New frontiers in Higgs Physics:
h → Vff form factors and rare modes

Gino Isidori
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- Introduction (EWPO vs. Higgs Physics)
- The h → Vff amplitude
- Measuring the form factors in h → Z+ll decays
- The from factors in hV associated production
- The rare h → V+P decays
- Conclusions
The 4th of July 2012 we entered in the “Higgs era”...

Clear evidence of a new “light degree of freedom”, completing the picture of a remarkably simple effective theory:

\[ \mathcal{L}_{\text{SM+}\nu} = \mathcal{L}_{\text{gauge}} (A_a, \psi_i) + \mathcal{L}_{\text{Symm. Break.}} (\phi, A_a, \psi_i) \]
**Introduction**

The evidence of the new boson, compatible with the properties of the massive excitation of the Higgs field, indicates that the symmetry breaking sector of the effective theory has a *minimal* and *weakly coupled* structure:

\[
\mathcal{L}_{\text{Symm. Break.}}(\phi, A_a, \psi_i) = D\phi^+ D\phi - V(\phi) + ...
\]

\[
V(\phi) = - \mu^2 \phi^+ \phi + \lambda (\phi^+ \phi)^2 + Y^{ij} \psi_L^i \psi_R^j \phi
\]

But we are far from having established that only the SM (d=4) operators play a relevant role (*or that the cut-off of the effective theory is very high*)

We need to understand if there are additional terms in this series (*natural to expect non-vanishing couplings in d>4 operators involving the Higgs field*)

**N.B.**: the vast majority (and the less know) couplings of the Higgs field are couplings to the SM fermions
\textbf{Introduction}

Several attempts in this direction have already started

\[ \mathcal{L} = \frac{1}{2} (\partial_{\mu} h)^2 - \frac{1}{2} m_h^2 h^2 - \frac{d_3}{6} \left( \frac{3m_h^2}{v} \right) h^3 - \frac{d_4}{24} \left( \frac{3m_h^2}{v^2} \right) h^4 \ldots \]

\[- \left( m_W^2 W_\mu W_\mu + \frac{1}{2} m_Z^2 Z_\mu Z_\mu \right) \left( 1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} + \ldots \right) \]

\[- \sum_{\psi = u, d, l} m_{\psi (i)} \bar{\psi}^{(i)} \psi^{(i)} \left( 1 + c_{\psi} \frac{h}{v} + c_{2\psi} \frac{h^2}{v^2} + \ldots \right) + \ldots \]

Contino et al. '10, '13
Introduction

Several attempts in this direction have already started...

...but the peculiar value $m_h \sim 125 \text{ GeV}$ offers many more interesting tests.

Three (almost) unexplored directions:

- Richness of 3-body amplitudes (and related decay distributions)
- Rare exclusive semi-hadronic decays
- Possible new flavor-violating couplings beside the Yukawa couplings

References:
Blankenburg, Ellis, G.I. '12
Harnik, Koop, Zupan, '12

This talk:
GI, Manohar, Trott, '13
GI, Trott, '13
Introduction: EWPO vs. Higgs Physics

1) LEP/Tevatron [EWPO]

Amplitudes probed

Model-indep. param. of the exp. result

W, Z

S, T (U)

W, Z

J^b_{\mu}

ε_b, ε_τ, ...

(“two-point functions”)

N.B.: The identification of these parameters is independent of the possible interpretation in terms of EFTs (or BSM framework)

→ most efficient way to encode the exp. result
Introduction: EWPO vs. Higgs Physics

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Model-indep. param. of the exp. result

\begin{align*}
S, T (U) \\
\epsilon_b, \epsilon_\tau, \ldots
\end{align*}

Interpretation in terms of eff. ops.

\begin{align*}
(\phi D_\mu \phi^+)^2, \\
(\phi D_\mu \phi^+) \psi \gamma_\mu \psi, \ldots \\
\text{[linear realization]} \\
(\Sigma D_\mu \Sigma^+)^2, \\
(\Sigma D_\mu \Sigma^+) \psi \gamma_\mu \psi, \ldots \\
\text{[non-linear real.]} \\
\end{align*}

N.B.: The identification of these parameters is independent of the possible interpretation in terms of EFTs (or BSM framework)

→ most efficient way to encode the exp. result
Introduction: EWPO vs. Higgs Physics

2) Higgs Physics [3-point functions involving h (both in production & decay)]

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The analog of the EWPO are appropriate sets of form factors whose total number depends on general assumptions on the underlying theory (e.g.: lepton univers., ...)

The f.f. encode all the available dynamical information relying on a minimal set of theoretical assumptions → this is what experiments should aim to extract!!
2) Higgs Physics [3-point functions involving $h$ (both in production & decay)]

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The $h \rightarrow V_{ff}$ amplitude

ATLAS and CMS have reported results about the $h \rightarrow WW^*$ & $h \rightarrow ZZ^*$ couplings. However, what is really measured are 4-lepton modes.

With suitable cuts what can be probed in experiments is the $h \rightarrow V_{ff}$ amplitude ($V=W, Z$) and, in general,

$$A(h \rightarrow V_{ff}) \neq A(h \rightarrow VV^*)$$

$$J_{\mu}^f = \bar{f} \gamma_\mu \left( v^f + a^f \gamma_5 \right) f$$

![Diagram showing experimental results and signal strength](CERN, 10th Oct. 2013)
The $h \to Vff$ amplitude

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The “offshellness” of the second lepton pair allows to probe a richer dynamical structure:

- We are far enough from the pole of the amplitude at $q^2 = m_V^2$ (the only pole within the SM)
- Measuring the $q^2$ dependence we could possibly reveal new “distant poles” ($\leftrightarrow$ contact interactions) or even new “light poles” ($\leftrightarrow$ new light states coupled to Higgs & fermions)
**The $h \to Vff$ amplitude**

Assuming $J_{\text{CP}}^V(h)=0^+$ → general decomposition of the amplitude in terms of 4 independent form factors:

$$A_V^F = C_V g_V^2 m_V \frac{\varepsilon_\mu J_\nu^F}{(q^2 - m_V^2)} \left[ f_1^V (q^2) g^{\mu\nu} + f_2^V (q^2) q^\mu q^\nu ight. \\
+ f_3^V (q^2) (p \cdot q g^{\mu\nu} - q^\mu p^\nu) + f_4^V (q^2) \varepsilon^{\mu\nu\rho\sigma} p_\rho q_\sigma \right]$$

- **SM limit:** $f_1 = 1$, $f_2 = -1/m_V^2$, $f_{3,4} = 0$
- $f_2$ do not contribute to conserved currents
- $f_3$ do not contribute if $J_\mu \sim q_\mu$
- Re($f_4$) is CP odd for VV*
- Im($f_4$) is CP even, and allowed only for a hWlv local interaction

GI, Manohar, Trott, '13
The $h \to Vff$ amplitude

Assuming $J^{CP}(h) = 0^+$ → general decomposition of the amplitude in terms of 4 independent form factors:

$$A^F_V = C_V g^2 V m_V \frac{\varepsilon_\mu J^F_V}{(q^2 - m^2_V)} \left[ f_1^V(q^2) g^{\mu\nu} + f_2^V(q^2) q^\mu q^\nu + f_3^V(q^2)(p \cdot q) g^{\mu\nu} - q^\mu p^\nu \right] + f_4^V(q^2) \epsilon^{\mu\nu\rho\sigma} p_\rho q_\sigma$$

N.B.: This structure is more general than what presently used to analyze data:

$$A_{VV*} = \frac{\kappa}{(q^2 - m^2_V)} \left[ a_1 g^{\mu\nu} + a_2 q^\mu p^\nu + a_3 \epsilon^{\mu\nu\rho\sigma} p_\rho q_\sigma \right]$$

- No $f_2$ term → no problem for $l=e,\mu$
- Constant $a_i$ → potential problem (general form only for $q^2 \sim m_V^2$)
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Assuming $J^{CP}(h)= 0^+ \to$ general decomposition of the amplitude in terms of 4 independent form factors:

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… but is trivial to relate the two parameterizations for $h \to Z+ll$

$$a_1(t) = f_1(t) + f_3(t) \times (m_h^2 - m_V^2 - t)/2$$  \hspace{1cm}  $$a_3(t) = -f_3(t)$$  \hspace{1cm}  $$a_4(t) = f_4(t)$$
**The $h \rightarrow Vff$ amplitude**

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In generic NP models with no new light states (and sufficiently far from $q^2=0 \leftrightarrow$ photon pole), we expect

$$f_1^V = (1 + c_1) + c_2 (q^2 - m_V^2)/m_V^2$$
$$f_2^V = -(1 + c_1)/m_V^2$$
$$f_3^V = c_3/m_V^2$$
$$f_4^V = c_4/m_V^2$$

$c_i = O(v^2/\Lambda^2)$ from d=6 ops., such as $D_\mu \phi^+ D_\nu \phi W_{\mu\nu}$, $\phi^+ \phi W_{\mu\nu} W_{\mu\nu}$, $\phi^+ \phi D_\mu \phi^+ D_\nu \phi$, ... or NLO ops. in the non-linear representation

$$h D_\mu \Sigma^+ D_\mu \Sigma, \quad h \Sigma^+ D_\nu \Sigma D_\mu W_{\mu\nu}, \ldots$$

GI, Manohar, Trott, '13
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\end{aligned} \]

**Four independent parameters** (3 CP even + 1 CP odd) for each $h \to V + ll$ (V=W,Z and $l=e,\mu,\tau$)

- **Custodial symmetry** → same f.f. for W & Z
- **Lepton Universality** → same f.f. for $l=e,\mu,\tau$
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$$f_1^V = (1 + c_1) + c_2 \frac{(q^2-m_V^2)}{m_V^2}$$

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- **Four independent parameters** (3 CP even + 1 CP odd) for each $h \rightarrow V+ll$ ($V=W,Z$ and $l=e,\mu,\tau$)

- The contact term $c_2$ (no pole for $q^2 \rightarrow m_V^2$) might have a different structure for L and R currents

GI, Manohar, Trott, '13
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Four independent parameters (3 CP even + 1 CP odd) for each $h \rightarrow V+ll$ (V=W,Z and $l=e,\mu,\tau$)

We can (and should) test all these possibilities extracting the f.f. from data using appropriate kinematical studies and looking at different final states.
Measuring the form factors in $h \rightarrow Z + ll$

So far the $h \rightarrow 4l$ analysis were focused on determining

- The signal strength ( = total rate)
- The $J^{CP}$ properties of $h$
Measuring the form factors in $h \rightarrow Zl\bar{l}$

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However, we know very little yet about possible modification of the $q^2=m_{ll}^2$ spectrum, that can easily occur even if $h$ is a $0^+$ state

Possible modifications of the spectrum with $|c_i| < 1$, leading to the same total rate
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Possible modifications of the spectrum with $|c_i| < 1$, leading to the same total rate

→ **significant constraints in the linear realiz. from EPWO + TGC** [Pomarol & Riva, '13]

*However:* significant deviations still possible [Max Carrel, '13]

- testing if such constraints are verified is a powerful tool to test if $h$ is indeed part of an SU(2) doublet [0h vs. 1h]  
  
*GI, Trott, '13*
Measuring the form factors in $h \rightarrow Zll$

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The (spin-averaged) double differential distribution

$$\frac{d^2 \Gamma}{d q^2 d \cos \theta}$$

is the most efficient way to perform a model-independent analysis aimed to extract the CP-conserving $f_i (q^2)$
Measuring the form factors in $h \rightarrow Zll$

- Easy to modify the $q^2$ spectrum without visible effects in the total rate and in the energy spectra

**N.B.:**
- The largest modifications -at fixed signal strength- are expected at low $q^2$ (*difficult experimental region*)
Measuring the form factors in $h \rightarrow Zl\bar{l}$

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Measuring the form factors in $h \rightarrow Zll$

*Ideally*... future experimental results on $h \rightarrow Zll$ could appear in a form not very different than present results in $B \rightarrow K^* + ll$:

![Graph showing $dB/dq^2$ vs $q^2$]
The form factors in $V+h$ associated production

A possible non-standard $q^2$ dependence in the f. factors could show-up in large deviations from the SM at high $V+h$ invariant mass.

$$SM \frac{d\sigma(\hat{s})}{d\hat{s}}$$

$$pp \rightarrow h+Z \ [ \@ 8 \text{ TeV}]$$

GI, Trott, '13
The form factors in $V+h$ associated production

The $hVff$ form factors are accessible also in $V+h$ associated production in a different kinematical regime

\[ 0 < q^2 < (m_h - m_V)^2 \]

\[ q^2 > (m_h + m_V)^2 \]

Of course the f.f. probed in associated production at LHC maybe different from those appearing in $h \rightarrow Zll$, in case of flavor-non-universal contact interactions.
A possible non-standard $q^2$ dependence in the f. factors could show-up in large deviations from the SM at high $V+h$ invariant mass.
The rare $h \rightarrow VP$ decays

On general grounds, it is very difficult to investigate the following two aspects of the $h \rightarrow Vff$ amplitude:

- The $f=q$ case
- The terms relevant for $q_{\mu}J_{\mu} \neq 0$

A possible handle on both these problems is provided by the rare $h \rightarrow VP$ decays, where $P$ is a single hadron state and, in particular, a (quasi-)stable pseudo-scalar hadron.

The pseudo-scalar case is particularly interesting and simple: in the $g \rightarrow 0$ limit it projects out the Goldstone-boson component of the amplitude.

\[ A^{SM} \propto \frac{f_\pi}{V} \]

ratio of the two order parameters controlling the SU(2)$_L$ breaking
The rare $h \rightarrow VP$ decays

The SM rates are suppressed but not outrageously small (thanks to $m_h \sim 125$ GeV), and some channels may have a (relatively...) clean signature

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GI, Manohar, Trott, '13
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$BR[ h \to W^{\pm}D_s^{\mp}(\gamma) ] \approx 10^{-4}$

GI, Manohar, Trott, '13
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Quite easy to get $O(1)$ modifications in “conservative” BSM frameworks (even without introducing new contact interactions).

They definitely deserve a dedicated experimental search!
Conclusions

The 125 GeV scalar is certainly compatible with the properties of the SM Higgs boson, but we are still far from having explored its properties in great detail.

Beside the “usual suspects” (=signal strengths in the 5 dominant channels) it is worth to start exploring less trivial, but by no means less interesting, properties, such as

- Model-independent extraction of the $hV_{ff}$ form factors from the double-differential $h \rightarrow Z \ell\ell$ decay distribution and from the $h+W/Z$ associated production

- Search for rare exclusive semi-hadronic decays of the type $h \rightarrow V+P$ (with SM rates in the $10^{-5}$ range)