Probing the flavour of New Physics with dipoles

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Work in collaboration with **S. Jäger** and **K. Leslie** (U. Sussex)
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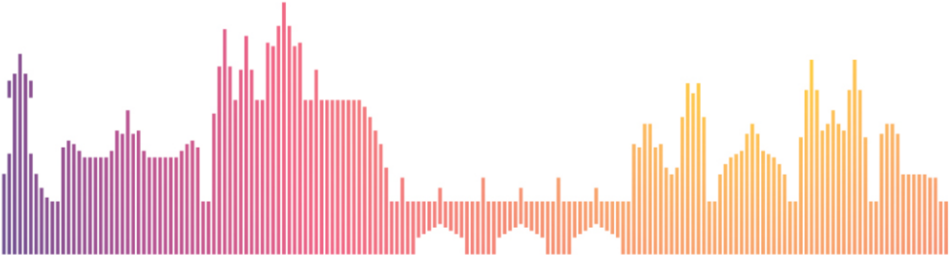
Outline



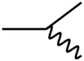
1. Introduction
2. Four-fermion operators
3. Conclusions

Flavour physics & radiative processes

→ Dipole operators: $\mathcal{L}_{dipole} = e\frac{v_{\rm EW}}{\sqrt{2}}\mathcal{C}_{\psi\gamma}^{\beta\alpha}\bar{\psi}_\beta\sigma^{\mu\nu}P_R\psi_\alpha F_{\mu\nu} + \text{h.c.}$

E.M. form factors: *Magnetic Dipole Moment* (MDM), *Electric Dipole Moment* (EDM), etc.

Flavour transitions: $\mu \to e\gamma$, $\tau \to (e,\mu)\gamma$, $\nu' \to \nu\gamma$, $s \to d\gamma$, $b \to (s,d)\gamma$, etc.



→ Multitask tool: structure of flavour (e.g., LFV), sources of CPV of the SM and beyond, in both quark and lepton sectors

eEDM: $|\text{Im}[\mathcal{C}_{e\gamma}^{ee}]| \lesssim (8\times 10^5\ \text{TeV})^{-2}$ [ACME]

$\mu \to e\gamma$: $\sqrt{|\mathcal{C}_{e\gamma}^{e\mu}|^2 + |\mathcal{C}_{e\gamma}^{\mu e}|^2} \lesssim (4\times 10^4\ \text{TeV})^{-2}$ [MEG]

nEDM: $\left|\text{Im}[\mathcal{C}_{d\gamma}^{dd}]\right|, \left|\text{Im}[\mathcal{C}_{u\gamma}^{uu}]\right| \lesssim (2\times 10^4\ \text{TeV})^{-2}$ [nEDM]

ICHEP20: various talks on LFV and EDM (*Flavour, BSM, Top, etc.*)

SMEFT way: NP sector much above EW scale

$\rightarrow$ Persistent absence of experimental evidence for non-SM particles below the EW scale

$\rightarrow$ Generic NP involving new heavy d.o.f. $\sim \Lambda \gg v_{\rm EW}$

$\rightarrow$ Consider operators $Q^{(n)}$ respecting SM local symmetries and containing SM d.o.f. only

$\rightarrow$ Non-SM interaction strengths $C^{(n)}$ among the d.o.f. that we know

$$\frac{C^{(5)} \times Q^{(5)}}{\Lambda}, \; \frac{C^{(6)} \times Q^{(6)}}{\Lambda^2}, \; \frac{C^{(7)} \times Q^{(7)}}{\Lambda^3}, \; \frac{C^{(8)} \times Q^{(8)}}{\Lambda^4}, \text{ etc.}$$

$\rightarrow$ New weak sector: typically effects from lower-dimensionality operators are more important for low-energy observables

Basis of dimension-six operators

$\rightarrow$ Focus on operators of **dimension-six**

$\rightarrow$ Equations Of Motion (EOMs) eliminate redundant cases:
59 linearly independent operators,
with 1350 CP-even + 1149 CP-odd couplings,
assuming SM global symmetries, $B_{\rm tot}$ and $L_{\rm tot}$

Warsaw: X^3, H^6, H^4D^2, ψ^2H^3, X^2H^2, ψ^2XH, ψ^2H^2D, ψ^4

[ψ fermions; D cov. derivative; X field strengths]

[Buchmüller, Wyler '86; Grzadkowski, Iskrzyński, Misiak, Rosiek '10]

$\underbrace{\psi^2XH \text{ class:}}_{\mathcal{L}_{dipole} \text{ @ tree}}$ $(\bar{q}\sigma^{\mu\nu}d)HB_{\mu\nu}$, $(\bar{q}\sigma^{\mu\nu}d)\tau^IHW^I_{\mu\nu}$, $(\bar{q}\sigma^{\mu\nu}T^Ad)HG^A_{\mu\nu}$, etc.

[q (d) $SU(2)$ doublet (singlet)]

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[Buchmüller, Wyler '86; Grzadkowski, Iskrzyński, Misiak, Rosiek '10]

ψ^4 class: $(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$, $(\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)$, $(\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d)$, etc.

[q (d) $SU(2)$ doublet (singlet)]

Probing **non-dipole** operators

Here, $\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i C_i Q_i$, C_i scales as Λ^{-2}

Mixing with dipole:

$$16\pi^2 \frac{d}{d\ell n(\mu)} C_{\psi^2 XH}(\mu) = \Sigma_i (C_{\psi^2 XH}, C_{\psi^4}, C_{X^3}, C_{X^2H^2})_i(\mu)\gamma^{(\text{1-loop})}_{i,\psi^2 XH}$$

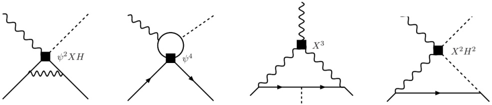
[1-loop: Alonso, Jenkins, Manohar, Trott '13]

$$\{\psi^2 XH, \psi^4, X^3, X^2H^2\} \xrightarrow[1Loop]{RGE} \psi^2 XH$$

Ex. of bound: [ACME]

$$\left|\mathrm{Im}\, C^{(3),eett}_{\ell equ}\right| \lesssim (3\times 10^5\ \mathrm{TeV})^{-2}$$

[■: possible vertices]



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$\{\psi^2 XH, \psi^4, X^3, X^2H^2\} \xrightarrow[1Loop]{RGE} \psi^2 XH$

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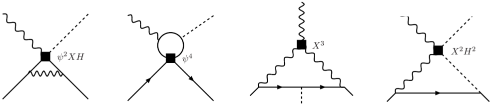
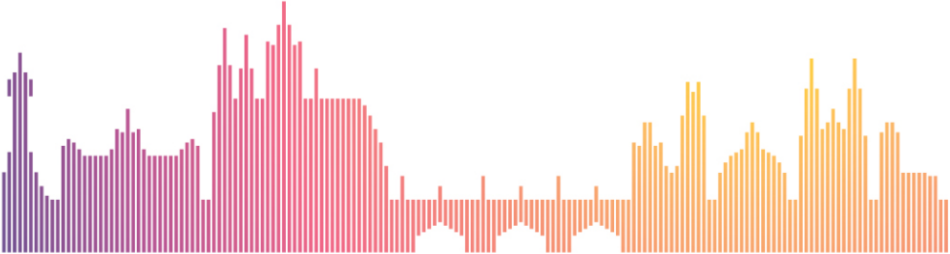


HERE: 4-fermion ops. for which $\gamma^{(1\text{-loop})}_{i,\psi^2 XH} = 0$ (i.e., no mix. at 1-loop)

→ Leading Order mixing with the dipole arriving at 2-loops

→ How flavour in non-dipoles feed into dipole operators

Outline



→ **Four-fermions**: only $Q^{(3)}_{\ell equ}$ mixes directly w/ dipoles at 1-loop

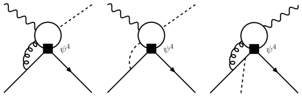
$$Q^{(1)}_{\ell equ} \xrightarrow[1Loop]{RGE} Q^{(3)}_{\ell equ} \xrightarrow[1Loop]{RGE} \psi^2 XH$$

LRLR operators

$$Q^{(1)}_{\ell equ}(prst) = (\bar\ell^j_p e_r)\epsilon_{jk}(\bar q^k_s u_t)$$
$$Q^{(3)}_{\ell equ}(prst) = (\bar\ell^j_p \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar q^k_s \sigma^{\mu\nu} u_t)$$
$$Q^{(1)}_{\ell\nu qd}(prst) = (\bar\ell^j_p \nu_r)\epsilon_{jk}(\bar q^k_s d_t)$$
$$Q^{(3)}_{\ell\nu qd}(prst) = (\bar\ell^j_p \sigma_{\mu\nu} \nu_r)\epsilon_{jk}(\bar q^k_s \sigma^{\mu\nu} d_t)$$

LRLR operators

$$Q_{\ell\nu\ell e}(prst) = (\bar\ell^j_p \nu_r)\epsilon_{jk}(\bar\ell^k_s e_t)$$
$$Q^{(1)}_{quqd}(prst) = (\bar q^j_p u_r)\epsilon_{jk}(\bar q^k_s d_t)$$
$$Q^{(8)}_{quqd}(prst) = (\bar q^j_p T^A u_r)\epsilon_{jk}(\bar q^k_s T^A d_t)$$



LRRL operators

$$Q_{\ell edq}(prst) = (\bar\ell_p e_t)(\bar d_s q_r)$$
$$Q_{\ell\nu uq}(prst) = (\bar\ell_p \nu_t)(\bar u_s q_r)$$

[Fierzed] LLRR operators

$$Q_{\ell e}(prst) = (\bar\ell_p e_t)(\bar e_s \ell_r)$$
$$Q_{\ell\nu}(prst) = (\bar\ell_p \nu_t)(\bar\nu_s \ell_r)$$
$$Q^{(1)}_{qu}(prst) = (\bar q^\alpha_p u^\beta_t)(\bar u^\beta_s q^\alpha_r)$$
$$Q^{(8)}_{qu}(prst) = (\bar q^\alpha_p T^A_{\alpha\tilde\alpha} u^{\tilde\beta}_t)(\bar u^\beta_s T^A_{\beta\tilde\beta} q^{\tilde\alpha}_r)$$
$$Q^{(1)}_{qd}(prst) = (\bar q^\alpha_p d^\beta_t)(\bar d^\beta_s q^\alpha_r)$$
$$Q^{(8)}_{qd}(prst) = (\bar q^\alpha_p T^A_{\alpha\tilde\alpha} d^{\tilde\beta}_t)(\bar d^\beta_s T^A_{\beta\tilde\beta} q^{\tilde\alpha}_r)$$

[Fierzed] LLRR operators

$$Q_{\ell u}(prst) = (\bar\ell_p u_t)(\bar u_s \ell_r)$$
$$Q_{\ell d}(prst) = (\bar\ell_p d_t)(\bar d_s \ell_r)$$
$$Q_{qe}(prst) = (\bar q_p e_t)(\bar e_s q_r)$$
$$Q_{q\nu}(prst) = (\bar q_p \nu_t)(\bar\nu_s q_r)$$

LLLL operators

$$Q_{\ell\ell}(prst) = (\bar\ell_p\gamma_\mu\ell_r)(\bar\ell_s\gamma^\mu\ell_t)$$
$$Q^{(1)}_{qq}(prst) = (\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$$
$$Q^{(3)}_{qq}(prst) = (\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$$
$$Q^{(1)}_{\ell q}(prst) = (\bar\ell_p\gamma_\mu\ell_r)(\bar q_s\gamma^\mu q_t)$$
$$Q^{(3)}_{\ell q}(prst) = (\bar\ell_p\gamma_\mu\tau^I\ell_r)(\bar q_s\gamma^\mu\tau^I q_t)$$

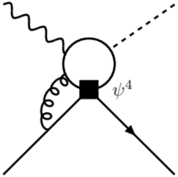
RRRR operators

$$Q_{ee}(prst) = (\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$$
$$Q_{\nu\nu}(prst) = (\bar\nu_p\gamma_\mu \nu_r)(\bar\nu_s\gamma^\mu \nu_t)$$
$$Q_{uu}(prst) = (\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$$
$$Q_{dd}(prst) = (\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$$
$$Q_{eu}(prst) = (\bar u_p\gamma^\mu u_r)(\bar e_s\gamma_\mu e_t)$$
$$Q_{ed}(prst) = (\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$$
$$Q_{\nu u}(prst) = (\bar\nu_p\gamma_\mu \nu_r)(\bar u_s\gamma^\mu u_t)$$
$$Q_{\nu d}(prst) = (\bar\nu_p\gamma_\mu \nu_r)(\bar d_s\gamma^\mu d_t)$$
$$Q_{e\nu}(prst) = (\bar\nu_p\gamma_\mu \nu_r)(\bar e_s\gamma^\mu e_t)$$
$$Q^{(1)}_{ud}(prst) = (\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$$
$$Q^{(8)}_{ud}(prst) = (\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$$
$$Q_{du\nu e}(prst) = (\bar d_p\gamma_\mu u_r)(\bar\nu_s\gamma^\mu e_t)$$

→ Focus on light external fermions: ☐ LRLR, ☐ LRRL, ☐ LRLR

→ ☐ 1-loop, ☐ main interest (preliminary), ☐ ongoing calculation

Mixing of four-fermion ops. into dipoles



Possible enhancements: large Yukawa, strong coupling, color factor

→ Analogous to Barr-Zee diagrams

→ Off-shell renormalization

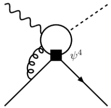
→ In the following: preliminary bounds from $\mu \to e\gamma$, EDMs

CP violation in quark dipoles

→ One-loop: $Q^{(1)}_{\ell equ}$, $Q^{(3)}_{\ell equ}$

→ Two-loop, y_t-enhancement: $Q^{(1)}_{qu}$, $Q^{(8)}_{qu}$, $Q^{(1)}_{quqd}$, $Q^{(8)}_{quqd}$

→ Two-loop: $Q^{(1)}_{qd}$, $Q^{(8)}_{qd}$, $Q_{\ell edq}$



$$(16\pi^2)^2 \frac{d}{d\ell n(\mu)} C_{\psi^2 XH}(\mu) = \left(g_Y^2 \gamma_Y^X + g_L^2 \gamma_L^X + g_C^2 \gamma_c^X + Y^2 \gamma^X \right) \times Y \times C_{\psi^4}(\mu)$$

$$Q^{(1)}_{qu} = (\bar{q}_p^\alpha u_t^\beta)(\bar{u}_s^\beta q_r^\alpha)$$

$$Q^{(8)}_{qu} = (\bar{q}_p^\alpha T^A_{\alpha\tilde{\alpha}} u_t^{\tilde{\beta}})(\bar{u}_s^\beta T^A_{\beta\tilde{\beta}} q_r^{\tilde{\alpha}})$$

ext → int ↓	$X = B$	$X = W$	$X = G$
γ_Y^X	$-\frac{1655}{6912}$	$+\frac{701}{2304}$	$+\frac{7}{72}$
γ_L^X	$+\frac{587}{768}$	$-\frac{923}{768}$	$+\frac{5}{8}$
γ_c^X	$-\frac{20}{9}$	$-\frac{4}{3}$	$+\frac{11}{3}$

ext → int ↓	$X = B$	$X = W$	$X = G$
γ_Y^X	$-\frac{1655}{1296}$	$+\frac{701}{432}$	$-\frac{679}{576}$
γ_L^X	$+\frac{587}{144}$	$-\frac{923}{144}$	$-\frac{935}{192}$
γ_c^X	$+\frac{\mathbf{760}}{\mathbf{27}}$	$+\frac{\mathbf{152}}{\mathbf{9}}$	$+\frac{\mathbf{446}}{\mathbf{9}}$

→ $X = G$: Chromo-Magnetic Dipole Moment

Quark EDMs, pheno

→ Electric Dipole Moment:

$$\mathcal{C}_{u\gamma}(\mu) \simeq \frac{1}{(16\pi^2)^2} \times \ell n\left(\frac{\Lambda^2}{\mu^2}\right) \times \mathrm{y_{top}} \times \left\{ C_{qu}^{(1)}(\Lambda)\left(-0.9 \times g_L^2 + 0.4 \times g_c^2\right) + C_{qu}^{(8)}(\Lambda)\left(-4.8 \times g_L^2 - 5.6 \times g_c^2\right) \right\}$$

→ Chromo-MDM generates a CPV πNN coupling [see, e.g., Pospelov, Ritz '05]

$$\mathcal{C}_{uG}(\mu) \simeq \frac{1}{(16\pi^2)^2} \times \ell n\left(\frac{\Lambda^2}{\mu^2}\right) \times \mathrm{y_{top}} \times \left\{ C_{qu}^{(1)}(\Lambda)\left(-0.3 \times g_L^2 - 1.8 \times g_c^2\right) + C_{qu}^{(8)}(\Lambda)\left(2.6 \times g_L^2 - 24.8 \times g_c^2\right) \right\}$$

	$y_{top} \times \lvert\mathrm{Im}\{\tilde{C}_{qu}^{(1)}(\Lambda)\}\rvert$	$y_{top} \times \lvert\mathrm{Im}\{\tilde{C}_{qu}^{(8)}(\Lambda)\}\rvert$
$\lvert d_N\rvert$	$\mathcal{O}(10^{-4})\,\mathrm{TeV}^{-2}$	$\mathcal{O}(10^{-5})\,\mathrm{TeV}^{-2}$
$\lvert d_{Hg}\rvert$	$\mathcal{O}(10^{-6})\,\mathrm{TeV}^{-2}$	$\mathcal{O}(10^{-7})\,\mathrm{TeV}^{-2}$

→ No tops below EW scale: effects only from mixing in SMEFT

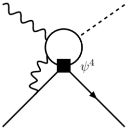
→ Wilson coefficients $\lesssim (700\ \mathrm{TeV})^{-2} - (3000\ \mathrm{TeV})^{-2}$

Charged lepton dipoles

eEDM, $\mu \to e\gamma$:

$\to$ One-loop: $Q^{(1)}_{\ell equ}$, $Q^{(3)}_{\ell equ}$

$\to$ Two-loop, y_τ, y_b-enhanced: $Q_{\ell e}$, $Q_{\ell edq}$



$$(16\pi^2)^2 \frac{d}{d\ell n(\mu)} C_{\psi^2 XH}(\mu) = \left(g_Y^2 \gamma_Y^X + g_L^2 \gamma_L^X + g_C^2 \gamma_c^X + Y^2 \gamma^X\right) \times Y \times C_{\psi^4}(\mu)$$

$$Q_{\ell e} = (\bar{\ell}_p e_t)(\bar{e}_s \ell_r) \qquad Q_{\ell edq} = (\bar{\ell}_p e_t)(\bar{d}_s q_r)$$

ext → int ↓	$X = B$	$X = W$	$X = G$
γ_Y^X	$+\frac{185}{256}$	$+\frac{331}{768}$	0
γ_L^X	$-\frac{249}{256}$	$-\frac{923}{768}$	0
γ_c^X	0	0	0

ext → int ↓	$X = B$	$X = W$	$X = G$
γ_Y^X	$-\frac{135}{256}$	$+\frac{619}{768}$	0
γ_L^X	$-\frac{345}{256}$	$-\frac{923}{768}$	0
γ_c^X	0	0	0

$$\mathcal{C}_{e\gamma}(\mu) \simeq \frac{1}{(16\pi^2)^2} \times \ell n\left(\frac{\Lambda^2}{\mu^2}\right) \times \{-0.2 \times C_{\ell e}(\Lambda) \times \mathbf{y}_\tau + 0.3 \times C_{\ell edq}(\Lambda) \times \mathbf{y_b}\} \times g_L^2$$

Charged lepton dipoles, pheno

Mixing below EW scale, e.g., $(\bar{\ell} P_L \ell')(\bar{f} P_R f)$, $\ell, \ell' = \mu, e$, $f = b, \tau$

[Estimate of RGE below EW scale: Crivellin, Davidson, Pruna, Signer '17]

eEDM: $Q_{\ell edq}$, $Q_{\ell e}$

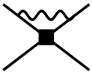
$$|\mathrm{Im}\{\tilde{C}^{eebb(,ee\tau\tau)}_{\ell edq(,\ell e)}(\Lambda)\}| \times y_{b(,\tau)} \lesssim \mathcal{O}(10^{-7})\,\mathrm{TeV}^{-2}$$

[Similar bounds found by Panico, Pomarol, Riembau '18]

$\mu \to e\gamma$: $Q_{\ell e}$

$$|\tilde{C}^{\mu e\tau\tau}_{\ell e}(\Lambda)| \times y_\tau \lesssim \mathcal{O}(10^{-5})\,\mathrm{TeV}^{-2}$$

$\mu \to e$ conversion in nuclei: $Q_{\ell edq}$, effect at 1-loop



Bound on $\tilde{C}^{\mu ebb}_{\ell edq}(\Lambda)$ stronger by a factor ~ 20 [Crivellin, Davidson, Pruna, Signer '17]

$\to$ Wilson coefficients $\lesssim (10\,\mathrm{TeV})^{-2} - (400\,\mathrm{TeV})^{-2}$

Summary

$\rightarrow$ 2-loops in many cases: better bounds than tree and 1-loop

[e.g., (semi-)leptonic, low-energy + LHC: Falkowski, González-Alonso, Mimouni '15 '17]

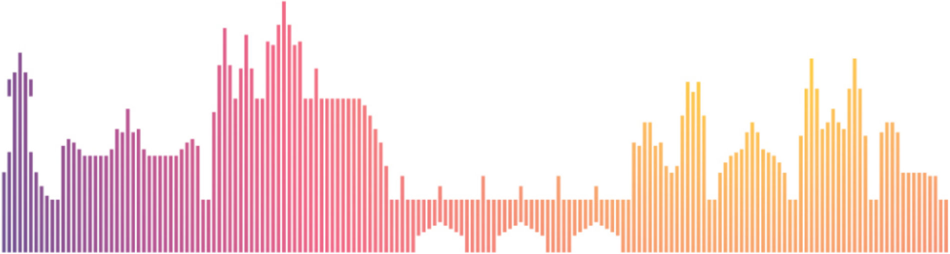
$$\psi^4 \xrightarrow[2Loop]{RGE} \psi^2 XH\text{, preliminary}$$

	Observable	Coupling	Bound
$Q_{qu}^{(1)}$	Hg-EDM	$y_{top} \times \lvert \mathrm{Im}[\tilde{C}_{qu}^{(1),uutt}(\Lambda)] \rvert$	$\lesssim \mathcal{O}(10^{-6})\ \mathrm{TeV}^{-2}$
$Q_{qu}^{(8)}$		$y_{top} \times \lvert \mathrm{Im}[\tilde{C}_{qu}^{(8),uutt}(\Lambda)] \rvert$	$\lesssim \mathcal{O}(10^{-7})\ \mathrm{TeV}^{-2}$
$Q_{\ell e}$	$\mu \to e\gamma$	$y_\tau \times \sqrt{\lvert \tilde{C}_{\ell e}^{e\mu\tau\tau}(\Lambda)\rvert^2 + \lvert \tilde{C}_{\ell e}^{\mu e\tau\tau}(\Lambda)\rvert}$	$\lesssim \mathcal{O}(10^{-5})\ \mathrm{TeV}^{-2}$
	eEDM	$y_\tau \times \lvert \mathrm{Im}[\tilde{C}_{\ell e}^{ee\tau\tau}(\Lambda)] \rvert$	$\lesssim \mathcal{O}(10^{-7})\ \mathrm{TeV}^{-2}$
$Q_{\ell edq}$	eEDM	$y_b \times \lvert \mathrm{Im}[\tilde{C}_{\ell edq}^{eebb}(\Lambda)] \rvert$	$\lesssim \mathcal{O}(10^{-7})\ \mathrm{TeV}^{-2}$
	$\mu \to e$ conv.	$y_b \times \sqrt{\lvert \tilde{C}_{\ell edq}^{e\mu bb}(\Lambda)\rvert^2 + \lvert \tilde{C}_{\ell edq}^{\mu ebb}(\Lambda)\rvert}$	(*1Loop*)

(ongoing analysis for further operators, channels, and couplings)

2-Loop effects set most important bounds in many cases

Outline



Conclusions

$\rightarrow$ Dipoles: probe very high energy scales, e.g., EDMs, $\mu \rightarrow e\gamma$, leading to a broad physics program

$\rightarrow$ **Generic tool** for improving our understanding of flavour and CPV

$\rightarrow$ SMEFT: systematic approach in the absence of new d.o.f. (so far)

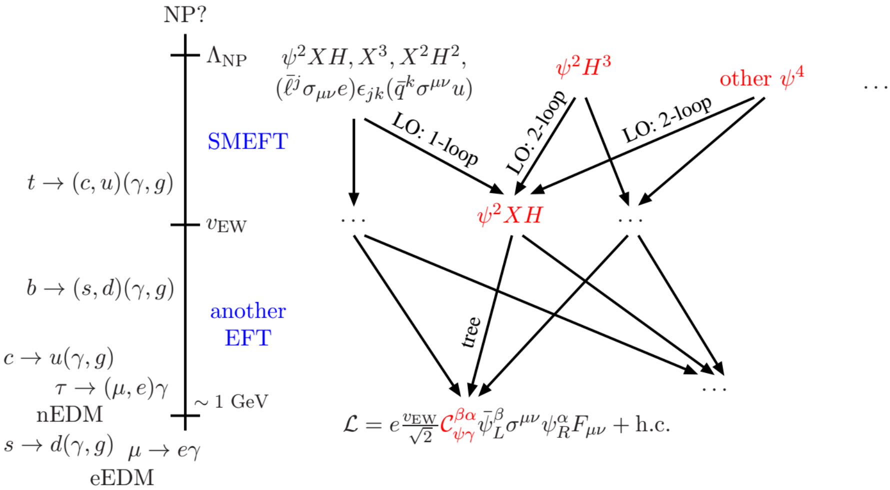
$\rightarrow$ Here: Leading-Order 2-loop effects generated by operator mixing

$\rightarrow$ Present measurements already allow strong bounds, future data will scrutinize even better the flavour structure of NP

Thanks! Díky! (luizva -*- ific.uv.es)

Backup

Roadmap to phenomenology



Basic formulas

$$\frac{dC^T}{d\ell n(\mu)} = -C^T \left(\frac{dZ}{d\ell n(\mu)} Z^{-1} - Z(\epsilon\Delta + \gamma_M N) Z^{-1} \right) \equiv C^T \gamma$$

for $\psi^2 H^3$: $\Delta = -3, n = 2$;
for ψ^4: $\Delta = -2, n = 2$;
for $g_X \psi^2 XH$: $\Delta = -1, n = 2$.

$$\mathcal{L}^{(6)}(\beta\alpha) = \Sigma_i M^{-2} \mu^{-\Delta_i \epsilon} [C_i(\mu)]^{\beta\alpha} [Q_i^{bare}]^{\beta\alpha} + \Sigma_{i,j,f,g} M^{-2} \mu^{-\Delta_j \epsilon} [C_i(\mu)]^{\beta\alpha} [(Z_{ij}^X - \delta_{ij})]^{\beta\alpha fg} [Q_j^{bare}]^{fg} + \ldots + \mathrm{h.c.}$$

$$Z^{X,\ \beta\alpha fg}_{\psi^2 H^3, g_X \psi^2 XH} = \Bigg[\left(\frac{g_Y^2}{(4\pi)^4} (Z_Y^X)_1^{(1)} + \frac{g_L^2}{(4\pi)^4} (Z_L^X)_1^{(1)} + \frac{g_c^2}{(4\pi)^4} (Z_c^X)_1^{(1)} + \frac{\lambda}{(4\pi)^4} (Z_\lambda^X)_1^{(1)} + \frac{\Sigma_{k,l} Y_{kl}^* \times Y_{lk}}{(4\pi)^4} (Z_{\mathrm{det}^2}^X)_1^{(1)} \right) \delta_{f\beta}\delta_{g\alpha} + \frac{\Sigma_l (Y^\dagger)_{fl} \times Y_{l\beta}}{(4\pi)^4} \delta_{g\alpha} (Z_{y,y}^X)_1^{(1)} + \frac{(Y^\dagger)_{g\beta} \times (Y^\dagger)_{\alpha f}}{(4\pi)^4} (Z_{Y,y}^X)_1^{(1)} + \frac{\Sigma_k Y_{\alpha k} \times (Y^\dagger)_{kg}}{(4\pi)^4} \delta_{f\beta} (Z_{Y,Y}^X)_1^{(1)} \Bigg] \frac{1}{\epsilon} + \ldots$$

$$\mathcal{B}(h \to e\mu) < 6.1 \times 10^{-5} \text{ (95\% CL)}$$ [Aad:2019ojw]

$$\mathcal{B}(h \to e\tau) < 4.7 \times 10^{-3} \text{ (95\% CL)}$$ [Aad:2019ugc]

$$\mathcal{B}(h \to \mu\tau) < 2.5 \times 10^{-3} \text{ (95\% CL)}$$ [Sirunyan:2017xzt]

$$\mathcal{B}(\mu \to e\gamma) < 4.2 \times 10^{-13} \text{ (90\% CL)}$$ [TheMEG:2016wtm]

$$\mathcal{B}(\tau \to e\gamma) < 3.3 \times 10^{-8} \text{ (90\% CL)}$$ [Aubert:2009ag]

$$\mathcal{B}(\tau \to \mu\gamma) < 4.4 \times 10^{-8} \text{ (90\% CL)}$$ [Aubert:2009ag]

$$\Delta a_e = a_e^{\rm exp} - a_e^{\rm SM} = -0.88(0.36) \times 10^{-12} \text{ @ } 1\sigma$$ [Parker:2018]

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 268(63)(43) \times 10^{-11} \text{ @ } 1\sigma$$ [Tanabashi:2018oca]

$$|d_e|/e < 1.1 \times 10^{-29} \text{ cm (90\% CL)}$$ [Andreev:2018ayy]

$$|d_\mu|/e < 1.8 \times 10^{-19} \text{ cm (95\% CL)}$$ [Bennett:2008dy, PDG]

$$d_\tau/e \in [-2.2, 4.5] \times 10^{-17} \text{ cm (95\% CL)}$$ [Inami:2002ah]

$$|d_N|/e < 1.8 \times 10^{-26} \text{ cm (90\% CL)}$$ [Abel:2020gbr]

$$|d_{\rm Hg}|/e < 7.4 \times 10^{-30} \text{ cm (95\% CL)}$$ [Graner:2016ses]

Summary $\psi^2 H^3$

$\psi^2 H^3 \xrightarrow[2Loop]{RGE} \psi^2 XH$, preliminary

Observable	Coupling	Bound
$\mu \to e\gamma$	$\sqrt{\lvert\tilde{C}_{eH}^{e\mu}(\Lambda)\rvert^2 + \lvert\tilde{C}_{eH}^{\mu e}(\Lambda)\rvert^2}$	$\lesssim 0.02 \times \frac{\sqrt{2m_e m_\mu}}{v_{\rm EW}^3}$
eEDM	$\lvert\mathrm{Im}[\tilde{C}_{eH}^{ee}(\Lambda)]\rvert$	$\lesssim 0.002 \times \frac{\sqrt{2}m_e}{v_{\rm EW}^3}$
$h \to e\tau$	$\sqrt{\lvert\tilde{C}_{eH}^{e\tau}\rvert^2 + \lvert\tilde{C}_{eH}^{\tau e}\rvert^2}$	(tree)
$h \to \mu\tau$	$\sqrt{\lvert\tilde{C}_{eH}^{\mu\tau}\rvert^2 + \lvert\tilde{C}_{eH}^{\tau\mu}\rvert^2}$	(tree)
$h \to ee$	$\lvert\tilde{C}_{eH}^{ee}\rvert$	(tree)
$h \to \mu\mu$	$\lvert\tilde{C}_{eH}^{\mu\mu}\rvert$	(tree)
nEDM	$\left\lvert\mathrm{Im}[\tilde{C}_{\psi H}^{\psi\psi}(\Lambda)]\right\rvert_{(\psi=u,d)}$	$\lesssim 3 \times \frac{\sqrt{2}m_d}{v_{\rm EW}^3}$
$\lvert\Delta q'\rvert, \lvert\Delta q\rvert = 2$ $(q, q' = u, d, s, c, b)$	$\lvert\tilde{C}_{\psi H}^{qq'}\rvert^2 + \lvert\tilde{C}_{\psi H}^{q'q}\rvert^2$	(tree)

2-Loop effects set most important bounds in many cases