Global fits for LHC Run II and the HE-LHC

[1812.07587, 1811.08401]

Anke Biekötter

with Tyler Corbett, Dorival Gonçalves, Tilman Plehn

Michihisa Takeuchi and Dirk Zerwas

CRC SMEFT Workshop 2019

UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

Outline

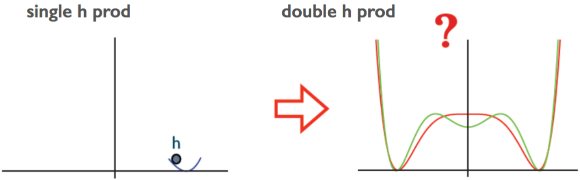
- basis + SFitter
- LHC Run-II fit

  fermionic operators + EWPD

- HE-LHC fit

  Higgs self-coupling

- Conclusion

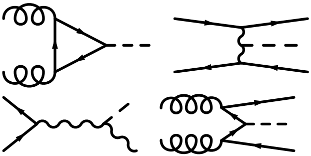


[Juan Rojo's slide]

Status of LHC Higgs physics

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

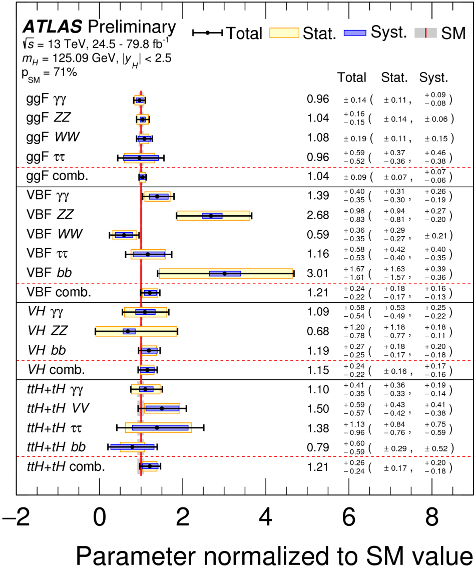
- ggF, WBF, Vh, ttH observed



- $h \to \gamma\gamma,\ ZZ,\ WW,\ b\bar{b},\ \tau\tau$ observed
- $\text{BR}_{\text{inv}} < 19\%$

[CMS, 1809.05937]

[ATLAS-CONF-2019-005]



Dimension-6 Lagrangian

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

HISZ basis [Hagiwara, Ishihara, Szalapski, Zeppenfeld]

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

modified Yukawa couplings

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

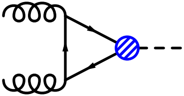
$$\mathcal{O}_{GG} = \phi^\dagger\phi\, G^a_{\mu\nu}G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\phi \qquad \mathcal{O}_{BB} = \phi^\dagger\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\phi$$

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

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

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

Higgs potential not modified



Dimension-6 Lagrangian

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

HISZ basis [Hagiwara, Ishihara, Szalapski, Zeppenfeld]

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

modified Higgs-gauge couplings

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

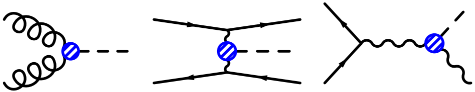
$$\mathcal{O}_{GG} = \phi^\dagger\phi\, G^a_{\mu\nu}G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\phi \qquad \mathcal{O}_{BB} = \phi^\dagger\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\phi$$

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

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

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

Higgs potential not modified



Dimension-6 Lagrangian

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

HISZ basis [Hagiwara, Ishihara, Szalapski, Zeppenfeld]

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

modified triple gauge couplings

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

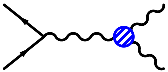
$$\mathcal{O}_{GG} = \phi^\dagger\phi\, G^a_{\mu\nu}G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\phi \qquad \mathcal{O}_{BB} = \phi^\dagger\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\phi$$

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

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

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

Higgs potential not modified



Dimension-6 Lagrangian

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

HISZ basis [Hagiwara, Ishihara, Szalapski, Zeppenfeld]

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

Higgs wave-function renormalization

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

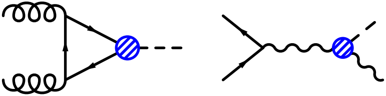
$$\mathcal{O}_{GG} = \phi^\dagger\phi\, G^a_{\mu\nu}G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\phi \qquad \mathcal{O}_{BB} = \phi^\dagger\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\phi$$

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

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

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

Higgs potential not modified



Dimension-6 Lagrangian

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

HISZ basis [Hagiwara, Ishihara, Szalapski, Zeppenfeld]

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

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

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

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

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

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

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

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

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

Higgs potential not modified

Dimension-6 Lagrangian

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

HISZ basis [Hagiwara, Ishihara, Szalapski, Zeppenfeld]

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

modified S and T oblique parameters

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

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

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

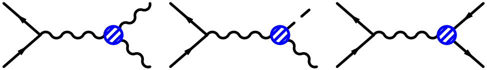
$$\mathcal{O}_{WWW} = \mathrm{Tr}\left(\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}^\mu_\rho\right) \qquad \mathcal{O}_{BW} = \phi^\dagger\hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\phi \qquad \mathcal{O}_{\phi,1} = (D_\mu\phi)^\dagger\phi\,\phi^\dagger(D^\mu\phi)$$

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

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

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

Higgs potential not modified



Dimension-6 Lagrangian

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

HISZ basis [Hagiwara, Ishihara, Szalapski, Zeppenfeld]

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

modified gauge-fermion couplings

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

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

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

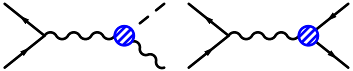
$$\mathcal{O}_{WWW} = \mathrm{Tr}\left(\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}^\mu_\rho\right) \qquad \mathcal{O}_{BW} = \phi^\dagger\hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\phi \qquad \mathcal{O}_{\phi,1} = (D_\mu\phi)^\dagger\,\phi\,\phi^\dagger\,(D^\mu\phi)$$

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

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

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

Higgs potential not modified



Dimension-6 Lagrangian

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

HISZ basis [Hagiwara, Ishihara, Szalapski, Zeppenfeld]

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

modified Fermi constant

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

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

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

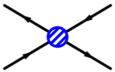
$$\mathcal{O}_{WWW} = \mathrm{Tr}\left(\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}^\mu_\rho\right) \qquad \mathcal{O}_{BW} = \phi^\dagger\hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\phi \qquad \mathcal{O}_{\phi,1} = (D_\mu\phi)^\dagger\,\phi\,\phi^\dagger\,(D^\mu\phi)$$

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

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

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

Higgs potential not modified



SFitter

- fits via toy Monte Carlo method

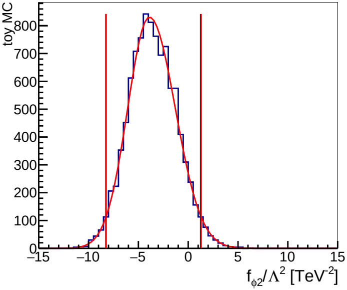
  shift the data according to uncertainties

  [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, ...



LHC Run II fit - What's new?

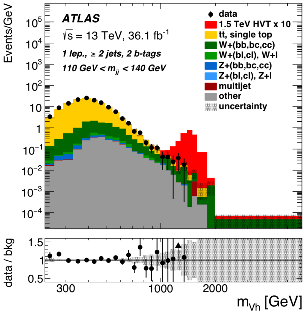
- fermionic operators

  [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



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

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

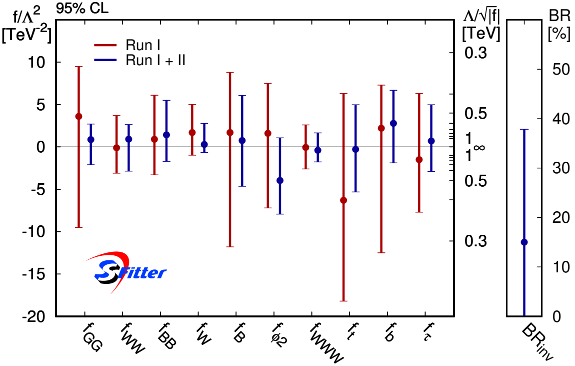
[LEP/SLD 0509008, PDG], [Corbett et al. (1705.09294)]

LHC Run II fit - without fermionic operators

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

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

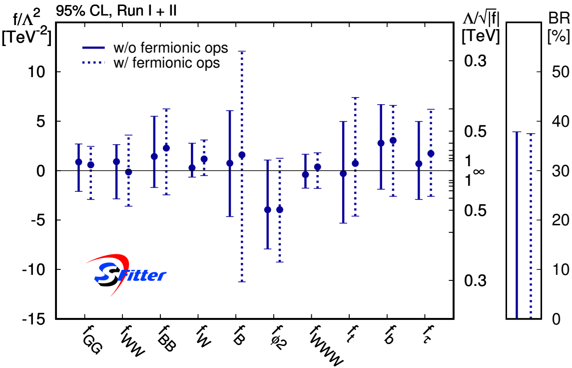
[da Silva Almeida, Alves, Rosa Agostinho, Éboli, Gonzalez-Garcia (1812.01009)]



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



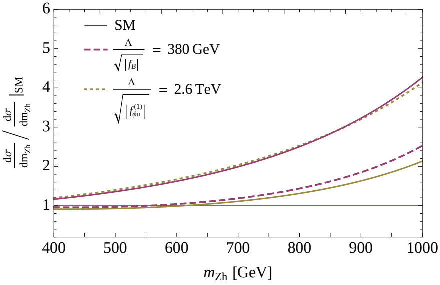
inclusion of fermionic operators weakens limits on bosonic operators

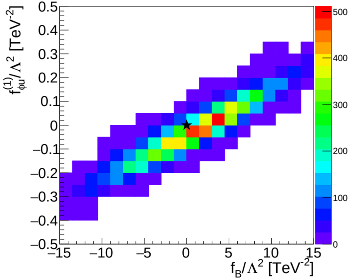
$$\mathcal{O}_{BW} = \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{\phi,1} = (D_\mu \phi)^\dagger \, \phi \, \phi^\dagger \, (D^\mu \phi)$$

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

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

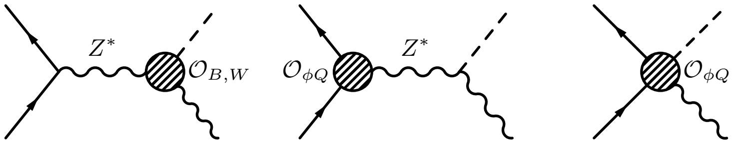
LHC Run II fit - influence of fermionic operators





positive Wilson coefficients dashed

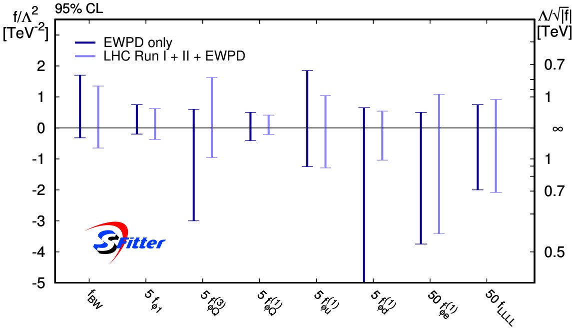
contributions to ZH production



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

LHC Run II fit - 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

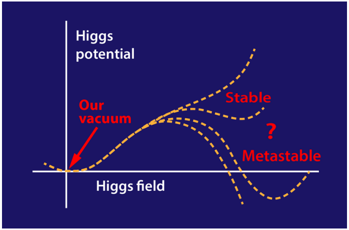
What can we do at 27 TeV?

- 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

global structure of the Higgs potential



[physics.aps.org]

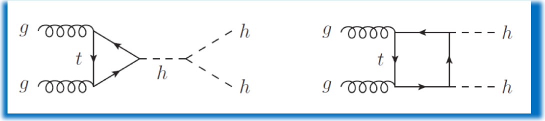
Measuring self-coupling is truly pain in the neck

1. No PDF for Higgs boson $\rightarrow$ 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 TeV

$\times$ BR

Very small signal rate

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

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

3. Threshold region = Big backgrounds

Everything goes against us!

[slide stolen from Minho Son]

Status of di-Higgs production

- current limit:

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

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

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

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

Status of di-Higgs production

- current limit:

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

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

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

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

- electroweak baryogenesis:

  required for a strong first-order phase transition

  [Reichert et al. (1711.00019)]

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

Status of di-Higgs production

- current limit:

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

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

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

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

- electroweak baryogenesis:

  required for a strong first-order phase transition

  [Reichert et al. (1711.00019)]

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

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

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

Higgs limits at a 27 TeV collider

interpolated from 8 TeV results

distributions

Higgs self-coupling included

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

(no fermionic operators)

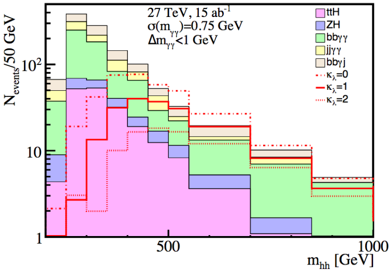
$$\mathcal{O}_{\phi,2} = \frac{1}{2}\partial^\mu\left(\phi^\dagger\phi\right)\partial_\mu\left(\phi^\dagger\phi\right) \quad \to \text{kinematics}$$

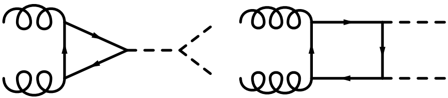
$$\mathcal{O}_{\phi 3} = -(\phi^\dagger\phi)^3/3 \quad \to \text{rate}$$

1-parameter fit [1802.04319]

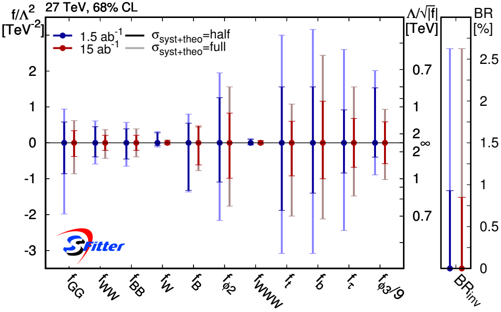
$$\left|\frac{\Lambda}{\sqrt{f_{\phi 3}}}\right| \gtrsim \begin{cases} 1\ \text{TeV} & 68\%\ \text{C.L.} \\ 700\ \text{GeV} & 95\%\ \text{C.L.} \end{cases}$$

[Gonçalves et al. (1802.04319)]





Higgs limits at a 27 TeV collider



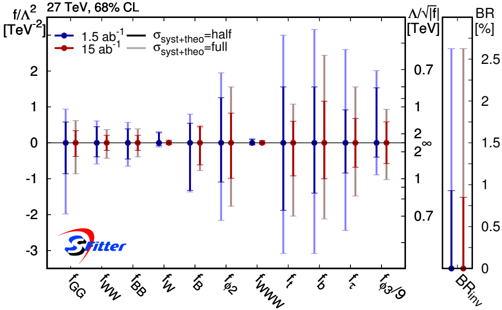
full = current systematic and theory uncertainties

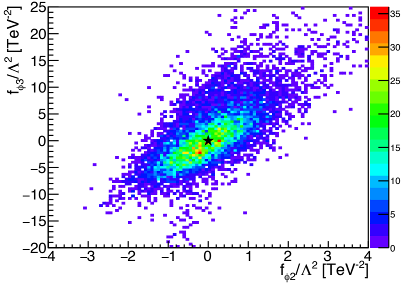
distributions always statistics dominated

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

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

Higgs limits at a 27 TeV collider





full $=$ current systematic and theory uncertainties

distributions always statistics dominated

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

need precise measurements of other Higgs couplings

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

Conclusions

LHC Run II - Higgs couplings

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

HE-LHC - global properties of potential

- Higgs self coupling
- TeV-scale reach for $\mathcal{O}(1)$ couplings (3 … 5% accuracy)
- precise probes of single-Higgs and di-boson production needed

Thank you for your attention!

Backup

How to combine all these measurements?

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

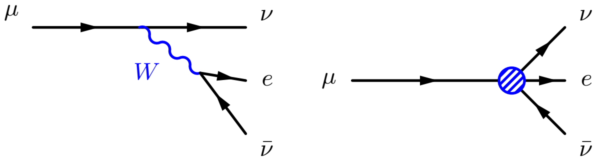
$$\mathcal{L} = \mathcal{L}_{\mathsf{SM}} + \Delta_W\; g m_W h\, W^\mu W_\mu + \Delta_Z\; \frac{g}{2c_W} m_Z h\, Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f\; \frac{m_f}{v} h \left(\bar{f}_R f_L + \text{h.c.}\right)$$
$$+ \Delta_g F_G\; \frac{h}{v}\; G_{\mu\nu} G^{\mu\nu} + \Delta_\gamma F_A\; \frac{h}{v}\;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

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



Toy Monte Carlos

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

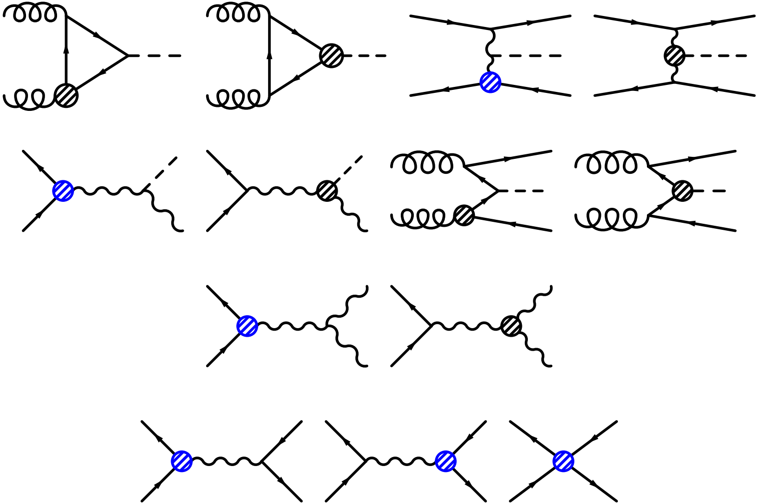
$$x_i^{\text{toy}} = x_i^{\text{exp}} + \Delta^{\text{shift}} + \text{sign}(\Delta^{\text{shift}})\Delta^{\text{flat}}\,,$$
$$\Delta^{\text{shift}} = \Delta^{\text{Gaus}} + \Delta^{\text{Pois}} + \Delta^{\text{syst}}\,,$$

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



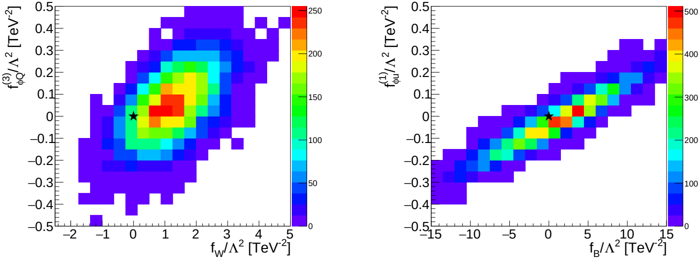
Higgs (+ decays) + di-boson production (WW, WZ) + EWPD

fermion-gauge couplings

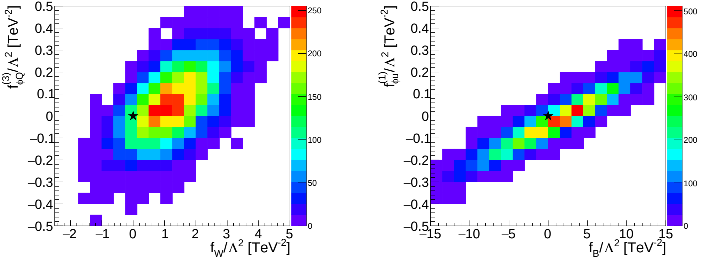
LHC Run II fit - Rate measurements

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]	

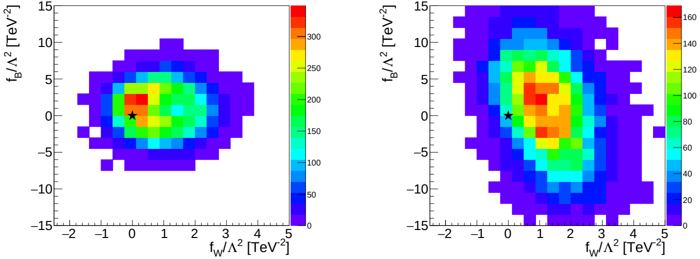
LHC Run II fit - correlations



LHC Run II fit - correlations



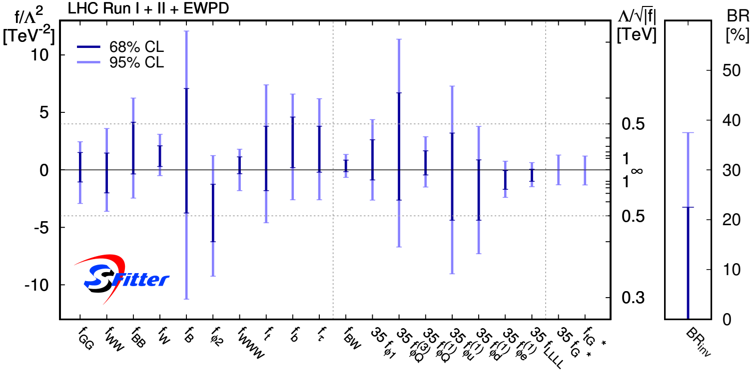
without fermionic operators   with fermionic operators



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)

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

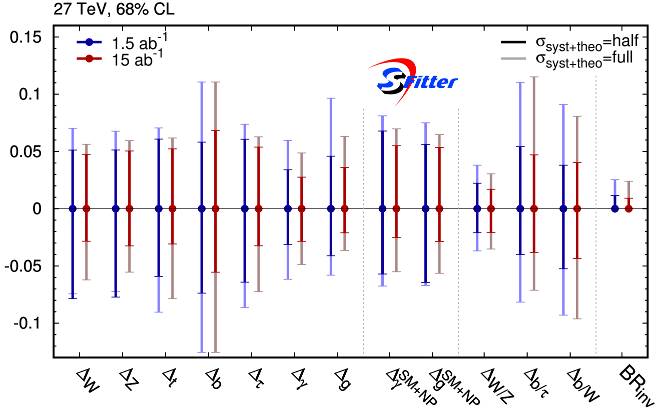
$$\mathcal{O}_{W} = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \qquad \mathcal{O}_{B} = (D_\mu \phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \phi) \qquad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial^\mu \left(\phi^\dagger \phi\right) \partial_\mu \left(\phi^\dagger \phi\right)$$

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

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

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 - Δ framework



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

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].