CEPC physics and computing workshop

An Exploratory study of Higgs Pair Production

張 蓉 Jung Chang NCTS

Based on : JHEP 1508 (2015) 133, arXiv : 1505.00957 and work in progress.
Collaborate with : Prof. Kingman Cheung, Prof. Jae Sik Lee and Dr. Chih-Ting Lu

Standard Model

	$SU(3)$	$SU(2)_L$	$U(1)_Y$
$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	1	2	$\frac{1}{2}$

$$V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2 \textbf{ EWSB} \supset \frac{1}{2} m_h^2 h^2 + \sqrt{\frac{\lambda}{2}} m_h h^3 + \frac{\lambda}{4} h^4$$

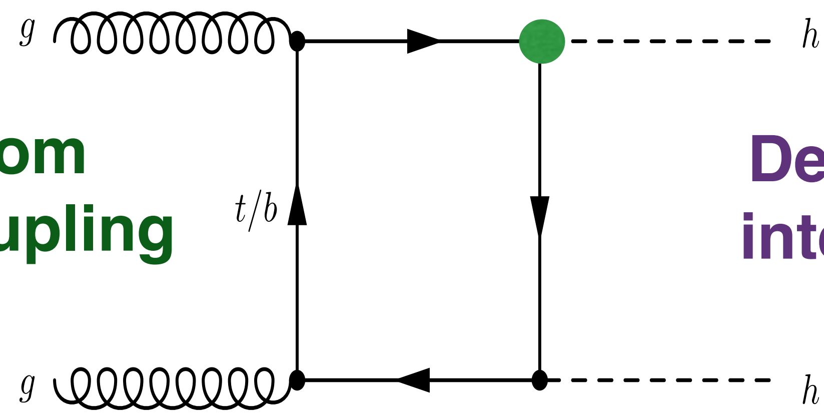
$m_h = \lambda v^2/2, v^2 = \mu^2/\lambda$

$$\lambda_{hhh}^{(0,SM)} = \frac{3m_h^2}{v}, \quad \lambda_{hhhh}^{(0,SM)} = \frac{3m_h^2}{v^2}$$

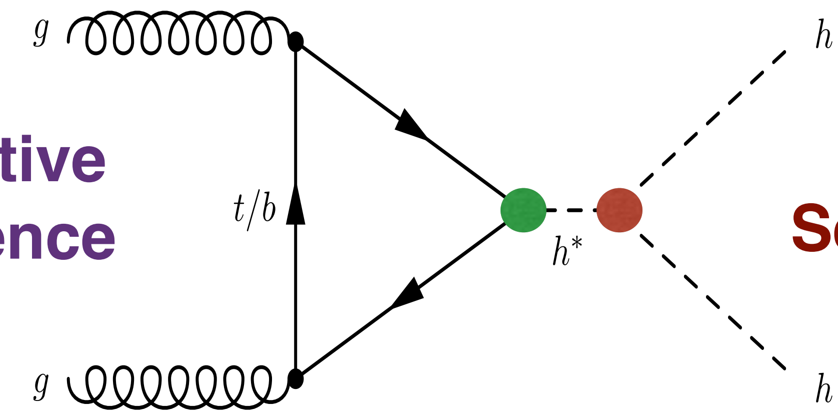
Borrow from Daniel de Florian's slide for LHC-HXSWG June 12, 2014

HHH coupling Measurement

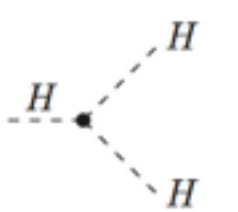
Top/Bottom Yukawa Coupling



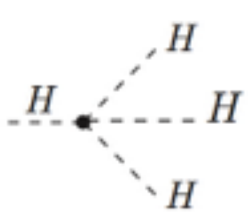
Destructive interference



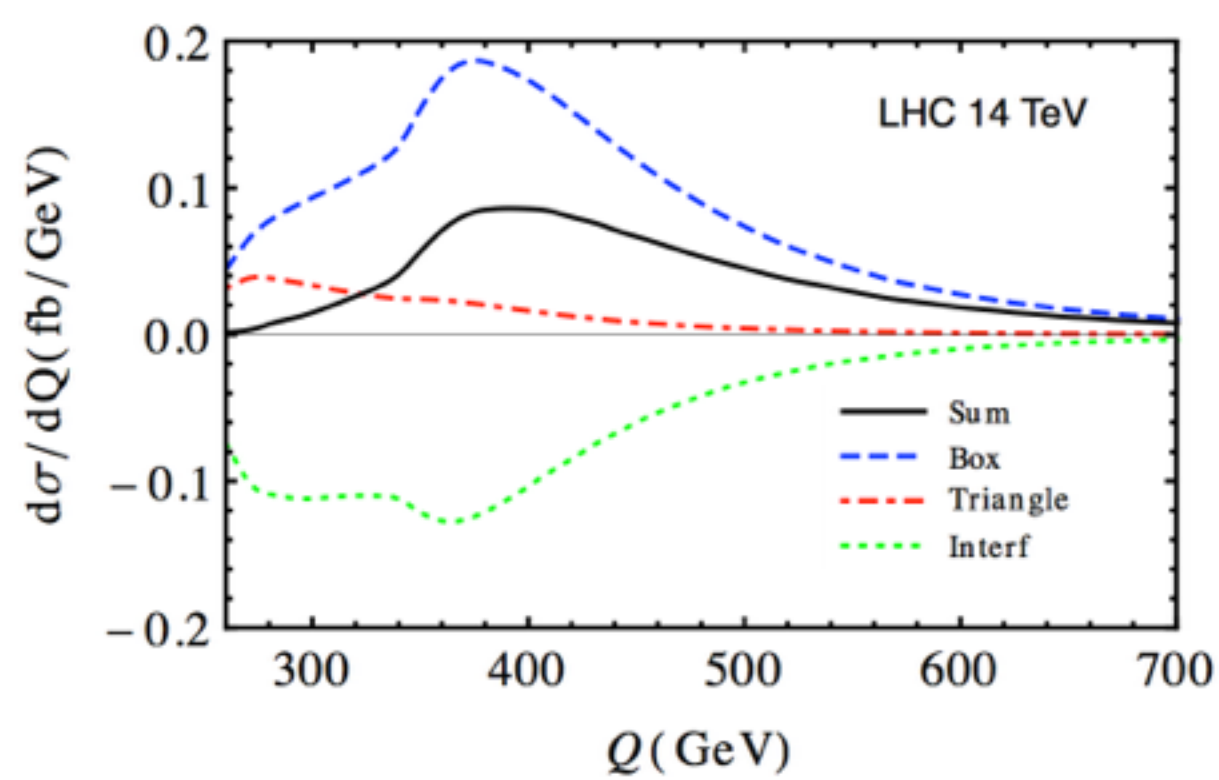
Higgs Self Coupling



~ 40 fb very challenging



~ 0.05 fb impossible



ATLAS

$\gamma\gamma bb$ (3.2 fb^{-1}): 3.9 pb,

4b (13.3 fb^{-1}, cross section times branch ratio) : 330 fb,

$$\sim 30 \times \sigma(pp \to hh)_{SM}$$

$\gamma\gamma WW^*$ (13.3 fb^{-1}, cross section times branch ratio) : 25 pb.

ATLAS Collaboration, ATLAS-CONF-2016-004; ATLAS-CONF-2016-049; ATLAS-CONF-2016-071.

CMS

$\tau\tau bb$ (12.9 fb^{-1}, cross section times branch ratio) : 508 fb.

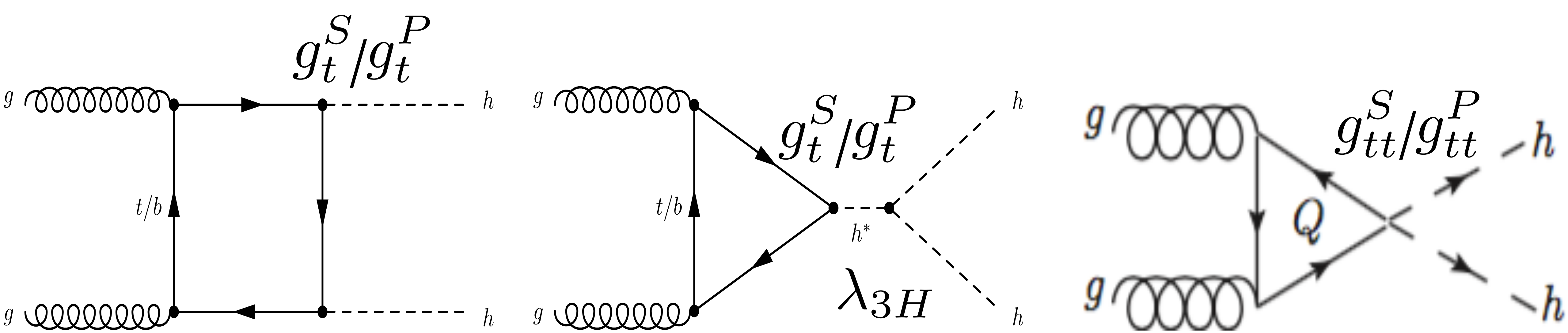
CMS Collaboration, CMS PAS HIG-16-028; CMS PAS HIG-16-029; CMS PAS HIG-16-012; CMS PAS HIG-16-013; CMS PAS HIG-16-024; CMS PAS HIG-16-026; CMS PAS HIG-16-028; CMS PAS HIG-16-029; CMS PAS HIG-16-032.

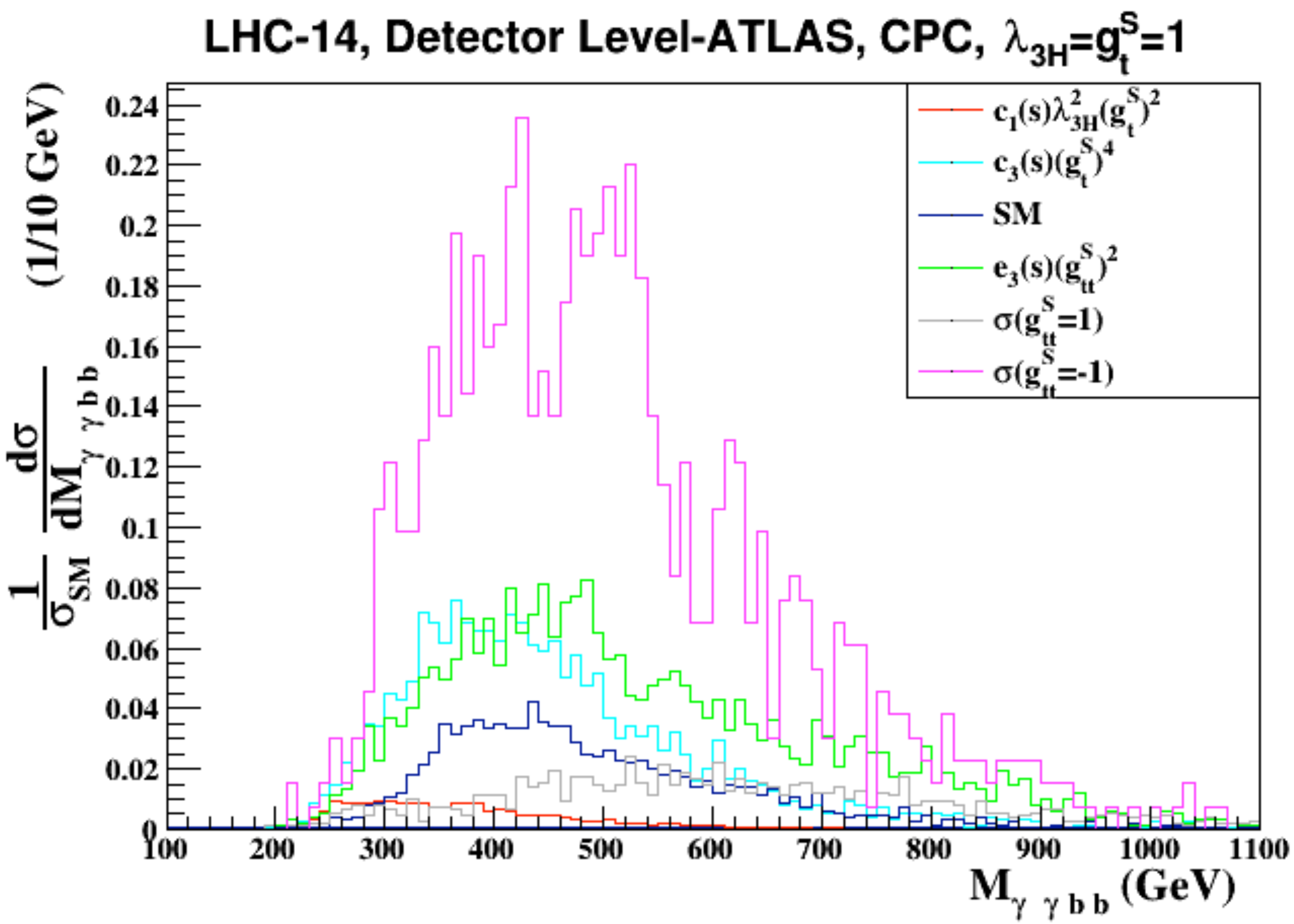
Formalism

Lagrangian involved for the Higgs Pair Production

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

In the SM, $\lambda_{3H}=g^S_t=1$, $g^P_t=0$ and $g^{S,P}_{tt}=0$.





Triangle : decrease as energy increase

Box : remain same as energy increase

Quartic : increase as energy increase

T. Plehn, M. Spira and P. M. Zerwas, Nucl. Phys. B 479, 46 (1996) [Erratum-ibid. B 531, 655 (1998)] [hep-ph/9603205]

HH cross section

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

$$+ \left| (g_t^S)^2 G_\Box^{SS} + (g_t^P)^2 G_\Box^{PP} \right|^2$$

$$\left. + \left| \left(\lambda_{3H} g_t^P D(\hat{s}) + g_{tt}^P\right) F_\triangle^P + g_t^S g_t^P F_\Box^{SP} \right|^2 + \left| g_t^S g_t^P G_\Box^{SP} \right|^2 \right\}.$$

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

and $\hat{s} = (p_1 + p_2)^2$, $\hat{t} = (p_1 - p_3)^2$, and $\hat{u} = (p_2 - p_3)^2$ with $p_1 + p_2 = p_3 + p_4$.

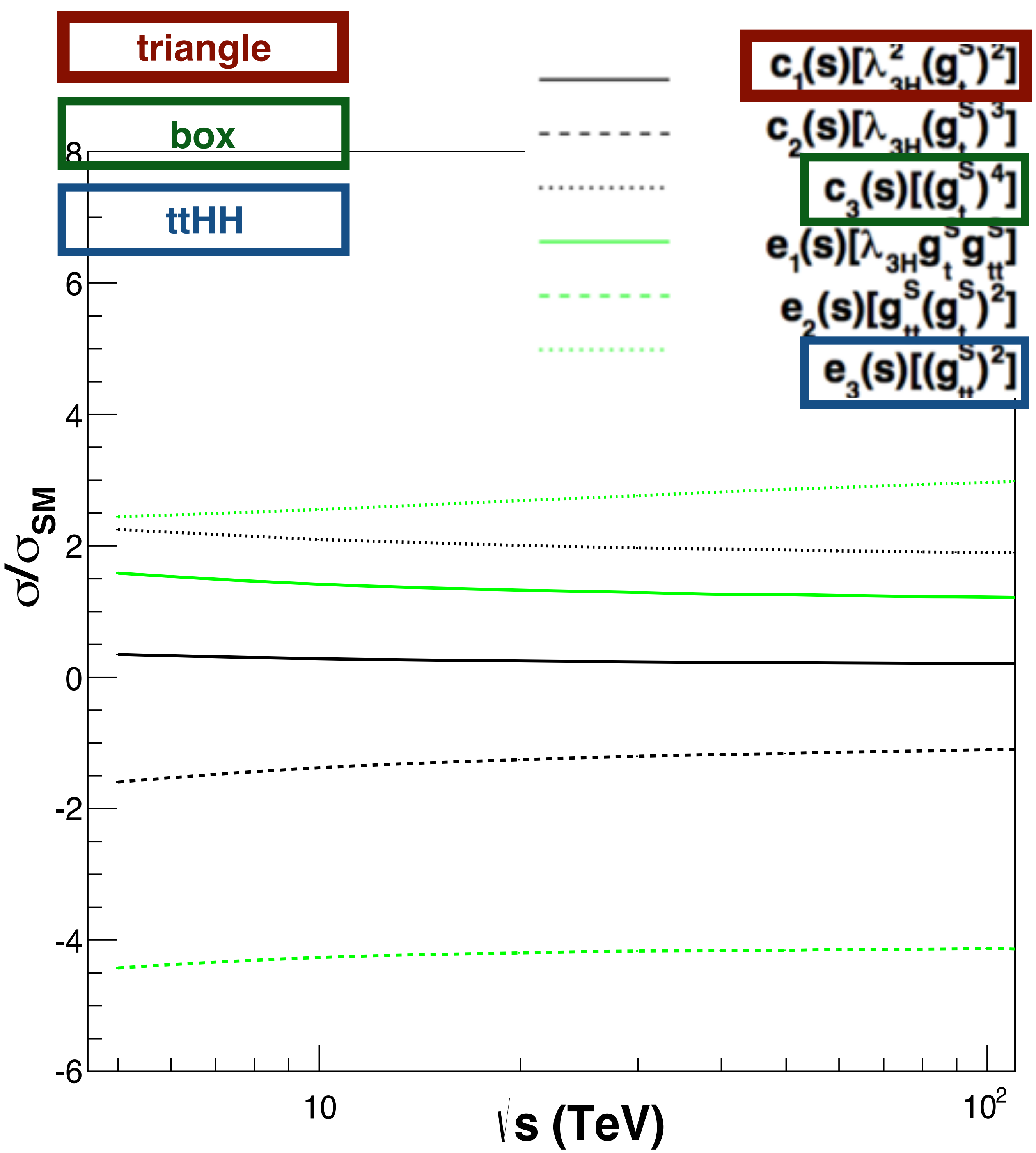
$$\frac{\sigma(gg \to HH)}{\sigma_{\rm SM}(gg \to HH)} = \lambda_{3H}^2 \left[c_1(s)(g_t^S)^2 + d_1(s)(g_t^P)^2\right] + \lambda_{3H} g_t^S \left[c_2(s)(g_t^S)^2 + d_2(s)(g_t^P)^2\right]$$

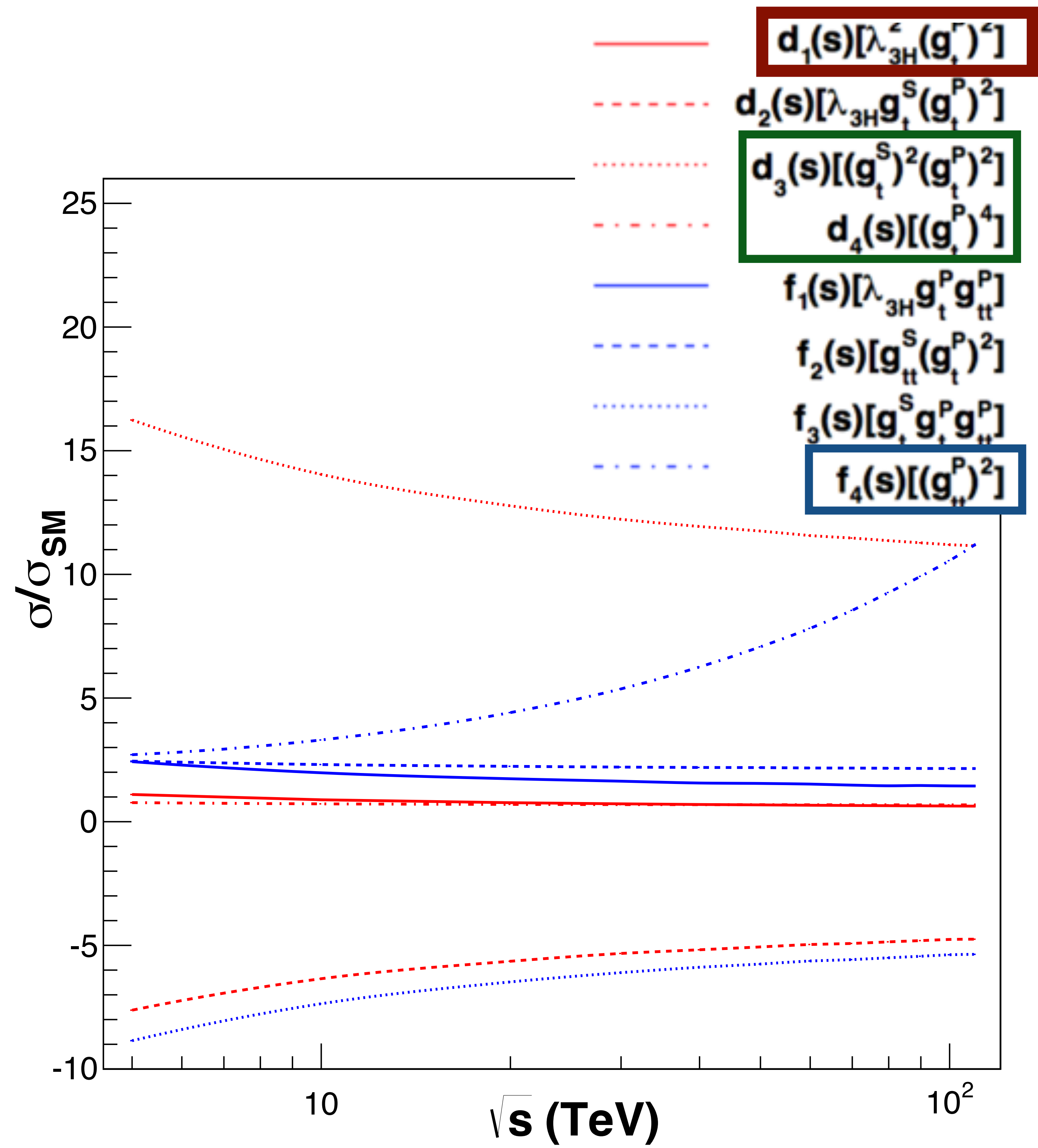
$$+ \left[c_3(s)(g_t^S)^4 + d_3(s)(g_t^S)^2(g_t^P)^2 + d_4(s)(g_t^P)^4\right]$$

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

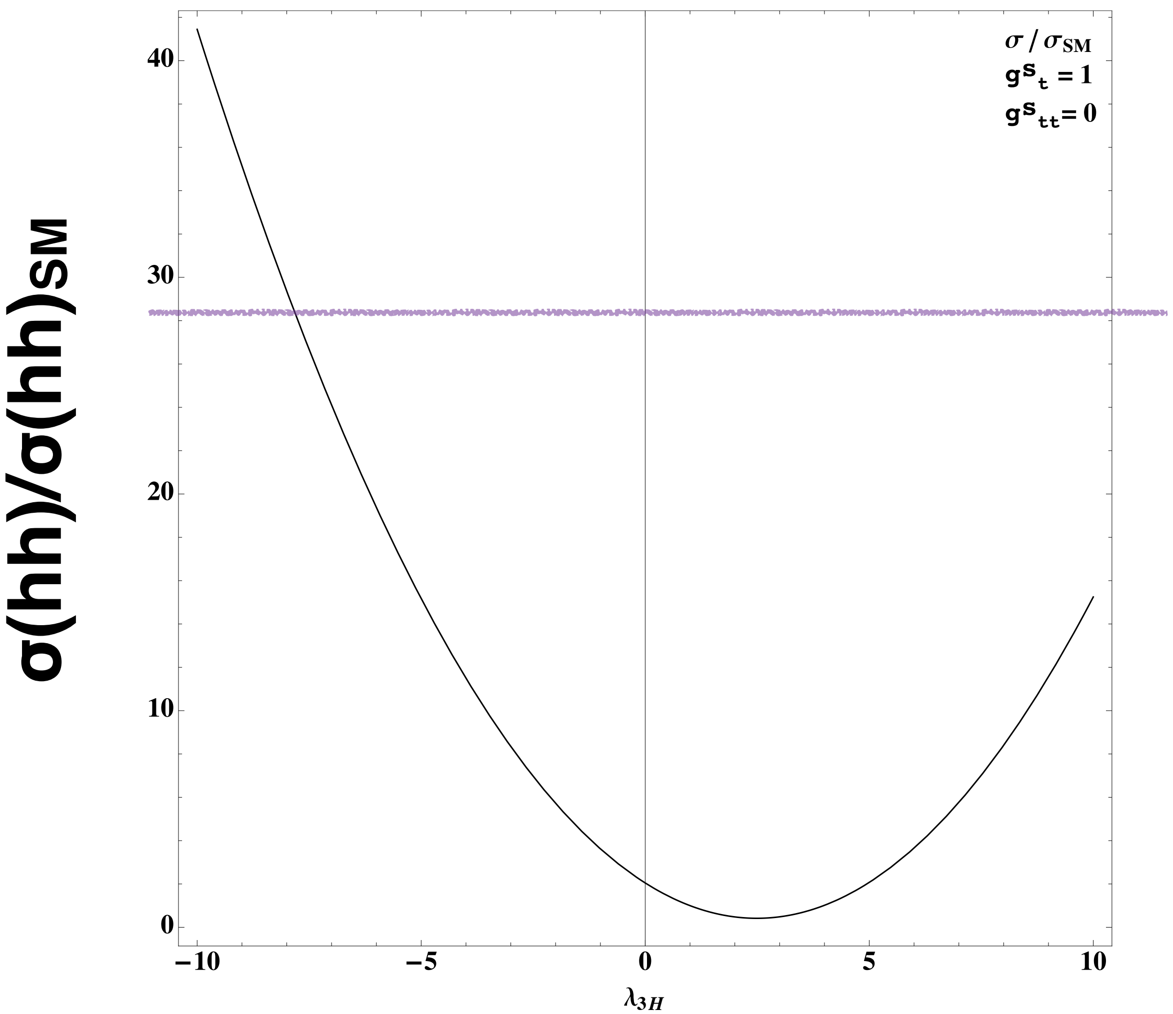
$$+ \left[e_3(s)(g_{tt}^S)^2 + f_3(s) g_t^S g_t^P g_{tt}^P + f_4(s)(g_{tt}^P)^2\right]$$

Cross sections vs Energies



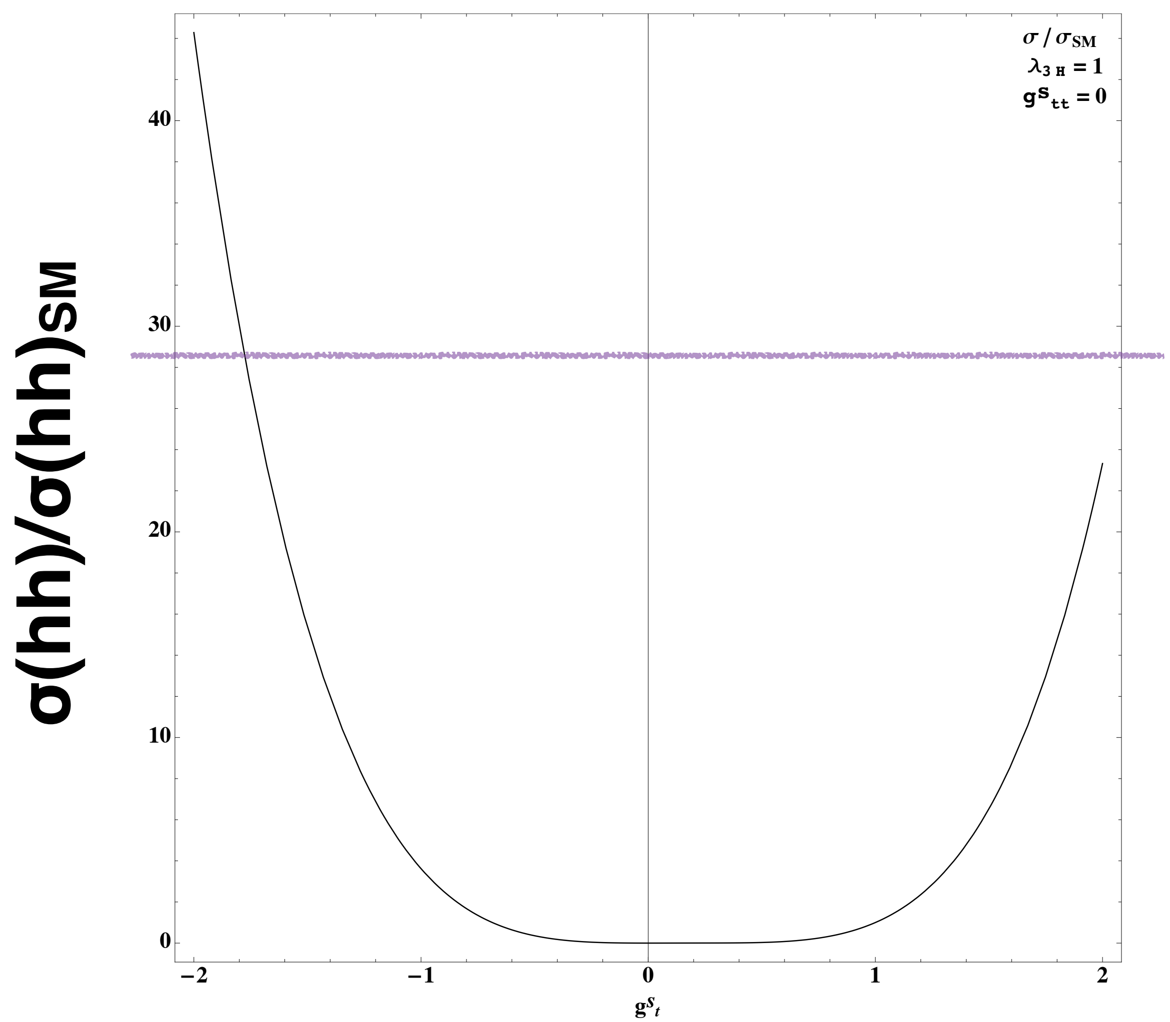


If Top Yukawa coupling = SM value



HHH Coupling

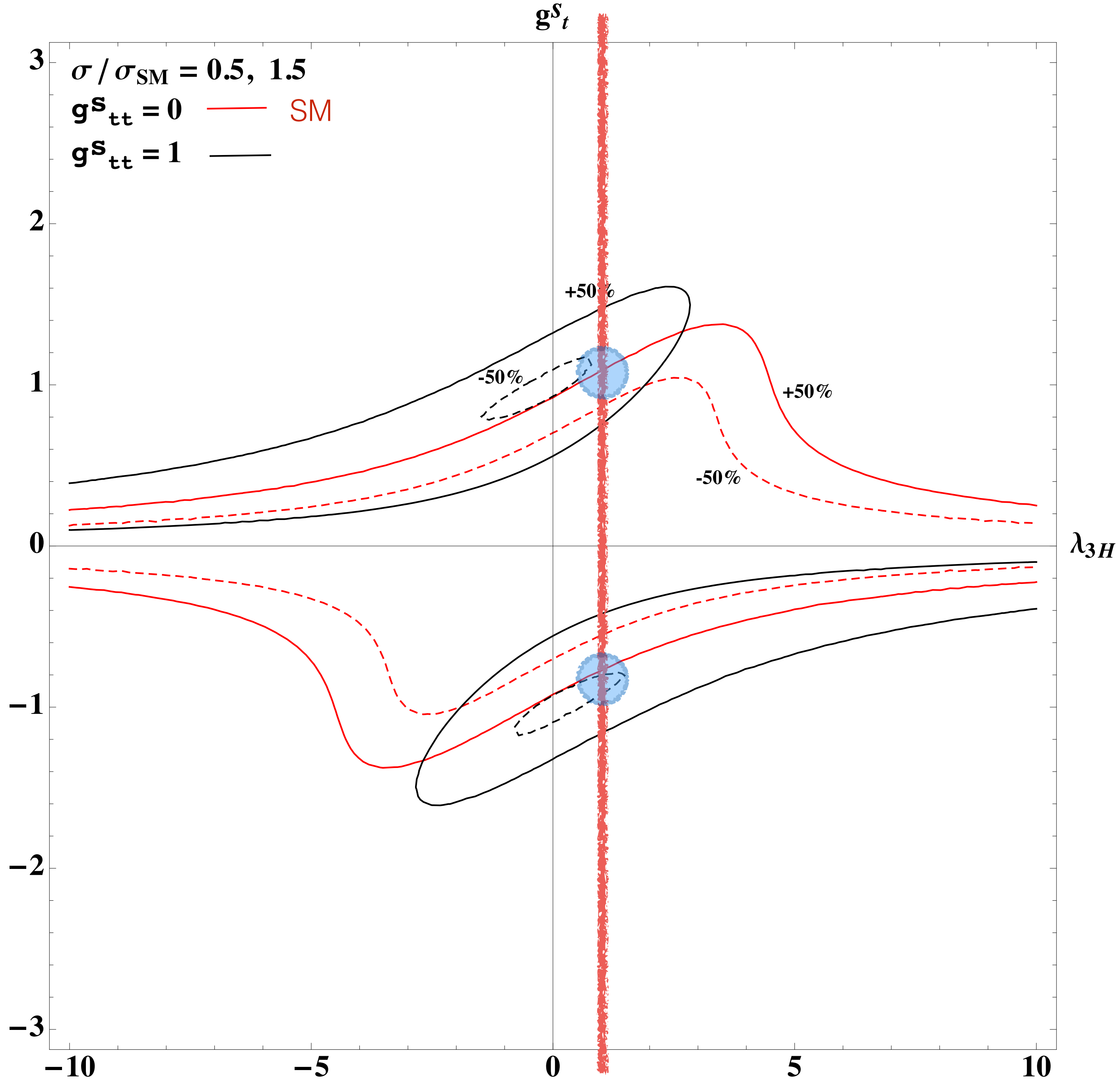
If Higgs Self Coupling = SM value



Top Yukawa Coupling

$$\frac{\sigma(gg \to HH)}{\sigma_{\rm SM}(gg \to HH)} = \lambda_{3H}^2 \left[c_1(s)(g_t^S)^2 + d_1(s)(g_t^P)^2\right] + \lambda_{3H} g_t^S \left[c_2(s)(g_t^S)^2 + d_2(s)(g_t^P)^2\right]$$
$$+ \left[c_3(s)(g_t^S)^4 + d_3(s)(g_t^S)^2(g_t^P)^2 + d_4(s)(g_t^P)^4\right]$$

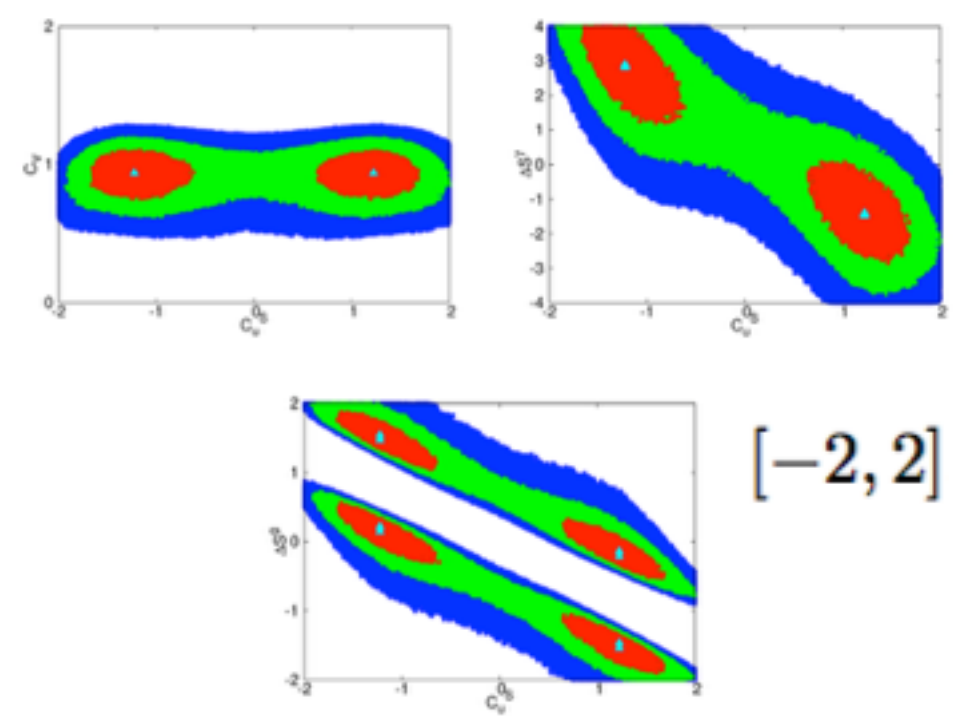
Top Yukawa Coupling



$\sqrt{s}$ (TeV)	$c_1(s)$ $[\lambda_{3H}^2(g_t^S)^2]$	$c_2(s)$ $[\lambda_{3H}(g_t^S)^3]$	$c_3(s)$ $[(g_t^S)^4]$
8	0.300	−1.439	2.139
14	0.263	−1.310	2.047
33	0.232	−1.193	1.961
100	0.208	−1.108	1.900

HHH Coupling

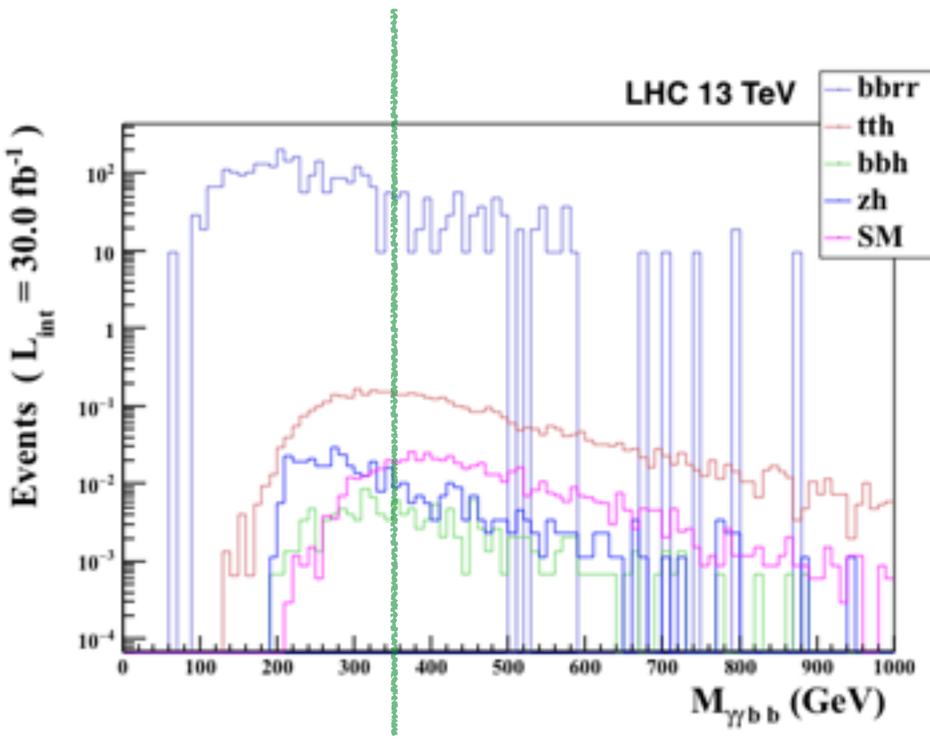
varying C_u^S, C_d^S, C_l^S, C_v, ΔS^γ and ΔS^g

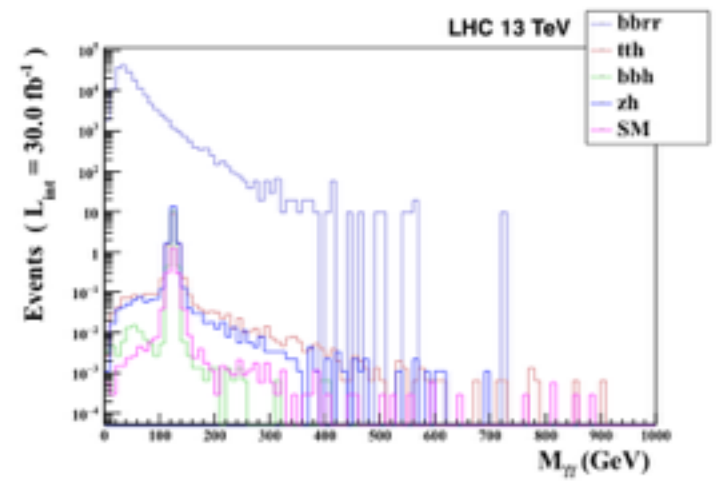


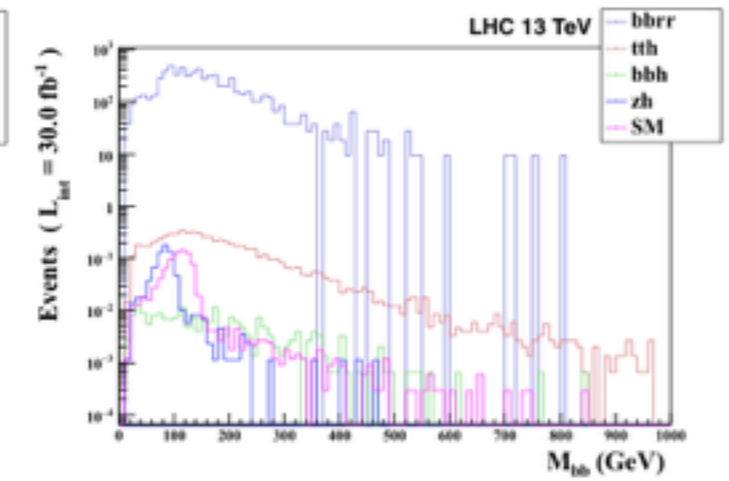
$[-2, 2]$

C.T. Lu, JC, K. Cheung, J. S. Lee, JHEP 1508 (2015) 133 [arXiv:1505.00957 [hep-ph]].

LHC 13 TeV
BG : b b r r, j j r r, t t h, b b h, z h

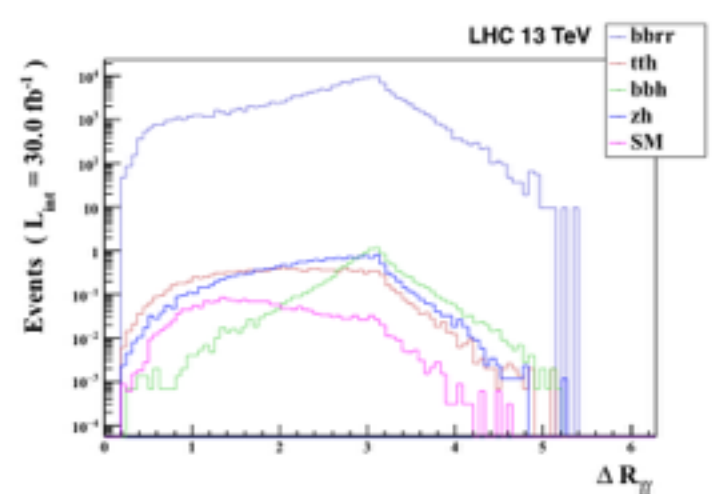


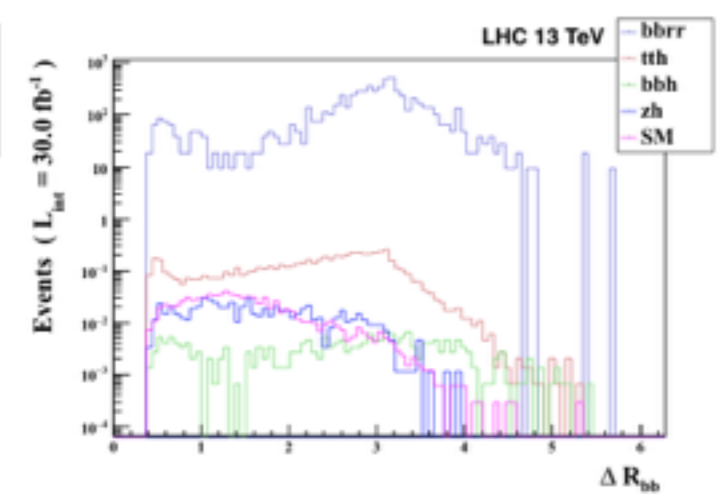




V. Barger, L. L. Everett, C. B. Jackson, G. Shaughnessy, arXiv : 1311.2931 [hep-ph]

$$p_T(b\bar{b}), \quad p_T(\gamma\gamma) \; > \; 100 \text{ GeV},$$
$$M_{b\bar{b}\gamma\gamma} \; > \; 350 \text{ GeV}.$$



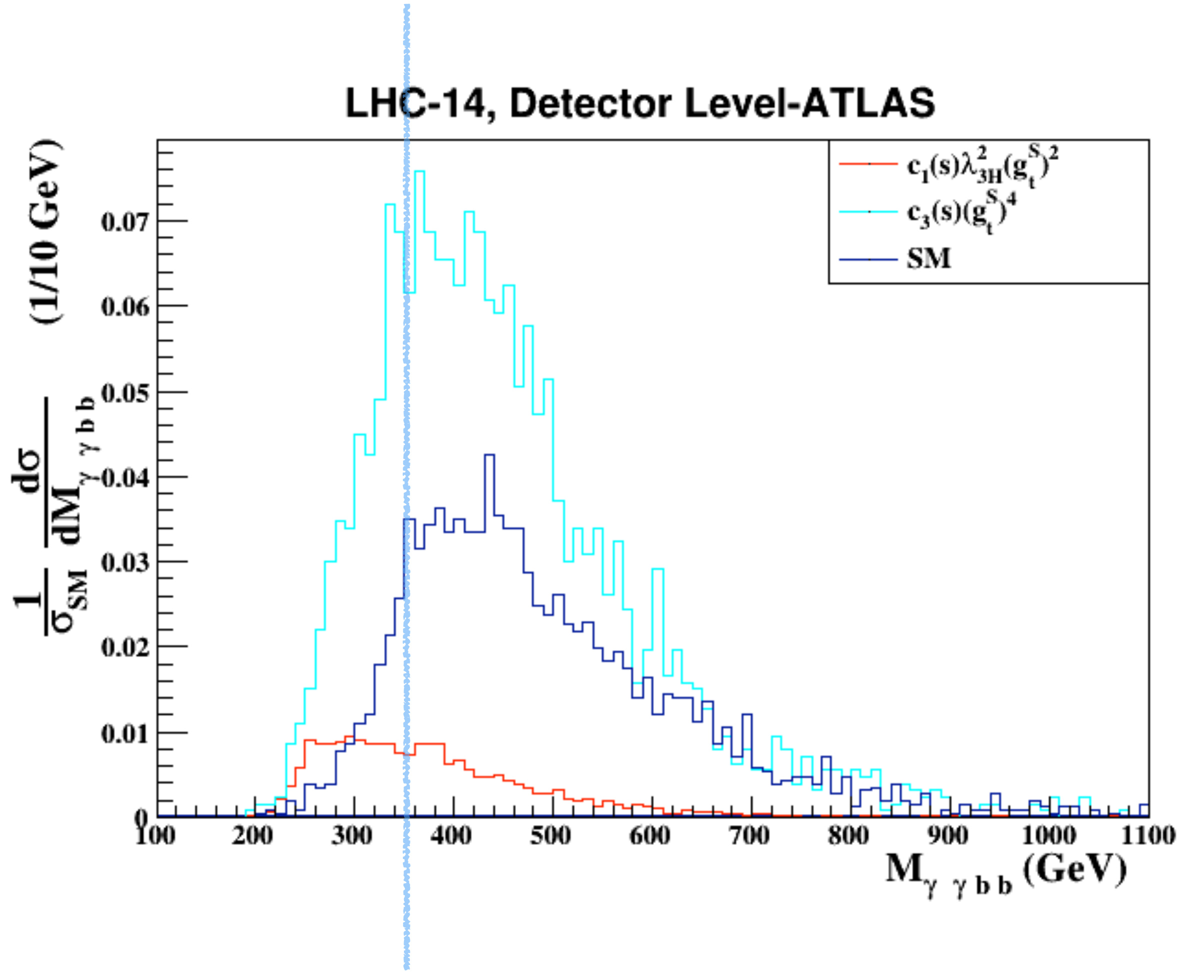


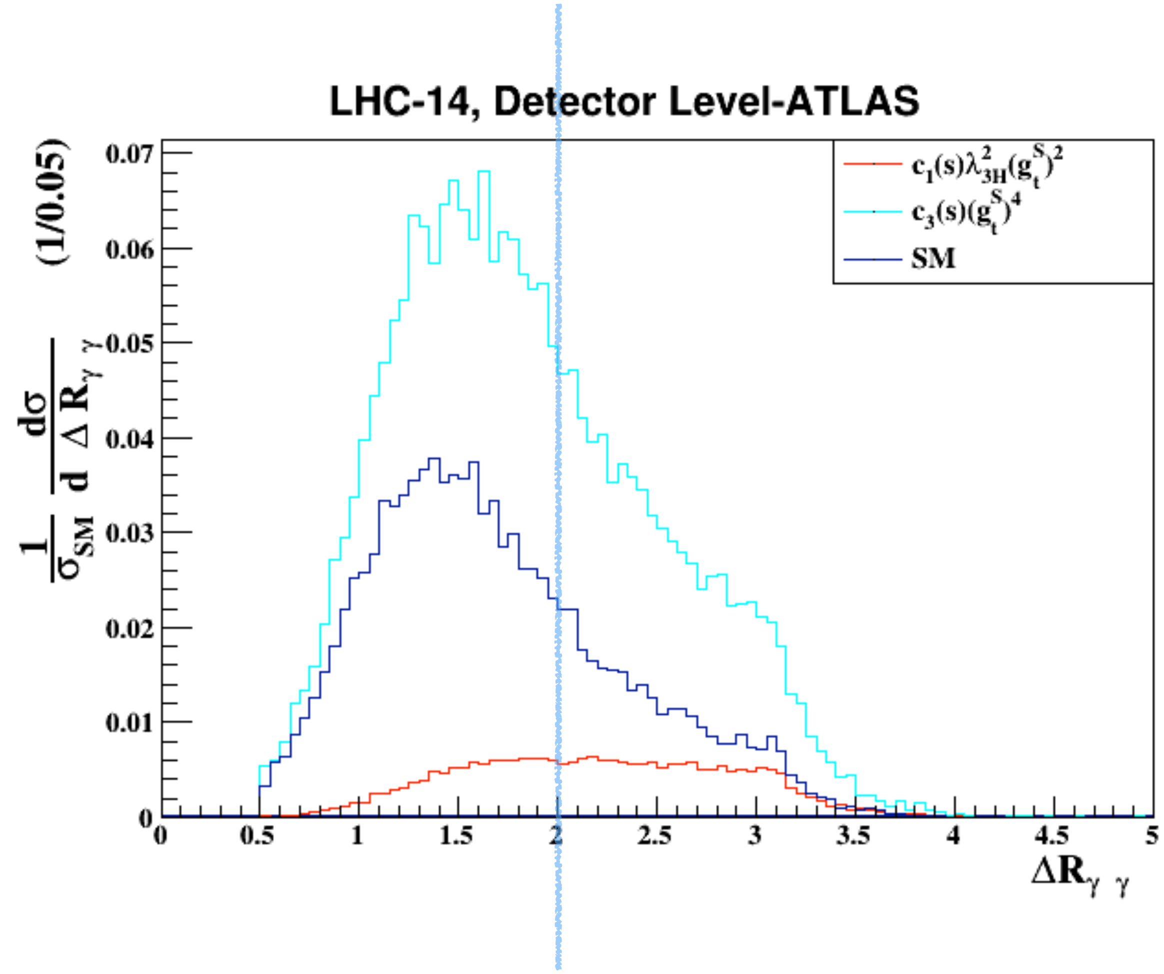
Cuts in ATLAS Collaboration, ATLAS-CONF-2016-004

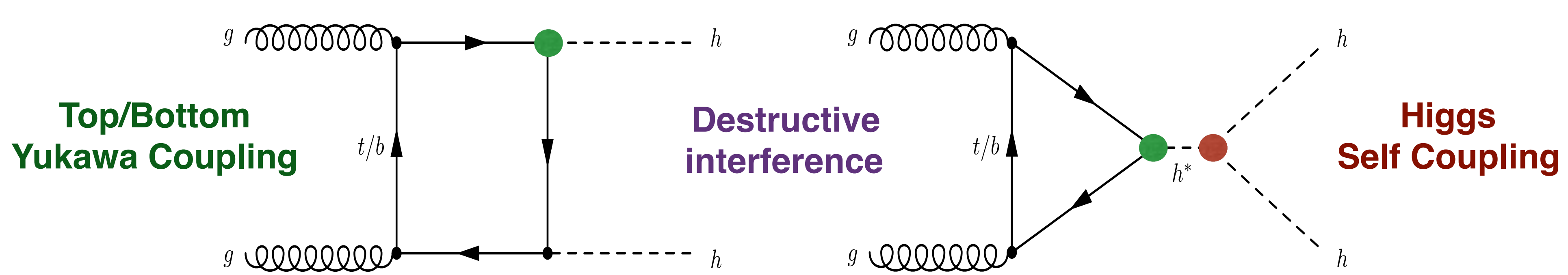
N(γ) >= 2, N(b) = 2, PT(j) > 25GeV, PT(b1,b2) > 55,35GeV,

105GeV < M(γγ) < 160GeV, 95GeV < M(bb) < 135GeV.

$$\frac{\sigma(gg\to HH)}{\sigma_{\rm SM}(gg\to HH)} = \lambda_{3H}^2\left[c_1(s)(g_t^S)^2 + d_1(s)(g_t^P)^2\right] + \lambda_{3H}g_t^S\left[c_2(s)(g_t^S)^2 + d_2(s)(g_t^P)^2\right] + \left[c_3(s)(g_t^S)^4 + d_3(s)(g_t^S)^2(g_t^P)^2 + d_4(s)(g_t^P)^4\right]$$







C.T. Lu, JC, K. Cheung, J. S. Lee, JHEP 1508 (2015) 133 [arXiv:1505.00957 [hep-ph]].

What we do in this work,…

- We are trying to disentangle Higgs trilinear coupling from top/bottom Yukawa coupling and other BSM coupling in Higgs boson pair production.

- Map out the sensitivity regions of parameter space that can be probed at the LHC.

- Working assumption : BG can be estimated & extracted from data.

- Considered :
  1. SM BG
  (can be estimated with uncertainties less than the NNLO corrections.can be estimated with uncertainties less than the NNLO corrections.)

  2. the NLO corrections
  (the NLO and NNLO corrections can be as large as 100% with uncertainty of order 10–20%.)

- We therefore adopt an approach that the signal cross sections (after background subtraction) are measured with uncertainties of order 25–50%.

We consider the SM NLO HH cross section: $\sigma_{SM}(pp \to HH) \simeq 34 fb$

used modified MADGRAPH implementation
PDF : CTEQ6L1, renormalization/factorization scales μ = M_H
|cross sections| decrease by about 20 % if μ = M_{HH}

p_T and η dependent b-tagging efficiency

τ tagging efficiency as 0.5

mis-tagging $P_{j \to \tau} = 0.01$

$$p_{T_\gamma} > 10\,\text{GeV}, \quad p_{T_b} > 10\,\text{GeV}, \quad |\eta_\gamma| < 2.5, \quad |\eta_b| < 2.5, \quad \Delta R_{\gamma\gamma} > 0.4, \quad \Delta R_{bb} > 0.4,$$
$$|M_H - M_{\gamma\gamma}| < 15\text{ GeV}, \quad |M_H - M_{bb}| < 25\text{ GeV}, \quad |M_H - M_{\tau\tau}| < 25\text{ GeV}.$$

Cuts	SM-14 ($\gamma\gamma b\bar{b}$)	SM-100 ($\gamma\gamma b\bar{b}$) Cross Section (fb)	SM-14 ($\tau^+\tau^- b\bar{b}$)
No cuts	8.92×10^{-2}	3.73	2.41
Basic Cuts	5.1×10^{-3}	2.05×10^{-1}	3.53×10^{-3}
$\Delta R_{\gamma\gamma/\tau^+\tau^-} > 2$	1.34×10^{-3}	4.34×10^{-2}	6.43×10^{-4}
$\Delta R_{\gamma\gamma/\tau^+\tau^-} < 2$	3.76×10^{-3}	1.61×10^{-1}	2.89×10^{-3}
$\Delta R_{bb} > 2$	7.61×10^{-4}	2.23×10^{-2}	4.82×10^{-4}
$\Delta R_{bb} < 2$	4.34×10^{-3}	1.83×10^{-1}	3.05×10^{-3}
$\Delta R_{bb} > 2$ & $\Delta R_{\gamma\gamma/\tau^+\tau^-} > 2$	4.79×10^{-4}	1.40×10^{-2}	3.21×10^{-4}
$\Delta R_{bb} < 2$ & $\Delta R_{\gamma\gamma/\tau^+\tau^-} < 2$	3.48×10^{-3}	1.53×10^{-1}	2.73×10^{-3}

14 TeV with 3000 fb^{-1} luminosity

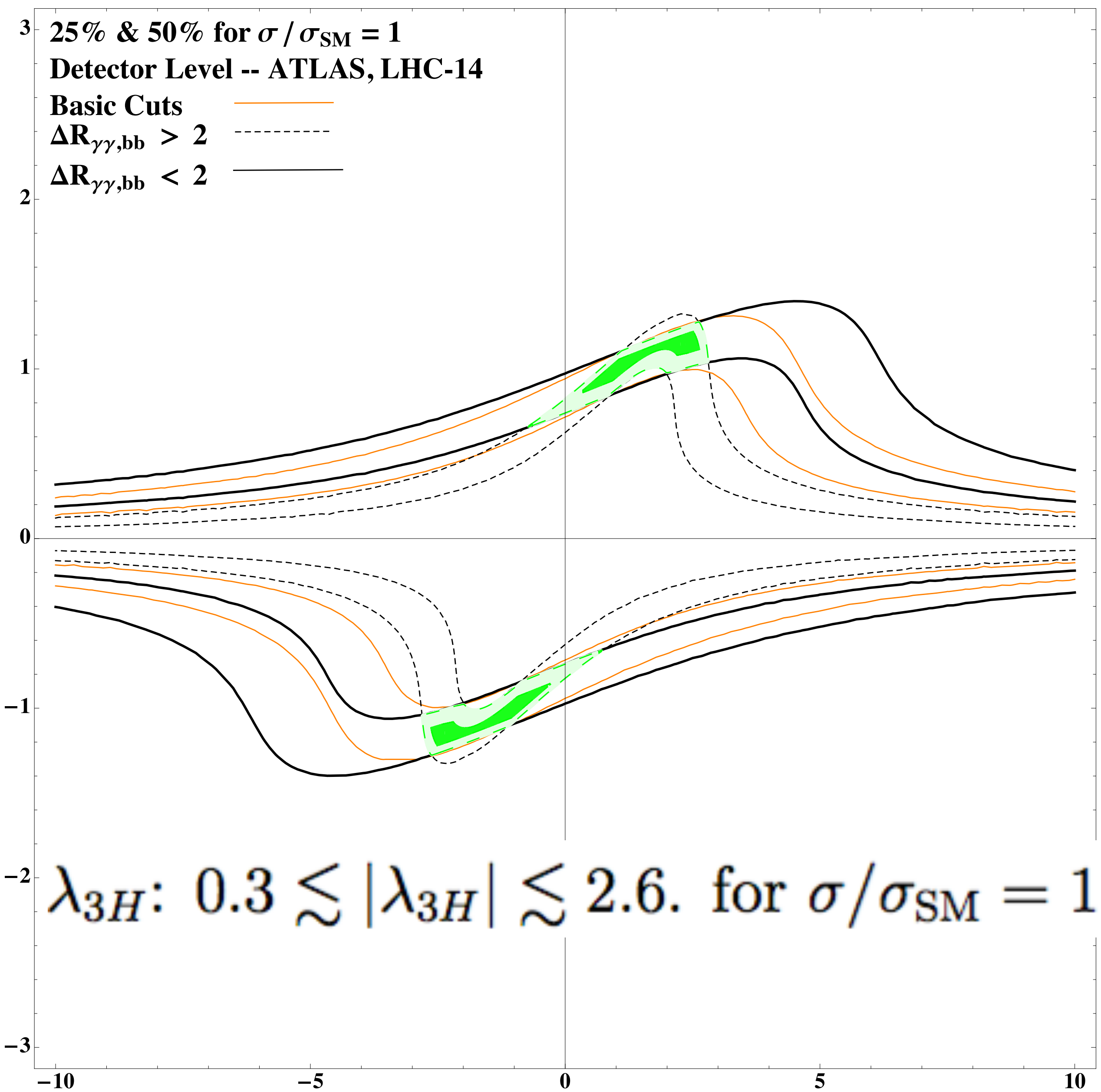
It would be challenging to measure this size of cross section only in the bbγγ mode and one may need to combine the measurements in different Higgs-decay channels.

$\sqrt{s}$: 14 TeV Cuts	$c_1(s)$ $[\lambda_{3H}^2(g_t^S)^2]$	$c_2(s)$ $[\lambda_{3H}(g_t^S)^3]$	$c_3(s)$ $[(g_t^S)^4]$	$d_1(s)$ $[\lambda_{3H}^2(g_t^P)^2]$	$d_2(s)$ $[\lambda_{3H}g_t^S(g_t^P)^2]$	$d_3(s)$ $[(g_t^S)^2(g_t^P)^2]$	$d_4(s)$ $[(g_t^P)^4]$
No cuts	0.263	−1.310	2.047	0.820	−5.961	13.348	0.707
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
$\Delta R_{bb} > 2$ & $\Delta R_{\gamma\gamma} > 2$	0.895	-3.150	3.255	2.613	-17.210	30.456	1.278
$\Delta R_{bb} < 2$ & $\Delta R_{\gamma\gamma} < 2$	0.121	-0.785	1.664	0.319	-2.630	8.257	0.563

$\sqrt{s}$: 14TeV Cuts	$e_1(s)$ $[\lambda_{3H}g_t^S g_{tt}^S]$	$e_2(s)$ $[g_{tt}^S(g_t^S)^2]$	$e_3(s)$ $[(g_{tt}^S)^2]$	$f_1(s)$ $[\lambda_{3H}g_t^P g_{tt}^P]$	$f_2(s)$ $[g_{tt}^S(g_t^P)^2]$	$f_3(s)$ $[g_t^S g_t^P g_{tt}^P]$	$f_4(s)$ $[(g_{tt}^P)^2]$
No cuts	1.364	−4.224	2.617	1.848	2.269	−6.886	3.769
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
$\Delta R_{bb} > 2$ & $\Delta R_{\gamma\gamma} > 2$	3.047	-5.947	2.780	7.274	3.759	-21.142	3.547
$\Delta R_{bb} < 2$ & $\Delta R_{\gamma\gamma} < 2$	1.238	-3.758	2.664	1.095	2.211	-2.716	3.500

$$\frac{\sigma(gg \to HH)}{\sigma_{\rm SM}(gg \to HH)} = \lambda_{3H}^2 \left[c_1(s)(g_t^S)^2 + d_1(s)(g_t^P)^2\right] + \lambda_{3H} g_t^S \left[c_2(s)(g_t^S)^2 + d_2(s)(g_t^P)^2\right]$$
$$+ \left[c_3(s)(g_t^S)^4 + d_3(s)(g_t^S)^2(g_t^P)^2 + d_4(s)(g_t^P)^4\right]$$

Top Yukawa Coupling



λ_{3H}: $0.3 \lesssim |\lambda_{3H}| \lesssim 2.6.$ for $\sigma/\sigma_{\rm SM} = 1$

HHH Coupling

$\sqrt{s}$: 14 TeV Cuts	$c_1(s)$ $[\lambda_{3H}^2 (g_t^S)^2]$	$c_2(s)$ $[\lambda_{3H} (g_t^S)^3]$	$c_3(s)$ $[(g_t^S)^4]$
No cuts	0.263	−1.310	2.047
Basic Cuts	0.221	-1.104	1.883
$\Delta R_{\gamma\gamma} > 2$	0.470	-1.868	2.398
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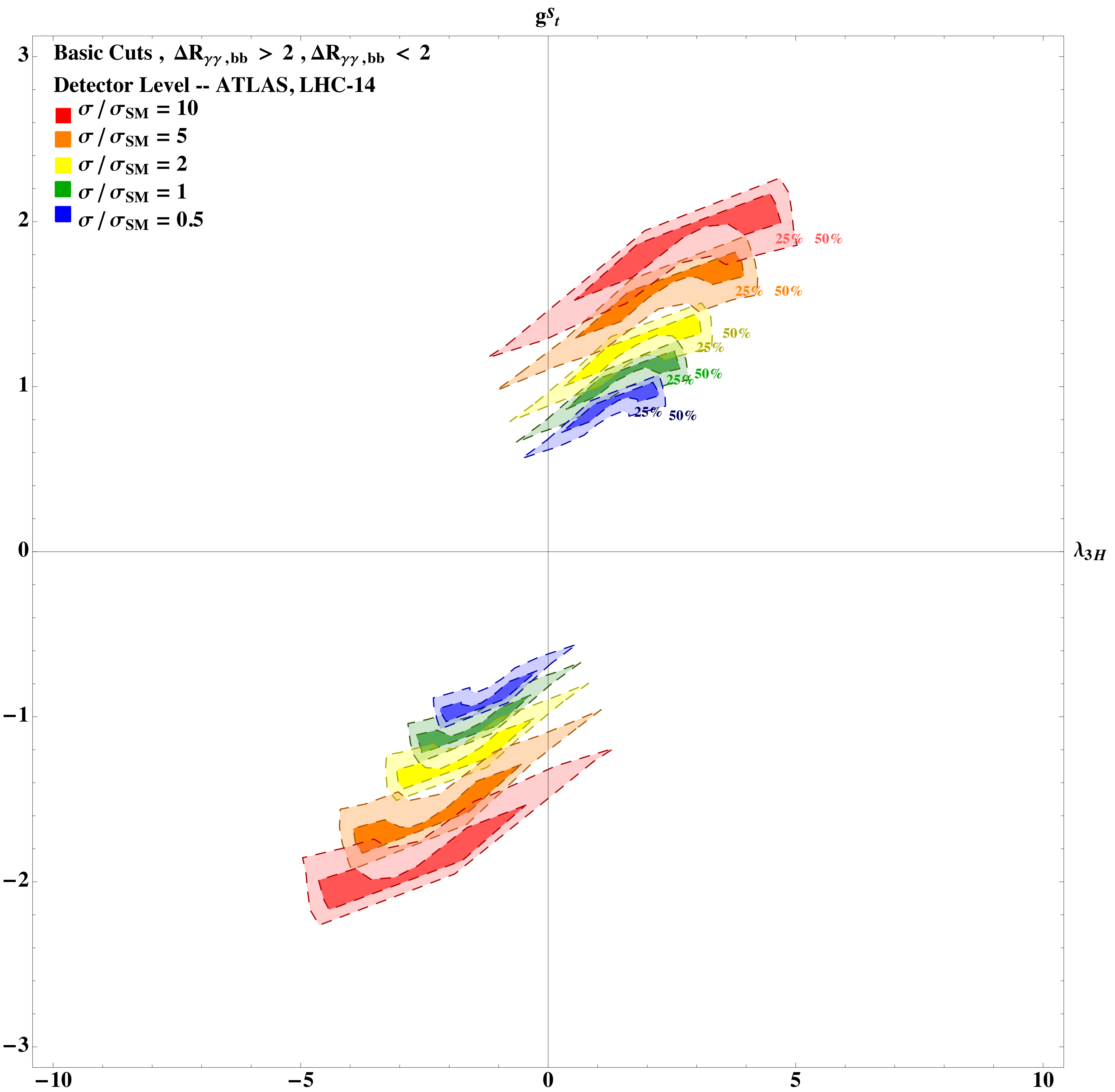
$\Delta R_{bb} > 2$	0.666	-2.512	2.847
$\Delta R_{bb} < 2$	0.143	-0.857	1.714
$\Delta R_{bb} > 2$ & $\Delta R_{\gamma\gamma} > 2$	0.895	-3.150	3.255
$\Delta R_{bb} < 2$ & $\Delta R_{\gamma\gamma} < 2$	0.121	-0.785	1.664

C.T. Lu, JC, K. Cheung, J. S. Lee, JHEP 1508 (2015) 133 [arXiv:1505.00957 [hep-ph]].

C.T. Lu, JC, K. Cheung, J. S. Lee, JHEP 1508 (2015) 133 [arXiv:1505.00957 [hep-ph]].



Higgs trilinear coupling in BSM models

L. Wu, J. M. Yang, C.P. Yuan, M. Zhang, arXiv : 1504.06932v2[hep-ph]

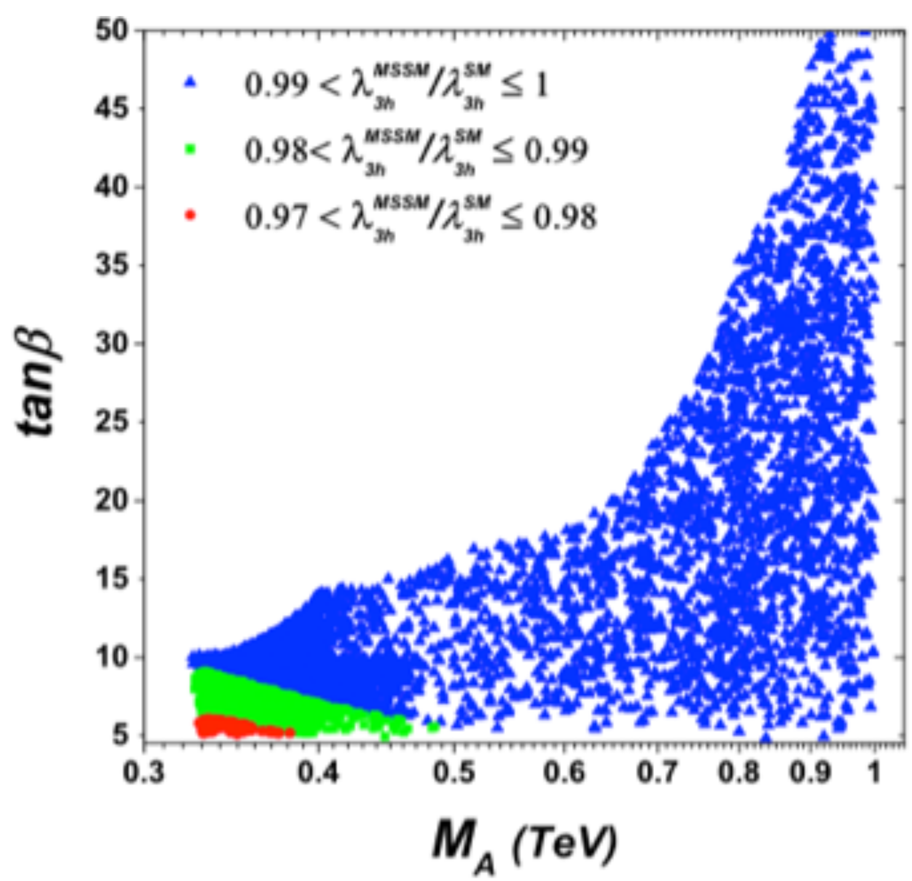
BSM Higgs self coupling

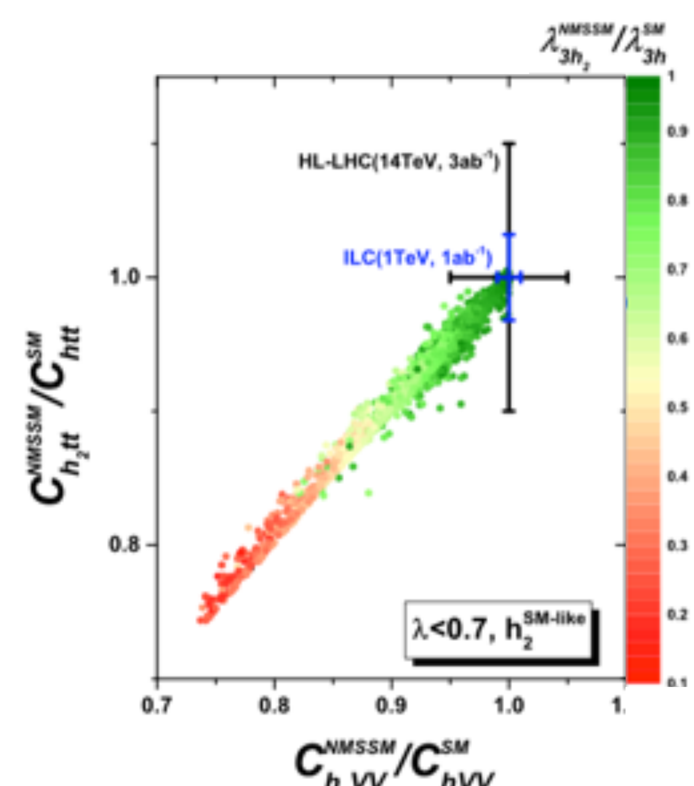
MSSM tree level Higgs Potential

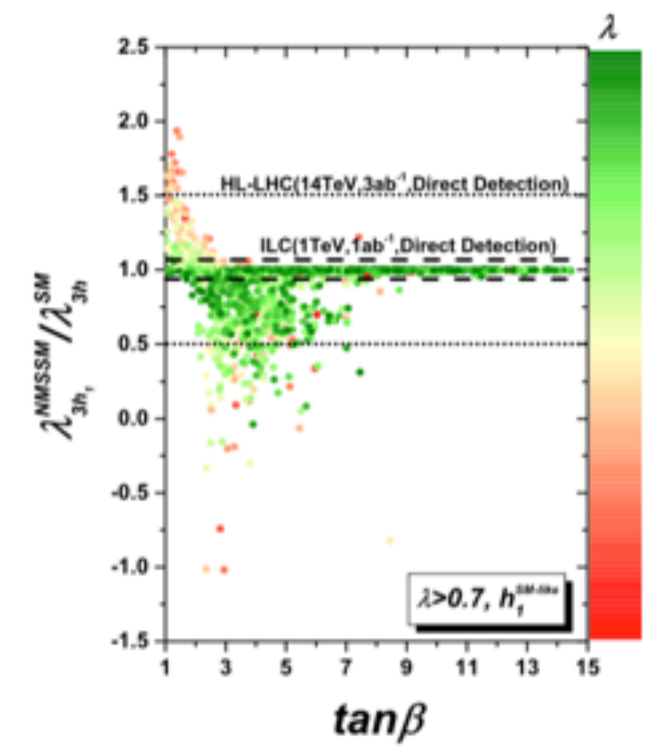
$$V^{(0,MSSM)} = m_1^2|H_u|^2 + m_2^2|H_d|^2 - B_\mu \epsilon_{\alpha\beta}(H_u^\alpha H_d^\beta + h.c.) + \frac{g^2+g'^2}{8}(|H_u|^2 - |H_d|^2)^2 + \frac{g^2}{2}|H_u^\dagger H_d|^2 ,$$

NMSSM tree level Higgs Potential

$$V^{(0,NMSSM)} = (|\lambda S|^2 + m_{H_u}^2)H_u^\dagger H_u + (|\lambda S|^2 + m_{H_d}^2)H_d^\dagger H_d + m_S^2|S|^2 + \frac{1}{8}(g_2^2 + g_1^2)(H_u^\dagger H_u - H_d^\dagger H_d)^2 + \frac{1}{2}g_2^2|H_u^\dagger H_d|^2 + |\epsilon^{\alpha\beta}\lambda H_u^\alpha H_d^\beta + \kappa S^2|^2 + [\epsilon^{\alpha\beta}\lambda A_\lambda H_u^\alpha H_d^\beta S + \frac{1}{3}\kappa A_\kappa S^3 + \text{ h.c}] ,$$







Liu Jing-Jing, Ma Wen-Gan, Li Gang, Zhang Ren-You and Hou Hong-Sheng, arXiv : 0404171[hep-ph]

BSM Higgs self coupling

Littlest Higgs Model Coleman-Weinberg potential

$$V_{CW} = \lambda_{\phi^2} f^2 \, \mathrm{tr}(\phi^\dagger \phi) + i\lambda_{h\phi h} f (h\phi^\dagger h^T - h^* \phi h^\dagger) - \mu^2 h h^\dagger + \lambda_{h^4} (h h^\dagger)^2$$

Higgs trilinear couplings :

$$g_{H^0H^0H^0} \;:\; -i\left(\frac{3m_{H^0}^2}{v} - \frac{33 m_{H^0}^2 v}{4f^2}\frac{x^2}{1-x^2}\right),$$

$$g_{H^0\bar{t}t} \;:\; -i\frac{m_t}{v}\left[1 + \frac{xv^2}{2f^2} - \frac{x^2v^2}{4f^2} - \frac{2}{3}\frac{v^2}{f^2} + \frac{v^2}{f^2}\frac{\lambda_1^2}{\lambda_1^2+\lambda_2^2}\left(1 + \frac{\lambda_1^2}{{\lambda_1}^2 + {\lambda_2}^2}\right)\right].$$

$$g_{HHTT} = -\frac{1}{f}\frac{\lambda_1^2}{\sqrt{\lambda_1^2+\lambda_2^2}} \qquad \langle h^0\rangle = v/\sqrt{2},\ \langle i\phi^0\rangle = v'$$

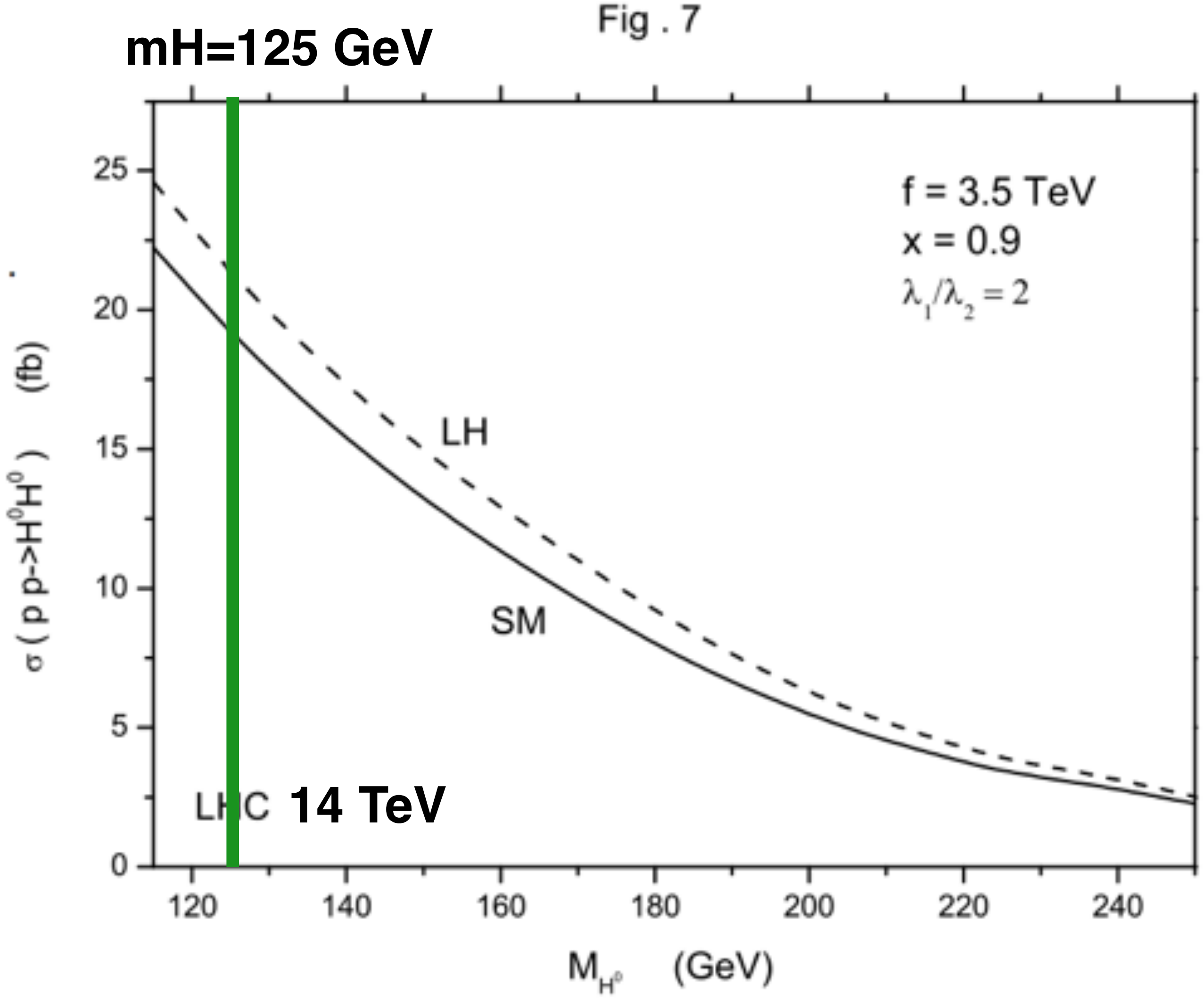
$$g_{HHtt} = \frac{m_t}{f^2}\frac{\lambda_1^2}{\lambda_1^2+\lambda_2^2-4fv'/v^2} \qquad x = 4fv'/v^2$$

EWPT , 95% exclusion for the global symmetry breaking scale :
Littlest Higgs model : f ≲ 5100 GeV,

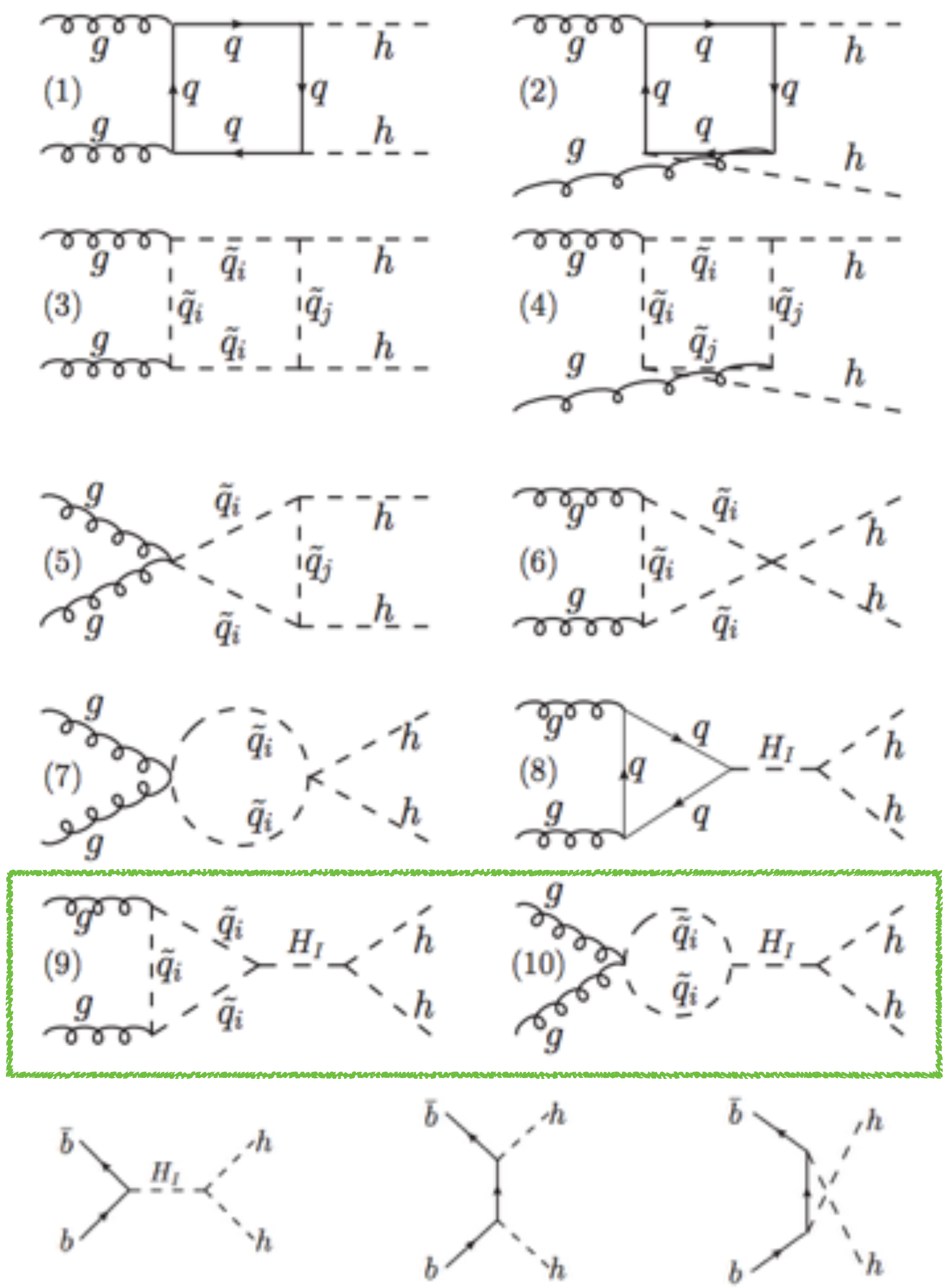
Simplest Little Higgs : f ≲ 3700 GeV,
LHT model : f ≲ 694 GeV.

Jurgen Reuter, Marco Tonini, Maikel de Vries, DESY 13-114 [arXiv:1307.5010 [hep-ph]].

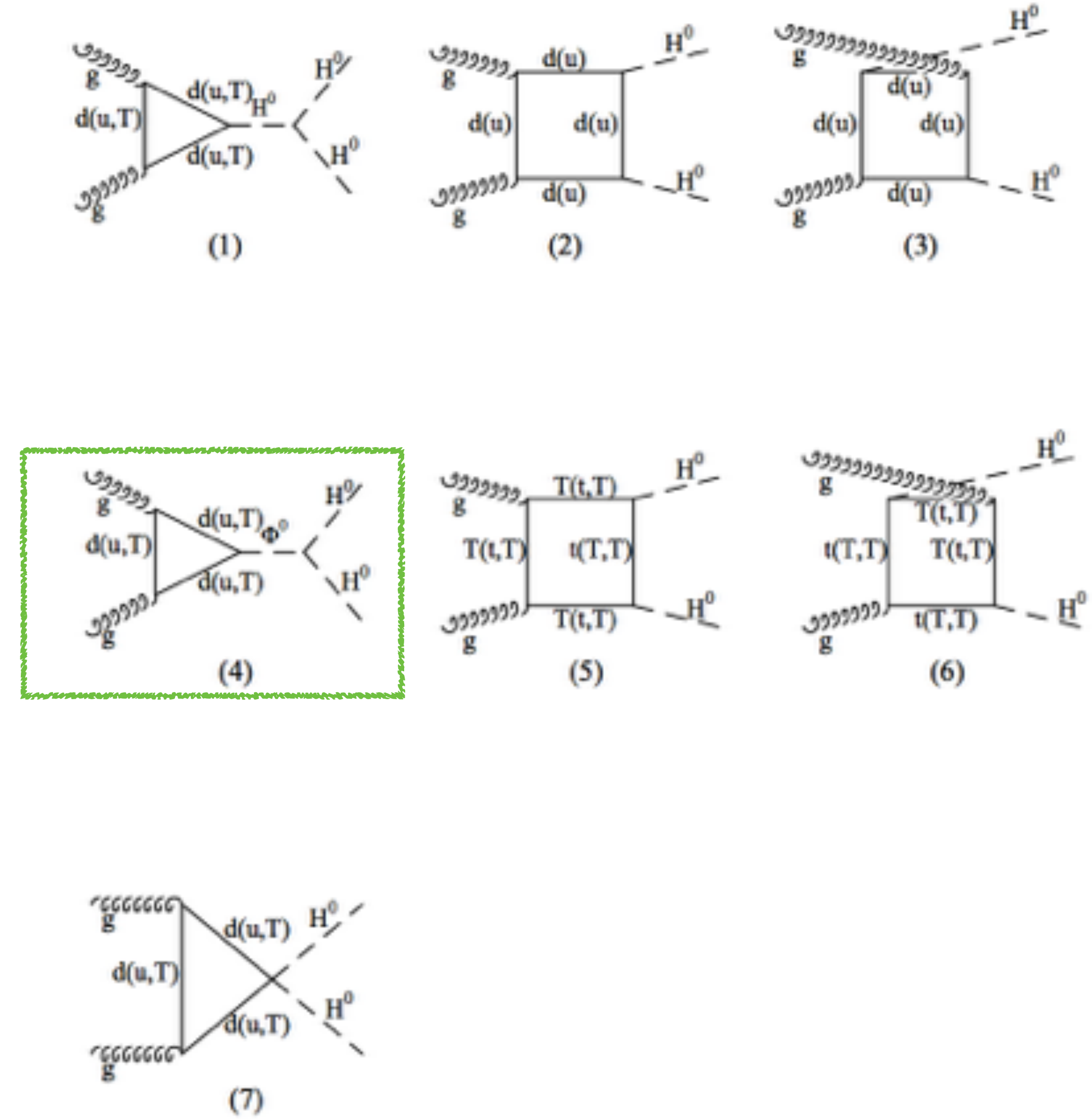
Fig . 7



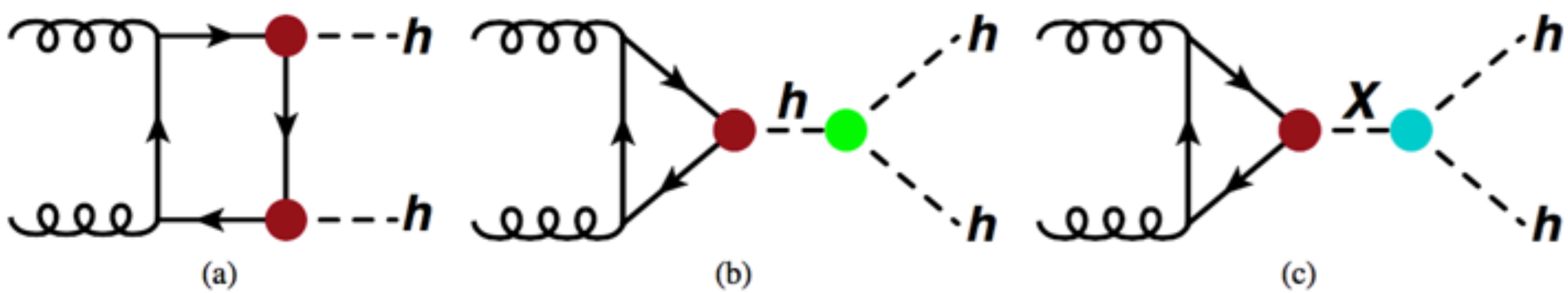
MSSM



Littlest Higgs Model



Exotic Higgs as S-channel propagator

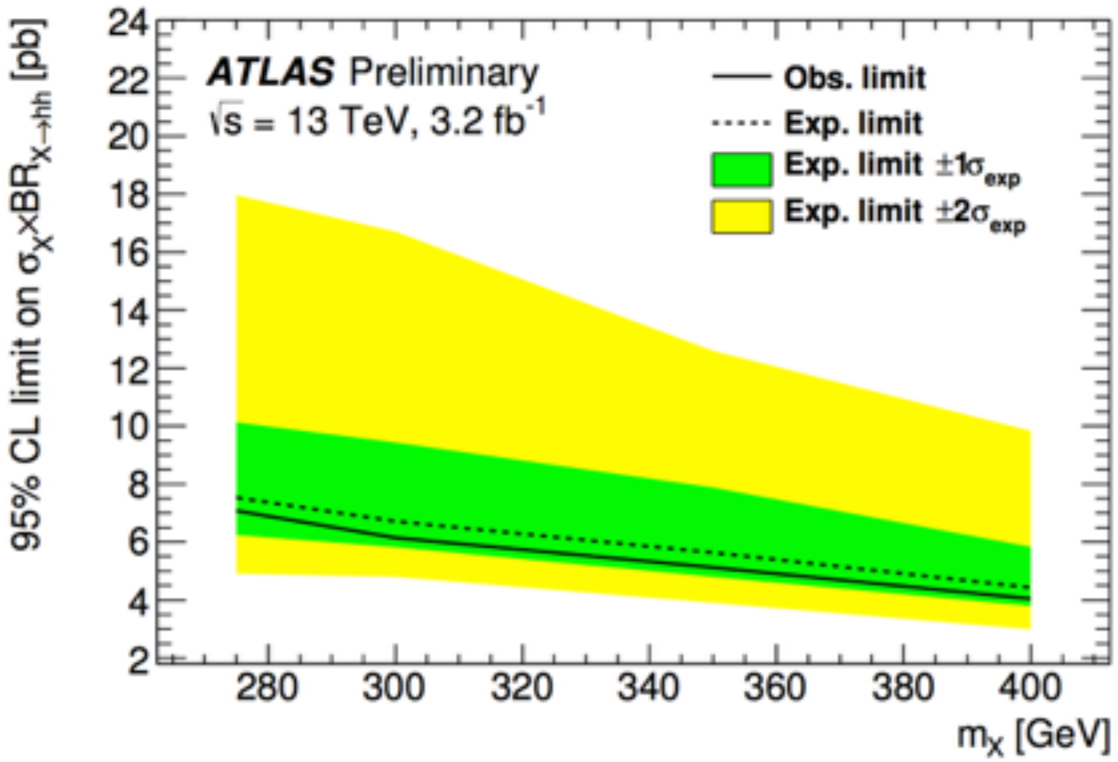


2HDM, MSSM, Littlest Higgs Models,…

ATLAS Collaboration, ATLAS-CONF-2016-004; ATLAS-CONF-2016-049; arXiv: 1606.04782 [hep-ex].

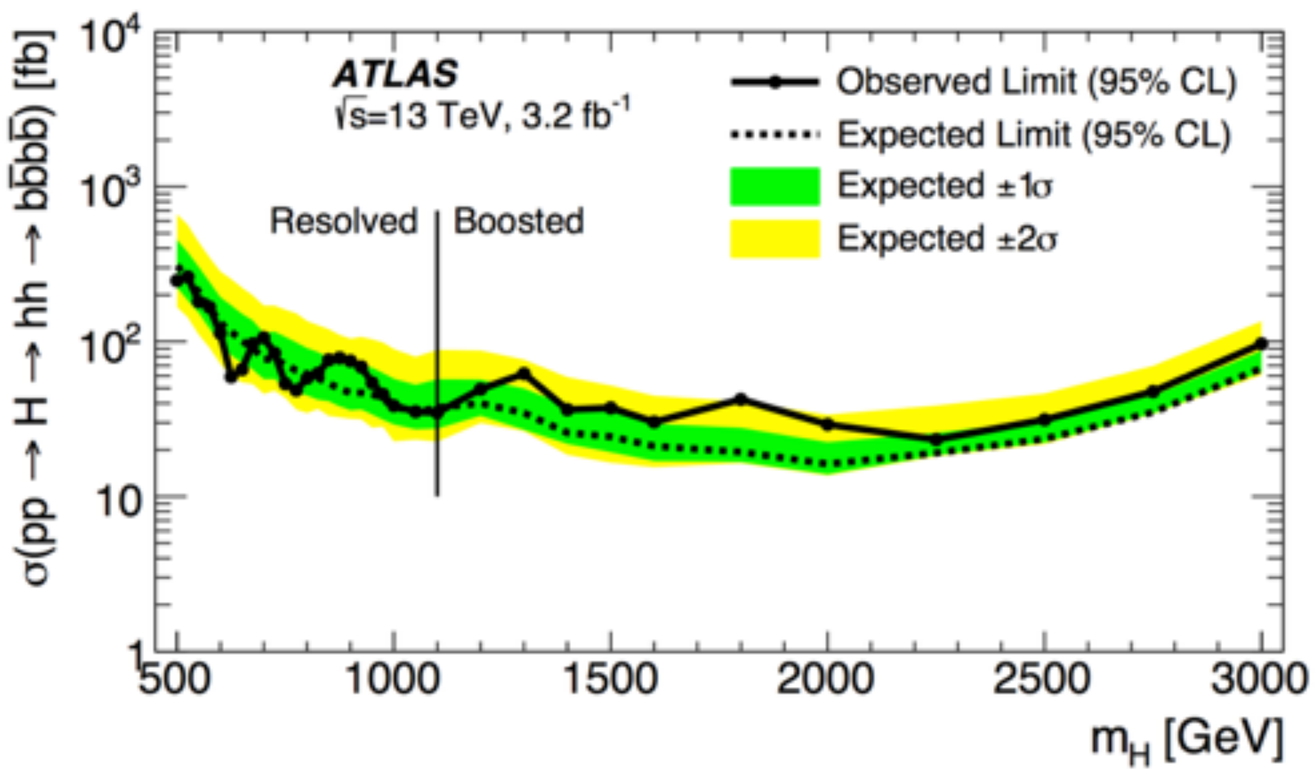
ATLAS

$\gamma\gamma bb$ (3.2 fb^{-1})



ATLAS

4b (3.2 fb^{-1})



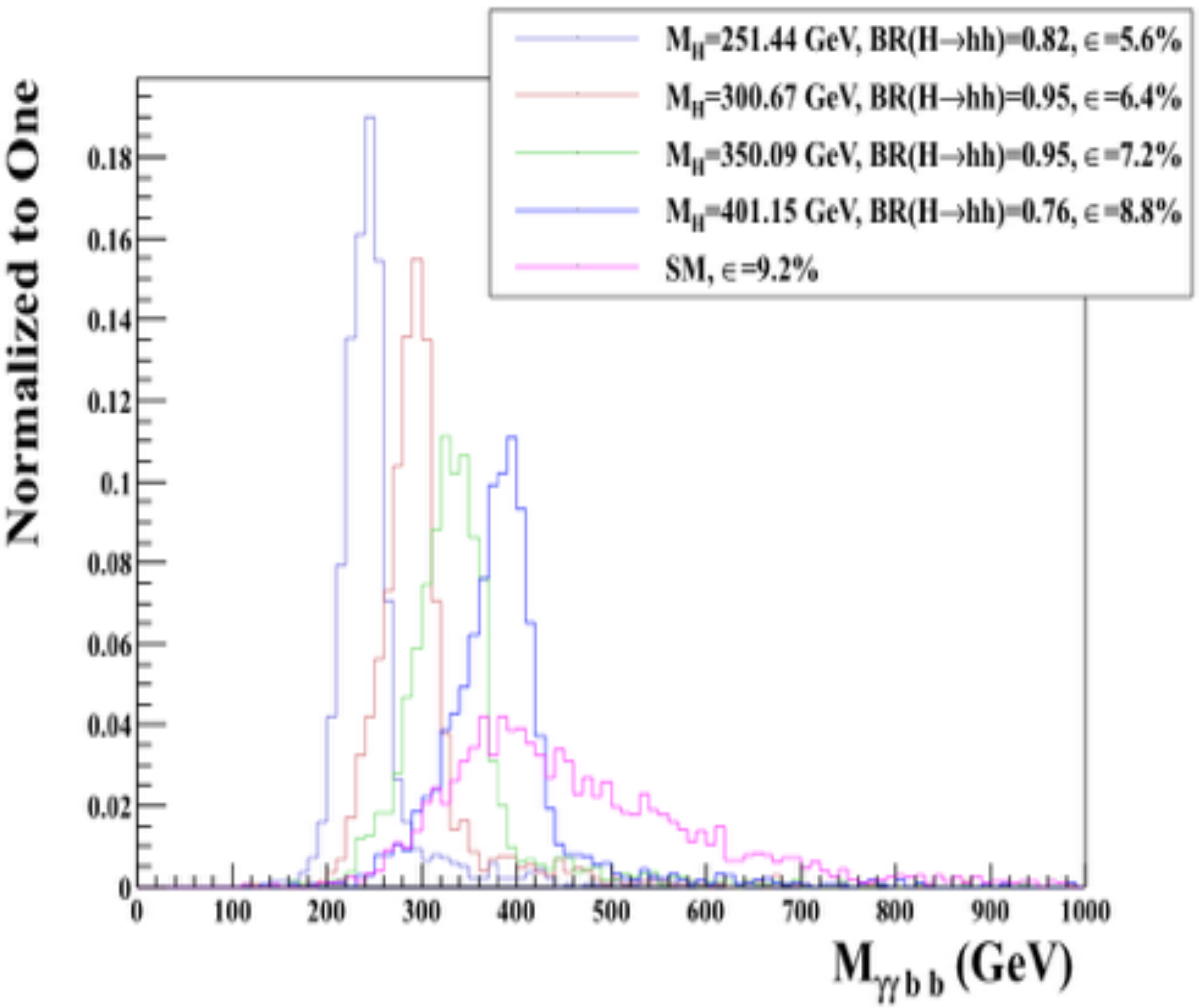
(c) Spin-0 narrow-width H boson

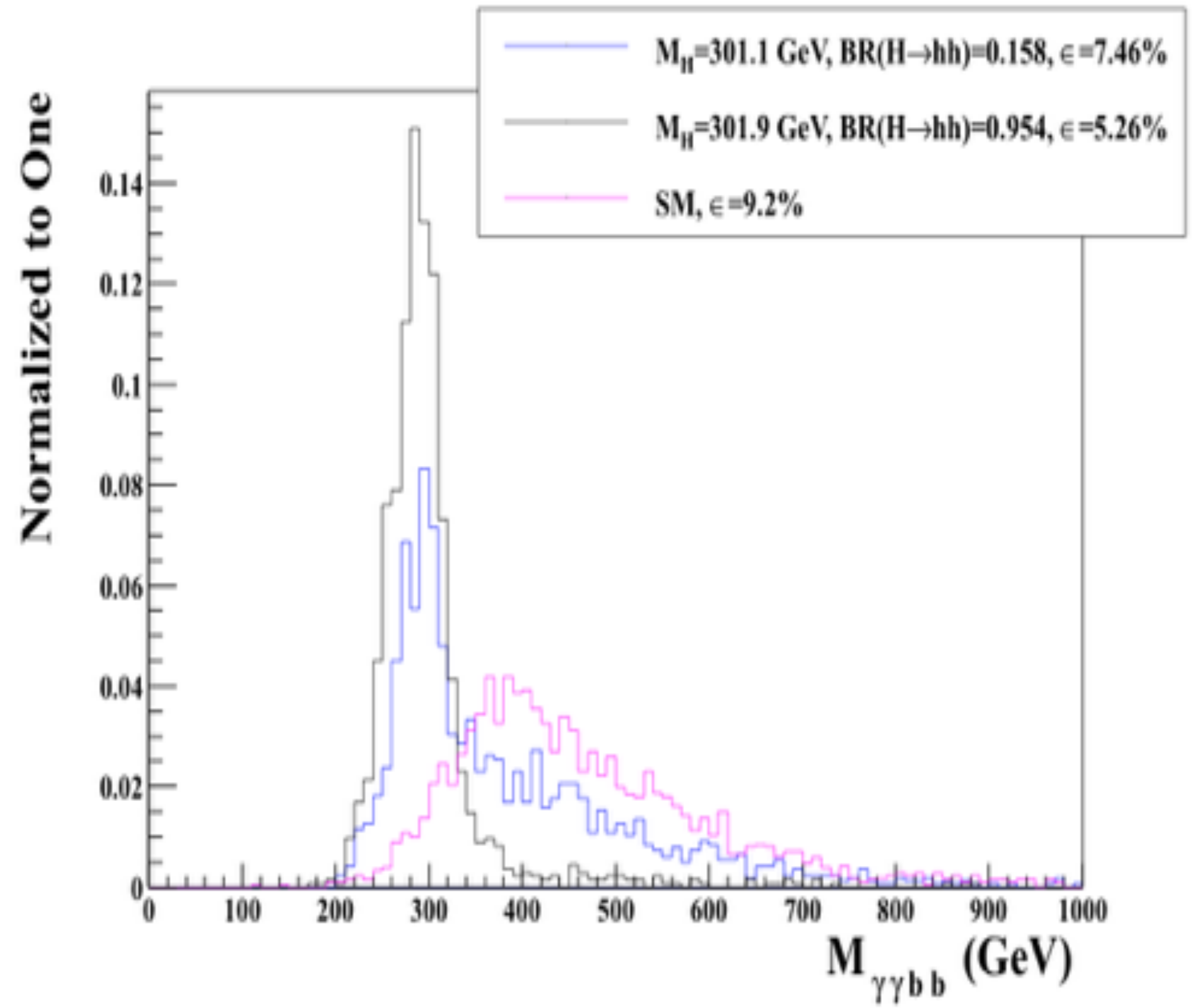
Vernon Barger, Lisa L. Everett, Chris B. Jackson, Andrea D. Peterson, and Gabe Shaughnessy, [arXiv:1408.2525[hep-ph]]

2HDM Physical Higgs : h, H, A, H+/-

$$\Gamma_{H\to hh} = \frac{(\lambda^{hhH})^2}{32\pi M_H}\sqrt{1-\frac{4m_h^2}{M_H^2}}$$

	A: $M_H = 300$ GeV, $t_\beta = 2$, $c_{\beta-\alpha} = 0.1$	**B**: $M_H = 300$ GeV, $t_\beta = 1$, $c_{\beta-\alpha} = 0.02$	**C**: $M_H = 500$ GeV, $t_\beta = 1$, $c_{\beta-\alpha} = 0.02$
$\lambda^{hhh}/\lambda^{hhh}_{SM}$	0.946	0.998	0.992
λ^{hhH} (GeV)	40.8	8.87	29.2
λ^{hHH} (GeV)	310	327	795
y_t^H	−0.40	−0.98	−0.98
$\sigma(pp \to hh)$ (fb)	340	810	37
$\sigma(pp \to hH)$ (fb)	7.7	44	26
$BF(H \to hh)$	18%	7.6%	0.1%
$BF(H \to tt)$	0.0%	0.0%	99%
$BF(H \to bb)$	34%	74%	0.2%
$BF(H \to ZZ + WW)$	49%	18%	0.2%





Cuts in ATLAS Collaboration, ATLAS-CONF-2016-004

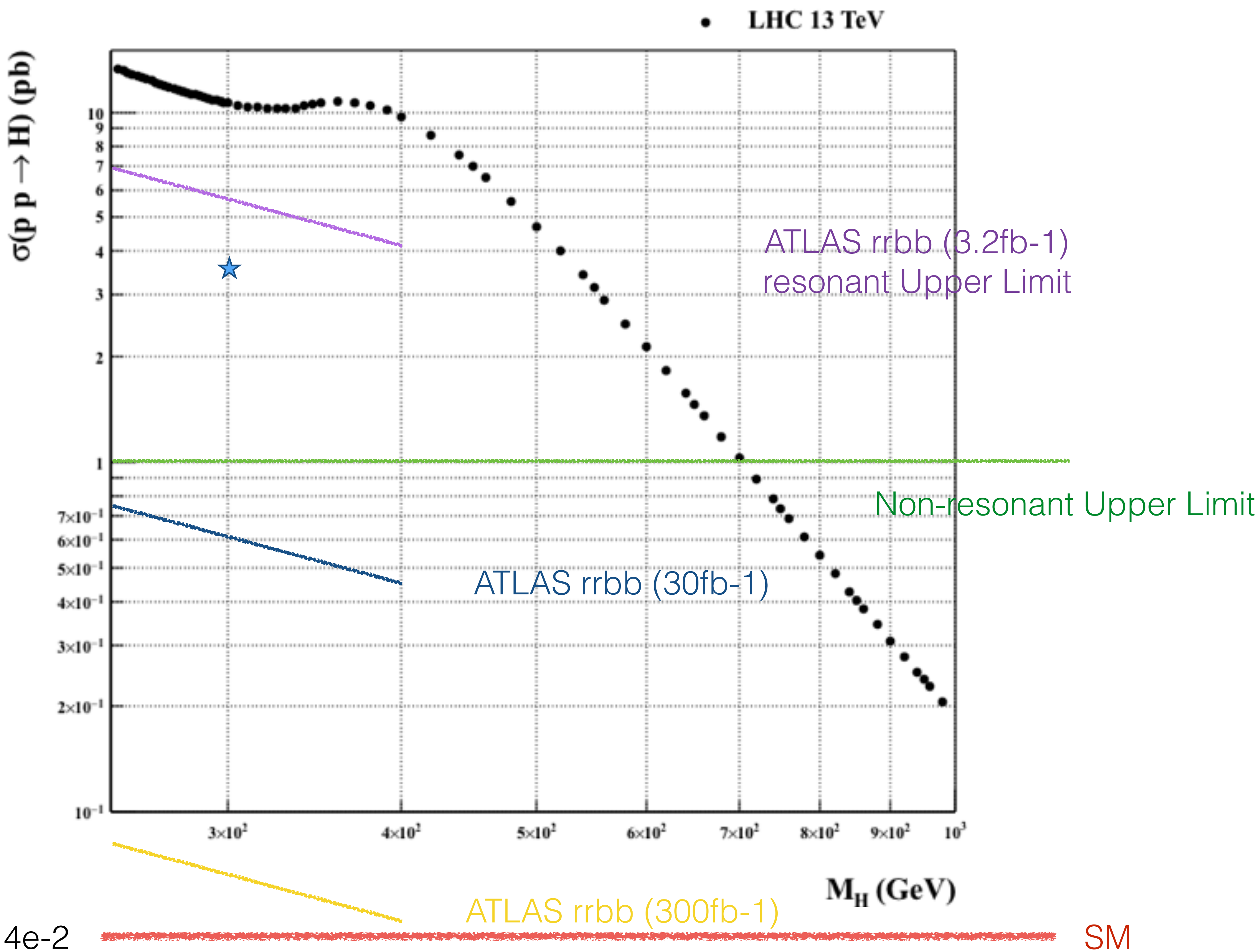
N(γ) >= 2, N(b) = 2, PT(j) > 25GeV, PT(b1,b2) > 55,35GeV,

105GeV < M(γγ) < 160GeV, 95GeV < M(bb) < 135GeV.

LHC Cross section Working Group

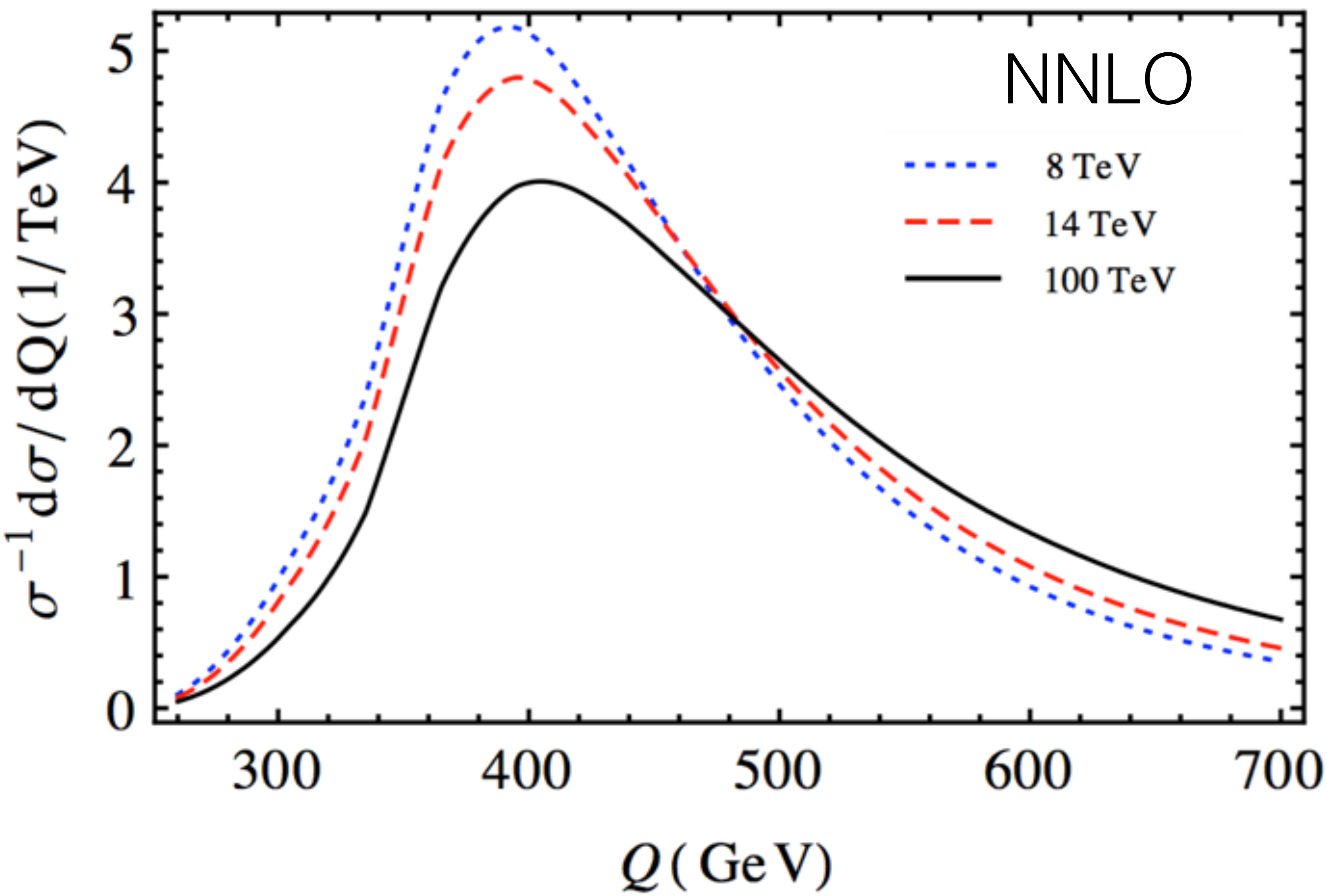
$$\sigma(pp \to H) \times k_{H_F}^2 \times BR(H \to hh)$$

★ i.e. at LHC 13 TeV, m_H=300 GeV : 10.62350x$(-0.6)^2$x0.95=3.63 pb



Daniel de Florian and Javier Mazzitelli, arXiv : 1405.4704 [hep-ph]

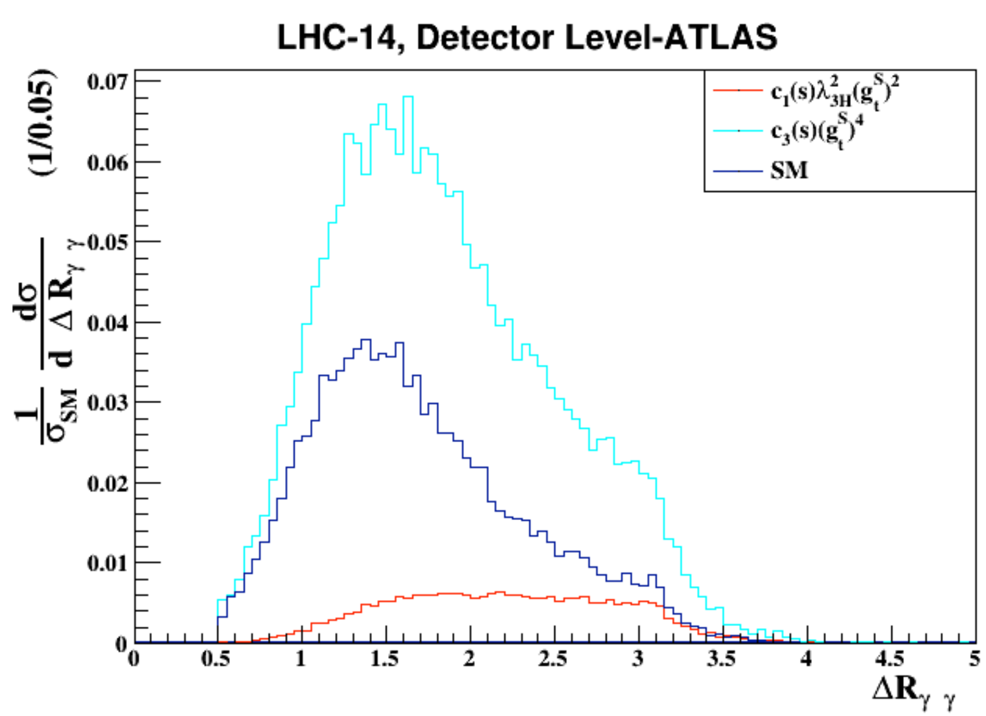
LHC-8, LHC-14, LHC-100

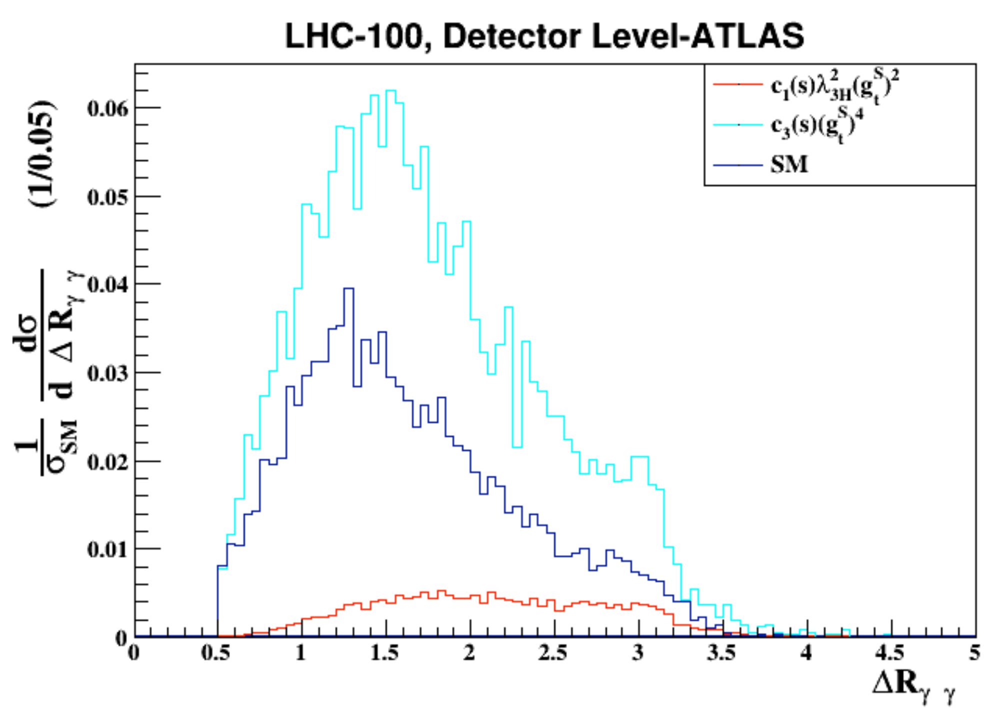


LHC-14 v.s. LHC-100

$\sqrt{s}$: 14 TeV Cuts	$c_1(s)$ $[\lambda_{3H}^2(g_t^S)^2]$	$c_2(s)$ $[\lambda_{3H}(g_t^S)^3]$	$c_3(s)$ $[(g_t^S)^4]$
No cuts	0.263	-1.310	2.047
Basic Cuts	0.221	-1.104	1.883
$\Delta R_{\gamma\gamma} > 2$	0.470	-1.868	2.398
$\Delta R_{\gamma\gamma} < 2$	0.133	-0.834	1.701
$\Delta R_{bb} > 2$	0.666	-2.512	2.847
$\Delta R_{bb} < 2$	0.143	-0.857	1.714
$\Delta R_{bb} > 2$ & $\Delta R_{\gamma\gamma} > 2$	0.895	-3.150	3.255
$\Delta R_{bb} < 2$ & $\Delta R_{\gamma\gamma} < 2$	0.121	-0.785	1.664

$\sqrt{s}$: 100 TeV Cuts	$c_1(s)$ $[\lambda_{3H}^2(g_t^S)^2]$	$c_2(s)$ $[\lambda_{3H}(g_t^S)^3]$	$c_3(s)$ $[(g_t^S)^4]$
No cuts	0.208	-1.108	1.900
Basic Cuts	0.173	-1.032	1.860
$\Delta R_{\gamma\gamma} > 2$	0.389	-1.904	2.515
$\Delta R_{\gamma\gamma} < 2$	0.115	-0.798	1.683
$\Delta R_{bb} > 2$	0.607	-2.419	2.813
$\Delta R_{bb} < 2$	0.120	-0.863	1.743
$\Delta R_{bb} > 2$ & $\Delta R_{\gamma\gamma} > 2$	0.753	-2.662	2.909
$\Delta R_{bb} < 2$ & $\Delta R_{\gamma\gamma} < 2$	0.102	-0.733	1.632





Summary

- Triangle diagram (s-channel propagator) not increase much as CM energy increase
- Decay product's Open angle is useful
- Well-Measured Top-Yukawa Coupling can help to narrow down the range of Higgs trilinear coupling size.
- However it is difficult to probe it even at HL-LHC. Need to combine the LHC results with future e+e- linear collider.
- Probing resonant Higgs boson pair production can help us understand BSM model scalar sector more.

Thanks!

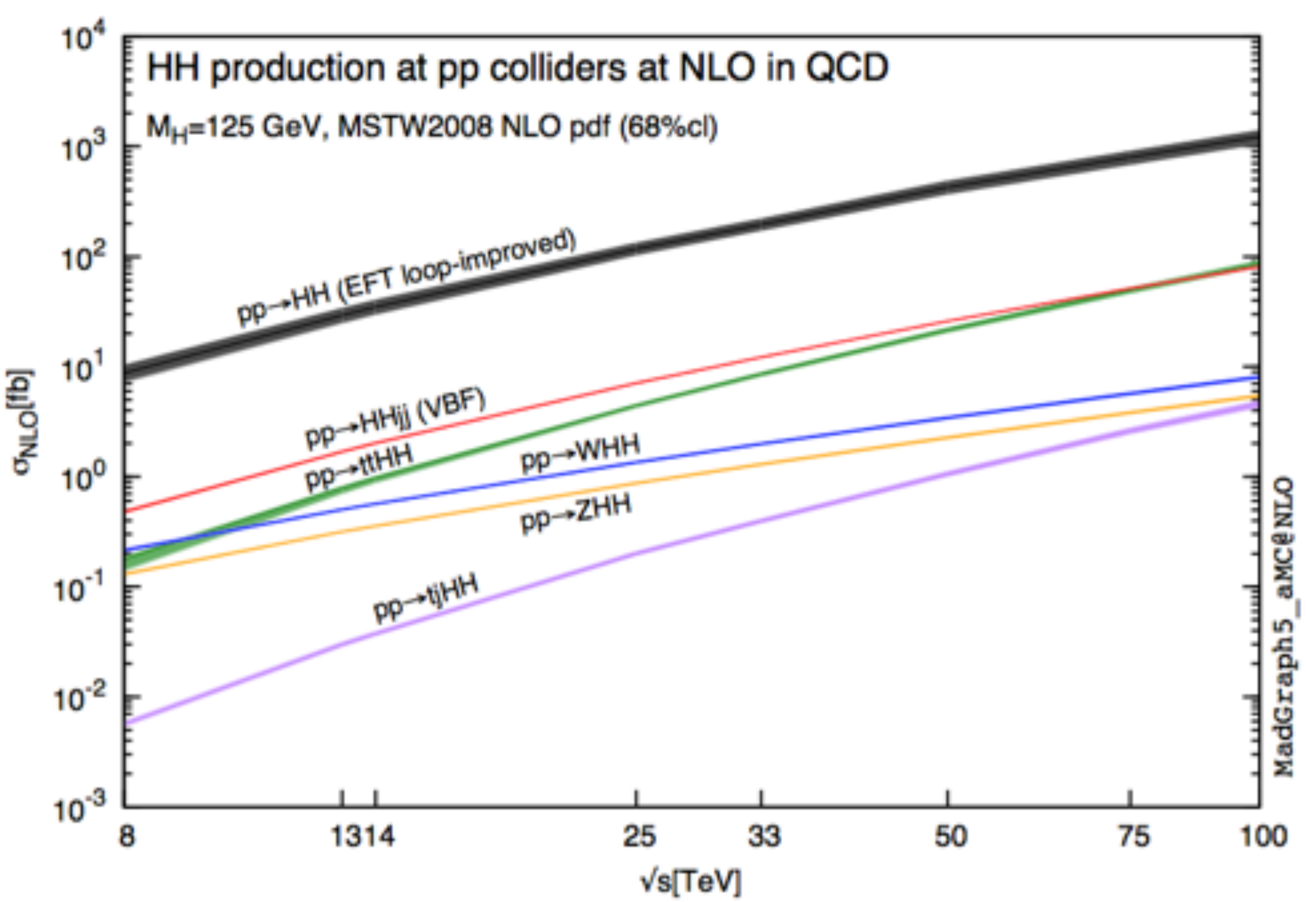
Back Up

Higgs Pair Production at the LHC

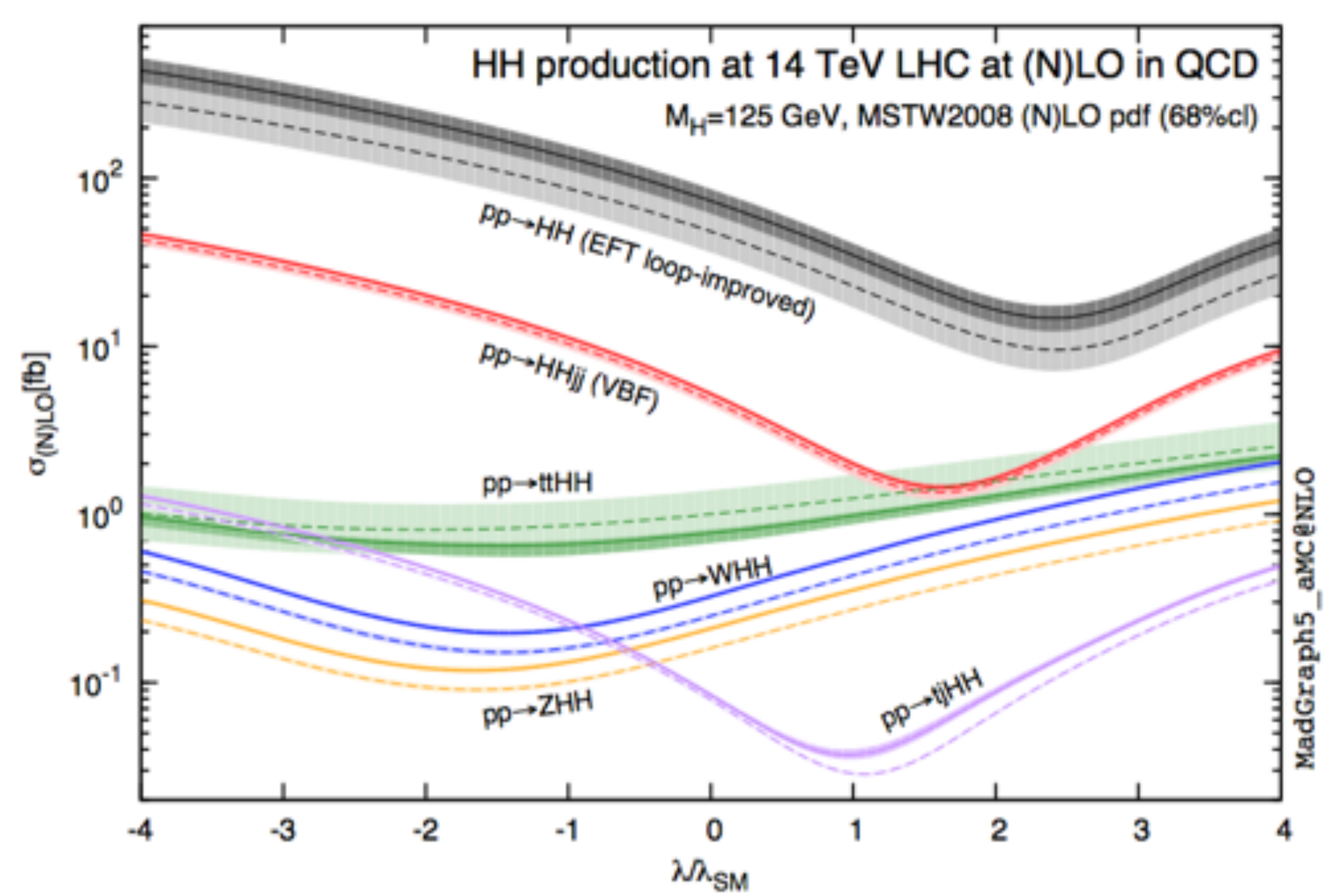
R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, P. Torrielli, E. Vryonidou, M. Zaro
PLB(2014), arXiv : 1401.7340 [hep-ph]

	$\sqrt{s} = 8$ TeV (LO) NLO		$\sqrt{s} = 13$ TeV (LO) NLO		$\sqrt{s} = 14$ TeV (LO) NLO	
HH (EFT loop-improv.)	$(5.44^{+38\%}_{-26\%})$	$8.73^{+17+2.9\%}_{-16-3.7\%}$	$(19.1^{+33\%}_{-23\%})$	$29.3^{+15+2.1\%}_{-14-2.5\%}$	$(22.8^{+32\%}_{-23\%})$	$34.8^{+15+2.0\%}_{-14-2.5\%}$

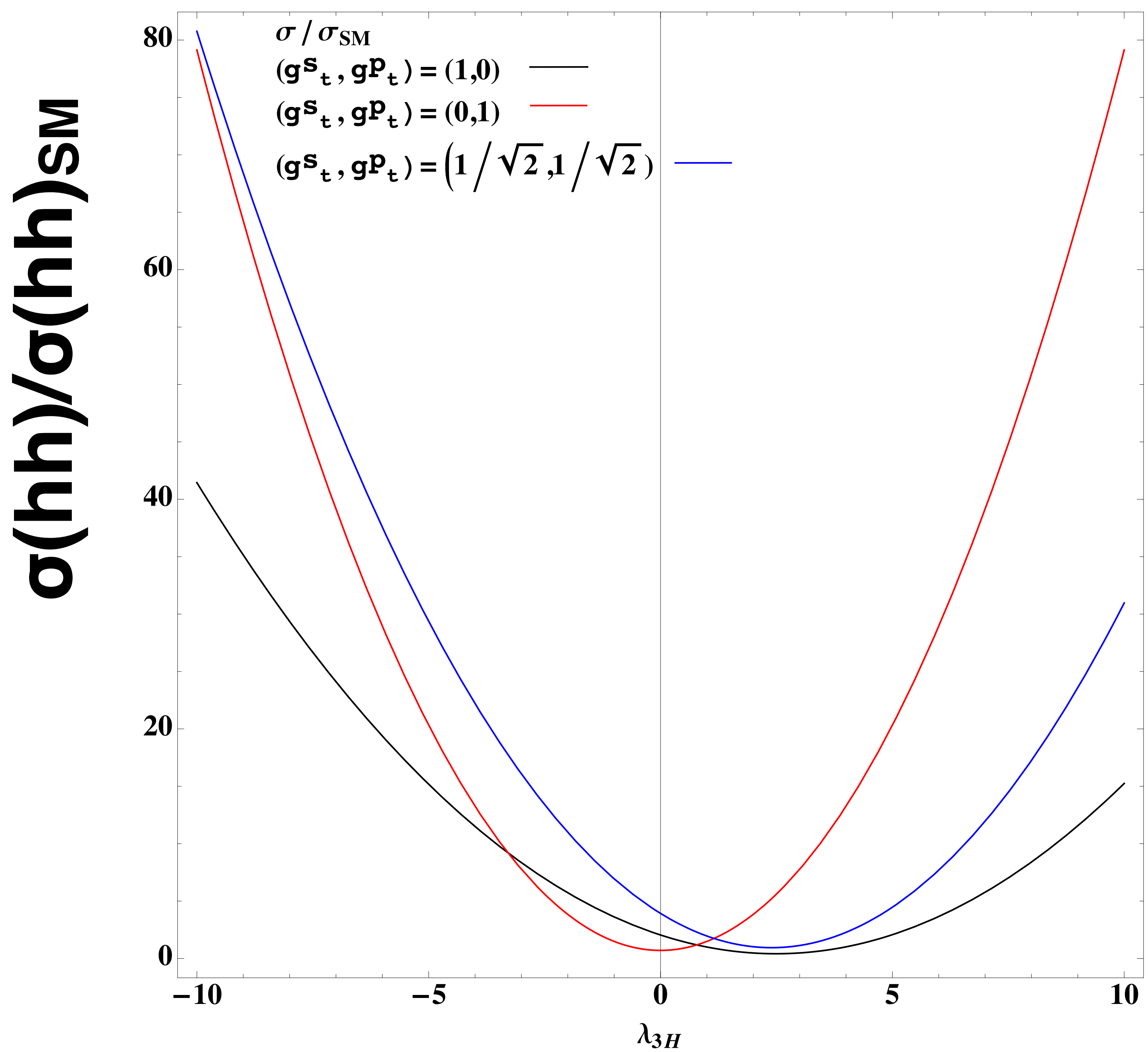
Total cross sections at the NLO in QCD



LHC-14, cross section as function of λ/λ_{SM}

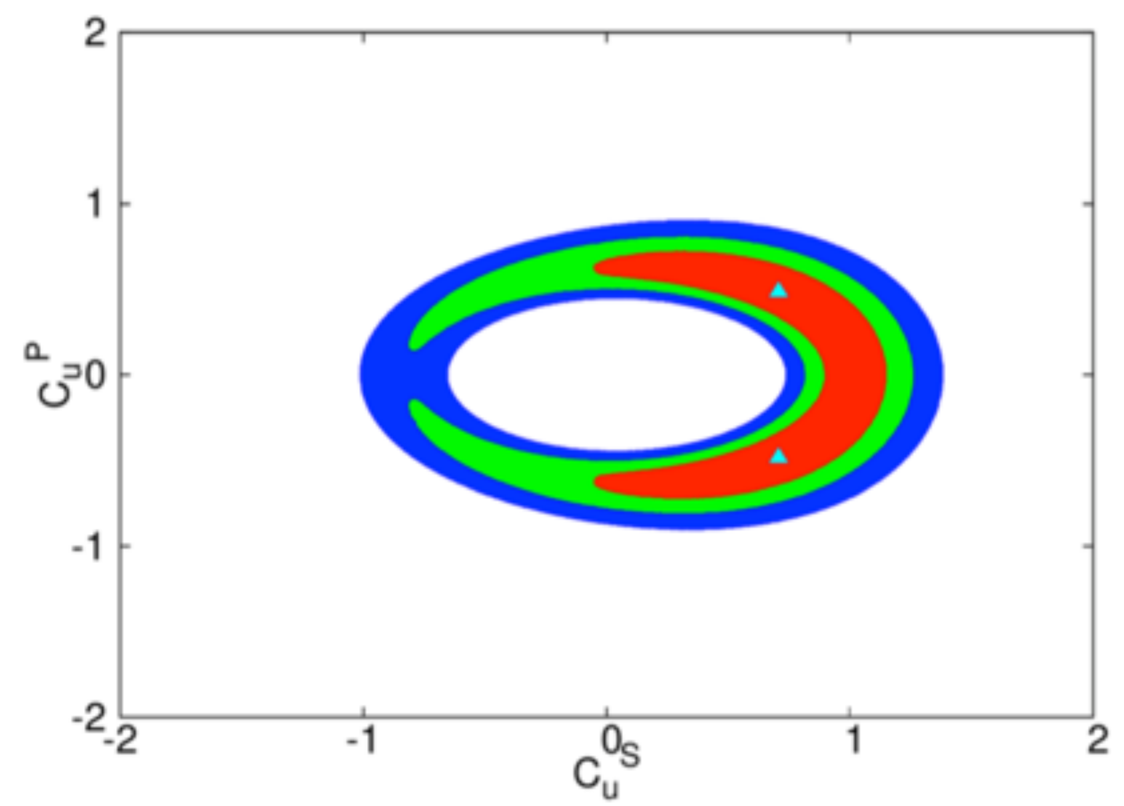


Effect of
Top pseudo-Yukawa Coupling



HHH Coupling

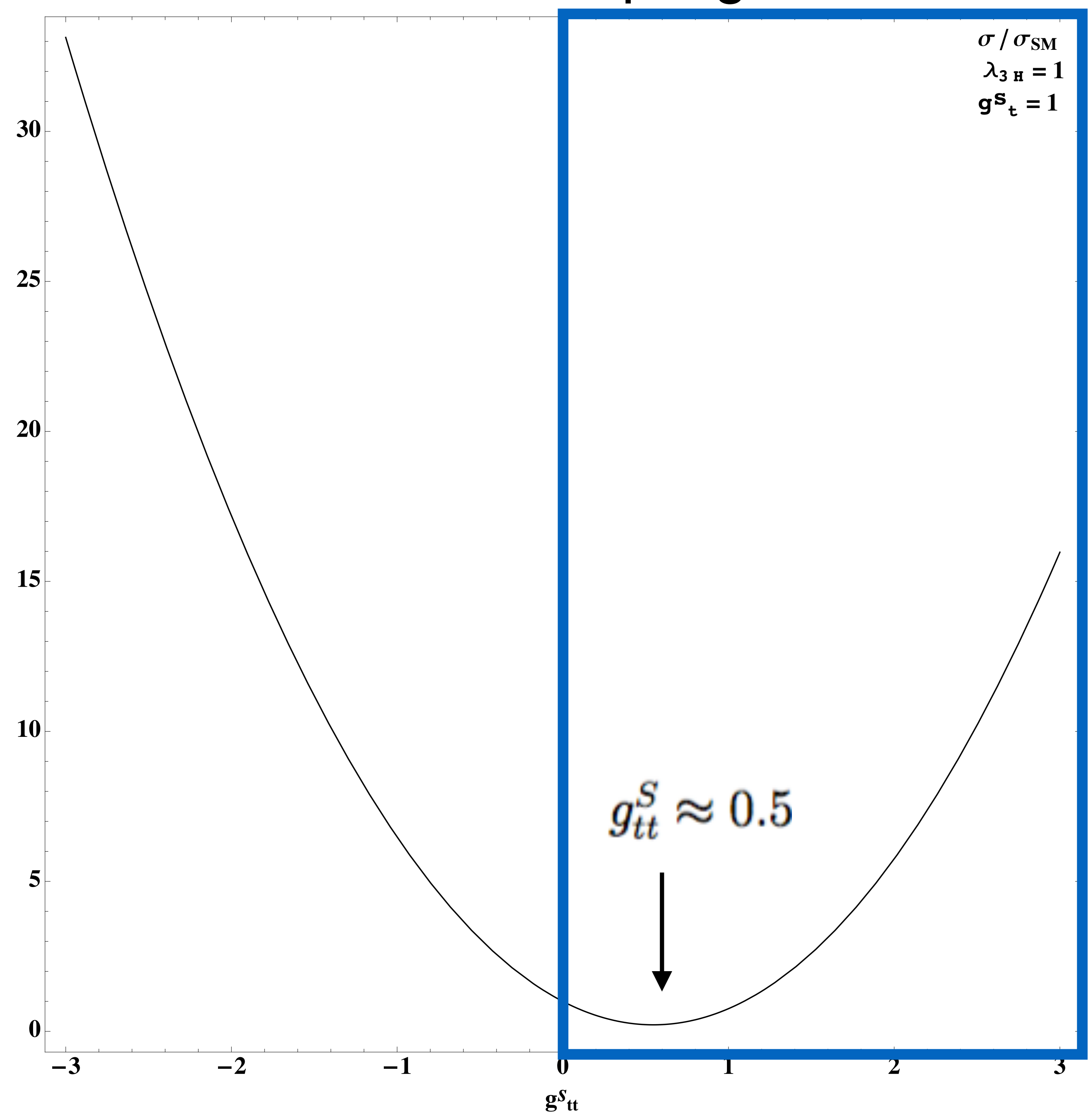
K. Cheung, J. S. Lee and P. Y. Tseng, Higgcision



Relation with Quartic Coupling

If HHH Yukawa coupling = SM value

$\sigma(hh)/\sigma(hh)_{SM}$

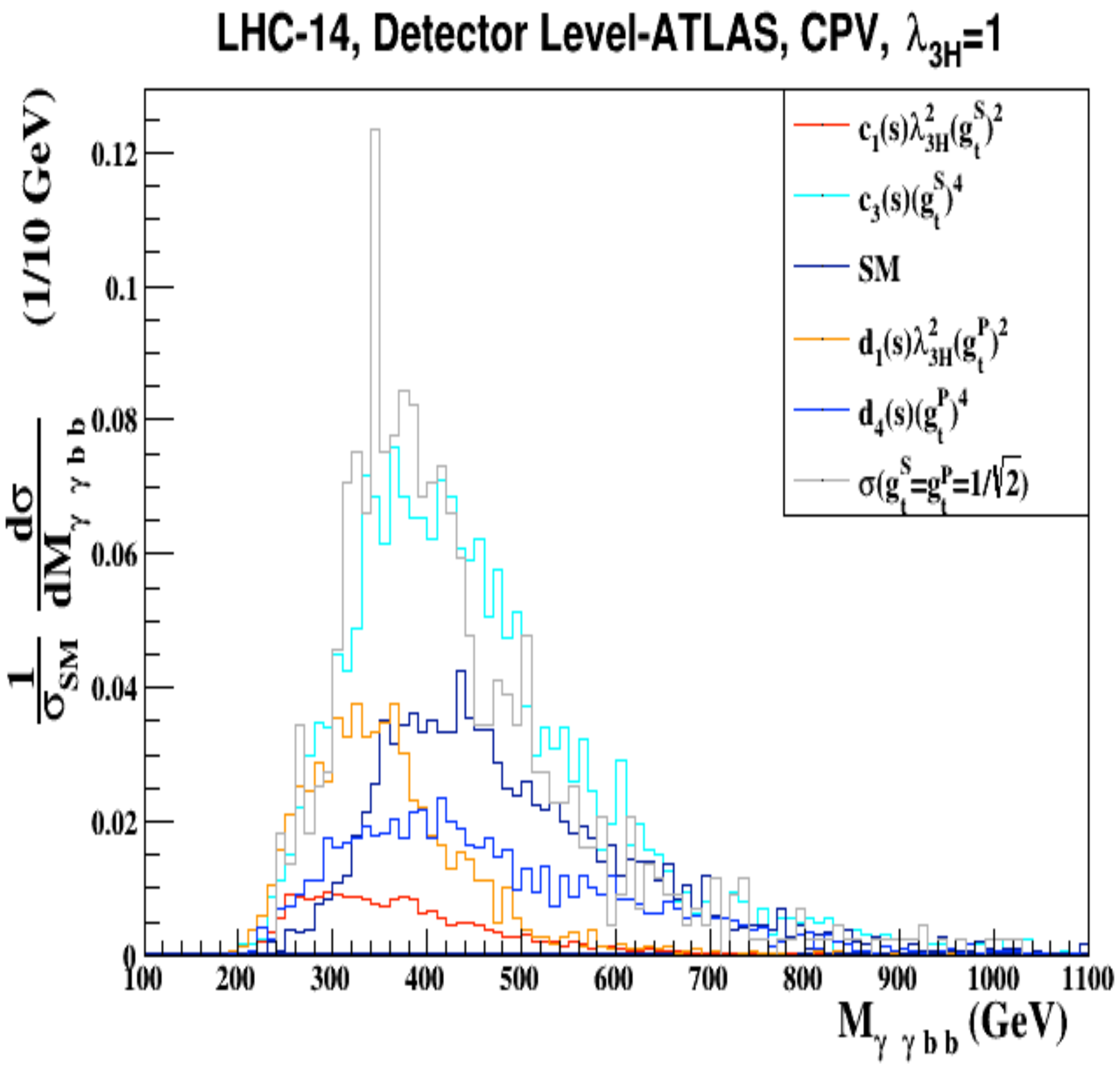


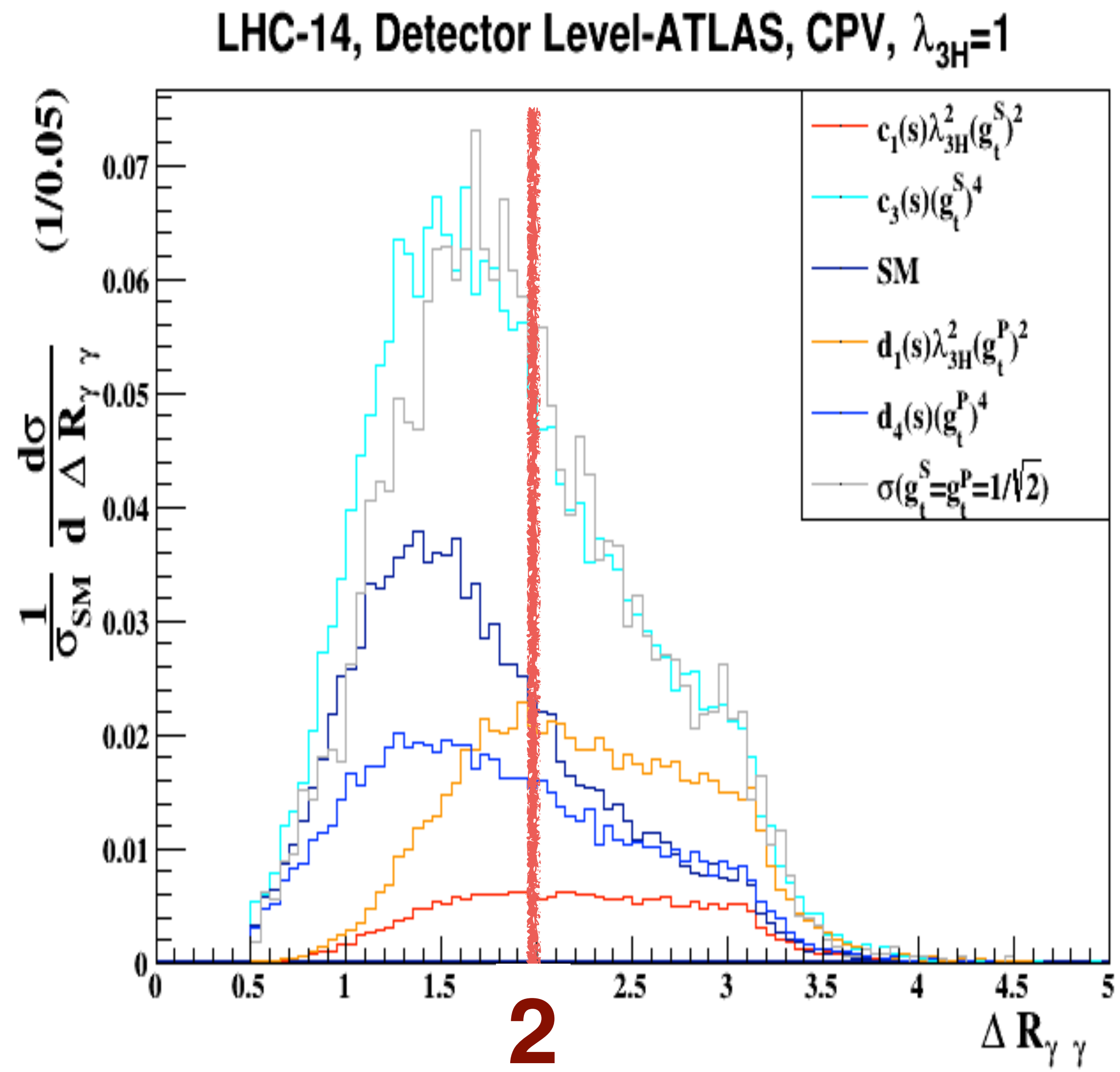
Quartic Coupling

Interferes
constructively triangle diagram
destructively box diagram

Dominance of the box diagram totally destructive interference

BSM CPV contribution





λ, $g^s{}_t$, $g^p{}_t$

general 2HDM

B. Hespel, D. Lopez-Val and E. Vryonidou, JHEP 1409, 124 (2014) [arXiv: 1407.0281 [hep-ph]]

$$\lambda_{h^0h^0h^0}: \quad -\frac{3}{\sin 2\beta}\left[\frac{4\cos(\alpha+\beta)\cos^2(\beta-\alpha)\, m_{12}^2}{\sin 2\beta} - m_{h^0}^2\left(2\cos(\alpha+\beta) + \sin 2\alpha\, \sin(\beta-\alpha)\right)\right]$$

$$= 3m_{h^0}^2 + \xi^2\left[\frac{9m_{h^0}^2}{2} - \frac{12m_{12}^2}{\sin 2\beta}\right] + \mathcal{O}(\xi^3)$$

$$\lambda_{h^0h^0H^0}: \quad \frac{\cos(\beta-\alpha)}{\sin 2\beta}\left[\sin 2\alpha\,(2m_{h^0}^2 + m_{H^0}^2) - \frac{2m_{12}^2}{\sin 2\beta}(3\sin 2\alpha - \sin 2\beta)\right]$$

$$= -\xi\left(2m_{h^0}^2 + m_{H^0}^2 - \frac{8m_{12}^2}{\sin 2\beta}\right) - \frac{2\xi^2}{\tan 2\beta}\left(2m_{h^0}^2 + m_{H^0}^2 - \frac{6m_{12}^2}{\sin 2\beta}\right) + \mathcal{O}(\xi^3)$$

$$\lambda_{H^0H^0h^0}: \quad -\frac{\sin(\beta-\alpha)}{\sin 2\beta}\left[\sin 2\alpha\,(m_{h^0}^2 + 2m_{H^0}^2) - \frac{2m_{12}^2}{\sin 2\beta}(3\sin 2\alpha + \sin 2\beta)\right]$$

$$= m_{h^0}^2 + 2m_{H^0}^2 - \frac{4\,m_{12}^2}{\sin 2\beta} + \frac{2\xi}{\tan 2\beta}\left(m_{h^0}^2 + 2m_{H^0}^2 - \frac{6m_{12}^2}{\sin 2\beta}\right)$$

$$+\xi^2\left(\frac{14m_{12}^2}{\sin 2\beta} - \frac{5}{2}(m_{h^0}^2 + 2m_{H^0}^2)\right) + \mathcal{O}(\xi^3)$$

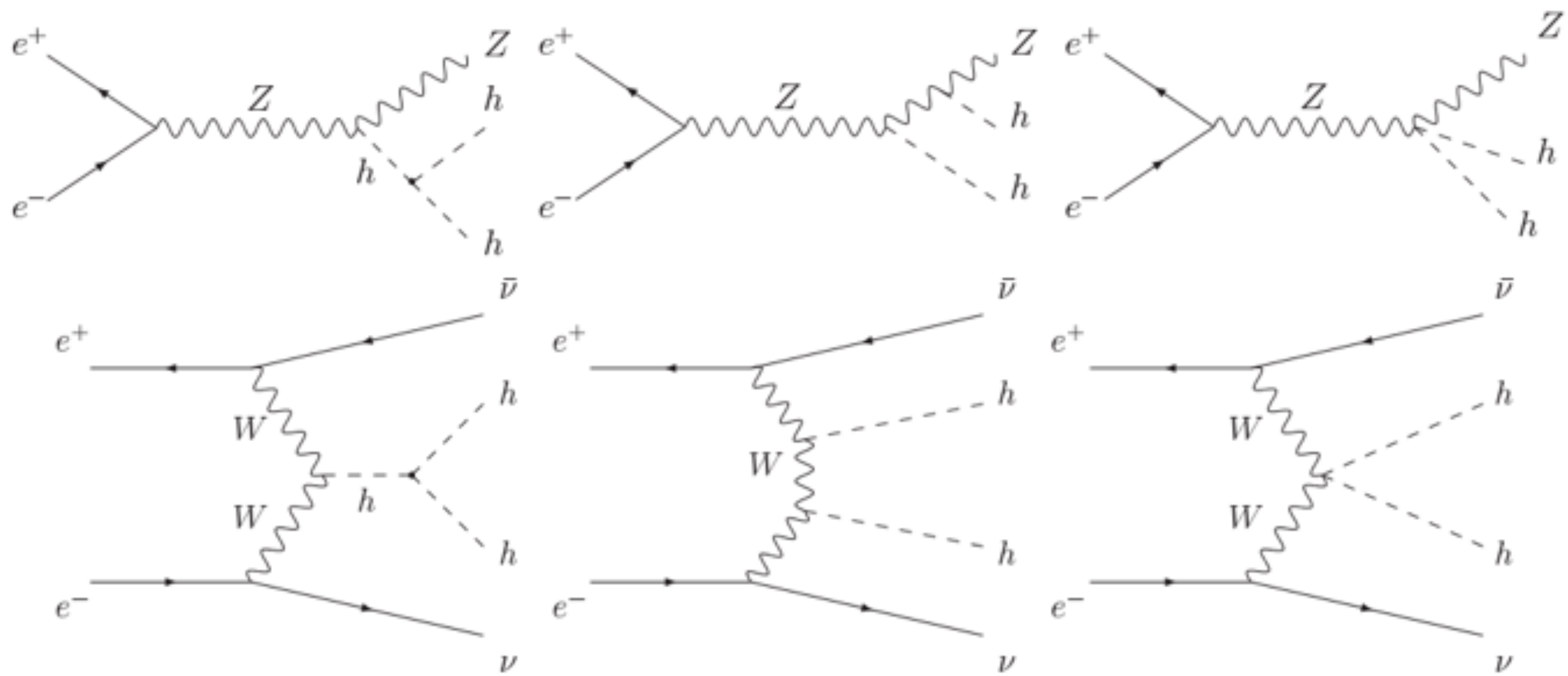
$$\lambda_{H^0H^0H^0}: \quad -\frac{3}{\sin 2\beta}\left[m_{H^0}^2\left(\cos(\beta-\alpha)\,\sin 2\alpha - 2\sin(\alpha+\beta)\right) + \frac{4\,m_{12}^2\,\sin(\alpha+\beta)\,\sin^2(\beta-\alpha)}{\sin 2\beta}\right]$$

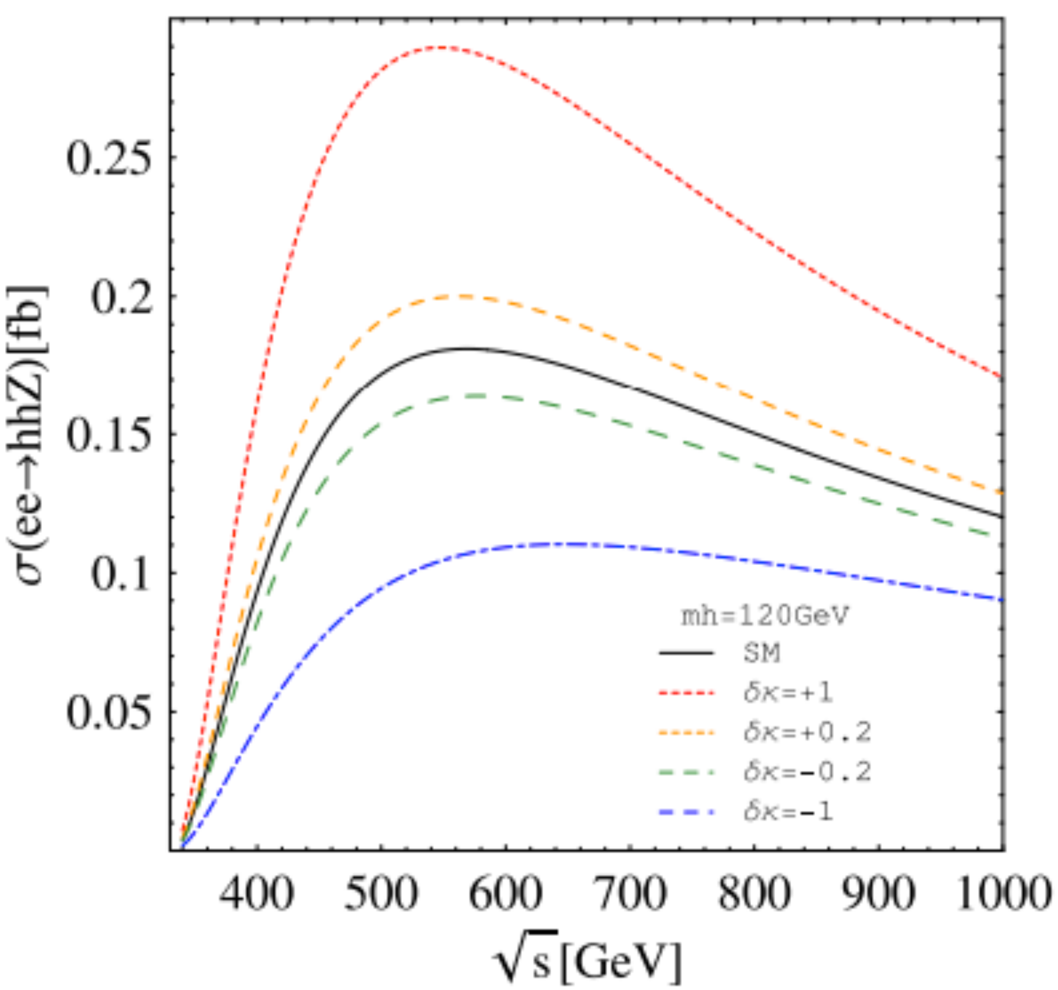
$$= \frac{-6}{\tan 2\beta}\left[m_{H^0}^2 - \frac{2m_{12}^2}{\sin 2\beta}\right] + \xi\left(9m_{H^0}^2 - \frac{12\,m_{12}^2}{\sin 2\beta}\right)$$

$$+\frac{3\xi^2}{\tan 2\beta}\left(3m_{H^0}^2 - \frac{6m_{12}^2}{\sin 2\beta}\right) + \mathcal{O}(\xi^3)$$

ILC & photon collider

arXiv : 1009.4670 [hep-ph]





arXiv : 1009.4670 [hep-ph]

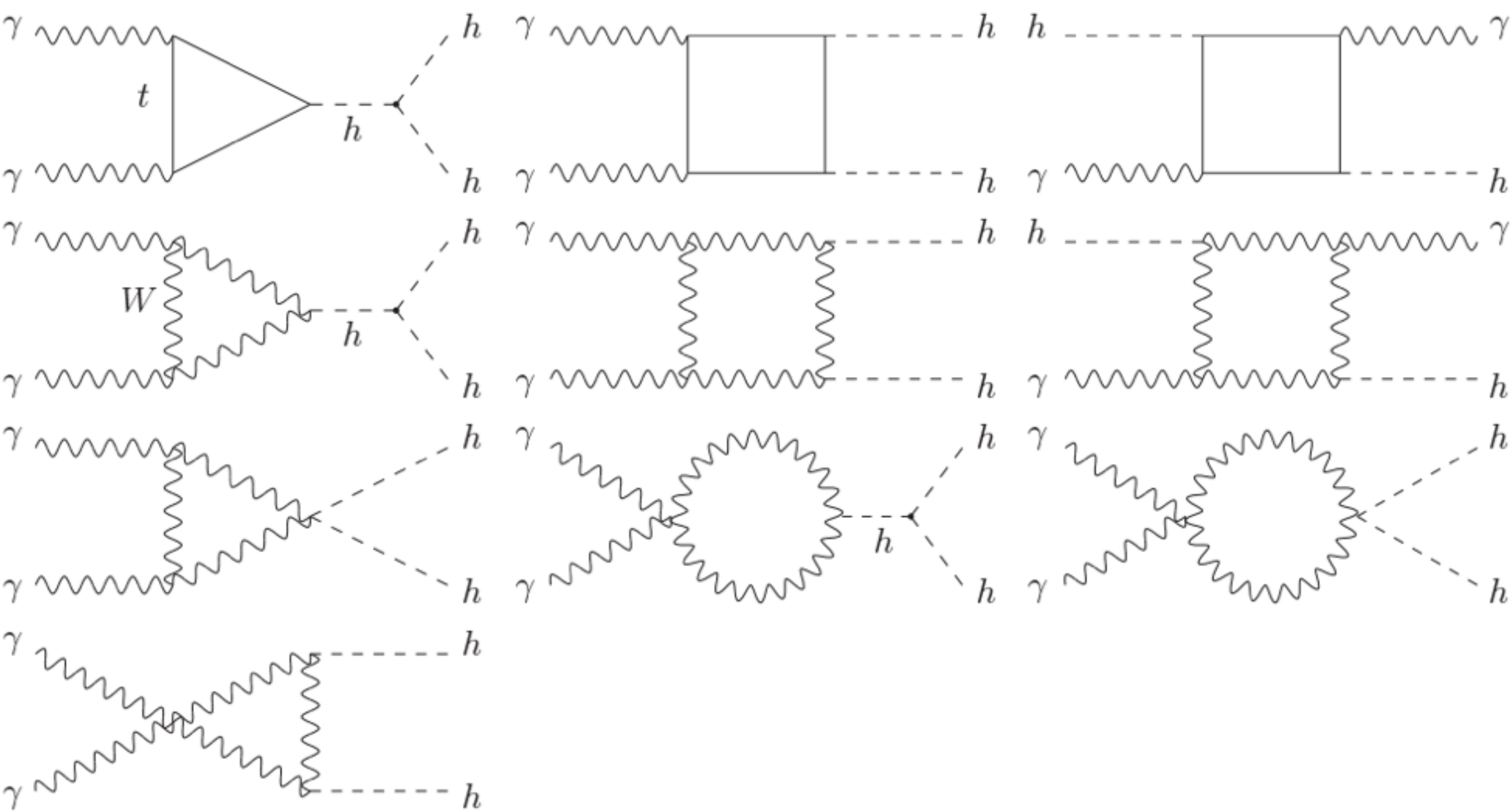


FIG. 5: The double Higgs boson production process $\gamma\gamma \to hh$ at the photon collider.

arXiv : 1009.4670 [hep-ph]

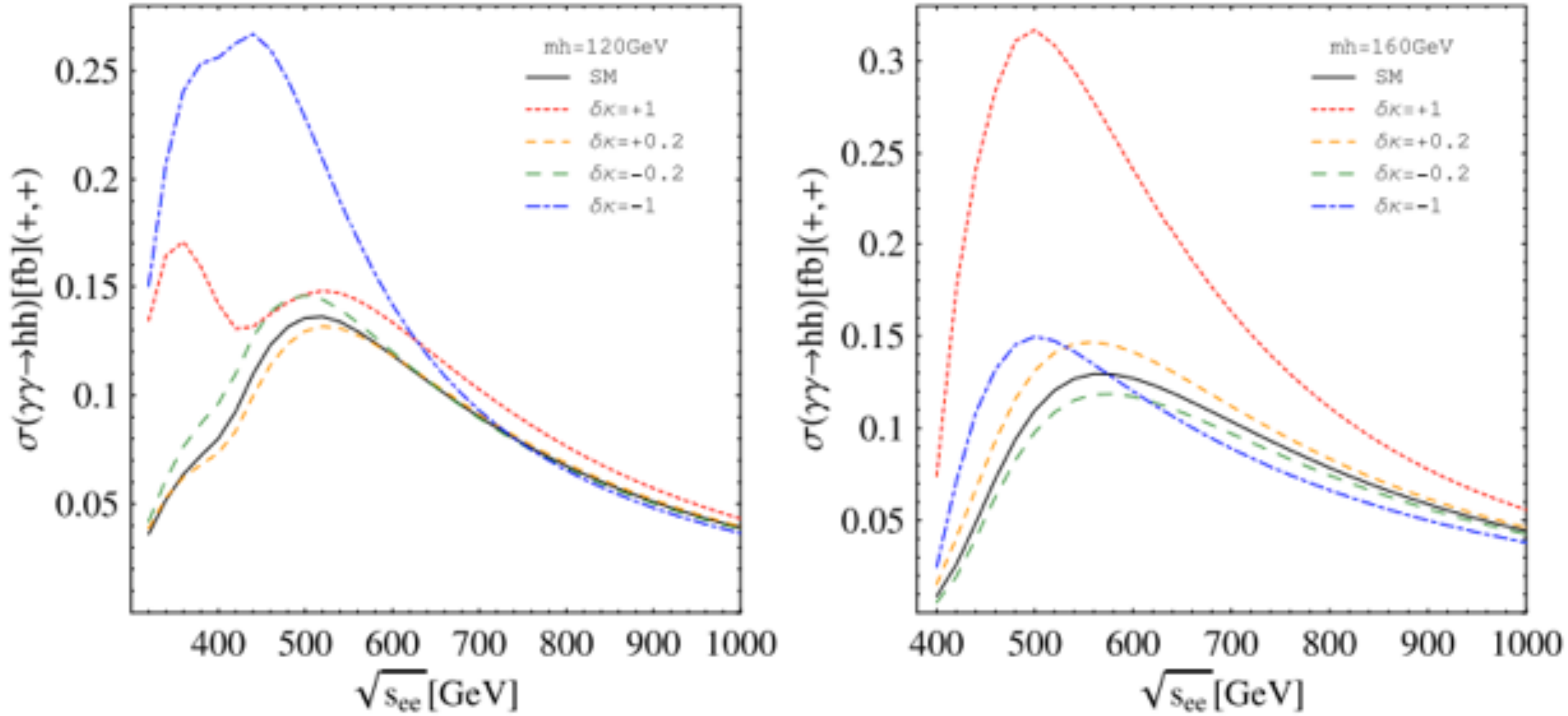


FIG. 6: The full cross section of e^-e^- $(\gamma(+)\gamma(+)) \to hh$ process as a function of $\sqrt{s}_{ee}$ for $m_h = 120$ GeV (left) and $m_h = 160$ GeV (right).

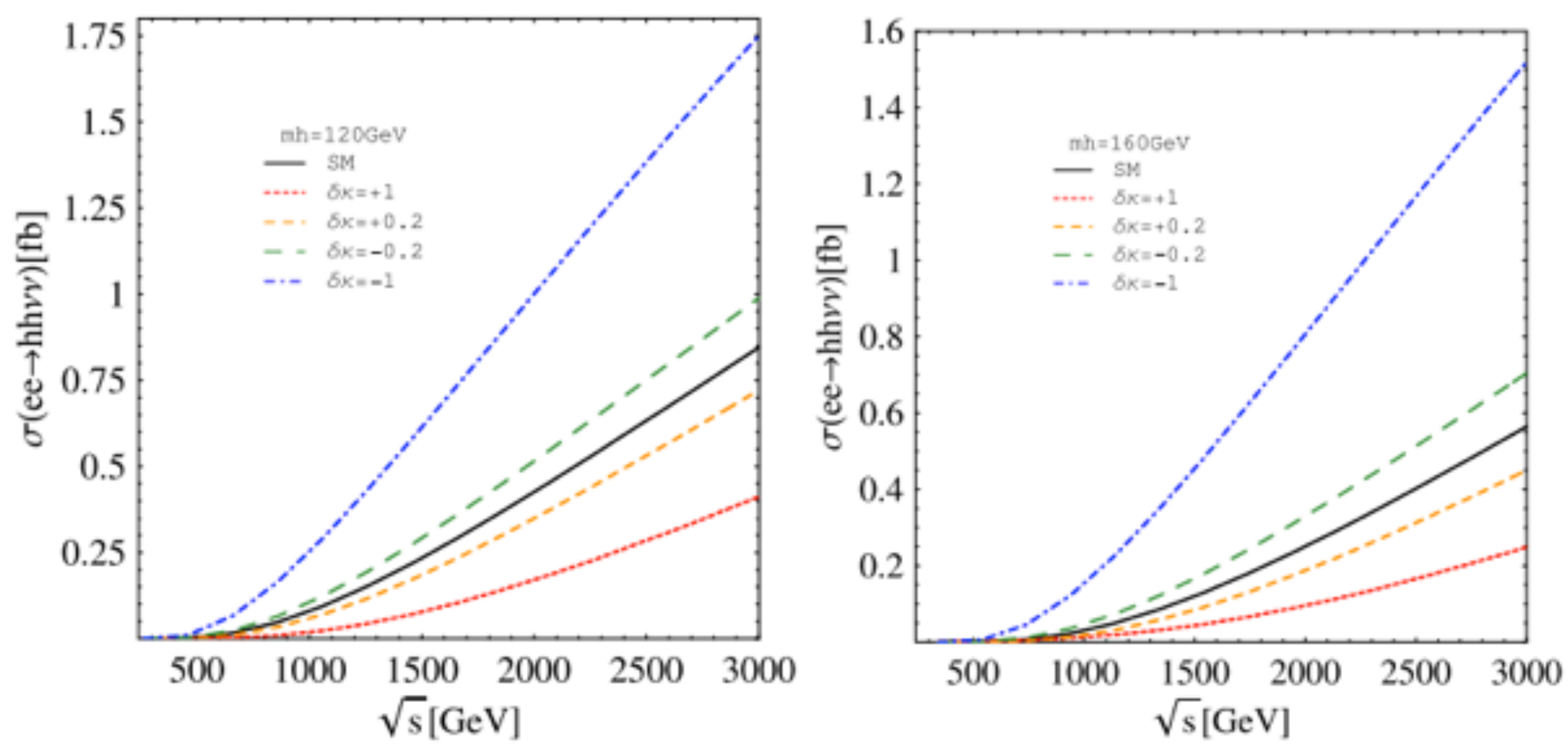


FIG. 7: The cross sections of $e^+e^- \to hh\nu\bar{\nu}$ process at the ILC as a function of collision energy $\sqrt{s}$ for $m_h = 120$ GeV (left) and $m_h = 160$ GeV (right).

Hespel, L´opez-Val and Vryonidou (2014)

Additional Destructive Interference from BSM physics

- Arises between the top and bottom–mediated loops, although the bottom quark effects are very small in the SM.

- For example : 2HDM.

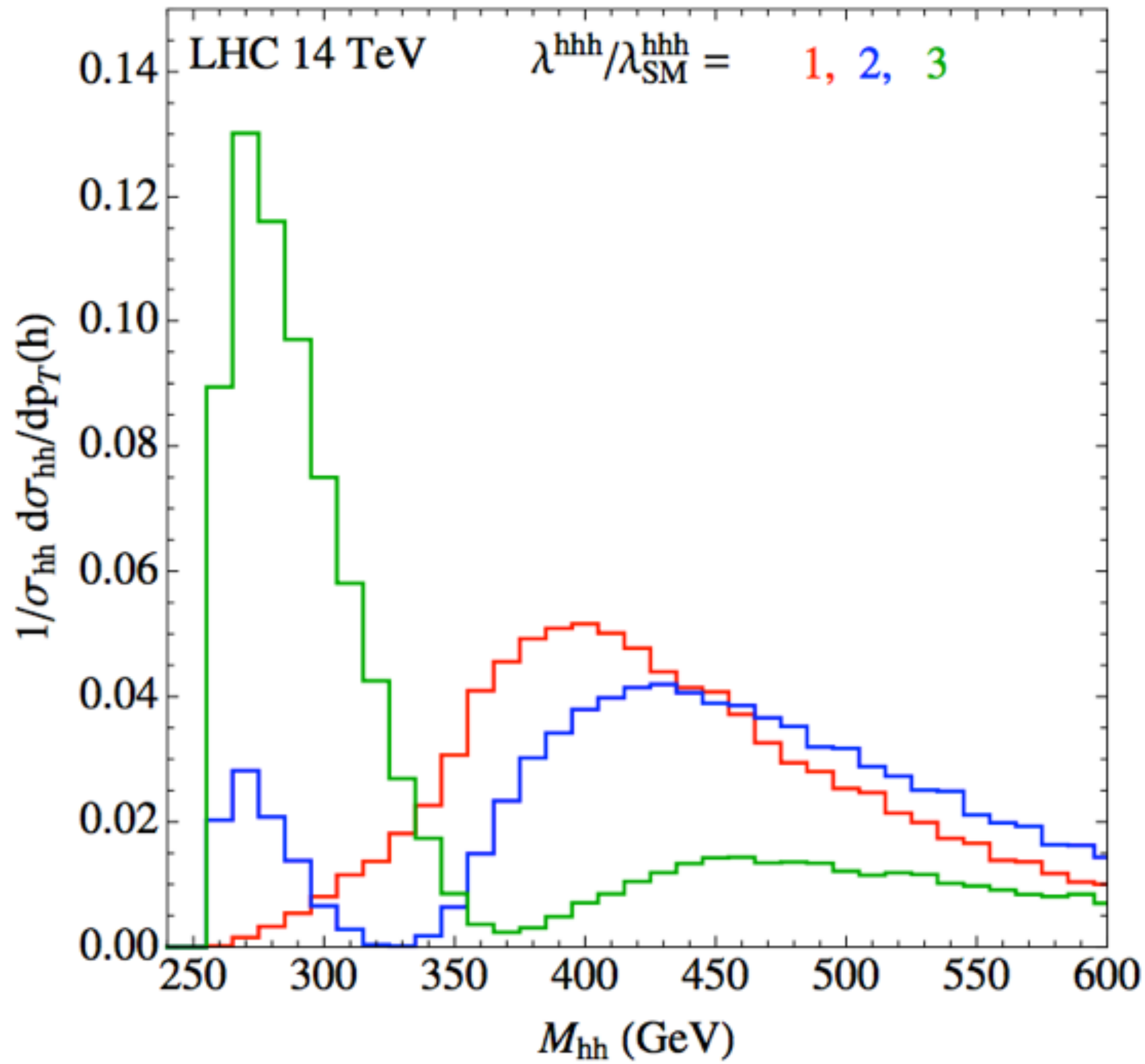
- Sign–flipped bottom–quark Yukawa :
  the top and bottom–mediated triangles to interfere constructively.
  Slightly enhanced triangle amplitudes, which thus reinforce the interference with the boxes.

- O(20)% enhanced bottom Yukawa :
  reinforces the destructive interference between the top and bottom–mediated triangles.
  Slightly suppressed Higgs-self coupling to pull down triangle contribution.
  Reduced the triangle and box interference term.
  Slightly above SM expectation.

Vernon Barger, Lisa L. Everett, C. B. Jackson, Gabe Shaughnessy, arXiv : 1311.2931 [hep-ph]

Kinematics of HH production

Kinematic Distribution of HH production depends on HHH coupling



Examine the ttHH validity

C.T. Lu, JC, K. Cheung and J. S. Lee (2015)

projecting out the leading partial-wave coefficient for the scattering

At high energy, the amplitude

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

The leading partial-wave coefficient is given by

$$a_0 = \frac{1}{64\pi}\int_{-1}^{1} d(\cos\theta) P_0(\cos\theta)(i\mathcal{M}) = g^S_{tt}\frac{m_t\sqrt{\hat{s}}}{32\pi v^2}$$

Requiring $|a_0| < 1/2$ for unitary, we got :

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

Therefore, the anomalous ttHH contact term can be safely applied at the LHC for $g^S_{tt} \lesssim 3-5$ as most of the collisions occur at $\sqrt{\hat{s}} \lesssim$ a few TeV.

N. Liu, S. Hu, B. Yang and J. Han, JHEP 1501, 008 (2015) [arXiv:1408.4191 [hep-ph]]

Top-Yukawa Coupling

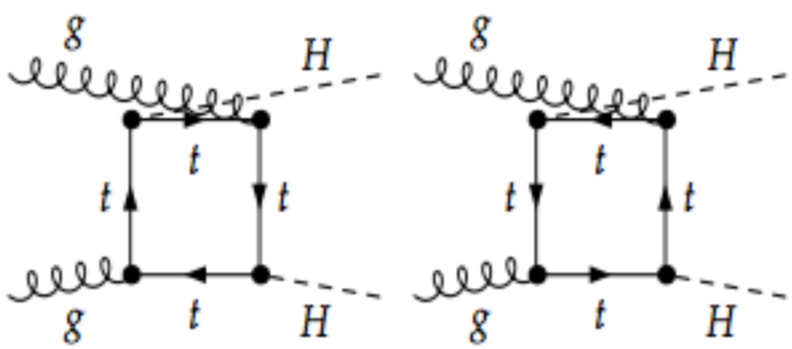
SM top-Higgs interaction

$$\mathcal{L}_{t\bar{t}h}^{SM} = -y_{t_{SM}} \overline{Q}_{3L} t_R \tilde{\phi} + \text{ h.c.},$$

$$y_{t_{SM}} = \sqrt{2} m_t / v$$

New Physics model independent
dim-6 effective top-Higgs coupling

$$\mathcal{L}_{t\bar{t}h}^{6} = -\frac{C_{u\phi}^{33}}{\Lambda^2} (\phi^\dagger \phi)(\overline{Q}_{3L} t_R \tilde{\phi}) + \text{ h.c.}$$



7 8

After EWSB, the most general top Higgs interactions :
SM+dim-6 operator contributions

$$\mathcal{L}_{t\bar{t}h} = -\frac{y_t}{\sqrt{2}} \bar{t}(\cos\theta + i \sin\theta \gamma^5) t h,$$

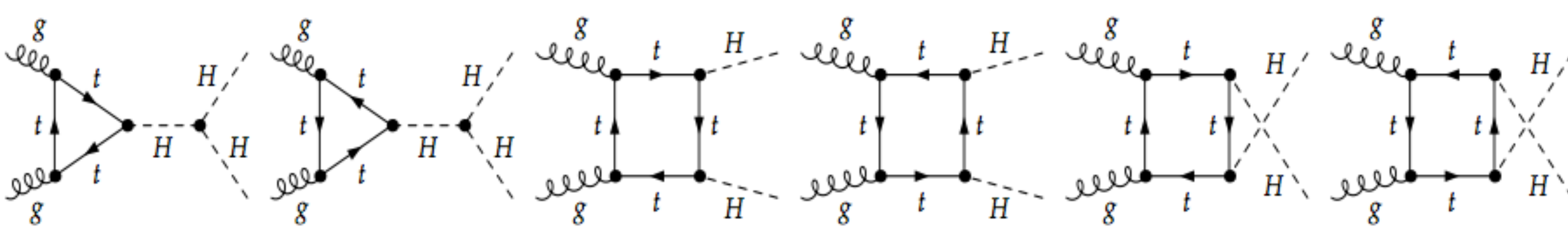
$$y_t \cos\theta = y_{t_{SM}} + \frac{v^2}{\Lambda^2} \text{Re } C_{u\phi}^{33}, \quad y_t \sin\theta = \frac{v^2}{\Lambda^2} \text{Im } C_{u\phi}^{33}.$$

$$c_t = y_t \cos\theta / y_{t_{SM}} \text{ and } \tilde{c}_t = y_t \sin\theta / y_{t_{SM}}$$

The most relevant indirect constraint ggF and hγγ,
Parameterized signal strength for hgg and hγγ

$$\mu_{hgg} \simeq c_t^2 + 2.6 \tilde{c}_t^2 + 0.11 c_t (c_t - 1),$$

$$\mu_{h\gamma\gamma} \simeq (1.28 - 0.28 c_t)^2 + (0.43 \tilde{c}_t)^2$$



1 2 3 4 5 6