Higgs boson into fermions at ATLAS

Dimitris Varouchas
on behalf of the ATLAS Collaboration

La Thuile 2014 conference, Friday 28th February 2014
Higgs boson discovery

• Summer 2012: Historic observation of Higgs boson particle with a mass of $m_H \approx 125.5$ GeV from ATLAS and CMS

• Autumn 2013: The Nobel Prize in Physics 2013

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs “for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider”
What did we discover exactly?

- Observation via $ZZ^*$, $WW^*$ and $\gamma\gamma$ decay modes

- **Results** strongly favour $J^P=0^+$ quantum numbers, consistent with **Standard Model** theory
  - See Magda’s and Jean-Baptiste’s talk in a while

- **Is the discovered Higgs boson coupling to fermions?**
  - **quarks?**
    Most likely yes, because of the quark loop in gg-fusion/photon decay.
    *Nevertheless a direct measurement to quarks is necessary: $H\rightarrow bb$*
  - **leptons?**
    *This is the question that the $H\rightarrow \mu\mu$ and $H\rightarrow \tau\tau$ analyses are addressing*
• ATLAS results covered in this talk
  ✦ Search for $\text{SM } H \to bb$ with full 2011 & 2012 (7 & 8 TeV) dataset
    ✤ ATLAS-CONF-2013-079
  ✦ Search for $\text{SM } H \to \mu\mu$ with full 2012 (8 TeV) dataset
    ✤ ATLAS-CONF-2013-010
  ✦ Search for $\text{SM } H \to \tau\tau$ with full 2012 (8 TeV) dataset
    ✤ ATLAS-CONF-2013-108

• Not covered here
  ✦ ttH (See Magda’s talk in a while)
  ✦ BSM searches for $H \to ff$
- **gg-Fusion**, dominant production mode
- **VBF** offers interesting topology for $\tau\tau$ with two forward jets
- **V(W,Z)H** smaller production rate but the most powerful channel to search for decays to b-quarks

<table>
<thead>
<tr>
<th>$m$</th>
<th>$\tau\tau$</th>
<th>VH(bb)</th>
<th>$\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma \times \text{BR} [\text{pb}]$</td>
<td>$\sim 1.4$</td>
<td>$\sim 0.08$</td>
<td>$\sim 0.0002$</td>
</tr>
</tbody>
</table>
Probing fermionic couplings

- Decays
  - $\text{SM} \ VH \rightarrow \text{bb}$ with full 2011 & 2012 (7 & 8 TeV) dataset
    - ATLAS-CONF-2013-079
  - $\text{SM} \ H$
    - ATLAS-CONF-2013-010
  - $\text{SM} \ H$
    - ATLAS-CONF-2013-108
H→bb: Exploit unique production mode VH

- Production in association with a **leptonically** decaying W/Z

- Main challenges are **triggering** and large **backgrounds** over very small expected signals
  - Trigger using leptonic W/Z decays or MET
  - Boost of W/Z to control backgrounds

- Cut-based analysis in **3 final states** according to the number of leptons from W or Z decay
  - ZH→ll+bb: 2 opposite-sign leptons, 2 b-tagged jets
    - Backgrounds: Z+heavy flavour
  - ZH→νν+bb: large MET, 2 b-tagged jets, 0 leptons
    - Backgrounds: top, Z/W+heavy flavour
  - WH→lν+bb: 1 lepton, MET, 2 b-tagged jets
    - Backgrounds: top, W+heavy flavour

- To maximise sensitivity split into bins of \( N_{\text{jets}}, p_T^V \)
- Search for peak in di-jet \( m_{bb} \) invariant mass
Background modelling

- Multijet: **Data driven** method
- Non multijet backgrounds: **Shape from MC, normalisation from Data**

Control regions (CR) included in the fit

<table>
<thead>
<tr>
<th>3 $p_T(V)$ bins</th>
<th>0-leptons</th>
<th>2 jets 1 b-tag</th>
<th>3 jets 1 b-tag</th>
<th>2 jets 2 b-tags</th>
<th>3 jets 2 b-tags</th>
<th>Top CR $e\mu$ events</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 $p_T(V)$ bins</td>
<td>0-leptons</td>
<td>CR</td>
<td>CR</td>
<td>SR</td>
<td>SR</td>
<td>CR</td>
</tr>
<tr>
<td>5 $p_T(V)$ bins</td>
<td>1-lepton</td>
<td>CR</td>
<td>CR</td>
<td>SR</td>
<td>SR</td>
<td>CR</td>
</tr>
<tr>
<td>5 $p_T(V)$ bins</td>
<td>2-leptons</td>
<td>CR</td>
<td>CR</td>
<td>SR</td>
<td>SR</td>
<td>CR</td>
</tr>
</tbody>
</table>

- Simultaneous fit in 26 signal regions (SR), 26 1b-tag CR’s and 5 top CR’s
- **Common nuisance parameters** (reflecting the systematic uncertainties) across SR’s and CR’s and channels/categories
H → bb: Cross-check with VZ(bb)

- **VZ(bb)** similar signature with 5 times larger cross section than VH(bb)
- Measure VZ(bb): a direct **test** of the analysis procedure
- The obs. (exp.) significance of VZ is **4.8 (5.1) \( \sigma \)**
- \( \mu_{\text{VZ}} = \sigma_{\text{meas}(\text{VZ})}/\sigma_{\text{SM}(\text{VZ})}=0.9\pm0.2 \)
**H→bb: Measured signal strength**

**For m_H = 125 GeV**
- **7 TeV**
  - 2σ deficit wrt SM expectation
- **8 TeV**
  - Consistent with both S+B and B-only hypotheses within 1σ
- Combined result
  - \[ \mu = \frac{\sigma_{VH→bb}}{\sigma_{SM}} = 0.2^{+0.7}_{-0.6} \]

**Observed (expected) upper limit at 95% CL:**
- **1.4 (1.3) x \sigma_{SM}**

**Dominant uncertainties**
- ttbar modelling
- b-tagging jet efficiency
- Multijet normalisation in 1-lepton channel

**ATLAS Prelim.**

<table>
<thead>
<tr>
<th>Channel</th>
<th>( \mu )</th>
<th>( \sigma_{stat} )</th>
<th>( \sigma_{sys} )</th>
<th>( \sigma_{theo} )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>VH(bb), 7 TeV</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VH, 0 lepton</td>
<td>( -2.1^{+1.4}_{-1.4} )</td>
<td>( 0.1^{+0.1}_{-0.1} )</td>
<td>( 0.0^{+0.0}_{-0.0} )</td>
<td>( -0.2^{+0.2}_{-0.2} )</td>
</tr>
<tr>
<td>VH, 1 lepton</td>
<td>( -2.7^{+2.2}_{-1.9} )</td>
<td>( 0.1^{+0.1}_{-0.1} )</td>
<td>( 0.0^{+0.0}_{-0.0} )</td>
<td>( -0.2^{+0.2}_{-0.2} )</td>
</tr>
<tr>
<td>VH, 2 leptons</td>
<td>( -2.5^{+2.0}_{-1.9} )</td>
<td>( 0.1^{+0.1}_{-0.1} )</td>
<td>( 0.0^{+0.0}_{-0.0} )</td>
<td>( -0.2^{+0.2}_{-0.2} )</td>
</tr>
</tbody>
</table>

| **VH(bb), 8 TeV**|               |                      |                    |                     |
| VH, 0 lepton     | \( 0.6^{+0.7}_{-0.7} \) | \( 0.1^{+0.1}_{-0.1} \) | \( 0.0^{+0.0}_{-0.0} \) | \( -0.1^{+0.1}_{-0.1} \) |
| VH, 1 lepton     | \( 0.9^{+1.0}_{-0.9} \) | \( 0.1^{+0.1}_{-0.1} \) | \( 0.0^{+0.0}_{-0.0} \) | \( -0.1^{+0.1}_{-0.1} \) |
| VH, 2 leptons    | \( 0.7^{+1.1}_{-1.1} \) | \( 0.1^{+0.1}_{-0.1} \) | \( 0.0^{+0.0}_{-0.0} \) | \( -0.1^{+0.1}_{-0.1} \) |

| **Comb. VH(bb)** | \( 0.2^{+0.7}_{-0.6} \) | \( 0.1^{+0.1}_{-0.1} \) | \( 0.0^{+0.0}_{-0.0} \) | \( -0.1^{+0.1}_{-0.1} \) |
| VH, 0 lepton     | \( 0.5^{+0.9}_{-0.9} \) | \( 0.1^{+0.1}_{-0.1} \) | \( 0.0^{+0.0}_{-0.0} \) | \( -0.1^{+0.1}_{-0.1} \) |
| VH, 2 leptons    | \( 0.1^{+1.0}_{-1.0} \) | \( 0.1^{+0.1}_{-0.1} \) | \( 0.0^{+0.0}_{-0.0} \) | \( -0.1^{+0.1}_{-0.1} \) |

- **Most powerful channel:** 0-lepton
- **Small theory uncertainties for VH mode**
Probing fermionic couplings

- Decays
  - **SM VH**
    - ATLAS-CONF-2013-079
  - **SM $H \rightarrow \mu \mu$** with full 2012 (8 TeV) dataset
    - ATLAS-CONF-2013-010
  - **SM $H$**
    - ATLAS-CONF-2013-108
H→μμ: Analysis overview

- σ×BR (H→μμ) very small ~2×10⁻⁴ pb
- Very good di-muon, m_{μμ}, mass resolution
- Two categories based on muon resolution
  - a) Central: |η|<1.0
  - b) Non-central: rest
- Two isolated, opposite-charge muons: p_T(μ₁)>25 GeV, p_T(μ₂)>15 GeV
**H → μμ: Analysis overview**

- $\sigma \times \text{BR} (H \rightarrow \mu\mu)$ very small $\sim 2 \times 10^{-4}$ pb
- Very good di-muon, $m_{\mu\mu}$, mass resolution
- Two categories based on muon resolution
  - a) Central: $|\eta| < 1.0$
  - b) Non-central: rest
- Two isolated, opposite-charge muons: $p_T(\mu_1) > 25$ GeV, $p_T(\mu_2) > 15$ GeV
- Fit $m_{\mu\mu}$ with analytic Signal+Background shape
  - **Background model:** Breit-Wigner + exponential PDFs
  - **Signal model:** Crystal Ball(CB) + Gaussian PDFs
\( H \to \mu \mu: \) Results

- Dominant systematic uncertainties
  - Cross section: 15%
  - BR\((H \to \mu \mu)\): 6%
  - Acceptance uncertainty
    - Theory: ~3%
    - Experimental: ~4%

ATLAS results with 20.7 fb\(^{-1}\) at 8 TeV

- No significant deviations observed
- Current sensitivity not sufficient for conclusive statement
- 95% CL limit @ 125 GeV: observed\(\) (expected) \(9.8(8.2)\times \sigma_{SM}\)
Probing fermionic couplings

- Decays
  - **SM VH**
    - ATLAS-CONF-2013-079
  - **SM H**
    - ATLAS-CONF-2013-010
  - **SM H → ττ** with full 2012 (8 TeV) dataset
    - ATLAS-CONF-2013-108
H$\rightarrow\tau\tau$ search: Analysis concept

• Question that this analysis attempts to address
  ✦ Does the Higgs boson with $m_H \approx 125.5$ GeV decay to a pair of $\tau$-leptons?

• Analysis strategy
  ✦ Achieve maximum sensitivity by performing a multivariate analysis: Boosted Decision Trees (BDT)

• Perform analysis in 3 channels according to the $\tau$ lepton decay
  - $H_{\text{HadHad}}$
  - $H_{\text{LepHad}}$
  - $H_{\text{LepLep}}$

• And in 2 categories per channel
  ✦ $VBF$: 2 jets with leading(sub-leading) $p_T > 50(30)$ GeV, $\Delta\eta(jj) > 3$
  ✦ $Boosted$: $p_T(H) > 100$ GeV , $p_T(H): \text{MET} + p_T(\tau_1) + p_T(\tau_2)$

• Different BDT per channel and per category: 6 BDT’s
  ✦ Keep simple selection and let the BDT separate signal and background
  ✦ Final discriminant: BDT score
**Input variables to BDT**

- **Probe resonance properties**
  - $m_{\tau\tau}$, $\Delta R(\tau\tau)$
  - $m_{\tau\tau}$: **Missing Mass Calculator (MMC)**
    Precise di-tau mass estimator based on a kinematics likelihood, $\sigma_{m_{\tau\tau}} \sim 16\%$

- **Explore event topology**
  - MET, $m_T$, object centralities

- **VBF specific**, for the 2 VBF jets

- $m_{\tau\tau}$ the most important discriminating variable

- Careful **validation** of BDT input variables and BDT output score distribution in dedicated **background enriched control regions**
Estimating the backgrounds

• Dominant $Z \rightarrow \tau\tau$
  ✦ Embedded samples: Except for tau decays, all event properties are taken from data $Z \rightarrow \mu\mu$ events

• Others
  ✦ Di-boson, $Z \rightarrow ee/\mu\mu$, top
  ✦ $H \rightarrow WW$ for LepLep channel
  ✦ Shape from simulation, normalisation from data

• Fake $\tau$
  ✦ Multijet, $W$+jets
  ✦ Data-driven methods
## Signal extraction

### Table: Signal Regions (SR) & Control Regions (CR)

<table>
<thead>
<tr>
<th>Rest Category</th>
<th>VBF Category</th>
<th>Boosted Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>CR</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>CR</td>
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<tr>
<td>CR</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

- We fit the **Background + μ×Signal** model to the data using the BDT score distributions.
- **6 Signal Regions (SR)** & **9 Control Regions (CR)** used in the fit.

### Diagram: LepLep, Z→ⅡⅡ CR

\[
\mu = \frac{\sigma_{\text{measured}}}{\sigma_{\text{SM}}}
\]

*Rest category:
Events failing VBF & Boosted selection
Signal extraction

- We fit the **Background + \( \mu \times \text{Signal} \)** model to the data using the BDT score distributions
- **6 Signal Regions (SR)** & **9 Control Regions (CR)** used in the fit

\[
\mu = \frac{\sigma_{\text{measured}}}{\sigma_{\text{SM}}}
\]

*Rest category:
Events failing VBF & Boosted selection*
**Signal Strength $\mu$**

**ATLAS Prelim.**

$m_H = 125$ GeV

<table>
<thead>
<tr>
<th>Process</th>
<th>$\mu$ (statistical)</th>
<th>$\mu$ (syst. incl. theory)</th>
<th>$\mu$ (theory)</th>
<th>$\pm 1\sigma$ on $\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>$1.4^{+0.5}_{-0.4}$</td>
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<td>$1.4$</td>
</tr>
<tr>
<td>Boosted</td>
<td>$1.2^{+0.8}_{-0.6}$</td>
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<td>$1.2$</td>
</tr>
<tr>
<td>VBF</td>
<td>$1.6^{+0.6}_{-0.5}$</td>
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<td>$1.6$</td>
</tr>
<tr>
<td>$H \rightarrow \tau_{\text{lep}}\tau_{\text{lep}}$</td>
<td>$2.0^{+1.0}_{-0.9}$</td>
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<td>$2.0^{+1.0}_{-0.9}$</td>
<td>$2.0$</td>
</tr>
<tr>
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<tr>
<td>$H \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$</td>
<td>$1.4^{+0.6}_{-0.5}$</td>
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<td>$1.0$</td>
</tr>
</tbody>
</table>

- Measured signal strength
  - $\mu = 1.4^{+0.5}_{-0.4}$
  - Boosted category: $\mu = 1.2^{+0.8}_{-0.6}$
  - VBF category: $\mu = 1.6^{+0.6}_{-0.5}$

Consistent with SM Higgs boson predictions!

- Leading uncertainty due to **limited statistics** in the high BDT score bins that drive the best fit value
- **Theory uncertainty** ranked high
- Leading experimental uncertainties come from the **background normalisation**

$s = 8$ TeV $\int L dt = 20.3$ fb$^{-1}$
ATLAS observes significant excess of data events in high S/B region

- **Expected** significance @ $m_H=125$ GeV : $3.2\sigma$ (Probability: $6.6 \times 10^{-4}$)
- **Observed** significance @ $m_H=125$ GeV : $4.1\sigma$ (Probability: $2 \times 10^{-5}$)
- Excess observed in all three channels
- **Observed** signal compatible with $m_H=125$ GeV

- **Direct evidence of** $4.1\sigma$ that the Higgs boson couples to leptons
Conclusions

• Fermionic sector: an exciting and active constituent of the Higgs boson physics programme in ATLAS

• Presented the ATLAS results
  ✦ $VH(bb): \mu = 0.2 \pm 0.7$ compatible both with signal+background and background-only hypothesis
  ✦ $\mu\mu$: 95% CL limit: $< 10 \times \sigma_{SM}$
  ✦ $\tau\tau$: Strong evidence of $4.1\sigma$, signal strength $\mu = 1.4 \pm 0.5_{-0.4}$

• Stay tuned, preliminary results will be updated by papers
VBF $H \rightarrow \tau\tau$ event

- LepLep event from May 2012
- $\mu$ $p_T$ = 53 GeV
- $e$ $p_T = 34$ GeV
- $E_T^{miss} = 102$ GeV
- $m_{\tau\tau} = 127$ GeV
- BDT = 0.99