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 etal, 1511.08188]

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \Delta_W \; g m_W H \; W^\mu W_\mu + \Delta_Z \; \frac{g}{2c_w} m_Z H \; Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f \; \frac{m_f}{v} H \left(\bar{f}_R f_L + \text{h.c.} \right)$$
$$+ \Delta_g F_G \; \frac{H}{v} \; G_{\mu\nu} G^{\mu\nu} + \Delta_\gamma F_A \; \frac{H}{v} \; A_{\mu\nu} A^{\mu\nu} + \text{invisible decays}$$

$gg \to H$
$qq \to qqH$
$gg \to t\bar{t}H$
$qq' \to VH$

$\longleftrightarrow$ $g_{HXX} = g^{\text{SM}}_{HXX} \; (1 + \Delta_X) \equiv g^{\text{SM}}_{HXX} \; \kappa_X$ $\longleftrightarrow$

$H \to ZZ$
$H \to WW$
$H \to b\bar{b}$
$H \to \tau^+\tau^-$
$H \to \gamma\gamma$
$H \to \vec{p}_T$

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$$\boxed{\begin{array}{l} gg \to H \\ qq \to qqH \\ gg \to t\bar{t}H \\ qq' \to VH \end{array}} \longleftrightarrow \boxed{g_{HXX} = g^{\text{SM}}_{HXX} \; (1 + \Delta_X) \equiv g^{\text{SM}}_{HXX} \; \kappa_X} \longleftrightarrow \boxed{\begin{array}{l} H \to ZZ \\ H \to WW \\ H \to b\bar{b} \\ H \to \tau^+\tau^- \\ H \to \gamma\gamma \\ H \to \vec{p}_T \end{array}}$$

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]

$$\mathcal{O}_{GG} = \Phi^\dagger \Phi G^a_{\mu\nu} G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \qquad \mathcal{O}_{BB} = \cdots$$

$$\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \qquad \mathcal{O}_{W} = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi) \qquad \mathcal{O}_{B} = \cdots$$

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

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

– 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^a_{\mu\nu} G^{a\mu\nu} + g_\gamma \, H A_{\mu\nu} A^{\mu\nu} \\
&\quad + 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 \\
&\quad + 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} + \cdots
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- plus Yukawa structure $f_{\tau,b,t}$

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- plus Yukawa structure $f_{\tau,b,t}$
- 7 EFT couplings identical to Δ_x, suppressed by v^2/Λ^2 [with $\Delta_W = \Delta_Z$]
  4 EFT couplings $g^{(1,2)}_{W,Z}$ in addition, suppressed by ∂/Λ [as in Eq.(1)]

SFitter D6 fit

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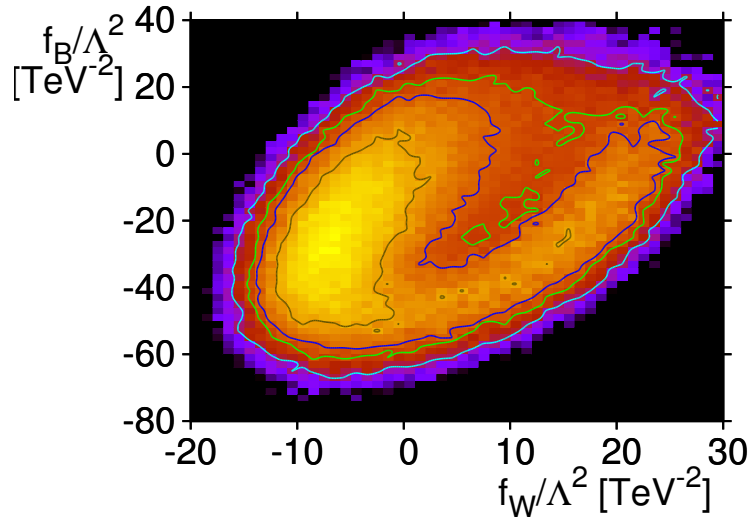
SFitter analysis [Corbett, Eboli, Goncalves, Gonzalez-Fraile, TP, Rauch]

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

– ew-renormalizable: #1

– including $p_{T,V}$, $\Delta\Phi_{jj}$: #2



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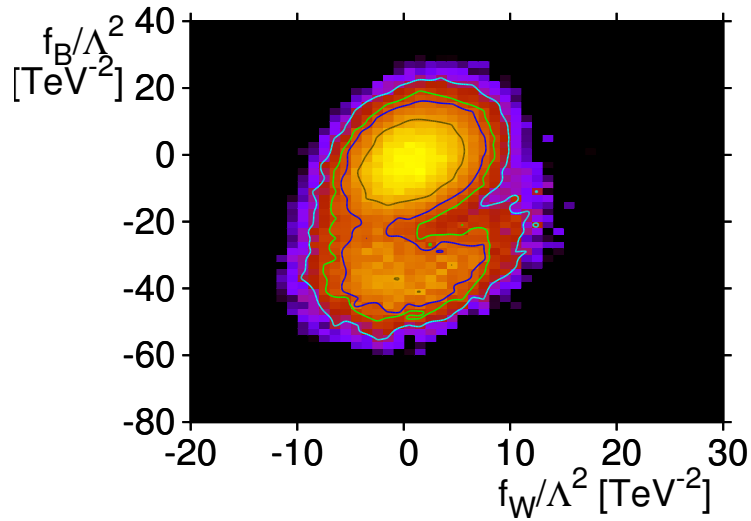

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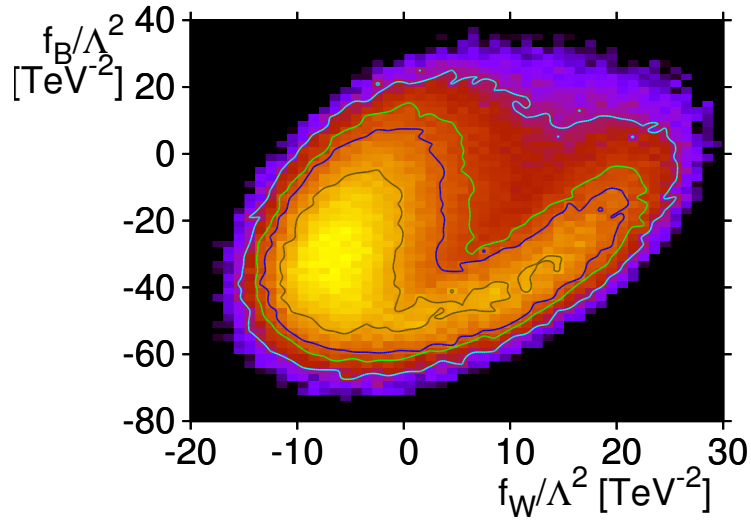

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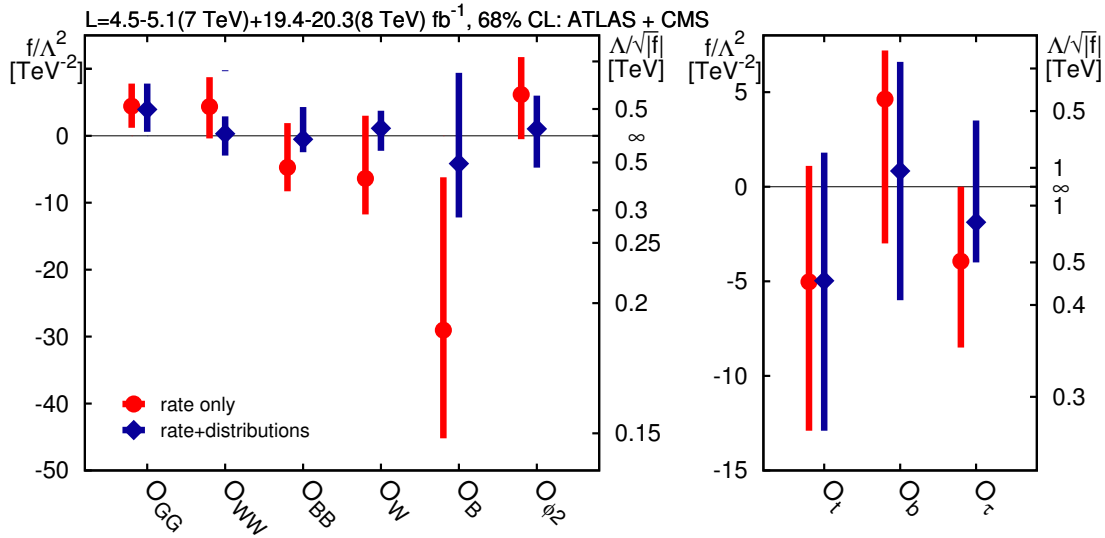
– TGVs for $\mathcal{O}_{B,W}$: #3

(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)]

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

no scale hierarchy for testable models?!

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- construct and match D6-Lagrangian to full model

  coupling modifications v^2/Λ^2 vs new kinematics ∂/Λ?

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

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- construct and match D6-Lagrangian to full model

  coupling modifications v^2/Λ^2 vs new kinematics ∂/Λ?
  matching conditions with $v \lesssim \Lambda$, v-improved matching?
- run LHC simulations: D6-Lagrangian vs full model

  production: WBF, VH, HH
  decays: $H \to \gamma\gamma, 4\ell$
- check where differences appear at 13 TeV

  kinematic distributions like $p_{T,j}$ or m_{VH}?
  resonance peaks of new states?

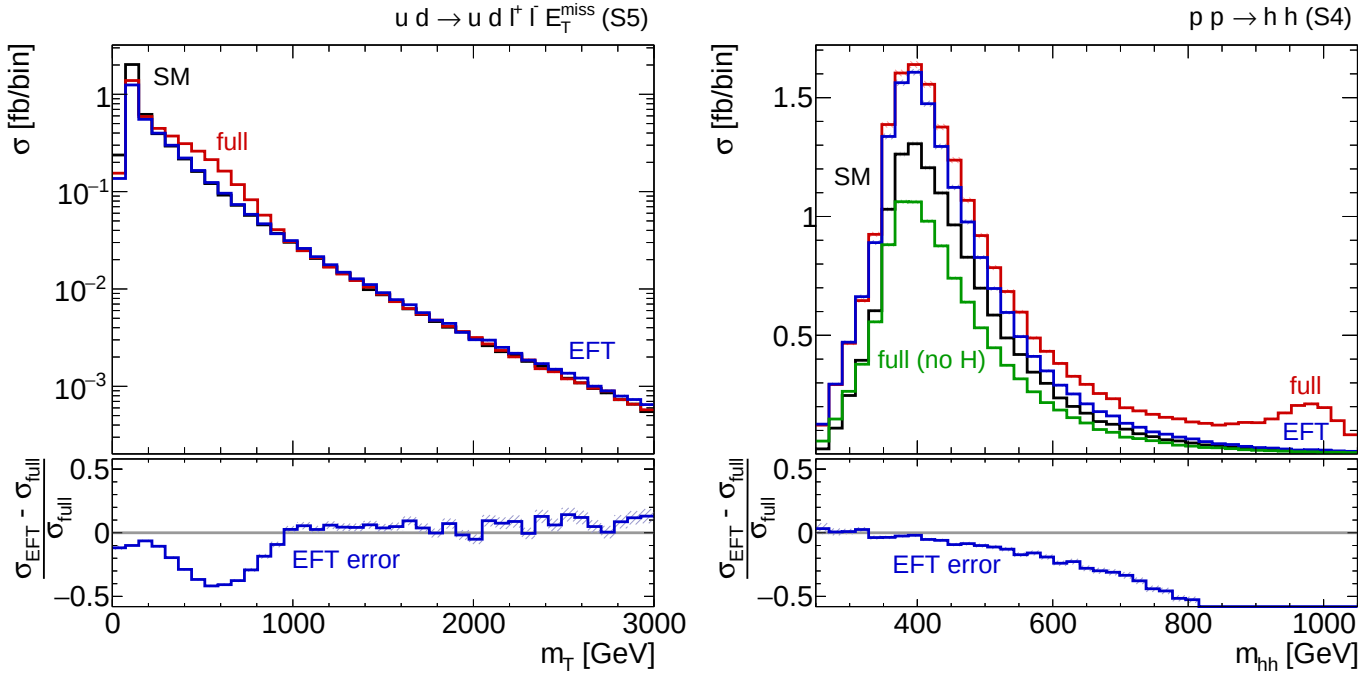
D6 description vs full models

Higgs portal

– testable benchmarks for LHC

Singlet				EFT			EFT (v-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]



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Higgs portal

- testable benchmarks for LHC
- effects in WBF and hh [Fig.5]

2HDM

- testable benchmarks for LHC

2HDM							EFT		
Type	$\tan\beta$	α/π	m_{12}	m_{H^0}	m_{A^0}	$m_{H^\pm}$	$\lvert\Lambda\rvert$ [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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- effects in $H \to \gamma\gamma$ [not in note]

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Top partners

- testable benchmarks for LHC

Scalar top-partner model						EFT		
M	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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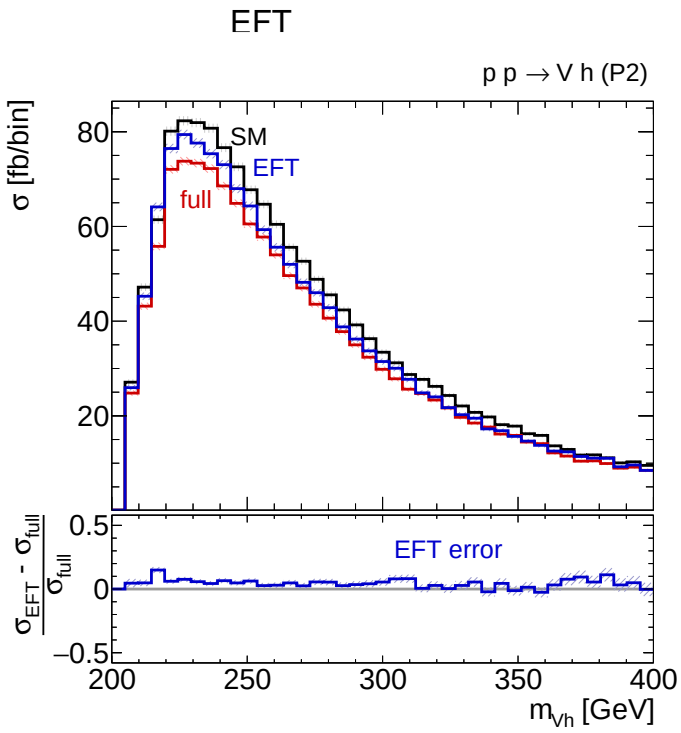
500	−7.51	−7.17	0.012	173	200	1.66

- effects in WBF and Vh [Fig.6]



D6 description vs full models

Higgs portal

- testable benchmarks for LHC
- effects in WBF and hh [Fig.5]

2HDM

- testable benchmarks for LHC
- effects in $H \to \gamma\gamma$ [not in note]

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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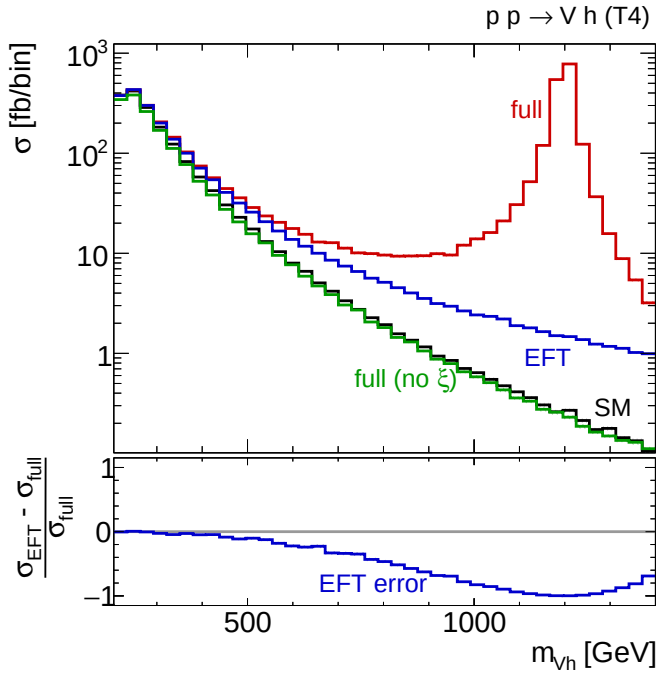
Triplet model

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	–

- effects in Vh and WBF [Fig.7]



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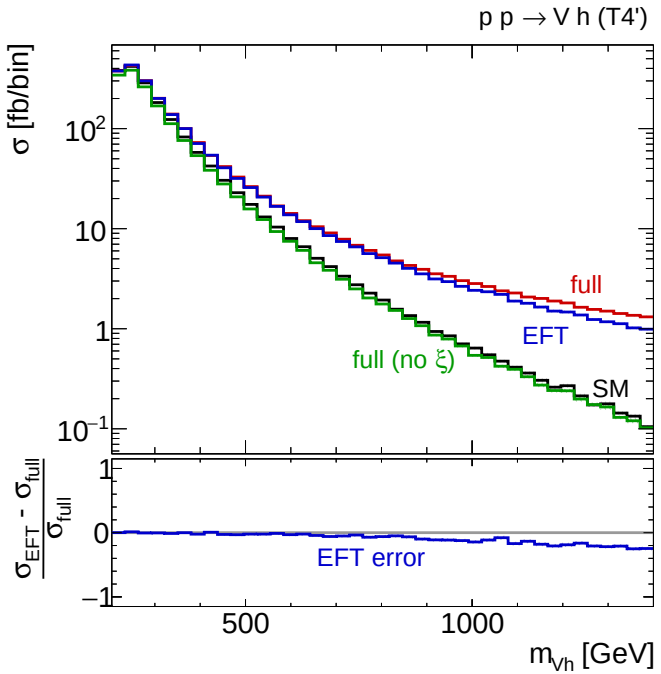

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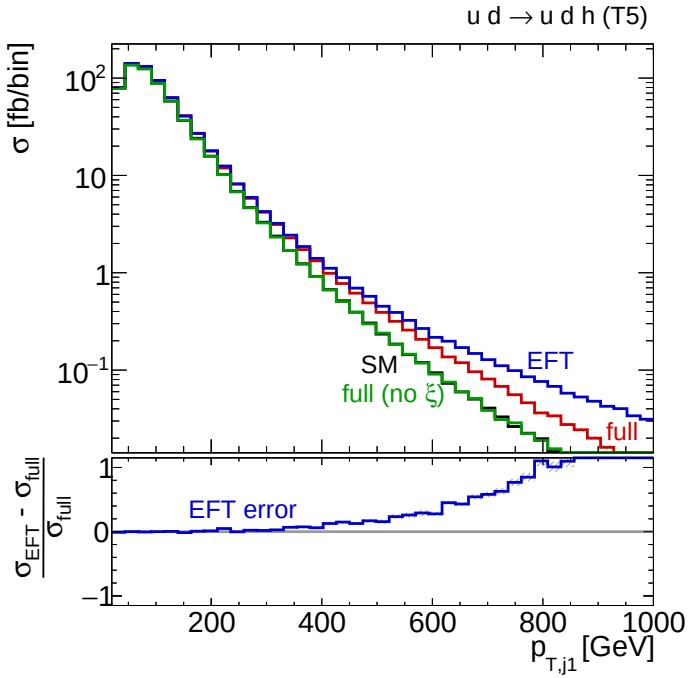

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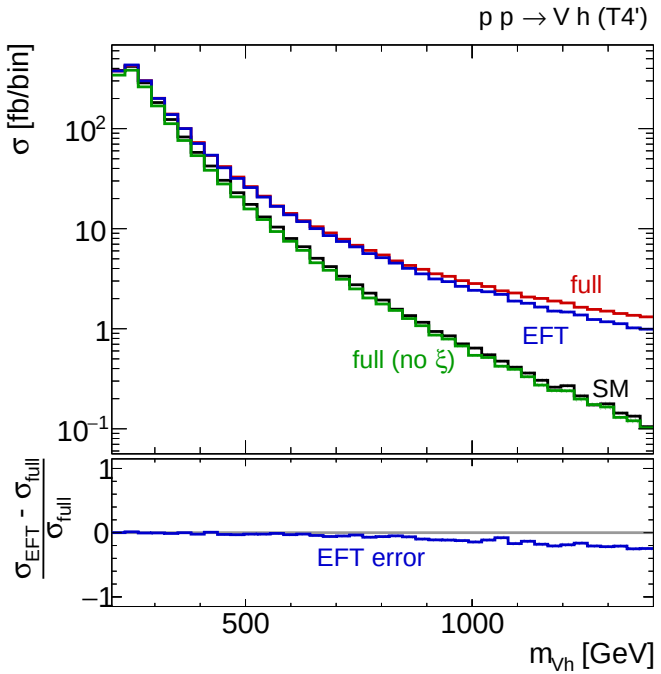

D6 description vs full models

Reasons for D6-breakdown

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

D6 description vs full models

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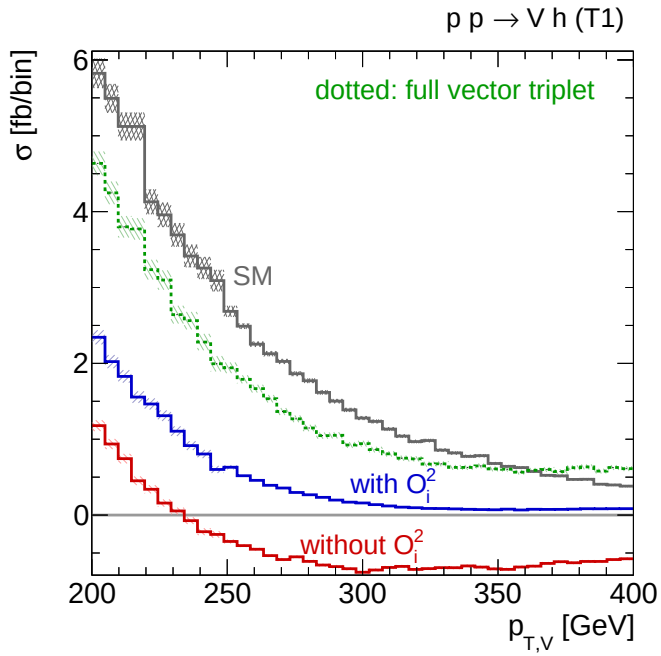
	off-shell $H \to \gamma\gamma$, ...		(×)	×
	hh	×	×	×
top partner	WBF, Vh			×
vector triplet	WBF		(×)	×
	Vh	×	(×)	×

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]



D6 description vs full models

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Model	Process	EFT failure		
		resonance	kinematics	matching
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	hh	×	×	×
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	off-shell $H \to \gamma\gamma$, ...		(×)	×
	hh	×	×	×
top partner	WBF, Vh			×
vector triplet	WBF		(×)	×
	Vh	×	(×)	×

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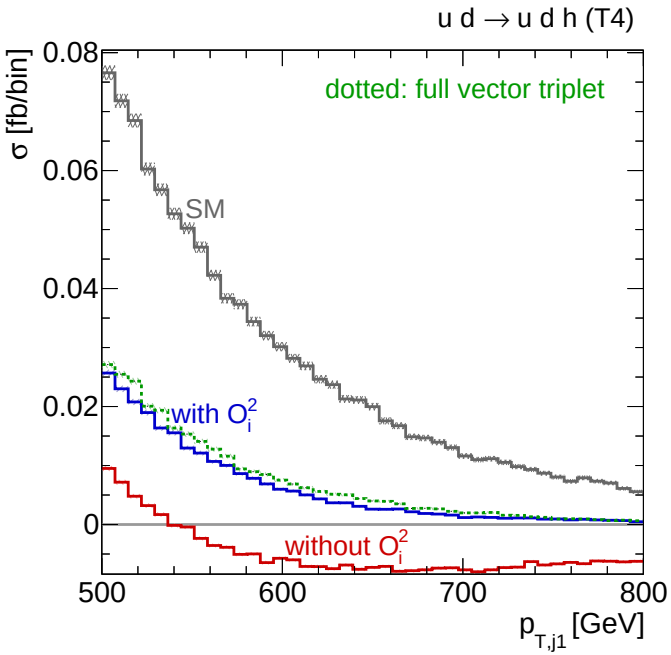

D6 description vs full models

Reasons for D6-breakdown

Model	Process	EFT failure		
		resonance	kinematics	matching
singlet	on-shell $h \to 4\ell$, WBF, Vh, ...			×
	off-shell WBF, ...		(×)	×
	hh	×	×	×
2HDM	on-shell $h \to 4\ell$, WBF, Vh, ...			×
	off-shell $H \to \gamma\gamma$, ...		(×)	×
	hh	×	×	×
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