Higgs Properties:
Mass, Width, Spin, Parity

CIPANP 2015
Sarah Demers (Yale University)
on behalf of the ATLAS & CMS Collaborations
The* Question of Run 2:

Is this the standard model Higgs?

*Note: Do Not use your jean’s waist and inseam size. Please measure as described.

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The* Question of Run 2: Is this the standard model Higgs?

And, of course, the question: What can the LHC access beyond the Higgs?

*Note: Do Not rely on measurements from only one experiment.

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*And, of course, the question: What can the LHC access beyond the Higgs?
Many People, Many Numbers, Little Time

- **Mass**
  - CMS + ATLAS: Combination: $\gamma\gamma$ and ZZ

- **Width**
  - CMS & ATLAS: Relative on- and off-shell ZZ, WW prod
  - Direct limit from mass

- **Spin & Parity**
  - CMS: Combined ZZ, WW and $\gamma\gamma$
  - ATLAS: Combined ZZ, WW and $\gamma\gamma$
Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments

10.1103/PhysRevLett.114.191803
Mass Distributions: ATLAS

Photon Measurement
Large irreducible background, many channels based on quality of photons reconstructed

ZZ\rightarrow 4l Measurement
Small statistics, challenging ZZ\ast background
Mass Distributions: CMS

Photon Measurement
Large irreducible background, many channels based on quality of photons reconstructed

ZZ→4l Measurement
Small statistics, challenging ZZ* background

![Graph showing CMS H→γγ mass distributions]

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

\[
\hat{\mu} = 1.14^{+0.26}_{-0.23}
\]

\[
\hat{m}_H = 124.70 \pm 0.34 \text{ GeV}
\]

![Graph showing ZZ→4l event distributions]

\(\sqrt{s} = 7 \text{ TeV}, L = 5.1 \text{ fb}^{-1}; \sqrt{s} = 8 \text{ TeV}, L = 19.7 \text{ fb}^{-1}\)
Mass Combination

$\text{ATLAS and CMS}$

$LHC$ Run 1

$\text{ATLAS } H \rightarrow \gamma \gamma$
$\text{CMS } H \rightarrow \gamma \gamma$

$\text{ATLAS } H \rightarrow ZZ \rightarrow 4l$

$\text{CMS } H \rightarrow ZZ \rightarrow 4l$

$\text{ATLAS+CMS } \gamma \gamma$

$\text{ATLAS+CMS } 4l$

$\text{ATLAS+CMS } \gamma \gamma + 4l$

$125.09 \pm 0.24 (\pm 0.21 \pm 0.11)$ GeV

$m_H \text{ [GeV]}$
Observed (solid bars) and Expected (empty bars) impact of nuisance parameters.
Width

Width Measurements: use mass distribution width

Constraints on the Higgs boson width from off-shell production and decay to Z-boson pairs, CMS
10.1016/j.physletb.2014.06.077

Determination of the off-shell Higgs boson signal strength in the high-mass ZZ and WW final states with the ATLAS detector
ATLAS Width Measurement

$H \rightarrow \gamma \gamma$: 95% Confidence Level upper limit on width of 5.0 GeV

uses observed width of mass peak assuming no interference with background processes.

$H \rightarrow ZZ$: 95% Confidence Level upper limit on width of 2.6 GeV

A 4–lepton mass is computed per event by convolving the estimated detector response for each lepton with the nonrelativistic Breit–Wigner function describing the generated Higgs mass line shape with no Z mass constraint applied.

Similar results from CMS
g^2_{ggH}: couplings of Higgs to gluons

g^2_{HZZ}: couplings of Higgs to Zs

\[ \frac{\sigma_{\text{on-shell}}}{\sigma_{\text{off-shell}}} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m_H \Gamma_H} \quad \text{and} \quad \frac{\sigma_{\text{on-shell}}}{\sigma_{\text{off-shell}}} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(2m_Z)^2} \]

CMS Technique: Measure ratio of on-shell (105.6 GeV – 140.6 GeV) to off-shell (> 220 GeV) H \rightarrow ZZ production to extract width

Use llll and llvv final states

ATLAS: Measure on- to off- shell ratio for H \rightarrow ZZ \rightarrow 4l and H \rightarrow ZZ \rightarrow 2l2\nu and H \rightarrow WW \rightarrow e\nu\mu\nu to place a limit on the ratio of the width to the SM width

Expected SM Value: \[ \Gamma_H^{\text{SM}} = 4.15 \text{ MeV} \]
$m_T^2 = \left( \sqrt{p_{T,2\ell}^2 + m_{2\ell}^2 + \sqrt{E_{T}^{\text{miss}}^2 + m_{2\ell}^2}} \right)^2 - \left( \vec{p}_{T,2\ell} + \vec{E}_{T}^{\text{miss}} \right)^2$

2011 + 2012 Data (CMS)

4l channel uses mass distribution

<table>
<thead>
<tr>
<th></th>
<th>4l</th>
<th>2\ell 2\nu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total gg ($\Gamma_H = \Gamma_H^{SM}$)</td>
<td>1.8 ± 0.3</td>
<td>9.6 ± 1.5</td>
</tr>
<tr>
<td>gg Signal component ($\Gamma_H = \Gamma_H^{SM}$)</td>
<td>1.3 ± 0.2</td>
<td>4.7 ± 0.6</td>
</tr>
<tr>
<td>gg Background component</td>
<td>2.3 ± 0.4</td>
<td>10.8 ± 1.7</td>
</tr>
<tr>
<td>Total gg ($\Gamma_H = 10 \times \Gamma_H^{SM}$)</td>
<td>9.9 ± 1.2</td>
<td>39.8 ± 5.2</td>
</tr>
<tr>
<td>Total VBF ($\Gamma_H = \Gamma_H^{SM}$)</td>
<td>0.23 ± 0.01</td>
<td>0.90 ± 0.05</td>
</tr>
<tr>
<td>VBF signal component ($\Gamma_H = \Gamma_H^{SM}$)</td>
<td>0.11 ± 0.01</td>
<td>0.32 ± 0.02</td>
</tr>
<tr>
<td>VBF background component</td>
<td>0.35 ± 0.02</td>
<td>1.22 ± 0.07</td>
</tr>
<tr>
<td>Total VBF ($\Gamma_H = 10 \times \Gamma_H^{SM}$)</td>
<td>0.77 ± 0.04</td>
<td>2.40 ± 0.14</td>
</tr>
<tr>
<td>qq background</td>
<td>9.3 ± 0.7</td>
<td>47.6 ± 4.0</td>
</tr>
<tr>
<td>Other backgrounds</td>
<td>0.05 ± 0.02</td>
<td>35.1 ± 4.2</td>
</tr>
<tr>
<td>Total expected ($\Gamma_H = \Gamma_H^{SM}$)</td>
<td>11.4 ± 0.8</td>
<td>93.2 ± 6.0</td>
</tr>
<tr>
<td>Total expected ($\Gamma_H = 10 \times \Gamma_H^{SM}$)</td>
<td>20.1 ± 1.4</td>
<td>124.9 ± 7.8</td>
</tr>
</tbody>
</table>

llvv channel uses $m_T$ only off-shell production studied
CMS: Zooming in to high mass tail

Matrix Element Likelihood approach (MELA)
For $WW$, define $R_8$ as

$$R_8 = \sqrt{m_{\ell\ell}^2 + (a \cdot m_T^{WW})^2}$$

where $a = 0.8$ and $R_8 (> 450 \text{ GeV})$ are optimized for off-shell production.

Mass of 4l system

Transverse mass for 2l2$\nu$
Results

**CMS**
Combined unbinned log likelihood fit upper limit:

\[
\Gamma_H < 22 \text{ MeV at a } 95\% \text{ CL} \\
(5.4 \text{ times the expected SM width})
\]

**ATLAS**
95% CL upper limit on \(\Gamma_H/\Gamma^{SM}_H\) in the range 4.5--7.5 (6.5--11.2)

observed (expected) 95% CL upper limit on the Higgs boson total width of 22.7 (33.0) MeV.
Spin & Parity

Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV, CMS

Combination of the Higgs Boson Spin and Parity Analyses of the Higgs Boson in the H\rightarrow ZZ\rightarrow llll, H\rightarrow WW\rightarrow l\nu l\nu, and H\rightarrow \gamma\gamma final states, ATLAS
http://cds.cern.ch/record/2002414
\[ A(HVV) \sim \left[ a_1^{VV} + \frac{\kappa_1^{VV} q_{v1}^2 + \kappa_2^{VV} q_{v2}^2}{(\Lambda_1^{VV})^2} \right] \left( m_{V1} e_{V1}^* e_{V2}^* + a_2^{VV} f_{\mu \nu}^{(1)} f^{(2), \mu \nu} + a_3^{VV} f_{\mu \nu}^{(1)} f^{(2), \mu \nu} \right) \]

### Phenomenology

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Anomalous Coupling</th>
<th>Coupling Phase</th>
<th>Effective Fraction</th>
<th>Translation Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>HZZ</td>
<td>(\Lambda_1)</td>
<td>(\phi_{\Lambda_1})</td>
<td>(f_{\Lambda_1})</td>
<td>(\sigma_1 / \sigma_{\Lambda_1} = 1.45 \times 10^4 \text{ TeV}^{-4})</td>
</tr>
<tr>
<td></td>
<td>(a_2)</td>
<td>(\phi_{a_2})</td>
<td>(f_{a_2})</td>
<td>(\sigma_1 / \sigma_2 = 2.68)</td>
</tr>
<tr>
<td></td>
<td>(a_3)</td>
<td>(\phi_{a_3})</td>
<td>(f_{a_3})</td>
<td>(\sigma_1 / \sigma_3 = 6.36)</td>
</tr>
<tr>
<td>HWW</td>
<td>(\Lambda_1^{WW})</td>
<td>(\phi_{\Lambda_1^{WW}})</td>
<td>(f_{\Lambda_1^{WW}})</td>
<td>(\sigma_1^{WW} / \sigma_{\Lambda_1^{WW}} = 1.87 \times 10^4 \text{ TeV}^{-4})</td>
</tr>
<tr>
<td></td>
<td>(a_2^{WW})</td>
<td>(\phi_{a_2^{WW}})</td>
<td>(f_{a_2^{WW}})</td>
<td>(\sigma_1^{WW} / \sigma_2^{WW} = 1.25)</td>
</tr>
<tr>
<td></td>
<td>(a_3^{WW})</td>
<td>(\phi_{a_3^{WW}})</td>
<td>(f_{a_3^{WW}})</td>
<td>(\sigma_1^{WW} / \sigma_3^{WW} = 3.01)</td>
</tr>
<tr>
<td></td>
<td>(\Lambda_1^{Z\gamma})</td>
<td>(\phi_{\Lambda_1^{Z\gamma}})</td>
<td>(f_{\Lambda_1^{Z\gamma}})</td>
<td>(\sigma_1^{Z\gamma} / \sigma_{\Lambda_1^{Z\gamma}} = 5.76 \times 10^3 \text{ TeV}^{-4})</td>
</tr>
<tr>
<td>HZ(\gamma)</td>
<td>(\Lambda_1^{Z\gamma})</td>
<td>(\phi_{\Lambda_1^{Z\gamma}})</td>
<td>(f_{\Lambda_1^{Z\gamma}})</td>
<td>(\sigma_1^{Z\gamma} / \sigma_{\Lambda_1^{Z\gamma}} = 22.4 \times 10^{-4})</td>
</tr>
<tr>
<td></td>
<td>(a_2^{Z\gamma})</td>
<td>(\phi_{a_2^{Z\gamma}})</td>
<td>(f_{a_2^{Z\gamma}})</td>
<td>(\sigma_1^{Z\gamma} / \sigma_2^{Z\gamma} = 27.2 \times 10^{-4})</td>
</tr>
<tr>
<td></td>
<td>(a_3^{Z\gamma})</td>
<td>(\phi_{a_3^{Z\gamma}})</td>
<td>(f_{a_3^{Z\gamma}})</td>
<td>(\sigma_1^{Z\gamma} / \sigma_3^{Z\gamma} = 28.8 \times 10^{-4})</td>
</tr>
<tr>
<td>H(\gamma)  (\gamma)</td>
<td>(\Lambda_1^{\gamma\gamma})</td>
<td>(\phi_{\Lambda_1^{\gamma\gamma}})</td>
<td>(f_{\Lambda_1^{\gamma\gamma}})</td>
<td>(\sigma_1^{\gamma\gamma} / \sigma_{\Lambda_1^{\gamma\gamma}} = 28.2 \times 10^{-4})</td>
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<tr>
<td></td>
<td>(a_2^{\gamma\gamma})</td>
<td>(\phi_{a_2^{\gamma\gamma}})</td>
<td>(f_{a_2^{\gamma\gamma}})</td>
<td>(\sigma_1^{\gamma\gamma} / \sigma_2^{\gamma\gamma} = 28.8 \times 10^{-4})</td>
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<td>(\phi_{a_3^{\gamma\gamma}})</td>
<td>(f_{a_3^{\gamma\gamma}})</td>
<td>(\sigma_1^{\gamma\gamma} / \sigma_3^{\gamma\gamma} = 28.8 \times 10^{-4})</td>
</tr>
</tbody>
</table>

\(\Lambda_1\): Scale of new physics at 1 TeV
Definitions of Observables
(Same angles for CMS and ATLAS)

In $X$ (Higgs) rest frame: $\theta^* \Phi_1$

In $V$ ($W$, $Z$ or $\gamma$) rest frame: $\theta_1 \theta_2 \Phi$

$H \rightarrow ZZ \rightarrow llll$
\[ \theta^* \theta_1 \theta_2 \Phi \Phi_1 m_{Z1} m_{Z2} m_4 \]

$H \rightarrow WW \rightarrow l\nu l\nu$
neutrinos lead to information loss, but the nature of the V-A coupling to $Ws$ gives pronounced kinematic effects: $m_{ll} m_T$

$H \rightarrow \gamma\gamma$
Only $\theta^*$ is accessible - isotropic for spin 0
H → ZZ → 4l

Mass: 4 lepton system  
Mass: on-shell Z candidate  
Mass: off-shell Z candidate

All plots but $m_{4l}$ have the requirement imposed that $121.5 \text{ GeV} < m_{4l} < 130.5 \text{ GeV}$
Analysis in categories of # of extra jets

0 jets shown above

1 jet shown below
CMS Combination: Exotic Spin 1 and Spin 2 Models

signal strength floated to fit data

<table>
<thead>
<tr>
<th>$J^P$ Model</th>
<th>$J^P$ Prod.</th>
<th>Expected $X \rightarrow ZZ$</th>
<th>Expected $X \rightarrow WW$</th>
<th>Expected $X \rightarrow \gamma\gamma$</th>
<th>Expected $(\mu=1)$</th>
<th>Obs. $0^+$</th>
<th>Obs. $J^P$</th>
<th>CL$_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2^+_m$</td>
<td>$gg$</td>
<td>1.9$\sigma$</td>
<td>1.8$\sigma$</td>
<td>1.6$\sigma$</td>
<td>3.0$\sigma$ (3.7$\sigma$)</td>
<td>$-0.2\sigma$</td>
<td>$+3.3\sigma$</td>
<td>0.13%</td>
</tr>
<tr>
<td>$2^+_m$</td>
<td>$q\bar{q}$</td>
<td>1.7$\sigma$</td>
<td>2.7$\sigma$</td>
<td>1.2$\sigma$</td>
<td>3.3$\sigma$ (4.4$\sigma$)</td>
<td>$-0.9\sigma$</td>
<td>$+4.7\sigma$</td>
<td>0.001%</td>
</tr>
</tbody>
</table>
### CMS Results:
**Study of Spin 0 HVV Couplings**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Observed</th>
<th>Expected</th>
<th>$f_{ai}^{\text{VV}} = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{\Lambda 1} \cos(\phi_{\Lambda 1})$</td>
<td>$0.22^{+0.10}_{-0.16}$ $[-0.25, 0.37]$</td>
<td>$0.00^{+0.16}_{-0.87}$ $[-1.00, 0.27]$ $\cup [0.92, 1.00]$</td>
<td>$1.1% (16%)$</td>
</tr>
<tr>
<td>$f_{a 2} \cos(\phi_{a 2})$</td>
<td>$0.00^{+0.41}_{-0.06}$ $[-0.66, -0.57]$ $\cup [-0.15, 1.00]$</td>
<td>$0.00^{+0.38}_{-0.08}$ $[-0.18, 1.00]$</td>
<td>$5.2% (5.0%)$</td>
</tr>
<tr>
<td>$f_{a 3} \cos(\phi_{a 3})$</td>
<td>$0.00^{+0.14}_{-0.11}$ $[-0.40, 0.43]$ $\cup [-0.15, 1.00]$</td>
<td>$0.00^{+0.33}_{-0.33}$ $[-0.70, 0.70]$</td>
<td>$0.02% (0.41%)$</td>
</tr>
<tr>
<td>$f_{\Lambda 1} \cos(\phi_{\Lambda 1}^W)$</td>
<td>$0.21^{+0.18}_{-1.21}$ $[-1.00, 1.00]$ $\cup [0.49, 1.00]$</td>
<td>$0.00^{+0.34}_{-1.00}$ $[-1.00, 0.41]$</td>
<td>$78% (67%)$</td>
</tr>
<tr>
<td>$f_{a 2} \cos(\phi_{a 2}^W)$</td>
<td>$-0.02^{+1.02}_{-0.16}$ $[-1.00, -0.54]$ $\cup [-0.29, 1.00]$</td>
<td>$0.00^{+1.00}_{-0.12}$ $[-1.00, -0.58]$ $\cup [-0.22, 1.00]$</td>
<td>$42% (46%)$</td>
</tr>
<tr>
<td>$f_{a 3} \cos(\phi_{a 3}^W)$</td>
<td>$-0.03^{+1.03}_{-0.97}$ $[-1.00, 1.00]$</td>
<td>$0.00^{+1.00}_{-1.00}$ $[-1.00, 1.00]$</td>
<td>$34% (49%)$</td>
</tr>
<tr>
<td>$f_{\Lambda 1} \cos(\phi_{\Lambda 1}^Z)$</td>
<td>$-0.27^{+0.34}_{-0.49}$ $[-1.00, 1.00]$</td>
<td>$0.00^{+0.83}_{-0.53}$ $[-1.00, 1.00]$</td>
<td>$26% (16%)$</td>
</tr>
<tr>
<td>$f_{a 2} \cos(\phi_{a 2}^Z)$</td>
<td>$0.00^{+0.14}_{-0.20}$ $[-0.49, 0.46]$</td>
<td>$0.00^{+0.51}_{-0.51}$ $[-0.78, 0.79]$</td>
<td>$&lt;0.01% (0.01%)$</td>
</tr>
<tr>
<td>$f_{a 3} \cos(\phi_{a 3}^Z)$</td>
<td>$0.02^{+0.21}_{-0.13}$ $[-0.40, 0.51]$</td>
<td>$0.00^{+0.51}_{-0.51}$ $[-0.75, 0.75]$</td>
<td>$&lt;0.01% (&lt;0.01%)$</td>
</tr>
<tr>
<td>$f_{a 2} \cos(\phi_{a 2}^\gamma)$</td>
<td>$0.12^{+0.20}_{-0.11}$ $[-0.04, +0.51]$</td>
<td>$0.00^{+0.11}_{-0.09}$ $[-0.32, 0.34]$</td>
<td>$&lt;0.01% (&lt;0.01%)$</td>
</tr>
<tr>
<td>$f_{a 3} \cos(\phi_{a 3}^\gamma)$</td>
<td>$-0.02^{+0.06}_{-0.13}$ $[-0.35, 0.32]$</td>
<td>$0.00^{+0.15}_{-0.11}$ $[-0.37, 0.40]$</td>
<td>$&lt;0.01% (&lt;0.01%)$</td>
</tr>
</tbody>
</table>

**Assumptions above:** Couplings are real, ranges truncated at physical values.

**Allowed 68\% CL shown, with 95\% range in square brackets.**
For 2+ models, no constraints on quark or gluon couplings so various choices are made. The high pT tail is removed due to potential impact of new physics scale $\Lambda$.
**ATLAS Spin/Parity Measurements**

\[
\mathcal{L}^V_0 = \left\{ c_\alpha \kappa_{\text{SM}} \left[ \frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HW\nu} W^{+\mu} W^{-\mu} \right] \right. \\
- \frac{1}{4} \Lambda \left[ c_\alpha \kappa_{HZ\nu} Z_{\mu\nu} Z_{\mu\nu}^{\nu} + s_\alpha \kappa_{AZ\nu} Z_{\mu\nu} Z_{\mu\nu}^{\nu} \right] \\
- \frac{1}{2} \Lambda \left[ c_\alpha \kappa_{HW\nu} W^{+\mu} W^{-\mu} + s_\alpha \kappa_{AW\nu} W^{+\mu} W^{-\mu} \right] \right\} X_0.
\]

*\(\kappa_{HV\nu}\): BSM CP-even spin 0 particle  
*\(\kappa_{AV\nu}\): BSM CP-odd spin 0 particle

**Results**

<table>
<thead>
<tr>
<th>Coupling ratio</th>
<th>Best fit value</th>
<th>95% CL Exclusion Regions</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Expected</em></td>
<td><em>Observed</em></td>
<td><em>Expected</em></td>
</tr>
<tr>
<td>(H \to WW^* \to e\nu\mu\nu)</td>
<td>(\tilde{\kappa}<em>{HV\nu} / \kappa</em>{\text{SM}})</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>(\tilde{\kappa}<em>{AV\nu} / \kappa</em>{\text{SM}} \cdot \tan \alpha)</td>
<td>0.0</td>
</tr>
</tbody>
</table>

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<tr>
<td><em>Expected</em></td>
<td><em>Observed</em></td>
<td><em>Expected</em></td>
</tr>
<tr>
<td>(H \to ZZ^* \to 4\ell)</td>
<td>(\tilde{\kappa}<em>{HV\nu} / \kappa</em>{\text{SM}})</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>(\tilde{\kappa}<em>{AV\nu} / \kappa</em>{\text{SM}} \cdot \tan \alpha)</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Conclusions

• ATLAS and CMS have been aggressively and successfully characterizing the Higgs boson

• Many Run 1 studies are statistics limited, so progress can be expected in Run 2
  o cross sections increase with higher energy
  o more luminosity expected

• Run 2 will also allow the measurements to be extended to more channels

• Stay tuned!