Higgcision

&

Higgs Boson Pair Production

KC, Jae-Sik Lee, Po-Yan Tseng;
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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

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

- Φ 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 $\mathcal{L}_Y$:

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

So far, the gauge boson couplings and b, τ, 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

$$\mathcal{L}_{H\bar{f}f} = -\sum_{f=u,d,l} \frac{g m_f}{2M_W} \sum_{i=1}^{3} H\, \bar{f} \left(g^S_{H\bar{f}f} + i g^P_{H\bar{f}f} \gamma_5 \right) f \, .$$

For the SM $g^S_{H\bar{f}f} = 1$ and $g^P_{H\bar{f}f} = 0$.

- 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:

$$\mathcal{M}_{\gamma\gamma H} = -\frac{\alpha M_H^2}{4\pi\, v} \left\{ S^\gamma(M_H)\, \left(\epsilon^*_{1\perp} \cdot \epsilon^*_{2\perp}\right) - P^\gamma(M_H) \frac{2}{M_H^2} \langle \epsilon^*_1 \epsilon^*_2 k_1 k_2 \rangle \right\},$$

$$\begin{aligned} S^\gamma(M_H) &= 2 \sum_{f=b,t,\tau} N_C\, Q_f^2\, g^S_{H\bar{f}f}\, F_{sf}(\tau_f) - g_{HWW}\, F_1(\tau_W) + \Delta S^\gamma\,, \\ P^\gamma(M_H) &= 2 \sum_{f=b,t,\tau} N_C\, Q_f^2\, g^P_{H\bar{f}f}\, F_{pf}(\tau_f) + \Delta P^\gamma\,, \end{aligned}$$

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

$$\begin{aligned} S^\gamma &\simeq -8.35\, g_{HWW} + 1.76\, g^S_{H\bar{t}t} + (-0.015 + 0.017\, i)\, g^S_{H\bar{b}b} \\ &\quad + (-0.024 + 0.021\, i)\, g^S_{H\bar{\tau}\tau} + (-0.007 + 0.005\, i)\, g^S_{H\bar{c}c} + \Delta S^\gamma \\ P^\gamma &\simeq 2.78\, g^P_{H\bar{t}t} + (-0.018 + 0.018\, i)\, g^P_{H\bar{b}b} \\ &\quad + (-0.025 + 0.022\, i)\, g^P_{H\bar{\tau}\tau} + (-0.007 + 0.005\, i)\, g^P_{H\bar{c}c} + \Delta P^\gamma \end{aligned}$$

giving $S^\gamma_{\rm SM} = -6.64 + 0.043\, i$ and $P^\gamma_{\rm SM} = 0$.

- two gluons

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

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

$$\begin{aligned} S^g &\simeq 0.688\, g_{H\bar{t}t}^S + (-0.037 + 0.050\, i)\, g_{H\bar{b}b}^S + \Delta S^g \\ P^g &\simeq 1.047\, g_{H\bar{t}t}^P + (-0.042 + 0.050\, i)\, g_{H\bar{b}b}^P + \Delta P^g \end{aligned}$$

Signal Strengths:

- The signal strength can be written as the product of

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

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

- On the production side:

$$\begin{aligned}
\widehat{\mu}(\mathrm{ggF}) &= \frac{|S^g(M_H)|^2 + |P^g(M_H)|^2}{\left|S^g_{\mathrm{SM}}(M_H)\right|^2} \\
\widehat{\mu}(\mathrm{VBF}) &= g^2_{HWW,HZZ} \\
\widehat{\mu}(\mathrm{VH}) &= g^2_{HWW,HZZ} \\
\widehat{\mu}(\mathrm{ttH}) &= \left(g^S_{H\bar{t}t}\right)^2 + \left(g^P_{H\bar{t}t}\right)^2
\end{aligned}$$

- On the decay side

$$\widehat{\mu}(\mathcal{D}) = \frac{B(H \to \mathcal{D})}{B(H_{\mathrm{SM}} \to \mathcal{D})}$$

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

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

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

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

Fitting analysis

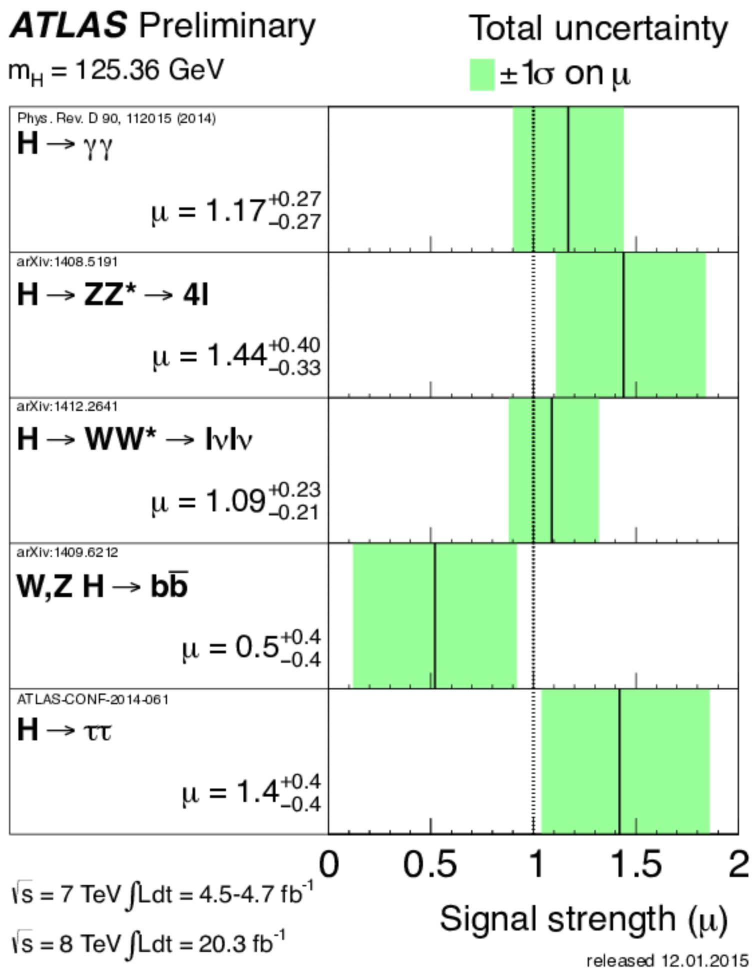
- Ratios of Yukawa and gauge couplings

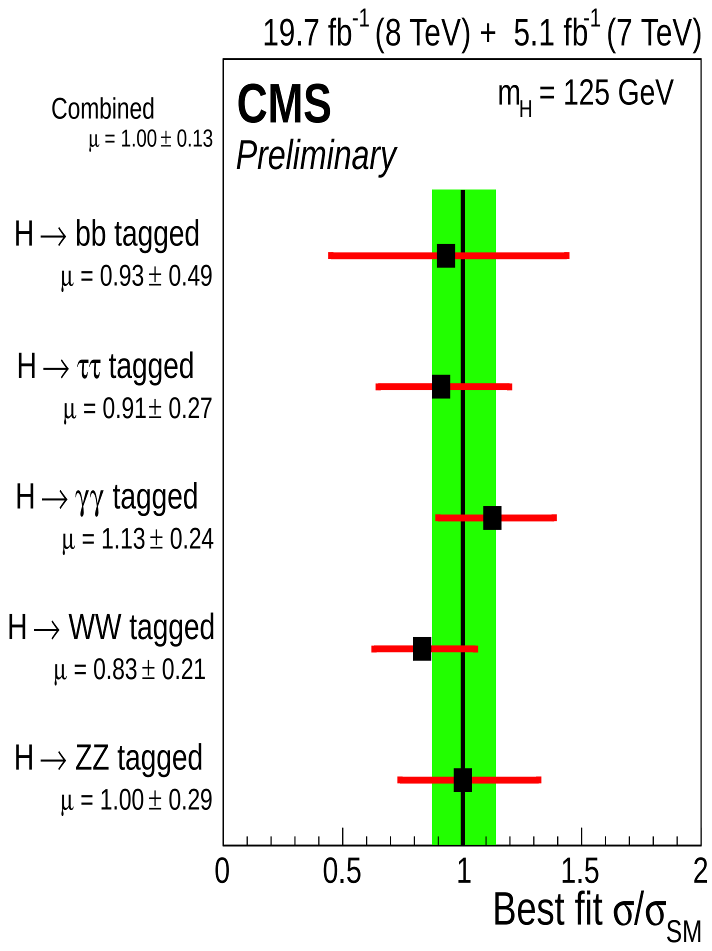
$$C_u^S = g^S_{H\bar{u}u}\,, \quad C_d^S = g^S_{H\bar{d}d}\,, \quad C_\ell^S = g^S_{H\bar{l}l}\,; \quad C_v = g_{HVV}\,;$$
$$C_u^P = g^P_{H\bar{u}u}\,, \quad C_d^P = g^P_{H\bar{d}d}\,, \quad C_\ell^P = g^P_{H\bar{l}l}\,.$$

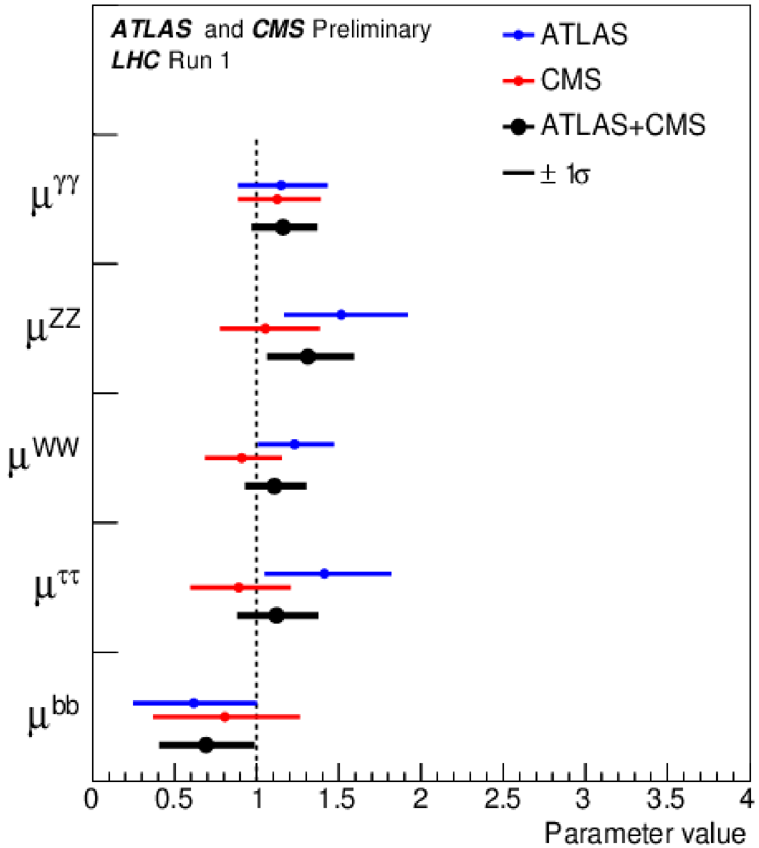
- Extra loop contributions other than the Yukawa and gauge couplings:

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

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


ATLAS Preliminary
m_H = 125.36 GeV
Total uncertainty
±1σ on μ
Phys. Rev. D 90, 112015 (2014)
H → γγ
μ = 1.17 +0.27 −0.27
arXiv:1408.5191
H → ZZ* → 4l
μ = 1.44 +0.40 −0.33
arXiv:1412.2641
H → WW* → lνlν
μ = 1.09 +0.23 −0.21
arXiv:1409.6212
W,Z H → bb̄
μ = 0.5 +0.4 −0.4
ATLAS-CONF-2014-061
H → ττ
μ = 1.4 +0.4 −0.4
0 0.5 1 1.5 2
√s = 7 TeV ∫Ldt = 4.5-4.7 fb⁻¹
√s = 8 TeV ∫Ldt = 20.3 fb⁻¹
Signal strength (μ)
released 12.01.2015


19.7 fb⁻¹ (8 TeV) + 5.1 fb⁻¹ (7 TeV)
CMS
Preliminary
m_H = 125 GeV
Combined
μ = 1.00 ± 0.13
H → bb tagged
μ = 0.93 ± 0.49
H → ττ tagged
μ = 0.91 ± 0.27
H → γγ tagged
μ = 1.13 ± 0.24
H → WW tagged
μ = 0.83 ± 0.21
H → ZZ tagged
μ = 1.00 ± 0.29
0 0.5 1 1.5 2
Best fit σ/σ_SM


ATLAS and CMS Preliminary
LHC Run 1
ATLAS
CMS
ATLAS+CMS
± 1σ
$\mu^{\gamma\gamma}$
μ^{ZZ}
μ^{WW}
$\mu^{\tau\tau}$
μ^{bb}
0 0.5 1 1.5 2 2.5 3 3.5 4
Parameter value

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

Cases	**CPC 1**	**CPC 2**	**CPC 3**	**CPC 4**	**CPC 6**
Parameters	Vary $\Delta\Gamma_{\rm tot}$	ΔS^γ, ΔS^g	ΔS^γ, ΔS^g, $\Delta\Gamma_{\rm tot}$	C_u^S, C_d^S, C_ℓ^S, C_v	C_u^S, C_d^S, C_ℓ^S, C_v ΔS^γ, ΔS^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_ℓ^S	1	1	1	$0.99^{+0.17}_{-0.17}$	$1.00^{+0.18}_{-0.17}$
C_v	1	1	1	$0.98^{+0.10}_{-0.11}$	$0.94^{+0.11}_{-0.12}$
ΔS^γ	0	$-0.72^{+0.76}_{-0.74}$	$-0.84^{+0.80}_{-0.82}$	0	$-1.43^{+1.02}_{-0.95}$
ΔS^g	0	$-0.009^{+0.047}_{-0.048}$	$0.02^{+0.10}_{-0.08}$	0	$-0.22^{+0.28}_{-0.24}$
$\Delta\Gamma_{\rm tot}$	$-0.020^{+0.45}_{-0.37}$	0	$0.39^{+1.13}_{-0.76}$	0	0
χ^2/dof	16.76/28	15.81/27	15.59/26	16.70/25	14.83/23
p-value	0.953	0.956	0.945	0.892	0.901

CPC1: Vary only $\Delta\Gamma_{\rm tot}$

- 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

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

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

$$\Delta\Gamma_{\rm tot} < 0.97\ \mathrm{MeV}$$

- 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

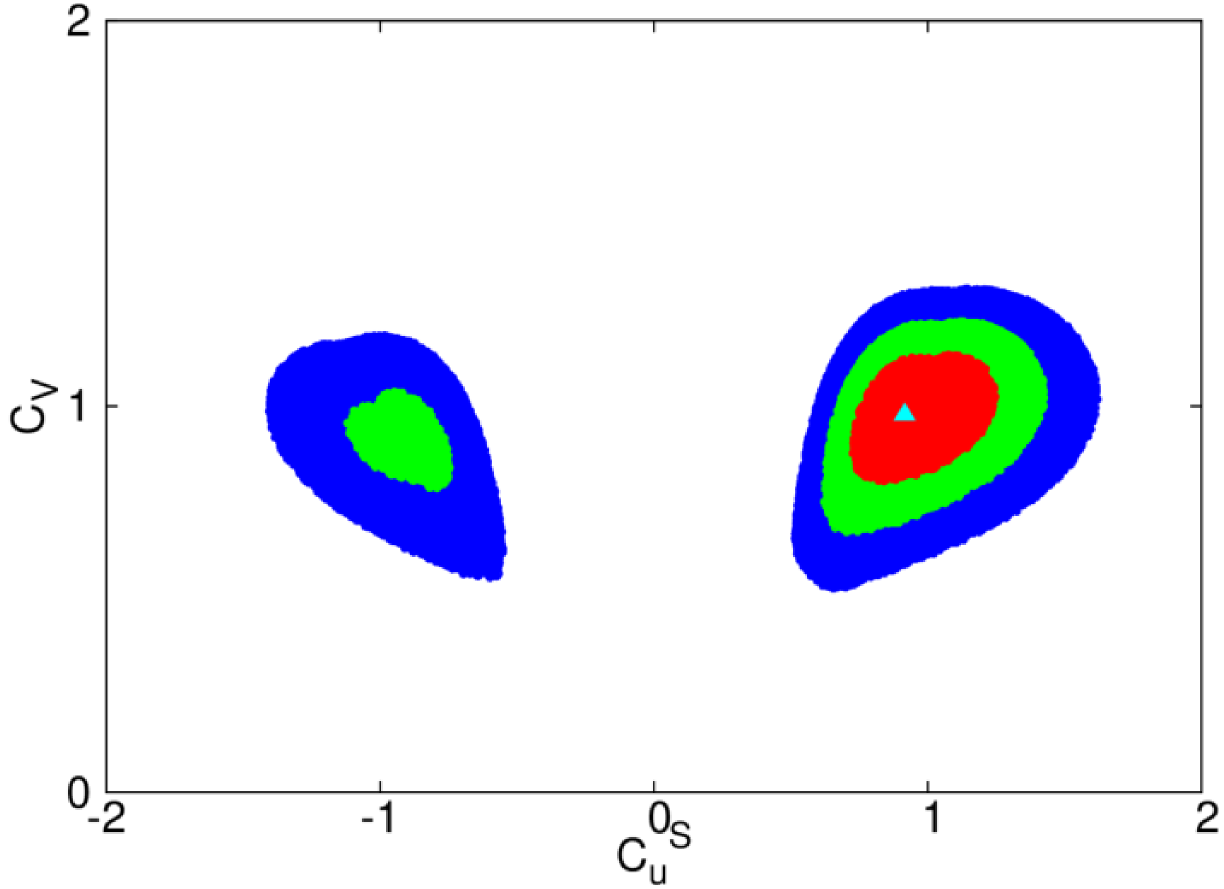
$$B(H \to \mathrm{nonstandard}) < 19\%$$

CPC4: Vary C_u^S, C_d^S, C_ℓ^S, C_v

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

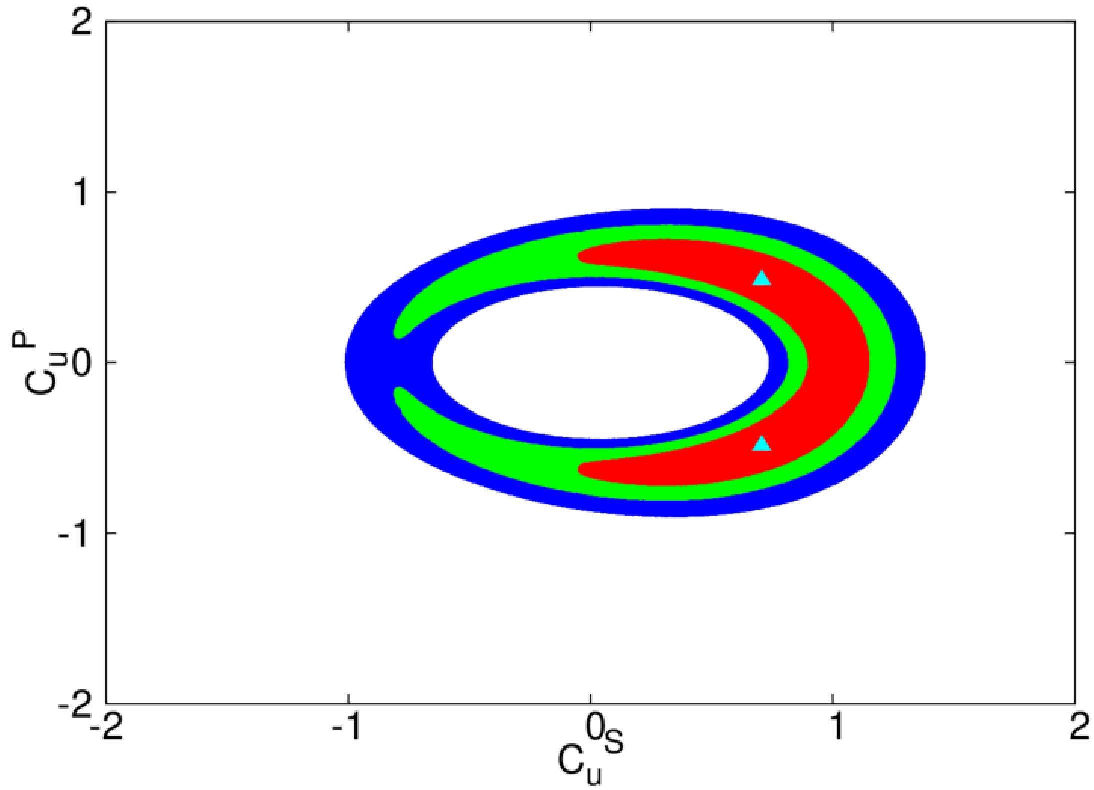
$$C_d^S \leftrightarrow -C_d^S\,, \;\; C_\ell^S \leftrightarrow -C_\ell^S$$

- 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 ΔS^γ and ΔS^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.

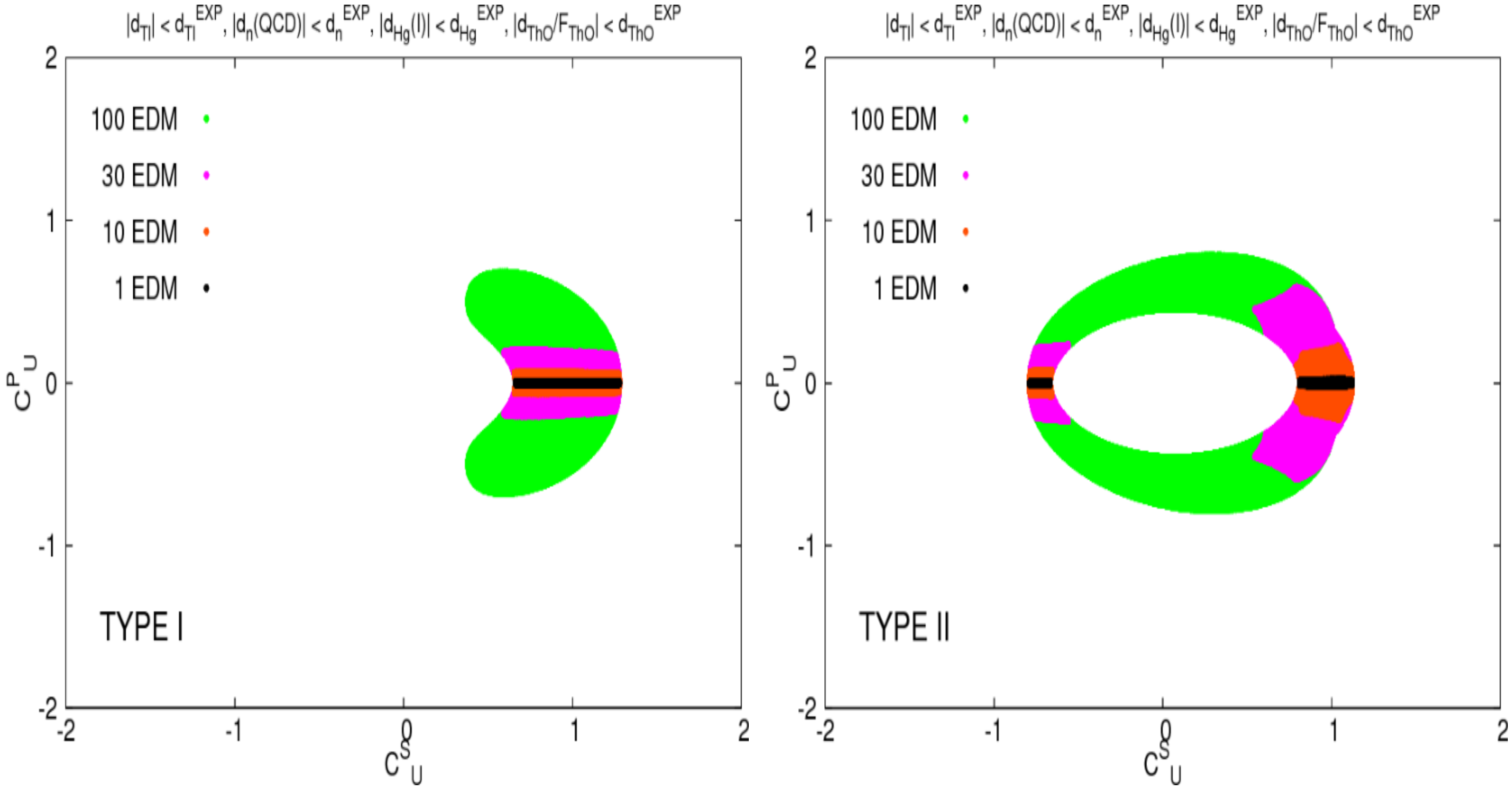
Zoom in for the Higgs boson

- Use EDMs to constrain the pseudoscalar Higgs couplings, such as C_u^P and ΔP^γ.
- 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.



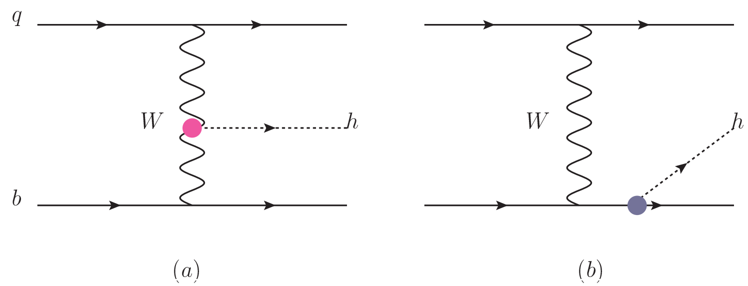
KC, Lee, Senaha, Tseng

Associated Production of Higgs with a single top quark

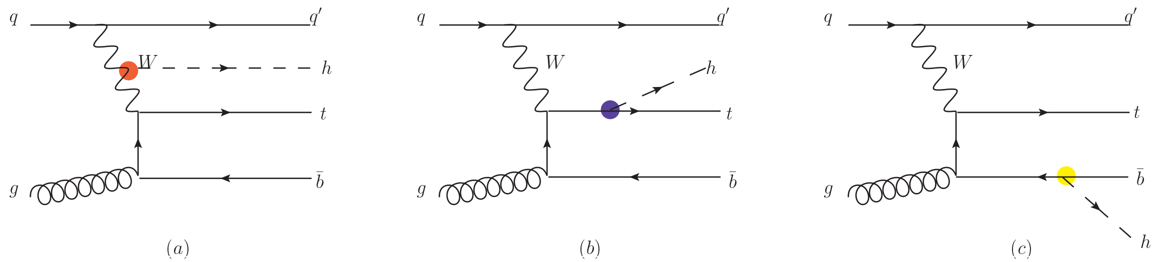
Jung Chang, KC, Jae-Sik Lee, Chih-Ting Lu, 1403.2053

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

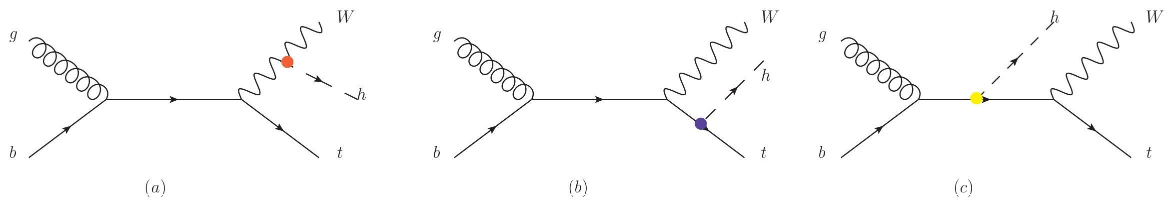
$qb \to thq'$



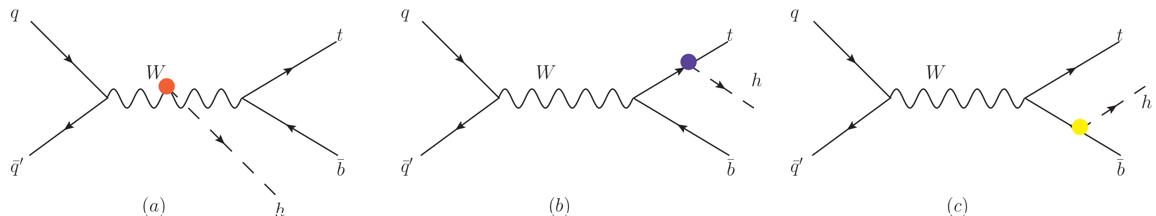
$qg \to thq'b$



$gb \to thW$



$q\bar{q}' \to th\bar{b}$



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

$$\mathcal{L}_{hVV} = g m_W \left(g_{hWW} W_\mu^+ W^{-\mu} + g_{hZZ} \frac{1}{2c_W^2} Z_\mu Z^\mu \right) h \,,$$

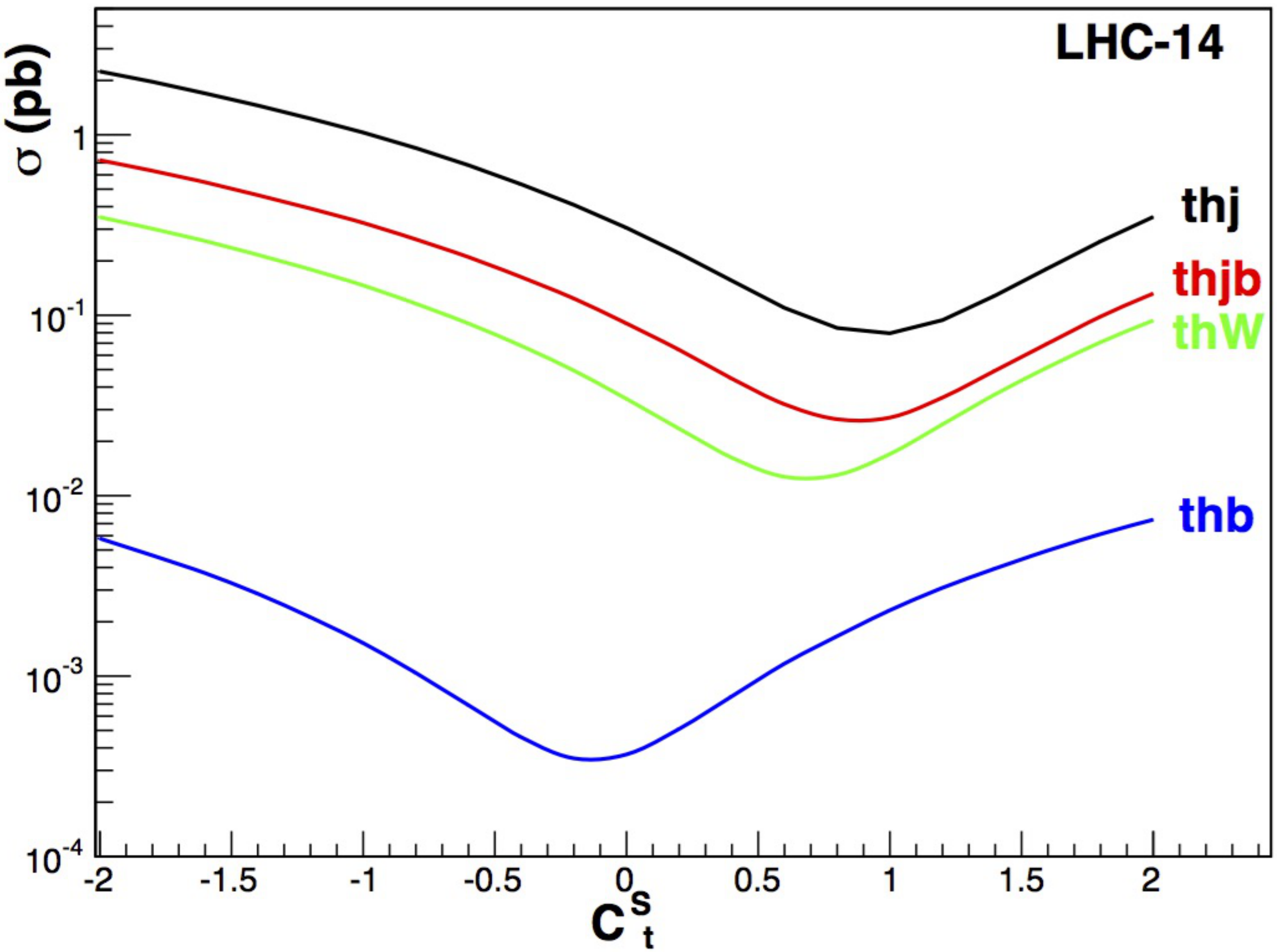
$$\mathcal{L}_{hff} = - \sum_{f=t,b,c,\tau} \frac{g m_f}{2 m_W} \bar{f} \left(g_{hff}^S + i g_{hff}^P \gamma_5 \right) f \, h$$

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

$$Wb \to ht$$

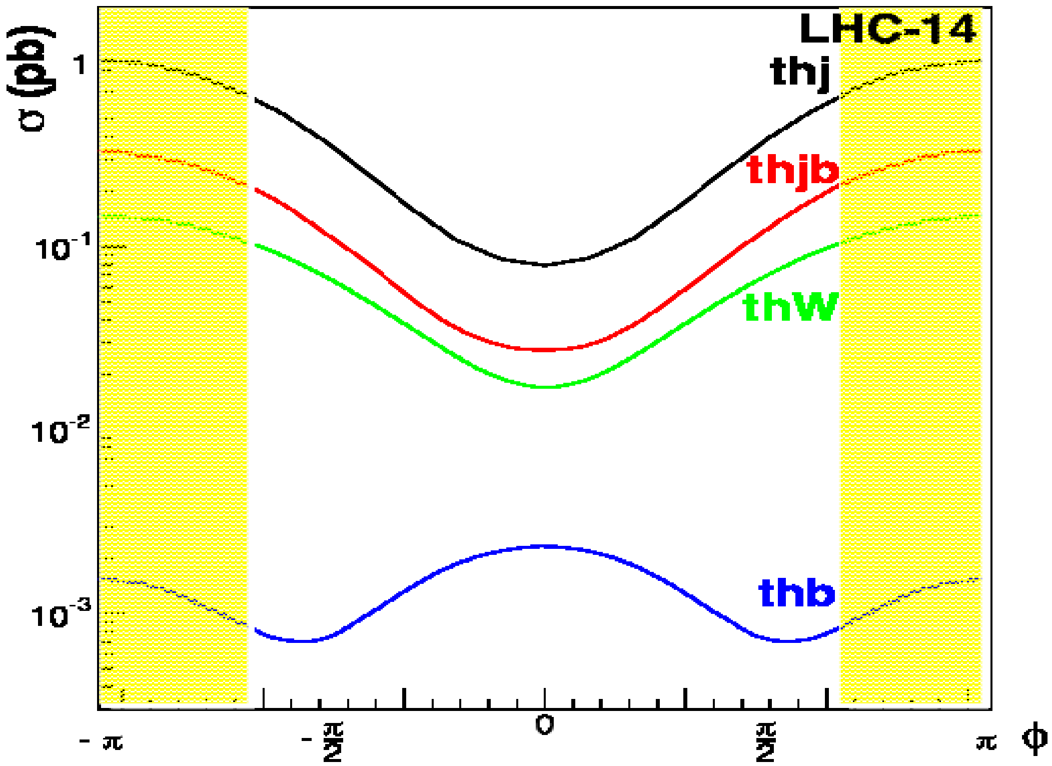
- At high energy, it is dominated by longitudinal W:

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


LHC-14
σ (pb)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
thj
thjb
thW
thb
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
C^s_t

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

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:

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

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

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

and

$$t \to bjj, \qquad h \to ZZ^* \to 4\ell$$

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

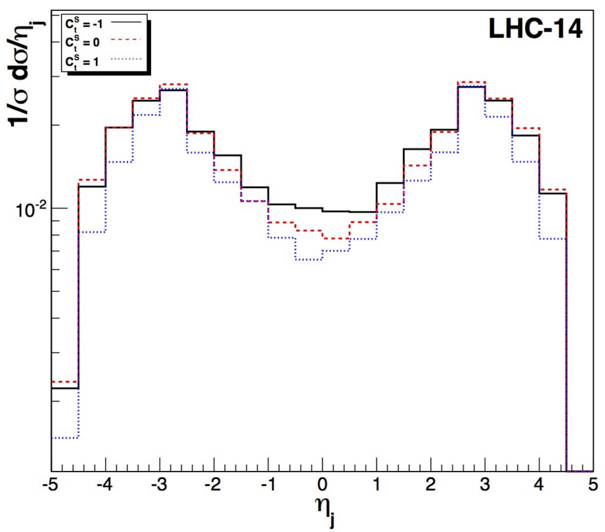
Detection efficiencies				Mistag probability			
ϵ_b	ϵ_τ	ϵ_ℓ	ϵ_γ	$P_{c\to b}$	$P_{udsg\to b}$	$P_{j\to\tau}$	$P_{j\to\gamma}$
0.7 (0.6)	0.5	1.0	1.0	0.2 (0.08)	0.015 (0.004)	0.01	10^{-3}

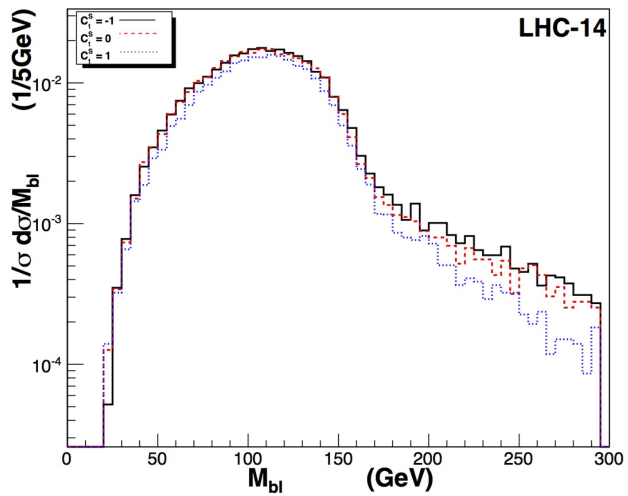
$h \to b\bar{b}$ Mode with $t \to b\ell\nu$

- Basic cuts:

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

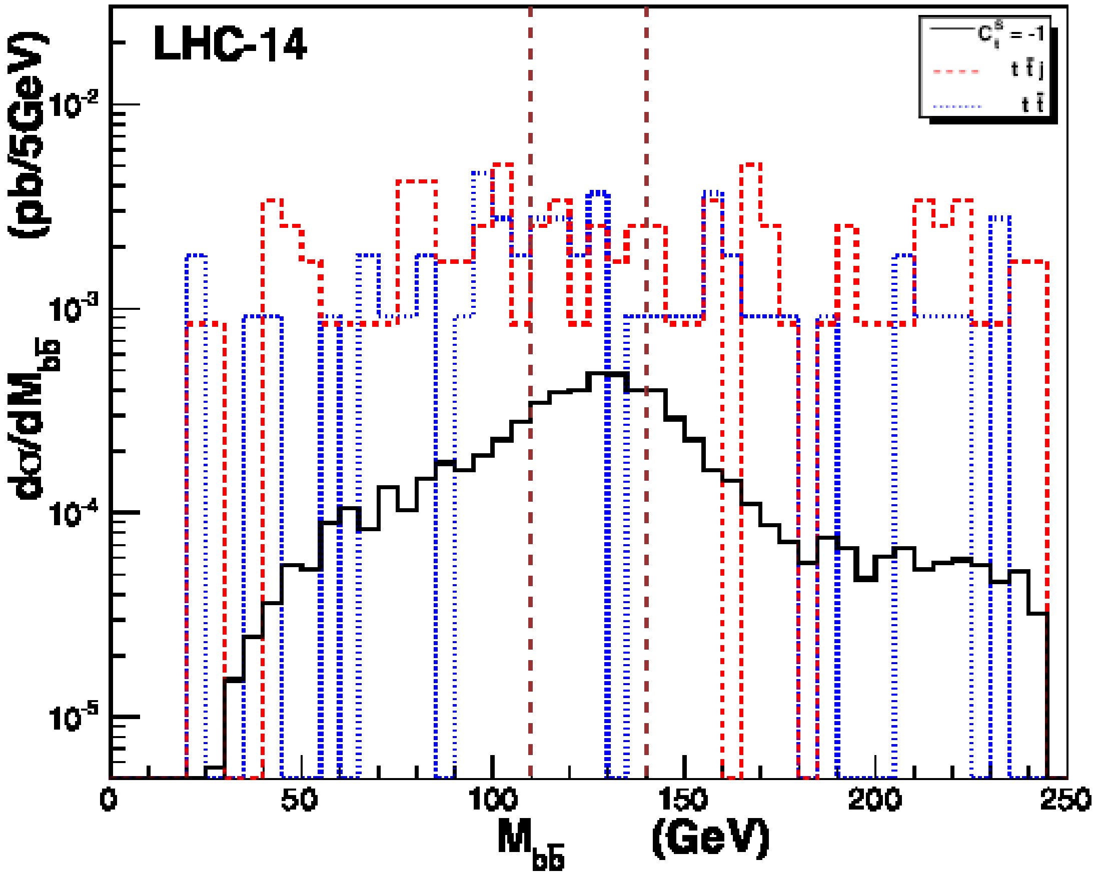
- Forward jet tag and top mass constraint





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

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

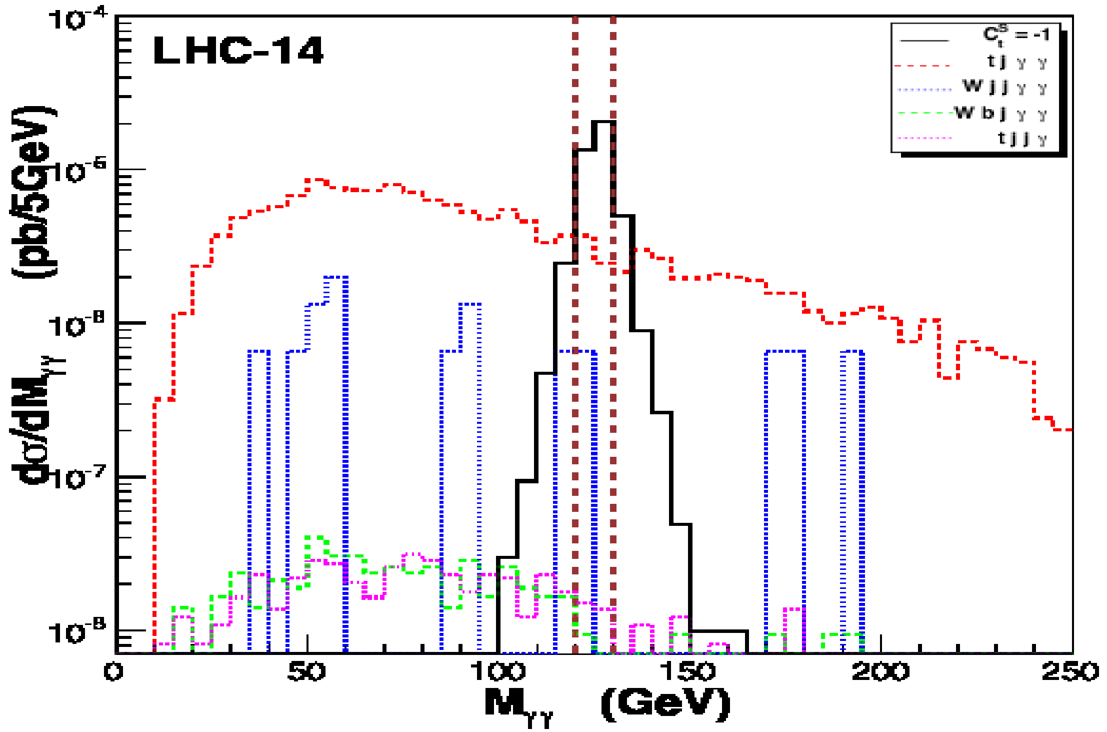


The cut flow

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

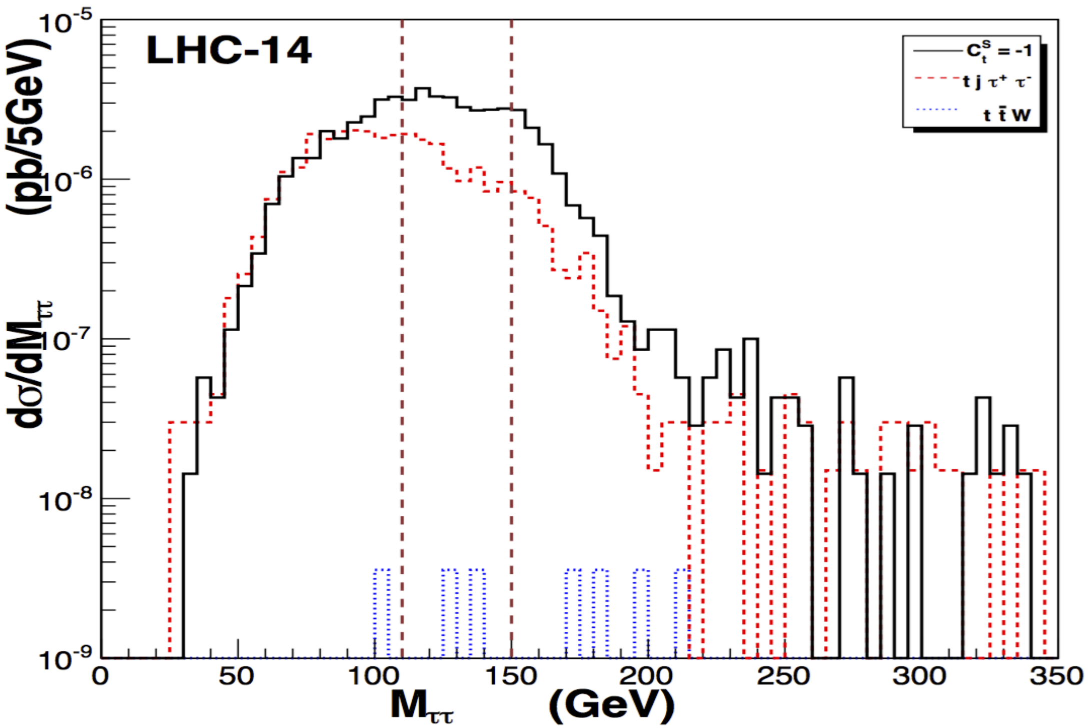
$h \to \gamma\gamma$ Mode with $t \to b\ell\nu$

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



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

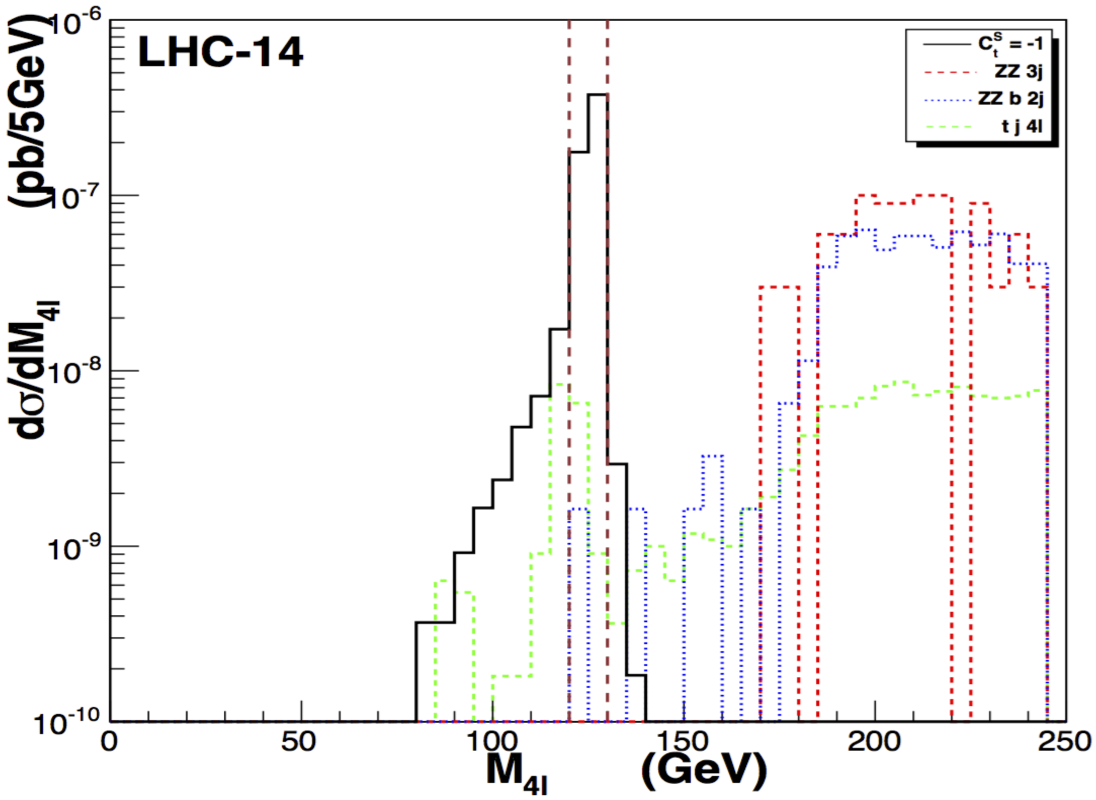
- Tau has a BR ~ 0.06. Tau decays always contain neutrino, thus the momentum cannot be fully reconstructed. But it can estimated in fast moving tau and in hadronic decay. Currently, the scale factor is 1.37 in Delphes 3.
- The $M_{\tau\tau}$ peak at m_h is broad. We apply the cuts:
$110\,\text{GeV} 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



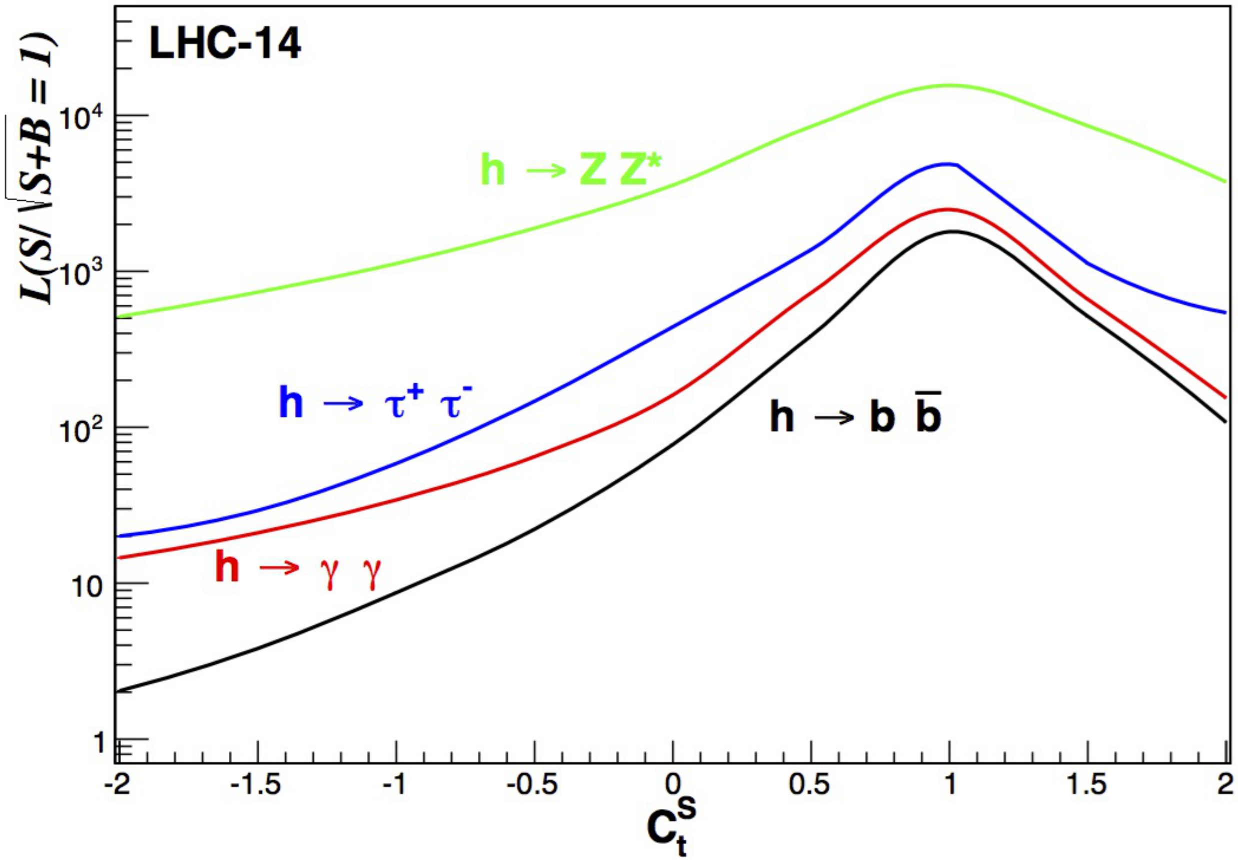
$h \to ZZ^* \to 4\ell$ Mode with $t \to bj_1j_2$

Cuts on leptons:

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

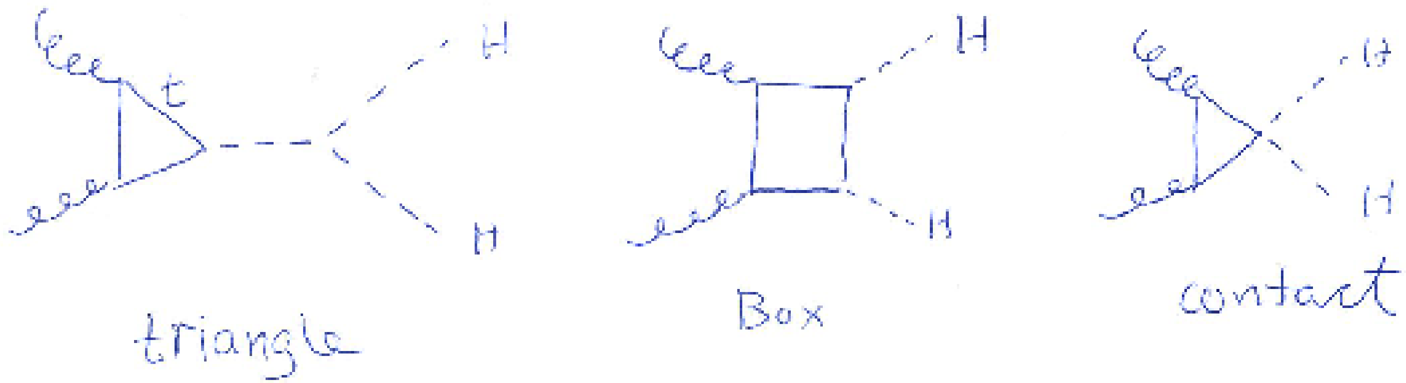


Required luminosity at LHC-14 to achieve $S/\sqrt{S+B} > 1$



Higgs boson Pair Production

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


t
H
H
triangle
H
H
Box
H
H
contact

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:

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

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

- Extensions to CP-odd and contact terms:

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

- Production cross section normalized to the SM one is

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

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 $t\bar{t} \to HH$ will saturate unitarity at high enough $\sqrt{s}$:

$$i\mathcal{M}(t\bar{t} \to HH) \sim g^S_{tt} \frac{m_t\sqrt{\hat{s}}}{v^2}$$

Requiring $|a_0| < 1/2$:

$$\sqrt{\hat{s}} \leq \frac{17.6}{g^S_{tt}} \text{ TeV} .$$

$\sqrt{s}$ (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

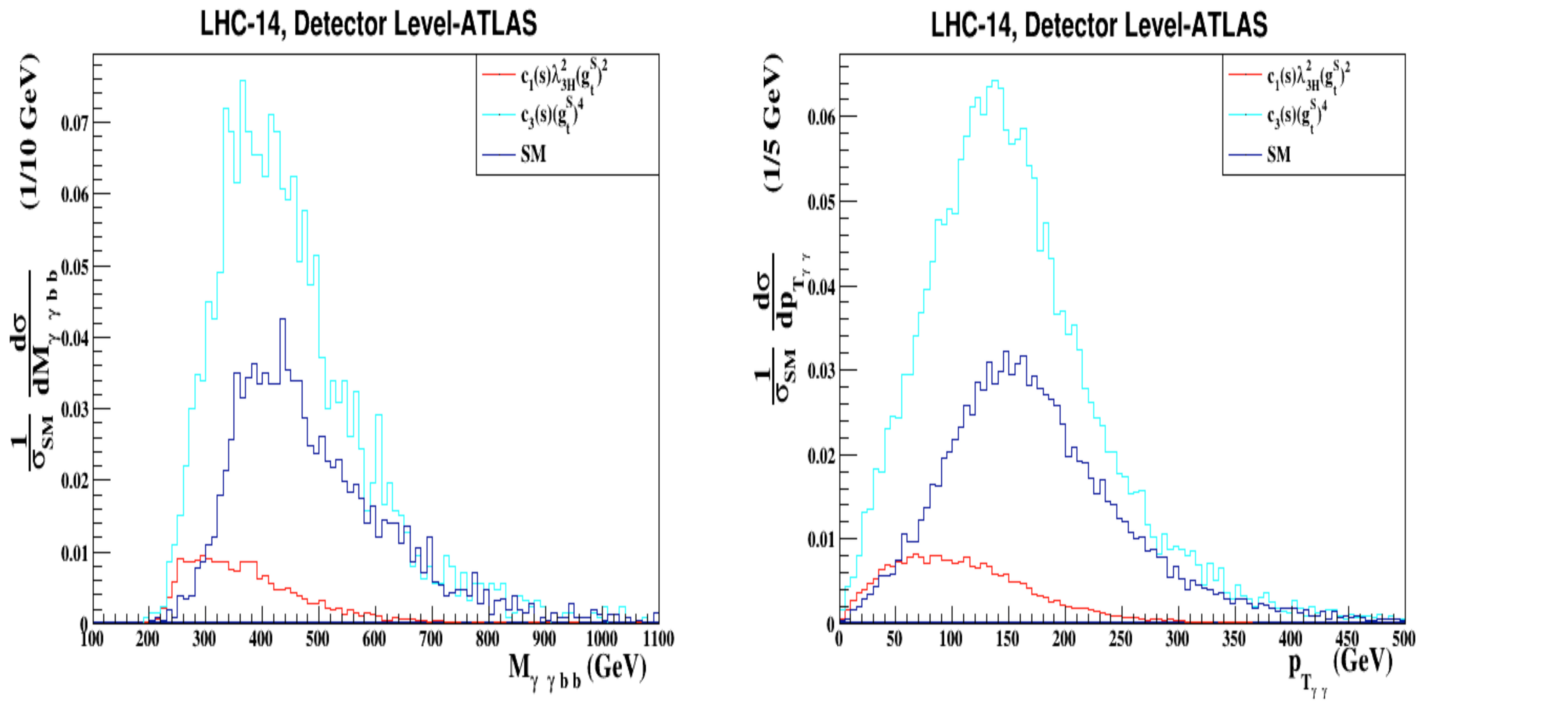
$\sqrt{s}$ (TeV)	$e_1(s)$ $\lambda_{3H}\,g_t^S\,g_{tt}^S$	$e_2(s)$ $g_{tt}^S(g_t^S)^2$	$e_3(s)$ $(g_{tt}^S)^2$	$f_1(s)$ $\lambda_{3H}\,g_t^P\,g_{tt}^P$	$f_2(s)$ $g_{tt}^S(g_t^P)^2$	$f_3(s)$ $g_t^S\,g_t^P\,g_{tt}^P$	$f_4(s)$ $(g_{tt}^P)^2$
8	1.460	−4.313	2.519	2.104	2.350	−7.761	3.065
14	1.364	−4.224	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

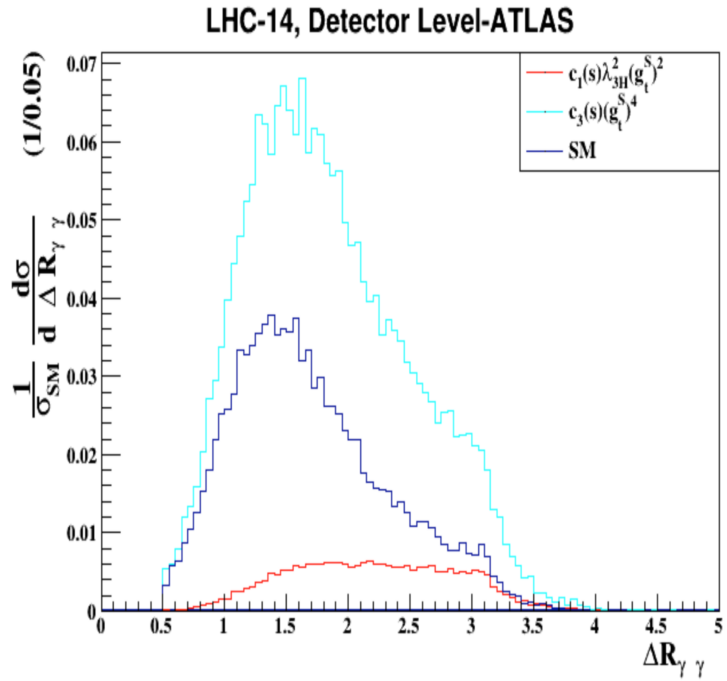
CPC1: g_t^S and λ_{3H}

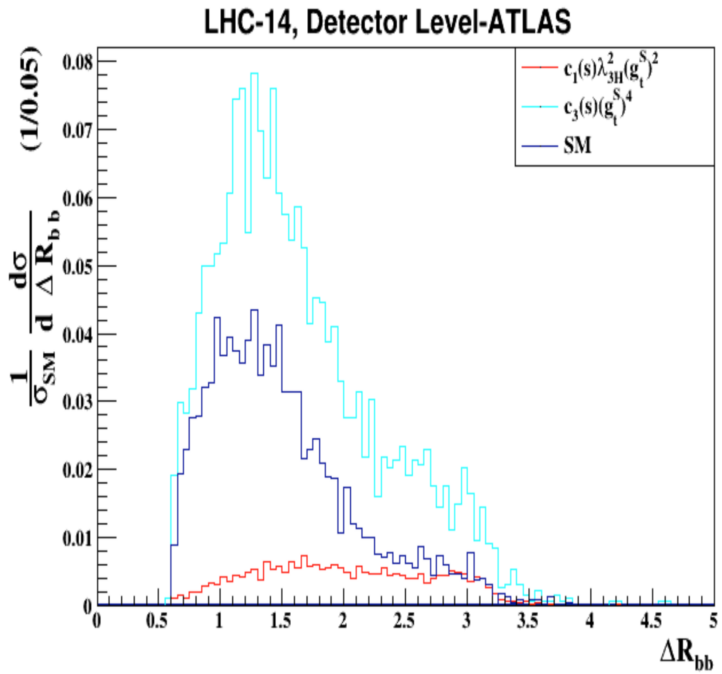
- Attempt to isolate the Higgs self coupling in the triangle diagram.
- The triangle diagram has the $1/s$ behavior, so more profound at low invariant mass region. Thus, the angular separation between the decay product is larger:

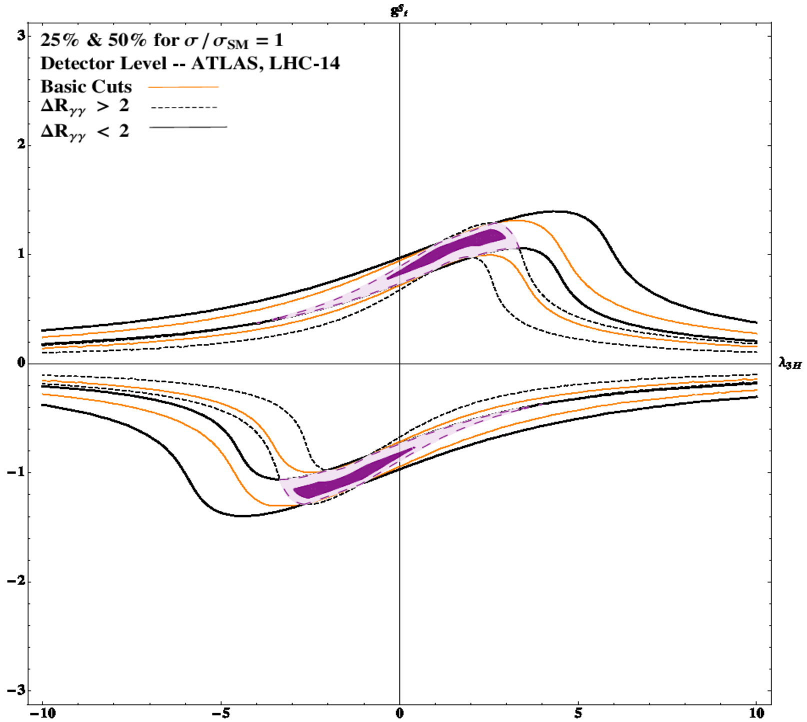
$$HH \to (\gamma\gamma)(b\bar{b})$$

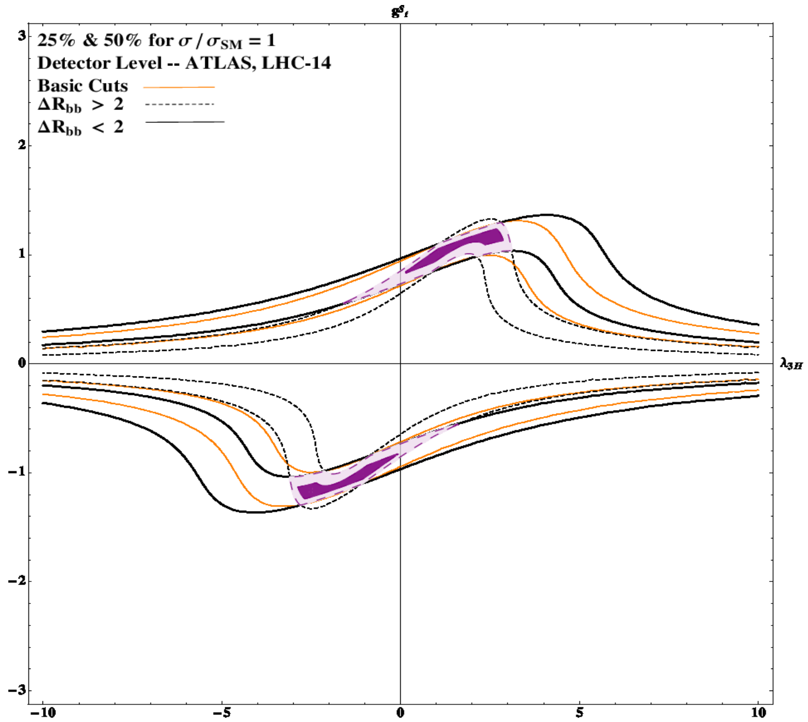
- We can make use of simultaneous cross section measurements: (i) no cuts, (ii) $\sigma(\Delta R_{\gamma\gamma} > 2)$, (iii) $\sigma(\Delta R_{\gamma\gamma} < 2)$.
- Repeat using $\Delta R_{b\bar{b}}$, and both $\Delta R_{\gamma\gamma}$ and $\Delta R_{b\bar{b}}$.

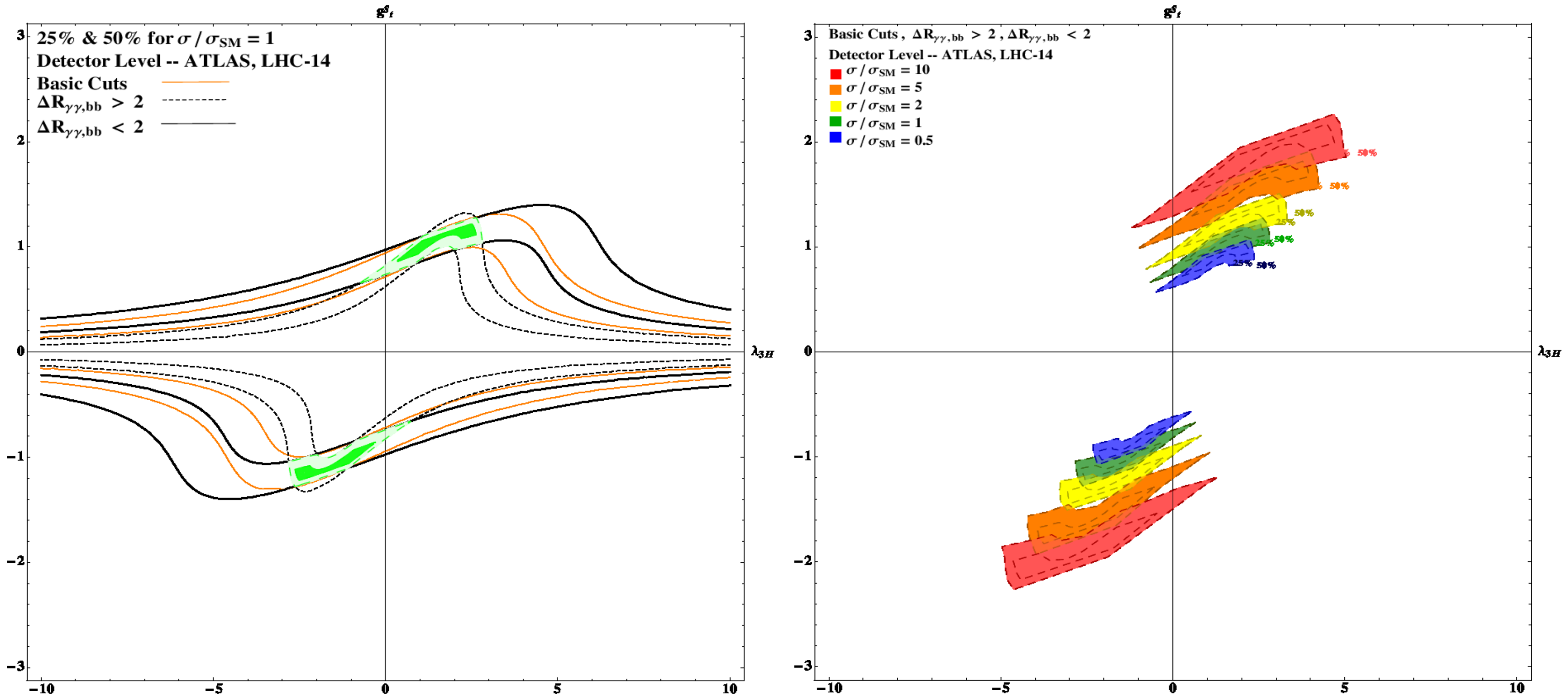

LHC-14, Detector Level-ATLAS
$c_1(s)\lambda^2_{3H}(g^S_t)^2$
$c_3(s)(g^S_t)^4$
SM
$\frac{1}{\sigma_{SM}} \frac{d\sigma}{dM_{\gamma\gamma bb}}$ (1/10 GeV)
$M_{\gamma\gamma bb}$ (GeV)
LHC-14, Detector Level-ATLAS
$c_1(s)\lambda^2_{3H}(g^S_t)^2$
$c_3(s)(g^S_t)^4$
SM
$\frac{1}{\sigma_{SM}} \frac{d\sigma}{dp_{T_{\gamma\gamma}}}$ (1/5 GeV)
$p_{T_{\gamma\gamma}}$ (GeV)


LHC-14, Detector Level-ATLAS
$c_1(s)\lambda_{3H}^2(g_t^S)^2$
$c_3(s)(g_t^S)^4$
SM
$\frac{1}{\sigma_{SM}} \frac{d\sigma}{d\,\Delta R_{\gamma\gamma}}$ (1/0.05)
$\Delta R_{\gamma\gamma}$


LHC-14, Detector Level-ATLAS
$c_1(s)\lambda_{3H}^2(g_t^S)^2$
$c_3(s)(g_t^S)^4$
SM
$\frac{1}{\sigma_{SM}} \frac{d\sigma}{d\,\Delta R_{bb}}$ (1/0.05)
ΔR_{bb}


25% & 50% for σ / σSM = 1
Detector Level -- ATLAS, LHC-14
Basic Cuts
ΔRγγ > 2
ΔRγγ < 2
λ3H

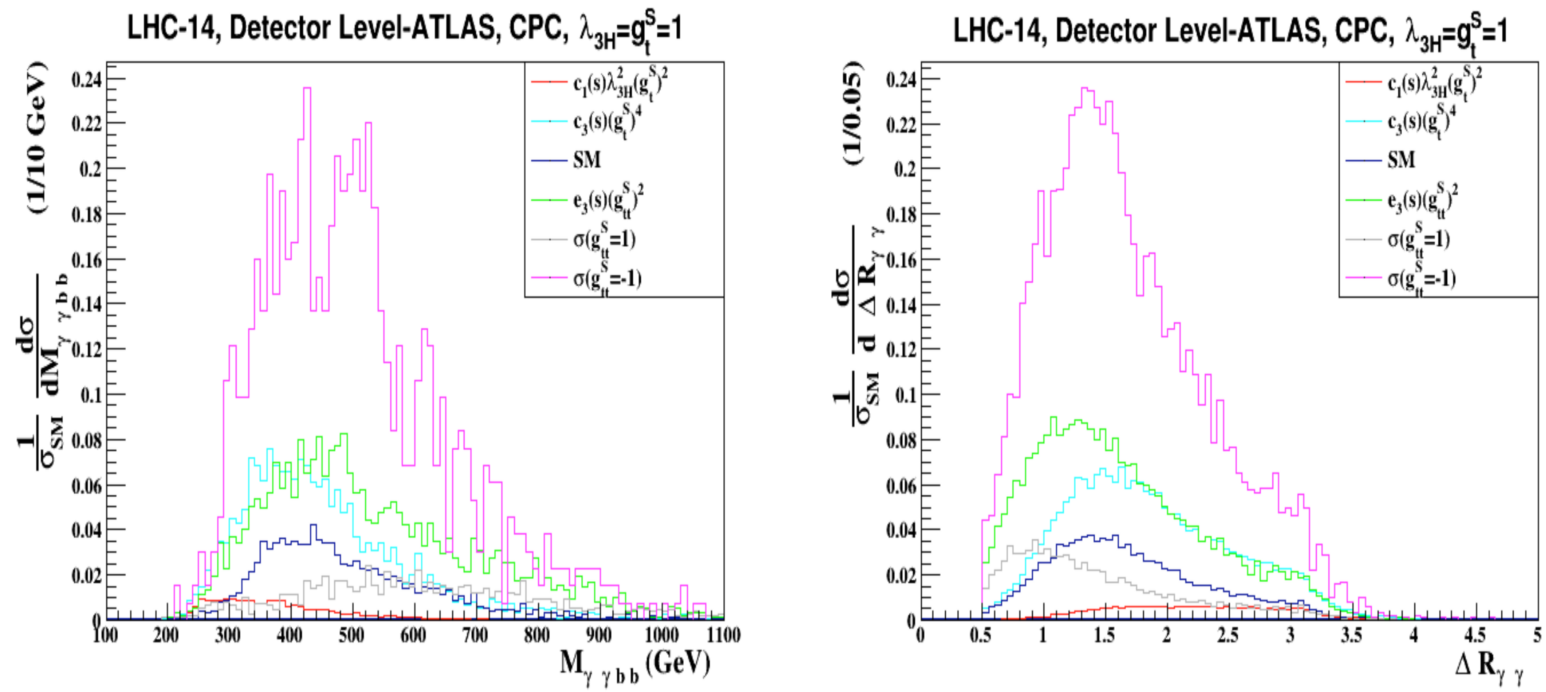

25% & 50% for σ / σSM = 1
Detector Level -- ATLAS, LHC-14
Basic Cuts
ΔRbb > 2
ΔRbb < 2
λ3H

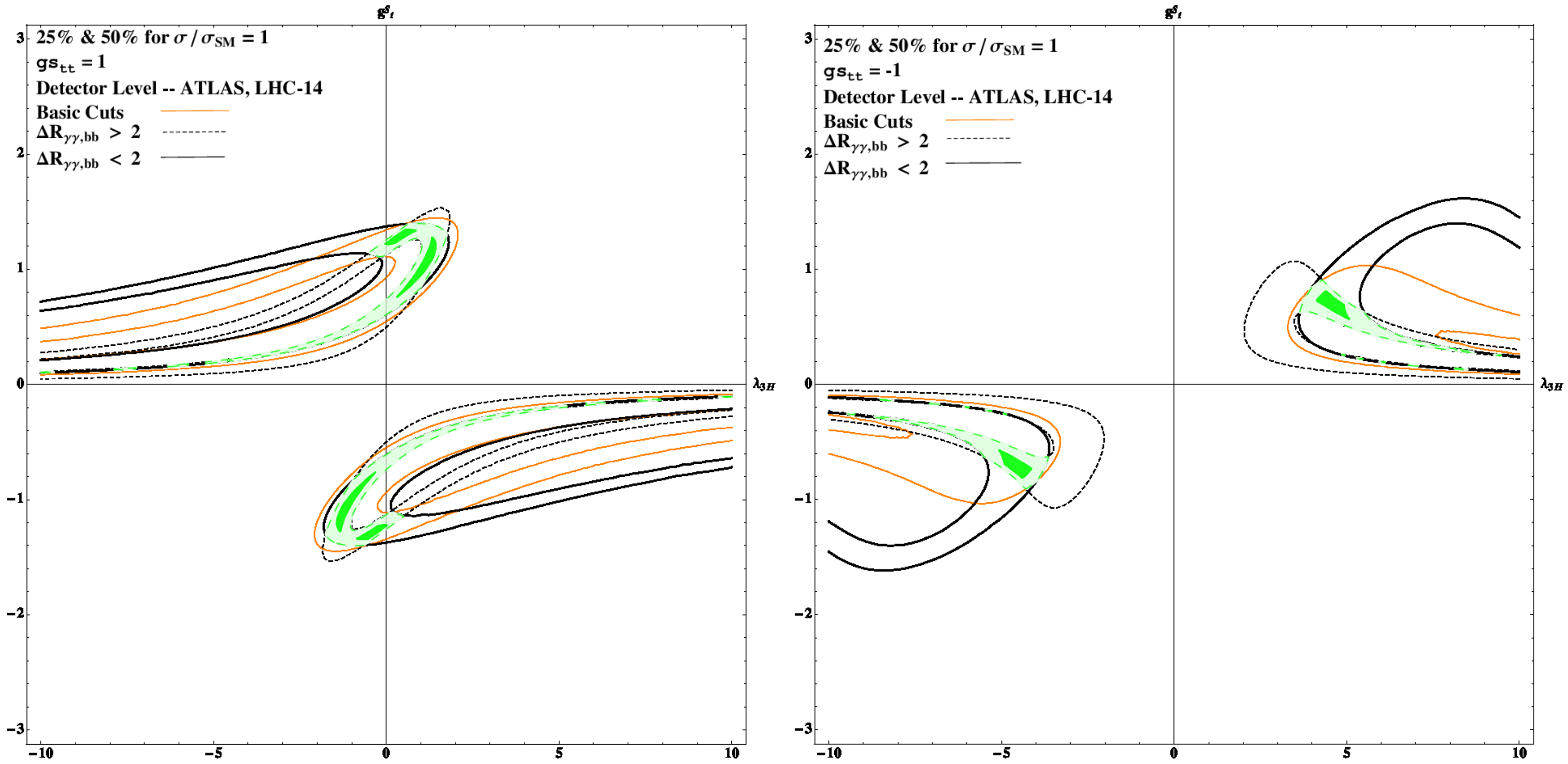


Only with both $\Delta R_{\gamma\gamma}$ and $\Delta R_{b\bar{b}}$ can one really tell if δ_{3H} is significantly distinct from zero.

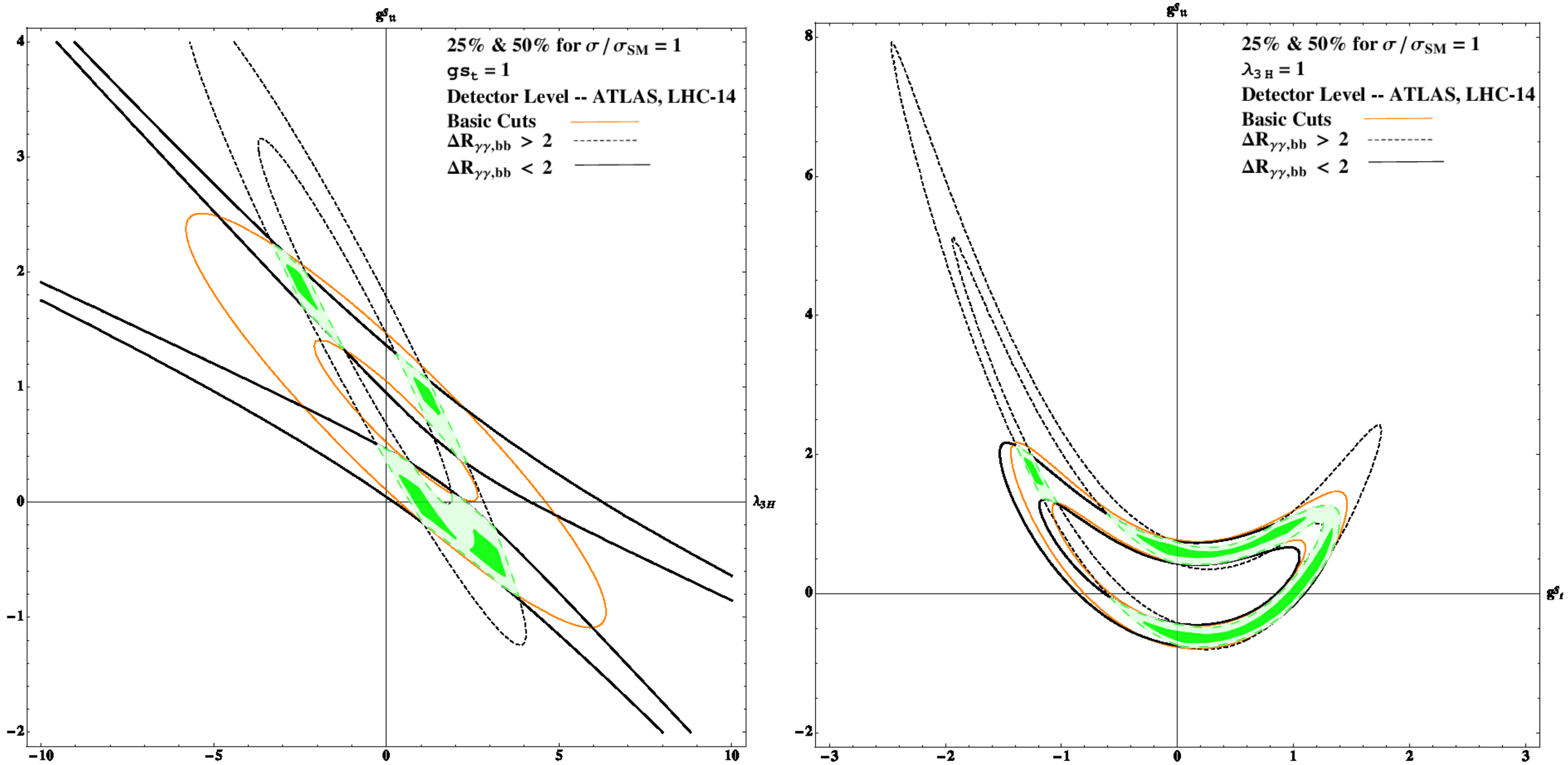
CPC2: g_t^S, λ_{3H}, g_{tt}^S

- 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) $\sigma(\Delta R_{\gamma\gamma}, \Delta R_{b\bar{b}} < 2)$.


LHC-14, Detector Level-ATLAS, CPC, $\lambda_{3H}=g_t^S=1$
$c_1(s)\lambda_{3H}^2(g_t^S)^2$
$c_3(s)(g_t^S)^4$
SM
$e_3(s)(g_{tt}^S)^2$
$\sigma(g_{tt}^S=1)$
$\sigma(g_{tt}^S=-1)$
$\frac{1}{\sigma_{SM}} \frac{d\sigma}{dM_{\gamma\gamma bb}}$ (1/10 GeV)
$M_{\gamma\gamma bb}$ (GeV)
LHC-14, Detector Level-ATLAS, CPC, $\lambda_{3H}=g_t^S=1$
$\frac{1}{\sigma_{SM}} \frac{d\sigma}{d\Delta R_{\gamma\gamma}}$ (1/0.05)
$\Delta R_{\gamma\gamma}$

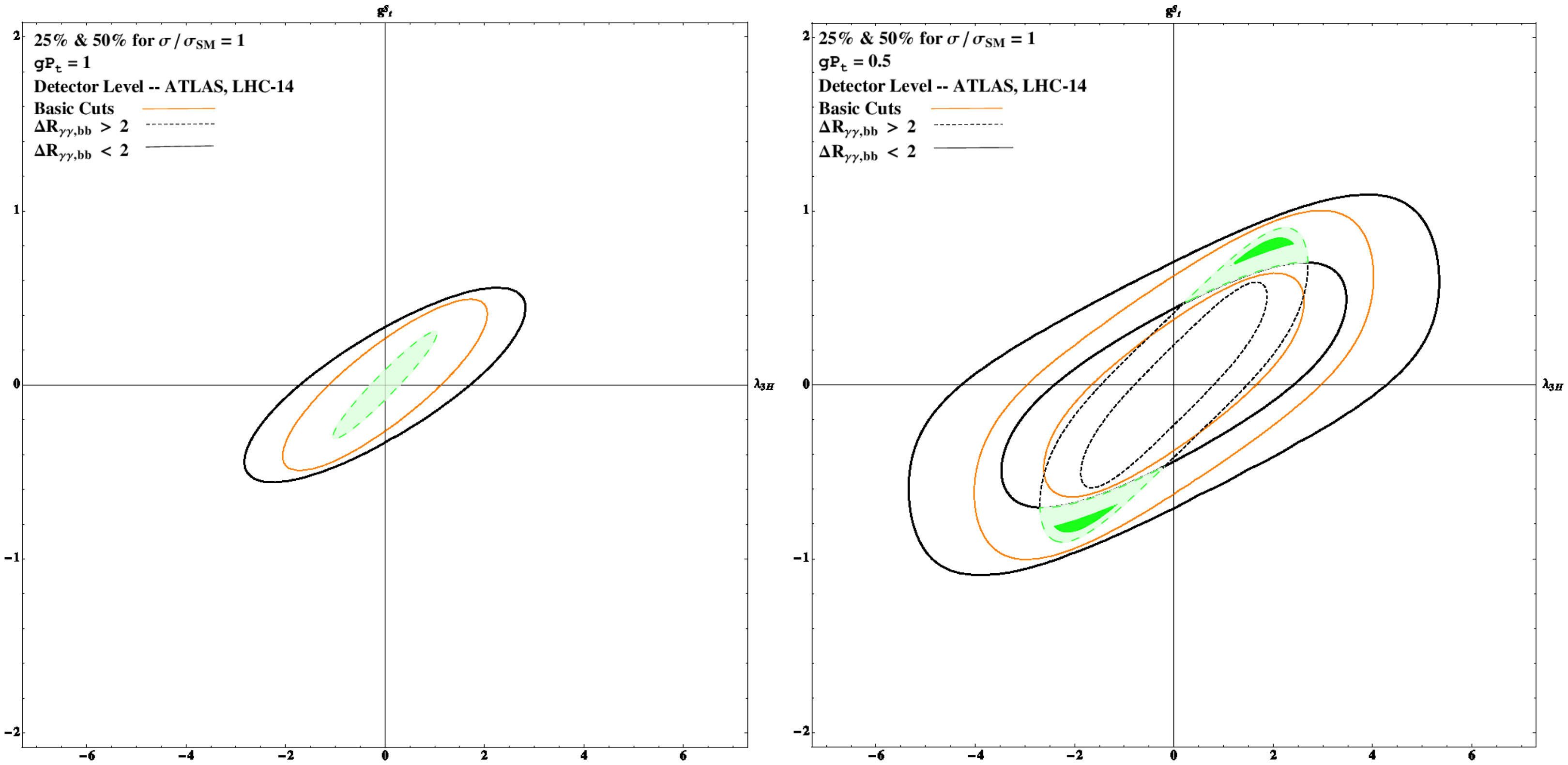


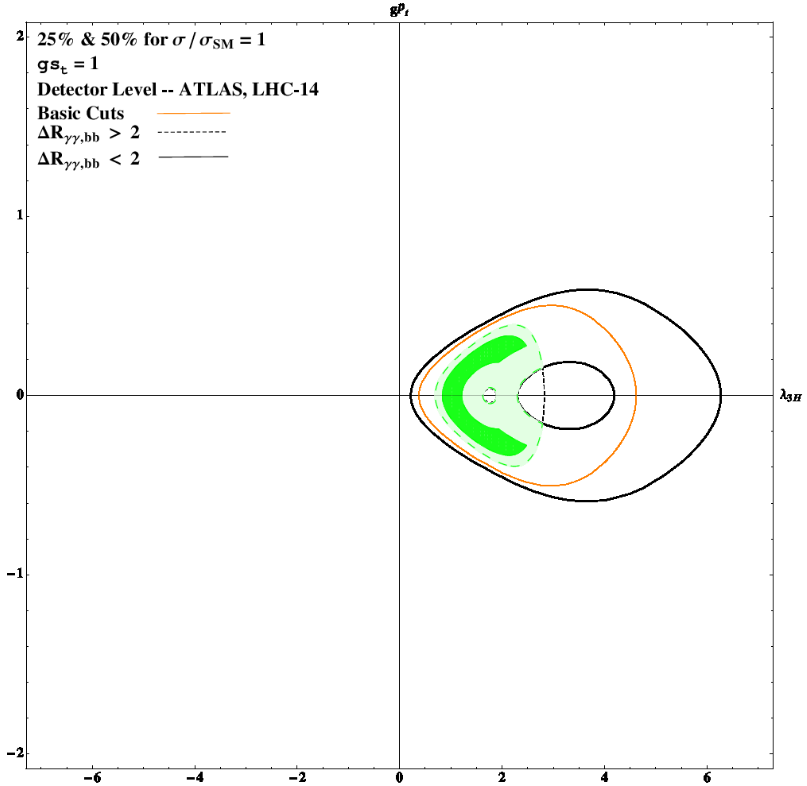
25% & 50% for σ / σSM = 1
gstt = 1
Detector Level -- ATLAS, LHC-14
Basic Cuts
ΔRγγ,bb > 2
ΔRγγ,bb < 2
λ3H
25% & 50% for σ / σSM = 1
gstt = -1
Detector Level -- ATLAS, LHC-14
Basic Cuts
ΔRγγ,bb > 2
ΔRγγ,bb < 2
λ3H

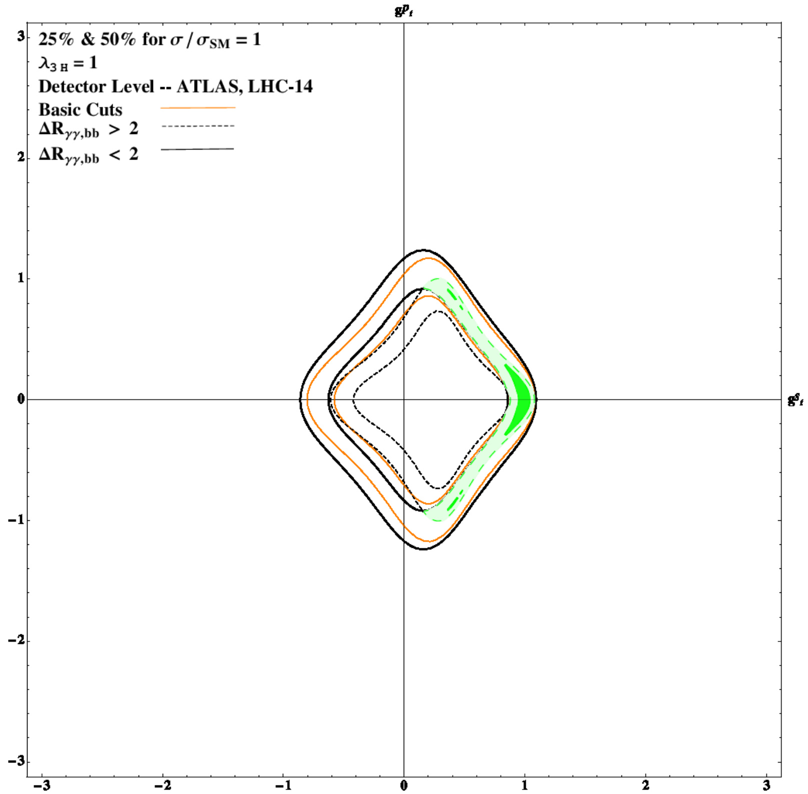

25% & 50% for σ / σSM = 1
gst = 1
Detector Level -- ATLAS, LHC-14
Basic Cuts
ΔRγγ,bb > 2
ΔRγγ,bb < 2
λ3H
25% & 50% for σ / σSM = 1
λ3H = 1
Detector Level -- ATLAS, LHC-14
Basic Cuts
ΔRγγ,bb > 2
ΔRγγ,bb < 2

CPV1: g_t^S, g_t^P, and λ_{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) $\sigma(\Delta R_{\gamma\gamma}, \Delta R_{b\bar{b}} < 2)$.


25% & 50% for σ / σSM = 1
gPt = 1
Detector Level -- ATLAS, LHC-14
Basic Cuts
ΔRγγ,bb > 2
ΔRγγ,bb < 2
25% & 50% for σ / σSM = 1
gPt = 0.5
Detector Level -- ATLAS, LHC-14
Basic Cuts
ΔRγγ,bb > 2
ΔRγγ,bb < 2
λ3H


25% & 50% for σ / σSM = 1
gst = 1
Detector Level -- ATLAS, LHC-14
Basic Cuts
ΔRγγ,bb > 2
ΔRγγ,bb < 2
λ3H


25% & 50% for σ / σSM = 1
λ3H = 1
Detector Level -- ATLAS, LHC-14
Basic Cuts
ΔRγγ,bb > 2
ΔRγγ,bb < 2

$\sqrt{s}$: 14 TeV Cuts	$c_1(s)$ $\lambda_{3H}^2(g_t^S)^2$	$c_2(s)$ $\lambda_{3H}(g_t^S)^3$	$c_3(s)$ $(g_t^S)^4$	$d_1(s)$ $\lambda_{3H}^2(g_t^P)^2$	$d_2(s)$ $\lambda_{3H}g_t^S(g_t^P)^2$	$d_3(s)$ $(g_t^S)^2(g_t^P)^2$	$d_4(s)$ $(g_t^P)^4$
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

$\sqrt{s}$: 14TeV Cuts	$e_1(s)$ $\lambda_{3H}g_t^S g_{tt}^S$	$e_2(s)$ $g_{tt}^S(g_t^S)^2$	$e_3(s)$ $(g_{tt}^S)^2$	$f_1(s)$ $\lambda_{3H}g_t^P g_{tt}^P$	$f_2(s)$ $g_{tt}^S(g_t^P)^2$	$f_3(s)$ $g_t^S g_t^P g_{tt}^P$	$f_4(s)$ $(g_{tt}^P)^2$
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 TeV Cuts	$c_1(s)$ $\lambda_{3H}^2(g_t^S)^2$	$c_2(s)$ $\lambda_{3H}(g_t^S)^3$	$c_3(s)$ $(g_t^S)^4$	$d_1(s)$ $\lambda_{3H}^2(g_t^P)^2$	$d_2(s)$ $\lambda_{3H}\,g_t^S(g_t^P)^2$	$d_3(s)$ $(g_t^S)^2(g_t^P)^2$	$d_4(s)$ $(g_t^P)^4$
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

$\sqrt{s}$: 100TeV Cuts	$e_1(s)$ $\lambda_{3H}\,g_t^S\,g_{tt}^S$	$e_2(s)$ $g_{tt}^S(g_t^S)^2$	$e_3(s)$ $(g_{tt}^S)^2$	$f_1(s)$ $\lambda_{3H}\,g_t^P\,g_{tt}^P$	$f_2(s)$ $g_{tt}^S(g_t^P)^2$	$f_3(s)$ $g_t^S\,g_t^P\,g_{tt}^P$	$f_4(s)$ $(g_{tt}^P)^2$
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 $H \to \gamma\gamma$ (full data set)

Channel	Signal strength μ	M_H(GeV)	$\chi^2_{\rm SM}$(each)
ATLAS ($4.5 fb^{-1}$ at 7TeV + $20.3 fb^{-1}$ at 8TeV): (Aug. 2014)			
μ_{ggH}	1.32 ± 0.38	125.40	0.71
μ_{VBF}	0.8 ± 0.7	125.40	0.08
μ_{WH}	1.0 ± 1.6	125.40	0.00
μ_{ZH}	$0.1^{+3.7}_{-0.1}$	125.40	0.06
μ_{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)			
μ_{ggH}	$1.12^{+0.37}_{-0.32}$	124.70	0.14
μ_{VBF}	$1.58^{+0.77}_{-0.68}$	124.70	0.73
μ_{VH}	$-0.16^{+1.16}_{-0.79}$	124.70	1.00
μ_{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 $\gamma\gamma b\bar{b}$, $\tau^+\tau^- b\bar{b}$, $\pi\pi \not{E}_T$, $\mu\mu \not{E}_T$, etc.

Collider Signatures

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

$$gg \to H \to \sigma\sigma \to (\pi\pi)\,(\alpha\alpha)$$

- The cross section at the LHC-8 would be

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

  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 τ jet.

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

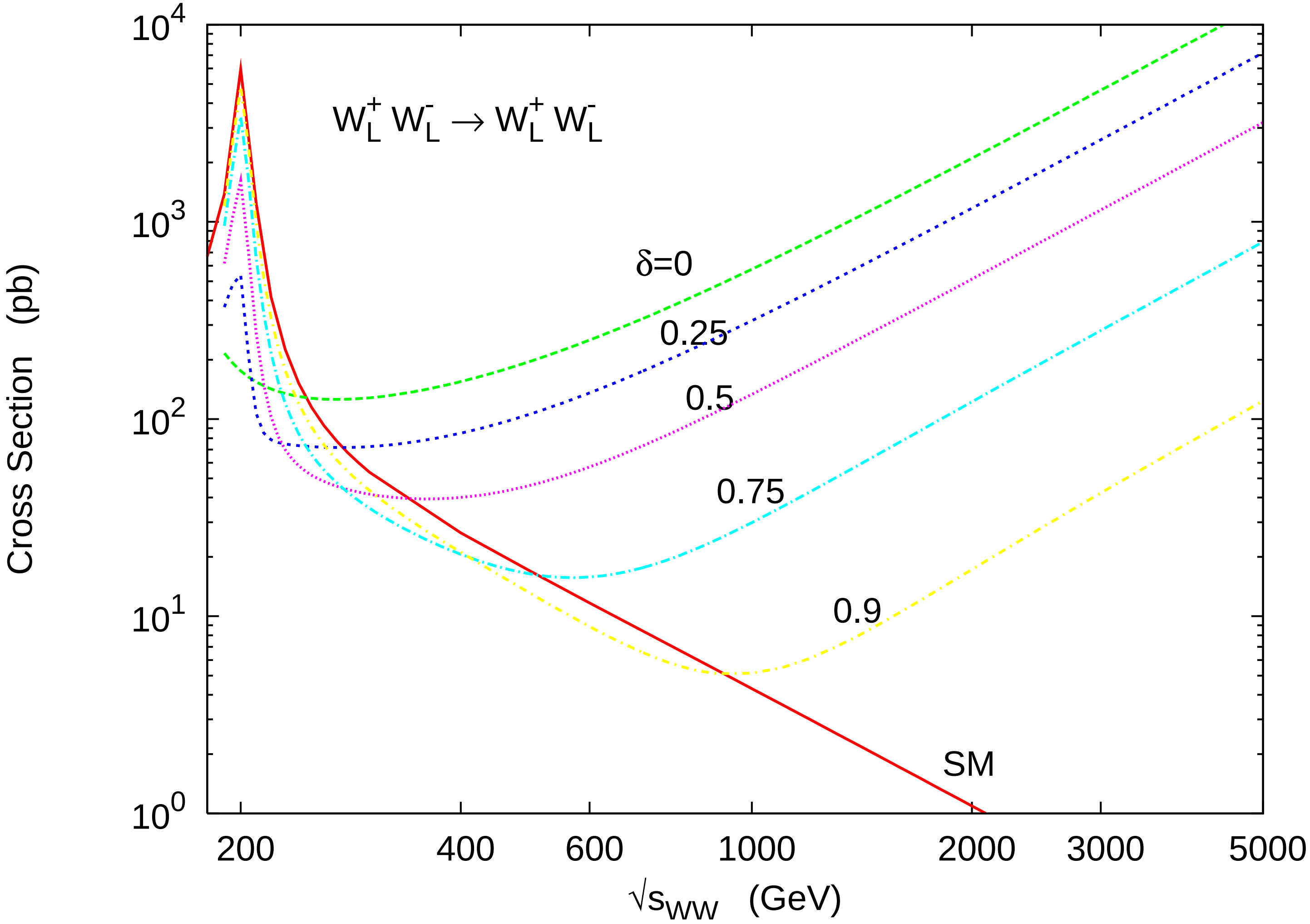
Jung Chang, KC, Yuan, 1303.6335; KC, Chiang, Yuan, 0803.2661

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 $W_L^+ W_L^- \to W_L^+ W_L^-$ scattering amplitude will grow with s.

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

$$
\begin{aligned}
i\mathcal{M}^{\text{gauge}} &= -i\frac{g^2}{4m_W^2}\, u + \mathcal{O}((E/m_W)^0) \\
i\mathcal{M}^{\text{higgs}} &= i\frac{g^2}{4m_W^2}\, u\,\delta + \mathcal{O}((E/m_W)^0) \\
i\mathcal{M}^{\text{all}} &= -i\frac{g^2}{4m_W^2} u(1-\delta) + \mathcal{O}((E/m_W)^0)
\end{aligned}
$$

Cheung, Chiang, Yuan



Cross Sections (fb) for the LHC at 13 TeV

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

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

SM cross section (fb) Cuts	14 TeV	100 TeV
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
$\Delta R(b_1, \bar{b}_1) > 2$ & $\Delta R(\gamma_1, \gamma_2) > 2$	7.20e-4	1.79e-2
$\Delta R(b_1, \bar{b}_1) < 2$ & $\Delta R(\gamma_1, \gamma_2) < 2$	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 $p_{T_\tau} > 25\,\mathrm{GeV}$, $\lvert\eta_\tau\rvert < 2.5$	0.00682	0.0257	0.1026	0.0701	0.420	0.000672
(2) $2.5 < \lvert\eta_j\rvert < 4.7$	0.00355	0.0148	0.0585	0.0333	0.0	4.27×10^{-5}
(3) $M_{bl} < 200$ GeV	0.00345	0.0141	0.0555	0.0319	0.0	4.27×10^{-5}
(4) $110 < M_{\tau\tau} < 150\,\mathrm{GeV}$	0.00158	0.00616	0.0244	0.0105	0.0	1.904×10^{-5}
$S/\sqrt{S+B}$ for 300 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 $p_{T_{j_{1,2}}} > 25$ GeV, $\lvert\eta_{j_{1,2}}\rvert < 2.5$ but with $p_{T_\ell} > 5\,\text{GeV}$	0.136	0.531	1.77	0.955	20.1	10.0
(2) $2.5 < \lvert\eta_j\rvert < 4.7$	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) $\lvert M_{4\ell} - m_h\rvert < 5\,\text{GeV}$	0.072	0.289	0.901	8.65×10^{-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 $p_{T_\gamma} > 20\,\text{GeV}, \lvert\eta_\gamma\rvert < 2.5$	4.45	22.7	80.0	318	2.59	10.5	217
(2) $2.5 < \lvert\eta_j\rvert < 4.7$	2.35	13.1	45.2	164	0.650	1.04	20.5
(3) $M_{bl} < 200$ GeV	2.30	12.7	43.6	162	0.609	0.609	11.2
(4) $\lvert M_{\gamma\gamma} - m_h\rvert < 5\,\text{GeV}$	1.83	10.2	34.7	5.77	0.027	0.018	0.661
$S/\sqrt{S+B}$ for 300 fb^{-1}	0.35	1.4	3.0				