Search for di-Higgs decaying to WW^*WW^* with final state of two same sign leptons plus four jets at LHC

Jing Ren[a] Ruiqing Xiao[b] Hongjian He[b],
Weiming Yao[c] Yaquan Fang[d] Maosen Zhou[d]

[a]University of Toronto, Canada
[b]Tsinghua University, China
[c]Lawrence Berkeley National Laboratory, USA
[d]Institute of High Energy Physics, China

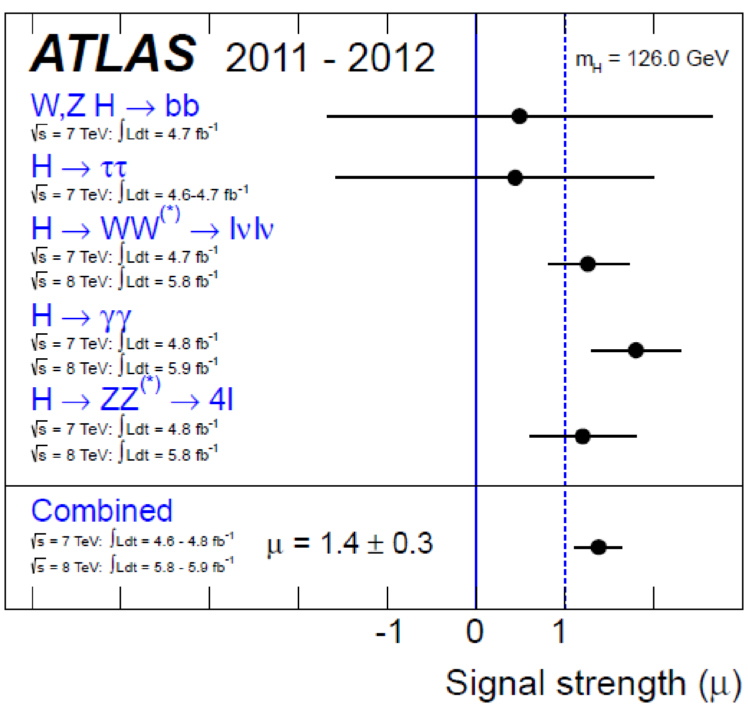
International Symposium on Higgs Boson and Beyond Standard Model Physics, WeiHai

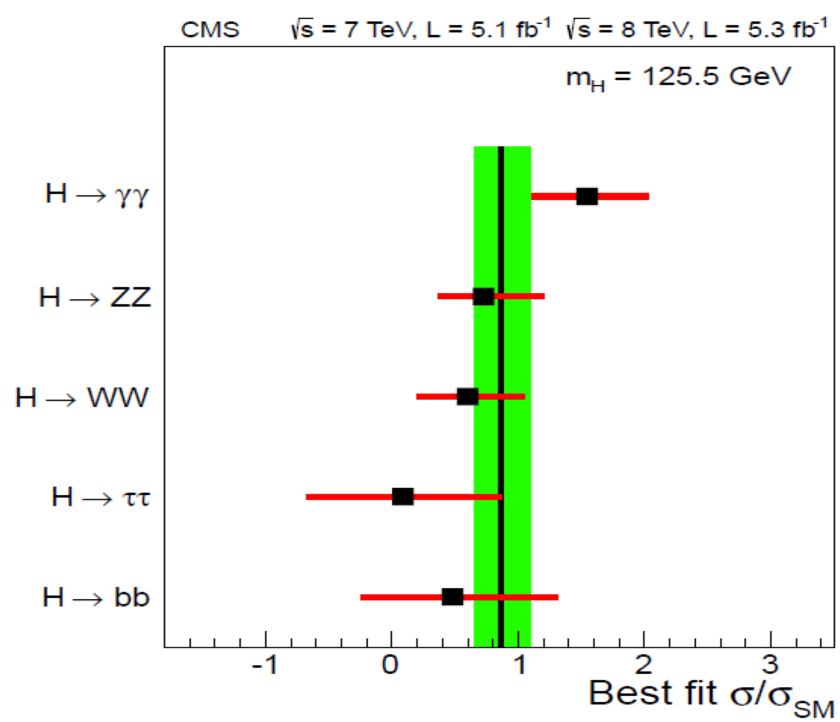
Outline

1. Introduction
   - Why 2HDM ?
   - Why $H \to hh \to WW^*WW^* \to \ell^\pm\ell^\pm\nu\nu qqqq$?
2. The WW^*WW^* production via heavier Higgs Boson H^0
   - Review on 2HDM
   - $hh \to WW^*WW^*$ production
3. Signal and backgrounds simulations
   - Simulations + pre-selections
   - Kinematic variables
   - Results
4. Probing 2HDM parameter space at LHC
5. Conclusions

Why 2HDM ?

- Higgs signal strength is consistent with prediction (P.L.B716 (2012), P.L.B716 (2012)), but it can't exclude that there is mixed beyond Standard Model neutral scalar
- 2HDM can provide additional neutral scalar
  - two higgs doublet model, a common framework for new physics with extended higgs sector
  - Although building extended higgs potenial with a singlet is simpler, singlet scalar fields coupling with SM particles is depreciated

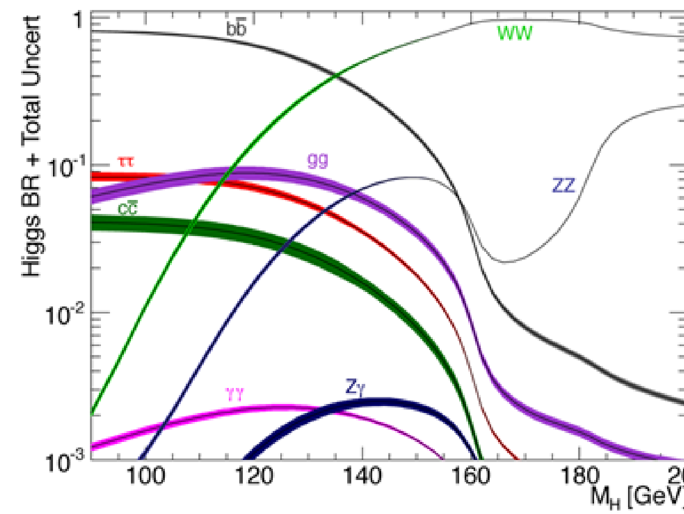




Why $H \to hh \to WW^*WW^* \to \ell^\pm\ell^\pm\nu\nu qqqq$?

- $H \to hh$?
  - Important complement to conventional search, namely $H \to (WW, ZZ, t\bar{t})$
  - $H \to hh$ decay mode can be dominant within certain parameter space
- $hh \to WW^*WW^*$?

  Although $bb\gamma\gamma$(P.R.D 89, 115006) is most sensitive, but:
  - Considerable production rate
  - $WW^*WW^* \to \ell^\pm\ell^\pm\nu\nu qqqq$?
    - Highly suppress QCD backgrounds
    - The studies(PRL 89 (2002), 151801) presented the possibility to measure the higgs self-coupling at HL-LHC
    - Tiny deviation in $W^\pm W^\pm jj$ search in Run-I at ATLAS (ATL-PHYS-PROC-2014-174)



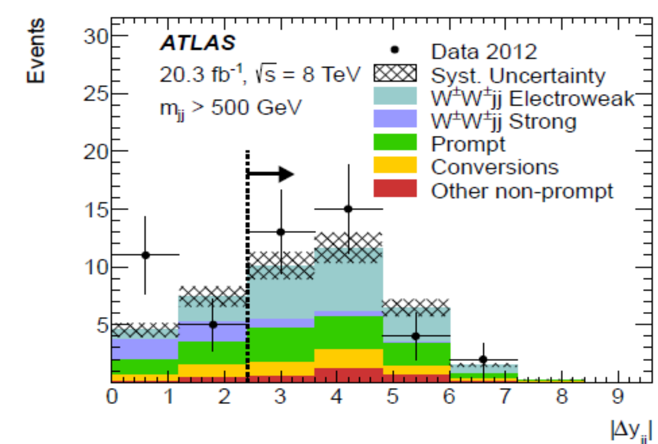


Figure 3: Separation in rapidity of the two tagging jets in the inclusive region. The dashed line with the arrow indicates the VBS region.

Review on 2HDM

- The vacuum expectation values(VEV) is

$$\left\langle \Phi_1^\dagger \right\rangle = \left(0, v_1/\sqrt{2}\right), \quad \left\langle \Phi_2^\dagger \right\rangle = \left(0, v_2/\sqrt{2}\right), \quad \tan\beta = v_2/v_1$$

- Five scalars $(h_1, h_2, A^0, H^\pm)$
- α is the mixing angle

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_2 \\ h_1 \end{pmatrix},$$

- h coupling with SM fermions and gauge bosons are solely controlled by (α, β)
- Focus on Type-I and Type-II.

$hh \to WW^*WW^*$ production

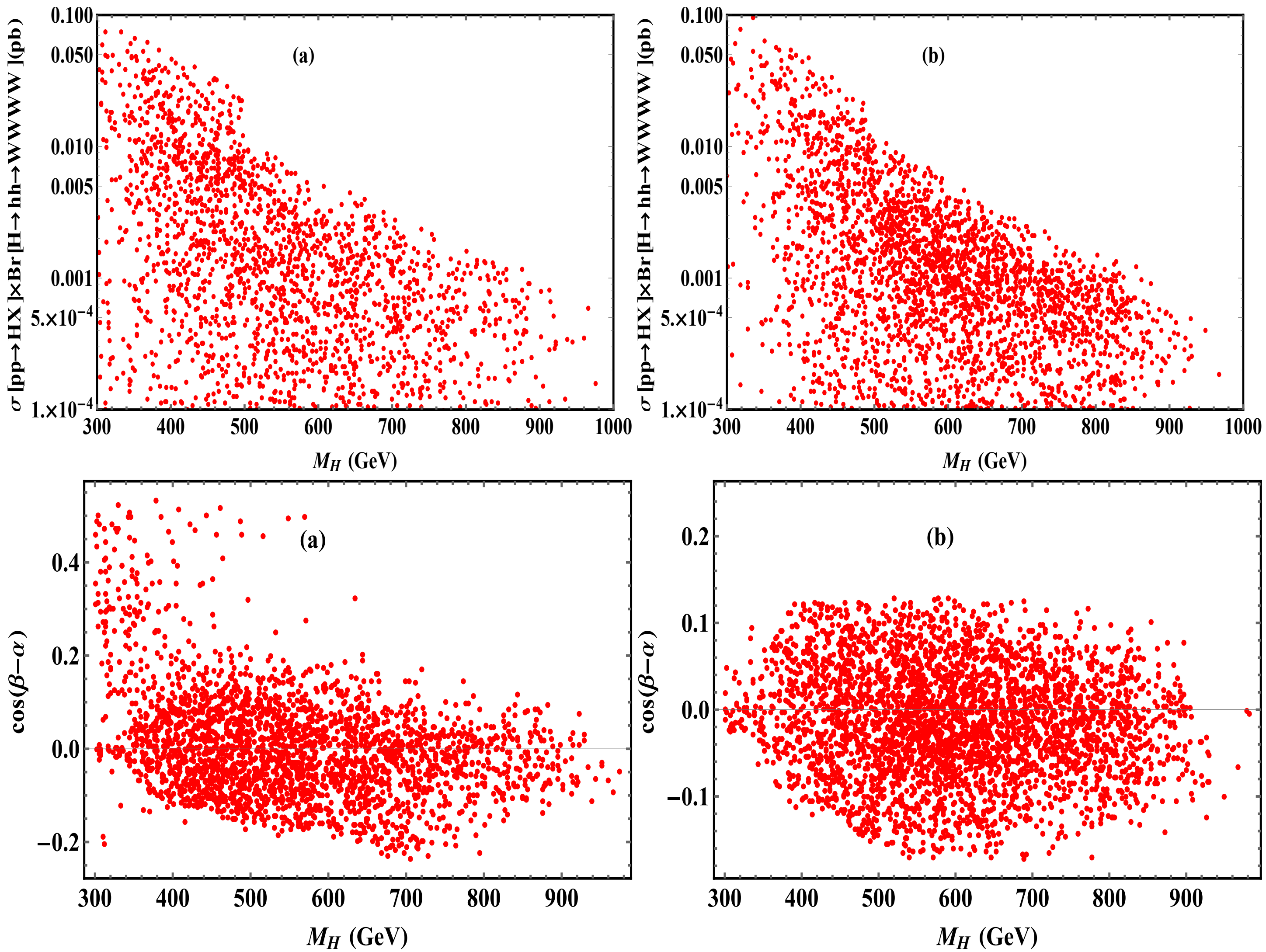
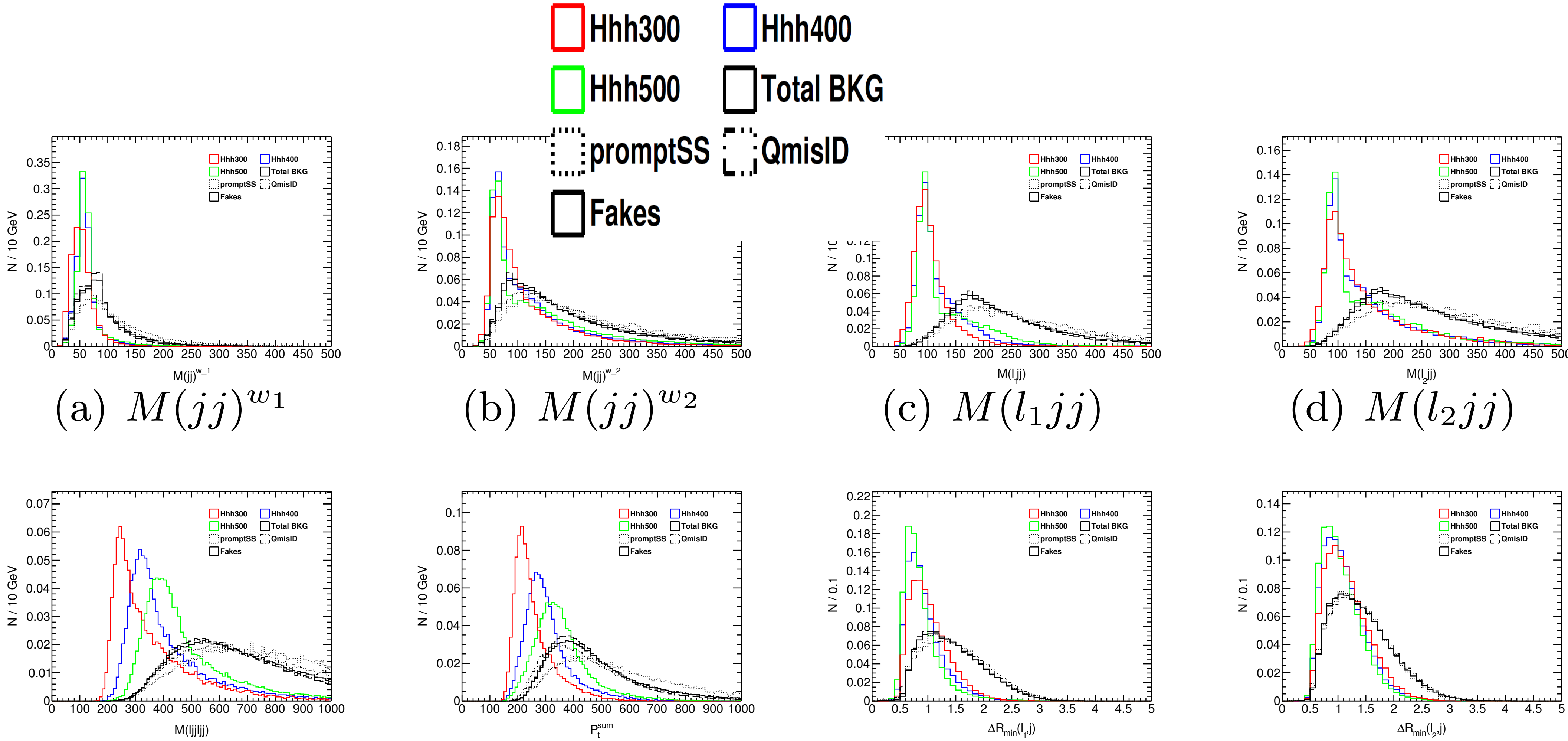


Figure 1: Upper: cross section $\sigma(pp \to HX) \times \mathrm{Br}(H \to hh \to WW^*WW^*)$ in 2HDM with $\tan\beta \in [1, 10]$ with $\sqrt{s}$= 14TeV at LHC, plot(a) and plot(b) present the results for 2HDM-I and 2HDM-II, respectively. Lower: the $M_H - \cos(\beta - \alpha)$ space, plot(a) and (b) present the results for 2HDM-I and 2HDM-II, respectively.

Simulations + pre-selections

- Signal: $M_H = 300, 400\ GeV$
- Samples Production
  - Generator: MG5_aMC
  - Showering: Pythia8
  - Fast simulation/reconstruction: Delphes3.3
- Background components
  - Prompt SS: $t\bar{t}W, t\bar{t}H, W^{\pm}W^{\pm}jjjj, Whjj, WZjjjj$
  - Charge mis-identification: $t\bar{t}(full - leptonical), Z + 4jets$
  - Fakes(jet faking lepton): $t\bar{t}(semi - leptonical), W + 5jets$
- basic cuts + event selection
  - $P_t(\ell) > 10\ GeV, |\eta(\ell)| < 2.5$
  - $P_t(j) > 25\ GeV, |\eta(j)| < 2.5$
  - Overlap removal
  - $n_\ell^{SS} = 2, n_j \geq 4$

Kinematic variables



(a) $M(jj)^{w_1}$ (b) $M(jj)^{w_2}$ (c) $M(l_1jj)$ (d) $M(l_2jj)$

(e) $M(ljjljj)$ (f) P_t^{sum} (g) $\Delta R_{min}(l_1, j)$ (h) $\Delta R_{min}(l_2, j)$

Figure 2: Kinematic distributions of different discriminant variables: 2(a) invariant mass of two closet jets, 2(b) invariant mass of remaining two jets, 2(c) invariant mass of leading lepton and two jets closet to the lepton, 2(d) invariant mass of sub-leading lepton and two remaining jets, 2(e) invariant mass of two leptons and four leading jets, 2(f) linear p_T sum of two leptons and four leading jets, 2(g) minimum ΔR of leading lepton and jet, 2(h) minimum ΔR of sub-leading lepton and jet.

Results-H300

Fake backgrounds(jet faking lepton) dominant, especially $t\bar{t}(semi-leptonical)$
A MVA method(BDT) is used to enhance significance.

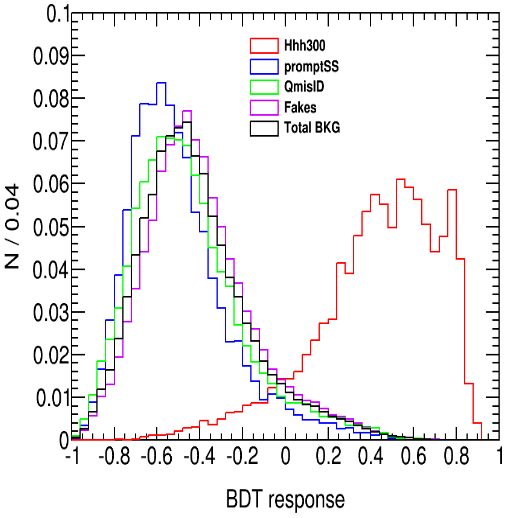


Table 1: Table of cross section after selections and significance with the assumption of $M_H = 300$ GeV at $\int Ldt = 300\ fb^{-1}$

	cross section(fb)	basic cuts + event selection	b-veto	$p_T^{l_1}$, $\not{E}_T$	$BDT > 0.52$
H300	11.4	1.40	1.23	0.86	0.37
ttW	50.5	8.2	1.0	0.92	0.0028
tth	12.6	2.00	0.28	0.25	0.00364
$Whjj$	3.9	0.28	0.24	0.21	0.0030
$WW4j$	19.6	2.74	2.43	2.28	0.00379
$WZ4j$	155	14.1	12.6	10.2	0.0144
$Z+4jets$	51.5	5.6	5.1	1.6	0.00144
$t\bar{t}(full-leptonical)$	36.3	6.7	0.89	0.80	0.0023
$W+5jets$	88.7	0.66	0.60	0.52	0.00082
$t\bar{t}(semi-leptonical)$	1014	100.0	62.4	56.6	0.106
total bkg	1432.1	140.28	85.54	73.38	0.138
Z_0	1.9	1.05	1.2	1.7	13

$$Z_0 = \sqrt{2[(S+B)ln(\frac{S+B}{B}) - S]}$$

Results-H400

Table 2: Table of cross section after selections and significance with the assumption of $M_H = 400$ GeV at $\int Ldt = 300\ fb^{-1}$

	cross section(fb)	basic cuts + event selection	b-veto	$p_T^{l_1}$, $\not{E}_T$	BDT
H400	4.1	0.72	0.62	0.48	0.12
ttW	50.5	8.2	1.0	0.92	0.0015
tth	12.6	2.00	0.28	0.25	0.0020
$Whjj$	3.9	0.28	0.24	0.21	0.0014
$WW4j$	19.6	2.74	2.43	2.28	negligible
$WZ4j$	155	14.1	12.6	10.2	0.010
$Z+4jets$	51.5	5.6	5.1	1.6	0.00062
$t\bar{t}(full-leptonical)$	36.3	6.7	0.89	0.80	0.0016
$W+5jets$	88.7	0.66	0.60	0.52	0.0
$t\bar{t}(semi-leptonical)$	1014	100.0	62.4	56.6	0.0479
total bkg	1432.1	140.28	85.54	73.38	0.065
Z_0	1.9	1.05	1.2	0.95	6.6

Probing 2HDM parameter space at LHC

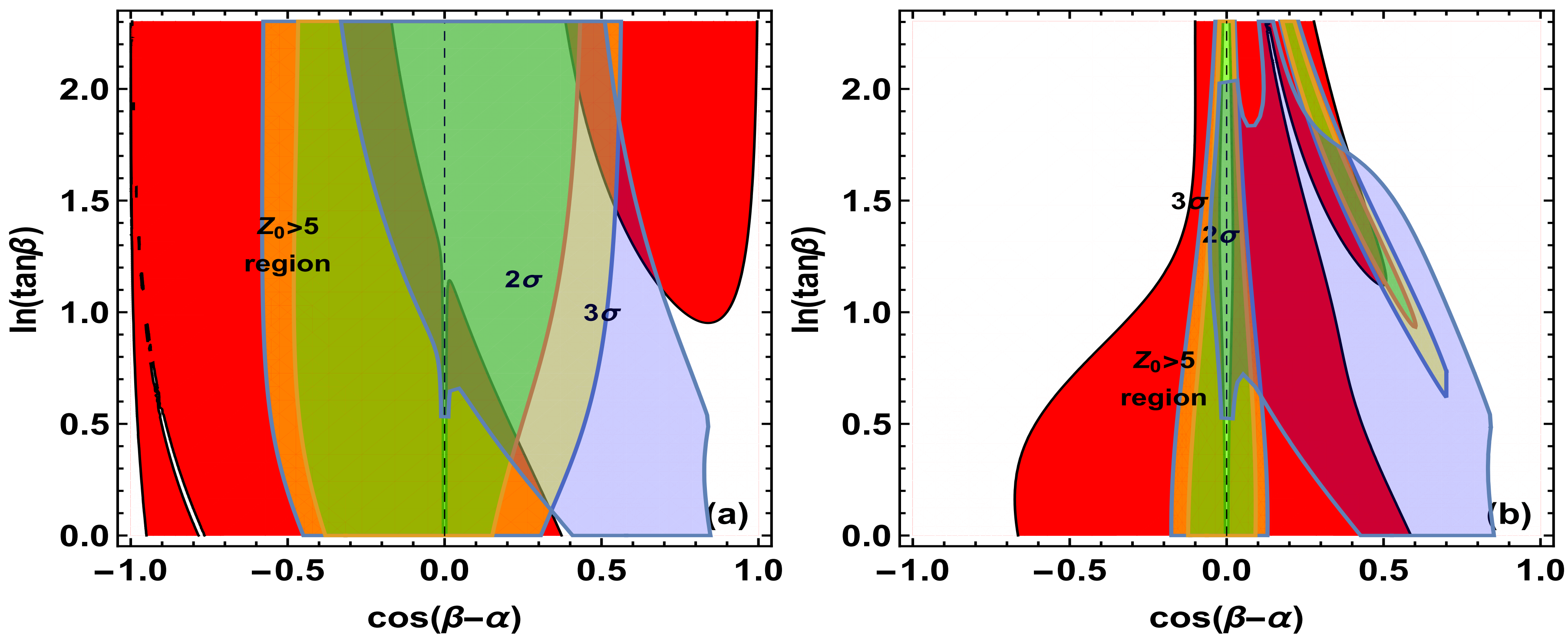


Figure 3: $M_H = 300\ GeV$, Left: 2HDM-I, Right: 2HDM-II; brown and blue regions are corresponding to SM higgs constraints under 3σ confidence level and $H \to hh, H \to VV$ constraints, respectively; red represents the discovery region via $hh \to WW^*WW^*$. Both cases are under the assumption of at $\int Ldt = 300 fb^{-1}$ with $\sqrt{s} = 14\ TeV$.

Probing 2HDM parameter space at LHC

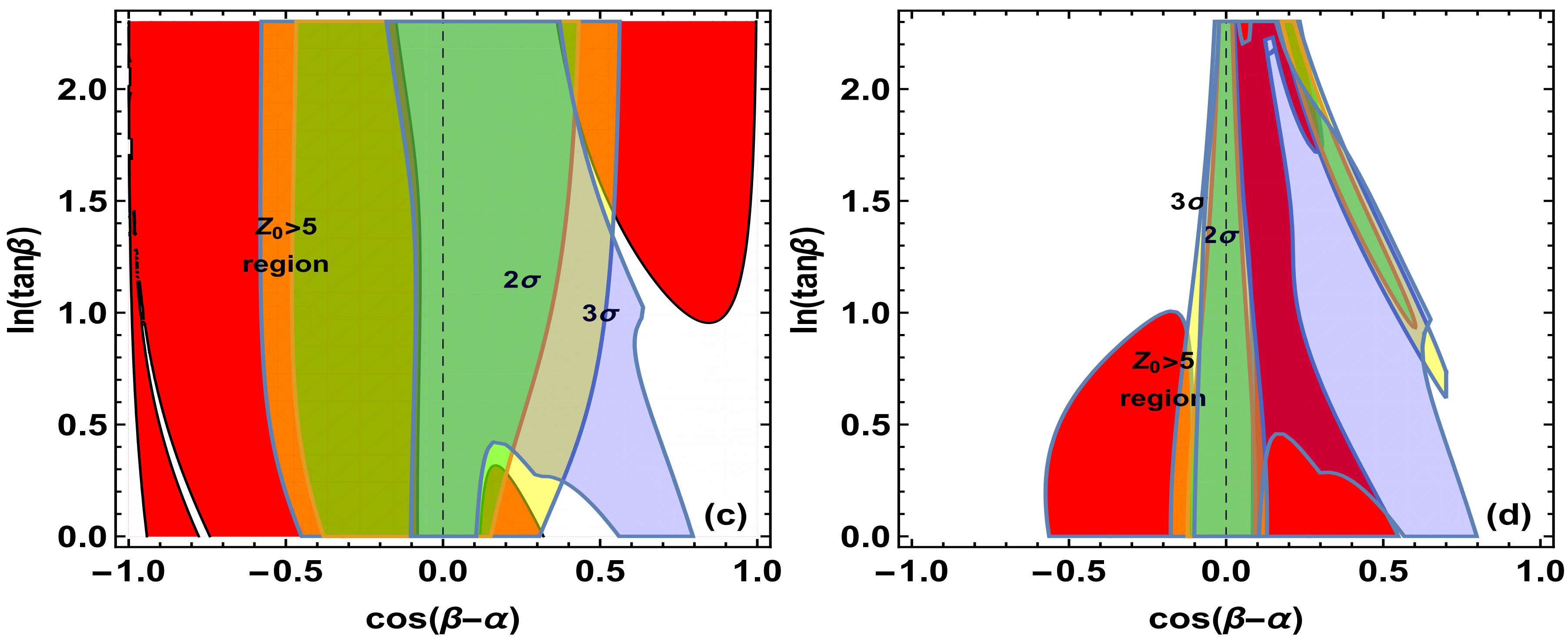


Figure 4: $M_H = 400\ GeV$, Left: 2HDM-I, Right: 2HDM-II; brown and blue regions are corresponding to SM higgs constraints under 3σ confidence level, and $H \to hh, H \to VV$ constraints, respectively. red represents the discovery region via $hh \to WW^*WW^*$. Both cases are under the assumption of at $\int Ldt = 300fb^{-1}$ with $\sqrt{s} = 14\ TeV$.

Conclusions

- $H \to hh \to WW^*WW^*$ phenomenological study was performed within 2HDM; with kinematic selections, the signal significance could be enhanced to 5;
- For low mass of H, both types keep potential parameter space for discovery, but type-I is more sensitive;
- For high mass of H, it's less sensitive and type-II is worse;
- It is encouraged to perform $hh \to WW^*WW^*$ search at LHC.

Thank you!

Comparisons with $WW\gamma\gamma$

Table 2: Signal and background cross sections of $pp \to WW^*\gamma\gamma \to \ell\nu\ell\nu\gamma\gamma$ and $pp \to WW^*\gamma\gamma \to q\bar{q}'\ell\nu\gamma\gamma$ processes at the LHC (14 TeV) after each set of cuts. The signal significance(Z_0) is computed for the LHC (14 TeV) runs with 300 fb^{-1} integrated luminosity. We input the heavier Higgs mass $M_H = 300$ GeV, and set the sample signal cross section as $\sigma(pp \to H \to hh \to WW^*\gamma\gamma) = 5$ fb. From the 3rd to 5th columns, we show the signals and backgrounds after imposing each set of cuts. The "Selection + Basic Cuts" are choosing according to Eqs. (11)–(12). In the pure leptonic mode, we impose the Final Cuts $M_T(\ell\ell\nu\nu), M(\ell\ell)$, $M_T(\ell\ell\nu\nu\gamma\gamma)$, $\Delta\phi(\ell\ell)$, $\Delta R(\ell\ell)$, and $\Delta R(\gamma\gamma)$. In the semi-leptonic mode, we add the Final Cuts $P_T(\gamma)$ $M_T(q\bar{q}'\ell\nu)$, and $\Delta R(\gamma\gamma)$.

$pp \to \ell\nu\ell\nu\gamma\gamma$	Sum	Selection+Basic Cuts	$M_{\gamma\gamma}, \not{E}_T$	Final Cuts
Signal (fb)	0.525	0.0251	0.0214	0.0161
BG[$\ell\nu\ell\nu\gamma\gamma+\ell\ell\gamma\gamma$] (fb)	153.3	0.937	0.00225	0.000215
BG[$t\bar{t}h$] (fb)	0.0071	0.000493	0.000419	0.000076
BG[Zh] (fb)	0.175	0.0331	0.00210	0.000078
BG[hh] (fb)	0.00222	0.000132	0.000102	0.000062
BG[Total] (fb)	153.48	0.971	0.00488	0.00043
Significance(Z_0)	0.734	0.439	3.70	5.15
$pp \to q\bar{q}'\ell\nu\gamma\gamma$	Sum	Selection+Basic Cuts	$M_{\gamma\gamma}, M_{qq}, \not{E}_T$	Final Cuts
Signal (fb)	2.2	0.124	0.0937	0.0749
BG[$q\bar{q}'\ell\nu\gamma\gamma$] (fb)	31.59	0.580	0.0192	0.00912
BG[$\ell\nu\gamma\gamma$] (fb)	143.3	0.0642	0.00349	0.00182
BG[Wh] (fb)	0.42	0.00509	0.00234	0.00140
BG[WWh] (fb)	0.0023	0.000210	0.000104	0.000050
BG[$t\bar{t}h$] (fb)	0.0148	0.00163	0.000802	0.000420
BG[hh] (fb)	0.00462	0.000291	0.000160	0.000106
BG[th] (fb)	0.0129	0.000479	0.000186	0.000099
BG[Total] (fb)	175.35	0.652	0.0264	0.0130
Significance(Z_0)	2.87	2.59	7.29	7.47

Table 3: Signal and background cross sections of both $pp \to WW^*\gamma\gamma \to \ell\nu\ell\nu\gamma\gamma$ and $pp \to WW^*\gamma\gamma \to q\bar{q}'\ell\nu\gamma\gamma$ processes at the LHC (14 TeV) after each set of cuts. The signal significance(Z_0) is computed for the LHC (14 TeV) runs with 300 fb^{-1} integrated luminosity. We input the heavier Higgs mass $M_H = 400$ GeV, and set the sample signal cross section $\sigma(pp \to H \to hh \to WW^*\gamma\gamma) = 3$ fb. From the 3rd to 5th columns, we present the signals and backgrounds after imposing each set of cuts. In the pure leptonic mode, we impose the Final Cuts $M_T(\ell\ell\nu\nu)$, $M(\ell\ell)$, $M_T(\ell\ell\nu\nu\gamma\gamma)$, $\Delta\phi(\ell\ell)$, $\Delta R(\ell\ell)$, $\Delta\phi(\gamma\gamma)$, and $\Delta R(\gamma\gamma)$. In the semi-leptonic mode, we add the Final Cuts $P_T(\gamma)$, $M_T(q\bar{q}'\ell\nu)$, $\Delta\phi(\gamma\gamma)$, and $\Delta R(\gamma\gamma)$.

$pp \to \ell\nu\ell\nu\gamma\gamma$	Sum	Selection+Basic Cuts	$M_{\gamma\gamma}, \not{E}_T$	Final Cuts
Signal (fb)	0.315	0.0165	0.0147	0.0107
BG[$\ell\nu\ell\nu\gamma\gamma+\ell\ell\gamma\gamma$] (fb)	153.3	0.937	0.00394	0.000169
BG[$t\bar{t}h$] (fb)	0.0071	0.000493	0.000452	0.000051
BG[Zh] (fb)	0.175	0.0331	0.00247	0.000065
BG[hh] (fb)	0.00222	0.000132	0.000116	0.000074
BG[Total] (fb)	153.48	0.971	0.00698	0.000359
Significance(Z_0)	0.440	0.289	2.44	4.05
$pp \to q\bar{q}'\ell\nu\gamma\gamma$	σ_{total}	Selection+Basic Cuts	$M_{\gamma\gamma}, M_{qq}, \not{E}_T$	Final Cuts
Signal (fb)	1.32	0.0891	0.0671	0.0533
BG[$qq\ell\nu\gamma\gamma$] (fb)	31.59	0.581	0.0291	0.00672
BG[$\ell\nu\gamma\gamma$] (fb)	143.3	0.0642	0.00454	0.000891
BG[Wh] (fb)	0.42	0.00509	0.00335	0.00139
BG[WWh] (fb)	0.0023	0.000210	0.000127	0.000057
BG[$t\bar{t}h$] (fb)	0.0148	0.00163	0.00111	0.000441
BG[hh] (fb)	0.00462	0.000291	0.000197	0.000155
BG[th] (fb)	0.0129	0.000479	0.000247	0.000104
BG[Total] (fb)	175.35	0.653	0.0386	0.0098
Significance(Z_0)	1.72	1.87	4.86	6.22

Assuming same cross-section($\sigma(pp \to H \to hh) = 1\ pb$):

	$M_H = 300\ GeV$	$M_H = 400\ GeV$
$Z_0(WW^*WW^*)/Z_0(WW^*\gamma\gamma)$	0.84	0.99