Search for SM Higgs Boson in $H \rightarrow bb$

at the LHC

Second MCTP Spring Symposium on Higgs Boson Physics

April 16-20, 2012

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On behalf of the ATLAS and CMS Collaborations
H→bb has highest decay BR at low mass ($m_H < \sim 135$ GeV)
Search for Low Mass Higgs Boson

- $\sigma(m_H=120 \text{ GeV}) \sim 17 \text{ pb}$
- $\sigma(m_H=120 \text{ GeV}) \sim 1.3 \text{ pb}$

- Search in $b\bar{b}$ or qqbb final state will encounter huge multi-jet background
- Higgs production in association with $W$ or $Z$
  - 3rd and 4th highest production rate ($\sigma(WH)\sim0.66 \text{ pb}, \sigma(ZH)\sim0.36 \text{ pb}$ @ $m_H=120 \text{ GeV}$)
  - Final states with leptonic decays of $W$ and $Z$ can help to reduce contribution from multi-jet background
### Detectors

<table>
<thead>
<tr>
<th>Component</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inner tracker</strong></td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>$\sigma(P_T)/P_T$ at $P_T=100$ GeV</td>
<td>3.8%</td>
<td>1.5%</td>
</tr>
<tr>
<td><strong>EM calorimeter</strong></td>
<td>3.2</td>
<td>3.0</td>
</tr>
<tr>
<td>$\sigma(E)/E$</td>
<td>10%/\sqrt{E+0.7}%</td>
<td>3%/\sqrt{E+0.5}%</td>
</tr>
<tr>
<td><strong>HAD calorimeter</strong></td>
<td>4.9</td>
<td>5.2</td>
</tr>
<tr>
<td>$\sigma(E)/E$ (EM+HAD combined)</td>
<td>50%/\sqrt{E+3}%</td>
<td>85%/\sqrt{E+7}%</td>
</tr>
<tr>
<td><strong>Muon system</strong></td>
<td>2.7</td>
<td>2.4</td>
</tr>
<tr>
<td>$\sigma(P_T)/P_T$ at $P_T=1$ TeV (standalone)</td>
<td>12% ($</td>
<td>\eta</td>
</tr>
</tbody>
</table>

B field: 2T solenoid, 4T toroid

B field: 3.8T solenoid
A Toroidal LHC Apparatus (ATLAS) Detector

- Weight: 7000 ton (same as Eiffel tower)
- Size: 45x25x25 m³
- #Readout chs.: 8.8 M (pixel: 8 M)
- 3000 km cables

Diagram showing:
- Muon Detectors
- Tile Calorimeter
- Liquid Argon Calorimeter
- Toroid Magnets (3.8T)
- Solenoid Magnet (2T)
- SCT Tracker
- Pixel Detector
- TRT Tracker
Search for Higgs Boson in Associated Production

WH → lν bb

ZH → l⁺l⁻ bb

ZH → νν bb

**WH (lνbb)**
- 1 high $p_T$ lepton
  - e or $µ$
- Missing Transverse Energy ($E_T^{miss}$)
- 2 b jets

**ZH (l±bb)**
- 2 high $p_T$ leptons
  - $e^+e^-$ or $µ^+µ^-$
- Z resonance peak
- small $E_T^{miss}$
- 2 b jets

**ZH (ννbb)**
- 0 lepton
- Large $E_T^{miss}$
- 2 b jets

• ATLAS : ATLAS-CONF-2012-015
Background Sources

Main Physics Background

• Top quark production (ttbar, single top)
• $Z + \text{jets}$ ($Z + \text{light-flavor (LF) jets, } Z + \text{heavy-flavor (HF) jets}$)
• Diboson ($WW$, $WZ$, $ZZ$)
• $W + \text{jets}$ ($W + \text{LF jets, } W + \text{HF jets}$)
• QCD multi-jet

Other Sources

• Extra jets from pile-up
• Fake large $E_T^{\text{miss}}$ sources
  • Noise in calorimeter
  • Beam gas, beam halo

\{ only for $WH(lvbb)$ and $ZH(vvbb)$ searches \}
Data Samples

- Perform searches on data samples with $\int L = 4.7$ fb$^{-1}$ at $\sqrt{s} = 7$ TeV, collected in 2011

Average number of interactions per p-p bunch crossing is $\sim 10$

Triggers to collect data samples:

- **WH(l\nu bb)**: single e/\mu triggers (efficiency $\sim 90$-$100\%$)
- **ZH(llbb)**: single or double e/\mu triggers (efficiency $\sim 95$-$100\%$)

- **ZH(\nu\nu bb)**:
  - CMS: $E_T^{\text{miss}}$ and $E_T^{\text{miss}}+\text{jet}$ triggers (efficiency $\sim 98\%$ at $E_T^{\text{miss}}$(offline)$=160$ GeV)
  - ATLAS: $E_T^{\text{miss}}$ trigger (efficiency $\sim 50\%$ at $E_T^{\text{miss}}$(offline)$=120$ GeV, 100\% at $E_T^{\text{miss}}$(offline)$=170$ GeV)

Efficiency measured w.r.t. offline selections
Physics Objects Reconstruction

**Electron**
- Inner detector track from primary vertex matched to energy cluster in electromagnetic calorimeter
- $|\eta|<2.5$
- $Pt>\sim20-30$ GeV, isolated

**Muon**
- Inner detector track from primary vertex matched to track in muon system
- $|\eta|<2.5$
- $Pt>\sim20-25$ GeV, isolated
Jets

• Reconstructed using anti-kt algorithm (cone size: 0.5 (CMS), 0.4 (ATLAS))
• Minimum Pt(jet) > ∼ 20-30 GeV, |η| < 2.5
• Subtract extra energy from pile-up
• Remove extra jets coming from pile-up interactions (not from the main hard interaction)

JVF: fraction of momentum of tracks associated to the jet from main primary vertex
**Missing Transverse Energy** ($E_T^{\text{miss}}$)

**CMS**

$E_T^{\text{miss}}$: negative vector sum of transverse momentum of all particle flow objects in event

**ATLAS**

$E_T^{\text{miss}}$: negative vector sum of cluster transverse energy in calorimeter.

- Correct cluster energy if associate to physics objects (e, µ, τ, γ)

**Pile-up Effect:**

- Additional interactions in bunch crossing can degrade $E_T^{\text{miss}}$ resolution

- $E_T^{\text{miss}}$ (from high $p_T$ multi-jet events) broaden with increase in multiple interactions

- Simulation needs right pile-up profile as seen in data

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**Multijet events**

![Graph](image1.png)

![Graph](image2.png)
Missing Transverse Energy ($E_T^{\text{miss}}$)

- Simulated events re-weighted to have pile-up profile matches data
- $E_T^{\text{miss}}$ performance in simulation is under control for 2011 analyses

$p_T^{\text{miss}}$ (ATLAS):

- Alternative quantity to $E_T^{\text{miss}}$
  - Based on tracks
  - $p_T^{\text{miss}}$: negative vector sum $p_T$ of tracks
  - $E_T^{\text{miss}}$ and $p_T^{\text{miss}}$ point in same direction for events with real $E_T^{\text{miss}}$
  - Use correlation in directions of $E_T^{\text{miss}}$ and $p_T^{\text{miss}}$ to reduce multi-jet background
- Apply in ATLAS’s ZH($\nu\nu\bb$) analysis to reduce QCD multi-jet background
B-Jet Tagging

• **b-jet**: identified based on relatively long lifetime \((c\tau \sim 450 \mu m)\) of B hadron

• Construct single discriminant using information from track impact parameters and secondary vertices reconstructed in jet

  • to separate b-jet from light, c and gluon jets

• **CMS**:
  
  • apply b-tagging algorithm at several working points in Higgs search

<table>
<thead>
<tr>
<th></th>
<th>Eff(B) (%)</th>
<th>Reject C rate</th>
<th>Reject LF rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Loose” (CSV&gt;0.244)</td>
<td>82</td>
<td>2.5</td>
<td>8.3</td>
</tr>
<tr>
<td>“Tight” (CSV&gt;0.90)</td>
<td>50</td>
<td>17</td>
<td>670</td>
</tr>
</tbody>
</table>

• **ATLAS**:

  • apply b-tagging algorithm at 1 working point

  • Eff(B)=70%, reject C~5, reject LF~130

![Graph showing light jet rejection vs. b-jet efficiency](image)
Event Selection

•CMS has two approaches:
  •“BDT Analysis”
    •Pre-select events with looser cuts and apply boosted-decision-tree (BDT) algorithm to further separate signal from background
    •Search for signal in the output of the BDT discriminant
  •“Mjj Analysis”
    •Apply tighter selection cuts and search for signal in the di-jet mass distribution (Mjj) of the H→bb candidates

•ATLAS employs the “Mjj Analysis” approach

•CMS performs search in 5 channels:
  •WH(ενbb), WH(μνbb), ZH(εεbb), ZH(μμbb) and ZH(ννbb)

•ATLAS performs search in 3 channels:
  •WH(ε/μνbb), ZH(εε/μμbb) and ZH(ννbb)
## Event Selection (CMS)

<table>
<thead>
<tr>
<th>channel</th>
<th>WH(lvbb)</th>
<th>ZH(llbb)</th>
<th>ZH(vvbb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>leptons</td>
<td>e or μ</td>
<td>e⁺e⁻ or μ⁺μ⁻</td>
<td>0</td>
</tr>
<tr>
<td>Invariant mass (GeV)</td>
<td>-</td>
<td>75&lt;M(l⁺l⁻)&lt;105</td>
<td>-</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ (GeV)</td>
<td>$&gt;35$ (only for electron)</td>
<td>-</td>
<td>$&gt;160$</td>
</tr>
<tr>
<td>$p_T$(JJ) (GeV)</td>
<td>$&gt;150$ [$&gt;160$]</td>
<td>$&gt;100$</td>
<td>$&gt;160$</td>
</tr>
<tr>
<td>$p_T$(V) (GeV)</td>
<td>$&gt;150$ [$&gt;160$]</td>
<td>$&gt;100$</td>
<td>-</td>
</tr>
<tr>
<td>$\Delta\phi$(V,H) (rad)</td>
<td>- [$&gt;2.95$]</td>
<td>- [$&gt;2.90$]</td>
<td>- [$&gt;2.90$]</td>
</tr>
<tr>
<td>B-tagging</td>
<td>medium,medium [tight,medium]</td>
<td>loose,loose [tight,medium]</td>
<td>medium,medium [tight,medium]</td>
</tr>
<tr>
<td>$\Delta\phi$(E$_T^{\text{miss}}$,Jet) (rad)</td>
<td>-</td>
<td>-</td>
<td>$&gt;0.5$ [$&gt;1.5$]</td>
</tr>
</tbody>
</table>

- “[ ]”: tighter thresholds use for “Mjj” analysis
- Events pass loose selection are used for “BDT” analysis
- Requiring significant boost in V and H (high $p_T$(V) and $p_T$(JJ)) help to reduce background from W/Z+Jets
# Event Selection (ATLAS)

<table>
<thead>
<tr>
<th>Channel</th>
<th>WH(lvbb)</th>
<th>ZH(llbb)</th>
<th>ZH(vvbb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton</td>
<td>e or µ</td>
<td>ee or µ⁺µ⁻</td>
<td>0</td>
</tr>
<tr>
<td>Transverse or Invariant mass (GeV)</td>
<td>M_T&gt;40</td>
<td>83&lt;M(l⁺l⁻)&lt;99</td>
<td>-</td>
</tr>
<tr>
<td>E_T^{miss} (GeV)</td>
<td>&gt;25</td>
<td>&lt;50</td>
<td>&gt;120</td>
</tr>
<tr>
<td>p_T^{miss} (GeV)</td>
<td>-</td>
<td>-</td>
<td>&gt;30</td>
</tr>
<tr>
<td>NJet</td>
<td>=2</td>
<td>≥2</td>
<td>=2</td>
</tr>
<tr>
<td>B-tagging</td>
<td>Exactly 2 b-tagged jets (@ Eff(b)=70%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

• Addition cuts for ZH(vvbb) channel to suppress QCD multi-jet and W/Z+Jets
  
  • $\Delta\phi(E_T^{miss}, p_T^{miss}) < \pi/2$ rad
  
  • $\Delta R$(Jet1, Jet2) < 1.7 - 2.0
  
  • $\Delta\phi$(V,H) > 2.7-2.9 rad
  
  • $\Delta\phi$(E_T^{miss}, Jet) > 1.8 rad
Event Selection (ATLAS)

• Search for H signal in 4 $p_T(V)$ bins and 3 $E_T^{\text{miss}}$ bins:

• WH(lvbb), ZH(llbb):
  - $p_T(V)$: <50 GeV, 50-100 GeV, 100-200 GeV, >200 GeV

• ZH(vvbb):
  - $E_T^{\text{miss}}$: 120-160 GeV, 160-200 GeV, >200 GeV
Background Estimation

- W+Jet, Z+Jet, Top, Diboson background contributions are estimated from simulation.
- Corrections to background normalization are obtained from control regions with negligible signal contamination.
Multi-jet Background Estimation

• QCD multi-jet background is estimated from data

• WH(lvbh) (ATLAS)
  • Obtain multi-jet template shape in events failing lepton identification
  • Determine normalization by fitting template to $E_T^{\text{miss}}$ distribution of signal region (but loosening the $E_T^{\text{miss}}$ and $M_T$ cuts)

• ZH(vvbh) (CMS, ATLAS)
  • Use control regions defined by two un-correlated variables to estimate multi-jet background in signal region
    • CMS: sum of b-tagging discriminating weights vs $\Delta \phi(E_T^{\text{miss}}, \text{Jet})$
    • ATLAS: $\Delta \phi(E_T^{\text{miss}}, p_T^{\text{miss}})$ vs $\Delta \phi(E_T^{\text{miss}}, \text{Jet})$
  • Both CMS and ATLAS estimated negligible QCD multi-jet background in signal region of ZH(vvbh), not included in the limit calculation.
• Cut on BDT distribution to define signal region to search for Higgs signal
BDT Discriminant Output and Di-Jet Mass (CMS)

M_{bb} distribution for “MJJ” analysis
$M_{bb}$ Distribution (ATLAS)

**WH → lνbb**, $0 < p_T(W) < 50$ GeV

**ZH → llbb**, $0 < p_T(Z) < 50$ GeV

**WH → lνbb**, $p_T(W) > 200$ GeV

**ZH → llbb**, $p_T(Z) > 200$ GeV
$M_{bb}$ Distribution (ATLAS)

ZH→ννbb, $120<E_T^{miss}<160$ GeV

ZH→ννbb, $E_T^{miss}>200$ GeV

• Better sensitivity at higher $p_T^W$, $p_T^Z$, $E_T^{miss}$
## Systematic Uncertainties

<table>
<thead>
<tr>
<th></th>
<th>CMS (%)</th>
<th>ATLAS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>4.5</td>
<td>3.9</td>
</tr>
<tr>
<td>Lepton Efficiency</td>
<td>3 (include trigger, per lepton)</td>
<td>1-6</td>
</tr>
<tr>
<td>Trigger (ZH(ννbb))</td>
<td>2</td>
<td>5 ((120&lt;E_T^{\text{miss}}&lt;160 \text{ GeV}))</td>
</tr>
<tr>
<td>Jet Energy Scale</td>
<td>2-3</td>
<td>~2-17</td>
</tr>
<tr>
<td>Jet Energy Resolution</td>
<td>3-6</td>
<td></td>
</tr>
<tr>
<td>(E_T^{\text{miss}})</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>B-Tagging</td>
<td>3-15</td>
<td>3-20</td>
</tr>
<tr>
<td>Signal cross section</td>
<td>6-14</td>
<td>5-13</td>
</tr>
<tr>
<td>Background estimation</td>
<td>10-35</td>
<td>3-24</td>
</tr>
</tbody>
</table>
Limits from Individual Channel (ATLAS)

**WH → ℓνbb**

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

\[ 95\% \text{ C.L. limit on } \sigma/\sigma_{SM} \]

**ZH → llbb**

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

\[ 95\% \text{ C.L. limit on } \sigma/\sigma_{SM} \]

**ZH → ννbb**

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

\[ 95\% \text{ C.L. limit on } \sigma/\sigma_{SM} \]
Combined Limits from All Channels (CMS, ATLAS)

Limits ($\sigma/\sigma_{SM}$)

<table>
<thead>
<tr>
<th></th>
<th>$m_H$ [GeV]</th>
<th>110</th>
<th>115</th>
<th>120</th>
<th>125</th>
<th>130</th>
<th>135</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS</td>
<td>BDT Exp.</td>
<td>2.7</td>
<td>3.1</td>
<td>3.6</td>
<td>4.3</td>
<td>5.3</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
<td>BDT Obs.</td>
<td>3.1</td>
<td>5.2</td>
<td>4.4</td>
<td>5.7</td>
<td>9.0</td>
<td>7.5</td>
</tr>
<tr>
<td>ATLAS</td>
<td>Exp.</td>
<td>2.6</td>
<td>3.0</td>
<td>3.2</td>
<td>3.8</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Obs.</td>
<td>2.7</td>
<td>3.9</td>
<td>3.1</td>
<td>3.5</td>
<td>5.3</td>
<td></td>
</tr>
</tbody>
</table>

- CMS “MJJ analysis” is ~10% less sensitive than the “BDT analysis”
Summary

• CMS and ATLAS have searched for SM Higgs boson in the associated VH production via $H \rightarrow bb$ decay channel, using 5 fb$^{-1}$ data sample

• No evidence of Higgs signal is observed

• Both experiments have similar search sensitivity for $110 < M_H < 130$ GeV
  • Expected limit :
    • CMS : 2.7 - 5.3 times the SM
    • ATLAS : 2.6 - 5.1 times the SM
  • Observed limit :
    • CMS : 3.1 - 9 times the SM
    • ATLAS : 2.7 - 5.3 times the SM

• Main systematic uncertainties are dominated by jet/$E_T^{\text{miss}}$ reconstruction, b-tagging and background estimation

• Started taking data in 2012 at $\sqrt{s}=8$TeV, face new challenges (e.g. higher pile-up)

• If the Higgs boson is indeed light, $H \rightarrow bb$ will be an important channel to estimate the Higgs parameters
Multi-jet Background Estimation

- QCD multi-jet background is estimated from data

**WH(lνbb) (ATLAS)**

- Obtain multi-jet template shape in events failing lepton identification
- Determine normalization by fitting template to $E_T^{\text{miss}}$ distribution of signal region (but loosening the $E_T^{\text{miss}}$ and $M_T$ cuts)

**ZH(ννbb) (CMS, ATLAS)**

- Use control regions defined by two un-correlated variables to estimate multi-jet background in signal region

- Both CMS and ATLAS estimated negligible QCD multi-jet background in signal region of ZH(ννbb), not included in the limit calculation.