HL-LHC Higgs Potential

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On behalf of the ATLAS & CMS collaborations

Aix les Bains
1st October 2013

- Analysis methodology
- Single channel expectations
- The big picture
Benchmark Scenario

- Approved running to deliver 300 fb\(^{-1}\) by \(\sim 2021\)
  - With 20x Higgs boson production so far
- Post LS3 operation at \(5 \times 10^{34}\) cm\(^{-2}\)s\(^{-1}\) (lumi leveling)
  - 25 ns bunch spacing
  - 140 events per bunch crossing
  - 3000 fb\(^{-1}\) over 10 years
- Detector upgrades needed
  - to cope with radiation damage and pileup
  - aim to maintain or enhance physics performance
- Trigger is a key component:
  - Thresholds not too dissimilar to today
    - Mandated by need to study the Higgs boson
Event complexity

Experiments were designed for mean 23 events per bunch-crossing

- And continue to do an excellent job with 35
- Or even 78

But they will not handle 140 events of pileup
What have we learned?

- The experiments are working remarkably well.
  - Operations, detector performance and simulation
- The SM is in great shape.
  - N(N)LO calculations match data very well
- \( \rho, \omega, \phi, J/\psi, \eta, \psi', Y(1,2,3S) \)
- \( \mu^+\mu^- \) mass
  - CMS Preliminary
  - \( \sqrt{s} = 7 \text{ TeV}, \ L_{\text{int}} = 40 \text{ pb}^{-1} \)
- \( \phi, \psi, \Psi, W, Z, \text{top}, \) all well-behaved
HL-LHC Physics goals

HL-LHC will be alone exploring multi-TeV
- There will be a wide physics programme
- I report on some of the Higgs boson studies

Higgs Sector
- Rare decays & Couplings
- CP studies
- BSM Higgs boson searches
- Higgs boson pair production
Higgs bosons: 14 TeV, 3ab⁻¹

- Over 100M Higgs bosons
- 20K $H \rightarrow ZZ \rightarrow llll$
- 400K $\gamma\gamma$
- 50 $H \rightarrow J/\psi\gamma$

Over 1M in all major production modes
Trigger upgrades

- No physics can be done if the data are not recorded.
- Plot contrasts current and Phase 1 CMS trigger eff.
- Physics with $5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ will need an effective trigger.
Tools used for study here

- ATLAS derived detector response functions from full G4 simulation under two conditions:
  - $<\mu> \sim 50$ assumed for 300fb$^{-1}$
    - Includes IBL and LAr trigger upgrades
  - $<\mu> \sim 140$ assumed for 3000fb$^{-1}$
    - Full ITK inside ATLAS
    - Also studies of pileup variation on calorimetry.
  - Largely validate ES extrapolations
    - Photons slightly worse, MET and b-tag improved

- CMS
  - Studies scale current analyses
  - Assume detector upgrades keep current performance
  - Augmented with full-simulation studies
Full G4 studies

- CMS muon momentum in fullsim compared with Delphes parametrization used here
- ATLAS muon $p_T$ resolution in ITK and current ID compared
  - Important gains at low $p_T$
- Both detectors use more pessimistic performance for current studies
More G4 studies

- ATLAS $E_T^{\text{miss}}$ resolution with parametrization overlayed
- ATLAS b-tag fake rate for 70% efficiency compared with rate assumed for ES studies
  - ITK brings enhanced tracking
  - Mistag below 0.5% for $<\mu>=140$ $p_T=100\text{GeV}$
Higgs results so far

- Sensitivity of 'big 5' differs only by about a factor 3
- There is a rich programme
High purity signal possible
Separate into all 5 production modes
WH, ZH use lepton tags

Selected signal event rates

<table>
<thead>
<tr>
<th></th>
<th>ttH</th>
<th>ZH</th>
<th>WH</th>
<th>VBF</th>
<th>ggH</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000fb^{-1}</td>
<td>35</td>
<td>5.7</td>
<td>67</td>
<td>97</td>
<td>3800</td>
</tr>
</tbody>
</table>

ttH, H → ZZ
Only possible HL-LHC
ttH, H → γγ

3000 fb⁻¹ at 14 TeV offers new possibilities

- ttH, H → γγ
  - Sensitive to top in both production and decay
  - Yields top Yukawa coupling
H → ZZ: $\eta$ acceptance

- Contrast CMS detector with $|\eta|<2.5$ with $|\eta|<4$ extension
- Acceptance increases 40%
- Worth full study
Yield of 0-jet scales well with $\sigma \times L$

But VBF signal rate is only 10x current

Selected signal event rates

<table>
<thead>
<tr>
<th></th>
<th>0 jet</th>
<th>1 jet</th>
<th>2 jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000fb$^{-1}$</td>
<td>490,000</td>
<td>12000</td>
<td>210</td>
</tr>
</tbody>
</table>

ttH, WH and ZH from ES study
ATLAS has done studies with re-weighting 8TeV
  - Applying the HL-LHC performance smearings
  - Jet $p_T$ 30/35 GeV (300/3000fb)

Backgrounds from $t\bar{t}$,WW rise with event pileup
  - But s/b is good enough to exploit increased rate

VBF like, 300fb$^{-1}$

VBF like, 3000fb$^{-1}$
The event yields in the WW mode are large. The systematic errors are therefore critical. And need work.

The bottom right table shows the estimated error on the background processes in current estimate, the European Strategy analysis and the published results.

<table>
<thead>
<tr>
<th>Error, %</th>
<th>14 TeV</th>
<th>ES</th>
<th>8 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW</td>
<td>1.5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>VV</td>
<td>2</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>top</td>
<td>7</td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td>Z+jets</td>
<td>10</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>W+jets</td>
<td>20</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>
H → Zγ

- Tests loop structure
- Signal to background marginal
- But a measurement is possible

<table>
<thead>
<tr>
<th></th>
<th>eγγ</th>
<th>μγγ</th>
</tr>
</thead>
<tbody>
<tr>
<td>eγγ VBF</td>
<td>1500</td>
<td>1700</td>
</tr>
<tr>
<td>μγγ VBF</td>
<td>21</td>
<td>23</td>
</tr>
</tbody>
</table>

ATL-PHYS-PUB-2013-014
$H \rightarrow \mu\mu$

- Allows direct study of coupling to two different leptons
- Test lepton flavour-violation carefully

3000 fb$^{-1}$ at 14 TeV offers new possibilities
### Higgs strength: $\mu$

<table>
<thead>
<tr>
<th></th>
<th>$H\rightarrow\gamma\gamma$</th>
<th>$H\rightarrow WW$</th>
<th>$H\rightarrow ZZ$</th>
<th>$H\rightarrow bb$</th>
<th>$H\rightarrow tt$</th>
<th>$H\rightarrow Z\gamma$</th>
<th>$H\rightarrow \mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>300 fb^{-1}</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATLAS</td>
<td>[9,14]</td>
<td>[8,13]</td>
<td>[6,12]</td>
<td>N/a</td>
<td>[16,22]</td>
<td>[145,147]</td>
<td>[38,39]</td>
</tr>
<tr>
<td>CMS</td>
<td>[6,12]</td>
<td>[6,11]</td>
<td>[7,11]</td>
<td>[11,14]</td>
<td>[8,14]</td>
<td>[62,62]</td>
<td>[40,42]</td>
</tr>
<tr>
<td><strong>3000 fb^{-1}</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATLAS</td>
<td>[4,10]</td>
<td>[5,9]</td>
<td>[4,10]</td>
<td>N/a</td>
<td>[12,19]</td>
<td>[54,57]</td>
<td>[12,15]</td>
</tr>
<tr>
<td>CMS</td>
<td>[4,8]</td>
<td>[4,7]</td>
<td>[4,7]</td>
<td>[5,7]</td>
<td>[5,8]</td>
<td>[20,24]</td>
<td>[14,20]</td>
</tr>
</tbody>
</table>

- The ranges [x,y] above are not directly comparable
- ATLAS compares two results
  - Systematic errors as estimated today
    - Experimental control region statistics rise helps a lot
  - With no theory systematic uncertainties
- CMS
  - Systematic errors as today
  - Scale systematic errors: $1/\sqrt{L}$ (exp.) & $1/2$ (theo.)
### Signal strength: details

- **Total μ**
  is only part of the story.

- **Separation of production modes**
  is also vital.

<table>
<thead>
<tr>
<th></th>
<th>$\Delta \mu / \mu$</th>
<th>300 fb$^{-1}$</th>
<th>3000 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All unc.</td>
<td>No theory unc.</td>
<td>All unc.</td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$ (comb.)</td>
<td>0.39</td>
<td>0.38</td>
<td>0.15</td>
</tr>
<tr>
<td>(incl.)</td>
<td>0.47</td>
<td>0.45</td>
<td>0.19</td>
</tr>
<tr>
<td>(ttH-like)</td>
<td>0.73</td>
<td>0.72</td>
<td>0.26</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$ (VBF-like)</td>
<td>0.22</td>
<td>0.16</td>
<td>0.19</td>
</tr>
<tr>
<td>$H \rightarrow ZZ$ (comb.)</td>
<td>0.12</td>
<td>0.06</td>
<td>0.10</td>
</tr>
<tr>
<td>(VH-like)</td>
<td>0.32</td>
<td>0.31</td>
<td>0.13</td>
</tr>
<tr>
<td>(ttH-like)</td>
<td>0.46</td>
<td>0.44</td>
<td>0.20</td>
</tr>
<tr>
<td>(VBF-like)</td>
<td>0.34</td>
<td>0.31</td>
<td>0.21</td>
</tr>
<tr>
<td>(ggF-like)</td>
<td>0.13</td>
<td>0.06</td>
<td>0.12</td>
</tr>
<tr>
<td>$H \rightarrow WW$ (comb.)</td>
<td>0.13</td>
<td>0.08</td>
<td>0.09</td>
</tr>
<tr>
<td>(VBF-like)</td>
<td>0.21</td>
<td>0.20</td>
<td>0.12</td>
</tr>
<tr>
<td>(+1j)</td>
<td>0.36</td>
<td>0.17</td>
<td>0.33</td>
</tr>
<tr>
<td>(+0j)</td>
<td>0.20</td>
<td>0.08</td>
<td>0.19</td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma$ (incl.)</td>
<td>1.47</td>
<td>1.45</td>
<td>0.57</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$ (comb.)</td>
<td>0.14</td>
<td>0.09</td>
<td>0.10</td>
</tr>
<tr>
<td>(VH-like)</td>
<td>0.77</td>
<td>0.77</td>
<td>0.26</td>
</tr>
<tr>
<td>(ttH-like)</td>
<td>0.55</td>
<td>0.54</td>
<td>0.21</td>
</tr>
<tr>
<td>(VBF-like)</td>
<td>0.47</td>
<td>0.43</td>
<td>0.21</td>
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<td>0.14</td>
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<td>(+0j)</td>
<td>0.22</td>
<td>0.12</td>
<td>0.20</td>
</tr>
</tbody>
</table>
This shows the Higgs-signal strength in many analysis channels
• Nb ggF like shows TOTAL Higgs strength accepted in analysis, not the VBF strength
  • Needs coupling fit
• Strong anti-correlation between 0j/1j strengths is exploited in fit
Outline of fits:

- Extracting Higgs couplings from the $\sigma x \text{BR}$ requires assumptions at LHC

\[
\sigma \cdot B(i \rightarrow H \rightarrow f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}
\]

- As $\Gamma_H$ is not measurable, assume it is sum of SM channel widths
  - Total width controlled by $H \rightarrow \bar{b}b$
  - $\bar{c}c$ is a 5% unmeasured contribution
    - Assumed to scale with $bb$
    - For ATLAS $bb/\bar{c}c$ scale with $\tau\tau$
  - Assume no new invisible/undetectable modes

- Cross sections and decay widths to particle $a$ scale with $\kappa_a^2$. 

W.Murray STFC/Warwick 23
### Coupling fit results

<table>
<thead>
<tr>
<th></th>
<th>$K_Y$</th>
<th>$K_W$</th>
<th>$K_Z$</th>
<th>$K_g$</th>
<th>$K_b$</th>
<th>$K_t$</th>
<th>$K_\tau$</th>
<th>$K_{Z\gamma}$</th>
<th>$K_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300fb$^{-1}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>ATLAS</td>
<td>[8,13]</td>
<td>[6,8]</td>
<td>[7,8]</td>
<td>[8,11]</td>
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<td>[20,22]</td>
<td>[13,18]</td>
<td>[78,79]</td>
<td>[21,23]</td>
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<tr>
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<td>[5,7]</td>
<td>[4,6]</td>
<td>[4,6]</td>
<td>[6,8]</td>
<td>[10,13]</td>
<td>[14,15]</td>
<td>[6,8]</td>
<td>[41,41]</td>
<td>[23,23]</td>
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<tr>
<td>3000fb$^{-1}$</td>
<td></td>
<td></td>
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<td>[5,9]</td>
<td>[4,6]</td>
<td>[4,6]</td>
<td>[5,7]</td>
<td>N/a</td>
<td>[8,10]</td>
<td>[10,15]</td>
<td>[29,30]</td>
<td>[8,11]</td>
</tr>
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<td>[2,5]</td>
<td>[2,5]</td>
<td>[2,4]</td>
<td>[3,5]</td>
<td>[4,7]</td>
<td>[7,10]</td>
<td>[2,5]</td>
<td>[10,12]</td>
<td>[8,8]</td>
</tr>
</tbody>
</table>

- Fits assumes no new undetectable modes
- The upper ranges are directly comparable
- Sensitivity is a factor 2 apart
  - ATLAS fit lacks $b\bar{b}$ mode; uses $\tau\bar{\tau}$ to fix fermions
- Next: look at ratios of couplings for more stability
## Coupling ratio fits

<table>
<thead>
<tr>
<th></th>
<th>$K_g K_Z / K_H$</th>
<th>$K_w / K_Z$</th>
<th>$K_y / K_Z$</th>
<th>$K_g / K_Z$</th>
<th>$K_b / K_Z$</th>
<th>$K_\tau / K_Z$</th>
<th>$K_\mu / K_Z$</th>
<th>$\kappa_{Z\gamma} K_Z$</th>
<th>$K_t / K_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300fb$^{-1}$</td>
<td>ATLAS</td>
<td>[3,6]</td>
<td>[4,5]</td>
<td>[5,11]</td>
<td>[11,12]</td>
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</tr>
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<td></td>
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<td>[4,7]</td>
<td>[5,8]</td>
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<td>[6,9]</td>
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<td>ATLAS</td>
<td>[2,5]</td>
<td>[2,3]</td>
<td>[2,7]</td>
<td>[5,6]</td>
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<td>[7,10]</td>
<td>[6,9]</td>
<td>[29,30]</td>
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<tr>
<td></td>
<td>CMS</td>
<td>[2,5]</td>
<td>[2,3]</td>
<td>[2,5]</td>
<td>[3,5]</td>
<td>[3,5]</td>
<td>[2,4]</td>
<td>[7,8]</td>
<td>[12,12]</td>
</tr>
</tbody>
</table>

- Generally good agreement between the two estimates
- HL-LHC offers roughly a factor 2-3 improvement in coupling ratio determinations.
  - Especially if theory errors can be reduced.
Coupling expectations

**ATLAS Preliminary**

$\sqrt{s} = 14$ TeV: $|Ldt|=300 \text{ fb}^{-1}$; $|Ldt|=3000 \text{ fb}^{-1}$

- $\kappa_{gZ}$
- $\kappa_{WZ}$
- $\lambda_t g$
- $\lambda_t Z$
- $\lambda_{tZ}$
- $\lambda_{tZ}$
- $\lambda_{(Z_t)Z}$

$\Delta \lambda_{XY} = \Delta \left( \frac{\kappa_X}{\kappa_Y} \right)$
Invisible Higgs search

- ATLAS has studied ZH→llXX events
- Sensitive to invisible Br about 10% with 3 ab⁻¹
- $E_T^{miss}$ control vital

<table>
<thead>
<tr>
<th></th>
<th>300fb⁻¹</th>
<th>3000fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>[22,31]</td>
<td>[8,17]</td>
</tr>
</tbody>
</table>

ATLAS Simulation Preliminary
ZH → ll+invisible
$\sqrt{s}=14$ TeV, $\int L dt = 3000$ fb⁻¹

Higgs-portal Model for ATLAS
Direcct Higgs width study

- CMS extract $\Gamma_H < 6.9\text{GeV}$ from width of $\gamma\gamma$
  - But $\Gamma_H^{\text{SM}} = 4.2\text{MeV}$
- Interference exists between signal and bkd
  - Shifts the apparent peak position

Could compare $\gamma\gamma$ and ZZ peak: systematics :(
Higgs width in $\gamma\gamma$

- Interference depends on s/b & hence $p_T$
- Compare $H\rightarrow\gamma\gamma$ divided at $p_T=30\text{GeV}$

Comparing peak positions gives sensitivity:
- $\Gamma_H<920\text{MeV}$ from $300\text{fb}^{-1}$, $200\text{MeV}$ from $3\text{ab}^{-1}$ (full)
- $\Gamma_H<880\text{MeV}$ from $300\text{fb}^{-1}$, $160\text{MeV}$ from $3\text{ab}^{-1}$ (stat)

Systematic errors not dominating
HZZ coupling structure

- Analyze decay angles of ZZ system
- Express CP-odd(CP-even) structure as $g_4(g_2)$
- Big sensitivity gains from HL-LHC
2HDM sensitivity

- 2HDM's have extra doublet (H, A, H⁺, H⁻)
- Coupling patterns Type I to IV are studied
  - Type II includes MSSM
- Studies of neutral sector sensitive to the mixing, tanβ and mₐ.
  - H/A decays have tt threshold
- Example search for H to ZZ
  - Discovery potential mₜ < 2mₐ for type II.
Both experiments study $A \rightarrow Zh$ search and coupling analysis of same model

Two approaches complementary
  - Couplings independent of $m_A$

$A \rightarrow Zh$

CMS Simulation 2013 $\sqrt{s} = 14$ TeV, $L = 3000$ fb$^{-1}$

$95\%$ CL exclusion
$5\sigma$ significance
Allowed (couplings)

Type II
$A \rightarrow Zh$
$m_A = 300$ GeV

CMS PAS FTR-13-024

$\tan(\beta)$

$\cos(\beta - \alpha)$

$\tan(\beta)$

$\cos(\beta - \alpha)$

ATLAS Preliminary, Simulation

$\sqrt{s} = 14$ TeV

95\% CL upper limit
2HDM Type-II

$A \rightarrow Zh$

ATL-PHYS-PUB-2013-016

ATL-PHYS-PUB-2013-015
t→cH sensitivity

- t→cH can be $O(10^{-3})$ in 2HDM-III models, 10x allowed t→cZ rate.
- tt→WbHc is studied with H→γγ
- Look for γγj peak
- Combine W→lν and W→qq

- Sensitivity to Br of $1.5 \times 10^{-4}$
- Other decay modes only add.
Can we see the BEH field?

- The observation of a field filling space with weak charge and energy density poses questions about its gravitational impact.
- We have seen the decay to ZZ, where the weak charge of the Higgs is absorbed by the vacuum.
- But we need to demonstrate the potential, i.e. measure the self-coupling.
Higgs boson pair-production

- Needs observation of Higgs pairs
  - Expected $\sigma_{HH} = 40 \pm 3$ fb $\rightarrow 120K$ events
  - Finding one was tough with $\sim 500K$ events
- But it is not enough
  - Both the above diagrams (and more) contribute
  - Negative interference :(
- Ongoing studies suggest some sensitivity
  - Low rate makes high demands on detectors & lumi
  - Theoretical studies suggest possible: 1309.6318
New ideas

- Expect improvements to the programme
- Experimentally many analysis improvements will be made in 15 years
- New theoretical ideas too. e.g.
  - ArXiv:1306.5770v1
  - Possible Hcc vertex
  - ArXiv:1305.3854
  - Width through interference

- The programme will be richer than we see
  - Thanks to huge Higgs sample + work
Putting it all together

The Higgs coupling strength plot
- Is this the 'blueband' plot for the next decade?
Summary

- 30 fb\(^{-1}\) of LHC data has allowed the Higgs discovery
- 300 fb\(^{-1}\) at 14 TeV allows many measurements
- 3000 fb\(^{-1}\) allows much more:
  - Precision Higgs couplings to 8 particles
  - Coupling structure
  - Higgs invisible width
  - Discovery potential for heavier Higgs bosons
  - Some sensitivity to self coupling
- The physics possible at a hadron collider grows with experience
  - We will surely exceed this programme
Backup
2HDM: $H \rightarrow ZZ$
2HDM: $A \rightarrow Z\phi$ study
Several ATLAS analyses use set of jet thresholds designed to give 1% pileup fake rate
- ZZ, γγ, Zγ
- These are calorimeter jets
- Validated by tracks from PV
  - When available
- Inside |η|<2.1 tracks are available
- For η~4 a 50 GeV $p_T$ jet has $E=1.4$TeV: rare
- But for $2.1<|\eta|<2.8$ the threshold is high
  - This impacts their physics