H(125) mass, width, tensor structure, and couplings measurements

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on behalf of the CMS Collaboration
Outline

→ Presenting results from CMS:
  → Signal strength and significance (short summary of Run I)
  → Mass measurement
  → Width measurement
  → Anomalous couplings (tensor structure)
    with Run I CMS-only measurements
    and Run II progress in each measurement
→ Details on the particular final states presented:
  → $\gamma\gamma$ by Vittorio Raoul Tavolaro
  → 4l by Simon Regnard
  → WW by Andrea Massironi
  → Dilepton by Pooja Saxena
  → $b\bar{b}$ by Chris Palmer
Run I: Signal strength from CMS

Using $m_H = 125.0$ GeV,

$$\mu = 1.00^{+0.14}_{-0.13}$$

$$\frac{\mu_{VBF,VH}}{\mu_{ggH,t\bar{t}H}} = 1.25^{+0.62}_{-0.44}$$


Latest Run I CMS+ATLAS 7 and 8 TeV couplings combination: arXiv:1606.02266 (submitted to JHEP)
Run I: Mass measurement from CMS

Latest Run I CMS+ATLAS 7 and 8 TeV mass measurement:

Observed $m_H = 125.02^{+0.29}_{-0.31}$ GeV

4$l$ and $\gamma\gamma$ channels compatible within 1.6 $\sigma$

Run II: Mass measurement (4l and $\gamma\gamma$)

$D_{mass}$ from lepton momentum errors → Corrected in data and MC using Z decay events → Improves resolution by 8%

Using 4l 3D measurement, observed $m_H = 124.50^{+0.48}_{-0.46}$ (stat $^{+0.47}_{-0.45}$, syst $^{+0.13}_{-0.11}$) GeV

$\gamma\gamma$ observed best-fit: $m_H = 126.0$ GeV → Stat. unc. ~0.3 GeV → Syst. unc. ~0.2-0.4 GeV → Details of the systematic uncertainties on the mass require further refinement and are still under study.
Run I: Width lower bound from lifetime

Expected \( c\tau_H < 56 \mu m \)
Observed \( c\tau_H < 57 \mu m \)

Translates to
Expected \( \Gamma_H > 3.6 \times 10^{-9} \text{ MeV} \)
Observed \( \Gamma_H > 3.5 \times 10^{-9} \text{ MeV} \)

Run I: Width upper bound

\[ \sigma_{\text{on-shell}} \sim \mu_{\nu\nu H} \]
\[ \Rightarrow \sigma_{\text{off-shell}} \sim \mu_{\nu\nu H} \times \Gamma_H \]

Expected \( \Gamma_H < 26 \text{ MeV} \)

Observed \( \Gamma_H < 13 \text{ MeV} \)

- Tight constraints on \( \Gamma_H \) with SM-like tensor structure
- Light BSM particles in the loop

Latest width combination using \( 4l \), and \( \text{WW and } ZZ \rightarrow 2l2\nu \) using on-shell + off-shell combination of events

(\textit{arxiv:1605.02329}, submitted to JHEP)
Run II: Width-mass measurement (4l result)

Using continuous 4l on-shell region only

Using continuous 4l parameterization on-shell+off-shell
Run II: Width-mass measurement (4l cont.)

$m_H$ unconstrained
On-shell only

Expected $\Gamma_H < 2.7$ GeV
Observed $\Gamma_H < 3.9$ GeV

$m_H$ unconstrained
On-shell+off-shell

Expected $\Gamma_H < 32$ MeV
Observed $\Gamma_H < 41$ MeV
HVV anomalous couplings

\[
A(HVV) \sim \left[ a_1 - e^{i\phi_{\Lambda Q}} \frac{(q_{V1} + q_{V2})^2}{\Lambda_Q^2} - e^{i\phi_{\Lambda_1}} \frac{(q_{V1}^2 + q_{V2}^2)}{\Lambda_{\Lambda_1}^2} \right] m_{V^*}^2 \varepsilon_{V1}^* \varepsilon_{V2}^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}
\]

Any anomalous coupling can be described with an effective on-shell cross sectional fraction and a phase

\[
f_{ai} = \frac{|a_i|^2 \sigma_i}{\Sigma_j |a_j|^2 \sigma_j} \quad \phi_{ai} = \tan^{-1}(a_i/a_1)
\]

\(f_{\Lambda Q}\) observable only from off-shell. Others can be measured from either on-shell or off-shell.

In 4l, use discriminants based on MELA from JHUGen/MCFM:

\[
D_{A \text{ vs } B} = \frac{P_A}{P_A + P_B}
\]

\[
D_{A-B \text{ int.}} = \frac{P_{A+B} - P_A - P_B}{P_A + P_B}
\]

(See Dr. Meng Xiao’s talk for different use cases)
Run II: Anomalous couplings ($f_{a3}$ result)

Expected: $0.00^{+0.26}_{-0.26}$ (95% CL: $[-0.59, 0.59]$)
Observed: $-0.56^{+0.38}_{-0.32}$ (95% CL: $[-1.00, 1.00]$)

CMS-PAS-HIG-16-033
Run II: Anomalous couplings ($f_{a2}$ result)

From 4l:

**Expected:** $0.00^{+0.24}_{-0.06}$ (95% CL: [-0.15, 0.92])

**Observed:** $-0.06^{+0.06}_{-0.09}$ (95% CL: [-0.22, 0.24])

CMS-PAS-HIG-16-033
Run II: Anomalous couplings ($f_{\Lambda_1}$ result)

From 4l

- Expected:
  - $0.00^{+0.13}_{-0.69}$ (95% CL: [-1.00, 0.24]U[0.98, 1.00])
  - $-0.93^{+0.90}_{-0.16}$ (95% CL: [-1.00, 0.10]U[0.77,1.00])

- Observed:
  - $-0.93^{+0.90}_{-0.16}$ (95% CL: [-1.00, 0.10]U[0.77,1.00])

CMS-PAS-HIG-16-033
Run I: Anomalous couplings combination

4l+W+W → 2l2ν combination (+γγ for spin-2 couplings)


$\Lambda_Q$ vs $\Gamma_H$
joint constraints
using 4l
on-shell+off-shell

$\phi_{\Lambda Q} (68\%)$ [95% CL]
when $\Gamma_H = \Gamma_H^{SM}$
Expected: (-0.4, 1.1) [-3.6,4.4]×10⁻³
Observed: (-0.4, 1.0) [-1.4, 3.8] × 10⁻³

$f_{\Lambda Q} \cos(\phi_{\Lambda Q})$ (68%) [95% CL]
when $\Gamma_H = \Gamma_H^{SM}$
Expected: (-0.4, 1.1) [-3.6,4.4]×10⁻³
Observed: (-0.4, 1.0) [-1.4, 3.8] × 10⁻³
Run I: Anomalous couplings using production

$\mathcal{L} = \left( 0, 0.00050 \right) [0,0.0011]$

Observed: (0.00047, 0.0021) [0,0.0034]

$\mathcal{L} = \left( 0, 0.0062 \right) [0,0.44]$

Observed: (0.00011, 0.0021) [0,0.25]
Summary

→ Presented results from CMS:
  → Signal strength and significance, brief overview from Run I
  → Mass measurement
    → Demonstrated in 4l and could be done in γγ
  → Width measurement
    → Model-independent lower bound from 4l lifetime analysis
    → Sensitivity improvement with the inclusion of off-shell tail
    → Combination of final states can also be done as in Run I
  → Anomalous HVV couplings (tensor structure)
    → Most couplings already have good sensitivity from on-shell
    → Including off-shell also could improve sensitivity
      → Could apply joint constraints on $f_{ai}$ vs $\Gamma_H$ as exemplified in the Run I $f_{\Lambda Q}$ vs $\Gamma_H$ result
    → Using production side could improve the anomalous coupling constraints
      → Exemplified in recent $VH \rightarrow b\bar{b}$ and $H \rightarrow VV$ combination for $f_{a3}$ using Run I data
Backup
Run II: Signal strength (4l method)

→ In 4l final state,
→ Split events into 6 categories based on the type and kinematics of associated particles:
  → VBF-2 jet, VBF-1 jet, VH hadronic, VH leptonic, $t\bar{t}H$ and untagged categories

Contributions of each production mechanism to the 6 different categories
Run II: Signal strength (4l method cont.)

$m_{4l}$ and $D_{bkg}^{kin}$ used in signal modelling

$D_{2jet}$, $D_{ZH}$ and similar discriminants used in most of the categorization
→ In $\gamma\gamma$ final state,
→ Split events into $t\bar{t}H$ leptonic, $t\bar{t}H$ hadronic, VBF (2) and untagged (4) categories based on kinematics, b-tagging and MVA

<table>
<thead>
<tr>
<th>Event Categories</th>
<th>SM 125 GeV Higgs boson expected signal</th>
<th>Bkg (GeV$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>$ggh$</td>
</tr>
<tr>
<td>Untagged Tag 0</td>
<td>11.92</td>
<td>79.10%</td>
</tr>
<tr>
<td>Untagged Tag 1</td>
<td>128.78</td>
<td>85.98%</td>
</tr>
<tr>
<td>Untagged Tag 2</td>
<td>220.12</td>
<td>91.11%</td>
</tr>
<tr>
<td>Untagged Tag 3</td>
<td>258.50</td>
<td>92.35%</td>
</tr>
<tr>
<td>VBF Tag 0</td>
<td>9.35</td>
<td>29.47%</td>
</tr>
<tr>
<td>VBF Tag 1</td>
<td>15.55</td>
<td>44.91%</td>
</tr>
<tr>
<td>TTH Hadronic Tag</td>
<td>2.42</td>
<td>16.78%</td>
</tr>
<tr>
<td>TTH Leptonic Tag</td>
<td>1.14</td>
<td>1.07%</td>
</tr>
<tr>
<td>Total</td>
<td>647.79</td>
<td>87.93%</td>
</tr>
</tbody>
</table>

Expected contributions of each production mechanism to the different categories

CMS-PAS-HIG-16-020
Run II: Signal strength ($\gamma\gamma$ method cont.)

Untagged category with second best $m_{\gamma\gamma}$ resolution

VBF category with best $m_{\gamma\gamma}$ resolution

CMS-PAS-HIG-16-020

Hadronic $t\bar{t}H$ category

Leptonic $t\bar{t}H$ category
Run II: Signal strength (4l results)

With $m_H = 125.09$ GeV,

$\mu = 0.99^{+0.33}_{-0.26}$

$\mu_{g g H, t \bar{t} H} = 1.00^{+0.39}_{-0.32}$

$\mu_{VBF, VH} = 0.91^{+1.56}_{-0.91}$

Obs. (exp.) significance:

$m_H = 125.09$ GeV, 6.2 (6.5) $\sigma$

$m_H = 124.3$ GeV, 6.4 (6.3) $\sigma$
Run II: Signal strength ($\gamma \gamma$ results)

\[ m_H = 125.09 \text{ GeV}: \]
\[ \mu = 0.90^{+0.21}_{-0.19} \]

\[ m_H\text{-profiled:} \]
\[ \mu = 0.95^{+0.21}_{-0.18} \]
\[ \mu_{ggH,t\bar{t}H} = 0.80^{+0.14}_{-0.18} \]
\[ \mu_{VBF,VH} = 1.59^{+0.73}_{-0.45} \]

Observed significance:
\[ m_H = 125.09 \text{ GeV}, 5.6 \sigma \]
\[ m_H = 126.00 \text{ GeV}, 6.1 \sigma \]
Run I: Width upper bound from CMS

Observed:
\[ \mu_{GF}^{\text{off-shell}} < 2.4 \]
\[ \mu_{VBF}^{\text{off-shell}} < 19.3 \]

Expected:
\[ \mu_{GF}^{\text{off-shell}} < 6.2 \]
\[ \mu_{VBF}^{\text{off-shell}} < 34.4 \]

Latest width combination using 4\(l\), and WW and ZZ \(\to 2l2\nu\) using on-shell + off-shell combination of events

(\texttt{arxiv:1605.02329}, submitted to JHEP)
Run I: Anomalous couplings combination


4l+WW → 2l2ν combination (+γγ for spin-2 couplings)

$$R_{ai} = \frac{\frac{a_{WW}^{ai}}{a_{1}^{WW}}}{1 + \left(\frac{a_{i}^{ZZ}}{a_{1}^{ZZ}}\right)^2}$$
Run I: Anomalous couplings combination

4l+WW → 2l2ν combination (+γγ for spin-2 couplings)


a_1^{ZZ} = a_1^{WW}

Run I: Anomalous couplings from off-shell

\[ A(HVV) \sim \left[ a_1 - e^{i\phi_{\Lambda Q}} \frac{(q_{V1} + q_{V2})^2}{\Lambda_Q^2} \right] m_{\tilde{\nu}}^2 \epsilon_{V1}^* \epsilon_{V2}^* \]

\[ f_{\Lambda Q} \cos(\phi_{\Lambda Q}) \ (68\%) \ [95\% \ CL] \]

when \( \Gamma_H = \Gamma_H^{SM} \)

Expected: \((-0.4, 1.1) \ [-3.6, 4.4] \times 10^{-3}\)

Observed: \((-0.4, 1.0) \ [-1.4, 3.8] \times 10^{-3}\)

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Expected: \((-0.4, 1.1) \ [-3.6, 4.4] \times 10^{-3}\)

Observed: \((-0.4, 1.0) \ [-1.4, 3.8] \times 10^{-3}\)