ATLAS Results On Higgs Boson Searches in Fermion Final States

Sasha Pranko (LBNL)

On behalf of the ATLAS collaboration
Higgs Boson Discovery

First observations of a new particle in the search for the Standard Model Higgs boson at the LHC

The Nobel Prize in Physics 2013

ATLAS 2011-12 $\sqrt{s} = 7-8$ TeV

www.elsevier.com/locate/physletb
Which Higgs Boson Did We Find?

• Higgs boson was discovered in ZZ*, γγ, and WW* decays

• Higgs boson mass is ~125.6 GeV
  – measured in H→ZZ*→4l, and H→γγ
  – ATLAS: \( M_H = 125.5 \pm 0.2 \) (stat) ± 0.6 (syst) GeV
  – CMS: \( M_H = 125.7 \pm 0.3 \) (stat) ± 0.3 (syst) GeV

• ATLAS and CMS data strongly favor \( J^P = 0^+ \) SM quantum numbers
  – All alternative \( J^P \) models tried are excluded at >95%CL

• Signal strength \( \mu = \sigma / \sigma_{SM} \) and all couplings are consistent with 1
  – ATLAS: \( \mu = 1.33 \pm 0.20 \)
  – CMS: \( \mu = 0.80 \pm 0.14 \)
  – Tevatron: \( \mu = 1.44 \pm 0.60 \)

• >3σ evidence for V-boson mediated (VBF) production

• All measured properties are compatible with SM Higgs hypothesis
Higgs Boson: What is Next?

• Evidence of coupling to fermions so far
  – Tevatron VH(→bb) combination: 2.8σ excess @ $M_H=125$ GeV
  – CMS VH(→bb): 2.1σ excess @ $M_H=125$ GeV
  – CMS $H\rightarrow\tau\tau$: 2.85σ excess @ $M_H=125$ GeV
    • CMS $H\rightarrow\tau\tau$ and $H\rightarrow bb$ combination: 3.4σ excess @ $M_H=125$ GeV

• Search for $H\rightarrow$fermions decays is one of the most important goals for the Higgs program
  – In particular, does Higgs couple to leptons?
    • We already indirectly know that it couples to quarks
  – Are $\Gamma_{H\rightarrow ff}$ consistent with SM predictions?
  – Is it the same Higgs decaying to $H\rightarrow VV$ & $H\rightarrow ff$?
    • Is mass the same? CP properties?

\[
\Gamma_{H\rightarrow ff} = \frac{N_C M_H}{8\pi v^2} m_f^2 \beta_f^3, \quad \beta_f = \sqrt{1 - \frac{4 m_f^2}{M_H^2}}
\]

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Talk Outline

• Higgs boson production

• Highlights of ATLAS Performance

• Results covered in this talk
  – Search for SM $H \rightarrow \mu\mu$ with full 8 TeV dataset
    • ATLAS-CONF-2013-010
  – Search for SM $H \rightarrow bb$ with full 7+8 TeV dataset
    • ATLAS-CONF-2013-079
  – Search for SM $H \rightarrow \tau\tau$ with 20.3 fb$^{-1}$ of 8 TeV data
    • ATLAS-CONF-2013-108

• Not covered in this talk
  – Results on BSM $H \rightarrow ff$ searches at ATLAS
SM Higgs Production (for $M_H=125$ GeV)

**Gluon Fusion**

Largest production mode: ~88% 
Utilized by $H \to \tau \tau$ & $H \to \mu \mu$ analyses

**VBF**

Unique signature of two jets with large $M_{jj}$ & $|\Delta\eta_{jj}|$ 
Utilized by $H \to \tau \tau$

**Associated Production**

Unique signature with leptons & neutrinos 
Utilized by VH($\to bb$)

<table>
<thead>
<tr>
<th></th>
<th>$gg \to H$</th>
<th>VBF</th>
<th>VH</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC: 8 TeV</td>
<td>19.5 pb</td>
<td>1.57 pb</td>
<td>1.08 pb</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$H \to bb$</th>
<th>$H \to \tau \tau$</th>
<th>$H \to \mu \mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Br</td>
<td>57.8%</td>
<td>6.32%</td>
<td>0.0219%</td>
</tr>
</tbody>
</table>
• Higgs boson discovery in 2012 would not be possible without outstanding performance of LHC

• Outstanding ATLAS detector performance in challenging high pile-up conditions with 90% efficiency for Physics
Electrons & Muons @ ATLAS

- Stable 97% (98%) muon (electron) reconstruction efficiencies
- Stable (within a few %) electron identification efficiency as a function of $N_{\text{vertex}}$
- ~2 GeV mass resolution for $Z \rightarrow \mu\mu$ peak
  - Good muon resolution is very important for $H \rightarrow \mu\mu$ search
**Hadronic Tau’s @ ATLAS**

- **ATLAS employs multivariate hadronic tau identification techniques**
  - Use information about shower shape in calorimeter and tracking detectors
  - TauID systematic uncertainties are 2.5% (5.6%-6.8%) for 1-prong (3-prong) taus

- **Tau energy scale (TES) is derived using *in situ* calibration based on $Z \rightarrow \tau \tau$ peak position**

1-prong decays

$H \rightarrow \tau \tau$ search uses ~60% and 35-45% Signal efficiency working points

Stable hadronic tau trigger efficiency as a function of $N_{\text{vertex}}$
Jets @ ATLAS

- $H \rightarrow bb$ and $H \rightarrow \tau\tau$ searches rely on jets and benefit from reduced jet energy scale (JES) uncertainties.
- Jet energy resolution (JER) is very important for $H \rightarrow bb$ search.

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b-Tagging @ ATLAS

- H→bb and H→ττ searches use NN b-tagging algorithm with working point corresponding to 70% b-tagging efficiency
  - Provides rejection factor of ~5 and ~150 against c-jets and light flavor jets
  - b-jet data-to-MC scale factors (SF) derived using ttbar di-lepton events
  - b-jet SF uncertainty in the range 2-10%
    - ~2% in the most important P_T(jet) range for H→bb search
  - c-jet SF uncertainty in the range 8-15%
Good MET resolution is very important for H→bb and H→ττ searches
  - MET is used in event selection and in M_{ττ} reconstruction
  - MET trigger is very important for ZH→νν+bb final state

Great improvement in MET resolution is achieved by using track-based pile-up suppression
  - Correction is based on the ratio of the Σp_T of the tracks associated to the primary vertex and all tracks
Search for $H \rightarrow \mu \mu$
H→μμ Search: Analysis Overview

- **Analysis strategy**
  - Inclusive search
  - Fit $M(\mu\mu)$ with analytic Signal + Bckg shape
  - Two analysis categories based on muon resolution:
    - Central: $|\eta(\mu_1,2)|<1.0$
    - Non-central: rest

- **Event selection for signal region**
  - Single muon trigger
  - Two isolated opposite-sign muons
  - $P_T(\mu_1)>25$ GeV, $P_T(\mu_2)>15$ GeV
  - $P_T(\mu\mu)>15$ GeV

Search window: 110-150 GeV
MC background predictions are not used in the search (for optimization only)
H→μμ Search: Signal & Background Models

**Signal model** is a sum of Crystal Ball (CB) and Gaussian (GS) PDFs

**Background model** is a sum of Breit-Wigner and exponential PDFs

– No statistically significant biases in fits to simulation and control regions
H→μμ Search: Results

• Systematic uncertainties on signal normalization @125 GeV
  – Cross-section: 15%
  – Br(H→μμ): ~6%
  – Acceptance uncertainty
    • Theory: ~2.6%
    • Experimental: ~4.2%

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

• ATLAS results with 20.7 fb\(^{-1}\) of data at 8 TeV
  – No significant deviations outside uncertainty bands are observed
  – 95% CL limit on μ @ 125 GeV: expected (μ=0) 8.2×SM, observed 9.8×SM
Search for $H \rightarrow bb$ in VH Production
H→bb Search: Exploit Unique VH Production Signature

- **Cut-based analysis in 3 final states**
- **ZH→ll+bb**
  - **Signature:** two opposite sign leptons and 2 b-tagged jets
  - **Major backgrounds:** Z+ heavy flavor jets
- **ZH→vv+bb**
  - **Signature:** large MET and 2 b-tagged jets
  - **Major backgrounds:** top, Z/W+ heavy flavor jets
- **WH→l+v+bb**
  - **Signature:** one lepton, MET and 2 b-tagged jets
  - **Major backgrounds:** top, W+ heavy flavor jets
**H→bb Search: Event Selection**

- **Common selection**
  - At least two jets with $P_T(jet1)>45$ GeV, $P_T(jet2)>20$ GeV and $|\eta|<2.5$
  - Isolated leading (sub-leading) leptons (e,\(\mu\)) with $P_T>25$ (10) GeV
  - Additional channel-specific requirements for boson selection and QCD rejection

- **To maximize sensitivity with optimized cuts events split into bins of $P_T(V)$, $N_{jets}$, $N_{b-tags}$**

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**ATLAS Preliminary**

- $\sqrt{s} = 7$ TeV, $L dt = 4.7$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV, $L dt = 20.3$ fb$^{-1}$

1 lep., 2 jets, 2 tags

<table>
<thead>
<tr>
<th>$P_T(V)$, GeV</th>
<th>0-90</th>
<th>90-120</th>
<th>120-160</th>
<th>160-200</th>
<th>&gt;200</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-lep, 2-jet</td>
<td>1-lep, 2-jet</td>
<td>All channels</td>
<td>All channels</td>
<td>All channels</td>
<td></td>
</tr>
<tr>
<td>2-lep</td>
<td>2-lep</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**$P_T(V)$ for events with 1 lepton, 2 jets, 2 b-tags**
H→bb Search: Signal & Control Regions

<table>
<thead>
<tr>
<th>3 p_T(V) bins</th>
<th>5 p_T(V) bins</th>
<th>5 p_T(V) bins</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 p_T(V) bins</td>
<td>1-lepton</td>
<td>2-leptons</td>
</tr>
<tr>
<td>0-leptons</td>
<td>CR</td>
<td>CR</td>
</tr>
<tr>
<td>CR</td>
<td>SR</td>
<td>SR</td>
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<tr>
<td>CR</td>
<td>SR</td>
<td>CR</td>
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<tr>
<td>CR</td>
<td>SR</td>
<td>CR</td>
</tr>
<tr>
<td>SR</td>
<td>SR</td>
<td>CR</td>
</tr>
</tbody>
</table>

• **Simultaneous fit in 26 2b-tag signal regions, 26 1b-tag control regions and 5 top control regions**
  - CR=control region; normalization of backgrounds (1-bin only)
  - SR=signal region; shape and normalization to m_{bb} distribution
  - Common nuisance parameters (NP) across SR’s and CR’s and channels
**H→bb Search: Inner Workings Of The Fit**

- Signal and control regions have different background compositions & shape
- Simultaneous fit allows to reduce effect of systematic uncertainties and constrain flavor composition of backgrounds

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H→bb Search: Cross-Check With VZ(→bb)

**Signal strength**

\[ \mu_{VZ} = \frac{\sigma_{\text{measured}}^{VZ}}{\sigma_{SM}^{VZ}} \]

- **Measured VZ(→bb) production cross-section is consistent with SM**
  - 4.8σ significance; \( \mu_{VZ} = 0.9 \pm 0.2 \)
  - Same signature as VH(→bb) allows for direct test of analysis procedure
**H → bb Search: Results**

**ATLAS Prelim.**

$m_H = 125$ GeV

| $(\sigma_{\text{stat}} + \sigma_{\text{sys}} + \sigma_{\text{theo}})$ | Total uncertainty
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>$\pm 1.1$</td>
<td>$\pm 0.9$</td>
</tr>
<tr>
<td>$\pm 1.8$</td>
<td>$\pm 1.6$</td>
</tr>
<tr>
<td>$\pm 3.1$</td>
<td>$\pm 1.8$</td>
</tr>
</tbody>
</table>

- **Fitted signal strength**
  - 7+8 TeV: $\mu = 0.2^{+0.7}_{-0.6}$

- **95% CLs @125 GeV**
  - Expected: $1.3\times$SM
  - Observed: $1.4\times$SM

- **Results consistent with SM $H \rightarrow bb$ and background-only hypotheses**

- **Dominant uncertainties:**
  - Modeling of $t\bar{t}V$, $P_T(V)$, 2-jet/3-jet ratio
  - $c$-jet tagging efficiency
  - Multijet normalization in 1-lepton channel
  - Signal acceptance

**Signal strength** $\mu = \frac{\sigma_{\text{measured}}}{\sigma_{23\text{SM}}}$

<table>
<thead>
<tr>
<th>$\sqrt{s}$ = 7 TeV $\int L dt = 4.7$ fb$^{-1}$</th>
<th>$\sqrt{s}$ = 8 TeV $\int L dt = 20.3$ fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu = -2.1^{+1.4}_{-1.4}$</td>
<td>$\mu = 0.2^{+0.7}_{-0.6}$</td>
</tr>
<tr>
<td>$\mu = -2.7^{+2.3}_{-1.9}$</td>
<td>$\mu = 0.3^{+1.6}_{-1.3}$</td>
</tr>
<tr>
<td>$\mu = -2.5^{+2.0}_{-1.9}$</td>
<td>$\mu = 0.3^{+1.6}_{-1.3}$</td>
</tr>
<tr>
<td>$\mu = 0.6^{+4.0}_{-3.6}$</td>
<td>$\mu = 0.2^{+0.7}_{-0.6}$</td>
</tr>
<tr>
<td>$\mu = 0.9^{+1.0}_{-0.9}$</td>
<td>$\mu = 0.5^{+0.9}_{-0.9}$</td>
</tr>
<tr>
<td>$\mu = 0.7^{+1.1}_{-1.1}$</td>
<td>$\mu = 0.1^{+1.0}_{-0.9}$</td>
</tr>
<tr>
<td>$\mu = -0.3^{+1.5}_{-1.3}$</td>
<td>$\mu = -0.4^{+1.5}_{-1.4}$</td>
</tr>
<tr>
<td>$\mu = 0.8$</td>
<td>$\mu = 0.8$</td>
</tr>
<tr>
<td>$\mu = 0.8$</td>
<td>$\mu = 0.8$</td>
</tr>
<tr>
<td>$\mu &lt; 0.1$</td>
<td>$\mu &lt; 0.1$</td>
</tr>
</tbody>
</table>
Search for $H \rightarrow \tau\tau$
**H→ττ Search: Analysis Concept**

- **Question that this analysis attempts to address**
  - Does the Higgs boson with \( M_H = 125.5 \) GeV decay to pair of \( τ \)-leptons?
    - Is the \( H→ττ \) decay rate consistent with SM predictions?

- **Analysis strategy**
  - Achieve maximum sensitivity for SM Higgs boson with \( M_H = 125.5 \) GeV
    - Design and perform multivariate analysis (based on BDT technique)
    - Perform “blind” analysis

- **Perform analysis in all final states of tau decays**
  - Lep-lep channel: \( H→ττ→2l+4ν, \) Br=12.4%
  - Lep-had channel: \( H→ττ→l+τ_{had}+3ν, \) Br=45.6%
  - Had-had channel: \( H→ττ→2τ_{had}+2ν, \) Br=42%

- **Major backgrounds**
  - \( Z→ττ \) (irreducible), \( Z(ee/μμ)+jets, \) W+jets, top, QCD multijets and di-bosons
H→ττ Search: Event Selection

• Triggers
  – **Lep-lep channel**: combination of single- and di-lepton triggers
  – **Lep-had channel**: single-lepton triggers
  – **Had-had channel**: di-tau triggers

• Strategy
  – Keep simple common selection and let MVA separate signal and background
  – Use events after common selection to validate background modeling

• Common selection
  – **Lep-lep channel**: \( N_{\text{lepton}} = 2, N_{\text{jet}} (P_T > 40 \text{ GeV}) \geq 1 \)
    • \( M_\parallel \) and MET cuts to suppress Drell-Yan and multijet backgrounds
  – **Lep-had channel**: \( N_{\text{lepton}} = 1, N_\tau = 1 \)
    • \( M_\tau < 70 \text{ GeV} \) cut to suppress W+jets background
  – **Had-had channel**: \( N_\tau = 2 \)
    • MET > 20 GeV, \( \Delta R(\tau\tau) \) and \( \Delta \eta(\tau\tau) \) cuts to suppress multijet background


**H→ττ Search: Analysis Categories**

- **Analysis is performed in two simple categories**
  - **VBF**: 2 jets with leading (sub-leading) $P_T > 40-50$ (30-35) GeV; $\Delta\eta(jj)$ cut
    - targeting VBF Higgs production (VBF signal fraction: 54%-63%)
  - **Boosted**: $P_T(H) > 100$ GeV
    - dominated by gluon fusion (ggF signal fraction 71%-74%)
  - **Lep-lep & Lep-had**: veto events with b-tags to suppress top background
- **“Rest” category in Had-had**: events failing Boosted & VBF selection used to constrain multijet and $Z\rightarrow\tau\tau$ backgrounds

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**ATLAS Preliminary**

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

- Data
- $50 \times H(125)\rightarrow\tau\tau$
- $Z\rightarrow\tau\tau$
- Others
- Multijet
- Uncert.

**Events / 0.5**

**Δη(\(j_1,j_2\))**

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**ATLAS Preliminary**

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

- Data
- $50 \times H(125)\rightarrow\tau\tau$
- $Z\rightarrow\tau\tau$
- Others
- Others
- Fake τ
- Uncert.

**Events / 15 GeV**

**$p_T^H$ [GeV]**

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**H→ττ Search: Background Estimation**

- All major backgrounds are either directly estimated from data or normalized to data in dedicated control regions.

**Z→ττ**: major background; modeled by data.

**“Fakes”**: multijet, W+jets, top (with fake tau); modeled by data.

**“Others”**: Dibosons & H→WW* modeled by MC; Z→ee/μμ & top modeled by MC and normalized to data.
H→ττ Search: Z→ττ Background

- **Z→ττ embedding**: except for τ-decays, all properties of a Z→ττ event are modeled by actual Z→μμ data.
- **Major advantages of embedding**: Z-boson kinematics, jets, MET resolution, pile-up, and VBF/EWK production are directly modeled by data.

Data Z→μμ events

Replace μμ→ττ

τ-decays: Tauola + Simulation

Embed τ-decays back into Z event

Hybrid Z→ττ event
H$\rightarrow$ττ Search: Backgrounds With “Fakes”

- “Fakes” are estimated directly from data
  - Lep-lep: from sample of “anti-isolated” leptons
  - Lep-had: from sample where hadronic tau fails ID requirements
  - Had-had: from not OS data events (where OS pairs removed)
  - Modeling of “Fakes” is checked in same-sign (SS) events
  - Uncertainties vary from 8% to 50% (depending on channel & category)

Examples of MET distributions after pre-selection

“Fakes” are shown by green histogram
**H→ττ Search: Top Background**

- Top background is modeled by MC (shape) and normalized in b-tag control region to total integral of events
  - Separate normalization for Boosted & VBF categories
  - Modeling is also cross-checked in validation regions defined by $M_{ll}>100$ GeV (lep-lep) and $H_T>350$ GeV (lep-had) cuts

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**Boosted lep-lep**

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

**ATLAS Preliminary**

- Data
- $50 \times H(125) \to \tau\tau$
- $Z \to \tau\tau$
- $Z \to ee, \mu\mu$
- $t\bar{t}$+single-top
- $WW/WZ/ZZ$
- Fake Lepton
- Uncert.

---

**VBF lep-lep**

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

**ATLAS Preliminary**

- Data
- $50 \times H(125) \to \tau\tau$
- $Z \to \tau\tau$
- $Z \to ee, \mu\mu$
- $t\bar{t}$+single-top
- $WW/WZ/ZZ$
- Fake Lepton
- Uncert.
**H→ττ Search: Input Variables to BDT**

- **Resonance properties**
  - \(m(ττ), ΔR(ττ),\) etc
- **VBF topology**
  - \(m_{jj}, Δη_{jj},\) etc
- **Event activity**
  - Scalar & vector \(P_T\)-sum
- **Event topology**
  - \(m_T,\) object centralities, \(P_T(τ_1)/P_T(τ_2),\) etc
- **Number of variables**
  - VBF: 7-9
  - Boosted: 6-9
**H → ττ Search: m(ττ) Reconstruction**

- **Good m(ττ) resolution is single most effective tool against Z → ττ**
  - m(ττ) is one most highly ranked BDT input variables
- **m(ττ) reconstructed by Missing Mass Calculator (MMC)**
  - MMC is sophisticated technique to reconstruct m(ττ) in presence of neutrinos from τ-decays
- **MMC resolution in events with at least one jet (table below)**
  - MMC resolution depends on τ-decay type and event topology
  - It is better in VBF and Boosted category

\[
\begin{array}{|c|c|}
\hline
 & Z → ττ \\
\hline
\text{Lep-lep} & 21.4\% \\
\text{Lep-had} & 18.1\% \\
\text{Had-had} & 14.3\% \\
\hline
\end{array}
\]
H→ττ Search: Cross-Checks

• Rigorous checks of background model and fitting technique
  ✓ Check modeling of all input variables
  ✓ Check modeling of correlation between each pair of input variables: \( <V_i> \) vs \( V_j \)
  ✓ Dedicated control regions (CR) for all major backgrounds
    • \( Z\rightarrow ee/\mu\mu + \text{jets CR} \) in lep-lep & lep-had
    • \( \text{Top CR} \) in lep-lep & lep-had
    • \( \text{W+jets CR} \) in lep-had
    • “Fakes”-enriched CR in lep-lep
    • \( \text{QCD-enriched CR} \) in had-had
  ✓ Perform fit in mass sidebands (outside 100-140 GeV window)
    • Check of \( Z\rightarrow\tau\tau \) background and overall background model
  ✓ Study each constrained or pulled fit nuisance parameter
H → ττ Search: Building Confidence in Background Model

- Examples of BDT distributions in data CR’s for major backgrounds

Lep-lep VBF: Z → ee/μμ CR

Good agreement in all BDT distributions with background normalizations before fit!

Lep-lep VBF: Top CR

Lep-had VBF: Z → ττ CR

Lep-had VBF: W+jets CR
**H→ττ Search: Signal Extraction**

**Lep-lep & Lep-had channels**

- **Signal region (BDT shape)**

**Had-had channels**

- **Z→ll CR (1 bin)**
- **Top CR (1 bin)**

**Rest category**

**Δη(ττ) shape**

- **Fit BDT shape with signal+background templates**
  - Simultaneous fit in 6 SR and 5 CR with common systematics NP’s
  - Z→ττ, Top, multijet (in had-had) & Z→ll normalizations are free in the fit
    - Control regions to constrain normalization of Top & Z→ll
    - **Had-had channel**: multijet & Z→ττ constrained in Rest category
H → ττ Search: BDT-score Distributions After Fit

Lep-lep channel

Had-had channel

Lep-had channel
H→ττ Search: Leading Uncertainties

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Uncertainty on μ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal region statistics (data)</td>
<td>0.30</td>
</tr>
<tr>
<td>Z → ℓℓ normalization (τlepτhad boosted)</td>
<td>0.13</td>
</tr>
<tr>
<td>ggF dσ/dpt</td>
<td>0.12</td>
</tr>
<tr>
<td>JES η calibration</td>
<td>0.12</td>
</tr>
<tr>
<td>Top normalization (τlepτhad VBF)</td>
<td>0.12</td>
</tr>
<tr>
<td>Top normalization (τlepτhad boosted)</td>
<td>0.12</td>
</tr>
<tr>
<td>Z → ℓℓ normalization (τlepτhad VBF)</td>
<td>0.12</td>
</tr>
<tr>
<td>QCD scale</td>
<td>0.07</td>
</tr>
<tr>
<td>di-τhad trigger efficiency</td>
<td>0.07</td>
</tr>
<tr>
<td>Fake backgrounds (τlepτlep)</td>
<td>0.07</td>
</tr>
<tr>
<td>τhad identification efficiency</td>
<td>0.06</td>
</tr>
<tr>
<td>Z → τ⁺τ⁻ normalization (τlepτhad)</td>
<td>0.06</td>
</tr>
<tr>
<td>τhad energy scale</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Signal strength \( \mu = \frac{\sigma_{measured}}{\sigma_{SM}} \)

\[ \Delta \mu \approx 0.5 \]

MC statistical uncertainties not included in Table

- Leading theory uncertainty is due to effect of top & bottom quark masses on \( P_T(H) \) spectrum in gluon fusion production (\(~30\%)\)
- Leading experimental uncertainties are due to background normalizations (up to \(~20\%)\)
**H→ττ Search: Results**

- **ATLAS observes significant excess of data events in high S/B region**
  - Excess is observed in all three channels
  - **Expected** significance at $M_H=125$ GeV corresponds to **3.2 sigma**
  - **Observed** significance at $M_H=125$ GeV corresponds to **4.1 sigma**

### Numbers of events in highest BDT-score bin

<table>
<thead>
<tr>
<th></th>
<th>Lep-lep</th>
<th>Lep-had</th>
<th>Had-had</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>VBF</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signal</td>
<td>5.7±1.7</td>
<td>8.7±2.5</td>
<td>8.8±2.2</td>
</tr>
<tr>
<td>Bckg</td>
<td>13.5±2.4</td>
<td>8.7±2.4</td>
<td>11.8±2.6</td>
</tr>
<tr>
<td>Data</td>
<td>19</td>
<td>18</td>
<td>19</td>
</tr>
</tbody>
</table>

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Boosted</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signal</td>
<td>2.6±0.8</td>
<td>8.0±2.5</td>
<td>3.6±1.1</td>
</tr>
<tr>
<td>Bckg</td>
<td>20.2±1.8</td>
<td>32±4</td>
<td>11.2±1.9</td>
</tr>
<tr>
<td>Data</td>
<td>20</td>
<td>34</td>
<td>15</td>
</tr>
</tbody>
</table>
**H→ττ Search: Compatibility With M_H=125 GeV**

- Each event is weighted by ln(1+S/B) for corresponding bin in BDT-score
- Excess of data events is consistent with presence of Higgs at 125 GeV

Signals at M_H=110, 125 and 150 GeV are shown at best fit μ; post-fit background normalizations
### ATLAS Prelim.

\( m_H = 125 \text{ GeV} \)

<table>
<thead>
<tr>
<th>Channel</th>
<th>( \mu = \sigma_{\text{mes}} / \sigma_{\text{SM}} )</th>
<th>Total uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \rightarrow \tau\tau )</td>
<td>1.4(^{+0.5}_{-0.4})</td>
<td>( \pm 1\sigma ) on ( \mu )</td>
</tr>
<tr>
<td>Boosted</td>
<td>1.2(^{+0.8}_{-0.6})</td>
<td></td>
</tr>
<tr>
<td>VBF</td>
<td>1.6(^{+0.6}_{-0.5})</td>
<td></td>
</tr>
<tr>
<td>( H \rightarrow \tau_{\text{lep}}\tau_{\text{lep}} )</td>
<td>2.0(^{+1.0}_{-0.9})</td>
<td></td>
</tr>
<tr>
<td>Boosted</td>
<td>2.0(^{+1.8}_{-1.5})</td>
<td></td>
</tr>
<tr>
<td>VBF</td>
<td>2.2(^{+1.2}_{-1.1})</td>
<td></td>
</tr>
<tr>
<td>( H \rightarrow \tau_{\text{lep}}\tau_{\text{had}} )</td>
<td>1.4(^{+0.6}_{-0.5})</td>
<td></td>
</tr>
<tr>
<td>Boosted</td>
<td>1.2(^{+1.1}_{-0.8})</td>
<td></td>
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<tr>
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</tr>
<tr>
<td>( H \rightarrow \tau_{\text{had}}\tau_{\text{had}} )</td>
<td>1.0(^{+0.8}_{-0.6})</td>
<td></td>
</tr>
<tr>
<td>Boosted</td>
<td>0.8(^{+1.2}_{-1.0})</td>
<td></td>
</tr>
<tr>
<td>VBF</td>
<td>1.0(^{+0.9}_{-0.7})</td>
<td></td>
</tr>
</tbody>
</table>

**Uncertainties on \( \mu \):**
- Statistical: ±0.3
- Systematic: +0.3/-0.2
- Theory: +0.3/-0.2

\( \sqrt{s} = 8 \text{ TeV} \int \mathcal{L} \mathcal{d}t = 20.3 \text{ fb}^{-1} \)
**H→ττ Search: VBF vs Gluon Fusion**

- Results are consistent with SM predictions within 68% contour
- Best fitted values: $\mu_{ggF} \times B/B_{SM} = 1.1^{+1.3}_{-1.1}$; $\mu_{VH+VBF} \times B/B_{SM} = 1.6^{+0.8}_{-0.7}$
$H \rightarrow \tau \tau$ Candidate Event In Had-Had Channel

Run: 209074
Event: 29487501
2012-08-23
15:06:35 UTC
Summary

- **H → μμ**: no excess over background observed
  - Observed limit: 9.8×SM
  - Expected limit: 8.2×SM

- **H → bb**: no excess over background observed
  - Observed limit: 1.4×SM
  - Expected limit: 1.3×SM

- **ATLAS observed 4.1σ evidence for H → ττ decays**

- **ATLAS results show that the Higgs boson does not universally couple to fermions (leptons)**