Recent Higgs boson measurements

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• Introduction
• Mass measurement
• Production cross section: total and differential
• Couplings
• Outlook
• Conclusions
After discovery in 2012 LHC is entering a phase of precision measurement of the Higgs boson properties, with 139 fb$^{-1}$ integrated luminosity

- Are all Higgs couplings exactly what expected by the Standard Model?
- Are there any other Higgs-related bosons?
- Is the Higgs boson a possible “bridge” to the dark matter sector?

- Precisely measure diff. cross sections
- Precisely measure decay ratios
- Search for more production and decay modes
- Look for invisible decays of Higgs bosons
- Look for new Higgs-like resonances
- Precisely measure Higgs mass
Higgs mass measurement

**ATLAS**

- **Run 1**: $\sqrt{s} = 7-8$ TeV, 25 fb$^{-1}$, **Run 2**: $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

**Run 1**
- $H \rightarrow 4l$: 124.51 ± 0.52 (± 0.52) GeV
- $H \rightarrow \gamma \gamma$: 126.02 ± 0.51 (± 0.43) GeV
- $H \rightarrow 4l$: 124.79 ± 0.37 (± 0.36) GeV
- $H \rightarrow \gamma \gamma$: 124.93 ± 0.40 (± 0.21) GeV

**Run 2**
- $H \rightarrow 4l$: 124.93 ± 0.40 (± 0.37) GeV
- $H \rightarrow \gamma \gamma$: 124.86 ± 0.35 (± 0.35) GeV

**Run 1+2**
- $H \rightarrow 4l$: 124.71 ± 0.30 (± 0.30) GeV
- $H \rightarrow \gamma \gamma$: 125.32 ± 0.35 (± 0.19) GeV

**Combined**
- ATLAS: 125.38 ± 0.41 (± 0.37) GeV
- Run 1 Combined: 124.86 ± 0.27 (± 0.18) GeV
- Run 2 Combined: 124.97 ± 0.24 (± 0.16) GeV
- ATLAS + CMS Run 1: 125.09 ± 0.24 (± 0.21) GeV

Combined ATLAS systematics now > statistical error

mass as Higgs self coupling later in this talk

**ATLAS**

\[ H^* \rightarrow ZZ \rightarrow 4l, 2l2v \]

13 TeV, 36.1 fb\(^{-1}\)

\[ \kappa_{g/V, \text{on-shell}} = \kappa_{g/V, \text{off-shell}} \]

Limits at 95\% C.L.

- Observed \( \Gamma_H \leq 14.4 \) MeV
- Expected \( \Gamma_H \leq 15.2 \) MeV

In SM Higgs very narrow

\( \Gamma_H(SM) = 4.07 \) MeV

Present limits

\( \Gamma_H \leq 3.5 \Gamma_H(SM) \)

Experimental resolution in detected decay modes.

Not a direct measurement of width, SM parameters assumed.
Fiducial cross section: corrected by local detector efficiency in each region and globally.
Definition: (+ γ isolation criteria)

<table>
<thead>
<tr>
<th>Particles</th>
<th>Requirements</th>
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<tbody>
<tr>
<td>Photons</td>
<td>$</td>
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<tr>
<td>Jets</td>
<td>Anti-$k_t$, $R = 0.4$, $</td>
</tr>
<tr>
<td>Di-photons</td>
<td>$N_{\gamma} \geq 2$; $105 &lt; m_{\gamma\gamma} &lt; 160$ GeV, $p_T^{\gamma 1}/m_{\gamma\gamma} &gt; 0.35$; $p_T^{\gamma 2}/m_{\gamma\gamma} &gt; 0.25$</td>
</tr>
</tbody>
</table>

Detector-related correction factors $c_i$ calculated with Monte Carlo, including statistical and systematic bin migration. Results also checked with migration matrix inversion.

Results for integrated fiducial cross section $\sigma_B(\gamma\gamma)$

$$
\left( \frac{d\sigma}{dx} \right)_{bin=i} = \frac{N_{i}^{\text{sig}}}{c_i \Delta x_i L}
$$

$\sigma_{\text{fid}} = (65.2 \pm 4.5\, \text{(stat.)} \pm 5.6\, \text{(syst.)} \pm 0.3\, \text{(th.)})$ fb

Standard Model ($\sigma_{SM} = 63.6 \pm 3.3$) fb

Most precise fiducial $\sigma$ measurement (11%)

At fixed $m_H = 125.09$ GeV; main systematics: $\gamma$ energy scale and resolution, background modelling. Systematics starts to dominate.
Fiducial cross section:

c_i calculated by matrix inversion method

2 lepton pairs Same Flavour Opposite Sign (SFOS)

Fiducial Definition:

- **Leptons**: \( p_T > 5 \text{ GeV} ; |\eta| < 2.7 \)
- **Jets**: Anti-\( k_t \), \( R = 0.4 \), \( p_T > 30 \text{ GeV} \), \( |\eta| < 4.5 \)
- **\( \ell \) pairs**: \( N_\ell \geq 4 \); \( 50 < m_{12} < 106 \text{ GeV} \), \( m_{\text{min}} < m_{34} < 115 \)
- **Inv. mass**: \( 115 < m_{4\ell} < 130 \text{ GeV} \)

**Results for integrated fiducial cross section** \( \sigma \)

\[ \sigma B(H \rightarrow ZZ^*) = 1.38 \pm 0.11(\text{stat.}) \pm 0.05(\text{exp.}) \pm 0.03(\text{th.}) \text{ pb} \]

Standard Model \( (\sigma B)_{\text{SM}} = 1.33 \pm 0.09 \text{ pb} \) Consistent at 73% C.L.

Matrix Element method for event classification;
detector response matrix inversion, checked against bin-to-bin correction.

Events can also be assigned to production process: Simplified Template Cross Section (STXS) split by production mode in reconstruction categories.
Overview:

- separate Monte Carlo samples generated with POWHEG BOX-V2 for each production process. $ggF$, $VBF$, $ZH$, $ttH$; different initial/final states: $gg$, $qq$
- Data events assigned to production process with Neural Network.
- STXS model takes into account reconstructed event categories ($p_T$ and jets multiplicity).
Simplified template cross section:

From particle-level Monte Carlo to reconstructed quantities

### Stage 0

- **ggF**
  - $p_T^{H} < 10$ GeV
  - $p_T^{H} > 10$ GeV
  - $60 < p_T^{H} < 120$ GeV
  - $p_T^{H} > 120$ GeV

- **VBF**
  - $p_T^{H} < 200$ GeV
  - $p_T^{H} > 200$ GeV

- **VH**
  - Hadronic $V$ decay
  - Leptonic $V$ decay

- **ttH**

### Reduced Stage 1.1

- **ggF**
  - $0$-jet
  - $1$-jet
  - $2$-jets

- **VBF**
- **VH**
- **ttH**

### Signal Region

- **0$\to p_T^{H}$-Low
- **1$\to p_T^{H}$-Low
- **1$\to p_T^{H}$-Medium
- **1$\to p_T^{H}$-High

### Side-Band Region

- **SB - 0$\to p_T^{H}$-Low
- **SB - 1$\to p_T^{H}$-Medium
- **SB - 2$\to p_T^{H}$-High

**ATLAS Preliminary**

13 TeV, 139 fb$^{-1}$
ATLAS Preliminary

H → ZZ* → 4l

13 TeV, 139 fb⁻¹

Recent Higgs boson measurements

production cross section measured for each of the “stage1-1” categories

$\text{ggF } \sigma \cdot B(H \rightarrow ZZ^*) = 1.15 \pm 0.13 \text{ pb}$

$\text{VBF } \sigma \cdot B(H \rightarrow ZZ^*) = 0.13 \pm 0.04 \text{ pb}$

for $|y_H| < 2.5$
Cross Section

Differential Cross Section: \(d\sigma/dp_T\)

**ATLAS-CONF-2019-025** \(H \rightarrow 4\ell\)

- **ATLAS** Preliminary
  - Data
  - Syst. uncertainties
  - MG5 FxFx \(K = 1.47, +XH\)
  - NNLOPS \(K = 1.1, +XH\)
  - \(XH = VBF+VH+ttH+bbH\)
  - Total stat. @ syst. uncertainty
  - Fitted ZZ Normalization

\(p_T\) value NNLOPS = 11%
\(p_T\) value MG5 FxFx = 13%

Combination based on same phase space and bin-by-bin unfolding method
Statistical uncertainty dominates;
Theoretical uncertainties include PDF, \(\alpha_s\), and missing higher orders.
Systematics dominated by background model (\(\gamma\gamma\)) and luminosity.

Integrated Higgs cross section \(\sigma = (55.4 \pm 4.3)\) pb of which \(\pm 3.1\) from stat. and 3.0 from systematics
Cross section as a function of number of jets

\( p_T > 30 \text{ GeV}, \text{ anti-} k_t, R = 0.4; \)

\( |y| < 4.4, \text{ lepton isolation cut}. \)
Production kinematics sensitive to modifier of *charm coupling*: other production processes become important modified ggF Higgs-boson $p_T$ distribution obtained with RadISH at NNLL+NLO accuracy using PDF4LHC15 PDF set $\kappa_c \neq 1$ also varies interference effects in loop

From experimental distribution $-19 < \kappa_c < 24$ at 95% C.L.; expected limits $[-15, 19]$
S.M. Higgs characteristics: couplings proportional to mass: Coupling modifiers $\kappa$ to parametrize deviation from SM couplings. $\kappa_{\#}(\text{SM}) = 1$.

- $\kappa_F$ common fermion coupling modifier,
- $\kappa_V$ common vector boson coupling modifier.

Limits on coupling modifiers:

- $\kappa_V = 1.05 \pm 0.04$; $\kappa_F = 1.05 \pm 0.09$ assuming no invisible decay and $\kappa_V > 0$, $\kappa_F > 0$
- $\kappa_\gamma = 0.97 \pm 0.06$; $\kappa_F = 0.95 \pm 0.08$

Invisible and undetected decays constrained (95%CL) by the fit: $B_{\text{inv}} < 43\%$ and $B_{\text{undet}} < 12\%$
Higgs Couplings

Direct couplings to $\ell = e, \mu$

Lepton couplings important to verify the model and possible handle to measure Higgs width. Search for decay modes $H \rightarrow e^+e^-$ and $H \rightarrow \mu^+\mu^-$

Limits at 95% C.L. with 139 fb$^{-1}$:

- $\sigma B_{\mu\mu} < 1.7 \times \sigma B_{SM}(H \rightarrow \mu^+\mu^-)$
- $B(H \rightarrow e^+e^-) < 3.6 \times 10^{-4}$

Signal strength for di-muon channel $\mu = 0.5 \pm 0.7$
Top-Higgs coupling is strongest; measured with $t\bar{t}H$ production rate (tree-level+ . . . ) and with $ggF$ production (loop only)

\[ \mu(ttH) = 1.38^{+0.33}_{-0.31} \text{(stat.)}^{+0.13}_{-0.11}\text{(syst.)}^{+0.22}_{-0.14}\text{(th.)} \]
\[ \sigma(ttH) = 670 \pm 90\text{(stat.)}^{+110}_{-100}\text{(syst.)} \text{ fb} \]

See Zhi Li’s talk for $V^*V$ multilepton decay analysis
Higgs potential $V = \frac{1}{2} (2\lambda v^2) h^2 + \lambda v h^3 + \frac{1}{4} \lambda h^4$

SM coupling defined by Higgs mass $\lambda \approx 0.13$

3-Higgs coupling: Di-Higgs production. Destructive interference with box diagrams.

Limits measured with $b\bar{b}\tau^+\tau^-$, $b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$, $W^+W^-W^+W^-$, $W^+W^\gamma\gamma$, $W^+W^\gamma b\bar{b}$

At $\sqrt{s} = 13$ TeV expect $\sigma_{ggF}(HH) = 33.5^{+2.4}_{-2.8}$ fb

Using up to 36.1 fb$^{-1}$ combined limit

$\sigma(HH) < 6.9 \times \sigma_{ggF}^{SM}(pp \rightarrow HH)$

Coupling modifier limits $\kappa\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$

$-5.0 < \kappa\lambda < 12.0$ expected ($-5.8 < \kappa\lambda < 12.0$)
Higgs self coupling $\lambda$ also affects single-Higgs production rate:

Limits on $\kappa_\lambda$ improved combining most sensitive $HH$ searches ($b\bar{b}\tau^+\tau^-$, $b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$) (up to $36.1 \text{ fb}^{-1}$) with production $\sigma$ of single $H$ decaying to $\gamma\gamma$, $Z^*Z$, $W^*W$, $\tau^+\tau^-$, $b\bar{b}$ (up to $79.8 \text{ fb}^{-1}$)

$-2.3 < \frac{\lambda_{HHH}}{\lambda_{HHH}(SM)} < 10.3$ at 95% C.L.
expected $-5.1 < \kappa_\lambda < 11.2$. assuming SM couplings
for all other processes; $\kappa_\lambda = 4.6 \pm 3.2$;

\[
\begin{align*}
\kappa_\lambda & = & 4.6 & \pm 3.2; \\
\end{align*}
\]
**ATLAS-CONF-2019-030**

VBF Di-Higgs cross section includes VVHH vertex, EW couplings \( m_Z^2/(2v^2) \) and \( m_W^2/v^2 = 1/4g^2 \approx 0.11 \)

\[ \text{MG5}_\text{aMC@NLO NNNLO} \quad \sigma_{VBF}^{\text{SM}}(pp \to HH) = 1.73 \text{ fb} \] (compare with \( \sigma_{ggF} = 11.3^{+0.9}_{-1.0} \text{ fb} \))

All-hadronic decay: b-jet trigger selection \( \geq 4b\text{-jets} \) \( p_T \geq 40 \text{ GeV} \)

\( |\eta| < 2.0, \) VBF topology two higherst \( p_T \) jets at opposite sign \( \eta \)

Main background: multijet, data driven estim.
More details in L. Gerlach’s talk
Analysis using 126 fb\(^{-1}\)

Non-resonant VBF HH production limit
\[ \sigma_{VBF} < 1600 \text{ fb} \] (expected 1000).
\[ \frac{\sigma_{VBF}}{\sigma_{VBF}^{\text{SM}}} < 925 \] @95% C.L.

Limit on coupling modifier \( \kappa_{VV} \) or
\[ -1.02 < c_{2V} < 2.71 \] (expected range \([−1.09; 2.82]\))
Single Higgs Production and Decay summary for “Run-2”

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>ggF or inclusive</th>
<th>VBF</th>
<th>WH</th>
<th>ZH</th>
<th>$t\bar{t}H$</th>
<th>$tH$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>Obs. ✓</td>
<td>Evid. ✓</td>
<td>Lim. □</td>
<td>Lim. □</td>
<td>Obs. ✓</td>
<td>Lim. □</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 4\ell$</td>
<td>Obs. ✓</td>
<td>Lim. □</td>
<td>Lim. □</td>
<td>Lim. □</td>
<td>Lim. □</td>
<td>Lim. □</td>
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<tr>
<td>$H \rightarrow Z\gamma$</td>
<td>Lim. □</td>
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<tr>
<td>$H \rightarrow WW \rightarrow l\nu l\nu$</td>
<td>Obs. ✓</td>
<td>Evid. ✓</td>
<td>Evid. ✓</td>
<td>Evid. ✓</td>
<td>Lim. □</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>Obs. ✓ (*)</td>
<td>Lim. □</td>
<td>Evid. ✓</td>
<td>Evid. ✓</td>
<td>Lim. □</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \Upsilon(1S)\gamma$</td>
<td>Lim. □</td>
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<tr>
<td>$H \rightarrow c\bar{c}$</td>
<td></td>
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<td></td>
<td></td>
<td>Lim. □</td>
<td></td>
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<tr>
<td>$H \rightarrow J/\psi\gamma$</td>
<td>Lim. □</td>
<td></td>
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<tr>
<td>$H \rightarrow \phi\gamma$</td>
<td>Lim. □</td>
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<tr>
<td>$H \rightarrow \rho\gamma$</td>
<td>Lim. □</td>
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</tr>
<tr>
<td>$H \rightarrow \tau^+\tau^-$</td>
<td>Obs. ✓</td>
<td></td>
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<tr>
<td>$H \rightarrow \mu^+\mu^-$</td>
<td>Lim. □</td>
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<tr>
<td>$H \rightarrow e^+e^-$</td>
<td>Lim. □</td>
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</table>

(*) $H \rightarrow b\bar{b}$ observation mostly from VH channel
LHC “run-3 “ data taking will start in 2021 and will double statistics, reaching 300 \( fb^{-1} \). Improve several measurements:

- differential cross sections: presently use full data set, statistics limited
- \( H \to \mu^+\mu^- \) and \( \kappa_{\mu} \)
- \( ttH \) in various decay channels (\( VV, bb, \gamma\gamma \))
- Multi-Higgs production: combinations improve present limits

High-Luminosity LHC will improve precision on Higgs boson couplings

Will address multi-Higgs production and \( \kappa_{\lambda} \) measurements

ATL-PHYS-PUB-2018-053,
Conclusions

- LHC experiment entering precision measurement of Higgs boson
- Differential cross section measured still limited by statistics
- Couplings in agreement with Standard Model
- Couplings to light leptons being sought for
- Searches for HH to allow direct measurement of Higgs self couplings
- Analyses using full run-2 statistics being finalised
- More statistics in Run-3 and HL-LHC will allow precision measurement of rare channels
- Inputs from theory are very important for precision measurements
Additional slides
Coupling modifiers

\[ \mathcal{L} = \kappa_W \frac{2m_W^2}{v} h W^\mu W^-_\mu + k_Z \frac{m_Z^2}{v} h Z^\mu Z^-_\mu + \]

\[ k_\gamma \frac{\alpha}{2\pi v} h A^{\mu\nu} A_{\mu\nu} + \kappa_g \frac{\alpha_s}{12\pi v} \sum_{a=1}^{8} h G^{(a)\mu\nu} G^{(a)}_{\mu\nu} + \kappa_\gamma Z \frac{\alpha}{\pi v} h A^{\mu\nu} Z_{\mu\nu} \]  

(1a)

\[ + \kappa_{VV} \frac{m_W^2}{v^2} h^2 W^\mu W^-_\mu + \kappa_{VV} \frac{m_Z^2}{2v^2} Z^\mu Z^-_\mu + \]

(1b)

\[ - \frac{h}{v} \sum_{f=1}^{3} \left[ \kappa_b m_D^f \bar{d}^f d^f + \kappa_t m_U^f \bar{d}^f d^f + \kappa_\tau m_L^f \bar{e}^f e^f \right] + \]

(1c)

\[ - \kappa_3 \lambda v h^3 - \frac{1}{4} \lambda h^4 \]  

(1d)

(1e)