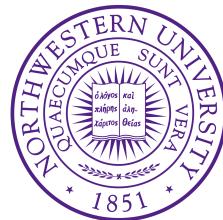


Marrying charged-lepton flavour violation to neutrino masses

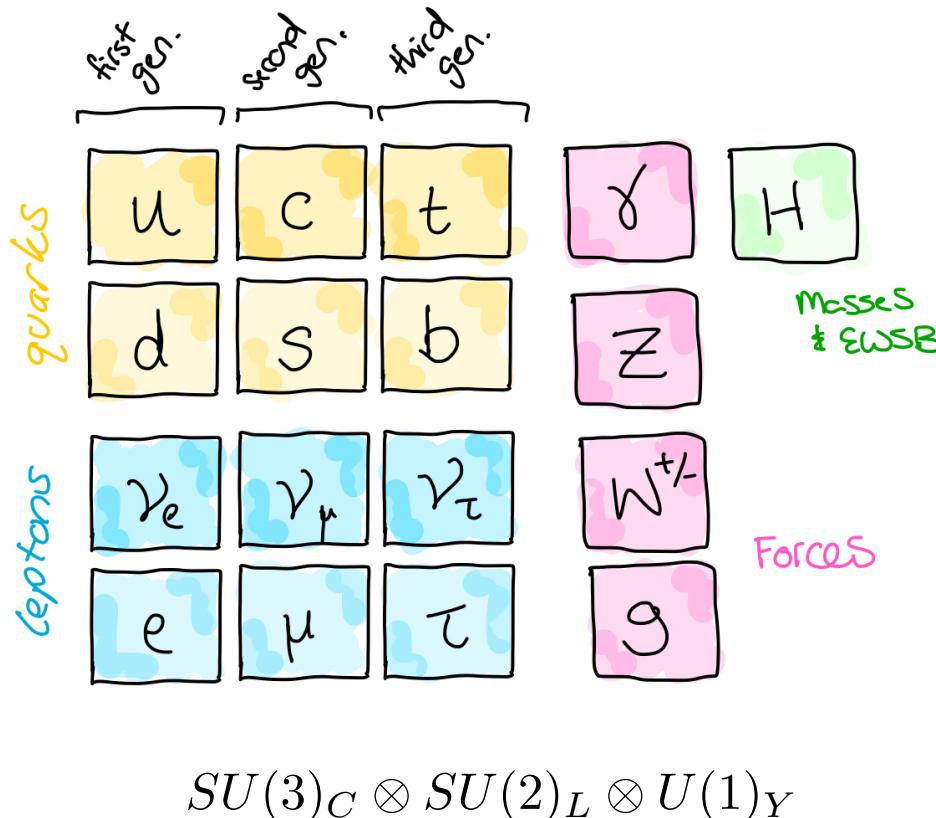
Innes Bigaran



Overview

1. Standard Model leptons
2. Neutrino masses are new physics
3. (Majorana) neutrino mass generation
4. Complementarity of cLFV and neutrino masses

Standard Model leptons



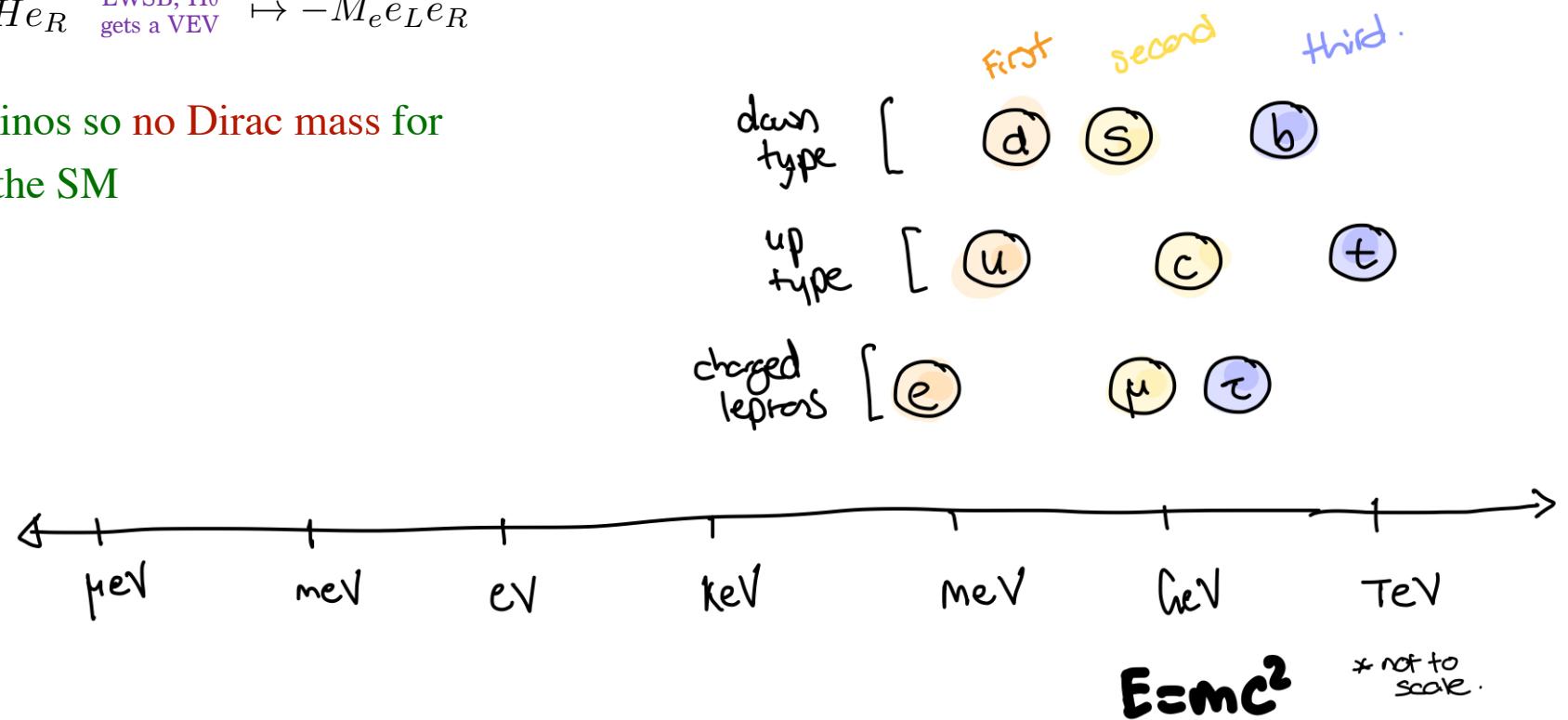
- If all the SM leptons were massless, the accidental global symmetry $U(3)_{E_L} \otimes U(3)_{E_R}$
- Lepton masses break this symmetry into the subgroup $\mathcal{G}_L = U(1)_e \otimes U(1)_\mu \otimes U(1)_\tau$
- Corresponds to a perturbative conservation of lepton flavour. Total lepton number (L) (sum of flavoured QN) also conserved.

ν mass = ν physics

- One (Dirac) lepton mass term in SM:

$$\mathcal{L} \supset -y_e \overline{L}_L H e_R \xrightarrow[\text{EWSB, } H_0 \text{ gets a VEV}]{} -M_e \overline{e}_L e_R$$

- No RH neutrinos so no Dirac mass for neutrinos in the SM



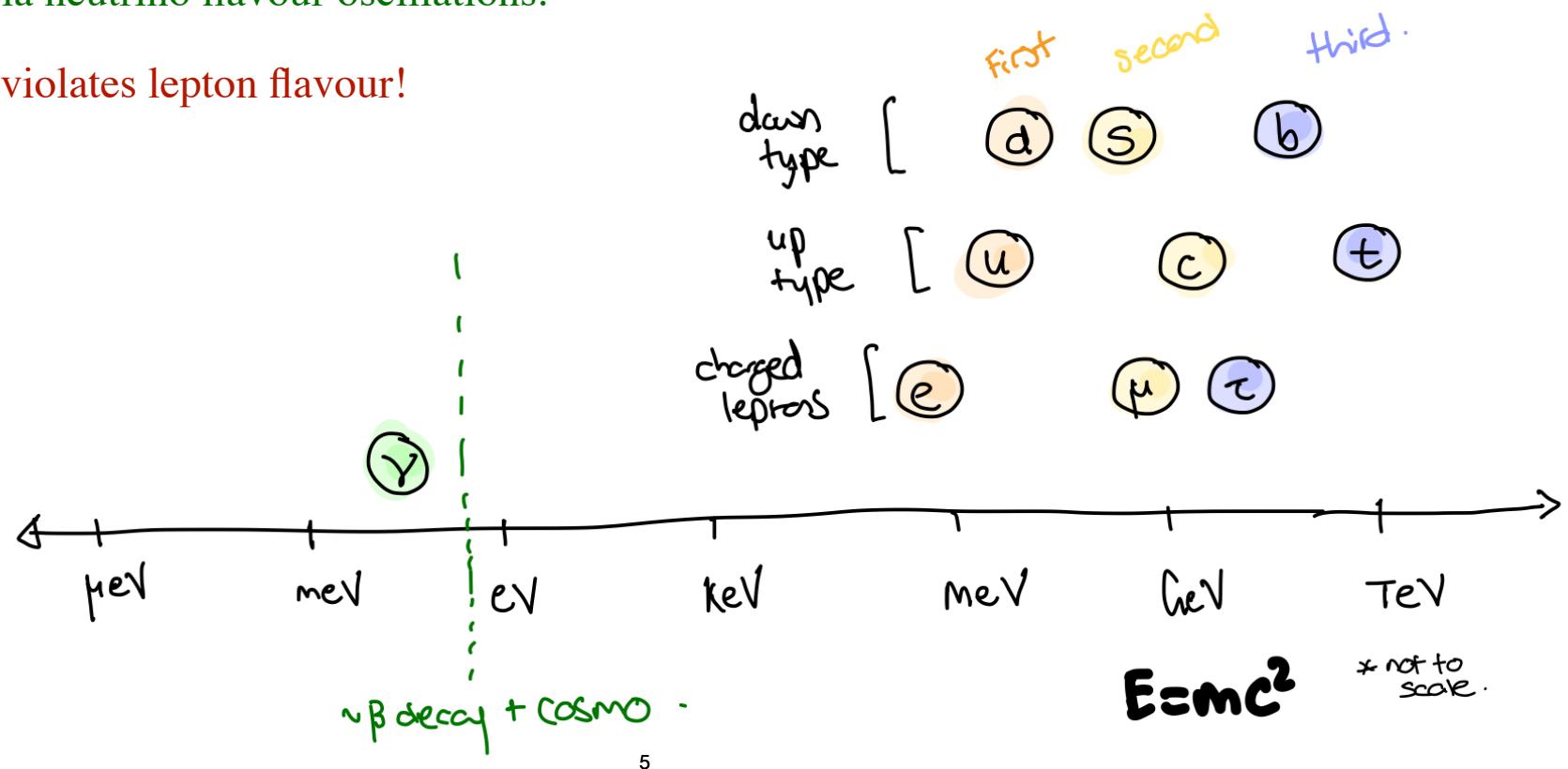
- Small (but nonzero) neutrino masses:

▪ need new physics!

- We measure it via neutrino flavour oscillations:

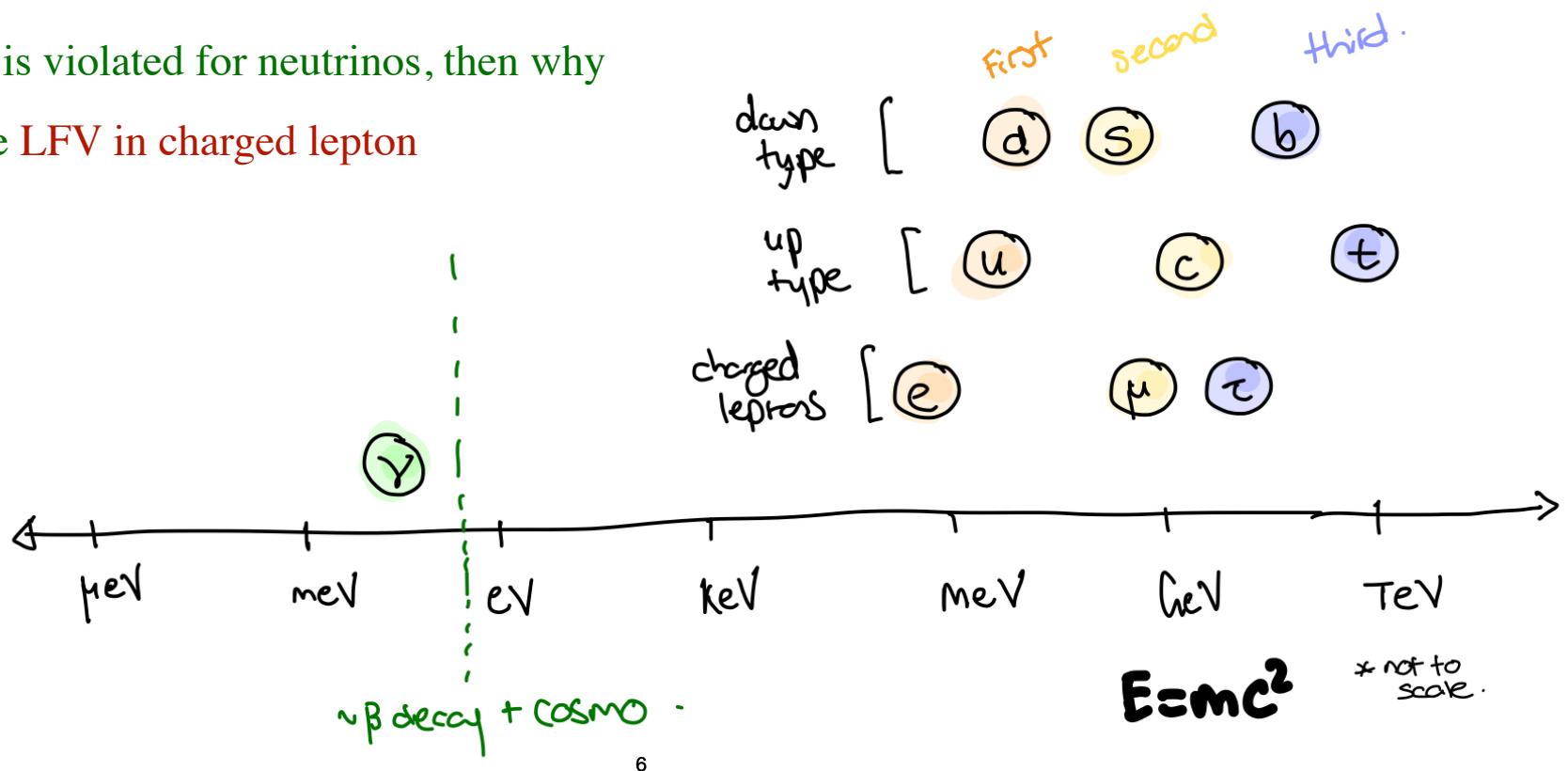
▪ new physics violates lepton flavour!

ν mass = ν physics

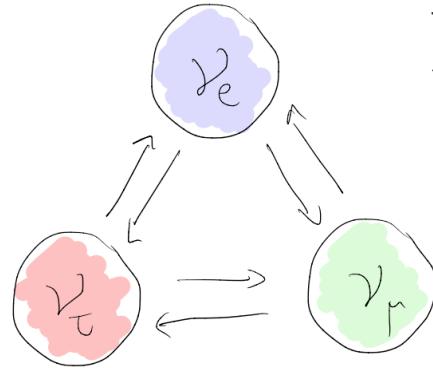


ν mass = ν physics

- Relative size of neutrino masses when contrasted with the rest of the SM fermions: new mass generation mechanism?
- If lepton flavour is violated for neutrinos, then why don't we also see LFV in charged lepton interactions?



Neutrino mass generation beyond the SM



Majorana ν mass

$$\mathcal{L} \supset -m_{\text{maj}} \bar{\nu}_L^c \nu_L$$

Dirac ν mass

$$\mathcal{L} \supset -m_{\text{Dirac}} \bar{\nu}_R \nu_L (+ m'_{\text{maj}} \bar{\nu}_R \nu_R)$$

- Neutrinos could have either **Majorana** or **Dirac** masses
- Dirac masses: introduce new field content (RH neutrino) and possibly also mechanism for forbidding lepton-number violating Majorana mass term for RH neutrino
- LH Majorana masses: introduce new source(s) of violation of lepton number
- Either way, this is **physics beyond the (vanilla) Standard Model**
- For the remainder of this talk, focus on **Majorana** masses

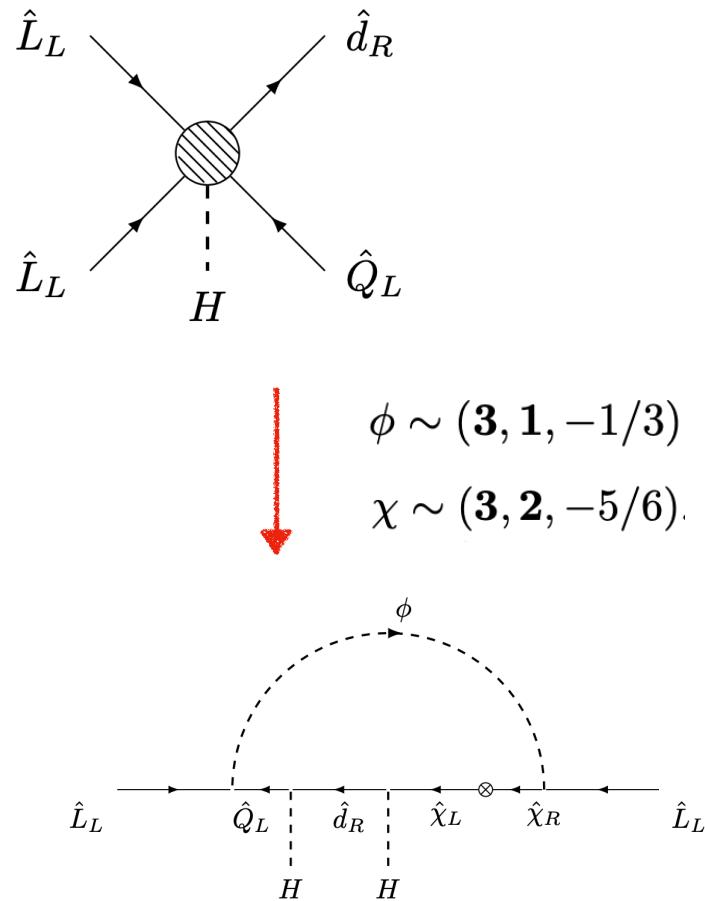
Neutrino mass generation beyond the SM

- Extending beyond the SM, write down effective interactions higher mass dimension (non-renormalisable)
- These effective operators can be “opened-up” by introducing new field content, and writing down a complete model that generates that interaction

e.g. the Weinberg operator (D=5)

$$\mathcal{L}_{\text{effective}} \supset \frac{\lambda}{\Lambda} L_L L_L H H \quad \xrightarrow{\text{red arrow}} \quad m_\nu \sim \lambda \frac{v^2}{\Lambda}$$

λ is a dimensionless coupling
 Λ is a new “mass scale”
 v is the Higgs vev



[Cai et al 1704.05849](#) & [IB, Gargalionis, Volkas 1906.01870](#)

Majorana neutrino masses

- One can systematically study $\Delta L = 2$ effective operators from the SMEFT
- Opening up (a.k.a. UV completing) these operators motivates particular SM extensions
- Generalised Weinberg operators, e.g.

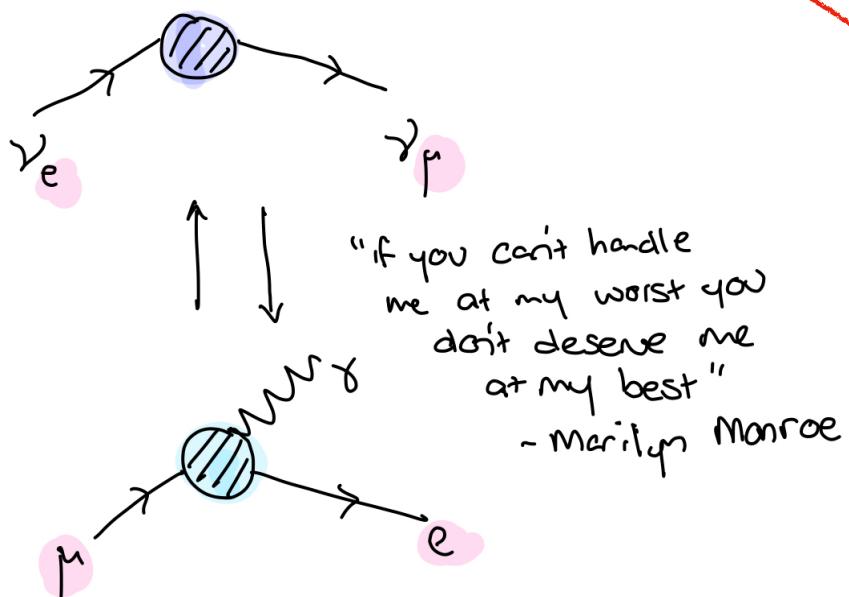
$$\frac{\lambda}{\Lambda^{1+2n}} LLHH(H^\dagger H)^n$$
See, e.g. Hirsch, Cepedello et al (many papers)
- non-Weinberg operators,
e.g.
$$\frac{\lambda}{\Lambda^6} L_L Q_L L_L \bar{d}_R H$$
See, e.g. Babu and Leung 0106054, de Gouvea and Jenkins [0708.1344](#)
- Loop level masses naturally suppressed — **radiative neutrino masses** explain relative size of neutrino masses?

- Generalised Weinberg operators, e.g.

$$\frac{\lambda}{\Lambda^{1+2n}} LLHH(H^\dagger H)^n$$

- non-Weinberg operators, e.g.

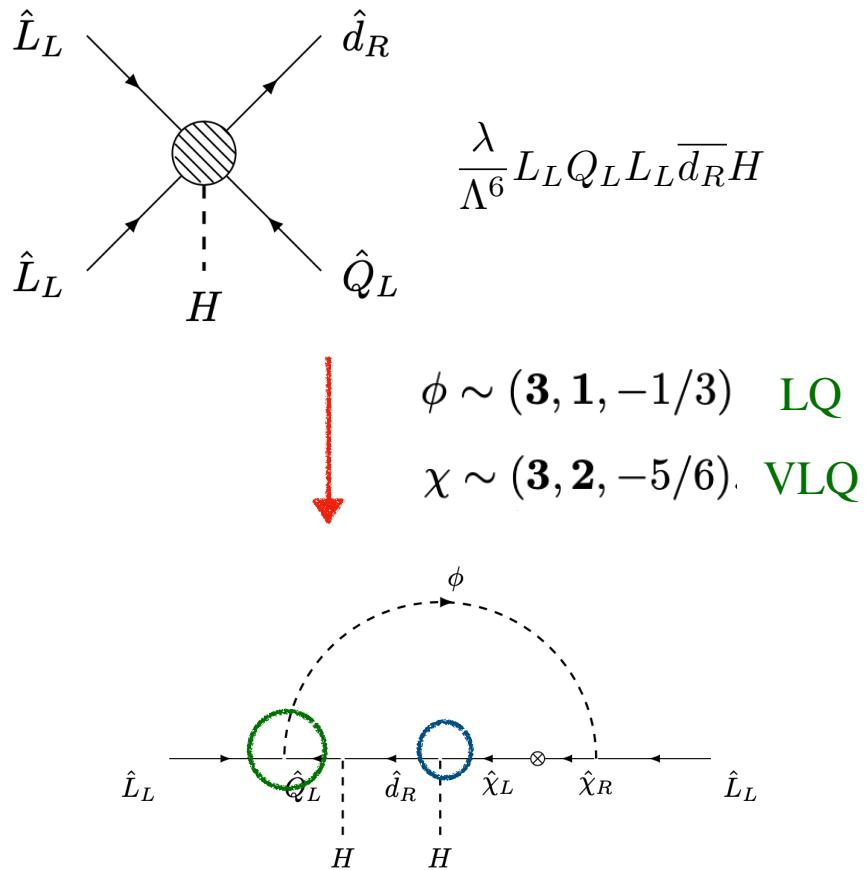
$$\frac{\lambda}{\Lambda^6} L_L Q_L L_L \bar{d}_R H$$



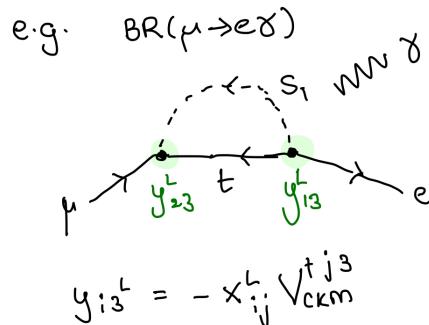
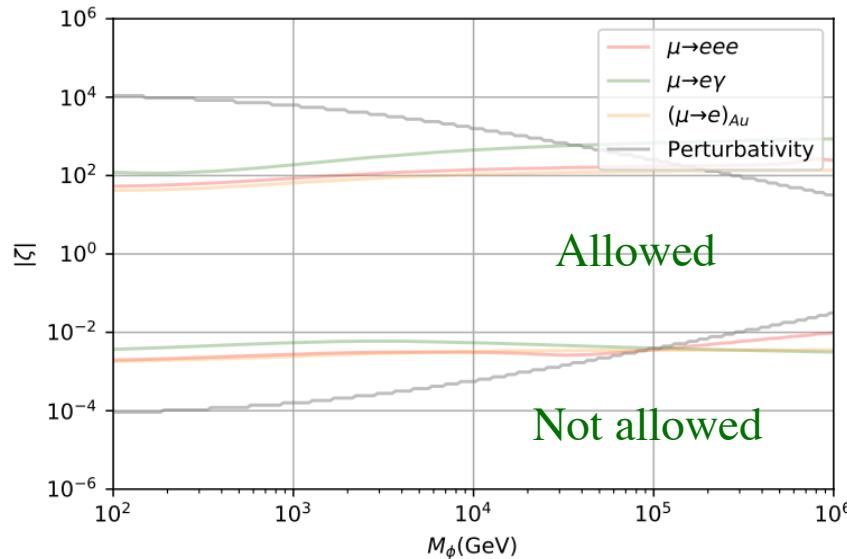
Radiative Majorana neutrino masses

- When we look at these effective operators, note that we are talking about the SMEFT
 - Left-handed SM lepton doublet includes both the neutrino and charged lepton
- $$L_L \sim \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \sim (1, 2, -1/2)$$
- Models that give Majorana neutrino flavour mixing will result in charged lepton flavour violation (cLFV).
 - cLFV not necessarily generated by the same effective operator in a UV-completion

Case study: one-loop radiative neutrino mass



- Constraints study in [1906.01870](#): limit Vector-like quark mixing to with the bottom quark for neutrino mass generation. Small mixing, large VLQ mass.
- TeV scale LQ mass
- Neutrino mass generation necessarily requires all neutrino flavours coupling to the bottom quark via LQ



[Cai et al 1704.05849](#) & [IB, Gargalionis, Volkas 1906.01870](#)

Case study: mu to e transitions

- Expression for neutrino mass matrix:

$$(m_\nu)_{ij} = \frac{3m_{\chi_1}m_b}{8\pi^2} \hat{m}_{\text{mix},3} \frac{\ln(\frac{m_{\chi_1}}{m_\phi})}{m_{\chi_1}^2 - m_\phi^2} \times (x_{i3}w_j + w_i^* x_{j3}^*)$$

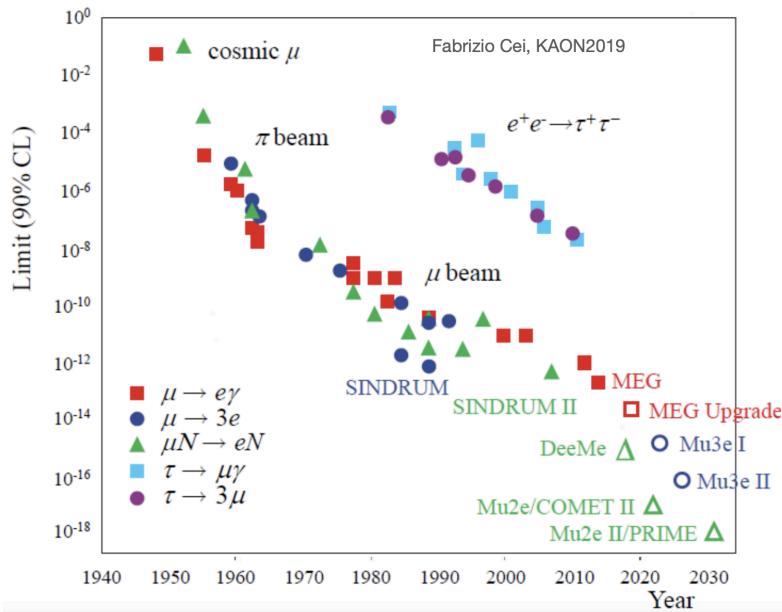
Via Casas-Ibarra like parametrisation ([hep-ph/0103065](#))

$$x_{i3}^L = \frac{\zeta}{\sqrt{2m_0}} (\sqrt{m_2}U_{i2}^* + i\sqrt{m_k}U_{ik}^*)$$

Similar expression for "w", the VLQ coupling

- After EWSB, CKM mixing generates nonzero couplings between all generations of charged leptons and up-type quarks

$$\begin{aligned} \mathcal{L}_{\text{int}}^{S_1} &= \left(\overline{L}_L^c \lambda_{LQ} Q_L + \overline{e}_R^c \lambda_{eu} u_R \right) S_1^\dagger + h.c., \\ &\supset (x^L \overline{\nu}_L^C d_L + y^L \overline{e}_L^C u_L) S_1^\dagger \quad \text{where} \quad x^L = -y^L V_{CKM} \end{aligned}$$



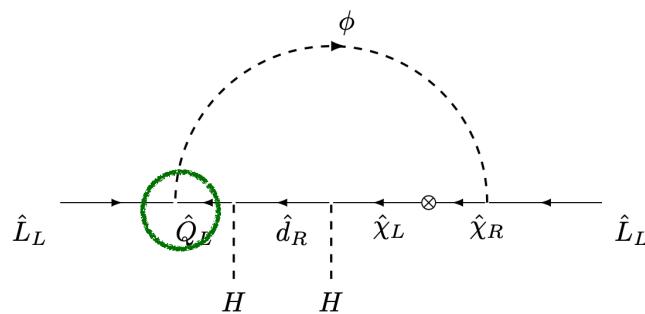
- For example:

Process	Present	Projected
$\text{BR}(\mu \rightarrow 3e)$	1.0×10^{-12} (SINDRUM)	$\sim 10^{-16}$ (Mu3e)
$\text{BR}(\mu \rightarrow e\gamma)$	4.2×10^{-13} (MEG)	6×10^{-14} (MEG-II)
$\text{BR}(\tau \rightarrow 3\mu)$	2.1×10^{-8} (Belle)	3.6×10^{-10} (Belle-II)
$\text{BR}(\tau \rightarrow \mu\gamma)$	4.2×10^{-8} (Belle)	6.9×10^{-9} (Belle-II)

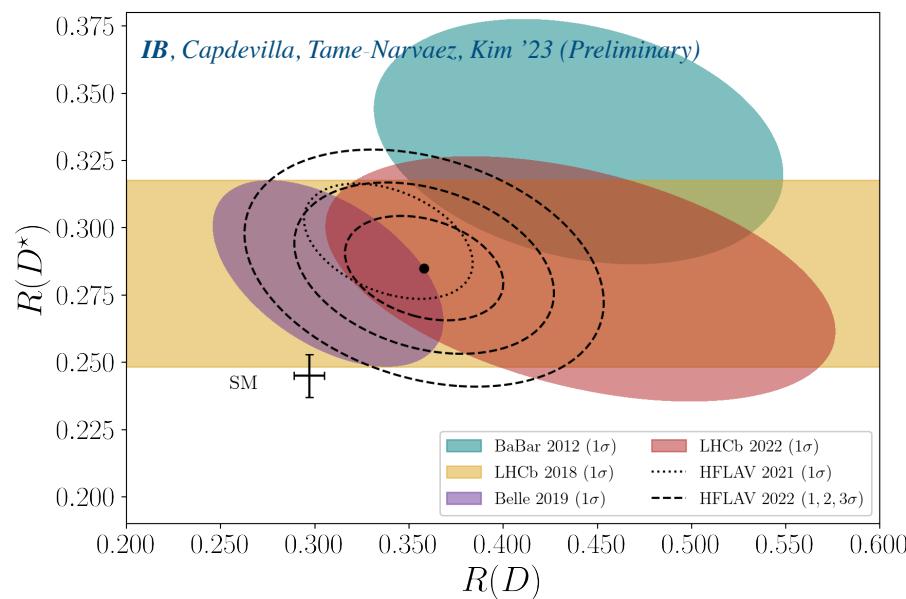
Take-away message no. 1:

cLFV processes provide some of the strongest constraints on (Majorana) neutrino mass models

These processes are also set to be measured much more precisely in the near future!



[Cai et al 1704.05849](#) & [IB, Gargalionis, Volkas 1906.01870](#)



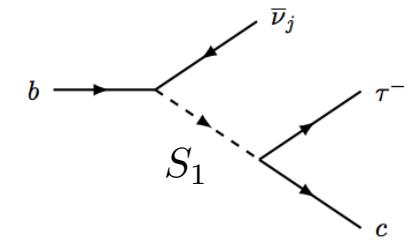
For a discussion of how S1 can be embedded a flavour symmetry model and addressing b to c tau nu and g-2 of the muon, see [IB, Hagedorn, Felkl, Schmidt 2207.06197](#)

Case study: b to c tau nu

$$\mathcal{L}_{\text{int}}^{S_1} = (\overline{L}_L^c \lambda_{LQ} Q_L + \overline{e}_R^c \lambda_{eu} u_R) S_1^\dagger + h.c.,$$

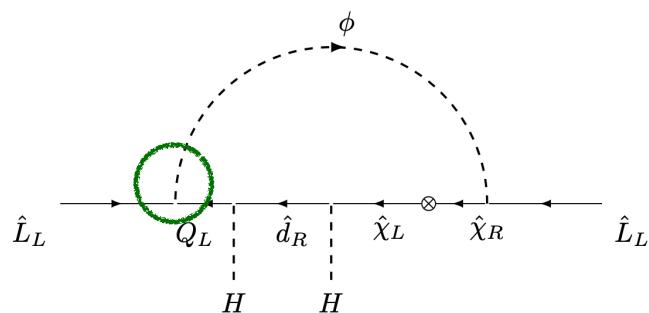
$$\supset (x^L \overline{\nu}_L^C d_L + y^L \overline{e}_L^C u_L) S_1^\dagger$$

$$R_{D^{(*)}} = \frac{Br(B \rightarrow D^{(*)}\tau\nu_\tau)}{Br(B \rightarrow D^{(*)}\ell\nu_\ell)}$$

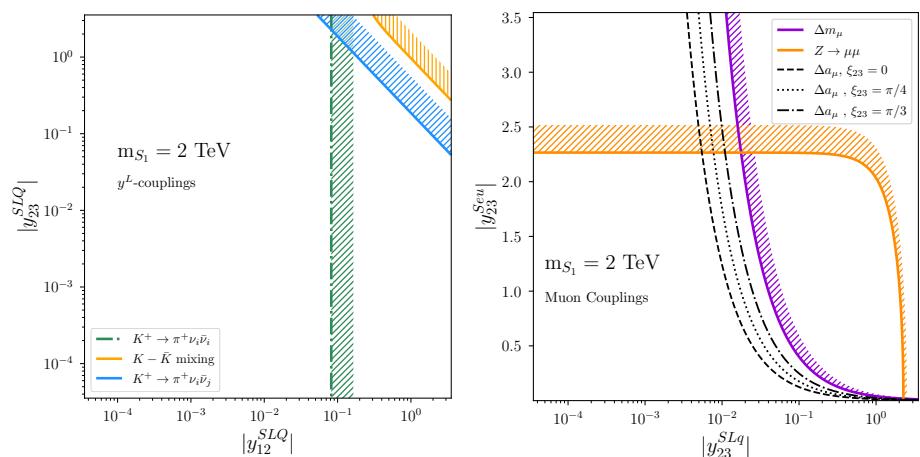


- The same LFV interactions that generate neutrino mass can generate hints of lepton flavour universality
- Flavour-specific new physics couplings can be exploited to simultaneously anomalies and neutrino masses

[IB, Gargalionis, Volkas 1906.01870](#)



Cai et al [1704.05849](#) & IB, Gargalionis, Volkas [1906.01870](#)

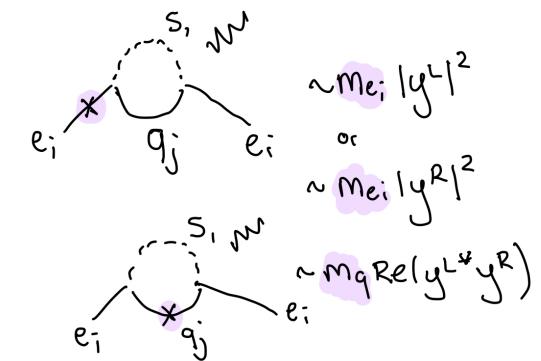


IB, Volkas [2002.12544](#) & [2110.03707](#)

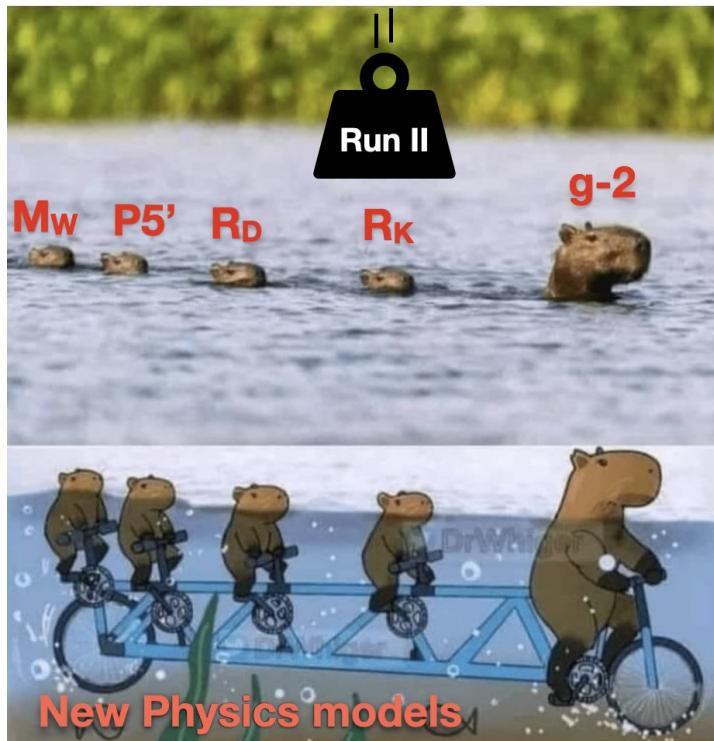
Case study: Muon and electron g-2

$$\begin{aligned} \mathcal{L}_{\text{int}}^{S_1} &= (\overline{L_L^c} \lambda_{LQ} Q_L + \overline{e_R^c} \lambda_{eu} u_R) S_1^\dagger + h.c., \\ &\supset (x^L \overline{\nu_L^C} d_L + y^L \overline{e_L^C} u_L) S_1^\dagger \end{aligned}$$

Deviation from SM prediction	Significance
$\Delta a_\mu = (2.86 \pm 0.76) \times 10^{-9}$	4.2σ
$\Delta a_e^{\text{Cs}} = -(0.88 \pm 0.36) \times 10^{-12}$ Parker et al 1812.04130	2.5σ
$\Delta a_e^{\text{Rb}} = (4.8 \pm 3.0) \times 10^{-13}$ Morel et al 2020, INSPIRE: 1837309	1.6σ



$$\Delta a_\ell^{S_1} \sim -\frac{m_\ell m_q}{4\pi^2 m_{S_1}^2} \left[\frac{7}{4} - 2 \log \left(\frac{m_{S_1}}{m_q} \right) \right] \text{Re}(y_{\ell q}^{L*} y_{\ell q}^R),$$

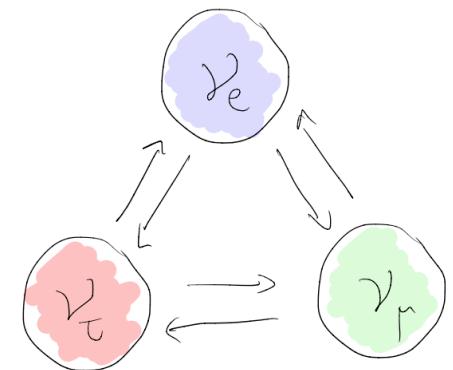


Take-away message no. 2:

We have many models now in the literature addressing violation of lepton-flavour universality (anomalies) with lepton-flavour violating new physics. We need LFV in BSM physics.

Conclusions

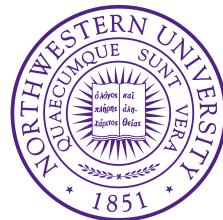
- Neutrino masses are evidence for new physics
- The SM preserves lepton flavour, so flavour oscillations mean this new physics violates lepton flavour
- Majorana neutrino mass \rightarrow LH lepton doublets — new physics necessarily leads to new (LFV) interactions with charged leptons
- Charged lepton searches are becoming increasingly precise (exciting!)
- Hints of LFU can be resolved with LFV new physics - learn from these models
- Keep looking for (more) new physics with leptons because it should be there !



Thank you for listening

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