Status of Higgs coupling strength determination from ATLAS and CMS

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(for the ATLAS and CMS collaborations)
Outline

- Introduction
  - Higgs at the LHC
  - Higgs production channels and decays modes
  - Higgs couplings

- Signal strength measurements

- Higgs coupling-strength fits
  - Framework for the analysis of Higgs couplings
  - Benchmark models:
    - New physics in vertices?
    - Fermions vs. bosons?
    - Custodial symmetry?
    - New physics in loops?
    - Decay invisibly?

- Summary
The quest for the Higgs boson

Save the date: July 4th 2012
over the last ~1150 days…

Questions to answer after the discovery

• Is this the Higgs boson of the SM?
• Are the signal strengths as expected in the SM?
• Is the new boson a scalar, and not a pseudo-scalar or a tensor?
• Does it couple to itself?
• Are there any other Higgs bosons to observe?
• Is this Higgs boson a window to new physics?
LHC is a Higgs factory

Luminosity \( (25 \text{ fb}^{-1}) \) * cross-section \( (20 \text{ pb}) \) = 0.5 M Higgs per experiment!!

Only one in \( \sim 10^{10} \) events contains a Higgs boson
Plays a role in electroweak symmetry breaking

Higgs field serves as the source of mass generation in the fermion sector, through a Yukawa interaction
LHC Run I tells us there exists one CP even scalar boson.

Its measured mass is $125.09 \pm 0.21 \text{ (stat.)} \pm 0.11 \text{ (syst.) GeV}$. 

It was observed in the bosonic decay channels: $ZZ$, $\gamma\gamma$ and $WW$.

There is evidence that couples to $\tau^+ \tau^-$. 

Preliminary combined analysis of all channels presented in July 2014.

In the last months: coupling measurements!!

Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV

CMS Collaboration*
CERN, 1211 Geneva 23, Switzerland


arXiv: 1507.04548

Measurements of the Higgs boson production and decay rates and coupling strengths using $pp$ collision data at $\sqrt{s} = 7$ and 8 TeV in the ATLAS experiment

The ATLAS Collaboration
What is included in the combination?
### Several channels...

<table>
<thead>
<tr>
<th>Production</th>
<th>ggH</th>
<th>VBF</th>
<th>VH</th>
<th>ttH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow ZZ(4\ell)$</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>$H \rightarrow WW(2\ell2\nu)$</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>$H \rightarrow bb$</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
</tbody>
</table>

**Rare channels:**
- $H \rightarrow \mu\mu$
- $H \rightarrow Z\gamma$
Gluon Fusion (ggF)

Vector Boson Fusion (VBF)

Associated production with vector bosons (VH)

Associated production with top quarks (ttH, tH, WtH)
• to fermions $\sim m_f$

• to massive Gauge bosons $\sim m_V^2$

• to massless Gauge bosons via loops: photons and gluons

• self-couplings $\sim m_H^2$

Very precise predictions (only unpredicted parameter: $m_H$)

SM branching ratio at $m_H \sim 125$ GeV

- $H \rightarrow bb$ 58%
- $H \rightarrow WW^*$ 22%
- $H \rightarrow \tau\tau$ 6.3%
- $H \rightarrow ZZ^*$ 2.6%
- $H \rightarrow \gamma\gamma$ 0.23%
Are the observed yields compatible with the SM Higgs boson?
The compatibility between the measured rates and the SM prediction is tested using signal strength parameters for each production and decay mode:

\[
\mu = \frac{N_{\text{obs}}}{N_{\text{exp}}} = \frac{\sigma_i \times BR_f}{\sigma_i \times BR_f}^{\text{SM}} = \frac{\sigma_i^{\text{SM}} \times BR_f^{\text{SM}}}{\sigma_i \times BR_f} = \mu_i \times \mu_f
\]
From yields to signal strengths

**ATLAS**

Individual analysis

<table>
<thead>
<tr>
<th>Process</th>
<th>Input measurements</th>
<th>m_H (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H → γγ</td>
<td>Overall: μ = 1.17_{-0.37}^{+0.27}</td>
<td>125.4</td>
</tr>
<tr>
<td></td>
<td>ggF: μ = 1.32_{-0.33}^{+0.35}</td>
<td>125.4</td>
</tr>
<tr>
<td></td>
<td>VBF: μ = 0.8_{-0.3}^{+0.3}</td>
<td>125.4</td>
</tr>
<tr>
<td></td>
<td>WH: μ = 1.0_{-0.4}^{+0.4}</td>
<td>125.4</td>
</tr>
<tr>
<td></td>
<td>ZH: μ = 0.1_{-0.3}^{+0.3}</td>
<td>125.4</td>
</tr>
<tr>
<td>H → ZZ*</td>
<td>Overall: μ = 1.44_{-0.39}^{+0.40}</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>ggF + tH: μ = 1.7_{-0.4}^{+0.4}</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>VBF + VH: μ = 0.3_{-0.3}^{+0.3}</td>
<td>125.36</td>
</tr>
<tr>
<td>H → WW*</td>
<td>Overall: μ = 1.16_{-0.40}^{+0.40}</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>ggF: μ = 0.98_{-0.30}^{+0.30}</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>VBF: μ = 1.2_{-0.4}^{+0.4}</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>WH: μ = 3.0_{-0.3}^{+0.3}</td>
<td>125.36</td>
</tr>
<tr>
<td>H → ττ</td>
<td>Overall: μ = 1.43_{-0.37}^{+0.37}</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>ggF: μ = 2.0_{-0.4}^{+0.4}</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>VBF + VH: μ = 1.2_{-0.4}^{+0.4}</td>
<td>125.36</td>
</tr>
<tr>
<td>V H → V bb</td>
<td>Overall: μ = 0.52_{-0.40}^{+0.40}</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>WH: μ = 1.1_{-0.2}^{+0.2}</td>
<td>125.5</td>
</tr>
<tr>
<td></td>
<td>ZH: μ = 0.05_{-0.3}^{+0.3}</td>
<td>125.5</td>
</tr>
<tr>
<td>H → μμ</td>
<td>Overall: μ = 0.7_{-0.3}^{+0.3}</td>
<td>125.5</td>
</tr>
<tr>
<td>tH</td>
<td>Overall: μ = 2.7_{-1.3}^{+1.3}</td>
<td>125.4</td>
</tr>
</tbody>
</table>

\[ \sigma_{\text{SM}} = 1 \]

Total signal strengths

- H → γγ (untagged) \[ \sigma_{\text{SM}} = 1 \]
- H → γγ (VH tag) \[ \sigma_{\text{SM}} = 0.84 \]
- H → γγ (ttH tag) \[ \sigma_{\text{SM}} = 0.84 \]
- H → ZZ (0/1-jet) \[ \sigma_{\text{SM}} = 0.84 \]
- H → WW (0/1-jet) \[ \sigma_{\text{SM}} = 0.84 \]
- H → WW (VBF tag) \[ \sigma_{\text{SM}} = 0.84 \]
- H → ττ (0/1-jet) \[ \sigma_{\text{SM}} = 0.84 \]
- H → ττ (VBF tag) \[ \sigma_{\text{SM}} = 0.84 \]
- H → ττ (ttH tag) \[ \sigma_{\text{SM}} = 0.84 \]
- H → bb (VH tag) \[ \sigma_{\text{SM}} = 0.84 \]
- H → bb (ttH tag) \[ \sigma_{\text{SM}} = 0.84 \]

Combined \[ \sigma = 1.00 \pm 0.14 \]

CMS

\[ m_H = 125 \text{ GeV} \]

\[ p_{\text{SM}} = 0.84 \]

19.7 fb\(^{-1}\) (8 TeV) + 5.1 fb\(^{-1}\) (7 TeV)
Combinations
Combining diff. measurements...

**Simplest model: one overall signal strength**

**best-fit $\mu$**

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu = 1.18 \pm 0.10$ (stat) $\pm 0.07$ (syst) $^{+0.08}_{-0.07}$ (theory)</td>
<td>$\mu = 1.00 \pm 0.09$ (stat) $\pm 0.07$ (syst) $^{+0.08}_{-0.07}$ (theory)</td>
</tr>
</tbody>
</table>

- Good agreement with theoretical predictions.
- Theoretical and experimental uncertainties have similar size as the statistical ones.

**Grouping by decay mode**

- Various signal strength parameters, one per decay channel: $\mu_{\gamma\gamma}$, $\mu_{ZZ}$, $\mu_{WW}$, $\mu_{\tau\tau}$, $\mu_{bb}$, $\mu_{\mu\mu}$ and $\mu_{Z\gamma}$
- Very good compatibility with SM Higgs predictions.
Grouping by production mechanism

Four parameters: $\mu_{ggF}$, $\mu_{VBF}$, $\mu_{VH}$ and $\mu_{ttH}$
- $\mu_{ttH}$ is 1-2$\sigma$ higher than SM prediction, mostly driven by multilepton analysis

Bosonic and fermionic production modes

For each decay mode, the ratio $\mu_{ggF+ttH}/\mu_{VBF+VH}$ is independent of BR.
Is the observed data compatible with the SM Higgs boson couplings?
Beyond the parametrisations using signal strength parameters, “coupling modifiers $\kappa_i$,” (also called scale factors) based on a LO motivated framework are used to interpret the data and check for deviations from the SM.

**$\kappa$-framework (coupling formalism)**

- **Parametrise $\mu$’s in terms of $\kappa_i$, fit all them simultaneously and test diff. assumptions on relation between $\kappa_i$’s**

Assumptions:
- single and narrow resonance
- kinematics unmodified (tensor structure as in the SM)

- $\kappa_H$ parametrises change in total width: independent parameter or as a function of other $\kappa_i$’s

- invisible or undetected decays have $BR_{i,u}$.

- overall width scales as $\Gamma_H^{SM} = \frac{\Gamma_{i,u}}{1 - BR_{i,u}} \cdot \Gamma_H^{SM}$

- loop-induced couplings either **resolved** (in terms of SM particle $\kappa$) or **unresolved** (own $\kappa$)

$$\lambda_{ij} = \frac{\kappa_i}{\kappa_j}$$
<table>
<thead>
<tr>
<th>Production</th>
<th>Loops</th>
<th>Interference</th>
<th>Expression in fundamental coupling-strength scale factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(ggF)$</td>
<td>$\checkmark$</td>
<td>$b-t$</td>
<td>$\kappa_{g}^2 \sim 1.06 \cdot \kappa_{t}^2 + 0.01 \cdot \kappa_{b}^2 - 0.07 \cdot \kappa_{t} \kappa_{b}$</td>
</tr>
<tr>
<td>$\sigma(VBF)$</td>
<td>-</td>
<td>-</td>
<td>$\sim 0.74 \cdot \kappa_{W}^2 + 0.26 \cdot \kappa_{Z}^2$</td>
</tr>
<tr>
<td>$\sigma(WH)$</td>
<td>-</td>
<td>-</td>
<td>$\sim \kappa_{W}^2$</td>
</tr>
<tr>
<td>$\sigma(q\bar{q} \rightarrow ZH)$</td>
<td>-</td>
<td>-</td>
<td>$\sim \kappa_{Z}^2$</td>
</tr>
<tr>
<td>$\sigma(gg \rightarrow ZH)$</td>
<td>$\checkmark$</td>
<td>$Z-t$</td>
<td>$\kappa_{ggZH}^2 \sim 2.27 \cdot \kappa_{Z}^2 + 0.37 \cdot \kappa_{t}^2 - 1.64 \cdot \kappa_{Z} \kappa_{t}$</td>
</tr>
<tr>
<td>$\sigma(bbH)$</td>
<td>-</td>
<td>-</td>
<td>$\sim \kappa_{b}^2$</td>
</tr>
<tr>
<td>$\sigma(ttH)$</td>
<td>-</td>
<td>-</td>
<td>$\sim \kappa_{t}^2$</td>
</tr>
<tr>
<td>$\sigma(gb \rightarrow Wth)$</td>
<td>-</td>
<td>$W-t$</td>
<td>$\sim 1.84 \cdot \kappa_{t}^2 + 1.57 \cdot \kappa_{W}^2 - 2.41 \cdot \kappa_{t} \kappa_{W}$</td>
</tr>
<tr>
<td>$\sigma(qb \rightarrow tHq')$</td>
<td>-</td>
<td>$W-t$</td>
<td>$\sim 3.4 \cdot \kappa_{t}^2 + 3.56 \cdot \kappa_{W}^2 - 5.96 \cdot \kappa_{t} \kappa_{W}$</td>
</tr>
</tbody>
</table>

Partial decay width

<table>
<thead>
<tr>
<th>Component</th>
<th>±</th>
<th>$\kappa_{W}^2$</th>
<th>$\kappa_{Z}^2$</th>
<th>$\kappa_{b}^2$</th>
<th>$\kappa_{t}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_{bb}$</td>
<td>±</td>
<td>$\kappa_{b}^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{WW}$</td>
<td>±</td>
<td>$\kappa_{W}^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{ZZ}$</td>
<td>±</td>
<td>$\kappa_{Z}^2$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{\tau\tau}$</td>
<td>±</td>
<td></td>
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<tr>
<td>$\Gamma_{\mu\mu}$</td>
<td>±</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{\gamma\gamma}$</td>
<td>±</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{Z\gamma}$</td>
<td>±</td>
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</tbody>
</table>

Total decay width

<table>
<thead>
<tr>
<th>Component</th>
<th>±</th>
<th>$\kappa_{W}^2$</th>
<th>$\kappa_{Z}^2$</th>
<th>$\kappa_{b}^2$</th>
<th>$\kappa_{t}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_{H}$</td>
<td>±</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
Check couplings relative to SM
Higgs gives mass? Check scaling of couplings with particle masses

Assume only SM particles, no new decay modes. Best constraints ~15% precision.
The current dataset does not allow the determination of all the coupling modifiers → test specific scenarios: **different benchmark models** defined by LHC-XS-WG [arXiv:1307.1347]

The current dataset does not allow the determination of all the coupling modifiers → test specific scenarios: **different benchmark models** defined by LHC-XS-WG [arXiv:1307.1347]

- **custodial symmetry: W and Z couplings**
  - \( \lambda_{WZ} = 0.92^{+0.14}_{-0.12} \)  
  - \( \kappa_V = 1.01^{+0.07}_{-0.07} \)  
  - \( \kappa_f = 0.87^{+0.14}_{-0.13} \)  

- **up-/down-type fermions**
  - \( \lambda_{du} = 0.99^{+0.19}_{-0.18} \)

- **leptons/quarks**
  - \( \lambda_{lq} = 1.03^{+0.23}_{-0.21} \)  
  - \( \kappa_g = 0.89^{+0.11}_{-0.10} \)  
  - \( \kappa_Y = 1.14^{+0.12}_{-0.13} \)

- **BR\(_{BSM}\) (extra width)**
  - \( \text{BR}_{BSM} < 0.14 \)

No significant deviations from SM.
The current dataset does not allow the determination of all the coupling modifiers to test specific scenarios: **different benchmark models** defined by LHC-XS-WG [arXiv:1307.1347](https://arxiv.org/abs/1307.1347)

**custodial symmetry: W and Z couplings**

\[ \lambda_{WZ} = 0.92^{+0.14}_{-0.12} \]

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**up-/down-type fermions**

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**leptons/quarks**

\[ \lambda_{l_q} = 1.03^{+0.23}_{-0.21} \]

\[ \kappa_g = 0.89^{+0.11}_{-0.10} \]

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**loops**

**BR\text{_{BSM} (extra width)}**

Since $\Gamma_H$ is not experimentally constrained in a model-independent to a meaningful precision at the LHC, only ratios of couplings strengths can be measured in the more general models.

![Graph showing CMS results](https://via.placeholder.com/150)
Test the universal scale for bosons and for fermions ($\kappa_V$ vs $\kappa_F$)

As result of the EWSB, the nature of Higgs couplings to fermions (via Yukawa int.) and massive vector bosons is different.

$\rightarrow$ Tested by fitting two scale factors: $\kappa_V$ and $\kappa_F$
$\rightarrow$ Parametrise loop-mediated couplings as in SM

CMS approach: $\Gamma_{BSM}=0$
Notice interplay of different channels.
$\kappa_V[0.87, 1.14]$ and $\kappa_F[0.63, 1.15]$ @ 95% CL

$H\rightarrow\gamma\gamma$ is sensitive to the relative sign
Massive vector bosons vs. fermions

Approach 1: \( \Gamma_{BSM} = 0 \rightarrow 2 \) pars: \( \kappa_V = 1.09 \pm 0.07, \kappa_F = 1.11 \pm 0.16 \)

Relaxing assumptions...

\( BR_{i,u} \neq 0 \)

Approach 2: allowing for extra contributions \( BR_{i,u} \neq 0 \);

Constraints for upper bound on \( \Gamma_H \): \( \kappa_V < 1 \) or \( \kappa_{on} = \kappa_{off} \)

\( \rightarrow BR_{i,u} < 0.13 \) (0.52) if \( \kappa_V < 1 \) (\( \kappa_{on} = \kappa_{off} \))

Approach 3: no assumption on \( \Gamma_H \)

\( \lambda_{FV} = \frac{\kappa_F}{\kappa_V} = 1.02^{+0.15}_{-0.13} \)

\( \kappa_{VV} = \frac{\kappa_V}{\kappa_H} = 1.07^{+0.14}_{-0.13} \)

\( \lambda_{FV} = -1 \) disfavoured at \(~4\sigma~\)
Custodial symmetry: W vs Z bosons couplings ($\kappa_W$ vs $\kappa_Z$)

At tree level in SM, the ratio of W and Z masses (and thus couplings) is related due to the “custodial symmetry” (approx. symmetry):

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} = 1$$

However, large radiative corrections are possible in NP models:

$$\rho = 1 + \Delta \rho$$

→ Test if data are compatible with the amount of violation allowed by the SM at NLO

→ 3 free params.: $\lambda_{WZ} = \kappa_W / \kappa_Z$ (POI), $\kappa_F$ and $\kappa_Z$ (profiled)

Fermion couplings grouped together assuming loops contain only SM particles

$$\lambda_{WZ} = \kappa_W / \kappa_Z = 0.92^{+0.14}_{-0.12}$$
Isospin universality? check up/down fermion coupling ratio $\lambda_{du}$

In many extensions of the SM, the Higgs bosons couple differently to different types of fermions. In Two-Higgs-Doublet Models (2HDM), couplings to up- and down-type fermions are modified.

- In this benchmark, the ratio $\lambda_{du} = \kappa_d / \kappa_u$ is probed
  - $\kappa_u$: constrained by ggF (top quark loop), also weakly from $t\bar{t}H$
  - $\kappa_d$: constrained through the $H \to bb$, $H \to \tau\tau$ and $H \to \mu\mu$
  - vector boson couplings grouped together

ATLAS approach: no assumption on $\Gamma_H$
three fits depending on POI, profiling other two

$\lambda_{du} = 0.90^{+0.14}_{-0.15}$

insensitive to the sign

CMS approach: $\Gamma_{BSM}=0$
3 free parameters
ratio $\lambda_{du} (= \kappa_d / \kappa_u)$ (POI)
$\kappa_u$, $\kappa_V$ (profiled)

$\lambda_{du} [0.65, 1.39]$ @95%CL

$\lambda_{V\mu} = \kappa_{V \mu} / \kappa_{H}$

$\kappa_{uu} = \kappa_{uu}^{H} / \kappa_{H}$
Lepton/quark universality in coupling scale factors? Test ratio $\lambda_{lq}$

Extensions of the SM can also contain diff. couplings strengths to leptons and quarks…

As before, one can test the lepton/quark universality by testing the ratio $\lambda_{lq} = \kappa_l / \kappa_q$

**ATLAS approach:**
- no assumption on $\Gamma_H$
- 3 params.
  - ratio $\lambda_{lq} (=\kappa_l / \kappa_q)$
  - ratio $\lambda_{Vq} (=\kappa_V / \kappa_q)$
  - $\kappa_{qq}$

**CMS approach:** $\Gamma_{BSM}=0$
- 3 free params
- ratio $\lambda_{lq} (=\kappa_l / \kappa_q)$ (POI)
- $\kappa_q$ (profiled)
- $\kappa_V$ (profiled)

**ATLAS approach:**
- ratio $\lambda_{lq} (=\kappa_l / \kappa_q)$
- ratio $\lambda_{Vq} (=\kappa_V / \kappa_q)$
- $\kappa_{qq}$

**Best fit:**
- $\lambda_{lq} = 1.12^{+0.22}_{-0.18}$
- $[0.62, 1.50]$ @ 95 CL
Model with 6 parameters in which the coupling to vector bosons, to different types of fermions (charged leptons, up- and down-type quarks), and to gluons and photons are allowed to scale **keeping** $\Gamma_{BSM}=0$. 

**Presence of BSM particles in $gg\rightarrow H$ and $H\rightarrow\gamma\gamma$ loops ($\kappa_g$ vs $\kappa_\gamma$) and scaling factors for SM particles**

Loop-induced processes: unresolved

- $\kappa_g$, $\kappa_\gamma$ (vertices)
- Resolved loops (for comparison)

- Mostly from ggF
- From ttH mostly from ggF
- Resolved loops (for comparison)

**CMS**

- $\kappa_V = 0.96^{+0.14}_{-0.15}$
- $\kappa_b = 0.64^{+0.28}_{-0.29}$
- $\kappa_\tau = 0.82^{+0.18}_{-0.18}$
- $\kappa_t = 1.60^{+0.34}_{-0.32}$
- $\kappa_g = 0.75^{+0.15}_{-0.13}$
- $\kappa_\gamma = 0.98^{+0.17}_{-0.16}$

- 19.7 fb$^{-1}$ (8 TeV) + 5.1 fb$^{-1}$ (7 TeV)
More general: no assumptions on $\Gamma_H$

- $\kappa_W$, $\kappa_Z$, $\kappa_B$, $\kappa_\tau$, $\kappa_\mu$ and $\kappa_\nu$ are treated independently
- do not resolve any loops ($\kappa_g$, $\kappa_\gamma$, $\kappa_\gamma Z$)
- no assumptions on total width, embedded in $\kappa_g Z$
- only ratios can be determined

New particles in loops and no assumptions on total width

$\kappa_{g Z} = 0.98^{+0.14}_{-0.13}$

$\lambda_W Z = 0.87^{+0.15}_{-0.13}$

$\lambda_Z g = 1.39^{+0.36}_{-0.28}$

$\lambda_{b Z} = 0.59^{+0.22}_{-0.23}$

$\lambda_{t Z} = 0.79^{+0.19}_{-0.17}$

$\lambda_{t g} = 2.18^{+0.54}_{-0.46}$

Precision 15%-40%

compatibility with SM is 73%
More general: no assumptions on $\Gamma_H$

- $\kappa_W$, $\kappa_Z$, $\kappa_t$, $\kappa_b$, $\kappa_\gamma$, and $\kappa_\mu$ are treated independently
- do not resolve any loops ($\kappa_g$, $\kappa_\gamma$, $\kappa_\gamma Z$)
- no assumptions on total width, embedded in $\kappa_g Z$
- only ratios can be determined

New particles in loops and no assumptions on total width

$$\kappa_{gZ} = 0.98^{+0.14}_{-0.13}$$
$$\lambda_{WZ} = 0.87^{+0.15}_{-0.13}$$
$$\lambda_{Zg} = 1.39^{+0.36}_{-0.28}$$
$$\lambda_{bZ} = 0.59^{+0.22}_{-0.23}$$
$$\lambda_{tZ} = 0.79^{+0.17}_{-0.17}$$
$$\lambda_{tg} = 2.18^{+0.54}_{-0.46}$$

Precision 15%-40%

Comaptibility with SM is 73%

Most model-independent determination (only $\kappa$ ratios currently possible)
Allowing beyond SM Higgs decays (invisible or undetected)

\[
BR_{\text{BSM}} = BR_{\text{i.,u.}} = BR_{\text{inv.}} + BR_{\text{undet.}} > 0
\]

Direct limits from \( H \rightarrow E_{T,\text{miss}} \) (mostly from VBF)
- ATLAS: \( BR_{\text{inv.}} < 29\% @ 95\% \text{C.L.} \)
- CMS: \( BR_{\text{inv.}} < 57\% @ 95\% \text{C.L.} \)

Indirect from coupling fits (\( \kappa_V \leq 1 \))
- ATLAS: \( BR_{\text{i.,u.}} < 49\% @ 95\% \text{C.L.} \)
- CMS: \( BR_{\text{i.,u.}} < 57\% @ 95\% \text{C.L.} \)

Combining with \( BR_{\text{inv.}} \) direct meas.: \( BR_{\text{i.,u.}} < 32\% \)

Assuming \( BR_{\text{undet.}} = 0 \)

These results represent the most model-independent measurements of the \( \Gamma_H \).
Higgs boson discovery was an amazing experimental success although… the found Higgs boson looks very similar to SM prediction.

Now, focus on measuring its fundamental properties in the most precise way:

- coupling measurements established and tested in diff. benchmark models:
  - fermions vs. bosons $\rightarrow$ good to 10-20%
  - vertices, loops? $\rightarrow$ good to 10-20%
  - BSM decays? $\text{BR}_{i,u} < 50$

- ATLAS+CMS coupling combination ongoing

- Run 2 will be sensitive to additional production and decay channels (promising)

- its self-couplings (very challenging!)

→ **Higgs physics moved on from discovery to precision studies!!**
→ **Check if portal to non-SM physics.**
THANKS FOR YOUR ATTENTION
BACK-UP
**Inputs to the coupling measurements**

### ATLAS Individual analysis

<table>
<thead>
<tr>
<th>Process</th>
<th>Input measurements</th>
<th>$m_H$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>Overall: $\mu = 1.17^{+0.27}_{-0.27}$</td>
<td>125.4</td>
</tr>
<tr>
<td></td>
<td>$ggF$: $\mu = 1.32^{+0.38}_{-0.38}$</td>
<td>125.4</td>
</tr>
<tr>
<td></td>
<td>$VBF$: $\mu = 0.8^{+0.7}_{-0.7}$</td>
<td>125.4</td>
</tr>
<tr>
<td></td>
<td>$WH$: $\mu = 1.0^{+1.6}_{-1.5}$</td>
<td>125.4</td>
</tr>
<tr>
<td></td>
<td>$ZH$: $\mu = 0.1^{+0.7}_{-0.1}$</td>
<td>125.4</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^*$</td>
<td>Overall: $\mu = 1.44^{+0.43}_{-0.33}$</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>$ggF+VH$: $\mu = 1.7^{+0.3}_{-0.4}$</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>$VBF+VH$: $\mu = 0.2^{+1.6}_{-0.9}$</td>
<td>125.36</td>
</tr>
<tr>
<td>$H \rightarrow WW^*$</td>
<td>Overall: $\mu = 1.16^{+0.28}_{-0.21}$</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>$ggF$: $\mu = 0.98^{+0.39}_{-0.26}$</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>$VBF$: $\mu = 1.28^{+0.50}_{-0.47}$</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>$WH$: $\mu = 3.0^{+1.8}_{-1.3}$</td>
<td>125.36</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>Overall: $\mu = 1.43^{+0.43}_{-0.37}$</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>$ggF$: $\mu = 2.0^{+1.2}_{-1.2}$</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>$VBF+VH$: $\mu = 1.24^{+0.50}_{-0.54}$</td>
<td>125.36</td>
</tr>
<tr>
<td>$VH \rightarrow Vbb$</td>
<td>Overall: $\mu = 0.52^{+0.48}_{-0.46}$</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>$WH$: $\mu = 1.1^{+0.46}_{-0.44}$</td>
<td>125.36</td>
</tr>
<tr>
<td></td>
<td>$ZH$: $\mu = 0.05^{+0.52}_{-0.49}$</td>
<td>125.36</td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$</td>
<td>Overall: $\mu = -0.7^{+0.7}_{-0.7}$</td>
<td>125.5</td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma$</td>
<td>Overall: $\mu = 2.7^{+4.5}_{-4.3}$</td>
<td>125.5</td>
</tr>
<tr>
<td>$ttH$</td>
<td>$bb$: $\mu = 1.5^{+0.8}_{-0.6}$</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td>Multi-lepton: $\mu = 2.1^{+0.8}_{-0.9}$</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td>$t\bar{t}$: $\mu = 1.3^{+0.7}_{-0.5}$</td>
<td>125.4</td>
</tr>
</tbody>
</table>

$\sqrt{s} = 7$ TeV, 4.5-4.7 fb$^{-1}$

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

**Combined**

- $H \rightarrow \gamma\gamma$ (untagged)
- $H \rightarrow \gamma\gamma$ (VBF tag)
- $H \rightarrow \gamma\gamma$ (ttH tag)
- $H \rightarrow ZZ$ (0/1-jet)
- $H \rightarrow ZZ$ (2-jet)
- $H \rightarrow WW$ (0/1-jet)
- $H \rightarrow WW$ (VBF tag)
- $H \rightarrow WW$ (ttH tag)
- $H \rightarrow \tau\tau$ (0/1-jet)
- $H \rightarrow \tau\tau$ (VBF tag)
- $H \rightarrow \tau\tau$ (ttH tag)
- $H \rightarrow bb$ (VBF tag)
- $H \rightarrow bb$ (ttH tag)

**CMS**

$\sigma = 125$ GeV

$\sigma_{SM} = 0.84$

**Table: Channel grouping**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Significance ($\sigma$)</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow ZZ$ tagged</td>
<td>6.5</td>
<td>6.3</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$ tagged</td>
<td>5.6</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow WW$ tagged</td>
<td>4.7</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$ tagged</td>
<td>3.8</td>
<td>3.9</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow bb$ tagged</td>
<td>2.0</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$ tagged</td>
<td>&lt; 0.1</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Model parameters</td>
<td>Table in Ref. [169]</td>
<td>Parameter</td>
<td>Best-fit result</td>
</tr>
<tr>
<td>------------------</td>
<td>---------------------</td>
<td>-----------</td>
<td>----------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>68% CL</td>
<td>95% CL</td>
</tr>
<tr>
<td>$\kappa_Z$, $\lambda_{WW}$ ($\kappa_1 = 1$)</td>
<td>—</td>
<td>$\lambda_{WW}$</td>
<td>$0.94^{+0.22}_{-0.18}$</td>
</tr>
<tr>
<td>$\kappa_Z$, $\lambda_{WW}$, $\kappa_t$</td>
<td>44 (top)</td>
<td>$\lambda_{WW}$</td>
<td>$0.92^{+0.14}_{-0.12}$</td>
</tr>
<tr>
<td>$\kappa_Z$, $\lambda_W$, $\lambda_t$</td>
<td>43 (top)</td>
<td>$\kappa_V$</td>
<td>$1.01^{+0.07}_{-0.07}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\kappa_t$</td>
<td>$0.87^{+0.14}_{-0.13}$</td>
</tr>
<tr>
<td>$\kappa_V$, $\lambda_{du}$, $\kappa_u$</td>
<td>46 (top)</td>
<td>$\lambda_{du}$</td>
<td>$0.99^{+0.19}_{-0.18}$</td>
</tr>
<tr>
<td>$\kappa_V$, $\lambda_{eq}$, $\kappa_q$</td>
<td>47 (top)</td>
<td>$\lambda_{eq}$</td>
<td>$1.03^{+0.23}_{-0.21}$</td>
</tr>
<tr>
<td>$\kappa_W$, $\kappa_Z$, $\kappa_t$</td>
<td>Extends 51</td>
<td>$\kappa_W$</td>
<td>$0.95^{+0.14}_{-0.13}$</td>
</tr>
<tr>
<td>$\kappa_Z$, $\kappa_t$</td>
<td>$\kappa_W$, $\kappa_Z$, $\kappa_t$</td>
<td>$\kappa_Z$</td>
<td>$1.05^{+0.16}_{-0.16}$</td>
</tr>
<tr>
<td>$\kappa_q$</td>
<td>$0.81^{+0.19}_{-0.15}$</td>
<td>$[0.53, 1.20]$</td>
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<tr>
<td>$\kappa_T$</td>
<td>$0.74^{+0.33}_{-0.29}$</td>
<td>$[0.09, 1.44]$</td>
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</tr>
<tr>
<td>$\kappa_R$</td>
<td>$0.84^{+0.19}_{-0.18}$</td>
<td>$[0.50, 1.24]$</td>
<td></td>
</tr>
<tr>
<td>$\kappa_P$</td>
<td>$0.49^{+1.38}_{-0.49}$</td>
<td>$[0.00, 2.77]$</td>
<td></td>
</tr>
</tbody>
</table>

$M_{\ell\ell}$, $e$ [Ref. [202]]

<table>
<thead>
<tr>
<th>$M$ (GeV)</th>
<th>$e$</th>
<th>$245 \pm 15$</th>
<th>$0.014^{+0.041}_{-0.036}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\ell\ell}$ with $H(\text{inv})$ searches</td>
<td>$BR_{\ell\ell}$</td>
<td>$0.03^{+0.12}_{-0.05}$</td>
<td>$[0.00, 0.32]$</td>
</tr>
<tr>
<td>$BR_{\ell\ell}$ with $H(\text{inv})$ and $\kappa_1 = 1$</td>
<td>$BR_{\ell\ell}$</td>
<td>$0.06^{+0.11}_{-0.06}$</td>
<td>$[0.00, 0.27]$</td>
</tr>
</tbody>
</table>

$\kappa_{bL}$, $\kappa_t$, $BR_{\ell\ell}$

<table>
<thead>
<tr>
<th>$\kappa_b$, $\kappa_t$</th>
<th>$BR_{\ell\ell}$</th>
<th>$\leq 0.14$</th>
<th>$[0.00, 0.32]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{WW}$, $\lambda_{ZL}$, $\lambda_{bL}$</td>
<td>$\leq 0.14$</td>
<td>$[0.00, 0.32]$</td>
<td></td>
</tr>
<tr>
<td>$\lambda_{ZL}$, $\lambda_{bL}$, $\lambda_{1G}$</td>
<td>$\leq 0.14$</td>
<td>$[0.00, 0.32]$</td>
<td></td>
</tr>
<tr>
<td>$\lambda_{1G}$</td>
<td>$2.18^{+0.54}_{-0.46}$</td>
<td>$[1.30, 3.35]$</td>
<td></td>
</tr>
</tbody>
</table>

$\kappa_V$, $\kappa_b$, $\kappa_t$, $\kappa_1$, $\kappa_5$

<table>
<thead>
<tr>
<th>$\kappa_V$, $\kappa_b$, $\kappa_t$, $\kappa_1$, $\kappa_5$</th>
<th>$\lambda_{WW}$</th>
<th>$0.98^{+0.14}_{-0.15}$</th>
<th>$[0.73, 1.27]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{WW}$</td>
<td>$0.87^{+0.18}_{-0.14}$</td>
<td>$[0.63, 1.19]$</td>
<td></td>
</tr>
<tr>
<td>$\lambda_{ZL}$</td>
<td>$1.39^{+0.28}_{-0.26}$</td>
<td>$[0.87, 2.18]$</td>
<td></td>
</tr>
<tr>
<td>$\lambda_{bL}$</td>
<td>$0.59^{+0.22}_{-0.25}$</td>
<td>$[0.32, 0.82]$</td>
<td></td>
</tr>
<tr>
<td>$\lambda_{1G}$</td>
<td>$0.93^{+0.17}_{-0.14}$</td>
<td>$[0.67, 1.31]$</td>
<td></td>
</tr>
<tr>
<td>$\lambda_{1G}$</td>
<td>$0.79^{+0.19}_{-0.17}$</td>
<td>$[0.47, 1.20]$</td>
<td></td>
</tr>
<tr>
<td>$\lambda_{1G}$</td>
<td>$2.18^{+0.54}_{-0.46}$</td>
<td>$[1.30, 3.35]$</td>
<td></td>
</tr>
</tbody>
</table>

$\kappa_V$, $\kappa_b$, $\kappa_t$, $\kappa_1$, $\kappa_5$

<table>
<thead>
<tr>
<th>$\kappa_V$, $\kappa_b$, $\kappa_t$, $\kappa_1$, $\kappa_5$</th>
<th>$BR_{\ell\ell}$</th>
<th>$\leq 0.34$</th>
<th>$[0.00, 0.57]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BR_{\ell\ell}$ with $\kappa_1 \leq 1$ and $H(\text{inv})$</td>
<td>$BR_{\ell\ell}$</td>
<td>$0.17^{+0.17}_{-0.17}$</td>
<td>$[0.00, 0.49]$</td>
</tr>
<tr>
<td>$BR_{\ell\ell}$, and $BR_{\text{undet}}$</td>
<td>$BR_{\ell\ell}$</td>
<td>$\leq 0.23$</td>
<td>$[0.00, 0.52]$</td>
</tr>
</tbody>
</table>

Notes:
- $\lambda_{WW} = \kappa_{WW}/\kappa_t$ from $ZZ$ and $0/1$-jet WW channels.
- $\kappa_V$ scales couplings to $W$ and $Z$ bosons.
- $\kappa_t$ scales couplings to all fermions.
- $\lambda_{du} = \kappa_d/\kappa_t$, relates up-type and down-type fermions.
- $\lambda_{eq} = \kappa_e/\kappa_q$, relates leptons and quarks.
- $\kappa_{bL}$ scales the coupling to muons.

$M_{\ell\ell}$, $e$:
- Effective couplings to gluons ($g$) and photons ($\gamma$).
- Allows for BSM decays.
- $H(\text{inv})$ use implies $BR_{\text{undet}} = 0$.
- Assumes $\kappa_t = 1$ and uses $H(\text{inv})$.
- Down-type quarks (via $t$).
- Charged leptons (via $t$).
- $H(\text{inv})$ and $BR_{\text{undet}}$.
- $BR_{\text{inv}} = BR_{\text{inv}} + BR_{\text{undet}}$.
Table 1: SM predictions of the Higgs boson production cross sections and decay branching ratios and their uncertainties for $m_H = 125.36$ GeV, obtained by linear interpolations from those at 125.3 and 125.4 GeV from Ref. [11] except for the $tH$ production cross section which is obtained from Refs. [23, 26]. The uncertainties of the cross sections are the sum in quadrature of the uncertainties resulting from variations of QCD scales, parton distribution functions and $\alpha_s$. The uncertainty on the $tH$ cross section is calculated following the procedure in Refs. [11, 23].

<table>
<thead>
<tr>
<th>Production</th>
<th>Cross section [pb] $\sqrt{s} = 7$ TeV</th>
<th>$\sqrt{s} = 8$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF</td>
<td>15.0 ± 1.6</td>
<td>19.2 ± 2.0</td>
</tr>
<tr>
<td>VBF</td>
<td>1.22 ± 0.03</td>
<td>1.57 ± 0.04</td>
</tr>
<tr>
<td>WH</td>
<td>0.573 ± 0.016</td>
<td>0.698 ± 0.018</td>
</tr>
<tr>
<td>ZH</td>
<td>0.332 ± 0.013</td>
<td>0.412 ± 0.013</td>
</tr>
<tr>
<td>bbH</td>
<td>0.155 ± 0.021</td>
<td>0.202 ± 0.028</td>
</tr>
<tr>
<td>ttH</td>
<td>0.086 ± 0.009</td>
<td>0.128 ± 0.014</td>
</tr>
<tr>
<td>tH</td>
<td>0.012 ± 0.001</td>
<td>0.018 ± 0.001</td>
</tr>
<tr>
<td>Total</td>
<td>17.4 ± 1.6</td>
<td>22.3 ± 2.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Branching ratio [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to b\bar{b}$</td>
<td>57.1 ± 1.9</td>
</tr>
<tr>
<td>$H \to WW^*$</td>
<td>22.0 ± 0.9</td>
</tr>
<tr>
<td>$H \to gg$</td>
<td>8.53 ± 0.85</td>
</tr>
<tr>
<td>$H \to \tau\tau$</td>
<td>6.26 ± 0.35</td>
</tr>
<tr>
<td>$H \to c\bar{c}$</td>
<td>2.88 ± 0.35</td>
</tr>
<tr>
<td>$H \to ZZ^*$</td>
<td>2.73 ± 0.11</td>
</tr>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>0.228 ± 0.011</td>
</tr>
<tr>
<td>$H \to Z\gamma$</td>
<td>0.157 ± 0.014</td>
</tr>
<tr>
<td>$H \to \mu\mu$</td>
<td>0.022 ± 0.001</td>
</tr>
</tbody>
</table>
Binned profile likelihood fit $L(\mu, \theta)$

$$L(\mu, \theta) = L_{\text{Pois}}(\mu, \theta) \cdot \prod_p \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{\theta^2}{2}\right) \cdot \prod_{i,j} \frac{1}{\sqrt{2\pi}\sigma_{\gamma,ij}} \exp\left(-\frac{(\gamma_{ij} - 1)^2}{2\sigma_{\gamma,ij}^2}\right)$$

- parameter of interest: signal strength $\mu = \sigma/\sigma_{\text{SM}}$
- nuisance parameters $\theta_p$: systematic uncertainties
- nuisance parameters $\sigma_{\gamma,ij}$: MC statistical uncertainty per bin

$\rightarrow$ Find the best values for $\mu$ and $\theta_p$ by minimizing the log $L$
$\rightarrow$ obtain fitted uncertainty on $\mu$
$\rightarrow$ data can contrain the “a priori” nuisance parameters values

$\rightarrow$ Calculate the experimental sensitivity in terms of the significance (i.e. level of disagreement between the data and the background-only hypothesis expressed as Gaussian standard deviations $\sigma$)

To obtain the final result, a simultaneous fit to the data is performed to the distributions of the discriminants in all regions under the signal-plus-background hypothesis.
Five major decay channels and rare processes
Higgs properties can be inferred from the event rates measured in all the channels.

**γγ**

\[ m_\gamma \]

- \[ N_{\text{sig}} \approx 200-500 \]
- \[ N_{\text{bkg}} \approx 5000 \]
- 5.2-5.6σ observed

**ZZ**

\[ m_{4l} \]

- \[ N_{\text{sig}} \approx 20 \]
- \[ N_{\text{bkg}} \approx 20 \]
- 6.5-8.1σ observed

**WW**

\[ m_T \]

- \[ N_{\text{sig}} \approx 500 \]
- \[ N_{\text{bkg}} \approx 7000 \]
- 4.7-6.5σ observed

**ττ**

\[ m_H \]

- \[ N_{\text{sig}} \approx 400-650 \]
- \[ N_{\text{bkg}} \approx \text{huge} \]
- 3.8-4.5σ observed

**bb**

- \[ N_{\text{sig}} \approx 60-100 \]
- \[ N_{\text{bkg}} \approx \text{huge} \]
- 1.4-2.1σ observed

Rare decays: \( \mu\mu, \ Z\gamma, \ldots \)
- look for a narrow signal on top of a smoothly failing bkg.
- split events into exclusive categories
- background estimated from a fit to $m_{\gamma\gamma}$
best-fit $\mu = \sigma/\sigma_{SM}$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS (7+8 TeV)</td>
<td>$1.17 \pm 0.27$</td>
</tr>
<tr>
<td>CMS (7+8 TeV)</td>
<td>$1.14^{+0.26}_{-0.23}$</td>
</tr>
</tbody>
</table>
BR = $1.3 \times 10^{-4}$, $l = e, \mu$

- excellent mass resolution: 1-2%
- select four isolated leptons (low $p_T$ is important)
- split events into exclusive categories
- fold angular information in a kinematic discriminant to separate signal and background

**Table:**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Best-fit $\mu = \sigma/\sigma_{SM}$</th>
<th>Obs. (exp.) significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS (7+8 TeV)</td>
<td>$1.66^{+0.39}<em>{-0.34}$ (stat.) $^{+0.21}</em>{-0.14}$ (syst.)</td>
<td>$8.2\sigma$ ($5.8\sigma$)</td>
</tr>
<tr>
<td>CMS (7+8 TeV)</td>
<td>$0.93^{+0.26}<em>{-0.23}$ (stat.) $^{+0.13}</em>{-0.09}$ (syst.)</td>
<td>$6.8\sigma$ ($6.7\sigma$)</td>
</tr>
</tbody>
</table>
• mass resolution : 20%
• final state cannot be fully reconstructed
• main observable : $m_T$, $m_{ll}$, lepton $p_T$
• analysis performed in categories
• angular correlations used to reject bkg.
• large expected yield for property measurements once the mass is known

$BR = 1.1 \times 10^{-2}$, $l = e, \mu$

**ATLAS**

$\sqrt{s} = 8$ TeV, $20.3 \text{ fb}^{-1}$

<table>
<thead>
<tr>
<th></th>
<th>best-fit $\mu = \sigma/\sigma_{SM}$</th>
<th>Obs. (exp.) significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>$1.09^{+0.23}_{-0.21}$</td>
<td>$6.1\sigma$ (5.8$\sigma$)</td>
</tr>
<tr>
<td>CMS</td>
<td>$0.72^{+0.20}_{-0.18}$</td>
<td>$4.3\sigma$ (5.8$\sigma$)</td>
</tr>
</tbody>
</table>

ATLAS: arXiv:1412.2641
CMS: JHEP 1401 (2014) 096
BR = 6.3x10^{-2}

- look into $e\tau_h$, $e\tau_h$, $ee$, $e\mu$, $\mu\mu$, $\tau_h\tau_h$
- mass resolution: 10-20%
- experimental challenges: hadronic $\tau$ ID, $m_{\tau\tau}$ reconstruction
- categories motivated by production
  - sensitivity mainly driven by VBF

<table>
<thead>
<tr>
<th></th>
<th>best-fit $\mu = \sigma/\sigma_{\text{SM}}$</th>
<th>Obs. (exp.) significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS (7+8 TeV)</td>
<td>$1.43^{+0.43}_{-0.37}$</td>
<td>4.5$\sigma$ (3.4$\sigma$)</td>
</tr>
<tr>
<td>CMS (7+8 TeV)</td>
<td>$0.86 \pm 0.29$</td>
<td>3.4$\sigma$ (3.6$\sigma$)</td>
</tr>
</tbody>
</table>
BR = 0.58

- mass resolution : 10%
- two b-tagged jets (very challenging)
- look into VH (VBF and ttH)
- both experiments use boosted decision trees

<table>
<thead>
<tr>
<th></th>
<th>best-fit $\mu = \sigma/\sigma_{SM}$</th>
<th>Obs. (exp.) significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS (7+8 TeV)</td>
<td>0.5 ± 0.4</td>
<td>1.4$\sigma$ (2.6$\sigma$)</td>
</tr>
<tr>
<td>CMS (7+8 TeV)</td>
<td>1.0 ± 0.5</td>
<td>2.1$\sigma$ (2.1$\sigma$)</td>
</tr>
</tbody>
</table>
**Virtues:**

- Many possible final states
- Several channels are defined depending on the final signature

**Challenges:**

- low production cross section
- large tt background (ttH:tt ~ 1:20)

**ATLAS:**

- $t\bar{t}H(\gamma\gamma)$: PLB 740 (2015) 222
- $t\bar{t}H$ (multileptons): arXiv:1506.05988
- CMS: JHEP 09 (2014) 087

**ATLAS**

<table>
<thead>
<tr>
<th>Best-fit $\mu$ = $\sigma/\sigma_{SM}$</th>
<th>Obs. (exp.) significance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ATLAS</strong> ($H\rightarrow bb$)</td>
<td>1.5 ± 1.1 @ 125.0 GeV</td>
</tr>
<tr>
<td><strong>CMS</strong> (7+8 TeV)</td>
<td>2.8 ± 1.0 @ 125.6 GeV</td>
</tr>
</tbody>
</table>

**Higgs→bb:** dominant mode but large background  
**Higgs→WW, ZZ, ττ:** multilepton final state  
**Higgs→γγ:** tiny but clean signature