Higgs Boson Results from the LHC Run-2

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on behalf of the ATLAS and CMS collaborations
Introduction

- After the Higgs discovery in 2012, the emphasis shifted towards measuring the properties of this new particle.
  - The mass, the only free parameter in the Higgs sector in the SM.
  - The width, very challenging as the intrinsic width around 4 MeV.
  - Spin and parity, is it $0^+$ as expected in the SM?
  - Couplings, several models for physics beyond the SM predict (small) deviations in the couplings for the Higgs boson. Not covered in this talk.

- This talk will review the latest results using the Run 2 dataset.
  - Comparing this with the Run 1 results, in most cases the analysis strategy is following closely what was done in Run 1.
  - Increased collision energy (13 TeV) means an increased cross section for signal and background, with the most significant gain for processes involving heavy particles like multiple top quarks.
  - The luminosity ($\sim 3 \text{ fb}^{-1}$) from the first year of Run 2 means that most results are not competitive with the Run 1 results yet.
• Given the mass of 125 GeV, we know the branching fractions from theory.

• Several production modes of the Higgs boson possible at the LHC, sometimes with associated particles.

  - Highlighted production and decay modes will be mentioned in this talk.

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Branching ratio [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow bb$</td>
<td>$57.5 \pm 1.9$</td>
</tr>
<tr>
<td>$H \rightarrow WW$</td>
<td>$21.6 \pm 0.9$</td>
</tr>
<tr>
<td>$H \rightarrow gg$</td>
<td>$8.56 \pm 0.86$</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>$6.30 \pm 0.36$</td>
</tr>
<tr>
<td>$H \rightarrow cc$</td>
<td>$2.90 \pm 0.35$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ$</td>
<td>$2.67 \pm 0.11$</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$0.228 \pm 0.011$</td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma$</td>
<td>$0.155 \pm 0.014$</td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$</td>
<td>$0.022 \pm 0.001$</td>
</tr>
</tbody>
</table>
Run 1 and Run 2 Datasets

- Essentially three years of data taking used in analyses covered here:
  - 2011, at 7 TeV, with $\int \mathcal{L} \approx 5 \text{ fb}^{-1}$ for analysis.
  - 2012, at 8 TeV, with $\int \mathcal{L} \approx 20 \text{ fb}^{-1}$ for analysis.
  - 2015, at 13 TeV, with $\int \mathcal{L} \approx 3 \text{ fb}^{-1}$ for analysis.

- The higher collision energy in Run 2 leads to an increase of $\sigma$ for both signal and backgrounds.

<table>
<thead>
<tr>
<th></th>
<th>$\sqrt{s}=7 \text{ TeV}$</th>
<th>$\sqrt{s}=8 \text{ TeV}$</th>
<th>$\sqrt{s}=13 \text{ TeV}$</th>
<th>Ratio 13/8 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ggH$</td>
<td>15.3 pb</td>
<td>19.4 pb</td>
<td>44.1 pb</td>
<td>2.27</td>
</tr>
<tr>
<td>VBF</td>
<td>1.25 pb</td>
<td>1.6 pb</td>
<td>3.8 pb</td>
<td>2.38</td>
</tr>
<tr>
<td>$ttH$</td>
<td>88.6 fb</td>
<td>133 fb</td>
<td>507 fb</td>
<td>3.81</td>
</tr>
<tr>
<td>$tt$</td>
<td>177 pb</td>
<td>253 pb</td>
<td>832 pb</td>
<td>3.29</td>
</tr>
</tbody>
</table>
The H→ZZ*→4ℓ Channel in Run I

- Look for two pairs of leptonically decaying Z bosons, one off-shell.
  - Invariant mass of the 4 leptons should peak at the Higgs boson mass.
  - Very clean channel, but statistics limited, main background from SM ZZ production.
  - Use data (Z→ℓℓ, J/ψ) for calibration of energy and momentum of leptons.

**ATLAS**

H → ZZ* → 4ℓ

\[ \sqrt{s} = 7 \text{ TeV}: \int \text{Ldt} = 4.5 \text{ fb}^{-1} \]
\[ \sqrt{s} = 8 \text{ TeV}: \int \text{Ldt} = 20.3 \text{ fb}^{-1} \]

**CMS**

\[ \sqrt{s} = 7 \text{ TeV}, L = 5.1 \text{ fb}^{-1} ; \sqrt{s} = 8 \text{ TeV}, L = 19.7 \text{ fb}^{-1} \]


The Higgs Boson Channel in Run I

- The Higgs boson can decay to a pair of photons through a loop of heavier particles.
  - Low branching ratio, but good signal to background and invariant mass of the two photons should peak at the Higgs boson mass.

- To increase the sensitivity, events are divided into categories according to associated particles from the production mode and the quality of the photons.
  - When combining categories, effective S/(S+B) ratio is taken into account.

- Main backgrounds from SM γγ production and γj production.

Signal strengths in CMS γγ event categories:

\[ \hat{\mu}_{\text{combined}} = 1.14^{+0.26}_{-0.23} \]
[\( m_H = 124.7 \text{ GeV} \)]

• The Higgs boson signal clearly visible on top of the continuous $\gamma\gamma$ background. Background can be extracted from a fit to the sidebands.

• Mass peak with events weighted according to their expected S and B:

\[ \hat{\mu} = 1.14 \pm 0.26 \]
\[ \hat{m}_H = 124.70 \pm 0.34 \text{ GeV} \]

[Graphs and data from ATLAS and CMS showing signal and background distributions with mass peaks and fit results.]
The Higgs Boson Mass

- The Higgs boson mass is estimated from a combination of the four results in the $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ channels for ATLAS and CMS.
  - The four measurements compatible with a p-value of 10%.
- The total systematic uncertainty on the combined Higgs boson mass is dominated by the contribution from the photon energy scale.

Phys. Rev. Lett. 114, 191803
The Higgs Boson Mass

**ATLAS and CMS**

**LHC Run 1**

**ATLAS** $H \rightarrow \gamma\gamma$

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

**ATLAS** $H \rightarrow ZZ \rightarrow 4l$

**CMS** $H \rightarrow ZZ \rightarrow 4l$

**ATLAS+CMS** $\gamma\gamma$

**ATLAS+CMS** $4l$

**ATLAS+CMS** $\gamma\gamma+4l$

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**Combined ATLAS and CMS best estimate of the Higgs boson mass:**

$m_H = 125.09 \pm 0.24$ GeV (uncertainty dominated by statistical component).

*Phys. Rev. Lett. 114, 191803*
• Limited luminosity in 2015 compared to Run 1 means that the results for the traditional Higgs channels are still significantly less sensitive in Run 2.

Higgs Boson Results from the LHC Run-2

Higgs Boson Results from the LHC Run-2
• ATLAS seeing a downward fluctuation in the yield in the signal region for both the \( H \to ZZ^* \to 4\ell \) and the \( H \to \gamma \gamma \) channels.

  - In Run 1 there was instead a slight excess compared to SM expectations in both channels.
  - The \( H \to \gamma \gamma \) channel still to make use of the full event categorisation in Run 2.
• Look for pair of leptons and high $E_T^{miss}$.
  - To cope with ttbar background, divide analysis according to jet multiplicity.
• High BR, good S/B, poor mass resolution.
• Uncertainty dominated by theoretical knowledge of the WW background.

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The Higgs Boson Width

- In the standard model, $\Gamma_H \sim 4.1$ MeV (for $m_H = 125$ GeV).
  - Limited by the experimental resolution, $\sim 1$-2%.
  - Direct upper limit on $\Gamma_H < 1.7$ GeV (CMS). 

- The high mass region ($>2m_V$, with $V=W,Z$) is sensitive to off-shell Higgs boson production and background interference effects.

- Limit on $\Gamma_H$ under the assumptions:
  - $q \sim m_H$ (on shell) $\to \sigma \sim (\text{couplings})/\Gamma_H$
  - $q >> m_H$ (off shell) $\to \sigma \sim (\text{couplings})$
  - Ratio $\sim \Gamma_H$.

- Negative interference with $gg\to ZZ$ taken into account.

- Results derived using both the $H\to ZZ$ and the $H\to WW$ channels.
The Higgs Boson Width

- Limits $\Gamma_H < 22.7$ MeV (ATLAS) and $\Gamma_H < 26$ MeV (CMS) derived assuming no change in couplings and no new physics at high mass.

- Analyses can eventually probe off-shell couplings as a function of $4\ell$ mass.

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**ATLAS**

$H \to ZZ \to 4\ell$

- Data
- SM (stat $\oplus$ syst)
- Total ($\mu_{\text{off-shell}}=10$)
- $gg+VBF \to (H^* \to ZZ)$
- Background $qq\to ZZ$
- Background $Z+\text{jets}, \tau$

**CMS**

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

- Observed
  - $\Gamma_H=10\times\Gamma_H^{\text{SM}}$
  - $\Gamma_H=10\times\Gamma_H^{\text{SM}}$, $f_{\lambda_{\phi}}=2\times10^{-4}$
  - $f_{\lambda_{\phi}}=5\times10^{-3}$, $\mu_{VVH}=0$
  - $f_{\lambda_{\phi}}=4.5\times10^{-4}$, $\phi_{\lambda_{\phi}}=\pi$

**Graphs:**

- Events / 60 GeV
- $m_{4\ell}$ (GeV)
- Events / 30 GeV
- $m_{4\ell}$ [GeV]

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The Spin and Parity of the Higgs Boson

Jonas Strandberg

- Test various alternative spin-parity options against the SM hypothesis $J^P = 0^+$ using angular and kinematic distributions in Higgs decays to diboson final states.
  - $H \rightarrow \gamma\gamma$ (sensitivity to $2^+$, excludes spin 1).
  - $H \rightarrow ZZ^* \rightarrow 4l$ (sensitivity to all spin/parity).
  - $H \rightarrow WW^* \rightarrow l\ell\nu\nu$ (sensitivity to spin 1 and 2).


Higgs Boson Results from the LHC Run-2

• All pure alternative spin-parity hypotheses are strongly disfavoured compared to the SM $0^{+}$ scenario.
  - With the larger dataset foreseen in Run 2 expect to be sensitive to various mixing scenarios, e.g. with small anomalous $J^{P}$ admixture.
Differential cross-sections for quantities like $p_T(H)$, $|y_H|$ and jet multiplicity, unfolded to the particle level, have also been measured.

- Statistical uncertainties (23%-75%) still dominate all the differential measurements.
• ATLAS and CMS recently released the first differential measurements in the $H \rightarrow WW$ channel.

![Graph showing differential cross sections in ATLAS and CMS channels.](image)

**ATLAS** $gg \rightarrow H$
- data, tot. unc.
- sys. unc.

**CMS**
- Data
- Statistical uncertainty
- Systematic uncertainty
- Model dependence
- $ggH$ (POWHEGv2+JHUGen) + XH
- $ggH$ (HRos) + XH
- $XH = VBF + VH$

$\sqrt{s} = 8\text{ TeV}, 20.3\text{ fb}^{-1}$

$H \rightarrow WW \rightarrow e\nu\mu\nu$

![Graph showing ratios to NNLOPS and HRes+XH.](image)

arXiv:1604.02997

Higgs Boson Results from the LHC Run-2
The $H \rightarrow \tau \tau$ Channel in Run I

- The most sensitive of the fermionic Higgs boson decay modes.
  - Events classified in categories depending on decays of the two $\tau$ leptons.
- Analysis also binned in jet multiplicity and the $p_T$ of the leptons.

JHEP 04 (2015) 117

J. High Energy Phys. 05 (2014) 104
• The ttH production mode is important to directly probe the coupling between the Higgs boson and the top quark.
  - Crucial for probing for new particles contributing to the loops in the Higgs boson production or decay.

• Very rich experimental signature, depending on the decay of the top quarks and the Higgs boson.
  - Critical to model the ttbar background, in regions of phase-space that are not simple.
- Higgs boson decays to $WW$, $ZZ$ or $\tau\tau$ can be probed in multilepton final states.
  - For example 3 leptons, or requiring a pair of same-charge leptons.
  - Can additionally require b-tagged jets to further increase the signal to background.
• Even combining the results for all different ttH channels, the observed significance in Run 1 was only a few standard deviations.
  - Still an important input to determining the Higgs boson couplings.
• Below are a summary of the results in the $\gamma\gamma$, $bb$ and various multi-lepton final states, and the results when combining all ttH channels together.
• The ttH channels get a boost by almost a factor of 4 in LHC Run 2.
  - So far studied $H \rightarrow bb$, $H \rightarrow \gamma\gamma$ and $H \rightarrow WW$, each then gets divided into multiple sub-channels depending on the decays of the two W bosons from the top quark decays and the potential additional W bosons from the Higgs decay.
• So far all results consistent with the standard model.
  - Slight deficits in data for the analyses targeting $H \to bb$ decays.
  - Similar sensitivity as with the full Run 1 dataset.
Conclusions

• From the Run 1 data, all Higgs boson properties are consistent with the expectations from the standard model:
  - The spin and parity confirmed to be according to the SM.
  - The mass, not predicted by the SM, is measured to a precision of a few ‰.
• A combination of all the results in the various Higgs boson channels can be used to determine the Higgs boson couplings to other particles.
  - You will hear much more about that in the next talk by Silvio!
• The 2015 data does not have the sensitivity of Run 1 but have been used by ATLAS and CMS to re-establish the analysis of the Higgs boson.
  - The channel that gains the most from the increased collision energy, ttH production, start to have comparable sensitivity to Run 1 already.
• With the 2016 data (around 20-25 fb⁻¹) the sensitivity of all analyses will significantly improve compared to the Run 1 results.
  - Just waiting for more data now. Very encouraging start so far this year!
Backup
Both experiments also define multi-variate discriminants to further increase the separation between the signal and the background.

- Discriminant values for events passing the analysis selections shown below.
• The $H \rightarrow bb$ decay channel has the highest branching ratio, but is swamped by SM bb production at the LHC.
  
  - Make use of the rarer production modes, where the associated particles give additional handles for background rejection.
  
  - Tagging efficiency for b-quarks and jet-jet invariant mass resolution critical.

**ATLAS**

$\sqrt{s} = 7$ TeV | $L dt = 4.7$ fb$^{-1}$

2 lep., 2 jets, 2 tags

$p_T^F \gtrsim 120$ GeV

**CMS**

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

Category 4

- Data
- Fitted signal ($m_V = 125$ GeV)
- Bkg. + signal
  
- Bkg.
- QCD

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• Higgs boson decays to $\gamma\gamma$ suffers from low statistics due to the small branching fraction but gives a very clean signal.
  - Expected to become an increasingly important channel in Run 2 and beyond.

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Differential Distributions

- Differential cross-sections for quantities like $p_T(H)$, $|y_H|$ and jet multiplicity, unfolded to the particle level, have also been measured.
  - Statistical uncertainties (23%-75%) still dominate all the differential measurements.