Higgs boson pair production at LHC and ILC

Kunio Kaneta (Kavli IPMU)

Based on

- PLB718 (2013) 1441. Collaboration with N. Haba, Y. Mimura, R. Takahashi
- Work in progress with T. Enkhbat, N. Haba, Y. Mimura, R. Takahashi

Scalars 2013 @ Warsaw (12 - 16 Sept. 2013)

Outline

1, Motivation

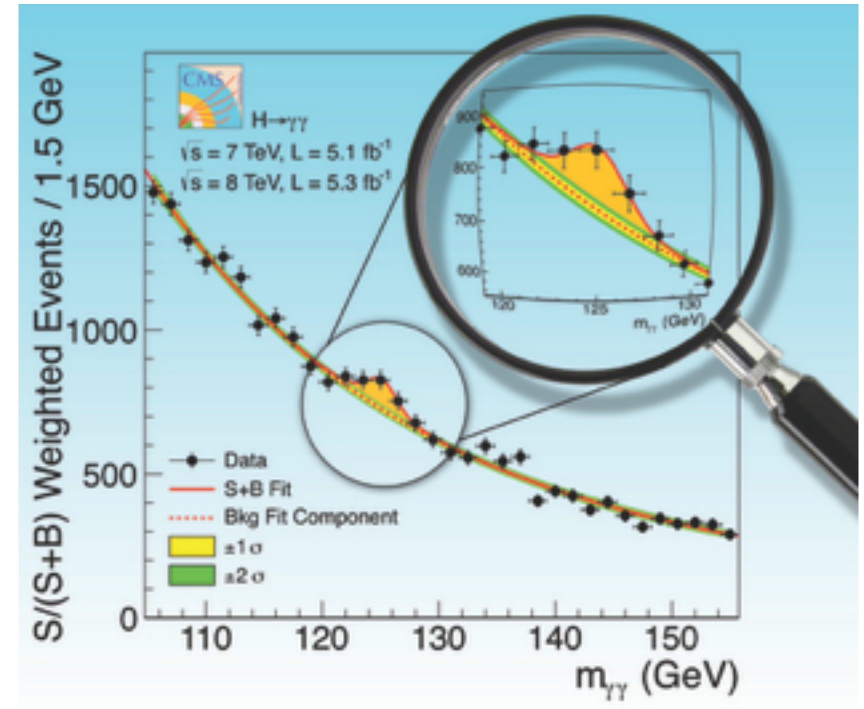
2, Higgs potential and the Higgs self-interaction

3, Non-perturbative Higgs model

4, Summary

1, Motivation

☆ Higgs has been discovered at $m_h \simeq 125 \text{ GeV}$



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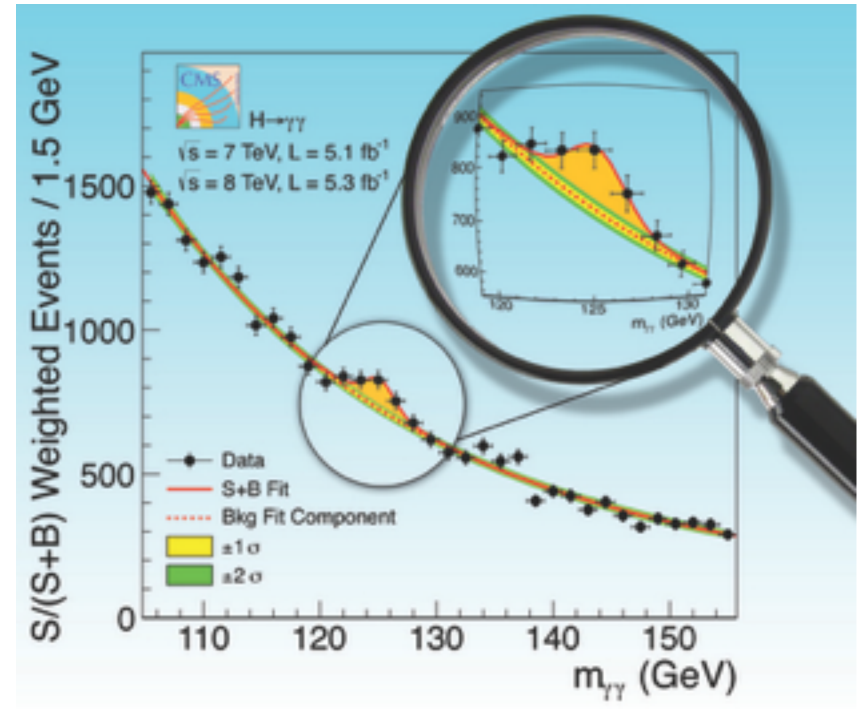

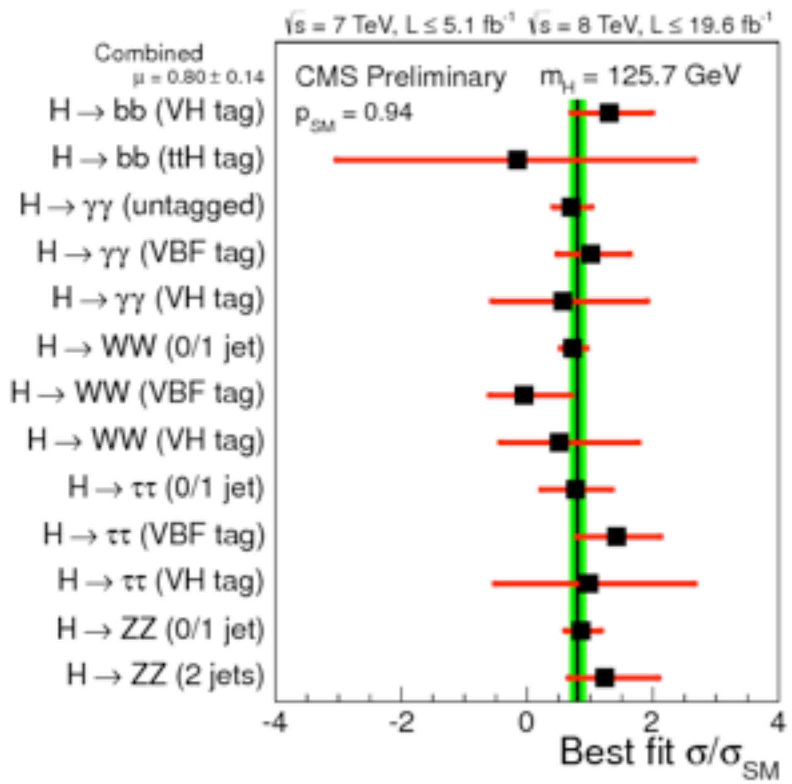

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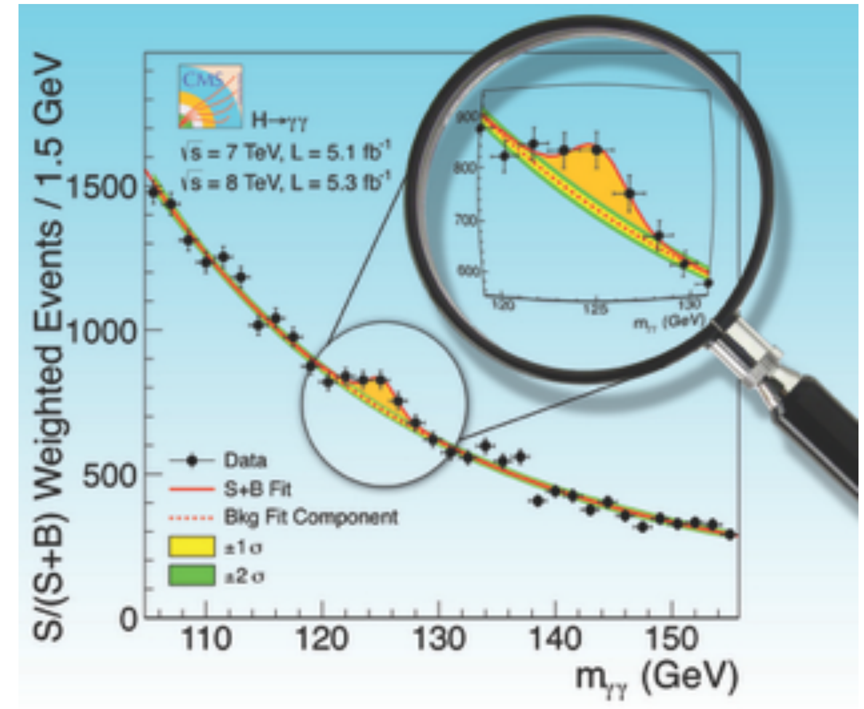

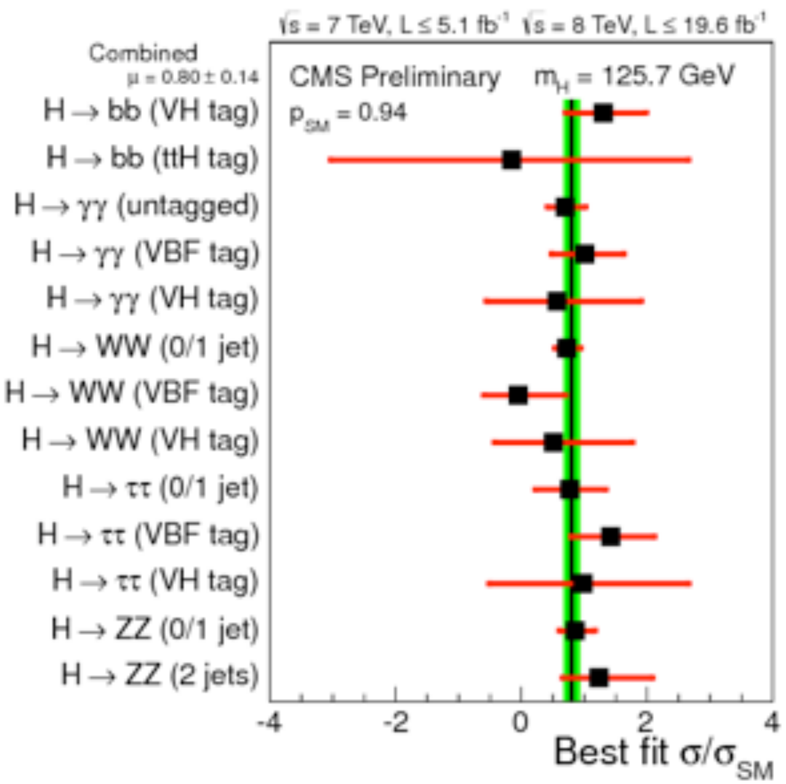

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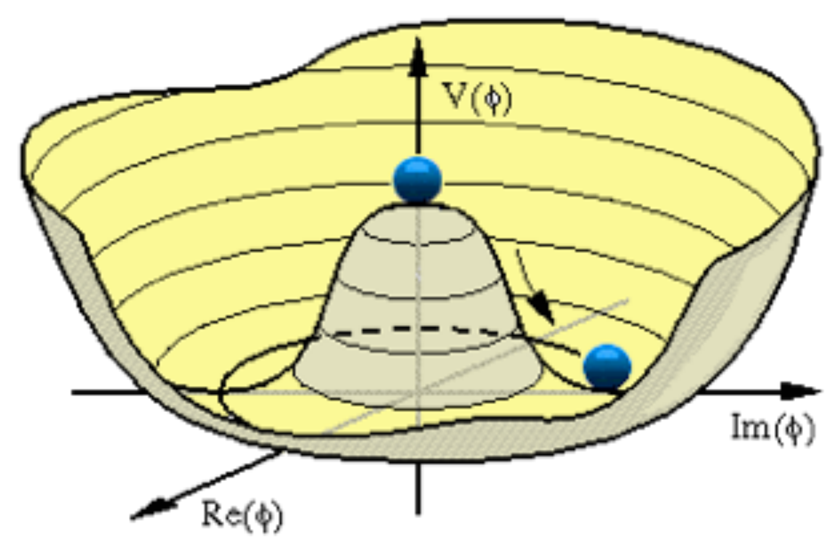

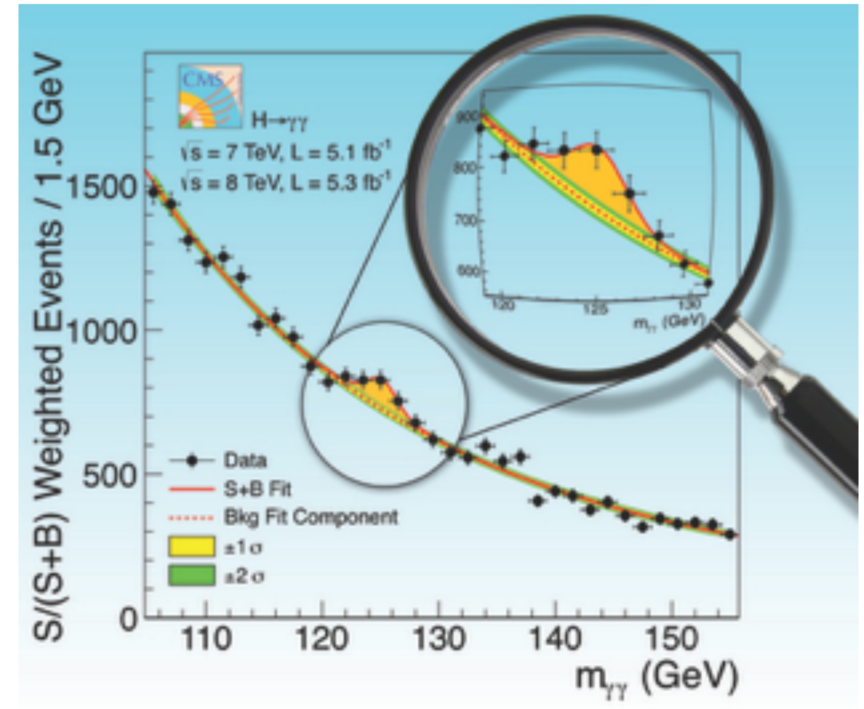

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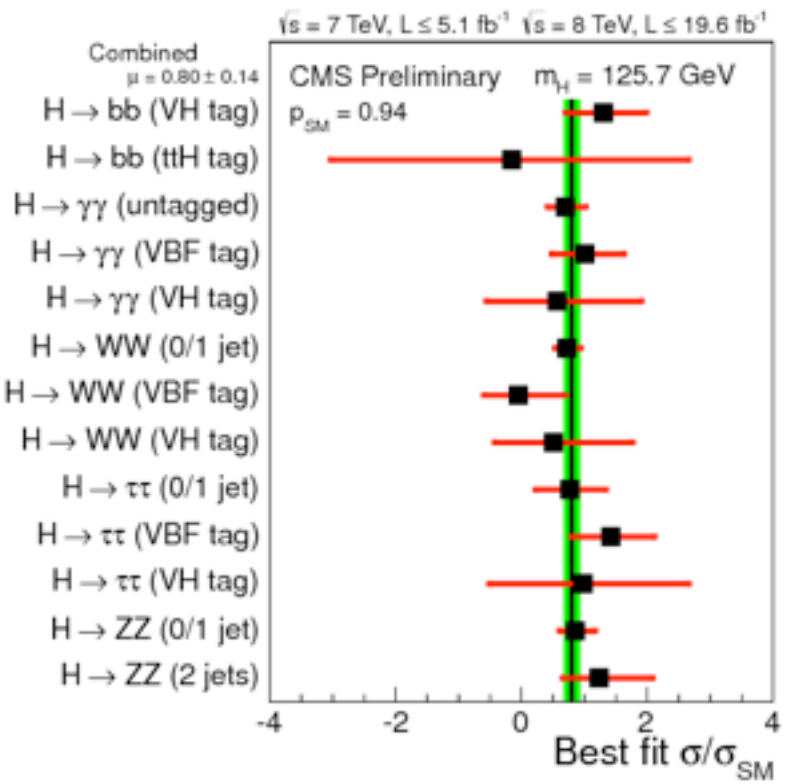

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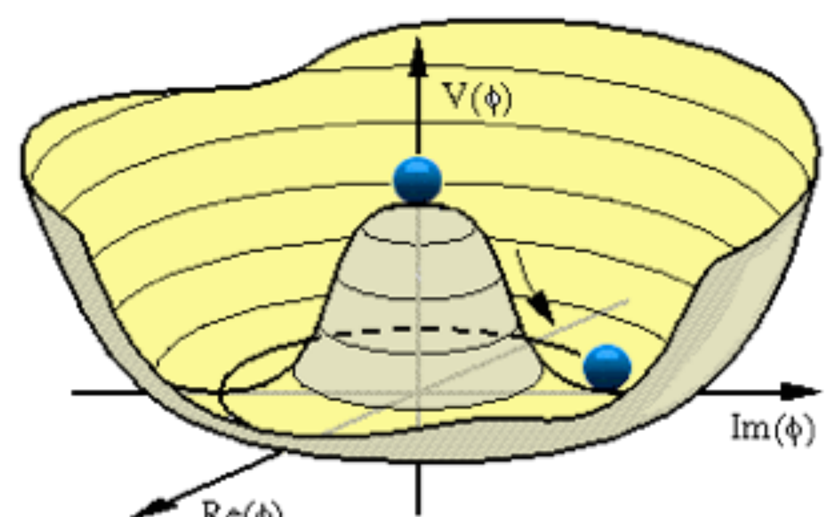

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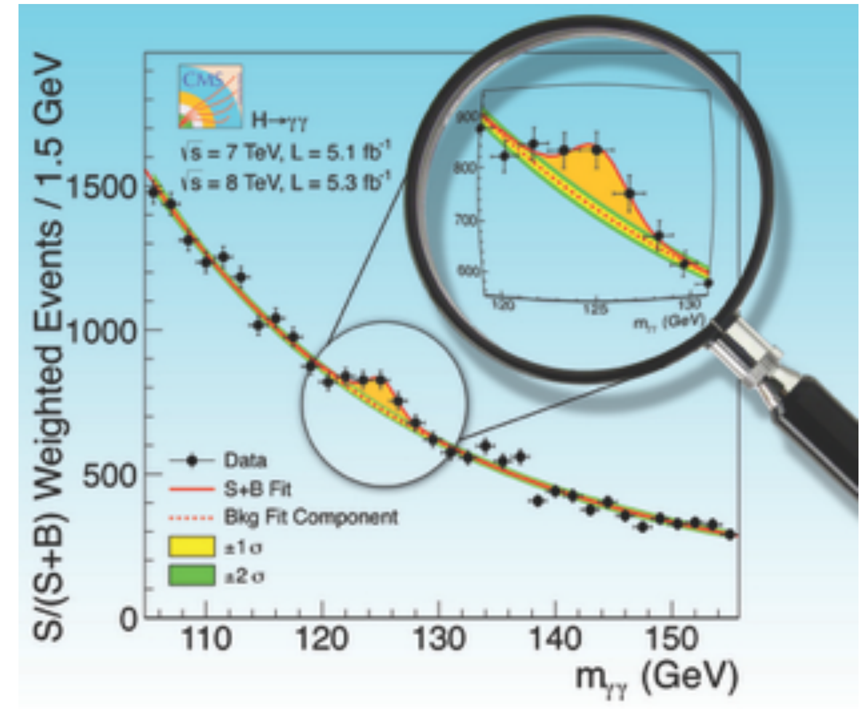

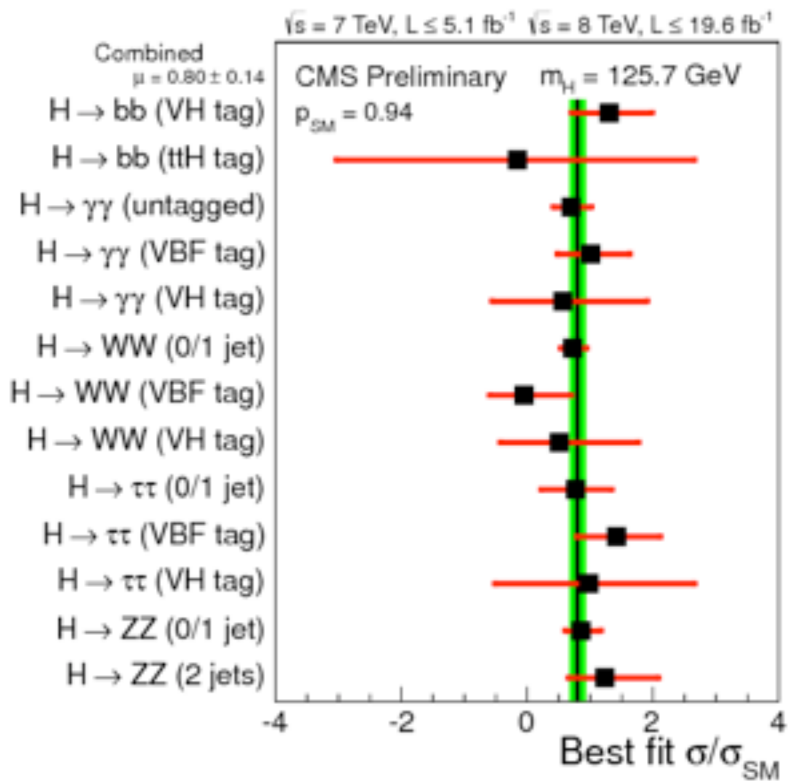

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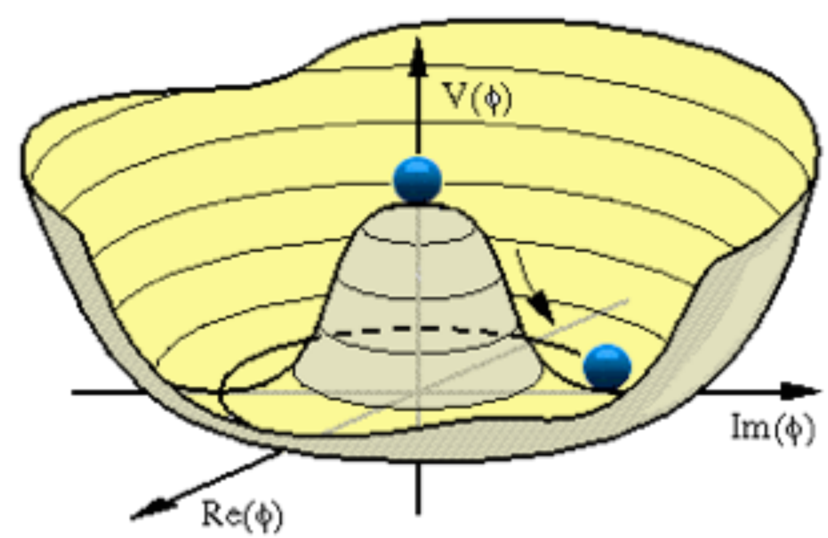
- How does the Higgs field acquire a VEV?
- What kind of interaction works on there?



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Gauge forces

“Higgs forces”

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Gauge forces

☆ Gauge interaction stems from

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

☆ For fermions: $\bar{Q}\ i\gamma^\mu D_\mu\ Q$

For Higgs boson: $|D_\mu H|^2$

Self-interaction: $-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}$

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☆ Higgs self-interaction gives

$$\langle H \rangle = \frac{v}{\sqrt{2}}$$

☆ Lagrangian

$$-\mathcal{L}_{\mathrm{Higgs}} = m^2|H|^2 + \lambda(|H|^2)^2$$

(We really do not know)

(☆ Yukawa interaction) (out of my talk)

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key point is ...

- Higgs self-interaction is an origin of EW symmetry breaking.
- It is important to probe the Higgs self-coupling.

2, Higgs potential and the Higgs self-interaction

☆ Higgs potential as a function of $|H|^2$

$$V = V(|H|^2)$$

We know the Higgs field acquires a VEV. $H = \begin{pmatrix} \chi^+ \\ (v+h+i\chi)/\sqrt{2} \end{pmatrix}, \quad |H|^2 = \frac{v^2}{2} + vh + \frac{h^2}{2} + \frac{\chi^2}{2} + \chi^+\chi^-$

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vanished

stationary condition

$$V'\left(\frac{v^2}{2}\right) = 0$$

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higher dimensional OPs

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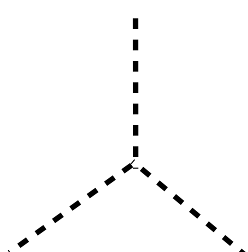
cubic Higgs coupling



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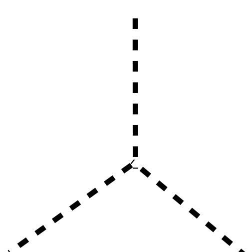

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$C_h = 0$ for the SM Higgs potential

We focus on $C_h \neq 0$ case.

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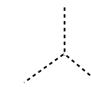

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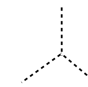

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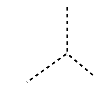

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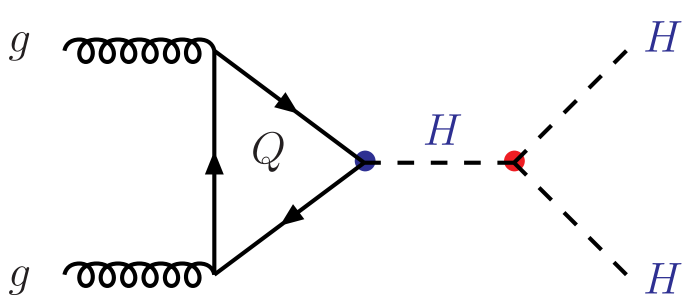

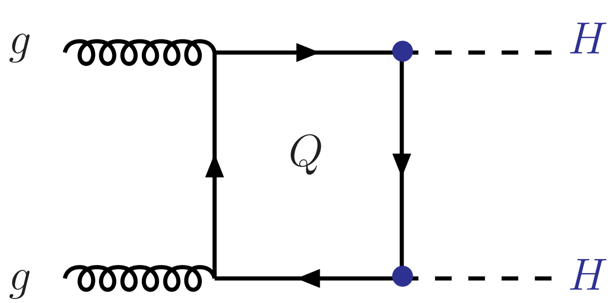

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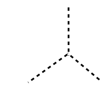

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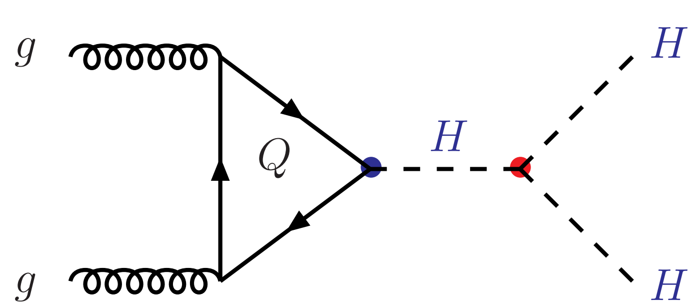
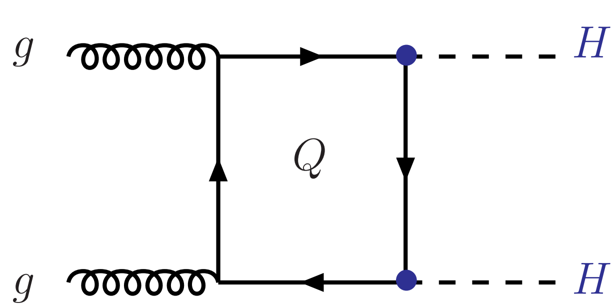
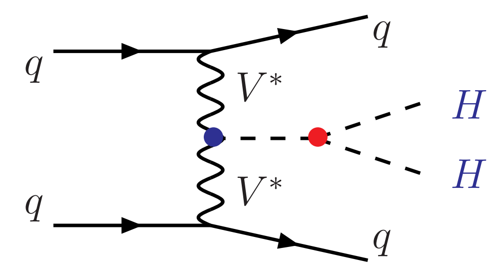
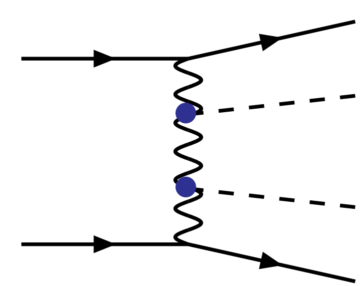
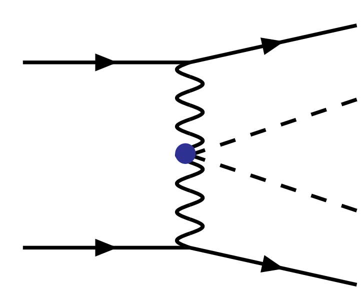




- Vector boson fusion







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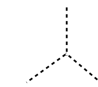
$V'\left(\frac{v^2}{2}\right) = 0$

physical Higgs mass
$m_h^2 \equiv v^2 V''\left(\frac{v^2}{2}\right)$

Beyond the SM contribution

cubic Higgs coupling



$\lambda_{hhh}^{\mathrm{SM}} \equiv \frac{v}{2}V'' \left(= \frac{m_h^2}{2v}\right)$ $\quad C_h \equiv \frac{v^2}{3}\frac{V'''}{V''}$

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☆ Possible enhancement of Higgs boson pair production

☆ $pp \to hhX$ @ ***LHC*** (3 contributions)

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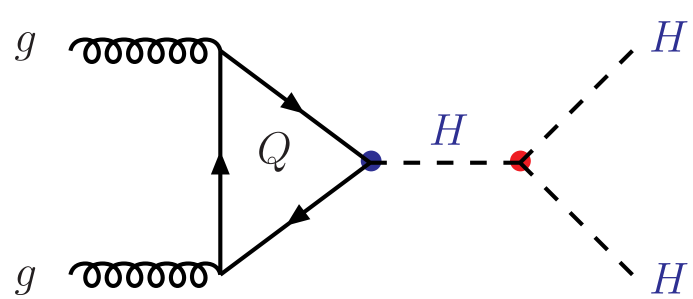
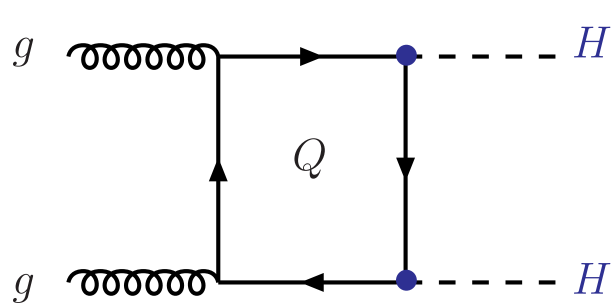
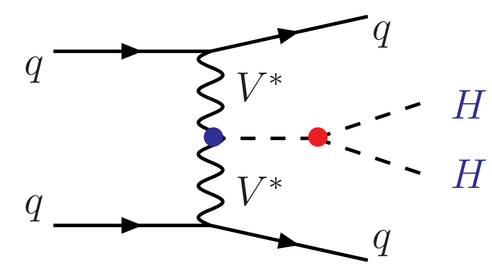
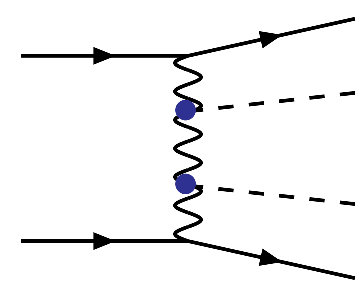
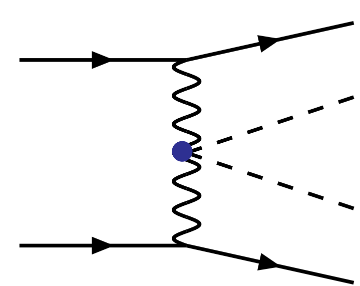




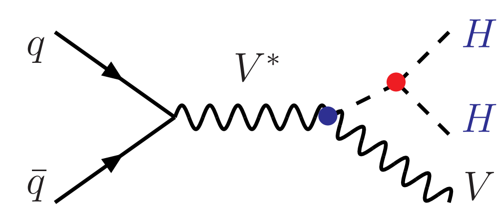
- Vector boson fusion

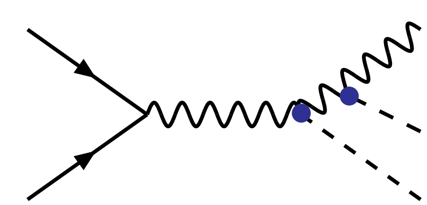


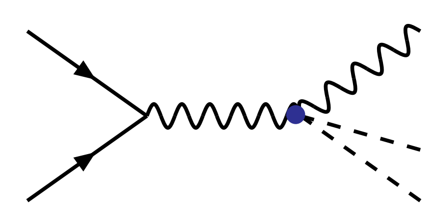




- Higgs-strahlung







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☆ Possible enhancement of Higgs boson pair production

$$V = V\left(\frac{v^2}{2}\right) + V'\left(\frac{v^2}{2}\right)\left(vh + \frac{h^2}{2} + \frac{\chi^2}{2} + \chi^+\chi^-\right) + \frac{1}{2}V''\left(\frac{v^2}{2}\right)\left(vh + \frac{h^2}{2} + \frac{\chi^2}{2} + \chi^+\chi^-\right)^2 + \frac{1}{6}V'''\left(\frac{v^2}{2}\right)\left(vh + \frac{h^2}{2} + \frac{\chi^2}{2} + \chi^+\chi^-\right)^3 \cdots$$

stationary condition $V'\left(\frac{v^2}{2}\right) = 0$

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Beyond the SM contribution

cubic Higgs coupling

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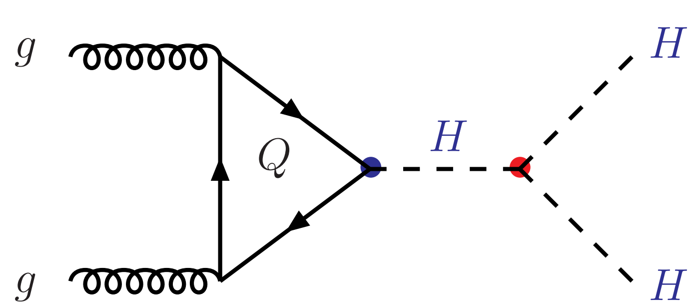

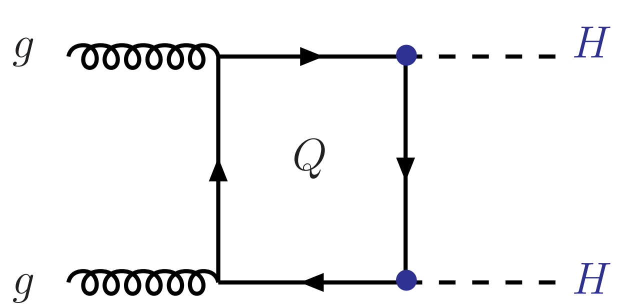

$$\sigma(pp \to gg \to hh)^{\rm LO}_{\rm SM,14TeV} \sim 20 \text{ fb}$$

$\gg$

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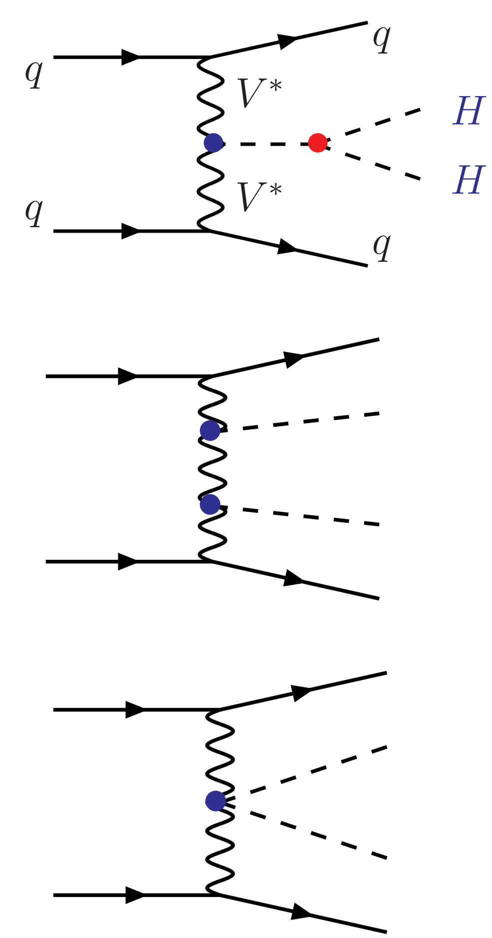

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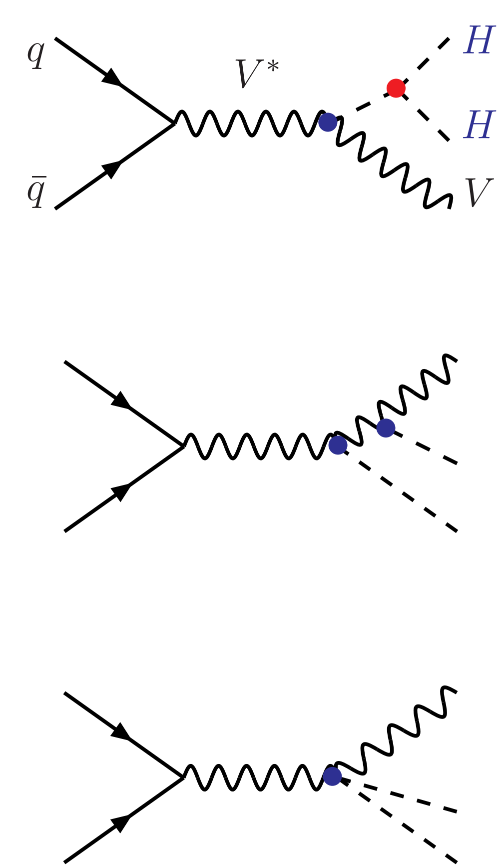

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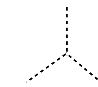

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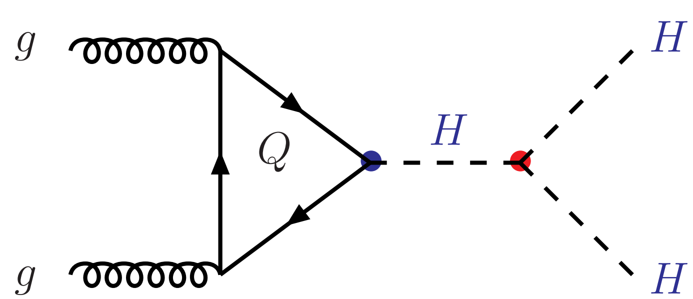

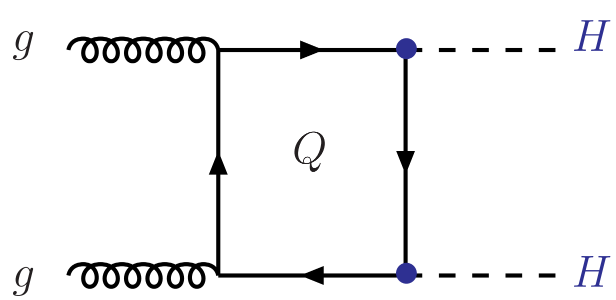

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In order to understand C_h contribution,
we utilize the following effective theory for gluon-Higgs interaction

$$\mathcal{L}_{\rm eff} = \frac{\alpha_s}{12\pi}G^a_{\mu\nu}G^{a\mu\nu}\ln\left(1 + \frac{h}{v}\right)$$
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(Hagiwara and Murayama)

Amplitude with C_h is obtained by

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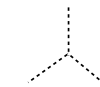

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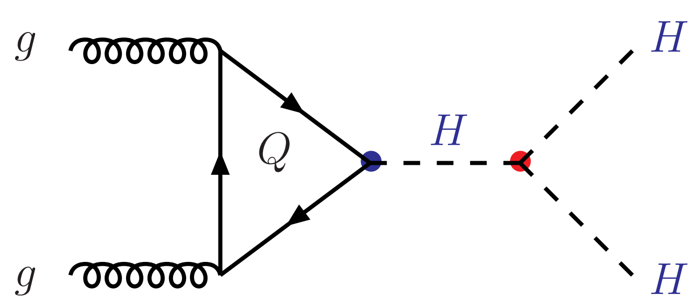

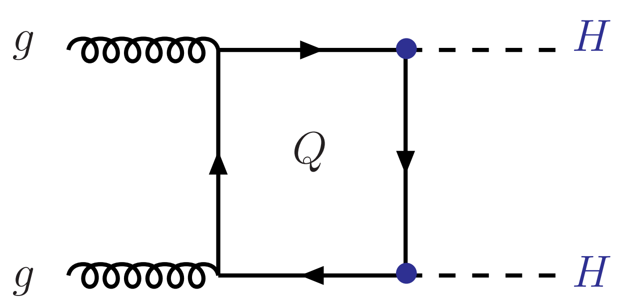

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- $C_h > 0$ provides $\mathcal{M} = 0$ at some $\hat{s}$
- $C_h < 0$, there is no cancellation for any $\hat{s} > 4m_h^2$

We focus on $C_h \neq 0$ case.

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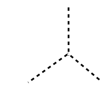

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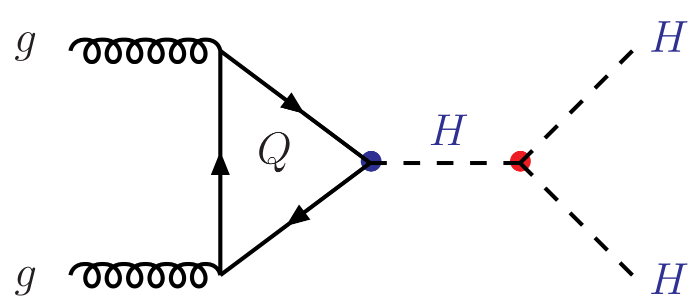

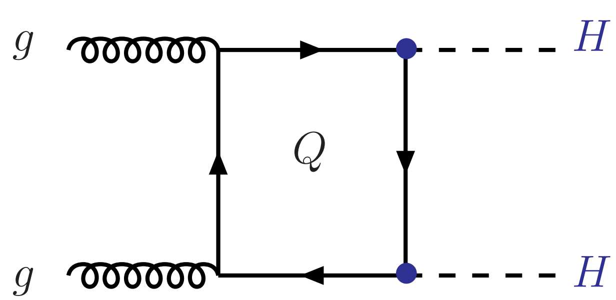

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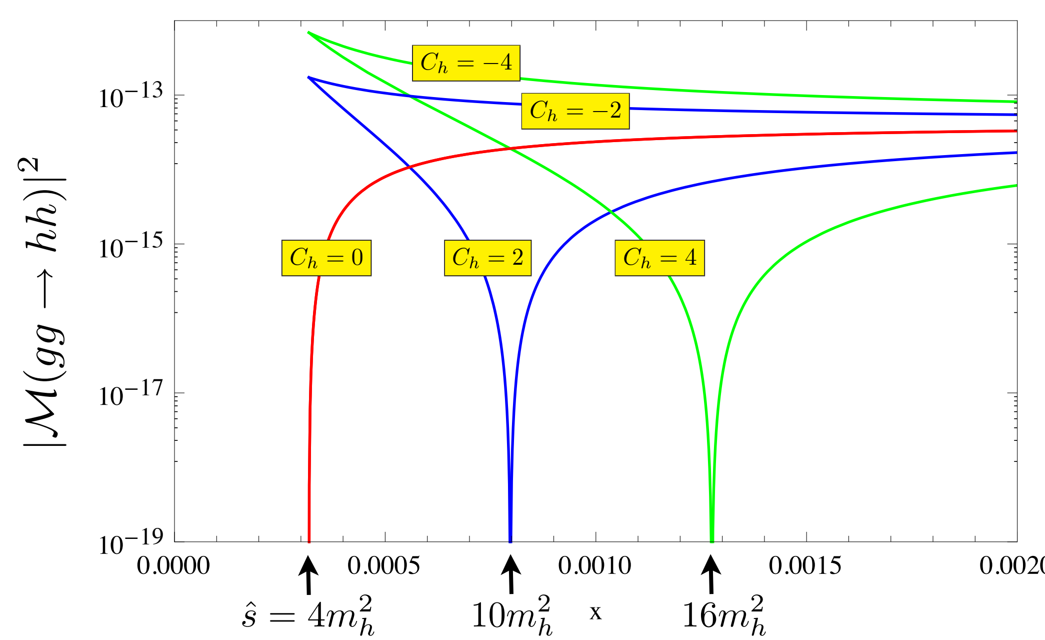

$x = \hat{s}/(14\text{TeV})^2$

$C_h < 0$ enhances $gg \to hh$

We focus on $C_h \neq 0$ case.

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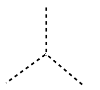

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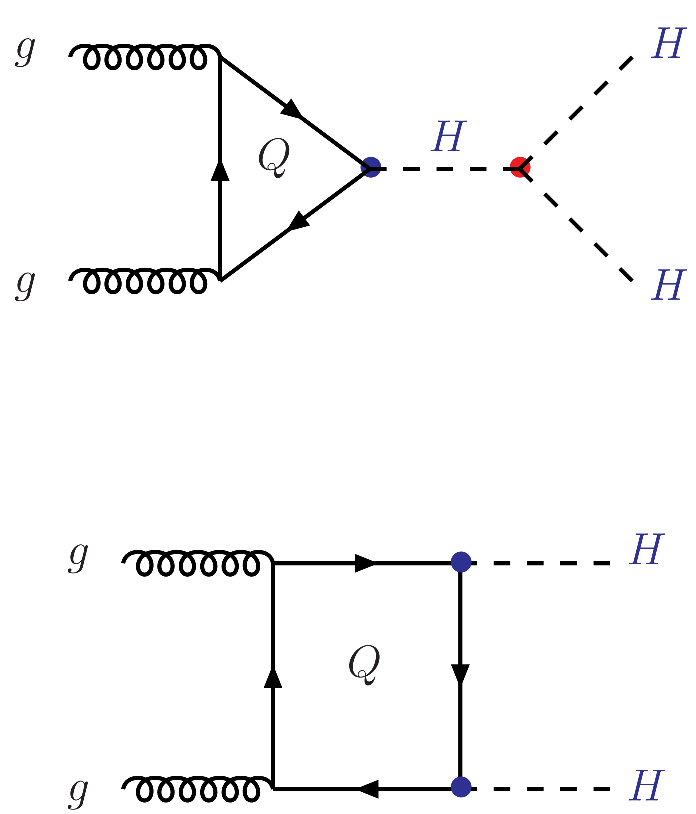
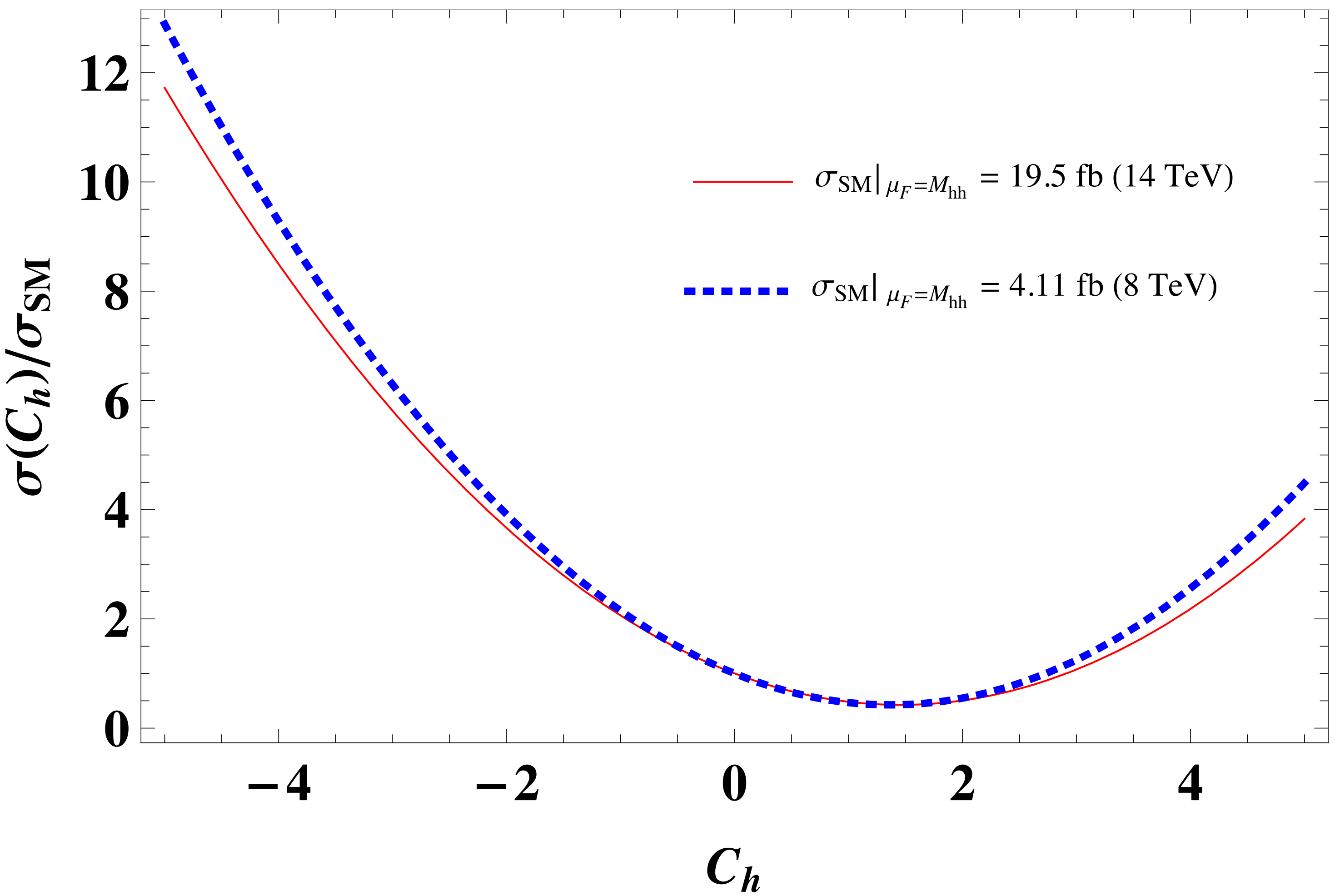


$$\sigma(pp \to gg \to hh)^{\rm LO}_{\rm SM,14TeV} \sim 20\ {\rm fb}$$

Ratio of $\sigma(C_h \neq 0)$ and $\sigma(C_h = 0) = \sigma({\rm SM})$



The crosse section can reach ~ $10 \times \sigma_{\rm SM}$

necessary luminosity ~ O(1000) fb^{-1} (SM) ⟶ ~ O(100) fb^{-1} realistic target @ LHC

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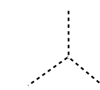

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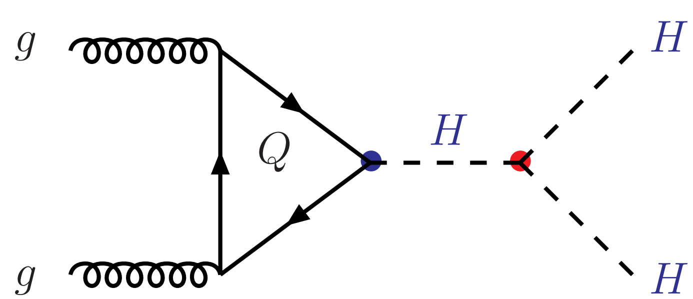

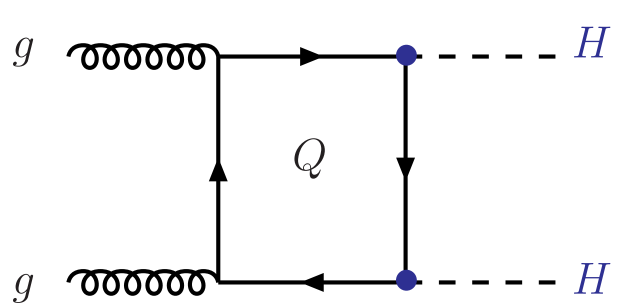

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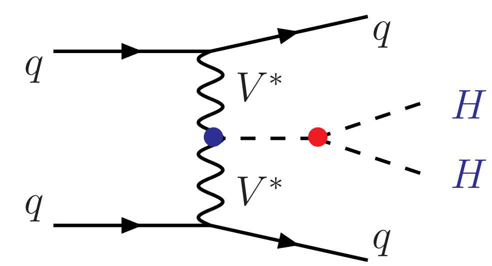

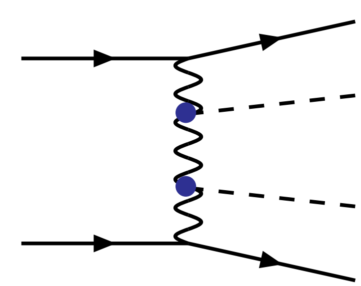

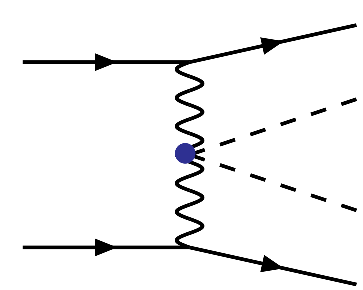

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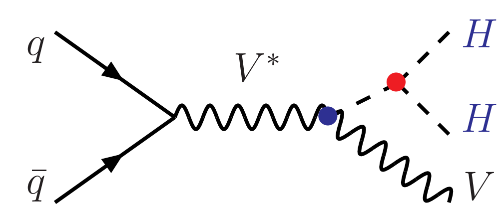

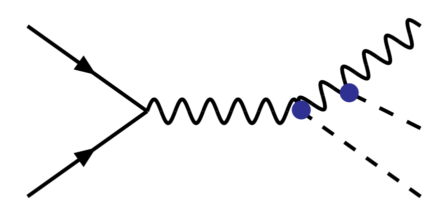

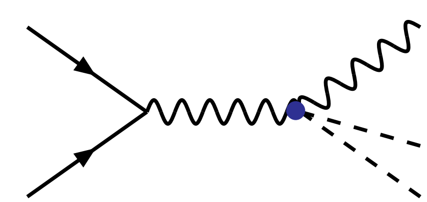

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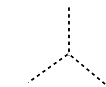


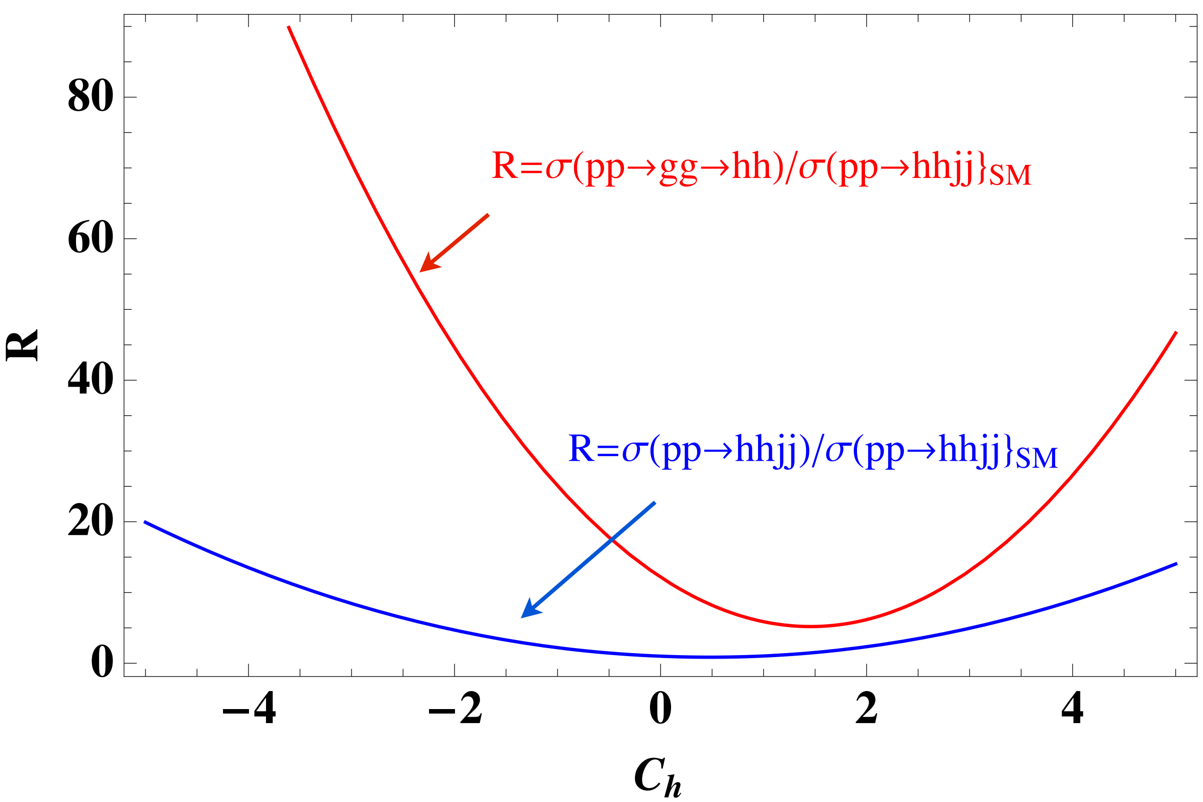
$\lambda_{hhh}^{\rm SM} \equiv \frac{v}{2}V''$ $\left(= \frac{m_h^2}{2v}\right)$ $\quad C_h \equiv \frac{v^2}{3}\frac{V'''}{V''}$

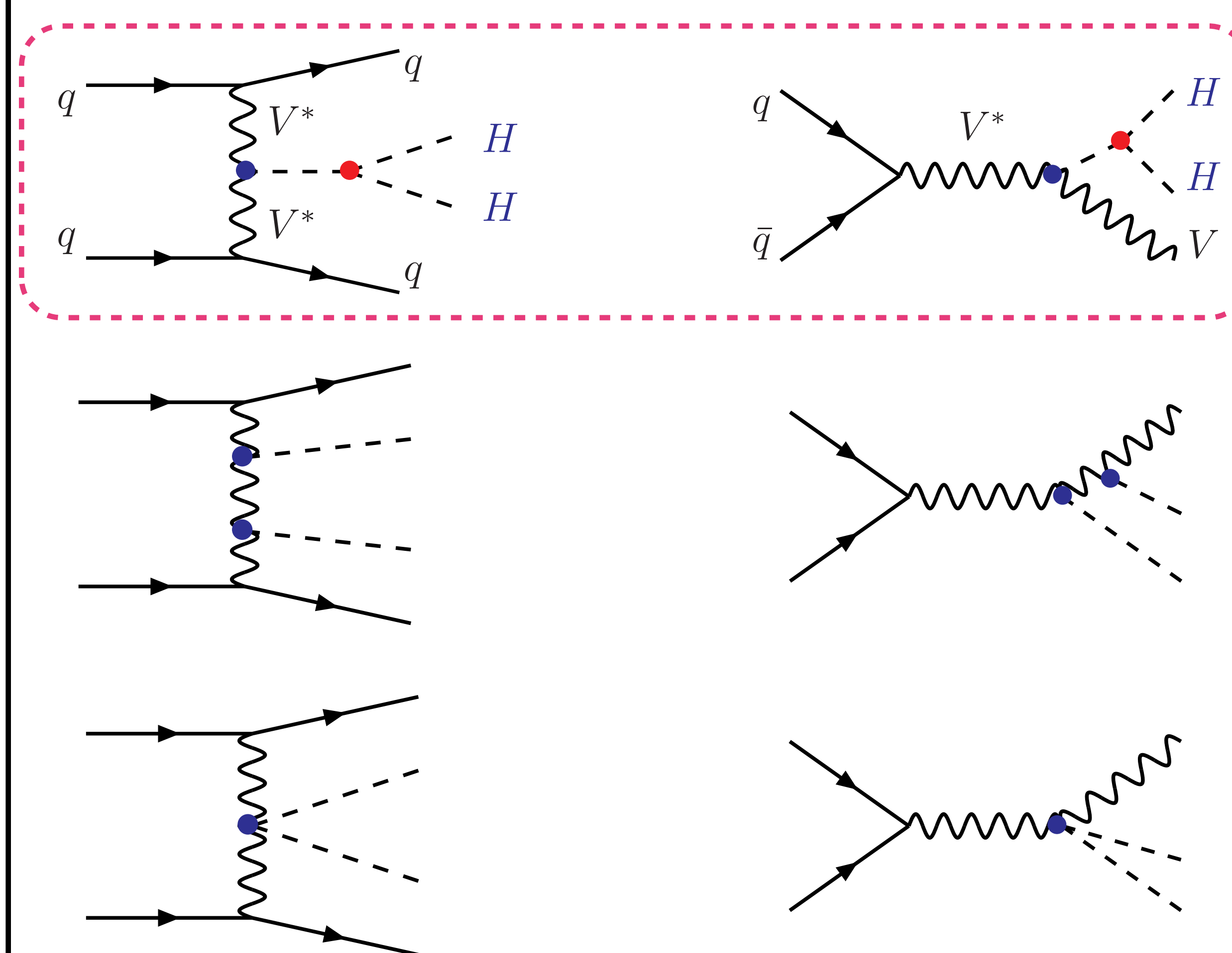
$$-i6\left[\frac{1}{2}vV'' + \frac{1}{6}v^3V'''\right] = -i6\lambda_{hhh}^{\rm SM}(1 + C_h)$$

$C_h = 0$ for the SM Higgs potential

- Vector boson fusion
- Higgs-strahlung

How about these contributions?





$$\sigma(pp \to hhjj)^{\rm LO}_{\rm SM, 14TeV} \sim 1.6\ {\rm fb}$$

we can see

$gg \to hh$ always dominate for any C_h

3, Non-perturbative Higgs model

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Now we have found that $C_h < 0$ easily enhance the Higgs pair production.

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☆ An example for realizing $C_h < 0$

- Toy model

$$V(|H|^2) = m^2|H|^2 + \Lambda^{4-2a}(|H|^2)^a \qquad \begin{cases} m_h^2 = 2m^2(1-a) \\ C_h = \frac{v^2}{3}\frac{V'''}{V''} = \frac{2}{3}(a-2) \end{cases}$$

$$< 0 \qquad (\text{when } a < 0)$$

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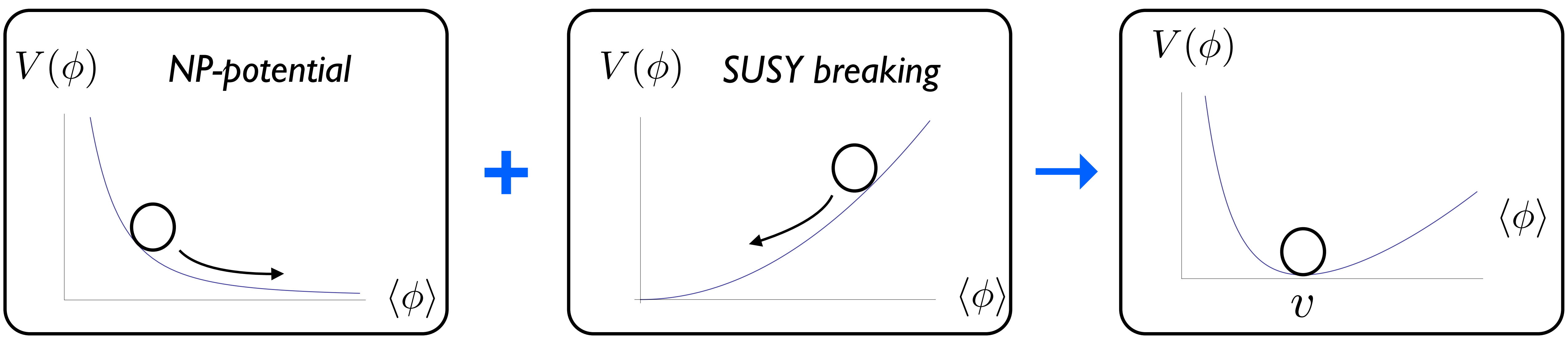
This kind of potential can be realized in context of SQCD.

- Non-perturbative Higgs model (SQCD)

$$W_{np} = \Lambda^3 \left(\frac{\Lambda^2}{H_u H_d}\right)^{\kappa} \qquad C_h \simeq -\frac{5}{3} - \frac{4}{3}\kappa \qquad < 0 \ (\kappa > 0)$$



(D'Hoker-Mimura-Sakai)

3, Non-perturbative Higgs model

Let us consider other possibility of new physics effect.

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☆ Non-canonical kinetic term

$$\boxed{\mathcal{L}_{\rm kin} = F\left(\frac{|H|^2}{v^2/2}\right) D_\mu H^\dagger D^\mu H}$$

i.e. non-canonical Kahler potential

$F(x) = 1$ in SM

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$G(x) \equiv xF(x)$ and expand around $x = 1$

$$\Rightarrow \quad (M_W^2 W^+ W^- + \frac{M_Z^2}{2} Z^2)\left(1 + G'(1)\frac{2h}{v} + (G'(1) + 2G''(1))\frac{h^2}{v^2} + \cdots\right)$$

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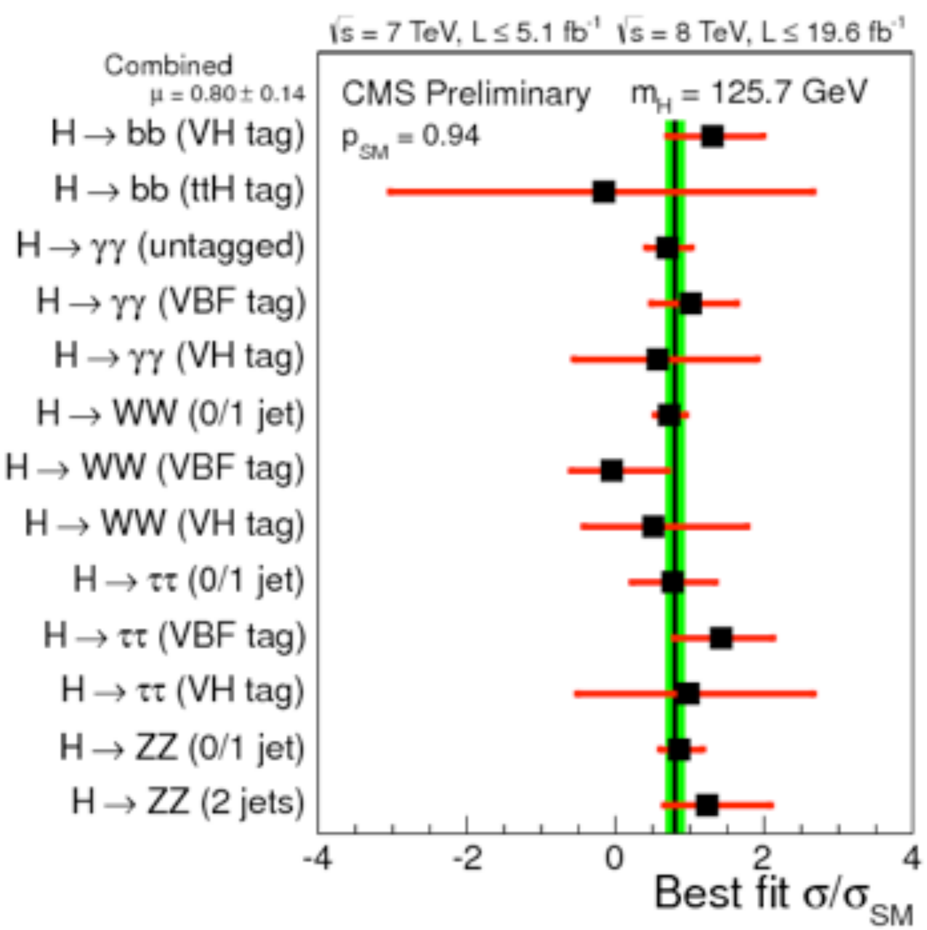


From the Higgs coupling measurements, (at least)

Higgs to W^+W^-/ZZ coupling is consistent with SM.

$$G'(1) \simeq 1$$

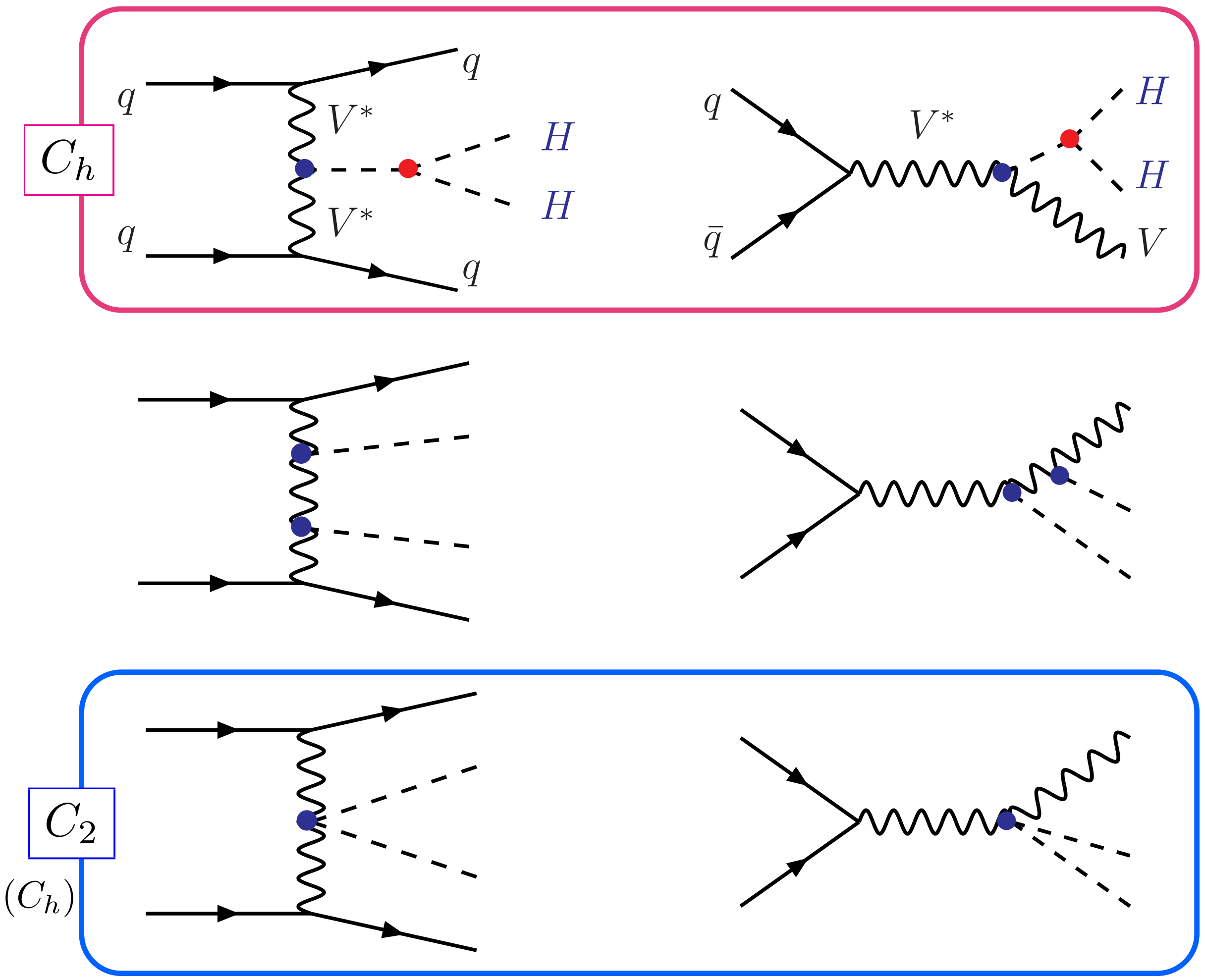
Here we have two parameters related to New Physics

C_h and $C_2 \equiv 2G''(1)$

→ How can these two parameters change Higgs pair production?

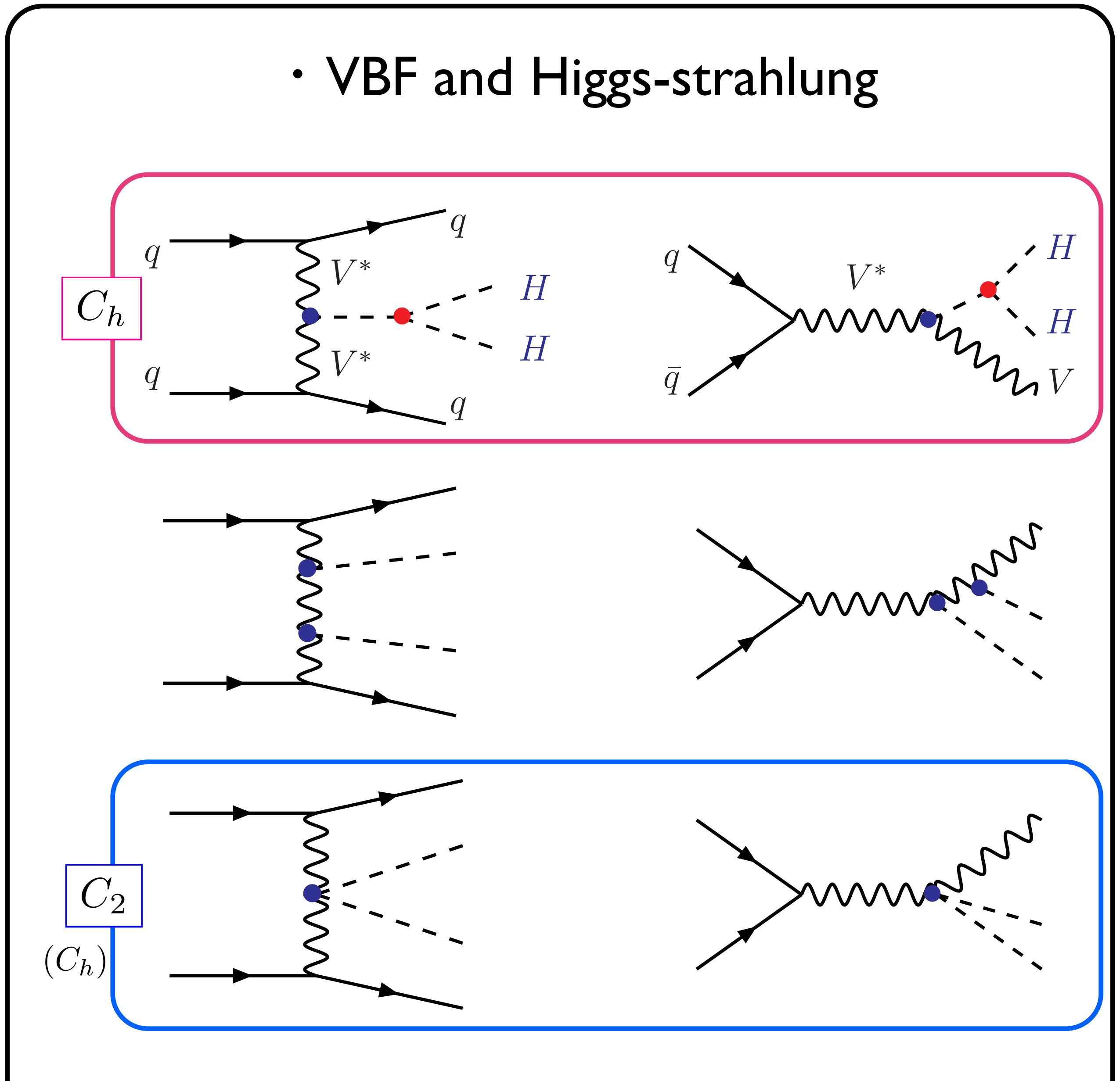
☆ $pp \to hhjj$ @ LHC

• VBF and Higgs-strahlung

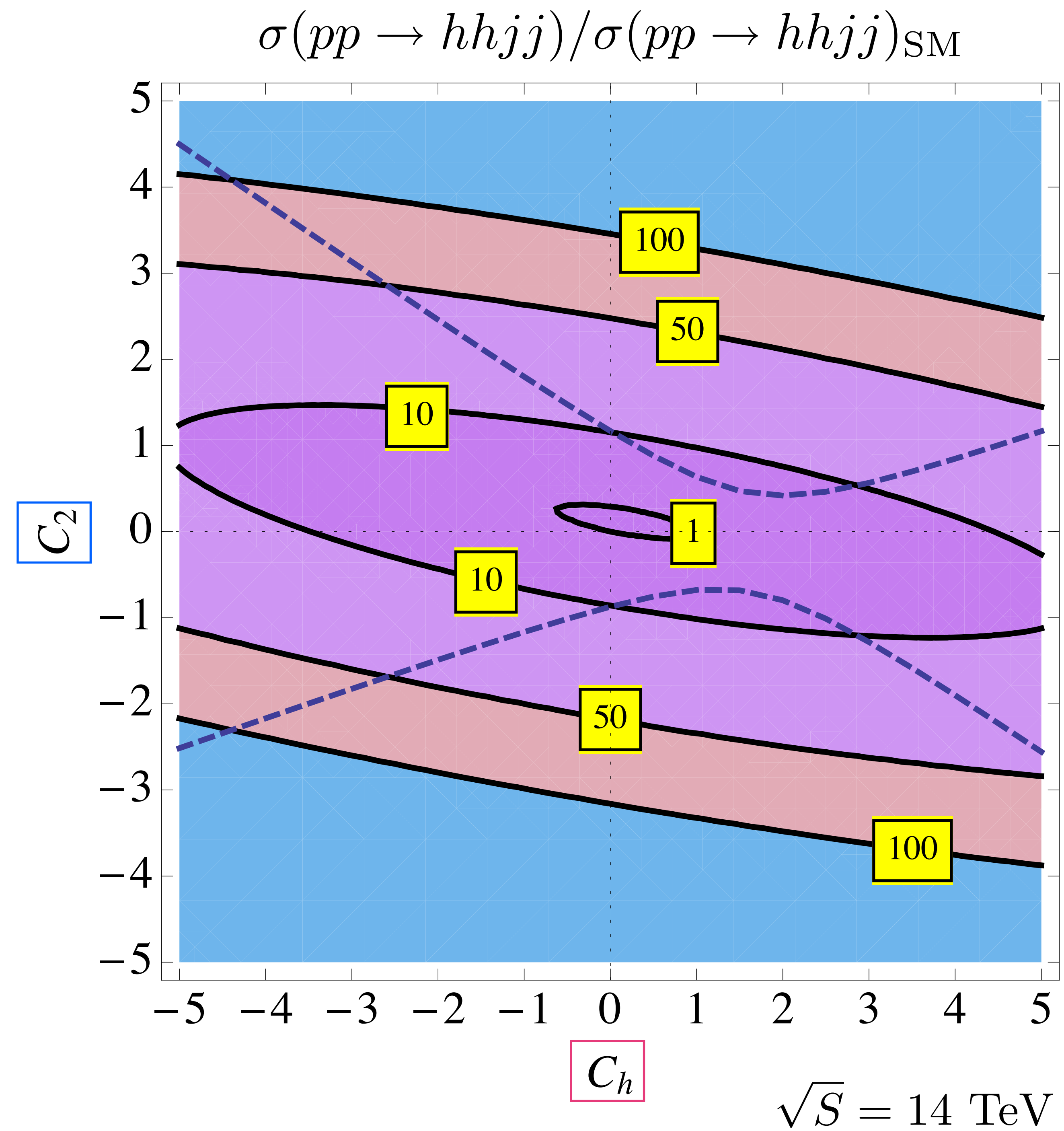


$$\sigma(pp \to hhjj)^{\mathrm{LO}}_{\mathrm{SM,14TeV}} \sim 1.6 \text{ fb}$$

☆ $pp \to hhjj$ @ **LHC**



$\sigma(pp \to hhjj)^{\rm LO}_{\rm SM,14TeV} \sim 1.6$ fb



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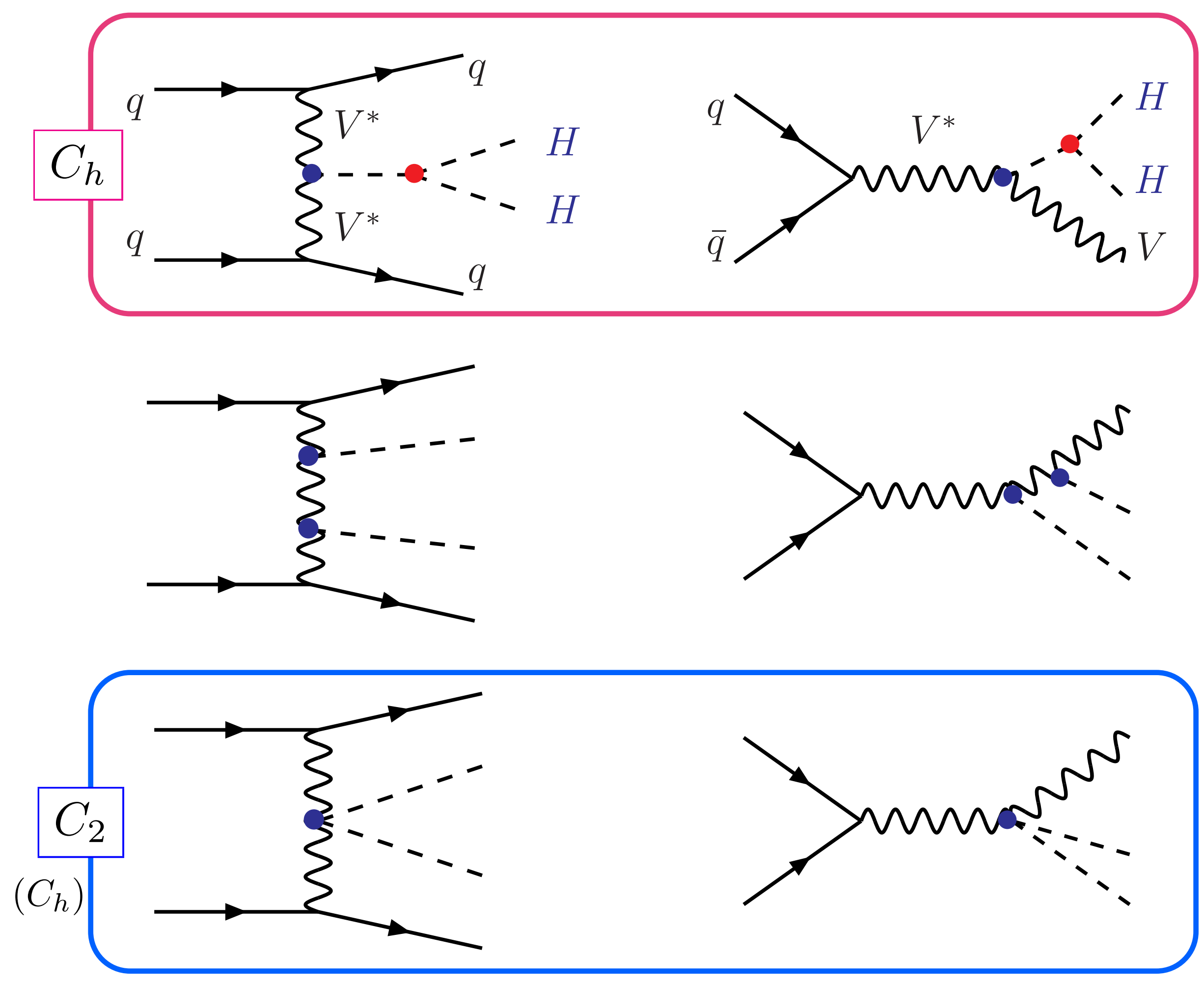

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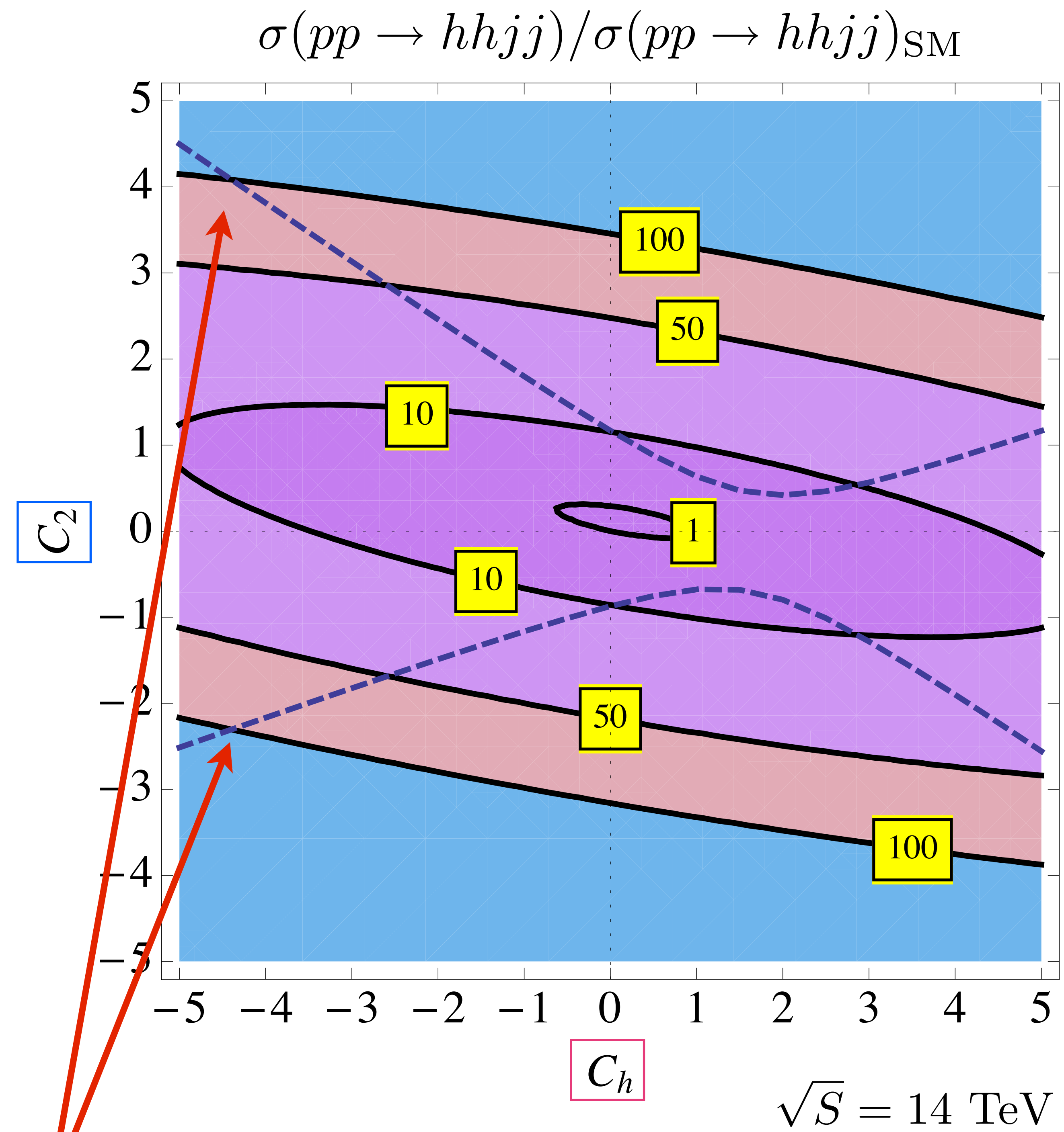
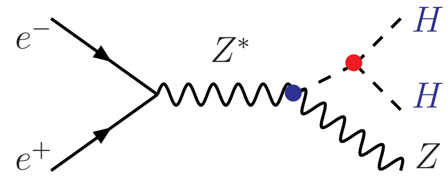
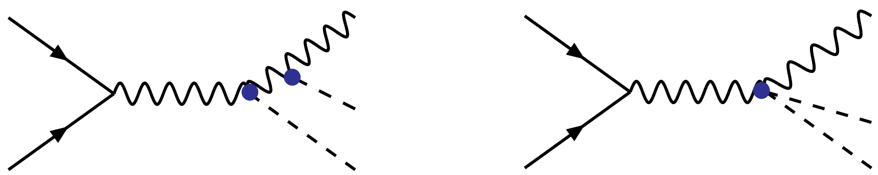


$$\sigma(pp \to hhjj) = \sigma(pp \to gg \to hh)$$

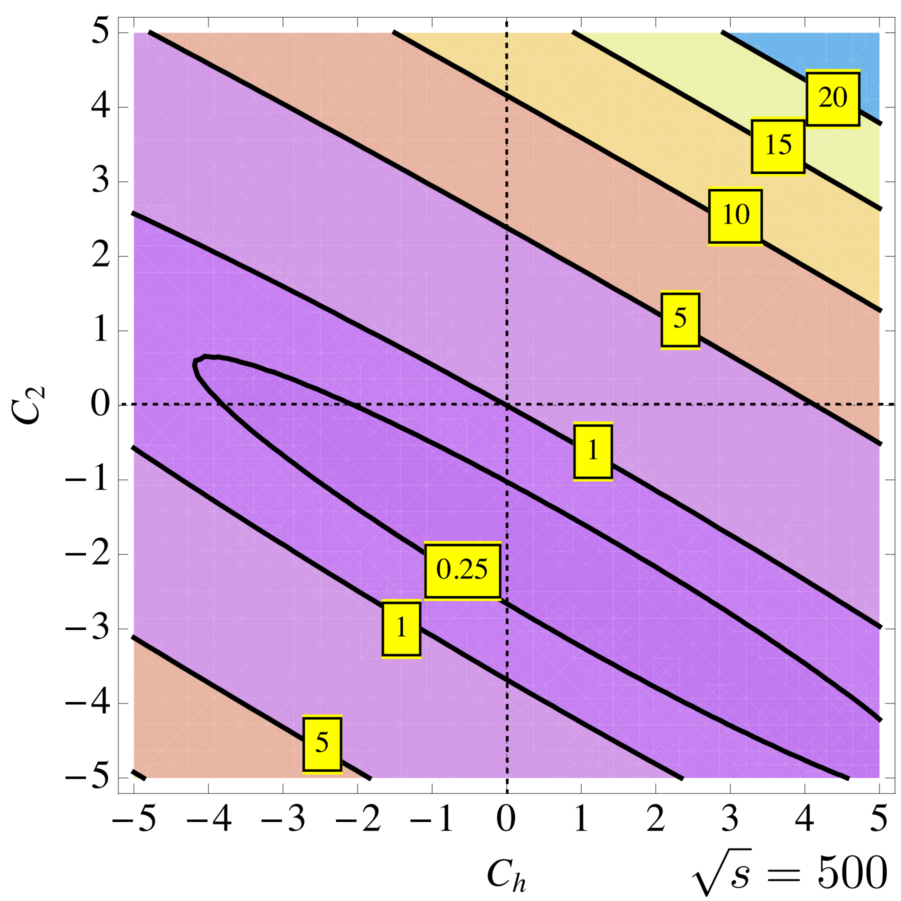
☆ $e^+e^- \to hhX$ @ ILC

- Higgs-strahlung





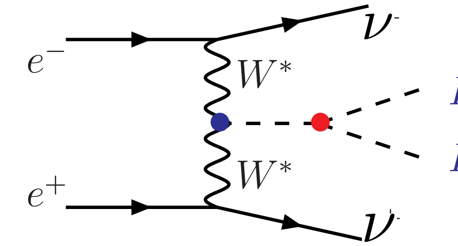
$$\sigma(e^+e^- \to Zhh)/\sigma(\mathrm{SM})$$

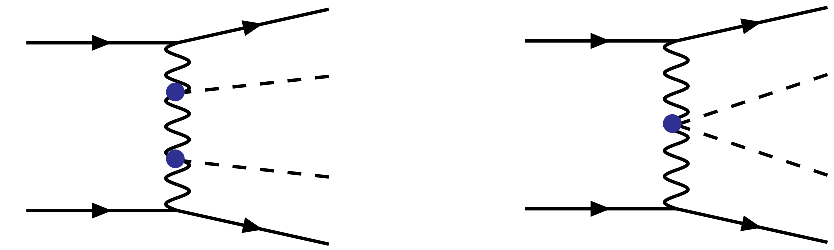


$\sqrt{s} = 500$ GeV

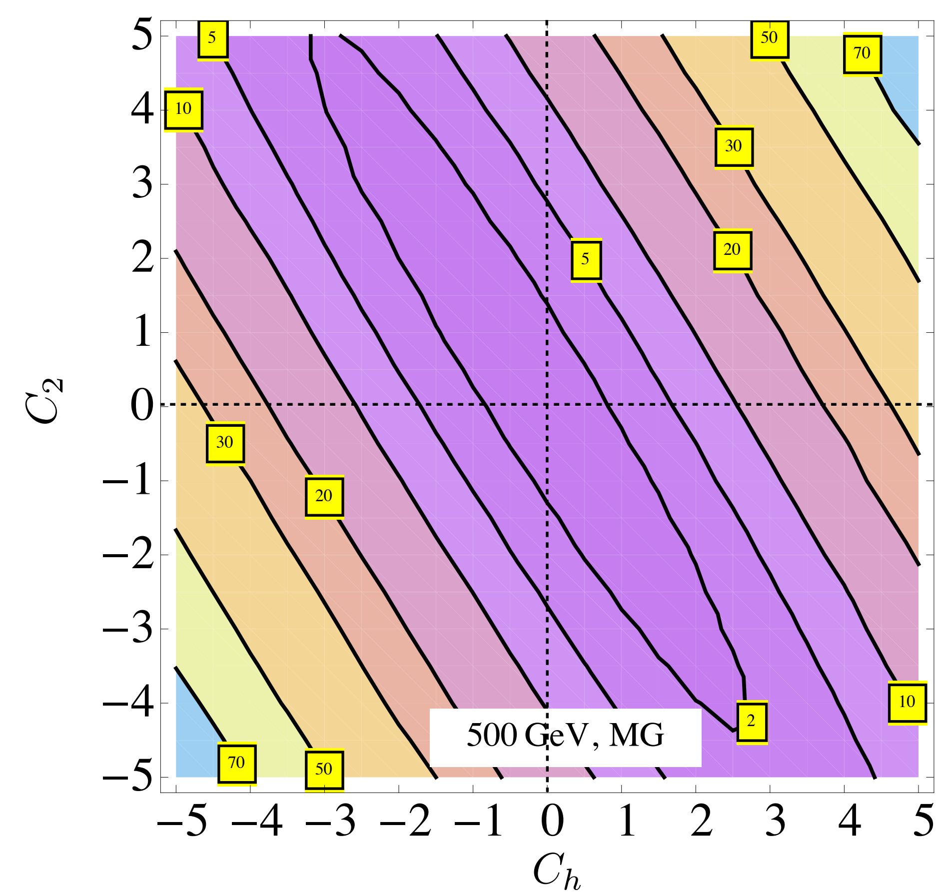
$$\sigma(e^+e^- \to Zhh)_{\mathrm{SM,500GeV}} \sim 0.16\ \mathrm{fb}$$

- Vector boson fusion





$$\sigma(e^+e^- \to \nu\bar{\nu}hh)/\sigma(\mathrm{SM})$$



$$\sigma(e^+e^- \to \nu\bar{\nu}hh)_{\mathrm{SM,500GeV}} \sim 0.033\ \mathrm{fb}$$

Summary

☆ Higgs self-interaction is still unknown.

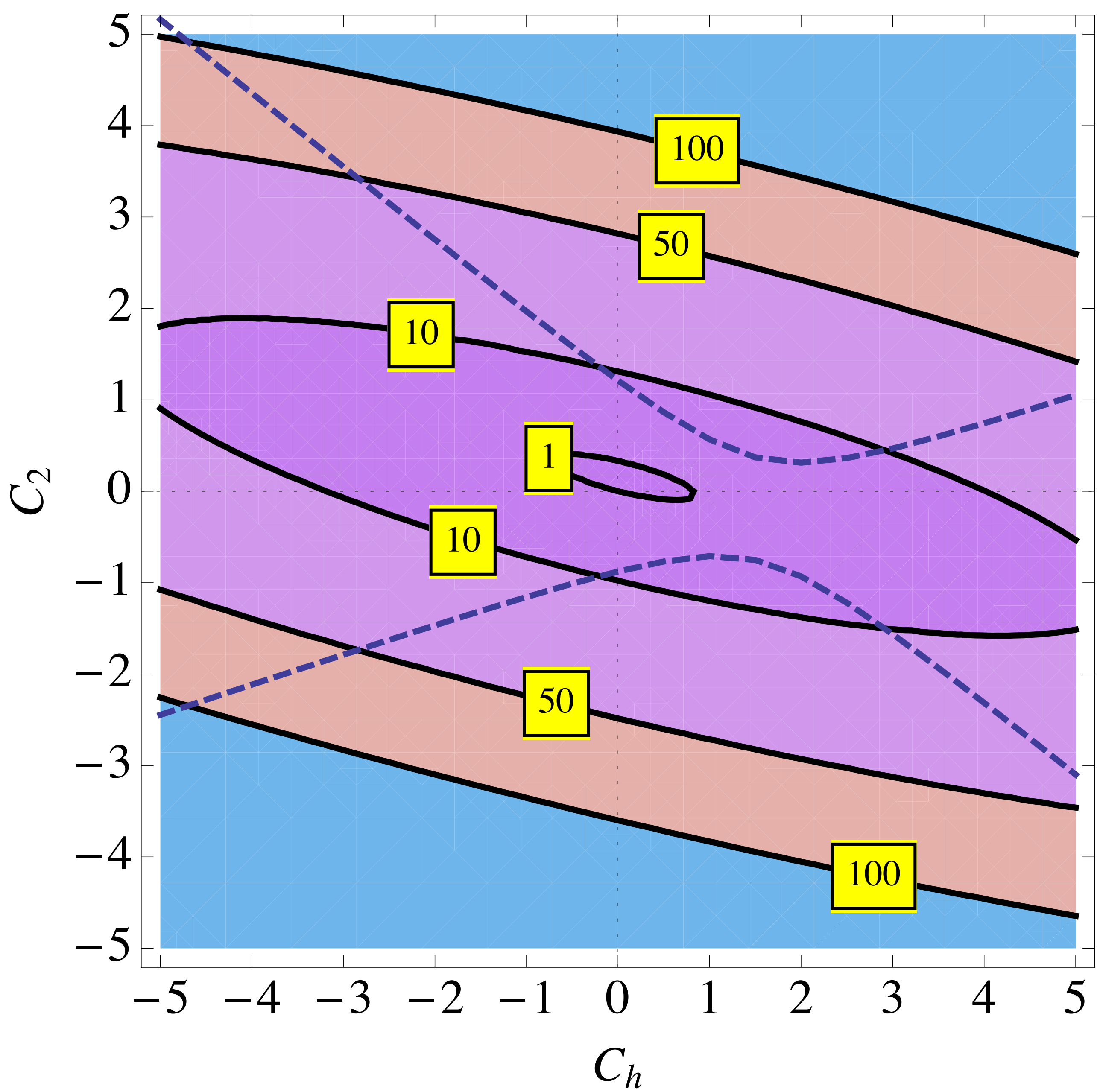
☆ Self-coupling measurement is important to understand how the Higgs field acquires a VEV.

☆ Non-perturbative Higgs model is suggested.

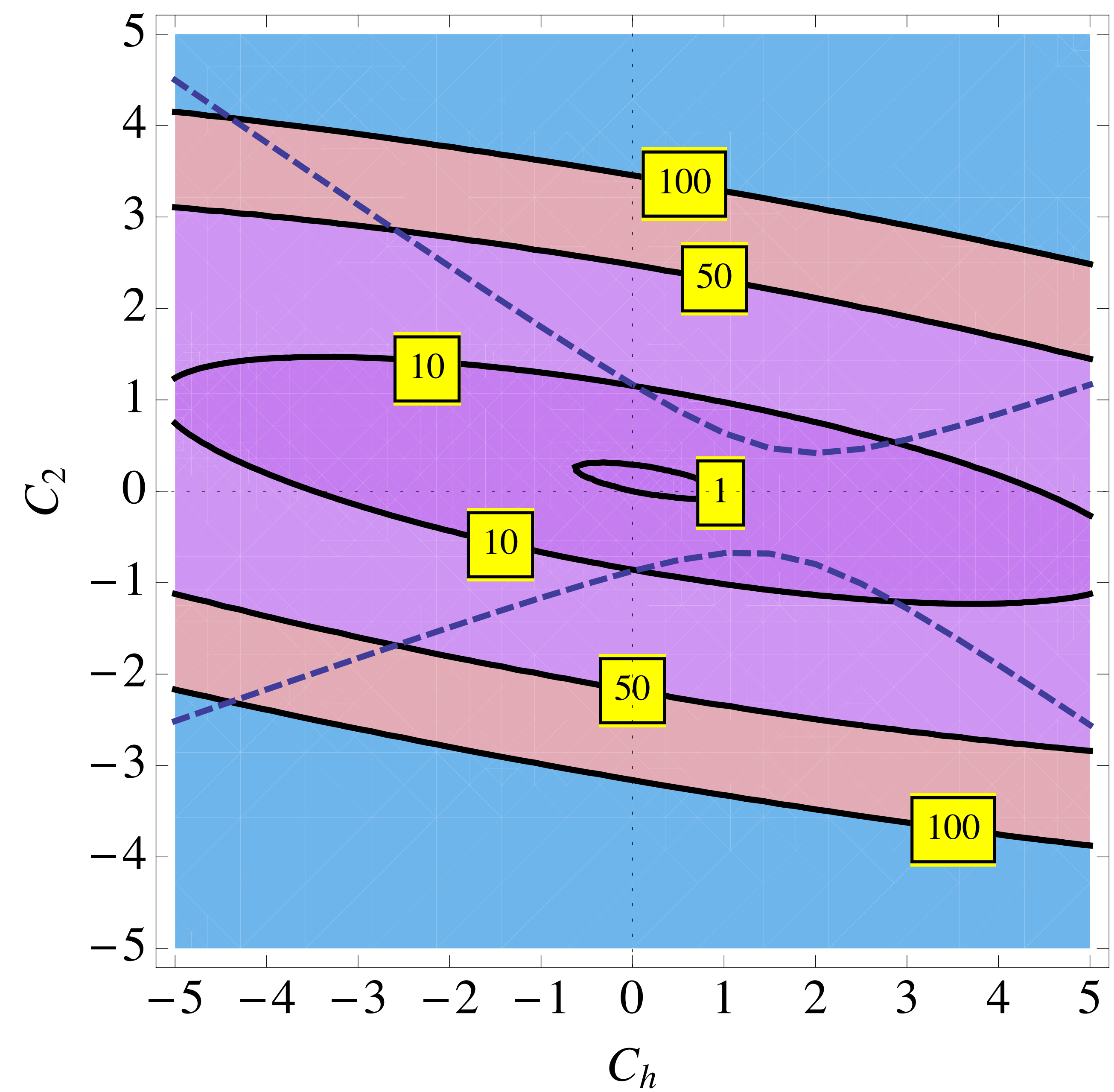
☆ We pointed out that sizable enhancement of Higgs pair production is induced by non-zero C_h and C_2 .

Thank you for your attention

$$\sigma(pp \to hhjj)/\sigma(pp \to hhjj)_{\text{SM}}$$



8TeV LHC



14TeV LHC