Searching for Di-Higgs → bbττ at ATLAS

Katharine Leney

20th November 2015
Overview

• Motivation for searching for di-Higgs pairs (and in the bbττ channel).
• ATLAS Run 1 HH→ bbττ analysis.
• Combination of all ATLAS HH channels.
• Prospects for HH→ bbττ searches in Run 2 and beyond.
Motivation

• TeV-scale resonances decaying to two 125 GeV Higgs bosons (h) predicted by several models, including:
  ‣ RS KK Graviton
  ‣ 2 Higgs Doublet Models (2HDM)
  ‣ Higgs portal models
  ‣ Composite models with hh resonances

• Enhancement of non-resonant di-Higgs production, e.g.
  ‣ Models with heavy top-partners
  ‣ Composite Higgs models
  ‣ Pseudo-dilaton models

• SM di-Higgs production at HL-LHC.
  ‣ Need ~3000 fb\(^{-1}\) to measure this.
  ‣ Sensitivity studies now drive upgrade design and performance requirements.
Supersymmetric extensions to Standard Model require two Higgs doublets → 5 observable Higgs bosons:

- 3 neutral (h/A/H)
- 2 charged (H±)

Assume the observed 125 GeV Higgs boson is the light Higgs (h).

Heavy Higgs (H) can decay to a pair of light Higgses (h).

Branching ratio to hh can be large, depending on parameters of model.

Range \( m_H < 500 \text{ GeV} \) theoretically favoured.

Couplings can be expressed as functions of \( \alpha \) (mixing angle) and \( \tan \beta \) (ratio of vacuum expectation values).
## Di-Higgs Decay Channels

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- **bb**
  - Largest branching ratio
  - Harder to trigger on (especially for low mass resonances and SM)

20th November 2015

Katharine Leney
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**xxWW**
- Take a hit on branching ratio to have events where W decays leptonically (~34%).
- Reconstructing hadronic W decays difficult (large QCD backgrounds).
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- **Clean signature** (thanks to di-photon pair in final state).
- **Tiny branching ratios**...
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**ZZZZ**
- Possibility to select clean final states with 2 or 4 leptons, but large hit on branching ratio.
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**bbττ**
- Possibility to trigger on lepton from tau decays (58% of events).
- Fully hadronic tau-tau channels have comparable sensitivity to $e\tau_h$ and $\mu\tau_h$ channels at ATLAS.

**Katharine Leney**
20th November 2015
**Tau Decay Characteristics**

**Hadronic**
- Well collimated, low multiplicity jet
- Deposits in both hadronic and EM calorimeters.
- One or three tracks matching the calorimeter deposition.

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**τ Channels**
- Di-Lepton: 41.9%
- Lepton-Hadron: 12.4%
- Hadron-Hadron: 45.8%
Tau Reconstruction and ID in ATLAS

- Taus seeded from anti-\( k_t \) jets with \( \Delta R = 0.4 \).
- Candidates required to be associated with 1 or 3 tracks within a core region \( \Delta R < 0.2 \).
- Isolated in annulus \( 0.2 < \Delta R < 0.4 \).
- Various discriminating variables combined in Boosted Decision Trees to reject tau-fakes from electrons and jets.
  - BDTs trained separately for 1 and 3-prong taus.
b-Jet Decay Characteristics

b–jet tagging relies on B–hadron properties:

• Long lifetime → displaced vertex (secondary vertex, SV) typically few mm from primary vertex (PV).
• Large impact parameter (d0).
• Large B–hadron mass.
• Semi–leptonic (e/µ) decay of B–hadron
  ‣ (~40% including b→c→ℓνX decay).
b-Tagging in ATLAS

- Use outputs of 3 algorithms as inputs to MVA:
  - IP3D: Use transverse and longitudinal IP significance.
  - SV1: Reconstruct SV and use information about:
    - SV mass
    - $\Sigma$(P_T SV tracks)/$\Sigma$(P_T all tracks in jet)
    - Number of two-track vertices
    - $\Delta$R (jet–direction, PV→SV direction)
  - JetFitter: Exploit the topology of weak B/C–hadron decay chain ($b\rightarrow c\rightarrow X$) inside jets.
Run 1 HH → bbττ Analysis

**Preselection**
- Select all objects in bbττ final state (ℓ + τ + 2-jets).
- Only lepton-hadron decay mode considered in Run 1.

**Kinematic Cuts**
- Addition rejection against Z+jets, W+jets and ttbar.

**Event Categorisation**
- Number of b-jets.
- $p_T$ of τ-pair.

**Resonant Search**
- $m(ττ)$ cut
- Final discriminant: $m(bbττ)$.

**Non-Resonant Search**
- Final discriminant: $m(ττ)$

**Event Preselection**
- Single lepton trigger
- One isolated lepton (e/µ), $p_T > 26$ GeV
- Di-lepton veto
- One hadronic tau, $p_T > 20$ GeV
- Charge correlation between lepton and tau
- Two or more jets, $p_T > 30$ GeV

√s = 8 TeV
$\int \mathcal{L} = 20$ fb$^{-1}$
Top-Pair Production

- Contribution where the hadronic tau is real estimated from MC (Powheg).
- Fraction where hadronic W-decay fakes tau calculated separately (see later slide).

**ATLAS** $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

preselection $\mu\tau_{\text{had}} + e\tau_{\text{had}}$

<table>
<thead>
<tr>
<th>Events / 10 GeV</th>
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<tbody>
<tr>
<td>2000</td>
</tr>
<tr>
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</tr>
<tr>
<td>1600</td>
</tr>
<tr>
<td>1400</td>
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<tr>
<td>1200</td>
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<tr>
<td>1000</td>
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<td>800</td>
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<tr>
<td>600</td>
</tr>
<tr>
<td>400</td>
</tr>
<tr>
<td>200</td>
</tr>
<tr>
<td>0</td>
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**m_{\tau\tau} [GeV]**

- Data
- Top quark
- $Z\rightarrow\tau\tau+\text{jets}$
- Others
- Fake $\tau$
- Systematics
- $H(300)\, hh(20\, \text{pb})$
- Non-reso. $hh(20\, \text{pb})$
Backgrounds

**Z→ττ Background**
- Estimated from data using embedding method:
  - Z→μμ events selected from data.
  - Muons replaced with simulated taus.
  - Missing E_T corrections applied.
- Normalised to data in 40 < M^{vis}(ττ) < 70 GeV region.
Backgrounds

Others
• Single top, di-boson, $Z \rightarrow \ell\ell$ all estimated from MC.
• Small contribution.
Fake Taus
• Fake-factor method to estimate all backgrounds where the tau is faked by a jet.
  ‣ Multijets.
  ‣ Semi-leptonic ttbar.
  ‣ W+jets.
  ‣ Z→ττ+jets (where one tau is missed).
Fake-Factor Method

\[ N_{\text{Bkg}}^{\text{Est.}} = (N_{\text{data,SR}}^{\text{anti-}\tau} - N_{\text{true,SR}}^{\text{anti-}\tau}) \times \text{FF}_{\text{CR}} \]

\[ \text{FF}_{\text{CR}} = \frac{N_{\text{identified-}\tau}^{\text{CR}}}{N_{\text{CR}}^{\text{anti-}\tau}} \]

- Number of anti-tau events (failing signal tau ID, but passing looser selection).
- Contribution from real taus subtracted.
- Separate FFs for each contributing process.
- Calculated as a function of \( p_T \) and \#-tracks.

\[ \text{FF}(p_T, n_{\text{prong}}) = \sum_{i=bkg} R_i \text{FF}_i(p_T, n_{\text{prong}}) \]

\( R_i = \) fraction of each source
\( \text{FF}_i = \) FF of each source
Kinematic Cuts

<table>
<thead>
<tr>
<th>Kinematic Cut</th>
<th>Description</th>
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<tbody>
<tr>
<td>Transverse mass</td>
<td>Reject W+jets and ttbar ( m_T &lt; 60 \text{ GeV} )</td>
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<tr>
<td>Missing ( E_T \phi ) centrality</td>
<td>Missing ( E_T ) should point between the lepton and tau.</td>
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<tr>
<td>Lepton-tau ( p_T ) balance</td>
<td>( \Delta p_T(\ell,\tau) &lt; 20 \text{ GeV} )</td>
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<tr>
<td>( m_W ) vs. ( m_{\text{top}} )</td>
<td>Elliptical cuts on ( W ) and top masses</td>
</tr>
<tr>
<td>( m_{bb} ) mass window</td>
<td>( 90 &lt; m_{bb} &lt; 160 \text{ GeV} )</td>
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![Graph showing kinematic cuts](image)
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Leptons from W decay tend to be harder than those from taus because of number of accompanying neutrinos.
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**Diagram:**
- $m(jj)$ → $W$ mass
- $m(jjb) → top$ mass
- 2D cut on $m_{top}$ vs $m_W$
## Kinematic Cuts

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### Graph

- **ATLAS $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$**
- Preselection
- $\mu\tau_{had} + e\tau_{had}$

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</tr>
<tr>
<td>Top quark</td>
<td>Green</td>
<td>Top quark</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau +$ jets</td>
<td>Blue</td>
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</tr>
<tr>
<td>Others</td>
<td>Yellow</td>
<td>Others</td>
</tr>
<tr>
<td>Fake $\tau$</td>
<td>Cyan</td>
<td>Fake $\tau$</td>
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<td>Systematics</td>
<td>Grey</td>
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<td>Non-reso. hh</td>
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- $m_{\tau\tau}$ reconstructed using Missing Mass Calculator (MMC), arXiv: 1012.4686
- Weights the kinematically allowed $\tau$ decay solutions by a likelihood function.
Event Categorisation

Preselection

Kinematic Cuts

Event Categorisation

One or two b-tagged jets

Tau pair $p_T$ is low ($< 100$ GeV)
or high ($> 100$ GeV)
Non-Resonant Analysis

- Use $m_{\tau\tau}$ as final discriminant

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<td>1.6 pb</td>
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<table>
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<tr>
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<td>Expected</td>
<td>130</td>
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<td>Observed</td>
<td>160</td>
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**ATLAS** $\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

- Data
- Top quark
- $Z\rightarrow\tau\tau$ + jets
- Others
- Fake $\tau$
- Systematics
- Non-reso. hh(10 pb)
Resonant Analysis

• Apply scale factors $m_h/m_{bb}$ and $m_h/m_{\tau\tau}$ to 4-momenta of $bb$ and $\tau\tau$ systems.
  ‣ $m_h = 125$ GeV (SM Higgs)
• Improves mass resolution of heavy resonances.
Resonant Analysis

\[ \text{ATLAS} \sqrt{s} = 8 \text{ TeV, } 20.3 \text{ fb}^{-1} \]

\[ hh \rightarrow bb\tau\tau \text{ (} bb\mu\tau_{\text{had}} + bb\nu\tau_{\text{had}} \text{)} \]

\[ \sigma(gg\rightarrow H) \times BR(H\rightarrow hh) \text{ [pb]} \]

- **Observed**
- **Expected**
- \(\pm 1\sigma \) expected
- \(\pm 2\sigma \) expected

\[ m_H \text{ [GeV]} \]

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Combination With Other Channels

\[ \sigma (gg \rightarrow H) \times \text{BR}(H \rightarrow hh) \text{ [pb]} \]

**ATLAS** \( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)

- Observed
- Expected
- \( \pm 1\sigma \) expected
- \( \pm 2\sigma \) expected
- \( bb\tau\tau \) exp
- \( WW\gamma\gamma \) exp
- \( bb\gamma\gamma \) exp
- \( bbbb \) exp

![Graph showing the combination of Higgs production and decay rates with other channels.](image)
Constraints on 2HDM Models

**hMSSM**
Lighter h boson has a mass of 125 GeV. Non-observation of superparticles at the LHC indicates that SUSY-breaking scale $M_S \gtrsim 1$ TeV. Approx. “model-independent” approach of the MSSM Higgs sector.


**low-tb-high:**
Lighter h boson has a mass of 125 GeV. Preferred region is low tan-β and heavy SUSY.

*LHCHXSWG-2015-002*
**Expected Improvements For Run 2**

**LHC Run 2:**
- 2015-2018
- $\sqrt{s} = 13$ TeV
- 100 fb$^{-1}$
- $\mu = 50$

Access processes with smaller cross-sections and/or higher mass

![Graph showing luminosity ratios](image)

**2015 Summary:**
- 4 fb$^{-1}$ collected (3.34 fb$^{-1}$ after data quality requirements).
- Expect to have slightly better sensitivity to $X \rightarrow hh \rightarrow bb\tau\tau$ process than in Run 1 with the 2015 dataset.
Expected Improvements For Run 2

- Include fully hadronic tau-tau decay channel.
  ‣ Similar sensitivity to lepton-hadron channel.
  ‣ Fully leptonic channel adds very little, but can be useful as a cross-check.

- Further analysis optimisation.

- Improved object identification for Run 2.
Expected Improvements For Run 2

- Include fully hadronic tau-tau decay channel.
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- Further analysis optimisation.

- Improved object identification for Run 2.
  - Taus

---

**Run 1**

ATLAS

Data 2012, $\sqrt{s}=8\text{ TeV}$

---

**Run 2**

ATLAS Simulation

Preliminary

$P_T \geq 20 \text{ GeV}$

---

20th November 2015

Katharine
Expected Improvements For Run 2

- Include fully hadronic tau-tau decay channel.
  - Similar sensitivity to lepton-hadron channel.
  - Fully leptonic channel adds very little, but can be useful as a cross-check.

- Further analysis optimisation.

- Improved object identification for Run 2.
  - Taus
  - b-jets

---

**ATLAS Simulation Preliminary**

\[ \sqrt{s} = 13 \text{ TeV}, \bar{t}t \]

**Run 1**

- ATLAS Preliminary
- \( p_T^{\text{jet}} > 20 \text{ GeV}, |\eta| < 2.5 \)

**Run 2**

- MV1
- \( \varepsilon_b = 70\% \)

**Jet \( p_T \) [GeV]**

- Light-flavour jets
- \( c \) jets
- \( b \) jets
Expected Improvements For Run 2

- Dedicated analysis using sub-structure techniques to reconstruct boosted tau and b-jet pairs will follow later in 2016.

- Current analysis has a natural end-point of ~1 TeV, where $\Delta R(\tau,\tau) \sim 0.4$ and tau ID fails.
  - Normal tau ID relies on an isolation annulus ($0.2 < \Delta R < 0.4$) so fails if the taus are too close together.
  - Dedicated boosted tau-pair finding algorithm to recover these events and extend mass reach of the analysis.

- $b$-tagging performance also degrades as a function of $\Delta R(b,b)$.
  - Less of a ‘cliff’ than tau ID.
  - Dedicated tagger for finding boosted pairs of $b$-jets developed.
  - $HH\rightarrow bbbb$ analysis shows significant gains when using it.
HL-LHC

QUITE A LONG WAY OFF
(2023-2035-ISH)
SM Higgs Pair Production
SM Higgs Pair Production
• Higgs self-coupling crucial check of EWSB mechanism.

• Possibly *the* most challenging measurement at the LHC!

• Direct measurement of the Higgs trilinear self-coupling ($\lambda_{hhh}$) can be made by studying Higgs pair-production.

• Need to dis-entangle top box-diagram and diagram containing the HHH vertex...

• Destructive interference with diagrams not containing the HHH vertex.
  - Box diagram dominates in boosted events.
  - Absolutely crucial to push down to lower $p_T$’s in order to access $\lambda_{hhh}$. 

20th November 2015

Katharine Leney
SM Higgs: Pair Production

- For $\lambda_{HHH}/\lambda_{hhh}^{\text{SM}} = 0/1/2$, cross-section = 71/34/16 fb.
- With 3000 fb$^{-1}$ a $\sim 3\sigma$ combined measurement by ATLAS+CMS should be possible.
SM HH→bbττ Sensitivity Study

• Truth-level, `cut-and-count’ study for first estimate of sensitivity.
  ‣ Detector response parameterised.
  ‣ More sophisticated analyses (using MVAs) will be necessary.

• Assume 3000 fb\(^{-1}\) data, √s = 14 TeV, and 140 proton-proton collisions per bunch-crossing.

• All tau-tau decay modes considered:
  ‣ Fully leptonic (τ\(ℓ\)τ\(ℓ\))
  ‣ Semi-leptonic (τ\(ℓ\)τ\(h\))
  ‣ Fully hadronic (τ\(h\)τ\(h\))

• SM Higgs processes that have been negligible backgrounds in the new physics searches so far become more important.
  ‣ e.g. VH, ttV, ttH

• Higgs bosons produced by λ\(_{HHH}\) process have low \(p_T\).
  ‣ Those produced via top box-diagram are more boosted.
  ‣ Lower \(p_T\) objects harder to separate from multi-jets backgrounds.
  ‣ Need to find the right balance...
Event Selection

<table>
<thead>
<tr>
<th>Event Selection Criteria</th>
<th>Example Cut Value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{bb}$ mass window</td>
<td>$95 &lt; m_{bb} &lt; 145$ GeV</td>
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<tr>
<td>$m_{\tau\tau}$ mass window</td>
<td>$90 &lt; m_{\tau\tau} &lt; 160$ GeV</td>
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<tr>
<td>$p_T(bb)$</td>
<td>$p_T(bb) &gt; 200$ GeV</td>
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<td>bb-pair separation</td>
<td>$\Delta R(bb) &lt; 1.0$</td>
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<td>Transverse mass</td>
<td>$m_T &lt; 80$ GeV</td>
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<td>Stransverse mass</td>
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* Slight variations in exact cut values between channels
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* Slight variations in exact cut values between channels

---

Stransverse mass: Generalisation of the transverse mass when applied to signatures with two (or more) invisible particles in the final state.

Prospects for Measuring $\lambda_{HHH}$ at the HL-LHC

<table>
<thead>
<tr>
<th>Channel</th>
<th>Significance</th>
<th>Combined in channel</th>
<th>Total combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e + \text{jets}$</td>
<td>0.31</td>
<td>0.43</td>
<td>0.60</td>
</tr>
<tr>
<td>$\mu + \text{jets}$</td>
<td>0.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau_{\text{had}}\tau_{\text{had}}$</td>
<td>0.41</td>
<td>0.41</td>
<td></td>
</tr>
</tbody>
</table>

- Use of more sophisticated analysis techniques can improve sensitivity.
- Combination across many channels will be necessary.
- Large correlation between total di-Higgs production cross-section and $\lambda_{HHH}$.
  ‣ $\lambda_{HHH}$ better studied using shape analysis of key observables.

$\sigma / \sigma_{SM}$ as a function of $\lambda / \lambda_{SM}$

$\tau_\ell\tau_\ell$ channels order of magnitude less sensitive than $\tau_\ell\tau_h$ or $\tau_h\tau_h$ channels.
Summary & Conclusions

• Di-Higgs physics is a new and exciting avenue for searching for new physics.
  ‣ Many new physics models predict enhanced rates, either as resonant or non-resonant production.
  ‣ Also predicted by the SM where it will be a crucial test of the Higgs mechanism.
  ‣ $b\bar{b}\tau\tau$ is a promising channel, particularly in the SM/lower mass/non-resonant regime.

• Run 1 searches showed no signal in the $b\bar{b}\tau\tau$, or any other channel.
  ‣ Limits set on resonant and non-resonant HH production.

• Will significantly extend this reach during the LHC Run 2.
  ‣ Even with 2015 data alone should do better than Run 1.
  ‣ Extra analysis optimisations will improve the sensitivity further, particularly at higher masses.

• The $b\bar{b}\tau\tau$ channel is a promising one for measuring di-Higgs production and $\lambda_{HHH}$ at the HL-LHC.
Back Up
Obligatory ATLAS Detector Slide

20th November 2015

Katharine Leney
Combination With Other Channels

Local $\rho_0$

$\sqrt{s} = 8$ TeV 20.3 fb$^{-1}$

ATLAS
Resonant Analysis - Comparison with CMS

**ATLAS**: Only $\tau_\ell \tau_h$ channels
**CMS**: $\tau_\ell \tau_h$ and $\tau_h \tau_h$ channels.

**ATLAS**: $\sigma \times \text{BR}(H \rightarrow hh)$
**CMS**: $\sigma \times \text{BR}(H \rightarrow hh \rightarrow bb\tau\tau)$

Limit at 300 GeV:
**ATLAS**: 3 pb $\times$ BR(hh $\rightarrow$ bb$\tau\tau$) = 0.21 pb
**CMS**: 0.2 pb
CMS hh→bbττ Results

Figure 8: Upper limits at 95% CL on the H→hh→bbττ cross section times branching fraction for the τ→µτ (top left), τ→eτ (top right), τ→ττ (bottom left), and for final states combined (bottom right)
ATLAS H$\rightarrow$hh$\rightarrow$ bb$\gamma\gamma$

$\int\text{L}dt = 20 \text{ fb}^{-1} \text{ at } \sqrt{s} = 8 \text{ TeV}$

- Observed 95% CL Limit
- Expected Limit $\pm 1\sigma$
- Expected Limit $\pm 2\sigma$
- Type I 2HDM:
  $\tan\beta = 1$, $\cos(\beta-\alpha) = -0.05$
ATLAS H → hh → bbb

**ATLAS**
\[ \sqrt{s} = 8 \text{ TeV} \int L dt = 19.5 \text{ fb}^{-1} \]

- **Observed Limit (95% CL)**
- **Expected Limit (95% CL)**
- **Expected ±1σ**
- **Expected ±2σ**

\[ \Gamma_H = 1 \text{ GeV} \]
2HDM Models

• Higgs sector of 2HDM models described by parameters:
  ‣ 4 Higgs masses
  ‣ tan-β (ratio of vacuum expectation values, vev)
  ‣ α (mixing between the two neutral CP even states h,H).

• Several different ‘types’ of 2HDM:
  ‣ Type I: One doublet couples to V(“fermiophobic”), one to fermions.
  ‣ Type II: “MSSM like” model, one doublet couples to up-type quarks, one to down-type quarks.
  ‣ Type III: “Lepton-specific” model, Higgs bosons have same couplings to quarks as type I and to leptons as in type II.
  ‣ Type IV: “Flipped” model, Higgs bosons have same couplings to quarks as in type II and to leptons as in type I.

• For more specific MSSM models $m_h$ fully determined at tree level by $m_A$ and tan-β.
# Prospects for Measuring $\lambda_{HHH}$ at the HL-LHC

<table>
<thead>
<tr>
<th>Signal Significance</th>
<th>had-had</th>
<th>lep-had (e channel)</th>
<th>lep-had ($\mu$ channel)</th>
<th>lep-lep ($ee$ channel)</th>
<th>lep-lep ($\mu\mu$ channel)</th>
<th>lep-lep ($e\mu$ channel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S/\sqrt{B} (\lambda = 0\lambda_{\text{SM}})$</td>
<td>0.66</td>
<td>0.49</td>
<td>0.45</td>
<td>0.044</td>
<td>0.055</td>
<td>0.091</td>
</tr>
<tr>
<td>$S/B (\lambda = 0\lambda_{\text{SM}})$</td>
<td>0.023</td>
<td>0.023</td>
<td>0.023</td>
<td>0.00092</td>
<td>0.0016</td>
<td>0.0017</td>
</tr>
<tr>
<td>$S/\sqrt{B} (\lambda = 1\lambda_{\text{SM}})$</td>
<td>0.47</td>
<td>0.35</td>
<td>0.33</td>
<td>0.033</td>
<td>0.036</td>
<td>0.062</td>
</tr>
<tr>
<td>$S/B (\lambda = 1\lambda_{\text{SM}})$</td>
<td>0.016</td>
<td>0.016</td>
<td>0.017</td>
<td>0.00069</td>
<td>0.0010</td>
<td>0.0012</td>
</tr>
<tr>
<td>$S/\sqrt{B} (\lambda = 2\lambda_{\text{SM}})$</td>
<td>0.29</td>
<td>0.25</td>
<td>0.23</td>
<td>0.023</td>
<td>0.025</td>
<td>0.044</td>
</tr>
<tr>
<td>$S/B (\lambda = 2\lambda_{\text{SM}})$</td>
<td>0.010</td>
<td>0.012</td>
<td>0.011</td>
<td>0.00048</td>
<td>0.00074</td>
<td>0.00084</td>
</tr>
<tr>
<td>$S/\sqrt{B} (\lambda = 10\lambda_{\text{SM}})$</td>
<td>1.0</td>
<td>0.56</td>
<td>0.52</td>
<td>0.062</td>
<td>0.072</td>
<td>0.14</td>
</tr>
<tr>
<td>$S/B (\lambda = 10\lambda_{\text{SM}})$</td>
<td>0.036</td>
<td>0.027</td>
<td>0.026</td>
<td>0.0013</td>
<td>0.0021</td>
<td>0.0027</td>
</tr>
</tbody>
</table>
The Unbearable Lightness of $M_H$...

$M_H^2 = M_{\text{bare}}^2 + (\text{Radiative corrections, top loop dominates: } \sim m_t^2 \Lambda^2) + (\Lambda^2: \text{the energy scale at which the SM breaks down})$

Observed mass (~125 GeV)

Bare mass to cancel radiative corrections

Need a cancellation to 33 digits if $\Lambda$ is at the Planck scale (~$10^{19}$ GeV) - fine tuning!

Very strong motivation for new physics at TeV scale!