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Contact interactions and high-Q^2 events in e^+p collisions at HERA

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Global study of electron-quark contact interactions

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Higgs Boson Pair Production

Work in progress by KC, Jae-Sik Lee, Jung Chang, Chih-Ting Lu 2015

Outlines

1. Present status of the Higgs boson – Higgcision.
2. A few "Zoom In" into the Higgs boson.
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

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

- 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

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

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

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

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

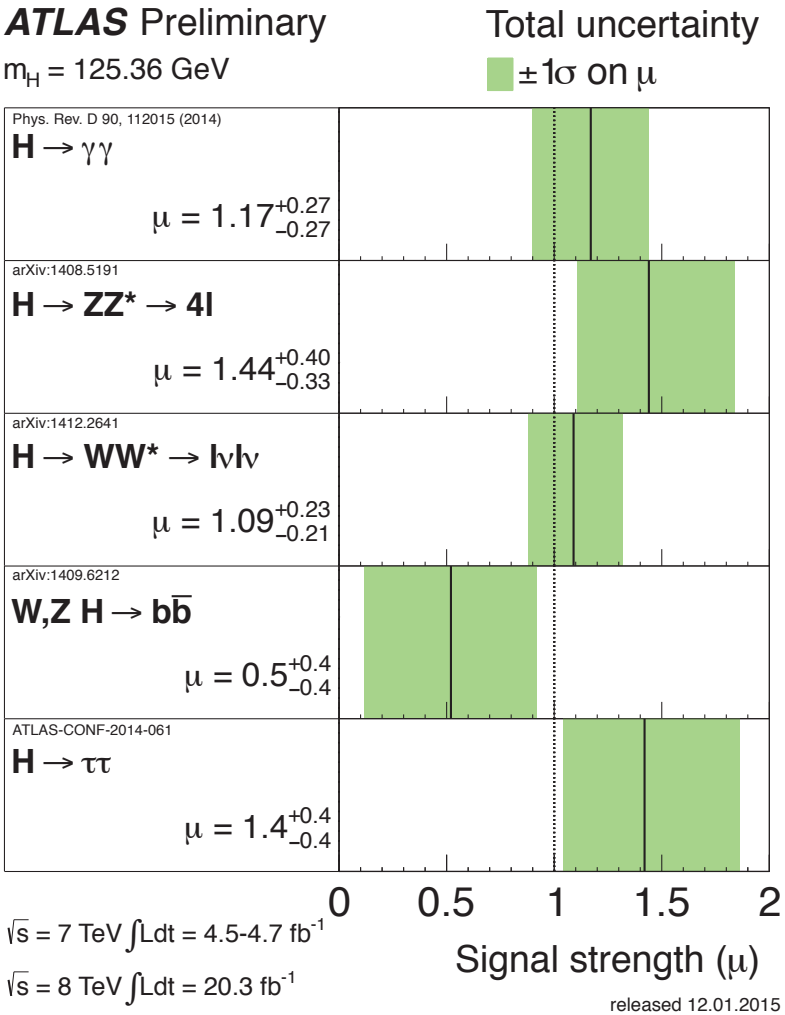
- Ratios of Yukawa and gauge couplings

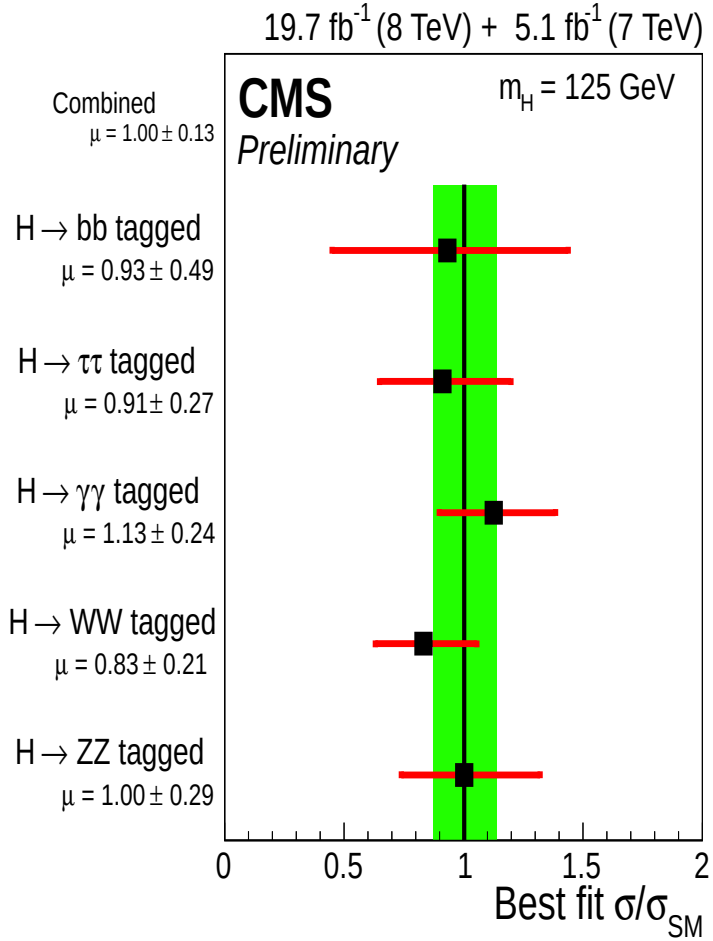
$$C_u^S = g^S_{H\bar{u}u}\,, \quad C_d^S = g^S_{H\bar{d}d}\,, \quad C_\ell^S = g^S_{H\bar{l}l}\,; \quad C_v = g_{HVV}\,;$$
$$C_u^P = g^P_{H\bar{u}u}\,, \quad C_d^P = g^P_{H\bar{d}d}\,, \quad C_\ell^P = g^P_{H\bar{l}l}\,.$$

- 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

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

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

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

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

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

- 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

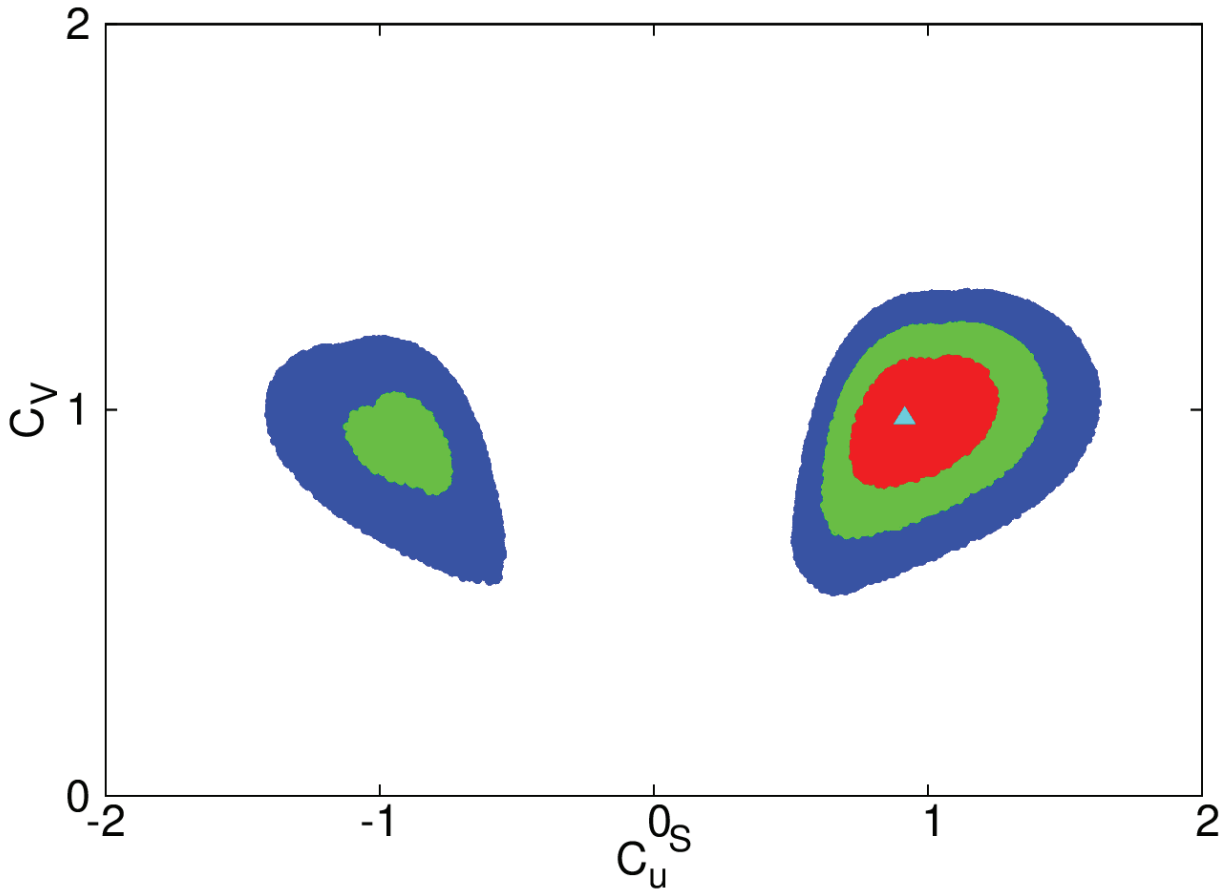
$$B(H \to \text{nonstandard}) < 19\%$$

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:

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

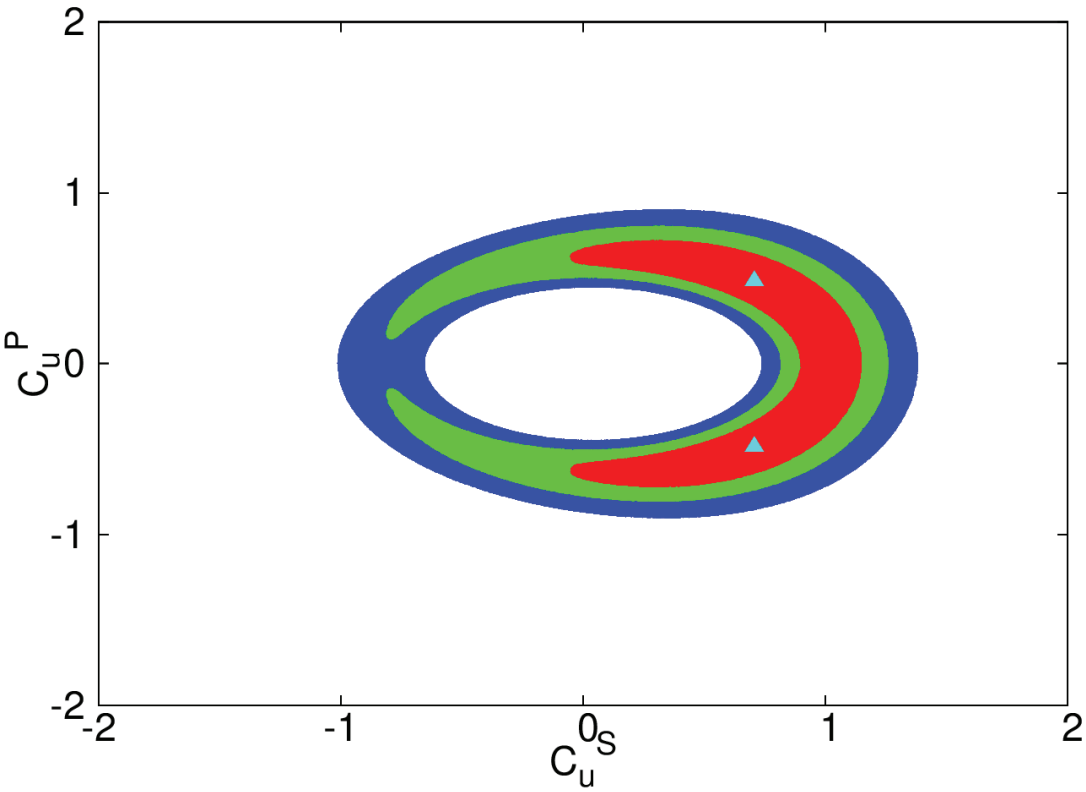
- Sign of C_u^S is important. The W and the top contributions are in opposite sign.



$C_u^S > 0$ 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

- 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.
- Use EDMs to constrain the pseudoscalar Higgs couplings, such as C_u^P and ΔP^γ.
- Higgs boson pair production: (Chang, Cheung, Lee, Lu in progress.)

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

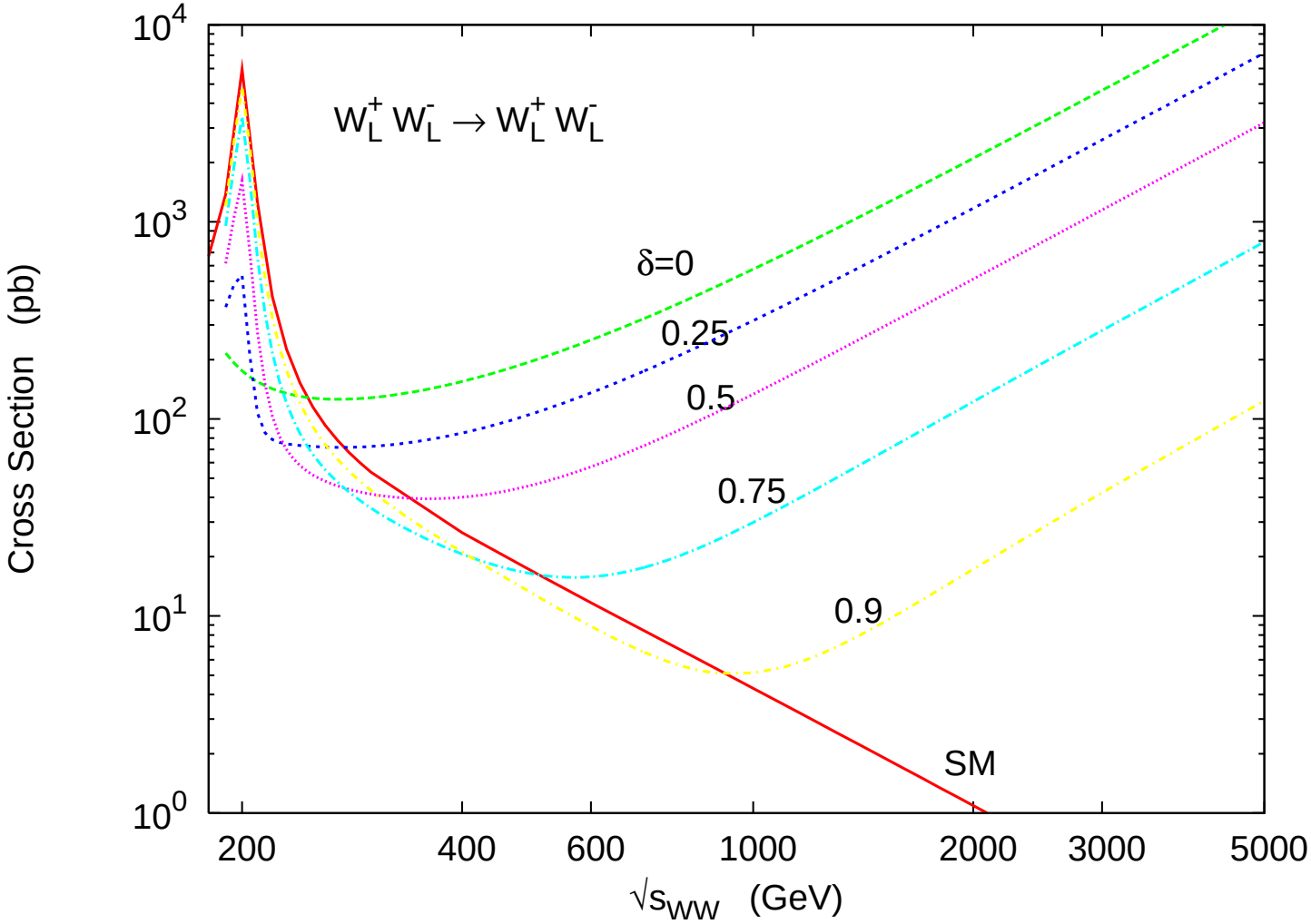
Jung Chang, KC, Yuan, 1303.6335; KC, Chiang, Yuan, 0803.2661

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

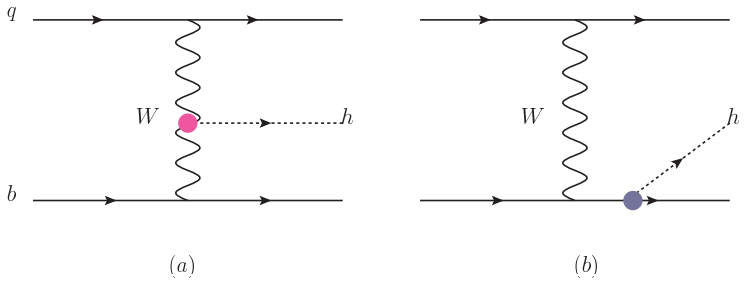
Channels	$\sin(\beta-\alpha)=0.5$	0.7	0.9	SM ($C_v=1$)
$W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$	0.51	0.46	0.40	0.39
$W^+W^+ \to \ell^+\nu\ell^+\nu$	0.20	0.17	0.14	0.14
$W^-W^- \to \ell^-\bar{\nu}\ell^-\bar{\nu}$	0.083	0.075	0.070	0.069
$W^+Z \to \ell^+\nu\ell^+\ell^-$	0.016	0.013	0.011	0.010
$W^-Z \to \ell^-\bar{\nu}\ell^+\ell^-$	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}

Associated Production of Higgs with a single top quark

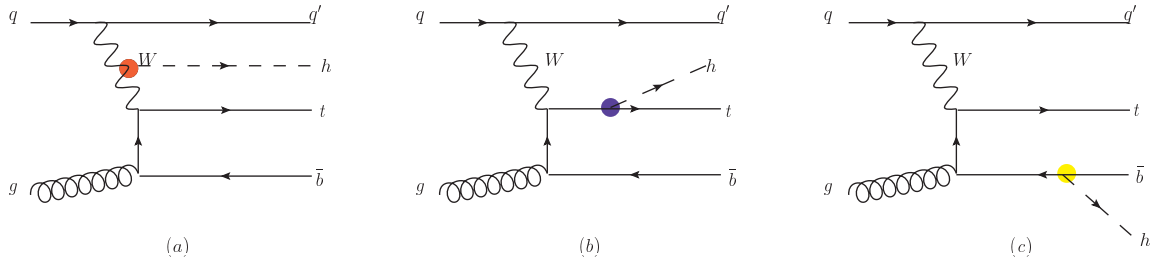
Jung Chang, KC, Jae-Sik Lee, Chih-Ting Lu, 1403.2053

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

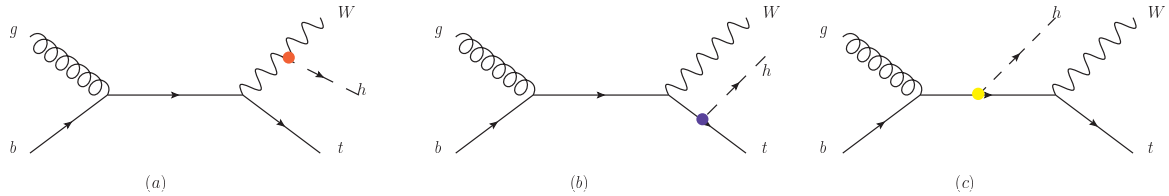
$qb \to thq'$



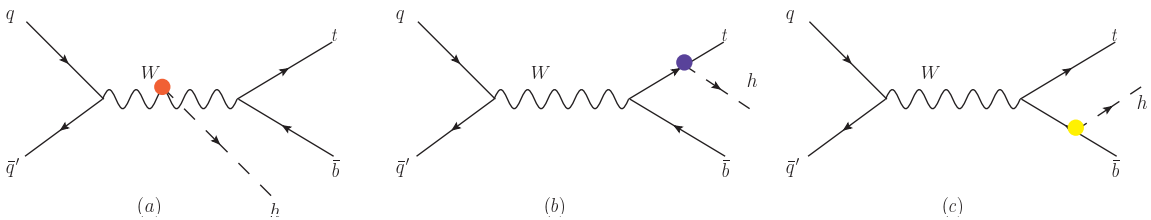
$qg \to thq'b$

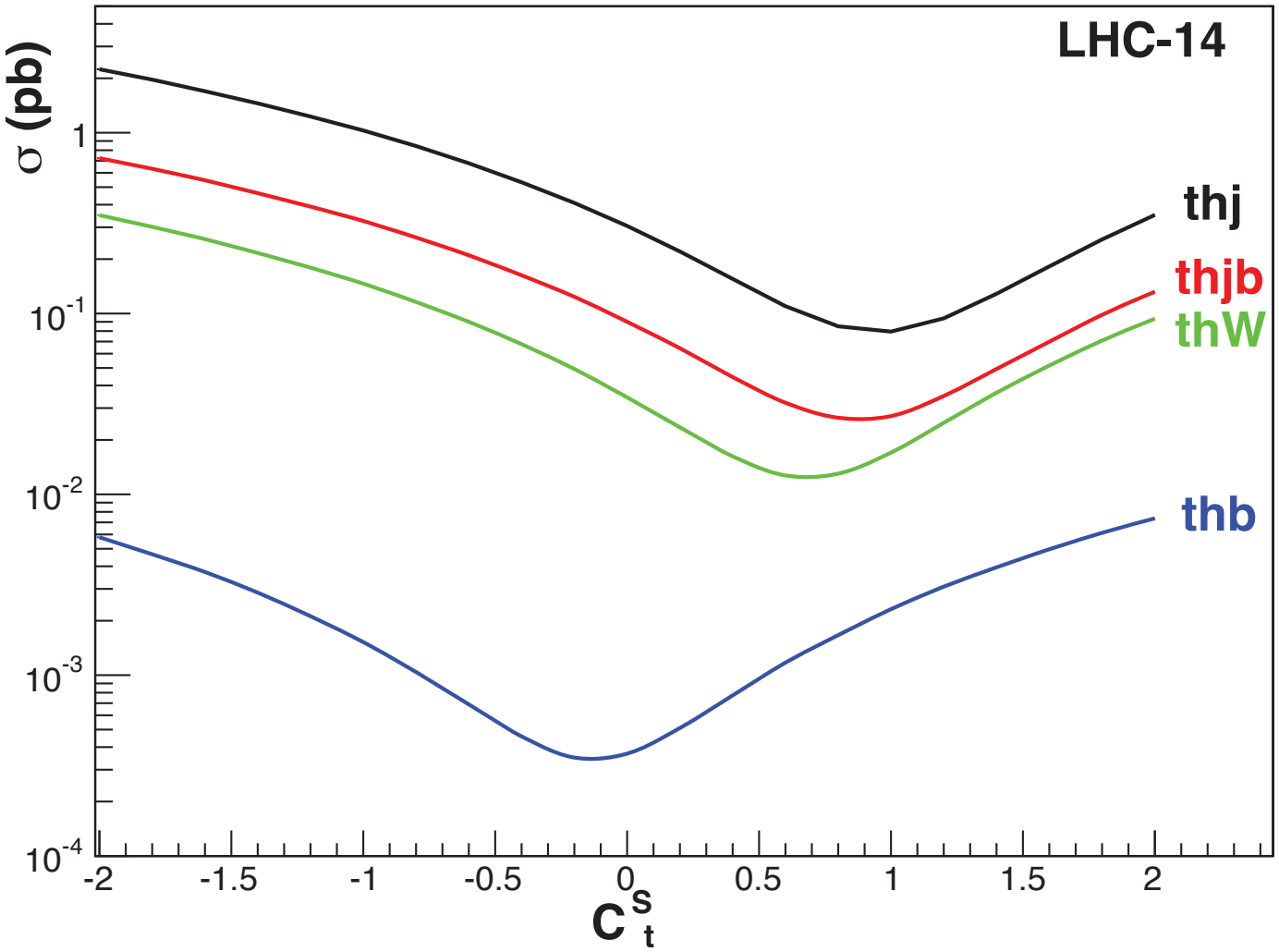


$gb \to thW$



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

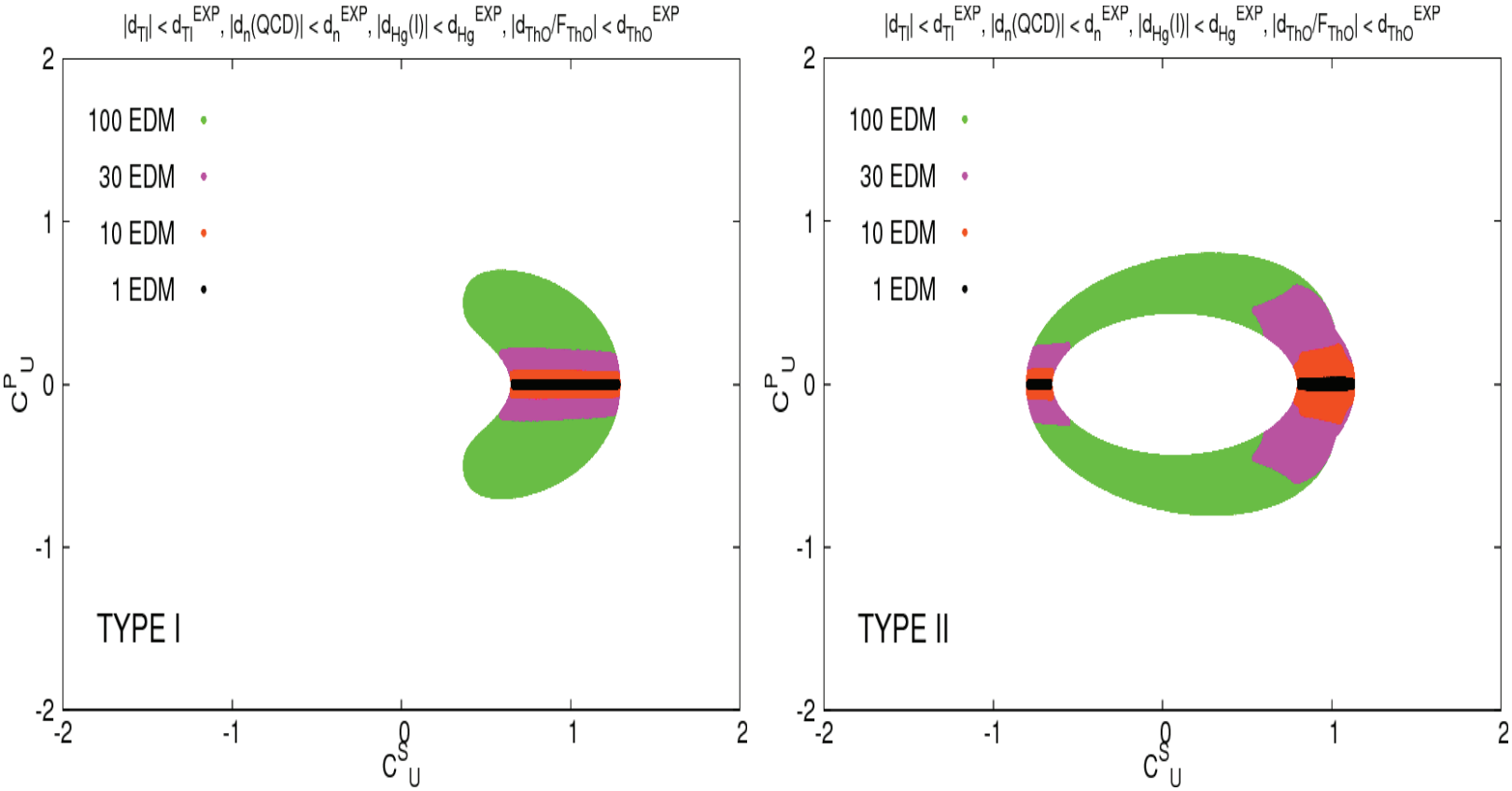



LHC-14
σ (pb)
1
10^-1
10^-2
10^-3
10^-4
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
C^s_t
thj
thjb
thW
thb

Confronting Higgcision with Electric dipole moments

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

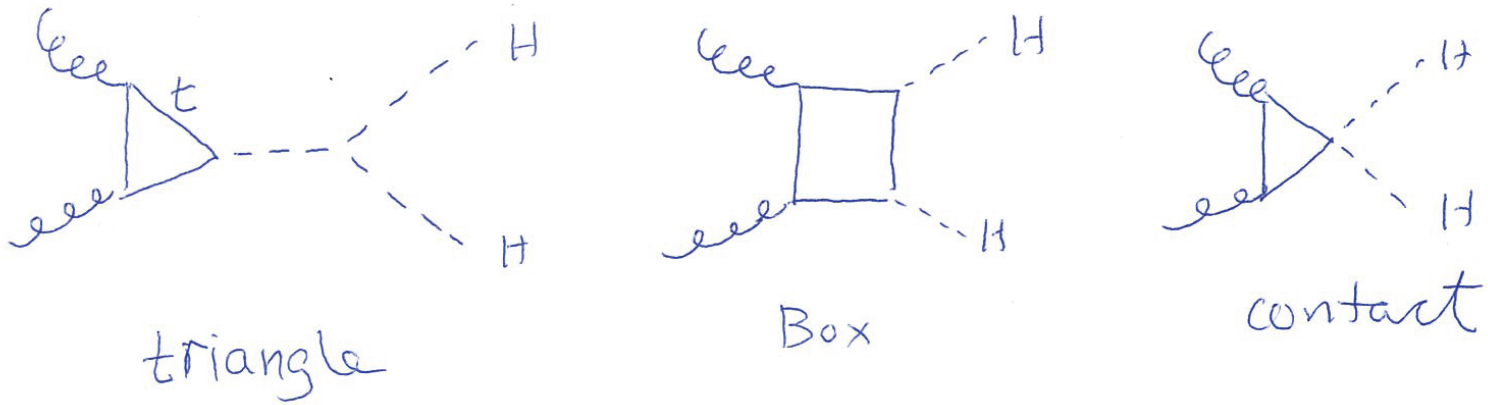
- Higgs signal strength data cannot restrict the pseudoscalar coupling.
- But the EDM predicted is mostly proportional to $C_u^S\ C_u^P$.
- By limiting the predictions to be less than the current limits of Thallium, neutron, Mercury, and Thorium monoxide EDMs, one can constrain the C_u^P.


|d_Tl| < d_Tl^EXP, |d_n(QCD)| < d_n^EXP, |d_Hg(I)| < d_Hg^EXP, |d_ThO/F_ThO| < d_ThO^EXP
100 EDM
30 EDM
10 EDM
1 EDM
TYPE I
TYPE II
C^P_U
C^S_U
2
1
0
-1
-2

KC, Lee, Tseng

Higgs boson Pair Production

Jung Chang, KC, Jae-Sik Lee, Chih-Ting Lu, in progress



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:

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

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

- Extensions to CP-odd and contact terms:

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

- Production cross section normalized to the SM one is

$$\frac{\sigma(gg \to HH)}{\sigma_{\rm SM}(gg \to HH)} = \lambda_{3H}^2 \left[c_1(s)(g_t^S)^2 + d_1(s)(g_t^P)^2\right] + \lambda_{3H} g_t^S \left[c_2(s)(g_t^S)^2 + d_2(s)(g_t^P)^2\right]$$

$$+ \left[c_3(s)(g_t^S)^4 + d_3(s)(g_t^S)^2(g_t^P)^2 + d_4(s)(g_t^P)^4\right]$$

$$+\lambda_{3H} \left[e_1(s) g_t^S g_{tt}^S + f_1(s) g_t^P g_{tt}^P\right] + g_{tt}^S \left[e_2(s)(g_t^S)^2 + f_2(s)(g_t^P)^2\right]$$

$$+ \left[e_3(s)(g_{tt}^S)^2 + f_3(s) g_t^S g_t^P g_{tt}^P + f_4(s)(g_{tt}^P)^2\right]$$

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 $\sqrt{s}$:

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

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

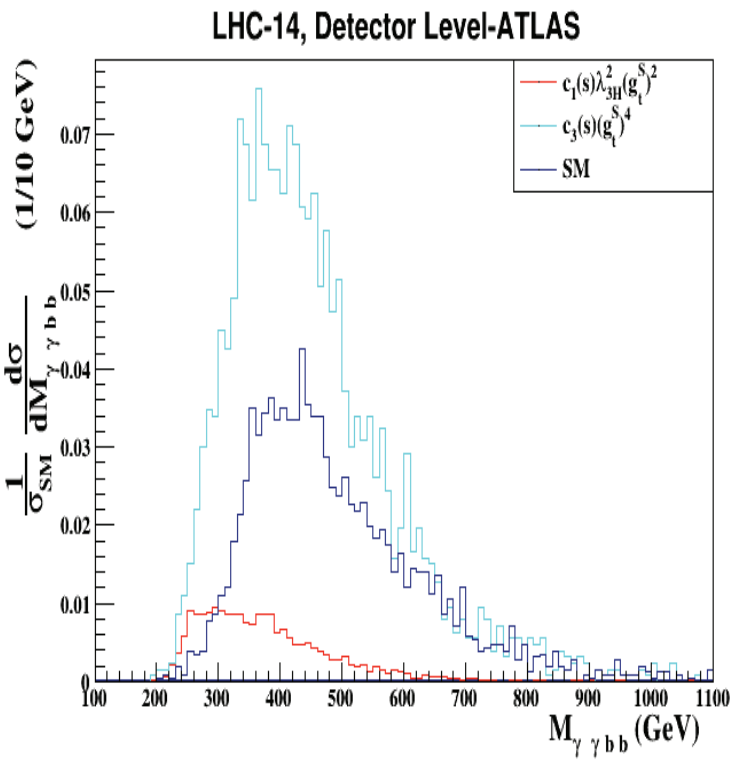
$\sqrt{s}$ (TeV)	$e_1(s)$ $\lambda_{3H} g_t^S g_{tt}^S$	$e_2(s)$ $g_{tt}^S (g_t^S)^2$	$e_3(s)$ $(g_{tt}^S)^2$	$f_1(s)$ $\lambda_{3H} g_t^P g_{tt}^P$	$f_2(s)$ $g_{tt}^S (g_t^P)^2$	$f_3(s)$ $g_t^S g_t^P g_{tt}^P$	$f_4(s)$ $(g_{tt}^P)^2$
8	1.460	−4.313	2.519	2.104	2.350	−7.761	3.065
14	1.364	−4.224	2.617	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

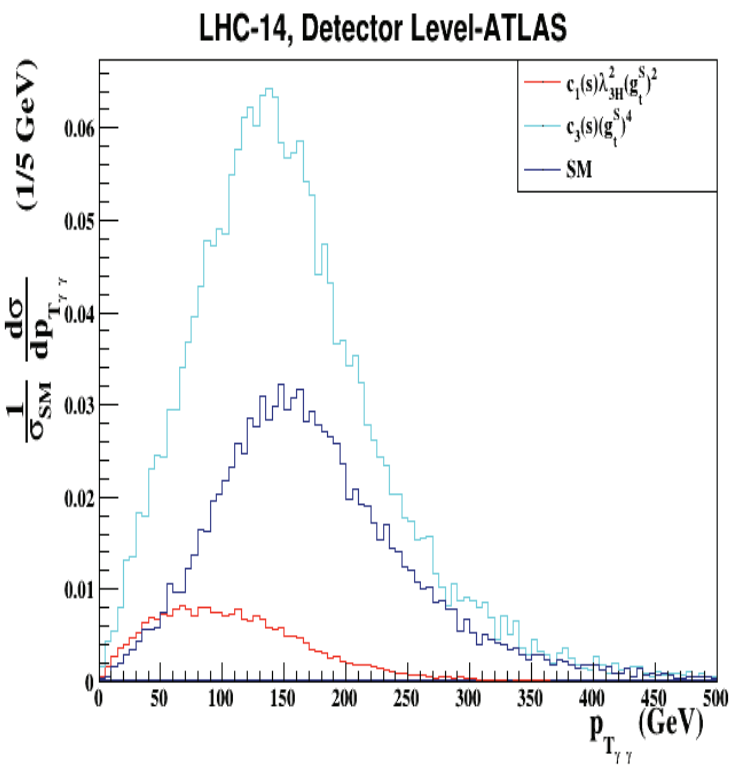
CPC1: g_t^S and λ_{3H}

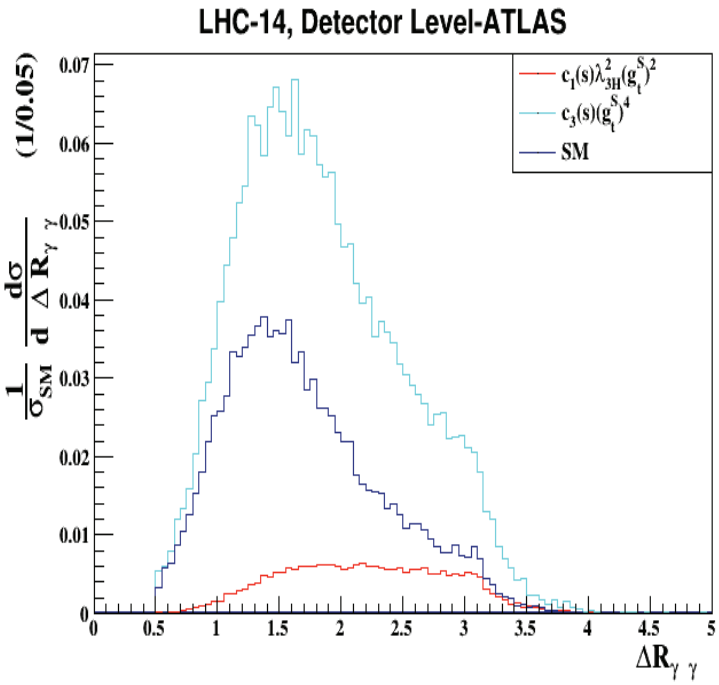
- Attempt to isolate the Higgs self coupling in the triangle diagram.
- The triangle diagram has the $1/s$ behavior, so more profound at low invariant mass region. Thus, the angular separation between the decay product is larger:

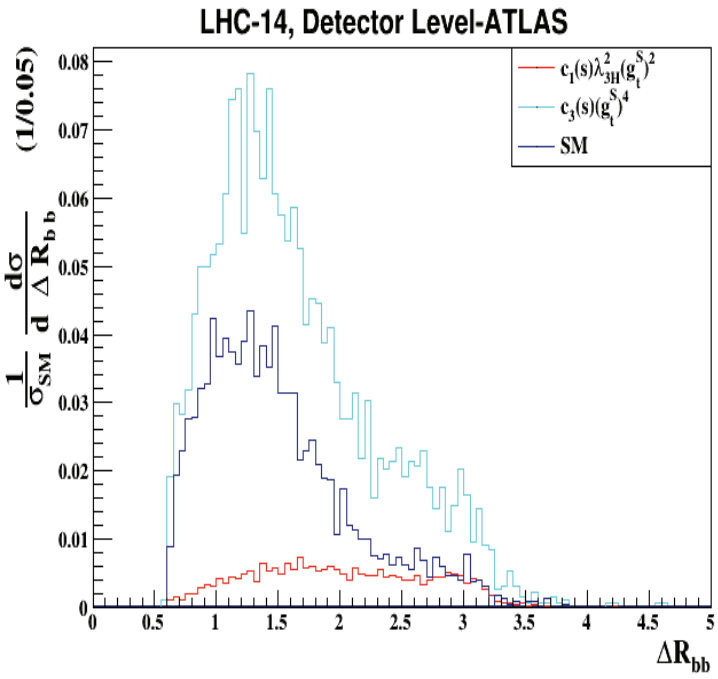
$$HH \to (\gamma\gamma)(b\bar{b})$$

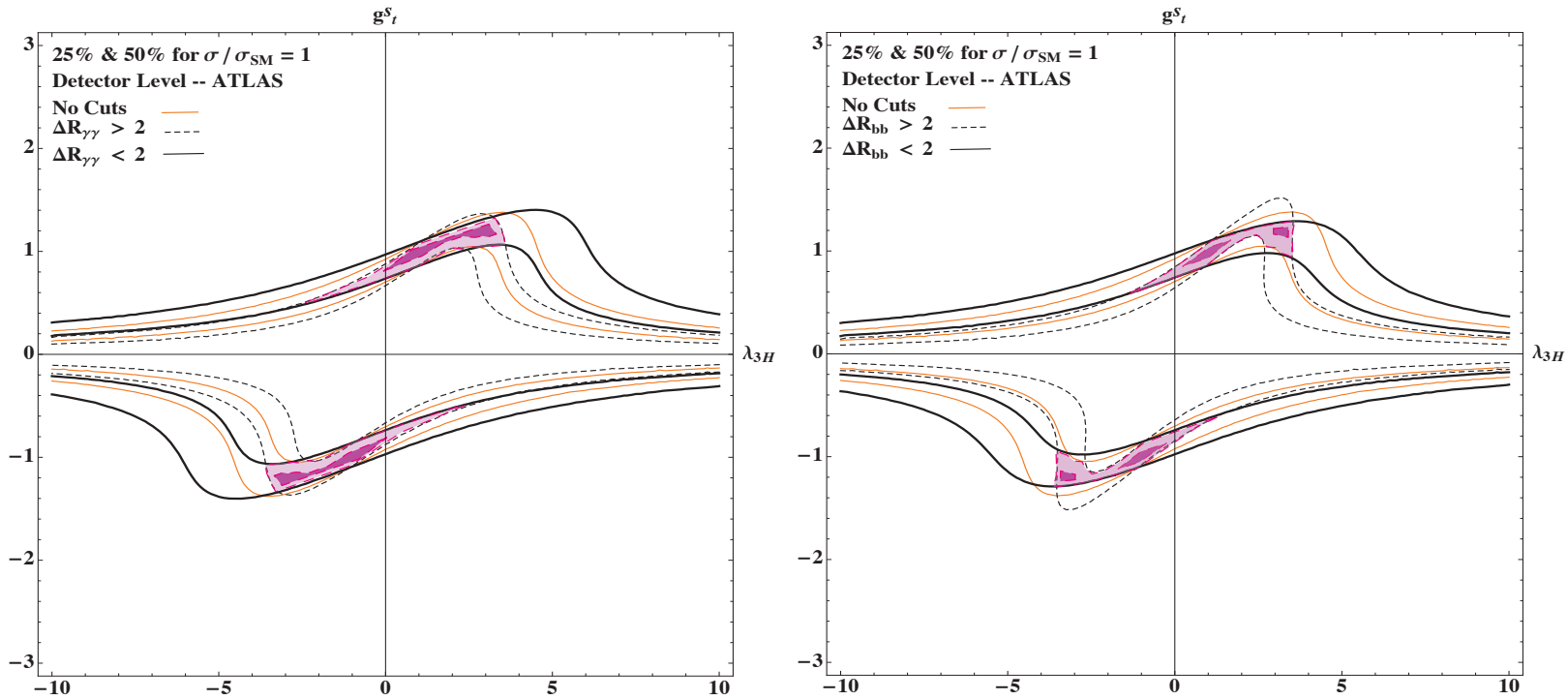
- We can make use of simultaneous cross section measurements: (i) no cuts, (ii) $\sigma(\Delta R_{\gamma\gamma} > 2)$, (iii) $\sigma(\Delta R_{\gamma\gamma} < 2)$.
- Repeat using $\Delta R_{b\bar{b}}$, and both $\Delta R_{\gamma\gamma}$ and $\Delta R_{b\bar{b}}$.

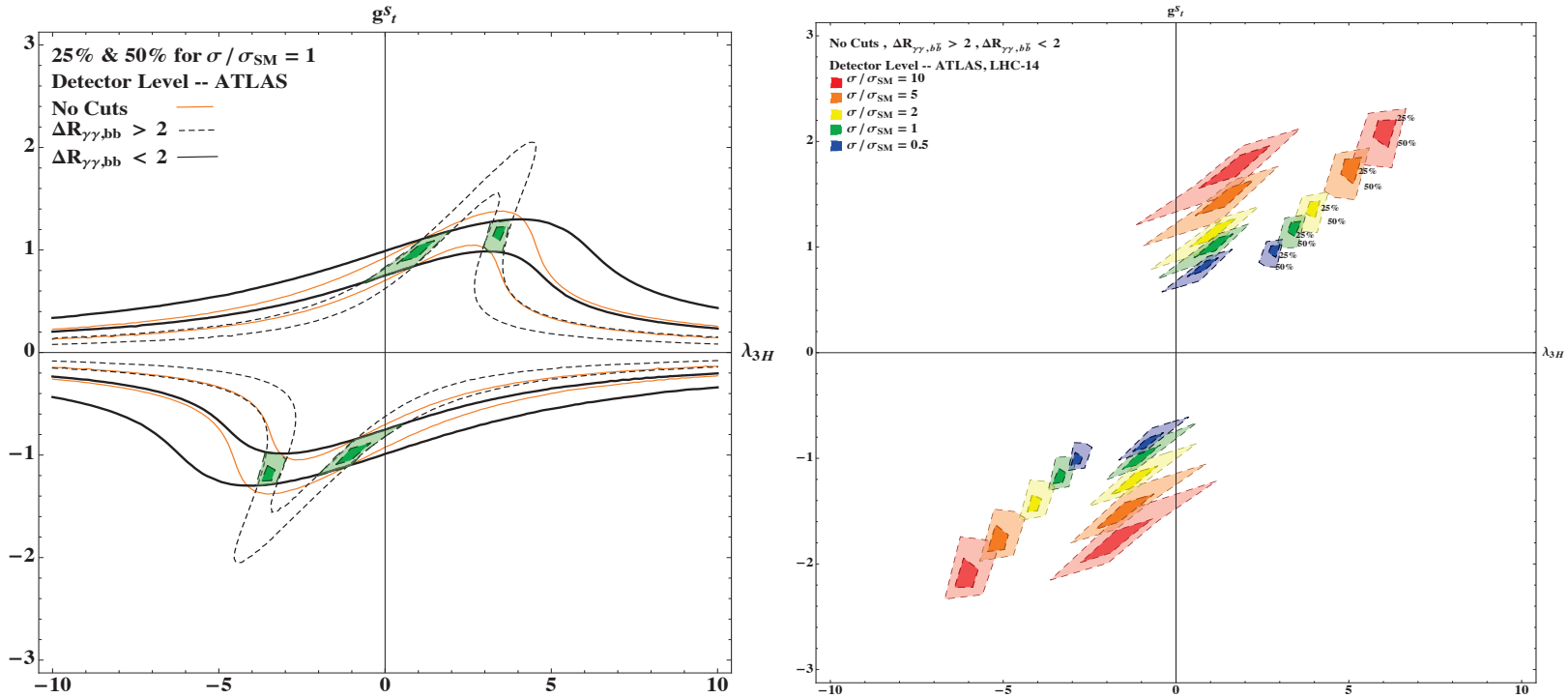

LHC-14, Detector Level-ATLAS
$c_1(s)\lambda_{3H}^2(g_t^S)^2$
$c_3(s)(g_t^S)^4$
SM
$\frac{1}{\sigma_{SM}}\frac{d\sigma}{dM_{\gamma\gamma bb}}$ (1/10 GeV)
$M_{\gamma\gamma bb}$ (GeV)


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


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

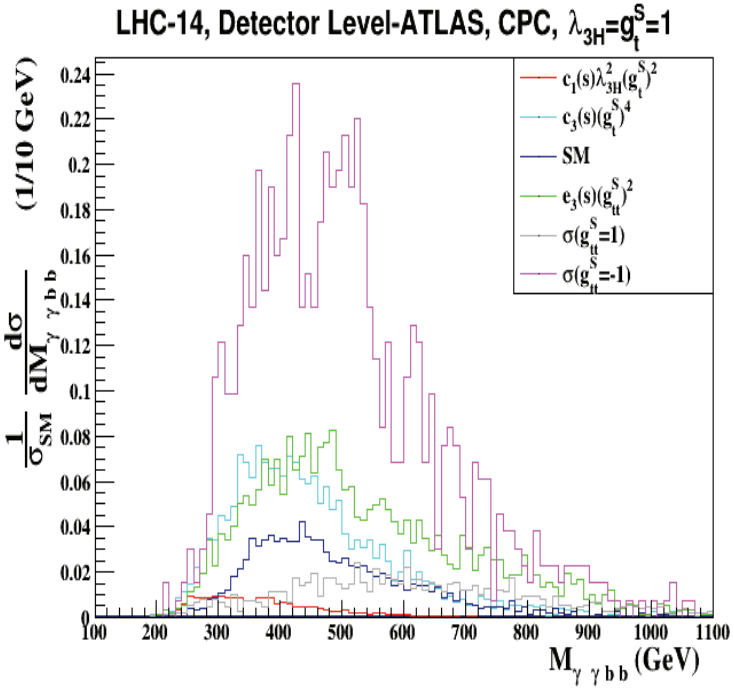

g^S_t
25% & 50% for $\sigma / \sigma_{SM} = 1$
Detector Level -- ATLAS
No Cuts
$\Delta R_{\gamma\gamma} > 2$
$\Delta R_{\gamma\gamma} < 2$
λ_{3H}
g^S_t
25% & 50% for $\sigma / \sigma_{SM} = 1$
Detector Level -- ATLAS
No Cuts
$\Delta R_{bb} > 2$
$\Delta R_{bb} < 2$
λ_{3H}

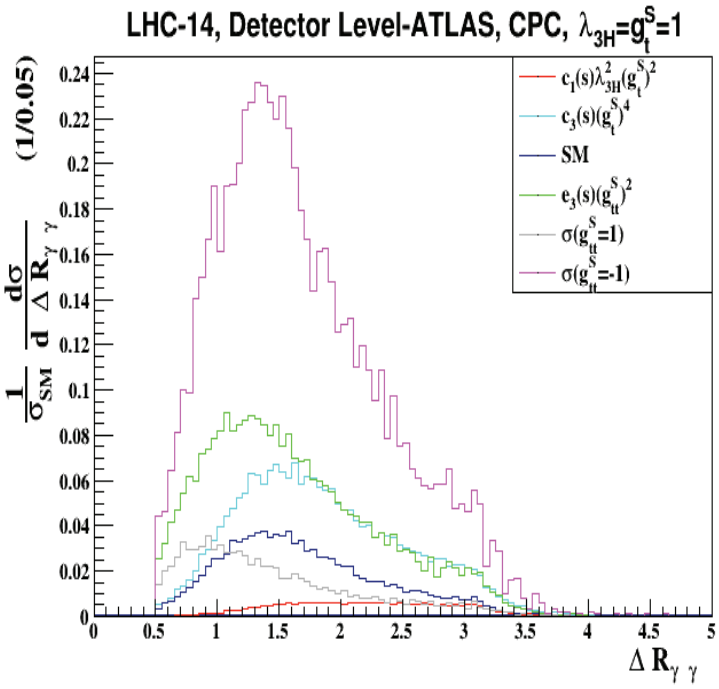


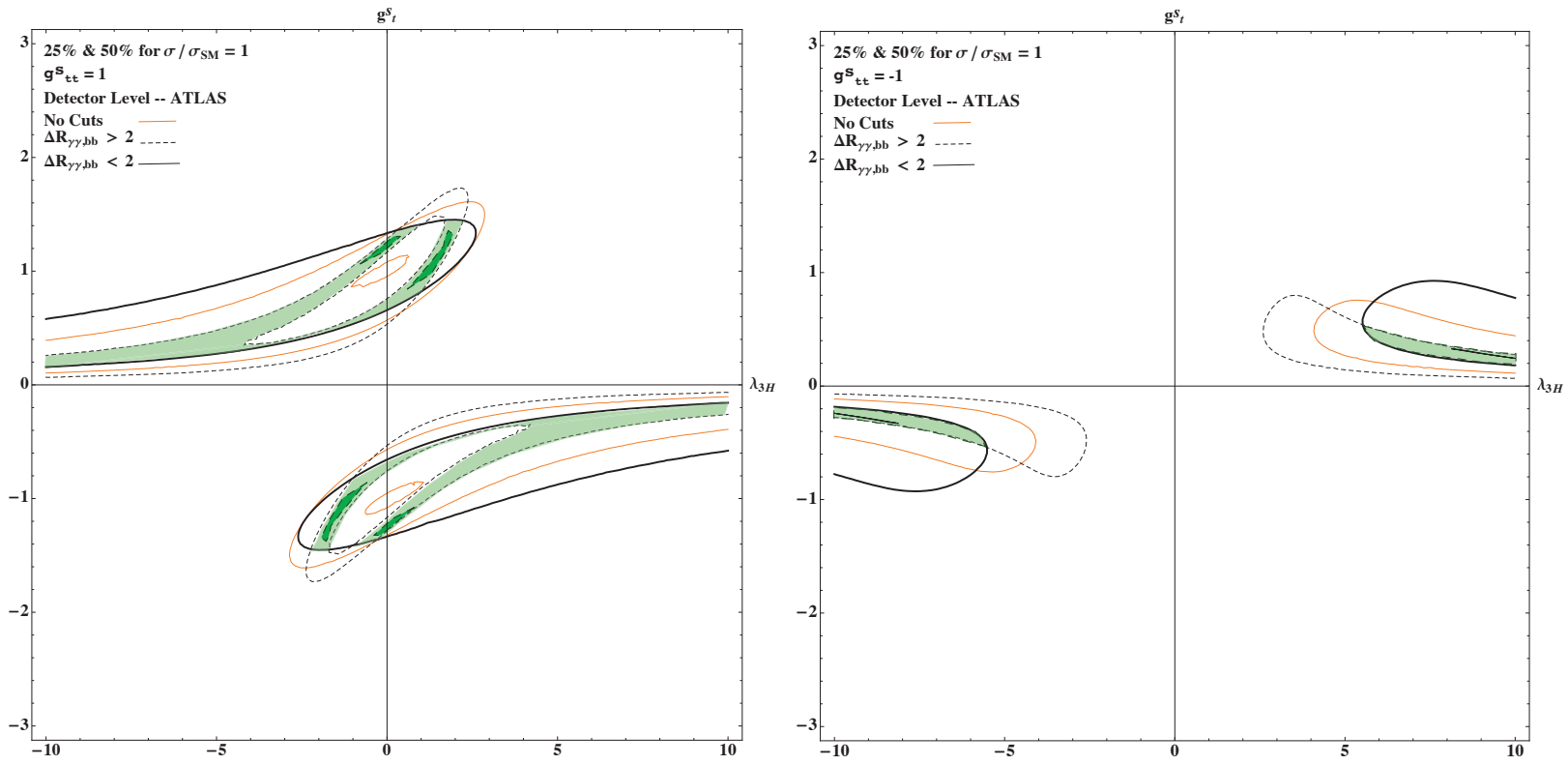
Only with both $\Delta R_{\gamma\gamma}$ and $\Delta R_{b\bar{b}}$ can one really tell if δ_{3H} is significantly distinct from zero.

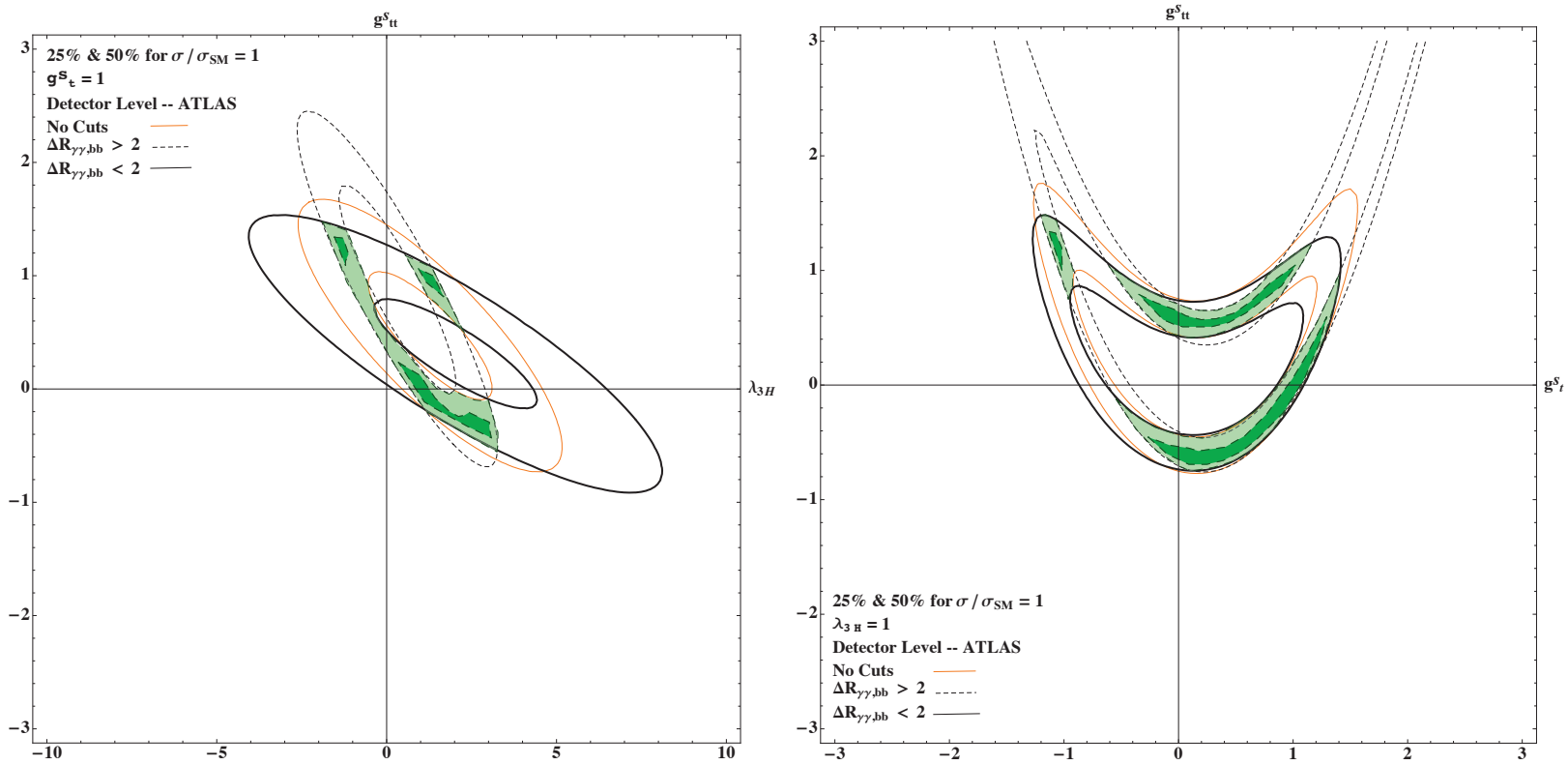
CPC2: g_t^S, λ_{3H}, g_{tt}^S

- 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) no cuts, (ii) $\sigma(\Delta R_{\gamma\gamma},\, \Delta R_{b\bar{b}} > 2)$, (iii) $\sigma(\Delta R_{\gamma\gamma}, \Delta R_{b\bar{b}} < 2)$.


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

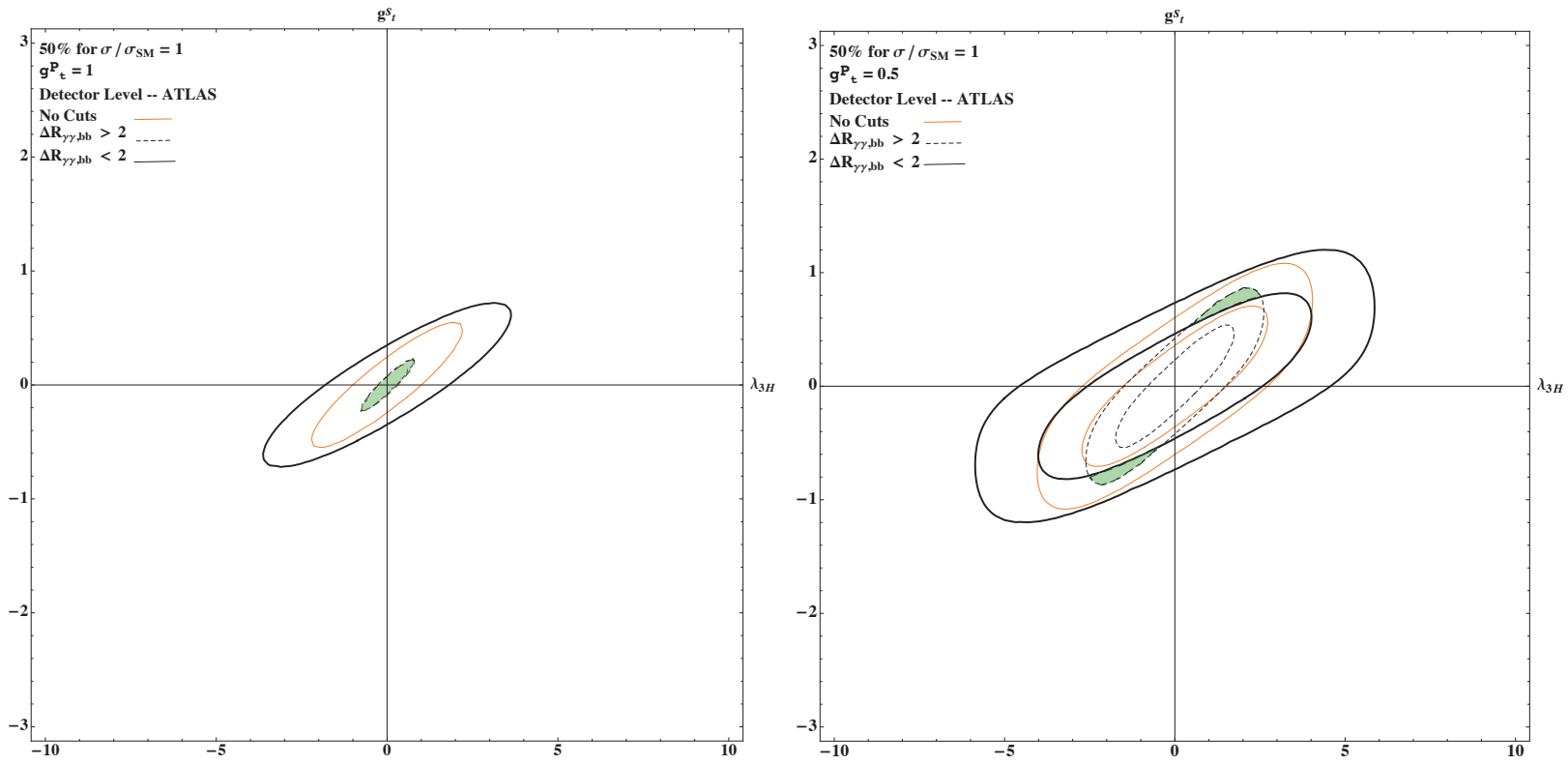

LHC-14, Detector Level-ATLAS, CPC, $\lambda_{3H}=g_t^S=1$
$\frac{1}{\sigma_{SM}}\frac{d\sigma}{d\Delta R_{\gamma\gamma}}$ (1/0.05)
$\Delta R_{\gamma\gamma}$
$c_1(s)\lambda_{3H}^2(g_t^S)^2$
$c_3(s)(g_t^S)^4$
SM
$e_3(s)(g_{tt}^S)^2$
$\sigma(g_{tt}^S=1)$
$\sigma(g_{tt}^S=-1)$

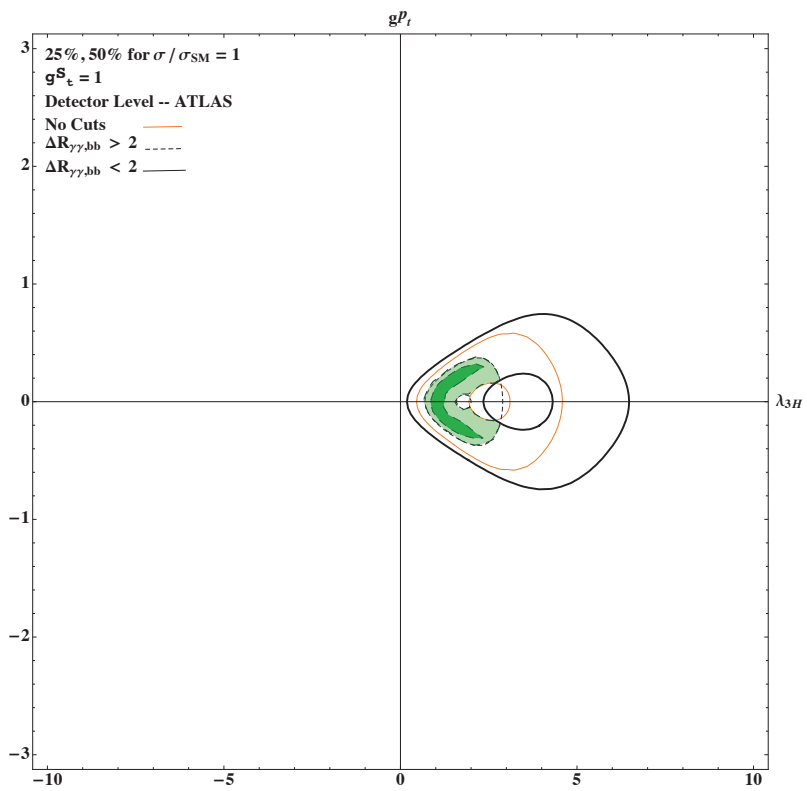

g^S_t
25% & 50% for $\sigma / \sigma_{SM} = 1$
$g^S_{tt} = 1$
Detector Level -- ATLAS
No Cuts
$\Delta R_{\gamma\gamma,bb} > 2$
$\Delta R_{\gamma\gamma,bb} < 2$
λ_{3H}
g^S_t
25% & 50% for $\sigma / \sigma_{SM} = 1$
$g^S_{tt} = -1$
Detector Level -- ATLAS
No Cuts
$\Delta R_{\gamma\gamma,bb} > 2$
$\Delta R_{\gamma\gamma,bb} < 2$
λ_{3H}

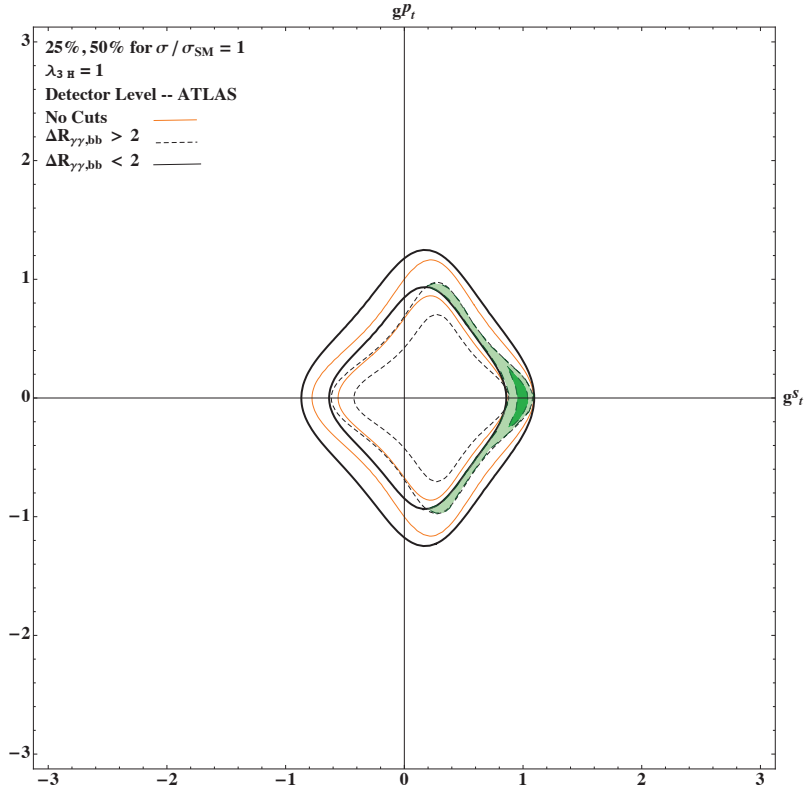

g^S_{tt}
25% & 50% for $\sigma / \sigma_{SM} = 1$
$g^S_t = 1$
Detector Level -- ATLAS
No Cuts
$\Delta R_{\gamma\gamma,bb} > 2$
$\Delta R_{\gamma\gamma,bb} < 2$
λ_{3H}
g^S_{tt}
g^S_t
25% & 50% for $\sigma / \sigma_{SM} = 1$
$\lambda_{3H} = 1$
Detector Level -- ATLAS
No Cuts
$\Delta R_{\gamma\gamma,bb} > 2$
$\Delta R_{\gamma\gamma,bb} < 2$

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


g^S_t
50% for $\sigma / \sigma_{SM} = 1$
$g^P_t = 1$
Detector Level -- ATLAS
No Cuts
$\Delta R_{\gamma\gamma,bb} > 2$
$\Delta R_{\gamma\gamma,bb} < 2$
λ_{3H}
g^S_t
50% for $\sigma / \sigma_{SM} = 1$
$g^P_t = 0.5$
Detector Level -- ATLAS
No Cuts
$\Delta R_{\gamma\gamma,bb} > 2$
$\Delta R_{\gamma\gamma,bb} < 2$
λ_{3H}


g^p_t
25%, 50% for $\sigma / \sigma_{SM} = 1$
$g^S_t = 1$
Detector Level -- ATLAS
No Cuts
$\Delta R_{\gamma\gamma,bb} > 2$
$\Delta R_{\gamma\gamma,bb} < 2$
λ_{3H}
3
2
1
0
−1
−2
−3
−10
−5
0
5
10


g^p_t
25%, 50% for $\sigma / \sigma_{SM} = 1$
$\lambda_{3H} = 1$
Detector Level -- ATLAS
No Cuts
$\Delta R_{\gamma\gamma,bb} > 2$
$\Delta R_{\gamma\gamma,bb} < 2$
g^s_t
3
2
1
0
−1
−2
−3
−3
−2
−1
0
1
2
3

$\sqrt{s}$: 14 TeV	$c_1(s)$	$c_2(s)$	$c_3(s)$	$e_1(s)$	$e_2(s)$	$e_3(s)$
Cuts	$\lambda_{3H}^2(g_t^S)^2$	$\lambda_{3H}(g_t^S)^3$	$(g_t^S)^4$	$\lambda_{3H}g_t^S g_{tt}^S$	$g_{tt}^S(g_t^S)^2$	$(g_{tt}^S)^2$
No Cuts	0.263	-1.31	2.047	1.364	-4.224	2.617
$\Delta R(\gamma_1,\gamma_2) > 2$	0.480	-2.001	2.521	1.859	-4.782	2.422
$\Delta R(\gamma_1,\gamma_2) < 2$	0.132	-0.838	1.706	1.057	-3.743	2.596
$\Delta R(b_1,\bar{b}_1) > 2$	0.625	-2.576	2.951	2.341	-5.525	2.731
$\Delta R(b_1,\bar{b}_1) < 2$	0.143	-0.800	1.657	0.965	-3.673	2.497
$\Delta R(b_1,\bar{b}_1;\gamma_1,\gamma_2) > 2$	0.713	-3.020	3.307	2.844	-5.907	2.704
$\Delta R(b_1,\bar{b}_1;\gamma_1,\gamma_2) < 2$	0.108	-0.675	1.567	0.954	-3.548	2.542

$\sqrt{s}$: 14TeV	$d_1(s)$	$d_2(s)$	$d_3(s)$	$d_4(s)$
Cuts	$\lambda_{3H}^2(g_t^P)^2$	$\lambda_{3H}g_t^S(g_t^P)^2$	$(g_t^S)^2(g_t^P)^2$	$(g_t^P)^4$
No Cuts	0.820	-5.961	13.348	0.707
$\Delta R(\gamma_1,\gamma_2) > 2$	1.561	-10.352	20.409	0.892
$\Delta R(\gamma_1,\gamma_2) < 2$	0.380	-3.266	8.943	0.570
$\Delta R(b_1,\bar{b}_1) > 2$	2.042	-13.668	24.037	1.033
$\Delta R(b_1,\bar{b}_1) < 2$	0.417	-3.081	9.214	0.570
$\Delta R(b_1,\bar{b}_1;\gamma_1,\gamma_2) > 2$	2.402	-12.980	24.976	1.172
$\Delta R(b_1,\bar{b}_1;\gamma_1,\gamma_2) < 2$	0.271	-3.504	7.900	0.541

100 TeV pp Collider

$\sqrt{s}$: 100 TeV Cuts	$c_1(s)$ $\lambda_{3H}^2(g_t^S)^2$	$c_2(s)$ $\lambda_{3H}(g_t^S)^3$	$c_3(s)$ $(g_t^S)^4$	$e_1(s)$ $\lambda_{3H}g_t^S g_{tt}^S$	$e_2(s)$ $g_{tt}^S(g_t^S)^2$	$e_3(s)$ $(g_{tt}^S)^2$
No Cuts	0.208	-1.108	1.900	1.214	-4.137	2.974
$\Delta R(\gamma_1,\gamma_2) > 2$	0.384	-1.619	2.235	1.437	-4.183	2.126
$\Delta R(\gamma_1,\gamma_2) < 2$	0.119	-0.859	1.740	1.085	-4.080	3.281
$\Delta R(b_1,\bar{b}_1) > 2$	0.479	-2.070	2.592	2.620	-5.302	3.026
$\Delta R(b_1,\bar{b}_1) < 2$	0.126	-0.769	1.643	1.624	-4.285	3.519
$\Delta R(b_1,\bar{b}_1;\gamma_1,\gamma_2) > 2$	0.607	-2.536	2.929	2.553	-5.920	3.160
$\Delta R(b_1,\bar{b}_1;\gamma_1,\gamma_2) < 2$	0.099	-0.680	1.581	1.592	-4.059	3.468

$\sqrt{s}$: 100TeV Cuts	$d_1(s)$ $\lambda_{3H}^2(g_t^P)^2$	$d_2(s)$ $\lambda_{3H}g_t^S(g_t^P)^2$	$d_3(s)$ $(g_t^S)^2(g_t^P)^2$	$d_4(s)$ $(g_t^P)^4$
No Cuts	0.635	-4.789	11.225	0.683
$\Delta R(\gamma_1,\gamma_2) > 2$	1.209	-7.687	13.519	0.728
$\Delta R(\gamma_1,\gamma_2) < 2$	0.336	-3.367	9.955	0.642
$\Delta R(b_1,\bar{b}_1) > 2$	1.883	-11.795	20.282	1.062
$\Delta R(b_1,\bar{b}_1) < 2$	0.422	-3.804	11.404	0.706
$\Delta R(b_1,\bar{b}_1;\gamma_1,\gamma_2) > 2$	2.434	-14.111	20.250	1.494
$\Delta R(b_1,\bar{b}_1;\gamma_1,\gamma_2) < 2$	0.284	-3.286	10.148	0.685

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

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