EFT in Neutrino Physics and B & L Violation

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Outline

- Effective L-violating operators
- Small neutrino masses as radiative corrections
- UV completion: Explicit models and their tests
- Nonstandard neutrino interactions (NSI)
- Effective B-violating operators for nucleon decay
- $\Delta B = 2$ effective operators and neutron-antineutron oscillations
- Conclusions

Current knowledge of neutrino oscillations

- Global fit to neutrino masses and mixing angles:

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.7$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK-atm	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.580^{+0.017}_{-0.021}$	$0.418 \to 0.627$	$0.584^{+0.016}_{-0.020}$	$0.423 \to 0.629$
	$\theta_{23}/^\circ$	$49.6^{+1.0}_{-1.2}$	$40.3 \to 52.4$	$49.8^{+1.0}_{-1.1}$	$40.6 \to 52.5$
	$\sin^2\theta_{13}$	$0.02241^{+0.00065}_{-0.00065}$	$0.02045 \to 0.02439$	$0.02264^{+0.00066}_{-0.00066}$	$0.02068 \to 0.02463$
	$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.65^{+0.13}_{-0.13}$	$8.27 \to 9.03$
	$\delta_{CP}/^\circ$	215^{+40}_{-29}	$125 \to 392$	284^{+27}_{-29}	$196 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.525^{+0.033}_{-0.032}$	$+2.427 \to +2.625$	$-2.512^{+0.034}_{-0.032}$	$-2.611 \to -2.412$

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou (2019)

- The type of mass hierarchy, *CP* violation in oscillation, lightest neutrino mass, and whether neutrinos are Dirac or Majorana are still unknown.

EFT for neutrino masses and oscillations

- Neutrino masses are zero in the Standard Model
- Neutrino masses and oscillations can be explained in terms of the celebrated Weinberg operator
- It is the leading operator in SMEFT and arises at dimension-five, suppressed by one power of an inverse mass scale
- It violates lepton number by two units and generates neutrino masses:

$$
\begin{aligned}
\mathcal{O}_1 &= \frac{\kappa_{ab}}{2}(L_a^i L_b^j) H^k H^l \epsilon_{ik}\epsilon_{jl} \\
&= \frac{\kappa_{ab}}{2}(\nu_a H^0 - \ell_a H^+)(\nu_b H^0 - \ell_b H^+)
\end{aligned}
$$

$$
\Rightarrow \quad (M_\nu)_{ab} = (\kappa)_{ab} v^2
$$

- $\kappa^{-1} \sim (10^{14}\ \mathrm{GeV})$ can be inferred from data

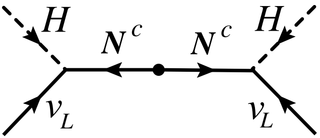
Strong reasons to not stop at EFT

- EFT description cannot be the end goal, or else important phenomen would be missed
- What if neutrinos are Dirac particles? $\mathcal{O}_1$ is then the wrong description
- What if neutrino masses arose from $d = 7$ operators or $d = 9$ operatos in a fundamental theory, and not through $\mathcal{O}_1$?
- Even when the scale of new physics is beyond reach to current experiments, opening the EFT operator can give new insight
- An example is baryon asymmetry generation via leptogensis
- Requires opening up the Weinberg operator. Baryon asymmetry originates from the decays of N^c, the mediator of $\mathcal{O}_1$

The origin of neutrino mass: Seesaw mechanism

- Adding right-handed neutrino N^c which transforms as singlet under $SU(2)_L$,

$$\mathcal{L} = f_\nu \, (L \cdot H) \, N^c + \tfrac{1}{2} M_R N^c N^c$$



- Integrating out the N^c, $\Delta L = 2$ operator is induced:

$$\mathcal{L}_{\text{eff}} = -\frac{f_\nu^2}{2} \frac{(L \cdot H)\,(L \cdot H)}{M_R}$$

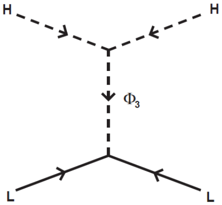
- Once H acquires VEV, neutrino mass is induced:

$$m_\nu \simeq f_\nu^2 \frac{v^2}{M_R}$$

Minkowski (1977)
Yanagida (1979)
Gell-Mann, Ramond, Slansky (1980)
Mohapatra & Senjanovic (1980)

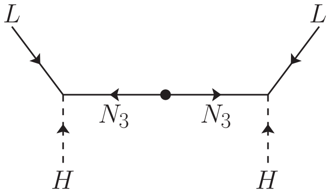
- For $f_\nu v \simeq 100$ GeV, $M_R \simeq 10^{14}$ GeV.

Seesaw mechanism (cont.)



Type II seesaw: $\Phi_3 \sim (1, 3, 1)$

Mohapatra & Senjanovic (1980)
Schechter & Valle (1980)
Lazarides, Shafi, & Wetterich (1981)



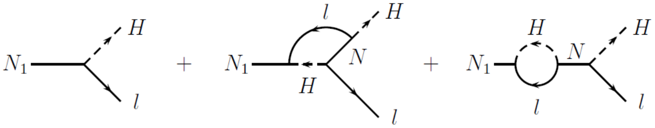
Type III seesaw: $N_3 \sim (1, 3, 0)$

Foot, Lew, He, & Joshi (1989)

$$\mathcal{L}_{\text{eff}} = \frac{LLHH}{M} \Rightarrow m_\nu \sim \frac{v^2}{M}$$

Baryogenesis via leptogenesis and type-I seesaw

- In the early history of the universe, a lepton asymmetry may be dynamically generated in the decay of N Fukugita, Yanagida (1986)
- N being a Majorana fermion can decay to $L + H$ as well as $\overline{L} + H^*$



- Three Sakharov conditions can be satisfied: B violation via electroweak sphaleron, C and CP violation in Yukawa couplings of N, and out of equilibrium condition via expanding universe
- Lepton asymmetry in decay of N_1 (with $M_1 \ll M_{2,3}$):

$$\varepsilon_1 \simeq \frac{3}{16\pi} \frac{1}{(f_\nu f_\nu^\dagger)_{11}} \sum_{i=2,3} \mathrm{Im}\left[(f_\nu f_\nu^\dagger)^2_{i1}\right] \frac{M_1}{M_i}$$

- $\varepsilon \sim 10^{-6}$ can explain observed baryon asymmetry of the universe
- Indirect tests in Majorana nature of ν and in CP violation in oscillations

Radiative neutrino mass generation

- An alternative to seesaw is radiative neutrino mass generation, where neutrino mass is absent at tree level but arises via quantum loop correction
- The smallness of neutrino mass is explained by loop and chiral suppressions
- Loop diagrams may arise at 1-loop, 2-loop or 3-loop levels
- New physics scale typically near TeV and thus accessible to LHC
- Further tests in observable LFV processes and as nonstandard neutrino interaction (NSI) in oscillations

Effective $\Delta L = 2$ Operators

$$\mathcal{O}_1 = L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl}$$

$$\mathcal{O}_2 = L^i L^j L^k e^c H^l \epsilon_{ij}\epsilon_{kl}$$

$$\mathcal{O}_3 = \{L^i L^j Q^k d^c H^l \epsilon_{ij}\epsilon_{kl}, \quad L^i L^j Q^k d^c H^l \epsilon_{ik}\epsilon_{jl}\}$$

$$\mathcal{O}_4 = \{L^i L^j \bar{Q}_i \bar{u^c} H^k \epsilon_{jk}, \quad L^i L^j \bar{Q}_k \bar{u^c} H^k \epsilon_{ij}\}$$

$$\mathcal{O}_5 = L^i L^j Q^k d^c H^l H^m \bar{H}_i \epsilon_{jl}\epsilon_{km}$$

$$\mathcal{O}_6 = L^i L^j \bar{Q}_k \bar{u^c} H^l H^k \bar{H}_i \epsilon_{jl}$$

$$\mathcal{O}_7 = L^i Q^j \bar{e^c} \bar{Q}_k H^k H^l H^m \epsilon_{il}\epsilon_{jm}$$

$$\mathcal{O}_8 = L^i \bar{e^c} \bar{u^c} d^c H^j \epsilon_{ij}$$

$$\mathcal{O}_9 = L^i L^j L^k e^c L^l e^c \epsilon_{ij}\epsilon_{kl}$$

$$\mathcal{O}_1' = L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl} H^{*m} H_m$$

Babu & Leung (2001)

de Gouvea & Jenkins (2008)

Angel & Volkas (2012)

Cai, Herrero-Garcia, Schmidt, Vicente, Volkas (2017)

Lehman (2014) – all $d = 7$ operators

Li, Ren, Xiao, Yu, Zheng (2020); Liao, Ma (2020) – all $d = 9$ operators

B & L selection rules and EFT dimension

- In SMEFT, lepton number violation arises via odd dimensional operators ($d = 5, 7, 9, 11, ...$)

- In fact, selection rule in terms of $B - L$ is more intuitive

- All odd dimensional EFT operators carry $|\Delta(B - L)| = 2$, while all even EFT operators have $\Delta(B - L) = 0$

- Eg: For $p \to e^+\pi^0$ with $\Delta(B - L) = 0$, EFT operator arises at $d = 6$, while for $n \to e^-\pi^+$ with $\Delta(B - L) = -2$, the EFT operator arises at $d = 7$

- Eg: $n - \overline{n}$ oscillations are mediated by $d = 9$ operators and have $\Delta(B - L) = -2$

Kobach (2016)

Neutrino masses through operator $\mathcal{O}'_1$

- $\mathcal{O}'_1$ has dimension 7 and is suppressed by $1/\Lambda^3$

$$\mathcal{O}'_1 = L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl} H^{*m} H_m$$
$$\Rightarrow m_\nu \sim \frac{v^4}{\Lambda^3}$$

- Allows for the new physics scale $\Lambda \sim 10^8$ GeV
- For $\mathcal{O}'_1$ to be the leading neutrino mass source, a pair of fermions (Σ and $\overline{\Sigma}$) and a new scalar field (Φ) are introduced:

$$\begin{aligned}\Sigma(1,3,2) &= (\Sigma^{++}, \Sigma^{+}, \Sigma^{0}), \quad \overline{\Sigma}(1,3,-2) = (\overline{\Sigma^0}, \Sigma^{-}, \Sigma^{--}) \\ \Phi(1,4,3) &= (\Phi^{+++}, \Phi^{++}, \Phi^{+}, \Phi^{0})\end{aligned}$$

- A new feature of the model is the triply charged scalar
- Neutrino masses arise at tree level

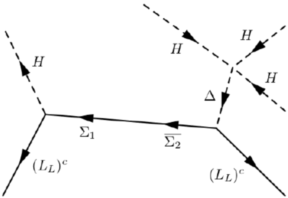
Babu, Nandi, Tavartkiladze (2009)

Bambhaniya, J. Chakraborty, Goswami, Konar (2013)

K. Ghosh, S. Jana, S. Nandi (2018)

T. Ghosh, S. Jana, S. Nandi (2018)

Neutrino mass from $\mathcal{O}_1'$ (cont.)



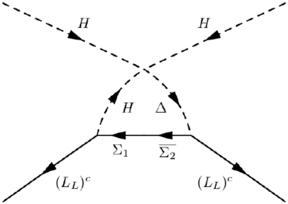
- Neutrino mass at tree level is given by:

$$(M_\nu)_{ij} = \frac{(Y_i Y_j' + Y_i' Y_j) v_\Phi v}{M_\Sigma}$$

- v_Φ is an induced VEV and is given by

$$v_\Phi = -\frac{\lambda_5 v^3}{2M_\Phi^2}$$

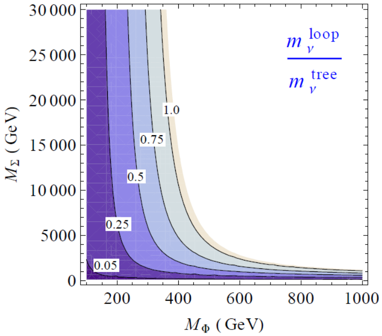
Neutrino mass from $\mathcal{O}_1'$ (cont.)



- At one-loop, the model produces $d = 5$ Weinberg operator
- The loop diagram is finite, showing the consistency of model
- Loop-induced neutrino mass is:

$$(M_\nu)_{ij}^{\text{loop}} = \frac{(3+\sqrt{3})\lambda_5 v^2 M_\Sigma (Y_i Y_j' + Y_i' Y_j)}{32\pi^2 (M_\Phi^2 - M_H^2)} \left(\frac{M_\Phi^2 \log\left(\frac{M_\Sigma^2}{M_\Phi^2}\right)}{M_\Sigma^2 - M_\Phi^2} - \frac{M_H^2 \log\left(\frac{M_\Sigma^2}{M_H^2}\right)}{M_\Sigma^2 - M_H^2} \right)$$

Neutrino mass constraints from $\mathcal{O}'_1$



Bambhaniya, J. Chakraborty, Goswami, Konar (2013)

- For $d = 7$ operator to be leading over $d = 5$ operator, mass of Φ should be less than a few TeV
- Φ^{+++} can be pair produced at LHC, with subsequent decay to $W^+W^+W^+$ or $W^+\ell^+\ell^+$
- High luminosity LHC reach is about 900 GeV on Φ^{+++} mass

T. Ghosh, S. Jana, S. Nandi (2018)

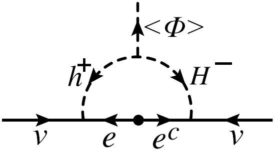
Operator $\mathcal{O}_2$ and the Zee model

- Introduce a singly charged scalar and a second Higgs doublet to standard model:

$$\mathcal{L} = f_{ij} L_i^a L_j^b h^+ \epsilon_{ab} + \mu H^a \Phi^b h^- \epsilon_{ab} + \text{h.c.}$$
$$\Downarrow$$
$$\mathcal{O}_2 = L^i L^j L^k e^c H^l \epsilon_{ij} \epsilon_{kl}$$

Zee (1980)

- Neutrino mass arises at one-loop.



- The minimal version of this model in which only one Higgs doublet couples to a given fermion sector yields

$$m_\nu = \begin{pmatrix} 0 & m_{e\mu} & m_{e\tau} \\ m_{e\mu} & 0 & m_{\mu\tau} \\ m_{e\tau} & m_{\mu\tau} & 0 \end{pmatrix}, \quad m_{ij} \simeq \frac{f_{ij}}{16\pi^2} \frac{(m_i^2 - m_j^2)}{\Lambda}$$

It requires $\theta_{12} \simeq \pi/4 \to$ ruled out by solar + KamLAND data.

Koide (2001); Frampton *et al.* (2002); He (2004)

Neutrino oscillations in the Zee model

- Neutrino oscillation data can be fit to the Zee model consistently without the Z_2 symmetry

- Some benchmark points for Yukawa couplings of second doublet:

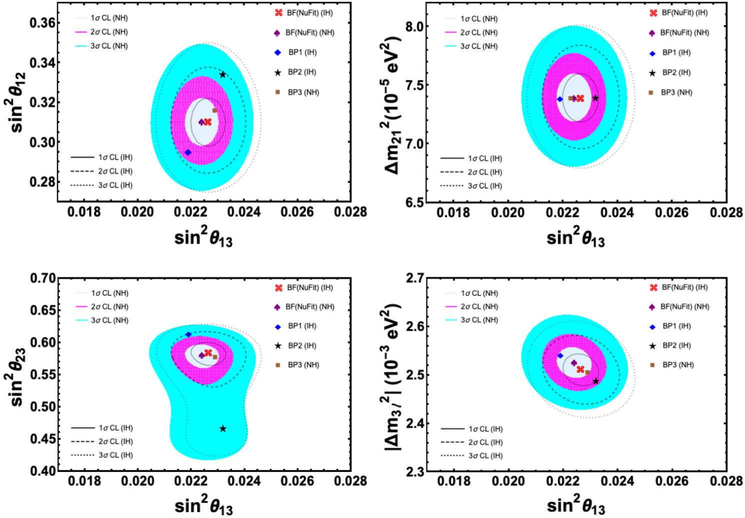
$$\text{BP I}: \; Y = \begin{pmatrix} Y_{ee} & 0 & Y_{e\tau} \\ 0 & Y_{\mu\mu} & Y_{\mu\tau} \\ 0 & Y_{\tau\mu} & Y_{\tau\tau} \end{pmatrix}$$

$$\text{BP II}: \; Y = \begin{pmatrix} 0 & Y_{e\mu} & Y_{e\tau} \\ Y_{\mu e} & 0 & Y_{\mu\tau} \\ 0 & Y_{\tau\mu} & Y_{\tau\tau} \end{pmatrix}$$

$$\text{BP III}: \; Y = \begin{pmatrix} Y_{ee} & 0 & Y_{e\tau} \\ 0 & Y_{\mu\mu} & Y_{\mu\tau} \\ Y_{\tau e} & 0 & Y_{\tau\tau} \end{pmatrix}$$

Babu, Dev, Jana, Thapa (2019)

Neutrino fit in the Zee model



Babu, Dev, Jana, Thapa (2019)

Neutrino Non-Standard Interactions (NSI)

- Neutrino oscillation picture would change if there are non-standard interactions
- Modification of matter effects most important
- EFT for neutrino NSI:

$$\mathcal{L}_{\rm NSI}^{\rm NC} = -2\sqrt{2}G_F \sum_{f,X,\alpha,\beta} \varepsilon_{\alpha\beta}^{fX} \left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right) \left(\bar{f}\gamma_\mu P_X f\right) ,$$

$$\mathcal{L}_{\rm NSI}^{\rm CC} = -2\sqrt{2}G_F \sum_{f,f',X,\alpha,\beta} \varepsilon_{\alpha\beta}^{ff'X} \left(\bar{\nu}_\alpha \gamma^\mu P_L \ell_\beta\right) \left(\bar{f}'\gamma_\mu P_X f\right)$$

Wolfenstein (1978)

- Effective Hamiltonian for neutrino propagation in matter is now:

$$H = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + \sqrt{2}G_F N_e(x) \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^\star & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^\star & \varepsilon_{\mu\tau}^\star & \varepsilon_{\tau\tau} \end{pmatrix}$$

- $\epsilon_{\alpha\beta}$ measure of NSI normalized to weak interaction strength

Neutrino NSI

- For neutrino propagation in matter, $\epsilon_{\alpha\beta}$ are related to the effective Lagrangian parameters as:

$$\varepsilon_{\alpha\beta} = \sum_{f\in\{e,u,d\}} \left\langle \frac{N_f(x)}{N_e(x)} \right\rangle \varepsilon^{fV}_{\alpha\beta}$$
$$= \varepsilon^{eV}_{\alpha\beta} + \left\langle \frac{N_p(x)}{N_e(x)} \right\rangle (2\varepsilon^{uV}_{\alpha\beta} + \varepsilon^{dV}_{\alpha\beta}) + \left\langle \frac{N_n(x)}{N_e(x)} \right\rangle (\varepsilon^{uV}_{\alpha\beta} + 2\varepsilon^{dV}_{\alpha\beta})$$

- For neutral matter, we have, with $Y_n(x) \equiv \frac{N_n(x)}{N_p(x)}$:

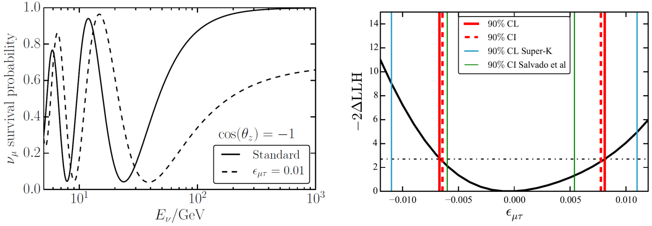
$$\varepsilon_{\alpha\beta} = \varepsilon^{eV}_{\alpha\beta} + [2 + Y_n(x)]\,\varepsilon^{uV}_{\alpha\beta} + [1 + 2Y_n(x)]\,\varepsilon^{dV}_{\alpha\beta}$$

- $Y_n(x) = (1.012 - 1.137)$ in Earth; $Y_n(x) = (0.5 - 0.15)$ in Sun

- Neutrino oscillation experiments sensitive to sub-percent $\epsilon_{\alpha\beta}$

IceCube Limits on $\epsilon_{\mu\tau}$

- IceCube Collaboration has analyzed atmospheric neutrino data with real $\epsilon_{\mu\tau} \neq 0$ with all other $\epsilon_{\alpha\beta} = 0$



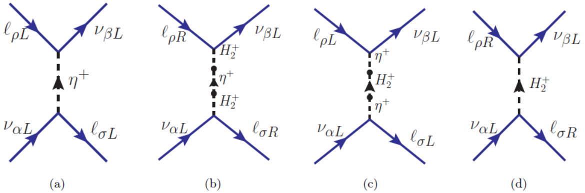
- (a) ν_μ survival probability for up-going ν_μ; and (b) 90% CL limit on $\epsilon_{\mu\tau}$ are shown

$$-0.0067 < \epsilon_{\mu\tau} < 0.0081$$

- Even sub-percent NSI can affect future determination of mass ordering!

Neutrino NSI in the Zee model

- The two charged scalars of the Zee model mediate NSI



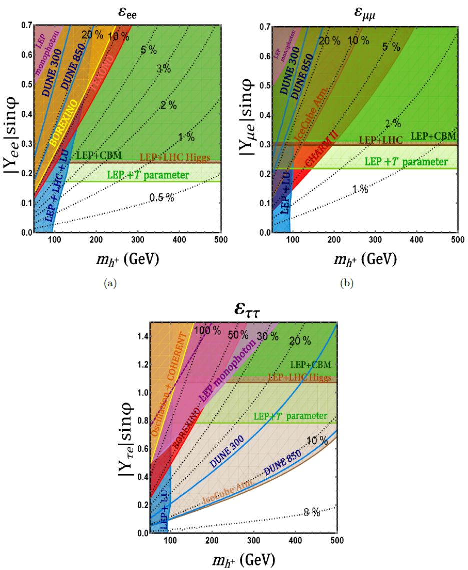
- The NSI parameters are given by:

$$\varepsilon_{\alpha\beta} = \frac{1}{4\sqrt{2}G_F} Y_{\alpha e} Y^*_{\beta e} \left(\frac{\sin^2\varphi}{m^2_{h^+}} + \frac{\cos^2\varphi}{m^2_{H^+}} \right)$$

- Constrained by LHC and LEP direct limits; cLFV; precision electroweak tests; neutrino oscillation data; and theory

Babu, Dev, Jana, Thapa (2019)

Zee model NSI



Babu, Dev, Jana, Thapa (2019)

Operator $\mathcal{O}_9$ and 2-loop neutrino mass

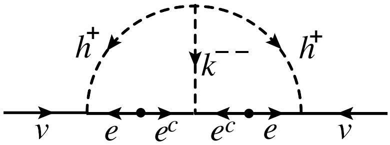
- Introduce a singly charged scalar h^+ and a doubly charged scalar k^{++} to SM. This leads to lepton number violation:

$$\mathcal{L} = f_{ij} L_i^a L_j^b h^+ \epsilon_{ab} + g_{ij} e_i^c e_j^c k^{--} + \mu h^+ h^+ k^{--} + \text{h.c.}$$

$$\Downarrow$$

$$\mathcal{O}_9 = L^i L^j L^k e^c L^l e^c \epsilon_{ij} \epsilon_{kl}$$

Zee (1985); Babu (1988)



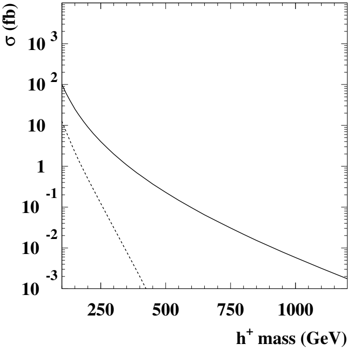
$$(m_\nu)_{\rm largest} \simeq \frac{f^2 g}{(16\pi^2)^2} \frac{m_\tau^2}{\Lambda}$$

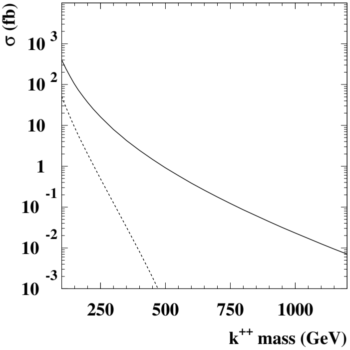
- One of the neutrinos is (nearly) massless.
- $\Lambda \sim 1$ TeV for $f \sim g \sim 0.1$.
- Fully consistent with neutrino oscillation data.

Babu & Macesanu (2002); M. Nebot *et al.* (2008)

Operator $\mathcal{O}_9$ (cont.)

Cross section for h^+ and k^{++} at LHC and Tevatron



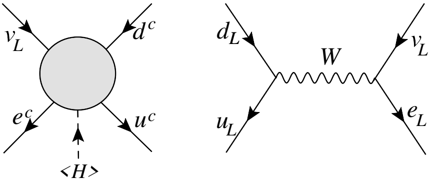


LHC: solid line, Tevatron: dashed line

Babu & Macesanu (2002)
Aristizabal-Sierra & Hirsch (2006)
Nebot, Oliver, Paolo, & Santamaria (2008)

Operator $\mathcal{O}_8$

- Operator $\mathcal{O}_8 = L_i H_j d^c \bar{u^c} \bar{e^c} \epsilon_{ij}$ induces neutrino mass at two–loop:



$$m_\nu \sim \frac{m_\tau m_b m_t v}{(16\pi^2)^2 \Lambda^3}$$

- Scale of new physics is near TeV
- Leptoquarks are needed for UV completion
- The same leptoquarks may be relevant for B meson decay anomalies
- $\tilde{R}_2$ and S_1 leptoquarks can induce $\mathcal{O}_8$
  Babu, Julio (2010)

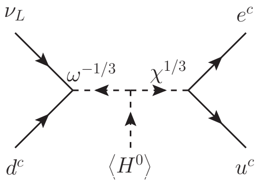
Leptoquark model for $\mathcal{O}_8$

- Introduce new particles under $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge group:

$$\mathcal{L} = Y_{ij} L_i^\alpha d_j^c \Omega^\beta \epsilon_{\alpha\beta} + F_{ij} e_i^c u_i^c \chi^{-1/3} + \mu \Omega^\dagger H \chi^{-1/3} + \text{h.c.}$$

$$\Omega \equiv \begin{pmatrix} \omega^{2/3} \\ \omega^{-1/3} \end{pmatrix} \sim (3, 2, 1/6); \quad \chi^{-1/3} \sim (3, 1, -1/3)$$

- The simultaneous presence of these three terms will break lepton number.

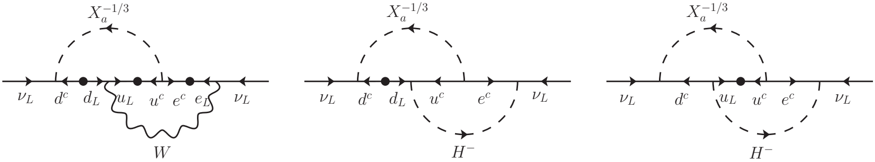


- The μ parameter will cause mixing between $\chi^{-1/3}$ and $\omega^{-1/3}$,

$$\begin{pmatrix} m_\omega^2 & \mu v \\ \mu v & m_\chi^2 \end{pmatrix} \Rightarrow \sin 2\theta = \frac{2\mu v}{M_2^2 - M_1^2}$$

$$M_{1,2}^2 = \tfrac{1}{2}\left[m_\omega^2 + m_\chi^2 \mp \sqrt{(m_\omega^2 - m_\chi^2)^2 + 4\mu^2 v^2}\right]$$

Neutrino mass generation



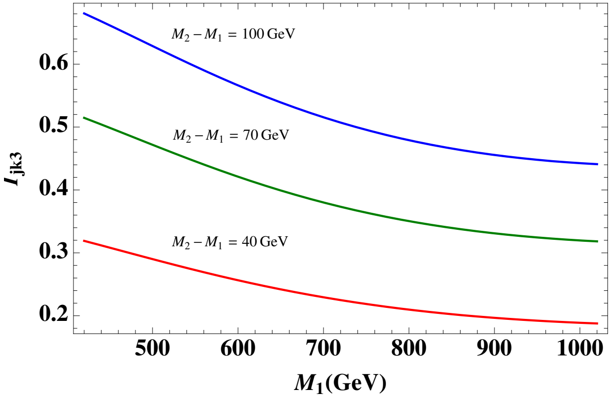
$$(M_\nu)_{ij} = \hat{m}_0 Y_{ik} (D_d)_k (V^T)_{kl} (D_u)_l (F^\dagger)_{lj} (D_\ell)_j I_{jkl} + \text{transpose},$$

$$\hat{m}_0 = \left(\frac{3g^2 \sin 2\theta}{(16\pi^2)^2} \right) \left(\frac{m_t m_b m_\tau}{M_1^2} \right)$$

$$D_u = \text{diag.} \left[\frac{m_u}{m_t}, \frac{m_c}{m_t}, 1 \right], \; D_d = \text{diag.} \left[\frac{m_d}{m_b}, \frac{m_s}{m_b}, 1 \right], \; D_\ell = \text{diag.} \left[\frac{m_e}{m_\tau}, \frac{m_\mu}{m_\tau}, 1 \right]$$

Neutrino mass generation (cont.)

$$I_{jkl} = \sum_{a=1}^{2}(-1)^a \frac{M_1^2}{M_a^2 - m_{d_k}^2} \int_0^1 dx \int_0^\infty dt\ t \left(1 + \frac{t}{4m_W^2}\right) \frac{1}{t + M_W^2} \frac{1}{t + m_{e_j}^2}$$
$$\times \ln\left[\frac{x(1-x)t + xm_{u_l}^2 + (1-x)M_a^2}{x(1-x)t + xm_{u_l}^2 + (1-x)m_{d_k}^2}\right]$$



Neutrino mass matrix

$$M_\nu \simeq m_0 \begin{pmatrix} 0 & \frac{1}{2}\frac{m_\mu}{m_\tau}xy & \frac{1}{2}y \\ \frac{1}{2}\frac{m_\mu}{m_\tau}xy & \frac{m_\mu}{m_\tau}xz & \frac{1}{2}z + \frac{1}{2}\frac{m_\mu}{m_\tau}x \\ \frac{1}{2}y & \frac{1}{2}z + \frac{1}{2}\frac{m_\mu}{m_\tau}x & 1 + w \end{pmatrix}$$

$$x \equiv \frac{F_{23}^*}{F_{33}^*}, \quad y \equiv \frac{Y_{13}}{Y_{33}}, \quad z \equiv \frac{Y_{23}}{Y_{33}}; \quad w \equiv \frac{F_{32}^*}{F_{33}^*}\frac{Y_{32}}{Y_{33}}\left(\frac{m_c}{m_t}\right)\left(\frac{m_s}{m_b}\right)\frac{I_{jk2}}{I_{jk3}}$$

$$m_0 = 2\ \hat{m}_0 F_{33}^* Y_{33} I_{jk3}; \quad (M_\nu)_{11} \simeq y\frac{F_{13}^*}{F_{33}^*}\frac{m_e}{m_\tau}m_0$$

- This mass matrix has normal hierarchy structure.
- The (1,1) entry is highly suppressed, i.e. $\ll 0.01$ eV.
- w may be significant for $M_{LQ} \leq 1$TeV.

Predictions for $w \ll 1$

- For $w \ll 1$,

$$M_\nu \simeq m_0 \begin{pmatrix} 0 & \frac{1}{2}\frac{m_\mu}{m_\tau}xy & \frac{1}{2}y \\ \frac{1}{2}\frac{m_\mu}{m_\tau}xy & \frac{m_\mu}{m_\tau}xz & \frac{1}{2}z + \frac{1}{2}\frac{m_\mu}{m_\tau}x \\ \frac{1}{2}y & \frac{1}{2}z + \frac{1}{2}\frac{m_\mu}{m_\tau}x & 1 \end{pmatrix}$$

- $\det M_\nu = 0$, together with $(M_\nu)_{11} \simeq 0$,

$$m_1 \simeq 0, \ \alpha \simeq 0, \ \beta \simeq 2\delta + \pi$$

$$\tan^2\theta_{13} \simeq \sqrt{\frac{\Delta m^2_{21}}{\Delta m^2_{31}}}\sin^2\theta_{12}$$

$$\sin^2 2\theta_{13} \simeq 0.16$$

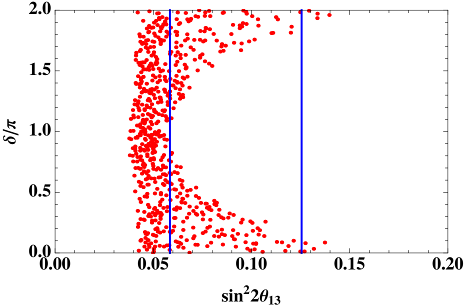
which differs by 4.2σ from recent $\sin^2 2\theta_{13}$ results.
$(\sin^2 2\theta_{13})_{\rm exp} = 0.092 \pm 0.016 \pm 0.005$

Predictions for $w \gg 1$

- For $w \gg 1$,

$$w \equiv \frac{F_{32}^*}{F_{33}^*}\frac{Y_{32}}{Y_{33}}\left(\frac{m_c}{m_t}\right)\left(\frac{m_s}{m_b}\right)\frac{I_{jk2}}{I_{jk3}} \gg 1 \quad \rightarrow \quad |F_{33}Y_{33}| \ll |F_{32}Y_{32}|$$

- This could generate $(M_\nu)_{13} \simeq (M_\nu)_{11} \simeq 0$.
  Glashow, Frampton, & Marfatia (2002)
  Xing (2002)



- The value of θ_{13} is consistent with current measurements (the blue lines correspond to 2σ allowed value from Daya Bay).

A full list of $d = 9$ six-fermion operators

- The $\Delta L = 2$ operators at $d = 9$ has been fully classified
  Li, Ren, Xiao, Yu, Zheng (2020); Liao, Ma (2020)

- We have looked into all such same-sign dilepton operators
  Babu, Ismail, Goncalves (to appear)

- We impose that there be no neutrinos in these operators. This is a requirement to observe L violation at LHC

- Missing energy associated with events would lead to confusion on whether positive lepton number (ν) or negative lepton number ($\overline{\nu}$) carried them

- Identities that are used: Fierze rearrangement; equations of motions, integration by parts; color identities; $SU(2)_L$ identities

- $n^3(5 + 5n - n^2 + 35n^3)/4$ operators

- For $n = 1$, this is 11 operators, relevant for neutrinoless double beta decay

- For $n = 3$, there are 6453 operators of this type

A full list of $d = 9$ six-fermion operators

Operator	Multiplicity
$K_{(ab)(ef)(pq)} L^{ia}\tau^k_{ij}L^{jb}Q^{le\alpha}\tau^k_{lm}\delta_{\alpha\beta}Q^{mf\beta}(D^c)^{p\gamma}\delta_{\gamma\delta}(D^c)^{q\delta}$	$n^3(n+1)^3/8$
$K_{(ab)[ef][pq]} L^{ia}\tau^k_{ij}L^{jb}Q^{le\alpha}\tau^k_{lm}\epsilon_{\alpha\beta\lambda}Q^{mf\beta}(D^c)^{p\gamma}\epsilon^{\lambda}_{\gamma\delta}(D^c)^{q\delta}$	$n^3(n+1)(n-1)^2/8$
$K_{(ab)[ef][pq]} L^{ia}\tau^k_{ij}L^{jb}Q^{le\alpha}\sigma^{\mu\nu}\tau^k_{lm}\delta_{\alpha\beta}Q^{mf\beta}(D^c)^{p\gamma}\sigma_{\mu\nu}\delta_{\gamma\delta}(D^c)^{q\delta}$	$n^3(n+1)(n-1)^2/8$
$K_{(ab)(ef)(pq)} L^{ia}\tau^k_{ij}L^{jb}Q^{le\alpha}\sigma^{\mu\nu}\tau^k_{lm}\epsilon_{\alpha\beta\lambda}Q^{mf\beta}(D^c)^{p\gamma}\sigma_{\mu\nu}\epsilon^{\lambda}_{\gamma\delta}(D^c)^{q\delta}$	$n^3(n+1)^3/8$
$K_{[ab](ef)[pq]} L^{ia}\sigma^{\mu\nu}\tau^k_{ij}L^{jb}Q^{le\alpha}\tau^k_{lm}\delta_{\alpha\beta}Q^{mf\beta}(D^c)^{p\gamma}\sigma_{\mu\nu}\delta_{\gamma\delta}(D^c)^{q\delta}$	$n^3(n+1)(n-1)^2/8$
$K_{[ab][ef](pq)} L^{ia}\sigma^{\mu\nu}\tau^k_{ij}L^{jb}Q^{le\alpha}\tau^k_{lm}\epsilon_{\alpha\beta\lambda}Q^{mf\beta}(D^c)^{p\gamma}\sigma_{\mu\nu}\epsilon^{\lambda}_{\gamma\delta}(D^c)^{q\delta}$	$n^3(n+1)(n-1)^2/8$
$K_{[ab][ef](pq)} L^{ia}\sigma^{\mu\nu}\tau^k_{ij}L^{jb}Q^{le\alpha}\sigma_{\mu\nu}\tau^k_{lm}\delta_{\alpha\beta}Q^{mf\beta}(D^c)^{p\gamma}\delta_{\gamma\delta}(D^c)^{q\delta}$	$n^3(n+1)(n-1)^2/8$
$K_{[ab](ef)[pq]} L^{ia}\sigma^{\mu\nu}\tau^k_{ij}L^{jb}Q^{le\alpha}\sigma_{\mu\nu}\tau^k_{lm}\epsilon_{\alpha\beta\lambda}Q^{mf\beta}(D^c)^{p\gamma}\epsilon^{\lambda}_{\gamma\delta}(D^c)^{q\delta}$	$n^3(n+1)(n-1)^2/8$
$K_{[ab][ef][pq]} L^{ia}\sigma^{\mu\nu}\tau^k_{ij}L^{jb}Q^{le\alpha}\sigma^{\rho}_{\mu}\tau^k_{lm}\delta_{\alpha\beta}Q^{mf\beta}(D^c)^{p\gamma}\sigma_{\nu\rho}\delta_{\gamma\delta}(D^c)^{q\delta}$	$n^3(n-1)^3/8$
$K_{[ab](ef)(pq)} L^{ia}\sigma^{\mu\nu}\tau^k_{ij}L^{jb}Q^{le\alpha}\sigma^{\rho}_{\mu}\tau^k_{lm}\epsilon_{\alpha\beta\lambda}Q^{mf\beta}(D^c)^{p\gamma}\sigma_{\nu\rho}\epsilon^{\lambda}_{\gamma\delta}(D^c)^{q\delta}$	$n^3(n+1)^2(n-1)/8$
$K_{(ab)(gh)(ef)} L^{ia}\tau^k_{ij}L^{jb}((U^c)^{g\alpha})^\dagger\delta_{\alpha\beta}((U^c)^{h\beta})^\dagger(Q^{le\gamma})^\dagger\tau^k_{lm}\delta_{\gamma\delta}(Q^{mf\delta})^\dagger$	$n^3(n+1)^3/8$
$K_{(ab)[gh][ef]} L^{ia}\tau^k_{ij}L^{jb}((U^c)^{g\alpha})^\dagger\epsilon_{\alpha\beta\lambda}((U^c)^{h\beta})^\dagger(Q^{le\gamma})^\dagger\tau^k_{lm}\epsilon^{\lambda}_{\gamma\delta}(Q^{mf\delta})^\dagger$	$n^3(n+1)(n-1)^2/8$
$K_{(ab)[gh][ef]} L^{ia}\tau^k_{ij}L^{jb}((U^c)^{g\alpha})^\dagger\bar{\sigma}^{\mu\nu}\delta_{\alpha\beta}((U^c)^{h\beta})^\dagger(Q^{le\gamma})^\dagger\tau^k_{lm}\bar{\sigma}_{\mu\nu}\delta_{\gamma\delta}(Q^{mf\delta})^\dagger$	$n^3(n+1)(n-1)^2/8$
$K_{(ab)(gh)(ef)} L^{ia}\tau^k_{ij}L^{jb}((U^c)^{g\alpha})^\dagger\bar{\sigma}^{\mu\nu}\epsilon_{\alpha\beta\lambda}((U^c)^{h\beta})^\dagger(Q^{le\gamma})^\dagger\tau^k_{lm}\bar{\sigma}_{\mu\nu}\epsilon^{\lambda}_{\gamma\delta}(Q^{mf\delta})^\dagger$	$n^3(n+1)^3/8$
$K_{[ab][gh][ef]} L^{ia}\sigma^{\mu\nu}\tau^k_{ij}L^{jb}((U^c)^{g\alpha})^\dagger\bar{\sigma}^{\rho}_{\mu}\delta_{\alpha\beta}((U^c)^{h\beta})^\dagger(Q^{le\gamma})^\dagger\tau^k_{lm}\bar{\sigma}_{\nu\rho}\delta_{\gamma\delta}(Q^{mf\delta})^\dagger$	$n^3(n-1)^3/8$
$K_{[ab](gh)(ef)} L^{ia}\sigma^{\mu\nu}\tau^k_{ij}L^{jb}((U^c)^{g\alpha})^\dagger\bar{\sigma}^{\rho}_{\mu}\epsilon_{\alpha\beta\lambda}((U^c)^{h\beta})^\dagger(Q^{le\gamma})^\dagger\tau^k_{lm}\bar{\sigma}_{\nu\rho}\epsilon^{\lambda}_{\gamma\delta}(Q^{mf\delta})^\dagger$	$n^3(n+1)^2(n-1)/8$
$K_{(ab)egpf} L^{ia}\tau^k_{ij}L^{jb}Q^{le\alpha}\sigma^{\mu}\tau^k_{lm}\delta_{\alpha\beta}((U^c)^{g\beta})^\dagger(D^c)^{p\gamma}\sigma_{\mu}\delta_{\gamma\delta}(Q^{mf\delta})^\dagger$	$n^5(n+1)/2$
$K_{(ab)egpf} L^{ia}\tau^k_{ij}L^{jb}Q^{le\alpha}\sigma^{\mu}\tau^k_{lm}\epsilon_{\alpha\beta\lambda}((U^c)^{g\beta})^\dagger(D^c)^{p\gamma}\sigma_{\mu}\epsilon^{\lambda}_{\gamma\delta}(Q^{mf\delta})^\dagger$	$n^5(n+1)/2$
$K_{[ab]egpf} L^{ia}\sigma^{\mu\nu}\tau^k_{ij}L^{jb}Q^{le\alpha}\sigma_{\mu}\tau^k_{lm}\delta_{\alpha\beta}((U^c)^{g\beta})^\dagger(D^c)^{p\gamma}\sigma_{\nu}\delta_{\gamma\delta}(Q^{mf\delta})^\dagger$	$n^5(n-1)/2$
$K_{[ab]egpf} L^{ia}\sigma^{\mu\nu}\tau^k_{ij}L^{jb}Q^{le\alpha}\sigma_{\mu}\tau^k_{lm}\epsilon_{\alpha\beta\lambda}((U^c)^{g\beta})^\dagger(D^c)^{p\gamma}\sigma_{\nu}\epsilon^{\lambda}_{\gamma\delta}(Q^{mf\delta})^\dagger$	$n^5(n-1)/2$
$K_{(cd)(gh)(pq)}((E^c)^c)^\dagger((E^c)^d)^\dagger((U^c)^{g\alpha})^\dagger\delta_{\alpha\beta}((U^c)^{h\beta})^\dagger(D^c)^{p\gamma}\delta_{\gamma\delta}(D^c)^{q\delta}$	$n^3(n+1)^3/8$
$K_{(cd)[gh][pq]}((E^c)^c)^\dagger((E^c)^d)^\dagger((U^c)^{g\alpha})^\dagger\epsilon_{\alpha\beta\lambda}((U^c)^{h\beta})^\dagger(D^c)^{p\gamma}\epsilon^{\lambda}_{\gamma\delta}(D^c)^{q\delta}$	$n^3(n+1)(n-1)^2/8$
$K_{[cd][gh](pq)}((E^c)^c)^\dagger\bar{\sigma}^{\mu\nu}((E^c)^d)^\dagger((U^c)^{g\alpha})^\dagger\bar{\sigma}_{\mu\nu}\delta_{\alpha\beta}((U^c)^{h\beta})^\dagger(D^c)^{p\gamma}\delta_{\gamma\delta}(D^c)^{q\delta}$	$n^3(n+1)(n-1)^2/8$
$K_{[cd](gh)[pq]}((E^c)^c)^\dagger\bar{\sigma}^{\mu\nu}((E^c)^d)^\dagger((U^c)^{g\alpha})^\dagger\bar{\sigma}_{\mu\nu}\epsilon_{\alpha\beta\lambda}((U^c)^{h\beta})^\dagger(D^c)^{p\gamma}\epsilon^{\lambda}_{\gamma\delta}(D^c)^{q\delta}$	$n^3(n+1)(n-1)^2/8$
$K_{[cd][gh][pq]}((E^c)^c)^\dagger\bar{\sigma}^{\mu\nu}((E^c)^d)^\dagger((U^c)^{g\alpha})^\dagger\bar{\sigma}^{\rho}_{\mu}\delta_{\alpha\beta}((U^c)^{h\beta})^\dagger(D^c)^{p\gamma}\sigma_{\nu\rho}\delta_{\gamma\delta}(D^c)^{q\delta}$	$n^3(n-1)^3/8$
$K_{[cd](gh)(pq)}((E^c)^c)^\dagger\bar{\sigma}^{\mu\nu}((E^c)^d)^\dagger((U^c)^{g\alpha})^\dagger\bar{\sigma}^{\rho}_{\mu}\epsilon_{\alpha\beta\lambda}((U^c)^{h\beta})^\dagger(D^c)^{p\gamma}\sigma_{\nu\rho}\epsilon^{\lambda}_{\gamma\delta}(D^c)^{q\delta}$	$n^3(n+1)^2(n-1)/8$
$K_{acegpq} L^{ia}\sigma^{\mu}\delta_{ij}((E^c)^c)^\dagger Q^{je\alpha}\sigma_{\mu}\delta_{\alpha\beta}((U^c)^{g\beta})^\dagger(D^c)^{p\gamma}\delta_{\gamma\delta}(D^c)^{q\delta}$	n^6
$K_{acegpq} L^{ia}\sigma^{\mu}\delta_{ij}((E^c)^c)^\dagger Q^{je\alpha}\sigma^{\nu}\epsilon_{\alpha\beta\lambda}((U^c)^{g\beta})^\dagger(D^c)^{p\gamma}\sigma_{\mu\nu}\epsilon^{\lambda}_{\gamma\delta}(D^c)^{q\delta}$	n^6
$K_{acghep} L^{ia}\sigma^{\mu}\delta_{ij}((E^c)^c)^\dagger((U^c)^{g\alpha})^\dagger\delta_{\alpha\beta}((U^c)^{h\beta})^\dagger(Q^{je\gamma})^\dagger\bar{\sigma}_{\mu}\delta_{\gamma\delta}(D^c)^{p\delta}$	n^6
$K_{acghep} L^{ia}\sigma^{\mu}\delta_{ij}((E^c)^c)^\dagger((U^c)^{g\alpha})^\dagger\sigma_{\mu\nu}\epsilon_{\alpha\beta\lambda}((U^c)^{h\beta})^\dagger(Q^{je\gamma})^\dagger\bar{\sigma}^{\nu}\epsilon^{\lambda}_{\gamma\delta}(D^c)^{p\delta}$	n^6

EFT for baryon number violation

- The leading B-violating operators in SMEFT arise at $d = 6$:

$$
\begin{aligned}
\mathcal{O}_1 &= (d^c u^c)^*(Q_i L_j)\epsilon_{ij}, \quad \mathcal{O}_2 = (Q_i Q_j)(u^c e^c)^*\epsilon_{ij}, \quad \mathcal{O}_3 = (Q_i Q_j)(Q_k L_l)\epsilon_{ij}\epsilon_{kl} \\
\mathcal{O}_4 &= (Q_i Q_j)(Q_k L_l)(\vec{\tau}\epsilon)_{ij} \cdot (\vec{\tau}\epsilon)_{kl}, \quad \mathcal{O}_5 = (d^c u^c)^*(u^c e^c)^*
\end{aligned}
$$

- These have $\Delta(B - L) = 0$, and can lead to proton decay such as $p \to e^+\pi^0$
- At $d = 7$ there are new operators:

$$
\begin{aligned}
\tilde{\mathcal{O}}_1 &= (d^c u^c)^*(d^c L_i)^* H_j^* \epsilon_{ij}, \qquad \tilde{\mathcal{O}}_2 = (d^c d^c)^*(u^c L_i)^* H_j^* \epsilon_{ij}, \\
\tilde{\mathcal{O}}_3 &= (Q_i Q_j)(d^c L_k)^* H_l^* \epsilon_{ij}\epsilon_{kl}, \quad \tilde{\mathcal{O}}_4 = (Q_i Q_j)(d^c L_k)^* H_l^* (\vec{\tau}\epsilon)_{ij} \cdot (\vec{\tau}\epsilon)_{kl}, \\
\tilde{\mathcal{O}}_5 &= (Q_i e^c)(d^c d^c)^* H_i^*, \qquad \tilde{\mathcal{O}}_6 = (d^c d^c)^*(d^c L_i)^* H_i, \\
\tilde{\mathcal{O}}_7 &= (d^c D_\mu d^c)^*(\overline{L}_i \gamma^\mu Q_i), \qquad \tilde{\mathcal{O}}_8 = (d^c D_\mu L_i)^*(\overline{d^c}\gamma^\mu Q_i), \\
\tilde{\mathcal{O}}_9 &= (d^c D_\mu d^c)^*(\overline{d^c}\gamma^\mu e^c)
\end{aligned}
$$

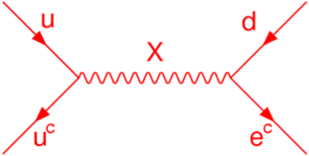
- These lead to $\Delta(B - L) = -2$, and decays such as $n \to e^-\pi^+$

Proton Decay in GUTs

- $d = 6$ operators arise mediated by super-heavy X and Y gauge bosons of GUT
- Effective operator has the form:

$$\mathcal{L}_{\rm eff} = \frac{g^2}{2M_X^2}(\overline{u^c}\gamma_\mu u)(\overline{e^c}\gamma^\mu d)$$

- Leads to $p \to e^+\pi^0$ decay



Proton Decay in GUTs (cont.)

- Current limit on $p \to e^+\pi^0$ is $\tau_p < 1.7 \times 10^{34}$ yrs. (SuperK)

- In non-SUSY $SO(10)$ GUT with an intermediate symmetry $SU(4)_c \times SU(2)_L \times SU(2)_R \times P$, the lifetime was estimated including threshold corrections:

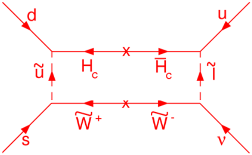
  Babu, Khan (2015)

$$\Gamma^{-1}(p \to e^+\pi^0) \approx (8.2 \times 10^{34}\ \text{yr}) \times \left(\frac{\alpha_H}{0.0122\ \text{GeV}^3}\right)^{-2} \left(\frac{\alpha_G}{1/34.7}\right)^{-2} \left(\frac{A_R}{3.35}\right)^{-2} \left(\frac{M_X}{10^{16}\ \text{GeV}}\right)^{4}$$

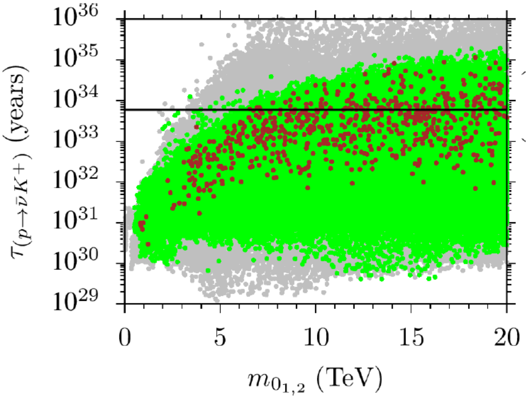
- $\tau_p < 2 \times 10^{35}$ yrs. is found

Proton Decay in SUSY GUTs

- New decays open up, mediated by color triplet Higgsino
- Decay rate depends on SUSY particle masses
- Dominant decay is $p \to \overline{\nu} K^+$
- For TeV scale SUSY scalars, $\tau \approx 10^{32}$ yrs.



Proton Decay in SUSY SU(5)



Winberg, Sakai, Yanagida, Murayama, Hisano, Yanagida, Perez, Nath
Gogoladze, Un, KB (2020), Ellis et.al. (2019)

$n - \bar{n}$ oscillation

- In presence of $\Delta B = 2$ EFT operators, neutron can oscillate into anti-neutron

- n and $\bar{n}$ have opposite magnetic moments: $\mu_n = -1.9\mu_N$

- Oscillation in vacuum is inhibited by $\vec{\mu}.\vec{B}$ interactions with earth's magnetic field

- Time evolution of $n - \bar{n}$ system governed by:

$$\mathcal{M}_{\mathcal{B}} = \begin{pmatrix} m_n - \vec{\mu}_n \cdot \vec{B} - i\lambda/2 & \delta m \\ \delta m & m_n + \vec{\mu}_n \cdot \vec{B} - i\lambda/2 \end{pmatrix}$$

Here $1/\lambda = \tau_n = 880$ sec., m_n is neutron mass.

$$\mathcal{L} = m_n \bar{n}\, n + \frac{\delta m}{2} n^T C\, n$$

δm violates B by 2 units. ($\delta m = 0$ in standard model)

- Discovery of $n - \bar{n}$ oscillations would prove violation of baryon number

$n - \bar{n}$ oscillation Phenomenology (cont.)

- $n \to \bar{n}$ transition probability:

$$P(n \to \bar{n}) = \sin^2(2\theta)\sin^2(\Delta E t/2)e^{-\lambda t}$$
$$\Delta E \simeq 2|\vec{\mu_n}.\vec{B}|, \quad \tan(2\theta) = -\frac{\delta m}{\vec{\mu_n}.\vec{B}}$$

- Quasifree condition holds:

$$|\vec{\mu_n}.\vec{B}|t << 1$$

$$P(n \to \bar{n}) \simeq [(\delta m)t]^2 = [t/\tau_{n-\bar{n}}]^2$$

- Number of $\bar{n}$ created after time t is

$$N_{\bar{n}} = P(n \to \bar{n})N_n \simeq \phi T_{\mathrm{run}}[t/\tau_{n-\bar{n}}]^2$$

- Best limit on free neutron oscillation: $\tau_{n-\bar{n}} > 8.6 \times 10^7$ sec.
  Baldo-ceolin et. al., ILL (1994)

$n - \bar{n}$ oscillation Phenomenology (cont.)

- $n - \bar{n}$ transition can occur in nuclei. However, energy difference is of order 30 MeV, suppressing oscillation by a large factor:

$$\tau_{Nuc} = R\tau_{n\bar{n}}^2, \quad R \simeq 5 \times 10^{22}\,\mathrm{sec}^{-1}$$

Chetyrkin et. al (1981); Dover, Gal, Richards (1995); Kopeliovich et. al. (2012),...

- Best limit from SuperK: $\tau_{n\bar{n}} > 3.5 \times 10^8$ sec.

- $\Rightarrow \delta m < 10^{-23}$ eV

- For free neutron oscillations degaussing of earth's magnetic field to level nano-Tesla required for improved determination
- There are plans to improve sensitivity by two to three orders at a proposed experiment at ESS

Models of $n - \bar{n}$ oscillations

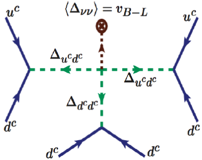
- Effective $\Delta B = 2$ operator that mediates neutron oscillation is:

$$\mathcal{L}_{\text{eff}} = \frac{(udd)^2}{\Lambda^5}$$

- High dimension implies oscillations probe scale of $\Lambda \sim 10^6$ GeV

- This operator naturally arises in quark-lepton unified theories based on $SU(2)_L \times SU(2)_R \times SU(4)_C$ as partners of seesaw mechanism for neutrinos

- Δ fields are color sextet scalars, which do not mediate proton decay. $\mathcal{L}_{\text{eff}} = (\lambda f^3 v_{BL})/M^6$



Mohapatra, Marshak (1980)

From quarks to nucleons

- The quark level Lagrangian needs to be converted to nucleon level δm
- MIT bag model calculations showed $\delta m \simeq \Lambda_{QCD}^6/\Lambda^5$ with $\Lambda_{QCD} \simeq 200$ MeV
  Shrock-Rao (1982)
- Recent lattice calculations show enhancement of oscillation probability by an order of magnitude
  Rinaldi et. al. (2018)
- For $n - \bar{n}$ transition in nuclei, nuclear physics calculations have been improving
  Friedman, Gal (2008)

Effective $n - \bar{n}$ operators

- There are 12 quark level operators:

$$\mathcal{L}_{\text{eff}} \supset \sum_{i=1}^{6} c_i \mathcal{O}_i + \bar{c}_i \bar{\mathcal{O}}_i + \text{h.c.}$$

- These operators have the form (Wagman-Buchoff basis):

$$\begin{aligned}
\mathcal{O}_1 &= \frac{1}{2}\epsilon_{ijk}\epsilon_{i'j'k'}(\bar{u}_i^c P_R d_j)(\bar{u}_{i'}^c P_R d_{j'})(\bar{d}_k^c P_R d_{k'}) \,, \\
\mathcal{O}_2 &= \epsilon_{ijk}\epsilon_{i'j'k'}(\bar{u}_i^c P_L d_j)(\bar{u}_{i'}^c P_R d_{j'})(\bar{d}_k^c P_R d_{k'}) \,, \\
\mathcal{O}_3 &= \frac{1}{2}\epsilon_{ijk}\epsilon_{i'j'k'}(\bar{u}_i^c P_L d_j)(\bar{u}_{i'}^c P_L d_{j'})(\bar{d}_k^c P_R d_{k'}) \,, \\
\mathcal{O}_4 &= \epsilon_{ijk}\epsilon_{i'j'k'}(\bar{u}_i^c P_R u_{i'})(\bar{d}_j^c P_L d_{j'})(\bar{d}_k^c P_L d_{k'}) \,, \\
\mathcal{O}_5 &= \left(\epsilon_{ijk}\epsilon_{i'j'k'} + \epsilon_{i'jk}\epsilon_{ij'k'}\right)(\bar{u}_i^c P_R d_{i'})(\bar{u}_j^c P_L d_{j'})(\bar{d}_k^c P_L d_{k'}) \,, \\
\mathcal{O}_6 &= \epsilon_{ijk}\epsilon_{i'j'k'}(\bar{u}_i^c P_L u_{i'})(\bar{d}_j^c P_L d_{j'})(\bar{d}_k^c P_R d_{k'}) \\
&\quad + \left(\epsilon_{ijk}\epsilon_{i'j'k'} + \epsilon_{i'jk}\epsilon_{ij'k'}\right)(\bar{u}_i^c P_L d_{i'})(\bar{u}_j^c P_L d_{j'})(\bar{d}_k^c P_R d_{k'})
\end{aligned}$$

Rinaldi et. al. (2019)

- $n - \overline{n}$ oscillations may be related to baryon asymmetry

Conclusions

- EFT description is extremely good for B and L violation in the SM
- Stopping at EFT may miss important phenomena such as leptogenesis
- Various $d = 7$ and $d = 9$ lepton number violating EFT operators can lead to interesting neutrino mass models
- These models may be realized near the TeV scale, with potential signals for NSI, cFLV and direct detection at colliders
- Baryon number violation well described by EFT, leading to proton decay and neutron-antineutron oscillations
- Let us push these ideas from all sides! Directly and indirectly!