Higgs physics at HL-LHC

Bill Murray,
Higgs Hunting, 29rd July 2019
On behalf of the ATLAS collaboration

“Vague but exciting”

ATL-PHYS-PUB-2018-053 HH & self coupling
ATL-PHYS-PUB-2018-054 H properties
ATL-PHYS-PUB-2019-008 H → ττ CP
“A hunched black beast made of razor edges and barbs and ribbons of sharp metal; a chair that could kill a man”

George R R Martin

Is HL-LHC going to be able to melt it?
LS3 in 2024 has major accelerator & ATLAS work
From mid 2026 move into 200 pile-up events/BX
- Luminosity limited by detectors constraints
- Maintain maximum digestible rate for hours
The REAL Higgs factory

All very difficult.....

“Men were real men, women were real women, small green furry creatures from alpha centauri were real small green furry creatures from alpha centauri”

Seriously, it is a dirty, dangerous (for detectors) and harsh environment

But it will work... if we can work out how to handle it

Most results so far are from 36fb⁻¹

Extrapolations and HL-LHC studies are for 3-4ab⁻¹

It’s a big jump and not all will be done perfectly.

It is unlikely the final analyses will be done the same way
ATLAS upgrades

**Muons:**
- Innermost layers upgraded,
- New Small Wheels

**Tracker:**
- New: All-silicon Itk

**Timing:**
- High Granularity Timing Detector in endcaps
ATLAS upgrades

Calorimeter: front end electronics replaced
- Higher granularity

Trigger total rebuild for 10x rate
- Aim for similar thresholds
- Non-trivial as pileup makes events more complex
HL-LHC events

- Harsh environment
- Pileup goes from $O(40)$ mean to $O(200)$
- Tracking scales factorially with hit density
  - Currently we do not have affordable solutions
  - This needs intellectual input now.
Computing model

- Assume a flat budget gives 20% improvement per year
  - Not guaranteed
- Revised 2018 computing model reduces demand
- Then with fast sim / reco / generators we ~ cope
  - Run 4 will be tough
Systematic assumptions

- MC stats assumed negligible
- S1: Assume current uncertainties (safe)
- S2: Theory $\frac{1}{2}$, lumi 1%
- Detectors as detailed below

<table>
<thead>
<tr>
<th>Source</th>
<th>Component</th>
<th>Run 2 unc.</th>
<th>Projection minimum unc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon ID</td>
<td></td>
<td>1–2%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Electron ID</td>
<td></td>
<td>1–2%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Photon ID</td>
<td></td>
<td>0.5–2%</td>
<td>0.25–1%</td>
</tr>
<tr>
<td>Hadronic $\tau$ ID</td>
<td></td>
<td>6%</td>
<td>0.1–0.2%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>Absolute</td>
<td>0.5%</td>
<td>Same as Run 2</td>
</tr>
<tr>
<td></td>
<td>Relative</td>
<td>0.1–3%</td>
<td>0.1–0.5%</td>
</tr>
<tr>
<td></td>
<td>Pileup</td>
<td>0–2%</td>
<td>Same as Run 2</td>
</tr>
<tr>
<td></td>
<td>Method and sample</td>
<td>0.5–5%</td>
<td>No limit</td>
</tr>
<tr>
<td></td>
<td>Jet flavour</td>
<td>1.5%</td>
<td>0.75%</td>
</tr>
<tr>
<td></td>
<td>Time stability</td>
<td>0.2%</td>
<td>No limit</td>
</tr>
<tr>
<td>Jet energy res. $p_T^{\text{miss}}$ scale</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b-Tagging</td>
<td>$b$-/c-jets (syst.)</td>
<td>Varies with $p_T$ and $\eta$</td>
<td>Half of Run 2</td>
</tr>
<tr>
<td></td>
<td>light mis-tag (syst.)</td>
<td>Varies with $p_T$ and $\eta$</td>
<td>Half of Run 2</td>
</tr>
<tr>
<td></td>
<td>$b$-/c-jets (stat.)</td>
<td>Varies with $p_T$ and $\eta$</td>
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</tr>
<tr>
<td></td>
<td>light mis-tag (stat.)</td>
<td>Varies with $p_T$ and $\eta$</td>
<td>No limit</td>
</tr>
<tr>
<td>Integrated lumi.</td>
<td></td>
<td>2.5%</td>
<td>1%</td>
</tr>
</tbody>
</table>
Higgs Production x decay

**ZZ, qq, WW, tt and bb modes**
Production and decay modes

Assume decay, measure production & vice versa

All systematics limited, except $\mu\mu$ & $Z\gamma$
  - Expect $\mu\mu$ clearly seen, $4.9\sigma$ for $Z\gamma$
Extracted couplings v mass

ATLAS Preliminary
Projection from Run 2 data
\( \sqrt{s} = 14 \text{ TeV}, 3000 \text{ fb}^{-1} \)

SM Higgs boson

\( \kappa_F \) or \( \sqrt{\kappa_V} \)

Particle mass [GeV]

S2 sys
Extracted couplings

10 parameter general fit
- Imposing UL on W, Z
Gives 2-4% precision
- Except μ & Zγ
3.3% limit on non-SM decays, e.g. DM

\[ \sqrt{s} = 14 \text{ TeV}, \; 3000 \text{ fb}^{-1} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Total</th>
<th>Stat.</th>
<th>Syst.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \kappa_W )</td>
<td>± 0.022 (± 0.008 ± 0.020)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \kappa_Z )</td>
<td>± 0.017 (± 0.008 ± 0.015)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \kappa_t )</td>
<td>± 0.040 (± 0.012 ± 0.037)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \kappa_b )</td>
<td>± 0.037 (± 0.014 ± 0.034)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \kappa_\tau )</td>
<td>± 0.026 (± 0.010 ± 0.024)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \kappa_g )</td>
<td>± 0.029 (± 0.011 ± 0.027)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \kappa_\gamma )</td>
<td>± 0.021 (± 0.009 ± 0.020)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \kappa_\mu )</td>
<td>± 0.070 (± 0.064 ± 0.028)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \kappa_{Z\gamma} )</td>
<td>± 0.123 (± 0.097 ± 0.076)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( B_{BSM} )</td>
<td>± 0.033 (± 0.015 ± 0.029)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Hcc coupling

Several approaches target Hcc (H → J/ψγ or H pT)
- Most straightforward is VH, H → cc

Four regions considered
- 1 or 2 c tags
- High or low p_T Z → ll
- Best is shown right
  - Signal multiplied by 100!

Observation not expected
- But expected limit 6.3xSM cross-section (stat only)
- Z → neutrinos will add some sensitivity
- As will analysis optimisation
Differential distributions: ZZ+$\gamma\gamma$

- Higgs $p_T$ up to 1 TeV 10% precision or better
  - Statistics important here
- High-$p_T$ bin can be divided
- May be possible to add $H \rightarrow bb$ at high $p_T$. 

![Graph showing differential distributions of Higgs pT](image-url)
H → ττ CP properties

Analysing tau decays probes coupling to fermions
- CPX in MSSM hidden in bosons
Use ττ → ρνρν decays
Analyse ρ → π⁺π⁰ energy sharing
- As a probe of angle
Use VBF and ggF production
- In low/high pT modes
Results depend upon π⁰ resolution
- 18° ↔ 33° mixing angle resol.
- for 1 ↔ 2x nominal π⁰ resolution
Di Higgs production

- Right: Branching ratios of various decay modes
- Red circled channels have ATLAS projections
- Purple have results at 13 TeV
- Many weak channels are not exploited – some gain possible
Extrapolating 36fb$^{-1}$ analysis
- Assumed 8% improvement in btag
- From Itk improved performance
Cocktail of multi-b triggers
- 1 hard b, 225 GeV pT
- 2 soft b, 35 or 55 GeV
- Finally 90% efficient for SM
The multijet background error is hard to predict
UL from 1.5 to 3.3 x SM
- Depending on this error
The **36fb-1 analysis** is extrapolated

lh and hh channels analyses

- hh, shown right, most powerful

<table>
<thead>
<tr>
<th>Last bin</th>
<th>( \tau_{\text{lep}} \tau_{\text{had}} ) channel (SLT)</th>
<th>( \tau_{\text{had}} \tau_{\text{had}} ) channel (LTT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t\bar{t} ) fake-( \tau_{\text{had}} )-vis</td>
<td>-</td>
<td>12.9 ± 2.0</td>
</tr>
<tr>
<td>( t\bar{t} )</td>
<td>235 ± 6</td>
<td>360 ± 30</td>
</tr>
<tr>
<td>Single top</td>
<td>283 ± 15</td>
<td>54 ± 3</td>
</tr>
<tr>
<td>Multijet fake-( \tau_{\text{had}} )-vis</td>
<td>-</td>
<td>33.7 ± 7.2</td>
</tr>
<tr>
<td>Fake-( \tau_{\text{had}} )-vis</td>
<td>300 ± 10</td>
<td>97 ± 9</td>
</tr>
<tr>
<td>( Z \to \tau \tau + (bb, bc, cc) )</td>
<td>340 ± 20</td>
<td>470 ± 40</td>
</tr>
<tr>
<td>Other</td>
<td>105 ± 5</td>
<td>61 ± 7</td>
</tr>
<tr>
<td>SM Higgs boson</td>
<td>78 ± 4</td>
<td>31 ± 2</td>
</tr>
<tr>
<td>Total background</td>
<td>1343 ± 25</td>
<td>1069 ± 55</td>
</tr>
<tr>
<td>SM ( HH )</td>
<td>32.8 ± 1.6</td>
<td>9.8 ± 0.5</td>
</tr>
</tbody>
</table>

**Expected UL 1xSM\( \sigma \)**
**HH → bbγγ**

- **H → γγ** has good resolution & triggering; **H → bb** is high rate,
- Use BDT to separate from background
- Two comparable backgrounds:
  - Continuum (sidebands) 3.7 in 123-127
  - Single Higgs peaking 3.2 in 123-127 (50% ttH)
- **Signal 6.5 expected**
- **Expected UL 1.2xSMσ**

### Dominant Systematics

<table>
<thead>
<tr>
<th></th>
<th>Signal</th>
<th>H Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon energy resolution</td>
<td>14%</td>
<td>14%</td>
</tr>
<tr>
<td>Jet Energy Resolution</td>
<td>2.9%</td>
<td>7.8%</td>
</tr>
<tr>
<td>QCD scale</td>
<td>2.5%</td>
<td>~11%</td>
</tr>
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</table>
Combined sensitivity to HH

<table>
<thead>
<tr>
<th>Channel</th>
<th>Statistical-only</th>
<th>Statistical + Systematic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$HH \rightarrow b\bar{b}bb\bar{b}$</td>
<td>1.4</td>
<td>0.61</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}\tau^+\tau^-$</td>
<td>2.5</td>
<td>2.1</td>
</tr>
<tr>
<td>$HH \rightarrow b\bar{b}\gamma\gamma$</td>
<td>2.1</td>
<td>2.0</td>
</tr>
<tr>
<td>Combined</td>
<td>3.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>

The fitted HH signal $\mu$ can be extracted with about a 40% error.
Caution on predictions

ATLAS 36fb⁻¹ HH summary

- bbWW at 305 x SM!
- Looks pretty hopeless?

\[ \sigma_{ggF}^{\text{SM}}(pp \rightarrow HH) = 33.5 \text{ fb} \]

\[ \sqrt{s} = 13 \text{ TeV}, \text{ 27.5 - 36.1 fb}^{-1} \]

- Observed
- Expected
- Expected ± 1σ
- Expected ± 2σ
ATLAS 36fb⁻¹ HH summary

- bbWW at 305 x SM!
- Looks pretty hopeless?

But 139fb⁻¹ bbWW

- Dileptonic; previous was single-lepton
- Expected limit 29xSM
- Factor 10 improvement

Good ideas and hard work can still improve all the results
Di Higgs interpretation

- Destructive interference between box and triangle
- Varying $\kappa_\lambda$ injects signal
  - Mostly at low $m_{HH}$
- Example for $b\bar{b}\gamma\gamma$ right
- Low mass is harder to trigger for $b\bar{b}$ and $\tau\tau$ modes
- Limits degrade

**Box Diagram**

**Triangle Diagram**

**ATLAS Simulation Preliminary**

$\sqrt{s} = 14$ TeV, 3000 fb$^{-1}$

$HH \rightarrow b\bar{b}\gamma\gamma$

HH signal + background

$123 \text{ GeV} < m_{\gamma\gamma} < 127 \text{ GeV}$

- $\kappa_\lambda = -6$
- $\kappa_\lambda = 0$
- $\kappa_\lambda = 1$
- $\kappa_\lambda = 10$

Events / 20 GeV vs $m_{HH}$ [GeV]
Cross-section at SM $\kappa_\lambda = 1$
and $\kappa_\lambda = 4$ similar
Therefore approx degeneracy
But kinematics is different
Result is second minimum in LR $\nu \kappa_\lambda \, g g$
Could be reduced by more detailed $m_{HH}$ study
Expected exclusion: $\kappa_\lambda < 0.4$ or $> 7.4$
Searches continue: h/A to $\tau\tau$

- Tau pair in l-h and h-h channels
- with b-tag or b-veto

- Expect to be sensitive to $\tan\beta > 12$ for $m_A < 1\text{TeV}$ in hMSSM
- Still sensitive at $m_A = 2\text{TeV}$
More searches

The list is long and incomplete
Many potential new physics scenarios are possible
  • Many of them weakly coupled / aligned
Examples:
  • h125 → Za
    • A light `a’ decaying to photons or even stable
  • H_3 → H_2 H_1 with any of these 125 GeV
  • H^+ → Wh τν or tb
  • bH,H → μμ
  • H → aa → {bb, ττ, μμ, jj, γγ, invisible}^2
  • H^{++} → W^+W^+
One small Higgs can ruin all your plans
Conclusions

The HL-LHC programme holds many exciting Higgs Hunting opportunities
- The H125 couplings potential is excellent
  - The rare, and invisible decays will be strongly probed
- The diHiggs studies are a must
  - 3 sigma evidence for HH seems possible
  - All studies of the BEH field are critical right now
- And the search programme extended

But to make it real we have to invest effort in hardware and software upgrades
- These are comparable to building ATLAS (&CMS)
- And will not happen without dedicated effort
How to punch a hole?
Higgs mass and width

Higgs mass will improve from current 240 MeV (ATLAS)
- 52 MeV if no improvements made
- 47 MeV if Ltk yields 30% resolution improvement
- 33-38 MeV if also scale uncertainty reduced 50-80%

Width
- CMS project range 2-6 MeV @95%CL
  - S1/S2 similar here
Self coupling from single H

Higgs self coupling is major target

Loop diagrams mean single Higgs rates are sensitive
- Especially using distributions
- \( t \bar{t}H \) structure different

Extract limits on coupling:

\[
\kappa_{\lambda} = 4.0^{+3.7}_{-3.6} \text{(stat.)}^{+1.6}_{-1.5} \text{(exp.)}^{+1.3}_{-0.9} \text{(sig.th)}^{+0.8}_{-0.9} \text{(bkg.th)}
\]

\[-3.2 < \kappa_{\lambda} < 11.9 \quad @ \text{95\% CL}\]

Tighter than direct \( HH \):
- \(-5 < \kappa_{\lambda} < 12.1\)
- But using more data
Invisible Higgs

- CMS released a new combination of datasets
  - Most powerful invisible Higgs limit
  - 15% expected, 19% observed
- ATLAS 13 TeV result:
  - 17% expected, 26% observed
  - Both have small preference for positive decay fraction?