Know its limits

Constraining Higgs couplings at the LHC and beyond

[1812.07587, 1811.08401]

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Student Lecture, May 10, 2019

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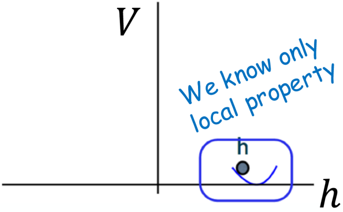
Outline

- status of LHC Higgs physics

  upper limit - evidence - observed
- dimension-6 Lagrangian
- LHC Run-II fit

  fermionic operators + EWPD
- HE-LHC fit

  Higgs self-coupling
- Conclusion



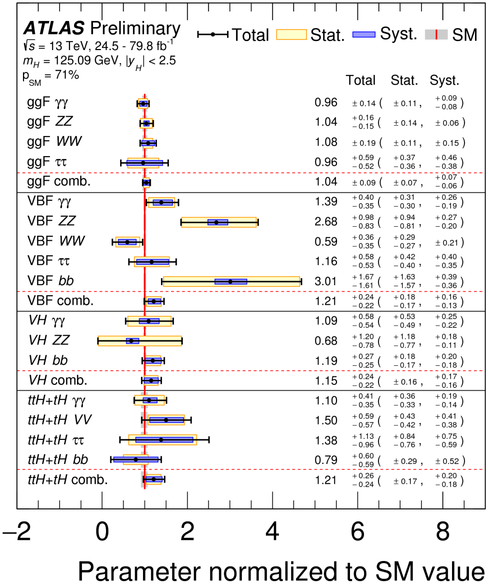
[Minho Son's slide]

Status of Higgs physics

$$\mu = \frac{\sigma \times \mathrm{BR}}{(\sigma \times \mathrm{BR})_{\mathrm{SM}}}$$

branching ratios

$b\bar{b}$	58.2 %
WW^*	21.4 %
gg	8.2 %
$\tau\tau$	6.2 %
$c\bar{c}$	2.9 %
ZZ^*	2.6 %
$Z\gamma$,	$\sim$ 0.2 %
$\gamma\gamma$	$\sim$ 0.2 %



Dimension-6 Lagrangian

HISZ basis [Hagiwara, Ishihara, Szalapski, Zeppenfeld]

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

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

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

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

$$\mathcal{O}_{WWW} = \text{Tr} \left(\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}_\rho^\mu \right)$$

$\hat{B}_{\mu\nu} = ig' B_{\mu\nu}/2, \quad \hat{W}_{\mu\nu} = ig\sigma^a W^a_{\mu\nu}/2$

di-higgs not included for LHC Run II ($\mathcal{O}_{\phi 3}$ not included)

Dimension-6 Lagrangian

HISZ basis [Hagiwara, Ishihara, Szalapski, Zeppenfeld]

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

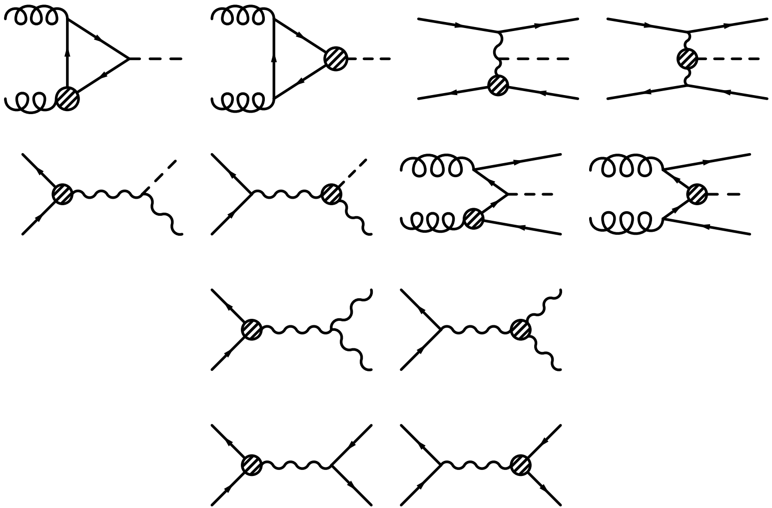
$$\mathcal{O}^{(1)}_{\phi Q} = \phi^\dagger (i \overleftrightarrow{D}_\mu \phi)(\bar{Q}\gamma^\mu Q) \qquad \mathcal{O}^{(3)}_{\phi Q} = \phi^\dagger (i \overleftrightarrow{D}^a_\mu \phi)(\bar{Q}\gamma^\mu \sigma^a Q) \qquad \mathcal{O}^{(1)}_{\phi u} = \phi^\dagger (i \overleftrightarrow{D}_\mu \phi)(\bar{u}_R \gamma^\mu u_R)$$

$$\mathcal{O}^{(1)}_{\phi d} = \phi^\dagger (i \overleftrightarrow{D}_\mu \phi)(\bar{d}_R \gamma^\mu d_R) \qquad \mathcal{O}^{(1)}_{\phi e} = \phi^\dagger (i \overleftrightarrow{D}_\mu \phi)(\bar{e}_R \gamma^\mu e_R) \qquad \mathcal{O}_{LLLL} = \phi^\dagger (\bar{L}\gamma_\mu)(\bar{L}\gamma^\mu L)$$

$\hat{B}_{\mu\nu} = ig' B_{\mu\nu}/2, \quad \hat{W}_{\mu\nu} = ig\sigma^a W^a_{\mu\nu}/2$

di-higgs not included for LHC Run II ($\mathcal{O}_{\phi 3}$ not included)

Processes



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

SFitter

- fits via toy Monte Carlo method

  shift the data according to uncertainties -

  fit Gaussian to best fit points

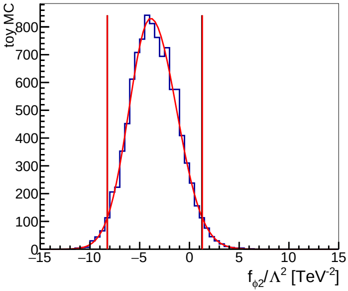
  [Monte Carlo replica method]

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

- full correlation of systematic uncertainties

  luminosity, JES, JER, lepton efficiency,

  b-tagging, ...

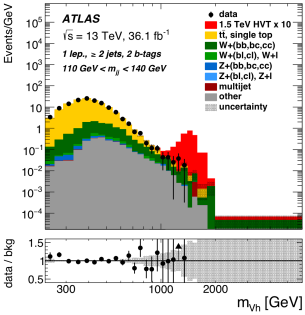


LHC Run II fit - What's new?

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

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

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



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

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

[LEP/SLD 0509008, PDG]

LHC Run II fit - Rate measurements

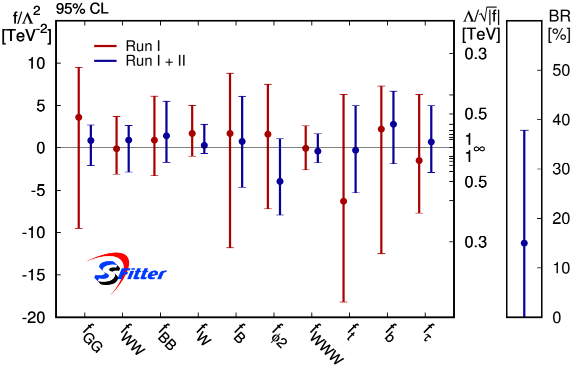
production/decay mode	ATLAS	CMS
$H \to WW$	Ref. [11]	Ref. [12]
$H \to ZZ$	Ref. [15]	Ref. [16, 17]
$H \to \gamma\gamma$	Ref. [1]	Ref. [2]
$H \to \tau\bar{\tau}$		Ref. [9, 10]
$H \to \mu\bar{\mu}$	Ref. [7]	Ref. [8]
$H \to b\bar{b}$	Ref. [3]	Ref. [4]
$H \to Z\gamma$	Ref. [13]	Ref. [14]
$H \to$ invisible		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 - without fermionic operators

[SFitter Run I: Butter, Éboli, Gonzalez-Fraile, Gonzalez-Garcia, Plehn, Rauch (1604.03105)]

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

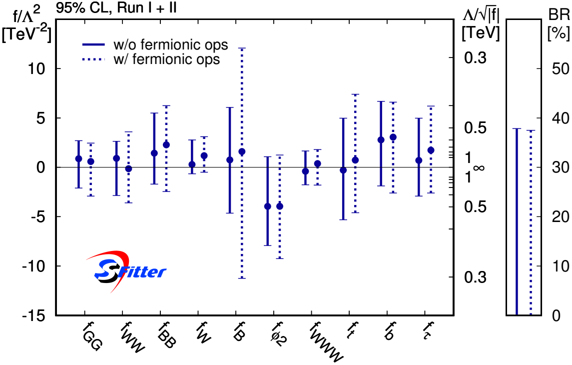
[da Silva Almeida, Alves, Rosa Agostinho, Éboli, Gonzalez-Garcia (1812.01009)]



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

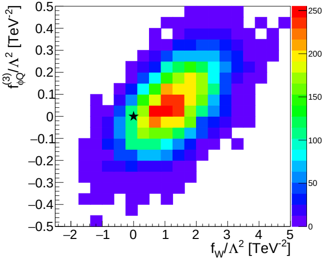
limits on bosonic operators improved by distributions

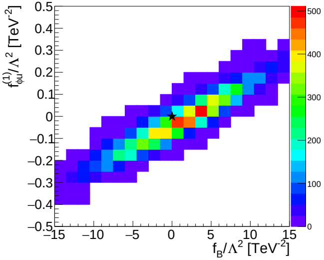
LHC Run II fit - influence of fermionic operators



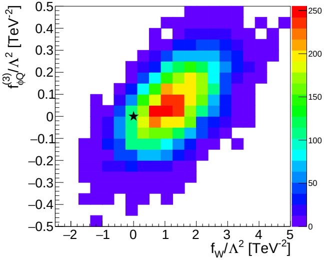
inclusion of fermionic operators weakens limits on bosonic operators

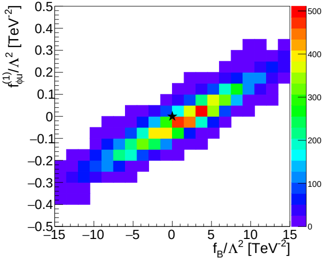
LHC Run II fit - correlations





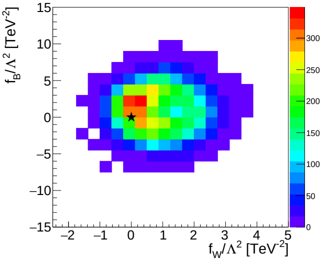
LHC Run II fit - correlations

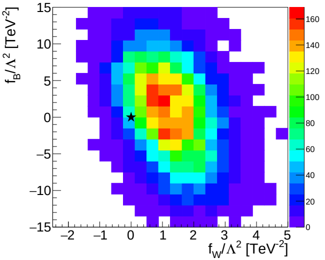




without fermionic operators

with fermionic operators





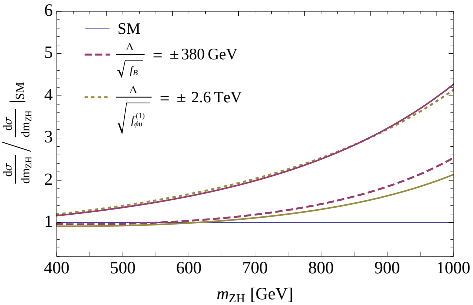
correlation between f_B and f_W reintroduced

LHC Run II fit - influence of fermionic operators

	Zqq	Wqq'	$HZqq$	$HWqq'$	$Zl\bar{l}$	$Wl\nu$
$\mathcal{O}_{\phi 1}$	$\times$	$\times$			$\times$	$\times$
$\mathcal{O}_{BW}$	$\times$	$\times$			$\times$	$\times$
$\mathcal{O}_{\phi Q}^{(3)}$	$\times$	$\times$	$\times$	$\times$		
$\mathcal{O}_{\phi Q}^{(1)}$	$\times$		$\times$			
$\mathcal{O}_{\phi u}^{(1)}$	$\times$		$\times$			
$\mathcal{O}_{\phi d}^{(1)}$	$\times$		$\times$			
$\mathcal{O}_{\phi e}^{(1)}$					$\times$	

LHC Run II fit - influence of fermionic operators

	Zqq	Wqq'	$HZqq$	$HWqq'$	$Zl\bar{l}$	$Wl\nu$
$\mathcal{O}_{\phi 1}$	×	×			×	×
$\mathcal{O}_{BW}$	×	×			×	×
$\mathcal{O}_{\phi Q}^{(3)}$	×	×	×	×		
$\mathcal{O}_{\phi Q}^{(1)}$	×		×			
$\mathcal{O}_{\phi u}^{(1)}$	×		×			
$\mathcal{O}_{\phi d}^{(1)}$	×		×			
$\mathcal{O}_{\phi e}^{(1)}$					×	

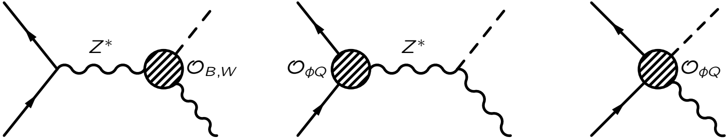


positive Wilson coefficients dashed

LHC Run II fit - influence of fermionic operators

	Zqq	Wqq'	$HZqq$	$HWqq'$	$Zl\bar{l}$	$Wl\nu$
$\mathcal{O}_{\phi 1}$	×	×			×	×
$\mathcal{O}_{BW}$	×	×			×	×
$\mathcal{O}_{\phi Q}^{(3)}$	×	×	×	×		
$\mathcal{O}_{\phi Q}^{(1)}$	×		×			
$\mathcal{O}_{\phi u}^{(1)}$	×		×			
$\mathcal{O}_{\phi d}^{(1)}$	×		×			
$\mathcal{O}_{\phi e}^{(1)}$					×	

contributions to ZH production



LHC Run II fit - including fermionic operators

[SFitter Run I: Butter, Éboli, Gonzalez-Fraile, Gonzalez-Garcia, Plehn, Rauch (1604.03105)]

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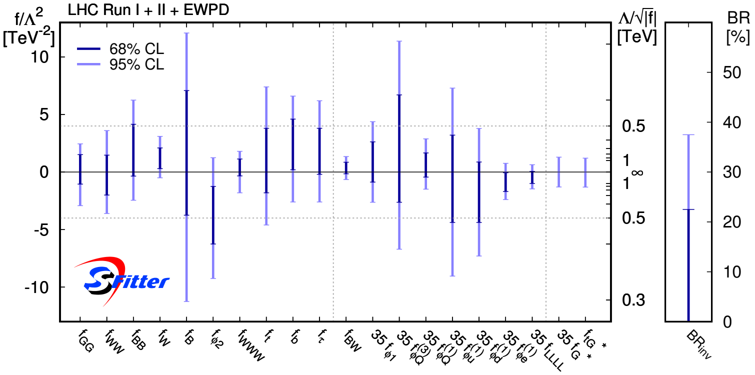
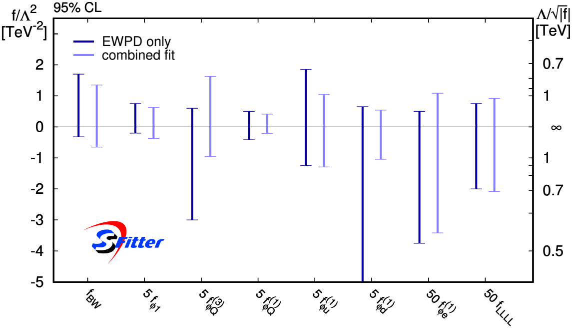


inclusion of fermionic operators weakens limits on bosonic operators

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

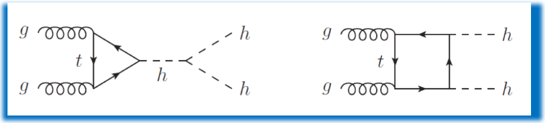
Measuring self-coupling is truly pain in the neck

1. No PDF for Higgs boson → small cross section

: producing extra H costs $\sim 10^{-3}$

HH production via gluon fusion
known as the best channel

2. Negatively Interfere

σ [

] $\sim$ 40 fb @14 TeV

$\sim \frac{m_h^2}{\hat{s}}$

$\times$ BR

Very small
signal rate

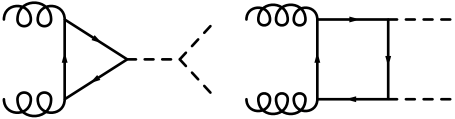
e.g. $b\bar{b}\gamma\gamma$ (0.264%)

3. Threshold region = Big backgrounds

Everything goes against us!

[slide stolen from Minho Son]

Higgs limits at a 27 TeV collider



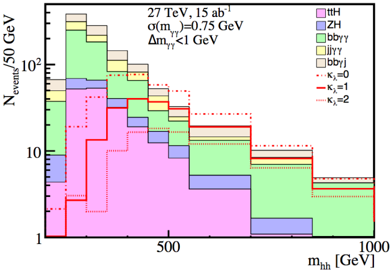
Higgs self-coupling included

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

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

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

[Gonçalves, Han, Kling, Plehn, Takeuchi]



after wave function renormalization $H = \sqrt{1 + \frac{f_{\phi,2}v^2}{\Lambda^2}}\,\tilde{H}$

$$\mathcal{L}_{\text{self}} = -\frac{m_H^2}{2v}\left[\left(1 - \frac{f_{\phi,2}\,v^2}{2\Lambda^2 m_H^2} - \frac{2f_{\phi,3}\,v^4}{3\Lambda^2 m_H^2}\right)H^3 + \frac{2f_{\phi,2}\,v^2}{\Lambda^2 m_H^2}H\partial_\mu H\partial^\mu H\right]$$

Higgs limits at a 27 TeV collider

interpolated from 8 TeV results

Higgs self-coupling included [Gonçalves, Han, Kling, Plehn, Takeuchi, (1802.04319)]

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

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

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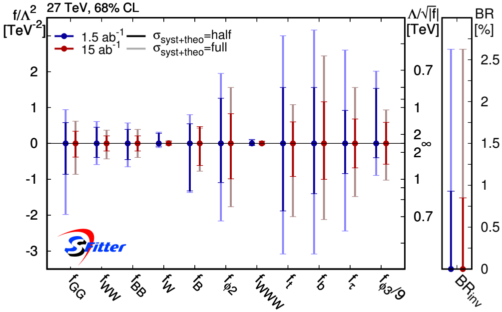
channel	observable	# bins	range [GeV]
$WW \to (\ell\nu)(\ell\nu)$	$m_{\ell\ell'}$	10	$0 - 4500$
$WW \to (\ell\nu)(\ell\nu)$	$p_T^{\ell_1}$	8	$0 - 1750$
$WZ \to (\ell\nu)(\ell\ell)$	m_T^{WZ}	11	$0 - 5000$
$WZ \to (\ell\nu)(\ell\ell)$	$p_T^{\ell\ell}$ (p_T^Z)	9	$0 - 2400$
WBF, $H \to \gamma\gamma$	$p_T^{\ell_1}$	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



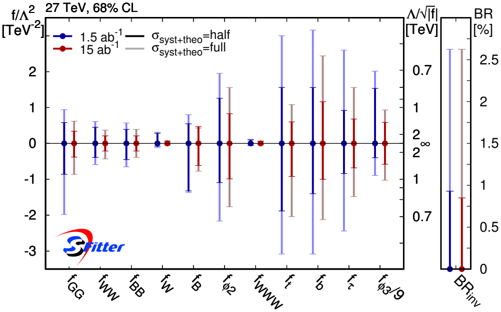
full = current systematic and theory uncertainties

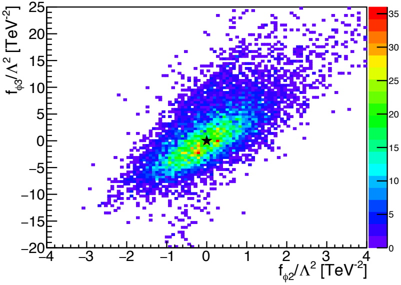
95 % CL limits on $\frac{\Lambda}{\sqrt{|f_{\phi,3}|}} > 250$ GeV (700 GeV single param fit)

need precise measurements of other Higgs couplings

distributions always statistics dominated

Higgs limits at a 27 TeV collider





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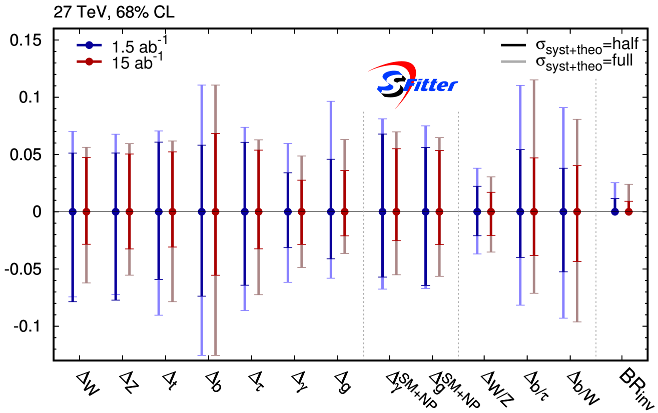
Higgs limits at a 27 TeV collider - Δ framework



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

full = current systematic and theory uncertainties

rate measurements systematics dominated

Conclusions

LHC Run II

- tth measurements disentangle top and gluon couplings
- fermionic operators and EWPD included
- inclusion of fermionic operators weakens limits on (some) operators

HE-LHC

- Higgs self coupling
- TeV-scale reach for $\mathcal{O}(1)$ couplings

Real conclusions

- EFTs are a flexible framework to describe deviations from the SM
- global fits allow to combine data from different sectors and to account for correlations
- LHC is testing **local** properties of the Higgs potential
- future (colliders): **global** Higgs potential

Thank you for your attention!

Backup

[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].

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

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

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

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

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[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.

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