Overview of SM Higgs Physics and BSM Effects

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PRiSMA+

Current status

- After the 125 GeV Higgs discovery, the SM has no more free parameters
- We are now in an era with a boundless set of experimental measurements, and every measurement is an opportunity to refute the SM
- Q: What do we learn from ongoing Higgs measurements?

Refresher: SM Higgs phenomenology

- The SM Higgs potential is the familiar $\lambda\phi^4$ potential

$$\mathcal{L} \supset |D_\mu H|^2 - \mu^2 |H|^2 - \lambda |H|^4$$

- Spontaneous symmetry breaking of SU(2)×U(1) occurs since $\mu^2 < 0$

Through the $|D_\mu H|^2$ term, three Goldstone fields are "eaten" and become the longitudinal modes of $W^\pm$ and Z bosons

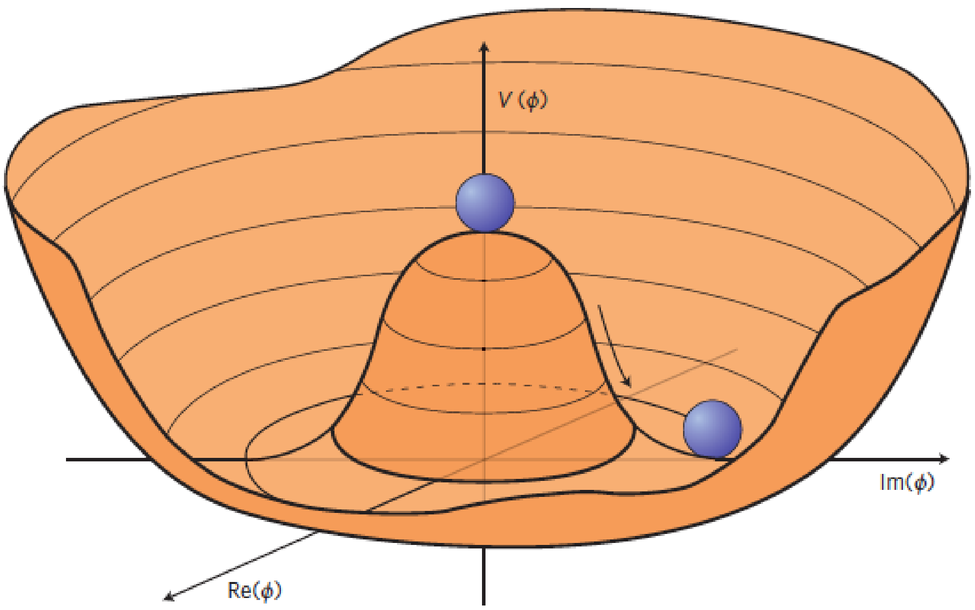


Fig. from Ellis, Gaillard, Nanopoulos, [1201.6045]

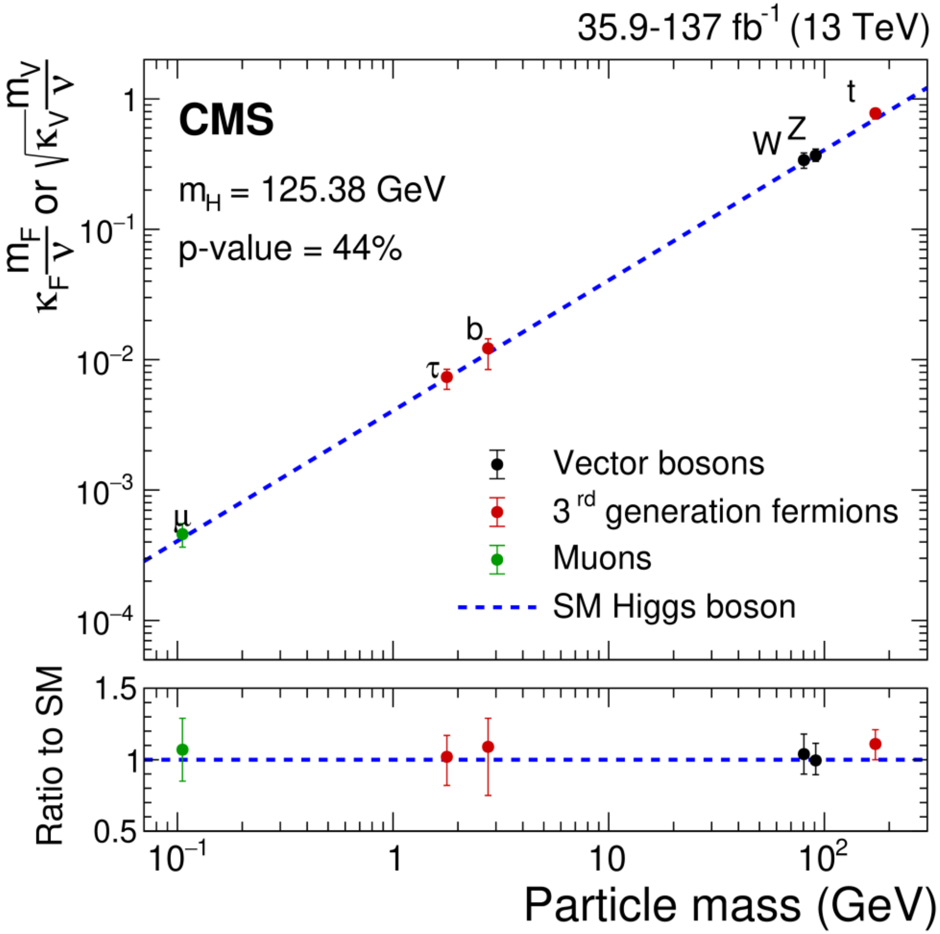
Refresher: SM Higgs phenomenology

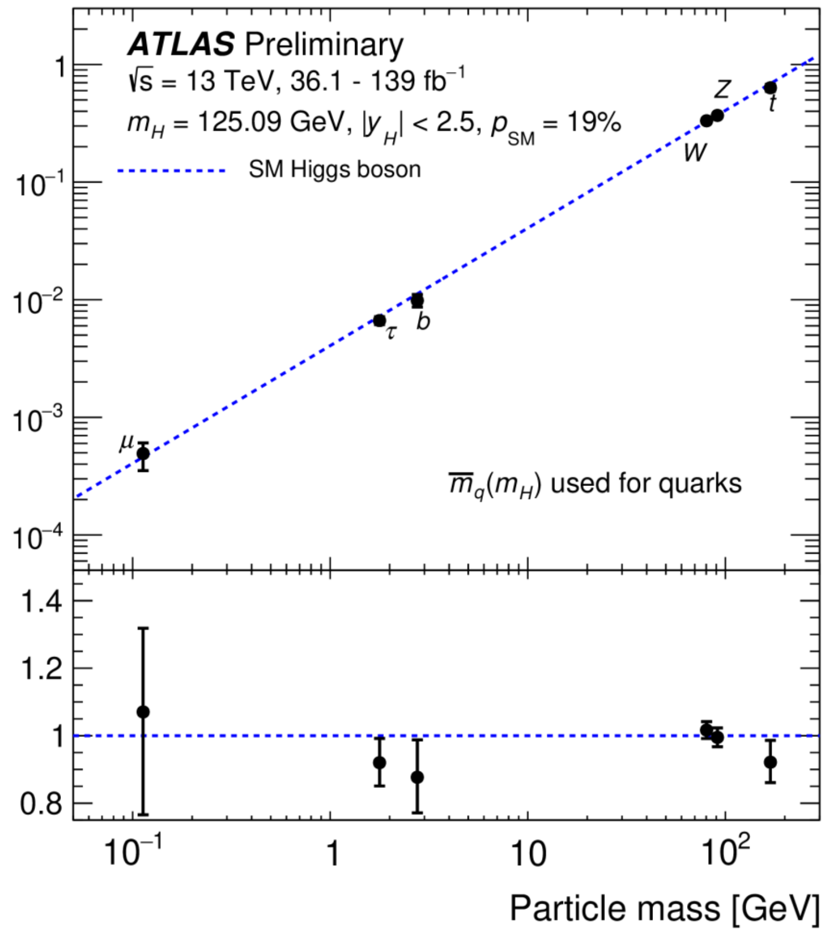
- Chiral SM fermions only become massive after SSB

$$\mathcal{L} \supset -y_u \overline{Q}_L \tilde{H} u_R - y_d \overline{Q}_L H d_R - y_e \overline{L}_L H e_R + \text{ h.c.}$$

- Diagonalizing the arbitrary Yukawa matrices uses the global $U(3)^5$ flavor symmetry, leading to V_{CKM} (and V_{PMNS} for Dirac neutrino masses)
  - Central prediction: Higgs (and Z) interactions are flavor diagonal in fermion mass basis
    - Higgs Yukawa couplings are real, proportional to fermion mass
    - Also true for Higgs couplings to massive gauge bosons

Testing SM Higgs phenomenology





CMS HIG-17-031 and updates, ATLAS-CONF-2021-053

Top-level dichotomy

- Given: the Higgs mechanism underpins the SM
  - Q: How do we conceptualize the space of BSM effects on SM Higgs physics?

Top-level dichotomy

- Given: the Higgs mechanism underpins the SM
  - Q: How do we conceptualize the space of BSM effects on SM Higgs physics?
  - A: This is the fundamental interplay at the heart of BSM Higgs phenomenology

Higgs physics touches (most) all of BSM ⟷ (Most all) BSM changes Higgs physics

Key reason: $|H|^2$ is the lowest-dimension, gauge- and Lorentz-invariant operator, hence sensitive to any NP (This is also relevant for the hierarchy problem)

Non-exhaustive list of Higgs decays

  - [Implicit marriage of production modes and decay]
- Thus, NP can appear in any Higgs production/decay mode
- Yukawa-mediated two-body decays
  - bb, cc, ττ, μμ, ee (tt, ss, uu, dd)
- Vector coupling-induced decays
  - 4l, lνlν, lνqq
- Loop-induced decays
  - gg, γγ, Zγ
- Rare decays
  - J/ψ γ, ϒγ, ϕγ

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Test Yukawa patterns, CPV phases

- Vector coupling-induced decays
  - 4l, lνlν, lνqq

Test EWSB, probe VV unitarization, additional Higgs states, CPV

- Loop-induced decays
  - gg, γγ, Zγ

Test new colored states, new EM charged states

- Rare decays
  - J/ψ γ, ϒγ, ϕγ

Test Yukawa couplings, loop-induced couplings

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Schopf, Arnold, Sauerburger, Tzovara, Cardini

- Vector coupling-induced decays
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Aggarwal

- Loop-induced decays
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Gillwald

- Rare decays
  - J/ψ γ, ϒγ, ϕγ

Example: Motivating non-standard Yukawas

- Effective dim-6 operator correction for Yukawas

$$\mathcal{L} \supset -y_u \bar{Q}_L \tilde{H} u_R - y_u' \frac{|H|^2}{\Lambda^2} \bar{Q} \tilde{H} u_R - y_\ell \bar{L} H \ell_R - y_\ell' \frac{|H|^2}{\Lambda^2} \bar{L} H \ell_R$$

$$- \quad y_d \bar{Q}_L H d_R - y_d' \frac{|H|^2}{\Lambda^2} \bar{Q} H d_R + \text{ h.c.}$$

  – Diagonalize the mass combinations $m_f = \frac{y_f v}{\sqrt{2}} + \frac{y_f' v^3}{2\sqrt{2}\Lambda^2}$

- Resulting Yukawa interactions are not necessarily diagonal, or CP-conserving

$$\frac{y_{f,\text{ eff}}}{\sqrt{2}} = \frac{y_f}{\sqrt{2}} + \frac{3 y_f' v^2}{2\sqrt{2}\Lambda^2} = \frac{m_f}{v} + \frac{2 y_f' v^2}{2\sqrt{2}\Lambda^2}$$

  – Depends sensitively on symmetries assumed at dim-6
    - Fine-tune mass generation ↔ large BSM effects

New Physics Lamppost

- Two categories of searches: SM vs. SM-ish decays
  - SM Higgs decay: target sensitivity is nonzero SM prediction
  - SM-ish Higgs decay: target is testing a SM zero
    - Flavor-violating decay, CPV, exotic decay
- Logic also valid for production modes! FY [1404.2924]
  - SM vs. SM-ish production modes also need testing
  - Current framework uses STXS

In Higgs physics, any SM zero is readily *nonzero* in a NP model

Summary

- Rich and diverse program of post-discovery studies of Higgs properties at LHC
  - Mass, spin/parity, couplings, width, exotic production modes, exotic decay modes

Exotic decay h → aa: Rodriguez, Hoefer (BSM session)

- Boundless set of experimental measurements, and every measurement is an opportunity to refute the SM
  - Not addressed: κ-framework, EFT approach
  - Forthcoming highlight: HH studies

HH results: Veatch, Deutsch

- Patterns of deviations from data will point the path to new physics scales

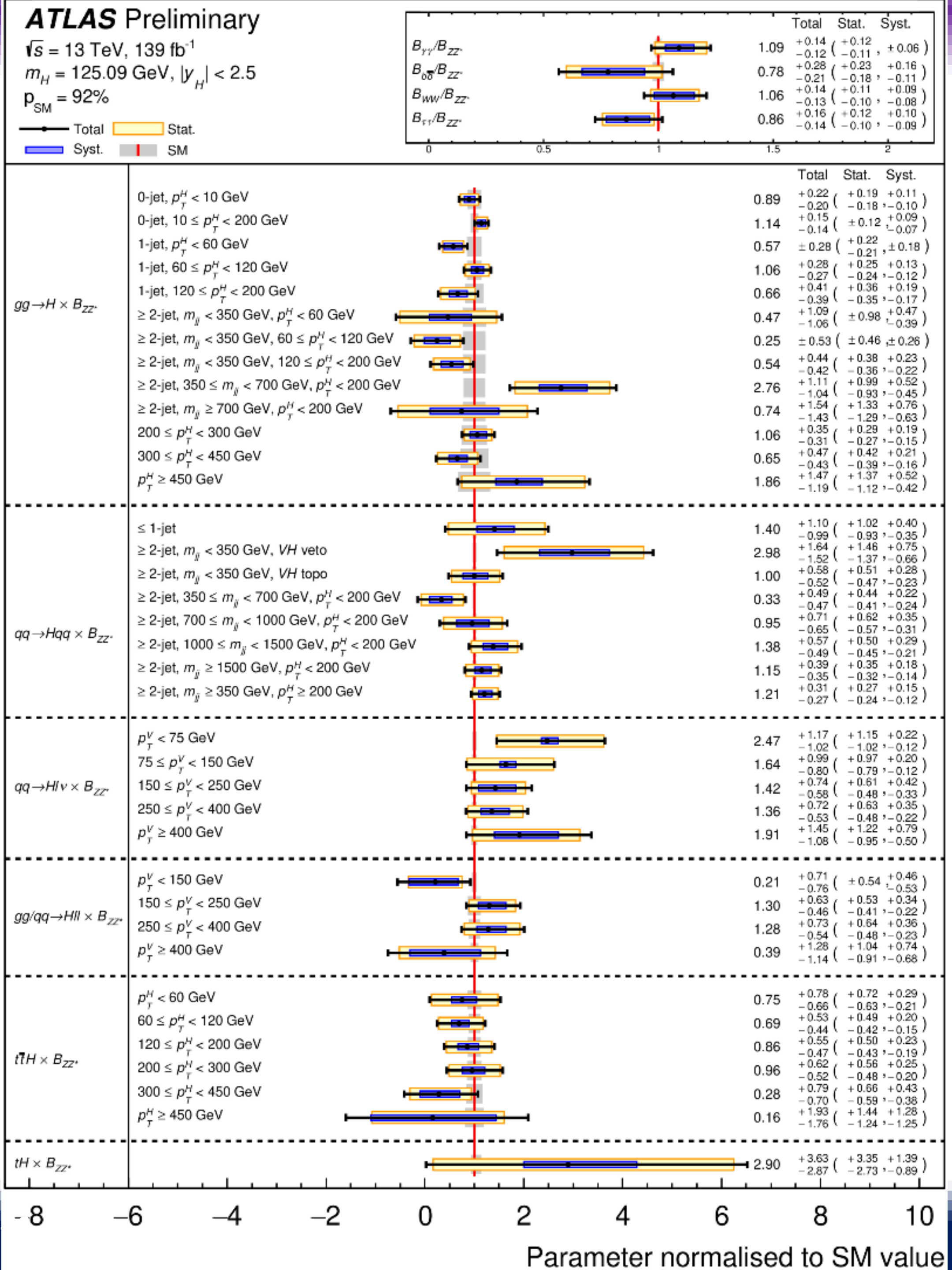
Motivating patterns of characteristic deviations: EFT vs. UV-complete

- Assume no light degrees of freedom, use effective operators for Higgs characterization
  - HEFT and SMEFT approaches differ in scope, but patterns of deviations require assumptions belying model dependence, symmetry assumptions for NP
    - dim-6: 76 vs. 2499 operators (global B, L conservation, one vs. three fermion generations)

      Buchmuller, Wyler NPB 268 (1986) 621
      Grzadkowski, Iskrzynski, Misiak, Rosiek [1008.4884]
      Alonso, Jenkins, Manohar, Trott [1312.2014]
    - e.g. SILH basis

      Giudice, Grojean, Pomarol, Rattazzi [hep-ph/0703164]
      Liu, Pomarol, Rattazzi [1603.03064]
- Adopt concrete, robust models
  - SM+singlet, 2HDM, G-M, MSSM, composite Higgs, …

Current status



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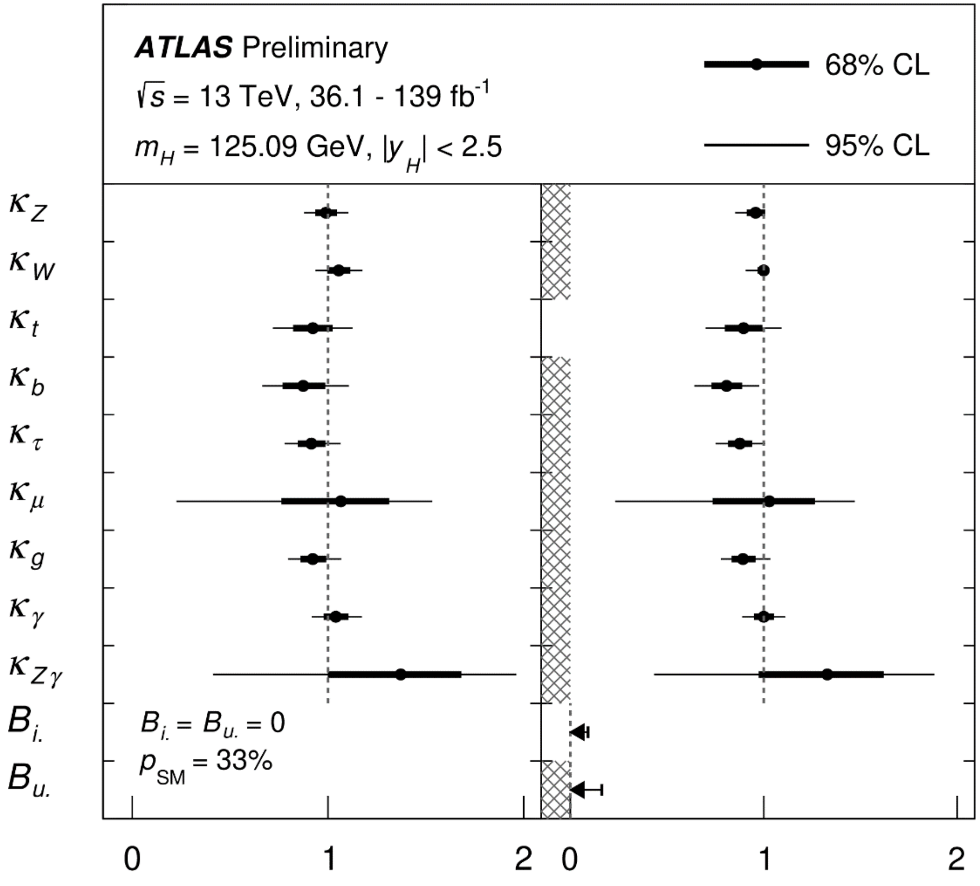
Current κ-framework measurements



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Current κ-framework measurements

Production cross section	Loops	Main interference	Effective modifier	Resolved modifier
$\sigma(\text{ggF})$	✓	t–b	κ_g^2	$1.040\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.038\,\kappa_t\kappa_b - 0.005\,\kappa_t\kappa_c$
$\sigma(\text{VBF})$	-	-	-	$0.733\,\kappa_W^2 + 0.267\,\kappa_Z^2$
$\sigma(qq/qg \to ZH)$	-	-	-	κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z	$\kappa_{(ggZH)}$	$2.456\,\kappa_Z^2 + 0.456\,\kappa_t^2 - 1.903\,\kappa_Z\kappa_t$ $- 0.011\,\kappa_Z\kappa_b + 0.003\,\kappa_t\kappa_b$
$\sigma(WH)$	-	-	-	κ_W^2
$\sigma(H)$	-	-	-	κ_t^2
$\sigma(tHW)$	-	t–W	-	$2.909\,\kappa_t^2 + 2.310\,\kappa_W^2 - 4.220\,\kappa_t\kappa_W$
$\sigma(tHq)$	-	t–W	-	$2.633\,\kappa_t^2 + 3.578\,\kappa_W^2 - 5.211\,\kappa_t\kappa_W$
$\sigma(H)$	-	-	-	κ_b^2
Partial decay width				
Γ^{bb}	-	-	-	κ_b^2
Γ^{WW}	-	-	-	κ_W^2
Γ^{gg}	✓	t–b	κ_g^2	$1.111\,\kappa_t^2 + 0.012\,\kappa_b^2 - 0.123\,\kappa_t\kappa_b$
$\Gamma^{\tau\tau}$	-	-	-	κ_τ^2
Γ^{ZZ}	-	-	-	κ_Z^2
Γ^{cc}	-	-	-	$\kappa_c^2\ (= \kappa_t^2)$
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.589\,\kappa_W^2 + 0.072\,\kappa_t^2 - 0.674\,\kappa_W\kappa_t$ $+0.009\,\kappa_W\kappa_\tau + 0.008\,\kappa_W\kappa_b$ $-0.002\,\kappa_t\kappa_b - 0.002\,\kappa_t\kappa_\tau$
$\Gamma^{Z\gamma}$	✓	t–W	$\kappa_{(Z\gamma)}^2$	$1.118\,\kappa_W^2 - 0.125\,\kappa_W\kappa_t + 0.004\,\kappa_t^2 + 0.003\,\kappa_W\kappa_b$
Γ^{ss}	-	-	-	$\kappa_s^2\ (= \kappa_b^2)$
$\Gamma^{\mu\mu}$	-	-	-	κ_μ^2
Total width ($B_{\text{i.}} = B_{\text{u.}} = 0$)				
Γ_H	✓	-	κ_H^2	$0.581\,\kappa_b^2 + 0.215\,\kappa_W^2 + 0.082\,\kappa_g^2$ $+0.063\,\kappa_\tau^2 + 0.026\,\kappa_Z^2 + 0.029\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2$ $+0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$

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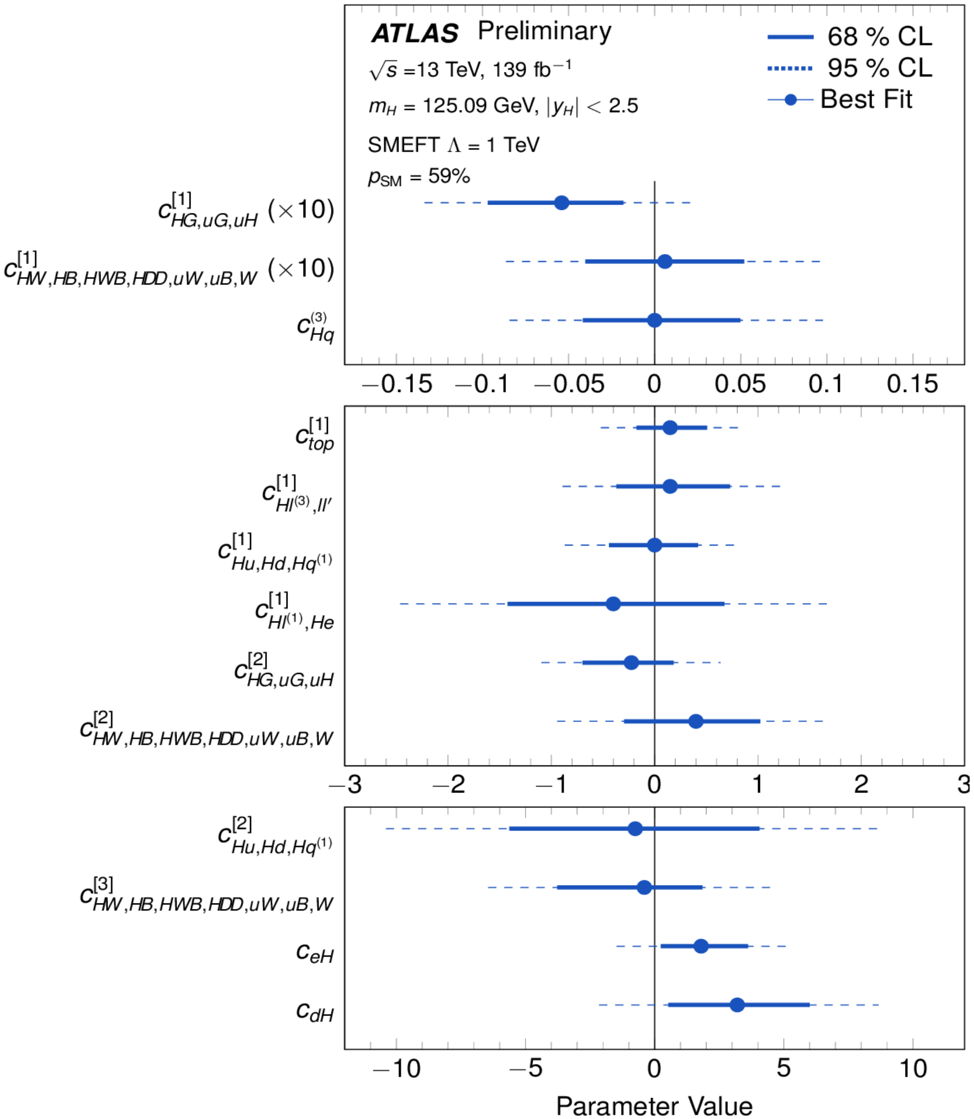
EFT Interpretation



Wilson coefficient	Operator	Wilson coefficient	Operator
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	c_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\,G^A_{\mu\nu}$
c_{HDD}	$\left(H^\dagger D^\mu H\right)^*\left(H^\dagger D_\mu H\right)$	c_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}\,W^I_{\mu\nu}$
c_{HG}	$H^\dagger H\,G^A_{\mu\nu}G^{A\mu\nu}$	c_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\,B_{\mu\nu}$
c_{HB}	$H^\dagger H\,B_{\mu\nu}B^{\mu\nu}$	c'_{ll}	$(\bar{l}_p\gamma_\mu l_t)(\bar{l}_r\gamma^\mu l_s)$
c_{HW}	$H^\dagger H\,W^I_{\mu\nu}W^{I\mu\nu}$	$c^{(1)}_{qq}$	$(\bar{q}_p\gamma_\mu q_t)(\bar{q}_r\gamma^\mu q_s)$
c_{HWB}	$H^\dagger\tau^I H\,W^I_{\mu\nu}B^{\mu\nu}$	$c^{(3)}_{qq}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	c_{qq}	$(\bar{q}_p\gamma_\mu q_t)(\bar{q}_r\gamma^\mu q_s)$
c_{uH}	$(H^\dagger H)(\bar{q}_p u_r\widetilde{H})$	$c^{(31)}_{qq}$	$(\bar{q}_p\gamma_\mu\tau^I q_t)(\bar{q}_r\gamma^\mu\tau^I q_s)$
c_{dH}	$(H^\dagger H)(\bar{q}_p d_r\widetilde{H})$	c_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
$c^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$	$c^{(1)}_{uu}$	$(\bar{u}_p\gamma_\mu u_t)(\bar{u}_r\gamma^\mu u_s)$
$c^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p\tau^I\gamma^\mu l_r)$	$c^{(1)}_{qu}$	$(\bar{q}_p\gamma_\mu q_t)(\bar{u}_r\gamma^\mu u_s)$
c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$	$c^{(8)}_{ud}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$
$c^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$	$c^{(8)}_{qu}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$c^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p\tau^I\gamma^\mu q_r)$	$c^{(8)}_{qd}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$	c_W	$\epsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$	c_G	$f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$

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EFT Interpretation

Model Parameter		Observed		Expected	
($\Lambda = 1$ TeV)	Best-fit	68% CI	95% CI	68% CI	95% CI
$c_{Hq}^{(3)}$	0.0	[−0.04, 0.05]	[−0.08, 0.1]	[−0.04, 0.05]	[−0.08, 0.09]
c_{dH}	3.2	[0.5, 6]	[−2.1, 9]	[−2.7, 2.7]	[−5, 5]
c_{eH}	1.8	[0.23, 4]	[−1.5, 5]	[−1.7, 1.7]	[−3.5, 3.2]
$c_{HW,HB,HWB,HDD,uW,uB,W}^{[1]}$	0.001	[−0.004, 0.005]	[−0.009, 0.01]	[−0.005, 0.004]	[−0.009, 0.009]
$c_{HW,HB,HWB,HDD,uW,uB,W}^{[2]}$	0.4	[−0.30, 1.0]	[−0.9, 1.7]	[−0.6, 0.6]	[−1.3, 1.3]
$c_{HW,HB,HWB,HDD,uW,uB,W}^{[3]}$	−0.4	[−4, 1.9]	[−6, 5]	[−2.7, 2.8]	[−5, 6]
$c_{Hl^{(1)},He}^{[1]}$	−0.4	[−1.4, 0.7]	[−2.5, 1.7]	[−1.0, 1.0]	[−2.0, 2.0]
$c_{Hu,Hd,Hq^{(1)}}^{[1]}$	0.0	[−0.4, 0.4]	[−0.9, 0.8]	[−0.4, 0.4]	[−0.9, 0.8]
$c_{Hu,Hd,Hq^{(1)}}^{[2]}$	−0.8	[−6, 4]	[−10, 9]	[−5, 5]	[−10, 10]
$c_{Hl^{(3)},ll'}^{[1]}$	0.15	[−0.4, 0.7]	[−0.9, 1.3]	[−0.5, 0.5]	[−1.0, 1.0]
$c_{HG,uG,uH}^{[1]}$	−0.005	[−0.01, −0.0018]	[−0.013, 0.0021]	[−0.004, 0.004]	[−0.008, 0.008]
$c_{HG,uG,uH}^{[2]}$	−0.23	[−0.7, 0.18]	[−1.1, 0.6]	[−0.4, 0.5]	[−0.9, 0.9]
$c_{top}^{[1]}$	0.15	[−0.18, 0.5]	[−0.5, 0.8]	[−0.4, 0.4]	[−0.7, 0.7]

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