Distiguishing models with $\mu \to e$ observables

Marco Ardu
Univ. de Valencia, IFIC

Zurich, UZH
05/06/2024

Based on 2308.16897 and 2401.06214, in collaboration with S. Davidson and S. Lavignac

Neutrino masses imply Lepton Flavour Violation

The Standard Model Lagrangian (without right-handed neutrinos) is accidentally invariant under a phase rotation of each lepton flavor $U(1)_{L_\alpha}$

$$\ell_\alpha = \begin{pmatrix} \nu_\alpha \\ \alpha_L \end{pmatrix}, e_\alpha = \alpha_R \quad \text{with} \quad \alpha = e, \mu, \tau$$

$$U(1)_{L_\alpha} : \begin{cases} \ell_\alpha \to e^{i\chi_\alpha} \ell_\alpha \\ e_\alpha \to e^{i\chi_\alpha} e_\alpha \end{cases}$$

Neutrino masses imply Lepton Flavour Violation

The Standard Model Lagrangian (without right-handed neutrinos) is accidentally invariant under a phase rotation of each lepton flavor $U(1)_{L_\alpha}$

$$\ell_\alpha = \begin{pmatrix} \nu_\alpha \\ \alpha_L \end{pmatrix}, e_\alpha = \alpha_R \quad \text{with} \quad \alpha = e, \mu, \tau$$

$$U(1)_{L_\alpha} : \begin{cases} \ell_\alpha \to e^{i\chi_\alpha} \ell_\alpha \\ e_\alpha \to e^{i\chi_\alpha} e_\alpha \end{cases}$$

Neutrino masses break all symmetries

$$\begin{tikzcd} & \nu_\tau \arrow[dl, leftrightarrow] \arrow[dr, leftrightarrow] & \\ \nu_\mu \arrow[rr, leftrightarrow] & & \nu_e \end{tikzcd}$$

Neutrino masses imply Lepton Flavour Violation

The Standard Model Lagrangian (without right-handed neutrinos) is accidentally invariant under a phase rotation of each lepton flavor $U(1)_{L_\alpha}$

$$\ell_\alpha = \begin{pmatrix} \nu_\alpha \\ \alpha_L \end{pmatrix}, e_\alpha = \alpha_R \quad \text{with} \quad \alpha = e, \mu, \tau \qquad\qquad U(1)_{L_\alpha} : \begin{cases} \ell_\alpha \to e^{i\chi_\alpha} \ell_\alpha \\ e_\alpha \to e^{i\chi_\alpha} e_\alpha \end{cases}$$

Neutrino masses break all symmetries

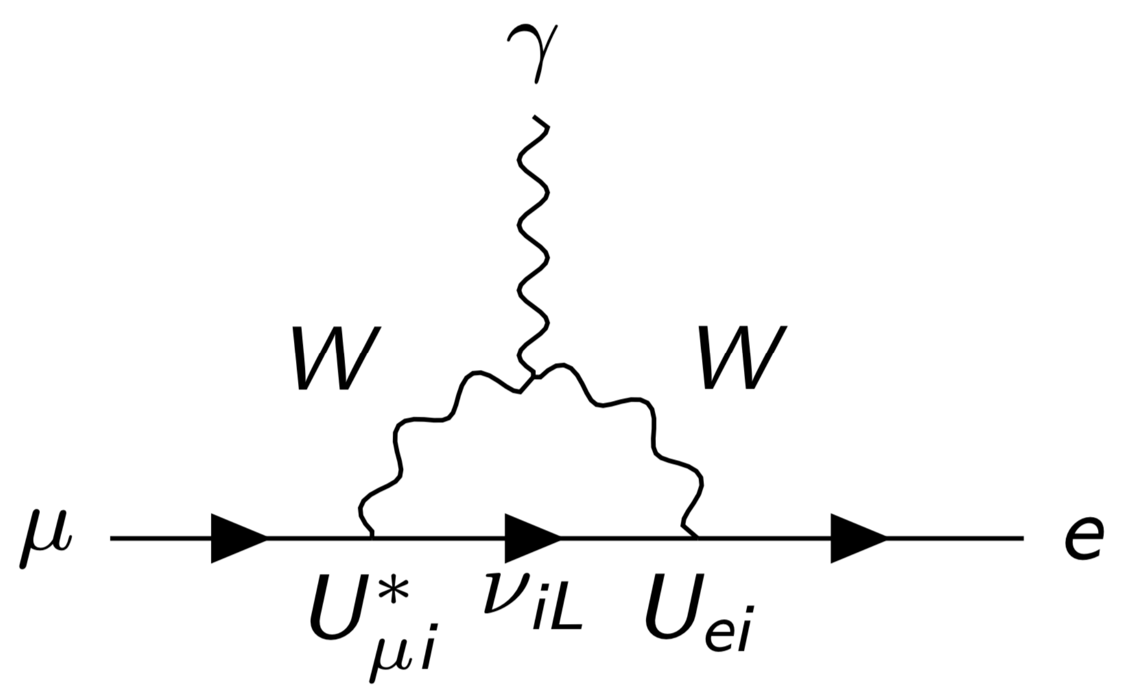
$$\begin{tikzcd} & \nu_\tau \arrow[dl, leftrightarrow] \arrow[dr, leftrightarrow] & \\ \nu_\mu \arrow[rr, leftrightarrow] & & \nu_e \end{tikzcd}$$

Since there is no symmetry that forbids it, lepton flavour violation in the charged sector is inevitable:

$$\mu^\pm \to e^\pm \gamma \qquad \tau^\pm \to e^\pm e^+ e^- \qquad h \to \tau^\pm \mu^\mp \ldots$$

must happen, but at what rates?

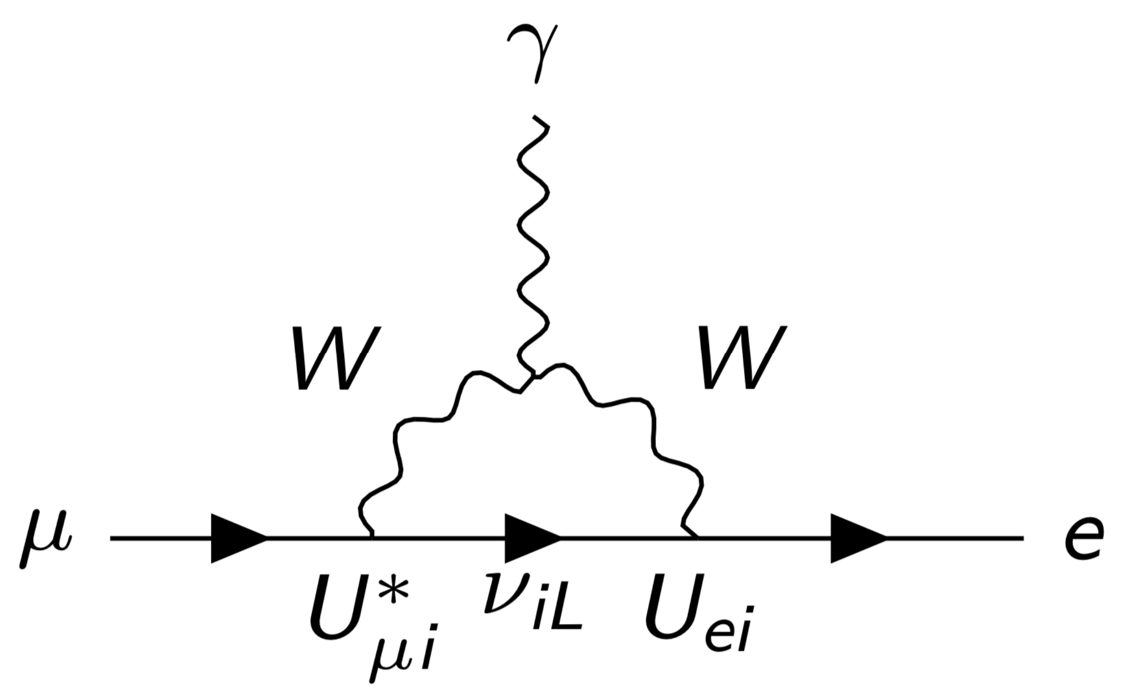
Charged Lepton Flavour Violation (LFV)



- SM+ν_R predicts small LFV

$$Br(\mu \to e\gamma) \simeq G_F^2(\Delta m_\nu^2)^2 \lesssim 10^{-50}$$

Charged Lepton Flavour Violation (LFV)



- SM+ν_R predicts small LFV

$$Br(\mu \to e\gamma) \simeq G_F^2(\Delta m_\nu^2)^2 \lesssim 10^{-50}$$

- An observation of LFV would be a clear signature of new physics

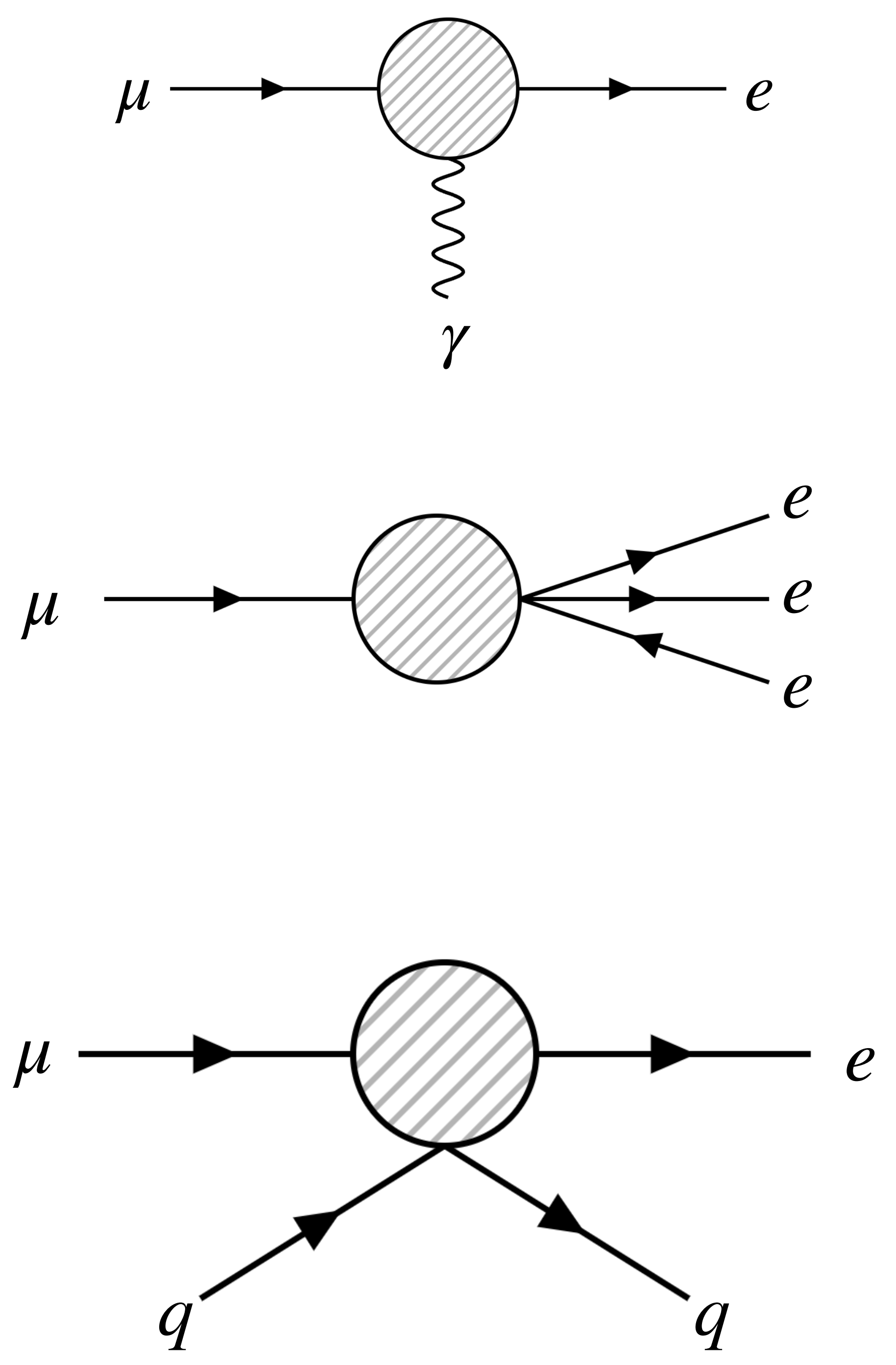
- It could shed light on the mechanism behind neutrino masses (and potentially on the baryon asymmetry if generated via leptogenesis?)

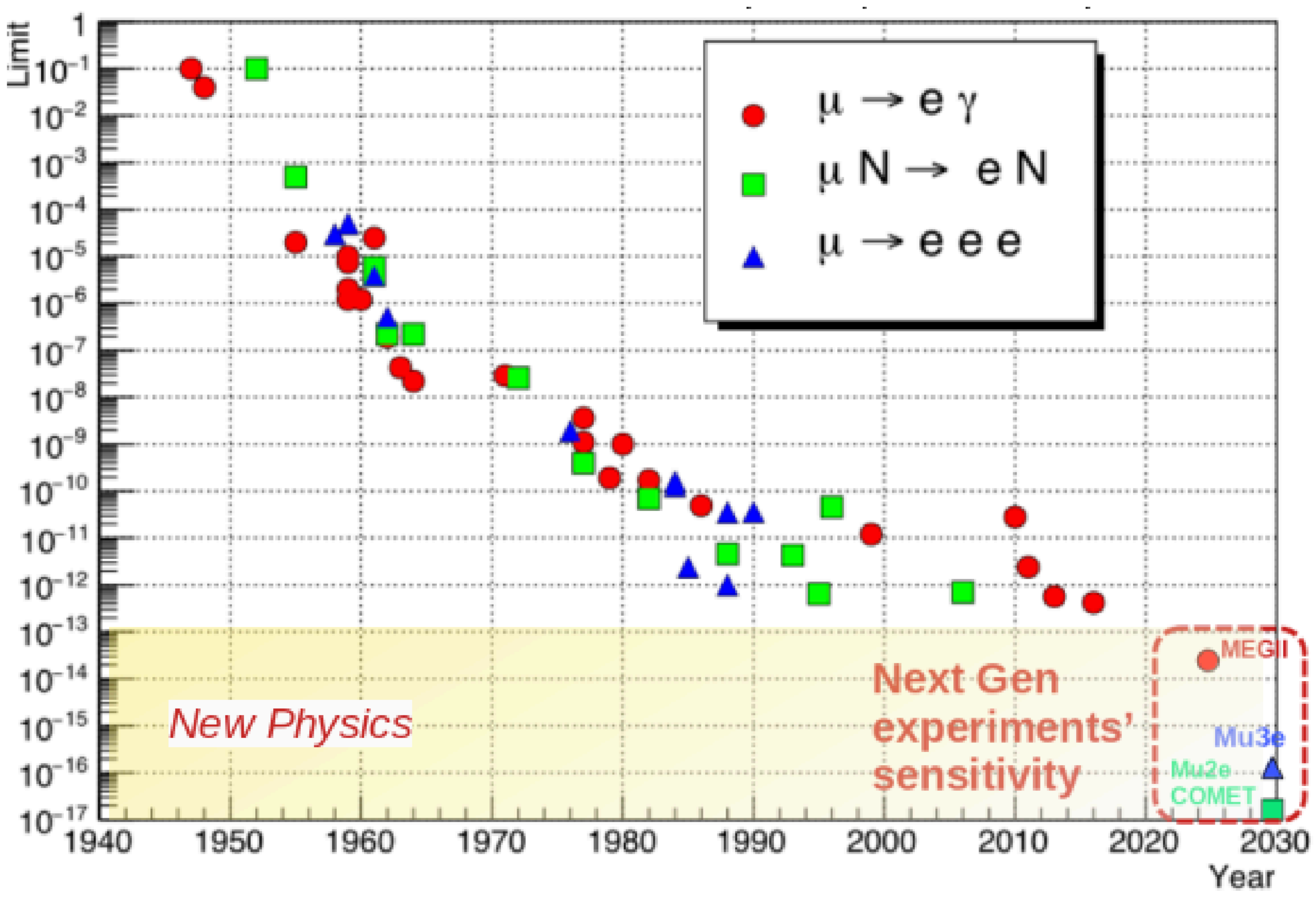
- Many models that address unresolved puzzles (independently from neutrino masses) predict potentially observable LFV signals

$\mu \to e\gamma,\ \mu \to 3e,\ \mu A \to eA$

- The possibility of extremely intense muon beams make these the golden channels for LFV

- Experimental sensitivities are expected to be improved by up to five orders of magnitude





Effective Field Theory for LFV

- Many models predict LFV = would be nice to analyse data in a model-independent way

Effective Field Theory for LFV

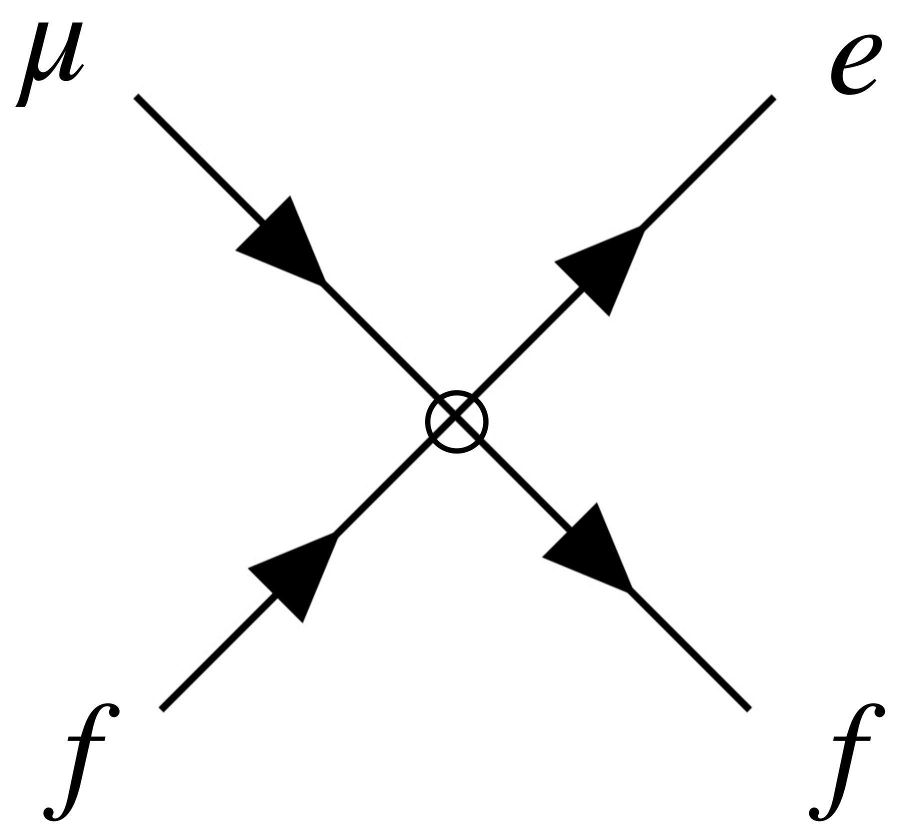
- Many models predict LFV = would be nice to analyse data in a model-independent way

- If LFV New Physics is heavy $(\Lambda \gtrsim \mathrm{few} \times \mathrm{TeV})$ and it can be integrated out

Effective Field Theory for LFV

- Many models predict LFV = would be nice to analyse data in a model-independent way

- If LFV New Physics is heavy $(\Lambda \gtrsim \text{few} \times \text{TeV})$ and it can be integrated out

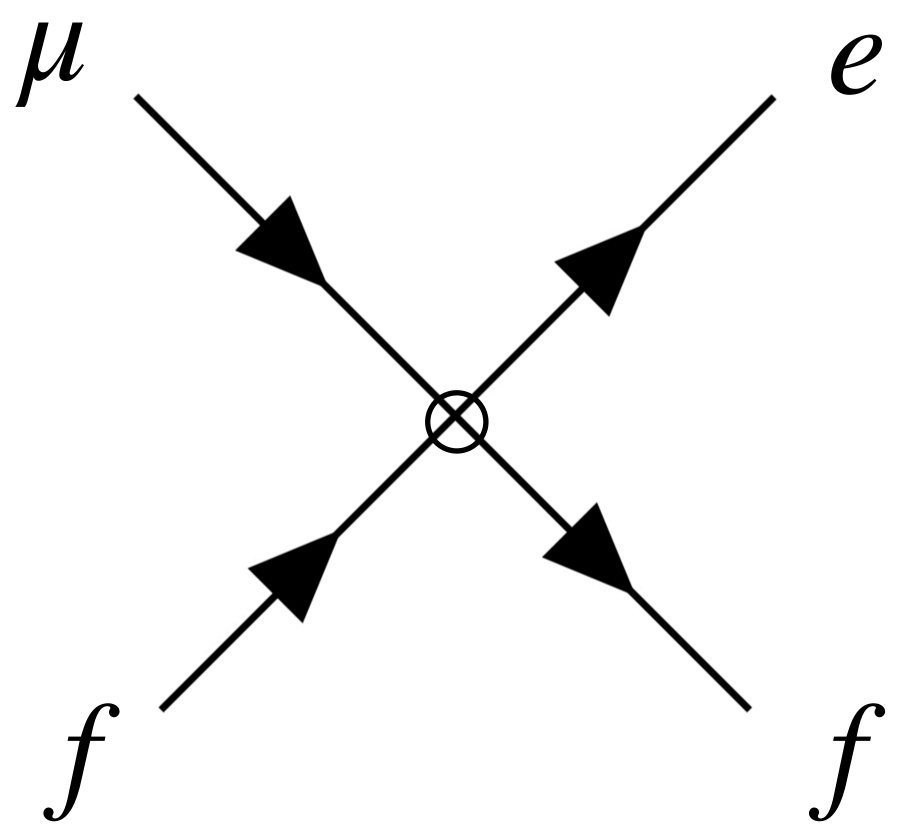


$$\sim \frac{C}{\Lambda^2}$$

Effective Field Theory for LFV

- Many models predict LFV = would be nice to analyse data in a model-independent way

- If LFV New Physics is heavy $(\Lambda \gtrsim \text{few} \times \text{TeV})$ and it can be integrated out



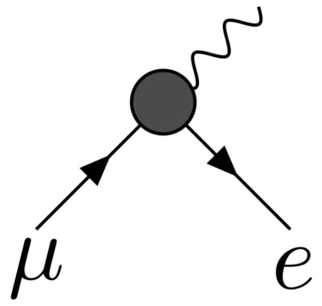
$$\sim \frac{C}{\Lambda^2}$$

- Add to the Lagrangian the contact interactions (non-renormalizable operators) compatible with the symmetries

$$\mathscr{L}_{\text{EFT}} = \mathscr{L}_{d \leq 4} + \sum_{n>4} \frac{C_n \mathcal{O}_n}{\Lambda^{n-4}}$$

Effective Field Theory for LFV

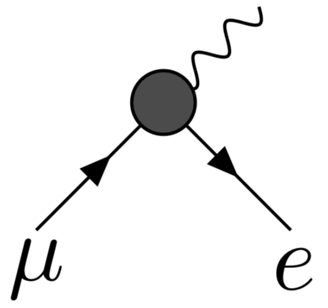
- Observables are calculated in terms of the operator coefficients



$$\delta\mathscr{L}_{\mu\to e\gamma} = \frac{m_\mu}{\Lambda^2}(C^{e\mu}_{D,R}\overline{e}\sigma_{\alpha\beta}P_R\mu + C^{e\mu}_{D,L}\overline{e}\sigma_{\alpha\beta}P_L\mu)F^{\alpha\beta}$$

Effective Field Theory for LFV

- Observables are calculated in terms of the operator coefficients



$$\delta\mathscr{L}_{\mu\to e\gamma} = \frac{m_\mu}{\Lambda^2}(C^{e\mu}_{D,R}\bar{e}\sigma_{\alpha\beta}P_R\mu + C^{e\mu}_{D,L}\bar{e}\sigma_{\alpha\beta}P_L\mu)F^{\alpha\beta}$$

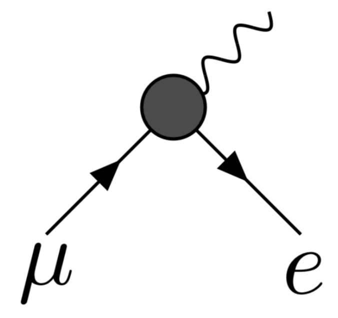
$$Br(\mu \to e\gamma) = 384\pi^2\left(\frac{v}{\Lambda}\right)^4(|C^{e\mu}_{D,R}|^2 + |C^{e\mu}_{D,L}|^2) < 4.2\times 10^{-13} \quad \longrightarrow \quad \left(\frac{v}{\Lambda}\right)^2|C^{e\mu}_{D,X}| < 10^{-8}$$

$v^2 = (2\sqrt{2}G_F)^{-1} \sim (174\ \text{GeV})^2$

$\Lambda \gtrsim 10^4 v$ (if $C_D \sim 1$)

Effective Field Theory for LFV

- Observables are calculated in terms of the operator coefficients

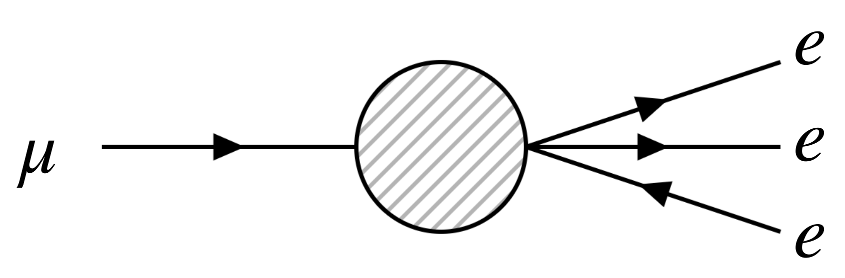


$$\delta\mathscr{L}_{\mu\to e\gamma} = \frac{m_\mu}{\Lambda^2}(C^{e\mu}_{D,R}\bar{e}\sigma_{\alpha\beta}P_R\mu + C^{e\mu}_{D,L}\bar{e}\sigma_{\alpha\beta}P_L\mu)F^{\alpha\beta}$$

$$Br(\mu\to e\gamma) = 384\pi^2\left(\frac{v}{\Lambda}\right)^4(|C^{e\mu}_{D,R}|^2 + |C^{e\mu}_{D,L}|^2) < 4.2\times 10^{-13} \longrightarrow \left(\frac{v}{\Lambda}\right)^2|C^{e\mu}_{D,X}| < 10^{-8}$$

$v^2 = (2\sqrt{2}G_F)^{-1} \sim (174\ \mathrm{GeV})^2$

$\Lambda \gtrsim 10^4 v$ (if $C_D \sim 1$)

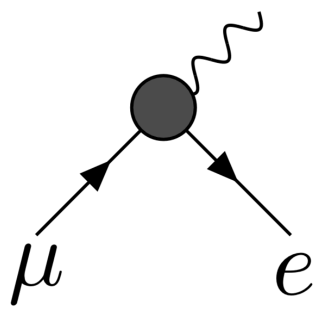


$$\delta\mathscr{L}_{\mu\to e\bar{e}e} = \frac{1}{\Lambda^2}\sum_{X,Y=L,R}[C_{V,XY}(\bar{e}\gamma^\alpha P_X\mu)(\bar{e}\gamma_\alpha P_Y e) + C_{S,X}(\bar{e}P_X\mu)(\bar{e}P_X e)]$$

$$Br(\mu\to e\bar{e}e) = \left(\frac{v}{\Lambda}\right)^4\left[2|C_{V,LL}+4eC_{D,R}|^2 + |C_{V,LR}+4eC_{D,R}|^2 + |C_{S,R}|^2/8 + (64\log(m_\mu/m_e) - 136)|eC_{D,R}|^2 + L\leftrightarrow R\right]$$

Effective Field Theory for LFV

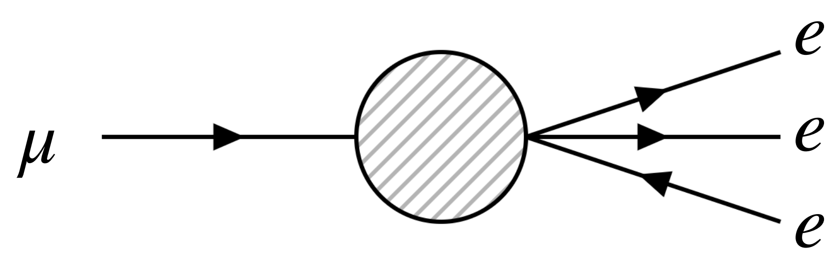
- Observables are calculated in terms of the operator coefficients



$$\delta\mathscr{L}_{\mu\to e\gamma} = \frac{m_\mu}{\Lambda^2}\left(C^{e\mu}_{D,R}\bar{e}\sigma_{\alpha\beta}P_R\mu + C^{e\mu}_{D,L}\bar{e}\sigma_{\alpha\beta}P_L\mu\right)F^{\alpha\beta}$$

$$Br(\mu\to e\gamma) = 384\pi^2\left(\frac{v}{\Lambda}\right)^4\left(|C^{e\mu}_{D,R}|^2 + |C^{e\mu}_{D,L}|^2\right) < 4.2\times 10^{-13} \longrightarrow \left(\frac{v}{\Lambda}\right)^2 |C^{e\mu}_{D,X}| < 10^{-8}$$

$v^2 = (2\sqrt{2}G_F)^{-1} \sim (174\ \mathrm{GeV})^2$ $\qquad$ $\Lambda \gtrsim 10^4 v$ (if $C_D \sim 1$)



$$\delta\mathscr{L}_{\mu\to e\bar{e}e} = \frac{1}{\Lambda^2}\sum_{X,Y=L,R}\left[C_{V,XY}(\bar{e}\gamma^\alpha P_X\mu)(\bar{e}\gamma_\alpha P_Y e) + C_{S,X}(\bar{e}P_X\mu)(\bar{e}P_X e)\right]$$

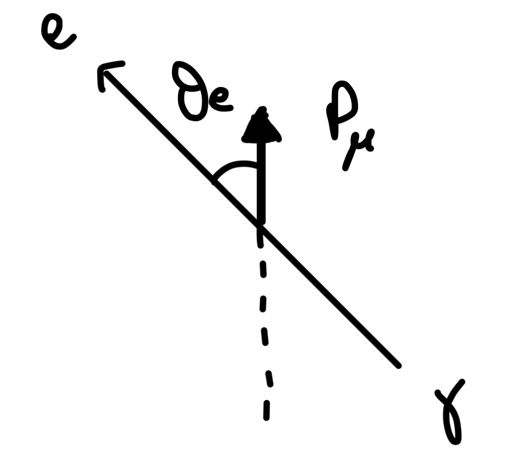
$$Br(\mu\to e\bar{e}e) = \left(\frac{v}{\Lambda}\right)^4\left[2|C_{V,LL}+4eC_{D,R}|^2 + |C_{V,LR}+4eC_{D,R}|^2 + |C_{S,R}|^2/8 + (64\log(m_\mu/m_e)-136)|eC_{D,R}|^2 + L\leftrightarrow R\right]$$

For $\mu A \to eA$ see the standard calculation in Kuno+Okada [hep-ph/9909265]

Polarising the muon to distinguish operators

Kuno, Okada hep-ph/9909265

$$\frac{dB\left(\mu \to e\gamma\right)}{d\left(\cos\theta_e\right)} = 192\pi^2 \left(\frac{v}{\Lambda}\right)^4 \left[\left|C_{D,R}\right|^2 \left(1 - P_\mu \cos\theta_e\right) + \left|C_{D,L}\right|^2 \left(1 + P_\mu \cos\theta_e\right)\right]$$



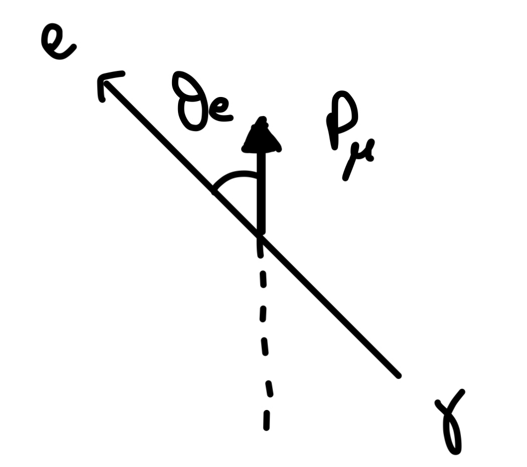
Polarising the muon to distinguish operators

Kuno, Okada hep-ph/9909265

$$\frac{dB\left(\mu \to e\gamma\right)}{d\left(\cos\theta_e\right)} = 192\pi^2\left(\frac{v}{\Lambda}\right)^4\left[\left|C_{D,R}\right|^2\left(1 - P_\mu \cos\theta_e\right) + \left|C_{D,L}\right|^2\left(1 + P_\mu \cos\theta_e\right)\right]$$

Muon polarization vector

Angle between e momentum and $\overrightarrow{P}_\mu$

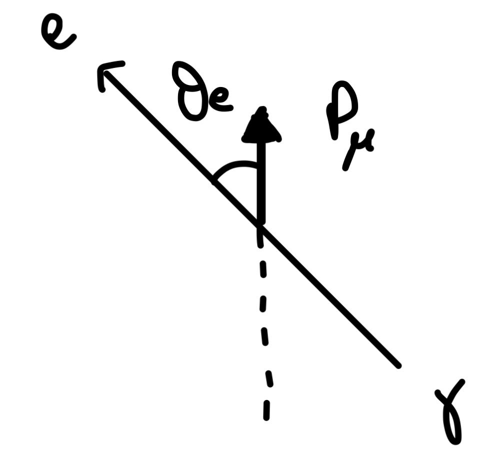


Polarising the muon to distinguish operators

Kuno, Okada hep-ph/9909265

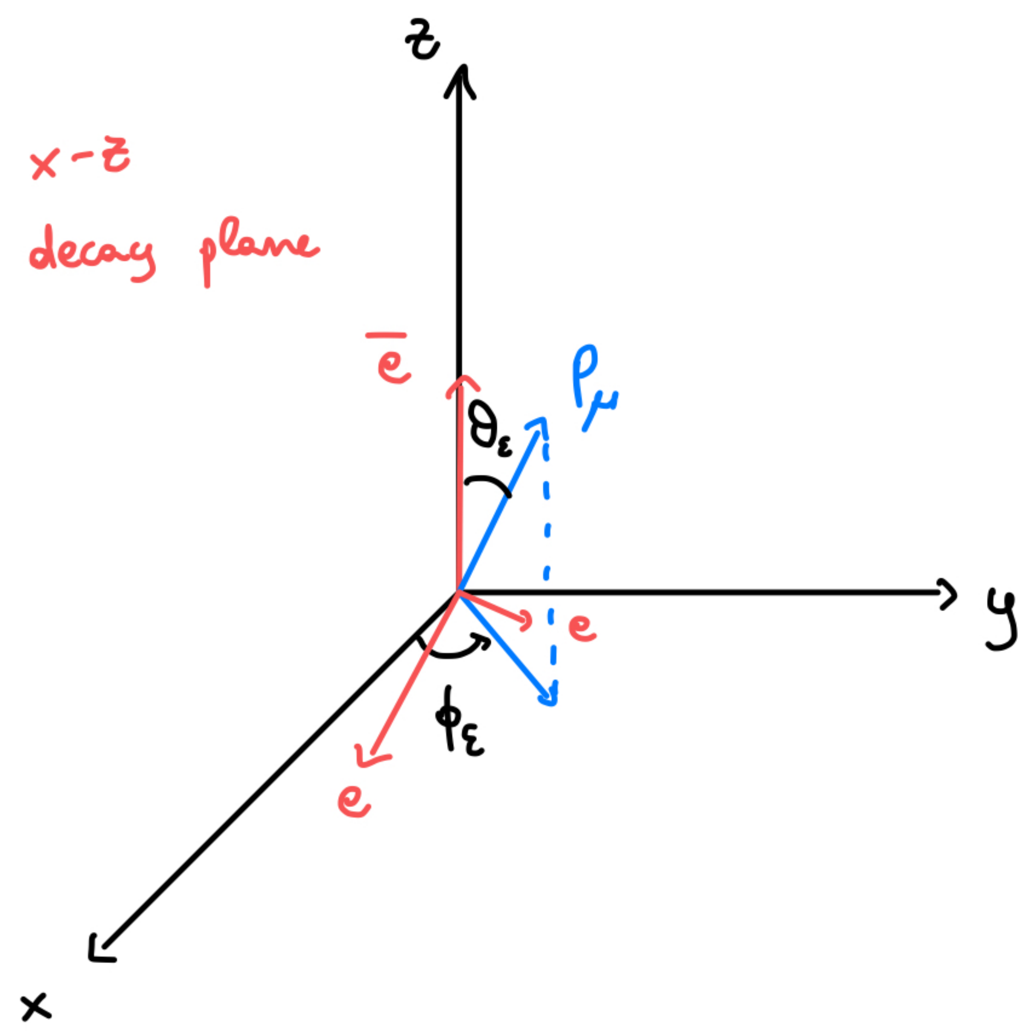
$$\frac{dB\left(\mu \to e\gamma\right)}{d\left(\cos\theta_e\right)} = 192\pi^2\left(\frac{v}{\Lambda}\right)^4\left[\left|C_{D,R}\right|^2\left(1 - P_\mu \cos\theta_e\right) + \left|C_{D,L}\right|^2\left(1 + P_\mu \cos\theta_e\right)\right]$$

Muon polarization vector **Angle between e momentum and $\overrightarrow{P}_\mu$**



Petcov, Bolton 2204.03468

$$\frac{dB_{\mu\to 3e}}{dx_1 dx_2 d\Omega_\varepsilon} = \frac{3}{2\pi}\left[C_1\left(x_1,x_2\right) + C_2\left(x_1,x_2\right)P_\mu\cos\theta_\varepsilon + C_3\left(x_1,x_2\right)P_\mu\sin\theta_\varepsilon\cos\phi_\varepsilon + C_4\left(x_1,x_2\right)P_\mu\sin\theta_\varepsilon\sin\phi_\varepsilon\right]$$

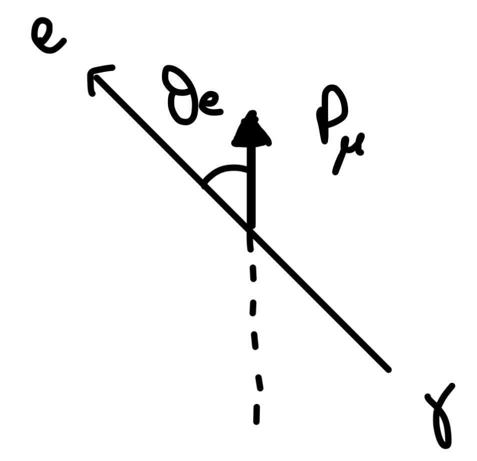


Polarising the muon to distinguish operators

Kuno, Okada hep-ph/9909265

$$\frac{dB\left(\mu \to e\gamma\right)}{d\left(\cos\theta_e\right)} = 192\pi^2 \left(\frac{v}{\Lambda}\right)^4 \left[\left|C_{D,R}\right|^2 \left(1 - P_\mu \cos\theta_e\right) + \left|C_{D,L}\right|^2 \left(1 + P_\mu \cos\theta_e\right)\right]$$

Muon polarization vector **Angle between e momentum and $\vec{P}_\mu$**

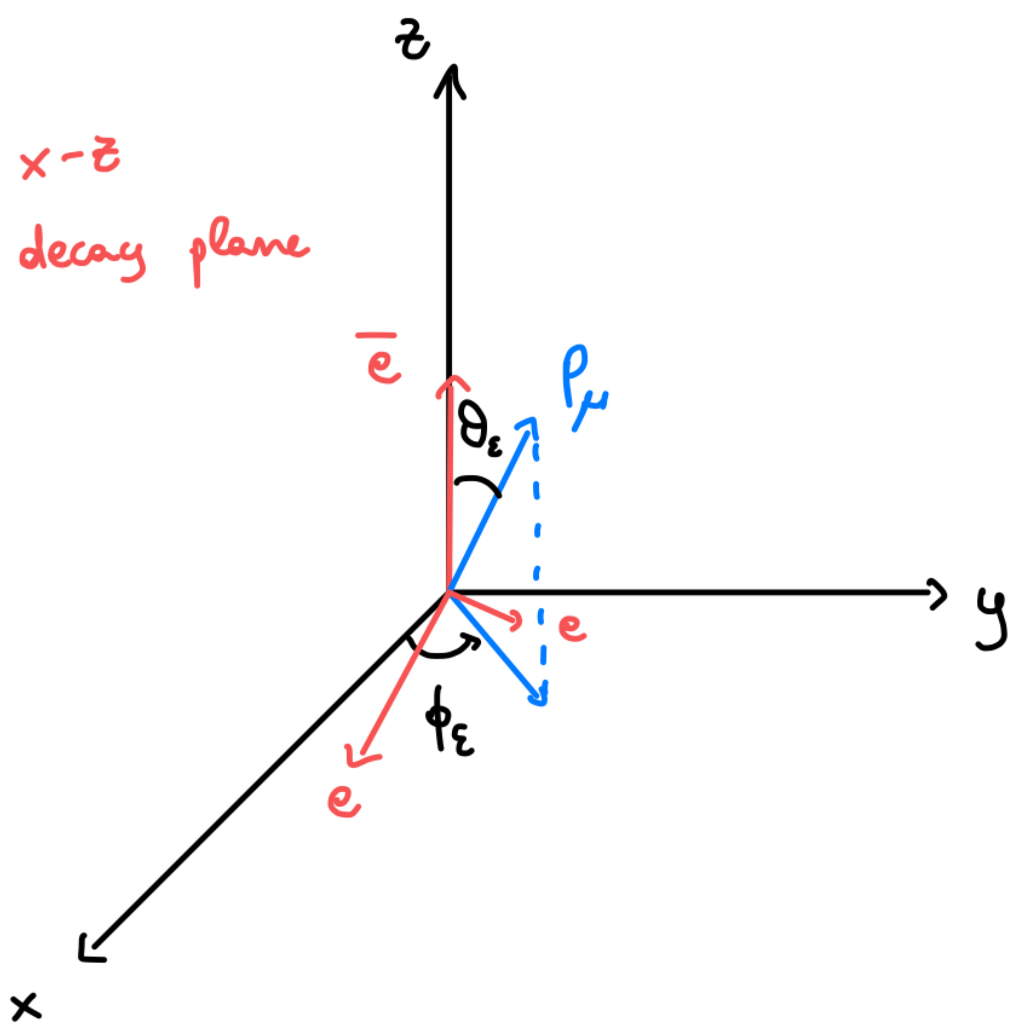


Petcov, Bolton 2204.03468

$$\frac{dB_{\mu\to 3e}}{dx_1 dx_2 d\Omega_\varepsilon} = \frac{3}{2\pi}\left[C_1\left(x_1, x_2\right) + C_2\left(x_1, x_2\right) P_\mu \cos\theta_\varepsilon + C_3\left(x_1, x_2\right) P_\mu \sin\theta_\varepsilon \cos\phi_\varepsilon + C_4\left(x_1, x_2\right) P_\mu \sin\theta_\varepsilon \sin\phi_\varepsilon\right]$$

Can distinguish $C_{V,LX}, C_{V,LX}, C_{S,R}$ from $C_{V,RX}, C_{V,RX}, C_{S,L}$ but not scalars from vectors

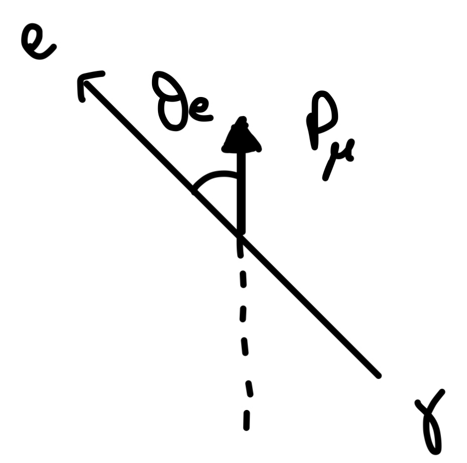
CP asymmetries are also measureable (phase between dipoles and vectors)



Polarising the muon to distinguish operators

Kuno, Okada hep-ph/9909265

$$\frac{dB\left(\mu \to e\gamma\right)}{d\left(\cos\theta_e\right)} = 192\pi^2\left(\frac{v}{\Lambda}\right)^4\left[\left|C_{D,R}\right|^2\left(1 - P_\mu \cos\theta_e\right) + \left|C_{D,L}\right|^2\left(1 + P_\mu \cos\theta_e\right)\right]$$



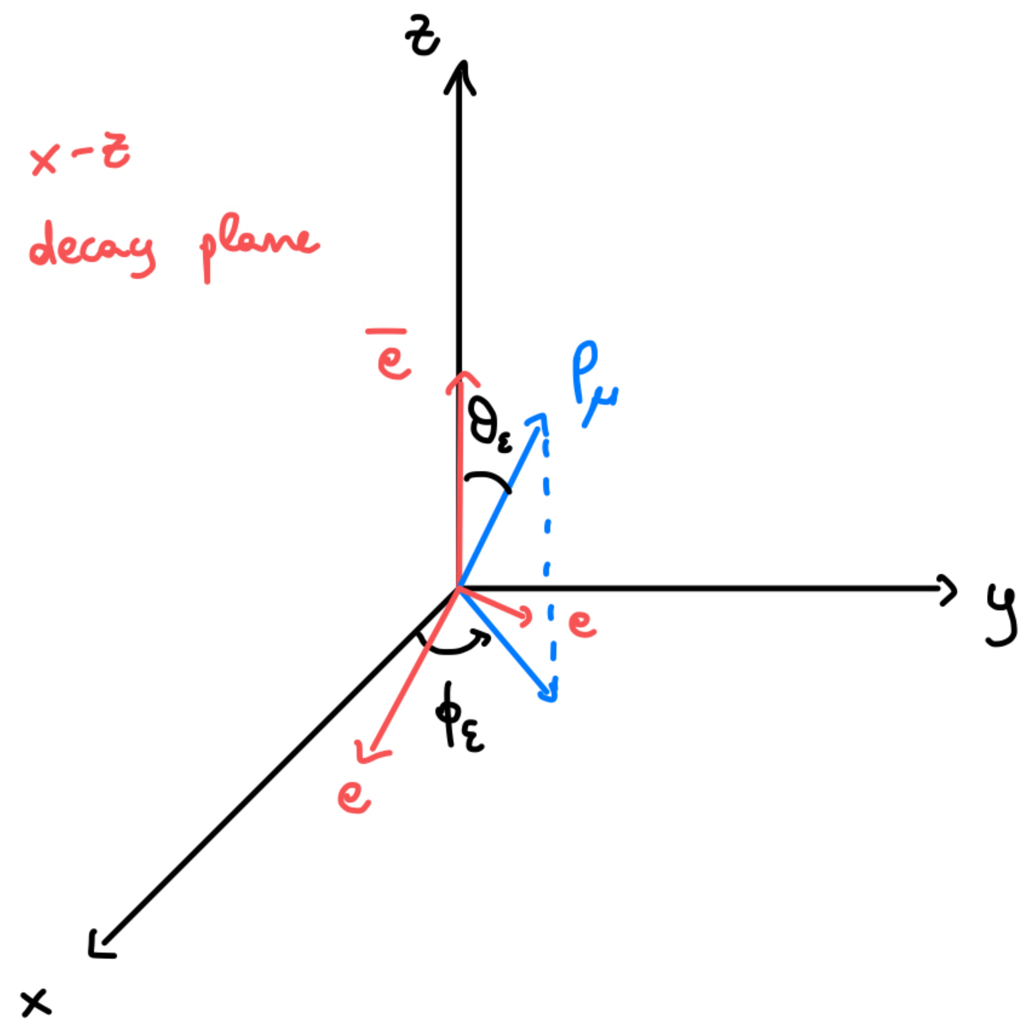
Muon polarization vector

Angle between e momentum and $\overrightarrow{P}_\mu$

Petcov, Bolton 2204.03468

$$\frac{dB_{\mu\to 3e}}{dx_1 dx_2 d\Omega_\varepsilon} = \frac{3}{2\pi}\left[C_1\left(x_1, x_2\right) + C_2\left(x_1, x_2\right) P_\mu \cos\theta_\varepsilon + C_3\left(x_1, x_2\right) P_\mu \sin\theta_\varepsilon \cos\phi_\varepsilon + C_4\left(x_1, x_2\right) P_\mu \sin\theta_\varepsilon \sin\phi_\varepsilon\right]$$

Can distinguish $C_{V,LX}, C_{V,LX}, C_{S,R}$ from $C_{V,RX}, C_{V,RX}, C_{S,L}$ but not scalars from vectors
CP asymmetries are also measureable (phase between dipoles and vectors)



- Dalitz plots for the three body also possible to distinguish operators (vector vs scalar)

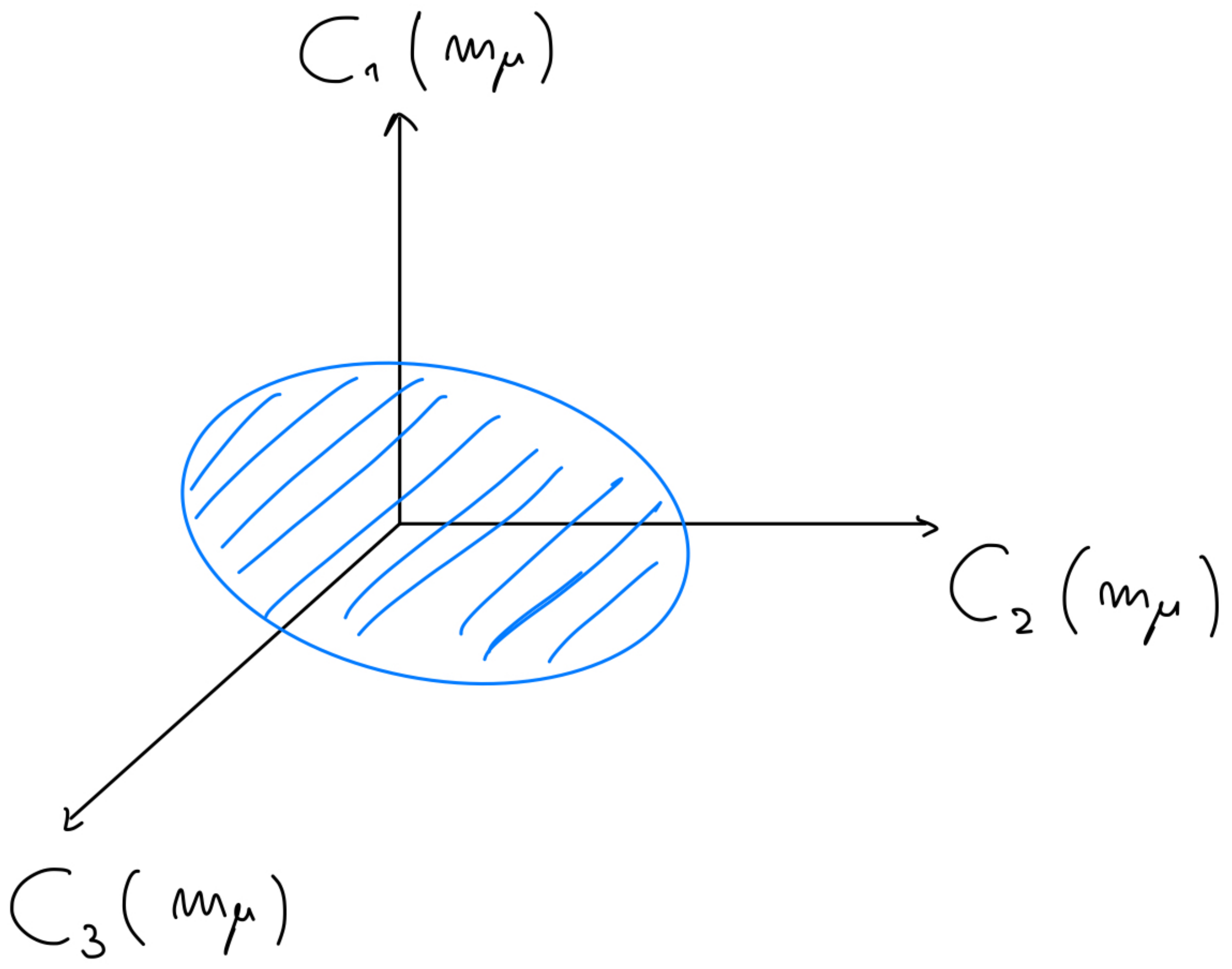
Davidson+Echenard 22

EFT for $\mu \to e$

- Low-energy EFT for $\mu \to e$ observables

$$\mathscr{L}_{|m_\mu} = \frac{1}{v^2} \sum_{X \in \{L,R\}} \Big[C^{e\mu}_{D,X} (m_\mu \bar{e} \sigma^{\alpha\beta} P_X \mu) F_{\alpha\beta} + C^{e\mu ee}_{S,XX} (\bar{e} P_X \mu)(\bar{e} P_X e) + C^{e\mu ee}_{V,LX} (\bar{e}\gamma^\alpha P_L \mu)(\bar{e}\gamma_\alpha P_X e) + C^{e\mu ee}_{V,RX} (\bar{e}\gamma^\alpha P_R \mu)(\bar{e}\gamma_\alpha P_X e) + C_{Alight,X} \mathcal{O}_{Alight,X} + C_{Aheavy\perp,X} \mathcal{O}_{Aheavy\perp,X} \Big] + h.c.$$

- Data ($\mu \to e_X \gamma$, $\mu \to e_X \bar{e}_Y e_Z$, $\mu A \to e_X A \times 2$) constrain 12 operator coefficients at low energy to the interior of an ellipse in 12 dimensions

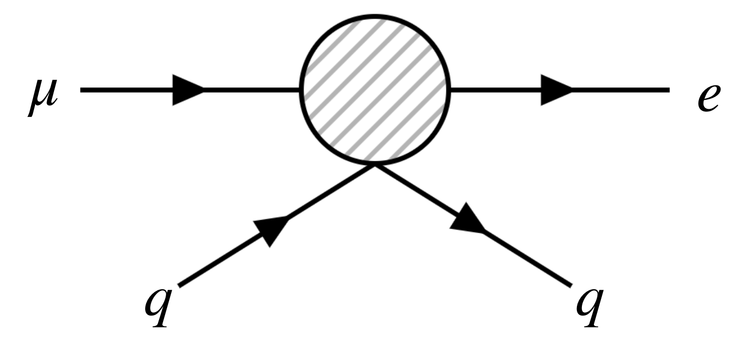


- Including loops: the RGEs can tell us what these constrained directions are at the high scale Λ

$$\vec{C}(m_\mu) = \vec{C}(\Lambda) \cdot U(m_\mu, \Lambda)$$

EFT for $\mu \to e$

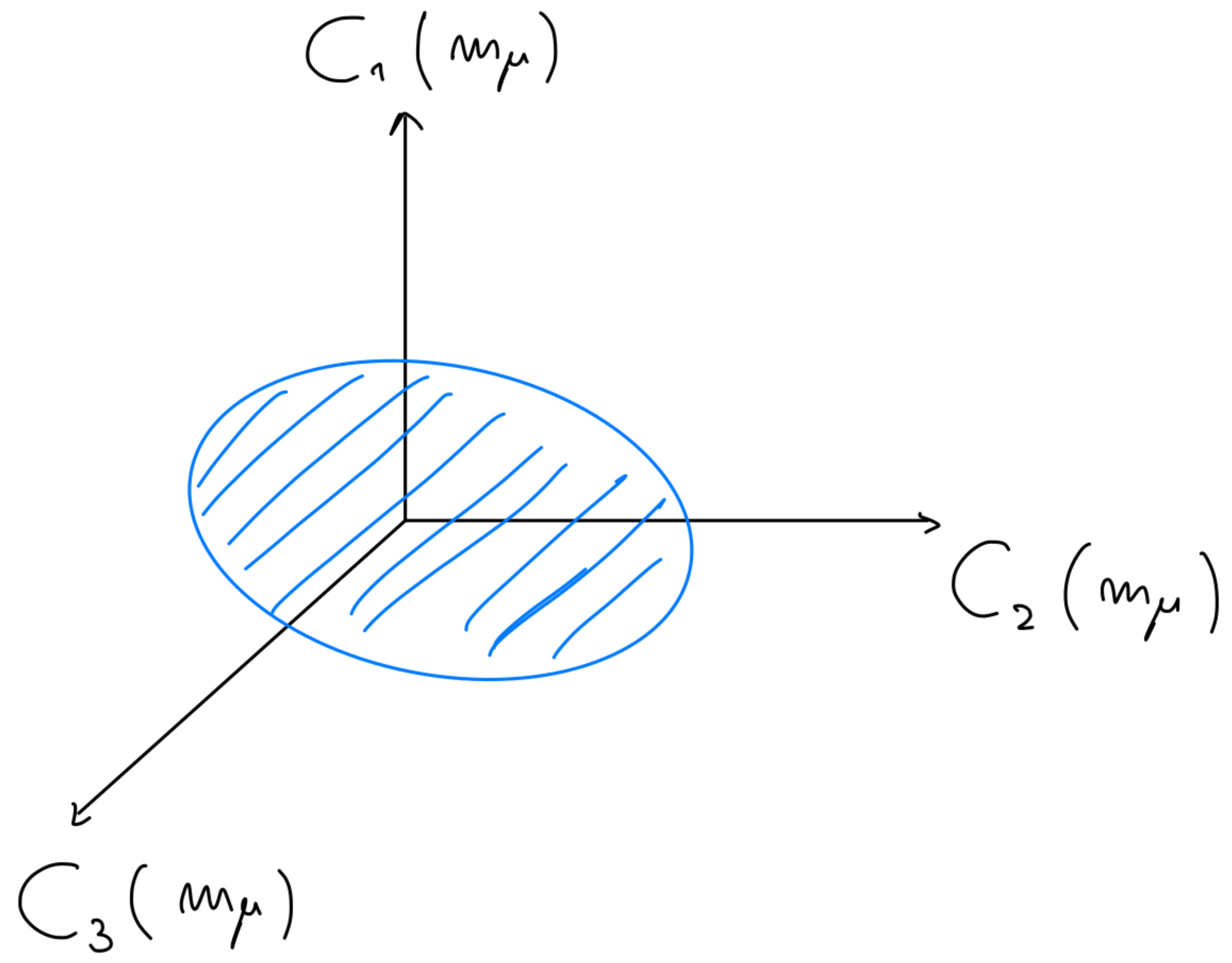
Davidson+Echenard 22



- Low-energy EFT for $\mu \to e$ observables

$$\mathscr{L}_{|m_\mu} = \frac{1}{v^2} \sum_{X \in \{L,R\}} \left[C^{e\mu}_{D,X} (m_\mu \bar{e} \sigma^{\alpha\beta} P_X \mu) F_{\alpha\beta} + C^{e\mu ee}_{S,XX} (\bar{e} P_X \mu)(\bar{e} P_X e) + C^{e\mu ee}_{V,LX} (\bar{e} \gamma^\alpha P_L \mu)(\bar{e} \gamma_\alpha P_X e) + C^{e\mu ee}_{V,RX} (\bar{e} \gamma^\alpha P_R \mu)(\bar{e} \gamma_\alpha P_X e) + C_{Alight,X} \mathcal{O}_{Alight,X} + C_{Aheavy\perp,X} \mathcal{O}_{Aheavy\perp,X} \right] + h.c.$$

- Data ($\mu \to e_X \gamma$, $\mu \to e_X \bar{e}_Y e_Z$, $\mu A \to e_X A \times 2$) constrain 12 operator coefficients at low energy to the interior of an ellipse in 12 dimensions



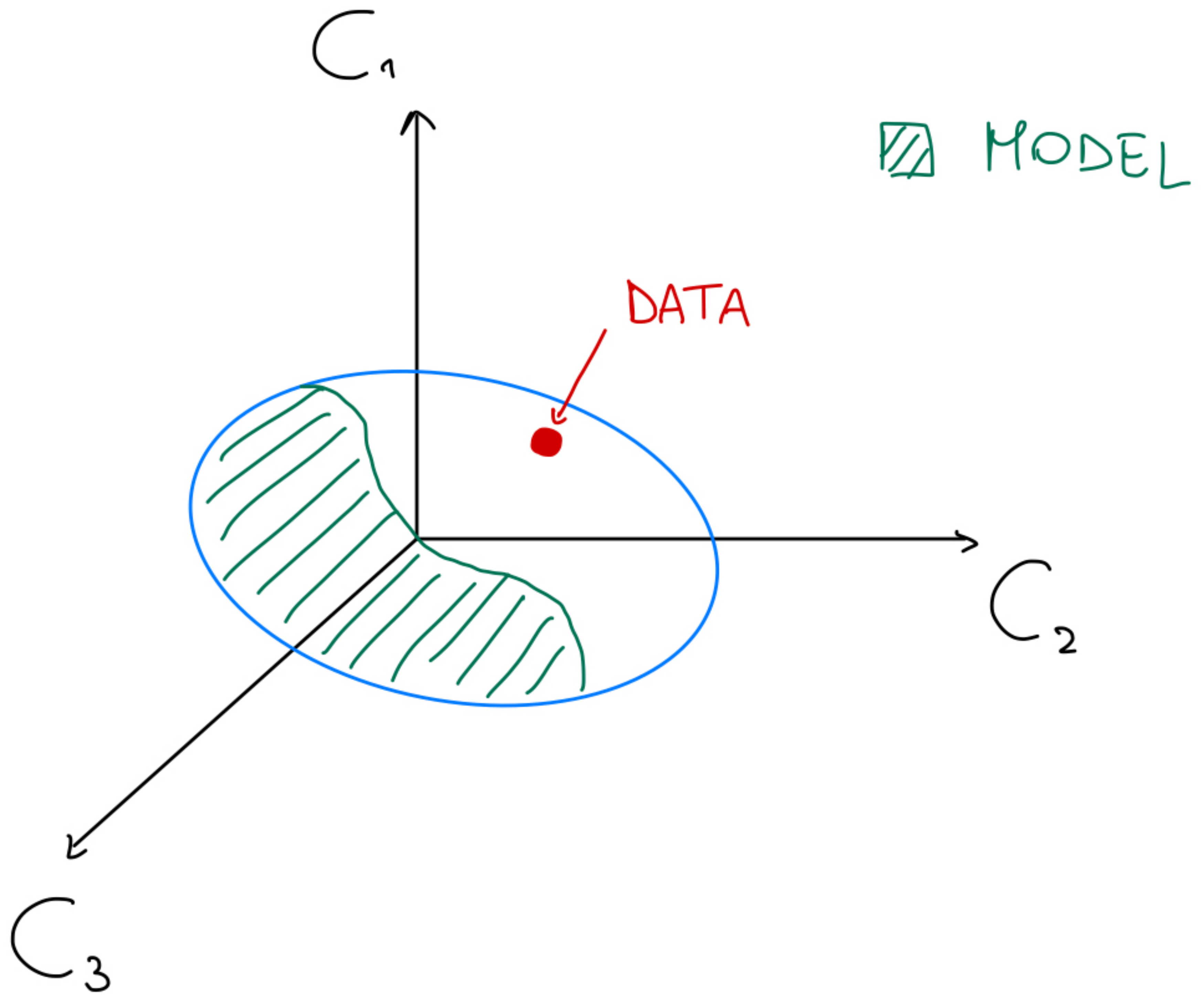
- Including loops: the RGEs can tell us what these constrained directions are at the high scale Λ

$$\vec{C}(m_\mu) = \vec{C}(\Lambda) \cdot U(m_\mu, \Lambda)$$

MA, Davidson, Lavignac 23-24

Excluding models?

- Suppose we observe $\mu \to e$ in the upcoming experiments (with theoretical optimism means a point in the 12-d ellipse)



- And suppose I know regions where a model CAN NOT sit = If I see $\mu \to e$ there I can exclude it

- Complementary to the usual top-down approach+parameter scan

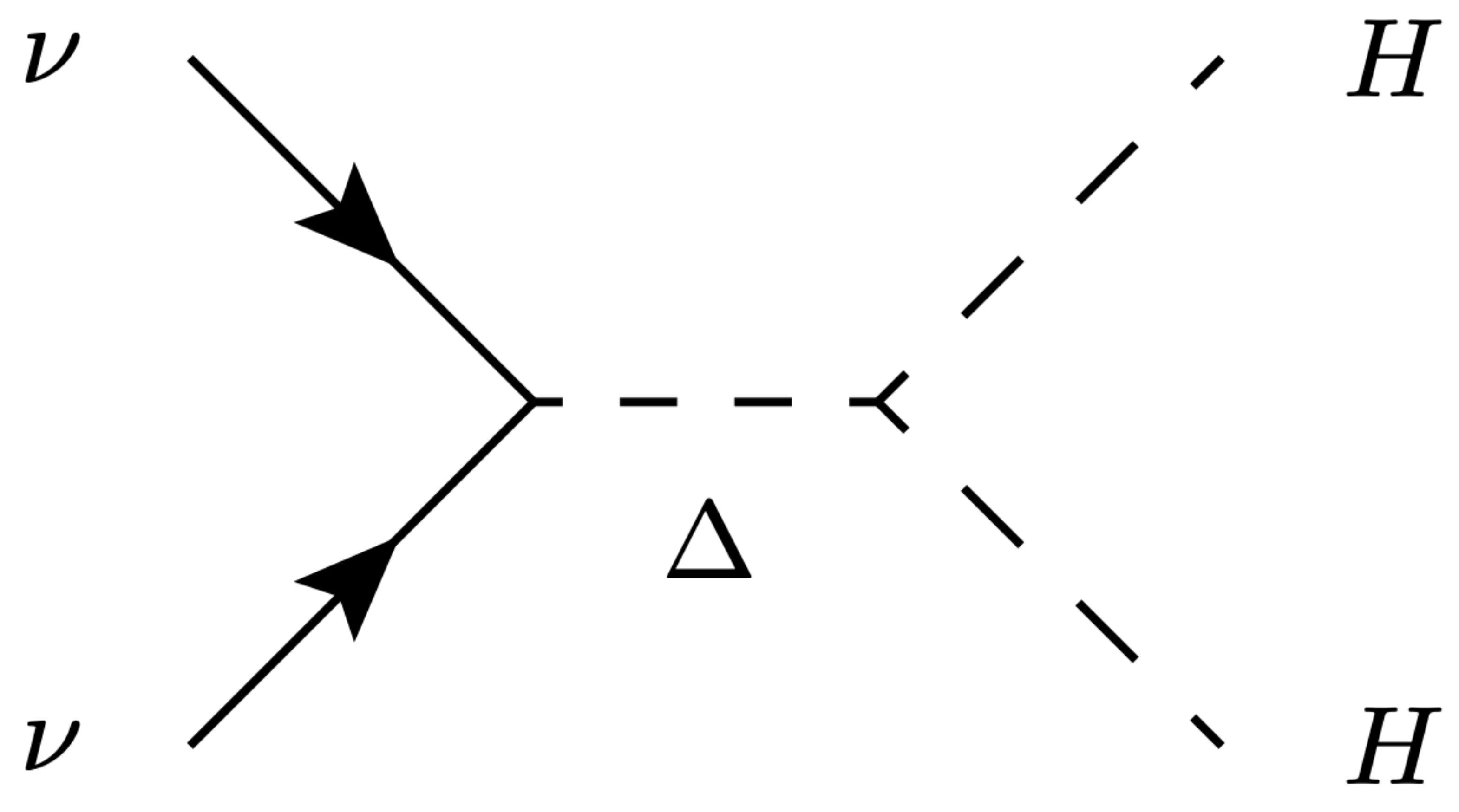
Apply this approach to some New Physics models…

Type-II seesaw (SM + Triplet Δ)

$$\mathscr{L} \supset F_{\alpha\beta}\overline{\ell^c_\alpha}\epsilon\Delta\cdot\tau\ell_\beta + M_\Delta\lambda_H H^T\epsilon\Delta\cdot\tau H + \ldots$$

Type-II seesaw (SM + Triplet Δ)

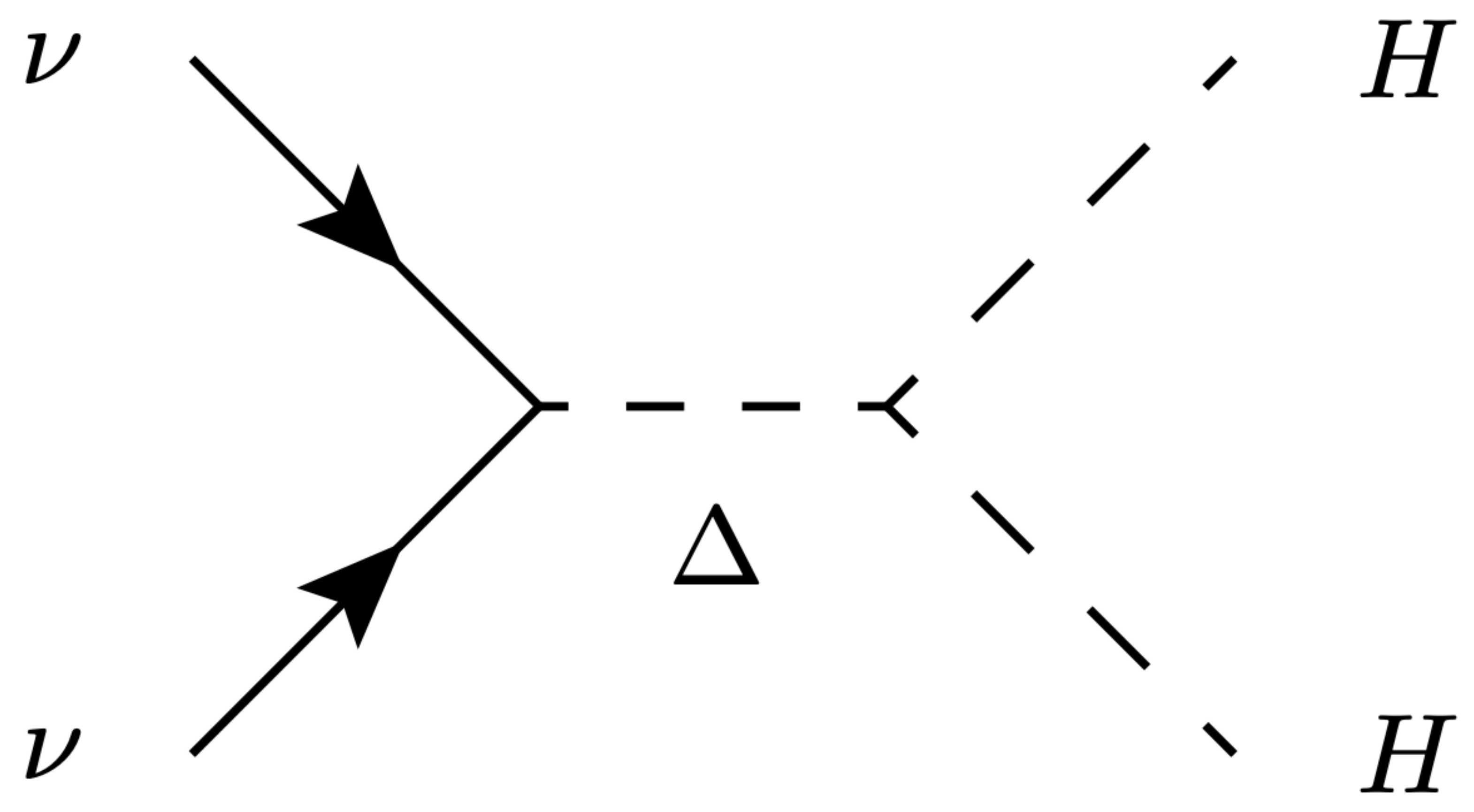
$$\mathscr{L} \supset F_{\alpha\beta}\overline{\ell^c_\alpha}\epsilon\Delta\cdot\tau\ell_\beta + M_\Delta\lambda_H H^T\epsilon\Delta\cdot\tau H + \ldots$$



$$[m_\nu]_{\alpha\beta} \sim 0.03\ \text{eV}\ F_{\alpha\beta}\frac{\lambda_H}{10^{-12}}\frac{\text{TeV}}{M_\Delta}$$

Type-II seesaw (SM + Triplet Δ)

$$\mathscr{L} \supset F_{\alpha\beta}\overline{\ell^c_\alpha}\epsilon\Delta\cdot\tau\ell_\beta + M_\Delta\lambda_H H^T\epsilon\Delta\cdot\tau H + \ldots$$

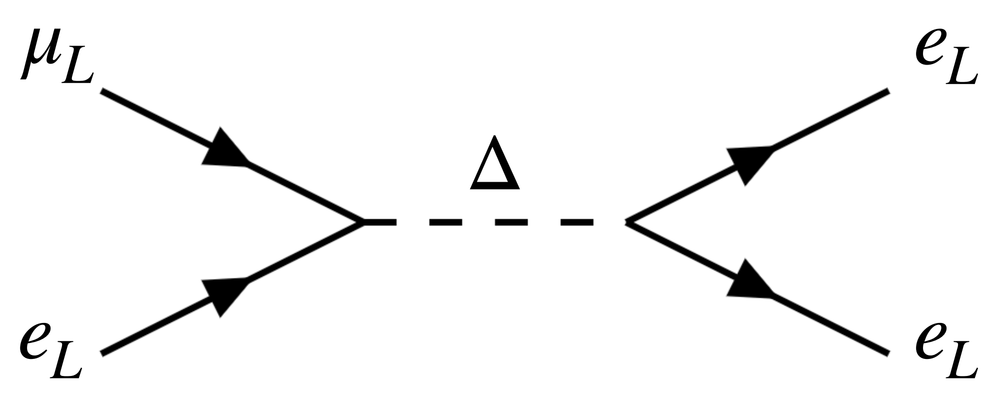


$$[m_\nu]_{\alpha\beta} \sim 0.03\ \text{eV}\ F_{\alpha\beta}\frac{\lambda_H}{10^{-12}}\frac{\text{TeV}}{M_\Delta}$$

- Neutrino masses directly related to the Triplet Yukawas, but ordering, lightest mass and Majorana phases are unknown

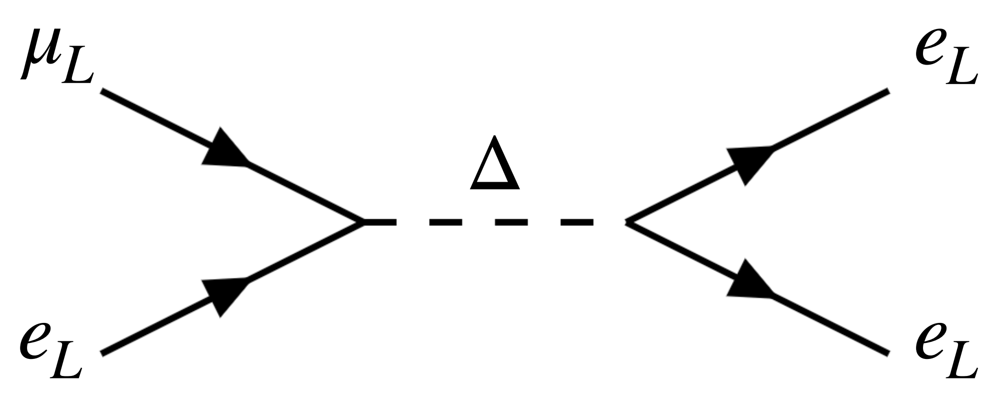
Type-II seesaw LFV

Type-II seesaw LFV

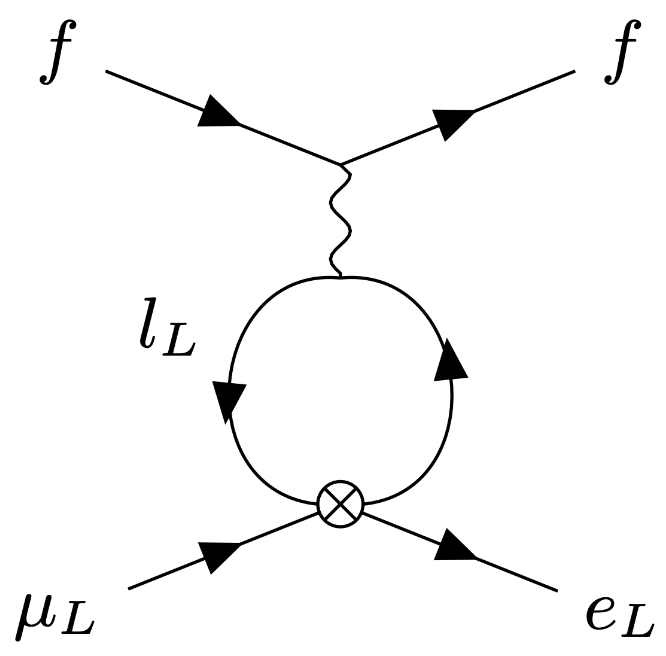


$$C_{V,LL}^{e\mu ee} \qquad (\mu \to e_L \bar{e}_L e_L)$$

Type-II seesaw LFV

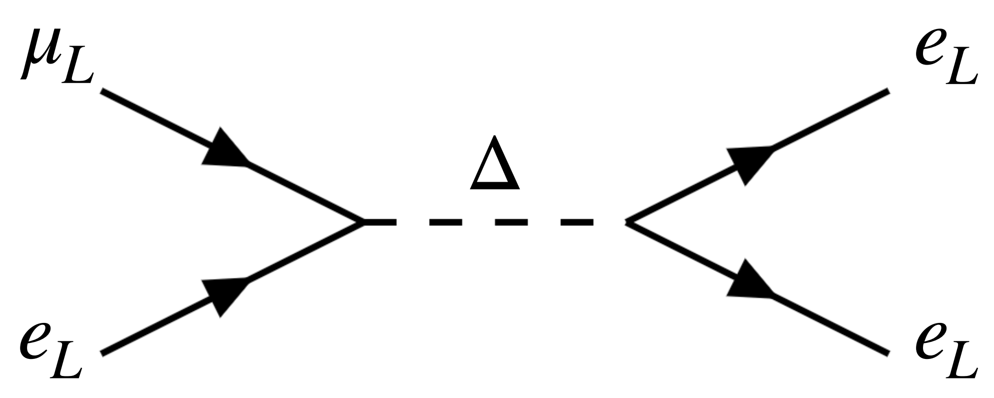


$C^{e\mu ee}_{V,LL} \qquad (\mu \to e_L \bar{e}_L e_L)$

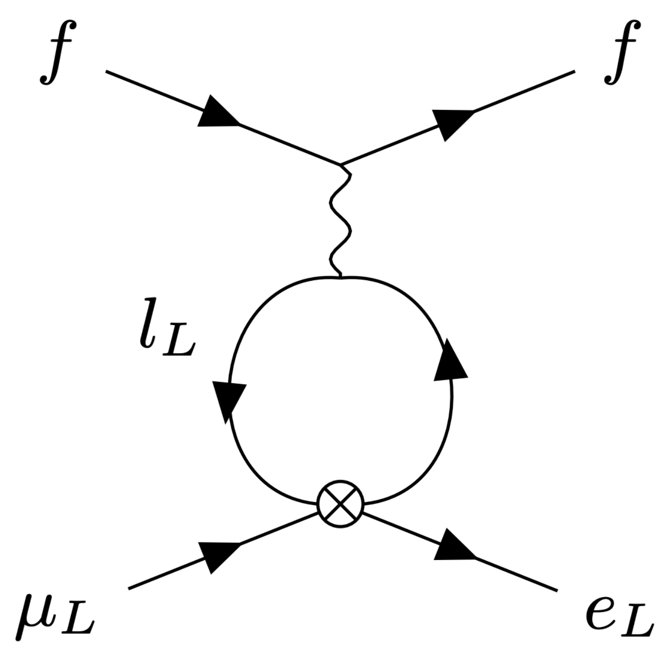


$C^{e\mu ee}_{V,LX} \quad (\mu \to e_L \bar{e}_X e_X) \qquad C^{e\mu}_{A,L} \quad (\mu A \to e_L A)$

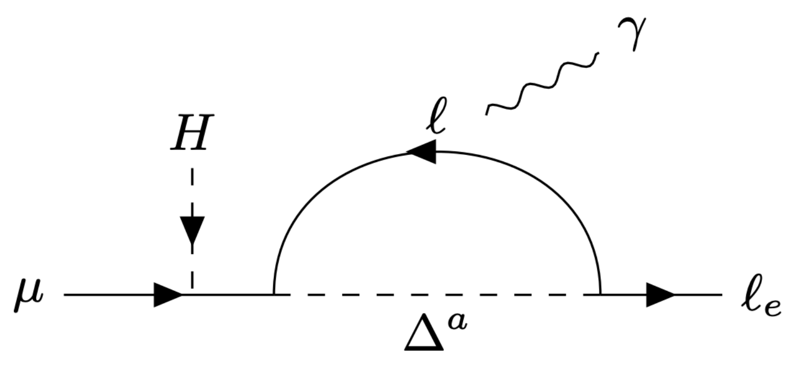
Type-II seesaw LFV

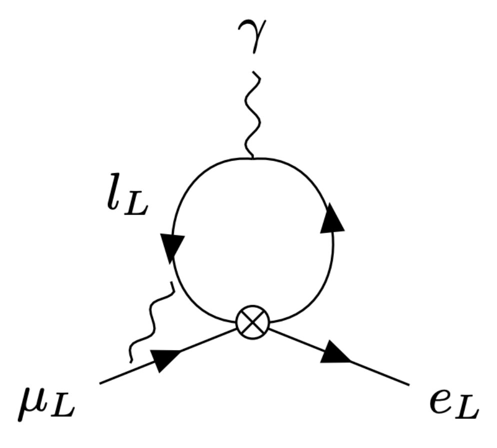


$C^{e\mu ee}_{V,LL} \qquad (\mu \to e_L \bar{e}_L e_L)$



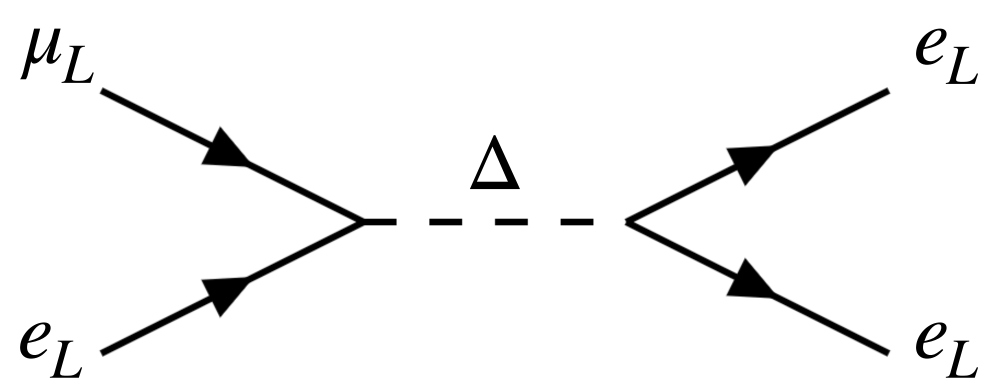
$C^{e\mu ee}_{V,LX} \quad (\mu \to e_L \bar{e}_X e_X) \qquad C^{e\mu}_{A,L} \quad (\mu A \to e_L A)$



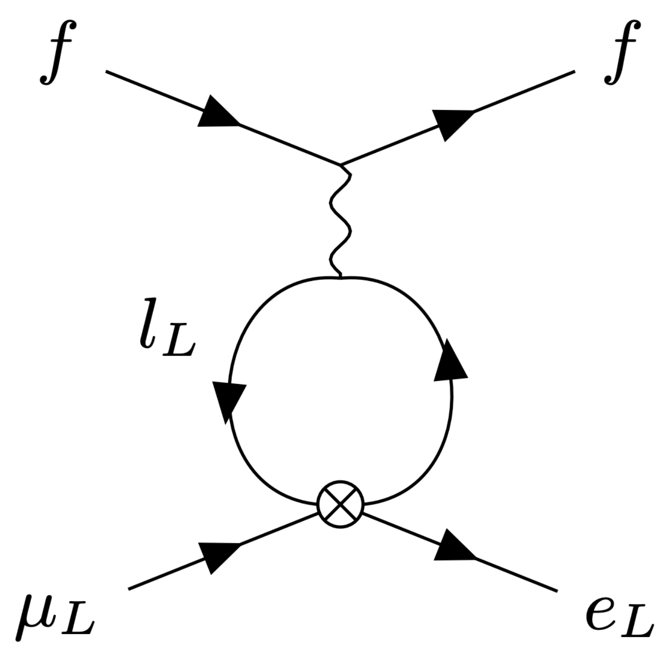


$C^{e\mu}_{D,R} \quad (\mu \to e_L \gamma)$

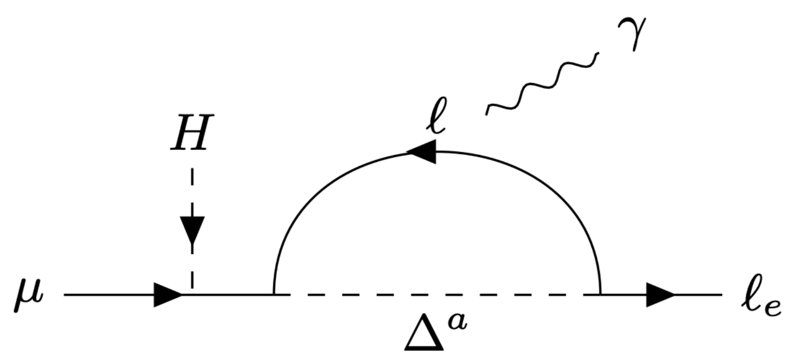
Type-II seesaw LFV

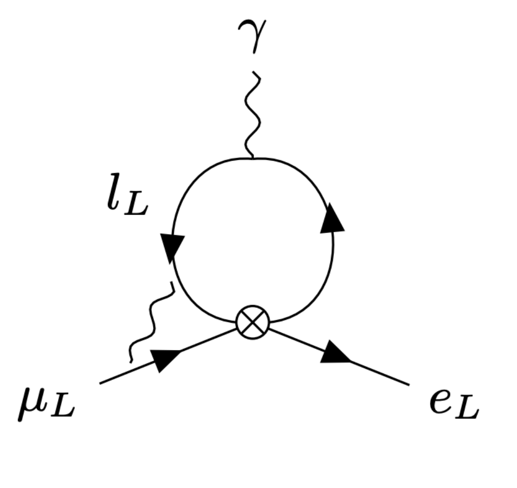


$C^{e\mu ee}_{V,LL}$ $(\mu \to e_L \bar{e}_L e_L)$



$C^{e\mu ee}_{V,LX}$ $(\mu \to e_L \bar{e}_X e_X)$ $C^{e\mu}_{A,L}$ $(\mu A \to e_L A)$

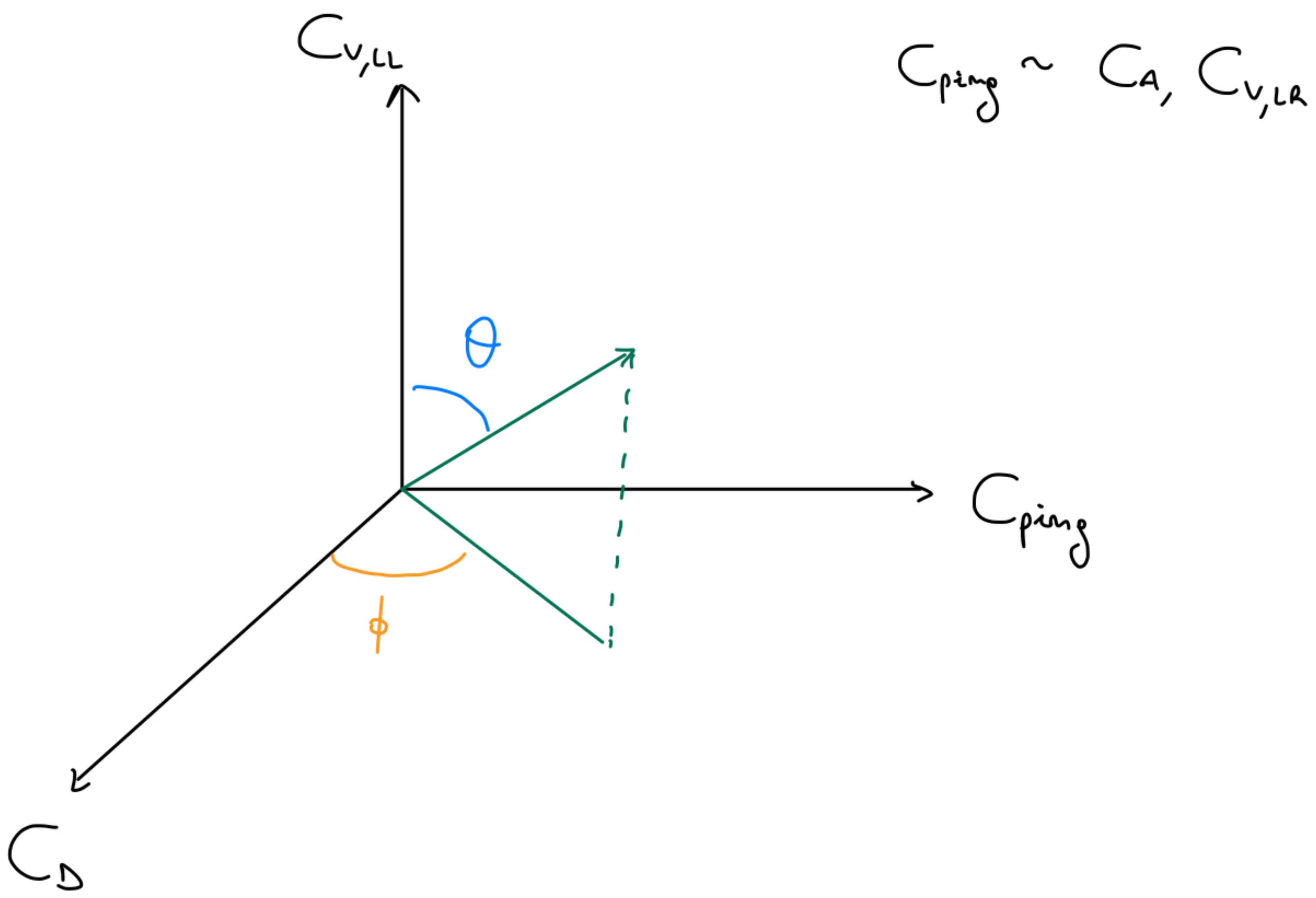


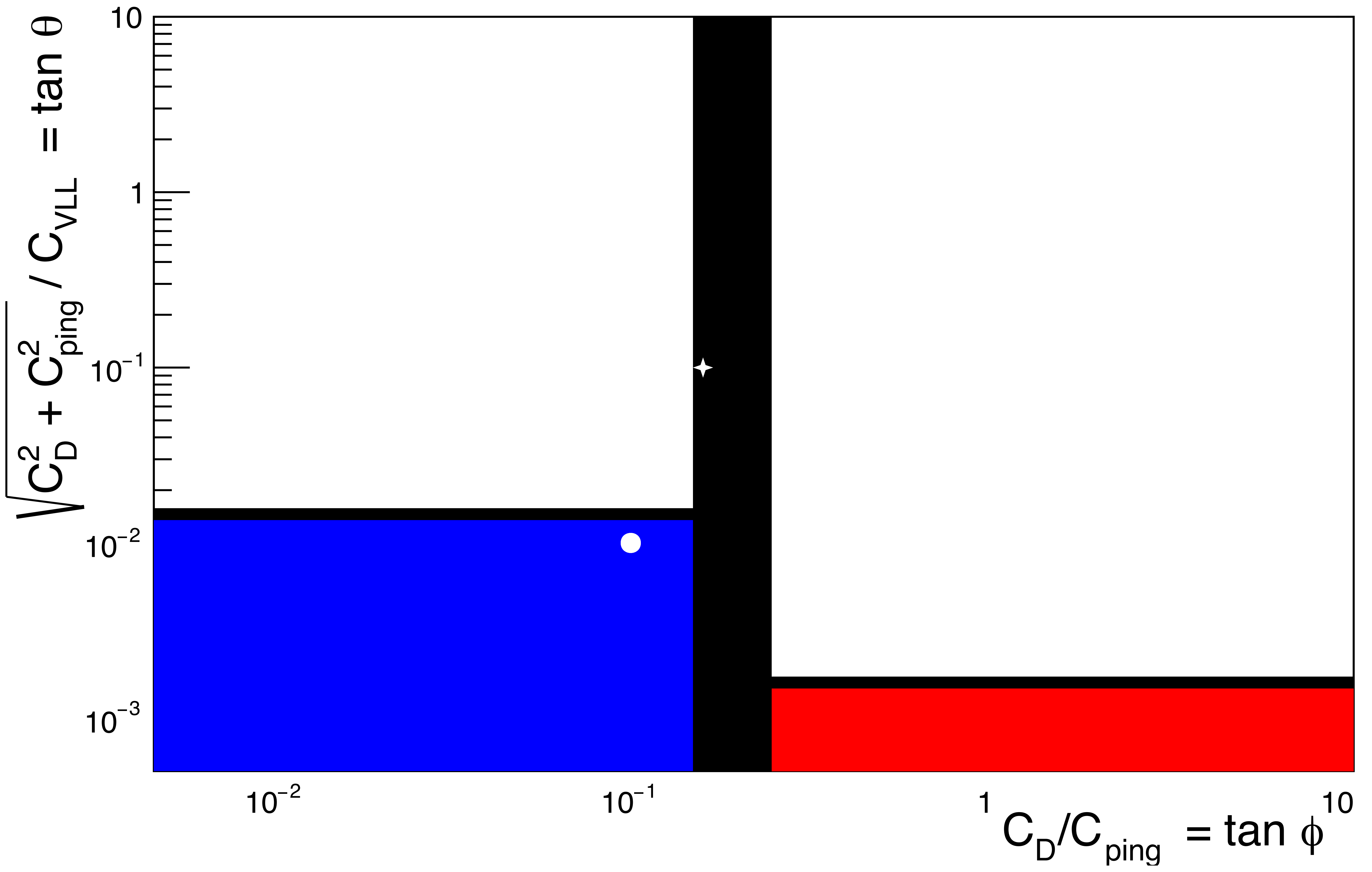


$C^{e\mu}_{D,R}$ $(\mu \to e_L \gamma)$

- Cannot predict sizable $\mu \to e_R$ (the new states interact with left-handed doublets, so right-handed LFV is suppresed by y_e)

Type-II: where does it live in the ellipse?





- Any observations outside the colored region can exclude the type-II seesaw!

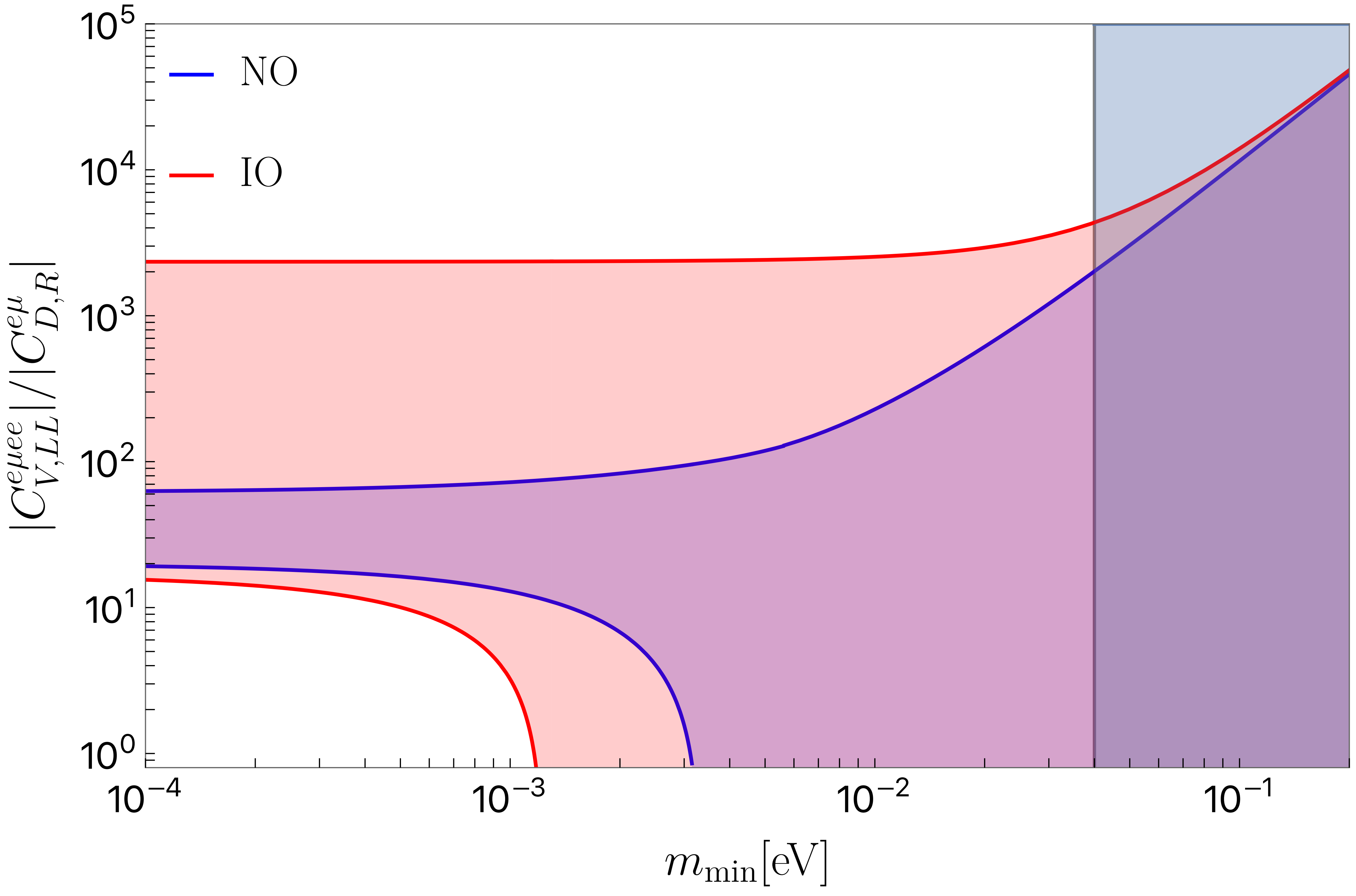
Conclusions

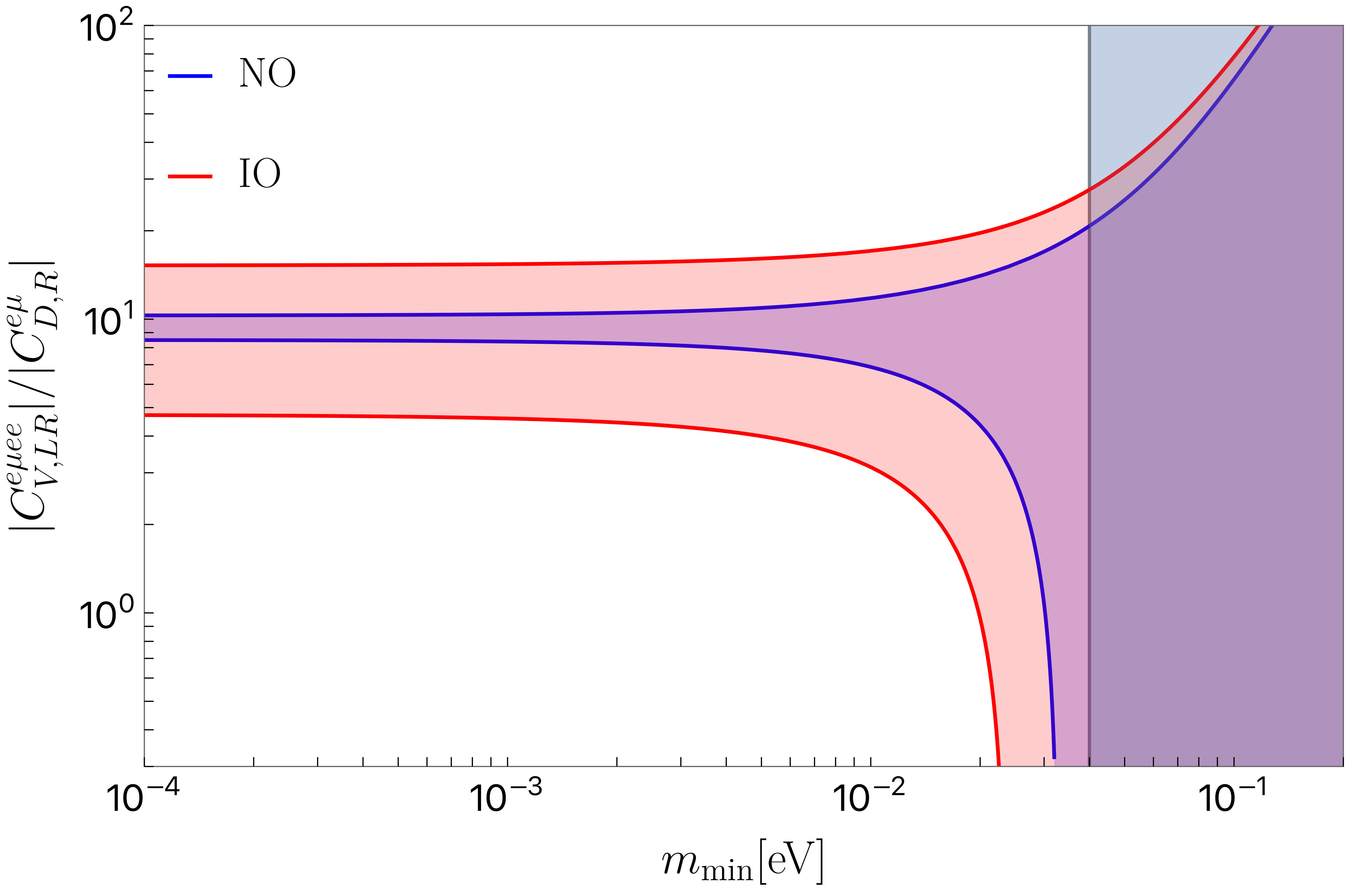
- Lepton Flavour Violation is new physics that must exist because we see it in neutrino oscillations
- $\mu \to e$ observables are the most promising channels for a discovery thanks to the impressive experimental sensitivities of the upcoming searches
- By parametrising data in a bottom-up EFT, we have (in principle) more observables than just branching ratios, which correspond to 12 directions in the Wilson coefficient space
- Analysing what regions of this 12-d coefficient space models can reach we could have a way to distinguish/exclude models by combination of $\mu \to e$ observations/non-observations
- Is it possible for upcoming $\mu \to e$ to exclude popular TeV-scale models

Back-up

Type-II seesaw and neutrino mass scale

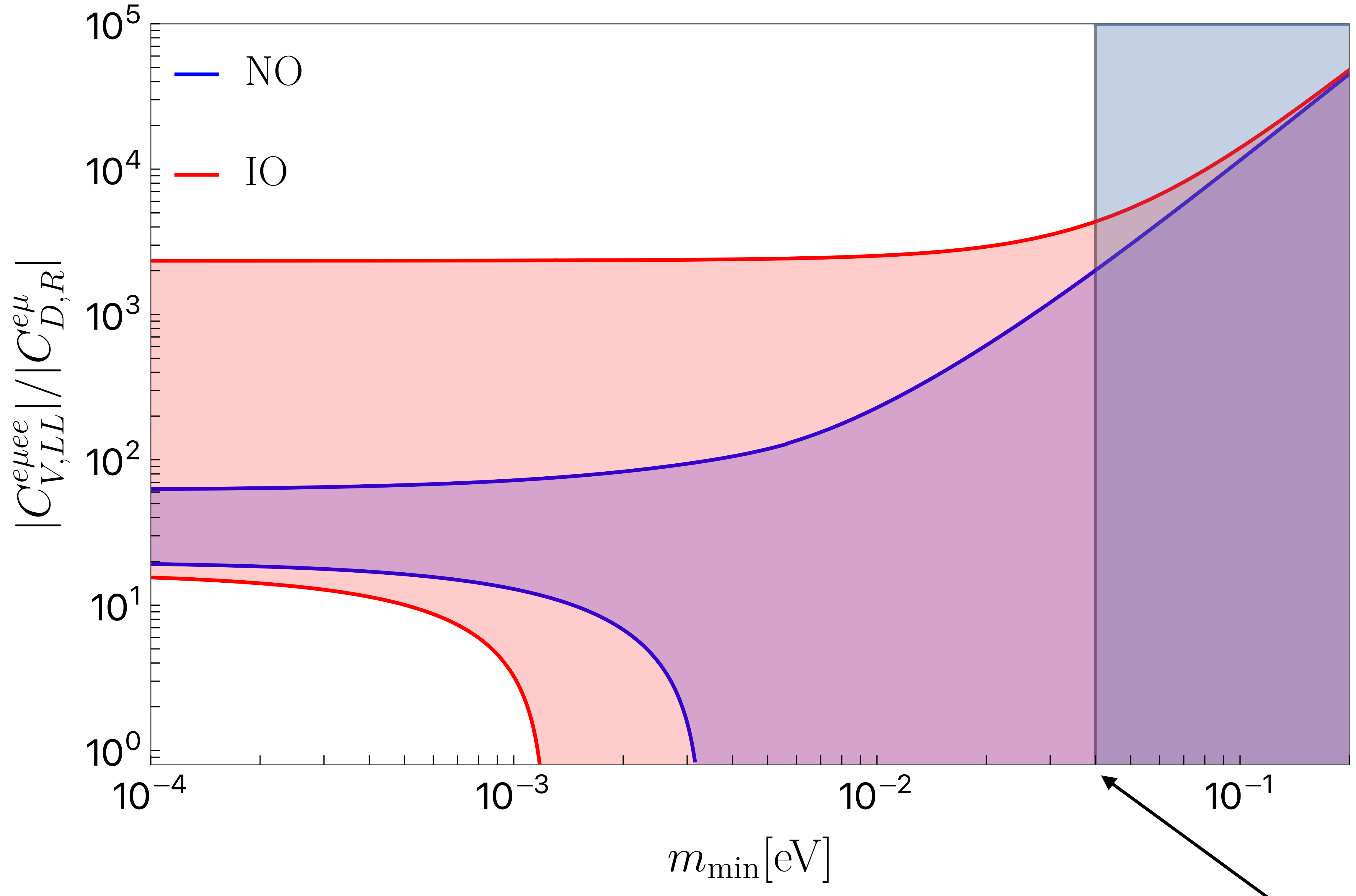
- Wilson coefficients are function of the neutrino mass scale, hence one can constrain their size knowing $m_{\min}$

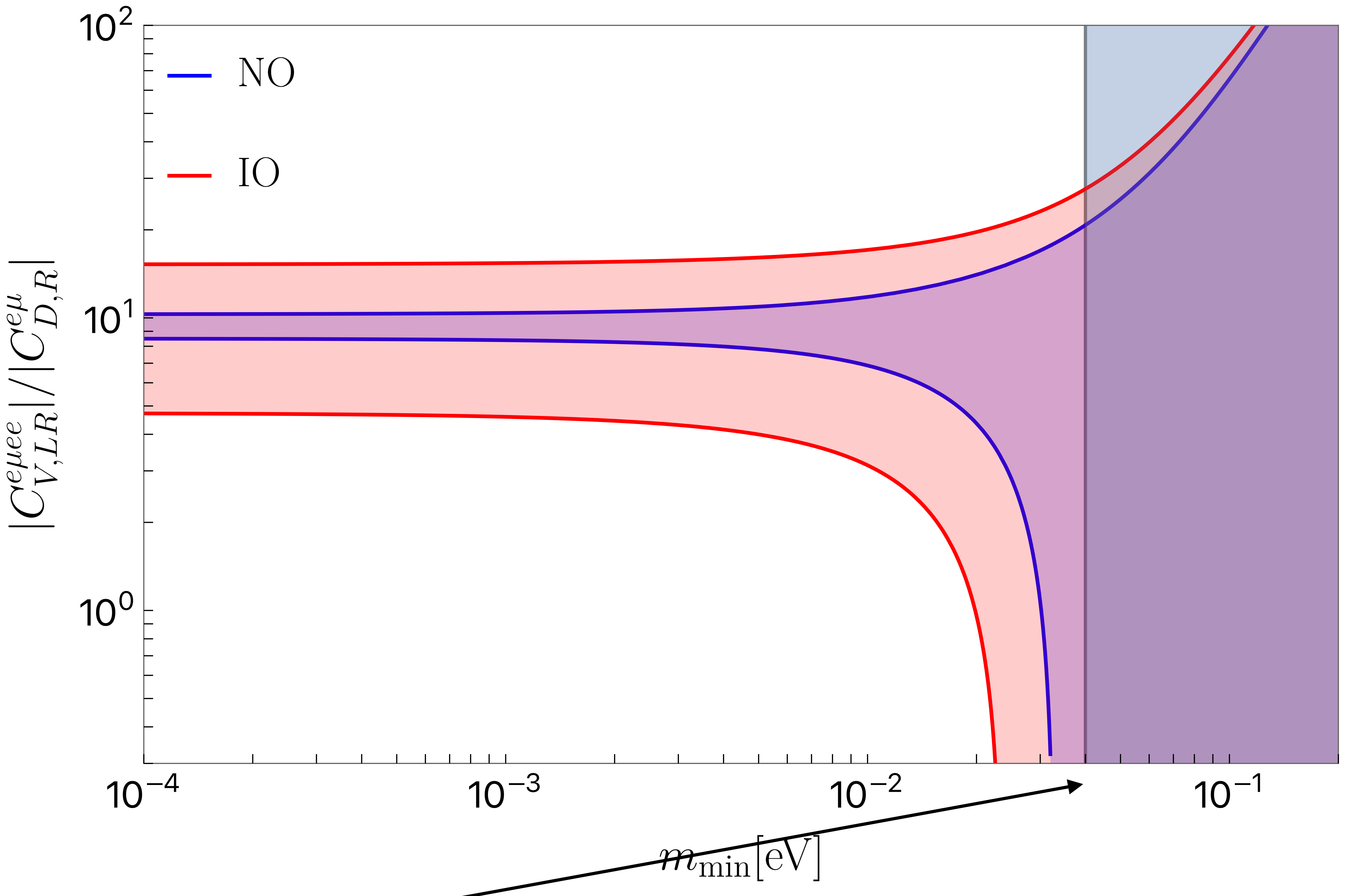




Type-II seesaw and neutrino mass scale

- Wilson coefficients are function of the neutrino mass scale, hence one can constrain their size knowing $m_{\min}$





Cosmological bound on $\sum m_\nu$

Inverse seesaw

Inverse seesaw

- Add to the Lagrangian pairs of gauge singlet fermions N, S with opposite chirality

Inverse seesaw

- Add to the Lagrangian pairs of gauge singlet fermions N, S with opposite chirality

$$\delta\mathscr{L}_{NS} = i\bar{N}\partial N + i\bar{S}\partial S - \left(Y_\nu^{\alpha a}\left(\bar{\ell}_\alpha \tilde{H} N_a\right) + M_{ab}\bar{S}_a N_b + \frac{1}{2}\mu_{ab}\overline{S_a} S_b^c + \mathrm{h.c}\right)$$

Inverse seesaw

- Add to the Lagrangian pairs of gauge singlet fermions N, S with opposite chirality

$$\delta\mathscr{L}_{NS} = i\bar{N}\partial N + i\bar{S}\partial S - \left(Y_\nu^{\alpha a}\left(\bar{\ell}_\alpha \tilde{H} N_a\right) + M_{ab}\bar{S}_a N_b + \frac{1}{2}\mu_{ab}\overline{S_a} S_b^c + \mathrm{h.c} \right)$$

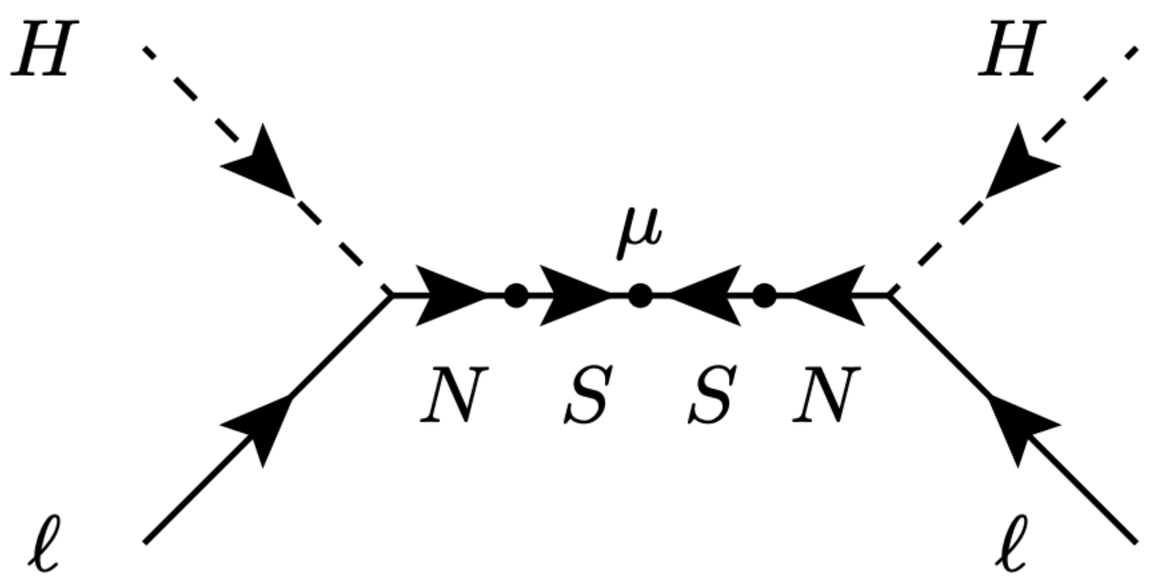
Lepton Number Violating

Inverse seesaw

- Add to the Lagrangian pairs of gauge singlet fermions N, S with opposite chirality

$$\delta\mathscr{L}_{NS} = i\bar{N}\partial N + i\bar{S}\partial S - \left(Y_\nu^{\alpha a}\left(\bar{\ell}_\alpha \tilde{H} N_a\right) + M_{ab}\bar{S}_a N_b + \frac{1}{2}\mu_{ab}\overline{S_a} S_b^c + \mathrm{h.c} \right)$$

Lepton Number Violating



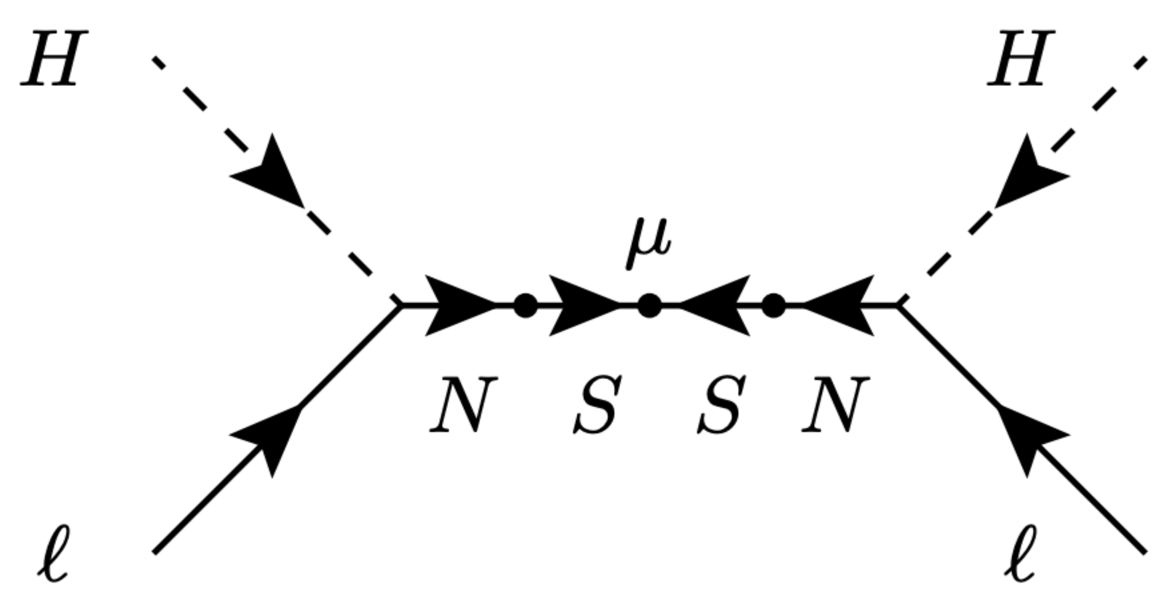
$$\xrightarrow{\;Y_\nu v,\ \mu \ll M\;} \qquad m_\nu = v^2\left(Y_\nu\left(M^{-1}\right)\mu\left(M^T\right)^{-1} Y_\nu^T\right)$$

Inverse seesaw

- Add to the Lagrangian pairs of gauge singlet fermions N, S with opposite chirality

$$\delta\mathscr{L}_{NS} = i\bar{N}\partial N + i\bar{S}\partial S - \left(Y_\nu^{\alpha a}\left(\bar{\ell}_\alpha \tilde{H} N_a\right) + M_{ab}\bar{S}_a N_b + \frac{1}{2}\mu_{ab}\overline{S_a} S_b^c + \mathrm{h.c}\right)$$

Lepton Number Violating



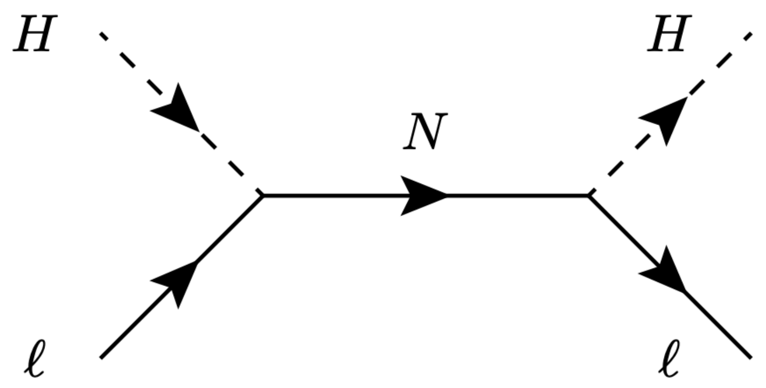
$$\xrightarrow{Y_\nu v,\ \mu \ll M}$$

$$m_\nu = v^2\left(Y_\nu\left(M^{-1}\right)\mu\left(M^T\right)^{-1} Y_\nu^T\right)$$

- I can suppress m_ν with μ while keeping Y_ν large. In principle, if I add enough pairs of sterile, Y_ν is independent from neutrino masses

Inverse seesaw LFV

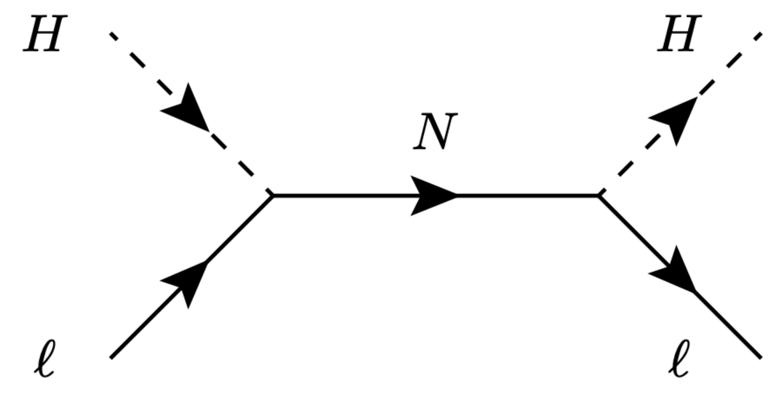
Inverse seesaw LFV



- PMNS non-unitary contribution, leads to modified $W - l - \nu$ couplings

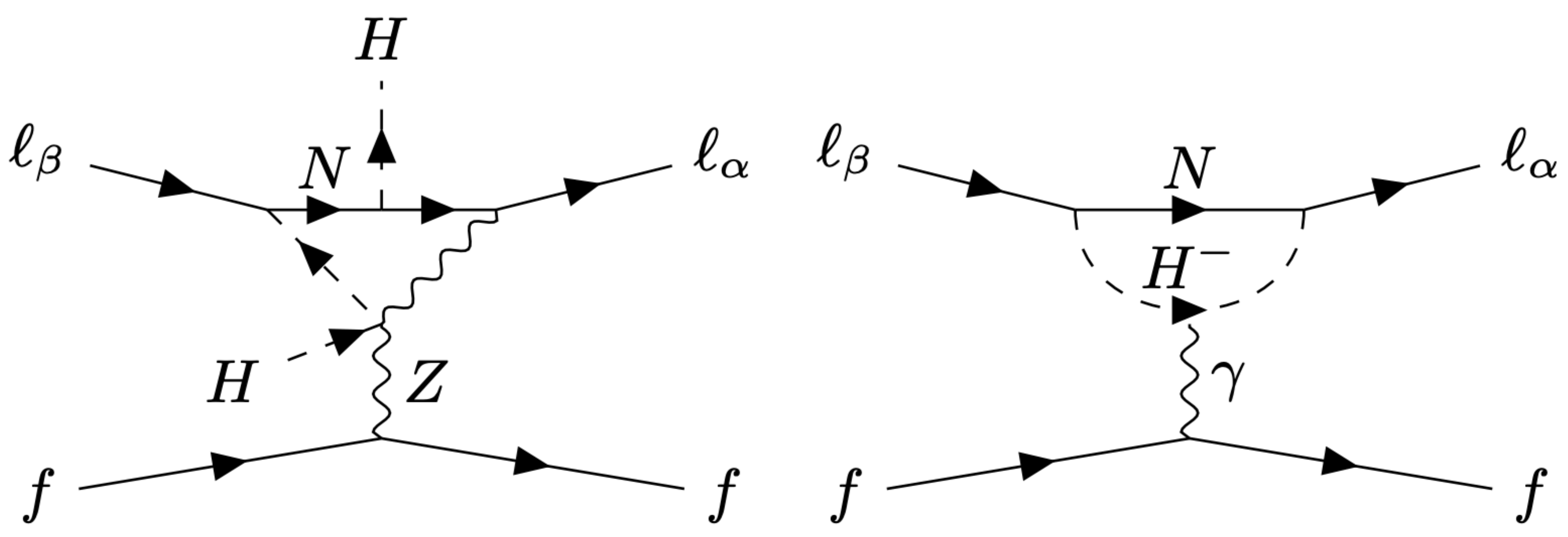
$$\propto v^2(Y_\nu M^{-2} Y_\nu^\dagger)_{\alpha\beta}$$

Inverse seesaw LFV



- PMNS non-unitary contribution, leads to modified $W - l - \nu$ couplings

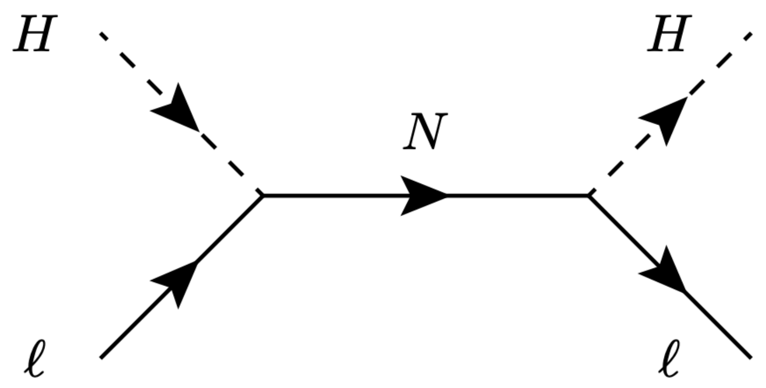
$$\propto v^2 (Y_\nu M^{-2} Y_\nu^\dagger)_{\alpha\beta}$$



- Match onto four-vector operators

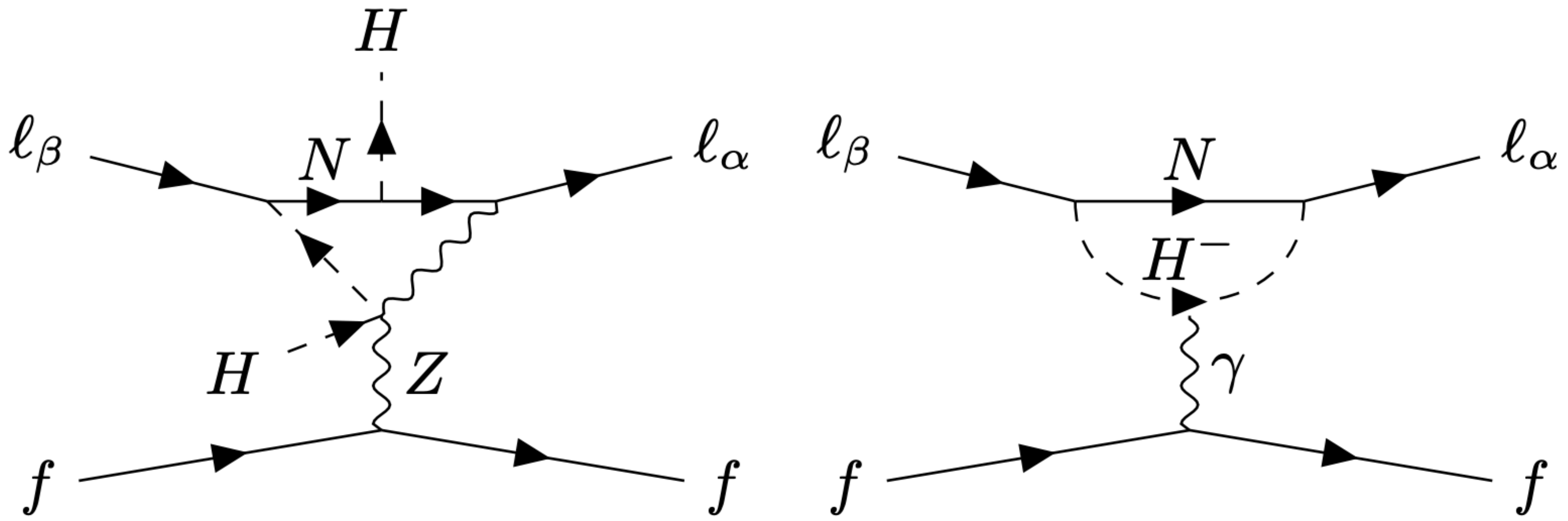
$$C^{\alpha\beta ff}_{V,LX} \propto \frac{\alpha_e}{4\pi} v^2 (Y_\nu M_a^{-2} Y_\nu^\dagger)_{\alpha\beta} (\log(m_W^2/M_a^2) + \text{const.})$$

Inverse seesaw LFV



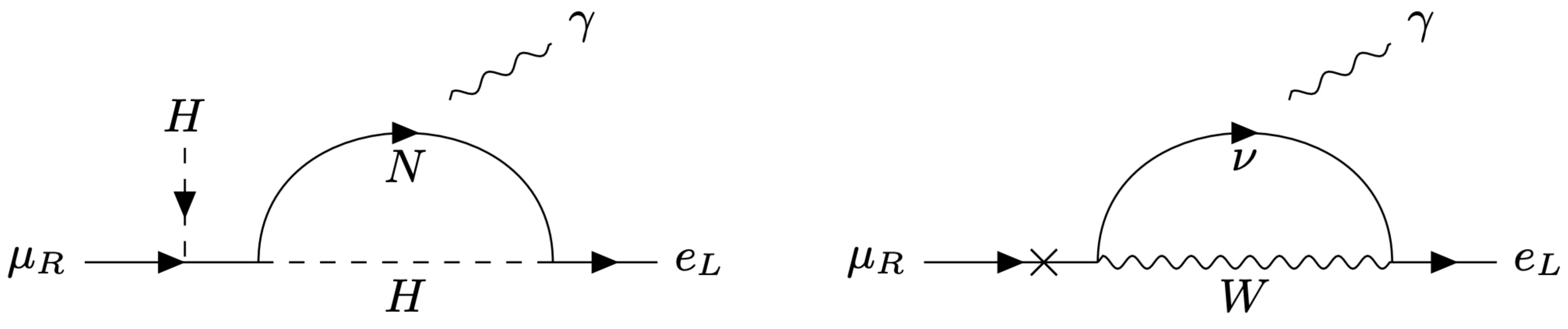
- PMNS non-unitary contribution, leads to modified $W - l - \nu$ couplings

$$\propto v^2 (Y_\nu M^{-2} Y_\nu^\dagger)_{\alpha\beta}$$



- Match onto four-vector operators

$$C^{\alpha\beta ff}_{V,LX} \propto \frac{\alpha_e}{4\pi} v^2 (Y_\nu M_a^{-2} Y_\nu^\dagger)_{\alpha\beta} (\log(m_W^2/M_a^2) + \text{const.})$$



- Match onto the dipole

$$C^{\alpha\beta}_{D,R} \propto \frac{\alpha_e}{4\pi e} v^2 (Y_\nu M^{-2} Y_\nu^\dagger)_{\alpha\beta}$$

Inverse seesaw LFV

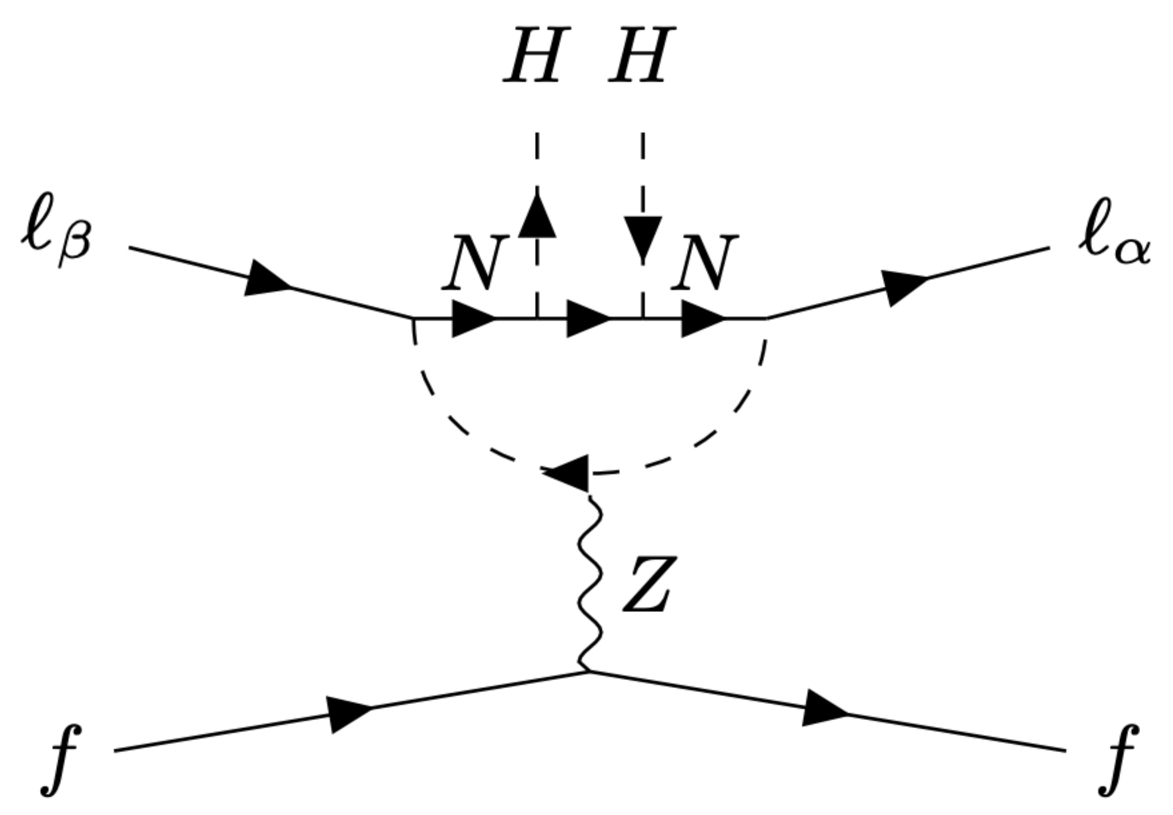
Inverse seesaw LFV

- So far, coefficients proportional to two matrix element: $v^2(Y_\nu M^{-2} Y_\nu^\dagger)_{\alpha\beta}, \quad v^2(Y_\nu M_a^{-2} Y_\nu^\dagger)_{\alpha\beta}(\log(m_W^2/M_a^2) + \text{const.})$

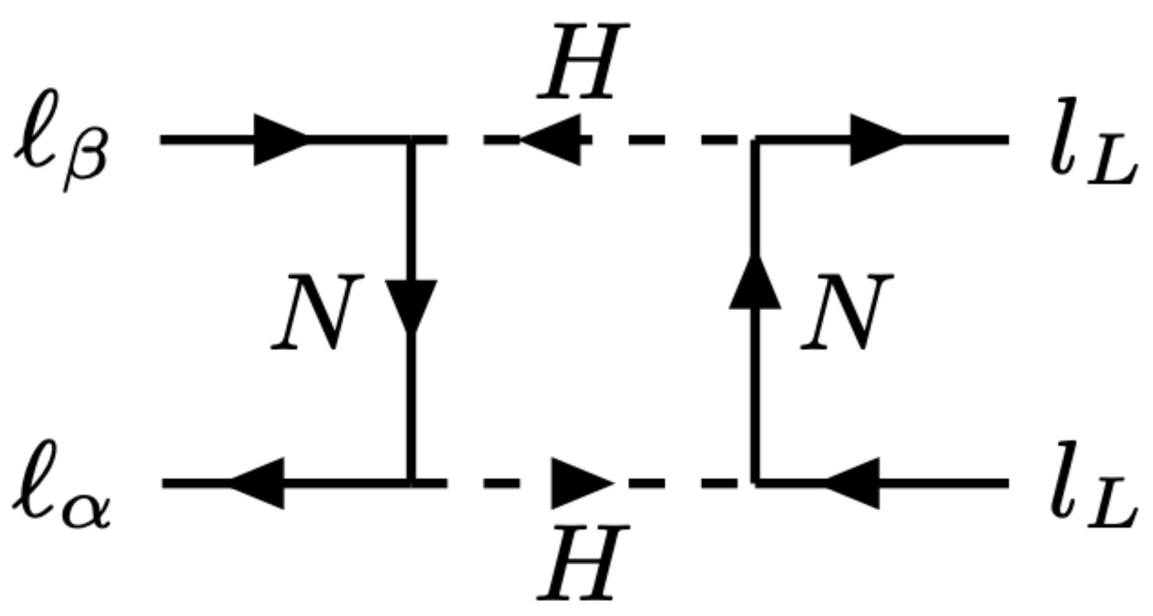
Inverse seesaw LFV

- So far, coefficients proportional to two matrix element: $v^2(Y_\nu M^{-2} Y_\nu^\dagger)_{\alpha\beta}$, $\quad v^2(Y_\nu M_a^{-2} Y_\nu^\dagger)_{\alpha\beta}(\log(m_W^2/M_a^2) + \text{const.})$

- But Yukawas can be large, and there are diagrams $\mathcal{O}(Y_\nu^4)$



$$\propto \left[Y_\nu \left(Y_\nu^\dagger Y_\nu \right)_{ab} \frac{1}{M_a^2 - M_b^2} \ln\left(\frac{M_a^2}{M_b^2}\right) Y_\nu^\dagger \right]_{\alpha\beta}$$

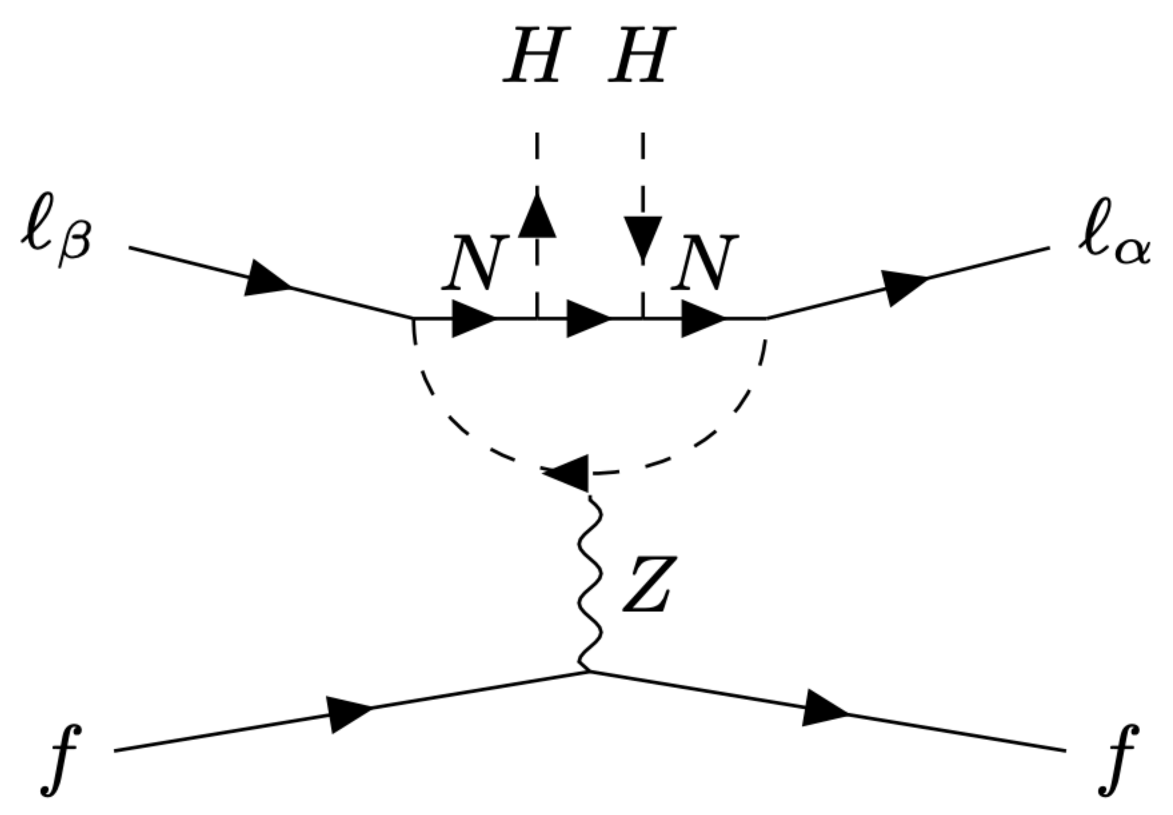


$$\propto Y_\nu^{\alpha a} Y_\nu^{*\beta a} Y_\nu^{lb} Y_\nu^{*lb} \frac{1}{M_a^2 - M_b^2} \ln\left(\frac{M_a^2}{M_b^2}\right)$$

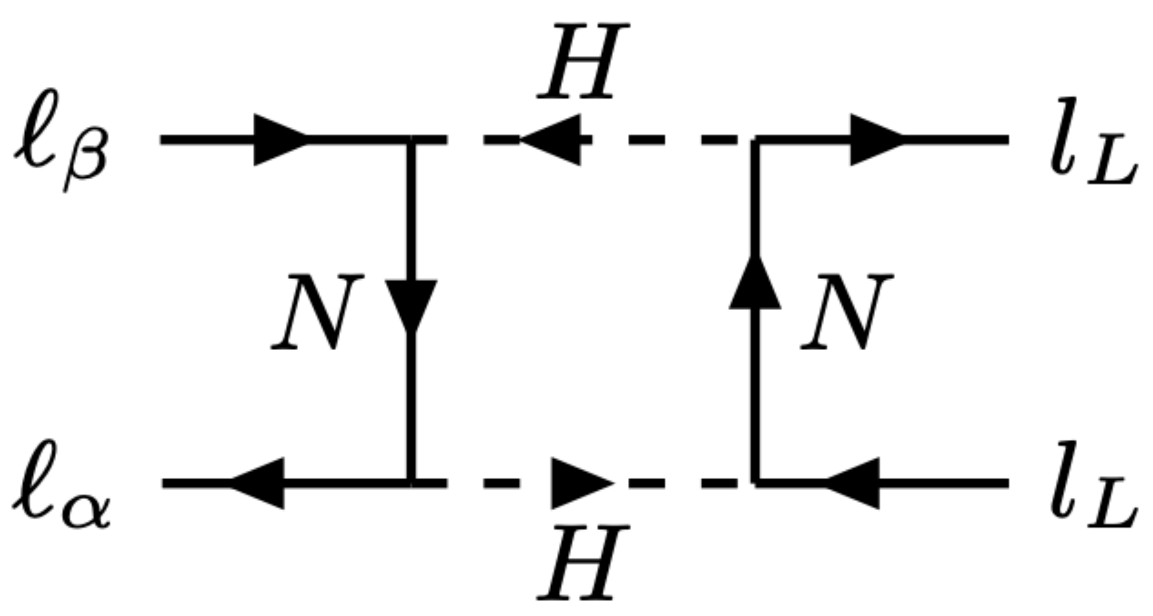
Inverse seesaw LFV

- So far, coefficients proportional to two matrix element: $v^2(Y_\nu M^{-2} Y_\nu^\dagger)_{\alpha\beta}$, $v^2(Y_\nu M_a^{-2} Y_\nu^\dagger)_{\alpha\beta}(\log(m_W^2/M_a^2) + \text{const.})$

- But Yukawas can be large, and there are diagrams $\mathcal{O}(Y_\nu^4)$



$$\propto \left[Y_\nu \left(Y_\nu^\dagger Y_\nu \right)_{ab} \frac{1}{M_a^2 - M_b^2} \ln\left(\frac{M_a^2}{M_b^2} \right) Y_\nu^\dagger \right]_{\alpha\beta}$$



$$\propto Y_\nu^{\alpha a} Y_\nu^{*\beta a} Y_\nu^{lb} Y_\nu^{*lb} \frac{1}{M_a^2 - M_b^2} \ln\left(\frac{M_a^2}{M_b^2} \right)$$

- In general, four “invariants” parametrize the size of the $\mu \to e$ coefficients

Inverse seesaw: $\mu \to e$

Inverse seesaw: $\mu \to e$

- Cannot predict sizable $\mu \to e_R$ (like in the type-II seesaw, the new states interact with left-handed doublets)

Inverse seesaw: $\mu \to e$

- Cannot predict sizable $\mu \to e_R$ (like in the type-II seesaw, the new states interact with left-handed doublets)

$$v^2 (Y_\nu M^{-2} Y_\nu^\dagger)_{e\mu}$$

$$v^2 (Y_\nu M_a^{-2} Y_\nu^\dagger)_{e\mu} (\ln(m_W^2/M_a^2) + \text{const.})$$

$C_{D,R}^{e\mu}$, $C_{V,LL}^{e\mu ee}$, $C_{V,LR}^{e\mu ee}$, $C_{Alight,L}^{e\mu}$ **Parametrized in terms of** $$[Y_\nu \left(Y_\nu^\dagger Y_\nu\right)_{ab} \frac{1}{M_a^2 - M_b^2} \ln\left(\frac{M_a^2}{M_b^2}\right) Y_\nu^\dagger]_{e\mu}$$

$$Y_\nu^{ea} Y_\nu^{*\mu a} Y_\nu^{eb} Y_\nu^{*eb} \frac{1}{M_a^2 - M_b^2} \ln\left(\frac{M_a^2}{M_b^2}\right)$$

Inverse seesaw: $\mu \to e$

- Cannot predict sizable $\mu \to e_R$ (like in the type-II seesaw, the new states interact with left-handed doublets)

$C^{e\mu}_{D,R}$, $C^{e\mu ee}_{V,LL}$, $C^{e\mu ee}_{V,LR}$, $C^{e\mu}_{Alight,L}$ **Parametrized in terms of**

$$v^2(Y_\nu M^{-2} Y_\nu^\dagger)_{e\mu}$$

$$v^2(Y_\nu M_a^{-2} Y_\nu^\dagger)_{e\mu}(\ln(m_W^2/M_a^2) + \text{const.})$$

$$[Y_\nu \left(Y_\nu^\dagger Y_\nu\right)_{ab} \frac{1}{M_a^2 - M_b^2} \ln\left(\frac{M_a^2}{M_b^2}\right) Y_\nu^\dagger]_{e\mu}$$

$$Y_\nu^{ea} Y_\nu^{*\mu a} Y_\nu^{eb} Y_\nu^{*eb} \frac{1}{M_a^2 - M_b^2} \ln\left(\frac{M_a^2}{M_b^2}\right)$$

- For generic sterile masses the model can completely fill the experimentally allowed ellipse for the four coefficients above

- Possibly, the four fermion combination contributing to $\mu \to e$ conversion on heavy target is predicted once the four are measured

Inverse seesaw: $\mu \to e$ with quasi-degenerate sterile neutrinos

Inverse seesaw: $\mu \to e$ with quasi-degenerate sterile neutrinos

- If sterile neutrinos have quasi-degenerate masses $M_a^2 - M_b^2 \sim \mathcal{O}(v^2)$, $\mu \to e$ observables depend on only two/three invariants

Inverse seesaw: $\mu \to e$ with quasi-degenerate sterile neutrinos

- If sterile neutrinos have quasi-degenerate masses $M_a^2 - M_b^2 \sim \mathcal{O}(v^2)$, $\mu \to e$ observables depend on only two/three invariants

$C^{e\mu}_{D,R}$, $C^{e\mu ee}_{V,LL}$, $C^{e\mu ee}_{V,LR}$, $C^{e\mu}_{Alight,L}$ **Parametrized in terms of**

$$v^2(Y_\nu M^{-2} Y_\nu^\dagger)_{e\mu}$$

$$(v^2/M^2)(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger)_{e\mu}$$

$$v^2(Y_\nu M^{-2} Y_\nu^\dagger)_{e\mu}(Y_\nu Y_\nu^\dagger)_{ee}$$

Inverse seesaw: $\mu \to e$ with quasi-degenerate sterile neutrinos

- If sterile neutrinos have quasi-degenerate masses $M_a^2 - M_b^2 \sim \mathcal{O}(v^2)$, $\mu \to e$ observables depend on only two/three invariants

$C^{e\mu}_{D,R}$, $C^{e\mu ee}_{V,LL}$, $C^{e\mu ee}_{V,LR}$, $C^{e\mu}_{Alight,L}$ **Parametrized in terms of**

$$v^2(Y_\nu M^{-2} Y_\nu^\dagger)_{e\mu}$$

$$(v^2/M^2)(Y_\nu Y_\nu^\dagger Y_\nu Y_\nu^\dagger)_{e\mu}$$

$$v^2(Y_\nu M^{-2} Y_\nu^\dagger)_{e\mu}(Y_\nu Y_\nu^\dagger)_{ee}$$

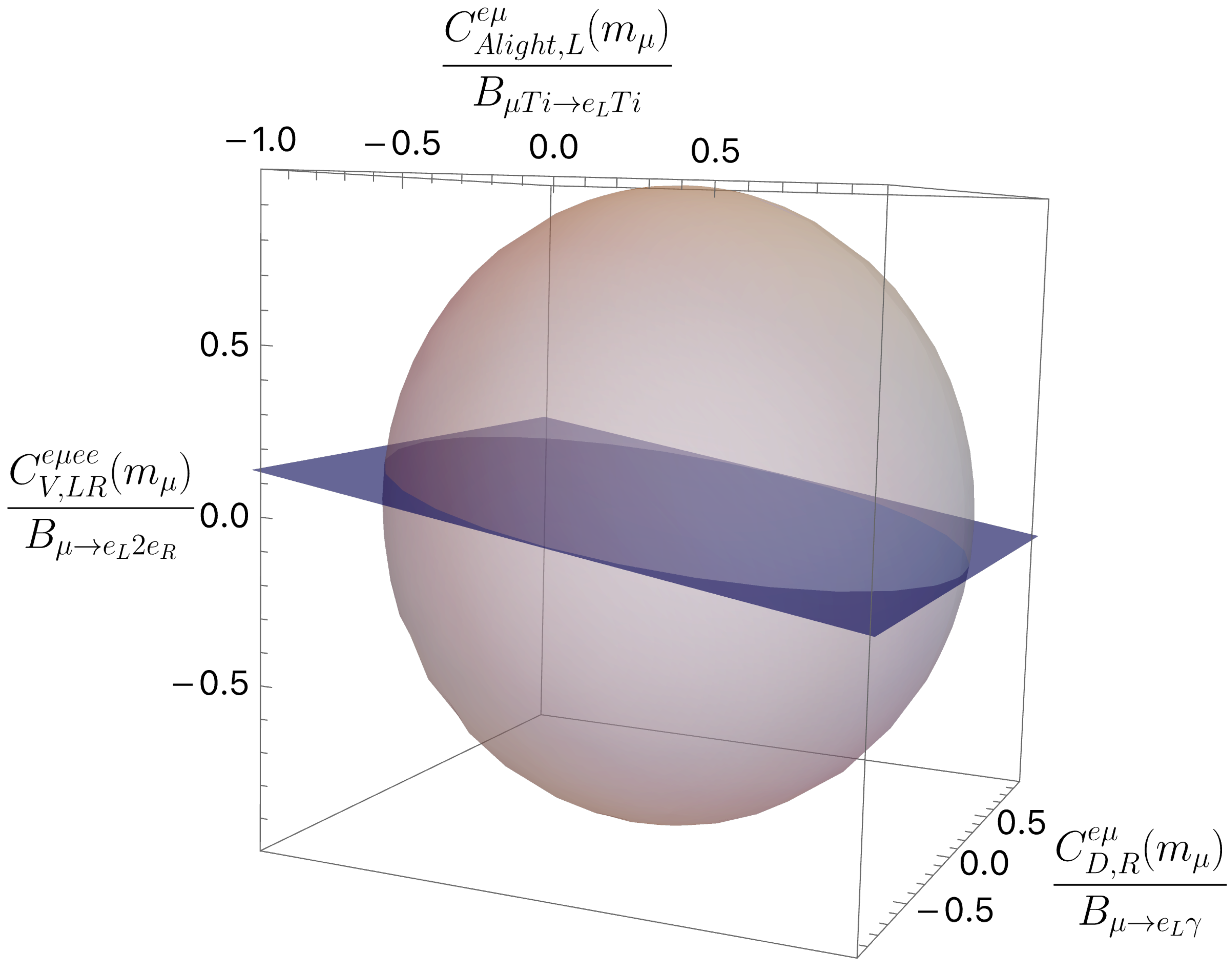
- One coefficient is known once two/three of them are measured

$$C^{e\mu ee}_{V,LR}(m_\mu) = -2.4 C^{e\mu}_{Alight,L}(m_\mu) + 0.02 C^{e\mu}_{D,R}(m_\mu)$$

$$C^{e\mu ee}_{V,LL}(m_\mu) = 2.4 C^{e\mu}_{Alight,L}(m_\mu) + c_d C^{e\mu}_{D,R}(m_\mu) \qquad -1.99 \lesssim c_d \lesssim -0.57$$

Inverse seesaw: $\mu \to e$ with quasi-degenerate sterile neutrinos

Any point outside the plane is not compatible with the inversee seesaw



Scalar Singlet Leptoquark

Scalar Singlet Leptoquark

- Add to the SM a scalar SU(2) singlet leptoquark S with a mass $m_{LQ} \sim$ TeV (can fit the $R_{D^{(*)}}$ anomaly)

Scalar Singlet Leptoquark

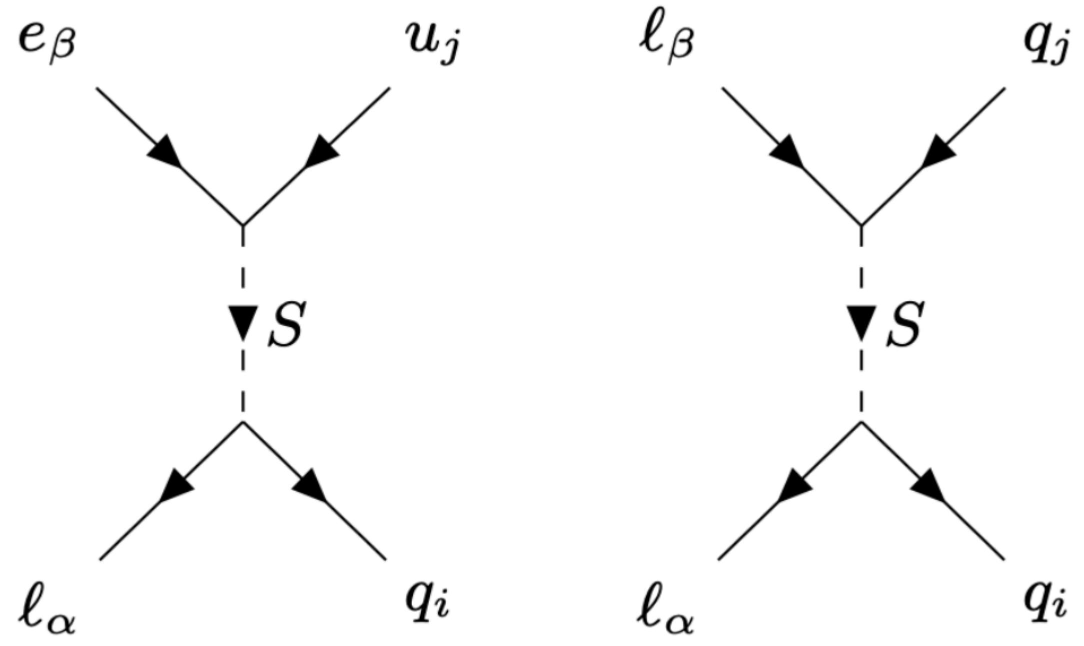
- Add to the SM a scalar SU(2) singlet leptoquark S with a mass $m_{LQ} \sim$ TeV (can fit the $R_{D^{(*)}}$ anomaly)

$$\mathscr{L}_S = (D_\rho S)^\dagger D^\rho S - m_{LQ}^2 S^\dagger S + (-\lambda_L^{\alpha j} \overline{\ell}_\alpha i\tau_2 q_j^c + \lambda_R^{\alpha j} \overline{e}_\alpha u_j^c) S + (\lambda_L^{\alpha j *} \overline{q^c}_j i\tau_2 \ell_\alpha + \lambda_R^{\alpha j *} \overline{u^c}_j e_\alpha) S^\dagger$$

Scalar Singlet Leptoquark

- Add to the SM a scalar SU(2) singlet leptoquark S with a mass $m_{LQ} \sim$ TeV (can fit the $R_{D^{(*)}}$ anomaly)

$$\mathscr{L}_S = (D_\rho S)^\dagger D^\rho S - m_{LQ}^2 S^\dagger S + (-\lambda_L^{\alpha j}\overline{\ell}_\alpha i\tau_2 q_j^c + \lambda_R^{\alpha j}\overline{e}_\alpha u_j^c)S + (\lambda_L^{\alpha j*}\overline{q^c}_j i\tau_2 \ell_\alpha + \lambda_R^{\alpha j*}\overline{u^c}_j e_\alpha)S^\dagger$$

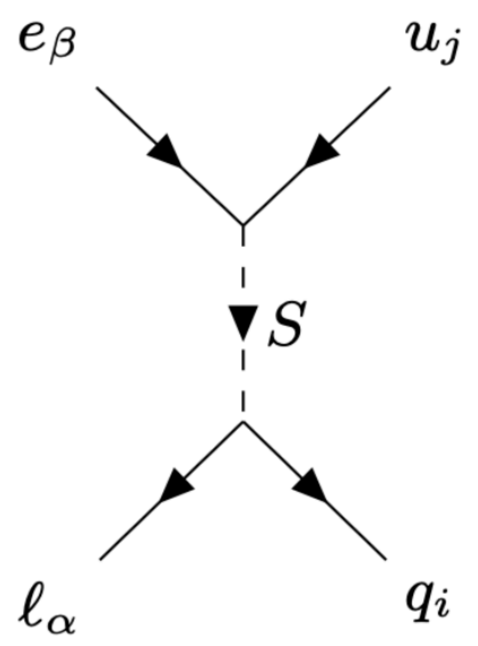


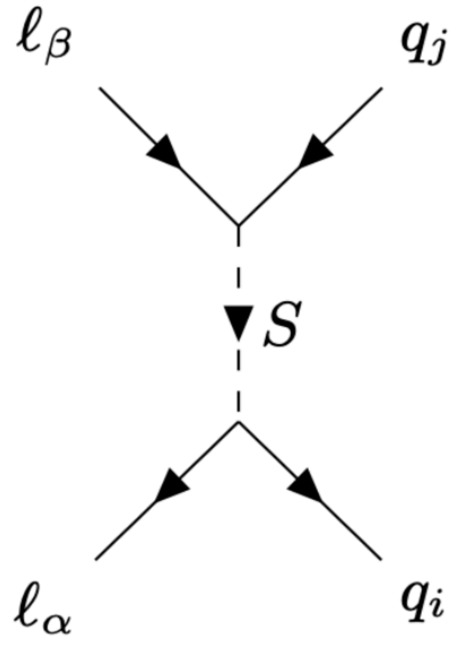
Scalar, tensors and vectors + RGEs mixing

Scalar Singlet Leptoquark

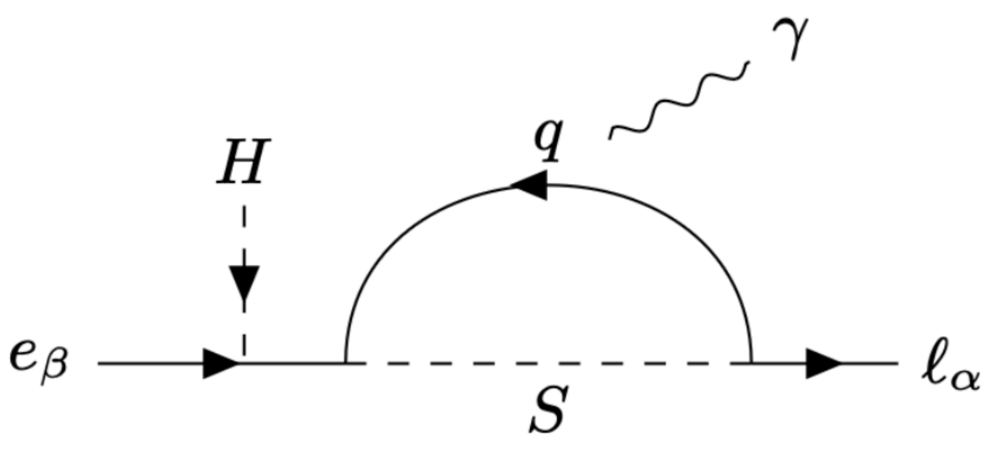
- Add to the SM a scalar SU(2) singlet leptoquark S with a mass $m_{LQ} \sim$ TeV (can fit the $R_{D^{(*)}}$ anomaly)

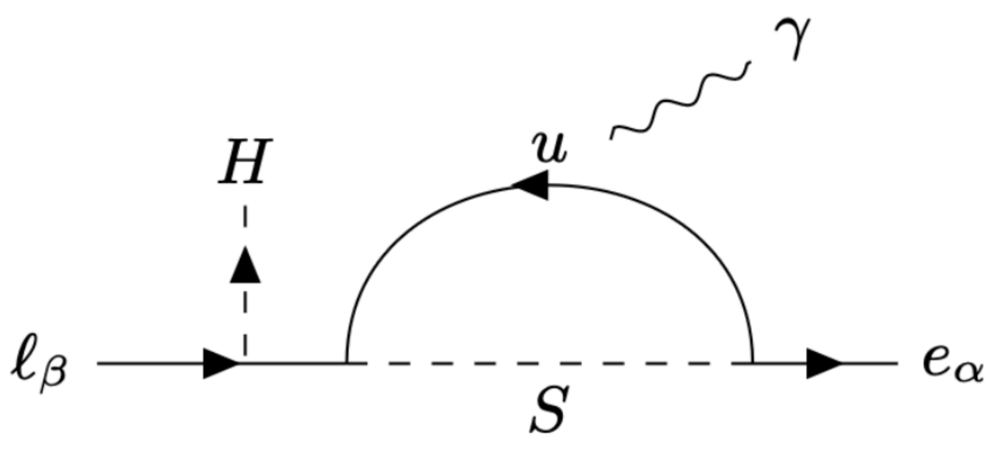
$$\mathscr{L}_S = (D_\rho S)^\dagger D^\rho S - m_{LQ}^2 S^\dagger S + (-\lambda_L^{\alpha j}\overline{\ell}_\alpha i\tau_2 q_j^c + \lambda_R^{\alpha j}\overline{e}_\alpha u_j^c)S + (\lambda_L^{\alpha j*}\overline{q^c}_j i\tau_2 \ell_\alpha + \lambda_R^{\alpha j*}\overline{u^c}_j e_\alpha)S^\dagger$$





Scalar, tensors and vectors + RGEs mixing



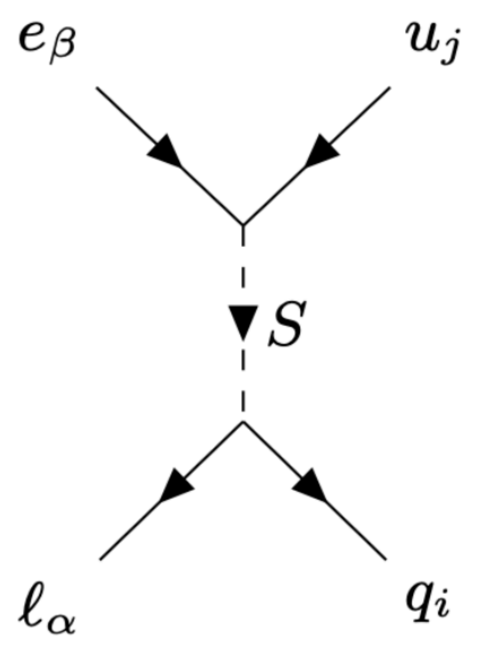


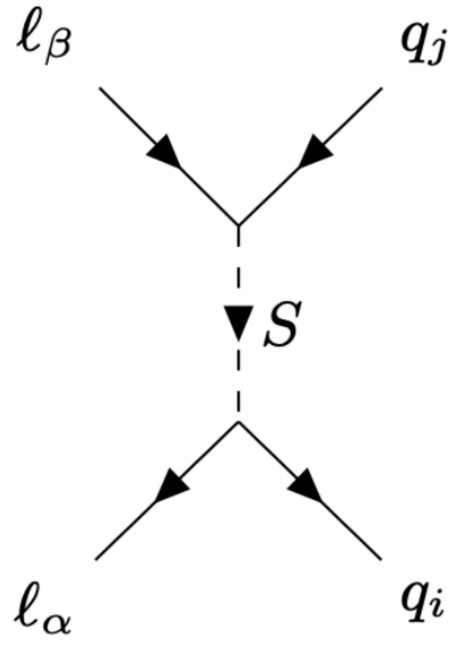
Dipole with left-handed and right-handed outgoing leptons

Scalar Singlet Leptoquark

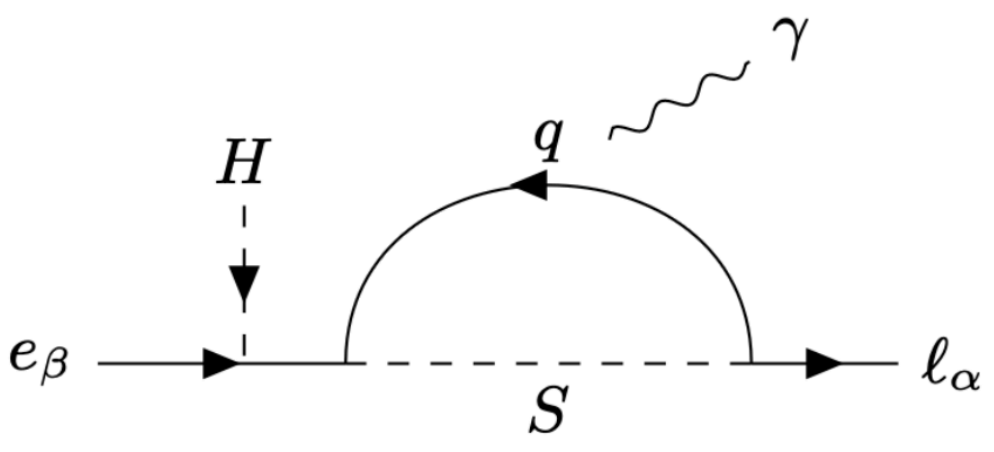
- Add to the SM a scalar SU(2) singlet leptoquark S with a mass $m_{LQ} \sim$ TeV (can fit the $R_{D^{(*)}}$ anomaly)

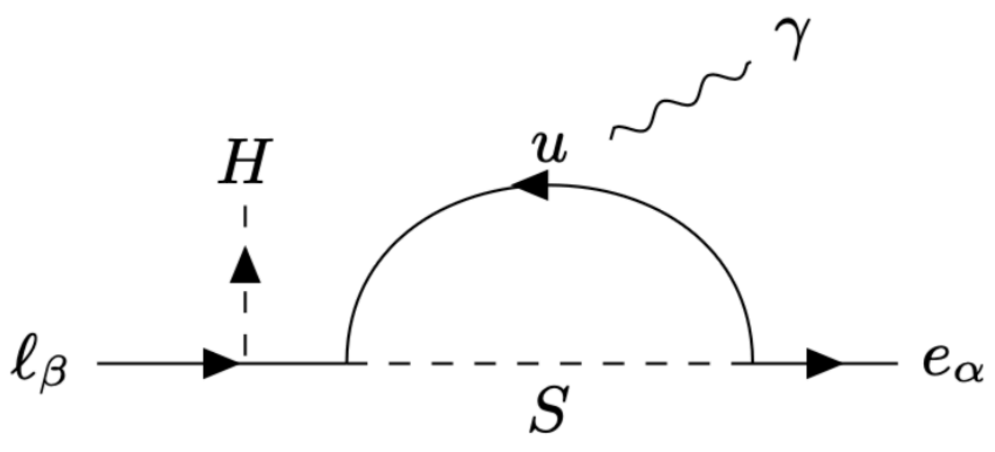
$$\mathscr{L}_S = (D_\rho S)^\dagger D^\rho S - m_{LQ}^2 S^\dagger S + (-\lambda_L^{\alpha j}\overline{\ell}_\alpha i\tau_2 q_j^c + \lambda_R^{\alpha j}\overline{e}_\alpha u_j^c)S + (\lambda_L^{\alpha j*}\overline{q^c}_j i\tau_2 \ell_\alpha + \lambda_R^{\alpha j*}\overline{u^c}_j e_\alpha)S^\dagger$$



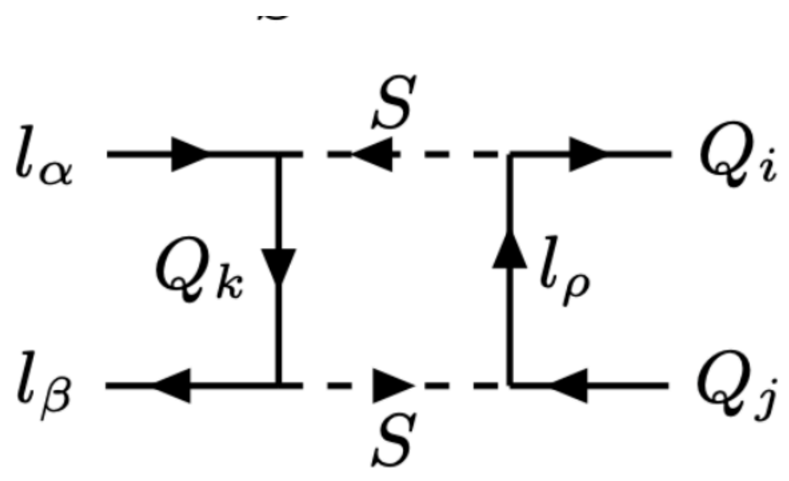


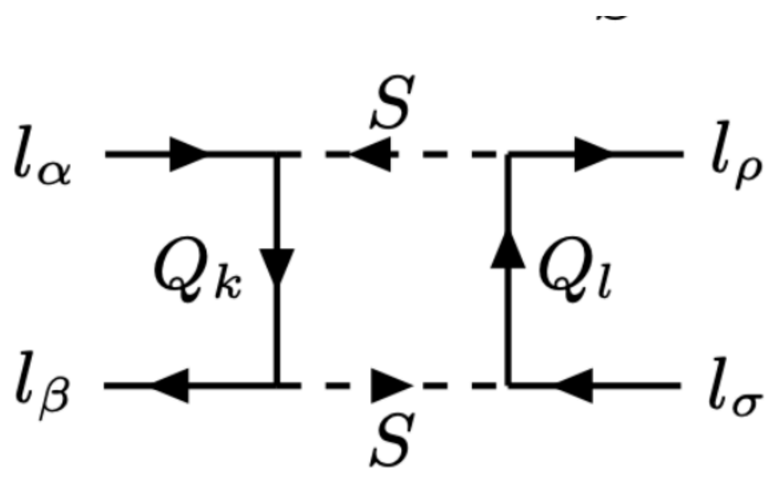
Scalar, tensors and vectors + RGEs mixing





Dipole with left-handed and right-handed outgoing leptons





$\mathcal{O}(\lambda^4)$ matching contribution to scalars and vectors

Scalar Singlet Leptoquark: $\mu \to e$

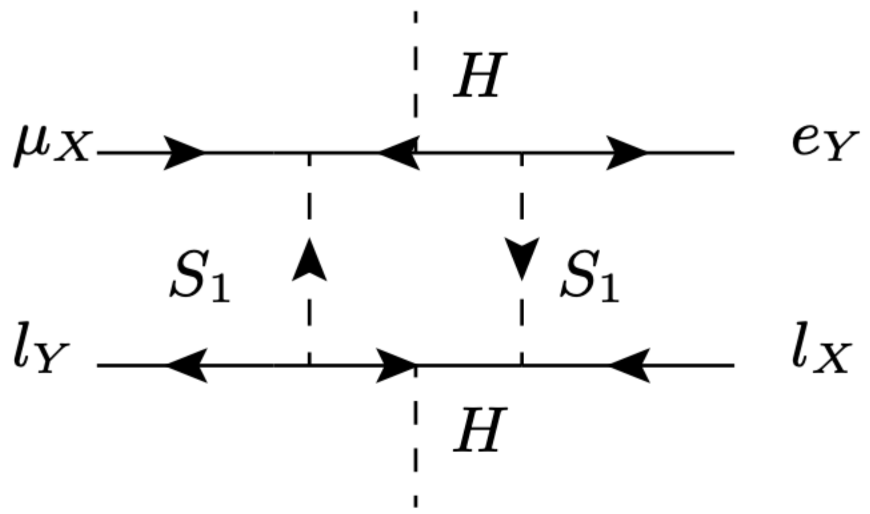
Scalar Singlet Leptoquark: $\mu \to e$

- The leptoquark can generate both $\mu \to e_L$ and $\mu \to e_R$ transitions

Scalar Singlet Leptoquark: $\mu \to e$

- The leptoquark can generate both $\mu \to e_L$ and $\mu \to e_R$ transitions

- The scalar four-lepton operator is too small to be observable

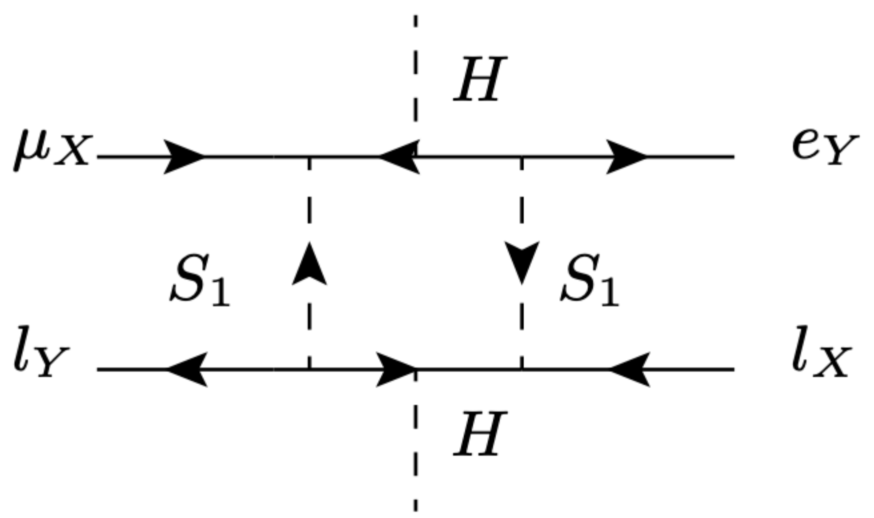


$$C^{e\mu ee}_{S,RR},\ C^{e\mu ee}_{S,LL} < \text{sensitivity}$$

Scalar Singlet Leptoquark: $\mu \to e$

- The leptoquark can generate both $\mu \to e_L$ and $\mu \to e_R$ transitions

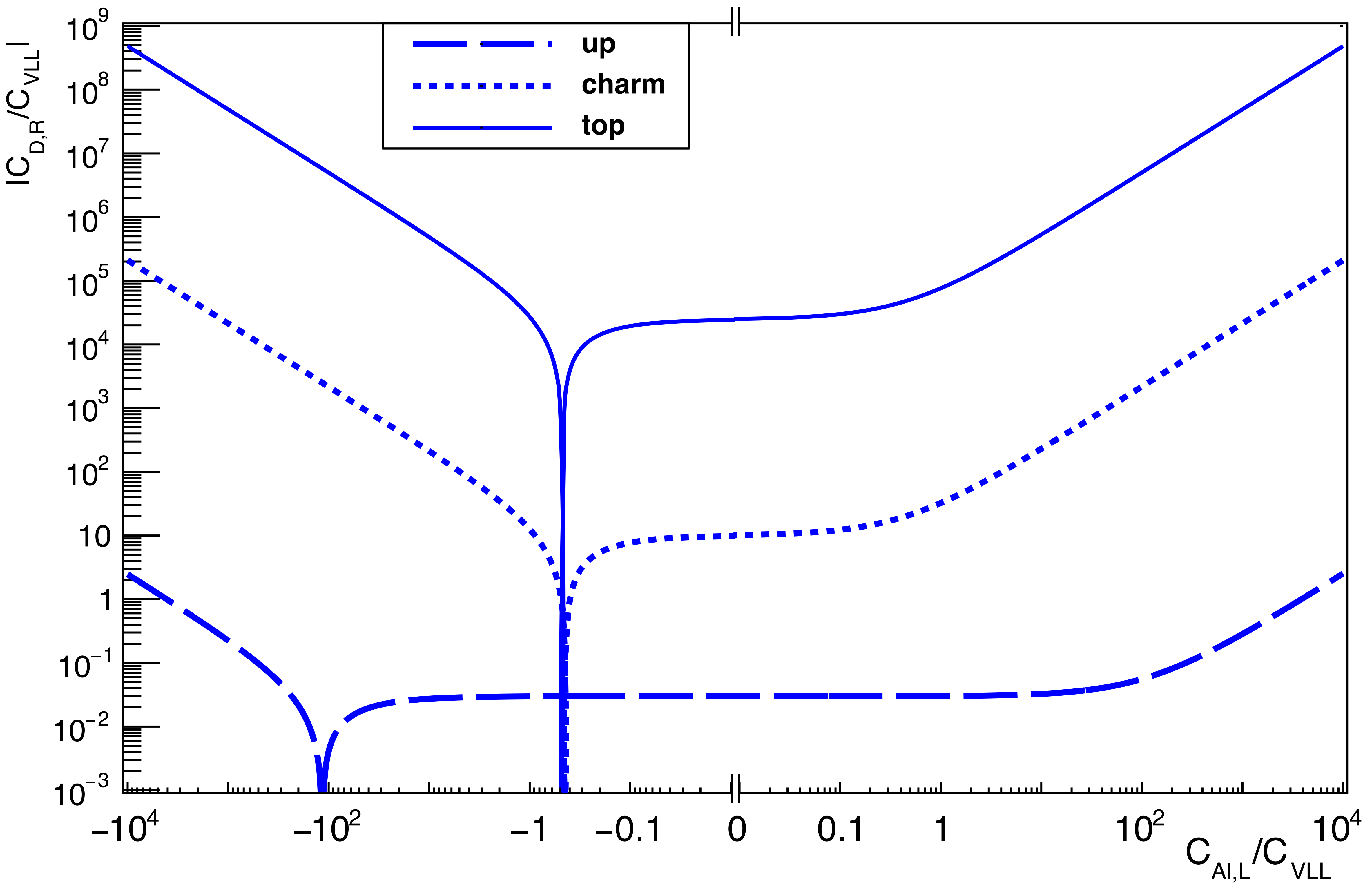
- The scalar four-lepton operator is too small to be observable



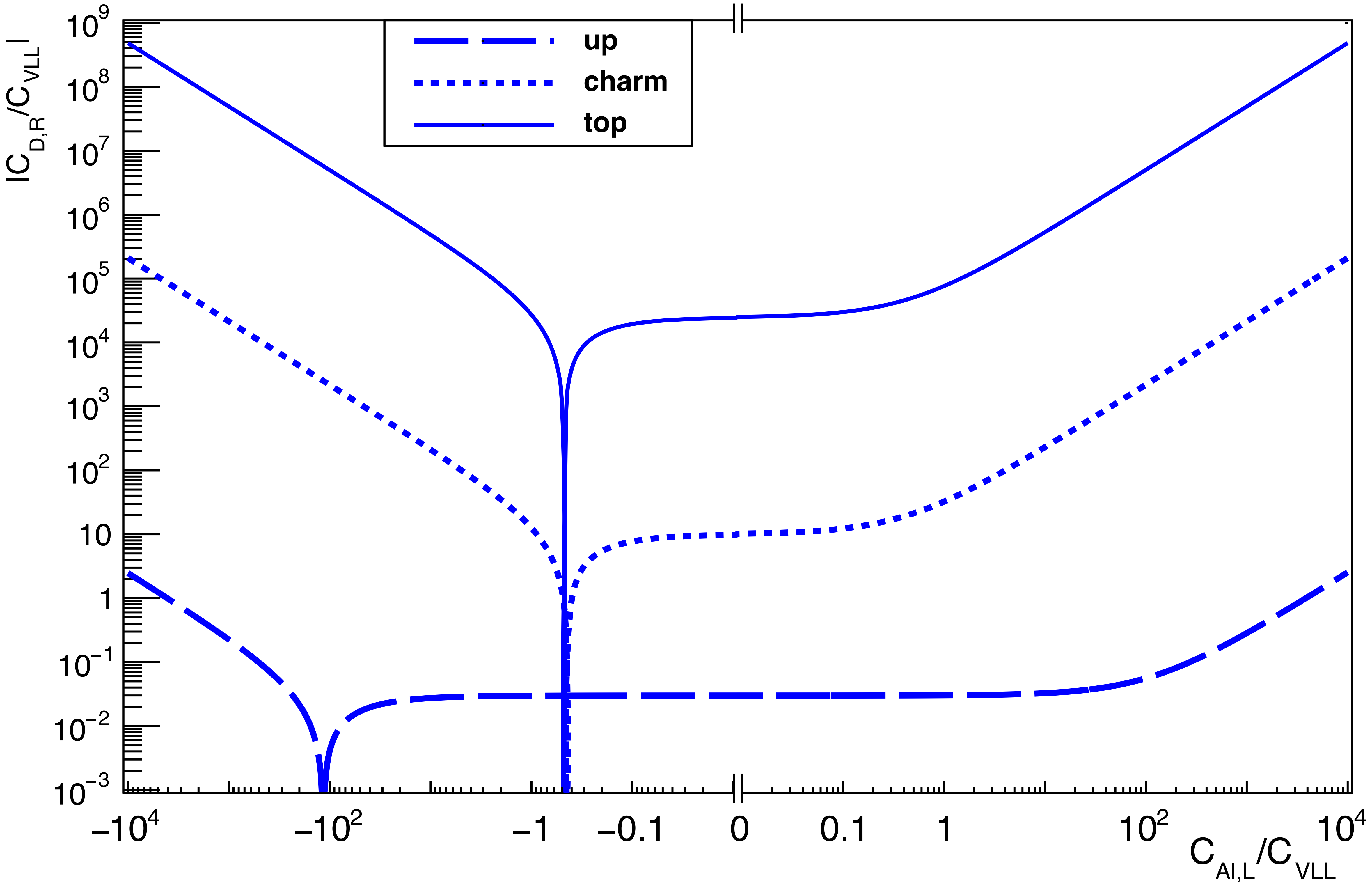
$$C^{e\mu ee}_{S,RR},\ C^{e\mu ee}_{S,LL} < \text{sensitivity}$$

- The leptoquark could in principle fill completely the remaining 10-dimension of the $\mu \to e$ observables (too many parameters…)

Leptoquark: $\mu \to e$ with one-generation-at-a-time



Leptoquark: $\mu \to e$ with one-generation-at-a-time



- Assuming the leptoquark to couple only with one generation at a time reduces the number of “invariants”
- But cancellations between coefficients are in principle possible, so combination of observations could exclude “generic” parameter points, but not the model

Low-energy basis

$$\begin{aligned}
\mathcal{O}^{ll}_{V,YY} &= (\bar{e}\gamma^{\alpha}P_Y\mu)(\bar{l}\gamma_{\alpha}P_Y l), & \mathcal{O}^{ll}_{V,YX} &= (\bar{e}\gamma^{\alpha}P_Y\mu)(\bar{l}\gamma_{\alpha}P_X l) \\
\mathcal{O}^{ll}_{S,YY} &= (\bar{e}P_Y\mu)(\bar{l}P_Y l) & \mathcal{O}^{\tau\tau}_{S,YX} &= (\bar{e}P_Y\mu)(\bar{\tau}P_X\tau) \\
\mathcal{O}^{\tau\tau}_{T,YY} &= (\bar{e}\sigma^{\alpha\beta}P_Y\mu)(\bar{\tau}\sigma_{\alpha\beta}P_Y\tau)
\end{aligned}$$

$$\begin{aligned}
\mathcal{O}^{qq}_{V,YY} &= (\bar{e}\gamma^{\alpha}P_Y\mu)(\bar{q}\gamma_{\alpha}P_Y q) &,\quad \mathcal{O}^{qq}_{V,YX} &= (\bar{e}\gamma^{\alpha}P_Y\mu)(\bar{q}\gamma_{\alpha}P_X q) \\
\mathcal{O}^{qq}_{S,YY} &= (\bar{e}P_Y\mu)(\bar{q}P_Y q) &,\quad \mathcal{O}^{qq}_{S,YX} &= (\bar{e}P_Y\mu)(\bar{q}P_X q) \\
\mathcal{O}^{qq}_{T,YY} &= (\bar{e}\sigma^{\alpha\beta}P_Y\mu)(\bar{q}\sigma_{\alpha\beta}P_Y q)
\end{aligned}$$

$$\begin{aligned}
\mathcal{O}_{D,L} &= m_{\mu}\overline{e_R}\sigma^{\alpha\beta}\mu_L F_{\alpha\beta} & & m_{\mu}\overline{e_L}\sigma^{\alpha\beta}\mu_R F_{\alpha\beta} \\
\mathcal{O}_{GG,Y} &= \frac{1}{v}(\bar{e}P_Y\mu)G_{\alpha\beta}G^{\alpha\beta} &,\quad \mathcal{O}_{G\tilde{G},Y} &= \frac{1}{v}(\bar{e}P_Y\mu)G_{\alpha\beta}\widetilde{G}^{\alpha\beta} \\
\mathcal{O}_{GGV,Y} &= \frac{1}{v^2}(\bar{e}\gamma_{\sigma}P_Y\mu)G_{\alpha\beta}\partial_{\beta}G^{\alpha\sigma} &,\quad \mathcal{O}_{G\tilde{G}V,Y} &= \frac{1}{v^2}(\bar{e}\gamma_{\sigma}P_Y\mu)G_{\alpha\beta}\partial_{\beta}\widetilde{G}^{\alpha\sigma} \\
\mathcal{O}_{FF,Y} &= \frac{1}{v}(\bar{e}P_Y\mu)F_{\alpha\beta}F^{\alpha\beta} &,\quad \mathcal{O}_{F\tilde{F},Y} &= \frac{1}{v}(\bar{e}P_Y\mu)F_{\alpha\beta}\widetilde{F}^{\alpha\beta} \\
\mathcal{O}_{FFV,Y} &= \frac{1}{v}(\bar{e}\gamma^{\sigma}P_Y\mu)F^{\alpha\beta}\partial_{\beta}F_{\alpha\sigma} &,\quad \mathcal{O}_{F\tilde{F}V,Y} &= \frac{1}{v}(\bar{e}\gamma^{\sigma}P_Y\mu)F^{\alpha\beta}\partial_{\beta}\widetilde{F}_{\alpha\sigma}
\end{aligned}$$

where $l \in \{e, \mu\}, q \in \{u, d, s, c, b\}$

SMEFT basis dimension six

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde W}$	$\epsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D^\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar l_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
Q_{dH}	$(H^\dagger H)(\bar q_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde W B}$	$H^\dagger \tau^I H\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde H\, G^A_{\mu\nu}$
Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde H\, W^I_{\mu\nu}$
Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde H\, B_{\mu\nu}$
Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar l_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar l_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar e_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar q_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar q_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar u_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar d_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde H^\dagger D_\mu H)(\bar u_p \gamma^\mu d_r)$

$8: (\bar L L)(\bar L L)$	
Q_{ll}	$(\bar l_p \gamma^\mu l_r)(\bar l_s \gamma_\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma^\mu q_r)(\bar q_s \gamma_\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma^\mu \tau^I q_r)(\bar q_s \gamma_\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma^\mu l_r)(\bar q_s \gamma_\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma^\mu \tau^I l_r)(\bar q_s \gamma_\mu \tau^I q_t)$

$8: (\bar R R)(\bar R R)$	
Q_{ee}	$(\bar e_p \gamma^\mu e_r)(\bar e_s \gamma_\mu e_t)$
Q_{uu}	$(\bar u_p \gamma^\mu u_r)(\bar u_s \gamma_\mu u_t)$
Q_{dd}	$(\bar d_p \gamma^\mu d_r)(\bar d_s \gamma_\mu d_t)$
Q_{eu}	$(\bar e_p \gamma^\mu e_r)(\bar u_s \gamma_\mu u_t)$
Q_{ed}	$(\bar e_p \gamma^\mu e_r)(\bar d_s \gamma_\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar u_p \gamma^\mu u_r)(\bar d_s \gamma_\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar u_p \gamma^\mu T^A u_r)(\bar d_s \gamma_\mu T^A d_t)$

$8: (\bar L L)(\bar R R)$	
Q_{le}	$(\bar l_p \gamma^\mu l_r)(\bar e_s \gamma_\mu e_t)$
Q_{lu}	$(\bar l_p \gamma^\mu l_r)(\bar u_s \gamma_\mu u_t)$
Q_{ld}	$(\bar l_p \gamma^\mu l_r)(\bar d_s \gamma_\mu d_t)$
Q_{qe}	$(\bar q_p \gamma^\mu q_r)(\bar e_s \gamma_\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar q_p \gamma^\mu q_r)(\bar u_s \gamma_\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar q_p \gamma^\mu T^A q_r)(\bar u_s \gamma_\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar q_p \gamma^\mu q_r)(\bar d_s \gamma_\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar q_p \gamma^\mu T^A q_r)(\bar d_s \gamma_\mu T^A d_t)$

$8: (\bar L R)(\bar R L) + \text{h.c.}$	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_{tj})$

$8: (\bar L R)(\bar L R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\epsilon_{jk}(\bar q_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\epsilon_{jk}(\bar q_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\epsilon_{jk}(\bar q_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$

$8: (\not B) + \text{h.c.}$	
Q_{duql}	$\epsilon_{\alpha\beta\gamma}\epsilon_{jk}(d_p^\alpha C u_r^\beta)(q_s^{j\gamma} C l_t^k)$
Q_{qque}	$\epsilon_{\alpha\beta\gamma}\epsilon_{jk}(q_p^{j\alpha} C q_r^{k\beta})(u_s^\gamma C e_t)$
Q_{qqql}	$\epsilon_{\alpha\beta\gamma}\epsilon_{mn}\epsilon_{jk}(q_p^{m\alpha} C q_r^{j\beta})(q_s^{k\gamma} C l_t^n)$
Q_{duue}	$\epsilon_{\alpha\beta\gamma}(d_p^\alpha C u_r^\beta)(u_s^\gamma C e_t)$

$\mu \to e$ Rates

$$BR(\mu \to e\gamma) = 384\pi^2(|C^{e\mu}_{DL}|^2 + |C^{e\mu}_{DR}|^2)$$

$$BR(\mu \to e\bar{e}e) = \frac{|C^{e\mu ee}_{S,LL}|^2 + |C^{e\mu ee}_{S,RR}|^2}{8} + 2|C^{e\mu ee}_{V,RR} + 4eC^{e\mu}_{D,L}|^2 + 2|C^{e\mu ee}_{V,LL} + 4eC^{e\mu}_{D,R}|^2$$
$$+(64\ln\frac{m_\mu}{m_e} - 136)(|eC^{e\mu}_{D,R}|^2 + |eC^{e\mu}_{D,L}|^2) + |C^{e\mu ee}_{V,RL} + 4eC^{e\mu}_{D,L}|^2 + |C^{e\mu ee}_{V,LR} + 4eC^{e\mu}_{D,R}|^2$$

$$BR_{SI}(\mu A \to eA) = B_A(|d_A C^{e\mu}_{DR} + C_{A,L}|^2 + |d_A C^{e\mu}_{DL} + C_{A,R}|^2)$$

Type-II coefficients

- We list here the EFT coefficients in the type-II seesaw

$$C_{DR}^{e\mu} = \frac{3e}{128\pi^2}\left[\frac{[m_\nu m_\nu^\dagger]_{e\mu}}{\lambda_H^2 v^2}\left(1 + \frac{32}{27}\frac{\alpha_e}{4\pi}\ln\frac{M_\Delta}{m_\tau}\right) + \frac{116\alpha_e}{27\pi}\ln\frac{m_\tau}{m_\mu}\sum_{\alpha\in e\mu}\frac{[m_\nu]_{\mu\alpha}[m_\nu^*]_{e\alpha}}{\lambda_H^2 v^2}\right] \qquad v = 174 \text{ GeV}$$

$$C_{V,LL}^{e\mu ee} = \frac{[m_\nu^*]_{\mu e}[m_\nu]_{ee}}{2\lambda_H^2 v^2} + \frac{\alpha_e}{3\pi\lambda_H^2 v^2}\left[m_\nu^\dagger \ln\left(\frac{M_\Delta}{m_\alpha}\right) m_\nu\right]_{\mu e}$$

$$C_{V,LR}^{e\mu ee} = \frac{\alpha_e}{3\pi\lambda_H^2 v^2}\left[m_\nu^\dagger \ln\left(\frac{M_\Delta}{m_\alpha}\right) m_\nu\right]_{\mu e}$$

Inverse seesaw

- We list here the EFT coefficients in the type-I seesaw

$$C^{e\mu ee}_{V,LR} \simeq v^2 \frac{\alpha_e}{4\pi}\left(1.5[Y_\nu M_a^{-2}\left(\frac{11}{6}+\ln\left(\frac{m_W^2}{M_a^2}\right)\right)Y_\nu^\dagger]_{e\mu} - 2.7[Y_\nu(Y_\nu^\dagger Y_\nu)_{ab}\frac{1}{M_a^2-M_b^2}\ln\left(\frac{M_a^2}{M_b^2}\right)Y_\nu^\dagger]_{e\mu} + \mathcal{O}\left(\frac{\alpha_e}{4\pi}\right)\right)$$

$$C^{e\mu}_{Alight,L} \simeq v^2 \frac{\alpha_e}{4\pi}\left(-0.6[Y_\nu M_a^{-2}\left(\frac{11}{6}+\ln\left(\frac{m_W^2}{M_a^2}\right)\right)Y_\nu^\dagger]_{e\mu} + 1.1[Y_\nu(Y_\nu^\dagger Y_\nu)_{ab}\frac{1}{M_a^2-M_b^2}\ln\left(\frac{M_a^2}{M_b^2}\right)Y_\nu^\dagger]_{e\mu} + \mathcal{O}\left(\frac{\alpha_e}{4\pi}\right)\right)$$

$$C^{e\mu ee}_{V,LL} \simeq v^2 \frac{\alpha_e}{4\pi}\left(-1.8[Y_\nu M_a^{-2}\left(\frac{11}{6}+\ln\left(\frac{m_W^2}{M_a^2}\right)\right)Y_\nu^\dagger]_{e\mu} + 2.7[Y_\nu(Y_\nu^\dagger Y_\nu)_{ab}\frac{1}{M_a^2-M_b^2}\ln\left(\frac{M_a^2}{M_b^2}\right)Y_\nu^\dagger]_{e\mu}\right.$$

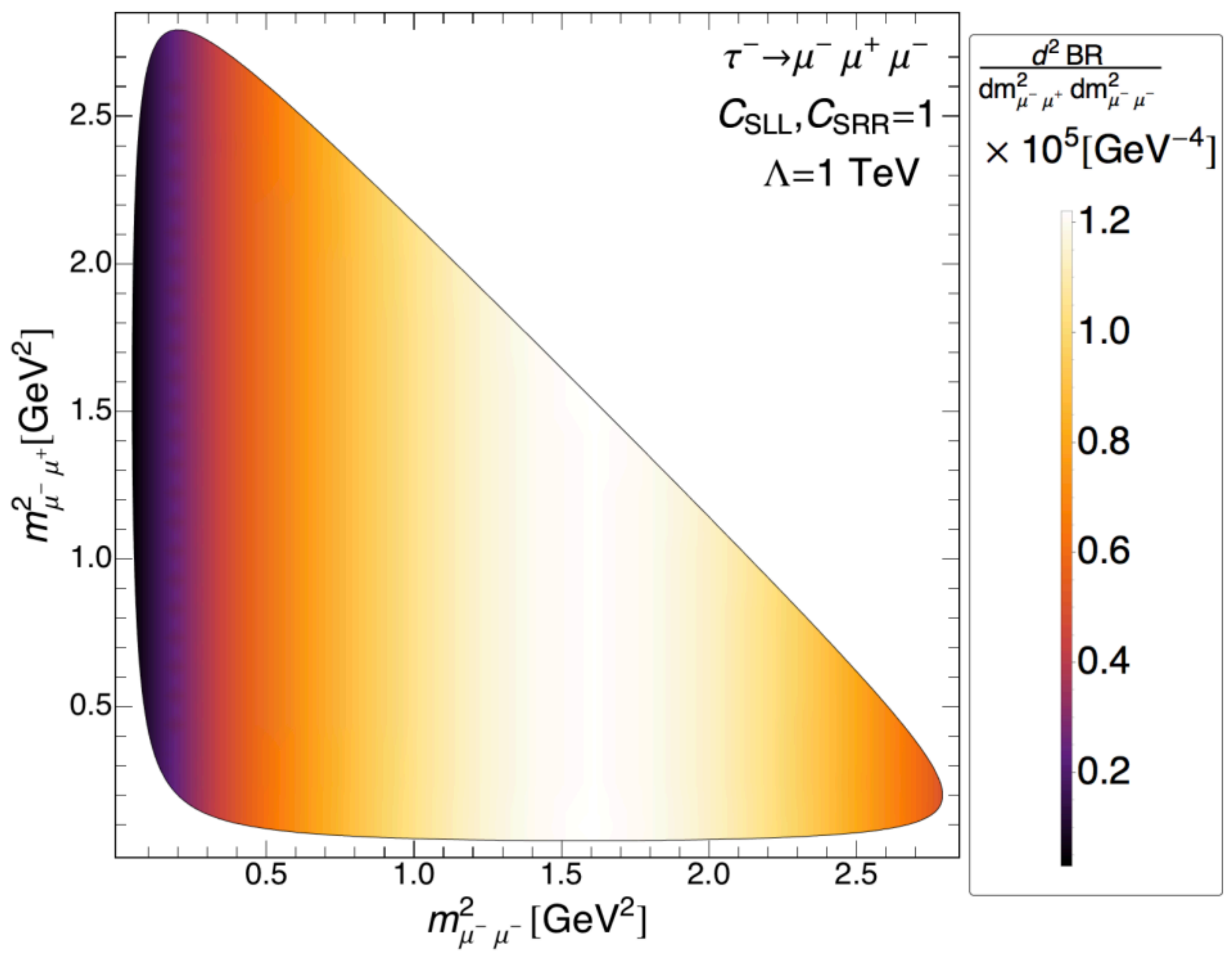
$$\left. +2.5 Y_\nu^{ea} Y_\nu^{*\mu a} Y_\nu^{eb} Y_\nu^{*eb}\frac{1}{M_a^2-M_b^2}\ln\left(\frac{M_a^2}{M_b^2}\right) + \mathcal{O}\left(\frac{\alpha_e}{4\pi}\right)\right)$$

$$C^{e\mu}_{D,R} \simeq -\frac{v^2}{2}\left(\frac{\alpha_e}{4\pi e}\right)[Y_\nu M^{-2} Y_\nu^\dagger]_{e\mu}$$

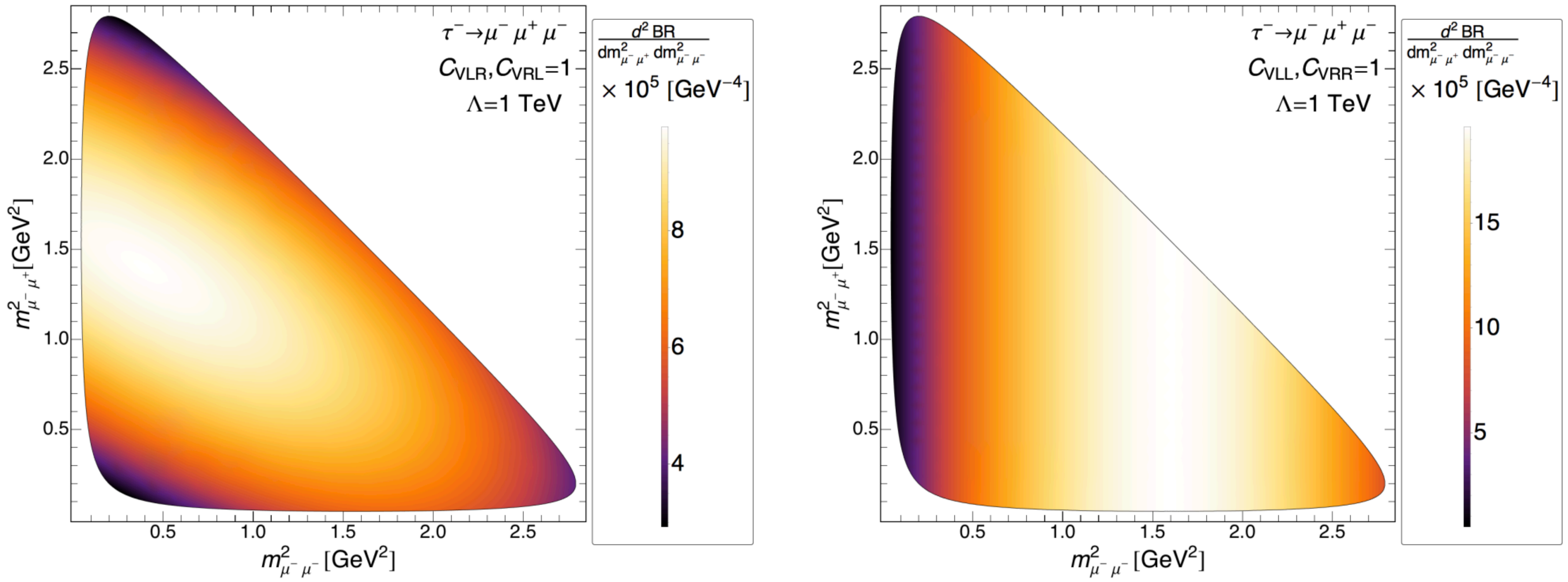
Three body decay: Dalitz plots

Celis, Passemar, Cirigliano 1403.5781

- Dalitz plots could also assist in distinguishing operators



Scalars



Vectors

$\mu \to e$ conversion in nuclei

- The muon gets captured by the (Z,A) nucleus and tumbles down to the 1s state

- The SM processes that can happen are:

  A. $\mu + p \to \nu_\mu + n$ (capture)

  B. $\mu \to \nu_\mu + e + \overline{\nu_e}$ (Decay-In-Orbit)

- If there are LFV interactions with nucleons, an electron can be emitted without a neutrino (conversion)

$$\mu + (Z, A) \to e + (Z, A)$$

$\mu \to e$ conversion in nuclei

- The muon gets captured by the (Z,A) nucleus and tumbles down to the 1s state
- The SM processes that can happen are:

  A. $\mu + p \to \nu_\mu + n$ (capture)

  B. $\mu \to \nu_\mu + e + \overline{\nu_e}$ (Decay-In-Orbit)

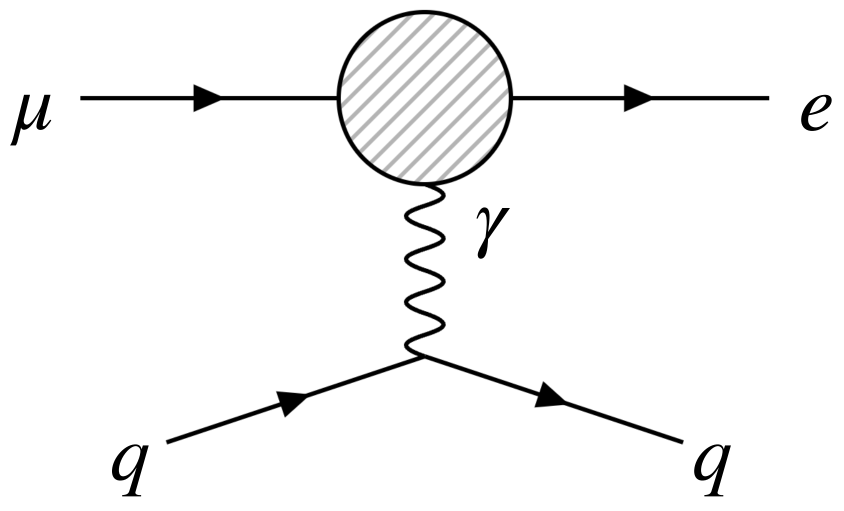
- If there are LFV interactions with nucleons, an electron can be emitted without a neutrino (conversion)

$$\mu + (Z, A) \to e + (Z, A)$$

- Spin-Independent rate is enhanced by $\propto A^2$ because the process is coherent (similar to WIMP scattering)
- The upcoming experiments (COMET, Mu2e) will deliver extremely intense muon beams allowing to probe $Br(\mu A \to eA) \sim 10^{-17}$

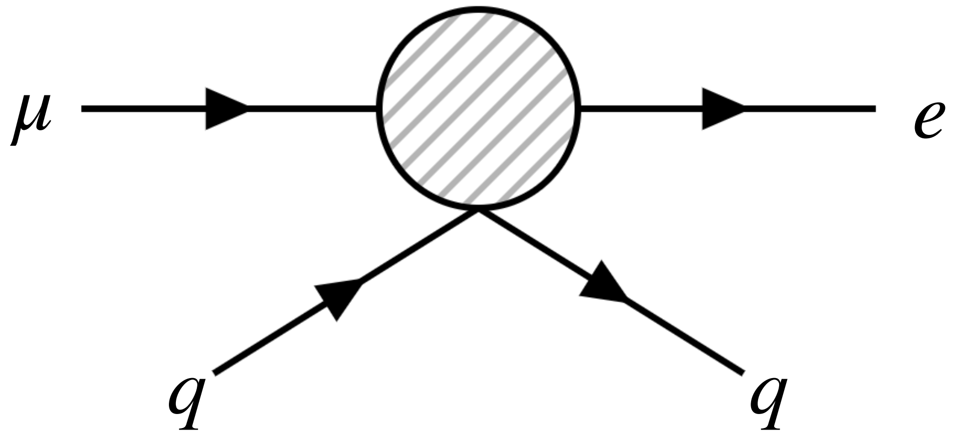
$\mu \to e$ conversion in nuclei

- Sensitivity to the dipole that could compete with $\mu \to e\gamma$ searches

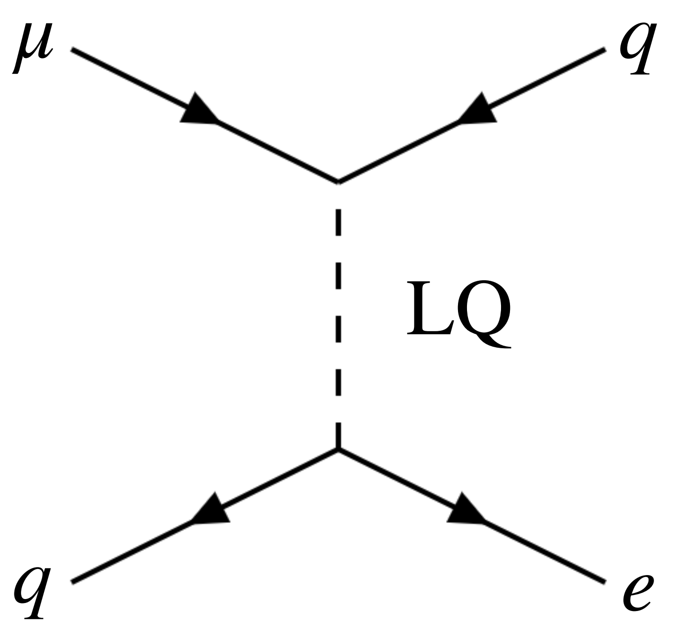


$q = u, d$

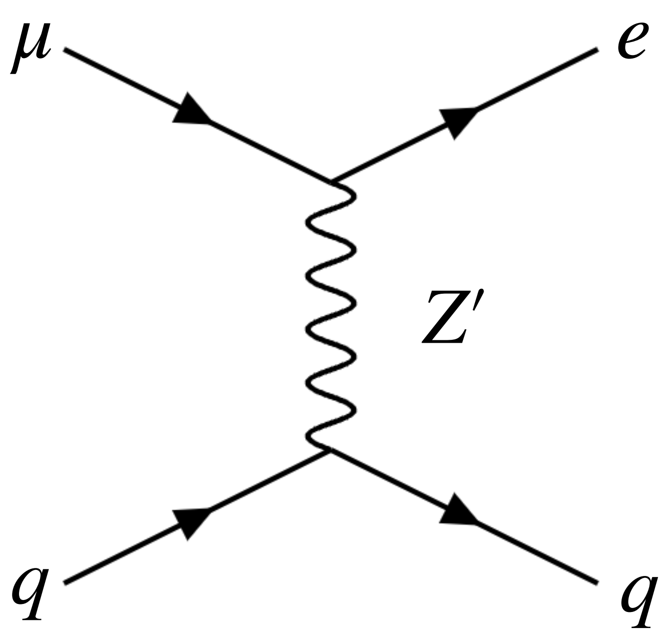
- But can also probe new interactions



$=$



Leptoquarks



Z prime

$\ldots ?$