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

Pheno 2016, Pittsburgh

SM effective field theory

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

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

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

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

SM effective field theory

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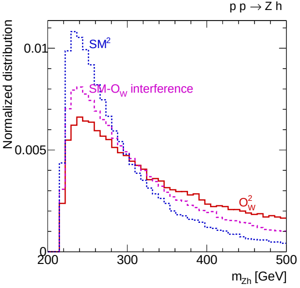
$$\text{e.g. } \mathcal{O}_{GG} = (\phi^\dagger \phi)\, G^a_{\mu\nu}\, G^{\mu\nu\, a} \,,$$

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

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



Dimension 6 vs LHC accuracy

- 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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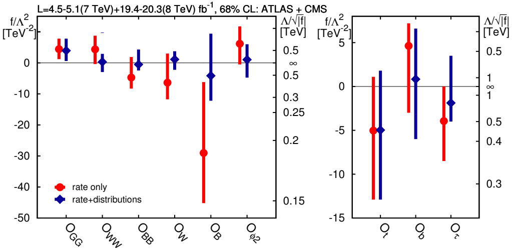
- Global fit: [T. Corbett, O. Eboli, D. Goncalves, J. Gonzalez-Fraile, T. Plehn, M. Rauch 1505.05516; A. Butter, O. Éboli, J. Gonzalez-Fraile, M. Gonzalez-Garcia, T. Plehn 1604.03105 → next talk by A. Butter]



⇒ Weakly interacting models currently probed in LHC Higgs observables have no clear scale hierarchy $\Lambda \gg E$. Is the dimension-6 model valid?

[for strongly interacting new physics, see A. Pomarol's talk]

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;
M. Gorbahn, J. M. No, V. Sanz 1502.07352; A. Drozd, J. Ellis, J. Quevillon, T. You 1504.02409;
R. Contino, A. Falkowski, F. Goertz, C. Grojean, F. Riva 1604.06444;
A. Freitas, J. Gonzalez-Fraile, D. Lopez-Val, T. Plehn 16xx.xxxxx]

EFT matching without a clear scale hierarchy

- Higgs vev v introduces new scales:

$$\underbrace{m^2}_{\text{physical mass}} = \underbrace{M^2}_{\text{new physics scale in } \mathcal{L}} \pm \underbrace{gv^2}_{\text{mixing with } \phi}$$

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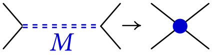
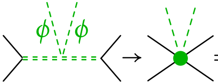
- Standard matching in unbroken phase of electroweak symmetry:



$$= \frac{f^{(6)}}{M^2} \, \mathcal{O}^{(6)}$$



$$= \frac{f^{(8)}}{M^4} \, \phi^\dagger \phi \, \mathcal{O}^{(6)} \quad \Rightarrow \quad \mathcal{O}^{(6)} \text{ blind to vev effects}$$

EFT matching without a clear scale hierarchy

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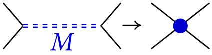

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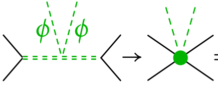
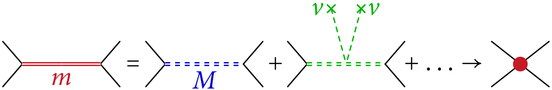


$$= \frac{f^{(8)}}{M^4}\,\phi^\dagger\phi\,\mathcal{O}^{(6)} \quad \Rightarrow \quad \mathcal{O}^{(6)} \text{ blind to vev effects}$$

- v-improved matching absorbs vev effects in $f^{(6)}$:



$$= \frac{f^{(6)}}{m^2}\,\mathcal{O}^{(6)}$$

Vector triplet

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Full model:

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

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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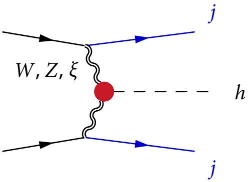
Dim-6 approximation:

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

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]

WBF Higgs production



Tagging jets probe energy flow through VVh vertex

WBF Higgs production

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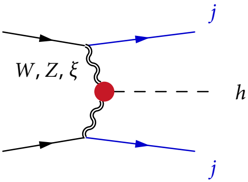

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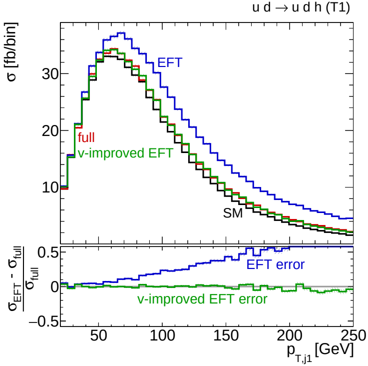

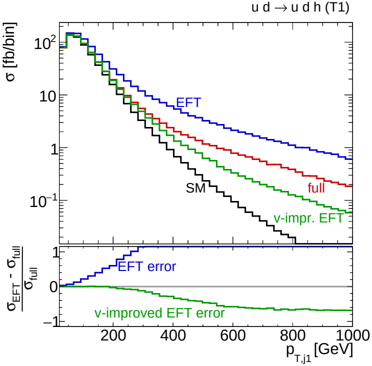

Benchmark: $m_\xi = 1.2$ TeV, $g_V = 3$, $c_H = -0.47$, $c_F = -5$, $c_{VVHH} = 2$

EFT breakdown summary

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

Conclusions

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- LHC precision does not guarantee that dimension-8 (and higher) operators can be neglected
- In practice, dimension-6 model performs well…
  - Higgs rates (with v-improved matching)
  - Distributions in WBF, Vh, …
- …with exceptions:
  - New light resonances
  - Extreme high-energy tails in WBF, Vh
  - Higgs pair production
  - Naive matching procedure

Conclusions

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- LHC precision does not guarantee that dimension-8 (and higher) operators can be neglected
- In practice, dimension-6 model 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 (limits as function of E_{max}?)
  - Higgs pair production …irrelevant for now
  - Naive matching procedure …irrelevant for fits

⇒ Dimension-6 description of LHC Higgs physics works (but handle with care)

Backup

Dimension-6 basis

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

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

$$\mathcal{O}_{\phi 2} = \frac{1}{2} \partial^\mu (\phi^\dagger \phi) \, \partial_\mu (\phi^\dagger \phi)$$

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

$$\mathcal{O}_B = \mathrm{i} \frac{g}{2} (D^\mu \phi^\dagger)(D^\nu \phi) \, B_{\mu\nu}$$

$$\mathcal{O}_W = \mathrm{i} \frac{g}{2} (D^\mu \phi)^\dagger \sigma^k (D^\nu \phi) \, W^k_{\mu\nu}$$

$$\mathcal{O}_{\phi 3} = \frac{1}{3} (\phi^\dagger \phi)^3$$

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

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

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

$$\mathcal{O}_f = (\phi^\dagger \phi) \, \bar{F}_L \phi f_R + \text{h.c.}$$

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

Singlet

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Full model:

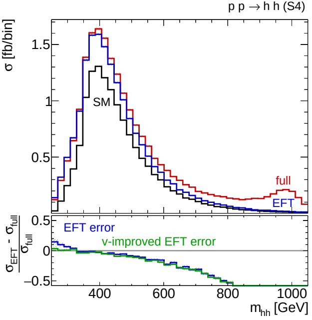
$$\mathcal{L} \supset \frac{1}{2}\partial_\mu S \partial^\mu S - \mu_2^2 S^2 - \lambda_2 S^4 - \lambda_3 |\phi^\dagger \phi| S^2$$

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



Singlet: matching

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

$$m_H^2 = \lambda_1 \, v^2 + \lambda_2 \, v_s^2 + |\lambda_1 \, v^2 - \lambda_2 \, v_s^2| \sqrt{1 + \tan^2(2\alpha)}$$

$$= \sqrt{2\lambda_2} \, v_s + \mathcal{O}\left(v^2/v_s^2\right)$$

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

with mixing angle α and singlet VEV v_s

Singlet: benchmarks

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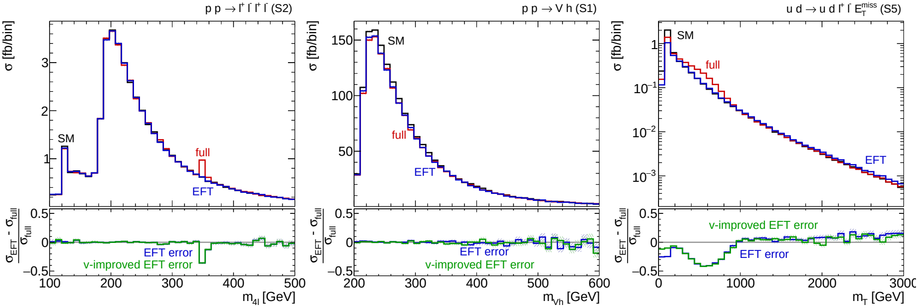
	Setup			Relative coupling shifts		
	m_H [GeV]	$\sin\alpha$	v_s/v	$\Delta_x^{\text{singlet}}$	$\Delta_x^{\text{default EFT}}$	$\Delta_x^{v\text{-improved EFT}}$
S1	500	0.2	10	−0.020	−0.018	−0.020
S2	350	0.3	10	−0.046	−0.037	−0.046
S3	200	0.4	10	−0.083	−0.031	−0.083
S4	1000	0.4	10	−0.083	−0.092	−0.083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

Singlet: more results



Vector triplet: matching

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$$\mathcal{L} = \mathcal{L}_{\mathsf{SM}} - \frac{1}{4} V^a_{\mu\nu} V^{\mu\nu\,a} + \frac{M_V^2}{2} V^a_\mu V^{\mu\,a} + \frac{g_w^2}{2g_V} V^a_\mu\, c_F \overline{F}_L \gamma^\mu \sigma^a F_L$$
$$+ \mathrm{i}\,\frac{g_V}{2} c_H V^a_\mu \left[\phi^\dagger \sigma^a \overleftrightarrow{D}^\mu \phi\right] + g_V^2\, c_{VVHH} V^a_\mu V^{\mu a} \phi^\dagger\phi + \mathcal{O}\left(V^2 W, V^3\right)$$

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

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

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

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

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

Vector triplet: benchmarks

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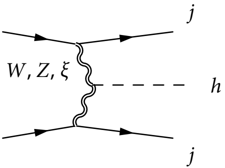
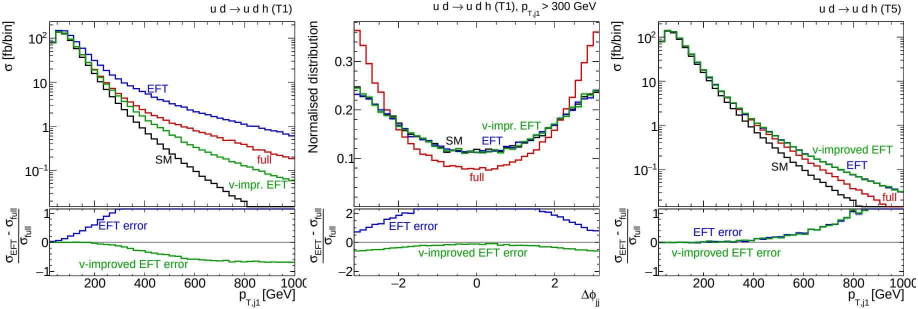
	m_ξ [GeV]	M_V [GeV]	g_V	c_H	c_F	c_{VVHH}
T1	1200	591	3.0	−0.47	−5.00	2.00
T2	1200	946	3.0	−0.47	−5.00	1.00
T3	1200	941	3.0	−0.28	3.00	1.00
T4	1200	1246	3.0	−0.50	3.00	−0.20
T5	849	846	1.0	−0.56	−1.32	0.08

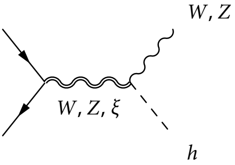
	$\sigma_{\text{default EFT}}/\sigma_{\text{full}}$		$\sigma_{v\text{-improved EFT}}/\sigma_{\text{full}}$	
	WBF	Vh	WBF	Vh
T1	1.30	0.30	0.98	0.79
T2	1.05	0.74	0.99	0.91
T3	0.92	1.07	0.97	1.02
T4	1.03	0.97	1.01	0.98
T5	1.00	1.04	1.00	1.04

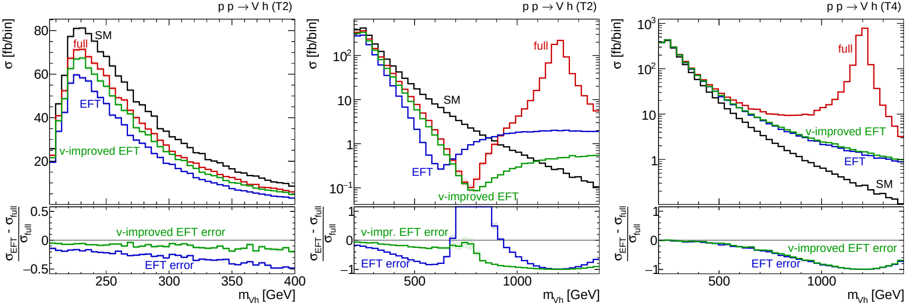
Vector triplet: more WBF





Vector triplet: Vh

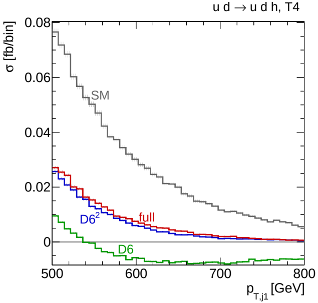




Vector triplet: to square or not to square

$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + 2\,\mathrm{Re}\,\mathcal{M}_{SM}^*\mathcal{M}_{D6} \overset{?}{+} |\mathcal{M}_{D6}|^2$$

- We ignore $\mathrm{Re}\,\mathcal{M}_{SM}^*\mathcal{M}_{D8}$ at the same order $1/\Lambda^4$
- But: $|\mathcal{M}_{D6}|^2$ necessary to avoid negative cross sections

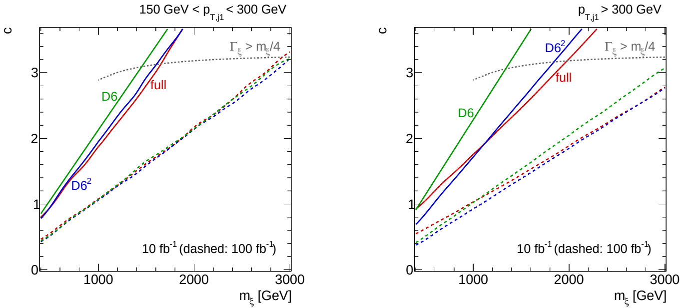


Vector triplet: toy limits

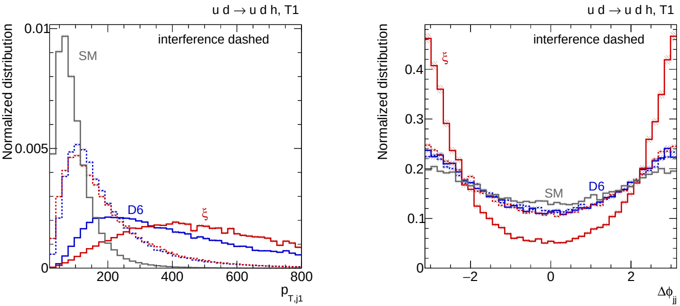
- 2-dimensional parameter space (m_ξ, c):

$$g_V = 1\,, \quad c_H = c\,, \quad c_F = c/(2g^2)\,, \quad c_{HHVV} = c^2$$

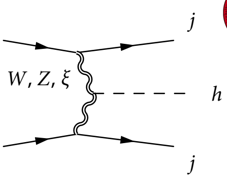
- "Analysis":
  - Parameter point is excluded if $S/\sqrt{B} > 2$
  - Parton level, no non-Higgs backgrounds
- Limits in the absence of a signal:



Vector triplet: EFT breakdown anatomy



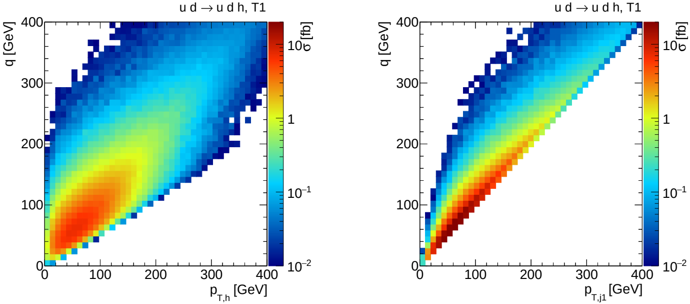
Vector triplet: WBF observables (1)



- Momentum transfer for $ud \to udh$:

$$q = \begin{cases} \max\left(\sqrt{|(p_{u'} - p_d)^2|},\ \sqrt{|(p_{d'} - p_u)^2|}\right) & \text{for } W\text{-like phase-space points} \\ \max\left(\sqrt{|(p_{u'} - p_u)^2|},\ \sqrt{|(p_{d'} - p_d)^2|}\right) & \text{for } Z\text{-like phase-space points} \end{cases}$$

- Correlation with observables:



Vector triplet: WBF observables (2)

- Looking for phase-space region with…
  - …large sensitivity to new physics

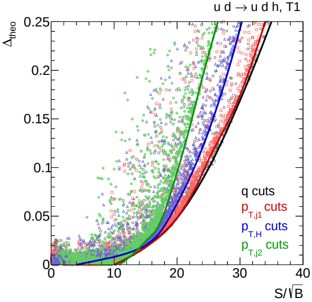
$$S/\sqrt{B} = \sqrt{30\text{fb}^{-1}} \left| \frac{\sigma_{\text{full}} - \sigma_{\text{SM}}}{\sqrt{\sigma_{\text{SM}}}} \right|$$

  - …small EFT error

$$\Delta_{\text{theo}} = \left| \frac{\sigma_{\text{EFT}} - \sigma_{\text{full}}}{\sigma_{\text{full}}} \right|$$

- 1-dimensional cut windows in different observables:

Only cuts are shown where at least 20 fb (before Higgs decay) survive



2HDM

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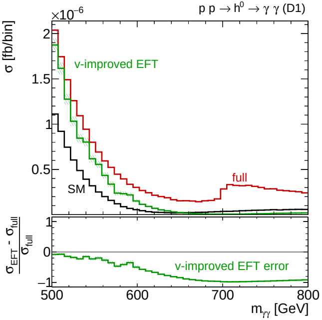
Full model:	Dim-6 approximation:
$$\mathcal{L} \supset (D_\mu \phi_1)^\dagger D^\mu \phi_1 + (D_\mu \phi_2)^\dagger D^\mu \phi_2 - V(\phi_1, \phi_2)$$	$$\mathcal{L} \supset -\frac{f_{BB}}{\Lambda^2} \frac{g'^2}{4} (\phi^\dagger \phi) B_{\mu\nu} B^{\mu\nu} + \sum_f \frac{f_f}{\Lambda^2} (\phi^\dagger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

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

Full model:

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

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	$(\times)$