Search for the Higgs boson in fermionic channels using ATLAS detector

2014 Dec 1st
Discovery Physics at the LHC

Kruger 2014, South Africa

Kazuya Mochizuki,
on behalf of the ATLAS collaboration
Centre de Physique des Particules de Marseille (CPPM)
Since the discovery...

2012 July 4th, observation of a new boson @ $m \sim 125$ GeV

2013 March
Spin 0 with positive parity compatible with SM Higgs boson with Spin CP measurement

2013 Oct.
Nobel Prize in physics 2013

2013 Nov.
Evidence for $H \rightarrow \tau \tau$

2014 Dec.
Everything seems consistent with the SM. ⇒ Precise measurement is very important with

- Mass
- Couplings
  Especially with fermions
- Spin / CP

$H \rightarrow \gamma \gamma$

$H \rightarrow Z \gamma$

$H \rightarrow Z^0 Z^0 \rightarrow 4 \ell$

$H \rightarrow \tau \tau$

$H \rightarrow \nu \nu$

Long shutdown

LHC Run 1

2012

2013

2014

2015
# Higgs searches with fermions at ATLAS

**Recently updated. Main topics in this talk.**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Reference and released date</th>
<th>Paper submitted to</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$H \rightarrow \tau\tau$</strong></td>
<td>ATLAS-CONF-2014-061 2014 Oct 7</td>
<td>-</td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$</td>
<td>Physics Letters B doi:10.1016 2014 Jun 30</td>
<td>PLB</td>
</tr>
<tr>
<td><strong>$VH \rightarrow Vbb$</strong></td>
<td>arXiv: 1409.6212 2014 Sep 22</td>
<td>JHEP</td>
</tr>
<tr>
<td>$ttH \rightarrow ttbb$</td>
<td>ATLAS-CONF-2014-011 2014 Mar 24</td>
<td>-</td>
</tr>
<tr>
<td>$ttH \rightarrow tt\gamma\gamma$</td>
<td>arXiv:1408.7084 2014 Aug 27</td>
<td>PRD</td>
</tr>
<tr>
<td>$tH \rightarrow tbb$</td>
<td>arXiv:1409.3122 2014 Sep 10</td>
<td>PLB</td>
</tr>
</tbody>
</table>

**Other related talks on SM Higgs**

| For Higgs combinations and properties | 9:15 | Kyle CRANMER |
| For prospect studies | 10:45 | Philip CLARK |
| For ttH channels | 14:30 | Giuseppe SALAMANNA |
Higgs production modes

- Largest cross section: 19.27 pb @ 125 GeV
- Large theory uncertainty ~10%

- 2nd Largest cross section: 1.58 pb @ 125 GeV
- Discriminative topology with 2 forward jets
- Main target of $H \rightarrow \tau\tau$ analysis

- Cross section @ 125 GeV: 0.7 (0.42) pb for WH (ZH)
- Associated leptonic W/Z for trigger
- Main target of $H \rightarrow b\bar{b}$ analysis

- Cross section: 0.13 pb @ 125 GeV
- Important for top Yukawa coupling measurement
- Busy and complex final state
1. **Searches with leptons**
   1. $H \rightarrow \tau\tau$
   2. $H \rightarrow \mu\mu$

2. **Searches with quarks**
   1. $VH$, $H \rightarrow bb$

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

\[ Br(H \rightarrow \tau\tau) = 6.3\% \]
\[ Br(H \rightarrow \mu\mu) = 0.02\% \]
\[ Br(H \rightarrow bb) = 58\% \]
VBF $H \rightarrow \tau_e \tau_{\text{had}}$ candidate in Run 1
$H \rightarrow \tau\tau$ analysis channels

- The search is split into 3 sub-channels based on $\tau$ decay modes.

\begin{itemize}
  \item $\tau_{\text{had}}\tau_{\text{had}}$
  \begin{itemize}
    \item 42%
    \item Large BR
    \item 2 isolated $\tau_{\text{had}}$
    \item $E_T^{\text{miss}}$
  \end{itemize}
  \item $\tau_{\text{lep}}\tau_{\text{had}}$
  \begin{itemize}
    \item 45.6%
    \item Large BR
    \item 1 isolated lepton
    \item 1 isolated $\tau_{\text{had}}$
    \item $E_T^{\text{miss}}$
  \end{itemize}
  \item $\tau_{\text{lep}}\tau_{\text{lep}}$
  \begin{itemize}
    \item 12.4%
    \item Small BR
    \item 2 isolated lepton
    \item Higher $E_T^{\text{miss}}$
  \end{itemize}
\end{itemize}

- 2 main production modes targeted
  - **Boosted** category ($gg \rightarrow H$):
    The Higgs candidates have high $p_T$ (> 100 GeV)
  - **VBF** category:
    VBF event topology tagged with 2 jets with large $\Delta\eta(j_1, j_2)$
$H \rightarrow \tau\tau$ analysis strategy

- **2 analyses to confirm each other**
  - **Multi-variate analysis (MVA):**
    Fit BDT output which combines kinematic variables together with $m_{\tau\tau}^{\text{MMC}}$.
  - **Cut-based analysis:**
    Fit $m_{\tau\tau}^{\text{MMC}}$ ($m_{\tau\tau}$ reconstructed with missing mass calculator).
    Cross-check for MVA.

**Missing mass calculator (MMC)**
Use tau-decay PDFs to pick most likely di-tau invariant mass given visible decay products and $E_T^\text{miss}$

- **Main backgrounds: modeled by data-driven methods**
  - **$Z \rightarrow \tau\tau$, irreducible background**
    Modeling is based on embedding sample (next page).
  - **Tau fakes or lepton fakes (W+jets, multi-jets)**
    Cannot be predicted by MC => data-driven methods below

<table>
<thead>
<tr>
<th>Channel</th>
<th>Estimation method</th>
<th>Control region (CR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{\text{lep}}\tau_{\text{lep}}$</td>
<td>Multijet-fit on $p_T^{\ell_2}$</td>
<td>Inverted lepton isolation</td>
</tr>
<tr>
<td>$\tau_{\text{lep}}\tau_{\text{had}}$</td>
<td>Fake-factor method</td>
<td>Inverted $\tau$-id with dedicated CR for different processes</td>
</tr>
<tr>
<td>$\tau_{\text{had}}\tau_{\text{had}}$</td>
<td>Multijet-fit on $\Delta\eta_{\tau\tau}$</td>
<td>OS$\leftrightarrow$SS inversion, $\tau$ isolation inversion</td>
</tr>
</tbody>
</table>

Charge requirements on $\tau$ decay product: OS=opposite sign, SS=same sign
**Z → ττ background estimation**

**Tau-embedding technique**

- Estimate shape of $Z \rightarrow \tau\tau$ from $Z \rightarrow \mu\mu$ data
  - Remove $\mu$ tracks and calorimeter cells
  - Replace $\mu$ with $\tau$ from full-simulated $Z \rightarrow \tau\tau$ decays generated with TAUOLA

- Event content from data except $\tau$ decay
- Validation of the procedure with
  - $\mu \rightarrow \mu$ replacement in data
  - $\mu \rightarrow \tau$ replacement in MC

---

**Background Estimation**

- **Data**: $Z \rightarrow \mu\mu$
- **MC**: $Z \rightarrow \tau\tau$ had

**Run reconstruction after replacement**

**Validation of procedure**

- $Z \rightarrow \mu\mu$, data vs data(emb)
- $Z \rightarrow \tau\tau$, MC vs MC(emb)

**Calo-isolation**

**Event Content**

- Run reconstruction after replacement
- Validation of the procedure with $\mu \rightarrow \mu$ replacement in data, $\mu \rightarrow \tau$ replacement in MC

**Graphs**

- $Z \rightarrow \mu\mu$, data vs data(emb)
- $Z \rightarrow \tau\tau$, MC vs MC(emb)
$H \to \tau\tau$ BDT analysis

- 6 BDT trainings for 2(Boosted, VBF) * 3($\tau_{\text{lep}}\tau_{\text{lep}}$, $\tau_{\text{lep}}\tau_{\text{had}}$, $\tau_{\text{had}}\tau_{\text{had}}$)
- Simultaneous fit on the 6 BDT output + control regions

- For $m_H = 125.36$ GeV, 4.5$\sigma$ (3.5$\sigma$) significance is observed (expected)
  
  Evidence for Higgs coupling to tau: $\gamma_\tau$

- Dominant uncertainties
  - Jet energy scale
  - Background normalization
  - BR ($H \to \tau\tau$)
  - Tau energy scale / identification

![Graphs and plots related to BDT analysis and Higgs signal](image-url)
**H → ττ results**

- **Signal strength:**
  
  MVA: $\mu = 1.42^{+0.27}_{-0.26}({\text{stat.}})^{+0.32}_{-0.24}({\text{syst.}}) \pm 0.10({\text{theo.}})$ for $m_H = 125.36$ GeV

  Cut based cross-check (8 TeV only):
  $\mu = 1.37^{+0.57}_{-0.48}(\text{tot.})$

- **Compatible with SM**

  \[ \mu^{\tau \tau}_{ggF} = 1.93^{+0.78}_{-0.77}({\text{stat.}})^{+1.19}_{-0.80}({\text{syst.}}) \pm 0.29({\text{theo.}}) \]

  \[ \mu^{\tau \tau}_{VBF+VH} = 1.24^{+0.48}_{-0.45}({\text{stat.}})^{+0.31}_{-0.28}({\text{syst.}}) \pm 0.08({\text{theo.}}) \]

  for $m_H = 125.36$ GeV
1. Searches with leptons
   1. $H \rightarrow \tau\tau$
   2. $H \rightarrow \mu\mu$

2. Searches with quarks
   1. $VH, H \rightarrow bb$

Br($H \rightarrow \tau\tau$) = 6.3%
Br($H \rightarrow \mu\mu$) = 0.02%
Br($H \rightarrow bb$) = 58%

$m_H = 125$ GeV
**H → μμ analysis**

**Overview**
- Important to measure the 2nd generation couplings
- Search for a narrow resonance of $H \rightarrow \mu\mu$
- Fit $m_{\mu\mu}$ in 110-160 GeV range
- Overwhelming irreducible Drell-Yan background
  Precise background modeling is an important key

**Categorization**
- ggH, VBF with 2 jets
- For ggH, further categorization based on $\eta^\mu$:
  - Central category: $|\eta^{\mu_1}|<1$ and $|\eta^{\mu_2}|<1$
  - Non-central category: events not passing above
- $p_T^{\mu\mu}$:
  - Low ($p_T^{\mu\mu}<15$ GeV)
  - Medium ($15<p_T^{\mu\mu}<50$ GeV)
  - High ($50<p_T^{\mu\mu}$ GeV)

**Pre-selection**
- 2 isolated opposite sign muons
- $p_T^{\mu_1}>25$ GeV, $p_T^{\mu_2}>15$ GeV
- $E_T^{\text{miss}}<80$ GeV

**Fit**
- Central Muons, $p_T^{\mu\mu}<15$ GeV
- Non-central Muons, $p_T^{\mu\mu}<15$ GeV
- Central Muons, $15<p_T^{\mu\mu}<50$ GeV
- Non-central Muons, $15<p_T^{\mu\mu}<50$ GeV
- VBF≥2 jets, $M_{jj}>500$ GeV, $\Delta\eta_{jj}>3$, $\eta_{j_1}\times\eta_{j_2}<0$
$H \rightarrow \mu\mu$ results

- Observed (expected) limit at 125.5 GeV with 95% CL: 7.0 (7.2) x SM
- 95% CL limit on BR: $1.5 \times 10^{-3}$
- Result limited by data statistics => Run 2
- Confirmation of non-universality of Higgs-lepton couplings
1. **Searches with leptons**
   1. $H \rightarrow \tau\tau$
   2. $H \rightarrow \mu\mu$

2. **Searches with quarks**
   1. $VH, H \rightarrow bb$
      - $ZH \rightarrow \nu\nu bb$
      - $WH \rightarrow \ell\nu bb$
      - $ZH \rightarrow \ell\ell bb$

\[ Br(H \rightarrow \tau\tau) = 6.3\% \]
\[ Br(H \rightarrow \mu\mu) = 0.02\% \]
\[ Br(H \rightarrow bb) = 58\% \]

$m_H = 125$ GeV
$WH \rightarrow \mu vbb$ candidate in Run 1
**VH → Vbb analysis I**

- Large BR (~58%), but \( pp \rightarrow bb \) overwhelms ggH and VBF production to search

  ⇒ Use associated W/Z production for probe and distinguish signal from backgrounds

- 2 analyses to confirm each other
  - Multi-variate analysis (MVA): fit BDT output which combines kinematic variables in addition to \( m_{bb} \)
  - Cut-based analysis: fit di-jet invariant mass (\( m_{bb} \)). Cross-check for MVA.

- Analysis splits into 3 sub-channels based on decay modes of W/Z: 0-, 1-, 2-lepton

<table>
<thead>
<tr>
<th>Process</th>
<th>( Z \rightarrow \nu\nu )</th>
<th>( W \rightarrow e\nu / W \rightarrow \mu\nu )</th>
<th>( Z \rightarrow e\bar{e} / Z \rightarrow \mu\mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>#leptons</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Branching fraction</td>
<td>20%</td>
<td>11% / 11%</td>
<td>3.3% / 3.3%</td>
</tr>
<tr>
<td>Main background</td>
<td>Top, W/Z+jets</td>
<td>Top, W+jets</td>
<td>Z+jets</td>
</tr>
</tbody>
</table>
| Event signature (Selection/BDT-input) | • Large \( E_T^{\text{miss}} \) and \( p_T^{\text{miss}} \)
  • \( E_T^{\text{miss}} \) and di-jet in back-to-back | • \( E_T^{\text{miss}} \) and \( H_T \)
  to kill multi-jet | • Low \( E_T^{\text{miss}} \)
  • \( m_T^W \)
  • \( m_{\ell\ell} \) window cut for \( m_Z \) |

\( p_T^{\text{miss}} \): track based \( E_T^{\text{miss}} \)

\( H_T \): Scalar sum of jets, lepton, and \( E_T^{\text{miss}} \)
**VH → Vbb analysis II**

- To maximize sensitivity and cope with different background composition, analysis further splits into
  - 2-jet and 3-jet categories
  - Low and high $p_T^V$ categories ($p_T^V$ boundary @ 120 GeV)
- Select exactly 2 tagged b-jets
  - MV1c tagger is used: improved c-jet rejection
  - Thanks to **continuous calibration** of b-tagging, three 2-tag categories are used based on tightness of MV1c tagger.
- In addition to three 2-tag regions, simultaneously fit **MC1c in 1-tag region to constraint background**

**Graphs:**
- **ATLAS:**
  - $\ell \nu b b$ events vs $m_{bb}$ [GeV] for data 2012, VH(bb) (μ=1.0), diboson, single top, multijet, W+hf, W+I, Z+hf, and uncertainty.
  - **Boosted decision trees** for $\ell \nu b b$ events.

**Legend:**
- Data 2012
- VH(bb) (μ=1.0)
- Diboson
- Single top
- Multijet
- W+hf
- W+I
- Z+hf
- Uncertainty
- Pre-fit background
- VH(bb)=20

**Diagram:**
- MV1c(j) categories with 80%, 70%, 50% boundaries.
- 1-tag, TT, MM, LL regions.
- Continuous calibration of b-tagging.
**VH improvements**

- $m_{bb}$ resolution improvement
  - Most important variable in BDT inputs
  - Muon-in-jet correction
  - Kinematic likelihood fit in 2-lepton channel
    
    No intrinsic $E_T^{\text{miss}}$ except semi-leptonic $b$-decay

- $E_T^{\text{miss}}$ triggered muon channel in $WH \rightarrow \ell vbb$
  
  Compensate the inefficiency of muon trigger

- Low $E_T^{\text{miss}}$ ($100 < E_T^{\text{miss}} < 120$ GeV) bin
  in $ZH \rightarrow \nu \nu bb$

- Improvement from MVA

Use BDTs in 3(0-, 1-, 2-) lepton-channels x 2(2-,3-) jet bins x 2(low, high) $p_T^V$ bins x 3(LL, MM, TT) 2-tag regions

**Combination across channels**
For SM Higgs search at $m_H=125.36$ GeV:
MVA: $1.4\sigma$ ($2.6\sigma$) significance is observed (expected)
Cut-based cross check: $2.2\sigma$ ($1.9\sigma$) observed (expected)

Signal strength:
MVA: $\mu = 0.52 \pm 0.32$ (stat.) $\pm 0.24$ (syst.) for $m_H = 125.36$ GeV
Cut based cross-check: $\mu = 1.23 \pm 0.44$ (stat.) $\pm 0.41$ (syst.)
Dominant systematic source:
$W/Z +$ heavy flavor modeling (shape, normalization)

Compatible with SM

Combination across channels

Diboson ($VZ$) production is measured as a cross-check
$\Rightarrow$ compatible with the SM

$- 4.9 \sigma$ ($6.3\sigma$) is observed (expected) for VZ production
$- $ Signal strength $\mu = 0.74 \pm 0.09$ (stat.) $\pm 0.14$ (syst.)
### Summary

<table>
<thead>
<tr>
<th>Decay channels</th>
<th>Signal strength ($\mu$)</th>
<th>Significance / limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>$1.4^{+0.3,\text{(stat)}}_{-0.3,\text{(sys)}}$</td>
<td>$4.5\ (3.5) \ \sigma$</td>
</tr>
<tr>
<td>$H \rightarrow \mu\mu$</td>
<td>$-$</td>
<td>$\mu/\mu_{\text{SM}}=7.0\ (7.2)$</td>
</tr>
<tr>
<td>$VH \rightarrow Vbb$</td>
<td>$0.5^{+0.3,\text{(stat)}}_{-0.2,\text{(sys)}}$</td>
<td>$1.4\ (2.6) \ \sigma$</td>
</tr>
</tbody>
</table>

- **$H \rightarrow \tau\tau$: Evidence for $Y_\tau$**
- **$H \rightarrow \mu\mu$:** No excess observed yet at $m_H=125$ GeV
- **$H \rightarrow bb$:** An excess with 1.4 $\sigma$ significance observed at $m_H=125$ GeV

- So far, everything looks compatible with the SM expectations

LHC will restart next year!!
- Increased luminosity
- New innermost pixel layer (IBL) in ATLAS

STAY TUNED!
BACKUP BUCKET
**VH → Vbb selection**

- Cut-based selection has 5 bins in $p_T^V$ in stead of 2 bins of MVA.
- To cope with the different background composition, cuts vary in $p_T^V$ bins in cut-based selection, e.g. $\Delta R_{jj}$.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Dijet-mass analysis</th>
<th>Multivariate analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^V$ [GeV]</td>
<td>0–90 90(+)–120 120–160 160–200 &gt; 200</td>
<td>0–120 &gt; 120</td>
</tr>
<tr>
<td>$\Delta R_{(jet_1,jet_2)}$</td>
<td>0.7–3.4 0.7–2.3 0.7–1.8 &lt; 1.4</td>
<td>&gt; 0.7 ($p_T^V&lt;200$ GeV)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>0-lepton selection</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^{miss}$ [GeV]</td>
<td></td>
<td>&gt; 30</td>
</tr>
<tr>
<td>$\Delta \phi(E_T^{miss},E_T^{miss,vec})$</td>
<td></td>
<td>&lt; $\pi/2$</td>
</tr>
<tr>
<td>$\min[\Delta \phi(E_T^{miss},jet)]$</td>
<td></td>
<td>&gt; 1.5</td>
</tr>
<tr>
<td>$\Delta \phi(E_T^{miss},dijet)$</td>
<td></td>
<td>&gt; 2.8</td>
</tr>
<tr>
<td>$\sum_{i=1}^{N_{jet}^{=2}(3)} p_T^{jet_i}$ [GeV]</td>
<td></td>
<td>&gt; 120 (NU)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 120 (150)</td>
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<tr>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>1-lepton selection</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_T^W$ [GeV]</td>
<td></td>
<td>&gt; 180</td>
</tr>
<tr>
<td>$H_T$ [GeV]</td>
<td></td>
<td>&lt; 120</td>
</tr>
<tr>
<td>$E_T^{miss}$ [GeV]</td>
<td></td>
<td>&gt; 180</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2-lepton selection</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\ell\ell}$ [GeV]</td>
<td></td>
<td>83–99</td>
</tr>
<tr>
<td>$E_T^{miss}$ [GeV]</td>
<td></td>
<td>71–121</td>
</tr>
</tbody>
</table>

**$E_T^{miss}$ triggered $\mu$-ch in WH**

- Single muon trigger does not reach 100% efficiency
- Thanks to well measured $E_T^{miss}$ trigger turn on, we can apply $E_T^{miss}$ trigger for the recovery of muon trigger in $WH \rightarrow \ell \nu b\bar{b}$, applied in $p_T^W > 120$ GeV.
- Contribution to significance gain: $\sim 2\%$
\( \Delta \phi \) correction

Sub-division of signal regions based on \( p_T^V \)

\( \Rightarrow \) Modeling of \( p_T^V \) is crucial
$VH \rightarrow Vbb \ p_T^V$ distributions

**Figure 1:**
- **Title:** ATLAS
- **Subtitle:** $\sqrt{s} = 8$ TeV \[ \int L dt = 20.3 \text{ fb}^{-1} \]
- **Legend:**
  - Data 2012
  - VH(bb) ($\mu=1.0$)
  - Diboson
  - tt
  - Single top
  - Multi-Jet
  - W+H
  - W+Cl
  - Z+H
  - Z+Cl
  - Uncertainty
  - Pre-fit background
  - VH(bb)-30

**Graphs:**
- **Left:** 0 lep., 2 jets, 2 Medium+Tight tags
- **Middle:** 1 lep., 2 jets, 2 Medium+Tight tags
- **Right:** 2 lep., 2 jets, 2 Medium+Tight tags

**Axes:**
- **X-axis:** $p_T^V$ [GeV]
- **Y-axis:** Events / bin

**Legend Entries:**
- Data 2012
- VH(bb) ($\mu=1.0$)
- Diboson
- tt
- Single top
- Multi-Jet
- W+H
- W+Cl
- Z+H
- Z+Cl
- Uncertainty
- Pre-fit background
- VH(bb)-30

**Contrast:**
- Red: VH(bb) ($\mu=1.0$)
- Yellow: Diboson
- Orange: tt
- Green: Single top
- Blue: Multi-Jet
- Light Green: W+H
- Light Blue: W+Cl
- Pink: Z+H
- Purple: Z+Cl
- Gray: Uncertainty
- Black: Pre-fit background
- Dark Green: VH(bb)-30
$VH \rightarrow Vbb$ $m_{bb}$ distributions
**VH → Vbb input variables**

**ATLAS**

1s = 8 TeV \( |\Delta t| = 20.3 \text{ fb}^{-1} \)

0 lep., 2 jets, 2 tags

- Data 2012
- VH(bb) \((\times 1.0)\)
- Diboson
- tt
- Single top
- Multi-jet
- W+ \(t\)
- W+ \(c\)
- W+ \(\ell\)
- Z+ \(t\)
- Z+ \(c\)
- Z+ \(\ell\)
- Uncertainty
- Pre-fit background
- VH(bb)-10

Events / 25 GeV

Data/Pred vs. \(m_{bb} \) [GeV]

Events / 20 GeV

Data/Pred vs. \(E_T^{miss} \) [GeV]

\(\Delta R(b_1, b_2)\)

Events / 20 GeV

Data/Pred vs. \(p_T(b_1) \) [GeV]

\(\Delta R(V,bb)\)
VH → Vbb cross-check with diboson production (VZ)

- Use VZ as cross-check which produces exactly the same final states
- Data and background + signal yield are compatible
- Significance for VZ:
  - 4.9 σ observed
  - 6.3 σ expected
- Signal strength for VZ:
  \[ \mu = 0.52 \pm 0.32 \text{ (stat.)} \pm 0.24 \text{ (syst.)} \]
$VH \rightarrow bb$ Cut-based (di-jet) mass analysis

**ATLAS**

$\sqrt{s} = 8 \text{ TeV}$, $Ldt = 20.3 \text{ fb}^{-1}$

- 0+1 lep., 2+3 jets, 2 tags
- Weighted by Higgs S/B

**ATLAS**

$\sqrt{s} = 7 \text{ TeV}$, $Ldt = 4.7 \text{ fb}^{-1}$

- 0+1 lep., 2+3 jets, 2 tags
- Weighted by Higgs S/B

**Graphs:**

- Weighted events after subtraction / 20.0 GeV
- $m_{bb}$ [GeV]

---

**ATLAS**

$\sqrt{s} = 8 \text{ TeV}$, $Ldt = 20.3 \text{ fb}^{-1}$

- 0 lep., 2+3 jets, 2 tags
- Weighted by Higgs S/B

**ATLAS**

$\sqrt{s} = 8 \text{ TeV}$, $Ldt = 20.3 \text{ fb}^{-1}$

- 1 lep., 2+3 jets, 2 tags
- Weighted by Higgs S/B

**ATLAS**

$\sqrt{s} = 8 \text{ TeV}$, $Ldt = 20.3 \text{ fb}^{-1}$

- 2 lep., 2+3 jets, 2 tags
- Weighted by Higgs S/B

---

**Data 2012**

- VH(bb) ($\mu=1.0$)
- Diboson
- Uncertainty

---

**ATLAS**

- Data 2011
- VH(bb) ($\mu=1.0$)
- Diboson
- Uncertainty
VH → Vbb S/B sorted events

0-lepton

1-lepton

2-lepton
# BDT inputs

## $H \rightarrow \tau\tau$

<table>
<thead>
<tr>
<th>Variable</th>
<th>$VBF$</th>
<th>$Boosted$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\tau_{lep}\tau_{lep}$</td>
<td>$\tau_{lep}\tau_{had}$</td>
</tr>
<tr>
<td>$m_{\tau\tau}^{\text{MME}}$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>$\Delta R(\tau_1, \tau_2)$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>$\Delta \eta(j_1, j_2)$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>$m_{j_1, j_2}$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>$\eta_{j_1} \times \eta_{j_2}$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>$p_T^{\text{total}}$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Sum $p_T$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>$p_T(\tau_1)/p_T(\tau_2)$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>$\phi$ centrality</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>$m_{\ell, \ell, j_1}$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>$m_{\ell, \ell, j_2}$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>$\Delta \phi(\ell_1, \ell_2)$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Sphericity</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>$p_T^{\ell_1}$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>$p_T^{\ell_2}$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}/p_T^{\ell_1}$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>$m_T$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>$\min(\Delta R(\ell_1, \ell_2))$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>$C_{m_1, m_2}(\eta_{\ell_1}) \cdot C_{m_1, m_2}(\eta_{\ell_2})$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>$C_{m_1, m_2}(\eta_{\ell_1})$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>$C_{m_1, m_2}(\eta_{\ell_2})$</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>$C_{m_1, m_2}(\eta_{\ell_2})$</td>
<td>•</td>
<td>•</td>
</tr>
</tbody>
</table>

## $VH \rightarrow Vbb$

<table>
<thead>
<tr>
<th>Variable</th>
<th>0-Lepton</th>
<th>1-Lepton</th>
<th>2-Lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^V$</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$p_T^{b_1}$</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$p_T^{b_2}$</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$m_{bb}$</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$\Delta R(b_1, b_2)$</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \eta(b_1, b_2)</td>
<td>$</td>
<td>x</td>
</tr>
<tr>
<td>$\Delta \phi(V, bb)$</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$</td>
<td>\Delta \eta(V, bb)</td>
<td>$</td>
<td>x</td>
</tr>
<tr>
<td>$H_T$</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$\min(\Delta \phi(\ell, b))$</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$m_t^W$</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$m_{\ell\ell}$</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$MV1c(b_1)$</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$MV1c(b_2)$</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

Only in 3-jet events:

<table>
<thead>
<tr>
<th>Variable</th>
<th>0-Lepton</th>
<th>1-Lepton</th>
<th>2-Lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^{\text{jet}_3}$</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>$m_{b bj}$</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>
### SR & CR

#### $H \rightarrow \tau\tau$ CR

<table>
<thead>
<tr>
<th>Process</th>
<th>$\tau_{lep}\tau_{lep}$</th>
<th>$\tau_{lep}\tau_{had}$</th>
<th>$\tau_{had}\tau_{had}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \ell\ell$-enriched</td>
<td>$80 &lt; m_{\tau\tau}^{vis} &lt; 100$ GeV (same-flavour)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top control region</td>
<td>invert $b$-jet veto</td>
<td>invert $b$-jet veto and $m_T &gt; 40$ GeV</td>
<td>pass preselection, fail VBF and Boosted selections</td>
</tr>
<tr>
<td>Rest category</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$-enriched</td>
<td>$m_{\tau\tau}^{HPTO} &lt; 100$ GeV</td>
<td>$m_T &lt; 40$ GeV and $m_{\tau\tau}^{MMC} &lt; 110$ GeV</td>
<td></td>
</tr>
<tr>
<td>Fake-enriched</td>
<td>same sign $\tau$ decay products</td>
<td>same sign $\tau$ decay products</td>
<td></td>
</tr>
<tr>
<td>$W$-enriched</td>
<td></td>
<td>$m_T &gt; 70$ GeV</td>
<td></td>
</tr>
<tr>
<td>Mass sideband</td>
<td></td>
<td></td>
<td>$m_{\tau\tau}^{MMC} &lt; 110$ GeV or $m_{\tau\tau}^{MMC} &gt; 150$ GeV</td>
</tr>
</tbody>
</table>

- These CRs are used together with 6 BDT output in SR

#### VH → Vbb SR

<table>
<thead>
<tr>
<th>Channel</th>
<th>Dijet-mass analysis</th>
<th>MVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel</td>
<td>0-lepton</td>
<td>1-lepton</td>
</tr>
<tr>
<td>1-tag</td>
<td>$MV1c$</td>
<td>$MV1c$</td>
</tr>
<tr>
<td>LL</td>
<td>$m_{bb}$</td>
<td>BDT(*)</td>
</tr>
<tr>
<td>MM</td>
<td>$m_{bb}$</td>
<td>BDT(*)</td>
</tr>
<tr>
<td>TT</td>
<td>$m_{bb}$</td>
<td>BDT</td>
</tr>
</tbody>
</table>

- MV1c in 1-tag is used for background constraint.
**H → τ_{lep}τ_{had}** fake factor method

- **Quark / gluon contribution for fake-$\tau$**
  - Fake-$\tau$ contribution from $W+$jets is dominated by quark-jets
  - Fake-$\tau$ contribution from multi-jet production is dominated by gluon-jets

- **Define “anti-$\tau$” control regions by inverting $\tau$-identification criteria**
  - Inverting $m_T$ selection for $W+$jets
  - Low $E_T^{miss}$ and loose lepton isolation for multi-jet

- **Obtain different mis-identification probabilities (“Fake-Factor”), calculate weighted mean value according to**

  $$r_W = \frac{N_W}{N_W + N_{QCD}}, \quad F = r_W F_W + (1 - r_W) F_{QCD}$$

---

**ATLAS** Preliminary

- **1-Prong**
  - $\int L \, dt = 20.3fb^{-1}$
  - $\sqrt{s} = 8\text{TeV}$

- **3-Prong**
  - $\int L \, dt = 20.3fb^{-1}$
  - $\sqrt{s} = 8\text{TeV}$

- **Differences between quark- and gluon-dominated Fake-Factors used as systematic uncertainty (combined with statistical uncertainty from anti-$\tau$ data)**

---

ATLAS-CONF-2013-108
$H \rightarrow \tau\tau$ important input variables

$e^- e^+ + \mu^\pm \mu^\mp$ VBF

$\mu^\tau_{\text{had}} + \sigma^\tau_{\text{had}}$ VBF

$\tau^\tau_{\text{had}}$ Boosted

$\Delta R(\tau^\tau_1, \tau^\tau_2)$
$H \rightarrow \tau\tau$ boosted signal regions
$H \rightarrow \tau\tau$ results

**ATLAS Preliminary**

$s = 7$ TeV, $4.5$ fb$^{-1}$
$s = 8$ TeV, $20.3$ fb$^{-1}$