Search for a generic heavy Higgs at the LHC

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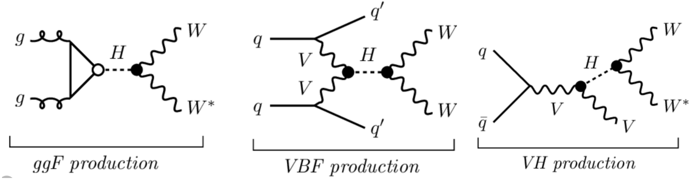
Introduction

Many BSM predict heavy Higgs particles decaying to heavy quarks or bosons

- 2HDM, MSSM, and so on...

ATLAS and CMS have some researches on heavy Higgs

- gluon-gluon fusion (ggF)
- vector-boson fusion (VBF)
- associated production with vector boson (VH)

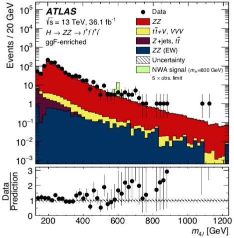


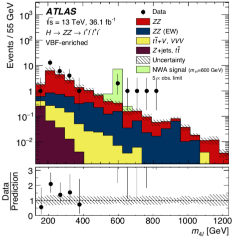
Introduction

- $H \to ZZ \to 4\ell$ research in ATLAS

CERN-EP-2017-251

ggF



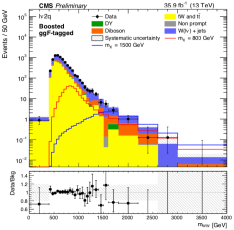


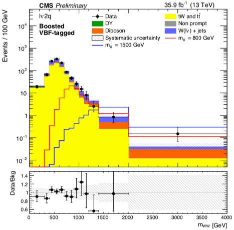
VBF

- $X \to WW$ research in CMS

CMS-PAS-HIG-17-033

ggF





VBF

Dim-4 and Dim-6 Interaction

- Multiple Higgs field: contains one SM-like lightest Higgs(h) and one next to lightest generic neutral heavy Higgs(H)
- A generic heavy Higgs: both dim-4 and effective dim-6 interactions with SM particles
- dim-4 operator Lagrangian:

$$\mathcal{L}^{(4)}_{hWW} = \rho_h g m_W h W^\mu W_\mu$$

$$\mathcal{L}^{(4)}_{hZZ} = \rho_h \frac{g m_W}{2cos^2\theta_W} h Z^\mu Z_\mu$$

$$\mathcal{L}^{(4)}_{HWW} = \rho_H g m_W H W^\mu W_\mu$$

$$\mathcal{L}^{(4)}_{HZZ} = \rho_H \frac{g m_W}{2cos^2\theta_W} H Z^\mu Z_\mu$$

$$\rho_h = \frac{g_h^2 \nu_h}{g^2 \nu}, \quad \rho_H = \frac{g_H^2 \nu_H}{g^2 \nu}$$

ν_h and ν_H: VEVs , g_h and g_H: gauge couplings
ν and g: SM VEV and coupling , θ_W: weak mixing angle

Dim-4 and Dim-6 Interaction

- dim-6 operator effective Lagrangian:

$$\mathcal{L}^{(6)}_{HVV} = \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n, \quad \Lambda = 5TeV$$

$$\begin{aligned}\mathcal{L}^{(6)}_{HWW} &= \rho_H g m_W \frac{f_W}{2\Lambda^2}(W^+_{\mu\nu}W^{-\mu}\partial^\nu H + h.c.) \\ &- \rho_H g m_W \frac{f_{WW}}{\Lambda^2}W^+_{\mu\nu}W^{-\mu\nu}H \\ \mathcal{L}^{(6)}_{HZZ} &= \rho_H g m_W \frac{c^2 f_W + s^2 f_B}{2c^2\Lambda^2}Z_{\mu\nu}Z^\mu\partial^\nu H \\ &- \rho_H h m_W \frac{c^4 f_{WW} + s^4 f_{BB}}{2c^2\Lambda^2}Z_{\mu\nu}Z^{\mu\nu}H \\ s &= sin\theta_W, \quad c = cos\theta_W\end{aligned}$$

Production Channels

- Yukawa coupling between heavy Higgs and fermions is small
- The associated VH(V=W/Z) production channel is considered(VBF production channel is accompanied by large bkg)
- heavy Higgs decay modes:

$$
\begin{aligned}
H &\to WW \to l\nu jj \\
H &\to WW \to l\nu l\nu \\
H &\to WW \to jjjj \\
H &\to ZZ \to lljj \\
l &= e/\mu
\end{aligned}
$$

- final states with $2\ell 0\nu$, $3\ell 1\nu$ and 2(same-sign)$\ell 2\nu$from three bosons' decays are used

Background Estimation

$2\ell 0\nu$ channel:

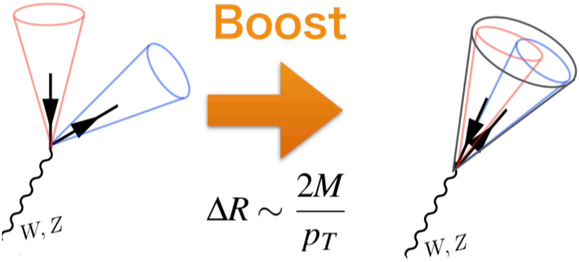
- single boson($\ell\ell$) plus four QCD partons
- diboson ($\ell\ell + jj$) plus two QCD partons
- triboson process $\ell\ell + 4j$ (VBF included)
- $t\bar{t}$ with $t \to \ell\nu b$ and $t\bar{t}Z$ with $Z \to \ell\ell$

2(same-sign)$\ell 2\nu$ and $3\ell 1\nu$ channel:

- diboson plus two QCD partons
- triboson process (VBF included)
- $t\bar{t}V$ process

Boosted Boson jet

- $V \to jet + jet$ process is accompanied by large SM bkg
- boosted boson jet: high p_T, variable τ_2 and τ_1 describing jet substructure

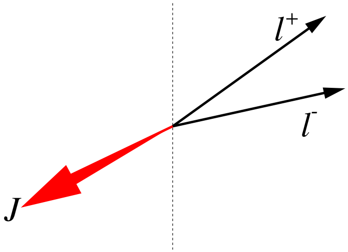


by Toshi SUMIDA

600GeV Heavy Higgs Mass:$2\ell 0\nu$ final state

Region 1:
$V_0 H \to l^- l^+ + V_1$(subjet of leading fatjet)V_2(subjet of leading fatjet)
cut:

- $p_{T,V_0} > 950GeV$
- $80GeV < m_{V_0} < 100GeV$
- $fatjet\_sj\_n$ of leading fatjet $= 2$
- $70GeV < m_{V_1}, m_{V_2} < 150GeV$
- $\frac{\tau_2}{\tau_1}$ of leading fatjet < 0.45
- $p_{T,HH} > 750GeV$



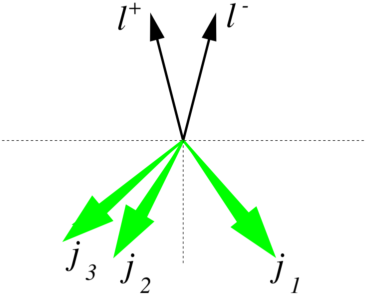
600GeV Heavy Higgs Mass:$2\ell 0\nu$ final state

Region 2:

$V_0 H \to l^- l^+ + V_1(jet) V_2(jet + jet)$

cut:

- $p_{T,V_0} > 550GeV$,
  $p_{T,V_1} > 300GeV$, $p_{T,V_2} > 150GeV$
- $80GeV < m_{V_0} < 100GeV$,
  $70GeV < m_{V_1} < 150GeV$,
  $70GeV < m_{V_2} < 110GeV$
- $\frac{\tau_2}{\tau_1}$ of $V_1 < 0.4$
- $p_{T,HH} > 550GeV$



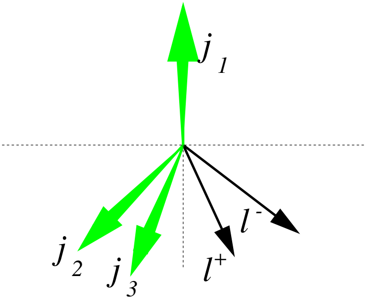
600GeV Heavy Higgs Mass:$2\ell 0\nu$ final state

Region 3:

$V_0 H \rightarrow jet + V_1(l^+l^-)V_2(jet + jet)$

cut:

- $p_{T,V_0} > 700GeV$,
  $p_{T,V_1} > 300GeV$, $p_{T,V_2} > 50GeV$
- $70GeV < m_{V_0} < 150GeV$,
  $80GeV < m_{V_1} < 100GeV$,
  $75GeV < m_{V_2} < 115GeV$
- $\frac{\tau_2}{\tau_1}$ of $V_0 < 0.6$
- $p_{T,HH} > 700GeV$



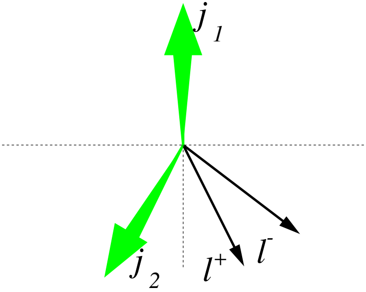
600GeV Heavy Higgs Mass: $2\ell 0\nu$ final state

Region 4:

$$V_0 H \rightarrow jet + V_1(l^+ l^-) V_2(jet)$$

cut:

- $p_{T,V_0} > 700GeV$,
  $p_{T,V_1} > 300GeV$, $p_{T,V_2} > 250GeV$
- $70GeV < m_{V_0} < 150GeV$,
  $80GeV < m_{V_1} < 100GeV$,
  $75GeV < m_{V_2} < 150GeV$
- $\frac{\tau_2}{\tau_1}$ of $V_0 < 0.52$, $\frac{\tau_2}{\tau_1}$ of $V_2 < 0.52$
- $p_{T,HH} > 700GeV$



600GeV Heavy Higgs Mass: $3\ell 1\nu$ final state

Region 1, 2 and 3:

$$V_0 H \rightarrow l^{\pm}\nu_{l^{\pm}} + V_1(l^+l^-)V_2(jet)$$

$$V_0 H \rightarrow l^{\pm}\nu_{l^{\pm}} + V_1(l^+l^-)V_2(fatjet)$$

$$V_0 H \rightarrow l^{\pm}\nu_{l^{\pm}} + V_1(l^+l^-)V_2(jet + jet)$$

cut:

- $p_{T,V_0} > 600GeV$, $p_{T,\nu_{l^{\pm}}} > 50GeV$
- $80GeV < m_{V_0} < 100GeV$,
- $p_{T,HH} > 600GeV$
- $60GeV < m_{V_2} < 160GeV$(region 1),
  $70GeV < m_{V_2} < 140GeV$(region 2) or
  $60GeV < m_{V_2} < 120GeV$(region 3)
- $\frac{\tau_2}{\tau_1}$ of $V_2 < 0.6$(region 1) or < 0.5(region 2)

600GeV Heavy Higgs Mass: $3\ell 1\nu$ final state

Region 4, 5 and 6:

$$V_0H \to l^+l^- + V_1(l^{\pm}\nu_{l^{\pm}})V_2(jet)$$

$$V_0H \to l^+l^- + V_1(l^{\pm}\nu_{l^{\pm}})V_2(fatjet)$$

$$V_0H \to l^+l^- + V_1(l^{\pm}\nu_{l^{\pm}})V_2(jet + jet)$$

cut:

- $p_{T,V_0} > 600GeV$, $p_{T,\nu_{l^{\pm}}} > 50GeV$
- $80GeV < m_{V_0} < 100GeV$,
- $p_{T,HH} > 600GeV$
- $60GeV < m_{V_2} < 160GeV$(region 4),
  $70GeV < m_{V_2} < 140GeV$(region 5) or
  $60GeV < m_{V_2} < 120GeV$(region 6)
- $\frac{\tau_2}{\tau_1}$ of $V_2 < 0.6$(region 4) or < 0.5(region 5)

600GeV Heavy Higgs Mass: 2(same-sign)$\ell 2\nu$ final state

Region 1, 2 and 3:

$$W^{\pm}H \to l^{\pm}\nu_{l^{\pm}} + W^{\pm}(l^{\pm}\nu_{l^{\pm}})W^{\mp}(1jet)$$

$$W^{\pm}H \to l^{\pm}\nu_{l^{\pm}} + W^{\pm}(l^{\pm}\nu_{l^{\pm}})W^{\mp}(2jets)$$

$$W^{\pm}H \to l^{\pm}\nu_{l^{\pm}} + W^{\pm}(l^{\pm}\nu_{l^{\pm}})W^{\mp}(fatjet)$$

fatjet case and boosted jet case:

- $60GeV < m_{W^{\mp}} < 150GeV$, $m_{LL} > 300GeV$,$MET > 100GeV$, $\Delta\phi_{LL} > 2.0$
- $p_{T,LL} > 100GeV$, $p_{T,L1} > 300GeV$, $p_{T,L2} > 50GeV$
- $\frac{\tau_2}{\tau_1} < 0.6$, $p_{T,W^{\mp}} > 100GeV$ (fatjet)
- $p_{T,W^{\mp}} > 400GeV$ (boosted jet)

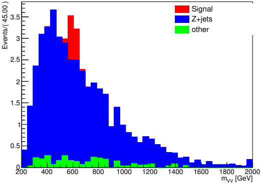
two jet case:

- $m_{LL} > 400GeV$,$MET > 100GeV$, $\Delta\phi_{LL} > 1.6$
- $p_{T,LL} > 100GeV$, $p_{T,L1} > 450GeV$, $p_{T,L2} > 50GeV$

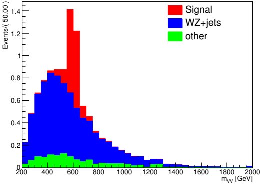
600GeV Heavy Higgs Mass

- $\int Ldt = 300 fb^{-1}$
- $\rho_H = 0.05,\ f_W = 700,\ f_{WW} = 700$
- observable distributions for $2\ell 0\nu$, $3\ell 1\nu$ and $2(\text{same-sign})\ell 2\nu$

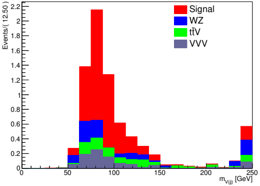
2l0v



3l1v



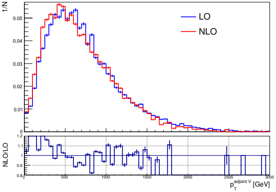
2(same-sign)l2v

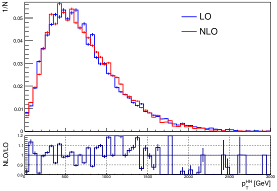


final state	Signal	Background
$2\ell 0\nu$	2.0	44.8
$3\ell 1\nu$	1.9	8.5
$2(\text{same-sign})\ell 2\nu$	4.5	3.0

Re-scale LO cross-section to NLO cross-section

- $\int Ldt = 300fb^{-1}$, $\rho_H = 0.05$, $f_W = 700$, $f_{WW} = 700$
- p_T distribution of the adjoint V and heavy Higgs in $pp \to VH$ process with $m_{HH} = 600GeV$





- $k - factor = \frac{cs_{LO}}{cs_{NLO}}$

Mass(GeV)	300	600	900
k-factor	1.61	1.63	1.63

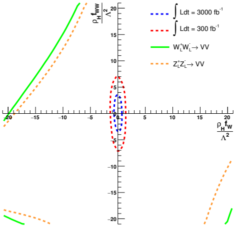
95% Confidence Level Exclusion

- the mass of gauge boson is equal to SM mass

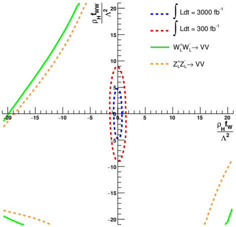
$$\rho_h \frac{\nu_h}{\nu} + \rho_H \frac{\nu_H}{\nu} + \ldots = 1$$

- take $\rho_h = 1$ and $\rho_H = 0.05$ as benchmark value
- get CL of each parameter point by number counting method

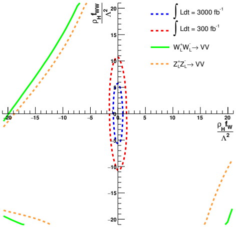
300GeV



600GeV



900GeV



Conclusion

- Three final states ($2\ell0\nu$, $3\ell1\nu$ and 2(same-sign)$\ell2\nu$) are considered
- SM background can be suppressed by appling of boosted boson jets
- We focus on dim-6 operator effect and the dim-4 effect is small
- A big part of parameter space which is among unitarity bound can be excluded
- This part of phase space is waiting for discovery

BACKUP

300GeV Heavy Higgs Mass:2lep final state

Region	Process
1	$V_0H \to l^-l^+ + V_1(\text{subjet of L-fatjet})V_2(\text{subjet of L-fatjet})$
2	$V_0H \to l^-l^+ + V_1(jet)V_2(jet + jet)$
3	$V_0H \to jet + V_1(l^+l^-)V_2(jet + jet)$

- take out process: $V_0H \to jet + V_1(l^+l^-)V_2(jet)$
- a bit tighter mass window cut

900GeV Heavy Higgs Mass: 2lep final state

Region	Process
1	$V_0H \to l^-l^+ + V_1(\text{jet})V_2(\text{jet+jet})$
2	$V_0H \to jet + V_1(l^-l^+)V_2(\text{jet})$
3	$V_0H \to l^-l^+ + V_1(\text{jet})V_2(\text{jet})$

- take out process: $V_0H \to l^-l^+ + V_1$(subjet of leading fatjet)V_2(subjet of leading fatjet)
- take out process: $V_0H \to jet + V_1(l^+l^-)V_2(jet + jet)$
- add process: $V_0H \to l^-l^+ + V_1(\text{jet})V_2(\text{jet})$