Prospects for the Determination of Higgs boson properties at LHC

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For the ATLAS and CMS collaborations
One major objective at the LHC: Understand electroweak symmetry breaking

- Many ways to describe it in theory
  - Discovery of a new particle by itself might not provide a unique answer
- Model parameters need to be measured to fix predictions
- Predictions need to be tested
  \[ \Rightarrow \text{Determination of particle properties will be important} \]

Properties of the Higgs boson to be determined include:

- Mass, Width
- Couplings to gauge bosons, fermions, itself
- Quantum numbers: Charge, spin, CP
Mass

- Fit mass peak in $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$
  - Small relative uncertainty: $< 0.3\%$ up to $m_H \approx 300$ GeV, depending on $\int L$

CMS, $30$ fb$^{-1}$

only statistical errors taken into account
Mass

- Measurement more difficult if $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$ are suppressed
- Reconstruct mass in $H \rightarrow bb$, $H \rightarrow \tau\tau$ (using collinear approximation):
  - Fit transverse mass in $H \rightarrow WW$:
    - $H \rightarrow WW^* \rightarrow eevv$, $m_H = 140$ GeV, CMS 10 fb$^{-1}$
  - $H \rightarrow \tau\tau \rightarrow ljet$, CMS 30 fb$^{-1}$

- $M_H$ precision observable for SM Higgs, fixes model predictions (couplings, width...)
- Further measurements test the SM
Mass resolution $\gg$ width of Higgs boson for $m_H < 200$ GeV
- direct measurement for $m_H > 250$ GeV, precision $< 10\%$ above 300 GeV
Couplings to Fermions and Gauge Bosons

- Likelihood fit to expected event numbers from ATLAS analyses for 13 channels
- Systematic errors (luminosity, detector effects, background normalisation, theoretical, PDF uncertainties) taken into account

\[ \sigma \cdot BR \propto \frac{\Gamma_{\text{prod.}}}{\Gamma_H} \frac{\Gamma_{\text{decay}}}{\Gamma_H} \]

- \( \Gamma_H \) not directly measured
- Model independent: only fit of ratios of partial widths

- Assumptions: Spin 0, CP even, only one Higgs boson contributes

- Ratios with respect to \( \Gamma_W \):
  - \( H \rightarrow WW \) channel with highest precision in mass range

- Relative error 10\% - 35\% for \( \Gamma_Z, \Gamma_\gamma \) ratios, between 30\% and 60\% for \( \Gamma_\tau, \Gamma_b \) ratios

ATLAS

\[
\int L \, dt = 300 \text{ fb}^{-1}
\]

WBF: 30 fb^{-1}
Absolute Couplings and Width

- Lower bound on $\Gamma_H$ from observation of Higgs boson production
- Additional Assumption: $\Gamma_V < \Gamma_V^{SM}$ ($V = W/Z$), valid in multi-Higgs doublet models
- Upper bound from constraint and measurement of $\Gamma_V^2/\Gamma_H \Rightarrow$ fit absolute couplings and $\Gamma_H$, allowing for unknown particles in $Hgg$, $H\gamma\gamma$ loops and undetected decays
Exclusion of MSSM Scenarios

- Use coupling fit to calculate expected exclusion of MSSM parameter regions
  - Assume MSSM event rates and statistical errors
  - Identify regions in which SM shows discrepancy of $\Delta \chi^2 \geq 9$ ("3$\sigma$")
• No production in $H_{gg}$ and decay in $H\gamma\gamma$ for Spin 1
• Spin and CP affect angular distributions of decay leptons in $H \rightarrow ZZ \rightarrow 4l$

• Observables in $H \rightarrow ZZ \rightarrow 4l$:
  • Angle $\phi$ between planes spanned by leptons
  • Angle $\theta$ between negatively charged lepton in $Z$ rest frame and $Z$ in Higgs rest frame

• $H \rightarrow ZZ \rightarrow 2e2\mu$
• SM vertex + $\tan\xi / m_V^2$ times scalar CP odd coupling contribution
• $t\bar{t}, Zb\bar{b}$ backgrounds suppressed by cuts
Spin and CP Quantum Numbers

- $H \rightarrow ZZ \rightarrow 4l$, test for combinations of Spin and CP quantum numbers
- Parametrisations of angular distributions used in fit:
  \[
  F(\phi) = 1 + \alpha \cdot \cos(\phi) + \beta \cdot \cos(2\phi)
  \]
  \[
  G(\theta) = T \cdot (1 + \cos^2(\theta)) + L \cdot \sin^2(\theta)
  \]
  \[
  R \equiv \frac{L - T}{L + T}
  \]

Expected deviations from SM divided by expected SM uncertainties:

ATLAS 100 fb$^{-1}$

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

- SM-Higgs
- Spin 1, CP ± 1
- Spin 0, CP -1
Structure of HVV Couplings

- Study of HVV \((V = W/Z)\) coupling structure in VBF, using fast detector simulation
- Scalar vertex with SM + CP even/CP odd dimension 5 terms
- Observable: \(\Delta \phi\) between tagging jets
- \(\chi^2\) hypothesis test to determine dominant coupling
- Channels: \(H \rightarrow \tau\tau\) at \(m_H = 120\) GeV
  \[H \rightarrow WW \rightarrow ll\nu\nu\] at \(m_H = 160\) GeV

Signal \(H \rightarrow WW\), high statistics, after cuts:

SM pseudo-data including backgrounds, compared to non-SM reference distributions:
Structure of HVV Couplings

- Test repeated for 10 000 Standard Model pseudo-data samples

CP odd coupling hypothesis:

- Median deviation of SM from CPE
  - $H \rightarrow WW$ 10 fb$^{-1}$: $5.4 \sigma$
  - $H \rightarrow \tau\tau$ 30 fb$^{-1}$: $2.5 \sigma$

<table>
<thead>
<tr>
<th></th>
<th>CPE</th>
<th>CPO</th>
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</thead>
<tbody>
<tr>
<td>Median</td>
<td>5.4 σ</td>
<td>4.6 σ</td>
</tr>
<tr>
<td>Mean</td>
<td>-1.61</td>
<td></td>
</tr>
<tr>
<td>RMS</td>
<td>1.156</td>
<td></td>
</tr>
<tr>
<td>Underflow</td>
<td>8</td>
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</tr>
</tbody>
</table>
Structure of HVV Couplings

- Likelihood fit: SM + contribution by CP even effective coupling
- Observe interference in $\Delta \phi_{jj}$ distribution

Signal, high statistics:

- Fit results effective coupling:
- Pulls of fit results:

Expected sensitivity ($g_{HZZ}^{HZZ} = 1/cos^2\theta_W$ gives SM cross section for pure CPE coupling):

- $H \rightarrow WW$ 30 $fb^{-1}$: $0.11$ $1.00$
- $H \rightarrow \tau\tau$ 30 $fb^{-1}$: $0.24$ $0.97$

- 10% uncertainty on background rate: additional uncertainty of order $0.02$

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Summary

- Mass measurement considered possible with relative uncertainty of 0.1% - 1%

- Higgs boson width directly accessible above 250 GeV
  - Fit below 200 GeV with assumption $\Gamma_V < \Gamma_V^{\text{SM}}$
  - Expected precision <10% (direct $H \rightarrow ZZ$), 15% - 50% (fit)

- Determination of relative widths through fit to results from different channels
  - Fit of absolute couplings possible with additional assumptions
  - Typical expected precision few 10%

- Spin, CP determination in $H \rightarrow ZZ \rightarrow 4l$ studied for masses above 200 GeV
  - > 5$\sigma$ discrimination between SM and non-SM cases above 230 GeV expected

- Structure of HVV couplings and CP properties studied in vector boson fusion
  - > 5$\sigma$ exclusion of non-SM cases at 160 GeV, > 2$\sigma$ appears possible at 120 GeV
  - Fit sensitive to interference between SM and CP even effective coupling
<table>
<thead>
<tr>
<th>Production</th>
<th>Decay</th>
<th>Mass range</th>
</tr>
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<tbody>
<tr>
<td>GF: $g g \rightarrow H$</td>
<td>$H \rightarrow ZZ^{(*)} \rightarrow 4l$</td>
<td>110 GeV - 200 GeV</td>
</tr>
<tr>
<td>Gluon Fusion</td>
<td>$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$</td>
<td>110 GeV - 200 GeV</td>
</tr>
<tr>
<td>(gg → H)</td>
<td>$H \rightarrow \gamma\gamma$</td>
<td>110 GeV - 150 GeV</td>
</tr>
<tr>
<td>WBF: $q' w, z \rightarrow H \rightarrow H \rightarrow 4l$</td>
<td>$H \rightarrow ZZ^{(*)} \rightarrow 4l$</td>
<td>110 GeV - 200 GeV</td>
</tr>
<tr>
<td>Weak Boson Fusion</td>
<td>$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$</td>
<td>110 GeV - 190 GeV</td>
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<tr>
<td>(qq H)</td>
<td>$H \rightarrow \tau\tau \rightarrow l\nu l\nu$</td>
<td>110 GeV - 150 GeV</td>
</tr>
<tr>
<td>(qq H)</td>
<td>$H \rightarrow \tau\tau \rightarrow l\nu l\nu$ had$\nu$</td>
<td>110 GeV - 150 GeV</td>
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<tr>
<td>(qq H)</td>
<td>$H \rightarrow \gamma\gamma$</td>
<td>110 GeV - 150 GeV</td>
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<tr>
<td>$t\bar{t}H$</td>
<td>$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu (l\nu)$</td>
<td>120 GeV - 200 GeV</td>
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<tr>
<td></td>
<td>$H \rightarrow \nu\nu$</td>
<td>110 GeV - 140 GeV</td>
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<tr>
<td></td>
<td>$H \rightarrow \nu\nu$ (not included)</td>
<td>110 GeV - 150 GeV</td>
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<tr>
<td></td>
<td>$H \rightarrow \gamma\gamma$</td>
<td>110 GeV - 120 GeV</td>
</tr>
<tr>
<td>$W H$</td>
<td>$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu (l\nu)$</td>
<td>150 GeV - 190 GeV</td>
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<tr>
<td></td>
<td>$H \rightarrow \gamma\gamma$</td>
<td>110 GeV - 120 GeV</td>
</tr>
<tr>
<td>$Z H$</td>
<td>$H \rightarrow \gamma\gamma$</td>
<td>110 GeV - 120 GeV</td>
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References

CMS Physics TDR, Volume II, CERN-LHCC-2006-021

ATLAS detector and physics performance TDR, Volume 2, CERN-LHCC-99-015


M. Dührssen, *Prospects for the measurement of Higgs boson coupling parameters in the mass range from 110 – 190 GeV/c²*, ATL-PHYS-2003-030

