

# Higgcision & Higgs Boson Pair Production

KC, Jae-Sik Lee, Po-Yan Tseng:: 1302.3794, 1310.3937, 1403.2053, 1407.8236  
Jung Chang, KC, Jae-Sik Lee, Chih-Ting Lu 1403.2053  
Jung Chang, KC, Jae-Sik Lee, Chih-Ting Lu 1505.00957

## Outlines

---

1. Present status of the Higgs boson – Higgcision.
2. Single top plus Higgs production.
3. Higgs boson pair production.

## Higgs Mechanism

---

- So far the Higgs mechanism for masses of gauge bosons and fermions, and interactions of Higgs with gauge bosons and fermions are consistent with a simple Higgs doublet.
- The scalar sector Lagrangian

$$\mathcal{L}_\Phi = |D_\mu \Phi|^2 - V(\Phi) + \mathcal{L}_Y$$

where

$$V(\Phi) = \mu^2 |\Phi|^2 + \lambda |\Phi|^4$$

and

$$D_\mu = \partial_\mu + ieQA_\mu + i\frac{g}{\sqrt{2}}(\tau^+ W_\mu^+ + \tau^- W_\mu^-) + i\frac{g}{\cos\theta_w} \left( \frac{\tau^3}{2} - \sin^2\theta_w \right) Z_\mu$$

- $\Phi$  develops a true vacuum at  $\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$ , where  $v = \sqrt{-\mu^2/\lambda}$ .
- The mass and interactions of gauge bosons are fixed

$$\mathcal{L} = (v^2 + 2vH + H^2) \left( \frac{1}{4} g^2 W_\mu^+ W^{-\mu} + \frac{1}{8} g_z^2 Z^\mu Z_\mu \right)$$

- The mass and interactions of fermions are also fixed in  $\mathcal{L}_Y$ :

$$\mathcal{L}_Y = -\frac{y_e v}{\sqrt{2}} (\overline{e_L} e_R + \overline{e_R} e_L) - \frac{y_e}{\sqrt{2}} H (\overline{e_L} e_R + \overline{e_R} e_L)$$

So far, the gauge boson couplings and  $b, \tau, t$  Yukawa couplings are consistent with data.

- We have no information about  $V(\Phi)$  except that it gives a nontrivial VEV. In the SM,

$$V(\phi) = -\frac{\lambda}{4} v^4 + \frac{1}{2} m_H^2 H^2 + \frac{m_H^2}{2v} H^3 + \frac{\lambda}{4} H^4$$

This is the simplest structure. The self couplings are fixed. But for extended Higgs sector it is not the case.

## Higgs Precision – Higgcision

---

KC, JS Lee, PY Tseng 1302.3794, 1310.3937, 1403.4775, 1407.8236, 1501.03552.

We have established formalism to compare the Higgs signal strengths versus the Higgs boson couplings, including CP-even and CP-odd ones, in model-independent, 2HDMs, MSSM.

### **Formalism:**

- Fermionic couplings

$$\mathcal{L}_{H\bar{f}f} = - \sum_{f=u,d,l} \frac{gm_f}{2M_W} \sum_{i=1}^3 H \bar{f} \left( g_{H\bar{f}f}^S + ig_{H\bar{f}f}^P \gamma_5 \right) f .$$

For the SM  $g_{H\bar{f}f}^S = 1$  and  $g_{H\bar{f}f}^P = 0$ .

- gauge boson couplings:

$$\mathcal{L}_{HVV} = g M_W \left( g_{HWW} W_\mu^+ W^{-\mu} + g_{HZZ} \frac{1}{2c_W^2} Z_\mu Z^\mu \right) H .$$

- two photons:

$$\mathcal{M}_{\gamma\gamma H} = -\frac{\alpha M_H^2}{4\pi v} \left\{ S^\gamma(M_H) (\epsilon_{1\perp}^* \cdot \epsilon_{2\perp}^*) - P^\gamma(M_H) \frac{2}{M_H^2} \langle \epsilon_1^* \epsilon_2^* k_1 k_2 \rangle \right\},$$

$$S^\gamma(M_H) = 2 \sum_{f=b,t,\tau} N_C Q_f^2 g_{H\bar{f}f}^S F_{sf}(\tau_f) - g_{HWW} F_1(\tau_W) + \Delta S^\gamma,$$

$$P^\gamma(M_H) = 2 \sum_{f=b,t,\tau} N_C Q_f^2 g_{H\bar{f}f}^P F_{pf}(\tau_f) + \Delta P^\gamma,$$

Numerically, taking  $M_H = 125.5$  GeV, we find that

$$\begin{aligned} S^\gamma &\simeq -8.35 g_{HWW} + 1.76 g_{H\bar{t}t}^S + (-0.015 + 0.017 i) g_{H\bar{b}b}^S \\ &\quad + (-0.024 + 0.021 i) g_{H\bar{\tau}\tau}^S + (-0.007 + 0.005 i) g_{H\bar{c}c}^S + \Delta S^\gamma \end{aligned}$$

$$\begin{aligned} P^\gamma &\simeq 2.78 g_{H\bar{t}t}^P + (-0.018 + 0.018 i) g_{H\bar{b}b}^P \\ &\quad + (-0.025 + 0.022 i) g_{H\bar{\tau}\tau}^P + (-0.007 + 0.005 i) g_{H\bar{c}c}^P + \Delta P^\gamma \end{aligned}$$

giving  $S_{\text{SM}}^\gamma = -6.64 + 0.043 i$  and  $P_{\text{SM}}^\gamma = 0$ .

- two gluons

$$\mathcal{M}_{ggH} = -\frac{\alpha_s M_H^2 \delta^{ab}}{4\pi v} \left\{ S^g(M_H) (\epsilon_{1\perp}^* \cdot \epsilon_{2\perp}^*) - P^g(M_H) \frac{2}{M_H^2} \langle \epsilon_1^* \epsilon_2^* k_1 k_2 \rangle \right\},$$

$$S^g(M_H) = \sum_{f=b,t} g_{H\bar{f}f}^S F_{sf}(\tau_f) + \Delta S^g, \quad P^g(M_H) = \sum_{f=b,t} g_{H\bar{f}f}^P F_{pf}(\tau_f) + \Delta P^g$$

$$S^g \quad \simeq \quad 0.688 g_{H\bar{t}t}^S + (-0.037 + 0.050 i) g_{H\bar{b}b}^S + \Delta S^g$$

$$P^g \quad \simeq \quad 1.047 g_{H\bar{t}t}^P + (-0.042 + 0.050 i) g_{H\bar{b}b}^P + \Delta P^g$$

## Signal Strengths:

- The signal strength can be written as the product of

$$\hat{\mu}(\mathcal{P}, \mathcal{D}) \simeq \hat{\mu}(\mathcal{P}) \hat{\mu}(\mathcal{D})$$

where  $\mathcal{P} = \text{ggF}, \text{VBF}, \text{VH}, \text{ttH}$  denote the production mechanisms and  $\mathcal{D} = \gamma\gamma, ZZ, WW, b\bar{b}, \tau\bar{\tau}$  the decay channels.

- On the production side:

$$\hat{\mu}(\text{ggF}) = \frac{|S^g(M_H)|^2 + |P^g(M_H)|^2}{|S_{\text{SM}}^g(M_H)|^2}$$

$$\hat{\mu}(\text{VBF}) = g_{HWW, HZZ}^2$$

$$\hat{\mu}(\text{VH}) = g_{HWW, HZZ}^2$$

$$\hat{\mu}(\text{ttH}) = \left(g_{H\bar{t}t}^S\right)^2 + \left(g_{H\bar{t}t}^P\right)^2$$

- On the decay side

$$\hat{\mu}(\mathcal{D}) = \frac{B(H \rightarrow \mathcal{D})}{B(H_{\text{SM}} \rightarrow \mathcal{D})}$$

$$B(H \rightarrow \mathcal{D}) = \frac{\Gamma(H \rightarrow \mathcal{D})}{\Gamma_{\text{tot}}(H) + \Delta\Gamma_{\text{tot}}}$$

- Experimentally observed signal strength is a sum over all production mechanisms:

$$\mu(Q, \mathcal{D}) = \sum_{\mathcal{P}=\text{ggF, VBF, VH, ttH}} C_{Q\mathcal{P}} \hat{\mu}(\mathcal{P}, \mathcal{D})$$

the decomposition coefficients  $C_{Q\mathcal{P}}$  may depend on the relative Higgs production cross sections for a given Higgs-boson mass, experimental cuts, etc.

## Fitting analysis

---

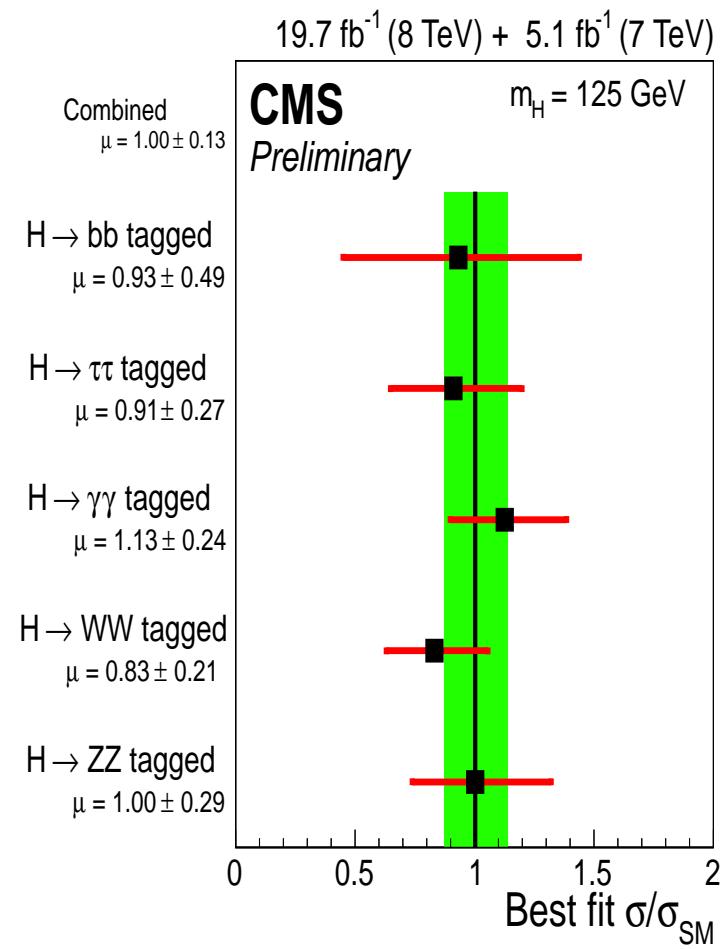
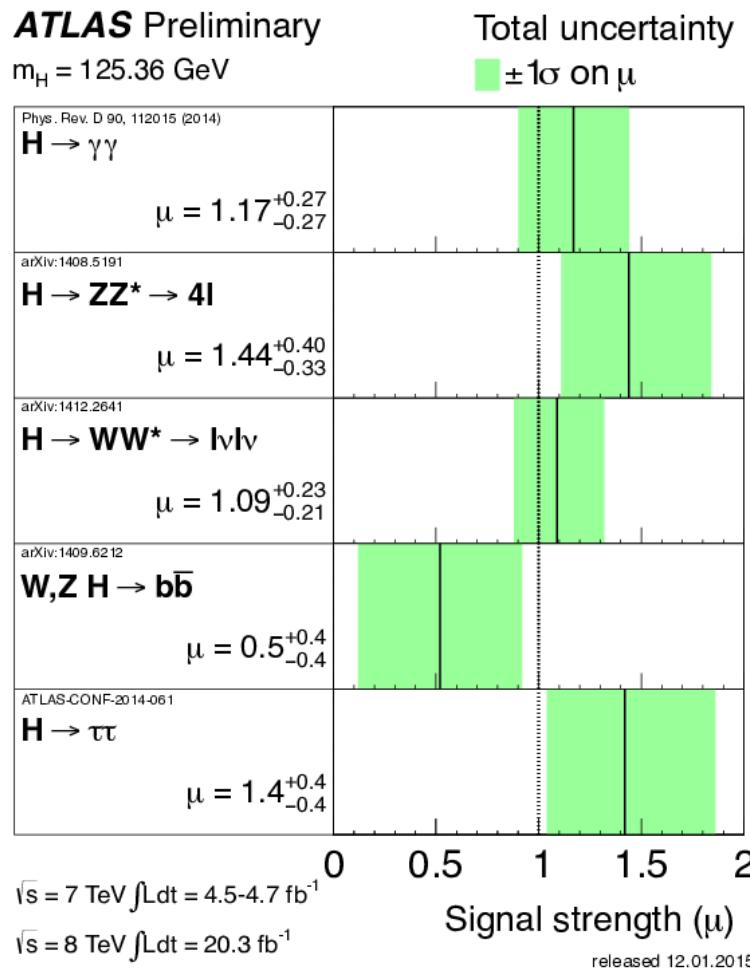
- Ratios of Yukawa and gauge couplings

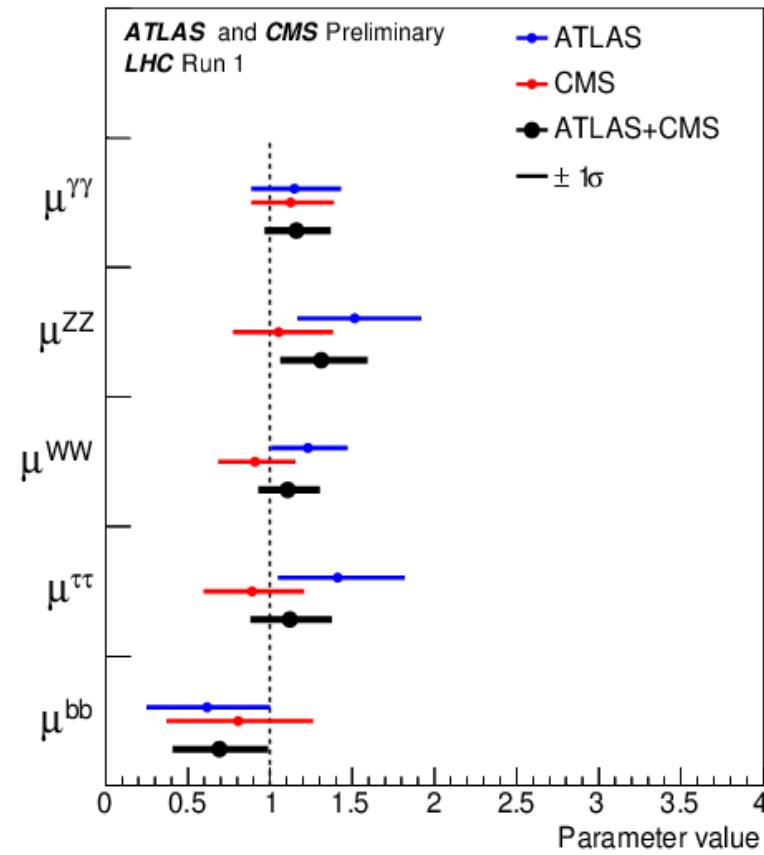
$$\begin{aligned} C_u^S &= g_{H\bar{u}u}^S, & C_d^S &= g_{H\bar{d}d}^S, & C_\ell^S &= g_{H\bar{l}l}^S; & C_v &= g_{HVV}; \\ C_u^P &= g_{H\bar{u}u}^P, & C_d^P &= g_{H\bar{d}d}^P, & C_\ell^P &= g_{H\bar{l}l}^P. \end{aligned}$$

- Extra loop contributions other than the Yukawa and gauge couplings:

$$\Delta S^g, \quad \Delta S^\gamma; \quad \Delta P^g, \quad \Delta P^\gamma$$

- $\Delta\Gamma_{\text{tot}}$





The SM:  $\chi^2/dof = 16.76/29$ ,  $p\text{-value} = 0.966$ .

Cases	<b>CPC 1</b>	<b>CPC 2</b>	<b>CPC 3</b>	<b>CPC 4</b>	<b>CPC 6</b>
Parameters	Vary $\Delta\Gamma_{\text{tot}}$	$\Delta S^\gamma$ , $\Delta S^g$	$\Delta S^\gamma$ , $\Delta S^g$ , $\Delta\Gamma_{\text{tot}}$	$C_u^S$ , $C_d^S$ , $C_\ell^S$ , $C_v$	$C_u^S$ , $C_d^S$ , $C_\ell^S$ , $C_v$ $\Delta S^\gamma$ , $\Delta S^g$
$C_u^S$	1	1	1	$0.92^{+0.15}_{-0.13}$	$1.22^{+0.32}_{-0.38}$
$C_d^S$	1	1	1	$-1.00^{+0.29}_{-0.30}$	$-0.97^{+0.30}_{-0.34}$
$C_\ell^S$	1	1	1	$0.99^{+0.17}_{-0.17}$	$1.00^{+0.18}_{-0.17}$
$C_v$	1	1	1	$0.98^{+0.10}_{-0.11}$	$0.94^{+0.11}_{-0.12}$
$\Delta S^\gamma$	0	$-0.72^{+0.76}_{-0.74}$	$-0.84^{+0.80}_{-0.82}$	0	$-1.43^{+1.02}_{-0.95}$
$\Delta S^g$	0	$-0.009^{+0.047}_{-0.048}$	$0.02^{+0.10}_{-0.08}$	0	$-0.22^{+0.28}_{-0.24}$
$\Delta\Gamma_{\text{tot}}$	$-0.020^{+0.45}_{-0.37}$	0	$0.39^{+1.13}_{-0.76}$	0	0
$\chi^2/dof$	16.76/28	15.81/27	15.59/26	16.70/25	14.83/23
$p\text{-value}$	0.953	0.956	0.945	0.892	0.901

## CPC1: Vary only $\Delta\Gamma_{\text{tot}}$

---

- This can be used to constrain some dark matter model, in which the Higgs boson decays invisibly.
- The  $\chi^2/dof = 16.72/27$ ,  $p$ -value = 0.938.
- The 95% allowed range of

$$\Delta\Gamma_{\text{tot}} = -0.020 {}^{+0.97}_{-0.66} \text{ MeV}$$

The central value consistent with zero, so the 95% C.L. upper limit is

$$\Delta\Gamma_{\text{tot}} < 0.97 \text{ MeV}$$

- For a  $M_H = 125$  GeV the standard width is about  $4.1 - 4.2$  MeV. So nonstandard decay branching ratio has to be less than

$$B(H \rightarrow \text{nonstandard}) < 19\%$$

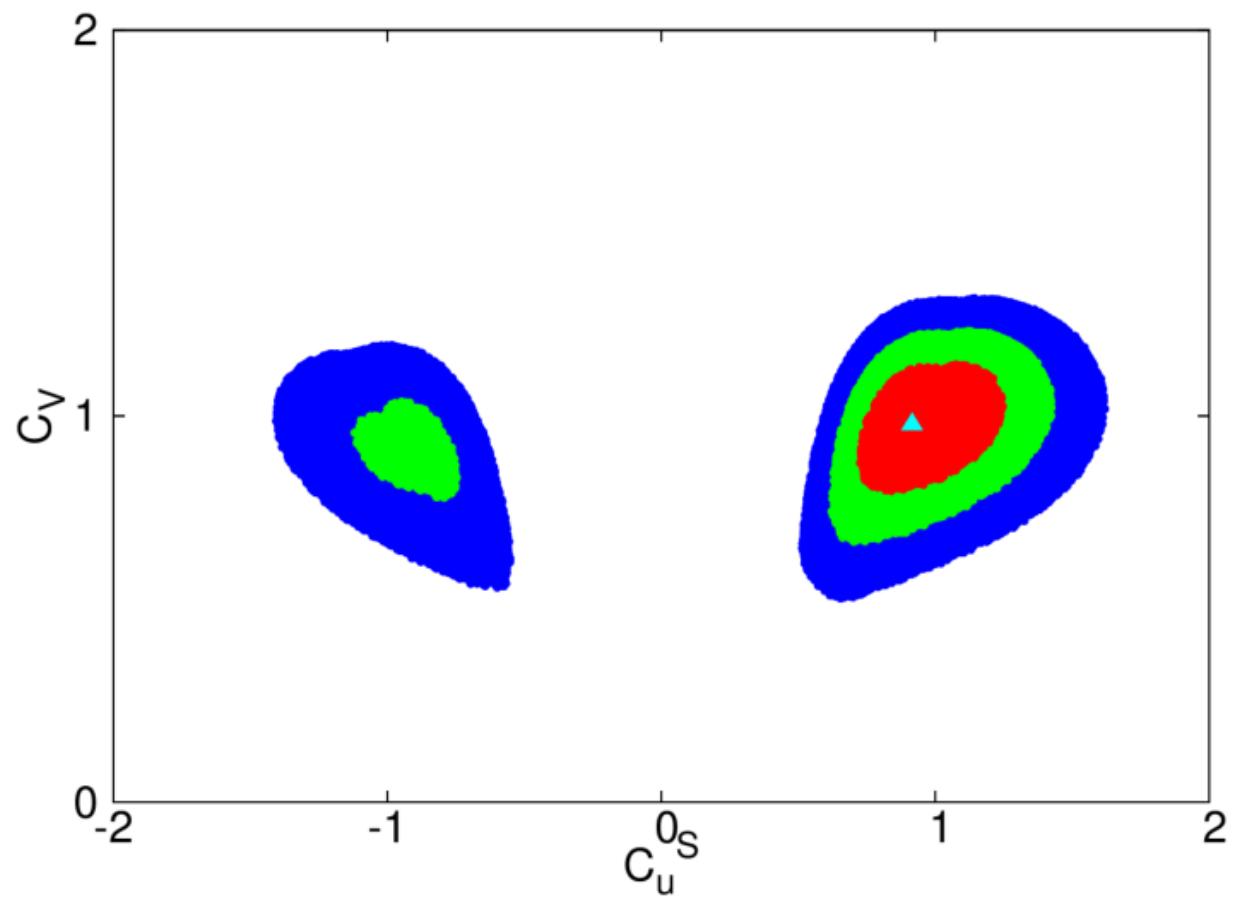
CPC4: Vary  $C_u^S, C_d^S, C_\ell^S, C_v$

---

- Only modified Yukawa and gauge couplings while no light particles running in the triangle loops.
- Approximate symmetry in the results:

$$C_d^S \leftrightarrow -C_d^S, \quad C_\ell^S \leftrightarrow -C_\ell^S$$

- Sign of  $C_u^S$  is important. The  $W$  and the top contributions are in opposite sign.

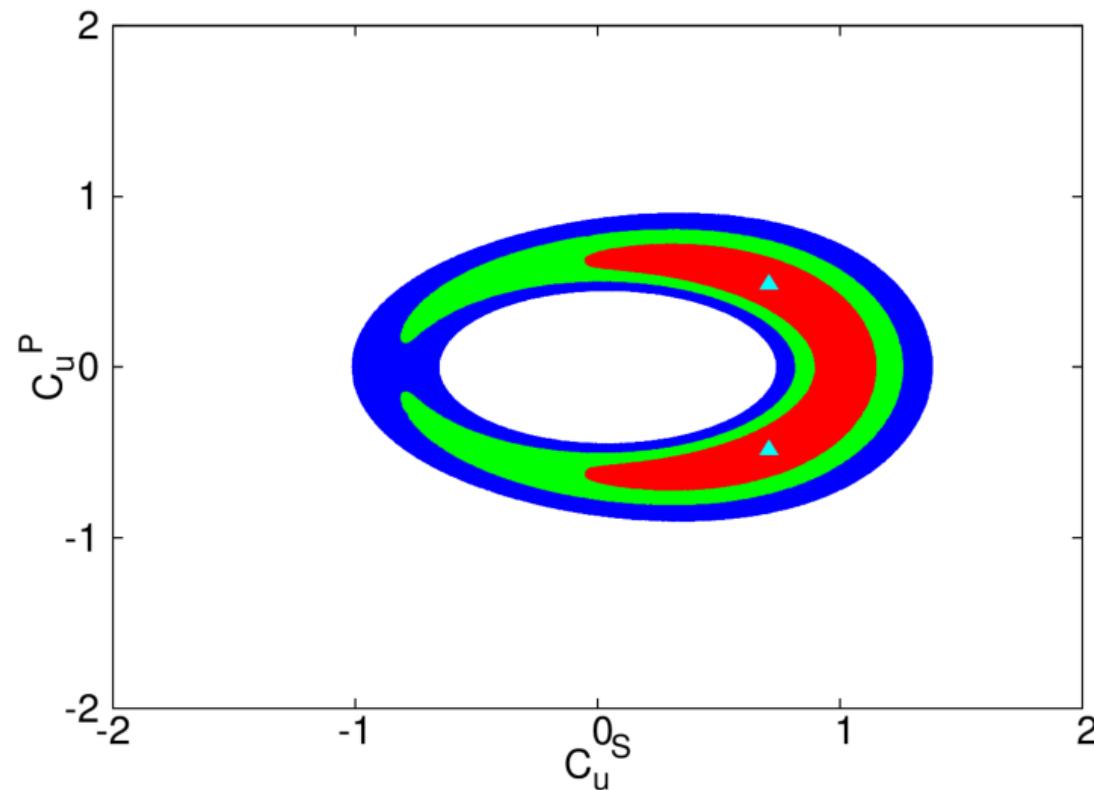


$C_u^S > 0$  is preferred but  $C_u^S < 0$  is still allowed at 95% CL;

$$C_v = 0.98^{+0.10}_{-0.11}$$

CPV3: Vary  $C_u^S$ ,  $C_u^P$ ,  $C_v$

---



The  $\chi^2/dof = 16.03/26$ ,  $p$ -value = 0.935.

## Remarks

---

- The  $HVV$  coupling is the most restrictive:

$$C_v = 0.93 - 1.0$$

with 7 – 12% uncertainty.

- The CPC top-Yukawa coupling  $C_u^S$  is preferred to be positive in those fits with  $\Delta S^\gamma$  and  $\Delta S^g$  fixed at zero.  $C_u^S < 0$  is ruled out at 68.3% CL, but allowed at 95%CL.
- The nonstandard Higgs decay is limited to be below 19%.
- The Higgs signal strengths cannot rule out the pseudoscalar couplings, and only a combination of  $C_u^S$  and  $C_u^P$  is constrained in the form of an elliptical equation.

## Zoom in for the Higgs boson

---

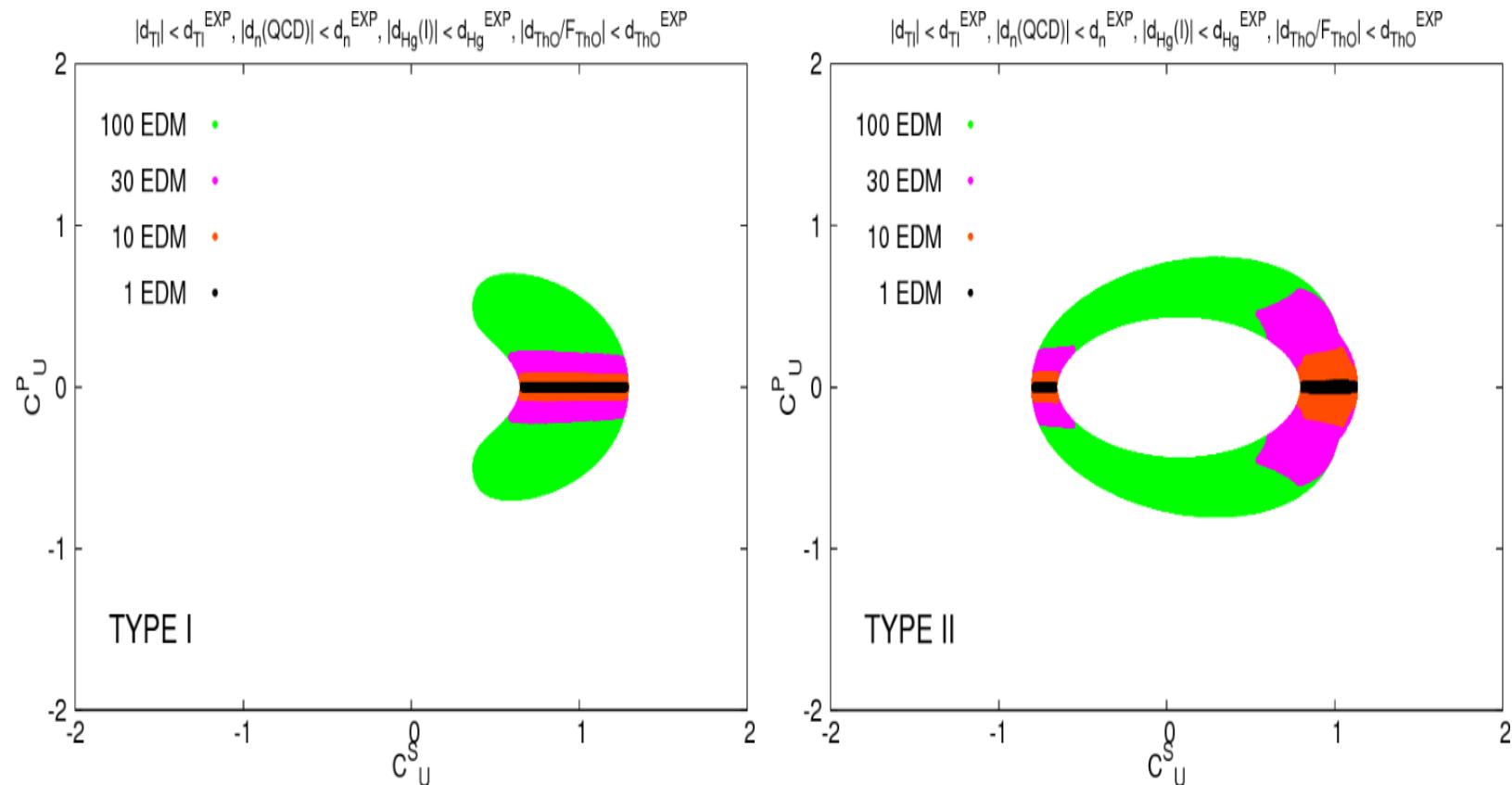
- Use EDMs to constrain the pseudoscalar Higgs couplings, such as  $C_u^P$  and  $\Delta P^\gamma$ .
- Search for non-standard decays of the Higgs boson, e.g. dark matter, Goldstone bosons, etc.
- Investigate the  $WW$  scattering.
- The associated production of Higgs with  $W$ ,  $Z$ ,  $t\bar{t}$ , or a single top.  
Probe the Yukawa couplings.
- Use the single top + Higgs production to determine the sign and the size of top-Yukawa coupling.
- Higgs boson pair production: (Chang, Cheung, Lee, Lu, 1505.00957)

## Confronting Higgcision with Electric dipole moments

---

KC, Jae-Sik Lee, Eibun Senaha, Po-Yan Tseng 1403.4775

- Higgs signal strength data cannot restrict the pseudoscalar coupling.
- But the EDM predicted is mostly proportional to  $C_u^S C_u^P$ .
- By limiting the predictions to be less than the current limits of Thallium, neutron, Mercury, and Thorium monoxide EDMs, one can constrain the  $C_u^P$ .



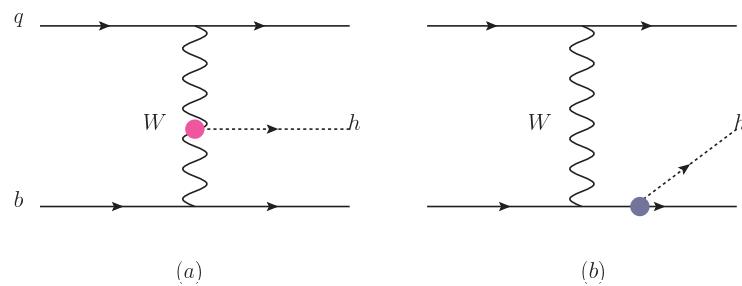
KC, Lee, Senaha, Tseng

# Associated Production of Higgs with a single top quark

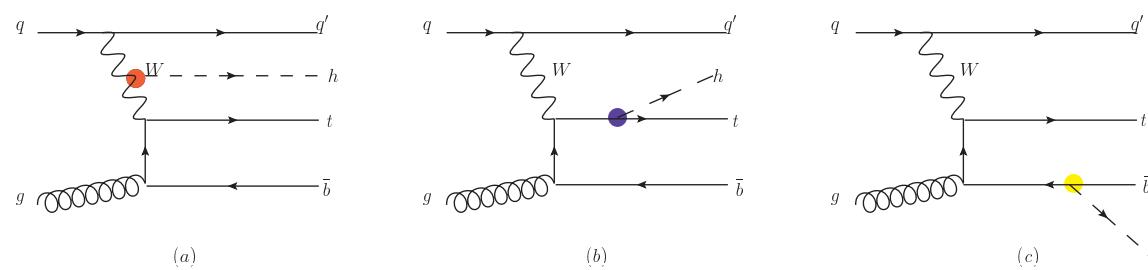
Jung Chang, KC, Jae-Sik Lee, Chih-Ting Lu, 1403.2053

The associated Higgs production with a single top quark can indeed probe the size and the sign of the top Yukawa.

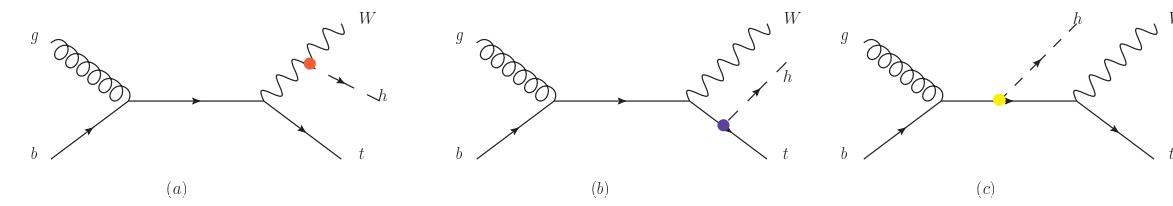
$$qb \rightarrow thq'$$



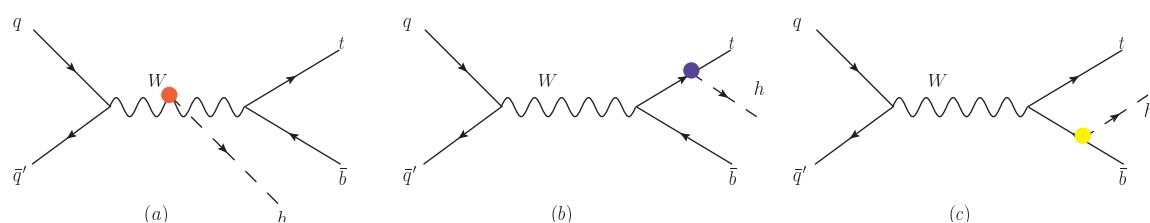
$$qg \rightarrow thq'b$$



$$gb \rightarrow thW$$



$$q\bar{q}' \rightarrow tb\bar{b}$$



## Variations of Cross section Vs $C_t^{S,P}$

---

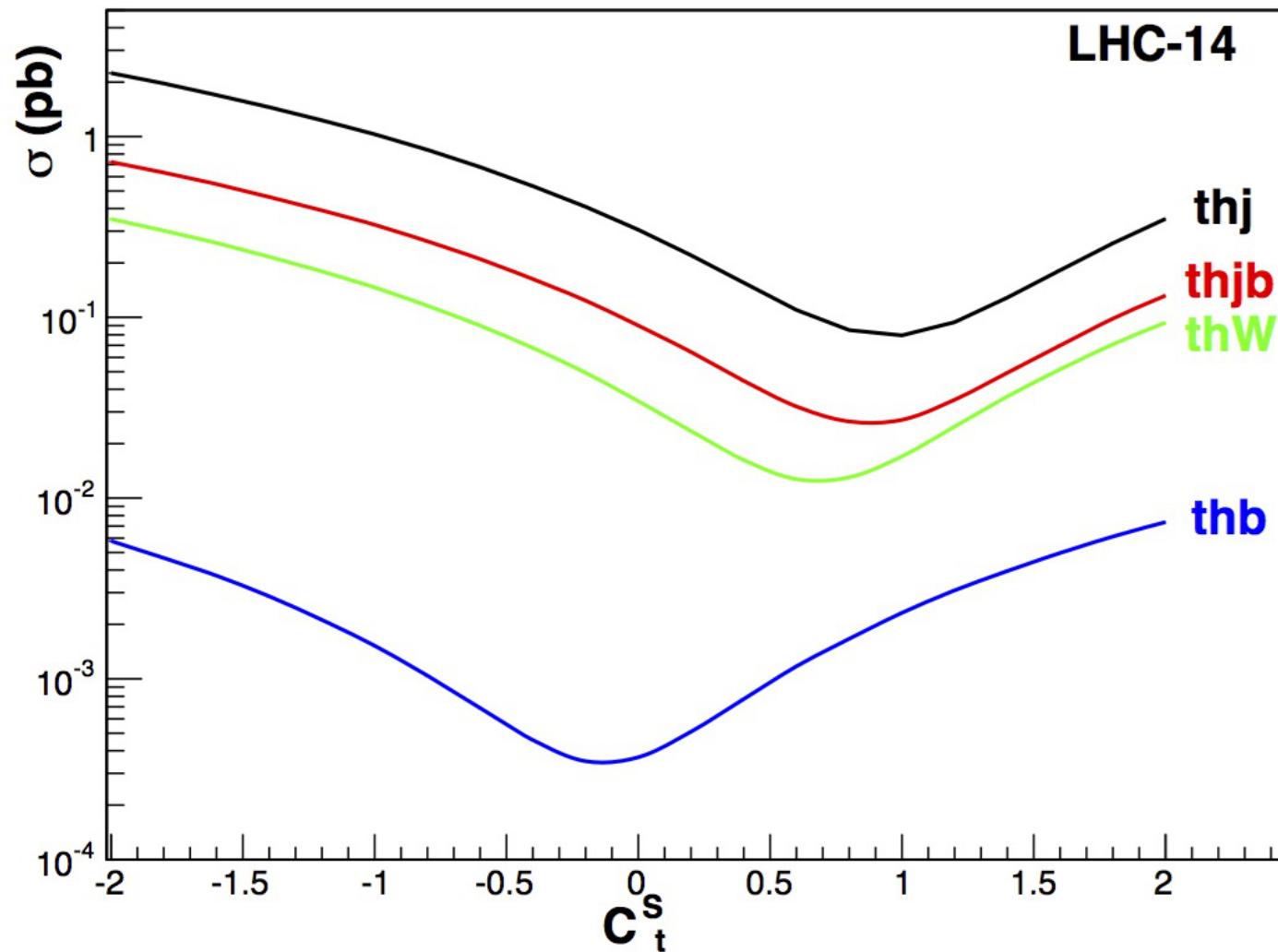
$$\begin{aligned}\mathcal{L}_{hVV} &= gm_W \left( g_{hWW} W_\mu^+ W^{-\mu} + g_{hZZ} \frac{1}{2c_W^2} Z_\mu Z^\mu \right) h, \\ \mathcal{L}_{hff} &= - \sum_{f=t,b,c,\tau} \frac{gm_f}{2m_W} \bar{f} \left( g_{hff}^S + ig_{hff}^P \gamma_5 \right) f h\end{aligned}$$

- We can understand the process  $qb \rightarrow q'th$  by looking at the near-shell region of the  $W$ :

$$Wb \rightarrow ht$$

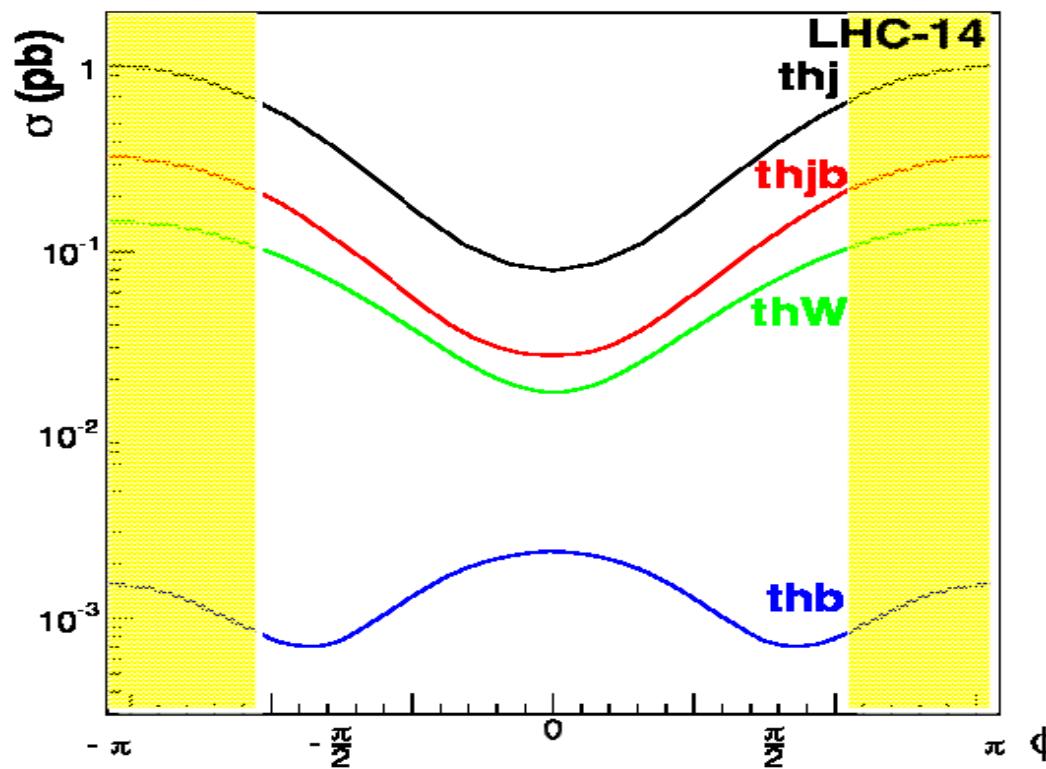
- At high energy, it is dominated by longitudinal  $W$ :

$$\mathcal{M} = -\frac{g^2 m_t}{2\sqrt{2} m_W^2} \left[ (C_v - C_t^S) + iC_t^P \right] \bar{u}(p_t) P_L u(p_b)$$



$C_t^S$  and  $C_t^P$  are roughly constrained by  $1 = \frac{(C_t^S)^2}{(0.86)^2} + \frac{(C_t^P)^2}{(0.56)^2}$ .

We can parameterize by the angle  $\tan \phi \equiv \frac{C_t^P}{C_t^S} = \frac{0.56 \sin \theta}{0.86 \cos \theta} = 0.66 \tan \theta$ , with the allowed  $-2\pi/3 \leq \phi \leq 2\pi/3$  at 68% CL



## Potential at the LHC

---

- Many decay channels:

$$t \rightarrow b\ell\nu, \quad t \rightarrow bjj; \quad h \rightarrow b\bar{b}, \gamma\gamma, \tau^+\tau^-, ZZ^* \rightarrow 4\ell, WW^* \rightarrow \ell^+\nu\ell^-\bar{\nu}$$

- Focus on  $pp \rightarrow thj$  production, and

$$t \rightarrow b\ell\nu, \quad h \rightarrow b\bar{b}, \gamma\gamma, \tau^+\tau^-$$

and

$$t \rightarrow bjj, \quad h \rightarrow ZZ^* \rightarrow 4\ell$$

- We use MADGRAPH, Pythia, Delphes 3 for calculations, parton showering, and detector simulations.

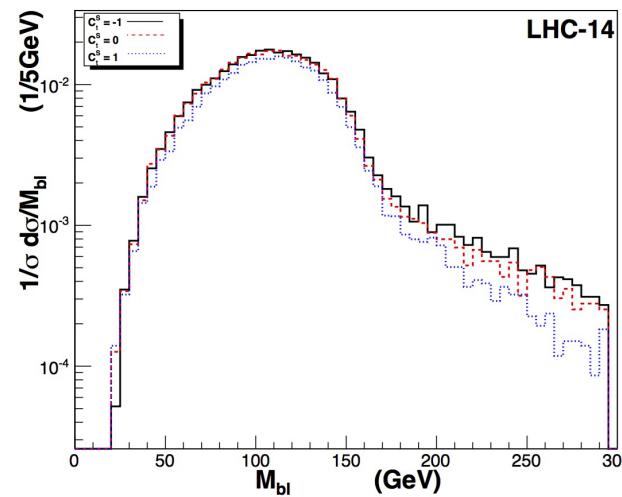
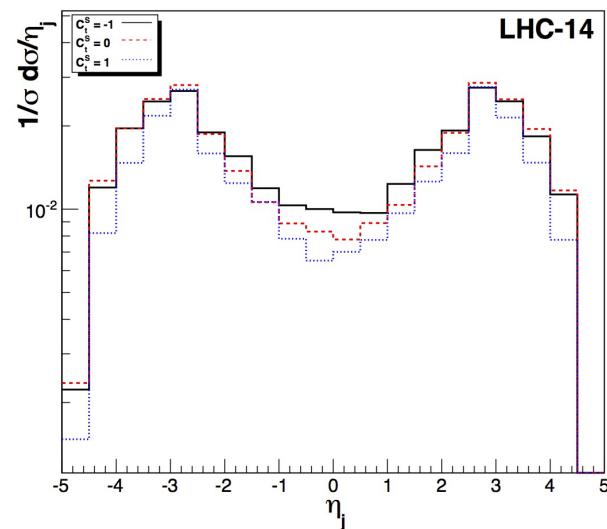
Detection efficiencies				Mistag probability			
$\epsilon_b$	$\epsilon_\tau$	$\epsilon_\ell$	$\epsilon_\gamma$	$P_{c \rightarrow b}$	$P_{uds g \rightarrow b}$	$P_{j \rightarrow \tau}$	$P_{j \rightarrow \gamma}$
0.7 (0.6)	0.5	1.0	1.0	0.2 (0.08)	0.015 (0.004)	0.01	$10^{-3}$

$h \rightarrow b\bar{b}$  Mode with  $t \rightarrow b\ell\nu$

- Basic cuts:

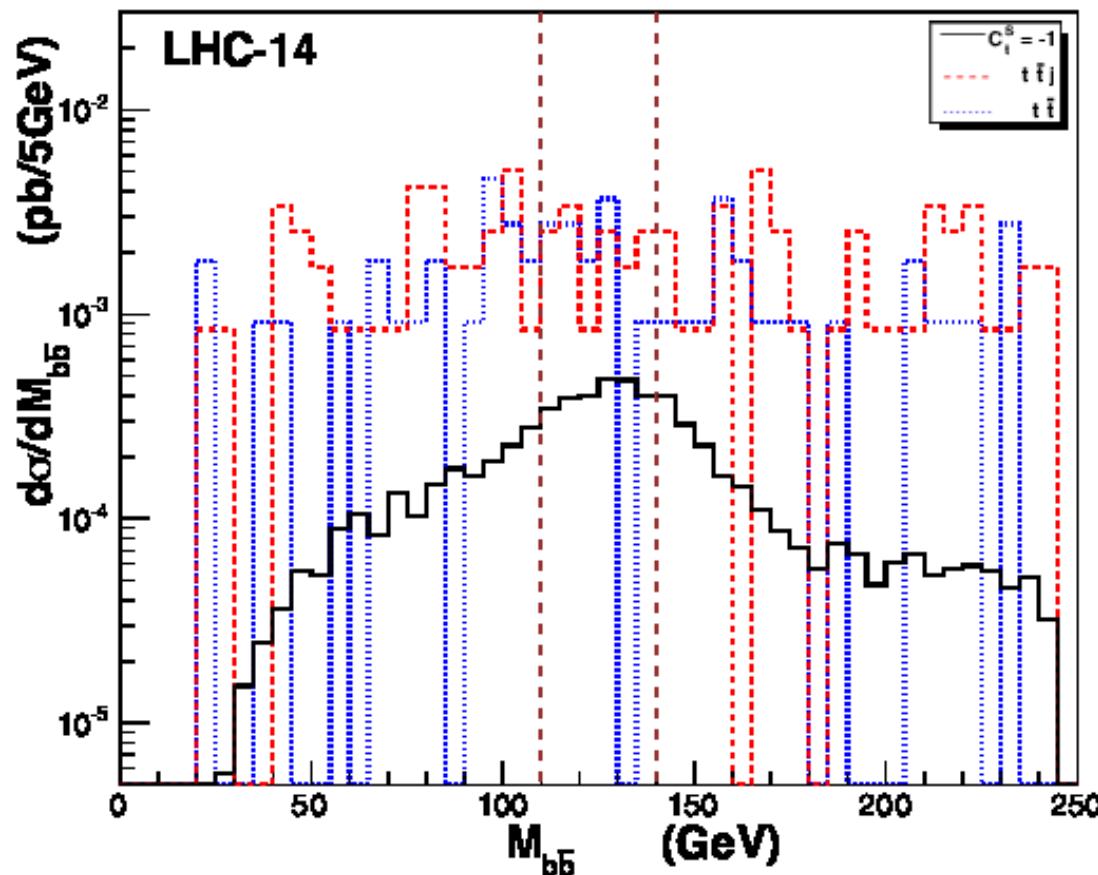
$$\begin{aligned} \Delta R_{ij} &> 0.4, & p_{T_b} &> 25 \text{ GeV}, & |\eta_b| &< 2.5, \\ p_{T_\ell} &> 25 \text{ GeV}, & |\eta_\ell| &< 2.5, & p_{T_j} &> 25 \text{ GeV}, & |\eta_j| &< 4.7 \end{aligned}$$

- Forward jet tag and top mass constraint



Backgrounds:  $t\bar{t} \rightarrow t(\bar{b}j_1j_2) \rightarrow tb\bar{b}j$        $t\bar{t}j \rightarrow t(\bar{b}j_1j_2) \rightarrow tb\bar{b}j$

Apply:  $|M_{b_1b_2} - m_h| < 15 \text{ GeV}$ ,       $M_{b_1b_2j} > 300 \text{ GeV}$

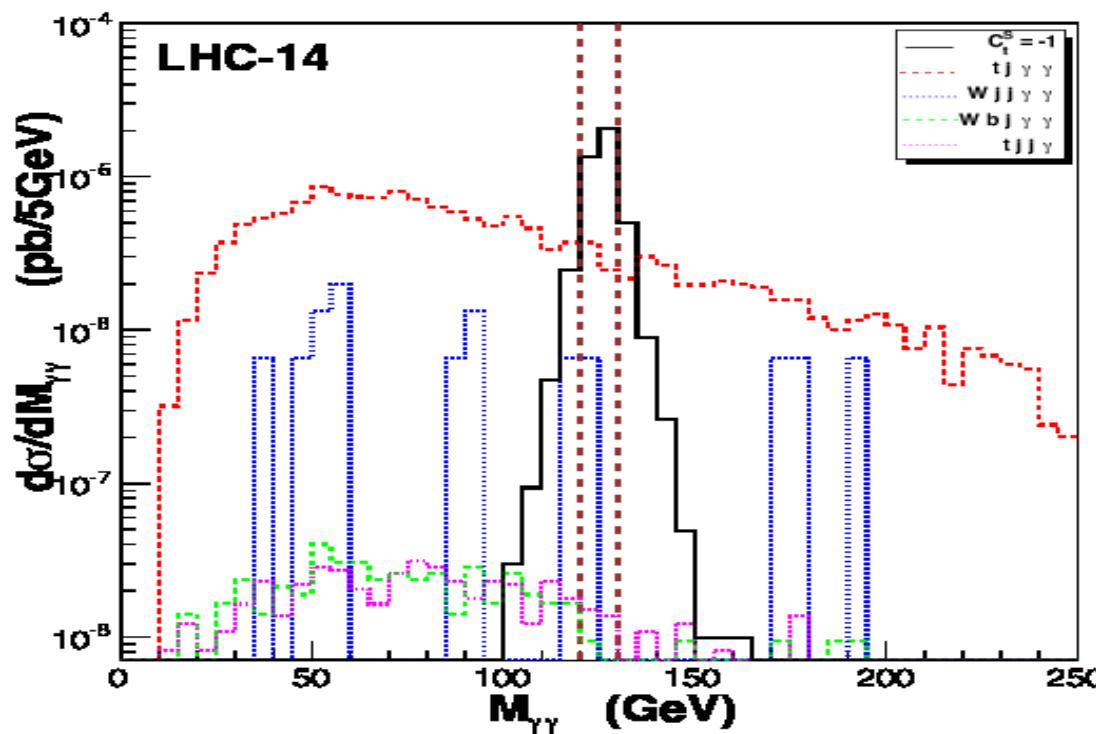


### The cut flow

Cuts	Signals (fb)			Backgrounds (fb)	
	$C_t^S = 1$	$C_t^S = 0$	$C_t^S = -1$	$t\bar{t}$	$t\bar{t}j$
(1) Basic cuts and $p_{T b_{1,2}} > 25 \text{ GeV},  \eta_{b_{1,2}}  < 2.5$	0.793	4.23	15.29	655	797
(2) $2.5 <  \eta_j  < 4.7$	0.388	2.20	7.68	46.2	95.6
(3) $(M_{bl})^{\min} < 200 \text{ GeV}$	0.387	2.19	7.59	46.2	95.6
(4) $ M_{b_1 b_2} - m_h  < 15 \text{ GeV}$	0.13	0.74	2.5	6.69	15.2
(5) $M_{b_1 b_2 j} > 300 \text{ GeV}$	0.06	0.3	0.9	1.34	5.41
$S/\sqrt{S+B}$ for $300 \text{ fb}^{-1}$	0.40	2.0	5.6		

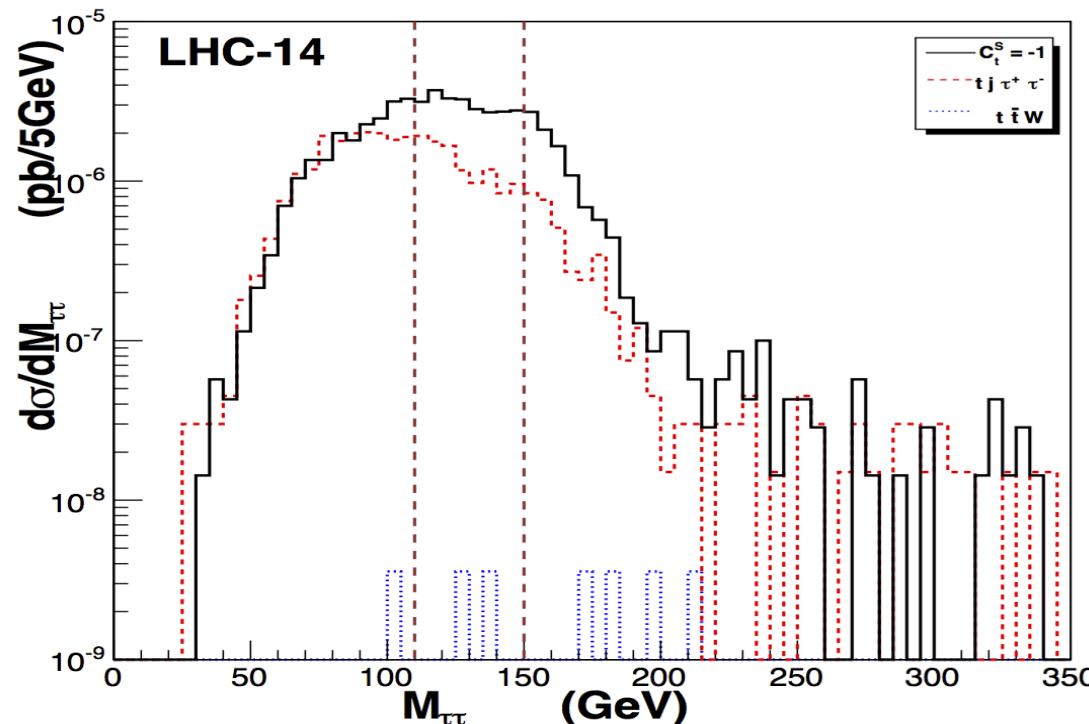
$h \rightarrow \gamma\gamma$  Mode with  $t \rightarrow b\ell\nu$

- Diphoton mode has much less QCD background, but the BR is  $2.3 \times 10^{-3}$ .
- Backgrounds:  $tj\gamma\gamma$ ,  $tjj\gamma$ ,  $Wbj\gamma\gamma$ ,  $Wjj\gamma\gamma$ .
- Further cuts:  $|M_{\gamma\gamma} - m_h| < 5$  GeV,  $p_{T\gamma} > 20$  GeV,  $|\eta_\gamma| < 2.5$



$h \rightarrow \tau^+ \tau^-$  Mode with  $t \rightarrow b\ell\nu$

- Tau has a BR  $\sim 0.06$ . Tau decays always contain neutrino, thus the momentum cannot be fully reconstructed. But it can be estimated in fast moving tau and in hadronic decay. Currently, the scale factor is 1.37 in Delphes 3.
- The  $M_{\tau\tau}$  peak at  $m_h$  is broad. We apply the cuts:  
 $110 \text{ GeV} < M_{\tau\tau} < 150 \text{ GeV}, \quad p_{T\tau} > 25 \text{ GeV}, \quad |\eta_\tau| < 2.5$

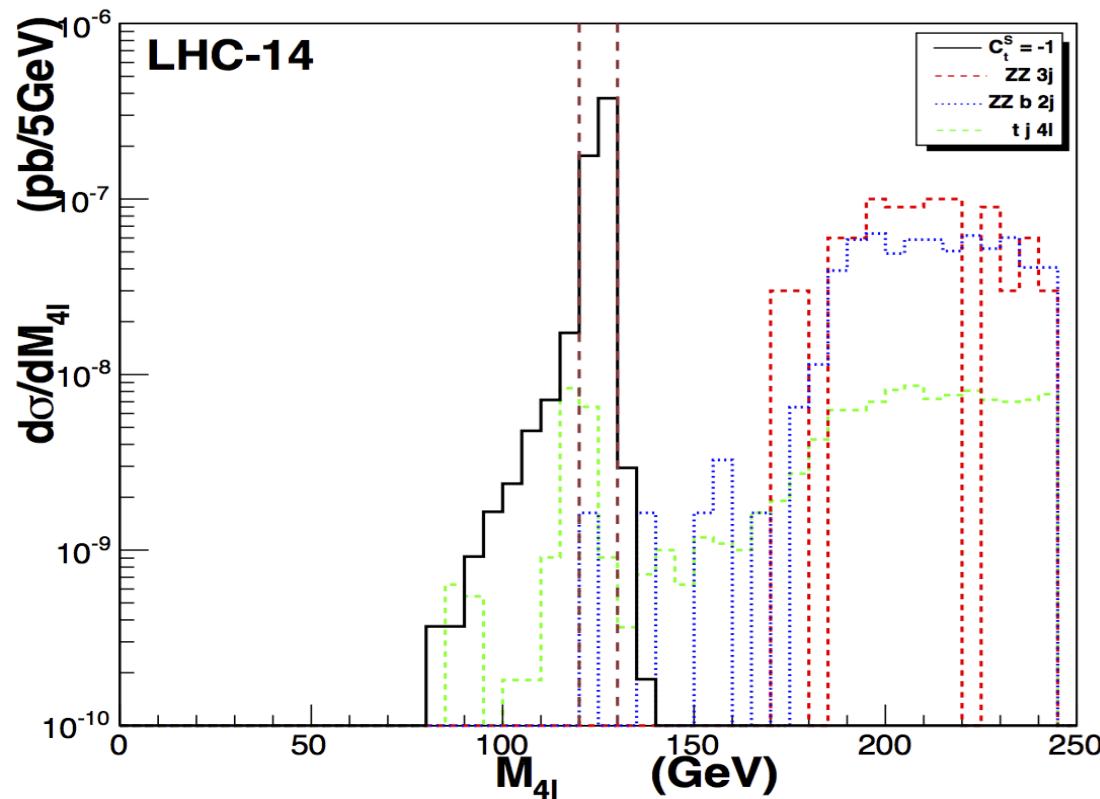


$h \rightarrow ZZ^* \rightarrow 4\ell$  Mode with  $t \rightarrow bj_1j_2$

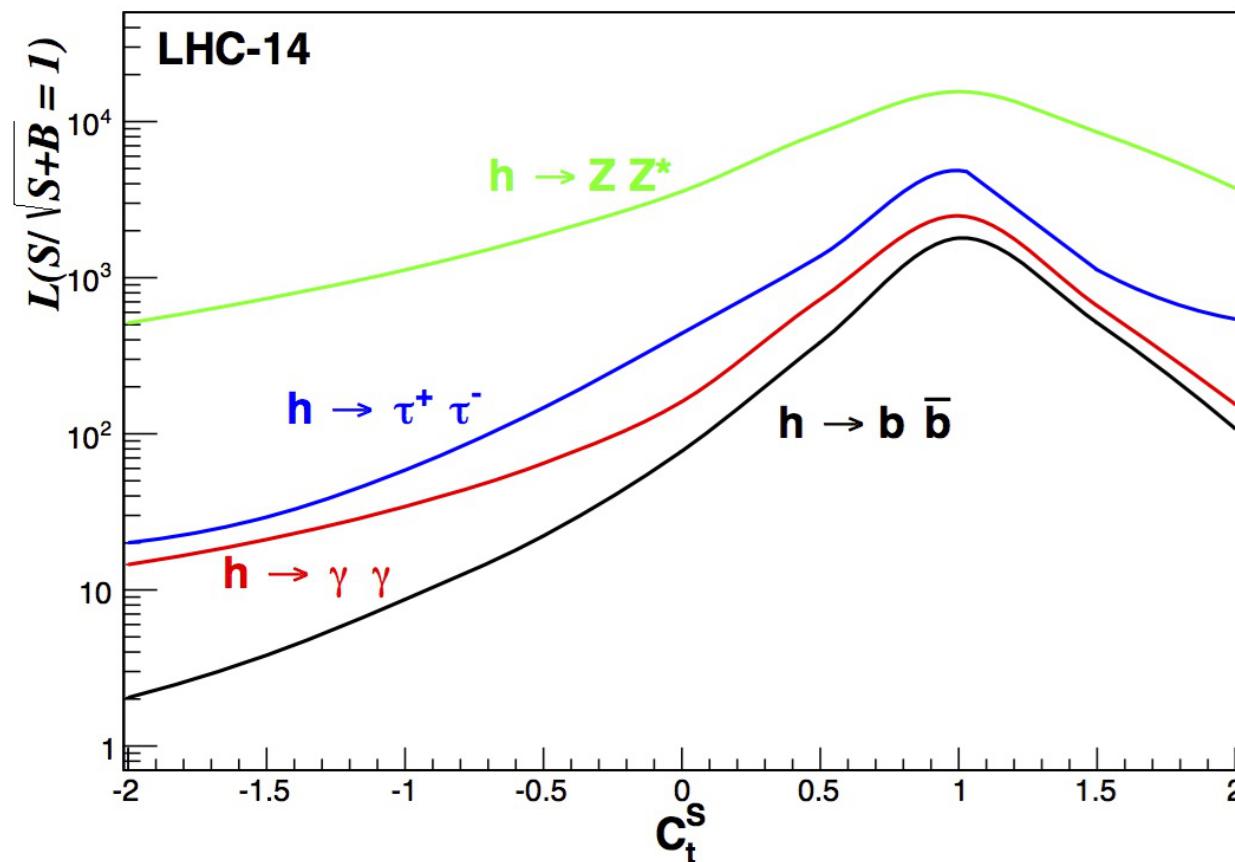
---

Cuts on leptons:

$$p_{T\ell} > 5 \text{ GeV}, \quad |\eta_\ell| < 2.5, \quad |M_{4\ell} - m_h| < 5 \text{ GeV}$$



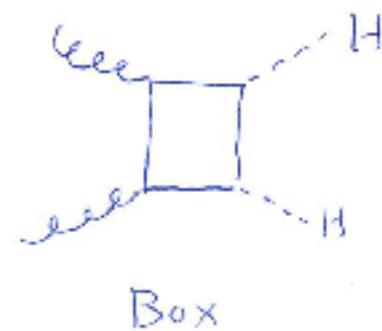
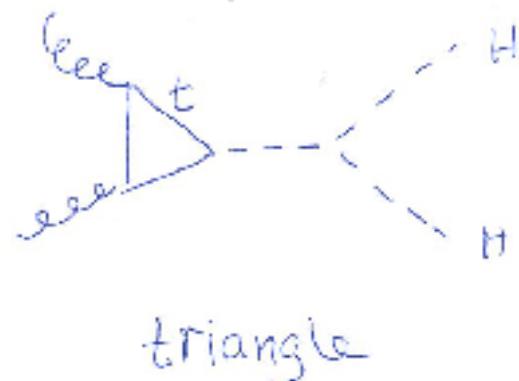
Required luminosity at LHC-14 to achieve  $S/\sqrt{S+B} > 1$



# Higgs boson Pair Production

---

Jung Chang, KC, Jae-Sik Lee, Chih-Ting Lu 1505.00957



## Formalism

---

- Interactions:

$$-\mathcal{L} = \frac{1}{3!} \left( \frac{3M_H^2}{v} \right) \lambda_{3H} H^3 + \frac{m_t}{v} \bar{t} \left( g_t^S + i\gamma_5 g_t^P \right) t H + \frac{1}{2} \frac{m_t}{v^2} \bar{t} \left( g_{tt}^S + i\gamma_5 g_{tt}^P \right) t H^2$$

- In the SM,  $\lambda_{3H} = g_t^S = 1$  and  $g_t^P = 0$  and  $g_{tt}^{S,P} = 0$ .
- The SM result:

$$\frac{d\hat{\sigma}(gg \rightarrow HH)}{d\hat{t}} = \frac{G_F^2 \alpha_s^2}{512(2\pi)^3} \left[ \left| \lambda_{3H} g_t^S D(\hat{s}) F_\Delta^S + (g_t^S)^2 F_\square^{SS} \right|^2 + \left| (g_t^S)^2 G_\square^{SS} \right|^2 \right]$$

where  $D(\hat{s}) = \frac{3M_H^2}{\hat{s} - M_H^2 + iM_H \Gamma_H}$ .

- Extensions to CP-odd and contact terms:

$$\begin{aligned} \frac{d\hat{\sigma}(gg \rightarrow HH)}{d\hat{t}} &= \frac{G_F^2 \alpha_s^2}{512(2\pi)^3} \left\{ \left| \left( \lambda_{3H} g_t^S D(\hat{s}) + g_{tt}^S \right) F_\Delta^S + (g_t^S)^2 F_\square^{SS} + (g_t^P)^2 F_\square^{PP} \right|^2 \right. \\ &\quad + \left| (g_t^S)^2 G_\square^{SS} + (g_t^P)^2 G_\square^{PP} \right|^2 \\ &\quad \left. + \left| \left( \lambda_{3H} g_t^P D(\hat{s}) + g_{tt}^P \right) F_\Delta^P + g_t^S g_t^P F_\square^{SP} \right|^2 + \left| g_t^S g_t^P G_\square^{SP} \right|^2 \right\}. \end{aligned}$$

- Production cross section **normalized** to the SM one is

$$\begin{aligned}
 \frac{\sigma(gg \rightarrow HH)}{\sigma_{\text{SM}}(gg \rightarrow HH)} &= \lambda_{3H}^2 \left[ c_1(s)(g_t^S)^2 + d_1(s)(g_t^P)^2 \right] + \lambda_{3H} g_t^S \left[ c_2(s)(g_t^S)^2 + d_2(s)(g_t^P)^2 \right] \\
 &\quad + \left[ c_3(s)(g_t^S)^4 + d_3(s)(g_t^S)^2(g_t^P)^2 + d_4(s)(g_t^P)^4 \right] \\
 &\quad + \lambda_{3H} \left[ e_1(s)g_t^S g_{tt}^S + f_1(s)g_t^P g_{tt}^P \right] + g_{tt}^S \left[ e_2(s)(g_t^S)^2 + f_2(s)(g_t^P)^2 \right] \\
 &\quad + \left[ e_3(s)(g_{tt}^S)^2 + f_3(s)g_t^S g_t^P g_{tt}^P + f_4(s)(g_{tt}^P)^2 \right]
 \end{aligned}$$

## Behavior of cross sections

---

- The triangle diagram has the  $1/s$  behavior of the Higgs propagator, more suppressed at high  $\sqrt{s}$ .
- The contact term  $t\bar{t} \rightarrow HH$  will saturate unitarity at high enough  $\sqrt{s}$ :

$$i\mathcal{M}(t\bar{t} \rightarrow HH) \sim g_{tt}^S \frac{m_t \sqrt{\hat{s}}}{v^2}$$

Requiring  $|a_0| < 1/2$ :

$$\sqrt{\hat{s}} \leq \frac{17.6}{g_{tt}^S} \text{ TeV} .$$

$\sqrt{s}$ (TeV)	$c_1(s)$ $\lambda_{3H}^2 (g_t^S)^2$	$c_2(s)$ $\lambda_{3H} (g_t^S)^3$	$c_3(s)$ $(g_t^S)^4$	$d_1(s)$ $\lambda_{3H}^2 (g_t^P)^2$	$d_2(s)$ $\lambda_{3H} g_t^S (g_t^P)^2$	$d_3(s)$ $(g_t^S)^2 (g_t^P)^2$	$d_4(s)$ $(g_t^P)^4$
8	0.300	-1.439	2.139	0.942	-6.699	14.644	0.733
14	0.263	-1.310	2.047	0.820	-5.961	13.348	0.707
33	0.232	-1.193	1.961	0.713	-5.274	12.126	0.690
100	0.208	-1.108	1.900	0.635	-4.789	11.225	0.683

$\sqrt{s}$ (TeV)	$e_1(s)$ $\lambda_{3H} g_t^S g_{tt}^S$	$e_2(s)$ $g_{tt}^S (g_t^S)^2$	$e_3(s)$ $(g_{tt}^S)^2$	$f_1(s)$ $\lambda_{3H} g_t^P g_{tt}^P$	$f_2(s)$ $g_{tt}^S (g_t^P)^2$	$f_3(s)$ $g_t^S g_t^P g_{tt}^P$	$f_4(s)$ $(g_{tt}^P)^2$
8	1.460	-4.313	2.519	2.104	2.350	-7.761	3.065
14	1.364	-4.224	2.617	1.848	2.269	-6.886	3.769
33	1.281	-4.165	2.783	1.622	2.207	-6.033	5.635
100	1.214	-4.137	2.974	1.474	2.154	-5.342	10.568

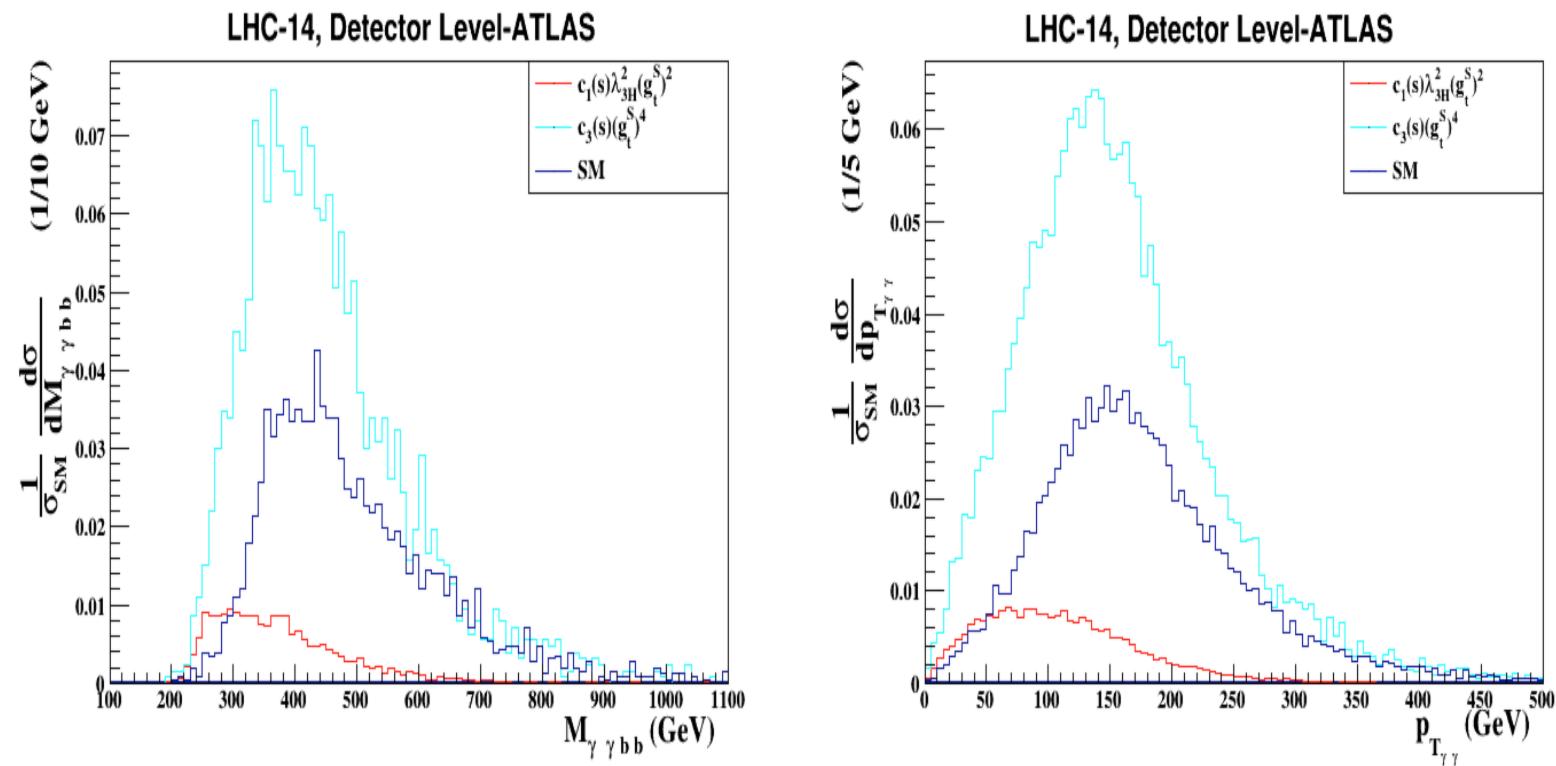
CPC1:  $g_t^S$  and  $\lambda_{3H}$

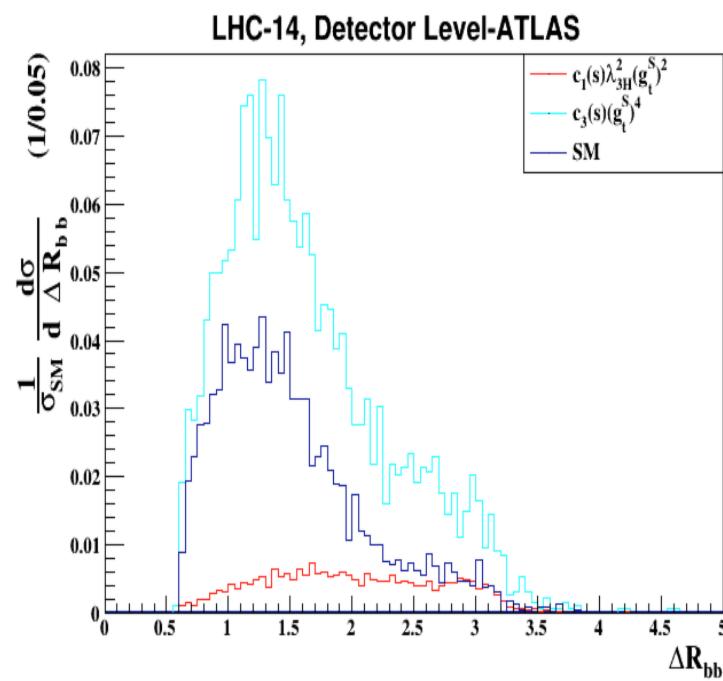
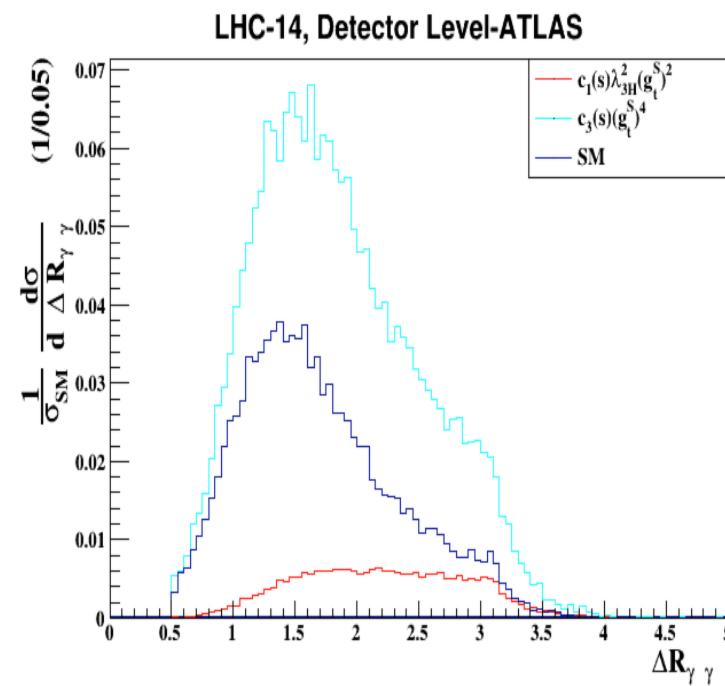
---

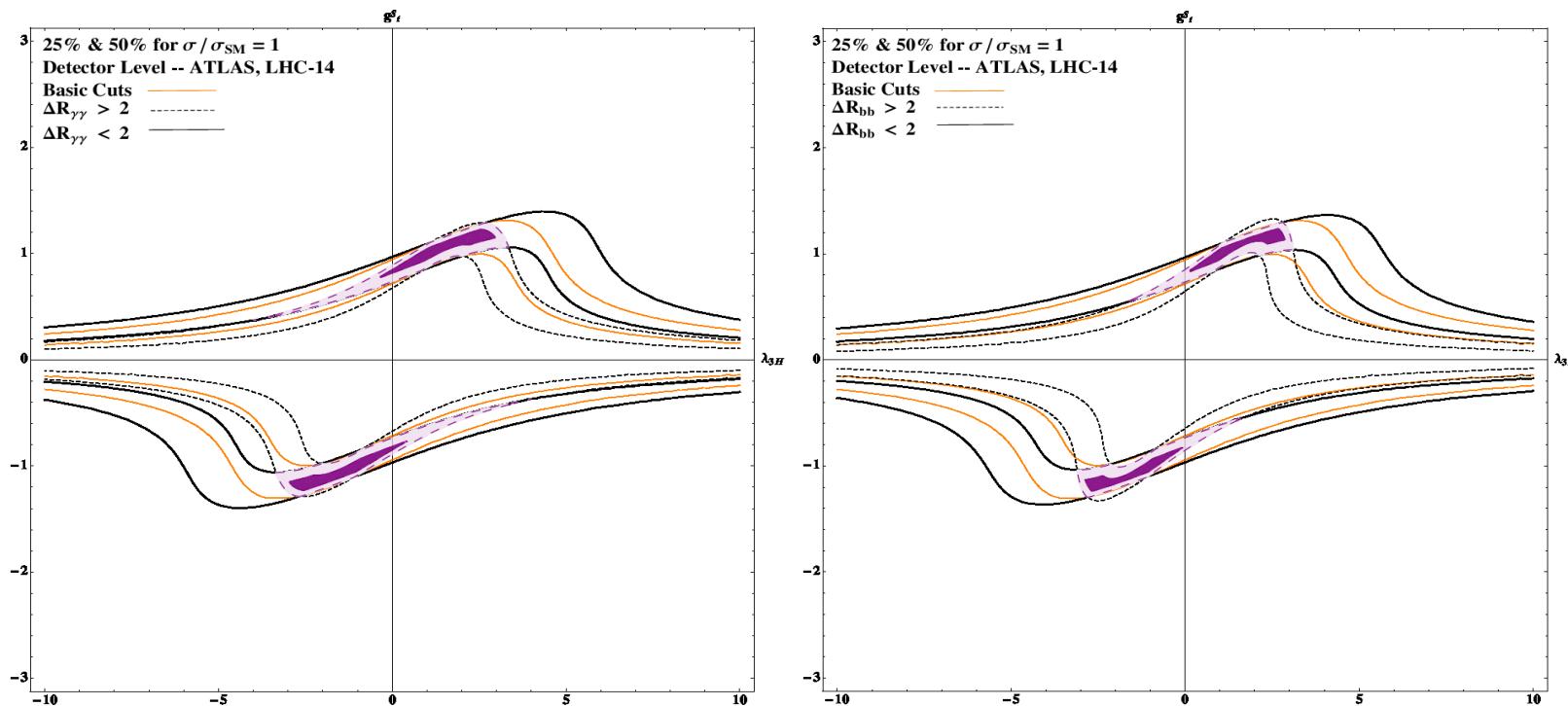
- Attempt to isolate the Higgs self coupling in the triangle diagram.
- The triangle diagram has the  $1/s$  behavior, so more profound at low invariant mass region. Thus, the angular separation between the decay product is larger:

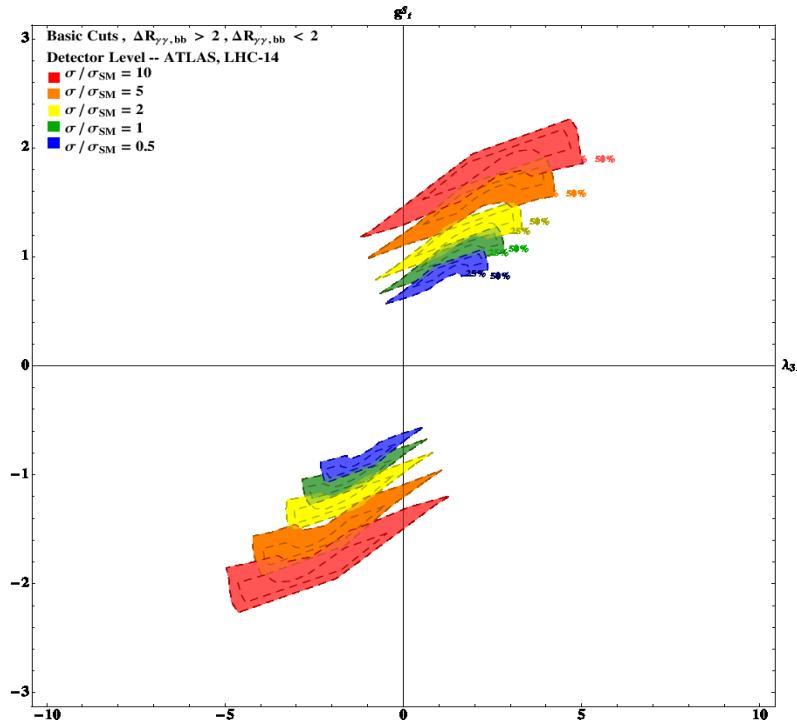
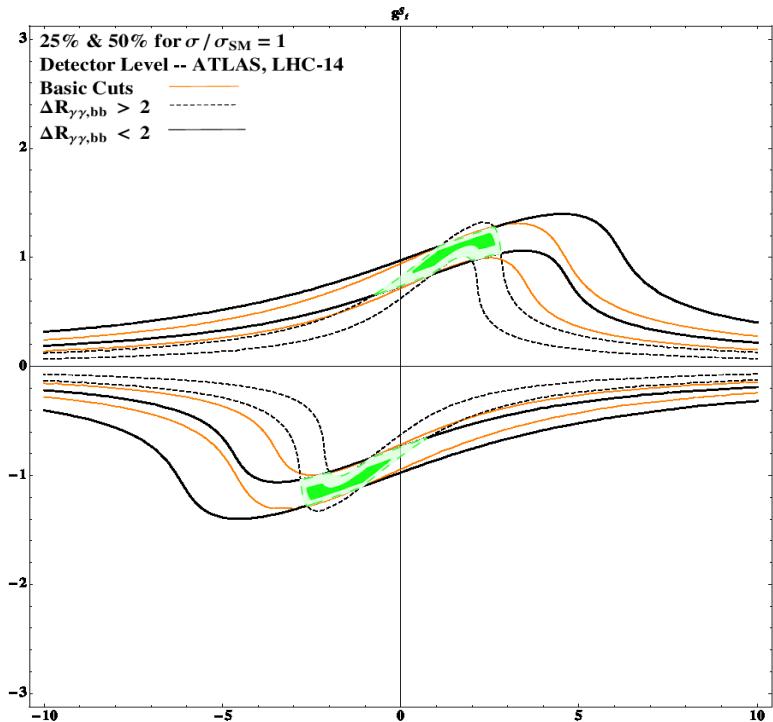
$$HH \rightarrow (\gamma\gamma)(b\bar{b})$$

- We can make use of simultaneous cross section measurements: (i) no cuts, (ii)  $\sigma(\Delta R_{\gamma\gamma} > 2)$ , (iii)  $\sigma(\Delta R_{\gamma\gamma} < 2)$ .
- Repeat using  $\Delta R_{b\bar{b}}$ , and both  $\Delta R_{\gamma\gamma}$  and  $\Delta R_{b\bar{b}}$ .







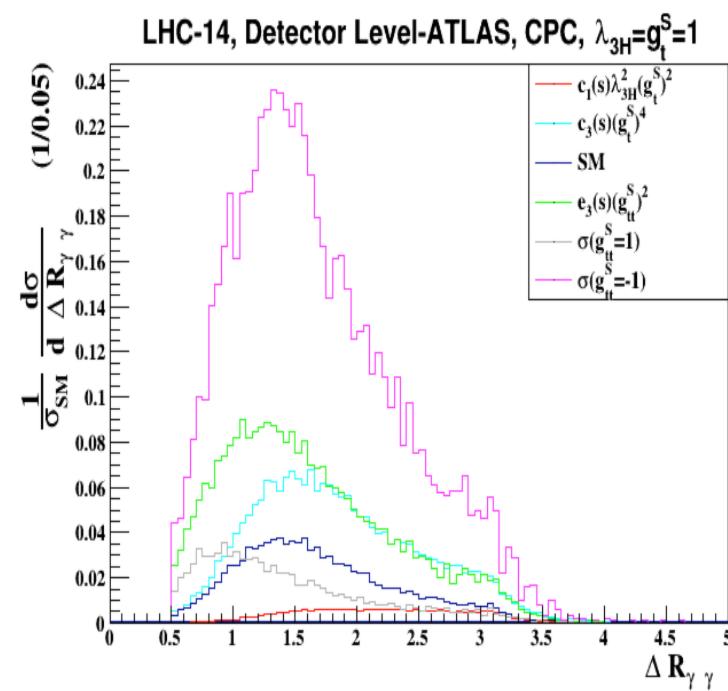
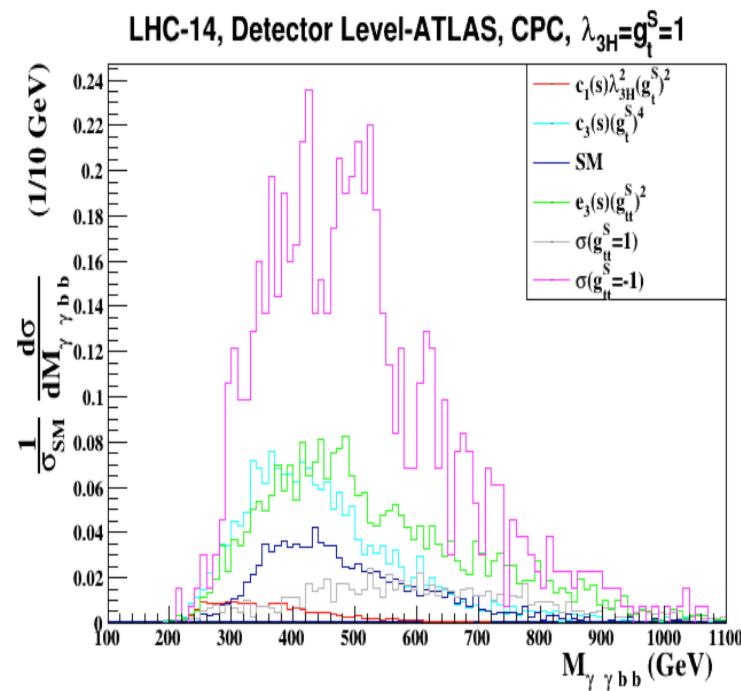


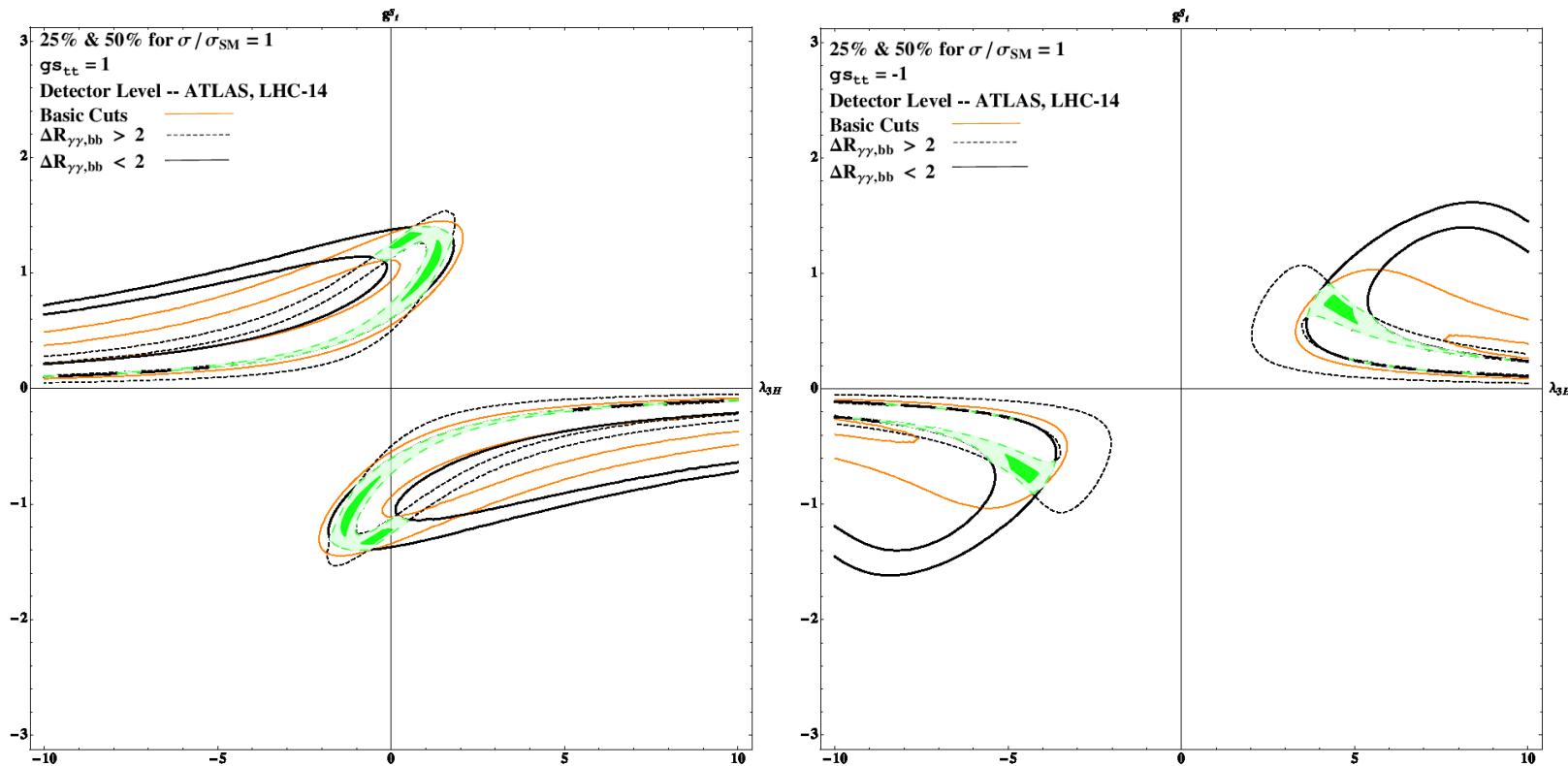
Only with both  $\Delta R_{\gamma\gamma}$  and  $\Delta R_{b\bar{b}}$  can one really tell if  $\delta_{3H}$  is significantly distinct from zero.

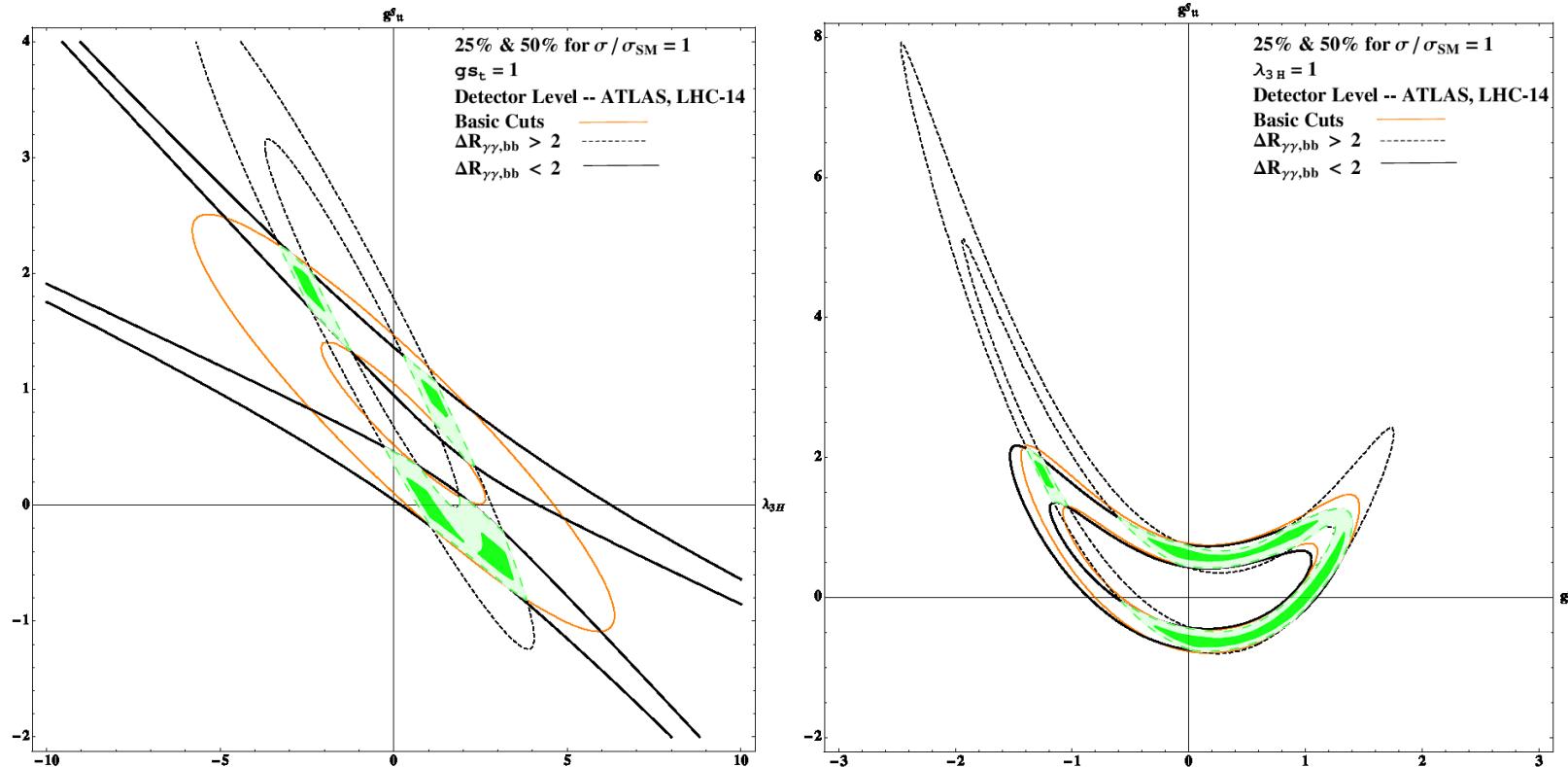
CPC2:  $g_t^S$ ,  $\lambda_{3H}$ ,  $g_{tt}^S$

---

- The contact diagram contributes in the same way as the triangle diagram, except for the  $1/s$  propagator. Also becomes important at high  $\sqrt{\hat{s}}$ .
- We can make use of simultaneous cross section measurements: (i) Basic cuts, (ii)  $\sigma(\Delta R_{\gamma\gamma}, \Delta R_{b\bar{b}} > 2)$ , (iii)  $\sigma(\Delta R_{\gamma\gamma}, \Delta R_{b\bar{b}} < 2)$ .



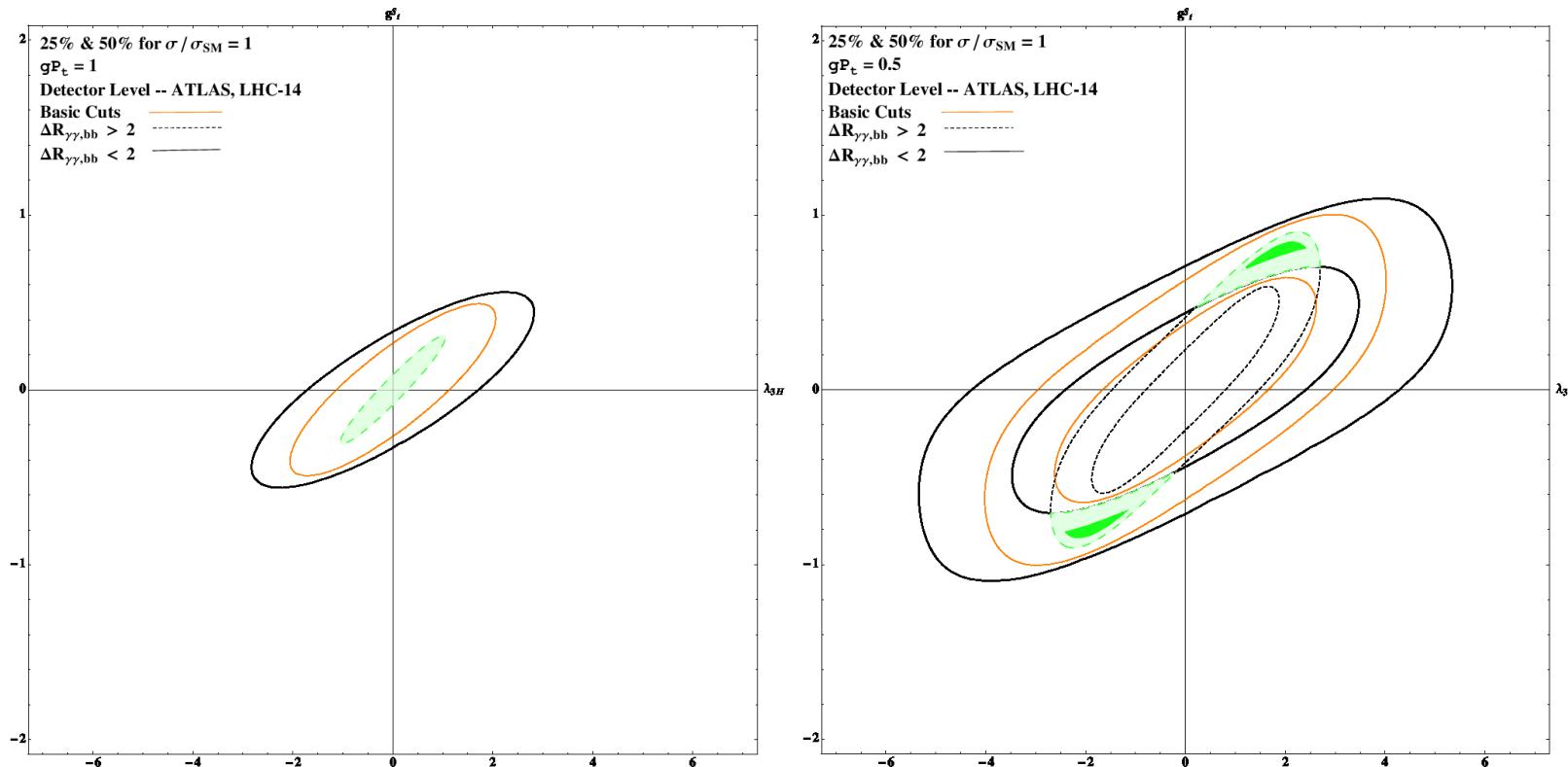


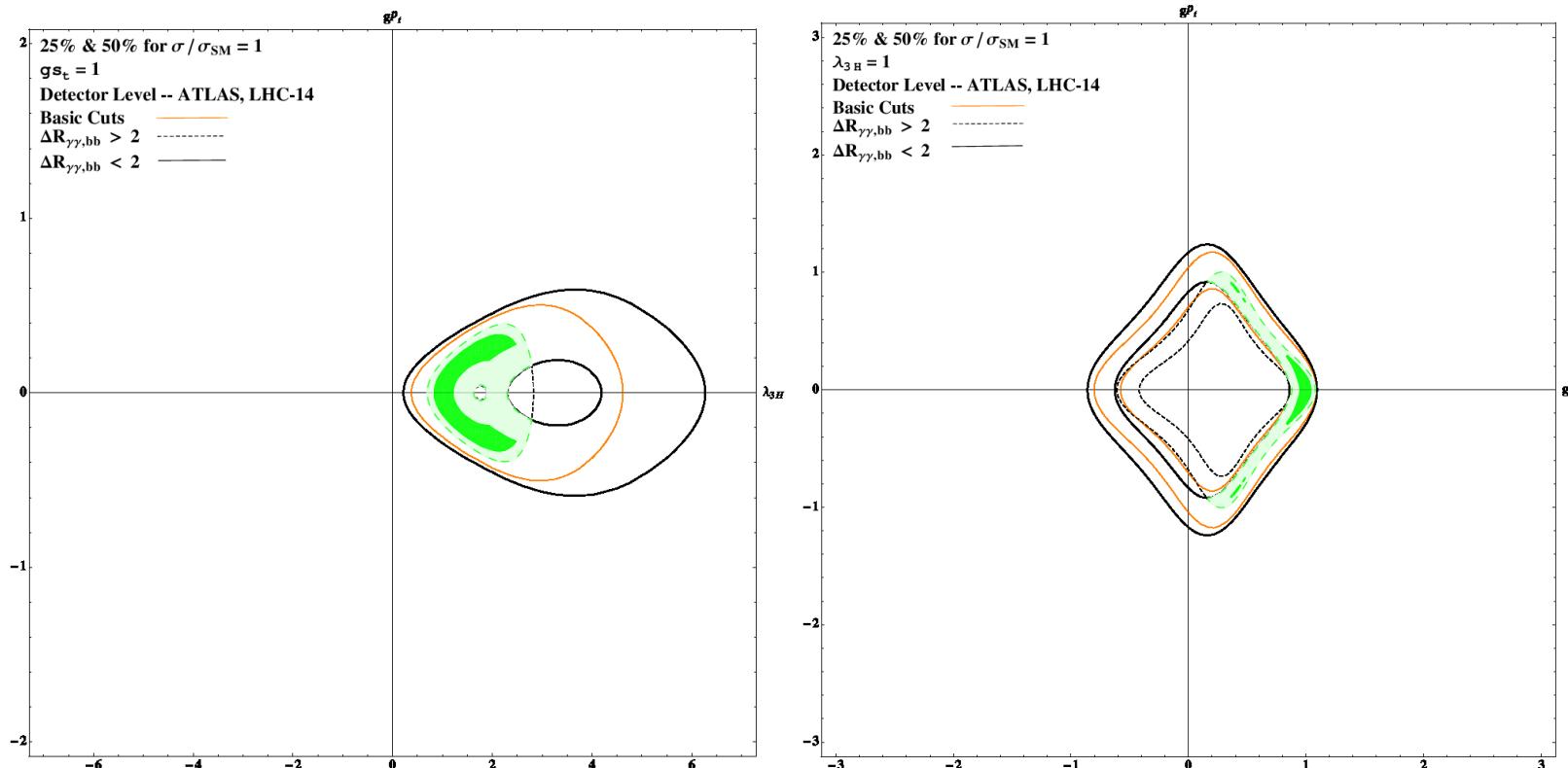


CPV1:  $g_t^S$ ,  $g_t^P$ , and  $\lambda_{3H}$ ,

---

- Unless stringent EDM constraints are imposed, the pseudoscalar coupling cannot be ruled out.
- Again, we can make use of simultaneous cross section measurements:  
(i) no cuts, (ii)  $\sigma(\Delta R_{\gamma\gamma}, \Delta R_{b\bar{b}} > 2)$ , (iii)  $\sigma(\Delta R_{\gamma\gamma}, \Delta R_{b\bar{b}} < 2)$ .





$\sqrt{s} : 14 \text{ TeV}$	$c_1(s)$	$c_2(s)$	$c_3(s)$	$d_1(s)$	$d_2(s)$	$d_3(s)$	$d_4(s)$
Cuts	$\lambda_{3H}^2 (g_t^S)^2$	$\lambda_{3H} (g_t^S)^3$	$(g_t^S)^4$	$\lambda_{3H}^2 (g_t^P)^2$	$\lambda_{3H} g_t^S (g_t^P)^2$	$(g_t^S)^2 (g_t^P)^2$	$(g_t^P)^4$
Basic Cuts	0.221	-1.104	1.883	0.665	-4.738	11.757	0.650
$\Delta R_{\gamma\gamma} > 2$	0.470	-1.868	2.398	1.481	-9.754	19.859	0.858
$\Delta R_{\gamma\gamma} < 2$	0.133	-0.834	1.701	0.376	-2.959	8.884	0.576
$\Delta R_{bb} > 2$	0.666	-2.512	2.847	2.040	-13.425	25.316	1.074
$\Delta R_{bb} < 2$	0.143	-0.857	1.714	0.424	-3.214	9.378	0.575
$\Delta R_{bb,\gamma\gamma} > 2$	0.895	-3.150	3.255	2.613	-17.210	30.456	1.278
$\Delta R_{bb,\gamma\gamma} < 2$	0.121	-0.785	1.664	0.319	-2.630	8.257	0.563

$\sqrt{s} : 14 \text{TeV}$	$e_1(s)$	$e_2(s)$	$e_3(s)$	$f_1(s)$	$f_2(s)$	$f_3(s)$	$f_4(s)$
Cuts	$\lambda_{3H} g_t^S g_{tt}^S$	$g_{tt}^S (g_t^S)^2$	$(g_{tt}^S)^2$	$\lambda_{3H} g_t^P g_{tt}^P$	$g_{tt}^S (g_t^P)^2$	$g_t^S g_t^P g_{tt}^P$	$(g_{tt}^P)^2$
Basic Cuts	1.381	-3.966	2.521	1.939	2.328	-5.239	3.178
$\Delta R_{\gamma\gamma} > 2$	1.857	-4.506	2.267	4.014	2.555	-11.188	2.569
$\Delta R_{\gamma\gamma} < 2$	1.212	-3.774	2.611	1.203	2.247	-3.130	3.394
$\Delta R_{bb} > 2$	2.248	-5.214	2.474	5.517	3.367	-16.349	3.003
$\Delta R_{bb} < 2$	1.229	-3.747	2.529	1.311	2.146	-3.290	3.208
$\Delta R_{bb,\gamma\gamma} > 2$	3.047	-5.947	2.780	7.274	3.759	-21.142	3.547
$\Delta R_{bb,\gamma\gamma} < 2$	1.238	-3.758	2.664	1.095	2.211	-2.716	3.500

100 TeV  $pp$  Collider

$\sqrt{s} : 100 \text{ TeV}$	$c_1(s)$	$c_2(s)$	$c_3(s)$	$d_1(s)$	$d_2(s)$	$d_3(s)$	$d_4(s)$
Cuts	$\lambda_{3H}^2 (g_t^S)^2$	$\lambda_{3H} (g_t^S)^3$	$(g_t^S)^4$	$\lambda_{3H}^2 (g_t^P)^2$	$\lambda_{3H} g_t^S (g_t^P)^2$	$(g_t^S)^2 (g_t^P)^2$	$(g_t^P)^4$
Basic Cuts	0.173	-1.032	1.860	0.503	-4.045	10.019	0.633
$\Delta R_{\gamma\gamma} > 2$	0.389	-1.904	2.515	1.275	-6.972	13.375	0.853
$\Delta R_{\gamma\gamma} < 2$	0.115	-0.798	1.683	0.295	-3.258	9.116	0.574
$\Delta R_{bb} > 2$	0.607	-2.419	2.813	1.845	-9.336	17.393	1.057
$\Delta R_{bb} < 2$	0.120	-0.863	1.743	0.340	-3.400	9.119	0.581
$\Delta R_{bb,\gamma\gamma} > 2$	0.753	-2.662	2.909	2.248	-10.518	17.691	1.245
$\Delta R_{bb,\gamma\gamma} < 2$	0.102	-0.733	1.632	0.249	-3.041	8.700	0.565
$\sqrt{s} : 100 \text{TeV}$	$e_1(s)$	$e_2(s)$	$e_3(s)$	$f_1(s)$	$f_2(s)$	$f_3(s)$	$f_4(s)$
Cuts	$\lambda_{3H} g_t^S g_{tt}^S$	$g_{tt}^S (g_t^S)^2$	$(g_{tt}^S)^2$	$\lambda_{3H} g_t^P g_{tt}^P$	$g_{tt}^S (g_t^P)^2$	$g_t^S g_t^P g_{tt}^P$	$(g_{tt}^P)^2$
Basic Cuts	1.170	-4.081	2.848	1.300	1.935	-3.379	7.802
$\Delta R_{\gamma\gamma} > 2$	1.782	-4.886	2.591	3.675	2.151	-2.696	5.511
$\Delta R_{\gamma\gamma} < 2$	1.006	-3.865	2.917	0.662	1.878	-3.563	8.419
$\Delta R_{bb} > 2$	2.011	-5.585	2.957	6.947	2.576	-4.961	5.373
$\Delta R_{bb} < 2$	1.068	-3.898	2.834	0.612	1.857	-3.186	8.099
$\Delta R_{bb,\gamma\gamma} > 2$	2.483	-5.858	3.106	8.165	2.694	-4.722	6.079
$\Delta R_{bb,\gamma\gamma} < 2$	0.995	-3.798	2.928	0.437	1.851	-3.466	8.647

## Conclusions

---

- It is just the beginning of an exciting era.
- Global fitting of Higgs parameters – Higgcision.
- If the  $WW$  scattering becomes strong, it means the light Higgs boson is only partially responsible for EWSB.
- The associated Higgs production with a single top quark has the potential to measure the size and sign of the top Yukawa.
- Non-standard decay of the Higgs boson is still exciting.
- Higgs boson pair production is the beginning of probing into the Higgs sector itself.

# Backup Slides

### Signal strengths of $H \rightarrow \gamma\gamma$ (full data set)

Channel	Signal strength $\mu$	$M_H$ (GeV)	$\chi^2_{\text{SM}}$ (each)
ATLAS ( $4.5 fb^{-1}$ at 7TeV + $20.3 fb^{-1}$ at 8TeV): (Aug. 2014)			
$\mu_{ggH}$	$1.32 \pm 0.38$	125.40	0.71
$\mu_{VBF}$	$0.8 \pm 0.7$	125.40	0.08
$\mu_{WH}$	$1.0 \pm 1.6$	125.40	0.00
$\mu_{ZH}$	$0.1^{+3.7}_{-0.1}$	125.40	0.06
$\mu_{ttH}$	$1.6^{+2.7}_{-1.8}$	125.40	0.11
CMS ( $5.1 fb^{-1}$ at 7TeV + $19.7 fb^{-1}$ at 8TeV): (July 2014)			
$\mu_{ggH}$	$1.12^{+0.37}_{-0.32}$	124.70	0.14
$\mu_{VBF}$	$1.58^{+0.77}_{-0.68}$	124.70	0.73
$\mu_{VH}$	$-0.16^{+1.16}_{-0.79}$	124.70	1.00
$\mu_{ttH}$	$2.69^{+2.51}_{-1.81}$	124.70	0.87
Tevatron ( $10.0 fb^{-1}$ at 1.96TeV): (Nov. 2012)			
Combined	$6.14^{+3.25}_{-3.19}$	125	2.60
		subtot: 6.30	

# Search for Goldstone Boson in Higgs Decay

KC, Wai-Yee Keung, Tzu-Chiang Yuan 1308.4235

Typically, the Higgs boson can decay into non-SM particles, which further decay into SM particles. Signatures include  $\gamma\gamma b\bar{b}$ ,  $\tau^+\tau^- b\bar{b}$ ,  $\pi\pi E_T$ ,  $\mu\mu E_T$ , etc.

## Collider Signatures

---

- Nonstandard decay of the Higgs is less than about 20%. Take  $B(H \rightarrow \sigma\sigma) \approx 10\%$  and  $B(\sigma \rightarrow \pi\pi) \approx 20\%$  we can have

$$gg \rightarrow H \rightarrow \sigma\sigma \rightarrow (\pi\pi)(\alpha\alpha)$$

- The cross section at the LHC-8 would be

$$\begin{aligned} \sigma(gg \rightarrow H) \times B(H \rightarrow \sigma\sigma) \times B(\sigma \rightarrow \pi\pi) \times B(\sigma \rightarrow \alpha\alpha) &\approx 19 \text{ pb} \times 0.1 \times 0.2 \times 0.8 \\ &\approx 300 \text{ fb} \end{aligned}$$

At the LHC-14, it would be 2.8 times as much.

- Difficulties: the angular separation between the two pions is very small:  $1/60 \sim 2m_\sigma/p_{T\sigma} \approx 0.015$ . It appears to be a **microjet** having two pions, and experimentally like a  $\tau$  jet.

## $WW$ Scattering to test the degree of EWSB of the Discovered Higgs

---

Jung Chang, KC, Yuan, 1303.6335; KC, Chiang, Yuan, 0803.2661

If the cancellation from the Higgs diagrams is not complete, due to, e.g., the  $g_{hww}$  coupling is smaller than the SM value. The  $W_L^+ W_L^- \rightarrow W_L^+ W_L^-$  scattering amplitude will grow with  $s$ .

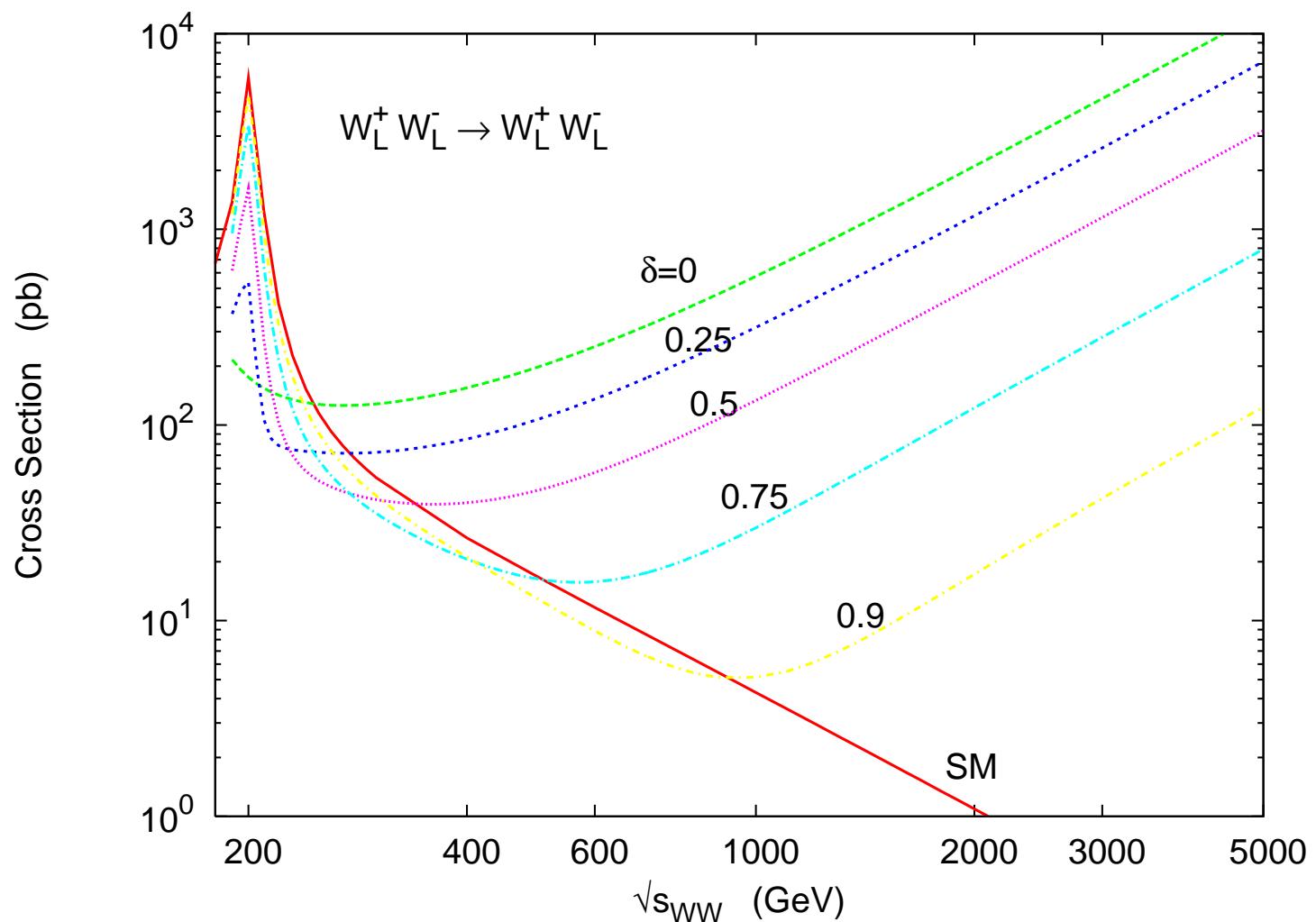
Suppose the Higgs- $W$ - $W$  coupling is  $\sqrt{\delta}$  of the SM value, then amplitudes become

$$i\mathcal{M}^{\text{gauge}} = -i \frac{g^2}{4m_W^2} u + \mathcal{O}((E/m_W)^0)$$

$$i\mathcal{M}^{\text{higgs}} = i \frac{g^2}{4m_W^2} u \delta + \mathcal{O}((E/m_W)^0)$$

$$i\mathcal{M}^{\text{all}} = -i \frac{g^2}{4m_W^2} u(1 - \delta) + \mathcal{O}((E/m_W)^0)$$

Cheung, Chiang, Yuan



Cross Sections (fb) for the LHC at 13 TeV

Channels	$\sin(\beta - \alpha) = 0.5$	0.7	0.9	SM ( $C_v = 1$ )
$W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$	0.51	0.46	0.40	0.39
$W^+W^+ \rightarrow \ell^+\nu\ell^+\nu$	0.20	0.17	0.14	0.14
$W^-W^- \rightarrow \ell^-\bar{\nu}\ell^-\bar{\nu}$	0.083	0.075	0.070	0.069
$W^+Z \rightarrow \ell^+\nu\ell^+\ell^-$	0.016	0.013	0.011	0.010
$W^-Z \rightarrow \ell^-\bar{\nu}\ell^+\ell^-$	$1.0 \times 10^{-2}$	$8.5 \times 10^{-3}$	$7.6 \times 10^{-3}$	$7.4 \times 10^{-3}$
$ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$	$8.4 \times 10^{-3}$	$6.4 \times 10^{-3}$	$4.6 \times 10^{-3}$	$4.4 \times 10^{-3}$

SM cross section value in fb for LHC-14 and LHC-100.

SM cross section (fb)	14 TeV	100 TeV
Cuts		
No Cuts	8.92e-2	3.73
$\Delta R(\gamma_1, \gamma_2) > 2$	1.81e-2	6.86e-1
$\Delta R(\gamma_1, \gamma_2) < 2$	4.58e-2	1.84
$\Delta R(b_1, \bar{b}_1) > 2$	2.04e-3	6.46e-2
$\Delta R(b_1, \bar{b}_1) < 2$	1.00e-2	3.42e-1
$\Delta R(b_1, \bar{b}_1) > 2 \text{ \& } \Delta R(\gamma_1, \gamma_2) > 2$	7.20e-4	1.79e-2
$\Delta R(b_1, \bar{b}_1) < 2 \text{ \& } \Delta R(\gamma_1, \gamma_2) < 2$	5.89e-3	2.05e-1

## The cut flow

	Signals (fb)			Backgrounds (fb)		
	$C_t^S = 1$	$C_t^S = 0$	$C_t^S = -1$	$tj\tau\tau$	$t\bar{t}$	$t\bar{t}W$
(1) Basic cuts and						
$p_{T\tau} > 25 \text{ GeV},  \eta_\tau  < 2.5$	0.00682	0.0257	0.1026	0.0701	0.420	0.000672
(2) $2.5 <  \eta_j  < 4.7$	0.00355	0.0148	0.0585	0.0333	0.0	$4.27 \times 10^{-5}$
(3) $M_{bl} < 200 \text{ GeV}$	0.00345	0.0141	0.0555	0.0319	0.0	$4.27 \times 10^{-5}$
(4) $110 < M_{\tau\tau} < 150 \text{ GeV}$	0.00158	0.00616	0.0244	0.0105	0.0	$1.904 \times 10^{-5}$
$S/\sqrt{S+B}$ for $300 \text{ fb}^{-1}$	0.25	0.83	2.3			

## The cut flow

	Signals ( $10^{-3}$ fb)			Backgrounds ( $10^{-3}$ fb)		
	$C_t^S = 1$	$C_t^S = 0$	$C_t^S = -1$	$tj4\ell$	$ZZ3j$	$ZZb2j$
(1) Basic cuts and $p_{Tj_{1,2}} > 25$ GeV, $ \eta_{j_{1,2}}  < 2.5$ but with $p_{T\ell} > 5$ GeV	0.136	0.531	1.77	0.955	20.1	10.0
(2) $2.5 <  \eta_j  < 4.7$	0.091	0.366	1.18	0.539	8.01	5.01
(3) $M_{bj_1j_2} < 300$ GeV	0.081	0.324	1.02	0.438	3.79	1.97
(4) $ M_{4\ell} - m_h  < 5$ GeV	0.072	0.289	0.901	$8.65 \times 10^{-3}$	0.0	0.0
$S/\sqrt{S + B}$ for $300$ fb $^{-1}$	0.14	0.29	0.52			

## The cut flow

	Signals ( $10^{-3}$ fb)			Backgrounds ( $10^{-3}$ fb)			
	$C_t^S = 1$	$C_t^S = 0$	$C_t^S = -1$	$tj\gamma\gamma$	$tjj\gamma$	$Wbj\gamma\gamma$	$Wjj\gamma\gamma$
(1) Basic cuts and							
$p_{T\gamma} > 20 \text{ GeV},  \eta_\gamma  < 2.5$	4.45	22.7	80.0	318	2.59	10.5	217
$(2) 2.5 <  \eta_j  < 4.7$	2.35	13.1	45.2	164	0.650	1.04	20.5
$(3) M_{bl} < 200 \text{ GeV}$	2.30	12.7	43.6	162	0.609	0.609	11.2
$(4)  M_{\gamma\gamma} - m_h  < 5 \text{ GeV}$	1.83	10.2	34.7	5.77	0.027	0.018	0.661
$S/\sqrt{S+B}$ for $300 \text{ fb}^{-1}$	0.35	1.4	3.0				