Higgs prospects at HL-LHC

Nikos Konstantinidis (UCL)
On behalf of the ATLAS and CMS Collaborations

EPS HEP Conference, Stockholm, 20/07/2013
• HL-LHC: timelines, targets and assumptions

• Higgs properties
  – Rare Higgs processes
  – Couplings to fermions and bosons
  – Self-couplings

• Vector boson scattering

• Conclusions
The HL-LHC programme

- Start at 2024 after a ~2-year shutdown (LS3)
  - LHC: new IR magnets, crab cavities, …

- LHC peak luminosity: \( \sim 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1} \)
  - \( \sim 140 \) pp collisions per bunch crossing

- Collect \( \sim 250-300 \text{fb}^{-1}/\text{year} \) for a total of \( \sim 3000 \text{fb}^{-1} \) per experiment by the early 2030s

- An ambitious programme of detector upgrades proposed by ATLAS and CMS to maintain/improve current performance
  - In trigger, offline reconstruction, identification of physics objects
  - Also to address key experimental systematics that would limit in particular the Higgs studies

More details on LHC upgrades in plenary talk by Mike Lamont and in several parallel sessions

Nikos Konstantinidis

Higgs prospects at HL-LHC
• Projections use realistic/conservative assumptions about detector performance at HL-LHC and the evolution of systematic uncertainties
  – Impressible progress in minimizing the impact of pile-up during 2012
  – In 2012, $\langle \mu \rangle$ up to $\sim 35$; extrapolation to $\langle \mu \rangle \sim 140$ not huge

• ATLAS performed generator-level studies, applying resolution and efficiency parameterisation functions for the HL-LHC conditions
  – With realistic/conservative assumptions for the effects of pile-up
    • E.g. full sim. studies of b-tagging with tracker upgrade now show better performance

• CMS extrapolate current results with different assumptions
  (1) Pessimistic: experimental and theory systematics as of today
  (2) Optimistic: experimental systematics scale as $1/\sqrt{L}$, theory systematics halved

• Past experience: projections almost invariably proved conservative!
• **H → μμ**
  - ATLAS finds ~2σ with 300fb^{-1} and ~6σ with 3000fb^{-1}
  - CMS should achieve similar sensitivity

• **ttH, H → μμ (ATLAS)**
  - Involves only fermion couplings
  - Only ~30 events in 3000fb-1, but very pure: s/b~1

• **ttH, H → γγ (ATLAS)**
  - Another rare, but relatively pure process (s/b~20%)
  - Important probe of top Yukawa coupling
Higgs couplings at the LHC

• At the LHC, only possible to measure $\sigma \times \text{BR}$’s
  – Expressed as ratio to the SM values: $\mu = (\sigma \times \text{BR})/(\sigma \times \text{BR})_{SM}$

• Ratios of partial widths can be derived without any model assumptions

• Interpretation in terms of couplings is model dependent
  – Expressed in terms of scale factors, $\kappa$, wrt SM values; $\Gamma_X/\Gamma_Y \sim (\kappa_X/\kappa_Y)^2$
Minimal fit: only two coupling scale factors, $\kappa_F$ for fermions and $\kappa_V$ for vector bosons
- No BSM contributions in either loops or in the total Higgs width

Sensitivity without (with) theory uncertainties:

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>300 fb$^{-1}$</th>
<th>3000 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_V$</td>
<td>3.0 % (5.6 %)</td>
<td>1.9 % (4.5 %)</td>
</tr>
<tr>
<td>$K_F$</td>
<td>8.9 % (10 %)</td>
<td>3.6 % (5.9 %)</td>
</tr>
</tbody>
</table>

A big improvement, esp. on $\kappa_F$, with 3000 fb$^{-1}$ provided the theory uncertainties are reduced!
Ultimately, combined ATLAS+CMS precision down to a few %.

Nikos Konstantinidis

Higgs prospects at HL-LHC
• Arguably, the most challenging measurement at the LHC!
  – Look for Higgs-pair production; destructive interference with diagrams not containing the self-coupling vertex $\lambda_{hhh}$
  – For $\lambda_{HHH}/\lambda_{HHH}^{SM} = 0/1/2$, the cross section is 71/34/16fb

• Preliminary ATLAS studies indicate that $h\bar{h}\rightarrow b\bar{b}\gamma\gamma$ is promising
  – $\sigma \times \text{BR} \sim 0.1\text{fb}$, backgrounds are largely $Xh(h\rightarrow\gamma\gamma)$ and continuum $bb\gamma\gamma$
  – Additional signal channels under study, e.g. $b\bar{b}\tau\tau$
  – New set of results to appear at the ECFA HL-LHC workshop in October

• A measurement by ATLAS+CMS with $3000\text{fb}^{-1}$ may be possible
• Crucial test of EWSB dynamics and the nature of the Higgs

• Big gains in sensitivity with 3000fb\(^{-1}\)
  – ZZ→4leptons: low backgrounds, clear peak in \(m_{4l}\), high sensitivity
    • Factor \(\sim 3\) improvement in measuring the SM \(\sigma\times\text{BR}\)
    • Increased sensitivity to models predicting TeV-scale resonances

<table>
<thead>
<tr>
<th>model</th>
<th>300 fb(^{-1})</th>
<th>3000 fb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m_{\text{resonance}} = 500\text{ GeV}, g = 1.0)</td>
<td>2.4(\sigma)</td>
<td>7.5(\sigma)</td>
</tr>
<tr>
<td>(m_{\text{resonance}} = 1\text{ TeV}, g = 1.75)</td>
<td>1.7(\sigma)</td>
<td>5.5(\sigma)</td>
</tr>
<tr>
<td>(m_{\text{resonance}} = 1\text{ TeV}, g = 2.5)</td>
<td>3.0(\sigma)</td>
<td>9.4(\sigma)</td>
</tr>
</tbody>
</table>
Great prospects for pinning down the properties of the 125GeV Higgs boson at the HL-LHC with 3000fb$^{-1}$ per experiment

- Studies and projections indicate ~few % precision in all fermion and vector boson couplings

Input from the theory community vital
- Theory uncertainties will quickly become an important limiting factor

Vector Boson Scattering, direct searches for BSM partners of the Higgs and BSM interpretation of results are all very crucial for elucidating the path beyond the Standard Model
Back up slides
• $\mu = (\sigma_{xBR})/(\sigma_{xBR})_{SM}$

**ATLAS Simulations**

$\sqrt{s} = 14$ 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)
- $H \rightarrow \gamma \gamma$
### $\mu$ uncertainties at 300 fb$^{-1}$

<table>
<thead>
<tr>
<th>Channel</th>
<th>Uncertainty on $\mu$ value with 300 fb$^{-1}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experimental only</td>
</tr>
<tr>
<td></td>
<td>ATLAS</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>8</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>9</td>
</tr>
<tr>
<td>$WW$ (1)</td>
<td>26</td>
</tr>
<tr>
<td>$\tau\tau$ (2)</td>
<td>11</td>
</tr>
<tr>
<td>$\tau\tau$</td>
<td>19</td>
</tr>
</tbody>
</table>

1. **ATLAS** uncertainty based on old result
2. **ATLAS** uncertainty extrapolated with **CMS** approach
CP violation in Higgs sector (ATLAS)

\[ A(X \rightarrow VV) \sim (a_1 M_X^2 g_{\mu\nu} + a_2 (q_1 + q_2)_{\mu(q_1 + q_2)_{\nu}} + a_3 \epsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta) \epsilon_1^{*\mu} \epsilon_2^{*\nu} \]

- HZZ amplitude can have CP-even & CP-odd terms: CP violation

<table>
<thead>
<tr>
<th>Integrated Luminosity</th>
<th>Signal (S) and Background (B)</th>
<th>6 + 6i</th>
<th>6i</th>
<th>4 + 4i</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 fb(^{-1})</td>
<td>(S = 158; B = 110)</td>
<td>3.0</td>
<td>2.4</td>
<td>2.2</td>
</tr>
<tr>
<td>200 fb(^{-1})</td>
<td>(S = 316; B = 220)</td>
<td>4.2</td>
<td>3.3</td>
<td>3.1</td>
</tr>
<tr>
<td>300 fb(^{-1})</td>
<td>(S = 474; B = 330)</td>
<td>5.2</td>
<td>4.1</td>
<td>3.8</td>
</tr>
</tbody>
</table>

3000 fb\(^{-1}\) would give sensitivity to much smaller levels of CP violation.
More on VBS

New physics parametrised in terms of higher-dimension, gauge-invariant terms:

\[ \mathcal{L}_{T,1} = \frac{f_{T_1}}{\Lambda^4} \text{Tr}[\hat{W}_{\alpha\nu}\hat{W}_{\mu\beta}] \times \text{Tr}[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}] \]

<table>
<thead>
<tr>
<th>Model</th>
<th>( f_{T_1}/\Lambda^4 )</th>
<th>( 300 \text{ fb}^{-1} )</th>
<th>( 3000 \text{ fb}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1.3 \text{ TeV}^{-4}</td>
<td>0.6 \text{ TeV}^{-4}</td>
</tr>
</tbody>
</table>

\[ \mathcal{L}_{S,0} = \frac{f_{S_0}}{\Lambda^4} [(D_\mu \phi)^\dagger D_\nu \phi] \times [(D_\mu \phi)^\dagger D_\nu \phi] \]

<table>
<thead>
<tr>
<th>Model</th>
<th>( f_{S_0}/\Lambda^4 )</th>
<th>( 300 \text{ fb}^{-1} )</th>
<th>( 3 \text{ ab}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>10 \text{ TeV}^{-4}</td>
<td>4.5 \text{ TeV}^{-4}</td>
</tr>
</tbody>
</table>