Challenging Majorana neutrino effects in $B \to K^{(*)}\nu\nu$ decays

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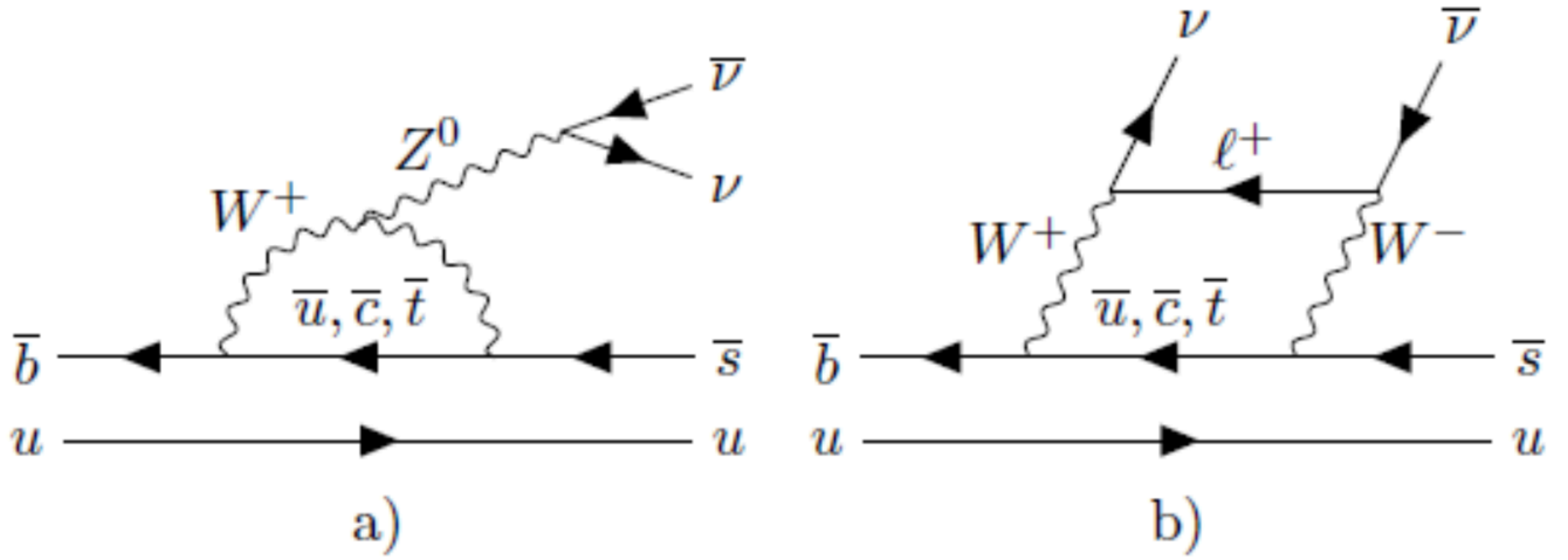
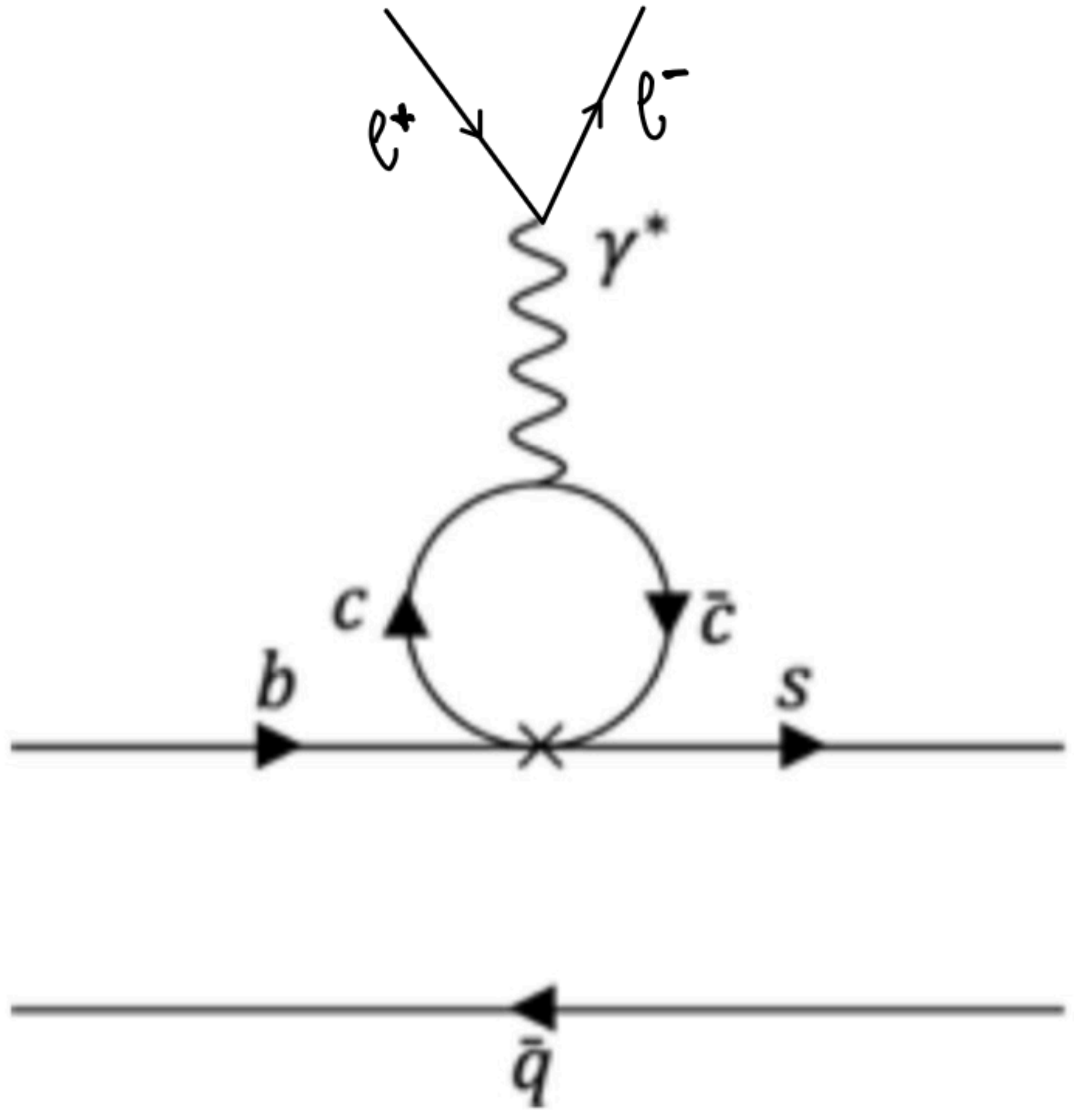
Motivation: $b \to s\nu\nu$ transitions

- FCNCs very suppressed in the SM (GIM/loop) → sensitive probes of New Physics (NP)
- Cleaner than the analogous decay modes with charged leptons (i.e., $b \to s\ell\ell$) → not dominated by long-distance contributions
- Belle-II obtained results for $B^+ \to K^+\nu\nu$ that present mild discrepancies from their SM predictions





Belle II Collaboration, *Phys. Rev. D* **109**, 112006 (2024)
Bahinipati, *Symmetry* **15**, 1963 (2023)
Gligorov, *Int. J. Mod. Phys. A* **38**, 2330009 (2023)

B-decays vs Neutrino mass bounds

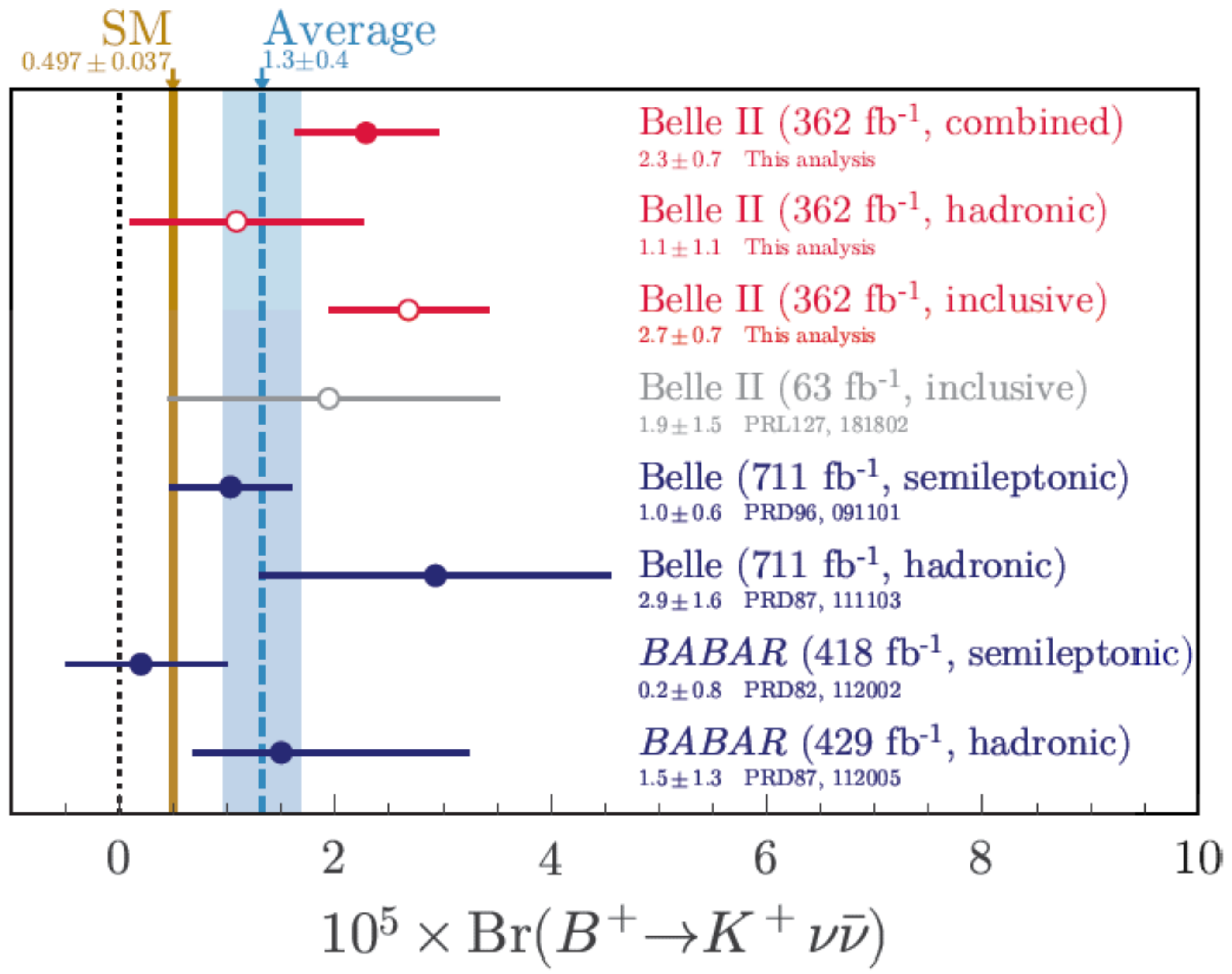
Dimension-6 NP operators can accommodate the experimental excess in B-decays.

Alternatively,

Dimension-7 operators can probe Lepton-Number-Violating (LNV) scenarios

$$\mathcal{O}_{\substack{S_{LL}\\ ij\alpha\beta}} = \left(\bar{d}_{Ri} d_{Lj}\right)\left(\overline{\nu^C_{L\alpha}} \nu_{L\beta}\right) \qquad \mathcal{O}_{\substack{S_{LR}\\ ij\alpha\beta}} = \left(\bar{d}_{Li} d_{Rj}\right)\left(\overline{\nu^C_{L\alpha}} \nu_{L\beta}\right)$$

$$\mathcal{O}_{\substack{T_{L}\\ ij\alpha\beta}} = \left(\bar{d}_{Ri} \sigma^{\mu\nu} d_{Lj}\right)\left(\overline{\nu^C_{L\alpha}} \sigma_{\mu\nu} \nu_{L\beta}\right)$$



Can $B \to K^{(*)}\nu\nu$ decays probe LNV while remaining consistent with limits from neutrino physics?

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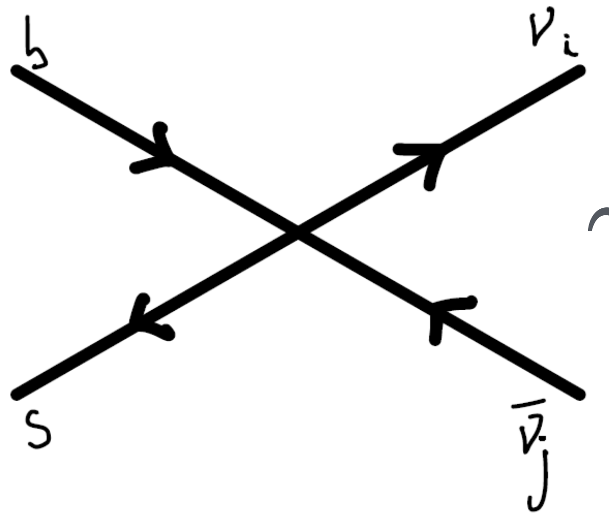
Effective Field Theory approach

$E \ll m_Z$



SM

$\sim (\bar{s}\gamma^{\mu}P_L b)(\bar{\nu}_{\alpha}\gamma_{\mu}P_L\nu_{\beta})$

LEFT

$$\mathscr{L}_{\text{LEFT}} \supset \frac{1}{v^2}\sum_{X=L,R} C_{V_{XL}} O_{V_{XL}} + \frac{1}{v^3}\left[\sum_{X=L,R} C_{S_{XL}} O_{S_{XL}} + C_{T_L} O_{T_L} + \text{h.c.}\right]$$

d=6

$$\underset{ij\alpha\beta}{O_{V_{LL}}} = \left(\bar{d}_{Li}\gamma^{\mu}d_{Lj}\right)\left(\bar{\nu}_{L\alpha}\gamma_{\mu}\nu_{L\beta}\right) \qquad \underset{ij\alpha\beta}{O_{V_{RL}}} = \left(\bar{d}_{Ri}\gamma^{\mu}d_{Rj}\right)\left(\bar{\nu}_{L\alpha}\gamma_{\mu}\nu_{L\beta}\right)$$

d=7 (LNV)

$$\underset{ij\alpha\beta}{O_{S_{LL}}} = \left(\bar{d}_{Ri}d_{Lj}\right)\left(\overline{\nu^C_{L\alpha}}\nu_{L\beta}\right) \qquad \underset{ij\alpha\beta}{O_{S_{LR}}} = \left(\bar{d}_{Li}d_{Rj}\right)\left(\overline{\nu^C_{L\alpha}}\nu_{L\beta}\right)$$

$$\underset{ij\alpha\beta}{O_{T_L}} = \left(\bar{d}_{Ri}\sigma^{\mu\nu}d_{Lj}\right)\left(\overline{\nu^C_{L\alpha}}\sigma_{\mu\nu}\nu_{L\beta}\right)$$

SMEFT

Operator basis

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \frac{1}{2\Lambda}\left(\mathscr{C}^{(5)}_{LH}\mathscr{O}^{(5)}_{LH} + \text{h.c}\right) + \frac{1}{\Lambda^2}\sum_I \mathscr{C}^{(6)}_I\mathscr{O}^{(6)}_I + \frac{1}{\Lambda^3}\sum_I\left(\mathscr{C}^{(7)}_I\mathscr{O}^{(7)}_I + \text{h.c}\right) + \ldots$$

d=7

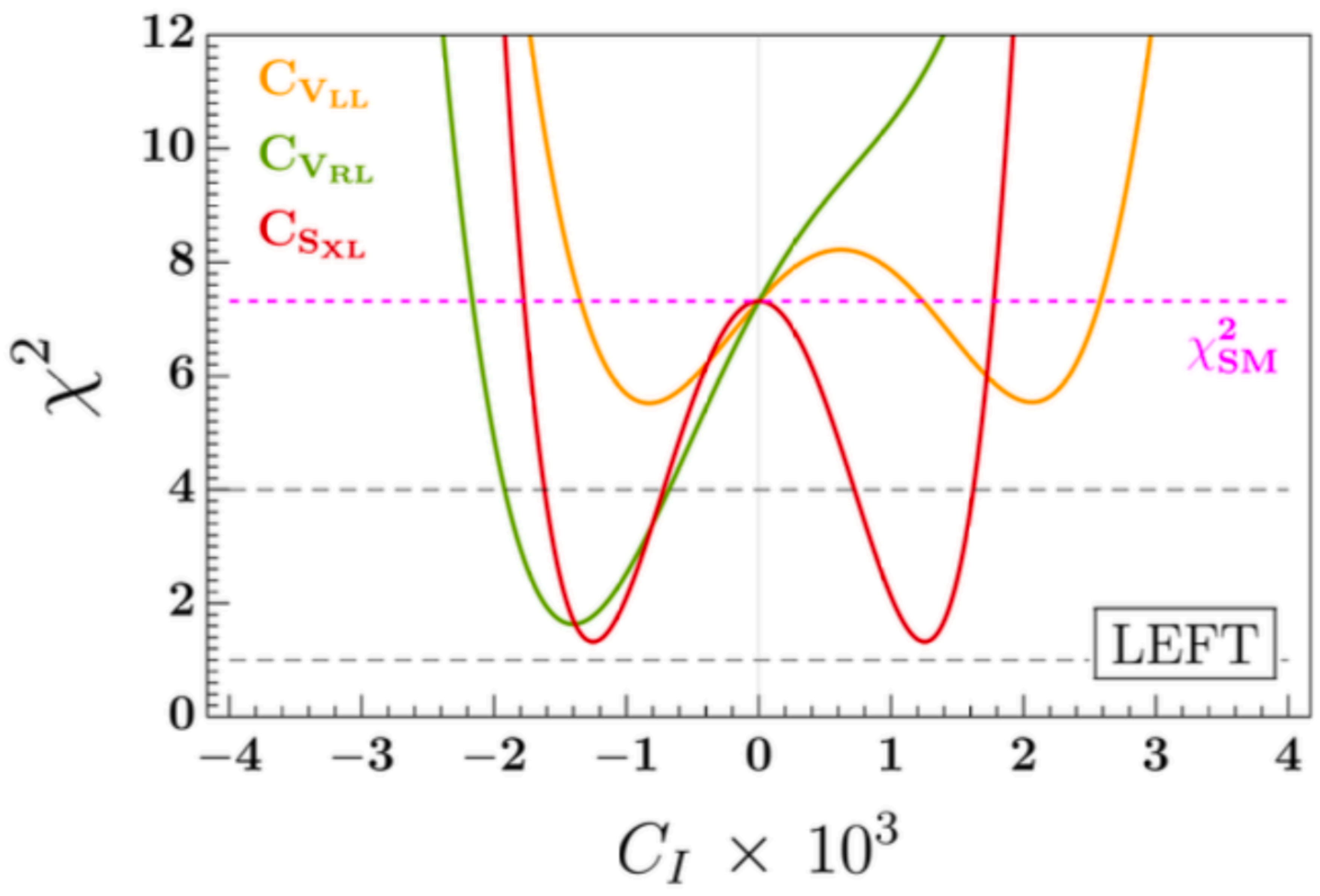
$$\underset{i\alpha j\beta}{\mathscr{O}_{\bar{d}lqlH1}} = \epsilon^{ab}\epsilon^{de}\left(\bar{d}_i\, l^a_{\alpha}\right)\left(q^{b\,T}_j C\, l^d_{\beta}\right)H^e$$

→generates scalar and tensor operators (LNV)

$$\underset{ij\alpha\beta}{C_{S_{LL}}}(\mu_{\text{ew}}) = -\frac{1}{2\sqrt{2}}\frac{v^3}{\Lambda^3}\underset{i\beta j\alpha}{\mathscr{C}^{[S]}_{\bar{d}lqlH1}}(\mu_{\text{ew}}), \qquad \underset{ij\alpha\beta}{C_{T_L}}(\mu_{\text{ew}}) = -\frac{1}{8\sqrt{2}}\frac{v^3}{\Lambda^3}\underset{i\beta j\alpha}{\mathscr{C}^{[A]}_{\bar{d}lqlH1}}(\mu_{\text{ew}})$$

Low-energy fit

$B \to K^{(*)}\nu\nu$



$$\Lambda_S^{(7)}\Big|_{\text{best fit}} \equiv \frac{v}{\sqrt[3]{|C_{S_{XL}}|}} \simeq 2\ \text{TeV}$$

We are interested in evaluating the scenario with one single flavor of active neutrinos and the scalar operator $C_{S_{LL}}$

↓

Changes the q^2-shapes

↓

Can be tested experimentally

$$\mathcal{B}(B^+ \to K^+ + \text{inv})^{\text{exp}} = (2.3 \pm 0.5^{+0.5}_{-0.4}) \times 10^{-5}\,, \qquad \mathcal{B}(B^0 \to K^{*0} + \text{inv})^{\text{exp}} < 2.7 \times 10^{-5}\ (90\,\%\ \text{CL})$$

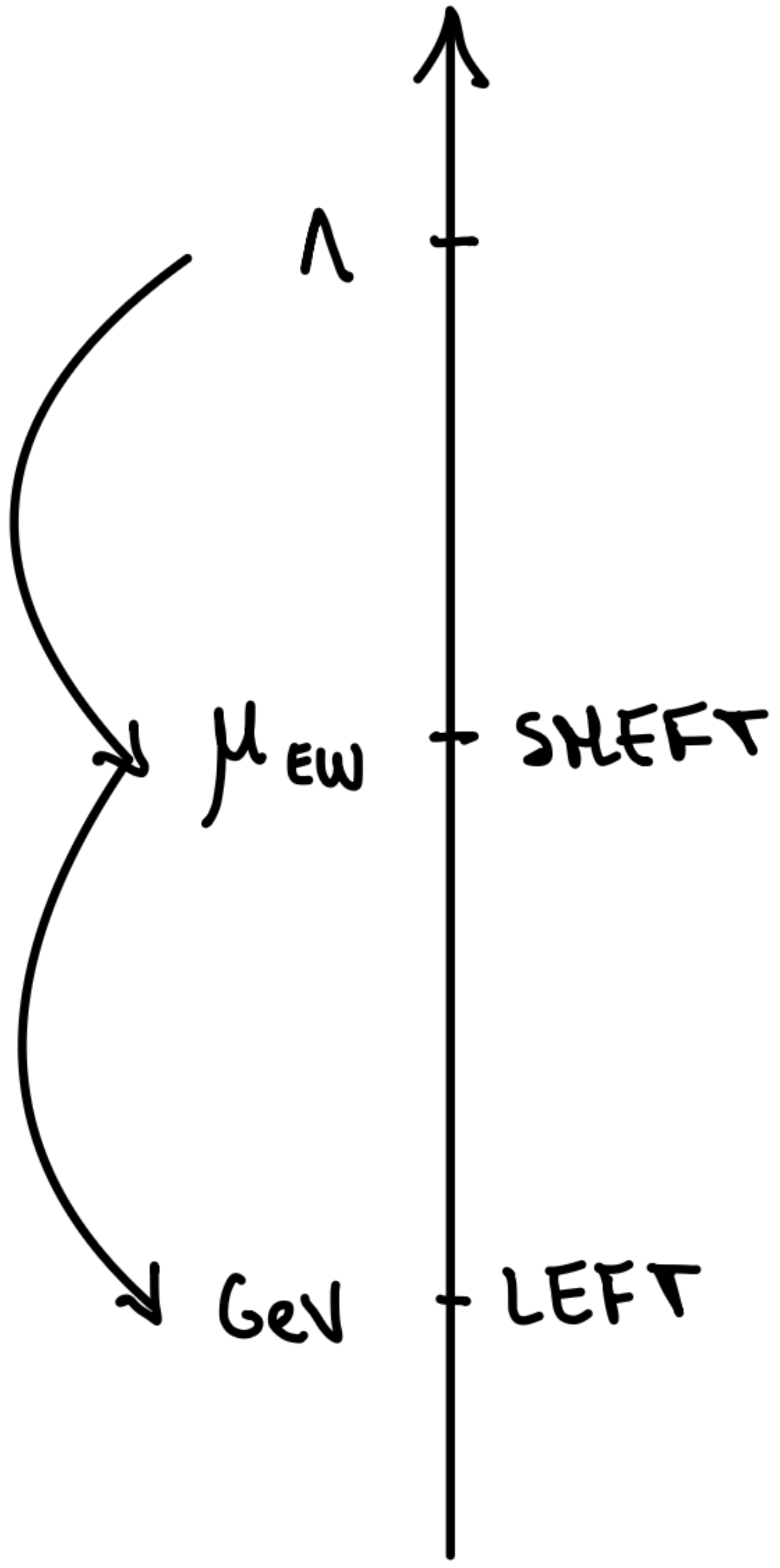
$$\mathcal{B}(B^+ \to K^+\nu\nu)^{\text{SM}} = (4.44 \pm 0.22^{V_{cb}} \pm 0.17^{\text{th}}) \times 10^{-6} \qquad \mathcal{B}(B^0 \to K^{*0}\nu\nu)^{\text{SM}} = (9.0 \pm 0.46^{V_{cb}} \pm 0.85^{\text{th}}) \times 10^{-6}$$

SMEFT phenomenology

d=7

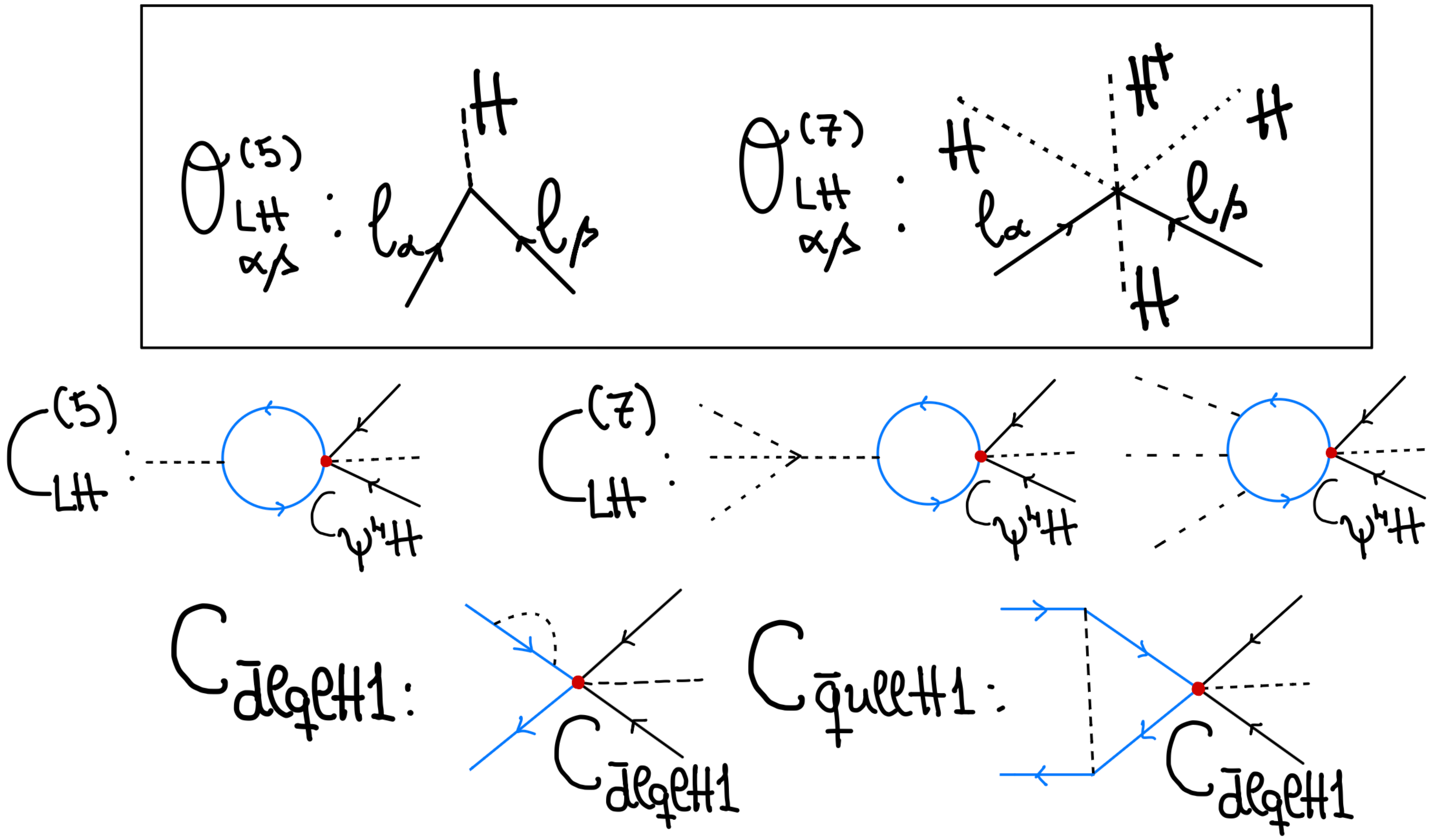
$$\mathcal{O}_{\substack{\bar{d}lqlH1\\ i\alpha j\beta}} = \epsilon^{ab}\epsilon^{de}\left(\overline{d}_i\, l^a_\alpha\right)\left(q_j^{b\,T} C\, l^d_\beta\right) H^e$$

→generates scalar and tensor operators (LNV)



Neutrino masses and operator mixing

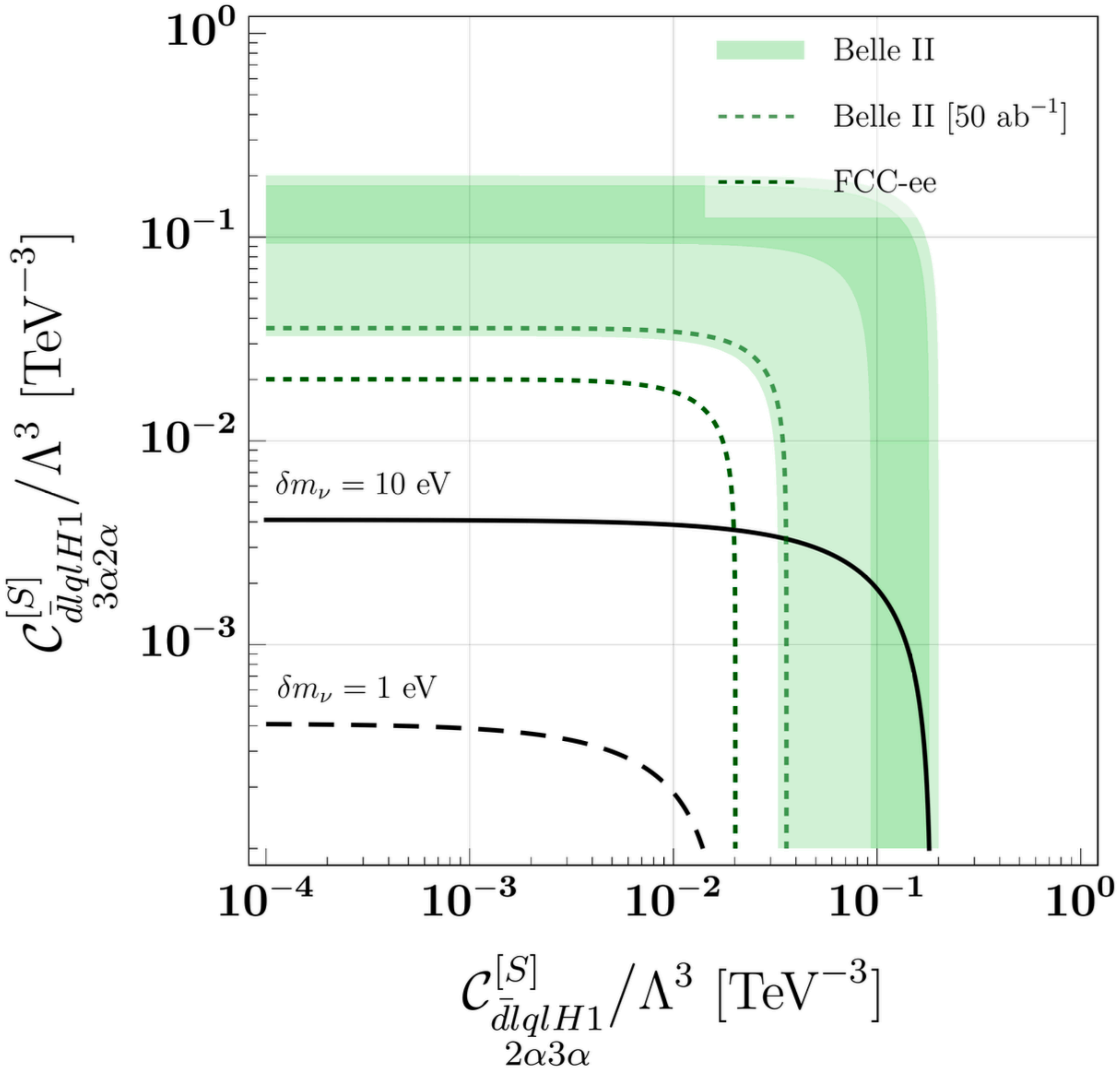
$$m_\nu^{(0)} = -\frac{v^2}{2\Lambda}\left[\mathscr{C}^{(5)}_{LH} + \mathscr{C}^{(7)}_{LH}\frac{v^2}{\Lambda^2}\right]$$



- The dominant contribution comes from dimension-7.

Numerical analysis

$B \to K^{(*)}\nu\nu$



Fine-tuning required: the parameter space allowed by the Belle-II results is excluded by the bounds on neutrino masses

Way out: Including a light RH ν

$N \sim (1,1,0)$

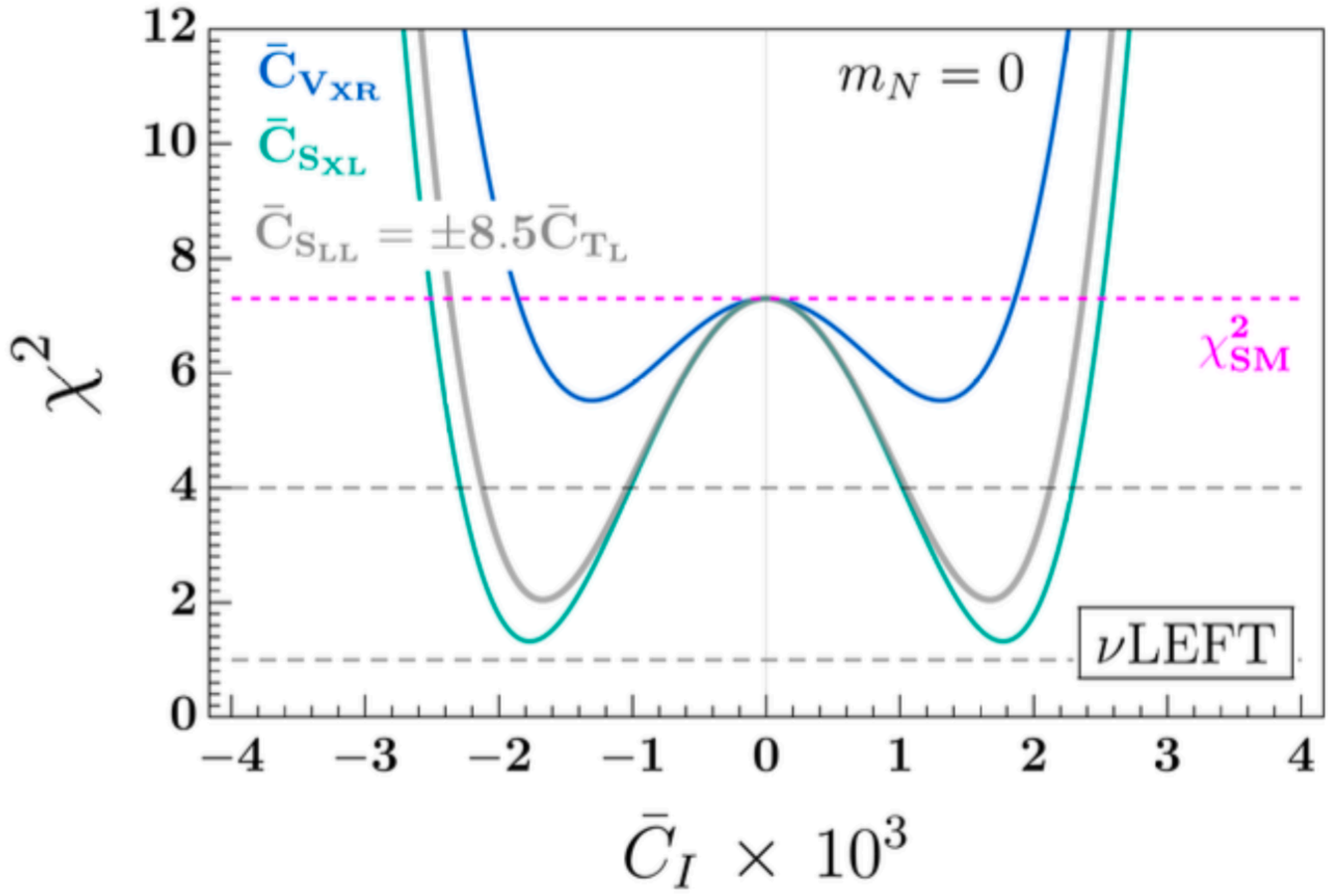
- Scalar and tensor NP operators are generated at dimension 6

$$\bar{O}_{\substack{S_{LL}\\ ijN\beta}} = (\bar{d}_{Ri} d_{Lj})(\bar{N}\nu_{L\beta})$$

$$\bar{O}_{\substack{T_{L}\\ ijN\beta}} = (\bar{d}_{Ri}\sigma^{\mu\nu} d_{Lj})(\bar{N}\sigma_{\mu\nu}\nu_{L\beta})$$

- The seesaw mechanism makes the contributions to neutrino masses smaller.

$B \to K^{(*)}\nu\nu$



$$\bar{\Lambda}_S^{(6)}\Big|_{\text{best fit}} \equiv \frac{v}{\sqrt{|\bar{C}_{S_{XL}}|}} \simeq 6 \text{ TeV}$$

Effective Field Theory Approach

νLEFT with $N \sim (1,1,0)$

$$\mathcal{L}_{\nu\mathrm{LEFT}} \supset \frac{1}{v^2} \sum_{X=L,R} \bar{C}_{V_{XR}} \bar{O}_{V_{XR}} + \frac{1}{v^2} \left[\sum_{X=L,R} \bar{C}_{S_{XL}} \bar{O}_{S_{XL}} + \bar{C}_{T_L} \bar{O}_{T_L} + \mathrm{h.c.} \right]$$

d=6

$$\bar{O}_{\substack{V_{LR} \\ ijNN}} = \left(\bar{d}_{Li} \gamma^\mu d_{Lj}\right)\left(\bar{N}\gamma_\mu N\right) \qquad \bar{O}_{\substack{V_{RR} \\ ijNN}} = \left(\bar{d}_{Ri} \gamma^\mu d_{Rj}\right)\left(\bar{N}\gamma_\mu N\right)$$

$$\bar{O}_{\substack{S_{LL} \\ ijN\beta}} = \left(\bar{d}_{Ri} d_{Lj}\right)\left(\bar{N}\nu_{L\beta}\right) \qquad \bar{O}_{\substack{S_{RL} \\ ijN\beta}} = \left(\bar{d}_{Li} d_{Rj}\right)\left(\bar{N}\nu_{L\beta}\right)$$

$$\bar{O}_{\substack{T_L \\ ijN\beta}} = \left(\bar{d}_{Ri} \sigma^{\mu\nu} d_{Lj}\right)\left(\bar{N}\sigma_{\mu\nu}\nu_{L\beta}\right)$$

νSMEFT

$$\mathcal{L}_{\nu\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_N + \sum_{d\geq 5} \frac{1}{\Lambda^{d-4}} \sum_I \bar{\mathcal{C}}_I^{(d)} \bar{\mathcal{O}}_I^{(d)} + \dots$$

$$\mathcal{L}_N = \bar{N} i \not{\partial} N - \left[\frac{m_N}{2} \overline{N^C} N + (y_N)_{\alpha N} \bar{l}_\alpha \widetilde{H} N + \mathrm{h.c.} \right]$$

d=6

$$\bar{\mathcal{O}}_{\substack{lNqd \\ \alpha Nij}} = (\bar{l}_\alpha N)\epsilon(\bar{q}_i d_j)$$

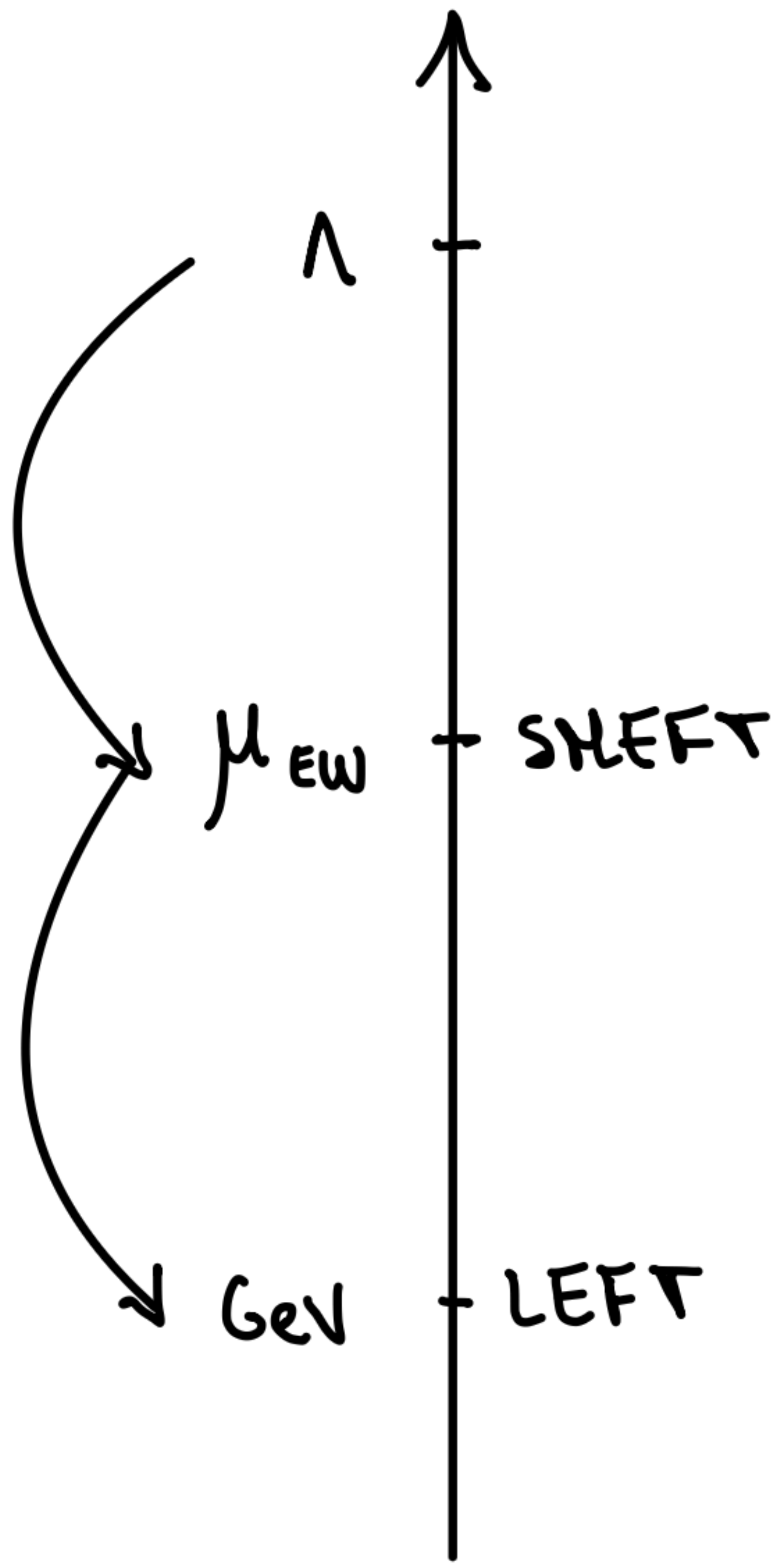
→generates scalar and tensor operators

νSMEFT phenomenology

d=6

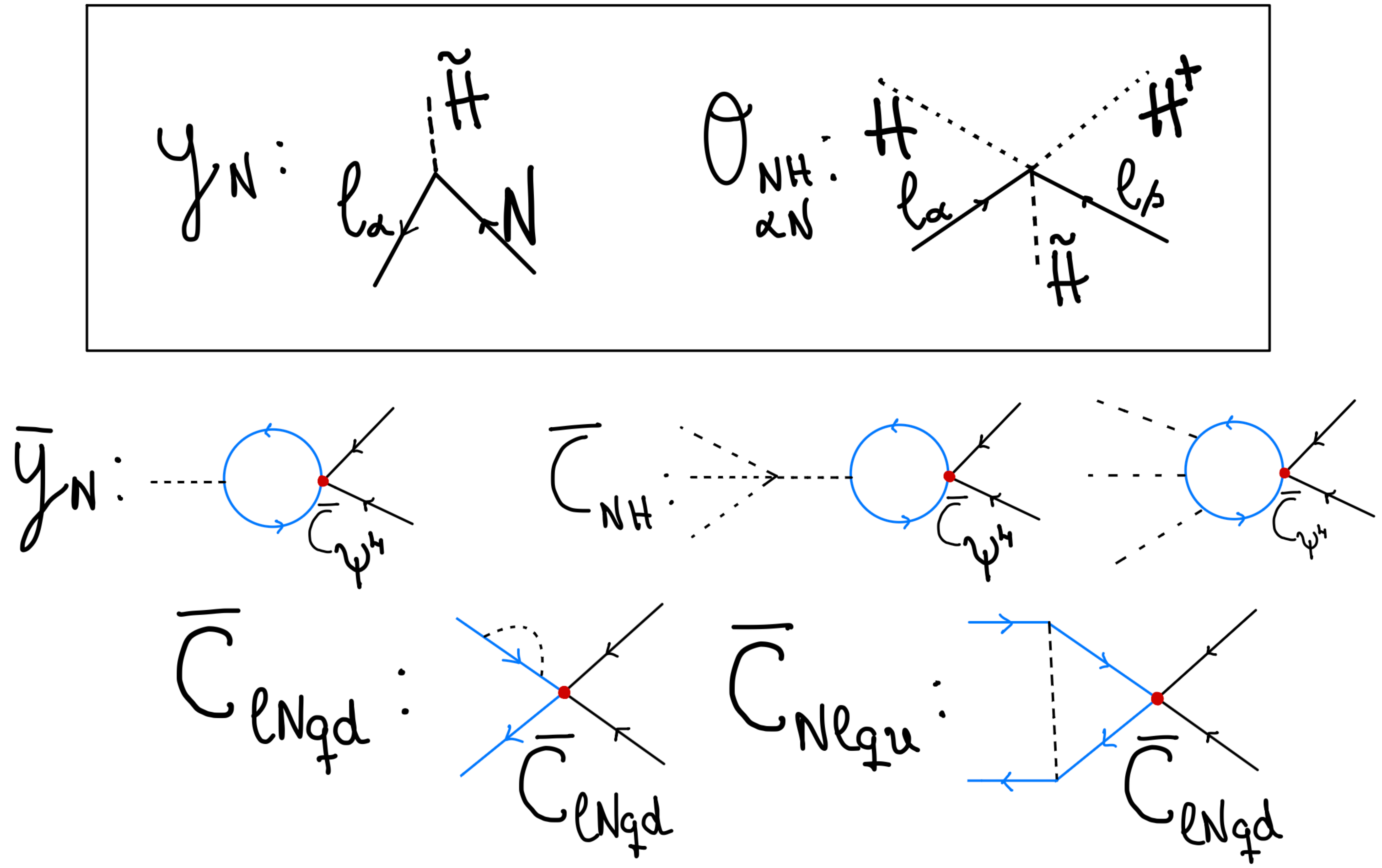
$$\bar{\mathcal{O}}_{\substack{lNqd\\ \alpha Nij}} = (\bar{l}_\alpha N)\epsilon(\bar{q}_i d_j)$$

→generates scalar and tensor operators



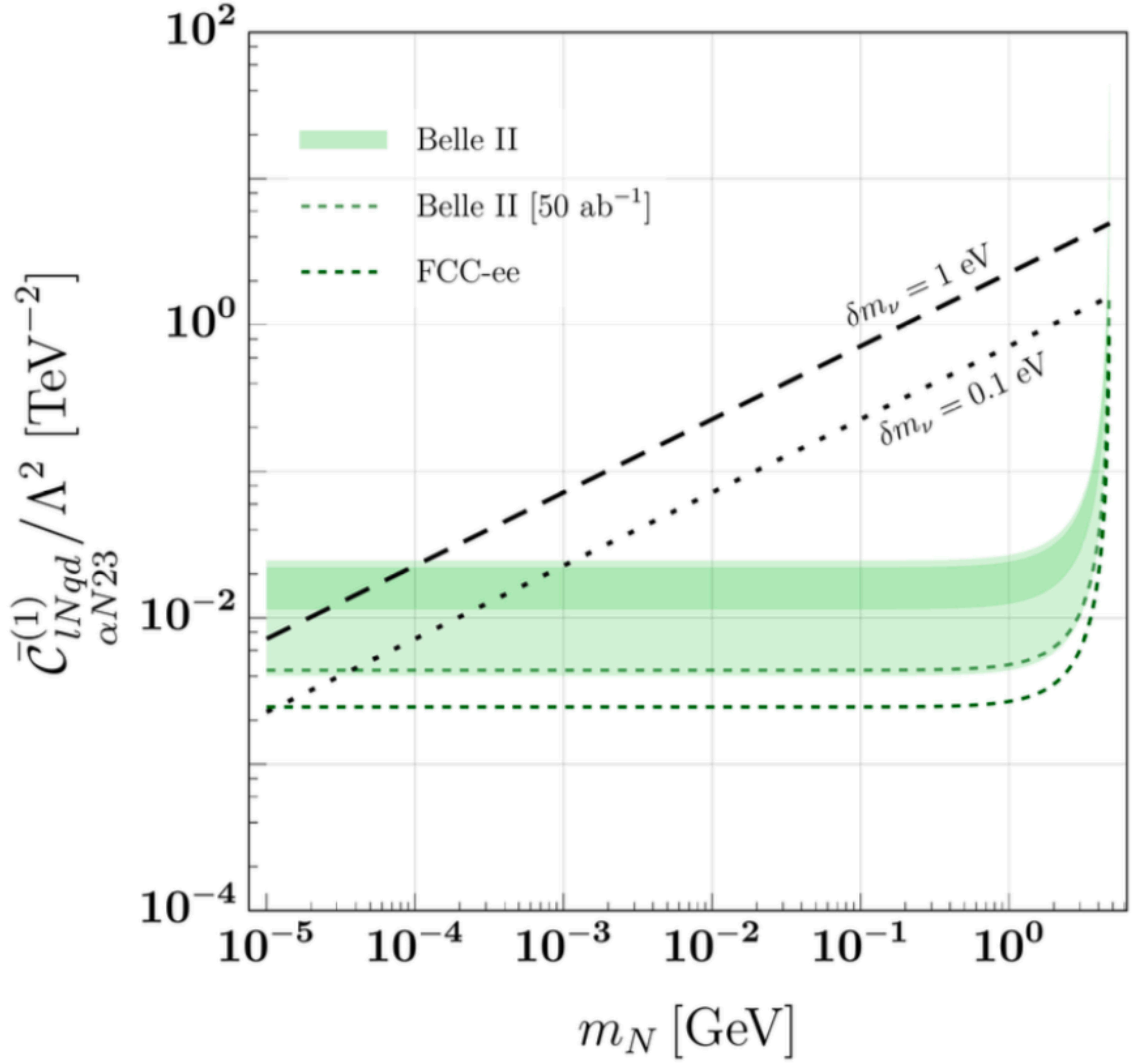
RG effects and neutrino Yukawa

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & m_N \end{pmatrix}, \qquad m_D = \frac{v}{\sqrt{2}}\left(y_N - \frac{v^2}{2\Lambda^2}\bar{\mathscr{C}}_{NH}\right)$$



Numerical analysis

$B \to K^{(*)}\nu\nu$



There is no fine-tuning required: The experimental bounds for neutrino masses don't exclude the allowed region by the Belle-II experiment.

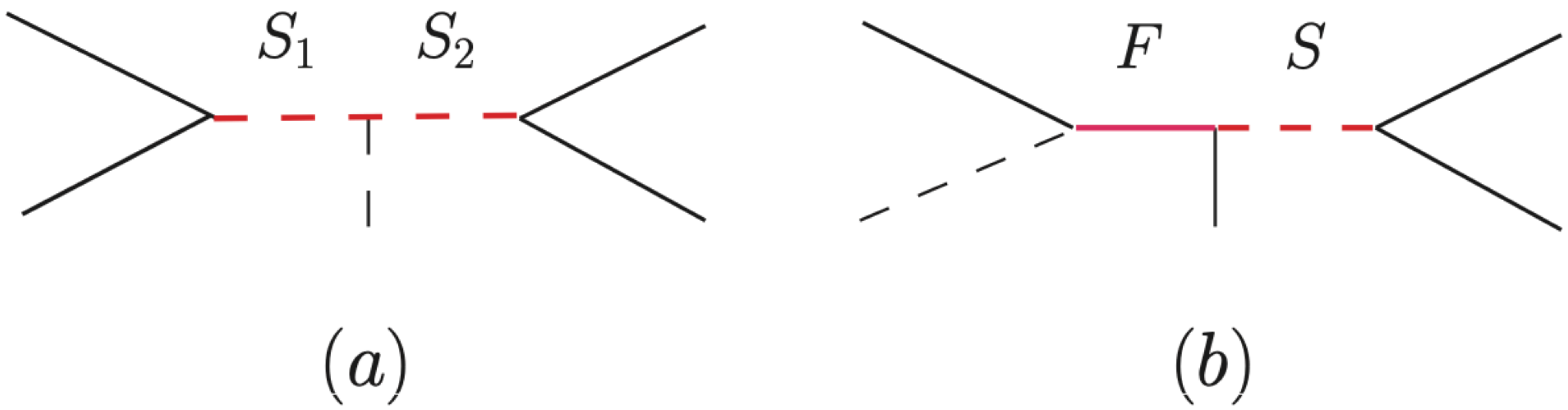
Conclusions

- The scalar NP operator can accommodate the experimental excess on B-meson decays, changing the q^2-shape (testable prediction).
- The SMEFT scenario involving only SM fields generates sizable contributions to neutrino masses, which require a high degree of fine-tuning to be consistent with $m_\nu < \mathcal{O}(0.1\,\mathrm{eV})$.
- A scenario including right-handed neutrinos does not raise a similar issue, thanks to the seesaw-like suppression of the mass.
- It is possible to accommodate the excess in B-meson decays in a way that it is testable (change in q^2-distribution) while not spoiling neutrino masses.

Thank you for your attention

Backup slides

SMEFT UV completions



Generates d=7 operator,

$$\mathscr{C}_{\substack{\bar{d}lqlH1\\ i\alpha j\beta}} = -\lambda\frac{y_{1L}^{j\beta}\,y_{2L}^{i\alpha}}{m_{S_1}^2\,m_{\tilde{R}_2}^2},$$

BUT also d=6,

$$\frac{1}{\Lambda^2}\mathscr{C}^{(1)}_{\substack{lq\\ \alpha\beta ij}} = -\frac{1}{\Lambda^2}\mathscr{C}^{(3)}_{\substack{lq\\ \alpha\beta ij}} = +\frac{y_{1L}^{j\beta}\,y_{1L}^{i\alpha\,*}}{4\,m_{S_1}^2},$$

$$\frac{1}{\Lambda^2}\mathscr{C}_{\substack{ld\\ \alpha\beta ij}} = -\frac{y_{2L}^{i\beta}\,y_{2L}^{j\alpha\,*}}{2\,m_{\tilde{R}_2}^2}$$

Generates the Weinberg operator at tree-level

νSMEFT UV completions

The scenario with $S_1 \sim (\bar{3},1,1/3)$ and $\tilde{R}_2 \sim (3,2,1/6)$ is of particular interest because it introduces scalar and tensor current through Fierz transformations

$$\frac{1}{\Lambda^2}\bar{\mathscr{C}}^{(3)}_{\substack{lNqd \\ \alpha jiN}} = -\frac{\bar{y}^{jN}_{1L}\, y^{i\alpha\,*}_{1L}}{8\, m^2_{S_1}} + \frac{\bar{y}^{iN}_{2R}\, y^{j\alpha\,*}_{2L}}{8\, m^2_{\widetilde{R}_2}}\,, \qquad \frac{1}{\Lambda^2}\bar{\mathscr{C}}_{\substack{Nq \\ NNij}} = -\frac{\bar{y}^{iN}_{2R}\, \bar{y}^{jN\,*}_{2R}}{2\, m^2_{\widetilde{R}_2}}\,,$$

$$\frac{1}{\Lambda^2}\bar{\mathscr{C}}^{(1)}_{\substack{lNqd \\ \alpha Nij}} = +\frac{\bar{y}^{jN}_{1R}\, y^{i\alpha\,*}_{1L}}{2\, m^2_{S_1}} + \frac{\bar{y}^{iN}_{2R}\, y^{j\alpha\,*}_{2L}}{2\, m^2_{\widetilde{R}_2}}\,, \qquad \frac{1}{\Lambda^2}\bar{\mathscr{C}}_{\substack{Nd \\ NNij}} = +\frac{\bar{y}^{jN}_{1R}\, \bar{y}^{iN\,*}_{1R}}{m^2_{S_1}}\,.$$

For the scalar and tensor operators to dominate $|y_{1L}| \ll |\bar{y}_{1L}|$ and $|y_{2L}| \ll |\bar{y}_{2R}|$