Higgs coupling measurements at LHC: challenges for QCD

D. Zeppenfeld
UW-Madison

Intro: LHC goals in Higgs physics
Overview of channels
Accuracy of coupling extraction
Requirements for signal and background predictions

Introduction
Higgs search = search for SU(2) x U(1) breaking
dynamics of Higgs boson
measure Higgs couplings
How to identify $H$ as remnant of $SU(2) \times U(1)$ breaking

$$\phi \rightarrow \left( \frac{\chi^+}{\sqrt{2}(\nu + H + i \chi^0)} \right)$$

A tree level $HWW$ or $HZZ$ coupling is the smoking gun: requires vev.

$$(D^a \phi)^+ (D^a \phi) \rightarrow \frac{y^2}{2} \frac{(\nu + H)^2}{2} W^+_\mu W^\mu$$

$$(\frac{g}{\sqrt{2}})^2 W^+_\mu W^\mu \leftrightarrow W \text{ mass}$$

$$\frac{g^2}{2} H W^+_\mu W^\mu \leftrightarrow HWW \text{ coupling}$$

Gauge interactions of non-vev scalar

$\sim \phi^+ \phi W, \, \phi^+ \phi WW$

are bilinear in $\phi$

- Probe fermion mass generation

$$\lambda \bar{L} \phi \tau_R \rightarrow \frac{m_F}{\nu} (\nu + H) \bar{\tau}_L \tau_R$$

measures relation between

fermion mass $\leftrightarrow$ $Hff$ coupling

$\Rightarrow$ measure Higgs' Yukawa coupl.

$H\tau \tau$

$Hbb$

$Htt$ etc.

measure couplings to gauge bosons

$HWW$

$HZZ$

$H\gamma \gamma$

$Hgg$
Principal production modes at hadron colliders

- Gluon fusion
  - Tevatron LHC

- WH/ZH production
  - Tevatron

- Weak boson fusion
  - LHC

- t\bar{t}H production
  - LHC

LHC cross sections

Dominant production processes

- Gluon fusion
  - 10-30 pb

- Weak boson fusion
  - 3-5 pb

- t\bar{t}H production
  - 0.2-2 pb
Intermediate Mass Higgs

- $H \rightarrow ZZ \rightarrow \ell^+\ell^- \ell^+\ell^- \ (\ell = e, \mu)$
  - Very clean
  - Resolution: better than 1 GeV
  - Valid for the mass range $130 < M_H < 500$ GeV/$c^2$

$H \rightarrow ZZ^* \rightarrow 4\ell^\pm$
**Important for $m_H \leq 120-130$ GeV**

$gq \rightarrow t\bar{t}H$, $H \rightarrow b\bar{b}$

---

**CMS**

$L_{\text{int}} = 30$ fb$^{-1}$

- $k = 1.5$
- gen. $m_H$: 115 GeV/c$^2$
- const.: $13.63 \pm 3.76$
- mean: $110.3 \pm 4.14$
- sigma: $14.32 \pm 3.70$

---

**Background and signal have similar shape**

$\Rightarrow$ must know $b$-tag normalization precisely
Weak boson fusion (WBF) has emerged as a powerful tool for

- Higgs search
- Higgs analysis

\[ \begin{array}{c}
\text{H} \\
\text{jet} \\
\text{jet}
\end{array} \]

- sizable rate (\(\frac{1}{5}\) of gluon fusion)
- 2 forward tagging jets for efficient background rejection
- color singlet exchange: no central jets
- well known SM cross section: small NLO correction of order 10\%.

WBF is crucial for Higgs coupling measurements: \(H\gamma\gamma\) & \(HWW/HZZ\)
Results from VBF Cut Analyses

J. Asai et al. SN-ATLAS-2003-024

Bruce Mellado, Les Houches 2003, 29/05/03
Summary of main SM Higgs channels:

- $gg \to H \to \gamma\gamma$:
  - $m_H \lesssim 150$ GeV
  - $\sim \frac{\Gamma_H}{\Gamma} \approx \gamma_{\gamma}$

- $gg \to H \to ZZ \to 4\ell$:
  - $m_H \gtrsim 120$ GeV
  - $\sim \frac{\Gamma_H}{\Gamma} \approx \gamma_{Z}$

- $gg \to H \to WW \to \ell^{+}\ell^{-}j_{T}$:
  - $m_H \gtrsim 130$ GeV
  - $\sim \frac{\Gamma_H}{\Gamma} \approx X_{W}$

- $qq \to qq H, H \to \gamma\gamma$:
  - $m_H \lesssim 150$ GeV
  - $\sim \frac{\Gamma_W}{\Gamma} \approx X_{\gamma}$

- $qq \to qq H, H \to \tau\tau$:
  - $100$ GeV $\leq m_H < 150$ GeV
  - $\sim \frac{\Gamma_W}{\Gamma} \approx X_{\tau}$

- $qq \to qq H, H \to WW \to \ell^{+}\ell^{-}j_{T}$:
  - $m_H \gtrsim 115$ GeV
  - $\sim \frac{\Gamma_W}{\Gamma} = X_{W}$

Statistical errors with 200 fb$^{-1}$:

- $gg \to H$
- $WW \to H + WW$
- $WBF$

Systematic errors:
- QCD/pdf uncertainties: $\pm 5\%$, for $WBF$
- $\pm 20\%$, for gluon fusion
- Luminosity/acceptance error $\pm 5\%$

Largely cancel in cross section ratios:

$$\frac{\Gamma_W}{\Gamma}, \frac{\gamma_{\gamma}}{\Gamma}, \frac{\gamma_{Z}}{\Gamma}, \frac{\gamma_{\tau}}{\Gamma}, \frac{\gamma_{W}}{\Gamma}$$
Generic problem for model-independent analysis at LHC:

\[
\text{observed} \equiv \hat{\gamma} = \frac{\Gamma_p \Gamma_d}{\Gamma} = \frac{x \Gamma_p \Gamma_d}{x^2 \Gamma}
\]

Limits on rescaling factor \( x \):

a) total width = sum of partial widths

\[
x^2 \Gamma = \sum_i x \Gamma_i \geq \sum_{i \in \{p,d,\text{obser.}\}} \Gamma_i
\]

\( \Rightarrow \ x \geq \frac{\sum \Gamma_i}{\Gamma} \) = order 1

observation of production puts lower bound on \( x \Gamma_p \).

b) total width < experimental resolution (or is measured directly!)

see \( H \to \gamma\gamma \) or \( H \to 4\ell \)

\( \Rightarrow \ x \leq \sqrt{\frac{1 \text{ GeV}}{\Gamma}} \)

Fit LHC data within constrained models:

- \( \frac{g_{Hxx}}{g_{Hbb}} = \text{SM value} \)
- \( \frac{g_{HWW}}{g_{HZZ}} = \text{SM value} \)
- no exotic channels

Assume 100 fb\(^{-1}\) of data in each of two detectors

Coupling ratios may differ from SM values in generic models.
Example: Large bottom squark corrections to the $hbb$ vertex in SUSY models

Assume Higgs doublets/singlets only

$$g_{HWW}^2 = (g_{HWW}^2)^{SM} \sin^2(\alpha - \beta) < (g_{HWW}^2)^{SM}$$

Perform global fit to couplings for expected LHC data

QCD requirements

Signal: would like to have theory errors on production cross section at 5-10% level

<table>
<thead>
<tr>
<th>Process</th>
<th>Theory Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(gg \rightarrow H)$</td>
<td>$\pm 10-20%$ @NNLL $\rightarrow$ Harlander</td>
</tr>
<tr>
<td>$\sigma(WBF)$</td>
<td>$\pm 4%$ @NLO $\rightarrow$ Grazzini</td>
</tr>
<tr>
<td>$\sigma(t\bar{t}H)$</td>
<td>$\pm 10-15%$ @NLO $\rightarrow$ Reina</td>
</tr>
</tbody>
</table>

QCD corrections are available for all relevant production processes

- Would like to have NLO MC for $t\bar{t}H$ including $t \rightarrow bW$ in narrow width approx.
- Interface with parton shower MC
- Separation of $Hjj$ events: $gg \rightarrow Hgg$ vs. WBF
**Backgrounds**

1. **Narrow resonances:** $H \rightarrow \gamma \gamma$, $H \rightarrow ZZ \rightarrow 4\ell$
   
   Obtain background experimentally from sideband analysis.

2. **$H \rightarrow \tau \tau$ in WBF**
   
   Dominant backgrounds: $(Z \rightarrow \tau \tau) + 2$ jets
   
   NLO MC's are available
   
   Measure bkgd in $Z \rightarrow \mu \mu$ events

3. **$H \rightarrow b \bar{b}$ in $t\bar{t}H$ production**
   
   Dominant background: $t\bar{t}b\bar{b}$
   
   Need background shape at 10% level
   
   $\rightarrow$ sideband analysis with LO MC
   
   NLO calculation ???

(4) **$H \rightarrow WW \rightarrow e^+e^-\nu\bar{\nu}$**

   Dominant background: $t\bar{t} \rightarrow W^+W^-b\bar{b}$

(a) **inclusive search (Grazzini)**

   $\sigma(t\bar{t}) < \sigma(tbW)$ after severe jet veto

(b) **$WBF$: $H+jj \rightarrow WWjj$**

   Need $t\bar{t}j$ at NLO
   
   Off-shell effects give $\sim 15\%$ correction at LO
Other areas where improvement is needed

- Use of central jet veto for
  - WBF
  - $t\bar{t} \rightarrow WWbb$ suppression

- Disentangling WBF and $gg \rightarrow Hgg$

Conclusion:

Higgs discovery is "easy"

Higgs measurements are the true challenge