QCD Tools for LHC Physics: From 8 to 14 TeV. What is needed and why?
November 15th, 2013
Markus Klute (MIT)

Higgs Coupling Measurements at 8 and 14 TeV
First three year of the LHC

\[ N_{\text{evt}} = \sigma \cdot L_{\text{int}} \]

Higgs Discovery

2010 7 TeV
2011 7 TeV
2012 8 TeV
The Large Hadron Collider (LHC) at CERN, Switzerland
LHC Roadmap

The Large Hadron Collider (LHC) at CERN, Switzerland

The Large Hadron Collider (LHC) at CERN, Switzerland
Higgs production and decay

**Process** | **Diagram** | **Cross section [fb]** | **Unc. [%]**
---|---|---|---
Gluon-gluon fusion | ![Gluon-Gluon Fusion Diagram](image1) | 19520 | 15
Vector boson fusion | ![Vector Boson Fusion Diagram](image2) | 1578 | 3
WH | ![WH Diagram](image3) | 697 | 4
ZH | ![ZH Diagram](image4) | 394 | 5
ttH | ![ttH Diagram](image5) | 130 | 15

**m_H = 125 GeV**

<table>
<thead>
<tr>
<th>Decay</th>
<th>BR [%]</th>
<th>Unc. [%]</th>
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<td>(\Gamma_H) [MeV]</td>
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* uncertainties need improvements for future precision measurements
### Status of Higgs physics program

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<tr>
<td>$H \rightarrow ZZ \rightarrow 4l$</td>
<td>4.6+20.7</td>
<td>5.1+19.6</td>
<td>mass, discovery, spin/parity</td>
<td>4 leptons</td>
<td>6.6 (4.4)</td>
<td>124.3 ±0.6 (stat) ±0.5 (sys)</td>
<td>1.5 ± 0.4</td>
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<td>4.6+20.7</td>
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<td>cross section, coupling</td>
<td>2 leptons, MET</td>
<td>3.8 (3.7)</td>
<td>consistent</td>
<td>0.99+0.31-0.32</td>
<td>√</td>
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<td>126.8 ±0.2 (stat) ±0.7 (sys)</td>
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<td>coupling to fermions</td>
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<td>consistent</td>
<td>0.2+0.7-0.6</td>
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<td>1.1 (1.7)</td>
<td>consistent</td>
<td>0.8 ± 0.7</td>
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Status of Higgs studies at CMS

Fantastic progress since discovery July 2012
- Observation in three bosonic channels
- Evidence for fermion couplings
- Precision mass measurement
- Spin determined
- Looks more and more like the SM Higgs boson
- No evidence for non-SM decays
- No evidence for additional Higgs boson

Summary of the Higgs boson properties
- Mass
  - \( M = 125.7 \pm 0.3 \pm 0.3 \text{ GeV} \)
  - 0.5% precision
- Signal strength
  - \( \mu = 0.80 \pm 0.14 \)
- Spin/CP
  - \( J^{CP} = 0^{++} \) (SM-like Higgs boson) preferred
  - \( 0^{-+} (2^{++}) \) disfavored
Status of Higgs studies at ATLAS

Fantastic progress since discovery July 2012

• Observation in three bosonic channels

• Precision mass measurement
• Spin determined
• Looks more and more like the SM Higgs boson
• No evidence for non-SM decays
• No evidence for additional Higgs boson

Summary of the Higgs boson properties

• Mass
  • $M = 125.5 \pm 0.2 \pm 0.6$ GeV
  • 0.5% precision
• Signal strength
  • $\mu = 1.30 \pm 0.20$
• Spin/CP
  • $J^{CP} = 0^{++}$ (SM-like Higgs boson) preferred
  • $0^{+-} (2^{++})$ disfavored

Discovery opened a new era of Higgs precision measurements
Higgs signal strength

**ATLAS** Preliminary

- $W,Z \ H \rightarrow bb$
- $s = 7 \text{ TeV}: \ L\text{int} = 4.7 \text{ fb}^{-1}$
- $s = 8 \text{ TeV}: \ L\text{int} = 13 \text{ fb}^{-1}$
- $H \rightarrow \tau \tau$
- $s = 7 \text{ TeV}: \ L\text{int} = 4.6 \text{ fb}^{-1}$
- $s = 8 \text{ TeV}: \ L\text{int} = 13 \text{ fb}^{-1}$
- $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$
- $s = 7 \text{ TeV}: \ L\text{int} = 4.6 \text{ fb}^{-1}$
- $s = 8 \text{ TeV}: \ L\text{int} = 20.7 \text{ fb}^{-1}$
- $H \rightarrow \gamma \gamma$
- $s = 7 \text{ TeV}: \ L\text{int} = 4.8 \text{ fb}^{-1}$
- $s = 8 \text{ TeV}: \ L\text{int} = 20.7 \text{ fb}^{-1}$
- $H \rightarrow ZZ^{(*)} \rightarrow 4l$
- $s = 7 \text{ TeV}: \ L\text{int} = 4.6 \text{ fb}^{-1}$
- $s = 8 \text{ TeV}: \ L\text{int} = 20.7 \text{ fb}^{-1}$

**Combined**

- $\mu = 1.30 \pm 0.20$

**CMS Preliminary**

- $m_H = 125.7 \text{ GeV}$
- $p_{SM} = 0.65$

- $H \rightarrow bb$
  - $\mu = 1.15 \pm 0.62$

- $H \rightarrow \tau \tau$
  - $\mu = 1.10 \pm 0.41$

- $H \rightarrow \gamma \gamma$
  - $\mu = 0.77 \pm 0.27$

- $H \rightarrow WW$
  - $\mu = 0.68 \pm 0.20$

- $H \rightarrow ZZ$
  - $\mu = 0.92 \pm 0.28$

Combined: $\mu = 0.80 \pm 0.14$
### Sensitive Higgs channels

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<th>VH</th>
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<td>$H \to ZZ \to 4l$</td>
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<td>$H \to \mu\mu$</td>
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</table>

Measure rate of Higgs events with different production and decay combinations.

Cross-contamination of production and decay channels in categories.
# Sensitive Higgs channels

Measure rate of Higgs events with different production and decay combinations.

Cross-contamination of production and decay channels in categories.
**Coupling “Measurements”**

Investigate the consistency of the “new scalar boson” with the SM Higgs boson.

Assume the observed signal stems from one narrow resonance.

\[
(\sigma \cdot \text{BR}) (\ii \rightarrow H \rightarrow ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H}
\]

Parametrize deviations w.r.t. the SM in **production and decay**. This implies precise knowledge of the SM Higgs. Not considered are BSM acceptance effects.
Benchmarks fits and parameter choices

Probe interesting BSM physics scenarios directly in limited dataset

- one common scale factor
- scale vector and fermion coupling
- custodial symmetry
- new physics in loops
- BSM Higgs decays
- ...
Benchmarks fits and parameter choices

**ATLAS** Preliminary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1σ</th>
<th>2σ</th>
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<td>$\lambda_{FV}$</td>
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<td>$\kappa_{ZZ}$</td>
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<td>$\lambda_{W}$</td>
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<td>$\lambda_{Z}$</td>
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<td>$\lambda_{F}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\kappa_{Z}$</td>
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<tr>
<td>$\kappa_{g}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\kappa_{y}$</td>
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<tr>
<td>1-$\text{BR}_{BSM}$</td>
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</tbody>
</table>

$m_H = 125.5$ GeV

**CMS** Preliminary

- 68% CL
- 95% CL

- $p_{SM} = 0.37$
- $p_{SM} = 0.41$
- $p_{SM} = 0.39$
- $p_{SM} = 0.49$
- $p_{SM} = 0.23$
- $p_{SM} = 0.41$
General coupling fit

$K_g, K_\gamma$: loop diagrams $\rightarrow$ allow potential new physics

$K_V$: assume custodial symmetry

$K_t, K_b$: up- and down-type quarks

$K_\tau$: charged leptons

**total width from sum of partial widths**

Alternatively:

$$\Gamma_{tot} = \sum \Gamma_{ii} + \Gamma_{BSM} \quad BR_{BSM} = \frac{\Gamma_{BSM}}{\Gamma_{tot}}$$

assumption here $K_W, K_Z < 1$
Significant progress in $t\bar{t}H$ channel in CMS

- $H \rightarrow \gamma\gamma$ → HIG-13-015
- $H \rightarrow bb$ → HIG-13-019
- $H \rightarrow \tau\tau$ → HIG-13-019
- $H \rightarrow ZZ$ → HIG-13-020
- $H \rightarrow WW$

Sensitivity approaching SM Higgs, directly to top Yukawa coupling

$\mu = 2.5 \pm 1.1$
The Large Hadron Collider (LHC) at CERN, Switzerland
Potential for future LHC couplings fits

Assumptions on systematic uncertainties
Scenario 1: no change
Scenario 2: $\Delta$ theory / 2, rest $\propto 1/\sqrt{L}$

Based on parametric simulation
Extrapolated from 2011/12 results

**ATLAS Preliminary (Simulation)**

- $\sqrt{s} = 14$ TeV: $\int L dt = 300$ fb$^{-1}$ ; $\int L dt = 3000$ fb$^{-1}$
- $\int L dt = 300$ fb$^{-1}$ extrapolated from 7+8 TeV

- $H \rightarrow \mu\mu$
- $ttH, H \rightarrow \mu\mu$
- $VBF, H \rightarrow \tau\tau$
- $H \rightarrow ZZ$
- $VBF, H \rightarrow WW$
- $H \rightarrow WW$
- $VH, H \rightarrow \gamma\gamma$
- $ttH, H \rightarrow \gamma\gamma$
- $VBF, H \rightarrow \gamma\gamma$
- $H \rightarrow \gamma\gamma$ ($+j$)
- $H \rightarrow \gamma\gamma$

Relative uncertainty on signal rate $\frac{\Delta \mu}{\mu}$

**CMS Projection**

Expected uncertainties on Higgs boson signal strength

<table>
<thead>
<tr>
<th>L (fb$^{-1}$)</th>
<th>$H \rightarrow \gamma\gamma$</th>
<th>$H \rightarrow WW$</th>
<th>$H \rightarrow ZZ$</th>
<th>$H \rightarrow bb$</th>
<th>$H \rightarrow \tau\tau$</th>
<th>$H \rightarrow Z\gamma$</th>
<th>$H \rightarrow inv.$</th>
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<td>[6, 12]</td>
<td>[6, 11]</td>
<td>[7, 11]</td>
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<td>[4, 7]</td>
<td>[4, 7]</td>
<td>[5, 7]</td>
<td>[5, 8]</td>
<td>[20, 24]</td>
<td>[6, 17]</td>
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</table>
Higgs Boson coupling fits

\( \kappa_g, \kappa_Y, \kappa_{Z}\gamma \): loop diagrams \( \rightarrow \) allow potential new physics

\( \kappa_W, \kappa_Z \): vector bosons

\( \kappa_t, \kappa_b \): up- and down-type quarks

\( \kappa_{\tau}, \kappa_{\mu} \): charged leptons

total width from sum of partial widths

alternatively:

\[ \Gamma_{\text{tot}} = \sum \Gamma_{ii} + \Gamma_{\text{BSM}} \]

\[ \text{BR}_{\text{BSM}} = \Gamma_{\text{BSM}} / \Gamma_{\text{tot}} \]

assumption here \( \kappa_W, \kappa_Z < 1 \)

CMS Projection

<table>
<thead>
<tr>
<th>L (fb(^{-1}))</th>
<th>( \kappa_\gamma )</th>
<th>( \kappa_W )</th>
<th>( \kappa_Z )</th>
<th>( \kappa_g )</th>
<th>( \kappa_b )</th>
<th>( \kappa_t )</th>
<th>( \kappa_{\tau} )</th>
<th>( \kappa_{Z,\gamma} )</th>
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<td>[7,10]</td>
<td>[2,5]</td>
<td>[10,12]</td>
<td>[8,8]</td>
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</table>

coupling precision 2-10 \% factor of \( \sim 2 \) improvement from HL-LHC

Theoretical uncertainties

To test the importance of theoretical uncertainties we show the effect of removing them.

Theoretical uncertainties dominated by QCD scale and PDF uncertainties. Uncertainty on BR and acceptance uncertainties become relevant at few % precision.

<table>
<thead>
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<th>Process</th>
<th>Cross section (pb)</th>
<th>Relative uncertainty in percent</th>
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<tr>
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<td>WH</td>
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Δ theory = 0, rest unchanged

![CMS Projection](image)

Comparison of ATLAS and CMS

<table>
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<tr>
<th>L(fb⁻¹)</th>
<th>Exp.</th>
<th>γγ</th>
<th>WW</th>
<th>ZZ</th>
<th>bb</th>
<th>ττ</th>
<th>Zγ</th>
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<td>[20, 24]</td>
<td>[14,20]</td>
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Uncertainty on signal strength
- Ranges [x,y] are not directly comparable
- ATLAS
  - [no theory uncertainty, Scenario 1]
- CMS
  - [Scenario 2, Scenario 1]

Overall reasonable agreement, but
- ATLAS does not include $H \rightarrow bb$ mode
- CMS outperforms ATLAS $H \rightarrow \tau\tau$ mode
- Large differences in $H \rightarrow Z\gamma$ mode due to photon id
Comparison with ATLAS and CMS

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<th>κ_W</th>
<th>κ_Z</th>
<th>κ_g</th>
<th>κ_b</th>
<th>κ_t</th>
<th>κ_τ</th>
<th>κ_{Zγ}</th>
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<td>[7,10]</td>
<td>[2,5]</td>
<td>[10,12]</td>
<td>[8,8]</td>
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</tbody>
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Large differences in fits for coupling strength

- ATLAS connects K_τ with K_b to overcome H \to bb mode, but H \to ττ then becomes overall limitation in constraining total width.

\[
\kappa_H^2 = \sum_X \kappa_X^2 \text{BR}_{\text{SM}}(H \to X)
\]
Conclusion

• Comprehensive set of Higgs coupling fits performed on Run I (7 & 8 TeV) dataset by ATLAS and CMS
  • No significant deviation observed
  • Measurements mostly limited by statistical uncertainties

• Large program for Higgs coupling measurements in Run II (13-14 TeV) to stay ahead of systematical uncertainties
  • Models need to be advanced
  • Theoretical (scale, $\alpha_s$, and PDF) uncertainties will become dominant
  • Experimental challenges due to large pileup and detector longevity effects