HIGGS PROPERTIES
MEASUREMENTS @CMS
Rencontres de Moriond Electroweak 2019

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On behalf of the CMS Collaboration
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INTRODUCTION & OUTLOOK

• After the Higgs boson discovery, the focus shifted toward the measurement its properties
• The measurements of the Higgs boson properties are a fundamental check of Standard Model
• This talk shows a glimpse of the most recent CMS results on:
  • Mass and Width
  • Simplified template cross sections (STXS)
    • Stage 0: combination of various decay channels using 2016 dataset [arXiv:1809.10733]
    • (NEW) Stage 1 with $H \rightarrow \gamma\gamma$ decay channel using 2016+2017 datasets [CMS-PAS-HIG-18-029]
  • Total and differential cross sections
    • With $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$ and boosted $H \rightarrow bb$ decay channels and their combination [arXiv:1812.06504]
  • HVV Anomalous couplings
    • Using production and decay information in $H \rightarrow ZZ \rightarrow 4l$ and $H \rightarrow \tau\tau$ [arXiv:1901.00174, CMS-HIG-17-034]
• A 3D-fit combining 4-lepton mass, per-event mass resolution, and kinematic discriminant designed to reduce the ZZ background
  • Run 2 with 35.9 fb\(^{-1}\): \(M_H = 125.26 \pm 0.20\) (stat) \(\pm 0.08\) (syst)

• Detector resolutions are much larger than the expected SM width. There is, therefore, no sensitive direct measurement
  • Best limit so far from a direct peak reconstruction in \(H \rightarrow 4l\) is 1.10 GeV @ 95% C.L. [JHEP 11 (2017) 047]
  • Indirect limits are set by measuring the on- and off-shell signal strengths: Run 1 + Run 2: \(\Gamma_H < 9.16\) MeV @ 95% C.L.
SIMPLIFIED TEMPLATE CROSS-SECTIONS

- Simplified Template Cross Section (STXS):
  - Defined as a very simple independent fiducial regions for each Higgs production mode based on its kinematics and associated particles
  - The experimental selection can be different and use advanced techniques (MVAs)
  - Aims to balance experimental precision and theory uncertainties
  - Common to ATLAS, CMS, and theory.

- Combined results for STXS Stage 0
  - Combination of various decay channels with 35.9 fb\(^{-1}\) from 2016 dataset

- (NEW) Results for STXS Stage 1 ggH and VBF bins using \(H \rightarrow \gamma \gamma\)
  - Based on 77.4 fb\(^{-1}\) from 2016+2017 datasets

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• VH split into H+V(qq), H+W(lv), H+Z(ll/νν)
• Cross sections and BR are measured using as reference the \(σ_{ggF}(ZZ)\) and the \(B^{ZZ}\)
• Very good agreement to SM prediction:
  • best precision < 20% reached
• New results using 2016 and 2017 dataset with 77.4 fb⁻¹
• \( H \rightarrow \gamma \gamma \) events are sorted into 24 experimental categories, roughly matching the STXS bins
• Improve sensitivity by in S/B
• Dedicated MVA used to increase the separation between \( qqH \) and \( ggH \) and reduce background

**STXS STAGE 1: WITH H→\gamma\gamma**

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**CMS Simulation Preliminary**

**H→\gamma\gamma**

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**Category signal composition (%)**

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**Event category**

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**New results using 2016 and 2017 dataset with 77.4 fb⁻¹**

**H→\gamma\gamma** events are sorted into 24 experimental categories, roughly matching the STXS bins

**Improve sensitivity by in S/B**

**Dedicated MVA used to increase the separation between \( qqH \) and \( ggH \) and reduce background**

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**Yacine Haddad (yhaddad@cern.ch)**
Some bins need to be merged due to limited sensitivity

Used 2 merging scenarios:

• Option 1: 10 ggH + 3 VBF parameters
• Option 2: 6 ggH + 1 VBF parameters
Some bins need to be merged due to limited sensitivity

Used 2 merging scenarios:
- Option 1: 10 ggH + 3 VBF parameters
- Option 2: 6 ggH + 1 VBF parameters
TOTAL CROSS SECTION @ 13 TeV

- Results in agreement with the expected SM value $\sigma=55.6 \pm 2.5$ pb
  - Also fitted the relative $\text{BR}(\gamma\gamma) / \text{BR}(ZZ)$

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Differential Measurements

- Combined differential cross sections using $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$, as well as boosted $H \rightarrow bb$ in the high $p_T(H)$ tail
- 20-30% improvement over best single-channel measurement

Unprecedented precision reached, compatible with SM prediction.
Differential cross-section: $P_T(H)$

- Higgs $P_T$ distribution is sensitive to charm-Yukawa coupling due to interference between charm and top-mediated contributions in ggF.

**CMS**


- Coupling-dependent branching fractions
  - Assumes no invisible BR, resolved loops
  - 1D profiled (95% CL):
    
    $$-1.1 < \kappa_b < 1.1$$
    $$-4.9 < \kappa_c < 4.8$$

**Combination**

$\delta\ln L$
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• Higgs $p_T$ distribution is sensitive to charm-Yukawa coupling due to interference between charm and top-mediated contributions in ggF

CMS

DIFFERENTIAL CROSS-SECTION: $p_T(H)$

- Freely-floating branching fractions
  - Constraint from shape only
  - 1D profiled (95% CL):

$-8.5 < \kappa_b < 18$

$-33 < \kappa_c < 38$

• EFT-based parametrisation in $\kappa_b$, $\kappa_t$ and $c_g$, where $c_g$ is direct Higgs-gluon coupling in heavy top limit.
• Search for anomalous HVV couplings in production and decay with the $H \rightarrow 4l$ and $H \rightarrow \tau\tau$ channels
  
  • $\text{arXiv:1901.00174}$ (submitted to PRD), CMS-HIG-17-034 (submitted to PRD)
  
  • Run1 and Run2 combined results: $5.1 \text{ fb}^{-1}$ ($7 \text{ TeV}$) + $19.7 \text{ fb}^{-1}$ ($8 \text{ TeV}$) + $80.2 \text{ fb}^{-1}$ ($13 \text{ TeV}$)

  • Analyses exploits the kinematic distributions of the production modes (VBF +VH) decay products ($H \rightarrow 4l + H \rightarrow \tau\tau$)

  $A(\text{HVV}) \sim a_1^{\text{HVV}} + a_2^{\text{HVV}} f_{\mu\nu}^{(1)} f_{\mu\nu}^{(2)} + a_3^{\text{HVV}} f_{\mu\nu}^{(1)} \tilde{f}_{\mu\nu}^{(2)}$

  • $a_2$ : CP-even interaction
  • $a_3$ : CP-odd interaction (pure pseudo-scalar)
  • $\Lambda_1$ : leading momentum expansion

  • HVV amplitude parameterised as fractional cross section $f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j}$

  • $a_{2,3}^{ZZ,YY}$ are already constrained from on-shell photons
HVV ANOMALOUS COUPLING: $H \rightarrow \tau \tau + \text{ON-SHELL } H \rightarrow 4L$

![Graphs showing $a_2$ and $a_3$](image-url)
SUMMARY OF HVV ANOMALOUS COUPLINGS

- Exclusion at 2 sigma of sub-percent anomalous couplings from VBF production
- Results on the off-shell coupling in the backup
CONCLUSIONS

• Most of the inclusive measurements are now established, focused shifted toward differential measurements
  • LHC most precise mass and width measurements so far
  • CMS Higgs properties analyses presented include up to ~80 fb⁻¹ of 13 TeV collisions
  • Differential and EFT interpretations
  • HVV anomalous couplings and off-shell effects
  • STXS Stage 0 and 1

• No significant deviation from the SM prediction has been observed
  • Current measurements are in excellent agreement with the SM

• Far from exhausting the potential of the full LHC Run-2 dataset
BACKUP
### Event category

- **VBF BSM**
  - 0J Tag0
  - 0J Tag1
  - 0J Tag2

- **2J BSM**
  - Tag0
  - Tag1

- **2J high Tag0**
  - Tag0
  - Tag1

- **1J BSM**
  - Tag0
  - Tag1

- **VBF VH-like**
  - 2J
  - 3J

- **STXS process**
  - 0J Tag0
  - 0J Tag1
  - 0J Tag2
  - 0J Tag3
  - 0J Tag4

### Category signal composition (%)

<table>
<thead>
<tr>
<th>Category</th>
<th>ggH 0J</th>
<th>ggH 1J low</th>
<th>ggH 1J high</th>
<th>ggH 2J med</th>
<th>ggH 2J high</th>
<th>ggH 2J BSM</th>
<th>ggH VBF-like 2J</th>
<th>ggH VBF-like 3J</th>
<th>VBF rest</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2J BSM Tag0</strong></td>
<td>52</td>
<td>22</td>
<td>19</td>
<td>7</td>
<td>19</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td><strong>2J BSM Tag1</strong></td>
<td>22</td>
<td>55</td>
<td>54</td>
<td>22</td>
<td>16</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>

**Note:** The table above shows the percentage composition of signals for different categories, with columns representing various signal processes and rows showing different event categories. The values indicate the percentage of events falling into each category.
# H → γγ: STXS-STAGE-1

<table>
<thead>
<tr>
<th>Signal parameter</th>
<th>Cross section (fb)</th>
<th>Uncertainty on ( \sigma / \sigma_{SM} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggH 0J</td>
<td>61</td>
<td>72</td>
</tr>
<tr>
<td>ggH 1J low</td>
<td>15</td>
<td>21</td>
</tr>
<tr>
<td>ggH 1J med</td>
<td>10</td>
<td>7.6</td>
</tr>
<tr>
<td>ggH 1J high</td>
<td>1.7</td>
<td>2.9</td>
</tr>
<tr>
<td>ggH 2J</td>
<td>11</td>
<td>8.4</td>
</tr>
<tr>
<td>ggH BSM</td>
<td>1.3</td>
<td>2.9</td>
</tr>
<tr>
<td>qqH</td>
<td>11</td>
<td>9.1</td>
</tr>
</tbody>
</table>
STXS FRAMEWORK: BIN MERGING OPTION 1

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STXS FRAMEWORK: BIN MERGING OPTION 2

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**DIFFERENTIAL CROSS-SECTION:** $y(H)$, $P_T^{\text{jet}}$

**Table:**

<table>
<thead>
<tr>
<th>Observable</th>
<th>$y$</th>
<th>$\Delta/\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$H \rightarrow ZZ$</td>
<td>$\sigma_{\text{SM}}$ from CYRM-2017-002</td>
</tr>
</tbody>
</table>

**Figure:**

- **CMS:** 35.9 fb$^{-1}$ (13 TeV)
- **Data / prediction:**
  - $|y_H|$ vs. $|y_H|$
  - $p_T^{\text{jet}}$ (GeV) vs. $p_T^{\text{jet}}$

**Plots:**

- Combination
- Syst. unc.
- $\Delta\sigma/\Delta y_H$ (pb)
- $\Delta\sigma/\Delta p_T^{\text{jet}}$ (pb/GeV)

**Legend:**

- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ$
- $\sigma_{\text{SM}}$ from CYRM-2017-002
- aMC@NLO, NNLOPS
- Overflow norm.

**Other Information:**

- YM: $35.9$ fb$^{-1}$
- CMS (13 TeV)
- from CYRM-2017-002
- SM $\sigma$
- Overflow norm.
DIFFERENTIAL CROSS-SECTION: $p_T(H)$

CMS

35.9 fb$^{-1}$ (13 TeV)

$\begin{array}{cccccc}
0.0074 & 0.019 & 0.016 & 0.0015 & 0.0083 & 0.0083 & 0.0098 & -0.0084 & 1 \\
0.0042 & 0.018 & 0.016 & -0.0018 & 0.0046 & 0.008 & 0.0048 & 1 & -0.0084 \\
0.031 & 0.064 & 0.032 & 0.038 & 0.042 & 0.024 & 1 & 0.0048 & 0.0098 \\
0.024 & 0.046 & 0.031 & 0.016 & -0.18 & 0.024 & 0.008 & 0.0083 & 1 \\
0.036 & 0.055 & 0.034 & 0.018 & 1 & 0.024 & 0.042 & 0.0046 & 0.0083 \\
0.033 & 0.036 & -0.27 & 1 & 0.018 & 0.016 & 0.038 & -0.0018 & 0.0015 \\
0.023 & 0.04 & 1 & -0.27 & 0.034 & 0.031 & 0.032 & 0.016 & 0.016 \\
0.013 & 1 & 0.04 & 0.036 & 0.055 & 0.046 & 0.064 & 0.018 & 0.019 \\
-0.013 & 1 & -0.013 & 0.023 & 0.033 & 0.036 & 0.024 & 0.031 & 0.0042 & 0.0074 \\
1 & -0.013 & 0.023 & 0.033 & 0.036 & 0.024 & 0.031 & 0.0042 & 0.0074 & 1 \\
\end{array}$

Correlation

$\begin{array}{cccccc}
0.0048 & 0.0069 & 0.006 & -0.00081 & 0.0032 & 0.0021 & -0.00019 & -0.0039 & 1 \\
0.0082 & 0.02 & 0.015 & 0.00083 & 0.012 & 0.014 & 0.016 & 1 & -0.0039 \\
0.088 & 0.13 & 0.076 & 0.037 & 0.071 & 0.044 & 0.0014 & 0.021 & 0.00019 \\
0.048 & 0.073 & 0.048 & 0.021 & -0.15 & 0.044 & 0.014 & 0.00021 & 0.0032 \\
0.084 & 0.12 & 0.072 & -0.0028 & 0.041 & 0.044 & 0.014 & 0.00021 & 0.0032 \\
0.037 & 0.063 & -0.27 & 1 & -0.0028 & 0.021 & 0.037 & 0.00083 & -0.00081 \\
0.099 & 0.086 & 1 & -0.27 & 0.072 & 0.048 & 0.076 & 0.015 & 0.006 \\
0.074 & 1 & 0.086 & 0.063 & 0.12 & 0.073 & 0.13 & 0.02 & 0.0069 \\
1 & 0.074 & 0.099 & 0.037 & 0.084 & 0.048 & 0.088 & 0.0082 & 0.0048 \\
1 & -0.013 & 0.023 & 0.033 & 0.036 & 0.024 & 0.031 & 0.0042 & 0.0074 & 1 \\
\end{array}$

Correlation

$\begin{array}{cccccc}
35.9 fb$^{-1}$ (13 TeV)

CMS

$\begin{array}{cccccc}
\text{Correlation}
\end{array}$
COUPLING MODIFIERS

• Use the LO coupling modifier or "kappa" framework to probe for deviations from the SM
• Parameters scale cross sections and partial widths relative to SM

\[
\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\text{SM}}} \quad \text{and} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\text{SM}}}
\]

\[
\frac{\sigma_i \cdot \text{BR}^f}{\Gamma_H} = \frac{\sigma_i(\kappa') \cdot \Gamma^f(\kappa')}{\Gamma_H} \quad \text{Where} \quad \frac{\Gamma_H}{\Gamma^{\text{SM}}} = \frac{\kappa_H^2}{1 - (\text{BR}_{\text{undet}} - \text{BR}_{\text{inv}})}
\]

\[
\kappa_H^2 = \sum_j \text{BR}_{\text{SM}}^j \kappa_j^2
\]
The branching fractions are considered dependent on the values of the couplings.

The branching fractions are implemented as nuisance parameters with no prior constraint.

\[ -1.1 < \kappa_b < 1.1 \]
\[ -4.9 < \kappa_c < 4.8 \]

\[ -8.5 < \kappa_b < 18 \]
\[ -33 < \kappa_c < 38 \]
• EFT-based parametrisation in $\kappa_b$, $\kappa_t$ and $c_g$, where $c_g$ is direct Higgs-gluon coupling in heavy top limit. Based on predictions in arXiv:1705.05143
HVV ANOMALOUS COUPLING: ON-SHELL + OFF-SHELL H→4L

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