Multi-Higgs boson@LHC and future colliders

Xiaoran Zhao[1,2]
with Qi-Shu Yan, etc.
arXiv:1503.07611 & arXiv:1510.04013

[1]University of Chinese Academy of Sciences,
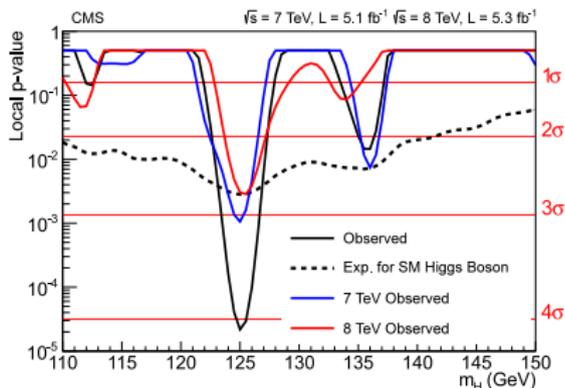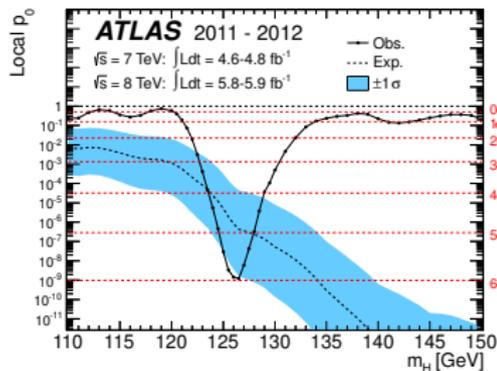[2]Institute of High Energy Physics, CAS

20/11/2015

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Higgs discovery

4th July, 2012, observation of a Higgs-like boson by ATLAS and CMS.
Is it SM Higgs?

[0] 1207.7214, 1207.7235
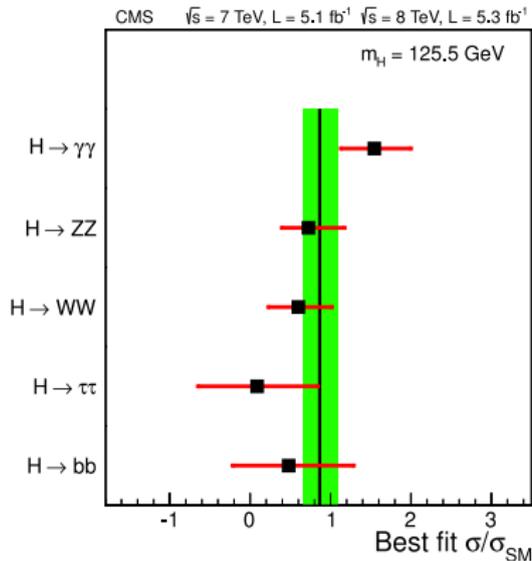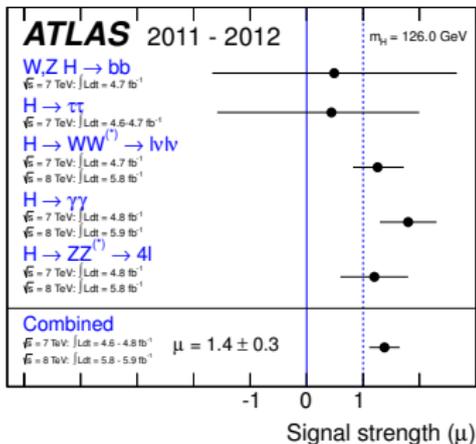
Higgs coupling

Higgs self coupling and pair production

After EWSB:

$$V = \frac{1}{2}m_h^2 h^2 + \lambda_3 \lambda_{\mathrm{SM}} v h^3 + \lambda_4 \frac{1}{4} \lambda_{\mathrm{SM}} h^4$$

$$\lambda_{\mathrm{SM}} = \frac{m_h^2}{2v^2}$$

- λ_3: 14TeV LHC, future hadron collider, ILC/CEPC/other lepton collider.
- λ_4: future hadron collider ?

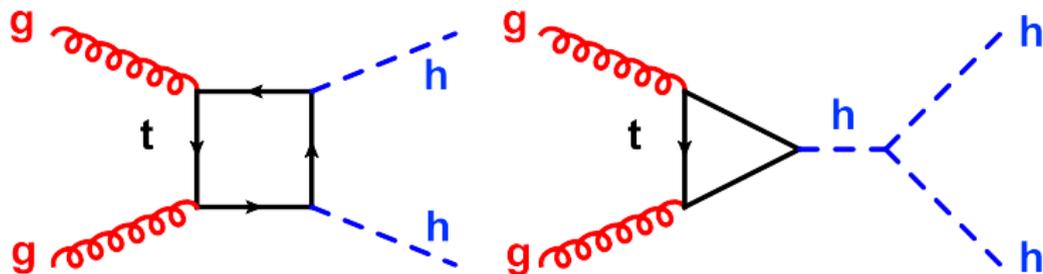# Higgs decay and previous study about Higgs pair

Branching Ratios for 125GeV SM Higgs:

Mode	Branching Ratio
$b\bar{b}$	57.8%
$\tau^+\tau^-$	6.37%
$\ell\nu jj$	6.34%
$\ell\ell\nu\nu$	1.07%
$\gamma\gamma$	0.230%
$Z\gamma$	0.155%
$\mu^+\mu^-$	0.0221%
$\ell\ell\ell\ell$	0.0126%

Studied Mode for Higgs pair production:
$b\bar{b}\gamma\gamma, b\bar{b}b\bar{b}, b\bar{b}\tau^+\tau^-, b\bar{b}\ell\nu jj, b\bar{b}\ell\ell\nu\nu$

$HH \rightarrow WWWW$ mode

$BR(H \rightarrow WW^*) \approx 21.6\%$

Only same signed di-lepton mode $\ell^\pm \ell^\pm jjjj\nu\nu$ and three leptons mode $\ell\ell\ell jj\nu\nu$ are reachable at 14TeV LHC.

They have been considered by Baur,Plehn,Rainwater(02,03), but for $m_H > 140\,\text{GeV}$. For 125GeV Higgs boson, the branching ratio of Higgs decaying to WW^* is much smaller, and one of the two W bosons is off-shell.

Solution: Partial reconstruction for $3\ell 2j + \not{E}_T$ final-state, m_{T2}, and multivariate analysis.

lepton flavour

Signal and main background cross sections at 14TeV LHC:

processes	$\sigma^{\mathrm{LO}} \times \mathrm{BR}$(fb)
Signal	3.0×10^{-2}
$Z(\gamma)W$	233
$t\bar{t}W^{\pm}$	4.6
$t\bar{t}H$	2.1
$HW^{\pm}$	1.2
WWW	1.4

Huge ZW background $\rightarrow$ only consider $\ell^{\pm}\ell^{\pm}\ell'^{\mp}$ mode:
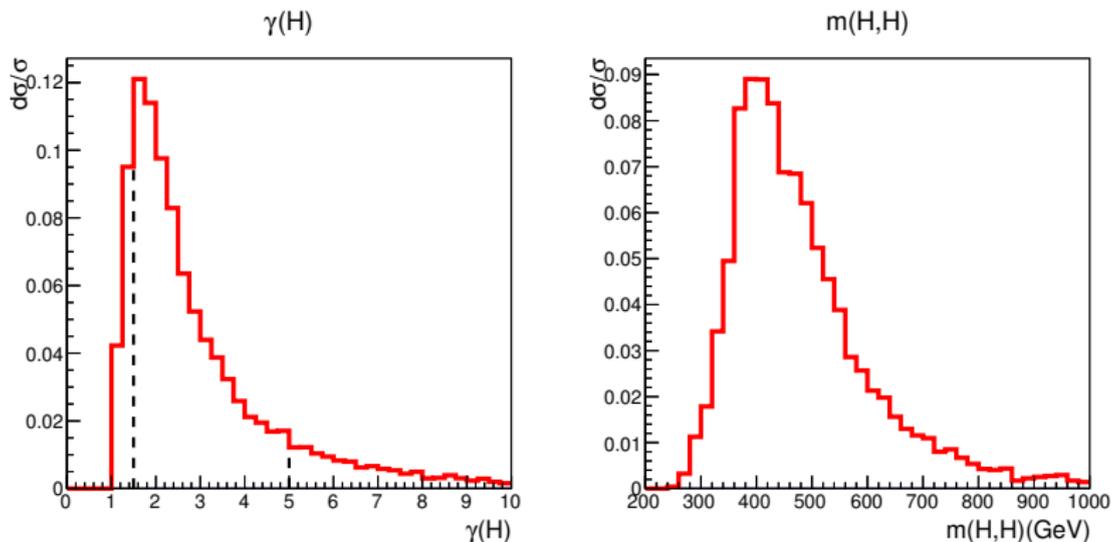$e^+e^+\mu^-, e^-e^-\mu^+, \mu^+\mu^+e^-, \mu^-\mu^-e^+$

Higgs partial reconstruction

For the decay mode $\ell_1^\pm \ell_2^\pm \ell_3^\mp 2j + E$, ignoring neutrinos, two combination exist:

- $H(\ell_1^\pm \ell_3^\mp), H(\ell_2^\pm jj)$
- $H(\ell_2^\pm \ell_3^\mp), H(\ell_1^\pm jj)$

Using the property of boosted Higgs boson to determinate combination.

Higgs boost

γ factor ($\gamma = E(H)/m_H$) and the invariant mass of Higgs pair. Higgs boson is moderately boosted due to top quark loop.

Choices

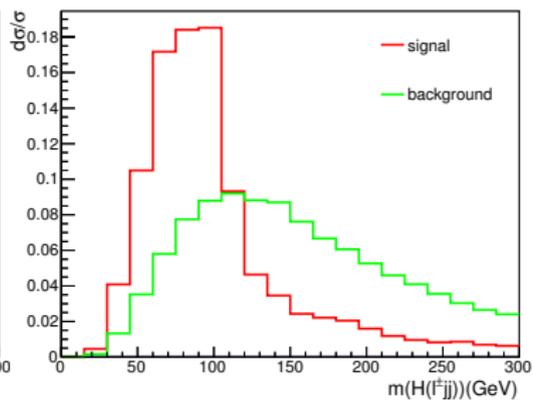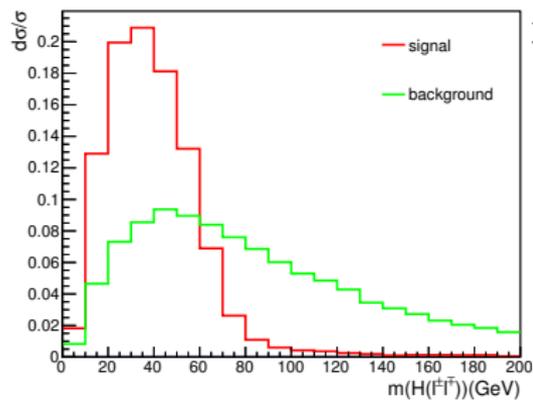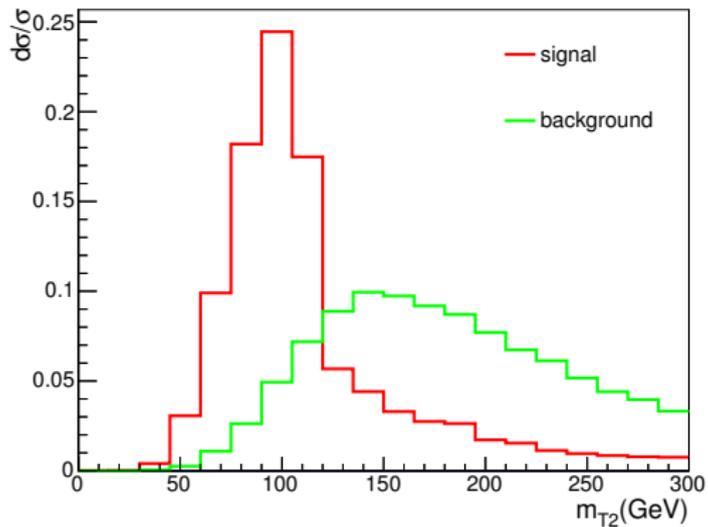| Methods	The percentage of correctness (%)
$\lvert m_{H(ll)} - m_{H(ljj)} \rvert$	68.9
$\Delta_R(l^\pm, l^\mp)$	85.0
$\Delta_R(l^\pm, W_{jj})$	89.9
$P_t[H(ll)] + P_t[H(ljj)]$	90.3
$\Delta_R(H(ll), H(ljj))$	92.0
$m_{H(ll)} + m_{H(ljj)}$	95.4

The percentage of correctness at the parton level.

W jets
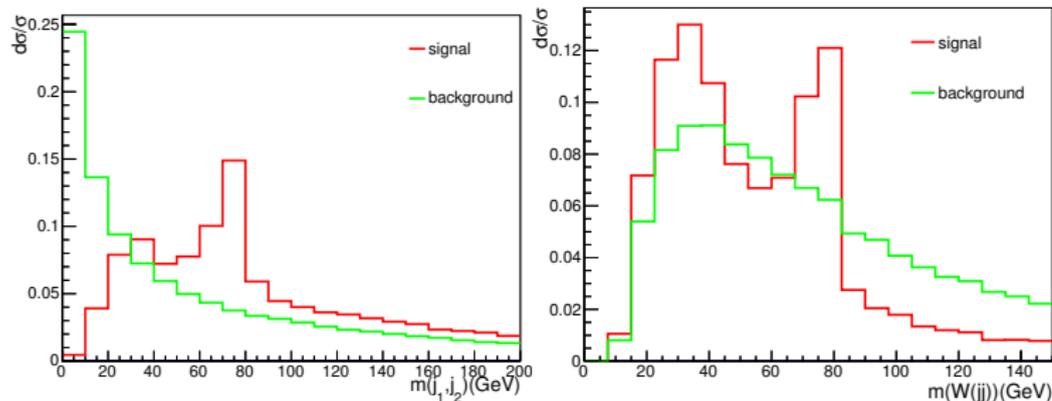
left:the invariant mass of two hardest jets
right:the reconstructed $W(jj)$ mass with $PT(j) > 15 GeV$
Choose two jets which make $m_{H(ll)} + m_{H(ljj)}$ smallest.

Reconstruction results

m_{T2}

$$H_1 \rightarrow (ll) + (\nu\nu)$$
$$H_2 \rightarrow (ljj) + (\nu)$$

The end point of m_{T2} should be about higgs mass.

Significance

14TeV, 3000fb^{-1}

	after preselection	Cut	MLP	BDT
Signal	13.7	6.2	5.7	3.8
Background	913.5	36.8	21.7	6.2
S/B	1.5×10^{-2}	0.17	0.26	0.62
$S/\sqrt{B}$	0.45	1.0	1.2	1.5

100TeV, 3000fb^{-1}

	after preselection	Cut	MLP	BDT
Signal	416.8	160.0	80.4	104.0
Background	14801.8	523.6	107.3	67.1
S/B	2.8×10^{-2}	0.31	0.75	1.5
$S/\sqrt{B}$	3.43	7.0	7.8	12.7

λ_3

Sensitivity at LHC 14 TeV with a 3000/fb dataset

No. of signal events
95% C.L.
1σ region
2σ region

Sensitivity at LHC 100 TeV

No. of signal events
2.5σ exclusion bound
5σ discovery bound

χ_2 fit
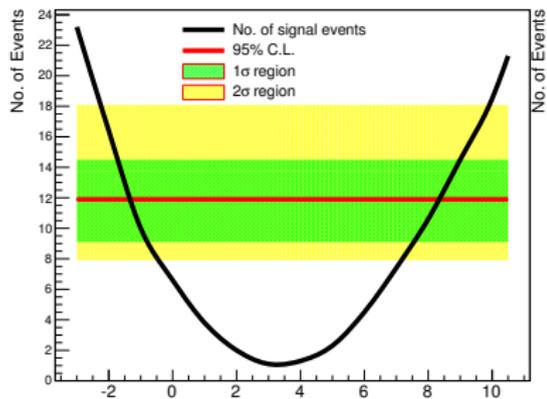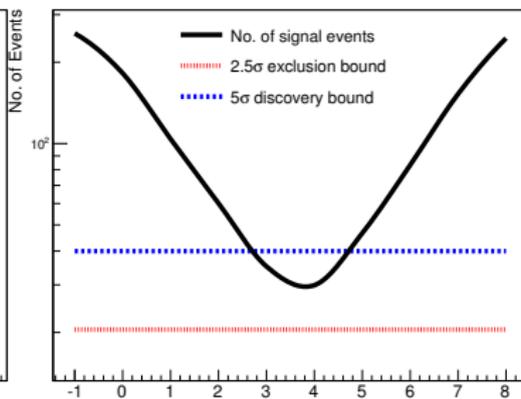
Fit m_{lll} distribution
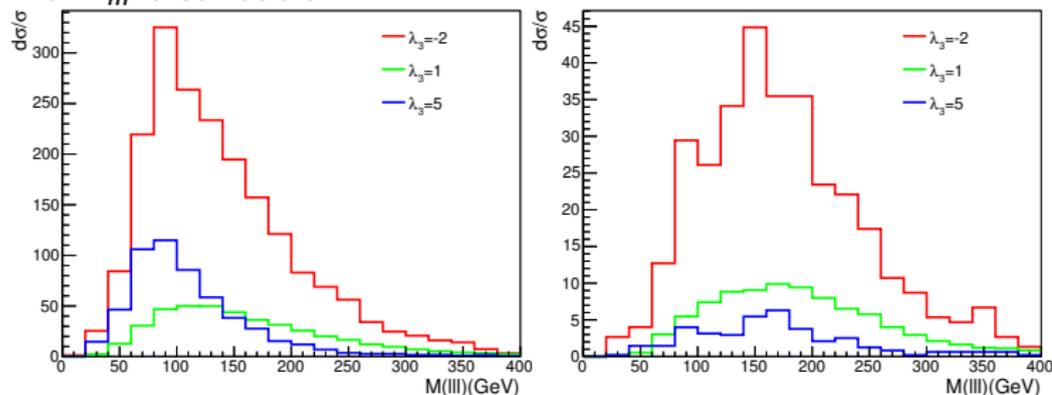
$$\chi^2(\lambda_3) = \sum_{i=1}^{n_D} \frac{(N_i - fN_i^0)^2}{fN_i^0} + (n_D - 1),$$

[0]U. Baur, T. Plehn and D. L. Rainwater, Phys. Rev. D 67, 033003 (2003)
[0]U. Baur and E. L. Berger, Phys. Rev. D 47, 4889 (1993).

$\chi^2(\lambda_3)$ extracted from fitting m(lll)

$\chi^2(\lambda_3)$ extracted from fitting m(lll)
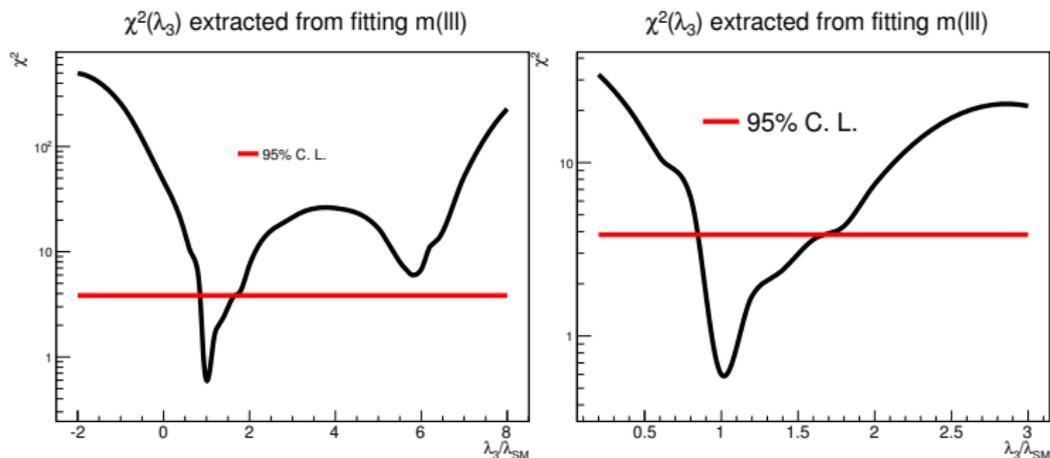
We can distinguish $\lambda_3 = 1$ and $\lambda_3 \approx 6$ though the total event number after cut is same.

The value of λ_3 can be determined as $1^{+0.6}_{-0.3}$ in the 95% confidence level.

tiny cross section at e^+e^- colliders
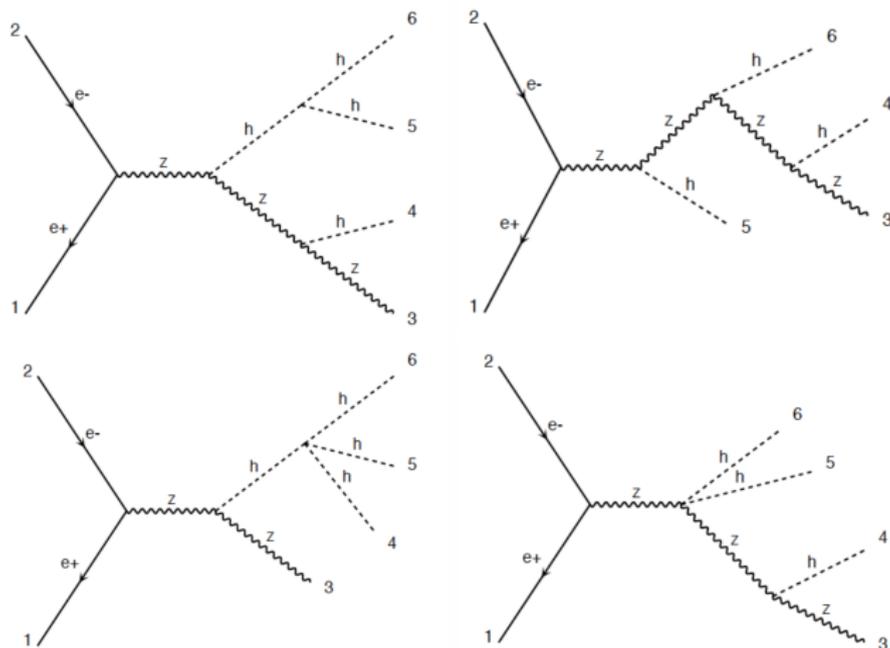
E_{CM}	500 GeV	1 TeV	3 TeV
$\sigma(e^+e^- \to Zhhh)$	3.3×10^{-3} ab	4.1×10^{-1} ab	1.5×10^{-1} ab

Table: Production rates of triple Higgs boson at e^+e^- colliders@LO

triple Higgs production at hardon colliders
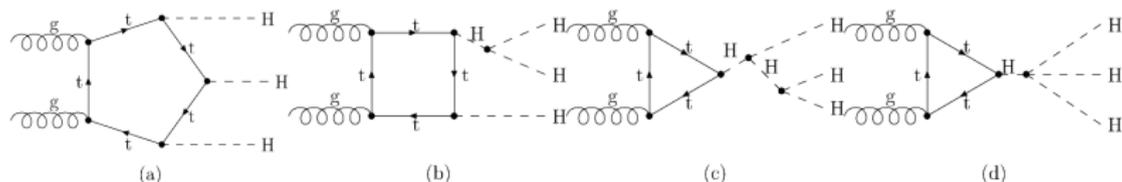
E_{CM}	14 TeV	33 TeV	100 TeV
$\sigma(gg \rightarrow hhh)$	4.1×10^{-2} fb	0.33 fb	3.2 fb

Table: Production rates of triple Higgs boson at pp colliders@LO

- What is the minimal luminosity to observe the signature of triple Higgs production via $4b2\gamma$ at a 100TeV hadron collider?
- What will be the bounds to λ_3 and λ_4 at a 100TeV collider with assumend integrated luminosity $30\,\text{ab}^{-1}$
- What is the discovery potential to new physcis via $pp \to hhh \to 4b2\gamma$

Decay Channel	Branching Ratio
$HHH \rightarrow b\bar{b}b\bar{b}W^+W^-$	22.34%
$HHH \rightarrow b\bar{b}b\bar{b}b\bar{b}$	20.30%
$HHH \rightarrow b\bar{b}W^+W^-W^+W^-$	8.20%
$HHH \rightarrow b\bar{b}b\bar{b}\tau^+\tau^-$	7.16%
$HHH \rightarrow b\bar{b}b\bar{b}gg$	6.54%
$HHH \rightarrow b\bar{b}b\bar{b}ZZ$	2.69%
$HHH \rightarrow W^+W^-W^+W^-W^+W^-$	1.00%
$HHH \rightarrow W^+W^-W^+W^-\tau^+\tau^-$	0.96%
$HHH \rightarrow W^+W^-W^+W^-gg$	0.88%
$HHH \rightarrow W^+W^-W^+W^-ZZ$	0.36%
$HHH \rightarrow b\bar{b}b\bar{b}\gamma\gamma$	0.29%

Why $hhh \rightarrow 4b2\gamma$

Preselection Cuts	Description
1	Number of tagged b jets $n_b \geq 2$ and $P_t(j) > 30$ GeV with $4 \leq n_j \leq 5$
2	Number of photons $n_\gamma = 2$ with $P_t(\gamma) > 30$ GeV
3	Number of leptons $n_l = 0$
4	Missing energy cut $MET < 50$ GeV

TABLE IV. The preselection cuts in our analysis are listed.

	$\sigma \times BR$ (fb)	K factors	Events after preselection cuts
Signal	9.5×10^{-3}	2.0	50
$b\bar{b}jj\gamma\gamma$	1.9×10^2	1.0	2.3×10^5
$H(\gamma\gamma)t\bar{t}$	77	1.2	2.2×10^4
S/B	1.9×10^{-4}		
$S/\sqrt{S+B}$	9.8×10^{-2}		
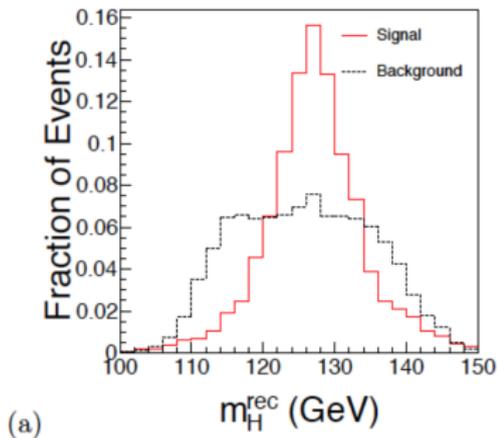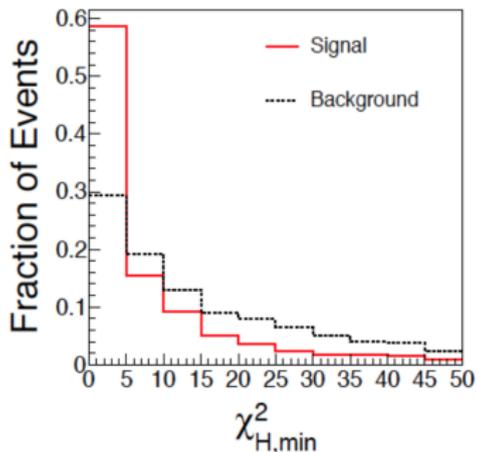
(a)

$$\chi_H^2(m) = \frac{(M(j_1, j_2) - m)^2}{\sigma_j^2} + \frac{(M(j_3, j_4) - m)^2}{\sigma_j^2} + \frac{(M(\gamma, \gamma) - m)^2}{\sigma_\gamma^2}$$

	Signal	$b\bar{b}jj\gamma\gamma$	$Ht\bar{t}$
preselection	50	2.3×10^5	2.2×10^4
$\chi^2_{H,min} < 6.1$	26	4.6×10^4	9.9×10^3
$|m_H^{rec} - 126 \text{ GeV}| < 5.1 \text{ GeV}$	20	1.7×10^4	7.0×10^3
S/B	8.3×10^{-4}		
$S/\sqrt{S+B}$	0.13		
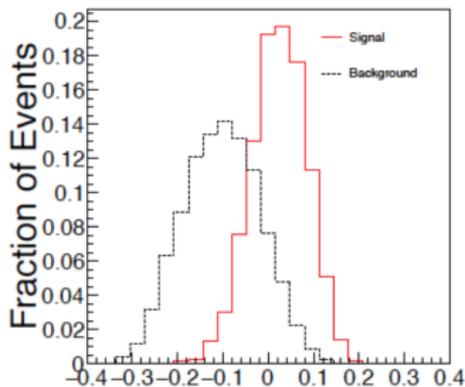
(a) BDT
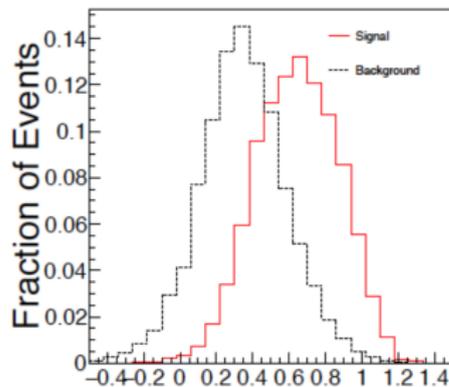
(b) MLP

	Cuts based method	BDT> 0.02	MLP> 0.51
Signal	20	34	49
Background	2.4×10^4	2.8×10^4	9.9×10^4
S/B	8.3×10^{-4}	1.2×10^{-3}	5.0×10^{-4}
$S/\sqrt{S+B}$	0.13	0.20	0.16

Integrated Luminosity (ab^{-1})	30	300	3000	1.83×10^4
$S/\sqrt{S+B}$	0.2	0.6	2.0	5.0

To discover the signal is challenging!
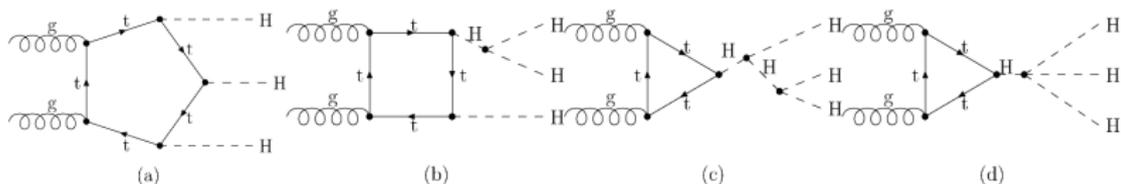
(a)   (b)   (c)   (d)

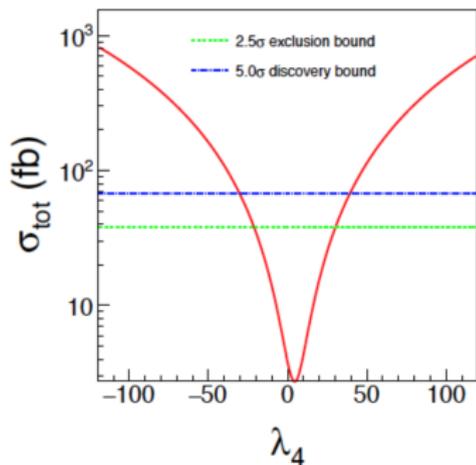$$\sigma(\lambda_3, \lambda_4) = A\lambda_4^2 + (B\lambda_3^2 + C\lambda_3 + D)\lambda_4$$
$$+ E\lambda_3^4 + F\lambda_3^3 + G\lambda_3^2 + H\lambda_3 + I$$

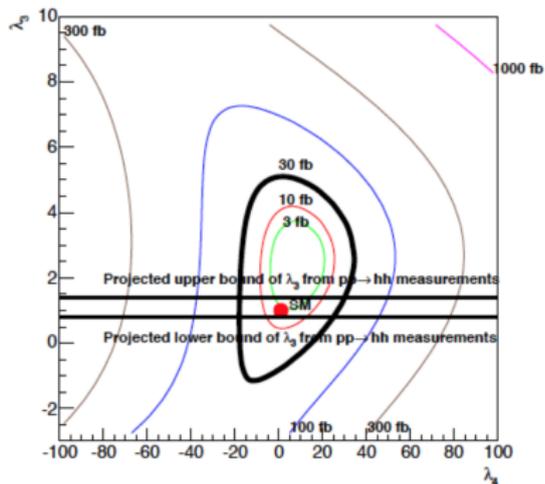| A	B	C	D	E	F	G	H	I
5.28×10^{-2}	0.14	-0.76	0.15	2.28×10^{-2}	-5.36×10^{-2}	3.11	-14.57	15.36

If we fixed $\lambda_3 = 1$

$$\sigma(\lambda_4) = 0.0528\lambda_4^2 - 0.47\lambda_4 + 3.82 \tag{1}$$

Directly detecting quartic coupling is difficult!

(a)The fitted cross section when λ_3 is fixed

(b)The feasibility of λ_3 and λ_4

# Benchmark study for New Physics

SM + Singlet:

$$V(\phi_0, S) = \lambda \left(\phi_0^2 - \frac{v_{EW}^2}{2} \right)^2 + \frac{a_1}{2} \left(\phi_0^2 - \frac{v_{EW}^2}{2} \right) S + \frac{a_2}{2} \left(\phi_0^2 + \frac{v_{EW}^2}{2} \right)$$

$$+ \frac{1}{4} \left(2b_2 + a_2 v_{EW}^2 \right) S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$

	B1	B2	B3
m_{H_2} (GeV)	460	500	490
θ	0.354	0.354	0.354
a_2	3.29	3.48	3.43
b_3 (GeV)	-706	-612	-637
b_4	8.38	8.38	8.38

	B1	B2	B3
$\Gamma_{\text{tot}}(H_2)$ (GeV)	5.6	7.5	7.0
$BR(H_2 \to W^+W^-)$	0.57	0.56	0.57
$BR(H_2 \to ZZ)$	0.27	0.27	0.27
$BR(H_2 \to t\bar{t})$	0.15	0.16	0.16
$BR(H_2 \to b\bar{b})$	3.4×10^{-4}	2.8×10^{-4}	2.9×10^{-4}
$BR(H_2 \to HH)$	5.3×10^{-7}	8.8×10^{-7}	1.5×10^{-7}
$BR(H_2 \to HHH)$	1.0×10^{-3}	1.4×10^{-3}	1.3×10^{-3}
$\sigma(gg \to H_2)$ @ 14 TeV (fb)	3.2×10^2	2.3×10^2	2.5×10^2
$\sigma(gg \to HHH)$ @ 14 TeV (fb)	0.70	0.69	0.71
$\sigma(gg \to H_2)$ @ 100 TeV (fb)	1.4×10^4	1.1×10^4	1.2×10^4
$\sigma(gg \to HHH)$ @ 100 TeV (fb)	37	38	39

(a)

(b)
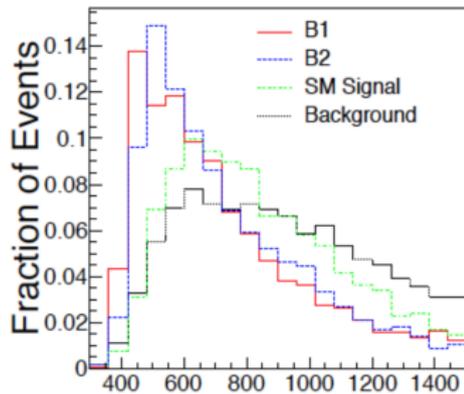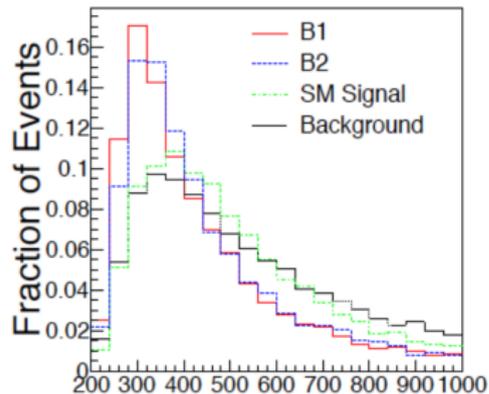
	SM(BDT> 0.02)	B1(BDT> -0.02)	B2(BDT> -0.02)	B3(BDT> -0.03)
Signal	34	3.7×10^2	4.4×10^2	4.6×10^2
Background	2.8×10^4	3.0×10^4	3.1×10^4	4.0×10^4
S/B	1.2×10^{-3}	1.2×10^{-2}	1.4×10^{-2}	1.1×10^{-2}
$S/\sqrt{S+B}$	0.20	2.1	2.5	2.3

conclusion

$HH \to 3\ell 2j + \not{E}_T$: 1.5σ at LHC 14TeV 3000 fb^{-1} determine λ_3 into the range $1^{+0.6}_{-0.3}$ at 100TeV 3000 fb^{-1} pp collider.
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$: at 100TeV pp collider, require 1.83×10^4 ab^{-1} to reach 5σ, and to determine λ_4 is still challenging.

Thank you!