

Probing the flavor of New Physics with dipoles

Luiz Vale Silva

University of Sussex

12 July, 2019



Work in collaboration with **S. Jäger** and **K. Leslie** (U. Sussex)
EPS - HEP2019, Ghent

Outline



- 1 Introduction
- 2 Quick overview of ren. of SMEFT
- 3 Dim. 6 corrections to Yukawa couplings
- 4 Conclusions

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Radiative processes

→ Low-energy dipole ops.: $\mathcal{L} = e \frac{\nu_{\text{EW}}}{\sqrt{2}} \mathcal{C}_{\psi\gamma}^{\beta\alpha} \bar{\psi}_\beta \sigma^{\mu\nu} P_R \psi_\alpha F_{\mu\nu} + \text{h.c.}$

→ Address the structure of flavor, sources of CP violation

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

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

→ Reach to NP scales:

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

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

$$\text{nEDM: } |\text{Im}[\mathcal{C}_{d\gamma}^{dd}]|, |\text{Im}[\mathcal{C}_{u\gamma}^{uu}]| \lesssim (2 \times 10^5 \text{ TeV})^{-2} \quad [\text{PRD92, 092003 (2015)}]$$

SMEFT way: NP sector much above EW scale

- Higher dimensional operators respecting SM local symmetries and containing SM d.o.f. only, suppressed by $\Lambda_{\text{NP}} \gg v_{\text{EW}}$
- Equations Of Motion (EOMs) eliminate redundant cases:
59 linearly independent operators of **dimension six**,
with 1350 CP-even + 1149 CP-odd couplings,
assuming SM global symmetries, B and L

Warsaw: $X^3, H^6, H^4 D^2, \psi^2 H^3, X^2 H^2, \psi^2 XH, \psi^2 H^2 D, \psi^4$

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

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

$\psi^2 XH$ class: $(\bar{q}\sigma^{\mu\nu}d)HB_{\mu\nu}, (\bar{q}\sigma^{\mu\nu}d)\tau^I HW_{\mu\nu}^I, (\bar{q}\sigma^{\mu\nu}T^A d)HG_{\mu\nu}^A$, etc.
[q (d) $SU(2)$ doublet (singlet)]

Probing non-dipole operators

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i C_i Q_i, \quad C_i \text{ scales as } \Lambda_{\text{NP}}^{-2}$$

Mixing with dipole:

$$16\pi^2 \frac{d}{d\ln(\mu)} C_{\psi^2 X H}(\mu) = \sum_i (C_{\psi^2 X H}, C_{\psi^4}, C_{X^3}, C_{X^2 H^2})_i(\mu) \gamma_{i, \psi^2 X H}^{(1\text{-loop})}$$

[Alonso, Jenkins, Manohar, Trott '13]

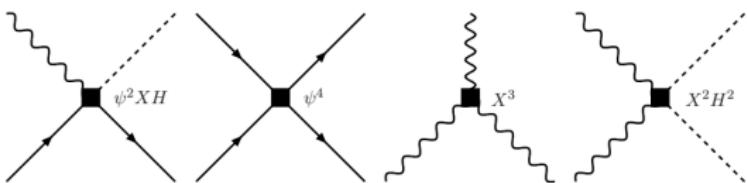
[Pruna, Signer '14; Davidson '16; Crivellin, Davidson, Pruna, Signer '17]

Ex. of bound:

[ACME]

$$\left| \frac{m_t}{m_e} \text{Im} C_{\ell equ}^{(3), eett} \right| \lesssim 3 \times 10^{-6} \text{ TeV}^{-2}$$

[■: possible vertices]



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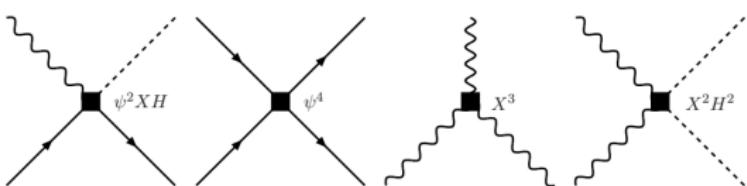
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HERE: Operators for which $\gamma_{i, \psi^2 X H}^{(1\text{-loop})} = 0$ (i.e., no mixing at 1-loop)
 \Rightarrow Leading Order mixing with the dipole arriving at 2-loops

Outline



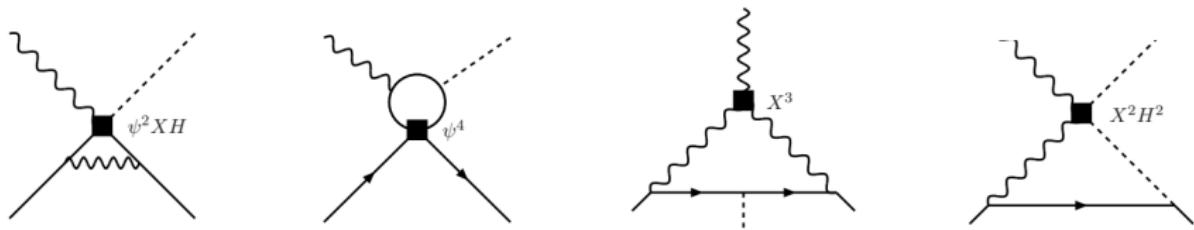
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(Off-shell) Renormalization of SM + dim.=6 ops.

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i C_i Q_i, \quad C_i \text{ scales as } \Lambda_{\text{NP}}^{-2}$$

$$\begin{aligned} \mathcal{L}_{\text{SM}} = & -\frac{1}{4} G_{\mu\nu}^A G^{A\mu\nu} - \frac{1}{4} W_{\mu\nu}^I W^{I\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + (D_\mu H^\dagger)(D^\mu H) + \sum_{\psi=q,u,d,\ell,e} \bar{\psi} i \not{D} \psi \\ & - \lambda \left(H^\dagger H - \frac{1}{2} v_{\text{EW}}^2 \right)^2 - \left[H^{\dagger j} \bar{d} Y_d q_j + \tilde{H}^{\dagger j} \bar{u} Y_u q_j + H^{\dagger j} \bar{\ell} Y_e \ell_j + \text{h.c.} \right] \end{aligned}$$

[plus gauge fixing and ghost terms]



Full set of local operators required in the renormalization program?

Full basis of operators

class \mathcal{O} : gauge-invariant operators, e.g., *Warsaw basis*

class \mathcal{A} : BRST-exact operators, i.e., $\mathcal{A} = \delta_{BRST} A'$

class \mathcal{B} : vanish via the equations of motion

$$\begin{pmatrix} [\mathcal{O}]^{\text{ren}} \\ [\mathcal{A}]^{\text{ren}} \\ [\mathcal{B}]^{\text{ren}} \end{pmatrix} = \begin{pmatrix} Z_{OO} & Z_{OA} & Z_{OB} \\ 0 & Z_{AA} & Z_{AB} \\ 0 & 0 & Z_{BB} \end{pmatrix} \begin{pmatrix} \mathcal{O} \\ \mathcal{A} \\ \mathcal{B} \end{pmatrix} \quad \begin{aligned} \langle 0 | T\{\mathcal{A}\Phi\} | 0 \rangle_{\text{on-shell}} &= 0 \\ \langle 0 | T\{\mathcal{B}\Phi\} | 0 \rangle_{\text{on-shell}} &= 0 \\ \Phi &\text{: set of local fields} \end{aligned}$$

[Dixon, Taylor '74; Kluberg-Stern, Zuber '75; Joglekar, Lee '76; Joglekar '77; Collins '84]

[cf. Herrlich, Nierste '96 for double insertions]

Non-phys. ops. are enumerated systematically by extending BRST

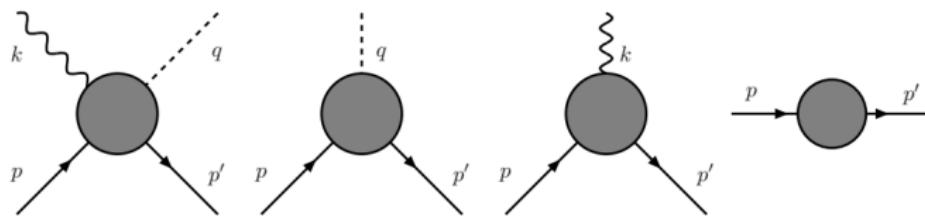
[Henneaux '93; Barnich, Brandt, Henneaux '00]

Ex. of gauge non-inv. structure from non-physical operators:

$$g_A [(\partial_\nu \bar{\psi}_L) \Gamma^{\mu\nu} t' \xi_R \varphi] A'_\mu, \dots$$

Mixing into dipole operators

Consider **all** operators Q that contribute to $\sum_Q Z_{OQ} \mathcal{G}_Q^{\text{tree}}(\cdot) = \mathcal{G}_O(\cdot)$



$\Rightarrow Z_{OQ} = \text{linear combination of } \mathcal{G}_O(\psi^2 A^\mu H), \mathcal{G}_O(\psi^2 H), \mathcal{G}_O(\psi^2 A^\mu), \mathcal{G}_O(\psi^2)$

$[\mathcal{G}_O: \text{Green's functions of single insertions of (bare) operator } O]$

[cf., e.g., Grinstein, Springer, Wise '88 on $b \rightarrow s\gamma$]

Again, we want to determine $Z_{O,\psi^2 XH}$ for O such that $\gamma_{O,\psi^2 XH}^{(1\text{-loop})} = 0$

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Renormalization of $\psi^2 H^3$ operators

→ Case we will be focusing upon: $\psi^2 H^3$,
generated in many concrete extensions of the SM

[Davidson '16; Panico, Pomarol, Riembau '18]

- 1-loop: $\psi^2 H^3$ mix only into $\psi^2 H$ (dim.=4), & $H^6, \psi^2 H^3$ (dim.=6)
- Mixing with the dipole: **Leading Order at 2-loops**

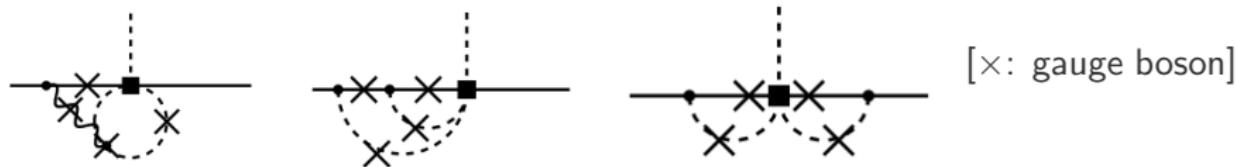
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- Mixing with the dipole: **Leading Order at 2-loops**

Ex. of diagrams necessary to determine the mixing with dipoles:



Neglecting Yukawa couplings: $Z_{\psi^2 H^3, \psi^2 \chi H} \stackrel{(-)}{\underset{1/\epsilon}{=}} \text{Coef.}[\mathcal{G}_{\psi^2 H^3}(\psi^2 A H), k \not{e}(k)]$

[Kinetic basis: $p \cdot \epsilon(k), p' \cdot \epsilon(k), k \cdot \epsilon(k), p \not{e}(k), p' \not{e}(k), k \not{e}(k)$]

Anomalous Dimension Matrix elements

Dipole: $g_X(\bar{\psi}_L \sigma^{\mu\nu} t^I \xi_R \varphi) X_{\mu\nu}^I, (q_L, u_R), (q_L, d_R), (\ell_L, e_R), (\ell_L, \nu_R)$

$$(16\pi^2)^2 \frac{d}{d\ln(\mu)} C_{\psi^2 X H}(\mu) = \left(g_Y^2 \gamma_Y^X + g_L^2 \gamma_L^X + g_C^2 \gamma_c^X + Y^2 \gamma^X \right) C_{\psi^2 H^3}(\mu)$$

	$X = B$	$X = W$	$X = G$
γ_Y^X	$3Q_\varphi^Y Q_\varphi^Y (Q_L^Y + Q_R^Y)$	$\frac{1}{2} Q_\varphi^Y (Q_L^Y + Q_R^Y)$	0
γ_L^X	$\frac{3}{4} Q_\varphi^Y$	$\frac{3}{8}$	0
γ_c^X	0	0	0

$$Q_\phi^Y = -Q_{\bar{\phi}}^Y = 1/2; Q_{\ell_L}^Y = -1/2, Q_{e_R}^Y = -1, Q_{\nu_R}^Y = 0; Q_{q_L}^Y = 1/6, Q_{u_R}^Y = +2/3, Q_{d_R}^Y = -1/3$$

γ^X : cases involving dim.=4 Yukawas Y given in the spare slides

Checks: arbitrary Feynman gauge ✓

independence of specific set of Green's functions ✓

Also, results agree with γ_Y^X, γ_L^X discussed by [Panico, Pomarol, Riembau '18]

Running of dipole Wilson coef.

$$\mathcal{L} = e \frac{v_{\text{EW}}}{\sqrt{2}} C_{\psi\gamma}^{\beta\alpha} \bar{\psi}_\beta \sigma^{\mu\nu} P_R \psi_\alpha F_{\mu\nu} + \text{h.c.}$$

$$\begin{aligned} C_{e\gamma} &= C_{g_Y e B} - C_{g_L e W}, & C_{d\gamma} &= C_{g_Y d B} - C_{g_L d W} \\ C_{\nu\gamma} &= C_{g_Y \nu B} + C_{g_L \nu W}, & C_{u\gamma} &= C_{g_Y u B} + C_{g_L u W} \end{aligned}$$

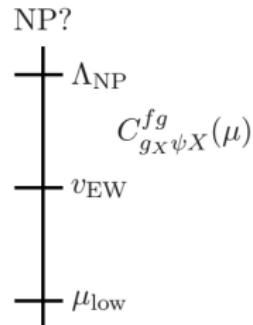
[ex. pheno: Crivellin, Najjari, Rosiek '13; Panico, Pomarol, Riembau '18]

Consider the pheno. of $C_{\psi H}^{fg}(\Lambda_{\text{NP}}) \neq 0$; and $C(\Lambda_{\text{NP}}) = 0$ otherwise

Solution of the RGE:

$$C_{g_X \psi X}^{fg}(\mu) = \cancel{C_{g_X \psi X}^{fg}(\Lambda_{\text{NP}})}$$

$$\begin{aligned} -\ell n \left(\frac{\Lambda_{\text{NP}}}{\mu} \right) \times C_{\psi H}^{fg}(\Lambda_{\text{NP}}) \times \left(\frac{g_Y^2}{(4\pi)^4} \gamma_Y^X + \frac{g_L^2}{(4\pi)^4} \gamma_L^X \right) \\ + (\text{sub-leading terms}) \end{aligned}$$



Tree-level constraints on $\psi^2 H^3$

$\psi^2 H^3$ changes couplings of the physical Higgs h :

$$\mathcal{L} = -\bar{u}' \textcolor{green}{M}_u u' - h \bar{u}' \textcolor{orange}{Y}_u u' + \dots$$

$$[\textcolor{green}{M}_\psi]_{ij} \simeq \frac{v_{\text{EW}}}{\sqrt{2}} \left([Y_\psi]_{ij} - \frac{1}{2} v_{\text{EW}}^2 [\textcolor{magenta}{C}_{\psi H}^\dagger]_{ij} \right),$$

$$[\textcolor{orange}{Y}_\psi]_{ij} \simeq \frac{1}{v_{\text{EW}}} [\textcolor{green}{M}_\psi]_{ij} - \frac{v_{\text{EW}}^2}{\sqrt{2}} [\textcolor{magenta}{C}_{\psi H}^\dagger]_{ij}, \quad \psi = u, d, e$$

- $\textcolor{blue}{M}_\psi$ combines the Wilson coefficients of $\psi^2 H$ and $\psi^2 H^3$
- **Meson-mixing** (K^0, D^0, B_d^0, B_s^0 systems) dominates constraints on s, c, b, t flavor-changing currents w.r.t. $s \rightarrow d\gamma, b \rightarrow (s, d)\gamma$, etc.

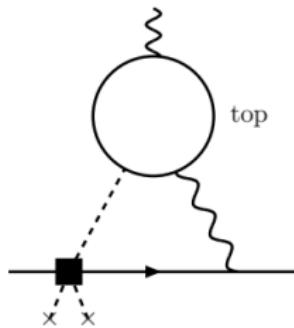
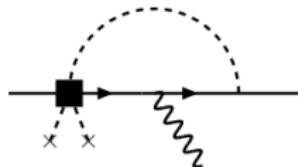
[cf., e.g., Harnik, Kopp, Zupan '12]

Finite parts of loop diagrams

→ Loop-induced **finite** effects from flavor violating Higgs couplings:

Ex. of Barr-Zee diagram:

Ex. of 1-loop diagram:



[cf. Barr, Zee '90; Harnik, Kopp, Zupan '12; Brod, Haisch, Zupan '13]

- By **avoiding a small Yukawa** coupling, 2-loop diagrams may (over) compensate for the loop-suppression
- Analogously, the **2-loop mixing-induced** effect will also be enhanced compared to 1-loop finite terms

Bounds from effects induced at 2-loop

→ Pheno. results, comparison with Barr-Zee ($\tilde{C}_{\psi H} = V_\psi^\dagger C_{\psi H}$):

$$\text{eEDM: } |\text{Im}[\tilde{C}_{eH}^{ee}(\Lambda_{\text{NP}})]| \lesssim 0.004 \times \frac{\sqrt{2}m_e}{v_{\text{EW}}^3}$$

[ACME]

$$\mu \rightarrow e\gamma: (|\tilde{C}_{eH}^{e\mu}(\Lambda_{\text{NP}})|^2 + (\mu \leftrightarrow e))^{1/2} \lesssim 0.1 \times \frac{\sqrt{2}m_e m_\mu}{v_{\text{EW}}^3}$$

[MEG]

$$\text{nEDM: } \left| \text{Im}[\tilde{C}_{\psi H}^{\psi\psi}(\Lambda_{\text{NP}})] \right|_{(\psi=u,d)} \lesssim 12 \times \frac{\sqrt{2}m_d}{v_{\text{EW}}^3}$$

[PRD92, 092003 (2015); theory: e.g., Pospelov, Ritz '05]

[Values for $\Lambda_{\text{NP}} = 1$ TeV, and $\mu = M_H$: further RGE corrections are omitted]

Bounds from effects induced at 2-loop

→ Pheno. results, comparison with Barr-Zee ($\tilde{C}_{\psi H} = V_\psi^\dagger C_{\psi H}$):

$$\text{eEDM: } |\text{Im}[\tilde{C}_{eH}^{ee}(\Lambda_{\text{NP}})]| \lesssim 0.004 \times \frac{\sqrt{2}m_e}{v_{\text{EW}}^3} \xrightarrow{\text{Barr-Zee}} 0.002 \times \frac{\sqrt{2}m_e}{v_{\text{EW}}^3}$$

[ACME]

$$\mu \rightarrow e\gamma: (|\tilde{C}_{eH}^{e\mu}(\Lambda_{\text{NP}})|^2 + (\mu \leftrightarrow e))^{1/2} \lesssim 0.1 \times \frac{\sqrt{2m_e m_\mu}}{v_{\text{EW}}^3} \xrightarrow{\text{Barr-Zee}} 0.02 \times \frac{\sqrt{2m_e m_\mu}}{v_{\text{EW}}^3}$$

[MEG]

$$\text{nEDM: } \left| \text{Im}[\tilde{C}_{\psi H}^{\psi\psi}(\Lambda_{\text{NP}})] \right|_{(\psi=u,d)} \lesssim 12 \times \frac{\sqrt{2}m_d}{v_{\text{EW}}^3} \xrightarrow{\text{Barr-Zee}} 3 \times \frac{\sqrt{2}m_d}{v_{\text{EW}}^3}$$

[PRD92, 092003 (2015); theory: e.g., Pospelov, Ritz '05]

[Values for $\Lambda_{\text{NP}} = 1$ TeV, and $\mu = M_H$: further RGE corrections are omitted]

→ Enhancements in the **finite** corrections (such as $N_c = 3$) compared to **mixing**-induced effects (for which $\gamma^X \sim 1/4$)

Renormalization of four-fermion ops.

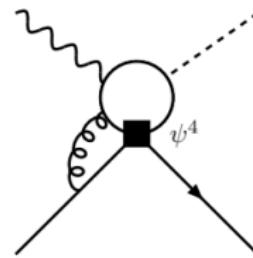
- **Four-fermions:** only $Q_{\ell equ}^{(3)}$ mixes directly w/ the dipole at 1-loop
- **Ongoing** analysis of four-fermion operators mixing into dipoles

eEDM: $Q_{\ell equ}^{(1)}, Q_{\ell equ}^{(3)}; Q_{\ell edq}, Q_{\ell e}$

$$|\text{Im } C_{\ell edq, \ell e}^{eett}| \lesssim 10^{-5}, 10^{-6} \text{ TeV}^{-2}$$

[eEDM: Panico, Pomarol, Riembau '18]

nEDM: $Q_{\ell equ}^{(1)}, Q_{\ell equ}^{(3)}; Q_{qu}^{(1)}, Q_{qu}^{(8)},$
 $Q_{qd}^{(1)}, Q_{qd}^{(8)}, Q_{quqd}^{(1)}, Q_{quqd}^{(8)}, Q_{\ell edq}$



Possible enhancements: color factor,
large Yukawa, strong coupling

- Analogously to Barr-Zee type of contributions: top in loops
- Typically, Wilson coefficients $< \mathcal{O}(0.1) \text{ TeV}^{-2}$ **w/o** considering **mixing with dipoles**

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

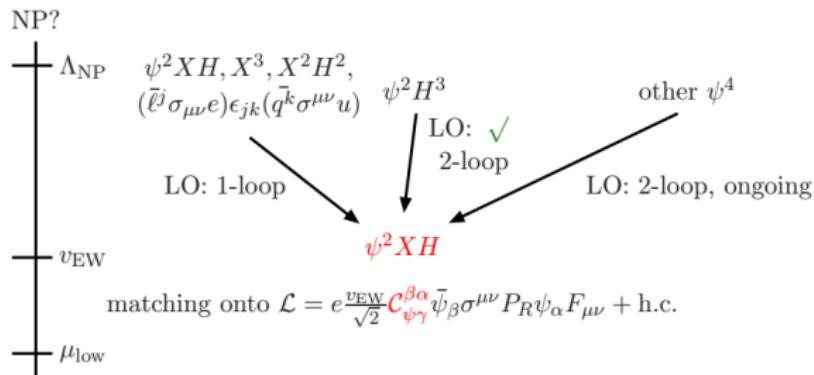
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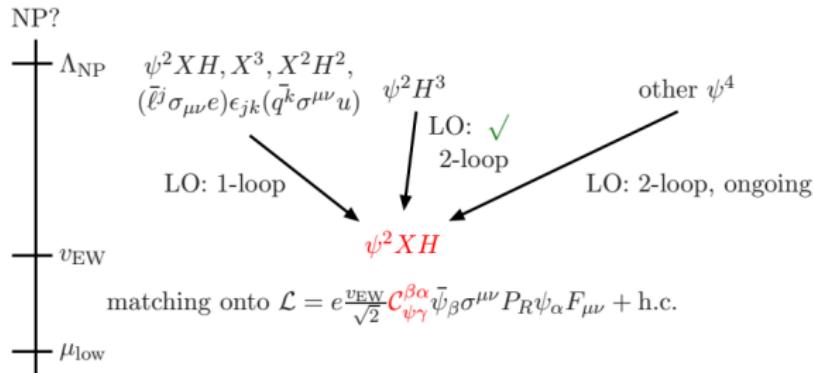
Conclusions

- Dipoles: probe very high energy scales, e.g., EDM, $\mu \rightarrow e\gamma$
- **Generic tool** for improving our understanding of flavor and CPV
- SMEFT: **systematic approach** in the absence of new d.o.f. (so far)
- Finite contributions dominate bounds on $\psi^2 H^3$ Wilson coef.



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Thanks!



Extended BRST-variation

- Extend BRST-variation to “anti-fields”; $\delta_{BRST} = \delta + \gamma$ increases the mass power counting and the ghost number by one unit
- Consider all polynomials of dim. ≤ 5 , and ghost number -1

Z	δZ	γZ
A_μ^I	0	$D_\mu C^I$
ξ^i	0	$-eC^I T_{lj}^i \xi^j$
C^I	0	$\frac{1}{2} e f_{KJ}^I C^K C^K$
C_I^\dagger	$-D_\mu A_I^{\dagger\mu} - e \xi_i^\dagger T_{lj}^i \xi^j$	$e f_{JI}^K C^J C_K^\dagger$
$A_I^{\dagger\mu}$	L_I^μ	$e f_{JI}^K C^J A_K^{\dagger\mu}$
ξ_i^\dagger	L_i	$e C^I \xi_j^\dagger T_{li}^j$

$D_\mu C^I = \partial_\mu C^I + e f_{JK}^I A_\mu^J C^K$, $D_\mu A_I^{\dagger\mu} = \partial_\mu A_I^{\dagger\mu} - e f_{JI}^K A_\mu^J A_K^{\dagger\mu}$, and $L_I^\mu = \frac{\delta L}{\delta A_\mu^I}$,

$L_i = (-1)^{\epsilon_i} \frac{\delta L}{\delta \xi^i}$, where L is the action.

The field ξ designates a fermion or a scalar.

[Batalin-Vilkovisky; Henneaux '93; Collins, Scalise '94; Barnich, Brandt, Henneaux '00]

Some calculation aspects

$\int f[\text{internal momenta } q, \text{ external momenta } p, \text{ masses } M]$

Expansion in external momenta for simplifying integrals:

$$\underbrace{\frac{1}{(q+p)^2 - M^2}}_{\text{sup. deg. of div. +2}} \stackrel{\text{exact}}{=} \underbrace{\frac{1}{q^2 - m_R^2}}_{\text{sup. deg. of div. +2}} + \underbrace{\frac{M^2 - p^2 - 2q \cdot p - m_R^2}{q^2 - m_R^2}}_{\text{sup. deg. of div. +3}} \underbrace{\frac{1}{(q+p)^2 - M^2}}_{\text{sup. deg. of div. +3}}$$

[Chetyrkin, Misiak, Münz '97; Gambino, Gorbahn, Haisch '03; Zoller '14]

Basic formulas

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

for $\psi^2 H^3$: $\Delta = -3, n = 2$;

for ψ^4 : $\Delta = -2, n = 2$;

for $g\psi^2 XH$: $\Delta = -1, n = 2$.

$$\begin{aligned} \mathcal{L}^{(6)}(\beta\alpha) &= \sum_i M^{-2} \mu^{-\Delta_i \epsilon} [C_i(\mu)]^{\beta\alpha} [Q_i^{\text{bare}}]^{\beta\alpha} \\ &+ \sum_{i,j,f,g} M^{-2} \mu^{-\Delta_j \epsilon} [C_i(\mu)]^{\beta\alpha} [(Z_{ij}^X - \delta_{ij})]^{\beta\alpha fg} [Q_j^{\text{bare}}]^{fg} + \dots + \text{h.c.} \end{aligned}$$

$$\begin{aligned} Z_{\psi^2 H^3, g\psi^2 XH}^{X, \beta\alpha fg} &= \left[\left(\frac{g_Y^2}{(4\pi)^4} (Z_Y^X)_1^{(1)} + \frac{g_L^2}{(4\pi)^4} (Z_L^X)_1^{(1)} + \frac{g_C^2}{(4\pi)^4} (Z_c^X)_1^{(1)} + \frac{\lambda}{(4\pi)^4} (Z_\lambda^X)_1^{(1)} + \frac{\Sigma_{k,I} Y_{kl}^* \times Y_{lk}}{(4\pi)^4} (Z_{\det 2}^X)_1^{(1)} \right) \delta_{f\beta} \delta_{g\alpha} \right. \\ &\quad \left. + \frac{\Sigma_I (Y^\dagger)_f \times Y_{I\beta}}{(4\pi)^4} \delta_{g\alpha} (Z_{y,y}^X)_1^{(1)} + \frac{(Y^\dagger)_{g\beta} \times (Y^\dagger)_{\alpha f}}{(4\pi)^4} (Z_{Y,y}^X)_1^{(1)} + \frac{\Sigma_k Y_{\alpha k} \times (Y^\dagger)_{kg}}{(4\pi)^4} \delta_{f\beta} (Z_{Y,Y}^X)_1^{(1)} \right] \frac{1}{\epsilon} + \dots \end{aligned}$$

Dipole: $g_X(\bar{\psi}_L \sigma^{\mu\nu} t^I \xi_R \varphi) X_{\mu\nu}^I$, $(q_L, u_R), (q_L, d_R), (\ell_L, e_R), (\ell_L, \nu_R)$

	$X = B$	$X = W$	$X = G$
$(Z_Y^X)_1^{(1)}$	$\frac{3}{4} Q_\varphi^Y Q_\varphi^Y (Q_L^Y + Q_R^Y)$	$\frac{1}{8} Q_\varphi^Y (Q_L^Y + Q_R^Y)$	0
$(Z_L^X)_1^{(1)}$	$\frac{3}{16} Q_\varphi^Y$	$\frac{3}{32}$	0
$(Z_c^X)_1^{(1)}$	0	0	0
$(Z_\lambda^X)_1^{(1)}$	0	0	0
$(Z_{y,y}^X)_1^{(1)}$	$\frac{1}{16}(5 Q_L^Y + Q_R^Y)$	$\frac{1}{32}$	$\frac{3}{8}$
$(Z_{Y,y}^X)_1^{(1)}$	0	0	0
$(Z_{Y,Y}^X)_1^{(1)}$	$\frac{1}{16}(Q_L^Y + 5 Q_R^Y)$	$\frac{1}{96}$	$\frac{3}{8}$
$(Z_{\det^2}^X)_1^{(1)}$	0	0	0

$$Q_\phi^Y = -Q_{\tilde{\phi}}^Y = 1/2; Q_{\ell_L}^Y = -1/2, Q_{e_R}^Y = -1, Q_{\nu_R}^Y = 0; Q_{q_L}^Y = 1/6, Q_{u_R}^Y = +2/3, Q_{d_R}^Y = -1/3$$

Channel	Coupling	Bound
$\mu \rightarrow e\gamma$	$\sqrt{ Y_{\mu e} ^2 + Y_{e\mu} ^2}$	$< \boxed{0.63} \times 10^{-6}$
$\mu \rightarrow 3e$	$\sqrt{ Y_{\mu e} ^2 + Y_{e\mu} ^2}$	$\lesssim 3.1 \times 10^{-5}$
electron $g - 2$	$\text{Re}(Y_{e\mu} Y_{\mu e})$	$\boxed{-0.0022 \dots -0.0009}$
electron EDM	$ \text{Im}(Y_{e\mu} Y_{\mu e}) $	$< \boxed{0.10} \times 10^{-8}$
$\mu \rightarrow e$ conversion	$\sqrt{ Y_{\mu e} ^2 + Y_{e\mu} ^2}$	$< 1.2 \times 10^{-5}$
$M - \tilde{M}$ oscillations	$ Y_{\mu e} + Y_{e\mu}^* $	< 0.079
$\tau \rightarrow e\gamma$	$\sqrt{ Y_{\tau e} ^2 + Y_{e\tau} ^2}$	< 0.014
$\tau \rightarrow 3e$	$\sqrt{ Y_{\tau e} ^2 + Y_{e\tau} ^2}$	$\lesssim 0.12$
electron $g - 2$	$\text{Re}(Y_{e\tau} Y_{\tau e})$	$\boxed{-0.24 \dots -0.10} \times 10^{-3}$
electron EDM	$ \text{Im}(Y_{e\tau} Y_{\tau e}) $	$< \boxed{0.01} \times 10^{-8}$
$\tau \rightarrow \mu\gamma$	$\sqrt{ Y_{\tau\mu} ^2 + Y_{\mu\tau} ^2}$	0.016
$\tau \rightarrow 3\mu$	$\sqrt{ Y_{\tau\mu}^2 + Y_{\mu\tau} ^2}$	$\lesssim 0.25$
muon $g - 2$	$\text{Re}(Y_{\mu\tau} Y_{\tau\mu})$	$(\boxed{2.5} \pm \boxed{0.71}) \times 10^{-3}$
muon EDM	$ \text{Im}(Y_{\mu\tau} Y_{\tau\mu}) $	$-0.8 \dots 1.0$
$\mu \rightarrow e\gamma$	$((Y_{\tau\mu} Y_{\mu\tau} ^2 + Y_{\mu\tau} Y_{\tau\mu} ^2)^{1/4}$	$< \boxed{0.60} \times 10^{-4}$
neutron EDM [37, 52]	$ \text{Im}(Y_{ut} Y_{tu}) $	$< \boxed{4.4} \times 10^{-7}$
	$ \text{Im}(Y_{ct} Y_{tc}) $	$< \boxed{5.2} \times 10^{-4}$

[Table adapted from Harnik, Kopp, Zupan '12]

$$\mathcal{B}(h \rightarrow \ell\ell') @ 95\% \text{ CL:}$$

$$\sqrt{|\tilde{C}_{eH}^{e\mu}|^2 + |\tilde{C}_{eH}^{\mu e}|^2} < 1.3 \times 10^{-2} \text{ TeV}^{-2}$$

$$\sqrt{|\tilde{C}_{eH}^{e\tau}|^2 + |\tilde{C}_{eH}^{\tau e}|^2} < 5.6 \times 10^{-2} \text{ TeV}^{-2}$$

$$\sqrt{|\tilde{C}_{eH}^{\mu\tau}|^2 + |\tilde{C}_{eH}^{\tau\mu}|^2} < 8.1 \times 10^{-2} \text{ TeV}^{-2}$$

$$Y_{ij}^{HKZ} \rightarrow -\frac{v_{EW}^2}{\sqrt{2}} [\tilde{C}^\dagger]_{ij}$$

$$\mathcal{B}(h \rightarrow e\mu) < 3.5 \times 10^{-4} \text{ (95% CL)} \quad [\text{Khachatryan:2016rke}]$$

$$\mathcal{B}(h \rightarrow e\tau) < 6.9 \times 10^{-3} \text{ (95% CL)} \quad [\text{Khachatryan:2016rke}]$$

$$\mathcal{B}(h \rightarrow \mu\tau) < 1.43\% \text{ (95% CL)} \quad [\text{Aad:2016blu}]$$

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

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

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

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

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

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

$$|d_\mu|/e < 1.9 \times 10^{-19} \text{ cm (95% CL)} \quad [\text{Bennett:2008dy}]$$

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

$$|d_N|/e < 3.0 \times 10^{-26} \text{ cm (90% CL)} \quad [\text{Afach:2015sja}]$$