Measurements of the Higgs boson properties at LHC

Nicola De Filippis - Politecnico & INFN, Bari

On behalf of ATLAS and CMS collaborations

XLIXth Rencontres de Moriond, 2014: QCD AND HIGH ENERGY INTERACTION
22-29 Mar 2014, La Thuile
Outline

- Introduction / History
- Measurement of Higgs properties:
  - mass
  - spin/parity
  - width

N. B.
- Details about $H \rightarrow VV$ analyses in the talk by T. Donszelman
- New Higgs combination results in the talk by B. Di Micco
- $H \rightarrow ff$ results in the talk by R. Lane
- BSM Higgs results in the talk by P. Meridiani.
A bit of history: where we are

4th July 2012: Announcement of the discovery of a new boson, compatible with the BEH particle.

Moriond 2013: Measurement of the properties in favour of a $0^+$ particle and consistent with SM

October 2013: Nobel prize in Physics awarded to prof. F. Englert and P. Higgs.

Study the EWK SSB and tests of SM predictions through the measurements of the Higgs properties:

• mass
• spin
• width
• couplings
• ..etc
Higgs decay channels

At $m_H = 125$ GeV:

- $H(bb) \approx 57\%$
- $H(WW) \approx 22\%$
- $H(\tau\tau) \approx 6.2\%$
- $H(ZZ) \approx 2.8\%$
- $H(\gamma\gamma) \approx 0.23\%$

What really matters for the precise measurement of the properties are:
the S/B ratio, the mass peak reconstruction quality and the mass resolution
Mass measurements
**H→ZZ→4l: the most sensitive channel**

- **Signatures:** $4e$, $4\mu$ and $2e2\mu$ final state  
  - clean but demanding the **highest lept. eff.**  
  - $\sigma \times \text{BR} \approx \text{few fb}$  
  - $S/B \approx 2$  
  - mass peak is reconstructed with resolution 1-2%

- **Backgrounds:** Irreducible: ZZ*  
  Reducible: Z+jets, tt+jets, WZ+jets

- **Challenges for the mass measurement:**
  - maximize efficiency for low $p_T$ leptons  
  - precise calibration of lepton $p_T$ scale and resolution  
  - calculation of per event 4l mass error (CMS)

- **Strategy for mass measurement:**
  - **CMS:** use $m_{4l}$ vs kin. discriminant (MELA) for $S/B$ separation + **event per event mass error**  
  - **ATLAS:** use $m_{4l}$ for $S/B$ separation. Categorize events into VBF-like, VH-like and untagged.
Mass meas.: $H \rightarrow ZZ \rightarrow 4l$

**CMS:** 3D fit with $m_{4l}$, MELA, $\sigma(m_{4l})/m_{4l}$

$\sigma(m_{4l})/m_{4l}$ computed from the uncertainty on $p_T/E$ of each lepton $\rightarrow 8\%$ of improvement on the uncertainty on mass

**ATLAS:** 1D fit to $m_{4l}$ +

kinematic constraint to $Z_1$ candidate

---

<table>
<thead>
<tr>
<th></th>
<th>CMS</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Measured mass</strong></td>
<td>$125.6 \pm 0.4$ (stat) $\pm 0.2$ (syst) GeV</td>
<td>$124.3^{+0.6}<em>{-0.5}$ (stat) $^{+0.5}</em>{-0.3}$ (syst) GeV</td>
</tr>
<tr>
<td><strong>Syst. Uncert.</strong></td>
<td>Electron e/p-scale $\approx 0.1$-$0.3%$</td>
<td>Electron e/p-scale $\approx 0.2$-$0.4%$</td>
</tr>
<tr>
<td></td>
<td>Muon p-scale $\approx 0.1%$</td>
<td>Muon p-scale $\approx 0.1$-$0.2%$</td>
</tr>
</tbody>
</table>
H→γγ in a nutshell

**Important channel** for Higgs with 110< m_H<140 GeV
- clear signature of two isolated high E_T photons
- small B.R. (0.2%)
- S/B ≈1/1 ÷ 1/20
- narrow mass peak with mass resolution 1-2%

**Background:**
- irreducible: γγ→γγ, qqbar, qg→γγ from QCD
- reducible: pp → γ+jets (1 prompt γ + 1 fake γ)
  - pp → jets (2 fake γ), fake γ from π^0→γγ

**Challenges for mass measurement:**
- maintain good mass-resolution in high-pile-up (for both energy and angle).
- understand **electron/photon extrapolation** for E-scale (material, shower description, etc.).

**Strategy for the analysis:**
- events categorized according to photon resolution and kinematics.
- additional exclusive channels targeting VBF and VH
Mass meas.: $H \rightarrow \gamma\gamma$ and combination

- signal extracted from simultaneous S+B fit to all categories.
- background modeled with polynomials or falling power-law or exponentials.

<table>
<thead>
<tr>
<th></th>
<th>CMS</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meas. mass ($H \rightarrow \gamma\gamma$)</td>
<td>125.4 ± 0.5(stat) ± 0.6(syst) GeV</td>
<td>126.8 ± 0.2(stat) ± 0.7(syst) GeV</td>
</tr>
<tr>
<td>Combination $H \rightarrow ZZ \rightarrow 4l + H \rightarrow \gamma\gamma$</td>
<td>125.7 ± 0.3(stat) ± 0.3(syst) GeV</td>
<td>125.5+0.2(stat)-0.5-0.6(syst) GeV</td>
</tr>
</tbody>
</table>
Spin/parity
Spin-parity: $J^{CP}$ hypotheses

- Same approach for **ATLAS** and **CMS** to probe the spin from angular distributions
- First we measure the compatibility with the $0^+$ hypothesis
- Then we test alternative hypotheses by using the most general scattering amplitude for different spin/parity combinations

Spin 0:
\[
A(X_{J=0} \rightarrow VV) = v^{-1} \left( g_1 m_v^2 \epsilon_1^* \epsilon_2^* + g_2 f^{(1)}_{\mu \nu} f^{* (2)}_{\mu \nu} + g_3 f^{(1)}_{\mu \nu} f^{* (2)}_{\mu \alpha} \frac{q_{\mu} q_{\alpha}}{\Lambda^2} + g_4 f^{(1)}_{\mu \nu} \bar{f}^{* (2)}_{\mu \nu} \right)
\]

Spin 1:
\[
A(X_{J=1} \rightarrow VV) = g_1^{(1)} \left[ (\epsilon_1^* q)(\epsilon_2^* \epsilon_\chi) + (\epsilon_2^* q)(\epsilon_1^* \epsilon_\chi) \right] + g_2^{(1)} \epsilon_{\alpha \mu \nu} \beta \epsilon_\chi^* \epsilon_1^* \epsilon_2^* \frac{1}{2} q^\beta
\]

- So far test done with $H \rightarrow ZZ \rightarrow 4\ell$, $H \rightarrow \gamma\gamma$ and $H \rightarrow WW \rightarrow 2\ell 2\nu$ analyses
Spin-parity: $0^+ \text{ vs } 0^-$ from $H \rightarrow ZZ \rightarrow 4l$

CMS $H \rightarrow ZZ \rightarrow 4l$ uses a 2D likelihood for the spin measurement with MELA KD:

$$\mathcal{L}_{\text{2D}}^P \equiv \mathcal{L}_{\text{2D}}^P(D_{\text{bkg}}, D_{JP}) \quad D_{JP} = \left[1 + \frac{\mathcal{P}_P^{\text{kin}}(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_4 \ell)}{\mathcal{P}_{0+}^{\text{kin}}(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_4 \ell)}\right]^{-1}$$

ATLAS $H \rightarrow ZZ \rightarrow 4l$ uses the five angles and the two invariant masses, combined to build a BDT discriminant

ATLAS and CMS: exclude $0^-$ hypothesis at > 3σ level

0$^-$ hypothesis is excluded @ 97.8% CL
Spin-parity: $0^+ vs 2^+_m$ from $H \rightarrow WW \rightarrow 2l2\nu$

Hypothesis test from 2D template fit to data:

- **CMS**: $m_\parallel$ vs $m_T$
- **ATLAS**: use two BDT discriminants ($\Delta \phi_\parallel$, $m_\parallel$, $m_T$)
  - $\text{BDT}_0$ (discriminate SM from background)
  - $\text{BDT}_{\text{alt}}$ (discriminate alternative hypotheses from background).

Observed results disfavor $2^+$ hypothesis at $>3\sigma$
# Statistical analysis: $J^P$ summary

### CMS $H \to ZZ \to 4l$

<table>
<thead>
<tr>
<th>$J^P$ model</th>
<th>$J^P$ production</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^-$</td>
<td>any pseudoscalar ($0^-$), discriminate against SM Higgs boson</td>
</tr>
<tr>
<td>$0^+_h$</td>
<td>any BSM scalar with higher dim operators ($0^+_h$)</td>
</tr>
<tr>
<td>$1^-$</td>
<td>$q\bar{q} \to X$ Exotic vector ($1^-$), $q\bar{q} \to X$</td>
</tr>
<tr>
<td>$1^-$</td>
<td>any Exotic vector ($1^-$), decay-only information</td>
</tr>
<tr>
<td>$1^+_h$</td>
<td>$q\bar{q} \to X$ Exotic pseudovector ($1^+_h$), $q\bar{q} \to X$</td>
</tr>
<tr>
<td>$1^+_h$</td>
<td>any Exotic pseudovector ($1^+_h$), decay-only information</td>
</tr>
<tr>
<td>$2^+_h$</td>
<td>$gg \to X$ KK Graviton-like with minimal couplings ($2^+_m$), $gg \to X$</td>
</tr>
<tr>
<td>$2^+_h$</td>
<td>$q\bar{q} \to X$ KK Graviton-like with minimal couplings ($2^+_m$), $q\bar{q} \to X$</td>
</tr>
<tr>
<td>$2^+_h$</td>
<td>any KK Graviton-like with minimal couplings ($2^+_m$), decay-only in</td>
</tr>
<tr>
<td>$2^+_h$</td>
<td>$gg \to X$ KK Graviton-like with SM in the bulk ($2^+_h$), $gg \to X$</td>
</tr>
<tr>
<td>$2^+_h$</td>
<td>$gg \to X$ BSM tensor with higher dim operators ($2^+_h$), $gg \to X$</td>
</tr>
<tr>
<td>$2^-_h$</td>
<td>$gg \to X$ BSM pseudotensor with higher dim operators ($2^-_h$), $gg \to X$</td>
</tr>
</tbody>
</table>

---

**ATLAS**

- **$H \to \gamma\gamma$**
  - $\sqrt{s} = 8$ TeV, $L = 20.7$ fb$^{-1}$
  - $H \to ZZ \to 4l$
  - $\sqrt{s} = 8$ TeV, $L = 20.7$ fb$^{-1}$

- **$H \to WW^* \to e\nu\mu\nu$**
  - $\sqrt{s} = 8$ TeV, $L = 20.7$ fb$^{-1}$

![Graph showing CL$_s$ expected assuming $J^P = 0^+$](image)

- **Strong exclusion of a spin-1 resonance**
- **$0^-$ excluded at $>3\sigma$ level**
- **Graviton-like resonances excluded at $>3\sigma$**

---

N. De Filippis

Moriond QCD, La Thuile, Italy, March 22-29, 2014
Width measurements
Direct constraint on the $\Gamma_H$

- Standard model prediction: $\Gamma_{H}^{\text{SM}} \approx 4.15$ MeV at $m_H = 125.6$ GeV
- Direct measurement heavily limited by experimental resolution
- Current upper limits from $\gamma\gamma(4l)$ decay modes by a likelihood scan

$$\Gamma_H < 6.9 \text{ GeV @ 95\%C.L.}$$

$$\Gamma_H < 3.4 \text{ GeV @ 95\%C.L.}$$
Constraint on the $\Gamma_H$ from $H^*(126) \rightarrow ZZ$

- **Off-shell $H^*(126) \rightarrow VV$ ($V=W,Z$)**
  - In N. Kauer and G. Passarino, JHEP 08 (2012) 11 it has been shown that the off-shell production cross section is sizeable at high ZZ invariant mass.
  - that comes from a peculiar cancellation between BW trend and $\Gamma(H \rightarrow VV)$
  - Enhancement of **7.6%** of total cross section in the ZZ final state

<table>
<thead>
<tr>
<th>Total [pb]</th>
<th>$M_{ZZ} &gt; 2M_Z$ [pb]</th>
<th>$R$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \rightarrow H \rightarrow all$</td>
<td>19.146</td>
<td>0.1525</td>
</tr>
<tr>
<td>$gg \rightarrow H \rightarrow ZZ$</td>
<td>0.5462</td>
<td>0.0416</td>
</tr>
</tbody>
</table>
Constraint on the $\Gamma_H$ from $H^*(126) \to ZZ$

F. Caola, K. Melnikov (Phys. Rev. D88 (2013) 054024) and J. Campbell et al. (arXiv:1311.3589) showed how this feature can be turned into a constraint on the total Higgs width

\[
\frac{d\sigma_{gg \to H \to ZZ}}{dm_{ZZ}^2} \propto g_{ggH}^2 g_{HZZ} \frac{F(m_{ZZ})}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}
\]

\[
\frac{\sigma_{on-peak}}{\sigma_{gg \to H \to ZZ}} \propto \frac{\frac{g_{ggH}^2 g_{HZZ}^2}{\Gamma_H}}{\Gamma_H}, \quad \frac{\sigma_{off-peak}}{\sigma_{gg \to H \to ZZ}} \propto g_{ggH}^2 g_{HZZ}^2
\]

--> so measuring the ratio of $\sigma^{\text{off-peak}}$ and $\sigma^{\text{on-peak}} \rightarrow$ measurement of $\Gamma_H$

\[
\sigma_{on-peak}^{\text{gg \to H \to ZZ}} = \frac{\kappa_g^2 \kappa_Z^2}{r} (\sigma \cdot \text{BR})_{SM} \equiv \mu (\sigma \cdot \text{BR})_{SM}
\]

\[
\sigma_{off-peak}^{\text{gg \to H \to ZZ}} = \frac{\kappa_g^2 \kappa_Z^2 \cdot \sigma_{off-peak,SM}^{\text{gg \to H \to ZZ}}}{\sigma_{on-peak}^{\text{gg \to H \to ZZ}}} = \mu r \frac{\sigma_{off-peak,SM}^{\text{gg \to H \to ZZ}}}{\sigma_{on-peak}^{\text{gg \to H \to ZZ}}}
\]

Once $\mu$ is fixed a determination of $r$ is obtained and so for $\Gamma_H$:

$\mu$ from CMS 4l paper arXiv:1312.5333 and provide result in two ways:

\[
\begin{align*}
\mu & \text{ expected} \rightarrow \text{ use expected signal strength} \\
\mu & \text{ observed} \rightarrow \text{ use observed signal strength}
\end{align*}
\]

The interference with continuum $gg \to ZZ$ is taken into account at high mass $\rightarrow$ gg2VV/MCFM

VBF production is 10% at high mass $\rightarrow$ PHANTOM
Constraint on the $\Gamma_H$ from $H^*(126) \to ZZ \to 4l$

$H \to ZZ \to 4l$ analysis:
- same as CMS, arXiv:1312.5333
- $m_{4l} > 220$ GeV region analysed
- a NEW MELA discriminant for $gg \to ZZ$ production (including signal background and interference) vs $qq \to ZZ$:

![Graphs showing the constraint on $\Gamma_H$ from $H^*(126) \to ZZ \to 4l$.](image)

\[
D_{gg,a} = \frac{P_{gg,a}}{P_{gg,a} + P_{qq}}
\]
Constraint on the $\Gamma_H$ from $H^*(126) \rightarrow ZZ \rightarrow 2l2\nu$

**H→ZZ→2l2ν analysis:**

- cuts on $p_T(Z)$ and $E_{\text{T,miss}}$
- vetoing 3rd lepton and b-tagged jets
- Events split in 3 purity categories according to number of selected jets ($p_T > 30$ GeV and $|\eta| < 4.7$)
  - VBF-like: two jets with $m_{JJ} > 500$ GeV and $|\Delta\eta_{JJ}| > 4$
  - $\geq 1$ jets: excluding events in VBF-like category
  - 0 jets
- discriminating variables:
  - $m_T$ for 0 and 1-jet category:
    $$m_T^2 = \left[ \sqrt{p_{T,\ell\ell}^2 + m_{\ell\ell}^2} + \sqrt{E_{\text{T,miss}}^2 + m_{\ell\ell}^2} \right]^2 - \left[ \vec{p}_{T,\ell\ell} + \vec{E}_{\text{T,miss}} \right]^2$$
  - $E_{\text{T,miss}}$ for VBF-like category

**Constraint on the $\Gamma_H$ from $H^*(126) \rightarrow ZZ \rightarrow 2l2\nu$**
Constraint on the $\Gamma_H$ from $H^*(126) \rightarrow ZZ$

4l analysis: 2D likelihood in $m_{4l}$ and $D_g^g$

2l2$\nu$ analysis: 1D likelihood with $m_T$ or $E_{t\text{miss}}$

Combined fit using the measured yield at the peak in $H \rightarrow ZZ \rightarrow 4l$ as constraint

<table>
<thead>
<tr>
<th></th>
<th>4l</th>
<th>2l2$\nu$</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected 95% CL</td>
<td>11.5</td>
<td>10.7</td>
<td>8.5</td>
</tr>
<tr>
<td>Observed 95% CL</td>
<td>6.6</td>
<td>6.4</td>
<td>4.2</td>
</tr>
<tr>
<td>Observed 95% CL, $\Gamma_H$ (MeV)</td>
<td>27.4</td>
<td>26.6</td>
<td>17.4</td>
</tr>
<tr>
<td>Observed best fit, $r$</td>
<td>$0.5^{+2.3}_{-0.5}$</td>
<td>$0.2^{+2.2}_{-0.2}$</td>
<td>$0.3^{+1.5}_{-0.3}$</td>
</tr>
<tr>
<td>Observed best fit, $\Gamma_H$ (MeV)</td>
<td>$2.0^{+9.6}_{-2.0}$</td>
<td>$0.8^{+9.1}_{-0.8}$</td>
<td>$1.4^{+8.1}_{-1.4}$</td>
</tr>
</tbody>
</table>

Obs. (exp.) $\text{@95\% C.L.}$:

$\Gamma_H < 4.2 (8.5) \Gamma_H^{SM}$

$\Gamma_H < 17.4 (35.3) \text{ MeV}$

Considerable improvement w.r.t. previous CMS direct constraint on $\Gamma_H$
Conclusions

- Run I data from CMS and ATLAS proved the existence of a boson from the BEH mechanism and the consistency with the predictions of the SM.
- We moved to a “precision measurements” phase now.
- Mass is measured precisely.
- Data disfavors all alternative spin hypotheses tested at more than 95% C.L.
- **First experimental constraint on Higgs total width by \( H^*(126) \rightarrow ZZ \)**
  - \( \Gamma / \Gamma_{SM} < 4.2 \) (8.5 expected) @ 95% CL
  - \( \Gamma < 17.4 \) MeV (35.3 MeV expected) @ 95% CL
Backup
# The origin of the BEH mechanism

<table>
<thead>
<tr>
<th>Article</th>
<th>Reception date</th>
<th>Publication date</th>
</tr>
</thead>
</table>
SM Higgs production at LHC

Gluon-gluon fusion:

$\rightarrow$ radiative corrections at:

- NLO QCD
- NNLO QCD
- NNLL QCD
- NLO EW

Cross section [pb] at $m_H = 125.5$ GeV

<table>
<thead>
<tr>
<th>Process</th>
<th>$\kappa_{\text{NNLO/NLO}}$</th>
<th>Scale</th>
<th>PDF+$a_s$</th>
<th>Total error</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF</td>
<td>$+25%$ ($+100%$)</td>
<td>$+12%$ - $7%$</td>
<td>$\pm8%$</td>
<td>$+20$ - $15%$</td>
</tr>
<tr>
<td>VBF</td>
<td>$&lt;1%$ ($+5$ - $10%$)</td>
<td>$\pm1%$</td>
<td>$\pm4%$</td>
<td>$\pm5%$</td>
</tr>
<tr>
<td>WH/ZH</td>
<td>$+2$ - $6%$ ($+30%$)</td>
<td>$\pm1%$</td>
<td>$\pm4%$</td>
<td>$\pm5%$</td>
</tr>
<tr>
<td>ttH</td>
<td>$-1$ ($+5$ - $20%$)</td>
<td>$+4%$ - $10%$</td>
<td>$\pm8%$</td>
<td>$+12$ - $18%$</td>
</tr>
</tbody>
</table>
Data samples: CMS / ATLAS

- Excellent machine and detector performance
- Very high quality data
  - $\approx 95\%$ of delivered data were recorded
  - $\approx 90\%$ certified and used in physics analyses
- Dataset of 2011-2012 of:
  - $L = 5.1$ (CMS) – $4.7$ (ATLAS) $fb^{-1}$ (7 TeV)
  - $L = 19.7$ (CMS) – $20.7$ (ATLAS) $fb^{-1}$ (8 TeV)
- Successfull pileup handling
CMS in a nutshell

\[ \eta < 2.5 : \text{Tracker} \]
\[ \sigma / p_T = 10^{-4} p_T + 0.005 \]

\[ \eta < 4.9 : \text{EM Calorimeter} \]
\[ \sigma / E = 0.03 / \sqrt{E} + 0.003 \]

\[ \eta < 4.9 : \text{HAD Calorimeter} \]
\[ \sigma / E = 1.0 / \sqrt{E} + 0.05 \]

\[ \eta < 2.4 : \text{Muon spectrometer} \]
\[ \sigma / p_T = 0.10 \text{ (1TeV muons)} \]
ATLAS in a nutshell
<table>
<thead>
<tr>
<th>Sub System</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design</strong></td>
<td><img src="image" alt="Diagram of ATLAS and CMS designs" /></td>
<td><img src="image" alt="Diagram of ATLAS and CMS designs" /></td>
</tr>
<tr>
<td><strong>Magnet(s)</strong></td>
<td>Solenoid (within EM Calo) 2T</td>
<td>Solenoid 3.8T</td>
</tr>
<tr>
<td></td>
<td>3 Air-core Toroids</td>
<td>Calorimeters Inside</td>
</tr>
<tr>
<td><strong>Inner Tracking</strong></td>
<td>Pixels, Si-strips, TRT</td>
<td>Pixels and Si-strips</td>
</tr>
<tr>
<td></td>
<td>PID w/ TRT and dE/dx</td>
<td>PID w/ dE/dx</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{p_T}/p_T \sim 5 \times 10^{-4} p_T \oplus 0.01$</td>
<td>$\sigma_{p_T}/p_T \sim 1.5 \times 10^{-4} p_T \oplus 0.005$</td>
</tr>
<tr>
<td><strong>EM Calorimeter</strong></td>
<td>Lead-Larg Sampling</td>
<td>Lead-Tungstate Crys. Homogeneous</td>
</tr>
<tr>
<td></td>
<td>w/ longitudinal segmentation</td>
<td>w/o longitudinal segmentation</td>
</tr>
<tr>
<td></td>
<td>$\sigma_E/E \sim 10%/\sqrt{E} \oplus 0.007$</td>
<td>$\sigma_E/E \sim 3%/\sqrt{E} \oplus 0.5%$</td>
</tr>
<tr>
<td><strong>Hadronic Calorimeter</strong></td>
<td>Fe-Scint. &amp; Cu-Larg (fwd)</td>
<td>Brass-scint.</td>
</tr>
<tr>
<td></td>
<td>$\sigma_E/E \sim 50%/\sqrt{E} \oplus 0.03$</td>
<td>$\sigma_E/E \sim 100%/\sqrt{E} \oplus 0.05$</td>
</tr>
<tr>
<td></td>
<td>$\geq 11 \lambda_0$</td>
<td>$\geq 7 \lambda_0$</td>
</tr>
<tr>
<td><strong>Muon Spectrometer System</strong></td>
<td>Instrumented Air Core (std. alone)</td>
<td>Instrumented Iron return yoke</td>
</tr>
<tr>
<td></td>
<td>$\sigma_{p_T}/p_T \sim 4%$ (at 50 GeV)</td>
<td>$\sigma_{p_T}/p_T \sim 1%$ (at 50 GeV)</td>
</tr>
<tr>
<td></td>
<td>$\sim 11%$ (at 1 TeV)</td>
<td>$\sim 10%$ (at 1 TeV)</td>
</tr>
</tbody>
</table>
Statistical approach – ATLAS and CMS

- Hypothesis testing using the Profile likelihood ratio and CL_s method
  \[ L(data | \mu, \theta) = Poisson(data | \mu \cdot s(\theta) + b(\theta)) \cdot p(\tilde{\theta} | \theta) \]
  \[ \tilde{q}_\mu = -2 \ln \frac{L(data | \mu, \hat{\theta}_\mu)}{L(data | \hat{\mu}, \hat{\theta})} \] is the test statistics
  \[ CL_s(\mu) = \frac{P\left(q_\mu \geq q_\mu^{obs} | \mu, s(\hat{\theta}_\mu^{obs}) + b(\hat{\theta}_\mu^{obs})\right)}{P\left(q_\mu \geq q_\mu^{obs} | b(\hat{\theta}_\mu^{obs})\right)} \] for exclusion
  p-value: probability that the background can fluctuate to give an excess of events equal or larger than what observed

- Sistematic uncertainties and correlations modelled by introduction nuisance parameters \( \theta \) with related distribution

- Choice of parameters of interest depends on test with the remaining parameters being “profiled” (set to the values that maximise the likelihood function for the given fixed values of the parameter of interest)
H→ZZ→4l analysis: lepton scale

CMS:

Electron scale calibrations flow

- ECAL cluster calibrations
- Absolute scale corrections (on Z→ee), dependent on f(run, η, R9)
- Residual corrections for linearity vs $p_T$ (check with Z→4e: $m(4e)=91.19 \pm 0.58$ GeV)

Muon scale corrections with MuScle fit

ATLAS:

- uncertainty on the energy scale for electrons with $E_T < 15$ GeV is verified using $J/\psi \rightarrow ee$ decays; agreement at the level of < 1%, → uncertainty on mass measurement 0.1%.
- The uncertainty on the global mass scale coming from muons is estimated to be 0.2%(0.1%) for the 4µ (2µ2e)
H→ZZ→4l analysis: lepton resolution

**CMS:**
Extra smearings derived and applied to the MC to match the resolution in data
- in categories of η (different material, ECAL) and R₉ for electrons
- in η, p_T categories for muons: improved by using MuScle fit

**ATLAS:**
Use of Z-mass constraint to improve resolution
Lepton momentum uncertainty propagated to predict $m_{4l}$ uncertainty: $D_{mass} = \sigma_{m4l}/m_{4l}$

3D fit for the mass: $P(m_{4l}, D^{kin}_{bkg}, D_{mass})$

- 8% exp. improvement on mass uncertainty from $D_{mass}$
- Average resolution is substituted, event-by-event, with $D_{mass}$.
- wrt Moriond: resolution tails are also modified per-event
- $D_{mass}$ calibrated with $Z$, $J/\Psi$, $Y$ resonances

Systematics from the data-MC agreement in $Z\rightarrow ll$ events:
- electron and muon resolution/per-event: 20%
- $D_{mass}$ validated with $Z\rightarrow 4l$
H→ZZ→4l analysis: systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>Signal (m_{ll}=126 GeV)</th>
<th>Backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>gluon fusion</td>
<td>VBF</td>
</tr>
<tr>
<td>α_s + PDF (gg)</td>
<td>7.2%</td>
<td>-</td>
</tr>
<tr>
<td>α_s + PDF (qq)</td>
<td>-</td>
<td>2.7%</td>
</tr>
<tr>
<td>missing high-orders</td>
<td>7.5%</td>
<td>0.2%</td>
</tr>
<tr>
<td>signal acceptance</td>
<td>2%</td>
<td>-</td>
</tr>
<tr>
<td>BR(H → ZZ)</td>
<td>2%</td>
<td>-</td>
</tr>
<tr>
<td>luminosity</td>
<td>2.6%</td>
<td>-</td>
</tr>
<tr>
<td>muon efficiency</td>
<td>4.3% (4µ), 2.1% (2e2µ)</td>
<td>-</td>
</tr>
<tr>
<td>electron efficiency</td>
<td>10% (4e), 4.3% (2e2µ)</td>
<td>-</td>
</tr>
<tr>
<td>control region</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal yield</td>
<td>4µ</td>
</tr>
<tr>
<td>Muon reconstruction and identification</td>
<td>±0.8</td>
</tr>
<tr>
<td>Electron reconstruction and identification</td>
<td>-</td>
</tr>
<tr>
<td>Reducible background (inclusive analysis)</td>
<td>±24</td>
</tr>
<tr>
<td>Migration between categories</td>
<td></td>
</tr>
<tr>
<td>ggF/VBF/VH contributions to VBF–like cat.</td>
<td>±32/11/11</td>
</tr>
<tr>
<td>ZZ* contribution to VBF–like cat.</td>
<td>±36</td>
</tr>
<tr>
<td>ggF/VBF/VH contributions to VH–like cat.</td>
<td>±15/5/6</td>
</tr>
<tr>
<td>ZZ* contribution to VH–like cat.</td>
<td>±30</td>
</tr>
<tr>
<td>Mass measurement</td>
<td>4µ</td>
</tr>
<tr>
<td>Lepton energy and momentum scale</td>
<td>±0.2</td>
</tr>
</tbody>
</table>
H→ZZ→4l: likelihood

- **ATLAS** uses a 1D likelihood with \( m_{4l} \) as discriminating variable
- **CMS** uses a 3D likelihood for:
  - exclusion limits, signal significance, signal strength \( \mu = \sigma/\sigma_{SM} \)

Events split in:
- 0/1 jet category
- di-jets with at least two jets
$H \rightarrow ZZ \rightarrow 4l$: p-value and $\sigma_{95}/\sigma_{SM}$

- **Observation at 95% C.L.:**
  - $114.5 < m_H < 119.0$ GeV
  - $129.5 < m_H < 832.0$ GeV

- **Experiment:**
  - $115 < m_H < 740$ GeV

- **Expected:**
  - $115 < m_H < 740$ GeV

**Observed and Expected Significance:**

<table>
<thead>
<tr>
<th>obs(exp)</th>
<th>1D sig.</th>
<th>2D sig.</th>
<th>3D sig.</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>expected</td>
<td>$5.6\sigma$</td>
<td>$6.6\sigma$</td>
<td>$6.7\sigma$</td>
<td>$1$</td>
</tr>
<tr>
<td>observed</td>
<td>$5.0\sigma$</td>
<td>$6.9\sigma$</td>
<td>$6.8\sigma$</td>
<td>$0.93$</td>
</tr>
</tbody>
</table>
$H \rightarrow ZZ \rightarrow 4l$, $H \rightarrow \gamma\gamma$: p-value

$\bar{p}_0$ min @ $m_H = 124.3$ GeV
6.6$\sigma$ (4.4$\sigma$ expected)

$\bar{p}_0$ min @ $m_H = 126.5$ GeV
7.4$\sigma$ (4.3$\sigma$ expected)

$\bar{p}_0$ min @ $m_H = 125$ GeV
3.2$\sigma$ (4.2$\sigma$ expected)

$\min @ m_H = 146$ GeV
(2.7$\sigma$)

$\min @ m_H = 125.6$ GeV
6.8$\sigma$ (6.7$\sigma$ expected)
Signal strength $\mu = \sigma / \sigma_{\text{SM}}$

$\mu$ from a fit to data for a fixed mass hypothesis corresponding to the measured value

**CMS** $H \rightarrow ZZ \rightarrow 4l$ @ mass $m_H = 125.6$ GeV

<table>
<thead>
<tr>
<th>Category</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0/1-jet</td>
<td>0.83 $^{+0.31}_{-0.25}$</td>
</tr>
<tr>
<td>di-jet</td>
<td>1.45 $^{+0.89}_{-0.62}$</td>
</tr>
<tr>
<td><strong>combined</strong></td>
<td>$0.93^{+0.26}<em>{-0.23}$ (stat.) $^{+0.13}</em>{-0.09}$ (syst.)</td>
</tr>
</tbody>
</table>

$\mu$ consistent with 1 within uncertainties

**ATLAS**

$m_H = 125.5$ GeV

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma$(stat)</th>
<th>$\sigma$(sys)</th>
<th>$\sigma$(theo)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma \gamma$</td>
<td>$\mu = 1.56^{+0.33}_{-0.28}$</td>
<td>$\pm 0.23$</td>
<td>$\pm 0.15$</td>
</tr>
<tr>
<td>Low $p_T$</td>
<td>$\mu = 1.6^{+0.5}_{-0.4}$</td>
<td>$\pm 0.3$</td>
<td>$\pm 0.15$</td>
</tr>
<tr>
<td>High $p_T$</td>
<td>$\mu = 1.7^{+0.7}_{-0.6}$</td>
<td>$\pm 0.5$</td>
<td>$\pm 0.14$</td>
</tr>
<tr>
<td>2 jet high mass (VBF)</td>
<td>$\mu = 1.9^{+0.6}_{-0.6}$</td>
<td>$\pm 0.6$</td>
<td>$\pm 0.14$</td>
</tr>
<tr>
<td>VH categories</td>
<td>$\mu = 1.3^{+1.2}_{-1.1}$</td>
<td>$\pm 0.9$</td>
<td>$\pm 0.14$</td>
</tr>
</tbody>
</table>

**CMS, arXiv:1312.5333, submitted to PRD**
Signal strength $\mu_{\text{ggH,ttH}}, \mu_{\text{VBF,VH}}$

Data fitted separating the production through couplings to fermions ($\text{ggH, ttH}$) or vector bosons ($\text{VBF, VH}$)

**CMS H$\to$ZZ$\to$4l @ mass $m_H=125.6\text{ GeV}$**

**ATLAS @ mass $m_H=125.5\text{ GeV}$**

In a model-independent way (i.e. without assumptions on the Higgs boson BR):

<table>
<thead>
<tr>
<th>Coupling</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{ggH,ttH}$</td>
<td>$0.80^{+0.46}_{-0.36}$</td>
</tr>
<tr>
<td>$\text{VBF,VH}$</td>
<td>$1.7^{+2.2}_{-2.1}$</td>
</tr>
</tbody>
</table>

N. De Filippis  
Moriond QCD, La Thuile, Italy, March 22-29, 2014
H→γγ in a nutshell

Similar analysis strategy for both CMS and ATLAS:

- Events categorized according to photon resolution and kinematics.
- Additional exclusive channels targeting VBF and associated production.
- Signal extracted from simultaneous S+B fit to all categories
- Background modeled with polynomials or falling power-law or exponentials
- Analytic signal model accounting for data/MC corrections and associated uncertainties

\[ m_H = 126.8 \pm 0.2 \text{ (stat.)} \pm 0.7 \text{ (syst.) GeV} \]

\[ m_H = 125.4 \pm 0.5 \text{ (stat.)} \pm 0.6 \text{ (syst.) GeV} \]
H→γγ: p-value and $\sigma_{95}/\sigma_{SM}$

$p_0$ min @ $m_H = 126.5$ GeV
7.4σ (4.3σ expected)

CMS PAS-HIG-13-002

$\sigma^0$ min @ $m_H = 125$ GeV
3.2σ (4.2σ expected)

N. De Filippis
Moriond QCD, La Thuile, Italy, March 22-29, 2014
**H→γγ: systematics**

### CMS:

<table>
<thead>
<tr>
<th>Sources of systematic uncertainty</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Per photon</td>
<td></td>
</tr>
<tr>
<td>Energy resolution ($\Delta \sigma/E_{MC}$) $R_\eta &gt; 0.94$ (low $\eta$, high $\eta$)</td>
<td>0.23%, 0.72%</td>
</tr>
<tr>
<td>Energy scale ($</td>
<td>E_{data} - E_{MC}</td>
</tr>
<tr>
<td>Energy scale ($</td>
<td>E_{data} - E_{MC}</td>
</tr>
<tr>
<td>Photon identification efficiency</td>
<td>1.0%</td>
</tr>
<tr>
<td>$R_\eta &gt; 0.94$ efficiency (results in class migration)</td>
<td>4.0%</td>
</tr>
<tr>
<td>$R_\eta &lt; 0.94$ efficiency (results in class migration)</td>
<td>6.5%</td>
</tr>
<tr>
<td>Photon identification BDT</td>
<td>±0.01 (shape shift)</td>
</tr>
<tr>
<td>Photon energy resolution BDT</td>
<td>±10% (shape scaling)</td>
</tr>
</tbody>
</table>

### ATLAS:

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%) on signal yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>±0.5</td>
</tr>
<tr>
<td>Photon identification</td>
<td>±2.4</td>
</tr>
<tr>
<td>Isolation</td>
<td>±1.0</td>
</tr>
<tr>
<td>Photon energy scale</td>
<td>±0.25</td>
</tr>
<tr>
<td>ggF (theory), tight high-mass two-jet cat.</td>
<td>±48</td>
</tr>
<tr>
<td>ggF (theory), loose high-mass two-jet cat.</td>
<td>±28</td>
</tr>
<tr>
<td>ggF (theory), low-mass two-jet cat.</td>
<td>±30</td>
</tr>
<tr>
<td>Impact of background modelling</td>
<td>±(2 - 14), cat.-dependent</td>
</tr>
</tbody>
</table>

### Production cross sections

<table>
<thead>
<tr>
<th>Source</th>
<th>Scale</th>
<th>PDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluon fusion</td>
<td>+7.6% -8.2%</td>
<td>+7.6% -7.0%</td>
</tr>
<tr>
<td>Vector boson fusion</td>
<td>+0.3% -0.8%</td>
<td>+2.6% -2.8%</td>
</tr>
<tr>
<td>Associated production with W/Z</td>
<td>+2.1% -1.8%</td>
<td>4.2%</td>
</tr>
<tr>
<td>Associated production with t\bar{t}</td>
<td>+4.1% -9.4%</td>
<td>8.0%</td>
</tr>
</tbody>
</table>
H → WW → 2l2ν in a nutshell

- **Signatures:** 2 isolated high $p_T$ leptons + MET, no hard jet in the central region, no mass peak (mass resolution ≈ 20%)

- **Backgrounds:** tt, DY, WW, tW, W+jets

- **Preselection:**
  - single lepton triggers + muon/ele ID
  - isolated leptons opp. charge, $p_T$

- **Main selection observables:**
  - Central jet veto
  - Angular correlations btw leptons related to the **scalarity** $\Delta\phi$
  - Discriminating variables:
    - Di-lepton mass, transverse mass, leptons $p_T, \Delta\phi$
  - cut based and MVA approaches
  - Main challenge = control from data of:
    - MET measurement and fake rate
    - modeling of tt and WW bkg
Higgs signal strength summary

\[ \mu_{\gamma\gamma} = 1.57^{+0.33}_{-0.28} \]
\[ \mu_{ZZ} = 1.44^{+0.40}_{-0.35} \]
\[ \mu_{WW} = 1.00^{+0.32}_{-0.29} \]
\[ \mu_{\tau\tau} = 1.4^{+0.5}_{-0.4} \]
\[ \mu_{bb} = 0.2^{+0.7}_{-0.6} \]

Combined fit
\[ \mu_{\gamma\gamma} = 1.30^{+0.16}_{-0.17} \]
\[ \mu_{ZZ} = 0.77^{+0.27}_{-0.27} \]
\[ \mu_{WW} = 0.92^{+0.28}_{-0.28} \]
\[ \mu_{\tau\tau} = 0.68^{+0.2}_{-0.2} \]
\[ \mu_{bb} = 1.10^{+0.41}_{-0.41} \]

Combined fit
\[ \mu_{\gamma\gamma} = 0.80^{+0.14}_{-0.14} \]

ATLAS
\[ [m_H=125.5 \text{ GeV}] \]

CMS
\[ [m_H=125.7 \text{ GeV}] \]
### Constraint on the $\Gamma_H$ from off-shell $H \rightarrow ZZ$

#### Event yield

<table>
<thead>
<tr>
<th></th>
<th>Full region</th>
<th>Signal-enriched region</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg + VBF \rightarrow 4\ell$ (signal, $\Gamma_H/\Gamma_H^{SM} = 1$)</td>
<td>$2.22^{+0.15}_{-0.17}$</td>
<td>$1.20^{+0.08}_{-0.09}$</td>
</tr>
<tr>
<td>$gg + VBF \rightarrow 4\ell$ (background)</td>
<td>$31.1^{+3.0}_{-3.1}$</td>
<td>$2.12 \pm 0.21$</td>
</tr>
<tr>
<td>$gg + VBF \rightarrow 4\ell$ (total, $\Gamma_H/\Gamma_H^{SM} = 1$)</td>
<td>$29.6^{+2.8}_{-2.9}$</td>
<td>$1.73^{+0.16}_{-0.17}$</td>
</tr>
<tr>
<td>$gg + VBF \rightarrow 4\ell$ (total, $\Gamma_H/\Gamma_H^{SM} = 15$)</td>
<td>$51.8^{+4.9}_{-5.0}$</td>
<td>$13.1 \pm 1.1$</td>
</tr>
<tr>
<td>$q\bar{q}$</td>
<td>$154.7 \pm 7.4$</td>
<td>$8.6 \pm 0.4$</td>
</tr>
<tr>
<td>Reducible background</td>
<td>$3.7 \pm 0.6$</td>
<td>$0.44 \pm 0.08$</td>
</tr>
<tr>
<td>Total expected ($\Gamma_H/\Gamma_H^{SM} = 1$)</td>
<td>$188.0 \pm 7.9$</td>
<td>$10.8 \pm 0.4$</td>
</tr>
<tr>
<td>Observed</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>ee</th>
<th>$\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg + VBF$ (signal, $\Gamma_H/\Gamma_H^{SM} = 1$)</td>
<td>$2.30 \pm 0.03$</td>
<td>$2.72 \pm 0.03$</td>
</tr>
<tr>
<td>$gg + VBF$ (background)</td>
<td>$5.4 \pm 0.2$</td>
<td>$6.5 \pm 0.2$</td>
</tr>
<tr>
<td>$gg + VBF$ (total, $\Gamma_H/\Gamma_H^{SM} = 1$)</td>
<td>$4.8 \pm 0.1$</td>
<td>$5.7 \pm 0.3$</td>
</tr>
<tr>
<td>$gg + VBF$ (total, $\Gamma_H/\Gamma_H^{SM} = 10$)</td>
<td>$19.2 \pm 0.6$</td>
<td>$22.6 \pm 1.2$</td>
</tr>
<tr>
<td>$q\bar{q} \rightarrow ZZ$</td>
<td>$25.0 \pm 0.5$</td>
<td>$29.4 \pm 0.5$</td>
</tr>
<tr>
<td>$WZ$</td>
<td>$11.6 \pm 0.4$</td>
<td>$13.5 \pm 0.4$</td>
</tr>
<tr>
<td>$t\bar{t}/tW/WW$</td>
<td>$3.3 \pm 1.1$</td>
<td>$4.2 \pm 1.4$</td>
</tr>
<tr>
<td>$Z +$ jets</td>
<td>$1.5 \pm 0.9$</td>
<td>$2.4 \pm 1.4$</td>
</tr>
<tr>
<td>Total expected ($\Gamma_H/\Gamma_H^{SM} = 1$)</td>
<td>$46.2 \pm 1.6$</td>
<td>$55.3 \pm 2.1$</td>
</tr>
<tr>
<td>Observed</td>
<td>$39$</td>
<td>$52$</td>
</tr>
</tbody>
</table>
Constraint on the $\Gamma_H$ from $H^*(126) \rightarrow ZZ$

At 95% CL:

- Expected $r < 11.5$
- Observed $r < 6.6$

Main systematic uncertainties:
- QCD scale and PDFs for $q\bar{q} \rightarrow ZZ$ and $gg \rightarrow ZZ$
- $\mu$ uncertainties from CMS 4l low-mass paper
- Uncertainty on k-factor approximation for $gg \rightarrow ZZ$ continuum
- Experimental uncertainties (lepton trigger/reconstruction efficiencies etc.)
Spin-parity: strategy

A large number of options to probe the spin directly from angular distributions:

- From the decay angles and the spin correlation when applicable
- From the production angle $\cos \theta^*$ distribution
- From the associated production modes (VH, VBF or ggF+jets)

The philosophy of the approach:

- Measure compatibility with the $0^+$ hypothesis
- Try to exclude alternative hypotheses simulated using an
  - anomalous couplings compatible with Lorentz and gauge invariance most general (JHUGEN via the matrix element approach)
  - effective Lagrangian including higher order couplings compatible with Lorentz and gauge invariance (MADGRAPH)
Spin-parity: anomalous coupling approach


Spin 0:

\[ A(X_{J=0} \rightarrow VV) = v^{-1} \left( g_1 m_v^2 \epsilon_1^* \epsilon_2^* + g_2 f_{\mu \nu}^{* (1)} f^{* (2)}_{\mu \nu} + g_3 f^{* (1)}_{\mu \alpha} f^{* (2)}_{\mu \alpha} \frac{q_\nu q_\alpha}{\Lambda^2} + g_4 f_{\mu \nu}^{* (1)} f_{\mu \nu}^{* (2)} \right) \]

Spin 1:

\[ A(X_{J=1} \rightarrow VV) = g_1^{(1)} \left[ (\epsilon_1^* q)(\epsilon_2^* \epsilon_X) + (\epsilon_2^* q)(\epsilon_1^* \epsilon_X) \right] + g_2^{(1)} \epsilon_{\alpha \mu \nu \beta} \epsilon_X^* \epsilon_1^* \epsilon_2^* \epsilon_X^* q^\beta \]

Spin 2:

\[ A(X_{J=2} \rightarrow VV) = \Lambda^{-1} \left[ 2g_2^{(2)} t_{\mu \nu} f^{* 1, \mu \alpha} f^{* 2, \nu \alpha} + 2g_2^{(2)} t_{\mu \nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{* 1, \mu \alpha} f^{* 2, \nu \beta} \right. \\
+ g_3^{(2)} \frac{q^\beta q^\alpha}{\Lambda^2} t_{\beta \nu} (f^{* 1, \mu \nu} f^{* 2, \mu \nu} f^{* 1, \mu \alpha} f^{* 2, \mu \alpha}) + g_4^{(2)} \frac{q^\nu q^\mu}{\Lambda^2} t_{\mu \nu} f^{* 1, \alpha \beta} f^{* 2, \alpha \beta} \\
+ m_V^2 \left( 2g_5^{(2)} t_{\mu \nu} \epsilon_1^* \epsilon_2^* \epsilon_X^* + 2g_6^{(2)} \frac{q^\mu q_\alpha}{\Lambda^2} t_{\mu \nu} (\epsilon_1^* \epsilon_2^* \epsilon_X^* - \epsilon_1^* \epsilon_1^* \epsilon_X^*) + g_7^{(2)} \frac{q^\nu q^\mu}{\Lambda^2} t_{\mu \nu} \epsilon_1^* \epsilon_2^* \epsilon_X^* \right) \\
+ g_8^{(2)} \frac{q_\mu q_\nu}{\Lambda^2} t_{\mu \nu} f^{* 1, \alpha \beta} f^{* 2, \alpha \beta} + g_9^{(2)} t_{\mu \nu} \epsilon_{\mu \rho \sigma} \epsilon_{\alpha \beta} \epsilon_{\nu}^* \epsilon_{\sigma}^* q^\rho q^\sigma \\
+ \left. g_{10}^{(2)} t_{\mu \nu} \epsilon_{\mu \rho \sigma} q^\rho q^\sigma (\epsilon_1^* \epsilon_2^* (q \epsilon_X^*) + \epsilon_2^* \epsilon_1^* (q \epsilon_X^*)) \right] , \]
Spin-parity: $0^+ \text{ vs } 2^+_m$ from $H \rightarrow \gamma\gamma$

- Distribution of production angle $\cos\theta^*$ sensitive to $J^{CP}$ (spin 1 is forbidden by the Landau-Yang theorem)
- Event selection similar to $H \rightarrow \gamma\gamma$ mass analysis
  - **ATLAS**: no correlation between $m_{\gamma\gamma}$ and $\cos\theta^*$ for the baseline analysis
  - **CMS**: simple 4 categories cut-based categorization based on $\eta$ and R9

**CMS not able to exclude $2^+$ models at 95%CL while a better sensitivity for ATLAS analysis partially driven by higher observed excess. SM hypothesis generally favored in data**
CP-odd fraction fit

Test of possible CP violating components of the amplitude so a possible mixture of CP-even and CP-odd components

The spin-zero models $0^+, 0^+_h$, and $0^-$ correspond to the terms with $a_1$, $a_2$, and $a_3$, respectively, appearing in the decay amplitude for a spin-zero boson

$$A(H \rightarrow ZZ) = v^{-1}(a_1 m_Z^2 e_1^* e_2^* + a_2 f^{*(1)}_{\mu\nu} f^{*(2)}_{\mu\nu} + a_3 f^{*(1)}_{\mu\nu} f^{*(2)}_{\mu\nu}).$$


- SM case $a_1 = 1$ and $a_2 = a_3 = 0$
- $a_3$ is a CP-odd amplitude
- Measure $f_{a_3} = a_3/a_1$ (assuming $a_2 = 0$)

$$f_{a_3} = \frac{|a_3|^2 \sigma_3}{|a_1|^2 \sigma_1 + |a_3|^2 \sigma_3} \quad \frac{|a_3|}{|a_1|} = \sqrt{\frac{f_{a_3}}{1 - f_{a_3}}} \times \sqrt{\frac{\sigma_1}{\sigma_3}}$$

$$\sigma_1/\sigma_3 = 6.240$$ for a 126 GeV Higgs boson

Best fit $f_{a_3} = 0.00^{+0.17}_{-0.00}$

$f_{a_3} < 0.51$ @ 95% CL
The signals observed in the different search channels originate from a single resonance with mass of 125.5 GeV.

The width of the Higgs boson is narrow → the zero-width approximation

\[ \sigma \cdot B (i \rightarrow H \rightarrow f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H} \]

Only modifications of coupling strengths are considered while the tensor structure of the lagr. is the SM one → observed 0^+

The coupling scale factors \( K_i \) are defined in such a way that

- the cross sections \( \sigma_{ii} \)
- the partial decay widths \( \Gamma_{ii} \) associated with the SM particle \( i \) scale with \( K^2_i \) compared to the SM prediction

significant deviations of any \( K_i \) from unity would imply new physics BSM

results are extracted from fits to the data using the profile likelihood ratio where the \( \kappa_i \) couplings are treated either as parameters of interest or as nuisance parameters, depending on the measurement
Test of custodial symmetry

\[ \lambda_{WZ} = \kappa_W / \kappa_Z \]

this value is expected to be protected and consistent with unity. Large deviations from 1 indicate new physics.

To fit the \( \lambda_{WZ} \) from data **CMS** uses:
- untagged pp \( \rightarrow H \rightarrow WW \)
- inclusive pp \( \rightarrow H \rightarrow ZZ \)

since the production mechanism is dominated by ggF and the result is more model independent.

The scale factor \( k_Z \) is treated as a nuisance parameter, and \( k_f \approx 1 \) for all Higgs boson couplings to fermions.

<table>
<thead>
<tr>
<th>Method</th>
<th>95% C.I. ( \lambda_{WZ} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS</td>
<td>H ( \rightarrow VV(0,1 ) jet ) ( k_Z ) profiled, ( k_f \approx 1 )</td>
</tr>
<tr>
<td></td>
<td>[0.60, 1.4]</td>
</tr>
<tr>
<td>CMS</td>
<td>Overall ( k_Z, k_f ) profiled</td>
</tr>
<tr>
<td></td>
<td>[0.62, 1.19]</td>
</tr>
<tr>
<td>ATLAS</td>
<td>Overall ( \lambda_{fZ}, k_{ZZ} ) profiled</td>
</tr>
<tr>
<td></td>
<td>( 0.81^{+0.16}_{-0.15} )</td>
</tr>
</tbody>
</table>

Data show consistency of \( \lambda_{WZ} = \kappa_W / \kappa_Z \) with the unity

N. De Filippis  
Moriond QCD, La Thuile, Italy, March 22-29, 2014
Test of couplings to the VV and ff

Assumptions :

- \( \lambda_{WZ} = k_W/k_Z = 1 \) so \( k_W = k_Z = k_V \) common factor
- \( \Gamma_{BSM} = 0 \) i.e. no new Higgs boson decay modes are open

At leading order (LO)

- all partial widths scale either as \( k_V^2 \) or \( k_f^2 \) except \( \Gamma_{\gamma\gamma} \)
- \( \Gamma_{\gamma\gamma} \) is induced via W and top loop diagrams and scales as \( |\alpha k_V + \beta k_f|^2 \)
- so \( \gamma\gamma \) is the only channel sensible to the sign of \( k_V \) or \( k_f \)

The data are compatible with the expectation for the SM: the point \((k_V, k_f) = (1,1)\) is within the 68% confidence region defined by the data.
Test of presence of BSM

Processes induced by loop diagrams ($H \rightarrow \gamma \gamma$ and $gg \rightarrow H$) can be particularly susceptible to the presence of new particles.

So fit the data for the scale factors $k_g$ and $k_\gamma$ for these two processes.
Fermion universality

- 2-Higgs-Doublet models can affect
  - up-type, down-type fermions differently
  - leptons, quarks differently

$k_v$ and $k_q$ ($k_u$) profiled

\[ [0.00, 2.11] \text{ @ } 95\% \text{ CL} \]

\[ [0.45, 1.66] \text{ @ } 95\% \text{ CL} \]
Test of presence of BSM

Letting $\text{BR}_{\text{BSM}}$ floating for the best fit with $k_g$ and $k_\gamma$ profiled together with all other nuisance parameters

Scale total width: $\text{BR}_{\text{BSM}} = \frac{\Gamma_{\text{BSM}}}{\Gamma_{\text{tot}}}$

$[-2\Delta \ln L, 5.0]$ for the best fit with $k_g$ and $k_\gamma$ profiled together with all other nuisance parameters

$[0.00, 0.52] @ 95\% \text{ CL}$
From BEH to dark matter

Can interpret limit on invisible BR as limit on DM candidates coupling to BEH boson.

\[
\sigma_{S-N} = \frac{4 \Gamma_{\text{inv.}}}{m_H^3 v^2 \beta (M_X + m_N)^2} \cdot \frac{m_N^4 f_N^2}{m^4 f_N^2}
\]
Higgs couplings summary

<table>
<thead>
<tr>
<th>Model</th>
<th>Probed couplings</th>
<th>Parameters of interest</th>
<th>Functional assumptions</th>
<th>Example: $gg \to H \to \gamma\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Couplings to fermions and bosons</td>
<td>$\kappa_V, \kappa_F$</td>
<td>$\checkmark$ $\checkmark$ $\checkmark$ $\checkmark$ $\checkmark$</td>
<td>$\kappa_F^2 \cdot \kappa_F^2 (\kappa_F, \kappa_V) / \kappa_H^2 (\kappa_F, \kappa_V)$</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>$\kappa_{LV}, \kappa_{VV}$</td>
<td>$\checkmark$ $\checkmark$ $\checkmark$ $\checkmark$ $\checkmark$</td>
<td>$\kappa_{LV}^2 \cdot \kappa_{LV}^2 (\kappa_{LV}, \kappa_{VV}, 1)$</td>
</tr>
<tr>
<td>3</td>
<td>Custodial symmetry</td>
<td>$\lambda_{WZ}, \lambda_{FZ}, \kappa_{ZZ}$</td>
<td>$-$ $\checkmark$ $\checkmark$ $\checkmark$ $-$</td>
<td>$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \cdot \lambda_{FZ}^2 (\lambda_{WZ}, \lambda_{FZ}, \lambda_{WZ})$</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>$\lambda_{WZ}, \lambda_{FZ}, \lambda_{YZ}, \kappa_{ZZ}$</td>
<td>$-$ $\checkmark$ $\checkmark$ $\checkmark$ $-$</td>
<td>$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \cdot \lambda_{FZ}^2$</td>
</tr>
<tr>
<td>5</td>
<td>Vertex loops</td>
<td>$\kappa_g, \kappa_y$</td>
<td>$1$ $1$ $\checkmark$ $\checkmark$</td>
<td>$\kappa_g^2 \cdot \kappa_y^2 / \kappa_H^2 (\kappa_g, \kappa_y)$</td>
</tr>
</tbody>
</table>

---

CMS

<table>
<thead>
<tr>
<th>Model parameters</th>
<th>Assessed scaling factors (68% and 95% CL intervals)</th>
<th>Total uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_{WZ}, \kappa_Z$</td>
<td>$\lambda_{WZ}$</td>
<td>$[0.75,1.13] [0.60,1.40]$</td>
</tr>
<tr>
<td>$\lambda_{WZ}, \kappa_Z, \kappa_f$</td>
<td>$\lambda_{WZ}$</td>
<td>$[0.73,1.00] [0.62,1.19]$</td>
</tr>
<tr>
<td>$\kappa_V, \kappa_f$</td>
<td>$\kappa_V$</td>
<td>$[0.81,0.97] [0.73,1.05]$</td>
</tr>
<tr>
<td></td>
<td>$\kappa_f$</td>
<td>$[0.71,1.11] [0.55,1.31]$</td>
</tr>
<tr>
<td>$\kappa_y, \kappa_g$</td>
<td>$\kappa_g$</td>
<td>$[0.79,1.14] [0.59,1.30]$</td>
</tr>
<tr>
<td></td>
<td>$\kappa_y$</td>
<td>$[0.73,0.94] [0.63,1.05]$</td>
</tr>
<tr>
<td>$B(H \to BSM), \kappa_y, \kappa_g$</td>
<td>$B(H \to BSM)$</td>
<td>$[0.00,0.24] [0.00,0.52]$</td>
</tr>
<tr>
<td>$\lambda_{d_\mu}, \kappa_V, \kappa_u$</td>
<td>$\lambda_{d_\mu}$</td>
<td>$[1.00,1.60] [0.74,1.95]$</td>
</tr>
<tr>
<td>$\lambda_{t_q}, \kappa_V, \kappa_q$</td>
<td>$\lambda_{t_q}$</td>
<td>$[0.89,1.62] [0.57,2.05]$</td>
</tr>
<tr>
<td>$\kappa_V, \kappa_b, \kappa_t, \kappa_t, \kappa_g, \kappa_y$</td>
<td>$\kappa_V$</td>
<td>$[0.84,1.23] [0.60,1.39]$</td>
</tr>
<tr>
<td></td>
<td>$\kappa_b$</td>
<td>$[0.61,1.69] [0.00,2.63]$</td>
</tr>
<tr>
<td></td>
<td>$\kappa_t$</td>
<td>$[0.82,1.45] [0.53,1.81]$</td>
</tr>
<tr>
<td></td>
<td>$\kappa_t$</td>
<td>$[0.00,2.03] [0.00,4.20]$</td>
</tr>
<tr>
<td></td>
<td>$\kappa_g$</td>
<td>$[0.65,1.15] [0.49,1.77]$</td>
</tr>
<tr>
<td></td>
<td>$\kappa_y$</td>
<td>$[0.77,1.27] [0.55,1.55]$</td>
</tr>
</tbody>
</table>

as above + $B(H \to BSM)$, but $\kappa_V \leq 1$ | $B(H \to BSM)$ | $[0.00,0.80] [0.00,0.64]$ |
# Higgs couplings summary

![Graph showing Higgs couplings](image)

- $\lambda_{WZ} = 0.94^{+0.14}_{-0.29}$, ATLAS
- $\lambda_{WZ} = 0.73-1.0$, CMS
- $\kappa_F = 0.99^{+0.17}_{-0.15}$, ATLAS
- $\kappa_F = 0.71-1.11$, CMS
- $\kappa_V = 1.15^{+0.08}_{-0.08}$, ATLAS
- $\kappa_V = 0.81-0.97$, CMS
- $\lambda_{FV} = 0.86^{+0.14}_{-0.12}$, ATLAS
- $\kappa_g = 1.08^{+0.15}_{-0.13}$, ATLAS
- $\kappa_g = 0.73-0.94$, CMS
- $\kappa_\gamma = 1.19^{+0.15}_{-0.12}$, ATLAS
- $\kappa_\gamma = 0.79-1.14$, CMS
- $\lambda_{d_R} = 0.78-1.15$, ATLAS
- $\lambda_{d_R} = 1.0-1.6$, CMS
- $|\lambda_{lq}| = 0.99-1.5$, ATLAS
- $|\lambda_{lq}| = 0.89-1.62$, CMS
- $B_{l_R} < 0.55$, ATLAS
- $B_{l_R} < 0.64$, CMS