Global Bayesian Analysis of the Higgs-boson Couplings

Jorge de Blas

Istituto Nazionale di Fisica Nucleare
Sezione di Roma

SUSY 2015
Lake Tahoe, Aug 27, 2015

In collaboration with:
M. Ciuchini, E. Franco, D. Ghosh, S. Mishima, M. Pierini,
L. Reina, L. Silvestrini, and the **HEPfit** group

Introduction

- Particle physics after the LHC run 1:
  - We have found the Higgs
  - No (conclusive) evidence of new resonances
  - In general, no significant deviations in the data with respect to the SM predictions.
- Indirect searches after the LHC run 1:
  - No hint of the nature of physics BSM⇒ Model Independent
  - Experimental data suggest that the new physics scale must be well above the EW scale ⇒ Effective Lagrangians

Effective Lagrangian description of NP

- The SM as an Effective Theory

$$\mathcal{L}_{\text{Eff}} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad\qquad [\mathcal{O}_i] = d$$

- General parametrization compatible with assumptions

- Provides an ordering principle (Power counting)

- Provides (Lorentz & Gauge invariance) correlations between different types of observables

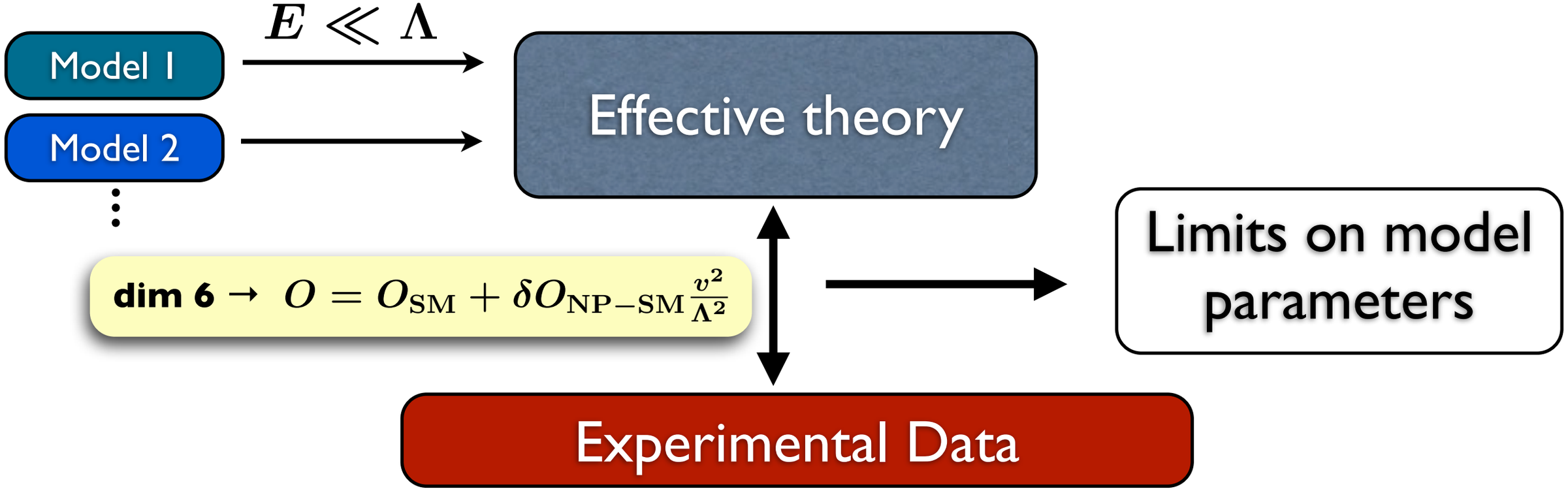
Effective Lagrangian description of NP

- The SM as an Effective Theory

$$\mathcal{L}_{\text{Eff}} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad\qquad [\mathcal{O}_i] = d$$

- General parametrization compatible with assumptions



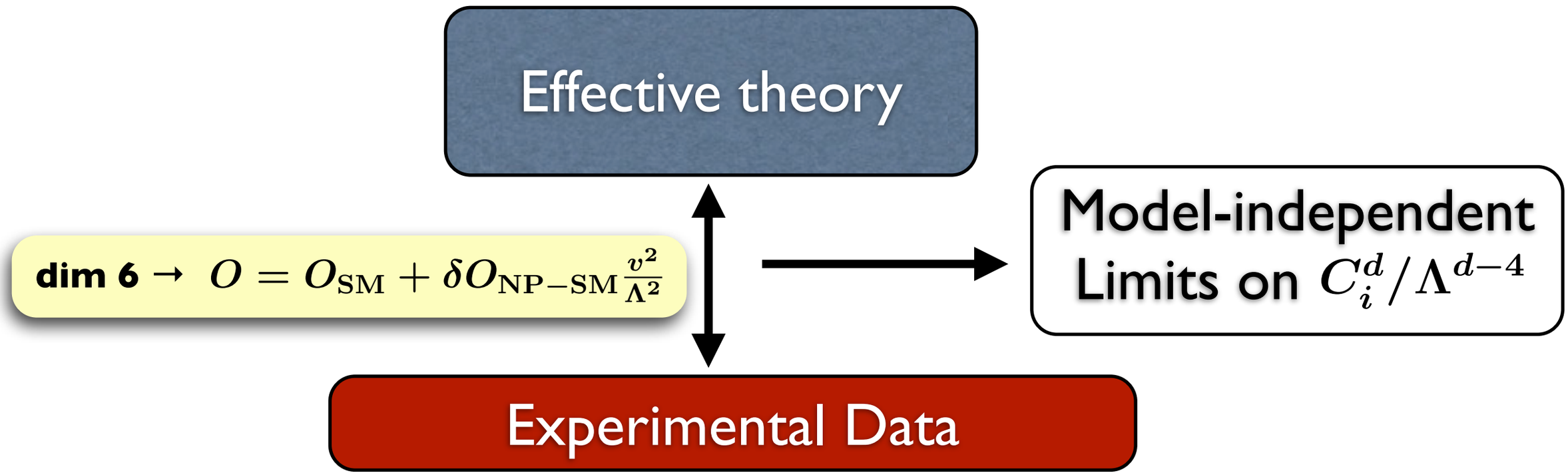
Effective Lagrangian description of NP

- The SM as an Effective Theory

$$\mathcal{L}_{\text{Eff}} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad\qquad [\mathcal{O}_i] = d$$

- Model-Independent description of physics BSM



Effective Lagrangian description of NP

- The SM as an Effective Theory

$$\mathcal{L}_{\text{Eff}} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad\qquad [\mathcal{O}_i] = d$$

- Dimension 5: 1 operator — S. Weinberg, Phys. Rev. Lett. 43 (1979) 1566
- Dimension 6: 59 operators — W. Buchmüller, D. Wyler, Nucl. Phys. B268 (1986) 621; C. Arzt, M.B. Einhorn, J. Wudka, Nucl. Phys. B433 (1995) 41; B.Grzadkowski, M.Iskrynski, M.Misiak, J.Rosiek, JHEP 1010 (2010) 085
  - We use the GIMR/Warsaw basis
- (Dimension 7: 20 operators — L Lehman, Phys. Rev. D90 (2014) 12, 125023)

Effective Lagrangian description of New Physics in the Higgs boson couplings

Jorge de Blas
INFN- Sezione di Roma

SUSY 2015
Lake Tahoe, Aug 27, 2015

Eff. Lag. description of NP in Higgs couplings

- Effective Lagrangian for single Higgs prod. & decay (hVV interactions)

$$\mathcal{L}_{hVV} = h\left(g^{(1)}_{hZZ} Z_{\mu\nu} Z^{\mu\nu} + g^{(2)}_{hZZ} Z_\nu \partial_\mu Z^{\mu\nu} + g^{(3)}_{hZZ} Z_\mu Z^\mu + g_{hAA} A_{\mu\nu} A^{\mu\nu}\right.$$
$$+ g^{(1)}_{hZA} Z_{\mu\nu} A^{\mu\nu} + g^{(2)}_{hZA} Z_\nu \partial_\mu A^{\mu\nu} + g^{(1)}_{hWW} W^+_{\mu\nu} W^{-\,\mu\nu}$$
$$+ \left(g^{(2)}_{hWW} W^+_\nu D_\mu W^{-\,\mu\nu} + (g^{(2)}_{hWW})^* W^-_\nu D_\mu W^{+\,\mu\nu}\right) + g^{(3)}_{hWW} W^+_\mu W^{-\,\mu} +$$
$$\left. + g_{hGG} \mathrm{Tr}\left[G_{\mu\nu} G^{\mu\nu}\right]\right)$$

- To dimension six these receive direct contributions from

Higgs WFR →

$$\mathcal{O}_{H\Box} = \left(H^\dagger H\right) \Box \left(H^\dagger H\right)$$
$$\mathcal{O}_{HG} = \left(H^\dagger H\right) G^A_{\mu\nu} G^{A\,\mu\nu}$$
$$\mathcal{O}_{HW} = \left(H^\dagger H\right) W^a_{\mu\nu} W^{a\,\mu\nu}$$
$$\mathcal{O}_{HB} = \left(H^\dagger H\right) B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{HWB} = \left(H^\dagger \sigma_a H\right) W^a_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{HD} = \left|H^\dagger i D_\mu H\right|^2$$

→ g_{hGG}, $g^{(1)}_{hWW}$, $g^{(1)}_{hZZ}$ g_{hAA} $g^{(1)}_{hZA}$, $g^{(3)}_{hZZ}$

$$\left(\begin{array}{cc} g^{(2)}_{hZZ} = 0 & g^{(2)}_{hZA} = 0 \\ g^{(2)}_{hWW} = 0 & \end{array}\right)$$

Eff. Lag. description of NP in Higgs couplings

- Effective Lagrangian for single Higgs prod. & decay (***hff*** interactions)

$$\mathcal{L}_{hff} = h \sum_f g_{hff} \overline{f_L} f_R + \text{h.c.}$$

- To dimension six these receive direct contributions from:

Higgs WFR →

$$\mathcal{O}_{H\Box} = (H^\dagger H) \Box (H^\dagger H)$$
$$\mathcal{O}_{eH} = (H^\dagger H) (\overline{l_L} H e_R) \rightarrow g_{h\tau\tau}$$
$$\mathcal{O}_{uH} = (H^\dagger H) (\overline{q_L} \tilde{H} u_R) \rightarrow g_{htt,hcc}$$
$$\mathcal{O}_{dH} = (H^\dagger H) (\overline{q_L} H d_R) \rightarrow g_{hbb}$$

Eff. Lag. description of NP in Higgs couplings

- Effective Lagrangian for single Higgs prod. & decay (***hVff*** interactions)

$$\mathcal{L}_{hVff} = hZ_\mu \left(\sum_f g^{(L)}_{hZff} \overline{f_L} \gamma^\mu f_L + \sum_f g^{(R)}_{hZff} \overline{f_R} \gamma^\mu f_R \right) +$$
$$h \left[g^{(L)}_{hWud} \left(W^+_\mu \overline{u_L} \gamma^\mu d_L + \text{h.c.} \right) + g^{(L)}_{hWe\nu} \left(W^+_\mu \overline{e_L} \gamma^\mu \nu_L + \text{h.c.} \right) + \right.$$
$$\left. g^{(R)}_{hWud} \left(W^+_\mu \overline{u_R} \gamma^\mu d_R + \text{h.c.} \right) \right]$$

Relevant for EW Higgs production, e.g. ***Zh***

- To dimension six these receive direct contributions from

$$\mathcal{O}^{(1)}_{Hf} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{f} \gamma^\mu f)$$
$$\mathcal{O}^{(3)}_{Hf} = (H^\dagger i \overleftrightarrow{D}^a_\mu H)(\overline{f} \gamma^\mu \sigma_a f)$$

$g^{(R)}_{hZff}$, $g^{(L)}_{hZff}$, $g^{(L)}_{hWud}$

LHC: $f \in$ quarks

Eff. Lag. description of NP in Higgs couplings

- Higgs observables also sensitive to other operators via indirect effects: NP corrections modifying the values of the SM input parameters

  - Example: G_F extracted from μ decay. Modified by

$$\mathcal{O}_{Hl}^{(3)} = (H^\dagger i \overleftrightarrow{D}_\mu^a H)(\bar{l}\gamma^\mu \sigma_a l) \qquad \mathcal{O}_{ll} = (\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$$

$$\delta_{G_F} = \left((C_{H\ell}^{(3)})_{11} + (C_{H\ell}^{(3)})_{22} - \tfrac{1}{2}((C_{\ell\ell})_{1221} + (C_{\ell\ell})_{2112}) \right) \frac{v^2}{\Lambda^2}$$

(Some *"hVV"* operators also enter in indirect corrections (via $M_Z, \alpha_{\rm em}$)

$$\mathcal{O}_{HD} = \left| H^\dagger i D_\mu H \right|^2 \qquad \mathcal{O}_{HWB} = (H^\dagger \sigma_a H) W_{\mu\nu}^a B^{\mu\nu}$$

)

Indirect effects propagate to all EW observables

Eff. Lag. description of NP in Higgs couplings

- Summary: Dim 6 operators contributing to single Higgs prod & decay

hVV

$$\mathcal{O}_{H\Box} = (H^\dagger H)\,\Box\,(H^\dagger H)$$
$$\mathcal{O}_{HG} = (H^\dagger H)\,G^A_{\mu\nu}G^{A\,\mu\nu}$$
$$\mathcal{O}_{HW} = (H^\dagger H)\,W^a_{\mu\nu}W^{a\,\mu\nu}$$
$$\mathcal{O}_{HB} = (H^\dagger H)\,B_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{O}_{HWB} = (H^\dagger \sigma_a H)W^a_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{O}_{HD} = \left|H^\dagger i D_\mu H\right|^2$$

hff

$$\mathcal{O}_{H\Box} = (H^\dagger H)\,\Box\,(H^\dagger H)$$
$$\mathcal{O}_{eH} = (H^\dagger H)\,(\overline{l_L} H e_R)$$
$$\mathcal{O}_{uH} = (H^\dagger H)\,(\overline{q_L}\tilde{H} u_R)$$
$$\mathcal{O}_{dH} = (H^\dagger H)\,(\overline{q_L} H d_R)$$

hVff

$$\mathcal{O}^{(1)}_{Hf} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{f}\gamma^\mu f)$$
$$\mathcal{O}^{(3)}_{Hf} = (H^\dagger i\overleftrightarrow{D}^a_\mu H)(\bar{f}\gamma^\mu \sigma_a f)$$

Indirect

$$\mathcal{O}_{ll} = (\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$$
$$\mathcal{O}^{(3)}_{Hl} = (H^\dagger i\overleftrightarrow{D}^a_\mu H)(\bar{l}\gamma^\mu \sigma_a l)$$
$$\mathcal{O}_{HD} = \left|H^\dagger i D_\mu H\right|^2$$
$$\mathcal{O}_{HWB} = (H^\dagger \sigma_a H)W^a_{\mu\nu}B^{\mu\nu}$$

Eff. Lag. description of NP in Higgs couplings

- Summary: Dim 6 operators contributing to single Higgs prod & decay

hVV

$$\mathcal{O}_{H\Box} = (H^\dagger H)\,\Box\,(H^\dagger H)$$
$$\mathcal{O}_{HG} = (H^\dagger H)\,G^A_{\mu\nu}G^{A\,\mu\nu}$$
$$\mathcal{O}_{HW} = (H^\dagger H)\,W^a_{\mu\nu}W^{a\,\mu\nu}$$
$$\mathcal{O}_{HB} = (H^\dagger H)\,B_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{O}_{HWB} = (H^\dagger \sigma_a H)W^a_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{O}_{HD} = \left|H^\dagger i D_\mu H\right|^2$$

Also constrained by EWPD

hff

$$\mathcal{O}_{H\Box} = (H^\dagger H)\,\Box\,(H^\dagger H)$$
$$\mathcal{O}_{eH} = (H^\dagger H)\,(\overline{l_L} H e_R)$$
$$\mathcal{O}_{uH} = (H^\dagger H)\,(\overline{q_L}\tilde{H} u_R)$$
$$\mathcal{O}_{dH} = (H^\dagger H)\,(\overline{q_L} H d_R)$$

Not directly testable with EWPD

hVff

$$\mathcal{O}^{(1)}_{Hf} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{f}\gamma^\mu f)$$
$$\mathcal{O}^{(3)}_{Hf} = (H^\dagger i\overleftrightarrow{D}^a_\mu H)(\bar{f}\gamma^\mu \sigma_a f)$$

Strongly constrained by EWPD
(induce modified *Vff* couplings)

Indirect

$$\mathcal{O}_{ll} = (\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$$
$$\mathcal{O}^{(3)}_{Hl} = (H^\dagger i\overleftrightarrow{D}^a_\mu H)(\bar{l}\gamma^\mu \sigma_a l)$$
$$\mathcal{O}_{HD} = \left|H^\dagger i D_\mu H\right|^2$$
$$\mathcal{O}_{HWB} = (H^\dagger \sigma_a H)W^a_{\mu\nu}B^{\mu\nu}$$

Also constrained by EWPD

Effective Lag. description of NP in EWPO

- EWPO sensitive to:
  - Oblique corrections

$$\mathcal{O}_{HD} = \left|H^\dagger i D_\mu H\right|^2 \qquad \mathcal{O}_{HWB} = (H^\dagger \sigma_a H) W^a_{\mu\nu} B^{\mu\nu}$$

$$T = -\frac{1}{2\alpha} C_{HD} \frac{v^2}{\Lambda^2} \qquad S = \frac{4 s_W c_W}{\alpha} C_{HWB} \frac{v^2}{\Lambda^2}$$

  - Corrections to EW *Vff* couplings

$$\mathcal{O}^{(1)}_{Hf} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{f}\gamma^\mu f) \qquad \mathcal{O}^{(3)}_{Hf} = (H^\dagger i \overleftrightarrow{D}^a_\mu H)(\bar{f}\gamma^\mu \sigma_a f)$$

$$\delta g_L^{u(\nu),d(e)} = -\frac{1}{2}\left(C^{(1)}_{Hq(l)} \mp C^{(3)}_{Hq(l)}\right)\frac{v^2}{\Lambda^2} \qquad \delta g_R^{u,d,e} = -\frac{1}{2} C^{(1)}_{Hu,d,e} \frac{v^2}{\Lambda^2}$$

$$\delta V_L^{q,l} = C^{(3)}_{Hq,l} \frac{v^2}{\Lambda^2}$$

- Also sensitive to $\mathcal{O}_{ll} = (\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$ through indirect effects

Combined EWPD+Higgs data constraints on dim 6 Higgs interactions

Jorge de Blas
INFN- Sezione di Roma

SUSY 2015
Lake Tahoe, Aug 27, 2015

Higgs data included in the analysis

Higgs signal strengths

- **ATLAS & CMS:**

ATLAS: arXiv: 1408.7084
CMS: arXiv: 1407.0558
$h \to \gamma\gamma$

ATLAS: arXiv: 1408.5191
CMS: arXiv: 1412.8662
$h \to ZZ$

ATLAS: arXiv: 1412.2641, 1506.06641
CMS: arXiv: 1312.1129
$h \to W^+W^-$

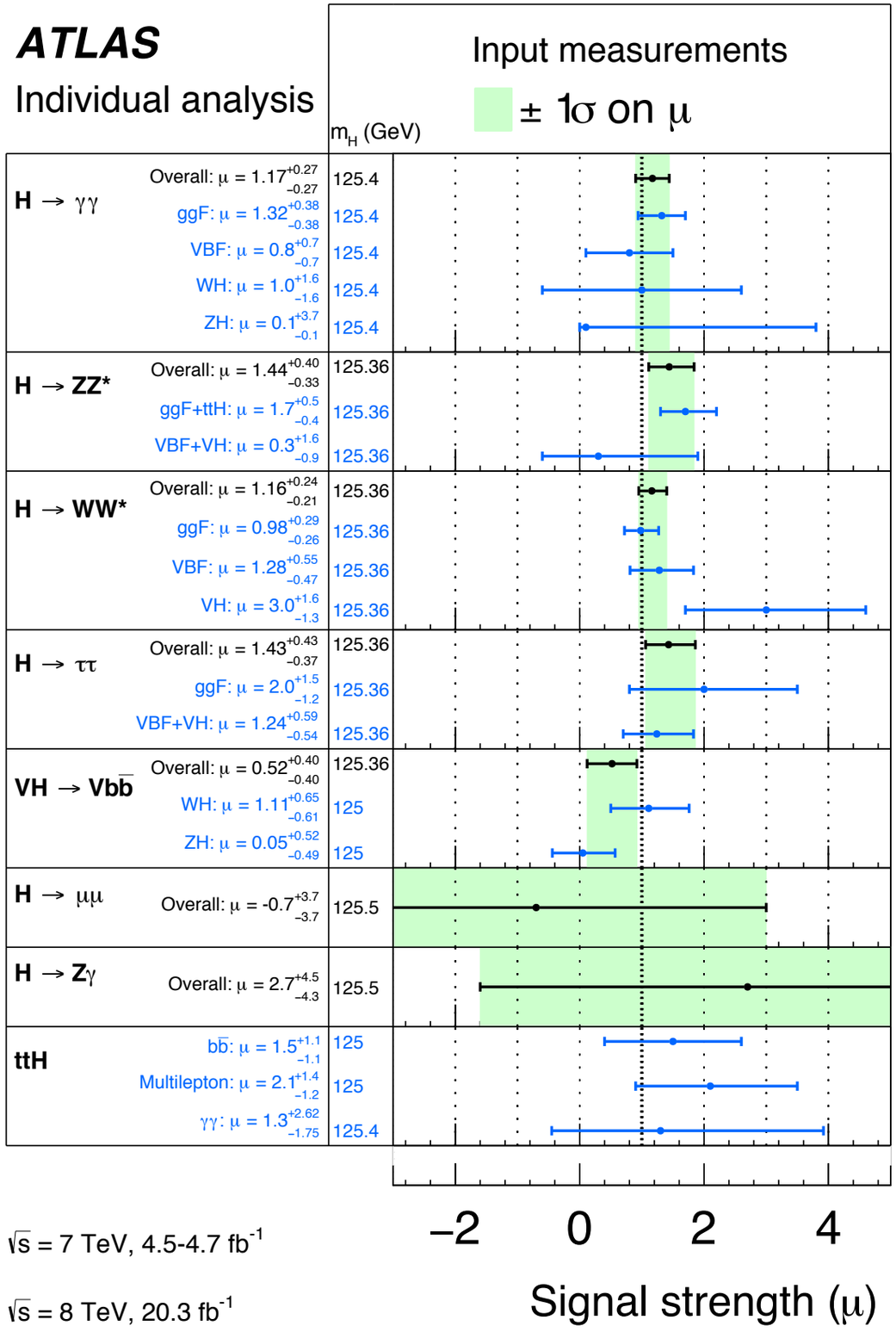
ATLAS: arXiv: 1501.04943
CMS: arXiv: 1401.5041
$h \to \tau^+\tau^-$

ATLAS: arXiv: 1409.6212,1503.05066
CMS: arXiv: 1310.3687,1408.1682
$h \to b\bar{b}$

- **CDF & D0:**

CDF: arXiv: 1301.6668
D0: arXiv: 1303.0823
$h \to b\bar{b}$

All individual exp. cathegories included in the analysis



Higgs data included in the analysis

- Higgs signal strengths:

$$\mu = \sum_i w_i r_i \qquad r_i = \frac{[\sigma \times \mathrm{BR}]_i}{[\sigma_{\mathrm{SM}} \times \mathrm{BR}_{\mathrm{SM}}]_i}$$

$$w_i = \frac{\epsilon_i [\sigma_{\mathrm{SM}} \times \mathrm{BR}_{\mathrm{SM}}]_i}{\sum_j \epsilon_j^{\mathrm{SM}} [\sigma_{\mathrm{SM}} \times \mathrm{BR}_{\mathrm{SM}}]_j}$$

Assume efficiencies similar to the SM ones $\epsilon_i \approx \epsilon_i^{\mathrm{SM}}$

- Calculations of cross-sections and decay widths

$$\sigma_i = \sigma_i^{\mathrm{SM}} + \sum_X a_{hX}^{\sigma_i} g_{hX} + \mathcal{O}(g_{hX}^2)$$

Depend on the production mode. Encode effects from PDFs, ...

Computed using FR+Madgraph + SM K-factors

Handbook of LHC Higgs cross sections

$$\Gamma_i = \Gamma_i^{\mathrm{SM}} + \sum_X a_{hX}^{\Gamma_i} g_{hX} + \mathcal{O}(g_{hX}^2)$$

Computed using eHdecay

EWPD INCLUDED IN THE ANALYSIS

		Data	SM Fit	SM Indirect	Pull
LEP	$\alpha_s(M_Z^2)$	0.1185 ± 0.0005	0.1185 ± 0.0005	0.1184 ± 0.0028	-0.0
	$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$	0.02750 ± 0.00033	0.02741 ± 0.00026	0.02725 ± 0.00042	-0.5
	M_Z [GeV]	91.1875 ± 0.0021	91.1879 ± 0.0020	91.199 ± 0.011	$+1.0$
LHC & Tev	m_t [GeV]	173.34 ± 0.76	173.6 ± 0.7	176.9 ± 2.5	$+1.3$
LHC	m_h [GeV]	125.09 ± 0.24	125.09 ± 0.24	97.40 ± 25.59	-0.9
LEP 2	M_W [GeV]	80.385 ± 0.015	80.365 ± 0.006	80.361 ± 0.007	-1.4
& Tev	Γ_W [GeV]	2.085 ± 0.042	2.0890 ± 0.0005	2.0890 ± 0.0005	$+0.1$
	Γ_Z [GeV]	2.4952 ± 0.0023	2.4945 ± 0.0004	2.4945 ± 0.0004	-0.3
SLD & LEP	σ_h^0 [nb]	41.540 ± 0.037	41.488 ± 0.003	41.488 ± 0.003	-1.4
	$\sin^2\theta^{\rm lept}_{\rm eff}(Q^{\rm had}_{\rm FB})$	0.2324 ± 0.0012	0.23144 ± 0.00009	0.23144 ± 0.00009	-0.8
	$P_\tau^{\rm pol}$	0.1465 ± 0.0033	0.1477 ± 0.0007	0.1477 ± 0.0007	$+0.4$
	A_ℓ(SLD)	0.1513 ± 0.0021	0.1477 ± 0.0007	0.1472 ± 0.0008	-1.9
	A_c	0.670 ± 0.027	0.6682 ± 0.0003	0.6682 ± 0.0003	-0.1
	A_b	0.923 ± 0.020	0.93466 ± 0.00006	0.93466 ± 0.00006	$+0.6$
	$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010	0.0164 ± 0.0002	0.0163 ± 0.0002	-0.8
	$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035	0.0740 ± 0.0004	0.0740 ± 0.0004	$+0.9$
	$A_{\rm FB}^{0,b}$	0.0992 ± 0.0016	0.1035 ± 0.0005	0.1039 ± 0.0005	$+2.8$
	R_ℓ^0	20.767 ± 0.025	20.752 ± 0.003	20.752 ± 0.003	-0.6
	R_c^0	0.1721 ± 0.0030	0.17224 ± 0.00001	0.17224 ± 0.00001	$+0.0$
	R_b^0	0.21629 ± 0.00066	0.21578 ± 0.00003	0.21578 ± 0.00003	-0.8

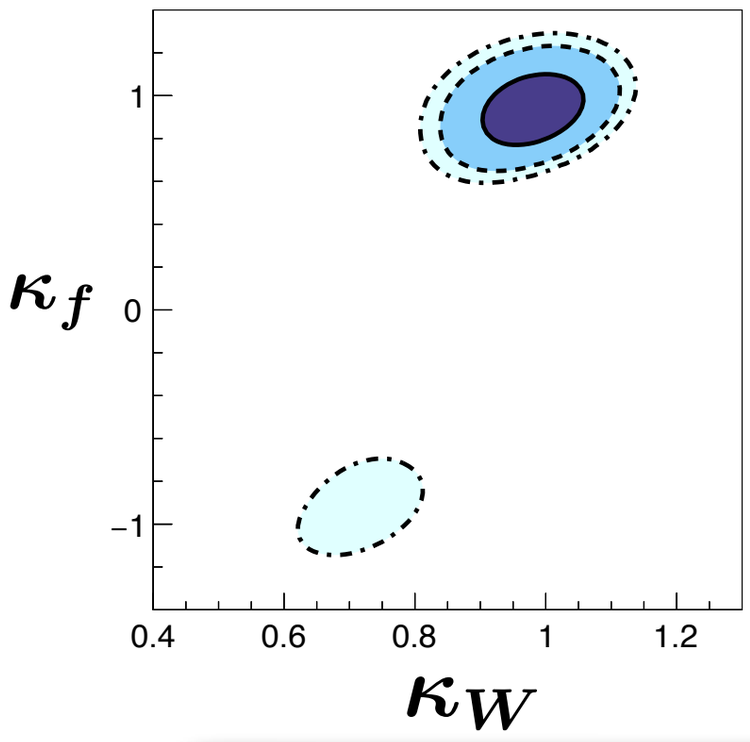
The HEPfit code

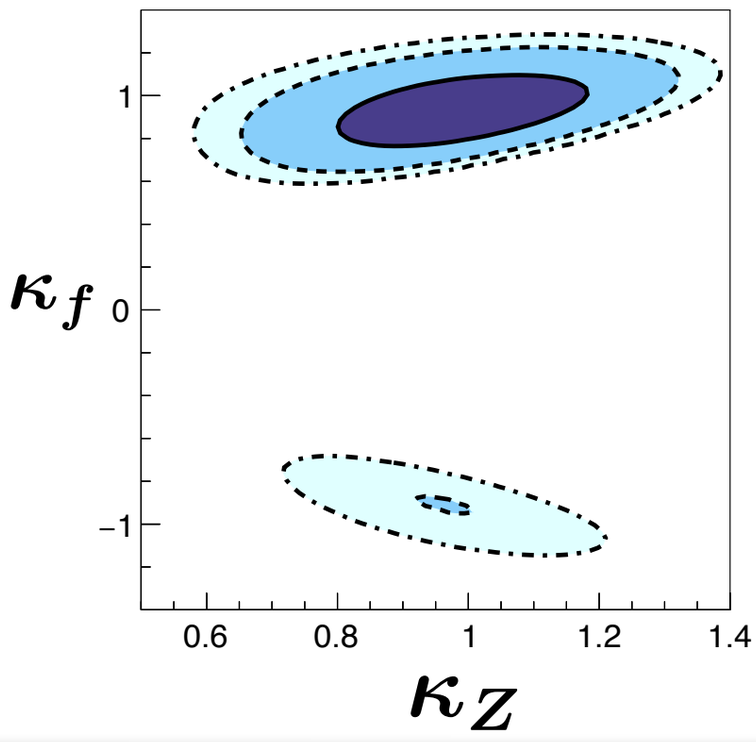
- Dim 6 Effective Lagrangian implemented as a model class within the **HEPfit** code (formerly know as **SUSYfit**):
  - General **H**igh **E**nergy **P**hysics **fit**ting tool to combine indirect and direct searches of new physics (available under GPL on github)
  - Bayesian statistical analysis
  - Stand-alone and library modes to compute observables in a given model
  - Add your own models and observables as external modules
- For technical description of the code see A. Paul's talk on tuesday

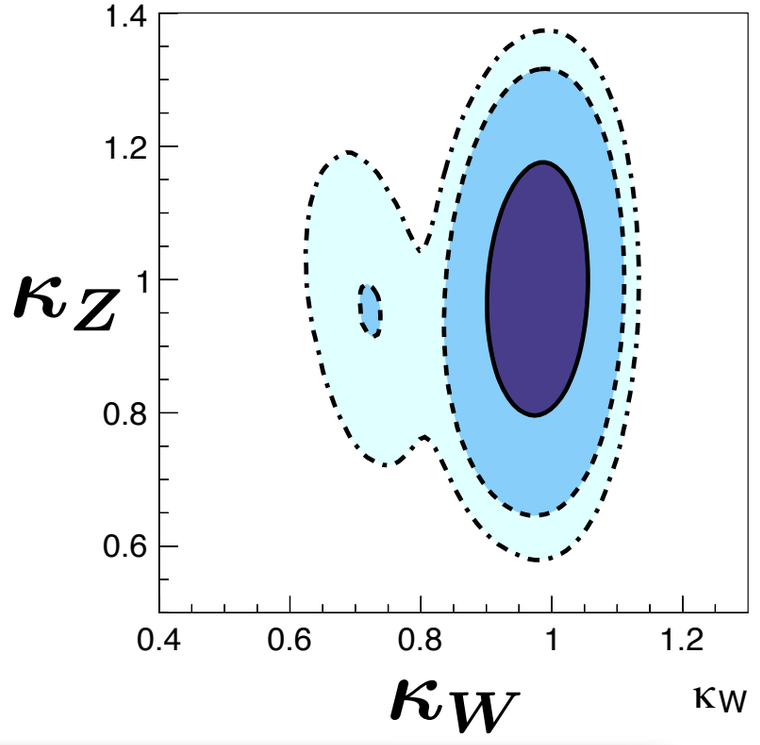
95% prob. Bounds on dim. 6 interactions

- Example: κ parameters ($\delta_h = \left(-\frac{1}{4}C_{HD} + C_{H\Box}\right)\frac{v^2}{\Lambda^2}$)

$$\kappa_Z = 1 + \delta_h + \frac{1}{2}C_{HD}\frac{v^2}{\Lambda^2} - \frac{1}{2}\delta_{G_F}$$
$$\kappa_W = 1 + \delta_h - \frac{1}{2(c_W^2 - s_W^2)}\left(4 s_W c_W C_{HWB}\frac{v^2}{\Lambda^2} + c_W^2 C_{HD}\frac{v^2}{\Lambda^2} + \delta_{G_F}\right)$$
$$\kappa_f = 1 + \delta_h - \frac{1}{2}\delta_{G_F} - \frac{v}{m_f}\frac{C_{fH}}{\sqrt{2}}\frac{v^2}{\Lambda^2}$$







Preliminary Results (Fit to Higgs signal strengths)

95% prob. Bounds on dim. 6 interactions

Operator		95% prob. bound on $\frac{C_i}{\Lambda^2}$ [TeV^{-2}] Only EW	Only Higgs	EW + Higgs
$\mathcal{O}_{HG}$	$\left(H^\dagger H\right) G^A_{\mu\nu} G^{A\,\mu\nu}$	—	$[-0.0051, 0.0092]$	$[-0.0051, 0.0092]$
$\mathcal{O}_{HW}$	$\left(H^\dagger H\right) W^a_{\mu\nu} W^{a\,\mu\nu}$	—	$[-0.034, 0.014]$	$[-0.034, 0.014]$
$\mathcal{O}_{HB}$	$\left(H^\dagger H\right) B_{\mu\nu} B^{\mu\nu}$	—	$[-0.0087, 0.0040]$	$[-0.0087, 0.0040]$
$\mathcal{O}_{HWB}$	$\left(H^\dagger \sigma_a H\right) W^a_{\mu\nu} B^{\mu\nu}$	$[-0.010, 0.004]$	$[-0.008, 0.017]$	$[-0.0073, 0.0053]$
$\mathcal{O}_{HD}$	$\left\lvert H^\dagger D_\mu H\right\rvert^2$	$[-0.032, 0.005]$	$[-1.1, 1.6]$	$[-0.032, 0.005]$
$\mathcal{O}_{H\Box}$	$\left(H^\dagger H\right) \Box \left(H^\dagger H\right)$	—	$[-1.4, 1.3]$	$[-1.4, 1.3]$
$\mathcal{O}^{(1)}_{Hl}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right) \left(\overline{l_L}\gamma^\mu l_L\right)$	$[-0.005, 0.012]$	—	$[-0.005, 0.012]$
$\mathcal{O}^{(3)}_{Hl}$	$\left(H^\dagger i\overleftrightarrow{D}^a_\mu H\right) \left(\overline{l_L}\gamma^\mu \sigma_a l_L\right)$	$[-0.012, 0.006]$	$[-0.47, 0.66]$	$[-0.012, 0.006]$
$\mathcal{O}_{He}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right) \left(\overline{e_R}\gamma^\mu e_R\right)$	$[-0.017, 0.005]$	—	$[-0.017, 0.005]$
$\mathcal{O}^{(1)}_{Hq}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right) \left(\overline{q_L}\gamma^\mu q_L\right)$	$[-0.027, 0.041]$	$[-2, 11]$	$[-0.027, 0.041]$
$\mathcal{O}^{(3)}_{Hq}$	$\left(H^\dagger i\overleftrightarrow{D}^a_\mu H\right) \left(\overline{q_L}\gamma^\mu \sigma_a q_L\right)$	$[-0.011, 0.013]$	$[-0.42, 0.05]$	$[-0.012, 0.013]$
$\mathcal{O}_{Hu}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right) \left(\overline{u_R}\gamma^\mu u_R\right)$	$[-0.071, 0.077]$	$[-4.6, 0.8]$	$[-0.072, 0.076]$
$\mathcal{O}_{Hd}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right) \left(\overline{d_R}\gamma^\mu d_R\right)$	$[-0.14, 0.06]$	$[-2, 14]$	$[-0.14, 0.06]$
$\mathcal{O}_{eH}$	$\left(H^\dagger H\right) \left(\overline{l_L} H e_R\right)$	—	$[-0.027, 0.049]$	$[-0.027, 0.049]$
$\mathcal{O}_{uH}$	$\left(H^\dagger H\right) \left(\overline{q_L} \tilde{H} u_R\right)$	—	$[-0.62, 0.33]$	$[-0.62, 0.33]$
$\mathcal{O}_{dH}$	$\left(H^\dagger H\right) \left(\overline{q_L} H d_R\right)$	—	$[-0.062, 0.059]$	$[-0.062, 0.059]$
$\mathcal{O}_{ll}$	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	$[-0.010, 0.022]$	$[-1.3, 0.9]$	$[-0.010, 0.022]$

1 operator at a time

Preliminary Results

95% prob. Bounds on dim. 6 interactions

Operator		95% prob. bound on $\frac{C_i}{\Lambda^2}$ [TeV^{-2}] Only EW	Only Higgs	EW + Higgs
$\mathcal{O}_{HG}$	$\left(H^\dagger H\right) G^A_{\mu\nu} G^{A\,\mu\nu}$	—	$[-0.0051, 0.0092]$	$[-0.0051, 0.0092]$
$\mathcal{O}_{HW}$	$\left(H^\dagger H\right) W^a_{\mu\nu} W^{a\,\mu\nu}$	—	$[-0.034, 0.014]$	$[-0.034, 0.014]$
$\mathcal{O}_{HB}$	$\left(H^\dagger H\right) B_{\mu\nu} B^{\mu\nu}$	—	$[-0.0087, 0.0040]$	$[-0.0087, 0.0040]$
$\mathcal{O}_{HWB}$	$\left(H^\dagger \sigma_a H\right) W^a_{\mu\nu} B^{\mu\nu}$	$[-0.010, 0.004]$	$[-0.008, 0.017]$	$[-0.0073, 0.0053]$
$\mathcal{O}_{HD}$	$\left\lvert H^\dagger D_\mu H\right\rvert^2$	$[-0.032, 0.005]$	$[-1.1, 1.6]$	$[-0.032, 0.005]$
$\mathcal{O}_{H\Box}$	$\left(H^\dagger H\right) \Box \left(H^\dagger H\right)$	—	$[-1.4, 1.3]$	$[-1.4, 1.3]$
$\mathcal{O}^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)\,(\overline{l_L}\gamma^\mu l_L)$	$[-0.005, 0.012]$		
$\mathcal{O}^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^a_\mu H)\,(\overline{l_L}\gamma^\mu \sigma_a l_L)$	$[-0.012, 0.006]$		
$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)\,(\overline{e_R}\gamma^\mu e_R)$	$[-0.017, 0.005]$		
$\mathcal{O}^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)\,(\overline{q_L}\gamma^\mu q_L)$	$[-0.027, 0.041]$		
$\mathcal{O}^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^a_\mu H)\,(\overline{q_L}\gamma^\mu \sigma_a q_L)$	$[-0.011, 0.013]$		
$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)\,(\overline{u_R}\gamma^\mu u_R)$	$[-0.071, 0.077]$		
$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)\,(\overline{d_R}\gamma^\mu d_R)$	$[-0.14, 0.06]$	$[-2, 14]$	$[-0.14, 0.06]$
$\mathcal{O}_{eH}$	$\left(H^\dagger H\right)\left(\overline{l_L} H e_R\right)$	—	$[-0.027, 0.049]$	$[-0.027, 0.049]$
$\mathcal{O}_{uH}$	$\left(H^\dagger H\right)\left(\overline{q_L}\tilde{H} u_R\right)$	—	$[-0.62, 0.33]$	$[-0.62, 0.33]$
$\mathcal{O}_{dH}$	$\left(H^\dagger H\right)\left(\overline{q_L} H d_R\right)$	—	$[-0.062, 0.059]$	$[-0.062, 0.059]$
$\mathcal{O}_{ll}$	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	$[-0.010, 0.022]$	$[-1.3, 0.9]$	$[-0.010, 0.022]$

$$\left|\frac{\delta g^f_L}{g^f_L}\right|, \left|\frac{\delta g^e_R}{g^e_R}\right| \lesssim 0.002$$

$$\left|\frac{\delta g^{u,d}_R}{g^{u,d}_R}\right| \lesssim 0.01, 0.04$$

1 operator at a time

Preliminary Results

95% prob. Bounds on dim. 6 interactions

Operator		95% prob. bound on $\frac{C_i}{\Lambda^2}$ [TeV^{-2}] Only EW	Only Higgs	EW + Higgs
$\mathcal{O}_{HG}$	$\left(H^\dagger H\right) G^A_{\mu\nu} G^{A\,\mu\nu}$	—	$[-0.0051, 0.0092]$	$[-0.0051, 0.0092]$
$\mathcal{O}_{HW}$	$\left(H^\dagger H\right) W^a_{\mu\nu} W^{a\,\mu\nu}$	—	$[-0.034, 0.014]$	$[-0.034, 0.014]$
$\mathcal{O}_{HB}$	$\left(H^\dagger H\right) B_{\mu\nu} B^{\mu\nu}$	—	$[-0.0087, 0.0040]$	$[-0.0087, 0.0040]$
$\mathcal{O}_{HWB}$	$\left(H^\dagger \sigma_a H\right) W^a_{\mu\nu} B^{\mu\nu}$	$[-0.010, 0.004]$	$[-0.008, 0.017]$	$[-0.0073, 0.0053]$
$\mathcal{O}_{HD}$	$\left\lvert H^\dagger D_\mu H\right\rvert^2$	$[-0.032, 0.005]$	$[-1.1, 1.6]$	$[-0.032, 0.005]$
$\mathcal{O}_{H\Box}$	$\left(H^\dagger H\right) \Box \left(H^\dagger H\right)$			
$\mathcal{O}^{(1)}_{Hl}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right) \left(\overline{l_L} \gamma^\mu l_L\right)$	$[-0.005, 0.012]$	—	$[-0.005, 0.012]$
$\mathcal{O}^{(3)}_{Hl}$	$\left(H^\dagger i\overleftrightarrow{D}^a_\mu H\right) \left(\overline{l_L} \gamma^\mu \sigma_a l_L\right)$	$[-0.012, 0.006]$	$[-0.47, 0.66]$	$[-0.012, 0.006]$
$\mathcal{O}_{He}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right) \left(\overline{e_R} \gamma^\mu e_R\right)$	$[-0.017, 0.005]$	—	$[-0.017, 0.005]$
$\mathcal{O}^{(1)}_{Hq}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right) \left(\overline{q_L} \gamma^\mu q_L\right)$	$[-0.027, 0.041]$	$[-2, 11]$	$[-0.027, 0.041]$
$\mathcal{O}^{(3)}_{Hq}$	$\left(H^\dagger i\overleftrightarrow{D}^a_\mu H\right) \left(\overline{q_L} \gamma^\mu \sigma_a q_L\right)$	$[-0.011, 0.013]$	$[-0.42, 0.05]$	$[-0.012, 0.013]$
$\mathcal{O}_{Hu}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right) \left(\overline{u_R} \gamma^\mu u_R\right)$	$[-0.071, 0.077]$	$[-4.6, 0.8]$	$[-0.072, 0.076]$
$\mathcal{O}_{Hd}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right) \left(\overline{d_R} \gamma^\mu d_R\right)$	$[-0.14, 0.06]$	$[-2, 14]$	$[-0.14, 0.06]$
$\mathcal{O}_{eH}$	$\left(H^\dagger H\right) \left(\overline{l_L} H e_R\right)$	—	$[-0.027, 0.049]$	$[-0.027, 0.049]$
$\mathcal{O}_{uH}$	$\left(H^\dagger H\right) \left(\overline{q_L} \tilde{H} u_R\right)$	—	$[-0.62, 0.33]$	$[-0.62, 0.33]$
$\mathcal{O}_{dH}$	$\left(H^\dagger H\right) \left(\overline{q_L} H d_R\right)$	—	$[-0.062, 0.059]$	$[-0.062, 0.059]$
$\mathcal{O}_{ll}$	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	$[-0.010, 0.022]$	$[-1.3, 0.9]$	$[-0.010, 0.022]$

Comparable to EWPD bounds

1 operator at a time

Preliminary Results

95% prob. Bounds on dim. 6 interactions

Operator		95% prob. bound on $\frac{C_i}{\Lambda^2}$ [TeV^{-2}] Only EW	Only Higgs	EW + Higgs
$\mathcal{O}_{HG}$	$\left(H^\dagger H\right) G^A_{\mu\nu} G^{A\,\mu\nu}$	—	[−0.0051, 0.0092]	[−0.0051, 0.0092]
$\mathcal{O}_{HW}$	$\left(H^\dagger H\right) W^a_{\mu\nu} W^{a\,\mu\nu}$			
$\mathcal{O}_{HB}$	$\left(H^\dagger H\right) B_{\mu\nu} B^{\mu\nu}$			0]
$\mathcal{O}_{HWB}$	$\left(H^\dagger \sigma_a H\right) W^a_{\mu\nu} B^{\mu\nu}$	[−0.010, 0.004]	[−0.008, 0.017]	[−0.0073, 0.0053]
$\mathcal{O}_{HD}$	$\left\lvert H^\dagger D_\mu H\right\rvert^2$	[−0.032, 0.005]	[−1.1, 1.6]	[−0.032, 0.005]
$\mathcal{O}_{H\Box}$	$\left(H^\dagger H\right) \Box \left(H^\dagger H\right)$	—	[−1.4, 1.3]	[−1.4, 1.3]
$\mathcal{O}^{(1)}_{Hl}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right) \left(\overline{l_L}\gamma^\mu l_L\right)$	[−0.005, 0.012]	—	[−0.005, 0.012]
$\mathcal{O}^{(3)}_{Hl}$	$\left(H^\dagger i\overleftrightarrow{D}^a_\mu H\right) \left(\overline{l_L}\gamma^\mu \sigma_a l_L\right)$	[−0.012, 0.006]	[−0.47, 0.66]	[−0.012, 0.006]
$\mathcal{O}_{He}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right) \left(\overline{e_R}\gamma^\mu e_R\right)$	[−0.017, 0.005]	—	[−0.017, 0.005]
$\mathcal{O}^{(1)}_{Hq}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right) \left(\overline{q_L}\gamma^\mu q_L\right)$	[−0.027, 0.041]	[−2, 11]	[−0.027, 0.041]
$\mathcal{O}^{(3)}_{Hq}$	$\left(H^\dagger i\overleftrightarrow{D}^a_\mu H\right) \left(\overline{q_L}\gamma^\mu \sigma_a q_L\right)$	[−0.011, 0.013]	[−0.42, 0.05]	[−0.012, 0.013]
$\mathcal{O}_{Hu}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right) \left(\overline{u_R}\gamma^\mu u_R\right)$	[−0.071, 0.077]	[−4.6, 0.8]	[−0.072, 0.076]
$\mathcal{O}_{Hd}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right) \left(\overline{d_R}\gamma^\mu d_R\right)$	[−0.14, 0.06]	[−2, 14]	[−0.14, 0.06]
$\mathcal{O}_{eH}$	$\left(H^\dagger H\right) \left(\overline{l_L} H e_R\right)$	—	[−0.027, 0.049]	[−0.027, 0.049]
$\mathcal{O}_{uH}$	$\left(H^\dagger H\right) \left(\overline{q_L} \tilde{H} u_R\right)$	—	[−0.62, 0.33]	[−0.62, 0.33]
$\mathcal{O}_{dH}$	$\left(H^\dagger H\right) \left(\overline{q_L} H d_R\right)$	—	[−0.062, 0.059]	[−0.062, 0.059]
$\mathcal{O}_{ll}$	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	[−0.010, 0.022]	[−1.3, 0.9]	[−0.010, 0.022]

Dominated by EWPD

1 operator at a time

Preliminary Results

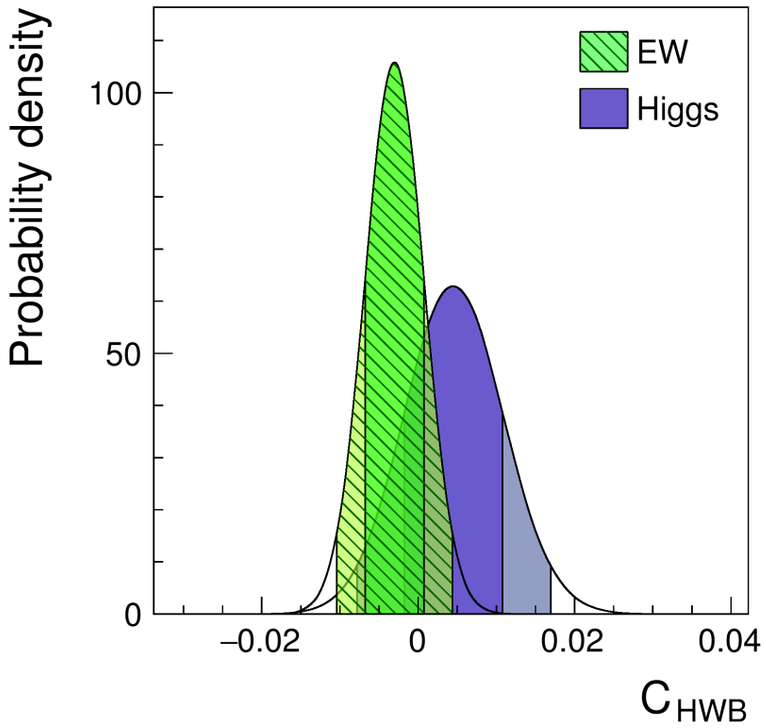
95% prob. Bounds on dim. 6 interactions

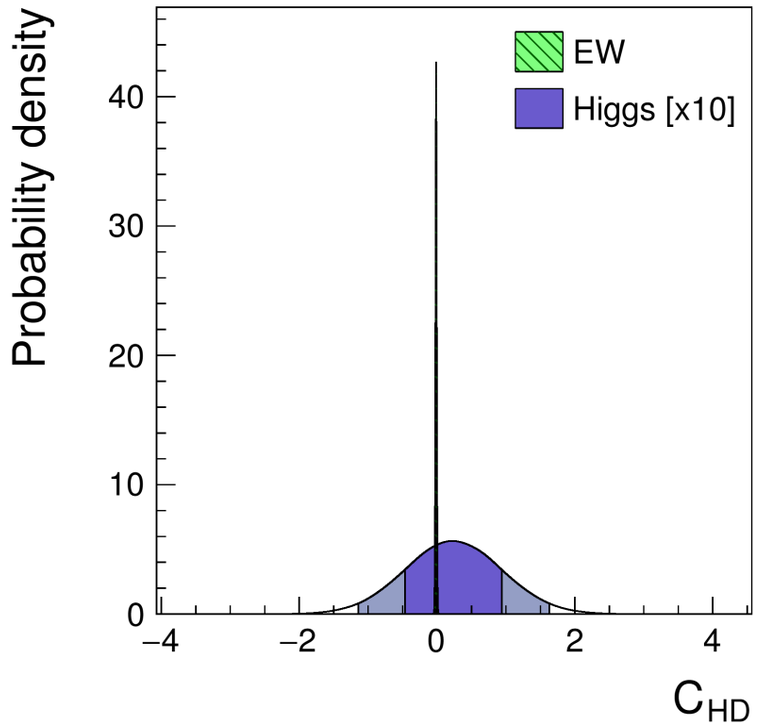
- EWPD vs. Higgs constraints:

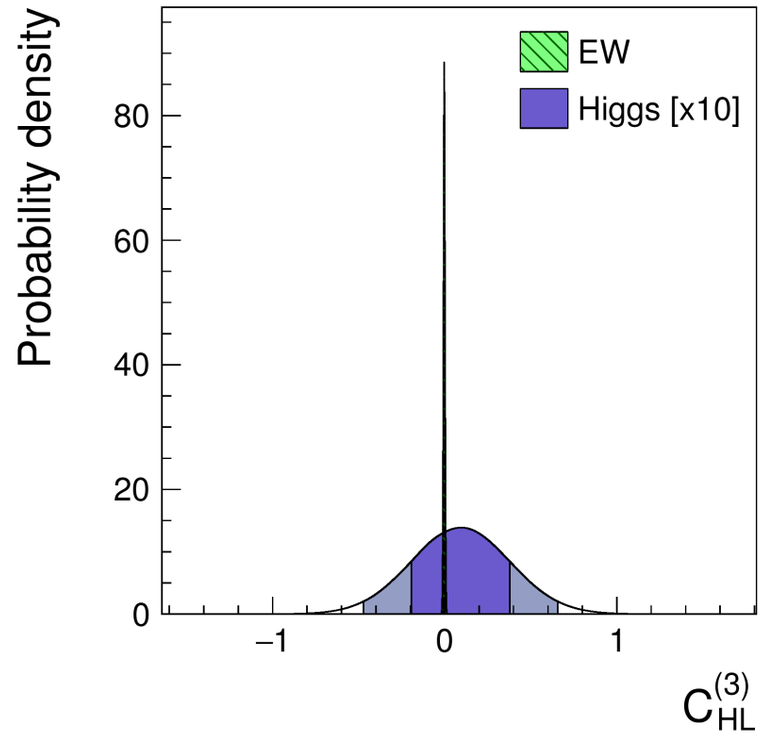
Dominated by EWPD

Compatible at the 1-2 σ level

EXCEPTION







$$\left(H^\dagger \sigma_a H\right) W^a_{\mu\nu} B^{\mu\nu}$$

$$\left|H^\dagger i D_\mu H\right|^2$$

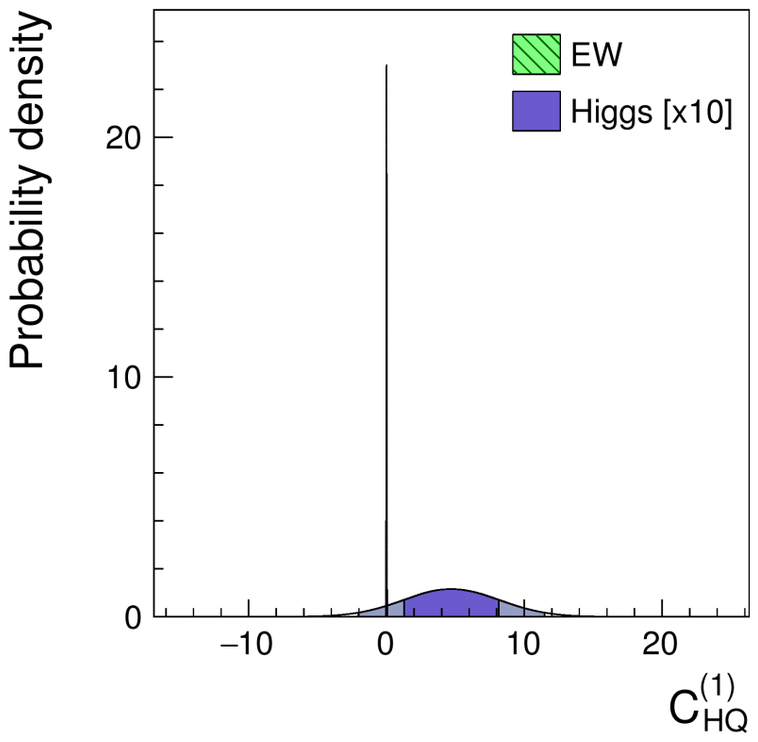
$$\left(H^\dagger i \overleftrightarrow{D}^a_\mu H\right) \left(\overline{l_L} \gamma^\mu \sigma_a l_L\right)$$

95% prob. Bounds on dim. 6 interactions

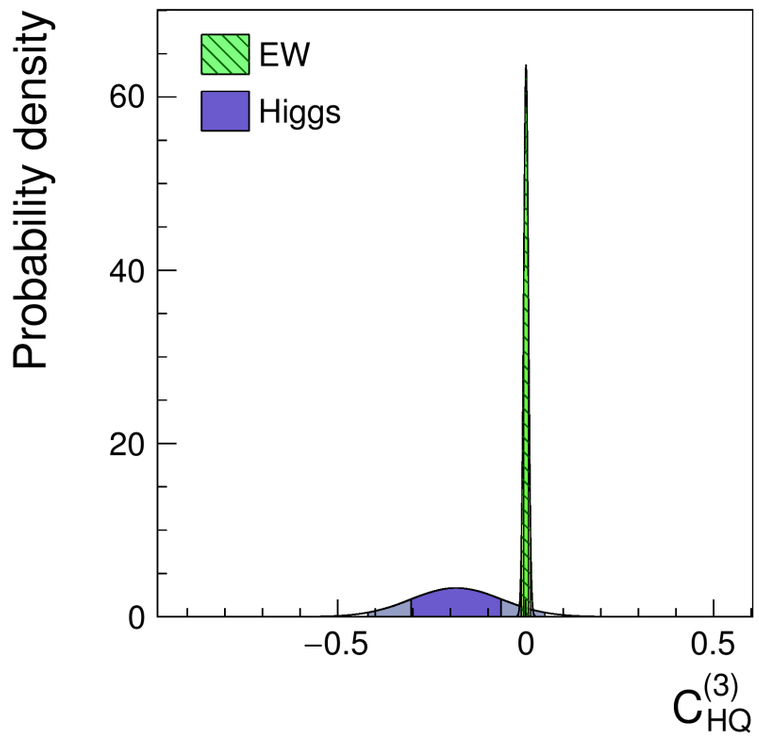
- EWPD vs. Higgs constraints:

Dominated by EWPD

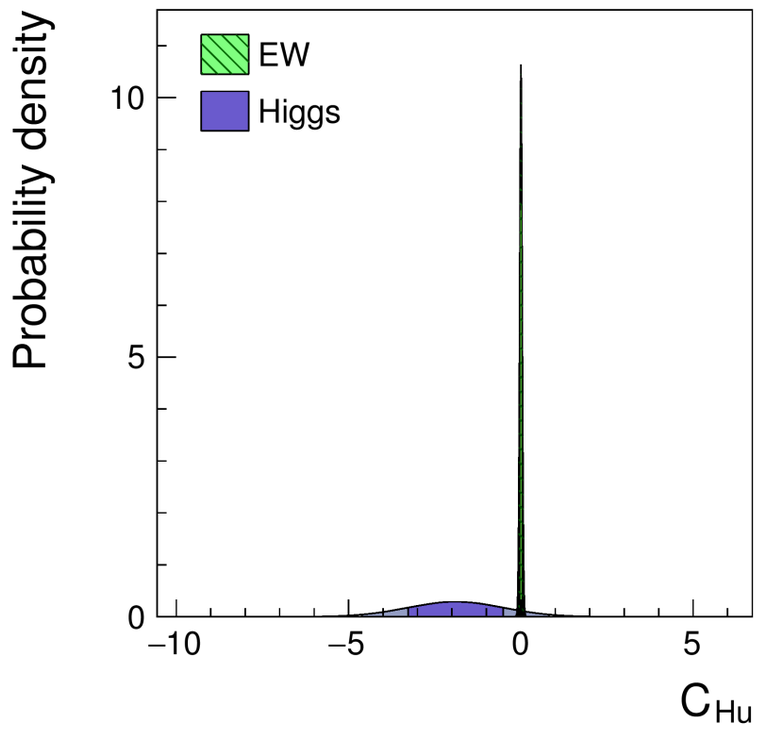
Compatible at the 1-2 σ level



$$(H^\dagger i\overleftrightarrow{D}_\mu H)\,(\overline{q_L}\gamma^\mu q_L)$$



$$(H^\dagger i\overleftrightarrow{D}^a_\mu H)\,(\overline{q_L}\gamma^\mu \sigma_a q_L)$$



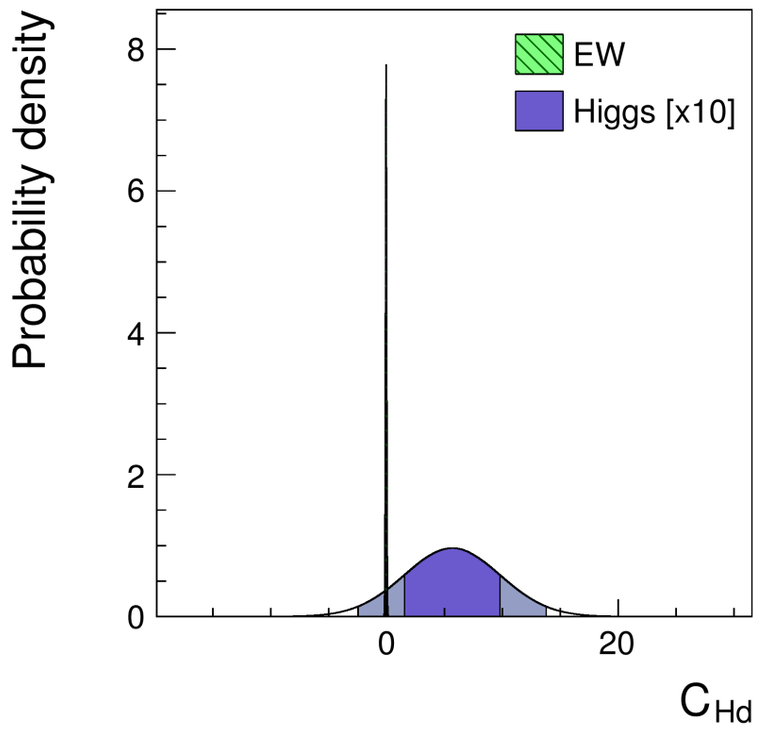
$$(H^\dagger i\overleftrightarrow{D}_\mu H)\,(\overline{u_R}\gamma^\mu u_R)$$

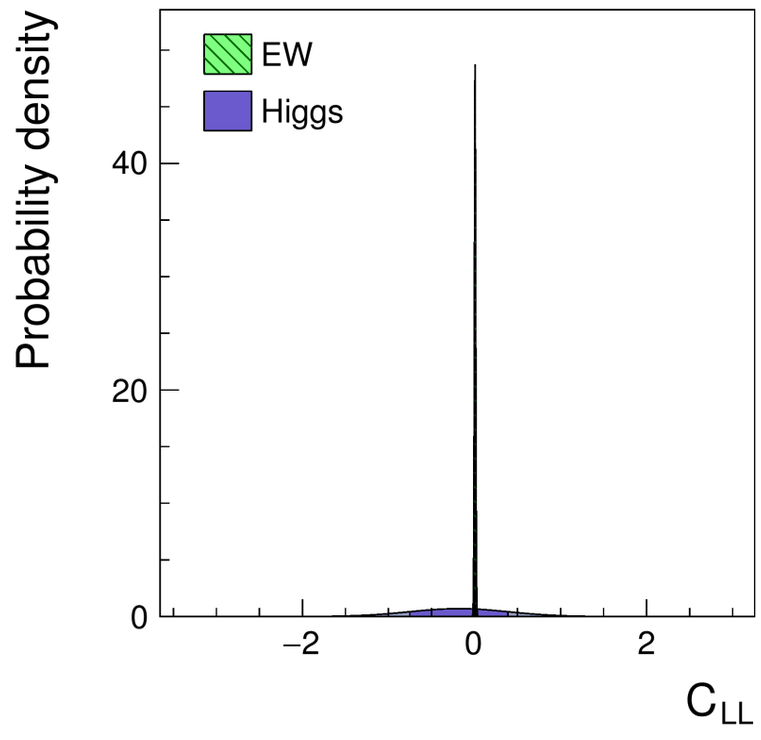
95% prob. Bounds on dim. 6 interactions

- EWPD vs. Higgs constraints:

Dominated by EWPD

Compatible at the 1-2 σ level

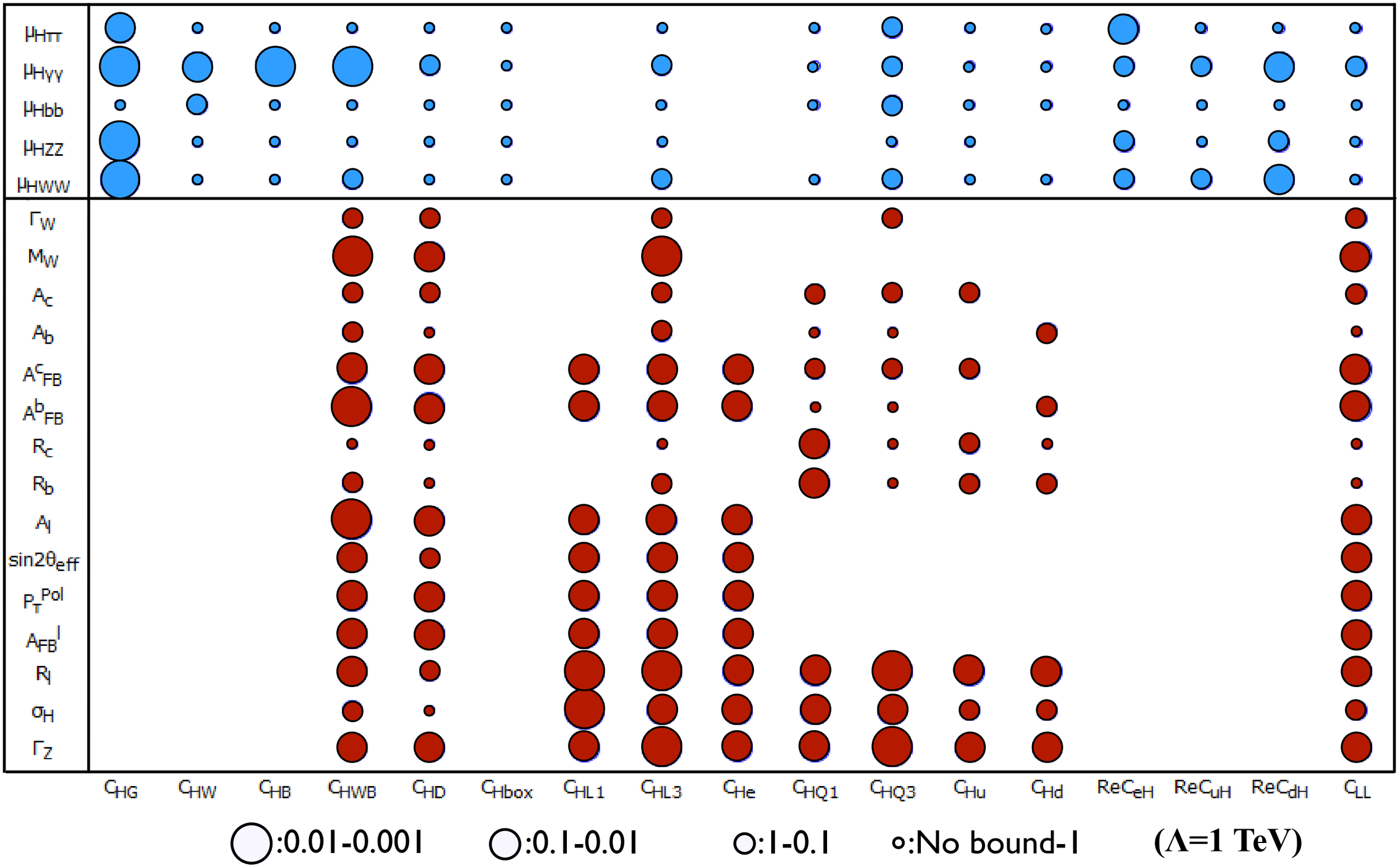




$$(H^\dagger i\overleftrightarrow{D}_\mu H)\,(\overline{d_R}\gamma^\mu d_R)$$

$$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$$

95% prob. Bounds on dim. 6 interactions



95% prob. Bounds on the New Physics scale

Operator		95% prob. bound on Λ [TeV] Only EW $C_i=-1$	Only EW $C_i=1$	Only Higgs $C_i=-1$	Only Higgs $C_i=1$	EW + Higgs $C_i=-1$	EW + Higgs $C_i=1$
$\mathcal{O}_{HG}$	$\left(H^\dagger H\right) G^A_{\mu\nu} G^{A\,\mu\nu}$	—	—	14.1	10.4	14.1	10.4
$\mathcal{O}_{HW}$	$\left(H^\dagger H\right) W^a_{\mu\nu} W^{a\,\mu\nu}$	—	—	5.5	8.4	5.5	8.4
$\mathcal{O}_{HB}$	$\left(H^\dagger H\right) B_{\mu\nu} B^{\mu\nu}$	—	—	10.7	15.7	10.7	15.7
$\mathcal{O}_{HWB}$	$\left(H^\dagger \sigma_a H\right) W^a_{\mu\nu} B^{\mu\nu}$	9.8	15.1	11.3	7.7	11.7	13.7
$\mathcal{O}_{HD}$	$\left\lvert H^\dagger D_\mu H\right\rvert^2$	5.6	14.1	0.9	0.8	5.6	14.0
$\mathcal{O}_{H\Box}$	$\left(H^\dagger H\right) \Box \left(H^\dagger H\right)$	—	—	0.8	0.9	0.8	0.9
$\mathcal{O}^{(1)}_{Hl}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right) \left(\overline{l_L}\gamma^\mu l_L\right)$	14.1	9.3	—	—	14.1	9.3
$\mathcal{O}^{(3)}_{Hl}$	$\left(H^\dagger i\overleftrightarrow{D}^a_\mu H\right) \left(\overline{l_L}\gamma^\mu \sigma_a l_L\right)$	9.3	12.8	1.5	1.2	9.3	12.7
$\mathcal{O}_{He}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right) \left(\overline{e_R}\gamma^\mu e_R\right)$	7.7	13.6	—	—	7.7	13.6
$\mathcal{O}^{(1)}_{Hq}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right) \left(\overline{q_L}\gamma^\mu q_L\right)$	6.0	5.0	0.7	0.3	6.0	5.0
$\mathcal{O}^{(3)}_{Hq}$	$\left(H^\dagger i\overleftrightarrow{D}^a_\mu H\right) \left(\overline{q_L}\gamma^\mu \sigma_a q_L\right)$	9.4	8.7	1.5	4.4	9.2	8.9
$\mathcal{O}_{Hu}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right) \left(\overline{u_R}\gamma^\mu u_R\right)$	3.8	3.6	0.5	1.1	3.7	3.6
$\mathcal{O}_{Hd}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right) \left(\overline{d_R}\gamma^\mu d_R\right)$	2.7	4.0	0.6	0.3	2.7	4.0
$\mathcal{O}_{eH}$	$\left(H^\dagger H\right) \left(\overline{l_L} H e_R\right)$	—	—	6.0	4.5	6.0	4.5
$\mathcal{O}_{uH}$	$\left(H^\dagger H\right) \left(\overline{q_L} \tilde{H} u_R\right)$	—	—	1.3	1.7	1.3	1.7
$\mathcal{O}_{dH}$	$\left(H^\dagger H\right) \left(\overline{q_L} H d_R\right)$	—	—	4.0	4.1	4.0	4.1
$\mathcal{O}_{ll}$	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	10.0	6.8	0.9	1.0	10.0	6.8

1 operator at a time

Preliminary Results

Conclusions

- Indirect searches are as relevant as ever after the Higgs discovery:
  - No hint of the possible nature of new physics

    Focus on model-independent analyses ⇒ Effective Lagrangians

- EWPO + Higgs signal strengths (final Run I data) can already test a large set of dimension 6 effective Lagrangian interactions:

  - Bounds on the NP scale in many cases beyond the LHC reach for $|C_i| \sim 1$. Still accesible for small C_i.

  - Complementarity between EWPD & Higgs observables:

    - Higgs data sensitive to interactions not seen by EWPD

    - For the others, EWPD bounds usually dominate over the 8 TeV Higgs bounds

- Observables and dim 6 SM EFT included within the framework of the **HEPfit** project