The determination of Higgs boson parameters at the LHC

- Experimental Input
- How well can the LHC determine
  - Higgs boson mass
  - Couplings to fermions and bosons
  - Spin and CP quantum numbers, tensor coupling
  - Higgs boson self coupling
Important remarks / disclaimer:

• The focus of the experimental collaborations is at present in the areas of commissioning and understanding of the experimental signatures / reconstruction;
  (and rightly so, since otherwise there will be no understanding of early data !)

⇒ The new / updated results from ATLAS (CSC-Studies, arxiv:09010512) and CMS
  (TDR, J. Phys. G 34 (2006) 995) are not yet included in all studies shown in the following;
  Important differences will be pointed out !

• Studies on the Higgs boson self coupling are very preliminary, and we know that they
  are optimistic !!
  (fast simulations, even for sLHC, missing backgrounds, ……)
  To be trustable, they will need to be repeated using a more detailed simulation and more
  realistic assumptions on the sLHC performance.

• Vector boson fusion channels have been assumed to scale with luminosity;
  (relevant for results given for integrated luminosities above 30 fb⁻¹)

• For Jochum (and others): All estimates of measurement uncertainties given in the following
  are based on the assumption of Standard Model counting rates;
  (no diluted and washed-out Higgs bosons have been considered so far)
The experimental situation

- Comparable performance in the two experiments
  [at high mass: more channels (in WW and ZZ decay modes) available than shown here]
- Several channels and production processes available over most of the mass range
  → calls for a separation of the information + global fit (see below)

Important changes w.r.t. previous studies:
- \( H \rightarrow \gamma \gamma \) sensitivity of ATLAS and CMS comparable
- \( ttH \rightarrow tt \ bb \) disappeared in both ATLAS and CMS studies from the discovery plot
• Complex final states: $H \rightarrow bb$, $t \rightarrow bjj$, $t \rightarrow b\ell\nu$
  \hspace{1cm} $t \rightarrow b\ell\nu$, $t \rightarrow b\ell\nu$
  \hspace{1cm} $t \rightarrow bjj$, $t \rightarrow bjj$

• Main backgrounds:
  - combinatorial background from signal (4b in final state)
  - $ttjj$, $ttbb$, $ttZ$, …
  - $Wjjjjjj$, $WWbbjj$, etc. (excellent b-tag performance required)

• Updated ATLAS and CMS studies: matrix element calculations for backgrounds
  → larger backgrounds ($ttjj$ and $ttbb$)

\begin{itemize}
  \item \textbf{ATLAS}
    \begin{itemize}
      \item [ ] $ttH$
      \item [ ] $ttbb$ (QCD)
      \item [ ] $ttbb$ (EW)
      \item [ ] $ttjj$
    \end{itemize}

\end{itemize}

\begin{itemize}
  \item \textbf{Signal significance vs. syst. BG uncertainty}
    \begin{itemize}
      \item cut-based
      \item pairing likelihood
      \item constrained mass fit
    \end{itemize}

\end{itemize}

\begin{itemize}
  \item $M (bb)$ after final cuts, 30 fb$^{-1}$

\end{itemize}

estimated uncertainty on the background: $\pm$ 25% (theory, + exp (b-tagging))

$\Rightarrow$ Normalization from data + precise calculations needed to reduce this (non trivial, …)
(i) Measurement of the Higgs boson mass

- The mass value itself is important for precision tests of the Standard Model, but moderate precision seems to be adequate; (as compared to the anticipated $m_t$ and $m_W$ uncertainties)

- In addition: the Higgs mass value is important for the parameter measurements (in particular for the extraction of ratios of couplings) …..

… as many experimental observables / input values need to be compared to the theoretical predictions, which in turn depend -sometimes rather strongly- on $m_H$
Precision on mass is achieved in el.magn. final states

Dominant systematic uncertainty:
\(\gamma / \ell \) energy scale.
assumed: \(1\%\) (goal \(0.2\%\))
Scale from \(Z \rightarrow \ell \ell\) (close to light Higgs)

Precision below 1% can be achieved over a large mass range for 30 fb\(^{-1}\);
syst. limit can be reached for higher integrated luminosities \(\rightarrow 100\) fb\(^{-1}\)
Note: no theoretical errors, e.g. mass shift for large \(\Gamma_H\) (interference resonant/non-resonant production) taken into account
Higgs boson mass (cont.)

In case of exotic Higgs boson couplings (e.g. suppressed $H \to WW / ZZ$ couplings) the situation is more difficult (even the $\gamma\gamma$ decay mode would be affected, since the WW loop contribution is dominant)

Remaining channels at low mass:

- $H \to \tau\tau$
- $H \to bb$ (difficult S:B situation, difficult as a discovery channel; mass value is most likely needed to extract a signal, if background and mass known, it might be useful and add to coupling measurements)

** qq H → qq ττ → qq ℓνν had ν **

![CMS](image)

** tt H, H → bb **

![ATLAS](image)

Requires good understanding of the detector ($\tau$, $E_T^{miss}$), resolution limited
Direct extraction of the Higgs boson width:

![Graph showing the measured Higgs width as a function of m_H (GeV)].

- **L = 30 fb^{-1}**
- **CMS**

Graph legend:
- Dashed line: \( \Gamma_H \) from theory
- Convolution
- Gaussian
- Breit-Wigner
- Red line: Upper limit at 95% C.L.
(ii) Higgs boson couplings to fermions and bosons

The Higgs boson couplings can in principle be extracted from rate measurements,

$$\sigma_{yy \to H} \cdot \text{BR}(H \to xx) \sim \Gamma_y \cdot \Gamma_x / \Gamma_H$$

however, $\Gamma_H$ is needed, which cannot be directly measured at the LHC for $m_H < 200$ GeV.

Two options:

(i) Measure ratios of couplings
   Systematic uncertainties taken into account;

(ii) Include more theoretical assumptions and measure absolute couplings
    M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. Weiglein, D. Zeppenfeld,

→ For both options, the information from all visible Higgs boson production and decay modes can be combined into one global maximum likelihood fit
### Experimental input:

<table>
<thead>
<tr>
<th>Production</th>
<th>Decay</th>
<th>mass range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g \rightarrow H$</td>
<td>$H \rightarrow ZZ \rightarrow 4l$</td>
<td>110 GeV - 200 GeV</td>
</tr>
<tr>
<td>$g \rightarrow H$</td>
<td>$H \rightarrow WW \rightarrow lv lv$</td>
<td>110 GeV - 200 GeV</td>
</tr>
<tr>
<td>$g \rightarrow H$</td>
<td>$H \rightarrow \gamma\gamma$</td>
<td>110 GeV - 150 GeV</td>
</tr>
<tr>
<td>$W, Z \rightarrow H$</td>
<td>$H \rightarrow ZZ \rightarrow 4l$</td>
<td>110 GeV - 200 GeV</td>
</tr>
<tr>
<td>$W, Z \rightarrow H$</td>
<td>$H \rightarrow WW \rightarrow lv lv$</td>
<td>110 GeV - 190 GeV</td>
</tr>
<tr>
<td>$W, Z \rightarrow H$</td>
<td>$H \rightarrow \tau\tau \rightarrow lv lv$</td>
<td>110 GeV - 150 GeV</td>
</tr>
<tr>
<td>$W, Z \rightarrow H$</td>
<td>$H \rightarrow \tau\tau \rightarrow lv lv$ had$\nu$</td>
<td>110 GeV - 150 GeV</td>
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</tr>
</tbody>
</table>

Most significant differences: ttH channels with $H \rightarrow bb$ and $H \rightarrow WW$
Higgs-Boson Couplings (cont.)

**Global fit**

(all channels at a given mass point)

Analysis is done with increasing level of theoretical assumptions

Fit parameters:

\[
\begin{align*}
\frac{g_Z^2}{g_W^2} & \quad \frac{g^2_\tau}{g_W^2} & \quad \frac{g_b^2}{g_W^2} & \quad \frac{g_t^2}{g_W^2} & \quad \frac{g_W^2}{\sqrt{\Gamma_H}}
\end{align*}
\]

Production cross-sections

- \( \sigma_{ggH} = \alpha_{ggH} \cdot g_t^2 \)
- \( \sigma_{VBF} = \alpha_{WF} \cdot g_w^2 + \alpha_{ZF} \cdot g_Z^2 \)
- \( \sigma_{ttH} = \alpha_{ttH} \cdot g_t^2 \)
- \( \sigma_{WH} = \alpha_{WH} \cdot g_W^2 \)
- \( \sigma_{ZH} = \alpha_{ZH} \cdot g_Z^2 \)

(b loop neglected so far in ggH)

Branching ratios

- \( \text{BR}(H \rightarrow WW) = \beta_w \frac{g_W^2}{\Gamma_H} \)
- \( \text{BR}(H \rightarrow ZZ) = \beta_z \frac{g_Z^2}{\Gamma_H} \)
- \( \text{BR}(H \rightarrow \gamma\gamma) = \left( \beta_{\gamma(W)} g_w - \beta_{\gamma(t)} g_t \right)^2 \frac{1}{\Gamma_H} \)
- \( \text{BR}(H \rightarrow \tau\tau) = \beta_\tau \frac{g_\tau^2}{\Gamma_H} \)
- \( \text{BR}(H \rightarrow bb) = \beta_b \frac{g_b^2}{\Gamma_H} \)

\( \alpha, \beta \) from theory with assumed Uncertainties:

- \( \Delta \alpha_{ggH} = 20\% \)
- \( \Delta \alpha_{WF} = \alpha_{ZF} = 4\% \)
- \( \Delta \alpha_{ttH} = 15\% \)
- \( \Delta \alpha_{WH} = \Delta \alpha_{ZH} = 7\% \)

\( \Delta \beta = 1\% \)
Step 1: measurement of ratios of partial decay width:

Assumption: only one light Higgs boson

To cancel $\Gamma_H$, normalization to $\Gamma_W$ is made
(suitable channel, measurable over a large mass range ~120–200 GeV)

Note: optimistic assumptions for $H \rightarrow bb$ (based on old studies)
Step 2: measurement of ratios of couplings:

**Additional assumption**: particle content in the gg- and $\gamma\gamma$-loops are known;

**Information from Higgs production** is now used as well;

Important for the determination of the top-Yukawa coupling
Step 3: measurement of couplings (absolute values):

Needs additional ("mild") theoretical assumptions:
- use lower limit on $\Gamma_H$ from visible decay modes
- assume that $g(H,W)$ are bound from above by the Standard Model value:
  $$g^2(H,W) \leq g^2(H,W,\text{SM});$$  (valid for any model that contains only Higgs doublets and singlets)
  (upper value is motivated from WW scattering unitarity arguments)

Total width is "measured" as well
Discrimination between MSSM and SM Higgs?
Updated MSSM scan for different benchmark scenarios

Benchmark scenarios as defined by M.Carena et al. (h mainly affected)

ATLAS preliminary,  30 fb⁻¹,  5σ discovery

**MHMAX scenario**  \( (M_{\text{SUSY}} = 1 \text{ TeV/c}^2) \)
maximal theoretically allowed region for \( m_h \)

**Nomixing scenario**  \( (M_{\text{SUSY}} = 2 \text{ TeV/c}^2) \)
(1TeV almost excl. by LEP)
small \( m_h \) → difficult for LHC

**Gluophobic scenario**  \( (M_{\text{SUSY}} = 350 \text{ GeV/c}^2) \)
coupling to gluons suppressed
(cancellation of top + stop loops)
small rate for \( gg \rightarrow H, H \rightarrow \gamma\gamma \) and \( Z \rightarrow 4\ell \)

**Small \( \alpha \) scenario**  \( (M_{\text{SUSY}} = 800 \text{ GeV/c}^2) \)
coupling to b (and t) suppressed
(cancellation of sbottom, gluino loops) for large \( \tan\beta \) and \( M_A \) 100 to 500 GeV/c²

The full parameter space is covered for all scenarios
Discrimination between a SM or MSSM Higgs

In some regions of MSSM parameter space only one light Higgs boson is visible

⇒ Try to exclude MSSM using a $\chi^2$ analysis of coupling fits
Discrimination between a SM or MSSM Higgs (cont.)

Similar analysis based on direct comparison of ratios of rates in different final states, using VBF production
M. Schumacher et al., hep-ph/0410112

Consider variables

\[ R = \frac{\text{BR}(h \rightarrow \tau\tau)}{\text{BR}(h \rightarrow WW)} \]

\[ \Delta = \frac{(R_{\text{MSSM}} - R_{\text{SM}})}{\sigma_{\text{exp}}} \]

(only stat. errors considered so far, \( m_H \) assumed to be known with high precision)
(iii) Spin and CP quantum numbers

**Spin:**
- Spin 1: no $H \rightarrow \gamma\gamma$ decay
- Spin 0: angular correlations in $H \rightarrow WW \rightarrow ℓν ℓν$ decays
- More general: Angular distributions in the decay channel $H \rightarrow ZZ(\ast) \rightarrow 4 ℓ$ are sensitive to spin and CP eigenvalues
  - Azimuthal angle $\phi$
  - Polar angle $\theta$

CMS TDR - M.Bluj CMS NOTE 2006/094

**CP information:**
- Angular distributions in the decay channel $H \rightarrow ZZ(\ast) \rightarrow 4 ℓ$
- Angular correlation of tagging jets in vector boson fusion production
- Angular correlations in $ttH$ decays

Exploiting angular correlations in $H \rightarrow ZZ(*) \rightarrow 4\ell$ decays:

Fit to

$$F(\phi) = \alpha \cos(\phi) + \beta \cos(2\phi)$$

$$F(\theta) = T (1+\cos^2 \theta) + L \sin^2 \theta$$

$$R = (L-T) / (L+T)$$

Exploiting angular correlations in $H \rightarrow ZZ(*) \rightarrow 4\ell$ decays:

**Expected results:**

![Graphs showing significance for exclusion of Spin 1 CP+1, Spin 1 CP-1, and Spin 0 CP-1.]

Evidence for spin-0 in $H \rightarrow WW \rightarrow \ell\nu\ell\nu$

- Cuts can be relaxed, to get background shape from the data + Monte Carlo:

No kinematical cuts on leptons applied: (ATLAS study)

Evidence for spin-0 of the Higgs boson, $\Delta\phi$ distribution

Spin-0 $\rightarrow WW \rightarrow \ell\nu\ell\nu$ expect leptons to be close by in space

Tensor structure of Higgs couplings in VBF events

• General parametrization of the coupling of a scalar to vector bosons:

\[ T^{\mu\nu}(q_1, q_2) = a_1(q_1, q_2) g^{\mu\nu} \]
\[ + a_2(q_1, q_2) [ q_1 \cdot q_2 g^{\mu\nu} - q_2^{\mu} q_1^{\nu} ] \]
\[ + a_3(q_1, q_2) \varepsilon^{\mu\nu\rho\sigma} q_1^\rho q_2^\sigma. \]

CP even Standard Model term
anomalous CPE term
anomalous CPO term

• Contributions and admixtures can be determined in VBF using the \( \Delta \phi \) distribution between the two tag jets

Shapes of \( \Delta \phi \) distributions
(no backgrounds, large statistics)

Tensor structure of Higgs couplings in VBF events (cont.)

- ATLAS study using the $qqH \to qqWW$ and $qqH \to qq\tau\tau$ channels:

- Apply typical VBF selection cuts: central leptons, two tag jets: $M_{jj}$, $P_T$

After (fast) detector simulation

ATLAS, $qqH \to qqWW$, $L = 10\text{ fb}^{-1}$

Expectations:

**WW decay mode:** $m_H = 160\text{ GeV}$
Anomalous CP-even and CP-odd couplings can be excluded with $5\sigma$, for $10\text{ fb}^{-1}$

**$\tau\tau$ decay mode:** $m_H = 120\text{ GeV}$
Exclusion with a $2\sigma$ significance requires $30\text{ fb}^{-1}$
CMS analysis: search for a pseudoscalar admixture

- Use again the angular correlations in $H \rightarrow ZZ \rightarrow 4\ell$ decays
- Assume Spin-0 Higgs boson and allow for a pseudoscalar admixture $\phi = H + \xi A$

(Standard Model (scalar) case: $\xi = 0$)
Results from Monte Carlo experiments for a maximum likelihood fit to the angular distributions and the 4-lepton invariant mass (including signal and background).

- $m_\phi = 200$ GeV, $L = 60$ fb$^{-1}$
- $m_\phi = 300$ GeV, $L = 60$ fb$^{-1}$
- $m_\phi = 400$ GeV, $L = 60$ fb$^{-1}$

Allows precise measurement of pseudoscalar admixture for 60 fb$^{-1}$

(iv) Higgs boson self-coupling?

To finally establish the Higgs mechanism the Higgs boson self-coupling has to be measured:

\[ \lambda_{HHH}^{SM} = 3 \frac{m_H^2}{v}, \quad \lambda_{HHHH}^{SM} = 3 \frac{m_H^2}{v^2} \]

Cross sections for HH production:

small signal cross-sections, large backgrounds from tt, WW, WZ, WWW, tttt, Wtt,...

⇒ no significant measurement possible at the LHC

need Super LHC \( L = 10^{35} \text{ cm}^{-2} \text{ sec}^{-1}, 6000 \text{ fb}^{-1} \)
Most sensitive channel: \[ gg \rightarrow HH \rightarrow WW \; WW \rightarrow \ell\nu \; jj \; \ell\nu \; jj \]

- accessible in mass range around 160 GeV
- \(bb\)- or \(\gamma\gamma\) decay modes at lower masses are hopeless

**Selection (old analysis):**

- 2 isolated, high \(P_T\), like sign leptons (from different Higgs bosons)
- 4 high \(P_T\) jets, compatible with W-mass

<table>
<thead>
<tr>
<th>(m_H)</th>
<th>Signal</th>
<th>(tt)</th>
<th>(W^{\pm}Z)</th>
<th>(W^{\pm}W^{\mp}W^{\mp})</th>
<th>(ttW^{\pm})</th>
<th>(tttt)</th>
<th>(S/\sqrt{B})</th>
</tr>
</thead>
<tbody>
<tr>
<td>170 GeV</td>
<td>350</td>
<td>90</td>
<td>60</td>
<td>2400</td>
<td>1600</td>
<td>30</td>
<td>5.4</td>
</tr>
<tr>
<td>200 GeV</td>
<td>220</td>
<td>90</td>
<td>60</td>
<td>1500</td>
<td>1600</td>
<td>30</td>
<td>3.8</td>
</tr>
</tbody>
</table>

6000 fb \(^{-1}\) \(\Rightarrow\) \[ \Delta \lambda_{HHH}/\lambda_{HHH} = 19\% \; (\text{stat.}) \quad \text{(for} \; m_H = 170 \; \text{GeV)} \]

\[ \Delta \lambda_{HHH}/\lambda_{HHH} = 25\% \; (\text{stat.}) \quad \text{(for} \; m_H = 200 \; \text{GeV)} \]

Note: - background contributions (tt and WWW) underestimated
- Estimates are based on fast detector simulation
- No pile-up effects and no realistic sLHC performance assumed

\(\Rightarrow\) Study needs to be updated with more realistic simulations, before more reliable estimates can be given
1. **Mass**

Higgs boson mass can be measured with high precision < 1% over a large mass range (130 - ~450 GeV) using $\gamma\gamma$ and $ZZ\rightarrow 4\ell$ resonances.

2. **Couplings to bosons and fermions**

- Ratios of major couplings can be measured with reasonable precision;
- Absolute coupling measurements need further theory assumptions
  (Methods established, exp. Updates are needed, in particular for VBF channels at high luminosity)

3. **Spin and CP**

Angular correlations in $H \rightarrow ZZ(*) \rightarrow 4\ell$ and $\Delta\phi_{jj}$ in VBF events 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 sLHC, there might be sensitivity in $HH \rightarrow WW WW$ for $m_H \sim 160$ GeV
Situation needs to be re-assessed with more realistic simulations, timescale unknown
Motivation:

• After a discovery of a significant excess of “Higgs-like” events at the LHC one has to measure its parameters and consolidate the evidence for a Higgs boson.

• 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, “Exotic” Higgs boson.

“This could be the discovery of the century. Depending, of course, on how far down it goes.”