New Physics models giving rise to LFV

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Outline

- LFV in minimally extended SM
- What to expect from observation of LFV
- LFV in BSM models and its connections to other phenomena

(LFV= lepton flavor violation)
(cLFV= charged lepton flavor violation)

Standard Model (SM)

Global Symmetries in the SM

$$\mathcal{G}_{\rm SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$
$$Q_{L_i} \sim (3,2)_{+1/6}, \quad u_{R_i} \sim (3,1)_{+2/3}, \quad d_{R_i} \sim (3,1)_{-1/3}$$
$$L_{L_i} \sim (1,2)_{-1/2}, \quad \ell_{R_i} \sim (1,1)_{-1}$$

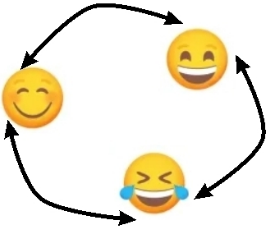
$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm kin} + \mathcal{L}_{\rm Yuk} + \mathcal{L}_{\rm Hig}$$
$$\mathcal{L}_{\rm Yuk} \to 0: \quad \mathcal{G}_{\rm flavor} = U(3)_q^3 \times U(3)_{\rm lep}^2$$

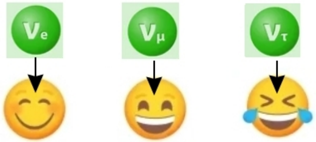
$$m_{\rm fermions}^{\rm charged} \neq 0: \quad \mathcal{G}_{\rm flavor}^{\rm (global)} \to U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$$

- individual lepton-flavor numbers are conserved by the SM Lagrangian

$B+L$ broken at quantum level; 't Hooft 1976

Discovery of Neutrino Oscillations: $m_\nu \neq 0$





$$Y_\ell \not\propto 1 : U(3)_L \times U(3)_\ell \to U(1)_e \times U(1)_\mu \times U(1)_\tau$$

$$Y_u \not\propto 1 : U(3)_Q \times U(3)_u \to U(1)_u \times U(1)_c \times U(1)_t$$

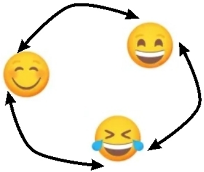
$$Y_d \not\propto 1 : U(3)_Q \times U(3)_d \to U(1)_d \times U(1)_s \times U(1)_b$$

$$[Y_u, Y_d] \neq 0 : U(1)_q^6 \to U(1)_B \qquad (V_{\mathrm{CKM}})$$

$$[Y_\ell, Y_\nu] \neq 0 : U(1)_\ell^3 \to U(1)_L \qquad (V_{\mathrm{PMNS}})$$

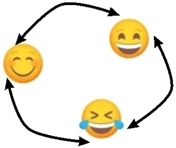
Neutrino oscillations: Consequences

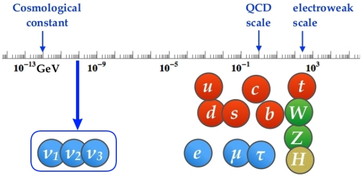
- Individual lepton flavor no longer conserved (Transition between flavors)
- Direct consequence → cLFV
- Total L could still be conserved

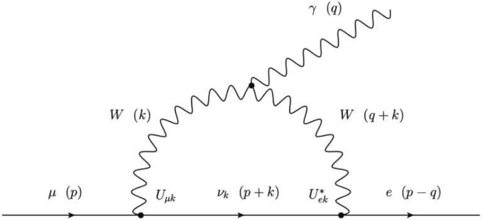


$$m^{\nu}_{\text{Dirac}} \neq 0: \quad \mathcal{G}^{(\text{global})}_{\text{flavor}} \to U(1)_B \times U(1)_L$$
$$m^{\nu}_{\text{Majorana}} \neq 0: \quad \mathcal{G}^{(\text{global})}_{\text{flavor}} \to U(1)_B$$

cLFV with SM Particles







$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W} \right|^2 < 10^{-54},$$

- $\mathcal{G}^{(\text{global})}_{\text{flavor}} \supset\sim U(1)_e \times U(1)_\mu \times U(1)_\tau$

Neutrino mass & cLFV

- $m_\nu \neq 0 \Rightarrow \nu$FV processes
- νFV $\Rightarrow$ cLFV (at some order in perturbation theory)
- m_ν mechanism depends on new physics (NP) scenario
- cLFV depends completely on NP model
- NP can lead to cLFV $\gg$ the ones in the SM (with $m_\nu \neq 0$)
- observation of cLFV $\Rightarrow$ direct implication of NP
- Standard convention: processes with $\Delta L = 0$
- Two $U(1)$ factors:
  $U(1)_e \times U(1)_\mu \times U(1)_\tau \to U(1)_{\mu-\tau} \times U(1)_{\mu+\tau-2e}$

cLFV Grouping

- Model independent expectations from observations?

Grouping	Process	Current bound	Future sensitivity
$\Delta(L_e - L_\mu) = 2$	$\mu \to e\gamma$	4.2×10^{-13}	4×10^{-14}
	$\mu \to e\bar{e}e$	1.0×10^{-12}	10^{-16}
	$\mu \to e$ conv.	$\mathcal{O}(10^{-12})$	10^{-17}
	$h \to e\bar{\mu}$	3.5×10^{-4}	2×10^{-4}
	$Z \to e\bar{\mu}$	7.5×10^{-7}	–
	had$\to e\bar{\mu}$(had)	4.7×10^{-12}	10^{-12}
$\Delta(L_e - L_\tau) = 2$	$\tau \to e\gamma$	3.3×10^{-8}	10^{-9}
	$\tau \to e\bar{e}e$	2.7×10^{-8}	10^{-9}
	$\tau \to e\bar{\mu}\mu$	2.7×10^{-8}	10^{-9}
	$\tau \to e$ had	$\mathcal{O}(10^{-8})$	10^{-9}
	$h \to e\bar{\tau}$	6.9×10^{-3}	5×10^{-3}
	$Z \to e\bar{\tau}$	9.8×10^{-6}	–
	had$\to e\bar{\tau}$(had)	$\mathcal{O}(10^{-6})$	–
$\Delta(L_\mu - L_\tau) = 2$	$\tau \to \mu\gamma$	4.4×10^{-8}	10^{-9}
	$\tau \to \mu\bar{e}e$	1.8×10^{-8}	10^{-9}
	$\tau \to \mu\bar{\mu}\mu$	2.1×10^{-8}	10^{-9}
	$\tau \to \mu$ had	$\mathcal{O}(10^{-8})$	10^{-9}
	$h \to \mu\bar{\tau}$	1.2×10^{-2}	5×10^{-3}
	$Z \to \mu\bar{\tau}$	1.2×10^{-5}	–
	had$\to \mu\bar{\tau}$(had)	$\mathcal{O}(10^{-6})$	–
$\Delta(L_\mu + L_\tau - 2L_e) = 6$	$\tau \to ee\bar{\mu}$	1.5×10^{-8}	10^{-9}
$\Delta(L_\tau + L_e - 2L_\mu) = 6$	$\tau \to \mu\mu\bar{e}$	1.7×10^{-8}	10^{-9}
$\Delta(L_e + L_\mu - 2L_\tau) = 6$	$\mu e \to \tau\tau$	–	–

Heeck 2016

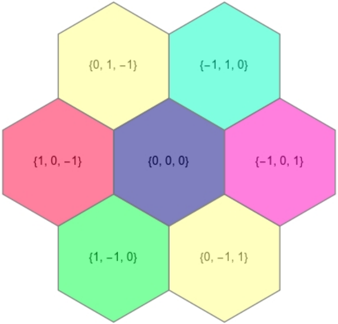
cLFV grouping: $U(1)_e \times U(1)_\mu \times U(1)_\tau$

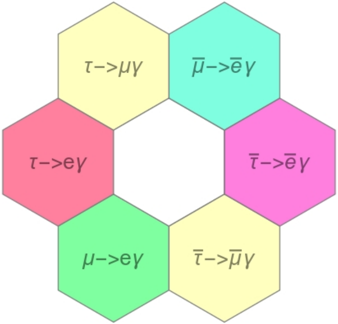
- observation of 1 process (1 linear combination is violated) $\Rightarrow$ all other processes within that group (rates: model dependent)
- it does not violate the other groups
- two unequal vectors [quantum number] need to be observed to know that all cLFV (typically)

Representative	$\Delta(e,\mu,\tau)$	Vector $(e+\mu+\tau=0)$
$\mu \to e\gamma$	(1,-1,0)	minimal
$\tau \to e\gamma$	(1,0,-1)	minimal
$\tau \to \mu\gamma$	(0,1,-1)	minimal
$\tau \to ee\overline{\mu}$	(2,-1,-1)	next to minimal
$\tau \to \mu\mu\overline{e}$	(-1,2,-1)	next to minimal
$\mu e \to \tau\tau$	(-1,-1,2)	next to minimal

cLFV on the Hexagonal Grid

Representative	$\Delta(e, \mu, \tau)$	Vector $(e + \mu + \tau = 0)$
$\mu \to e\gamma$	(1,-1,0)	minimal
$\tau \to e\gamma$	(1,0,-1)	minimal
$\tau \to \mu\gamma$	(0,1,-1)	minimal

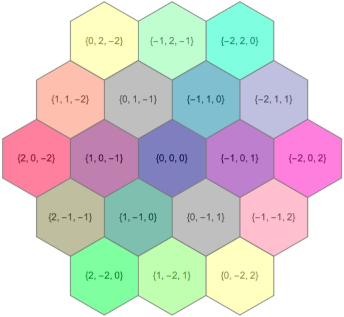


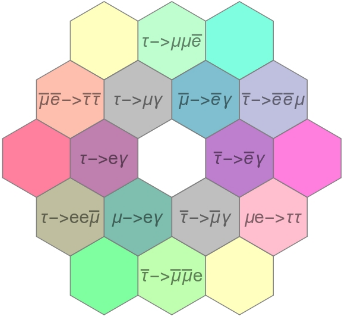


Each Hexagon preserves L number (cube coordinates)

cLFV on the Hexagonal Grid

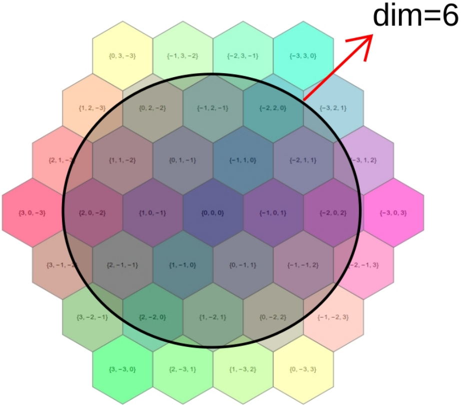
Representative	$\Delta(e, \mu, \tau)$	Vector $(e + \mu + \tau = 0)$
$\tau \to ee\overline{\mu}$	(2,-1,-1)	next to minimal
$\tau \to \mu\mu\overline{e}$	(-1,2,-1)	next to minimal
$\mu e \to \tau\tau$	(-1,-1,2)	next to minimal

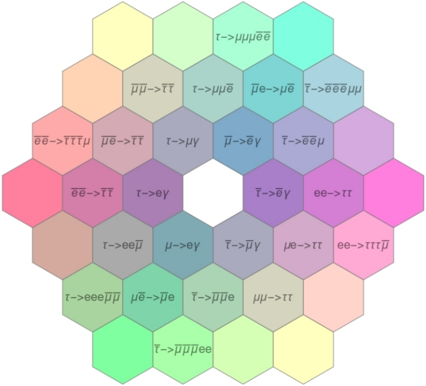




cLFV on the Hexagonal Grid

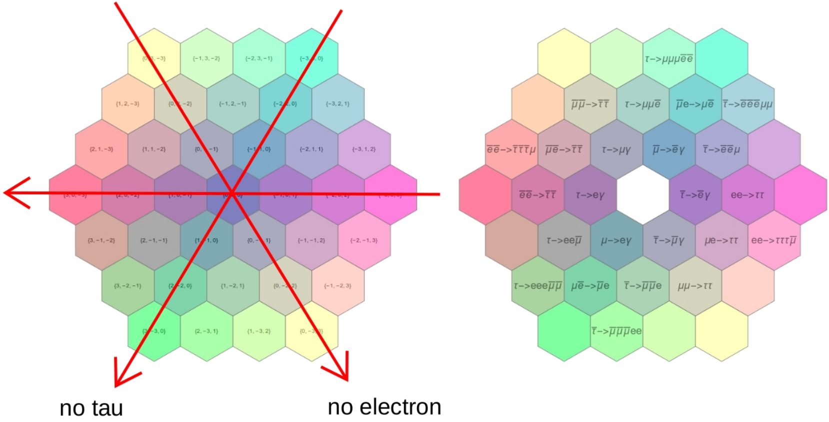
Beyond Next to Minimal Vectors



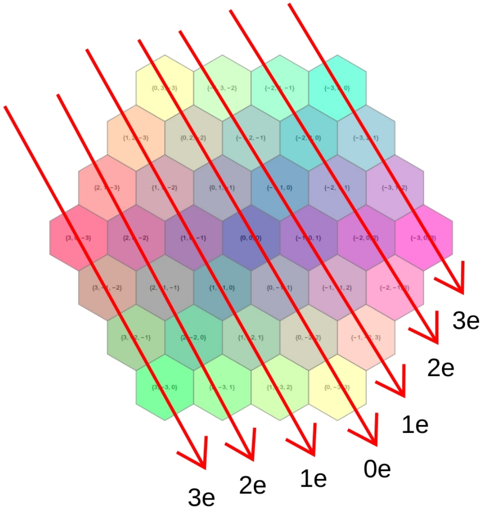


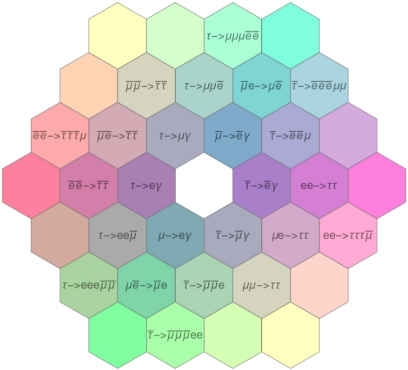
examples: (1,-1,0):$\sqrt{2}$; (2,-1,-1):$\sqrt{6}$; (2,-2,0):$2\sqrt{2}$; (3,-2,-1):$\sqrt{14}$;

cLFV on the Hexagonal Grid



cLFV on the Hexagonal Grid

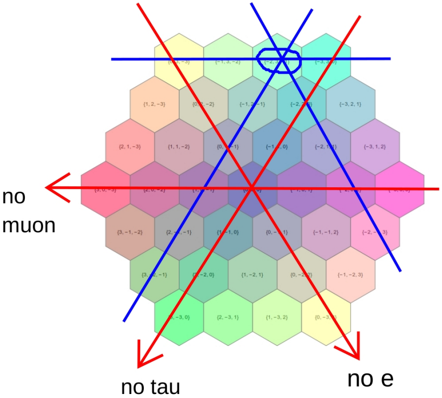


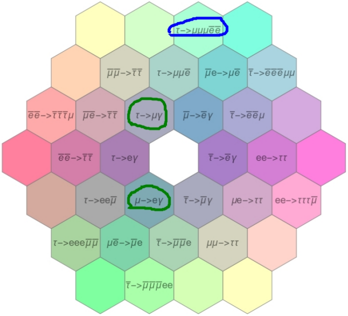


(similar for muon, tau)

cLFV on the Hexagonal Grid

- If $\mu \to e\gamma$ and $\tau \to \mu\gamma$ are observed: all other cLFV must occur
- Any other cLFV$= x(1,-1,0) + y(0,1,-1)$; $\quad x, y \in \mathbb{Z}$
- $x = -2, y = 1 \Rightarrow cLFV = (-2,3,-1) \Rightarrow \tau \to \mu\mu\mu\overline{ee}$





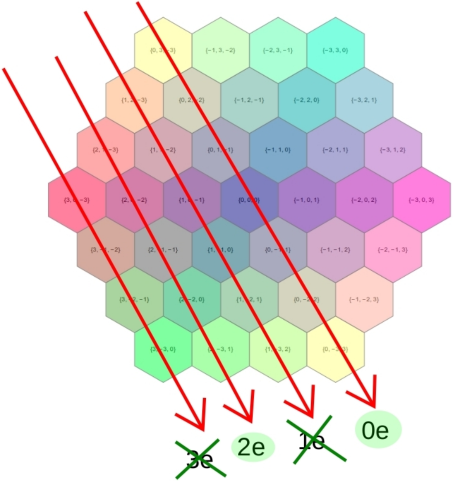
cLFV: Orthogonal

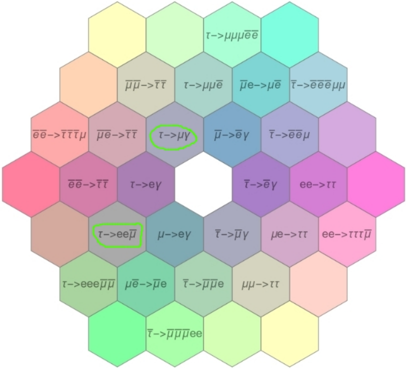
Representative	$\Delta(e,\mu,\tau)$	Vector $(e+\mu+\tau=0)$
$\mu \to e\gamma$	(1,-1,0)	minimal
$\tau \to e\gamma$	(1,0,-1)	minimal
$\tau \to \mu\gamma$	(0,1,-1)	minimal
$\tau \to ee\overline{\mu}$	(2,-1,-1)	next to minimal
$\tau \to \mu\mu\overline{e}$	(-1,2,-1)	next to minimal
$\mu e \to \tau\tau$	(-1,-1,2)	next to minimal

$\vec{a}.\vec{b} = 0$:

$$(\mu \to e\gamma) \perp (\mu e \to \tau\tau)$$
$$(\tau \to e\gamma) \perp (\tau \to \mu\mu\overline{e})$$
$$(\tau \to \mu\gamma) \perp (\tau \to ee\overline{\mu})$$

$$(\tau \to \mu\gamma) \perp (\tau \to ee\overline{\mu})$$

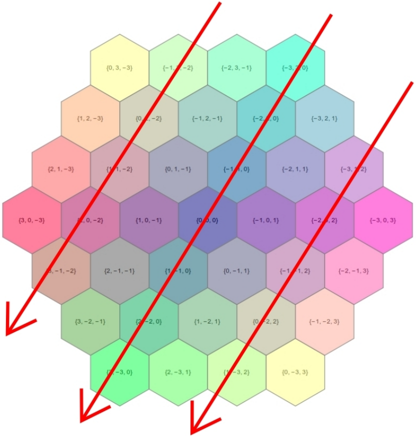




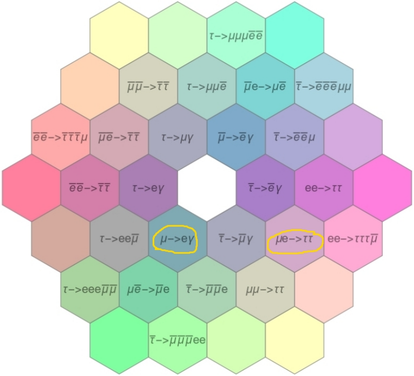
Leftover $\mathcal{Z}_2^e$ (further observation required ...) (no solution with $x, y \in \mathbb{Z}$)

cLFV on the Hexagonal Grid

$$(\mu \to e\gamma) \perp (\mu e \to \tau\tau)$$



even taus



Leftover $\mathcal{Z}_2^\tau$ (further observation required ...)

New Physics Models for Neutrino Mass

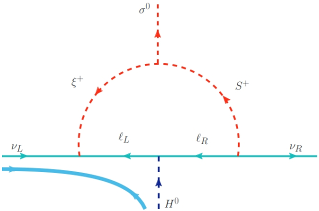
cLFV in BSM: Simplest Dirac Scenario

- NP states: singlets ν_{R_i}, $\quad L = +1$
- $\mathcal{L} \supset Y_\nu \overline{L} H \nu_R$
- $m_\nu \Rightarrow Y_\nu \sim 10^{-12}$
- cLFV highly suppressed

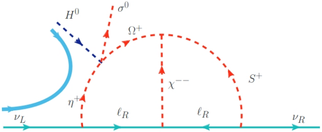
In the presence of other BSM states, one can achieve unsuppressed cLFV with Dirac neutrinos (next page)

Radiative Dirac schemes

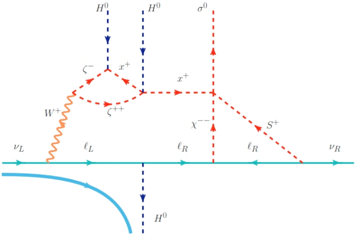
Topology	$SU(2)_L \times U(1)_Y \times U(1)_{B-L}$
T-I-F-i	$\sigma^0(1,0,3)$ $S^+(1,1,5)$ $\xi^+(1,1,2)$



Topology	$SU(2)_L \times U(1)_Y \times U(1)_{B-L}$
T-II-S-i	$\sigma^0(1,0,3)$ $S^+(1,1,5)$ $\chi^{++}(1,2,2)$ $\eta(2,\frac{1}{2},0)$ $\Omega^+(1,1,-3)$



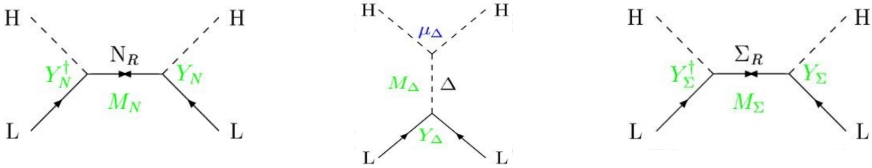
Topology	$SU(2)_L \times U(1)_Y \times U(1)_{B-L}$
T-III-F-i	$\sigma^0(1,0,3)$ $S^+(1,1,5)$ $\chi^{++}(1,2,2)$ $\zeta(2,-\frac{3}{2},0)$ $x^+(1,1,0)$



Saad 2019

Tree Level Majorana Scheme

- $|\Delta L| = 2$
- $\mathcal{L} \supset \frac{c_5}{\Lambda} LLHH \to m_\nu \sim \frac{c_5 v^2}{\Lambda}$ Weinberg 1979

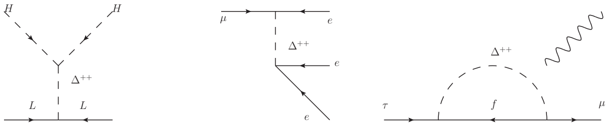


$N_R \sim (1,1,0)^{\rm F}_{+1}, \qquad \Delta \sim (1,3,1)^{\rm S}_{-2}, \qquad \Sigma_R \sim (1,3,0)^{\rm F}_{+1}$

Minkowski 1977; ...

(see talk by Enrique Fernandez Martinez)

cLFV in Type-II Seesaw



- $\Delta \sim (1,3,1)^{\mathrm{S}}_{-2} \supset (\Delta^{++}, \Delta^{+}, \Delta^{0})$
- tree-level $\mu \to eee, \dots$
- loop-level $\mu \to e\gamma, \dots$

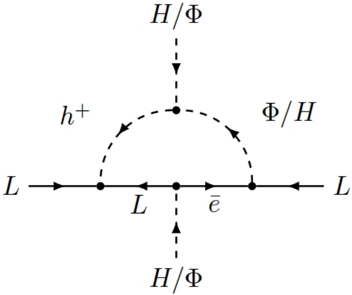
$$\mathcal{L} \supset \mu \widetilde{H}^T \epsilon \Delta \widetilde{H} + \overline{L^c} \epsilon Y_\Delta \Delta L$$

$$\mathcal{L}_5 \to m_\nu \sim Y_\Delta \mu \frac{v^2}{m_\Delta^2} \sim 0.1 eV \to Y_\Delta \sim 10^{-2.5} \Rightarrow \frac{\mu}{m_\Delta(TeV)} \sim 10^{-9}$$

$$\mathcal{L}_6 \supset \frac{Y_\Delta^\dagger Y_\Delta}{2 m_\Delta^2} \left(\overline{L}\gamma_\mu L\right)\left(\overline{L}\gamma^\mu L\right) \to Br(\mu \to eee) \sim \frac{Y_\Delta^4}{m_\Delta^4 G_F^2} \to \mathrm{saturates}_{expt}$$

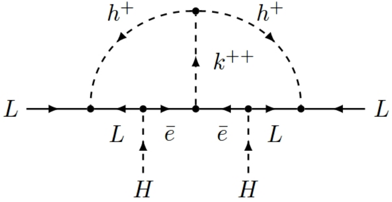
Abada et. al. 2007; Dinh et. al. 2012; UV completion– Antusch, Hinze, Saad 2023

Radiative Majorana Scheme



2HDM$+h^{+}(1,1,1)$

Zee 1980

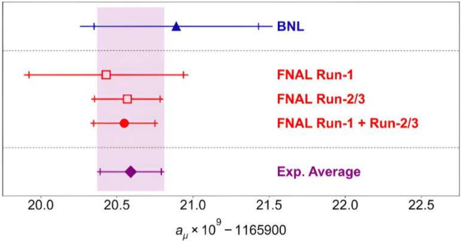


$h^{+}(1,1,1)+k^{++}(1,1,2)$

Babu 1988

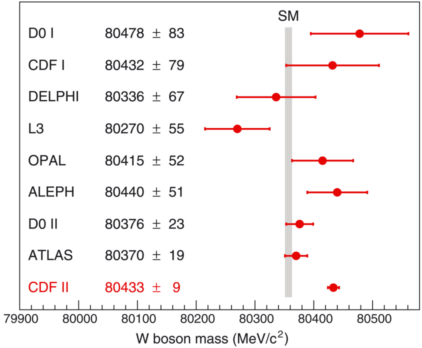
cLFV and its connection to other phenomena

m_W, $(g-2)_\mu$, cLFV in the Zee model



$\sim 5\sigma$

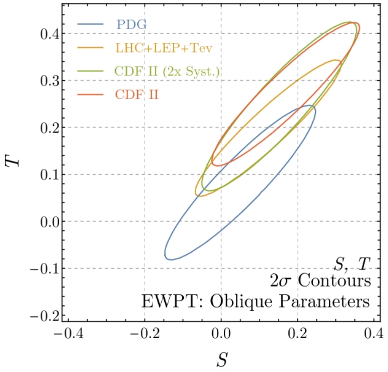
Phys. Rev. Lett. 131, 161802



$\sim 7\sigma$

Science 376 no. 6589, (2022) 170–176

m_W, $(g-2)_\mu$, cLFV in the Zee model



Asadi et. al. 2022

$$M_W^2 = M_{W,\mathrm{SM}}^2\left[1+\frac{\alpha_{em}\left(c_W^2 T - \frac{1}{2}S + \frac{c_W^2 - s_W^2}{4 s_W^2}U\right)}{c_W^2 - s_W^2}\right]$$

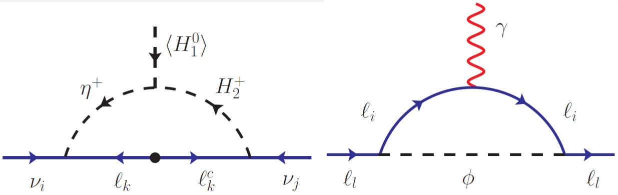
Grimus et. al. 2008

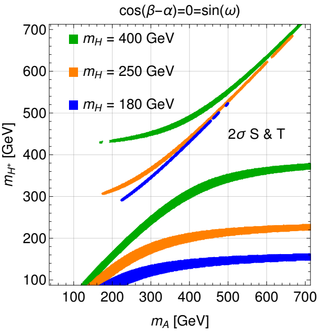
Coupling of the 2nd Higgs Doublet:

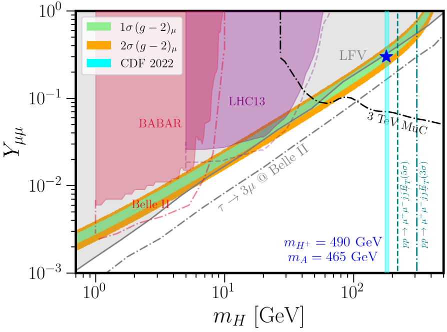
$$\begin{pmatrix} 0 & y_{e\mu} & 0 \\ * & 0 & * \\ 0 & * & * \end{pmatrix}, \begin{pmatrix} * & 0 & * \\ 0 & y_{\mu\mu} & 0 \\ 0 & * & 0 \end{pmatrix}, \begin{pmatrix} 0 & * & 0 \\ * & 0 & y_{\mu\tau} \\ 0 & y_{\tau\mu} & * \end{pmatrix}$$

Heeck, Saad et. al. 2022

m_W, $(g-2)_\mu$, cLFV in the Zee model



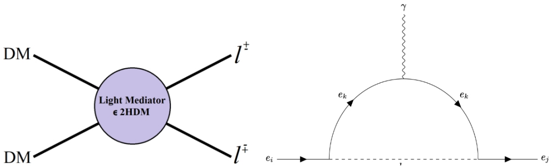


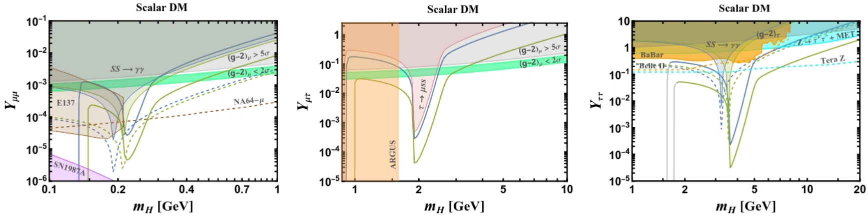


Heeck, Saad et. al. 2022

cLFV in Zee Model + sub-GeV Singlet DM

- Light mediator from two-Higgs-doublet model
- DM mass$\sim$ lepton mass
- Natural resolution to $(g-2)_\mu$
- MEG-II will fully test $\mu \to e\gamma$

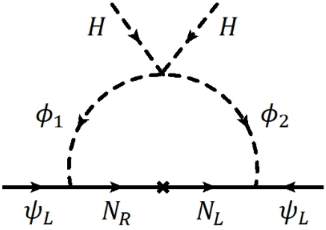




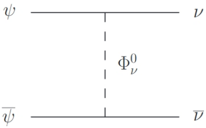
Herms, Jana, Vishnu, Saad 2022

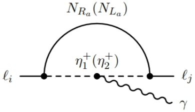
sub-GeV DM & cLFV in Scotogenic Framework

$$SU(2)_L \times U(1)_Y \times \mathcal{Z}_3$$
$$N_{R,L} \sim (1, 0; \omega),$$
$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} \sim (2, \frac{1}{2}; \omega),$$
$$\phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \sim (2, \frac{1}{2}; \omega^2)\,,$$



$$(M_N, m_{S_1}) = (20, 100) \times 10^{-3}\ GeV,$$
$$\left(m_{S_2}, m_{\phi_1^+}, m_{\phi_2^+}\right) = (110, 110, 110)\ \ GeV.$$
$$Y_1 = 10^{-2} \begin{pmatrix} -0.24402 \\ -1.76064 \\ 3 \end{pmatrix},\ Y_2 = 10^{-7} \begin{pmatrix} -3.31953 \\ 8.39950 \\ -3.22219 \end{pmatrix}$$





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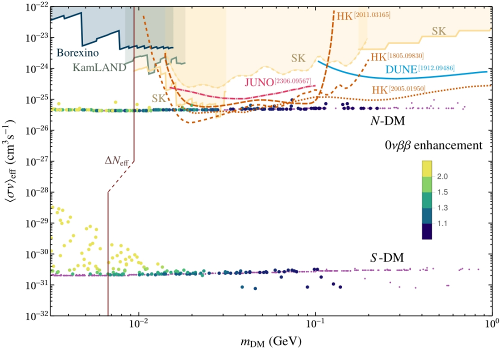
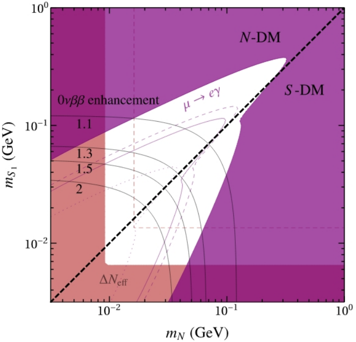
sub-GeV DM & cLFV in Scotogenic Framework





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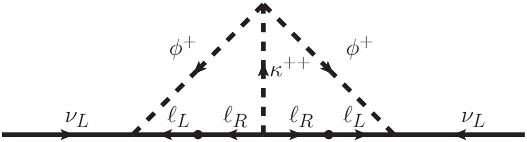
Zee-Babu States at the Muon Collider



Benchmark point	BP1	BP2	BP3	BP4	BP5
			Parameters		
m_κ (GeV)	1250	1250	2500	1250	3750
m_ϕ (GeV)	1250	2500	1250	3750	1250
μ (GeV)	1903.01	1957.01	1994.75	1730.09	2067.06
$f_{e\mu}$	-0.03809	-0.06687	-0.02157	-0.1026	-0.03558
$f_{e\tau}$	0.02037	0.03577	0.02918	0.05487	0.01925
$f_{\mu\tau}$	0.06297	0.11052	0.05291	0.16973	0.05893
g_{ee}	-0.19669	-0.02474	-0.02499	-0.01731	-0.00269
$g_{e\mu}$	9.89×10^{-6}	-5.05×10^{-4}	-0.00237	-0.00160	0.00132
$g_{e\tau}$	0.00462	0.00289	0.04409	0.02005	-0.00699
$g_{\mu\mu}$	0.48	0.487	0.99	0.488	1.0
$g_{\mu\tau}$	0.02542	0.02579	0.05029	0.02582	0.05270
$g_{\tau\tau}$	0.00222	0.00225	0.00420	0.00225	0.00457

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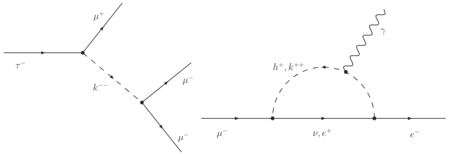
Unsuppressed cLFV



Benchmark point	BP1	BP2	BP3	BP4	BP5
			$\text{BR}(\ell_i \to \ell_j \gamma)$		
$\text{BR}(\mu \to e\gamma)$	$\mathbf{2.93 \times 10^{-13}}$	$\mathbf{2.15 \times 10^{-13}}$	$\mathbf{3.73 \times 10^{-13}}$	$\mathbf{3.06 \times 10^{-13}}$	$\mathbf{2.29 \times 10^{-13}}$
$\text{BR}(\tau \to e\gamma)$	5.19×10^{-13}	9.77×10^{-14}	6.62×10^{-14}	1.56×10^{-13}	1.22×10^{-13}
$\text{BR}(\tau \to \mu\gamma)$	6.51×10^{-11}	6.90×10^{-11}	6.74×10^{-11}	6.91×10^{-11}	1.50×10^{-11}
			$\text{BR}(\ell_i \to \ell_j \ell_k \ell_k)$		
$\text{BR}(\mu^- \to e^+e^-e^-)$	$\mathbf{2.85 \times 10^{-15}}$	$\mathbf{1.17 \times 10^{-13}}$	$\mathbf{1.65 \times 10^{-13}}$	$\mathbf{5.78 \times 10^{-13}}$	$\mathbf{1.18 \times 10^{-16}}$
$\text{BR}(\tau^- \to e^+e^-e^-)$	1.11×10^{-10}	6.88×10^{-13}	1.02×10^{-11}	1.62×10^{-11}	5.87×10^{-16}
$\text{BR}(\tau^- \to e^+e^-\mu^-)$	5.06×10^{-19}	5.74×10^{-16}	1.84×10^{-13}	2.67×10^{-13}	2.84×10^{-16}
$\text{BR}(\tau^- \to e^+\mu^-\mu^-)$	6.59×10^{-10}	2.66×10^{-10}	$\mathbf{1.59 \times 10^{-8}}$	$\mathbf{1.28 \times 10^{-8}}$	8.11×10^{-11}
$\text{BR}(\tau^- \to \mu^+e^-e^-)$	$\mathbf{3.26 \times 10^{-9}}$	5.32×10^{-11}	1.29×10^{-11}	2.61×10^{-11}	3.24×10^{-14}
$\text{BR}(\tau^- \to \mu^+e^-\mu^-)$	1.65×10^{-17}	4.44×10^{-14}	2.32×10^{-13}	4.46×10^{-13}	1.57×10^{-14}
$\text{BR}(\tau^- \to \mu^+\mu^-\mu^-)$	$\mathbf{1.94 \times 10^{-8}}$	$\mathbf{2.06 \times 10^{-8}}$	$\mathbf{2.02 \times 10^{-8}}$	$\mathbf{2.07 \times 10^{-8}}$	$\mathbf{4.48 \times 10^{-9}}$

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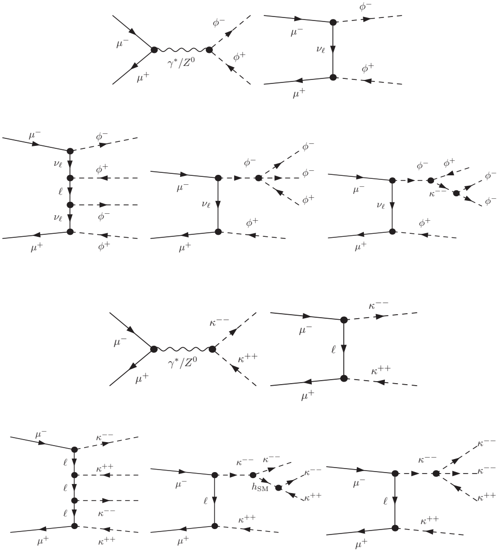

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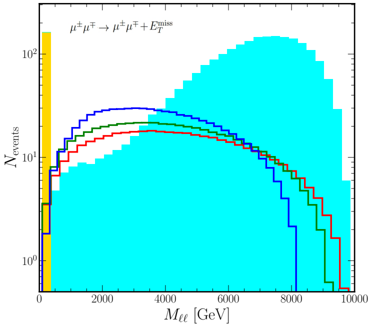
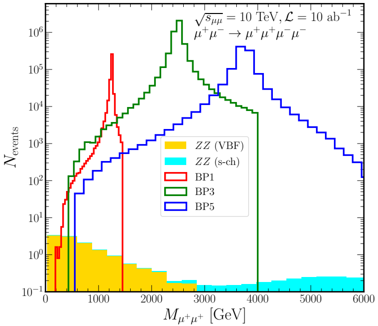
Muon Collider Probes





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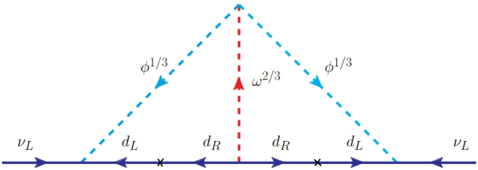
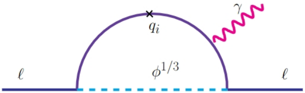
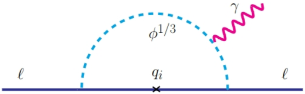
Zee-Babu Model: Colored version

Leptoquark: $S_1 \sim (\overline{3}, 1, 1/3)$ Di-quark: $\omega \sim (\overline{6}, 1, 2/3)$



- Cannot escape to high energies: reach collider prospect
- Expected large rates for cLFV
- Flavor anomalies ...





Babu, Leung 2001; Khoda et. al. 2012; Saad 2020

(see talk by Nejc Košnik)

SU(5) grand Unification

Georgi-Glashow Model

- Fermions

$$\bar{\mathbf{5}}_F = \begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \\ e \\ -\nu \end{pmatrix}, \quad \mathbf{10}_F = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ -u_2^c & 0 & u_1^c & u_2 & d_2 \\ u_2^c & -u_1^c & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^c \\ -d_1 & -d_2 & -d_3 & -e^c & 0 \end{pmatrix}.$$

- Scalars

$$\mathbf{24}_H : \quad SU(5) \to SU(3)_C \times SU(2)_L \times U(1)_Y$$
$$\mathbf{5}_H : \quad SU(3)_C \times SU(2)_L \times U(1)_Y \to SU(3)_C \times U(1)_{em}$$

Georgi, Glashow 1974

Limitations & Resolutions

Georgi, Glashow 1974

- $\overline{\mathbf{5}}^i_F + \mathbf{10}^i_F + \mathbf{5}_H + \mathbf{24}_H$

✗ $M_d = M_e^T$

✗ $M_\nu = 0$

✗ Gauge coupling unification

Georgi, Jarlskog 1979

- $\overline{\mathbf{5}}^i_F + \mathbf{10}^i_F + \mathbf{5}_H + \mathbf{24}_H + \mathbf{45}_H$

✓ $M_d \neq M_e^T$

✗ $M_\nu = 0$

✓ Gauge coupling unification

✓ Proton decay (safe)

Dorsner, Perez 2006

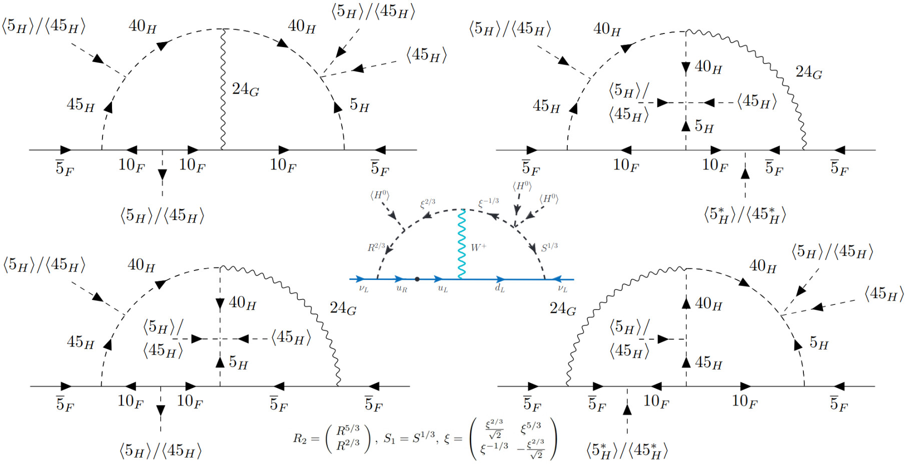
Neutrino Mass: Leptoquark option

Hinze, Saad 2024

$$
\begin{aligned}
\mathbf{5}_{\boldsymbol{H}} \equiv \phi &= \phi_1(1,2,\tfrac{1}{2}) \oplus \phi_2(3,1,-\tfrac{1}{3}),\\
\mathbf{45}_{\boldsymbol{H}} \equiv \Sigma &= \Sigma_1(1,2,\tfrac{1}{2}) \oplus \Sigma_2(3,1,-\tfrac{1}{3}) \oplus \Sigma_3(\overline{3},1,\tfrac{4}{3})\\
&\oplus \Sigma_4(\overline{3},2,-\tfrac{7}{6}) \oplus \Sigma_5(3,3,-\tfrac{1}{3})\\
&\oplus \Sigma_6(\overline{6},1,-\tfrac{1}{3}) \oplus \Sigma_7(8,2,\tfrac{1}{2}).\\
\mathbf{40}_{\boldsymbol{H}} \equiv \eta &= \eta_1(1,2,-\tfrac{3}{2}) \oplus \eta_2(\overline{3},1,-\tfrac{2}{3}) \oplus \eta_3(3,2,\tfrac{1}{6})\\
&\oplus \eta_4(\overline{3},3,-\tfrac{2}{3}) \oplus \eta_5(\overline{6},2,\tfrac{1}{6}) \oplus \eta_6(8,1,1).
\end{aligned}
$$

cf. Saad 2019; IIja, Saad 2019; IIja, Saad 2021; Julio, Saad, Thapa 2022

Neutrino Mass: Leptoquark option



Hinze, Saad 2024

Fermion masses

$$-\mathcal{L}_Y = Y_A 10_F \overline{5}_F 5_H^* + Y_B 10_F 10_F 5_H + Y_C 10_F \overline{5}_F 45_H^* + Y_D 10_F 10_F 45_H \, .$$

$$M_D = \frac{v_5}{2} Y_A - \frac{v_{45}}{2\sqrt{6}} Y_C \, ,$$

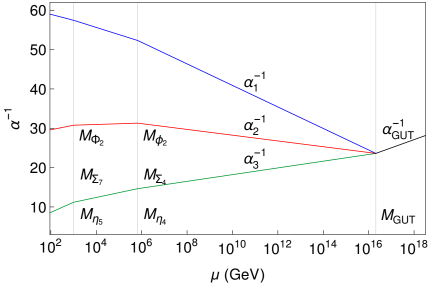
$$M_E = \frac{v_5}{2} Y_A^T + \frac{\sqrt{3} v_{45}}{2\sqrt{2}} Y_C^T \, ,$$

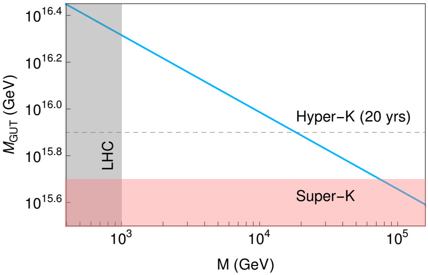
$$M_U = \sqrt{2} v_5 \left(Y_B + Y_B^T \right) + \frac{v_{45}}{\sqrt{3}} \left(Y_D - Y_D^T \right) \, ,$$

$$M_N = -\frac{3g^2}{\sqrt{2}\,(16\pi^2)^2} \Big\{ 2 Y_L^T M_U^{\mathrm{diag}} F_L + M_E^{\mathrm{diag}} Y_R^\dagger F_L + M_E^{\mathrm{diag}} Y_L^T F_R^* \Big\} J_0 + (\mathrm{transpose}) \, .$$

Hinze, Saad 2024

Neutrino Mass in SU(5)





- m_ν: masses of the leptoquarks $\phi_2, \Sigma_4, \eta_4 \Rightarrow M_{\rm LQ} \lesssim 10^8$ GeV
- Proton decay: $\phi_2 \Rightarrow M_{\rm LQ} \gtrsim 10^{12}$ GeV
- Suppression: $(U_L^\dagger(Y_B + Y_B^T)D_L^*)_{1\beta} = (D_R^\dagger Y_A^\dagger U_R^*)_{\beta 1} = 0$ for $\beta = 1, 2$

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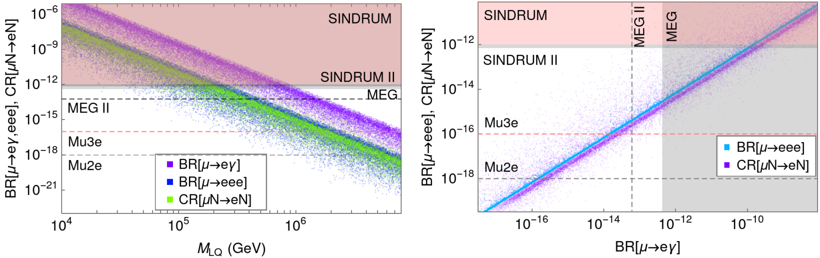
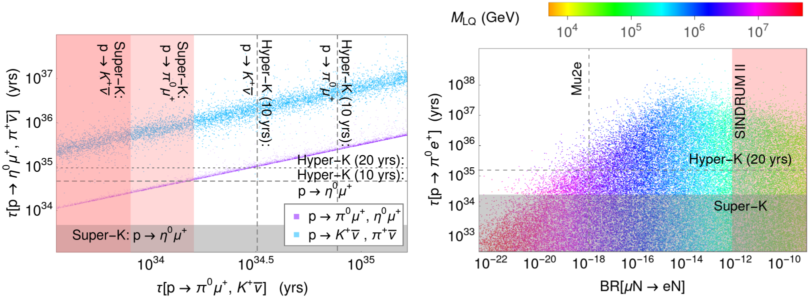
Neutrino Mass in SU(5)



- Fermion mass+PD suppression determine the couplings
- LFV: typically $M_{\mathrm{LQ}} \gtrsim 10^5$ GeV

Hinze, Saad 2024



Hinze, Saad 2024

Summary

❄ Neutrino oscillations $\Longrightarrow$ cLFV

❄ Origin of neutrino mass $\Longrightarrow$ New Physics

❄ New Physics $\Longrightarrow$ unsuppressed cLFV

❄ Observation of cLFV $\Longrightarrow$ Direct signature of New Physics

❄ cLFV rates $\Longrightarrow$ Model dependent

❄ NP models: cLFV $\Longleftrightarrow$ Complementary probes

THANK YOU!