Opening up neutrino Majorana mass operators

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Evidence of New Physics

The Standard Model (SM) is a very successful theory, but it is known to be imcomplete by several different observations.

Neutrino masses

Evidence from neutrino oscillations.

One possibility: Dirac mass $\nu_L \neq \nu_R^c$
Very small neutrino masses imply very small Yukawa couplings: $y_\nu \sim 10^{-12}$

Well motivated scenario: Majorana mass
Neutrino Majorana mass implies Lepton Number Violation (LNV) $\nu_L = \nu_R^c$

Can LNV be studied in a model-independent way?

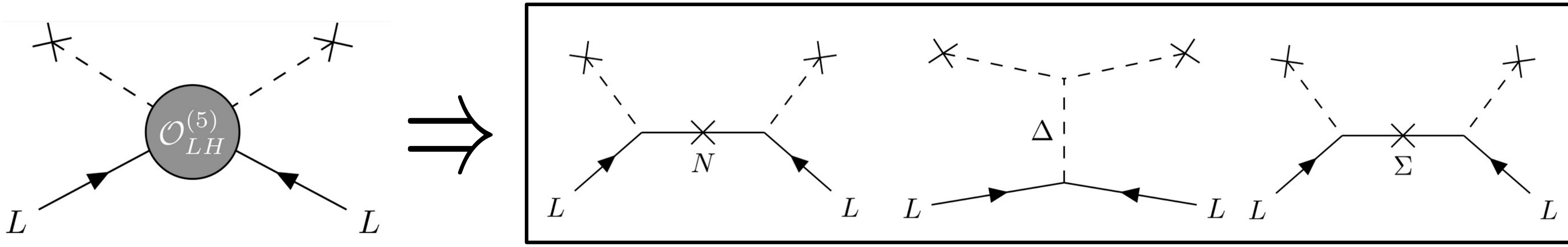
SM Effective field theory

$$\mathcal{L}_{\rm EFT} = \sum_i C_i \mathcal{O}_i + \text{h.c.} \qquad \text{Wilson coefficient: } C_i \propto \frac{1}{\Lambda^{(D-4)}},\ \Lambda = \text{New Physics (NP) scale}$$

LNV only occurs at odd mass dimension: $\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda_1}\mathcal{O}_1^{(5)} + \sum_i \frac{1}{\Lambda_i^3}\mathcal{O}_i^{(7)} + \sum_i \frac{1}{\Lambda_i^5}\mathcal{O}_i^{(9)} + \cdots$

Babu, Leung (2001), de Gouvêa, Jenkins (2007), Deppisch et. al. (2018)

Lowest dimension for ΔL = 2 LNV: The dimension-5 operator $\mathcal{O}_{LH}^{(5)} = L^\alpha L^\beta H^\rho H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}$



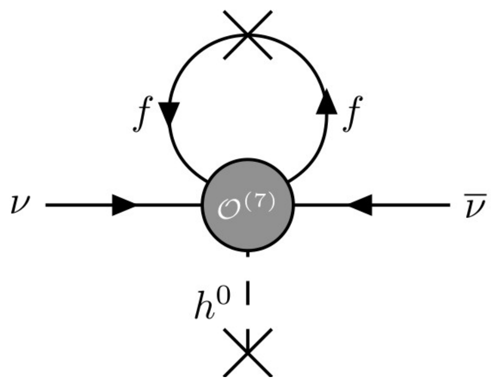
Neutrino mass in general EFT: $m_\nu \approx \frac{v^2}{\Lambda} \quad m_\nu \approx 0.1\ \text{eV} \rightarrow \Lambda \approx 10^{14}\ \text{GeV}$

LNV at dimension-7

Second-most simple realization: LNV at dimension-7

e.g. Lehman (2014), Liao, Ma (2019)

- 12 operators instead of one
- Can lead to radiative neutrino mass



$$m_\nu \approx \frac{1}{16\pi^2}\frac{v^2}{\Lambda}$$

$$m_\nu \approx 0.1 \text{ eV} \quad \rightarrow \quad \Lambda \approx 10^{12} \text{ GeV}$$

Type	$\mathcal{O}$	Operator
$\Psi^2 H^4$	$\mathcal{O}^{pr}_{LH}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{L^{ci}_p} L^m_r\right) H^j H^n \left(H^\dagger H\right)$
$\Psi^2 H^3 D$	$\mathcal{O}^{pr}_{LeHD}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{L^{ci}_p}\gamma_\mu e_r\right) H^j \left(H^m i D^\mu H^n\right)$
$\Psi^2 H^2 D^2$	$\mathcal{O}^{pr}_{LHD1}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{L^{ci}_p} D_\mu L^j_r\right)\left(H^m D^\mu H^n\right)$
	$\mathcal{O}^{pr}_{LHD2}$	$\epsilon_{im}\epsilon_{jn}\left(\overline{L^{ci}_p} D_\mu L^j_r\right)\left(H^m D^\mu H^n\right)$
$\Psi^2 H^2 X$	$\mathcal{O}^{pr}_{LHB}$	$g\epsilon_{ij}\epsilon_{mn}\left(\overline{L^{ci}_p}\sigma_{\mu\nu} L^m_r\right) H^j H^n B^{\mu\nu}$
	$\mathcal{O}^{pr}_{LHW}$	$g'\epsilon_{ij}\left(\epsilon\tau^I\right)_{mn}\left(\overline{L^{ci}_p}\sigma_{\mu\nu} L^m_r\right) H^j H^n W^{I\mu\nu}$
$\Psi^4 D$	$\mathcal{O}^{prst}_{\bar{d}uLLD}$	$\epsilon_{ij}\left(\overline{d_p}\gamma_\mu u_r\right)\left(\overline{L^{ci}_s} i D^\mu L^j_t\right)$
$\Psi^4 H$	$\mathcal{O}^{prst}_{\bar{e}LLLH}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{e_p} L^i_r\right)\left(\overline{L^{cj}_s} L^m_t\right) H^n$
	$\mathcal{O}^{prst}_{\bar{d}LueH}$	$\epsilon_{ij}\left(\overline{d_p} L^i_r\right)\left(\overline{u^c_s} e_t\right) H^j$
	$\mathcal{O}^{prst}_{\bar{d}LQLH1}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{d_p} L^i_r\right)\left(\overline{Q^{cj}_s} L^m_t\right) H^n$
	$\mathcal{O}^{prst}_{\bar{d}LQLH2}$	$\epsilon_{im}\epsilon_{jn}\left(\overline{d_p} L^i_r\right)\left(\overline{Q^{cj}_s} L^m_t\right) H^n$
	$\mathcal{O}^{prst}_{\bar{Q}uLLH}$	$\epsilon_{ij}\left(\overline{Q_p} u_r\right)\left(\overline{L^c_s} L^i_t\right) H^j$

How good is this estimate for the neutrino mass?

Operator explosion

"Explode" an operator to find all possible tree-level UV completions using combinatorics

$$\mathcal{O}_{\bar{Q}uLLH} = \epsilon_{ij}(\overline{Q}u)(\overline{L^c}L^i)H^j \quad \rightarrow \quad \epsilon_{ij}\overline{Q}^k u L^k L^i H^j$$

χ_1 ϕ_1 ψ_1 ω_1

$$\mathcal{O}_{\bar{Q}uLLH} \quad \rightarrow \quad \epsilon_{ij}\chi_1{}^k L^k L^i H^j \;/\; \epsilon_{ij}\psi_1{}^k u L^i H^j \;/\; \epsilon_{ij}\phi_1{}^k u L^k H^j \;/\; \epsilon_{ij}\omega_1{}^k u L^k L^i$$

χ_3 χ_2 χ_4 ψ_2 ψ_4 ψ_3 ϕ_2 ϕ_4 ϕ_3 ω_2 ω_4 ω_3

Pair field with index "1" together with either "2", "3", or "4" to get a model. This leads to several different models, but not all of them are unique.

$$\begin{array}{llll}
\chi_1 \sim S(1,2,1/2) & \psi_1 \sim V(\overline{3},1,-2/3) & \phi_1 \sim V(\overline{3},3,-2/3) & \omega_1 \sim F_L(\overline{3},3,1/3) \\
\chi_2 \sim F_R(1,1,0) & \psi_2 \sim F_R(1,1,0) & \phi_2 \sim F_R(1,3,0) & \omega_2 \sim S(1,3,1) \\
\chi_3 \sim F_R(1,3,0) & \psi_3 \sim F_L(\overline{3},2,-7/6) & \phi_3 \sim F_L(\overline{3},2,-7/6) & \omega_3 \sim V(\overline{3},2,-1/6) \\
\chi_4 \sim S(1,3,1) & \psi_4 \sim V(\overline{3},2,-1/6) & \phi_4 \sim V(\overline{3},2,-1/6) & \omega_4 \sim V(\overline{3},2,-1/6)
\end{array}$$

Neutrino mass topologies

The different UV-completions can be classified in terms of which neutrino mass topology they generate:

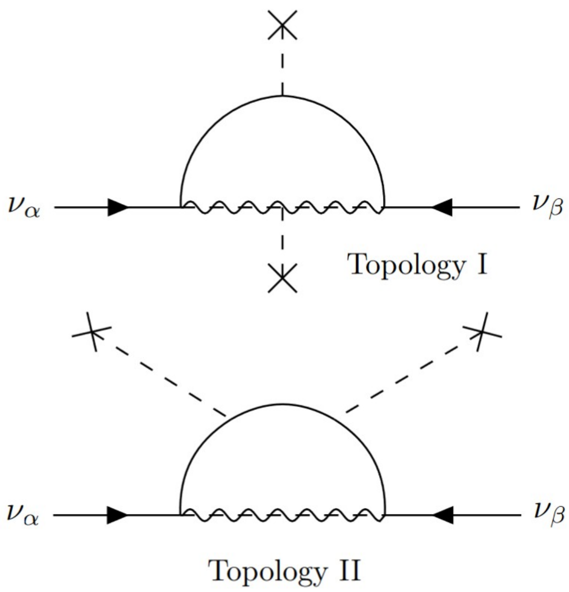
$$\mathcal{O}_{\overline{Q}uLLH} = \epsilon_{ij}\left(\overline{Q_p}u_r\right)\left(\overline{L_s^c}L_t^i\right)H^j$$

	Δ	φ	N	Σ	Q_7	$T_1^\dagger$	U_1	$\bar{V}_2^\dagger$	U_3
Δ		I			II	II			
φ			○	○					
N							○	○	
Σ								○	○
Q_7							II		II
$T_1^\dagger$								II	
U_1								I	
$\bar{V}_2^\dagger$									I
U_3									

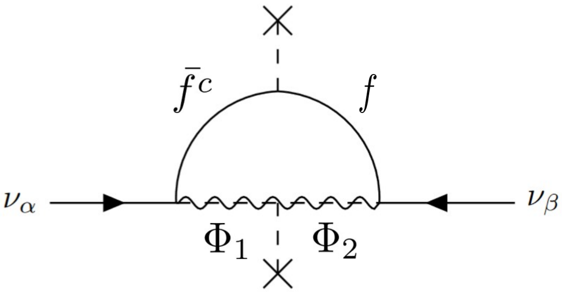
KF, Graf, Harz, Hati (2022)

○ = Generates the dimension-5 LNV operator

Field	Rep $(SU(3)_c, SU(2)_L, U(1)_Y)(3B)$
Δ	$S(1,3,1)(0)$
φ	$S(1,2,1/2)(0)$
N	$F(1,1,0)(0)$
Σ	$F(1,3,0)(0)$
Q_7	$F(3,2,7/6)(1)$
T_1	$F(3,3,-1/3)(1)$
U_1	$V(3,1,2/3)(1)$
$\bar{V}_2$	$V(\bar{3},2,-1/6)(-1)$
U_3	$V(3,3,2/3)(1)$



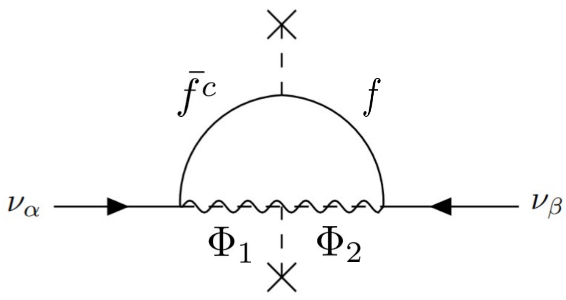
Leptoquark model example



General simplified model estimate of neutrino mass in Topology I:

$$(m_\nu)_{ij} \approx \frac{1}{16\pi^2} \frac{v^2 \mu (\lambda_{\Phi_1} \lambda_{\Phi_2} y_f)_{ij}}{\max(m_{\Phi_1}^2, m_{\Phi_2}^2)}$$

Leptoquark model example

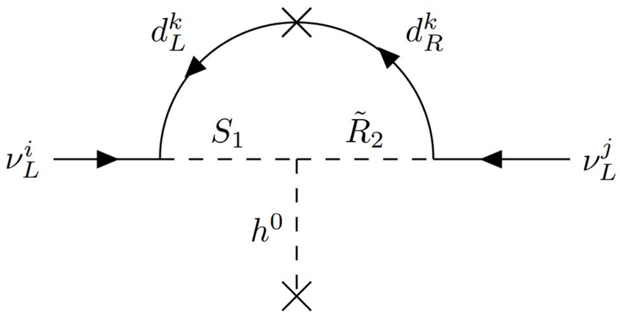


General simplified model estimate of neutrino mass in Topology I:

$$(m_\nu)_{ij} \approx \frac{1}{16\pi^2} \frac{v^2 \mu (\lambda_{\Phi_1} \lambda_{\Phi_2} y_f)_{ij}}{\max(m^2_{\Phi_1}, m^2_{\Phi_2})}$$

We can compare this estimate with a “real“ leptoquark model:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}^{\rm kin}_{\rm LQ} + \mu S_1 H^{\dagger\alpha} \tilde{R}_{2\alpha} - g_1 \bar{L}_\alpha i\sigma_2^{\alpha\beta} \bar{d}^c - g_2 Q^\alpha L^\beta \epsilon_{\alpha\beta} S_1 + \text{h.c.}$$

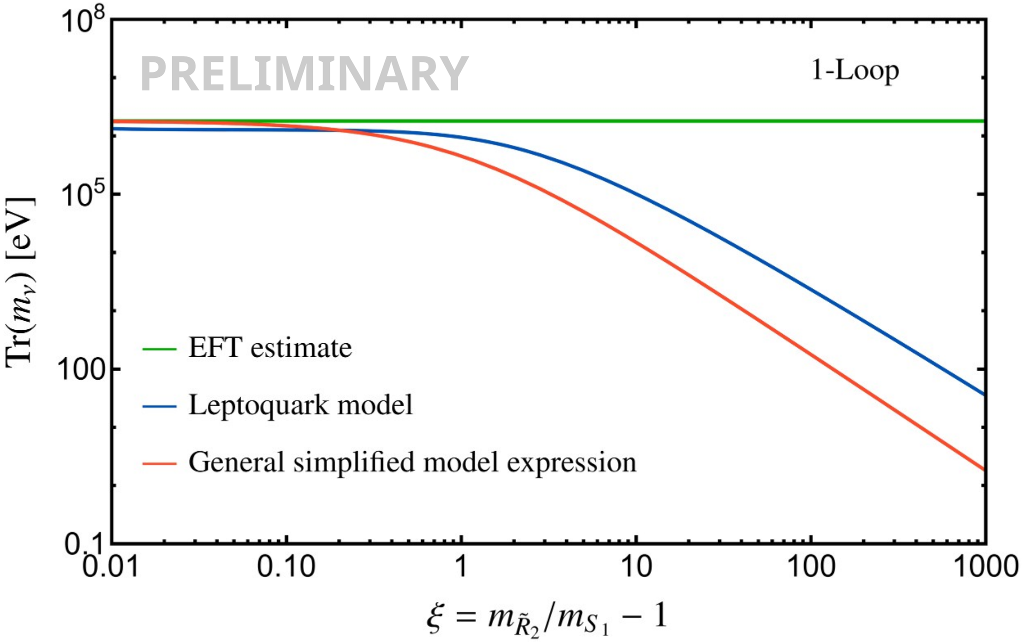


$S_1 \in (\bar{3}, 1, 1/3) \qquad \tilde{R}_2 \in (\bar{3}, 2, 1/6)$

$$m^2_{{\rm LQ}_{1,2}} = \frac{1}{2}\left(m^2_{\tilde{R}_2} + m^2_{S_1} \pm \sqrt{(m^2_{\tilde{R}_2} - m^2_{S_1})^2 + \mu^2 v^2}\right)$$

$$(m_\nu)_{ij} = \frac{3\sin(2\theta) v (y_d g_1 g_2)_{ij}}{32\pi^2} \log\frac{m_{{\rm LQ}_1}}{m_{{\rm LQ}_2}}$$

Comparison of mass expressions



$$(m_\nu)_{ij} = \frac{v^2 \left(y_d C^{-1/3}_{\bar{d}LQLH1}\right)_{ij}}{16\pi^2}$$

$$(m_\nu)_{ij} = \frac{3\sin(2\theta) v (y_d g_1 g_2)_{ij}}{32\pi^2} \log \frac{m_{\mathrm{LQ}_1}}{m_{\mathrm{LQ}_2}}$$

$$(m_\nu)_{ij} \approx \frac{1}{16\pi^2} \frac{v^2 \mu (\lambda_{\Phi_1} \lambda_{\Phi_2} y_f)_{ij}}{\max(m^2_{\Phi_1}, m^2_{\Phi_2})}$$

Hierarchy parameter: $\xi = \frac{\max(m_{\Phi_1}, m_{\Phi_2})}{\min(m_{\Phi_1}, m_{\Phi_2})} - 1$

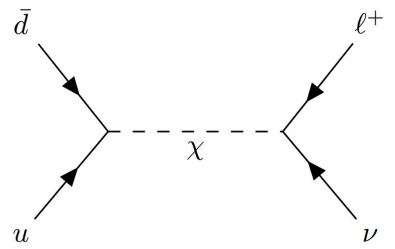
Our generic model expression captures well the effect of an increasing hierarchy, while the conventional EFT-based estimate does not.

What are the different constraints on the neutrino mass in terms of the mass hierarchy of a UV model?

UV-complete models: Global fits

Constraints on the indivdual fields that are contained in the UV-completions are obtained from global fits of dimension-6 SMEFT operators using LHC data

Field	Rep	Mass constraint 95% CL
φ	$S(1,2,1/2)(0)$	$m_\varphi \geq 1.0$ TeV
N	$F(1,1,0)(0)$	$m_N \geq 5.0$ TeV
Σ	$F(1,3,0)(0)$	$m_\Sigma \geq 4.6$ TeV
Q_7	$F(3,2,7/6)(1)$	$m_{Q_7} \geq 2.6$ TeV
$T_1^\dagger$	$F(\bar{3},3,1/3)(-1)$	$m_{T_1} \geq 2.1$ TeV
U_1	$V(3,1,2/3)(1)$	$m_{U_1} \geq 5.6$ TeV
$\tilde{V}_2^\dagger$	$V(3,2,1/6)(1)$	$m_{\tilde{V}_2} \geq 3.7$ TeV
U_3	$V(3,3,2/3)(1)$	$m_{U_3} \geq 9.9$ TeV



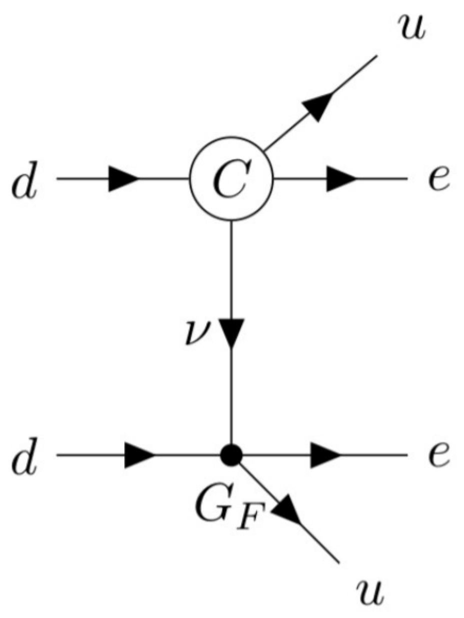
Ellis, Madigan, Mimasu, Sanz, You (2021)
Crivellin, Hoferichter, Kirk, Manzari, Schnell (2021)

These constraints are obtained under the assumption that the coupling constant with the interaction to SM fields is set to one

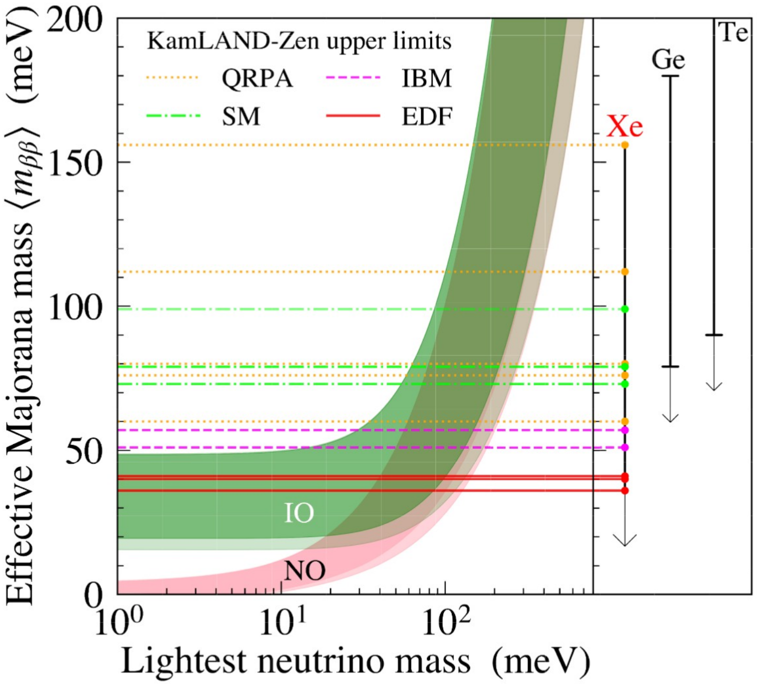
EFT: Neutrinoless double beta decay

Constraints on the Wilson coefficients of the different EFT operators are obtained from neutrinoless double beta (0νββ) decay searches

Currently most stringent limit: $T_{1/2}^{^{136}\mathrm{Xe}} \leq 2.3 \times 10^{26}$ yrs, 90% C.L.



e.g. Cirigliano et. al. (2017)

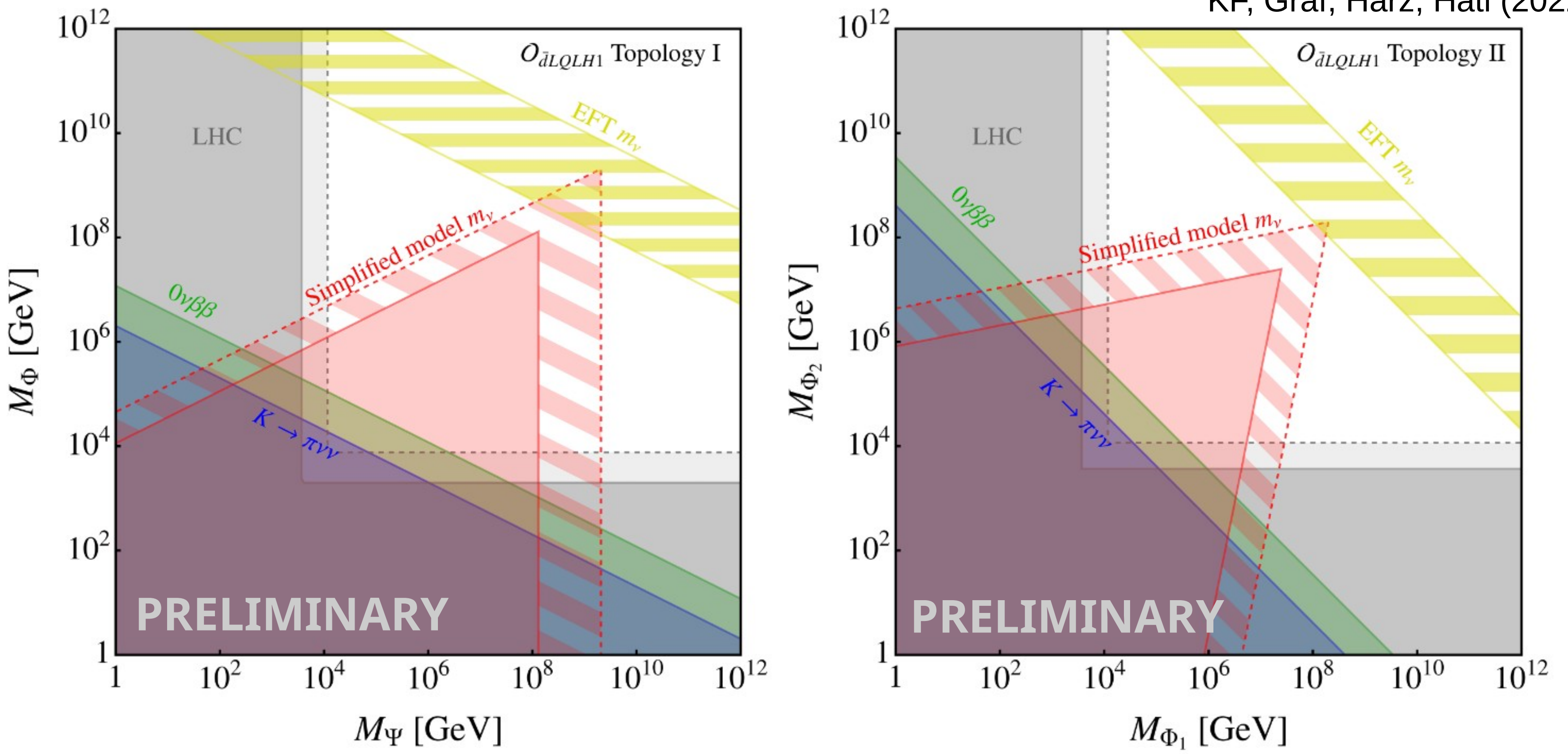


KamLAND-Zen collaboration (2022)

Mass-mass plane of UV-completions

We find that 0νββ, LHC, and Neutrino mass searches are all roughly competitive in the same region of parameter space

KF, Graf, Harz, Hati (2022)



Here all dimensionless couplings are set to unity

Striped region means that the observed value for the neutrino mass is obtained

Conclusion

- Neutrino masses may originate from lepton number violating effective operators.
- For higher dimensional operators, a hierarchy in the internal degrees of freedom significantly alters the neutrino mass.
- Taking this into account, we find that the regions of parameter space that leads to radiative neutrino masses close to current observational limits are simultaneously constrained by neutrinoless double beta decay and LHC searches.

Thank you

Backup slides

Absolute neutrino mass determination

An upper limit on the electron-row of the neutrino mass matrix comes from the KATRIN experiment

$$(m_\nu)_e = U_{ei}(m_\nu)_i < 0.8 \text{ eV}$$ KATRIN collaboration (2022)

A lower limit on the most massive mass eigenstate in normal ordering comes from from the mass splitting between the first and third mass eigenstates (second and third for inverse ordering)

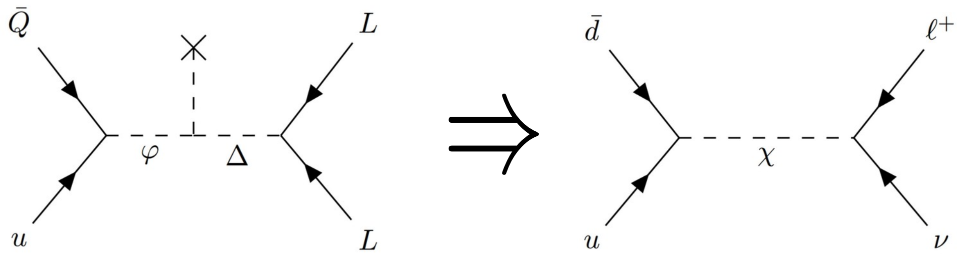
$$\sqrt{\Delta m^2_{13}} = 0.05 \text{ eV}$$ NUFIT collaboration (2022)

Since the lowest neutrino mass cannot be less than zero this gives an effective lower limit on the heaviest mass eigenstate

In a flavour-agnostic analysis we therefore use the approximate mass range

$$0.05 \text{ eV} \lesssim m_\nu \lesssim 0.8 \text{ eV}$$

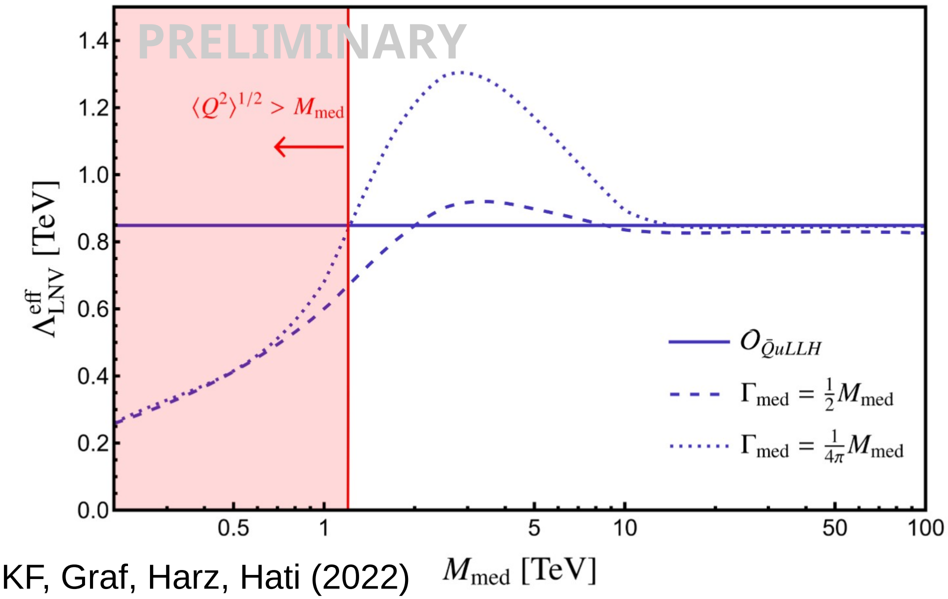
EFT vs UV model at the LHC



$$\Delta \in (1,3,1)$$
$$\varphi \in (1,2,1/2)$$

$$\mathcal{L} \supset \lambda_1 \bar{d}_L u_R \chi^* + \lambda_2 \bar{e}^c_L \nu_L \chi + \text{h.c.}$$

EFTs are only valid for $M^2_{\text{med}} > Q^2$



KF, Graf, Harz, Hati (2022)

Using the relation

$$\frac{\lambda_1 \lambda_2}{M^2_{\text{med}}} = \frac{v}{(\Lambda^{\text{eff}}_{\text{LNV}})^3}$$

we naively expect the same cross section for the simplified model and EFT operator

This analysis needs to be done on a model-by-model basis. It's a subject for future work.