

Dimension-6 Analyses of the Higgs Sector

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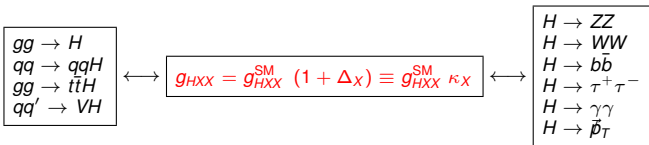
Higgs Couplings

Standard Model operators [SFitter: Gonzalez-Fraile, Klute, TP, Rauch, Zerwas]

- Lagrangian [in terms of non-linear sigma model: Buchalla et al, 1511.08188]

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \Delta_W g m_W H W^\mu W_\mu + \Delta_Z \frac{g}{2c_W} m_Z H Z^\mu Z_\mu - \sum_{\tau, b, t} \Delta_f \frac{m_f}{v} H (\bar{f}_R f_L + \text{h.c.})$$

$$+ \Delta_g F_G \frac{H}{v} G_{\mu\nu} G^{\mu\nu} + \Delta_\gamma F_A \frac{H}{v} A_{\mu\nu} A^{\mu\nu} + \text{invisible decays}$$



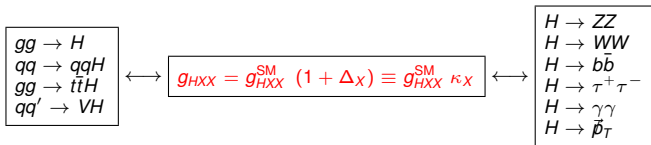
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Executive summary as mentioned in introduction

- couplings fit works great
 - offers perfect th-ex interface [Cranmer, Kreiss, Lopez-Val, TP]
- (1) has issues with **electroweak renormalization**
 - (2) does not describe **kinematic distributions**
 - (3) is hard to relate to **other sectors**

Higgs Couplings

Aim of the writeup, as stated in the introduction

- a fit of dimension-6 Wilson coefficients to LHC Higgs data can be done (and has been done for Run I data) by non-members of the ATLAS and CMS collaborations and based on published results;
- kinematic distributions can significantly improve the multi-dimensional parameter fit by resolving strong correlations induced by total rate measurements;
- communicating the relevant information, in particular related to kinematic distributions, is a challenge which needs to be resolved in close collaboration with the fitting projects;
- the results of a dimension-6 fit can be translated into weakly interacting extensions of the Standard Model, and many of the theoretical issues are clearly separated from experimental uncertainties;
- the language of dimension-6 Lagrangians can intuitively be linked to the structure of ultraviolet completions of the Standard Model gauge and Higgs sectors.

SFitter D6 fit

Higgs sector effective field theory [following Corbett, Eboli, Gonzalez-Fraile, Goncales-Garcia]

- set of Higgs-gauge operators [adjust with Rosetta]

$$\mathcal{O}_{GG} = \Phi^\dagger \Phi G_{\mu\nu}^a G^{a\mu\nu} \quad \mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \quad \mathcal{O}_{BB} = \dots$$

$$\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \quad \mathcal{O}_W = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi) \quad \mathcal{O}_B = \dots$$

$$\mathcal{O}_{\Phi,1} = (D_\mu \Phi)^\dagger \Phi \Phi^\dagger (D^\mu \Phi) \quad \mathcal{O}_{\Phi,2} = \frac{1}{2} \partial^\mu (\Phi^\dagger \Phi) \partial_\mu (\Phi^\dagger \Phi)$$

$$\mathcal{O}_{\Phi,3} = \frac{1}{3} (\Phi^\dagger \Phi)^3 \quad \mathcal{O}_{\Phi,4} = (D_\mu \Phi)^\dagger (D^\mu \Phi) (\Phi^\dagger \Phi)$$

- relevant part after equation of motion, etc

$$\mathcal{L}^{HVV} = -\frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_{\Phi,2}}{\Lambda^2} \mathcal{O}_{\Phi,2}$$

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- Higgs couplings to SM particles

$$\begin{aligned} \mathcal{L}^{HVV} &= g_g H G_{\mu\nu}^a G^{a\mu\nu} + g_\gamma H A_{\mu\nu} A^{\mu\nu} \\ &+ g_Z^{(1)} Z_{\mu\nu} Z^\mu \partial^\nu H + g_Z^{(2)} H Z_{\mu\nu} Z^{\mu\nu} + g_Z^{(3)} H Z_\mu Z^\mu \\ &+ g_W^{(1)} \left(W_{\mu\nu}^+ W^{-\mu} \partial^\nu H + \text{h.c.} \right) + g_W^{(2)} H W_{\mu\nu}^+ W^{-\mu\nu} + g_W^{(3)} H W_\mu^+ W^{-\mu} + \dots \end{aligned}$$

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- plus Yukawa structure $f_{\tau,b,t}$

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- 7 EFT couplings identical to Δ_x , suppressed by v^2/Λ^2 [with $\Delta_W = \Delta_Z$]

4 EFT couplings $g_{W,Z}^{(1,2)}$ in addition, suppressed by ∂/Λ [as in Eq.(1)]

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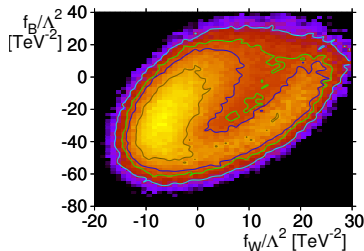
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SFitter analysis [Corbett, Eboli, Goncalves, Gonzalez-Fraile, TP, Rauch]

⇒ setup and data identical to SFitter Δ_x fit [Eqs.(3,4)]

- ew-renormalizable: #1
- including $\rho_{T,V}$, $\Delta\Phi_{jj}$: #2



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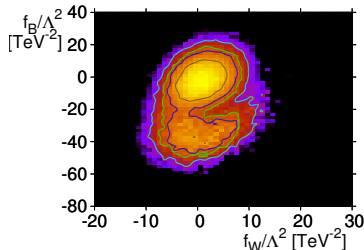
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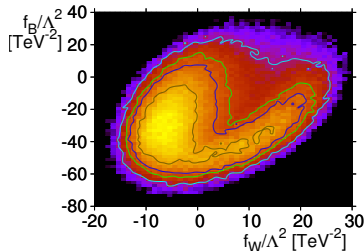
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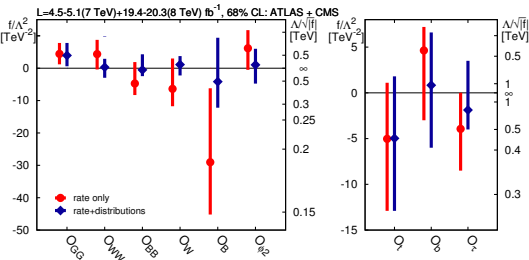
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- including $p_{T,V}, \Delta\Phi_{jj}$: #2
- TGVs for $\mathcal{O}_{B,W}$: #3

- (1) D6 fit works
- (2) D6 is not EFT



D6 description vs full models

D6-Lagrangian breakdown [Brehmer, Freitas, Lopez-Val, TP]

- phenomenology: does D6 capture all model features at LHC?
theory: how do D6 vs EFT vs full model differences appear?

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- push **models** to visible deviations at 13 TeV
Higgs portal, 2HDM, stops, vector triplet [weakly interacting, Eq.(2)]

$$\left| \frac{\sigma \times \text{BR}}{(\sigma \times \text{BR})_{\text{SM}}} - 1 \right| = \frac{g^2 m_h^2}{\Lambda^2} \gtrsim 10\% \quad \Leftrightarrow \quad \Lambda \lesssim 400 \text{ GeV}$$

no scale hierarchy for testable models?!

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matching conditions with $v \lesssim \Lambda$, v -improved matching?

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- run **LHC simulations**: D6-Lagrangian vs full model
production: WBF, VH , HH
decays: $H \rightarrow \gamma\gamma, 4\ell$
- check where **differences** appear at 13 TeV
kinematic distributions like $p_{T,j}$ or m_{VH} ?
resonance peaks of new states?

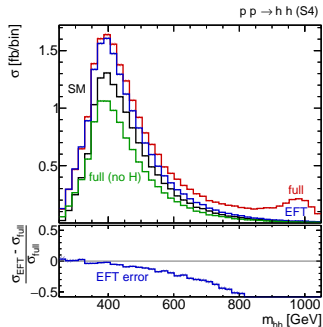
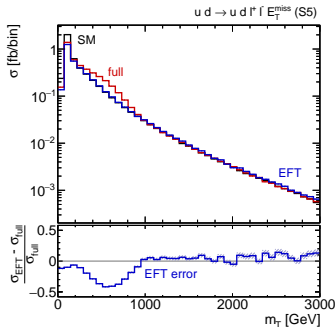
D6 description vs full models

Higgs portal

- testable benchmarks for LHC

Singlet				EFT			EFT (ν -improved)	
m_H	$\sin \alpha$	v_S/v	$\Delta_x^{\text{singlet}}$	Λ	\bar{c}_H	Δ_x^{EFT}	\bar{c}_H	Δ_x^{EFT}
500	0.2	10	-0.020	491	0.036	-0.018	0.040	-0.020
350	0.3	10	-0.046	336	0.073	-0.037	0.092	-0.046
200	0.4	10	-0.083	190	0.061	-0.031	0.167	-0.083
1000	0.4	10	-0.083	918	0.183	-0.092	0.167	-0.092
500	0.6	10	-0.200	407	0.461	-0.231	0.400	-0.200

- effects in WBF and hh [Fig.5]



D6 description vs full models

Higgs portal

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2HDM

- testable benchmarks for LHC

Type	2HDM						EFT		
	$\tan\beta$	α/π	m_{12}	m_{H^0}	m_{A^0}	m_{H^\pm}	$ \Lambda $ [GeV]	\bar{c}_u	$\bar{c}_{d,\ell}$
I	1.5	-0.086	45	230	300	350	100	-0.744	-0.744
II	15	-0.023	116	449	450	457	448	0.000	0.065
II	10	0.032	157	500	500	500	99	0.465	-46.5
I	20	0	45	200	500	500	142	0.003	0.003

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I	20	0	45	200	500	500	142	0.003	0.003

- effects in $H \rightarrow \gamma\gamma$ [not in note]

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Top partners

- testable benchmarks for LHC

M	Scalar top-partner model					EFT		
	κ_{LL}	κ_{RR}	κ_{LR}	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	\bar{c}_H	\bar{c}_W	\bar{c}_{HW}
500	-1.16	2.85	0.147	500	580	$6.22 \cdot 10^{-3}$	$-3.11 \cdot 10^{-7}$	$3.99 \cdot 10^{-7}$
350	-3.16	-2.82	0.017	173	200	$4.30 \cdot 10^{-3}$	$-2.55 \cdot 10^{-4}$	$2.55 \cdot 10^{-4}$
500	-7.51	-7.17	0.012	173	200	$1.66 \cdot 10^{-2}$	$-2.97 \cdot 10^{-4}$	$2.97 \cdot 10^{-4}$

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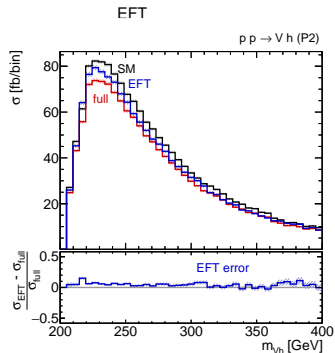
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500	-1.16	2.85	0.147	500	580	6.2%
350	-3.16	-2.82	0.017	173	200	4.3%
500	-7.51	-7.17	0.012	173	200	1.6%

- effects in WBF and Vh [Fig.6]



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Top partners

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Vector triplet [Brehmer, Biekötter, Krämer, TP]

- testable benchmarks for LHC

Triplet model						EFT			
M_V	g_V	c_H	c_F	c_{VVHH}	m_ξ	\bar{c}_W	\bar{c}_H	\bar{c}_6	\bar{c}_f
591	3.0	-0.47	-5.0	2.0	1200	-0.044	0.000	0.000	0.000
946	3.0	-0.47	-5.0	1.0	1200	-0.017	0.000	0.000	0.000
941	3.0	-0.28	3.0	1.0	1200	0.006	0.075	0.100	0.025
1246	3.0	-0.50	3.0	-0.2	1200	0.006	0.103	0.138	0.034
846	1.0	-0.56	-1.32	0.08	849	-0.007	-0.020	-0.027	-0.007

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2HDM

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- effects in $H \rightarrow \gamma\gamma$ [not in note]

Top partners

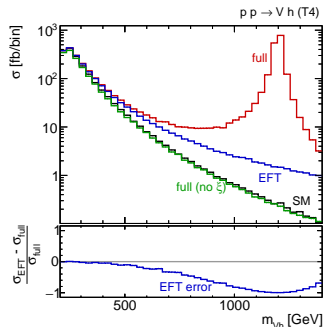
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Vector triplet [Brehmer, Biekötter, Krämer, TP]

- testable benchmarks for LHC

Triplet model						
M_V	g_V	c_H	c_F	c_{VVHH}	m_ξ	
591	3.0	-0.47	-5.0	2.0	1200	-
946	3.0	-0.47	-5.0	1.0	1200	-
941	3.0	-0.28	3.0	1.0	1200	-
1246	3.0	-0.50	3.0	-0.2	1200	-
846	1.0	-0.56	-1.32	0.08	849	-

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D6 description vs full models

Higgs portal

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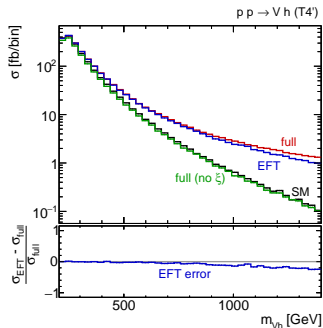
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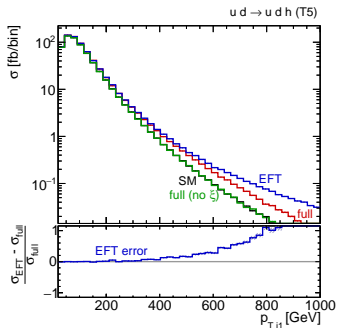
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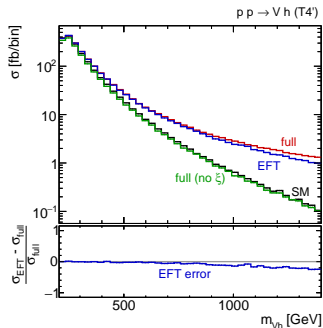
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D6 description vs full models

Reasons for D6-breakdown

Model	Process	EFT failure		
		resonance	kinematics	matching
singlet	on-shell $h \rightarrow 4\ell, \text{WBF}, Vh, \dots$			×
	off-shell WBF, ...		(×)	×
	hh	×	×	×
2HDM	on-shell $h \rightarrow 4\ell, \text{WBF}, Vh, \dots$			×
	off-shell $H \rightarrow \gamma\gamma, \dots$		(×)	×
	hh	×	×	×
top partner	WBF, Vh			×
vector triplet	WBF		(×)	×
	Vh	×	(×)	×

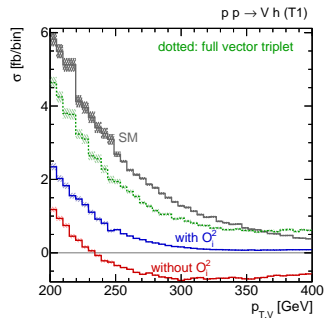
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	Vh	×	(×)	×

D6-squared terms [Brehmer, Biekötter, Krämer, TP]

- EFT: same order as $D4 \times D8$, neglect
- D6-Lagrangian: keep or neglect
- negative rates in phase space? [Fig.9]



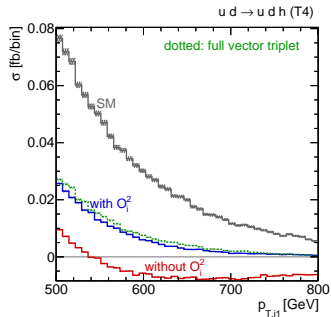
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top partner	WBF, Vh			×
vector triplet	WBF		(×)	×
	Vh	×	(×)	×

In practice

- ex: D6-Lagrangian at weak scale as hypothesis for rates and distributions
- th: calculations including loop effects
- ex: correlated Wilson coefficients
- th: matching to favorite model
- th: RG running to where you want to live
- th: error from EFT convergence