Pushing Higgs Effective Theory to its Limits

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based on 1510.03443, 1602.05202

with Anke Biekötter, Ayres Freitas, David Lopez-Val, and Tilman Plehn

ABHM meeting in Mainz, March 07, 2016

What's on

- This talk: [JB, A. Freitas, D. Lopez-Val, T. Plehn 1510.03443]
  - Higgs EFT to dimension 6
  - Validity at the LHC
  - Explicit comparison with full models in main Higgs observables
    - Scalar singlet
    - Vector triplet
- Next: [A. Biekötter, JB, T. Plehn 1602.05202]
  - To square or not to square dimension-6 amplitudes?
  - How to improve description where dimension-6 approximation fails?

Higgs effective field theory

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- New physics at $\Lambda \gg E_{\text{LHC}} \sim v$? [W. Buchmuller, D. Wyler 85; ...]

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \underbrace{\sum_i^{59} \frac{f_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)}}_{} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

$$\text{e.g. } \mathcal{O}_{GG} = (\phi^\dagger \phi)\, G^a_{\mu\nu}\, G^{\mu\nu\, a} \,,$$

$$\mathcal{O}_W = (D^\mu \phi)^\dagger \sigma^k (D^\nu \phi)\, W^k_{\mu\nu} \,\ldots$$

Higgs effective field theory

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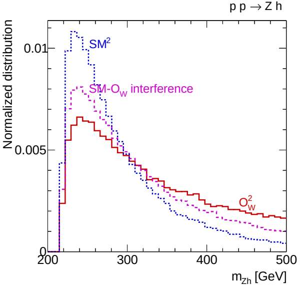
$$\mathcal{O}_W = (D^\mu \phi)^\dagger \sigma^k (D^\nu \phi)\, W^k_{\mu\nu}\ \ldots$$

- Perfect language for indirect signatures at electroweak scale?
  - Model independence?
  - Correlations between LEP, LHC TGV, Higgs, ...
  - Total rates + distributions



Dimension 6 vs LHC accuracy

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- LHC new physics reach (based on Higgs rates at 10% accuracy):

$$\left| \frac{\sigma \times \mathrm{BR}}{(\sigma \times \mathrm{BR})_{\mathrm{SM}}} - 1 \right| \sim \frac{g^2\, m_h^2}{\Lambda^2} > 10\% \qquad \Leftrightarrow \qquad \Lambda < \frac{g\, m_h}{\sqrt{10\%}} \overset{g<1}{<} 400~\mathrm{GeV}$$

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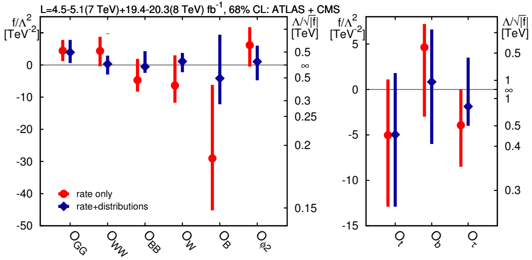
- Global fit: [T. Corbett, O. Eboli, D. Goncalves, J. Gonzalez-Fraile, T. Plehn, M. Rauch 1505.05516]



$\Rightarrow$ Weakly interacting models currently probed at LHC do not guarantee a scale hierarchy $\Lambda \gg E$

Testing the dimension-6 approach

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- Idea: compare full models vs their dimension-6 approximation explicitly

- Benchmarks:
  - Scalar singlet
  - Two-Higgs-doublet model
  - Scalar top partners
  - Vector triplet

- Observables:
  - Higgs production in gluon fusion, WBF, Higgs-strahlung
  - Representative decays: $\gamma\gamma$, 4ℓ, $2\ell\,2\nu$, $\tau\tau$
  - Higgs pair production

- Tools:
  - Tree level: `MadGraph` with `FeynRules` models [A. Alloul, B. Fuks, V. Sanz 1310.5150]
  - Loop effects: reweighting technique based on `LoopTools`
  - `HDecay`, `HiggsSignals`, `HiggsBounds`, `2HDMC`...

[see also A. Biekötter, A. Knochel, M. Krämer, D. Liu, F. Riva 1406.7320;
C. Englert, M. Spannowsky 1408.5147; M. de Vries 1409.4657;
N. Craig, M. Farina, M. McCullough, M. Perelstein 1411.0676;
S. Dawson, I. M. Lewis, M. Zeng 1501.04103; A. Drozd, J. Ellis, J. Quevillon, T. You 1504.02409;
A. Freitas, J. Gonzalez-Fraile, D. Lopez-Val, T. Plehn 16xx.xxxxx]

EFT matching without a clear scale hierarchy

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- Electroweak VEV introduces new scales:

$$\underbrace{m^2}_{\text{physical mass}} = \underbrace{M^2}_{\text{new physics scale in } \mathcal{L}} \pm g v^2$$

- Standard matching [B. Henning, X. Lu, H. Murayama 1412.1837]
  - Defined in unbroken electroweak phase: $\Lambda = M$
  - Truncates all dim-8 terms $\Rightarrow$ blind to VEV effects

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- Standard matching [B. Henning, X. Lu, H. Murayama 1412.1837]
  - Defined in unbroken electroweak phase: $\Lambda = M$
  - Truncates all dim-8 terms $\Rightarrow$ blind to VEV effects
- v-improved matching
  - Incorporates VEV effects into matching: $\Lambda = m$
  - Can be understood as partial absorption of higher-dimensional operators:

$$\frac{c_i^{(6)}}{M^2}\,\mathcal{O}_i^{(6)} + \frac{c_i^{(8)}}{M^4}\left(\phi^\dagger\phi\right)\mathcal{O}_i^{(6)} \to \frac{c_i^{(6)} + c_i^{(8)}\,v^2/M^2 + \dots}{M^2}\,\mathcal{O}_i^{(6)} = \frac{c_i^{(6)}}{m^2}\,\mathcal{O}_i^{(6)}$$

Singlet

Full model:

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu S \partial^\mu S - \mu_2^2\, S^2 - \lambda_2\, S^4 - \lambda_3\, |\phi^\dagger\, \phi| S^2$$

New H resonance

Universal reduction of hxx couplings

hh structures

Singlet

Full model:

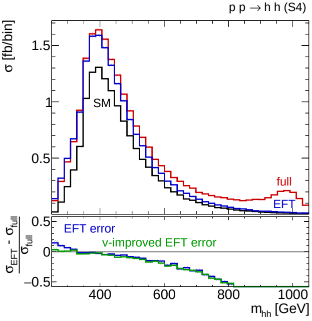
$$\mathcal{L} \supset \frac{1}{2}\partial_\mu S \partial^\mu S - \mu_2^2 S^2 - \lambda_2 S^4 - \lambda_3 |\phi^\dagger \phi| S^2$$

Dim-6 approximation:

$$\mathcal{L} \supset \frac{f_{\phi 2}}{\Lambda^2} \partial^\mu (\phi^\dagger \phi) \partial_\mu (\phi^\dagger \phi)$$

	Dim-6 approximation
New H resonance	×
Universal reduction of hxx couplings	✓
hh structures	(×)

	$\sigma_{\text{default EFT}}/\sigma_{\text{full}}$			$\sigma_{v\text{-improved EFT}}/\sigma_{\text{full}}$		
	ggF	WBF	Vh	ggF	WBF	Vh
S1	1.01	1.01	1.00	1.00	1.00	1.00
S2	1.02	1.02	1.02	1.00	1.00	1.00
S3	1.12	1.12	1.12	1.00	1.00	1.00
S4	0.98	0.98	0.98	1.00	1.00	1.00
S5	0.93	0.93	0.93	1.00	1.00	1.00



Vector triplet

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Full model:

$$\mathcal{L} \supset -\frac{1}{4} V^a_{\mu\nu} V^{\mu\nu\, a} + \frac{M_V^2}{2} V^a_\mu V^{\mu\, a} + \frac{g^2}{2g_V} V^a_\mu\, c_F \overline{F}_L \gamma^\mu \sigma^a F_L + \mathrm{i}\,\frac{g_V}{2} c_H V^a_\mu \left[\phi^\dagger \sigma^a \overleftrightarrow{D}^\mu \phi\right] + g_V^2\, c_{VVHH} V^a_\mu V^{\mu a} \phi^\dagger \phi$$

New ξ resonance
Modification of hxx couplings
New structures in WBF and Vh

[D. Pappadopulo, A. Thamm, R. Torre, A. Wulzer 1402.4431;
A. Biekötter, A. Knochel, M. Krämer, D. Liu, F. Riva 1406.7320]

Vector triplet

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Full model:

$$\begin{aligned}\mathcal{L} \supset -\frac{1}{4}\, V^a_{\mu\nu}\, V^{\mu\nu\, a} + \frac{M_V^2}{2}\, V^a_\mu\, V^{\mu\, a} \\ + \frac{g^2}{2g_V}\, V^a_\mu\, c_F \overline{F}_L\, \gamma^\mu\, \sigma^a\, F_L \\ + \mathrm{i}\,\frac{g_V}{2}\, c_H\, V^a_\mu \left[\phi^\dagger \sigma^a \overleftrightarrow{D}^\mu\, \phi\right] \\ + g_V^2\, c_{VVHH}\, V^a_\mu\, V^{\mu a}\, \phi^\dagger \phi\end{aligned}$$

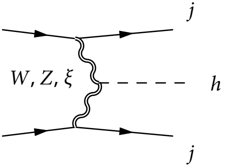
Dim-6 approximation:

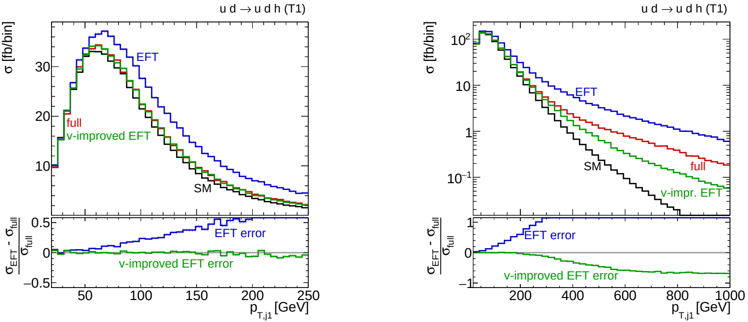
$$\begin{aligned}\mathcal{L} \supset -\frac{f_{WW}}{\Lambda^2}\, \frac{g^2}{4}\, (\phi^\dagger \phi)\, W^k_{\mu\nu}\, W^{\mu\nu\, k} \\ - \frac{f_W}{\Lambda^2}\, \frac{\mathrm{i}g}{2} (D^\mu \phi^\dagger) \sigma^k (D^\nu \phi)\, W^k_{\mu\nu} \\ + \ldots\end{aligned}$$

New ξ resonance	×
Modification of hxx couplings	✓
New structures in WBF and Vh	(✓)

[D. Pappadopulo, A. Thamm, R. Torre, A. Wulzer 1402.4431;
A. Biekötter, A. Knochel, M. Krämer, D. Liu, F. Riva 1406.7320]

Vector triplet: WBF





Benchmark: $m_\xi = 1.2$ TeV, $g_V = 3$, $c_H = -0.47$, $c_F = -5$, $c_{VVHH} = 2$

More on this in the next talk!

EFT breakdown summary

Model	Process	Dimension-6 errors		
		Resonance	Kinematics	Matching
Singlet	on-shell $h \to 4\ell$, WBF, $Vh, \ldots$			×
	off-shell WBF, …		(×)	×
	hh	×	×	×
2HDM	on-shell $h \to 4\ell$, WBF, $Vh, \ldots$			×
	off-shell $h \to \gamma\gamma, \ldots$		(×)	×
	hh	×	×	×
Top partners	WBF, Vh			×
Vector triplet	WBF		(×)	×
	Vh	×	(×)	×

Conclusions

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- LHC precision does not guarantee EFT convergence
- In practice, dimension-6 approximation performs well…
  - Higgs rates (with v-improved matching)
  - Distributions in WBF, Vh, …

Conclusions

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- LHC precision does not guarantee EFT convergence
- In practice, dimension-6 approximation performs well…
  - Higgs rates (with v-improved matching)
  - Distributions in WBF, Vh, …
- …with exceptions:
  - New light resonances — obvious
  - Extreme high-energy tails in WBF, Vh — probably irrelevant
  - Higgs pair production — irrelevant for now
  - Naive matching procedure — irrelevant for fits

$\Rightarrow$ Dimension-6 description of LHC Higgs physics works

Backup

Dimension-6 basis

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$$\mathcal{L}_{\text{dim-6}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{f_i}{\Lambda^2}\,\mathcal{O}_i$$

$$\mathcal{O}_{\phi 1} = (D_\mu \phi)^\dagger \phi\, \phi^\dagger (D^\mu \phi) \qquad \mathcal{O}_{\phi 3} = \frac{1}{3}(\phi^\dagger \phi)^3$$

$$\mathcal{O}_{\phi 2} = \frac{1}{2}\,\partial^\mu(\phi^\dagger\phi)\,\partial_\mu(\phi^\dagger\phi) \qquad \mathcal{O}_{GG} = (\phi^\dagger\phi)\,G^a_{\mu\nu}\,G^{\mu\nu\, a}$$

$$\mathcal{O}_{BW} = -\frac{g\,g'}{4}\,(\phi^\dagger\sigma^k\phi)\,B_{\mu\nu}\,W^{\mu\nu\, k} \qquad \mathcal{O}_{BB} = -\frac{g'^2}{4}\,(\phi^\dagger\phi)\,B_{\mu\nu}\,B^{\mu\nu}$$

$$\mathcal{O}_{B} = \mathrm{i}\frac{g}{2}\,(D^\mu\phi^\dagger)(D^\nu\phi)\,B_{\mu\nu} \qquad \mathcal{O}_{WW} = -\frac{g^2}{4}\,(\phi^\dagger\phi)\,W^k_{\mu\nu}\,W^{\mu\nu\, k}$$

$$\mathcal{O}_{W} = \mathrm{i}\frac{g}{2}\,(D^\mu\phi)^\dagger\sigma^k(D^\nu\phi)\,W^k_{\mu\nu} \qquad \mathcal{O}_{f} = (\phi^\dagger\phi)\,\bar{F}_L\,\phi\, f_R + \text{h.c.}$$

[K. Hagiwara, S. Ishihara, S. R. Szalapski, D. Zeppenfeld 93]

Singlet: matching

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$$V(\phi, S) = \mu_1^2 \, (\phi^\dagger \, \phi) + \lambda_1 \, |\phi^\dagger \phi|^2 + \mu_2^2 \, S^2 + \lambda_2 \, S^4 + \lambda_3 \, |\phi^\dagger \, \phi| S^2$$

$$\begin{aligned} m_H^2 &= \lambda_1 \, v^2 + \lambda_2 \, v_s^2 + |\lambda_1 \, v^2 - \lambda_2 \, v_s^2| \sqrt{1 + \tan^2(2\alpha)} \\ &= \sqrt{2\lambda_2} \, v_s + \mathcal{O}\left(v^2/v_s^2\right) \end{aligned}$$

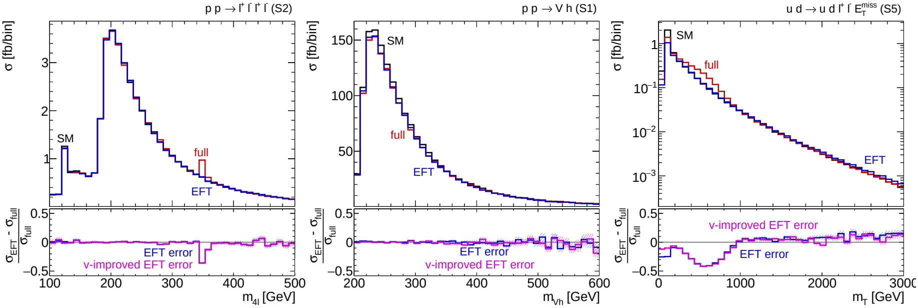
$$\frac{f_{\phi 2}}{\Lambda^2} = \begin{cases} \dfrac{\lambda_3^2}{4\lambda_2^2 v_s^2} & \text{default matching} \\ \dfrac{2(1 - \cos\alpha)}{v^2} & v\text{-improved matching} \end{cases}$$

with mixing angle α and singlet VEV v_s

Singlet: benchmarks

	Setup			Relative coupling shifts		
	m_H [GeV]	$\sin\alpha$	v_s/v	$\Delta_x^{\text{singlet}}$	$\Delta_x^{\text{default EFT}}$	$\Delta_x^{v\text{-improved EFT}}$
S1	500	0.2	10	−0.020	−0.018	−0.020
S2	350	0.3	10	−0.046	−0.037	−0.046
S3	200	0.4	10	−0.083	−0.031	−0.083
S4	1000	0.4	10	−0.083	−0.092	−0.083
S5	500	0.6	10	−0.200	−0.231	−0.200

Singlet: results



Vector triplet: matching

$$\mathcal{L} = \mathcal{L}_{\mathsf{SM}} - \frac{1}{4}\, V^a_{\mu\nu}\, V^{\mu\nu\, a} + \frac{M_V^2}{2}\, V^a_\mu\, V^{\mu\, a} + \frac{g_w^2}{2 g_V}\, V^a_\mu\, c_F \overline{F}_L\, \gamma^\mu\, \sigma^a\, F_L$$

$$+\, \mathrm{i}\, \frac{g_V}{2}\, c_H\, V^a_\mu \left[\phi^\dagger \sigma^a \overleftrightarrow{D}^\mu\, \phi \right] + g_V^2\, c_{VVHH}\, V^a_\mu\, V^{\mu a}\, \phi^\dagger \phi + \mathcal{O}\left(V^2 W, V^3 \right)$$

$$m_\xi^2 = M_V^2 + \left(g_V^2 c_{VVHH} + \frac{g_V^2 c_H^2}{4} \right) v^2 + \mathcal{O}\left(v^4 / M_V^2 \right)$$

$$\Lambda = \begin{cases} M_V & \text{default matching} \\ m_\xi & v\text{-improved matching} \end{cases}$$

$$f_{WW} = f_{BW} = -\frac{1}{2}\, f_W = c_F\, c_H$$

$$f_{\phi 2} = -\frac{1}{4\lambda}\, f_{\phi 3} = \frac{3}{4} \left(-2\, c_F\, g^2 + c_H\, g_V^2 \right)$$

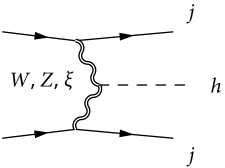
$$f_f = -\frac{1}{4}\, y_f\, c_H \left(-2\, c_F\, g^2 + c_H\, g_V^2 \right)$$

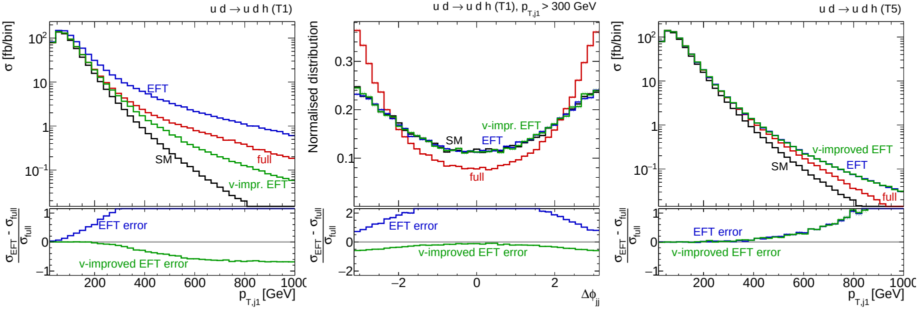
Vector triplet: benchmarks

	m_ξ [GeV]	M_V [GeV]	g_V	c_H	c_F	c_{VVHH}
T1	1200	591	3.0	−0.47	−5.00	2.00
T2	1200	946	3.0	−0.47	−5.00	1.00
T3	1200	941	3.0	−0.28	3.00	1.00
T4	1200	1246	3.0	−0.50	3.00	−0.20
T5	849	846	1.0	−0.56	−1.32	0.08

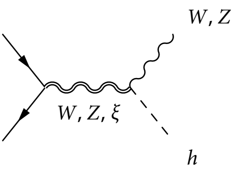
	$\sigma_{\text{default EFT}}/\sigma_{\text{full}}$		$\sigma_{\nu\text{-improved EFT}}/\sigma_{\text{full}}$	
	WBF	Vh	WBF	Vh
T1	1.30	0.30	0.98	0.79
T2	1.05	0.74	0.99	0.91
T3	0.92	1.07	0.97	1.02
T4	1.03	0.97	1.01	0.98
T5	1.00	1.04	1.00	1.04

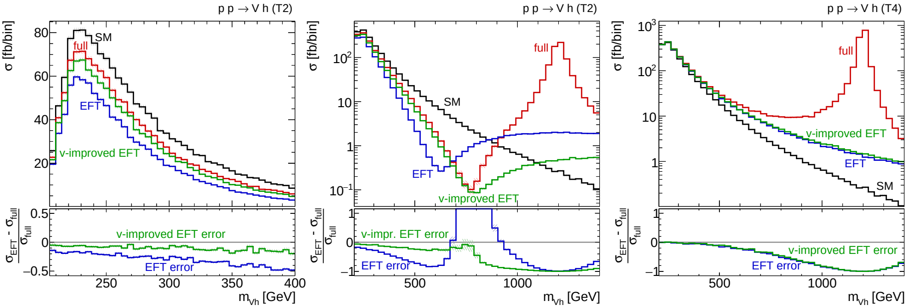
Vector triplet: more WBF





Vector triplet: Vh





2HDM

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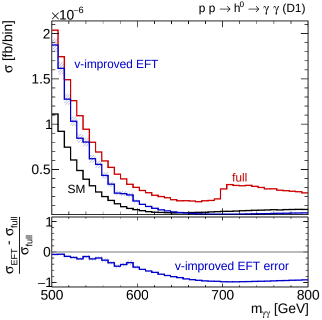
Full model:	Dim-6 approximation:
$\mathcal{L} \supset (D_\mu \phi_1)^\dagger D^\mu \phi_1 + (D_\mu \phi_2)^\dagger D^\mu \phi_2 - V(\phi_1, \phi_2)$	$\mathcal{L} \supset -\frac{f_{BB}}{\Lambda^2} \frac{g'^2}{4} (\phi^\dagger \phi) B_{\mu\nu} B^{\mu\nu} + \sum_f \frac{f_f}{\Lambda^2} (\phi^\dagger \phi) \bar{F}_L \phi f_R + \text{h. c.}$
New $H^0, A^0, H^\pm$ resonances	$\times$
hff coupling shifts	$(\checkmark)$
(Small) hVV coupling shifts	$\times$
$H^\pm$ loop in $h\gamma\gamma$	$(\checkmark)$
hh structures	$(\times)$

2HDM: benchmarks, results

	Type	$\tan\beta$	α/π	m_{12}	m_{H^0}	m_{A^0}	$m_{H^\pm}$
D1	I	1.5	−0.086	45	230	300	350
D2	II	15	−0.023	116	449	450	457
D3	II	10	0.032	157	500	500	500
D4	I	20	0	45	200	500	500

	$\sigma_{v\text{-improved EFT}}/\sigma_{\text{full}}$		
	ggF	WBF	Vh
D1	0.87	1.11	1.11
D2	1.00	1.00	1.00
D3	1.02	1.04	1.04
D4	1.00	1.00	1.00



Scalar top partners

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Full model:

$$\mathcal{L} \supset (D_\mu \tilde{Q})^\dagger (D^\mu \tilde{Q}) + (D_\mu \tilde{t}_R)^* (D^\mu \tilde{t}_R) - \tilde{Q}^\dagger M^2 \tilde{Q} - M^2 \tilde{t}_R^* \tilde{t}_R - \kappa_{LL} (\phi \cdot \tilde{Q})^\dagger (\phi \cdot \tilde{Q}) - \kappa_{RR} (\tilde{t}_R^* \tilde{t}_R)(\phi^\dagger \phi) - \left[\kappa_{LR} M \tilde{t}_R^* (\phi \cdot \tilde{Q}) + \text{h.c.}\right]$$

Dim-6 approximation:

$$\mathcal{L} \supset \sum_i \frac{f_i}{\Lambda^2} \mathcal{O}_i$$

Loop effects in $hgg, h\gamma\gamma$	$(\checkmark)$ [S. Dawson, I. M. Lewis, M. Zeng 1501.04103; A. Drozd, J. Ellis, J. Quevillon, T. You 1504.02409]
(Small) loop effects in WBF, Vh	$(\times)$