Higgs Decay to Light Jets

Zhuoni Qian (IBS)
July 5th, 2018

Photo from https://www.internationaltraveller.com

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Current Status

ATLAS+CMS combined analysis 7&8 TeV (2015):

Production: ggF, VBF, WH, ZH, ttH

Decay: ZZ, γγ, WW, ττ, μμ, Zγ, bb, gg, cc, ss, uu, dd, ee
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14 TeV LHC, HL-LHC(300, 3000 fb⁻¹):

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7&8&13 TeV (2017):

H>bb measurement keeps improving with VH, VBF, ttH, inclusive boosted Higgs inclusive channels and accumulated data.

Data used  Significance expected  Significance observed  Signal strength observed

Run 1  2.5  2.1  0.89±0.44
Run 2  2.8  3.3  1.19±0.40
Combined  3.8  3.8  1.06±0.31

• arXiv: 1709.15543, 1709.07497, 1708.03299
• Nuclear and Particle Physics Proceedings 273–275 (2016) 733–739
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### CMS (+ 35.9 fb-1 @ 13 TeV)

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</tr>
<tr>
<td>Combined</td>
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<td>3.8</td>
<td>1.06+0.31−0.29</td>
</tr>
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of 1.5 (0.7) standard deviations. The measured cross section times branching fraction for production via gluon fusion of H → b̅b with reconstructed $p_T > 450$ GeV and

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Higgs Decay to Light Jets
Signal Process
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Signal Process
Higgs Decay to Light Jets
Signal Process

(a) 

(b) 

(c) 

\( p \) 

\( V^* (W, Z) \) 

\( V \) 

\( l/\nu \) 

\( g \) 

\( g \)
Higgs Decay to Light Jets
Signal Process

3 Channels:

- 2 leptons, 2 jets
- 1 lepton + MET, 2 jets
- MET, 2 jets
the final state radiation (FSR) or back-to-back near jet separation of three kinematic discriminants for the where

At high according to the zero, one, or two charged leptons from the vector boson decays. In addition, In further studying the signal characteristics in Eqs. (2.3)

Table 1. Cross sections in units of fb for signal and dominant background processes, with the parton-parton → jet, jet hadronization, and the decay product hadronization corrections.

<table>
<thead>
<tr>
<th>Process</th>
<th>σ (fb)</th>
<th>cuts Eq. (2.3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q\bar{q} \rightarrow Zh \rightarrow ℓ^+ℓ^- gg$</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>$gg \rightarrow Zh \rightarrow ℓ^+ℓ^- gg$</td>
<td>0.71</td>
<td></td>
</tr>
<tr>
<td>$q\bar{q} \rightarrow Zjj \rightarrow ℓ^+ℓ^- jj$</td>
<td>$2.5 \times 10^5$</td>
<td></td>
</tr>
<tr>
<td>$q\bar{q} \rightarrow Wh \rightarrow ℓν gg$</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>$q\bar{q} \rightarrow Wjj \rightarrow ℓν jj$</td>
<td>$2.5 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td>$pp \rightarrow t\bar{t} \rightarrow ℓνjjb\bar{b}$</td>
<td>$1.1 \times 10^5$</td>
<td></td>
</tr>
<tr>
<td>$q\bar{q} \rightarrow Zh \rightarrow νν gg$</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>$gg \rightarrow Zh \rightarrow νν gg$</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>$q\bar{q} \rightarrow Zjj \rightarrow νν jj$</td>
<td>$7.4 \times 10^5$</td>
<td></td>
</tr>
</tbody>
</table>

**cut0**: $p_T(j) > 20$GeV, $|η_j| < 3$, $R_{jj} > 0.4$ (2.3)
Higgs Decay to Light Jets
Kinematics

Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)
Higgs Decay to Light Jets

Kinematics

\[ R_{jj} \approx \frac{1}{\sqrt{z(1 - z)}} \frac{m_h}{p_T(h)} \]

- \( p_{T(j,\ell)} > 30 \text{GeV} \), \( |\eta_{j,\ell}| < 2.5 \)
- \( p_{T(\ell,\ell,\nu,\nu)} > 200 \text{GeV} \), \( R_{jj} < 1.4 \)
Higgs Decay to Light Jets
Mass Reconstruction

Wh[bb] over pT (200-1000) GeV
Higgs Decay to Light Jets
Mass Reconstruction


Wh[bb] over pT (200-1000) GeV

Resolved+: Two Leading jets & additional jets within R<1.4
Higgs Decay to Light Jets
Mass Reconstruction

Wh[bb] over pT (200-1000) GeV

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Higgs Decay to Light Jets
Mass Reconstruction

Two Leading jets & additional jets within $R<1.4$

Figure 2. Kinematical distributions of the signal process $pp \rightarrow Zh, h \rightarrow gg$ (solid curves, scaled up by a factor of 5000) and the leading background $pp \rightarrow Zjj$ (dashed curves) for (a) $p_T(Z)$, (b) $R_{jj}$, (c) $m_{jj}$, and (d) event scatter plot in $R_{jj} p_T(Z)$ plane, with the (red) dense band with crosses as the signal events and (blue) dots as the background. Generator level cuts of Eqs. (2.3) and (2.4) have been applied. The (red) dense band with crosses presents the signal events and the (blue) dots show the background events. We see the strong correlation between the boosted $p_T(Z)$ and collimated jets with smaller $R_{jj}$.

To suppress the huge QCD di-jet backgrounds, we must optimize the reconstruction of the Higgs mass. There are two common methods to reconstruct hadronic decays of Higgs boson depending on the kinematical configurations. One is the sub-structure (fat-jet) approach: an early example for Higgs search in $b\bar{b}$ channel was introduced in Ref. [14]. Because of the highly boosted nature of the Higgs boson, a fat-jet identified as the hadronic decay products of the Higgs boson is first selected. Various jet substructure observables and techniques such as mass-drop and filtering [14], pruning [25], trimming [26], N-subjettiness [27] etc. -6-
Higgs Decay to Light Jets
Mass Reconstruction

Two Leading jets & additional jets within R<1.4

Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)
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$95 < m_H < 145$ (GeV)

Linda M. Carpenter, Tao Han, Khalida Hendricks, ZQ, Ning Zhou (2016)
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Mass Reconstruction

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Higgs Decay to Light Jets
Mass Reconstruction

Robustness with pileup
Higgs Decay to Light Jets
Mass Reconstruction

Robustness with pileup

Figure 3. Invariant mass distributions $m_{jj}$ of the signal process $pp \rightarrow Zh,h \rightarrow gg,Z$ (solid curves, scaled up by a factor of 5000) and the leading background $pp \rightarrow Zjj$ (dashed curves) for (a) with 2 jets only, (b) with 2 leading jets to reconstruct $m_{jj}$, (c) with 2 leading jets plus other jets together to reconstruct $m_{\text{jets}}$. All selection cuts as in Sec. 3.1 except for $m_{h}$ cut are applied.

Figure 4. Invariant mass distributions constructed from (a) two-jet events and (b) three-jet events with different pile-up values $\mu_{i}=0, 15, 50, 140$, respectively.

In the following, we describe the searches with the detailed signal and background analyses, for the channels with two, one and zero charged leptons, respectively. For simplicity, we use 2 jets reconstruction of the mass peak from now on.
Higgs Decay to Light Jets
Mass Reconstruction

Robustness with pileup

Figure 3. Invariant mass distributions \( m_{jj} \) of the signal process \( pp \rightarrow Zh,h \rightarrow gg,Z \) (solid curves, scaled up by a factor of 5000) and the leading background \( pp \rightarrow Zjj \) (dashed curves) for (a) with 2 jets only, (b) with 2 leading jets to reconstruct \( m_{jj} \), (c) with 2 leading jets plus other jets together to reconstruct \( m_{jets} \). All selection cuts as in Sec. 3.1 except for \( m_h \) cut are applied.

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3.1 \( \ell^+ \ell^- + jj \) channel

For the two-lepton channel, we simulate the signal processes as in Eq. (2.2) with \( Zh \rightarrow gg \). We require exactly one pair of charged leptons \( \ell^\pm = e^\pm \) or \( \mu^\pm \), same flavor, opposite charge, along with at least two energetic jets. The dominant background is by far from \( Z+jj \). The two leading \( p_T \) jets are required to be close by having a separation less than \( R_{max} = 1 \).
### Results

The interpretation of these results to bound on individual Higgs decay channels needs further analysis.

The table below shows the signal significance achieved from each channel and combined results for both statistics and systematics.

\[
N = \sigma \times 3000 fb^{-1}
\]

<table>
<thead>
<tr>
<th>(\sigma) (fb)</th>
<th>(\ell^+\ell^- + jj)</th>
<th>(\ell^\pm + \not{E}_T + jj)</th>
<th>(\not{E}_T + jj)</th>
<th>combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Vh) signal</td>
<td>(7.0 \times 10^{-2})</td>
<td>(4.1 \times 10^{-1})</td>
<td>(3.6 \times 10^{-1})</td>
<td></td>
</tr>
<tr>
<td>(Vjj) background</td>
<td>(2.4 \times 10^2)</td>
<td>(2.5 \times 10^3)</td>
<td>(1.6 \times 10^3)</td>
<td></td>
</tr>
<tr>
<td>(S)</td>
<td>0.25</td>
<td>0.61</td>
<td>0.49</td>
<td>0.82</td>
</tr>
<tr>
<td>(S_{sys})</td>
<td>0.09</td>
<td>0.17</td>
<td>0.17</td>
<td>0.26</td>
</tr>
</tbody>
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\[
S = \frac{N_{\text{sig}}}{\sqrt{N_{\text{bkg}}}} \quad S_{\text{sys}} = \frac{N_{\text{sig}}}{\epsilon_B \times N_{\text{bkg}}}
\]
Higgs Decay to Light Jets

Results

\[ N = \sigma \times 3000\text{fb}^{-1} \]

<table>
<thead>
<tr>
<th>( \sigma ) (fb)</th>
<th>( \ell^+\ell^- + jj )</th>
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S = \frac{N_{\text{sig}}}{\sqrt{N_{\text{bkg}}}} \quad S_{\text{sys}} = \frac{N_{\text{sig}}}{\epsilon_B \times N_{\text{bkg}}}
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Higgs Decay to Gluon Pair Improvements

Quark/Gluon Tagging

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<th>Percentage</th>
<th>qq</th>
<th>qg</th>
<th>gg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal $Zh[gg]$</td>
<td>0</td>
<td>0</td>
<td>100%</td>
</tr>
<tr>
<td>Background $Zjj$</td>
<td>9%</td>
<td>77%</td>
<td>14%</td>
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Asymmetry between the two leading jets defined as $A_{jj} = \frac{|p_T(j_1) - p_T(j_2)|}{p_T(j_1) + p_T(j_2)}$.

“Quark Jet Veto”
Higgs Decay to Gluon Pair Improvements

Quark/Gluon Tagging

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Table 1: Quark/Gluon Tagging

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<th>q-tagger</th>
<th>$q$</th>
<th>$g$</th>
<th>$S$</th>
<th>$B$</th>
<th>$S/\sqrt{B} - 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>20%</td>
<td>5%</td>
<td>90%</td>
<td>77%</td>
<td>+3%</td>
</tr>
<tr>
<td>B</td>
<td>40%</td>
<td>10%</td>
<td>81%</td>
<td>56%</td>
<td>+8%</td>
</tr>
<tr>
<td>C</td>
<td>50%</td>
<td>15%</td>
<td>72%</td>
<td>45%</td>
<td>+8%</td>
</tr>
<tr>
<td>D</td>
<td>60%</td>
<td>25%</td>
<td>56%</td>
<td>32%</td>
<td>-1%</td>
</tr>
<tr>
<td>E</td>
<td>80%</td>
<td>50%</td>
<td>25%</td>
<td>12%</td>
<td>-26%</td>
</tr>
</tbody>
</table>
Thanks!
• Alone in pp>VH, H>jj channel, we expect ~1 sigma significance with 3000 fb-1 data (HL-LHC)

Thanks!