Search for a SM Higgs Boson in semi-leptonic di-tau final states with ATLAS at the LHC

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• Higgs mechanism major ingredient of the SM
• Spontaneous breaking of the $U(1)_Y \otimes SU(2)_L$ symmetry leading to massive $W,Z$ states

$$\mathcal{L}_{EW} = \frac{1}{2} \partial_\mu H \partial^\mu H + \frac{g^2}{4} (v + H)^2 (W^+ W^- + \frac{1}{2 \cos^2 \Theta_W} Z_\mu Z^\mu) + \frac{1}{2} (-2 \mu^2) H^2 - \lambda v H^3 - \frac{1}{4} \lambda H^4 + \ldots$$

• Lepton masses generated via *independent* Yukawa couplings

$$- \frac{G_f v}{\sqrt{2}} f \bar{f} - \frac{G_f}{\sqrt{2}} f \bar{f} H$$
Introduction

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- Spontaneous breaking of the $U(1)^Y \otimes SU(2)_L$ symmetry leading to massive $W,Z$ states

$$\mathcal{L}_{EW} = \frac{1}{2} \partial_\mu H \partial^\mu H + \frac{g^2}{4} (v + H)^2 (W^\mu W^\mu - \frac{1}{2 \cos^2 \Theta_W} Z_\mu Z^\mu) + \frac{1}{2} (-2 \mu^2) H^2 - \lambda v H^3 - \frac{1}{4} \lambda H^4 + \ldots$$

- Lepton masses generated via ‘independent’ Yukawa couplings

$$- \frac{G_f v}{\sqrt{2}} f \bar{f} - \frac{G_f}{\sqrt{2}} f \bar{f} H$$

- Higgs Boson mass hardly constrained by EW data and theory (log. loop corr., stability bounds)
  \( m_H = 94 (+29 -24) \text{ GeV} \) - favouring low mass range

- LHC direct searches exclude broad range leaving a small window

ATLAS: 117.5 - 129 GeV
CMS: < 127.5 GeV

\( @ \ 95\% \ C.L. \)
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- Lepton masses generated via 'independent' Yukawa couplings

$$\frac{G_f v}{\sqrt{2}} f \bar{f} - \frac{G_f}{\sqrt{2}} f \bar{f} H$$

- Huge progress in the past 12 months
  - Discovery ✓
  - Mass measurement ✓
  - Coupling measurements ✓
  - Spin determination ✓

- Direct observation in fermionic decays (X)
  - Its up to $\tau\tau / \text{bb}$

\[ V(\phi^{\dagger}\phi) = \mu^2 \phi^{\dagger}\phi + \lambda(\phi^{\dagger}\phi)^2 \]
Branching ratios of a SM Higgs Boson

- Low mass Higgs Boson branching ratios **diverse**
  - $\gamma\gamma$: Clean signature - High mass resolution => **Discovery, mass measurement**
  - $ZZ$: Low background - High mass resolution => **Discovery, mass measurement**
  - $WW$: Experimentally challenging - Statistically powerful (**Spin determination**)
  - $bb$: Challenging due to multijet bkd - Accessible in association with W/Z (tt)
  - $\tau\tau$: Large BR - Probes leptonic Yukawa coupling - Large irreducible Z bkd
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Three $\tau$ decay channels:
- Leptonic (2 light leptons + 4 $\nu$) $ee/\mu\mu$ Large bkd, statistically limited
- Hadronic (2 hadronic $\tau$ + 2 $\nu$) Large QCD background - Trigger complicated
  High statistics
- Semi-leptonic (1 light lepton + 3 $\nu$ ) Presence of trigger lepton - Statistically powerful
Production mechanisms and backgrounds

- Mainly two production mechanisms important for $H \rightarrow \tau \tau$ searches

1. **Gluon-Fusion**
   - Largest cross-section
   - 0 Jets at LO
   - Additional partons due to QCD radiation
   - Categorisation to account for different bkd composition
     (0 Jets low/hig MET, 1 Jet)

2. **Vector-Boson-Fusion**
   - 2nd largest cross-section
   - 2 Jets at LO
   - Additional partons due to QCD + EW radiation
   - Topology allows strong bkd suppression

Main Backgrounds

- $Z \rightarrow \tau \tau + n$ jets
- $W + (n+1)$ jets
- QCD

- $Z \rightarrow \tau \tau + 2$ jets
- $W + 3$ jets
- $tt \rightarrow bbWW$
- QCD
Hadronic $\tau$-decay reconstruction

- Hadronic $\tau$ decays are identified by:
  - low track multiplicity
  - A narrow shower profile
  - A specific EM/HAD energy mix

<table>
<thead>
<tr>
<th>hadronic modes</th>
<th></th>
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<tbody>
<tr>
<td>$\tau^\pm \rightarrow \pi^\pm \nu_\tau$</td>
<td>10.9</td>
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<tr>
<td>$\tau^\pm \rightarrow \pi^\pm \pi^0 \nu_\tau$</td>
<td>25.5</td>
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<tr>
<td>$\tau^\pm \rightarrow \pi^\pm \pi^0 \pi^0 \nu_\tau$</td>
<td>9.3</td>
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<td>$\tau^\pm \rightarrow \pi^\pm \pi^0 \pi^0 \pi^0 \nu_\tau$</td>
<td>1.0</td>
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<td>9.3</td>
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<td>4.6</td>
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Hadronic $\tau$-decay reconstruction

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<th>Hadronic barrel/ extended barrel/ endcap</th>
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<td>$(\Delta \eta, \Delta \phi) =$</td>
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<td>(0.1, 0.1)</td>
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<th>LAr EM barrel/ endcap</th>
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<tr>
<td>3 (2) layers, middle layer:</td>
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<tr>
<td>$(\Delta \eta, \Delta \phi) =$</td>
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<td>(0.025, 0.025)</td>
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- Hadronic $\tau$ decays are identified by:
  - low track multiplicity
  - A narrow shower profile
  - A specific EM/HAD energy mix

- Identification based on multivariate classifier
- Using pile-up corrected input variables
- Typical background rejection of ~100 at signal efficiencies of 60%

- Energy calibrated to the visible $\tau_h$ scale
- Typical scale uncertainties ~3%
Preselection

- Events selected by: $e/\mu$ OR $l+\tau$ trigger

Fake $\tau$'s:
- $W+Jets$
- QCD

Tight lepton ID criteria
Crucial to reduce multijet background before actual $\tau$-ID

$\gamma$ 4-momenta fitted exploiting known $\tau$-decay kinematic properties
MET resolution dominates $\sigma_{\text{mass}}$

Real $\tau$'s:
- $Z \rightarrow \tau\tau$
- $WW/WZ$
- top

MET resolution crucial for mass reconstruction
Poor $m_{\tau\tau}$ resolution

Jet topology separates VBF like events
Background estimation

- Fake $\tau$-background **needs** data-driven estimation!
- Fake rates depend on shower variables => Tough to simulate
- Same sign events offer control region dominated by fake contributions

- QCD: Mainly gluon initiated fakes, no charge correlation OS \(\approx\) SS
- W + Jets: Quark enriched jet sample with charge correlation to lepton OS>SS

\[
\begin{align*}
n_{Bkd}^{OS} &= n_{SS}^{All} + n_{QCD}^{OS-SS} + n_{W+Jets}^{OS-SS} + n_{Z\rightarrow\tau\tau}^{OS-SS} + n_{other}^{OS-SS} \\
& \approx 0
\end{align*}
\]
Background estimation

- Fake \( \tau \) background **needs** data-driven estimation
- Same sign events offer control region dominated by fake contributions

\[ n_{Bkd}^{OS} = n_{SS}^{All} + n_{QCD}^{OS-SS} + n_{W+jets}^{OS-SS} + n_{Z\rightarrow\tau\tau}^{OS-SS} + n_{\text{other}}^{OS-SS} \approx 0 \]

- W normalisation measured in W control region

- Corrects Jet \( \rightarrow \tau \) fake rate
  - Depends on **Quark/Gluon composition** in the jet sample
  - Charge Correlation and Jet Multiplicity dependent

Additional control regions for cross-checks or normalisation corrections:
- tt
- Z\( \rightarrow \)ll

**ATLAS Simulation work in progress**
Background rejection : Real $\tau$'s

**Real $\tau$'s:**
- $Z \rightarrow \tau\tau$
- $WW/WZ$
- top

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

**ATLAS**
work in progress
Background rejection: $Z \rightarrow \tau\tau$

- Irreducible $Z \rightarrow \tau\tau$ background hard to separate
- Same final state including resonance event topology

VBF Production:
- Focus on specific Jet topology:
  - $Z$: Mainly Drell-Yan production (+radiation)
  - $H$: 2 Jets at leading order
    (large angular separation, high $p_T$)

Real $\tau'$s:
- $Z \rightarrow \tau\tau$
- WW/WZ
- top

Tagging jets bracket the leptons

Large rapidity separation of two tagging jets
Background rejection: Fake $\tau$'s

$\tau$'s:  
- $W+Jets$
- QCD

$\int L \, dt = 20.3 \, fb^{-1}$

$\sqrt{s} = 8 \, TeV$

Data 2012
SS Data
$t\bar{t}+$single-top
$Z\rightarrow ll$
$WW/WZ/ZZ$
$W+jets$
$Z\rightarrow \tau\tau$

$H(125)\rightarrow \tau\tau \times 50$

ATLAS
work in progress
Background rejection : Fake τ's

- W+Jets
- QCD

• Rejection of non-resonant backgrounds:
  Does the event look like a resonant ττ-system?

Is the 2:1 neutrino share reflected in the lepton/τ p_T?

m_ττ: Mass consistent with 125 GeV?

Small opening angle between two taus in case of high p_T recoil system
Categorisation

- **VBF**
  - 2 Jets
  - VBF like topology

- **1+ jets inclusive**
  - Not VBF
  - Not Boosted
  - \( N_{\text{Jet}} \geq 1 \)

- **Boosted H**
  - Not VBF
  - High \( p_T^{\tau\tau} \)
  - Good mass resolution

- **0-jet**
  - Not VBF
  - Not Boosted
  - \( N_{\text{Jet}} = 0 \)

Analyses categories aiming at:
- Best possible background rejection based on specific event topologies
- Partial enhancement of specific production modes allowing for dedicated Higgs coupling fits
- Split the phase space - Not restrict it
- Based on Jet and Resonance quantities
Results

- Result based on 13 fb\(^{-1}\) combined with 4.6 fb\(^{-1}\) of 7 TeV data
- No excess observed => Extract upper limit on cross-section
- Expected exclusion limit \(~1.7\ \sigma_{\text{SM}}\)

ATLAS Preliminary

\[ \int L \, dt = 13.0 \text{ fb}^{-1}, \ \sqrt{s} = 8 \text{ TeV} \]

\[ \int L \, dt = 13.0 \text{ fb}^{-1}, \ \sqrt{s} = 8 \text{ TeV} \]

\[ \pm 2\sigma \]

\[ \pm 1\sigma \]

Nils Ruthmann - ISSP 2013 Erice

26.06.2013
Results

- Result based on 13 fb\(^{-1}\) combined with 4.6 fb\(^{-1}\) of 7 TeV data
- No excess observed => Extract upper limit on cross-section
- Expected exclusion limit \(\sim 1.2 \sigma_{SM}\) when combined with other subchannels
Outlook

- Searching for leptonic Higgs Boson decays now more interesting than ever
- $H \rightarrow \tau \tau$ plays a crucial role in this challenge
- A preliminary analysis of a partial dataset shows no significant excess, but..

- our collaboration is currently reviewing a improved analysis of the full 21 fb$^{-1}$ dataset
- Aiming at a 3 $\sigma$ sensitivity - in the presence of a signal
- Stay tuned!
Thanks for your attention
#### TES Uncertainty

**E/p**
- $h^\pm, p_T < 20$ GeV
- $h^\pm, p_T > 20$ GeV

**Testbeam**
- Gaussian PDFs
  - Mean: Data/MC
  - Width: Uncertainty
- Toy experiments randomly shifted energy scales

- Single particle uncertainties propagated to composite objects (Jets, Taus)
- Bottom-up:
  - From single particles to a more complex object
- Pseudo-experiment approach
  - Sampling over various uncertainties:

**Figure:**
- Toy experiments randomly shifted energy scales
- Data/MC
- Non-closure
- Pile-Up
- Total uncertainty
- 2012 Data + Simulation

**Legend:**
- Data
- Simulation
- $|\eta| < 0.3$
- $p_T > 20$ GeV
- $p_T < 20$ GeV

**ATLAS Preliminary**
- $\sqrt{s} = 8$ TeV
- 2012 Data + Simulation

**Legend:**
- Single particle resp.
- Material modeling
- Underlying event
- Non-closure
- Pile-Up
- Total uncertainty

**Axes:**
- $p_T$ [GeV]
- Fractional uncertainty

**Data/MC**
- $0.9$ to $1.1$
- $|\eta| < 0.3$
- $p_T > 20$ GeV
- $p_T < 20$ GeV

**Nils Ruthmann**
22.04.2013
Multivariate analysis approach

• Based on the HCP results last year:
  • continuing the same analysis just adding data would not allow for a $3\sigma$ evidence within Run1

• Refined analysis techniques are needed to accomplish this goal
• $H\rightarrow\tau\tau$ fully focussed on a BDT analysis from the beginning

• Furthermore: Fully focussed on a Higgs Boson mass of 125 GeV

• Boosted Decision Trees widely used in ATLAS
  • Iterative training procedure on a signal and background sample
    • Mis-Classified events in one iteration will be amplified for the next one (boosting)
  • Final classification score *averages* the decision of all trees
Mass estimation

- $m_\tau << m_Z \Rightarrow$ Tau decay products heavily boosted
- Collinear approximation assumes $\theta(v, vis) = 0$
- Calculate visible energy fraction: $x_{1,2} \in (0, 1)$
  - Deviations from $\theta(v, vis) = 0$ broaden resolution
  - leading to unphysical solutions => efficiency loss

- Parametrized PDFs of $v$-angular distributions - $p_T$ and decay dependent
- Fit the best solution in multi-dimensional space of opening angles and MET $x$-$y$ resolution
- MET$x, METy, 1 + 2$ angles => 5 variables floating in the fit

- Improves mass resolution majorly:
  $\Delta RMS/RMS = 33\%$ for $Z +$ Jets
- Has high efficiency compared to collinear approximation

\[ H \rightarrow \tau\tau, \text{lep-had channel, } M_\tau=115 \text{ GeV/c}^2 \]

\[ \text{Missing Mass Calculator} \]
\[ \text{Collinear Approximation} \]

arXiv:1012.4686 [hep-ex]

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