Single-Higgs EFT fits and possible implications for di-Higgs

[1812.07587, 1811.08401]

Anke Biekötter

with Tyler Corbett, Dorival Gonçalves, Tilman Plehn

Michihisa Takeuchi and Dirk Zerwas

LHC-HH Subgroup Meeting

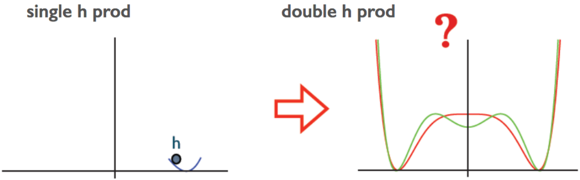
Outline

What are the implications of single-Higgs fits for di-Higgs in the EFT framework?

- Effective field theory
- LHC Run-II fit

  fermionic operators + EWPD
- HE-LHC fit

  Higgs self-coupling
- Conclusion

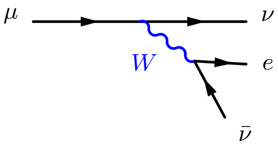


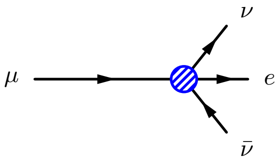
[Juan Rojo's slide]

SM effective field theory

E NP Λ E_{LHC} FT

- hierarchy of scales
- new physics at a high scale $> \Lambda$
- integrate out heavy degrees of freedom
- describe by higher-order interactions of SM particles





Dimension-6 Lagrangian

SMEFT: SM fields only, Higgs doublet structure [review: Brivio, Trott (1706.08945)]

HISZ basis [Hagiwara, Ishihara, Szalapski, Zeppenfeld; Corbett et al. (1211.4580)]

$$\mathcal{L} = \mathcal{L}_{\mathsf{SM}} + \sum_x \frac{f_x}{\Lambda^2}\mathcal{O}_x$$

modified Yukawa couplings

$$\mathcal{O}_{e\phi,33} = (\phi^\dagger\phi)(\bar{L}_3\phi e_{R,3}) \qquad \mathcal{O}_{u\phi,33} = (\phi^\dagger\phi)(\bar{Q}_3\tilde{\phi}u_{R,3}) \qquad \mathcal{O}_{d\phi,33} = (\phi^\dagger\phi)(\bar{Q}_3\phi d_{R,3})$$

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

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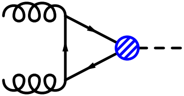

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modified Higgs-gauge couplings

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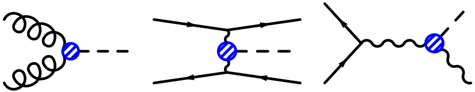

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modified triple gauge couplings

$$\mathcal{O}_{e\phi,33} = (\phi^\dagger\phi)(\bar{L}_3\phi e_{R,3}) \qquad \mathcal{O}_{u\phi,33} = (\phi^\dagger\phi)(\bar{Q}_3\tilde{\phi}u_{R,3}) \qquad \mathcal{O}_{d\phi,33} = (\phi^\dagger\phi)(\bar{Q}_3\phi d_{R,3})$$

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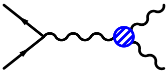

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Higgs wave-function renormalization

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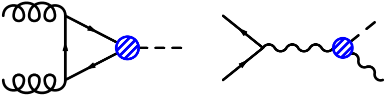

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modified fermion-gauge couplings? [Baglio, Dawson, Lewis (1708.03332)]

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modified S and T oblique parameters

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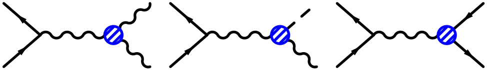

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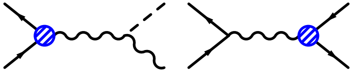

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modified Fermi constant

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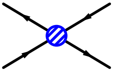
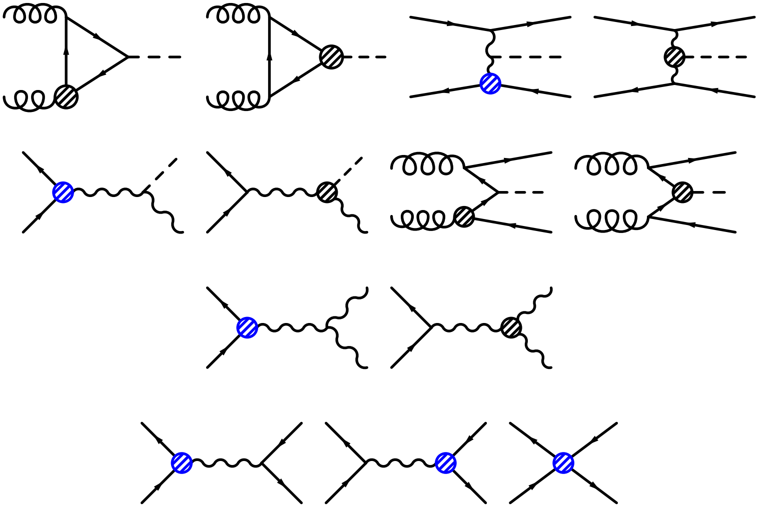


Processes



Higgs (+ decays) + di-boson production (WW, WZ) + EWPD

fermion-gauge couplings

LHC Run II fit - without operators constrained in EWPD

[SFitter Run I: Butter et al. (1604.03105)]

[Ellis, Murphy, Sanz, You (1803.03252)],

[da Silva Almeida, Alves, Rosa Agostinho, Éboli, Gonzalez-Garcia (1812.01009)]

What's new?

LHC Run II data (tth!)

including distributions

(WZ/Vh)

$$\mathcal{O}_{GG} = \phi^\dagger \phi \, G^a_{\mu\nu} G^{a\mu\nu}$$
$$\mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi$$
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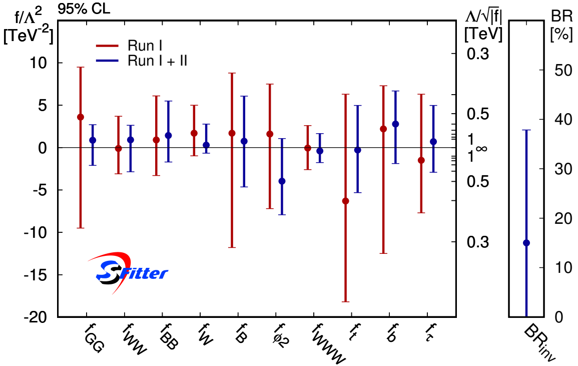
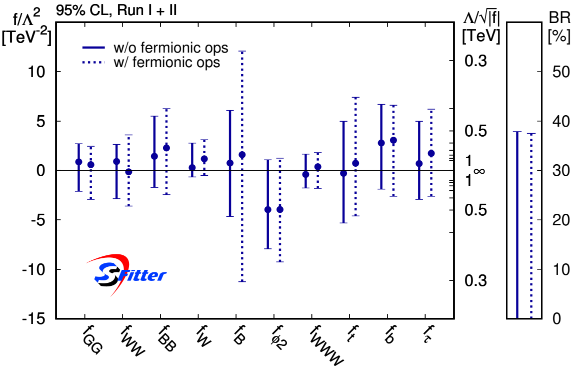
$$\mathcal{O}_{B} = (D_\mu \phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \phi)$$
$$\mathcal{O}_{\phi 2} = \frac{1}{2} \partial^\mu (\phi^\dagger \phi) \partial_\mu (\phi^\dagger \phi)$$
$$\mathcal{O}_{WWW} = \mathrm{Tr}\left(\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}^\mu_\rho\right)$$
$$\mathcal{O}_{\tau} = \phi^\dagger \phi \, \bar{L}_3 \phi e_{R,3}$$
$$\mathcal{O}_{t} = \phi^\dagger \phi \, \bar{Q}_3 \tilde{\phi} u_{R,3}$$
$$\mathcal{O}_{b} = \phi^\dagger \phi \, \bar{Q}_3 \phi d_{R,3}$$



tth measurements disentangle $\mathcal{O}_{GG}$ and $\mathcal{O}_t$

limits on bosonic operators improved by distributions

LHC Run II fit - influence of fermionic operators



inclusion of fermionic operators (relevant for EWPD) weakens limits on bosonic operators

$$\mathcal{O}_{BW} = \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{\phi,1} = (D_\mu \phi)^\dagger \, \phi \, \phi^\dagger \, (D^\mu \phi)$$

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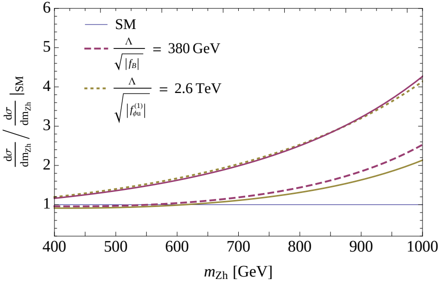
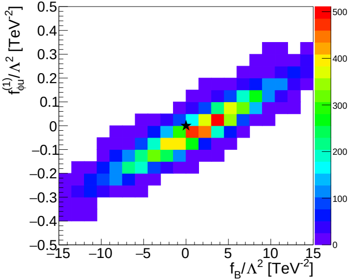
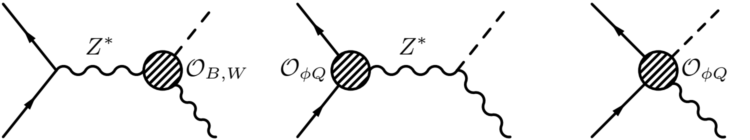
LHC Run II fit - influence of fermionic operators





positive Wilson coefficients dashed

contributions to ZH production

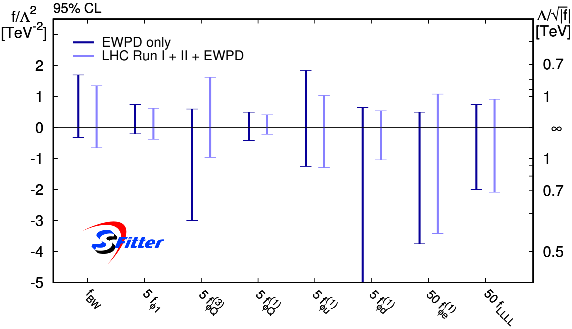


$$\mathcal{O}_B = (D_\mu \phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \phi) \qquad \mathcal{O}^{(1)}_{\phi Q} = \phi^\dagger (i \overleftrightarrow{D}_\mu \phi)(\bar{Q}\gamma^\mu Q)$$

[Banerjee, Englert, Gupta, Spannowsky (1807.01796)]

LHC Run II fit - tighter constraints on fermionic operators

[LEP/SLD 0509008, PDG]



limits on fermionic operators tightened or shifted towards SM values

Higgs limits at a 27 TeV collider

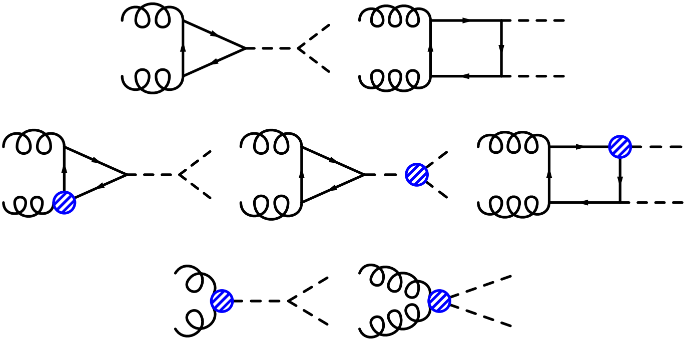
(... and finally di-Higgs production)

What can we do at 27 TeV?

- more accurate Higgs-coupling measurements
- distributions up to high energies

What can we do at 27 TeV?

- more accurate Higgs-coupling measurements
- distributions up to high energies
- di-Higgs production $\rightarrow$ Higgs self-coupling



Higgs limits at a 27 TeV collider

interpolated from 8 TeV results

10 distributions

(di-boson, WBF, VH, di-Higgs)

Higgs self-coupling included

10 operators $+\mathcal{O}_{\phi 3}$

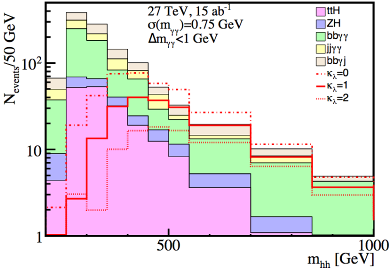
(no fermionic operators)

2 operators contribute to Higgs self-coupling

$$\mathcal{O}_{\phi,2} = \frac{1}{2}\partial^\mu \left(\phi^\dagger \phi\right) \partial_\mu \left(\phi^\dagger \phi\right) \quad \to \text{kinematics}$$

$$\mathcal{O}_{\phi 3} = -(\phi^\dagger \phi)^3/3 \quad \to \text{rate}$$

[Gonçalves et al. (1802.04319)]



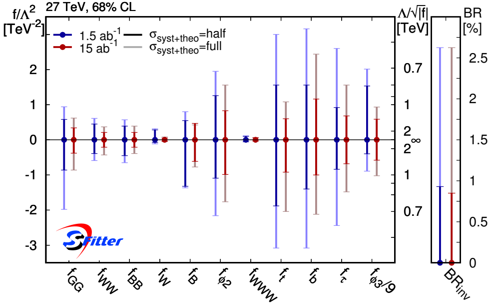
1-parameter fit

$$\left|\frac{\Lambda}{\sqrt{f_{\phi 3}}}\right| \gtrsim \begin{cases} 1\ \text{TeV} & 68\%\ \text{C.L.} \\ 700\ \text{GeV} & 95\%\ \text{C.L.} \end{cases}$$

How does these limit from the 1-parameter fit change in a global fit?

[Plehn et al. (1996); Djouadi et al. (hep-ph/9904287); Li, Voloshin (1311.5156), Dolan et al. (1206.5001)]

Higgs limits at a 27 TeV collider



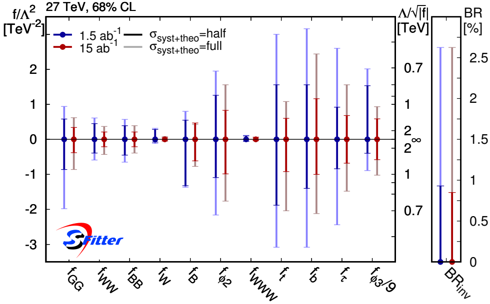
full = current systematic and theory uncertainties

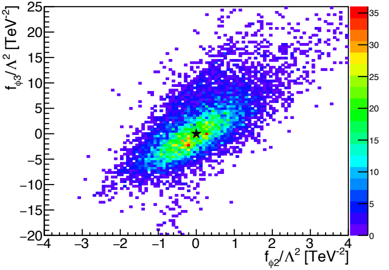
distributions always statistics dominated

95% CL limits on $\frac{\Lambda}{\sqrt{|f_{\phi,3}|}} > 250$ GeV (700 GeV single param fit)

$$\mathcal{O}_{\phi,2} = \frac{1}{2}\partial^{\mu}\left(\phi^{\dagger}\phi\right)\partial_{\mu}\left(\phi^{\dagger}\phi\right) \qquad \mathcal{O}_{\phi 3} = -\left(\phi^{\dagger}\phi\right)^{3}/3$$

Higgs limits at a 27 TeV collider





full = current systematic and theory uncertainties

distributions always statistics dominated

95% CL limits on $\frac{\Lambda}{\sqrt{|f_{\phi,3}|}} > 250$ GeV (700 GeV single param fit)

need precise measurements of other Higgs couplings

$\mathcal{O}_{\phi,2}$ influences **all** Higgs couplings (wave function renormalization)

$$\mathcal{O}_{\phi,2} = \frac{1}{2}\partial^\mu\left(\phi^\dagger\phi\right)\partial_\mu\left(\phi^\dagger\phi\right) \qquad \mathcal{O}_{\phi 3} = -(\phi^\dagger\phi)^3/3$$

Conclusions

LHC Run II - Higgs couplings

- tth measurements disentangle top and gluon couplings
- inclusion of fermionic operators weakens limits on (some) operators
- $\Lambda/\sqrt{f} = 400 \ldots 800$ GeV reach for bosonic operators

HE-LHC - including di-Higgs production

- Higgs self coupling
- TeV-scale reach for $\mathcal{O}(1)$ couplings (3 ... 5% accuracy)
- Global fit dilutes limits on $f_{\phi 3}$ by a factor ~ 3
  (with respect to a single parameter fit)

precise probes of single-Higgs **and** di-boson production needed

to test the Higgs self-coupling

Thank you for your attention!

Backup

SFitter

- fits via toy Monte Carlo method

  shift the data according to uncertainties

  [Rojo et al., NNPDF; SMEFiT (1901.05965)]

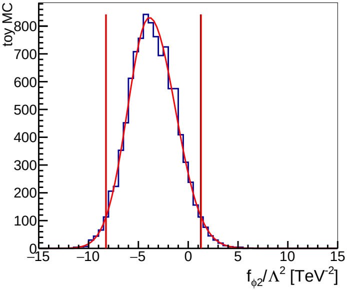
- uncertainties:
  - flat (theory)
  - Poisson (statistical)
  - Gaussian (systematics)

    [Hocker et al. (hep-ph/0104062)]

- full correlation of systematic uncertainties

  luminosity, JES, JER, lepton efficiency, b-tagging, ...

[Bayesian: Allanach et al. (hep-ph/0507283, 0704.0487)]



Toy Monte Carlos

We create a replica of measurement i with experimental value x_i^{exp} using

$$x_i^{\text{toy}} = x_i^{\text{exp}} + \Delta^{\text{shift}} + \text{sign}(\Delta^{\text{shift}})\Delta^{\text{flat}}\,,$$
$$\Delta^{\text{shift}} = \Delta^{\text{Gaus}} + \Delta^{\text{Pois}} + \Delta^{\text{syst}}\,,$$

where

$$\Delta^{\text{Gaus}} = r^{\text{Gaus}} \sqrt{\sum_j (\sigma_j^{\text{Gaus}})^2} \qquad \Delta^{\text{Pois}} = \frac{r^{\text{Pois}}(\tau x_i^{\text{toy}})}{\tau} - x_i^{\text{toy}}$$

$$\Delta^{\text{syst}} = \sum_{j=1}^{N_{\text{syst}}} r_j^{\text{syst}} \sigma_j^{\text{syst}} \qquad \Delta^{\text{flat}} = \sum_{j=1}^{N_{\text{flat}}} \sigma_j^{\text{flat}}\,.$$

LHC Run II fit - What's new?

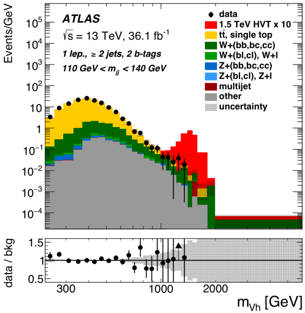
- fermionic operators

  [Baglio, Dawson, Lewis (1708.03332)]

- data
  - Run II rate measurements (tth!)
  - ATLAS WZ distribution

    [ATLAS-CONF-2018-034]
  - ATLAS Vh distribution

    [CERN-EP-2017-250,1712.06518v2]
  - EWPD



$$\Gamma_Z,\ \sigma_h^0, \mathcal{A}_l(\tau^{\text{pol}}),\ R_l^0,\ \mathcal{A}_l(\text{SLD}),\ A_{\text{FB}}^{0,l},\ R_c^0,\ R_b^0, \mathcal{A}_c,\ \mathcal{A}_b,\ A_{\text{FB}}^{0,c},\ A_{\text{FB,SLD/LEP}}^{0,b}$$

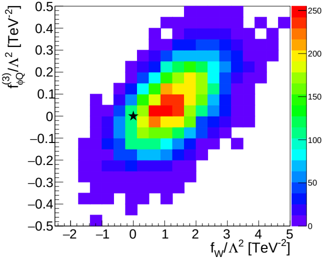
$$M_W,\ \Gamma_W,\ \text{BR}(W \to l\nu)$$

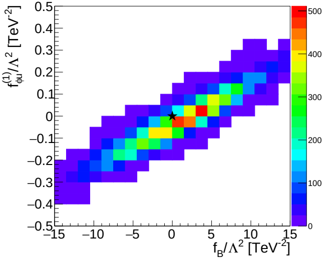
[LEP/SLD 0509008, PDG], [Corbett et al. (1705.09294)]

LHC Run II fit - Rate measurements

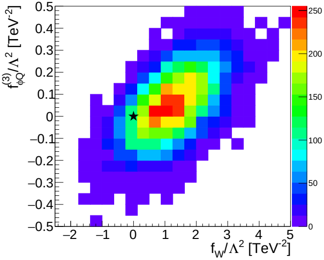
production/decay mode	ATLAS	CMS
$H \to WW$	Ref. [11]	Ref. [12]
$H \to ZZ$	Ref. [15]	Ref. [16, 17]
$H \to \gamma\gamma$	Ref. [1]	Ref. [2]
$H \to \tau\bar{\tau}$		Ref. [9, 10]
$H \to \mu\bar{\mu}$	Ref. [7]	Ref. [8]
$H \to b\bar{b}$	Ref. [3]	Ref. [4]
$H \to Z\gamma$	Ref. [13]	Ref. [14]
$H \to$ invisible		Ref. [5, 6]
$t\bar{t}H$ production		
$H \to \gamma\gamma$	Ref. [18]	Ref. [2]
$H \to$ leptons	Ref. [19]	Ref. [20, 21]
$H \to b\bar{b}$	Ref. [18]	Ref. [22]
kinematic distributions	Vh EXO Ref. [25]	
	WZ Ref. [23]	

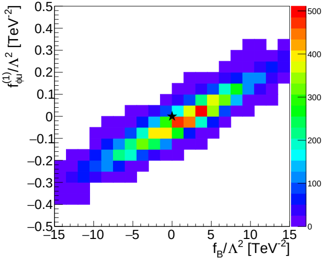
LHC Run II fit - correlations





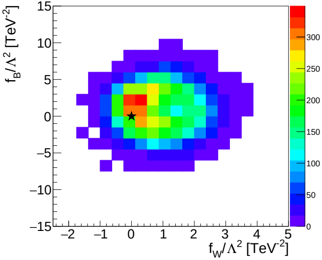
LHC Run II fit - correlations

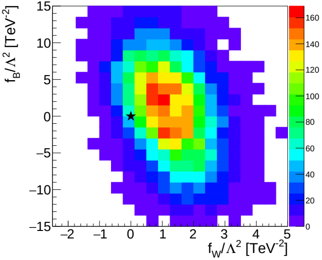




without fermionic operators

with fermionic operators

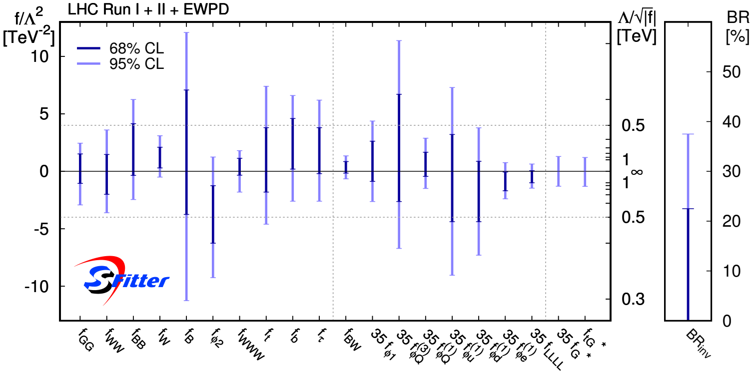




correlation between f_B and f_W reintroduced

LHC Run II fit - including fermionic operators

[Ellis et al. (1803.03252); da Silva Almeida et al. (1812.01009)]



inclusion of fermionic operators weakens limits on bosonic operators

* f_G, f_{tG} limits from multi-jet production and $t\bar{t}$ production (not included in fit)

[Buckley et al. (1512.03360); Krauss et al. (1611.00767)]

Higgs limits at a 27 TeV collider

interpolated from 8 TeV results

Higgs self-coupling included [Gonçalves et al. (1802.04319)]

10 operators $+\mathcal{O}_{\phi 3}$ (no fermionic operators)

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

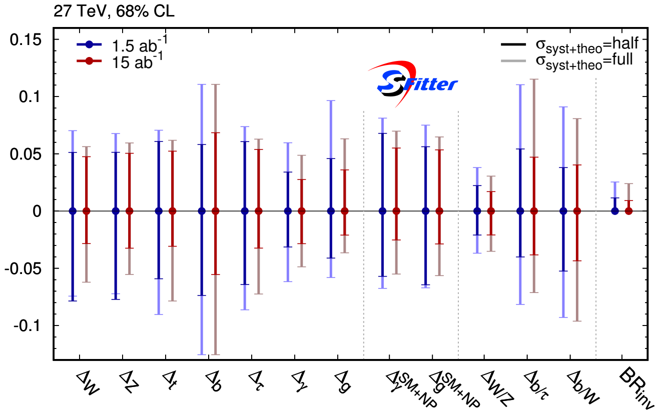
$$\mathcal{O}_{W} = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \qquad \mathcal{O}_{B} = (D_\mu \phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \phi) \qquad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial^\mu \left(\phi^\dagger \phi\right) \partial_\mu \left(\phi^\dagger \phi\right)$$

$$\mathcal{O}_{e\phi,33} = (\phi^\dagger \phi)(\bar{L}_3 \phi e_{R,3}) \qquad \mathcal{O}_{u\phi,33} = (\phi^\dagger \phi)(\bar{Q}_3 \tilde{\phi} u_{R,3}) \qquad \mathcal{O}_{d\phi,33} = (\phi^\dagger \phi)(\bar{Q}_3 \phi d_{R,3})$$

$$\mathcal{O}_{WWW} = \mathrm{Tr}\left(\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}_\rho^\mu\right) \qquad \mathcal{O}_{\phi 3} = -(\phi^\dagger \phi)^3/3$$

channel	observable	# bins	range [GeV]
$WW \to (\ell\nu)(\ell\nu)$	$m_{\ell\ell'}$	10	$0 - 4500$
$WW \to (\ell\nu)(\ell\nu)$	$p_T^{\ell_1}$	8	$0 - 1750$
$WZ \to (\ell\nu)(\ell\ell)$	m_T^{WZ}	11	$0 - 5000$
$WZ \to (\ell\nu)(\ell\ell)$	$p_T^{\ell\ell}$ (p_T^Z)	9	$0 - 2400$
WBF, $H \to \gamma\gamma$	$p_T^{\ell_1}$	9	$0 - 2400$
$VH \to (0\ell)(b\bar{b})$	p_T^V	7	$150 - 750$
$VH \to (1\ell)(b\bar{b})$	p_T^V	7	$150 - 750$
$VH \to (2\ell)(b\bar{b})$	p_T^V	7	$150 - 750$
$HH \to (b\bar{b})(\gamma\gamma)$, $2j$	m_{HH}	9	$200 - 1000$
$HH \to (b\bar{b})(\gamma\gamma)$, $3j$	m_{HH}	9	$200 - 1000$

Higgs limits at a 27 TeV collider - Δ framework



$$g_{hxx} = g_{hxx}^{\text{SM}} \left(1 + \Delta\right)$$

full = current systematic and theory uncertainties

limits below 5%

rate measurements systematics dominated

[1] M. Aaboud *et al.* [ATLAS Collaboration], arXiv:1802.04146 [hep-ex].

[2] A. M. Sirunyan *et al.* [CMS Collaboration], arXiv:1804.02716 [hep-ex].

[3] M. Aaboud *et al.* [ATLAS Collaboration], JHEP **1712**, 024 (2017) arXiv:1708.03299 [hep-ex].

[4] A. M. Sirunyan *et al.* [CMS Collaboration], Phys. Lett. B **780**, 501 (2018) [arXiv:1709.07497 [hep-ex].

[5] A. M. Sirunyan *et al.* [CMS Collaboration], Eur. Phys. J. C **78**, no. 4, 291 (2018) doi:10.1140/epjc/s10052-018-5740-1 [arXiv:1711.00431 [hep-ex]].

[6] A. M. Sirunyan [CMS Collaboration], CMS-PAS-HIG-17-023.

[7] M. Aaboud *et al.* [ATLAS Collaboration], Phys. Rev. Lett. **119**, no. 5, 051802 (2017) arXiv:1705.04582 [hep-ex].

[8] A. M. Sirunyan *et al.* [CMS Collaboration], arXiv:1807.06325 [hep-ex].

[9] A. M. Sirunyan *et al.* [CMS Collaboration], Phys. Lett. B **779**, 283 (2018) arXiv:1708.00373 [hep-ex].

[10] A. M. Sirunyan [CMS Collaboration], CMS-PAS-HIG-18-007.

[11] M. Aaboud *et al.* [ATLAS Collaboration], ATLAS-CONF-2018-004.

[12] A. M. Sirunyan *et al.* [CMS Collaboration], [arXiv:1806.05246 [hep-ex]].

[13] M. Aaboud *et al.* [ATLAS Collaboration], JHEP **1710**, 112 (2017) arXiv:1708.00212 [hep-ex].

[14] A. M. Sirunyan *et al.* [CMS Collaboration], arXiv:1806.05996 [hep-ex].

[15] M. Aaboud *et al.* [ATLAS Collaboration], JHEP **1803**, 095 (2018) arXiv:1712.02304 [hep-ex].

[16] A. M. Sirunyan *et al.* [CMS Collaboration], JHEP **1711**, 047 (2017) arXiv:1706.09936 [hep-ex].

[17] A. M. Sirunyan *et al.* [CMS Collaboration], CMS-PAS-HIG-18-001.

[18] M. Aaboud *et al.* [ATLAS Collaboration], Phys. Lett. B **784**, 173 (2018) arXiv:1806.00425 [hep-ex].

[19] M. Aaboud *et al.* [ATLAS Collaboration], Phys. Rev. D **97**, no. 7, 072003 (2018) doi:10.1103/PhysRevD.97.072003 [arXiv:1712.08891 [hep-ex]].

[20] A. M. Sirunyan *et al.* [CMS Collaboration], CMS-PAS-HIG-17-004.

[21] A. M. Sirunyan *et al.* [CMS Collaboration], arXiv:1803.05485 [hep-ex].

[22] A. M. Sirunyan *et al.* [CMS Collaboration], arXiv:1804.03682 [hep-ex].

[23] M. Aaboud *et al.* [ATLAS Collaboration], ATLAS-CONF-2018-034.

[24] A. M. Sirunyan *et al.* [CMS Collaboration], CMS-PAS-SMP-18-002.

[25] M. Aaboud *et al.* [ATLAS Collaboration], JHEP **1803**, 174 (2018) arXiv:1712.06518 [hep-ex].