SUSY Higgs with Non-perturbative effects

Yukihiro Mimura (National Taiwan University)

Based on
PLB718 (2013) 1441.
Collaboration with N. Haba, K. Kaneta, and R. Takahashi
Work in progress with Enkhbat Tsedenbaljir, Haba, Kaneta

Talk at SUSY2013 at ICTP, Trieste (2013.8.30)

Higgs pair-production at the LHC & ILC from general potential

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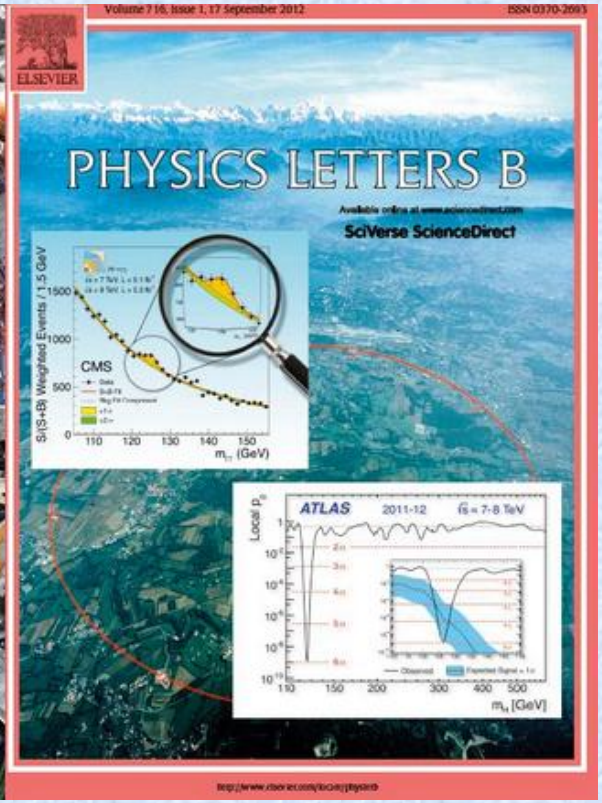
Menu

- Introduction (Higgs forces)
- Higgs potential and the cubic Higgs coupling
- Non-perturbative Higgs model in SUSY QCD
- Pair-Higgs production

  $pp \to gg \to hh$

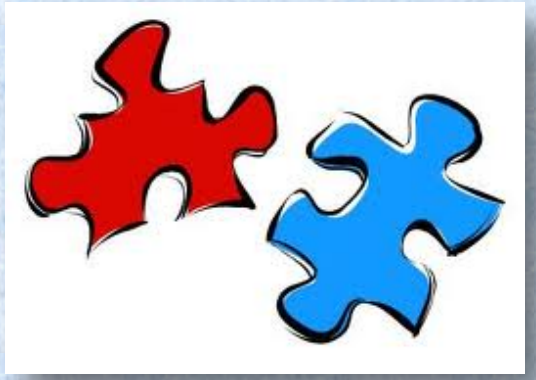
  $e^+e^- \to hh\bar{\nu}\nu \qquad e^+e^- \to Zhh$
- Conclusion

Discovery of the Higgs boson in July, 2012



SM Higgs?

We need to look at it carefully.



"Higgs Forces"

1. Higgs self-coupling

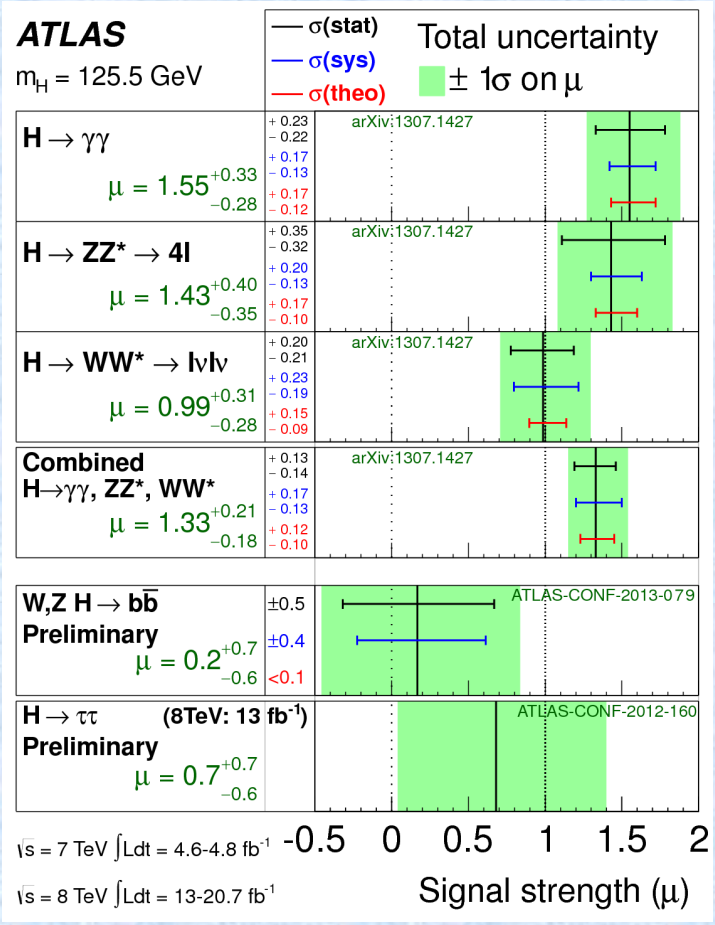
   How does the Higgs field acquire a VEV ?

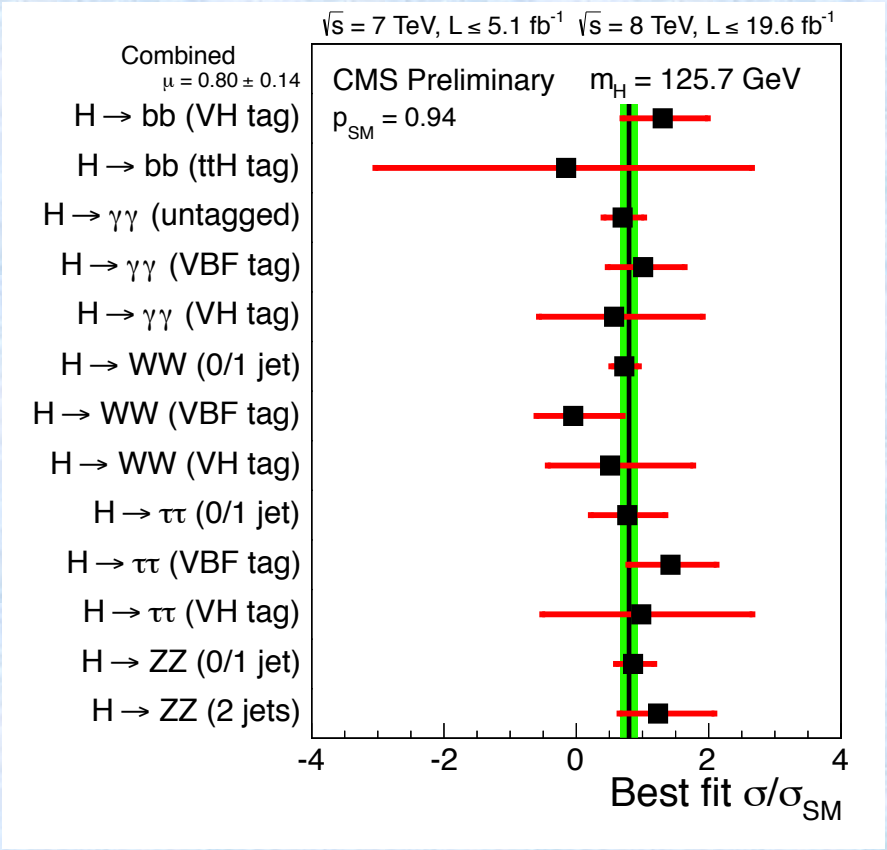
$$V = m_H^2 |H|^2 + \lambda |H|^4 \qquad m_H^2 < 0$$

2. Couplings to fermions (Yukawa coupling) $Y_t \overline{q_{3L}} t_R H$

   How does the Higgs VEV give masses to fermions?

3. Couplings to gauge bosons $\mathcal{L} = \left| (\partial - i\frac{g}{2} W^a \tau^a - i\frac{g'}{2} B) H \right|^2$





- Combined μ → Best accuracy but no strong physics motivation:
  - **ATLAS (γγ, WW* and ZZ*)** **μ = (1.33 ± 0.20)** (1.23±0.18 including bb and ττ)
  - **CMS (γγ, ττ, bb, WW* and ZZ*)** **μ = (0.80 ± 0.14)**
  - **TEVATRON (bb, γγ, ττ, WW*)** **μ = (1.44 ± 0.60)**

Compatible with SM Higgs boson expectation: Accuracy ~ 15%

“Higgs Forces”

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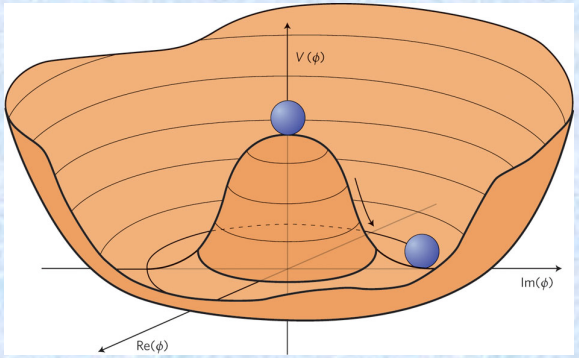
Probing the Higgs self-interaction

$$V = m_H^2|H|^2 + f(|H|^2)$$



$$H^0 = \frac{v+h+i\chi}{\sqrt{2}} \qquad |H|^2 = \frac{v^2}{2} + vh + \frac{h^2+\chi^2}{2} + \chi^+\chi^-$$

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

$$\text{Stationary condition}: \; m_H^2 + f'(v^2/2) = 0$$

$$\text{Mass of physical Higgs } (h): \; m_h^2 = v^2 f''(v^2/2)$$

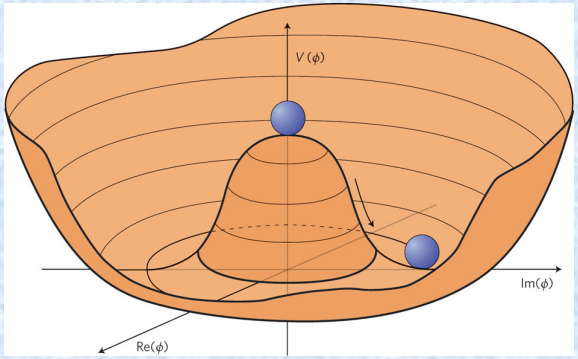
$$V = V(|H|^2) \quad \Longrightarrow \quad m_h^2 = v^2 V''$$

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

$$\begin{aligned} -\mathcal{L} \supset \quad & V''vh\left(\frac{\chi^2}{2} + \chi^+\chi^-\right) + \frac{1}{2}V''\left(\frac{\chi^2}{2} + \chi^+\chi^-\right)^2 \\ & + \frac{1}{2}\left(V'' + \frac{1}{3}v^2V'''\right)vh^3 \\ & + \frac{1}{2}\left(V'' + v^2V'''\right)\left(\frac{\chi^2}{2} + \chi^+\chi^-\right)h^2. \end{aligned}$$

(Chivukula-Koulovassilopoulos, Boudjema-Chopin, …)

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



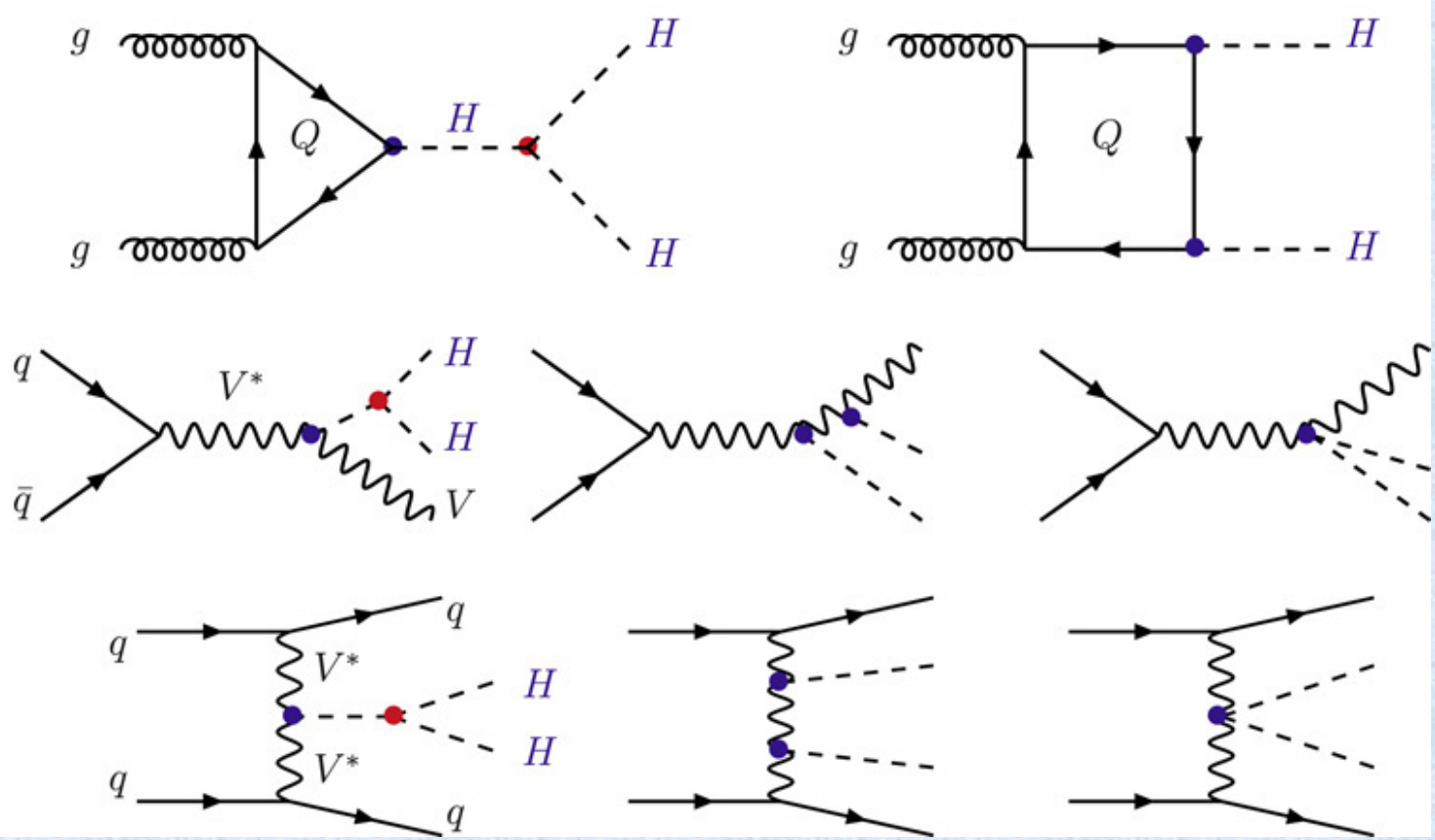
Mass of physical Higgs (h) : $m_h^2 = v^2 V''(v^2/2)$

Cubic Higgs coupling : λ_{hhh}

$$\lambda_{hhh} = 3vV'' + v^2 V''' = \frac{3m_h^2}{v}\left(1 + v^2 \frac{V'''}{3V''}\right)$$

$$\equiv C_h$$

Pair production of the Higgs boson at the LHC

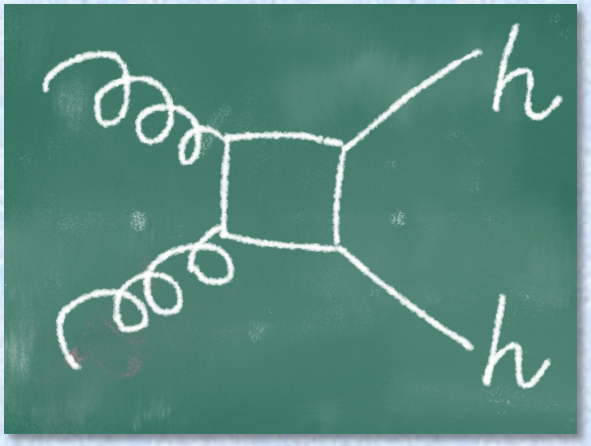


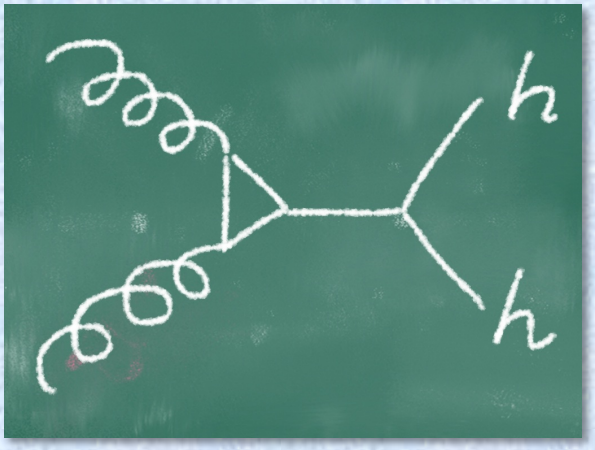
$$\sigma(pp \to gg \to hh)^{\rm NLO}_{\rm SM,14\ TeV} = 30 - 40\ ({\rm fb})$$

Gluon-gluon-Higgses effective interactions (Hagiwara-Murayama):

$$\mathcal{L}_{\rm eff} = \frac{\alpha_s}{12\pi}(\log H) G^a_{\mu\nu} G^{a\,\mu\nu}$$

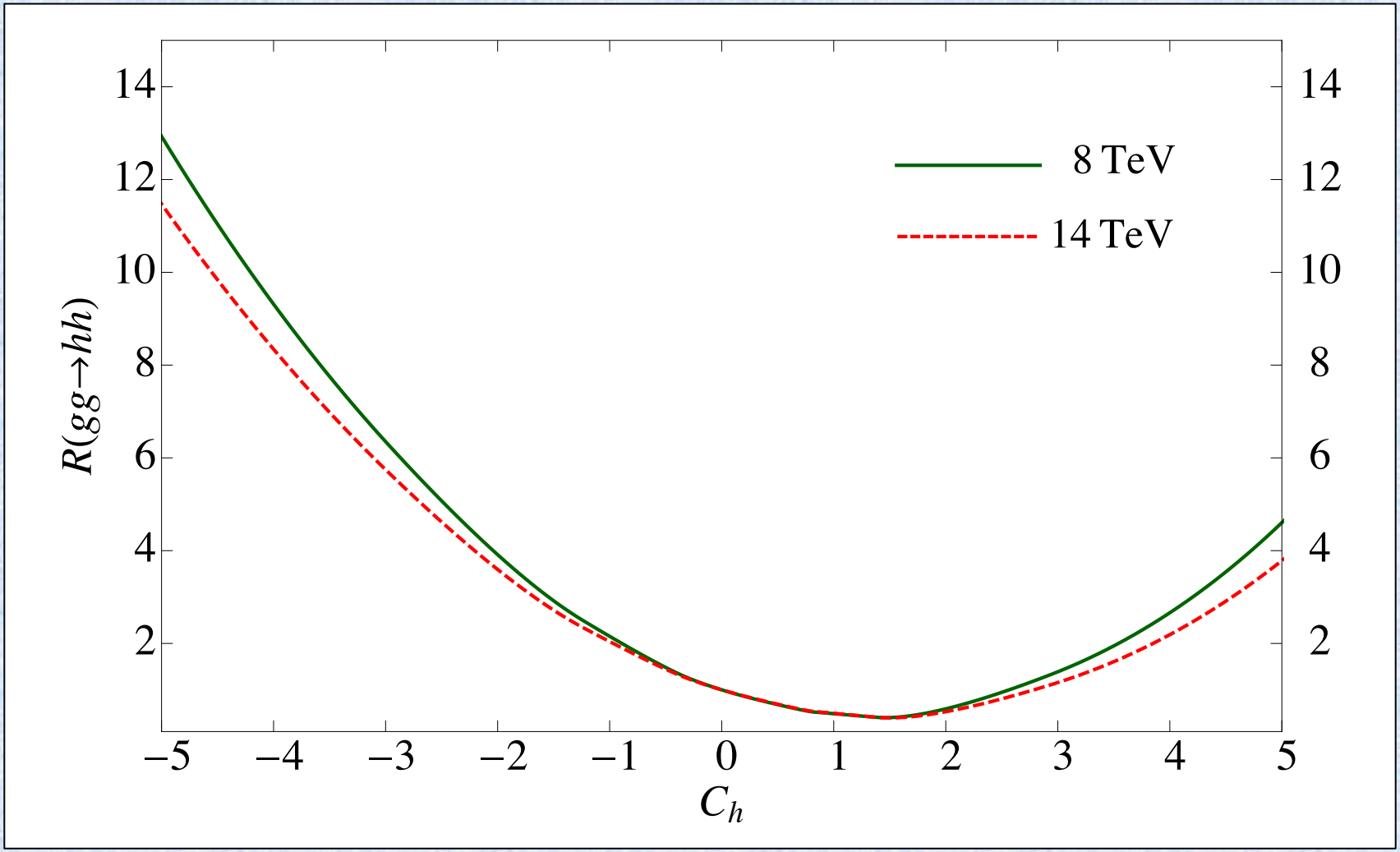
$$= \frac{\alpha_s}{12\pi}\left(\frac{h}{v} - \frac{h^2}{2v^2} + \frac{h^3}{3v^3} - \cdots\right) G^a_{\mu\nu} G^{a\,\mu\nu}$$





$$\mathcal{M}(gg \to hh) = \frac{\alpha_s}{3\pi v^2}\left(-1 + \frac{3m_h^2(1+C_h)}{\hat{s} - m_h^2}\right)$$

$$\lambda_{hhh} = 3\frac{m_h^2}{v}\left(1 + \frac{1}{3}v^2\frac{V'''}{V''}\right) \qquad C_h = \frac{1}{3}v^2\frac{V'''}{V''}$$



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(Plehn-Spira-Zerwas, Djouadi-Kilian-Muhlleitner-Zerwas, …)

(For 125 GeV Higgs, Shao-Li-Li-Wang, Goertz-Papaefstathiou-Yang-Zurita, …)

Toy potential :

$$V = V(|H|^2) = m^2|H|^2 + \Lambda^{4-2a}(|H|^2)^a.$$

$$\Rightarrow \quad \frac{v^2}{2}\frac{V'''}{V''} = a - 2$$

$$C_h = \frac{1}{3}v^2\frac{V'''}{V''} = \frac{2}{3}(a-2)$$

Run-away potential $(a < 0)$ makes C_h negative.

⇒ Pair-Higgs production is enlarged.

SUSY QCD (Seiberg et al, 90's)

$$SU(N_c) \times SU(N_f) \times SU(N_f) \times U(1)_B$$

$$Q : (\mathbf{N_c}, \mathbf{N_f}, \mathbf{1}, +1), \quad \bar{Q} : (\bar{\mathbf{N}}_\mathbf{c}, \mathbf{1}, \mathbf{N_f}, -1).$$

$$W \propto \frac{\Lambda^{3+\frac{2N_f}{N_c-N_f}}}{(\det \bar{Q}Q)^{\frac{1}{N_c-N_f}}}.$$

for $N_c > N_f$

Non-perturbative Higgs model

Higgs fields are moduli of SUSY QCD.

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

Hypercolor

$$\Lambda H_1^a = \bar{Q}_1 Q^a, \quad \Lambda H_2^a = \bar{Q}_2 Q^a.$$

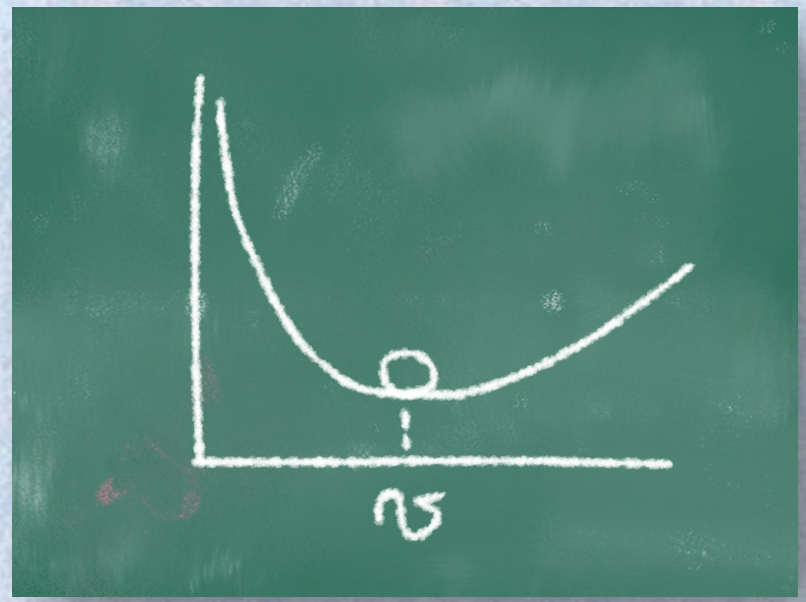
$$W = \frac{\Lambda^{3+2\kappa}}{(H_1 \cdot H_2)^\kappa} \qquad \kappa = \frac{1}{N_c - 2}$$

(Haba-Okada)

NP potential

SUSY breaking

(D'Hoker-YM-Sakai)



$$C_h \simeq -\frac{5}{3} - \frac{4}{3}\frac{1}{N_c - N_f}$$

"Higgs Forces"

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Non-canonical kinetic term

(Chivukula-Koulovassilopoulos,…)

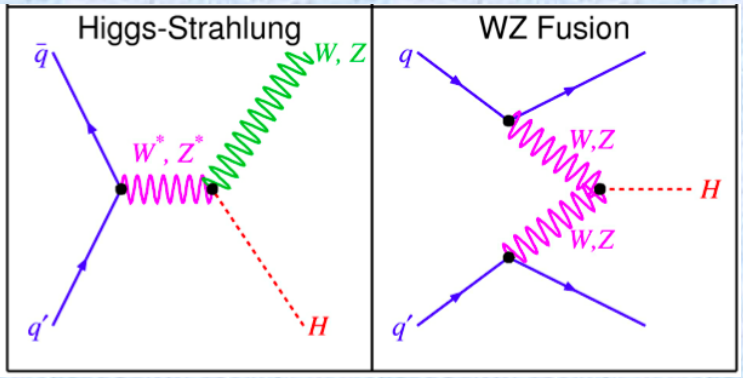
$$\mathcal{L}_{\rm kin} = F\left(\frac{|H|^2}{v^2/2}\right) D_\mu H^\dagger D^\mu H$$

In SM, $F(x) = 1$.

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

$$G(x) = xF(x)$$

In SM, $G' = 1$, $G'' = 0$.



CMS: Evidence for V-boson mediated production 3.2σ

ATLAS: Evidence for VBF production (VH "profiled") 3.3σ

$$G'(1) \sim 1 \ (\text{or} \ -1)$$

$$H = \bar{Q}Q \quad \Longrightarrow \quad K = \mathrm{tr}\sqrt{H^\dagger H}$$

(Affleck-Dine-Seiberg)

We obtain: $K = 2\sqrt{|H_1|^2 + |H_2|^2 + 2\sqrt{H_1 \cdot H_2}}$

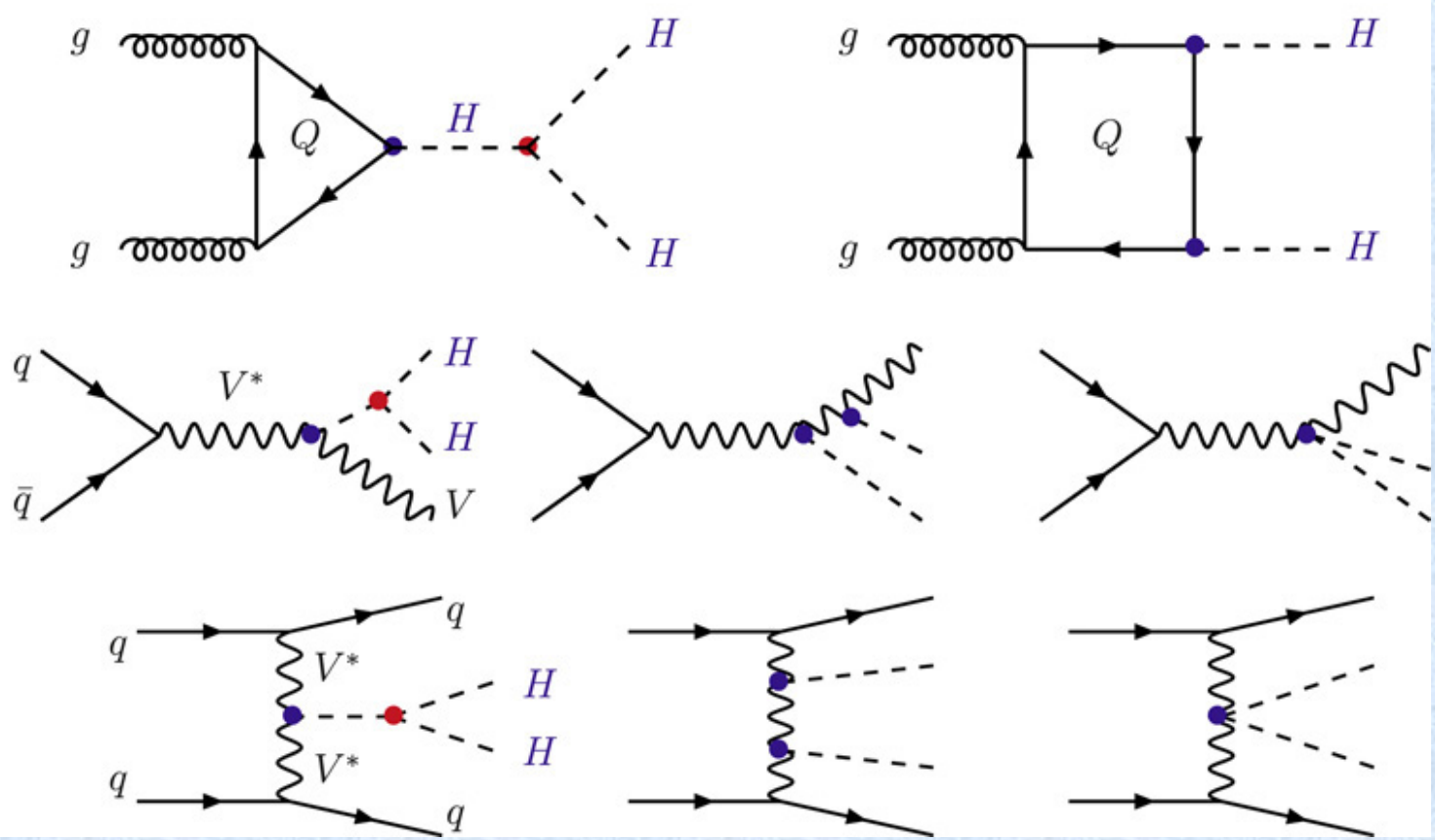
$$\mathcal{L}_{\rm kin} = \frac{K}{2} DH_i^* DH_i + \frac{2}{K}((H_i DH_i^*)(H_j^* DH_j) - (H \cdot DH)(H \cdot DH)^*)$$

$$\mathcal{L}_W = M_W^2 W^+ W^- \left(1 + 3\sin(\beta-\alpha)\frac{h}{v} + 3\frac{h^2}{v^2} + \cdots\right)$$

Cf. In 2HDM,

$$\mathcal{L}_W = M_W^2 W^+ W^- \left(1 + 2\sin(\beta-\alpha)\frac{h}{v} + \frac{h^2}{v^2}\right)$$

Pair production of the Higgs boson at the LHC

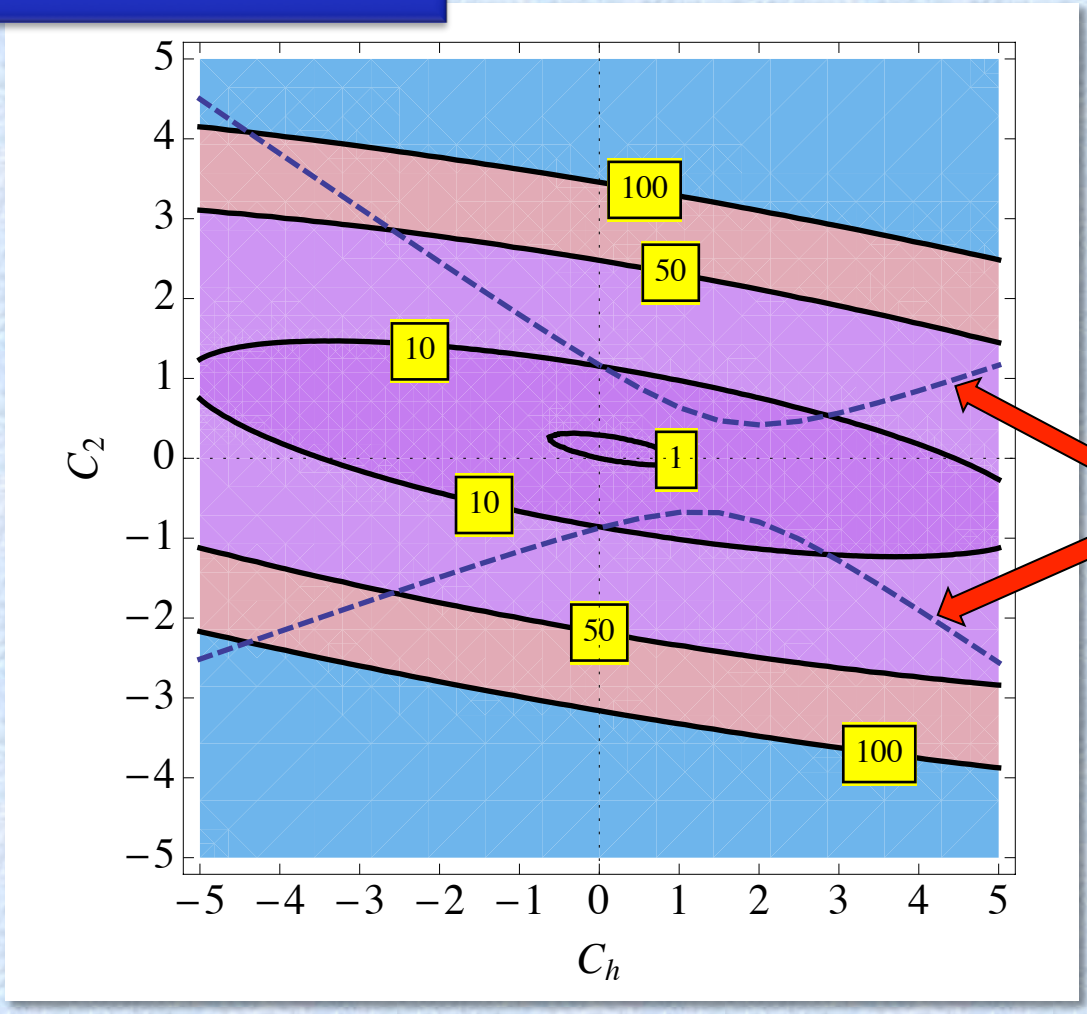


$$\sigma(pp \to gg \to hh)^{\rm NLO}_{\rm SM,14\ TeV} = 30 - 40\ ({\rm fb})$$

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

$$(M_W^2 W^+W^- + \frac{M_Z^2}{2} Z^2)\left(1 + \underbrace{G'(1)}_{=1}\frac{2h}{v} + \underbrace{(G'(1)+2G''(1))}_{\equiv 1+C_2}\frac{h^2}{v^2} + \cdots\right)$$

Ratio of cross sections

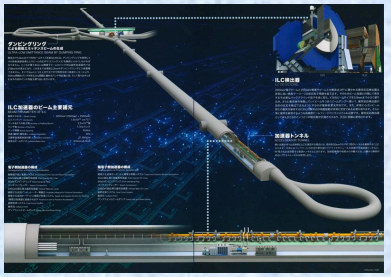


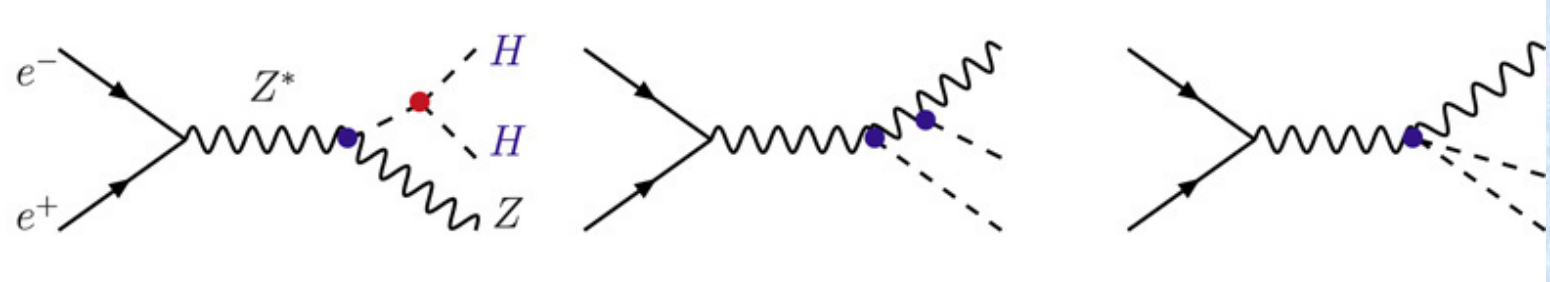
$\sigma(pp \to gg \to hh)$
$= \sigma(pp \to hhjj)$

$\sqrt{s} = 14\,\text{TeV}$

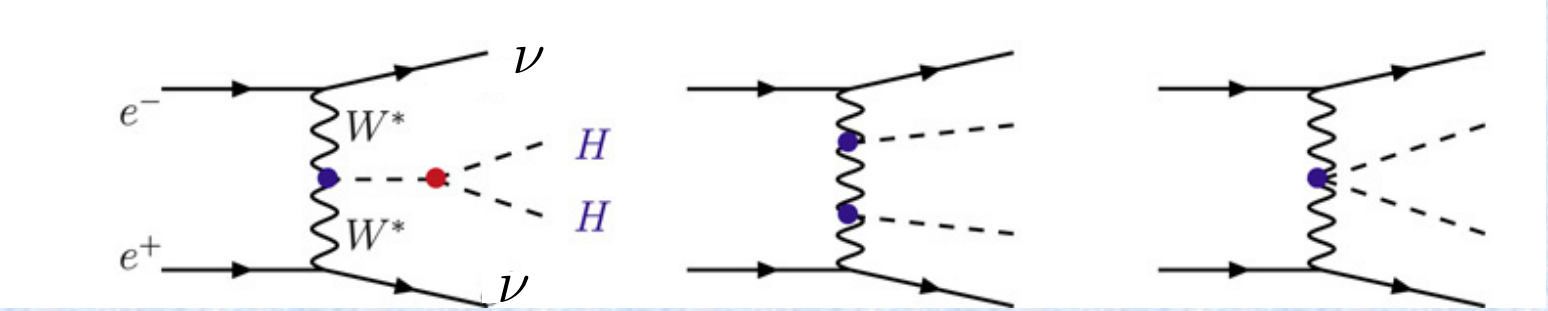
$\sigma(pp \to hhjj, C_2, C_h)/\sigma(C_2 = C_h = 0)$

Pair production of the Higgs boson at the ILC

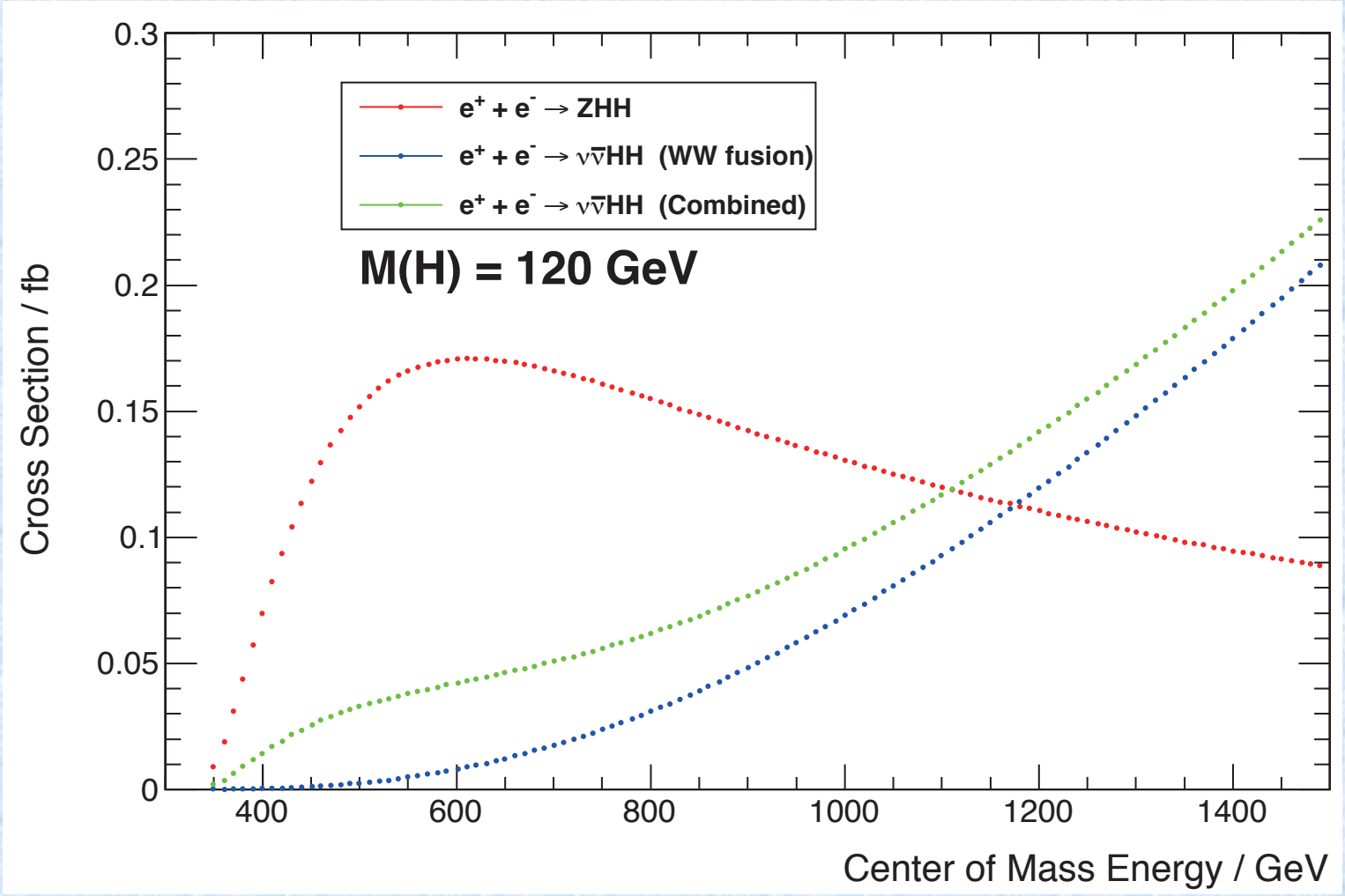




(double Higgs-strahlung)



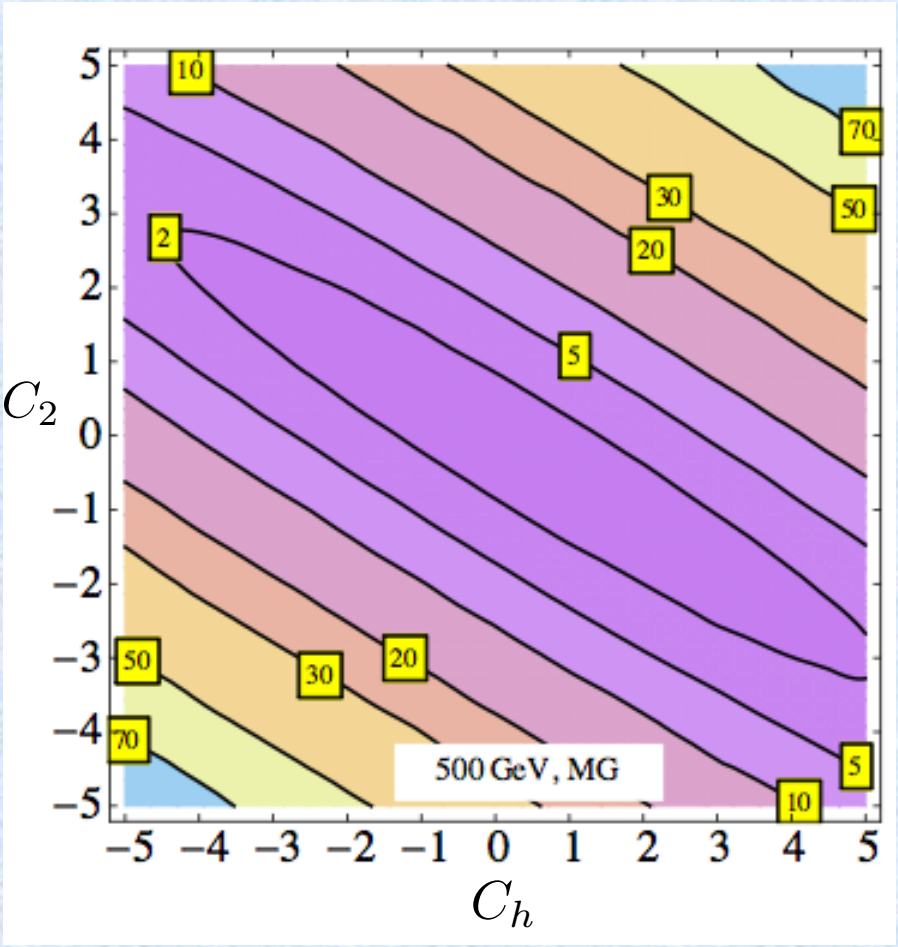
(WW fusion)

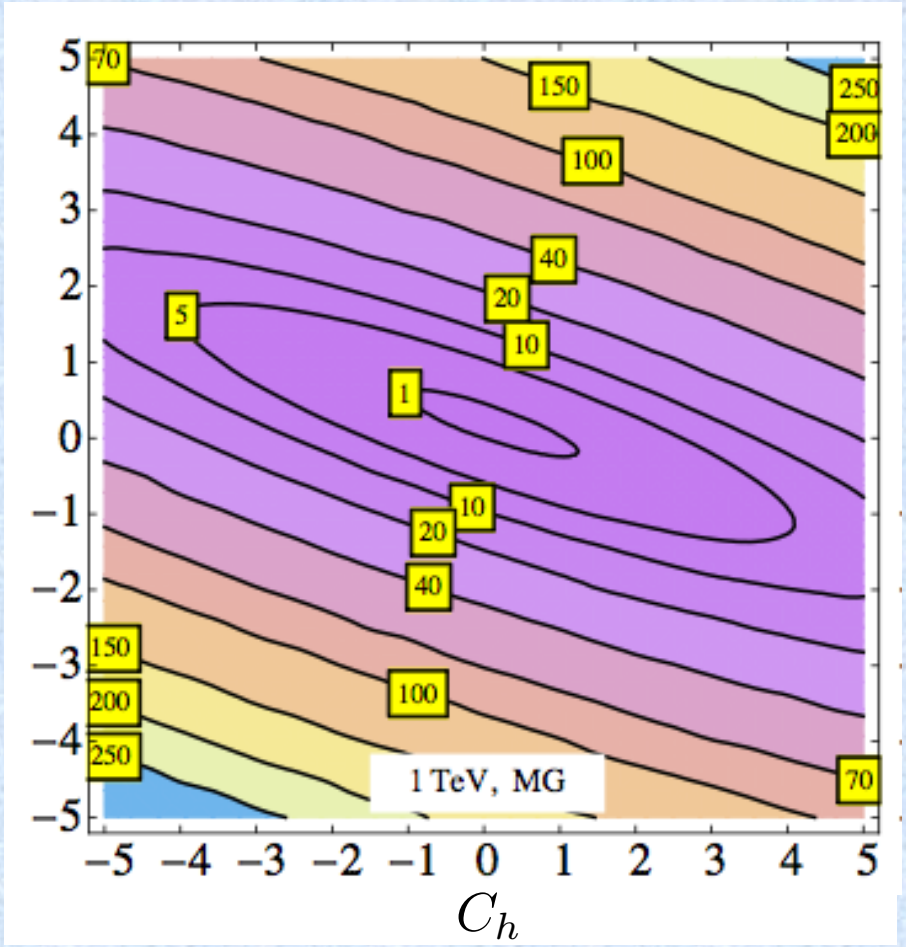


H. Baer et al, Physics Chapter of the ILC Detailed Baseline Design Report

Ratio of cross sections

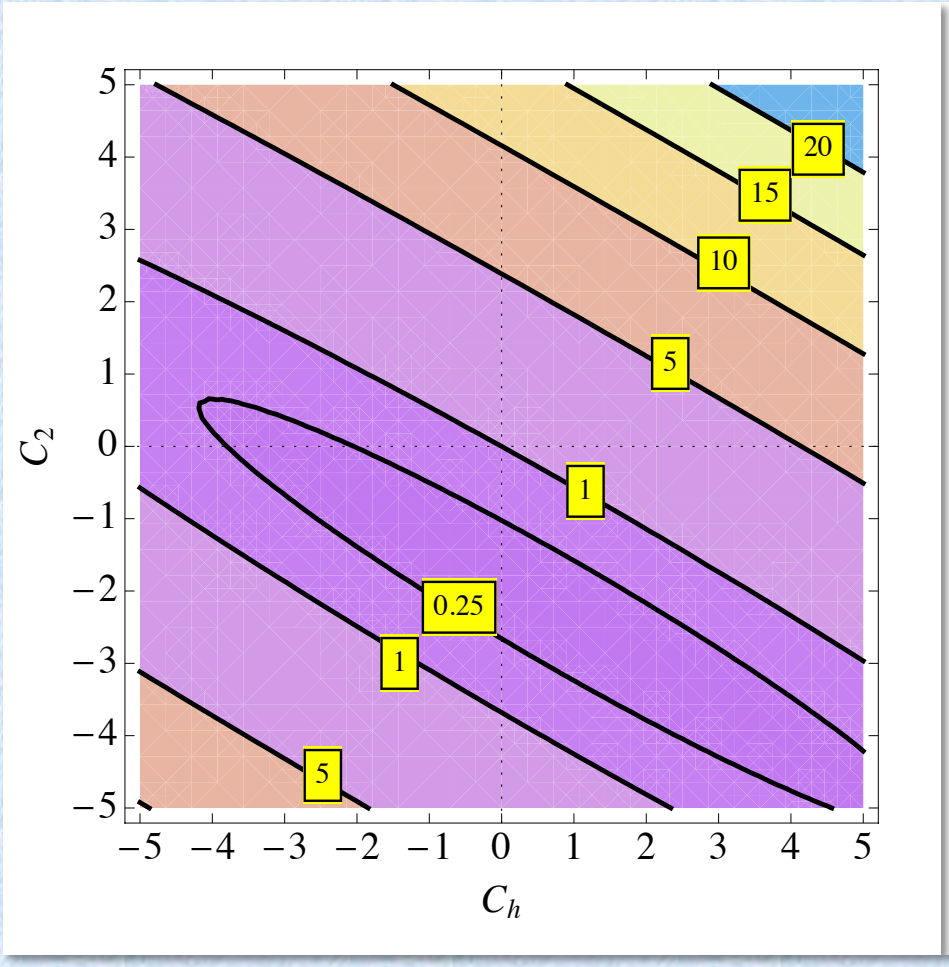
$$\sigma(e^+e^- \to hh\nu\bar{\nu})/\sigma(\mathrm{SM})$$

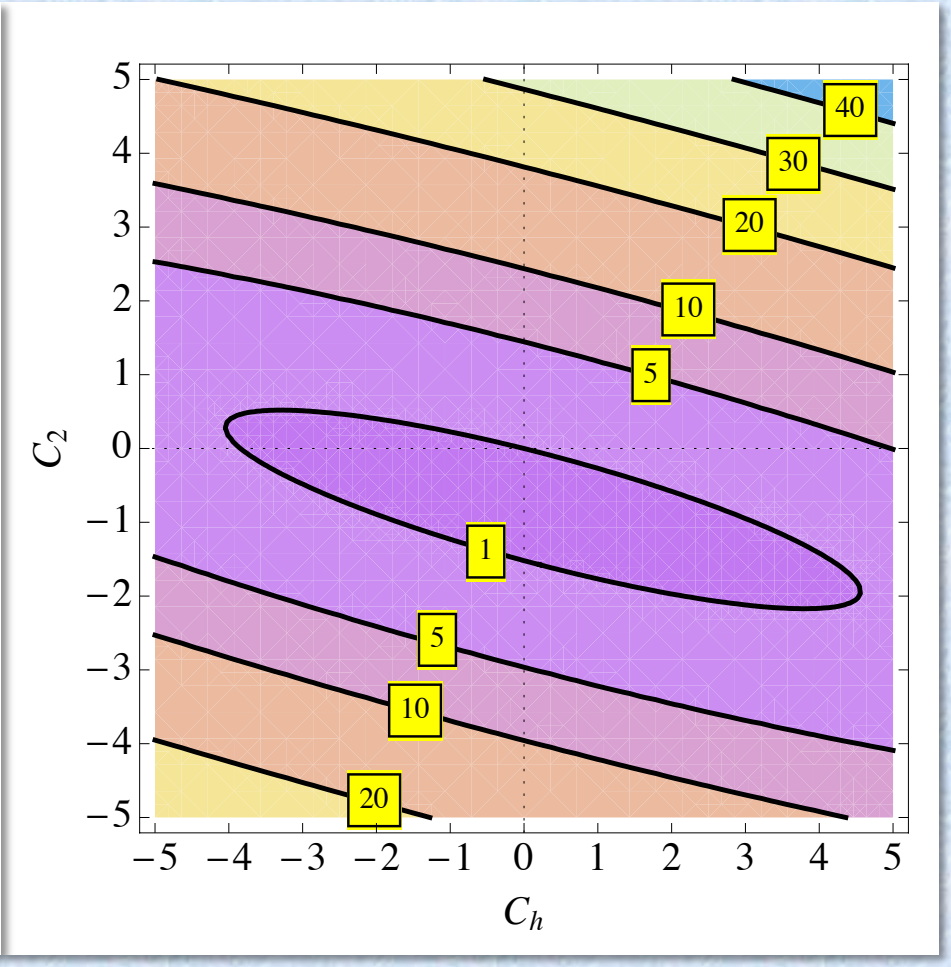




Ratio of cross sections

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



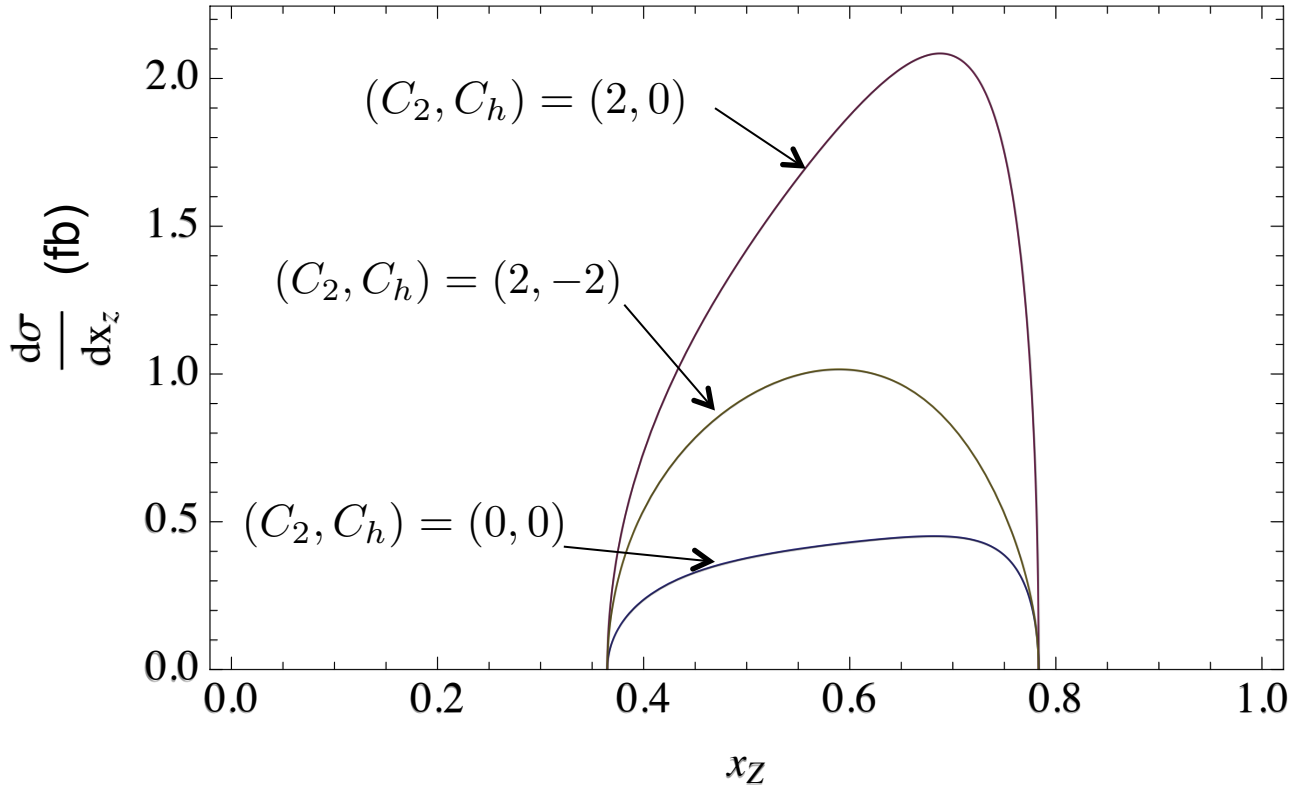


$\sqrt{s} = 500\,\mathrm{GeV}$

$\sqrt{s} = 1\,\mathrm{TeV}$

Energy distribution of Z in $e^+e^- \to Zhh$

$$x_z \equiv 2E_Z/\sqrt{s}$$



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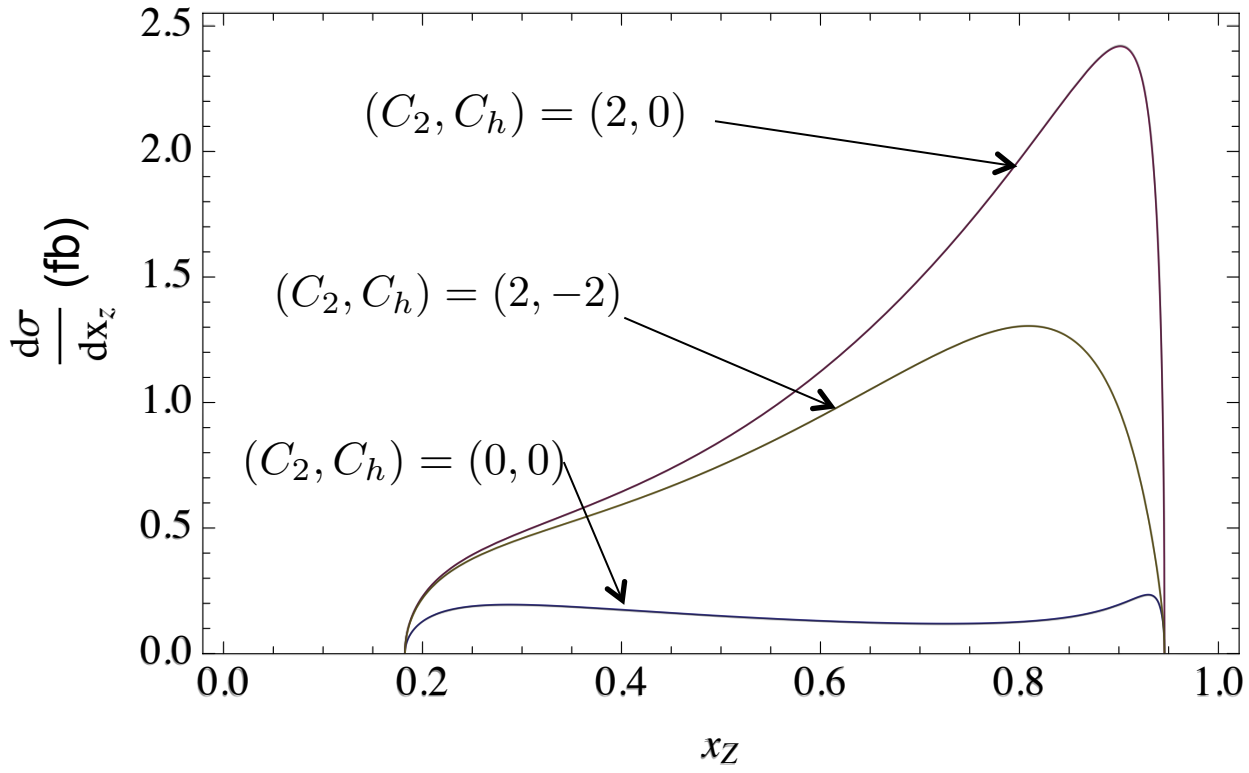

$$\sqrt{s} = 1\,\text{TeV}$$

Summary

- We still have missing pieces for the “Higgs forces”.
- It is important to probe the self-Higgs coupling.
- Non-perturbative Higgs model in SUSY QCD is proposed.
- Possible enhancement of pair-Higgs production is discussed.
- We look forward to more data to probe the “Higgs forces”.

$$O(100)\,\mathrm{fb}^{-1}\ \text{at the LHC;}\ \text{ILC (at Tohoku?)}$$