Constraints on BSM from the Higgs Sector

Jorge de Blas
University of Granada

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Introduction

- The discovery of the 125 GeV Higgs boson is arguably the major achievement of the LHC (so far)

✓ It finally provides evidence of the last ingredient required to confirm the validity of the SM at low energies...
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  ✓ …but also reminds us of the limitations of the Standard Model…
    ▸ How do we understand the mechanism of EWSB?
    ▸ Hierarchy problem: Why $M_h \ll M_P$ ?
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    - Hierarchy problem: Why \( M_h \ll M_P \)?

\[ \Rightarrow \text{BSM: } \Delta M_h^2 = \text{SM} + \text{New} \sim 0 \]
**Introduction**

- The discovery of the 125 GeV Higgs boson is arguably the major achievement of the LHC (so far)
  - It finally provides evidence of the last ingredient required to confirm the validity of the SM at low energies...

✓ ... and brings up further interesting (related) questions:
  - Is the Higgs an elementary particle or a composite state?
  - How does it interact with itself?
  - What is its role in answering other important questions?
  - Are there more scalars? Pseudo-scalars?
The Higgs connection to BSM

BSM scenarios dealing with these issues tend to:

1. Introduce modifications of the Higgs properties → indirect tests of new physics
2. Introduce new particles in the scalar sector → Direct searches

The LHC is the only current experiment with direct access to both ways of testing the Higgs sector
The Higgs at the LHC

The LHC is the only current experiment with direct access to both ways of testing the Higgs sector (directly and indirectly)

35.9-137 fb⁻¹ (13 TeV)

CMS Preliminary

Observed ±1σ
μ_i combined ±1σ

Limit 95% CL on σ

Signal strengths μ_f

Direct searches (Heavy scalars)

HH production

HH → bbγ

ATLAS Preliminary

√s = 13 TeV, 139 fb⁻¹
HH → bbγ

Observed: κ_A = [-1.5, 6.7]
Expected: κ_A = [-2.4, 7.7]
The Higgs at the LHC

The LHC is the only current experiment with direct access to both ways of testing the Higgs sector (directly and indirectly)

In this talk I will focus on what can we learn about BSM physics from all this information from the LHC after the Run 2, with special emphasis on the implications of the measurements of the properties of the Higgs
Constraints on BSM from Higgs Physics

Model-Independent
Modified Higgs couplings

- Several frameworks have been used to parameterise BSM deformations on Higgs interactions:
  
  ✓ The $\kappa$ framework $\leftarrow$ Used mainly during Run 1
  
  ✓ The EFT framework $\leftarrow$ Being adopted in Run 2 results and for future interpretations
  
  ✓ Two EFTs consistent with the SM particles and symmetries at low energies, differing in the treatment of the scalar sector:
    
    ‣ The non-linear/Higgs EFT (HEFT): EW symmetry non-linearly realised
    
    ‣ The (dimension-6) SMEFT: EW symmetry linearly realised

In short:
- **HEFT** when there are light BSM states (compared to EW scale) or BSM sources of sym. breaking
- **SMEFT** when heavy new states (compared to EW scale)

For a geometrical interpretation of the differences between HEFT and SMEFT
Effective Field Theories: HEFT

- **HEFT**: SM particles and symmetries at low energies, but does not assume relation between the Higgs scalar and the Goldstone bosons of EWSB (non-linear EWSB)

- **Leading order HEFT Lagrangian ($L=0$ in chiral ($\chi$) dimensions)**:

$$\mathcal{L}_{LO} = -\frac{1}{2} \langle G_{\mu\nu} G^{\mu\nu} \rangle - \frac{1}{2} \langle W_{\mu\nu} W^{\mu\nu} \rangle - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + i \bar{q}_L D\!\!\!\!L q_L + i \bar{\ell}_L D\!\!\!\!L \ell_L + i \bar{u}_R D\!\!\!\!U u_R + i \bar{d}_R D\!\!\!\!D d_R + i \bar{e}_R D\!\!\!\!e e_R + \frac{v^2}{4} \langle D_{\mu} U^\dagger D^{\mu} U \rangle (1 + F_U (h)) + \frac{1}{2} \partial_{\mu} h \partial^{\mu} h - V(h) - \frac{v}{\sqrt{2}} \left[ \bar{q}_L Y_u (h) U P + q_R + \bar{\ell}_L Y_d (h) U P - q_R + \bar{\ell}_L Y_e (h) U P - \ell_R + \text{ h.c.} \right]$$

Terms relevant for single-Higgs processes

$$\mathcal{L}_{\text{fit}} = 2c_V \left( m_W^2 W_\mu^+ W^-_{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu \right) \frac{h}{v} - \sum_\psi \frac{c_\psi m_\psi \bar{\psi} \psi h}{v}$$

Modifications of SM couplings (like $\kappa$ framework)

- [bosons]$_\chi = 0$
- $[\psi\psi]_\chi = [\partial]_\chi = [g_{\text{weak}}]_\chi = 1$
- $[\Delta \mathcal{L}]_\chi = 2L + 2$

$$U = \exp(2i \frac{G_a}{v} T_a)$$

$V(h), F_U(h), Y_\psi(h)$ polynomials in $h$
Effective Field Theories: HEFT

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- **Leading order HEFT Lagrangian** ($L=0$ in chiral ($\chi$) dimensions):

\[
\mathcal{L}_{\text{LO}} = -\frac{1}{2} \langle G_{\mu\nu} G^{\mu\nu} \rangle - \frac{1}{2} \langle W_{\mu\nu} W^{\mu\nu} \rangle - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \\
+ i q_L \slashed{D} q_L + i \bar{\ell}_L \slashed{D} \ell_L + i \bar{u}_R \slashed{D} u_R + i \bar{d}_R \slashed{D} d_R + i \bar{e}_R \slashed{D} e_R \\
+ \frac{v^2}{4} \langle D_\mu U^\dagger D^\mu U \rangle (1 + F_U(h)) + \frac{1}{2} \partial_\mu h \partial^\mu h - V(h) \\
- \frac{v}{\sqrt{2}} [\bar{q}_L Y_u(h) U P^+ q_R + \bar{q}_L Y_d(h) U P^- q_R + \bar{\ell}_L Y_e(h) U P^- \ell_R + \text{h.c.}] \]

Terms relevant for single-Higgs processes

\[
\mathcal{L}_{\text{fit}} = 2c_V \left( m_W^2 W^+ W^- + \frac{1}{2} m_Z^2 Z^+ Z^- \right) \frac{h}{v} - \sum_\psi c_\psi m_\psi \bar{\psi} \psi \frac{h}{v} \\
+ \frac{e^2}{16\pi^2} c_\gamma F_{\mu\nu} F^{\mu\nu} \frac{h}{v} + \frac{e^2}{16\pi^2} c_Z Z_{\mu\nu} F^{\mu\nu} \frac{h}{v} + \frac{g_s^2}{16\pi^2} c_g \langle G_{\mu\nu} G^{\mu\nu} \rangle \frac{h}{v},
\]

**Modifications of SM couplings**

(like $\kappa$ framework)

NLO local terms to properly parameterise corr. to SM rad. processes

(Different than $\kappa$ framework)
**Effective Field Theories: HEFT**

- **Fits to LHC Higgs observables:** Run 1 + Run 2 (~36-140 fb⁻¹)

<table>
<thead>
<tr>
<th>Fit result</th>
<th>95% Prob.</th>
<th>Correlations</th>
</tr>
</thead>
<tbody>
<tr>
<td>(c_V)</td>
<td>1.02±0.02</td>
<td>[0.99, 1.06]</td>
</tr>
<tr>
<td>(c_f)</td>
<td>0.96±0.03</td>
<td>[0.89, 1.02]</td>
</tr>
</tbody>
</table>

**Custodial**

<table>
<thead>
<tr>
<th>Fit result</th>
<th>95% Prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(c_V)</td>
<td>1.02±0.04</td>
</tr>
<tr>
<td>(c_g)</td>
<td>0.04±0.05</td>
</tr>
<tr>
<td>(c_\gamma)</td>
<td>0.02±0.14</td>
</tr>
<tr>
<td>(c_{Z\gamma})</td>
<td>0.00 (Fixed)</td>
</tr>
<tr>
<td>(c_t)</td>
<td>0.94±0.06</td>
</tr>
<tr>
<td>(c_b)</td>
<td>0.98±0.09</td>
</tr>
<tr>
<td>(c_\mu)</td>
<td>1.02±0.19</td>
</tr>
<tr>
<td>(c_\tau)</td>
<td>0.93±0.07</td>
</tr>
</tbody>
</table>

**EWPO:**

\[
\begin{align*}
\text{EWPO:} & \quad c_V = 1.02 \pm 0.03 \\
& \quad c_V \in [0.96, 1.08] \quad 95\% \text{ Prob.}
\end{align*}
\]

\[
S = \frac{1}{12\pi} (1 - c_V^2) \log \frac{\Lambda^2}{m_h^2}
\]

\[
T = -\frac{3}{16\pi c_\omega^2} (1 - c_V^2) \log \frac{\Lambda^2}{m_h^2}
\]

\[
\Lambda = -\frac{4\pi v}{\sqrt{1-c_V^2}}
\]

**Effective Field Theories: SMEFT**

- **SMEFT:** SM particles and symmetries at low energies, with *the Higgs scalar in an SU(2)_{L} doublet* + mass gap with new physics (entering at scale \( \Lambda \))

\[
\mathcal{L}_{\text{UV}} \rightarrow \quad \mathcal{L}_{\text{Eff}} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_{d} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_{5} + \frac{1}{\Lambda^{2}} \mathcal{L}_{6} + \cdots
\]

\[
\mathcal{L}_{d} = \sum_{i} C_{i}^{d} \mathcal{O}_{i} \quad \quad [\mathcal{O}_{i}] = d \quad \rightarrow \quad \left( \frac{q}{\Lambda} \right)^{d-4}
\]

- **LO SMEFT Lagrangian** (assuming B & L) \( \Rightarrow \) Dim-6 SMEFT: 2499 operators

---

**Warsaw basis operators (Neglecting flavour)**

<table>
<thead>
<tr>
<th>Operator</th>
<th>Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>((\tau_{\mu} \tau_{\nu}) (\tau_{\mu} \tau_{\nu}))</td>
<td>(O_{a}^{(1)})</td>
</tr>
<tr>
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<td>(O_{b}^{(1)})</td>
</tr>
<tr>
<td>((\tau_{\mu} \tau_{\nu}) (\tau_{\mu} \tau_{\nu}))</td>
<td>(O_{c}^{(1)})</td>
</tr>
<tr>
<td>((\tau_{\mu} \tau_{\nu}) (\tau_{\mu} \tau_{\nu}))</td>
<td>(O_{d}^{(1)})</td>
</tr>
<tr>
<td>((\tau_{\mu} \tau_{\nu}) (\tau_{\mu} \tau_{\nu}))</td>
<td>(O_{e}^{(1)})</td>
</tr>
<tr>
<td>((\tau_{\mu} \tau_{\nu}) (\tau_{\mu} \tau_{\nu}))</td>
<td>(O_{f}^{(1)})</td>
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<td>(O_{g}^{(1)})</td>
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<td>(O_{i}^{(1)})</td>
</tr>
<tr>
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<td>(O_{j}^{(1)})</td>
</tr>
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<td>(O_{n}^{(1)})</td>
</tr>
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<td>(O_{o}^{(1)})</td>
</tr>
<tr>
<td>((\tau_{\mu} \tau_{\nu}) (\tau_{\mu} \tau_{\nu}))</td>
<td>(O_{p}^{(1)})</td>
</tr>
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<td>(O_{q}^{(1)})</td>
</tr>
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<td>(O_{r}^{(1)})</td>
</tr>
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<td>((\tau_{\mu} \tau_{\nu}) (\tau_{\mu} \tau_{\nu}))</td>
<td>(O_{s}^{(1)})</td>
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<td>((\tau_{\mu} \tau_{\nu}) (\tau_{\mu} \tau_{\nu}))</td>
<td>(O_{t}^{(1)})</td>
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**LHCP 2021 - Constraints on BSM from the Higgs sector**

June 10, 2021

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Effective Field Theories: SMEFT

- Many EFT operators entering in Higgs processes at LO
  “Model-independent” only when including ALL contributing operators

- But SMEFT automatically incorporates correlations between Higgs and other processes imposed by gauge invariance + linearly realised EWSB

⇒ Use Global fit to constraint all directions

- Most EFT directions in Higgs processes in a LO EFT fit can be closed by combining Higgs with EWPO and Diboson (e.g. $WW$, $WZ$) observables
**Effective Field Theories: SMEFT**

- **SMEFT fit to EW/Higgs/diBoson:** LHC Run 1 + Run 2 (~36-140 fb⁻¹)

![Plot showing c/Λ² versus c_i for various new physics assumptions]

**New Physics assumptions: CP-even, U(3)⁵**

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Effective Field Theories: SMEFT

• SMEFT fit to EW/Higgs/diBoson/Top


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- Consistent treatment of non-flavour-universal interactions requires combination with flavour observables $\Leftarrow$ None yet
Constraints from Higgs Physics

Specific BSM scenarios
Effective Field Theories: Matching in the SMEFT

- EFT fits provide a useful phenomenological tool to learn from New Physics
Effective Field Theories: Matching in the SMEFT

- EFT fits provide a useful phenomenological tool to learn from New Physics

• Projecting (SM)EFT results to specific scenarios requires matching between the NP model and the EFT

Matching: Wilson coefficients as function of BSM model couplings and masses

Limits on EFT Wilson coefficients  \rightarrow  Limits on BSM
**Effective Field Theories: Matching in the SMEFT**

- EFT fits provide a useful phenomenological tool to learn from New Physics
- Projecting (SM)EFT results to specific scenarios requires matching between the NP model and the EFT

### Matching fully classified at tree-level

<table>
<thead>
<tr>
<th>Irrep</th>
<th>Name</th>
<th>$S$</th>
<th>$S_1$</th>
<th>$S_2$</th>
<th>$\varphi$</th>
<th>$\Xi$</th>
<th>$\Xi_1$</th>
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<table>
<thead>
<tr>
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<th>$\omega_2$</th>
<th>$\omega_4$</th>
<th>$\Pi_1$</th>
<th>$\Pi_7$</th>
<th>$\zeta$</th>
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<table>
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<th>Irrep</th>
<th>Name</th>
<th>$\Omega_1$</th>
<th>$\Omega_2$</th>
<th>$\Omega_4$</th>
<th>$\Upsilon$</th>
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**19 scalars bosons**

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<tr>
<th>Irrep</th>
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<th>$W$</th>
<th>$W_1$</th>
<th>$G$</th>
<th>$G_1$</th>
<th>$H$</th>
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<thead>
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<th>$U_2$</th>
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<th>$Q_5$</th>
<th>$X$</th>
<th>$Y_1$</th>
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**16 vector bosons**

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<th>Irrep</th>
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<th>$N$</th>
<th>$E$</th>
<th>$\Delta_1$</th>
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<th>$\Sigma$</th>
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<table>
<thead>
<tr>
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<th>Name</th>
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<th>$D$</th>
<th>$Q_1$</th>
<th>$Q_5$</th>
<th>$Q_7$</th>
<th>$T_1$</th>
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<td>$(3,3)_{-\frac{1}{2}}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**13 vector-like fermions**

**The full UV/IR tree-level dictionary:**

48 multiplets contribute to dim 6

\[ \mathcal{L}_{d=6}^{\text{Eff}} \]

~30 pages


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23
Effective Field Theories: Matching in the SMEFT

- EFT limits on simple BSM extensions contribution at tree-level to dimension 6:

<table>
<thead>
<tr>
<th>Description</th>
<th>Mass limits (in TeV)</th>
</tr>
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<tbody>
<tr>
<td>Neutrino singlet</td>
<td>$</td>
</tr>
<tr>
<td>Charged vector triplet</td>
<td>$</td>
</tr>
<tr>
<td>Neutral scalar triplet</td>
<td>$\kappa_N^2 &lt; 1.1 \times 10^{-2}$ (TeV$^2$)</td>
</tr>
<tr>
<td>Charged scalar singlet</td>
<td>$</td>
</tr>
<tr>
<td>Top singlet</td>
<td>$(s_t)^2 &lt; 0.04$</td>
</tr>
<tr>
<td>Neutral scalar singlet</td>
<td>$\kappa_S^2 &lt; 1.7$ (TeV$^2$)</td>
</tr>
<tr>
<td>Exotic lepton doublet</td>
<td>$</td>
</tr>
<tr>
<td>Exotic quark doublet</td>
<td>$</td>
</tr>
<tr>
<td>Lepton triplet</td>
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<tr>
<td>“Up-type” triplet</td>
<td>$</td>
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<tr>
<td>Charged lepton singlet</td>
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</tr>
<tr>
<td>Up-quark singlet</td>
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</tr>
<tr>
<td>Scalar doublet</td>
<td>$Z_u \cos \beta &lt; 0.995$</td>
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<tr>
<td>Quark bi-doublet</td>
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<tr>
<td>Exotic quark doublet</td>
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<tr>
<td>Down-quark singlet</td>
<td>$</td>
</tr>
<tr>
<td>Custodial vector pair</td>
<td>$\bar{\theta}_B B_1 &lt; 0.92$</td>
</tr>
<tr>
<td>Charged vector singlet</td>
<td>$</td>
</tr>
<tr>
<td>“Down-type” triplet</td>
<td>$</td>
</tr>
<tr>
<td>Lepton triplet</td>
<td>$</td>
</tr>
<tr>
<td>Lepton doublet</td>
<td>$</td>
</tr>
</tbody>
</table>

Classical “Higgs” BSM scenarios

- Well-motivated BSM scenarios designed to address specific issues of the SM. In particular,
  - Naturalness models: to solve or ameliorate the hierarchy problem, e.g.
    - SUSY
    - Composite Higgs scenarios
    - Neutral Naturalness models
    - Relaxion, …
  - These typically induce sizeable modifications of the Higgs couplings…
  - … and involve extensions of the scalar sector, e.g.
    - SUSY $\rightarrow$ Two Higgs Doublet Models
    - Models with axion-like particles

- In what follows we go over a few of these scenarios and summarise some implications of current LHC Higgs measurements
**Composite Higgs Models**

- The Higgs is a resonance of some strong dynamics not far from the TeV
  ✓ Dynamical explanation of strong dynamics scale $m_*$ (as in QCD)
  ✓ Motivated as solutions to the hierarchy problem

- Strongly Interacting Light Higgs (SILH) scenario: Strong dynamics, characterised by a single mass scale $m_*$ and coupling $g_*$, generates a $H$ doublet with same quantum numbers as the SM one (pNGB or accidentally light)
  ✓ Leading effects in Higgs couplings

\[
\Delta \mathcal{L}_{\text{SILH}} = \frac{g_\phi^2}{2m_*^2} C_\phi \partial_\mu (\phi^\dagger \phi) \partial^\mu (\phi^\dagger \phi) + \frac{g_y^2}{m_*^2} C_y \sum y_{\psi} \bar{\psi}_L \phi \psi_R (\phi^\dagger \phi) \\
+ \frac{g_\gamma^2 g_y^2}{16\pi^2 m_*^2} C_g (\phi^\dagger \phi) G_{\mu \nu}^A G^{A \mu \nu} + \frac{g_y^2 g_B^2}{16\pi^2 m_*^2} C_\gamma (\phi^\dagger \phi) B_{\mu \nu} B^{\mu \nu}
\]

**Modifications of Higgs couplings**

\[
c_V = 1 - \frac{C_\phi}{2} \xi, \quad c_f = 1 - (\frac{C_\phi}{2} + C_y) \xi, \quad c_g = 2 C_g \xi, \quad c_\gamma = C_\gamma \xi
\]

\[
\xi \equiv \frac{g_\phi^2 v^2}{m_*^2} \equiv \frac{v^2}{f^2} \quad C_{\phi, y, g, \gamma} \sim O(1)
\]
Composite Higgs Models

- 95% probability bounds from Higgs physics on generic SILH scenarios:

| Scenario   | $C_\phi$ | $C_y$ | $|C_g|$ | $|C_\gamma|$ | $\xi_{95\%}$ | $f_{95\%}$ [GeV] |
|------------|---------|-------|--------|--------------|-------------|-----------------|
| SILH1a     | 1       | 0     | 0      | 0            | 0.049       | 1107            |
| SILH1b     | 1       | 1     | 0      | 0            | 0.054       | 1057            |
| SILH2a     | 1       | 0     | 1      | 1            | 0.029       | 1433            |
| SILH2b     | 1       | 1     | 1      | 1            | 0.039       | 1253            |


- Reproduces well limits from minimal CH models based on SO(5)/SO(4):

$$c_V = \sqrt{1 - \xi}, \quad c_f^{(4)} = \sqrt{1 - \xi}, \quad c_f^{(5)} = \frac{1 - 2\xi}{\sqrt{1 - \xi}}$$

Fermion couplings depending on SO(5) irrep (here 4 or 5)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$\xi_{95%}$</th>
<th>$f_{95%}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min CH-4</td>
<td>0.049</td>
<td>1117</td>
</tr>
<tr>
<td>Min CH-5</td>
<td>0.053</td>
<td>1067</td>
</tr>
</tbody>
</table>

Neutral Naturalness

- SM comes with a Twin: Higgs sector invariant under a global $U(4)$ symmetry

$$H = \left( \begin{array}{c} h_A \\ h_B \end{array} \right) = \left( f + \frac{\sigma}{\sqrt{2}} \right) e^{i \frac{\sqrt{2} m_{T_2}}{f} \phi}$$

$$V(H) = -m^2 |H|^2 + \lambda |H|^4 + \delta (|h_A|^4 + |h_B|^4)$$

$U(4)$ symmetric

$\langle H \rangle$ breaks $U(4) \to U(3)$

1 radial mode + 7 Goldstones

3 Long. $W, Z$ / 3 Long. $W_{\text{Twin}}, Z_{\text{Twin}}$

1 light scalar $\leftarrow$ 125 GeV Higgs (pNGB)

- Higgs mass protected by approximate global symmetries:
  
  ✓ Higgs is a pNGB: Mixture of SM Higgs and Twin Higgs
  
  ✓ Symmetry also broken by Yukawas but $Z_2$ protects $H$ mass

$$\Delta \mathcal{L}_{\text{Yuk}} = y_t h_A Q_A U_A + y_t h_B Q_B U_B \to y_t h Q_A U_A + y_t \left( f - \frac{|h|^2}{2f} \right) Q_B U_B$$

Top divergences cancelled by non-coloured states $\Rightarrow$ Neutral naturalness

Z. Chacko
Neutral Naturalness

- SM comes with a Twin: Higgs sector invariant under a global U(4) symmetry

\[ H = \left( \begin{array}{c} h_A \\ h_B \end{array} \right) = \left( f + \frac{\sigma}{\sqrt{2}} \right) e^{i\frac{2\pi a T_3}{f}} \Phi \]

\[ V(H) = -m^2 |H|^2 + \lambda |H|^4 + \delta (|h_A|^4 + |h_B|^4) \]

\( \text{U(4) symmetric} \)

\(<H> \text{ breaks } U(4) \rightarrow U(3) \)

1 radial mode + 7 Goldstones

3 Long. W,Z / 3 Long. WTwin,ZTwin

1 light scalar \( \leftarrow \) 125 GeV Higgs (pNGB)

- Higgs mass protected by approximate global symmetries:

  ✓ Higgs is a pNGB: Mixture of SM Higgs and Twin Higgs

  ✓ Exotic decays and deviations in Higgs couplings

  Model dependent: depend on what is the lightest Twin particle
  
  Generically, invisible decays and displaced leptons or jets

  Current best constraint on invisible h decays: ATLAS Run 2 (ATLAS-CONF-2020-027)
  
  \( \text{Br}(h \rightarrow \text{inv.}) < 0.09 \) at 95% prob.
  
  From Higgs coupling fits, assuming \( c_V < 1 \)

See also A. Albert’s talk
Neutral Naturalness

- SM comes with a Twin: Higgs sector invariant under a global U(4) symmetry
  \[ H = \left( \begin{array}{c} h_A \\ h_B \end{array} \right) = \left( f + \frac{\sigma}{\sqrt{2}} \right) e^{i\frac{\sqrt{2}m_A T_3}{f}} \Phi \]
  \[ V(H) = -m^2 |H|^2 + \lambda |H|^4 + \delta \left( |h_A|^4 + |h_B|^4 \right) \]
  \begin{itemize}
  \item U(4) symmetric
  \item <H> breaks U(4) \rightarrow U(3)
  \item 1 radial mode + 7 Goldstones
  \item 3 Long. W, Z / 3 Long. \( W_{\text{Twin}}, Z_{\text{Twin}} \)
  \item 1 light scalar \( \leftarrow 125 \text{ GeV} \) Higgs (pNGB)
  \end{itemize}

- Higgs mass protected by approximate global symmetries:
  \begin{itemize}
  \item \( \checkmark \) Higgs is a pNGB: Mixture of SM Higgs and Twin Higgs
  \item \( \checkmark \) Exotic decays and deviations in Higgs couplings
  \end{itemize}

Exotic decays and deviations in Higgs couplings

Generically, universal O(1) deviations in \( h \) couplings, unless tuned

\[ \Delta L_{\text{EFT}} = \frac{1}{2f^2} C_\phi \partial_\mu (\phi^\dagger \phi) \partial^\mu (\phi^\dagger \phi) + \ldots \]

\[ C_\phi = \frac{1}{2} - 8\delta \frac{f^2}{m_s^2} \]

Tuning: \( \xi^{-1} \equiv \frac{f^2}{v^2} \)

From current LHC Higgs measurements (for \( \delta \ll 1 \))

\[ \xi \lesssim 0.108 \quad \text{at 95\% probability} \]
Two-Higgs Doublet Models

- THDM (with softly broken $Z_2$ symmetry):

Scalar Sector
\[
\Phi_i = \left( \frac{\phi^+_i}{v_i + \phi^0_i + iG_i} \right)_{\sqrt{2}}
\]
\[
\Phi^+_1 = c_\beta G^+ - s_\beta H^+,
\]
\[
\Phi^+_2 = s_\beta G^+ + c_\beta H^+,
\]
\[
\Phi^0 = \frac{1}{\sqrt{2}} [v_1 + c_\beta H - s_\beta h + i c_\beta G - i s_\beta A]
\]
\[
\Phi^0_2 = \frac{1}{\sqrt{2}} [v_2 + s_\beta H + c_\beta h + i s_\beta G + i c_\beta A]
\]

Yukawa interactions
\[
\mathcal{L}_Y = -Y_{11}^L \bar{q}_L \phi^0_2 \Phi^+ R - Y_{1,2}^L \bar{q}_L \phi^0_1 \Phi^+ R - Y_{1,2}^R \bar{q}_R \Phi^0 \Phi^+ R - Y_{1,2} \bar{q}_L \Phi^0_1 \Phi^+ R + h.c.
\]

<table>
<thead>
<tr>
<th>Type I</th>
<th>Type II</th>
<th>Type X (&quot;lepton specific&quot;)</th>
<th>Type Y (&quot;flipped&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y_{11} = Y_{12} = 0$</td>
<td>$Y_{12} = 0$</td>
<td>$Y_{12} = 0$</td>
<td>$Y_{12} = 0$</td>
</tr>
<tr>
<td>$Y_{1,2} = Y_{12} \sin \beta$</td>
<td>$Y_{1,2} = Y_{12} \cos \beta$</td>
<td>$Y_{1,2} = Y_{12} \sin \beta$</td>
<td>$Y_{1,2} = Y_{12} \sin \beta$</td>
</tr>
<tr>
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<td>$Y_{1,2} = Y_{12} \sin \beta$</td>
<td>$Y_{1,2} = Y_{12} \sin \beta$</td>
</tr>
</tbody>
</table>

Experimental constraints

\( \Phi_i = \left( \frac{\phi_i^+}{\nu + \phi_i^0 + G_i} \right) \)

\( t_\beta \equiv \tan \beta \equiv \frac{v_2}{v_1} \)

### Model Setup

Table 2 ranges and associated error correlation matrix are listed in Tab.

\[ \lambda \alpha \lambda \]

\[ \beta \lambda \]

In particular, we constrain the \( B_{\alpha} \)s, \( \lambda_{\beta} \)

### Impact of the various sets of constraints on the

Yukawa interactions

\[ Y_{\beta,1} Q \Phi_1 b, Y_{\beta,2} Q \Phi_2 b, Y_{\tau,1} L \Phi_1 \tau_R, Y_{\tau,2} L \Phi_2 \tau_R + h.c. \]

Type II

Type X ("lepton specific")

Type Y ("flipped")

<table>
<thead>
<tr>
<th>Channel</th>
<th>Experiment</th>
<th>Mass range [GeV]</th>
<th>( \mathcal{L} ) [fb(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( pp \to H/A \to bb )</td>
<td>CMS</td>
<td>75</td>
<td>0.55±1.2</td>
</tr>
<tr>
<td>( gg \to H/A \to \tau\tau )</td>
<td>ATLAS</td>
<td>76</td>
<td>0.2±2.25</td>
</tr>
<tr>
<td></td>
<td>CMS</td>
<td>77</td>
<td>0.09±3.2</td>
</tr>
<tr>
<td>( bb \to H/A \to \tau\tau )</td>
<td>ATLAS</td>
<td>76</td>
<td>0.2±2.25</td>
</tr>
<tr>
<td></td>
<td>CMS</td>
<td>77</td>
<td>0.09±3.2</td>
</tr>
<tr>
<td>( pp \to H/A \to \gamma\gamma )</td>
<td>ATLAS</td>
<td>78</td>
<td>0.2±2.7</td>
</tr>
<tr>
<td>( gg \to H/A \to \gamma\gamma )</td>
<td>CMS</td>
<td>79</td>
<td>0.5±4</td>
</tr>
<tr>
<td>( gg \to H/A \to Z\gamma )</td>
<td>ATLAS</td>
<td>85</td>
<td>0.25±2.4</td>
</tr>
<tr>
<td>( gg \to H/A \to Z\gamma )</td>
<td>CMS</td>
<td>86</td>
<td>0.4±3.4</td>
</tr>
<tr>
<td>( gg \to H/A \to Z\gamma \to (\ell\ell)(\ell\ell) )</td>
<td>ATLAS</td>
<td>85</td>
<td>0.2±1.2</td>
</tr>
<tr>
<td>( VV \to H/A \to Z\gamma \to (\ell\ell)(\ell\ell) )</td>
<td>ATLAS</td>
<td>85</td>
<td>0.2±1.2</td>
</tr>
<tr>
<td>( pp \to H/A \to Z\gamma \to (\ell\ell)(\ell\ell) )</td>
<td>CMS</td>
<td>85</td>
<td>0.6±2.5</td>
</tr>
<tr>
<td>( gg \to H/A \to Z\gamma \to (\ell\ell)(\ell\ell) )</td>
<td>CMS</td>
<td>85</td>
<td>0.2±2.6</td>
</tr>
<tr>
<td>( VV \to H/A \to Z\gamma \to (\ell\ell)(\ell\ell) )</td>
<td>CMS</td>
<td>85</td>
<td>0.2±2.6</td>
</tr>
<tr>
<td>( VV \to H/A \to Z\gamma \to (\ell\ell)(\ell\ell) )</td>
<td>CMS</td>
<td>85</td>
<td>0.2±2.6</td>
</tr>
<tr>
<td>( (V+VH) \to H \to ZZ \to (\ell\ell)(\ell\ell) )</td>
<td>CMS</td>
<td>84</td>
<td>0.13±2.5</td>
</tr>
<tr>
<td>( pp \to H/A \to ZZ \to (\ell\ell)(\ell\ell) )</td>
<td>CMS</td>
<td>85</td>
<td>0.5±2</td>
</tr>
<tr>
<td>( gg \to H/A \to ZZ \to (\ell\ell)(\ell\ell) )</td>
<td>CMS</td>
<td>85</td>
<td>0.5±2</td>
</tr>
<tr>
<td>( VV \to H/A \to ZZ \to (\ell\ell)(\ell\ell) )</td>
<td>CMS</td>
<td>85</td>
<td>0.5±2</td>
</tr>
<tr>
<td>( gg \to H/A \to WW \to (\mu\nu)(\mu\nu) )</td>
<td>ATLAS</td>
<td>87</td>
<td>0.25±4</td>
</tr>
<tr>
<td>( VV \to H/A \to WW \to (\mu\nu)(\mu\nu) )</td>
<td>ATLAS</td>
<td>87</td>
<td>0.25±4</td>
</tr>
<tr>
<td>( (gg+VV) \to H \to WW \to (\mu\nu)(\mu\nu) )</td>
<td>CMS</td>
<td>85</td>
<td>0.2±1.2</td>
</tr>
<tr>
<td>( gg \to H/A \to WW \to (\mu\nu)(\mu\nu) )</td>
<td>ATLAS</td>
<td>89</td>
<td>0.3±3</td>
</tr>
<tr>
<td>( VV \to H/A \to WW \to (\mu\nu)(\mu\nu) )</td>
<td>ATLAS</td>
<td>89</td>
<td>0.3±3</td>
</tr>
<tr>
<td>( pp \to H/A \to WW \to (\mu\nu)(\mu\nu) )</td>
<td>ATLAS</td>
<td>89</td>
<td>0.3±3</td>
</tr>
<tr>
<td>( pp \to H/A \to hh \to (bb)(bb) )</td>
<td>ATLAS</td>
<td>91</td>
<td>0.3±3</td>
</tr>
<tr>
<td>( pp \to H/A \to hh \to (bb)(bb) )</td>
<td>CMS</td>
<td>92</td>
<td>0.26±1</td>
</tr>
<tr>
<td>( pp \to H/A \to hh \to (bb)(bb) )</td>
<td>CMS</td>
<td>93</td>
<td>0.26±1.2</td>
</tr>
<tr>
<td>( pp \to H/A \to hh \to (bb)(\gamma) )</td>
<td>ATLAS</td>
<td>94</td>
<td>0.275±0.4</td>
</tr>
<tr>
<td>( pp \to H/A \to hh \to (bb)(\gamma) )</td>
<td>CMS</td>
<td>95</td>
<td>0.25±0.9</td>
</tr>
<tr>
<td>( pp \to H/A \to hh \to (bb)(\tau\tau) )</td>
<td>CMS</td>
<td>96</td>
<td>0.25±0.9</td>
</tr>
<tr>
<td>( pp \to H/A \to hh \to (bb)(\gamma)V )</td>
<td>ATLAS</td>
<td>97</td>
<td>0.26±0.9</td>
</tr>
<tr>
<td>( gg \to H/A \to hh \to (\gamma\gamma)(W) )</td>
<td>ATLAS</td>
<td>98</td>
<td>0.25±0.5</td>
</tr>
<tr>
<td>( gg \to A \to hZ \to (bb)Z )</td>
<td>ATLAS</td>
<td>99</td>
<td>0.2±2</td>
</tr>
<tr>
<td>( bb \to A \to hZ \to (bb)Z )</td>
<td>ATLAS</td>
<td>99</td>
<td>0.2±2</td>
</tr>
</tbody>
</table>

See J. Tao’s talk for the updates on new Higgs Boson searches

Two-Higgs Doublet Models

- THDM (with softly broken $Z_2$ symmetry):

$$\Phi_i = \left( \frac{\phi_i^+}{\sqrt{2}} \right)$$

Scalar Sector

- $\Phi_1^\pm = c_\beta G^\pm - s_\beta H^\pm$, Physical: $h, H, A, H^\pm$
- $\Phi_2^\pm = s_\beta G^\pm + c_\beta H^\pm$, Goldstones: $G, G^\pm$
- $t_\beta \equiv \tan \beta \equiv \frac{v_2}{v_1}$

$$t_\beta \equiv \tan \beta \equiv \frac{v_2}{v_1}$$

Yukawa interactions

$$L_Y = - Y_1 \overline{Q}_i i \sigma_2 \Phi_2^* \ell_R - Y_{b,1} \overline{Q}_i i \sigma_2 \Phi_1 b_R - Y_{\tau,1} \overline{\nu}_L \Phi_1 \tau_R - Y_{\tau,2} \overline{L}_L \Phi_2 \tau_R + h.c.$$  

Table 3

- Type I
- Type II
- Type X ("lepton specific")
- Type Y ("flipped")

Experimental constraints

Higgs signal strengths (LHC Run 1 + Run 2 [36 fb$^{-1}$]) push THDM towards alignment limit

$$|\cos(\beta - \alpha)| \ll 1$$

e.g. for type II (type I)

$$|\cos(\beta - \alpha)| < 0.05 (0.26)$$

Two-Higgs Doublet Models

- THDM (with softly broken $Z_2$ symmetry):

\[
\Phi_1 = \left( \frac{\phi^+_i}{\sqrt{v_i + \phi^0_i + i G_i}} \right)
\]

Scalar Sector

\[
\begin{align*}
\Phi_1^+ &= c_\beta G^+ - s_\beta H^+, \quad \text{Physical: } h, H, A, H^0 \\
\Phi_2^+ &= s_\beta G^+ + c_\beta H^+, \\
\Phi_1^0 &= \frac{1}{\sqrt{2}} [v_1 + c_\beta H - s_\beta h + i c_\beta G - i s_\beta A] \\
\Phi_2^0 &= \frac{1}{\sqrt{2}} [v_2 + s_\beta H + c_\beta h + i s_\beta G + i c_\beta A]
\end{align*}
\]

Goldstones: $G$, $G^0$

$t_\beta \equiv \tan \beta \equiv \frac{v_2}{v_1}$

Yukawa interactions

\[
L_Y = -Y_i \bar{Q}_i s_\beta \Phi^*_2 t_R - Y_{b,1} \bar{Q}_c \Phi^*_1 b_R - Y_{b,2} \bar{Q}_c \Phi_2 b_R - Y_{\tau,1} L \Phi^*_1 \tau_R - Y_{\tau,2} L \Phi_2 \tau_R + h.c.
\]

Experimental constraints

Higgs signal strengths (LHC Run 1 + Run 2 [36 fb$^{-1}$]) push THDM towards alignment limit

\[|\cos (\beta - \alpha)| < 0.05 \ (0.26) \]

Similar results using ATLAS full Run 2 data ALONE

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**ATLAS-CONF-2020-027**

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Jorge de Blas
University of Granada

LHCP 2021 - Constraints on BSM from the Higgs sector
June 10, 2021

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34
Axion-Like Particles (ALPs)

- Light, gauge-singlet pseudo-scalar particles arising as:
  - PQ solutions to strong CP problem (the original QCD axion)
  - pNGB of spontaneously broken global symmetries in extensions of the SM, e.g. in composite Higgs models
  - Dark Matter candidates or mediators

- Leading dim ≤ 6 axion interactions with SM particles

\[
\mathcal{L}_{\text{eff}}^{D \leq 5} = \frac{1}{2} (\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2} a^2 + \sum_f \frac{c_f}{2} \frac{\partial^\mu a}{\Lambda} f \gamma_\mu \gamma_5 f + g_s^2 \frac{a}{\Lambda} G^A_{\mu\nu} \tilde{G}^{\mu\nu,A} + e^2 \frac{C_{\gamma\gamma}}{\Lambda} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w} C_{\gamma Z} \frac{a}{\Lambda} F_{\mu\nu} \tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2} C_{ZZ} \frac{a}{\Lambda} Z_{\mu\nu} \tilde{Z}^{\mu\nu},
\]

\[
\mathcal{L}_{\text{eff}}^{D \geq 6} = \frac{C_{ah}}{\Lambda^2} (\partial_\mu a)(\partial^\mu a) \phi^\dagger \phi + \frac{C_{Zh}}{\Lambda^3} (\partial^\mu a) \left( \phi^\dagger iD_\mu \phi + \text{h.c.} \right) \phi^\dagger \phi + \ldots
\]

See also P. Foldenauer's talk
**Axion-Like Particles (ALPs)**

- Light, gauge-singlet pseudo-scalar particles arising as:
  - PQ solutions to strong CP problem (the original QCD axion)
  - pNGB of spontaneously broken global symmetries in extensions of the SM, e.g. in composite Higgs models
  - Dark Matter candidates or mediators

- Leading dim $\leq 6$ axion interactions with SM particles

\[
L_{\text{eff}}^{D\leq 5} = \frac{1}{2} \left( \partial_\mu a \right) \left( \partial^\mu a \right) - \frac{m_a^2}{2} a^2 + \sum_f \frac{c_{ff}}{2} \frac{\partial^\mu a}{\Lambda} \tilde{f}_5 + g_s^2 \frac{a}{\Lambda} G_{\mu\nu}^A \tilde{G}_{\mu\nu, A} + e^2 C_{\gamma\gamma} \frac{a}{\Lambda} F_{\mu\nu} \tilde{F}^{\mu\nu} + 2 e^2 \frac{C_{\gamma Z}}{s_w c_w} \frac{a}{\Lambda} F_{\mu\nu} \tilde{Z}^{\mu\nu} + e^2 \frac{C_{ZZ}}{s_w^2 c_w^2} \frac{a}{\Lambda} Z_{\mu\nu} \tilde{Z}^{\mu\nu},
\]

- Axion decays, e.g.
  \[ a \rightarrow \gamma\gamma \]

\[
L_{\text{eff}}^{D\geq 6} = \frac{C_{ah}}{\Lambda^2} \left( \partial_\mu a \right) \left( \partial^\mu a \right) \phi^\dagger \phi + \frac{C_{Zh}}{\Lambda^3} \left( \partial^\mu a \right) \left( \phi^\dagger i D_\mu \phi + \text{h.c.} \right) \phi^\dagger \phi + \ldots
\]

- Axion production in Higgs decays
  \[ h \rightarrow aa, Za \]

See also P. Foldenauer’s talk
Axion-Like Particles (ALPs)

- Leading dim $\leq 6$ axion interactions with SM particles

\[ L_{\text{eff}}^{D \leq 5} = \frac{1}{2} (\partial f a)(\partial^f a) - \frac{m_a^2}{2} a^2 + \sum_f \frac{e^2}{f} C_{Gf} \frac{a}{f} f \gamma_5 f + g_s^2 C_{GG} \frac{a}{f} G_{\mu
u} A \tilde{G}_{\mu
u} \]

Axion decays, e.g.
\[ a \rightarrow \gamma\gamma \]

\[ L_{\text{eff}}^{D \geq 6} = \frac{C_{ah}}{\Lambda^2} (\partial f a)(\partial^f a) \phi^\dagger \phi + \frac{C_{Zh}}{\Lambda^3} (\partial f a) \left( \phi^\dagger iD_\mu \phi + \text{h.c.} \right) \phi^\dagger \phi + \ldots \]

Axion production in Higgs decays
\[ h \rightarrow aa, Za \]

Testable at LHC in exotic Higgs decays


Jorge de Blas
University of Granada

LHCP 2021 - Constraints on BSM from the Higgs sector
June 10, 2021
Axion-Like Particles (ALPs)

- Leading dim $\leq 6$ axion interactions with SM particles

\[ \mathcal{L}_{\text{eff}}^{D \leq 5} = \frac{1}{2} (\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2} a^2 + \sum_f \frac{c_{ff}}{2} \frac{\partial^\mu a}{\Lambda} f \gamma_\mu \gamma_5 f + g_s^2 C_{GG} \frac{a}{\Lambda} G^A_{\mu\nu} \tilde{G}^{\mu\nu,A} \]

Axion decays, e.g.
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Axion production in Higgs decays
\[ h \to aa, \ Za \]

- Testable at LHC in exotic Higgs decays

See also P. Foldenauer's talk

See also K. Schmieden's an I.Riu's talks

Axion-Like Particles (ALPs)

- Leading dim $\leq 6$ axion interactions with SM particles

\[
L_{\text{eff}}^{D \leq 5} = \frac{1}{2} (\partial_\mu a) (\partial^\mu a) - \frac{m_{a,0}^2}{2} a^2 + \frac{c_{\gamma}}{\Lambda} \bar{f} \gamma_\mu \gamma_5 f + g_2^2 \frac{C_{GG} a}{\Lambda} G_{\mu\nu}^A \tilde{G}_{\mu\nu}^A
\]

\[
+ e^2 \frac{C_{\gamma\gamma} a}{\Lambda} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w} C_{\gamma Z} \frac{a}{\Lambda} F_{\mu\nu} \tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2} C_{ZZ} \frac{a}{\Lambda} Z_{\mu\nu} \tilde{Z}^{\mu\nu},
\]

Axion decays, e.g.

\[
a \rightarrow \gamma\gamma
\]

\[
L_{\text{eff}}^{D \geq 6} = \frac{C_{ah}}{\Lambda^2} (\partial_\mu a) (\partial^\mu a) \phi^\dagger \phi + \frac{C_{Zh}}{\Lambda^3} (\partial^\mu a) \left( \phi^\dagger iD_\mu \phi + \text{h.c.} \right) \phi^\dagger \phi + \ldots
\]

Axion production in Higgs decays

\[
h \rightarrow aa, Za
\]

Testable at LHC in exotic Higgs decays

From ATLAS+CM Run 1 combination:
\[
\text{Br}(h \rightarrow \text{BSM}) < 0.32 \quad \text{at 95\% prob. (Outdated)}
\]

e.g. ATLAS Run 2 (ATLAS-CONF-2020-027):
\[
\text{Br}(h \rightarrow \text{BSM}) < 0.19 \quad \text{at 95\% prob.}
\]

M. Bauer, M. Neubert, A. Thamm,
Two slides on Higgs pair production and BSM

- The measurement of the Higgs self-interaction is directly connected to our understanding of EWSB and can have important implications from the point of view of, e.g. EW baryogenesis

- Higgs pair production is a difficult process to measure at the LHC

---

**ATLAS** Preliminary
\[ \sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \]
\[ \text{HH} \rightarrow \text{bb} \gamma \gamma \]

- Observed limit (95% CL)
- Expected limit (95% CL)
- Expected limit \(\pm 1\sigma\)
- Expected limit \(\pm 2\sigma\)
- Theory prediction

\[ -1.5 \ (\ -2.4 \) \ < \ \kappa_\lambda \ < \ 6.7 \ (7.7) \]

**CMS** Preliminary

\[ \text{138 fb}^{-1} \ (13 \text{ TeV}) \]
\[ \text{All categories} \]
\[ \text{HH} \rightarrow \text{bbbb} \]
\[ \mu_\text{ggF} = 1, \ \mu_\text{VBF} = 1 \]

\[ -2.3 \ (\ -5.0 \) \ < \ \kappa_\lambda \ < \ 9.4 \ (12.0) \]

See L. Pereira’s and P. Bortignon’s talks

**HL-LHC projection (3 ab\(^{-1}\))**:
\[ 0.52 \leq \kappa_\lambda \leq 1.5 \]

68% prob.
Two slides on Higgs pair production and BSM

- New physics effects can enter the process in many different places, affecting the \( hh \) distributions, e.g. in the SMEFT:

  Most of these interactions can be better measured in other processes, using SMEFT correlations, with the exception of the \( h^3 \) coupling

- But from the point of view of models of naturalness, the bounds from single Higgs couplings dominate over any limit from \( hh \) that will be set at the (HL-)LHC

- Similarly, for models of the EWPT, large (tree-level) contrib. to \( O_6 = (H^\dagger H)^3 \) always come with other operators at the same order

  ✓ Exceptions: Custodial scalar quadruplets or fermio-phobic scalar doublets

  \( hh \) at (HL-)LHC could still provide some limited sensitivity to this type of scenarios

From R. Groeber's talk

M. Chala et al. , JHEP 07 (2018) 062
Summary
Summary

- Despite the LHC success in finding the Higgs boson, new physics beyond the Standard Model (BSM) still proves to be elusive to existing searches.

- Such searches, however, provide valuable information to constraint many of the ideas that theorist have proposed to address the problems of the SM.

- In particular, LHC Higgs physics provides crucial information to constrain solutions to the hierarchy problem:
  - The consistency of the Higgs couplings with the SM predictions imposes some of the strongest bounds on these scenarios.
  - Direct searches for exotic decays and non-SM extra scalars keep also pushing the scale of new physics.

- In this talk I have presented some of the implications of current LHC measurements of the Higgs properties on different BSM scenarios.

- With the Run 3, and the future HL-LHC we are entering the LHC precision era for measurements of the Higgs properties.
  - Indirect constraints will become more relevant...
  - …and hence also the precision with which we know the SM.
  - The (SM) theory role: to keep learning from BSM it is crucial to keep improving our SM calculations!

See B. Mistlberger’s talk.
Backup Slides
Modified Higgs couplings: The $\kappa$ framework

- Compact parameterisation of new physics in single Higgs processes:

\[
(\sigma \cdot \text{BR})(i \to H \to f) = \kappa_i^2 \sigma^{\text{SM}}(i \to H) \frac{\kappa_j^2 \Gamma^{\text{SM}}(H \to f)}{\Gamma_H} \]

\[
\Gamma_H = \Gamma_H^{\text{SM}} \frac{\sum_i \kappa_i^2 \text{BR}_i^{\text{SM}}}{1 - \text{BR}_{\text{inv}} - \text{BR}_{\text{unt}}}
\]

- $\kappa_i$ interpreted as modified Higgs couplings + describes non-SM decays

  - No BSM calculation needed per se
  - Applicable to a good approximation to interesting NP scenarios (e.g. Composite Higgs, MSSM)
  - Limited to single Higgs processes and total rates (no kinematics)
  - No consistent Lagrangian/EFT interpretation in the general case (i.e. with general $\kappa_{g,\gamma,Z\gamma}$)
**Modified Higgs couplings: The $\kappa$ framework**

- **Fits to LHC Higgs observables:** Run 1 + Run 2 (~36-140 fb⁻¹)

### Custodial + Universal fermion interactions

<table>
<thead>
<tr>
<th>Fit result</th>
<th>95% Prob.</th>
<th>Correlations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_V$</td>
<td>1.02±0.02</td>
<td>[0.99, 1.06]</td>
</tr>
<tr>
<td>$\kappa_f$</td>
<td>0.96±0.03</td>
<td>[0.89, 1.02]</td>
</tr>
</tbody>
</table>

### Non custodial + non universal fermion interactions

<table>
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<td>$\kappa_W$</td>
<td>1.03±0.04</td>
</tr>
<tr>
<td>$\kappa_Z$</td>
<td>0.99±0.04</td>
</tr>
<tr>
<td>$\kappa_t$</td>
<td>0.98±0.04</td>
</tr>
<tr>
<td>$\kappa_b$</td>
<td>0.96±0.08</td>
</tr>
<tr>
<td>$\kappa_\mu$</td>
<td>1.02±0.18</td>
</tr>
<tr>
<td>$\kappa_\tau$</td>
<td>0.90±0.07</td>
</tr>
</tbody>
</table>

### Non custodial + non universal fermion interactions

<table>
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<th>95% Prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_W$</td>
<td>1.05±0.04</td>
</tr>
<tr>
<td>$\kappa_Z$</td>
<td>0.99±0.04</td>
</tr>
<tr>
<td>$\kappa_\gamma$</td>
<td>1.01±0.05</td>
</tr>
<tr>
<td>$\kappa_{Z\gamma}$</td>
<td>1.04±0.05</td>
</tr>
<tr>
<td>$\kappa_t$</td>
<td>1.29±0.40</td>
</tr>
<tr>
<td>$\kappa_b$</td>
<td>0.94±0.06</td>
</tr>
<tr>
<td>$\kappa_\mu$</td>
<td>0.99±0.09</td>
</tr>
<tr>
<td>$\kappa_\tau$</td>
<td>1.02±0.19</td>
</tr>
</tbody>
</table>

- Non custodial + non universal fermion interactions
- + independent $\kappa$ for rad. processes
Two-Higgs Doublet Models

- “Flavour-Aligned” THDM:

\[ \Phi_1 = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}} (v + S_1 + i G^0) \end{bmatrix}, \quad \Phi_2 = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}} (S_2 + i S_3) \end{bmatrix}, \]

Physical CP-even neutral scalars

\[ \begin{pmatrix} h \\ H \end{pmatrix} = \begin{bmatrix} \cos \tilde{\alpha} & \sin \tilde{\alpha} \\ -\sin \tilde{\alpha} & \cos \tilde{\alpha} \end{bmatrix} \begin{pmatrix} S_1 \\ S_2 \end{pmatrix} \]

General scalar Potential

\[ V = \mu_1 \Phi_1^\dagger \Phi_1 + \mu_2 \Phi_2^\dagger \Phi_2 + \left[ \mu_3 \Phi_1^\dagger \Phi_2 + \mu_3^* \Phi_2^\dagger \Phi_1 \right] + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \left[ \frac{1}{2} \lambda_5 \Phi_1^\dagger \Phi_2 + \lambda_6 \Phi_1^\dagger \Phi_1 + \lambda_7 \Phi_2^\dagger \Phi_2 \right] (\Phi_1^\dagger \Phi_2) + \text{h.c.} , \]

Assume Yukawa interactions “aligned” in flavour space

\[ \mathcal{L}_{\text{Yuk}} = -\sqrt{2} v H^+ \left\{ \bar{u} \left[ \kappa_d V_{\text{CKM}} M_d P_R - \kappa_u M_u^\dagger V_{\text{CKM}} P_L \right] d + \kappa_e \bar{\nu} M_e P_R \ell \right\} - \frac{1}{v} \sum_{i,f} y^0_f \varphi_i^0 \left[ \bar{f} M_f P_R f \right] + \text{h.c.} , \quad \varphi_i^0 = h, H, A \]

SM-like Higgs couplings: Fit to LHC signal strengths

\[ g_{hVV} = \cos \tilde{\alpha} \ g_{hVV}^{\text{SM}} \]

\[ y^h_{d,\ell} = \cos \tilde{\alpha} + \sin \tilde{\alpha} \ k_{d,\ell} , \]

\[ y^h_u = \cos \tilde{\alpha} + \sin \tilde{\alpha} \ k^*_{u} , \]

Most LHC Higgs observables not sensitive to sign of Yukawas

\[ \rightarrow 2 \text{ types of solutions } y^h_i \approx \pm 1 \]

For the “right-sign” solution

\[ |\tilde{\alpha}| \leq 0.003 \ (68\% \ probability) , \]

\[ |\tilde{\alpha}| \leq 0.023 \ (95.5\% \ probability) . \]