Constraints on anomalous Higgs boson couplings and EFT with the CMS experiment

Lourdes Urda

CIEMAT

on behalf of the CMS Collaboration

November 8th, 2022
Motivation

10 years studying the Higgs boson
Run 1 → LHC data compatible with an SM H(125) of spin 0 and even CP
Run 2 → Precision era for Higgs physics +

JCP studies:
- Coupling to bosons
- Coupling to fermions

CP is a property of the interaction
&
Matter asymmetry
CP-violating baryon-generating interaction

Search for Higgs Anomalous Couplings (AC) to bosons and fermions
Higgs AC to bosons | HVV parametrization

\[
A(HVV) \sim \left[ a_{VV} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{(\Lambda_1^{VV})^2} \right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_{VV}^{WW} f_{\mu \nu}^{(1)} f_{\mu \nu}^{(2)} + a_{VV}^{Z \gamma} \tilde{f}_{\mu \nu}^{(1)} \tilde{f}_{\mu \nu}^{(2)}
\]

If \(VV = WW, ZZ, Z\gamma\) \(\rightarrow\) Tree-level SM

If \(VV = gg\) \(\rightarrow\) 1-loop SM

\[
A_{VV}^{WW} = a_{VV}^{WW} = a_{VV}^{ZZ} = a_{VV}^{Z \gamma} = a_{VV}^{Z \gamma}
\]

4 anomalous couplings:
- \(a_2\) (CP)
- \(a_3\) (CP)
- \(a_{A_1}\) (CP)
- \(a_{A_1}^{Z \gamma}\) (CP)

\[
a_{VV}^{WW} \neq a_{VV}^{ZW}
\]

3 anomalous couplings:
- \(a_2\) (CP)
- \(a_3\) (CP)
- \(a_{A_1}\) (CP)

If \(VV = gg\) \(\rightarrow\) 1 AC: \(a_3\) (CP)

1. Amplitude parametrization can be related to the Higgs basis EFT.

2. Cross-section fraction:

\[
f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_{j=1,2,3...} |a_j|^2 \sigma_j} \text{sign} \left( \frac{a_i}{a_1} \right)
\]
Higgs AC to fermions \( \mid \) Hff parametrization

\[
A(Hff) = -\frac{m_f}{v} \bar{\psi}_f \left( \kappa_f + i\bar{\kappa}_f \gamma_5 \right) \psi_f
\]

SM-like \( \rightarrow \) Anomalous contribution

AC approach/SMEFT approach

1 Anomalous coupling:
\( \bar{\kappa}_f : \mathbb{CP} \)

Cross-section fraction:

\[
f^{Hff}_{\text{CP}} = \frac{|\bar{\kappa}_f|^2}{|\kappa_f|^2 + |\bar{\kappa}_f|^2} \text{sign} \left( \frac{\bar{\kappa}_f}{\kappa_f} \right)
\]

\( \kappa_f \) and \( \bar{\kappa}_f \) are Yukawa coupling strength modifiers related to the mixing angle \( \alpha^{Hff} = \tan^{-1} \left( \frac{\bar{\kappa}_f}{\kappa_f} \right) \)
Higgs couplings analyses with the CMS experiment

Since 2021:

<table>
<thead>
<tr>
<th>CMS Analysis</th>
<th>Channel</th>
<th>Measurement</th>
<th>Combined with</th>
<th>REF</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIG-19-009</td>
<td>on-Shell $H \rightarrow ZZ$</td>
<td>HVV, Hgg, Htt</td>
<td>[Htt] $H \rightarrow \gamma\gamma$ (HIG-19-013)</td>
<td>PRD 104 (2021) 052004</td>
</tr>
<tr>
<td>HIG-21-013</td>
<td>off-Shell $H \rightarrow ZZ$</td>
<td>HVV</td>
<td>on-Shell $H \rightarrow ZZ$</td>
<td>NP (2022) 01682</td>
</tr>
<tr>
<td>HIG-20-007</td>
<td>$H \rightarrow \tau\tau$</td>
<td>HVV, Hgg, Htt</td>
<td>on-Shell $H \rightarrow ZZ + H \rightarrow \gamma\gamma$</td>
<td>arXiv:2205.05120 (PRD)</td>
</tr>
<tr>
<td>HIG-21-006</td>
<td>ttH and tH</td>
<td>Htt</td>
<td>on-Shell $H \rightarrow ZZ + H \rightarrow \gamma\gamma$</td>
<td>arXiv:2208.02686 (sub)</td>
</tr>
<tr>
<td>HIG-20-006</td>
<td>$H \rightarrow \tau\tau$</td>
<td>$H\tau\tau$</td>
<td>-</td>
<td>JHEP 06 (2022) 012</td>
</tr>
</tbody>
</table>
Higgs couplings analyses with the CMS experiment

Since 2021:

<table>
<thead>
<tr>
<th>CMS Analysis</th>
<th>Channel</th>
<th>Measurement</th>
<th>Combined with</th>
<th>REF</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIG-19-009</td>
<td>on-Shell $H \rightarrow ZZ$</td>
<td>$HVV, Hgg, Htt$</td>
<td>$[Htt] \rightarrow \gamma\gamma$ (HIG-19-013)</td>
<td>PRD 104 (2021) 052004</td>
</tr>
<tr>
<td>HIG-21-013</td>
<td>off-Shell $H \rightarrow ZZ$</td>
<td>$HVV$</td>
<td>on-Shell $H \rightarrow ZZ$</td>
<td>NP (2022) 01682</td>
</tr>
<tr>
<td>HIG-20-007</td>
<td>$H \rightarrow \tau\tau$</td>
<td>$HVV, Hgg, Htt$</td>
<td>on-Shell $H \rightarrow ZZ + H \rightarrow \gamma\gamma$</td>
<td>arXiv:2205.05120 (PRD)</td>
</tr>
<tr>
<td>HIG-21-006</td>
<td>ttH and tH</td>
<td>$Htt$</td>
<td>on-Shell $H \rightarrow ZZ + H \rightarrow \gamma\gamma$</td>
<td>arXiv:2208.02686 (sub)</td>
</tr>
<tr>
<td>HIG-20-006</td>
<td>$H \rightarrow \tau\tau$</td>
<td>$H\tau\tau$</td>
<td>-</td>
<td>JHEP 06 (2022) 012</td>
</tr>
</tbody>
</table>

“Constraints on anomalous Higgs boson couplings to vector bosons and fermions in its production and decay using the four-lepton final state”
Dedicated measurements (detector-level)
- Exploit full production and decay kinematic information with MELA-based discriminants.

\[
D_{\text{alt}}(\Omega) = \frac{P_{\text{sig}}(\Omega)}{P_{\text{sig}}(\Omega) + P_{\text{alt}}(\Omega)}
\]

\[
D_{\text{int}}(\Omega) = \frac{P_{\text{int}}(\Omega)}{2 \sqrt{P_{\text{sig}}(\Omega) P_{\text{alt}}(\Omega)}}
\]

Multi-dimensional analysis:
- Several parameters are simultaneously extracted.

Channels: 4\ell (4e, 4\mu, 2e2\mu)
Productions: ggH, VBF, VH, ttH.
**H → ZZ Results | HVV (AC approach)**

- **Fix**: Other couplings are fixed to the SM expectation.
- **Float**: Other couplings are profiled in the fit

**VBF & VH & H → 4ℓ**

fa₁ and fa₁Zγ scans are also available

Notice we can also perform fa₃, fa₂, and fa₁ scans in the SMEFT approach
HVV parametrization can be related to the EFT couplings using the Higgs basis.

+ Results on Warsaw Basis

\[
\delta c_z = \frac{1}{2} a_1 - 1 \\
c_{zz} = -\frac{s_w^2 c_w^2}{2\pi\alpha} a_2 \\
c_{z\square} = \frac{m_Z^2 s_w^2}{4\pi\alpha} \frac{\kappa_1}{(\Lambda_1)^2} \\
\tilde{c}_{zz} = -\frac{s_w^2 c_w^2}{2\pi\alpha} a_3
\]
Since 2021:

<table>
<thead>
<tr>
<th>CMS Analysis</th>
<th>Channel</th>
<th>Measurement</th>
<th>Combined with</th>
<th>REF</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIG-21-013</td>
<td>off-Shell H → ZZ</td>
<td>HVV</td>
<td>on-Shell H→ZZ</td>
<td>NP (2022) 01682</td>
</tr>
<tr>
<td>HIG-20-007</td>
<td>H → ττ</td>
<td>HVV, Hgg, Htt</td>
<td>on-Shell H→ZZ + H→γγ</td>
<td>arXiv:2205.05120 (PRD)</td>
</tr>
<tr>
<td>HIG-21-006</td>
<td>ttH and tH</td>
<td>Htt</td>
<td>on-Shell H→ZZ + H→γγ</td>
<td>arXiv:2208.02686 (sub)</td>
</tr>
<tr>
<td>HIG-20-006</td>
<td>H→ττ</td>
<td>Hττ</td>
<td>-</td>
<td>JHEP 06 (2022) 012</td>
</tr>
</tbody>
</table>

“Measurement of the Higgs boson width and evidence of its off-shell contributions to ZZ production”
Off-Shell H$\rightarrow$ZZ analysis

Channels: $2\ell 2\nu/4\ell$
Productions: ggH, VBF, VH.

$m_{ZZ}$ line shape is sensitive to the presence of anomalous HVV

- Could affect the measurement of $\Gamma_{Higgs}$

$$\sigma_{\text{off-Shell}} \propto \sigma_{\text{on-Shell}} \Gamma_{Higgs}$$

$2\ell 2\nu \rightarrow m_{TZZ}>300$ GeV

$4\ell$ events $\rightarrow$ MELA $D^{VBF}_{2j}$ $\rightarrow$ Sensitive to AC HVV.

Combined with:
Run 2 On-Shell $4\ell$ $\rightarrow$ PRD 104 (2021) 052004
2015 On-Shell $4\ell$ $\rightarrow$ Phys. Lett. B 775 (2017) 1
**Off-Shell H → ZZ analysis Results**

- **Combination with on-Shell H → ZZ**

\[ \Gamma_H = 3.2 \ [+2.4, -1.7] \text{ MeV (68\% CL)} \]

\[ \text{Combination} \]

\[ \text{HVV vertex} \]

\[ \text{AC approach} \]
Higgs couplings analyses with the CMS experiment

Since 2021:

<table>
<thead>
<tr>
<th>CMS Analysis</th>
<th>Channel</th>
<th>Measurement</th>
<th>Combined with</th>
<th>REF</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIG-19-009</td>
<td>on-Shell $H \rightarrow ZZ$</td>
<td>HVV, Hgg, Htt</td>
<td>[Htt] $H \rightarrow \gamma \gamma$ (HIG-19-013)</td>
<td>PRD 104 (2021) 052004</td>
</tr>
<tr>
<td>HIG-21-013</td>
<td>off-Shell $H \rightarrow ZZ$</td>
<td>HVV</td>
<td>on-Shell $H \rightarrow ZZ$</td>
<td>NP (2022) 01682</td>
</tr>
<tr>
<td>HIG-20-007</td>
<td>$H \rightarrow \tau \tau$</td>
<td>HVV, Hgg, Htt</td>
<td>on-Shell $H \rightarrow ZZ + H \rightarrow \gamma \gamma$</td>
<td>arXiv:2205.05120 (PRD)</td>
</tr>
<tr>
<td>HIG-21-006</td>
<td>ttH and tH</td>
<td>Htt</td>
<td>on-Shell $H \rightarrow ZZ + H \rightarrow \gamma \gamma$</td>
<td>arXiv:2208.02686 (sub)</td>
</tr>
<tr>
<td>HIG-20-006</td>
<td>$H \rightarrow \tau \tau$</td>
<td>$H \tau \tau$</td>
<td>-</td>
<td>JHEP 06 (2022) 012</td>
</tr>
</tbody>
</table>

“Constraints on anomalous Higgs boson couplings to vector bosons and fermions from the production of Higgs bosons using the $\tau \tau$ final state”
H→ττ analysis

Channels: \( \tau_h \tau_h, \mu \tau_h, e \tau_h, e \mu \)

VBF production analysis → HVV

ggH production analysis → Hgg

Combined to construct 2D and 3D kinematic discriminants
**H → ττ Results | HVV combining with H → ZZ (4ℓ)**

**HVV vertex**

fa_2, fa_{A1} and fa_{A1}Zγ also constrained (in backup)

**Hgg vertex**

+ Combination with H → ττ

The pure CP-odd scenario of the Higgs boson coupling to gluons is excluded at 2.4σ
**H → ττ Results** \| Hff combining with H → ZZ (4ℓ) + ttH (2γ)

**ggH loop is dominated by the top quark**

The combination improves the limits on the anomalous coupling parameters typically by about 20–50%
Higgs couplings analyses with the CMS experiment

Since 2021:

<table>
<thead>
<tr>
<th>CMS Analysis</th>
<th>Channel</th>
<th>Measurement</th>
<th>Combined with</th>
<th>REF</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIG-19-009</td>
<td>on-Shell $H \to ZZ$</td>
<td>HVV, Hgg, Htt</td>
<td>[Htt] $H \to \gamma\gamma$ (HIG-19-013)</td>
<td>PRD 104 (2021) 052004</td>
</tr>
<tr>
<td>HIG-21-013</td>
<td>off-Shell $H \to ZZ$</td>
<td>HVV</td>
<td>on-Shell $H \to ZZ$</td>
<td>NP (2022) 01682</td>
</tr>
<tr>
<td>HIG-20-007</td>
<td>$H \to \tau\tau$</td>
<td>HVV, Hgg, Htt</td>
<td>on-Shell $H \to ZZ + H \to \gamma\gamma$</td>
<td>arXiv:2205.05120 (PRD)</td>
</tr>
<tr>
<td>HIG-21-006</td>
<td>ttH and tH</td>
<td>Htt</td>
<td>on-Shell $H \to ZZ + H \to \gamma\gamma$</td>
<td>arXiv:2208.02686 (sub)</td>
</tr>
<tr>
<td>HIG-20-006</td>
<td>$H \to \tau\tau$</td>
<td>$H\tau\tau$</td>
<td>-</td>
<td>JHEP 06 (2022) 012</td>
</tr>
</tbody>
</table>

“Search for CP violation in ttH and tH production in multilepton channels in proton-proton collisions at $\sqrt{s} = 13$ TeV”
Channels: HWW/Hττ
Productions: ttH & tH

Machine learning techniques:
• BDT $\rightarrow m_{ttH}, \Delta R_{jj}, \Delta \eta$
\[ |f_{CP}^{Htt}| = 0 \text{ (SM expectation)} \]

\[ |f_{CP}^{Htt}| = 0.59 \text{ with an interval of (0.24, 0.81) at 68}\% \text{ CL} \]

Combination: \[ |f_{CP}^{Htt}| = 0.28 \text{ with an interval of } |f_{CP}^{Htt}| < 0.55 \text{ at 68}\% \text{ CL} \]
Since 2021:

<table>
<thead>
<tr>
<th>CMS Analysis</th>
<th>Channel</th>
<th>Measurement</th>
<th>Combined with</th>
<th>REF</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIG-21-013</td>
<td>off-Shell H → ZZ</td>
<td>HVV</td>
<td>on-Shell H→ZZ</td>
<td>NP (2022) 01682</td>
</tr>
<tr>
<td>HIG-20-007</td>
<td>H → ττ</td>
<td>HVV, Hgg, Htt</td>
<td>on-Shell H→ZZ + H→γγ</td>
<td>arXiv:2205.05120 (PRD)</td>
</tr>
<tr>
<td>HIG-21-006</td>
<td>ttH and tH</td>
<td>Htt</td>
<td>on-Shell H→ZZ + H→γγ</td>
<td>arXiv:2208.02686 (sub)</td>
</tr>
<tr>
<td>HIG-20-006</td>
<td>H→ττ</td>
<td>Hττ</td>
<td>-</td>
<td>JHEP 06 (2022) 012</td>
</tr>
</tbody>
</table>

“Analysis of the CP structure of the Yukawa coupling between the Higgs boson and τ leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV”
Higgs coupling to tau leptons

Channels: $\tau_h \tau_h$, $\tau_\mu \tau_h$, $\tau_e \tau_h$

Productions: ggH, VBF, VH

Angular correlation between the decay planes of $\tau$ leptons

- MVA scores
- $\phi_{CP}$ distributions

![Graph showing angular correlation between decay planes of tau leptons with CMS data at 137 fb⁻¹ (13 TeV)]
Higgs coupling to tau leptons

\[ \alpha^{Hff} = \tan^{-1}\left(\frac{\bar{k}_f}{k_f}\right) \]

The data disfavour the pure CP-odd scenario at 3.0\(\sigma\)

Observed (expected) \(\alpha^{H\tau\tau} = -1 \pm 19 \ (0 \pm 21)\) at the 68.3\% CL
• JCP studies in Higgs couplings to both fermions and bosons are important to determine its nature.

• The most stringent limits on CP violation and Higgs AC by the CMS experiment have been presented.

Growing field with many recent updates including new interpretations, and plenty more results to come in the future

• The leading uncertainty is statistical → the precision will increase with the accumulation of more collision data.

  • Additional Run 2 AC analyses are still to be released soon.
Back-up slides
$\kappa_f$ and $\tilde{\kappa}_f$ are Yukawa coupling strength modifiers related to the mixing angle $\alpha^{Hff} = \tan^{-1}\left(\frac{\tilde{\kappa}_f}{\kappa_f}\right)$.
Effective Field Theory

Direct searches at the LHC find no new particles
Suggests an energy gap between SM and BSM motivating the use of EFT.

\[ \mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i c_i^{(6)} O_i^{(6)} \]

- \( O_i^{(5)} \) → violate lepton number
- \( O_i^{(7)} \) → violate lepton or baryon number
- \( O_i^{(8)} \) → Suppressed by \( 1/\Lambda^4 \) → Typically neglected

Particles with \( m << \Lambda \) → Operators \( (O_i) \) obey SM symmetries.

Effects of new physics mapped onto \( O_i^{(6)} \) → contribution scale as \( (E/\Lambda)^2 \)

\( c_i^{(6)} \) (Wilson coefficient) → strength of the new interactions

EFT only valid at \( E < \Lambda \)
Measurement of Higgs couplings

Dedicated measurements (detector-level)

Dedicated discriminants and full simulation of Signal PDFs.

Exploit full production and decay kinematic information with ME or ML-based discriminants.

Sensitive to higher dimensional operators in the EFT

- Can target production mode, Higgs coupling and interference.
H→ττ analysis | Discriminants
## Constraints

<table>
<thead>
<tr>
<th>Approach</th>
<th>Parameter</th>
<th>Observed / (10^{-3})</th>
<th>Expected / (10^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>68% CL</td>
<td>95% CL</td>
</tr>
<tr>
<td>Approach 1</td>
<td>$f_{a3}$</td>
<td>$0.20^{+0.26}_{-0.16}$</td>
<td>$[-0.01, 0.88]$</td>
</tr>
<tr>
<td></td>
<td>$f_{a2}$</td>
<td>$0.7^{+0.8}_{-0.6}$</td>
<td>$[-1.0, 2.5]$</td>
</tr>
<tr>
<td></td>
<td>$f_{A1}$</td>
<td>$-0.04^{+0.04}_{-0.08}$</td>
<td>$[-0.22, 0.16]$</td>
</tr>
<tr>
<td></td>
<td>$f_{Z\gamma}$</td>
<td>$0.7^{+1.6}_{-1.3}$</td>
<td>$[-2.7, 4.1]$</td>
</tr>
<tr>
<td>Approach 2</td>
<td>$f_{a3}$</td>
<td>$0.28^{+0.39}_{-0.23}$</td>
<td>$[-0.01, 1.28]$</td>
</tr>
</tbody>
</table>

### $c_{gg}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scenario</th>
<th>68% CL / (10^{-2})</th>
<th>95% CL / (10^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{gg}$</td>
<td>Profiled</td>
<td>$-0.11^{+0.20}_{-0.26}$</td>
<td>$-1.85$, $-1.42$</td>
</tr>
<tr>
<td></td>
<td>Expected</td>
<td>$0.00^{+0.18}_{-0.27}$</td>
<td>$-1.91$, $-1.48$</td>
</tr>
<tr>
<td>$\tilde{c}_{gg}$</td>
<td>Profiled</td>
<td>$0.00 \pm 1.29$</td>
<td>$-1.79$, $1.79$</td>
</tr>
<tr>
<td>$c_{gg}$</td>
<td>Fixed</td>
<td>$-0.08^{+0.07}_{-0.15}$</td>
<td>$-1.65$, $-1.54$</td>
</tr>
<tr>
<td></td>
<td>Expected</td>
<td>$0.00^{+0.06}_{-0.14}$</td>
<td>$-1.73$, $-1.50$</td>
</tr>
<tr>
<td>$\tilde{c}_{gg}$</td>
<td>Fixed</td>
<td>$0.22^{+0.28}_{-0.22}$</td>
<td>$-0.50$, $0.00$</td>
</tr>
<tr>
<td></td>
<td>Expected</td>
<td>$0.00 \pm 0.45$</td>
<td>$-0.87$, $0.87$</td>
</tr>
</tbody>
</table>
"The parametrization of the amplitude can be related to a fundamental Lagrange density function using the Higgs basis which is based on an effective field theory expansion up to dimension six. The relevant $SU(3) \times SU(2) \times U(1)$ invariant Lagrangian for $H$ boson interactions with gauge bosons"
The generality of the amplitude parametrization allows to uniquely represent each EFT coefficient in the Lagrangian by an anomalous coupling limiting our couplings to real-valued numbers.
$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i c_i^{(6)} \mathcal{O}_i^{(6)}$

**Warsaw basis**

Popular SMEFT basis in the theoretical community

**Higgs basis**

Experimentally convenient to express EFT in terms of mass eigenstates after EWSB

Related to Warsaw basis through linear transformations
HVV parametrization can be related to the **EFT couplings** using the **Warsaw basis**.

---

**TABLE IX.** Summary of constraints on the HVV coupling parameters in the Warsaw basis of SMEFT. For each coupling constraint reported, three other independent operators are left unconstrained, where only one of the three operators $c_{{H\Delta}}$, $c_{{H\Delta B}}$, and $c_{{H\Delta B}}$ is independent, and only one of $c_{{H\Delta W}}$, $c_{{H\Delta W B}}$, and $c_{{H\Delta B}}$ is independent.

<table>
<thead>
<tr>
<th>Channels</th>
<th>Coupling</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF &amp; VH &amp; H → 4ℓ</td>
<td>$c_{{H\Delta}}$</td>
<td>$0.04^{+0.43}_{-0.45}$</td>
<td>$0.00^{+0.75}_{-0.93}$</td>
</tr>
<tr>
<td></td>
<td>$c_{{H\Delta D}}$</td>
<td>$-0.73^{+0.97}_{-4.21}$</td>
<td>$0.00^{+1.06}_{-4.60}$</td>
</tr>
<tr>
<td></td>
<td>$c_{{H\Delta W}}$</td>
<td>$0.01^{+0.18}_{-0.17}$</td>
<td>$0.00^{+0.39}_{-0.28}$</td>
</tr>
<tr>
<td></td>
<td>$c_{{H\Delta W B}}$</td>
<td>$0.01^{+0.20}_{-0.18}$</td>
<td>$0.00^{+0.42}_{-0.31}$</td>
</tr>
<tr>
<td></td>
<td>$c_{{H\Delta B}}$</td>
<td>$0.00^{+0.05}_{-0.05}$</td>
<td>$0.00^{+0.03}_{-0.08}$</td>
</tr>
<tr>
<td></td>
<td>$c_{{H\Delta W}}$</td>
<td>$-0.23^{+0.51}_{-0.52}$</td>
<td>$0.00^{+1.11}_{-1.11}$</td>
</tr>
<tr>
<td></td>
<td>$c_{{H\Delta W B}}$</td>
<td>$-0.25^{+0.56}_{-0.57}$</td>
<td>$0.00^{+1.21}_{-1.21}$</td>
</tr>
<tr>
<td></td>
<td>$c_{{H\Delta B}}$</td>
<td>$-0.06^{+0.15}_{-0.16}$</td>
<td>$0.00^{+0.33}_{-0.33}$</td>
</tr>
</tbody>
</table>
LHC Run 1 $\rightarrow$ Couplings to EW bosons

“Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV”

\[ f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_{j=1,2,3} |a_j|^2 \sigma_j} \text{sign} \left( \frac{a_i}{a_1} \right) \]