

Probing the generic flavour structure of semileptonic operators

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Standard Model Effective Field Theory

No discovery of New Particles at Large Hadron Collider -> Scale Gap!

- Field content same as that of Standard Model.
- Electroweak symmetry is broken by one Higgs-doublet.
- Full SM gauge symmetry is respected.

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{eff}}$$

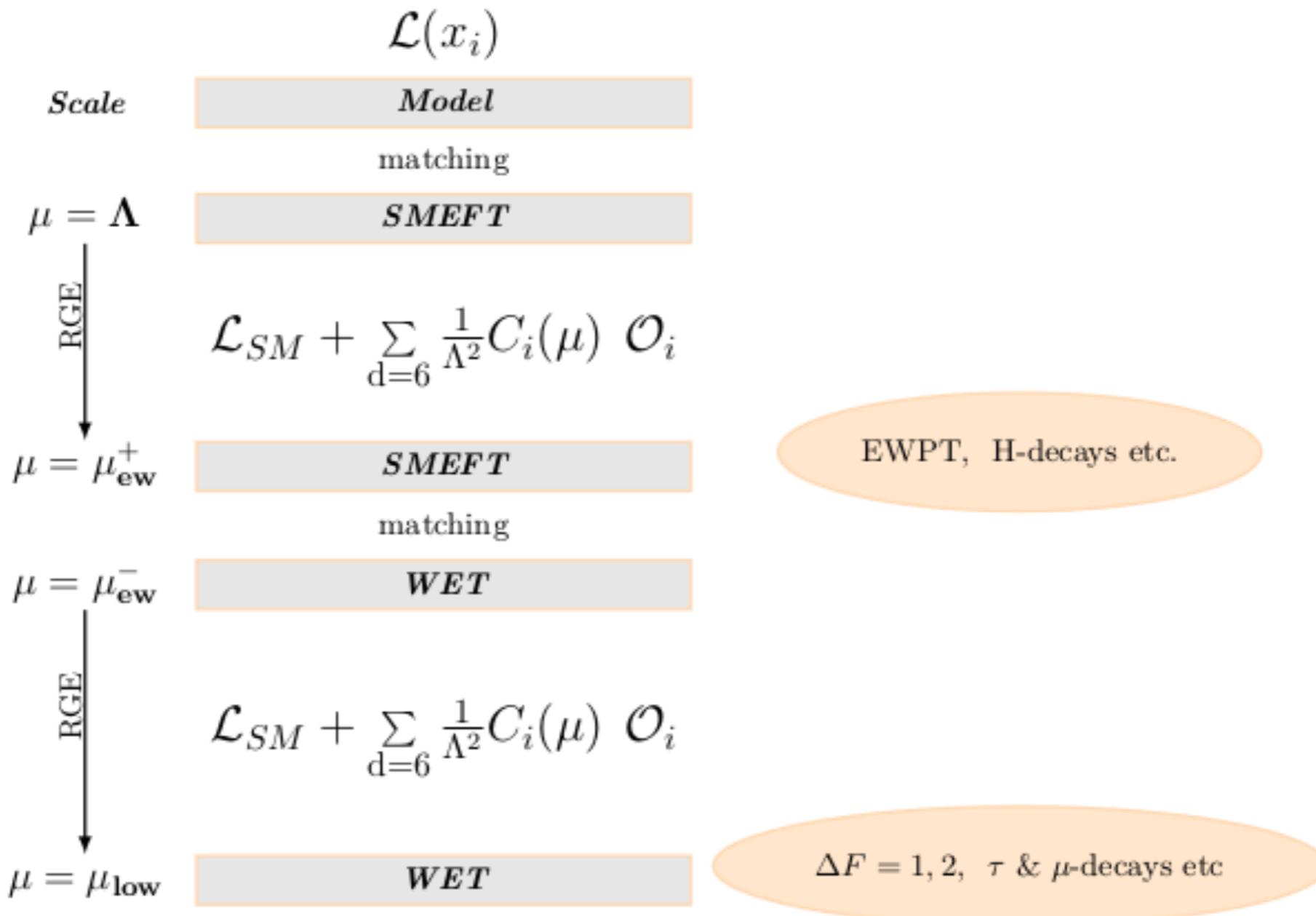
Buchmuller and Wyler 1986

$$\mathcal{L}_{\text{eff}} = \sum_{\text{dim}=5,6,\dots} c_j O_j$$

15 (Bosonic) +
19 (Single-fermion current) +
25 (Four-fermion) = 59 Operators

Warsaw Basis

General Strategy



Semileptonic operators

$$(\bar{L}_i X L_j)(\bar{Q}_k X Q_k)$$

$$\ell_i = \begin{pmatrix} \nu_{Li} \\ e_{Li} \end{pmatrix}, \quad q_i = \begin{pmatrix} u_{Li} \\ d_{Li} \end{pmatrix} \quad e_{Ri}, \quad u_{Ri}, \quad d_{Ri}$$

Total 7 vector operators **excluding flavours**

Assume: no quark flavour violation at NP scale.

$\Delta F = (0,0)$:

1111, 1122, 1133, 2211, 2222, 2233

$\Delta F = (1,0)$:

1211, 1222, 1233, 1311, 1322, 1333, 2311, 2322, 2333

Operators of our interest

Chirality

LL

$$O_{\ell q}^{(1)} = (\bar{\ell}_i \gamma_\mu \ell_j)(\bar{q}_k \gamma^\mu q_l)$$
$$O_{\ell q}^{(3)} = (\bar{\ell}_i \gamma_\mu \tau^I \ell_j)(\bar{q}_k \gamma^\mu \tau^I q_l)$$

LR

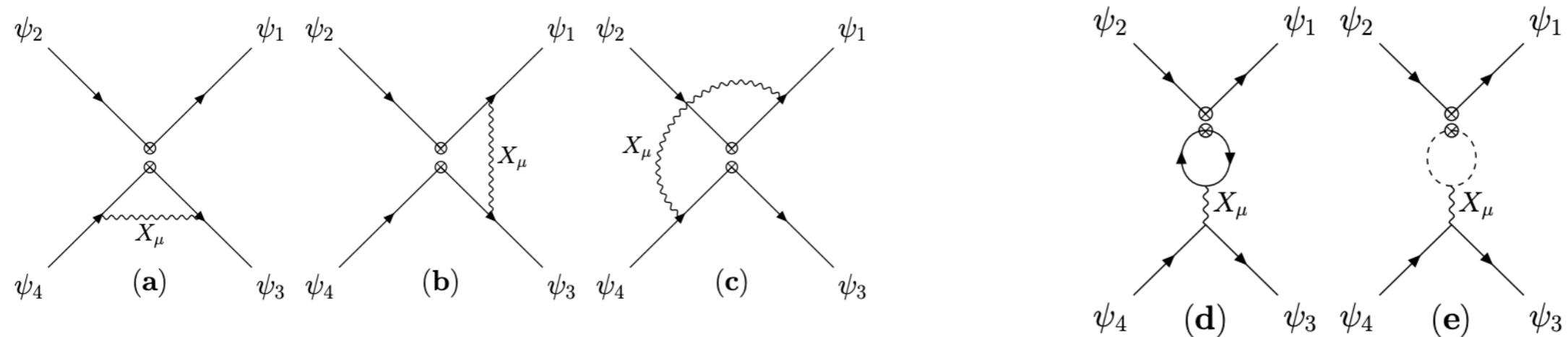
$$O_{\ell d} = (\bar{\ell}_i \gamma_\mu \ell_j)(\bar{d}_k \gamma^\mu d_l)$$
$$O_{\ell u} = (\bar{\ell}_i \gamma_\mu \ell_j)(\bar{u}_k \gamma^\mu u_l)$$
$$O_{qe} = (\bar{q}_i \gamma_\mu q_j)(\bar{e}_k \gamma^\mu e_l)$$

RR

$$O_{ed} = (\bar{e}_i \gamma_\mu e_j)(\bar{d}_k \gamma^\mu d_l)$$
$$O_{eu} = (\bar{e}_i \gamma_\mu e_j)(\bar{u}_k \gamma^\mu u_l)$$

Wilson coefficients are scale dependent quantities

$$\mathcal{L}_{\text{eff}} = C_j O_j$$



$$\dot{C}(\mu) \equiv 16\pi^2 \frac{dC(\mu)}{d\ln\mu} = \hat{\gamma}(\mu) C(\mu)$$

$$C(\mu) = (C_1(\mu), C_2(\mu), \dots)^T$$

$\hat{\gamma}$: Anomalous dimension matrix (ADM)

SMEFT ADMs: Alonso, Jenkins, Manohar, Trott

Operator mixing

At 1-loop semileptonic operators mix with:

$$\psi^2 \phi^2 D$$

$$\ell^4$$

$$[O_{\phi\ell}^{(1)}]_{ij} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{\ell}_i \gamma^\mu \ell_j)$$

$$[O_{\ell\ell}]_{ijkl} = (\bar{\ell}_i \gamma_\mu \ell_j)(\bar{\ell}_k \gamma^\mu \ell_l)$$

$$[O_{\phi\ell}^{(3)}]_{ij} = (\phi^\dagger i \overleftrightarrow{D}_\mu \tau^I \phi)(\bar{\ell}_i \gamma^\mu \tau^I \ell_j)$$

$$[O_{ee}]_{ijkl} = (\bar{e}_i \gamma_\mu e_j)(\bar{e}_k \gamma^\mu e_l)$$

$$[O_{\phi e}]_{ij} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{e}_i \gamma^\mu e_j)$$

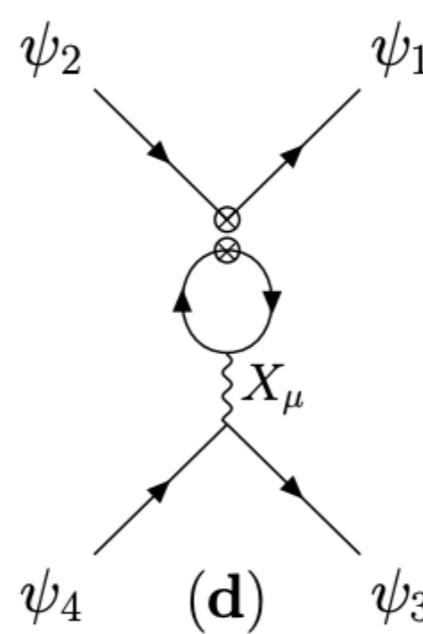
$$\psi_2 \qquad \qquad \qquad \psi_1$$

$$[O_{\phi q}^{(1)}]_{ij} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{q}_i \gamma^\mu q_j)$$

$$[O_{\phi q}^{(3)}]_{ij} = (\phi^\dagger i \overleftrightarrow{D}_\mu \tau^I \phi)(\bar{q}_i \gamma^\mu \tau^I q_j)$$

$$[O_{\phi u}]_{ij} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{u}_i \gamma^\mu u_j)$$

$$[O_{\phi d}]_{ij} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{d}_i \gamma^\mu d_j)$$



Operator mixing...

$\psi^2\phi^2D$ type operators

$\Delta F = (0,0)$

Semileptonic operators

$$\begin{pmatrix} [\mathcal{C}_{\phi\ell}^{(1)}]_{ii} \\ [\mathcal{C}_{\phi\ell}^{(3)}]_{ii} \\ [\mathcal{C}_{\phi e}]_{ii} \\ [\mathcal{C}_{\phi q}^{(1)}]_{kk} \\ [\mathcal{C}_{\phi q}^{(3)}]_{kk} \\ [\mathcal{C}_{\phi d}]_{kk} \\ [\mathcal{C}_{\phi u}]_{kk} \end{pmatrix} = L \begin{pmatrix} \frac{2}{3}g_1^2 & 0 & \frac{4}{3}g_1^2 & -\frac{2}{3}g_1^2 & 0 & 0 & 0 \\ 0 & 2g_2^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{2}{3}g_1^2 & \frac{4}{3}g_1^2 & \frac{2}{3}g_1^2 \\ -\frac{2}{3}g_1^2 & 0 & 0 & 0 & 0 & 0 & -\frac{2}{3}g_1^2 \\ 0 & \frac{2}{3}g_2^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{2}{3}g_1^2 & -\frac{2}{3}g_1^2 & 0 & 0 \\ 0 & 0 & -\frac{2}{3}g_1^2 & 0 & 0 & -\frac{2}{3}g_1^2 & 0 \end{pmatrix} \begin{pmatrix} [\mathcal{C}_{\ell q}^{(1)}]_{iikk} \\ [\mathcal{C}_{\ell q}^{(3)}]_{iikk} \\ [\mathcal{C}_{\ell u}]_{iikk} \\ [\mathcal{C}_{\ell d}]_{iikk} \\ [\mathcal{C}_{ed}]_{iikk} \\ [\mathcal{C}_{eu}]_{iikk} \\ [\mathcal{C}_{qe}]_{kkii} \end{pmatrix}$$

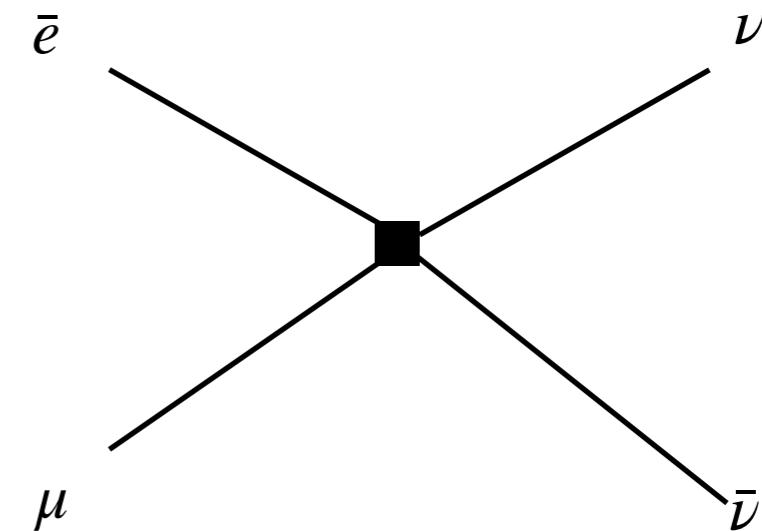
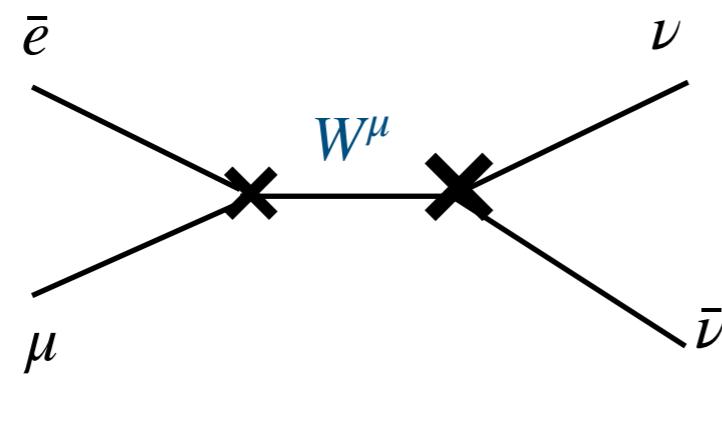
Gauge coupling dependence

$$L = \frac{1}{16\pi^2} \log \frac{\mu}{\Lambda}$$

ℓ^4 operator

Operator mixing...

$$[O_{\ell\ell}]_{1221} = (\bar{\ell}_1 \gamma_\mu \ell_2)(\bar{\ell}_2 \gamma^\mu \ell_1)$$



$$[\mathcal{C}_{\ell\ell}]_{1221} = 4g_2^2 L [\mathcal{C}_{\ell q}^{(3)}]_{iikk}, \quad \Delta F = (0,0) \quad \text{Semileptonic operators}$$

indices on the r.h.s. are summed over $ii = 11, 22$ and $k = 11, 22, 33$.

$$L = \frac{1}{16\pi^2} \log \frac{\mu}{\Lambda}$$

Operator mixing...

$\psi^2\phi^2D$ type and ℓ^4 operators

$\Delta F = (1,0)$
Semileptonic operators

$$\begin{pmatrix} [\mathcal{C}_{\ell\ell}]_{ijll} \\ [\mathcal{C}_{\ell e}]_{ijll} \\ [\mathcal{C}_{\ell e}]_{llij} \\ [\mathcal{C}_{ee}]_{ijll} \\ [\mathcal{C}_{\phi\ell}^{(1)}]_{ij} \\ [\mathcal{C}_{\phi\ell}^{(3)}]_{ij} \\ [\mathcal{C}_{\phi e}]_{ij} \end{pmatrix} = L \begin{pmatrix} -\frac{1}{3}g_1^2 & g_2^2 & -\frac{2}{3}g_1^2 & \frac{1}{3}g_1^2 & 0 & 0 & 0 \\ -\frac{4}{3}g_1^2 & 0 & -\frac{8}{3}g_1^2 & \frac{4}{3}g_1^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{2}{3}g_1^2 & -\frac{4}{3}g_1^2 & -\frac{2}{3}g_1^2 \\ 0 & 0 & 0 & 0 & \frac{2}{3}g_1^2 & -\frac{2}{3}g_1^2 & -\frac{1}{3}g_1^2 \\ \frac{2}{3}g_1^2 & 0 & \frac{4}{3}g_1^2 & -\frac{2}{3}g_1^2 & 0 & 0 & 0 \\ 0 & 2g_2^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{2}{3}g_1^2 & \frac{4}{3}g_1^2 & \frac{2}{3}g_1^2 \end{pmatrix} \begin{pmatrix} [\mathcal{C}_{\ell q}^{(1)}]_{ijkk} \\ [\mathcal{C}_{\ell q}^{(3)}]_{ijkk} \\ [\mathcal{C}_{\ell u}]_{ijkk} \\ [\mathcal{C}_{\ell d}]_{ijkk} \\ [\mathcal{C}_{ed}]_{ijkk} \\ [\mathcal{C}_{eu}]_{ijkk} \\ [\mathcal{C}_{qe}]_{kkij} \end{pmatrix}$$

Gauge coupling dependence

$$L = \frac{1}{16\pi^2} \log \frac{\mu}{\Lambda}$$

Operator mixing...

$\psi^2\phi^2D$ type operators

$$\begin{pmatrix} [\mathcal{C}_{\phi\ell}^{(1)}]_{ij} \\ [\mathcal{C}_{\phi\ell}^{(3)}]_{ij} \\ [\mathcal{C}_{\phi e}]_{ij} \end{pmatrix} \simeq 6y_t^2 L \begin{pmatrix} 1 & 0 & -1 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 \end{pmatrix} \begin{pmatrix} [\mathcal{C}_{\ell q}^{(1)}]_{ij33} \\ [\mathcal{C}_{\ell q}^{(3)}]_{ij33} \\ [\mathcal{C}_{\ell u}]_{ij33} \\ [\mathcal{C}_{qe}]_{33ij} \\ [\mathcal{C}_{eu}]_{ij33} \end{pmatrix}$$

$\Delta F = (1,0)$

Semileptonic operators

top-Yukawa dependence

$$L = \frac{1}{16\pi^2} \log \frac{\mu}{\Lambda}$$

Operator mixing...

Introduce NP interactions at high scale Λ

$$C_1(\Lambda) \quad C_2(\Lambda) \dots \quad C_i(\Lambda)$$



Low-energy observables $f(C_1(\mu), C_2(\mu) \dots C_i(\mu))$

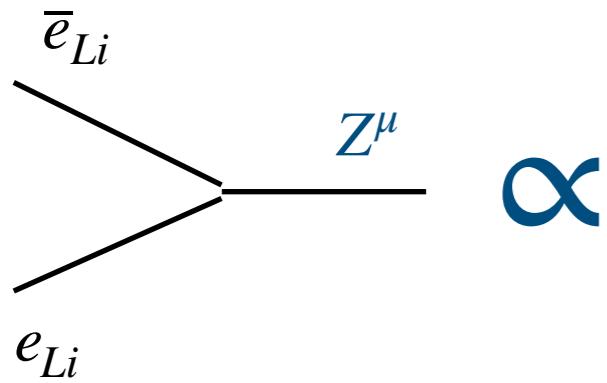
Important to include RG effects to correctly predict the low-energy implications of NP introduced at the high scale.

Where do these operators contribute?

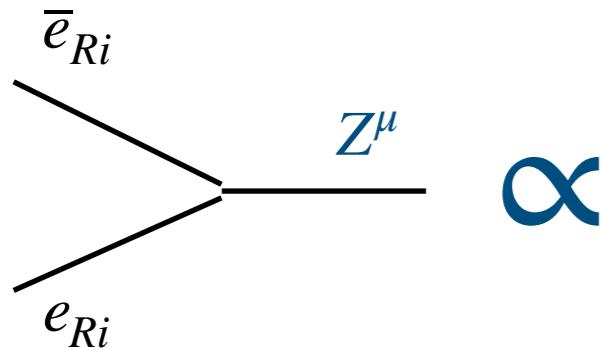
W/Z couplings

Electroweak symmetry breaking

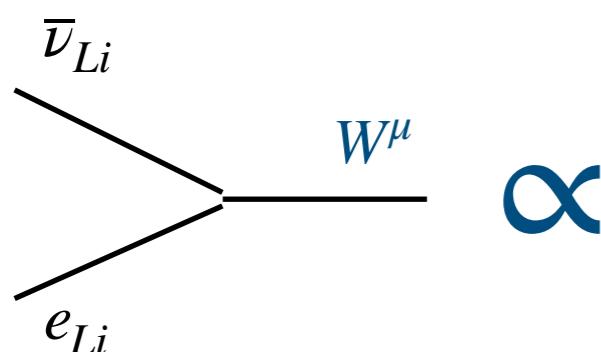
$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$



$$\propto -\frac{v^2}{2} \left([C_{\phi\ell}^{(1)}]_{ii} + [C_{\phi\ell}^{(3)}]_{ii} \right)$$



$$-\frac{v^2}{2} [C_{\phi e}^{(1)}]_{ii}$$



$$v^2 [C_{\phi\ell}^{(3)}]_{ii}$$

$$\Delta F = (0,0)$$

$$[O_{\phi\ell}^{(1)}]_{ii} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{\ell}_i \gamma^\mu \ell_i)$$

$$[O_{\phi\ell}^{(3)}]_{ii} = (\phi^\dagger i \overleftrightarrow{D}_\mu \tau^I \phi)(\bar{\ell}_i \gamma^\mu \tau^I \ell_i)$$

$$[O_{\phi e}]_{ii} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{e}_i \gamma^\mu e_i)$$

$$[O_{\phi q}^{(1)}]_{ii} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{q}_i \gamma^\mu q_i)$$

$$[O_{\phi q}^{(3)}]_{ii} = (\phi^\dagger i \overleftrightarrow{D}_\mu \tau^I \phi)(\bar{q}_i \gamma^\mu \tau^I q_i)$$

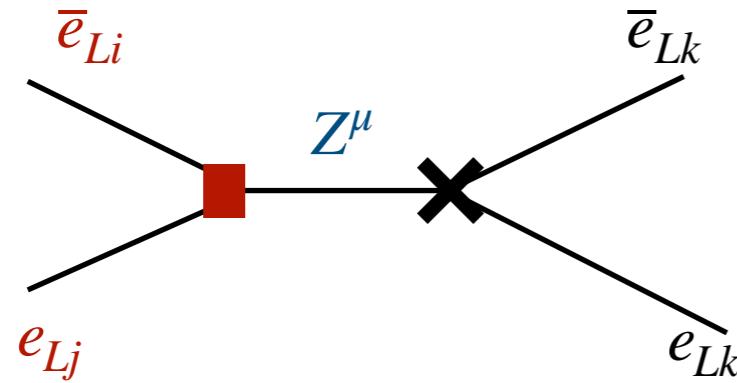
$$[O_{\phi u}]_{ii} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{u}_i \gamma^\mu u_i)$$

$$[O_{\phi d}]_{ii} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{d}_i \gamma^\mu d_i)$$

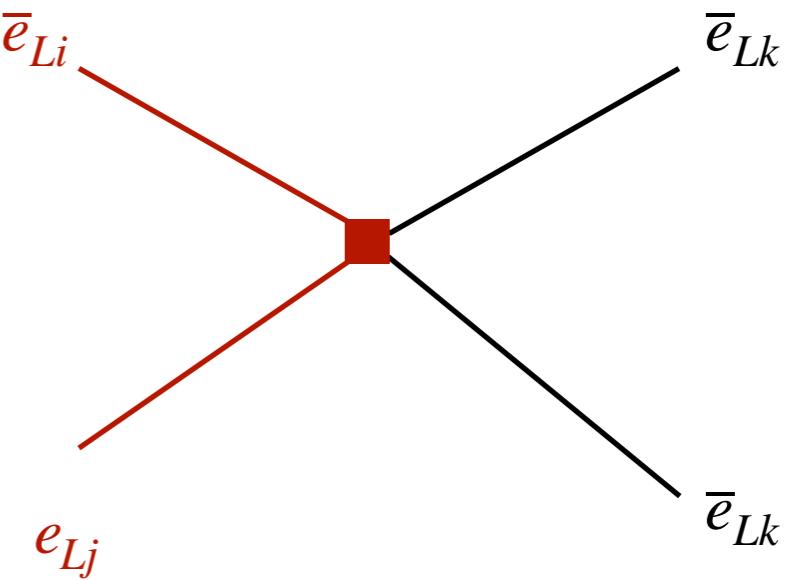
$$[O_{\ell\ell}]_{1221} = (\bar{\ell}_1 \gamma_\mu \ell_2)(\bar{\ell}_2 \gamma^\mu \ell_1)$$

Where else?

Lepton flavour violating (LFV) decays



+



$$-\frac{v^2}{2} \left([C_{\phi\ell}^{(1)}]_{ij} + [C_{\phi\ell}^{(3)}]_{ij} \right) \times \text{SM}$$

$$[C_{\ell\ell}]_{ijkk}$$

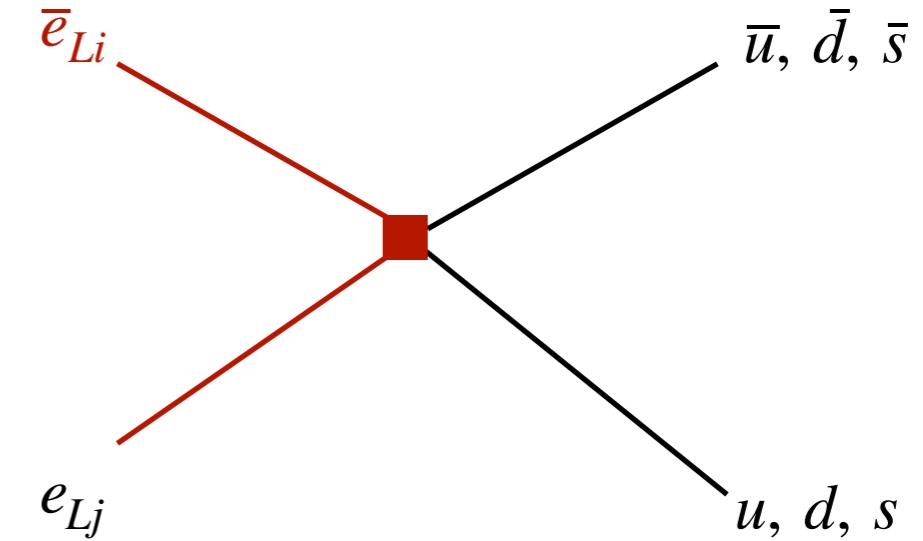
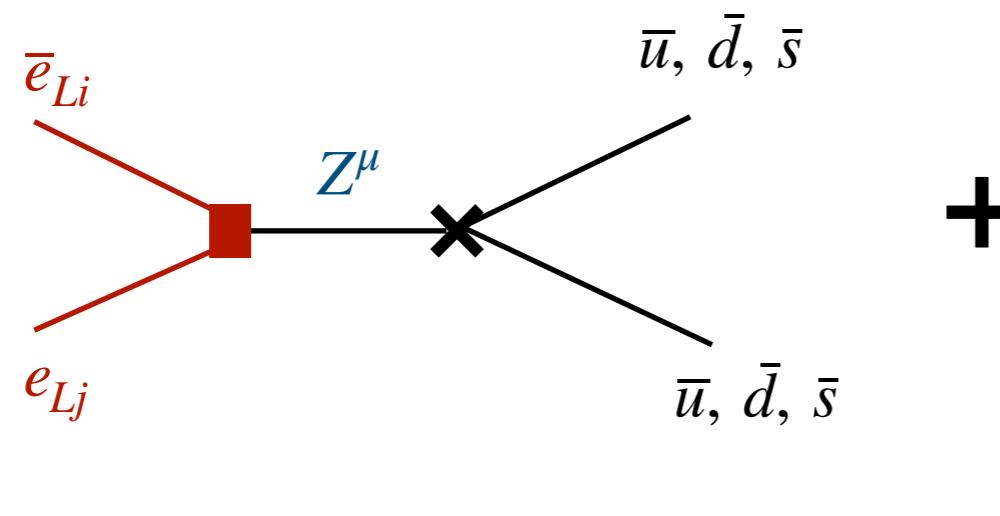


$$\tau \rightarrow e_i \bar{e}_j e_j$$

$$\mu \rightarrow 3e$$

Where else?

LFV Hadronic decays



$$-\frac{\nu^2}{2} \left([C_{\phi\ell}^{(1)}]_{ij} + [C_{\phi\ell}^{(3)}]_{ij} \right) \times \text{SM}$$

$$[C_{\ell q}^{(1)}]_{ij11}$$

Tree-level

$$[C_{\ell q}^{(1)}]_{ij22}$$

1-loop

$$[C_{\ell q}^{(1)}]_{ij33}$$



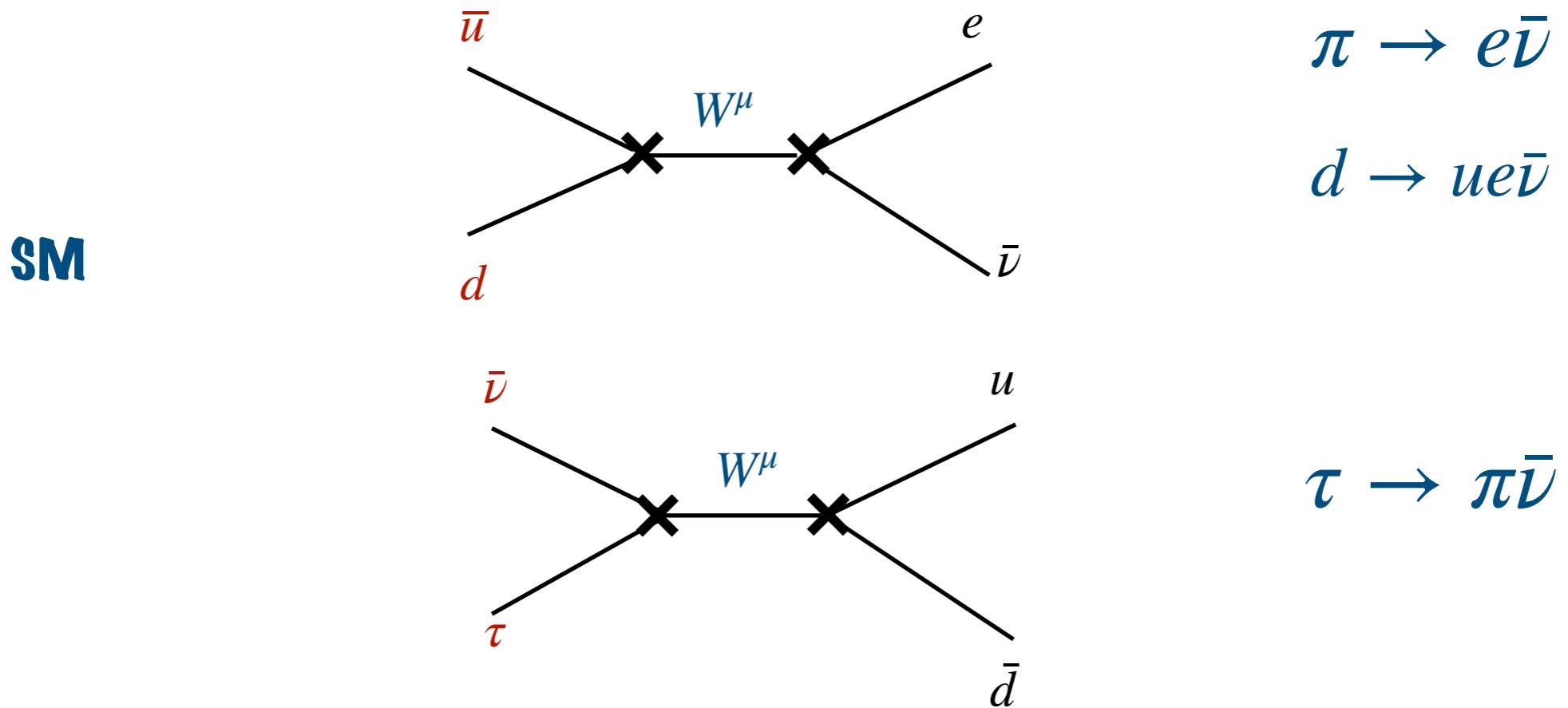
$$\tau \rightarrow \phi e, \tau \rightarrow \phi \mu$$

$$\tau \rightarrow \rho \mu, \tau \rightarrow \rho \mu$$

$$\tau \rightarrow \pi \mu, \tau \rightarrow \pi \mu$$

Charged current decays

$$\mathcal{L}_{\text{eff}}^{\text{c.c.}} \supset [C_{\nu e d u}^{V,LL}]_{ijkl} (\bar{\nu}_i \gamma_\mu P_L e_j)(\bar{d}_k \gamma_\mu P_L u_l) + h.c..$$



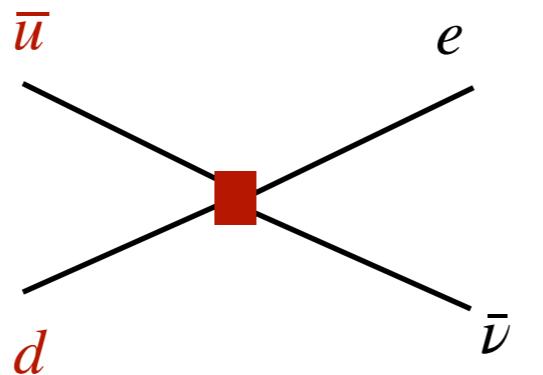
Charged current decays

$$\mathcal{L}_{\text{eff}}^{\text{c.c.}} \supset [C_{\nu e d u}^{V,LL}]_{ijkl} (\bar{\nu}_i \gamma_\mu P_L e_j) (\bar{d}_k \gamma_\mu P_L u_l) + h.c..$$

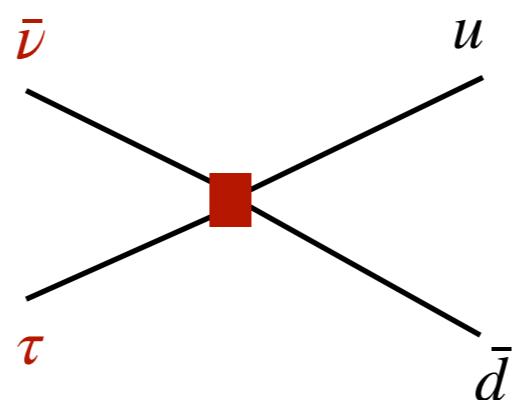
SMEFT

$$[C_{\nu e d u}^{V,LL}]_{ijkl} \supset 2[C_{\ell q}^{(3)}]_{ijkl}$$

$$O_{\ell q}^{(3)} = (\bar{\ell}_i \gamma_\mu \tau^I \ell_j) (\bar{q}_k \gamma^\mu \tau^I q_l)$$



$$\pi \rightarrow e \bar{\nu}$$



$$d \rightarrow u e \bar{\nu}$$

$$\tau \rightarrow \pi \bar{\nu}$$

$C_{\ell q}^{(1)}$ **mixes with** $C_{\ell q}^{(3)}$

$$\begin{pmatrix} [C_{\ell q}^{(1)}]_{iikk} \\ [C_{\ell q}^{(3)}]_{iikk} \end{pmatrix} = \frac{1}{16\pi^2} \log\left(\frac{\mu}{\Lambda}\right) \begin{pmatrix} - & 9g_2^2 \\ 3g_2^2 & - \end{pmatrix} \begin{pmatrix} [C_{\ell q}^{(1)}]_{iikk} \\ [C_{\ell q}^{(3)}]_{iikk} \end{pmatrix}$$

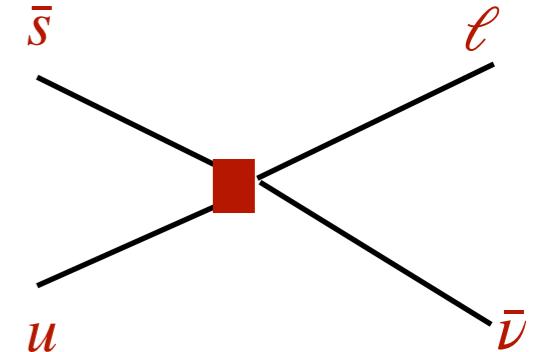
→ $[C_{\nu edu}^{V,LL}]_{ijkl} = 6g_2^2 \frac{1}{16\pi^2} \log\left(\frac{\mu}{\Lambda}\right) [C_{\ell q}^{(1)}]_{ijkm} [V^\dagger]_{ml}$

→ $C_{\ell q}^{(1)}$ **contributes to charged current decays at 1-loop**

Some examples

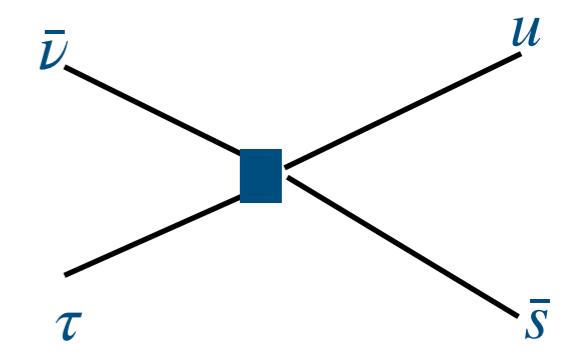
$$K \rightarrow \ell \bar{\nu}$$

$$[C_{\nu e d u}^{V,LL}]_{1121} \propto \left(V_{ud}^* [C_{\ell q}^{(1)}]_{1121} + \boxed{V_{us}^* [C_{\ell q}^{(1)}]_{1122}} + V_{ub}^* [C_{\ell q}^{(1)}]_{1123} \right)$$



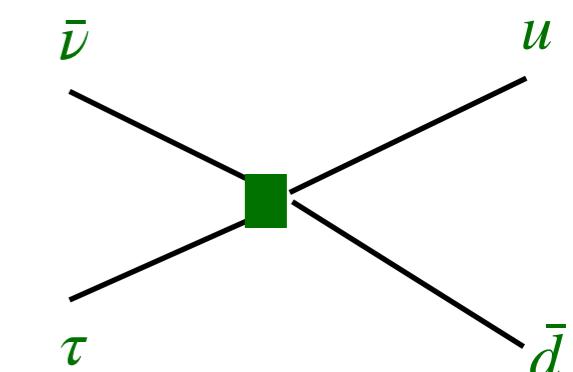
$$\tau \rightarrow K \bar{\nu}$$

$$[C_{\nu e d u}^{V,LL}]_{3321} \propto \left(V_{ud}^* [C_{\ell q}^{(1)}]_{3321} + \boxed{V_{us}^* [C_{\ell q}^{(1)}]_{3322}} + V_{ub}^* [C_{\ell q}^{(1)}]_{3323} \right)$$



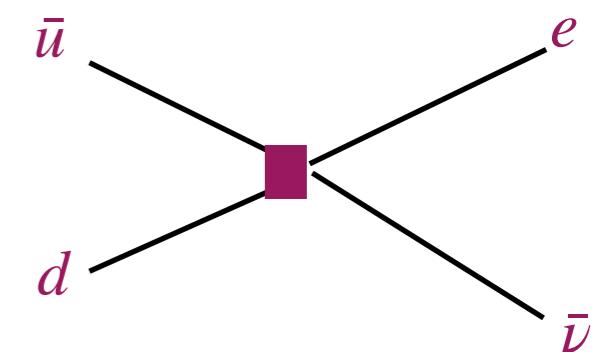
$$\tau \rightarrow \pi \bar{\nu}$$

$$[C_{\nu e d u}^{V,LL}]_{3311} \propto \left(V_{ud}^* [C_{\ell q}^{(1)}]_{3311} + \boxed{V_{us}^* [C_{\ell q}^{(1)}]_{3312}} + V_{ub}^* [C_{\ell q}^{(1)}]_{3313} \right)$$



$$\pi \rightarrow e \bar{\nu}, \quad d \rightarrow ue \bar{\nu}$$

$$[C_{\nu e d u}^{V,LL}]_{1111} \propto \left(V_{ud}^* [C_{\ell q}^{(1)}]_{1111} + \boxed{V_{us}^* [C_{\ell q}^{(1)}]_{1112}} + V_{ub}^* [C_{\ell q}^{(1)}]_{1113} \right)$$



Summary of observables

Correlations !!

$$O_{\ell q}^{(1)} = (\bar{\ell}_i \gamma_\mu \ell_j)(\bar{q}_k \gamma^\mu q_l)$$

$$O_{\ell d} = (\bar{\ell}_i \gamma_\mu \ell_j)(\bar{d}_k \gamma^\mu d_l)$$

$$O_{ed} = (\bar{e}_i \gamma_\mu e_j)(\bar{d}_k \gamma^\mu d_l)$$

$$O_{\ell q}^{(3)} = (\bar{\ell}_i \gamma_\mu \tau^I \ell_j)(\bar{q}_k \gamma^\mu \tau^I q_l)$$

$$O_{\ell u} = (\bar{\ell}_i \gamma_\mu \ell_j)(\bar{u}_k \gamma^\mu u_l)$$

$$O_{eu} = (\bar{e}_i \gamma_\mu e_j)(\bar{u}_k \gamma^\mu u_l)$$

1111, 1122, 1133, 2211, 2222, 2233

Electroweak precision observables

1211, 1222, 1233, 1311, 1322, 1333, 2311, 2322, 2333

$$\tau \rightarrow e_i \bar{e}_j e_j$$

$$\tau \rightarrow \phi e, \tau \rightarrow \phi \mu$$

$$\mu \rightarrow 3e$$

$$\tau \rightarrow \rho \mu, \tau \rightarrow \rho \mu$$

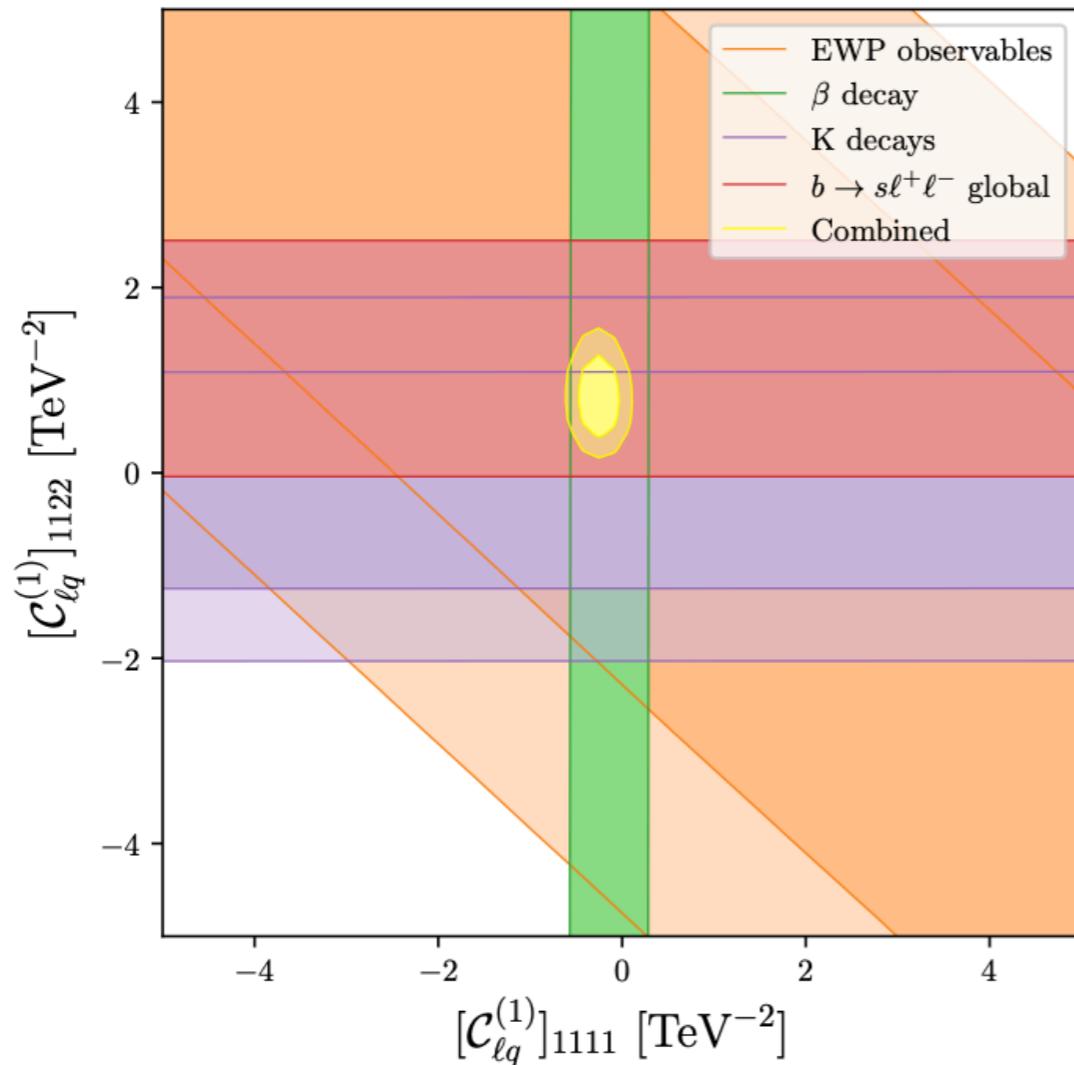
$$\tau \rightarrow \pi \mu, \tau \rightarrow \pi \mu$$

$O_{\ell q}^{(1)}$: 1122, 3322, 3311, 1111

$$\tau \rightarrow K \bar{\nu} \quad K \rightarrow \ell \bar{\nu} \quad \pi \rightarrow e \bar{\nu}, d \rightarrow ue \bar{\nu}$$

Correlations from operator mixing

$$[O_{\ell q}^{(1)}]_{1111} = (\bar{\ell}_1 \gamma_\mu \ell_1)(\bar{q}_1 \gamma^\mu q_1) \quad [O_{\ell q}^{(1)}]_{1122} = (\bar{\ell}_1 \gamma_\mu \ell_1)(\bar{q}_2 \gamma^\mu q_2)$$



Combined fit

EW P observables:

$$[O_{\ell q}^{(1)}]_{1111} \rightarrow [O_{\phi \ell}^{(1)}]_{11}, [O_{\phi q}^{(1)}]_{11}$$

$$[O_{\ell q}^{(1)}]_{1122} \rightarrow [O_{\phi \ell}^{(1)}]_{11}, [O_{\phi q}^{(1)}]_{22}$$

Beta decay

$$[O_{\ell q}^{(1)}]_{1111} \rightarrow [O_{\ell q}^{(3)}]_{1111}$$

K decays

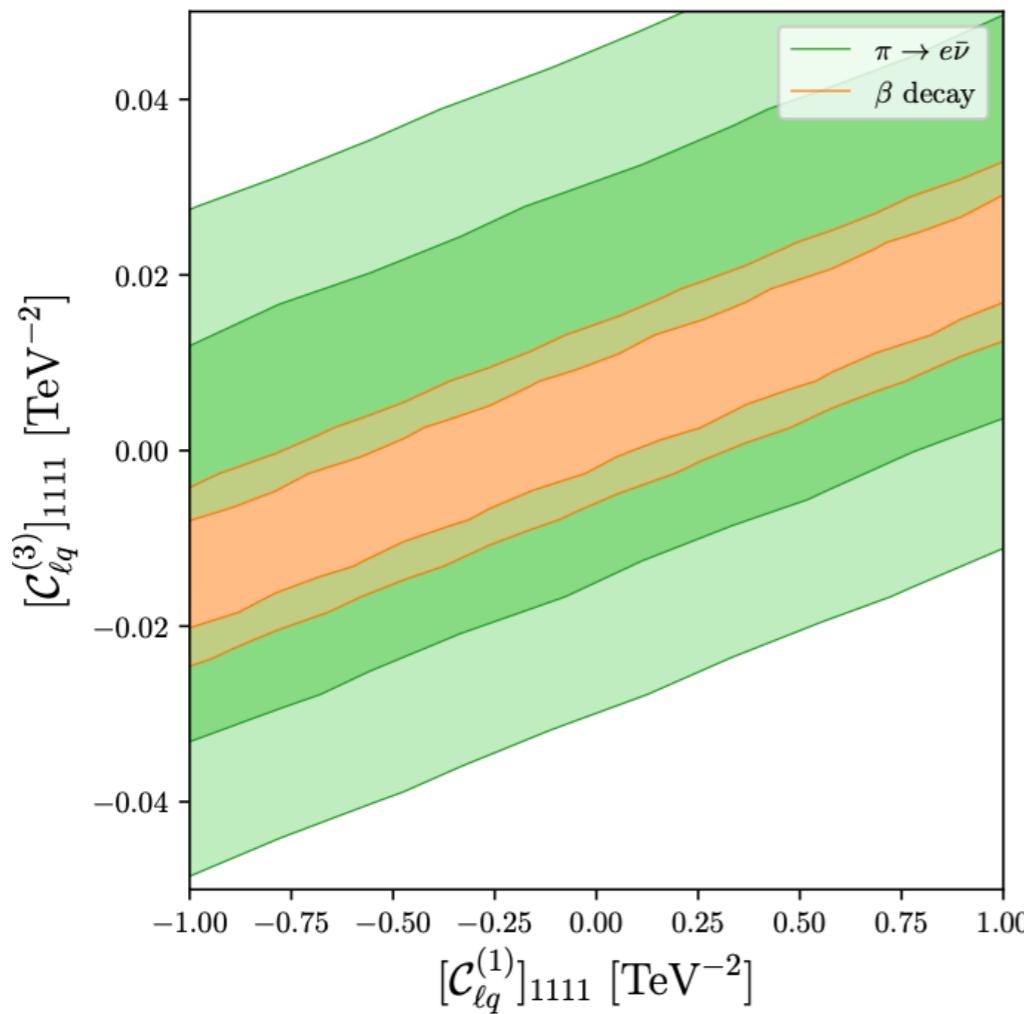
$$[O_{\ell q}^{(1)}]_{1122} \rightarrow [O_{\ell q}^{(3)}]_{1122}$$

$b \rightarrow s \ell^+ \ell^-$

$$[O_{\ell q}^{(1)}]_{1122} \rightarrow [O_{\ell q}^{(3)}]_{1123}$$

Correlations from operator mixing

$$[O_{\ell q}^{(1)}]_{1111} = (\bar{\ell}_1 \gamma_\mu \ell_1)(\bar{q}_1 \gamma^\mu q_1) \quad [O_{\ell q}^{(3)}]_{1122} = (\bar{\ell}_1 \gamma_\mu \ell_1)(\bar{q}_1 \gamma^\mu q_1)$$



Beta decay, $\pi \rightarrow e\bar{\nu}$

$$[O_{\ell q}^{(3)}]_{1111}$$

Tree-level

Beta decay, $\pi \rightarrow e\bar{\nu}$

$$[O_{\ell q}^{(1)}]_{1111} \rightarrow [O_{\ell q}^{(3)}]_{1111}$$

1-loop

Conclusions

RG running effects important to correctly predict the ***low energy implications*** of heavy NP

The ***semileptonic operators*** through ***operator mixing*** can contribute to a variety of EW scale and low energy such as:

- Electroweak precision observables
- Lepton flavour violating decays
- Lepton flavour violating hadronic decays
- Charged current decays
- B-decays

This can lead to interesting ***correlations*** between observables from different sectors

Thanks for your attention...

For more details please refer to arXiv preprint **2107.13005**

Backup

1-loop

W/Z couplings

$$[O_{\phi q}^{(1)}]_{ij} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{q}_i \gamma^\mu q_j)$$

$$[O_{\phi q}^{(3)}]_{ij} = (\phi^\dagger i \overleftrightarrow{D}_\mu \tau^I \phi)(\bar{q}_i \gamma^\mu \tau^I q_j)$$

$$[O_{\phi u}]_{ij} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{u}_i \gamma^\mu u_j)$$

$$[O_{\phi d}]_{ij} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{d}_i \gamma^\mu d_j)$$

1-loop

LFV decays: leptonic, hadronic

$$[O_{\phi \ell}^{(1)}]_{ij} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{\ell}_i \gamma^\mu \ell_j)$$

$$[O_{\phi \ell}^{(3)}]_{ij} = (\phi^\dagger i \overleftrightarrow{D}_\mu \tau^I \phi)(\bar{\ell}_i \gamma^\mu \tau^I \ell_j)$$

$$[O_{\phi e}]_{ij} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{e}_i \gamma^\mu e_j)$$

tree-level

LFV: hadronic

$$O_{\ell q}^{(1)} = (\bar{\ell}_i \gamma_\mu \ell_j)(\bar{q}_k \gamma^\mu q_k)$$

$$O_{\ell q}^{(3)} = (\bar{\ell}_i \gamma_\mu \tau^I \ell_j)(\bar{q}_k \gamma^\mu \tau^I q_k)$$

$$O_{\ell d} = (\bar{\ell}_i \gamma_\mu \ell_j)(\bar{d}_k \gamma^\mu d_k)$$

$$O_{\ell u} = (\bar{\ell}_i \gamma_\mu \ell_j)(\bar{u}_k \gamma^\mu u_k)$$

$$O_{ed} = (\bar{e}_i \gamma_\mu e_j)(\bar{d}_k \gamma^\mu d_k)$$

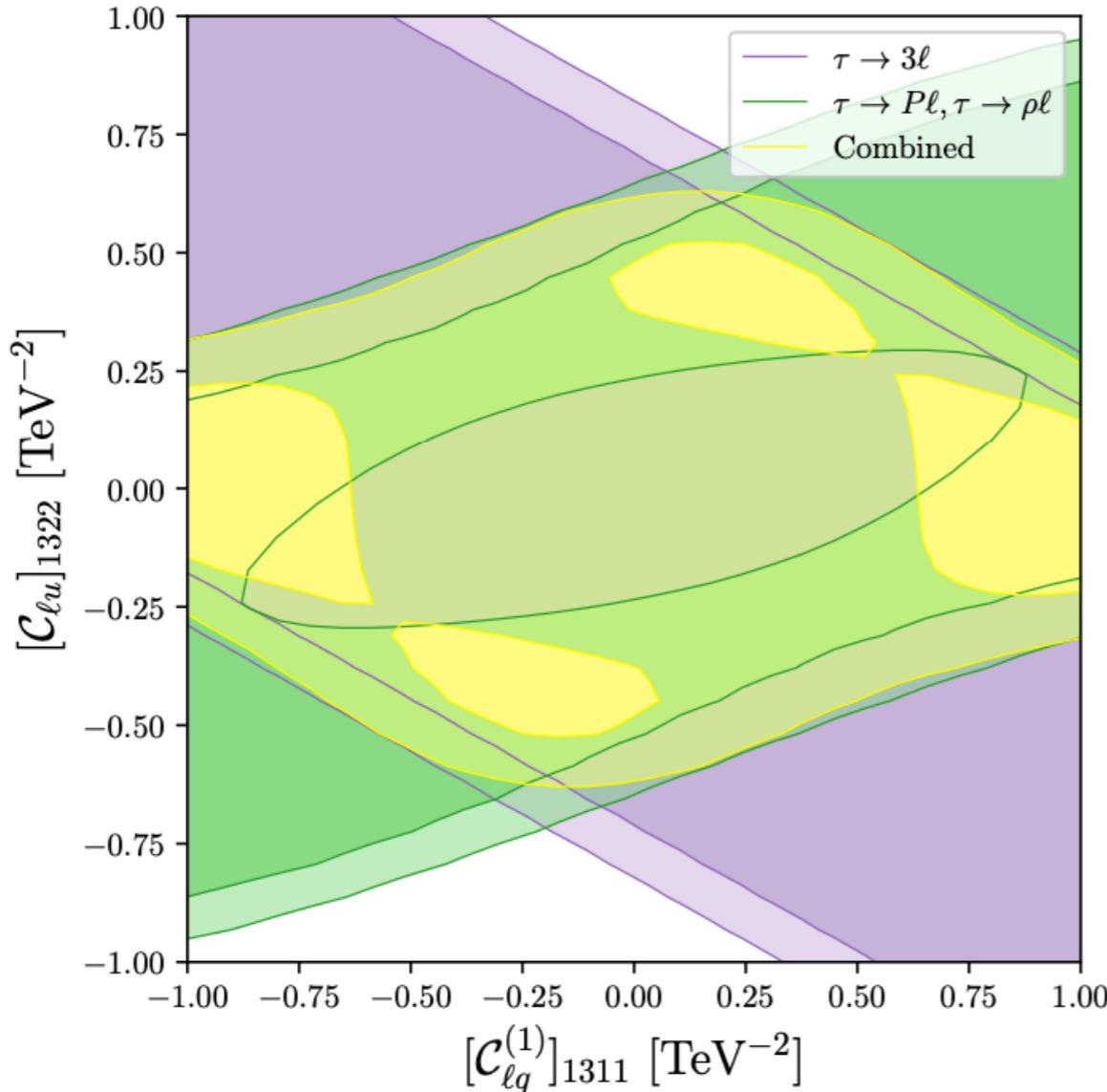
$$O_{eu} = (\bar{e}_i \gamma_\mu e_j)(\bar{u}_k \gamma^\mu u_k)$$

$$[O_{\ell e}]_{ijkl} = (\bar{\ell}_i \gamma_\mu \ell_j)(\bar{e}_k \gamma^\mu e_l)$$

$$[O_{ee}]_{ijkl} = (\bar{e}_i \gamma_\mu e_j)(\bar{e}_k \gamma^\mu e_l)$$

Correlations from operator mixing

$$[O_{\ell q}^{(1)}]_{1311} = (\bar{\ell}_1 \gamma_\mu \ell_3)(\bar{q}_1 \gamma^\mu q_1) \quad [O_{\ell u}]_{1322} = (\bar{\ell}_1 \gamma_\mu \ell_3)(\bar{u}_2 \gamma^\mu u_2)$$



$\tau \rightarrow 3\ell$

$[O_{\ell q}^{(1)}]_{1311} \rightarrow [C_{\ell\ell}]_{13ll}, [C_{\ell e}]_{13ll}, [C_{\phi\ell}^{(1)}]_{13}$
 $[O_{\ell u}]_{1322} \rightarrow [C_{\ell\ell}]_{13ll}, [C_{\ell e}]_{13ll}, [C_{\phi\ell}^{(1)}]_{13}$

$\tau \rightarrow P\ell, \tau \rightarrow \rho\ell$

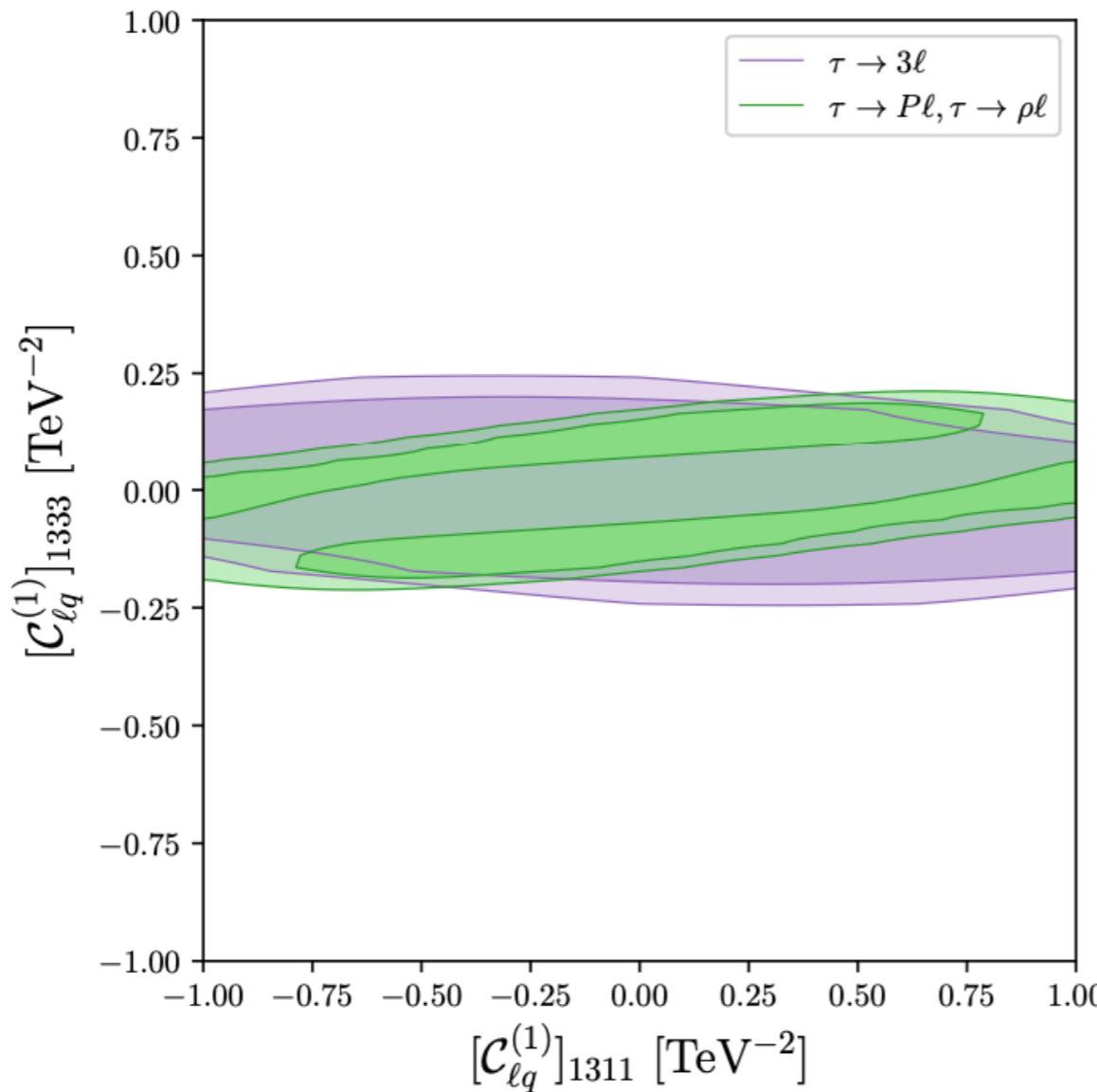
$[O_{\ell q}^{(1)}]_{1311} \rightarrow [O_{\phi\ell}^{(1)}]_{13}$

no tree-level contribution!

$[O_{\ell u}]_{1322} \rightarrow [O_{\phi\ell}^{(1)}]_{13}$

Correlations from operator mixing

$$[O_{\ell q}^{(1)}]_{1311} = (\bar{\ell}_1 \gamma_\mu \ell_3)(\bar{q}_1 \gamma^\mu q_1) \quad [O_{\ell q}^{(1)}]_{1333} = (\bar{\ell}_1 \gamma_\mu \ell_3)(\bar{q}_3 \gamma^\mu q_3)$$



$\tau \rightarrow 3\ell$

$[O_{\ell q}^{(1)}]_{1333} \rightarrow [C_{\phi\ell}^{(1)}]_{13}$

$\tau \rightarrow P\ell, \tau \rightarrow \rho\ell$

$[O_{\ell q}^{(1)}]_{1333} \rightarrow [O_{\phi\ell}^{(1)}]_{13}$

top-Yukawas at work !