Measurements of the properties of the Higgs boson with the ATLAS Detector

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on behalf of the ATLAS Collaboration

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Higgs boson production at LHC

<table>
<thead>
<tr>
<th>Production process</th>
<th>Cross section [pb] ( \sqrt{s} = 7) TeV</th>
<th>Cross section [pb] ( \sqrt{s} = 8) TeV</th>
<th>Order of calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF</td>
<td>15.0 ± 1.6</td>
<td>19.2 ± 2.0</td>
<td>NNLO(QCD)+NLO(EW)</td>
</tr>
<tr>
<td>VBF</td>
<td>1.22 ± 0.03</td>
<td>1.58 ± 0.04</td>
<td>NLO (QCD+EW)/NNLO(QCD)</td>
</tr>
<tr>
<td>WH</td>
<td>0.577 ± 0.016</td>
<td>0.703 ± 0.018</td>
<td>NNLO(QCD)+NLO(EW)</td>
</tr>
<tr>
<td>ZH</td>
<td>0.357 ± 0.015</td>
<td>0.446 ± 0.019</td>
<td>NNLO(QCD)+NLO(EW)</td>
</tr>
<tr>
<td>bbH</td>
<td>0.156 ± 0.021</td>
<td>0.203 ± 0.028</td>
<td>5FS + 4FS NLO(QCD)</td>
</tr>
<tr>
<td>ttH</td>
<td>0.086 ± 0.009</td>
<td>0.129 ± 0.014</td>
<td>NLO(QCD)</td>
</tr>
</tbody>
</table>

- A lot of progress on cross section and BR computation
- Uncertainties O(10%) in ggF, dominated by QCD scale and PDF+\(\alpha_s\)
**Higgs boson decays**

- All hadronic decay modes ($H \rightarrow b\bar{b}$ and $H \rightarrow ZZ, W^+W^- \rightarrow q\bar{q}q\bar{q}$) dominant but overwhelmed by QCD backgrounds → final states with isolated leptons, photons, missing transverse energy are the only viable ones at LHC.

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>BR @ $M_H = 125$ GeV</th>
<th>$\sigma \cdot BR$ [fb]</th>
<th>Events Produced with 25 fb$^{-1}$</th>
<th>Mass Resolution</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma\gamma$</td>
<td>$2.28 \cdot 10^{-3}$</td>
<td>50</td>
<td>1250</td>
<td>😊😊</td>
<td>😊</td>
</tr>
<tr>
<td>$Z\bar{Z} \rightarrow 4l$</td>
<td>$1.25 \cdot 10^{-4}$</td>
<td>2.7</td>
<td>67</td>
<td>😊😊</td>
<td>😊</td>
</tr>
<tr>
<td>$WW^* \rightarrow l\nu\nu$</td>
<td>$1.06 \cdot 10^{-2}$</td>
<td>230</td>
<td>5700</td>
<td>😊😊😊</td>
<td>😊</td>
</tr>
<tr>
<td>$\tau^+\tau^-$ (VBF)</td>
<td>$6.32 \cdot 10^{-2}$</td>
<td>100</td>
<td>2500</td>
<td>😊</td>
<td>😊😊</td>
</tr>
<tr>
<td>$b\bar{b}$ (VH)</td>
<td>$5.77 \cdot 10^{-1}$</td>
<td>106</td>
<td>2600</td>
<td>😊</td>
<td>😊😊</td>
</tr>
</tbody>
</table>

**ICPPA2015 - Moscow - 5-10 October 2015**

Daniela Rebuzzi (Pavia University)

Measurements of the properties of the Higgs boson with ATLAS

Higgs boson mass and width

[Measurement of the Higgs boson mass from the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ channels with the ATLAS detector using 25 fb$^{-1}$ of pp collision data - Phys. Rev. D. 90, 052004 (2014)]

ATLAS $M_H$ measurements use high resolution $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^{*} \rightarrow 4l$ channels and the full set of $\sim 25$ fb$^{-1}$ data at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV.

$H \rightarrow \gamma\gamma$: excellent mass resolution (1.7 GeV), narrow peak over smooth background.

- **Mass measurement method**: simultaneous fit of mass spectra of selected diphoton events separated into 10 mutually exclusive categories - syst uncertainties treated as nuisance parameters in the likelihood.

- **Signal modeling**: Crystal Ball + Gaussian.

- **Background modeling and estimation**: 
  - fit to diphoton mass distribution in the data over the [105, 160] GeV range
  - exponential function of first/second-order polynomial.

- **Main systematics**: photon energy scale uncertainties (0.17%-0.57%).

Results from $H \rightarrow \gamma\gamma$: $M_H = 125.98 \pm 0.42$ (stat) $\pm 0.28$ (syst) GeV.
Higgs mass measurements: $H \rightarrow ZZ^* \rightarrow 4l$

- $H \rightarrow ZZ^* \rightarrow 4l$: high signal-to-background ratio and excellent mass resolution (1.6 - 2.2 GeV)

- **Mass measurement method**: 2D fit to $m_{4l}$ and $BDT_{ZZ}$ output in the [110, 140] GeV range - 1D fit to $m_{4l}$ as cross-check
  - Multivariate discriminant $BDT_{ZZ}$ reduces the impact of irreducible background

- **Background modeling**: full 2D PDF from simulation for $ZZ^*$, data-driven techniques for reducible background

- **Main systematics**: electron energy scale and muon momentum scale uncertainties

- **Results from $H \rightarrow ZZ^* \rightarrow 4l$**: $M_H = 124.51 \pm 0.52(\text{stat}) \pm 0.06(\text{syst})$ GeV
Combined mass measurement results

- Hypothesized values of $m_H$ are tested using a profiled likelihood ratio:

$$\Lambda(m_H) = \frac{L(m_H, \hat{\mu}_{\gamma\gamma}(m_H), \hat{\mu}_{4l}(m_H), \hat{\theta}(m_H))}{L(\bar{m}_H, \bar{\mu}_{\gamma\gamma}, \bar{\mu}_{4l}, \bar{\theta})}$$

- Results are given in terms of $-2\ln \Lambda(\Delta m_H)$, assumed to follow a $\chi^2$ distribution

- Compatibility between the two mass measurements at 2σ level
- Results from the combination: $M_H = 125.36 \pm 0.37\text{(stat)} \pm 0.18\text{(syst)}$ GeV
- No significant correlation between the two fitted variables → model-independence of the mass measurement
• **Indirect limits:** measure off- to on-shell ratio for $H \rightarrow ZZ \rightarrow 4l$, $H \rightarrow WW \rightarrow 2l2\nu$ and $H \rightarrow WW \rightarrow ev\mu\nu$ channels in the *high-mass off-peak regions* beyond $2m_V$ ($V = Z, W$) → this allows to extract a limit on $\Gamma_H/\Gamma_H^{SM}$ *under the assumption* that on-shell and off-shell couplings are identical i.e. independent from the production energy scale

\[
\begin{align*}
\sigma_{\text{off-shell}}^{(*)} & \sim \frac{g_{ggH}^2 g_{ZZ}^2}{(2m_Z)^2} \\
\sigma_{\text{on-shell}} & \sim \frac{g_{ggH}^2 g_{ZZ}^2}{m_H \Gamma_H}
\end{align*}
\]

$g_{ggH}^2 = H - g$ coupling

$g_{ZZ}^2 = H - Z$ coupling

(*) calculation should include interference terms with $gg \rightarrow VV$ (huge negative effect for large $m_{4l}$)

• **Results:** 95% CL upper limit on $\Gamma_H/\Gamma_H^{SM}$ in the range $[4.5, 7.5]$ → Observed (Expected)

95% CL upper limit on the Higgs boson total width of $22.7$ ($33.0$) MeV ($\Gamma_H^{SM} = 4.12$ MeV at $M_H = 125.4$ GeV)

• **Direct limits:** from the width of the invariant mass peak, assuming no interference with background processes: observed (expected for $\mu = 1$) 95% CL

- $H \rightarrow \gamma\gamma$: $5.0$ ($6.2$) GeV
- $H \rightarrow ZZ^* \rightarrow 4l$: $2.6$ ($6.2$) GeV (due to higher signal strength observed in the data)

Spin, parity and tensor couplings of the observed Higgs boson studied in the \( H \rightarrow ZZ^* \rightarrow 4l \), \( H \rightarrow WW^* \rightarrow e\nu\mu\nu \) and \( H \rightarrow \gamma\gamma \) channels over the full set of \( \sim 25 \text{ fb}^{-1} \) data at \( \sqrt{s} = 7 \text{ TeV} \) and \( \sqrt{s} = 8 \text{ TeV} \).

- The SM \( J^P = 0^+ \) hypothesis has been tested against several alternative spin and parity models:
  - the observed resonance as a spin-2 particle
  - the observed resonance as a pure BSM spin-0 CP-even or CP-odd Higgs boson
  - the observed resonance as a mixture of the SM spin-0 state and a BSM spin-0 CP-even or CP-odd state

- \( H \rightarrow \gamma\gamma \) decay forbidden by Landau-Yang theorem for a spin-1 \( J^P = 1^{\pm} \) not studied and ruled out at \( >99\%\)CL by previous ATLAS studies.

- Only one resonance with a mass of 125 GeV is considered and an effective field theory (EFT- valid up to a scale \( \Lambda \), set to 1 TeV) approach is adopted to describe interactions with SM vector bosons.
In the **spin-0 hypothesis**, models with fixed spin and parity and models with mixed SM spin-0 and BSM spin-0 CP-even and CP-odd contributions considered (EFT approach)

\[
\mathcal{L}_0^V = \{ \cos(\alpha) \kappa_{SM}[1/2g_{HZZ}Z_\mu Z^\mu + g_{HWW}W^\mu_\mu W^{-\mu}] \\
-1/(4\Lambda)[\cos(\alpha)\kappa_{HZZ}Z_\mu \mu + \sin(\alpha)\kappa_{AZZ}Z_\mu \mu \ddot{Z}^{\mu\nu}] \\
-1/(2\Lambda)[\cos(\alpha)\kappa_{HWW}W^\mu_\mu W^{-\mu} + \sin(\alpha)\kappa_{AWW}W^\mu_\mu \ddot{W}^{-\mu}] \} \chi_0
\]

<table>
<thead>
<tr>
<th>( J^P )</th>
<th>Model</th>
<th>Values of tensor couplings</th>
</tr>
</thead>
<tbody>
<tr>
<td>0^+</td>
<td>SM Higgs boson</td>
<td>( \kappa_{SM} ) = 1, ( \kappa_{HVV} = 0 ), ( \kappa_{AVV} = 0 ), ( \alpha = 0 )</td>
</tr>
<tr>
<td>0^+_h</td>
<td>BSM spin-0 CP-even</td>
<td>( \kappa_{HVV} = 0 ), ( \kappa_{AVV} = 1 ), ( \alpha = 0 )</td>
</tr>
<tr>
<td>0^-</td>
<td>BSM spin-0 CP-odd</td>
<td>( \kappa_{HVV} = 0 ), ( \kappa_{AVV} = 1 ), ( \alpha = \pi/2 )</td>
</tr>
</tbody>
</table>

In the **spin-2 hypothesis** (graviton-like tensor), benchmark scenarios with only QCD production for the resonance considered (EW production \( O(10^{-4}) \) in UC scenario)

\[
\mathcal{L}_2 = -\frac{1}{\Lambda} \left[ \sum_V \kappa_V T^V_{\mu\nu} X^{\mu\nu} + \sum_f \kappa_f T^f_{\mu\nu} X^{\mu\nu} \right]
\]

\( \kappa_V/\kappa_f \) = couplings of \( T^{V/f} \) to spin-2 \( X \) field

| \( \kappa_q = \kappa_g \) | Universal couplings |
| \( \kappa_q = 0 \) | Low light-quark fraction |
| \( \kappa_q = 2\kappa_g \) | Low gluon fraction |
Results given in terms of the test statistics $\tilde{q}$, to test the SM scenario against alternative spin-parity hypotheses
- distributions of $\tilde{q}$ used to determine the corresponding $p$-values and exclusion CLs

\[ \tilde{q} = \log \frac{\mathcal{L}(J_{SM}^P, \hat{\mu} J_{SM}^P, \hat{\theta} J_{SM}^P)}{\mathcal{L}(J_{alt}^P, \hat{\mu} J_{alt}^P, \hat{\theta} J_{alt}^P)} \]

**Combined Spin/CP results**

- All alternative spin/CP models considered excluded at $>99.9\%$ CL in favor of the SM $0^+$
• Analysis based on the analysis of five production processes (ggF, VBF, WH, ZH and ttH) and of $H \rightarrow ZZ^*, WW^*, \gamma\gamma, \tau\tau, bb$ and $\mu\mu$ decay modes

• Integrated luminosities per experiment of $\sim 5$ fb$^{-1}$ at $\sqrt{s} = 7$ TeV and $\sim 20$ fb$^{-1}$ at $\sqrt{s} = 8$ TeV → Combination increases sensitivity by $\sqrt{2}$

• Overall assumptions:
  - the studied particle is a **single SM-like Higgs boson** state, i.e. a CP-even scalar particle with the tensor structure of the SM interactions ($J^{CP} = 0^{++}$)
  - the total width is assumed to be small such that the **narrow-width approximation is valid** and production and decay can be decomposed

• Combined ATLAS+CMS Higgs boson mass used $M_H = 125.09 \pm 0.21$ (stat) $\pm 0.11$ (syst) GeV [PRL 114 (2015) 191803, arXiv:1503.07589 [hep-ex]]
  - Measured using high resolution $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ channels

• Combination given in terms of **two generic parameterizations**:
  1. **Signal strength formalism** (ratios of cross sections and BRs)
  2. $\kappa$-framework (LO coupling framework which introduces coupling modifiers)
• In this parameterisation, based on ratios of cross sections and branching ratios, the dominant signal TH uncertainties cancel out → no effect on the observables

• **Signal strengths** for a specific production and decay channel $i \rightarrow H \rightarrow j$

$$\mu_i = \frac{\sigma_i}{\sigma_i^{SM}} \quad i = (ggF, VBF, WH, ZH, ttH, ...)
$$

$$\mu^f = \frac{BR^f}{BR^f_{SM}} \quad f = (ZZ, WW, \gamma\gamma, \tau\tau, b\bar{b}, ...)
$$

• Only the product of $\mu_i$ and $\mu^f$ can be extracted experimentally (w/o any additional assumption)

$$\mu_i^f \equiv \frac{\sigma_i \cdot BR^f}{(\sigma_i \cdot BR^f)_{SM}} = \mu_i \times \mu^f$$

• **Most restrictive signal-strength model**: $\mu_i$ and $\mu^f$ are independent of the production process and decay mode → one signal strength $\mu$

• Best fit value, combining ATLAS+CMS data at $\sqrt{7}$ and $\sqrt{8}$ TeV:

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07} \text{ (stat)}^{+0.04}_{-0.04} \text{ (expt)}^{+0.03}_{-0.03} \text{ (thbgd)}^{+0.06}_{-0.07} \text{ (thsig)}$$

• Consistency with the SM predictions at less than $1\sigma$ - $p$-value = 34% - very model-dependent
Individual production/decay signal strengths

- Assuming $\mu_f = 1$ - $p$-value = 24%

- Assuming $\mu_i = 1$ - $p$-value = 60%

- Signal strengths consistent with 1 (SM)
- Largest difference in $ttH \to 2.3\sigma$ measured excess w.r.t. SM

<table>
<thead>
<tr>
<th>Process</th>
<th>Significance meas (expected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF</td>
<td>5.4$\sigma$ (4.7$\sigma$)</td>
</tr>
<tr>
<td>$tt\bar{t}H$</td>
<td>4.4$\sigma$ (2.0$\sigma$)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Significance meas (expected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to \tau\tau$</td>
<td>5.5$\sigma$ (5.0$\sigma$)</td>
</tr>
</tbody>
</table>
• Potential deviations of boson and fermion couplings from the SM can be tested independently for each decay channel using $\mu^f_F$ ($ggF$ and $ttH$) and $\mu^f_V$ ($VBF$, $WH$, $ZH$)

• 10-parameter fit of the five decay modes for ATLAS+CMS combined measurements

• Ratio $\mu^f_V/\mu^f_F$ can be measured in the different decay channels - combined result (w/o assumptions on SM decays):

$$\frac{\mu^f_V}{\mu^f_F} = 1.06^{+0.35}_{-0.27}$$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ATLAS+CMS</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(obs/exp)</td>
<td>(obs)</td>
<td>(obs)</td>
</tr>
<tr>
<td>$\mu^f_V/\mu^f_F$</td>
<td>$1.06^{+0.35/0.34}_{-0.27/-0.26}$</td>
<td>$0.91^{+0.67}_{-0.46}$</td>
<td>$1.29^{+0.67}_{-0.46}$</td>
</tr>
<tr>
<td>$\mu^f_\gamma^\gamma$</td>
<td>$1.13^{+0.24/0.21}_{-0.21/-0.19}$</td>
<td>$1.18^{+0.23}_{-0.29}$</td>
<td>$1.03^{+0.30}_{-0.26}$</td>
</tr>
<tr>
<td>$\mu^f_{ZZ}$</td>
<td>$1.29^{+0.29/0.24}_{-0.25/-0.20}$</td>
<td>$1.54^{+0.44}_{-0.36}$</td>
<td>$1.00^{+0.33}_{-0.27}$</td>
</tr>
<tr>
<td>$\mu^f_{WW}$</td>
<td>$1.08^{+0.22/0.19}_{-0.19/-0.17}$</td>
<td>$1.26^{+0.29}_{-0.25}$</td>
<td>$0.85^{+0.25}_{-0.22}$</td>
</tr>
<tr>
<td>$\mu^f_{TT}$</td>
<td>$1.07^{+0.35/0.32}_{-0.28/-0.27}$</td>
<td>$1.50^{+0.66}_{-0.49}$</td>
<td>$0.75^{+0.39}_{-0.29}$</td>
</tr>
<tr>
<td>$\mu^f_{b\bar{b}}$</td>
<td>$0.65^{+0.37/0.45}_{-0.28/-0.34}$</td>
<td>$0.67^{+0.58}_{-0.42}$</td>
<td>$1.03^{+0.54}_{-0.36}$</td>
</tr>
</tbody>
</table>

$p$-value = 62%
If $gg \rightarrow H \rightarrow ZZ$ is chosen as reference (smallest systematic and overall uncertainties):

$$\sigma_i \cdot BR^f = \sigma(gg \rightarrow H \rightarrow ZZ) \times \left( \frac{\sigma_i}{\sigma_{ggF}} \right) \times \left( \frac{BR^f}{BR^{ZZ}} \right)$$

- Ratios do not rely on any additional assumptions and are independent of TH predictions $\rightarrow$ most generic parameterisation
- Fit result for each of the nine parameters normalized to the corresponding SM prediction
- Measurements are almost all consistent with the SM predictions within less than $2\sigma$ - SM $p$-value = 16%
- Few visible tensions:
  - $\sigma_{ttH}/\sigma_{ggF} = 3.3^{+1.0}_{-0.9}$, 2.3$\sigma$ excess
  - $\sigma_{ZH}/\sigma_{ggF} = 3.2^{+1.8}_{-1.4}$, 2.2$\sigma$ excess
  - $BR_{bb}/BR_{ZZ} = 0.19^{+0.21}_{-0.12}$, 2.5$\sigma$ deficit
  - which are strongly anti-correlated
• Second parameterisation based on a LO framework which introduces **coupling modifiers** to probe modifications of the Higgs boson couplings due to physics BSM  [arXiv:1307.1347 [hep-ph]]

\[ \sigma(i \rightarrow H \rightarrow f) \approx \sigma_i \cdot \text{BR}^f = \frac{\sigma_i(\bar{\kappa}) \cdot \Gamma^f(\bar{\kappa})}{\Gamma_H} \]

- Different production processes and decay modes probe different coupling modifiers

• Changes in the couplings may result in a variation of the Higgs boson width - if non-SM modification of the decays are allowed:

\[ \Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - \text{BR}_{BSM}} \]

- Since \( \Gamma_H \) is not (directly or indirectly) experimentally well constrained in a model-independent way at LHC, **only ratios of coupling modifiers** \( \kappa \) can be extracted

• To directly measure individual \( \kappa \), **assumptions on the Higgs boson width are necessary:**
  1. The Higgs boson does not have BSM decay modes, i.e. \( \text{BR}_{BSM} = 0 \)
  2. \( \kappa_W \leq 1 \) and \( \kappa_Z \leq 1 \), motivated by a wide class of BSM models (\( \text{BR}_{BSM} \) can be measured)
• Assuming no new particles in $gg \rightarrow H$ production and $H \rightarrow \gamma\gamma$ decay (and no invisible Higgs decays) i.e. $\kappa_g$ and $\kappa_\gamma$ consistent with the SM expectations

• This leads to a parameterisation with six free couplings modifiers: $\kappa_W$, $\kappa_Z$, $\kappa_b$, $\kappa_t$, $\kappa_\tau$ and $\kappa_\mu$

• Results expressed as reduced coupling modifiers

• Within current precision, Higgs boson couplings scale with particle masses, as in SM
BSM particles in SM loops and BSM decays

- BSM physics may manifest in loop-induced processes of $gg\to H$ production and $H\to \gamma\gamma$ decay → effective coupling modifiers $\kappa_g$ and $\kappa_\gamma$
- Fixing all other tree-level couplings to 1 → $\text{SM } p\text{-value} = 82\%$
- Allowing for potential deviations from the SM in the tree-level couplings to ordinary particles → 7 independent coupling modifiers $\kappa_g$, $\kappa_\gamma$, $\kappa_W$, $\kappa_Z$, $\kappa_b$, $\kappa_t$ and $\kappa_\tau$
- $\text{BR}_{\text{BSM}} < 0.34$ at 95\% CL (assuming $\kappa_V \leq 1$)
- ATLAS direct limit: $\text{BR}_{\text{BSM}} < 0.25$ at 95\% CL

[arXiv:1509.00672 [hep-ex]]

$\kappa_t$ dominated by $ttH$ processes - loops no longer contribute

$\text{SM } p\text{-value} = 11\%$
ATLAS has been successfully characterizing the Higgs boson:

- The Higgs boson mass measured with <0.2% precision (ATLAS+CMS)
- Evidence of VBF production and $H \rightarrow \tau \tau$, both at the 5.5$\sigma$ level (ATLAS+CMS)
- The new particle is compatible with a $J^P = 0^+$ state - several alternative states disfavored at >99.9% CL
- All coupling measurements (both ATLAS only and combined ATLAS+CMS) show no significant deviation from the SM prediction (SM $p$-value of all combined fits >10%)- but measurements affected by statistics, experimental effects and theory uncertainties

Many Run I studies are statistics limited, progress can be expected in Run II:

- Cross sections increase with higher energy
- More luminosity expected
- Analyses extended to more channels
- In parallel, expected progresses in theory predictions

LHC and its experiments have started Run II phase (13 TeV)
We are getting ready for Higgs boson studies with higher precision and for other surprises... Very exciting times ahead...
• **Extended likelihood function** \( \mathcal{L}(\vec{\alpha}, \vec{\nu}) \)

\[
- \ln \mathcal{L}(\vec{\alpha}, \vec{\nu}) = (n_s + n_b) - \sum_e [n_s \cdot f_s(x_e | \vec{\alpha}, \vec{\nu}_s) + n_b \cdot f_b(x_e | \vec{\nu}_b)] - \sum_k \ln \pi_k(\nu_k)
\]

- \( n_s, n_b = \) signal/background yields
- \( \vec{x} = \) observables
- \( f_s, f_b = \) signal/background pdfs

**Test statistics**: Profiled Likelihood Ratio (PRL)

\[
q_{\vec{\alpha}} = -2 \ln \Lambda(\vec{\alpha}) = -2 \ln \frac{\mathcal{L}(\vec{\alpha}, \hat{\nu}(\vec{\alpha}))}{\mathcal{L}(\vec{\alpha}, \nu)}
\]

\( \Lambda(\vec{\alpha}) \) ← likelihood for fixed \( \vec{\alpha} \) and “profiled” \( \vec{\nu} \)

\( \mathcal{L}(\vec{\alpha}, \nu) \) ← maximum likelihood for free \( \vec{\alpha}, \vec{\nu} \)

• The conversion from \( -2 \ln \Lambda \) to the \( p \)-value is performed using a two-sided distribution with the specific number of degrees of freedom

• **Wilks’ theorem**: if \( \vec{\alpha} = \vec{\alpha}^{true} \),

then \( q_{\vec{\alpha}} \) follows a \( \chi^2 \) distribution, with \( D \) being the number of parameters if interest →

compute confidence intervals for \( \vec{\alpha} \)
Direct limits on the decay width of the Higgs boson can be set from the observed width of the invariant mass peak ($\Gamma_{H^{SM}} = 4.12$ MeV at $M_H = 125.4$ GeV), assuming no interference with background processes.

- $H \rightarrow \gamma\gamma$: convolutions of detector resolution with a non relativistic Breit–Wigner distribution
  - Profile likelihood estimator with the width as main parameter

- $H \rightarrow ZZ^* \rightarrow 4l$: per-event resolution model
  - 4-lepton mass computed event-by-event by convolving detector response with nonrelativistic Breit-Wigner function describing the Higgs boson

Observed (expected for $\mu = 1$) 95% CL upper limit on:
- $H \rightarrow \gamma\gamma$: 5.0 (6.2) GeV
- $H \rightarrow ZZ^* \rightarrow 4l$: 2.6 (6.2) GeV (due to higher signal strength observed in the data)
Indirect limits on the Higgs boson width

- The high-mass off-peak regions beyond $2m_V$ ($V = Z, W$) in the $H \rightarrow ZZ/WW$ channels are sensitive to Higgs boson production through *off-shell and background interference effects*

$$\sigma_{\text{off-shell}}^{(*)} \approx \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$$

$$\sigma_{\text{on-shell}}^{(*)} \approx \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}$$

$$g^2_{ggH} = H - g \text{ coupling} \quad g^2_{HZZ} = H - Z \text{ coupling}$$

4-lepton production, CMS cuts, $\sqrt{s}=8$ TeV

$qq \rightarrow 4\text{leptons}$

$gg \rightarrow h \rightarrow 4\text{leptons}$

$gg \rightarrow 4\text{leptons(continuum)}$

$gg \rightarrow 4\text{leptons(total)}$

Higgs on-shell peak

$ZZ$ threshold

cancellation between amplitudes

tt threshold

$R^B_{H^*} = \frac{K(gg\rightarrow VV)}{K(gg\rightarrow H^*\rightarrow VV)}$
**Spin/CP sensitive variables**

- **$H \rightarrow \gamma\gamma$**: diphoton $p_T^{\gamma\gamma}$ and production angle of the two photons (in the Collins-Soper frame), $|\cos(\theta^*)|$
  - 11 categories, fit on the observed $m_{\gamma\gamma}$ for each of them

- **$H \rightarrow ZZ^* \rightarrow 4l$**: two production $\theta^*$ and $\Phi_1$ (in Higgs rest frame) plus three decay angels, $\Phi$, $\theta_1$ and $\theta_2$ (in $V$ rest frame)
  - 4 categories
  - Matrix element likelihood ratio analysis and BDT

- **$H \rightarrow WW^* \rightarrow e\nu\mu\nu$**: four variables $m_\parallel$, $\Delta\Phi_\parallel$, $p_T^{\parallel}$ and $m_T$
  - 5 BDTs for different spin-2 models + 1 BDT for SM $0^+$
  - BDT used also to test HWW tensor structure for spin-0 fixed hypothesis
For each decay mode, events are classified in different categories, based on their kinematic characteristics, with different purities (especially for production mode categories).

A total of $O(100)$ categories ($k$) per experiment are combined

$$n_{\text{signal}}(k) = \mathcal{L}(k) \times \sum_i \sum_f \{ \sigma_i \times A^f_i(k) \times \epsilon^f_i \times BR^f \}$$

$$= \mathcal{L}(k) \times \sum_i \sum_f \mu_i \mu^f \{ \sigma_i^{SM} \times A^f_i(k) \times \epsilon^f_i \times BR^f_{SM} \}$$

- Profile likelihood ratio test statistics:

$$\Lambda(\bar{\alpha}) = \frac{L(\bar{\alpha}, \hat{\theta}(\bar{\alpha}))}{L(\hat{\alpha}, \hat{\theta})}$$

- For each likelihood evaluation, all systematic uncertainties ($nuisances$) are varied to maximize the profiled likelihood (profiled) [cdsweb.cern.ch/record/1375842]

- Results are given in terms of $q(\bar{\alpha}) = -2 \ln \Lambda(\bar{\alpha})$, assumed to follow a $\chi^2$ distribution

$O(4200)$ nuisance parameters in the combined fit to describe the (systematic) uncertainties: finite MC statistics, Higgs signal TH uncertainties, TH uncertainties affecting background, other experimental uncertainties

Most experimental uncertainties assumed to be uncorrelated between the two experiments
### $\kappa$-framework - Overview of parameters

<table>
<thead>
<tr>
<th>Production</th>
<th>Loops</th>
<th>Interference</th>
<th>Multiplicative factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(ggF)$</td>
<td>✓</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>$\sim \kappa_Z^2$</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>✓</td>
<td>$Z-t$</td>
<td>$\sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_t \kappa_Z$</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>$\sigma(gb \rightarrow WhH)$</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>Partial decay width</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_{bb}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\Gamma_{WW}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\Gamma_{ZZ}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\Gamma_{\tau\tau}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\Gamma_{\mu\mu}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\Gamma_{\gamma\gamma}$</td>
<td>✓</td>
<td>$W-t$</td>
</tr>
</tbody>
</table>

#### Total width for BR$_{BSM} = 0$

| $\Gamma_H$ | ✓ | - | $\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_w^2 + 0.09 \cdot \kappa_g^2 + \ldots$ |


Common coupling modifications for *up-type fermions vs down-type fermions* or for *leptons vs quarks* are predicted by many extensions of the SM (2HDM e.g.)

- Directly parametrize model in terms of ratios of coupling strength modifiers, allowing the Higgs width to vary (and assuming no BSM physics in loop processes):

$$\lambda_{du} = \frac{\kappa_d}{\kappa_u}, \quad \lambda_{Vu} = \frac{\kappa_V}{\kappa_u}, \quad \lambda_{uu} = \frac{\kappa_u}{\kappa_u}$$

$$\lambda_{lq} = \frac{\kappa_l}{\kappa_q}, \quad \lambda_{Vq} = \frac{\kappa_V}{\kappa_q}, \quad \lambda_{qq} = \frac{\kappa_q}{\kappa_q}$$

- All results are consistent with the SM
• Combined input channels span five Higgs boson decay modes and five production channels $\rightarrow$ coupling ratios $\lambda$

• No assumptions on $\Gamma_H$ needed, as it cancels in ratios of coupling strengths

• Measurements normalized to $gg \rightarrow H \rightarrow ZZ$ in most cases

\[ \sigma \cdot BR(gg \rightarrow H \rightarrow ZZ) \Rightarrow \kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H \]

$\kappa_g =$ effective c.m. of $H$ in $ggF$

• All results are consistent with the SM predictions within $2\sigma$, except for $\lambda_{bZ}$ and $\lambda_{tg}$
  - This reflects the same tensions as ratios of $bb$ and $ZZ$ decays and of $ttH$ and $ggF$ production rates

\[ \begin{align*}
\lambda_{Zg} &= \kappa_{Zg} / \kappa_g \\
\lambda_{WZ} &= \kappa_{WZ} / \kappa_Z \\
\lambda_{\tau Z} &= \kappa_{\tau Z} / \kappa_Z \\
\lambda_{bZ} &= \kappa_{bZ} / \kappa_Z \\
\lambda_{\gamma Z} &= \kappa_{\gamma Z} / \kappa_Z \\
\lambda_{tg} &= \kappa_{tg} / \kappa_g
\end{align*} \]
Fermion and vector boson couplings

- Probe intrinsic difference between Higgs boson couplings to vector bosons and Yukawa couplings to fermions (assuming only SM physics in loops and no invisible Higgs decays)
- Assuming all boson couplings scale with $\kappa_V$ while all fermions with $\kappa_F$ : six fit performed, one per decay channel
  - Negative couplings would change sign of interference $\rightarrow$ physical quantities depend on product of two $\kappa$'s

- All results are in agreement with the SM prediction of $\kappa_V^f = 1$ and $\kappa_F^f = 1$ - almost $5\sigma$ exclusion of $\kappa_F < 0$