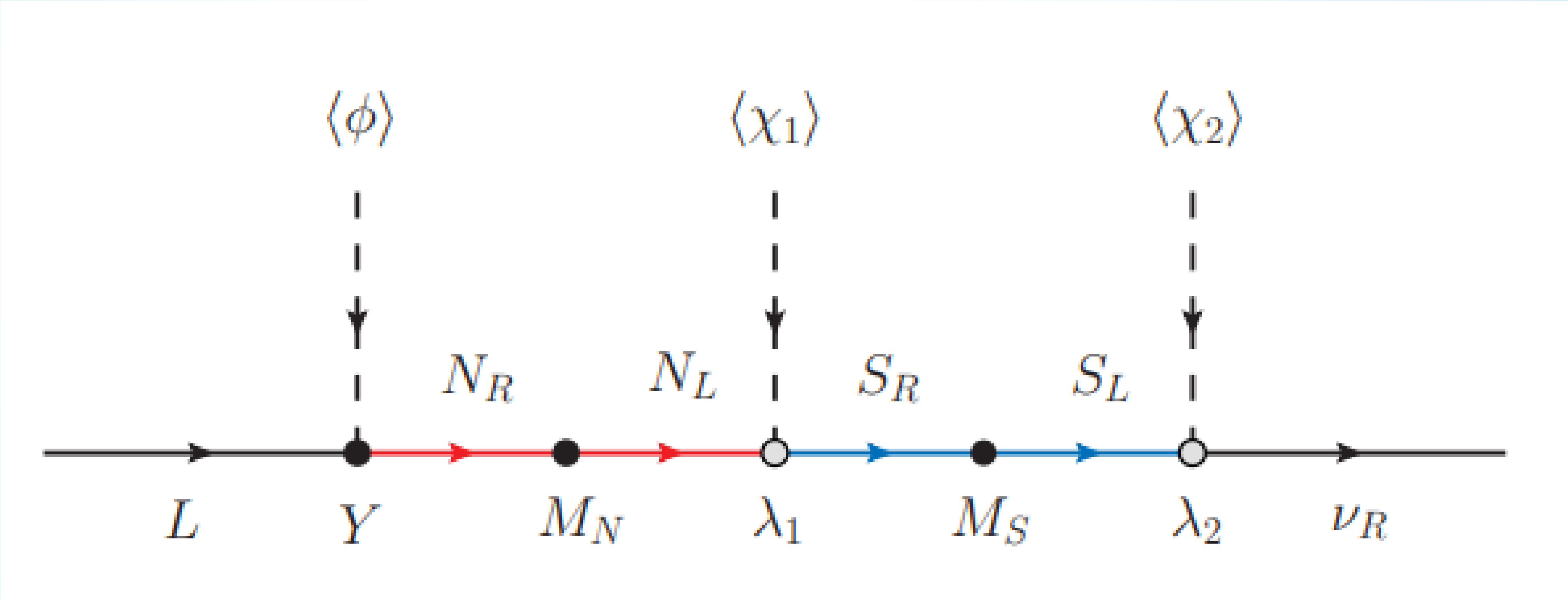
Generalizations

- We can also obtain extra suppression to neutrino mass with a double (and triple etc) seesaw.
- In the Majorana case one has to distinguish between the 2n and 2n+1 case.



Generalizations

- In the Dirac case one can describe the nth case directly.
- In all cases the symmetry assigment plays a crucial role!

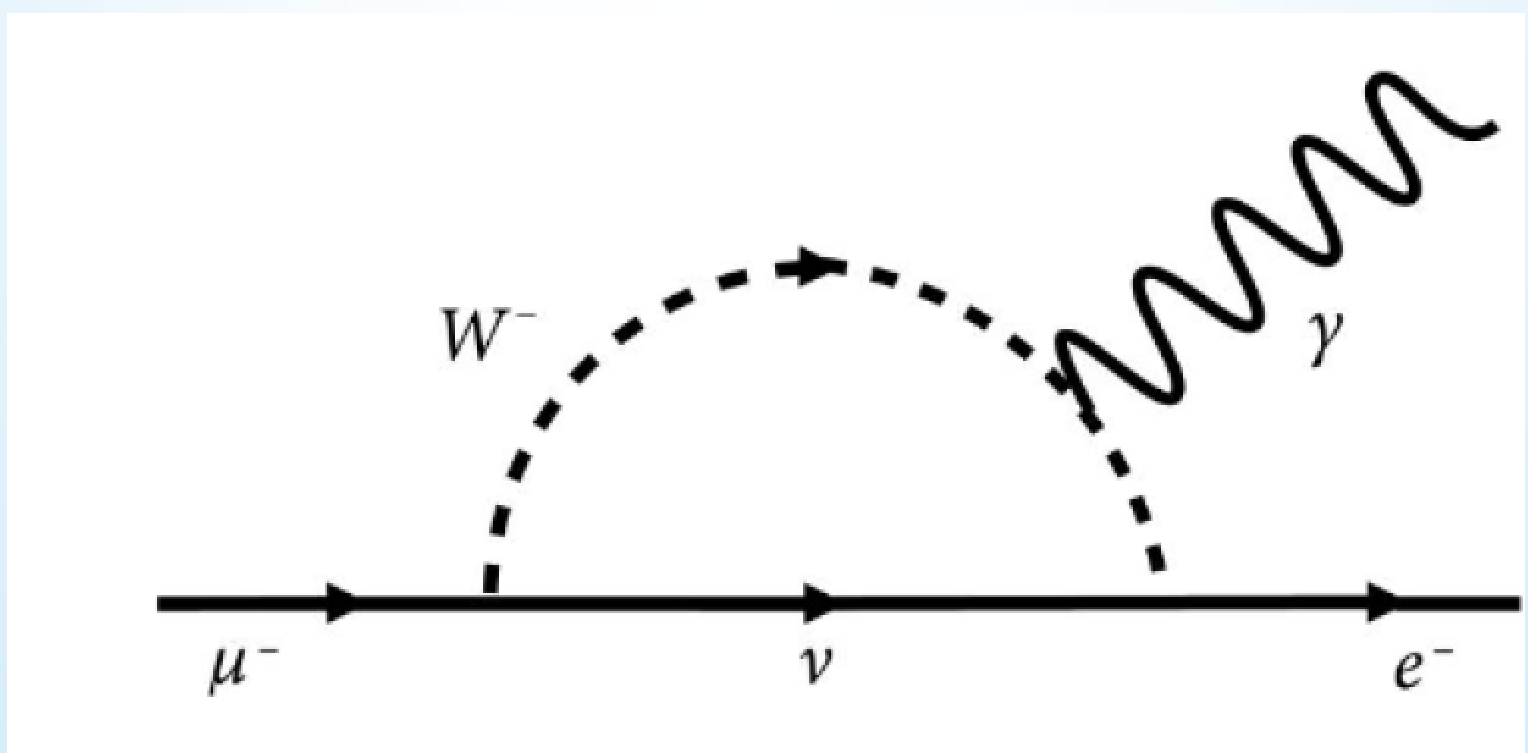


Generalizations

Model	m_ν formula	New fermions	New scalars
Majorana $(2n-1)$th inverse seesaw	$Y^2 v^2 \frac{\mu_n}{M_n^2} \prod_{i=1}^{i=n-1} \frac{\mu_i^2}{M_i^2}$	n VL pairs	n scalars
Majorana $2n$th inverse seesaw	$Y^2 v^2 \frac{1}{M_{n+1}} \prod_{i=1}^{i=n} \frac{\mu_i^2}{M_i^2}$	n VL pairs and a Weyl fermion	n scalars
Dirac nth inverse seesaw	$Y v \prod_{i=1}^{i=n} \frac{\mu_i}{M_i}$	n VL pairs	n scalars

$\mu^- \to e^-\gamma$

- Enhanced $\mu^- \to e^-\gamma$ in all the models $G_{\mu e} \sim \left(\frac{v\,Y}{M}\right)^2$.
- But the meaning of Y & M changes from model to model.



$\mu^- \to e^- \gamma$

- Majorana (2n-1)th inverse seesaw:
  - $G_{\mu e} \sim m_\nu \frac{1}{\mu_n} \frac{M_n^2}{M_1^2} \prod_{i=1}^{i=n-1} \frac{M_i^2}{\mu_i^2}$
- Majorana nth inverse seesaw:
  - $G_{\mu e} \sim m_\nu \frac{M_{n+1}}{M_1^2} \prod_{i=1}^{i=n} \frac{M_i^2}{\mu_i^2}$
- Dirac nth inverse seesaw:
  - $G_{\mu e} \sim m_\nu^2 \frac{1}{M_1^2} \prod_{i=1}^{i=n} \frac{M_i^2}{\mu_i^2}$

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Conclusions

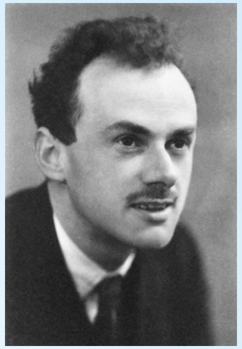
- The inverse seesaw model provides a very well motivated neutrino mass generation mechanism. Low scale seesaw!
- We provide the Dirac neutrino version.
- The B-L 445 solution plays a crucial role in these constructions.
- We show some generalizations with richer collider phenomenology and further suppresions of neutrino masses.

Thank you for your attention!

Back up: Majorana

Name of the model	ϕ	N_L and N_R	φ (μ-term)
Type I inverse seesaw - (2, 1, 0)	$(\mathbf{2}, 1/2) = H$	($\mathbf{1}$, 0)	($\mathbf{1}$,0)
Type III inverse seesaw - (2, 1, 0)	$(\mathbf{2}, 1/2) = H$	($\mathbf{3}$, 0)	($\mathbf{1}$,0)
Type III inverse seesaw - (2, 5, 0)	$(\mathbf{2}, 1/2) = H$	($\mathbf{3}$, 0)	($\mathbf{5}$,0)
Type III inverse seesaw - (2, 5, 2)	($\mathbf{2}$, -1/2) = H^c	($\mathbf{3}$, -1)	($\mathbf{5}$, 2)
Type III inverse seesaw - (4, 5, 1-2Y)	($\mathbf{4}$, Y=-1/2, 3/2)	($\mathbf{3}$, Y-1/2)	($\mathbf{5}$, 1-2Y)
Type IV inverse seesaw - (3, 7, 1-2Y)	($\mathbf{3}$, Y $= 0, \pm 1$)	$(\mathbf{4}, Y - 1/2)$	$(\mathbf{7}, 1 - 2Y)$
Type V inverse seesaw - (4, 1, 0)	($\mathbf{4}$, 1/2)	($\mathbf{5}$, 0)	($\mathbf{1}$,0)
Type V inverse seesaw - (4, 5 or 9, 0)	($\mathbf{4}$, 1/2)	($\mathbf{5}$, 0)	($\mathbf{5}$ or $\mathbf{9}$, 0)
Type V inverse seesaw - (4, 5 or 9, 1-2Y)	($\mathbf{4}$, Y=-1/2, 3/2)	($\mathbf{5}$, Y-1/2)	($\mathbf{5}$ or $\mathbf{9}$, 1-2Y)
Type V inverse seesaw - (4, 9, 4)	($\mathbf{4}$, -3/2)	($\mathbf{5}$, -2)	($\mathbf{9}$, 4)

Back up: Dirac



Name of the model	N_L and N_R	ϕ	φ (μ-term)
Standard Dirac Inverse seesaw	$(\mathbf{1}, 0)$	$(\mathbf{2}, 1/2)$	$(\mathbf{1}, 0)$
Type-III Dirac Inverse seesaw	$(\mathbf{3}, 0)$	$(\mathbf{2}, 1/2)$	$(\mathbf{3}, 0)$
Type-III Dirac Inverse seesaw variant I	$(\mathbf{3}, -1)$	$(\mathbf{2}, -1/2)$	$(\mathbf{3}, -1)$
Type-III Dirac Inverse seesaw variant II	$(\mathbf{3}, 1)$	$(\mathbf{4}, 3/2)$	$(\mathbf{3}, 1)$
Exotic or Type IV Dirac inverse seesaw	$(\mathbf{4}, Y - 1/2)$	$(\mathbf{3}, Y = 0, \pm 1)$	$(\mathbf{4}, Y - 1/2)$
Type-V Dirac Inverse seesaw	$(\mathbf{5}, 0)$	$(\mathbf{4}, 1/2)$	$(\mathbf{5}, 0)$
Type-V Dirac Inverse seesaw variant I	$(\mathbf{5}, 1)$	$(\mathbf{4}, 3/2)$	$(\mathbf{5}, 1)$
Type-V Dirac Inverse seesaw variant II	$(\mathbf{5}, -1)$	$(\mathbf{4}, -1/2)$	$(\mathbf{5}, -1)$
Type-V Dirac Inverse seesaw variant III	$(\mathbf{5}, -2)$	$(\mathbf{4}, -3/2)$	$(\mathbf{5}, -2)$

Table VI: A few examples of the generalized Dirac inverse seesaw.

Back up: $\mu^- \to e^-\gamma$

2 Majorana inverse seesaw

In the canonical Majorana inverse seesaw the neutrino mass matrix is given by

$$\mathcal{L}_m = \begin{pmatrix} \bar{\nu}^c & \bar{N}^c & \bar{S}^c \end{pmatrix} \begin{pmatrix} 0 & Y\,v & 0 \\ Y^T\,v & \mu' & M^T \\ 0 & M & \mu \end{pmatrix} \begin{pmatrix} \nu \\ N \\ S \end{pmatrix} . \tag{19}$$

Identifying the blocks with M and M_D of the previous section we find

$$m_\nu = \begin{pmatrix} Y\,v & 0 \end{pmatrix} \begin{pmatrix} \mu' & M^T \\ M & \mu \end{pmatrix}^{-1} \begin{pmatrix} Y^T\,v \\ 0 \end{pmatrix} \tag{20}$$

$$m_\nu \sim Y^2 \frac{v^2 \mu}{\mu\,\mu' - M^2} \sim Y^2 \frac{v^2 \mu}{M^2} \tag{21}$$

$$U_{\text{mix}} = m_D^* M^{-1} \sim \left(\frac{vY\mu}{M^2}, \frac{vY}{M} \right) \sim \frac{vY}{M} \tag{22}$$

$$G_{\mu e} \sim \left(\frac{vY}{M} \right)^2 \sim m_\nu / \mu \tag{23}$$

Back up: $\mu^- \to e^-\gamma$

3 Majorana double inverse seesaw

$$\mathcal{L}_m = (\bar{L}^c \quad \bar{N}_R \quad \bar{N}_L^c \quad \bar{S}_R) \begin{pmatrix} 0 & Y\,v & 0 & 0 \\ Y^T\,v & 0 & M_N & \mu' \\ 0 & M_N^T & 0 & \mu \\ 0 & \mu'^T & \mu^T & M_S \end{pmatrix} \begin{pmatrix} L \\ N_R^c \\ N_L \\ S_R^c \end{pmatrix}$$

$$\begin{aligned}
m_\nu &= (Y\,v \quad 0 \quad 0) \begin{pmatrix} 0 & M_N & \mu' \\ M_N^T & 0 & \mu \\ \mu^{T'} & \mu^T & M_S \end{pmatrix}^{-1} \begin{pmatrix} Y^T v \\ 0 \\ 0 \end{pmatrix} \\
m_\nu &\sim Y^2\,v^2 \frac{\mu^2}{2M_N\mu\mu' - M_N^2\,M_S} \sim Y^2\,v^2 \frac{\mu^2}{M_N^2\,M_S} \\
U_{\rm mix} &= m_D^* M^{-1} \sim \left(\frac{vY\mu^2}{M_N^2 M_S}, \frac{vY}{M_N}, \frac{vY\mu}{M_N M_S} \right) \sim \frac{vY}{M_N} \\
G_{\mu e} &\sim \left(\frac{vY}{M_N} \right)^2 \sim m_\nu M_S/\mu^2
\end{aligned}$$

Back up: $\mu^- \to e^-\gamma$

6 Dirac simple inverse seesaw

$$\begin{aligned}
\mathcal{M} &= (\bar{L} \quad \bar{N}_L) \begin{pmatrix} 0 & Y\,v \\ \mu & M \end{pmatrix} \begin{pmatrix} \nu_R \\ N_R \end{pmatrix} \\
m_\nu &\sim Y\,v\,\frac{\mu}{M} \\
U_{\rm mix} &\sim \frac{vY}{M} \\
G_{\mu e} &\sim m_\nu^2/\mu^2
\end{aligned}$$

7 Dirac double inverse seesaw

$$\begin{aligned}
\mathcal{L}_m &= (\bar{\nu}_L \quad \bar{N}_L \quad \bar{S}_L) \begin{pmatrix} 0 & Y\,v & 0 \\ 0 & M_N & \mu_1 \\ \mu_2 & \mu_1' & M_S \end{pmatrix} \begin{pmatrix} \nu_R \\ N_R \\ S_R \end{pmatrix} \\
m_\nu &\sim Y\,v\,\frac{\mu_1\mu_2}{M_N\,M_S} \\
U_{\rm mix} &\sim \frac{vY}{M_N} \\
G_{\mu e} &\sim \frac{m_\nu^2}{M_1^2}\,\frac{M_1^2}{\mu_1^2}\,\frac{M_2^2}{\mu_2^2}
\end{aligned}$$