New Physics Effects in Higgs Couplings
through Effective Lagrangian

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Plan

- Higgs self-coupling measurements at ILC

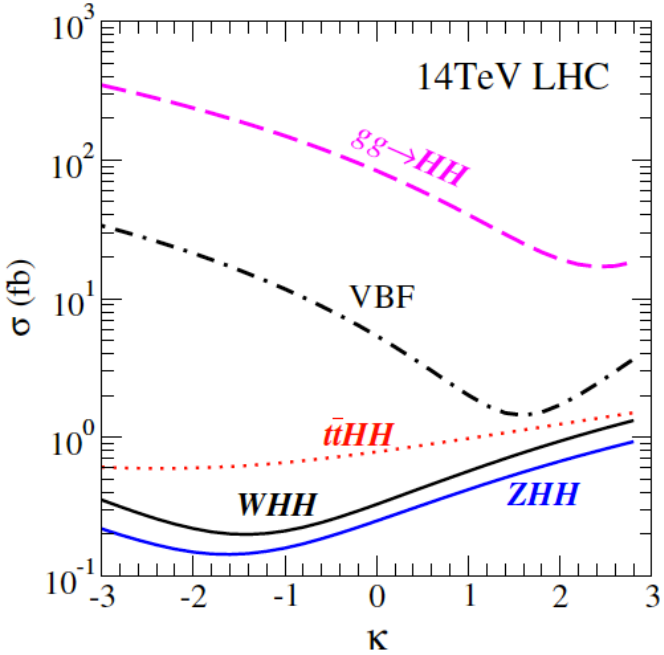
- (CP-violating) Higgs – Top Couplings

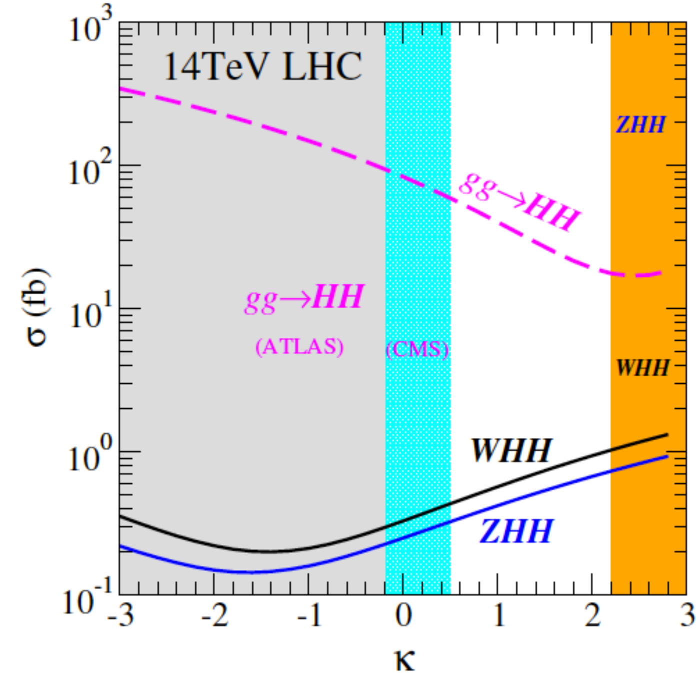
Higgs trilinear and quartic couplings

$$V = \lambda_{SM}\left(\left|\phi\right|^2 - \frac{v^2}{2}\right)^2 \qquad \phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

$$V = \lambda v^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4 \quad = \frac{m_H^2}{2} H^2 + \frac{m_H^2}{2v} H^3 + \frac{m_H^2}{8v^2} H^4$$

LHC





Lum. = 3000 /fb

Cao, Liu, Yan, 1511.03311

TABLE III: The sensitivity to $\lambda_{HHH} = \kappa\lambda_{HHH}^{\rm SM}$ in several production channels of Higgs boson pairs at the HL-LHC.

	SM ($\kappa = 1$)	5σ discovery potential	2σ exclusion bound
WHH	1.29σ	$\kappa \leq -7.7, \quad \kappa \geq 4.8$	$-5.1 \leq \kappa \leq 2.2$
ZHH	1.32σ	$\kappa \leq -8.1, \quad \kappa \geq 4.8$	$-5.4 \leq \kappa \leq 2.2$
GF($b\bar{b}\gamma\gamma$) [42]	1.19σ	$\kappa \leq -4.5, \quad \kappa \geq 8.1$	$-0.2 \leq \kappa \leq 4.9$
GF($b\bar{b}\gamma\gamma$) [43]	1.65σ	$\kappa \leq -2.6, \quad \kappa \geq 6.3$	$0.5 \leq \kappa \leq 4.1$
VBF [20]	0.59σ	$\kappa \leq -1.7, \quad \kappa \geq 5.0$	$-0.4 \leq \kappa \leq 3.5$
$t\bar{t}HH$ [21, 22]	1.38σ	$\kappa \leq -11.4, \kappa \geq 6.9$	$-7.2 \leq \kappa \leq 2.5$

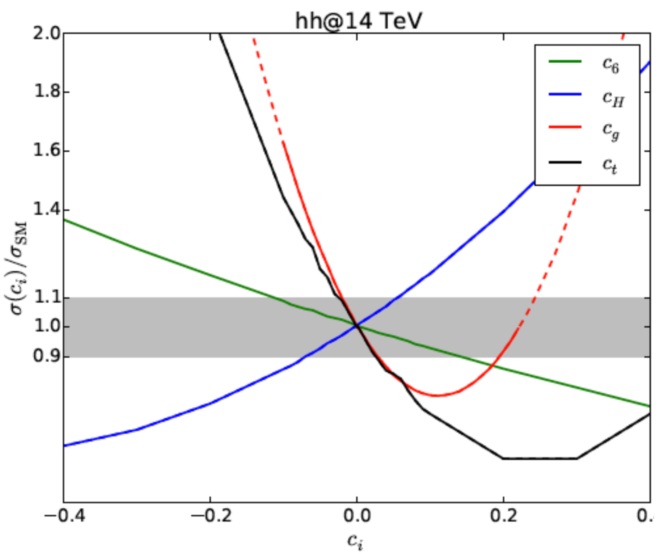
[20] Dolen, et al, EPJC75, 387
[21] Englert, et al, PLB 743,93
[22] Liu, Zhang, 1410.1855
[42] ATL-PHYS-PUB-2014-019
[43] CMS-PAS-FTR-15-002
Other literature
Baglio, et al, JHEP 1304, 151
and refs. fhere.

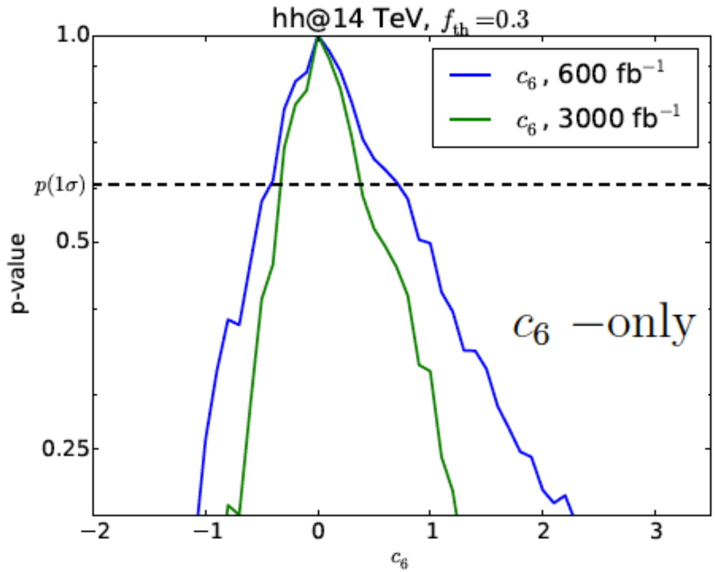
Effective Lag. @LHC

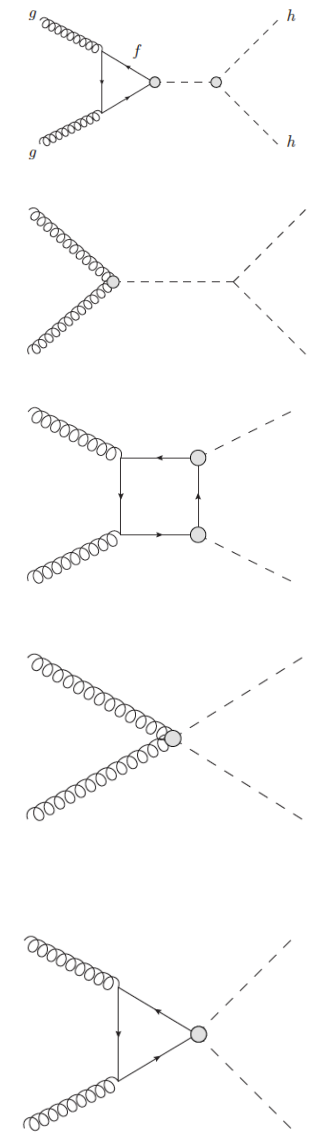
Goertz, Papaefstathiou, Yang, Zurita, JHEP 1504 (2015) 167

$$L_{eff} = L_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i$$

$$pp \to HH$$



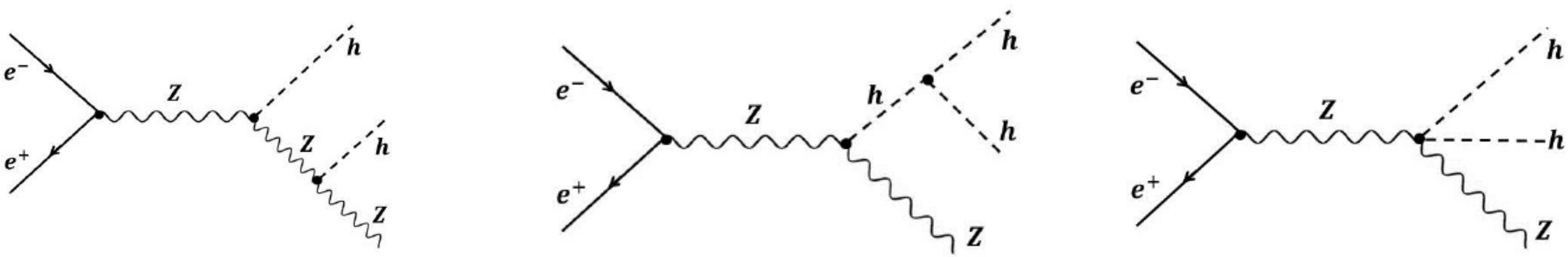




model	$L = 600\ \text{fb}^{-1}$	$L = 3000\ \text{fb}^{-1}$
c_6-only	$c_6 \in (-0.5, 0.8)$	$c_6 \in (-0.4, 0.4)$
full	$c_6 \gtrsim -1.3$	$c_6 \gtrsim -1.2$
$c_6 - c_t - c_\tau - c_b$	$c_6 \gtrsim -2.0$	$c_6 \in (-1.8, 2.3)$
full (**future**)	$c_6 \in (-0.8, 0.9)$	$c_6 \in (-0.6, 0.6)$
$c_6 - c_t - c_\tau - c_b$ (**future**)	$c_6 \in (-0.8, 0.8)$	$c_6 \in (-0.6, 0.5)$

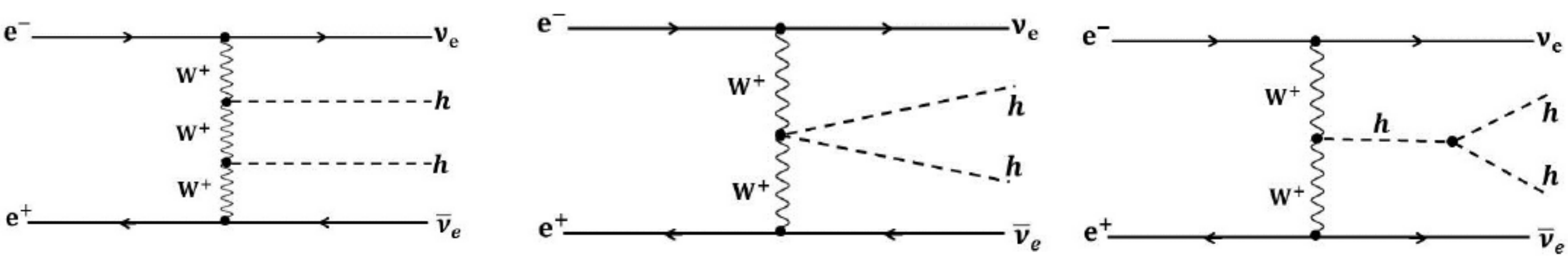
at e+e- Collider

$$e^+e^- \to Zhh$$



$$\sigma(500GeV) = 0.15fb$$

$$e^+e^- \to \nu\nu hh$$



$$\sigma(500\,GeV) = 0.05fb, \quad \sigma(2TeV) = 0.4fb$$

ILC

Killik, Kumar, Logan, PRD 88 (2013) 033015

$$\mathcal{L} \supset k_V M_V^2 V_\mu^* V^\mu \left[1 + a_V \frac{2h}{v_{\rm SM}} + b_V \frac{h^2}{v_{\rm SM}^2}\right] - \frac{1}{2} M_h^2 h^2 \left[1 + d_3 \frac{h}{v_{\rm SM}} + d_4 \frac{h^2}{4 v_{\rm SM}^2}\right],$$

I. SM + singlet $\quad b_W = b_Z \equiv b = \cos^2\theta = a^2$

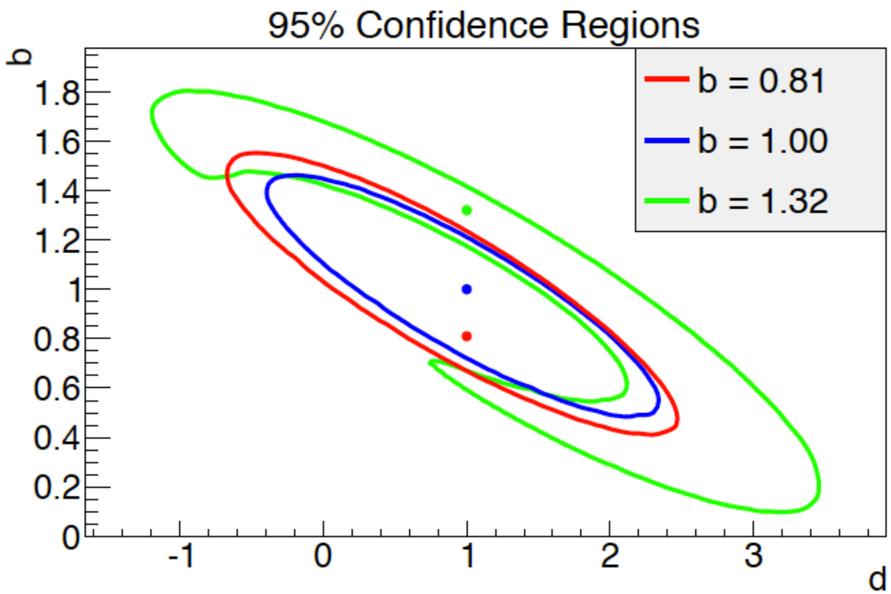
II. SM + doublets $\quad b_W = b_Z \equiv b = 1$

III. SM + triplets (Georgi-Machacek)

$$b_W = b_Z = a^2 + \frac{8}{3}(1 - a^2)$$

Model	b	$\sigma^{500}(Zhh)$	$\sigma^{1000}(Zhh)$	σ^{1000}(WBF)
Singlet	0.81	0.11 fb	0.082 fb	0.041 fb
Doublet	1	0.14 fb	0.11 fb	0.027 fb
GM	1.32	0.19 fb	0.18 fb	0.090 fb
SM	1	0.16 fb	0.12 fb	0.071 fb

Model	b	$\Delta\sigma/\sigma(Zhh, 500$ GeV$)$	$\Delta\sigma/\sigma(\nu\nu hh, 1$ TeV$)$
Singlet	0.81	38%	32%
Doublet	1	32%	42%
GM	1.32	24%	18%
SM	1	27%	23%



The Effective Lagrangian

Relevant to $e^+e^- \to Zhh, \quad \nu\nu hh$

$$\mathcal{L}_{\rm Higgs}^{\rm anom} = \frac{c_H}{\Lambda^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{\Lambda^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6}{\Lambda^2}\lambda\,(\Phi^\dagger\Phi)^3$$
$$+\frac{c_\gamma}{\Lambda^2} g'^2\, \Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{c_{HW}}{\Lambda^2} ig\,(D^\mu\Phi^\dagger\sigma_k D^\nu\Phi)W^k_{\mu\nu} + \frac{c_{HB}}{\Lambda^2} ig'\,(D^\mu\Phi^\dagger D^\nu\Phi)B_{\mu\nu}$$
$$+\frac{c_W}{\Lambda^2} ig\,(\Phi^\dagger\sigma_k \overleftrightarrow{D}^\mu\Phi)D^\nu W^k_{\mu\nu} + \frac{c_B}{\Lambda^2} ig'\,(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)\partial^\nu B_{\mu\nu},$$

Refs. for complete $L_{\rm eff}$ include:

W. Buechmuller, D. Wyler, Nucl. Phys. B268 (1986) 621,
B. Grzadkowski, M. Iskrzyński, M. Misiak, J. Rosiek JHEP 1010 (2010) 085
M.B. Einhorn and J. Wudka, Nucl. Phys. B876 (2013) 556,
R. Contino, M. Ghezzi, C. Grojean, M. Muhlleitner, M Spira JHEP 1307 (2013) 035
A. Alloul, B. Fuks and V. Sanz, JHEP 1404 (2014) 110 – FEYNRULES implementation

In terms of physics couplings

$$\mathcal{L}^{\rm anom}_{h,Z,W} = -v\lambda g^1_{hhh}h^3 + \frac{1}{2}g^2_{hhh}h\,\partial_\mu h\,\partial^\mu h - \frac{1}{4}g^1_{hZZ}Z_{\mu\nu}Z^{\mu\nu}h - g^2_{hZZ}Z_\nu\partial_\mu Z^{\mu\nu}h$$
$$+\frac{1}{2}g^3_{hZZ}Z_\mu Z^\mu h - \frac{1}{2}g^1_{h\gamma Z}Z_{\mu\nu}F^{\mu\nu}h - g^2_{h\gamma Z}Z_\nu\partial_\mu F^{\mu\nu}h$$
$$-\frac{1}{8}g^1_{hhZZ}Z_{\mu\nu}Z^{\mu\nu}h^2 - \frac{1}{2}g^2_{hhZZ}Z_\nu\partial_\mu Z^{\mu\nu}h^2 + \frac{1}{4}g^3_{hhZZ}Z_\mu Z^\mu h^2$$
$$-\frac{1}{2}g^1_{hWW}W^{\mu\nu}W^\dagger_{\mu\nu}h - \left[g^2_{hWW}W^\nu\partial^\mu W^\dagger_{\mu\nu}h + h.c.\right] + g\,\left(1-\frac{\bar{c}_H}{2}\right)m_W W^\dagger_\mu W^\mu h$$
$$-\frac{1}{4}g^1_{hhWW}W^{\mu\nu}W^\dagger_{\mu\nu}h^2 - \frac{1}{2}\left[g^2_{hhWW}W^\nu\partial^\mu W^\dagger_{\mu\nu}h^2 + h.c.\right] + \frac{1}{4}g^2 W^\dagger_\mu W^\mu h^2$$

$$\bar{c}_i = c_i\frac{M^2}{\Lambda^2}$$

$M \sim v \; or \; m_W$

$$g^{(1)}_{hhh} = 1 + \frac{7}{8}\bar{c}_6 - \frac{1}{2}\bar{c}_H, \qquad g^{(2)}_{hhh} = \frac{g}{m_W}\bar{c}_H$$

$$g^{(1)}_{hZZ} = \frac{2g}{c^2_W m_W}\left[\bar{c}_{HB}s^2_W - 4\bar{c}_\gamma s^4_W + c^2_W\bar{c}_{HW}\right]$$

$$g^{(2)}_{hZZ} = \frac{g}{c^2_W m_W}\left[(\bar{c}_{HW}+\bar{c}_W)c^2_W + (\bar{c}_B+\bar{c}_{HB})s^2_W\right]$$

$$g^{(3)}_{hZZ} = \frac{g m_Z}{c_W}\left[1 - \frac{1}{2}\bar{c}_H - 2\bar{c}_T - 8\bar{c}_\gamma\frac{s^4_W}{c^2_W}\right]$$

$$g^{(1)}_{h\gamma Z} = \frac{g s_W}{c_W m_W}\left[\bar{c}_{HW} - \bar{c}_{HB} + 8\bar{c}_\gamma s^2_W\right]$$

$$g^{(2)}_{h\gamma Z} = \frac{g s_W}{c_W m_W}\left[\bar{c}_{HW} - \bar{c}_{HB} - \bar{c}_B + \bar{c}_W\right]$$

$$g^{(1)}_{hhZZ} = \frac{g^2}{c^2_W m^2_W}\left[\bar{c}_{HB}s^2_W - 4\bar{c}_\gamma s^4_W + \bar{c}_{HW}c^2_W\right]$$

$$g^{(2)}_{hhZZ} = \frac{g^2}{2c^2_W m^2_W}\left[(\bar{c}_{HW}+\bar{c}_W)c^2_W + (\bar{c}_B+\bar{c}_{HB})s^2_W\right]$$

$$g^{(3)}_{hhZZ} = \frac{g^2}{2c^2_W}\left[1 - \bar{c}_H - 6\bar{c}_T + 8\bar{c}_\gamma\frac{s^4_W}{c^2_W}\right]$$

$$g^{(1)}_{hWW} = \frac{2g}{m_W}\bar{c}_{HW}, \qquad g^{(2)}_{hWW} = \frac{g}{2m_W}\left[\bar{c}_W + \bar{c}_{HW}\right]$$

$$g^{(1)}_{hhWW} = \frac{g^2}{m^2_W}\bar{c}_{HW}, \qquad g^{(2)}_{hhWW} = \frac{g^2}{4m^2_W}\left[\bar{c}_W + \bar{c}_{HW}\right]$$

Constraints on the couplings

Gfitter Group, EPJ C72 (2012) 2205
Maro, Espinosa, Masso, Pomarol, JHEP 1311, 066
Ellis, Sanz, You, JHEP 1407, 036
Ellis, Sanz, You, JHEP 1503, 157

$\overline{c}_6$ Relevant only to g_{hhh}. Not constrained

$\overline{c}_H, \overline{c}_T, \overline{c}_\gamma, \overline{c}_W, \overline{c}_B, \overline{c}_{HW}, \overline{c}_{HB}$ Relevant to VVH couplings

$$\bar{c}_T(m_Z) \in [-1.5, 2.2] \times 10^{-3},$$
$$(\bar{c}_W(m_Z) + \bar{c}_B(m_Z)) \in [-1.4, 1.9] \times 10^{-3}$$

EW precision constraints

Set: $\overline{c}_B = -\overline{c}_W$

$\bar{c}_W \in [-0.03, 0.01]$ TGC, H+V : LEP/LHC/TeVatron

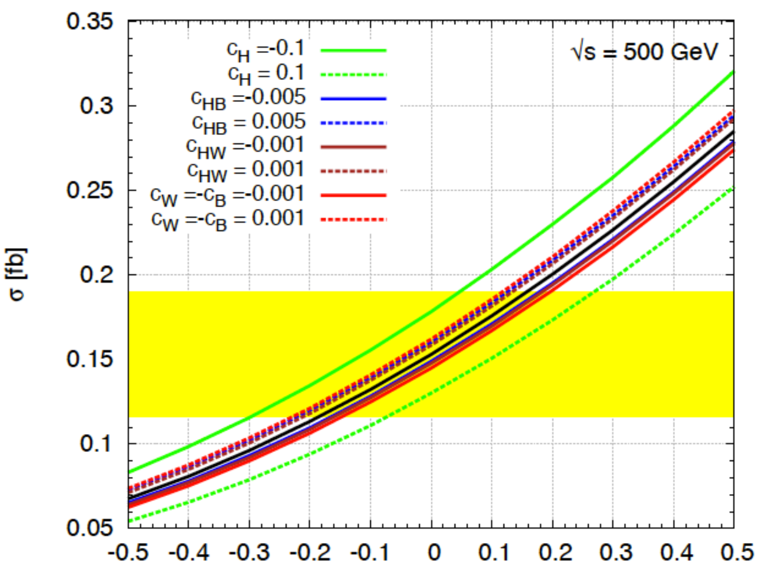
$\bar{c}_{HW} \in [-0.04, 0.01]$

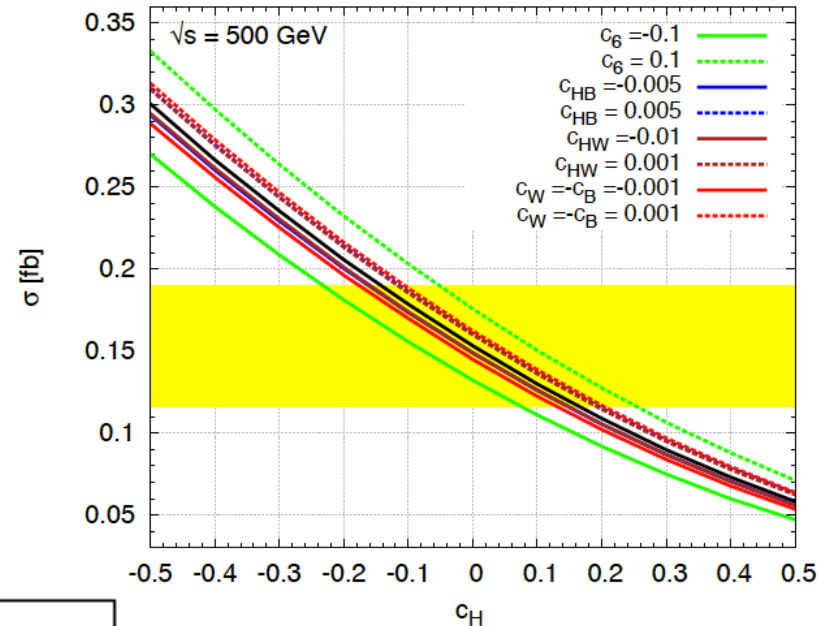
$\bar{c}_{HB} \in [-0.05, 0.05]$

$\bar{c}_\gamma \in [-0.0004, +0.00023$

Revisit $e^+e^- \to Zhh, \quad \nu\nu hh$ with L_{Eff}

S. Kumar and Poulose
Preliminary



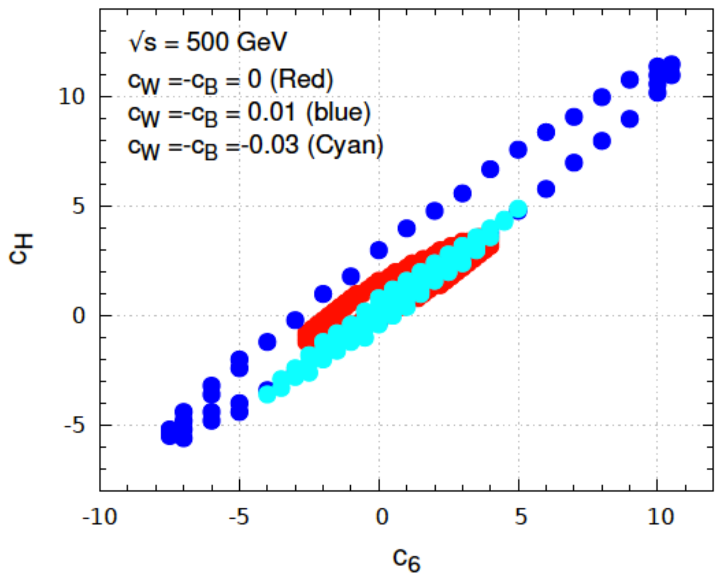


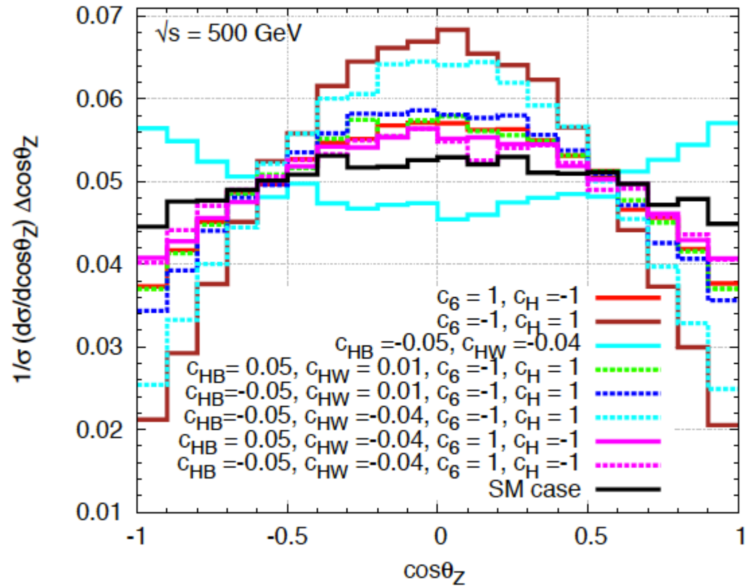
Other Couplings	$\bar{c}_6$	$\bar{c}_H$
SM	[-0.19, +0.16]	[-0.14, +0.16]
$\bar{c}_H$ or $\bar{c}_6 = -0.1$	[-0.30, +0.04]	[-0.22, +0.08]
$\bar{c}_H$ or $\bar{c}_6 = 0.1$	[-0.08, +0.26]	[-0.05, +0.26]
$\bar{c}_{HB} = -0.005$	[-0.16, +0.18]	[-0.16, +0.15]
$\bar{c}_{HB} = 0.005$	[-0.22, +0.12]	[-0.10, +0.20]
$\bar{c}_{HW} = -0.001$	[-0.15, +0.18]	[-0.16, +0.15]
$\bar{c}_{HW} = 0.001$	[-0.21, +0.14]	[-0.12, +0.20]
$\bar{c}_W = -\bar{c}_B = -0.001$	[-0.14, +0.20]	[-0.18, +0.13]
$\bar{c}_W = -\bar{c}_B = 0.001$	[-0.22, +0.12]	[-0.10, +0.20]

3σ limits

$L = 1000 \quad /fb$

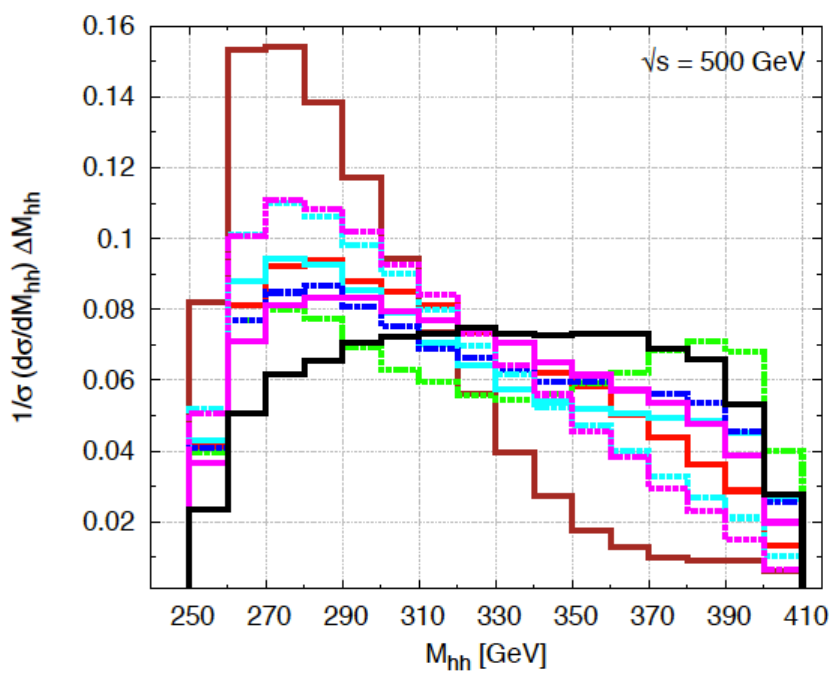
Need to include
BR's, and final states analyses



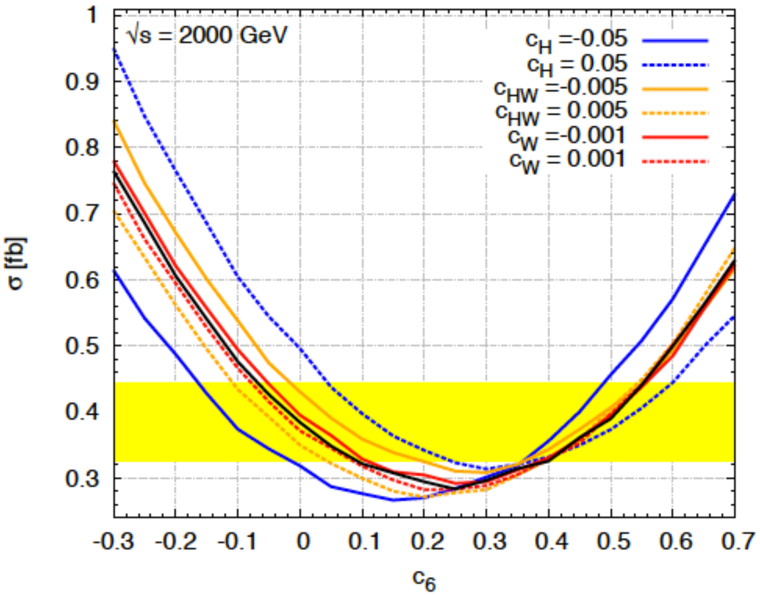


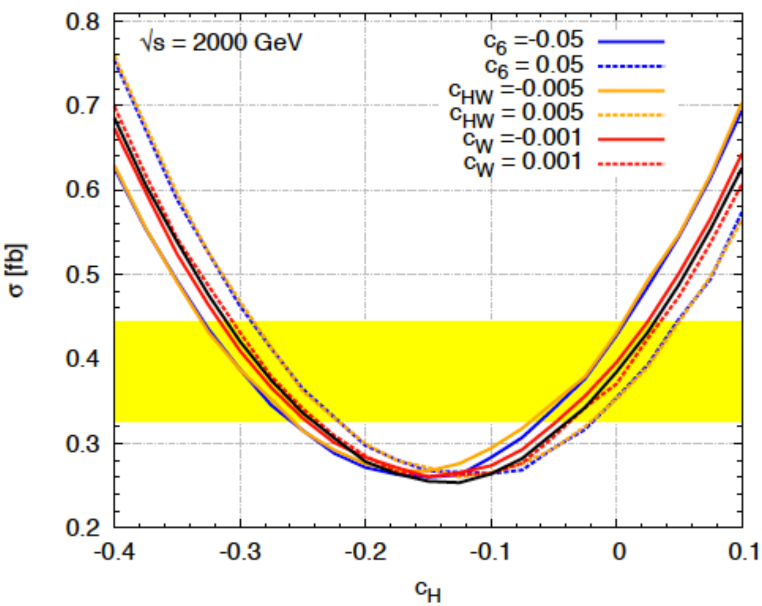
Need to include
BR's, and final states analyses

Here the purpose is to see if one can identify the relevant correlations and interference effects



$e^+e^- \to \nu_e \bar{\nu}_e hh$





Other Couplings	$\bar{c}_6$	$\bar{c}_H$
SM	[+0.40, +0.55] [-0.06, +0.08]	[-0.04, +0.03] [-0.31, +0.24]
$\bar{c}_H = -0.05$ or $\bar{c}_6 = -0.05$	[+0.32, +0.48] [-0.16, -0.02]	[-0.06, +0.01] [-0.33, -0.26]
$\bar{c}_H = 0.05$ or $\bar{c}_6 = 0.05$	[+0.38, +0.60] [+0.04, +0.24]	[-0.02, +0.05] [-0.29, +0.22]
$\bar{c}_{HW} = -0.005$	[+0.36, +0.54] [-0.02, +0.20]	[-0.07, +0.01] [-0.33, -0.26]
$\bar{c}_{HW} = 0.005$	[+0.40, +0.54] [-0.11, +0.04]	[-0.02, +0.05] [-0.29, -0.22]
$\bar{c}_W = -0.001$	[+0.40, +0.56] [-0.07, +0.10]	[-0.05, +0.02] [-0.31, -0.25]
$\bar{c}_W = 0.001$	[+0.40, +0.54] [-0.08, +0.09]	[-0.04, +0.03] [-0.30, -0.24]

3σ limits

$L = 1000 \quad /fb$