Exploring Extended Scalar Sectors with Di–Higgs Signals: A Higgs EFT Perspective

Tyler Corbett

Melbourne Node

arXiv:1705.02551, with Aniket Joglekar (Chicago), Hao-Lin Li (Amherst), Jiang-Hao Yu (Amherst).

Motivation

- Single Higgs data constrains operators relevant to single Higgs processes*

- No measurement of tri–Higgs coupling
  $\Rightarrow$ independent measurement of λ
  or wilson coefficient of $Q_H = (H^\dagger H)^3$ are not possible

- We consider simplest UV–completions which shift the tri–Higgs coupling
  $\rightarrow$ and work from an EFT point of view

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Topologies generating H^6 operator (tree level)

↓

UV models generating H^6 operator (tree level)

↓

UV and IR Lagrangians

↓

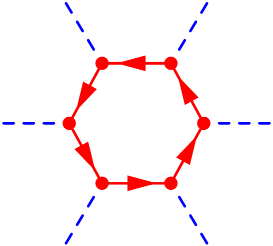
Single Higgs Constraints

↓

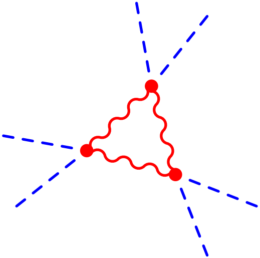
Di–Higgs predictions

$Q_H = (H^\dagger H)^3$ topologies

Note: Lorentz Invariance will prevent tree level Q_H from fermions or vectors:



$\sim \frac{g^6}{16\pi^2 M^2}$



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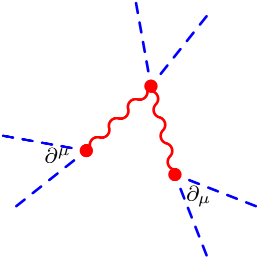
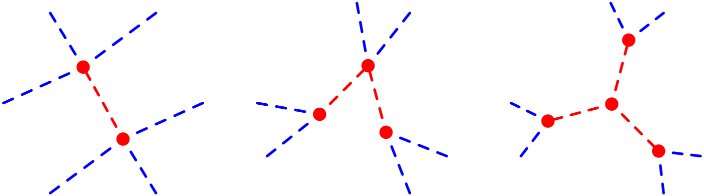


$\sim \frac{g^4}{M^4} p^2 \Rightarrow (H^\dagger H)^2 \partial^2 (H^\dagger H)$

$Q_H = (H^\dagger H)^3$ at Tree Level, cont.

With scalars tree–level Q_H is possible:



$\sim \frac{(\lambda')^2}{M^2}$ $\sim \frac{\mu^2\lambda'}{M^4}$ $\sim \frac{(\mu)^3\mu'}{M^6}$

Then the question is:

What extended scalar sectors can generate these topologies?

- Must be an $SU(3)_c$ singlet, the Higgs is uncolored.
- Must be in rep. of $SU(2)_L$ w/ $\lambda'(H^3\Phi)$ and/or $\mu(H^2\Phi)$ invariant
- From there hypercharge is a given:
  $\Rightarrow H^3\Phi \rightarrow Y_\phi = \{\pm 3Y_H, \pm Y_H\}$
  $\Rightarrow H^2\Phi \rightarrow Y_\phi = \{0, \pm 2Y_H\}$

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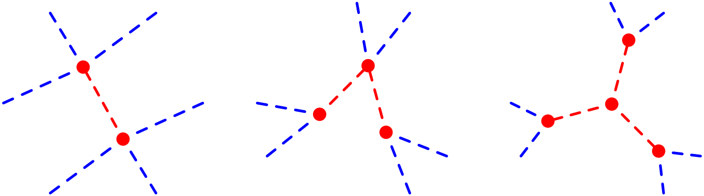

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Some Group Theory...

Clearly a SM singlet and a 2HDM work as we can form $H^3\Phi$.

What other representations work?

$$\begin{aligned} 2\otimes 2 &= 3_S + 1_A \\ 2\otimes 2\otimes 2 &= 4_S + 2 \end{aligned}$$

So triplets will work!

- $\mathbb{R}$ triplet w/ $H^\dagger H\phi$ must have $Y_\phi = 0$
- $\mathbb{C}$ triplet w/ $H^2\Phi$ must have $Y_\Phi = 2Y_H$

Quadruplets will also work!

- $\mathbb{R}$ quadruplet won't work, because we have either $(H^\dagger H)H\Phi$ or $H^3\Phi$ so $Y_\phi \neq 0$
- $\mathbb{C}$ quadruplet can have $H^3\Phi$ and $Y_{\Phi 1} = 3Y_H$
- $\mathbb{C}$ quadruplet can also have $(H^\dagger H)H\Phi$ and $Y_{\Phi 2} = Y_H$

However, we neglect quadruplet models (haven't completed the analyses yet)...

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$\mathbb{R}$ Scalar Singlet Example

Taking the $\mathbb{R}$ Scalar Singlet as an example:

$$\mathcal{L} = (D^\mu H)^\dagger (D_\mu H) + |\mu|^2 (H^\dagger H) - \lambda (H^\dagger H)^2 + \Delta\mathcal{L}$$

Where for this model $\Delta\mathcal{L}$ is given by:

$$\Delta\mathcal{L} = \frac{1}{2}(\partial^\mu S)(\partial_\mu S) - \frac{M^2}{2} S^2 - \frac{g}{3} S^3 - \boldsymbol{g_{HS}(H^\dagger H)S} - \frac{\lambda_S}{4} S^4 - \frac{\lambda_{HS}}{2}(H^\dagger H) S^2$$

Integrating out the heavy S at tree level we find,

$$\Delta\mathcal{L} = \frac{g_{HS}}{2M^2}|H|^4 - \left(\frac{\lambda_{HS}}{2} - \frac{g g_{HS}}{3M^2}\right)\frac{g_{HS}}{M^4}(H^\dagger H)^3 - \frac{g_{HS}}{2M^4}(H^\dagger H)\Box(H^\dagger H)$$

- Note we generate a finite–renormalization of λ
- We generate (as expected) $Q_H = (H^\dagger H)^3$,
  $\Rightarrow$ but also $Q_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$

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Preliminary Summary –

We can summarize our derived EFTs as follows,

$$Q_{H\Box} = (H^\dagger H)\Box(H^\dagger H) \qquad Q_{eH} = (H^\dagger H)(\bar{L}He_R)$$

$$Q_{HD} = (D^\mu H)^\dagger H H^\dagger (D_\mu H) \qquad Q_{uH} = (H^\dagger H)(\bar{Q}\tilde{H}u_R)$$

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W/ each model generating these operators as follows:

Theory	c_H	$c_{H\Box}$	c_{HD}	c_{HD2}	$c_{\psi H}$
ℝ Singlet	✓	✓	✗	✗	✗
ℂ Singlet	✓	✓	✗	✗	✗
2HDM, Type I	✓	✗	✗	✗	✓
ℝ Triplet	✓	✓	✓	✓	✗
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Higgs Global Fits

Since the Higgs discovery,

global fits of the Higgs EFT to single Higgs experimental results has become an industry*...

TC, OJP Éboli, J Gonzalez-Fraile, MC Gonzalez-Garcia, arXiv:1207.1344&1211.4580

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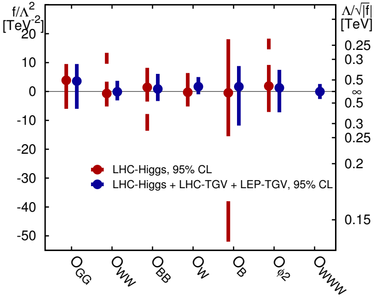

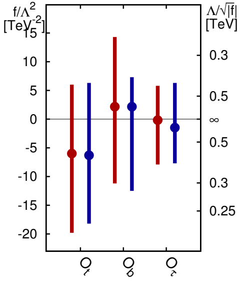

$$O_{GG} = (H^\dagger H) G^{A,\mu\nu} G^A_{\mu\nu}$$

$$O_{WW} = (H^\dagger H) W^{I,\mu\nu} W^I_{\mu\nu}$$

$$O_{BB} = (H^\dagger H) B^{\mu\nu} B_{\mu\nu}$$

$$O_W \sim (D^\mu H)^\dagger \tau^I (D_\nu H) W^{I,\mu\nu}$$

$$O_B \sim (D^\mu H)^\dagger (D_\nu H) B^{\mu\nu}$$

$$O_{\phi 2} = -2 Q_{H\Box}$$

$$O_{WWW} = W^{\mu\nu} W_{\nu\rho} W^\rho_\mu$$

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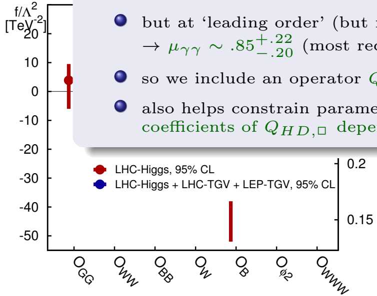
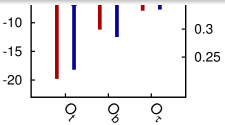
This list is too long for our EFTs...

- We only need three operators, $Q_{H\Box}$, Q_{HD}, and $Q_{\psi H}$...
- but at 'leading order' (but not tree–level) 2HDM and triplet change $H\gamma\gamma$ $\rightarrow \mu_{\gamma\gamma} \sim .85^{+.22}_{-.20}$ (most recent from ATLAS)
- so we include an operator $Q_{\gamma\gamma} \sim c_{\gamma\gamma} h F^{\mu\nu} F_{\mu\nu}$
- also helps constrain parameters of models: coefficients of $Q_{HD,\Box}$ depend on diff. parameters than $Q_{\gamma\gamma}$





$\tilde{G}^{A}_{\mu\nu}$

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ν

$H)W^{I,\mu\nu}$

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$O_{\phi 2} = -2 Q_{H\Box}$

$O_{WWW} = W^{\mu\nu} W_{\nu\rho} W^{\rho}_{\mu}$

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Reduced Global Fits

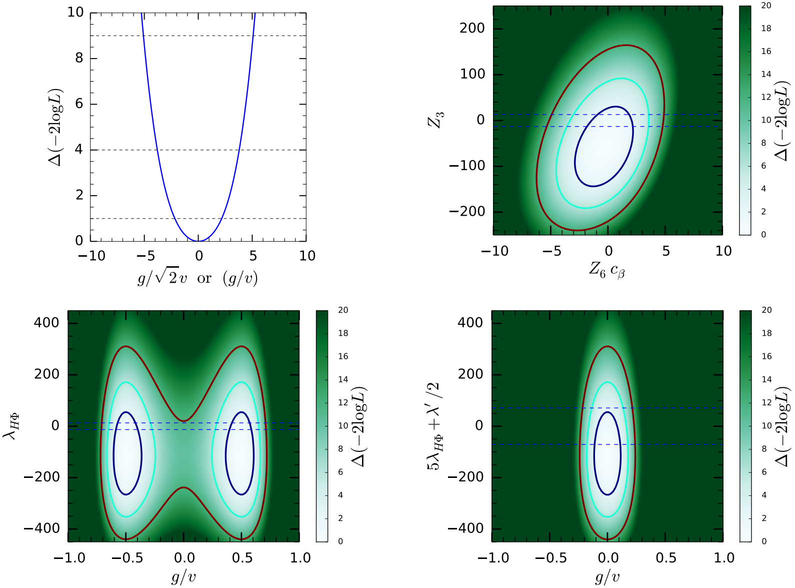
Clearly our EFTs are simpler, and they call for fits to a reduced basis of operators...

We employ Lilith to perform simple fits to the relevant operator bases.

$$\begin{pmatrix} v^2 * c_{tH} \\ v^2 * c_{bH} \\ v^2 * c_{\tau H} \\ v^2 * c_{HD} \\ v^2 * c_{H\Box} \\ c_{\gamma\gamma} \end{pmatrix} = \begin{pmatrix} -0.04967 \pm 0.4551 \\ -0.121 \pm 0.5917 \\ -0.003816 \pm 0.4722 \\ -0.0004666 \pm 0.0003861 \\ 0.02302 \pm 0.2184 \\ -0.1513 \pm 1.891 \end{pmatrix},$$

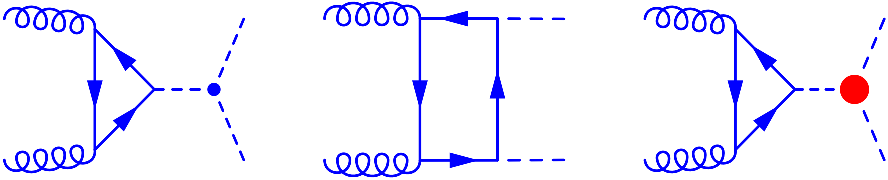
$$\rho = \begin{pmatrix} 1.00 & 0.58 & 0.35 & 0.07 & -0.32 & -0.43 \\ 0.58 & 1.00 & 0.35 & -0.08 & 0.39 & -0.44 \\ 0.35 & 0.35 & 1.00 & 0.04 & -0.18 & -0.40 \\ 0.07 & -0.08 & 0.04 & 1.00 & -0.20 & -0.05 \\ -0.32 & 0.39 & -0.18 & -0.20 & 1.00 & 0.27 \\ -0.43 & -0.44 & -0.40 & -0.05 & 0.27 & 1.00 \end{pmatrix}$$

Projected into the Models



DiHiggs Analysis

The motivation for studying the operator $Q_H = (H^\dagger H)^3$ is to enhance the DiHiggs signal,



Simulation Details:

- performed in $bb\gamma\gamma$ channel
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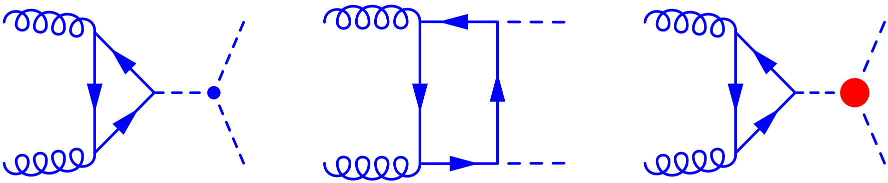

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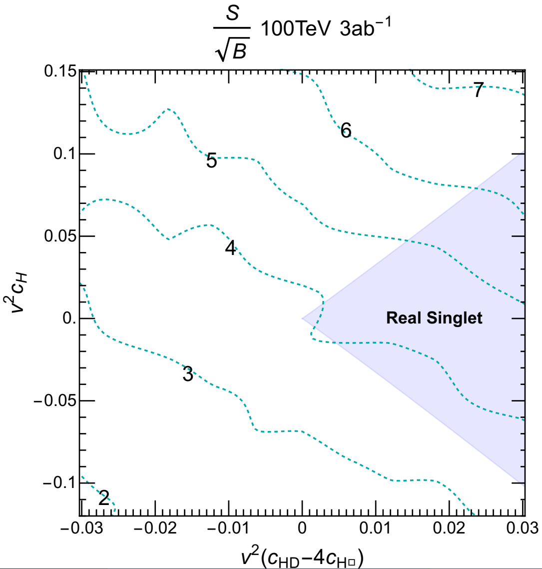
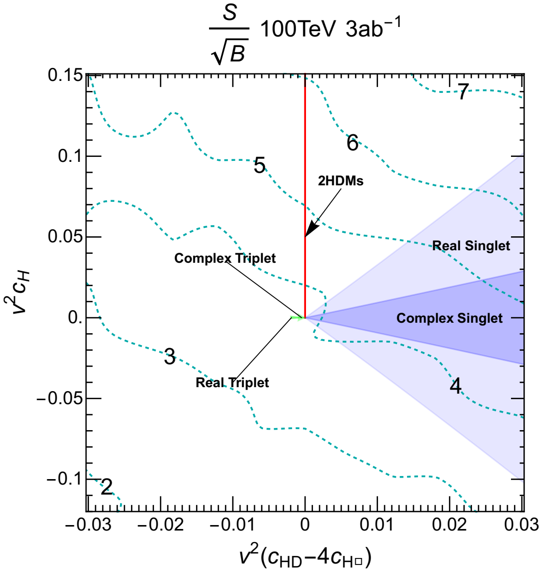
DiHiggs Analysis, ℝ Scalar Singlet

Looking at the ℝ Scalar Singlet at a future 100 TeV collider:



DiHiggs Analysis, All Models



An error in implementing *tth* and *tthh* vertices from EFT may shift these...

Conclusions

We have studied (simple) scalar extensions of the SM from an EFT perspective,

- only theories which generate tree level dimension–six $Q_H = (H^\dagger H)^3$ operator
- colored scalars won't give tree level amplitudes
- there were 4 different representations of $SU(2)_L$ we "considered"
  $\rightarrow$ Singlet
  $\rightarrow$ Doublet $Y_\phi = Y_H$
  $\rightarrow$ Triplet $Y_\phi = 0, 2Y_H$
  $\rightarrow$ Quadruplet (still need to include) $Y_\phi = \{3Y_H, Y_H\}$
- all other representations won't give tree level amplitudes

We simplified the basis of operators using the EOM,

$$\begin{array}{rclrcl} Q_H & = & (H^\dagger H)^3 & Q_{H\Box} & = & (H^\dagger H)\Box(H^\dagger H) \\ Q_{HD} & = & (D^\mu H)^\dagger H H^\dagger (D_\mu H) & Q_{\psi H} & = & (H^\dagger H)\Psi_L H \psi_R \end{array}$$

Simplified fit to single Higgs data $\Rightarrow$ relation between the parameters of the UV models

We simulated the DiHiggs signals

- Simulate dihiggs processes at 100 TeV
- Have identified the regions in $c_H \times (c_{HD} - 4c_{H\Box})$ plane relevant to our UV models
- Identified the significances with which the di–Higgs signal could be observed in plane

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  → Doublet $Y_\phi = Y_H$
  → Triplet $Y_\phi = 0, 2Y_H$
  → Quadruplet (still need to include) $Y_\phi = \{3Y_H, Y_H\}$
- all other representations won't give tree level amplitudes

We simplified the basis of operators using the EOM,

$$\begin{aligned} Q_H &= (H^\dagger H)^3 & Q_{H\Box} &= (H^\dagger H)\Box(H^\dagger H) \\ Q_{HD} &= (D^\mu H)^\dagger H H^\dagger (D_\mu H) & Q_{\psi H} &= (H^\dagger H)\Psi_L H \psi_R \end{aligned}$$

Simplified fit to single Higgs data ⇒ relation between the parameters of the UV models

We simulated the DiHiggs signals

- Simulate dihiggs processes at 100 TeV
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- Identified the significances with which the di–Higgs signal could be observed in plane

Conclusions

We have studied (simple) scalar extensions of the SM from an EFT perspective,

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Simplified fit to single Higgs data $\Rightarrow$ relation between the parameters of the UV models

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Channel	Pre-selection σ (fb)	Basic Cuts + #bjet=2;#γ=2		$110 < m_{bb} < 140$ GeV, $120 < m_{\gamma\gamma} < 130$ GeV		$pT_{bb} > 150$ GeV		$pT_{\gamma\gamma} > 140$ GeV	
		Efficiency	σ (fb)	Efficiency	σ (fb)	Efficiency	σ (fb)	Efficiency	σ (fb)
Backgrounds									
$b\bar{b}\gamma\gamma$	49530	1.74×10^{-2}	861.82	2.7×10^{-5}	1.34	10^{-6}	4.95×10^{-2}	10^{-6}	4.95×10^{-2}
$t\bar{t}h(\gamma\gamma)$	38.27	4.88×10^{-2}	1.87	5.28×10^{-3}	0.202	1.42×10^{-3}	5.43×10^{-2}	7.45×10^{-4}	2.85×10^{-2}
$c\bar{c}\gamma\gamma$	1458.6 [1]	0.13	189.62	1.97×10^{-4}	0.287	1.06×10^{-5}	1.55×10^{-2}	10^{-5}	1.46×10^{-2}
$b\bar{b}h(\gamma\gamma)$	35.16	6.06×10^{-2}	2.13	3.41×10^{-3}	0.120	3.57×10^{-4}	1.25×10^{-2}	3.27×10^{-4}	1.15×10^{-2}
$jj\gamma\gamma$	145.57 [2]	0.13	18.92	1.97×10^{-4}	2.87×10^{-2}	1.06×10^{-5}	1.54×10^{-3}	10^{-5}	1.46×10^{-3}
$Zh(\gamma\gamma)$	1.36	0.14	0.19	5.03×10^{-3}	6.84×10^{-3}	5×10^{-4}	6.8×10^{-4}	4.5×10^{-4}	6.12×10^{-4}
$b\bar{b}jj$	2068.42 [3]	6.79×10^{-3}	14.04	8.33×10^{-6}	1.72×10^{-2}	0	0	0	0
Total			1088.59		2.00		0.132		0.106
Signal BMs									
BM1, $(g^{(1)}_{HHH}/v, g^{(2)}_{HHH}v) = (0.0225, 0)$	4.94	0.149	0.736	1.94×10^{-2}	9.58×10^{-2}	8.32×10^{-3}	4.11×10^{-2}	7.69×10^{-3}	3.8×10^{-2}
BM2, $(g^{(1)}_{HHH}/v, g^{(2)}_{HHH}v) = (-0.032, 0.0152)$	4.74	0.150	0.711	2.05×10^{-2}	9.72×10^{-2}	9.39×10^{-3}	4.45×10^{-2}	8.61×10^{-3}	4.08×10^{-2}
BM3, $(g^{(1)}_{HHH}/v, g^{(2)}_{HHH}v) = (-0.141, 0.0152)$	2.88	0.148	0.426	2.04×10^{-2}	5.86×10^{-2}	1.1×10^{-2}	3.17×10^{-2}	1.03×10^{-2}	2.97×10^{-2}

Cut–flow table for the analysis we perform. Basic cuts refer to generator level cuts described in arXiv:1705.02551.

In the cross sections we have multiplied by the following NLO k–factors (Contino 2016): $k_{zh} = 0.87$, $k_{t\bar{t}h} = 1.3$, $k_{bbjj} = 1.08$, $k_{jj\gamma\gamma} = 1.43$.

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[1] including fake rate of $c \to b$: 10%.

[2] including fake rate of $j \to b$: 1%.

[3] including fake rate of $j \to \gamma$: 0.012%.

Backup: Unitarity and EFTs

EFTs are known to violate unitarity, e.g. in Chiral PT:

$$\begin{aligned}\mathcal{L}_2 &= \tfrac{F^2}{4}\mathrm{Tr}\left[\partial_\mu U \partial^\mu U\right] \\ &\sim (2\ \text{point}) + \tfrac{1}{6F^2}(\phi_i \partial^\mu \phi_i \partial_\mu \phi_j \phi_j - \phi_i \phi_i \partial_\mu \phi_j \partial^\mu \phi_j)\phi_j\end{aligned}$$

with

$$U = \exp\left(i\tfrac{\phi}{F}\right), \quad \phi = \sum \phi_i \tau_i$$

then,

$$A(s,t,u) = \tfrac{s}{F_\pi^2}$$

Violates Unitarity at some s!

Backup: Unitarity and EFTs II

The operators Q_{HD} and $Q_{H\Box}$ violate unitarity (as they have extra derivatives!), Partial wave unitarity tell us:

$$|T^J(V_{1\lambda_1}V_{2\lambda_2} \to V_{1\lambda_1}V_{2\lambda_2})| \leq 2$$

Calculating all $4V$ scattering amps we find the largest allowed values of c_{HD} and $c_{H\Box}$,

$$\begin{aligned} |c_{H\Box}S| &\leq 67 \\ |c_{HD}S| &\leq 67 \end{aligned}$$

For the $\mathbb{R}$ scalar singlet this gives,

$$|c_{H\Box}S| = \left|\frac{g_{HS}^2}{2M_S^4}S\right| \leq 67 \Rightarrow |g_{HS}| \lesssim \sqrt{2 \cdot 34\left(\frac{2M_S^4}{\text{TeV}^2}\right)} \quad (1)$$

So for $\sqrt{s} \sim 1$ TeV and $M_S \sim 1$ TeV we find,

$$|g_{HS}| \leq 11\text{TeV} \quad (2)$$

Which isn't so useful...

- similar bounds come from performing the search for the other models.
- Note: 2HDM doesn't generate $c_{H\Box}$ or c_{HD} $\to$ no unitarity bounds for this model