Search for the SM Higgs Boson in VBF Production Mode (with ATLAS)

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On behalf of the ATLAS Collaboration

Seoul, 06.19.08
SM Higgs Production at the LHC

- **gluon fusion**: dominant process
- **vector boson fusion (VBF)**: factor ~10 below gluon fusion
  - **BUT**: clear signature in the detector
- **ttH**: important $100 \text{ GeV} < M_H < 120 \text{ GeV}$
- **W(Z)H**: not for discovery due to huge background
SM Higgs Final States

Dominant decays for $M_H < 135$ GeV:
- $H \rightarrow bb$  Dominant decay, difficult final state (large $t\bar{t}$ background)
- $H \rightarrow \tau\tau$  Attractive discovery channel

Dominant decays for $M_H > 135$ GeV:
- $H \rightarrow WW$ and $H \rightarrow ZZ$
- $H \rightarrow \gamma\gamma$  Also important ($110 \text{ GeV} < M_H < 140 \text{ GeV}$)

VBF Channels investigated in ATLAS:
- VBF $H \rightarrow \tau\tau$
- VBF $H \rightarrow WW$  (not discussed in this talk)
Optimize analysis assuming an integrated luminosity of $30\text{fb}^{-1}$ using:

- State-of-the-art Monte Carlo generators
  (MC@NLO, ALPGEN, HERWIG, PYTHIA, ...)

- Detailed GEANT4-based simulation of the ATLAS detector
  (including misalignments and distortions)

**The first five years**

<table>
<thead>
<tr>
<th>Year</th>
<th>$\int \mathcal{L} dt$</th>
<th>$\mathcal{L}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>$\sim 40$ pb$^{-1}$</td>
<td>$10^{31} - 10^{32}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>2009</td>
<td>2 - 3 fb$^{-1}$</td>
<td>$8 \times 10^{32}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>2010</td>
<td>$\sim 10$ fb$^{-1}$</td>
<td>$2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>2011</td>
<td>$\sim 30$ fb$^{-1}$</td>
<td>$2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>2012</td>
<td>$\sim 100$ fb$^{-1}$</td>
<td>$10^{34}$ cm$^{-2}$ s$^{-1}$</td>
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VBF Higgs $\rightarrow \tau \tau$ Signature

- Two tagging jets in forward region
- Higgs boson decay products in the central region
- No color flow between quark lines:
  - No central jets
- Missing transverse momentum: associated to $\nu$'s from $\tau$ decays
H → ττ → hh (42%):
• Triggers for hh channel are under investigation
• Reliable estimate of the QCD jets background can only be provided with data
• Will not be discussed in this talk

H → ττ → lh+3ν (46%) AND H → ττ → ll+4ν (12%)
• Easy to trigger (high p_T leptons)
• Backgrounds to VBF H → ττ: Z + jets, W + jets, tt, diboson, WW/ZZ/ZW
Leptonic $\tau$ Decays

Decay leptons used for trigger:
- use simple robust trigger signatures (initially):
  - isolated electron with $p_T > 22$ GeV
  - or isolated $\mu$ with $p_T > 20$ GeV

Lepton selection:
- thresholds for $e/\mu$ identification optimised for identification efficiency and fake rejection
- electron:
  - $p_T > 25$ GeV for trigger electron
  - $p_T > 15$ GeV for the other electrons
- muon:
  - $p_T > 20$ GeV for trigger electron
  - $p_T > 10$ GeV for other muons
- energy isolation within a cone around the $e/\mu$ ($\text{Isolation } E_T / p_T \leq 0.1$)
Hadronic $\tau$ Decays

Hadronic $\tau$ decay:

- $\Gamma \sim 50\%$ single prong (1 charged $h$)
- $\Gamma \sim 15\%$ three prongs (3 charged $h$)
- Decay products collimated into a narrow region

\[ \rightarrow \text{collimated deposition in EM Calorimeter} \]
\[ \rightarrow \text{use shower shape variables} \]
\[ \rightarrow \text{reconstruct } \pi^0 \text{ sub-clusters} \]
\[ \rightarrow \text{isolation cone} \]
\[ \rightarrow \text{log-likelihood-based discrimination from QCD jets} \]

- Log-likelihood and $p_T$ cuts optimized with respect to $s/(s+b)^{1/2}$
- $p_T > 30$ GeV
Tagging Jets

- $|\eta|<4.9$ (jets as close as $1^\circ$ to the beam pipe!)
- **Tagging jets**: 2 highest $p_T$ jets (nearly 100% of the time correctly matches the quark-initiated tagging jets from the hard process)
- **Reconstruction efficiency** for 2 tagging jets (VBF selection) $\sim 95$
- **Cuts**: $p_T>40$ GeV and second jet $p_T>20$ GeV
  $$\eta_j \times \eta_j \leq 0, \Delta\eta_{jj} > 4.4, M_{jj} > 700 \text{ GeV}$$

ATLAS Preliminary

SUSY08

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Central Jet Veto

- No extra jet with $p_T > 20$ GeV within $|\eta| < 3.2$

Pileup?
- Studies in progress to suppress these effects using:
  - vertexing information
  - timing information in the calorimeter
Mass Reconstruction

- Use collinear approximation:
  - assume that the decay products of the \( \tau \) are collinear with the \( \tau \) in the laboratory frame
  - Resolution limited by the missing transverse energy resolution
Data-driven Background Estimation

\[ Z \rightarrow \mu\mu + \text{jets} \text{ has identical jet activity as } Z \rightarrow \tau\tau + \text{jets} \]

→ Procedure:

⇒ select \( Z \rightarrow \mu\mu + \text{jets} \) events

⇒ replace the \( \mu \)'s by the \( \tau \)'s

⇒ carefully treat the decay of the \( \tau \)

→ Full event selection is then applied to the emulated \( Z \rightarrow \tau\tau + \text{jets} \) control sample

→ Expected uncertainty \( \sim 10\% \)

→ Normalization can be directly obtained from data

\[ \text{ATLAS} \]
Signal Significance

- Extracted from $M_{\tau\tau}$ spectrum
- Simultaneous fit the signal candidates and the background control samples
  - constrain the shape and normalization of the background from the data-driven analysis
  - uncertainty of the background shape is directly incorporated
- The fit is performed twice:
  1) letting the signal and background parameters to float
  2) constrain signal normalization to be zero, floating background parameters
- Define the profile likelihood ratio $\lambda$

$$
\lambda(\mu = 0) = \frac{L(data|\mu = 0, \hat{b}(\mu = 0), \hat{\nu}(\mu = 0))}{L(data|\hat{\mu}, \hat{b}, \hat{\nu})}
$$

$\mu$ is the signal rate in units of SM expectation, $b$ is the rate and $\nu$ is the shape parameters
$\hat{\nu}$ and $\hat{b}$ are best fit with $\mu$ fixed to 0; $\hat{\nu}$ and $\hat{b}$ are best fit with $\mu$ left floating
- Wilk’s theorem states that under certain conditions the distribution of the profile likelihood ratio has an asymptotic form

$$-2\log \lambda(\mu = 0) \sim \chi^2_1$$

- Thus, significance $= \sqrt{-2\log \lambda(\mu = 0)}$
Expected Signal Significance (30 fb$^{-1}$)

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$\sqrt{s} = 14$ TeV, 30 fb$^{-1}$

- [ ] ll-channel
- [ ] lh-channel
- [ ] combined

NB: no pileup included in the signal significance estimation
- Limited by the missing transverse energy resolution ~ 10 GeV
- 2000 pseudo-experiments per input mass point
### Systematic Errors

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative uncertainty</th>
<th>Effect on signal efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>luminosity</td>
<td>± 3%</td>
<td>± 3%</td>
</tr>
<tr>
<td>tau energy scale</td>
<td>± 5%</td>
<td>± 4.9%</td>
</tr>
<tr>
<td>tau ID efficiency</td>
<td>± 5%</td>
<td>± 5%</td>
</tr>
<tr>
<td>jet energy scale</td>
<td>± 7% (</td>
<td>(\eta)</td>
</tr>
<tr>
<td></td>
<td>± 15% (</td>
<td>(\eta)</td>
</tr>
<tr>
<td></td>
<td>± 5% (on Etmiss)</td>
<td></td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>total summed in quadrature</td>
<td>-</td>
<td>± 20%</td>
</tr>
</tbody>
</table>

Jet energy/Etmiss scale is the dominant source of systematics
What if there is no signal?

**Expected Exclusion Limits (10 fb$^{-1}$)**

**ATLAS Preliminary**

$\sqrt{s} = 14$ TeV, 10 fb$^{-1}$

NB: no pileup included in the signal significance estimation
Conclusions

**VBF $H \rightarrow \tau \tau$:**

- Important discovery channel for SM Higgs with $105 \text{ GeV} < M_H < 140 \text{ GeV}$
- Rich experimental signature

**For 30 fb$^{-1}$ expect:**

- $\sim 3 - 5 \sigma$ evidence for light SM Higgs
- Powerful exclusion limits

**Outlook:**

- Include and limit the effect of pileup
- Continue to improve/optimize the analysis
- Use information from real data as soon as available
Backup slides
• **Particle identification:**
  - muons ($|\eta|<2.5$): Efficiency ~ 97%  Jet Rejection ~ $10^4$
  - electrons ($|\eta|<2.5$): Efficiency ~ 80%  Jet Rejection ~ $10^3$
  - hadronic tau ($|\eta|<2.5$): Efficiency ~ 50%  Jet Rejection ~ $10^2$
  - b-Jet ID: Efficiency ~ 60% light-quark Jet Rejection ~ $10^2$

• **Missing transverse energy**
  - hermetic calorimeter $\sigma_{E_{\text{miss}}} \sim 0.55 \left(\sum E_{T}\right)^{0.5}$

• **Jets ($|\eta|<4.9$)**
  - reconstruction efficiency ~ 95%
Expected Combined 95% CL Exclusion

![Combined 95% CL Exclusion](image)

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Influence of pileup

- e/μ quite robust against pile-up  

- jet and Etmiss performance are affected by pileup

- hadronic τ: efficiency can be maintained with pile-up
  but jet rejection drops ~ 50%

- mass resolution is degradate from ~ 9.5 to ~ 11.5 GeV for $M_H = 120$ GeV

- central jet veto drops from ~88% to 75% at $10^{33}$cm$^{-2}$s$^{-1}$ and ~65% at $2\times10^{33}$cm$^{-2}$s$^{-1}$

- Reconstruction and analysis are being re-optimized with pileup. No signal significance is reported under this condition.

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Figure 6: Background rejection versus signal sensitivity for the central jet veto with and without pileup. Also shown is the case for $t\bar{t}$-only background.
Cutflow VBF $H \rightarrow \tau\tau \rightarrow lh$

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Table 5: Signal cross-sections for the $lh$-channel for various Higgs boson masses.

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>105</th>
<th>110</th>
<th>115</th>
<th>120</th>
<th>125</th>
<th>130</th>
<th>135</th>
<th>140</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section (fb)</td>
<td>394.7</td>
<td>372.0</td>
<td>341.8</td>
<td>309.1</td>
<td>266.8</td>
<td>225.4</td>
<td>180.1</td>
<td>135.8</td>
</tr>
<tr>
<td>Trigger</td>
<td>65.6(3)</td>
<td>65.1(2)</td>
<td>61.1(2)</td>
<td>57.2(1)</td>
<td>51.5(2)</td>
<td>44.7(1)</td>
<td>36.5(1)</td>
<td>28.3(1)</td>
</tr>
<tr>
<td>Trigger lepton</td>
<td>56.4(3)</td>
<td>56.2(2)</td>
<td>53.2(2)</td>
<td>49.5(1)</td>
<td>44.7(2)</td>
<td>38.9(1)</td>
<td>31.8(1)</td>
<td>24.7(1)</td>
</tr>
<tr>
<td>Di-lepton veto</td>
<td>50.0(3)</td>
<td>49.6(2)</td>
<td>46.7(2)</td>
<td>43.4(1)</td>
<td>38.9(2)</td>
<td>34.0(1)</td>
<td>27.6(1)</td>
<td>21.3(1)</td>
</tr>
<tr>
<td>Hadronic $\tau$</td>
<td>7.7(1)</td>
<td>8.1(1)</td>
<td>8.1(1)</td>
<td>8.02(7)</td>
<td>7.4(1)</td>
<td>6.68(8)</td>
<td>5.72(7)</td>
<td>4.53(9)</td>
</tr>
<tr>
<td>Missing $E_T \geq 30$ GeV</td>
<td>4.8(1)</td>
<td>5.1(1)</td>
<td>5.08(9)</td>
<td>4.96(5)</td>
<td>4.63(8)</td>
<td>4.16(7)</td>
<td>3.51(6)</td>
<td>2.82(8)</td>
</tr>
<tr>
<td>Collinear Approx.</td>
<td>3.19(9)</td>
<td>3.50(8)</td>
<td>3.51(8)</td>
<td>3.34(5)</td>
<td>3.14(7)</td>
<td>2.77(6)</td>
<td>2.37(5)</td>
<td>1.91(6)</td>
</tr>
<tr>
<td>Transverse mass</td>
<td>2.53(8)</td>
<td>2.70(7)</td>
<td>2.67(7)</td>
<td>2.46(4)</td>
<td>2.26(6)</td>
<td>1.98(5)</td>
<td>1.64(4)</td>
<td>1.29(5)</td>
</tr>
<tr>
<td>N jets $\geq 2$</td>
<td>2.12(7)</td>
<td>2.22(7)</td>
<td>2.21(6)</td>
<td>2.02(4)</td>
<td>1.80(5)</td>
<td>1.60(4)</td>
<td>1.32(4)</td>
<td>1.00(5)</td>
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<tr>
<td>Forward jet</td>
<td>1.61(7)</td>
<td>1.66(6)</td>
<td>1.73(5)</td>
<td>1.52(3)</td>
<td>1.41(5)</td>
<td>1.20(4)</td>
<td>1.03(3)</td>
<td>0.78(4)</td>
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<td>Jet kinematics</td>
<td>0.88(5)</td>
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<td>0.82(2)</td>
<td>0.73(3)</td>
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<td>0.42(3)</td>
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<tr>
<td>Central jet veto</td>
<td>0.77(5)</td>
<td>0.77(4)</td>
<td>0.81(4)</td>
<td>0.72(2)</td>
<td>0.63(3)</td>
<td>0.55(2)</td>
<td>0.50(2)</td>
<td>0.38(3)</td>
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<tr>
<td>Mass window</td>
<td>0.68(4)</td>
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<td>0.70(3)</td>
<td>0.61(2)</td>
<td>0.52(3)</td>
<td>0.44(2)</td>
<td>0.40(2)</td>
<td>0.30(3)</td>
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Table 4: Signal cross-section for the $ll$-channel for various Higgs boson masses.

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<td>2.88(4)</td>
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<td>Missing $E_T \geq 40$ GeV</td>
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<td>1.26(3)</td>
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<td>0.29(1)</td>
<td>0.23(1)</td>
</tr>
</tbody>
</table>
• Many and large background processes
  • (tt + jets, W + jets, Z + jets, WW + jets, ZZ + jets, ...)
  • Clean access to Higgs-W-W-coupling

Example of background processes

Example cut variable: $\Delta \phi_{ll}$
A very complex final state

- Dominant background: $tt + \text{jets}$ production

Experimental issues:

- $b$-tagging (efficiency $\sim \varepsilon^4$)
- Good understanding of background shape
SM Higgs production at LHC

Fig. 1: Total cross sections for Higgs production at the LHC. The gluon fusion result is NNLO QCD with soft gluon resummation effects included at NNLL and uses MRST2002 PDFs with renormalization/factorization scales equal to $m_h$. The vector boson fusion curve is shown at NLO QCD with CTEQ6M PDFs and renormalization/factorization scales equal to $m_h$. The $Vh$ results ($V = W, Z$) include NNLO QCD corrections and NLO EW corrections and use MRST2002 PDFs with the renormalization/factorization scales equal to the $m_h - M_V$ invariant mass. The $b\bar{b} \rightarrow h$ result is NNLO QCD, with MRST2002 PDFs, renormalization scale equal to $m_h$ and factorization scale equal to $m_h/4$. The results for $t\bar{t}h$ production are NLO QCD, use CTEQ6M PDFs and set the renormalization/factorization scale to $m_t + m_h/2$ [100].
VBF $H \rightarrow \tau\tau$