Effective Field Theories for Physics Beyond the Standard Model. Lecture 2

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SM Summary

$$\mathcal{L}_{SM} = \bar{q}_L i\gamma^\mu D_\mu q_L + \bar{\ell}_L i\gamma^\mu D_\mu \ell_L + \bar{u}_R i\gamma^\mu D_\mu u_R + \bar{d}_R i\gamma^\mu D_\mu d_R + \bar{e}_R i\gamma^\mu D_\mu e_R$$
$$- \frac{1}{4} G^{a\mu\nu} G^a_{\mu\nu} - \frac{1}{4} \mathbf{W}_{\mu\nu} \cdot \mathbf{W}^{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} + (D_\mu \varphi)^\dagger D_\mu \varphi - V(\varphi^\dagger \varphi)$$
$$- Y_d \delta^{jk} \bar{q}^j_L \varphi^k d_R - Y_u \varepsilon^{jk} \bar{q}^j_L (\varphi^k)^\dagger u_R - Y_e \varepsilon^{jk} \bar{\ell}^j_L (\varphi^k)^\dagger e_R + \bar{\theta} \frac{g_s^2}{64\pi^2} \varepsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma} \,,$$

2. very small CP-violation in $\Delta F = 0$ observables

   no EDM, no baryogenesis (see Observational Tests of Antimatter Cosmologies; A matter-antimatter Universe)

3. quark flavor: no flavor changing neutral currents at tree level

   K-$\bar{K}$ oscillations, B-$\bar{B}$ oscillations, $B \to X_s\gamma$, $K \to \pi\nu\nu$

   suppressed by loop factors and masses or CKM factors

4. L and B: lepton and baryon number are conserved (in perturbation theory)

   no $0\nu\beta\beta$, no proton decay

5. lepton flavor is conserved

   no $e \to \tau$, $e \to \mu$, $\mu \to \tau$ transitions

6. neutrinos are massless

The Standard Model EFT

The Standard Model EFT

- SMEFT is the generalization of the SM to include $d > 4$ operators
- the most important are a $d = 5$ operator, the "Weinberg operator"

  S. Weinberg, '79
- and the set of $d = 6$ operators

  W. Buchmuller, D. Wyler '85, B. Grzadkowski *et al* '10.
- the construction has been pushed to $d = 8$ in the lepton-number conserving sector,

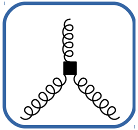
  B. Henning *et al* '15, C. Murphy, '20, H.-L. Li *et al*, '20,

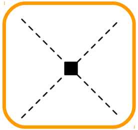
  and $d = 9$ in the lepton-number breaking sector

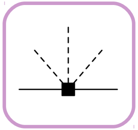
  H.-L. Li *et al*, '20, Y. Liao and X.-D. Ma, '22.
- the theory is renormalizable order by order in $1/\Lambda$
  $\Longrightarrow$ we need only a finite number of operators to make predictions that are accurate at $\mathcal{O}(1/\Lambda^n)$

The Standard Model EFT at dim-6

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$







B. Grzadkowski *et al* '10

- 3 gauge bosons: modify 3- and 4-boson interactions, with new CP-violation

  $e^+e^- \to W^+W^-$, $pp \to VV$, EDMs, ...
- 4 scalars: corrections to the Higgs potential and self-couplings
- 3 scalars and 2 fermions: break the correspondence between fermion masses and Yukawas

  $pp \to t\bar tH$, $H \to b\bar b$, ...

The Standard Model EFT at dim-6

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
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$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
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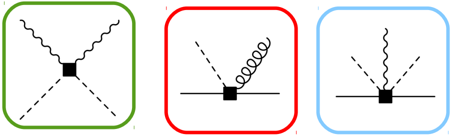


B. Grzadkowski *et al* ‘10

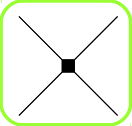
- 2 gauge and 2 scalars: corrections to electroweak precision and Higgs couplings
- 2 fermions, 1 scalar, 1 gauge: dipole operators
- 2 fermions, 2 scalars: corrections to *W* and *Z* couplings

electroweak precision, β decays and flavor physics

The Standard Model EFT at dim-6

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

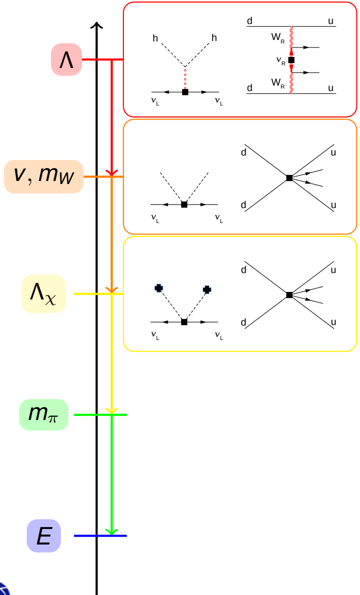


B. Grzadkowski *et al* ‘10

- in total 2499 *B*-conserving coefficients, 1149 CP-odd (for 3 generations of fermions)
- most of these coefficients in the 4-fermion sector

some symmetries (*B*) or almost symmetries (*CP* and flavor) of the SM are *accidental*
no symmetry breaking dim-4 operator, but easy to write higher dimensional ops.

Matching and running to low energy



new physics $\Lambda \gg v$

SMEFT operators

$SU(3)_c \times U(1)_{\rm em}$ operators

The Low-energy EFT

- the relevant scales for low-energy processes is $Q \lesssim 1$ GeV, much smaller than EW scale,
- we can switch from SMEFT to the "Low-energy EFT" (LEFT):

1. degrees of freedom: u, d, s quarks; e, μ and ν_ℓ leptons; photons and gluons;
2. symmetries: $SU(3)_c \times U(1)_{\rm em}$ (electroweak symmetry no longer manifest);
4. power counting:

- integrate out W, Z, H and t at the electroweak scale

power expansion in Q/v

- integrate out the b and c quarks, and the τ lepton, at their thresholds

power expansion in Q/m_ψ

- triple expansion in v/Λ, Q/m_W, Q/m_ψ

The Low-energy EFT

3. interactions: dipole and 4-fermions (+ QED and QCD)

$\nu\nu + \text{h.c.}$	
$\mathcal{O}_\nu$	$(\nu_{Lp}^T C \nu_{Lr})$

$(\nu\nu)X + \text{h.c.}$	
$\mathcal{O}_{\nu\gamma}$	$(\nu_{Lp}^T C \sigma^{\mu\nu} \nu_{Lr}) F_{\mu\nu}$

$(\overline{L}R)X + \text{h.c.}$	
$\mathcal{O}_{e\gamma}$	$\bar{e}_{Lp}\sigma^{\mu\nu} e_{Rr} F_{\mu\nu}$
$\mathcal{O}_{u\gamma}$	$\bar{u}_{Lp}\sigma^{\mu\nu} u_{Rr} F_{\mu\nu}$
$\mathcal{O}_{d\gamma}$	$\bar{d}_{Lp}\sigma^{\mu\nu} d_{Rr} F_{\mu\nu}$
$\mathcal{O}_{uG}$	$\bar{u}_{Lp}\sigma^{\mu\nu} T^A u_{Rr} G^A_{\mu\nu}$
$\mathcal{O}_{dG}$	$\bar{d}_{Lp}\sigma^{\mu\nu} T^A d_{Rr} G^A_{\mu\nu}$

X^3	
$\mathcal{O}_G$	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$

$(\overline{L}L)(\overline{L}L)$	
$\mathcal{O}_{\nu\nu}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu \nu_{Lr})(\bar{\nu}_{Ls}\gamma_\mu \nu_{Lt})$
$\mathcal{O}_{ee}^{V,LL}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{e}_{Ls}\gamma_\mu e_{Lt})$
$\mathcal{O}_{\nu e}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu \nu_{Lr})(\bar{e}_{Ls}\gamma_\mu e_{Lt})$
$\mathcal{O}_{\nu u}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu \nu_{Lr})(\bar{u}_{Ls}\gamma_\mu u_{Lt})$
$\mathcal{O}_{\nu d}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu \nu_{Lr})(\bar{d}_{Ls}\gamma_\mu d_{Lt})$
$\mathcal{O}_{eu}^{V,LL}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{u}_{Ls}\gamma_\mu u_{Lt})$
$\mathcal{O}_{ed}^{V,LL}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{d}_{Ls}\gamma_\mu d_{Lt})$
$\mathcal{O}_{\nu edu}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu e_{Lr})(\bar{d}_{Ls}\gamma_\mu u_{Lt}) + \text{h.c.}$
$\mathcal{O}_{uu}^{V,LL}$	$(\bar{u}_{Lp}\gamma^\mu u_{Lr})(\bar{u}_{Ls}\gamma_\mu u_{Lt})$
$\mathcal{O}_{dd}^{V,LL}$	$(\bar{d}_{Lp}\gamma^\mu d_{Lr})(\bar{d}_{Ls}\gamma_\mu d_{Lt})$
$\mathcal{O}_{ud}^{V1,LL}$	$(\bar{u}_{Lp}\gamma^\mu u_{Lr})(\bar{d}_{Ls}\gamma_\mu d_{Lt})$
$\mathcal{O}_{ud}^{V8,LL}$	$(\bar{u}_{Lp}\gamma^\mu T^A u_{Lr})(\bar{d}_{Ls}\gamma_\mu T^A d_{Lt})$

$(\overline{R}R)(\overline{R}R)$	
$\mathcal{O}_{ee}^{V,RR}$	$(\bar{e}_{Rp}\gamma^\mu e_{Rr})(\bar{e}_{Rs}\gamma_\mu e_{Rt})$
$\mathcal{O}_{eu}^{V,RR}$	$(\bar{e}_{Rp}\gamma^\mu e_{Rr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$
$\mathcal{O}_{ed}^{V,RR}$	$(\bar{e}_{Rp}\gamma^\mu e_{Rr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{uu}^{V,RR}$	$(\bar{u}_{Rp}\gamma^\mu u_{Rr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$
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$\mathcal{O}_{ud}^{V1,RR}$	$(\bar{u}_{Rp}\gamma^\mu u_{Rr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{ud}^{V8,RR}$	$(\bar{u}_{Rp}\gamma^\mu T^A u_{Rr})(\bar{d}_{Rs}\gamma_\mu T^A d_{Rt})$

$(\overline{L}L)(\overline{R}R)$	
$\mathcal{O}_{\nu e}^{V,LR}$	$(\bar{\nu}_{Lp}\gamma^\mu \nu_{Lr})(\bar{e}_{Rs}\gamma_\mu e_{Rt})$
$\mathcal{O}_{ee}^{V,LR}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{e}_{Rs}\gamma_\mu e_{Rt})$
$\mathcal{O}_{\nu u}^{V,LR}$	$(\bar{\nu}_{Lp}\gamma^\mu \nu_{Lr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$
$\mathcal{O}_{\nu d}^{V,LR}$	$(\bar{\nu}_{Lp}\gamma^\mu \nu_{Lr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{eu}^{V,LR}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$
$\mathcal{O}_{ed}^{V,LR}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{ue}^{V,LR}$	$(\bar{u}_{Lp}\gamma^\mu u_{Lr})(\bar{e}_{Rs}\gamma_\mu e_{Rt})$
$\mathcal{O}_{de}^{V,LR}$	$(\bar{d}_{Lp}\gamma^\mu d_{Lr})(\bar{e}_{Rs}\gamma_\mu e_{Rt})$
$\mathcal{O}_{\nu edu}^{V,LR}$	$(\bar{\nu}_{Lp}\gamma^\mu e_{Lr})(\bar{d}_{Rs}\gamma_\mu u_{Rt}) + \text{h.c.}$
$\mathcal{O}_{uu}^{V1,LR}$	$(\bar{u}_{Lp}\gamma^\mu u_{Lr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$
$\mathcal{O}_{uu}^{V8,LR}$	$(\bar{u}_{Lp}\gamma^\mu T^A u_{Lr})(\bar{u}_{Rs}\gamma_\mu T^A u_{Rt})$
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$\mathcal{O}_{ud}^{V8,LR}$	$(\bar{u}_{Lp}\gamma^\mu T^A u_{Lr})(\bar{d}_{Rs}\gamma_\mu T^A d_{Rt})$
$\mathcal{O}_{du}^{V1,LR}$	$(\bar{d}_{Lp}\gamma^\mu d_{Lr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$
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$\mathcal{O}_{dd}^{V8,LR}$	$(\bar{d}_{Lp}\gamma^\mu T^A d_{Lr})(\bar{d}_{Rs}\gamma_\mu T^A d_{Rt})$
$\mathcal{O}_{uddu}^{V1,LR}$	$(\bar{u}_{Lp}\gamma^\mu d_{Lr})(\bar{d}_{Rs}\gamma_\mu u_{Rt}) + \text{h.c.}$
$\mathcal{O}_{uddu}^{V8,LR}$	$(\bar{u}_{Lp}\gamma^\mu T^A d_{Lr})(\bar{d}_{Rs}\gamma_\mu T^A u_{Rt}) + \text{h.c.}$

$(\overline{L}R)(\overline{L}R) + \text{h.c.}$	
$\mathcal{O}_{ee}^{S,RR}$	$(\bar{e}_{Lp} e_{Rr})(\bar{e}_{Ls} e_{Rt})$
$\mathcal{O}_{eu}^{S,RR}$	$(\bar{e}_{Lp} e_{Rr})(\bar{u}_{Ls} u_{Rt})$
$\mathcal{O}_{eu}^{T,RR}$	$(\bar{e}_{Lp}\sigma^{\mu\nu} e_{Rr})(\bar{u}_{Ls}\sigma_{\mu\nu} u_{Rt})$
$\mathcal{O}_{ed}^{S,RR}$	$(\bar{e}_{Lp} e_{Rr})(\bar{d}_{Ls} d_{Rt})$
$\mathcal{O}_{ed}^{T,RR}$	$(\bar{e}_{Lp}\sigma^{\mu\nu} e_{Rr})(\bar{d}_{Ls}\sigma_{\mu\nu} d_{Rt})$
$\mathcal{O}_{\nu edu}^{S,RR}$	$(\bar{\nu}_{Lp} e_{Rr})(\bar{d}_{Ls} u_{Rt})$
$\mathcal{O}_{\nu edu}^{T,RR}$	$(\bar{\nu}_{Lp}\sigma^{\mu\nu} e_{Rr})(\bar{d}_{Ls}\sigma_{\mu\nu} u_{Rt})$
$\mathcal{O}_{uu}^{S1,RR}$	$(\bar{u}_{Lp} u_{Rr})(\bar{u}_{Ls} u_{Rt})$
$\mathcal{O}_{uu}^{S8,RR}$	$(\bar{u}_{Lp} T^A u_{Rr})(\bar{u}_{Ls} T^A u_{Rt})$
$\mathcal{O}_{ud}^{S1,RR}$	$(\bar{u}_{Lp} u_{Rr})(\bar{d}_{Ls} d_{Rt})$
$\mathcal{O}_{ud}^{S8,RR}$	$(\bar{u}_{Lp} T^A u_{Rr})(\bar{d}_{Ls} T^A d_{Rt})$
$\mathcal{O}_{dd}^{S1,RR}$	$(\bar{d}_{Lp} d_{Rr})(\bar{d}_{Ls} d_{Rt})$
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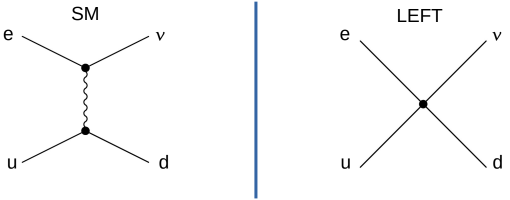
$(\overline{L}R)(\overline{R}L) + \text{h.c.}$	
$\mathcal{O}_{eu}^{S,RL}$	$(\bar{e}_{Lp} e_{Rr})(\bar{u}_{Rs} u_{Lt})$
$\mathcal{O}_{ed}^{S,RL}$	$(\bar{e}_{Lp} e_{Rr})(\bar{d}_{Rs} d_{Lt})$
$\mathcal{O}_{\nu edu}^{S,RL}$	$(\bar{\nu}_{Lp} e_{Rr})(\bar{d}_{Rs} u_{Lt})$

E. Jenkins, A. Manohar, P. Stoffer, ‘17

Matching

$$\frac{-ig^2}{q^2 - m_W^2} = \frac{ig^2}{m_W^2} + \mathcal{O}(q^2/m_W^4)$$



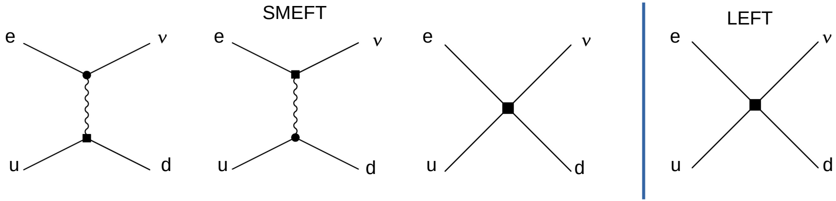
- equate amplitudes in SMEFT and LEFT, at a given order in the expansion in Q/v, Q/Λ
  e.g. for charged currents

$$\left[L^{VLL}_{\nu edu}\right]_{prst} = -\frac{2}{v^2}\left[V^\dagger_{\rm CKM}\right]_{st} \qquad \left[L^{VLR}_{\nu edu}\right]_{prst} = 0$$

$$\left[L^{SRR}_{\nu edu}\right]_{prst} = 0 \qquad \left[L^{SRL}_{\nu edu}\right]_{prst} = 0$$

$$\left[L^{TRR}_{\nu edu}\right]_{prst} = 0$$

Matching



- equate amplitudes in SMEFT and LEFT, at a given order in the expansion in Q/v, Q/Λ
  e.g. for charged currents

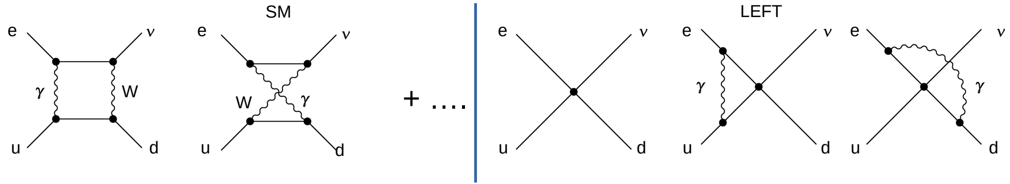
$$\left[L^{VLL}_{\nu edu}\right]_{prst} = -\frac{2}{v^2}\left[V^\dagger_{\rm CKM}\right]_{st} - 2\left[\left(C^{(3)}_{Hq} - C^{(3)}_{lq} + C^{(3)}_{Hl}\right) V^\dagger_{\rm CKM}\right]_{st} \qquad \left[L^{VLR}_{\nu edu}\right]_{prst} = \left[C^\dagger_{Hud}\right]_{st}$$

$$\left[L^{SRR}_{\nu edu}\right]_{prst} = \left[C^{(1)}_{lequ}\right]_{st} \qquad \left[L^{SRL}_{\nu edu}\right]_{prst} = \left[C_{ledq} V^\dagger_{\rm CKM}\right]_{st}$$

$$\left[L^{TRR}_{\nu edu}\right]_{prst} = \left[C^{(3)}_{lequ}\right]_{st}$$

- SMEFT populates all the structures identified by Lee and Yang — T. D. Lee and C. N. Yang, '56
- **but** with scalar, tensor and right-handed currents suppressed by v^2/Λ^2

Matching at higher order



- the LEFT matching coefficients can be computed order by order in α and α_s

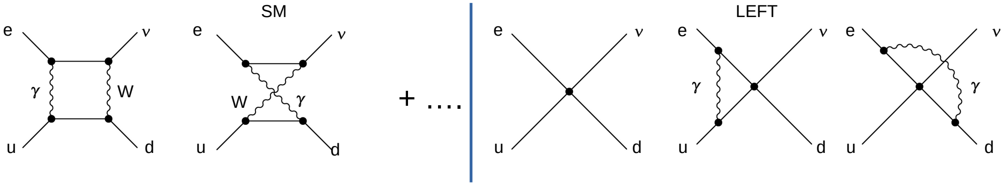
a. if the EFT is correct, it will exactly reproduce the infrared structure of the full theory

matching coefficients cannot depend on IR regulators or IR scales (light particle masses and external momenta)

b. the two theories will differ in the UV

- this is ok cause we cannot use the EFT for high-energy processes,
- the difference is accounted for by local operators in LEFT

Example: $\mathcal{O}(\alpha)$ corrections to β decay



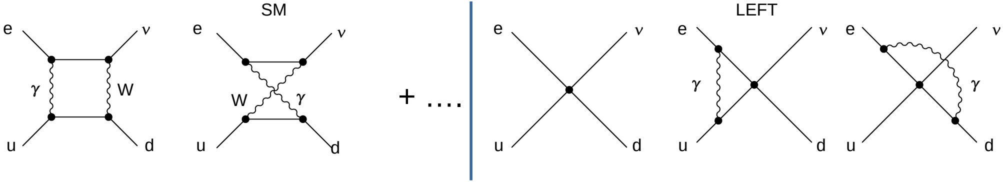
- the SM diagrams are UV finite, IR divergent

$$\mathcal{A}_{\rm SM} = i\frac{2}{v^2}V_{ud}^*\bar{u}(p_\nu)\gamma^\mu P_L u(p_e)\,\bar{u}(p_d)\gamma_\mu P_L u(p_u)\left[\frac{\alpha}{4\pi}Q_e(4Q_u - Q_d)\,\log\frac{m_W^2}{m_\gamma^2} + \ldots\right]$$

- the LEFT diagrams are UV and IR divergent, absorb UV divergence in $L_{\nu edu}^{\rm VLL}$

$$\mathcal{A}_{\rm LEFT} = i\frac{2}{v^2}V_{ud}^*\bar{u}(p_\nu)\gamma^\mu P_L u(p_e)\,\bar{u}(p_d)\gamma_\mu P_L u(p_u)\left[\frac{\alpha}{4\pi}Q_e(4Q_u - Q_d)\,\log\frac{\mu^2}{m_\gamma^2}\right.$$
$$\left. + \frac{\alpha}{4\pi}\left(-3Q_e\left(Q_u - \frac{1}{2}Q_d\right) + \ldots\right) + \frac{v^2}{2}L_{\nu edu}^{\rm VLL}(\mu)\right]$$

Example: $\mathcal{O}(\alpha)$ corrections to β decay



- the difference between the two amplitude is compensate by adjusting $L^{\mathrm{VLL}}_{\nu edu}$

$$L^{\mathrm{VLL}}_{\nu edu}(\mu) = -\frac{2}{v^2} V^*_{ud} \left[1 + \frac{\alpha}{4\pi} \left(Q_e(4Q_u - Q_d) \log \frac{\mu^2}{m_W^2} + 3Q_e \left(Q_u - \frac{1}{2} Q_d \right) + \dots \right) \right]$$

1. we can avoid large logs in the matching coefficient by taking $\mu \sim m_W$
2. and use the *renormalization group equation* to evolve the coefficients from $\mu \sim m_W$ to $\mu \sim$ few GeVs

$$\frac{d}{d \log \mu} L^{\mathrm{VLL}}_{\nu edu}(\mu) = -\frac{\alpha}{\pi}(\mu) L^{\mathrm{VLL}}_{\nu edu}(\mu)$$

(after calculating the remaining diagrams and asking the amplitude to be scale-independent)

Renormalization group evolution: operator mixing.

- as in the SM example, SMEFT operators depend on the renormalization scale μ
- at the loop level, operators can “mix” into each other
- operators that “naively” (i.e. at tree level) do not contribute to precision observables can indeed contribute at 1- or higher-loop
- the price of a 1- or 2-loop suppression can be easily overcome by the large sensitivity

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e.g. consider

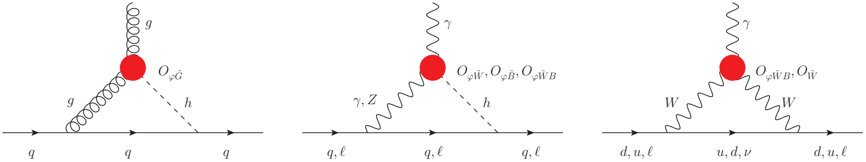
$$\begin{aligned}\mathcal{L} &= C_{\varphi\tilde{W}}\varphi^\dagger\varphi\tilde{W}^a_{\mu\nu}W^{a\,\mu\nu} \\ &= 2C_{\varphi\tilde{W}}v\,h\,\varepsilon^{\mu\nu\alpha\beta}\left[2\partial_\mu W^+_\nu\,\partial_\alpha W^-_\beta + s^2_w\partial_\mu A_\nu\partial_\alpha A_\beta + c^2_w\partial_\mu Z_\nu\,\partial_\alpha Z_\beta + 2s_w c_w\partial_\mu A_\nu\partial_\alpha Z_\beta\ldots\right]\end{aligned}$$

- induces CP-odd couplings of the Higgs to W, Z and photons

can we probe it via the eEDM?

- "naively" no, need $C_{e\gamma}\bar{e}\sigma^{\mu\nu}\gamma_5 eF_{\mu\nu}$ operator!

Renormalization group evolution: operator mixing.



- diagrams are UV divergent, with divergence with the same structure as a dipole operator

$$(16\pi^2)\,\frac{d}{d\log\mu}\mathrm{Im}\,C_{eB} = -\frac{m_e}{v}\left(2g'(\mathrm{y}_\ell+\mathrm{y}_e)C_{\varphi\tilde{B}} + \frac{3}{2}gC_{\varphi\tilde{W}B}\right)$$

$$(16\pi^2)\,\frac{d}{d\log\mu}\mathrm{Im}\,C_{eW} = -\frac{m_e}{v}\left(g'(\mathrm{y}_\ell+\mathrm{y}_e)C_{\varphi\tilde{W}B} + gC_{\varphi\tilde{W}}\right)$$

- leading to an electron EDM

$$d_e \approx \sqrt{2}m_e\frac{e}{16\pi^2}\left[-3C_{\varphi\tilde{B}} + C_{\varphi\tilde{W}} + 2\cot(2\theta_w)C_{\varphi\tilde{W}B}\right]\log\frac{m_H}{\Lambda}$$
$$= -(4.5\cdot 10^{-30}\,e\,\mathrm{cm})\times(400\,\mathrm{TeV})^2\left[-3C_{\varphi\tilde{B}} + C_{\varphi\tilde{W}} + 2\cot(2\theta_w)C_{\varphi\tilde{W}B}\right]$$

- even with loop suppression, the scale of these operators needs to be larger than 400 TeV!

Running and matching in SMEFT

- the complete 1-loop running in SMEFT is known ✓

E. Jenkins, A. Manohar, M. Trott, '13;
E. Jenkins, A. Manohar, M. Trott, '13;
R. Alonso, E. Jenkins, A. Manohar, M. Trott, '14;

- the complete 1-loop matching of SMEFT onto LEFT is known ✓
  (except for the dependence on light quark masses)

E. Jenkins, A. Manohar and P. Stoffer, '17;
W. Dekens and P. Stoffer, '19;

- the complete 1-loop running in LEFT is known ✓

E. Jenkins, A. Manohar, P. Stoffer, '17;

- a few groups already working on 2-loop running and matching

EFT for precision β decay

LEFT charged current operators

- at low-energy, weak charged-currents can be axial, vector, scalar, pseudoscalar and tensor

$$\mathcal{L} = \bar{\nu}_L \gamma^\mu e_L \left[L^{\rm VLL}_{\nu edu}\, \bar{d}_L \gamma_\mu u_L + L^{\rm VLR}_{\nu edu}\, \bar{d}_R \gamma_\mu u_R \right] + \bar{\nu}_L e_R \left(L^{\rm SRR}_{\nu edu} \bar{d}_L u_R + L^{\rm SRL}_{\nu edu} \bar{d}_R u_L \right) + L^{\rm TRR}_{\nu edu} \bar{\nu}_L \sigma^{\mu\nu} e_R \bar{d}_L \sigma_{\mu\nu} u_R$$

- these 5 coefficients can be disentangled by measuring several low-energy processes

Operators	Observables
Scalar and tensor	
$L^{\rm SRR}_{\nu edu} - L^{\rm SRL}_{\nu edu}$	$\Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$
$L^{\rm SRR}_{\nu edu} + L^{\rm SRL}_{\nu edu}$	β spectra in Fermi or mixed transitions
$L^{\rm TRR}_{\nu edu}$	$\Gamma(\pi \to \ell\nu\gamma)$, β spectra in GT/mixed transitions
Axial and vectors	
$L^{\rm VLL}_{\nu edu}$, $L^{\rm VLR}_{\nu edu}$	CKM unitarity tests, $g_A^{\rm LQCD}$ vs $g_A^{\rm exp}$

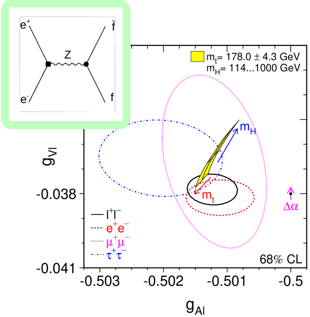
SMEFT charged current operators

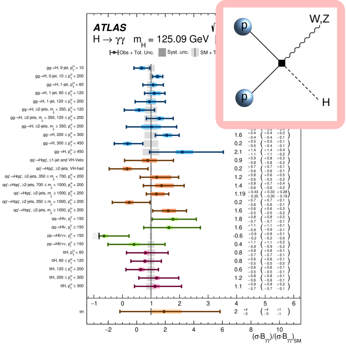
- even at tree level, going from SMEFT to LEFT introduces degeneracies

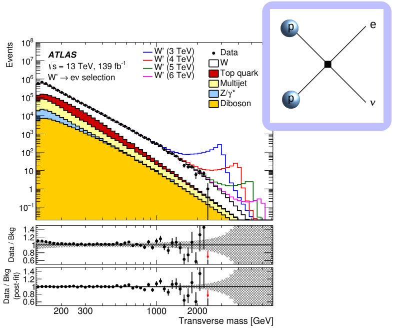
Operators		LEFT	β decays	Electroweak precision	Collider
$\psi^2 H^2 D$					
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	$\to L_{\nu edu}^{\mathrm{VLL}}$	✓		
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	$\to L_{\nu edu}^{\mathrm{VLL}}$	✓		
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$	$\to L_{\nu edu}^{\mathrm{VLR}}$	✓		
$(\bar{L}L)(\bar{L}L)$					
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma^\mu \tau^I l_r)(\bar{q}_s \gamma_\mu \tau^I q_t)$	$\to L_{\nu edu}^{\mathrm{VLL}}$	✓		
$(\bar{L}R)(\bar{R}L) + \mathrm{h.c.}$					
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$	$\to L_{\nu edu}^{\mathrm{SLR}}$	✓		
$(\bar{L}R)(\bar{L}R) + \mathrm{h.c.}$					
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$	$\to L_{\nu edu}^{\mathrm{SRR}}$	✓		
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$	$\to L_{\nu edu}^{\mathrm{TRR}}$	✓		

low-energy measurements cannot disentangle W-fermion couplings ($Q_{Hl}^{(3)}$, $Q_{Hq}^{(3)}$) from four-fermion operators ($Q_{lq}^{(3)}$)

High-energy vs low-energy complementarity





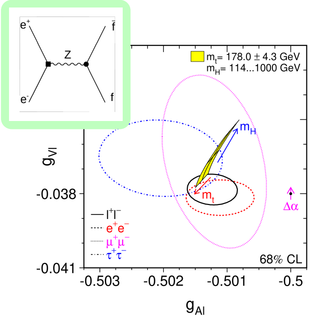


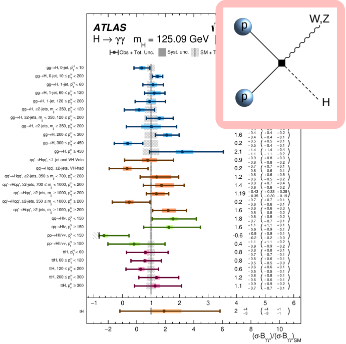
- $C_{Hl}^{(3)}$ and $C_{Hq}^{(3)}$:

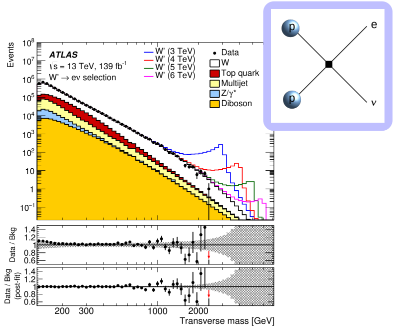
$$\mathcal{L} = C_{Hl}^{(3)} \left(1 + \frac{h}{v}\right) \left[\bar{e}_L \gamma^\mu \nu_L W_\mu^- + \bar{\nu}_L \gamma^\mu e_L W_\mu^+ + \bar{\nu}_L \gamma^\mu \nu_L Z_\mu - \bar{e}_L \gamma^\mu e_L Z_\mu + \right]$$

1. gauge invariance link them to $e^+e^- \to f\bar{f}$ and precision observables at LEP
2. and to important EW processes at LHC: $pp \to HZ, HW, ZZ$

High-energy vs low-energy complementarity







- $C_{lq}^{(3)}$:

1. small corrections at the Z pole
2. but large corrections to $pp \to e\nu + X$, enhanced at large invariant mass

$$\frac{d\sigma_{\text{SMEFT}}}{dm_{e\nu}^2} \propto \left(1 + \frac{2}{g^2} C_{lq}^{(3)} (m_{e\nu}^2 - m_W^2)\right) \times \frac{d\sigma_{\text{SM}}}{dm_{e\nu}^2}$$

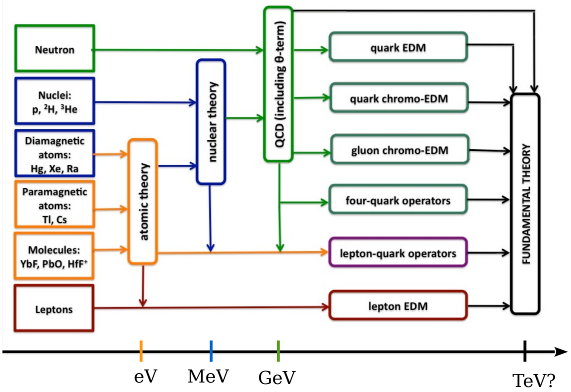
SMEFT charged current operators

Operators		LEFT	β decays	Electroweak precision	Collider
$\psi^2 H^2 D$					
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	$\to L^{\rm VLL}_{\nu edu}$	✓	✓	✓
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	$\to L^{\rm VLL}_{\nu edu}$	✓	✓	✓
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$	$\to L^{\rm VLR}_{\nu edu}$	✓	✗	✓
$(\bar{L}L)(\bar{L}L)$					
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma^\mu \tau^I l_r)(\bar{q}_s \gamma_\mu \tau^I q_t)$	$\to L^{\rm VLL}_{\nu edu}$	✓	✗	✓
$(\bar{L}R)(\bar{R}L) + \mathbf{h.c.}$					
Q_{ledq}	$(\bar{l}^j_p e_r)(\bar{d}_s q_{tj})$	$\to L^{\rm SLR}_{\nu edu}$	✓	✗	✓
$(\bar{L}R)(\bar{L}R) + \mathbf{h.c.}$					
$Q_{lequ}^{(1)}$	$(\bar{l}^j_p e_r)\epsilon_{jk}(\bar{q}^k_s u_t)$	$\to L^{\rm SRR}_{\nu edu}$	✓	✗	✓
$Q_{lequ}^{(3)}$	$(\bar{l}^j_p \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$	$\to L^{\rm TRR}_{\nu edu}$	✓	✗	✓

low energy + EWPO + high-energy data can disentangle different scenarios provided they have similar sensitivity

EFT for CP-violation and Electric Dipole Moments

$\Delta F = 0$ CPV in LEFT



How much info can we extract from EDM experiments?

thanks to J. de Vries

- dim-5 LEFT operators

$$\mathcal{L}^{(5)}_{\rm LEFT} = L_{e\gamma}\bar{e}_L\sigma^{\mu\nu}e_R\,F_{\mu\nu} + \sum_{q=u,d,s} L_{q\gamma}\bar{q}_L\sigma^{\mu\nu}q_R\,F_{\mu\nu} + \sum_{q=u,d,s} L_{qg}\bar{q}_L\sigma^{\mu\nu}t^a q_R\,G^a_{\mu\nu} + \text{h.c.},$$

- they are induced by dim-6 SMEFT operators after EWSB

$\Delta F = 0$ CPV in LEFT

- dim-6 LEFT operators

1. 3-gluon operator:

$$\mathcal{L}^{(6)}_{\rm LEFT} = L_{\tilde{G}} f^{abc} \tilde{G}^a_{\mu\nu} G^{b\,\nu\rho} G^{c\,\mu}_{\rho}$$

2. semi-leptonic:

$$\mathcal{L}^{(6)}_{\rm LEFT} = \sum_{q=u,d,s} L^{\rm SRL}_{eq} (\bar{e}_L e_R)(\bar{q}_R q_L) + L^{\rm SRR}_{eq} (\bar{e}_L e_R)(\bar{q}_L q_R) + L^{\rm TRR}_{eq} (\bar{e}_L \sigma^{\mu\nu} e_R)(\bar{q}_L \sigma_{\mu\nu} q_R) + {\rm h.c.}$$

- in SMEFT, gauge invariance relates them to β decay operators...

3. 4-fermion:

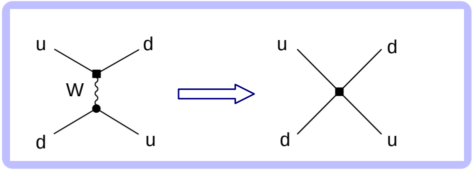
$$\mathcal{L}^{(6)}_{\rm LEFT} = L^{\rm V1LR}_{uddu} (\bar{u}_L \gamma^\mu d_L)(\bar{d}_R \gamma_\mu u_R) + L^{\rm S1RR}_{uu} (\bar{u}_L u_R)(\bar{u}_L u_R) + \dots$$

- 24 operators, 6 of the *LL RR* type, 18 of the *LR LR* type

ideally, we would like EDM experiments to disentangle these coeffs.
very hard to do for hadronic operators (see later)

$\Delta F = 0$ CPV in the SMEFT

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$



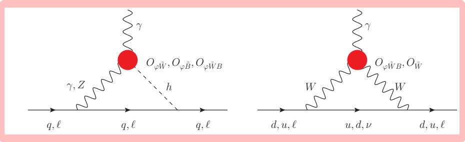
SMEFT operators can contribute to EDMs in several way

a. Tree level path

- 3-gluon operator, dipole and Yukawa couplings of light fermions, right-handed W couplings, 4-fermion

$\Delta F = 0$ CPV in the SMEFT

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star (\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde W B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

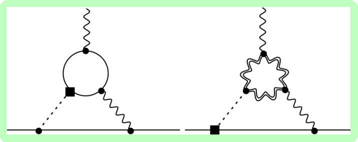


SMEFT operators can contribute to EDMs in several way

b. 1-loop path: 3-W, Higgs-gauge operators

$\Delta F = 0$ CPV in the SMEFT

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$



SMEFT operators can contribute to EDMs in several way

a. 2-loop path: dipole and Yukawas with heavy generations (c, b, t)

$\Delta F = 0$ CPV in the SMEFT

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
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$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
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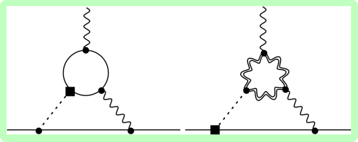


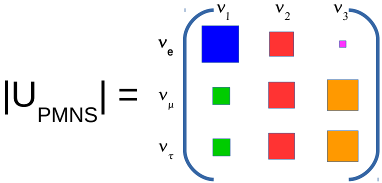
SMEFT operators can contribute to EDMs in several way

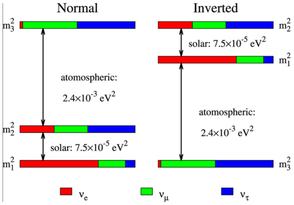
a. 2-loop path: dipole and Yukawas with heavy generations (c, b, t)

- EDMs are so strong that they severely constrain CPV even in Higgs and top sectors of SMEFT
- in presence of a signal, need complementary probes for disentangling (harder than in β decays, because colliders are in general less sensitive)

EFTs for Neutrino Masses and Lepton Number Violation

Neutrino masses and mixings



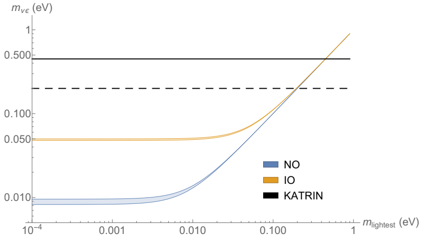


- neutrinos in weak interactions are linear combinations of 3 massive states

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle \qquad \alpha \in \{e, \mu, \tau\}$$

- mass splittings and mixings well determined
- mass ordering and CP phase in next generation of oscillation exps. DUNE and HYPER-KAMIOKANDE

Neutrino masses and mixings



- neutrinos in weak interactions are linear combinations of 3 massive states

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle \qquad \alpha \in \{e, \mu, \tau\}$$

- mass splittings and mixings well determined
- mass ordering and CP phase in next generation of oscillation exps. DUNE and HYPER-KAMIOKANDE
- neutrino absolute scale is small

$$m_{\nu\varepsilon} = \sqrt{\sum_i |m_i U_{ei}|^2} < 0.45\,\mathrm{eV} \qquad \text{KATRIN '24}$$

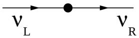
Neutrino masses and BSM physics

- the neutrinos (antineutrinos) in the weak interactions are purely L (R) handed
- need some right-handed component for a mass term

in the SM, $m_\nu = 0$
neutrino oscillations are BSM physics!

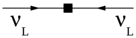
- For neutral particles, we can write two mass terms

Dirac



$m_i \bar{\nu}^i_R \nu^i_L$

Majorana



$m_i {\nu^T}^i_L C \nu^i_L$

- neither of them is gauge invariant!

Neutrino masses and BSM physics

Dirac mass

- need to add a new field to the SM, ν_R
- ν_R has zero weak, electromagnetic or strong charge (sterile)
- once we add ν_R, we can use the Higgs field to make the Dirac mass gauge invariant

$$\mathcal{L}_{m_\nu} = Y_\nu \varepsilon^{jk} \bar{\ell}^j_L \left(\varphi^k\right)^\dagger \nu_R$$

- 3 massive states ✓
- small values of m_ν fixed "by hand", by choosing small Y_ν
- ν_R does nothing in the theory, only needed to generate m_ν

Neutrino masses and BSM physics

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- 3 massive states ✓
- small values of m_ν fixed "by hand", by choosing small Y_ν
- ν_R does nothing in the theory, only needed to generate m_ν
- however, if ν_R is a singlet, nothing forbids a gauge-invariant, dim-3 Majorana mass

$$\mathcal{L}_{m_\nu} = Y_\nu \varepsilon^{jk} \bar{\ell}^j_L \left(\varphi^k\right)^\dagger \nu_R - \frac{1}{2} M_R \nu_R^T C \nu_R$$

- $M_R \neq 0$ immediately leads to $n > 3$ massive neutrinos

BSM in new light degrees of freedom!

Neutrino masses and BSM physics

Majorana mass

- cannot write down a dim-4, gauge-invariant Majorana mass

lepton number is an accidental symmetry of the SM

- but we can at dim-5!

$$\mathcal{L} = \frac{1}{\Lambda} C_{\nu\nu} \varepsilon_{jk} \varepsilon_{mn} \varphi^j \varphi^m \ell_L^{kT} C \ell_L^n \xrightarrow{EWSB} \frac{v^2}{2\Lambda} C_{\nu\nu} \nu_L^T C \nu_L + \mathcal{O}(H).$$

S. Weinberg, '79

- 3 massive states ✓
- $m_\nu \sim v^2/\Lambda$, small if Λ is very large ✓
- no need of new light degrees of freedom
- lepton number is not a symmetry of the theory

BSM in new high energy interactions!

- $0\nu\beta\beta$ might be the best way to discriminate between the two mechanisms

EFT for neutrino masses and non-standard interactions: νSMEFT

- since we do not know the mass mechanism, capture both in the EFT

νSMEFT!
same recipe as before + n_R sterile neutrinos

- dim-3 + dim-4 + dim 5: neutrino masses and sterile neutrino magnetic moments ✓
- after electroweak symmetry breaking

$$\mathcal{L} = -\frac{1}{2}\left(\nu_L^T, \bar{\nu}_R C\right) C M_\nu \begin{pmatrix} \nu_L \\ C\bar{\nu}_R^T \end{pmatrix}, \qquad M_\nu = \begin{pmatrix} M_L & M_D^* \\ M_D^\dagger & M_R^\dagger \end{pmatrix}$$

- M_ν is a symmetric $(3 + n_R) \times (3 + n_R)$ matrix, diagonalized by the unitary transformation U

EFT for neutrino masses and non-standard interactions: νSMEFT

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- M_ν is a symmetric $(3+n_R)\times(3+n_R)$ matrix, diagonalized by the unitary transformation U

1. $n_R = 0$ and $M_L \neq 0$: 3 light, massive, Majorana left-handed states

   "standard mechanism" for $0\nu\beta\beta$

2. $n_R > 0$, $M_R \neq 0$, $M_L = 0$: $3 + n_R$ Majorana states.

   $\sum_{i=1}^{3+n_R} U_{ei}^2 m_i = 0$

   LNV only in the sterile sector and $0\nu\beta\beta$ rate suppressed

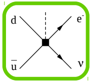
3. $n_R = 3$, $M_R = 0$, $M_L = 0$: 3 pure Dirac neutrinos

   no $0\nu\beta\beta$!

LNV operators in SMEFT

Class 1	$\psi^2 H^4$	Class 5	$\psi^4 D$
$\mathcal{O}^{(7)}_{LH}$	$\epsilon_{ij}\epsilon_{mn}(L_i^T C L_m) H_j H_n (H^\dagger H)$	$\mathcal{O}^{(7)}_{LL\bar{d}uD\,1}$	$\epsilon_{ij}(\bar{d}\gamma_\mu u)(L_i^T C (D^\mu L)_j)$
Class 2	$\psi^2 H^2 D^2$	Class 6	$\psi^4 H$
$\mathcal{O}^{(7)}_{LHD\,1}$	$\epsilon_{ij}\epsilon_{mn}(L_i^T C (D_\mu L)_j) H_m (D^\mu H)_n$	$\mathcal{O}^{(7)}_{Leu\bar{d}H}$	$\epsilon_{ij}(L_i^T C\gamma_\mu e)(\bar{d}\gamma^\mu u) H_j$
$\mathcal{O}^{(7)}_{LHD\,2}$	$\epsilon_{im}\epsilon_{jn}(L_i^T C (D_\mu L)_j) H_m (D^\mu H)_n$	$\mathcal{O}^{(7)}_{LLQ\bar{d}H\,1}$	$\epsilon_{ij}\epsilon_{mn}(\bar{d}L_i)(Q_j^T C L_m) H_n$
Class 3	$\psi^2 H^3 D$	$\mathcal{O}^{(7)}_{LLQ\bar{d}H\,2}$	$\epsilon_{im}\epsilon_{jn}(\bar{d}L_i)(Q_j^T C L_m) H_n$
$\mathcal{O}^{(7)}_{LHDe}$	$\epsilon_{ij}\epsilon_{mn}(L_i^T C\gamma_\mu e) H_j H_m (D^\mu H)_n$	$\mathcal{O}^{(7)}_{LL\bar{Q}uH}$	$\epsilon_{ij}(\bar{Q}_m u)(L_m^T C L_i) H_j$
Class 4	$\psi^2 H^2 X$		
$\mathcal{O}^{(7)}_{LHW}$	$\epsilon_{ij}(\epsilon\tau^I)_{mn} g (L_i^T C\sigma^{\mu\nu} L_m) H_j H_n W^I_{\mu\nu}$		

Class 1	$\psi^2 H^4$	Class 5	$\psi^4 D$
$\mathcal{O}^{(7)}_{\nu H}$	$(\nu_R^T C \nu_R)(H^\dagger H)^2$	$\mathcal{O}^{(7)}_{du\nu eD}$	$(\bar{d}\gamma_\mu u)(\nu_R^T C i D_\mu e)$
Class 2	$\psi^2 H^2 D^2$	$\mathcal{O}^{(7)}_{QL\nu uD}$	$(\bar{Q}\gamma_\mu L)(\nu_R^T C i D_\mu u)$
$\mathcal{O}^{(7)}_{\nu eD}$	$\epsilon_{ij}(\nu_R^T C D_\mu e)(H^i D^\mu H^j)$	$\mathcal{O}^{(7)}_{d\nu QLD}$	$\epsilon_{ij}(\bar{d}\gamma_\mu \nu_R)(Q^i C i D_\mu L^j)$
Class 3	$\psi^2 H^3 D$	Class 6	$\psi^4 H$
$\mathcal{O}^{(7)}_{\nu L1}$	$\epsilon_{ij}(\nu_R^T C\gamma_\mu L^i)(i D^\mu H^j)(H^\dagger H)$	$\mathcal{O}^{(7)}_{Q\nu QLH2}$	$\epsilon_{ij}(\bar{Q}\nu_R)(Q^i C L^j) H$
Class 4	$\psi^2 H^2 X$	$\mathcal{O}^{(7)}_{dL\nu uH}$	$\epsilon_{ij}(\bar{d}L^i)(\nu_R^T C u)\tilde{H}^j$
$\mathcal{O}^{(7)}_{\nu eW}$	$(\epsilon\tau^I)_{ij}(\nu_R^T C\sigma^{\mu\nu} e)(H^i H^j) W^I_{\mu\nu}$	$\mathcal{O}^{(7)}_{dQ\nu eH}$	$\epsilon_{ij}(\bar{d}Q^i)(\nu_R^T C e) H^j$
		$\mathcal{O}^{(7)}_{Qu\nu eH}$	$(\bar{Q}u)(\nu_R^T C e) H$
		$\mathcal{O}^{(7)}_{Qe\nu uH}$	$(\bar{Q}e)(\nu_R^T C u) H$



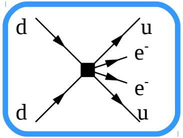
ν_L operators

ν_R operators

- the Weinberg operator is the first term in a series of $\Delta L = 2$ operators
- in SMEFT, $\Delta L = 2$ operators appear at odd dimension
- dim. 7 operators induce β decays with the "wrong" neutrino, $d \to u e^- \nu_e$

A. Kobach, '16

LNV operators in SMEFT. Dimension 9 operators



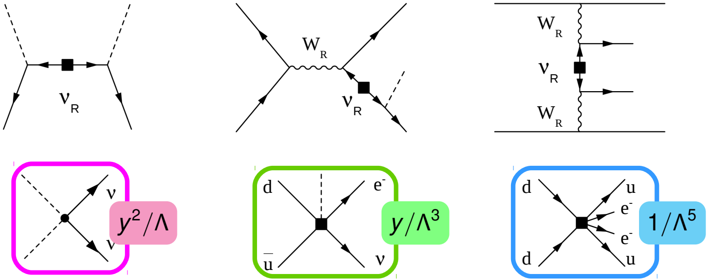
- after matching onto LEFT, dim-9 operators have the form

$$\mathcal{L}^{(9)}_{\Delta L=2} = \sum_i \left[\left(C^{(9)}_{i\,\mathrm{R}}\, \bar{e}_R C \bar{e}_R^T + C^{(9)}_{i\,\mathrm{L}}\, \bar{e}_L C \bar{e}_L^T \right) O_i + C^{(9)}_i \bar{e} \gamma_\mu \gamma_5 C \bar{e}^T\, O_i^\mu \right],$$

- the most important are the scalar operators

$$\begin{aligned}
O_1 &= \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha\ \bar{q}_L^\beta \gamma^\mu \tau^+ q_L^\beta\,, & O_1' &= \bar{q}_R^\alpha \gamma_\mu \tau^+ q_R^\alpha\ \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\beta\,,\\
O_2 &= \bar{q}_R^\alpha \tau^+ q_L^\alpha\ \bar{q}_R^\beta \tau^+ q_L^\beta\,, & O_2' &= \bar{q}_L^\alpha \tau^+ q_R^\alpha\ \bar{q}_L^\beta \tau^+ q_R^\beta\,,\\
O_3 &= \bar{q}_R^\alpha \tau^+ q_L^\beta\ \bar{q}_R^\beta \tau^+ q_L^\alpha\,, & O_3' &= \bar{q}_L^\alpha \tau^+ q_R^\beta\ \bar{q}_L^\beta \tau^+ q_R^\alpha\,,\\
O_4 &= \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha\ \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\beta\,, & &\\
O_5 &= \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\beta\ \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\alpha\,, & &
\end{aligned}$$

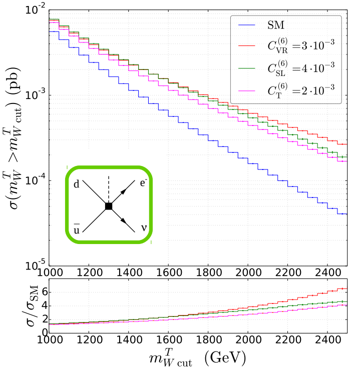
Connection to models

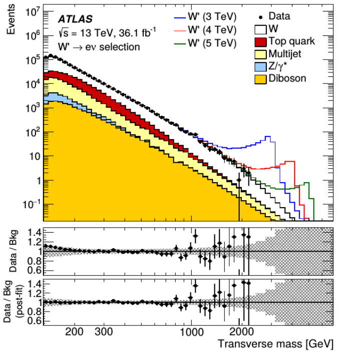


Do we really need to go to dim-9?

- specific models will match onto one or several operators
- e.g. Left-Right Symmetric Models match onto dim-5, -7, -9 with different numbers of Yukawas
- if $y_\nu \sim v^2/\Lambda^2$, all operators can give similar contributions

νSMEFT/LNV at LHC



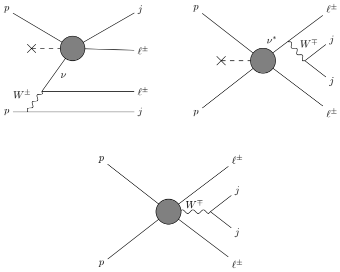


- dimension-5 hard to probe, $m_{\mu\mu} \sim 10$ GeV

B. Fuks, J. Neundorf, K. Peters, R. Ruiz, M. Saimpert, '21; CMS '22

- $pp \to e\nu$ probes dimension-7 operators with $\Lambda \sim 2.5$ TeV
- $pp \to \ell^+\ell^+ jj$ provide a direct test of the LNV nature of the operators
- no comprehensive analysis of dimension-9 ops

νSMEFT/LNV at LHC



Operator	$\sigma(pp \to \mu^\pm\mu^\pm jj)$ (pb)		Λ_{LNV} [TeV]	$\Lambda_{\text{LNV}}^{\text{future}}$ [TeV]
	LHC	FCC		
$\mathcal{O}_{\bar{Q}uLLH}$	2.4×10^{-4}	0.11	1.1	5.4
$\mathcal{O}_{\bar{d}LQLH2}$	1.5×10^{-5}	4.3×10^{-3}	0.68	3.1
$\mathcal{O}_{\bar{d}LQLH1}$	6.9×10^{-5}	0.030	0.86	4.3
$\mathcal{O}_{\bar{d}LueH}$	5.7×10^{-5}	0.035	0.84	4.5
$\mathcal{O}_{\bar{d}uLLD}$	0.64	210	4.0	19
$\mathcal{O}_{LDH2}$	2.7×10^{-12}	1.7×10^{-10}	0.050^*	0.18
$\mathcal{O}_{LDH1}$	1.9×10^{-5}	0.061	0.69	4.9
$\mathcal{O}_{LeHD}$	1.2×10^{-8}	3.1×10^{-8}	0.21^*	0.44
$\mathcal{O}_{LH}$	1.5×10^{-8}	2.0×10^{-6}	0.21^*	0.87

K. Fridell, L. Graf, J. Harz, C. Hati, ‘23

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