H(125) decays to leptons at CMS

Alexei Raspereza, DESY
(on behalf of CMS Collaboration)

HH Workshop, Orsay 2017/07/24
H(125) boson is discovered at 7/8 TeV and rediscovered at 13 TeV

• at the current level of precision the H(125) properties are consistent with expectations from the SM
• But what is the nature of H(125) state?

Leptonic decays of H(125)

• probe Yukawa couplings essential for testing mass-coupling relation for fermions
• provide access to CP quantum numbers of H(125)
• provide directly detectable signatures of new physics

lepton flavor violating (LVF) decays (covered in separate talk by Fanbo Meng)
Leptonic decays of H(125) : Results from CMS

- Main focus on recent results (Run II, 13 TeV)
  - also included results from Run I (7/8 TeV) and projections for the H → µµ search

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Documentation</th>
<th>Dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>H → µµ (projections)</td>
<td>HIG-13-007</td>
<td>14 TeV (up to 1500 fb⁻¹)</td>
</tr>
<tr>
<td>H → ττ</td>
<td>HIG-16-043</td>
<td>Run II, 35.9 fb⁻¹ at 13 TeV</td>
</tr>
</tbody>
</table>

Production modes exploited

Diagrams showing production modes involved in Higgs boson decays.
H(125) → μμ

- access to Yukawa coupling of 2nd generation of fermions
- low rate in SM (BR(H → μμ) ≃ 2 × 10⁻⁴) but clean signature
  narrow peak in the m_μμ spectrum on top of smoothly falling Z*→μμ background
- event categorization targeting various production modes
  based on multiplicity and kinematics of jets accompanying di-muon system
- further categorization exploiting difference in dimuon mass resolution
  for muons reconstructed in barrel and endcap

Signal extracted by simultaneous fit of the m_μμ spectrum in 15 categories
maximum-likelihood fit with superposition of analytical parametric
functions describing background and signal
H(125) → μμ: Results and Projections

Upper limit on production cross section times BR at \( m_H = 125 \text{ GeV} \)

\[
\frac{\sigma \mathcal{B}}{(\sigma \mathcal{B})_{\text{SM}}} < 7.4 \text{ (obs.)}
\]

\[
\frac{\sigma \mathcal{B}}{(\sigma \mathcal{B})_{\text{SM}}} < 6.5 \text{ (exp.)}
\]

Fitted value of the signal strength

\[
\frac{\sigma}{\sigma_{\text{SM}}} = 0.8^{+3.5}_{-3.4}
\]
H(125) → ττ

- second largest branching ratio (BR(H→ττ)=6.3%) among fermionic decays
- lower background compared to H → bb
- 4 final states considered, accounting for 94% of all ττ decays
  - eμ, μτh, eτh, τhτh
- 3 event categories targeting different production mechanisms
  - 0-jet, VBF, Boosted
- In all categories but one signal is extracted from 2-dimensions

<table>
<thead>
<tr>
<th>Selection</th>
<th>0-jet</th>
<th>VBF</th>
<th>Boosted</th>
</tr>
</thead>
<tbody>
<tr>
<td>eμ</td>
<td>No jet</td>
<td>2 jets, mjj &gt; 300 GeV</td>
<td>Others</td>
</tr>
<tr>
<td>μτh</td>
<td>No jet</td>
<td>≥ 2 jets, mjj &gt; 300 GeV, pTττ &gt; 50 GeV, pTτh &gt; 40 GeV</td>
<td>Others</td>
</tr>
<tr>
<td>eτh</td>
<td>No jet</td>
<td>≥ 2 jets, mjj &gt; 300 GeV, pTττ &gt; 50 GeV</td>
<td>Others</td>
</tr>
<tr>
<td>τhτh</td>
<td>No jet</td>
<td>≥ 2 jets, pTττ &gt; 100 GeV, Δηjj &gt; 2.5</td>
<td>Others</td>
</tr>
</tbody>
</table>

Variables used for the signal extraction

| eμ        | pTμ, mvis | mjj, mττ | pTττ, mττ |
| μτh       | τh decay mode, mvis | mjj, mττ | pTττ, mττ |
| eτh       | τh decay mode, mvis | mjj, mττ | pTττ, mττ |
| τhτh      | mττ         | mjj, mττ | pTττ, mττ |
Di-tau Mass Reconstruction

- Fully reconstructed di-tau mass is key variable discriminating signal against dominant $Z \rightarrow \tau\tau$ background
- Reconstruction of $m_{\tau\tau}$ with dynamic likelihood algorithm
- Inputs: $\vec{p}_{\tau_1}$, $\vec{p}_{\tau_2}$, $\vec{p}_{\text{mis}}$, $\text{COV}(\vec{p}_{\text{mis}})$
- Estimate of $m_{\tau\tau}$ is obtained by maximizing likelihood combining
  - matrix elements of tau decays
  - $\chi^2$ of $\vec{p}_{\text{mis}}$ measurement

- Better separation of $H \rightarrow \tau\tau$ signal and $Z \rightarrow \tau\tau$ background compared to the invariant mass of visible $\tau$ decay products
  - the peak position is shifted to the nominal value of resonance mass
  - mass resolution: 15-20%
Background estimation

**Z → ττ:**
- Simulation corrected for Z boson kinematics and kinematics of accompanying jets (corrections are derived from Z → μμ control region)

**QCD multijets:**
- Shape and normalization are estimated from sideband regions (same-sign lepton pairs, relaxed lepton identification/isolation)

**W+Jets and VV:**
- Shape estimated from simulation, normalization is determined from high-\(m_T\) sideband

**Z → ll with \( l \) faking \( τ_h \):**
- Simulation corrected for Z boson and jet kinematics (corrections derived from Z → μμ control region), additional corrections for \( l \rightarrow τ_h \) fake rate

**tt production:**
- Shape estimate from simulation with corrections for top \(p_T\) distributions, dedicated control region in \(eμ\) channel is used to constrain normalization
Signal Extraction

- Signal is extracted by simultaneous maximum-likelihood fit in 12 channels
  4 final states (e\(\mu\), e\(\tau_h\) \(\mu\tau_h\), \(\tau_h\tau_h\)) \(\times\) 3 event categories (0-jet, VBF, Boosted)

- Representative example of unrolled postfit 2D distribution: VBF \(\tau_h\tau_h\)
Observation of $H \to \tau\tau$ Decays

- Distribution of event yield in the analysis bins ordered by $S/(S+B)$

- Clearly visible excess in data w.r.t. background-only expectation

- Obs. (exp.) significance at $m_H = 125$ GeV

- $4.9\sigma$ ($4.7\sigma$) with Run II data only

- Combination with Run I CMS data yields $5.9\sigma$ ($5.9\sigma$)

- First observation of Yukawa coupling in single fermionic decay channel at CMS
Events are weighted by $S/(S+B)$ in bins of second variable of 2D distributions → unbiased mass spectrum

Signal is clearly visible in the distribution of physical observable $m_{\tau\tau}$
Measurements performed for different production modes and in different final states are compatible with each other and with the expectation for the SM Higgs boson.
Measurement of couplings

- probing universal coupling modifiers
  \[ \kappa_f = \frac{g_{Hff}}{g_{Hff}^{SM}} \] affects \(gg \to H\) and \(ttH\) production rates and \(H \to bb/\tau\tau\) decay rates

  \[ \kappa_V = \frac{g_{HVV}}{g_{HVV}^{SM}} \] affects VBF and VH production rates and \(H \to VV\) decay rates

- Contribution of VH is added but not targeted with specific category

- Contribution from \(H \to WW\) (significant in e\(\mu\) channel, sub-dominant in other channels) is treated as signal

- Measurement of couplings is compatible with SM expectation
Summary

- **H(125) → ττ decay** is observed with statistical significance of ~5.9 σ combining data collected at 7, 8, and 13 TeV
  
  - measured H(125) properties in the H → ττ decay channel are consistent with SM expectations

- **Search for H(125) → μμ decays** performed with Run I data collected at 7/8 TeV revealed no signal

  - upper limit is set on production cross section times BR(H→μμ)
    \[ \frac{\sigma \mathcal{B}}{(\sigma \mathcal{B})_{SM}} < 7.4 \text{ at 95\% CL} \]

  - search is being currently updated with Run II data collected at 13 TeV

  - one needs ~ 400 (1200) fb⁻¹ to observe H → μμ decay with statistical significance of 3 (5) standard deviations

- **Results of measurements** in the H → ττ and H → μμ decay channels indicate non-universality of the H(125) coupling to leptons