Higgs couplings after Moriond EW

Béranger Dumont (LPSC Grenoble)

based on:

Rencontres de Moriond – QCD and High Energy Interactions
March 14, 2013
The Higgs boson has been found

- previous updates at HCP2012 in Kyoto (in November) and at the open session of the CERN Council (in December)
- and now Moriond!
- Tevatron is very competitive for $H\rightarrow bb$ and results are not yet final
Standard Model Higgs... or New Physics?

(taken from Alexey Drozdetskiy's talk at HCP2012)
What we know about it before Moriond

\[ \mu_i = \frac{\left[ \sum_j \sigma_{j \to h} \times Br(h \to i) \right]_{\text{observed}}}{\left[ \sum_j \sigma_{j \to h} \times Br(h \to i) \right]_{\text{SM}}} \]

- **ATLAS** Preliminary
  - \( W, Z \to bb \)
    - \( \sqrt{s} = 7 \text{ TeV}, \ \text{L}\text{dt} = 4.7 \text{ fb}^{-1} \)
    - \( \sqrt{s} = 8 \text{ TeV}, \ \text{L}\text{dt} = 13 \text{ fb}^{-1} \)
  - \( H \to \tau \tau \)
    - \( \sqrt{s} = 7 \text{ TeV}, \ \text{L}\text{dt} = 4.6 \text{ fb}^{-1} \)
    - \( \sqrt{s} = 8 \text{ TeV}, \ \text{L}\text{dt} = 13 \text{ fb}^{-1} \)
  - \( H \to WW^{(*)} \to 4l \)
    - \( \sqrt{s} = 7 \text{ TeV}, \ \text{L}\text{dt} = 4.6 \text{ fb}^{-1} \)
    - \( \sqrt{s} = 8 \text{ TeV}, \ \text{L}\text{dt} = 13 \text{ fb}^{-1} \)
  - \( H \to \gamma\gamma \)
    - \( \sqrt{s} = 7 \text{ TeV}, \ \text{L}\text{dt} = 4.8 \text{ fb}^{-1} \)
    - \( \sqrt{s} = 8 \text{ TeV}, \ \text{L}\text{dt} = 13 \text{ fb}^{-1} \)

- **Combination**
  - \( \mu = 1.33 \pm 0.24 \)

- **CMS** Preliminary
  - \( m_h = 125.8 \text{ GeV} \)

**Graph:***
- \( \sqrt{s} = 7 \text{ TeV}, \ \text{L} = 5.1 \text{ fb}^{-1} \)
- \( \sqrt{s} = 8 \text{ TeV}, \ \text{L} = 12.2 \text{ fb}^{-1} \)

**Legend:**
- \( H \to bb \) (VH tag)
- \( H \to bb \) (ttH tag)
- \( H \to \tau \tau \) (0/1 jet)
- \( H \to \tau \tau \) (VBF tag)
- \( H \to \tau \tau \) (VH tag)
- \( H \to \gamma\gamma \) (untagged)
- \( H \to \gamma\gamma \) (VBF tag)
- \( H \to WW \) (0/1 jet)
- \( H \to WW \) (VBF tag)
- \( H \to ZZ \) (VH tag)
What we know about it before Moriond

\[ \mu_i = \frac{\sum_j \sigma_{j \rightarrow h} \times Br(h \rightarrow i)}{\sum_j \sigma_{j \rightarrow h} \times Br(h \rightarrow i)} \]

**ATLAS Preliminary**

- \( W, Z \rightarrow bb \)
  - \( \sqrt{s} = 7 \text{ TeV}, \mathcal{L} = 4.7 \text{ fb}^{-1} \)
  - \( \sqrt{s} = 8 \text{ TeV}, \mathcal{L} = 13 \text{ fb}^{-1} \)
- \( H \rightarrow \tau \tau \)
  - \( \sqrt{s} = 7 \text{ TeV}, \mathcal{L} = 4.6 \text{ fb}^{-1} \)
  - \( \sqrt{s} = 8 \text{ TeV}, \mathcal{L} = 13 \text{ fb}^{-1} \)
- \( H \rightarrow WW^{(*)} \rightarrow 4l \)
  - \( \sqrt{s} = 7 \text{ TeV}, \mathcal{L} = 4.6 \text{ fb}^{-1} \)
  - \( \sqrt{s} = 8 \text{ TeV}, \mathcal{L} = 13 \text{ fb}^{-1} \)

**Combined**

- \( \mu = 1.33 \pm 0.24 \)
  - \( \sqrt{s} = 7 \text{ TeV}, \mathcal{L} = 4.6 - 4.8 \text{ fb}^{-1} \)
  - \( \sqrt{s} = 8 \text{ TeV}, \mathcal{L} = 13 \text{ fb}^{-1} \)

**CMS Preliminary**

- \( m_H = 125.8 \text{ GeV} \)
- \( \sqrt{s} = 7 \text{ TeV}, \mathcal{L} = 5.1 \text{ fb}^{-1} \)
- \( \sqrt{s} = 8 \text{ TeV}, \mathcal{L} = 12.2 \text{ fb}^{-1} \)

- \( H \rightarrow bb (VH \text{ tag}) \)
- \( H \rightarrow bb (ttH \text{ tag}) \)
- \( H \rightarrow \tau \tau (0/1 \text{ jet}) \)
- \( H \rightarrow \tau \tau (VBF \text{ tag}) \)
- \( H \rightarrow \tau \tau (VH \text{ tag}) \)
- \( H \rightarrow \gamma \gamma \) (untagged)
- \( H \rightarrow \gamma \gamma (VBF \text{ tag}) \)
- \( H \rightarrow WW (0/1 \text{ jet}) \)
- \( H \rightarrow WW (VBF \text{ tag}) \)
- \( H \rightarrow WW (VH \text{ tag}) \)
- \( H \rightarrow ZZ \)
What we know about it after Moriond EW

ATLAS

CMS Preliminary \( \sqrt{s} = 7 \text{ TeV}, L = 5.1 \text{ fb}^{-1}, \sqrt{s} = 8 \text{ TeV}, L = 19.6 \text{ fb}^{-1} \)

\( H \rightarrow ZZ \)

- \( \text{68\% CL} \)
- \( \text{95\% CL} \)
- \( \text{best fit} \)
- \( \text{SM} \)

\( m_H = 125.5 \text{ GeV} \)

\( \mu_{gF+ttH} \times B/B_{SM} \)

[ATLAS-CONF-2013-012]
[ATLAS-CONF-2013-013]
[ATLAS-CONF-2013-014]

CMS

WW 0/1-jet: \( \mu = 0.76 \pm 0.21 \)

[CMS-PAS-HIG-13-003]
Tevatron results

Tevatron (HCP2012)

How can we go beyond this information to understand what is in the data?

How well do we know the Higgs couplings?
Deviation from the SM Higgs

- We first need to specify a Lagrangian. Our choice:

\[ \mathcal{L} = g \left[ C_V \left( m_W W_\mu W^\mu + \frac{m_Z}{\cos \theta_W} Z_\mu Z^\mu \right) - C_U \frac{m_t}{2m_W} \bar{t}t - C_D \frac{m_b}{2m_W} \bar{b}b - C_D \frac{m_\tau}{2m_W} \bar{\tau}\tau \right] H \]

Scaling factors \( C \) parametrize deviations from the SM

- We calculate \( \overline{C}_g \) (for gluon-gluon fusion) and \( \overline{C}_\gamma \) (for \( H \rightarrow \gamma\gamma \)) from \( C_U, C_D, C_V \)
  and we allow for additional particles in the loop: \( \Delta C_g \) and \( \Delta C_\gamma \)

\[ \rightarrow C_g = \overline{C}_g + \Delta C_g \quad \text{and} \quad C_\gamma = \overline{C}_\gamma + \Delta C_\gamma \]

- Total Higgs width: a priori not accessible at the LHC
  \( \rightarrow \) we can in general only determine ratio of couplings
  ... or fix an invisible/undetected Higgs width
Fitting procedure

- simple $\chi^2$ fit: $\chi^2 = \sum_k \frac{(\mu_k - \mu_k^{\text{exp}})^2}{\Delta \mu_k^2}$
- when we use ($\mu_{ggF+ttH}$, $\mu_{VBF+VH}$) information we take into account correlations
- $\mu_k$: rescaling of the SM prediction (given by the LHC Higgs XS WG)
- we take into account the different efficiencies for the various production mechanisms
- when showing contours of $\Delta \chi^2$: we profile the likelihood over the unseen parameters
A word on $H \rightarrow \gamma \gamma$

- contribution from the $W$ is 5 times larger than from the top quark and with opposite sign
- small contributions from bottom and lighter quarks
- new particles in the loop could change the $H \gamma \gamma$ rate (e.g. charged Higgses, charginos, staus, ...)

Moriond QCD  Béranger Dumont  March 14, 2013
1) $\Delta C_g, \Delta C_\gamma$ fit

- we assume $C_U = C_D = C_V = 1$ — $\Delta C_g$ and $\Delta C_\gamma$ are free to vary
  → new physics as additional particles in the loops
- relevant in the context of Universal Extra Dimensions, VLQ, ...

- SM: 2.2$\sigma$ away from best fit due to the excess in $H \rightarrow \gamma\gamma$
- Observed gluon-gluon fusion rate well compatible with the SM
II) $C_U$, $C_D$, $C_V$ fit

- we assume $\Delta C_g = \Delta C_\gamma = 0$ — $C_U$, $C_D$ and $C_V$ are free to vary
  $\rightarrow$ modified Higgs sector + no new particles in the loops
- can arise with extended Higgs sectors (e.g. 2HDM with heavy $H^+$)

- SM: 1.6$\sigma$ away from best fit due to the excess in $H\rightarrow\gamma\gamma$
- $C_U < 0$ (sign opposite to $C_V$)
  $\Rightarrow$ constructive interference with $W$
  preferred at the level of 1.8$\sigma$
- $C_D$ compatible with the SM
  (up to a minus sign)
II) $C_U, C_D, C_V$ fit

- $C_V$ tend to be larger for $C_U > 0$
- Strong correlation between $C_\gamma$ and $C_V$

Single top production in association with a Higgs boson could soon discriminate $C_U > 0$ and $C_U < 0$ [Biswas, Gabrielli and Mele '12; Farina et al. '12]
III) $C_U$, $C_D$, $C_V$, $\Delta C_g$, $\Delta C_\gamma$ fit

- general case: $C_U$, $C_D$, $C_V$, $\Delta C_g$ and $\Delta C_\gamma$ are free to vary
- encompasses a very broad class of models (incl. Higgs sector made of any number of doublets + singlets)

- $C_\gamma > 1$ is achieved with $\Delta C_\gamma > 0$
- anticorrelation between $C_U$ and $\Delta C_g$
III) \( C_U, C_D, C_V, \Delta C_g, \Delta C_\gamma \) fit

- general case: \( C_U, C_D, C_V, \Delta C_g \) and \( \Delta C_\gamma \) are free to vary
- encompasses a very broad class of models
  (incl. Higgs sector made of any number of doublets + singlets)

\[ \text{assuming } \mu(ttH) = 1 \pm 0.3 \]

\( C > 1 \) is achieved with \( \Delta C_\gamma > 0 \)

anticorrelation between \( C_U \) and \( \Delta C_g \)
16

III) $C_U, C_D, C_V, \Delta C_g, \Delta C_\gamma$ fit

- SM: $1.4\sigma$ away from best fit due to the excess in $H \rightarrow \gamma\gamma$
- the determination of $C_V$ is robust
- balance between $C_U$ and $\Delta C_\gamma$
Goodness-of-fit

<table>
<thead>
<tr>
<th>Fit</th>
<th>Standard Model</th>
<th>$\Delta C_\gamma$, $\Delta C_g$</th>
<th>$C_U$, $C_D$, $C_V$</th>
<th>$C_U$, $C_D$, $C_V$, $\Delta C_\gamma$, $\Delta C_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2_{\text{min}}$</td>
<td>22.1</td>
<td>15.1</td>
<td>16.2</td>
<td>14.4</td>
</tr>
<tr>
<td>$\chi^2_{\text{min}}$/d.o.f.</td>
<td>0.96</td>
<td>0.72</td>
<td>0.81</td>
<td>0.80</td>
</tr>
<tr>
<td>dominant contributions to $\chi^2_{\text{min}}$</td>
<td>ATLAS $\gamma\gamma$</td>
<td>ATLAS $ZZ$</td>
<td>ATLAS $ZZ$</td>
<td>ATLAS $ZZ$</td>
</tr>
<tr>
<td></td>
<td>CMS $\gamma\gamma$</td>
<td>CMS $WW$ VBF</td>
<td>Tevatron $\gamma\gamma$</td>
<td>CMS $\gamma\gamma$</td>
</tr>
<tr>
<td></td>
<td>Tevatron $\gamma\gamma$</td>
<td>Tevatron $\gamma\gamma$</td>
<td>Tevatron $\gamma\gamma$</td>
<td>Tevatron $\gamma\gamma$</td>
</tr>
</tbody>
</table>

- significant improvement of $\chi^2$/d.o.f. (hence the $p$-value) when allowing for an enhanced $H_{\gamma\gamma}$ rate
- no amelioration of the fit from 2 to 5 parameters
Invisible decays of the Higgs boson before Moriond EW

\[ \Delta \chi^2 \]

\[ \mathcal{B}(H \rightarrow \text{inv.}) \leq 0.23 \text{ at 95\% CL} \]

\[ \mathcal{B}(H \rightarrow \text{inv.}) \leq 0.36 \text{ at 95\% CL} \]

\[ \mathcal{B}(H \rightarrow \text{inv.}) \leq 0.61 \text{ at 95\% CL} \]

\[ \mathcal{B}(H \rightarrow \text{inv.}) \leq 0.88 \text{ at 95\% CL} \]

it needs to be updated with the Moriond results already shown, but not only...
Searches for invisible decays of the Higgs boson

$ZH \rightarrow \ell\ell + \text{invisible}$

$\mathcal{B}(H \rightarrow \text{inv.}) < 0.65$ at 95\% CL

[ATLAS-CONF-2013-011]
Searches for invisible decays of the Higgs boson

$ZH \rightarrow \ell\ell + \text{invisible}$

$C_V^2 \mathcal{B}(H \rightarrow \text{inv.}) < 0.65 \text{ at } 95\% \text{ CL}$

see also earlier studies based on e.g. monojet searches [Djouadi et al. '12]
Invisible decays of the Higgs boson after Moriond EW

If invisible = dark matter:
interplay between direct searches and H → invisible
(see backup)
Conclusion/Outlook

• better fit to the data are possible with enhanced $H\rightarrow\gamma\gamma$
  ... future will tell us whether it is a fluke or New Physics

• enhanced $H\rightarrow\gamma\gamma$ can be accommodated with:
  • $C_u \approx -C_v$ (difficult to achieve in a realistic model)
  • $\Delta C_\gamma > 0$ (light non-SM electrically charged particles)

• results from this morning have to be taken into account
  (effect of CMS $H\rightarrow\gamma\gamma$ on the excess?)

• many New Physics models to explore in light of what we learned on
  the 125 GeV Higgs boson!
Invisible decays of the Higgs boson and dark matter

Majorana dark matter

scalar dark matter
Pre-Moriond experimental data we use

<table>
<thead>
<tr>
<th>Channel</th>
<th>Signal strength $\mu$</th>
<th>$M_H$ (GeV)</th>
<th>Production mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$ (4.8 fb$^{-1}$ at 7 TeV + 13.0 fb$^{-1}$ at 8 TeV) [4]</td>
<td>1.85 ± 0.52</td>
<td>126.6</td>
<td>100% VBF VH ttH</td>
</tr>
<tr>
<td>$\mu(ggF + ttH, \gamma\gamma)$</td>
<td>2.01 ± 1.23</td>
<td>126.6</td>
<td>60% 40%</td>
</tr>
<tr>
<td>$H \rightarrow ZZ$ (4.6 fb$^{-1}$ at 7 TeV + 13.0 fb$^{-1}$ at 8 TeV) [6,11]</td>
<td>1.01$^{+0.45}_{-0.40}$</td>
<td>125</td>
<td>87% 7% 5% 1%</td>
</tr>
<tr>
<td>Inclusive $H \rightarrow WW$ (13.0 fb$^{-1}$ at 8 TeV) [8,11]</td>
<td>1.42$^{+0.58}_{-0.54}$</td>
<td>125.5</td>
<td>95% 3% 2%</td>
</tr>
<tr>
<td>$H \rightarrow bb$ (4.7 fb$^{-1}$ at 7 TeV + 13.0 fb$^{-1}$ at 8 TeV) [11,50]</td>
<td>-0.39 ± 1.02</td>
<td>125.5</td>
<td>100%</td>
</tr>
<tr>
<td>VH tag $H \rightarrow \tau\tau$ (4.6 fb$^{-1}$ at 7 TeV + 13.0 fb$^{-1}$ at 8 TeV) [51]</td>
<td>2.41 ± 1.57</td>
<td>125</td>
<td>100%</td>
</tr>
<tr>
<td>$\mu(ggF, \tau\tau)$</td>
<td>-0.26 ± 1.02</td>
<td>125</td>
<td>60% 40%</td>
</tr>
</tbody>
</table>

**ATLAS Preliminary**

- Best fit
- 68% CL
- 95% CL
- SM

**2011-2012**

$m_h = 126.6 \text{ GeV}$
Pre-Moriond experimental data we use

CMS

<table>
<thead>
<tr>
<th>Channel</th>
<th>Signal strength $\mu$</th>
<th>$M_H$ (GeV)</th>
<th>Production mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$ggF$</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$ (5.1 fb$^{-1}$ at 7 TeV + 5.3 fb$^{-1}$ at 8 TeV) [2, 5, 12]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu(ggF + t\bar{t}H, \gamma\gamma)$</td>
<td>$0.95 \pm 0.65$</td>
<td>125.8</td>
<td>100%</td>
</tr>
<tr>
<td>$\mu(VBF + VH, \gamma\gamma)$</td>
<td>$3.77 \pm 1.75$</td>
<td>125.8</td>
<td>--</td>
</tr>
<tr>
<td>$H \rightarrow ZZ$ (5.1 fb$^{-1}$ at 7 TeV + 12.2 fb$^{-1}$ at 8 TeV) [7, 12]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inclusive</td>
<td>$0.81^{+0.35}_{-0.28}$</td>
<td>125.8</td>
<td>87%</td>
</tr>
<tr>
<td>$H \rightarrow WW$ (up to 4.9 fb$^{-1}$ at 7 TeV + 12.1 fb$^{-1}$ at 8 TeV) [10, 12, 52]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0/1 jet</td>
<td>$0.77^{+0.27}_{-0.25}$</td>
<td>125.8</td>
<td>97%</td>
</tr>
<tr>
<td>VBF tag</td>
<td>$-0.05^{+0.74}_{-0.55}$</td>
<td>125.8</td>
<td>17%</td>
</tr>
<tr>
<td>VH tag</td>
<td>$-0.31^{+2.22}_{-1.94}$</td>
<td>125.8</td>
<td>--</td>
</tr>
<tr>
<td>$H \rightarrow bb$ (up to 5.0 fb$^{-1}$ at 7 TeV + 12.1 fb$^{-1}$ at 8 TeV) [12, 53, 54]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VH tag</td>
<td>$1.31^{+0.65}_{-0.60}$</td>
<td>125.8</td>
<td>--</td>
</tr>
<tr>
<td>ttH tag</td>
<td>$-0.80^{+2.10}_{-1.84}$</td>
<td>125.8</td>
<td>--</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$ (up to 5.0 fb$^{-1}$ at 7 TeV + 12.1 fb$^{-1}$ at 8 TeV) [12, 55, 56]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0/1 jet</td>
<td>$0.85^{+0.086}_{-0.066}$</td>
<td>125.8</td>
<td>76%</td>
</tr>
<tr>
<td>VBF tag</td>
<td>$0.82^{+0.82}_{-0.75}$</td>
<td>125.8</td>
<td>19%</td>
</tr>
<tr>
<td>VH tag</td>
<td>$0.86^{+1.92}_{-1.68}$</td>
<td>125.8</td>
<td>--</td>
</tr>
</tbody>
</table>
## Pre-Moriond experimental data we use

Tevatron

<table>
<thead>
<tr>
<th>Channel</th>
<th>Signal strength $\mu$</th>
<th>$M_H$ (GeV)</th>
<th>$H \rightarrow \gamma\gamma$ [59]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined</td>
<td>$6.14^{+3.25}_{-3.19}$</td>
<td>125</td>
<td>78% 5% 17% –</td>
</tr>
<tr>
<td>$H \rightarrow WW$ [59]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined</td>
<td>$0.85^{+0.88}_{-0.81}$</td>
<td>125</td>
<td>78% 5% 17% –</td>
</tr>
<tr>
<td>$H \rightarrow bb$ [14]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VH tag</td>
<td>$1.56^{+0.72}_{-0.73}$</td>
<td>125</td>
<td>– – 100% –</td>
</tr>
</tbody>
</table>
II) $C_U, C_D, C_V$ fit

$\Delta \chi^2$ vs $C_U$

$C_U > 0, C_D > 0, C_V$ fit

$C_D$ vs $C_U$
Two Higgs Doublet Model

- Model-dependent study: 2HDM type I and II
- 2 parameters (angles): $\alpha$ and $\beta$

<table>
<thead>
<tr>
<th>Higgs</th>
<th>Type I and II</th>
<th>Type I</th>
<th>Type II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$</td>
<td>$\sin(\beta - \alpha)$</td>
<td>$\cos \alpha / \sin \beta$</td>
<td>$\cos \alpha / \sin \beta$</td>
</tr>
<tr>
<td>$H$</td>
<td>$\cos(\beta - \alpha)$</td>
<td>$\sin \alpha / \sin \beta$</td>
<td>$\sin \alpha / \sin \beta$</td>
</tr>
<tr>
<td>$A$</td>
<td>0</td>
<td>$\cot \beta$</td>
<td>$\cot \beta$</td>
</tr>
</tbody>
</table>

- in both cases we have:
  - $|C_V| < 1$
  - $|C_U| < 1.4$ if $\tan \beta > 1$

- both $h$ and $H$ could be the 125.5 GeV observed state
Two Higgs Doublet Model results

Moriond QCD

Béranger Dumont

March 14, 2013