Global fits for LHC Run II and the HE-LHC

[1812.07587, 1811.08401]

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with Tyler Corbett, Dorival Gonçalves, Tilman Plehn

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Invisibles 2019

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SEIT 1386

Looking for BSM physics in the Higgs sector

We found the Higgs? Now what?

We wanted the Higgs for electroweak symmetry breaking

Study the local and global properties of the Higgs potential

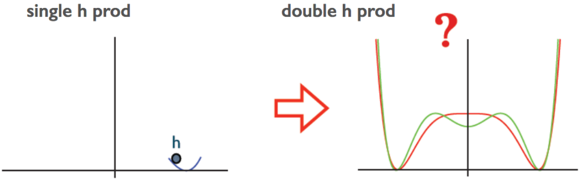
$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2 \quad + ...?$$

- SMEFT framework
- LHC Run-II fit

  fermionic operators + EWPD

- HE-LHC fit

  Higgs self-coupling



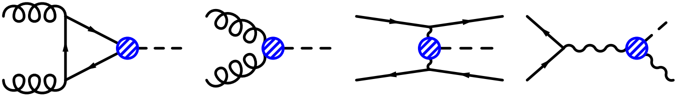
[Juan Rojo's slide]

Dimension-6 Lagrangian

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

HISZ basis [Hagiwara, Ishihara, Szalapski, Zeppenfeld]

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



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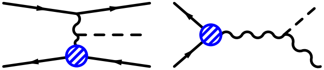


10 operators $\rightarrow$ 18 operators including fermionic Higgs-gauge operators

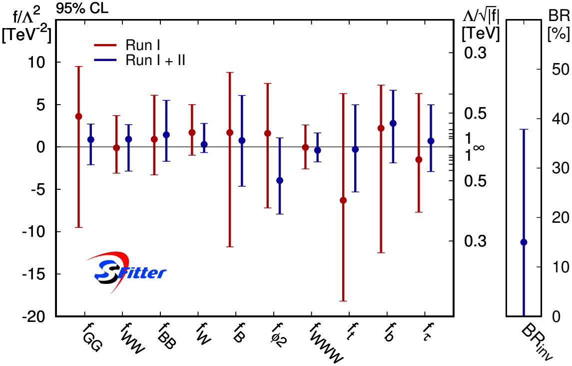
see Nuno's poster [da Silva Almeida, Alves, Rosa Agostinho, Éboli, Gonzalez-Garcia (1812.01009)]

LHC Run II fit - without fermionic operators

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

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

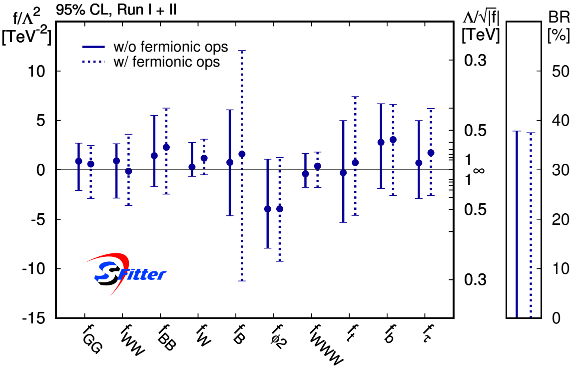
[da Silva Almeida, Alves, Rosa Agostinho, Éboli, Gonzalez-Garcia (1812.01009)]



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

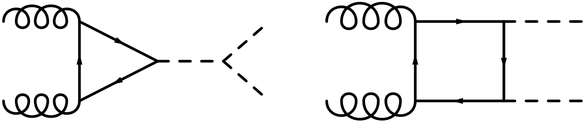


inclusion of fermionic operators weakens limits on bosonic operators

Higgs limits at a 27 TeV collider - global structures of the Higgs potential

distributions: operators are momentum dependent

Higgs self-coupling measured in di-Higgs production



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

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

Conclusions

LHC Run II - Higgs couplings

- new data: tth $+\ 3^{\text{rd}}$ gen. Yukawas
- fermionic operators and EWPD included
- $\Lambda/\sqrt{f} = 400\ ...\ 800$ GeV reach for bosonic operators

HE-LHC - global properties of potential

- Higgs self coupling
- TeV-scale reach (3 ... 5% accuracy)
- precise probes of single-Higgs and di-boson production needed

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Thank you and check out my poster!

Thank you for your attention!

Backup

Distributions

D6 operators induce new Lorentz structures

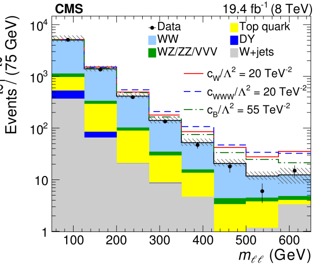
$$\Delta\mathcal{L}_{\mathsf{TGV}} = -\, ie\,(\kappa_\gamma - 1)\, W^+_\mu W^-_\nu \gamma^{\mu\nu} - \frac{ie\lambda_\gamma}{m_W^2}\, W^+_{\mu\nu} W^{-\nu\rho} \gamma^\mu_\rho - \frac{ig_Z\lambda_Z}{m_W^2}\, W^+_{\mu\nu} W^{-\nu\rho} Z_\rho{}^\mu$$
$$- ig_Z\,(\kappa_Z - 1)\, W^+_\mu W^-_\nu Z^{\mu\nu} - ig_Z\,(g_1^Z - 1)\,\left(W^+_{\mu\nu} W^{-\mu} Z^\nu - W^+_\mu Z_\nu W^{-\mu\nu}\right)$$

$$\kappa_\gamma = 1 + \frac{g^2 v^2}{8\Lambda^2}\left(f_W + f_B - 2 f_{BW}\right)$$

$$\kappa_Z = 1 + \frac{g^2 v^2}{8 c_w^2 \Lambda^2}\left(c_w^2 f_W - s_w^2 f_B + \frac{4 c_W^2 s_W^2}{c_W^2 - s_W^2} f_{BW}\right) - \frac{f_{\phi 1}}{4(c_W^2 - s_W^2)}\frac{v^2}{\Lambda^2}$$

$$g_1^Z = 1 + \frac{g^2 v^2}{8 c_w^2 \Lambda^2}\left(f_W + 2\frac{s_W^2}{c_W^2 - s_W^2} f_{BW}\right) - \frac{f_{\phi 1}}{4(c_W^2 - s_W^2)}\frac{v^2}{\Lambda^2}$$

$$\lambda_\gamma = \lambda_Z = \frac{3 g^2 m_W^2}{2\Lambda^2} f_{WWW}$$



[CMS WW (1507.03268)]

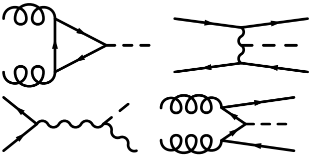
fit event numbers to ATLAS/CMS predictions for corrections, assuming same k-factors for SM and D6

[Baglio, Dawson, Lewis (1812.00214); Chiesa, Denner, Lang (1807.10190)]

Status of LHC Higgs physics

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

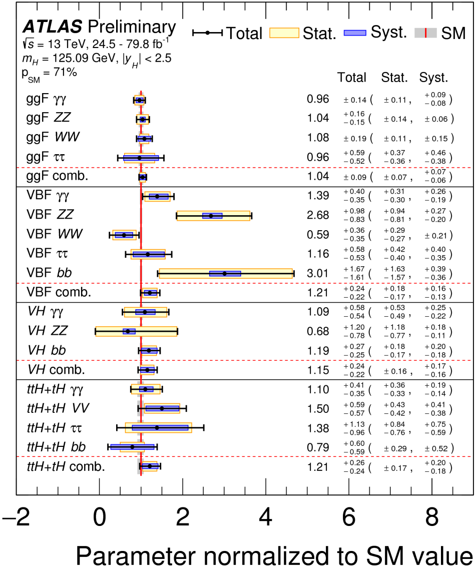
- ggF, WBF, Vh, ttH observed



- $h \to \gamma\gamma,\ ZZ,\ WW,\ b\bar{b},\ \tau\tau$ observed
- $\mathrm{BR_{inv}} < 19\%$

[CMS, 1809.05937]

[ATLAS-CONF-2019-005]



How to combine all these measurements?

$$g_x = g_x^{\mathsf{SM}}\,(1+\Delta_x), \qquad g_x = g_x^{\mathsf{SM}}\,\kappa_x$$

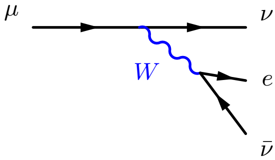
$$\mathcal{L} = \mathcal{L}_{\mathsf{SM}} + \Delta_W\; g m_W h\; W^\mu W_\mu + \Delta_Z\; \frac{g}{2c_W} m_Z h\; Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f\; \frac{m_f}{v} h \left(\bar{f}_R f_L + \text{h.c.}\right)$$
$$+ \Delta_g F_G\; \frac{h}{v}\; G_{\mu\nu} G^{\mu\nu} + \Delta_\gamma F_A\; \frac{h}{v}\;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

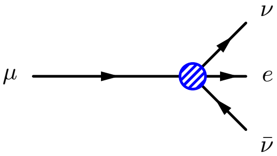
drawbacks:

- total rates only
- non-renormalizable
- Higgs sector only (hard to extend to full SM)

SM effective field theory

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





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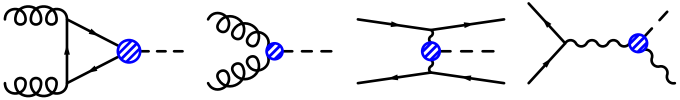
$$\mathcal{O}_{GG} = \phi^\dagger \phi \; G^a_{\mu\nu} G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{BB} = \phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \phi$$

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

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

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

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



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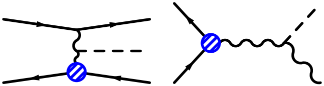
$$\mathcal{O}_{WWW} = \text{Tr}\left(\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}^{\mu}_{\rho}\right) \qquad \mathcal{O}_{BW} = \phi^\dagger\hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\phi \qquad \mathcal{O}_{\phi,1} = (D_\mu\phi)^\dagger\,\phi\,\phi^\dagger\,(D^\mu\phi)$$

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

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

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



SFitter

- fits via toy Monte Carlo method

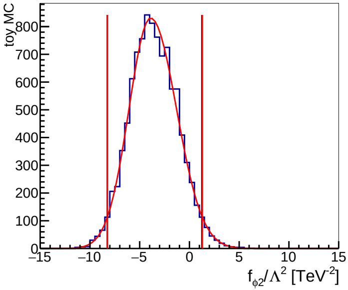
  shift the data according to uncertainties

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

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

- full correlation of systematic uncertainties

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



Toy Monte Carlos

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

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

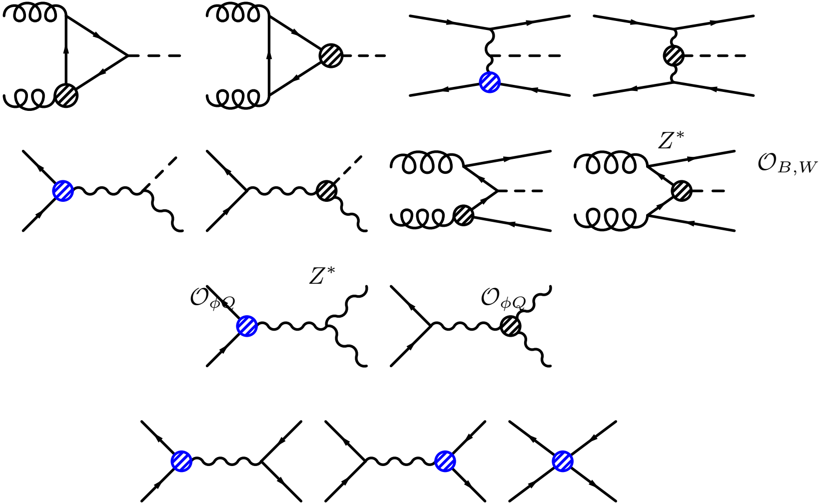
$$\Delta^{\text{shift}} = \Delta^{\text{Gaus}} + \Delta^{\text{Pois}} + \Delta^{\text{syst}} ,$$

where

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

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

Processes



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

fermion-gauge couplings

LHC Run II fit - What's new?

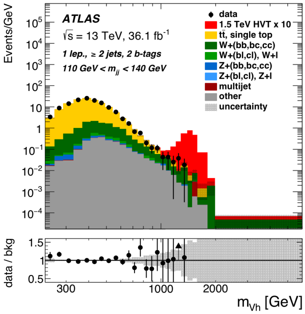
- fermionic operators

  [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



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

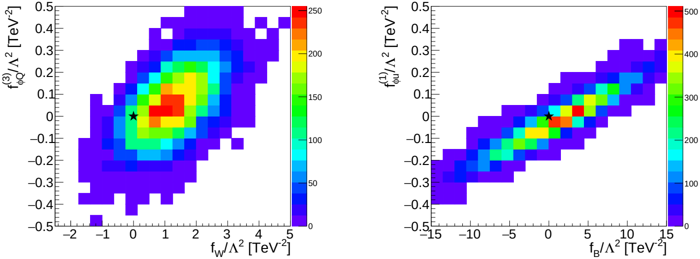
$$M_W,\ \Gamma_W,\ {\rm BR}(W\to l\nu)$$

[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



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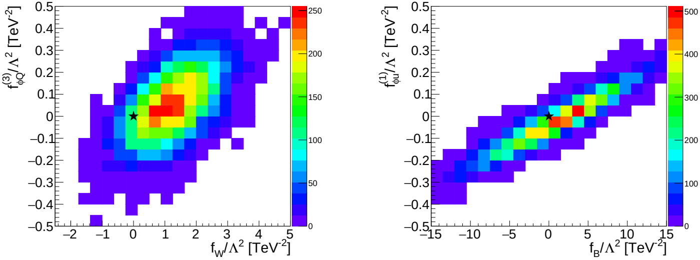
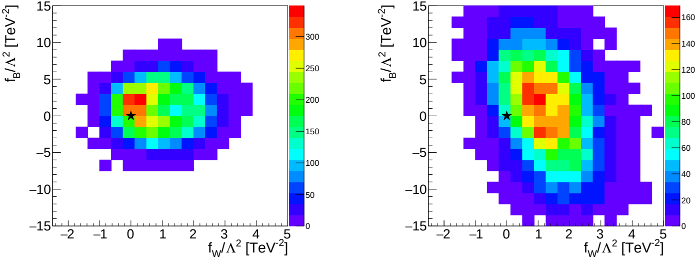
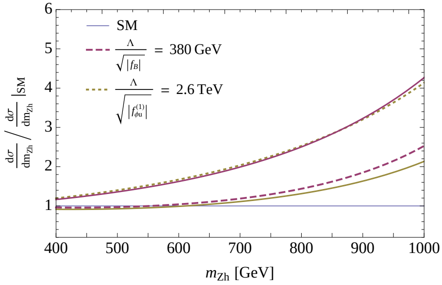


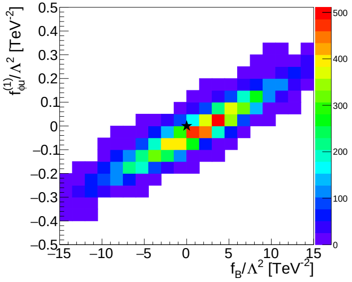
without fermionic operators   with fermionic operators



correlation between f_B and f_W reintroduced

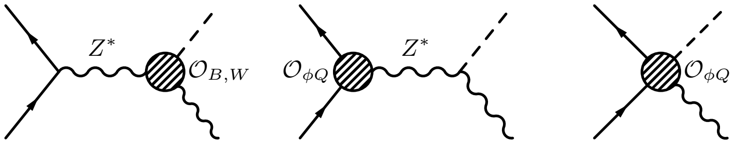
LHC Run II fit - influence of fermionic operators





positive Wilson coefficients dashed

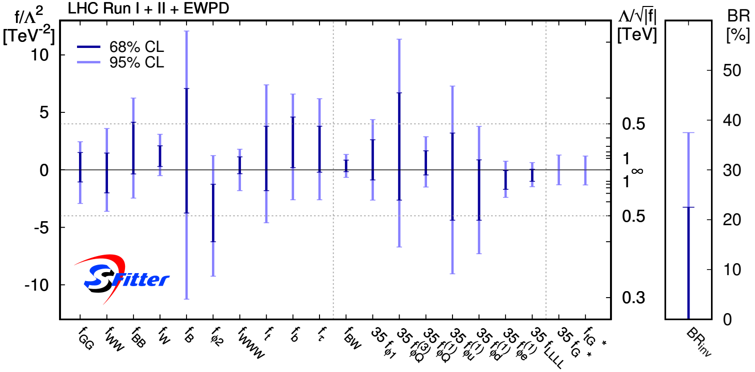
contributions to ZH production



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

LHC Run II fit - including fermionic operators

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



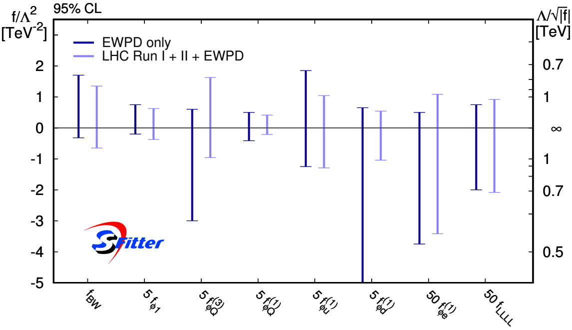
inclusion of fermionic operators weakens limits on bosonic operators

* 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)]

LHC Run II fit - tighter constraints on fermionic operators

[LEP/SLD 0509008, PDG]



limits on fermionic operators tightened or shifted towards SM values

Measuring self-coupling is truly pain in the neck

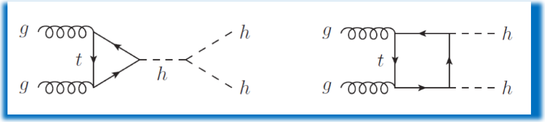
1. No PDF for Higgs boson → small cross section

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

HH production via gluon fusion
known as the best channel

2. Negatively Interfere

σ [



] $\sim$ 40 fb$^{@14\ \mathrm{TeV}}$

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

$\times$ 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]

Status of di-Higgs production

- current limit:

$$-5.0 < \frac{\lambda_{3h}}{\lambda_{3h}^{\mathsf{SM}}} < 12.1 \qquad \text{95\% CL, direct search in hh [ATLAS-CONF-2018-043]}$$

$$-3.2 < \frac{\lambda_{3h}}{\lambda_{3h}^{\mathsf{SM}}} < 11.9 \qquad \text{95\% CL, indirect serch in single-h [ATL-PHYS-PUB-2019-009]}$$

- HL-LHC direct search: [Kim, Sakaki, Son (1801.06093)]

$$-0.1 < \frac{\lambda_{3h}}{\lambda_{3h}^{\mathsf{SM}}} < 6.5 \qquad \text{95\% CL}$$

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- electroweak baryogenesis:

  required for a strong first-order phase transition

  [Reichert et al. (1711.00019)]

$$\frac{\lambda_{3h}}{\lambda_{3h}^{\mathsf{SM}}} > 1.5$$

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$$\frac{\lambda_{3h}}{\lambda_{3h}^{\mathsf{SM}}} > 1.5$$

- 27 TeV collider: [Goncalves et al. (1802.04319)]

$$\frac{\lambda_{3h}}{\lambda_{3h}^{\mathsf{SM}}} = 1 \pm 30\% \quad \text{95\% CL}$$

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)

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

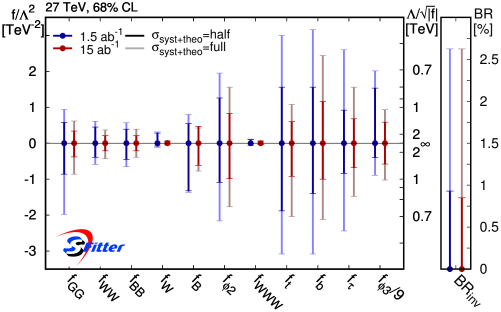
$$\mathcal{O}_{W} = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \qquad \mathcal{O}_{B} = (D_\mu \phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \phi) \qquad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial^\mu \left(\phi^\dagger \phi\right) \partial_\mu \left(\phi^\dagger \phi\right)$$

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

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

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

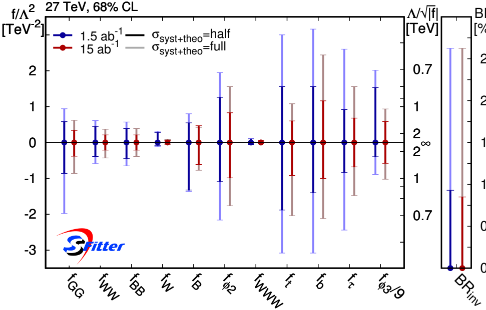


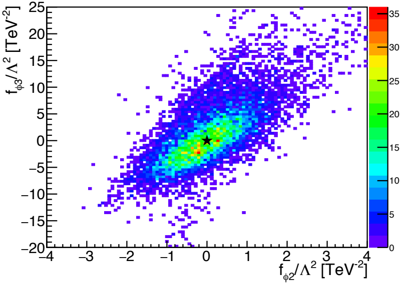
full $=$ current systematic and theory uncertainties

distributions always statistics dominated

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

Higgs limits at a 27 TeV collider





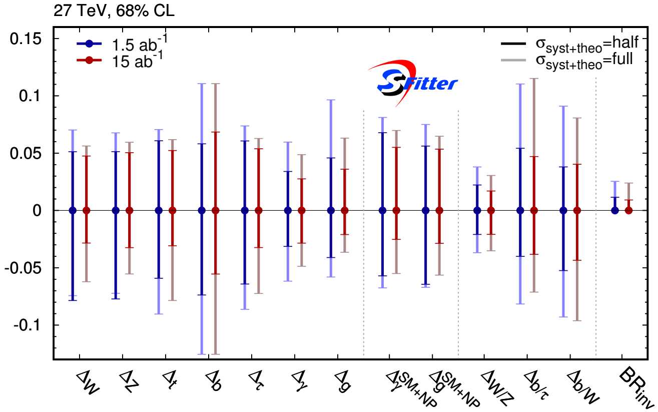
full = current systematic and theory uncertainties

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

Higgs limits at a 27 TeV collider - Δ framework



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

full $=$ current systematic and theory uncertainties

limits below 5%

rate measurements systematics dominated

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