Accessible Lepton-Number-Violating Models and Negligible Neutrino Masses

CP^3 Origins
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Warsaw

André de Gouvêa, WCH, Johannes König, Manibrata Sen, arXiv:1907.02541

Outline

- Neutrino oscillations, masses and PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix
- Charged-lepton flavor violation (CLFV) in the SM with a (very brief) experimental review
- Sizable CLFV from New physics
- Connections to LNV (lepton number violation)

Outline

- Effective operator O_s with sizable $\mu^- \to e^+$ but w/o large m_ν
- Exhaustive tree-level UV models
- Various experimental constraints
- Conclusions

CKM (Cabibbo-Kobayashi-Maskawa) matrix

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \quad , \; u_R \quad , \; d_R$$

$$\mathcal{L}_{Y_Q} \sim - y^d_{ij} \left(\overline{Q_{Li}} \cdot H \right) d_{Rj} - y^u_{ij} \left(\overline{Q_{Li}} \cdot H^\dagger \right) u_{Rj}$$

$$u_L^i = U_u^{ij} \, u_L'^{j} \qquad\qquad d_L^i = U_d^{ij} \, d_L'^{j}$$

(flavor) (mass)

$$u_R^i = V_u^{ij} \, u_R'^{j} \qquad\qquad d_R^i = V_d^{ij} \, d_R'^{j}$$

CKM (Cabibbo-Kobayashi-Maskawa) matrix

$$\Rightarrow \mathcal{L}_{m_Q} \sim -\frac{y_i'^{d}}{\sqrt{2}} v \, \overline{d'_{Li}} \, d'_{Ri} + (d \leftrightarrow u) + h.c.$$

$$\Rightarrow \mathcal{L}_W \sim \overline{u'_{Li}} \, \gamma^\mu \underbrace{(U_u^\dagger U_d)_{ij}}_{CKM} d'_{Lj} \, W_\mu$$

$\langle H \rangle$ breaks $SU(2)_L$

$\Rightarrow$ u_L, d_L transform differently between flavor and mass states.

Neutrino oscillations and masses

- In the SM, there is no tree-level CLFV

$$E_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} , \quad e_R$$

$$\mathcal{L}_{Y_e} \sim -y^e_{ij} \left(\overline{E}_{L_i} \cdot H \right) e_{R_j} - y^\nu_{ij} \left(\overline{E}_{L_i} \cdot H^\dagger \right) \nu_{R_j}$$

$$e_L^i = U_e^{ij} \, e_L'^{j} \qquad\qquad e_R^i = V_e^{ij} \, e_L'^{j}$$

$$\mathcal{L}_{m_e} \sim -\frac{y'^e_i}{\sqrt{2}} \, \overline{e'}_{L_i} \, e_{R_i} + h.c.$$

$$\Rightarrow \mathcal{L}_W \sim \overline{e'}_{L_i} \gamma^\mu \underbrace{\left(U_e^\dagger\right)_{ij}}_{\text{PMNS}\,??} \nu_{L_j} \, W_\mu$$

Neutrino oscillations and masses

- The lepton mixing matrix in the SM is unphysical if neutrinos are massless or degenerate in mass!

But one can redefine $\nu_L \to (U_e)\, \nu_L'$ to remove $(U_e^\dagger)$ in $\mathcal{L}_W$

* If neutrinos are massive and non-degenerate.

$$\Rightarrow \mathcal{L}_W \sim \overline{e_L'}\, \gamma^\mu \underbrace{(U_e^\dagger U_\nu)}_{\text{PMNS}} \nu_L'\, W_\mu$$

Neutrino oscillations and masses

$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle, \quad \Longrightarrow \quad |\nu(t,\vec{x})\rangle = \cos\theta e^{-ip_1x}|\nu_1\rangle + \sin\theta e^{-ip_2x}|\nu_2\rangle$$

$$p_i x = E_i t - \vec{p}_i\vec{x} \simeq (E_i - p_{z,i})L$$

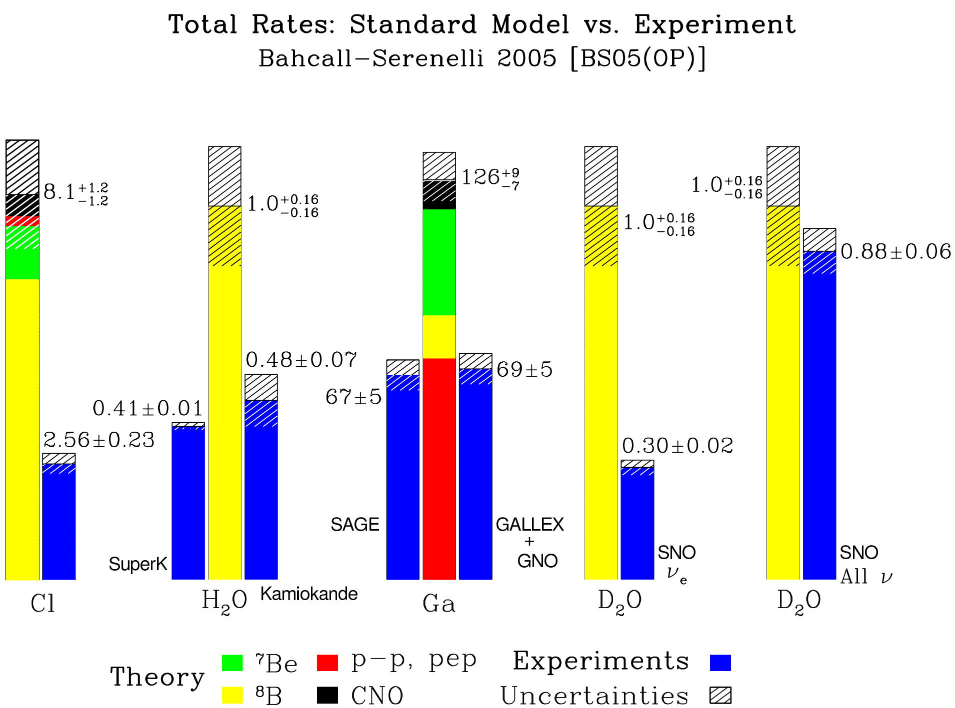
$$E_i - p_{z,i} = (E_i^2 - |\vec{p}|^2)/(E_i + p_{z,i}) \simeq m_i^2/2E_i \simeq m_i^2/2E$$

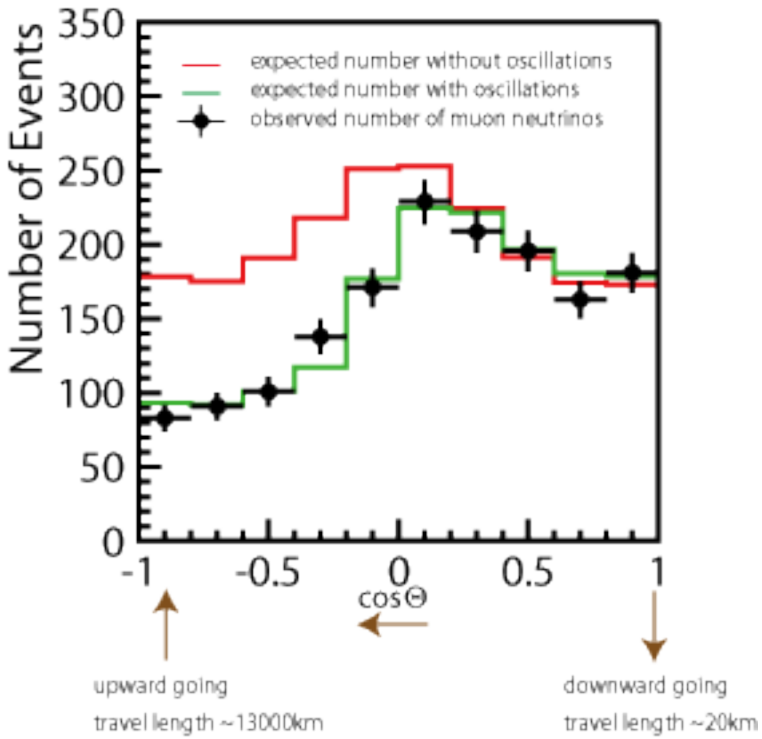
$$|\nu(L)\rangle = \cos\theta e^{-im_1^2L/2E}|\nu_1\rangle + \sin\theta e^{-im_2^2L/2E}|\nu_2\rangle$$

$$\begin{aligned} P_{ee} &= |\langle\nu_e|\nu(L)\rangle|^2, \\ &= \left|(\cos\theta\langle\nu_1| + \sin\theta\langle\nu_2|)\left(\cos\theta e^{-im_1^2L/2E}|\nu_1\rangle + \sin\theta e^{-im_2^2L/2E}|\nu_2\rangle\right)\right|^2, \\ &= \left|\cos^2\theta e^{-im_1^2L/2E} + \sin^2\theta e^{-im_2^2L/2E}\right|^2, \\ &= \cos^4\theta + \sin^4\theta + 2\sin^2\theta\cos^2\theta\Re\left(e^{-i(m_2^2-m_1^2)L/2E}\right), \\ &= 1 - 4\cos^2\theta\sin^2\theta\left(\frac{1-\cos(\Delta m^2L/2E)}{2}\right), \\ &= 1 - \sin^2 2\theta\sin^2\left(\frac{\Delta m^2 L}{4E}\right), \end{aligned} \qquad (27)$$

Andre de Gouvea, hep-ph/0411274

Neutrino oscillations and masses





http://www.sns.ias.edu/~jnb/

http://www-sk.icrr.u-tokyo.ac.jp/sk/physics/atmnu-e.html

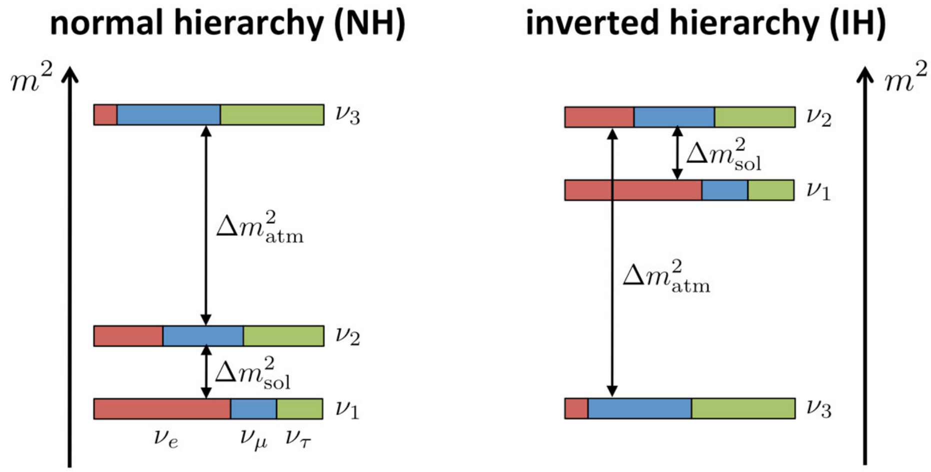
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right)$$

CKM versus PMNS

- CKM matrix has three rotation angles and only one CP phase

- PMNS has the same angles and the CP phase, but can have two more Majorana phases if they are Majorana.

Neutrino oscillations and masses



https://neutrinos.fnal.gov/mysteries/mass-ordering/

Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	6.93 – 7.96
$\Delta m^2_{31(23)}$ $[10^{-3}$ eV $^2]$	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	0.381 – 0.615
$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589	0.384 – 0.636
$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215	0.0190 – 0.0240
$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216	0.0190 – 0.0242
δ/π	1.38 (1.31)	2σ: (1.0 - 1.9) (2σ: (0.92-1.88))

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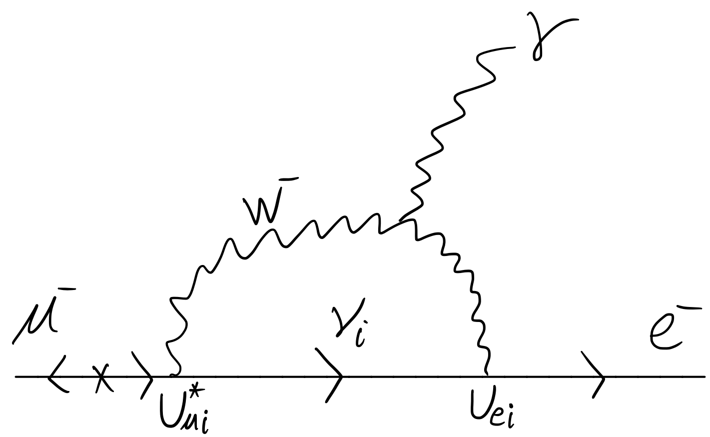
Loop-induced CLFV in SM



$$\overline{\mu}_L \sigma^{\mu\nu} e_R F_{\mu\nu} + (L \leftrightarrow R)$$

$$\text{Amplitude} \sim \sum_{i=1}^{3} U^*_{\mu i} \frac{i}{p^2 - m_i^2} U_{ei}$$

$$\sim \sum_{i=2}^{3} U^*_{\mu i} \frac{\Delta m_i^2}{p^2} U_{ei}$$

$$* \quad U^*_{\mu 1} U_{e1} = -(U_{\mu 2} U_{e2} + U_{\mu 3} U_{e3})$$

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

Hopelessly small!

e.g. A. de Gouvea, P. Vogel, 1303.4097

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Reaction	Present limit	C.L.	Experiment	Year	Reference
$\mu^+ \to e^+\gamma$	$< 4.2 \times 10^{-13}$	90%	MEG at PSI	2016	[49]
$\mu^+ \to e^+e^-e^+$	$< 1.0 \times 10^{-12}$	90%	SINDRUM	1988	[50]
$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}$ †	$< 6.1 \times 10^{-13}$	90%	SINDRUM II	1998	[51]
$\mu^-\mathrm{Pb} \to e^-\mathrm{Pb}$ †	$< 4.6 \times 10^{-11}$	90%	SINDRUM II	1996	[52]
$\mu^-\mathrm{Au} \to e^-\mathrm{Au}$ †	$< 7.0 \times 10^{-13}$	90%	SINDRUM II	2006	[54]
$\mu^-\mathrm{Ti} \to e^+\mathrm{Ca}^*$ †	$< 3.6 \times 10^{-11}$	90%	SINDRUM II	1998	[53]
$\mu^+e^- \to \mu^-e^+$	$< 8.3 \times 10^{-11}$	90%	SINDRUM	1999	[55]
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$	90%	BaBar	2010	[56]
$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$	90%	BaBar	2010	[56]
$\tau \to eee$	$< 2.7 \times 10^{-8}$	90%	Belle	2010	[57]
$\tau \to \mu\mu\mu$	$< 2.1 \times 10^{-8}$	90%	Belle	2010	[57]
$\tau \to \pi^0 e$	$< 8.0 \times 10^{-8}$	90%	Belle	2007	[58]
$\tau \to \pi^0 \mu$	$< 1.1 \times 10^{-7}$	90%	BaBar	2007	[59]
$\tau \to \rho^0 e$	$< 1.8 \times 10^{-8}$	90%	Belle	2011	[60]
$\tau \to \rho^0 \mu$	$< 1.2 \times 10^{-8}$	90%	Belle	2011	[60]
$\pi^0 \to \mu e$	$< 3.6 \times 10^{-10}$	90%	KTeV	2008	[61]
$K_L^0 \to \mu e$	$< 4.7 \times 10^{-12}$	90%	BNL E871	1998	[62]
$K_L^0 \to \pi^0\mu^+e^-$	$< 7.6 \times 10^{-11}$	90%	KTeV	2008	[61]
$K^+ \to \pi^+\mu^+e^-$	$< 1.3 \times 10^{-11}$	90%	BNL E865	2005	[63]
$J/\psi \to \mu e$	$< 1.5 \times 10^{-7}$	90%	BESIII	2013	[64]
$J/\psi \to \tau e$	$< 8.3 \times 10^{-6}$	90%	BESII	2004	[65]
$J/\psi \to \tau\mu$	$< 2.0 \times 10^{-6}$	90%	BESII	2004	[65]
$B^0 \to \mu e$	$< 2.8 \times 10^{-9}$	90%	LHCb	2013	[68]
$B^0 \to \tau e$	$< 2.8 \times 10^{-5}$	90%	BaBar	2008	[69]
$B^0 \to \tau\mu$	$< 2.2 \times 10^{-5}$	90%	BaBar	2008	[69]
$B \to K\mu e$ ‡	$< 3.8 \times 10^{-8}$	90%	BaBar	2006	[66]
$B \to K^*\mu e$ ‡	$< 5.1 \times 10^{-7}$	90%	BaBar	2006	[66]
$B^+ \to K^+\tau\mu$	$< 4.8 \times 10^{-5}$	90%	BaBar	2012	[67]
$B^+ \to K^+\tau e$	$< 3.0 \times 10^{-5}$	90%	BaBar	2012	[67]
$B_s^0 \to \mu e$	$< 1.1 \times 10^{-8}$	90%	LHCb	2013	[68]
$\Upsilon(1s) \to \tau\mu$	$< 6.0 \times 10^{-6}$	95%	CLEO	2008	[70]
$Z \to \mu e$	$< 7.5 \times 10^{-7}$	95%	LHC ATLAS	2014	[71]
$Z \to \tau e$	$< 9.8 \times 10^{-6}$	95%	LEP OPAL	1995	[72]
$Z \to \tau\mu$	$< 1.2 \times 10^{-5}$	95%	LEP DELPHI	1997	[73]
$h \to e\mu$	$< 3.5 \times 10^{-4}$	95%	LHC CMS	2016	[74]
$h \to \tau\mu$	$< 2.5 \times 10^{-3}$	95%	LHC CMS	2017	[75]
$h \to \tau e$	$< 6.1 \times 10^{-3}$	95%	LHC CMS	2017	[75]

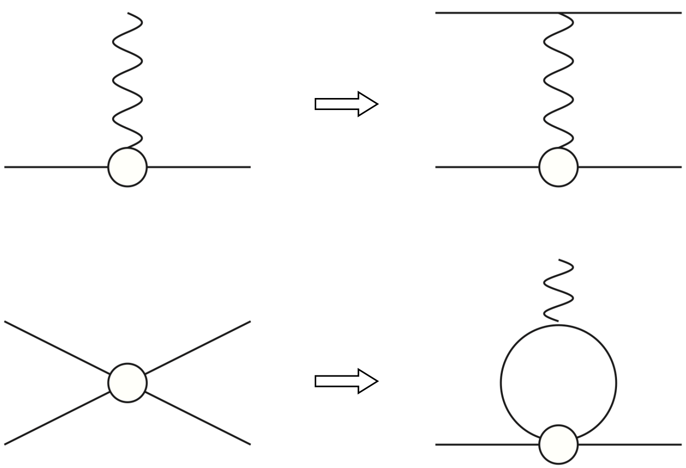
L. Calibbi, G. Signorelli, 1709.00294

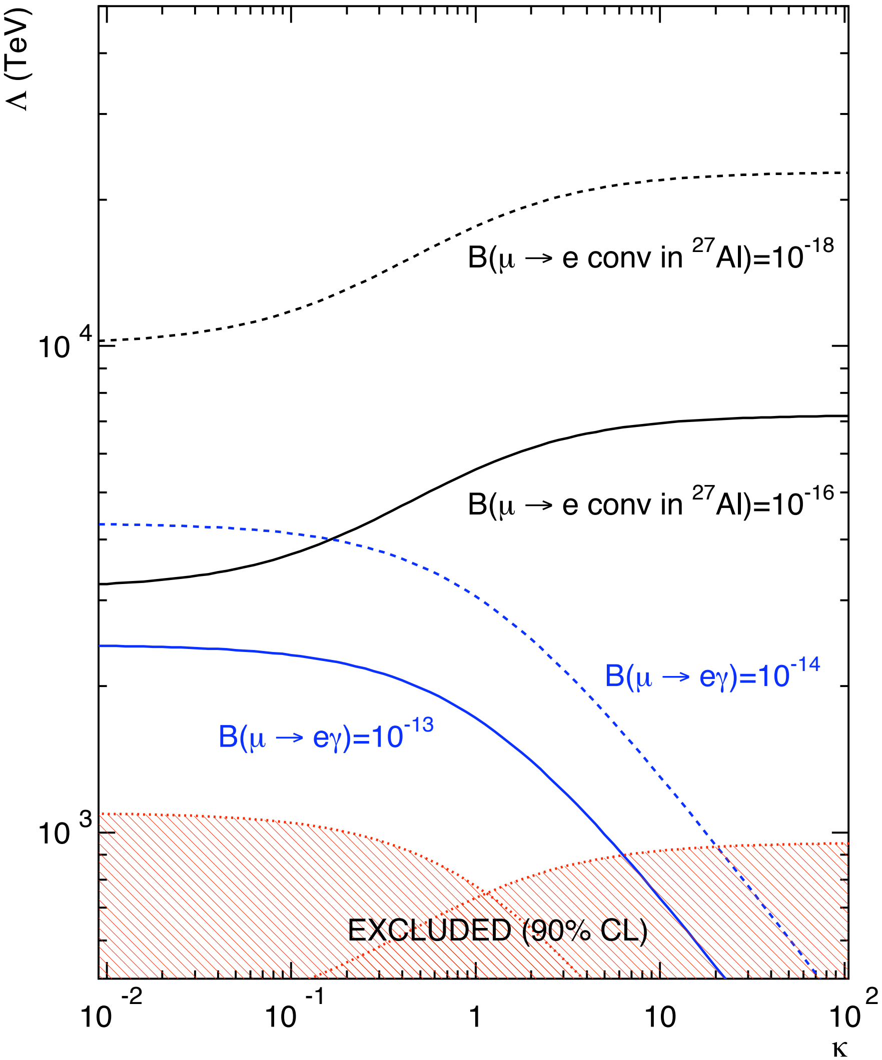
Reaction	Present limit	Expected Limit	Reference	Experiment
$\mu^+ \to e^+\gamma$	$< 4.2 \times 10^{-13}$	5×10^{-14}	[316]	MEG II
$\mu^+ \to e^+e^-e^+$	$< 1.0 \times 10^{-12}$	10^{-16}	[46]	Mu3e
$\mu^-\mathrm{Al} \to e^-\mathrm{Al}$ †	$< 6.1 \times 10^{-13}$	10^{-17}	[321, 324]	Mu2e, COMET
$\mu^-\mathrm{Si/C} \to e^-\mathrm{Si/C}$ †	–	5×10^{-14}	[282]	DeeMe
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$	5×10^{-9}	[339]	Belle II
$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$	10^{-9}	[339]	"
$\tau \to eee$	$< 2.7 \times 10^{-8}$	5×10^{-10}	[339]	"
$\tau \to \mu\mu\mu$	$< 2.1 \times 10^{-8}$	5×10^{-10}	[339]	"
$\tau \to e$ had	$< 1.8 \times 10^{-8}$ ‡	3×10^{-10}	[339]	"
$\tau \to \mu$ had	$< 1.2 \times 10^{-8}$ ‡	3×10^{-10}	[339]	"
had $\to \mu e$	$< 4.7 \times 10^{-12}$ §	10^{-12}	[340]	NA62
$h \to e\mu$	$< 3.5 \times 10^{-4}$	3×10^{-5} ¶	[341]	HL-LHC
$h \to \tau\mu$	$< 2.5 \times 10^{-3}$	3×10^{-4} ¶	[341]	"
$h \to \tau e$	$< 6.1 \times 10^{-3}$	3×10^{-4} ¶	[341]	"

L. Calibbi, G. Signorelli, 1709.00294

$\mu \to e\,\gamma$ versus $\mu \to eee$

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + h.c.$$
$$\frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{e}\gamma^\mu e\right) + h.c..$$





L. Calibbi, G. Signorelli, 1709.00294

A. de Gouvea, P. Vogel, 1303.4097

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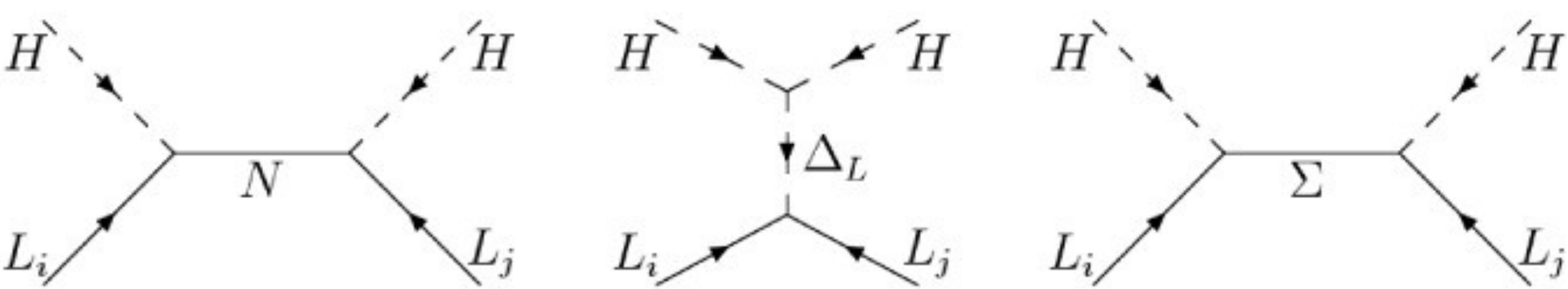
CLFV in BSM

- Two Higgs doublets models
- SUSY
- Majorana neutrinos
- ….. (Many others)

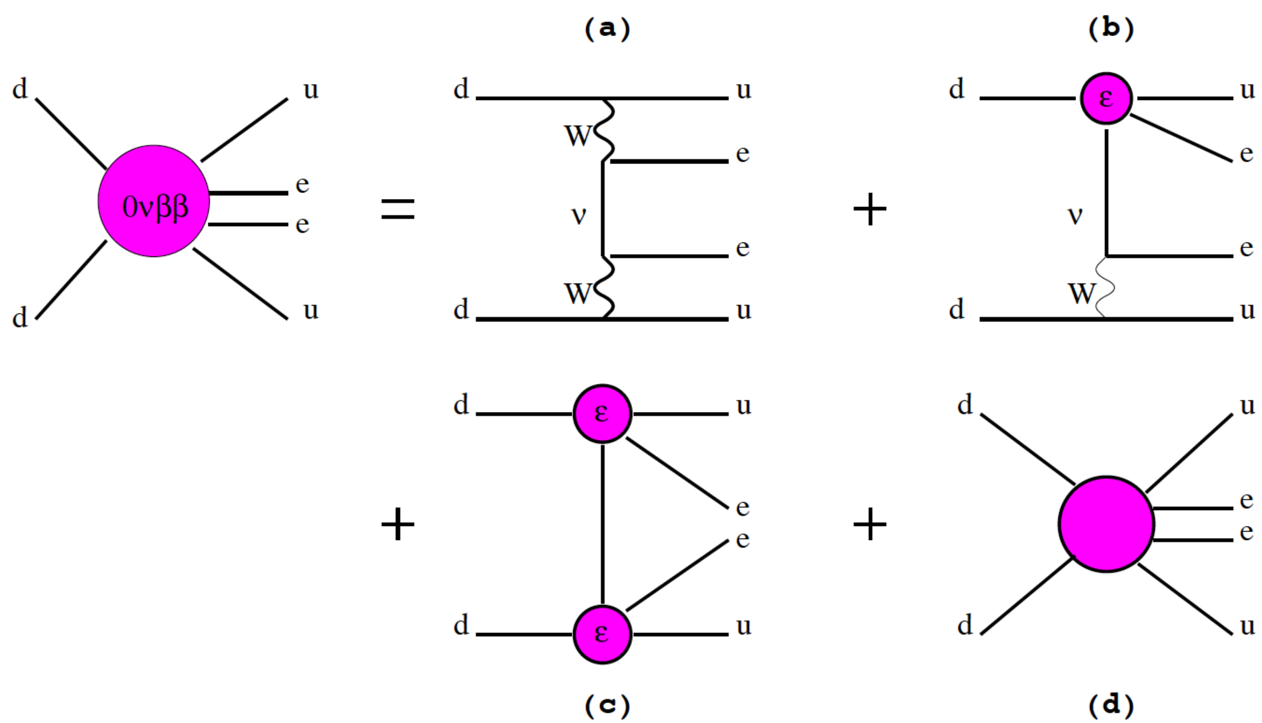
Majorana Neutrino mass

- Three UV-completions for dim-5 (ΔL = 2) Weinberg operator (LH)(LH)/Λ, dubbed as Type-I, Type-II and Type-III seesaw mechanism:



Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

- Lepton number is violated if $0\nu\beta\beta$ is observed and SM neutrinos contains a Majorana component. It would wash out not only L and but also B in light of the sphalerons



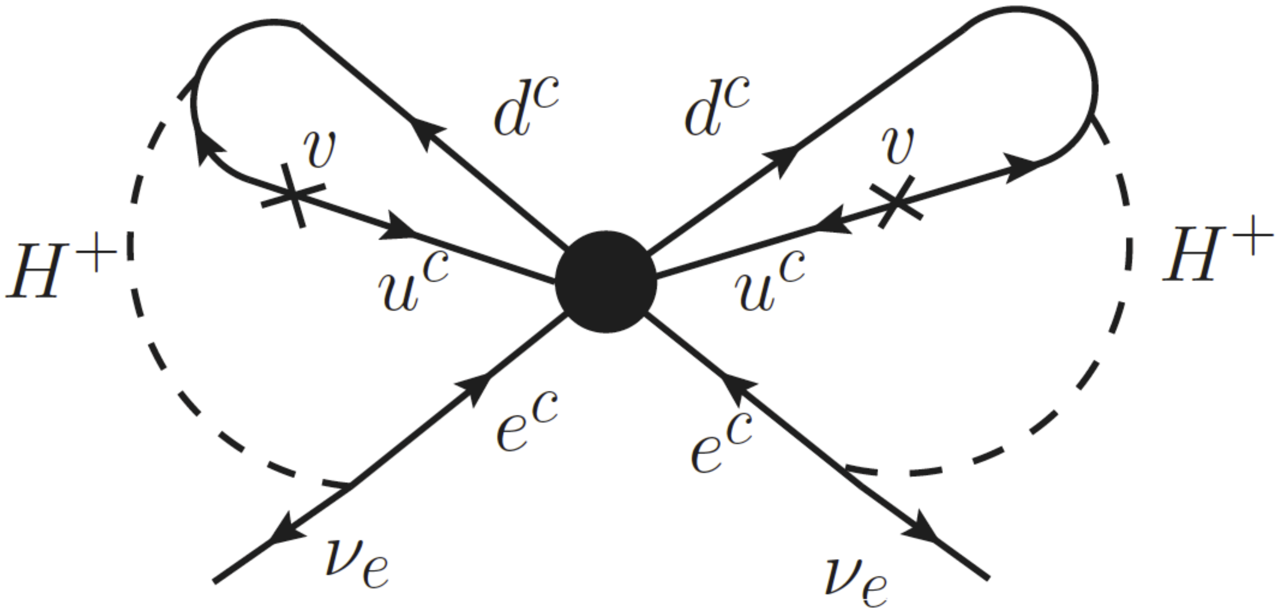
Deppisch et al. 1208.0721

LFV and LNV

- If the origin of neutrino masses arises from a LNV mechanism such as heavy Majorana neutrinos, then both LFV and LNV can in principle occur
- In this case, sizable LFV usually leads to (too) large light neutrino masses
- In this work, we discuss a special effective operator (made of singlets only) which will not induce large neutrino masses but with sizable $\mu^- \to e^+$

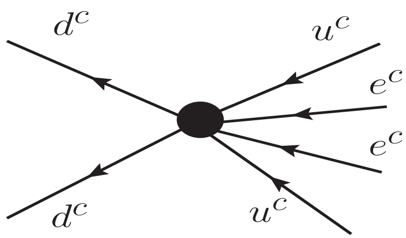
$$\mathcal{L} \supset \frac{g}{\Lambda^{d-4}} \mathcal{O}^d + h.c. \qquad \mathcal{O}_s^{\alpha\beta} = \ell^c_\alpha \ell^c_\beta u^c u^c \overline{d^c}\, \overline{d^c}$$

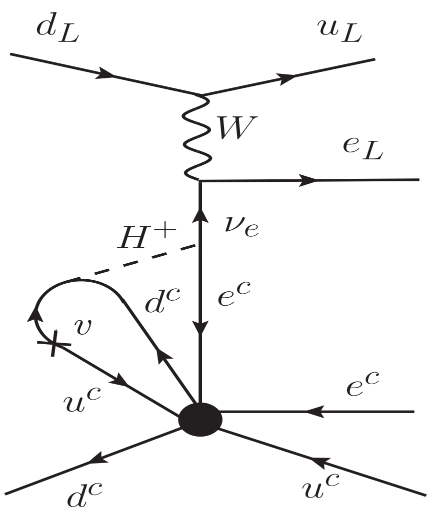
Induced neutrino mass by $O_S^{\alpha\beta}$

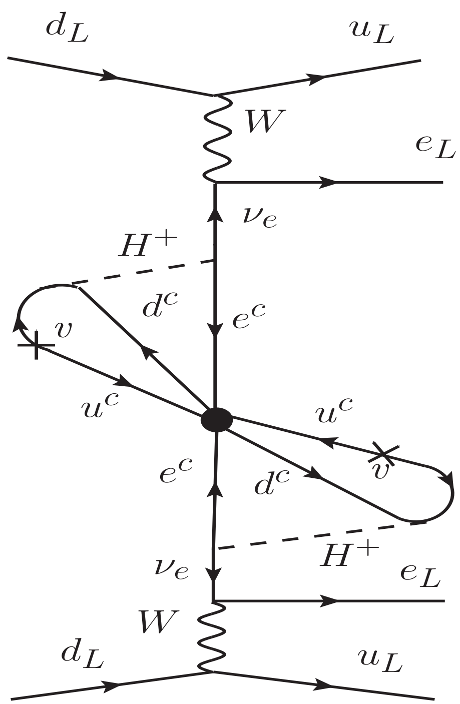


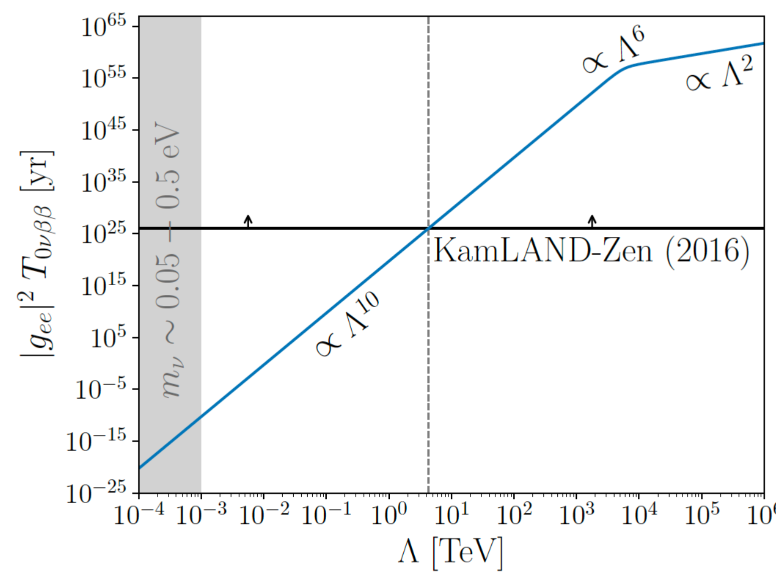
$$m_{\alpha\beta} = \frac{g_{\alpha\beta}}{\Lambda} \frac{y_\alpha y_\beta (y_t y_b v)^2}{(16\pi^2)^4}$$

Induced $0\nu\beta\beta$ by $O_S^{\alpha\beta}$



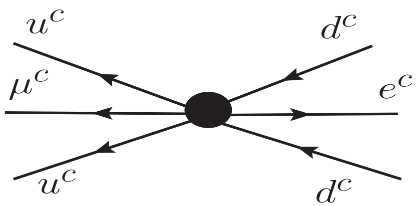


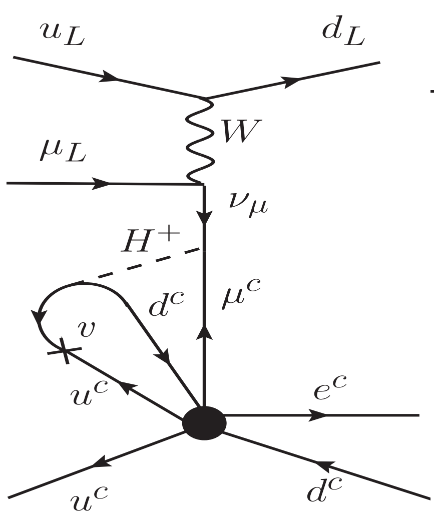


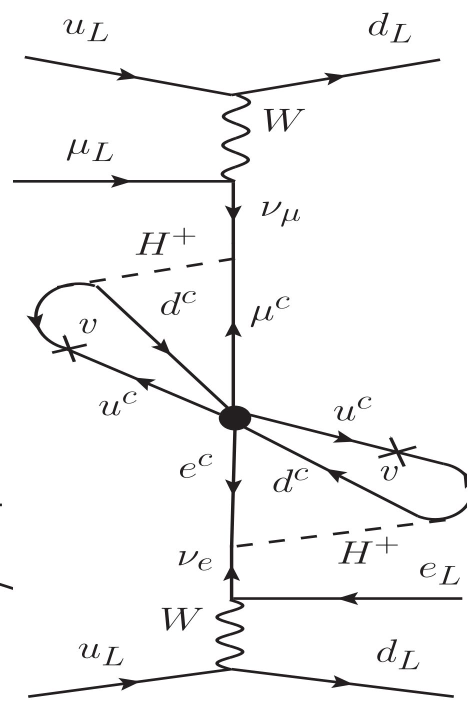


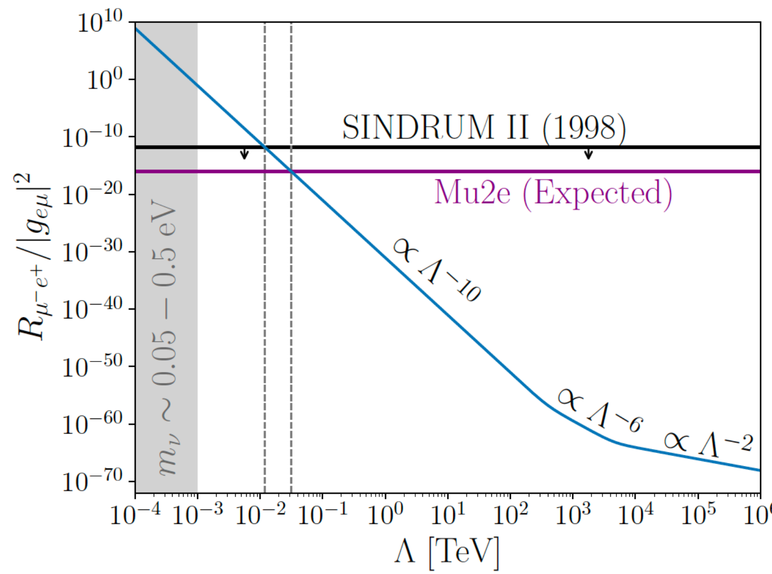
$$T_{0\nu\beta\beta} = \frac{\ln(2)}{|g_{ee}|^2}\frac{\Lambda^2}{Q^{11}}\left[\left(\frac{G_F}{\sqrt{2}}\right)^4\left(\frac{1}{q^2}\right)^2\left(\frac{y_t^2 y_b^2 y_e^2 v^2}{(16\pi^2)^4}\right)^2 + \left(\frac{G_F}{\sqrt{2}}\right)^2\frac{1}{q^2}\left(\frac{y_t y_b y_e v}{(16\pi^2)^2\Lambda^2}\right)^2 + \frac{1}{\Lambda^8}\right]^{-1}$$

Induced $\mu^- \to e^+$ by $O_S^{\alpha\beta}$



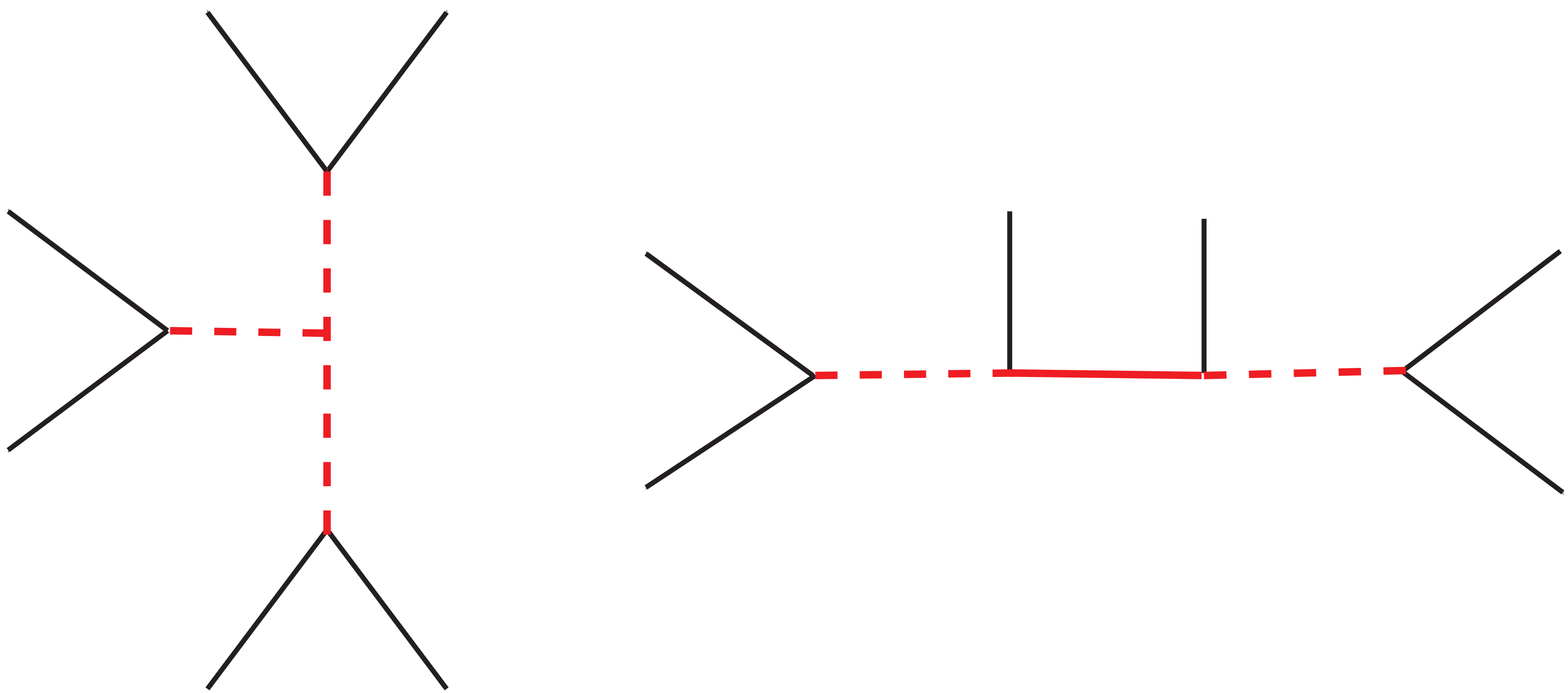






$$R_{\mu^- e^+} = |g_{e\mu}|^2 \frac{Q^6}{\Lambda^2}\left[\left(\frac{G_F}{\sqrt{2}}\right)^2\left(\frac{1}{q^2}\right)^2\left(\frac{y_t^2 y_b^2 y_\mu y_e v^2}{(16\pi^2)^4}\right)^2 + \frac{1}{q^2}\left(\frac{y_t y_b y_\mu v}{(16\pi^2)^2\Lambda^2}\right)^2 + \left(\frac{\sqrt{2}}{G_F}\right)^2\frac{1}{\Lambda^8}\right]$$

Tree-level topology



Topology I

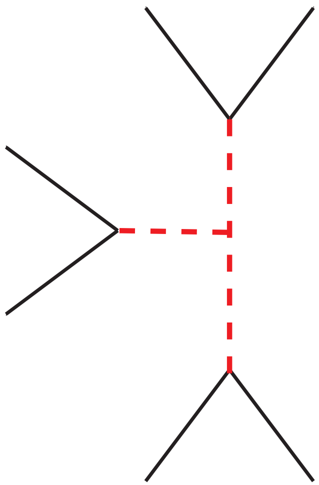


TABLE I: Quantum numbers of all possible pairs of the $SU(2)_L$ gauge singlet Standard Model fermions $\ell^c, u^c, \overline{d^c}$.

Pairs (Lorentz)	Representation under $(\mathrm{SU(3)_C},\ \mathrm{SU(2)_L})_{\mathrm{U(1)_Y}}$
$\ell^c\ell^c$ (scalar)	$(1,1)_1 \times (1,1)_1 = (1,1)_2$
$\ell^c u^c$ (scalar)	$(1,1)_1 \times (\overline{3},1)_{-2/3} = (\overline{3},1)_{1/3}$
$\ell^c\overline{d^c}$ (vector)	$(1,1)_1 \times (3,1)_{-1/3} = (3,1)_{2/3}$
$u^c u^c$ (scalar)	$(\overline{3},1)_{-2/3} \times (\overline{3},1)_{-2/3} = (3_a,1)_{-4/3} + (\overline{6}_s,1)_{-4/3}$
$u^c\overline{d^c}$ (vector)	$(\overline{3},1)_{-2/3} \times (3,1)_{-1/3} = (1,1)_{-1} + (8,1)_{-1}$
$\overline{d^c}\,\overline{d^c}$ (scalar)	$(3,1)_{-1/3} \times (3,1)_{-1/3} = (\overline{3}_a,1)_{-2/3} + (6_s,1)_{-2/3}$

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Topology II

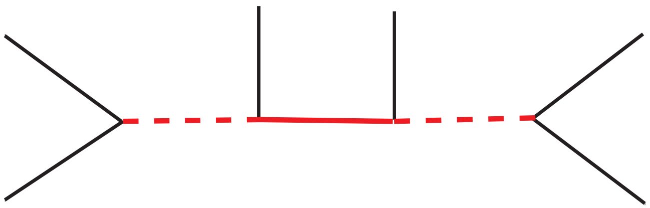


TABLE II: Quantum numbers of all the possible triplets of $SU(2)_L$ gauge singlet Standard Model fermions $\ell^c, u^c, \overline{d^c}$ (with at most two identical fields).

Triplets	Representation under $\left(\mathrm{SU(3)_C},\, \mathrm{SU(2)_L}\right)_{\mathrm{U(1)_Y}}$
$\ell^c\ell^c u^c$	$(1,1)_1 \times (1,1)_1 \times (\overline{3},1)_{-2/3} = (\overline{3},1)_{4/3}$
$\ell^c\ell^c\overline{d^c}$	$(1,1)_1 \times (1,1)_1 \times (3,1)_{-1/3} = (3,1)_{5/3}$
$\ell^c u^c u^c$	$(1,1)_1 \times (\overline{3},1)_{-2/3} \times (\overline{3},1)_{-2/3} = (3_a,1)_{-1/3} + (\overline{6}_s,1)_{-1/3}$
$\ell^c\overline{d^c}\,\overline{d^c}$	$(1,1)_1 \times (3,1)_{-1/3} \times (3,1)_{-1/3} = (\overline{3}_a,1)_{1/3} + (6_s,1)_{1/3}$
$\ell^c u^c\overline{d^c}$	$(1,1)_1 \times (\overline{3},1)_{-2/3} \times (3,1)_{-1/3} = (1,1)_0 + (8,1)_0$
$u^c u^c\overline{d^c}$	$(\overline{3},1)_{-2/3} \times (\overline{3},1)_{-2/3} \times (3,1)_{-1/3} = \left[(3_a,1)_{-4/3} + (\overline{6}_s,1)_{-4/3}\right] \times (3,1)_{-1/3} =$
	$(\overline{3},1)_{-5/3} + (6,1)_{-5/3} + (\overline{3},1)_{-5/3} + (\overline{15},1)_{-5/3}$
$u^c\overline{d^c}\,\overline{d^c}$	$(\overline{3},1)_{-2/3} \times (3,1)_{-1/3} \times (3,1)_{-1/3} = (\overline{3},1)_{-2/3} \times \left[(\overline{3}_a,1)_{-2/3} + (6_s,1)_{-2/3}\right] =$
	$(3,1)_{-4/3} + (\overline{6},1)_{-4/3} + (3,1)_{-4/3} + (15,1)_{-4/3}$

Bilinear fermion operators

TABLE III: Pairs of Standard Model fermions that share the same gauge quantum numbers. The pairs of interest here are in red. The pair $\ell^c\ell^c$ does not transform like any other pair of SM fields; the same is true of the color-symmetric pairs of $u^c u^c$ and $d^c d^c$.

Fermion pairs transforming as	$(\mathrm{SU(3)_C},\ \mathrm{SU(2)_L})_{\mathrm{U(1)_Y}}$
LL, $\overline{\ell^c}\,\overline{\nu^c}$	$(1,1)_{-1}$ scalar
$\overline{d^c}u^c$, $\overline{\ell^c}\nu^c$	$(1,1)_{-1}$ vector
$\ell^c u^c$, $\overline{u^c}\,\overline{d^c}$, Q^2, $\overline{L}\,\overline{Q}$, $d^c\nu^c$	$(\overline{3},1)_{1/3}$ scalar
$\overline{u^c}\,\overline{d^c}$, QQ	$(6,1)_{1/3}$ scalar
$d^c d^c$, $\overline{u^c}\,\overline{\nu^c}$	$(3,1)_{2,3}$ scalar
$\overline{d^c}\ell^c$, $\overline{L}Q$, $\overline{u^c}\nu^c$	$(3,1)_{2/3}$ vector
$u^c u^c$, $\overline{d^c}\,\overline{\ell^c}$	$(3,1)_{-4/3}$ scalar
$\nu^c\nu^c$, $\overline{\nu^c}\,\overline{\nu^c}$	$(1,1)_0$ scalar
$L\overline{L}$, $Q\overline{Q}$, $\ell^c\overline{\ell^c}$, $d^c\overline{d^c}$, $u^c\overline{u^c}$, $\overline{\nu^c}\nu^c$	$(1,1)_0$ vector
$Q\overline{Q}$, $d^c\overline{d^c}$, $u^c\overline{u^c}$	$(8,1)_0$ vector

- Avoid inducing other LNV dim-9 operator with new particles

New particle contents

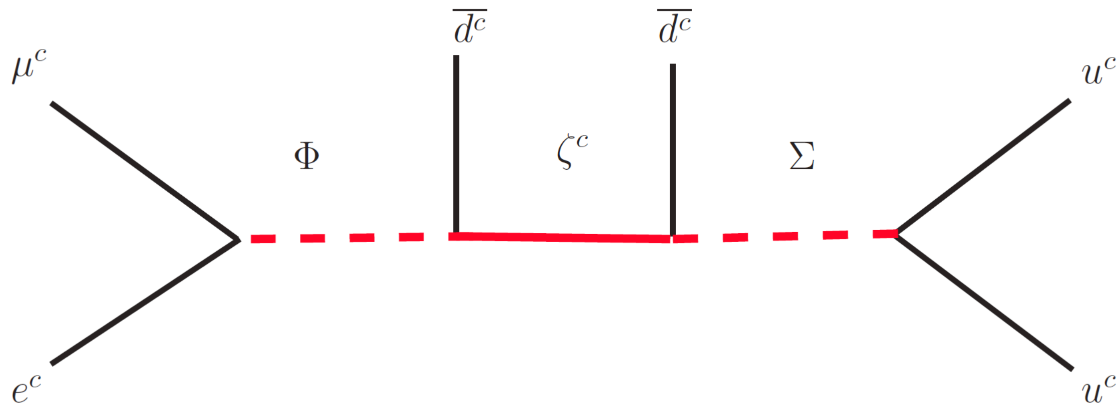
TABLE IV: All new particles required for all different tree-level realizations of the all-singlets dimension-nine operator $\mathcal{O}_s^{\alpha\beta}$, according to the restrictions discussed in the text. All particles are $SU(2)_L$ singlets. The fermions ψ, ζ, and χ come with a partner (ψ^c, ζ^c, and χ^c respectively), not listed. We don't consider fields that would couple to the antisymmetric combination of same-flavor quarks since these cannot couple quarks of the same generation.

New particles	$(\mathrm{SU}(3)_\mathrm{C}, \mathrm{SU}(2)_\mathrm{L})_{\mathrm{U}(1)_\mathrm{Y}}$	Spin
$\Phi \equiv (\overline{l^c}\,\overline{l^c})$	$(1,1)_{-2}$	scalar
$\Sigma \equiv (\overline{u^c}\,\overline{u^c})$	$(6,1)_{4/3}$	scalar
$\Delta \equiv (\overline{d^c}\,\overline{d^c})$	$(6,1)_{-2/3}$	scalar
$C \equiv (\overline{u^c}\,d^c)$	$(1,1)_1,\ (8,1)_1$	vector
$\psi \equiv (u^c\,l^c\,l^c)$	$(\overline{3},1)_{4/3}$	fermion
$\zeta \equiv (d^c\,\overline{l^c}\,\overline{l^c})$	$(\overline{3},1)_{-5/3}$	fermion
$\chi \equiv (l^c\,u^c\,u^c)$	$(\overline{6},1)_{-1/3}$	fermion
$N \equiv (l^c\,\overline{d^c}\,u^c)$	$(1,1)_0,\ (8,1)_0$	fermion

Model $\zeta\Phi\Sigma$

$$\mathcal{L}_{\zeta\Phi\Sigma} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} + y_{\Phi\alpha\beta}\,\Phi\ell^c_\alpha\ell^c_\beta + y_{\Sigma u}\,\Sigma u^c u^c$$

$$+\, y_{\Phi\zeta^c}\,\Phi\zeta^c d^c + y_{\Sigma\zeta}\,\Sigma\zeta d^c + m_\zeta\,\zeta\zeta^c + V(\Phi,\Sigma,0) + \text{h.c.}\,,$$



Induced $\mu^- \to e^+$ $\quad\Rightarrow\quad$ $$\frac{g_{\alpha\beta}}{\Lambda^5} \equiv \frac{y_{\Phi\alpha\beta}\, y^*_{\Phi\zeta^c}\, y^*_{\Sigma\zeta}\, y_{\Sigma u}}{M^2_\Phi\, M^2_\Sigma\, m_\zeta}$$

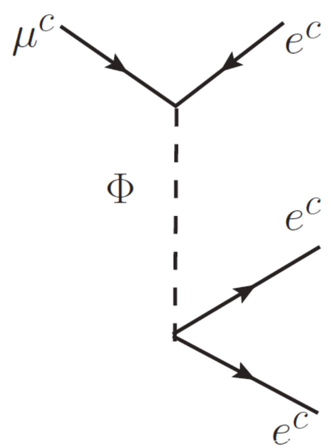
Model $\zeta\Phi\Sigma$

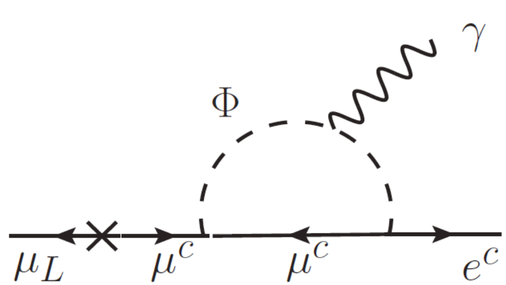
Various constraints from CLFV:

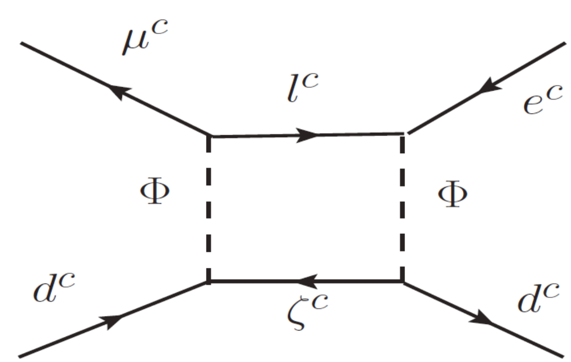
- $\mu \to 3\,e$ $\quad \mathcal{L}_{\mu\to 3e} = \frac{y_{\Phi e\mu}\, y^*_{\Phi ee}}{M_\Phi^2}\,(\mu^c e^c)\,(\overline{e^c}\,\overline{e^c})$ $\Longrightarrow$ $\frac{|y_{\Phi e\mu}\, y^*_{\Phi ee}|^2}{M_\Phi^4} \le 1.4\times 10^{-22}\,\mathrm{GeV}^{-4}$ $\quad \boxed{M_\Phi \ge 290\,\mathrm{TeV}}$

- $\mu \to e\,\gamma$ $\quad \mathcal{L}_{\mu^+\to e^+\gamma} = \frac{y^*_{\Phi\mu\mu}\, y_{\Phi\mu e}\,(2e)\, y_\mu}{16\pi^2 M_\Phi^2}(L\overline{H})\,\sigma^{\alpha\beta} e^c F_{\alpha\beta}$ $\Longrightarrow$ $5.3\times 10^{-6}\frac{|y^*_{\Phi\mu\mu}\, y_{\Phi\mu e}|^2}{M_\Phi^4\ (\mathrm{TeV})} < 4.2\times 10^{-13}$ $\quad \boxed{M_\Phi \gtrsim 60\ \mathrm{TeV}}$

- $\mu^- \to e^-$ $\quad \mathcal{L}_{\mu\to e} = \frac{y^*_{\Phi\mu\beta}\, y_{\Phi e\beta}\, y_{\Phi\zeta^c}\, y^*_{\Phi\zeta^c}}{16\pi^2\Lambda^2}\,(\overline{\mu^c}e^c)\,(\overline{d^c}d^c)$ $\Longrightarrow$ $\left|\frac{\sqrt{2}}{G_F}\,\frac{y^*_{\Phi\mu\beta}\, y_{\Phi e\beta}\, y_{\Phi\zeta^c}\, y^*_{\Phi\zeta^c}}{16\pi^2\Lambda^2}\right|^2 < 7\times 10^{-13}$ $\quad \boxed{\Lambda \ge 30\,\mathrm{TeV}}$



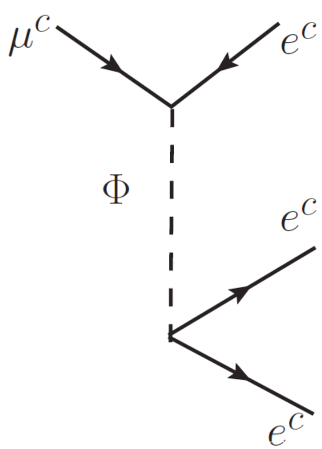


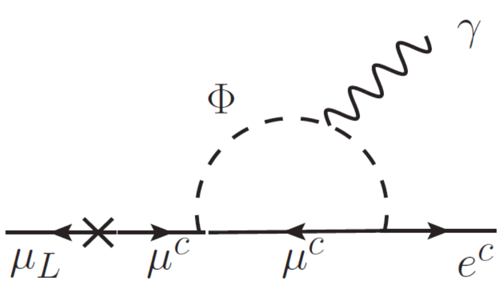


Model $\zeta\Phi\Sigma$

More leptonic constraints:

- $\mu^+ e^- \to \mu^- e^+$ $\quad \mathcal{L}_{\mathrm{Mu}-\overline{\mathrm{Mu}}} = \frac{y_{\Phi\mu\mu}\, y^*_{\Phi ee}}{M_\Phi^2} \left(\mu^c \mu^c\right) \left(\overline{e^c}\, \overline{e^c}\right)$ ⇨ $\frac{\left|y_{\Phi\mu\mu}\, y^*_{\Phi ee}\right|}{M_\Phi^2} \leq 2.5 \times 10^{-8}\, \mathrm{GeV}^{-2}$
- $e^+ e^- \to \mu^+ \mu^-$ $\quad \mathcal{L}_{e\mu} = \frac{y_{\Phi e\mu}\, y^*_{\Phi e\mu}}{M_\Phi^2}\, e^c \mu^c \overline{e^c}\, \overline{\mu^c}$ ⇨ $\frac{y_{\Phi e\mu}\, y^*_{\Phi e\mu}}{2\, M_\Phi^2} \leq \frac{4\pi}{\Lambda_\mu^2}$ and $\frac{y_{\Phi ee}\, y^*_{\Phi ee}}{2\, M_\Phi^2} \leq \frac{4\pi}{2\,\Lambda_e^2}$
- $(g-2)_\mu$ $\quad \Delta a_\mu = -\frac{m_\mu^2 \left(y_{\Phi e\mu}\, y^*_{\Phi e\mu} + y_{\Phi\mu\mu}\, y^*_{\Phi\mu\mu}\right)}{6\,\pi^2 M_\Phi^2}$ ⇨ $10.1 \times 10^{-10} < a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} < 42.1 \times 10^{-10}$





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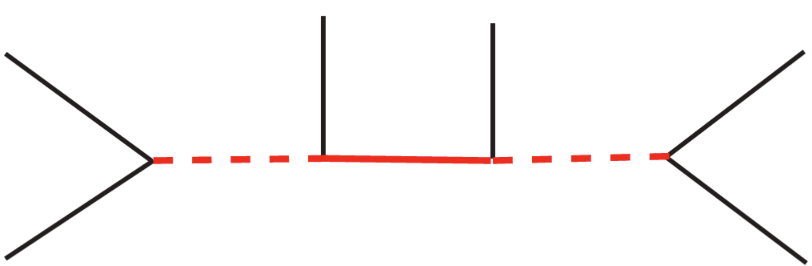
Model $\chi\Delta\Sigma$

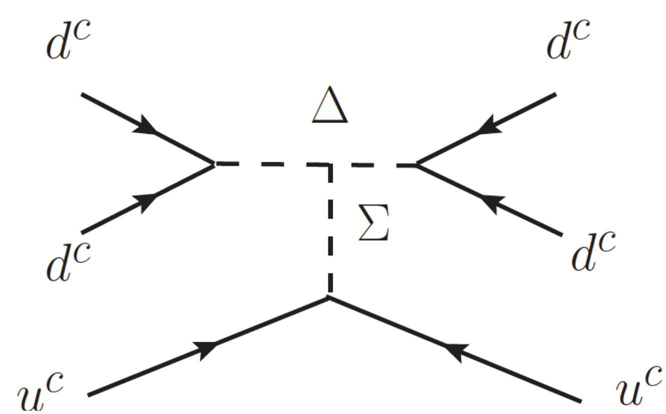
$$\mathcal{L}_{\chi\Delta\Sigma} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} + y_{\Sigma u}\,\Sigma u^c u^c + y_{\Delta d}\,\Delta d^c d^c + y_{\Delta\chi}\,\Delta\overline{\chi}\,\overline{\chi} + y_{\Delta\chi^c}\,\Delta\chi^c\chi^c + y_{\Sigma\alpha}\,\overline{\Sigma}\chi^c\ell^c_\alpha + y_{\Delta\alpha}\,\Delta\chi\ell^c_\alpha$$

Baryon constraints:

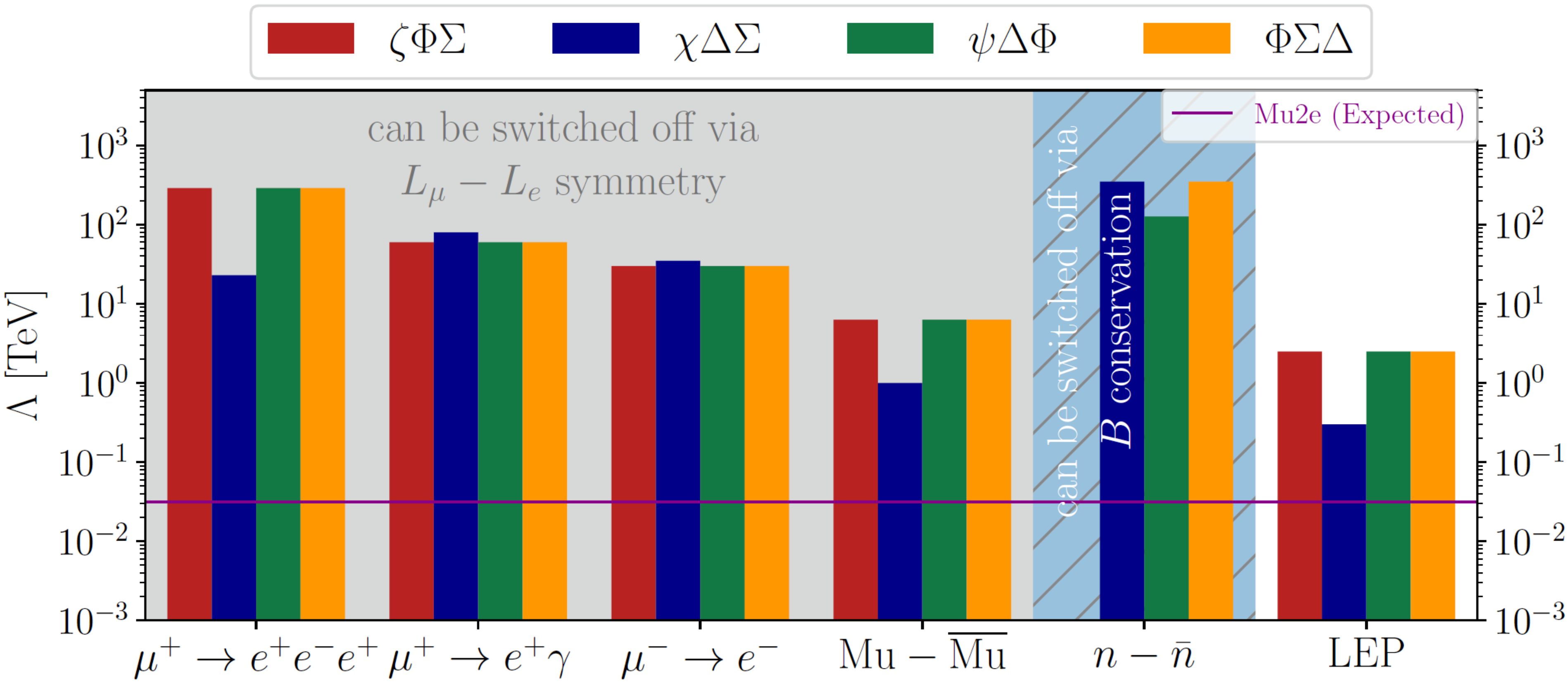
- $n \leftrightarrow \bar{n}$ $\quad \mathcal{L}_{n-\overline{n}} = \dfrac{y_{\Sigma u} y_{\Delta d}^2\, m_{\Sigma\Delta}}{M_\Delta^4\, M_\Sigma^2}(u^c d^c d^c)^2$ $\Rightarrow$ $\Lambda \gtrsim 350\ \text{TeV}$

- BNV with LNV $\quad (d^c d^c d^c \overline{\ell^c})^2$ and $(u^c u^c d^c \ell^c)^2$ $\Rightarrow$ $\Lambda \gtrsim 1\ \text{TeV}$
  $pp \to e^+ e^+$





Summary plot



Summaries

- Stringent CLFV constraints can be switched off or suppressed if $(L_\mu - L_e)$ is (approximately) conserved
- BNV limits can be avoided if baryon number is conserved by underlying UV theories
- Collider bounds can be weakened if mediator masses and/or couplings become small

Conclusions

- $O_s^{\alpha\beta}$ $(\ell_\alpha^c \ell_\beta^c u^c u^c\, \overline{d^c}\, \overline{d^c})$ is a special operator which consists of $SU(2)_L$ singlets only
- It can yield sizable $\mu^- \to e^+$ without generating too large neutrino masses
- Both of CLFV and BNV constraints can be avoided by imposing proper local/gauge symmetry while collider constraints of lepton-flavor-conserving can be alleviated by small couplings and/or masses