GeoSMEFT and an application

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Based on: TC, A. Helset, A. Martin, M. Trott, arXiv:2102.02819

SMEFT

In studying NP at $\Lambda_{\mathrm{NP}} \gg v$, we employ the Standard Model EFT

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots \qquad \mathcal{L}_d = \sum_i c_i Q_i$$

The SMEFT is formed of $\mathcal{L}_{\mathrm{SM}}$ and Q of $d > 4$ respecting SM symmetries & c_i embedding UV physics

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The leading operator:

$$\mathcal{L}_5 = c_{\alpha\beta}(\bar{L}^c_\alpha \tilde{H})(\tilde{H}^\dagger L_\beta) \sim v^2 \bar{\nu}_\alpha \nu_\beta$$

$$\Rightarrow m_\nu \sim v^2/\Lambda$$

The SMEFT at dimension-six

D6 operators from SM field content $\Rightarrow$ SMEFT @ D6

Type I: X^3		Type II, III: $H^6,\ H^4D^2$		Type V: Ψ^2H^3 + h.c.	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	Q_{eH}	$(H^\dagger H)(\bar L e H)$
$Q_{\tilde G}$	$f^{ABC}\tilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{uH}	$(H^\dagger H)(\bar Q u\tilde H)$
Q_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	Q_{HD}	$(H^\dagger D^\mu H)^*(H^\dagger D^\mu H)$	Q_{dH}	$(H^\dagger H)(\bar Q d H)$
$Q_{\tilde W}$	$\epsilon^{IJK}\tilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

Type IV: $X^2\Phi^2$		Type VI: Ψ^2H^3		Type VII: Ψ^2H^2D	
Q_{HG}	$(H^\dagger H)G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar L\sigma^{\mu\nu}e)\tau^I HW_{\mu\nu}^I$	$Q_{HL}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar L\gamma^\mu L)$
$Q_{H\tilde G}$	$(H^\dagger H)\tilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar L\sigma^{\mu\nu}e)\tau^I HB_{\mu\nu}$	$Q_{HL}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar L\tau^I\gamma^\mu L)$
Q_{HW}	$(H^\dagger H)W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar Q\sigma^{\mu\nu}T^A u)\tilde H G_{\mu\nu}^A$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e\gamma^\mu e)$
$Q_{H\tilde W}$	$(H^\dagger H)\tilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar Q\sigma^{\mu\nu}u)\tau^I\tilde H W_{\mu\nu}^I$	$Q_{HQ}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q\gamma^\mu q)$
Q_{HB}	$(H^\dagger H)B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar Q\sigma^{\mu\nu}u)\tilde H B_{\mu\nu}$	$Q_{HQ}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar q\tau^I\gamma^\mu q)$
$Q_{H\tilde B}$	$(H^\dagger H)\tilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar Q\sigma^{\mu\nu}T^A d)HG_{\mu\nu}^A$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u\gamma^\mu u)$
Q_{HWB}	$(H^\dagger\tau^I H)W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar Q\sigma^{\mu\nu}d)\tau^I HW_{\mu\nu}^I$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d\gamma^\mu d)$
$Q_{H\tilde WB}$	$(H^\dagger\tau^I H)\tilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar Q\sigma^{\mu\nu}d)\tilde H B_{\mu\nu}$	Q_{Hud}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u\gamma^\mu d)$

Type VIII: $5\times\underline{(\bar LL)(\bar LL)}+7\times\underline{(\bar RR)(\bar RR)}+8\times\underline{(\bar LL)(\bar RR)}$
$+(\bar LR)(\bar RL)+4[(\bar LR)(\bar LR)+\text{h.c.}]=25(\bar\Psi\Psi)(\bar\Psi\Psi)$

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$Q_{\tilde{G}}$					$(H^\dagger H)(\bar{Q}u\tilde{H})$
Q_W					$(H^\dagger H)(\bar{Q}dH)$
$Q_{\tilde{W}}$					

				VII: Ψ^2H^2D	
Q_{HG}					$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{L}\gamma^\mu L)$
$Q_{H\tilde{G}}$					$H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{L}\tau^I\gamma^\mu L)$
Q_{HW}					$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$
$Q_{H\tilde{W}}$					$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$
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Q_{HWB}	$(H^\dagger\tau^I H)W^I_{\mu\nu}B^{\mu\nu}$	Q_{dW}	$(\bar{Q}\sigma^{\mu\nu}d)\tau^I HW^I_{\mu\nu}$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$
$Q_{H\tilde{W}B}$	$(H^\dagger\tau^I H)\tilde{W}^I_{\mu\nu}B^{\mu\nu}$	Q_{dB}	$(\bar{Q}\sigma^{\mu\nu}d)\tilde{H}B_{\mu\nu}$	Q_{Hud}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu d)$

1. Take Field Content:
   X – Field Strengths
   Ψ – Fermions
   H – Higgs doublets
   D – Covariant Derivatives
2. Form D6 operators:
   $X^3,\ H^6,\ H^4D^2,\ \Psi^2H^3,\ H^2X^2,\ \Psi^2HX,\ \Psi^2H^2D,\ \Psi^4$
3. Remove, e.g., $XD\Psi^2$ and $(DX)^2$ via field redef./EOM

Type VIII: $5\times(\bar{L}L)(\bar{L}L)+7\times(\bar{R}R)(\bar{R}R)+8\times(\bar{L}L)(\bar{R}R)$
$+(\bar{L}R)(\bar{R}L)+4[(\bar{L}R)(\bar{L}R)+\mathrm{h.c.}]=25(\bar{\Psi}\Psi)(\bar{\Psi}\Psi)$

The geoSMEFT, or SMEFT to all orders $\frac{v}{\Lambda}$

(the very simplified version)

1. Take SM field content, X, Ψ, H, D
2. Form Lorentz invariant, but gauge variant combos of ≥ 3 fields
3. stick towers of $H^\dagger H$ and/or $H^\dagger \tau^A H \rightarrow$ gauge invariant
   use Hilbert Series to confirm all operators included/no redundancy
   (see e.g. Lehman & Martin 2015, Henning et al. 2015)

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For example:

$$\mathcal{L}_{\rm class3} = (DH)^\dagger (DH) + \frac{c_{H\Box}}{\Lambda^2}|H|^2\Box|H|^2 + \frac{c_{HD}}{\Lambda^2}|H^\dagger DH|^2 + \frac{c_{HD}^{(8)}}{\Lambda^4}|H|^4|DH|^2 + \frac{c_{HD,2}^{(8)}}{\Lambda^4}|H|^2(H^\dagger\tau^A H)(DH)^\dagger\tau^A(DH) + \mathcal{O}\left(\frac{1}{\Lambda^6}\right)$$

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&+ \frac{c_{HD}^{(8)}}{\Lambda^4} |H|^4 |DH|^2 + \frac{c_{HD,2}^{(8)}}{\Lambda^4} |H|^2 (H^\dagger \tau^A H)(DH)^\dagger \tau^A (DH) + \mathcal{O}\left(\frac{1}{\Lambda^6}\right) \\
&\rightarrow h_{IJ} (D\phi)^I (D\phi)^J
\end{aligned}
$$

$$
\begin{aligned}
h_{IJ} &\equiv \left[1 + \phi^2 \frac{c_{H\Box}}{\Lambda^2} + \sum_{n=0}^{\infty} \left(\frac{\phi^2}{2}\right)^{n+2} \left(\frac{c_{HD}^{(8+2n)} - c_{HD,2}^{(8+2n)}}{\Lambda^{2+2n}}\right)\right] \delta_{IJ} \\
&+ \frac{\Gamma_{A,J}^I \phi_K \Gamma_{A,L}^K \phi^L}{2} \left(\frac{c_{HD}^{(6)}}{2\Lambda^2} + \sum_{n=0}^{\infty} \left(\frac{\phi^2}{2}\right)^{n+1} \frac{c_{H,D2}^{(8+2n)}}{\Lambda^{2+2n}}\right)
\end{aligned}
$$

three–point functions from geoSMEFT

operator form	shifts:
$h_{IJ}(D\phi)^I(D\phi)^J$	SM 3–point functions + Masses
$g_{AB}W^A_{\mu\nu}W^{B,\mu\nu}$	SM triple gauge couplings + $h(\partial V)^2$ + mixing angles
$Y^\psi \bar{\Psi}_L \psi_R + h.c.$	SM Yukawas+ψ masses
$L^\psi_J (D^\mu\phi)^J(\bar{\psi}\Gamma_\mu\psi)$	SM gauge-fermion couplings
$d^\psi_A W^{A,\mu\nu}(\bar{\psi}\sigma_{\mu\nu}\psi)$	Dipoles
$f_{ABC}W^{A,\mu\nu}W^B_{\nu\rho}W^{C,\rho}_\mu$	new TGCs $(\partial V)^3$
$\kappa^A_{IJ}(D_\mu\phi)^I(D_\nu\phi)^J W^A_{\mu\nu}$	new TGCs $(\partial h)^2(\partial V)$, removed from D6 in Warsaw

geoSMEFT on the Z-pole

operator form	shifts:
$h_{IJ}(D\phi)^I(D\phi)^J$	SM 3–point functions + Masses
$g_{AB}W^A_{\mu\nu}W^{B,\mu\nu}$	SM triple gauge couplings + $h(\partial V)^2$ + mixing angles
$L^\psi_J(D^\mu\phi)^J(\bar{\psi}\Gamma_\mu\psi)$	SM gauge-fermion couplings

$$\Gamma_{Z\to\bar{\psi}\psi} = \frac{N_c^\psi}{24\pi}\bar{m}_Z|g_{\rm eff}^{Z,\psi}|^2\left(1-\frac{4\bar{m}_\psi^2}{\bar{m}_Z^2}\right)^{3/2}$$

$$g_{\rm eff}^{Z,\psi} = \frac{\bar{g}_Z}{2}\left[(2s^2_{\theta_Z}Q_\psi-\sigma_3)+\bar{v}_T\langle L^\psi_{3,4}\rangle+\sigma_3\bar{v}_T\langle L^\psi_{3,3}\rangle\right]$$

$$\bar{m}_Z^2 = \frac{\bar{g}_Z}{4}^2\langle h_{33}\rangle\bar{v}_T^2 \qquad s^2_{\theta_Z} = f(\langle g_{AB}\rangle, g_1, g_2)$$

Z-pole pheno, arXiv:2102.02819

1. **Calculate the following:**
   $\Gamma_{e,\mu}$, Γ_τ, Γ_ν, Γ_c, Γ_b, Γ_Z,
   R_l, R_c, R_b, $A^l_{\rm FB}$, $A^c_{\rm FB}$, $A^b_{\rm FB}$, $\sigma^0_{\rm Had}$
2. **Supplement with SM predictions up to two-loops**
   Awramik et al. hep-ph/0608099, Dubovyk et al. arXiv:1906.08815
   Freitas arXiv: 1401.2447, Awramik et al. hep-ph/0311148
3. **Interpolate SM pred. to $\{M_W, M_Z, G_F\}$ input scheme from $\{\alpha, M_Z, G_F\}$**
   $\rightarrow$ allows for comparison of scheme dependence

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   Need alternative approach to studying impact of D8
   Brivio, Trott, arXiv:1703.10924

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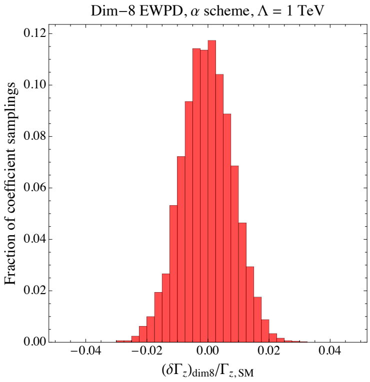
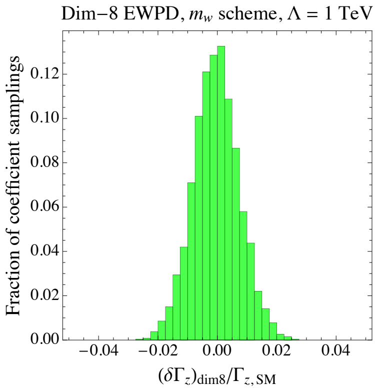
5. **use $\delta\mathcal{O}_8/\mathcal{O}_{\rm SM}$ as a measure of impact of D8 operators on $\mathcal{O}$**
6. **take $\Lambda = 1$ TeV**
7. **randomly sample values of c_i**
   between 1 ("tree"–) and .01 ("loop"–induced operator assumption)

Z-pole pheno, arXiv:2102.02819





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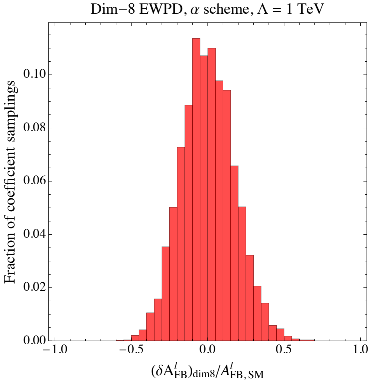

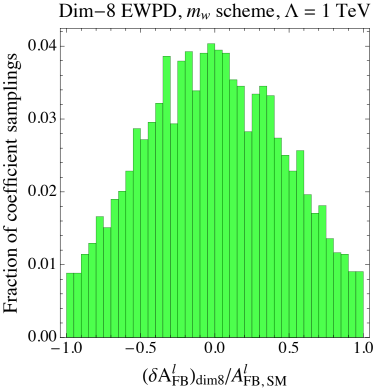

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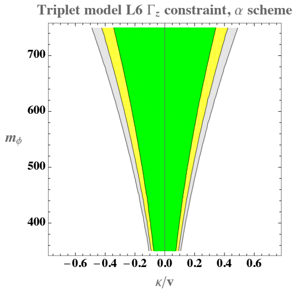
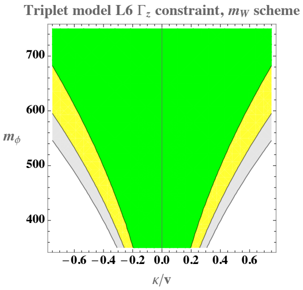
   Need alternative approach to studying impact of D8
   Brivio, Trott, arXiv:1703.10924
5. **Take triplet scalar model w $Y_\Phi = 0$ and match to SMEFT to D8**
6. **Perform χ^2 analysis to Z–pole data**
   gives constraints in the M_Φ–κ plane ($2\kappa H^\dagger \tau^a H \Phi^a$, $\eta |H|^2 \Phi^2$ w/ $\eta = .1$)

Z-pole pheno, arXiv:2102.02819





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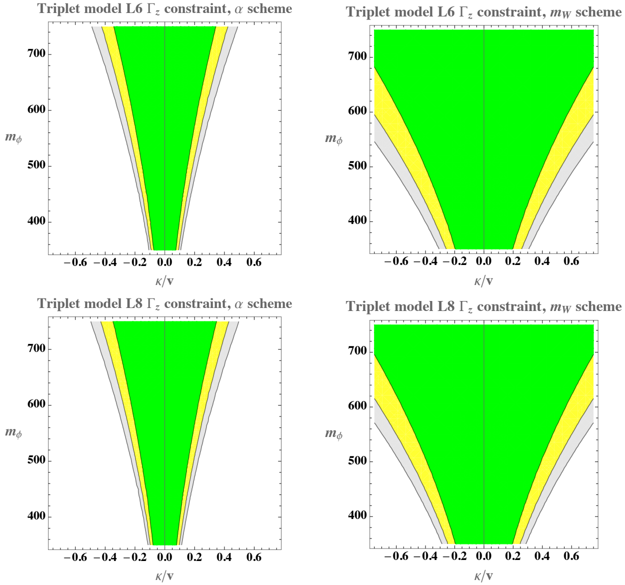

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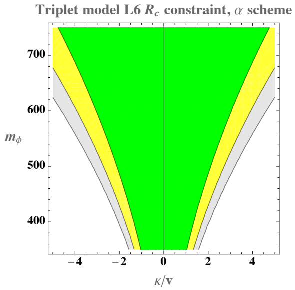

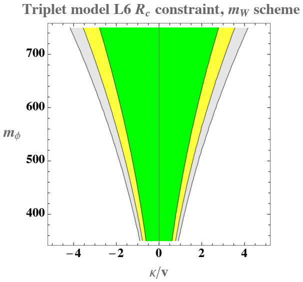

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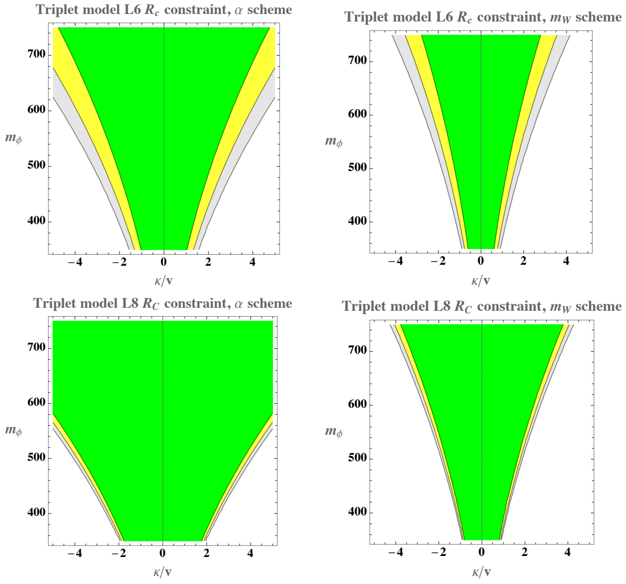

Truncation error

An amplitude squared in the SMEFT is defined perturbatively as:

$$|\mathcal{M}|^2 = |\mathcal{M}_{\rm SM}|^2 + \frac{2}{\Lambda^2}{\rm Re}\left[\mathcal{M}_{\rm SM}^*\mathcal{M}_6\right] + \frac{1}{\Lambda^4}\left(|\mathcal{M}_6|^2 + {\rm Re}\left[\mathcal{M}_{\rm SM}^*\mathcal{M}_8\right]\right) + \mathcal{O}\left(\frac{1}{\Lambda^6}\right)$$

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LO SMEFT contribution

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LO SMEFT contribution

Frequently used to "approximate" truncation error sometimes is **bigger** than LO contribution

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LO SMEFT contribution

Full NLO result possible with geoSMEFT
⇒ More consistent definition of truncation error

Frequently used to “approximate” truncation error
sometimes is **bigger** than LO contribution

Truncation error

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LO S

vith geoSMEFT
of truncation error

sometimes is **bigger** than LO contribution

A more consistent definition of truncation error

1. Calculate consistently to D8 (geoSMEFT)
2. Many new open parameters appear, $c_i^{(8)}$ (can't be constrained by current experiments)
3. Vary the new parameters in some way $\Rightarrow$ infer truncation error (similar to above examples)

Conclusions

1. the geoSMEFT allows for (some) all orders in v/Λ calculations in the SMEFT
   $\rightarrow$ most resonant processes doable, w/ some innovation can push to $\sim$all

2. all Z-pole observables have been full calculated to all orders in v/Λ
   $\rightarrow$ in two different input parameter schemes, M_W and α

3. inclusion of D8 can have impact of $\sim$ % in most cases
   $\rightarrow$ EWPD observables are (mostly) measured to per-mil accuracy
   $\rightarrow$ D8 is important for EWPD!

4. inclusion of D8 can have a large impact in other cases
   $\rightarrow$ HL-LHC precision goes to $\mathcal{O}(\%)$ for Higgs

5. geoSMEFT allows us to calculate beyond LO in SMEFT
   $\rightarrow$ a more reliable estimate of truncation error

Wednesday 10:30, Adam Martin talks more about geoSMEFT $\Rightarrow$ $HZ\gamma$, $H\gamma\gamma$

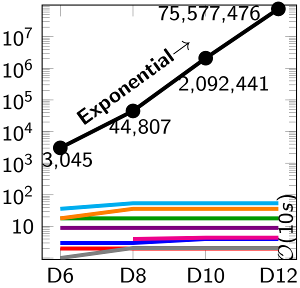
geoSMEFT in loops, TC arXiv:2106.10284

geoSMEFT D8 + Loops D6, $gg \rightarrow H \rightarrow \gamma\gamma$, TC, Martin, Trott, arXiv:2107.07470

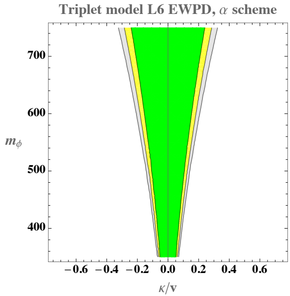
Saturation of number of operators

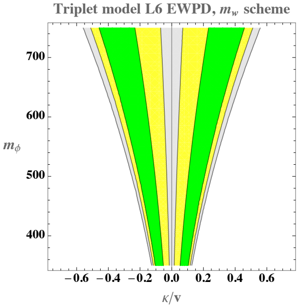
(This information is contained in the Hilbert Series)
(see e.g. Lehman & Martin 2015, Henning et al. 2015)

	Mass Dimension		
Operator form:	6	8	10
$h_{IJ}(D_\mu\phi)^I(D^\mu\phi)^J$	2	2	2
$g_{AB}W^A_{\mu\nu}W^{B,\mu\nu}$	3	4	4
$k_{IJA}(D^\mu\phi)^I(D^\nu\phi)^J W^A_{\mu\nu}$	0	3	4
$f_{ABC}W^A_{\mu\nu}W^{B,\nu\rho}W^{C,\mu}_\rho$	1	2	2
$Y^\psi_{pr}\bar{\Psi}_L\psi_R + h.c.$	$2N_f^2$	$2N_f^2$	$2N_f^2$
$d_A^{\psi,pr}\bar{\Psi}_L\sigma_{\mu\nu}\psi_R W_A^{\mu\nu} + h.c.$	$4N_f^2$	$6N_f^2$	$6N_f^2$
$L^{\psi_R}_{pr,J,A}(D^\mu\phi)^J(\bar{\psi}_{p,R}\gamma_\mu\sigma_A\psi_{r,R})$	N_f^2	N_f^2	N_f^2
$L^{\Psi_L}_{pr,J,A}(D^\mu\phi)^J(\bar{\Psi}_{p,L}\gamma_\mu\sigma_A\Psi_{r,L})$	$2N_f^2$	$4N_f^2$	$4N_f^2$

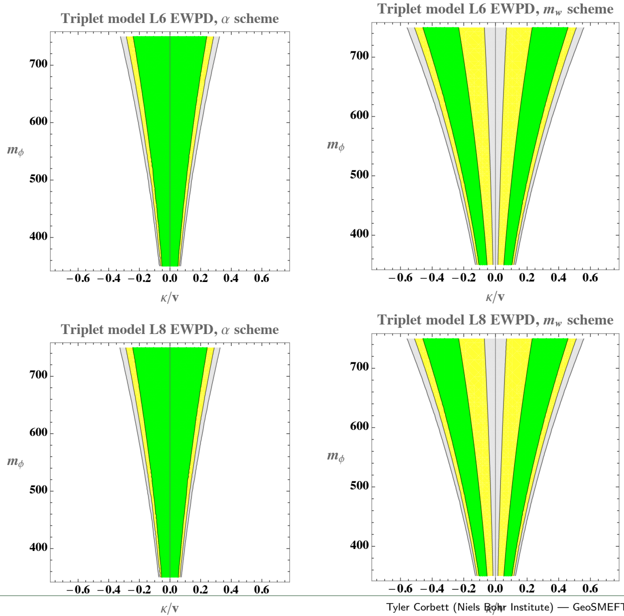


Z-pole pheno, arXiv:2102.02819

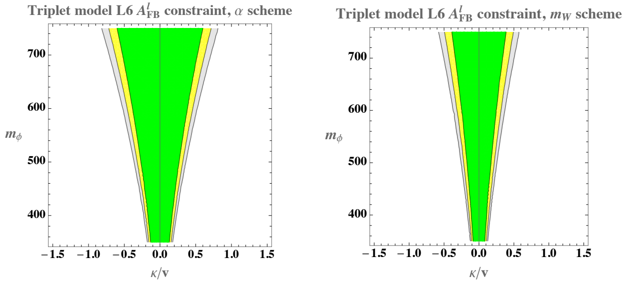




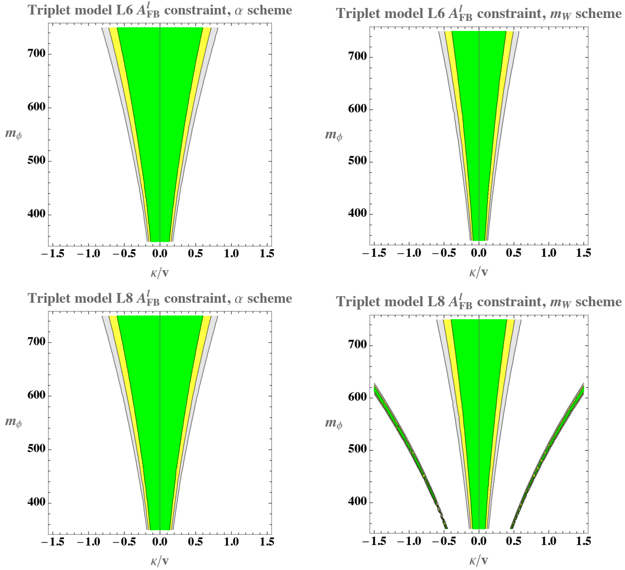
Z-pole pheno, arXiv:2102.02819



Z-pole pheno, arXiv:2102.02819



Z-pole pheno, arXiv:2102.02819



Backup: Inclusion of Cl 3 & 4 operators

Following geosmeft (Helset & Trott 1803.08001, + Martin 2001.01453) rewrite the doublet:

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_2 + i\phi_1 \\ \phi_4 - i\phi_3 \end{pmatrix} \Rightarrow \phi_I = \{\phi_1, \phi_2, \phi_3, \phi_4\}$$

Then defining the field-space metric, h:

$$h_{IJ} \equiv \delta_{IJ} - 2c_{H\Box}\phi_I\phi_J + \frac{1}{4}c_{HD}\Gamma^A_{IJ}\Gamma^A_{KL}\phi_K\phi_L \qquad (\Gamma \text{ are matrices})$$

Then the Class 3 operators are written in simple form:

$$\begin{aligned} \mathcal{L}_{\mathrm{cl3}} &= h_{IJ}(D^\mu\phi)^I(D_\mu\phi)^J \\ &= (D^\mu H)^\dagger(D_\mu H) + c_{H\Box}(H^\dagger H)\Box(H^\dagger H) + c_{HD}(H^\dagger D^\mu H)^*(H^\dagger D_\mu H) \end{aligned}$$

Backup: Inclusion of Cl 3 & 4 operators

Then the Class 3 and 4 operators are written in simple form:

$$
\begin{aligned}
\mathcal{L}_{\rm cl3} &= h_{IJ}(D^\mu\phi)^I(D_\mu\phi)^J \\
\mathcal{L}_{\rm cl4} &= -\frac{1}{4}g_{AB}W_{A\mu\nu}W_{B\mu\nu}
\end{aligned}
$$

Backup: Inclusion of Cl 3 & 4 operators

Then the Class 3 and 4 operators are written in simple form:

$$\begin{aligned} \mathcal{L}_{\mathrm{cl3}} &= h_{IJ}(D^\mu\phi)^I(D_\mu\phi)^J \\ \mathcal{L}_{\mathrm{cl4}} &= -\frac{1}{4}g_{AB}W_{A\mu\nu}W_{B\mu\nu} \end{aligned}$$

Can trivially include D8 ops. of Cl. 3 & 4 by updating h and g:

$$\begin{aligned} h_{IJ} &= \left[1+\frac{\phi^4}{4}\left(c_{HD}^{(8)}+c_{HD2}^{(8)}\right)\right]\delta_{IJ}-2c_{H\Box}\phi_I\phi_J \\ &+\frac{1}{4}\left(c_{HD}+\phi^2 c_{HD2}^{(8)}\right)\Gamma_{IJ}^A\Gamma_{KL}^A\phi_K\phi_L \\ g_{AB} &= \delta_{AB}-4\left[c_{HW}(1-\delta_{A4})+c_{HB}\delta_{A4}\right]\frac{\phi^2}{2}\delta_{AB} \\ &-4\left[c_{HW}^{(8)}(1-\delta_{A4})+c_{HB}^{(8)}\delta_{A4}\right]\frac{\phi^4}{4}\delta_{AB} \\ &+\left(c_{HWB}+c_{HWB}^{(8)}\frac{\phi^2}{2}\right)\left[(\phi_I\Gamma_{IJ}^A\phi_J)(1-\delta_{A4})\delta_{B4}+A\leftrightarrow B\right] \\ &-c_{HW2}^{(8)}(\phi_I\Gamma_{IJ}^A\phi_J)(\phi_L\Gamma_{LK}^B\phi_K)(1-\delta_{A4})(1-\delta_{B4}) \end{aligned}$$