Higgs Couplings

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Higgs Couplings ... without the Higgs

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LHC Exploration

Focus so far: Search for new light particles

Energy frontier (13 TeV)

Experimentally: First accessible signal/Easy to study
LHC Exploration

Focus now: Standard Model Precision Tests

(2035: 3000 fb$^{-1}$)

intensity frontier

(2019: 65 fb$^{-1}$)

Infinite Information

\[ f(E^2) = f(0) + f'(0)E^2 + f''(0)E^4 + \cdots \]
LHC Exploration

Focus now: **Standard Model Precision Tests**

- (2035: 3000 fb\(^{-1}\))
- (2019: 65 fb\(^{-1}\))

**Finite Information**

\[ \text{function}(E^2) = f(0) + f'(0)E^2 + f''(0)E^4 + \cdots \]

**Effective Field Theory (EFT)**

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2} \sum_i c_i \mathcal{O}_i + \cdots \]

**Systematic Taylor expansion for all observables**

**Effective field theory**

\[ O_i = \frac{(\bar{\psi} \gamma_\mu \psi)^2}{\Lambda^2} \]

**Most relevant effects from all heavy BSM**
**Precision Tests**

- e.g. $2>2$ processes ($WZ, ll, \ldots$)
  - small statistics
  - more challenging measurement
  - more space for improvement

- e.g. Higgs Couplings, Z-Pole,\ldots
  - big statistics
  - sooner or later systematic limited

$$\sigma = \sigma_{SM} \left( 1 + c \frac{E^2}{\Lambda^2} + \cdots \right)$$
In some processes, LHC more precise than LEP

Why?
**Precision Tests**

![Graph showing precision tests with a formula and measurements.](image)

**e.g. 2≥2 processes (WZ, ll, ...)**
- small statistics
- more challenging measurement
- more space for improvement
- signal so big that even a poor measurement can be precise

**e.g. Higgs Couplings, Z-Pole, ...**
- big statistics
- sooner or later systematic limited

\[ \sigma = \sigma_{SM} \left( 1 + c \frac{E^2}{\Lambda^2} + \cdots \right) \]

Imagine measuring \( \frac{\delta \sigma}{\sigma_{SM}} \mid \sim 10^{-4} \) (surely a precise measurement)

... equivalent to
\( \frac{\delta \sigma}{\sigma_{SM}} \mid \sim 10\% \) (naively not so precise)

Effect grows \( \propto E^2 \): \( \left( \frac{3000}{91.2} \right)^2 \approx 1000 \)
Precision Tests

- e.g. 2>2 processes (WZ, ll, ...)
  - small statistics
  - more challenging measurement
  - more space for improvement
  - signal so big that even a poor measurement can be precise

- e.g. Higgs Couplings, Z-Pole, ...
  - big statistics
  - sooner or later systematic limited

Experimentally very appealing
What to expect from a theory viewpoint?

Higgs Compositeness: Higgs must be a (pseudo)goldstone boson (like pions)

\[ \Lambda \sin \frac{h}{\Lambda} = h - \frac{h^3}{3! \Lambda^2} + \ldots \]

Supersymmetry: only $H_2$ exchanged at tree-level ($R$-parity)

Higgs Couplings are modified
Higgs Couplings

Modifications of Higgs couplings in EFT language:

\[ V = W, Z, \gamma, g \]

\[ O_r = |H|^2 \partial_\mu H^\dagger \partial^\mu H \]

\[ O_{BB} = g' |H|^2 B_{\mu\nu} B^{\mu\nu} \]

\[ O_{WW} = g^2 |H|^2 W^a_{\mu\nu} W^{a \mu\nu} \]

\[ O_{GG} = g_s^2 |H|^2 G^{a \mu\nu} G_{a \mu\nu} \]

\[ O_6 = |H|^6 \]

\[ \mathcal{L}_{SM} \times |H|^2 \text{ has no effect in vacuum } \langle H \rangle = v \]

\[ \frac{1}{g_s^2} G_{\mu\nu} G^{\mu\nu} + \frac{|H|^2}{\Lambda^2} G_{\mu\nu} G^{\mu\nu} = \left( \frac{1}{g_s^2} + \frac{v^2}{\Lambda^2} \right) G_{\mu\nu} G^{\mu\nu} + \frac{2v}{\Lambda^2} G_{\mu\nu} G^{\mu\nu} + \ldots \]
II and the analyses required at the HL/HE-LHC, differential information is needed and the formalism so that the SM is recovered for the measurements of the Higgs-boson couplings and characterize the nature of the Higgs boson. The translation of these results in terms of composite Higgs scenarios will be discussed in section 1.9.

For each measurement, the total uncertainty is indicated by a grey box while the statistical, experimental systematic uncertainties are indicated by a blue, green and red line respectively.

Expected uncertainty

Uncertainty [%]

HL-LHC Projection

Optimistic Systematics (S2) on-shell Higgs (E=125 GeV)

Combining 2 experiments

HL-LHC Reach (3000 fb−1)
Higgs Couplings at High-Energy

Higgs couplings: Theoretically Interesting
Experimentally not High-E measurements

but...

SM is the unique theory, with its particle content,
valid up to arbitrary energy:

Any coupling modification must induce energy-growth
in some process, reducing the validity energy-range
Any modifications of Higgs couplings induces $E^2$ growth in some process with longitudinal W,Z bosons!

One way of seeing this:

$$SM = \begin{array}{c}
\includegraphics[width=0.3\textwidth]{diagram1.png} \\
\includegraphics[width=0.3\textwidth]{diagram2.png}
\end{array} = \text{finite}$$
Higgs Couplings... without a Higgs

Any modifications of Higgs couplings induces $E^2$ growth in some process with longitudinal $W,Z$ bosons!

One way of seeing this:

$$SM = \begin{array}{c}
\text{modification of a coupling (h3)} \\
\text{compromises gauge cancellations in the SM}
\end{array} + E^2$$
Higgs Self Coupling

Another way of understanding E-growth:

\[ h^3 \in \frac{|H|^6}{\Lambda^2} \]

Golstones = \( W_L, Z_L \)

\[ |H|^2 = \frac{1}{2}(v^2 + 2hv + h^2 + 2\phi^+\phi^- + (\phi^0)^2) \]

Contact Interaction Among \( W_L, Z_L \)

\[ pp \rightarrow jj + 4 V_L, \quad V_L \sim \frac{H^2}{\Lambda^2} \quad \text{w.r.t. SM} \]

with 1 Higgs v.e.v.

\[ pp \rightarrow jjh + V_LV'_L, \quad V_L \sim \frac{v E}{\Lambda^2} \]

with 3 Higgs v.e.v.s

(= traditional Higgs Coupling measurement)
Higgs Self Coupling

Another way of understanding E-growth:

\[ h^3 \in \frac{|H|^6}{\Lambda^2} \]

Contact Interaction Among \( W_L, Z_L \)

Golstones = \( W_L, Z_L \)

\[ |H|^2 = \frac{1}{2} (v^2 + 2bh + h^2 + 2\phi^+\phi^- + (\phi^0)^2) \]

\[ \frac{\sigma(pp \to hh)}{\sigma(pp \to h)} \sim 10^{-3} \quad \text{Br}(h \to bb) \times \text{Br}(h \to \gamma \gamma) \sim 60\% \times 0.1\% \]

ATLAS Preliminary

HL-LHC @ 3 ab\(^{-1}\), 95\% CL

\[ \kappa \lambda \in \sim [-0.5, 2] ? \]

with 3 Higgs v.e.v.s

(= traditional Higgs Coupling measurement)

\[ \sim \frac{v^2}{\Lambda^2} \]
Higgs Self Coupling

Another way of understanding E-growth:

\[ h^3 \propto \frac{|H|^6}{\Lambda^2} \]

Golstones = \( W_L, Z_L \)

\[ |H|^2 = \frac{1}{2}(v^2 + 2hv + h^2 + 2\phi^+\phi^- + (\phi^0)^2) \]

Contact Interaction
Among \( W_L, Z_L \)

\[ p p \rightarrow j j + 4V_L \]

with 1 Higgs v.e.v.

\[ pp \rightarrow j j h + V_LV_L' \]

with 3 Higgs v.e.v.s

(= traditional Higgs Coupling measurement)
Higgs Self Coupling

Henning, Lombardo, Riembau, FR'18

$pp \rightarrow jjh + W^\pm W^\pm$

Same-sign leptons

- Enough events (50 events @ 3000 fb$^{-1}$)
- Low background $B$
  - $ttjj$
  - fake leptons?

$W \rightarrow l + \nu$

$H \rightarrow b\bar{b}$

VBF topology

$H_{wH}$: single channel, simple analysis, competitive with HC!
Higgs Self Coupling

... endless possibilities of improvement ...

- More Final states

- Look also at $E^2$-growing processes

- Keep differential information to exploit $E$-growth

- Develop polarization-sensitive analysis  
  (see Panico,FR,Wulzer’17)

(SM $V_T$ final states large and not interfering)
“Higgs without Higgs” Program

\[ \kappa_t \quad \sim \text{const} \quad \sim E^2 \]

\[ |H|^2 Q \tilde{H} t_R \]

\[ \kappa_G \quad |H|^2 G_{\mu\nu}^a G^{a\mu\nu} \]

\[ \kappa_\gamma \quad |H|^2 B_{\mu\nu} B^{\mu\nu} \]
\[ \kappa_{Z\gamma} \quad |H|^2 W_{\mu\nu}^a W^{a\mu\nu} \]

\[ \kappa_V \quad |H|^2 \partial_\mu H^{+} \partial^\mu H \]
**HwH Program: top Yukawa**

\[ \kappa_t \quad |H|^2 Q \tilde{H} t_R \]

**Lower threshold**

\[ \sim E^2 \]

**Signal classified by #leptons:**

<table>
<thead>
<tr>
<th>Process</th>
<th>0(\ell)</th>
<th>1(\ell)</th>
<th>(\ell^\pm \ell^\mp)</th>
<th>(\ell^\pm \ell^\mp)</th>
<th>3(\ell) (4(\ell))</th>
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<tr>
<td>(W^{\pm} W^{\mp})</td>
<td>3449/567</td>
<td>1724/283</td>
<td>216/35</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(W^{\pm} W^{\mp})</td>
<td>2850/398</td>
<td>1425/199</td>
<td>-</td>
<td>178/25</td>
<td>-</td>
</tr>
<tr>
<td>(W^{\pm} Z)</td>
<td>3860/632</td>
<td>965/158</td>
<td>273/45</td>
<td>-</td>
<td>68/11</td>
</tr>
<tr>
<td>(ZZ)</td>
<td>2484/364</td>
<td>-</td>
<td>351/49</td>
<td>-</td>
<td>(12/2)</td>
</tr>
</tbody>
</table>

**ttjj \rightarrow tWbjj**

\(p_T^t > 250\) GeV / \(p_T^t > 500\) GeV
easier to reconstruct

**Background manageable**

many final states

boosted top:
good discriminant,
easier to reconstruct

\(>2\ell: \text{Small Background}\)

Henning, Lombardo, Riembau, FR’18
Further improvements:

- **HwH competitive with HC!**

**Further improvements:**
- differential distributions (into larger $E^2$)
- better background estimate
More Top and Higgs at High-Energy

Top-Higgs: well motivated by naturalness

Other Top-Higgs effects grow in single-top

\[ i(H^\dagger D_\mu H)(\bar{t}\gamma^\mu t) \]

\[ W, Z, H, \gamma \]

\[ W, Z, H \]

Top-Higgs: well motivated by naturalness

Other Top-Higgs effects grow in single-top

\[ i(H^\dagger D_\mu H)(\bar{t}\gamma^\mu t) \]

\[ W, Z, H, \gamma \]

\[ W, Z, H \]

\[ \sigma_{\text{int.}} \]

\[ \sigma_{\text{SM}} \]

\[ \sigma_{\text{pp} \rightarrow tWj} \]

\[ \sigma_{\text{sq.}} \]

\[ \sigma_{\text{SM}} \]

Different effects
HwH Program

\[ \sim const \]

\[ \sim E^2 \]

\[
\kappa_t \langle H \rangle^2 Q \tilde{H} t_R
\]

\[
\kappa_G |H|^2 G^a_{\mu \nu} G^{a \mu \nu}
\]

\[
\kappa_\gamma |H|^2 B_{\mu \nu} B^{\mu \nu}
\]

\[
\kappa_{Z\gamma} |H|^2 W^a_{\mu \nu} W^{a \mu \nu}
\]

\[
\kappa_V |H|^2 \partial_{\mu} H^{\dagger} \partial^{\mu} H
\]
I. INTRODUCTION

The well-established method for testing HC is, of course, to measure processes in which a Higgs boson is produced on-shell. We will show that modifications of Higgs couplings induce high-energy aspects that we discuss in this article.

TABLE I. Growth of Higgs couplings without the Higgs resonance. On-shell measurements, but it also offers new observables, orthogonal to previous ones!

Important since Coupling measurements leave degeneracies...

HwH Program: Higgs-Gluons

Azatov, Grojean, Paul, Salvioni’14

$$\kappa G \left| H \right|^2 G^a_{\mu \nu} G^a_{\mu \nu}$$

Main H Production mode @ LHC: well measured

$$c_g$$

$$0.0 \quad 0.5 \quad 1.0 \quad 1.5 \quad 2.0$$

leptonic

semileptonic

hadronic

Non-resonant!
HwH Program

\[ \kappa_t |H|^2 Q \tilde{H} t_R \]

\[ \kappa_G |H|^2 G^a_{\mu \nu} G^{a \mu \nu} \]

\[ \kappa_\gamma |H|^2 B_{\mu \nu} B^{\mu \nu} \]

\[ \kappa_{Z \gamma} |H|^2 W^a_{\mu \nu} W^{a \mu \nu} \]

\[ \kappa_V |H|^2 \partial_\mu H^\dagger \partial^\mu H \]
HwH Program: h to gauge bosons

\[ \kappa_{\gamma} \left| H \right|^2 B_{\mu\nu} B^{\mu\nu} \]
\[ \kappa_{Z\gamma} \left| H \right|^2 W_\mu^a W^{a\mu\nu} \]

Simple analysis:
- VBF cuts
- Binning \( \sum |p_T^V| \)

So far interpreted with dim-8 operators (aQGC)

\[ \kappa_{Z\gamma} \text{ competitive, } \kappa_{\gamma} \text{ not} \]

In SM \( V_L \) suppressed by \( \approx 1/1000 \) w.r.t. \( V_T \)

\[ \delta_{KV} \lesssim 8\%, (HwH) \]
\[ \delta_{KV} \lesssim 5\% (HC) \]

Confino, Grojean, Moretti, Piccinini, Rattazzi'10

Bishara, Contino, Rojo'17
Many opportunities for improvement (contrary to HC):

- Precise SM theoretical predictions
- Experimental control of systematics/backgrounds
- Understanding of relevant kinematics, handle on transverse/longitudinal

Important for future colliders (HL-LHC, HE-LHC, CLIC, FCC, ...)
Supersymmetry:

\[ H/A \rightarrow \tau^+ \tau^- \]

Composite Higgs Models:

\[ \kappa \sim \frac{\nu^2}{\Lambda^2} \lesssim (1 - 5\%) \quad m_{NP} \sim g_* \Lambda \sim 30 \text{ TeV} \quad g_* \sim 4\pi \]

Here \( \Lambda \) analog of pion decay constant \( f \) (Direct Searches Poor for large \( g_* \) 3 TeV)

Gupta, Montull, FR'12 - updated
Modifications of the SM induce unitarity violation in some channel...

which channel first?

\[ \delta V(h) = \sum_{n=3}^{\infty} \frac{\delta \lambda_n}{n!} h^n. \]

Generic models valid to 5 TeV
(a) $W$-tagger: signal efficiency

(b) $W$-tagger: background rejection

(c) $Z$-tagger: signal efficiency

(d) $Z$-tagger: background rejection