Higgs boson pair production in new physics models at hadron, lepton, and photon colliders

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Introduction

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

The Higgs sector is the last unknown part of the Standard Model.
Once the Higgs boson is found at the Tevatron or the LHC, its property such as the mass, the decay width, production cross section and the decay branching ratios will be measured in order to confirm the SM.
The Higgs mechanism will be tested by determining the coupling constants of the Higgs boson to the weak gauge boson.
The measurement of the Yukawa coupling constants will clarify the mass generation mechanism of quarks and charged leptons.
It is also important to measure the Higgs self-coupling.

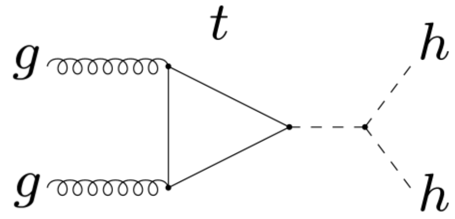
- Test for the Higgs potential
- Search for New Physics effect

We study the impacts of new physics effects on the hhh measurement at LHC, ILC / CLIC and PLC in several new physics model beyond the SM.

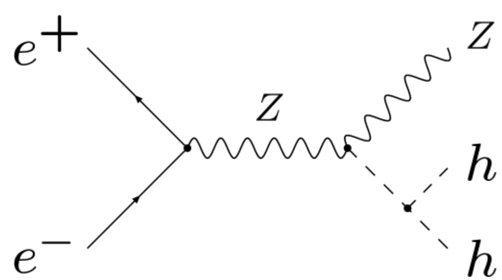
Measurement of hhh coupling

Measurement of hhh coupling at collider experiment

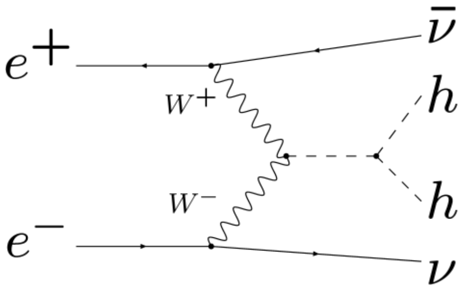
- LHC (SLHC) $gg \to hh$



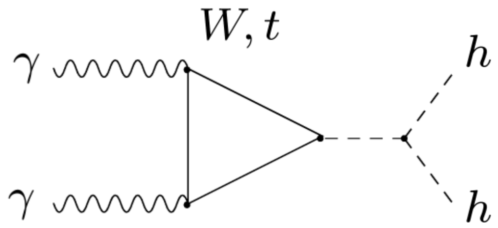
- ILC $e^+e^- \to Zhh$
  $\sqrt{s} = 500\text{GeV}$



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



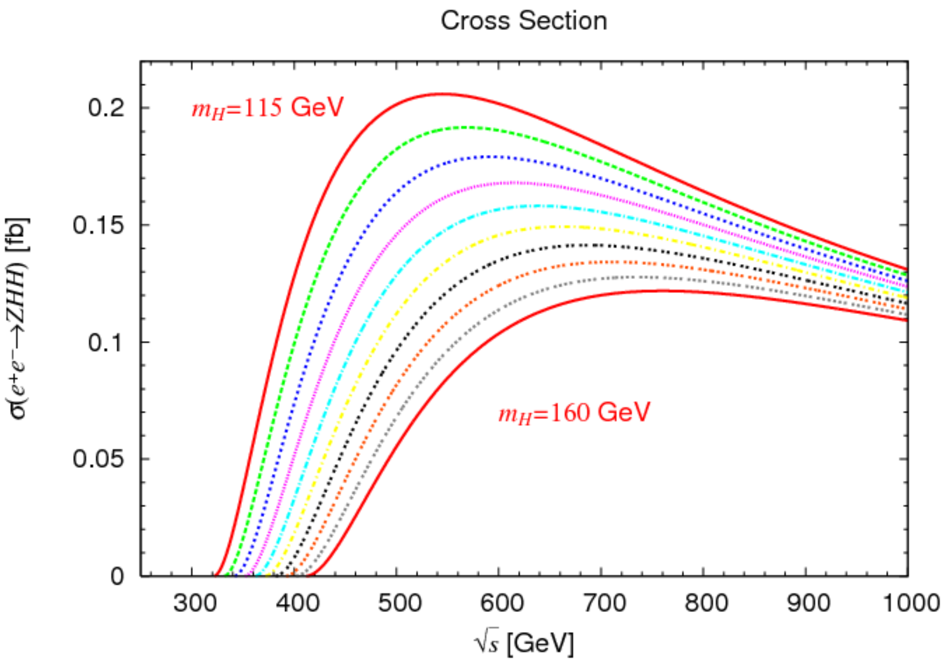
- Photon Collider (PLC) $\gamma\gamma \to hh$



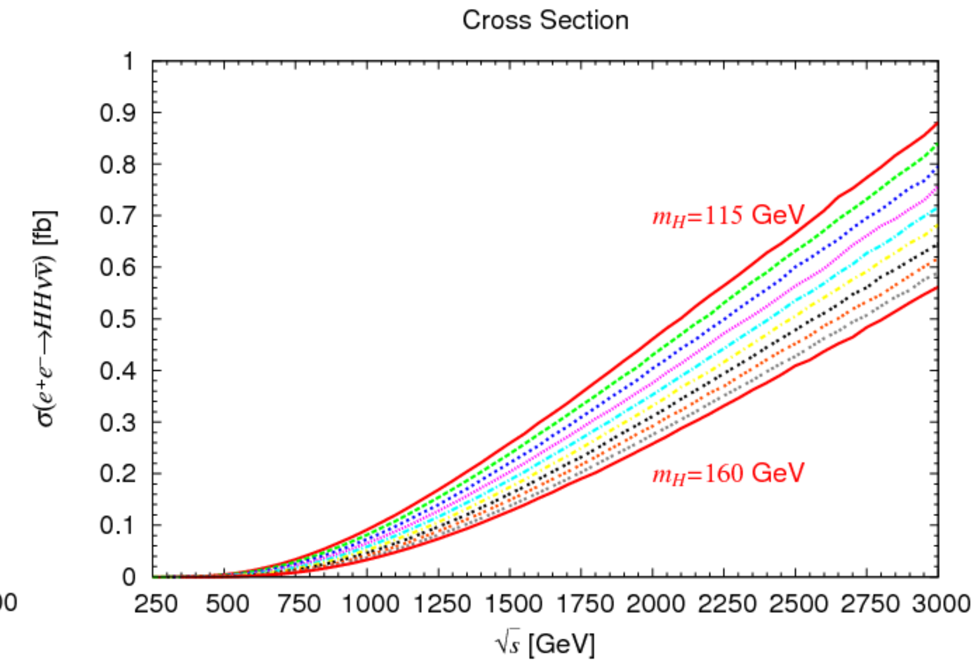
Cross section of Zhh and W-fusion

At the ILC / CLIC, we can use two processes to measure the hhh coupling.

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



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



The cross sections of Zhh and WW fusion processes at the ILC for $m_h = 115 - 160$ GeV

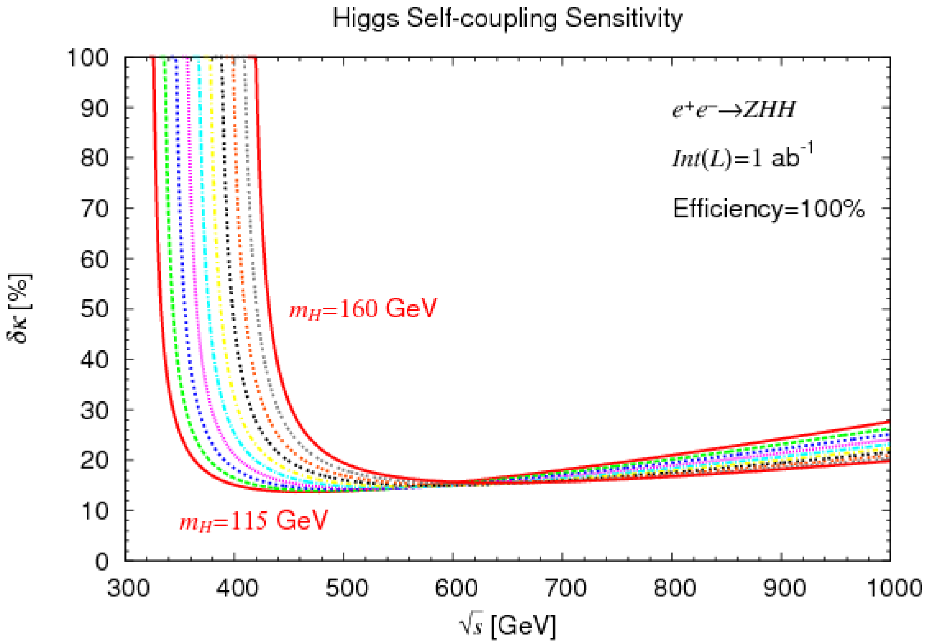
At the 2nd stage of ILC ($\sqrt{s} = 1$ TeV) and CLIC, WW fusion process becomes dominant due to the t-channel enhancement.

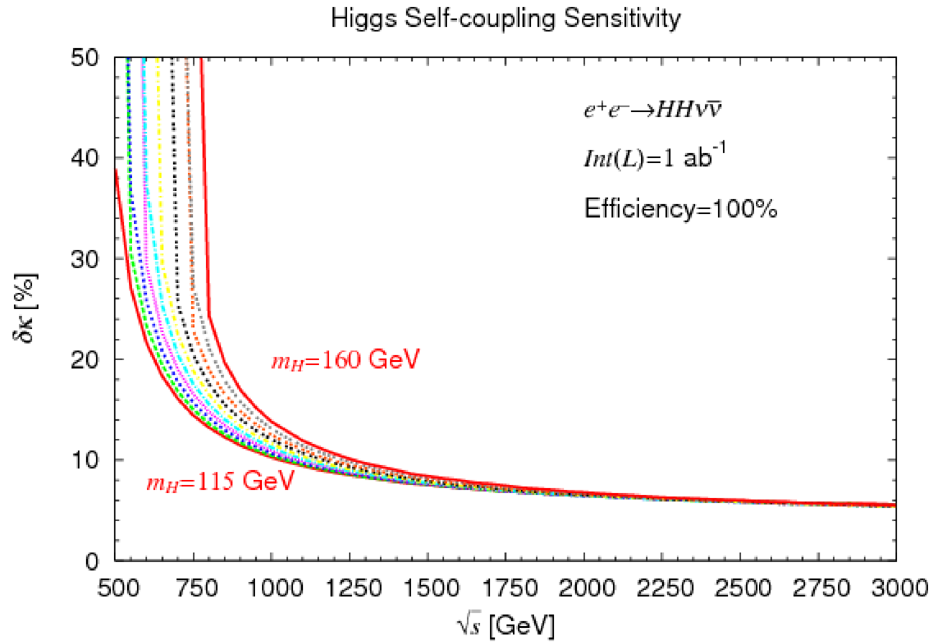
hhh measurement at ILC / CLIC

The statistical sensitivity for the hhh coupling constant at the ILC and CLIC.

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

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





At the 1st stage of the ILC ($\sqrt{s} < 500$ GeV), ZHH process is useful to measure the hhh coupling.

For $m_h = 120$ GeV

Optimal energy for Higgs self-coupling measurement is $\sqrt{s} = 400 - 500$ [GeV]

At multi-TeV collider, we can determine with an accuracy of 10% by using WW fusion process.

New Physics effect on hhh coupling

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

Effective Higgs potential

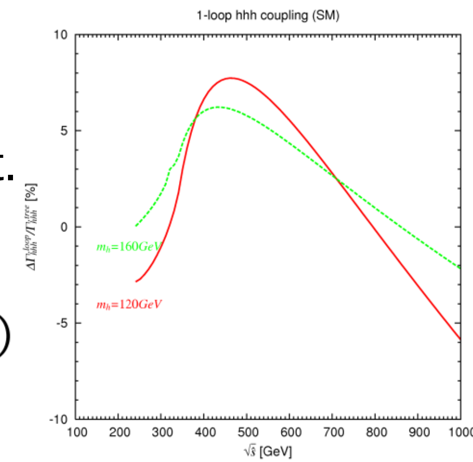
$$V = \frac{1}{2}m_h^2 h^2 + \frac{1}{3!}\lambda_{hhh} h^3 + \frac{1}{4!}\lambda_{hhhh} h^4 + \cdots.$$

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

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

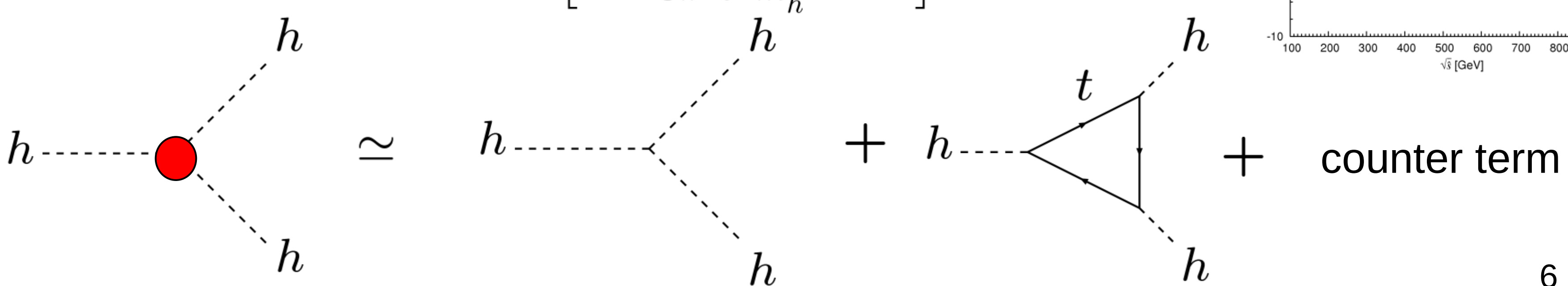
- Non-decoupling effect

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



Effective hhh coupling

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



m_t^4 term appears in 1-loop correction

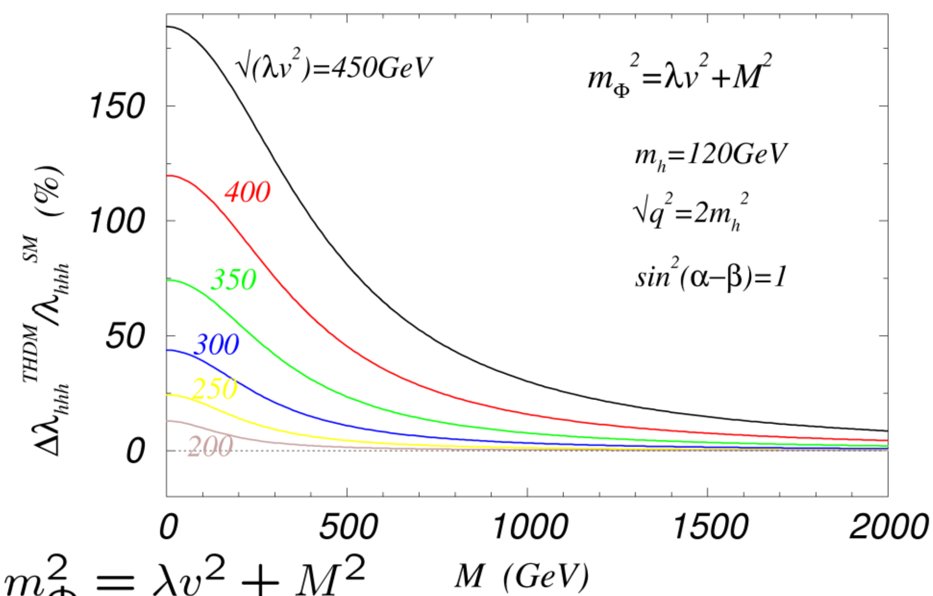
loop effect ~ -10%

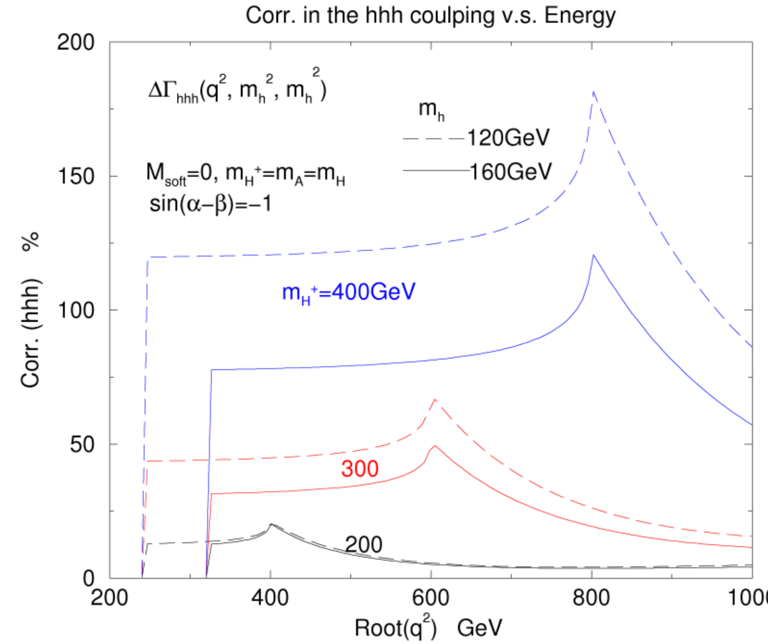
Effective hhh coupling in THDM

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

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

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

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 and Scalar LQ

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

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

Higgs potential

$$V_{\mathrm{THDM}} = \mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 - (\mu_3^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c.})$$

$$+\lambda_1|\Phi_1|^4 + \lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{\lambda_5}{2}\{(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c.}\}$$

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 ⟵ Colored scalar particle

Higgs potential

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

LQ-lepton-quark interaction

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

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

Chiral and Vector-like 4th generation

In addition to the SM Lagrangian, we introduce following Yukawa couplings.

These models have the colored fermion.

3. Chiral 4th generation model

$$Q'_L = \begin{pmatrix} t'_L \\ b'_L \end{pmatrix} \quad t'_R \quad b'_R$$

Yukawa coupling

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

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 constraint from S and T parameters, we set $m_{t'} - m_{b'} = 55\,\text{GeV}$

4. Vector-like 4th generation model

3rd generation quark + Vector-like singlet quark

$$Q_{0L} = \begin{pmatrix} t_{0L} \\ b_{0L} \end{pmatrix} \quad + \quad t'_L \quad t'_R$$

Yukawa coupling

$$\mathcal{L}_{\text{Yuk}} = -y_{t'}\bar{Q}_{0L} t'_{0R} \tilde{\Phi} - M\bar{t}'_{0L} t'_{0R} + \text{h.c.}$$

We assume that vector-like quark only mix with 3rd generation quark.

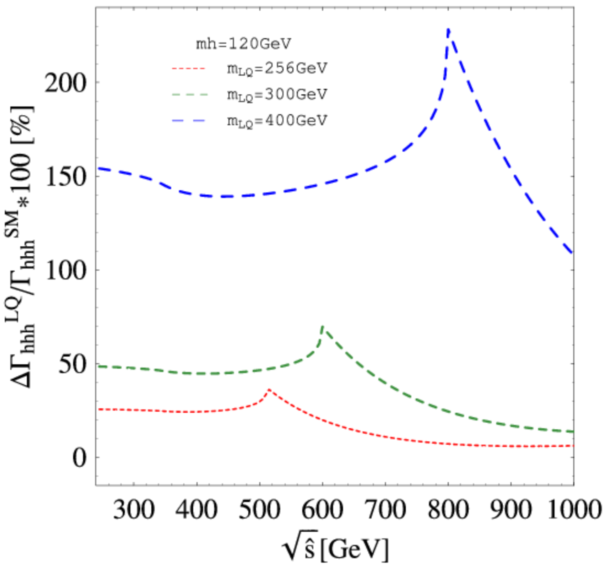
$$\begin{pmatrix} t_X \\ t'_X \end{pmatrix} = \begin{pmatrix} c_X & -s_X \\ s_X & c_X \end{pmatrix} \begin{pmatrix} t_{0X} \\ t'_{0X} \end{pmatrix} \quad (X = L, R)$$

S and T parameter → Allowed parameter space. $y_{t'} = 1,\ M \geq 1\,\text{TeV}$

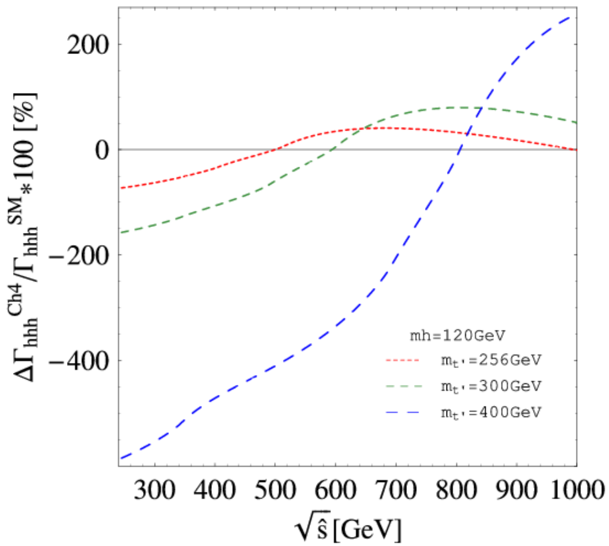
Effective hhh coupling in LQ and 4th generation model

For $m_h = 120$ GeV

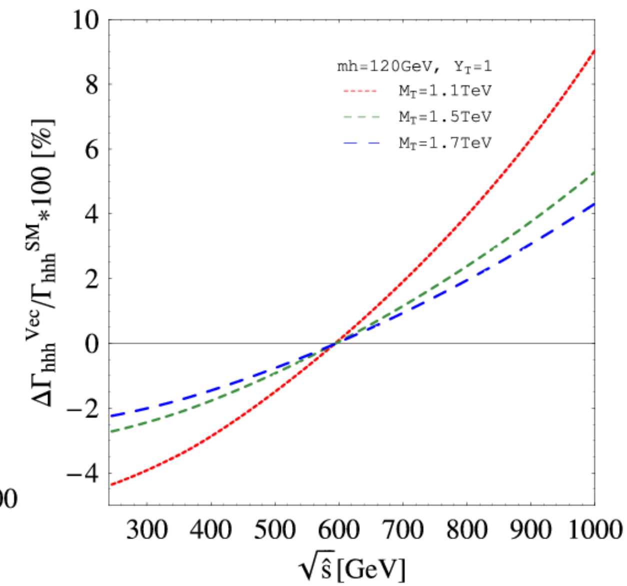
Scalar LQ



Chiral 4th generation



Vector-like 4th generation



Effective hhh coupling

Scalar LQ

We set $M_{LQ} = 0$

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

Chiral 4th generation

$$\Gamma^{\rm Ch4}_{hhh} \simeq \frac{3m_h^2}{v}\left[1 - \frac{N_c(m^4_{t'}+m^4_{b'})}{3\pi^2 v^2 m_h^2} - \frac{N_c m_t^4}{3\pi^2 v^2 m_h^2}\right]$$

Vector-like 4th generation

$$\Gamma^{\rm Vec}_{hhh} \simeq \frac{3m_h^2}{v}\left[1 - \frac{N_c m_t^4}{3\pi^2 v^2 m_h^2}\frac{m_t^2}{M^2} - \frac{N_c m_t^4}{3\pi^2 v^2 m_h^2}\right]$$

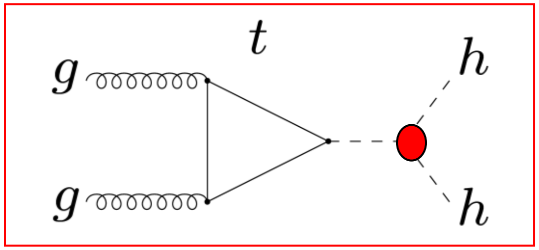
$(M \geq 1$ TeV$)$

LHC

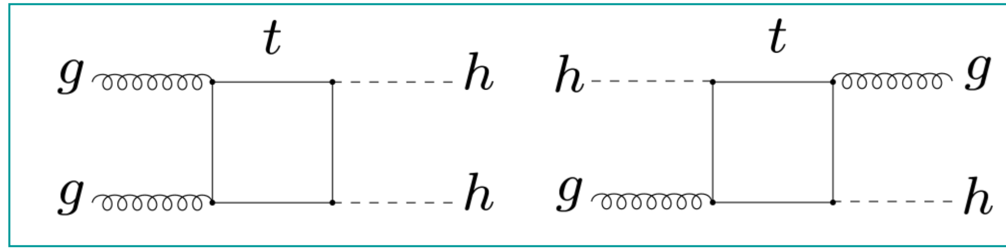
$gg \to hh$

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

triangle

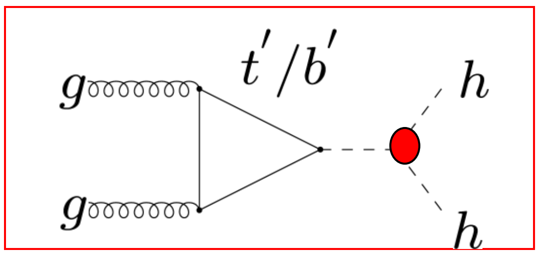


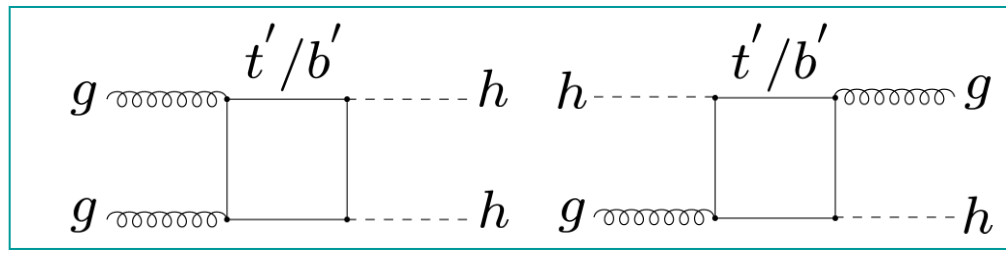
box



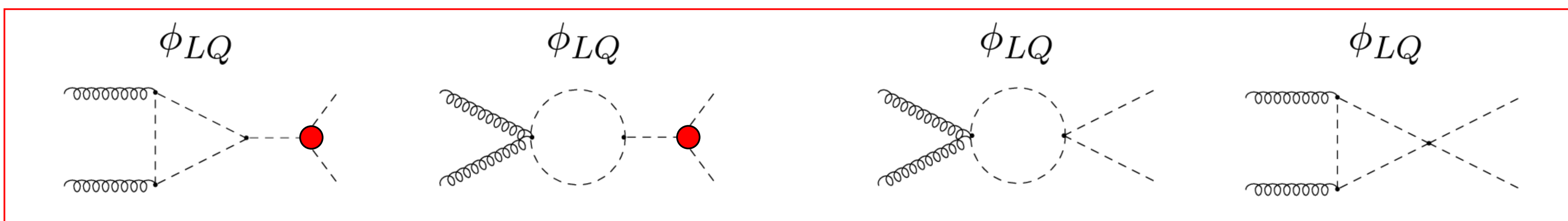
$\Delta\mathcal{M}(l_1, l_2)$ Additional one-loop diagrams

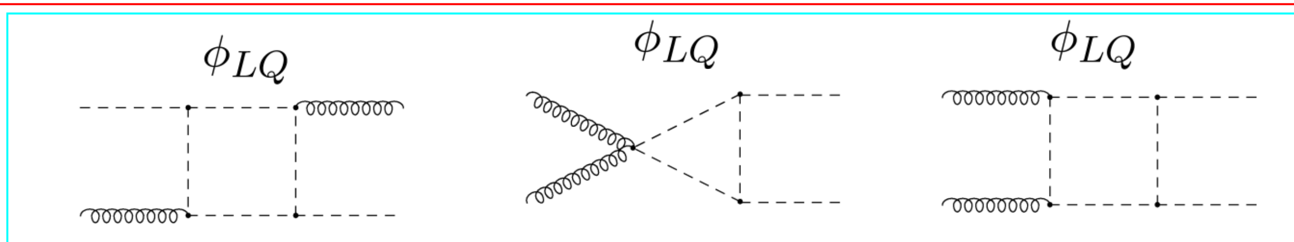
4th generation





Scalar LQ

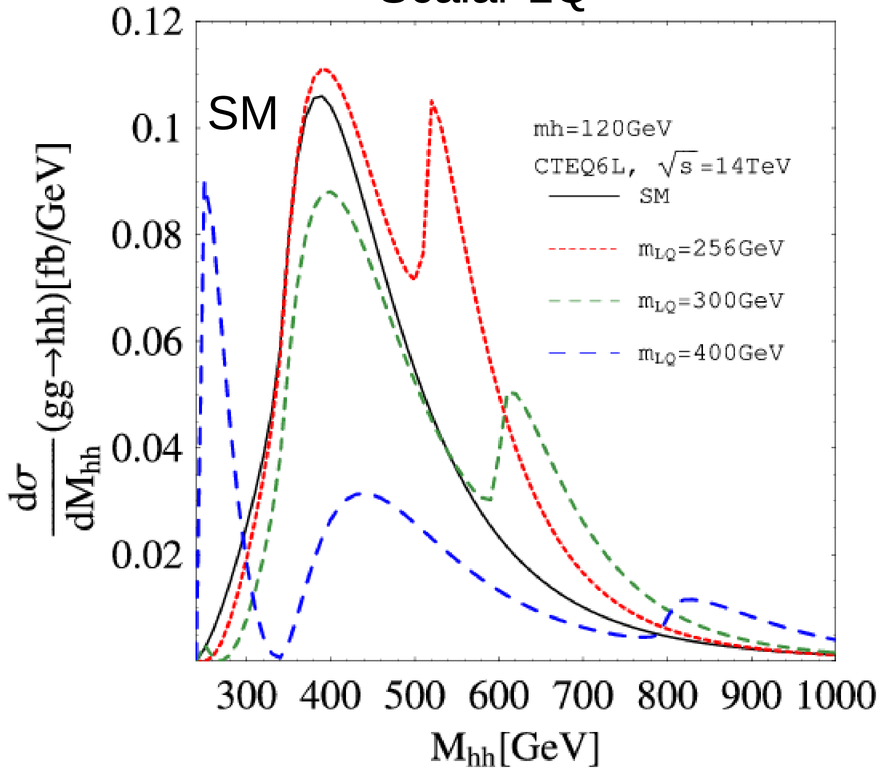


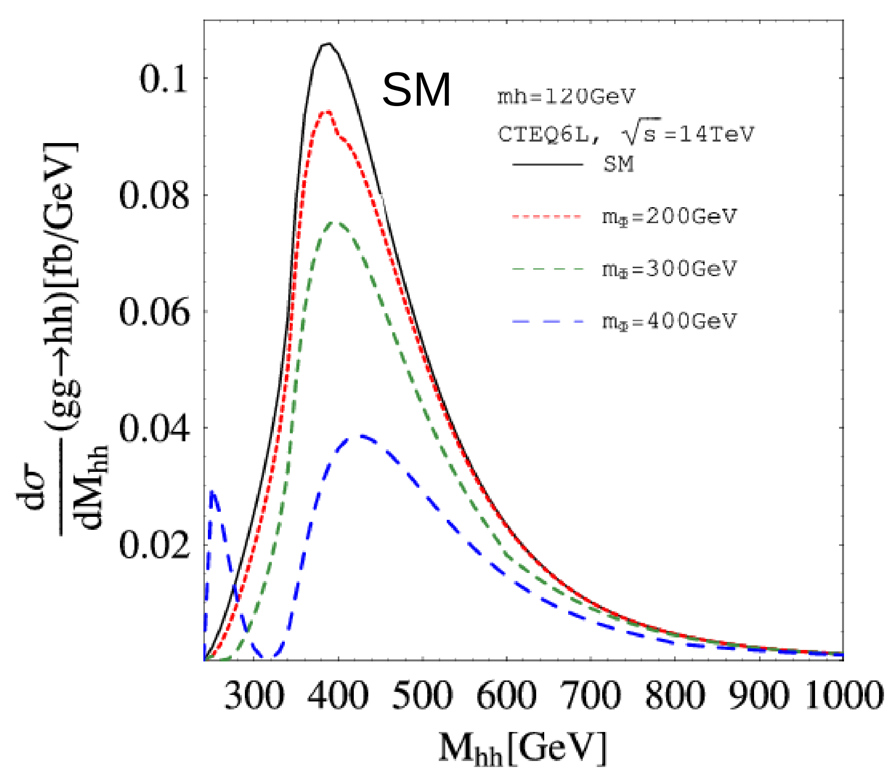


Gluon fusion process in Scalar LQ and THDM

Invariant mass distribution of gluon fusion process

For $m_h = 120$ GeV





$M_{hh} \sim 250$ GeV

This peak comes from the large hhh coupling constant through the triangle diagram

$M_{hh} \sim 400$ GeV

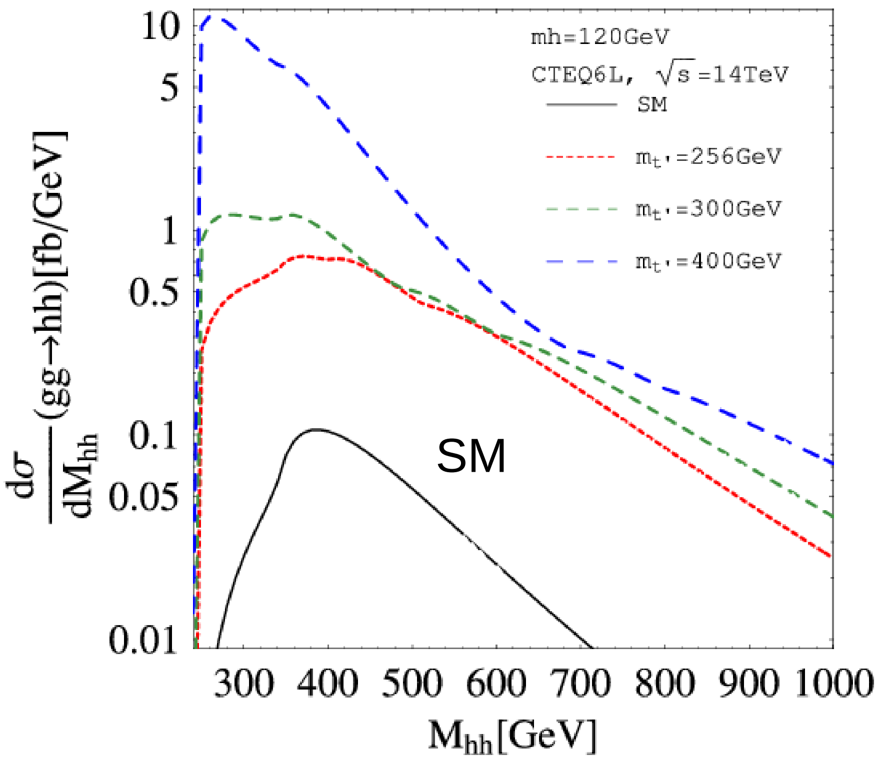
Interference effect of triangle and box diagrams.
These two contributions are destructive to each other

Gluon fusion process in 4th generation model

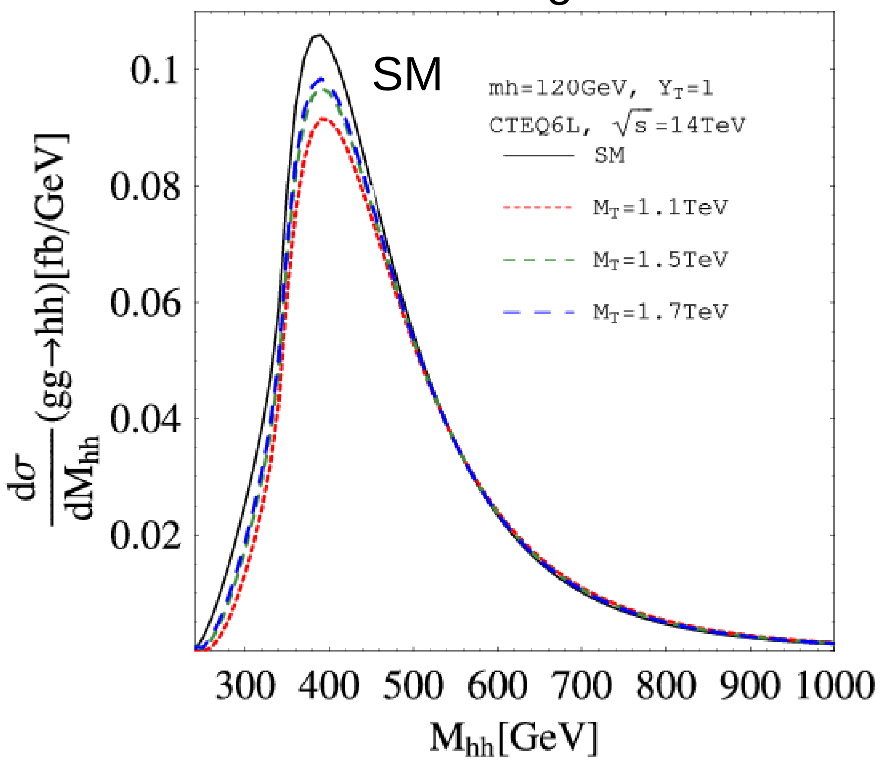
Invariant mass distribution of gluon fusion process

For $m_h = 120$ GeV

Chiral 4th generation



Vector-like 4th generation



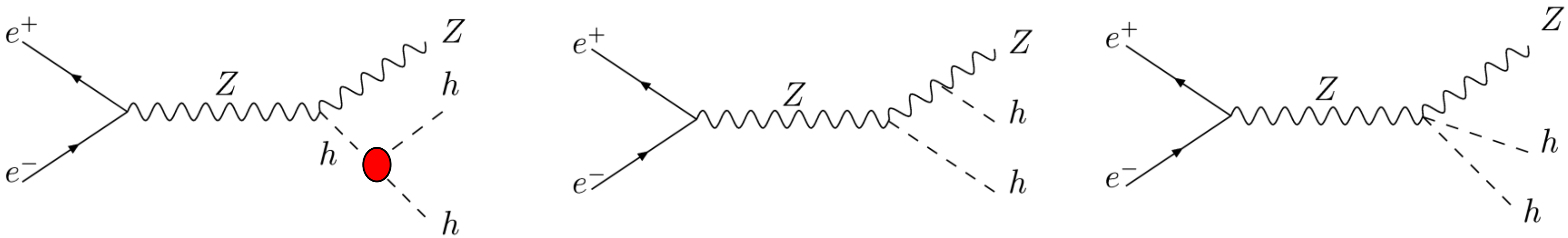
The cross section of the chiral 4th generation model can be 10-100 times larger than that of the SM.

In the vector-like 4th generation model, the deviations of the cross section from the SM value are at most 5%, which can not be large because of their decoupling nature.

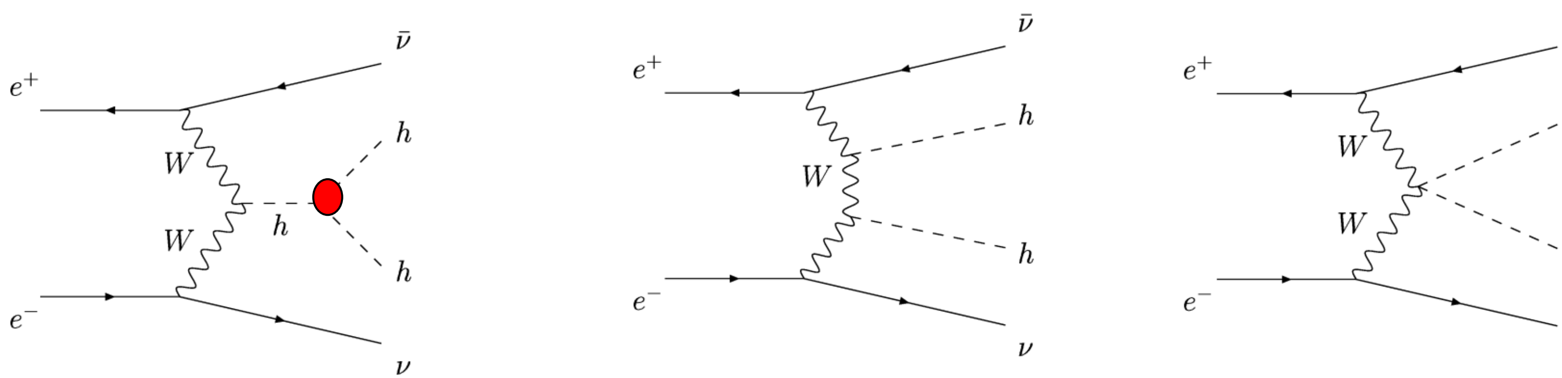
ILC / CLIC

New Physics effect on Zhh and WW fusion

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



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

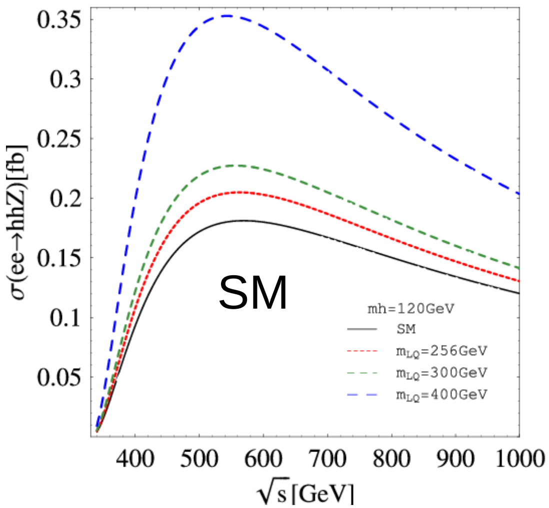


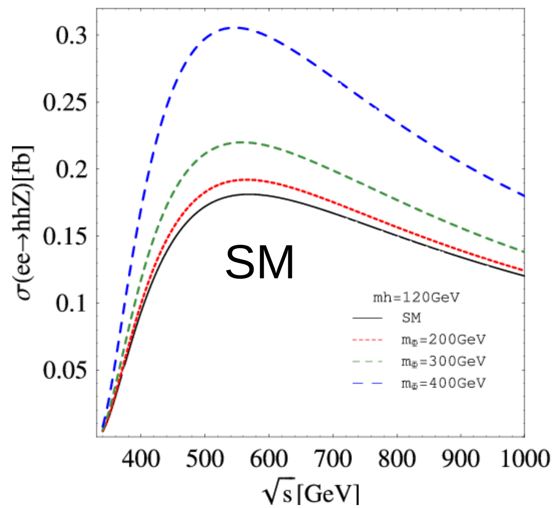
Zhh and WW fusion in Scalar LQ and THDM

For $m_h = 120$ GeV

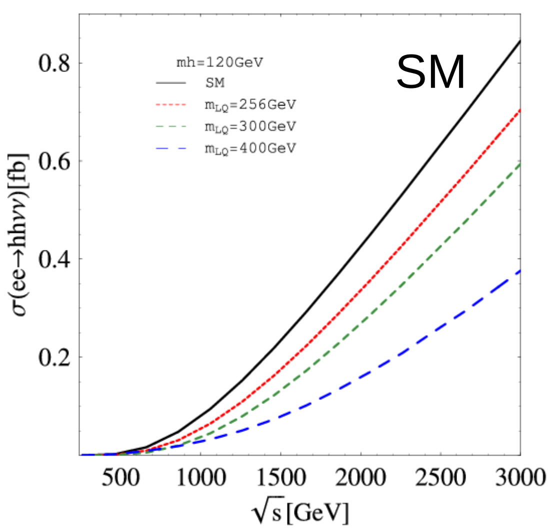
Scalar LQ | THDM

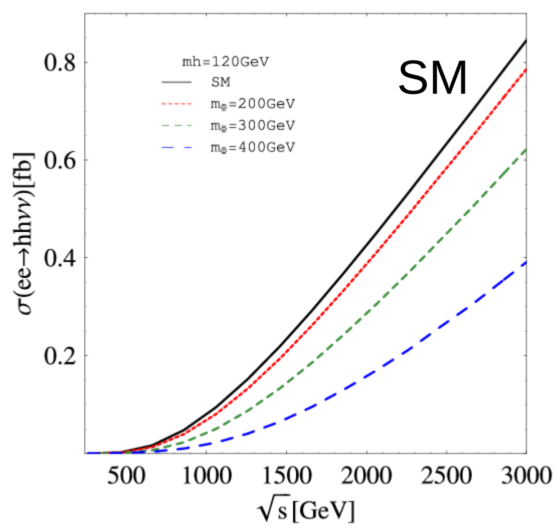
$e^+e^- \to Zhh$





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





The cross section of WW fusion becomes small because of the negative interference.

The anomalous hhh coupling dependence in the cross section of WW fusion is opposite to that in Zhh process.

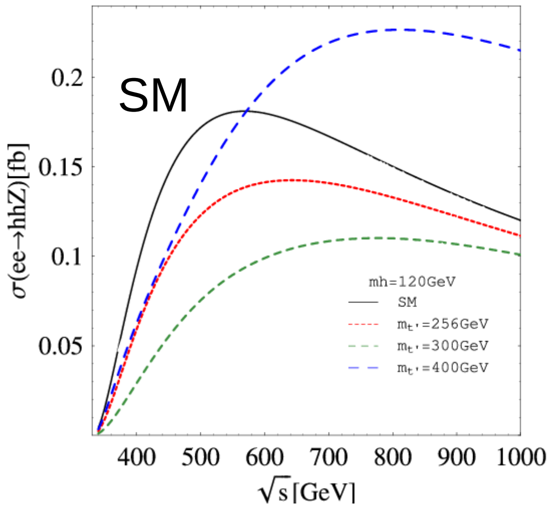
Zhh and WW fusion in 4th generation model

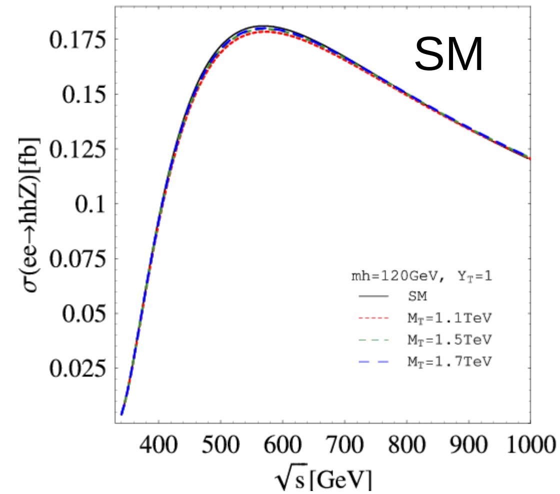
For $m_h = 120$ GeV

Chiral 4th generation | Vector-like 4th generation

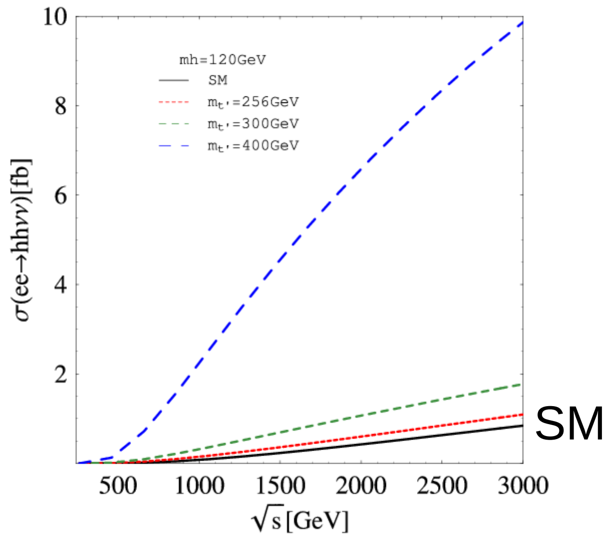
$$e^+e^- \to Zhh$$

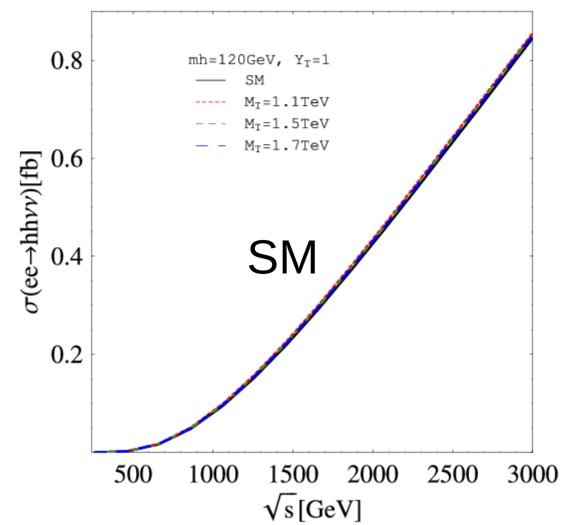
The cross section can be reduced by the suppression of the hhh coupling constant in the chiral 4th generation model.





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





In the chiral 4th generation model, the production rate becomes significantly large.

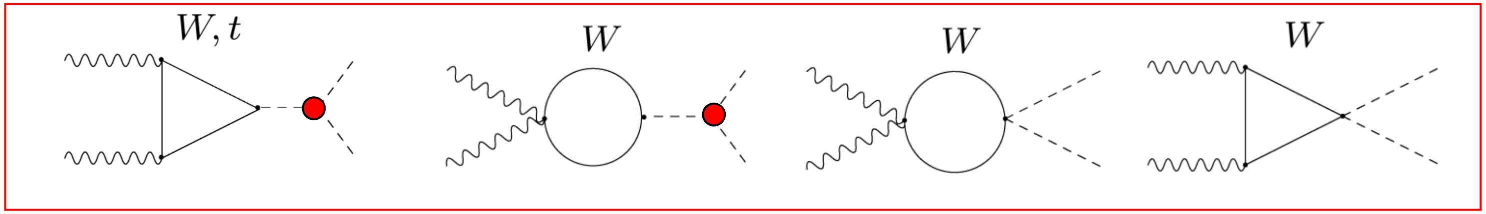
The impact of the vector-like quark is quite small in these processes.

PLC

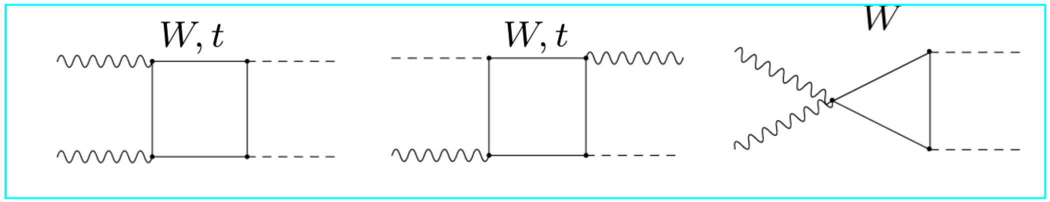
$\gamma\gamma \to hh$

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

triangle diagrams

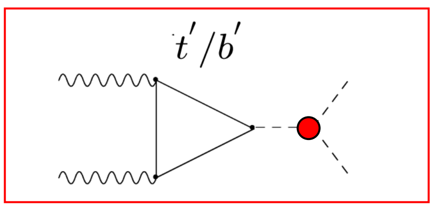


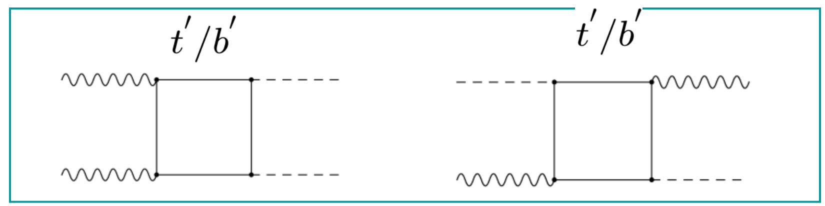
box diagrams



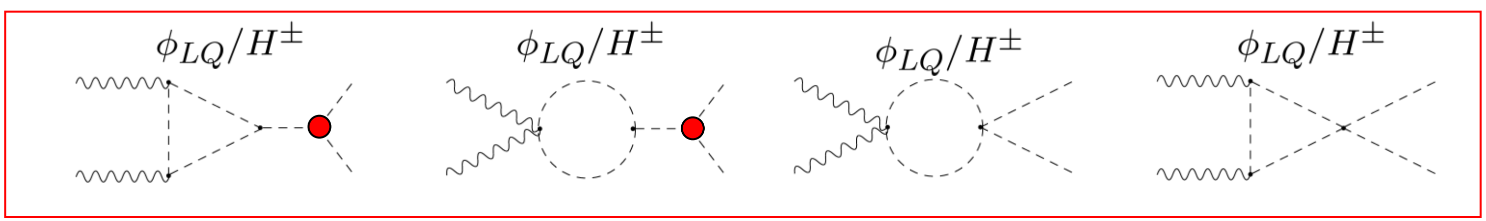
$\Delta\mathcal{M}(l_1, l_2)$ Additional one-loop diagrams

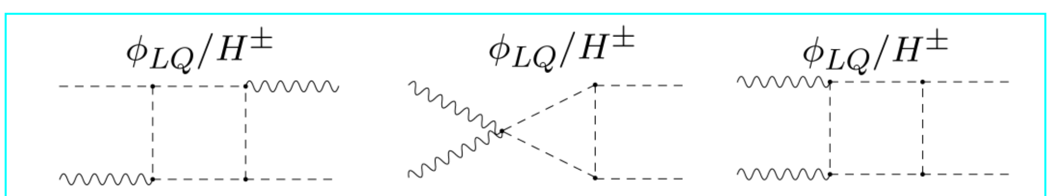
4th generation





Scalar LQ / THDM with SM-like limit



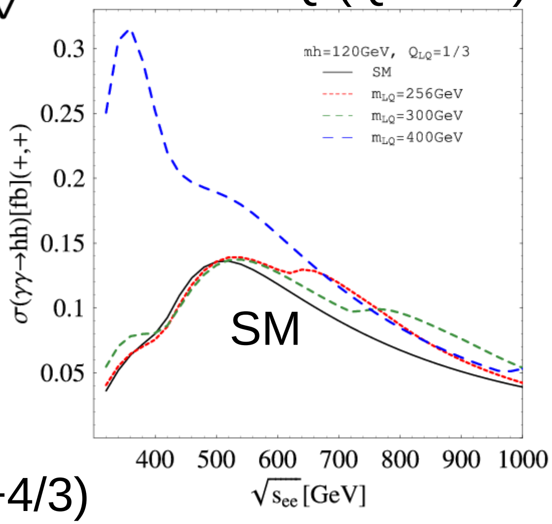


Full cross section in Scalar LQ and THDM

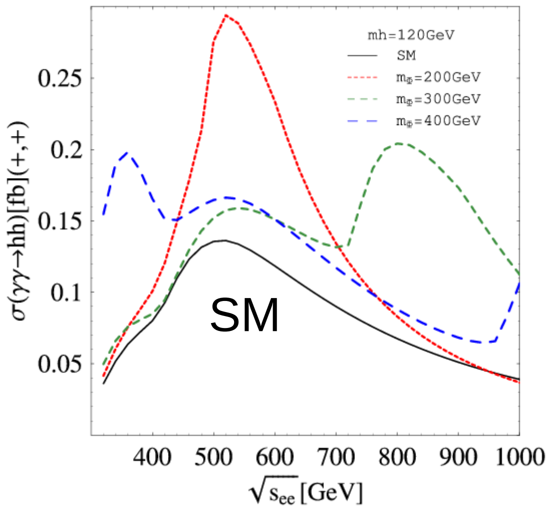
Cross section of $e^- e^- \to \gamma\gamma \to hh$ process at PLC

For $m_h = 120$ GeV

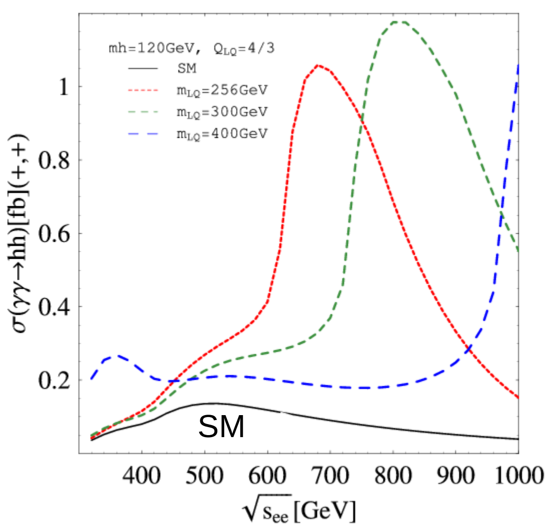
Scalar LQ (Q=+1/3)



THDM



Scalar LQ (Q=+4/3)



$\sqrt{s_{ee}} \sim 350$ GeV

Cross section is enhanced by the effective hhh coupling

$\sqrt{s_{ee}} \sim 500$ GeV

Threshold enhancement of top pair production

$\sqrt{s_{ee}} > 600$ GeV

Threshold enhancement of charged Higgs (Scalar LQ) pair production in THDM (LQ)

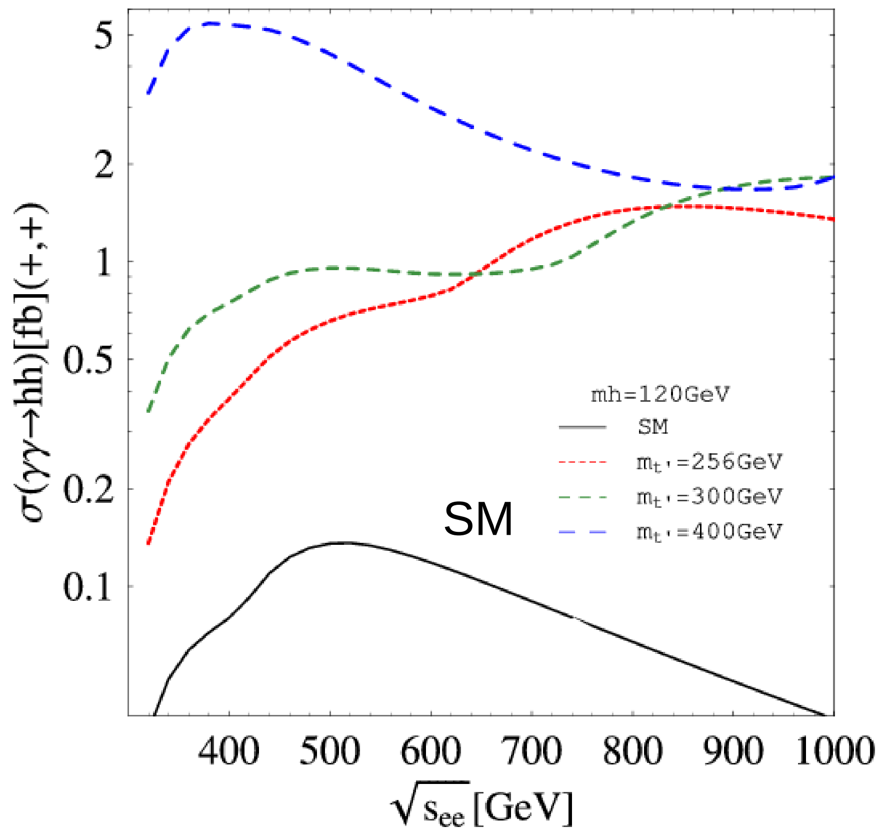
The effects of scalar LQs depend on not only their masses but also their electric charges. $\mathcal{M}_{LQ} \propto N_c Q_s^2$

Full cross section in 4th generation model

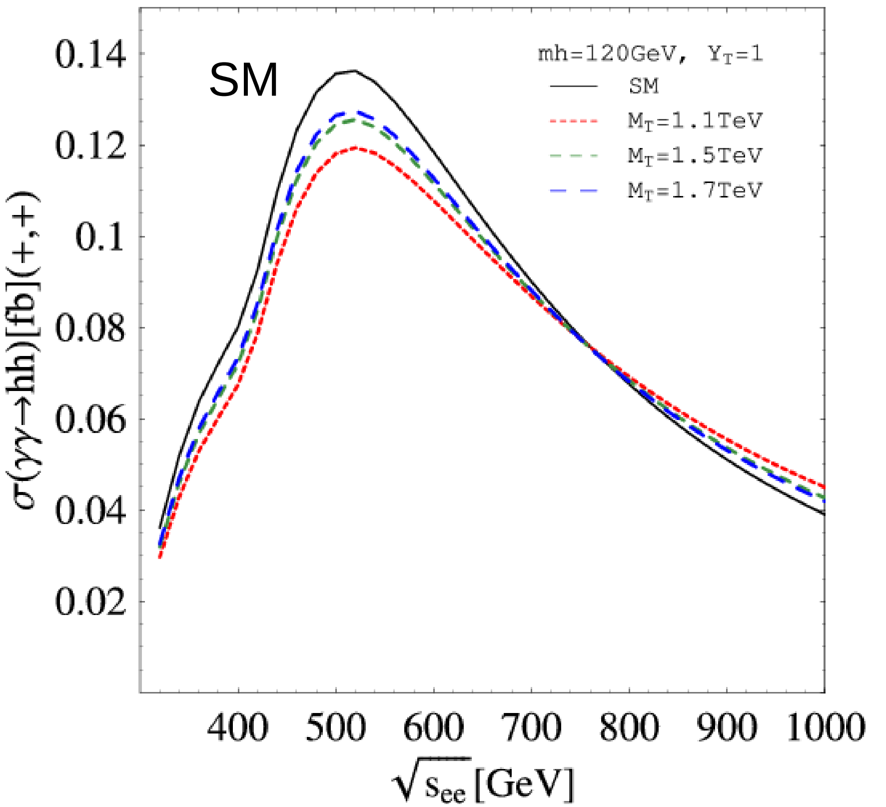
Cross section of $e^- e^- \to \gamma\gamma \to hh$ process at PLC

For $m_h = 120$ GeV

Chiral 4th generation



Vector-like 4th generation



In the chiral 4th generation model, fourth generation fermions contribute to both triangle and box diagrams can enhance the cross section by a factor of 10 for wide range of $\sqrt{s_{ee}}$

In the vector-like 4th generation model, new physics effects are small.

Summary

We studied double Higgs production processes at LHC, ILC / CLIC and PLC in THDM with SM-like limit, scalar LQ, chiral and vector-like 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 / CLIC, PLC, LHC
- These four Higgs boson pair production processes at different colliders can play complementary roles in exploring new physics through the Higgs sector.

  Additional particles in new physics model can also significantly affect the $gg \to hh$ and $\gamma\gamma \to hh$ processes according to their color and electric charges.
- Double Higgs production process is useful to distinguish 4^{th} generation quark is whether chiral or vector-like model.

  In the vector-like 4^{th} generation model, a non-decoupling limit cannot be taken due to the severe experimental constraints

- The deviation of the cross section from the SM strongly depend on each new physics model.

$\sqrt{s} = 400 - 500$ GeV $\sqrt{s} = 500$ GeV $\sqrt{s} = 1 - 3$ TeV

Model	m_h[GeV]	$\frac{\Gamma_{hhh}^{NP} - \Gamma_{hhh}^{SM}}{\Gamma_{hhh}^{SM}}$	$\Delta r_{NP}^{gg \to hh}$	$\Delta r_{NP}^{e^+e^- \to hhZ}$	$\Delta r_{NP}^{\gamma\gamma \to hh}$	$\Delta r_{NP}^{e^+e^- \to hh\nu\bar{\nu}}$
THDM	120	+120%	−50%	+(80–70)%	+50%	−(80–50)%
THDM	160	+70%	−50%	+(60–50)%	+110%	−(80–50)%
LQ($Q = 1/3, 4/3$)	120	+150%	−40%	+(110–100)%	+130%, +100%	−(70–60)%
LQ($Q = 1/3, 4/3$)	185	+60%	−30%	+50%	+150%, +150%	−(80–50)%
Ch4	120	−590%	+7800%	−(30–20)%	+3100%	+(260–110)%
Ch4	210	−140%	+2200%	——	——	+(970–210)%
Vec	120	−4%	−10%	−2%	−10%	+(5–1)%
Vec	160	−2%	−5%	−1%	−10%	+(3–0)%

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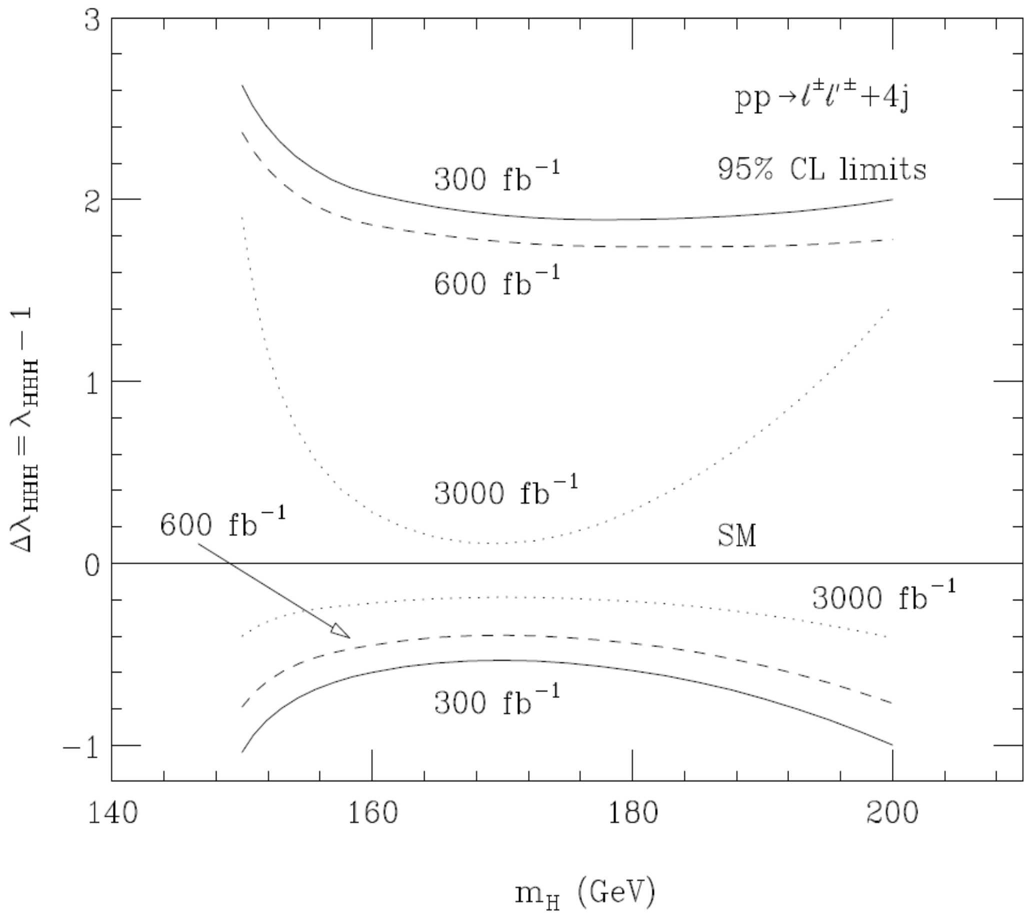
hhh measurement at the LHC

U. Baur, T. Plehn, D. Rainwater

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

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



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

$(\delta\kappa = 0)$

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

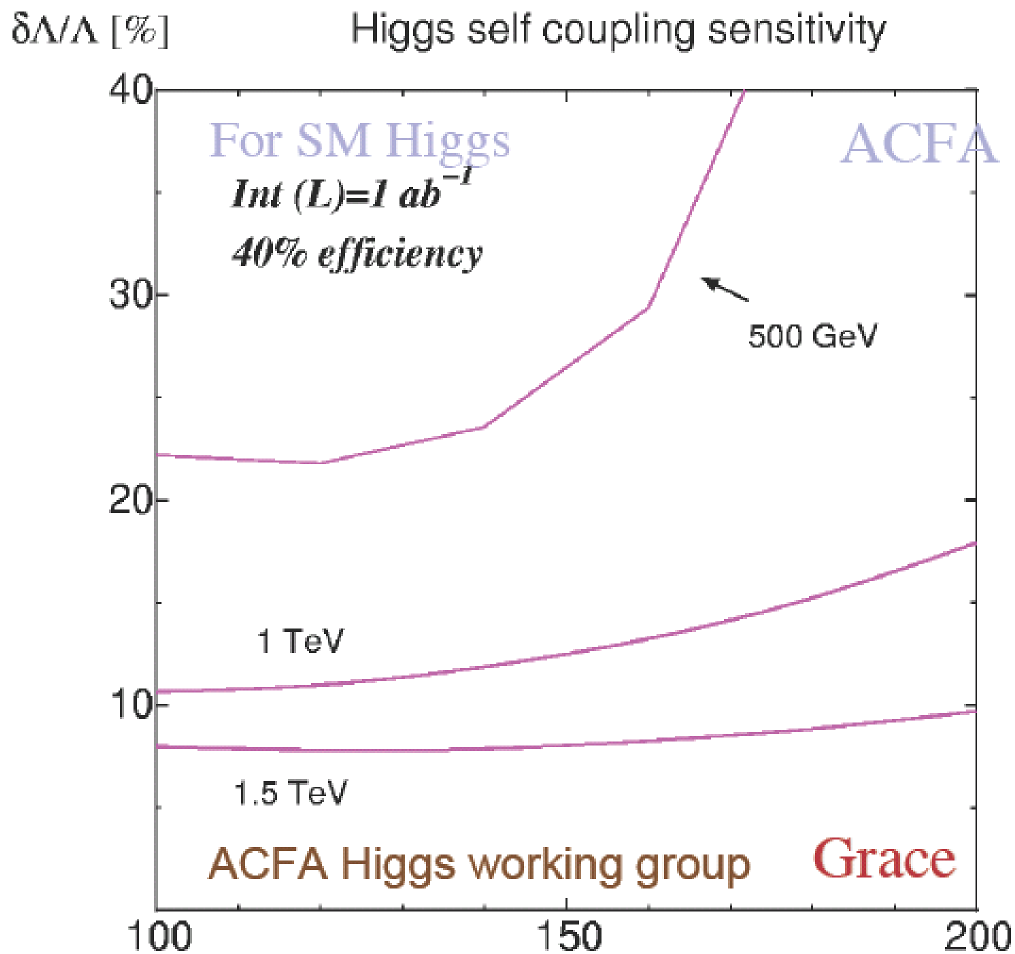
At the SLHC, Higgs self-coupling can be determined with an accuracy of 20-30 %.

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

hhh measurement at the ILC

ACFA Higgs Working Group 2002

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



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

1st ILC

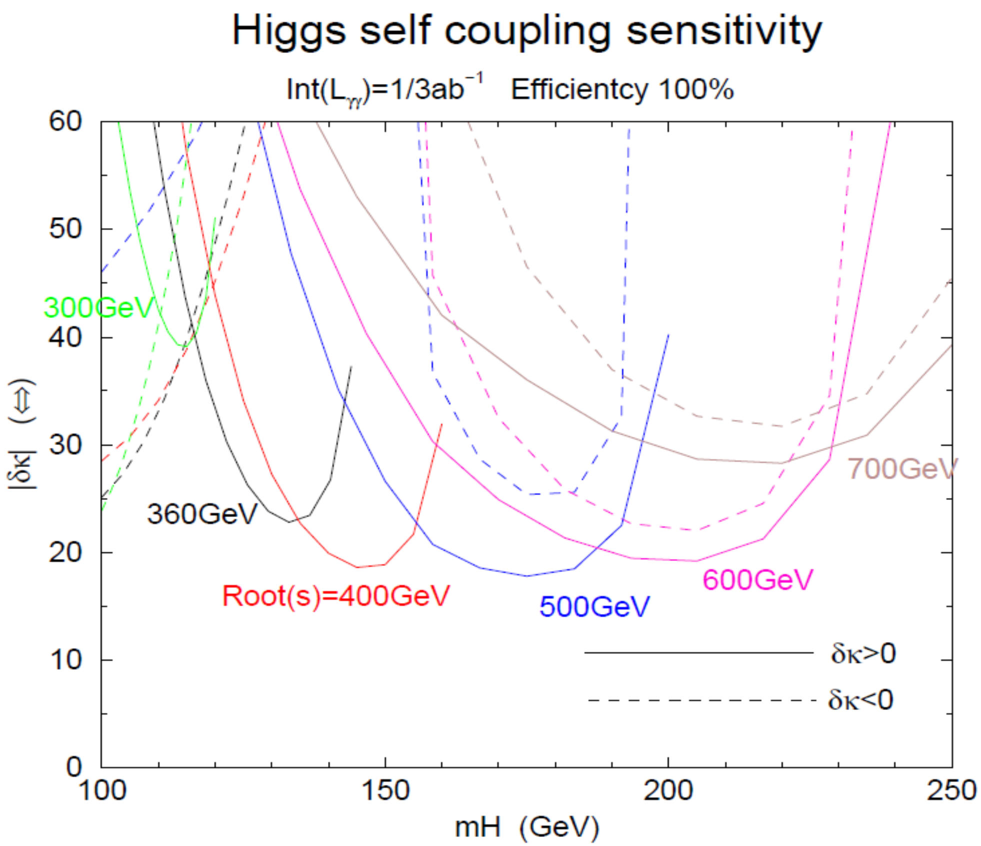
$\sqrt{s} = 500\mathrm{GeV}$

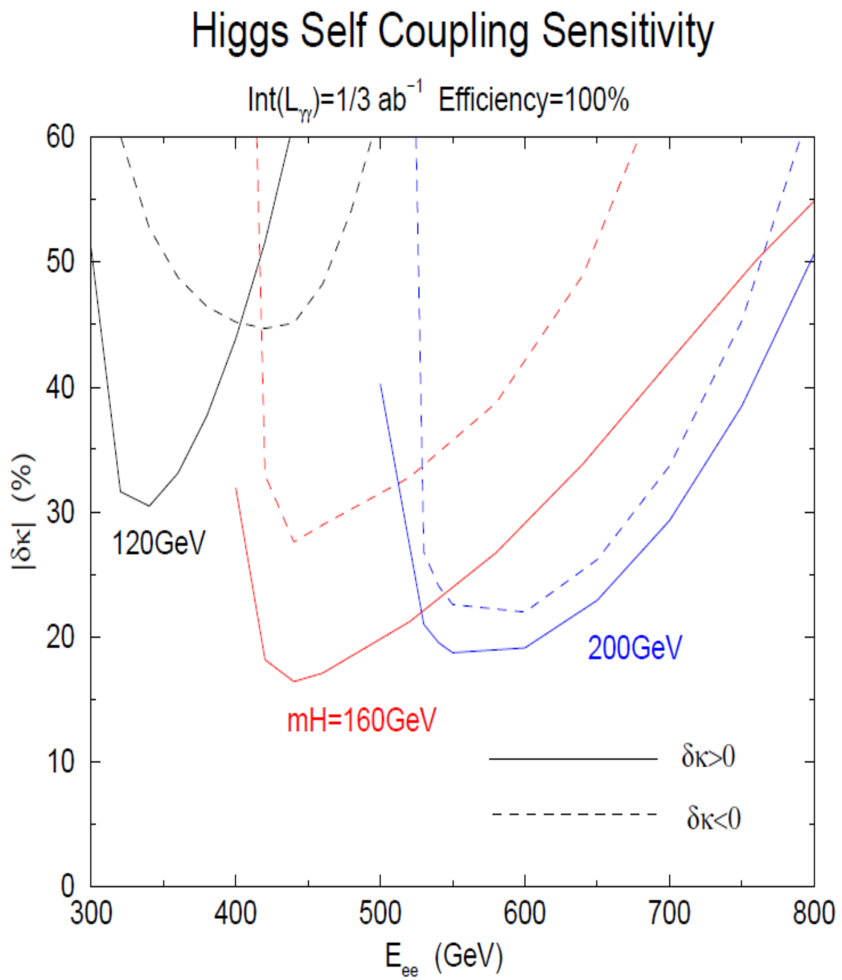
At the 1st ILC, Higgs self-coupling can be determined with an accuracy of 20-30 %.

$m_h < 170\mathrm{GeV}$

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.

Sensitivity

- Sensitivity

$$N = L_{\gamma\gamma}\sigma(0)$$

$$N \pm \sqrt{N} = L_{\gamma\gamma}\sigma(\Delta\kappa)$$

$L_{\gamma\gamma}\sigma(\delta\kappa)$