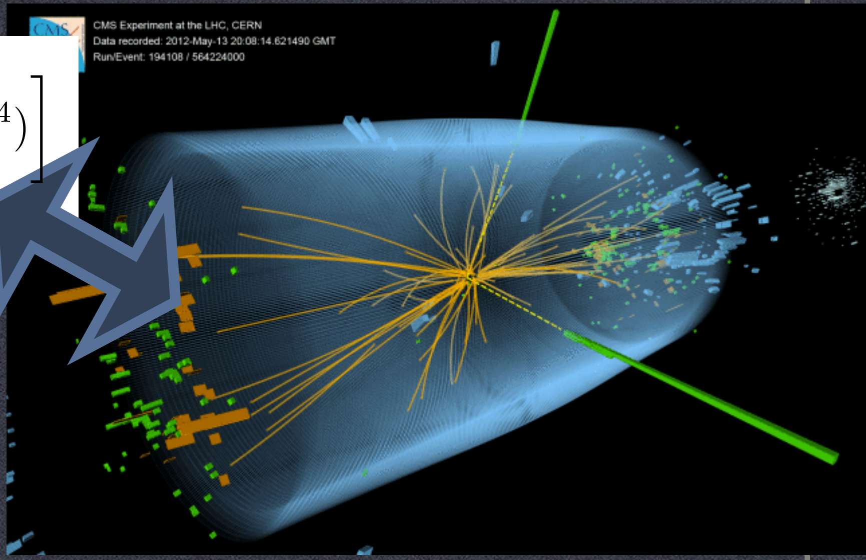
HIGGS THEORY: GENERAL AMPLITUDES FOR HIGGS AT COLLIDERS

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		[illegible]	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu} e_r)\tau^I\varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	[illegible]
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	[illegible]
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu \ldots$ [illegible]
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu} u_r)\tau^I\widetilde{\varphi}\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu \ldots$ [illegible]
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_p\tau^I\gamma \ldots$ [illegible]
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	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}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

$$\frac{c_1^{hZ\bar{f}f}}{v}(\bar{u}_{\rm L2}\not{\epsilon}_3^* u_{\rm L1})\left[1+\alpha_1\frac{s}{M^2}+\beta_1\frac{t}{M^2}+O(E^4/M^4)\right]$$



SPENCER CHANG (U. OREGON)

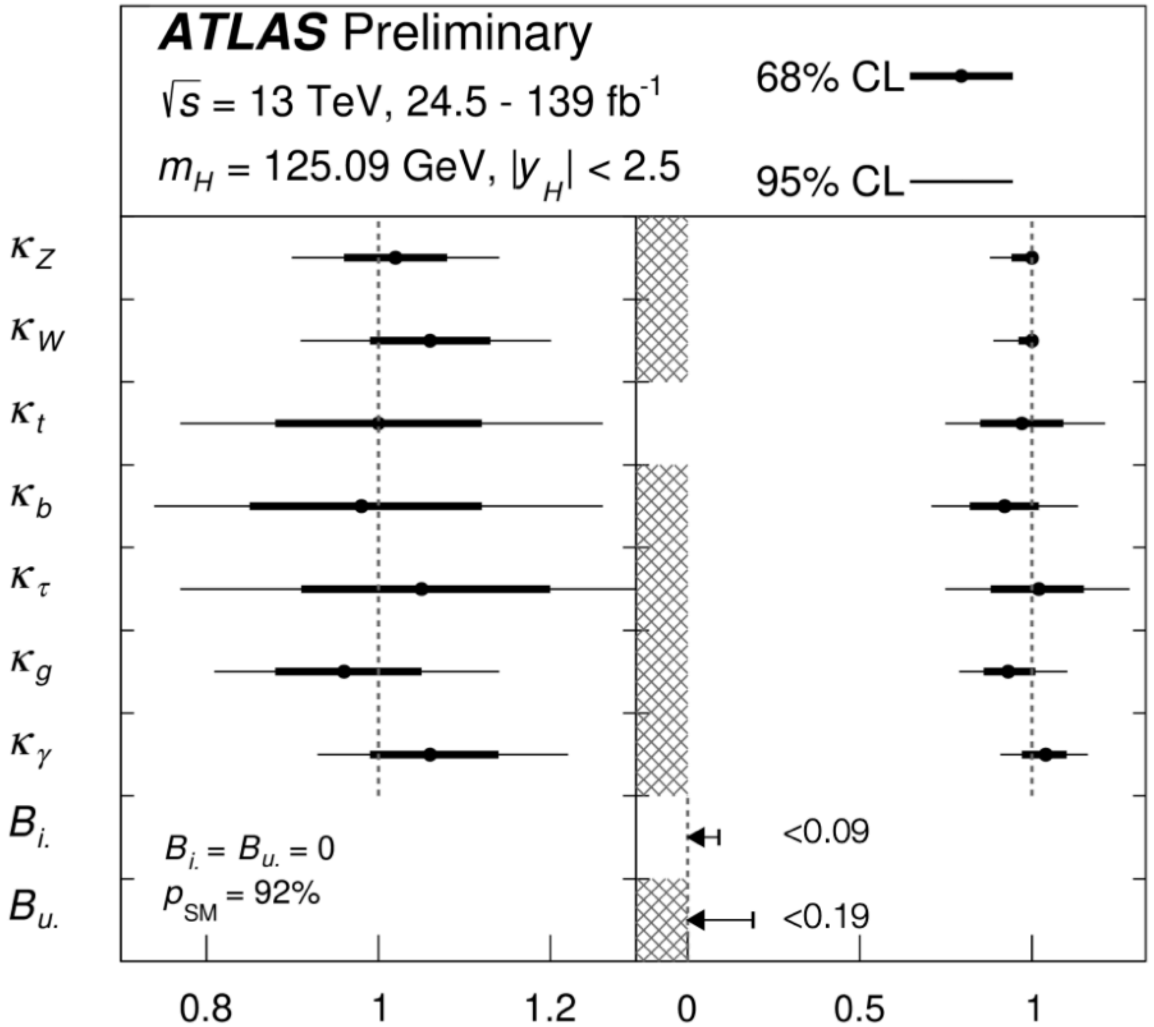
RECONTRES DE BLOIS 15/05/23

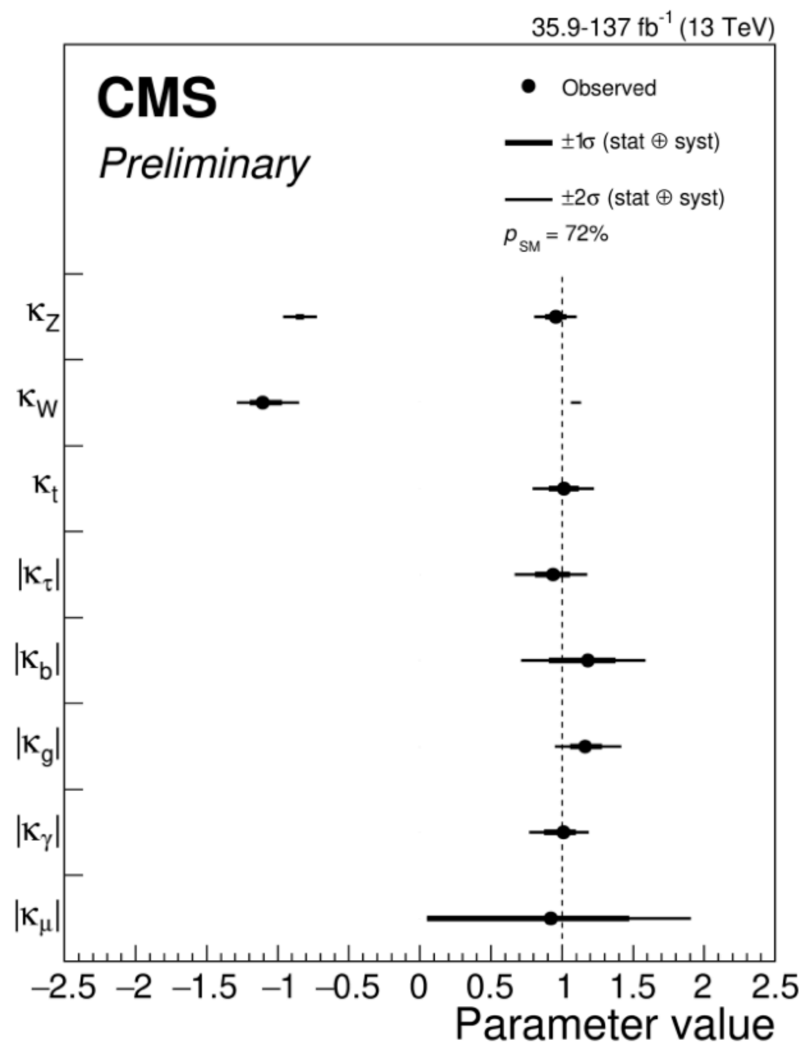
BASED ON 2212.06215 (W/ CHEN, LIU, & LUTY) AND 2304.06063 (W/ BRADSHAW)

SEE ALSO DURIEUX ET.AL. (1909.10551,2008.09652),

MA ET.AL. (2211.16515, 2301.11349)

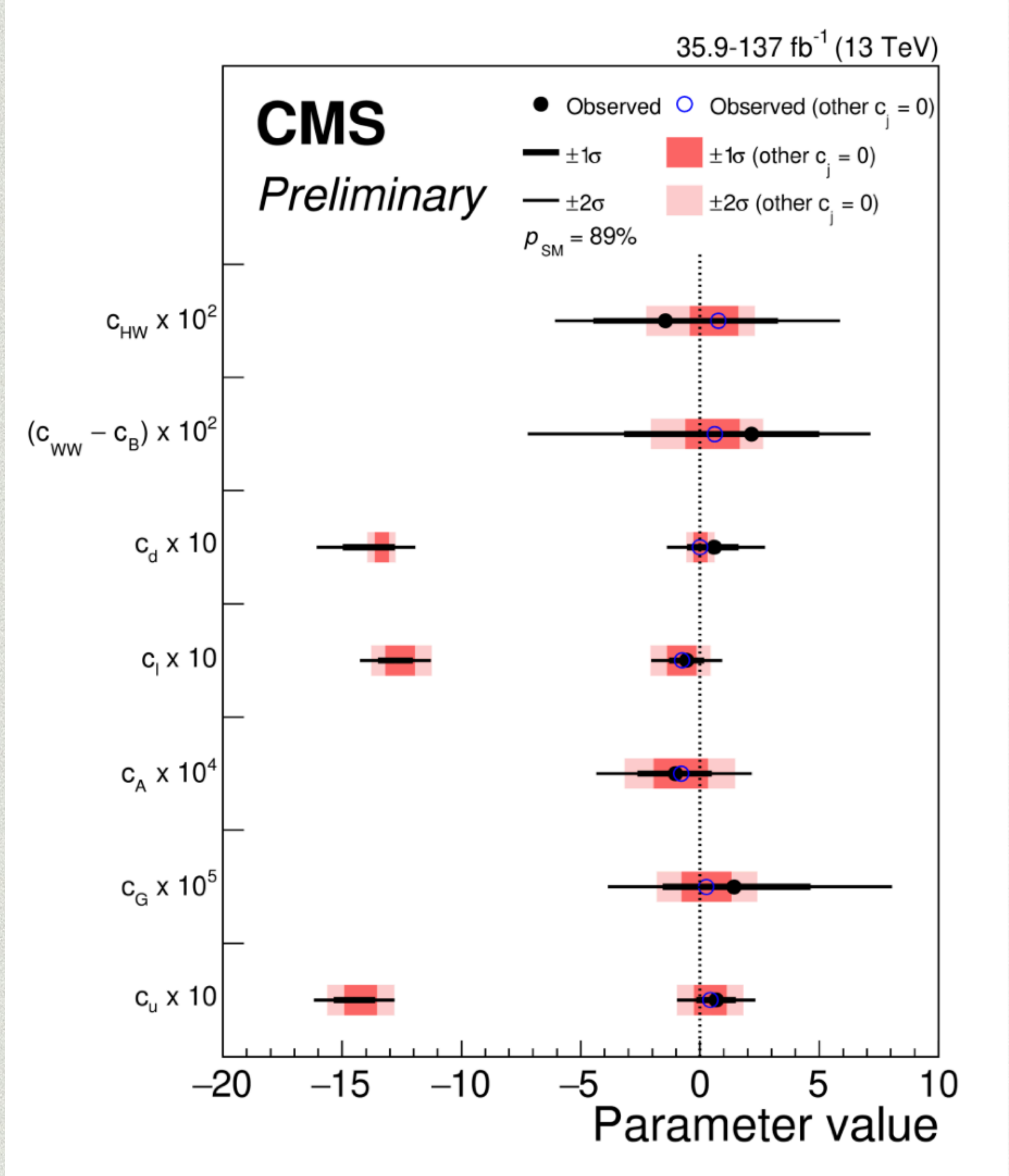
LHC Higgs

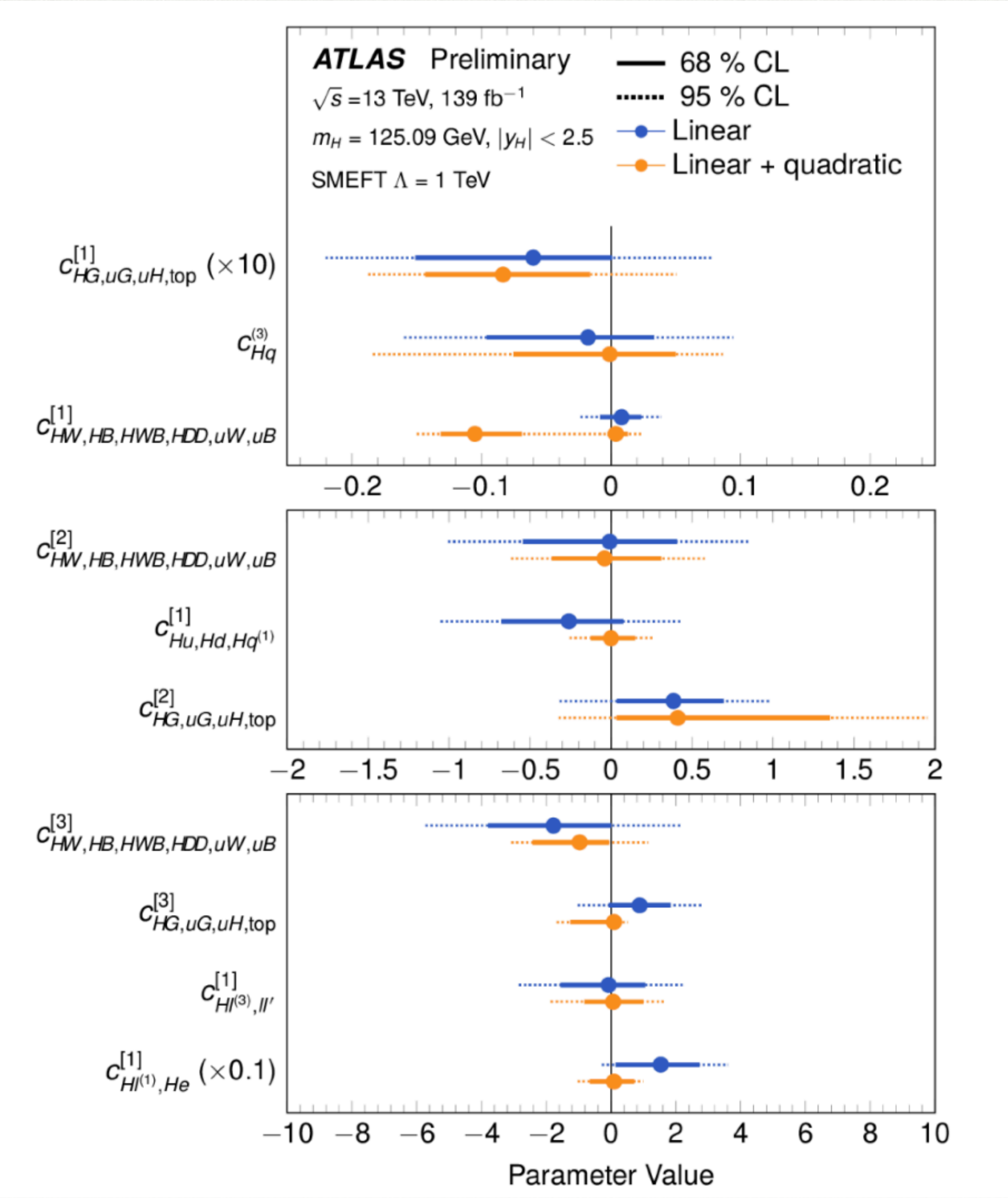




Current LHC data shows that Higgs is Standard Model-like, but as we enter the HL-LHC era, are we using the Higgs to look for new physics in the most general way?

Higgs EFT Analyses (SMEFT)





EFTs parametrize new physics, but make assumptions (e.g. linear vs nonlinear EWSB, power counting) and are nonintuitive

On-shell amplitudes as intermediary between theory (EFT, models) and experiment

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Theory

On-shell local amplitudes in one to one correspondence with independent EFT operators

(e.g. SMEFT operator basis from amplitudes Ma et.al. 1902.06752)

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Experiment

Experiments directly search for amplitudes not Wilson coefficients.

Since EFT is indirect, this motivated signal mapping (e.g. BSM primaries 1405.0181, pseudo-observables 1412.6038, Higgs basis)

EFT operator redundancies and on-shell amplitudes

Redundant Operators

Total Derivatives

$$\partial_\mu \mathcal{O}^\mu \approx 0$$

Equations of Motion

$$\frac{\delta S}{\delta \phi}\mathcal{O} = -(\Box\phi + m^2\phi + \cdots)\mathcal{O} \approx 0$$

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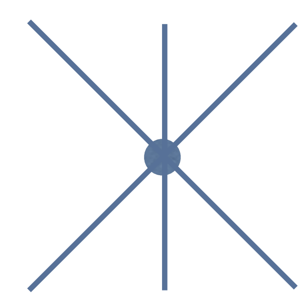
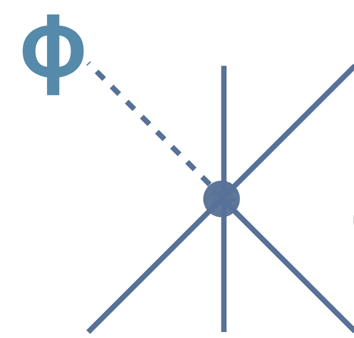
On-shell Amplitudes

Momentum Conservation



$$\left(\sum_{ext} p_\mu\right) X^\mu = 0$$

Mass Shell



$$(p^2 - m^2)X = 0$$

Independent Amplitudes

On-shell amplitudes M_i can be related to an operator O_i of lowest mass dimension, work in increasing dimension

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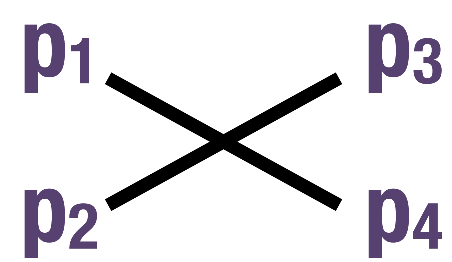
On-shell amplitudes M_i can be related to an operator O_i of lowest mass dimension, work in increasing dimension

Example: hhhh 4-Point Interaction

Dimension	M	# Independents	O
4	1	1	h^4
6	$s+t+u=4m_h^2$	None	None
8	$s^2+t^2+u^2$	1	$h^2\partial^\mu\partial^\nu h\partial_\mu\partial_\nu h$
10	stu	1	$\partial^\mu\partial^\nu\partial^\rho h\partial_\mu h\partial_\nu h\partial_\rho h$



$s = (p_1+p_2)^2$
$t = (p_1-p_3)^2$
$u = (p_1-p_4)^2$

2 to 2 scattering analysis
(w/ Chen, Liu, Luty)

Amplitude redundancies ($M = 0$), Taylor expansion of M in $\cos\Theta$, $|p_{initial}|$, $|p_{final}|$, E_{com} all coefficients must vanish

Allows numerical determination of independent amplitude terms

2 to 2 scattering analysis

(w/ Chen, Liu, Luty)

$$
\begin{aligned}
&M(f_1 \bar{f}_2 \to Z_3 h_4) = \\
&\epsilon^*_{3\mu} \bar{v}_2 \big[c_1 p_1^\mu + c_2 p_2^\mu + c_3 p_1^\mu \gamma_5 + c_4 p_2^\mu \gamma_5 + c_5 \gamma^\mu + c_6 p_1^\mu \not{p}_3 + c_7 p_2^\mu \not{p}_3 \\
&+ c_8 \gamma^\mu \gamma_5 + c_9 p_1^\mu \not{p}_3 \gamma_5 + c_{10} p_2^\mu \not{p}_3 \gamma_5 + c_{11} \gamma^{\mu\nu} p_{3\,\nu} \\
&+ \epsilon^{\mu\nu\rho\sigma} p_{1\,\nu} p_{2\,\rho} p_{3\,\sigma} \left(c_{12} + c_{13} \gamma_5 + c_{14} \not{p}_3 \right) \\
&+ \epsilon^{\mu\nu\rho\sigma} \gamma_\nu \left(c_{15} p_{1\,\rho} p_{2\,\sigma} + c_{16} p_{1\,\rho} p_{3\,\sigma} + c_{17} p_{2\,\rho} p_{3\,\sigma} \right) \\
&+ \epsilon^{\mu\nu\rho\sigma} p_{1\,\nu} p_{2\,\rho} p_{3\,\sigma} \left(c_{18} \not{p}_3 \gamma_5 \right) \\
&+ \epsilon^{\mu\nu\rho\sigma} \gamma_\nu \gamma_5 \left(c_{19} p_{1\,\rho} p_{2\,\sigma} + c_{20} p_{1\,\rho} p_{3\,\sigma} + c_{21} p_{2\,\rho} p_{3\,\sigma} \right) \\
&+ c_{22} \epsilon_{\nu\rho\sigma\gamma} \gamma^{\mu\nu} p_1^\rho p_2^\sigma p_3^\gamma \\
&+ \epsilon^{\mu\nu\rho\sigma} \gamma_{\nu\gamma} p_3^\gamma (c_{23} p_{1\,\rho} p_{2\,\sigma} + c_{24} p_{1\,\rho} p_{3\,\sigma} + c_{25} p_{2\,\rho} p_{3\,\sigma}) \\
&+ \epsilon^{\mu\nu\rho\sigma} \gamma_{\nu\rho} (c_{26} p_{1\,\sigma} + c_{27} p_{2\,\sigma} + c_{28} p_{3\,\sigma}) \\
&+ \epsilon^{\alpha\beta\gamma\delta} \gamma_\alpha p_{1\,\beta} p_{2\,\gamma} p_{3\,\delta} \left(c_{29} p_1^\mu + c_{30} p_2^\mu + c_{31} p_1^\mu \gamma_5 + c_{32} p_2^\mu \gamma_5 \right) \big] u_1
\end{aligned}
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&+ \epsilon^{\mu\nu\rho\sigma} p_{1\,\nu} p_{2\,\rho} p_{3\,\sigma}\left(c_{12} + c_{13}\gamma_5 + c_{14}\not{p}_3\right) \\
&+ \epsilon^{\mu\nu\rho\sigma}\gamma_\nu\left(c_{15} p_{1\,\rho} p_{2\,\sigma} + c_{16} p_{1\,\rho} p_{3\,\sigma} + c_{17} p_{2\,\rho} p_{3\,\sigma}\right) \\
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Amplitude redundancies (M = 0), Taylor expansion of M in cos Θ, |p_{initial}|, |p_{final}|, E_{com} all coefficients must vanish

i	$\mathcal{O}_i^{hZ\bar{f}f}$	CP	$d_{\mathcal{O}_i}$
1	$hZ^\mu\bar{\Psi}_L\gamma_\mu\Psi_L$	$+$	5
2	$hZ^\mu\bar{\Psi}_R\gamma_\mu\Psi_R$	$+$	
3	$hZ^{\mu\nu}\bar{\Psi}_L\sigma_{\mu\nu}\Psi_R + \text{h.c.}$	$+$	6
4	$h\tilde{Z}_{\mu\nu} i\bar{\Psi}_L\sigma^{\mu\nu}\Psi_R + \text{h.c.}$	$-$	
5	$i\,hZ^\mu(\bar{\Psi}_L\overleftrightarrow{\partial}_\mu\Psi_R) + \text{h.c.}$	$+$	6
6	$hZ^\mu\partial_\mu(\bar{\Psi}_L\Psi_R) + \text{h.c.}$	$-$	
7	$i\,hZ^\mu\partial_\mu(\bar{\Psi}_L\Psi_R) + \text{h.c.}$	$+$	
8	$hZ^\mu(\bar{\Psi}_L\overleftrightarrow{\partial}_\mu\Psi_R) + \text{h.c.}$	$-$	
9	$i\,h\tilde{Z}_{\mu\nu}(\bar{\Psi}_L\gamma^\mu\overleftrightarrow{\partial}^\nu\Psi_L)$	$+$	7
10	$h\tilde{Z}_{\mu\nu}\partial^\mu(\bar{\Psi}_L\gamma^\nu\Psi_L)$	$-$	
11	$i\,h\tilde{Z}_{\mu\nu}(\bar{\Psi}_R\gamma^\mu\overleftrightarrow{\partial}^\nu\Psi_R)$	$+$	
12	$h\tilde{Z}_{\mu\nu}\partial^\mu(\bar{\Psi}_R\gamma^\nu\Psi_R)$	$-$	

Allows numerical determination of independent amplitude terms

Note: need to include Mandelstams of lower dim operators

Hilbert Series Cross Check

A cross check comes from counting independent operators using the Hilbert series (Lehmann, Martin; Henning, et.al.; ...)

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Gives a generating function for number of operators
e.g. hhhh

$$H_{hhhh} = \frac{q^4}{(1-q^4)(1-q^6)} = q^4 + q^8 + q^{10} + \cdots$$

Interpretation: A term c q^n indicates c operators at dimension n

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Interpretation: A term $c\, q^n$ indicates c operators at dimension n

Note: Consistent with amplitude analysis, higher dimension operators are Mandelstam descendants of a single primary operator h^4, where denominator expansion gives factors of $s^2+t^2+u^2$ and stu

More detailed case hZff

$$H_{hZ\bar{f}f} = \frac{2q^5 + 6q^6 + 4q^7}{(1-q^2)^2}$$

Numerator suggests primary operators 2 at dim 5, 6 at dim 6, 4 at dim 7
Denominator gives factors of s, t to get descendants

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Denominator gives factors of s, t to get descendants

	i	$\mathcal{O}_i^{hZ\bar{f}f}$	CP	$d_{\mathcal{O}_i}$
2{	1	$hZ^\mu \bar{\Psi}_L \gamma_\mu \Psi_L$	+	5
	2	$hZ^\mu \bar{\Psi}_R \gamma_\mu \Psi_R$	+	
6{	3	$hZ^{\mu\nu} \bar{\Psi}_L \sigma_{\mu\nu} \Psi_R + \text{h.c.}$	+	6
	4	$h\tilde{Z}_{\mu\nu} i\bar{\Psi}_L \sigma^{\mu\nu} \Psi_R + \text{h.c.}$	−	
	5	$i\, hZ^\mu \big(\bar{\Psi}_L \overleftrightarrow{\partial}_\mu \Psi_R\big) + \text{h.c.}$	+	6
	6	$hZ^\mu \partial_\mu \big(\bar{\Psi}_L \Psi_R\big) + \text{h.c.}$	−	
	7	$i\, hZ^\mu \partial_\mu \big(\bar{\Psi}_L \Psi_R\big) + \text{h.c.}$	+	
	8	$hZ^\mu \big(\bar{\Psi}_L \overleftrightarrow{\partial}_\mu \Psi_R\big) + \text{h.c.}$	−	
4{	9	$i\, h\tilde{Z}_{\mu\nu} \big(\bar{\Psi}_L \gamma^\mu \overleftrightarrow{\partial}^\nu \Psi_L\big)$	+	7
	10	$h\tilde{Z}_{\mu\nu} \partial^\mu \big(\bar{\Psi}_L \gamma^\nu \Psi_L\big)$	−	
	11	$i\, h\tilde{Z}_{\mu\nu} \big(\bar{\Psi}_R \gamma^\mu \overleftrightarrow{\partial}^\nu \Psi_R\big)$	+	
	12	$h\tilde{Z}_{\mu\nu} \partial^\mu \big(\bar{\Psi}_R \gamma^\nu \Psi_R\big)$	−	

e.g. $\left(\frac{c_1}{v^2} + \frac{c_{1,s}}{v^4}s + \frac{c_{1,t}}{v^4}t + \frac{c_{1,ss}}{v^6}s^2 + \cdots\right) hZ^\mu \bar{\Psi}_L \gamma_\mu \Psi_L$

Interactions characterized

Higgs
(w/ Chen, Liu, Luty 2212.06215)
3pt: hhh, hff, hVV
4pt: hhhh, hhVV, hhff, hVff, hVVV
where V = W, Z, γ, g

Top
(w/ Bradshaw 2304.06063)
4pt: qqff, qqVV
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Top
(w/ Bradshaw 2304.06063)
4pt: qqff, qqVV
where V = W, Z, γ, g

Interestingly for qqff and qqVV, there are complete cancellations for some coefficients in the Hilbert Series numerator, where at certain mass dimensions, number of new primary operators requires amplitude analysis

Pheno Estimate Example (h→Zee)

1) Given an operator, e.g. at dim 6

$$i\frac{c}{v^2} h Z^\mu \bar{e}_L \overleftrightarrow{\partial}_\mu e_R + h.c.$$

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2) Find SMEFT realization to give conservative proxy for unitarity bound

$$(|H|^2 - \frac{v^2}{2})(H^\dagger \overleftrightarrow{D}^\mu H)(\bar{L}_L \overleftrightarrow{D}_\mu e_R)H + h.c.$$

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3) Unitarity bounds (e.g. 2009.11293)

WW→ee: $c \lesssim 0.1/(\mathrm{TeV}/E_{max})^3$

WWW→Wee: $c \lesssim 4/(\mathrm{TeV}/E_{max})^6$

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$WW \to ee$: $c \lesssim 0.1/(\mathrm{TeV}/E_{max})^3$

$WWW \to Wee$: $c \lesssim 4/(\mathrm{TeV}/E_{max})^6$

This interferes with SM amplitude, sensitivity estimate $N_{new} \gtrsim \sqrt{N_{SM}}$

At HL-LHC, requires $E_{max} \lesssim 5$ TeV, so this should be studied in detail

Pheno Summary

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- Unitarity bounds get more stringent for higher dimension amplitudes

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- Unitarity bounds get more stringent for higher dimension amplitudes
- Estimates show interesting amplitudes for Higgs and top decays at HL-LHC, e.g. $h \to f\bar{f}(Z,W)\gamma$ and $Z\gamma\gamma$) and $t \to c(\ell\ell, h\gamma, Z\gamma, \gamma\gamma)$ can occur at dim 8 and 10 in SMEFT

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- Understanding of primary and descendant amplitudes may enable approach to higher order uncertainties (work under discussion w/ Luty, Ma and Wulzer)

Thanks for your attention!

chang2@uoregon.edu

Extra Slides

Amplitude redundancies

$$\begin{aligned} 0 &= E_{\rm cm}^N \sum_a C_a \mathcal{M}_a \\ &= P + Qs + Rp_i + Sp_f + Tsp_i + Usp_f + Vp_ip_f + Wsp_ip_f \end{aligned}$$

P, Q, R, S, T, U, V, W are finite polynomials in E_{com}, which due to singularity structures, each polynomial must vanish exactly

$$X_\alpha^i = \frac{\partial d_\alpha}{\partial c_i}$$

Choose random particle masses and numerically take singular value decomposition of this matrix to find number of independent amplitudes (d_α are polynomial coefficients, c_i are operator coefficients)

hZff

i	$\mathcal{O}_i^{hZ\bar{f}f}$	CP	$d_{\mathcal{O}_i}$	SMEFT Operator	c Unitarity Bound
1	$hZ^\mu \bar{\Psi}_L \gamma_\mu \Psi_L$	$+$	5	$i(H^\dagger \overleftrightarrow{D}_\mu H)\bar{Q}_L\gamma^\mu Q_L$	$\frac{0.6}{E_{\text{TeV}}^2}, \frac{5}{E_{\text{TeV}}^4}$
2	$hZ^\mu \bar{\Psi}_R \gamma_\mu \Psi_R$	$+$		$i(H^\dagger \overleftrightarrow{D}_\mu H)\bar{u}_R\gamma^\mu u_R$	
3	$hZ^{\mu\nu} \bar{\Psi}_L \sigma_{\mu\nu} \Psi_R + \text{h.c.}$	$+$	6	$\bar{Q}_L\sigma^{\mu\nu}u_R\sigma^a\tilde{H}W^a_{\mu\nu} + \text{h.c.}$	$\frac{2}{E_{\text{TeV}}^2}, \frac{10}{E_{\text{TeV}}^4}$
4	$h\tilde{Z}_{\mu\nu} i\bar{\Psi}_L \sigma^{\mu\nu} \Psi_R + \text{h.c.}$	$-$		$\bar{Q}_L\sigma^{\mu\nu}u_R\sigma^a\tilde{H}\tilde{W}^a_{\mu\nu} + \text{h.c.}$	
5	$i\,hZ^\mu(\bar{\Psi}_L \overleftrightarrow{\partial}_\mu \Psi_R) + \text{h.c.}$	$+$	6	$(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L\overleftrightarrow{D}^\mu u_R)\tilde{H} + \text{h.c.}$	$\frac{0.1}{E_{\text{TeV}}^3}, \frac{4}{E_{\text{TeV}}^6}$
6	$hZ^\mu\partial_\mu(\bar{\Psi}_L\Psi_R) + \text{h.c.}$	$-$		$i(H^\dagger \overleftrightarrow{D}_\mu H)D^\mu(\bar{Q}_L u_R)\tilde{H} + \text{h.c.}$	
7	$i\,hZ^\mu\partial_\mu(\bar{\Psi}_L\Psi_R) + \text{h.c.}$	$+$		$(H^\dagger \overleftrightarrow{D}_\mu H)D^\mu(\bar{Q}_L u_R)\tilde{H} + \text{h.c.}$	
8	$hZ^\mu(\bar{\Psi}_L \overleftrightarrow{\partial}_\mu \Psi_R) + \text{h.c.}$	$-$		$i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L\overleftrightarrow{D}^\mu u_R)\tilde{H} + \text{h.c.}$	
9	$i\,h\tilde{Z}_{\mu\nu}(\bar{\Psi}_L\gamma^\mu\overleftrightarrow{\partial}^\nu\Psi_L)$	$+$	7	$i\lvert H\rvert^2\tilde{W}^{a\mu\nu}(\bar{Q}_L\gamma_\mu\sigma^a\overleftrightarrow{D}_\nu Q_L)$	$\frac{0.4}{E_{\text{TeV}}^3}, \frac{1}{E_{\text{TeV}}^4}$
10	$h\tilde{Z}_{\mu\nu}\partial^\mu(\bar{\Psi}_L\gamma^\nu\Psi_L)$	$-$		$\lvert H\rvert^2\tilde{W}^{a\mu\nu}D_\mu(\bar{Q}_L\gamma_\nu\sigma^a Q_L)$	
11	$i\,h\tilde{Z}_{\mu\nu}(\bar{\Psi}_R\gamma^\mu\overleftrightarrow{\partial}^\nu\Psi_R)$	$+$		$i\lvert H\rvert^2\tilde{B}^{\mu\nu}(\bar{u}_R\gamma_\mu\overleftrightarrow{D}_\nu u_R)$	
12	$h\tilde{Z}_{\mu\nu}\partial^\mu(\bar{\Psi}_R\gamma^\nu\Psi_R)$	$-$		$\lvert H\rvert^2\tilde{B}^{\mu\nu}D_\mu(\bar{u}_R\gamma_\nu u_R)$	

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i	$\mathcal{O}_i^{\bar q q Z\gamma}$	CP	$d_{\mathcal{O}_i}$	SMEFT Operator	c Unitarity Bound
1	$(\bar q\gamma^\nu q)\,(F_{\nu\mu}Z^\mu)$	$-$	6	$(\bar Q_L\gamma^\nu Q_L+\bar u_R\gamma^\nu u_R)\,(B_{\nu\mu}H^\dagger D^\mu H+\text{h.c.})$	$\frac{0.4}{E^3_{\text{TeV}}},\frac{1.2}{E^4_{\text{TeV}}}$
2	$(\bar q\gamma^\nu\gamma_5 q)\,(F_{\nu\mu}Z^\mu)$	$-$		$(\bar Q_L\gamma^\nu Q_L-\bar u_R\gamma^\nu u_R)\,(B_{\nu\mu}H^\dagger D^\mu H+\text{h.c.})$	
3	$(\bar q\gamma^\nu q)\left(\tilde F_{\nu\sigma}Z^\sigma\right)$	$+$		$(\bar Q_L\gamma^\nu Q_L+\bar u_R\gamma^\nu u_R)\left(\tilde B_{\nu\sigma}H^\dagger D^\sigma H+\text{h.c.}\right)$	
4	$(\bar q\gamma^\nu\gamma_5 q)\left(\tilde F_{\nu\sigma}Z^\sigma\right)$	$+$		$(\bar Q_L\gamma^\nu Q_L-\bar u_R\gamma^\nu u_R)\left(\tilde B_{\nu\sigma}H^\dagger D^\sigma H+\text{h.c.}\right)$	
5	$(\bar q q)\,(F_{\mu\nu}Z^{\mu\nu})$	$+$	7	$\left(\bar Q_L\tilde H u_R+\text{h.c.}\right)(B_{\mu\nu}B^{\mu\nu})$	$\frac{0.4}{E^3_{\text{TeV}}},\frac{1.2}{E^4_{\text{TeV}}}$
6	$(i\bar q\gamma_5 q)\,(F_{\mu\nu}Z^{\mu\nu})$	$-$		$\left(i\bar Q_L\tilde H u_R+\text{h.c.}\right)(B_{\mu\nu}B^{\mu\nu})$	
7	$(\bar q q)\left(\tilde F_{\mu\nu}Z^{\mu\nu}\right)$	$-$		$\left(\bar Q_L\tilde H u_R+\text{h.c.}\right)\left(B^{\mu\nu}\tilde B_{\mu\nu}\right)$	
8	$(i\bar q\gamma_5 q)\left(\tilde F_{\mu\nu}Z^{\mu\nu}\right)$	$+$		$\left(i\bar Q_L\tilde H u_R+\text{h.c.}\right)\left(B^{\mu\nu}\tilde B_{\mu\nu}\right)$	
9	$\left(i\bar q\overleftrightarrow{D}_\nu q\right)(F^{\nu\mu}Z_\mu)$	$-$	7	$\left(i\bar Q_L\overleftrightarrow{D}_\nu\tilde H u_R+\text{h.c.}\right)(B^{\nu\mu}H^\dagger D_\mu H+\text{h.c.})$	$\frac{0.09}{E^4_{\text{TeV}}},\frac{0.9}{E^6_{\text{TeV}}}$
10	$\left(\bar q\overleftrightarrow{D}_\nu\gamma_5 q\right)(F^{\nu\mu}Z_\mu)$	$+$		$\left(\bar Q_L\overleftrightarrow{D}_\nu\tilde H u_R+\text{h.c.}\right)(B^{\nu\mu}H^\dagger D_\mu H+\text{h.c.})$	
11	$\left(i\bar q\sigma_{\mu\nu}\overleftrightarrow{D}_\rho q\right)(F^{\mu\rho}Z^\nu)$	$+$		$\left(i\bar Q_L\sigma_{\mu\nu}\overleftrightarrow{D}_\rho\tilde H u_R+\text{h.c.}\right)(B^{\rho\mu}H^\dagger D^\nu H+\text{h.c.})$	
12	$(\bar q\sigma_{\mu\nu}q)\,(F^{\mu\rho}\partial_\rho Z^\nu)$	$-$		$\left(\bar Q_L\sigma_{\mu\nu}\tilde H u_R+\text{h.c.}\right)(B^{\mu\rho}H^\dagger D^\nu{}_\rho H+\text{h.c.})$	
13	$\left(\bar q\sigma_{\mu\nu}\gamma_5\overleftrightarrow{D}_\rho q\right)(F^{\mu\rho}Z^\nu)$	$-$		$\left(\bar Q_L\sigma_{\mu\nu}\overleftrightarrow{D}_\rho\tilde H u_R+\text{h.c.}\right)(B^{\mu\rho}H^\dagger D^\nu H+\text{h.c.})$	
14	$(i\bar q\sigma_{\mu\nu}\gamma_5 q)\,(F^{\mu\rho}\partial_\rho Z^\nu)$	$+$		$\left(i\bar Q_L\sigma_{\mu\nu}\tilde H u_R+\text{h.c.}\right)(B^{\mu\rho}H^\dagger D^\nu{}_\rho H+\text{h.c.})$	
15	$\left(i\bar q\overleftrightarrow{D}^\mu q\right)\left(\tilde F_{\mu\sigma}Z^\sigma\right)$	$+$		$\left(i\bar Q_L\overleftrightarrow{D}^\mu\tilde H u_R+\text{h.c.}\right)\left(\tilde B_{\mu\sigma}H^\dagger D^\sigma H+\text{h.c.}\right)$	
16	$\left(\bar q\gamma_5\overleftrightarrow{D}^\mu q\right)\left(\tilde F_{\mu\sigma}Z^\sigma\right)$	$-$		$\left(\bar Q_L\overleftrightarrow{D}^\mu\tilde H u_R+\text{h.c.}\right)\left(\tilde B_{\mu\sigma}H^\dagger D^\sigma H+\text{h.c.}\right)$	
17	$(\bar q\gamma^\nu q)\,([\partial_\nu F^{\mu\rho}]\,Z_{\mu\rho})$	$-$	8	$(\bar Q_L\gamma^\nu Q_L+\bar u_R\gamma^\nu u_R)\,([\partial_\nu B^{\mu\rho}]\,B_{\mu\rho})$	$\frac{0.09}{E^4_{\text{TeV}}}$
18	$(\bar q\gamma^\nu\gamma_5 q)\,([\partial_\nu F^{\mu\rho}]\,Z_{\mu\rho})$	$-$		$(\bar Q_L\gamma^\nu Q_L-\bar u_R\gamma^\nu u_R)\,([\partial_\nu B^{\mu\rho}]\,B_{\mu\rho})$	
19	$\left(i\bar q\gamma^\nu\overleftrightarrow{D}_\rho q\right)([\partial_\nu F^{\mu\rho}]\,Z_\mu)$	$+$	8	$\left(i\bar Q_L\gamma^\nu\overleftrightarrow{D}_\rho Q_L+i\bar u_R\gamma^\nu\overleftrightarrow{D}_\rho u_R\right)([\partial_\nu B^{\mu\rho}]\,H^\dagger D_\mu H+\text{h.c.})$	$\frac{0.02}{E^5_{\text{TeV}}},\frac{0.07}{E^6_{\text{TeV}}}$
20	$\left(i\bar q\gamma^\nu\gamma_5\overleftrightarrow{D}_\rho q\right)([\partial_\nu F^{\mu\rho}]\,Z_\mu)$	$+$		$\left(i\bar Q_L\gamma^\nu\overleftrightarrow{D}_\rho Q_L-\bar u_R\gamma^\nu\overleftrightarrow{D}_\rho u_R\right)([\partial_\nu B^{\mu\rho}]\,H^\dagger D_\mu H+\text{h.c.})$	
21	$\left(i\bar q\gamma^\nu\overleftrightarrow{D}_\mu q\right)(F^{\mu\rho}\partial_\rho Z_\nu)$	$+$		$\left(i\bar Q_L\gamma^\nu\overleftrightarrow{D}_\mu Q_L+i\bar u_R\gamma^\nu\overleftrightarrow{D}_\mu u_R\right)(B^{\mu\rho}H^\dagger D_{\nu\rho}H+\text{h.c.})$	
22	$\left(i\bar q\gamma^\nu\gamma_5\overleftrightarrow{D}_\mu q\right)(F^{\mu\rho}\partial_\rho Z_\nu)$	$+$		$\left(i\bar Q_L\gamma^\nu\overleftrightarrow{D}_\mu Q_L-i\bar u_R\gamma^\nu\overleftrightarrow{D}_\mu u_R\right)(B^{\mu\rho}H^\dagger D_{\nu\rho}H+\text{h.c.})$	
23	$\left(\bar q\gamma_\mu\overleftrightarrow{D}_{\nu\rho}q\right)(F^{\mu\rho}Z^\nu)$	$-$		$\left(\bar Q_L\gamma_\mu\overleftrightarrow{D}_{\nu\rho}Q_L+\bar u_R\gamma_\mu\overleftrightarrow{D}_{\nu\rho}u_R\right)(B^{\mu\rho}H^\dagger D^\nu H+\text{h.c.})$	
24	$\left(\bar q\gamma_\mu\gamma_5\overleftrightarrow{D}_{\nu\rho}q\right)(F^{\mu\rho}Z^\nu)$	$-$		$\left(\bar Q_L\gamma_\mu\overleftrightarrow{D}_{\nu\rho}Q_L-\bar u_R\gamma_\mu\overleftrightarrow{D}_{\nu\rho}u_R\right)(B^{\mu\rho}H^\dagger D^\nu H+\text{h.c.})$	
25	$\left(\bar q\overleftrightarrow{D}_{\mu\nu}q\right)(F^{\mu\rho}\partial_\rho Z^\nu)$	$+$	9	$\left(\bar Q_L\overleftrightarrow{D}_{\mu\nu}\tilde H u_R+\text{h.c.}\right)(B^{\mu\rho}H^\dagger D^\nu{}_\rho H+\text{h.c.})$	$\frac{0.006}{E^6_{\text{TeV}}},\frac{0.05}{E^8_{\text{TeV}}}$
26	$\left(i\bar q\gamma_5\overleftrightarrow{D}_{\mu\nu}q\right)(F^{\mu\rho}\partial_\rho Z^\nu)$	$-$		$\left(i\bar Q_L\overleftrightarrow{D}_{\mu\nu}\tilde H u_R+\text{h.c.}\right)(B^{\mu\rho}H^\dagger D^\nu{}_\rho H+\text{h.c.})$	

Hilbert Series (Higgs)

$$H_{h\bar{f}f} = 2q^4, \quad H_{h\gamma Z} = H_{h\gamma\gamma} = H_{hgg} = 2q^5, \quad H_{hZZ} = H_{hWW} = q^3 + 2q^5,$$
$$H_{hhZ} = H_{hh\gamma} = 0, \quad H_{hhh} = q^3,$$
$$H_{\gamma\bar{f}f} = 2q^5, \quad H_{Z\bar{f}f} = H_{W\bar{f}f'} = 2q^4 + 2q^5,$$
$$H_{WWZ} = 5q^4 + 2q^6, \quad H_{WW\gamma} = 2q^4 + 2q^6, \quad H_{ggg} = 2q^6,$$
$$H_{ZZZ} = H_{ZZ\gamma} = H_{Z\gamma\gamma} = H_{Zgg} = 0.$$

$$H_{hZ\bar{f}f} = H_{hW\bar{f}'f} = \frac{2q^5 + 6q^6 + 4q^7}{(1-q^2)^2}, \quad H_{h\gamma\bar{f}f} = H_{hg\bar{f}f} = \frac{2q^6 + 4q^7 + 2q^8}{(1-q^2)^2},$$
$$H_{hZ\gamma\gamma} = H_{hZgg} = \frac{3q^7 + 7q^9 + 2q^{11}}{(1-q^2)(1-q^4)}, \quad H_{hggg} = \frac{2q^7 + 2q^9 + 4q^{11} + 6q^{13} + 2q^{15}}{(1-q^4)(1-q^6)},$$
$$H_{h\gamma gg} = \frac{4q^9 + 4q^{11}}{(1-q^2)(1-q^4)}, \quad H_{h\gamma\gamma\gamma} = \frac{2q^{11} + 4q^{13} + 2q^{15}}{(1-q^4)(1-q^6)},$$
$$H_{hWW\gamma} = \frac{2q^5 + 14q^7 + 2q^9}{(1-q^2)^2}, \quad H_{hZZ\gamma} = \frac{8q^7 + 8q^9 + 2q^{11}}{(1-q^2)(1-q^4)},$$
$$H_{hWWZ} = \frac{9q^5 + 18q^7}{(1-q^2)^2}, \quad H_{hZZZ} = \frac{q^5 + 6q^7 + 8q^9 + 7q^{11} + 5q^{13}}{(1-q^4)(1-q^6)},$$
$$H_{hh\bar{f}f} = \frac{2q^5 + 2q^8}{(1-q^2)(1-q^4)},$$
$$H_{hhWW} = \frac{q^4 + 3q^6 + 5q^8}{(1-q^2)(1-q^4)}, \quad H_{hhZZ} = \frac{q^4 + 3q^6 + 2q^8}{(1-q^2)(1-q^4)}$$
$$H_{hhZ\gamma} = \frac{2q^6 + 4q^8}{(1-q^2)(1-q^4)}, \quad H_{hh\gamma\gamma} = H_{hhgg} = \frac{2q^6 + q^8}{(1-q^2)(1-q^4)},$$
$$H_{hhhZ} = \frac{q^7 + q^9 + q^{13}}{(1-q^4)(1-q^6)}, \quad H_{hhh\gamma} = \frac{2q^{13}}{(1-q^4)(1-q^6)},$$

Hilbert Series top

$$H_{WW\bar{f}f} = H_{WZ\bar{f}f'} = \frac{4q^5 + 12q^6 + 16q^7 + 6q^8 - 2q^9}{(1-q^2)^2},$$

$$H_{ZZ\bar{f}f} = \frac{2q^5 + 6q^6 + 12q^7 + 6q^8 + 6q^9 + 6q^{10} - 2q^{11}}{(1-q^2)(1-q^4)},$$

$$H_{Z\gamma\bar{f}f} = H_{Zg\bar{f}f} = H_{W\gamma\bar{f}f'} = H_{Wg\bar{f}f'} = \frac{4q^6 + 12q^7 + 8q^8 + (2-2)q^9}{(1-q^2)^2},$$

$$H_{g\gamma\bar{f}f} = \frac{6q^7 + 8q^8 + (4-2)q^9}{(1-q^2)^2}, \quad H_{\gamma\gamma\bar{f}f} = \frac{4q^7 + 2q^8 + 4q^9 + 6q^{10} + (2-2)q^{11}}{(1-q^2)(1-q^4)},$$

$$H_{gg\bar{f}f} = \frac{10q^7 + 10q^8 + (14-2)q^9 + 14q^{10} + (6-4)q^{11}}{(1-q^2)(1-q^4)},$$

$$H_{\bar{q}q\bar{\ell}\ell} = H_{\bar{q}q'\bar{e}\nu} = H_{q_1q_2q_3\ell} = \frac{10q^6 + 8q^7 - 2q^8}{(1-q^2)^2},$$

$$H_{qqq'\ell} = \frac{4q^6 + 6q^7 + (6-2)q^8 + 2q^9}{(1-q^2)(1-q^4)}, \quad H_{\bar{q}\bar{q}'qq'} = \frac{2(10q^6 + 8q^7 - 2q^8)}{(1-q^2)^2},$$

$$H_{\bar{q}\bar{q}'qq} = H_{\bar{q}\bar{q}qq'} = \frac{10q^6 + 8q^7 + (10-2)q^8 + 8q^9 - 2q^{10}}{(1-q^2)(1-q^4)},$$

$$H_{\bar{q}\bar{q}qq} = \frac{8q^6 + 4q^7 + (8-2)q^8 + 4q^9 - 2q^{10}}{(1-q^2)(1-q^4)}.$$

Hilbert Series Cancellation

$$H_{\gamma\gamma\bar{f}f} = \frac{4q^7 + 2q^8 + 4q^9 + 6q^{10} + (2-2)q^{11}}{(1-q^2)(1-q^4)}$$

i	$\mathcal{O}_i^{\bar{q}q\gamma\gamma}$	CP	$d_{\mathcal{O}_i}$	SMEFT Operator	c Unitarity Bound
1	$(\bar{q}q)\,(F^{\mu\nu}F_{\mu\nu})$	$+$	7	$\left(\bar{Q}_L\tilde{H}u_R + \text{h.c.}\right)(B^{\mu\nu}B_{\mu\nu})$	$\frac{0.4}{E_{\text{TeV}}^3}, \frac{1.2}{E_{\text{TeV}}^4}$
2	$(\bar{q}i\gamma_5 q)\,(F^{\mu\nu}F_{\mu\nu})$	$-$		$\left(i\bar{Q}_L\tilde{H}u_R + \text{h.c}\right)(B^{\mu\nu}B_{\mu\nu})$	
3	$(\bar{q}q)\left(F^{\mu\nu}\tilde{F}_{\mu\nu}\right)$	$-$		$\left(\bar{Q}_L\tilde{H}u_R + \text{h.c.}\right)\left(B^{\mu\nu}\tilde{B}_{\mu\nu}\right)$	
4	$(i\bar{q}\gamma_5 q)\left(F^{\mu\nu}\tilde{F}_{\mu\nu}\right)$	$+$		$\left(i\bar{Q}_L\tilde{H}u_R + \text{h.c.}\right)\left(B^{\mu\nu}\tilde{B}_{\mu\nu}\right)$	
5	$\left(i\bar{q}\gamma^\nu\overleftrightarrow{D}_\mu q\right)(F^{\mu\rho}F_{\rho\nu})$	$+$	8	$\left(i\bar{Q}_L\overleftrightarrow{D}_\mu\gamma^\nu Q_L + i\bar{u}_R\overleftrightarrow{D}_\mu\gamma^\nu u_R\right)(B^{\mu\rho}B_{\rho\nu})$	$\frac{0.09}{E_{\text{TeV}}^4}$
6	$\left(i\bar{q}\gamma^\nu\gamma_5\overleftrightarrow{D}_\mu q\right)(F^{\mu\rho}F_{\rho\nu})$	$+$		$\left(i\bar{Q}_L\overleftrightarrow{D}_\mu\gamma^\nu Q_L - i\bar{u}_R\overleftrightarrow{D}_\mu\gamma^\nu u_R\right)(B^{\mu\rho}B_{\rho\nu})$	
7	$\left(i\bar{q}\sigma_{\mu\nu}\overleftrightarrow{D}_\rho q\right)(F^{\mu\sigma}\partial^\rho F^\nu{}_\sigma)$	$+$	9	$\left(i\bar{Q}_L\sigma_{\mu\nu}\overleftrightarrow{D}_\rho\tilde{H}u_R + \text{h.c.}\right)(B^{\mu\sigma}\partial^\rho B^\nu{}_\sigma)$	$\frac{0.02}{E_{\text{TeV}}^5}, \frac{0.07}{E_{\text{TeV}}^6}$
8	$\left(\bar{q}\sigma_{\mu\nu}\gamma_5\overleftrightarrow{D}_\rho q\right)(F^{\mu\sigma}\partial^\rho F^\nu{}_\sigma)$	$-$		$\left(\bar{Q}_L\sigma_{\mu\nu}\overleftrightarrow{D}_\rho\tilde{H}u_R + \text{h.c.}\right)(B^{\mu\sigma}\partial^\rho B^\nu{}_\sigma)$	
9	$\left(\bar{q}\overleftrightarrow{D}_{\mu\nu}q\right)(F^{\mu\rho}F^\nu{}_\rho)$	$+$		$\left(\bar{Q}_L\overleftrightarrow{D}_{\mu\nu}\tilde{H}u_R + \text{h.c.}\right)(B^{\mu\rho}B^\nu{}_\rho)$	
10	$\left(i\bar{q}\gamma_5\overleftrightarrow{D}_{\mu\nu}q\right)(F^{\mu\rho}F^\nu{}_\rho)$	$-$		$\left(i\bar{Q}_L\overleftrightarrow{D}_{\mu\nu}\tilde{H}u_R + \text{h.c.}\right)(B^{\mu\rho}B^\nu{}_\rho)$	
11	$\left(i\bar{q}\gamma^\nu\overleftrightarrow{D}_\rho q\right)([\partial_\nu F^{\mu\sigma}]\,\partial^\rho F_{\mu\sigma})$	$+$	10	$\left(i\bar{Q}_L\gamma^\nu\overleftrightarrow{D}_\rho Q_L + i\bar{u}_R\gamma^\nu\overleftrightarrow{D}_\rho u_R\right)([\partial_\nu B^{\mu\sigma}]\,\partial^\rho B_{\mu\sigma})$	$\frac{0.006}{E_{\text{TeV}}^6}$
12	$\left(i\bar{q}\gamma^\nu\gamma_5\overleftrightarrow{D}_\rho q\right)([\partial_\nu F^{\mu\sigma}]\,\partial^\rho F_{\mu\sigma})$	$+$		$\left(i\bar{Q}_L\gamma^\nu\overleftrightarrow{D}_\rho Q_L - i\bar{u}_R\gamma^\nu\overleftrightarrow{D}_\rho u_R\right)([\partial_\nu B^{\mu\sigma}]\,\partial^\rho B_{\mu\sigma})$	
13	$\left(\bar{q}\gamma^\nu\overleftrightarrow{D}_{\mu\sigma}q\right)(F^{\mu\rho}\partial^\sigma F_{\nu\rho})$	$-$		$\left(\bar{Q}_L\gamma^\nu\overleftrightarrow{D}_{\mu\sigma}Q_L + \bar{u}_R\gamma^\nu\overleftrightarrow{D}_{\mu\sigma}u_R\right)(B^{\mu\rho}\partial^\sigma B_{\nu\rho})$	
14	$\left(\bar{q}\gamma^\nu\gamma_5\overleftrightarrow{D}_{\mu\sigma}q\right)(F^{\mu\rho}\partial^\sigma F_{\nu\rho})$	$-$		$\left(\bar{Q}_L\gamma^\nu\overleftrightarrow{D}_{\mu\sigma}Q_L - \bar{u}_R\gamma^\nu\overleftrightarrow{D}_{\mu\sigma}u_R\right)(B^{\mu\rho}\partial^\sigma B_{\nu\rho})$	
15	$\left(\bar{q}\gamma^\nu\overleftrightarrow{D}_{\alpha\beta}q\right)\left(\tilde{F}_{\nu\sigma}\partial^\beta F^{\sigma\alpha}\right)$	$+$		$\left(\bar{Q}_L\gamma^\nu\overleftrightarrow{D}_{\alpha\beta}Q_L + \bar{u}_R\gamma^\nu\overleftrightarrow{D}_{\alpha\beta}u_R\right)\left(\tilde{B}_{\nu\sigma}\partial^\beta B^{\sigma\alpha}\right)$	
16	$\left(\bar{q}\gamma^\nu\gamma_5\overleftrightarrow{D}_{\alpha\beta}q\right)\left(\tilde{F}_{\nu\sigma}\partial^\beta F^{\sigma\alpha}\right)$	$+$		$\left(\bar{Q}_L\gamma^\nu\overleftrightarrow{D}_{\alpha\beta}Q_L - \bar{u}_R\gamma^\nu\overleftrightarrow{D}_{\alpha\beta}u_R\right)\left(\tilde{B}_{\nu\sigma}\partial^\beta B^{\sigma\alpha}\right)$	
17	$\left(\bar{q}\sigma_{\mu\nu}\overleftrightarrow{D}_{\sigma\alpha}q\right)(F^{\mu\rho}\partial^\alpha_\rho F^{\nu\sigma})$	$-$	11	$\left(\bar{Q}_L\sigma_{\mu\nu}\overleftrightarrow{D}_{\sigma\alpha}\tilde{H}u_R + \text{h.c.}\right)(B^{\mu\rho}\partial^\alpha_\rho B^{\nu\sigma})$	$\frac{0.001}{E_{\text{TeV}}^7}, \frac{0.004}{E_{\text{TeV}}^8}$
18	$\left(i\bar{q}\sigma_{\mu\nu}\gamma_5\overleftrightarrow{D}_{\sigma\alpha}q\right)(F^{\mu\rho}\partial^\alpha_\rho F^{\nu\sigma})$	$+$		$\left(i\bar{Q}_L\sigma_{\mu\nu}\overleftrightarrow{D}_{\sigma\alpha}\tilde{H}u_R + \text{h.c.}\right)(B^{\mu\rho}\partial^\alpha_\rho B^{\nu\sigma})$	

At dim 11, O_{17} and O_{18} are new, but s O_7 and s O_8 are redundant so $-2q^{11}$ gets rid of terms s f(s,t) $O_{7/8}$