Phenomenology of the Zee model for Dirac neutrinos and general neutrino interactions
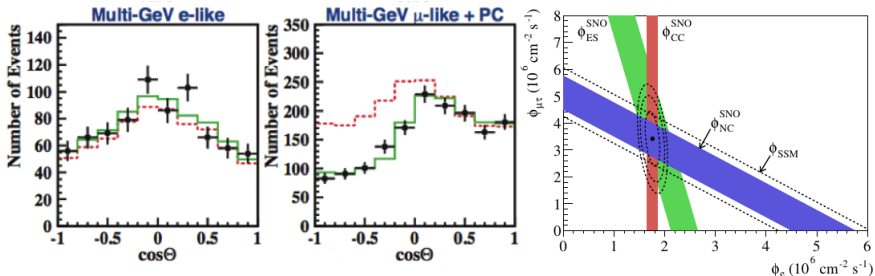
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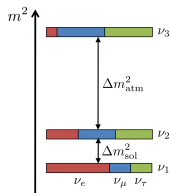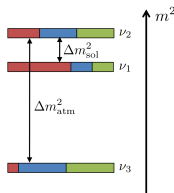
NuCo 2021.

- Genereting one-loop Dirac neutrino masses

- Zee model for Dirac neutrinos

- Phenomenology

- Summary

normal hierarchy (NH)   **inverted hierarchy (IH)**

From solar, atm, accel and reactor ν-exp:

- At least two massive neutrinos: $\Delta m_{12}^2 \sim 10^{-4} \text{eV}^2$, $\Delta m_{23}^2 \sim 10^{-3} \text{eV}^2$.
- Three non-zero mixing angles: $\theta_{12} \sim 33°$, $\theta_{23} \sim 49°$, $\theta_{13} \sim 8°$.

Neutrino masses in the SM

Dirac mass term: $m_D(\bar{\nu}_R \nu_L + h.c.)$

Majorana mass term: $m_L(\bar{\nu}_L^c \nu_L + h.c.)$

$\Rightarrow$ neutrino oscillations require physics beyond SM.

Generating Dirac neutrino masses

Dirac neutrino masses are generated via the $d = 4$ op.

$$\mathcal{O}_4 = y \overline{L} \widetilde{H} N_R + \text{h.c.},$$

- Assuming, e.g., L conservation or Z_n with $n \geq 3$ (to protect the Diracness of neutrinos) this operator leads to $m_\nu \sim$ sub-eV for $|y| \lesssim 10^{-13}$, thus leaving unsettled the explanation of the smallness of the m_ν.
- It seems reasonable to forbid $\mathcal{O}_4$ through a certain symmetry $\mathcal{X}$ while generating Dirac neutrino masses via higher dimensional operators, either at tree level or loop level.
- SM gauge symmetry implies that only even operators are allowed, $\mathcal{O}_{4+2n} = \overline{L} \widetilde{H} N_R (H^\dagger H)^n$
- The next allowed operator would be $\mathcal{O}_6$.
- $d = 5$ operators require new scalar fields.
  The simplest scenario: a singlet S.

$$\mathcal{O}_5 \sim \frac{y'}{\Lambda} \bar{L} \widetilde{H} N_R S$$

Tree level realizations of $\mathcal{O}_5$

$$\mathcal{O}_5 \sim \frac{y'}{\Lambda} \bar{L} \widetilde{H} N_R S \quad \Rightarrow \quad m_\nu \sim \frac{y' v v_S}{\Lambda}$$

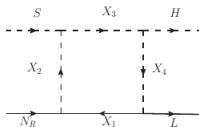At tree level there are only 3 realizations of $\mathcal{O}_5$

type-I   type-II   type-III
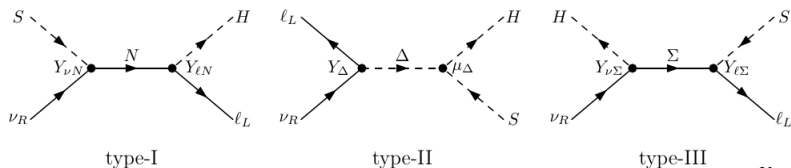
Yao/Ding2018

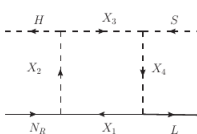| Dirac seesaw	mediator	$(m_\nu)_{\alpha\beta}/(\langle H\rangle\langle S\rangle)$
type-I	$N \sim \mathbf{1}_0^+$	$-\frac{(Y_{\ell N})_{\alpha i}(Y_{\nu N})_{i\beta}}{M_N^{(i)}}$
type-II	$\Delta \sim \mathbf{2}_1^-$	$-\frac{\mu_\Delta (Y_\Delta)_{\alpha\beta}}{M_\Delta}$
type-III	$\Sigma \sim \mathbf{2}_{-1}^-$	$-\frac{(Y_{\ell\Sigma})_{\alpha i}(Y_{\nu\Sigma})_{i\beta}}{M_\Sigma^{(i)}}$

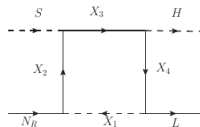Additional fields transforming as 1, 2, 3 under $SU(2)_L$, either scalars or vector-like fermions.

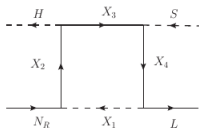At one-loop level there are 3 topologies leading $\mathcal{O}_5$. Yao/Ding2018

(a) T1-1-A model

(b) T1-1-B model

(c) T1-2-A model
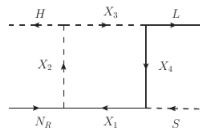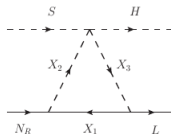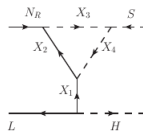
(d) T1-2-B model
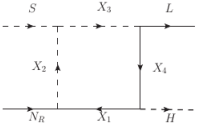
(e) T1-3-D model
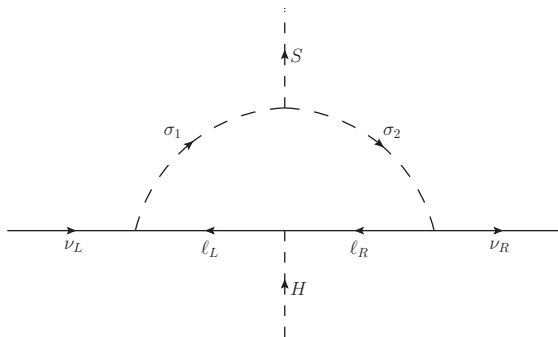
(f) T1-3-E model

(g) T3-1-A model

(h) T4-3-I model

Zee model for Dirac neutrinos

The simplest model leading to Dirac neutrino masses at one loop level:
T1-3-D model with SM charged leptons as mediators

Nasri, Mousa MPLA2002; Kanemura et.al PLB2011.
The tree level contribution of $\mathcal{O}_{5\nu}$ is forbidden by a softly-broken Z_2 symmetry

Gauge realization of the Zee model for Dirac neutrinos

The $U(1)_{B-L}$ gauge realization without new extra fermions requires:
- Two $SU(2)_L$-singlet charged scalars, $\sigma_1^{\pm}$ and $\sigma_2^{\pm}$.
- Two bosonic fields associated to the new symmetry: Z'_μ and S.

Symbol	$(SU(2)_L, U(1)_Y)$	L	Spin
L	$(2, -1/2)$	-1	$1/2$
H	$(2, 1/2)$	0	0
$\overline{\ell_R}$	$(1, 1)$	-1	$1/2$
$\overline{\nu_{R\,i,j}}$	$(1, 0)$	4	$1/2$
$\overline{\nu_{R\,k}}$	$(1, 0)$	-5	$1/2$
S	$(1, 0)$	3	0
σ_1^+	$(1, 1)$	2	0
σ_2^+	$(1, 1)$	5	0

- The tree level contribution of $\mathcal{O}_{5\nu}$ is forbidden without any extra *ad-hoc* symmetry.
- The charge assignment guarantees a successful anomaly cancellation and protects the Diracness of neutrinos. *Montero-Pleitez PLB2008.*

Interactions

New Yukawa terms

$$-\mathcal{L} \supset f_{\alpha\beta}\overline{L_\alpha^c}L_\beta\sigma_1^+ + h_{\beta j}\overline{\ell_{R\beta}^c}\nu_{Rj}\sigma_2^+ + \text{h.c.},$$

Scalar potential

$$\mathcal{V} \supset \mu_S^2 S^\dagger S + \lambda_S(S^\dagger S)^2 + \lambda_3(H^\dagger H)(S^\dagger S) + \mu_1^2|\sigma_1^+|^2 + \mu_2^2|\sigma_2^+|^2$$
$$+ \mu_3[\sigma_1^+\sigma_2^- S + \text{h.c.}].$$

We assume $\lambda_3 \ll 1$ such that the scalar S and H do not mix, allowing us to identify the CP even scalar particle in H as the SM Higgs boson.

$$H = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(h + v_H) \end{pmatrix}, \qquad S = \frac{1}{\sqrt{2}}(S_R + v_S),$$

$$\begin{pmatrix} s_1^\pm \\ s_2^\pm \end{pmatrix} = \begin{pmatrix} \cos\varphi & -\sin\varphi \\ \sin\varphi & \cos\varphi \end{pmatrix} \begin{pmatrix} \sigma_1^\pm \\ \sigma_2^\pm \end{pmatrix}, \tag{1}$$

$\sin(2\varphi) = \sqrt{2}\mu_3 v_S/(m_{s_2}^2 - m_{s_1}^2).$

Radiative neutrino masses

The interplay of the new Yukawa interactions and the trilinear interaction μ_3:

$$[M_\nu]_{\alpha i} = \kappa [f^T]_{\alpha\beta} [M_\ell]_{\beta\beta} h_{\beta i}, \qquad \kappa = \frac{\sin(2\varphi)}{16\pi^2} \ln \frac{m_{s_2}^2}{m_{s_1}^2}.$$

• Since f is antisymmetric one neutrino state remains massless.
• One can express six of the nine non-zero Yukawa-couplings in terms of m_i, θ_{ij}, m_{ℓ_i} and m_{s_i}.

$$h_{22} = \frac{(U_{11}U_{32} - U_{12}U_{31})(f_{13}h_{12}\kappa m_e - m_2 U_{32})}{f_{13}\kappa (U_{22}U_{31} - U_{21}U_{32}) m_\mu},$$

$$h_{32} = \frac{f_{13}h_{12}\kappa m_e(U_{12}U_{21} - U_{11}U_{22}) + m_2 U_{22}(-U_{12}U_{31} + U_{11}U_{32})}{f_{13}\kappa (U_{22}U_{31} - U_{21}U_{32}) m_\tau},$$

$$h_{21} = -\frac{(U_{12}U_{31} - U_{11}U_{32})(f_{13}h_{11}\kappa m_e - m_1 U_{31})}{f_{13}\kappa (U_{22}U_{31} - U_{21}U_{32}) m_\mu},$$

$$h_{31} = \frac{f_{13}h_{11}\kappa m_e(U_{12}U_{21} - U_{11}U_{22}) + m_1 U_{21}(-U_{12}U_{31} + U_{11}U_{32})}{f_{13}\kappa (U_{22}U_{31} - U_{21}U_{32}) m_\tau},$$

$$f_{12} = \frac{f_{13}(U_{12}U_{21} - U_{11}U_{22})}{U_{12}U_{31} - U_{11}U_{32}}, \qquad f_{23} = \frac{f_{13}(U_{22}U_{31} - U_{21}U_{32})}{U_{12}U_{31} - U_{11}U_{32}}.$$

LFV searches

• The same Yukawa interactions also induce charged LFV processes such as $\ell_i \to \ell_j \gamma$, $\ell_i \to 3\ell_j$ and $\mu - e$ conversion in nuclei.

• They are generated at one-loop level and are mediated by $s_k^\pm$ and neutrinos.

• $\mathcal{B}(\mu \to e\gamma) \propto \left[16 C_{\varphi 12}^2 |f_{13}|^2 |f_{23}|^2 + C_{\varphi 21}^2 (|h_{12}h_{22} + h_{13}h_{23}|^2) \right]$.
  $C_{\varphi ij} = \cos\varphi^2/m_{si}^2 + \sin\varphi^2/m_{sj}^2$.

• The branching ratios are not suppressed by the φ.

LHC searches
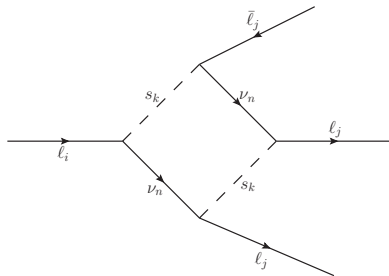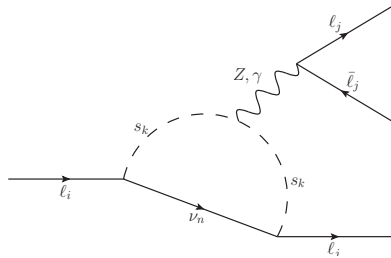
Collider bounds on the gauge boson:

- ATLAS search of dilepton resonances gives $M_{Z'} \gtrsim 6$ TeV for $g' \sim 0.5$.

- Since $M_{Z'} = 3g'v_S$, then $v_S \gtrsim 4$ TeV for $g' \sim 0.5$.

Collider bounds on the charged scalar $s_1^{\pm}$:

- For $f, h \lesssim 0.1$: produced via Drell-Yan processes.

- Signature of dileptons plus missing transverse momentum (analogous to electroweak production of sleptons) $pp \to \gamma^*/Z^* \to s_1^+ s_1^- \to \ell_i^+ \ell_j^- \nu\nu$.

- for large f, h: single production through the radiation from a lepton external leg in s-channel diagrams featuring a gauge boson (γ, Z or W).

- Assuming a 100% branching ratio into $\ell = e, \mu$ allows to exclude s_1 with masses below 200 GeV.

General neutrino interactions

• The $h_{\beta i}$ and $f_{\alpha \beta}$ interactions also induce new effective four-fermion interactions between neutrinos and charged leptons.

• They can modify the SM prospect for the neutrino-electron elastic scattering, and therefore be constrained by solar ν exp, eg, Borexino.

• Following Khan-Rodejohann-Xu(PRD2020)

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \sum_{a=S,P,V,A,T} (\overline{\nu}_\alpha \Gamma^a \nu_\beta) \left[\overline{\ell} \Gamma^a \left(\epsilon^a_{\alpha\beta} + \tilde{\epsilon}^a_{\alpha\beta} i^a \gamma^5 \right) \ell \right] ,$$

$$\{\Gamma^S, \Gamma^P, \Gamma^V, \Gamma^A, \Gamma^T\} \equiv \{I, i\gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu}\}, \{i^S, i^P, i^V, i^A, i^T\} \equiv \{i, i, 1, 1, i\}.$$

• The 3×3 real matrices ϵ and $\tilde{\epsilon}$ parametrize the departures of the SM result.

$$\epsilon^{V,A}_{ee} = \tilde{\epsilon}^{V,A}_{ee} = -\frac{\sqrt{2}}{8G_F} |h_{11}|^2 C_{\varphi 21},$$

$$\epsilon^{V,A}_{\mu\mu}[\tilde{\epsilon}^{V,A}_{\mu\mu}] = -\frac{\sqrt{2}}{8G_F} (|h_{12}|^2 C_{\phi 21} \pm 4|f_{12}|^2 C_{\varphi 12}),$$

$$\epsilon^{V,A}_{\tau\tau}[\tilde{\epsilon}^{V,A}_{\tau\tau}] = -\frac{\sqrt{2}}{8G_F} (|h_{13}|^2 C_{\varphi 21} \pm 4|f_{13}|^2 C_{\varphi 12}).$$

Scan

The set of free parameters of the model relevant for our analysis has been varied as

$$10^{-5} \leq |f_{13}| \leq 3 \ ;$$
$$0.1 \leq |h_{12}, h_{13}(h_{11}, h_{12})| \leq 3 \ ;$$
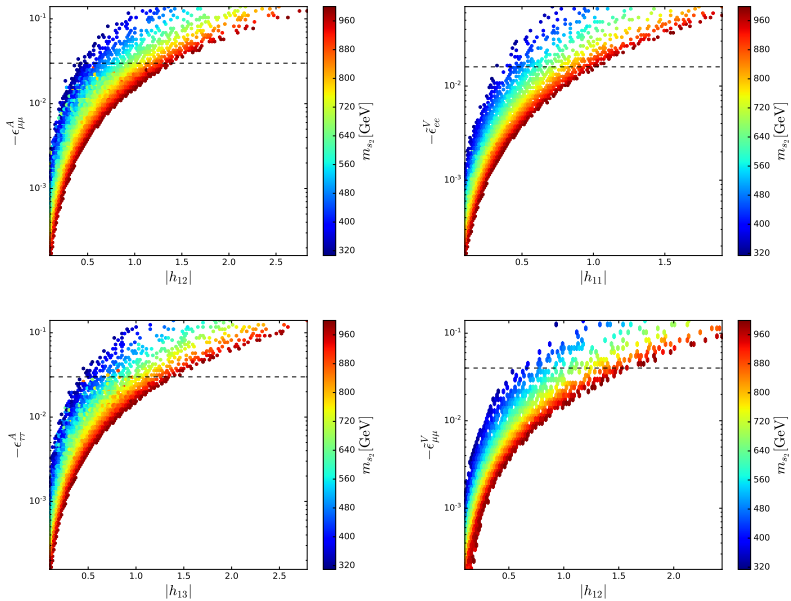$$10^{-6} \leq \varphi \leq \pi/2 \ ;$$
$$80 \, \text{GeV} \leq m_{s1} \leq 500 \, \text{GeV} \ ; m_{s_2} = [m_{s_1}, 1000 \, \text{GeV}].$$

The magnitude of the non-free Yukawa couplings: $[10^{-5}, 3]$, and
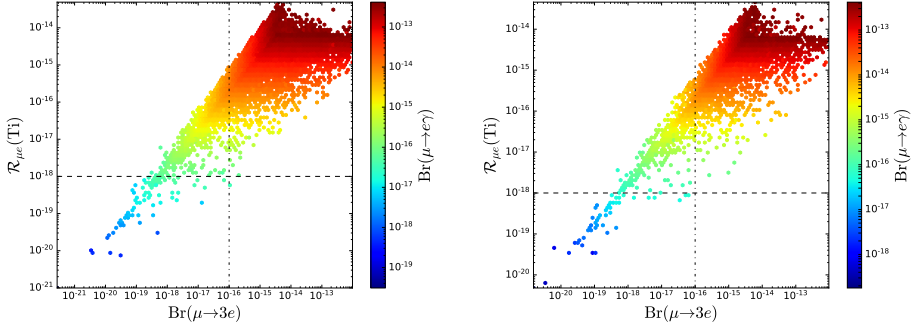$\lambda_i = 10^{-4}$, $i = 1, ..., 8$.
$M_{Z'} = 6$ TeV and $g' = 0.5$ in such a way $v_S = 4$ TeV.
All the viable benchmark points satisfy the current neutrino oscillation data
within the 3σ level, with $\delta_{\text{CP}} = \pi(0)$ for a NH (IH).

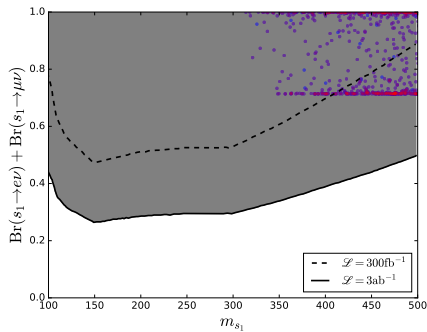GNI searches for NH (left) and IH (right).

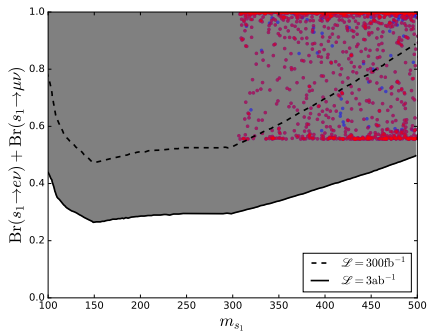LFV processes for NH (left) and IH (right).

The dotted (dashed) lines represent the sensitivity limit expected for the future searches for $\mathcal{R}_{\mu e}(\text{Ti})$ ($\mathcal{B}(\mu \to 3e)$).

Projected exclusion reach in the decay branching ratio of $s_1^{\pm}$ into electrons and muons for NH (left) and IH (right).

The red dots are within the future sensitivity of the LFV experiments

Summary

- Neutrino masses may originate from new physics at the TeV scale.

- The simplest model leading to Dirac masses at one loop level is obtained by adding a pair of charged scalars to the SM along with three ν_R.

- The Diracness of the neutrinos is protected by only one extra $U(1)_{B-L}$ gauge symmetry.

- We reported the expressions for GNI and identified the regions of parameter space that may be explored in future solar neutrino experiments.

- Future searches for charged scalars at the LHC will probe the entire parameter space considered in this analysis.

GNI bounds

GNI	Current bound	Projected sensitivity
ϵ_{ee}^V	$[-0.12, 0.08]$	$[-0.016, 0.016]$
ϵ_{ee}^A	$[-0.13, 0.07]$	$[-0.016, 0.016]$
$\tilde{\epsilon}_{ee}^V$	$[-0.07, 0.13]$	$[-0.016, 0.016]$
$\tilde{\epsilon}_{ee}^A$	$[-0.08, 0.13]$	$[-0.016, 0.016]$
$\epsilon_{\mu\mu}^V/\epsilon_{\tau\tau}^V$	$[-0.22, 0.08]$	$[-0.1, 0.1]$
$\epsilon_{\mu\mu}^A/\epsilon_{\tau\tau}^A$	$[-0.08, 0.08]$	$[-0.03, 0.03]$
$\tilde{\epsilon}_{\mu\mu}^V/\tilde{\epsilon}_{\tau\tau}^V$	$[-0.09, 0.08]$	$[-0.04, 0.04]$
$\tilde{\epsilon}_{\mu\mu}^A/\tilde{\epsilon}_{\tau\tau}^A$	$[-0.90, 0.22]$	$[-0.1, 0.1]$
$\epsilon_{\mu\mu}^S/\epsilon_{\tau\tau}^S$	$[-0.83, 0.83]$	$[-0.5, 0.5]$
$\epsilon_{\mu\mu}^P/\epsilon_{\tau\tau}^P$	$[-0.83, 0.83]$	$[-1.22, 1.22]$
$\epsilon_{\mu\mu}^T/\epsilon_{\tau\tau}^T$	$[-0.15, 0.15]$	$[-0.1, 0.1]$

Khan, Rodejohann, Xu PRD2020.
Use of Borexino solar neutrino measurements to set limits on the size of the new interactions. Focus on flavor diagonal interactions