Effective comparison of neutrino-mass models

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Outline

1. Motivation
2. The models, their EFTs and spurion analysis
3. Individual phenomenology
4. Effective comparison of models

Neutrinos have mass

- Neutrinos have mass: clearest evidence for new physics that couples to SM

- But it's extremely tiny, $m_\nu \lesssim 0.1$ eV
  - $\rightarrow$ Suggestive of very large scale (useful for GUTS, leptogenesis), very small couplings (useful for DM), or fine-tuning

- Could well have new physics which gives **small m_ν but larger effects elsewhere** because
  - $\rightarrow$ Tininess of lepton number violating couplings is technically natural
  - $\rightarrow$ Models may involve multiple mass scales

How will we know the true model of neutrino mass?

1. Directly: discovery of a new state (cf. Oleg's and Xabi's talks later this week)

2. Indirectly: discover a **pattern of deviations from the SM** which points to one specific mechanism

- Indirect approach is less obvious but arguably more promising:
  - → Great recent and expected progress in low energy and EW-scale observables: $\mu N \to eN$, $\mu \to 3e$, $a_{e,\mu}$, d_e, B decays, m_W,...
  - → Slower progress on energy frontier

New physics above the EW scale

Focusing exclusively on $\Lambda_{NP} \gg v$, there are two main approaches one can take:

1. An explicit model
   - ✓ UV complete
   - ✓ Is (somewhat) predictive
   - × Small part of theory space
   - × **Can we distinguish it?**

     Gore Vidal: *'It is not enough to succeed. Others must fail.'*
2. Effective Field Theory
   - ✓ (Reasonably) complete coverage of possibilities
   - ✓ Calculational ease
   - × Not UV complete
   - × **Many models match onto given Wilson Coefficient(s)**

Distinguishing new physics

- The problem: can't claim uniqueness

- A more useful approach: compare multiple observables (ideally with correlated predictions) in multiple models

- This has been done before, but not enough

  Ababda+Biggio+Bordone+Gavela+Hambye '07, Babu+Dev+Janu+Thapa '19,...

- Our work aims to:
  - → Show the usefulness of deriving EFTs of models
  - → Further develop this approach

Outline

The procedure

1. Pick a model
2. Integrate out heavy states at their mass scale, generate WCs

   de Blas+Criado+Perez-Victoria+Santiago '17 (tree-level dim-6),...
3. Run WCs down to scales of observables

   Jenkins+Manohar+Trott+Alonso+Stoffer '13, '17;...
4. Compare with established bounds on WCs from observables

   Crivellin+Najjari+Rosiek '13, Falkowski+Riva '14, Berthier+Trott '15, Feruglio+Paradisi+Pattori '15, Falkowski+Gonzalez-Alonso+Mimouni '17, Frigerio+Nardecchi+Serra+Vecchi '18, Calibbi+Marcano+Roy '21, RC+Frigerio '21,...

Models

Four different neutrino-mass models:

- Type-I seesaw (tree): $n \geq 2$ singlet fermions, $N \sim (1,1)_0$
- Type-III seesaw (tree): $n \geq 2$ fermion triplets, $\Sigma \sim (1,3)_0$
- Zee model (loop): two scalars, $H_2 \sim (1,2)_{1/2}$ and $\delta \sim (1,1)_1$
- Minimal LQ model (loop): two scalars, $S \sim (3,1)_{-1/3}$ and $D \sim (3,2)_{1/6}$ (in SUSY could call them $\tilde{d}_R$ and $\tilde{q}_L$)
  - $\rightarrow$ Only model with two LQs which induces both m_ν and charged lepton dipoles without y_e-suppression

Wilson Coefficients

WCs	Seesaw I	Seesaw III	Zee	Leptoquarks
c^{W}_{ab}	$\frac{1}{2}(\epsilon_N^T \mu_N \epsilon_N)_{ab}$	$\frac{1}{2}(\epsilon_\Sigma^T \mu_\Sigma \epsilon_\Sigma)_{ab}$	$-2\mu_Z(\epsilon_\delta y_e^\dagger \epsilon_2)_{ab}\boldsymbol{P}$ $-2\mu_Z(\epsilon_2^T y_e^* \epsilon_\delta^T)_{ab}\boldsymbol{P}$	$3\mu_{DS}(\epsilon_L^T y_d^\dagger \epsilon_D)_{ab}\boldsymbol{P}$ $+3\mu_{DS}(\epsilon_D^T y_d^* \epsilon_L)_{ab}\boldsymbol{P}$
c^{eB}_{ab}	$-\frac{g_1}{24}(\epsilon_N^\dagger \epsilon_N y_e^\dagger)_{ab}\boldsymbol{P}$	$-\frac{g_1}{8}(\epsilon_\Sigma^\dagger \epsilon_\Sigma y_e^\dagger)_{ab}\boldsymbol{P}$	$-\frac{g_1}{3}(\epsilon_\delta^\dagger \epsilon_\delta y_e^\dagger)_{ab}\boldsymbol{P}$ $+\frac{5g_1}{48}(\epsilon_2^\dagger \epsilon_2 y_e^\dagger)_{ab}\boldsymbol{P}$ $+\frac{g_1}{24}(y_e^\dagger \epsilon_2 \epsilon_2^\dagger)_{ab}\boldsymbol{P}$	$-\frac{5g_1}{4}(\epsilon_L^\dagger y_u^T \epsilon_R)_{ab}\boldsymbol{L}$
c^{eW}_{ab}	$-\frac{5g_2}{24}(\epsilon_N^\dagger \epsilon_N y_e^\dagger)_{ab}\boldsymbol{P}$	$-\frac{3g_2}{8}(\epsilon_\Sigma^\dagger \epsilon_\Sigma y_e^\dagger)_{ab}\boldsymbol{P}$	$-\frac{g_2}{6}(\epsilon_\delta^\dagger \epsilon_\delta y_e^\dagger)_{ab}\boldsymbol{P}$ $+\frac{g_2}{48}(\epsilon_2^\dagger \epsilon_2 y_e^\dagger)_{ab}\boldsymbol{P}$	$\frac{3g_2}{4}(\epsilon_L^\dagger y_u^T \epsilon_R)_{ab}\boldsymbol{L}$
$c^{Hl(1)}_{ab}$	$\frac{1}{4}(\epsilon_N^\dagger \epsilon_N)_{ab}$	$\frac{3}{4}(\epsilon_\Sigma^\dagger \epsilon_\Sigma)_{ab}$	$\frac{2g_1^2}{3}(\epsilon_\delta^\dagger \epsilon_\delta)_{ab}\boldsymbol{L}$ $-\frac{g_1^2}{3}(\epsilon_2^\dagger \epsilon_2)_{ab}\boldsymbol{L}$	$-\frac{g_1^2}{3}(\epsilon_D^\dagger \epsilon_D)_{ab}\boldsymbol{L}$ $-\frac{g_1^2}{6}(\epsilon_L^\dagger \epsilon_L)_{ab}\boldsymbol{L}$ $-\frac{3}{2}(\epsilon_L^\dagger y_u^T y_u^* \epsilon_L)_{ab}\boldsymbol{L}$
$c^{Hl(3)}_{ab}$	$-\frac{1}{4}(\epsilon_N^\dagger \epsilon_N)_{ab}$	$\frac{1}{4}(\epsilon_\Sigma^\dagger \epsilon_\Sigma)_{ab}$	$\frac{2g_2^2}{3}(\epsilon_\delta^\dagger \epsilon_\delta)_{ab}\boldsymbol{L}$	$\frac{1}{2}g_2^2(\epsilon_L^\dagger \epsilon_L)_{ab}\boldsymbol{L}$ $-\frac{3}{2}(\epsilon_L^\dagger y_u^T y_u^* \epsilon_L)_{ab}\boldsymbol{L}$
c^{He}_{ab}	$\frac{1}{2}(y_e \epsilon_N^\dagger \epsilon_N y_e^\dagger)_{ab}\boldsymbol{L}$ $-\frac{g_1^2}{3}\mathrm{tr}[\epsilon_N^\dagger \epsilon_N]\delta_{ab}\boldsymbol{L}$	$\frac{3}{2}(y_e \epsilon_\Sigma^\dagger \epsilon_\Sigma y_e^\dagger)_{ab}\boldsymbol{L}$ $-g_1^2\mathrm{tr}[\epsilon_\Sigma^\dagger \epsilon_\Sigma]\delta_{ab}\boldsymbol{L}$	$-\frac{g_1^2}{3}(\epsilon_2 \epsilon_2^\dagger)_{ab}\boldsymbol{L}$	$3(\epsilon_R^\dagger y_u^* y_u^T \epsilon_R)_{ab}\boldsymbol{L}$ $-\frac{g_1^2}{6}(\epsilon_R^\dagger \epsilon_R)_{ab}\boldsymbol{L}$
c^{eH}_{ab}	$2\lambda(\epsilon_N^\dagger \epsilon_N y_e^\dagger)_{ab}\boldsymbol{L}$ $+\frac{g_2^2}{3}\mathrm{tr}[\epsilon_N^\dagger \epsilon_N](y_e^\dagger)_{ab}\boldsymbol{L}$ $-6(c^{W\dagger} c^W y_e)_{ab}\boldsymbol{L}$ $+8\mathrm{tr}[c^{W\dagger} c^W](y_e^\dagger)_{ab}\boldsymbol{L}$	$(\epsilon_\Sigma^\dagger \epsilon_\Sigma y_e^\dagger)_{ab}$	$\epsilon_\lambda^*(\epsilon_2^\dagger)_{ab}$	$6(\epsilon_L^\dagger y_u^T y_u^* y_u^T \epsilon_R)_{ab}\boldsymbol{L}$ $-6\lambda(\epsilon_L^\dagger y_u^T \epsilon_R)_{ab}\boldsymbol{L}$

- Sample of WCs: light (dark) grey for 1-loop leading-log (finite)
- $\mathrm{L} \equiv \log(M/v)/(16\pi^2)$, $\mathrm{P} \equiv 1/(16\pi^2)$

A brief introduction to spurion analysis

- SM has a $U(3)_l \times U(3)_e \times U(3)_q \times U(3)_u \times U(3)_d$ symmetry, broken by Yukawas but restored if they are 'spurious' fields
- If $l_L \to V_l l_L$, $e_R \to V_e e_R$ and $y_e \to V_e y_e V_l^\dagger$, then

$$\mathcal{L} \supset -\overline{e_R} y_e H^\dagger l_L + h.c. \tag{1}$$

  remains invariant under the flavour symmetry
- Treat all new couplings and mass terms this way, enforce that EFT Lagrangian,

$$\mathcal{L} = \sum_i (\sqrt{2}/v)^{d_i - 4}\, c^i\, Q_i \tag{2}$$

  is invariant under symmetry (which may be extended by NP)
- Know how each operator transforms under each symmetry $\Rightarrow$ know how each WC should transform

Spurion analysis in the type-I and type-III seesaw

Initial spurion analysis is very illuminating

- First consider the seesaw mechanisms, with

$$\mathcal{L}_N = \overline{N}_R i\partial\!\!\!/ N_R - \left(\overline{N_R} Y_N \tilde{H}^\dagger l_L + \frac{1}{2}\overline{N_R} M_N N_R^c + h.c.\right) , \quad (3)$$

  for type-I and $N_R \to \Sigma_R^A$ for type-III

- Under $U(3)_l \times U(n)_N$ symmetry, have

$$Y_N \to V_N Y_N V_l^\dagger \,, \qquad M_N \to V_N M_N V_N^T \,, \quad (4)$$

- Define dimensionless parameters

$$\epsilon_N \equiv \frac{v}{\sqrt{2}} M_N^{-1} Y_N \,, \qquad \mu_N \equiv \frac{\sqrt{2}}{v} M_N \,, \quad (5)$$

Spurion analysis in the type-I and type-III seesaw

- All SMEFT operators Q_i are invariant under $U(n)_N$
- The only $U(n)_N$-invariant combinations at lowest orders in the EFT are

$$\mathcal{O}(M^{-1}) : (\epsilon_N^T \mu_N \epsilon_N)_{\alpha\beta} \,, \quad \mathcal{O}(M^{-2}) : (\epsilon_N^\dagger \epsilon_N)_{\alpha\beta} \;, \; [\mathcal{O}(M^{-1})]^2$$

- So $m_\nu \propto \epsilon_N^T \mu_N \epsilon_N$ and all dim-6 WCs are $c \propto (\epsilon_N^\dagger \epsilon_N)$ or $c \propto m_\nu^2$
- Then setting $m_\nu \propto \epsilon_N^T \mu_N \epsilon_N \to 0$ implies (for $n = 2, 3$)

$$(\epsilon_N^\dagger \epsilon_N)_{\alpha\beta} \propto \lambda_\alpha \lambda_\beta \,, \tag{6}$$

$\lambda_\alpha \in \mathbb{R}$, $\alpha = e, \mu, \tau$, i.e. all dim-6 pheno fixed by three parameters

Spurion analysis in the type-I and type-III seesaw

- One-loop dipole WCs are $c_{\alpha\beta}^{eB,eW} \propto (\epsilon_N^\dagger \epsilon_N y_e^\dagger)_{\alpha\beta}$, so $c_{\alpha\alpha}^{eB,eW} \in \mathbb{R} \Rightarrow$ EDM $d_e = 0$ at leading order

- From spurion analysis, find largest imaginary part arises at two-loops,

$$|d_e| \sim \frac{4em_e}{(16\pi^2)^2 v^2} \mathrm{Im}\{[\epsilon_N^\dagger \epsilon_N y_e^\dagger y_e \epsilon_N^\dagger \epsilon_N, \epsilon_N^\dagger \epsilon_N]_{ee}\}$$
$$= \frac{em_e(m_\tau^2 - m_\mu^2)}{16\pi^4 v^4} \mathrm{Im}\{(\epsilon_N^\dagger \epsilon_N)_{e\tau}(\epsilon_N^\dagger \epsilon_N)_{\tau\mu}(\epsilon_N^\dagger \epsilon_N)_{\mu e}\}$$
$$\lesssim 10^{-37}\, e \text{ cm} \quad (7)$$

Spurion analysis in the Zee model

- The Zee Lagrangian is

$$\mathcal{L}_{\text{Zee}} = |D_\mu \delta|^2 + |D_\mu H_2|^2 - M_\delta^2 \delta^\dagger \delta - M_2^2 H_2^\dagger H_2 - M_{\delta 2} \tilde{H}^\dagger H_2 \delta^\dagger$$
$$- \lambda_2 (H^\dagger H)(H^\dagger H_2) - \overline{l_L^c} Y_\delta i\sigma_2 l_L \delta - \overline{e_R} Y_2 H_2^\dagger e_R + h.c. + \ldots \quad (8)$$

- Here we have a $U(3)_l \times U(3)_e \times U(1)_\delta \times U(1)_{H_2}$ symmetry, with dimensionless parameters

$$\mu_Z \equiv \frac{\sqrt{2} M_{\delta 2}}{v} \to \mu_Z e^{i(\phi_\delta - \phi_2)}\,, \quad \epsilon_\lambda \equiv \frac{v \lambda_2}{\sqrt{2} M_2} \to \epsilon_\lambda e^{-i\phi_2}\,,$$
$$\epsilon_\delta \equiv \frac{v Y_\delta}{\sqrt{2} M_\delta} \to V_l^* \epsilon_\delta V_l^\dagger e^{-i\phi_\delta}\,, \quad \epsilon_2 \equiv \frac{v Y_2}{\sqrt{2} M_2} \to V_e \epsilon_2 V_l^\dagger e^{i\phi_2}$$

Spurion analysis in the Zee model

- Again, we can classify $U(1)_\delta \times U(1)_{H_2}$-invariant combinations at lowest order

$$\mathcal{O}(M^{-1}) : \mu_Z(\epsilon_\delta)_{\alpha\beta}(\epsilon_2)_{\gamma\delta} \ , \ \mu_Z\epsilon^*_\lambda(\epsilon_\delta)_{\alpha\beta} \ ,$$

$$\mathcal{O}(M^{-2}) : (\epsilon^*_\delta)_{\alpha\beta}(\epsilon_\delta)_{\gamma\delta} \ , \ (\epsilon^*_2)_{\alpha\beta}(\epsilon_2)_{\gamma\delta} \ , \ \epsilon^*_\lambda\epsilon_\lambda \ , \ (\epsilon_2)_{\alpha\beta}\epsilon_\lambda \ , \ [\mathcal{O}(M^{-1})]^2$$

- Neutrino mass $m_\nu \propto \mu_Z(\epsilon_\delta y_e^\dagger \epsilon_2)_{\alpha\beta} + ()^T$ since ϵ_δ anti-symmetric
- Small m_ν achieved by $\mu_Z \to 0$, $\epsilon_\delta \to 0$, $\epsilon_2 \to 0$ (all limits conserve lepton number), or by fine-tuning if all non-zero
- See that a) dim-6 WCs can be large while m_ν small, and b) pheno of δ and H_2 are seperate: no $\epsilon_\delta\epsilon_2$ terms at dim-6

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EFT phenomenology

Placed bounds on WCs from various observables (these plus others)

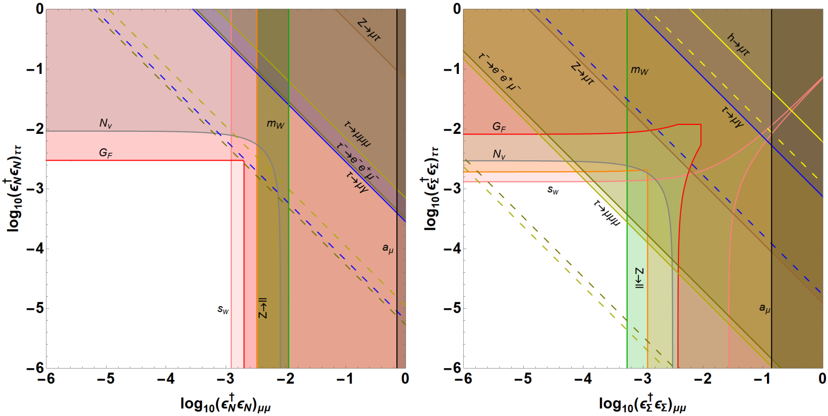
Observable	Bound	C.L.
m_W	$0.23c^G - 0.77c^{HD} \in [-0.6, 13] \times 10^{-4}$	anom
s_w^2	$c^{HD} - c^G - 1.40c^{Hl(1+3)} - 1.62c^{He} \in [-6.1, 9.1] \times 10^{-4}$	2σ
$G_F^{\mu\tau}/G_F^{e\tau}$	$c^{ll}_{\tau ee\tau} + c^{ll}_{e\tau\tau e} - c^{ll}_{\tau\mu\mu\tau} - c^{ll}_{\mu\tau\tau\mu} + 2c^{Hl(3)}_{\mu\mu} - 2c^{Hl(3)}_{ee} \in [-1.0, 4.6] \times 10^{-3}$	2σ
$G_F^{e\tau}/G_F$	$c^{ll}_{e\mu\mu e} + c^{ll}_{\mu ee\mu} - c^{ll}_{e\tau\tau e} - c^{ll}_{\tau ee\tau} + 2c^{Hl(3)}_{\tau\tau} - 2c^{Hl(3)}_{\mu\mu} \in [-1.9, 4.1] \times 10^{-3}$	2σ
$G_F^{\mu\tau}/G_F$	$c^{ll}_{\mu ee\mu} + c^{ll}_{e\mu\mu e} - c^{ll}_{\mu\tau\tau\mu} - c^{ll}_{\tau\mu\mu\tau} + 2c^{Hl(3)}_{\tau\tau} - 2c^{Hl(3)}_{ee} \in [-1.5, 6.0] \times 10^{-3}$	anom
$Z \to e\mu$	$\sqrt{\lvert c^{Hl(1)}_{e\mu} + c^{Hl(3)}_{e\mu}\rvert^2 + \lvert c^{He}_{e\mu}\rvert^2 + \frac{1}{2}\left\lvert s_w c^{eB}_{e\mu} + c_w c^{eW}_{e\mu}\right\rvert^2 + \frac{1}{2}\left\lvert s_w c^{eB}_{\mu e} + c_w c^{eW}_{\mu e}\right\rvert^2} \lesssim 1.2 \times 10^{-3}$	95%
$Z \to e\tau$	$\sqrt{\lvert c^{Hl(1)}_{e\tau} + c^{Hl(3)}_{e\tau}\rvert^2 + \lvert c^{He}_{e\tau}\rvert^2 + \frac{1}{2}\left\lvert s_w c^{eB}_{e\tau} + c_w c^{eW}_{e\tau}\right\rvert^2 + \frac{1}{2}\left\lvert s_w c^{eB}_{\tau e} + c_w c^{eW}_{\tau e}\right\rvert^2} \lesssim 3.1 \times 10^{-3}$	95%
$Z \to \mu\tau$	$\sqrt{\lvert c^{Hl(1)}_{\mu\tau} + c^{Hl(3)}_{\mu\tau}\rvert^2 + \lvert c^{He}_{\mu\tau}\rvert^2 + \frac{1}{2}\left\lvert s_w c^{eB}_{\mu\tau} + c_w c^{eW}_{\mu\tau}\right\rvert^2 + \frac{1}{2}\left\lvert s_w c^{eB}_{\tau\mu} + c_w c^{eW}_{\tau\mu}\right\rvert^2} \lesssim 3.5 \times 10^{-3}$	95%
$Z \to e^+e^-$	$1.19(c^G - c^{HD}) + 4.27(c^{Hl(1)}_{ee} + c^{Hl(3)}_{ee}) - 3.68c^{He}_{ee} \in [-4.2, 2.0] \times 10^{-3}$	2σ
$Z \to \mu^+\mu^-$	$1.19(c^G - c^{HD}) + 4.27(c^{Hl(1)}_{\mu\mu} + c^{Hl(3)}_{\mu\mu}) - 3.68c^{He}_{\mu\mu} \in [-4.7, 4.3] \times 10^{-3}$	2σ
$Z \to \tau^+\tau^-$	$1.19(c^G - c^{HD}) + 4.27(c^{Hl(1)}_{\tau\tau} + c^{Hl(3)}_{\tau\tau}) - 3.68c^{He}_{\tau\tau} \in [-2.2, 8.2] \times 10^{-3}$	2σ
N_ν	$0.58(c^{HD} - c^G) + 11.1c^{He} - 24.8c^{Hl(1)} - 0.82c^{Hl(3)} \in [-0.019, 0.011]$	2σ
a_e	$\lvert \mathrm{Re}\ c^{e\gamma,obs}_{ee}\rvert \lesssim 3 \times 10^{-8}$	anom
a_μ	$\mathrm{Re}[c^{e\gamma,obs}_{\mu\mu} + 4.3 \times 10^{-7}(c^G - c^{HD})] \in [-0.5, 4.6] \times 10^{-7}$	anom

Bounds derived using LEP, ATLAS, CMS, CDF II, Muon G-2, PDG, Hanneke+ '08, Pich '13, Parker+ '18, Morel+ '20, Aoyama+ '20, de Blas+ '22

EFT phenomenology

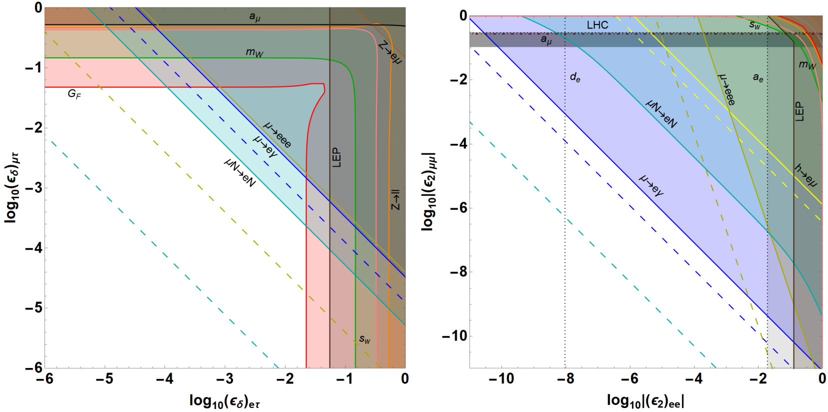
- Having done this once, only have to change it when there's improved experimental data
- Don't include all WCs, but all those obtained at tree or one-loop leading-log in any of the four models
- How to deal with $\geq 2\sigma$ anomalies when imposing 2σ limits? For a $n\sigma$ anomaly, we allowed a shift of $\lceil n \rceil \sigma$, so as not to rule out NP which negligibly modifies the observable
  - $\rightarrow$ For 4.2σ in a_μ, allowed $a_\mu^{\text{exp}} - 5\sigma \leq a_\mu^{\text{SM}} + \Delta a_\mu \leq a_\mu^{\text{exp}} + 2\sigma$
- Now applied these to each model: looked at two flavours at a time and set couplings to the third to zero

Type-I and type-III seesaw, $\mu - \tau$ sector



- Recall $\epsilon_{N,\Sigma} = (v/\sqrt{2})Y_{N,\Sigma}/M_{N,\Sigma}$, took $M = 10$ TeV for logs
- Have correlated predictions for $n \leq 3$. Flavour conservation (violation) strongest in type-I (type-III) since CLFV induced at loop (tree)
- Type-I gives $\Delta m_W > 0$ but too small, type-III gives $\Delta m_W < 0$

Zee model, $e - \mu$ sector



- ϵ_δ fully determined, for ϵ_2 took $|(\epsilon_2)_{\alpha\beta}| = \sqrt{|(\epsilon_2)_{\alpha\alpha}(\epsilon_2)_{\beta\beta}|}$
- δ interferes with muon decay (thus G_F, m_W,...), H_2 does not
- Large $\mu \to e\gamma$ induced by H_2 from 2-loop Barr-Zee
- Can explain $(g-2)_\mu$ for $|(\epsilon_2)_{ee}| \lesssim 10^{-10}$

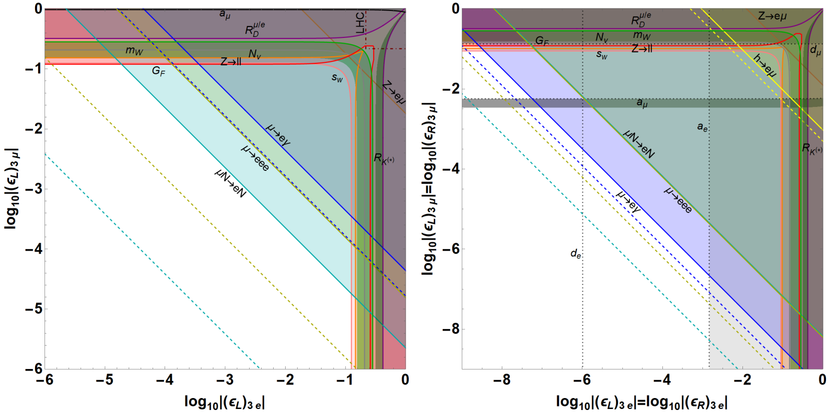
LQ model

LQ model Lagrangian is

$$\mathcal{L}_{LQ} = |D_\mu S|^2 + |D_\mu D|^2 - V(D,S) \qquad (9)$$
$$- (\overline{q_L^c} Y_L i\sigma_2 l_L S^\dagger + \overline{u_R^c} Y_R e_R S^\dagger + \overline{d_R} Y_D D^T i\sigma_2 l_L + h.c.)$$

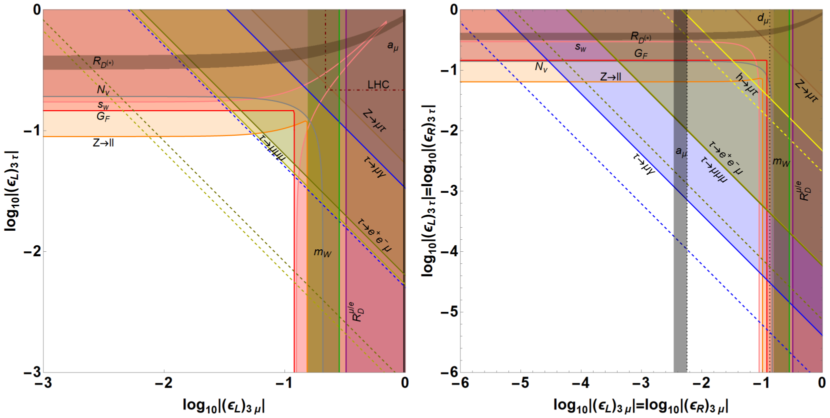
- Assume LQ couples to only 3rd family quarks in m_d basis:
  - $\rightarrow$ Avoid bounds from pions, kaons etc., focus on lepton sector
  - $\rightarrow$ Captures relevant loops $\propto y_t$
- Y_L is most interesting coupling since
  - $\rightarrow$ It generates interference with muon decay
  - $\rightarrow$ Couples to light quarks via CKM, so induces e.g. $b \rightarrow c\ell\nu$
  - $\rightarrow$ Combination of Y_L and Y_R gives top-enhanced loops, $\sim N_c y_t^2 \gg g_{1,2}^2$

LQ model, $e - \mu$ sector



- Correlated observables, $\mu \to e$ strongest by far, others weak but complementary
- Solutions to m_W and $R_{K^{(*)}}$ anomalies ruled out, but can explain $(g-2)_\mu$ for $|(\epsilon_{L,R})_{ee}| \lesssim 10^{-7}$
- Changing ϵ_R relative to ϵ_L modifies observables depending on dipole

LQ model, $\mu - \tau$ sector



- With only ϵ_L, LFC and LFV bounds similar, y_t-enhancement for $\epsilon_L = \epsilon_R$ makes LFV much stronger
- Solution to $R_{D(*)}$ also ruled-out, $(g-2)_\mu$ explanation persists, even d_μ relevant

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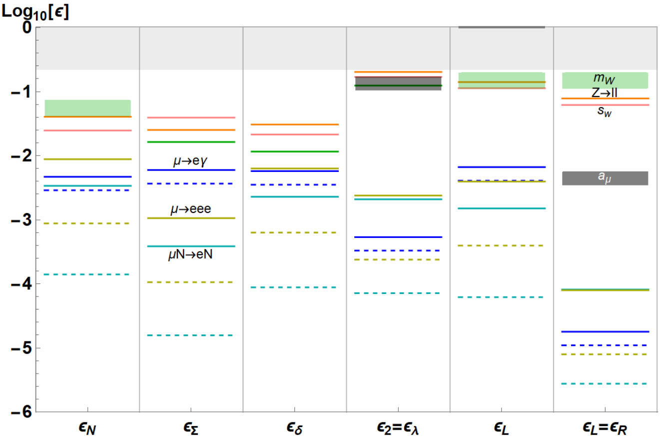
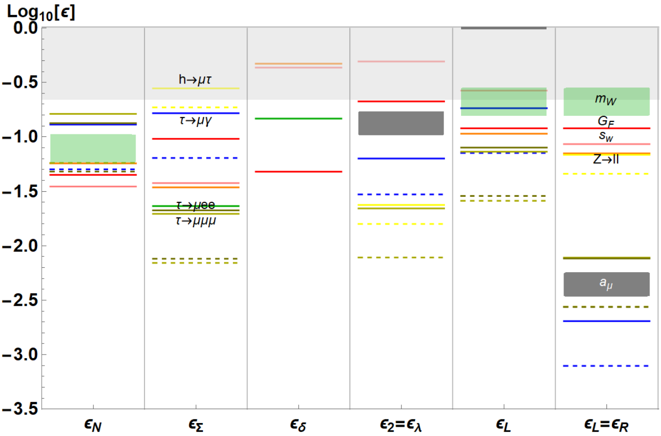
Comparison: all $\epsilon_{\alpha\beta}$ equal



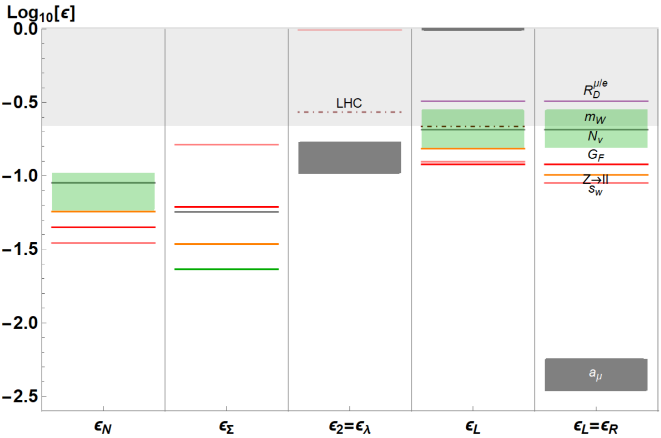
- $\mu \to e$ always wins: strongest in LQ since no y_μ
- Future $\mu \to e$ bounds has clear order
- Flavour-conserving bounds more discriminatory

Comparison: no NP coupling to electrons



- $(\epsilon_\delta)_{\mu\tau}$ only $\Rightarrow$ no flavour violation at dim-6
- Bounds from $\tau \to \mu$ competitive with flavour-conserving ones
- Strong potential to distinguish between models

Comparison: NP couples only to muons



- No ϵ_δ column since $(\epsilon_\delta)_{\mu\mu} = 0$ by antisymmetry
- Can explain $(g-2)_\mu$ anomalies in Zee and LQ models
- Mainly expect shift in s_W, G_F before m_W, but not in type-III

Conclusions

1. Precision low-energy and EW-scale observables are excellent places to look for evidence of the neutrino mass mechanism
2. EFT is a useful framework: spurion analysis and power-counting is powerful, systematic pheno analysis
   - → Strength of bounds obtained reinforces that EFT approach is valid
3. Looking at correlations **within and between models** could be key to discovering mass mechanism if no direct discoveries

Back-up slides

SMEFT operators

Name	Operator
$Q_{W,ab}$	$(\overline{l^c_{La}}\tilde{H}^*)(\tilde{H}^\dagger l_{Lb})$
$Q_{eB,ab}$	$(\overline{l_{La}}\sigma_{\mu\nu}e_{Rb})HB^{\mu\nu}$
$Q_{eW,ab}$	$(\overline{l_{La}}\sigma_{\mu\nu}e_{Rb})\sigma^A HW^{A\mu\nu}$
$Q^{(1)}_{Hl,ab}$	$(\overline{l_{La}}\gamma_\mu l_{Lb})(H^\dagger i\overleftrightarrow{D}^\mu H)$
$Q^{(3)}_{Hl,ab}$	$(\overline{l_{La}}\gamma_\mu\sigma^A l_{Lb})(H^\dagger i\overleftrightarrow{D}^\mu \sigma^A H)$
$Q_{He,ab}$	$(\overline{e_{Ra}}\gamma_\mu e_{Rb})(H^\dagger i\overleftrightarrow{D}^\mu H)$
$Q_{eH,ab}$	$(\overline{l_{La}}He_{Rb})(H^\dagger H)$
Q_H	$(H^\dagger H)^3$
Q_{HD}	$(H^\dagger D_\mu H)^*(H^\dagger D^\mu H)$
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$

Name	Operator
$Q_{ll,ab}$	$(\overline{l_{La}}\gamma_\mu l_{Lb})(\overline{l_{Lc}}\gamma^\mu l_{Ld})$
$Q_{le,ab}$	$(\overline{l_{La}}\gamma_\mu l_{Lb})(\overline{e_{Rc}}\gamma^\mu e_{Rd})$
$Q_{ee,ab}$	$(\overline{e_{Ra}}\gamma_\mu e_{Rb})(\overline{e_{Rc}}\gamma^\mu e_{Rd})$
$Q^{(1)}_{lq,abcd}$	$(\overline{l_{La}}\gamma_\mu l_{Lb})(\overline{q_{Lc}}\gamma^\mu q_{Ld})$
$Q^{(3)}_{lq,abcd}$	$(\overline{l_{La}}\gamma_\mu\sigma^A l_{Lb})(\overline{q_{Lc}}\gamma^\mu\sigma^A q_{Ld})$
$Q_{qe,abcd}$	$(\overline{q_{La}}\gamma_\mu q_{Lb})(\overline{e_{Rc}}\gamma^\mu e_{Rd})$
$Q_{lu,abcd}$	$(\overline{l_{La}}\gamma_\mu l_{Lb})(\overline{u_{Rc}}\gamma^\mu u_{Rd})$
$Q_{ld,abcd}$	$(\overline{l_{La}}\gamma_\mu l_{Lb})(\overline{d_{Rc}}\gamma^\mu d_{Rd})$
$Q_{eu,abcd}$	$(\overline{e_{Ra}}\gamma_\mu e_{Rb})(\overline{u_{Rc}}\gamma^\mu u_{Rd})$
$Q_{ed,abcd}$	$(\overline{e_{Ra}}\gamma_\mu e_{Rb})(\overline{d_{Rc}}\gamma^\mu d_{Rd})$
$Q^{(1)}_{lequ,abcd}$	$(\overline{l_{La}}e_{Rb})\,\epsilon\,(\overline{q_{Lc}}u_{Rd})$
$Q^{(3)}_{lequ,abcd}$	$(\overline{l_{La}}\sigma_{\mu\nu}e_{Rb})\,\epsilon\,(\overline{q_{Lc}}\sigma^{\mu\nu}u_{Rd})$
$Q_{ledq,abcd}$	$(\overline{l_{La}}e_{Rb})(\overline{d_{Rc}}q_{Ld})$

Wilson Coefficients 2

WCs	Seesaw I	Seesaw III	Zee	Leptoquarks
c^H	$\frac{4}{3}\lambda g_2^2 \mathrm{tr}[\epsilon_N^\dagger \epsilon_N]\mathsf{L}$ $-32\lambda \mathrm{tr}[c^{W\dagger} c^W]\mathsf{L}$	$-\frac{4}{3}\lambda g_2^2 \mathrm{tr}[\epsilon_\Sigma^\dagger \epsilon_\Sigma]\mathsf{L}$ $-32\lambda \mathrm{tr}[c^{W\dagger} c^W]\mathsf{L}$	$\epsilon_\lambda^* \epsilon_\lambda$	—
$c^{H\square}$	$\frac{g_1^2+3g_2^2}{6} \mathrm{tr}[\epsilon_N^\dagger \epsilon_N]\mathsf{L}$ $+2\mathrm{tr}[c^{W\dagger} c^W]\mathsf{L}$	$\frac{g_1^2-g_2^2}{2} \mathrm{tr}[\epsilon_N^\dagger \epsilon_N]\mathsf{L}$ $+2\mathrm{tr}[c^{W\dagger} c^W]\mathsf{L}$	—	—
c^{HD}	$\frac{2g_2^2}{3} \mathrm{tr}[\epsilon_N^\dagger \epsilon_N]\mathsf{L}$ $+16\mathrm{tr}[c^{W\dagger} c^W]\mathsf{L}$	$2g_2^2 \mathrm{tr}[\epsilon_N^\dagger \epsilon_N]\mathsf{L}$ $+16\mathrm{tr}[c^{W\dagger} c^W]\mathsf{L}$	—	—
c^{ll}_{abcd}	$\frac{g_1^2-g_2^2}{24}(\epsilon_N^\dagger \epsilon_N)_{ab}\delta_{cd}\mathsf{L}$ $+\frac{g_1^2-g_2^2}{24}\delta_{ab}(\epsilon_N^\dagger \epsilon_N)_{cd}\mathsf{L}$ $+\frac{g_2^2}{12}(\epsilon_N^\dagger \epsilon_N)_{ad}\delta_{cb}\mathsf{L}$ $+\frac{g_2^2}{12}\delta_{ad}(\epsilon_N^\dagger \epsilon_N)_{cb}\mathsf{L}$ $+2(c^{W\dagger})_{ac}(c^W)_{bd}\mathsf{L}$	$\frac{3g_1^2+g_2^2}{24}(\epsilon_\Sigma^\dagger \epsilon_\Sigma)_{ab}\delta_{cd}\mathsf{L}$ $+\frac{3g_1^2+g_2^2}{24}\delta_{ab}(\epsilon_\Sigma^\dagger \epsilon_\Sigma)_{cd}\mathsf{L}$ $-\frac{g_2^2}{12}(\epsilon_\Sigma^\dagger \epsilon_\Sigma)_{ad}\delta_{cb}\mathsf{L}$ $-\frac{g_2^2}{12}\delta_{ad}(\epsilon_\Sigma^\dagger \epsilon_\Sigma)_{cb}\mathsf{L}$ $+2(c^{W\dagger})_{ac}(c^W)_{bd}\mathsf{L}$	$(\epsilon_\delta^\dagger)_{ac}(\epsilon_\delta)_{db}$	$\frac{g_1^2}{6}(\epsilon_D^\dagger \epsilon_D)_{ab}\delta_{cd}\mathsf{L}$ $+\frac{g_1^2}{6}\delta_{ab}(\epsilon_D^\dagger \epsilon_D)_{cd}\mathsf{L}$ $+\frac{g_2^2}{2}(\epsilon_L^\dagger \epsilon_L)_{ad}\delta_{bc}\mathsf{L}$ $+\frac{g_2^2}{2}\delta_{ad}(\epsilon_L^\dagger \epsilon_L)_{cb}\mathsf{L}$ $+\frac{g_1^2-3g_2^2}{12}(\epsilon_L^\dagger \epsilon_L)_{ab}\delta_{cd}\mathsf{L}$ $+\frac{g_1^2-3g_2^2}{12}\delta_{ab}(\epsilon_L^\dagger \epsilon_L)_{cd}\mathsf{L}$
c^{le}_{abcd}	$\frac{g_1^2}{6}(\epsilon_N^\dagger \epsilon_N)_{ab}\delta_{cd}\mathsf{L}$	$\frac{g_1^2}{2}(\epsilon_\Sigma^\dagger \epsilon_\Sigma)_{ab}\delta_{cd}\mathsf{L}$	$-\frac{1}{2}(\epsilon_2^\dagger)_{ad}(\epsilon_2)_{cb}$	$\frac{3}{2}(\epsilon_L^\dagger y_u^T \epsilon_R)_{ad}(y_e)_{cb}\mathsf{L}$ $+\frac{3}{2}(y_e^\dagger)_{ad}(\epsilon_R^\dagger y_u^* \epsilon_L)_{cb}\mathsf{L}$ $+\frac{g_1^2}{3}(\epsilon_L^\dagger \epsilon_L)_{ab}\delta_{cd}\mathsf{L}$ $+\frac{2g_1^2}{3}(\epsilon_D^\dagger \epsilon_D)_{ab}\delta_{cd}\mathsf{L}$ $+\frac{2g_1^2}{3}\delta_{ab}(\epsilon_R^\dagger \epsilon_R)_{cd}\mathsf{L}$
c^{ee}_{abcd}	—	—	$\frac{g_1^2}{3}(\epsilon_2 \epsilon_2^\dagger)_{ab}\delta_{cd}\mathsf{L}$ $+\frac{g_1^2}{3}\delta_{ab}(\epsilon_2 \epsilon_2^\dagger)_{cd}\mathsf{L}$	$\frac{2g_1^2}{3}(\epsilon_R^\dagger \epsilon_R)_{ab}\delta_{cd}\mathsf{L}$ $+\frac{2g_1^2}{3}\delta_{ab}(\epsilon_R^\dagger \epsilon_R)_{cd}\mathsf{L}$

Wilson Coefficients 3

WCs	Seesaw I	Seesaw III	Zee	Leptoquarks
$c^{lq(1)}_{abcd}$	$-\frac{1}{4}(\epsilon_N^\dagger\epsilon_N)_{ab}(y_u^\dagger y_u)_{cd}\mathsf{L}$ $-\frac{g_1^2}{36}(\epsilon_N^\dagger\epsilon_N)_{ab}\delta_{cd}\mathsf{L}$	$-\frac{3}{4}(\epsilon_\Sigma^\dagger\epsilon_\Sigma)_{ab}(y_u^\dagger y_u)_{cd}\mathsf{L}$ $-\frac{g_1^2}{12}(\epsilon_\Sigma^\dagger\epsilon_\Sigma)_{ab}\delta_{cd}\mathsf{L}$	$\frac{2g_1^2}{9}(\epsilon_\delta^\dagger\epsilon_\delta)_{ab}\delta_{cd}\mathsf{L}$ $-\frac{g_1^2}{9}(\epsilon_2^\dagger\epsilon_2)_{ab}\delta_{cd}\mathsf{L}$	$\frac{1}{4}(\epsilon_L^\dagger)_{ac}(\epsilon_L)_{db}$
$c^{lq(3)}_{abcd}$	$-\frac{1}{4}(\epsilon_N^\dagger\epsilon_N)_{ab}(y_u^\dagger y_u)_{cd}\mathsf{L}$ $+\frac{g_2^2}{12}(\epsilon_N^\dagger\epsilon_N)_{ab}\delta_{cd}\mathsf{L}$	$\frac{1}{4}(\epsilon_\Sigma^\dagger\epsilon_\Sigma)_{ab}(y_u^\dagger y_u)_{cd}\mathsf{L}$ $-\frac{g_2^2}{12}(\epsilon_\Sigma^\dagger\epsilon_\Sigma)_{ab}\delta_{cd}\mathsf{L}$	$\frac{2g_2^2}{3}(\epsilon_\delta^\dagger\epsilon_\delta)_{ab}\delta_{cd}\mathsf{L}$	$-\frac{1}{4}(\epsilon_L^\dagger)_{ac}(\epsilon_L)_{db}$
c^{qe}_{abcd}	—	—	$-\frac{g_1^2}{9}\delta_{ab}(\epsilon_2\epsilon_2^\dagger)_{cd}\mathsf{L}$	$\frac{1}{2}(\epsilon_L^* y_e^T)_{ac}(y_u^T\epsilon_R)_{bd}\mathsf{L}$ $+\frac{1}{2}(y_u^\dagger\epsilon_R^*)_{ac}(\epsilon_L y_e^\dagger)_{bd}\mathsf{L}$ $+\frac{1}{2}(y_u^\dagger\epsilon_R^*)_{ac}(y_u^T\epsilon_R)_{wd}\mathsf{L}$ $-\frac{g_1^2}{3}(\epsilon_L^*\epsilon_L^T)_{ab}\delta_{cd}\mathsf{L}$ $-\frac{2g_1^2}{9}\delta_{ab}(\epsilon_R^\dagger\epsilon_R)_{cd}\mathsf{L}$
c^{lu}_{abcd}	$\frac{1}{2}(\epsilon_N^\dagger\epsilon_N)_{ab}(y_u y_u^\dagger)_{cd}\mathsf{L}$ $-\frac{g_1^2}{9}(\epsilon_N^\dagger\epsilon_N)_{ab}\delta_{cd}\mathsf{L}$	$\frac{3}{2}(\epsilon_\Sigma^\dagger\epsilon_\Sigma)_{ab}(y_u y_u^\dagger)_{cd}\mathsf{L}$ $-\frac{g_1^2}{3}(\epsilon_\Sigma^\dagger\epsilon_\Sigma)_{ab}\delta_{cd}\mathsf{L}$	$\frac{8g_1^2}{9}(\epsilon_\delta^\dagger\epsilon_\delta)_{ab}\delta_{cd}\mathsf{L}$ $-\frac{4g_1^2}{9}(\epsilon_2^\dagger\epsilon_2)_{ab}\delta_{cd}\mathsf{L}$	$\frac{1}{2}(\epsilon_L^\dagger y_u^T)_{ac}(\epsilon_R y_e)_{db}\mathsf{L}$ $+\frac{1}{2}(\epsilon_L^\dagger y_u^T)_{ac}(y_u^*\epsilon_L)_{db}\mathsf{L}$ $+\frac{1}{2}(y_e^\dagger\epsilon_R^\dagger)_{ac}(y_u^*\epsilon_L)_{db}\mathsf{L}$ $-\frac{2g_1^2}{9}(\epsilon_L^\dagger\epsilon_L)_{ab}\delta_{cd}\mathsf{L}$ $-\frac{4g_1^2}{9}(\epsilon_D^\dagger\epsilon_D)_{ab}\delta_{cd}\mathsf{L}$ $-\frac{g_1^2}{3}\delta_{ab}(\epsilon_R^*\epsilon_R^T)_{cd}\mathsf{L}$
c^{ld}_{abcd}	$\frac{g_1^2}{18}(\epsilon_N^\dagger\epsilon_N)_{ab}\delta_{cd}\mathsf{L}$	$\frac{g_1^2}{6}(\epsilon_\Sigma^\dagger\epsilon_\Sigma)_{ab}\delta_{cd}\mathsf{L}$	$-\frac{4g_1^2}{9}(\epsilon_\delta^\dagger\epsilon_\delta)_{ab}\delta_{cd}\mathsf{L}$ $+\frac{2g_1^2}{9}(\epsilon_2^\dagger\epsilon_2)_{ab}\delta_{cd}\mathsf{L}$	$-\frac{1}{2}(\epsilon_D^\dagger)_{ad}(\epsilon_D)_{cb}$

Wilson Coefficients 4

WCs	Seesaw I	Seesaw III	Zee	Leptoquarks
c^{eu}_{abcd}	—	—	$-\frac{4g_1^2}{9}(\epsilon_2\epsilon_2^\dagger)_{ab}\delta_{cd}\text{L}$	$\frac{1}{2}(\epsilon_R^\dagger)_{ac}(\epsilon_R)_{db}$
c^{ed}_{abcd}	—	—	$\frac{2g_1^2}{9}(\epsilon_2\epsilon_2^\dagger)_{ab}\delta_{cd}\text{L}$	$\frac{2g_1^2}{3}\delta_{ab}(\epsilon_D\epsilon_D^\dagger)_{cd}\text{L}$ $+\frac{4g_1^2}{9}(\epsilon_R^\dagger\epsilon_R)_{ab}\delta_{cd}\text{L}$
$c^{lequ(1)}_{abcd}$	—	—	$2\text{tr}[y_e^\dagger\epsilon_2](\epsilon_2^\dagger)_{ab}(y_u^\dagger)_{cd}\text{L}$	$-\frac{1}{2}(\epsilon_L^\dagger)_{ac}(\epsilon_R)_{db}$
$c^{lequ(3)}_{abcd}$	—	—	—	$\frac{1}{8}(\epsilon_L^\dagger)_{ac}(\epsilon_R)_{db}$
c^{ledq}_{abcd}	—	—	$2\text{tr}[y_e^\dagger\epsilon_2](\epsilon_2^\dagger)_{ab}(y_d)_{cd}\text{L}$	$-3(\epsilon_L^\dagger y_u^T\epsilon_R)_{ab}(y_d)_{cd}\text{L}$ $-(\epsilon_D^\dagger y_d)_{ad}(\epsilon_D y_e^\dagger)_{cb}\text{L}$ $+(\epsilon_L^\dagger y_d^T)_{ac}(\epsilon_L y_e^\dagger)_{db}\text{L}$ $+(\epsilon_L^\dagger y_d^T)_{ac}(y_u^T\epsilon_R)_{db}\text{L}$

One example: c^G

- Important effect is NP interference with muon decay, since this affects measured G_F which is used as an EW input parameter

  Fernandez-Martinez+Hernandez-Garcia+Lopez-Pavon '16, Jenkins+Manohar+Stoffer '17,...

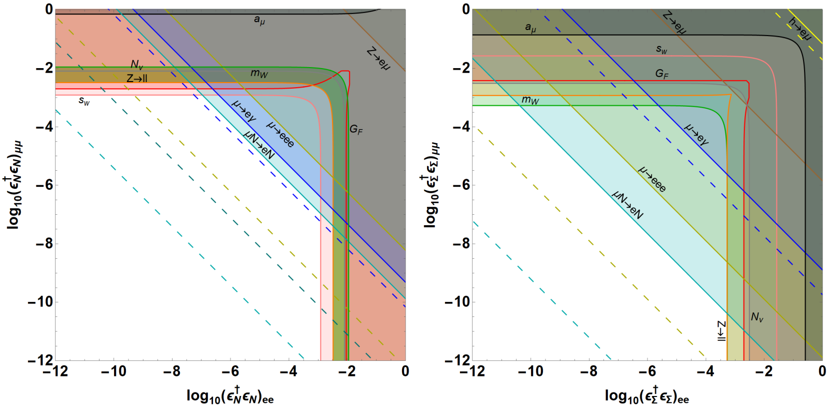
- In EFT at leading-order, the Fermi constant is

$$G_F \simeq \frac{1}{\sqrt{2}v^2}(1-c^G)\,,\ c^G \equiv c^{ll}_{e\mu\mu e}+c^{ll}_{\mu ee\mu}-2c^{Hl(3)}_{ee}-2c^{Hl(3)}_{\mu\mu} \quad (10)$$

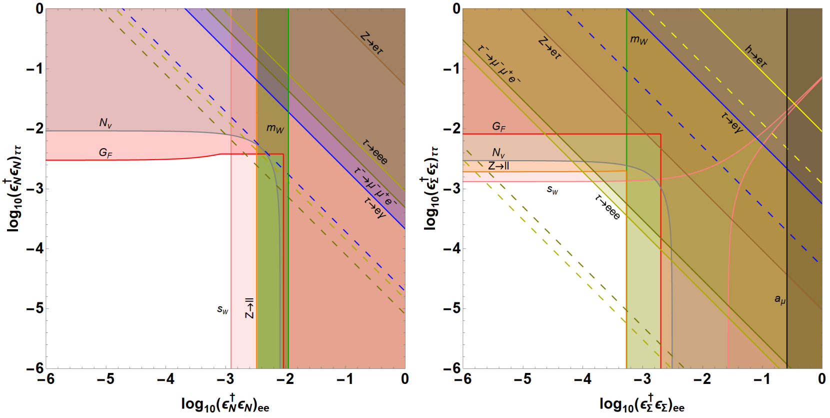
- This (and other effects) enters into EW observables:

$$m_W^2 = \frac{m_Z^2}{2}\left[1+\left(1-\frac{2\sqrt{2}\pi\alpha}{G_F m_Z^2}\right)^{1/2}\right]\,,\quad \sin^2 2\theta_w = \frac{2\sqrt{2}\pi\alpha}{G_F m_Z^2}\,. \quad (11)$$

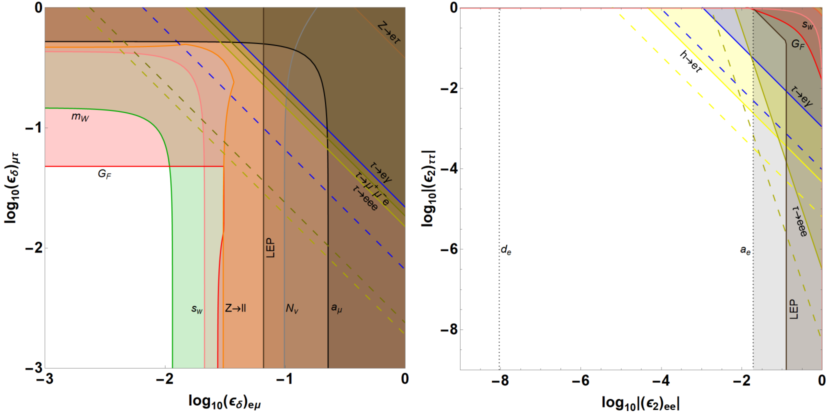
Type-I and type-III seesaw, $e - \mu$ sector



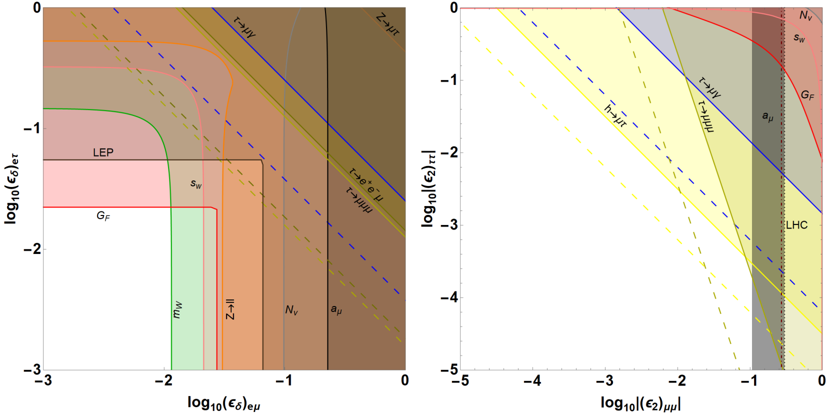
Type-I and type-III seesaw, $e - \tau$ sector



Zee model, $e - \tau$ sector



Zee model, $\mu - \tau$ sector



LQ model, $e - \tau$ sector