

Higgs couplings (theory)

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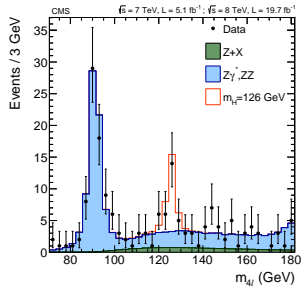
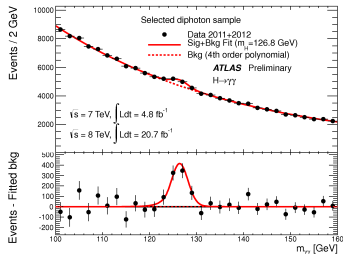
'BSM Higgs Workshop @ LPC'

Fermilab – 3 November 2014

Introduction

Introduction

The recent discovery of an Higgs-like state opens a **new era** in particle physics



We can **directly test**
the mechanism of **ElectroWeak** symmetry breaking

Introduction

Interpreting the data requires a dedicated theoretical framework:

- ▶ selecting **motivated** scenarios
- ▶ compare them with the experiments by developing and testing hypothetical models

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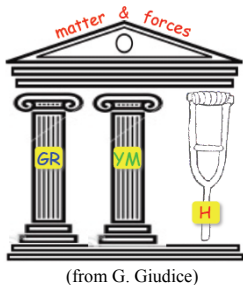
- ▶ selecting **motivated** scenarios
- ▶ compare them with the experiments by developing and testing hypothetical models

The Standard Model realization

- **minimal** implementation of EWSB
- the Higgs is an **elementary scalar**
- several **accidental symmetries**
 - compatible with EW precision data (LEP)
 - consistent with flavor measurements

Introduction

... but the SM Higgs is a **weird** object!



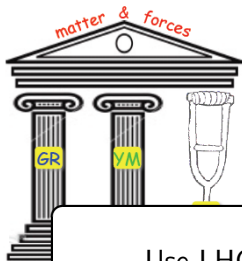
- all other known scalars are **emergent** (composite): eg. the pions
- its couplings are **not dictated** by a gauge symmetry
- its mass is unstable: huge amount of **tuning** (Hierarchy Problem)

Several alternative theories have been proposed

- Supersymmetry
- Composite Higgs
- Extra dimensions
- ...

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of

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Introduction: Determining the Higgs properties

Primary task: extract the Higgs properties!

- What are the Higgs couplings?
- Is the Higgs part of an $SU(2)_L$ doublet?

Possible strategies

- test **explicit models**
 - usually few parameters
 - but huge number of models
- adopt an **EFT approach**
 - encode results in a model-independent way

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➤ adopt an **EFT approach**

- encode results in a model-independent way

General EFT for single-Higgs processes

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Construct a general EFT to encode single-Higgs couplings

A few (mild) working **assumptions**:

- Higgs as a parity even scalar
- absence of new light degrees of freedom
- validity of momentum expansion (analogous to χPT)

General EFT for single-Higgs processes

Effective Lagrangian for a light Higgs-like scalar

[Contino et al. 2010, Pomarol 2014]

$$\begin{aligned}\mathcal{L}_{eff} = & \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - m_\psi \bar{\psi}\psi c_\psi \frac{h}{v} \\ & - 2m_W^2 \left[W_\mu^+ W^{-\mu} + \frac{1}{2c_w^2} Z_\mu Z^\mu \right] a \frac{h}{v} - m_Z^2 Z_\mu Z^\mu c_{hZZ} \frac{h}{v} \\ & + \frac{g^2}{16\pi^2} (c_{WW} W_{\mu\nu}^+ W^{-\mu\nu} + c_{ZZ} Z_{\mu\nu}^2 + c_{Z\gamma} Z_{\mu\nu} \gamma^{\mu\nu}) \frac{h}{v} \\ & + \frac{g^2}{16\pi^2} \gamma_{\mu\nu}^2 c_{\gamma\gamma} \frac{h}{v} + \frac{g_s^2}{16\pi^2} G_{\mu\nu}^2 c_{gg} \frac{h}{v} \\ & + c_{Zff} \left(Z_\mu J_{Nf}^\mu + \text{h.c.} \right) \frac{h}{v} + c_{Wff} \left(W_\mu^+ J_{Cf}^\mu + \text{h.c.} \right) \frac{h}{v}\end{aligned}$$

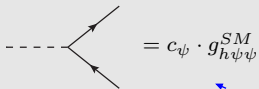
$\left. \begin{array}{l} \text{---} \\ \text{---} \end{array} \right\} \mathcal{O}(p^2)$
 $\left. \begin{array}{l} \text{---} \\ \text{---} \\ \text{---} \end{array} \right\} \mathcal{O}(p^4)$

In the SM: $a = c_\psi = 1$, $c_{hZZ} = c_{VV} = c_{Vff} = 0$

► **New physics** can give contributions to **each** coupling

General EFT for single-Higgs processes

Control the $h\psi\psi$ coupling



$$= c_\psi \cdot g_{h\psi\psi}^{SM}$$

light Higgs-like scalar

[Contino et al. 2010, Pomarol 2014]

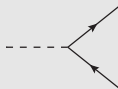
$$\begin{aligned} \mathcal{L}_{eff} = & \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - m_\psi \bar{\psi}\psi \frac{h}{v} c_\psi \\ & - 2m_W^2 \left[W_\mu^+ W^{-\mu} + \frac{1}{2c_w^2} Z_\mu Z^\mu \right] a \frac{h}{v} - m_Z^2 Z_\mu Z^\mu c_{hZZ} \frac{h}{v} \\ & + \frac{g^2}{16\pi^2} (c_{WW} W_{\mu\nu}^+ W^{-\mu\nu} + c_{ZZ} Z_{\mu\nu}^2 + c_{Z\gamma} Z_{\mu\nu} \gamma^{\mu\nu}) \frac{h}{v} \\ & + \frac{g^2}{16\pi^2} \gamma_{\mu\nu}^2 c_{\gamma\gamma} \frac{h}{v} + \frac{g_s^2}{16\pi^2} G_{\mu\nu}^2 c_{gg} \frac{h}{v} \\ & + c_{Zff} \left(Z_\mu J_{Nf}^\mu + \text{h.c.} \right) \frac{h}{v} + c_{Wff} \left(W_\mu^+ J_{Cf}^\mu + \text{h.c.} \right) \frac{h}{v} \end{aligned}$$

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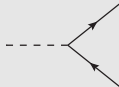
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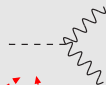
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Corrections to hVV



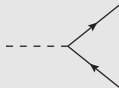
$$\propto c_{VV}$$

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$$\begin{aligned} \mathcal{L}_{eff} = & \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - m_\psi \bar{\psi}\psi \underbrace{c_\psi}_{\text{blue}} \frac{h}{v} \\ & - 2m_W^2 \left[W_\mu^+ W^{-\mu} + \frac{1}{2c_w^2} Z_\mu Z^\mu \right] \underbrace{a}_{\text{red}} \frac{h}{v} - m_Z^2 Z_\mu Z^\mu \underbrace{c_{hZZ}}_{\text{red}} \frac{h}{v} \\ & + \frac{g^2}{16\pi^2} \left(\underbrace{c_{WW}}_{\text{green}} W_{\mu\nu}^+ W^{-\mu\nu} + \underbrace{c_{ZZ}}_{\text{green}} Z_{\mu\nu}^2 + \underbrace{c_{Z\gamma}}_{\text{green}} Z_{\mu\nu} \gamma^{\mu\nu} \right) \frac{h}{v} \\ & + \frac{g^2}{16\pi^2} \gamma_{\mu\nu}^2 \underbrace{c_{\gamma\gamma}}_{\text{green}} \frac{h}{v} + \frac{g_s^2}{16\pi^2} G_{\mu\nu}^2 \underbrace{c_{gg}}_{\text{green}} \frac{h}{v} \\ & + \underbrace{c_{Zff}}_{\text{purple}} \left(Z_\mu J_{Nf}^\mu + \text{h.c.} \right) \frac{h}{v} + \underbrace{c_{Wff}}_{\text{purple}} \left(W_\mu^+ J_{Cf}^\mu + \text{h.c.} \right) \frac{h}{v} \end{aligned}$$

Corrections to hVV



$$\propto c_{VV}$$

Corrections to $hV\psi\psi$



$$\propto c_{Vff}$$

In the SM: $a = c_\psi = 1$, $c_{hZZ} = c_{VV} =$

► New physics can give contribution

General EFT for single-Higgs processes

The general effective Lagrangian contains **many parameters**

It is **very difficult** to measure all of them!

- they can be tested only in Higgs processes
- we can not extract all of them with only inclusive searches
(more on this later)

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Can we do better?

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Can we do better?

Look for additional assumptions!

General EFT for single-Higgs processes

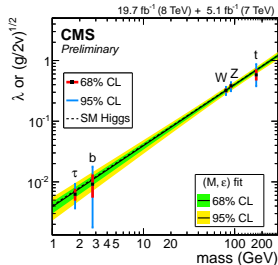
The current fits of the Higgs couplings are in good agreement with the SM

Important fact:

couplings proportional to the masses

$$g_{ff}^h = -\frac{g m_f}{2 m_W} \quad g_{VV}^h = g m_W$$

- **difficult** to explain if the Higgs is a generic scalar (we would expect arbitrary couplings)
- **natural** if the Higgs is part of an $SU(2)_L$ **doublet** and is **responsible for EWSB**



EFT for a doublet Higgs

EFT for a doublet Higgs

We now assume that the Higgs is part of an $SU(2)_L$ **doublet**

$$h \rightarrow H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ h + v \end{pmatrix}$$

and we consider deformations of the SM Lagrangian with operators up to dimension 6

- ▶ several new operators are still present
- ▶ but many of them have **already been tested!**

EFT for a doublet Higgs

On the vacuum several BSM operators induce corrections to SM processes not involving the Higgs

Example: the $(H^\dagger D_\mu H) \bar{f} \gamma^\mu f$ operator

The diagram shows an equation between two Feynman diagrams. The left diagram represents the process $h \rightarrow Z f \bar{f}$. It features a central black vertex. A dashed line labeled h enters from the top left, and a dashed line labeled v (with a circle containing an \otimes) enters from the top right. Two solid lines labeled f exit from the vertex, one upwards and one downwards. A wavy line labeled Z exits from the left. The right diagram represents the process $Z \rightarrow f \bar{f}$. It has a similar central black vertex. Two dashed lines labeled v (each with a circle containing an \otimes) enter from the top. Two solid lines labeled f exit from the vertex, one upwards and one downwards. A wavy line labeled Z enters from the left. Between the two diagrams is an equals sign followed by the factor $\frac{1}{2v}$.

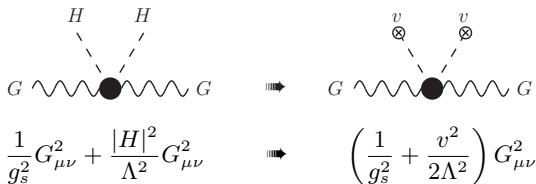
The corrections to $h \rightarrow Z f \bar{f}$ are related to $Z \rightarrow f \bar{f}$

- **Tested** at LEP with high precision!
- Allowed corrections too small to influence Higgs physics

EFT for a doublet Higgs

... **but** some BSM operators on the Higgs vacuum just induce a **redefinition** of the SM parameters

Example: the $|H|^2 G_{\mu\nu} G^{\mu\nu}$ operator



The diagram shows two Feynman diagrams connected by a double arrow. The left diagram has two external Higgs lines (dashed) labeled 'H' meeting at a black vertex, which is also connected to two external gluon lines (wavy) labeled 'G'. The right diagram is identical but the external Higgs lines are replaced by external vacuum expectation value lines (dashed) labeled 'v' with a circle and cross symbol. Below the diagrams is an equation: $\frac{1}{g_s^2} G_{\mu\nu}^2 + \frac{|H|^2}{\Lambda^2} G_{\mu\nu}^2 \Rightarrow \left(\frac{1}{g_s^2} + \frac{v^2}{2\Lambda^2} \right) G_{\mu\nu}^2$. A double arrow points from the equation to the right diagram.

► Can only be measured in Higgs physics



The diagram shows a Feynman diagram with two external gluon lines (wavy) labeled 'G' meeting at a black vertex, which is also connected to two external lines: a Higgs line (dashed) labeled 'h' and a vacuum expectation value line (dashed) labeled 'v' with a circle and cross symbol. To the right of the diagram is a double arrow pointing to the text 'affects $gg \rightarrow h$ '.

EFT for a doublet Higgs: Primary operators

Only **8 primary** Higgs operators (CP-conserving)

[Pomarol, Riva 2013; Elias-Miro et al. 2013; Gupta, Pomarol, Riva 2014]

g_s

$$|H|^2 G_{\mu\nu}^A G^{A\mu\nu}$$

g'

$$|H|^2 B_{\mu\nu} B^{\mu\nu}$$

g

$$|H|^2 W_{\mu\nu}^a W^{a\mu\nu}$$

m_W

$$|H|^2 |D_\mu H|^2$$

m_f

$$|H|^2 \bar{f}_L H f_R + \text{h.c.}$$

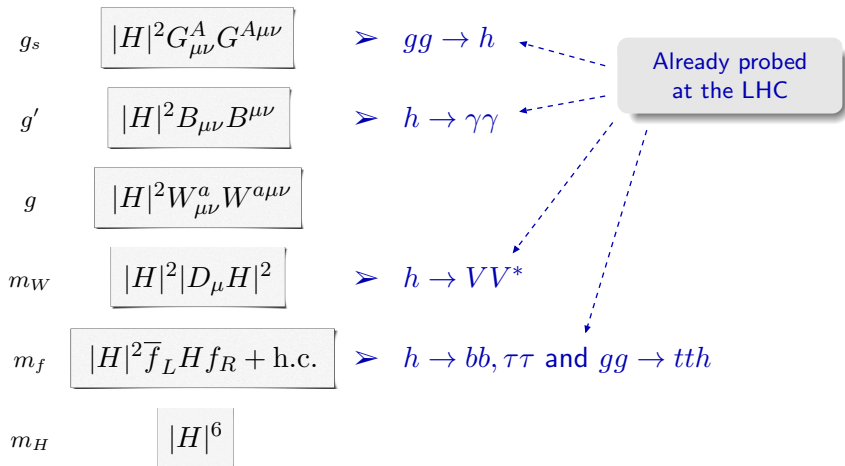
m_H

$$|H|^6$$

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$$g_s \quad \boxed{|H|^2 G_{\mu\nu}^A G^{A\mu\nu}} \quad \text{➤} \quad gg \rightarrow h$$

$$g' \quad \boxed{|H|^2 B_{\mu\nu} B^{\mu\nu}} \quad \text{➤} \quad h \rightarrow \gamma\gamma$$

$$g \quad \boxed{|H|^2 W_{\mu\nu}^a W^{a\mu\nu}} \quad \text{➤} \quad h \rightarrow Z\gamma$$

Now only upper bound
wait for next LHC run

$$m_W \quad \boxed{|H|^2 |D_\mu H|^2} \quad \text{➤} \quad h \rightarrow VV^*$$

$$m_f \quad \boxed{|H|^2 \bar{f}_L H f_R + \text{h.c.}} \quad \text{➤} \quad h \rightarrow bb, \tau\tau \text{ and } gg \rightarrow tth$$

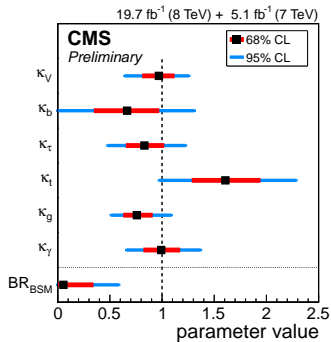
$$m_H \quad \boxed{|H|^6} \quad \text{➤} \quad \text{affects } h^3$$

Probed in $gg \rightarrow hh$
very late LHC

EFT for a doublet Higgs

Combined fit of 6 Higgs primary operators

- some operators already tested with fair accuracy ($\sim 20\%$ error)



Testing the doublet hypothesis

Testing the doublet hypothesis

How can we test if the Higgs is really part of a **doublet**?

Possible strategies:

- ❖ probe relations between couplings in the general Higgs parametrization
- ❖ look for multi-Higgs processes

Testing the doublet hypothesis

Measuring all the couplings in the effective Lagrangian for a singlet Higgs is not easy

Inclusive cross sections give access only to specific combinations of the new physics operators

To distinguish all of them we need to measure the **differential distributions**

$$c_{VV} V_{\mu\nu} V^{\mu\nu} \frac{h}{v} \quad \Rightarrow \quad \text{---} \otimes \text{---} \propto i c_{VV} \left(\eta^{\mu\nu} \left(\frac{\hat{s}}{2} - m_V^2 \right) - p_3^\mu p_2^\nu \right)$$

Testing the doublet hypothesis

Kick the Higgs with extra objects in the final state

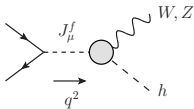
- ▶ kicking with a jet: $H + jets$ [Harlander, Naumann; Banfi, Martin, Sanz; Azatov, Paul; Grojean et al.; Schlaffer et al.; Buschman et al.]
- ▶ kicking with two jets: VBF [Eboli et al.; Plehn, Rainwater, Zeppenfeld; Zang et al.; Hamkele, Klamke, Zeppenfeld; Alloul, Fucks, Sanz]
- ▶ kicking with a gauge boson: HV [Ellis, You, Sanz; Isidori, Trott; Godbole et al.; Beneke, Boito, Wang; Biekötter et al.]

Testing the doublet hypothesis

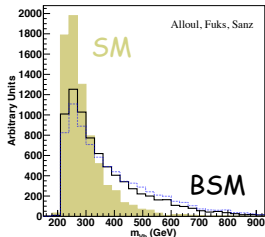
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Boosted Higgs in HV



Large effects at high m_{Vh} or p_T
can be used to probe
derivative operators



Testing the doublet hypothesis

The primary Higgs operators also fix the **multi-Higgs interactions**

$$\begin{aligned} |H|^2 G_{\mu\nu} G^{\mu\nu} &\Rightarrow \text{Diagram 1} + \frac{1}{2v} \times \text{Diagram 2} \\ |H|^2 \bar{q}_L H t_R + \text{h.c.} &\Rightarrow \text{Diagram 3} + \frac{1}{v} \times \text{Diagram 4} \end{aligned}$$

The diagrams represent the following:

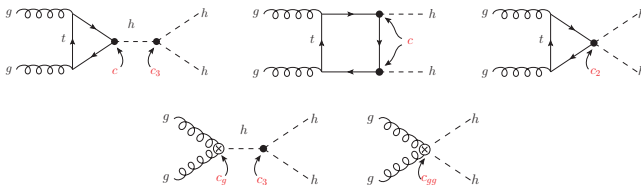
- Diagram 1:** Two incoming gluon lines (g) merging into a Higgs boson (h).
- Diagram 2:** Two incoming gluon lines (g) merging into two Higgs bosons (h).
- Diagram 3:** Two incoming top quark lines (t) merging into a Higgs boson (h).
- Diagram 4:** Two incoming top quark lines (t) merging into two Higgs bosons (h).

- Deviations in single-Higgs processes are related to deviations in multi-Higgs processes
- Multi-Higgs channels can also test the Higgs trilinear: $|H|^6$

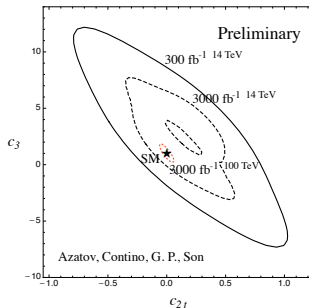
Testing the doublet hypothesis

The $gg \rightarrow hh$ process gives access to these couplings

[Baur, Plehn, Rainwater; Grober, Muhlleitner; Contino et al.;
Dolan, Englert, Spannowsky; Baglio et al.; Barger et al.; ...]



- ▶ Small cross section: very hard at the LHC
- ▶ Much more promising at future high-energy colliders



Conclusions

Conclusions

After the discovery, measuring the Higgs couplings is the primary step to fully understand the Higgs sector

Effective field theories provide a general and simple framework to **interpret** the data and **parametrize BSM effects**

Minimal parametrizations (assuming a doublet Higgs) contain only a small set operators and can be tested with inclusive searches

Testing the **doublet structure** requires more effort

- ▶ look for kinematic distributions in single-Higgs channels
- ▶ probe multi-Higgs processes