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Charged Lepton Flavor Violation in a Flavor Portal Matter Model

The Institute For Elementary Particle Physics

Lepton Photon 2025 Presentation

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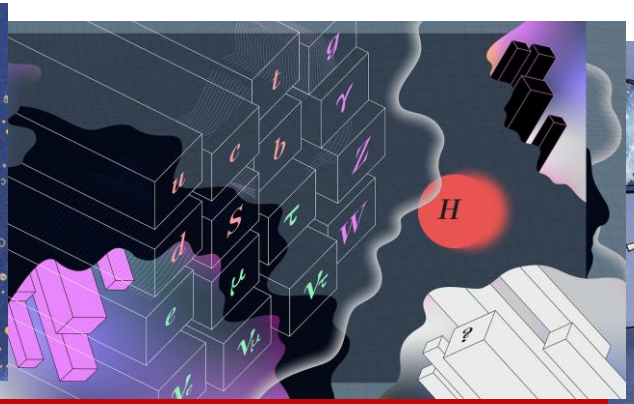
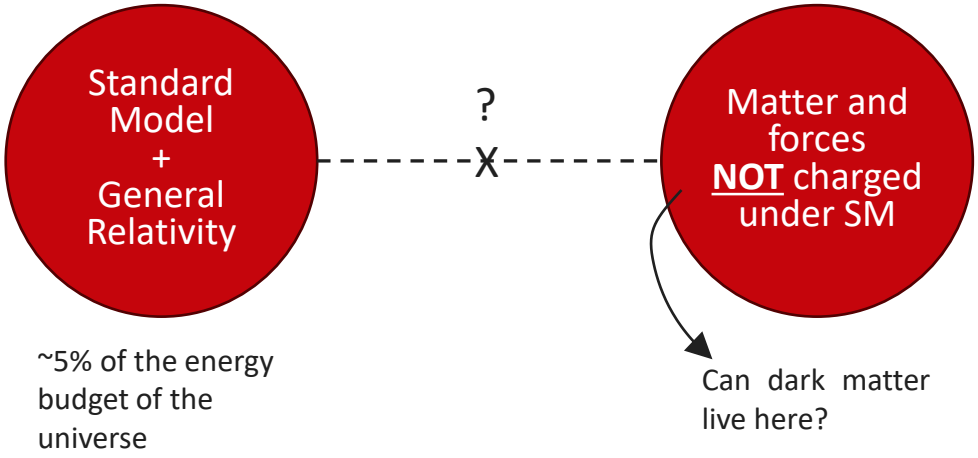


Image Credit: Symmetry Magazine

Introduction: DM and Vector Portal/KM

- ΛCDM & The Universe Energy Budget: $\Omega_m = \Omega_B + \Omega_{DM}$
  - Baryonic matter: $\Omega_B = 0.05$
  - DM: $\Omega_{DM} = 0.26$ corresponding to dark matter (DM)
    - Plethora of evidence: galaxy rotation curves, gravitational lensing, etc.

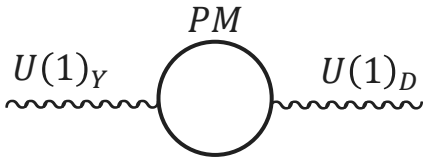


- DM in sub-GeV mass range: Vector Portal/Kinetic Mixing (KM) framework

Drawing from Philip Schuster TASI lectures

Introduction: Vector Portal/KM and PM

- SM gauge group augmented by a local $U(1)_D$
  - Gauge boson A_D dark photon (DP)
  - $U(1)_D$ spontaneously broken by dark Higgs h_D
- Kinetic mixing between $U(1)_D$ and $U(1)_Y$: $\frac{\epsilon}{2c_w} B_D^{\mu\nu} B_{Y\mu\nu}$
  - DM/DP in sub-GeV range: $\epsilon \sim 10^{-(3-5)}$ due to pheno constraints.
  - As noted by Holdom [1]: KM in this range generated at one loop by portal matter (PM) fields charged under both $U(1)_D$ and $U(1)_Y$:



- Fermion PM: to avoid gauge anomalies and pheno constraints, assume vector-like leptons (VLL) and/or vector-like quarks (VLQ)
  - In both cases, unstable: Same quantum number as SM fermions
- Focus here on VLL

[1] - Phys. Lett. B 166, 196 (1986) and Phys. Lett. B 178, 65 (1986)

Previous and Current Work

- Prior work [1]: minimal $\mathrm{U(1)_D}$ PM construction $(L^{\pm}, E^{\pm})$
  - $Q_D = \pm 1$ electroweak doublet $L^{\pm}$
  - $\mathrm{Q_D} = \pm 1$ electroweak singlet $E^{\pm}$
  - Constraints from flavor diagonal observable $(g-2)_{\mu}$
- Prior work [2]: TeV-scale completion of this minimal PM construction
  - SM and PM fields as members of the same dark gauge multiplets
  - Naturally leads to a setup in which VLL PM $(L^{\pm}, E^{\pm})$ coexist with a with a $\mathrm{U(1)_D}$-neutral VLL (L^0, E^0)
- Here, $U(1)_D$ with VLL PM $(L^{\pm}, E^{\pm})$ and $\mathrm{U(1)_D}$-neutral VLL (L^0, E^0):
  - Charged lepton flavor conserving (CLFC): MDM
  - Charged lepton flavor violation (CLFV): $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^-e^+$ constraints on model parameter space

[1] - Physics Letters B 841 (2023): 137931, [2] - Physical Review D 108.5 (2023): 055033

The Model

	Name	Field	Mass
Leptons	PM VLL	$L^{\pm}, E^{\pm}$	~TeV
	$U(1)_D$ - Neutral VLL	L^0, E^0	~TeV
Dark Sector	Dark Photon	A_D	Sub-GeV
	Dark Higgs	h_D	Sub-GeV

Field	$SU(2)_L \times U(1)_Y$	$U(1)_D$
L^0	$\mathbf{2}_{-\frac{1}{2}}$	0
$L^{\pm}$	$\mathbf{2}_{-\frac{1}{2}}$	± 1
E^0	$\mathbf{1}_{+1}$	0
$E^{\pm}$	$\mathbf{1}_{+1}$	± 1

- PM-PM/SM Couplings:

	e_R^i	$E_R^{\pm}$	$L_R^{\pm}$
e_L^i	0	0	$y_{iL}^{\pm}$
$E_L^{\pm}$	$y_{Ei}^{\pm}$	0	$y_{EL}^{\pm}$
$L_L^{\pm}$	0	$y_{LE}^{\pm}$	0

- Neutral VLL/SM Couplings:

	e_R^i	E_R^0	L_R^0
e_L^i	0	λ_{iE}	0
E_L^0	0	0	y_{EL}^0
L_L^0	λ_{Li}	y_{LE}^0	0

- Neutral VLL/PM Couplings:

	L_R^0	$L_R^{\pm}$	E_R^0	$E_R^{\pm}$
L_L^0	0	$\lambda_L^{0\pm}$	0	0
$L_L^{\pm}$	$\lambda_L^{\pm 0}$	0	0	0
E_L^0	0	0	0	$\lambda_E^{0\pm}$
$E_L^{\pm}$	0	0	$\lambda_E^{\pm 0}$	0

Higgs Dark Higgs

Lepton Interactions

- Lepton fields ($a = L, R$):
  - Charged Leptons: $\psi_a^0 = (e, \mu, \tau, L^0, L^+, L^-, E^0, E^+, E^-)_a^T$ with $\psi_a^0 = U_a^e \psi_a$
  - Neutrinos: $n_a^0 = (\nu^e, \nu^\mu, \nu^\tau, N^0, N^+, N^-)_a^T$ with $n_a^0 = U_a^\nu n_a$
- Perturbative expansion: $\frac{v_S}{M_{VLL}} \sim \mathcal{O}(10^{-(3-4)})$ and $\frac{v_H}{M_{VLL}} < \mathcal{O}(0.1)$

v_S dependent variables		v_H dependent variables	
$\kappa_{Li}^{\pm} = \frac{y_{iL}^{\pm}}{\sqrt{2}}\left(\frac{v_S}{M_L^{\pm}}\right)$	$\rho_{L(E)L}^{\pm} = \frac{\left(M_{L(E)}^{\pm}\lambda_{L(E)}^{0\pm} + M_{L(E)}^{0}\lambda_{L(E)}^{\pm 0}\right)}{\left(M_{L(E)}^{\pm\,2} - M_{L(E)}^{0\,2}\right)}\left(\frac{v_S}{\sqrt{2}}\right)$	$q_{Li} = \frac{\lambda_{iE}}{\sqrt{2}}\left(\frac{v_H}{M_E^0}\right)$	$p_L^{0(\pm)} = \frac{\left(M_L^{0(\pm)}\lambda_{EL}^{0(\pm)} + M_E^{0(\pm)}y_{LE}^{0(\pm)}\right)}{\left(M_{L(E)}^{\pm\,2} - M_{L(E)}^{0\,2}\right)}\left(\frac{v_S}{\sqrt{2}}\right)$
$\kappa_{Ri}^{\pm} = \frac{y_{Ei}^{\pm}}{\sqrt{2}}\left(\frac{v_S}{M_E^{\pm}}\right)$	$\rho_{L(E)L}^{\pm} = \frac{\left(M_{L(E)}^{\pm}\lambda_{L(E)}^{0\pm} + M_{L(E)}^{0}\lambda_{L(E)}^{\pm 0}\right)}{\left(M_{L(E)}^{\pm\,2} - M_{L(E)}^{0\,2}\right)}\left(\frac{v_S}{\sqrt{2}}\right)$	$q_{Ri} = \frac{\lambda_{Li}}{\sqrt{2}}\left(\frac{v_H}{M_L^0}\right)$	$p_R^{0(\pm)} = \frac{\left(M_E^{0(\pm)}\lambda_{EL}^{0(\pm)} + M_L^{0(\pm)}y_{LE}^{0(\pm)}\right)}{\left(M_E^{0(\pm)^2} - M_L^{0(\pm)^2}\right)}\left(\frac{v_H}{\sqrt{2}}\right)$

- Scalar/Vector Interactions:

$$\mathcal{L} = \bar{\psi}\not{Z}[(g_L^Z)P_L + (g_R^Z)P_R]\psi + \bar{\psi}\not{A}_D[(g_L^D)P_L + (g_R^D)P_R]\psi - e\bar{\psi}\not{A}\psi$$
$$-\frac{h}{\sqrt{2}}\overline{\psi}y_h\psi - \frac{h_D}{\sqrt{2}}\overline{\psi}y_D\psi + \overline{n}\not{W}^+[(g_L^W)P_L + (g_R^W)P_R]\psi + h.c.$$

  - Higgs and dark Higgs: $y_h \sim g_h^{SM} + \frac{v_H^2}{M_{VLL}^2}$ and $y_D \sim \frac{v_H v_S}{M_{VLL}^2}$
  - Z-boson and dark photon: $g_{L,R}^Z \sim g_{SM\,L,R}^Z + \frac{v_H^2}{M_{VLL}^2}$ and $g_{L,R}^D \sim \frac{v_S^2}{M_{VLL}^2}$

Minimal Model

Δa_μ & Reinforcement Learning [1]

- Model (a,b):$\{L^\pm, E^\pm\}$
  - No correction to SM-Z vertex
  - SM flavor diagonal Z/h vertex

$$\delta g_L^Z = 0 = \delta g_R^Z$$

- Model (c,d):$\{L^0, L^\pm\}$
  - Corrections to SM-Z vertex
  - Induced SM flavor off-diagonal Z/h vertex

$$\delta g_L^Z = 0 \qquad (\delta g_R^Z)_{ij} = -\frac{1}{2s_w^2} q_{Ri} q_{Rj}$$

- Model (e,f):$\{E^0, E^\pm\}$
  - Correction to SM-Z vertex
  - Induced SM flavor off-diagonal Z/h vertex

$$\delta g_L^Z = -\frac{1}{c_{2w}} q_{Li} q_{Lj} \qquad \delta g_R^Z = 0$$

	e_L^i	$L_L^\pm$	$E_L^\pm$
e_{ML}^i	1	$\kappa_{Li}^\pm$	0
$L_{ML}^\pm$	0	1	$p_L^\pm$
$E_{ML}^\pm$	0	$p_L^\pm$	1

	e_R^i	$L_R^\pm$	$E_R^\pm$
e_{MR}^i	1	0	$\kappa_{Ri}^\pm$
$L_{MR}^\pm$	0	1	$p_R^\pm$
$E_{MR}^\pm$	0	$p_R^\pm$	1

	e_L^i	L_L^0	$L_L^\pm$
e_{ML}^i	1	0	$\kappa_{Li}^\pm$
L_{ML}^0	0	1	$\rho_{LL}^\pm$
$L_{ML}^\pm$	$\kappa_{Li}^\pm$	$\rho_{LL}^\pm$	1

	e_R^i	L_R^0	$L_R^\pm$
e_{MR}^i	1	q_{Ri}	0
L_{MR}^0	q_{Ri}	1	0
$L_{MR}^\pm$	0	$\rho_{LR}^\pm$	1

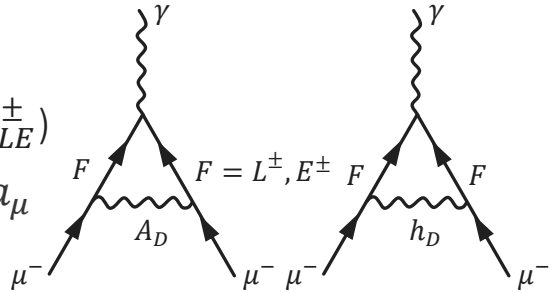
	e_L^i	E_L^0	$E_L^\pm$
e_{ML}^i	1	q_{Li}	0
E_{ML}^0	q_{Li}	1	0
$E_{ML}^\pm$	0	$\rho_{EL}^\pm$	1

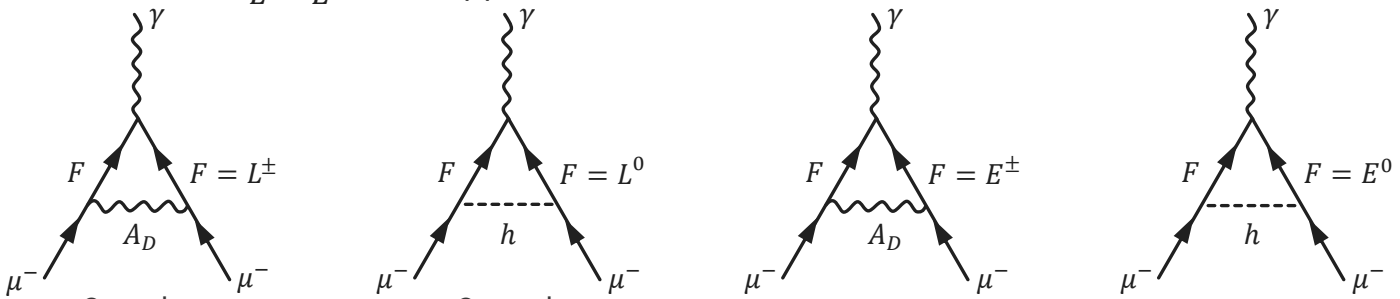
	e_R^i	E_R^0	$E_R^\pm$
e_{MR}^i	1	0	$\kappa_{Ri}^\pm$
E_{ML}^0	$\rho_{ER}^\pm$	1	0
$E_{ML}^\pm$	$\kappa_{Ri}^\pm$	$\rho_{ER}^\pm$	1

Observables: $(g-2)_\mu$

- Model (a,b) $\{L^\pm, E^\pm\}$:
  - Chiral enhancement: Higgs coupling with different VLL $(y_{LE}^\pm)$
  - $y_{\mu L}^\pm, y_{E\mu}^\pm \sim 0(1) \Rightarrow y_{LE}^\pm < 10^{-2}$ to accommodate a possible Δa_μ

$$\Delta a_\mu^{(a,b)} \approx -\frac{1}{16\pi^2}\left(\frac{m_\mu^2}{M_L^\pm M_E^\pm}\right)\frac{y_{E\mu}^\pm y_{\mu L}^\pm y_{LE}^\pm}{y_{\mu\mu}}$$

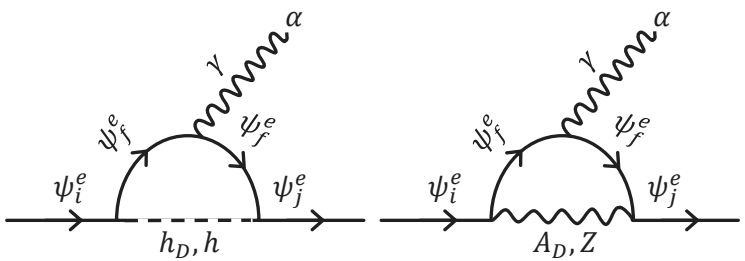




- Model (c,d) $\{L^0, L^\pm\}$ and (e,f) $\{E^0, E^\pm\}$:
  - Chiral enhancement: Dark-Higgs coupling with different VLL $(\lambda_L^{\pm 0}, \lambda_E^{0\pm})$
  - $\lambda_{L\mu}, y_{\mu L}^\pm \sim 0(1) \Rightarrow \lambda_L^{\pm 0} < 10^{-2}$ to accommodate a possible Δa_μ
  - $\lambda_{\mu E}, y_{E\mu}^\pm \sim O(1) \Rightarrow \lambda_E^{0\pm} < 10^{-2}$ to accommodate a possible Δa_μ

$$\Delta a_\mu^{(c,d)} \approx -\frac{1}{16\pi^2}\left(\frac{m_\mu^2}{M_L^0 M_L^\pm}\right)\frac{\lambda_{L\mu} y_{\mu L}^\pm \lambda_L^{\pm 0}}{y_{\mu\mu}} \qquad \Delta a_\mu^{(e,f)} \approx -\frac{1}{16\pi^2}\left(\frac{m_\mu^2}{M_E^0 M_E^\pm}\right)\frac{\lambda_{\mu E} y_{E\mu}^\pm \lambda_E^{0\pm}}{y_{\mu\mu}}$$

Observables: $\mu^+ \to e^+\gamma$



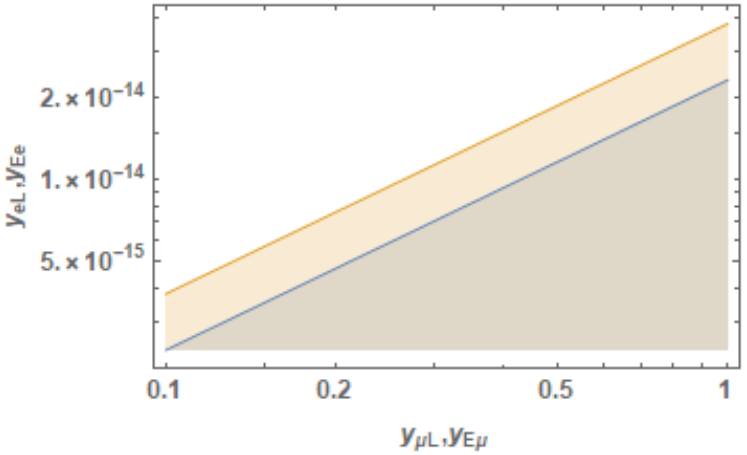
- Branching Ration: $\mathrm{BR} < 4.2 \times 10^{-13}$[1] (current) and $\mathrm{BR} < 10^{-14}$[2] (future)
- Model (a,b) $\{L^{\pm}, E^{\pm}\}$:

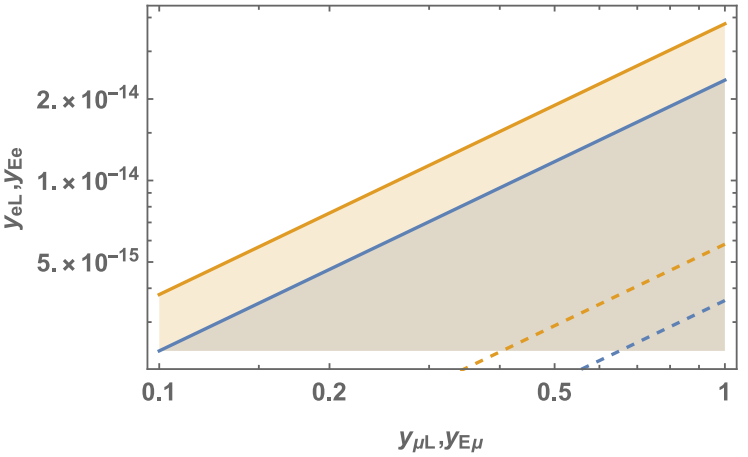
$$BR^{(a,b)}(\mu \to e\gamma) = \frac{3(4\pi)^3\alpha}{32}\left(\frac{\Delta a_\mu^{(a,b)}}{G_F m_\mu^2}\right)^2\left[\left(\frac{y_{eL}^{\pm}}{y_{\mu L}^{\pm}}\right)^2 + \left(\frac{y_{Ee}^{\pm}}{y_{E\mu}^{\pm}}\right)^2\right]$$

  - $y_{\mu L}^{\pm}, y_{E\mu}^{\pm} \sim 0(1) \Rightarrow y_{eL}^{\pm}, y_{Ee}^{\pm} < 2.9 \times 10^{-14}$
- Model (c,d) $\{L^0, L^{\pm}\}$ and Model (e,f) $\{E^0, E^{\pm}\}$:
  - $\lambda_{L\mu}, y_{\mu L}^{\pm} \sim 0(1) \Rightarrow \lambda_{Le}, y_{eL}^{\pm} < 2.9 \times 10^{-14}$
  - $\lambda_{\mu E}, y_{E\mu}^{\pm} \sim 0(1) \Rightarrow \lambda_{eE}, y_{Ee}^{\pm} < 2.9 \times 10^{-14}$

$$BR^{(c,d)}(\mu \to e\gamma) = \frac{3(4\pi)^3\alpha}{32}\left(\frac{\Delta a_\mu^{(c,d)}}{G_F m_\mu^2}\right)^2\left[\left(\frac{\lambda_{Le}}{\lambda_{L\mu}}\right)^2 + \left(\frac{y_{eL}^{\pm}}{y_{\mu L}^{\pm}}\right)^2\right]$$

$$BR^{(e,f)}(\mu \to e\gamma) = \frac{3(4\pi)^3\alpha}{32}\left(\frac{\Delta a_\mu^{(e,f)}}{G_F m_\mu^2}\right)^2\left[\left(\frac{\lambda_{eE}}{\lambda_{\mu E}}\right)^2 + \left(\frac{y_{Ee}^{\pm}}{y_{E\mu}^{\pm}}\right)^2\right]$$

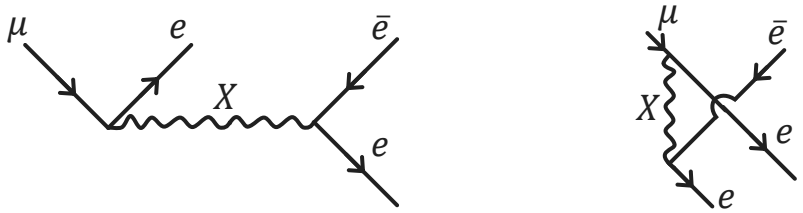




[1] - arXiv:1605.05081 and [2] - Proceedings of Science 452 (2024)

Observables: $\mu^+ \to e^+e^-e^+$

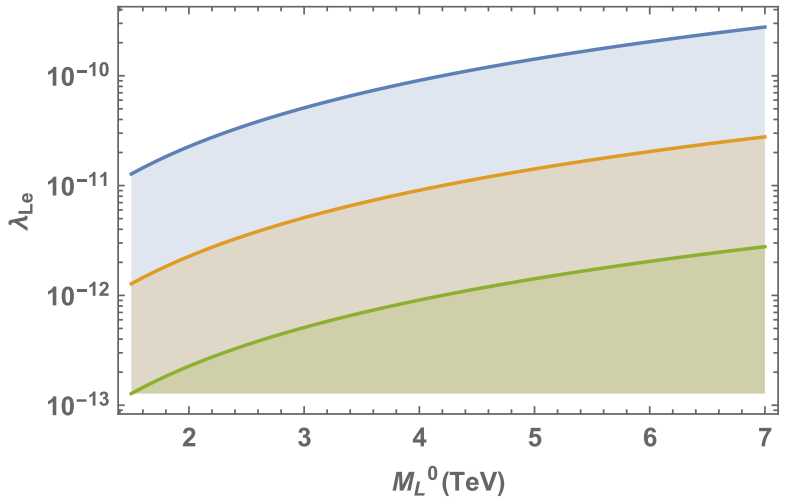
- Branching Ration: $\mathrm{BR} < 10^{-13}$[1] (current) and $\mathrm{BR} < 2 \times 10^{-15}$ (future)
- Model (a,b) $\{L^{\pm}, E^{\pm}\}$:
  - Induced at loop level only
  - Broader parameter space available

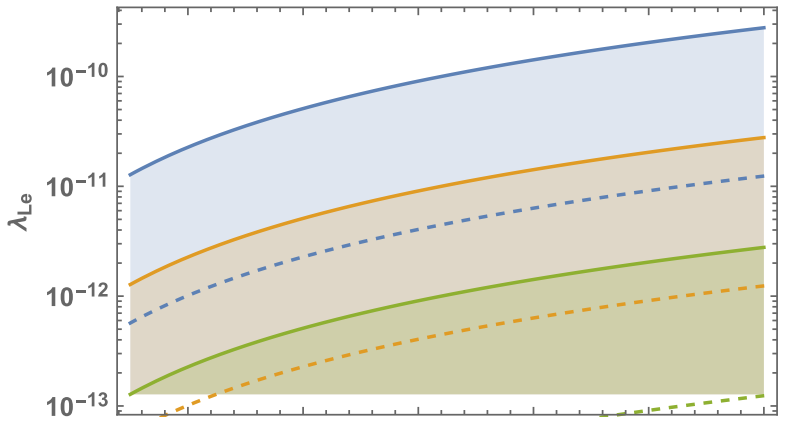


- Models (c,d) $\{L^0, L^{\pm}\}$ and (e,f) $\{E^0, E^{\pm}\}$:
  - Induced at tree level via Z-boson exchange
  - More constrained parameter space

$$BR \approx \frac{1}{128}\left(\frac{g_L q_{Re} q_{R\mu}}{G_F M_Z^2 c_w^2}\right)^2 (7 - 8c_{2w} + 3c_{4w})$$

$$BR \approx \frac{1}{128}\left(\frac{g_L q_{Le} q_{L\mu}}{G_F M_Z^2 c_w^2}\right)^2 (7 - 8c_{2w} + 3c_{4w})$$





[1] - arXiv:2204.00001

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Conclusion and Perspectives

- CLFV: Clear BSM signal with even stronger constraints expected from future experiments
- Observables with significant h_D and A_D appear in loops with much heavier VLL
  - The observables considered here are agnostic to the sub-GeV BSM field content
  - Identifying a viable sub-GeV parameter space is orthogonal to what we are doing here
- Loop level contributions to $\mu^+ \to e^+ e^- e^+$ for models (a,b)
- EW precision measurements
  - Models (a,b) are relatively safe
  - Working on results for models (c,d,e,f)
- $\mu - e$ conversion in nuclei


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