EFT parameterization for VBS

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The SMEFT

SMEFT = Effective Field Theory with SM fields + symmetries

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots$$

$\mathcal{L}_n = \sum_i C_i \mathcal{Q}_i^{d=n}$

C_i - free parameters (Wilson coefficients)

$\mathcal{Q}_i$ - gauge invariant operators that form a complete basis

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- any UV compatible with the SM in the low energy limit can be matched onto the SMEFT
- a convenient phenomenological approach: systematically classifies all the possible new physics signals
- allows to compute with no reference to the UV

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We consider B, L conservation and only first order deviations → only $\mathcal{L}_6$

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\mathcal{L}_6 \qquad\qquad \mathcal{L}_6 = \sum_i C_i \mathcal{Q}_i$$

there are 59 operators = 76 (2499) real parameters for 1 (3) generation(s)

The Warsaw basis

Gzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

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}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
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$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
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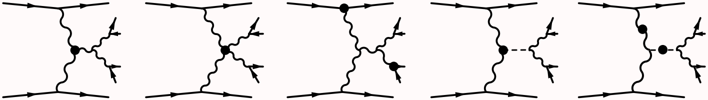
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

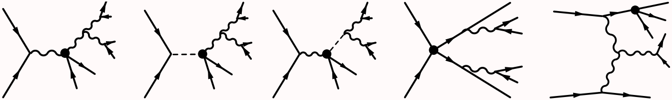
Which operators are relevant for VBS?

1. Identify all the terms that can contribute

(a) corrections to SM diagrams : TGC / QGC, hVV, Vff, $\delta\Gamma_{Z,W,h}$, δm_W, (gqq)



(b) BSM vertices that give new diagrams : VVff, Vhff, ffff . . .



2. Verify which are phenomenologically relevant. Depends on:

- symmetries assumed on the Lagrangian (CP, flavor)
- signal selection cuts
- complementary constraints?

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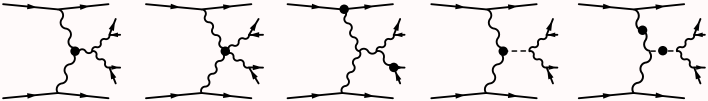

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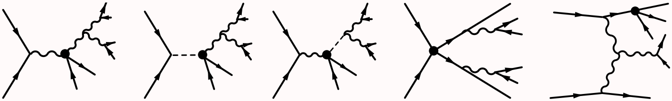

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VBS with the Warsaw basis - general case

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$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\,\widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
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$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
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$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Summary - most general case

Corrections to SM couplings/propagators

Vff ($\to \Gamma_W, \Gamma_Z$)	$\mathcal{Q}_{HD}$ $\mathcal{Q}_{HWB}$ $\mathcal{Q}_{ll}$ $\mathcal{Q}^3_{Hl}$ $\mathcal{Q}^1_{Hl}$ $\mathcal{Q}^3_{Hq}$ $\mathcal{Q}^1_{Hq}$ $\mathcal{Q}_{He}$ $\mathcal{Q}_{Hu}$ $\mathcal{Q}_{Hd}$ $\mathcal{Q}_{Hud}$
Vff (dipole)	$\mathcal{Q}_{eW}$ $\mathcal{Q}_{eB}$ $\mathcal{Q}_{uW}$ $\mathcal{Q}_{dB}$ $\mathcal{Q}_{dW}$ $\mathcal{Q}_{dB}$ ($\mathcal{Q}_{uG}$, $\mathcal{Q}_{dG}$)
TGC/QGC	$\mathcal{Q}_{HD}$ $\mathcal{Q}_{HWB}$ $\mathcal{Q}_{ll}$ $\mathcal{Q}^3_{Hl}$ $\mathcal{Q}_{W}$ $\mathcal{Q}_{\tilde{W}}$ $\mathcal{Q}_{H\tilde{W}B}$
hVV	$\mathcal{Q}_{HD}$ $\mathcal{Q}_{HWB}$ $\mathcal{Q}_{ll}$ $\mathcal{Q}^3_{Hl}$ $\mathcal{Q}_{HW}$ $\mathcal{Q}_{H\tilde{W}}$ $\mathcal{Q}_{HB}$ $\mathcal{Q}_{H\tilde{B}}$ $\mathcal{Q}_{H\tilde{W}B}$ $\mathcal{Q}_{H\Box}$
m_W	$\mathcal{Q}_{HD}$ $\mathcal{Q}_{HWB}$ $\mathcal{Q}^3_{Hl}$ $\mathcal{Q}_{ll}$
Γ_h	$\mathcal{Q}_{HD}$ $\mathcal{Q}_{ll}$ $\mathcal{Q}^3_{Hl}$ $\mathcal{Q}_{eH}$ $\mathcal{Q}_{dH}$ $\mathcal{Q}_{uH}$ $\mathcal{Q}_{H\Box}$

Couplings giving new diagrams

VVff	$\mathcal{Q}_{eW}$ $\mathcal{Q}_{eB}$ $\mathcal{Q}_{uW}$ $\mathcal{Q}_{dB}$ $\mathcal{Q}_{dW}$ $\mathcal{Q}_{dB}$ $\mathcal{Q}_{ll}$
Vhff	$\mathcal{Q}^3_{Hl}$ $\mathcal{Q}^1_{Hl}$ $\mathcal{Q}^3_{Hq}$ $\mathcal{Q}^1_{Hq}$ $\mathcal{Q}_{He}$ $\mathcal{Q}_{Hu}$ $\mathcal{Q}_{Hd}$ $\mathcal{Q}_{Hud}$
4-fermions	...

---

28 (30) operators and **254 (290)** parameters counting phases and flavor indices

+ four-fermion operators!

Reducing the set – symmetries

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I\varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Reducing the set – symmetries

Assume CP conservation

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	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
		$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu}G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W^I_{\mu\nu}$	$Q^{(1)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
		Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q^{(3)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$	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_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W^I_{\mu\nu}$	$Q^{(1)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q^{(3)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
		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_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

Reducing the set – symmetries

Assume CP conservation + approx. $U(3)^5$ flavor sym

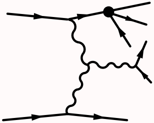
X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$		
		$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$		
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$		

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$			$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
				$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$			$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
				$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$			$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
				$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$			$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$

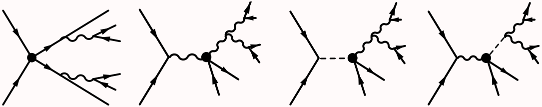
Reducing the set – selection cuts

Cuts can help removing (new) diagrams.

Examples:



→ non-resonant fermion pair



→ kinematics ≠ VBS signal could be removed

4-fermion operators (apart from $\mathcal{Q}_{ll}$) and new diagrams are likely to be negligible in resonant VBS

⚠ Simulation studies required to make solid statements

Reducing the set – complementary constraints

Ideal statement: "the operator XX is very constrained from another measurement, so it can be neglected"

it's OK to use this argument to reduce the parameter set (for now)

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suppose I have a theory that produces $(D^\mu W^i_{\mu\nu})(i\Phi^\dagger \overleftrightarrow{D}^{i\nu}\Phi)$
$\Rightarrow$ deviations in processes with TGC/QGC

In the Warsaw basis it corresponds to a combination of $C_{H\Box}$, $C^{(3)}_{Hq}, C^{(3)}_{Hl}, C_H$ + others

$$(D^\mu W^i_{\mu\nu})(i\Phi^\dagger \overleftrightarrow{D}^{i\nu}\Phi) = g\left(2\Phi^\dagger\Phi(D_\mu\Phi^\dagger D^\mu\Phi) + \frac{\mathcal{Q}_{H\Box}}{2} + \frac{\mathcal{Q}^{(3)}_{Hq} + \mathcal{Q}^{(3)}_{Hl}}{2}\right)$$

Grzadkowski et al: $(\varphi^\dagger\varphi)\left[(D_\mu\varphi)^\dagger(D^\mu\varphi)\right] \overset{(5.1)}{=} \frac{1}{2}(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi) + \boxed{\psi^2\varphi^3} + \boxed{\varphi^6} + m^2\boxed{\varphi^4} + \boxed{E}.$

LEP measurements tell $C^{(3)}_{Hq}, C^{(3)}_{Hl} \ll 1 \rightarrow$ I remove them from the fit
$\rightarrow$ no parameter left to account for the deviation in processes with TGC/QGC!

Reducing the set – complementary constraints

Ideal statement: "the operator XX is very constrained from another measurement, so it can be neglected"

it's OK to use this argument to reduce the parameter set (for now)

My skepticism: this statement is basis dependent as the EFT is *not* intuitive

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What this means:

- the operators in a basis don't capture only new physics contributing directly to them, but also to other invariants that were removed from the basis
- their physical interpretation is not obvious! ($\sim$ no control on the structures that were removed)
- to my knowledge it is not possible to select a basis that "minimizes" this
- reducing the parameter set "intuitively" is ok as long as there is no deviation. If anything appears it is necessary to include *all* to interpret it correctly

Operators relevant for VBS - minimal set

imposing CP + $U(3)^5$ flavor symmetry, neglecting contributions $\propto y_f,\ f \neq b, t$
and assuming non-standard diagrams give negligible impact

Corrections to SM couplings/propagators

Operator	Vff	TGC/QGC	hVV	m_W
$\mathcal{Q}_{HD} = (H^\dagger D_\mu H)^*(H^\dagger D^\mu H)$	●	●	●	●
$\mathcal{Q}_{H\Box} = (H^\dagger H)(H^\dagger \Box H)$			●	
$\mathcal{Q}_{W} = \varepsilon_{ijk} W^i_{\mu\nu} W^{j\nu\rho} W^{k\mu}_\rho$		●		
$\mathcal{Q}_{HB} = (H^\dagger H) B_{\mu\nu} B^{\mu\nu}$			●	
$\mathcal{Q}_{HW} = (H^\dagger H) W^i_{\mu\nu} W^{i\mu\nu}$			●	
$\mathcal{Q}_{HWB} = (H^\dagger \sigma^i H) W^i_{\mu\nu} B^{\mu\nu}$	●	●	●	●
$\mathcal{Q}_{ll} = (\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	●	●		●

Operator	Vff	TGC/QGC	hVV	m_W
$\mathcal{Q}^{(1)}_{Hl} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)$	●			
$\mathcal{Q}^{(3)}_{Hl} = (H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar{l}\sigma^i\gamma^\mu l)$	●	●	●	●
$\mathcal{Q}^{(1)}_{Hq} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$	●			
$\mathcal{Q}^{(3)}_{Hq} = (H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar{q}\sigma^i\gamma^\mu q)$	●			
$\mathcal{Q}_{He} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$	●			
$\mathcal{Q}_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$	●			
$\mathcal{Q}_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$	●			

● = Vff ($\Gamma_{W,Z}$) ● = TGC/QGC ● = hVV (Γ_h) ● = m_W

14 operators and **14** parameters

HEFT = Non-linear EFT = EW chiral Lagrangian

Main idea: the Higgs does not need to be in a doublet

$$H = \frac{v+h}{\sqrt{2}}\,\mathbf{U}\begin{pmatrix}0\\1\end{pmatrix}$$

independent

h

treated as a singlet
with arbitrary couplings

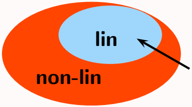
$$\mathcal{F}(h) = 1 + 2a\frac{h}{b} + b\frac{h^2}{v^2} + \dots$$

$\mathbf{U} = e^{i\pi^I\sigma^I/v}$

adimensional

derivative expansion $\sim$ χPT

$\longrightarrow$ a **very general** EFT



contains the linear as a particular limit

$\longrightarrow$ matches composite Higgs models + other UVs with significant nonlinear effects in the EWSB sector

HEFT operators for VBS - minimal set

restricting to CP + $U(3)^5$ and neglecting 4-fermion interactions

$$\mathbf{T} = U\sigma^3\mathbf{U}^\dagger \qquad \mathbf{V}_\mu = D_\mu\mathbf{U}\mathbf{U}^\dagger$$

29 operators

$\mathcal{P}_C = \text{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu)\mathcal{F}_C$

$\mathcal{P}_T = \text{Tr}(\mathbf{T}\mathbf{V}_\mu)\,\text{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathcal{F}_T$

$\mathcal{P}_B = B_{\mu\nu}B^{\mu\nu}\mathcal{F}_B$

$\mathcal{P}_W = W^a_{\mu\nu}W^{a\mu\nu}\mathcal{F}_W$

$\mathcal{P}_1 = B_{\mu\nu}\,\text{Tr}(\mathbf{T}W^{\mu\nu})\mathcal{F}_1$

$\mathcal{P}_2 = B_{\mu\nu}\,\text{Tr}(\mathbf{T}[\mathbf{V}^\mu,\mathbf{V}^\nu])\mathcal{F}_2$

$\mathcal{P}_3 = \text{Tr}(W_{\mu\nu}[\mathbf{V}^\mu,\mathbf{V}^\nu])\mathcal{F}_3$

$\mathcal{P}_4 = B_{\mu\nu}\,\text{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_4$

$\mathcal{P}_5 = \text{Tr}(W_{\mu\nu}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_5$

$\mathcal{P}_6 = (\text{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu))^2\mathcal{F}_6$

$\mathcal{P}_{11} = (\text{Tr}(\mathbf{V}_\mu\mathbf{V}_\nu))^2\mathcal{F}_{11}$

$\mathcal{P}_{12} = (\text{Tr}(\mathbf{T}W_{\mu\nu}))^2\mathcal{F}_{12}$

$\mathcal{P}_{13} = i\,\text{Tr}(\mathbf{T}W_{\mu\nu})\,\text{Tr}(\mathbf{T}[\mathbf{V}^\mu,\mathbf{V}^\nu])\mathcal{F}_{13}$

$\mathcal{P}_{14} = \varepsilon^{\mu\nu\rho\lambda}\,\text{Tr}(\mathbf{T}\mathbf{V}_\mu)\,\text{Tr}(\mathbf{V}_\nu W_{\rho\lambda})\mathcal{F}_{14}$

$\mathcal{P}_{17} = \text{Tr}(\mathbf{T}W_{\mu\nu})\,\text{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_{17}$

$\mathcal{P}_{18} = \text{Tr}(\mathbf{T}[\mathbf{V}_\mu,\mathbf{V}_\nu])\,\text{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_{18}$

$\mathcal{P}_{23} = \text{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu)(\text{Tr}(\mathbf{T}\mathbf{V}_\nu))^2\mathcal{F}_{23}$

$\mathcal{P}_{24} = \text{Tr}(\mathbf{V}_\mu\mathbf{V}_\nu)\,\text{Tr}(\mathbf{T}\mathbf{V}^\mu)\,\text{Tr}(\mathbf{T}\mathbf{V}^\nu)\mathcal{F}_{24}$

$\mathcal{P}_{26} = (\text{Tr}(\mathbf{T}\mathbf{V}_\mu)\,\text{Tr}(\mathbf{T}\mathbf{V}_\nu))^2\mathcal{F}_{26}$

$\mathcal{P}_{WWW} = \frac{\varepsilon_{abc}}{\Lambda^2}W^{a\nu}_\mu W^{b\rho}_\nu W^{c\mu}_\rho\mathcal{F}_{WWW}$

$\mathcal{N}^{\mathcal{Q}}_1 = i\bar{Q}_L\gamma_\mu\mathbf{V}^\mu Q_L\mathcal{F}$

$\mathcal{N}^{\mathcal{Q}}_2 = i\bar{Q}_R\gamma_\mu\mathbf{U}^\dagger\mathbf{V}^\mu\mathbf{U}\,Q_R\mathcal{F}$

$\mathcal{N}^{\mathcal{Q}}_5 = i\bar{Q}_L\gamma_\mu\{\mathbf{V}^\mu,\mathbf{T}\}\,Q_L\mathcal{F}$

$\mathcal{N}^{\mathcal{Q}}_6 = i\bar{Q}_R\gamma_\mu\mathbf{U}^\dagger\{\mathbf{V}^\mu,\mathbf{T}\}\mathbf{U}\,Q_R\mathcal{F}$

$\mathcal{N}^{\mathcal{Q}}_7 = i\bar{Q}_L\gamma_\mu\mathbf{T}\mathbf{V}^\mu\mathbf{T}\,Q_L\mathcal{F}$

$\mathcal{N}^{\mathcal{Q}}_8 = i\bar{Q}_R\gamma_\mu\mathbf{U}^\dagger\mathbf{T}\mathbf{V}^\mu\mathbf{T}\mathbf{U}\,Q_R\mathcal{F}$

$\mathcal{N}^{\ell}_2 = i\bar{L}_R\gamma_\mu\mathbf{U}^\dagger\{\mathbf{V}^\mu,\mathbf{T}\}\mathbf{U}\,L_R\mathcal{F}\,.$

$R^\ell_2 = (\bar{L}_L\gamma_\mu L_L)(\bar{L}_L\gamma^\mu L_L)\mathcal{F}$

$R^\ell_5 = (\bar{L}_L\gamma_\mu\mathbf{T}\,L_L)(\bar{L}_L\gamma^\mu\mathbf{T}\,L_L)\mathcal{F}$

Quick dictionary:

$$\text{Tr}(\mathbf{T}\mathbf{V}_\mu) \to Z_\mu$$
$$\text{Tr}(\mathbf{V}_\mu\mathbf{V}_\nu) \to Z_\mu Z_\nu + W^+_\mu W^-_\mu$$
$$\mathcal{F}_i \to 1 + h/v + \ldots$$

basis of 1604.06801

HEFT operators for VBS - minimal set

restricting to CP + $U(3)^5$ and neglecting 4-fermion interactions

$$\mathbf{T} = U\sigma^3\mathbf{U}^\dagger$$
$$\mathbf{V}_\mu = D_\mu\mathbf{U}\mathbf{U}^\dagger$$

29 operators

$\mathcal{P}_C = \mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu)\mathcal{F}_C$

$\mathcal{P}_T = \mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\,\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathcal{F}_T$

$\mathcal{P}_B = B_{\mu\nu}B^{\mu\nu}\mathcal{F}_B$

$\mathcal{P}_W = W^a_{\mu\nu}W^{a\mu\nu}\mathcal{F}_W$

$\mathcal{P}_1 = B_{\mu\nu}\,\mathrm{Tr}(\mathbf{T}W^{\mu\nu})\mathcal{F}_1$

$\mathcal{P}_2 = B_{\mu\nu}\,\mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu,\mathbf{V}^\nu])\mathcal{F}_2$

$\mathcal{P}_3 = \mathrm{Tr}(W_{\mu\nu}[\mathbf{V}^\mu,\mathbf{V}^\nu])\mathcal{F}_3$

$\mathcal{P}_4 = B_{\mu\nu}\,\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_4$

$\mathcal{P}_5 = \mathrm{Tr}(W_{\mu\nu}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_5$

$\mathcal{P}_6 = (\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu))^2\mathcal{F}_6$ $F_{S,0}$

$\mathcal{P}_{11} = (\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}_\nu))^2\mathcal{F}_{11}$ $F_{S,1}$

$\mathcal{P}_{12} = (\mathrm{Tr}(\mathbf{T}W_{\mu\nu}))^2\mathcal{F}_{12}$

$\mathcal{P}_{13} = i\,\mathrm{Tr}(\mathbf{T}W_{\mu\nu})\,\mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu,\mathbf{V}^\nu])\mathcal{F}_{13}$

$\mathcal{P}_{14} = \varepsilon^{\mu\nu\rho\lambda}\,\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\,\mathrm{Tr}(\mathbf{V}_\nu W_{\rho\lambda})\mathcal{F}_{14}$

$\mathcal{P}_{17} = \mathrm{Tr}(\mathbf{T}W_{\mu\nu})\,\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_{17}$

$\mathcal{P}_{18} = \mathrm{Tr}(\mathbf{T}[\mathbf{V}_\mu,\mathbf{V}_\nu])\,\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_{18}$ $F_{S,0}$

$\mathcal{P}_{23} = \mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu)(\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2\mathcal{F}_{23}$ $F_{S,0}$

$\mathcal{P}_{24} = \mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}_\nu)\,\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\,\mathrm{Tr}(\mathbf{T}\mathbf{V}^\nu)\mathcal{F}_{24}$ $F_{S,0}$

$\mathcal{P}_{26} = (\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\,\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2\mathcal{F}_{26}$

$\mathcal{P}_{WWW} = \frac{\varepsilon_{abc}}{\Lambda^2}W^{a\nu}_\mu W^{b\rho}_\nu W^{c\mu}_\rho\mathcal{F}_{WWW}$

$\mathcal{N}^{\mathcal{Q}}_1 = i\bar{Q}_L\gamma_\mu\mathbf{V}^\mu Q_L\mathcal{F}$

$\mathcal{N}^{\mathcal{Q}}_2 = i\bar{Q}_R\gamma_\mu\mathbf{U}^\dagger\mathbf{V}^\mu\mathbf{U}Q_R\mathcal{F}$

$\mathcal{N}^{\mathcal{Q}}_5 = i\bar{Q}_L\gamma_\mu\{\mathbf{V}^\mu,\mathbf{T}\}Q_L\mathcal{F}$

$\mathcal{N}^{\mathcal{Q}}_6 = i\bar{Q}_R\gamma_\mu\mathbf{U}^\dagger\{\mathbf{V}^\mu,\mathbf{T}\}\mathbf{U}Q_R\mathcal{F}$

$\mathcal{N}^{\mathcal{Q}}_7 = i\bar{Q}_L\gamma_\mu\mathbf{T}\mathbf{V}^\mu\mathbf{T}Q_L\mathcal{F}$

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correspond to $d \geqslant 8$ in the SMEFT

basis of 1604.06801

Discussion points

Analysis @ d=6: we can restrict to a minimal set of 14 parameters

1. preliminary study: which diagrams are negligible?
   can L/T polarizations be distinguished?
   any sensitivity to CP violation?
   which input scheme ($\{\alpha_{\rm em}, m_Z, G_f\}$ or $\{m_W, m_Z, G_f\}$)?
2. start with a feasible subset of parameters if 14 are too many.
3. tools: compare available codes for SMEFT predictions
4. including more parameters: possibility of combining / comparing with other datasets

Later extensions:

1. switch to a HEFT analysis
2. including some d=8 operators

Extra slides

TGC vs QGC in the SMEFT

TGC

$$-ig_{WWV}\left[g_1^V\left(W^+_{\mu\nu}W^{-\mu}V^\nu - W^-_{\mu\nu}W^{+\mu}V^\nu\right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu}\right] - i\lambda_V V^{\mu\nu}W^{+\rho}_\nu W^-_{\rho\mu}$$

g_1^γ	1	g_1^Z	$1-\frac{v^2}{4c_{2\theta}}\left(C_{HD}+4C_{Hl}^{(3)}-2C_{ll}+4t_\theta C_{HWB}\right)$
κ_γ	$1+\frac{v^2}{t_\theta}C_{HWB}$	κ_Z	$1-\frac{v^2}{4c_{2\theta}}\left(C_{HD}+4C_{Hl}^{(3)}-2C_{ll}+4s_{2\theta}C_{HWB}\right)$
λ_γ	$6C_W s_\theta$	λ_Z	$6C_W c_\theta$

QGC

$$g^2/2\left[g^{(1)}_{WW}\left((W^+_\mu W^-_\nu)^2-(W^+_\mu W^{-\mu})^2\right)+g^{(1)}_{VV'}\left(W^{+\mu}W^{-\nu}\frac{V_\mu V'_\nu+V_\nu V'_\mu}{2}-W^+_\mu W^{-\mu}V_\nu V'^\nu\right)\right]$$

$g^{(1)}_{WW}$	$1-\frac{v^2c_\theta^2}{2c_{2\theta}}\left(C_{HD}+4C_{Hl}^{(3)}-2C_{ll}+4t_\theta C_{HWB}\right)$	$g^{(1)}_{\gamma\gamma}/s_\theta^2$	1
$g^{(1)}_{Z\gamma}/s_{2\theta}$	$1-\frac{v^2}{4c_{2\theta}}\left(C_{HD}+4C_{Hl}^{(3)}-2C_{ll}+4t_\theta C_{HWB}\right)$		
$g^{(1)}_{ZZ}/c_\theta^2$	$1-\frac{v^2}{2c_{2\theta}}\left(C_{HD}+4C_{Hl}^{(3)}-2C_{ll}+4t_\theta C_{HWB}\right)$		

+ structures from $C_W\epsilon_{IJK}W^I_{\mu\nu}W^{J\nu\rho}W^{K\mu}_\rho$

aTGC in the SMEFT - schemes

	$\alpha_{\rm em}$ **scheme**	m_W **scheme**
δg_1^γ	0	$\frac{v^2}{4}\Big(-c_{HD}\frac{c_\theta^2}{s_\theta^2}-4c_{H\ell}^{(3)}+2c_{ll}-4c_{HWB}\frac{c_\theta}{s_\theta}\Big)$
δg_1^Z	$-\frac{v^2}{4c_{2\theta}}\left(c_{HD}+4c_{H\ell}^{(3)}-2c_{ll}+4\frac{s_\theta}{c_\theta}c_{HWB}\right)$	$\frac{v^2}{4}\Big(c_{HD}-4c_{H\ell}^{(3)}+2c_{ll}+4\frac{s_\theta}{c_\theta}c_{HWB}\Big)$
$\delta\kappa_\gamma$	$v^2\frac{c_\theta}{s_\theta}c_{HWB}$	$\frac{v^2}{4}\Big(-c_{HD}\frac{c_\theta^2}{s_\theta^2}-4c_{H\ell}^{(3)}+2c_{ll}\Big)$
$\delta\kappa_Z$	$-\frac{v^2}{4c_{2\theta}}\left(c_{HD}+4c_{H\ell}^{(3)}-2c_{ll}+4s_{2\theta}c_{HWB}\right)$	$\frac{v^2}{4}\Big(c_{HD}-4c_{H\ell}^{(3)}+2c_{ll}\Big)$
$\delta\lambda_\gamma$	$6c_W s_\theta$	$6c_W s_\theta$
$\delta\lambda_Z$	$6c_W c_\theta$	$6c_W c_\theta$

aTGC in the HEFT

$$\mathcal{L}_{WWV} = -\ ig_{WWV}\Big\{g_1^V\left(W^+_{\mu\nu}W^{-\,\mu}V^\nu - W^+_\mu V_\nu W^{-\,\mu\nu}\right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu}$$
$$- ig_5^V\varepsilon^{\mu\nu\rho\sigma}\left(W^+_\mu\partial_\rho W^-_\nu - W^-_\nu\partial_\rho W^+_\mu\right)V_\sigma +$$
$$+ g_6^V\left(\partial_\mu W^{+\mu}W^{-\nu} - \partial_\mu W^{-\mu}W^{+\nu}\right)V_\nu\Big\}$$

1311.1823

$g_{WWZ} = g\cos\theta\,,\quad g_{WW\gamma} = e$

	Coeff. $\times e^2/s^2_\theta$	Chiral
$\Delta\kappa_\gamma$	1	$-2c_1 + 2c_2 + c_3 - 4c_{12} + 2c_{13}$
Δg_6^γ	1	$-c_9$
Δg_1^Z	$\frac{1}{c_\theta^2}$	$\frac{s^2_{2\theta}}{4e^2 c_{2\theta}}c_T + \frac{2s^2_\theta}{c_{2\theta}}c_1 + c_3$
$\Delta\kappa_Z$	1	$\frac{s^2_\theta}{e^2 c_{2\theta}}c_T + \frac{4s^2_\theta}{c_{2\theta}}c_1 - \frac{2s^2_\theta}{ct^2}c_2 + c_3 - 4c_{12} + 2c_{13}$
Δg_5^Z	$\frac{1}{c_\theta^2}$	c_{14}
Δg_6^Z	$\frac{1}{c_\theta^2}$	$s^2_\theta c_9 - c_{16}$

aQGC in the HEFT

$$\mathcal{L}_{4X} \equiv g^2\Big\{ g^{(1)}_{ZZ}(Z_\mu Z^\mu)^2 + g^{(1)}_{WW}\, W^+_\mu W^{+\mu} W^-_\nu W^{-\nu} - g^{(2)}_{WW}(W^+_\mu W^{-\mu})^2 + g^{(3)}_{VV'} W^{+\mu}W^{-\nu}\left(V_\mu V'_\nu + V'_\mu V_\nu\right) - g^{(4)}_{VV'} W^+_\nu W^{-\nu} V^\mu V'_\mu + i g^{(5)}_{VV'} e^{\mu\nu\rho\sigma} W^+_\mu W^-_\nu V_\rho V'_\sigma \Big\}$$

1311.1823

	Coeff. $\times e^2/4s^2_\theta$	Chiral
$\Delta g^{(1)}_{WW}$	1	$\frac{s^2_{2\theta}}{e^2 c_{2\theta}} c_T + \frac{8s^2_\theta}{c_{2\theta}} c_1 + 4c_3 + 2c_{11} - 16c_{12} + 8c_{13}$
$\Delta g^{(2)}_{WW}$	1	$\frac{s^2_{2\theta}}{e^2 c_{2\theta}} c_T + \frac{8s^2_\theta}{c_{2\theta}} c_1 + 4c_3 - 4c_6 - \frac{v^2}{2} c_{\Box h} - 2c_{11} - 16c_{12} + 8c_{13}$
$\Delta g^{(1)}_{ZZ}$	$\frac{1}{c^4_\theta}$	$c_6 + \frac{v^2}{8} c_{\Box h} + c_{11} + 2c_{23} + 2c_{24} + 4c_{26}$
$\Delta g^{(3)}_{ZZ}$	$\frac{1}{c^2_\theta}$	$\frac{s^2_{2\theta} c^2_\theta}{e^2 c_{2\theta}} c_T + \frac{2s^2_{2\theta}}{c_{2\theta}} c_1 + 4c^2_\theta c_3 - 2s^4_\theta c_9 + 2c_{11} + 4s^2_\theta c_{16} + 2c_{24}$
$\Delta g^{(4)}_{ZZ}$	$\frac{1}{c^2_\theta}$	$\frac{2s^2_{2\theta} c^2_\theta}{e^2 c_{2\theta}} c_T + \frac{4s^2_{2\theta}}{c_{2\theta}} c_1 + 8c^2_\theta c_3 - 4c_6 - \frac{v^2}{2} c_{\Box h} - 4c_{23}$
$\Delta g^{(3)}_{\gamma\gamma}$	s^2_θ	$-2c_9$
$\Delta g^{(3)}_{\gamma Z}$	$\frac{s_\theta}{c_\theta}$	$\frac{s^2_{2\theta}}{e^2 c_{2\theta}} c_T + \frac{8s^2_\theta}{c_{2\theta}} c_1 + 4c_3 + 4s^2_\theta c_9 - 4c_{16}$
$\Delta g^{(4)}_{\gamma Z}$	$\frac{s_\theta}{c_\theta}$	$\frac{2s^2_{2\theta}}{e^2 c_{2\theta}} c_T + \frac{16s^2_\theta}{c_{2\theta}} c_1 + 8c_3$
$\Delta g^{(5)}_{\gamma Z}$	$\frac{s_\theta}{c_\theta}$	$8c_{14}$