Measuring the Higgs boson couplings

Michael Rauch | June 1st, 2011
Higgs properties

Verify that observed resonance is “Higgs”

- spin-0 particle
  - spin-1 excluded by $H \rightarrow \gamma\gamma$
  - spin-2: look at angular correlations

- CP-nature
  - SM-Higgs CP-even; extended Higgs sectors also CP-odd or mixed states
  - look at angular correlations

- couplings
  - unitarity in $W_L W_L \rightarrow W_L W_L$ scattering
    $\rightarrow$ fixed coupling $g_{WWH} \propto m_W$
  - fermion masses
    $\rightarrow$ $g_{f\bar{f}H} \propto m_f$
  - Higgs self-couplings
    determine shape of Higgs potential via trilinear and quartic couplings
    SM: $V = \mu^2 |\Phi|^2 + \lambda |\Phi|^4 + \text{const.}$
    new scale $\Lambda$: $V = \sum_{n \geq 0} \frac{\lambda^n}{\Lambda^{2n}} \left(|\Phi|^2 + \frac{v^2}{2}\right)^{2+n}$
    $\rightarrow$ very challenging for LHC

[Landau-Yang theorem]
[Hagiwara, Mawatari, Li; Frank, MR, Zeppenfeld]
[Plehn, Rainwater, Zeppenfeld; Klämke, Zeppenfeld]
[Choi, Eberle, Miller, Mühlleitner, Zerwas]
[Englert, Hackstein, Spannowsky]
[Plehn et al.; Baur et al.; MR et al.; Binoth et al.; ...]
Generalized Higgs sector

How well can we determine the SM Higgs couplings?
Can we distinguish a non-Standard-Model-like Higgs sector?

- Theory: Standard Model plus general Higgs sector
- For Higgs couplings present in the Standard Model $j = W, Z, t, b, \tau$
  
  replace general couplings by
  
  $$g_{jjH} \rightarrow g_{jjH}^{\text{SM}} \left(1 + \Delta_{jjH}\right) \quad (\rightarrow \Delta = -2 \text{ means sign flip})$$

- For loop-induced Higgs couplings $j = \gamma, g$
  replace by
  
  $$g_{jjH} \rightarrow g_{jjH}^{\text{SM}} \left(1 + \Delta_{jjH}^{\text{SM}} + \Delta_{jjH}\right)$$

  where $g_{jjH}^{\text{SM}}$: (loop-induced) coupling in the Standard Model
  $\Delta_{jjH}^{\text{SM}}$: contribution from modified tree-level couplings
  to Standard-Model particles
  $\Delta_{jjH}$: additional (dimension-five) contribution

- Additional free parameters:
  - Higgs boson mass $m_H$
  - top- and bottom-quark mass $m_t$, $m_b$

- Neglecting couplings only available from high-luminosity analyses
  ($g_{H\mu\mu}, g_{HZ\gamma}^{\text{eff}}, g_{HHH}, g_{HHHH}$)
SFitter

- Need to scan high-dimensional parameter space
- → SFitter
- General Higgs couplings from modified version of HDecay
- Three scanning techniques:
  - Weighted Markov Chain
  - Cooling Markov Chain (equivalent to simulated annealing)
  - Gradient Minimisation (Minuit)
- Output of SFitter:
  - Fully-dimensional log-likelihood map
  - Reduction to plotable one- or two-dimensional distributions via both
    - Bayesian (marginalisation) or
    - Frequentist (profile likelihood) techniques
  - List of best points
- Already successfully used for SUSY parameter extraction study

[EPJC 54(2008) [arXiv:0709.3985]]
Higgs at the LHC

[Zeppenfeld, Kinnunen, Nikitenko, Richter-Was; Dührssen et al.]

<table>
<thead>
<tr>
<th>production</th>
<th>decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \rightarrow H$</td>
<td>$ZZ$</td>
</tr>
<tr>
<td>$qqH$</td>
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</tr>
<tr>
<td>$gg \rightarrow H$</td>
<td>$WW$</td>
</tr>
<tr>
<td>$qqH$</td>
<td>$WW$</td>
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<tr>
<td>$ttH$</td>
<td>$WW(3\ell)$</td>
</tr>
<tr>
<td>$\bar{t}tH$</td>
<td>$WW(2\ell)$</td>
</tr>
<tr>
<td>inclusive</td>
<td>$\gamma\gamma$</td>
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<tr>
<td>$qqH$</td>
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<td>$WH$</td>
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</tr>
<tr>
<td>$ZH$</td>
<td>$\gamma\gamma$</td>
</tr>
<tr>
<td>$qqH$</td>
<td>$\tau\tau(2\ell)$</td>
</tr>
<tr>
<td>$qqH$</td>
<td>$\tau\tau(1\ell)$</td>
</tr>
<tr>
<td>$\bar{t}tH$</td>
<td>$b\bar{b}$</td>
</tr>
</tbody>
</table>

WH/ZH | $bb$ (subjet)

Total width

- degeneracy $\sigma \cdot BR \propto g_p^2 g_a^2 \left( \frac{\Gamma}{\Gamma_H} \propto g^2 \right)$
- Here: $\Gamma_H = \sum_{SM} \Gamma_i$

$\int L dt = 2 \cdot 30$ fb$^{-1}$
Higgs at the LHC

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<td>$t\bar{t}H$</td>
<td>$bb$ (subjet)</td>
</tr>
</tbody>
</table>

Total width

- degeneracy $\sigma \cdot BR \propto g_p^2 g_d^2 \frac{1}{\Gamma_H} \quad (\Gamma_H \propto g^2)$
- Here: $\Gamma_H = \Sigma_{SM} \Gamma_i$
Error analysis

Errors obtained by 10,000 toy experiments:
SM hypothesis, $m_H = 120$ GeV, $\mathcal{L} = 30$ fb$^{-1}$
Fit with Gaussian of the central part within one standard deviation

<table>
<thead>
<tr>
<th></th>
<th>no eff. couplings</th>
<th>with eff. couplings</th>
<th>ratio $\Delta_{jjH}/WWH$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_{symm}$</td>
<td>$\sigma_{neg}$</td>
<td>$\sigma_{pos}$</td>
</tr>
<tr>
<td>$\Delta_{WWH}$</td>
<td>± 0.23</td>
<td>− 0.21 + 0.26</td>
<td>± 0.24</td>
</tr>
<tr>
<td>$\Delta_{ZZH}$</td>
<td>± 0.36</td>
<td>− 0.40 + 0.35</td>
<td>± 0.31</td>
</tr>
<tr>
<td>$\Delta_{ttH}$</td>
<td>± 0.41</td>
<td>− 0.37 + 0.45</td>
<td>± 0.53</td>
</tr>
<tr>
<td>$\Delta_{bbH}$</td>
<td>± 0.45</td>
<td>− 0.33 + 0.56</td>
<td>± 0.44</td>
</tr>
<tr>
<td>$\Delta_{\tau\tau H}$</td>
<td>± 0.33</td>
<td>− 0.21 + 0.46</td>
<td>± 0.31</td>
</tr>
<tr>
<td>$\Delta_{\gamma\gamma H}$</td>
<td>—</td>
<td>—</td>
<td>± 0.31</td>
</tr>
<tr>
<td>$\Delta_{ggH}$</td>
<td>—</td>
<td>—</td>
<td>± 0.61</td>
</tr>
</tbody>
</table>

$\mathcal{L} = 30$ fb$^{-1}$
with eff. couplings
SM hypothesis
Invisible vs. Unobserved

- Invisible Higgs decays actually observable
  - Vector-Boson Fusion: tagging jets plus missing $E_T$ [Eboli, Zeppenfeld]
  - $WH/ZH$: recoil against nothing [Choudhury, Roy; Godbole, Guchait, Mazumdar, Moretti, Roy]

- Unobservable decays into particles with large backgrounds (like $H \rightarrow \text{jets}$)
  - e.g. increased $ccH$ coupling (corresponding to 15.4 GeV Yukawa coupling)
Invisible vs. Unobserved

- Unobservable decays into particles with large backgrounds (like $H \to \text{jets}$)
  - e.g. increased $ccH$ coupling (corresponding to 15.4 GeV Yukawa coupling)
  - $\mathcal{L} = 30 \text{ fb}^{-1}$, SM data / increased $ccH$ / increased $ccH$ plus free width

$1/\chi^2$

- $\Delta_{WWH}$
- $\Delta_{ttH}$
- $\Delta_{ggH}$

$\text{free width only}$

- $Yc$
- SM 5.4 50 100

$\Delta_{\Gamma}$
The Higgs Portal

Additional hidden sector as singlet under SM gauge groups

Only possible connection to SM:

\[ \mathcal{L} \propto \Phi_s^\dagger \Phi_s \Phi_h^\dagger \Phi_h \]

\( \Phi_{s/h} \): Higgs field of SM/hidden sector

Electro-weak symmetry breaking:

\[ \phi_{s/h} \rightarrow (v_{s/h} + H_{s/h})/\sqrt{2} \]

\[ \sigma = \cos^2 \chi \cdot \sigma^{SM} \]

\[ \Gamma_{vis} = \cos^2 \chi \cdot \Gamma_{vis}^{SM} \]

\[ \Gamma_{inv} = \cos^2 \chi \cdot \Gamma_{inv}^{SM} + \Gamma_{hid} \]

\((\Gamma_{inv}^{SM}: \text{Decay } H \rightarrow ZZ \rightarrow 4\nu \text{ (negligible)} ) \)
The Higgs Portal

Fit of $\cos^2 \chi_{\text{fit}}$ without constraints

- No invisible decay modes
  $\cos^2 \chi_{\text{th}} = 1.0$

- $\cos^2 \chi_{\text{th}} = 0.8$

- $\cos^2 \chi_{\text{th}} = 0.6$

$\Rightarrow$ If $\cos^2 \chi_{\text{th}} < 0.6$ can exclude SM at the 95% CL with 30 $fb^{-1}$

- Measuring invisible decays in VBF-Higgs production
  Signature: Two VBF-jets plus missing $E_T$

$\Gamma_{\text{hid}} = \sin^2 \chi \cdot \Gamma_{\text{tot}}^{\text{SM}}$ (rhs: $\cos^2 \chi_{\text{th}} = 0.6$)
Observation Bias

Significant backgrounds in Higgs measurement channels

- Measure signal plus background in signal region
- Extrapolate background from signal-free control regions (sidebands, etc.) and subtract
- Background from theory typically not better
- ⇒ B from control regions can be larger than S+B in signal region

positive number of signal events

\[
S > 2 \times \Delta S \quad \text{for nominal SM rate}
\]

\[
S > 2 \times \Delta S \quad \text{for actual rate}
\]

⇒ Careful treatment necessary
Observation of Higgs bosons favors larger couplings
Cross-check using all predicted channels
Strongly-Interacting Light Higgs

Higgs pseudo-Goldstone boson of new strongly interacting sector
Modifications parametrized by $\xi = (v/f)^2$ (f: Goldstone scale)

**MCHM4:**
Scaling of all couplings with $\sqrt{1 - \xi}$
$\Rightarrow$ Identify $\cos^2 \chi = 1 - \xi$
$\Gamma_{hid} = 0$

**MCHM5:**
Scaling:

$g_{VVH} = g_{VVH}^{SM} \cdot \sqrt{1 - \xi}$
$g_{f\bar{f}H} = g_{f\bar{f}H}^{SM} \cdot \frac{1-2\xi}{\sqrt{1-\xi}}$

Significant and observable deviations also in Higgs self-couplings

[Giudice, Grojean, Pomarol, Rattazzi; Espinosa, Grojean, Mühlleitner]

[Gröber, Mühlleitner]
Secondary solutions appear (sign of $\bar{f}fH$ coupling)

$m_H = 120$ GeV

$m_H = 160$ GeV

$m_H = 200$ GeV

$\mathcal{L} = 300$ fb$^{-1}$

Gluon fusion $H \rightarrow \gamma\gamma$

$WH/ZH, H \rightarrow b\bar{b}$

Not a true degeneracy
→ Each (smeared) toy experiment has unique solution
Secondary solutions appear (sign of $\bar{t}tH$ coupling)

$m_H = 120$ GeV

$m_H = 160$ GeV

$m_H = 200$ GeV

Independent fit of common vector and fermion couplings

Not a true degeneracy

$\rightarrow$ Each (smeared) toy experiment has unique solution
Conclusions

- Determining the Higgs-boson couplings next step after discovery
  Important for our understanding of electroweak symmetry breaking
- Independent of explicit realisation of new physics (if any):
  Standard Model with effective Higgs couplings
- Expected accuracy of 20 – 50% in Standard Model at 30 fb$^{-1}$
- Recent jet substructure analysis significantly improves
  result on bottom-quark coupling
- Influences accuracy of all other couplings via total width
- Extended Models (Portal Higgs, SILH) can lead to simple one-parameter
  deviations which can be tested
- Beware of observation bias and degenerate solutions
Higgs production modes

Main Higgs-boson production modes:

- gluon-gluon fusion

- vector-boson fusion

- associated production with gauge bosons

- associated production with top-quark–antiquark pair
Higgs decay modes

- $H \rightarrow b\bar{b}$
  - main decay mode ($\sim 90\%$) for light Higgs bosons, as suggested by electroweak precision data
  - hard to extract from QCD backgrounds
  - recent suggestion of $WH/ZH$ production plus jet substructure analysis looks promising
    (3.7$\sigma$ @ 30 fb$^{-1}$ & 14 TeV)
    [Butterworth, Davison, Rubin, Salam; ATL-PHYS-PUB-088]
- $H \rightarrow \tau\bar{\tau}$
  - need to reconstruct invariant mass of the two taus
  - limits production channel to vector-boson fusion
  - one of the discovery channels for light Higgs bosons
    [Plehn, Rainwater, Zeppenfeld]
- $H \rightarrow WW$
- $H \rightarrow ZZ$
- $H \rightarrow \gamma\gamma$
Higgs decay modes

- $H \rightarrow b\bar{b}$
- $H \rightarrow \tau\bar{\tau}$
- $H \rightarrow WW$
  - main decay mode for heavier Higgs bosons ($m_H \gtrsim 140$ GeV)
  - gluon and vector-boson fusion relevant even if $Ws$ are off-shell
- $H \rightarrow ZZ$
  - “Golden Channel” due to four-lepton final state
  - statistically limited to larger Higgs masses
- $H \rightarrow \gamma\gamma$
Higgs decay modes

- $H \rightarrow b\bar{b}$
- $H \rightarrow \tau\bar{\tau}$
- $H \rightarrow WW$
- $H \rightarrow ZZ$
- $H \rightarrow \gamma\gamma$

- Loop-induced coupling by (mainly) $W$ and $t$
- Only fully reconstructable channel for a light Higgs boson
- Small branching ratio ($\lesssim 0.2\%$)
- Promising discovery channel for light Higgs bosons, background can be subtracted via sidebands
- Higgs mass measurement up to 100 MeV

Graph showing branching ratios as a function of $M_H$ [GeV].

Discovery prospects for 7 and 8 TeV

Graph showing significance, $\sigma$, as a function of mass [GeV] for 7 and 8 TeV LHC.
Discovering the Higgs boson

Tevatron results

Prospects for 7 and 8 TeV

M. Rauch – Measuring the Higgs boson couplings

June 1st, 2011
**Higgs at the LHC**

**Input data**  
[Dührrsen (ATL-PHYS-2002-030), ATLAS CSC Note; CMS results comparable]  
\[ m_H = 120 \text{ GeV}; \quad \mathcal{L} = 30 \text{ fb}^{-1} \]

<table>
<thead>
<tr>
<th>production ( gg \rightarrow H )</th>
<th>decay ( S + B )</th>
<th>( S )</th>
<th>( \Delta S^{(\text{exp})} )</th>
<th>( \Delta S^{(\text{theo})} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( gg \rightarrow H )</td>
<td>( ZZ )</td>
<td>13.4</td>
<td>6.6 (( \times 5 ))</td>
<td>6.8</td>
</tr>
<tr>
<td>( qqH )</td>
<td>( ZZ )</td>
<td>1.0</td>
<td>0.2 (( \times 5 ))</td>
<td>0.8</td>
</tr>
<tr>
<td>( gg \rightarrow H )</td>
<td>( WW )</td>
<td>1019.5</td>
<td>882.8 (( \times 1 ))</td>
<td>136.7</td>
</tr>
<tr>
<td>( qqH )</td>
<td>( WW )</td>
<td>59.4</td>
<td>37.5 (( \times 1 ))</td>
<td>21.9</td>
</tr>
<tr>
<td>( t\bar{t}H )</td>
<td>( WW(3\ell) )</td>
<td>23.9</td>
<td>21.2 (( \times 1 ))</td>
<td>2.7</td>
</tr>
<tr>
<td>( \bar{t}tH )</td>
<td>( WW(2\ell) )</td>
<td>24.0</td>
<td>19.6 (( \times 1 ))</td>
<td>4.4</td>
</tr>
<tr>
<td>inclusive</td>
<td>( \gamma\gamma )</td>
<td>12205.0</td>
<td>11820.0 (( \times 10 ))</td>
<td>385.0</td>
</tr>
<tr>
<td>( qqH )</td>
<td>( \gamma\gamma )</td>
<td>38.7</td>
<td>26.7 (( \times 10 ))</td>
<td>12.0</td>
</tr>
<tr>
<td>( t\bar{t}H )</td>
<td>( \gamma\gamma )</td>
<td>2.1</td>
<td>0.4 (( \times 10 ))</td>
<td>1.7</td>
</tr>
<tr>
<td>( WH )</td>
<td>( \gamma\gamma )</td>
<td>2.4</td>
<td>0.4 (( \times 10 ))</td>
<td>2.0</td>
</tr>
<tr>
<td>( ZH )</td>
<td>( \gamma\gamma )</td>
<td>1.1</td>
<td>0.7 (( \times 10 ))</td>
<td>0.4</td>
</tr>
<tr>
<td>( qqH )</td>
<td>( \tau\tau(2\ell) )</td>
<td>26.3</td>
<td>10.2 (( \times 2 ))</td>
<td>16.1</td>
</tr>
<tr>
<td>( qqH )</td>
<td>( \tau\tau(1\ell) )</td>
<td>29.6</td>
<td>11.6 (( \times 2 ))</td>
<td>18.0</td>
</tr>
<tr>
<td>( t\bar{t}H )</td>
<td>( b\bar{b} )</td>
<td>244.5</td>
<td>219.0 (( \times 1 ))</td>
<td>25.5</td>
</tr>
<tr>
<td>( WH/ZH )</td>
<td>( b\bar{b} )</td>
<td>228.6</td>
<td>180.0 (( \times 1 ))</td>
<td>48.6</td>
</tr>
</tbody>
</table>

Last line obtained using subjet techniques ([Butterworth, Davison, Rubin, Salam]),  
thetheoretical results confirmed by ATLAS ([ATL-PHYS-PUB-2009-088])  
(stricter cuts, statistical significance basically unchanged)
Distribution of parameters

One-dimensional distributions
- Slow-falling distributions with single peaks prefer profile likelihood
- Higher luminosity qualitatively similar, quantitatively better
- Including effective couplings allows sign degeneracy for $ttH$ coupling
- Smearing the dataset does not change picture substantially either

True dataset, 30 fb$^{-1}$; Profile likelihood vs. Bayesian
Distribution of parameters

One-dimensional distributions

- Slow-falling distributions with single peaks prefer profile likelihood
- Higher luminosity qualitatively similar, quantitatively better
- Including effective couplings allows sign degeneracy for $ttH$ coupling
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True dataset, Profile likelihood; $30 \text{ fb}^{-1}$ vs. $300 \text{ fb}^{-1}$

![Histograms of $\Delta_{WWH}$, $\Delta_{ttH}$, and $\Delta_{bbH}$]
Distribution of parameters

One-dimensional distributions

- Slow-falling distributions with single peaks prefer profile likelihood
- Higher luminosity qualitatively similar, quantitatively better
- Including effective couplings allows sign degeneracy for $ttH$ coupling
- Smearing the dataset does not change picture substantially either

True dataset, Profile likelihood, 30 fb$^{-1}$; Without vs. including eff. couplings
Distribution of parameters

One-dimensional distributions

- Slow-falling distributions with single peaks prefer profile likelihood
- Higher luminosity qualitatively similar, quantitatively better
- Including effective couplings allows sign degeneracy for $ttH$ coupling
- Smearing the dataset does not change picture substantially either

Profile likelihood, 30 fb$^{-1}$; True vs. smeared dataset
Non-decoupling Supersymmetric Higgs

SPS1a-inspired scenario with
\[ t_β = 7, \quad A_t = -1100 \text{ GeV}, \quad m_A = 151 \text{ GeV}, \quad m_{h^0} = 120 \text{ GeV} \]

LHC data set with \( \mathcal{L} = 30 \text{ fb}^{-1} \), Profile likelihood, True dataset

\[
\frac{1}{\Delta \chi^2} \quad \text{true: } -0.13 \quad -0.19 \quad 3.27 \quad 3.29 \quad -0.28 = \Delta
\]

- Clear deviation from Standard Model:
  \[ q(d_{\text{SUSY}}|m_{\text{SM}}) < q(d_{\text{SM}}|m_{\text{SM}}) : 77\% \text{ at } 90\% \text{ CL} \]
- Favouring of new physics more difficult: only 4\% better described by SUSY model
- Strong correlation between \( \Delta_{bbH} \) and \( \Delta_{\tau \tau H} \) via total width
- No upper limit on \( g_{bbH} \) as \( BR \approx 1 \) compatible with data
Fat Jets

- Decay into $b\bar{b}$ main channel for light Higgs ($\sim 80\%$)
- Suffers from large QCD backgrounds $\rightarrow$ Use high-$p_T$ region
  - Higgs and $W/Z$ more likely to be central, $Z \rightarrow \nu\bar{\nu}$ visible
  - $t\bar{t}$ kinematics cannot simulate background
  - Much smaller cross section ($1/20$ for $p_T(H) > 200$ GeV)
  - $R \gtrsim \frac{3m_H}{p_T}$: resolve one jet in 75% of cases

- Algorithm to find fat jet”:
  0. Start with high-$p_T$ jet (Cambridge/Aachen algorithm)
  1. Undo last stage of clustering ($\equiv$ reduce $R$): $J \rightarrow J_1, J_2$
  2. If $\max(m_1, m_2) \lesssim 0.67m$, call this a mass drop
  3. Require $y_{12} = \frac{\min(p_{T1}^2, p_{T2}^2)}{m_{T12}^2} \Delta R_{12} \simeq \frac{\min(z_1, z_2)}{\max(z_1, z_2)} > 0.09$
  4. Require each subjet to have b-tag
  5. Filter the jet: Reconsider region of interest at smaller $R_{\text{filt}} = \min(0.3, R_{bb}/2)$
  6. Take 3 hardest subjets

[Butterworth, Davison, Rubin, Salam]
Fat Jets in Higgs channels

- **WH/ZH**
  - [Butterworth, Davison, Rubin, Salam; ATLAS]
  - ATLAS $\mathcal{L} = 30 \text{ fb}^{-1}$, $m_H = 120$ GeV
  - Significance:
    - No systematics: 3.7
    - 15% systematics: 3.0

- **$t\bar{t}H$**
- **$H$ plus new physics (SUSY, . . .)**

- [Plehn, Salam, Spannowsky]
- [Kribs, Martin, Roy, Spannowsky]
Fat Jets in Higgs channels

- **WH/ZH**
  
  ![Graph](attachment:image1.png)
  
  [Butterworth, Davison, Rubin, Salam; ATLAS]
  
  ATLAS $\mathcal{L} = 30 \text{ fb}^{-1}$, $m_H = 120$ GeV
  
  Significance:
  
  - No systematics: 3.7
  - 15% systematics: 3.0

- **$\bar{t}tH$**
  
  ![Graph](attachment:image2.png)
  
  [Plehn, Salam, Spannowsky]
  
  \[
  \begin{array}{c|ccc|c}
  \mathcal{L} & S & B & S/B & S/\sqrt{B} \\
  \hline
  \bar{t}\bar{t}H & 100 \text{ fb}^{-1} & 57 & 118 & 1/2.1 & 5.2 \\
  m_H = 115 \text{ GeV} & 120 \text{ GeV} & 48 & 115 & 1/2.4 & 4.5 \\
  & 130 \text{ GeV} & 29 & 103 & 1/3.6 & 2.9 \\
  \end{array}
  \]

- **$H$ plus new physics (SUSY, ...)**
  
  [Kribs, Martin, Roy, Spannowsky]