New Physics effect on Higgs boson pair production processes at LHC and ILC

Daisuke Harada
(KEK, Graduate University for Advanced Studies)

in collaboration with
E. Asakawa (Meiji-Gakuin), S. Kanemura (U. of Toyama),
Y. Okada (KEK), K. Tsumura (ICTP)

Phys. Lett. B 672 (2009) 354-360;
Papers in preparation

LCWS 2010@Beijing, March. 28. 2010

Introduction

The standard model for elementary particles is very successful in describing high energy phenomena up to O(100) GeV.

The SM has several problems. If the SM is an effective theory up to Planck scale, Higgs mass is O(100) GeV comes from large fine-tuning cancellation between its bare mass and quadratic radiative corrections. This problem is known as Hierarchy problem.
This fine tuning problem suggests that new physics beyond the SM should appear at TeV scale.

The Higgs sector is the last unknown part of the Standard Model.
After the discovery of Higgs boson, it is important to measure the Higgs self-coupling.

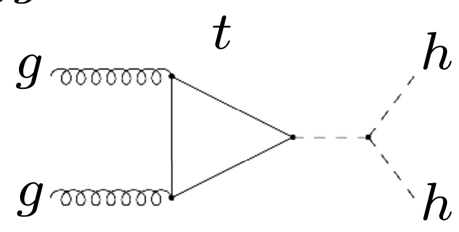
- Test for the Higgs potential
- Search for New Physics effect

We study the impacts of new physics effects on the hhh measurement at LHC and ILC in THDM with SM-like limit, scalar LQ and chiral 4^{th} generation model.

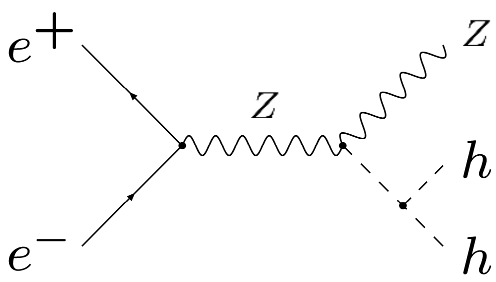
Measurement of hhh coupling

Measurement at collider experiment

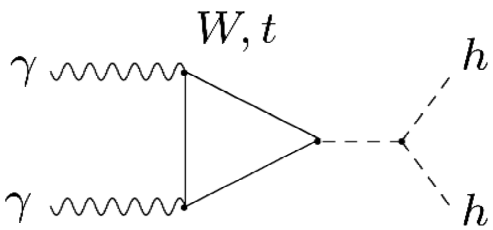
- LHC (SLHC) $gg \to hh$

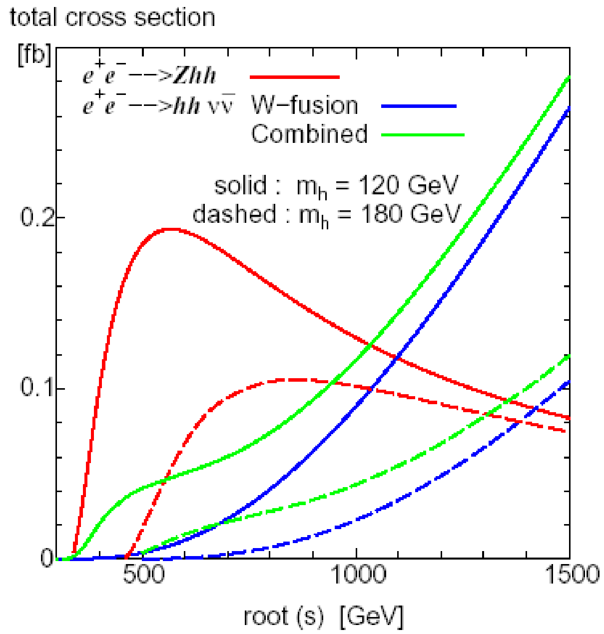


- ILC $e^+e^- \to Zhh$
  $\sqrt{s} = 500\text{GeV}$

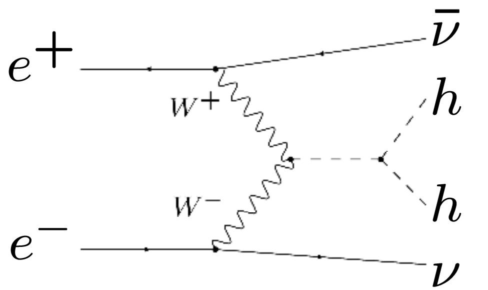


- Photon Collider (PLC) $\gamma\gamma \to hh$





- ILC $e^+e^- \to hh\bar{\nu}\nu$
  $\sqrt{s} = 1\text{TeV}$



We focus on these processes.

New Physics effect on hhh coupling

Higgs mass is the only free parameter in the Higgs potential.

Effective Higgs potential

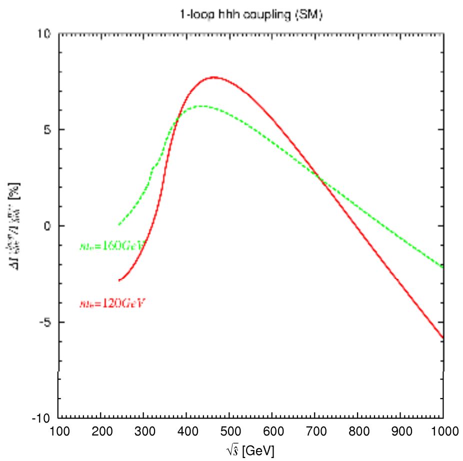
$$V = \frac{1}{2} m_h^2 h^2 + \frac{1}{3!} \lambda_{hhh} h^3 + \frac{1}{4!} \lambda_{hhhh} h^4 + \cdots.$$

In the SM, tree level hhh (hhhh) couplings are uniquely defined by Higgs boson mass.

$$\lambda_{hhh}^{\mathrm{SM}} = \frac{3m_h^2}{v} \qquad \lambda_{hhhh}^{\mathrm{SM}} = \frac{3m_h^2}{v^2}$$

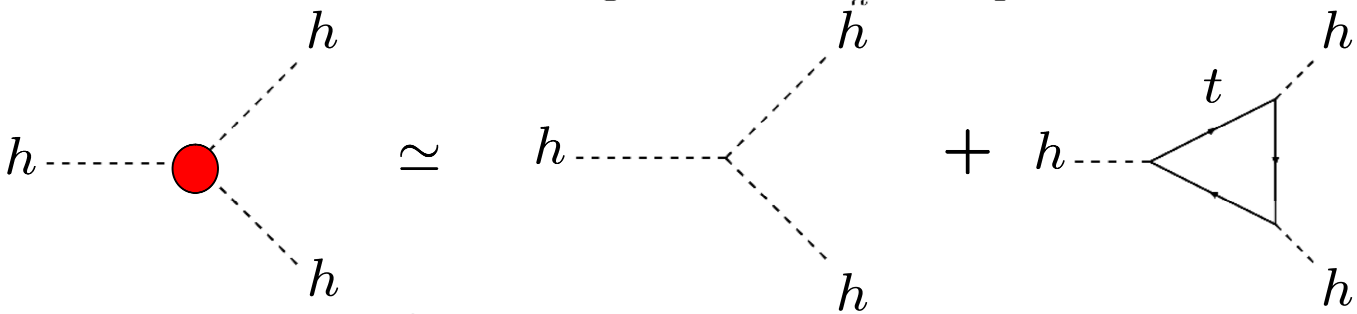
- Non-decoupling effect

In the SM, top loop correction is known as non-decoupling effect.



Effective hhh coupling

$$\lambda_{hhh}^{\mathrm{eff}} \simeq \frac{3m_h^2}{v} - \frac{N_c m_t^4}{\pi^2 v^3} = \frac{3m_h^2}{v}\left[1 - \frac{N_c m_t^4}{3\pi^2 v^2 m_h^2} + \cdots\right] \equiv \lambda_{hhh}^{\mathrm{SM}}(1 + \delta\kappa)$$



$+$ counter term

m_t^4 term appears in 1-loop correction

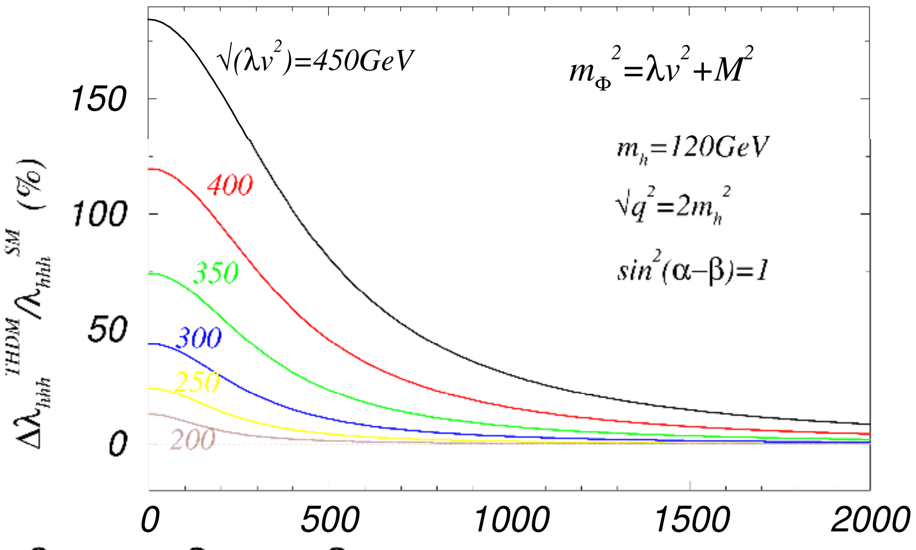
loop effect ~ -10%

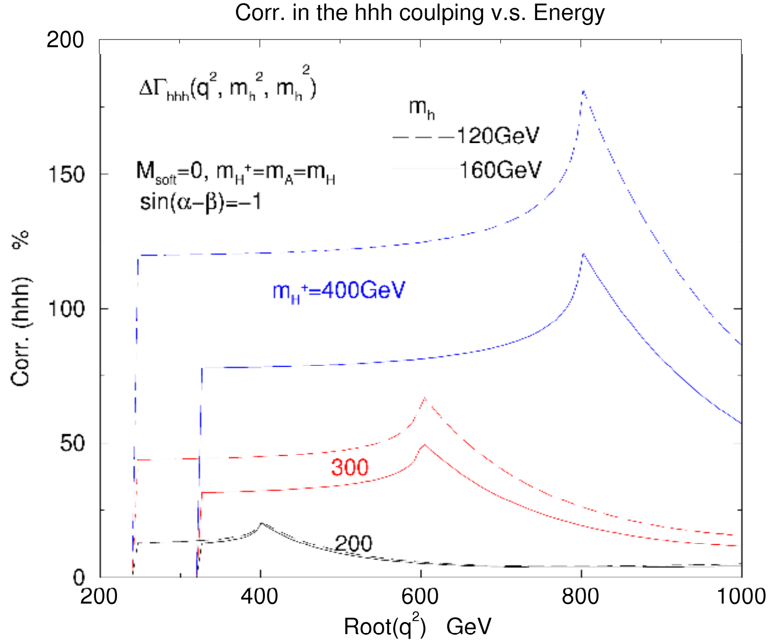
Effective hhh coupling in THDM

S. Kanemura, Y. Okada, E. Senaha, C. P. Yuan

$M \sim 0$
non-decoupling

$M \gg v$
decoupling





$$m_\Phi^2 = \lambda v^2 + M^2$$

Effective hhh coupling $\quad (\Phi = H, A, H^\pm)$

$$\frac{\Delta\Gamma_{hhh}^{\text{THDM}}}{\Gamma_{hhh}^{\text{SM}}} \equiv \frac{\Gamma_{hhh}^{\text{THDM}} - \Gamma_{hhh}^{\text{SM}}}{\Gamma_{hhh}^{\text{SM}}}$$

$$\lambda_{hhh}^{\text{eff}} \simeq \frac{3m_h^2}{v}\left[1 + \sum_\Phi \frac{m_\Phi^4}{12\pi^2 v^2 m_h^2}\left(1 - \frac{M^2}{m_\Phi^2}\right)^3 - \frac{N_c m_t^4}{3\pi^2 v^2 m_h^2}\right]$$

m_Φ^4 term appear in 1-loop correction

We set M=0. $\quad H, A, H^\pm$ receive their masses from the VEV.

heavier Higgs boson loop effect ~ 100% non-decoupling

THDM, Scalar LQ and 4th generation

In order to study the impact of the new physics effect on the double Higgs production processes at the LHC and ILC, we focus on the following models.

1. Two Higgs doublet model (THDM) with SM-like limit $\longleftarrow$ Charged scalar particle

Higgs potential

$$V_{\text{THDM}} = \mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 - (\mu_3^2\Phi_1^\dagger\Phi_2 + \text{h.c.})$$
$$+\lambda_1|\Phi_1|^4 + \lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{\lambda_5}{2}\{(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\}$$

SM-like limit $\sin(\alpha-\beta) = -1$

Lightest Higgs has the same tree-level coupling as the SM Higgs boson and the other Higgs bosons do not couple to gauge bosons.

2. Scalar leptoquark (LQ) model $\longleftarrow$ Colored scalar particle

Higgs potential

$$V_{\text{LQ}} = V_{\text{SM}} + M_{\text{LQ}}^2|\phi_{\text{LQ}}|^2 + \lambda_{\text{LQ}}|\phi_{\text{LQ}}|^4 + \lambda'|\phi_{\text{LQ}}|^2|\Phi|^2$$

LQ-lepton-quark interaction

$$\mathcal{L} = (g_{1L}\bar{Q}^c i\tau_2 L + g_{1R}\bar{u}_R^c e_R)S_1 + \tilde{g}_{1R}\bar{d}_R^c e_R\tilde{S}_1 + \text{h.c.}$$

These couplings do not contribute to the double Higgs production processes.

3. Chiral 4th generation model $\longleftarrow$ Colored fermion

Yukawa coupling

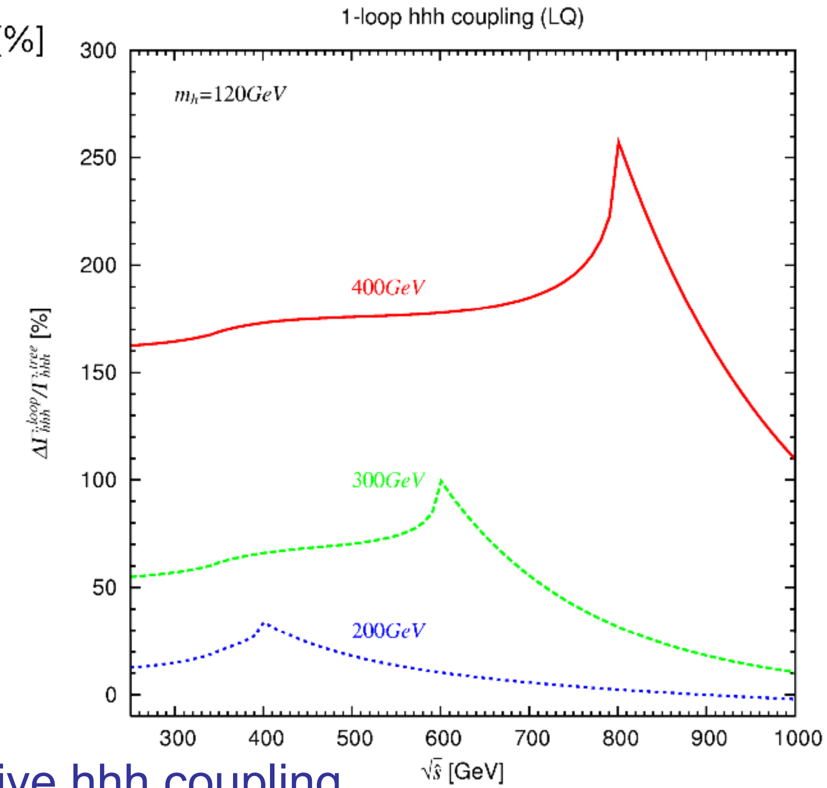
$$\mathcal{L}_{\text{Yuk}} = -y_{t'}\bar{Q}_L t'_R\tilde{\Phi} - y_{b'}\bar{Q}_L b_R\Phi + \text{h.c.} \qquad Q_L = \begin{pmatrix} t'_L \\ b'_L \end{pmatrix}$$

Effective hhh coupling in Scalar LQ and 4th generation

For $m_h = 120$ GeV

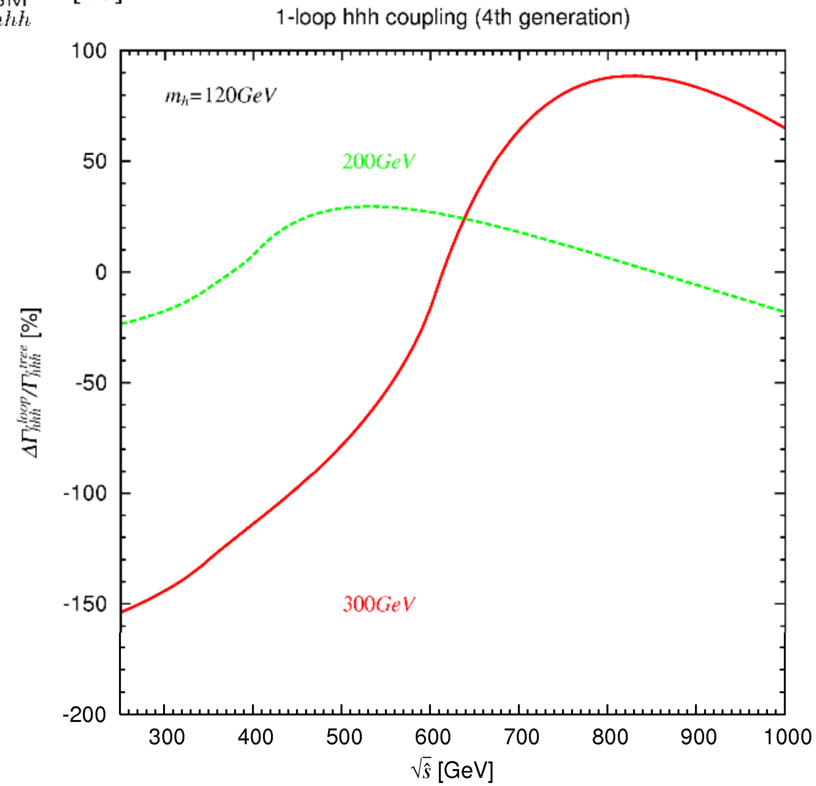
Scalar LQ

$\frac{\Delta\Gamma^{LQ}_{hhh}}{\Gamma^{SM}_{hhh}}$ [%]



Chiral 4th generation

$\frac{\Delta\Gamma^{4th}_{hhh}}{\Gamma^{SM}_{hhh}}$ [%]



Effective hhh coupling

Scalar LQ

$$\lambda^{\rm eff}_{hhh} \simeq \frac{3m_h^2}{v}\left[1 + \frac{N_c m^4_{\phi_{LQ}}}{12\pi^2 v^2 m_h^2}\left(1 - \frac{M^2}{m^2_{\phi_{LQ}}}\right)^3 - \frac{N_c m_t^4}{3\pi^2 v^2 m_h^2}\right]$$

We set M=0.

Chiral 4th generation

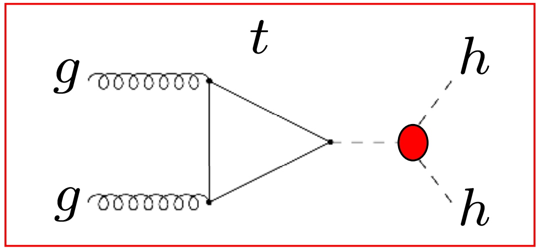
$$\lambda^{\rm eff}_{hhh} \simeq \frac{3m_h^2}{v}\left[1 - \frac{N_c(m^4_{t'} + m^4_{b'})}{3\pi^2 v^2 m_h^2} - \frac{N_c m_t^4}{3\pi^2 v^2 m_h^2}\right]$$

LHC

$gg \to hh$

$\mathcal{M}(l_1, l_2)$ top loop diagrams

pole



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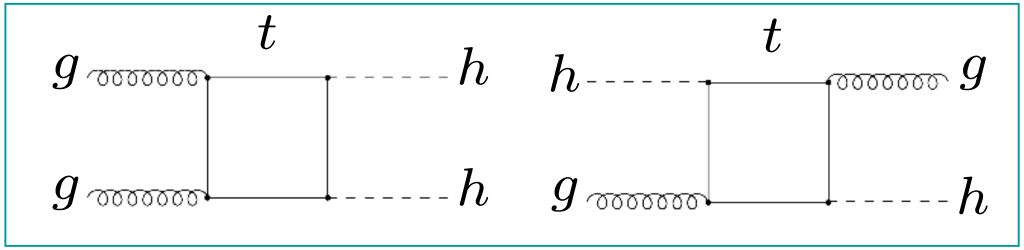
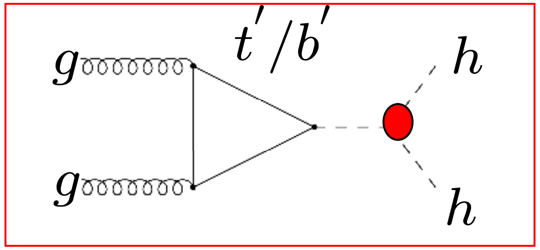
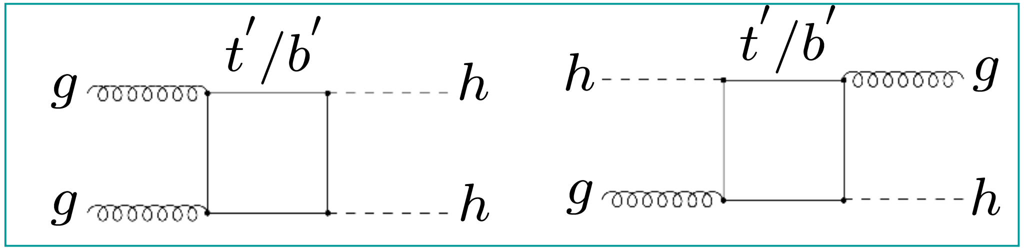


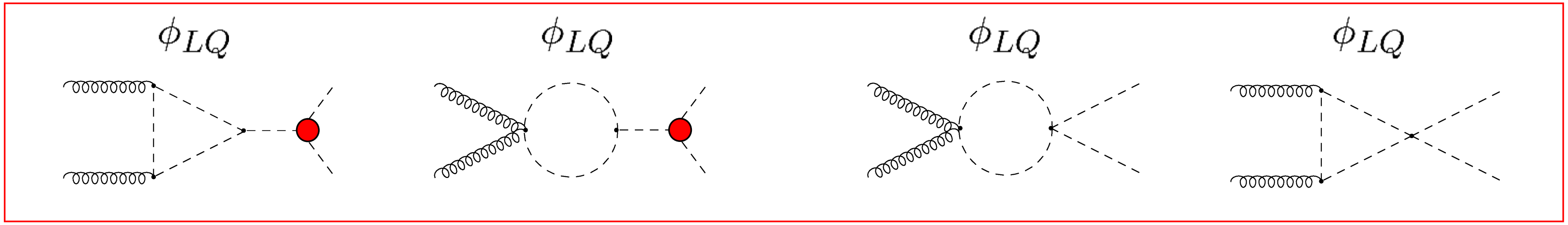
$\Delta\mathcal{M}(l_1, l_2)$ Additional one-loop diagrams

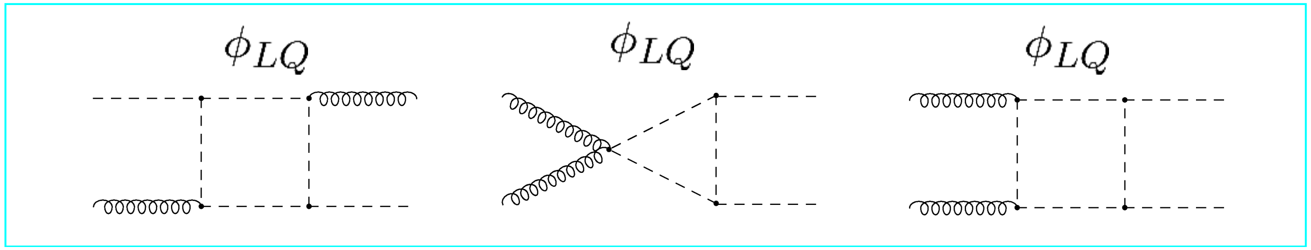
4th generation





Scalar LQ





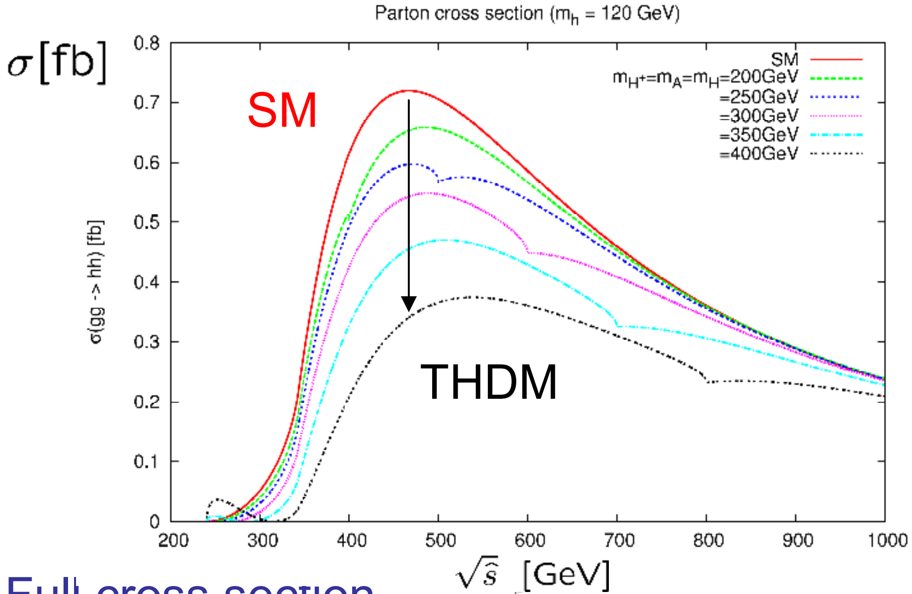
Sub/Full Cross Section in THDM and LQ

For $m_h = 120\ \text{GeV}$

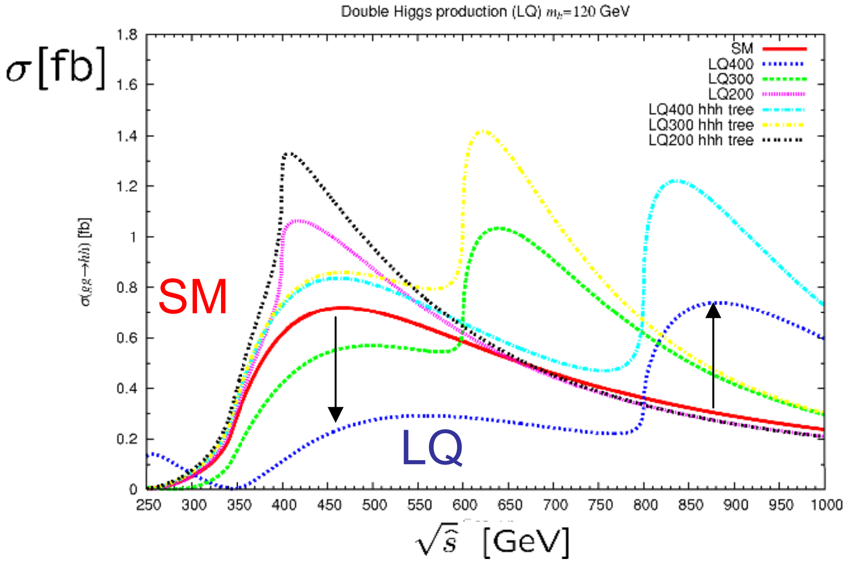
$m_H = m_A = m_{H^\pm} = 400\text{GeV}$ $\quad \dfrac{\Delta\Gamma^{\text{THDM}}_{hhh}}{\Gamma^{\text{SM}}_{hhh}} \sim 120\%$

$m_{\phi_{LQ}} = 400\text{GeV}$ $\quad \dfrac{\Delta\Gamma^{\text{LQ}}_{hhh}}{\Gamma^{\text{SM}}_{hhh}} \sim 160\%$

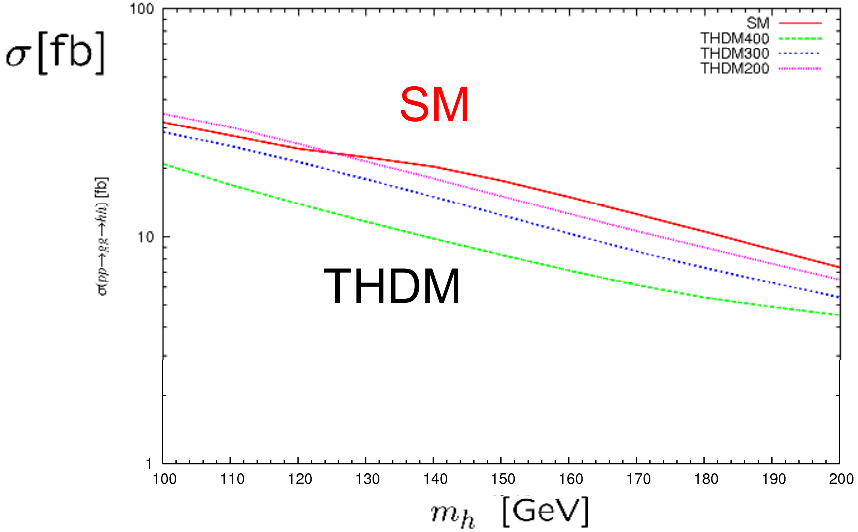
Sub cross section



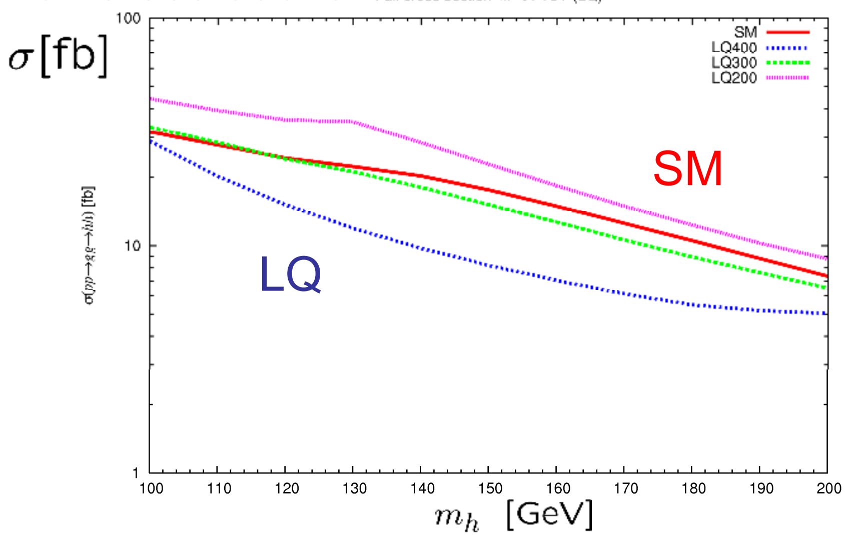
Sub cross section



Full cross section

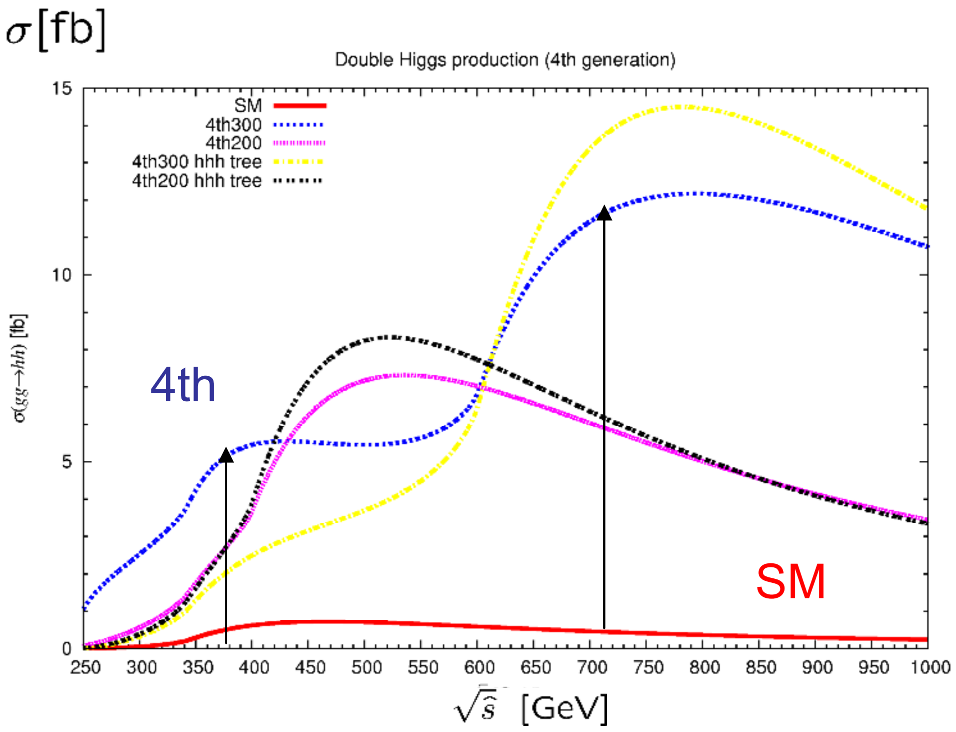


Full cross section

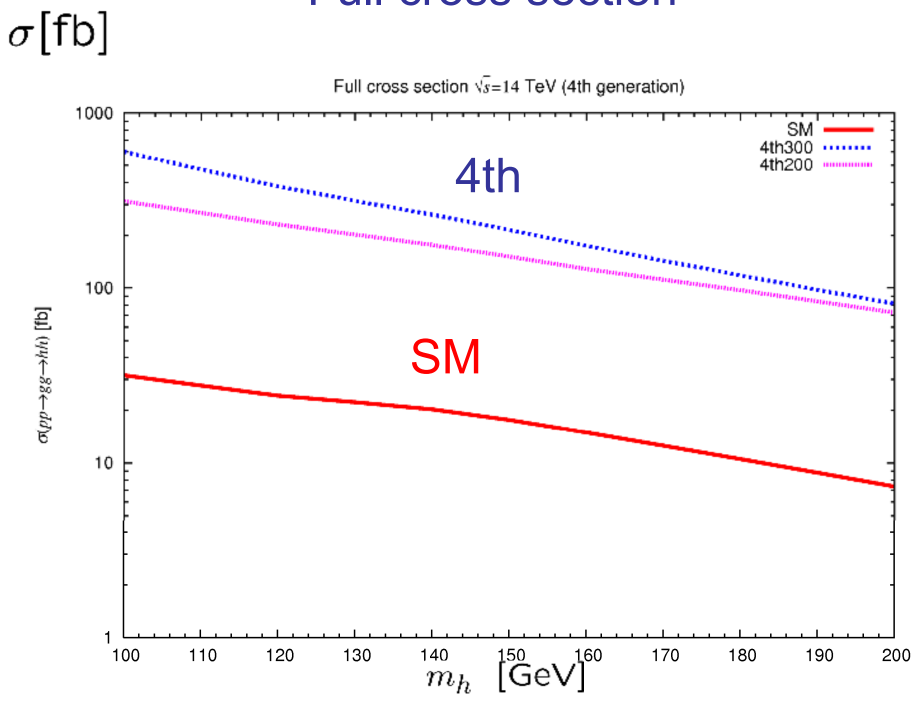


Sub/Full Cross Section in 4th generation

Sub cross section



Full cross section



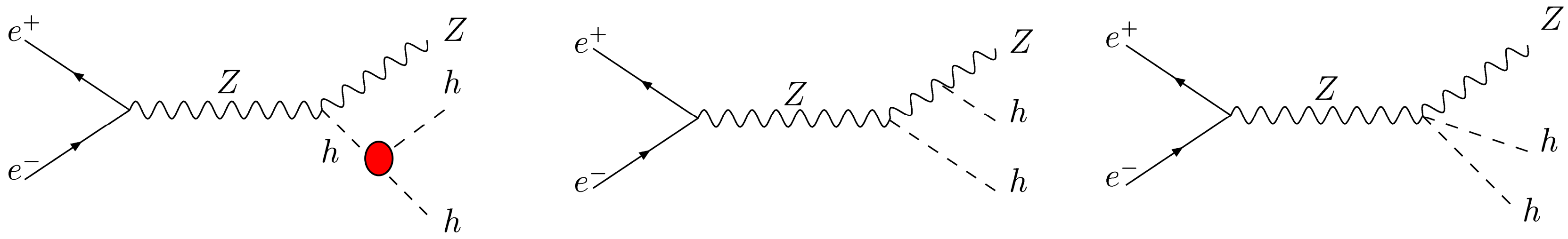
The cross section is enhanced because the amplitude of top loop triangle diagram becomes small.

For $m_h = 120$ GeV $m_{t'} = m_{b'} = 300$ GeV $\frac{\Delta\Gamma^{4th}_{hhh}}{\Gamma^{SM}_{hhh}} \sim -150\%$

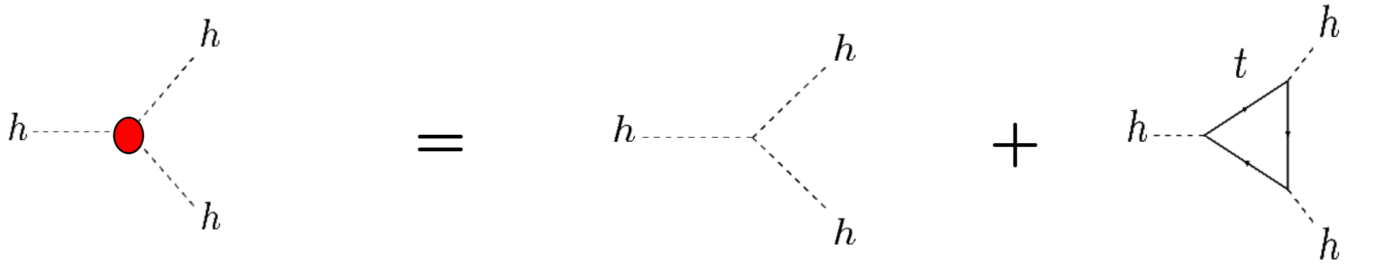
ILC

New Physics effect on Zhh process

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



Effective hhh coupling



$+$ counter term

In addition to the top loop, there are following loop effects of new particles in each models.

THDM	Heavy Higgs $H, A, H^{\pm}$
Scalar LQ	Scalar LQ S_1
Chiral 4th	4^{th} quark t', b'

New Physics effect on Zhh process

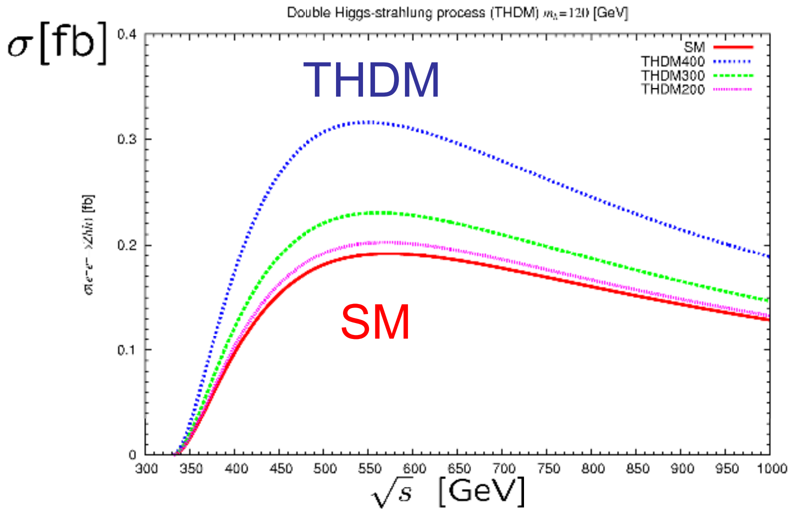
For $m_h = 120$ GeV

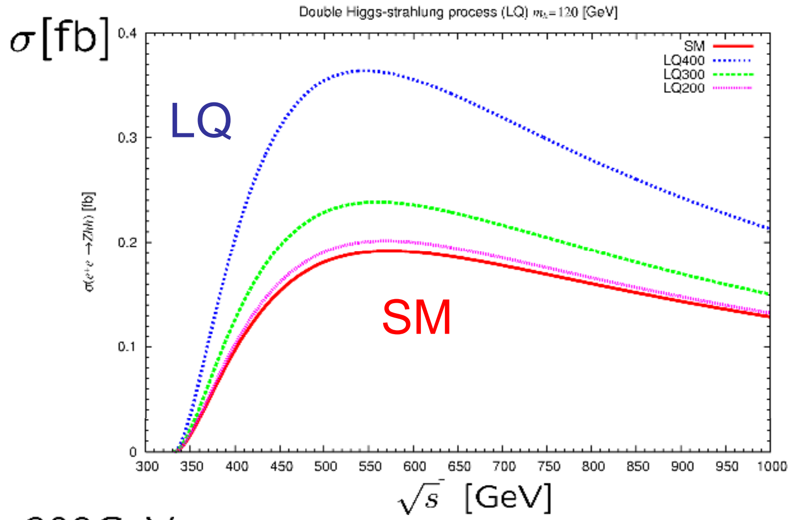
$m_H = m_A = m_{H^\pm} = 400\text{GeV}$

THDM $\dfrac{\Delta\Gamma^{\text{THDM}}_{hhh}}{\Gamma^{\text{SM}}_{hhh}} \sim 120\%$

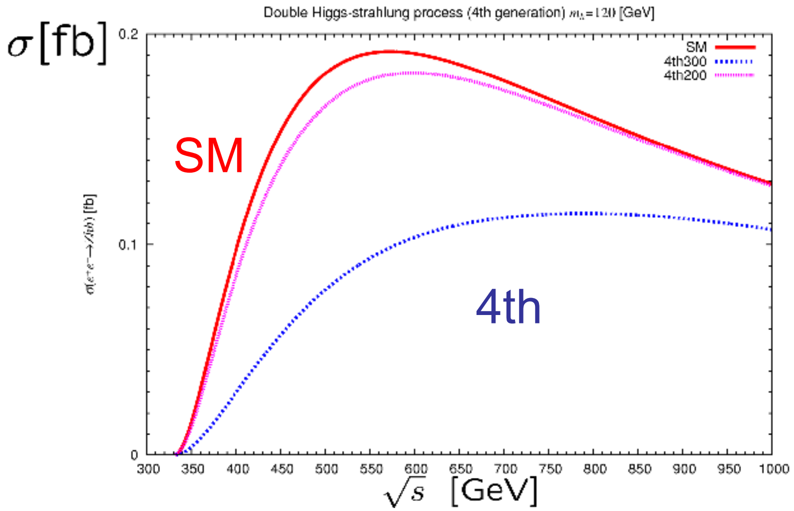
$m_{\phi_{LQ}} = 400\text{GeV}$

Scalar LQ $\dfrac{\Delta\Gamma^{\text{LQ}}_{hhh}}{\Gamma^{\text{SM}}_{hhh}} \sim 160\%$





Chiral 4th generation $m_{t'} = m_{b'} = 300\text{GeV}$



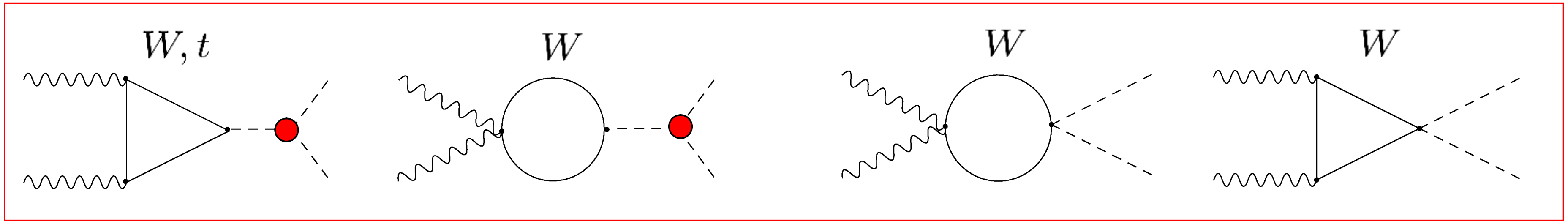
This process at the ILC with a center of mass energy of 500 GeV is useful to distinguish whether the new particle is boson or fermion.
The cross section becomes large (small)
If new particle is boson (fermion).
In this process, the cross section shift the same direction as the effective hhh coupling.

$\dfrac{\Delta\Gamma^{\text{4th}}_{hhh}}{\Gamma^{\text{SM}}_{hhh}} \sim -150\%$

PLC

New Physics effect on $\gamma\gamma \to hh$ process

$\mathcal{M}(l_1, l_2)$ W boson and top loop diagrams $\gamma\gamma \to hh$ pole



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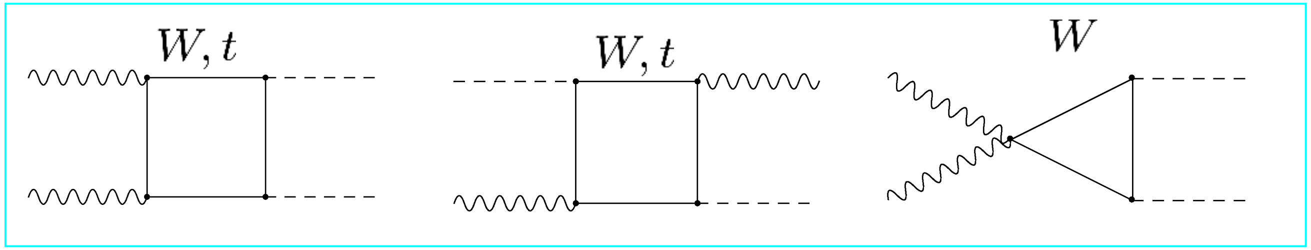
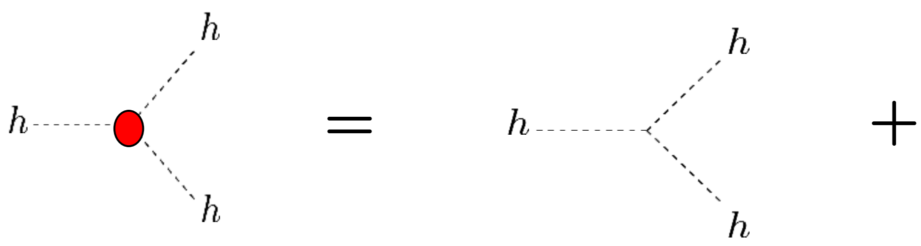


Effective hhh coupling

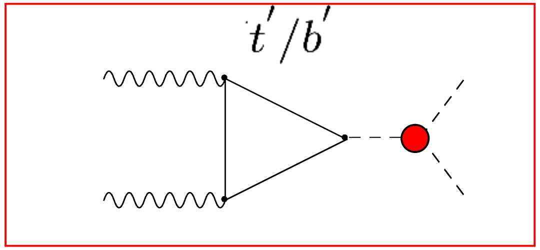


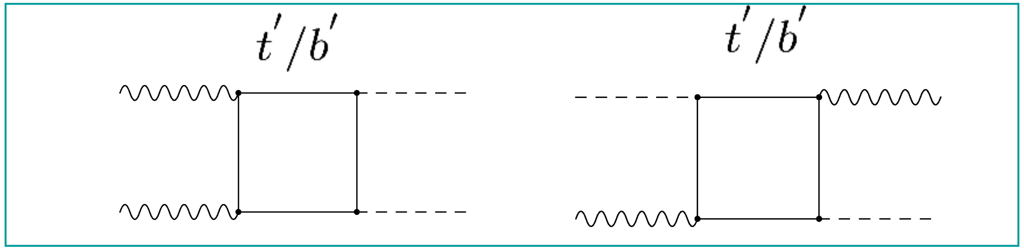
“New particle / top” loop effect

In addition to the W boson and top loop contribution to the loop induced process, there are following diagrams.

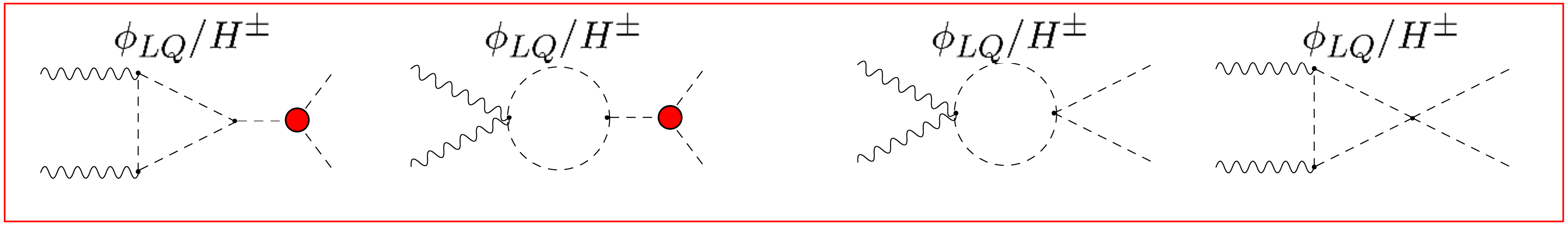
$\Delta\mathcal{M}(l_1, l_2)$ Additional one-loop diagrams

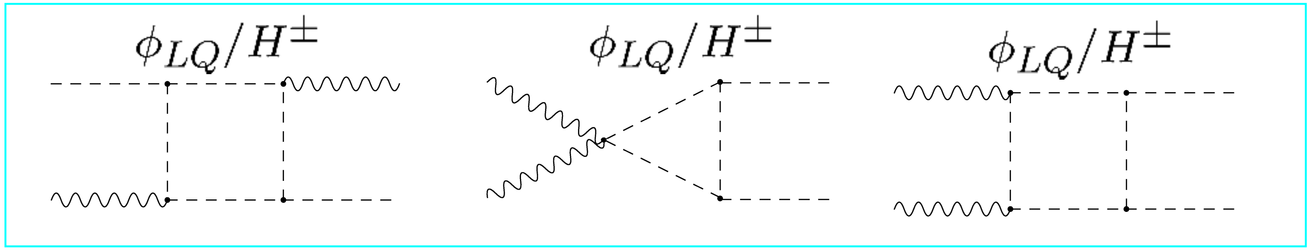
4th generation





Scalar LQ / THDM with SM-like limit



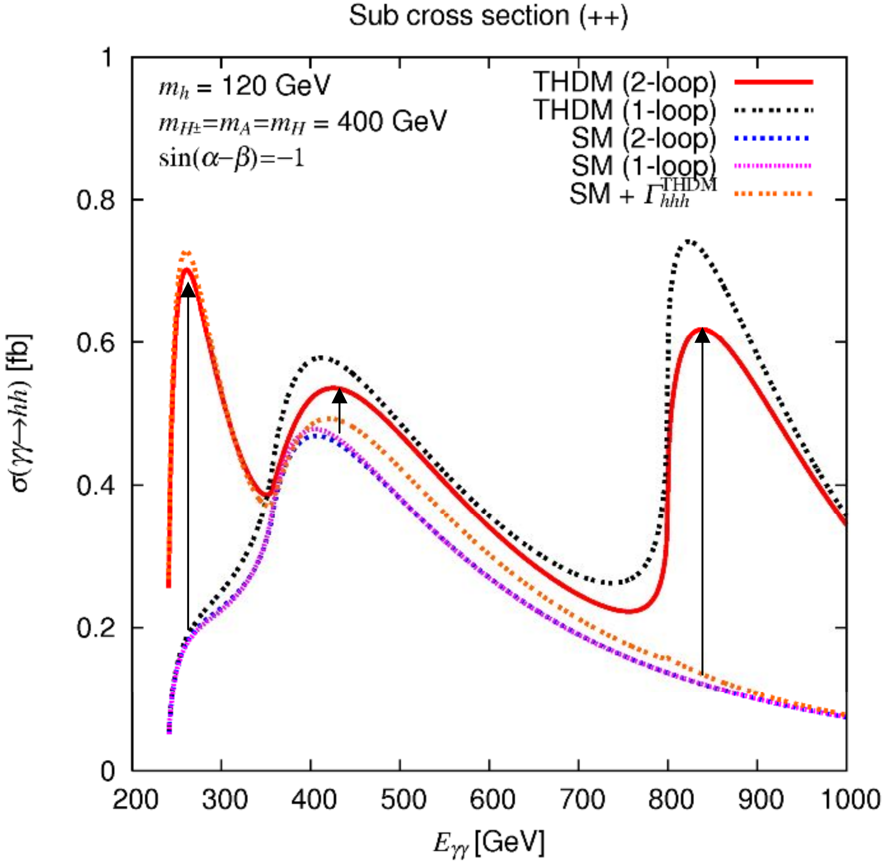


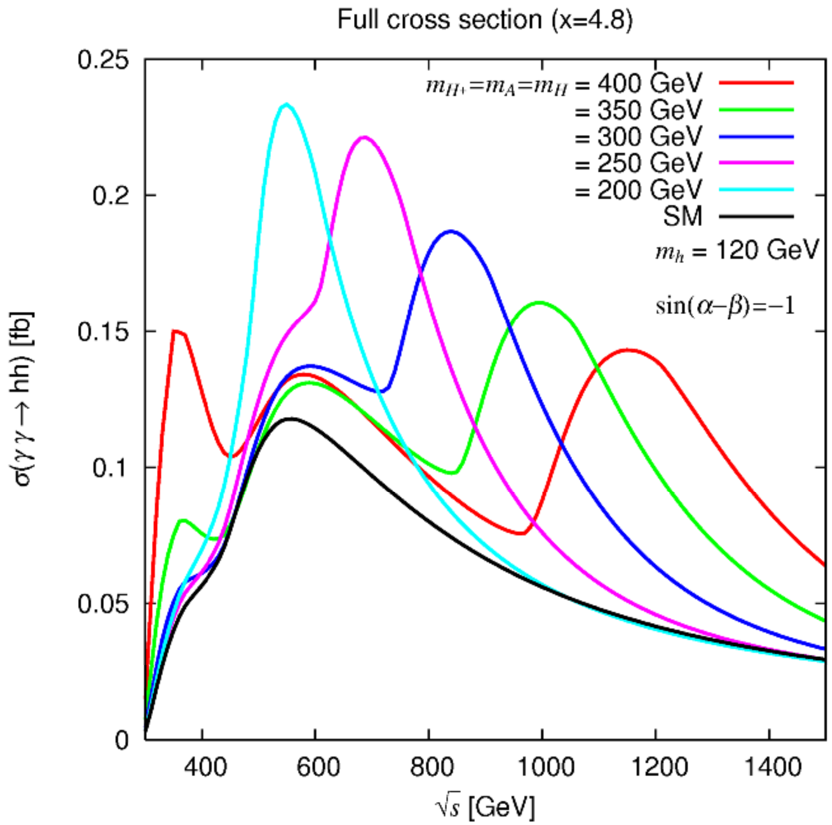
Sub/Full Cross Section in THDM

$m_H = m_A = m_{H^\pm} = 400\text{GeV}$

For $m_h = 120$ GeV

$e^-e^- \to \gamma\gamma \to hh$





$E_{\gamma\gamma} \sim 250$ GeV Cross section is enhanced by the effect of $\frac{\Delta\Gamma_{hhh}^{\rm THDM}}{\Gamma_{hhh}^{\rm SM}} \sim 120\%$

$E_{\gamma\gamma} \sim 400$ GeV Threshold enhancement of top pair production

$E_{\gamma\gamma} \sim 850$ GeV Threshold enhancement of charged Higgs pair production

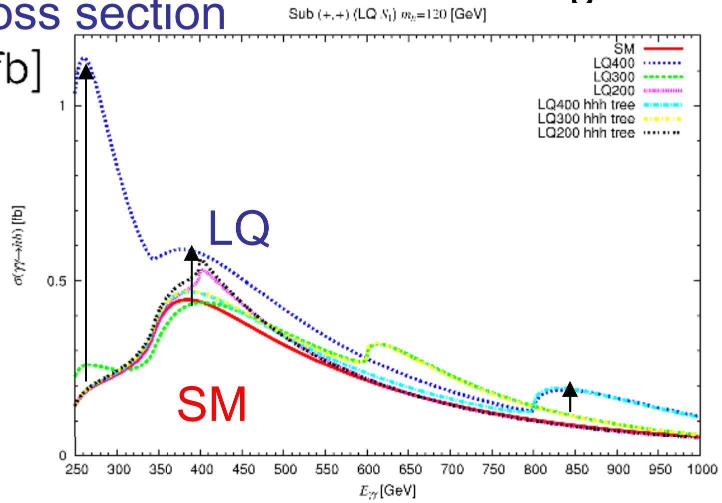
Sub/Full Cross Section in LQ and 4th generation

For $m_h = 120$ GeV $\quad \mathcal{M}_{LQ} \propto N_c Q_s^2$

Scalar LQ S_1 with charge +1/3

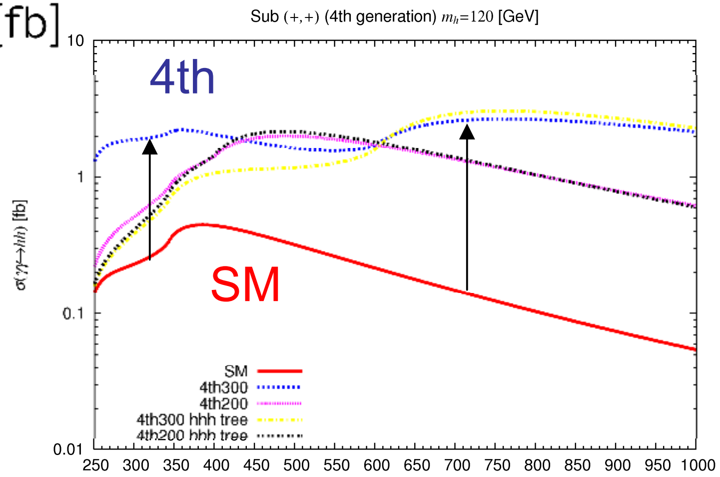
Chiral 4th generation

Sub cross section



σ[fb]

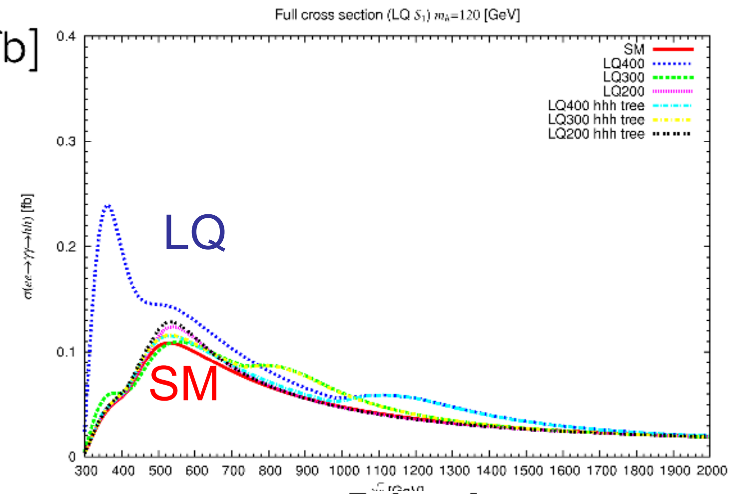
Sub cross section



σ[fb]

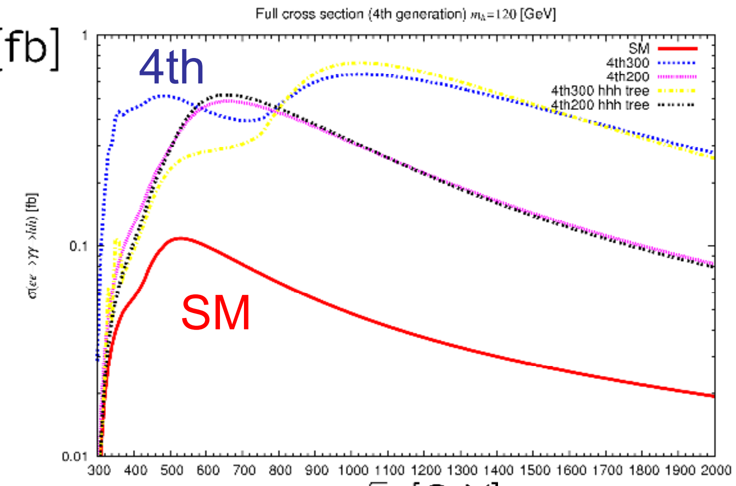
Full cross section $\quad E_{\gamma\gamma}$ [GeV]

Full cross section $\quad E_{\gamma\gamma}$ [GeV]



σ[fb]

$\sqrt{s}$ [GeV]



σ[fb]

$\sqrt{s}$ [GeV]

$m_{\phi_{LQ}} = 400\text{GeV} \quad \frac{\Delta\Gamma^{LQ}_{hhh}}{\Gamma^{SM}_{hhh}} \sim 160\%$

$m_{t'} = m_{b'} = 300\text{GeV} \quad \frac{\Delta\Gamma^{4th}_{hhh}}{\Gamma^{SM}_{hhh}} \sim -150\%$

Summary

We studied double Higgs production process in THDM with SM-like limit, scalar LQ and chiral 4th generation model.

- The cross section is largely changed by two effects.
  - additional contribution of new particle loop

    PLC, LHC
  - Effective 1-loop hhh vertex enhanced by the non-decoupling effect

    ILC, PLC, LHC
- The cross section strongly depend on each new physics model.

For $m_h = 120\text{GeV}$ $m_\Phi = 400\text{GeV}$ S_1 with charge +1/3 $m_{t'} = m_{b'} = 300\text{GeV}$

	THDM	Scalar LQ S_1	4th generation
hhh coupling	$\frac{\Delta\Gamma^{\text{THDM}}_{hhh}}{\Gamma^{\text{SM}}_{hhh}} \sim +120\%$	$\frac{\Delta\Gamma^{\text{LQ}}_{hhh}}{\Gamma^{\text{SM}}_{hhh}} \sim +160\%$	$\frac{\Delta\Gamma^{\text{4th}}_{hhh}}{\Gamma^{\text{SM}}_{hhh}} \sim -150\%$
ILC $\sqrt{s} = 500\text{GeV}$	$\frac{\Delta\sigma^{\text{THDM}}}{\sigma^{\text{SM}}} \sim +70\%$	$\frac{\Delta\sigma^{\text{LQ}}}{\sigma^{\text{SM}}} \sim +95\%$	$\frac{\Delta\sigma^{\text{4th}}}{\sigma^{\text{SM}}} \sim -55\%$
LHC $\sqrt{s} = 14\text{TeV}$	$\frac{\Delta\sigma^{\text{THDM}}}{\sigma^{\text{SM}}} \sim -50\%$	$\frac{\Delta\sigma^{\text{LQ}}}{\sigma^{\text{SM}}} \sim -40\%$	$\frac{\Delta\sigma^{\text{4th}}}{\sigma^{\text{SM}}} \sim +1400\%$
PLC $\sqrt{s} = 500\text{GeV}$	$\frac{\Delta\sigma^{\text{THDM}}}{\sigma^{\text{SM}}} \sim +10\%$	$\frac{\Delta\sigma^{\text{LQ}}}{\sigma^{\text{SM}}} \sim +40\%$	$\frac{\Delta\sigma^{\text{4th}}}{\sigma^{\text{SM}}} \sim +390\%$

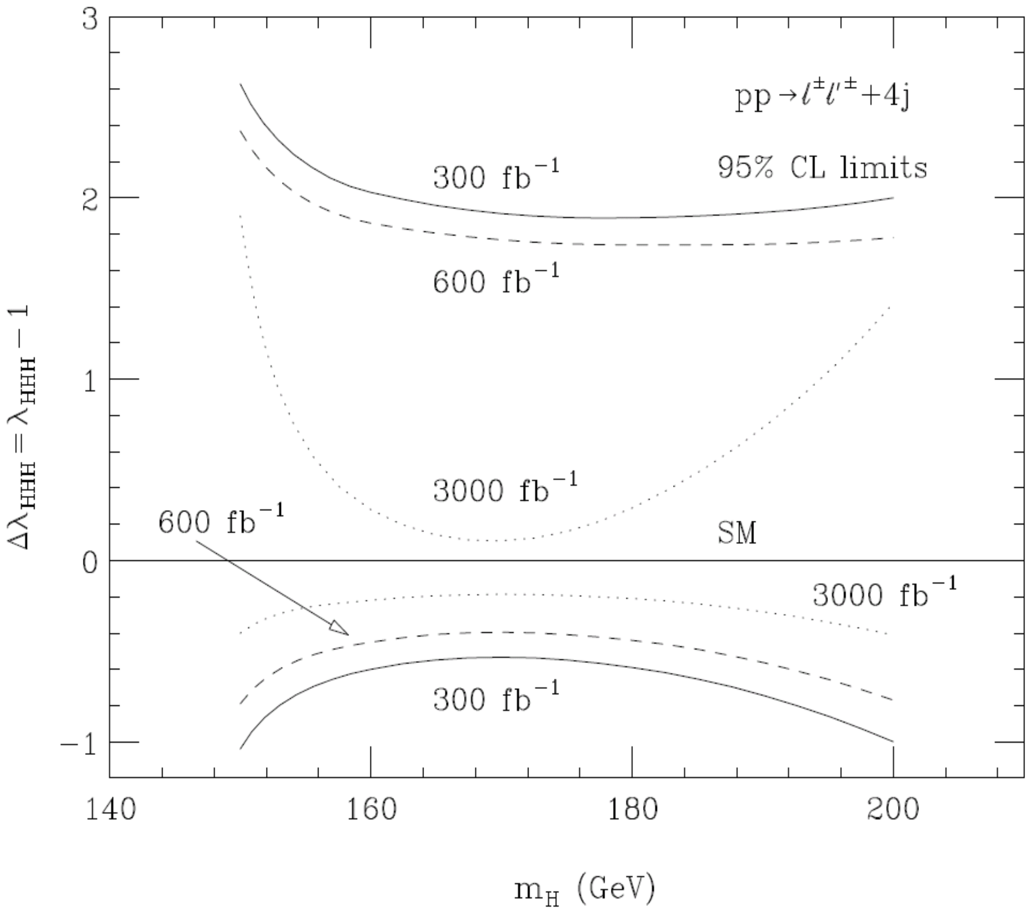
Backup Slide

hhh measurement at the LHC

U. Baur, T. Plehn, D. Rainwater

$\lambda_{hhh} = \lambda_{hhh}^{\text{SM}}(1 + \delta\kappa)$

$pp \to hh \to (W^+W^-)(W^+W^-) \to l^{\pm}l'^{\pm} + 4j$



$\lambda_{hhh} = \lambda_{hhh}^{\text{SM}} = \frac{3m_h^2}{v}$

$(\delta\kappa = 0)$

At the LHC, vanishing Higgs self-coupling is excluded. $\lambda_{hhh} = 0 \quad (\delta\kappa = -1)$

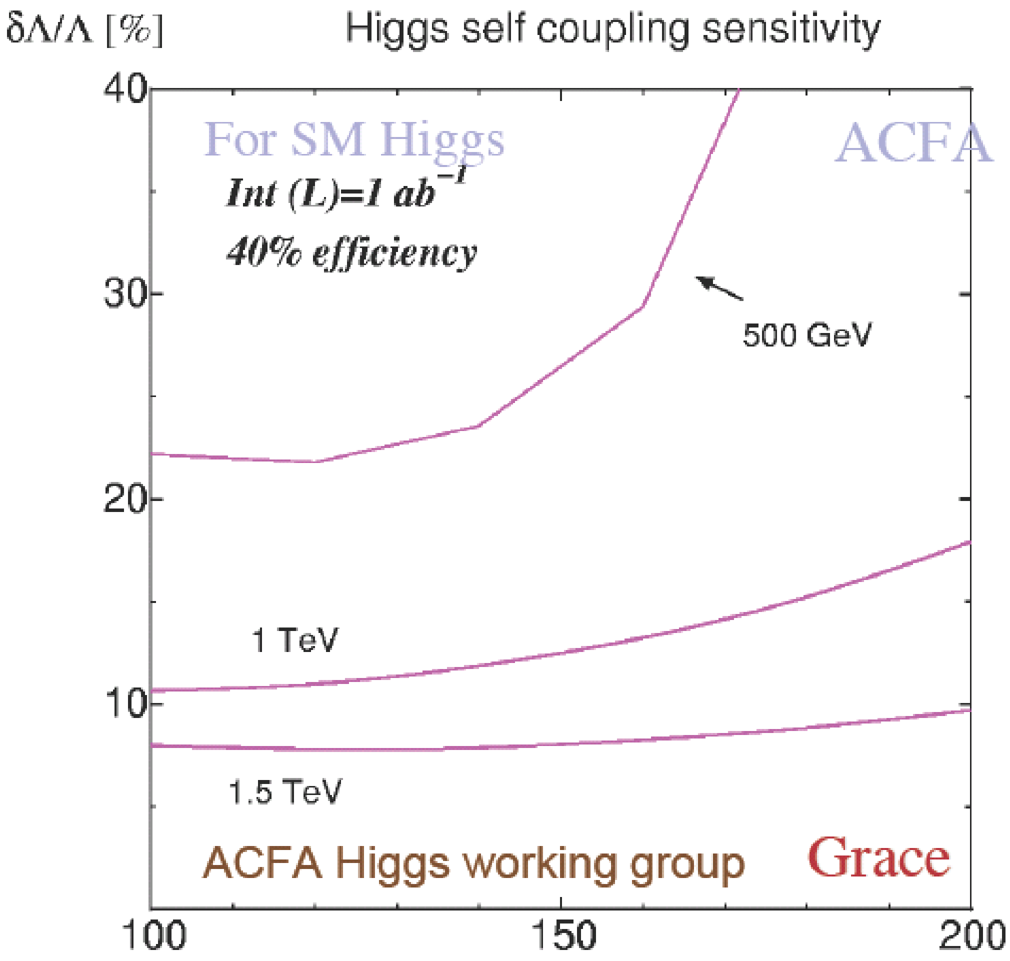
At the SLHC, Higgs self-coupling can be determined with an accuracy of 20-30 %.

$160\text{GeV} \leq m_h \leq 180\text{GeV}$

hhh measurement at the ILC

ACFA Higgs Working Group 2002

$$\lambda_{hhh} = \lambda_{hhh}^{\text{SM}}(1 + \delta\kappa)$$



$\int \mathcal{L} dt = 1\text{ab}^{-1}$

1st ILC

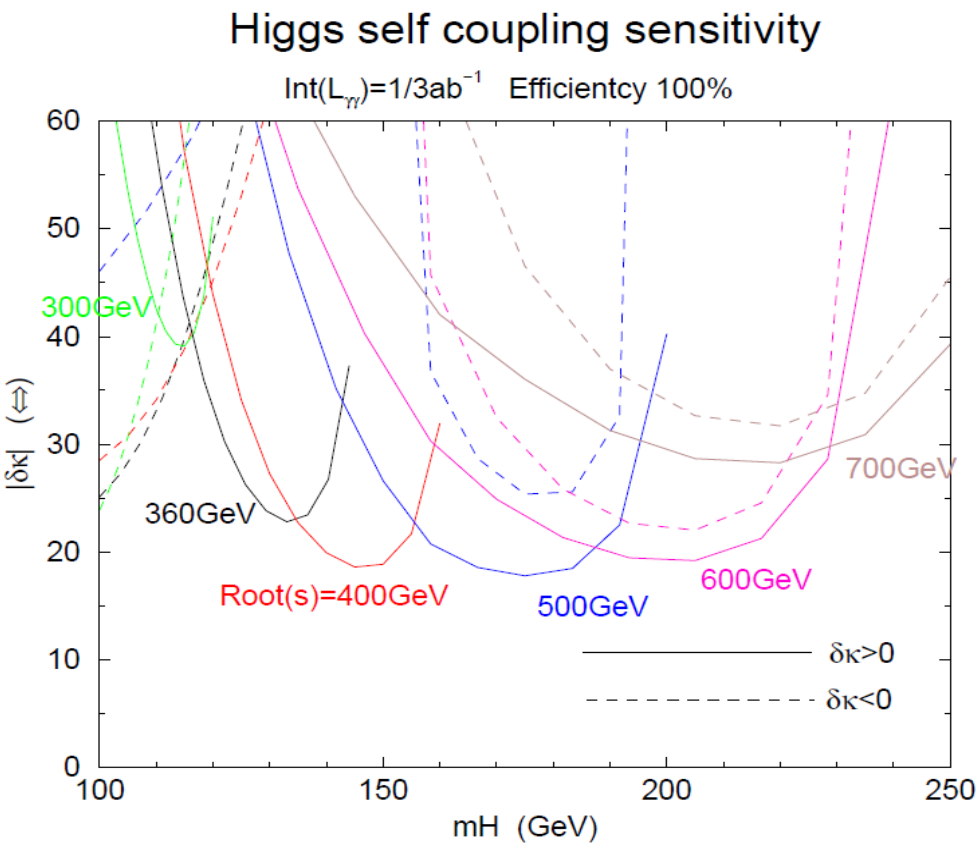
$\sqrt{s} = 500\text{GeV}$

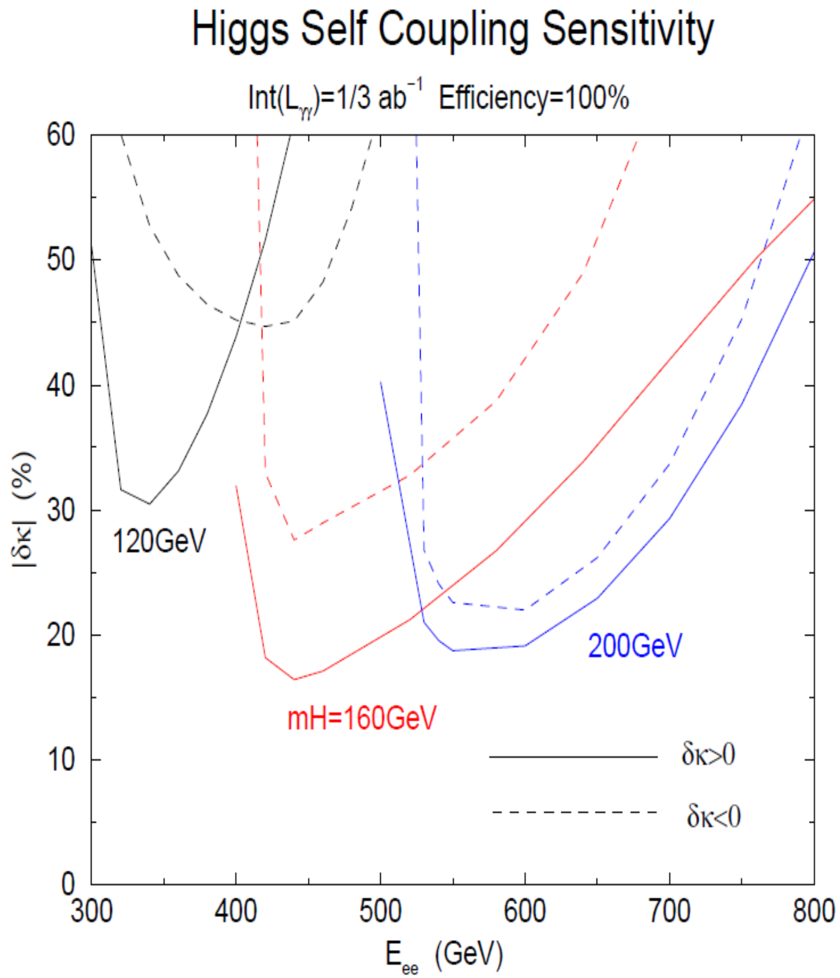
At the 1st ILC, Higgs self-coupling can be determined with an accuracy of 20-30 %.

$m_h < 170\text{GeV}$

hhh measurement at the PLC

E.Asakawa, D. Harada, S. Kanemura, Y. Okada, K. Tsumura at TILC 08





Photon linear collider (Eee < 500GeV) is useful to measure the HHH coupling for mH = 150-200.

Two Higgs Doublet Model

Higgs potential

$$V_{\text{THDM}} = \mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 - (\mu_3^2\Phi_1^\dagger\Phi_2 + \text{h.c.})$$
$$+\lambda_1|\Phi_1|^4 + \lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{\lambda_5}{2}\{(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\}$$

Higgs doublets

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = R(\alpha)\begin{pmatrix} H \\ h \end{pmatrix}$$

$$\begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = R(\beta)\begin{pmatrix} z \\ A \end{pmatrix}$$

$$\begin{pmatrix} \omega_1^+ \\ \omega_2^+ \end{pmatrix} = R(\beta)\begin{pmatrix} \omega^+ \\ H^+ \end{pmatrix} \qquad R(\theta) = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

$$\Phi_i = \begin{pmatrix} \omega_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i + iz_i) \end{pmatrix} \quad (i = 1, 2)$$

$$\tan\beta = \frac{v_2}{v_1} \qquad v^2 = v_1^2 + v_2^2 \simeq (246\text{GeV})^2$$

CP-even h, H CP-odd A Charged bosons $H^\pm$

$$m_h^2 = \{\lambda_1\cos^4\beta + \lambda_2\sin^4\beta + 2(\lambda_3+\lambda_4+\lambda_5)\cos^2\beta\sin^2\beta\}v^2$$

$$m_H^2 = M^2 + \frac{1}{8}\{\lambda_1 + \lambda_2 - 2(\lambda_3 + \lambda_4 + \lambda_5)\}(1 - \cos 4\beta)v^2$$

$$m_A^2 = M^2 - \lambda_5 v^2$$

$$m_{H^\pm}^2 = M^2 - \frac{\lambda_4+\lambda_5}{2}v^2 \qquad M = \frac{|\mu_3|}{\sqrt{\sin\beta\cos\beta}}$$

We consider following parameters

- SM-like limit $\sin(\alpha - \beta) = -1$

Lightest Higgs has the same tree-level coupling as the SM Higgs boson and the other Higgs bosons do not couple to gauge bosons.

- Non-decoupling limit $M = 0$

In the THDM, extra Higgs boson loop correction is known as non-decoupling effect.

- rho parameter constrain $\rho = \dfrac{m_W^2}{m_Z^2 \cos\theta_W}$

$$m_H \simeq m_A \simeq m_{H^\pm}$$

We assume that the masses of the extra Higgs bosons degenerate.

$$m_H = m_A = m_{H^\pm}$$

Scalar LQ model

In addition to the SM, we introduce the scalar LQ.

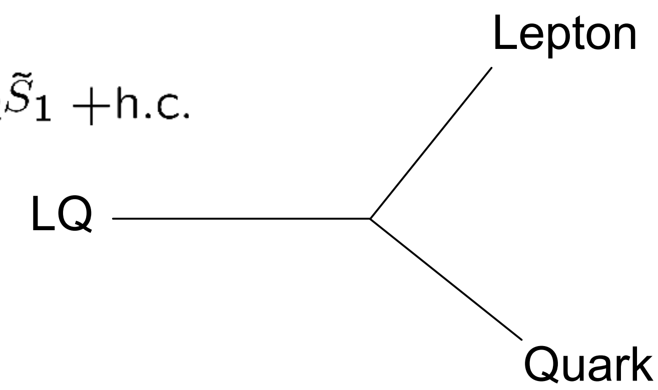
Higgs potential

$$V_{\mathrm{LQ}} = V_{\mathrm{SM}} + M_{\mathrm{LQ}}^2 |\phi_{\mathrm{LQ}}|^2 + \lambda_{\mathrm{LQ}} |\phi_{\mathrm{LQ}}|^4 + \lambda' |\phi_{\mathrm{LQ}}|^2 |\Phi|^2$$

$$m_{\phi_{LQ}}^2 = M_{\mathrm{LQ}}^2 + \frac{\lambda' v^2}{2}$$

LQ-lepton-quark interaction

$$\mathcal{L} = (g_{1L} \bar{Q}^c i\tau_2 L + g_{1R} \bar{u}_R^c e_R) S_1 + \tilde{g}_{1R} \bar{d}_R^c e_R \tilde{S}_1 + \mathrm{h.c.}$$



Scalar LQ S_1 with charge +1/3

$\tilde{S}_1$ with charge +4/3

These couplings do not contribute to the double Higgs production processes

Lower bounds of masses

$m_{\phi_{LQ}} > 275 - 325\mathrm{GeV}$ HERA for $g_{lq} = e$

$m_{\phi_{LQ}} > 256\mathrm{GeV}$ Tevatoron

Chiral 4th generation model

In addition to the SM, we introduce the chiral 4th generation quark t' and b'

Yukawa coupling

$$\mathcal{L}_{\text{Yuk}} = -y_{t'}\bar{Q}_L t'_R \tilde{\Phi} - y_{b'}\bar{Q}_L b_R \Phi + \text{h.c.} \qquad Q_L = \begin{pmatrix} t'_L \\ b'_L \end{pmatrix}$$

Lower bounds of masses

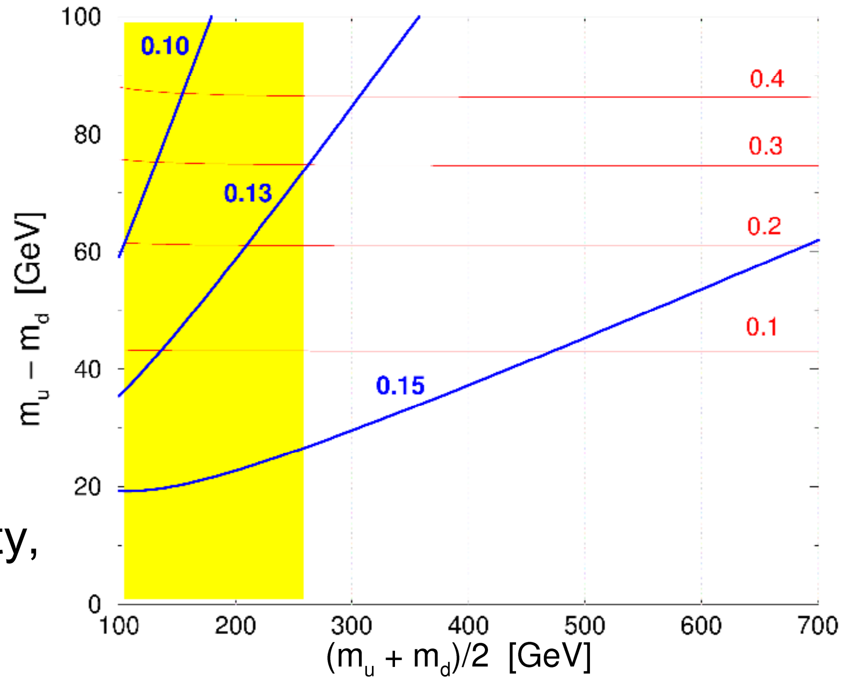
$$m_{t'} > 256\text{GeV} \qquad m_{b'} > 128\text{GeV}$$

For simplicity, we assume that masses of the chiral 4th generation quark are degenerate.

S parameter

$$\Delta S = \frac{N_c}{6\pi}\left(1 - 2Y \ln \frac{m_u^2}{m_d^2}\right)$$

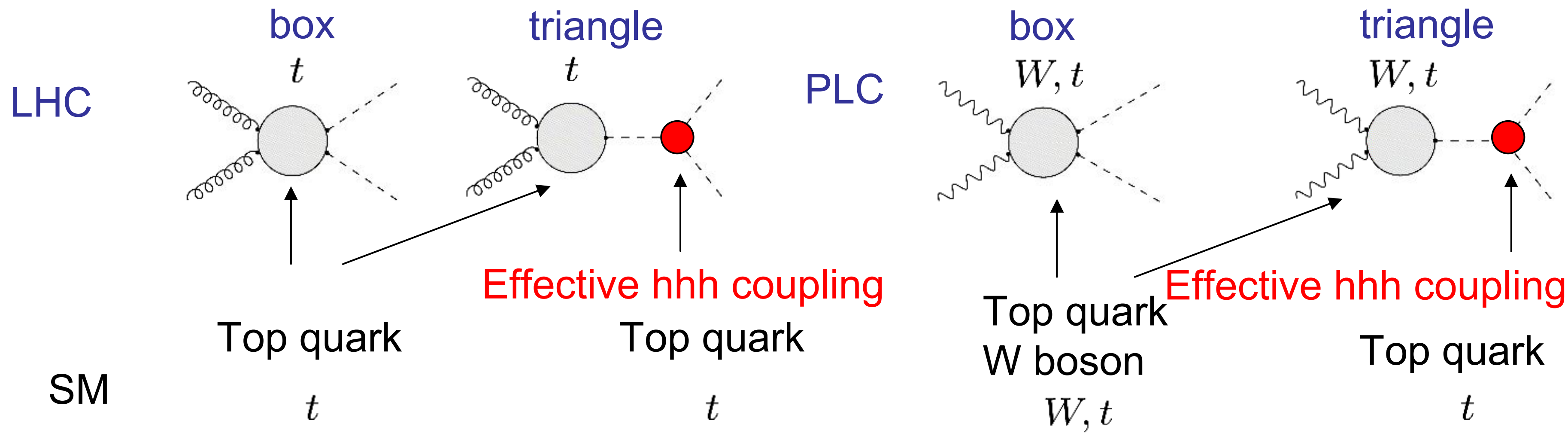
In order to avoid the constraint from CKM unitarity, we assume that 4th generation quark do not mix with the SM quarks.



G. Kribs, T. Plehn, M. Spanowsky and T. Tait

Double Higgs production process

In the SM, the top quark contribute to the gluon fusion process at LHC.
On the other hand, there are loop diagrams of W boson and top quark at PLC.

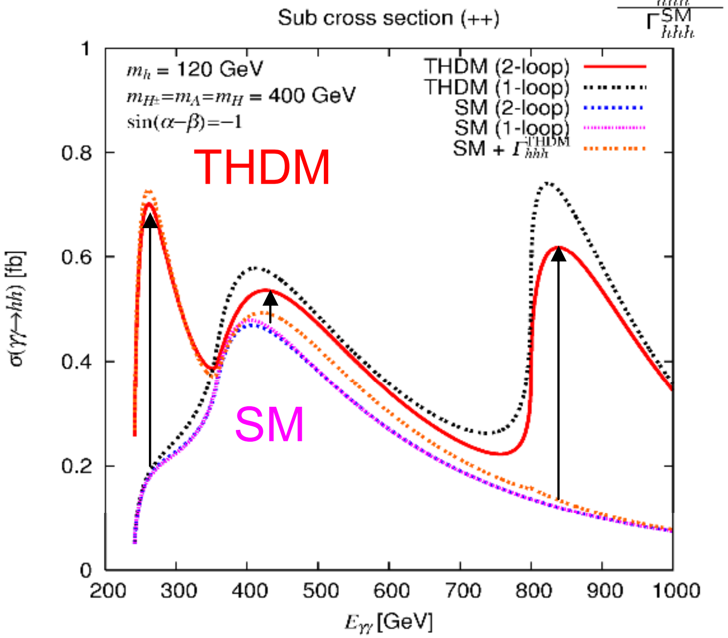


In addition to SM particles, there are following loop effects of new particles

THDM		Heavy Higgs $H, A, H^{\pm}$	Charged Higgs $H^{\pm}$	Heavy Higgs $H, A, H^{\pm}$
Scalar LQ	Scalar LQ S_1	Scalar LQ S_1	Scalar LQ S_1	Scalar LQ S_1
Chiral 4th	4^{th} quark t', b'	4^{th} quark t', b'	4^{th} quark t', b'	4^{th} quark t', b'

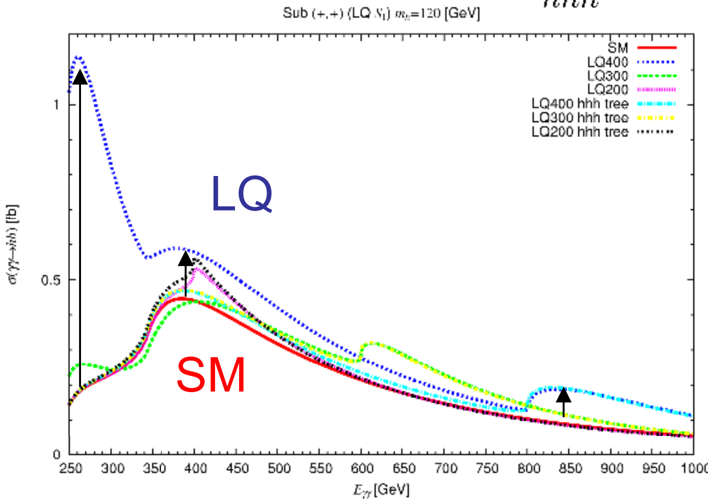
Sub Cross Section at Photon Collider

For $m_h = 120$ GeV THDM $m_H = m_A = m_{H^\pm} = 400\text{GeV}$ $\frac{\Delta\Gamma^{\text{THDM}}_{hhh}}{\Gamma^{\text{SM}}_{hhh}} \sim 120\%$



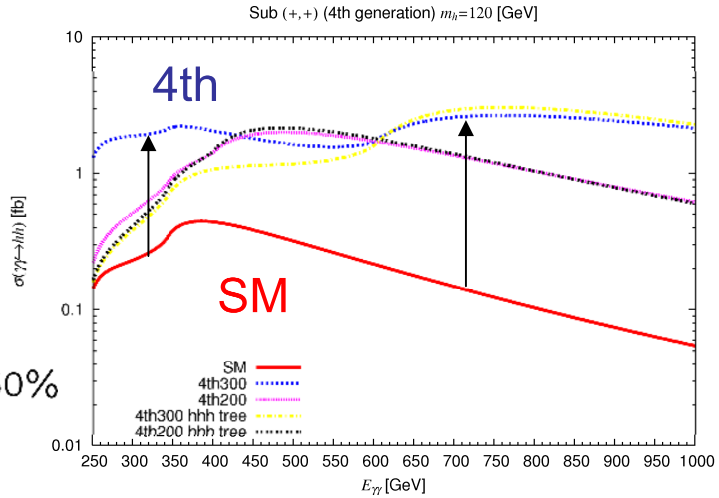
Scalar LQ S_1 with charge +1/3

$m_{\phi_{LQ}} = 400\text{GeV}$ $\frac{\Delta\Gamma^{\text{LQ}}_{hhh}}{\Gamma^{\text{SM}}_{hhh}} \sim 160\%$



$\mathcal{M}_{LQ} \propto N_c Q_s^2$

$m_{t'} = m_{b'} = 300\text{GeV}$ Chiral 4th generation



$\frac{\Delta\Gamma^{\text{4th}}_{hhh}}{\Gamma^{\text{SM}}_{hhh}} \sim -150\%$

$E_{\gamma\gamma} \sim 250$ GeV

Cross section is enhanced by the effect of the effective hhh coupling.

$E_{\gamma\gamma} \sim 400$ GeV

Threshold enhancement of top pair production

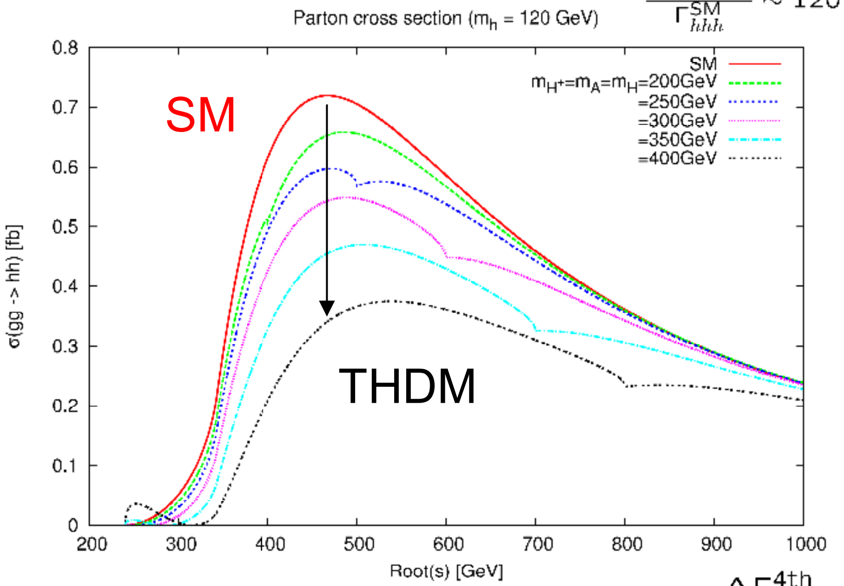
$E_{\gamma\gamma} \sim 850[700 \text{ in 4th}]$ GeV

Threshold enhancement of new particle pair production

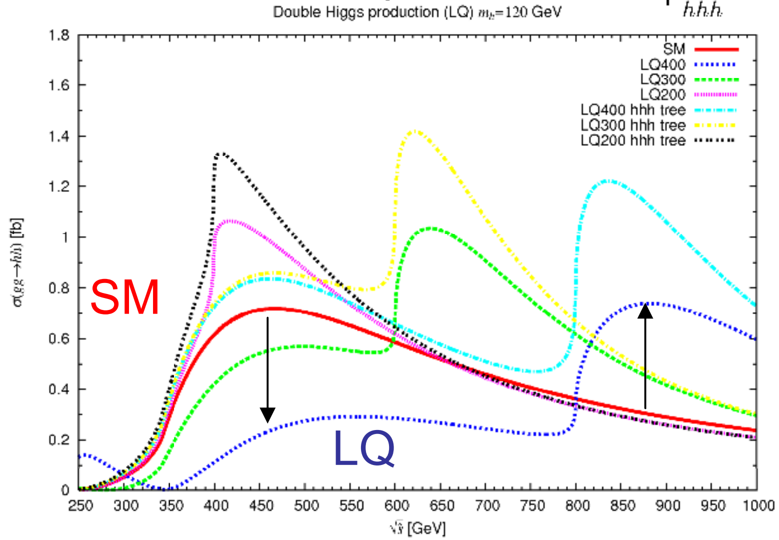
Sub Cross Section at LHC

For $m_h = 120$ GeV

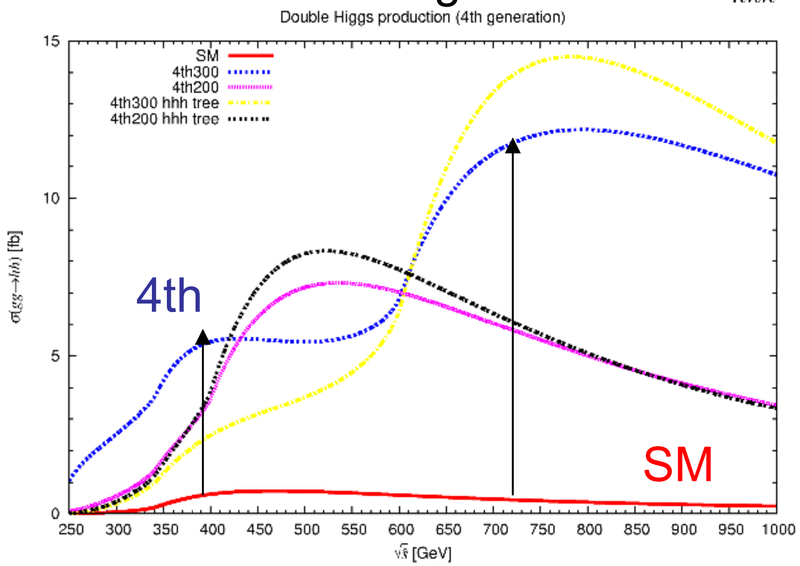
THDM $m_H = m_A = m_{H\pm} = 400\text{GeV}$ $\frac{\Delta\Gamma^{\text{THDM}}_{hhh}}{\Gamma^{\text{SM}}_{hhh}} \sim 120\%$



Scalar LQ S_1 with charge +1/3 $m_{\phi_{LQ}} = 400\text{GeV}$ $\frac{\Delta\Gamma^{\text{LQ}}_{hhh}}{\Gamma^{\text{SM}}_{hhh}} \sim 160\%$



$m_{t'} = m_{b'} = 300\text{GeV}$ Chiral 4th generation $\frac{\Delta\Gamma^{\text{4th}}_{hhh}}{\Gamma^{\text{SM}}_{hhh}} \sim -150\%$



$E_{\gamma\gamma} \sim 400$ GeV

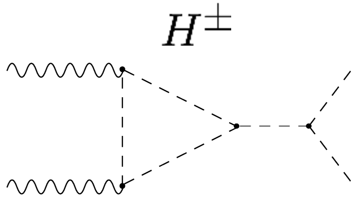
Threshold enhancement of top pair production

$E_{\gamma\gamma} \sim 850[700 \text{ in 4th}]$ GeV

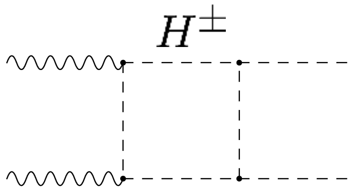
Threshold enhancement of new particle pair production

Appendix

$$m_{H^\pm} \gg \sqrt{s} > 2m_h$$



$$\mathcal{M}_{trig}^{1-loop} \propto \frac{1}{16\pi}\frac{q^2}{v}\frac{1}{s-m_h^2}\left(\frac{m_h^2}{v}\right) \sim \frac{q^2}{(4\pi v)^2}$$



$$\mathcal{M}_{box}^{1-loop} \propto \frac{1}{16\pi^2}\frac{q^2}{v^2} \sim \frac{q^2}{(4\pi v)^2}$$

$$\lambda_{hH^+H^-} \propto \frac{m_{H^\pm}^2}{v} \qquad \lambda_{hhH^+H^-} \propto \frac{m_{H^\pm}^2}{v^2}$$

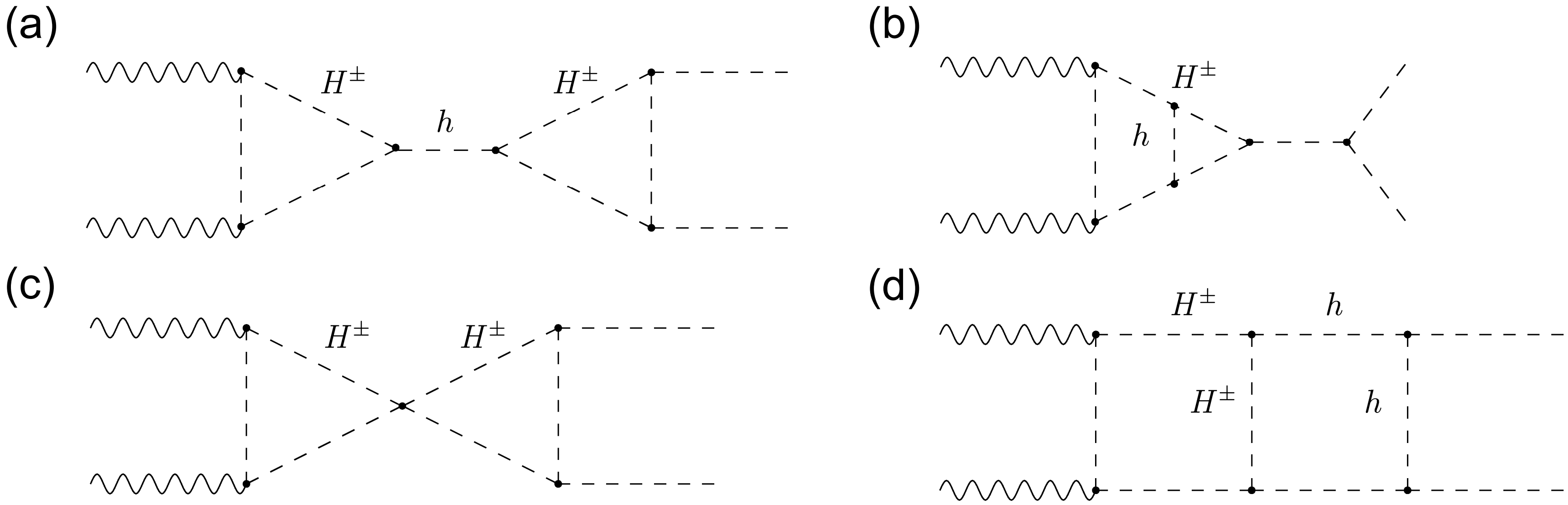
effective $\gamma\gamma h$ and $\gamma\gamma hh$ vertices come from dimension-6 operator $|\Phi_i|^2 F_{\mu\nu}F^{\mu\nu}$

$$g_{\gamma\gamma h} \propto \frac{q^2}{v} \qquad g_{\gamma\gamma hh} \propto \frac{q^2}{v^2}$$

$$m_{H^\pm} \gg m_h$$

$$\mathcal{M}^{2-loop} \propto \frac{q^2}{(4\pi v)^2}\left[1 + \mathcal{O}\left(\frac{m_{H^\pm}^4}{(4\pi v)^2 m_h^2}\right) + \mathcal{O}\left(\frac{m_{H^\pm}^2}{(4\pi v)^2}\right)\right]$$

Appendix



$$\mathcal{M}_{(a)}^{2-loop} \propto \left(\frac{1}{16\pi^2}\right)^2 \frac{q^2}{v}\frac{1}{s-m_h^2}\left(\frac{m_{H^\pm}^2}{v}\right)^3 \frac{d^4k}{(k^2-m_{H^\pm}^2)^3} \sim \frac{q^2}{(4\pi v)^2}\left(\frac{m_{H^\pm}^4}{(4\pi v)^2 m_h^2}\right)$$

$$\mathcal{M}_{(b)}^{2-loop} \propto \left(\frac{1}{16\pi^2}\right)^2 \frac{q^2}{v}\left(\frac{m_{H^\pm}^2}{v}\right)^2 \frac{d^4k}{(k^2-m_{H^\pm}^2)^3}\frac{1}{s-m_h^2}\left(\frac{m_h^2}{v}\right)^2 \sim \frac{q^2}{(4\pi v)^2}\left(\frac{m_{H^\pm}^2}{(4\pi v)^2}\right)$$

$$\mathcal{M}_{(c)}^{2-loop} \propto \left(\frac{1}{16\pi^2}\right)^2 \frac{q^2}{v^2}\frac{d^4k}{(k^2-m_{H^\pm}^2)^3}\left(\frac{m_{H^\pm}^2}{v}\right)^2 \sim \frac{q^2}{(4\pi v)^2}\left(\frac{m_{H^\pm}^2}{(4\pi v)^2}\right)$$

$$\mathcal{M}_{(d)}^{2-loop} \propto \left(\frac{1}{16\pi^2}\right)^2 \frac{q^2}{v^2}\frac{d^4k}{(k^2-m_h^2)^3}\left(\frac{m_h^2}{v}\right)^2 \sim \frac{q^2}{(4\pi v)^2}\left(\frac{m_h^4}{(4\pi v)^2 m_{H^\pm}^2}\right)$$