Higgs boson rare and exotic decays at CMS

Fengwangdong Zhang (University of California, Davis)

On behalf of CMS Collaboration
Motivation

- Higgs boson (125 GeV — scalar sector):
  - Discovery in 2012 completed the Standard Model (SM) theory
  - Measurements of Higgs coupling to SM particles consistent with predictions for the moment
  - Beyond Standard Model decays (BSM) not completely excluded by current physics limits
    - Branching ratio of $H \rightarrow$ BSM less than 34% with LHC RunI results
    - Deviations from the SM predictions might give a hint of BSM

\[ \text{ATLAS and CMS} \quad \begin{bmatrix} \kappa_Z, \kappa_W, \kappa_T, \kappa_B, \kappa_G, \kappa_V, B_{\text{BSM}} \end{bmatrix} \]

\[ -2 \ln \Lambda \quad \begin{array}{c}
\text{Observed} \\
\text{SM expected}
\end{array} \]

\[ \text{JHEP08 (2016) 045} \]
Exotic & rare decays of Higgs boson

Class 1: Decays to SM particles:
- Very small branching ratio increases difficulty of observation (eg: H→μμ)
- Invisible decays with neutrinos in the final states
- An excess on SM prediction (decay rates & cross section) might be a sign of BSM

Class 2: Decays in BSM modes:
- Decays to light pseudo-scalar bosons (eg: H→aa)
- Invisible decays with large missing transverse energy (eg: H→dark photon)
- Decays with lepton flavor violation (LFV) (eg: H→μτ)

<table>
<thead>
<tr>
<th>Process</th>
<th>SM Branching ratio</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>H → μμ</td>
<td>~ 2 × 10^{-4}</td>
<td>1</td>
</tr>
<tr>
<td>H → J/ψ J/ψ</td>
<td>~ 1.5 × 10^{-10}</td>
<td>1</td>
</tr>
<tr>
<td>H → YY</td>
<td>~ 2 × 10^{-9}</td>
<td>1</td>
</tr>
<tr>
<td>H → aa → μμττ</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>H → aa → 4τ</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>H → invisible</td>
<td>~ 1 × 10^{-3}</td>
<td>1/2</td>
</tr>
<tr>
<td>LFV</td>
<td>-</td>
<td>2</td>
</tr>
</tbody>
</table>

- LFV results in backup page & Dermot’s talk
- This talk presents two recent examples of many H → aa searches at CMS
Higgs decays to $\mu^+\mu^-$ pair

- Generated Next-to-leading order (NLO) for mass ranges: 120, 125, 130 GeV
- Background estimated from data
- Boost decision tree (BDT) method applied for distinguishing signal & background shapes
- Dimuon mass resolution is incorporated for optimizing the signal sensitivity
Higgs decays to $\mu^+\mu^-$ pair

- Expected upper limits: 2.2 $\sigma$
- Observed upper limits: 2.9 $\sigma$

- Expected signal significance: 0.9
- Observed signal strength: $1.0 \pm 1.0$ (stat.) $\pm 0.1$ (syst.)

To measure the signal strength:
- Maximum likelihood fit to dimuon invariant mass spectrum:
- Main experimental uncertainties:
  - Jet energy scale & resolution: 6%
- Main theoretical uncertainty:
  - Factorization & renormalization scales: 6%

Combined RunI and RunII data

- SM branching ratio: $2.17 \times 10^{-4}$
- Observed branching ratio upper limits: $6.4 \times 10^{-4}$

Phys. Rev. Lett. 122, 021801
Rare exclusive decays of Higgs to mesons
- Promising lab to study **Yukawa couplings & BSM**
- $4\mu$ final state offers a clean signature
- Observed upper limits set for H $\rightarrow$ unpolarized mesons

**Channel** | **Branching ratio**
--- | ---
$H \rightarrow J/\psi J/\psi$ | $1.5 \times 10^{-10}$
$H \rightarrow YY$ | $2 \times 10^{-9}$

**Exclusion limits**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow J/\psi J/\psi$</td>
<td>$1.8 \times 10^{-3}$</td>
<td>$1.8 (\pm 0.2/-0.1) \times 10^{-3}$</td>
</tr>
<tr>
<td>$H \rightarrow YY$</td>
<td>$1.4 \times 10^{-3}$</td>
<td>$1.4 (\pm 0.1) \times 10^{-3}$</td>
</tr>
</tbody>
</table>
Exotic decays in 2HDM + S

- **Two-Higgs-Doublet Model (2HDM)**: two doublets of scalar fields ($\phi_1, \phi_2$) in the SM Lagrangian
  - Type-2: *minimal supersymmetry model (MSSM)*
- Further extension: **a scalar singlet (2HDM + S)**
  - Type-2: *Next-to-minimal-supersymmetry-model (NMSSM)*
- Symmetry breaking $\rightarrow$ five physical states are predicted:
  - Neutral scalars: $h_1, h_2, h_3$
  - Neutral pseudo-scalars: $a_1, a_2$
  - Charged scalars: $H^\pm$
- Four types of 2HDM (doublets couplings to fermions):

<table>
<thead>
<tr>
<th>Type</th>
<th>Type-1</th>
<th>Type-2</th>
<th>Type-3 (lepton-specific)</th>
<th>Type-4 (flipped)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up-type quarks</td>
<td>$\Phi_2$</td>
<td>$\Phi_2$</td>
<td>$\Phi_2$</td>
<td>$\Phi_2$</td>
</tr>
<tr>
<td>Down-type quarks</td>
<td>$\Phi_2$</td>
<td>$\Phi_1$</td>
<td>$\Phi_2$</td>
<td>$\Phi_1$</td>
</tr>
<tr>
<td>Charged leptons</td>
<td>$\Phi_2$</td>
<td>$\Phi_1$</td>
<td>$\Phi_1$</td>
<td>$\Phi_2$</td>
</tr>
</tbody>
</table>

- **Type-2**: MSSM-like
- **Type-3**: enhanced couplings to leptons at large $\tan\beta$
H $\rightarrow$ aa $\rightarrow$ $\mu\mu\tau\tau$

- Scan the reconstructed dimuon mass spectrum:
  - For a characteristic resonance structure
  - Invariant mass of four objects in the final state is below 100-130 GeV:
    - Compatibility with a Higgs boson decay
- Parametrized signal & background distribution:
  - Perform an unbinned maximum likelihood fit
- Final states with different tau decay modes:
  - $\mu\mu + e\mu$
  - $\mu\mu + e\tau_h$
  - $\mu\mu + \mu\tau_h$
  - $\mu\mu + \tau_h\tau_h$

Pseudo-scalar boson mass range: [15, 60] GeV
Isolated muons and taus

- In the scenario of type-3:
  - Results provide the tightest constraints in this mass range
H → aa → 4τ

- Pseudo-scalar boson mass range: [4, 15] GeV
- Lorentz-boosted taus with overlapping decay products
- Objects in the final states: 3τμ + τh (one prong)

- Signal event signature:
  - Two same sign muons with large angular separation
  - Each muon accompanied by a nearby opposite-sign particle (track)
- Compared to RunI, significantly improved upper limits:
  - 30% for low masses
  - ~ 80% for intermediate masses

2D pseudo-scalar boson mass [GeV]
2HDM + S type II Summary

CMS Preliminary

2HDM+S type II
\( \tan \beta = 2.0 \)

\[ \frac{\sigma_h}{\sigma_{SM}} \left( \frac{B(h \to \text{aa})}{B(h \to \text{SM})} \right) \]

95% CL on \( \frac{\sigma_h}{\sigma_{SM}} \left( \frac{B(h \to \text{aa})}{B(h \to \text{SM})} \right) \)

Boosted topology

Isolated decay products

https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG
H \rightarrow invisible (association with top-quark pair)

- Allow to significantly suppress and constrain SM backgrounds
- Provide higher sensitivity for BSM with enhanced top quark Yukawa coupling than other Higgs production modes
- Constraint:
  - Weaker than limits using VBF topology
  - Comparable with limits from VH
  - Stronger than limits from ggH
H $\rightarrow$ invisible (VBF & VH & ggH)

arXiv:1809.05937

Channel combination:

- Consistent with backgrounds from SM prediction
- Most sensitive channel in the combination: VBF
- **Strongest constraints on fermion (scalar) dark-matter** particles with masses smaller than 18 (7) GeV
Search for dark photons in ZH decays


- $\gamma_D$: a massless dark photon coupling to Higgs boson through a dark charged sector
- No significant excess of events is found
- First time to set upper limits based on the full RunII data

Also see Varun’s talk
Summary & Conclusion

• CMS collaboration has made many progresses in Higgs rare & exotic decays
  • No significant excess above SM prediction has been found
  • In general, more stringent constraints were set using partial RunII data than RunI
• More data are needed for some decay channels to reach the sensitivity
  • First limit setting based on full RunII data analysis:
    • H → photon + dark photon (in association with a Z boson)
• More interesting results are coming out

Stay tuned!
Backup
Table 1: The optimized event categories, the product of acceptance and selection efficiency in % for the different production processes, the total expected number of SM signal events \( m_H = 125 \text{GeV} \), the estimated number of background events per GeV at 125 GeV, the FWHM of the signal peak, the background functional fit form, and the \( S/\sqrt{B} \) ratio within the FWHM of the expected signal distribution.

| BDT response quantile [%] | Maximum muon \(|\eta|\) [%] | ggH [%] | VBF [%] | WH [%] | ZH [%] | ttH [%] | Signal Bkg/GeV @125 GeV | FWHM [GeV] | Bkg fit function | \( S/\sqrt{B} \) @ FWHM |
|--------------------------|------------------|--------|--------|--------|--------|--------|------------------------|----------|-------------------|------------------|
| 0 – 8                    | \(|\eta| < 2.4\) | 4.9    | 1.3    | 3.3    | 6.3    | 21.2   | 3.13 \times 10^3       | 4.2      | mBW              | 0.12             |
| 8 – 39                   | \(1.9 < \eta < 2.4\) | 5.6    | 1.7    | 3.9    | 3.5    | 1.3    | 22.3                   | 1.34 \times 10^3 | 7.2               | mBW \( B_{deg4} \) | 0.16               |
| 8 – 39                   | \(0.9 < \eta < 1.9\) | 10     | 2.8    | 6.5    | 6.4    | 5.2    | 41.1                   | 2.24 \times 10^3 | 4.1               | mBW \( B_{deg4} \) | 0.29               |
| 8 – 39                   | \( \eta < 0.9\) | 3.2    | 0.8    | 1.9    | 2.1    | 3.5    | 12.7                   | 7.83 \times 10^2 | 2.9               | mBW \( B_{deg4} \) | 0.18               |
| 39 – 61                  | \(1.9 < \eta < 2.4\) | 2.9    | 1.7    | 2.7    | 2.7    | 0.3    | 11.8                   | 4.37 \times 10^2 | 7.0               | mBW \( B_{deg4} \) | 0.14               |
| 39 – 61                  | \(0.9 < \eta < 1.9\) | 7.2    | 3.3    | 6.1    | 5.2    | 1.3    | 29.2                   | 9.70 \times 10^2 | 4.0               | mBW \( B_{deg4} \) | 0.31               |
| 39 – 61                  | \( \eta < 0.9\) | 3.6    | 1.1    | 2.6    | 2.2    | 0.9    | 14.5                   | 4.81 \times 10^2 | 2.8               | mBW              | 0.26               |
| 61 – 76                  | \(1.9 < \eta < 2.4\) | 1.2    | 1.5    | 1.8    | 1.7    | 0.2    | 5.2                    | 1.48 \times 10^2 | 7.6               | mBW \( B_{deg4} \) | 0.11               |
| 61 – 76                  | \(0.9 < \eta < 1.9\) | 4.8    | 3.6    | 4.5    | 4.4    | 0.7    | 20.3                   | 5.12 \times 10^2 | 4.2               | mBW \( B_{deg4} \) | 0.29               |
| 61 – 76                  | \( \eta < 0.9\) | 3.2    | 1.6    | 2.3    | 2.1    | 0.6    | 13.1                   | 3.22 \times 10^2 | 3.0               | mBW              | 0.28               |
| 76 – 91                  | \(1.9 < \eta < 2.4\) | 1.2    | 3.1    | 2.2    | 2.1    | 0.2    | 5.8                    | 1.04 \times 10^2 | 7.1               | mBW \( B_{deg4} \) | 0.14               |
| 76 – 91                  | \(0.9 < \eta < 1.9\) | 4.4    | 8.7    | 6.2    | 6.0    | 1.1    | 20.3                   | 3.60 \times 10^2 | 4.2               | mBW \( B_{deg4} \) | 0.35               |
| 76 – 91                  | \( \eta < 0.9\) | 3.1    | 4.0    | 3.8    | 3.6    | 0.9    | 13.7                   | 2.36 \times 10^2 | 3.2               | mBW              | 0.34               |
| 91 – 95                  | \( \eta < 2.4\) | 1.7    | 6.4    | 2.5    | 2.6    | 0.5    | 8.6                    | 96.0      | 4.0               | mBW              | 0.28               |
| 95 – 100                 | \( \eta < 2.4\) | 2.0    | 19     | 1.5    | 1.4    | 0.7    | 13.7                   | 83.4      | 4.1               | mBW              | 0.48               |

**FWHM:** Full Width at Half Maximum of the expected signal distribution
$H \rightarrow aa \rightarrow 2\mu 2\tau/4\tau$

Pseudo-scalar boson mass range: [15, 60] GeV

JHEP11 (2018) 018
H \rightarrow aa \rightarrow 2\mu 2\tau/4\tau

Pseudo-scalar boson mass range: [15, 60] GeV
$H \rightarrow aa \rightarrow 4\tau$

Pseudo-scalar boson mass range: $[4, 15]$ GeV
H → invisible (association with top-quark pair)
H → invisible (association with top-quark pair)

**Graph:**
- **X-axis:** Events
- **Y-axis:** Data/pred.
- **Legend:**
  - Lost Lepton
  - Other (not from t)
  - tH, H→invisible
  - Z→νν
  - Total uncertainty
  - B(H→invisible) = 100%

**Data Points:**
- A: \( N_\ell \leq 3, t_{mod} > 10, M_{b} \leq 175 \text{ GeV} \)
- B: \( N_\ell \leq 3, t_{mod} > 10, M_{b} > 175 \text{ GeV} \)
- C: \( N_\ell \leq 4, t_{mod} \leq 0, M_{b} \leq 175 \text{ GeV} \)
- D: \( N_\ell \leq 4, t_{mod} \leq 0, M_{b} > 175 \text{ GeV} \)
- E: \( N_\ell \geq 4, 0 < t_{mod} \leq 10, M_{b} \leq 175 \text{ GeV} \)
- F: \( N_\ell \geq 4, 0 < t_{mod} \leq 10, M_{b} > 175 \text{ GeV} \)
- G: \( N_\ell \geq 4, t_{mod} > 10, M_{b} \leq 175 \text{ GeV} \)
- H: \( N_\ell \geq 4, t_{mod} > 10, M_{b} > 175 \text{ GeV} \)

**Table:**

<table>
<thead>
<tr>
<th>Source</th>
<th>All-hadronic</th>
<th>Semi-leptonic</th>
<th>Di-leptonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD scale cross section</td>
<td>+5.8/-9.2%</td>
<td>+5.8/-9.2%</td>
<td>+5.8/-9.2%</td>
</tr>
<tr>
<td>QCD scale acceptance</td>
<td>0.7–14.0%</td>
<td>0.8–30.0%</td>
<td>1.0–7.0%</td>
</tr>
<tr>
<td>PDF cross section</td>
<td>3.6%</td>
<td>3.6%</td>
<td>3.6%</td>
</tr>
<tr>
<td>PDF acceptance</td>
<td>0.6–3.7%</td>
<td>0.5–4.0%</td>
<td>1.0–1.9%</td>
</tr>
<tr>
<td>Sample statistics</td>
<td>1.0–10.0%</td>
<td>1.6–11.2%</td>
<td>3.3–26.4%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.5%</td>
<td>2.5%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Trigger</td>
<td>2.0 %</td>
<td>2.0%</td>
<td>0.2–0.5%</td>
</tr>
<tr>
<td>Pileup</td>
<td>0.2–2.0%</td>
<td>0.1–2.5%</td>
<td>0.0–3.0%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>2.8–7.6%</td>
<td>2.8–9.7%</td>
<td>0.0–9.0%</td>
</tr>
<tr>
<td>B-tagging scale factor</td>
<td>0.3–3.3%</td>
<td>1.2–1.6%</td>
<td>0.1–1.3%</td>
</tr>
<tr>
<td>Lepton efficiency</td>
<td>0.0–0.7%</td>
<td>3.0–3.1%</td>
<td>3.8–5.5%</td>
</tr>
<tr>
<td>Unclustered ( \not{p}_{T}^{miss} )</td>
<td>0.2–1.8%</td>
<td>–</td>
<td>0.1–12.3%</td>
</tr>
<tr>
<td>Top/W tagging</td>
<td>1.0 – 20%</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
H $\rightarrow$ invisible (VBF & VH & ggH)

[Graphs and plots showing distributions of m$_{jj}$ and $\Delta\eta_{jj}$ for CMS simulations and data from arXiv:1809.05937]
H $\rightarrow$ invisible (VBF & VH & ggH)

**Shape analysis**
- Observed
- Median expected
- 68% expected
- 95% expected

**Cut-and-count**
- Observed
- Median expected
- 68% expected
- 95% expected

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

**4.9 fb$^{-1}$ (7 TeV) + 19.7 fb$^{-1}$ (8 TeV) + 38.2 fb$^{-1}$ (13 TeV)**

**$\kappa_F$ vs $\kappa_V$**
- LHC best fit
- 68% CL
- 95% CL
- SM production

**$-2\Delta\log(L)$ vs $B(H \rightarrow \text{inv})$**
- Observed
- Expected
- Combined 7+8 TeV
- Combined 13 TeV
- Combined 7+8+13 TeV
Search for dark photons in ZH decays

CMS-EXO-19-007

<table>
<thead>
<tr>
<th>Process</th>
<th>Yields</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>14</td>
</tr>
<tr>
<td>Nonresonant bkg.</td>
<td>2.4 ± 1.1</td>
</tr>
<tr>
<td>WZ</td>
<td>8.1 ± 2.0</td>
</tr>
<tr>
<td>ZZ</td>
<td>1.5 ± 0.3</td>
</tr>
<tr>
<td>Zγ</td>
<td>0.7 ± 0.7</td>
</tr>
<tr>
<td>Other bkg.</td>
<td>0.6 ± 0.3</td>
</tr>
<tr>
<td>Total bkg.</td>
<td>13.3 ± 3.8</td>
</tr>
</tbody>
</table>

ZH_{125} (BR=10%)   17.9 ± 1.2 (1.42 ± 0.09 %)
ZH_{200} (BR=10%)   12.3 ± 0.8 (4.32 ± 0.28 %)
ZH_{300} (BR=10%)   3.9 ± 0.2 (6.80 ± 0.34 %)

Lepton flavor violation of Higgs decaying to $\mu \tau$ and $e \tau$

- Use boost decision tree approach to distinguish signal and background
- Misidentified lepton background estimated from data
- Final states with different Higgs decay modes:
  - $\mu \tau_h$
  - $\mu \tau_e$
  - $e \tau_h$
  - $e \tau_\mu$

Presence of LFV Higgs boson couplings would allow $\tau \rightarrow \mu$ or $\tau \rightarrow e$ through a virtual Higgs boson

LFV Higgs boson decay to $\mu e$ is strongly constrained by the $\mu \rightarrow e\gamma$ limit
Lepton flavor violation of Higgs decaying to $\mu \tau$ and $e \tau$

Upper limits on the off-diagonal $\mu \tau$ and $e \tau$ Yukawa couplings at 95% confidence level

$$\sqrt{|Y_{\mu \tau}|^2 + |Y_{\tau \mu}|^2} < 1.43 \times 10^{-3}$$

$$\sqrt{|Y_{e \tau}|^2 + |Y_{\tau e}|^2} < 2.26 \times 10^{-3}$$