Couplings to fermions and bosons

- Assume only one scale factor for fermion and vector couplings:
  \[ \kappa_V = \kappa_W = \kappa_Z \]
  \[ \kappa_F = \kappa_t = \kappa_b = \kappa_{\tau} \]

- Assume that \( H \to \gamma\gamma \) and \( gg \to H \) 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 \( H \to \gamma\gamma \) decays (assume \( \kappa_V > 0 \))

Results:
- Data consistent with the SM expectation;
  Two-dimensional consistency: 12%

- 68\% CL intervals: \( \kappa_F \in [0.76, 1.18] \) \( \kappa_V \in [1.05, 1.22] \)
Ratio of couplings to the W and Z bosons

- Custodial symmetry requires: \( \lambda_{WZ} := \frac{\kappa_W}{\kappa_Z} = 1 \)

- Sensitivity via VBF and VH production and \( H \to WW \) and \( H \to ZZ \) rates

68% CL intervals: \( \lambda_{WZ} \in [0.61, 1.04] \)
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
- Introduce effective scale factors $\kappa_g$ and $\kappa_\gamma$

**Best fit values:**

$\kappa_g = 1.04 \pm 0.14$

$\kappa_\gamma = 1.20 \pm 0.15$
Summary of coupling scale factor measurements

**ATLAS Preliminary**

$m_H = 125.5$ GeV

<table>
<thead>
<tr>
<th>Parameter value</th>
<th>Total uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-1$</td>
<td>$0$</td>
</tr>
<tr>
<td>$1$</td>
<td></td>
</tr>
</tbody>
</table>

$\lambda_{FV} = \kappa_F / \kappa_V$

$\kappa_V = \kappa_V \kappa_V / \kappa_H$

If assumption of no contributions from new particles to the Higgs boson width is relaxed, only the ratio of $\kappa_F/\kappa_V$ can be measured

Extended fit, decouple $H \rightarrow \gamma\gamma$ event rate from the measurement of $\lambda_{WZ}$

- $\kappa_V$ constrained at $\pm10\%$ level
- Couplings to fermions indirectly observed ($5\sigma$)
- $\kappa_W/\kappa_Z$ found to be consistent with one
- No evidence for significant anomalous contributions to the $gg \rightarrow H$ and $H \rightarrow \gamma\gamma$ loops

(for fixed nominal couplings of SM particles and no BSM contributions to Higgs width)

\[ \sqrt{s} = 7 \text{ TeV} \int \mathrm{Ldt} = 4.6-4.8 \, \text{fb}^{-1} \]

\[ \sqrt{s} = 8 \text{ TeV} \int \mathrm{Ldt} = 20.7 \, \text{fb}^{-1} \]
Spin and Parity

Standard Model Higgs boson: \( J^P = 0^+ \)

→ strategy is to falsify other hypotheses 
\( (0^-, 1^-, 1^+, 2^-, 2^+) \)

and demonstrate consistency with the \( 0^+ \) hypothesis

Spin 1: strongly disfavoured by observed 
\( H \to \gamma\gamma \) decays, Landau-Yang theorem

Wolfgang Pauli and Niels Bohr studying the motion of a gyro
(1952, at the opening of the institute for theoretical physics in Lund /Sweden)
J^P = 0^- versus J^P = 0^+

- Masses of the two Z bosons
- Production angle $\theta^*$
- Four decay angles $\Phi_1$, $\Phi$, $\theta_1$ and $\theta_2$

Perform multivariate analysis
(Boosted decision tree, similar sensitivity using matrix-element method)

Exclude J^P=0^- (vs. 0^+) with 97.8% CL
J^P = 1^{+/-} \text{ versus } J^P=0^+ \quad (H \to ZZ^* \text{ and } H \to WW^* \text{ events})

- H → ZZ*: as before: BDT separation based on masses and angles
- H → WW*: m_{ℓℓ}, Δφ_{ℓℓ}, p_T(ℓℓ), m_T carry information on spin, combine these variables using a BDT analysis

<table>
<thead>
<tr>
<th></th>
<th>p_0 (0^+)</th>
<th>CL (1^+) Exclusion</th>
<th>p_0 (0^+)</th>
<th>CL (1^-) Exclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>H → ZZ*</td>
<td>0.55</td>
<td>99.8%</td>
<td>0.1</td>
<td>94%</td>
</tr>
<tr>
<td>H → WW*</td>
<td>0.70</td>
<td>92%</td>
<td>0.66</td>
<td>98%</td>
</tr>
<tr>
<td>Combination</td>
<td>0.62</td>
<td>99.97%</td>
<td>0.33</td>
<td>99.7%</td>
</tr>
</tbody>
</table>

q = \log \frac{\mathcal{L}(J^P = 0^+, \hat{\mu}_{0^+}, \hat{\theta}_{0^+})}{\mathcal{L}(J^P = 1^+, \hat{\mu}_{1^+}, \hat{\theta}_{1^+})}

q = \text{test statistics to discriminate between two spin hypotheses}
**JP = 2^+ versus JP=0^+**

(H → γγ, H → ZZ*, and H → WW* events)

- **Spin 2:** consider graviton-like tensor, equivalent to a Kaluza-Klein graviton

- Production via gluon fusion and qq annihilation possible;
  Studies are performed as a function of the qq annihilation fraction ($f_{qq}$)

- Specific model $2^+_m$:
  minimal couplings to SM particles
  ($f_{qq} = 4\%$ at LO, however, large uncertainties)

- Observed exclusion (combination of γγ, ZZ* and WW*) of $JP = 2^+$
  (versus the SM $JP =0^+$) exceeds 99.9%, independent of $f_{qq}$;
  Complementary behaviour of the different channels
Example: \( H \rightarrow \gamma\gamma \) contribution

Use decay angle w.r.t. collision axis in the Collins-Soper frame

\[
\cos \theta^* \text{ distribution in signal region, after background subtraction}
\]

Exclude \( J^P=2^+ \) (produced via gluon fusion, \( f_{qq} = 0 \)) (vs. \( 0^+ \)) via \( H \rightarrow \gamma\gamma \) decays with 99.3% CL
Conclusions

• A milestone discovery announced in July 2012

• Signals have been impressively confirmed with additional data; discovery phase has turned into the measurement phase

• ATLAS data are consistent with the expectations for the Standard Model Higgs boson (within present uncertainties)
  - Production rates and coupling strengths
  - Evidence for VBF production
  - Evidence for spin-0 (0+ disfavoured)

• Exciting times ahead of us to study the Higgs boson with higher precision (> 2015) and look for surprises (deviations? more Higgs bosons? …)