Search for the Standard Model Higgs boson in the $H \rightarrow \tau \tau$ decay mode with the ATLAS detector

Swagato Banerjee

On behalf of the ATLAS Collaboration

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Motivation

$H \rightarrow \tau \tau$ provides an unique opportunity to probe the Yukawa coupling, which gives mass to all the quarks and leptons.

$\sqrt{s} = 7\text{TeV}$

$\sigma \times \text{BR [pb]}$

$M_H \text{ [GeV]}$

$125 \text{ GeV}$

$H \rightarrow \gamma \gamma$:  

$H \rightarrow ZZ/WW$:  

$H \rightarrow \tau \tau/\bar{b}b$:  

$H \rightarrow \tau \tau$ has one of the largest branching ratios for low mass Higgs
The experimental signature is cleaner in presence of additional jets. Motivated by the production process, we split our search into:

- 0-jet category to cover the bulk of gluon fusion (ggH) process
- Boosted Higgs category to focus on ggH + high-$p_T$ jet(s) process
- Vector Boson associated (VH) category with 2 jets in same hemisphere
- Vector Boson fusion (VBF) category with 2 jets in opposite hemisphere
Final state reconstruction


$H \rightarrow \tau_{\text{lep}} \tau_{\text{lep}} \rightarrow \ell\ell4\nu$ (12.4%)  

$H \rightarrow \tau_{\text{lep}} \tau_{\text{had}} \rightarrow \ell h 3\nu$ (45.6%)  

$H \rightarrow \tau_{\text{had}} \tau_{\text{had}} \rightarrow hh 2\nu$ (42.0%)

2 leptons: for $e\mu, (ee, \mu\mu)$  
$30 < m_{\ell\ell} < 100$ (75) GeV  

1 lepton $p_T > 25/20$ GeV for $e/\mu$ and 1 tau-jet $p_T > 20$ GeV  

2 tau-jets: $p_T > 35$ (25) GeV

- 0 jet events: effective mass  
  $m_{\text{eff}} = (p_{\ell^+} + p_{\ell^-} + E_{T\text{miss}})^2$  

- $\geq 1$ jet events: collinear mass  
  $m_{\tau\tau} = m_{\ell\ell}/\sqrt{x_1x_2}$, where $x_1$ and $x_2$ are the visible energy fractions of the two leptons

$m_{\tau\tau}$ reconstructed with missing mass constraint (MMC) using measured momenta, $E_{T\text{miss}}$ and simulated distributions of the opening angle between visible and missing momentum

Collinear mass  
$m_{\tau\tau} = m_{hh}/\sqrt{x_1x_2}$, where $x_1$ and $x_2$ are the visible energy fractions of the two tau-jets
Tau-jet reconstruction in ATLAS

- Tau-jet reconstruction seeds with anti-$k_T$ jets reconstructed in the calorimeters within a cone of $\Delta R = 0.4$, $p_T > 10$ GeV, $|\eta| < 2.5$
- Count the number of tracks identified within a cone of $\Delta R = 0.2$
- Pile-up robust variables describing isolation, shower shape profile, EM/hadronic energy fractions and angular separation are optimized
- Tau-jet (QCD-jet) (mis-)identification efficiency $\sim 50\%$ ($<1\%$)
$Z \rightarrow \tau\tau$ modelling

$Z \rightarrow \tau\tau$ is the dominant background. Muons in di-muon data events are replaced with simulated $\tau$ decays from TAUOLA to simulate the shape of this background, which are then normalized to MC predictions. Good agreement in validation plots below:
\[ H \rightarrow \tau \text{lep} \tau \text{lep} \]

<table>
<thead>
<tr>
<th>( H + 0)-jet</th>
<th>( H + 1)-jet</th>
<th>( H + 2)-jet VH</th>
<th>( H + 2)-jet VBF</th>
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</thead>
<tbody>
<tr>
<td>e(\mu) only</td>
<td>( E_{T}^{\text{miss}} &gt; 20 ) (40) GeV for e(\mu), (ee, (\mu\mu))</td>
<td>( 0.5 &lt; \Delta \varphi_{\ell \ell} &lt; 2.5 )</td>
<td>( 0 &lt; x_1, x_2 &lt; 1 )</td>
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<td>( \Delta \varphi_{\ell \ell} &gt; 2.5 )</td>
<td>( \sum p_T &lt; 120 ) GeV</td>
<td>( \geq 1) jet, ( p_T &gt; 40 ) GeV</td>
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- \( Z \rightarrow \ell \ell \) backgrounds: shapes from MC, normalization from ratio of control regions with low \( E_{T}^{\text{miss}} \) and large \( m_{\ell \ell} \) in a data-driven approach
- Top-pair and single top backgrounds: shapes from MC, normalization from control region with large \( \sum p_T \) for \( H + 0\)-jet, inverted b-tag for \( H + 1/2\)-jets
- Backgrounds with fake leptons not from \( \tau \), \( W \) or \( Z \) decays: shape from data control regions with reversed isolation criteria, normalization fitted to \( p_T \) distribution of sub-leading lepton in data
$H \rightarrow \tau\text{lep} \tau\text{lep}$

**H + 0-jet**

$ggH:VBF:VH = 95:2:3\%$

**H + 1-jet**

$ggH:VBF:VH = 72:21:7\%$

**H + 2-jet (VH)**

$ggH:VBF:VH = 56:7:37\%$

**H + 2-jet (VBF)**

$ggH:VBF:VH = 19:80:1\%$

VBF and Boosted H+1-jet are most sensitive categories.
$H \rightarrow \tau_{lep} \tau_{had}$

**ATLAS EXPERIMENT**

Run 190872, Event 51447267
Time 2011-10-12, 12:09 CEST

$p_T(\tau_{had}) = 43 \text{ GeV}$
$p_T(\mu) = 52 \text{ GeV}$
$E_T^{\text{miss}} = 53 \text{ GeV}$
$m_{jj} = 390 \text{ GeV}$
$\text{MMC } m_{\tau\tau} = 123 \text{ GeV}$
### $H \rightarrow \tau\text{lep } \tau\text{had}$

<table>
<thead>
<tr>
<th></th>
<th>$H + 0$-jet</th>
<th>$H + 1$-jet</th>
<th>$H + 2$-jet VBF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$(e/\mu)$ separated</td>
<td>$(e/\mu)$ separated</td>
<td>$(e\oplus\mu)$ combined</td>
</tr>
<tr>
<td></td>
<td>no $p_T &gt; 25$ GeV jet</td>
<td>$\geq 1$ jet, $p_T &gt; 25$ GeV not VBF</td>
<td>2 jets, $p_T &gt; 25$ GeV</td>
</tr>
<tr>
<td></td>
<td>$E_T^{\text{miss}} &lt; 20$ GeV</td>
<td>$E_T^{\text{miss}} &gt; 20$ GeV</td>
<td>$E_T^{\text{miss}} &gt; 20$ GeV</td>
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</tbody>
</table>

### Signal region:

$m_T = \sqrt{2p_T^\ell E_T^{\text{miss}} (1 - \cos \Delta \phi)} < 30$ GeV

### Modeling the backgrounds:

$$n_{\text{bkg}}^{\text{OS}} = n_{\text{all}}^{\text{SS}} + n_{\text{W+jets}}^{\text{OS-SS}} + n_{Z\rightarrow\tau\tau}^{\text{OS-SS}} + n_{\text{other}}^{\text{OS-SS}}$$

- **Multi-jet**
- **Control region with** $m_T > 50$ GeV
- **Monte Carlo**
- **Embedded Sample**
$H \rightarrow \tau^{\pm} \tau^{\mp}$

$H + 0$-jet (low $E_T^{\text{miss}}$)
$ggH:VBF:VH = 98 : 1 : 1 \%$

$H + 1$-jet
$ggH:VBF:VH = 76 : 14 : 10 \%$

$H + 0$-jet (high $E_T^{\text{miss}}$)
$ggH:VBF:VH = 98 : 1 : 1 \%$

$H + 2$-jet (VBF)
$ggH:VBF:VH = 29 : 70 : 1 \%$

H+1-jet and H+2-jet VBF are the most sensitive categories
$H \rightarrow \tau_{\text{had}} \tau_{\text{had}}$

$E_\text{T}^{\text{miss}} = 28$ GeV

$p_T(\tau_{\text{had}}^{3\text{-prong}}) = 72$ GeV

$p_T(\tau_{\text{had}}^{1\text{-prong}}) = 45$ GeV

$p_T(\text{jet}) = 107$ GeV

Coll. mass = 121 GeV
Normalization of $Z \rightarrow \tau\tau$ and multi-jet backgrounds from 2-d fit to track multiplicity in a wider cone with $\Delta R = 0.6$ in data control region with visible energy fractions: $0 < x_1, x_2 < 1$, collinear $m_{\tau\tau} < 100$ GeV and $\Delta R_{\tau\tau} < 2.8$
$H \rightarrow \tau_{\text{had}} \tau_{\text{had}}$ is the most sensitive channel

$H + 1$-jet
- $E_{T}^{\text{miss}} > 20$ GeV
- $\Delta R_{\tau\tau} < 2.2$
- $0 < x_1, x_2 < 1$
- $\geq 1$ jet, $p_T > 40$ GeV
- $m_{\tau\tau j} > 225$ GeV

Integral $L \cdot dt = 4.7$ fb$^{-1}$
$\sqrt{s} = 7$ TeV
ATLAS

$\text{ggH:VBF:VH} = 59:29:12\%$
Building the combined model

Combining channels: take product of likelihoods.

For example, in $H \rightarrow \tau_{lep}\tau_{lep}$ channel: construct likelihood as Poisson for each bin of $m_{\tau\tau}$ with Gaussian constraints describing systematics.

$$L(\sigma_{sig}, L, \alpha_j) = \prod_{l \in \{ee, \mu\mu, e\mu\}} \left\{ \prod_{i \in bins} \left[ \text{Pois}(N_{i}^{obs} | N_{i,tot}^{exp}) \text{Gaus}(\tilde{L} | L, \sigma_{L}) \prod_{j \in syst} \text{Gaus}(0 | \alpha_j, 1) \right] \right\}$$

$$N_{tot}^{exp} = \mu \cdot N_{signal}^{exp} + N_{background}^{exp}$$

where the signal strength $\mu$ is the ratio of measured rate to SM prediction.

$$N_{k}^{exp} = L \sigma_{k} \prod_{j} \tilde{\epsilon}_{jk} \frac{\epsilon_{jk}(\alpha_j)}{\tilde{\epsilon}_{jk}} = \tilde{N}_{k}^{exp} \prod_{j} \frac{\epsilon_{jk}(\alpha_j)}{\tilde{\epsilon}_{jk}}$$

$N_{k}^{exp}$ incorporates systematic uncertainties via nuisance parameters $\alpha_j$

Precision limited by statistics of MC prediction or Data control region
Compatibility with s+b hypothesis

3 channels combined:
Observed (expected) upper limits lie between 2.9 (3.4) and 11.7 (8.2)

$H \rightarrow \tau_{\text{lep}} \tau_{\text{lep}}$

$H \rightarrow \tau_{\text{lep}} \tau_{\text{had}}$

$H \rightarrow \tau_{\text{had}} \tau_{\text{had}}$

$m_H \text{ (GeV)}$ | Observed | Expected
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>100</td>
<td>3.1</td>
<td>4.8</td>
</tr>
<tr>
<td>105</td>
<td>2.9</td>
<td>4.2</td>
</tr>
<tr>
<td>110</td>
<td>3.2</td>
<td>4.0</td>
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<tr>
<td>115</td>
<td>2.9</td>
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<tr>
<td>135</td>
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<td>3.9</td>
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<tr>
<td>140</td>
<td>6.1</td>
<td>4.7</td>
</tr>
<tr>
<td>145</td>
<td>8.0</td>
<td>6.0</td>
</tr>
<tr>
<td>150</td>
<td>11.7</td>
<td>8.2</td>
</tr>
</tbody>
</table>

$H \rightarrow \tau \tau$

Swagato Banerjee
At 125 GeV, observed (expected) significance = 0.2 (0.7) $\sigma$.

<table>
<thead>
<tr>
<th>125 GeV</th>
<th>$s/\sqrt{b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ll 2-jet VH</td>
<td>0.095</td>
</tr>
<tr>
<td>eh 0-jet low MET</td>
<td>0.104</td>
</tr>
<tr>
<td>$\mu$h 0-jet low MET</td>
<td>0.136</td>
</tr>
<tr>
<td>eh 0-jet high MET</td>
<td>0.150</td>
</tr>
<tr>
<td>$\mu$h 0-jet high MET</td>
<td>0.168</td>
</tr>
<tr>
<td>ll 0-jet</td>
<td>0.194</td>
</tr>
<tr>
<td>ll 1-jet</td>
<td>0.199</td>
</tr>
<tr>
<td>eh 1-jet high MET</td>
<td>0.200</td>
</tr>
<tr>
<td>ll 2-jet VBF</td>
<td>0.214</td>
</tr>
<tr>
<td>$\mu$h 1-jet high MET</td>
<td>0.224</td>
</tr>
<tr>
<td>lh 2-jet VBF</td>
<td>0.243</td>
</tr>
<tr>
<td>hh 1-jet</td>
<td>0.249</td>
</tr>
<tr>
<td>Quadrature sum</td>
<td>0.651</td>
</tr>
</tbody>
</table>

Contributions to $\sigma_b$:
- Acceptance of $Z \rightarrow \tau\tau$ (6%),
- PDF$_{qqH}$ (1.9%),
- QCD scale (1%),
- Lumi (3.9%),
- QCD/$Z \rightarrow \ell\ell$/Fake/W-jet backgrounds (2.6/1.5/1.1/0.5 %),
- $\tau/e/\mu$ Efficiency (2.1/1.6/0.6 %),
- $E_T^{miss}$ (1.8%),
- Energy Scale (0.7%)

Good agreement with $Z = s/\sqrt{(b + \sigma_b^2)}$.
Summary

Search for SM Higgs Boson decaying in the $H \rightarrow \tau\tau$ decay mode has been performed with the ATLAS detector. It uses the full 2011 data sample of $\int L = 4.7$ fb$^{-1}$ collected at $\sqrt{s} = 7$ TeV. The paper: arXiv:1206.5971v1 [hep-ex] has been submitted to JHEP for publication.

All the three decay channels: $\tau_{\text{lep}} \tau_{\text{lep}}$, $\tau_{\text{lep}} \tau_{\text{had}}$ and $\tau_{\text{had}} \tau_{\text{had}}$ have been studied, which are then further categorized in jet bins. The categories with additional jets, eg. $\geq 1$-jet Boosted Higgs and 2-jet VBF categories are most sensitive ones.

The analysis is being extended to the data collected at $\sqrt{s} = 8$ TeV with the ATLAS detector in 2012. Larger data sample helps in reducing the statistical uncertainty on modeling of the backgrounds, which are limited by size of the data control samples. Along with further improvements, the sensitivity is expected to scale better than $1/\sqrt{L}$. 

H$\rightarrow\tau\tau$