7.5 What are its properties?
Is it the Higgs boson of the Standard Model?
Is it a Higgs Boson?
-can the LHC measure its parameters?-

- Mass
- Couplings to bosons and fermions
- Spin and CP
- Higgs boson width, lifetime?
- Higgs self coupling

Motivation:
- After a discovery of a Higgs-boson at the LHC one has to measure its parameters and consolidate that it matches the SM predictions
- As many parameters as possible have to be measured in as many different production and decay channels as possible! (global fit, see later)
- Discriminate between: SM Higgs boson, MSSM like Higgs boson, Composite Higgs boson, ....
1. **Mass**

Higgs boson mass can be measured with high precision $\ll 1\%$ using $\gamma\gamma$ and $ZZ \rightarrow 4\ell$ resonances

2. **Couplings to bosons and fermions**

Ratios of major couplings can be measured with reasonable (~10-30%) precision; Absolute coupling measurements need further theory assumptions

3. **Spin and CP**

Angular correlations are sensitive to spin and CP (achievable precision is statistics limited, requires high luminosity)

4. **Higgs self coupling**

No measurement possible at the LHC; Very difficult at the HL-LHC
Higgs-boson mass

**Combine $H \rightarrow 4l$ and $H \rightarrow \gamma\gamma$:**

- Full kinematic information in photons and leptons
- Need excellent understanding and calibration of muon, electron, photon momentum scale

**New material description in front of the calorimeter**

- Determined from detailed analysis of $6.6M \, Z \rightarrow ee(\gamma)$ and $8M \, Z \rightarrow \mu\mu(\gamma)$
- Calibrate individual layers in EM calorimeter with muons, electrons, unconverted photons
- $\Delta X_0/X_0 < 10\%$

**Energy response of EM calorimeter**

- Very stable vs. time and pileup
- RMS $< 0.05\%$
Electron and Photon Energy Scale

- **Systematic uncertainties**
- <0.1% to 0.3% for 40 GeV electrons
- For 60 GeV photons:
  - 0.2-0.3% for $|\eta| < 1.37$ or $|\eta| > 1.8$
  - ~0.6% for $1.52 < |\eta| < 1.82$

![Graphs showing energy scale discrepancies for electrons and photons with calibration uncertainty and data points.](arXiv:1406.382)
Muon Momentum Calibration

- **New calibration for momentum scale and resolution:**
- Combination of two independent measurements (inner tracker and muon spectrometer)
- Using millions of $Z \rightarrow \mu\mu$, $\Upsilon \rightarrow \mu\mu$, and $J/\Psi \rightarrow \mu\mu$
- Impact on $H \rightarrow 4\mu$ mass measurement now <60 MeV

![Graphs showing the calibration results for $\mu\mu$ events](image-url)
Higgs-Boson Mass

- Combination of $H \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$

*arXiv:1406.3827*
Higgs-Boson Mass

- Systematic uncertainty on combined mass is ~180 MeV
  - (compared to ~540 MeV in PLB Summer 2013 publication)

<table>
<thead>
<tr>
<th>Systematic</th>
<th>Uncertainty on $m_H$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAr syst on material before presampler (barrel)</td>
<td>70</td>
</tr>
<tr>
<td>LAr syst on material after presampler (barrel)</td>
<td>20</td>
</tr>
<tr>
<td>LAr cell non-linearity (layer 2)</td>
<td>60</td>
</tr>
<tr>
<td>LAr cell non-linearity (layer 1)</td>
<td>30</td>
</tr>
<tr>
<td>LAr layer calibration (barrel)</td>
<td>50</td>
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<tr>
<td>Lateral shower shape (conv)</td>
<td>50</td>
</tr>
<tr>
<td>Lateral shower shape (unconv)</td>
<td>40</td>
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<tr>
<td>Presampler energy scale (barrel)</td>
<td>20</td>
</tr>
<tr>
<td>ID material model ($</td>
<td>\eta</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$ background model (unconv rest low $p_T$)</td>
<td>40</td>
</tr>
<tr>
<td>$Z \rightarrow ee$ calibration</td>
<td>50</td>
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<tr>
<td>Primary vertex effect on mass scale</td>
<td>20</td>
</tr>
<tr>
<td>Muon momentum scale</td>
<td>10</td>
</tr>
<tr>
<td>Remaining systematic uncertainties</td>
<td>70</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>180</strong></td>
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</tbody>
</table>

arXiv:1406.3827
Higgs-Boson Mass

<table>
<thead>
<tr>
<th>Channel</th>
<th>Mass measurement [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$125.98 \pm 0.42 \text{ (stat)} \pm 0.28 \text{ (syst)} = 125.98 \pm 0.50$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4\ell$</td>
<td>$124.51 \pm 0.52 \text{ (stat)} \pm 0.06 \text{ (syst)} = 124.51 \pm 0.52$</td>
</tr>
<tr>
<td>Combined</td>
<td>$125.36 \pm 0.37 \text{ (stat)} \pm 0.18 \text{ (syst)} = 125.36 \pm 0.41$</td>
</tr>
</tbody>
</table>

$\Delta m_H = 1.47 \pm 0.67 \text{ (stat)} \pm 0.28 \text{ (sys)} \text{ GeV} = 1.47 \pm 0.72 \text{ GeV}$

- 2.0σ compatibility (compared to 2.5σ from Summer 2013 publication)
Combination paper
(5154 authors):

Higgs-boson mass: ATLAS&CMS combination

\[ \text{Signal strength (}\mu\text{, LHC Run 1)} \]

\[ -2\ln \Lambda(m_H) \]

\[ m_H \text{ [GeV]} \]
Higgs-boson mass: ATLAS&CMS combination

**ATLAS** and **CMS**

LHC Run 1

Uncertainty in ATLAS combined result

<table>
<thead>
<tr>
<th>ATLAS ECAL non-linearity / CMS photon non-linearity</th>
</tr>
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<tbody>
<tr>
<td>Material in front of ECAL</td>
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<tr>
<td>ECAL longitudinal response</td>
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<tr>
<td>ECAL lateral shower shape</td>
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<tr>
<td>Photon energy resolution</td>
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<tr>
<td>ATLAS $H \rightarrow \gamma \gamma$ vertex &amp; conversion reconstruction</td>
</tr>
<tr>
<td>$Z \rightarrow ee$ calibration</td>
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<tr>
<td>CMS electron energy scale &amp; resolution</td>
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<tr>
<td>Muon momentum scale &amp; resolution</td>
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<tr>
<td>ATLAS $H \rightarrow \gamma \gamma$ background modeling</td>
</tr>
<tr>
<td>Integrated luminosity</td>
</tr>
<tr>
<td>Additional experimental systematic uncertainties</td>
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<tr>
<td>Theory uncertainties</td>
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</table>

Uncertainty in CMS combined result

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>Observed</th>
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<tr>
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<td>Expected</td>
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Uncertainty in LHC combined result

<table>
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$\delta m_H [GeV]$
**Higgs-boson mass: ATLAS&CMS combination**

<table>
<thead>
<tr>
<th><strong>ATLAS</strong> and <strong>CMS</strong></th>
<th><strong>LHC Run 1</strong></th>
<th><strong>Total</strong></th>
<th><strong>Stat.</strong></th>
<th><strong>Syst.</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ATLAS</strong> $H \rightarrow \gamma \gamma$</td>
<td></td>
<td>126.02 ± 0.51 (± 0.43 ± 0.27) GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CMS</strong> $H \rightarrow \gamma \gamma$</td>
<td></td>
<td>124.70 ± 0.34 (± 0.31 ± 0.15) GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ATLAS</strong> $H \rightarrow ZZ \rightarrow 4l$</td>
<td></td>
<td>124.51 ± 0.52 (± 0.52 ± 0.04) GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CMS</strong> $H \rightarrow ZZ \rightarrow 4l$</td>
<td></td>
<td>125.59 ± 0.45 (± 0.42 ± 0.17) GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ATLAS+CMS</strong> $\gamma \gamma$</td>
<td></td>
<td>125.07 ± 0.29 (± 0.25 ± 0.14) GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ATLAS+CMS</strong> $4l$</td>
<td></td>
<td>125.15 ± 0.40 (± 0.37 ± 0.15) GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ATLAS+CMS</strong> $\gamma \gamma + 4l$</td>
<td></td>
<td>125.09 ± 0.24 (± 0.21 ± 0.11) GeV</td>
<td></td>
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</tr>
</tbody>
</table>

$m_H$ [GeV]

**Better than 2 per-mille!!**
Higgs-boson coupling combination

Combination framework:

- Use all ATLAS Higgs-boson measurements in one global fit
- Fit for different combinations of parameters of interest

![Graph showing Higgs-boson coupling combination](image)
Higgs boson couplings

- Production and decay involve several couplings

Production:

Decays: e.g. $H \rightarrow \gamma\gamma$ (best example)

(Decay widths depends on W and top coupling, destructive interference)

- Standard Model couplings are tested by introducing coupling scale factors $\kappa$

$$g_i = \kappa g_i^{SM}$$

- Standard Model tree level amplitudes:

$$\Gamma_{ff} \propto \left(\kappa_f \frac{m_f}{v}\right)^2 = \kappa_f^2 \cdot \Gamma_{ff}^{SM}$$

$$\Gamma_{VV} \propto \left(\kappa_V \frac{m_V^2}{v}\right)^2 = \kappa_V^2 \cdot \Gamma_{VV}^{SM}$$
Higgs boson couplings

- Example: \( H \rightarrow \gamma\gamma \)
  \[ \Gamma_{\gamma\gamma} \propto \left| 1.28\kappa_W - 0.28\kappa_t \right|^2 \cdot \Gamma_{\gamma\gamma}^{\text{SM}} \]

- Loop scaling factors can be expressed in terms of \( \kappa_f \) and \( \kappa_V \)

- The analysis is also done in terms of effective loop couplings \( \kappa_g \) and \( \kappa_\gamma \)
Higgs boson couplings

• Benchmarks defined by LHC cross section working group (leading-order tree-level framework):

- Signals observed originate from a single resonance; (mass assumed here is 125.5 GeV)

- Narrow width approximation: → rates for given channels can be decomposed as:

\[
\sigma \cdot B (i \rightarrow H \rightarrow f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}
\]

\(i, f\) = initial, final state
\(\Gamma_f, \Gamma_H\) = partial, total width

- Modifications to coupling strength are considered (coupling scale factors \(\kappa\)), tensor structure of Lagrangian assumed as in Standard Model
Scaling of cross sections with $k_F$ and $k_V$ factors

\[
\sigma \cdot \text{BR} (gg \to H \to \gamma\gamma) = \sigma_{\text{SM}}(gg \to H) \cdot \text{BR}_{\text{SM}}(H \to \gamma\gamma) \cdot \frac{k_g^2 \cdot k_{\gamma}^2}{k_H^2}
\]

\[
\sigma(gg \to H) \cdot \text{BR}(H \to \gamma\gamma) \sim \frac{k_F^2 \cdot k_{\gamma}^2(k_F, k_V)}{0.75 \cdot k_F^2 + 0.25 \cdot k_V^2}
\]

\[
\sigma(qq' \to qq'H) \cdot \text{BR}(H \to \gamma\gamma) \sim \frac{k_V^2 \cdot k_{\gamma}^2(k_F, k_V)}{0.75 \cdot k_F^2 + 0.25 \cdot k_V^2}
\]

\[
\sigma(gg \to H) \cdot \text{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{k_F^2 \cdot k_V^2}{0.75 \cdot k_F^2 + 0.25 \cdot k_V^2}
\]

\[
\sigma(qq' \to qq'H) \cdot \text{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{k_V^2 \cdot k_V^2}{0.75 \cdot k_F^2 + 0.25 \cdot k_V^2}
\]

\[
\sigma(qq' \to qq'H, VH) \cdot \text{BR}(H \to \tau\tau, H \to b\bar{b}) \sim \frac{k_V^2 \cdot k_F^2}{0.75 \cdot k_F^2 + 0.25 \cdot k_V^2}
\]
(i) Couplings to fermions and bosons

• Assume only one scale factor for fermion and vector couplings:

$$\kappa_V = \kappa_W = \kappa_Z$$
$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$$

The size of the current data set is insufficient to quantify all parameters.

• Assume that $H \rightarrow \gamma\gamma$ and $gg \rightarrow H$ loops and the total Higgs boson width depend only on $\kappa_V$ and $\kappa_F$
  (no contributions from physics beyond the Standard Model)

• Sensitivity to relative sign between $\kappa_F$ and $\kappa_V$ only from interference term in $H \rightarrow \gamma\gamma$ decays (assume $\kappa_V > 0$)
(i) Couplings to fermions and bosons (cont).

Results: Data are consistent with the SM expectation;

Fit results: $k_V = 1.09 \pm 0.07$  \quad k_F = 1.11 \pm 0.16

Fit results: $k_V \in [0.87, 1.14]$ \quad (95% CL)

$k_F \in [0.63, 1.15]$ \quad (95% CL)
(ii) Ratio of couplings to the W and Z bosons

- Relation between $m_W$ and $m_Z$ in the Standard Model requires $\lambda_{WZ} := \frac{\kappa_W}{\kappa_Z} = 1$ ($\rho$ parameter required to be 1)

- Sensitivity via VBF and VH production and $H \rightarrow WW$ and $H \rightarrow ZZ$ rates

Data are consistent with $\lambda_{WZ} := \frac{\kappa_W}{\kappa_Z} = 1$
(iii) Constraints on production and decay loops

- Test on contributions from other particles contributing to loop-induced processes
- Assume nominal couplings for all SM particles $\kappa_i = 1$
  and that the new particles do not contribute to the Higgs boson width
- Fit for effective scale factors $\kappa_g$ and $\kappa_\gamma$

Best fit values: $k_\gamma = 1.00 \pm 0.12$

(ATLAS) $k_g = 1.12 \pm 0.12$
(iv) Constraints on invisible decays \((BR_{BSM})\)

- There might be invisible decays that would increase the total decay width:

\[ \Gamma_H = \Gamma_{SM} + \Gamma_{BSM} \quad (BR_{BSM} = \frac{\Gamma_{BSM}}{\Gamma_H}) \]

Assume nominal couplings for all SM particle \(\kappa_i = 1\)

Three fitted parameters: \(k_g, k_\gamma\) and \(BR_{BSM}\)
Higgs boson couplings

- Fit all coupling scale factors for relevant particles (W, Z, t, b, t, m) independently;
- Loop factors expressed in terms of these scale factors, assume SM particle content

For the first time, non-universal, mass-dependent couplings observed.
Ratios of Higgs boson couplings (model independent)

- In the most general model, only ratios of couplings can be measured independently on any assumptions on the total width (allowing also deviations in vertex loop coupling strength)

- $\kappa_{gZ}$: test of custodial symmetry
- $\lambda_{WZ}$: sensitive to new charged particles in $H \to \gamma\gamma$ loop w.r.t. $H \to ZZ$ decays
- $\lambda_{t\gamma}$: sensitive to new coloured particles contributing to $gg \to H$ production w.r.t. $ttH$ production

Good consistency with the Standard Model Higgs boson hypothesis
(i) Results of an ATLAS search on additional resonances $X$ decaying into $\gamma\gamma$.


**Observed and expected 95% CL limits on the fiducial cross section times branching ratio $\text{BR}(X \rightarrow \gamma\gamma)$ as a function of mass**

(note: 125 GeV signal was treated as “background” and contribution was subtracted)
Outlook towards Run 2

Expectations from LHC:

• $\sim 100 \text{ fb}^{-1}$ at 13-14 TeV
  $\Rightarrow$ Expect 10 times more Higgs-bosons compared to Run 1

Consequences for Higgs boson parameter extractions:

• $\kappa$-framework has shortcomings:
  - Neglects completely tensor structure of coupling operators
  - Strictly only interpretable for $\kappa=1$

• New approach: Effective Field Theor $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}}^{(4)} + \sum_i \frac{1}{\Lambda d_i - 4} c_i O_i$
  - Full tensor structure
  - Use Spin-CP measurements in the same framework
  - Can take differential measurements into account
  - Interpretable for all values of the parameters to high precision
Outlook towards HL-LHC

**ATLAS Simulation Preliminary**

\( \sqrt{s} = 14 \text{ TeV}: \int L_{\text{det}} = 300 \text{ fb}^{-1} ; \int L_{\text{det}} = 3000 \text{ fb}^{-1} \)

- \( H \rightarrow \mu\mu \) (comb.)
- \( H \rightarrow \tau\tau \) (VBF-like)
- \( H \rightarrow ZZ \) (comb.)
- \( H \rightarrow WW \) (comb.)
- \( H \rightarrow Z\gamma \) (incl.) \( \rightarrow 1.5 \)
- \( H \rightarrow \gamma\gamma \) (comb.)
Spin and Parity

- **Standard Model Higgs boson:** $J^P = 0^+$
  - Strategy is to falsify other hypothesis ($0^-, 1^+, 1^-, 2^+, 2^-$) and demonstrate consistency with SM $0^+$ hypothesis
  - Spin 1 already strongly disfavoured by observed $H \rightarrow \gamma\gamma$ and Landau-Yang theorem
  - Use angular variables and build a combined discriminant
  - Calculate likelihood ratio between alternative hypothesis and standard $0^+$ hypothesis
**Spin und CP**

*General:*

- Use $H\rightarrow\gamma\gamma$, $H\rightarrow ZZ^*$, and $H\rightarrow WW^*$ decays
- Build boosted-decision-trees or matrix-element-discriminants to combine distributions within one channel into one variable

---

![Graph](image-url)
Spin und CP

**General:**
- Build the likelihood ratio for SM and competing hypothesis
- Extract BSM coupling limits
Spin und CP Summary

- SM $J^P = 0^+$ favored
- $1^+, 1^-, 2^+$ are disfavored at the $3\sigma$ level
- $0^-$ excluded at 97.8% CL
Spin und CP Summary
Differential cross sections

**General:**
- Unfold measured distributions to true distributions using response matrix from MC
- Needed matrix inversion (with proper uncertainty propagation) non-trivial

**Number of associated jets:**
- Test QCD

**Higgs-boson $p_T$:**
- Test theoretical modeling
Higgs boson width

- The Standard Model Higgs boson width is expected to be small: \( \Gamma_H \sim 4 \text{ MeV} \)
- Experimental mass resolution in \( H \rightarrow \gamma\gamma \) and \( H \rightarrow ZZ^* \rightarrow 4\ell \) channel \( \sim 1 - 2 \text{ GeV} \)
  
  \( \rightarrow \) only upper limits can be extracted from the observed mass peaks

Results: 95\% CL limits

\( \Gamma_H \leq 1.7 \text{ GeV} \) (2.3 expected)
Indirect constraint on the Higgs boson width from “off-shell cross sections”

- Different sensitivity of on-shell and off-shell cross sections on the Higgs boson width
- However, model dependent: assumes that on-shell and off-shell couplings are the same
- Dependence on K-factors for signal and backgrounds (gg → VV)

Results: 95% CL limits

CMS: $\Gamma_H / \Gamma_{SM} < 5.4$ (= 22 MeV)

ATLAS: $\Gamma_H / \Gamma_{SM} < 5.5$ ($R_{B^+} = 1$)
Additional Higgs bosons?

Composite Higgs bosons

More Higgs bosons

SUSY Higgs

MSSM Higgs bosons

Dark Higgs

Heidi Higgs

No Higgs at the LHC
(ii) Results of a CMS search on additional SM-like Higgs bosons decaying into ZZ and WW

Observed and expected 95% CL limits on the cross section normalised to the SM value for individual channels and their combination.
(iii) Search for charged and heavy neutral MSSM Higgs bosons

Search for $H^\pm \rightarrow \tau V$ decays via $t\bar{t}$ production or $tH^\pm$ associated production

95% CL exclusion limits on branching ratios or cross sections times branching ratio

Expected and observed exclusion limits at 95% CL in the ($m_A$–$\tan \beta$) parameter plane for the MSSM $m_{h_{\text{mod}^+}}$ benchmark scenario
Mass in our Universe

- Radiation: 0.005%
- Chemical Elements: (other than H & He) 0.025%
- Neutrinos: 0.47%
- Stars: 0.5%
- Free H & He: 4%
- Cold Dark Matter: 25%
- Dark Energy ($\Lambda$): 70%
Dark matter

rotational velocity [km/s]

measured

calculated

distance from center (light years)
Dark Matter
Dark Matter

Indirect Detection

Direct Detection

SM

DM

Production at Collider
Search for invisible Higgs boson decays

- Some extensions of the Standard Model allow a Higgs boson to decay to stable or long-lived particles

- Search for excess in ZH associated production and VBF production

Assuming the ZH and VBF production rates for $m_H = 125$ GeV:

**ATLAS:**
- 95% CL on $\text{BR} (H \rightarrow \text{inv.}) < 0.75$ (from ZH production)
- 95% CL on $\text{BR} (H \rightarrow \text{inv.}) < 0.29$ (from VBF production)

**CMS:**
- 95% CL on $\text{BR} (H \rightarrow \text{inv.}) < 0.58$ (from ZH + VBF combination)

[ATLAS-CONF-2015-004]
Interpretation in Higgs-portal models

- Stable dark matter particles with couplings to the Higgs boson-

- For $m_\chi < m_H/2$, limits on invisible branching ratios can be translated to the spin-independent DM-nucleon elastic cross section for scalar, vector and fermionic DM particles

- Higgs-nucleon coupling, model dependent: assume $0.33^{+0.30}_{-0.07}$ (lattice calculations)

- Within this model, interesting limits for low $m_\chi$ masses