Run 1 LHC Higgs Coupling Combination

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Introduction

- Yesterday we reviewed how the analyses of each Higgs decay channels progressed in CMS during Run 1 of the LHC
- Same set of channels also studied in ATLAS
- Both experiments also published combination results
- Not a combination of results, a new combined result \( \Rightarrow \) perform fits to the data of all channels simultaneously
- At the beginning of 2015 CMS and ATLAS embarked on an effort to make a combined analysis of the Higgs couplings

1.5 years later… resulting paper submitted for publication
LHC Higgs Combination Group

- Launched at the end of 2010
- **Initial work:** *(ATL-PHYS-PUB-2011-11/CMS NOTE-2011/005)*:
  - Defining statistical procedures for setting exclusion limits on signals or quantifying an excess
  - Identifying common systematic uncertainties and how uncertainties will be modelled (in particular on the signal processes)
  - Toy combinations as a technical exercise / validation
- **Results:**
  - Established RooFit workspaces and fitting framework as common tools
  - Definition of test statistic and CLs criteria that would be used for virtually all ATLAS and CMS Higgs results

- CMS+ATLAS combination with 7 TeV data
  - *ATLAS-CONF-2011-157 / CMS PAS HIG-11-023*
  - ZZ, WW, γγ, ττ, bb final states
  - 268 nuisance parameters
  - CLs values determined by fitting toy datasets for test stat. distributions
  - Asymptotic formulae used as a cross check

![Graph showing 95% CL limit on \( \alpha/\sigma_{SM} \) vs. Higgs boson mass with observed and expected limits plotted.](image)
Run 1 Legacy Mass Combination

- Important to establish the best measurement of $m_H$ before attempting couplings
- Using high resolution $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ channels

$m_H = 125.09 \pm 0.24$ GeV $= \pm 0.21$ (stat.) $\pm 0.11$ (syst) GeV
Properties

- Indirect constraint on the width using ratio of off-shell to on-shell production in $H \to ZZ$
- SM predicts $\Gamma \sim 4$ MeV
- ATLAS and CMS find limits on $\Gamma/\Gamma_{SM} \sim 4-8$

Test many alternative hypotheses against SM CP-even scalar, $J^P = 0^+$, e.g. pseudoscalar, spin-2
- All rejected at 99.9% CL
Input Preparation
Combination Inputs

• Based on the inputs to the separate CMS and ATLAS combinations: the main five decay channels + ttH analyses

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>Untagged</th>
<th>VBF</th>
<th>VH</th>
<th>ttH</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$H \to ZZ \to 4l$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$H \to WW \to 2l2\nu$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$H \to \tau\tau$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$H \to bb$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$H \to \mu\mu$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

• Not included as not in both CMS and ATLAS combination results:
  • $H \to Z\gamma$ search
  • Off-shell measurements
  • $H \to$ invisible searches
  • VBF $H \to bb$

• $H \to \mu\mu$ only included for one particular result
• Each analysis targeting a particular production/decay mode may also consider contributions from other processes that are not specifically targeted, e.g. $H \to WW$ entering $H \to \tau\tau$ analysis, single-top + Higgs production in ttH
Nuisance Parameter Correlations

- Luminosity uncertainties partially correlated as for mass combination

- The conclusion of the review was that the majority of **background-related uncertainties are uncorrelated** between experiments, as:
  - many are fully or partially data-driven,
  - different MC generators, correction factors, analysis selections are used.
  - Exceptions include inclusive cross section uncertainties on $qq \rightarrow ZZ$ and $t\bar{t} + V$ processes

- **Signal theory uncertainties** are main source of correlation between experiments
  - **QCD scale:**
    - Simple to correlate inclusive uncertainty, jet bins more difficult
  - **PDFs:**
  - Correlate inclusive PDF uncertainties between experiments
  - **Underlying event, parton shower and branching ratio uncertainties:**
    - Generally a smaller effect but also correlated between experiments
Technical Implementation

- RooFit & RooStats packages (built on top of ROOT) are the frameworks of choice
- Big advantage of RooFit is its OOP design and abstraction of virtually every aspect of model-building. Everything is an object:

<table>
<thead>
<tr>
<th>Mathematical concept</th>
<th>RooFit class</th>
</tr>
</thead>
<tbody>
<tr>
<td>variable</td>
<td>$x$</td>
</tr>
<tr>
<td>function</td>
<td>$f(x)$</td>
</tr>
<tr>
<td>PDF</td>
<td>$f(x)$</td>
</tr>
<tr>
<td>space point</td>
<td>$\vec{x}$</td>
</tr>
<tr>
<td>integral</td>
<td>$\int_{x_{min}}^{x_{max}} f(x) dx$</td>
</tr>
</tbody>
</table>

$W. \ Verkerke$
Technical Implementation - An Example

- Every analysis category represented as a dataset (binned or un-binned)

- The signal + background described by a PDF, typically the sum of several signal and background PDFs

- Both data and PDF defined in terms of observables, e.g. di-tau mass here, but in principle any N-dimensional space

\[
\text{RooDataHist} \quad \text{(RooAbsData)}
\]

\[
\text{RooAddPdf}
\]

\[
\begin{align*}
\text{H} \rightarrow \tau\tau \\
\text{Z} \rightarrow \tau\tau \\
\text{W+jets} \\
\text{QCD}
\end{align*}
\]

\[
\text{dN/dm}_{\tau\tau} \quad [1/\text{GeV}]
\]

\[
\begin{align*}
\text{CMS, 19.7 fb}^{-1} \text{ at 8 TeV} \\
\text{SM H(125 GeV)} \rightarrow \tau\tau \\
\text{Observed} \\
\text{Z} \rightarrow \tau\tau \\
\text{t\bar{t}} \\
\text{Electroweak} \\
\text{QCD} \\
\text{Bkg. uncertainty}
\end{align*}
\]

\[
\text{Loose VBF tag}
\]
Technical Implementation - An Example

- PDF normalisations and shapes typically depend on a number of parameters:
  - Parameters of interest (POIs)
  - Nuisance parameters (NPs) e.g. to represent systematic uncertainties

![Diagram showing the technical implementation example with RooDataHist, RooAddPdf, and various parameters including POI: μ, NP: Tau ID Eff., NP: ggH QCD scale, NP: Luminosity.](image)
**Technical Implementation - An Example**

- Straightforward to combine PDFs and datasets of different categories
- The CMS+ATLAS combination is made by merging the simultaneous PDFs from both experiments
- Total categories: **574**
- Total NPs: **4268**

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**Parameters**

- **POI:** $\mu$
- **NP:** Tau ID Eff.
- **NP:** ggH QCD scale
- **NP:** Luminosity
- **NP:** Photon Eff.

---

**RooAddPdf**

- $H \rightarrow \tau\tau$
  - **RooHistPdf** ($\text{RooAbsPdf}$)
- $Z \rightarrow \tau\tau$
  - **RooHistPdf** ($\text{RooAbsPdf}$)
- $W+$jets
  - **RooHistPdf** ($\text{RooAbsPdf}$)
- QCD
  - **RooHistPdf** ($\text{RooAbsPdf}$)

---

**RooAddPdf**

- $H \rightarrow \gamma\gamma$
  - **Parametric** ($\text{RooAbsPdf}$)
- $\gamma\gamma$ Bkg.
  - **RooMultiPdf**
    - **Custom CMS PDF** ($\text{RooAbsPdf}$)

---

**RooDataHist** ($\text{RooAbsData}$)

- **RooDataHist** ($\text{RooAbsData}$)
- **RooDataHist** ($\text{RooAbsData}$)
- **RooDataHist** ($\text{RooAbsData}$)

---

**RooSimultaneous PDF**

- **RooAddPdf**
- **RooAddPdf**
- **RooAddPdf**

---

**RooRealVar**

- $m_{\tau\tau}$
- $m_{\gamma\gamma}$

---

**Graph**

- Events / GeV
- **CMS**
- 8 TeV Untagged 1
- Data
- S+B fit
- $\sigma_1 \pm \sigma_2$
- $\pm 1 \sigma$
- $\pm 2 \sigma$
- $19.7 \text{ fb}^{-1} (8 \text{ TeV}) + 5.1 \text{ fb}^{-1} (7 \text{ TeV})$
Technical Implementation - An Example

Minimizer
MINUIT

RooNLLVar
(RooAbsReal)

RooDataSet
(RooAbsData)

RooDataHist
(RooAbsData)

RooDataHist
(RooAbsData)

RooDataHist
(RooAbsData)

RooDataSet
(RooAbsData)

RooDataSet
(RooAbsData)

RooDataSet
(RooAbsData)

RooSimultaneous PDF

RooAddPdf

H→ττ
RooHistPdf
(RooAbsPdf)

Z→ττ
RooHistPdf
(RooAbsPdf)

W+jets
RooHistPdf
(RooAbsPdf)

QCD
RooHistPdf
(RooAbsPdf)

γγ Bkg.
RooMultiPdf
Custom CMS PDF
(RooAbsPdf)

Parameters

POI: μ

NP: Tau ID Eff.

NP: ggH QCD scale

NP: Luminosity

NP: Photon Eff.

Minimizer MINUIT

RooNLLVar
(RooAbsReal)
Technical Challenges

- **Fit convergence**: Minuit handles a 4300 parameter fit surprisingly well, few tricks used to reduce the time needed for convergence

- **Memory usage**: ~4-5GB needed for combination

- **Fitting time**:
  - *0.5 - 1 hours per combined fit* thanks to significant optimisations by previous combine developers
  - Each best-fit value + uncertainties from **scan of ~ 40 points**
  - Total number of fits = 150 (POIs) * 40 (points) * 2 (observed, asimov)
  - + *~10 2D scans* requiring 1600 fits each
  - Total CPU time ~ 12000 hours (fairly modest by HEP standards)
Methodology & Signal Parameterisation
Statistics

- Workhorse of the combination is the **profile likelihood ratio**, $\Lambda$

\[ \Lambda (\hat{\alpha}) = \frac{L(\hat{\alpha}, \hat{\theta}(\hat{\alpha}))}{L(\hat{\alpha}, \hat{\theta})} \]

- $\hat{\alpha} =$ Set of POIs at some fixed values to be tested
- $\hat{\theta} =$ Nuisance parameters

- Exploit the asymptotic limit:
  - Test statistic $q(\hat{\alpha}) = -2 \ln(\Lambda(\hat{\alpha}))$ is assumed to follow a $\chi^2$ distribution with $\hat{\alpha}$ degrees of freedom
  - $\Rightarrow$ To determine a confidence-level (CL) interval for a single parameter $\alpha$, we only need to find the values of $\alpha$ where $q(\hat{\alpha}) =$ the $\chi^2$ critical value for that CL, e.g.
    - 1D 68% CL at $q(\alpha) = 1.00$
Signal Parameterisation

Signal strengths, $\mu$

Parameters scale cross sections and BRs relative to SM

$$\mu_i = \frac{\sigma_i}{\sigma_i^{SM}}, \quad \mu^f = \frac{\text{BR}^f}{\text{BR}^f_{SM}}.$$  

Scaling of generic $i \rightarrow H \rightarrow f$ process

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

Couplings, $\kappa$

Parameters scale cross sections and partial widths relative to SM

$$\kappa_{j}^2 = \frac{\sigma_j}{\sigma_j^{SM}} \quad \kappa_{j}^2 = \frac{\Gamma_j}{\Gamma_j^{SM}}$$

$$\sigma_i \cdot \text{BR}^f = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H},$$

Total width determined as

$$\Gamma_H = \frac{\kappa_{H}^2 \cdot \Gamma_H^{SM}}{1 - \text{BR}_{BSM}}$$

Where

$$\kappa_H^2 = \sum_j \text{BR}_{j}^{SM} \kappa_{j}^2$$
Signal Processes - Production

- **Usual suspects:**
  - $ggF$
  - $VBF$
  - $WH / ZH$
  - $ttH$

- **Rare processes:**
  - $gg \rightarrow bbH$
  - $gg \rightarrow ZH$
  - $gb \rightarrow tHW$
  - $qg \rightarrow tHq$

**Interference:**

- $K_b \leftrightarrow K_t$
- $K_w + K_z$
- $K_t \leftrightarrow K_w$
Signal Processes - Production

<table>
<thead>
<tr>
<th>Production process</th>
<th>Cross section [pb] $\sqrt{s} = 7$ TeV</th>
<th>$\sqrt{s} = 8$ TeV</th>
<th>Order of calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ggF$</td>
<td>$15.0 \pm 1.6$</td>
<td>$19.2 \pm 2.0$</td>
<td>NNLO(QCD)+NLO(EW)</td>
</tr>
<tr>
<td>$VBF$</td>
<td>$1.22 \pm 0.03$</td>
<td>$1.58 \pm 0.04$</td>
<td>NLO(QCD+EW)+NNLO(QCD)</td>
</tr>
<tr>
<td>$WH$</td>
<td>$0.577 \pm 0.016$</td>
<td>$0.703 \pm 0.018$</td>
<td>NNLO(QCD)+NLO(EW)</td>
</tr>
<tr>
<td>$ZH$</td>
<td>$0.334 \pm 0.013$</td>
<td>$0.414 \pm 0.016$</td>
<td>NNLO(QCD)+NLO(EW)</td>
</tr>
<tr>
<td>$ggZH$</td>
<td>$0.023 \pm 0.007$</td>
<td>$0.032 \pm 0.010$</td>
<td>NLO(QCD)</td>
</tr>
<tr>
<td>$bbH$</td>
<td>$0.156 \pm 0.021$</td>
<td>$0.203 \pm 0.028$</td>
<td>5FS NNLO(QCD)+4FS NLO(QCD)</td>
</tr>
<tr>
<td>$ttH$</td>
<td>$0.086 \pm 0.009$</td>
<td>$0.129 \pm 0.014$</td>
<td>NLO(QCD)</td>
</tr>
<tr>
<td>$tH$</td>
<td>$0.012 \pm 0.001$</td>
<td>$0.018 \pm 0.001$</td>
<td>NLO(QCD)</td>
</tr>
<tr>
<td>Total</td>
<td>$17.4 \pm 1.6$</td>
<td>$22.3 \pm 2.0$</td>
<td></td>
</tr>
</tbody>
</table>

- **Rare processes:**
  - $gg \rightarrow bbH$
  - $gg \rightarrow ZH$
  - $gb \rightarrow tHW$
  - $qq \rightarrow thq$
Signal Processes - Decay

- **H → ZZ / WW**
  - $H → W^+W^-$
  - $H → Z^+Z^-$

- **H → bb / ττ / μμ**
  - $b, \tau^-, \mu^-$
  - $\bar{b}, \tau^+, \mu^+$

- **H → γγ**
  - $t/b$ interference
  - $t/b$ interference

### Table: Decay Channel Branching Ratios [\%]

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Branching ratio [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H → bb$</td>
<td>57.5 ± 1.9</td>
</tr>
<tr>
<td>$H → WW$</td>
<td>21.6 ± 0.9</td>
</tr>
<tr>
<td>$H → gg$</td>
<td>8.56 ± 0.86</td>
</tr>
<tr>
<td>$H → ττ$</td>
<td>6.30 ± 0.36</td>
</tr>
<tr>
<td>$H → cc$</td>
<td>2.90 ± 0.35</td>
</tr>
<tr>
<td>$H → ZZ$</td>
<td>2.67 ± 0.11</td>
</tr>
<tr>
<td>$H → γγ$</td>
<td>0.228 ± 0.011</td>
</tr>
<tr>
<td>$H → Zγ$</td>
<td>0.155 ± 0.014</td>
</tr>
<tr>
<td>$H → μμ$</td>
<td>0.022 ± 0.001</td>
</tr>
</tbody>
</table>

- **H → cc, H → gg, H → Zγ not targeted by the input analyses but contribute to the total width**
## Signal Processes - Summary

<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>$\sim \kappa_W^2$</td>
</tr>
<tr>
<td>$\sigma(qq/qg \to ZH)$</td>
<td></td>
<td></td>
<td>$\sim \kappa_Z^2$</td>
</tr>
<tr>
<td>$\sigma(gg \to ZH)$</td>
<td>✓</td>
<td>$Z-t$</td>
<td>$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$</td>
</tr>
<tr>
<td>$\sigma(ttH)$</td>
<td></td>
<td></td>
<td>$\sim \kappa_t^2$</td>
</tr>
<tr>
<td>$\sigma(gb \to WuH)$</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>$\sigma(qb \to tHq)$</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>
<tr>
<td>$\sigma(bbH)$</td>
<td></td>
<td></td>
<td>$\sim \kappa_b^2$</td>
</tr>
</tbody>
</table>

### Partial decay width

<table>
<thead>
<tr>
<th>Decay</th>
<th>Loops</th>
<th>Interference</th>
<th>Multiplicative factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma^{ZZ}$</td>
<td></td>
<td></td>
<td>$\sim \kappa_Z^2$</td>
</tr>
<tr>
<td>$\Gamma^{WW}$</td>
<td></td>
<td></td>
<td>$\sim \kappa_W^2$</td>
</tr>
<tr>
<td>$\Gamma^{\gamma\gamma}$</td>
<td>✓</td>
<td>$W-t$</td>
<td>$\kappa_Y^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$</td>
</tr>
<tr>
<td>$\Gamma^{tt}$</td>
<td></td>
<td></td>
<td>$\sim \kappa_t^2$</td>
</tr>
<tr>
<td>$\Gamma^{bb}$</td>
<td></td>
<td></td>
<td>$\sim \kappa_b^2$</td>
</tr>
<tr>
<td>$\Gamma^{\mu\mu}$</td>
<td></td>
<td></td>
<td>$\sim \kappa_\mu^2$</td>
</tr>
</tbody>
</table>

### Total width for BR_{BSM} = 0

<table>
<thead>
<tr>
<th>Decay</th>
<th>Loops</th>
<th>Multiplicative factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_H$</td>
<td>✓</td>
<td>$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + $</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$+ 0.06 \cdot \kappa_t^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + $</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$+ 0.0023 \cdot \kappa_Y^2 + 0.0016 \cdot \kappa_{ZY}^2 + $</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$+ 0.0001 \cdot \kappa_S^2 + 0.00022 \cdot \kappa_\mu^2$</td>
</tr>
</tbody>
</table>
Results

Signal strengths
Overall signal strength

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

- For this, and other key measurements, break uncertainty down into 4 components:
  - statistical, experimental, background theory, signal theory
- All \(~4300\) NPs assigned to one of these groups
- Each component determined by fixing successive group of NPs to best-fit values \(\hat{\theta}\) and repeating NLL scan

**Assumptions**
- SM ratios of all cross sections & BRs
- 7/8 TeV ratios as in SM

**Input:** Combined

- **ATLAS+CMS**
  - Observed
  - Freeze Exp.
  - Freeze Exp.+Bkg.Th.
  - Freeze Exp.+Bkg.Th.+Sig.Th.

- **Internal**
  - \(\mu = 1.094^{+0.111}_{-0.105}\)
  - \(\mu = 1.094^{+0.043}_{-0.039}(\text{Exp}) +0.035_{-0.032}(\text{BkgTh}) +0.067_{-0.061}(\text{SigTh}) +0.070_{-0.069}(\text{Stat})\)
Overall signal strength

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

- Useful for extrapolating results to higher luminosity and understanding what sources may limit future precision
- Signal theory uncertainty as large as statistical uncertainty
- However dominant parts will be reduced for Run 2:
  - **N3LO ggH scale**: 8% $\rightarrow$ 2-3%
  - **New PDF4LHC**: 7% $\rightarrow$ 2%

**Assumptions**
- SM ratios of all cross sections & BRs
- 7/8 TeV ratios as in SM

**Input: Combined**

- Observed
- Freeze Exp.
- Freeze Exp.+Bkg.Th.
- Freeze Exp.+Bkg.Th.+Sig.Th.

### ATLAS+CMS

**Internal**

\[ \mu = 1.094^{+0.111}_{-0.105} \]

\[ \mu = 1.094^{+0.043}_{-0.039} \text{(Exp)}^{+0.035}_{-0.032} \text{(BkgTh)}^{+0.067}_{-0.061} \text{(SigTh)}^{+0.070}_{-0.069} \text{(Stat)} \]
Production & Decay

Assumptions
- SM ratios of BRs or cross sections

Production Modes
- bbH grouped with ggF
- tH grouped with ttH

Decay Modes

- Most significant deviation from $\mu=1$ is ttH (2.3$\sigma$)
Production & Decay

Assumptions
- SM ratios of BRs or cross sections

- Largely driven by CMS ttH → leptons (WW) analysis
- Can have subtle effects in other models

Visible excess of events in $\mu^+\mu^-$ final state

Parameter value

1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3
3.1
3.2
3.3
3.4
3.5
3.6
3.7
3.8
3.9
4

Data/Pred.
0
1
2
3
4
5
6
7
8
9
10

BDT output
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
Significances

- Calculated with respect to $\mu=0$ using asymptotic formulae
- Now $\geq 5\sigma$ for: VBF production, $H\to\tau\tau$ decay

**Personal take:** 5σ was chosen as the threshold for claiming discovery, in part to due to the look-elsewhere effect - less relevant for specific production/decay modes once Higgs boson is discovered

<table>
<thead>
<tr>
<th>Production process</th>
<th>Measured significance ($\sigma$)</th>
<th>Expected significance ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF</td>
<td>5.4</td>
<td>4.6</td>
</tr>
<tr>
<td>$WH$</td>
<td>2.4</td>
<td>2.7</td>
</tr>
<tr>
<td>$ZH$</td>
<td>2.3</td>
<td>2.9</td>
</tr>
<tr>
<td>$VH$</td>
<td>3.5</td>
<td>4.2</td>
</tr>
<tr>
<td>$ttH$</td>
<td>4.4</td>
<td>2.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Measured significance ($\sigma$)</th>
<th>Expected significance ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to\tau\tau$</td>
<td>5.5</td>
<td>5.0</td>
</tr>
<tr>
<td>$H \to bb$</td>
<td>2.6</td>
<td>3.7</td>
</tr>
</tbody>
</table>
Signal Strengths
2D scans

- Perform scans of $\mu_i^F$, $\mu_i^V$ for each decay mode $i$ (10 parameter fit)
- Purpose is to measure vector boson and fermion-mediated production
- Also a 6 parameter fit with one common $\mu^V/\mu^F$ and five $\mu^F_i$
  - Ratio $\mu^V/\mu^F = 1.06^{+0.35}_{-0.27}$ is independent of assumptions on BRs

Assumptions
- VH/VBF and ttH/ggF rates as in SM

![Graph of signal strengths with ATLAS and CMS data]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ATLAS+CMS Measured</th>
<th>ATLAS+CMS Expected uncertainty</th>
<th>ATLAS Measured</th>
<th>CMS Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^F_V$</td>
<td>1.05^{+0.44}_{-0.41}</td>
<td>+0.42</td>
<td>-0.38</td>
<td>0.69^{+0.64}_{-0.58}</td>
</tr>
<tr>
<td>$\mu^V_V$</td>
<td>0.48^{+1.37}_{-0.91}</td>
<td>+1.16</td>
<td>-0.84</td>
<td>0.26^{+1.60}_{-1.01}</td>
</tr>
<tr>
<td>$\mu^F_Z$</td>
<td>1.38^{+0.41}_{-0.37}</td>
<td>+0.38</td>
<td>-0.35</td>
<td>1.56^{+0.52}_{-0.46}</td>
</tr>
<tr>
<td>$\mu^V_Z$</td>
<td>1.12^{+0.37}_{-0.36}</td>
<td>+0.38</td>
<td>-0.36</td>
<td>1.29^{+0.58}_{-0.53}</td>
</tr>
<tr>
<td>$\mu^F_W$</td>
<td>0.65^{+0.30}_{-0.29}</td>
<td>+0.32</td>
<td>-0.30</td>
<td>1.00^{+0.39}_{-0.37}</td>
</tr>
<tr>
<td>$\mu^V_W$</td>
<td>1.19^{+0.28}_{-0.25}</td>
<td>+0.25</td>
<td>-0.23</td>
<td>1.31^{+0.37}_{-0.34}</td>
</tr>
<tr>
<td>$\mu^{\gamma\gamma}$</td>
<td>1.44^{+0.38}_{-0.34}</td>
<td>+0.29</td>
<td>-0.25</td>
<td>1.73^{+0.51}_{-0.45}</td>
</tr>
<tr>
<td>$\mu^{ZZ}$</td>
<td>1.00^{+0.23}_{-0.20}</td>
<td>+0.21</td>
<td>-0.19</td>
<td>1.10^{+0.29}_{-0.26}</td>
</tr>
<tr>
<td>$\mu^{WW}$</td>
<td>1.10^{+0.58}_{-0.53}</td>
<td>+0.56</td>
<td>-0.53</td>
<td>1.72^{+1.13}_{-1.06}</td>
</tr>
<tr>
<td>$\mu^{bb}$</td>
<td>1.09^{+0.93}_{-0.89}</td>
<td>+0.91</td>
<td>-0.86</td>
<td>1.51^{+1.15}_{-1.08}</td>
</tr>
</tbody>
</table>

Assumptions:
- VH/VBF and ttH/ggF rates as in SM

- 68% CL
- Best fit
- SM expected

1/7/16
Signal strength ratios

- Only the 7/8 TeV ratios

**Assumptions**

- Introduced by ATLAS - **new model for CMS**
- Normalise the rate for any particular channel to a reference process using ratios of cross sections and branching ratios

**Motivation:**

- Explicitly no assumptions on relative cross sections or BRs (unlike other results)
- Measured values independent of SM prediction and inclusive theory uncertainties
- Cancellation of common systematic uncertainties in ratios

- Choose reference process as one measured with the smallest uncertainty: gg→H→ZZ

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

![Graph](ATLAS and CMS LHC Run 1)

\[
\begin{align*}
\sigma(gg\rightarrow H\rightarrow ZZ) & \\
\sigma_{VBF}/\sigma_{ggF} & \\
\sigma_{WH}/\sigma_{ggF} & \\
\sigma_{ZH}/\sigma_{ggF} & \\
\sigma_{tth}/\sigma_{ggF} & \\
B^{WW}/B^{ZZ} & \\
B^{VV}/B^{ZZ} & \\
B^{tt}/B^{ZZ} & \\
B^{bb}/B^{ZZ} & \\
\end{align*}
\]

Parameter value norm. to SM prediction

ATLAS+CMS
ATLAS
CMS
±1σ
±2σ
Th. uncert.
Signal strength ratios

- Largest disagreement in BR$^{bb}$/BR$^{ZZ}$ (2.4σ)
- Though some care needed with the uncertainties on ratios ⇒ non-Gaussian behaviour

Does this, and the other features of these results, make sense?
Signal strength ratios

1) Well measured ggF → ZZ: 0.85 $^{+0.27}_{-0.22}$

2) Known excess in ttH → WW ⇒ larger value ttH/ggF preferred in fit (5.1): 0.85 * 5.1 * 0.9 = 3.9, in good agreement with ttH result

CMS ttH Results

<table>
<thead>
<tr>
<th>CMS ttH Results</th>
<th>ATLAS and CMS LHC Run 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed/SM</td>
<td>ATLAS+CMS</td>
</tr>
<tr>
<td>ttH channel</td>
<td>ATLAS</td>
</tr>
<tr>
<td>jet multiplicity</td>
<td>CMS</td>
</tr>
<tr>
<td></td>
<td>±1σ</td>
</tr>
<tr>
<td></td>
<td>±2σ</td>
</tr>
<tr>
<td></td>
<td>Th. uncert.</td>
</tr>
</tbody>
</table>

- $\sqrt{s} = 7$ TeV, 5.0-5.1 fb$^{-1}$; $\sqrt{s} = 8$ TeV, 19.3-19.7 fb$^{-1}$

- Best fit $\sigma/\sigma_{SM}$ at $m_H = 125.6$ GeV

- Expected values where these lines intersect with the CL, respectively. The lower and upper horizontal lines correspond to the 68% and 95% statistic event yield must not be negative in either of the two jet multiplicity bins. Right: The 1D test to be below approximately

- Figure 13: Left: The best-fit values of the signal strength parameter

- Table 8: The best-fit values of the signal strength parameter

- $m_H = 125.6$ GeV are also shown.

- Observed/SM

- Median

- Combined

- Same-Sign 2l

- 4l

- 3l

- Combination

- $\gamma\gamma$

- $b\bar{b}$

- $\tau_{h}\tau_{h}$

- $\tau_{h}\tau_{b}$

- $\tau_{b}\tau_{b}$

- $\tau_{h}\tau_{h}$
Signal strength ratios

1) Well measured ggF → ZZ: 0.85 $^{+0.27}_{-0.22}$

2) Known excess in ttH

3) Prefer bb/WW low (0.20) for ttH → bb at the observed rate: 0.85 * 5.1 * 0.17 = 0.74
**Signal strength ratios**

1) Well measured ggF → ZZ: $0.85 \pm 0.27$

2) Known excess in ttH → WW, larger value $\frac{ttH}{ggF}$ preferred in fit ($5.1$): $0.85 \times 5.1 \times 0.9 = 3.9$, in good agreement with $ttH$ result

3) Prefer $bb/WW$ low ($0.20$) for $ttH → bb$ at the observed rate: $0.85 \times 5.1 \times 0.17 = 0.83$

4) The ZH production is not strongly constrained. Becomes large to get observed $ZH → bb$ rate: $0.85 \times 0.17 \times 5.70 (ZH/ggF) = 0.87$

**CMS VH Results**

**CMS VH Results**

- ATLAS and CMS LHC Run 1
- $\sigma(gg→H→ZZ)$
- $\sigma_{VBF}/\sigma_{ggF}$
- $\sigma_{WH}/\sigma_{ggF}$
- $\sigma_{ZH}/\sigma_{ggF}$
- $\sigma_{ttH}/\sigma_{ggF}$
- $B^{WW}/B^{ZZ}$
- $B^{\gamma\gamma}/B^{ZZ}$
- $B^{\tau\tau}/B^{ZZ}$
- $B^{bb}/B^{ZZ}$

**CMS VH Results**

- ATLAS+CMS
- ATLAS
- CMS
- $\pm 1\sigma$
- $\pm 2\sigma$
- Th. uncert.
Results

Couplings
Couplings - allowing for BSM loop/decay contributions

- Use effective couplings for ggH ($\kappa_g$) and $H \rightarrow \gamma\gamma$ ($\kappa_\gamma$)
- Consider two scenarios:
  - $BR_{BSM} = 0$
  - $BR_{BSM}$ floating, but $\kappa_w, \kappa_Z < 1$
- Care needed with $BR_{BSM}$: not just Higgs decays to new particles but also non-SM BRs to unmeasured final states, e.g. gg and cc
Couplings - allowing for BSM loop/decay contributions

- Alternatively assume BSM modification is **only** in the loops

- E.g. new heavy fermions with mass > m_H/2

- Fix \( \kappa_t = \kappa_b = \kappa_t = \kappa_Z = \kappa_W = 1 \), \( \text{BR}_{\text{BSM}} = 0 \) and scan \((\kappa_g, \kappa_\gamma)\)

- Result very compatible with \( \kappa_g = \kappa_\gamma = 1 \)
### Couplings - no BSM loop/decay contributions

- Resolve $ggH (\kappa_g)$ and $H \rightarrow \gamma\gamma (\kappa_\gamma)$ loops
- Include $H \rightarrow \mu\mu$ analyses here to make "publicity plot"

![Graph showing parameter values and intervals for different couplings](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_Z$</td>
<td>$-2$ to $3$</td>
</tr>
<tr>
<td>$\kappa_W$</td>
<td>$-2$ to $3$</td>
</tr>
<tr>
<td>$\kappa_t$</td>
<td>$-2$ to $3$</td>
</tr>
<tr>
<td>$</td>
<td>\kappa_\tau</td>
</tr>
<tr>
<td>$\kappa_b$</td>
<td>$-2$ to $3$</td>
</tr>
<tr>
<td>$</td>
<td>\kappa_\mu</td>
</tr>
</tbody>
</table>

![Graph showing coupling values vs. particle mass](image)

- $\kappa_{F,V}$ or $m_\gamma^F$ vs. particle mass [GeV]
- ATLAS+CMS fit
- SM Higgs boson
- 68% CL
- 95% CL
Couplings - no BSM loop/decay contributions

- Resolve ggH ($\kappa_g$) and H→γγ ($\kappa_\gamma$) loops
- Include H→μμ analyses here to make “publicity plot”

Main effect of resolving loops is on $\kappa_t$ which was previously only constrained by ttH production

Interesting feature alert! All $\kappa$ values ≤ 1 whereas overall signal strength is 1.09
Couplings - no BSM loop/decay contributions

- Couplings are not really independent
  - Correlation between $\kappa_b$, which is low, and the others due to large $\Gamma_{bb}$

**Interesting feature alert!** All $\kappa$ values $\leq 1$ whereas overall signal strength is 1.09
Coupling Ratios

- Similar concept to cross section ratios

- Generic model in which the total width is a free parameter embedded in: $\kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$

- All other parameters are ratios: $\lambda_{ij} = \kappa_i / \kappa_j$

- Relative signs become important…

<table>
<thead>
<tr>
<th>$\sigma$ and BR ratio model</th>
<th>Coupling-strength ratio model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(gg \rightarrow H \rightarrow ZZ)$</td>
<td>$\kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H$</td>
</tr>
<tr>
<td>$\sigma_{VBF} / \sigma_{ggF}$</td>
<td>$\lambda_{Zg} = \kappa_Z / \kappa_g$</td>
</tr>
<tr>
<td>$\sigma_{WH} / \sigma_{ggF}$</td>
<td>$\lambda_{tg} = \kappa_t / \kappa_g$</td>
</tr>
<tr>
<td>$\sigma_{ZH} / \sigma_{ggF}$</td>
<td>$\lambda_{WZ} = \kappa_W / \kappa_Z$</td>
</tr>
<tr>
<td>$\sigma_{t\tau H} / \sigma_{ggF}$</td>
<td>$\lambda_{\gamma Z} = \kappa_\gamma / \kappa_Z$</td>
</tr>
<tr>
<td>BR$<em>{WW}$ / BR$</em>{ZZ}$</td>
<td>$\lambda_{bZ} = \kappa_b / \kappa_Z$</td>
</tr>
<tr>
<td>BR$<em>{\gamma\gamma}$ / BR$</em>{ZZ}$</td>
<td></td>
</tr>
<tr>
<td>BR$<em>{\tau\tau}$ / BR$</em>{ZZ}$</td>
<td></td>
</tr>
<tr>
<td>BR$<em>{bb}$ / BR$</em>{ZZ}$</td>
<td></td>
</tr>
</tbody>
</table>
Coupling Ratios - Negative signs

• The signal processes scale as the square of the $\kappa$ parameters, meaning there is a sign ambiguity that for most processes we cannot resolve
• However for processes with interference between two effective couplings we are sensitive to relative signs
• In this model: $\lambda_{WZ}$ (via interference in VBF) and $\lambda_{tg}$ (via interference in ggZH, tHW, tHq)
• Can obtain up to four distinct likelihood curves for choices of $\lambda_{WZ}, \lambda_{tg} = (+, -), (-, +), (+, +), (-, -)$

Enhances tHq production by a factor $\sim 13$

Enhances ggZH production by a factor $\sim 4$
Couplings - Benchmark ratios

- Tests of up-down fermion symmetry and quark-lepton symmetry (relevant for 2HDM, MSSM etc)
2D scans of $\kappa_V$, $\kappa_F$

- Commonly-presented model in which
  - $\kappa_V = \kappa_W = \kappa_Z$
  - $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$

- Perform additional scans in a model with separate $\kappa_V^f$, $\kappa_F^f$ per decay-mode
  - But not that this is a 10 parameter fit instead of 5 x 2 parameter fits

- Here the best-fit is restricted to quadrant where $\kappa_V > 0$, $\kappa_F > 0$

- All channels compatible with $\kappa_V = \kappa_F = 1$
2D scans of $k_V$, $k_F$

- Most channels nearly degenerate in relative sign of $k_V$ and $k_F$
2D scans of $k_V, k_F$

- Most channels nearly degenerate in relative sign of $k_V$ and $k_F$

In the negative $k_F$ quadrant channels strongly disfavour common $k_V$
Summary

- A comprehensive combined measurement of ATLAS and CMS Higgs boson couplings has been performed
  - Strong picture of overall consistency with SM expectations, but still room for deviations!
  - Also a significant technical achievement

- By combining their datasets the two experiments are able to provide the best overall measurement of the Higgs boson couplings

- Results are given for more constrained (one $\mu$ value) and less constrained models (ratio models) in both the signal strength and coupling modifier models

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