Higgs physics programme at the High-Luminosity LHC with ATLAS

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On behalf of the ATLAS Collaboration

25th Workshop on Deep Inelastic Scattering 2017 and Related Topics

Birmingham, 5th April 2017
Outline

- High Luminosity LHC (HL-LHC)
- ATLAS detector upgrades and associated performances
- Higgs physics programme
  - Higgs rare decays
  - Higgs production through Vector Boson Fusion (VBF)
  - Higgs boson couplings
  - Higgs boson self-coupling
- Conclusion
High Luminosity LHC (2024-2037)

**LHC / HL-LHC Plan**

<table>
<thead>
<tr>
<th>HL-LHC mode</th>
<th>Peak Luminosity (cm(^{-2}) s(^{-1}))</th>
<th>Mean number of interactions per bunch-crossing (&lt;\mu_{PU})&gt;</th>
<th>Integrated luminosity (fb(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>5x10(^{34})</td>
<td>140</td>
<td>3000</td>
</tr>
<tr>
<td>Ultimate</td>
<td>7.5x10(^{34})</td>
<td>200</td>
<td>4000</td>
</tr>
</tbody>
</table>

**Physics targets**: precision measurements/rare decays/Beyond SM
Upgrade electronics
TileCal: J. Dandoy's talk

Longer latency trigger system, higher event rate

New all silicon Inner Tracker
with $\eta$ coverage up to 4
N. Calace's talk

New inner muon barrel trigger chambers

Options: Forward muon tagger and timing detector

2017: Different design/implementation possibilities being evaluated for each sub-detector Technical Design Report

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Expected pile-up jet contamination

- $\langle \mu_{PU} \rangle = 200$ : 4.8 pile-up jets per event with $p_T > 30$ GeV and $|\eta| < 3.8$
- Pile-up jet rejection based on vertex reconstruction from tracking information

Analyses typically use factor 50 rejection

- ~0.1 pile-up jet per event
- 85-70% efficiency on hard-scatter jets
Detector performances

Jet b-tagging

Light-jet rejection

$|\eta| < 2.7$

MV1 tagger

$|\eta| < 2.7$

$\bar{t}t$ ($\geq$ 1 lepton)

For 70% b-jet efficiency:

Light-jet rejection $\sim$ 300 for $<\mu_{PU}>$ = 200

(380 at Run-2)

More details in N. Calace's talk

Photon identification

$|\eta| < 2.37$

VBF $H \rightarrow \gamma \gamma$

Hard-scatter jet $\rightarrow \gamma$

fake rate: $2.5 \times 10^{-4}$

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Not possible to produce enough events fully simulated/reconstructed in the HL-LHC environment → Expected results are computed from:

- **Parametrised performances of upgraded detector layout**
  - Use fully simulated events with pile-up to parametrise efficiency/resolution for particle/object (e, γ, μ, τ, jet, missing-\(E_T\))
  - Particles at event-generator level smeared according to these functions
  - Overlay with pile-up jets

- **Extrapolation from Run-1/Run-2 results**
  - Assume similar detector performances and analysis approach as Run-1/Run-2
  - Scale signal and background level to higher luminosity/CM
Large event statistics \(\rightarrow\) systematic uncertainty can become critical

- **Theoretical systematics**: Implement the ones used for Run-1/Run-2 publications (will have decreased by HL-LHC time)

- **Experimental systematics**: Scaled to best guess for ATLAS upgraded detector at HL-LHC

Some systematics (background level and shape,...) will be well measured using data-driven methods
Higgs boson physics programme

- LHC: First Higgs factory
  - Many results using Run-1/Run-2 data presented in this conference

- HL-LHC will produce 10 times more Higgs events than end Run-3
  - Reach the precision measurement regime
  - Probe rare phenomena

→ Understanding Electroweak Symmetry Breaking

→ Physics Beyond the Standard Model

Higgs physics: an important benchmark to review ATLAS detector upgrades

Let's go through the recent ATLAS results on Higgs Physics at HL-LHC
Higgs boson rare decays

- $H \rightarrow J/\psi \gamma$ ; $J/\psi \rightarrow \mu^+\mu^-$

- $\star H \rightarrow \mu^+\mu^-$

ATL-PHYS-PUB-2013-014
H → J/ψ γ with J/ψ → μ⁺μ⁻

- Assume Run-1 detector performances

- μ⁺μ⁻ invariant mass compatible with J/ψ
- Multivariate analysis: \( p_T(γ), p_T(μμ), γ \) and μμ isolation
- \( m(μ⁺μ⁻γ) \): limited to 115-135 GeV window
- 3 signal events and 1700 background (non resonant J/ψ γ,...)

\[ \text{Expected branching ratio limit (no syst.) : } \mathcal{B}(H → J/ψ γ) < (44^{+19}_{-12}) \times 10^{-6} @ 95\% \text{ C.L.} \]

\[ \text{Standard Model expectation : } (2.9 ± 0.2) \times 10^{-6} \]
Vector Boson Fusion Higgs production

- $\text{VBF } H \rightarrow \text{WW}^* \rightarrow e\nu\mu\nu$

- $\star \text{VBF } H \rightarrow \text{ZZ}^* \rightarrow 4\ell$

ATL-PHYS-PUB-2016-008

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**VBF H → WW* → eνμν**

- Detector performances: Run-1 (e/μ) + SD (jets, missing-\(E_T\))

- Cut based analysis:
  - 2 forward jets in opposite hemispheres
  - e + μ / no other jet in between 2 jets
  - Missing-\(E_T\) > 20 GeV

- 200 signal events and 410 background (\(t\bar{t}\), ggF and WW)

- Main systematics: QCD scale uncertainty impacting ggF+ 2 jets rate

- Tracking coverage extension in \(η\) → stat.+ syst. uncertainty reduction by 40%

---

**Signal strength**

\[ \mu = \sigma / \sigma_{SM} \]

**Significance**

\[ Z_\sigma \]

<table>
<thead>
<tr>
<th></th>
<th>WW → eνμν stat.</th>
<th>WW → eνμν stat.+syst.</th>
<th>ZZ → 4ℓ stat.</th>
<th>ZZ → 4ℓ stat.+syst.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta \mu )</td>
<td>0.14</td>
<td>0.20</td>
<td>0.15</td>
<td>0.18</td>
</tr>
<tr>
<td>( Z_\sigma )</td>
<td>8.0</td>
<td>5.7</td>
<td>10.2</td>
<td>7.2</td>
</tr>
</tbody>
</table>

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Higgs boson couplings
 Extrapolation from Run-1 analysis

**ATLAS** Simulation Preliminary

\( \sqrt{s} = 14 \text{ TeV}; \int Ldt = 300 \text{ fb}^{-1}; \int Ldt = 3000 \text{ fb}^{-1} \)

- **H → γγ** (comb.)
- **H → ZZ** (comb.)
- **H → WW** (comb.)
- **H → Zγ** (incl.)
- **H → b\bar{b}** (comb.)
- **H → ττ** (VBF-like)
- **H → μμ** (comb.)

**Coupling precision for 3000 fb^{-1}**

- **W,Z : 3 %**
- **μ : 7%**
- **t,b,τ : 8-12 %**

**Experimental/theoretical uncertainties**

<μ_{PU}>=140
**Higgs boson self-coupling**

- $HH \rightarrow b\bar{b}\gamma\gamma$
- $HH \rightarrow b\bar{b}b\bar{b}$
- $t\bar{t}HH; HH \rightarrow b\bar{b}b\bar{b}$
- $\star HH \rightarrow b\bar{b}\tau^+\tau^-$  

ATL-PHYS-PUB-2015-046

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Non-resonant double Higgs production

First opportunity to measure Higgs boson trilinear self coupling ($\lambda_{HHH}$)

$\sigma(\text{HH}) \sim 40 \text{ fb}$

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Branching ratio (%)</th>
<th>$\sigma$.Br (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b}+b\bar{b}$</td>
<td>33</td>
<td>12.9</td>
</tr>
<tr>
<td>$b\bar{b}+W^+W^-$</td>
<td>25</td>
<td>9.9</td>
</tr>
<tr>
<td>$b\bar{b}+\tau^+\tau^-$</td>
<td>7.4</td>
<td>2.9</td>
</tr>
<tr>
<td>$W^+W^-+\tau^+\tau^-$</td>
<td>5.4</td>
<td>2.1</td>
</tr>
<tr>
<td>ZZ+$b\bar{b}$</td>
<td>3.1</td>
<td>1.2</td>
</tr>
<tr>
<td>ZZ+$W^+W^-$</td>
<td>1.2</td>
<td>0.48</td>
</tr>
<tr>
<td>$b\bar{b}+\gamma\gamma$</td>
<td>0.3</td>
<td>0.12</td>
</tr>
<tr>
<td>$\gamma\gamma+\gamma\gamma$</td>
<td>0.001</td>
<td>0.04</td>
</tr>
</tbody>
</table>
Assume SD detector performances for photons and most recent inner tracker layout for b-tagging (N. Calace's talk)

- Cut based analysis: narrow $\gamma\gamma$ mass peak, $m(bb)$, $p_T(\gamma\gamma/bb)$
- After selection: 9.5 signal events for 91 background ($bb\gamma\gamma$, $bbj\gamma$)
  → significance (no syst. uncertainty): $1.05 \sigma$

-0.8$< \frac{\lambda_{HHH}}{\lambda_{SM}}$< 7.7 @ 95% C.L. (no syst.)
Extrapolation from Run-2 analysis

Signal: 4 b-tagged jets

Main background: Multijet QCD → main systematic uncertainty (estimated from Run-2 data)

95% C.L. limits:

- $-0.2 < \frac{\lambda_{HHH}}{\lambda_{SM}} < 7$ (negligible syst.)
- $-3.5 < \frac{\lambda_{HHH}}{\lambda_{SM}} < 11$ (current syst.)

In case trigger $p_T$ threshold 30 → 75 GeV

- $-3.4 < \frac{\lambda_{HHH}}{\lambda_{SM}} < 12$ (negligible syst.)

@ 95% C.L.

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ttHH, HH → bbb

- ttHH cross section ~O(1 fb)
- Semileptonic final state for tt
- Assume SD detector performances

- Final state: 6 b-jets + 2 light jets
  + e or μ + missing-\(E_T\)

- Cut based analysis:
  - Main variables: Nb b-tagged jets, angle between jets
  - For ≥5 b-tag jets: 25 signal events and 7100 background (mainly ttbb + jets)

**Significance (no syst. error): 0.35 \(\sigma\)**
## Summary of HL-LHC Higgs results

<table>
<thead>
<tr>
<th>Channel</th>
<th>Result</th>
<th>HH final state</th>
<th>Significance Coupling limit (95 % C.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF $H \rightarrow WW$</td>
<td>$\Delta \mu/\mu \sim 14$ to $20%$</td>
<td>$HH \rightarrow b\bar{b}\gamma\gamma$ (stat. uncertainty only)</td>
<td>$1.05 \sigma$ $-0.8 &lt; \lambda_{HHH}/\lambda_{SM} &lt; 7.7$</td>
</tr>
<tr>
<td>VBF $H \rightarrow ZZ$</td>
<td>$\Delta \mu/\mu \sim 15$ to $18%$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}H, H \rightarrow \gamma\gamma$</td>
<td>$\Delta \mu/\mu \sim 17$ to $20%$</td>
<td>$HH \rightarrow b\bar{b}\tau^+\tau^-$ (with syst. uncertainties)</td>
<td>$0.6 \sigma$ $-4.0 &lt; \lambda_{HHH}/\lambda_{SM} &lt; 12.0$</td>
</tr>
<tr>
<td>VH, $H \rightarrow \gamma\gamma$</td>
<td>$\Delta \mu/\mu \sim 25$ to $35%$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow Z\gamma$</td>
<td>$\Delta \mu/\mu \sim 30%$</td>
<td>$HH \rightarrow b\bar{b}b\bar{b}$ (with syst. uncertainties)</td>
<td>$-3.5 &lt; \lambda_{HHH}/\lambda_{SM} &lt; 11.0$</td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$</td>
<td>$\Delta \mu/\mu \sim 15%$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow J/\psi \gamma$</td>
<td>BR $&lt; 44 \cdot 10^{-6}$ @ 95 % C.L.</td>
<td>$ttHH, HH \rightarrow b\bar{b}b\bar{b}$ (stat. uncertainty only)</td>
<td>$0.35 \sigma$</td>
</tr>
</tbody>
</table>

Detailed in this presentation
Conclusion

Even in the HL-LHC challenging environment, Higgs physics programme with ATLAS detector will benefit greatly from HL-LHC data.

The current expected ATLAS precisions at HL-LHC are still conservative:

- Still in detector optimisation phase (TDRs)
- More channels will be analysed and analysis techniques will be improved
- Better background control with data-driven methods
- Theoretical uncertainties expected to decrease with time

HL-LHC era will be an exciting period for Higgs physics studies.
Backup slides
Detector requirements to maximize benefits from high int. luminosity:

- Replace detector not sustaining integrated radiation dose
- Minimize pile-up effect (high granularity, fast timing)
- Higher trigger acceptance and event rate
- Improve or maintain current detector performances
## Trigger menu at HL-LHC

| Item                | Offline $p_T$ Threshold [GeV] | Offline $||$ Rate [kHz] | L0 Rate [kHz] | L1 Rate [kHz] | EF Rate [kHz] |
|---------------------|-------------------------------|-------------------------|---------------|---------------|---------------|
| isolated Single $e$ | 22                            | < 2.5                   | 200           | 40            | 2.20          |
| forward $e$         | 35                            | 2.4 – 4.0               | 40            | 8             | 0.23          |
| single $\gamma$     | 120                           | < 2.4                   | 66            | 33            | 0.27          |
| single $\mu$        | 20                            | < 2.4                   | 40            | 40            | 2.20          |
| di-$\gamma$         | 25                            | < 2.4                   | 8             | 4             | 0.18          |
| di-$e$              | 15                            | < 2.5                   | 90            | 10            | 0.08          |
| di-$\mu$            | 11                            | < 2.4                   | 20            | 20            | 0.25          |
| $e - \mu$           | 15                            | < 2.4                   | 65            | 10            | 0.08          |
| single $\tau$       | 150                           | < 2.5                   | 20            | 10            | 0.13          |
| di-$\tau$           | 40,30                         | < 2.5                   | 200           | 30            | 0.08          |
| single jet          | 180                           | < 3.2                   | 60            | 30            | 0.60*         |
| fat jet             | 375                           | < 3.2                   | 35            | 20            | 0.35*         |
| four-jet            | 75                            | < 3.2                   | 50            | 25            | 0.50*         |
| $H_T$               | 500                           | < 3.2                   | 60            | 30            | 0.60*         |
| $E_T^{miss}$        | 200                           | < 4.9                   | 50            | 25            | 0.50*         |
| jet + $E_T^{miss}$  | 140,125                       | < 4.9                   | 60            | 30            | 0.30*         |
| forward jet**       | 180                           | 3.2 - 4.9               | 30            | 15            | 0.30*         |
| Total               |                               | ~1000                   | ~400          | ~10           |               |

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Scoping Document Inner Tracker

- Long (47.8mm) Strips x 2 (r=762mm, 1000mm)
- Stub Layer x 1 (r=862mm)
- Disc Strips x 7 (z=1415mm, 1582mm, 1800mm, 2040mm, 2320mm, 2620mm, 3000mm)
- Pixel Barrel x 4 (r=39mm, 78mm, 155mm, 250mm)
- Short (23.8mm) Strips x 3 (r=405mm, 519mm, 631mm)
- Pixel Discs x 12 (877mm, 1059mm, 1209mm, 1358mm, 1509mm, 1675mm, 1875mm, 2075mm, 2275mm, 2500mm, 2750mm, 3000mm)
Hard-Scattered/Pile-up jet → $\gamma$

$<\mu_{PU}> = 200$

Hard Scattered jet → $b$

Pile-up → $\gamma$

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Pile-up jet rejection

CERN-LHCC-2015-020

ATLAS Simulation

\(\mu_{\text{PU}} = 140\)

ATL-PHYS-PUB-2016-026

ATLAS Simulation Preliminary

\(\mu_{\text{PU}} = 200\)

Pile-up → b

\(s = 14\ \text{TeV}, \mu = 130-150\)

PowhegPythia8 dijets

40<p_T<50 \text{ GeV}
Expected detector performances: electrons

\[ \sigma((E_{\text{rec}} - E_{\text{true}})/E_{\text{true}}) \% \]

**ATLAS Simulation**
- 7 < pT < 15 GeV
- 15 < pT < 20 GeV
- 20 < pT < 30 GeV
- 30 < pT < 50 GeV
- 50 < pT < 80 GeV
- 80 < pT < 120 GeV

\[ \langle \mu \rangle = 200 \]

**Z → ee**

*pT 30-50 GeV: 3-4% energy resolution*
Detector performances: Run-1 (e/µ) + SD (jets)

- Preselection cuts:
  - 2 jets with \( m(jj) > 130 \text{ GeV} \)
  - 4 leptons consistent with \( H \to ZZ^* \)

- Multivariate analysis (Boosted Decision Tree)
  \( \rightarrow 192 \) signal events and 326 background

- Main systematics: QCD scale uncertainty impacting ggF+ 2 jets rate
  - Tracking coverage extension in \( \eta \) (2.7 \( \to \) 4.0)
    \( \rightarrow \) stat.+ syst. uncertainty reduction by 14%

### Signal strength
\( \mu = \sigma / \sigma_{SM} \)

<table>
<thead>
<tr>
<th>( \mu_{PU} )</th>
<th>( \mu_{PU} = 140 ) stat.</th>
<th>( \mu_{PU} = 140 ) stat.+syst.</th>
<th>( \mu_{PU} = 200 ) stat.</th>
<th>( \mu_{PU} = 200 ) stat.+syst.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta \mu )</td>
<td>0.13</td>
<td>0.17</td>
<td>0.15</td>
<td>0.18</td>
</tr>
<tr>
<td>( Z_\sigma )</td>
<td>11.1</td>
<td>7.7</td>
<td>10.2</td>
<td>7.2</td>
</tr>
</tbody>
</table>

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Detector performances: Run-1 (e/μ) + SD (jets, missing-\(E_T\))

- Cut based analysis:
  - 2 forward jets in opposite hemispheres
  - \(e + \mu\) / no other jet in between 2 jets
  - Missing-\(E_T\) > 20 GeV

- 200 signal events and 410 background (tt, ggF and WW)
- Main systematics: QCD scale uncertainty impacting ggF+ 2 jets rate
- Tracking coverage extension in \(\eta\) → stat.+ syst. uncertainty reduction by 40%

\[
\begin{array}{|c|c|c|}
\hline
& \langle \mu_{PU} \rangle = 200 \text{ stat.} & \langle \mu_{PU} \rangle = 200 \text{ stat.+syst.} \\
\hline
\Delta \mu & 0.14 & 0.20 \\
\hline
Z_\sigma & 8.0 & 5.7 \\
\hline
\end{array}
\]
### ATLAS Simulation Preliminary

\( \sqrt{s} = 14 \text{ TeV}: \int L dt = 300 \text{ fb}^{-1}; \int L dt = 3000 \text{ fb}^{-1} \)

<table>
<thead>
<tr>
<th>H → γγ</th>
<th>(comb.)</th>
<th>(0j)</th>
<th>(1j)</th>
<th>(VBF-like)</th>
<th>(WH-like)</th>
<th>(ZH-like)</th>
<th>(ttH-like)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H → ZZ</td>
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<td>(0j)</td>
<td>(1j)</td>
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<td>(WH-like)</td>
<td>(ZH-like)</td>
<td>(ttH-like)</td>
</tr>
<tr>
<td>H → WW</td>
<td>(comb.)</td>
<td>(0j)</td>
<td>(1j)</td>
<td>(VBF-like)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H → Zγ</td>
<td>(incl.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H → bb</td>
<td>(comb.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H → ττ</td>
<td>(VBF-like)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H → μμ</td>
<td>(comb.)</td>
<td>(incl.)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>(ttH-like)</td>
<td></td>
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</tr>
</tbody>
</table>

\( \langle \mu_{PU} \rangle = 140 \)

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**Graphical Representation:**

- **H → γγ**
- **H → ZZ**
- **H → WW**
- **H → Zγ**
- **H → bb**
- **H → ττ**
- **H → μμ**

**Legend:**

- **Δμ/μ**
- **Ratio to SM**

**Axes:**

- **Y:**
- **Ratio to SM**
- **X:**
  - **m_i [GeV]**
  - **10^{-1}**
  - **10^{-2}**
  - **10^{-3}**
  - **10^{-4}**
  - **10^{0}**
  - **10^{1}**
  - **10^{2}**

**Labels:**

- **μ**
- **τ**
- **b**
- **W**
- **Z**
- **H → γγ, h → ZZ**
- **h → WW**
- **h → μμ, h → Zγ**
- **BR_{μ, μ} = 0**

**Footnote:**

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Higgs rare decay: $H \rightarrow \mu^+\mu^-$

- Signal extraction from high resolution of $\mu^+\mu^-$ invariant mass
- Results assuming same detector performance as Run-1
- $7\,\sigma$ significance

![ATLAS Simulation Preliminary](image)

$\sqrt{s} = 14$ TeV

$\int L \, dt = 3000$ fb$^{-1}$

- $H \rightarrow \mu\mu, m_H = 125$ GeV
- $Z \rightarrow \mu\mu$
- $t\bar{t}$
- $WW \rightarrow \mu\nu\nu$

ATL-PHYS-PUB-2013-014

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Non resonant double Higgs production


HH production at 14 TeV LHC at (N)LO in QCD
$M_H=125$ GeV, MSTW2008 (N)LO pdf (68%cl)

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Assume Run-1 detector performances

- Use fully hadronic (had-had) and semileptonic (had-e/µ) final states
- Main backgrounds: had-e/µ : tt ; had-had : Z→ττ + jets, bbjj, tt
- Main systematic source: Background modeling uncertainty (Run-1)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Significance</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>e/µ + jets</td>
<td>0.43</td>
<td>0.60</td>
</tr>
<tr>
<td>τhadτhad</td>
<td>0.41</td>
<td></td>
</tr>
</tbody>
</table>

\[ -4.0 < \frac{\lambda_{HHH}}{\lambda_{SM}} < 12 \text{ @ 95\% C.L.} \]
(with syst.)
HH $\rightarrow$ bbb\bar{b}

**ATLAS Preliminary**

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

- Expected 95% C.L. limit
- Expected 95% C.L. limit, background uncertainties $\times \sqrt{E}$
- Expected 95% C.L. limit, statistical uncertainties only

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