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Effective Field Theory Approach to Flavour and Dark Matter

Supported by a Marie Curie Intra-European Fellowship of the European Community’s 7th Framework Programme under the contract number (PIEF-GA-2012-326948).
Outline:

- Introduction: Higher Dimensional Operators
- Lepton Flavour Violation
  - Effects of gauge invariant dim-6 operators
- Determination of the $V_{ub}$ and $V_{cb}$
  - Can NP explain the differences in the determinations
- Dark Matter detection
  - Spin-independent cross section
  - Dim 5
  - Dim 6
  - Dim 7
- Conclusions
Introduction
Higher dimensional operators

- NP at the scale $\Lambda > v$ must be invariant under the SM gauge group.
- The heavy degrees of freedom can be integrated out. (T. Appelquist, J. Carazzone)

The resulting effective operators must be Lorentz invariant, respect the SM gauge group and are suppressed by powers of $1/\Lambda$.

B. Grzadkowski et al., arXiv:1008.4884
Why EFT methods:

- Argue indecently of the specific NP model
- Properly connect physics at different scales via
  - Running
  - Mixing
  - Matching
- Correlate different experiments (complementarily of searches)
- Can be easily extended to account for DM, right-handed neutrinos, …
Operator classification

\[ L_{SM} = L_{SM}^{(4)} + \frac{1}{\Lambda} \sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2} \sum_k C_k^{(6)} Q_k^{(6)} + O\left(\frac{1}{\Lambda^3}\right) \]

- **Dim 5:** 1 operator, the Weinberg operator
  \[ Q_{\nu\nu} = \varepsilon_{jk} \varepsilon_{mn} \phi^j \phi^m \left( \ell^k_p \right)^T C l^n_r = \left( \phi^* \ell_p \right)^T C \left( \phi^* \ell_r \right) \]

- **Dim 6:** 59 operators
  - 30 four-fermion operators \( Q_{le} = \left( \bar{\ell}_p \gamma_{\mu} \ell_r \right) \left( \bar{e}_s \gamma^{\mu} e_t \right) \)
  - 4 pure field-strength tensor operators \( Q_G = f^{ABC} G_{\mu}^{AV} G_{\nu}^{B\rho} G_{\rho}^{C\mu} \)
  - 3 SM-scalar-doublet operators \( Q_{\phi} = (\phi \phi^*)^3 \)
  - 8 Higgs-field-strength operators \( Q_{\phi G} = \phi^* \phi G_{\mu\nu}^{A} G^{A\mu\nu} \)
  - 3 Higgs-fermion operators \( Q_{\phi e} = \phi^* \phi \bar{\ell}_i \phi e_j \)
  - 8 “magnetic” operators \( Q_{eB} = \bar{\ell}_i \sigma_{\mu\nu} e_j \phi B^{\mu\nu} \)
  - 8 Higgs-fermion-derivative \( Q_{\phi \ell}^{(1)} = \phi^* D_\mu \phi \bar{\ell}_i \gamma^{\mu} \ell_j \)
General procedure

- Perform EW symmetry breaking
- Derive the Feynman rules
- Calculate the Feynman diagrams
- Perform the matching (integrate out W, Z, t and h)
- RGE evolution to the low scale
- Calculation of decay width, cross sections, etc.
Lepton Flavour Violation with dim-6 operators

A.C., S. Najjari, J. Rosiek, arXiv:1312.0632
A.C., M. Hoferichter, M. Procura, arXiv:1404.7134
Lepton flavour violation

In the SM (with massive neutrinos) lepton flavour violations is extremely suppressed by the small neutrino masses: $O(10^{-52})$

Any observation of LFV would establish physics beyond the SM.

- Current best limits on $\mu \to e$ transitions (from PSI):
  \[
  \text{Br}[\mu \to e\gamma] \leq 5.7 \times 10^{-13} \\
  \text{Br}[\mu \to eee] \leq 1 \times 10^{-12} \\
  \text{Br}^\text{conv}[\mu \to e] \leq 7 \times 10^{-13}
  \]

- Future prospects:
  \[
  \text{Br}[\mu \to e\gamma] \leq 6 \times 10^{-14} \quad \text{PSI} \\
  \text{Br}^\text{conv}[\mu \to e] \leq 5 \times 10^{-17} \quad \text{FNAL, J-PARC} \\
  \text{Br}[\mu \to eee] \leq 7 \times 10^{-17} \quad \text{PSI (proposed)}
  \]
Observables

Contributions of dim-6 operators to

- $\ell \to \ell' \gamma$ (one loop)
- $\tau \to \mu\mu\mu, \tau \to e\mu\mu$, etc.
- EDM, AMM (one loop)
- $Z \to \ell\ell'$
- $\mu \to e$ conversion

At leading loop-order and at leading order in $1/\Lambda^2$ and $m_\ell / m_W$
# Operators for LFV

<table>
<thead>
<tr>
<th>$llll$</th>
<th>$llX\varphi$</th>
<th>$ll\varphi^2D$ and $ll\varphi^3$</th>
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<tbody>
<tr>
<td>$Q_{\ell\ell}$</td>
<td>$Q_{eW}$</td>
<td>$Q_{\varphi^1}$</td>
</tr>
<tr>
<td>$(\bar{\ell}<em>i \gamma</em>\mu \ell_j)(\bar{\ell}_k \gamma^\mu \ell_l)$</td>
<td>$(\bar{\ell}<em>o \sigma^{\mu\nu} e_j)^{\top} \varphi W^I</em>{\mu\nu}$</td>
<td>$(\varphi^1 i \bar{D}_\mu \varphi)(\bar{\ell}<em>i \gamma</em>\mu \ell_j)$</td>
</tr>
<tr>
<td>$Q_{ee}$</td>
<td>$Q_{eB}$</td>
<td>$Q_{\varphi^2}$</td>
</tr>
<tr>
<td>$(\bar{e}<em>i \gamma</em>\mu e_j)(\bar{e}_k \gamma^\mu e_l)$</td>
<td>$(\bar{\ell}<em>i \sigma^{\mu\nu} e_j)\varphi B</em>{\mu\nu}$</td>
<td>$(\varphi^2 i \bar{D}_\mu \varphi)(\bar{\ell}<em>i \gamma</em>\mu \ell_j)$</td>
</tr>
<tr>
<td>$Q_{\ell e}$</td>
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<td>$Q_{\varphi^3}$</td>
</tr>
<tr>
<td>$(\bar{\ell}<em>i \gamma</em>\mu \ell_j)(\bar{e}_k \gamma^\mu e_l)$</td>
<td></td>
<td>$(\varphi^3 i \bar{D}_\mu \varphi)(\bar{\ell}<em>i \gamma</em>\mu \ell_j)$</td>
</tr>
</tbody>
</table>

| $llqq$ | | |
| $Q^{(1)}_{\ell q}$ | $Q^{(1)}_{\ell u}$ | $(\bar{\ell}_i \gamma_\mu \ell_j)(\bar{u}_k \gamma_\mu u_l)$ |
| $(\bar{\ell}_i \gamma_\mu \ell_j)(\bar{q}_k \gamma^\mu q_l)$ | $(\bar{\ell}_i \gamma_\mu \ell_j)(\bar{d}_k \gamma^\mu d_l)$ | |
| $Q^{(3)}_{\ell q}$ | $Q^{(3)}_{\ell u}$ | $(\bar{\ell}_i \gamma_\mu \ell_j)(\bar{q}_k \gamma^\mu q_l)$ |
| $(\bar{\ell}_i \gamma_\mu \ell_j)(\bar{q}_k \gamma^\mu q_l)$ | $(\bar{\ell}_i \gamma_\mu \ell_j)(\bar{d}_k \gamma^\mu d_l)$ | |
| $Q_{eq}$ | $Q_{eu}$ | $Q_{q_{eq}}^{(1)}$ |
| $(\bar{e}_i \gamma_\mu e_j)(\bar{q}_k \gamma^\mu q_l)$ | $(\bar{e}_i \gamma_\mu e_j)(\bar{u}_k \gamma^\mu u_l)$ | $(\bar{\ell}_i \gamma_\mu e_j)(\bar{q}_{k} \gamma^\mu q_l)$ |
| $Q_{\ell dq}$ | $Q_{q_{eq}}^{(3)}$ | $(\bar{e}_i \gamma_\mu e_j)(\bar{q}_{k} \gamma^\mu q_l)$ |
| $(\bar{\ell}_i \gamma_\mu e_j)(\bar{d}_k \gamma^\mu d_l)$ | $(\bar{e}_i \gamma_\mu e_j)(\bar{q}_{k} \gamma^\mu q_l)$ | $(\bar{\ell}_i \sigma_{\mu\nu} e_a)(\bar{q}_{k} \sigma^{\mu\nu} u_l)$ |

- $l$: left-handed lepton doublet
- $e$: right-handed charged lepton
- $\varphi$: SM-Scalar doublet
- $W^{\mu\nu}$: $SU(2)$ field-strength tensor
- $B^{\mu\nu}$: $U(1)$ field-strength tensor
- $\ell, j, k, l$: flavour indices
- $\bar{D}_\mu$: covariant derivative
Derivation of the modified Feynman rules

- After EW symmetry breaking
- General $R_\chi$ gauge

Example: Z-lepton coupling

\[
i \left( \gamma^\mu \left[ \Gamma^{ZL}_{fi} P_L + \Gamma^{ZR}_{fi} P_R \right] + i\sigma^{\mu\nu} \left[ C^{ZL}_{fi} P_L + C^{ZR}_{fi} P_R \right] q_\nu \right)
\]

\[
\Gamma^{ZL}_{fi} = \frac{e}{2s_W c_W} \left( \frac{v^2}{\Lambda^2} (C^{(1)}_{\phi\ell} + C^{(3)}_{\phi\ell}) + (1 - 2s^2_W) \delta_{fi} \right)
\]

\[
\Gamma^{ZR}_{fi} = \frac{e}{2s_W c_W} \left( \frac{v^2}{\Lambda^2} C_{\phi e}^{fi} - 2s^2_W \delta_{fi} \right)
\]

\[
C_{fi}^{ZR} = C_{fi}^{ZL*} = -\frac{v\sqrt{2}}{\Lambda^2} \left( s_W C_{eB}^{fi} + c_W C_{eW}^{fi} \right)
\]
Calculation of the diagrams

$\ell \rightarrow \ell' \gamma$

EDM

AMM
$$\text{Br} \left[ \ell_i \rightarrow \ell_f \gamma \right] = \frac{m_{\ell_i}^3}{16\pi \Lambda^4 \Gamma_{\ell_i}} \left( |F_{TR}^{fi}|^2 + |F_{TL}^{fi}|^2 \right)$$

$$F_{TL}^{ZG \ f i} = \frac{4e \left[ (C_{\phi \ell}^{(1)fi} + C_{\phi \ell}^{(3)fi}) m_f (1 + s_W^2) - C_{\phi \ell}^{fi} m_i \left( \frac{3}{2} - s_W^2 \right) \right]}{3(4\pi)^2}$$

$$F_{TR}^{ZG \ f i} = \frac{4e \left[ (C_{\phi \ell}^{(1)fi} + C_{\phi \ell}^{(3)fi}) m_i (1 + s_W^2) - C_{\phi \ell}^{fi} m_f \left( \frac{3}{2} - s_W^2 \right) \right]}{3(4\pi)^2}$$

$$F_{TL}^{WG \ f i} = -\frac{10em_f C_{\phi \ell}^{(3)fi}}{3(4\pi)^2}$$

$$F_{TR}^{WG \ f i} = -\frac{10em_i C_{\phi \ell}^{(3)fi}}{3(4\pi)^2}$$

$$F_{TL}^{4\ell \ f i} = \frac{2e}{(4\pi)^2} \sum_{j=1}^{3} C_{\ell e}^{ij ji} m_j$$

$$F_{TR}^{4\ell \ f i} = \frac{2e}{(4\pi)^2} \sum_{j=1}^{3} C_{\ell e}^{ij fj} m_j$$

$$F_{TL}^{ql \ f i} = -\frac{16e}{3(4\pi)^2} \sum_{j=1}^{3} C_{\ell e \text{equ}}^{(3)iji} m_{u_j} \left( \Delta - \log \frac{m_{u_j}^2}{\mu^2} \right)$$

$$F_{TR}^{ql \ f i} = -\frac{16e}{3(4\pi)^2} \sum_{j=1}^{3} C_{\ell e \text{equ}}^{(3)iji} m_{u_j} \left( \Delta - \log \frac{m_{u_j}^2}{\mu^2} \right)$$

Checks:

- Gauge invariant structure of the operators
- $R_\chi$ gauge
Numerical results

\[ \tau \rightarrow \text{eee}, \tau \rightarrow \text{e}\gamma \text{ and } Z \rightarrow \tau \text{e} \]
*\( \mu \rightarrow e \) conversion and
and Higgs mediated flavour violation

- Higgs contributions to \( \mu \rightarrow e\gamma \) and \( \mu \rightarrow eee \) by small Yukawa couplings
- Contributions to \( \mu \rightarrow e \) conversion involve also heavy quarks

\[ D_{\ell_i}^{\mu \rightarrow e} \text{ conversion sensitive to Higgs mediated FV} \]

**dim-6 operator**

\[ O_{\ell_i}^{\mu \rightarrow e} = \left( \phi^\dagger \phi \right) \left( \overline{\ell}_i e_f \phi \right) \]

\[ \Gamma_{\ell_f \ell_i}^{h^0} = -\frac{m_{\ell_i}}{v} + \frac{1}{\sqrt{2} \Lambda^2} \tilde{C}_{\ell_i}^{\ell_f \phi}, \tilde{C}_{\ell_i}^{\ell_f \phi} = \left( U^{L\dagger} C_{\ell_i \phi} U^R \right)_{\ell_f} \]
\( \mu \rightarrow e \) conversion

\[
\Gamma_{\mu e} : \mu-e-h^0 \text{ coupling}
\]
Determination of $V_{ub}$ and $V_{cb}$

A.C., Stefan Pokorski, arXiv:1407.1320
Different determinations

- \( V_{cb} \)
  \[ |V_{cb}| = (4.242 \pm 0.086) \times 10^{-2} \quad \text{(inclusive)} \]
  \[ |V_{cb}| = (3.904 \pm 0.075) \times 10^{-2} \quad (B \rightarrow D^* \ell \nu) \]
  \[ |V_{cb}| = (3.850 \pm 0.191) \times 10^{-2} \quad (B \rightarrow D \ell \nu) \]

- \( V_{ub} \)
  \[ |V_{ub}| = (4.41^{+0.21}_{-0.23}) \times 10^{-3} \quad \text{(inclusive)} \]
  \[ |V_{ub}| = (3.40^{+0.38}_{-0.33}) \times 10^{-3} \quad (B \rightarrow \pi \ell \nu) \]
  \[ |V_{ub}| = (4.3 \pm 0.6) \times 10^{-3} \quad (B \rightarrow \tau \nu) \]
  \[ |V_{ub}| = (3.4 \pm 0.3) \times 10^{-3} \quad (B \rightarrow \rho \ell \nu) \]
Effective operators (at the B scale)


- Four-fermion operators

\[ O^S_R = \overline{\ell} P_L \nu \overline{q} P_R b \]
\[ O^S_L = \overline{\ell} P_L \nu \overline{q} P_L b \]
\[ O^T_L = \overline{\ell} \sigma_{\mu\nu} P_L \nu \overline{q} \sigma^{\mu\nu} P_L b \]

contribute

\[ \sim |C^T_L|^2 \quad \text{all decays} \]
\[ \sim |C^S_R + C^S_L|^2 \quad B \to D(\pi)\ell\nu \]
\[ \sim |C^S_R - C^S_L|^2 \quad B \to D^*(\rho)\ell\nu \]
\[ \sim |C^S_R|^2 + |C^S_L|^2 \quad \text{inclusive} \]

- Modified W coupling

\[ H_{\text{eff}} = \frac{4 G_F V^{qb}}{\sqrt{2}} \overline{\ell} \gamma^\mu P_L \nu \left( (1 + c^{qb}_L) \overline{q} \gamma_\mu P_L b + g^{qb}_L \overline{q} i D^\mu \gamma_\nu P_L b + d^{qb}_L i D^\nu \left( \overline{q} i \sigma_{\mu\nu} P_L b \right) + L \to R \right) \]
Effects of NP

Exclusive determination at zero recoil:

- **$V_{cb}$**
  \[
  V_{cb} = \frac{V_{cb}^{SM}}{1 + c_L^{cb} + c_R^{cb} - 1.6\text{GeV}(d_R^{cb} + d_L^{cb}) + 5.5\text{GeV}(g_R^{cb} + g_L^{cb})} \quad (B \rightarrow D\ell\nu)
  \]
  \[
  V_{cb} = \frac{V_{cb}^{SM}}{1 + c_L^{cb} - c_R^{cb} + 3.3\text{GeV}(d_R^{cb} - d_L^{cb})} \quad (B \rightarrow D^*\ell\nu)
  \]

- **$V_{ub}$**
  \[
  V_{ub} = \frac{V_{ub}^{SM}}{1 + c_L^{ub} + c_R^{ub} - 4.9\text{GeV}(d_R^{ub} + d_L^{ub}) + 5.5\text{GeV}(g_R^{ub} + g_L^{ub})} \quad (B \rightarrow \pi\ell\nu)
  \]
  \[
  V_{ub} = \frac{V_{ub}^{SM}}{1 + c_L^{ub} - c_R^{ub} + 4.5\text{GeV}(d_R^{ub} - d_L^{ub})} \quad (B \rightarrow \rho\ell\nu)
  \]

Inclusive determination on weakly affected
New Physics Effects in $V_{cb}$

Right-handed W coupling

"magnetic" operator

```
B \rightarrow D^* \ell \nu
B \rightarrow D \ell \nu
```
New Physics Effects in $V_{ub}$

Right-handed $W$ coupling

„magnetic“ operator

$B \rightarrow \pi \ell \nu$

$B \rightarrow \tau \nu$

$B \rightarrow \rho \ell \nu$
Side remark:

Right-handed W-coupling in the MSSM

A.C. arXiv:0907.2461
Genuine vertex-correction

\[ -i \Lambda_{u_f d_i}^{W \tilde{g}} = \frac{g_2}{\sqrt{2}} \frac{i \alpha_s}{3\pi} \gamma^\mu \sum_{s,t=1}^6 \sum_{j,k=1}^3 \left( W_{f s}^{\tilde{u}} W_{ks}^{\tilde{u}*} V_{CKM}^{k j} W_{d t}^{\tilde{d}} W_{d t}^{\tilde{d}*} P_L \right) \left( W_{f+3,s}^{\tilde{u}} W_{k s}^{\tilde{u}*} V_{CKM}^{k j} W_{j t}^{\tilde{d}} W_{i+3,t}^{\tilde{d}*} P_R \right) c_2 \left( m_{\tilde{u}}, m_{\tilde{d}}, m_{\tilde{g}} \right) \]

- Corrections to the left-handed coupling suppressed because the hermitian part of the WFR cancels with the genuine vertex correction.
- Right-handed coupling not suppressed!
Where are SUSY effects possible?

- $\delta_{d LR/RL}^{u LR}$ strongly constrained from FCNC processes.
- $\delta_{13,23}^{u LR}$ less constrained from FCNCs $\left( B \rightarrow K^* \mu^+ \mu^- \right)$
- $\delta_{12,21}^{u LR,LL,RR}$ constrained from D mixing
- $\delta_{13,23}^{u RL}$ unconstrained from FCNCs
- Large $\delta_{33}^{d LR}$ possible if $A_b$ or $\tan(\beta)$ is large.
- $V_{ud}, V_{us}, V_{cd}, V_{cs}$ are too large for observable effects

Only $V_{ub}, V_{cb}$ can be affected by SUSY effects.
Largest SUSY effect in $V_{ub}$ possible.
Results

- In terms of SU(2) invariant operators $d_L$ corresponds to

$$Q_{uW}^{ij} = \frac{1}{\Lambda^2} \left( \overline{q}_i \sigma^{\mu\nu} u_j \right) \tau^I \tilde{\phi} W^I_{\mu\nu}$$

- Direct connection to Z-quark couplings

- Excluded order one corrections to Z-\(b\bar{b}\) couplings

**NP at the scale \(\Lambda\) cannot explain the differences in the determinations of \(V_{ub}\) and \(V_{cb}\).**
Effective field theory approach to Dark Matter

A.C., F. d’Eramo, M. Procura, arXiv:1402.1173
A.C., M. Hoferichter, M. Procura arXiv:1312.4951
Spin independent scattering cross section

- Up to Dim 7 (at the direct detection scale)

\[
\sigma_{N}^{\text{SI}} \approx \frac{m_N^2}{\pi \Lambda^4} \left| \sum_{q=u,d} C_{qq}^{VV} f_{V,q}^N + \frac{m_N}{\Lambda} \left( \sum_{q=u,d,s} C_{qq}^{SS} f_{q}^N - 12\pi C_{gg}^{S} f_{Q}^N \right) \right|^2
\]

\[
L_{\text{eff}} = \sum_{X} C_{X} O_{X}
\]

\[
O_{gg}^{S} = \frac{\alpha_s}{\Lambda^3} \overline{\chi} \chi G_{\mu \nu} G^{\mu \nu}
\]

\[
O_{qq}^{SS} = \frac{m_q}{\Lambda^3} \overline{\chi} \chi q q
\]

\[
O_{qq}^{VV} = \frac{1}{\Lambda^2} \overline{\chi} \gamma^\mu \chi \overline{q} \gamma_\mu q
\]

\(f^N\): nucleon couplings

\(m_N\): nucleon mass

The Wilson coefficients \( C_X \) must be connected to UV physics.
Scalar quark content of the nucleon

- Traditional approach: SU(3) chiral perturbation
- Better: SU(2) chiral perturbation theory and $f_s$ from lattice

![Graph showing $f_u^n$, $f_d^n$, and $f_{u,d}$ vs. $\sigma_{\pi N}$ in MeV with different colored lines representing our result, SU(3), and SU(3) with $f_s$.]
EFT for Dark Matter

- We assume that DM is:
  - A SM singlet (other choices are also possible)
  - A Dirac fermion (biggest number of operators)
- Interactions of DM with the SM arise through messengers at a high scale $\Lambda$
- Construct operators which are invariant under the SM gauge group
- This scale $\Lambda$ must be connected to the direct detection scale via running, mixing and threshold effects.
Operators dim-5

\[ O^T_M = \frac{1}{\Lambda} \bar{\chi} \sigma^{\mu\nu} \chi B_{\mu\nu}, \quad O^S_{HH} = \frac{1}{\Lambda} \bar{\chi} \chi H^\dagger H, \quad O^P_{HH} = \frac{1}{\Lambda} \bar{\chi} \gamma^5 \chi H^\dagger H \]

- \( O^T_M \): Tree-level contribution to direct detection
- \( O^P_{HH} \): Affects only spin dependent direct detection
- \( O^S_{HH} \): Enters only via matching corrections

Matching:

\[ C^S_{gg} = \frac{1}{12\pi m_{h^0}^2} C^S_{HH} \]

\[ C^{SS}_{qq} = -\frac{\Lambda^2}{m_{h^0}^2} C^S_{HH} \]

- Mixing turns out to be small

\[ C^{SS}_{qq}(\mu_0) = \left[ \frac{1}{12\pi} \left( U^{(s)}_{m_b,m_b} + 2 U^{(a)}_{\mu_0,m_b} \right) - 1 \right] \frac{\Lambda^2}{m_{h^0}^2} C^S_{HH} \]

\[ U^{(n_f)}_{\mu,\Lambda} = \frac{-3C_F}{\pi\beta_0} \ln \frac{\alpha_s(\Lambda)}{\alpha_s(\mu)}. \]
Operators dim-6

\[ O_{qq}^{VV} = \frac{1}{\Lambda^2} \overline{\chi} \gamma^\mu \chi \overline{q} \gamma_\mu q \]

\[ O_{qq}^{VA} = \frac{1}{\Lambda^2} \overline{\chi} \gamma^\mu \chi \overline{q} \gamma_\mu q \]

\[ O_{\phi\phi_3}^V = \frac{i}{\Lambda^2} \overline{\chi} \gamma^\mu \chi \phi^\dagger \slashed{D}_\mu \phi \]

- No QCD effects
- EW-mixing of \( O_{qq}^{VA} \) into \( O_{HHH}^V \)

\[ C_{\phi\phi_3}^V (\mu) = C_{\phi\phi_3} (\Lambda) - \frac{\alpha_t N_c}{\pi} C_{tt}^{VA} (\Lambda) \ln \frac{\mu}{\Lambda} (t \rightarrow b) \]

- Matching contributions

\[ C_{uu}^{VV} \rightarrow C_{uu}^{VV} + \frac{1}{2} C_{HHH}^V, \quad C_{dd}^{VV} \rightarrow C_{dd}^{VV} - \frac{1}{2} C_{HHH}^V \]

Bounds on previously unconstrained operators
Experimental constraints

\[ C_{qq}^{VA} = 1 \]
Operators dim-7

- Field strength tensors especially interesting

\[ O_B = \frac{1}{\Lambda^2} \overline{\chi} \chi B^\mu B_\mu, \quad O_W = \frac{1}{\Lambda^2} \overline{\chi} \chi W^\mu W_\mu \]

- Mixing into

\[ O_\phi^S = \frac{1}{\Lambda^3} \overline{\chi} \chi \phi^\dagger \phi^\dagger \]
\[ O_{qq}^\phi = \frac{Y_q}{\Lambda^3} \overline{\chi} \chi q \phi q \]

Contributions to direct detection after EW symmetry breaking and integrating out the Higgs.
Constraints on $C_{WW}$

- Interesting interplay between direct detection and LHC searches
Conclusions

- LVF is an excellent place to search for NP
  - $\mu \rightarrow e$ conversion sensitive to Higgs mediated flavour violation
- NP cannot explain the current differences in the determination of $V_{ub}$ and $V_{cb}$
- Interesting loop effects in DM direct detections: new constraints on operators
- EFT provide a consistent framework to search for NP in a model independent way