WHAT CMS UNCOVERED ABOUT THE BOSON

A. David (CERN) for the CMS Collaboration
17’600 hours ago in a conference
17’000 km away...
“Higgsdependence” day recap

- **5σ significance.**
  - Just under the SM expectation:
    \[ \mu = \frac{\sigma}{\sigma_{SM}} = 0.80 \pm 0.20 \text{ (at 125 GeV)}. \]
    \[ m_H = 125.3 \pm 0.6 \text{ GeV}. \]
  - “Proto-couplings” compatible with SM.

- “More data needed…”
The LHC Run 1: a bountiful harvest

- LHC delivered $\sim 30 \text{ fb}^{-1}$.
- Challenge: precision physics with $\sim 20$ simultaneous proton-proton collisions.

Event with 78 reconstructed vertices over some 10 cm.
On the shoulders of giants: detector makers & theory calculators

"Yesterday's discovery is today’s calibration, and tomorrow’s background." – V. L. Telegdi

Inelastic collisions: $\sim 7 \times 10^{10}$

Six orders of magnitude of EWK, top, and Higgs Physics

W and Z bosons

CMS Preliminary

- 7 TeV CMS measurement ($L \leq 5.0 \text{ fb}^{-1}$)
- 8 TeV CMS measurement ($L \leq 19.6 \text{ fb}^{-1}$)
- 7 TeV Theory prediction
- 8 TeV Theory prediction
- CMS 95%CL limit

Top quarks

Higgs

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How SM Higgses come to be

- **Gluon fusion**
  - $tq \rightarrow H$

- **VBF**
  - $qV \rightarrow H$

- **WH, ZH**
  - $qH$, $Wq$

- **bbH, ttH**
  - $bt \rightarrow H$

Total SM Higgs cross sections at the LHC

\[
(\sqrt{s} = 14 \text{ TeV})
\]

- $gg \rightarrow H$ (NNLO)
- $qq \rightarrow H$ (NLO)
- $gg/qq \rightarrow H$
- $tt \rightarrow H$

\[
M_H \quad \text{[GeV]}
\]

10^{-4} 
10^{-3} 
10^{-2} 
10^{-1} 
10^0 
10^1 
10^2 
10^3 
10^4 
10^5 
10^6 
10^7 
10^8 
10^9 
10^{10} 

\[
[\text{pb}]\]

- $s = 14 \text{ TeV}$

- NLO / NNLO

- MRST

- $pp \rightarrow q\bar{q}H$ (NLO QCD in SFS, NLO QCD in 4FS)
- $pp \rightarrow WH$ (NNLO QCD + NLO EW)
- $pp \rightarrow ZH$ (NNLO QCD + NLO EW)
- $pp \rightarrow ggH$ (NNLO QCD + NLO EW)
- $pp \rightarrow t\bar{t}H$ (NLO QCD)
Couplings and kinematics drive BR (b\bar{b}, WW, \tau\tau, ZZ).

Decays to photons (γγ, Zγ) through loops.
15 talks

- A. Vartak – $H \rightarrow ZZ \rightarrow 4\ell$
- L. Quertenmont – Off-shell production
- M. Kenzie – $H \rightarrow \gamma\gamma$
- M. Sani – Mass measurements
- L. Bianchini – Top-Higgs production
- P. Govoni – $H \rightarrow WW$
- C. Vernieri – VH, $H \rightarrow b\bar{b}$
- J. Steggemann – Signatures with leptons
- C. Veelken – (N)MSSM searches
- D. Trocino – Invisible Higgs searches
- M. Chen – Combination of measurements
- E. Di Marco – $J^p$ from decays to bosons
- O. Bondu – Searches with two Higgs
- O. Gonzalez Lopez – High-mass searches
- S. Zenz – Upgrades

4 posters

- S. Mukherjee – $H \rightarrow \gamma\gamma$ differential prospects
- S. Malhotra – Combination of measurements
- C.-P. Chang – $Z^{(*)}\gamma$ searches
- S. Fink – $tH$, $Hb\bar{b}$ prospects
## Oversimplified big picture

<table>
<thead>
<tr>
<th>“seen”</th>
<th>“tried”</th>
<th>$H \rightarrow b\bar{b}$</th>
<th>$H \rightarrow \tau\tau$</th>
<th>$H \rightarrow WW$</th>
<th>$H \rightarrow ZZ$</th>
<th>$H \rightarrow \gamma\gamma$</th>
<th>$H \rightarrow Z^{(*)}\gamma$</th>
<th>$H \rightarrow \text{inv.}$</th>
<th>$H \rightarrow \mu\mu$</th>
<th>$H \rightarrow cc$</th>
<th>$H \rightarrow HH$</th>
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<tbody>
<tr>
<td>ggH</td>
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<td>VBF</td>
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<td>ttH</td>
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</tbody>
</table>

- **Still much to explore on the rarer ends.**
  (to the right and to the bottom) (and outside this picture)
Episode 2014

THE SM HIGGS STRIKES BACK
All out & just outside in the foyer
All out & just outside in the foyer

VH, $H \rightarrow \bar{b}b$

- $\sigma(m_{\bar{b}b}) \sim 10\%$
- $2.1\sigma$ exp.

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All out & just outside in the foyer

$H \rightarrow WW$

- $\sigma(m_{WW})$  
  - $\sim 16\%$
- $5.8\sigma$ exp.
- High yield

$VH, \ H \rightarrow bb$

- $\sigma(m_{bb})$  
  - $\sim 10\%$
- $2.1\sigma$ exp.

High yield

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PRD 89 (2014) 012003
All out & just outside in the foyer

\[ H \rightarrow WW \]
- $\sigma(m_{WW}) \sim 16\%$
- 5.8$\sigma$ exp.
- High yield

\[ H \rightarrow ZZ \rightarrow 4\ell \]
- $\sigma(m_{4\ell}) = 1 - 2\%$
- 6.7$\sigma$ exp.
- Low Bkg.

\[ VH, H \rightarrow b\bar{b} \]
- $\sigma(m_{b\bar{b}}) \sim 10\%$
- 2.1$\sigma$ exp.

$H \rightarrow WW$
$H \rightarrow ZZ \rightarrow 4\ell$
$VH, H \rightarrow b\bar{b}$

$\sigma(m_{WW})$
$\sigma(m_{4\ell})$
$\sigma(m_{b\bar{b}})$

$H \rightarrow WW$
$H \rightarrow ZZ \rightarrow 4\ell$
$VH, H \rightarrow b\bar{b}$

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PRD 89 (2014) 092007
PRD 89 (2014) 012003

m$_H = 125.6 \pm 0.4$ (stat.) \pm 0.2 (syst.) GeV
All out & just outside in the foyer

H → WW
- $\sigma(m_{WW}) \sim 16\%$
- $5.8\sigma$ exp.
- High yield
- $m_H = 125.6 \pm 0.4 \text{ (stat.)} \pm 0.2 \text{ (syst.) GeV}$

H → ZZ → 4\ell
- $\sigma(m_{4\ell}) = 1 - 2\%$
- $6.7\sigma$ exp.

VH, H → b\bar{b}
- $\sigma(m_{b\bar{b}}) \sim 10\%$
- $2.1\sigma$ exp.

H → \tau\tau
- $\sigma(m_{\tau\tau}) = 10 - 20\%$
- $3.7\sigma$ exp.
- $3.2\sigma$ obs. published evidence for fermion coupling
- $m_H = 125.6 \pm 0.4 \text{ (stat.)} \pm 0.2 \text{ (syst.) GeV}$

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All out & just outside in the foyer

\[ H \rightarrow WW \]
- \( \sigma(m_{WW}) \sim 16\% \)
- \( 5.8\sigma \) exp.
- High yield
- \( m_H = 125.6 \pm 0.4 \) (stat.) \( \pm 0.2 \) (syst.) GeV

\[ H \rightarrow ZZ \rightarrow 4\ell \]
- \( \sigma(m_{4\ell}) = 1 - 2\% \)
- \( 6.7\sigma \) exp.
- Low Bkg.

\[ VH, H \rightarrow b\bar{b} \]
- \( \sigma(m_{bb}) \sim 10\% \)
- \( 2.1\sigma \) exp.

\[ H \rightarrow \tau\tau \]
- \( \sigma(m_{\tau\tau}) = 10 - 20\% \)
- \( 3.7\sigma \) exp.
- \( 3.2\sigma \) obs. published evidence for fermion coupling

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Fermion decay combination
3.8\sigma obs. (4.4\sigma exp.)
Nature Physics, doi:10.1038/nphys3005

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**H→WW**
- $\sigma(m_{WW}) \sim 16\%$
- 5.8σ exp.
- High yield

$H→ZZ→4\ell$
- $\sigma(m_{4\ell}) = 1 - 2\%$
- 6.7σ exp.
- Low Bkg.
- $m_H = 125.6 \pm 0.4$ (stat.)
- $\pm 0.2$ (syst.) GeV

**VH, H→b\bar{b}**
- $\sigma(m_{bb}) \sim 10\%$
- 2.1σ exp.

**H→ττ**
- $\sigma(m_{\tau\tau}) = 10 - 20\%$
- 3.7σ exp.
- 3.2σ obs.
- Published evidence for fermion coupling

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**Off-shell production**
arXiv:1405.3455
(accepted by PLB)

**Fermion decay combination**
3.8σ obs. (4.4σ exp.)
Nature Physics, doi:10.1038/nphys3005

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All out & just outside in the foyer

\( H \rightarrow WW \)
- \( \sigma(m_{WW}) \approx 16\% \)
- 5.8\( \sigma \) exp.
- High yield
- \( m_H = 125.6 \pm 0.4 \) (stat.)
  \( \pm 0.2 \) (syst.) GeV

\( H \rightarrow ZZ \rightarrow 4\ell \)
- \( \sigma(m_{4\ell}) = 1 - 2\% \)
- 6.7\( \sigma \) exp.

\( VH, H \rightarrow b\bar{b} \)
- \( \sigma(m_{b\bar{b}}) \sim 10\% \)
- 2.1\( \sigma \) exp.

\( H \rightarrow \tau\tau \)
- \( \sigma(m_{\tau\tau}) = 10 - 20\% \)
- 3.7\( \sigma \) exp.
- 3.2\( \sigma \) obs.
  published evidence for fermion coupling

\( H \rightarrow \gamma\gamma \)
- \( \sigma(m_{\gamma\gamma}) = 1 - 2\% \)
- 5.2\( \sigma \) exp.

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PRD 89 (2014) 092007
PRD 89 (2014) 012003
JHEP 05 (2014) 104
arXiv:1407.0558
(subm. to EPJC)

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@ICHEP2014
All out & just outside in the foyer

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<tr>
<td>$\sim 16%$</td>
<td>$6.7\sigma$ exp.</td>
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<td>$3.7\sigma$ exp.</td>
<td>$5.2\sigma$ exp.</td>
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<td></td>
<td>Low Bkg.</td>
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<td>High yield</td>
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<td>$m_H = 125.6$</td>
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<td>$\pm 0.4$ (stat.)</td>
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<td>$\pm 0.2$ (syst.)</td>
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Fermion decay combination
3.8\sigma obs. (4.4\sigma exp.)
Nature Physics, doi:10.1038/nphys3005

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Final Run 1 $H \rightarrow \gamma \gamma$ analysis
Final Run 1 $H \rightarrow \gamma \gamma$ analysis

- **Final calibration** of the CMS ECAL for Run 1 data.
- **Improved simulation/understanding** of:
  - ECAL noise evolution with time.
  - Effect of out-of-time collisions.
  - Amount and distribution of material in front of ECAL.
- **Improved** description of energy scale uncertainties.
- **25 event categories** targeting all production modes.
- **New background modeling** considers multiple functional forms simultaneously.

<table>
<thead>
<tr>
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<th>Improved energy resolution</th>
<th>New event selection</th>
<th>Background modeling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improvement on expected sensitivity since preliminary result:</td>
<td>$\sim 9%$</td>
<td>$\sim 9%$</td>
<td>$\sim 7%$</td>
</tr>
</tbody>
</table>

[arXiv:1407.0558, submitted to EPJC]
H → γγ significance

- Significance: $5.7\sigma$ obs.
  ($5.2\sigma$ exp.)

![Graph showing local p-value versus $m_H$ (GeV)]

- Observed 7 + 8 TeV
- Observed 7 TeV
- Observed 8 TeV
- Expected 7 + 8 TeV
- Expected 7 TeV
- Expected 8 TeV

19.7 fb$^{-1}$ (8 TeV) + 5.1 fb$^{-1}$ (7 TeV)
**H → γγ significance**

- **Significance:**  
  5.7σ obs.  
  (5.2σ exp.)
$$m_H = 124.70^{+0.35}_{-0.34} [\pm 0.31 \text{(stat.)} \pm 0.15 \text{(syst.)}] \text{ GeV}$$
$m_H = 124.70^{+0.35}_{-0.34} \ [\pm 0.31\text{(stat.)} \pm 0.15\text{(syst.)}] \text{ GeV}$

**Calibration**

$E(\gamma)$ scale & resolution correction uncertainty:

$\pm 0.05 \text{ GeV on } m_H$

$m_Z$ scale, electrons

CMS

$H \rightarrow \gamma\gamma$

$19.7 \text{ fb}^{-1} (8 \text{ TeV}) + 5.1 \text{ fb}^{-1} (7 \text{ TeV})$

$\hat{m}_H = 124.70^{+0.35}_{-0.34} \text{ GeV}$

$124.70 \pm 0.31 \text{ (stat)} \pm 0.15 \text{ (syst)} \text{ GeV}$

Floating $\mu_{VBF,VH}$ and $\mu_{ggH,t\bar{t}H}$

Total uncertainty

Statistical only

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$m_H = 124.70^{+0.35}_{-0.34} \ [\pm 0.31 \text{(stat.)} \pm 0.15 \text{(syst.)}] \ \text{GeV}$

**Calibration**

E($\gamma$) scale & resolution correction uncertainty:

\[ \pm 0.05 \ \text{GeV on } m_H \]

- **$m_Z$ scale**, electrons
- **$m_H$ scale**, electrons

---

**CMS**

$H \rightarrow \gamma \gamma$

$19.7 \text{ fb}^{-1} (8 \text{ TeV}) + 5.1 \text{ fb}^{-1} (7 \text{ TeV})$

$$\hat{m}_H = 124.70^{+0.35}_{-0.34} \ \text{GeV}$$

$124.70 \pm 0.31 \text{ (stat)} \pm 0.15 \text{ (syst)} \ \text{GeV}$

Floating $\mu_{\text{VBF,VH}}$ and $\mu_{\text{ggH,tH}}$

- Total uncertainty
- Statistical only

---

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a.david@cern.ch
H → γγ mass measurement

\[ m_H = 124.70^{+0.35}_{-0.34} \pm 0.31\text{(stat.)} \pm 0.15\text{(syst.)} \] GeV

**Calibration**
E(γ) scale & resolution correction uncertainty:
±0.05 GeV on \( m_H \)

**m_Z scale**, electrons

**Large \( p_T \) Z boson data**
Non-linearity uncertainty: ±0.10 GeV

**m_H scale**, electrons

CMS \( H \rightarrow \gamma\gamma \)
19.7 fb\(^{-1}\) (8 TeV) + 5.1 fb\(^{-1}\) (7 TeV)

\[ \hat{m}_H = 124.70^{+0.35}_{-0.34} \text{ GeV} \]

124.70 ± 0.31 (stat) ± 0.15 (syst) GeV

Floating \( \mu_{\text{VBF,VH}} \) and \( \mu_{\text{ggH,tth}} \)

Total uncertainty

Statistical only

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$m_H = 124.70^{+0.35}_{-0.34} \ [\pm 0.31 \text{(stat.)} \pm 0.15 \text{(syst.)}] \ \text{GeV}$

**Calibration**

E($\gamma$) scale & resolution correction uncertainty:

$\pm 0.05 \text{ GeV on } m_H$

$m_Z \text{ scale, electrons}$

Large $p_T$ $Z$ boson data

Non-linearity uncertainty: $\pm 0.10 \text{ GeV}$

$m_H \text{ scale, electrons}$

$m_H \text{ scale, photons}$

**CMS** $H \rightarrow \gamma\gamma$

$19.7 \text{ fb}^{-1} \ (8 \text{ TeV}) + 5.1 \text{ fb}^{-1} \ (7 \text{ TeV})$

$\hat{m}_H = 124.70^{+0.35}_{-0.34} \ \text{GeV}$

$124.70 \pm 0.31 \ (\text{stat}) \pm 0.15 \ (\text{syst}) \ \text{GeV}$

Floating $\mu_{VBF,VH}$ and $\mu_{ggH,t\bar{t}H}$

- Total uncertainty
- Statistical only

a.david@cern.ch    @CMSexperiment    @ICHEP2014
$$m_H = 124.70^{+0.35}_{-0.34} \ [\pm 0.31 \text{(stat.)} \pm 0.15 \text{(syst.)}] \text{ GeV}$$

**Calibration**

E(γ) scale & resolution correction uncertainty:

±0.05 GeV on $m_H$

- **$m_Z$ scale**, electrons

**Large $p_T$ Z boson data**

Non-linearity uncertainty: ±0.10 GeV

- **$m_H$ scale**, electrons

**From simulation**

Data-MC electron-photon differences: ±0.10 GeV

- **$m_H$ scale**, photons

--

**CMS**

$H \rightarrow \gamma\gamma$

19.7 fb$^{-1}$ (8 TeV) + 5.1 fb$^{-1}$ (7 TeV)

$$\hat{m}_H = 124.70^{+0.35}_{-0.34} \text{ GeV}$$

124.70 ± 0.31 (stat) ± 0.15 (syst) GeV

Floating $\mu_{VBF,VH}$ and $\mu_{ggH,t\bar{t}H}$

Total uncertainty

Statistical only

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\[ \frac{\sigma}{\sigma_{SM}} = 1.14^{+0.26}_{-0.23} \left[ \pm 0.21 \text{(stat.)}^{+0.13}_{-0.09} \text{(theo.)}^{+0.09}_{-0.05} \text{(syst.)} \right] \]
A combination of final results

High-resolution channels: combined mass measurement

PRD 89 (2014) 092007

arXiv:1407.0558 (subm. to EPJC)
Float 3 signal strengths to not depend on yields.
Combined mass measurement

\[ m_H = 125.03 \pm 0.30 \left[ +0.26^{+0.13}_{-0.27} \text{(stat.)} +0.15 \text{ (syst.)} \right] \text{ GeV} \]

- Float 3 signal strengths to not depend on yields.
Combined mass measurement

\[ m_H = 125.03 \pm 0.30 \left[ +0.26_{-0.27}^{+0.13} \text{(stat.)} +0.13_{-0.15}^{+0.06} \text{(syst.)} \right] \text{ GeV} \]

- Float 3 signal strengths to not depend on yields.
- \( H \rightarrow \gamma\gamma \) and \( H \rightarrow ZZ \rightarrow 4\ell \) results compatible at \( 1.6\sigma \) level.
One model

Fiat 124
One model

Fiat 124

Fiat 126
One model
One model

Fiat 125 ±0.3

Willys Motors
(AUSTRALIA) Pty. Ltd.
79 YARRABANK ROAD, SOUTH MELBOURNE, 69-7411
594 ELIZABETH STREET, MELBOURNE, Phone 34-1319

STAND No. 8

Fiat 124

Fiat 126
Other models?

Fiat 505
Other models?

Fiat 1400/1900

Fiat 505
Other models?

**Fiat 850**

**Fiat 1400/1900**

**Fiat 505**

[http://cern.ch/go/X6rC](http://cern.ch/go/X6rC)
Other models?

- Fiat 850
- Fiat 1400/1900
- Fiat 505
- Fiat 2300

[http://cern.ch/go/X6rC]
Other models?

Fiat 850

Fiat 1400/1900

Fiat 505

Fiat 2300

Fiat Seicento

[http://cern.ch/go/X6rC]
A combination of final results

$H \rightarrow WW$

$H \rightarrow ZZ \rightarrow 4\ell$

$VH, H \rightarrow b\bar{b}$

$H \rightarrow \tau\tau$

$H \rightarrow \gamma\gamma$

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arXiv:1407.0558 (subm. to EPJC)
A combination of final results

Also include further ttH searches:
- JHEP 05(2013)145 – ttH, $H \rightarrow b\bar{b}$ (7 TeV).
- CMS-PAS-HIG-13-019 – ttH, $H \rightarrow b\bar{b}$ and $H \rightarrow \tau\tau$ (8 TeV).
A combination of final results

> 200 channels

\[ H \rightarrow WW \]
\[ H \rightarrow ZZ \rightarrow 4\ell \]
\[ VH, H \rightarrow b\bar{b} \]
\[ H \rightarrow \tau\tau \]
\[ H \rightarrow \gamma\gamma \]

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Also include further \( ttH \) searches:
- JHEP 05(2013)145 – \( ttH, H \rightarrow b\bar{b} \) (7 TeV).
- CMS-PAS-HIG-13-019 – \( ttH, H \rightarrow b\bar{b} \) and \( H \rightarrow \tau\tau \) (8 TeV).
- CMS-PAS-HIG-13-020 – \( ttH \), with \( H \) decaying to multiple leptons.
A combination of final results

> 200 channels

> 2’500 floating parameters

Also include further ttH searches:
- JHEP 05(2013)145 – ttH, $H \rightarrow b\bar{b}$ (7 TeV).
- CMS-PAS-HIG-13-019 – ttH, $H \rightarrow b\bar{b}$ and $H \rightarrow \tau\tau$ (8 TeV).

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Signal strength

\[ \frac{\sigma}{\sigma_{\text{SM}}} = 1.00 \pm 0.13 \left[ \pm 0.09(\text{stat.})^{+0.08}_{-0.07}(\text{theo.}) \pm 0.07(\text{syst.}) \right] \]

- Grouped by dominant decay:
  - \( \chi^2/\text{dof} = 0.9/5 \)
  - p-value = 0.97 (asymptotic)
Signal strength

\[
\frac{\sigma}{\sigma_{\text{SM}}} = 1.00 \pm 0.13 \left[ \pm 0.09\,(\text{stat.})^{+0.08}_{-0.07}\,(\text{theo.}) \pm 0.07\,(\text{syst.}) \right]
\]

- Grouped by production tag:
  - $\chi^2/\text{dof} = 5.3/4$
  - p-value = 0.26 (asymptotic)
- **ttH-tagged** 2.0$\sigma$ above SM.

CMS Preliminary

<table>
<thead>
<tr>
<th>Tag</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined</td>
<td>$1.00 \pm 0.13$</td>
</tr>
<tr>
<td>Untagged</td>
<td>$0.87 \pm 0.16$</td>
</tr>
<tr>
<td>VBF tagged</td>
<td>$1.14 \pm 0.27$</td>
</tr>
<tr>
<td>VH tagged</td>
<td>$0.89 \pm 0.38$</td>
</tr>
<tr>
<td>ttH tagged</td>
<td>$2.76 \pm 0.99$</td>
</tr>
</tbody>
</table>

$m_H = 125$ GeV

19.7 fb\(^{-1}\) (8 TeV) + 5.1 fb\(^{-1}\) (7 TeV)
\[ \frac{\sigma}{\sigma_{SM}} = 1.00 \pm 0.13 \pm 0.07(\text{syst.}) \]

- Grouped by production tag and dominant decay:
  - \( \chi^2/\text{dof} = 10.5/16 \)
  - p-value = 0.84 (asymptotic)
- ttH-tagged 2.0\( \sigma \) above SM.
- Driven by one channel.
Scalar coupling structure
Scalar coupling structure

Gauge sector

\[ \begin{align*}
\tau & \quad Z \\
c & \quad W \\
b & \quad Y \\
g & \quad t
\end{align*} \]
Scalar coupling structure

Gauge sector

Mixed sector

Loops ($\gamma$, $g$) are sensitive to BSM contributions.
Scalar coupling structure

Yukawa sector

Gauge sector

Mixed sector

Loops ($\gamma$, $g$) are sensitive to BSM contributions.
Scalar coupling structure

Yukawa sector

Gauge sector

Mixed sector

Loops ($\gamma$, $g$) are sensitive to BSM contributions.
Loops (γ, g) are sensitive to BSM contributions.

Yukawa sector

Up type

Quark loop

Gauge sector

Mixed sector

Scalar coupling structure
Loops ($\gamma, g$) are sensitive to BSM contributions.
Scalar coupling deviations framework

Single state, spin 0, and CP-even.

Narrow-width approximation: \((\sigma \times \text{BR}) = \sigma \cdot \Gamma / \Gamma_H\)
Loops resolved at NLO QCD and LO EWK accuracy.

Peg the as-of-yet unmeasured to “closest of kin”.

Production modes

\[
\frac{\sigma_{ggH}}{\sigma_{SM\,ggH}} = \begin{cases} 
\kappa_5^2(k_b, \kappa_5, m_H) \\
\kappa_5^2 
\end{cases}
\]

\[
\frac{\sigma_{VBF}}{\sigma_{SM\,VBF}} = \kappa_{VBF}^2(k_W, \kappa_Z, m_H)
\]

\[
\frac{\sigma_{WH}}{\sigma_{SM\,WH}} = \kappa_W^2
\]

\[
\frac{\sigma_{ZH}}{\sigma_{SM\,ZH}} = \kappa_Z^2
\]

\[
\frac{\sigma_{t\bar{t}H}}{\sigma_{SM\,t\bar{t}H}} = \kappa_t^2
\]

Detectable decay modes

\[
\frac{\Gamma_{WW(*)}}{\Gamma_{SM\,WW(*)}} = \kappa_W^2
\]

\[
\frac{\Gamma_{ZZ(*)}}{\Gamma_{SM\,ZZ(*)}} = \kappa_Z^2
\]

\[
\frac{\Gamma_{b\bar{b}}}{\Gamma_{SM\,b\bar{b}}} = \kappa_b^2
\]

\[
\frac{\Gamma_{t\tau^+\tau^-}}{\Gamma_{SM\,t\tau^+\tau^-}} = \kappa_t^2
\]

\[
\frac{\Gamma_{\gamma\gamma}}{\Gamma_{SM\,\gamma\gamma}} = \begin{cases} 
\kappa_5^2(k_b, \kappa_5, \kappa_t, \kappa_W, m_H) \\
\kappa_5^2 
\end{cases}
\]

\[
\frac{\Gamma_{Z\gamma}}{\Gamma_{SM\,Z\gamma}} = \begin{cases} 
\kappa_{Z\gamma}^2(k_b, \kappa_5, \kappa_t, \kappa_W, m_H) \\
\kappa_{Z\gamma}^2 
\end{cases}
\]

Currently undetectable decay modes

\[
\frac{\Gamma_{tt}}{\Gamma_{SM\,tt}} = \kappa_t^2
\]

\[
\frac{\Gamma_{gg}}{\Gamma_{SM\,gg}} = \text{see Section 3.1.2}
\]

\[
\frac{\Gamma_{cc}}{\Gamma_{SM\,cc}} = \kappa_{b}^2
\]

\[
\frac{\Gamma_{ss}}{\Gamma_{SM\,ss}} = \kappa_{b}^2
\]

\[
\frac{\Gamma_{\mu^+\mu^-}}{\Gamma_{SM\,\mu^+\mu^-}} = \kappa_t^2
\]

Total width

\[
\frac{\Gamma_H}{\Gamma_{SM\,H}} = \begin{cases} 
\kappa_H^2(k_t, m_H) \\
\kappa_H^2 
\end{cases}
\]
Scalar coupling deviations framework

Production modes

\[ \frac{\sigma_{ggH}}{\sigma_{ggH}} = \kappa_g^2, \quad \frac{\sigma_{VBF}}{\sigma_{VBF}} = \kappa_{VBF}, \quad \frac{\sigma_{WH}}{\sigma_{WH}} = \kappa_W, \quad \frac{\sigma_{ZH}}{\sigma_{ZH}} = \kappa_Z, \quad \frac{\sigma_{ttH}}{\sigma_{ttH}} = \kappa_t^2 \]

Detectable decay modes

\[ \frac{\Gamma_{WW^{(*)}}}{\Gamma_{WW^{(*)}}} = \kappa_W^2, \quad \frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}} = \kappa_Z^2, \quad \frac{\Gamma_{bb}}{\Gamma_{bb}} = \kappa_b^2, \quad \frac{\Gamma_{t^+t^-+}}{\Gamma_{t^+t^-+}} = \kappa_t^2, \quad \frac{\Gamma_{yy^{(*)}}}{\Gamma_{yy^{(*)}}} = \left\{ \kappa_Y^2, \kappa_{YY}, \kappa_{YY}, \kappa_{YY}, \kappa_{YY} \right\}, \quad \frac{\Gamma_{Zy}}{\Gamma_{Zy}} = \left\{ \kappa_{Zy}^2, \kappa_{Zy}, \kappa_{Zy}, \kappa_{Zy}, \kappa_{Zy} \right\} \]

Currently undetectable decay modes

\[ \frac{\Gamma_{tt}}{\Gamma_{tt}} = \kappa_t^2, \quad \frac{\Gamma_{gg}}{\Gamma_{gg}} = \kappa_g^2, \quad \frac{\Gamma_{cc}}{\Gamma_{cc}} = \kappa_c^2, \quad \frac{\Gamma_{ss}}{\Gamma_{ss}} = \kappa_s^2, \quad \frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}} = \kappa_t^2 \]

Total width

\[ \frac{\Gamma_H}{\Gamma_{H_{\text{SM}}}} = \left\{ \kappa_H^2, \kappa_{H_{\text{SM}}}, \kappa_{H_{\text{SM}}}, \kappa_{H_{\text{SM}}}, \kappa_{H_{\text{SM}}} \right\} \]

- Total width as dependent function of all \( \kappa_i \).
- Total width scaled as free parameter: \( \kappa_H \).

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Coupling deviations

- Scaling the couplings to fermions ($\kappa_f$) and vector bosons ($\kappa_V$).
- Destructive interference in $H \rightarrow \gamma\gamma$ decay loop breaks degeneracy.

[CMS-PAS-HIG-14-009] [arXiv:1307.1347]
Coupling deviations

- Scaling the couplings to fermions ($\kappa_f$) and vector bosons ($\kappa_V$).

- All decay channels converging around SM expectation.
Coupling deviations summaries

- Summary of the fits of six benchmarks models probing:
  - Fermions and vector bosons.
  - Custodial symmetry.
  - Up/down fermion coupling ratio.
  - Lepton/quark coupling ratio.
  - BSM in loops: gluons and photons.
  - Extra width: $\text{BR}_{\text{BSM}}$.

- No significance deviations from SM.

$$\lambda_{xy} = \frac{\kappa_x}{\kappa_y}$$
Most general benchmark floating the total width.

Same $ttH$-related excess in

$$\lambda_{tg} = \kappa_{\text{top}} / \kappa_{\text{gluon}}.$$ 

$$\lambda_{xy} = \kappa_x / \kappa_y; \kappa_{xy} = \kappa_x \kappa_y / \kappa_H$$
H* – going off-shell

\[
\frac{d\sigma_{ggH \to ZZ}}{dm_{ZZ}^2} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}
\]

Threshold effects:
- \(2m_w\)
- \(2m_z\)
- \(2m_{\text{top}}\)

HTO powered by complex - pole - scheme

8 TeV

\(d\sigma/dM_{VV} [\text{pb}]\)
H* – going off-shell

\[ \frac{d\sigma_{gg\rightarrow H\rightarrow ZZ}}{dm_{ZZ}^2} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2} \]

\[ m_{ZZ} \sim m_H \]

\[ \sigma_{on-shell}^{gg\rightarrow H\rightarrow ZZ} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{m_H \Gamma_H} \]
H* – going off-shell

\[ \frac{d\sigma_{gg \to H \to ZZ}}{dm^2_{ZZ}} \sim \frac{\delta_{ggH}\delta_{HZZ}}{(m^2_{ZZ} - m_H^2)^2 + m_H^2 \Gamma_H^2} \]

\[ m^2_{ZZ} \sim m_H \]

\[ m^2_{ZZ} \gg m_H \]

Threshold effects

2m_W, 2m_Z, and 2m_{top}
H* – going off-shell

\[ \frac{d\sigma_{gg\to H\to ZZ}}{dm_{ZZ}^2} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2} \]

\[ \sigma_{\text{on-shell}}^{gg\to H\to ZZ} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{m_H \Gamma_H} \]

\[ \sigma_{\text{off-shell}}^{gg\to H\to ZZ} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(2m_Z)^2} \]

m_{ZZ} \sim m_H \quad \text{and} \quad m_{ZZ} \gg m_H

\[ \frac{\sigma_{\text{off-shell}}^{gg\to H\to ZZ}}{\sigma_{\text{on-shell}}^{gg\to H\to ZZ}} \sim \Gamma_H \]

2m_w, 2m_z, and 2m_{top} threshold effects

8 TeV

HTO powered by complex - pole - scheme

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Two channels exploited:

- \( \text{ZZ} \to 4\ell \)
  - 2D: \( m_{4\ell} \) and gg vs. qq discriminant.
- \( \text{ZZ} \to 2\ell 2\nu \)
  - Jet-inclusive \( m_T \) shape.

Observed limit lower than expected.

<table>
<thead>
<tr>
<th>( \Gamma^* ) vs. ( \Gamma_H^{\text{SM}} ) (95% CL)</th>
<th>4\ell</th>
<th>2\ell 2\nu</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Gamma_H / \Gamma_H^{\text{SM}} )</td>
<td>&lt; 8.0 (10.1)</td>
<td>&lt; 8.1 (10.6)</td>
<td>&lt; 5.4 (8.0)</td>
</tr>
</tbody>
</table>
Spin zero amplitude in $H \rightarrow V V$

- Anomalous couplings formalism:
  - $a_1$ is the SM amplitude.
  - $\Lambda_1$ is a higher-term of an expansion in momentum.
  - $a_2$ and $a_3$ control the CP-even and CP-odd amplitudes.

- Parameterized using fractions of cross-sections: $f_{a_1}, f_{a_2}, f_{a_3}, f_{\Lambda_1}$.

\[
A(X_{J=0} \rightarrow V_1 V_2) \sim \nu^{-1} \left( a_1 - e^{i\phi_{\Lambda_1}} \frac{q_{Z_1}^2 + q_{Z_2}^2}{(\Lambda_1)^2} \right) m_Z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^* \\
+ a_2 f_{\mu\nu}^*(Z_1) f^*(Z_2), \mu\nu + a_3 f_{\mu\nu}^*(Z_1) f^*(Z_2), \mu\nu \\
+ a_2^Z Z f_{\mu\nu}^*(Z) f^*(\gamma), \mu\nu + a_3^Z Z f_{\mu\nu}^*(Z) f^*(\gamma), \mu\nu \\
+ a_2^\gamma Z f_{\mu\nu}^*(\gamma_1) f^*(\gamma_2), \mu\nu + a_3^\gamma Z f_{\mu\nu}^*(\gamma_1) f^*(\gamma_2), \mu\nu
\]
Anomalous couplings formalism:
- $a_1$ is the SM amplitude.
- $\Lambda_1$ is a higher-term of an expansion in momentum.
- $a_2$ and $a_3$ control the CP-even and CP-odd amplitudes.

Parameterized using fractions of cross-sections: $f_{a_1}$, $f_{a_2}$, $f_{a_3}$, $f_{\Lambda_1}$.

$$A(X_{J=0} \rightarrow V_1 V_2) \sim \nu^{-1} \left( a_1 - e^{i\phi_{\Lambda_1}} \frac{q_{Z_1}^2 + q_{Z_2}^2}{(\Lambda_1)^2} \right) m_Z^2 \varepsilon_{Z_1}^* \varepsilon_{Z_2}^*$$

$$+ \ a_2 f_{\mu \nu}^* (Z_1) f^* (Z_2), \mu \nu + a_3 f_{\mu \nu}^* (Z_1) \bar{f}^* (Z_2), \mu \nu$$

$$+ \ a_2 f_{\gamma}^* (Z) f^* (\gamma), \mu \nu + a_3 f_{\mu \nu}^* (Z) \bar{f}^* (\gamma), \mu \nu$$

$$+ \ a_2 f_{\mu \nu}^* (\gamma_1) f^* (\gamma_2), \mu \nu + a_3 f_{\mu \nu}^* (\gamma_1) \bar{f}^* (\gamma_2), \mu \nu$$
Anomalous couplings formalism:

- $a_1$ is the SM amplitude.
- $\Lambda_1$ is a higher-term of an expansion in momentum.
- $a_2$ and $a_3$ control the CP-even and CP-odd amplitudes.

Parameterized using fractions of cross-sections: $f_{a1}, f_{a2}, f_{a3}, f_{\Lambda1}$.

$$A(X_{J=0} \to V_1 V_2) \sim \nu^{-1} \left( a_1 - e^{i\phi_{\Lambda_1}} \frac{q^2_{Z_1} + q^2_{Z_2}}{(\Lambda_1)^2} \right) m^2_Z \epsilon^*_Z \epsilon^*_Z$$

\[  + a_2 f^{*(Z)}_{\mu\nu} f^{*(Z_2),\mu\nu} + a_3 f^{*(Z)}_{\mu\nu} \tilde{f}^{*(Z_2),\mu\nu} \]

\[  + a_{2\gamma} f^{*(Z)}_{\mu\nu} f^{*(\gamma),\mu\nu} + a_{3\gamma} f^{*(Z)}_{\mu\nu} \tilde{f}^{*(\gamma),\mu\nu} \]

\[  + a_{2\gamma} f^{*(\gamma_1)}_{\mu\nu} f^{*(\gamma_2),\mu\nu} + a_{3\gamma} f^{*(\gamma_1)}_{\mu\nu} \tilde{f}^{*(\gamma_2),\mu\nu} \]
Anomalous couplings formalism:
- $a_1$ is the SM amplitude.
- $\Lambda_1$ is a higher-term of an expansion in momentum.
- $a_2$ and $a_3$ control the CP-even and CP-odd amplitudes.

Parameterized using fractions of cross-sections: $f_{a_1}, f_{a_2}, f_{a_3}, f_{\Lambda_1}$.

$$A(X_{J=0} \to V_1 V_2) \sim \nu^{-1} \left[ a_1 - e^{i\phi_{\Lambda_1}} \frac{q^2_{Z_1} + q^2_{Z_2}}{(\Lambda_1)^2} \right] m^2_Z e^*_Z e^*_Z$$

$$+ a_2 f^*_{\gamma\gamma}(\gamma_1) f^*_{\gamma\gamma}(\gamma_2),\mu\nu + a_3 f^*_{\mu\nu} f^*_{\gamma\gamma}(\gamma_1) f^*_{\gamma\gamma}(\gamma_2),\mu\nu$$

$a_2$ terms
CP-even (scalar)
Spin zero amplitude in H → VV

- Anomalous couplings formalism:
  - $a_1$ is the SM amplitude.
  - $\Lambda_1$ is a higher-term of an expansion in momentum.
  - $a_2$ and $a_3$ control the CP-even and CP-odd amplitudes.

- Parameterized using fractions of cross-sections: $f_{a1}$, $f_{a2}$, $f_{a3}$, $f_{\Lambda1}$.

$$A(XJ=0 \rightarrow V_1V_2) \sim \nu^{-1} \left( a_1 - e^{i\phi_{\Lambda_1}} \frac{q_1^2 + q_2^2}{(\Lambda_1)^2} \right) m_Z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^*$$

- $a_2$ terms
  - CP-even (scalar)

- $a_3$ terms
  - CP-odd (pseudoscalar)
Spin zero amplitude in $H \rightarrow VV$

- Anomalous couplings formalism:
  - $a_1$ is the SM amplitude.
  - $\Lambda_1$ is a higher-term of an expansion in momentum.
  - $a_2$ and $a_3$ control the CP-even and CP-odd amplitudes.
- Parameterized using fractions of cross-sections: $f_{a1}, f_{a2}, f_{a3}, f_{\Lambda1}$.

$$A(X_{J=0} \rightarrow V_1 V_2) \sim \nu^{-1} \left( a_1 - e^{i\phi_{\Lambda_1}} \frac{q_1^2 + q_2^2}{(\Lambda_1)^2} \right) m_Z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^*$$

- **$ZZ, WW$**
  - $a_2 f_{\mu\nu}^*(Z_1) f^*(Z_2), \mu\nu$
  - $a_3 f_{\mu\nu}^*(Z_1) f^*(Z_2), \mu\nu$

- **$Z\gamma^*$**
  - $a_2 f_{\mu\nu}^*(Z) f^*(\gamma), \mu\nu$
  - $a_3 f_{\mu\nu}^*(Z) f^*(\gamma), \mu\nu$

- **$\gamma^*\gamma^*$**
  - $a_2 f_{\mu\nu}^*(\gamma_1) f^*(\gamma_2), \mu\nu$
  - $a_3 f_{\mu\nu}^*(\gamma_1) f^*(\gamma_2), \mu\nu$
Spin zero amplitude in $H \rightarrow ZZ \rightarrow 4\ell$

- Full final state available:
  - **Kinematic discriminants** reduce 8D to 2D or 3D.
  - 2D scans of anomalous coupling fractions.
  - Assuming real phases and floating the phases.
- **No significant deviations from SM found.**

---

**Real phases**

- $f_{a_2} \cos(\phi_{a_2})$
- $f_{a_3} \cos(\phi_{a_3}) = 0$ or $\pi$

---

**Floating phases**

- $f_{a_2} \cos(\phi_{a_2})$
- $-2\Delta \ln L$

---

```latex
\text{CMS (preliminary)}
\begin{align*}
19.7 \text{ fb}^{-1} (8 \text{ TeV}) + 5.1 \text{ fb}^{-1} (7 \text{ TeV})
\end{align*}
```
H→VV combination on J>0 states

- Combination of H→WW→2ℓ2ν and H→ZZ→4ℓ.

Hypothesis test for 0⁺ vs. 1⁻
H→VV combination on J>0 states

- Combination of H→WW→2ℓ2ν and H→ZZ→4ℓ.
- All tested hypotheses excluded at more than 99.9% CLs.
Other models?

Fiat Turbina

[http://cern.ch/go/r8kv]
Other models?

Fiat Turbina

[http://cern.ch/go/r8kv]
Other models?

Fiat Turbina

Fiat Phylla at Triennale Design Museum (Milan), 2009.
Combination of VBF, $Z(\ell\ell)H$, and $Z(b\bar{b})H$ searches: $\text{BR}(H\rightarrow\text{inv}) < 0.58$ (0.44 exp.) at 95% CL.
Invisible Higgs search combination

- Combination of VBF, $Z(\ell\ell)H$, and $Z(b\bar{b})H$ searches: $\text{BR}(H\to\text{inv}) < 0.58$ (0.44 exp.) at 95% CL.
- Competitive limits for low mass DM in "Higgs portal" models.

$\text{BR}(H\to\text{inv}) < 0.58$ (0.44 exp.) at 95% CL.

Combination of VBF and $ZH$, $H\to\text{invisible}$
- $\ell's = 8.0$ TeV, $L = 18.9-19.7$ fb$^{-1}$ (VBF+$ZH$)
- $\ell's = 7.0$ TeV, $L = 4.9$ fb$^{-1}$ (ZH)

$B(H\to\text{inv}) < 0.51$ @ 90% CL

$m_H = 125$ GeV

DM-nucleon cross section $\sigma_{\chi-N}^S$ [pb]

- Scalar
- Fermion
- Vector

DM Mass $M_\chi$ [GeV]

[arXiv:1404.1344, submitted to EPJC]
Search for MSSM $\Phi \rightarrow \tau\tau$

- Minimal SuperSymmetric Model predicts:
  - $h^0, H^0, A^0$: generically $\Phi$.
  - $H^+$ and $H^-$.  

- Based on SM analysis but:
  - Using extra b-tags (production).
  - Extended to up to $m_{\tau\tau} = 1.5$ TeV.

---

**Graph**

- Observation compatible with presence of SM Higgs boson.

- CMS Preliminary, $H \rightarrow \tau\tau$, 4.9 fb$^{-1}$ at 7 TeV, 19.7 fb$^{-1}$ at 8 TeV

- MSSM $m_h^{\text{max}}$ scenario $M_{\text{SUSY}} = 1$ TeV

---

Not shown: model-independent limits on $gg \rightarrow \Phi$ and $gg \rightarrow \Phi b\bar{b}$. 

---

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Search for $H \rightarrow \mu \tau$

- $\tau$ lepton flavor violation not as well constrained as $\mu e$ (MEG).
- Based on SM $H \rightarrow \tau\tau$ analysis. Different kinematics allows good SM $H$ rejection.
  - $\text{BR}(H \rightarrow \mu \tau) < 1.57\%$ at 95%CL (expected limit of 0.75%)
Search for $H \rightarrow \mu \tau$

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Search for $H \rightarrow \mu\tau$

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  - $\text{BR}(H \rightarrow \mu\tau) < 1.57\%$ at 95%CL (expected limit of 0.75%)
Search for $H \rightarrow \mu \tau$

- Best limits on $\tau$ anomalous Yukawa couplings.

![Diagram showing CMS preliminary limits on $|\lambda|$ vs. $|\tilde{m}_h|$ for $H \rightarrow \mu \tau$ decay. The graph displays observed and expected limits at 95% confidence level, with a 4.4x suppression indicated near the observed limit.]
Best limits on τ anomalous Yukawa couplings.

Higgs flavor sector could hold surprises.

Search for $H \rightarrow \mu \tau$
New search for ttH with $H \rightarrow b\bar{b}$

- Improved performance:
  - Event probability ($P_{s/b}$) based on matrix element probabilities.
  - Single lepton (SL) and di-lepton (DL) topologies.
    - Best with identified $W \rightarrow jj$ (SL Cat-1).
  - Reduced dependency on $tt+HF$ modeling.

- Clearly a hot topic for Run 2.
New search for $ttH$ with $H \to bb$}

- Improved performance:
  - Event probability ($P_{s/b}$) based on matrix element probabilities.
  - Single lepton (SL) and di-lepton (DL) topologies.
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  - Reduced dependency on $tt+HF$ modeling.

- Clearly a hot topic for Run 2.
Looking ahead

- **300 fb⁻¹ at 14 TeV:**
  - Vast improvement over present datasets.
  - Room for theory improvements.

[arXiv:1307.7135] [CMS-PAS-HIG-13-007]
Looking ahead

300 fb$^{-1}$ at 14 TeV:
- Vast improvement over present datasets.
- Room for theory improvements.

For (HL-LHC) 3000 fb$^{-1}$:
- H$\rightarrow$μμ at > 5σ.
- Can we get to the Higgs self-coupling?

[arXiv:1307.7135] [CMS-PAS-HIG-13-007]
First step towards two-Higgs measurements at the HL-LHC.

For now setting limits on radion production from warped extra dimensions.
CMS closed a major chapter in the characterization of this Higgs boson.

- Main decay channels:
  - Final Run1 results published or submitted.
  - First combination of final results.

- Most precise Higgs mass measurement:
  \[ m_H = 125.03 \pm 0.30 \left[ +0.26^{+0.13}_{-0.27}^{\text{(stat.)}} +0.15^{\text{(syst.)}} \right] \text{ GeV} \]

- No new Higgs physics beyond the SM. Yet.

- We continue to turn all stones.
  - Few surprises need more work/data for a clear resolution.
CMS closed a major chapter in the characterization of this Higgs boson.

- Main decay channels:
  - Final Run1 results published or submitted.
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- No new Higgs physics beyond the SM. Yet.

We continue to turn all stones.

- Few surprises need more work/data for a clear resolution.
Conclusion

- We’ve just started and there’s a long and exciting way to go:
  - Go from O(10%) measurements to differential.
  - Go from “seen” to O(%) measurements.
  - Go from limits on rare things to observations.
  - Reduce theory uncertainties.
  - Explore the full potential of the LHC and its upgrades.

- All it takes is one deviation to point us on the right way beyond the SM.
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Young-Kee Kim on behalf of the ICHEP 2016 Local Organizing Committee

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Call for Submissions

We encourage you to contribute to and help shape the conference through paper submissions. For the technical research track, we invite high quality submissions of papers describing original and unpublished results of conceptual, constructive, empirical, experimental, or theoretical work in all areas of High Energy Physics. The conference solicits contributions of full-length papers, short papers, posters and abstracts, that address the themes and topics for the conference, including figures, tables and
ICHEP 2016
38th International Conference on High Energy Physics
August 3 - 10, 2016
Sheraton Hotel, Chicago, U.S.A.

The U.S. particle physics community is proud to host the 38th ICHEP conference in Chicago from the 3rd to the 10th August 2016. ICHEP is a focal point of the field of particle physics, bringing together leading experimentalists and theorists of the world. It was first held in 1950, and is biennial since 1960.

At ICHEP all areas of particle physics including neutrino, flavor, astro-particle and new physics beyond the Standard Model share the exciting results obtained in the field and exchange views among all experimental and theoretical scientists of the world including students and postdocs.

The conference will consist of parallel and invited plenary sessions. A poster session will emphasize the work of young students.

Please mark your calendar.

We look forward to seeing you at the ICHEP 2016 in Chicago.

Young-Kee Kim on behalf of the ICHEP 2016 Local Organizing Committee

The ICHEP 2016 is hosted by

Fermilab, Illinois Institute of Technology, NIU, UIC, Northwestern University, University of Illinois at Urbana-Champaign, Argonne National Laboratory, The University of Chicago.
18’000 hours from now in a conference 7’000 km away...
Episode 2016
THE RETURN OF THE LHC

Connection to the Dark Universe?
Supersymmetry?
Compositeness?
Top-Higgs coupling?
More bosons?
Deviations from SM?

...
Looking forward to LHC combination and surprises at higher energy: PeV neutrinos, LHC 13 TeV, …
Further reading
"…and references therein."

- All CMS Higgs results: [http://cern.ch/go/6qmZ](http://cern.ch/go/6qmZ)
- Results released during ICHEP 2014:
  - “Observation of the diphoton decay of the Higgs boson and measurement of its properties”
  - “Precise determination of the mass of the Higgs boson and studies of the compatibility of its couplings with the standard model”
    [CMS-PAS-HIG-14-009](http://cds.cern.ch/record/1728249), [http://cds.cern.ch/record/1728249](http://cds.cern.ch/record/1728249)
  - “Constraints on anomalous HVV interactions using H to 4\ell decays”
    [CMS-PAS-HIG-14-014](http://cds.cern.ch/record/1728251), [http://cds.cern.ch/record/1728251](http://cds.cern.ch/record/1728251)
  - “Constraints on Anomalous H→WW Interactions using Higgs boson decays to W^+W^- in the fully leptonic final state”
    [CMS-PAS-HIG-14-012](http://cds.cern.ch/record/1728250), [http://cds.cern.ch/record/1728250](http://cds.cern.ch/record/1728250)
  - “Search for Lepton Flavour Violating Decays of the Higgs Boson”
    [CMS-PAS-HIG-14-005](http://cds.cern.ch/record/1740976), [http://cds.cern.ch/record/1740976](http://cds.cern.ch/record/1740976)
  - “Search for ttH production using the Matrix Element Method”
    [CMS-PAS-HIG-14-010](http://cds.cern.ch/record/1728332), [http://cds.cern.ch/record/1728332](http://cds.cern.ch/record/1728332)
  - “Search for an Higgs Like resonance in the diphoton mass spectra above 150 GeV”
    [CMS-PAS-HIG-14-006](http://cds.cern.ch/record/1714076), [http://cds.cern.ch/record/1714076](http://cds.cern.ch/record/1714076)
  - “Search for H^+ → cs decay”
    [CMS-PAS-HIG-13-035](http://cds.cern.ch/record/1728343), [http://cds.cern.ch/record/1728343](http://cds.cern.ch/record/1728343)
High-mass diphoton searches

- Simplified cut-based selection.
- Signal model: double Crystal-Ball ⊗ Breit-Wigner.
  - Signal width and mean scale appropriately with $m_H$.
- Limits on $\sigma \times \text{BR}$ as a function of $\Gamma_X$ and $m_X$. 

![Graph showing limits on $\sigma \times \text{BR}$ as a function of $\Gamma_X$ and $m_X$.]
$H^+ \rightarrow cs$ in decays of $t \rightarrow H^+ + b$

2 jets + 2 b-tagged jets + lepton and MET.

Mass reconstructed using $m_W$ and $m_t$ constraints and likelihood fit.
More turned stones

- MSSM $\Phi \rightarrow b\bar{b}$
  PLB 722 (2013) 207

- MSSM $\Phi \rightarrow \mu\mu$
  CMS-PAS-HIG-12-011,
  [http://cds.cern.ch/record/1453716](http://cds.cern.ch/record/1453716)

- NMSSM $H \rightarrow 4\mu + X$ short-lived
  CMS-PAS-HIG-13-010,
  [http://cds.cern.ch/record/1563546](http://cds.cern.ch/record/1563546)
For discussion
CMS ECAL operation and calibration

The path towards the ultimate Run 1 photon energy determination.
Challenges of *in situ* operations

**Light yield variations:**
- scintillation light $\rightarrow$ temperature dependence: $\Delta S/S \sim -2\%/^\circ C$ @ 18 $^\circ C$
- crystal transparency $\rightarrow$ radiation dose-rate dependence

**Photo-detector response:**
- gain temperature dependence: $\Delta G/G \sim -2\%/^\circ C$
- APD $\rightarrow$ gain High-Voltage dependence: $\Delta G/G \sim 3\%/V$
- direct ionization effects, a.k.a. “spikes”
- VPT $\rightarrow$ response dependence on the incremental charge at the cathode

**Tracker material in front of ECAL:**
- photon conversions
- bremsstrahlung losses for electrons

**3.8 T solenoidal magnetic field:**
- spread of the $e, \gamma$ energy along $\varphi$, at $\approx$ constant $\eta$

$\rightarrow$ **Excellent environmental stability** ($\times 2$ to $\times 3$ better than required) [3]
$\rightarrow$ **Dedicated monitoring system and calibration techniques** [4, 5]
$\rightarrow$ **Specific energy reconstruction algorithms and corrections**
Monitoring and calibration signals

Laser monitoring measurements

Validation of the corrections with $E/p$

Inter-calibration precision

[F. De Guio’s talk]
Derive individual corrections \textit{in situ} by equalising the response to diphoton resonances ($\eta$, $\pi^0$).

- Cross check using $\phi$ invariance of energy flow.
- And $E/p$ ratio for electrons.

Effect of inter-calibration (IC) and light monitoring (LM) corrections:
Performance: energy resolution

With electrons from $Z$

CMS 2012 preliminary: $L = 19.5 \text{ fb}^{-1}$, $\sqrt{s} = 8\text{ TeV}$

- Prompt reconstruction, $R_{\eta} \geq 0.94$
- Winter2013 re-construction, $R_{\eta} \geq 0.94$
- MC, $R_{\eta} \geq 0.94$

CMS 2012 preliminary: $L = 19.5 \text{ fb}^{-1}$, $\sqrt{s} = 8\text{ TeV}$

- Prompt reconstruction, inclusive
- Winter2013 re-construction, inclusive
- MC, inclusive

↑ Fit to $Z \rightarrow ee$ of a Breit-Wigner convolved with a Gaussian function [4]

→ Simulation tuned to match performance observed in situ with $Z \rightarrow ee$ events

19.7 fb$^{-1}$ (6 TeV)

CMS
Barrel-Barrel

Data: $Z \rightarrow ee$ (MC)

CMS
Not Barrel-Barrel

Data: $Z \rightarrow ee$ (MC)
Accurate simulation

Noise model:
- realistic noise with sample-correlations and channel-to-channel variations
- increase of the APD dark current (expected)
- transparency variations for realistic light-yield (and corresponding photo-statistics)

Material description:
- including in-homogeneities in $\varphi$ of services in front of the endcaps
- for systematic uncertainties, being implemented in current simulation

Light propagation effects in the crystals (only relevant for upgrade studies)

Varying conditions used for a “run-dependent” simulation [N. Marinelli’s talk]
Performance evolution

- The energy resolution measured in data with $Z \rightarrow ee$ is used to model the expected $H \rightarrow \gamma\gamma$ signal in the simulation
- Steady progress and excellent results

PROMPT reconstruction within 48h from data taking

RECONSTRUCTION with improved conditions
ECAL-related systematic uncertainties on $m_H$

From $H \rightarrow \gamma \gamma$:

$$m_H = 124.70 \pm 0.31{\text{(stat)}} \pm 0.15{\text{(syst)}} \text{ GeV}$$

- Electron/photon differences in the simulation .................. 0.10 GeV
  - material distribution ........................................ 0.07 GeV
  - longitudinal light-yield non-uniformity .................. 0.02 GeV
  - Geant4 .................................................. 0.06 GeV

  * uncertainty on the single contribution: $\approx 10$ MeV

N.B.: the detector response to electrons and photons shows differences at the level of 0.5%. What matters is the difference of these differences between data and simulation.

- Residual non-linearity in scale .......................... 0.10 GeV

- Photon energy scale corrections ................................ 0.05 GeV

- $Z$ line shape ............................................. 0.01 GeV

- Checked and negligible contribution: gain switch of the electronics
More detail: residual non-linearity in scale

Residual non-linearity of the energy response in data relative to simulation, relevant in the extrapolation from the energy scale measured at the $Z$ peak ($\approx 90$ GeV) to the Higgs boson mass ($\approx 125$ GeV)

1. electron $E/p$ vs. $E_T$ with electrons from $Z$ and $W$ decays
2. di-electron invariant mass vs. $H_T = E_T^1 + E_T^2$ in $Z \rightarrow ee$ events

0.08% effect on the Higgs boson mass
More detail: longitudinal non-uniformity (NUF)

- **R&D achievements:** adequate uniformity of longitudinal light yield
  - one face of each barrel crystal depolished

- Simulation: rear non-uniformity of 0.15%, front part assumed uniform
- Ionizing radiation found to induce additional NUF of 30% of its initial value (worst case scenario) at the end of Run1 [6]
  → simulation modified to account for these effects

- at most **0.06% effect on the energy scale**, anti-correlated between converted and un-converted photons → **0.015% effect on the mass**
Final Run 1 $H \rightarrow \gamma\gamma$ analysis details
Use the raw supercluster energy and several other input variables
- To model shower shape, position etc. (label inputs as $x$)
- Correct for local containment of showers, bremsstrahlung losses, etc.

Use specialised BDT (not TMVA) to predict full probability distribution for $E_{\text{true}}/E_{\text{raw}}$
- Distribution is given by a double CB which has six free params ($\mu$, $\sigma$, $\alpha_L$, $\alpha_R$, $n_L$, $n_R$)
- “Regress” the non-parametric dependence of each of these variables on the BDT input variables whilst minimising the likelihood,

$$-\ln L = - \sum_{MC\text{photons}} \ln p(E_{\text{true}}/E_{\text{raw}} | \mu(x), \sigma(x), \alpha_L(x), \alpha_R(x), n_L(x), n_R(x))$$

Best estimate for the true energy:
$$E(\bar{x}, E_{\text{raw}}) = \mu(\bar{x}) E_{\text{raw}}$$

Per photon energy resolution:
$$\frac{\sigma_E(\bar{x}, E_{\text{raw}})}{E(\bar{x}, E_{\text{raw}})} = \frac{\sigma(\bar{x})}{\mu(\bar{x})}$$
H→γγ – energy scale and resolution corrections

- Apply residual scale corrections to the data and subsequent smearings to the MC
- Resolve differences between data and MC from Z→ee decays (with electrons reconstructed as photons)
- Employ a new multistep procedure:
  - Split data and MC into 59 run ranges, 4 η bins and 2 R_9 bins.
  - Fit Z line shape and find scale correction from data→MC in run × |η| bins.
  - Simultaneously fit scale with a Gaussian smearing term for MC in |η| × R_9.
    - In the barrel (for 8 TeV) the smearing term has an energy dependence by parameterisation through: $b/\sqrt{E_T} + c$
  - Then have a further residual scale correction in $E_T × |\eta| × R_9$. 

![Graph showing E-scale correction against E_T (GeV)](image-url)
 Corrections have uncertainties which enter the analysis as a systematic uncertainties.
Evolution of $m_{\gamma\gamma}$ resolution

7 TeV: 25% improvement in the first year

8 TeV: 20% improvement in the last year


FWHM = 4.23 GeV $\rightarrow$ 3.18 GeV $\rightarrow$ 3.15 GeV

7 TeV: 25% improvement in the first year

8 TeV: 20% improvement in the last year
Use a BDT to reject photon fakes. (mainly $\pi^0$)
- Uses shower shape & isolation variables.

Provides estimate of the per-photon quality.
Photon ID output (including systematic band) for $Z \rightarrow ee$ events.

![Graphs showing Photon ID output and Data/MC comparison for $N_{vtx} \leq 15$ and $N_{vtx} > 15$.](image)
Resolution on opening angle has negligible effect iff selected vertex is within 10 mm of true position.

Use a BDT to select vertex. Input variables designed to consider:
- Hardness of interactions (sum $p_T$).
- Recoil and asymmetry between the diphoton system and other tracks from the given vertex.
- Converted photon track information.

Test performance in $Z \rightarrow \mu\mu$ events (remove $\mu$ tracks and re-reco vertices) and also $\gamma$+jet events.

Construct BDT to complement resolution estimate whose output definition will map correct vertex efficiency (probability).

Exploit this information later when estimating the per event resolution.
Performance in $Z \rightarrow \mu\mu$ events.
Remove $\mu$ tracks and redo vertex reconstruction.
Event classifier which collapses event information into one discriminant.

- Assigns a high score to events with:
  - Signal-like kinematics. (mainly high $p_T^{\gamma\gamma}$)
  - Good diphoton mass resolution (i.e. good photon resolution and high vertex probability)
  - High photon quality.
- Independent of mass.

Place a cut on classifier value to cut out background.

- Categorise events using bins in the classifier value
- Use this as input to a further BDT which focuses on VBF di-jet + di-photon selection.
**H → γγ – diphoton MVA score**

- Classifier output is validated with Z → ee.
- Define systematics for shape distortions that affect categorisation: photon ID quality and energy resolution estimate.

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19.7 fb⁻¹ (8 TeV)

**CMS**

- Data
- Z → e⁺e⁻ (MC)
- MC cluster shape uncertainty

---

Data/MC

Transformed diphoton BDT classifier score
Use dijet variables to pick out VBF-like topology.

Use output to define a set of dijet categories.

Optimized for VBF signal strength alone.

Dijet Tag 0

Dijet Tag 2

Dijet Tag 1

Untagged

\( H \rightarrow \gamma \gamma \rightarrow \text{diphoton dijet MVA score} \)
**H → γγ event category selection**

<table>
<thead>
<tr>
<th>Label</th>
<th>No. of classes</th>
<th>Main requirements</th>
</tr>
</thead>
</table>
| ttH lepton tag         | 1              | \( p_T^\gamma(1) > m_{\gamma\gamma}/2 \)  
|                        |                | 1 b-tagged jet + 1 electron or muon |
| VH tight \( \ell \) tag| 1              | \( p_T^\gamma(1) > 3 \cdot m_{\gamma\gamma}/8 \)  
|                        | 1              | e or \( \mu \), \( p_T > 20 \) GeV, and \( \not{E}_T > 45 \) GeV OR  
|                        |                | 2e or 2\( \mu \), \( p_T > 10 \) GeV; 70 < \( m_{\ell\ell} \) < 110 GeV |
| VH loose \( \ell \) tag| 1              | \( p_T^\gamma(1) > 3 \cdot m_{\gamma\gamma}/8 \)  
|                        | 1              | e or \( \mu \), \( p_T > 20 \) GeV |
| VBF dijet tag 0-2      | 3              | \( p_T^\gamma(1) > m_{\gamma\gamma}/2 \)  
|                        | 2              | 2 jets; dijet and combined diphoton-dijet BDTs used |
| VH \( \not{E}_T \) tag | 1              | \( p_T^\gamma(1) > 3 \cdot m_{\gamma\gamma}/8 \)  
|                        | 1              | \( \not{E}_T > 70 \) GeV |
| ttH multijet tag       | 1              | \( p_T^\gamma(1) > m_{\gamma\gamma}/2 \)  
|                        |                | 1 b-tagged jet + 4 more jets |
| VH dijet tag           | 1              | \( p_T^\gamma(1) > 3 \cdot m_{\gamma\gamma}/8 \)  
|                        | 1              | jet pair, \( p_T > 40 \) GeV and 60 < \( m_{jj} \) < 120 GeV |
| Untagged 0-4           | 5              | The remaining events,  
|                        | 4              | classified using diphoton BDT |

* For the 7 TeV dataset, events in the ttH lepton tag and multijet tag classes are selected first, and combined to form a single event class.
H → γγ event categories

CMS Unpublished

- Untagged 0: 5.8 total expected signal
- Untagged 1: 22.7 total expected signal
- Untagged 2: 27.1 total expected signal
- Untagged 3: 34.1 total expected signal
- VBF Dijet Tag 0: 1.6 total expected signal
- VBF Dijet Tag 1: 3.8 total expected signal
- VH Lepton Tight: 0.3 total expected signal
- VH Lepton Loose: 0.2 total expected signal
- VH MET Tag: 0.3 total expected signal
- VH Dijet Tag: 0.4 total expected signal
- tH Tags: 0.5 total expected signal
- Combined: 0.6 total expected signal

5.1 fb⁻¹ (7 TeV)

- Width (GeV)
- S/(S+B) in ± σeff
**CMS Unpublished**

<table>
<thead>
<tr>
<th>Event Category</th>
<th>Signal Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untagged 0</td>
<td>6.0 total expected signal</td>
</tr>
<tr>
<td>Untagged 1</td>
<td>50.8 total expected signal</td>
</tr>
<tr>
<td>Untagged 2</td>
<td>117.2 total expected signal</td>
</tr>
<tr>
<td>Untagged 3</td>
<td>153.4 total expected signal</td>
</tr>
<tr>
<td>Untagged 4</td>
<td>121.4 total expected signal</td>
</tr>
<tr>
<td>VBF Dijet Tag 0</td>
<td>4.5 total expected signal</td>
</tr>
<tr>
<td>VBF Dijet Tag 1</td>
<td>5.6 total expected signal</td>
</tr>
<tr>
<td>VBF Dijet Tag 2</td>
<td>13.7 total expected signal</td>
</tr>
<tr>
<td>VH Lepton Tight</td>
<td>1.4 total expected signal</td>
</tr>
<tr>
<td>VH Lepton Loose</td>
<td>0.9 total expected signal</td>
</tr>
<tr>
<td>VH MET Tag</td>
<td>1.8 total expected signal</td>
</tr>
<tr>
<td>VH Dijet Tag</td>
<td>1.6 total expected signal</td>
</tr>
<tr>
<td>ttH Leptonic Tag</td>
<td>0.5 total expected signal</td>
</tr>
<tr>
<td>ttH Multijet Tag</td>
<td>0.6 total expected signal</td>
</tr>
<tr>
<td>Combined</td>
<td>479.0 total expected signal</td>
</tr>
</tbody>
</table>

**Width (GeV)**

- $\sigma_{eff}$
- FWHM/2.35

**S/(S+B) in $\pm \sigma_{eff}$**

- 19.7 fb$^{-1}$ (8 TeV)

---

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$H \rightarrow \gamma\gamma - A \times \varepsilon$

7 TeV
48.6%

8 TeV
49.3%

$\sigma_{1\sigma}$ fb$^{-1}$

CMS Unpublished

$\varepsilon \times A$

$\pm 1\sigma$ syst. error

$m_H$ (GeV)

[arXiv:1407.0558, submitted to EPJC]
H→γγ – MC comparison

[arXiv:1407.0558, submitted to EPJC]
Imagine a simple case with one POI, $x$, and one nuisance parameter, $\theta$:
- Black line – standard likelihood scan of $x$ profiling $\theta$
- Blue line – standard likelihood scan of $x$ freezing $\theta$ (stat. only)
- Red lines – standard likelihood scans of freezing $\theta$ to different values
- Pink line – Envelope around this

If you sample enough of the infinite $\theta$ phase-space eventually you can reproduce the black curve with the pink “envelope”.

- $\gamma\gamma \rightarrow BG$ estimation
Consider a toy example with
- One single category.
- Two function choices, $e^{-\mu m}$ and $m^{-\mu}$, both with 1 free parameter.

Profile “envelope” best fit is for $m^{-\mu}$.
- But 2σ interval is enlarged by the envelope.

Envelope method can only increase uncertainty.
In principle would like to sample the “infinite” phase space of all possible functions.

In practice this is impossible.

Instead, choose from four classes which we expect can reasonably cover the phase-space:

- Power law sum.
- Exponential sum.
- Laurent series.
- Bernstein polynomials.

Lowest order selected by loose G.O.F test.

Highest order selected by loose variant of the F-test.
3 alternative analyses:
- Check validity of MVA selection, categorisation, background model and VBF selection.
- All compatible at < 1σ level.
- Compatibility with preliminary result:
  - Using jackknife techniques to estimate correlations <2σ.
- Compatibility between 7 TeV and 8 TeV datasets:
  - At the level of 2σ.
- Compatibility across categories shown on right.

\( \hat{\mu} \text{ combined} = 1.14^{+0.26}_{-0.23} \) [ \( m_H = 124.7 \text{ GeV} \)]
Jack-knife provides estimate of expected width, $\sigma(\delta\mu)$, between two correlated analyses using sub-samples of each dataset. Used Bernstein polynomial background model for simplicity.

<table>
<thead>
<tr>
<th>Analysis 1</th>
<th>Analysis 2</th>
<th>$\sigma(\delta\mu)$</th>
<th>$\delta\mu$ (obs)</th>
<th>Linear correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final MVA 8 TeV</td>
<td>Final CiC 8 TeV</td>
<td>0.20</td>
<td>0.19</td>
<td>74%</td>
</tr>
<tr>
<td>Final MVA 7 TeV</td>
<td>Final CiC 7 TeV</td>
<td>0.42</td>
<td>0.17</td>
<td>72%</td>
</tr>
<tr>
<td>Final MVA 8 TeV</td>
<td>Moriond MVA 8 TeV</td>
<td>0.21</td>
<td>0.22</td>
<td>71%</td>
</tr>
<tr>
<td>Final CiC 8 TeV</td>
<td>Moriond CiC 8 TeV</td>
<td>0.21</td>
<td>0.03</td>
<td>76%</td>
</tr>
<tr>
<td>Final MVA (Envelope) 8 TeV</td>
<td>Final MVA (Bernsteins) 8 TeV</td>
<td>0.22</td>
<td>0.35</td>
<td>-</td>
</tr>
</tbody>
</table>
H → γγ – all selected events

CMS

Sum over all classes

Data
S+B fits (sum)
B component
±1σ
±2σ

B component subtracted

19.7 fb^{-1} (8 TeV) + 5.1 fb^{-1} (7 TeV)

Events / GeV

Events / GeV

m_{γγ} (GeV)

100 110 120 130 140 150 160 170 180

-200 0 200

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More on the combination
The challenge of combining

- Include five main decays and searches for $ttH$ production.
- 207 channels.
- 2519 parameters.
- 219 $H\to\gamma\gamma$ background parameters.

<table>
<thead>
<tr>
<th>Decay tag and production tag</th>
<th>Expected signal composition</th>
<th>$\sigma_{\text{int}}/\sigma_{\text{WH}}$</th>
<th>Luminosity (fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to \gamma\gamma$ [20], Section 2.1</td>
<td>Untagged</td>
<td>76-93% ggH</td>
<td>0.8-2.1%</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>2-jet VBF</td>
<td>50-80% VBF</td>
<td>1.0-1.3%</td>
</tr>
<tr>
<td></td>
<td>Leptonic VH</td>
<td>$\geq95%$ VH (WH/ZH = 5)</td>
<td>1.3%</td>
</tr>
<tr>
<td></td>
<td>2-jet VH</td>
<td>$\geq65%$ VH (WH/ZH = 1)</td>
<td>1.3%</td>
</tr>
<tr>
<td></td>
<td>Leptonic tH</td>
<td>$\geq95%$ tH</td>
<td>1.1%</td>
</tr>
<tr>
<td></td>
<td>Multijet tH</td>
<td>$&gt;90%$ tH</td>
<td>1.1%</td>
</tr>
</tbody>
</table>

- $H \to ZZ\rightarrow 4\ell$ [18], Section 2.2
  - 4 jets: $e^+e^-, \mu^+\mu^-$
  - 207 channels.
  - 2519 parameters.

- $H \to WW\rightarrow 4\ell\ell$ [17], Section 2.3
  - 3/3e WH
  - $\ell\ell + \tau^\pm\tau^\mp ZH$
  - Include $5%_{\text{THEO}}\%$ $Z\rightarrow\ell\ell$ parametrization.

- $H \to tt$ [19], Section 2.4
  - 4.9 | 19.7

- $H \to bb$ [16], Section 2.5
  - $W(\tau)V$ bins
  - $p_T(\tau)\text{bins}$

- $tH$ with hadrons [14, 28], Section 2.6
  - $H \to tt$ leptons+jets
  - $H \to \tau_{\text{had}}$ leptons+jets

- $tH$ with leptons [29], Section 2.6
  - 2FSS
  - $3\ell$
Combined $m_H$ measurement
Combined $m_H$ measurement

- Opposite sign from ATLAS.

$\Delta m_{H}^{\gamma\gamma} - m_{H}^{4\ell} = -0.87^{+0.54}_{-0.59} \text{ GeV}$

1.6σ
Extra Higgs sensitivity in $H \rightarrow \tau\tau$ analysis

- $H \rightarrow \tau\tau$ analysis has sensitivity to:
  - $H \rightarrow \tau\tau$ decays, and
  - $H \rightarrow WW$ decays.

- $H \rightarrow WW$ treatment:
  - In combination: signal.
    - $3.9\sigma$ obs. ($3.9\sigma$ exp.)
  - In $H \rightarrow \tau\tau$ paper: SM background.
    - $3.2\sigma$ obs. ($3.7\sigma$ exp.)
What changed?

- BR(H → VV) changes by 4 – 5%.
  - H → WW and H → ZZ paper results evaluated at H → ZZ $m_H$ result: $m_H = 125.6$ GeV.
  - Combined mass slightly lower: $m_H = 125.0$ GeV.
- In the combination H → WW includes the ttH, H decaying to multi-lepton result: $\sigma/\sigma_{SM} = 3.7 \pm 1.5$.

<table>
<thead>
<tr>
<th>$\sigma/\sigma_{SM}$</th>
<th>Individual publication</th>
<th>Combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>H → ZZ</td>
<td>0.93</td>
<td>1.00</td>
</tr>
<tr>
<td>H → WW</td>
<td>0.72</td>
<td>0.83</td>
</tr>
</tbody>
</table>
Very extensive cross-checks performed:
http://cern.ch/go/Xv8S
## Significance of excesses

<table>
<thead>
<tr>
<th>Channel grouping</th>
<th>Significance (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
</tr>
<tr>
<td>H → ZZ tagged</td>
<td>6.5</td>
</tr>
<tr>
<td>H → γγ tagged</td>
<td>5.6</td>
</tr>
<tr>
<td>H → WW tagged</td>
<td>4.7</td>
</tr>
<tr>
<td><strong>Grouped as in Ref. [17]</strong></td>
<td>4.3</td>
</tr>
<tr>
<td>H → ττ tagged</td>
<td>3.8</td>
</tr>
<tr>
<td><strong>Grouped as in Ref. [19]</strong></td>
<td>3.9</td>
</tr>
<tr>
<td>H → bb tagged</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>Grouped as in Ref. [16]</strong></td>
<td>2.1</td>
</tr>
</tbody>
</table>
Combined production measurement

<table>
<thead>
<tr>
<th>Channel grouping</th>
<th>Best fit ($\mu_{ggH,ttH}, \mu_{VBF,VH}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow ZZ$ tagged</td>
<td>(0.88, 1.75)</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$ tagged</td>
<td>(1.07, 1.24)</td>
</tr>
<tr>
<td>$H \rightarrow WW$ tagged</td>
<td>(0.87, 0.66)</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$ tagged</td>
<td>(0.52, 1.21)</td>
</tr>
<tr>
<td>$H \rightarrow bb$ tagged</td>
<td>(0.57, 0.96)</td>
</tr>
</tbody>
</table>

Combined best fit $\mu_{VBF,VH}/\mu_{ggH,ttH}$

Observed (expected)

$1.25^{+0.63}_{-0.45} (1.00^{+0.49}_{-0.35})$
Production mode scaling assuming SM BR structure

\[ \mu_{ggH} = 0.85^{+0.11}_{-0.09} \text{ (stat.)}^{+0.11}_{-0.08} \text{ (theo.)}^{+0.10}_{-0.09} \text{ (syst.)} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best fit result (68% CL) for full combination</th>
<th>Observed significance ((\sigma))</th>
<th>Expected sensitivity ((\sigma))</th>
<th>Pull to SM hypothesis ((\sigma))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mu_{ggH})</td>
<td>0.85^{+0.19}_{-0.17}</td>
<td>6.5</td>
<td>7.5</td>
<td>-0.8</td>
</tr>
<tr>
<td>(\mu_{VBF})</td>
<td>1.15^{+0.37}_{-0.35}</td>
<td>3.6</td>
<td>3.3</td>
<td>0.4</td>
</tr>
<tr>
<td>(\mu_{VH})</td>
<td>1.00^{+0.40}_{-0.40}</td>
<td>2.7</td>
<td>2.7</td>
<td>0.0</td>
</tr>
<tr>
<td>(\mu_{tH})</td>
<td>2.93^{+1.04}_{-0.97}</td>
<td>3.5</td>
<td>1.2</td>
<td>2.1</td>
</tr>
</tbody>
</table>

CMS Preliminary

19.7 fb^{-1} (8 TeV) + 5.1 fb^{-1} (7 TeV)

Parameter value

\(\mu_{ggH}\)
\(\mu_{VBF}\)
\(\mu_{VH}\)
\(\mu_{ttH}\)
Coupling deviations

- Scaling the couplings to fermions \((\kappa_f)\) and vector bosons \((\kappa_V)\).

- Interference in \(H \rightarrow \gamma\gamma\) decay resolves degeneracy.
Coupling deviations summaries

- 6 or 7 parameter fits with effective loops.
- $\text{BR}_{\text{BSM}}$ measured assuming $\kappa_V \leq 1$:
  - $\text{BR}_{\text{BSM}} < 0.34$ (95% CL)

[Graph showing CMS Preliminary results for $\kappa_V$, $\kappa_b$, $\kappa_\tau$, $\kappa_g$, $\kappa_\gamma$, and $\text{BR}_{\text{BSM}}$ with observed and expected values for SM Higgs.

19.7 fb$^{-1}$ (8 TeV) + 5.1 fb$^{-1}$ (7 TeV)
## Coupling deviations

<table>
<thead>
<tr>
<th>Model Parameters</th>
<th>Table in Ref. [27]</th>
<th>Best-fit result</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_Z, \lambda_{WZ}$ ($\kappa_f = 1$)</td>
<td>-</td>
<td>$\lambda_{WZ} = 0.94^{+0.22}_{-0.18}$ [0.61,1.45]</td>
<td>$\lambda_{WZ} = \kappa_W/\kappa_Z$ using ZZ and 0/1-jet WW channels.</td>
</tr>
<tr>
<td>$\kappa_Z, \lambda_{WZ}, \kappa_f$</td>
<td>44 (top)</td>
<td>$\lambda_{WZ} = 0.91^{+0.14}_{-0.12}$ [0.70,1.22]</td>
<td>$\lambda_{WZ} = \kappa_W/\kappa_Z$ from full combination.</td>
</tr>
<tr>
<td>$\kappa_V, \kappa_f$</td>
<td>43 (top)</td>
<td>$\kappa_V = 1.01^{+0.07}_{-0.07}$ [0.88,1.15]</td>
<td>$\kappa_V$ scales couplings to W and Z bosons.</td>
</tr>
<tr>
<td>$\kappa_f$</td>
<td></td>
<td>$\kappa_f = 0.89^{+0.14}_{-0.13}$ [0.64,1.16]</td>
<td>$\kappa_f$ scales couplings to all fermions.</td>
</tr>
<tr>
<td>$\kappa_g, \kappa_\gamma$</td>
<td>48 (top)</td>
<td>$\kappa_g = 0.89^{+0.10}_{-0.10}$ [0.69,1.10]</td>
<td>Effective couplings to gluons (g) and photons ($\gamma$).</td>
</tr>
<tr>
<td>$\kappa_g, \kappa_\gamma, \text{BR}_{BSM}$</td>
<td>48 (middle)</td>
<td>$\kappa_\gamma = 1.15^{+0.13}_{-0.13}$ [0.89,1.42]</td>
<td>Branching fraction for BSM decays.</td>
</tr>
<tr>
<td>$\kappa_V, \lambda_{d_u}, \kappa_u$</td>
<td>46 (top)</td>
<td>$\lambda_{d_u} = 1.01^{+0.20}_{-0.19}$ [0.66,1.43]</td>
<td>$\lambda_{d_u} = \kappa_u/\kappa_d$, relating up-type and down-type fermions.</td>
</tr>
<tr>
<td>$\kappa_V, \lambda_{\ell_q}, \kappa_q$</td>
<td>47 (top)</td>
<td>$\lambda_{\ell_q} = 1.02^{+0.22}_{-0.21}$ [0.61,1.49]</td>
<td>$\lambda_{\ell_q} = \kappa_\ell/\kappa_q$, relating leptons and quarks.</td>
</tr>
<tr>
<td>$\kappa_g, \kappa_\gamma, \kappa_V$, $\kappa_B, \kappa_\tau, \kappa_t$</td>
<td>Similar to 50 (top)</td>
<td>$\kappa_g = 0.76^{+0.15}_{-0.13}$ [0.51,1.09]</td>
<td>Down-type quarks (via b).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\kappa_\gamma = 0.99^{+0.18}_{-0.17}$ [0.66,1.37]</td>
<td>Charged leptons (via $\tau$).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\kappa_V = 0.97^{+0.15}_{-0.16}$ [0.64,1.26]</td>
<td>Up-type quarks (via t).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\kappa_B = 0.67^{+0.31}_{-0.32}$ [0.00,1.31]</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\kappa_\tau = 0.83^{+0.19}_{-0.18}$ [0.48,1.22]</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\kappa_t = 1.61^{+0.33}_{-0.32}$ [0.97,2.28]</td>
<td></td>
</tr>
<tr>
<td>as above plus BR$_{BSM}$ and $\kappa_V \leq 1$</td>
<td>-</td>
<td>BR$_{BSM} \leq 0.34$ [0.00,0.58]</td>
<td></td>
</tr>
</tbody>
</table>
Assuming no BSM particles.
Resolving SM contributions

- Individual coupling scaling factors:
  - $\kappa_W$, $\kappa_Z$, $\kappa_b$, $\kappa_t$, $\kappa_\tau$.
  - All loops resolved:
    - $\gamma_k(W, t)$
    - $\gamma_k(t, b)$
  - SMH width scaled.

- “Reduced” couplings as function of “mass”:
  - $\lambda_f = \kappa_f (m_f/\text{vev})$
  - $(g\sqrt{2\text{vev}})^{1/2} = \kappa_V^{1/2}$
    - $(m_V/\text{vev})$
Vev modifier and power of coupling to mass:

- **Gauge bosons:**
  \[ k_V = \text{vev} \times m_V^2 \varepsilon / M^{1+2 \varepsilon} \]

- **Fermions:**
  \[ k_f = \text{vev} \times m_f \varepsilon / M^{1+\varepsilon} \]

For SMH, \( M = \text{vev} = 246.22 \text{ GeV} \) and \( \varepsilon = 0 \).
Parameterization in terms of cross-section fractions:

\[ f_{a3} = \frac{|a_3|^2 \sigma_3}{|a_1|^2 \sigma_1 + |a_2|^2 \sigma_2 + |a_3|^2 \sigma_3 + \bar{\sigma}_{\Lambda_1} / (\Lambda_1)^4} \]  \[ \phi_{a3} = \arg \left( \frac{a_3}{a_1} \right) \]

\[ f_{a2} = \frac{|a_2|^2 \sigma_2}{|a_1|^2 \sigma_1 + |a_2|^2 \sigma_2 + |a_3|^2 \sigma_3 + \bar{\sigma}_{\Lambda_1} / (\Lambda_1)^4} \]  \[ \phi_{a2} = \arg \left( \frac{a_2}{a_1} \right) \]

\[ f_{\Lambda_1} = \frac{\bar{\sigma}_{\Lambda_1} / (\Lambda_1)^4}{|a_1|^2 \sigma_1 + |a_2|^2 \sigma_2 + |a_3|^2 \sigma_3 + \bar{\sigma}_{\Lambda_1} / (\Lambda_1)^4} \]  \[ \phi_{\Lambda_1} \]
Spin zero amplitude in $H \rightarrow ZZ \rightarrow 4\ell$

- Full final state available:
  - Kinematic discriminants reducing to 2D or 3D.
  - 8D likelihood fit.
- 2D scans of anomalous coupling fractions (real phases).
  - But also done profiling over the phases.
- No significant deviations from SM found.
H→ZZ→4ℓ – J=2 states

- Broad range of hypothesis tests based on the observables optimized for each case.
Broad range of hypothesis tests based on the observables used for the SM measurements.
H→VV combination on J>0 states

- Combination of H→WW→2ℓ2ν and H→ZZ→4ℓ.
- All tested hypotheses excluded at more than 99.9% CLs.
Direct searches
VBF and ZH topologies combined; $Z \rightarrow \ell \ell$ and $Z \rightarrow b \bar{b}$.

$\text{BR}(H \rightarrow \text{inv.}) < 0.58$ (0.44 exp.) at 95% CL
# Search for $H \rightarrow \mu \tau$

## Results

**CMS preliminary** | **19.7 fb$^{-1}$, $\sqrt{s} = 8$ TeV**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Observed</th>
<th>Expected $\pm 1\sigma$</th>
<th>Expected $\pm 2\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_\tau$, 0 Jets</td>
<td>×</td>
<td>●</td>
<td>X</td>
</tr>
<tr>
<td>$\mu_\tau$, 1 Jet</td>
<td>●</td>
<td>●</td>
<td>X</td>
</tr>
<tr>
<td>$\mu_\tau$, 2 Jets</td>
<td>●</td>
<td>●</td>
<td>X</td>
</tr>
<tr>
<td>$\mu_e$, 0 Jets</td>
<td>×</td>
<td>●</td>
<td>X</td>
</tr>
<tr>
<td>$\mu_e$, 1 Jet</td>
<td>●</td>
<td>●</td>
<td>X</td>
</tr>
<tr>
<td>$\mu_e$, 2 Jets</td>
<td>●</td>
<td>●</td>
<td>X</td>
</tr>
</tbody>
</table>

95% CL Limit on $\text{Br}(h \rightarrow \mu \tau)$, %

Best Fit to $\text{Br}(h \rightarrow \mu \tau)$, %

- **$\mu_\tau$, 0 Jets**
  - Observed: 0.72, $\pm 1.15\%$
  - Expected: $0.03, +1.07\%$ to $-1.12\%$
  - Expected $\pm 2\sigma$: $1.24, +1.09\%$ to $-0.88\%$

- **$\mu_\tau$, 1 Jet**
  - Observed: 1.24, $+0.66\%$ to $-0.62\%$
  - Expected: $0.81, +0.85\%$ to $-0.78\%$

- **$\mu_\tau$, 2 Jets**
  - Observed: 0.05, $+1.58\%$ to $-0.97\%$
  - Expected: $0.89, +0.40\%$ to $-0.37\%$

---

A. David@cern.ch  CMSexperiment@ICHEP2014
Search for $H \rightarrow \mu \tau$
New search for $ttH$ with $H \rightarrow bb$ 

- **Improved performance:**
  - Event probability ($P_{s/b}$) based on matrix element probabilities.
  - Single lepton (SL) and di-lepton (DL) topologies.
    - Best with identified $W \rightarrow jj$ (SL Cat-1).
  - Reduced dependency on $tt+HF$ modeling.

- Clearly a hot topic for Run 2.
Statistics
**Statistics interlude**

<table>
<thead>
<tr>
<th>Test statistic</th>
<th>Profiled?</th>
<th>Test statistic sampling</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_\mu = -2 \ln \frac{\mathcal{L}(\text{data}</td>
<td>\mu, \bar{\theta})}{\mathcal{L}(\text{data}</td>
<td>0, \bar{\theta})}$</td>
</tr>
<tr>
<td>$q_\mu = -2 \ln \frac{\mathcal{L}(\text{data}</td>
<td>\mu, \hat{\theta}_\mu)}{\mathcal{L}(\text{data}</td>
<td>0, \hat{\theta}_0)}$</td>
</tr>
<tr>
<td>$\tilde{q}_\mu = -2 \ln \frac{\mathcal{L}(\text{data}</td>
<td>\mu, \hat{\theta}_\mu)}{\mathcal{L}(\text{data}</td>
<td>\tilde{\mu}, \hat{\theta}_\mu)}$</td>
</tr>
</tbody>
</table>

- **LEP**: nuisances parameters ($\theta$) kept at nominal values (~).
- **Tevatron**: maximise likelihood against nuisances (^).
  - Denominator considers *background-only hypothesis* ($\mu=0$).
- **LHC**: frequentist profiled likelihood.
  - Denominator considers *global best-fit likelihood* with *floating signal strength*.
  - Nice asymptotic properties, savings in computational power.
Breaking down uncertainties

- Nuisances grouped into **stat**, **theo**, **other**.
  - **stat** includes $H \rightarrow \gamma \gamma$ background parameters.
  - **theo** includes QCD scales, PDF+$\alpha_s$, UEPS, and BR.
  - **syst** = **theo** $\cup$ **other**.

- Procedures:
  - **For** (stat)+(syst):
    - $\sigma_{all}$ from scan floating all nuisances.
    - $\sigma_{stat}$ from scan floating **stat** group only.
    - $\sigma_{syst} = \sigma_{all} \ominus \sigma_{stat}$.
  - **For** (stat)+(theo)+(other):
    - $\sigma_{all}$ from scan floating all nuisances.
    - $\sigma_{stat}$ from scan floating **stat** group only.
    - $\sigma_{stat+other}$ from scan floating **stat** and **other**.
    - $\sigma_{theo} = \sigma_{all} \ominus \sigma_{stat+other}$.
    - $\sigma_{other} = \sigma_{all} \ominus \sigma_{stat} \ominus \sigma_{theo}$. 
VH, $H \rightarrow b\bar{b}$ vignettes

- $2.1\sigma$ ($2.3\sigma$ exp.)
- $\sigma/\sigma_{SM} = 1.0 \pm 0.5$
H\rightarrow\tau\tau vignettes

- $3.2\sigma$ ($3.7\sigma$ exp.)
- $\sigma/\sigma_{SM} = 0.78 \pm 0.27$
Fermion decay combination vignette

- 3.8σ (4.4σ exp.)
- \( \sigma/\sigma_{SM} = 0.83 \pm 0.24 \)

**Fermion decay combination**

3.8σ obs. (4.4σ exp.)

Nature Physics, doi:10.1038/nphys3005
H$\rightarrow$WW vignettes

- $4.3\sigma$ ($5.8\sigma$ exp.)
- $\sigma/\sigma_{SM} = 0.72 \pm 0.19$

$H\rightarrow$WW (all channels)
$\sigma/\sigma_{SM} = 0.72^{+0.22}_{-0.18}$

$212\nu + 0/1$-jet
$\sigma/\sigma_{SM} = 0.74^{+0.22}_{-0.20}$

$212\nu + 2$-jets, VBF tag
$\sigma/\sigma_{SM} = 0.69^{+0.27}_{-0.46}$

$212\nu + 2$-jets, VH tag
$\sigma/\sigma_{SM} = 0.39^{+1.17}_{-1.37}$

$313\nu$, WH tag
$\sigma/\sigma_{SM} = 0.56^{+1.07}_{-0.63}$

$313\nu + 2$-jets ZH tag (not plotted)
$\sigma/\sigma_{SM} = 6.41^{+1.43}_{-0.38}$

Best fit for $\sigma/\sigma_{SM}$

$m_H = 125.6$ GeV

$4.9$ fb$^{-1}$ (7 TeV) + $19.4$ fb$^{-1}$ (8 TeV)
H→ZZ→4ℓ vignettes

- 6.8σ (6.7σ exp.)
- $m_H = 125.6 \pm 0.4$ (stat.) $\pm 0.2$ (syst.) GeV
- $\sigma/\sigma_{SM} = 0.93 \pm 0.25$ (stat.) $\pm 0.13$ (syst.)
Odds and ends
Off-shell – involved processes

Backgrounds

Strong interference

NNLO/LO k-factors depend on $m_{ZZ}$
[G. Passarino, arXiv:1312.2397]

Use the same k-factors for signal and gg continuum
[M. Bonvini et al., PRD 88 2013]

Signal

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**H^* – off-shell**

- Define \( r = \frac{\Gamma_H}{\Gamma_H^{SM}} \)

- On-mass-shell we have
  \[
  \sigma_{gg \to H \to ZZ}^{\text{on-peak}} = \frac{k_g^2 k_Z^2}{r} (\sigma \cdot B)^{\text{SM}}
  \]

- Off-mass-shell there is no \( r \):
  \[
  \frac{d\sigma_{gg \to H \to ZZ}^{\text{off-peak}}}{dm_{ZZ}} = \frac{k_g^2 k_Z^2}{r} \frac{d\sigma_{gg \to H \to ZZ}^{\text{off-peak,SM}}}{dm_{ZZ}}
  \]

- Can make inference on \( r \) from on- and off-shell assuming:
  - \( \mu_{\text{on-shell}} = \mu_{\text{off-shell}} \)
  - Only SM processes \( \rightarrow \) ZZ:
    - \( gg \rightarrow H^* \)
    - \( gg = |gg \rightarrow H^* + gg \rightarrow \text{non-H}|^2 \)
    - \( |gg \rightarrow H^*|^2 + |gg \rightarrow \text{non-H}|^2 \)
    - **Total** = \( gg + qq \)
A 2012 hit

Breakthrough of the Year, 2012

Every year, crowning one scientific achievement as Breakthrough of the Year is no easy task, and 2012 was no exception. The year saw leaps and bounds in physics, along with significant advances in genetics, engineering, and many other areas. In keeping with tradition, Science's editors and staff have selected a winner and nine runners-up, as well as highlighting the year's top news stories and areas to watch in 2013.

The Discovery of the Higgs Boson

A. Cho

Exotic particles made headlines again and again in 2012, making it no surprise that the breakthrough of the year is a big physics finding: confirmation of the existence of the Higgs boson. Hypothesized more than 40 years ago, the elusive particle completes the standard model of physics, and is arguably the key to the explanation of how other fundamental particles obtain mass. The only mystery that remains is whether its discovery marks a new dawn for particle physics or the final stretch of a field that has run its course.

Read more about the Higgs boson from the research teams at CERN.