Higgs couplings (theory)

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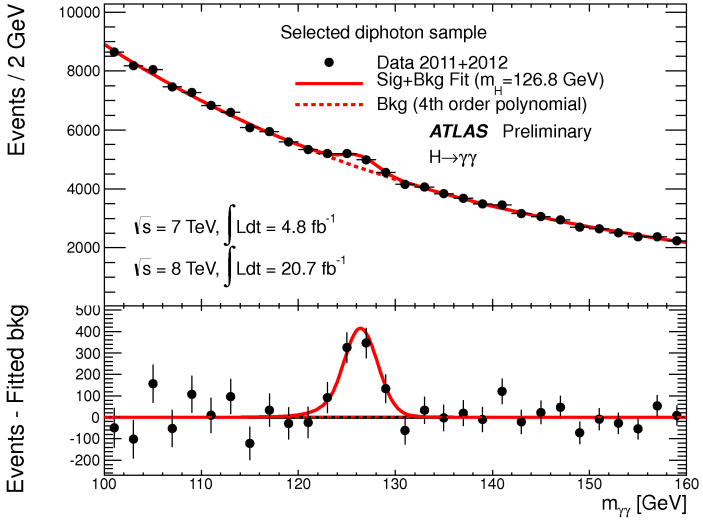
'BSM Higgs Workshop @ LPC'

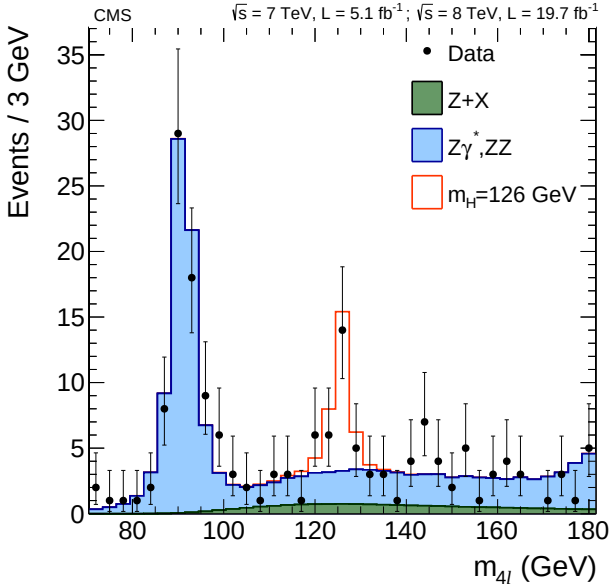
Fermilab – 3 November 2014

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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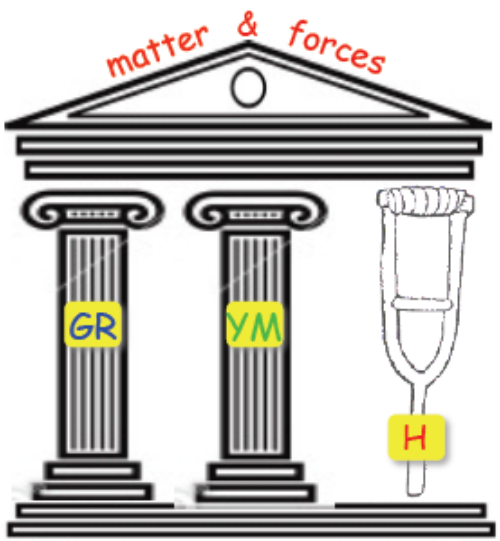
The Standard Model realization

- **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!



(from G. Giudice)

- 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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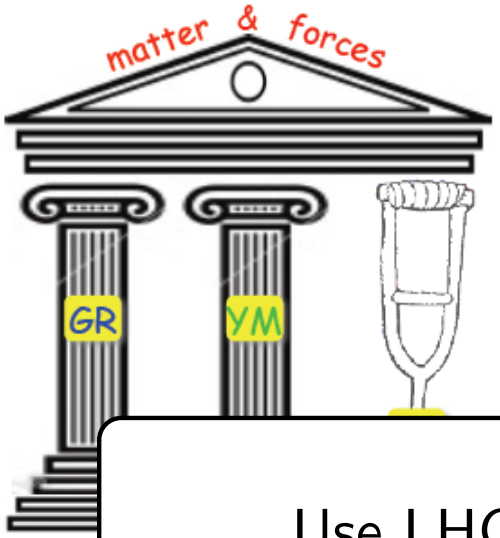

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of

Use LHC data to select the correct model!

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Introduction: Determining the Higgs properties

Primary task: extract the Higgs properties!

- What are the Higgs couplings?
- Is the Higgs parte 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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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]

$$\mathcal{L}_{eff} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - m_\psi \overline{\psi}\psi \, c_\psi \frac{h}{v}$$
$$-2m_W^2\left[W_\mu^+ W^{-\mu} + \frac{1}{2c_w^2} Z_\mu Z^\mu\right] a \frac{h}{v} - m_Z^2 Z_\mu Z^\mu \, c_{hZZ} \frac{h}{v}$$

$\mathcal{O}(p^2)$

$$+\frac{g^2}{16\pi^2}\left(c_{WW} W_{\mu\nu}^+ W^{-\mu\nu} + c_{ZZ} Z_{\mu\nu}^2 + c_{Z\gamma} Z_{\mu\nu}\gamma^{\mu\nu}\right)\frac{h}{v}$$
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$$+c_{Zff}\left(Z_\mu J_{Nf}^\mu + \text{h.c.}\right)\frac{h}{v} + c_{Wff}\left(W_\mu^+ J_{Cf}^\mu + \text{h.c.}\right)\frac{h}{v}$$

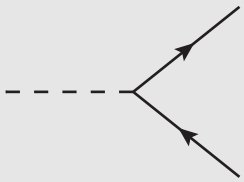
$\mathcal{O}(p^4)$

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



$= c_\psi \cdot g^{SM}_{h\psi\psi}$

light Higgs-like scalar

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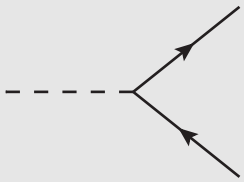

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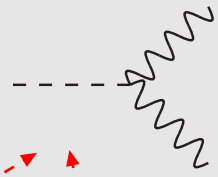

$= a \cdot g^{SM}_{hVV}$

$$
\begin{aligned}
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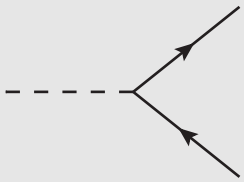

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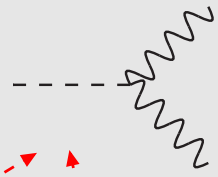

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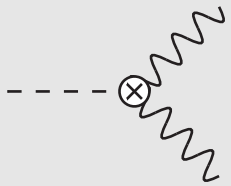
Corrections to hVV



$\propto c_{VV}$

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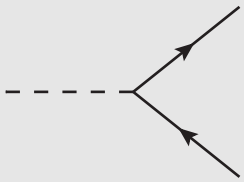

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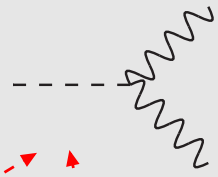
light Higgs

Control the hVV couplings



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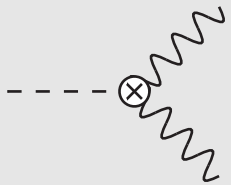
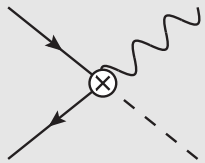


$\propto c_{VV}$

Corrections to $hV\psi\psi$



$\propto c_{Vff}$

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

- **New physics** can give contribut

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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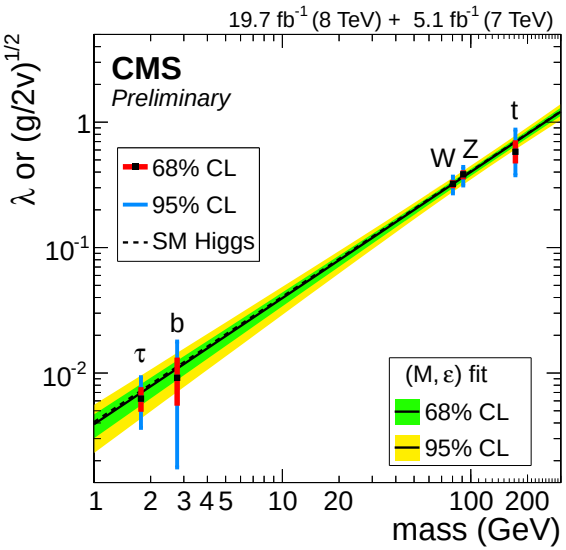
Can we do better?

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

$$g^h_{ff} = -\frac{g\, m_f}{2\, m_W} \qquad g^h_{VV} = g\, m_W$$

- **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

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

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

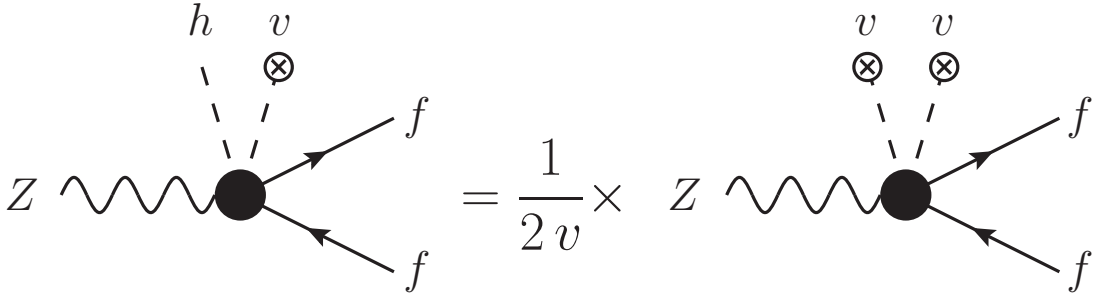
and we consider deformations of the SM Lagrangian with operators up to dimension 6

- 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 $(H^\dagger D_\mu H)\overline{f}\gamma^\mu f$ operator



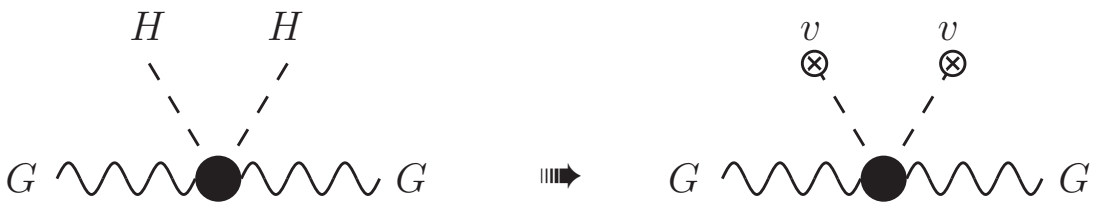
The corrections to $h \to Zff$ are related to $Z \to ff$

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

EFT for a doublet Higgs

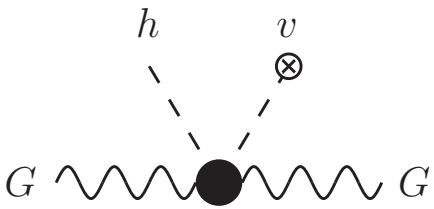
...but some BSM operators on the Higgs vacuum just induce a **redefinition** of the SM parameters

<u>**Example**</u>: the $|H|^2 G_{\mu\nu} G^{\mu\nu}$ operator



$$\frac{1}{g_s^2} G_{\mu\nu}^2 + \frac{|H|^2}{\Lambda^2} G_{\mu\nu}^2 \quad \Rightarrow \quad \left(\frac{1}{g_s^2} + \frac{v^2}{2\Lambda^2} \right) G_{\mu\nu}^2$$

- Can only be measured in Higgs physics



$\Rightarrow$ affects $gg \to h$

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	$\boxed{\lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}}$
g'	$\boxed{\lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}}$
g	$\boxed{\lvert H\rvert^2 W^a_{\mu\nu} W^{a\mu\nu}}$
m_W	$\boxed{\lvert H\rvert^2 \lvert D_\mu H\rvert^2}$
m_f	$\boxed{\lvert H\rvert^2 \overline{f}_L H f_R + \text{h.c.}}$
m_H	$\boxed{\lvert H\rvert^6}$

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Already probed at the LHC

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m_H	$\boxed{\lvert H\rvert^6}$	➢ affects h^3

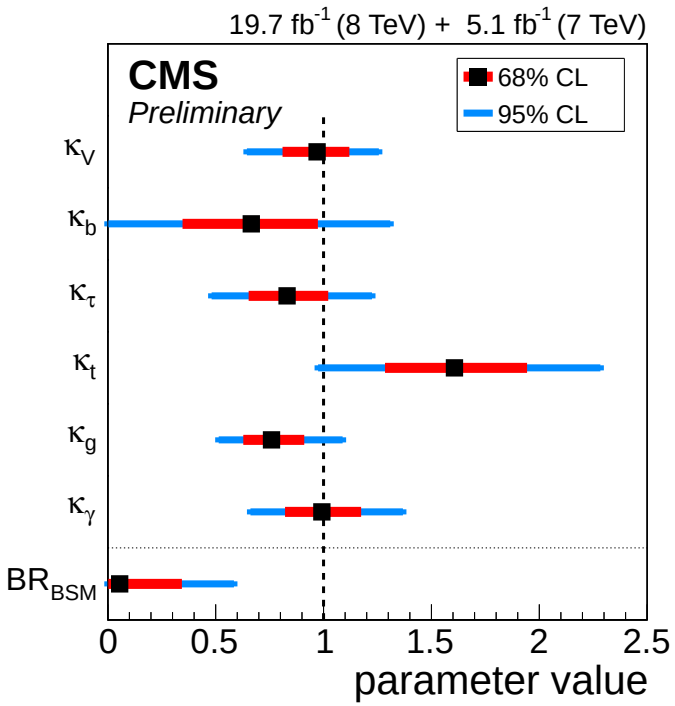
Now only upper bound
wait for next LHC run

Probed in $gg \to hh$
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

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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

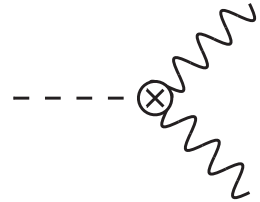
Testing the doublet hypothesis

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**

$c_{VV} V_{\mu\nu} V^{\mu\nu} \frac{h}{v}$ ➠



$\propto \; i\, c_{VV} \left(\eta^{\mu\nu} \left(\frac{\hat{s}}{2} - m_V^2 \right) - p_3^\mu p_2^\nu \right)$

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; Biekoetter et al.]

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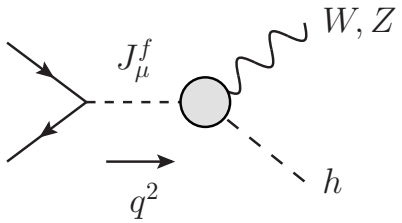
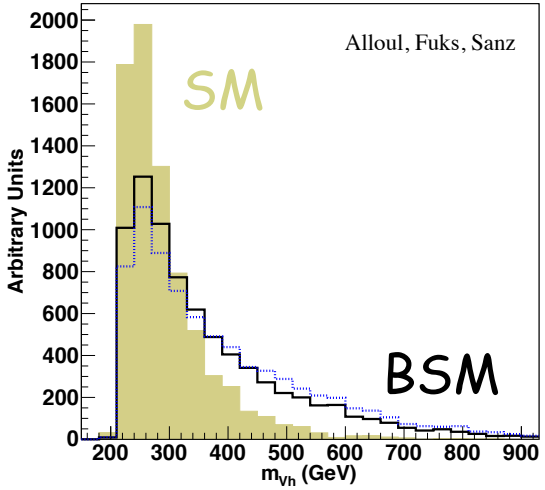
Boosted Higgs in HV



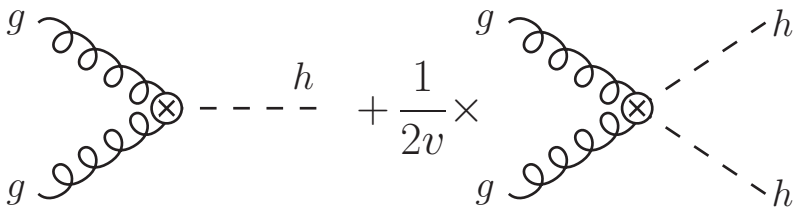


Large effects at high m_{Vh} or p_T can be used to probe derivative operators

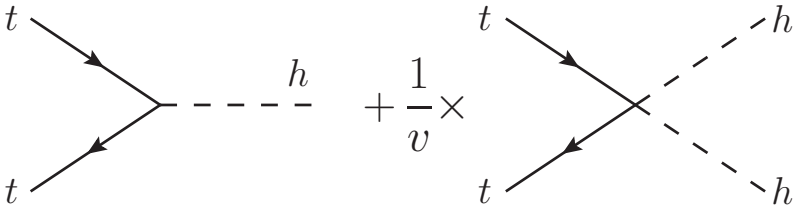
Testing the doublet hypothesis

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

$|H|^2 G_{\mu\nu} G^{\mu\nu}$ ➠



$|H|^2 \overline{q}_L H t_R + \text{h.c.}$ ➠

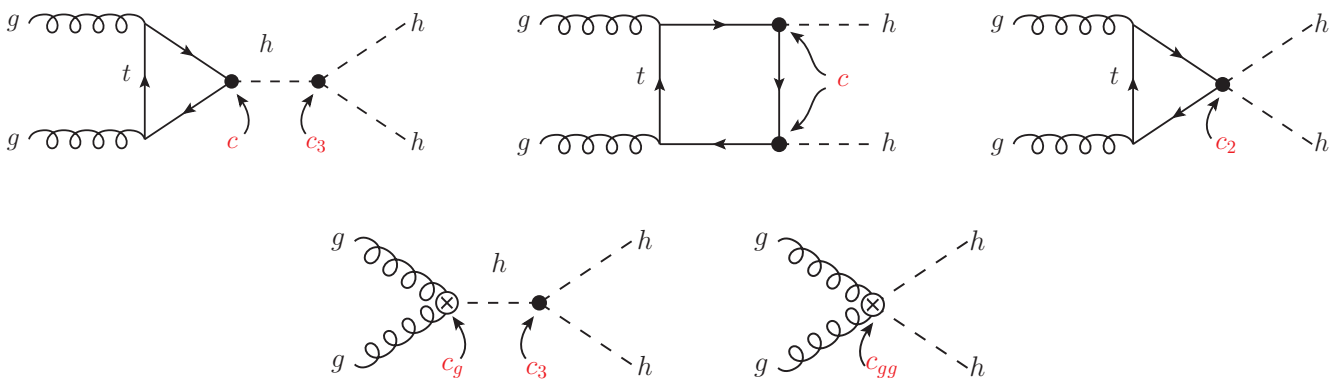


- ➢ Deviations in single-Higgs processes are related to deviations in multi-Higgs processes
- ➢ Multi-Higgs channels can also test the Higgs trilinear: $|H|^6$

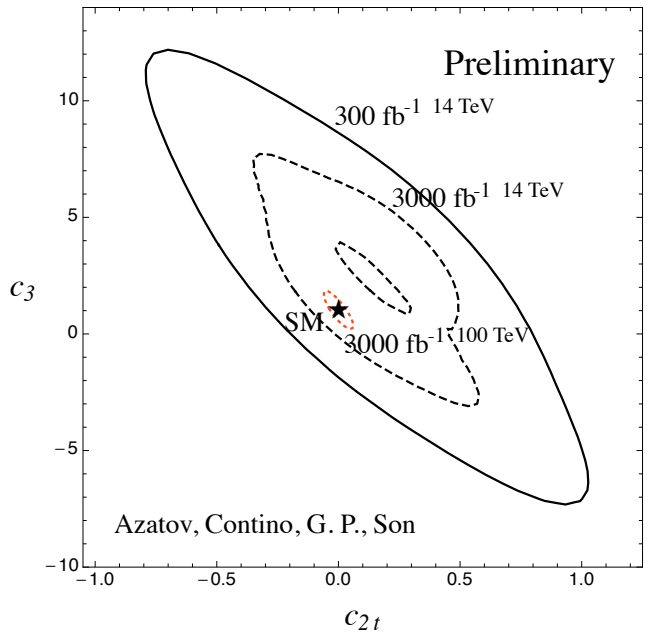
Testing the doublet hypothesis

The $gg \to hh$ 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