Illuminating the $H \rightarrow bb$ Discovery at ATLAS with the VBF + photon channel

Jacob M. Pasner
US LUA Meeting
Lightning Round Talk
26 October 2018
Overview

• What makes $H\to bb$ so interesting / difficult?

• The Vector Boson Fusion + Photon approach.

• $H\to bb$ observation and future for the channel!
H→bb: Why do we care?

• LHC Run 1 data was not sufficient to measure the coupling between the Higgs boson and bottom quarks, despite it being the largest branching ratio.
• Measurement of this coupling tests the Higgs properties.
• Higgs at high $p_T$ present a region where new physics is accessible via a number of effective field theories.

In the “early” days the bottom quark was sometimes referenced as “beauty” instead.

$\Gamma_{H\rightarrow bb} \sim 57.8\%$
H→bb Challenges

\( H \rightarrow \gamma \gamma \)
- Low statistics
- Photons have clean signal in detector
- First Higgs observation!
\( \Gamma_{H\rightarrow \gamma \gamma} \sim 0.227\% \)

\( H \rightarrow b\bar{b} \)
- High statistics
- Many backgrounds
- Hard to discover!!!
\( \Gamma_{H\rightarrow b\bar{b}} \sim 57.8\% \)

proton - (anti)proton cross sections

\[ \sigma_{\text{tot}} \]
\[ \sigma_b \]
\[ \sigma_{\text{tot}}(E_{T}^{\text{jet}} > \sqrt{s}/4) \]
\[ \sigma_{\text{tot}}(E_{T}^{\text{jet}} > \sqrt{s}/20) \]

H→γγ
• Low statistics
• Photons have clean signal in detector
• First Higgs observation!

H→bb
• High statistics
• Many backgrounds
• Hard to discover!!!

\( \Gamma_{H\rightarrow \gamma \gamma} \sim 0.227\% \)
\( \Gamma_{H\rightarrow b\bar{b}} \sim 57.8\% \)
VBF + photon example event

σ ~ 60 fb

Run: 302956
Event: 1228205769
2016–06–29 00:08:58 CEST
**m_{jj} Enhancement**
- $m_{jj} > 800$ GeV
- S-channel suppression
- Reduce Gluon initiated

**Central Photon Enhancement**
- Remove pure gluon initiated diagrams
- QCD cross section reduction

**INTERFERING DIAGRAMS!**

$\sigma_{signal} \over \sigma_{background} \left\{ \begin{array}{c} \sigma \left[ H \rightarrow b\bar{b} \gamma jj \right] \\ \sigma \left[ \bar{b}b \gamma jj \right] \\ \sigma \left[ H \rightarrow b\bar{b} jj \right] \\ \sigma \left[ \bar{b}b jj \right] \end{array} \right\} = 0.102(0)$

$\sigma_{signal} \over \sigma_{background} \left\{ \begin{array}{c} \sigma \left[ H \rightarrow b\bar{b} \gamma jj \right] \\ \sigma \left[ \bar{b}b \gamma jj \right] \\ \sigma \left[ H \rightarrow b\bar{b} jj \right] \\ \sigma \left[ \bar{b}b jj \right] \end{array} \right\} = 0.00309(5)$

**Note:** Calculation Only
How can we additionally improve the resolution of the Higgs?

• **μ-in-jet** correction: add nearby muon to b-jet 4 vector
• **PtReco**: MVA trained to correct losses from neutrino
• These corrections take into account errors from semi-leptonic b decays and energy resolution effects
H→bb Combination

- VBF+photon was stat-limited.
- Looking forward to more data!
- “By Eye” excess in VH channel!!!
- Combination → \(5.4\sigma\) observation.

Stat-limited! Want more data!
**What’s next? Boosted H→bb!**

- Initial State Radiation boost allows probing of **BSM physics** in ggF initiated top loop
- Look for **finite top mass corrections** to SM
- Benefits from past work with b-jet energy corrections
- QCD and ttbar bkg challenge

![Graph showing production cross-section for H→bb](image)

- **pp → H+j @ 13 TeV**
- **LO, NLO, NLO**
- **LOHEFT, NLOHEFT**
- **NLO**
- **NLO**

**incorporate finite top mass corrections**

**Could be a squark!**

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**MY THESIS IS BASED ON THIS**
**Results:** The H→bb channel has profited from multiple innovative analyses resulting in a 5.4σ observation.

**Innovation:** Continue to explore this Higgs decay mode and push for better resolution at higher energies
- Inner Tracker upgrade - larger η & better res.
- High Granularity Timing Detector upgrade - better res.
- Jet substructure Multi-Variate Analysis Techniques

**Future Goals:** Constrain Higgs couplings and collaborate with theorists to explore the possibility for BSM physics.
Backup
Why VBF?
• Better Triggering
• Unique Final State
• Innovative bkg reduction

\[ \sigma(pp \rightarrow H+X) \ [\text{pb}] \]

- \[ pp \rightarrow H \ (N3LO \ QCD + NLO \ EW) \]
- \[ pp \rightarrow qqH \ (NNLO \ QCD + NLO \ EW) \]
- \[ pp \rightarrow WH \ (NNLO \ QCD + NLO \ EW) \]
- \[ pp \rightarrow ZH \ (NNLO \ QCD + NLO \ EW) \]
- \[ pp \rightarrow bbH \ (NNLO \ QCD \ in \ 5FS, \ NLO \ QCD \ in \ 4FS) \]
- \[ pp \rightarrow tH \ (NLO \ QCD + NLO \ EW) \]
- \[ pp \rightarrow tH \ (NLO \ QCD, \ t-ch + s-ch) \]

\[ M(H) = 125 \ \text{GeV} \]

- \[ \sqrt{s} \ [\text{TeV}] \]
- \[ \sigma \ [\text{pb}] \]

- Better Triggering
- Unique Final State
- Innovative bkg reduction

\[ \sim 50 \ \text{pb} \]
\[ \sim 3 \ \text{pb} \]
\[ \sim 60 \ \text{fb} \]

26 October 2018
## Selection Decisions

<table>
<thead>
<tr>
<th>Selection</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Derivation</td>
<td>HIGG5D3</td>
</tr>
<tr>
<td>Trigger</td>
<td>HLT_g25_medium_L1EM22VHI_4j35_0eta490_invm700</td>
</tr>
</tbody>
</table>
| Event quality (data only) | pass GRL  
|              | no Tile, LAr, SCT and Core error                                           |
| Primary Vertex | At least one primary vertex                                                |
| Photon      | \( \geq 1 \) photon \( \text{ET} > 30 \text{ GeV} \)                     |
| Jets        | \( \geq 4 \) jets (\( p_T > 40 \) GeV, \( |\eta| < 4.5 \))  
|              | \( \geq 2 \) jets in \( |\eta| < 2.5 \) (central jets)                |
| Higgs signal jet (BB) | two central jets with highest MV2c10 weights                             |
| VBF jets (JJ) | pair of non-signal jets with highest invariant mass                     |
| b-jets      | 2 \( b \)-tagged jets \( \) (tagged on the BB pair with MV2c10 at 77\% fixed cut working point) |
| \( m_{JJ} \) | \( m_{JJ} > 800 \) GeV                                                   |
| \( p_T(BB) \) | \( p_T(BB) > 80 \) GeV                                                   |
Photon Enhancement

- WW over ZZ
- Require Central Photon
- No fully gluon channel

\[ \sqrt{s} = 14 TeV \]

\[
\begin{array}{|c|c|c|}
\hline
 & p_T^{\gamma,\text{cut}} & m_H = 120 \text{ GeV} \\
\hline
\sigma[H(\rightarrow bb)\gamma jj] & 20 \text{ GeV} & 3.59(7) \text{ fb} \\
 & 30 \text{ GeV} & 2.62(3) \text{ fb} \\
\hline
\sigma[bb\gamma jj] & 20 \text{ GeV} & 33.5(1) \text{ fb} \\
 & 30 \text{ GeV} & 25.7(1) \text{ fb} \\
\hline
\sigma[H(\rightarrow bb)jj] & 320(1) \text{ fb} \\
\sigma[bbjj] & 103.4(2) \text{ pb} \\
\hline
\end{array}
\]

\[
\frac{\sigma[H(\rightarrow bb)\gamma jj]}{\sigma[bb\gamma jj]} = 0.102(0)
\]

\[
\frac{\sigma[H(\rightarrow bb)jj]}{\sigma[bbjj]} = 0.00309(5)
\]
**mJJ Enhancement**
- Background suppression
- S-channel
- Gluon initiated

**Suppression Tally**

*Note: Parton level with kinematic cuts*

<table>
<thead>
<tr>
<th>sub-processes</th>
<th>$\sigma_i$ (fb)</th>
<th>$\sigma_i/\sigma$</th>
<th>$\sigma_i^\gamma$ (fb)</th>
<th>$\sigma_i^\gamma/\sigma^\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gq \to b\bar{b} q q' (\gamma)$</td>
<td>57.2(1)</td>
<td>55.3 %</td>
<td>17.3(1)</td>
<td>51.6 %</td>
</tr>
<tr>
<td>$gq \to b\bar{b} g g (\gamma)$</td>
<td>25.2(1)</td>
<td>24.4 %</td>
<td>3.93(3)</td>
<td>11.7 %</td>
</tr>
<tr>
<td>$qq' \to b\bar{b} q q' (\gamma)$</td>
<td>7.76(3)</td>
<td>7.5 %</td>
<td>4.04(2)</td>
<td>12.1 %</td>
</tr>
<tr>
<td>$qg \to b\bar{b} gq (\gamma)$</td>
<td>6.52(2)</td>
<td>6.3 %</td>
<td>4.49(3)</td>
<td>13.4 %</td>
</tr>
<tr>
<td>$qq' \to b\bar{b} q q' (\gamma)$</td>
<td>4.60(2)</td>
<td>4.4 %</td>
<td>2.28(2)</td>
<td>6.8 %</td>
</tr>
<tr>
<td>$gq \to b\bar{b} q q' (\gamma)$</td>
<td>2.13(2)</td>
<td>2.1 %</td>
<td>1.21(2)</td>
<td>3.6 %</td>
</tr>
<tr>
<td>$qg \to b\bar{b} q q' (\gamma)$</td>
<td>0.0332(7)</td>
<td>0.03 %</td>
<td>0.124(3)</td>
<td>0.37 %</td>
</tr>
<tr>
<td>$qq' \to b\bar{b} q q' (\gamma)$</td>
<td>0.0137(2)</td>
<td>0.01 %</td>
<td>0.094(2)</td>
<td>0.28 %</td>
</tr>
<tr>
<td>$q g \to b\bar{b} g q (\gamma)$</td>
<td>0.000080(3)</td>
<td>0.0007 %</td>
<td>0.00080(8)</td>
<td>0.002 %</td>
</tr>
</tbody>
</table>

*Note: Parton level with kinematic cuts*

<table>
<thead>
<tr>
<th>sub-processes</th>
<th>$\sigma_i^{\gamma \text{[no b rad]}}$ (fb)</th>
<th>$\sigma_i^{\gamma \text{[no b rad]}}/\sigma^{\gamma \text{[no b rad]}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gq \to b\bar{b} g q (\gamma)$</td>
<td>8.19(6)</td>
<td>47.8 %</td>
</tr>
<tr>
<td>$gq \to b\bar{b} g q (\gamma)$</td>
<td>0</td>
<td>0 %</td>
</tr>
<tr>
<td>$q q' \to b\bar{b} q q' (\gamma)$</td>
<td>2.80(2)</td>
<td>16.4 %</td>
</tr>
<tr>
<td>$q q' \to b\bar{b} q q' (\gamma)$</td>
<td>3.49(3)</td>
<td>20.4 %</td>
</tr>
<tr>
<td>$q q' \to b\bar{b} q q' (\gamma)$</td>
<td>1.57(2)</td>
<td>9.2 %</td>
</tr>
<tr>
<td>$q q' \to b\bar{b} q q' (\gamma)$</td>
<td>0.87(1)</td>
<td>5.1 %</td>
</tr>
<tr>
<td>$g g \to b\bar{b} q q (\gamma)$</td>
<td>0.10(2)</td>
<td>0.6 %</td>
</tr>
<tr>
<td>$q q' \to b\bar{b} q q' (\gamma)$</td>
<td>0.096(2)</td>
<td>0.6 %</td>
</tr>
<tr>
<td>$q q' \to b\bar{b} q q' (\gamma)$</td>
<td>0.009(1)</td>
<td>0.005 %</td>
</tr>
</tbody>
</table>