Study of Higgs Production in Bosonic Decays Channels in CMS

Christophe Ochando on behalf of the CMS collaboration

March 2013, Moriond QCD

\[ M_{\gamma\gamma} = 125.9 \text{ GeV} \]
\[ \sigma_M/M = 0.9\% \]
**Introduction/Outline**

- **H→VV**: Most sensitive channels
- Covers full mass range (110 – 1000 GeV)
- **Focus on low mass in this talk.**

<table>
<thead>
<tr>
<th>Channel</th>
<th>$m_H$ range (GeV)</th>
<th>$m_H$ resolution</th>
<th>$L$ (fb$^{-1}$) [7+8 TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H\rightarrow ZZ \rightarrow 4l$</td>
<td>110-1000</td>
<td>1-2%</td>
<td>5.1 + 19.6</td>
</tr>
<tr>
<td>$H\rightarrow \gamma\gamma$</td>
<td>110-150</td>
<td>1-2%</td>
<td>5.1 + 19.6</td>
</tr>
<tr>
<td>$H\rightarrow WW \rightarrow 2l2nu$</td>
<td>110-600</td>
<td>20%</td>
<td>4.9 + 19.5</td>
</tr>
</tbody>
</table>

**In back-up:**

- Rare mode
- High mass only

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</tr>
</thead>
<tbody>
<tr>
<td>$WH\rightarrow WWW \rightarrow 3l\nu$</td>
<td>110-200</td>
<td></td>
<td>4.9 + 19.5</td>
</tr>
<tr>
<td>$H\rightarrow Z\gamma$</td>
<td>120-150</td>
<td>5.0 + 19.6</td>
<td></td>
</tr>
<tr>
<td>$VH\rightarrow qq'2l2\nu$</td>
<td>120-190</td>
<td>4.9</td>
<td></td>
</tr>
<tr>
<td>$H\rightarrow ZZ \rightarrow 2l2q$</td>
<td>130-600</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>$H\rightarrow ZZ \rightarrow 2l2\nu$</td>
<td>200-600</td>
<td>5.1 + 5</td>
<td></td>
</tr>
<tr>
<td>$H\rightarrow ZZ \rightarrow 2l2\tau$ (with 4l at high mass)</td>
<td>180-1000</td>
<td>5.1 + 19.3</td>
<td></td>
</tr>
<tr>
<td>$H\rightarrow WW \rightarrow qq'lv$</td>
<td>170-600</td>
<td>5.0+12</td>
<td></td>
</tr>
</tbody>
</table>
Object Grand Summary

H→VV analysis critically depends on prompt photons & leptons:

Identified (Multivariate BDT technique for eID)

- As well on (b-)jets, MET & taus

ECAL energy BDT regression:
- ~10-25% resolution improvement for H→γγ & H→ZZ→4e

30% gain in signal efficiency for same background

With high energy/momentum resolution

Stable vs pile-up

Isolated (Particle Flow)
Search for excess of events with two high pT isolated leptons (e, μ) + moderate MET

- No mass peak but large $\sigma_{XBR}$.
- Split events in categories:
  - 0 and 1 jet (VBF not updated)
  - Different Flavor (DF), Same-Flavor (SF)
- Expect small $\Delta \phi (l,l)$ and $m(l,l)$ if SM Higgs boson
  - Can distinguish between different spin hypothesis (see Andrew’s talk)

Backgrounds control is the key!
- Irreducible: $qq/gg \rightarrow WW$
- Reducible: Top, W+jets, di-bosons, DY

Main improvements wrt November (CMS-HIG-12-042):
- 7 TeV re-analyzed.
- better understanding of main backgrounds
**H →WW→2l2ν: Analysis Strategy**

CMS-HIG-13-003

**Background**

CMS preliminary L = 19.5 fb⁻¹ (8TeV)

```
M_τ = \sqrt{2p_τ E_τ^{miss} \cos(\Delta_\phi - E_τ^{miss})}
```

**After Pre-Selection cuts (pT, MET, anti-btag,...)**

- **DF (0 & 1 jet):**
  - 2D \((M_T, m_{ll})\) shape analysis

- **SF (0 & 1 jet):**
  - Cut-based analysis
H → WW → 2l2ν: Results (1)

Clear excess
H → WW → 2l2ν: Results (2)

Significance @ 125 GeV: 4.0 σ (5.1 expected)

$\frac{\sigma}{\sigma_{SM}} @ 125 \text{ GeV} = 0.76 \pm 0.21$

Large excess at low mass

Significance vs mH

H → WW → 2l2ν
Higgs $\rightarrow$ ZZ $\rightarrow$ 4 leptons candidate
24 vertices
“Golden channel”: clean experimental signature, high precision on mass, information on $J^{PC}$

- Narrow resonance (1-2% resolution)
- 4 primary isolated leptons ($e, \mu$)
- Low signal yields… but low background:
  - $qq/gg \rightarrow ZZ$ (irreducible, from MC)
  - $Z+jets, Z+bb, tt, \ldots$ (reducible, from DATA)

Extremely demanding channel for selection:
- Electrons (muons) down to 7 (5) GeV.
- FSR $\gamma$ recovery
- Open phase space: 40(12)<$m_{Z1}$ ($m_{Z2}$)<120 GeV

Main improvements wrt November (CMS-HIG-12-041):
- improved Kinematic Discriminant.
- Categorization by # jets
- more detailed $J^{PC}$ & mass studies
H → ZZ → 4l: Mass spectrum

Good description of ZZ continuum

σ(pp → ZZ, 8TeV) = 8.4±1.0 (stat.) ± 0.7 (syst.) ± 0.4(lum.) pb

Clean signal peak at ~126 GeV

Z → 4l peak well visible
H→ZZ →4l: Beyond m4l

In addition to m4l, use more information in the final fit to:

further separate signal from background…

- **Build Kinematic Discriminant from Matrix Element techniques**

Other approaches give similar performances
In addition to m4l, use more information in the final fit to:

...and increase sensitivity to production mechanisms

Split events into 2 categories:

- Di-jet Tagged (>=2 jets)
  Use Fisher Discriminant \(m_{jj}, \Delta \eta_{jj}\)
  (VBF fraction~20%)

- Un-tagged (0/1 jet)
  Use \(pT_{m4l}/m_{4l}\)
  (VBF fraction~5%)
Significance @ 125.8 GeV: 6.7 $\sigma$ (7.2 expected)

with 3D ($m_{4l}$, $K_D$, $V_D$ or $pT/m_{4l}$) model

Consistent (but better) wrt 2D ($m_{4l}$, $K_D$) or 1D ($m_{4l}$) models.

$\sigma/\sigma_{SM} @ 125.8 \text{ GeV} = 0.91^{+0.30}_{-0.24}$
Key analyses features
- Energy Resolution
- Rejection of fake photons and optimized use of kinematics

Main improvements wrt July (CMS-HIG-12-015):
- Improved ECAL calibration on first 5.3 fb\(^{-1}\) 2012 data (after publication)
- Add more exclusive channels in 2012 analysis
- Add MVA dijet selection for MVA analysis

MC background not used for the BG estimation but only for analysis optimization
Very good ECAL performance in 2012
- $Z\rightarrow ee$ mass resolution better than 1.2% for electrons with low bremsstrahlung in the barrel.
- **Stable performance** already using promptly reconstructed data

$Z\rightarrow ee$ lineshape: good agreement between data/MC

$Z$ mass resolution as a function of time after application of analysis level corrections (energy scale)

Both electrons in ECAL Barrel with low bremsstrahlung
Higgs production vertex is selected using a Boosted Decision Tree (BDT)

- Inputs: \( \sum p_T^2 \) of vertex tracks, vertex recoil wrt diphoton system, pointing from converted photons.
- An additional BDT is used to estimate the per-event probability to identify the correct vertex.

Control samples: \( Z \rightarrow \mu\mu \) (removing \( \mu \)-tracks) for unconverted photons, \( \gamma + \text{jets} \) for converted photons.
Events are separated in exclusive categories with different S/B and resolution.

Special “tagged” categories enriched in VBF and VH signal production.
  ▪ Improve the sensitivity of the analysis for the coupling measurements.

Background directly estimated from data
  ▪ Fit the $\gamma\gamma$ invariant mass in categories using polynomials (3rd-5th order)

Two different analysis
  ▪ Cut-based (CiC)
  ▪ Multivariate (MVA): select and categorize events using a BDT

Baseline result: MVA approach (~15% better expected sensitivity)
A single discriminant (BDT) trained on MC signal and background using
- photon kinematics
- photon ID MVA score (shower shape, isolation)
- di-photon mass resolution

4 untagged categories are defined on the output of the di-photon BDT, ordered by S/B

Validation of the MVA inputs (photolonID, energy resolution) done on Z→ee and Z→µµγ

Output of the MVA validated using Z→ee (where e are recoed as γ) with corrected inputs
Cut-based analysis uses
- cut-based photon identification
- a different definition of event categories
  - Photon identification data/MC efficiency scale factors computed from $Z\rightarrow ee$ and $Z\rightarrow \mu\mu\gamma$.

4 untagged categories defined according to the $\gamma$ characteristics:
- Barrel-endcap and converted/unconverted from shower shape $R_9$
- Different mass resolution and S/B among the 4 categories

<table>
<thead>
<tr>
<th>Cat 0</th>
<th>Both photons in barrel</th>
<th>Both photons $R_9 &gt; 0.94$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cat 1</td>
<td>Both photons in barrel</td>
<td>At least one photon with $R_9 &lt; 0.94$</td>
</tr>
<tr>
<td>Cat 2</td>
<td>At least one photon in endcaps</td>
<td>Both photons $R_9 &gt; 0.94$</td>
</tr>
<tr>
<td>Cat 3</td>
<td>At least one photon in endcaps</td>
<td>At least one photon with $R_9 &lt; 0.94$</td>
</tr>
</tbody>
</table>
In addition to the untagged categories, high S/B categories are defined using additional objects in the event
  - Improve significantly the reach to measure Higgs couplings

**Di-jet:**
- 2 categories (loose/tight) with increasing VBF purity (loose ~50%, tight ~80%).
- MVA analysis uses a dijet BDT-based selection (validated using Z+jets events)

- **Additional leptons** (e or $\mu$, $p_T>$20 GeV)
- **MET** (>70 GeV): lepton categories have negligible gg contamination, 20% for MET

Events are assigned exclusively to a category following the S/B ordering:
In the following: results of the two analyses are shown side by side

**MVA mass-factorized**

**Cut-based**

**Significance @ 125.0 GeV:** 3.2 $\sigma$ (4.2 exp.)

**Significance @ 124.5 GeV:** 3.9 $\sigma$ (3.5 exp.)

With additional data and new analysis: significance decreased compared to the published results
H→γγ: Combined mass plot: 7+8 TeV

**MVA mass-factorized**

![MVA mass-factorized graph]

**Cut-based**

![Cut-based graph]

Bump at ~125 GeV consistent with expectations

Each event category is **weighted by its S/(S+B) only** for visualization purpose.
Compared to the published results, the measured $\sigma/\sigma_{SM}$ decreased.
H$\rightarrow\gamma\gamma$: Results (channel compatibility)  

**MVA mass-factorized**

<table>
<thead>
<tr>
<th>Channel</th>
<th>7 TeV</th>
<th>8 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untagged 0</td>
<td>1.69</td>
<td>0.55</td>
</tr>
<tr>
<td>Untagged 1</td>
<td>0.87</td>
<td>0.72</td>
</tr>
<tr>
<td>Untagged 2</td>
<td>0.59</td>
<td>0.44</td>
</tr>
<tr>
<td>Untagged 3</td>
<td>0.36</td>
<td>0.27</td>
</tr>
<tr>
<td>Di-jet loose</td>
<td>0.25</td>
<td>0.13</td>
</tr>
<tr>
<td>Di-jet tight</td>
<td>0.19</td>
<td>0.10</td>
</tr>
<tr>
<td>MVA 0</td>
<td>1.69</td>
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</tr>
<tr>
<td>MVA 4</td>
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<td>0.13</td>
</tr>
<tr>
<td>MVA 5</td>
<td>0.19</td>
<td>0.10</td>
</tr>
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</table>

**Cut-based**

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<th>Channel</th>
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<th>8 TeV</th>
</tr>
</thead>
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<tr>
<td>Untagged 0</td>
<td>2.27</td>
<td>0.93</td>
</tr>
<tr>
<td>Untagged 1</td>
<td>1.89</td>
<td>0.65</td>
</tr>
<tr>
<td>Untagged 2</td>
<td>1.52</td>
<td>0.47</td>
</tr>
<tr>
<td>Untagged 3</td>
<td>1.15</td>
<td>0.38</td>
</tr>
<tr>
<td>Di-jet loose</td>
<td>0.88</td>
<td>0.34</td>
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**Results**

7+8 TeV: $\sigma/\sigma_{SM} @ 124.5$ GeV = 1.11 $^{+0.32}_{-0.30}$

7 TeV: $\sigma/\sigma_{SM} @ 124.5$ GeV = 2.27 $^{+0.80}_{-0.74}$

8 TeV: $\sigma/\sigma_{SM} @ 124.5$ GeV = 0.93 $^{+0.34}_{-0.32}$

7+8 TeV: $\sigma/\sigma_{SM} @ 125.0$ GeV = 0.78 $^{+0.28}_{-0.26}$

7 TeV: $\sigma/\sigma_{SM} @ 125.0$ GeV = 1.69 $^{+0.65}_{-0.59}$

8 TeV: $\sigma/\sigma_{SM} @ 125.0$ GeV = 0.55 $^{+0.29}_{-0.27}$

- Despite the same names, the untagged categories in MVA and Cut-based are not equivalent.
H$\rightarrow\gamma\gamma$: Compatibility among the two analysis

- Low signal to background ratio a fundamental feature of this channel
  - Uncertainty on signal strength driven by statistical fluctuations of the background
  - Analysis changes can lead to statistical changes due to fluctuations in selected events and their mass

- The correlation coefficient between the MVA and cut-based signal strength measurements is found to be $r=0.76$ (estimated using jackknife techniques)

<table>
<thead>
<tr>
<th>Signal strength compatibility (including correlation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MVA vs CiC 7+8 TeV</td>
</tr>
<tr>
<td>MVA vs CiC 8 TeV only</td>
</tr>
<tr>
<td>Updated MVA vs published (5.3/fb 8TeV)</td>
</tr>
<tr>
<td>Updated CiC vs published (5.3/fb 8TeV)</td>
</tr>
</tbody>
</table>

- Observed changes in results and differences between analyses are all statistically compatible at less than 2$\sigma$
Mass measurement

\[ \text{H} \rightarrow \text{ZZ} \rightarrow 4\ell \]
- Lepton momentum scale & resolution validated with Z, J/ψ, and ϒ→ll samples.
- m_{4\ell} uncertainties due to lepton scale: 0.1% (4μ), 0.3% (4e)

\[ \text{m}_{\text{H}} = 125.8 \pm 0.5 \text{ (stat.)} \pm 0.2 \text{ (syst.)} \]

\[ \text{H} \rightarrow \gamma\gamma \]
- Systematic errors dominated by overall photon energy scale: 0.47% (mostly coming from extrapolation from Z→H and e→γ)

\[ \text{m}_{\text{H}} = 125.4 \pm 0.5 \text{ (stat.)} \pm 0.6 \text{ (syst.)} \]

Measurements in the two channels are well compatible.
Evidence for SM Higgs candidate at ~m_H=126 GeV is growing

- 3 major H→VV channels updated with full dataset. + rare modes (in back-up)

- Significance of observation:
  - H→ZZ→4l: 6.7σ (7.2 exp.)
  - H→WW: 4.1σ (5.1 exp.)
  - H→γγ: 3.2σ (4.2 exp)

So far, all individual channels are consistent with the SM, within uncertainties (statistically dominated)

- Moving to precise measurement of properties:
  - Mass: $m_H = 125.8 \pm 0.5$ (stat.) ± 0.2 (syst.)
  - $H\rightarrow ZZ\rightarrow 4l$
  - $m_H = 125.4 \pm 0.5$ (stat.) ± 0.6 (syst.)
  - $H\rightarrow \gamma\gamma$

- Production Mechanisms: See Andrew’s talk.
- Spin-Parity hypothesis tests:
New $H \rightarrow VV$ results for Moriond ‘13:

- $H \rightarrow \gamma\gamma$: CMS-HIG-13-001
- $H \rightarrow ZZ \rightarrow 4l+2l2\tau$: CMS-HIG-13-002
- $H \rightarrow WW \rightarrow 2l2\nu$: CMS-HIG-13-003
- $H \rightarrow Z\gamma$: CMS-HIG-13-006
- $WH \rightarrow WWW$: CMS-HIG-13-009

All CMS Higgs public results:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
BACK UP SLIDES
H→WW→2l2ν: Cut-Flow & Background suppression @ 8 TeV

Triggers: single/double lepton triggers

2 OS leptons, pT>20/10 GeV

**W+jets**: Tight lepton ID/Iso, cut on pT∥

**Z/γ**: MET, Z-veto

**Top (tt/tW)**: top-tagging, Njet binning (veto b-jet: soft muons or IP)

**WZ/ZZ**: veto on third lepton

**WW**: conversion rejection

**WW**: kinematics selection
H$\rightarrow$WW$\rightarrow$2l2$\nu$: Pre-Selection

0-jet bin (DF)

- Dominated by WWW background

1-jet bin (DF)

- Dominated by top background
H→WW →2l2ν: Background Control (1)

- **WW**:  
  - mH<200 GeV: events with mll>100 GeV (from data). MC to extrapolate into signal region  
  - mH>200 GeV: from MC.

- **Z/γ***:  
  - events with mll±7.5 GeV around Zmass. (residual bkg subtracted)  
  - extrapolation to signal region from MC. Cross-checked with data.

- **Wγ*:  
  - MC (Madgraph) for shape  
  - Normalization from high purity control sample (data).

- **WZ/ZZ/ Wγ**:  
  - from MC.  
  - Wγ estimate cross-checked
H→WW →2l2ν: Background Control (2)

- **W+jets/QCD:**
  - Control sample with “tight+fail” sample.
  - Extrapolation to signal region with mis-identified probability.
  - Validation on same-sign/DF control sample.

- **Top (tt/tW):**
  - Control sample with inverted top veto.
  - Background surviving the veto estimated by weighting events with per-event tagging efficiency per-jet tagging efficiency measured in separated control sample.
  - Validation in 1-jet DF top-enriched sample (inverting b-tag requirement).
H$\rightarrow$WW $\rightarrow$2l2$\nu$: WW background

- Shape uncertainty of qq$\rightarrow$WW: MC@NLO samples with up/down QCD scales (nominal shape = MADGRAPH)

- Additional uncertainties from kinematics differences between MADGRAPH & MC@NLO.

<table>
<thead>
<tr>
<th>7+8 TeV data sample</th>
<th>expected/observed significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC@NLO</td>
<td>POWHEG</td>
</tr>
<tr>
<td>5.3/4.2</td>
<td>5.1/3.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>best fit value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC@NLO</td>
</tr>
<tr>
<td>0.82 $\pm$ 0.24</td>
</tr>
</tbody>
</table>

Expected and observed significance and best fit value of $\sigma/\sigma_{SM}$ for a SM Higgs with a mass of 125 GeV for the shape-based analysis, where three different generators have been used to model the $q\bar{q} \rightarrow W^+W^-$ background process.
H→WW →2l2ν: 2D distributions

**Data - Background**

CMS preliminary L = 19.5 fb⁻¹ (8TeV)

<table>
<thead>
<tr>
<th>0-jet</th>
<th>1-jet</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="0-jet 2D distributions" /></td>
<td><img src="image2.png" alt="1-jet 2D distributions" /></td>
</tr>
</tbody>
</table>
Exclusion at 95% CL in the mass range 128 – 600 GeV.

Large excess in the low mass makes the limits weaker than expected.

When including mH=125 GeV as a part of background, no significant excess is seen over the entire range.
H$\rightarrow$WW $\rightarrow$2l2$\nu$: $\sigma/\sigma_{SM}$

Low mass resolution gives a shallow likelihood profile as a function of $m_H$

Consistent results among the exclusive categories & data taking periods
### Yields at cut-based selection final selection for mH=125 GeV

<table>
<thead>
<tr>
<th></th>
<th>H→WW</th>
<th>backgrounds</th>
<th>data</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-jet</td>
<td>ℓℓ</td>
<td>56.3 ± 12.2</td>
<td>359.8 ± 37.6</td>
</tr>
<tr>
<td></td>
<td>ℓℓ'</td>
<td>89.9 ± 19.3</td>
<td>429.4 ± 34.2</td>
</tr>
<tr>
<td>1-jet</td>
<td>ℓℓ</td>
<td>18.0 ± 5.2</td>
<td>111.3 ± 8.6</td>
</tr>
<tr>
<td></td>
<td>ℓℓ'</td>
<td>42.1 ± 12.2</td>
<td>208.5 ± 14.1</td>
</tr>
</tbody>
</table>

Table 5: Expected and observed significance and best fit value of $\sigma/\sigma_{SM}$ for a SM Higgs with a mass of 125 GeV. Results are reported for the cut-based approach, and for the shape-based analysis.
Kinematics of leptons sensitive to spin-parity state of the new boson. Test:

- SM: 0+ (POWHEG)
- VS spin-2 resonance with minimal couplings to dibosons: 2+m (JHU)

- only gg fusion considered for 2+m:
  - same initial normalization for both hypothesis
  - Assuming SM expectations for VBF/VH (tiny effect)

- only DF (0/1 jet) considered
Perform maximum likelihood fit to extract the best signal strength of each model
- Signal strength floated independently in the fit
- Test statistic: \( q = -2 \ln \left( \frac{L_{2+}}{L_{0+}} \right) \)

Expected separation at 2\(\sigma\) level.

<table>
<thead>
<tr>
<th>Case</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0(^+)</td>
<td>1.9</td>
<td>0.9</td>
</tr>
<tr>
<td>2(_{\text{min}}^+)</td>
<td>2.4</td>
<td>1.3</td>
</tr>
</tbody>
</table>

assuming \( \frac{\sigma}{\sigma_{SM}} \equiv 1 \)

assuming \( \frac{\sigma}{\sigma_{SM}} \approx 0.8 \)

<table>
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<th>Case</th>
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<td>0(^+)</td>
<td>1.5</td>
<td>0.5</td>
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<tr>
<td>2(_{\text{min}}^+)</td>
<td>1.9</td>
<td>1.3</td>
</tr>
</tbody>
</table>
- m4l parametric model for signal: Breit-Wigner convoluted with double-sided Crystal Ball

- MC: POWHEG (ggH, VBF), Pythia (associated production=)
  - low mass: narrow width approximation
  - high mass:
    - line shape corrected to match complex-pole scheme.
    - Interference between ggH and ggZZ are taken into account.
H→ZZ →4l: Resolution improvement
H\rightarrow ZZ \rightarrow 4l: Signal Efficiencies

Final State Radiation (FSR) Recovery:
- PF photons near the leptons from Z's (down to 2 GeV, \Delta R(l,\gamma) up to 0.5)
- 6% of event affected, 50% efficiency, 80% purity

@ m_H = 126 GeV, signal efficiencies:
- (within the geometrical acceptance for leptons):
  - 31% (4e), 42% (2e2\mu), 59% (4\mu)
H→ZZ →4l: Background Control

- qq/gg→ZZ: from MC (POWHEG & gg2zz)
- Reducible (Z+jets, tt, WZ,...): from DATA.
  - 2 “fake rate” methods:
    - **Method A:**
      - Control Regions:
        - Z1+2 OS-SF “failing” leptons (2P2F, 2 “prompt” + 2 failed”)
        - 3 prompt + 1 failing leptons (3P+1F):
          - target estimation of background WZ, Zγ, ...
          - Extrapolation to signal region: lepton mis-identified probability
    - **Method AA:**
      - Control Region (CR):
        - Z1+ 2 SS-SF “loose” leptons
      - Extrapolation to signal region:
        - SS/OS factor from MC, cross-checked with data
        - lepton mis-identified probability (corrected for difference in composition of converted photon between CR & sample to extract misID probability)

- **Validation:** samples with relaxed charged and/or flavor requirements
- **Final estimate:** combination of the two methods
  (yields in control regions & part of the uncertainties un-correlated)
H→ZZ →4l: m4l spectrum & tables

110 < m4l < 1000 GeV

<table>
<thead>
<tr>
<th>Channel</th>
<th>4e</th>
<th>4μ</th>
<th>2e2μ</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ background</td>
<td>78.9 ±10.9</td>
<td>118.9 ±15.5</td>
<td>192.8 ±24.8</td>
</tr>
<tr>
<td>Z+ X</td>
<td>6.5±2.6</td>
<td>3.8±1.5</td>
<td>9.9±4.0</td>
</tr>
<tr>
<td>All background expected</td>
<td>85.5±11.2</td>
<td>122.6±15.5</td>
<td>202.7±25.2</td>
</tr>
<tr>
<td>m_H = 125 GeV</td>
<td>3.5 ±0.5</td>
<td>6.8 ±0.8</td>
<td>8.9 ±1.0</td>
</tr>
<tr>
<td>m_H = 126 GeV</td>
<td>3.9 ±0.6</td>
<td>7.4 ±0.9</td>
<td>9.8 ±1.1</td>
</tr>
<tr>
<td>Observed</td>
<td>86</td>
<td>125</td>
<td>240</td>
</tr>
</tbody>
</table>

110 < m4l < 160 GeV

<table>
<thead>
<tr>
<th>Channel</th>
<th>4e</th>
<th>4μ</th>
<th>2e2μ</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ background</td>
<td>6.6 ±0.8</td>
<td>13.8 ±1.0</td>
<td>18.1 ±1.3</td>
</tr>
<tr>
<td>Z+ X</td>
<td>2.5 ±1.0</td>
<td>1.6 ±0.6</td>
<td>4.0 ±1.6</td>
</tr>
<tr>
<td>All background expected</td>
<td>9.1 ±1.3</td>
<td>15.4 ±1.2</td>
<td>22.0 ±2.0</td>
</tr>
<tr>
<td>m_H = 125 GeV</td>
<td>3.5 ±0.5</td>
<td>6.8 ±0.8</td>
<td>8.9 ±1.0</td>
</tr>
<tr>
<td>m_H = 126 GeV</td>
<td>3.9 ±0.6</td>
<td>7.4 ±0.9</td>
<td>9.8 ±1.1</td>
</tr>
<tr>
<td>Observed</td>
<td>16</td>
<td>23</td>
<td>32</td>
</tr>
</tbody>
</table>
$H \rightarrow ZZ \rightarrow 4l$: MZ1 vs MZ2

Statistical fluctuation at ICHEP that is filling in...

Distributions in $121.5 < m_{4l} < 130.5$ GeV range
In addition to m4l, use more information in the final fit to:

...and increase sensitivity to production mechanisms

- **Split events into 2 categories:**
  - **Di-jet Tagged (>=2 jets)**
    - Use Fisher Discriminant ($m_{jj}$, $\Delta\eta_{jj}$)
  - **Un-tagged (0/1 jet)**
    - Use $p_{T_{m4l}}/m_{4l}$

(Distributions in 121.5<m4l<130.5 GeV range)
$H \rightarrow ZZ \rightarrow 4l$: $K_D$ vs $m_{4l}$

- Background

- $m_H = 126$ GeV

- CMS preliminary

- $\sqrt{s} = 7$ TeV, $L = 5.1$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV, $L = 19.6$ fb$^{-1}$

- $K_D$ vs $m_{4l}$ (GeV)
H→ZZ→4l: V_D vs m_{4l}

**H→ZZ→4l: V_D vs m_{4l}**

- **background**
  - 4e
  - 4μ
  - 2e2μ

- **ggH**
  - 4e
  - 4μ
  - 2e2μ

- **VBF**
  - 4e
  - 4μ
  - 2e2μ
H→ZZ →4l: some more distributions

- Di-jet tagged category
  - Distribution in 121.5<m_4l<130.5 GeV range
- Un-tagged category
$H \rightarrow ZZ \rightarrow 4l$: p-values & limits (low mass)

Excess at ~126 GeV consistent per category & data taking periods

Exclude $m_H > 130$ @ 95%CL
Exclude SM-like Higgs boson in the range 130-827 GeV @ 95% CL
Production Mechanisms

H→ZZ→4l

H→γγ

Measurements are compatible with SM within <1 sigma
The kinematics of the production and decay of the new boson are sensitive to its spin-parity state

- Build Discriminator (D) based of ratio of LO Matrix Elements
  - Don’t use the system pT (NLO effect)
  - Don’t use the rapidity (mostly PDF’s)

- $D_{\text{bkg}}$: separate signal from background
  - 5 angles, $m_{Z1}$, $m_{Z2}$ and $m_{4\ell}$

- $D_{JP}$: separate SM Higgs from alternative $J^P$ hypothesis
  - 5 angles, $m_{Z1}$, $m_{Z2}$

$$D_{JP} = \frac{P_{SM}}{P_{SM} + P_{JP}} = \left[1 + \frac{P_{JP}(m_{Z1}, m_{Z2}, \tilde{\Omega} | m_{4\ell})}{P_{SM}(m_{Z1}, m_{Z2}, \tilde{\Omega} | m_{4\ell})}\right]^{-1}$$

- Perform statistical analysis in the 2D ($D_{\text{bkg}}, D_{JP}$) plane.
$H \rightarrow ZZ \rightarrow 4l$: $D_J^P$ distributions

Distributions after $D_{bkg} > 0.5$ (for illustration)
H→ZZ →4l: test statistic

![Graphs showing test statistic distributions for different scenarios.](image-url)
**H → ZZ → 4l: J^{PC} Analysis Results**

Table 3: List of models used in analysis of spin-parity hypotheses corresponding to the pure states of the type noted. The expected separation is quoted for two scenarios, when the signal strength for each hypothesis is pre-determined from the fit to data and when events are generated with SM expectation for the signal yield ($\mu=1$). The observed separation quotes consistency of the observation with the $0^+$ model or $J^p$ model, and corresponds to the scenario when the signal strength is pre-determined from the fit to data. The last column quotes $CL_s$ criterion for the $J^p$ model.

<table>
<thead>
<tr>
<th>$J^p$</th>
<th>production</th>
<th>comment</th>
<th>expect ($\mu=1$)</th>
<th>obs. $0^+$</th>
<th>obs. $J^p$</th>
<th>$CL_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^-$</td>
<td>$gg \to X$</td>
<td>pseudoscalar</td>
<td>2.6$\sigma$ (2.8$\sigma$)</td>
<td>0.5$\sigma$</td>
<td>3.3$\sigma$</td>
<td>0.16%</td>
</tr>
<tr>
<td>$0^+_h$</td>
<td>$gg \to X$</td>
<td>higher dim operators</td>
<td>1.7$\sigma$ (1.8$\sigma$)</td>
<td>0.0$\sigma$</td>
<td>1.7$\sigma$</td>
<td>8.1%</td>
</tr>
<tr>
<td>$2^+<em>{m</em>{gg}}$</td>
<td>$gg \to X$</td>
<td>minimal couplings</td>
<td>1.8$\sigma$ (1.9$\sigma$)</td>
<td>0.8$\sigma$</td>
<td>2.7$\sigma$</td>
<td>1.5%</td>
</tr>
<tr>
<td>$2^+<em>{m</em>{q\bar{q}}}$</td>
<td>$q\bar{q} \to X$</td>
<td>minimal couplings</td>
<td>1.7$\sigma$ (1.9$\sigma$)</td>
<td>1.8$\sigma$</td>
<td>4.0$\sigma$</td>
<td>$&lt;$0.1%</td>
</tr>
<tr>
<td>$1^-$</td>
<td>$q\bar{q} \to X$</td>
<td>exotic vector</td>
<td>2.8$\sigma$ (3.1$\sigma$)</td>
<td>1.4$\sigma$</td>
<td>$&gt;$4.0$\sigma$</td>
<td>$&lt;$0.1%</td>
</tr>
<tr>
<td>$1^+$</td>
<td>$q\bar{q} \to X$</td>
<td>exotic pseudovector</td>
<td>2.3$\sigma$ (2.6$\sigma$)</td>
<td>1.7$\sigma$</td>
<td>$&gt;$4.0$\sigma$</td>
<td>$&lt;$0.1%</td>
</tr>
</tbody>
</table>

The studied pseudo-scalar, spin-1 and spin-2 models are excluded at 95% CL or higher
$H \rightarrow ZZ \rightarrow 4l$: Mixed parity

$$A(X \rightarrow V_1 V_2) = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left( a_1 g_{\mu\nu} m_X^2 + a_2 q_{\mu} q_{\nu} + a_3 \epsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta \right)$$

$$f_{a3} = \frac{|A_3|^2}{(|A_1|^2 + |A_3|^2)}$$

- SM 0+ decay dominated by A1
- 0- decay dominated by A3

$$f_{a3} = 0.00^{+0.23}_{-0.00}$$
$$f_{a3} < 0.58 \text{ @ 95% C.L.}$$
Data/MC agrees on the e-scale within ~0.2% (high pT, barrel) to 1.5% (low pT, endcaps)

Data/MC agrees on the resolution within < 10%.
Muon scale & resolution validated with $Z$, $J/\psi$ & $\Upsilon \rightarrow \mu \mu$

- Data/MC agrees on the $\mu$-scale within 0.1%
- Data/MC agrees on the resolution within < 10%.
H→ZZ →4l: per-event m4l uncertainty

- Per-lepton momentum uncertainties are calibrated & validated using Z→ee & Z→μμ

Agreement between predicted & measured mass resolution within 20%

- Relative m4l mass uncertainty in good agreement between data & MC for various control regions: Z→4l, ZZ, Z+X (fakes).
Mass Measurements with different techniques:

- 1D (m_{4l}), 2D (m_{4l}, \delta m_{4l}) & 3D (m_{4l}, K_D)
- Gives consistent results

- Z\rightarrow 4l used to validate 1D mass measurement
- Good agreement between measured & PDG values
Results: limits

**MVA mass-factorized**

Exclude at 95% CL almost the full mass range except the region around 125 GeV

**Cut-based**
**H→γγ: published results**

- Maximum significance 4.1 σ at 125 GeV
- Sum of mass distributions for each event class, weighted by S/(S+B)
- Weighed data events and BG model parametrizations
### Expected signal and estimated background

<table>
<thead>
<tr>
<th>Event classes</th>
<th>SM Higgs boson expected signal ($m_H=125$ GeV)</th>
<th>Background $m_{\gamma\gamma} = 125$ GeV (ev./GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>$ggH$</td>
</tr>
<tr>
<td>7 TeV 5.1 fb$^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Untagged 0</td>
<td>3.2</td>
<td>61.4%</td>
</tr>
<tr>
<td>Untagged 1</td>
<td>16.3</td>
<td>87.6%</td>
</tr>
<tr>
<td>Untagged 2</td>
<td>21.5</td>
<td>91.3%</td>
</tr>
<tr>
<td>Untagged 3</td>
<td>32.8</td>
<td>91.3%</td>
</tr>
<tr>
<td>Dijet tag</td>
<td>2.9</td>
<td>26.8%</td>
</tr>
<tr>
<td>8 TeV 19.6 fb$^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Untagged 0</td>
<td>17.6</td>
<td>72.9%</td>
</tr>
<tr>
<td>Untagged 1</td>
<td>39.4</td>
<td>83.5%</td>
</tr>
<tr>
<td>Untagged 2</td>
<td>155.3</td>
<td>91.7%</td>
</tr>
<tr>
<td>Untagged 3</td>
<td>162.1</td>
<td>92.5%</td>
</tr>
<tr>
<td>Dijet tight</td>
<td>9.3</td>
<td>20.7%</td>
</tr>
<tr>
<td>Dijet loose</td>
<td>11.6</td>
<td>46.8%</td>
</tr>
<tr>
<td>Muon tag</td>
<td>1.4</td>
<td>0.0%</td>
</tr>
<tr>
<td>Electron tag</td>
<td>1.0</td>
<td>1.1%</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ tag</td>
<td>1.6</td>
<td>21.1%</td>
</tr>
</tbody>
</table>
H→γγ: Signal Model: MVA categories

8TeV Untagged cat 0

8TeV: All categories combined
# $H \rightarrow \gamma\gamma$: Systematic errors

<table>
<thead>
<tr>
<th>Sources of systematic uncertainty</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Per photon</strong></td>
<td></td>
</tr>
<tr>
<td>Energy resolution ($\Delta\sigma/E_{\text{MC}}$)</td>
<td>$R_\theta &gt; 0.94$ (low $\eta$, high $\eta$)</td>
</tr>
<tr>
<td></td>
<td>$R_\theta &lt; 0.94$ (low $\eta$, high $\eta$)</td>
</tr>
<tr>
<td>Energy scale ($\frac{E_{\text{data}} - E_{\text{MC}}}{E_{\text{MC}}}$)</td>
<td>$R_\theta &gt; 0.94$ (low $\eta$, high $\eta$)</td>
</tr>
<tr>
<td></td>
<td>$R_\theta &lt; 0.94$ (low $\eta$, high $\eta$)</td>
</tr>
<tr>
<td><strong>Cut-based</strong></td>
<td></td>
</tr>
<tr>
<td>Photon identification efficiency</td>
<td>1.0%</td>
</tr>
<tr>
<td>$R_\theta &gt; 0.94$ efficiency (results in class migration)</td>
<td>4.0%</td>
</tr>
<tr>
<td><strong>Mass-fit and mass-sidebands</strong></td>
<td></td>
</tr>
<tr>
<td>Photon identification BDT</td>
<td>±0.01 (shape shift)</td>
</tr>
<tr>
<td>Photon energy resolution BDT</td>
<td>±0.10 (shape scaling)</td>
</tr>
<tr>
<td><strong>Per event</strong></td>
<td></td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>4.4%</td>
</tr>
<tr>
<td>Vertex finding efficiency</td>
<td>0.2%</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>1.0%</td>
</tr>
<tr>
<td>Global energy scale</td>
<td>0.5%</td>
</tr>
<tr>
<td><strong>Dijet selection</strong></td>
<td></td>
</tr>
<tr>
<td>Dijet-tagging efficiency</td>
<td>10%</td>
</tr>
<tr>
<td>Gluon-gluon fusion process</td>
<td>28%</td>
</tr>
<tr>
<td>(Effect of up to 15% event migration among dijet classes.)</td>
<td></td>
</tr>
<tr>
<td><strong>Muon selection</strong></td>
<td></td>
</tr>
<tr>
<td>Muon identification efficiency</td>
<td>1.0%</td>
</tr>
<tr>
<td><strong>Electron selection</strong></td>
<td></td>
</tr>
<tr>
<td>Electron identification efficiency</td>
<td>1.0%</td>
</tr>
<tr>
<td><strong>$E_T^{\text{miss}}$ selection</strong></td>
<td></td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ cut efficiency</td>
<td>Gluon-gluon fusion</td>
</tr>
<tr>
<td></td>
<td>Vector boson fusion</td>
</tr>
<tr>
<td></td>
<td>Associated production with W/Z</td>
</tr>
<tr>
<td></td>
<td>Associated production with $t\bar{t}$</td>
</tr>
<tr>
<td><strong>Production cross sections</strong></td>
<td>Scale</td>
</tr>
<tr>
<td>Gluon-gluon fusion</td>
<td>+7.6% -8.2%</td>
</tr>
<tr>
<td>Vector boson fusion</td>
<td>+0.3% -0.8%</td>
</tr>
<tr>
<td>Associated production with W/Z</td>
<td>+2.1% -1.8%</td>
</tr>
<tr>
<td>Associated production with $t\bar{t}$</td>
<td>+4.1% -9.4%</td>
</tr>
</tbody>
</table>
$H \rightarrow \gamma\gamma$: Vertex from converted photons: $\gamma + \text{jet}$

Vertex pointing from converted photons is validated with $g + \text{jet}$
H$\rightarrow\gamma\gamma$: PhotonID MVA

- PhotonID MVA is checked with \(Z\rightarrow\text{ee}\) and \(Z\rightarrow\mu\mu\gamma\)

![Barrel](image1.png)

![Endcap](image2.png)
H→γγ: Energy scale vs time

Stability at 0.3% level before application of analysis level corrections with prompt reconstructed data

Uncorrected
Mean = -0.41
Std. dev. = 0.27
Mean Error = 0.02

Corrected
Mean = -0.41
Std. dev. = 0.03
Mean Error = 0.02
H$\rightarrow\gamma\gamma$: Di-photon MVA validation

- \(Z\rightarrow ee\) lineshape in MVA untagged categories

Untag cat0  Untag cat1  Untag cat2  Untag cat3
• Data-MC agreement in Z$\rightarrow$ee validation maintained across nvtx bins:
Cut-based Photon ID efficiency decreases with respect to pileup, well described by MC.
$H \rightarrow \gamma\gamma$: Overlap of selected events
Jackknife resampling can be used to estimate the variance of statistical estimators in a non-parametric way.

- Achieved evaluating the estimator on subsets of the statistical sample.
- Given analyses A and B, used to estimate the variance of \( m_A - m_B \) applying the jackknife resampling to the events selected by either analysis.
Observed $\mu$ in nvtx bins

MVA

Cut Based
• Different background estimation method
• Consistent results with the mass factorized analysis
Comparison of the prompt reconstruction (used for Moriond13 result) with improved available ECAL calibrations
Two leptons and one photon in the final state
Relatively simple analysis, but very low expected signal yields
Split in several categories to improve S/B and mass resolution
No significance excess over the entire search region
Public document: CMS-PAS-HIG-13-006
Three high $p_T$ isolated leptons with moderate $E_{T}^{\text{miss}}$

$Z$ veto and anti $b$-tagging to reject $WZ$ and top events

Two approaches: cut-based and shape-based (using $\Delta R_{\ell^+\ell^-}$)

$\sim$20% better performance with shape-based approach

Public document: CMS-PAS-HIG-13-009
W/ZH → qq’WW → qq’2l2v

- Two leptons, $E_T^{\text{miss}}$ and two jets in the final state
- Make use techniques from $H \rightarrow WW \rightarrow 2\ell 2\nu$ main analysis
H$\rightarrow$ZZ$\rightarrow$2lν

- Two leptons from a Z boson, large $E_T^{\text{miss}}$
- Using $m_T$ as final variable
- Split in several categories: electrons/muons, 0/1/2-jets
Two leptons from a Z boson, two jets from another Z boson

Using $m_{2q2\ell}$ as final variable

Split in several categories: electrons/muons, 0/1/2 $b$-jets