Searching for resonances in the Higgs cascade decay

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Work in progress with
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Plan

- Brief review of 2HDM status
- Higgs cascade decay
- Cut-based analysis
- MVA using BDT method
- Summary
Status of 2HDM

- LHC Higgs signal strength $\rightarrow$ Alignment limit
- No non-SM scalar is discovered $\rightarrow$ Heavy mass
- Electroweak precision test $\rightarrow$ $M_{H^0}, M_A, M_{H^\pm}$
  Two are degenerated
- Flavor physics constraint $\rightarrow$ $M_{H^\pm} > 480$ GeV
Heavy mass regime

• In alignment limit, $\cos(\beta - \alpha) \approx 0$
  (2HDM Type-II for example)

\[
H^\pm W^\mp h \propto \frac{g}{2} \cos(\beta - \alpha) \quad H^\pm W^\mp H \propto \frac{g}{2} \sin(\beta - \alpha) \quad H^\pm W^\mp A \propto \frac{g}{2}
\]

\[
H^- t \bar{b} \propto \frac{g}{2\sqrt{2}m_W} V_{tb} [m_t \cot \beta P_L + m_b \tan \beta P_R]
\]

$H^0 \rightarrow H^\pm W^{\mp}$ & $H^+ \rightarrow t \bar{b}$ channel is dominant!
Higgs cascade decay

CMS: 1212.3837, ATLAS: 1312.1956

H_{0} or A_{0}

\Phi \approx \alpha \cos(\beta - \alpha) \approx 0

Our work

J. Evans, B. Kilminster, M. A. Luty, D. Whiteson, 1201.3691
R. Dermisek, J. P. Hall, E. Lunghi, S. Shin, 1311.7208
Higgs cascade decay

$pp \rightarrow \Phi \rightarrow H^{\pm}W^{\mp} \rightarrow tbW \rightarrow bWbW \rightarrow bbjjlv$

- Semileptonic channel
  - Can reconstruct neutrino momentum
  - Can reconstruct full event
Higgs cascade decay

• Combinatorial issue
  ➢ Can solve by finding correct top (b W) candidate

\[
\chi^2_{top} = \left( \frac{m_{jj}-m_W}{\sigma_W} \right)^2 + \min \left( \left( \frac{m_{bjj}-m_{th}}{\sigma_{th}} \right)^2, \left( \frac{m_{bll}-m_{t\ell}}{\sigma_{t\ell}} \right)^2 \right)
\]

\[
p p \rightarrow \Phi \rightarrow H^\pm W^{\mp} \rightarrow tbW \rightarrow bWbwW \rightarrow bbjjlv
\]
Useful kinematic variables

• $\chi^2_{t\bar{t}}$

$$\chi^2_{t\bar{t}} = \left( \frac{m_{jj} - m_W}{\sigma_W} \right)^2 + \left( \frac{m_{jj} - m_{t_h} - m_W}{\sigma_{t_h-W}} \right)^2 + \left( \frac{m_{j\ell\nu} - m_{t\ell}}{\sigma_{t\ell}} \right)^2 + \left( \frac{(p_{T,jj} - p_{T,j\ell\nu}) - (p_{T,t_h} - p_{T,t_{\ell}})}{\sigma_{\text{diff}_{PT}}} \right)^2$$

• Mass difference of top candidates

$$\Delta_{t\bar{t}} = \frac{|M_{bjj} - M_{b\ell\nu}|}{M_{bjj} + M_{b\ell\nu}}$$

$t\bar{t}$ background

$M_{H^0} = 800$ GeV, $M_{H^\pm} = 600$ GeV
Useful kinematic variables

- Invariant masses

\[ M_{H^0} = 800 \text{ GeV}, \quad M_{H^\pm} = 600 \text{ GeV} \]
• $M_{H^0} - M_{H^\pm}$ is large, $W$ have larger $p_T$
• $M_{H^0} - M_{H^\pm}$ is small, but $M_{H^\pm}$ is larger than $M_{top}$, $b$ have larger $p_T$. 
Prompt b & W pT

$p_T^W$ vs $p_T^b$ (tt)

$p_T^W$ vs $p_T^b$ (800, 300)
Prompt b & W pT

$p_W^T$ vs $p_b^T$ (tt)

$p_W^T$ vs $p_b^T$ (800, 600)
Prompt b & W pT

$p_T^W$ vs $p_T^b$ (tt)

$p_T^W$ vs $p_T^b$ (800, 700)
Cut-based analysis results

- LHC 13 TeV, $\mathcal{L} = 100 \text{ fb}^{-1}$

![Graph](image)
Cut-based analysis results

- LHC 13 TeV, $\mathcal{L} = 100 \text{ fb}^{-1}$
Multi-variable analysis with BDT

- MVA is performed by boosted decision tree method with TMVA toolkit

- Input variables
  - $\chi_{t\bar{t}}^2$, $\Delta t\bar{t}$
  - Invariant masses
    - $M_{H^0}, M_{H^\pm}, M_{b\bar{b}}, \ldots$
  - Angular variables
    - $\Delta R_{ij}, \Delta \phi_{ij}, \ldots$
  - Transverse momentums
    - $p_T^W, p_T^b, p_T^l, \ldots$

$t\bar{t}$ background

$M_{H^0} = 800$ GeV, $M_{H^\pm} = 600$ GeV
Multi-variable analysis with BDT

- MVA is performed by boosted decision tree method with TMVA toolkit

- Input variables
  - $\chi^2_{t\bar{t}}$, $\Delta_{t\bar{t}}$
  - Invariant masses
    - $M_{H^0}, M_{H^\pm}, M_{b\bar{b}}$, ....
  - Angular variables
    - $\Delta R_{ij}, \Delta \phi_{ij}$, ....
  - Transverse momentums
    - $p_T^W, p_T^b, p_T^l$, ....

$M_{H^0} = 800$ GeV, $M_{H^\pm} = 600$ GeV

Efficiency (background)

Significance
BDT analysis results

- LHC 13 TeV, $\mathcal{L} = 100 \text{ fb}^{-1}$
BDT analysis results

- LHC 13 TeV, $\mathcal{L} = 100 \text{ fb}^{-1}$

b & $W$ $p_T$ cut with $\tan\beta = 1$

BDT best cut with $\tan\beta = 1$
Summary

• Heavy neutral higgs in alignment limit can dominantly decay to $H^0 \rightarrow H^\pm W^\mp \rightarrow tbW$

• We focus on the semileptonic decay channel and find $p_T$ of prompt $W$ & $b$ is powerful cut to discriminate signal from the $t\bar{t}$ background.

• BDT multivariable analysis largely improve the $S/\sqrt{B}$ (~1.5 times) and $S/B$ (~5 times).
Back up
Event generation: MG5aMC@NLO + Pythia8 + Delphes.

- **Background**: ttbar for simplicity

- **Electron**: $p_T > 25$ GeV and $|\eta| < 2.5$
- **Muon**: $p_T > 25$ GeV and $|\eta| < 2.5$
- **Jet**: $p_T > 25$ GeV and $|\eta| < 2.5$
- **MET**:
  - $E_T^{\text{miss}} > 35$ GeV
  - $E_T^{\text{miss}} + M_T > 60$ GeV
  - Neutrino: reconstructed by $(p_l + p_\nu)^2 = m_W^2$.
- **Hadronic W**: reconstructed by 2 jet with $M_{jj} = M_W$.
- **Top, Charged Higgs, Heavy Higgs**: using $\chi^2_{top}$ criteria.
Cross sections

\[ \sigma( pp \rightarrow H^\pm \rightarrow tbW^\mp ) \text{ [pb]} \]

\[ m_{H^\pm} [\text{GeV}] \]

\[ \sigma \text{ comparison with } pp \rightarrow tbH^\pm \rightarrow tbtb \text{ (solid line)} \]

- \( \tan \beta = 0.3 \)
- \( \tan \beta = 1 \)
- \( \tan \beta = 2 \)
- \( \tan \beta = 7 \)
- \( \tan \beta = 50 \)
BDT analysis results

- LHC 13 TeV, $\mathcal{L} = 100 \text{ fb}^{-1}$

![Plot 1: b & W $p_T$ cut with tan$\beta$ = 50](image1)

![Plot 2: BDT best cut with tan$\beta$ = 50](image2)
BDT analysis results

- LHC 13 TeV, $\mathcal{L} = 100 \text{ fb}^{-1}$
Status of 2HDM

A. Arbey, F. Mahmoudi, O. Stal, T. Stefaniak 1706.07414

THDM Type I - Higgs searches

THDM Type II - Higgs searches

THDM Type III - Higgs searches

THDM Type IV - Higgs searches

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