NORDITA Winter School 2024 in Particle Physics and Cosmology

Neutrino physics III: Neutrinos and Physics Beyond the Standard Modell

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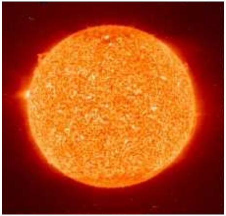
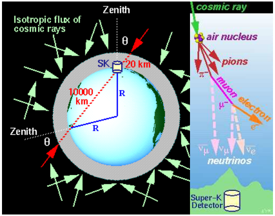
Karlsruher Institut für Technologie

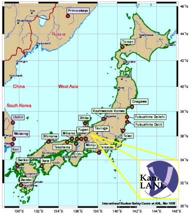
HIDDeν Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

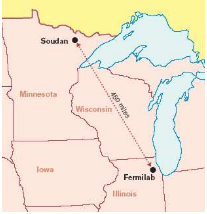
Stockholm, 15-17 Jan 2024

Neutrinos oscillate...









... and have mass $\Rightarrow$ physics beyond the Standard Model

- Part I: Neutrino Oscillations
- Part II: Neutrino mass - Dirac versus Majorana
- Part III: Neutrinos and physics beyond the Standard Model

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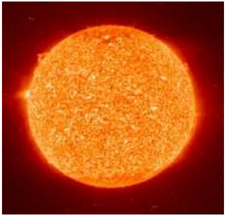
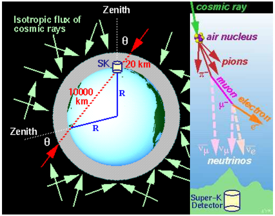
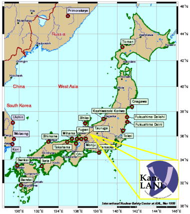
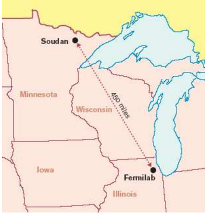








... and have mass ⇒ physics beyond the Standard Model

- Part I: Neutrino Oscillations
- Part II: Neutrino mass - Dirac versus Majorana
- Part III: Neutrinos and physics beyond the Standard Model

Outline - Neutrinos and physics beyond the SM

Outline

The Standard Model and neutrino mass

Giving mass to neutrinos
- Weinberg operator

Right-handed neutrinos
- Dirac vs Majorana neutrinos
- Type-I Seesaw

Extending the scalar sector of the SM
- Higgs-triplet / Type-II Seesaw
- Radiative neutrino mass models

Conclusions

Masses in the Standard Model

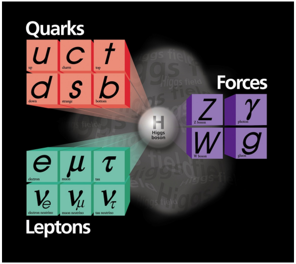
- The Standard Model has only one dimension full parameter: the vacuum expectation value of the Higgs:

$$\langle \phi \rangle \approx 174 \text{ GeV}$$

- All masses in the Standard Model are set by this single scale:

$$m_i = y_i \langle \phi \rangle$$

top quark: $y_t \approx 1$
electron: $y_e \approx 10^{-6}$



In the SM neutrinos are massless because...

- "right-handed" neutrinos would be complete gauge singlets in the SM
- no gauge interactions
- left out in the original formulation of the SM
  $\Rightarrow$ no Dirac mass term for neutrinos
- Why is there no Majorana mass term?
- Lepton-number is an accidental symmetry in the SM $\rightarrow$ given the gauge symmetry and the field content of the SM we cannot construct a Majorana mass term for neutrinos (true at any loop order)

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1. there are no right-handed neutrinos to form a Dirac mass term
2. because of the field content (scalar sector) and gauge symmetry lepton number[1] is an accidental global symmetry of the SM and therefore no Majorana mass term can be induced.
3. restriction to renormalizable terms in the Lagrangian

[1] B-L at the quantum level

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Neutrino mass implies physics beyond the Standard Model

At least one of the above items needs to be violated

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Famous historical example:

Assume there is new physics at a high scale Λ. It will manifest itself by non-renormalizable operators suppressed by powers of Λ.

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In the 1930's Fermi did not know about W and Z bosons, but he could write down a non-renormalizable dimension-6 operator to describe beta decay:

$$\frac{g^2}{\Lambda^2}(\bar{e}\gamma_\mu\nu)(\bar{n}\gamma^\mu p)$$

- Fermi knew about charge conservation $\to$ his operator is invariant under $U(1)_{\rm em}$
- Today we know that $\Lambda \simeq m_W$, and we know the UV completion of Fermi's operator, i.e. the electro-weak theory of the SM.

The Weinberg operator

Assume there is new physics at a high scale Λ. It will manifest itself by non-renormalizable operators suppressed by powers of Λ.

Weinberg 1979: there is only one dim-5 operator consistent with the gauge symmetry of the SM, and this operator will lead to a Majorana mass term for neutrinos after EWSB:

$$Y^2 \frac{\overline{L^c}\tilde{\phi}^* \, \tilde{\phi}^\dagger L}{\Lambda} \quad \longrightarrow \quad m_\nu \sim Y^2 \frac{\langle\phi\rangle^2}{\Lambda}$$

at dim-5 lepton number can be broken
(above operator not invariant under $L \to e^{i\alpha} L$)

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Seesaw:

neutrinos are light because of the presence of the large energy scale $\Lambda \gg \langle \phi \rangle$

High-scale versus low-scale seesaw

$$m_\nu \sim Y^2 \frac{\langle\phi\rangle^2}{\Lambda} \approx Y^2 \frac{(178\,\mathrm{GeV})^2}{\Lambda}$$

can obtain small neutrino masses by making Λ very large or Y very small (or both)

- High scale seesaw: $\Lambda \sim 10^{14}$ GeV, $Y \sim 1$
  - "natural" explanation of small neutrino masses
  - Leptogenesis
  - very hard to test experimentally

- Low scale seesaw: $\Lambda \sim$ TeV, $Y \sim 10^{-6}$
  - link neutrino mass generation to new physics testable at colliders
  - observable signatures in searches for LFV $\mu \to e\gamma, \tau \to \mu\gamma, \mu \to eee, \ldots$

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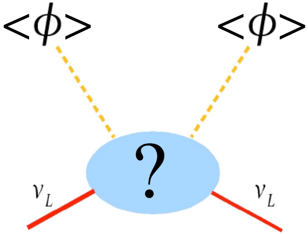

What is the new physics responsible for neutrino mass?

many realisations (too many?) are known:

at tree-level:

- Type I: fermionic singlet (right-handed neutrinos)
- Type II: scalar triplet
- Type III: fermionic triplet

many extended scenarios:

- extended Higgs sector
- realisations due to quantum effects (loop-induced)
- ...

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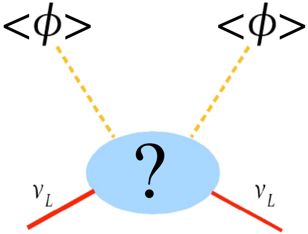

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Let's add right-handed neutrinos to the SM

What do we mean by "right-handed neutrino"?

A Majorana fermion field (2 dof) which is a singlet under the SM gauge group

- does not feel any of the gauge interactions of the SM, in particular also not the weak interaction ("sterile neutrino")
- note that a so-called "right-handed neutrino" contains a right-handed (N_R) and a left-handed (N_R^c) component

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quarks: $Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$, u_R, d_R leptons: $L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$, e_R, N_R

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$$\mathcal{L}_Y = -\lambda_e \bar{L}_L \phi e_R - \lambda_\nu \bar{L}_L \tilde{\phi} N_R + \mathrm{h.c.}$$

$$\text{EWSB} \rightarrow \quad -m_e \bar{e}_L e_R - m_D \bar{\nu}_L N_R + \mathrm{h.c.}$$

$$\tilde{\phi} \equiv i\sigma_2 \phi^*, \; m_e = \lambda_e \frac{v}{\sqrt{2}}, \; m_D = \lambda_\nu \frac{v}{\sqrt{2}}, \; \langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \; v = 246 \text{ GeV}$$

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SM + Dirac neutrinos:

- $\lambda_\nu \lesssim 10^{-11}$ for $m_D \lesssim 1$ eV ($\lambda_e \sim 10^{-6}$)
- why is there no Majorana mass term for N_R?
  $\Rightarrow$ have to impose lepton number conservation as additional ingredient of the theory to forbid Majorana mass

Dirac neutrinos in the SM

- Majorana mass term $\frac{M_R}{2} N_R^T C^{-1} N_R$ is allowed by gauge symmetry
- However, $M_R = 0$ is technically natural (protected by Lepton number)
  - the symmetry of the Lagrangian is increased by setting $M_R = 0$
  - M_R will remain zero to all loop order
- Also the Yukawas λ_ν are protected (chiral symmetry)
  tiny values are technically natural
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Charge quantization in the SM

Babu, Mohapatra, 89,90; Foot, Lew, Volkas, hep-ph/9209259

charge in the SM: $Q = (I_3 + Y/2)$ (for $y_\phi = 1$)

how to chose hyper-charges of fermions (SM, 1 gen): $y_{Q_L}, y_{u_R}, y_{d_R}, y_L, y_{e_R}$?

- gauge invariance of Yukawa terms:

$$y_{Q_L} = 1 + y_{d_R}\,, \quad y_{Q_L} = -1 + y_{u_R}\,, \quad y_L = 1 + y_{e_R}$$

- gauge anomaly cancellations:

$$SU(2)^2 U(1):\ Y_{Q_L} = -y_L/3\,, \quad U(1)^3:\ Y_L = -1$$

$\Rightarrow$ 5 constraints for 5 unknowns $\Rightarrow$ unique solution
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$$y_{d_R} = 2/3$$

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- SM + Dirac N_R: Yukawa and $U(3)^3$ same cond.: $y_L = -1 + y_N$
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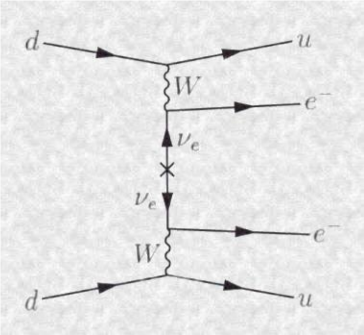
- SM (3 gen, no N_R + gravitational anomaly):
  $(L_e - L_\mu), (L_\mu - L_\tau), (L_e - L_\tau)$ anomaly free $\to$ dequantization
- SM (3 gen, Maj. N_R):
  Majorana mass breaks all $U(1)$'s $\to$ charge quantization

Neutrinoless double beta decay

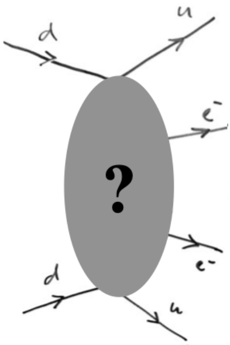
search for lepton-number violation via $(A, Z) \to (A, Z+2) + 2e^-$



- absent for Dirac neutrinos
- rate of the process is proportional to $m_{ee} = |\sum_i U_{ei}^2 m_i|$

Neutrinoless double beta decay

BUT: the process $(A,Z) \to (A,Z+2) + 2e^-$ can be mediated by other mechanisms than neutrino mass:



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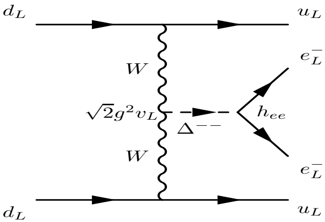
Higgs triplet



see e.g., W. Rodejohan, Int. J. Mod. Phys. E **20** (2011) 1833 [arXiv:1106.1334]

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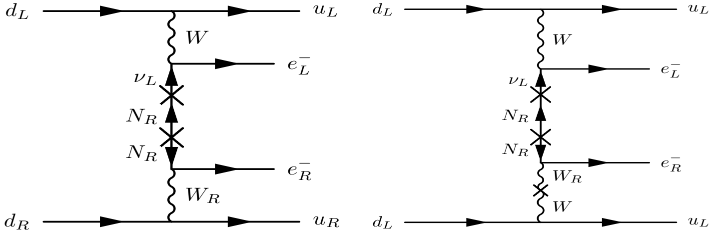
BUT: the process $(A, Z) \to (A, Z + 2) + 2e^-$ can be mediated by other mechanisms than neutrino mass:

N_R and W_R in left-right symmetric models



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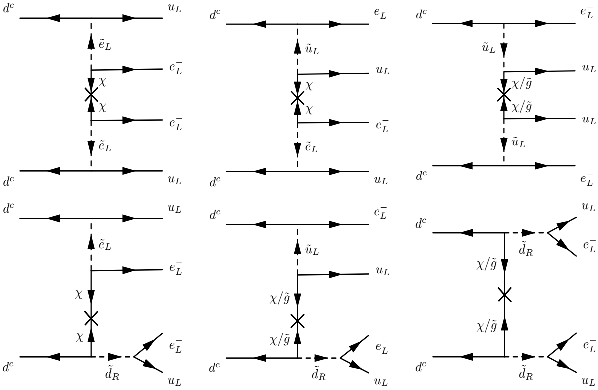
SUSY with R-parity violation



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Schechter-Valle theorem

- an observation of neutrinoless DBD $(A, Z) \to (A, Z+2) + 2e^-$ proves that L-number is violated
- this implies "Majorana nature" of neutrinos
  Schechter, Valle, 1982; Takasugi, 1984

> If neutrinoless DBD is observed, it is not possible to find a symmetry which forbids a Majorana mass term for neutrinos $\Rightarrow$ in a "natural" theory a Majorana mass will be induced at some level.

- in practice, however, the Majorana mass may still be tiny
  e.g., Duerr, Lindner, Merle, 2011

Let's add N_R and allow for lepton number violation

$$\mathcal{L}_Y = -\lambda_e \bar{L}_L \phi e_R - \lambda_\nu \bar{L}_L \tilde{\phi} N_R + \frac{1}{2} N_R^T C^{-1} M_R^* N_R + \text{h.c.}$$

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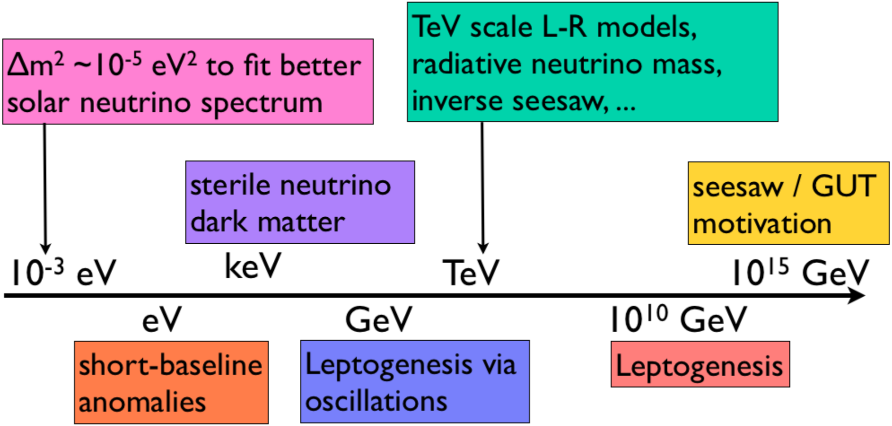
What is the value of M_R?

We do not know!

There is no guidance from the SM itself because N_R is a gauge singlet
M_R is a new scale in the theory, the scale of BSM physics

Right-handed neutrinos at which scale?



The Dirac+Majorana mass matrix

$$\mathcal{L}_Y = -\lambda_\nu \bar{L}_L \tilde{\phi} N_R + \frac{1}{2} N_R^T C^{-1} M_R^* N_R + \mathrm{h.c.}$$

EWSB $\rightarrow$ $$\mathcal{L}_\mathcal{M} = -m_D \bar{N}_R \nu_L + \frac{1}{2} N_R^T C^{-1} M_R^* N_R + \mathrm{h.c.}$$

using $\psi^T C^{-1} = -\overline{\psi^c}\,, \quad \psi^c \equiv C\overline{\psi}^T$

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ν_L contains 3 SM neutrino fields, N_R can contain any number r of fields ($r \geq 2$ if this is the only source for neutrino mass, often $r = 3$)

m_D is a general $3 \times r$ complex matrix, M_R is a symmetric $r \times r$ matrix

The Seesaw mechanism

let's assume $m_D \ll M_R$, then the mass matrix $\begin{pmatrix} 0 & m_D^T \\ m_D & M_R \end{pmatrix}$ can be approximately block-diagonalized to

$$\begin{pmatrix} m_\nu & 0 \\ 0 & M_R \end{pmatrix} \quad \text{with} \quad m_\nu = -m_D^T M_R^{-1} m_D \sim -\frac{m_D^2}{M_R}$$

where m_ν is the induced Majorana mass matrix for the 3 SM neutrinos.

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Seesaw:

ν_L are light because N_R are heavy

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$m_D = \lambda v/\sqrt{2}$

- assuming $\lambda \sim 1$ we need $M_R \sim 10^{14}$ GeV for $m_\nu \lesssim 1$ eV
  very high scale - close to $\Lambda_{\rm GUT} \sim 10^{16}$ GeV
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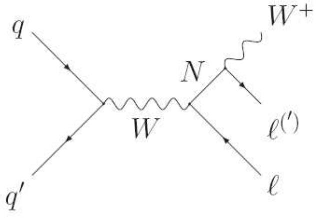
  GUT origin of neutrino mass?
- m_D could be lower, e.g., $m_D \sim m_e \Rightarrow M_R \sim$ TeV
  potentially testable at collider experiments like LHC

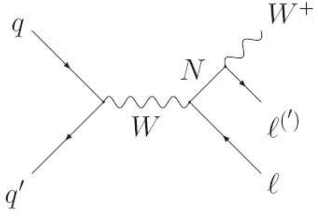
Type-I seesaw at LHC?



dilepton (or multi-lepton) events, e.g.:

- lepton number violating: $\ell^\pm \ell^\pm$ + jets
- lepton flavour violating: $\ell^\pm_\alpha \ell^\mp_\beta$ + jets

Type-I seesaw at LHC?



- in type-I seesaw N production is proportional to Y^2
  $Y \sim 10^{-6}$ for $M_N \sim$TeV $\to$ negligible
- invoke cancellations in $m^\nu_{\alpha\beta} \propto \sum_i Y_{\alpha i} Y_{\beta i}/M_i$ to obtain large Y
  cancellations motivated by symmetry (lepton number) $\to$
  decouple LHC signature from light neutrino mass Kersten, Smirnov, 07
- give N_R new interactions beyond the SM gauge interactions
  ex.: W_R in L-R symmetric models Keung, Senjanovic, 83

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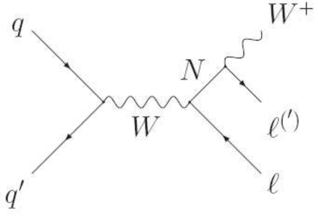

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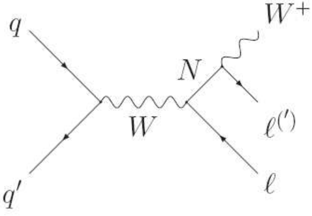

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Type-I seesaw

Type-I seesaw with 2 or 3 heavy right-handed neutrinos ($M_R \gtrsim 10^{10}$ GeV) is considered as "standard paradigm"

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(+) "natural" explanation of smallness of neutrino mass

(+) "simple" implementation of Leptogenesis

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νMSM Shaposhnikov,...

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(+) one N_R with $M_R \sim 1$ kev $\rightarrow$ provides Dark Matter (warm DM)

(+) two N_R with $M_R \sim 1$ GeV $\rightarrow$ provide neutrino mass and Leptogenesis

(+) does not require new physics up to the Planck scale

(−) requires tuning parameters to special values
(e.g., tiny Yukawas, highly degenerate N_R)

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In the SM neutrinos are massless because...

1. there are no right-handed neutrinos to form a Dirac mass term
2. because of the field content (scalar sector) and gauge symmetry lepton number[3] is an accidental global symmetry of the SM and therefore no Majorana mass term can be induced.
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3. restriction to renormalizable terms in the Lagrangian

We do not need right-handed neutrinos to give mass to ν_L!

[3] B-L at the quantum level

Outline

Extending the scalar sector of the SM

fermionic bilinears from SM leptons considering $\mathrm{SU}(2)_L$ quantum numbers

$$\left.\begin{array}{ll} L: & 2 \\ e_R: & 1 \end{array}\right\} \Rightarrow \left\{\begin{array}{lll} 2\times 1 = 2 & \bar{L}\phi e_R & \text{(SM doublet)} \\ 2\times 2 = 3+1 & L^T \Delta L & \text{(triplet)} \\ & L^T i\sigma_2 L h^+ & \text{(singlet)} \\ 1\times 1 = 1 & \overline{e_R^c} e_R k^{++} & \text{(singlet)} \end{array}\right.$$

Konetschny, Kummer, 1977; Cheng, Li, 1980

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- SU(2) triplet Higgs: $\Delta \to m_\nu$ at tree level ("type-II seesaw")
- one SU(2) singlet scalar with charge 1 and a second Higgs doublet
  $h^+, \phi' \to m_\nu$ at 1-loop level ("Zee model")
- two SU(2) singlet scalars with charge 1 and charge 2
  $h^+, k^{++} \to m_\nu$ at 2-loop level ("Zee–Babu model")

Higgs-triplet / Type-II Seesaw

Let's add a triplet Δ under $SU(2)_L$ to the SM:

$$\mathcal{L}_\Delta = f_{ab}\, L_a^T C^{-1}\, i\tau_2 \Delta\, L_b + \text{h.c.}\,,$$

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

The VEV of the neutral component $\langle H^0 \rangle \equiv v_T/\sqrt{2}$ induces a Majorana mass term for the neutrinos:

$$\frac{1}{2}\nu_{La}^T C^{-1} m_{ab}^\nu\, \nu_{Lb} + \text{h.c.} \qquad \text{with} \qquad m_{ab}^\nu = \sqrt{2}\, v_T\, f_{ab}$$

Type-II Seesaw

$$m^{\nu}_{ab} = \sqrt{2}\, v_T\, f_{ab} \lesssim 10^{-10}\,\mathrm{GeV}$$

scalar potential: $$\mathcal{L}_{\mathsf{scalar}}(\phi, \Delta) = -\frac{1}{2} M_\Delta^2 \mathrm{Tr}\Delta^\dagger \Delta + \mu \phi^\dagger \Delta \tilde{\phi} + \ldots$$

μ-term violates lepton number (Δ has $L = -2$)

minimisation of potential: $$v_T \simeq \mu \frac{v^2}{M_\Delta^2}$$

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Type-II seesaw: heavy triplet

$$\mu \sim M_\Delta \sim 10^{14}\,\mathrm{GeV} \qquad \Rightarrow \qquad v_T \sim \frac{v^2}{M_\Delta} \sim m^\nu\,,\; f_{ab} \sim \mathcal{O}(1)$$

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minimisation of potential: $v_T \simeq \mu \frac{v^2}{M_\Delta^2}$

triplet at the EW scale $\mathcal{O}$(100 GeV): $M_\Delta \sim v \quad \Rightarrow \quad v_T \sim \mu$

need combination of "small" μ and "small" f_{ab}

The triplet at LHC

$$pp \to Z^*(\gamma^*) \to H^{++} H^{--} \to \ell^+ \ell^+ \, \ell^- \ell^-$$

doubly charged component of the triplet:

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

very clean signature: two like-sign lepton paris with the same invariant mass and no missing transverse momentum; practically no SM background

Decays of the triplet:

$$\Gamma(H^{++} \to \ell_a^+ \ell_b^+) = \frac{1}{4\pi(1+\delta_{ab})} \, |f_{ab}|^2 M_\Delta \,,$$

$\Rightarrow$ proportional to the elements of the neutrino mass matrix!

$L - R$ symmetric theories

Type I+II seesaw:

assume N_R, Δ_L, Δ_R

$\langle \Delta_L \rangle$ gives Majorana mass term for ν_L
$\langle \Delta_R \rangle$ gives Majorana mass term for N_R
Yukawa with Higgs gives Dirac mass term

$$\begin{pmatrix} M_L & m_D^T \\ m_D & M_R \end{pmatrix} \quad \Rightarrow \quad m_\nu = M_L - m_D^T M_R^{-1} m_D$$

assuming $M_L \ll m_D \ll M_R$

SO(10) grand unified theory

- 16-dim representation contains all SM fermions + N_R

$$\begin{array}{ccccccc} (q_L & u_R & d_R & L_L & \ell_R & N_R) & \\ 6 & 3 & 3 & 2 & 1 & 1 & \mathbf{16} \end{array}$$

- 126-dim scalar representation
  - needed to break SO(10) down to the SM gauge group
  - contains triplets under $SU(2)_L$ and $SU(2)_R$
    $\to$ natural framework for type-I and type-II seesaw

- seesaw scale $M_\Delta, M_R \sim M_{\text{GUT}} \sim 10^{16}$ GeV

Mohapatra, Senjanovic,...

Radiative neutrino mass models

- neutrino mass vanishes at tree level, generated radiatively at *n*-loop order
- suppression by coupling constants and loop factors
- new physics cannot be too heavy, typically around TeV
- testable at colliders, charged lepton flavour violation

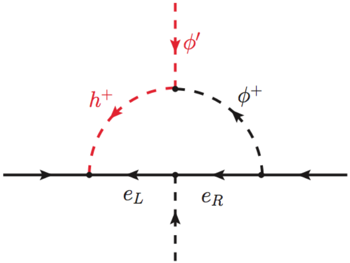
review: Cai, Herrero-Garcia, Schmidt, Vicente, Volkas, 1706.08524

Zee model (1-loop) Zee, 1980

introduce singly charged scalar h^+ and second Higgs doublet ϕ'

$$\mathcal{L}_\nu = f_{\alpha\beta} L_\alpha^T C i\sigma_2 L_\beta h^+ + \mu h^+ \phi^\dagger \tilde{\phi}' + \mathrm{h.c.}$$

$$m_\nu \sim \frac{\mu}{(4\pi)^2} f \frac{m_\ell^2}{m_h^2}$$



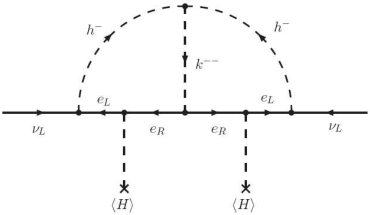
simplest version excluded, more complicated versions OK
Balaji, Grimus, Schwetz, 01; Herrero-Garcia, Ohlsson, Riad, Wiren, 17
rich phenomenology for LHC, FCNC, LFV $\mu \to e\gamma, \tau \to \mu\gamma, \mu \to eee, \ldots$

Zee-Babu model (2-loop) Zee, 85, 86; Babu 88

introduce $SU(2)$-singlet scalars: h^+, k^{++}

$$\mathcal{L}_\nu = f_{\alpha\beta} L_\alpha^T C^{-1} i\sigma_2 L_\beta h^+ + g_{\alpha\beta} \overline{e_{R\alpha}^c} e_{R\beta} k^{++} + \mu h^- h^- k^{++} + \text{h.c.}$$

$$m_\nu \approx \frac{\mu}{48\pi^2 m_k^2} f\, m_\ell\, g^*\, m_\ell\, f^T$$

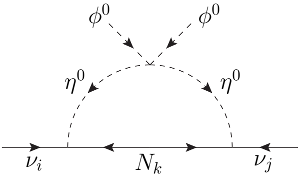


good prospects to see doubly-charged scalar at LHC $\to$ like-sign lepton events
if k^{++} is within reach for LHC, tight constrains by perturbativity requirements and bounds from LFV Babu, Macesanu, 02; Aristizabal, Hirsch, 06; Nebot et al., 07; Schmidt, TS, Zhang, 14; Herrero-Garcia, Nebot, Rius, Santamaria, 14

Combining neutrino mass with Dark Matter

"scotogenic" model E. Ma, hep-ph/0601225

- version of inert Higgs doublet model
- SM + 2nd Higgs doublet η + right-handed neutrinos N
- η and N are odd under a discrete Z_2 symmetry
  $\Rightarrow$ the lightest of them is a DM candidate
- neutrino masses generated at 1-loop:



many many variants discussed in literature

TeV scale neutrino mass

- (+) potentially test neutrino mass mechanism at LHC
- (+) typically signatures in LFV $\mu \to e\gamma, \tau \to \mu\gamma, \mu \to eee, \ldots$
- (+) radiative models explain smallness of neutrino mass by loop-factors
- (+) in general, for mass generation at n-loop order one needs to explain the absence of all terms at order $< n \to$ invoke symmetry (can be used for stabilizing a DM candidate, e.g., Ma, 06)
- (−) often TeV models appear ad-hoc and somewhat unmotivated

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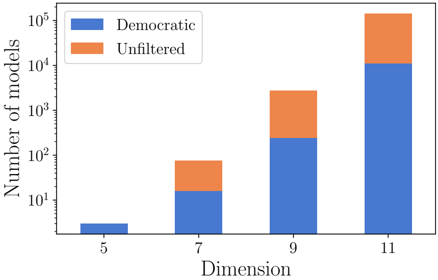
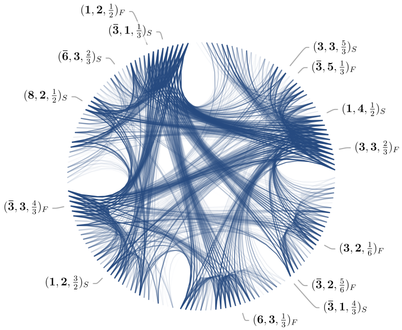
Automatized neutrino mass model building

Gargalionis, Volkas, 2009.13537; refs therein

- write down complete list of $\Delta L = 2$ operators
- systematically search for all possible UV completions (models)





Outline

Conclusions - neutrinos and BSM

- neutrino mass established by oscillations
- identifying the mechanism for neutrino mass is one of the most important open questions in particle physics
- ... this may be a difficult task (the answer could be elusive forever)
- does not point to a specific energy scale of new physics
- search for complementary signatures
  - neutrinoless double-beta decay
  - charged-lepton flavour violation ($\mu \to e\gamma, \mu \to 3e, ...$)
  - lepton-number violation at LHC
  - leptogenesis
  - exotic neutrino properties: sterile neutrinos, exotic neutrino interactions,...

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Supplementary Slides

Lepton flavour violation

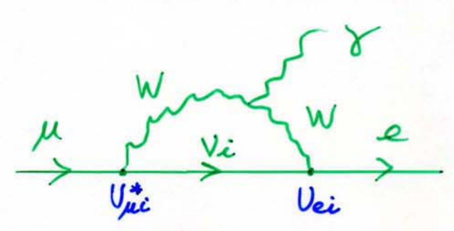
- Neutrino oscillations imply violation of lepton flavour, e.g.: $\nu_\mu \to \nu_e$
- Can we see also LFV in charged leptons?

$$\mu^\pm \to e^\pm \gamma$$
$$\tau^\pm \to \mu^\pm \gamma$$
$$\mu^+ \to e^+ e^+ e^-$$
$$\mu^- + N \to e^- + N$$

rich experimental program with sensitivities in the 10^{-13} to 10^{-18} range

Can we see also LFV in charged leptons?

Yes, BUT: $\mu^\pm \to e^\pm\gamma$ in the SM + ν mass:



$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{m^2_W}\right|^2 \lesssim 10^{-54}$$

- unobservably small (present limits: $\sim 10^{-13}$)
- observation of $\mu \to e\gamma$ implies new physics beyond neutrino mass

$\mu \to e\gamma$ and new physics

generically one expects

$$\text{Br}(\mu \to e\gamma) \sim 10^{-10} \left(\frac{\text{TeV}}{\Lambda_{\rm LFV}}\right)^4 \left(\frac{\theta_{e\mu}}{10^{-2}}\right)^2$$

- we are sensitive to new physics in the range 1 to 1000 TeV (TeV scale SUSY, TeV scale neutrino masses,...)
- cLFV does NOT probe neutrino Majorana mass (conserves lepton number) Majorana mass: dim-5 operator, LFV: dim-6 operators, e.g.

$$\mathcal{L}_{\rm LFV} = \frac{1}{\Lambda^2_{\rm LFV}}(\overline{\mu}e)(\overline{e}e) + \frac{1}{\Lambda^2_{\rm LFV}}(\overline{\mu}e)(\overline{q}q)$$

- cLFV is sensitive to new physics which may or may not be related to the mechanism for neutrino mass → extremely valuable information on BSM