H$\rightarrow\tau\tau$ at ATLAS

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Meeting of the APS Division of Particles and Fields
Santa Cruz Institute for Particle Physics
16 August 2013
Outline

Introduction to $H \rightarrow \tau \tau$

ATLAS and the LHC

Higgs searches at ATLAS

Tau leptons at ATLAS

$H \rightarrow \tau \tau$ at ATLAS

Overview

Common issues

Snapshot of the final states

Combination
Picture of the analysis

Seems simple!
In practice, not so simple. Let’s walk through this.

\[
\begin{align*}
\text{qq} &\rightarrow \text{qqH} \rightarrow \tau\tau \rightarrow h\nu\ell \nu\ell \nu\tau \\
\text{“VBF Higgs to tau-tau to lep-had”}
\end{align*}
\]

Most powerful category for \( H \rightarrow \tau\tau \)
Colliding partons with the LHC

\[ qq \rightarrow qqH \rightarrow \tau\tau \rightarrow h\nu_\tau \ell_\nu \ell \nu_\tau \]

“VBF Higgs to tau-tau to lep-had”

Most powerful category for H→\tau\tau
ATLAS and the LHC

The LHC collides protons at high energy and events are observed with the ATLAS detector.

Many pp collisions occur in a single bunch crossing. This is challenging for analysis.

\[ \sigma_{tot} \]

Cross-sections (nb) for SM processes at hadron colliders

Cross-sections (nb) for SM processes at hadron colliders

\[ \sigma_{jet}(E_T > \sqrt{s}/20) \]

\[ \sigma_{jet}(E_T > 100 \text{ GeV}) \]

\[ \sigma_{WW} \]

\[ \sigma_{ZZ} \]

\[ \sigma_{WZ} \]

\[ \sigma_{ggH} \]

\[ \sigma_{WH} \]

\[ \sigma_{VBF} \]

\[ M_Z = 125 \text{ GeV} \]

\[ \sqrt{s} \text{ (TeV)} \]

Parton Luminosity And Cross Section Plots
ATLAS and the LHC

Results from today’s talk use the full 2011 dataset and partial 2012 dataset.

The $H \rightarrow \tau \tau$ analysis with the full 2011+2012 datasets is in progress now. We hope to release a new result soon!
Higgs searches at ATLAS

$q q \rightarrow q q H \rightarrow \tau \tau \rightarrow h \nu_\tau \ell_\nu \nu_\tau$

“VBF Higgs to tau-tau to lep-had”

Most powerful category for $H \rightarrow \tau \tau$
Higgs @ ATLAS

The BEH electroweak symmetry breaking mechanism, and corresponding Higgs boson, were postulated in the 1960s. Searches for the Higgs boson are a major piece of the ATLAS program.

<table>
<thead>
<tr>
<th>Process</th>
<th>BR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$bb$</td>
<td>58</td>
</tr>
<tr>
<td>$WW$</td>
<td>22</td>
</tr>
<tr>
<td>$\tau\tau$</td>
<td>6.3</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>2.6</td>
</tr>
<tr>
<td>$YY$</td>
<td>0.23</td>
</tr>
</tbody>
</table>

There are lots of ways to make Higgs bosons.

And there are lots of ways for Higgs bosons to decay.

σ @ $m_H = 125$ GeV and $\sqrt{s} = 8$ TeV
Higgs @ ATLAS

The Higgs program at ATLAS has been awesome. Higgs searches have steadily improved since the observation of an excess on July 4, 2012, a.k.a. Higgsdependence Day.

CMS event display I photoshopped onto Independence Day image

http://www.imdb.com/title/tt0116629/

New York Times coverage of Higgsdependence day

http://www.nytimes.com/2012/07/05/science/cern-physicists-may-have-discovered-higgs-boson-particle.html
Higgs @ ATLAS

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Alexander Tuna (Penn)
Higgs @ ATLAS

The Higgs program at ATLAS has been awesome. Higgs searches have steadily improved since the observation of an excess on July 4, 2012, a.k.a. Higgsdependence Day.

H→di-boson: “discovery channels”

H→di-fermion: next wave of observation

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Picture of the analysis

qq \rightarrow qqH \rightarrow \tau\tau \rightarrow h\nu_\tau \ell_\nu \nu_\tau

“VBF Higgs to tau-tau to lep-had”

Most powerful category for H \rightarrow \tau\tau
Tau leptons are the 3rd and heaviest ($m_\tau \approx 1.8$ GeV) generation of leptons.

This large mass has two important consequences: tau leptons decay within the ATLAS beam pipe, and tau leptons can decay hadronically.

Identifying hadronic tau decays ($\tau_h$: $\tau \rightarrow h \nu_\tau$) is challenging because hadrons (“jets”) are produced copiously at the LHC.

Identifying leptonic tau decays ($\tau_\ell$: $\tau \rightarrow \ell \nu_\ell \nu_\tau$) is easier because leptons are not hadrons, and we have great “standard candles”: $W \rightarrow \ell \nu_\ell$ and $Z \rightarrow \ell \ell$.
\( \tau_h @ ATLAS \)

\( \tau_h \) candidates are seeded by calorimeter clusters and tracks are associated to the candidates.

\( \tau_h \) tend to have 1 or 3 tracks, narrow calorimeter showers, and a displaced vertex.

\( \tau \)→...
**τ_h @ ATLAS**

τ_h candidates are seeded by calorimeter clusters and tracks are associated to the candidates.

τ_h tend to have 1 or 3 tracks, narrow calorimeter showers, and a displaced vertex.

τ_h identification efficiency can be measured in data with Z→ττ τ_h tag-and-probe.
$\tau_h$ @ ATLAS

$\tau_h$ candidates are seeded by calorimeter clusters and tracks are associated to the candidates.

$\tau_h$ tend to have 1 or 3 tracks, narrow calorimeter showers, and a displaced vertex.

$\tau_h$ identification efficiency can be measured in data with $Z\rightarrow\tau\mu$ tag-and-probe.

The $\tau_h$ energy scale (TES) can be corrected with MC and CTB data and also measured with $Z\rightarrow\tau\mu$ T&P.
Most powerful category for $H \rightarrow \tau \tau$
Select events with well-identified $\tau_h, \ell$, and categorize the events by jet multiplicity and $p_T(H)$. Add topological cuts to reduce background contamination. Extract signal with maximum likelihood fit of $m(\tau\tau)$. 

$H \rightarrow \tau\tau$ strategy

<table>
<thead>
<tr>
<th>Nickname</th>
<th>$H \rightarrow \tau_\ell \tau_h$</th>
<th>$H \rightarrow \tau_h \tau_\ell$</th>
<th>$H \rightarrow \tau_\ell \tau_\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>single $\ell$ $\ell + \tau_h$</td>
<td>di-$\tau_h$</td>
<td>single $\ell$ di-$\ell$</td>
</tr>
<tr>
<td>ggF categories</td>
<td>0 jet 1 jet boosted H</td>
<td>0 jet 1 jet boosted H</td>
<td>0 jet 1 jet boosted H</td>
</tr>
<tr>
<td>VBF categories</td>
<td>2-jet VBF</td>
<td>2-jet VBF</td>
<td>2-jet VBF</td>
</tr>
</tbody>
</table>
Common issue: $Z \rightarrow \tau \tau$

**Issue**
- Difficult to find CR for largely irreducible $Z/\gamma^* \rightarrow \tau\tau$
- Dominant background in all final states

**Idea**
- Embed simulated $\tau$ decays in $Z \rightarrow \mu\mu$ data
- $Z \rightarrow \tau \tau$ “embedding”

<table>
<thead>
<tr>
<th>$Z \rightarrow \mu\mu$ in data</th>
<th>$\tau$ decays in MC</th>
<th>Embedded $Z \rightarrow \tau \tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replace $\mu$ Tracks Calorimeter cells</td>
<td>Simulate $\tau$ decay TAUOLA for polarization and spin correlations Full ATLAS simulation, digitization, reconstruction</td>
<td>Benefits Jets, underlying event, and pileup effects from data Significantly reduced systematics uncertainties</td>
</tr>
</tbody>
</table>
Common issue: $m(\tau\tau)$

Accurate mass reconstruction is challenging because there are 2 ($\tau_h\tau_h$), 3 ($\tau_h\tau_\ell$), or 4 ($\tau_\ell\tau_\ell$) neutrinos in the $\tau\tau$ decay. The Missing Mass Calculator (MMC) helps here.

<table>
<thead>
<tr>
<th>Unknowns:</th>
<th>6-8</th>
<th>$p(v_1), p(v_2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constraints:</td>
<td>4</td>
<td>$E_x^{\text{miss}}, E_y^{\text{miss}}, m(\tau_1), m(\tau_2)$</td>
</tr>
<tr>
<td>Scans:</td>
<td>2-4</td>
<td>$\Delta\phi(\tau_{\text{vis},1},v_1), \Delta\phi(\tau_{\text{vis},2},v_2), m(v_1), m(v_2)$</td>
</tr>
</tbody>
</table>

$v_i$ refers to neutrino system of $i$th tau lepton decay

$m(\tau\tau)$ is built for each scan point and weighted by the $\Delta\theta_{3D}(\tau_{\text{vis},i},v_i)$ probabilities. The maximally-probable $m(\tau\tau)$ is chosen.

$\Delta\theta_{3D}(\tau_{\text{vis},i},v_i)$ PDFs for three possible tau lepton decays.
$H \rightarrow \tau \ell \tau h$

$Z \rightarrow \tau \ell \tau h$ is estimated with embedding (non-VBF) and VBF-filtered MC (VBF).

Small contribution from other processes ($Z \rightarrow \ell \ell$, top, diboson) is estimated with MC and normalized in CR.

Jets-faking-$\tau_h$ ($W \rightarrow \ell v + j$, multi-jet) are estimated with SS data (non-VBF) and "fake factor" method (VBF) on $\tau_h$ PID

$H \rightarrow \tau \tau$ events (b) Multi-jet events

Figure 11: Templates of the 2-dimensional track multiplicity distribution in the 8 TeV analysis of leading and sub-leading $\tau$ candidates for simulated $Z \rightarrow \tau \tau$ events (a) and same-sign multi-jet events in data (b) used in the fit of the preselected events.

Selected systematic uncertainties (signal)
- JES: 3-9%
- TES: 2-9%
- TID: 4-5%
- TH: 18-23%

Selected systematic uncertainties (backg. est.)
- FF: 50%
$H \rightarrow \tau_h \tau_h$

$Z \rightarrow \tau_h \tau_h$ is estimated with embedding and normalized with 2D $\tau_h$-track fit.

Multi-jet is estimated with SS, not-OS, or fail-$\tau_h$-ID data and normalized with 2D $\tau_h$-track fit.

Small contribution from other processes ($W \rightarrow \tau \nu + j$, top, diboson) are estimated with MC.

Events / 16 GeV

Categories (ranked by sensitivity)

<table>
<thead>
<tr>
<th>VBF</th>
<th>Boosted H</th>
</tr>
</thead>
</table>

Selected systematic uncertainties (signal)

- JES: 2-4%
- TES: 4-6%
- TID: 10%
- TH: 3-20%

Selected systematic uncertainties (backg. est.)

- $Z \rightarrow \tau \tau$ (VBF): 11%
- multi-j (VBF): 10%
$Z\to\tau\ell\tau\ell$ is estimated with embedding and normalized to $Z\to\tau\ell\tau\ell$ MC.

Non-$\tau\tau$ EW backgrounds are estimated with MC and normalized in CR.

Jets-faking-leptons ($W\to\ell\nu+j$, multi-jet) are estimated with non-isolated leptons and sublead lepton $p_T$ template.

$H\to\tau\ell\tau\ell$

Categories (ranked by sensitivity)

- VBF
- Boosted H
- 1-jet
- VH
- 0-jet

Selected systematic uncertainties (signal)

- JES 1-5%
- TH 8-28%

Selected systematic uncertainties (backg. est.)

- Fake $\ell$ 20-40%
Results

<table>
<thead>
<tr>
<th>Year</th>
<th>ττH</th>
<th>τH H</th>
<th>ττττ</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>6</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>2012</td>
<td>6</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

ATLAS Preliminary

Observed $H \rightarrow \tau \tau$

- Local $p_0$
- Full $H \rightarrow \tau \tau$ combination

$H \rightarrow \tau \tau$ combination

1.2×SM expected, 1.9×SM observed

95% CL limit for $m_H = 125$ GeV

1.7σ expected, 1.1σ observed

Local significance for $m_H = 125$ GeV
Results

**ATLAS**

- \( m_H = 125.5 \text{ GeV} \)
- \( \mu = 1.55^{+0.33}_{-0.28} \)

**Total uncertainty**: \( \pm 1 \sigma \) on \( \mu \)

<table>
<thead>
<tr>
<th>( H \rightarrow \gamma \gamma )</th>
<th>( \mu = 1.55^{+0.33}_{-0.28} )</th>
<th>arXiv:1307.1427</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \rightarrow ZZ^* \rightarrow 4l )</td>
<td>( \mu = 1.43^{+0.40}_{-0.35} )</td>
<td>arXiv:1307.1427</td>
</tr>
<tr>
<td>( H \rightarrow WW^* \rightarrow 4l \nu \nu )</td>
<td>( \mu = 0.99^{+0.31}_{-0.28} )</td>
<td>arXiv:1307.1427</td>
</tr>
</tbody>
</table>

**Combined**

- \( H \rightarrow \gamma \gamma, ZZ^*, WW^* \)
- \( \mu = 1.33^{+0.21}_{-0.18} \)

**W, Z \rightarrow b \bar{b}**

- \( \mu = 0.2^{+0.7}_{-0.6} \)

**H \rightarrow \tau \tau**

- \( \mu = 0.7^{+0.7}_{-0.6} \)

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**ATLAS-CONF-2013-079**

**ATLAS-CONF-2013-014**

**Combined** \( H \rightarrow \tau \tau \) search is compatible with \( \mu = 0 \) and \( \mu = 1 \).

Best fit signal strength parameter (\( \mu \)) is \( 0.7 \pm \sim 0.7 \).

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The analysis has many improvements planned for the near future.

<table>
<thead>
<tr>
<th>Full 2012 dataset</th>
<th>MVA event selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Better objects ($\tau_h$, $\ell$, $E_T^{\text{miss}}$)</td>
<td>Better background estimates</td>
</tr>
<tr>
<td>Channel harmonization</td>
<td>More CRs in the fit</td>
</tr>
</tbody>
</table>

The analysis faces many challenges for 2015.

<table>
<thead>
<tr>
<th>Much tougher to trigger</th>
<th>Increased pileup</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_h$ identification in dense environment</td>
<td></td>
</tr>
</tbody>
</table>

Great time to be doing Higgs physics with taus.
Thanks for listening!
ATLAS and the LHC
Picture of the analysis
that both collaborations had discovered what appeared to tell the UA2 physicists that although he was convinced. There they met DiLella, Allan Clark and Peter Jenni, all UA2 league David Cline for a cup of coffee in the CERN cantina. de force physics was virtually the same, but what would have been a UA2 – in the same auditorium, to a slightly smaller crowd. The following day, Luigi DiLella presented the evidence from UA1 beats UA2 into print. Rubbia was nervous. He sipped at his winter, a CERN physicist and editor of Physics Letters...
VBF vs. non-VBF

Statistical analysis

Likelihood function: \( \mathcal{L}(\mu, \theta) = \prod_{\text{category}} \left( \frac{\text{Poisson}(N_j|\mu \cdot s_j + b_j) \prod \text{Gaussian}(t|\theta, 1)}{\mu} \right) \)

Test statistic: \( q_\mu = -2 \ln \left( \frac{\mathcal{L}(\mu, \hat{\theta}_\mu)}{\mathcal{L}(\hat{\mu}, \hat{\theta})} \right) \)  Binned variable: \( m_{\tau\tau} \)