Higgs Boson Review

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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**

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We can **directly test**

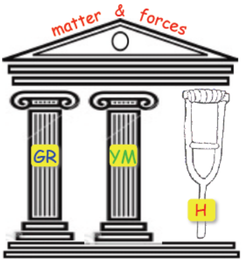
the mechanism of **ElectroWeak symmetry breaking**

✧ ✧ ✧ **The Standard Model realization** ✧ ✧ ✧

- **Minimal** extension of the EW theory
- The Higgs is an **elementary scalar**
- 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
- ...

Introduction

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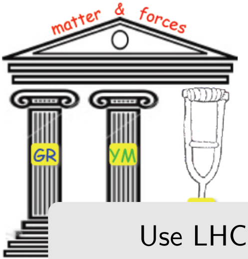

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Use LHC data to **test** the Higgs **properties**
and select the correct model!

Several **alternative theories** have been proposed

- Supersymmetry
- Composite Higgs
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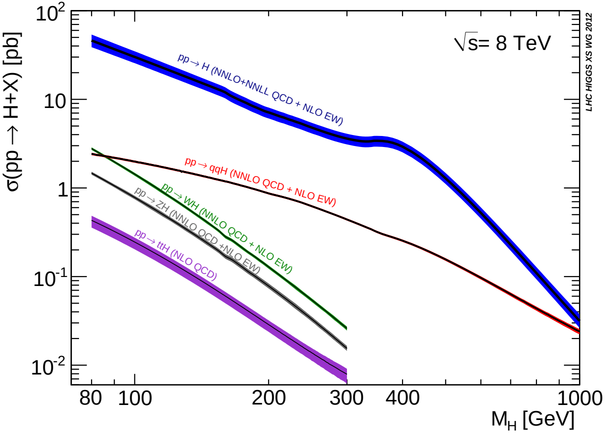
Outline

In this talk:

- Review of the **experimental results**
- Tools for an (almost) **model-independent analysis** of the Higgs properties

Higgs production in the SM

Many Higgs production channels **relevant** for the LHC



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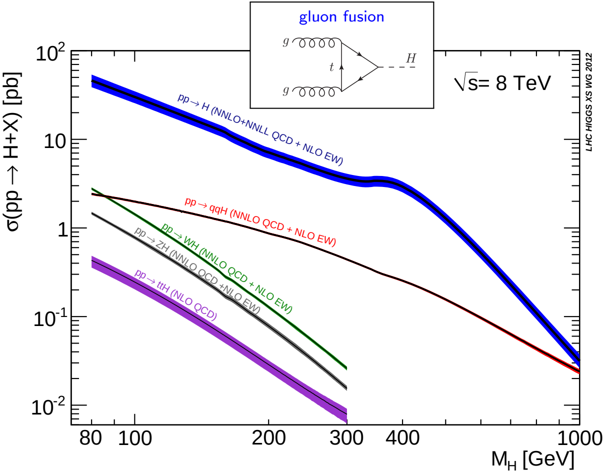

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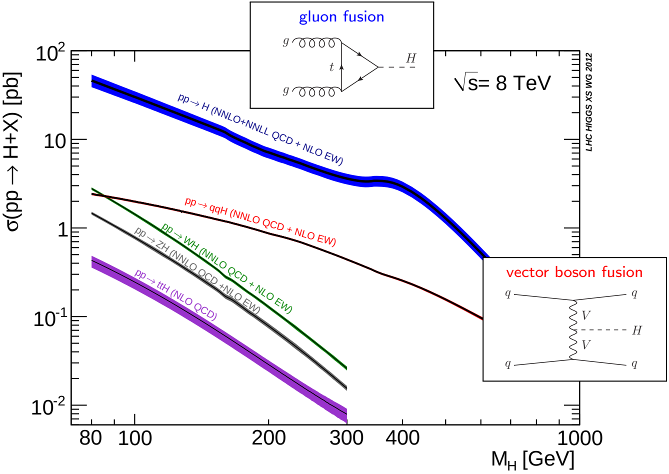

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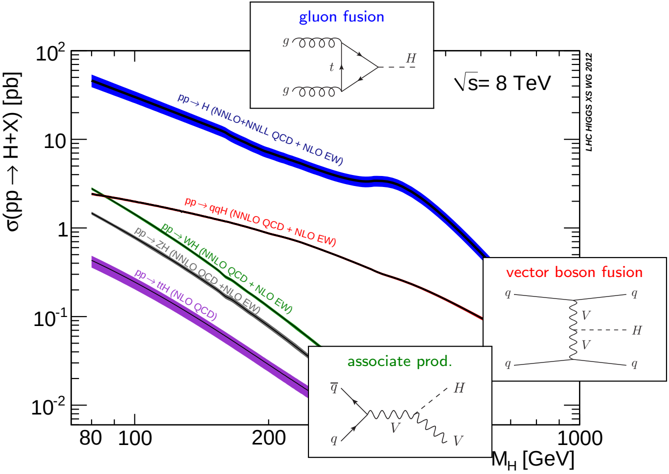

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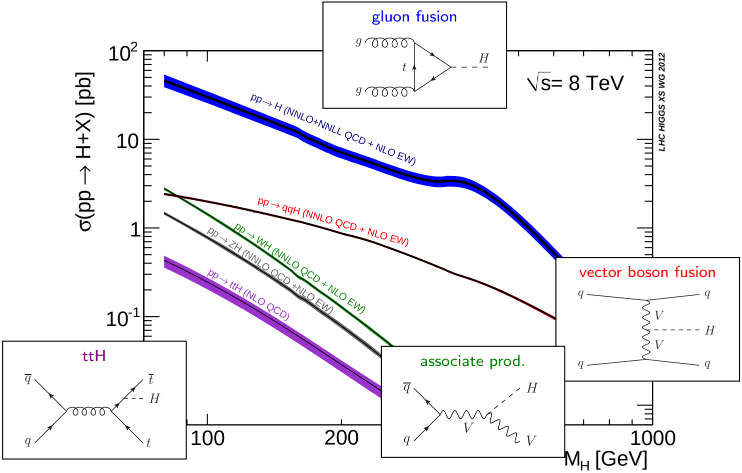
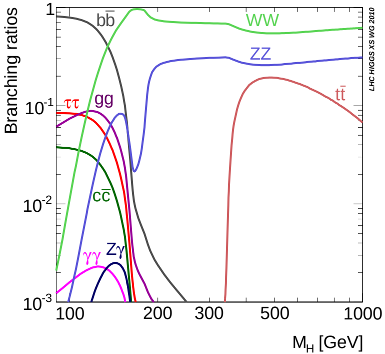
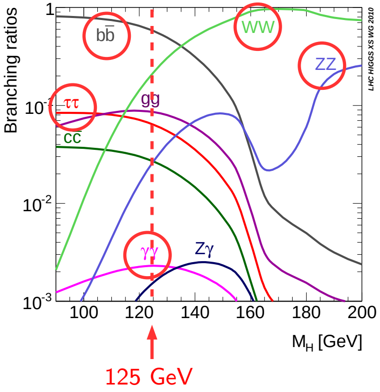


Higgs decays in the SM

A 125 GeV Higgs is a **very narrow** resonance ($\Gamma_H \sim 4$ MeV)

Many decay modes can be used to get information about the Higgs properties.





Main Higgs analyses

Experimentally relevant channels are **limited** by

- **Small** production cross section or branching ratio
- Presence of **large backgrounds**

Channel	mass resolution	ggH		VBF		VH		$\mathrm{t\bar{t}H}$	
		ATLAS	CMS	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
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$H \to \tau^+\tau^-$	15%	✓	✓	✓	✓	✓	✓		
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$\Rightarrow$ **Only leading** production channel relevant

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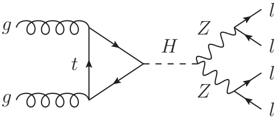
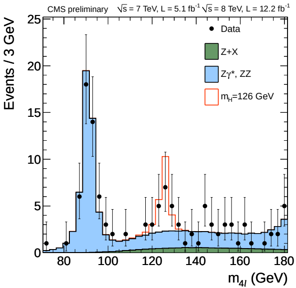
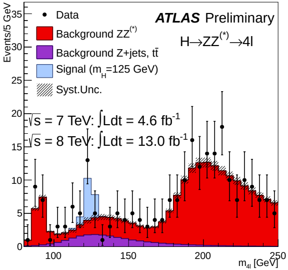
best channels

$H \to ZZ^{(*)} \to 4l$

Golden channel







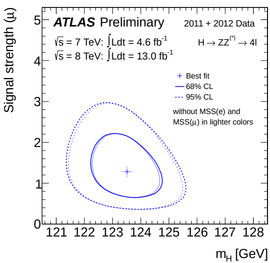
- Very **low** background

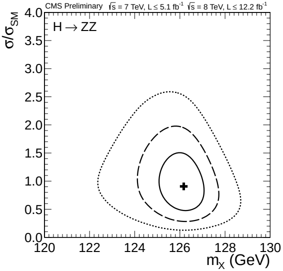
  Signal/Bkgd $\sim 2:1$

- Very **good** mass resolution

- **Fully reconstructed** mass peak

$H \to ZZ^{(*)} \to 4l$

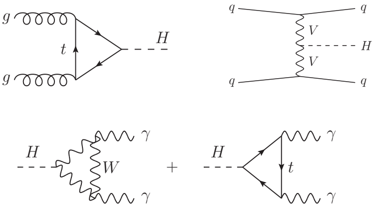


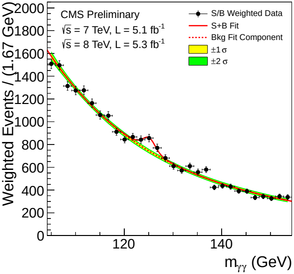


- Local significance $\gtrsim 4\sigma$
- Mass measurement
  - ATLAS: $\mathbf{m_H = 123.5 \pm 0.9\,(stat)\,^{+0.4}_{-0.2}\,(syst)\ GeV}$
  - CMS: $\mathbf{m_H = 126.2 \pm 0.6\,(stat) \pm 0.2\,(syst)\ GeV}$
- Signal strength compatible with the SM
  - ATLAS: $\hat{\mu} = \mathbf{1.3 \pm 0.4}$
  - CMS: $\hat{\mu} = \mathbf{0.8\,^{+0.35}_{-0.28}}$

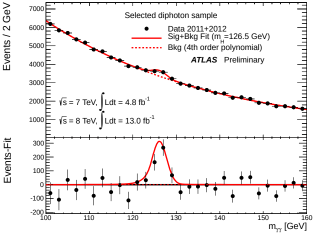
$H \to \gamma\gamma$

Good discovery channel



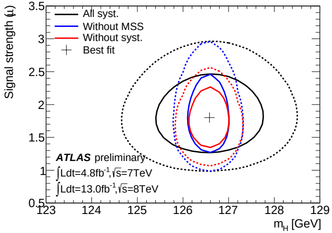


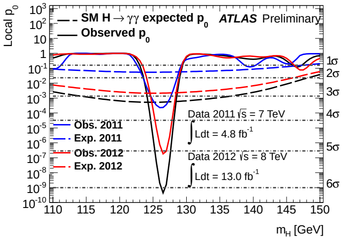
- Large but **smooth** QCD backgrounds ($\gamma\gamma$, γj, jj)



- **Excellent** mass resolution
- **Fully reconstructed** mass peak

$H \to \gamma\gamma$





ATLAS:

- Analysis with 13 fb^{-1} at 8 TeV
- Local significance 6.1σ (expected 3.3σ)
- Mass measurement: $\mathbf{m_H = 126.6 \pm 0.3(stat) \pm 0.7(syst)\ GeV}$

CMS:

- **Only** analysis with 5.3 fb^{-1} at 8 TeV available
- Local significance 4.1σ (expected 2.8σ)

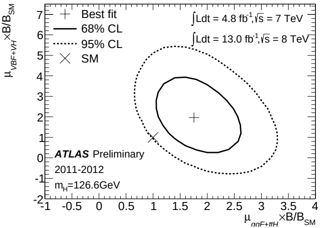
$H \to \gamma\gamma$

Both experiments show a signal strength **larger** than the SM

- Deviations **not** statistically significant

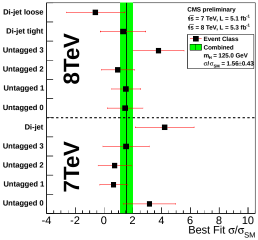
ATLAS:

$$\hat{\mu} = \mathbf{1.8} \pm \mathbf{0.3}\,(\mathbf{stat})\,^{+\mathbf{0.29}}_{-\mathbf{0.21}}\,(\mathbf{syst})$$

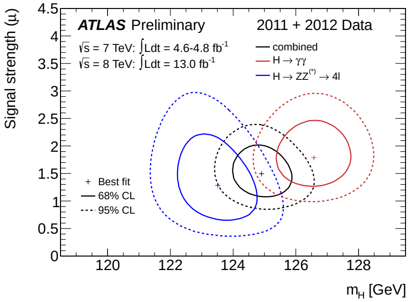


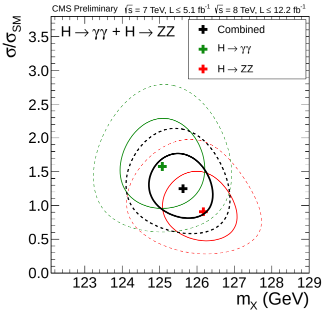
CMS:

$$\hat{\mu} = \mathbf{1.56} \pm \mathbf{0.43}$$



Combination of $H \to ZZ^{(*)}$ and $H \to \gamma\gamma$ channels



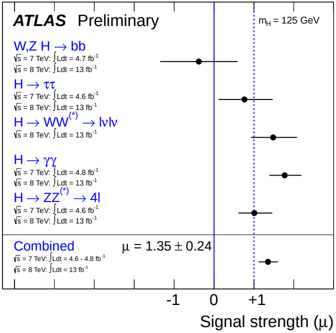


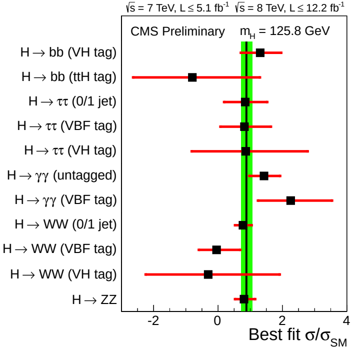
Combined **mass** measurement

- ATLAS: $\mathbf{m_H = 125.2 \pm 0.3\,(stat) \pm 0.6\,(syst)\ GeV}$
- CMS: $\mathbf{m_H = 125.8 \pm 0.4\,(stat) \pm 0.4\,(syst)\ GeV}$

▸ **Tension** between the $ZZ^{(*)}$ and $\gamma\gamma$ channels for ATLAS (**not** statistically significant)

Combination of all the channels





All channels **fairly consistent** with the SM.

Overall **signal strength**

- ATLAS: $\hat{\mu} = \mathbf{1.35} \pm \mathbf{0.19}\,(\mathbf{stat}) \pm \mathbf{0.15}\,(\mathbf{syst})$
- CMS: $\hat{\mu} = \mathbf{0.88} \pm \mathbf{0.21}$

Higgs properties

The discovery of an Higgs-like particle is only the **first step**!

Use the Higgs as a **portal** to explore the **EW symmetry breaking mechanism**

- test the **SM predictions**
- search for **new physics**

Use the data to extract the main **Higgs properties**:

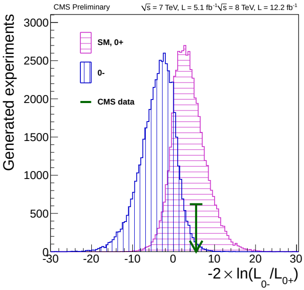
- spin and parity
- couplings
- quantum numbers

Spin and Parity measurements

The decay into two photons selects **integer spin** 0 **or** 2 (spin 1 **forbidden** by Landau–Yang theorem)

Spin and **parity** can be tested through the **angular correlations** of the $H \to ZZ^{(*)}$ events

- Odd parity **strongly disfavored** (at 2.45σ level)



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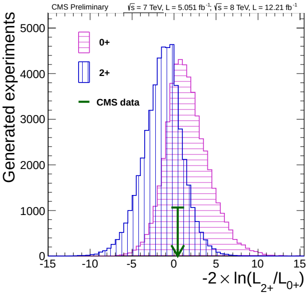
- Spin 2 hypothesis still **experimentally viable** (but **theoretically problematic**)



Higgs couplings

Is the new particle **the** SM Higgs or an **Higgs-like** state?

$\Rightarrow$ measure the Higgs **couplings**!

Use a **model-independent** approach: **effective Higgs Lagrangian**

Some initial **assumptions**:

- Higgs is a parity even scalar
- custodial symmetry (helps with EW precision data)
- no Higgs FCNC (protection of flavor)
- no extra light particles

Higgs couplings: Effective Higgs Lagrangian

We can write an **effective Lagrangian** for a **light Higgs-like scalar** [Contino, Grojean, Moretti, Piccinini, Rattazzi 2010]

$$
\left.\begin{aligned}
\mathcal{L}_{eff} = {} & \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - \sum_\psi m_\psi \overline{\psi}\psi \left(1 + c_\psi \frac{h}{v} + \cdots\right) \\
& - \left(m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu\right)\left(1 + 2\,a\frac{h}{v} + \cdots\right)
\end{aligned}\right\} \mathcal{O}(p^2)
$$

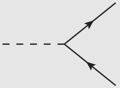
$$
\left.\begin{aligned}
& + \frac{g^2}{16\pi^2}\left(c_{WW} W_{\mu\nu}^+ W^{-\mu\nu} + c_{ZZ} Z_{\mu\nu}^2 + c_{Z\gamma} Z_{\mu\nu}\gamma^{\mu\nu}\right)\frac{h}{v} + \cdots \\
& + \frac{g^2}{16\pi^2}\gamma_{\mu\nu}^2\left(c_{\gamma\gamma}\frac{h}{v} + \cdots\right) + \frac{g_s^2}{16\pi^2} G_{\mu\nu}^2\left(c_{gg}\frac{h}{v} + \cdots\right)
\end{aligned}\right\} \mathcal{O}(p^4)
$$

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

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

Higgs couplings: Effective Higgs Lagrangian

Controls the $h\psi\psi$ coupling



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

W… **…grangian** for a **light Higgs-like**
sc… …ntino, Grojean, Moretti, Piccinini, Rattazzi 2010]

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& + \frac{g^2}{16\pi^2}\gamma^2_{\mu\nu}\left(c_{\gamma\gamma}\frac{h}{v} + \cdots\right) + \frac{g_s^2}{16\pi^2} G^2_{\mu\nu}\left(c_{gg}\frac{h}{v} + \cdots\right)
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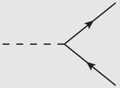

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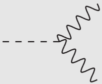
Controls the hVV couplings



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

W… **grangian**

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$$\mathcal{L}_{eff} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - \sum_\psi m_\psi \overline{\psi}\psi \left(1 + c_\psi \frac{h}{v} + \cdots\right)$$

$$- \left(m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu\right)\left(1 + 2\,a\,\frac{h}{v} + \cdots\right)$$

$$+ \frac{g^2}{16\pi^2}\left(c_{WW} W_{\mu\nu}^+ W^{-\mu\nu} + c_{ZZ} Z_{\mu\nu}^2 + c_{Z\gamma} Z_{\mu\nu}\gamma^{\mu\nu}\right)\frac{h}{v} + \cdots$$

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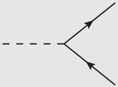
In the SM: $a = c_\psi = 1$, $c_{VV} = c_{\gamma\gamma} = c_{gg} = 0$

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

Higgs couplings: Effective Higgs Lagrangian

Controls the $h\psi\psi$ coupling



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

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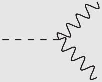
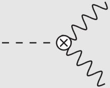
Controls the hVV couplings



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

Corrections to hVV couplings



$\propto c_{VV}$

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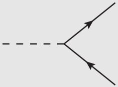

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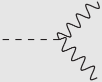

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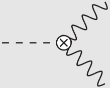
Corrections to hVV couplings



$\propto c_{VV}$

$$+ \frac{g^2}{16\pi^2}\left(c_{WW} W^+_{\mu\nu} W^{-\mu\nu} + c_{ZZ} Z^2_{\mu\nu} + c_{Z\gamma} Z_{\mu\nu}\gamma^{\mu\nu}\right)\frac{h}{v} + \cdots$$

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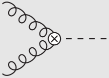
Modify gluon fusion and $\gamma\gamma$ decay



$\propto c_{\gamma\gamma}, c_{gg}$

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

- **New physics** can give contribut

Constraining the Higgs couplings

Current LHC sensitivity is **not enough** to constrain all the parameters.

To obtain a **fit** reduce them with **simplifying assumptions**:

- all fermion couplings scale with a common factor
- only SM fields contribute (at loop) to Hgg and $H\gamma\gamma$

We are left with **only** 2 **free parameters**: a and c_ψ.

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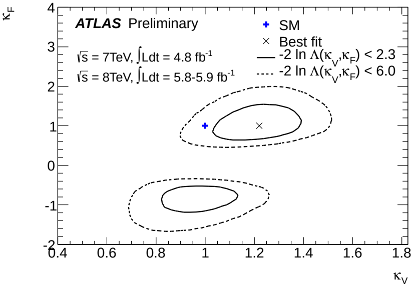
Several fits from theory groups:

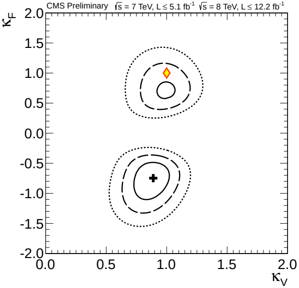
Carmi, Falkowski, Kuflik, Volansky, arXiv:1202.3144
Azatov, Contino, Galloway arXiv:1202.3415
Espinosa, Grojean, Muhlleitner, Trott, arXiv:1202.3697
Giardino, Kannike, Raidal, Strumia, arXiv:1203.4254
Ellis and You, arXiv:1204.0464
Klute, Lafaye, Plehn, Rauch, Zerwas, arXiv:1205.2699
Cacciapaglia, Deandrea, Drieu La Rochelle, Flament, arXiv:1210.8120
Bélanger, Dumont, Ellwanger, Gunion, Kraml, arXiv:1212.5244
...

- **See next talks!** (by Drieu La Rochelle and Dumont)

Fits of the Higgs couplings

The **experimental collaborations** started to produce fits



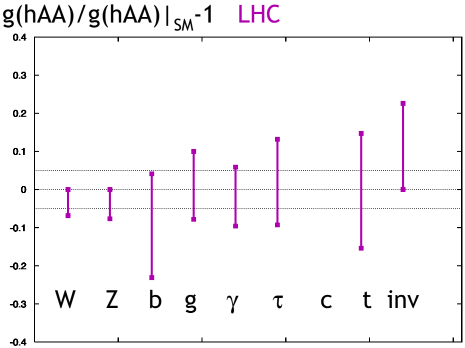


- **SM compatible** within 2σ but still **room for large deviations**

Higgs couplings: LHC reach

Ultimate **LHC reach** for model-independent Higgs **coupling measurements** $\sim 10 - 20\%$

LHC at 14 TeV with 300 fb^{-1}



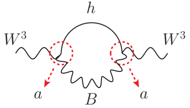
[Peskin 2012]

The legacy from LEP

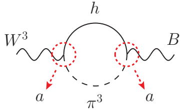
The **deviations** from the SM Higgs couplings induces **corrections** to the **EW precision observables**

The parameter a controls the size of the **one-loop effects**:

$$\Delta S = \frac{1}{12\pi}(\mathbf{1} - \mathbf{a^2}) \log\left(\frac{\mathbf{\Lambda^2_{NP}}}{m_h^2}\right)$$



$$\Delta T = -\frac{3}{16\pi^2 \cos^2\theta_W}(\mathbf{1} - \mathbf{a^2}) \log\left(\frac{\mathbf{\Lambda^2_{NP}}}{m_h^2}\right)$$

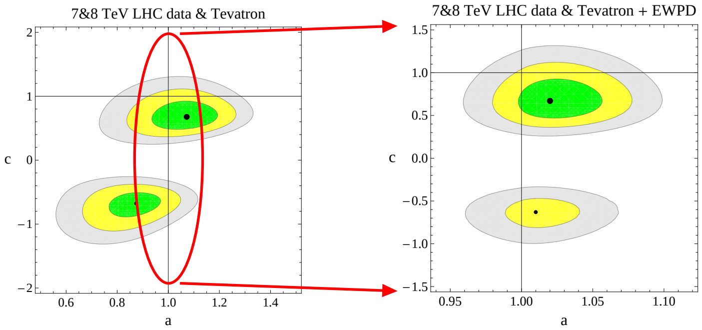


- The logarithmic divergence cancels only for the SM ($a = 1$)
- For $a \neq 1$ **logarithmic sensitivity** to **new physics** scale Λ_{NP}

[Barbieri, Bellazzini, Rychkov, Varagnolo 2007]

The legacy from LEP

The EW precision tests put **strong constraints** on the fit of the Higgs couplings [Espinosa, Grojean, Muhlleitner, Trott 2012]



- The SM value $a = 1$ is preferred.
- **New resonances** can contribute to the EWPT and modify the picture

Testing the Higgs quantum numbers

Test if the Higgs is part of an $SU(2)$ **doublet**.

Write an effective Lagrangian respecting the **full SM gauge group** $SU(2)_L \times U(1)_Y$. [Buchmuller, Wyler 1986; Grzadkowski et al. 2010]

Need to take into account <u>**non-linear Higgs couplings**</u>

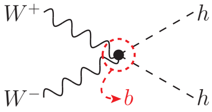
$$\begin{aligned}\mathcal{L}_{eff} = &\frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - \frac{d_3}{6}\left(\frac{3m_h^2}{v}\right)h^3 + \cdots \\ &- \left(m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2}m_Z^2 Z_\mu Z^\mu\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots\right) \\ &- \sum_\psi m_\psi \overline{\psi}\psi\left(1 + c_\psi\frac{h}{v} + c_{2\psi}\frac{h^2}{v^2} + \cdots\right)\end{aligned}$$

In the SM: $b = d_3 = 1,\ c_{2\psi} = 0$

Testing the Higgs quantum numbers

If the Higgs is part of a doublet: $b - 1 = 2(a^2 - 1)$

Coupling b related to **double Higgs production** in W fusion

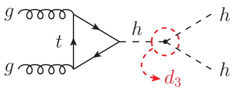


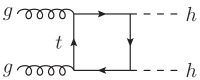
Small cross section: **difficult** to probe at the LHC!

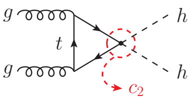
[Contino, Grojean, Moretti, Piccinini, Rattazzi 2010]

Higgs non-linear interactions

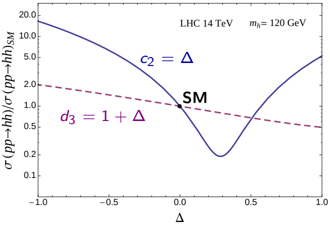
$gg \to hh$ is a **good channel** to test the Higgs **non-linear interactions** [Dib, Rosenfeld, Zerwekh 2006; Grober, Muhlleitner 2011]







- **large** dependence on non-SM coupling c_2
- **poor** sensitivity on Higgs trilinear d_3



[Contino, Ghezzi, Moretti, G. P., Piccinini, Wulzer 2012]

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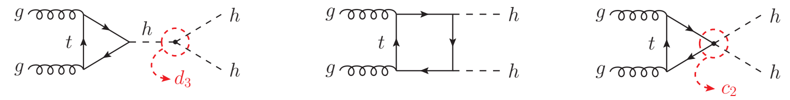
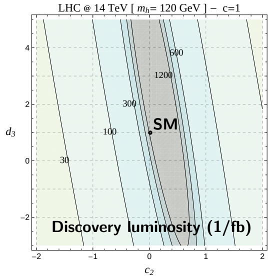


- **large** dependence on non-SM coupling c_2
- **poor** sensitivity on Higgs trilinear d_3
- **High luminosity** required ($\gtrsim 600\ \text{fb}^{-1}$ at 14 TeV for the SM)



[Contino, Ghezzi, Moretti, G. P., Piccinini, Wulzer 2012]

Conclusions

The recent **discovery** of an Higgs-like particle opens the doors for a **direct test** of the EW symmetry breaking mechanism.

Use the LHC results to **test the SM** and search for **new physics**

The experimental results start to probe the **Higgs properties**

- SM **compatible** with the results
- **Some tension** in the data: still **room** for **sizable deviations!**

Conclusions

Use of a **model-independent** approach:

- parametrize the Higgs physics through an **effective Lagrangian**

Current data can be used for some **(preliminary) fits**

In the **late LHC** stage:

- Higgs coupling measurements with $\mathbf{10-20\%}$ **accuracy**
- Analysis of **non-linear Higgs couplings**

Backup slides

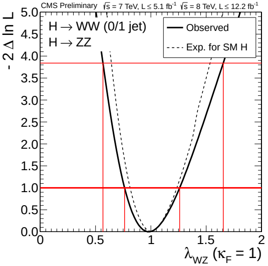
Test of custodial symmetry

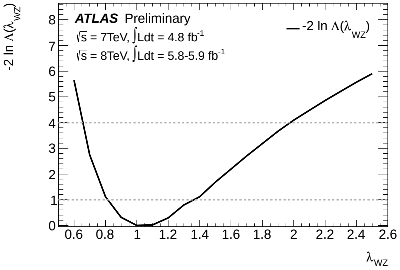
The SM Higgs sector is invariant under a global $SU(2)_L \times SU(2)_R$ only "mildly" broken (by the Yukawas and the $U(1)_Y$ gauging)

The symmetry relates the Z and W coupling to the Higgs:

$$\Lambda_{WZ} \equiv c_W / c_Z = 1$$

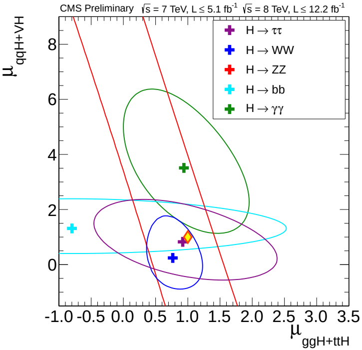
Experimental data **consistent** with the symmetry





Combination of all the channels

The main production mechanisms are all related to the Higgs coupling to the **top quark** (gluon fusion, $t\bar{t}H$) or to the **vector bosons** (VB fusion, associate prod.).



The SM is **within 95% CL** of each channel