Search for a generic heavy Higgs at LHC

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Overview

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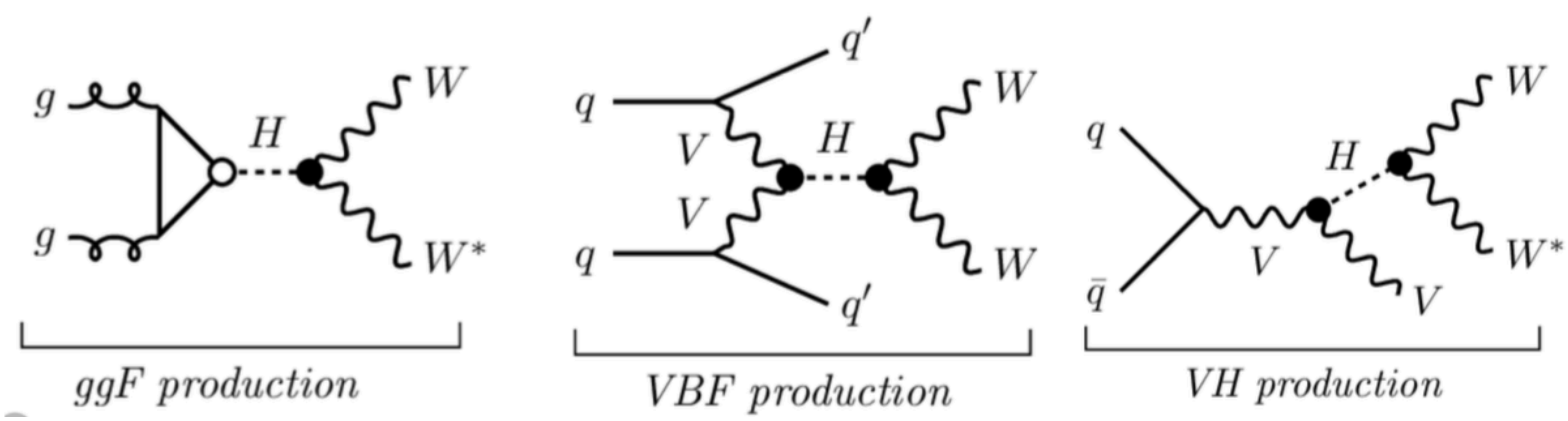
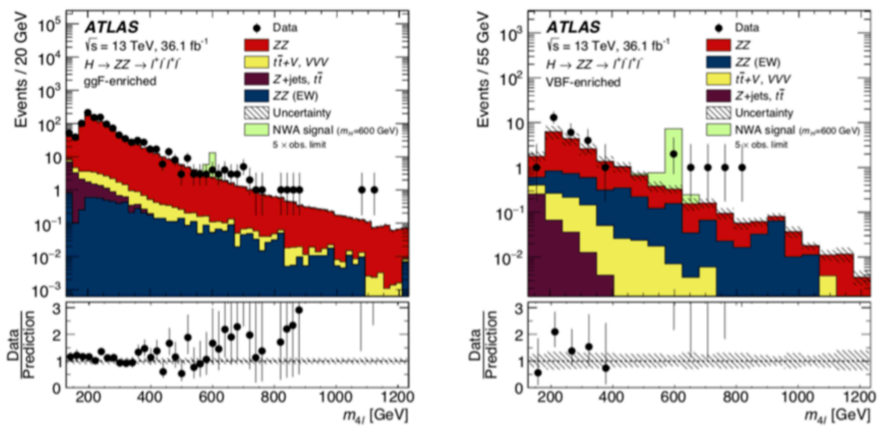
Introduction

- Many BSM predict heavy Higgs particles decaying to heavy quarks or bosons
  - 2HDM, MSSM…
- ATLAS and CMS have some researches on heavy Higgs boson
  - gluon-gluon fusion (ggF)
  - Vector-boson fusion (VBF)
  - Associated production with vector boson (VH)



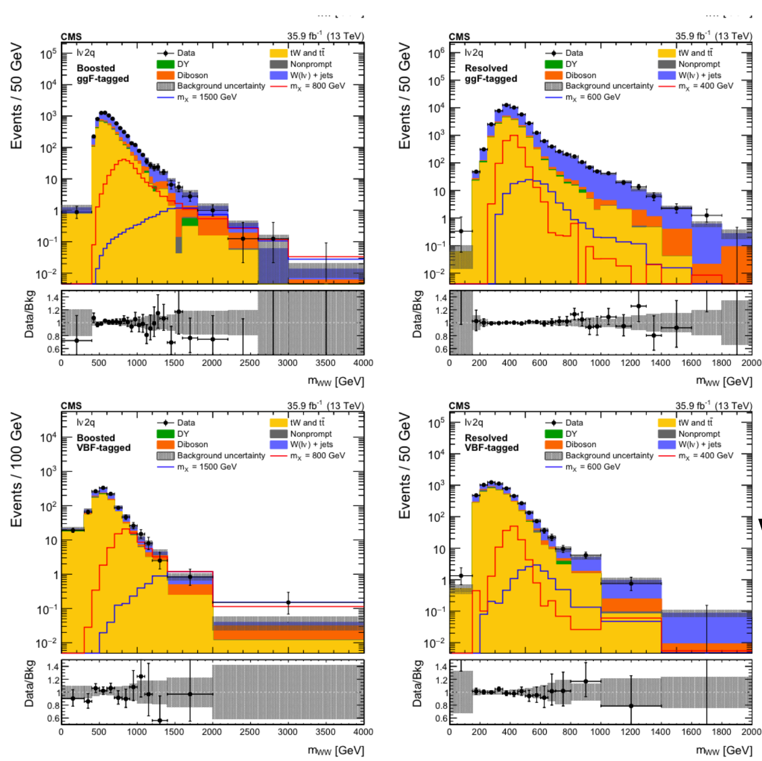
- $H \to ZZ \to 4\ell$ research in ATLAS. Eur.Phys.J.C 78 (2018) 4, 293

ggF



VBF

- $X \to WW$ research in CMS. JHEP 2020, 34 (2020)



ggF

VBF

Interactions

- Multiple Higgs field: one SM-like light Higgs (**h**) and one generic neutral heavy Higgs (**H**)
- A generic heavy Higgs: generic means model-independent, has both dim-4 and effective dim-6 interactions with SM particles.
- The dim-6 operators significantly enhance the Higgs momentum
- Only consider these **four dim-6 operators**, since we just consider the coupling between heavy Higgs and vector bosons(W/Z) and the rest is constrained by electroweak precision data or not relevant for the heavy Higgs.

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

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dim-6 effective operator Lagrangian

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

$$\mathcal{L}^{(6)}_{HWW} = \rho_H g m_W \frac{f_W}{2\Lambda^2}(W^+_{\mu\nu}W^{-\mu}\partial^\nu H + h.c.) - \rho_H g m_W \frac{f_{WW}}{\Lambda^2} W^+_{\mu\nu}W^{-\mu\nu} H$$

$$\mathcal{L}^{(6)}_{HZZ} = \rho_H g m_W \frac{c^2 f_W + s^2 f_B}{2c^2\Lambda^2} Z_{\mu\nu}Z^\mu\partial^\nu H - \rho_H h m_W \frac{c^4 f_{WW} + s^4 f_{BB}}{2c^2\Lambda^2} Z_{\mu\nu}Z^{\mu\nu} H$$

$$s = sin\theta_W, \quad c = cos\theta_W$$

Interactions

- f_W, f_{WW}, f_B, f_{BB}, ρ_H, ρ_h are the relevant parameters. f_B and f_{BB} are set to 0 to neglect terms of $O(s^2)$ and $O(s^4)$

- Take ρ_h=1 and ρ_H=0.05 as benchmark value, fixed. Since the mass of gauge boson should be equal to SM mass

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

- **Only m_H, f_W and f_{WW} are free parameters**

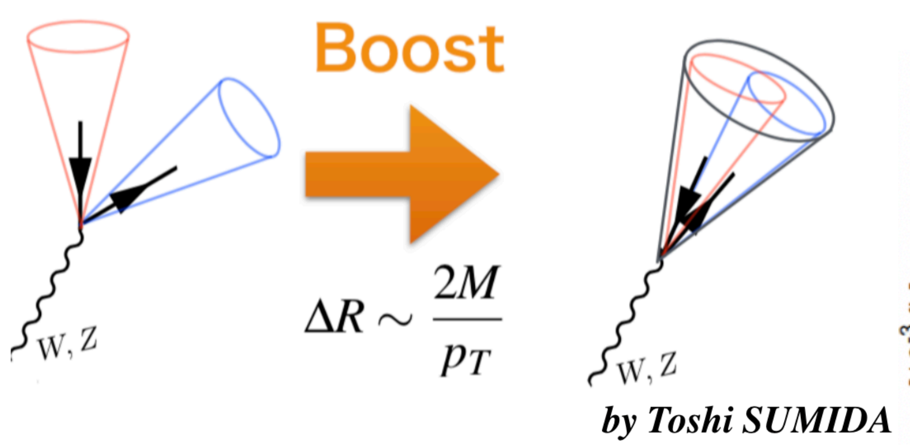
- Then the operators in slide 4 become:

$$\mathcal{L}^{(4)}_{hWW} = \rho_h g m_W h W^\mu W_\mu$$
$$\mathcal{L}^{(4)}_{hZZ} = \rho_h \frac{g m_W}{2\cos^2\theta_W} h Z^\mu Z_\mu$$
$$\mathcal{L}^{(4)}_{HWW} = \rho_H g m_W H W^\mu W_\mu$$
$$\mathcal{L}^{(4)}_{HZZ} = \rho_H \frac{g m_W}{2\cos^2\theta_W} H Z^\mu Z_\mu$$

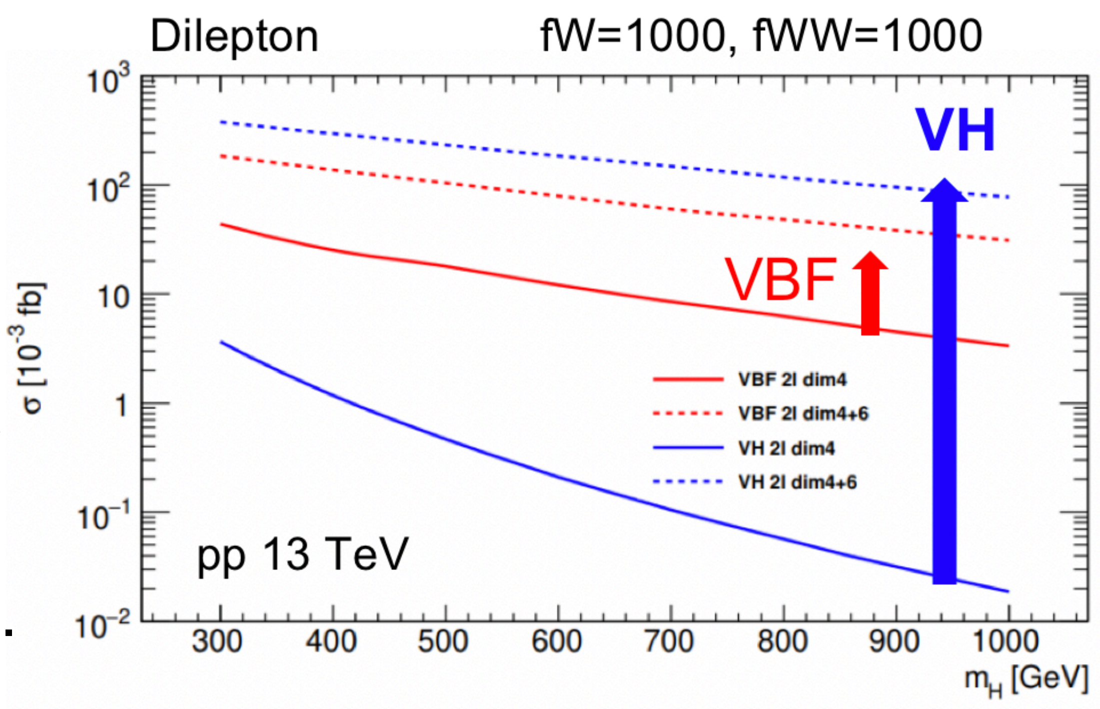
$$\begin{aligned}\mathcal{L}^{(6)}_{HWW} &= \rho_H g m_W \frac{f_W}{2\Lambda^2}\left(W^+_{\mu\nu} W^{-\mu}\partial^\nu H + h.c.\right) \\ &\quad -\rho_H g m_W \frac{f_{WW}}{\Lambda^2} W^+_{\mu\nu} W^{-\mu\nu} H, \\ \mathcal{L}^{(6)}_{HZZ} &= \rho_H g m_W \frac{c^2 f_W}{2c^2\Lambda^2} Z_{\mu\nu} Z^\mu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

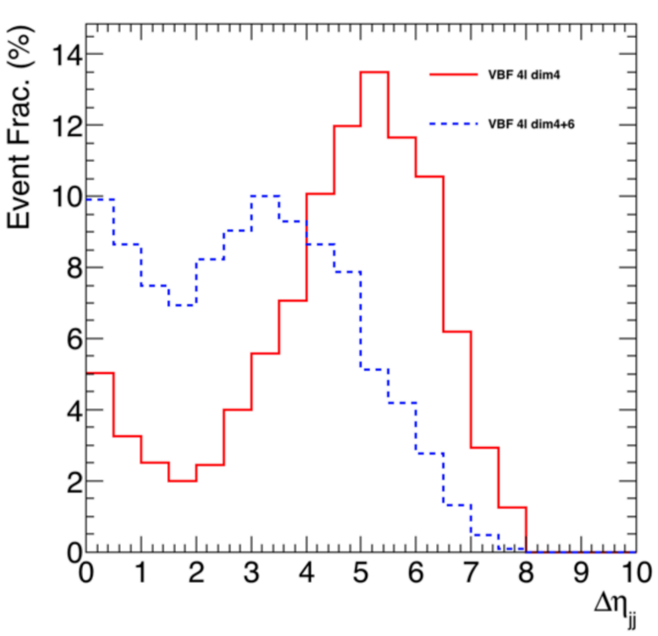
Physics process

- The associated VH(V=W/Z) production is considered, the V/H is boosted due to dim-6 operators.
    - Assume that Yukawa coupling between heavy Higgs and fermions is very small, so it can escape the direct production in gluon-fusion channel
    - Vector boson fusion(VBF) is NOT considered because of accompanied by large background
        - Some traditional variables e.g. $\Delta\eta_{jj}$ become more background-like due to dim-6 operators.



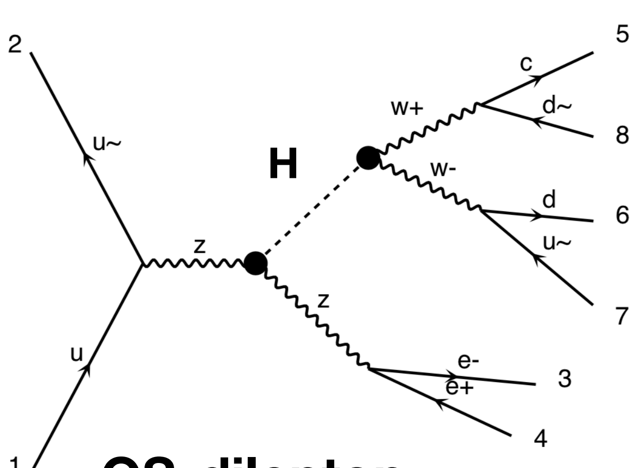
Boosted boson jet: high pT, variable τ_1 and τ_2 describing jet substructure.



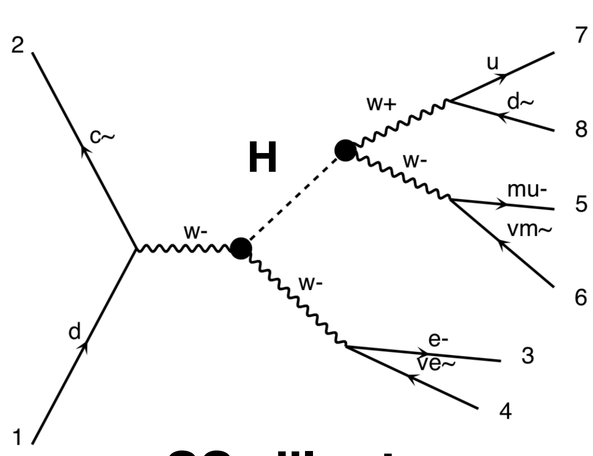


Physics process

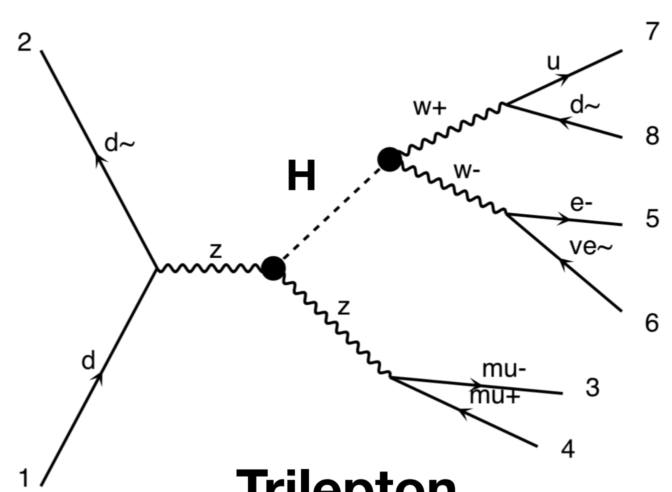
- Three final states are interested
    - **SS-dilepton**: 2 same-sign lepton final state with two neutrinos from WWW, e.g. p p > W+ H, W+ > l+ vl, H > l+ vl j j
    - **OS-dilepton**: 2 opposite-sign lepton final state without neutrino, e.g. p p> Z H, Z > l+ l-, H > j j j j
    - **Trilepton**: 3 lepton final state with one neutrino, e.g. p p > Z H, Z > l+ l-, H > l+ vl j j
- We don't study zero-lepton and one-lepton final state, because they are accompanied by large bkg. and the signal significance is very low



OS-dilepton



SS-dilepton



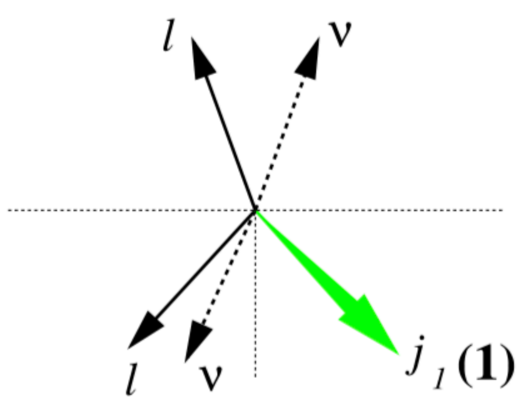
Trilepton

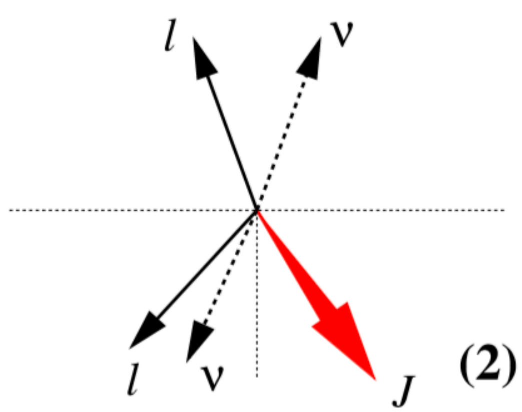
Signal regions: SS-dilepton

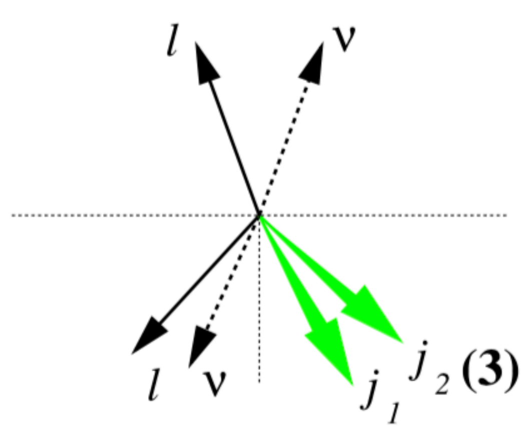
- SS-dilepton region:

1. $V_0 H \to l^{\pm}\nu_{l^{\pm}} + V_1(l^{\pm}\nu_{l^{\pm}})V_2(\text{jet})$
2. $V_0 H \to l^{\pm}\nu_{l^{\pm}} + V_1(l^{\pm}\nu_{l^{\pm}})V_2(\text{fatjet})$
3. $V_0 H \to l^{\pm}\nu_{l^{\pm}} + V_1(l^{\pm}\nu_{l^{\pm}})V_2(\text{jet + jet})$

region (1)	region (2)
$m_{\ell\ell} > 300$ GeV, $p_T^{\ell\ell} > 100$ GeV, $p_T^{\ell_1} > 300$ GeV, $p_T^{\ell_2} > 50$ GeV, $\Delta\phi_{\ell\ell} > 2.0$, $E_T^{\text{miss}} > 100$ GeV, no b-tagged jets	
$p_T^{j_1} > 400$ GeV	$p_T^{J} > 100$ GeV, $\tau_2^J/\tau_1^J < 0.6$
region (3)	
$m_{\ell\ell} > 400$ GeV, $p_T^{\ell\ell} > 100$ GeV, $p_T^{\ell_1} > 450$ GeV, $p_T^{\ell_2} > 50$ GeV, $\Delta\phi_{\ell\ell} > 1.6$, $E_T^{\text{miss}} > 100$ GeV	







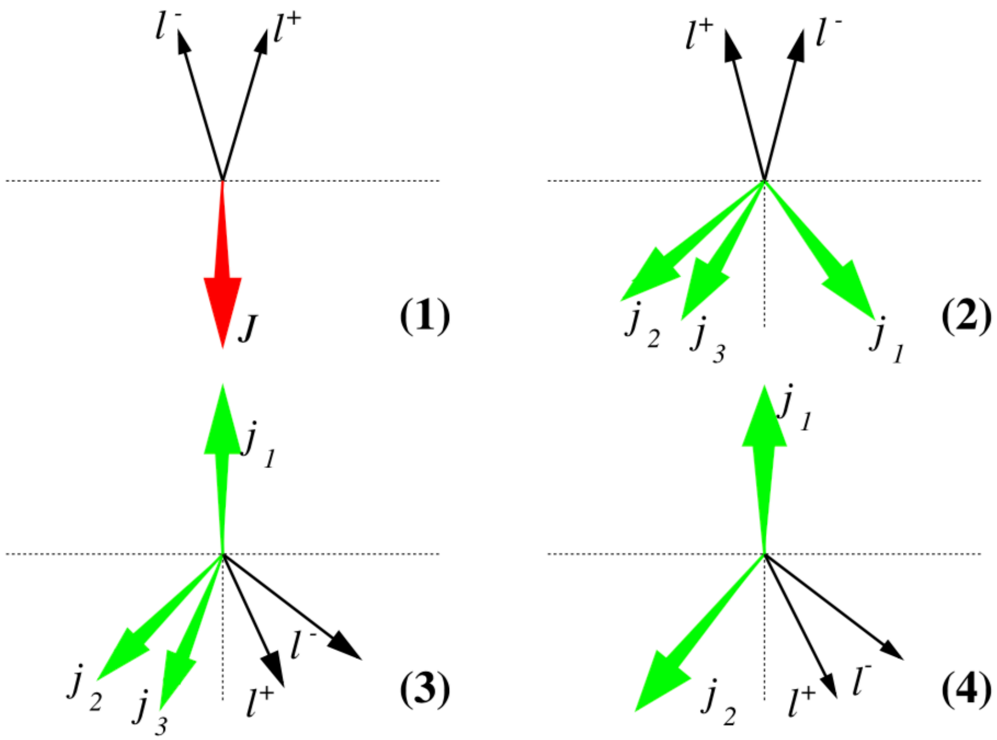
large-R jet (fatjet)
small-R jet

Signal regions: OS-dilepton

- OS-dilepton region:

1. $V_0 H \to l^- l^+ + V_1$(subjet of leading fatjet)V_2(subjet of leading fatjet)
2. $V_0 H \to l^- l^+ + V_1$(jet)V_2(jet + jet)
3. $V_0 H \to$ jet + $V_1(l^- l^+)V_2$(jet + jet)
4. $V_0 H \to$ jet + $V_1(l^- l^+)V_2$(jet)

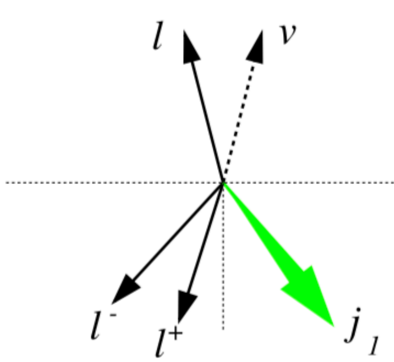
region (1)	region (2)
$80\ \text{GeV} < m_{\ell\ell} < 100\ \text{GeV}$	
$p_T^{\ell\ell} > 950$ GeV, $p_T^J > 750$ GeV, $N_{sj} = 2$, $70\ \text{GeV} < m_{sj_{1,2}} < 150$ GeV, $\tau_2^J/\tau_1^J < 0.45$	$p_T^{\ell\ell} > 550$ GeV, $p_T^{j_1} > 300$ GeV, $70\ \text{GeV} < m_{j_1} < 150$ GeV, $\tau_2^{j_1}/\tau_1^{j_1} < 0.40$, $70\ \text{GeV} < m_{j_{23}} < 110$ GeV, $p_T^{j_{23}} > 150$ GeV, $\Delta R(j_1, j_{23}) < \Delta R(\ell\ell, j_1)$, $\Delta R(j_1, j_{23}) < \Delta R(\ell\ell, j_{23})$, $p_T^{j_1+j_{23}} > 550$ GeV
region (3)	**region (4)**
$80\ \text{GeV} < m_{\ell\ell} < 100\ \text{GeV}$, $p_T^{\ell\ell} > 300$ GeV, $p_T^{j_1} > 700$ GeV, $70\ \text{GeV} < m_{j_1} < 150$ GeV	
$\tau_2^{j_1}/\tau_1^{j_1} < 0.60$, $75\ \text{GeV} < m_{j_{23}} < 115$ GeV, $p_T^{j_{23}} > 50$ GeV, $\Delta R(\ell\ell, j_{23}) < \Delta R(j_1, \ell\ell)$, $\Delta R(\ell\ell, j_{23}) < \Delta R(j_1, j_{23})$, $p_T^{\ell\ell+j_{23}} > 700$ GeV	$\tau_2^{j_1}/\tau_1^{j_1} < 0.52$, $p_T^{j_2} > 250$ GeV, $70\ \text{GeV} < m_{j_2} < 150$ GeV, $\tau_2^{j_2}/\tau_1^{j_2} < 0.52$, $\Delta R(\ell\ell, j_2) < \Delta R(j_1, \ell\ell)$, $\Delta R(\ell\ell, j_2) < \Delta R(j_1, j_2)$, $p_T^{\ell\ell+j_2} > 700$ GeV



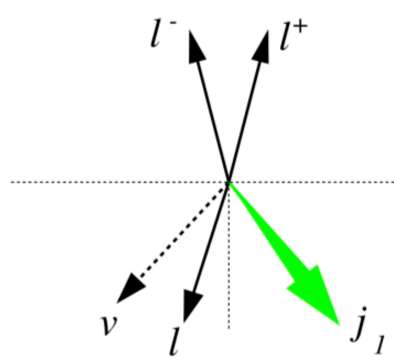
Signal regions: Trilepton

- Trilepton region:
  1. $V_0H \to l^{\pm}\nu_{l^{\pm}} + V_1(l^+l^-)V_2(\text{jet})$
  2. $V_0H \to l^{\pm}\nu_{l^{\pm}} + V_1(l^+l^-)V_2(\text{fatjet})$
  3. $V_0H \to l^{\pm}\nu_{l^{\pm}} + V_1(l^+l^-)V_2(\text{jet + jet})$
  4. $V_0H \to l^+l^- + V_1(l^{\pm}\nu_{l^{\pm}})V_2(\text{jet})$
  5. $V_0H \to l^+l^- + V_1(l^{\pm}\nu_{l^{\pm}})V_2(\text{fatjet})$
  6. $V_0H \to l^+l^- + V_1(l^{\pm}\nu_{l^{\pm}})V_2(\text{jet + jet})$

region (1)	region (4)
$p_T^{\ell\nu} > 600$ GeV	$p_T^{\ell\ell} > 600$ GeV
80 GeV $< m_{\ell\ell} <$ 100 GeV, 60 GeV $< m_{j_1} <$ 160 GeV, $\tau_2^{j_1}/\tau_1^{j_1} < 0.60$	
$\Delta R(\ell\ell, j_1) < \Delta R(\ell\nu, \ell\ell)$, $\Delta R(\ell\ell, j_1) < \Delta R(\ell\nu, j_1)$, $p_T^{\ell\ell+j_1} > 600$ GeV	$\Delta R(\ell\nu, j_1) < \Delta R(\ell\ell, \ell\nu)$, $\Delta R(\ell\nu, j_1) < \Delta R(\ell\ell, j_1)$, $p_T^{\ell\nu+j_1} > 600$ GeV
region (2)	**region (5)**
$p_T^{\ell\nu} > 600$ GeV	$p_T^{\ell\ell} > 600$ GeV
80 GeV $< m_{\ell\ell} <$ 100 GeV, 70 GeV $< m_J <$ 140 GeV, $\tau_2^J/\tau_1^J < 0.50$	
$\Delta R(\ell\ell, J) < \Delta R(\ell\nu, \ell\ell)$, $\Delta R(\ell\ell, J) < \Delta R(\ell\nu, J)$, $p_T^{\ell\ell+J} > 600$ GeV	$\Delta R(\ell\nu, J) < \Delta R(\ell\ell, \ell\nu)$, $\Delta R(\ell\nu, J) < \Delta R(\ell\ell, J)$, $p_T^{\ell\nu+J} > 600$ GeV
region (3)	**region (6)**
$p_T^{\ell\nu} > 600$ GeV	$p_T^{\ell\ell} > 600$ GeV
80 GeV $< m_{\ell\ell} <$ 100 GeV, 60 GeV $< m_{j_{12}} <$ 120 GeV	
$\Delta R(\ell\ell, j_{12}) < \Delta R(\ell\nu, \ell\ell)$, $\Delta R(\ell\ell, j_{12}) < \Delta R(\ell\nu, j_{12})$, $p_T^{\ell\ell+j_{12}} > 600$ GeV	$\Delta R(\ell\nu, j_{12}) < \Delta R(\ell\ell, \ell\nu)$, $\Delta R(\ell\nu, j_{12}) < \Delta R(\ell\ell, j_{12})$, $p_T^{\ell\nu+j_{12}} > 600$ GeV



(1)



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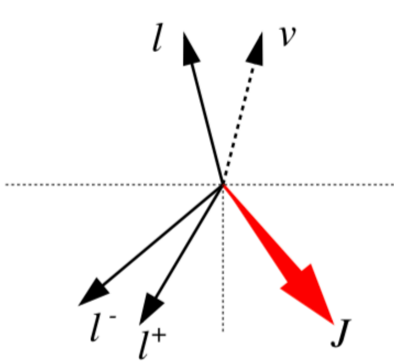

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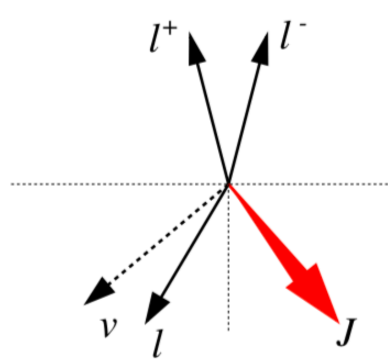
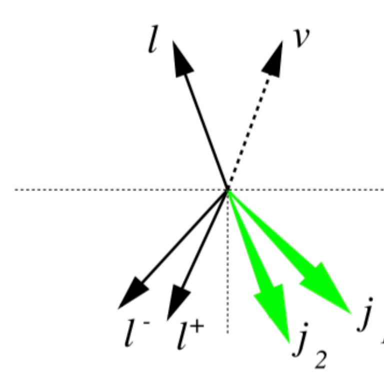
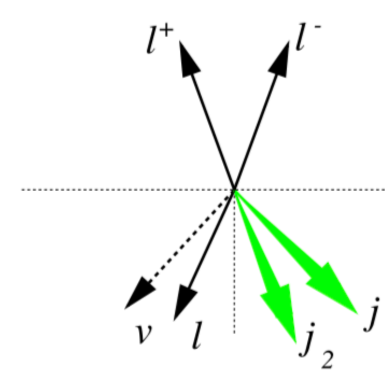


(5)



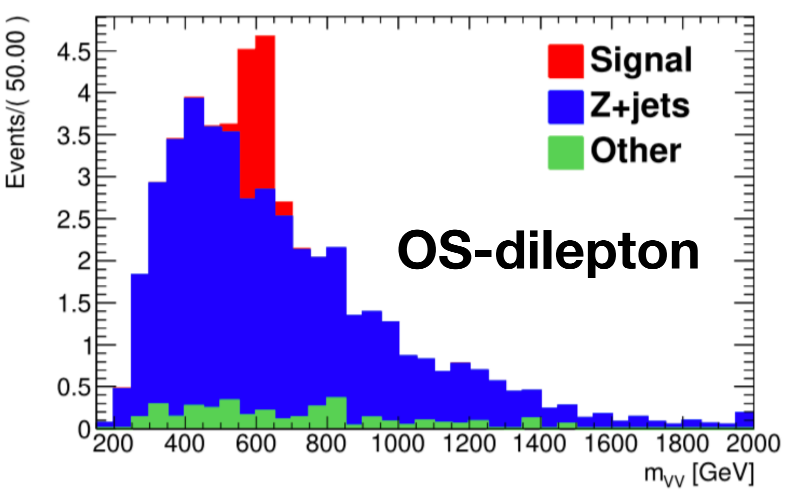
(3)

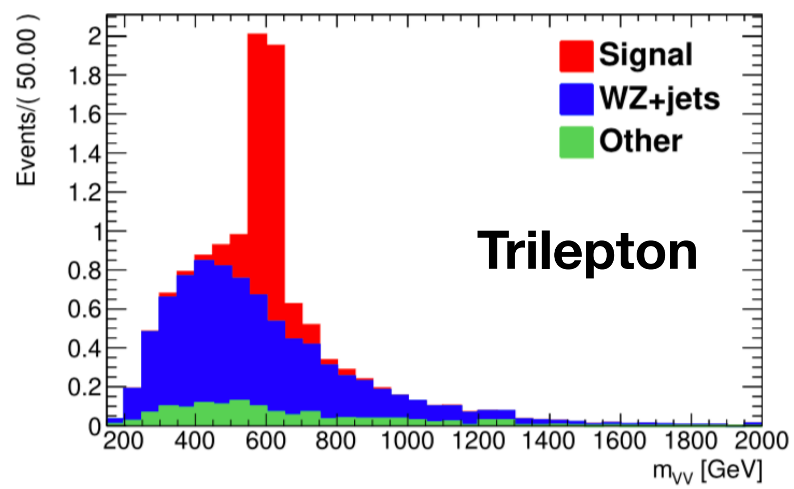


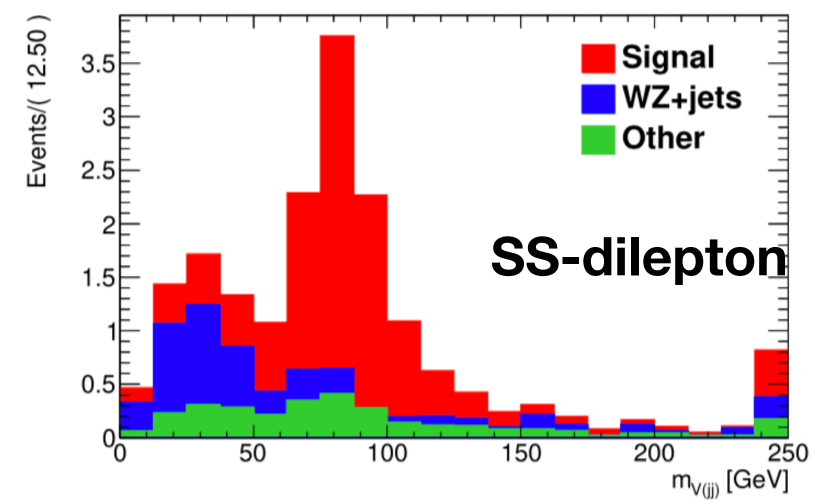
(6)

Distributions and Yields

- Distributions and yields with phenomenology study with signal point $m_H = 600$ GeV, $\rho_H = 0.05$, $f_W = f_{WW} = 1000$







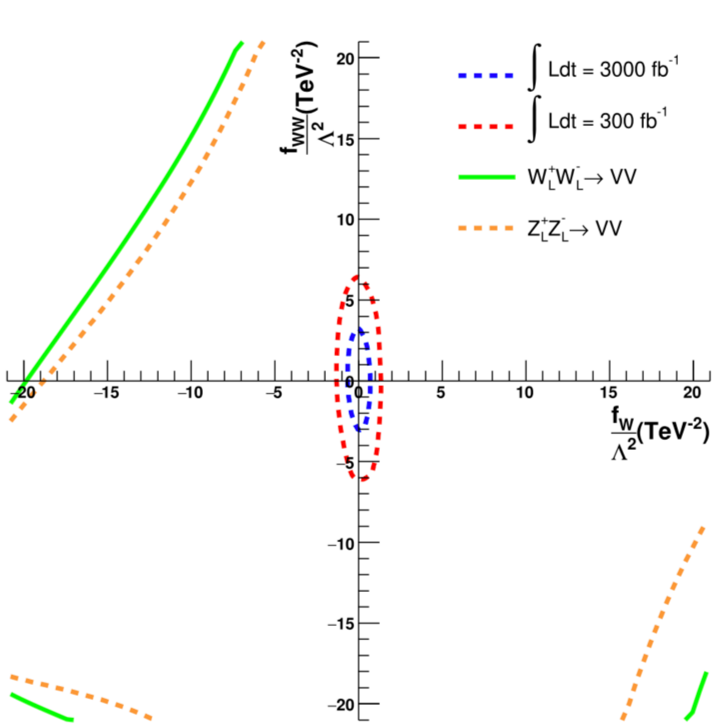
	Signal	Z+QCD jets	Other
2ℓ OS chan.	4.0	41.6	3.5
	Signal	WZ+QCD jets	Other
3ℓ chan.	3.6	7.2	1.3
	Signal	WZ+QCD jets	Other
2ℓ SS chan.	11.4	4.1	3.1

95% Confidence Level Exclusion

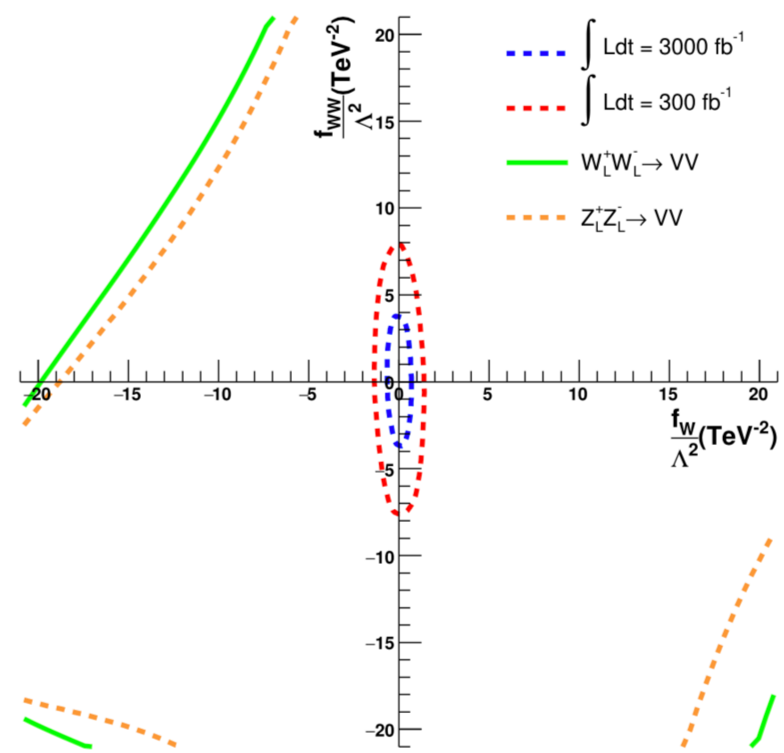
- The mass of gauge boson is equal to SM mass: $\rho_h \frac{\nu_h}{\nu} + \rho_H \frac{\nu_H}{\nu} + \ldots = 1$

- Take $\rho_h = 1$ and $\rho_H = 0.05$ as benchmark value.

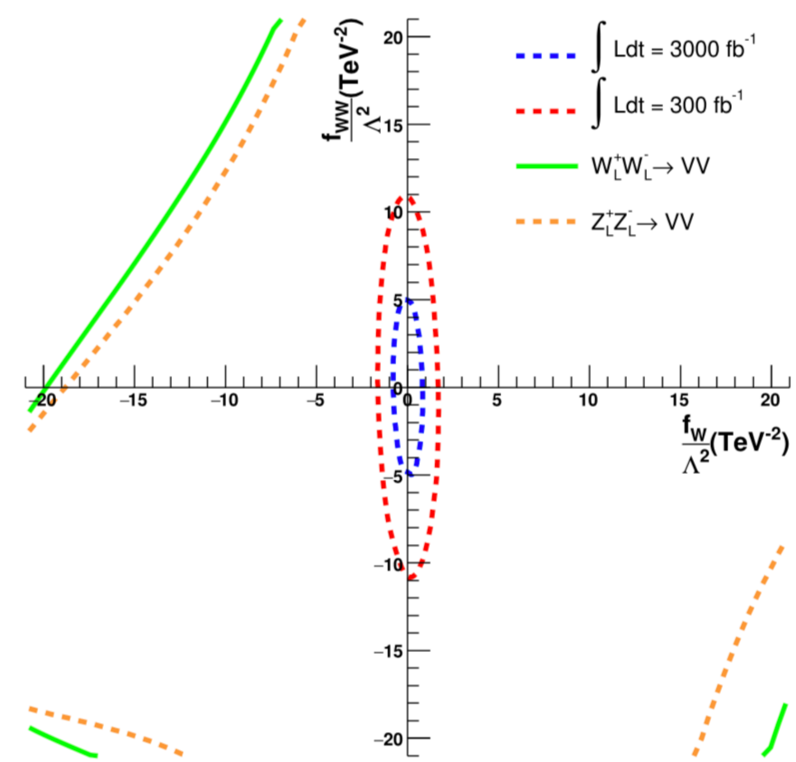
- Get confidence level (CL) of each parameter point by “template” fits with a large quantity of toy experiments.



300 GeV



600 GeV



900 GeV

Summary

- Two and three lepton final states 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

Thanks