

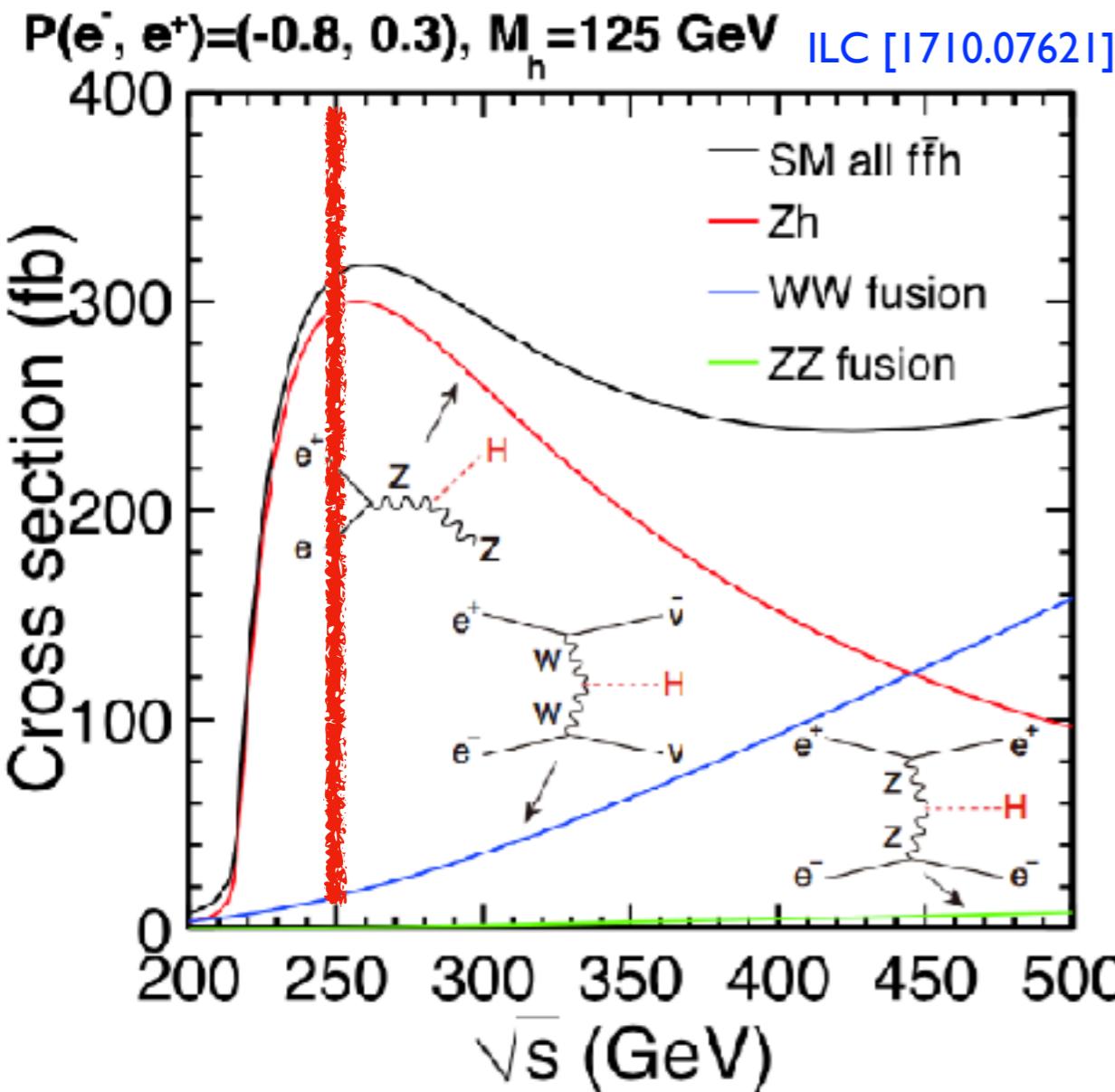
# Higgs production in association with a photon in extended Higgs models at ILC250

Kentarou Mawatari

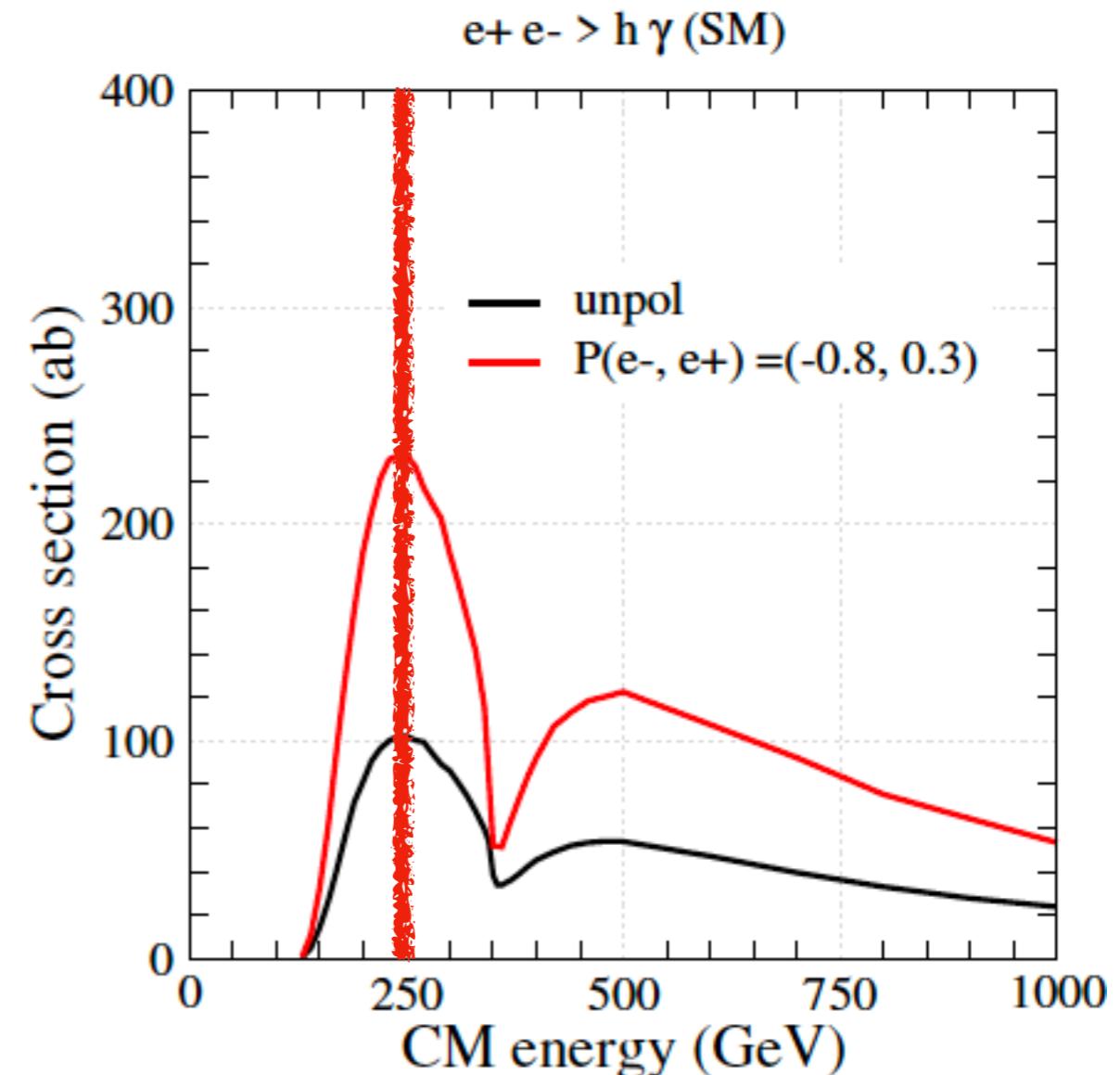


work in progress  
with Shinya Kanemura (Osaka U.) and  
Kodai Sakurai (Osaka U./U. of Toyama)

# Higgs productions at ILC250



This is not the only Higgs production which has a peak at 250GeV at  $e^+e^-$  colliders.



- $\sigma(h\gamma) \sim \sigma(hZ) \times 10^{-3}$  due to loop-induced.
- Beam polarization helps.  $E_\gamma = \frac{\sqrt{s}}{2} \left(1 - \frac{m_h^2}{s}\right)$
- A monochromatic photon.  $\sim 93.8 \text{ GeV} @ \sqrt{s} = 250 \text{ GeV}$
- **sensitive to New Physics!**

\*See Kodai Sakurai's talk on Thu.

# H-COUP

$$\hat{\Gamma}_{hVV}^{\mu\nu}(p_1^2, p_2^2, q^2) = g^{\mu\nu} \hat{\Gamma}_{hVV}^1 + \frac{p_1^\nu p_2^\mu}{m_V^2} \hat{\Gamma}_{hVV}^2 + i\epsilon^{\mu\nu\rho\sigma} \frac{p_1\rho p_2\sigma}{m_V^2} \hat{\Gamma}_{hVV}^3$$

H-COUP is a calculation tool composed of a set of Fortran codes to compute the renormalized Higgs boson couplings with radiative corrections in various non-minimal Higgs models, such as the Higgs singlet model, four types of two Higgs doublet models and the inert doublet model. The involved on-shell renormalization scheme is adopted, where the gauge dependence is eliminated.

Authors: Shinya Kanemura, Mariko Kikuchi, Kodai Sakurai and Kei Yagyu **+K. Mawatari**

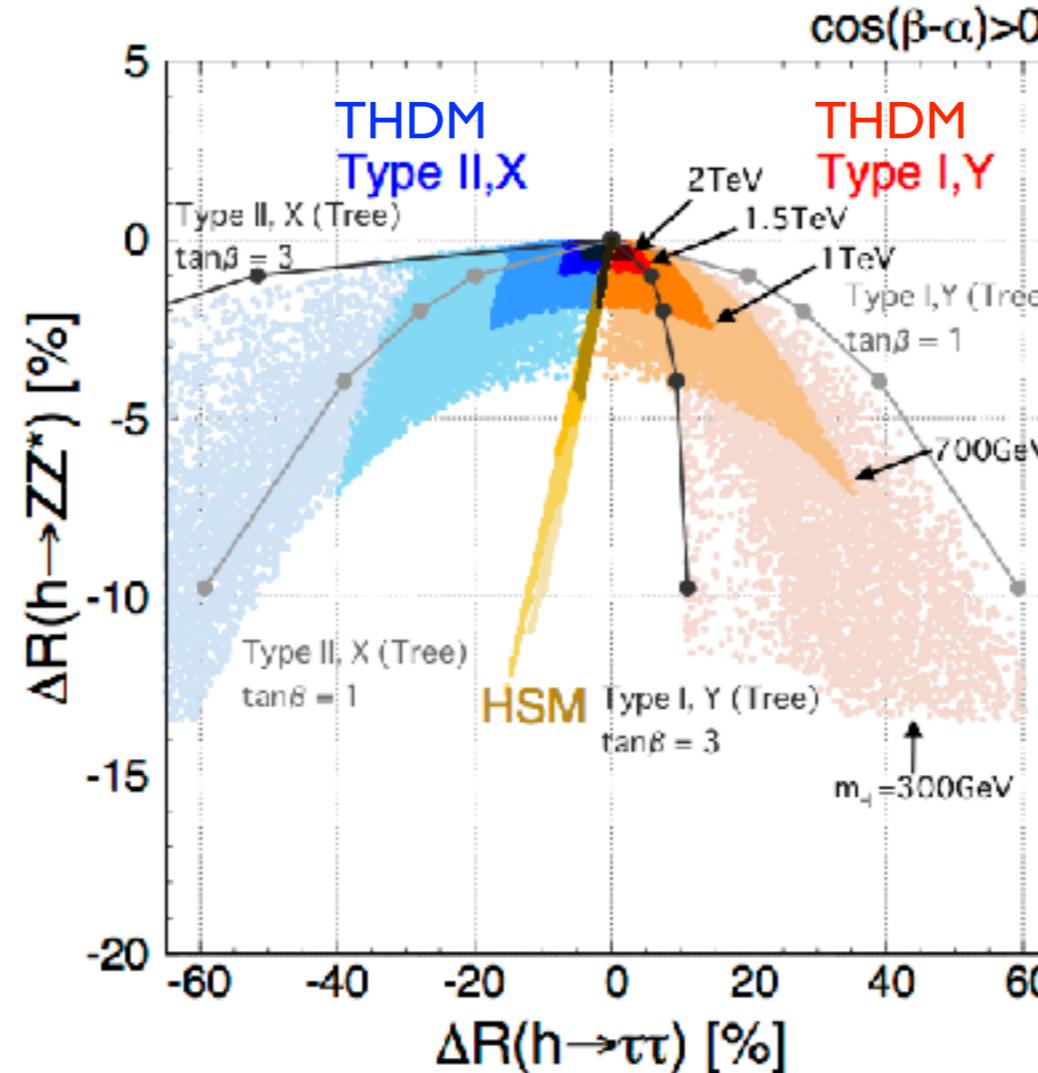
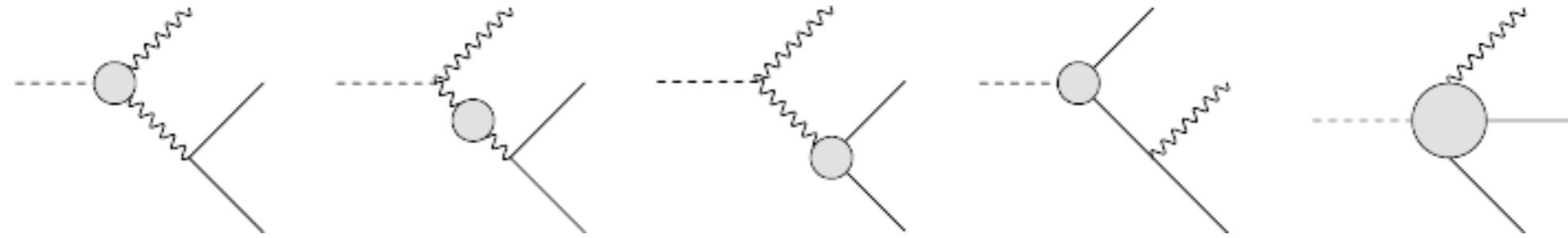
The manual for H-COUP version 1.0 can be taken on [arXiv:1710.04603 \[hep-ph\]](https://arxiv.org/abs/1710.04603).

**Loop effects on the Higgs decay widths  
in extended Higgs models [arXiv:1803.01456]**

## Downloads

- H-COUP version 1.0 : [[HCOUP-1.0.zip](#)] [The manual is [here](#)]

# Higgs decay: $h \rightarrow ZZ^* \rightarrow Z f \bar{f}$



Kanemura, Kikuchi, KM, Sakurai, Yagyu  
[1803.01456]

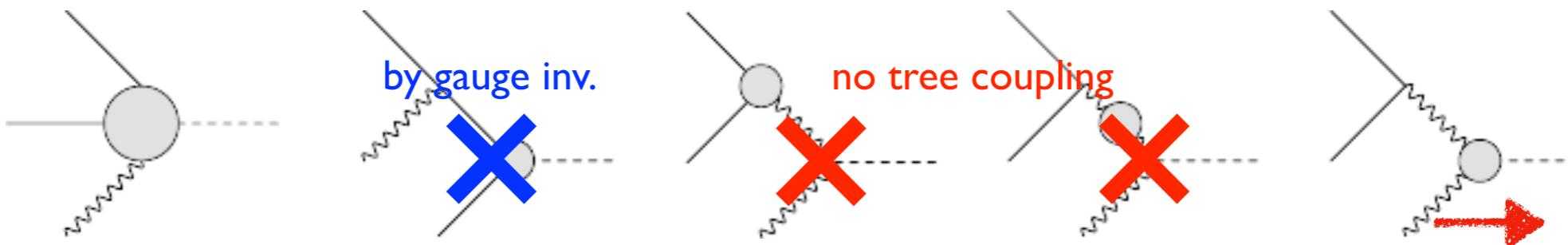
\*See Kodai Sakurai's talk on Thu.

**THDM**  
= Two Higgs Doublet Model

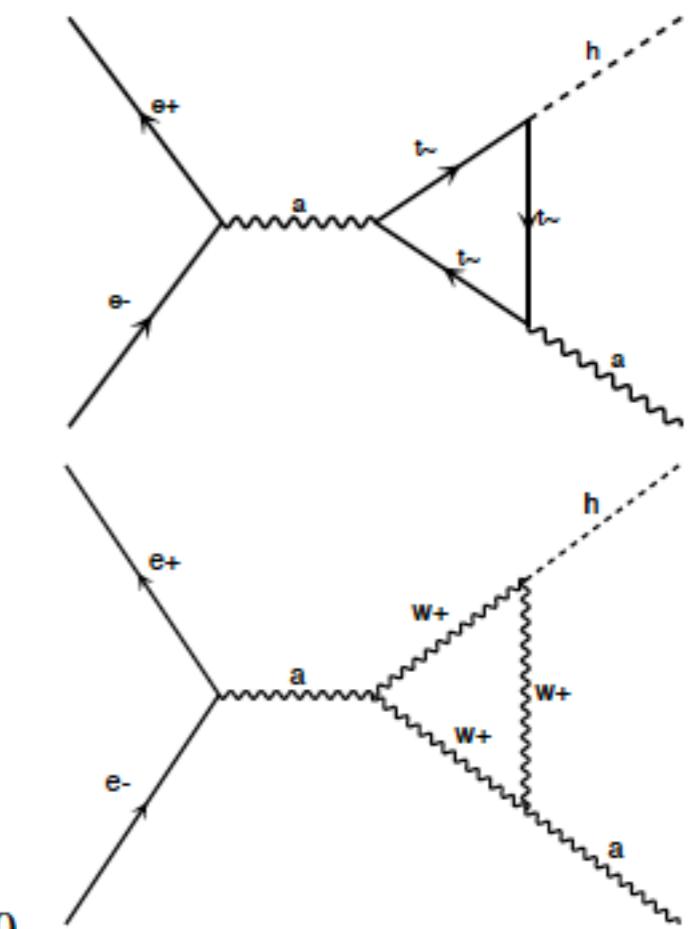
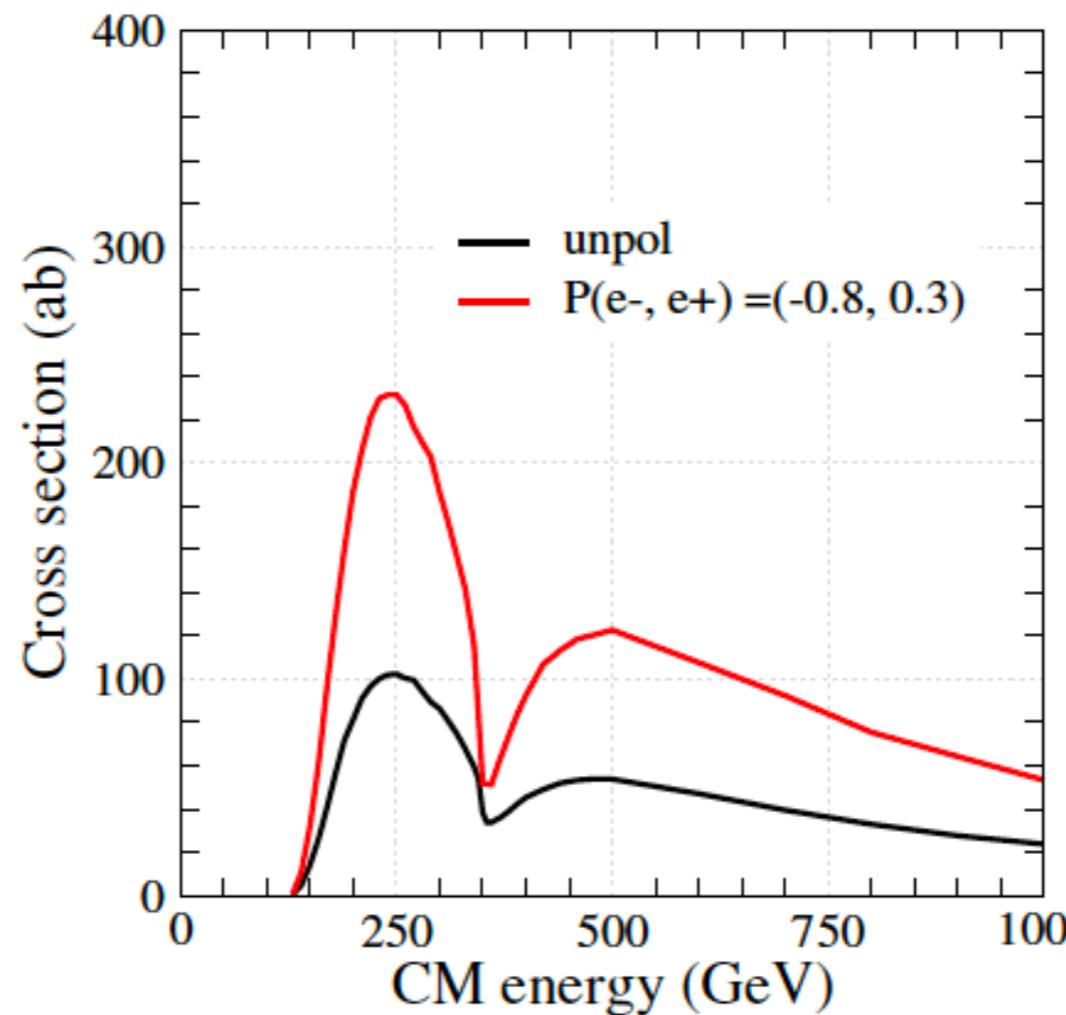
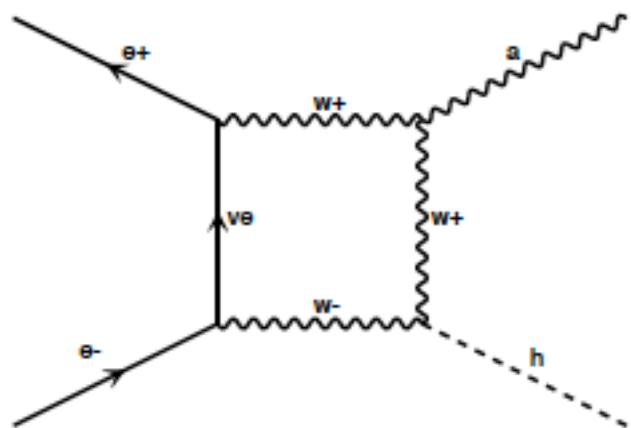
**HSM**  
= Higgs Singlet Model

$$\Delta R(h \rightarrow XX) = \frac{\Gamma_{\text{NP}}(h \rightarrow XX)}{\Gamma_{\text{SM}}(h \rightarrow XX)} - 1$$

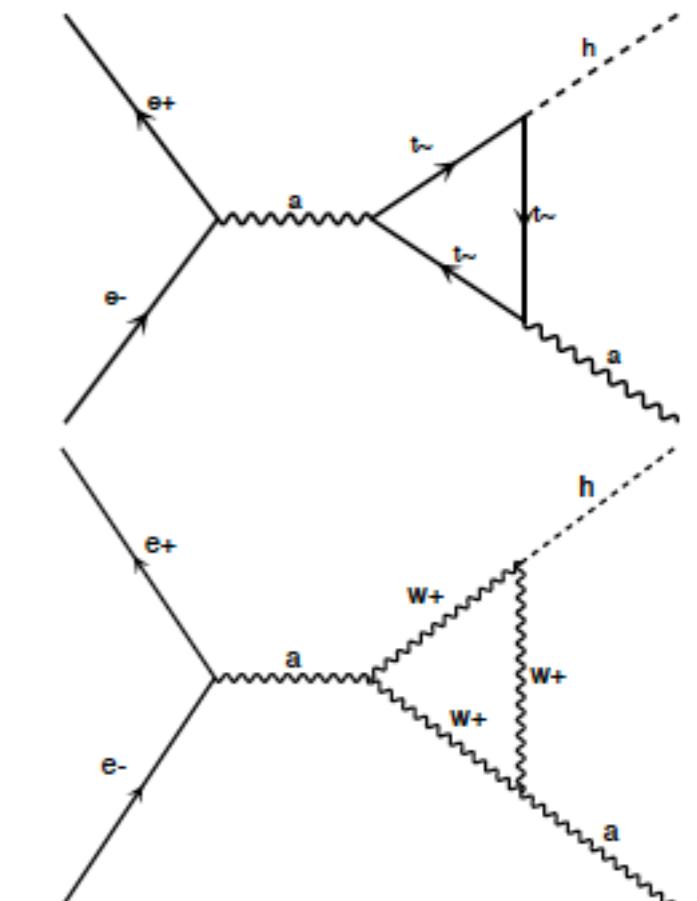
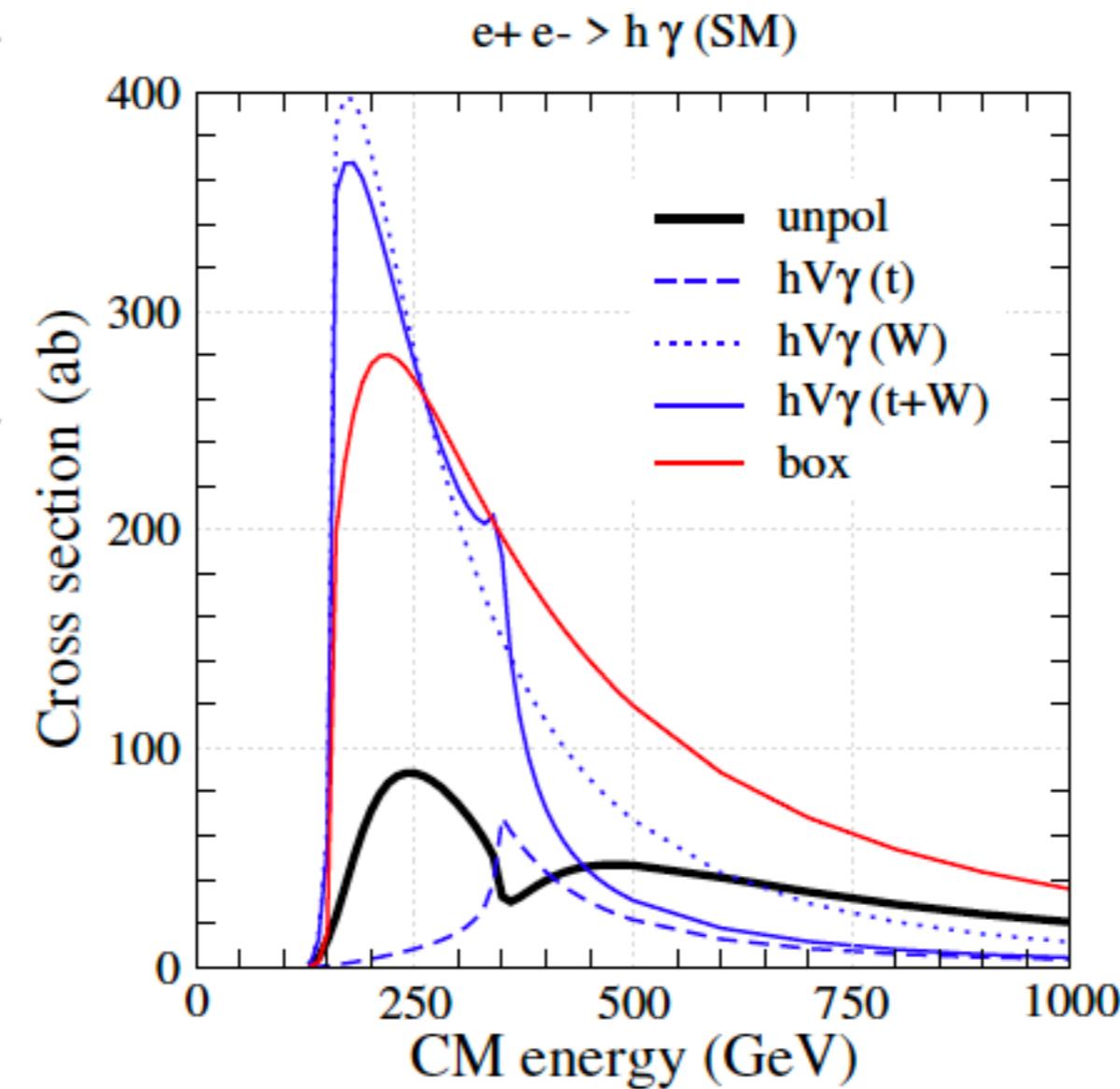
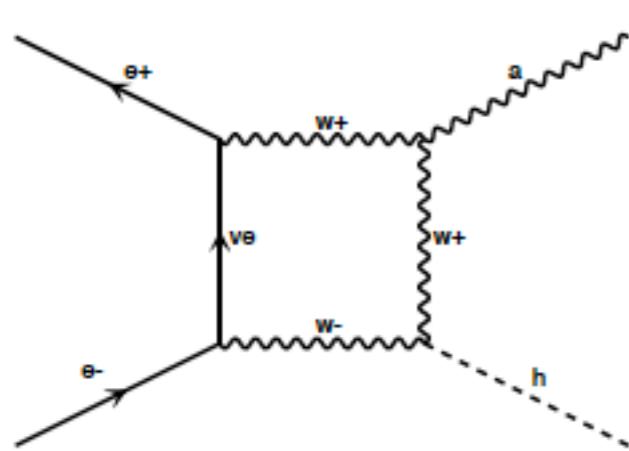
# Higgs production: $e^+ e^- \rightarrow h \gamma$



$e^+ e^- \rightarrow h \gamma$  (SM)

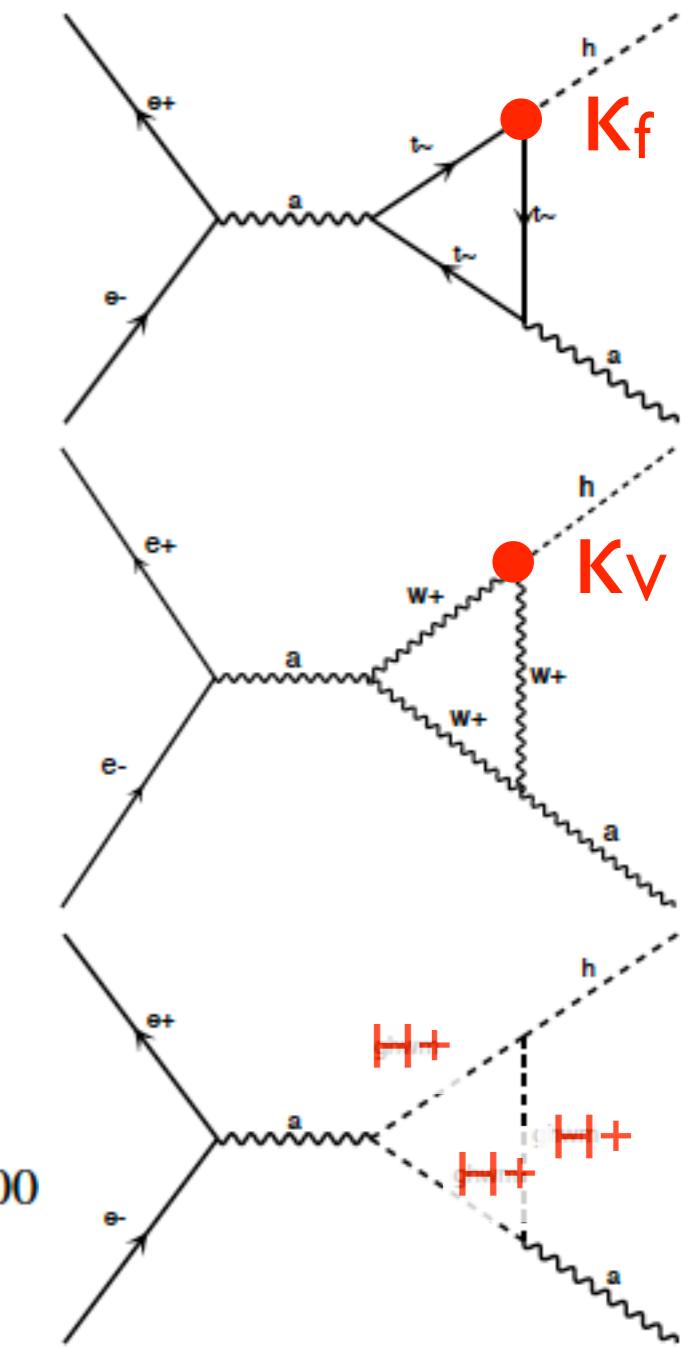
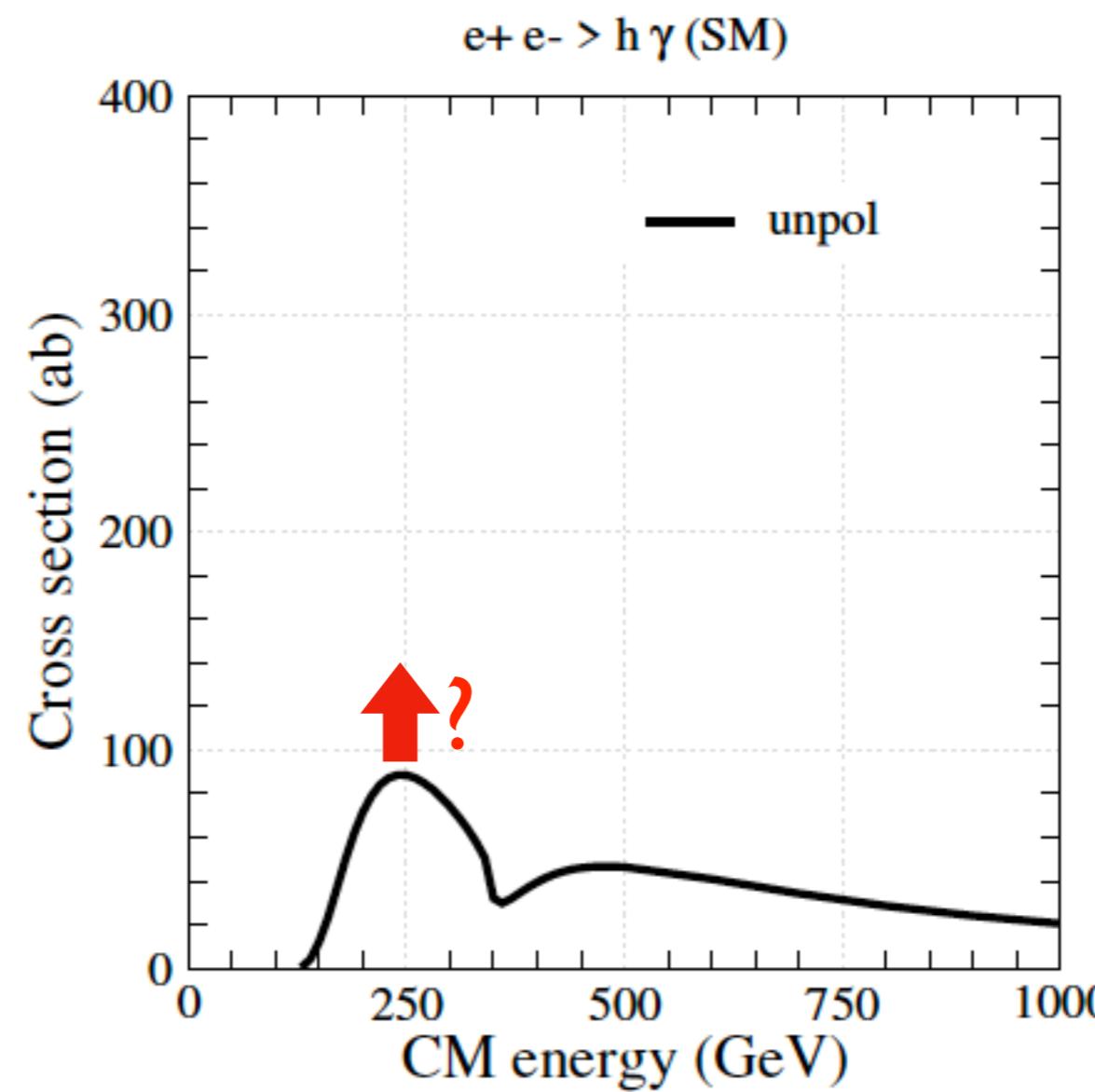
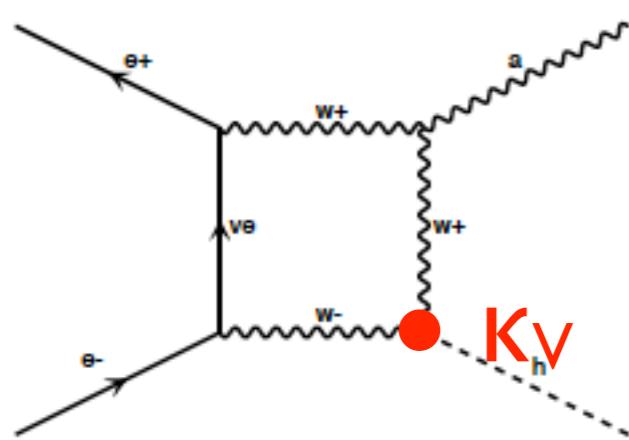


# $e^+ e^- \rightarrow h \gamma$ in the SM



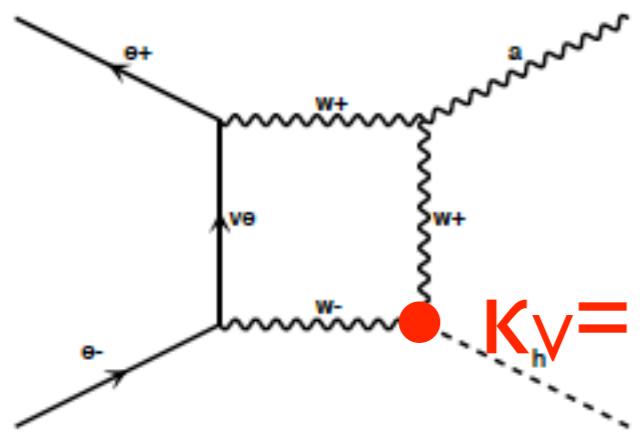
Unfortunate destructive interference among the different contributions...

# $e^+ e^- \rightarrow h \gamma$ in extended Higgs models



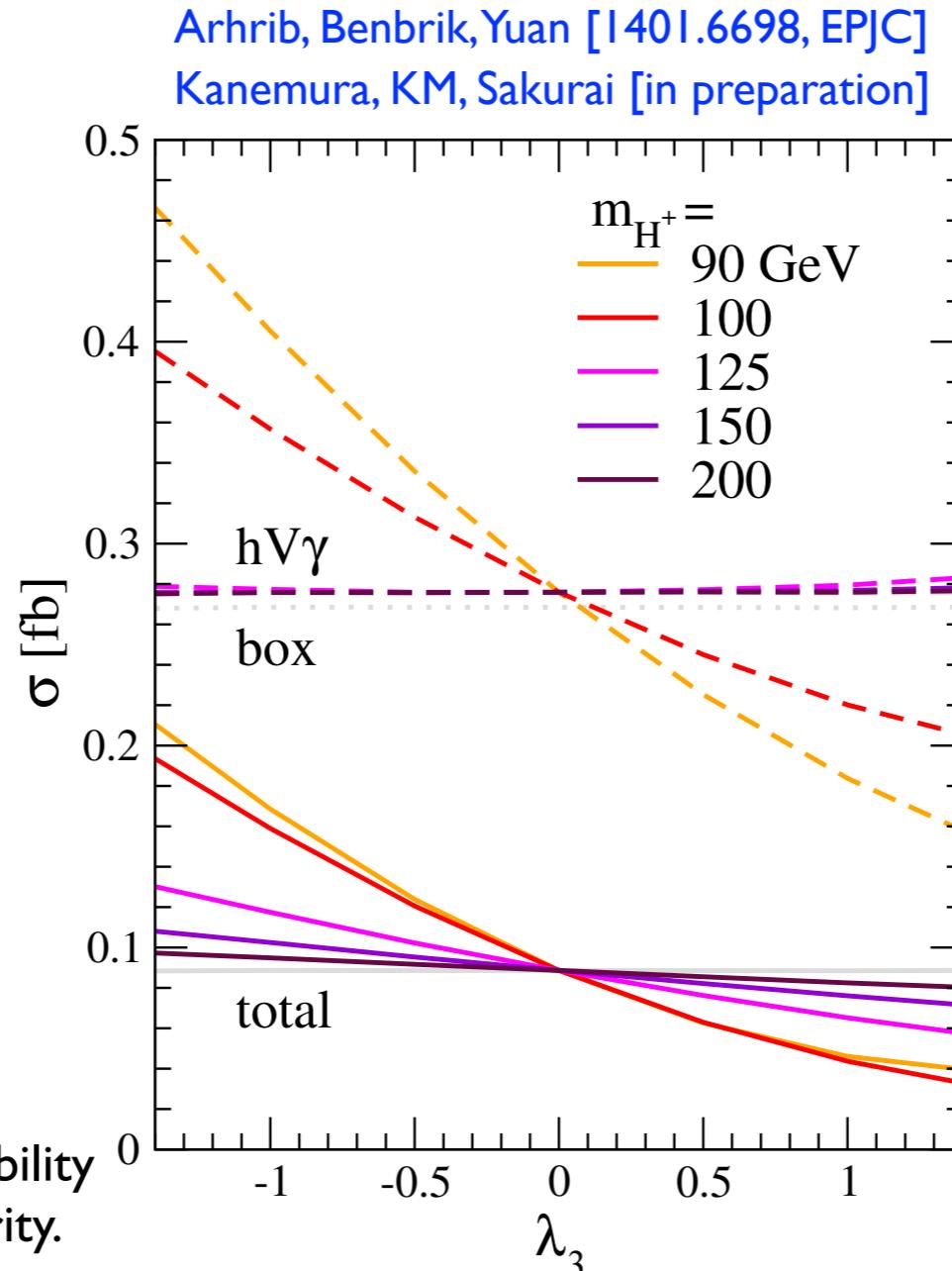
Can new physics effects enhance the production rate?

# $e^+ e^- \rightarrow h \gamma$ in the inert doublet model

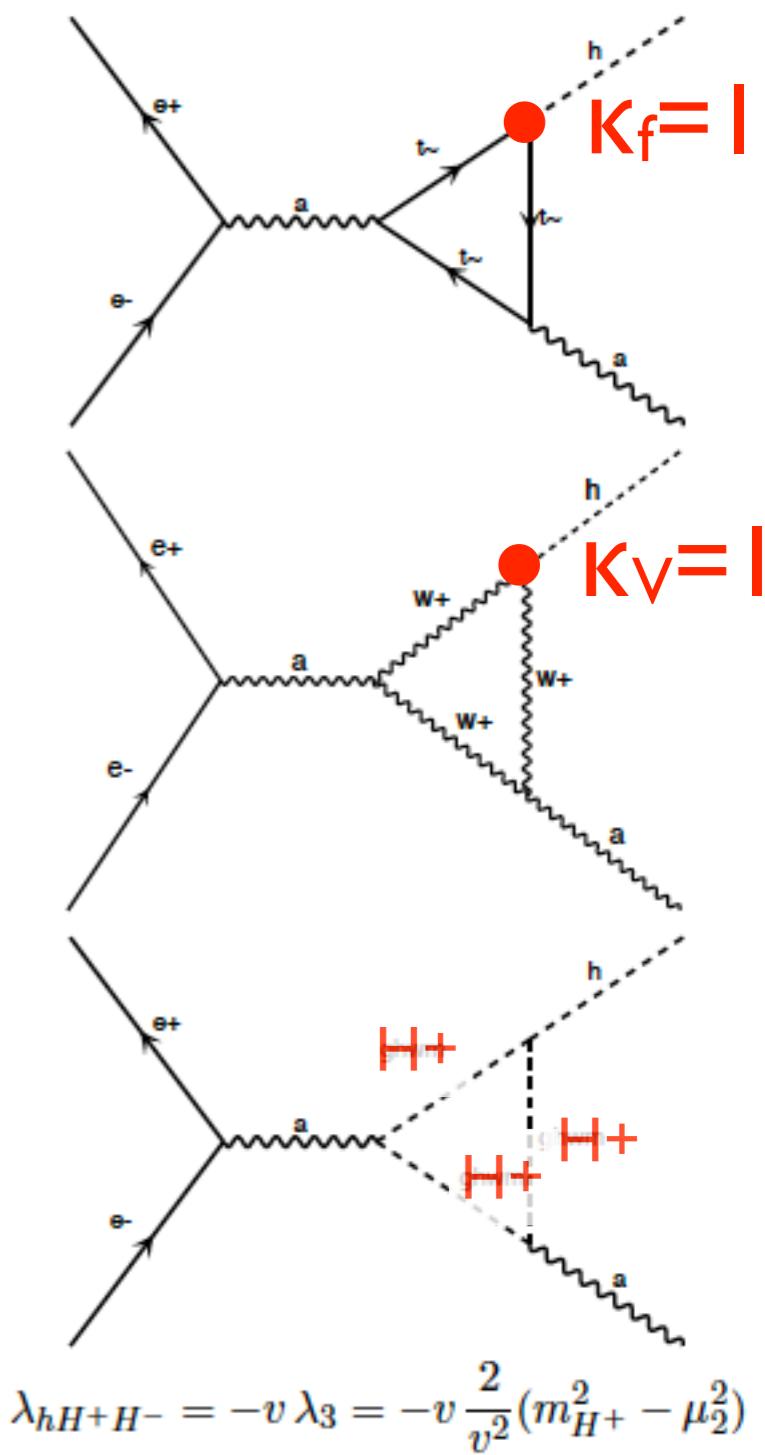


$$V = \mu_1^2 |\Phi|^2 + \mu_2^2 |\eta|^2 + \frac{1}{2} \lambda_1 |\Phi|^4 + \frac{1}{2} \lambda_2 |\eta|^4 + \lambda_3 |\Phi|^2 |\eta|^2 + \lambda_4 |\Phi^\dagger \eta|^2 + \frac{1}{2} \lambda_5 [(\Phi^\dagger \eta)^2 + \text{h.c.}]$$

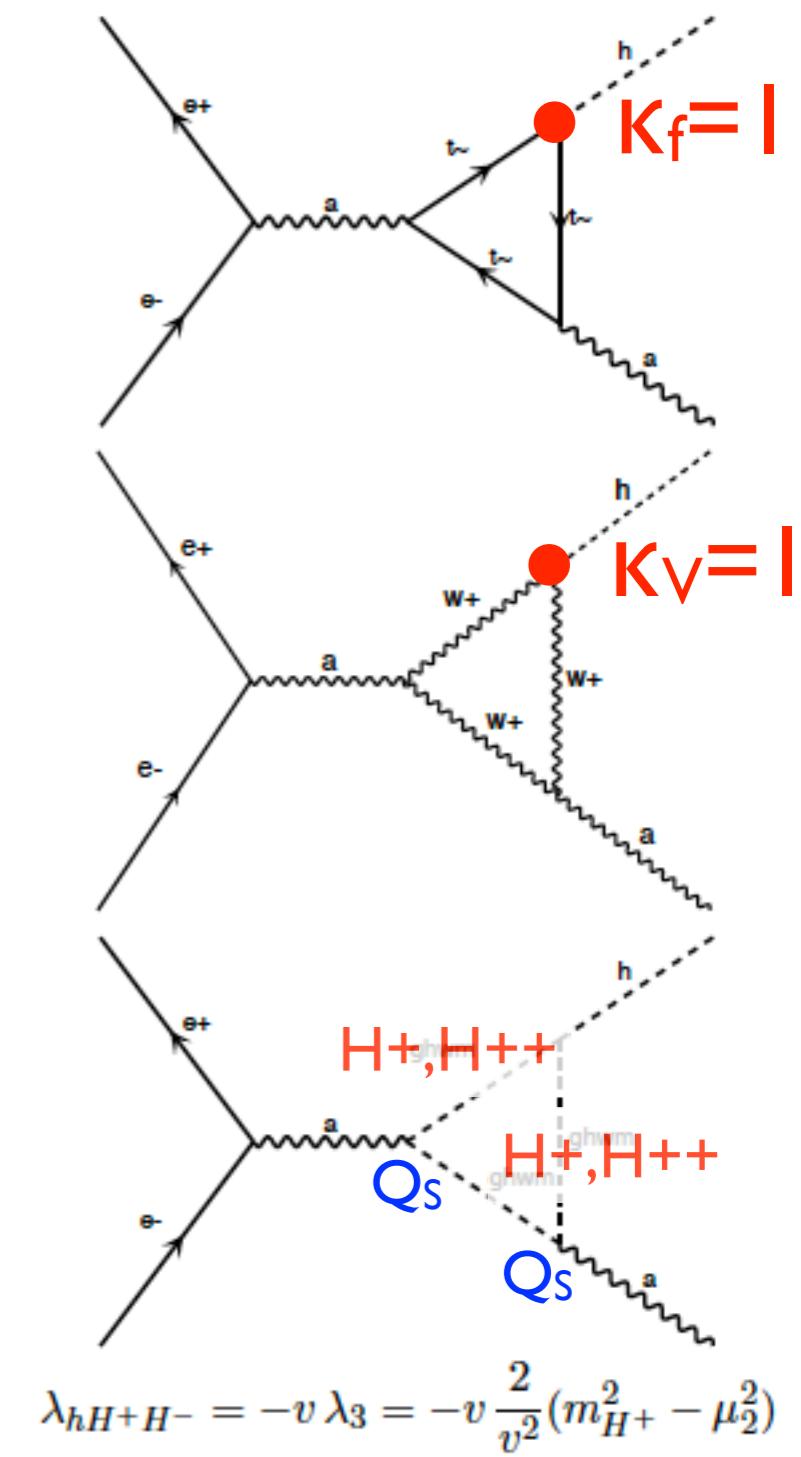
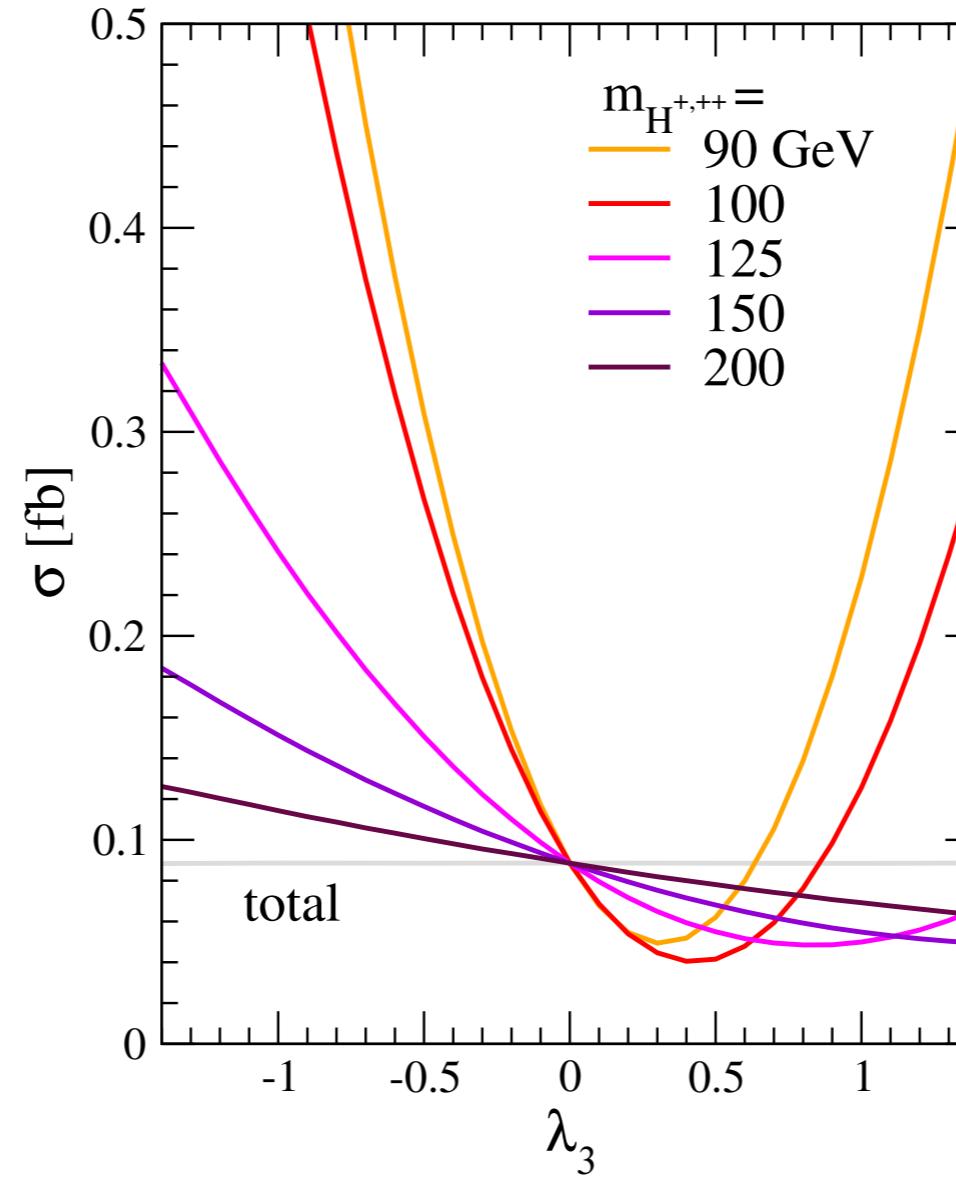
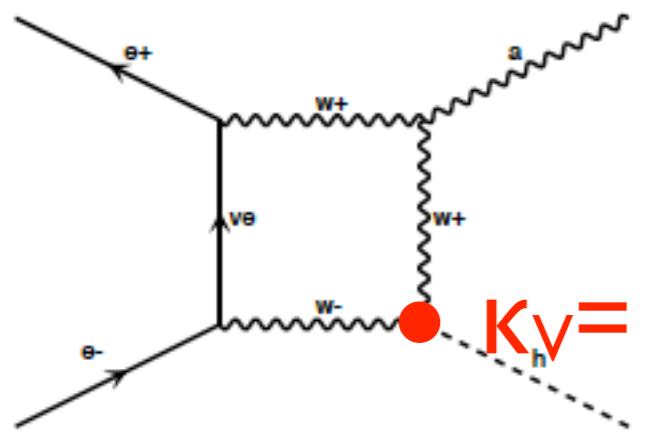
\*  $\lambda_3 > -1.4$  by vacuum stability and perturbative unitarity.



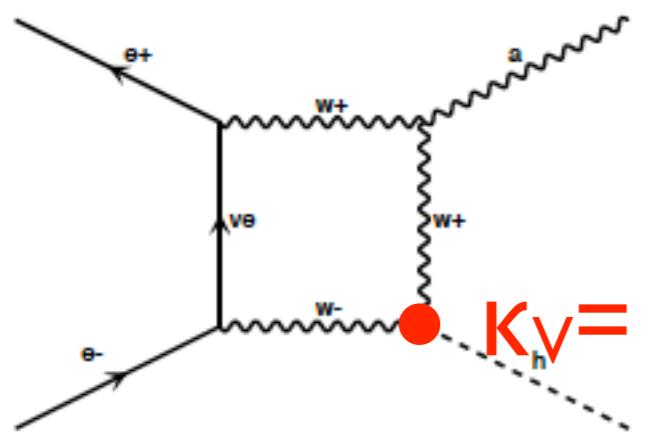
A lighter charged Higgs boson with a negative  $\lambda_3$  can enhance the production rate.



# $e^+ e^- \rightarrow h \gamma$ in the inert triplet model

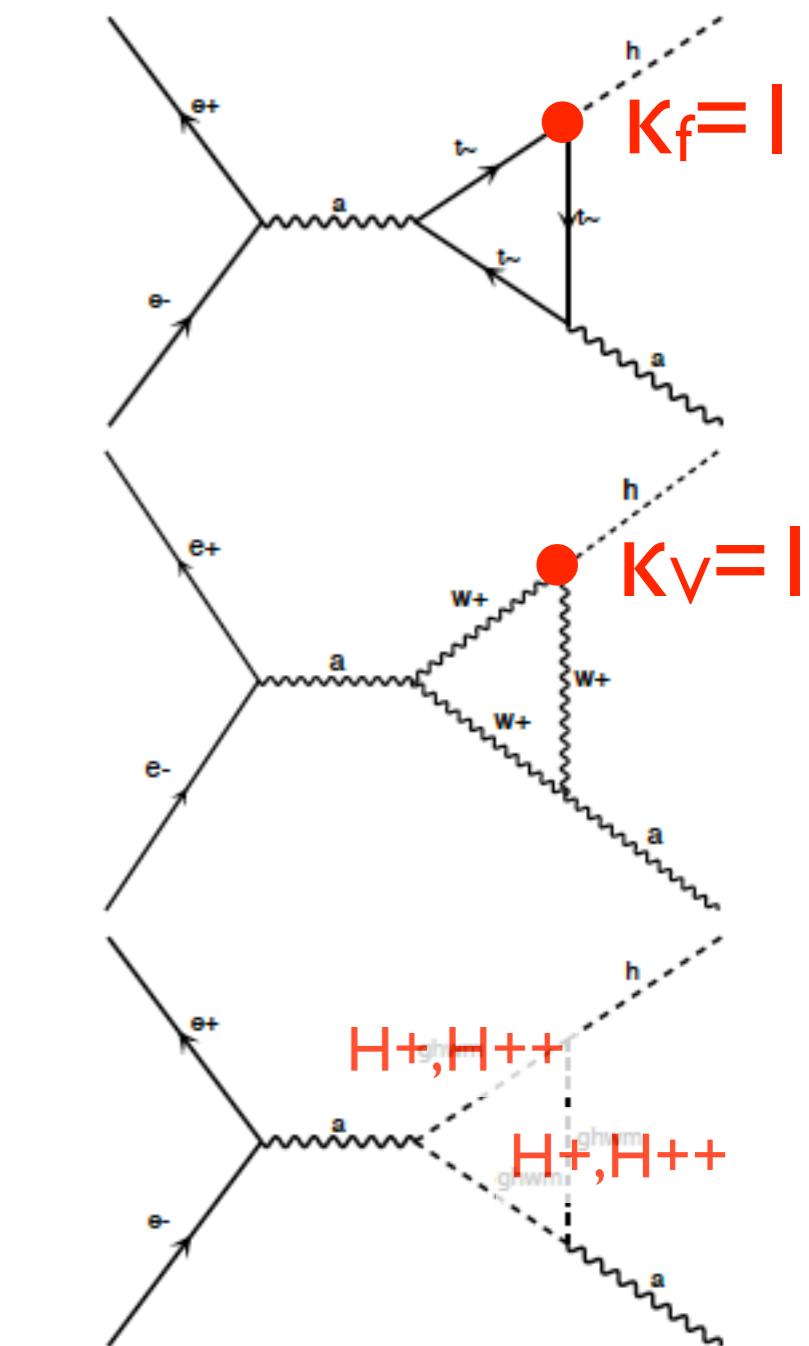
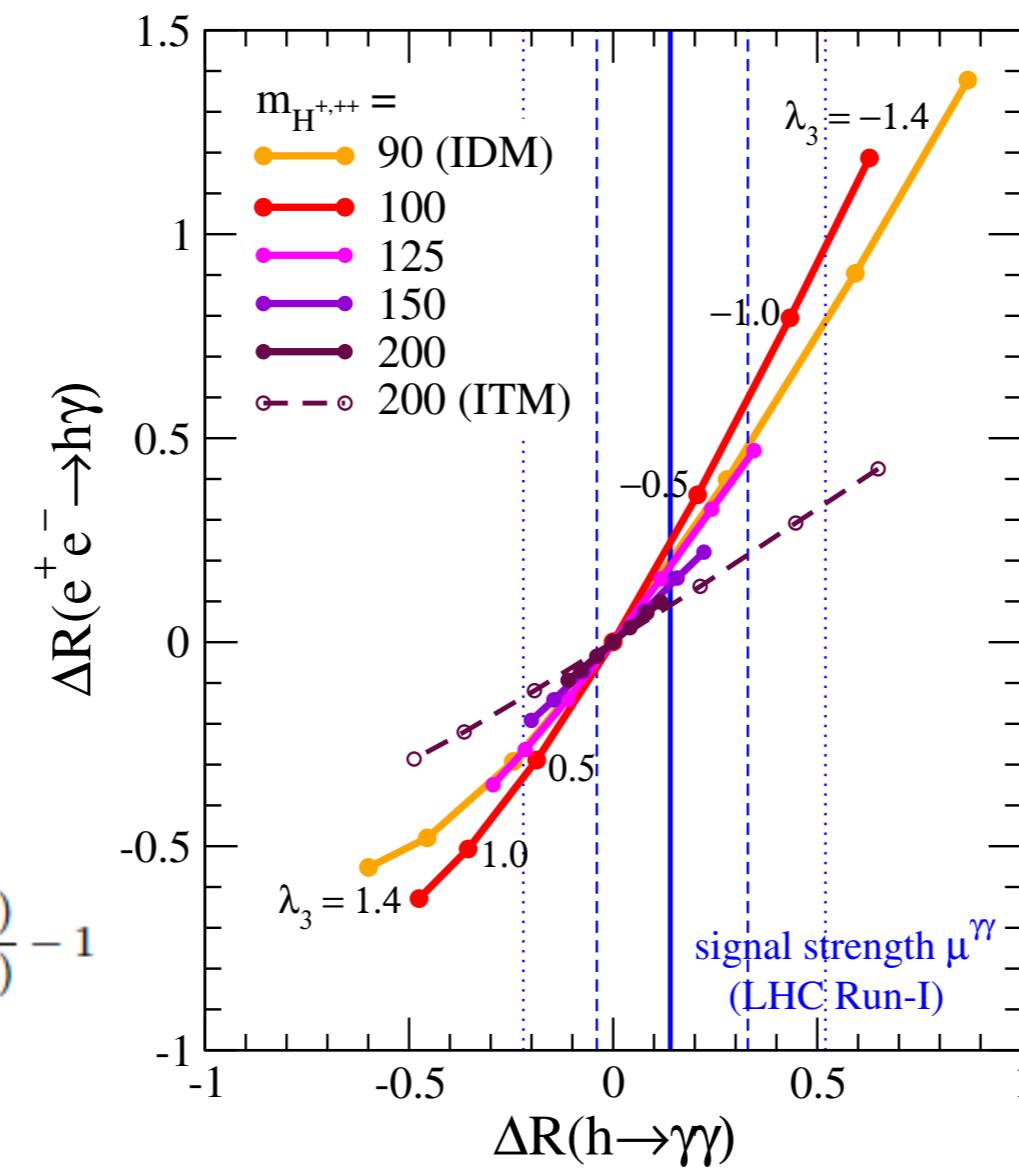


# $(e^+e^- \rightarrow h\gamma)$ vs. $(h \rightarrow \gamma\gamma)$ in IDM/ITM



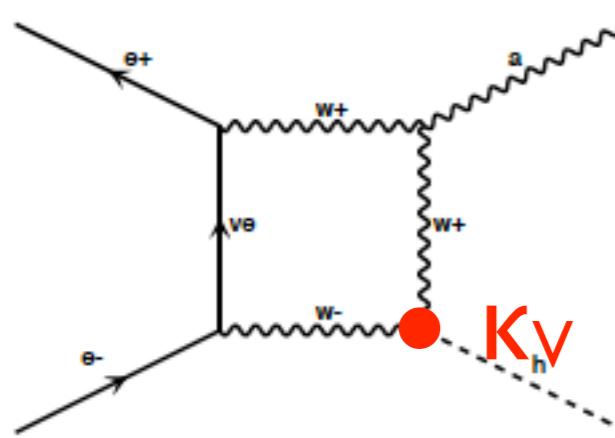
$$\Delta R(h \rightarrow \gamma\gamma) = \frac{\Gamma_{NP}(h \rightarrow \gamma\gamma)}{\Gamma_{SM}(h \rightarrow \gamma\gamma)} - 1$$

$$\Delta R(e^+e^- \rightarrow h\gamma) = \frac{\sigma_{NP}(e^+e^- \rightarrow h\gamma)}{\sigma_{SM}(e^+e^- \rightarrow h\gamma)} - 1$$



$$\lambda_{hH+H-} = -v \lambda_3 = -v \frac{2}{v^2} (m_H^2 - \mu^2)$$

# $e^+ e^- \rightarrow h \gamma$ in the two Higgs doublet model



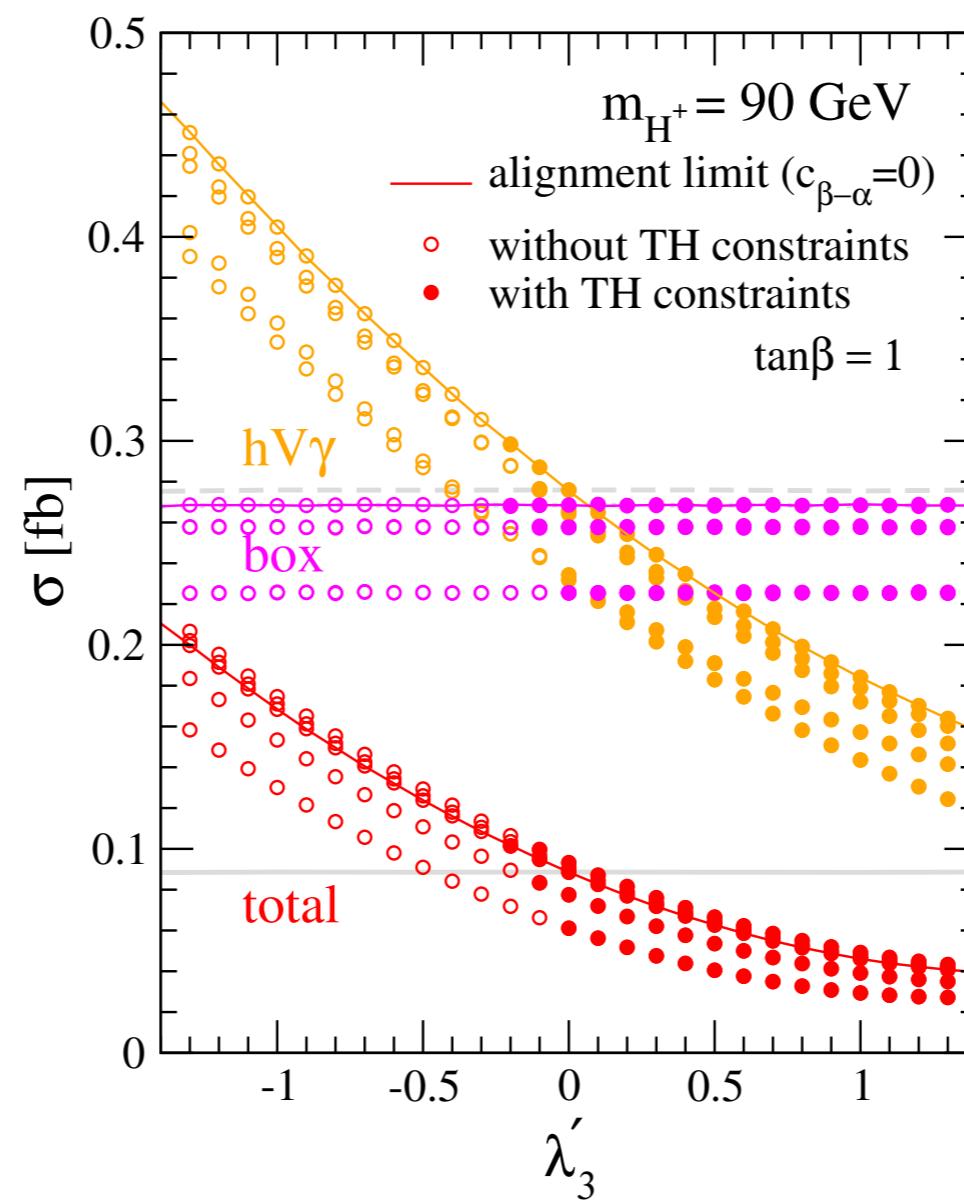
## Model parameters:

$m_H, m_A, m_{H^\pm}, M^2 (\equiv m_3^2/s_{\beta-\alpha}c_\beta)$

$\tan \beta, s_{\beta-\alpha} (\geq 0), \text{Sign}(c_{\beta-\alpha})$

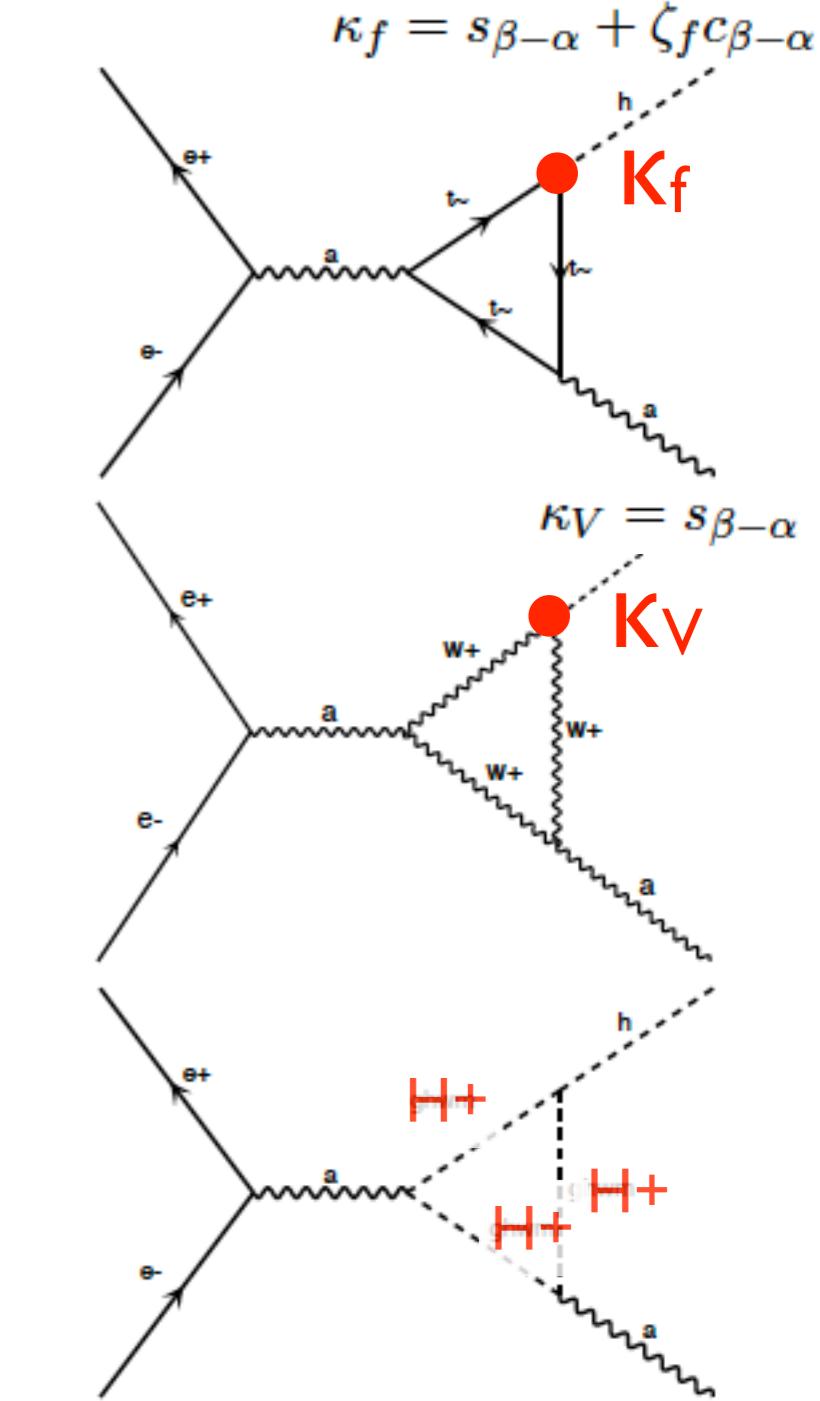
## TH Constraints:

- perturbative unitarity
- vacuum stability

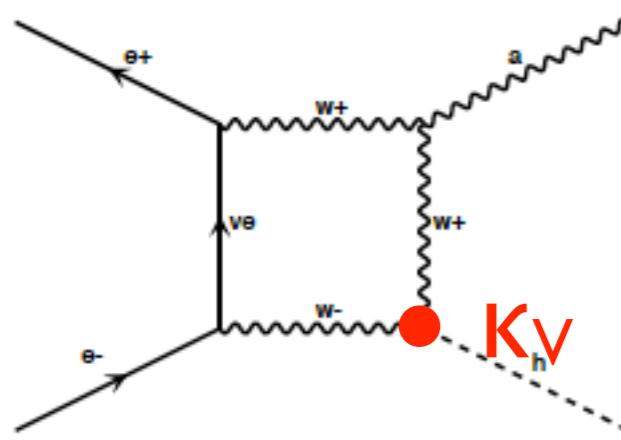


$$\lambda_{hH^+H^-} = -v \lambda'_3$$

$$= -v \frac{2}{v^2} [(m_{H^+}^2 + \frac{1}{2}m_h^2 - M^2)s_{\beta-\alpha} + (m_h^2 - M^2)\cot 2\beta c_{\beta-\alpha}]$$



# $(e^+e^- \rightarrow h\gamma)$ vs. $(h \rightarrow \gamma\gamma)$ in THDM



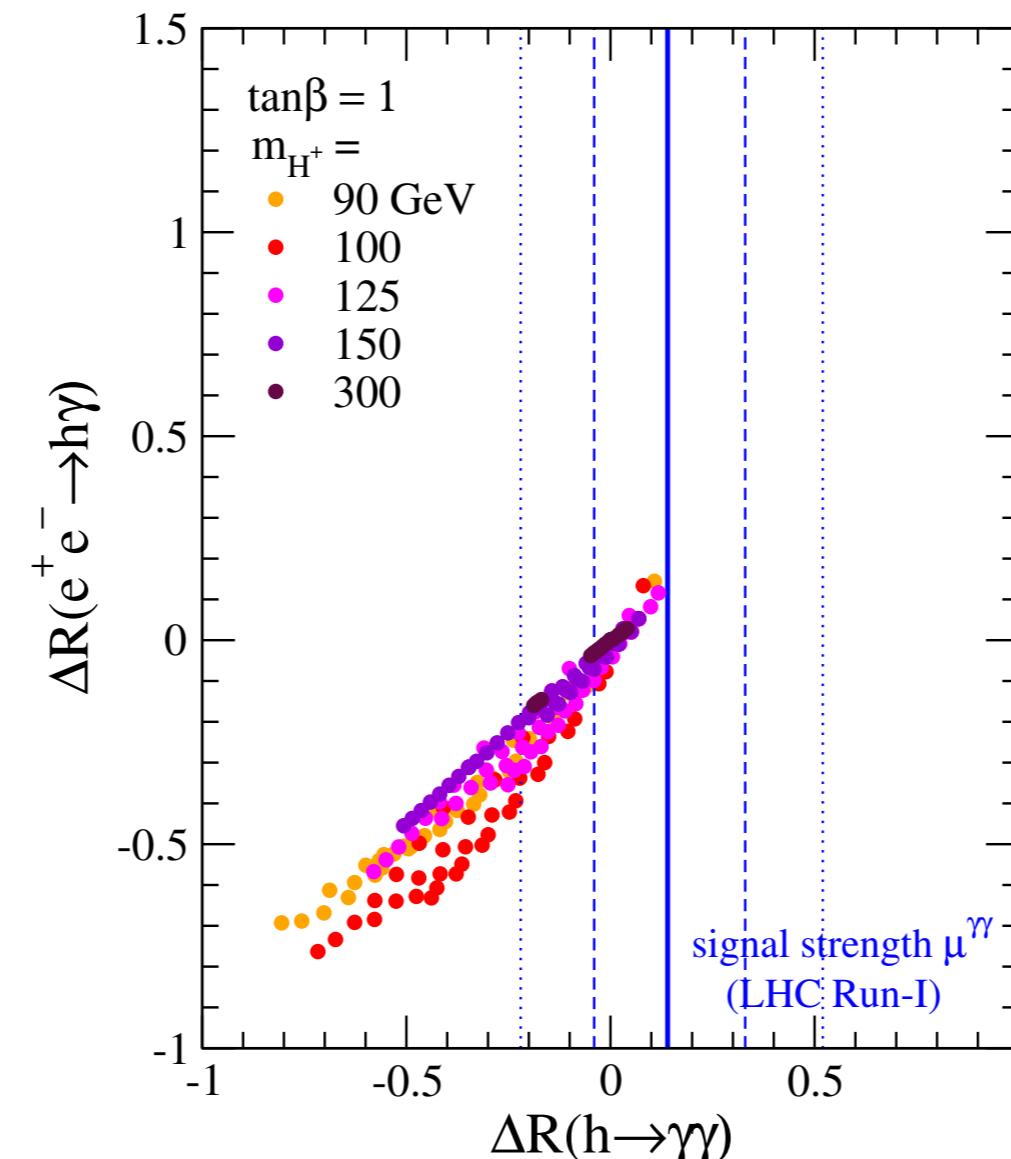
## Model parameters:

$m_H$ ,  $m_A$ ,  $m_{H^\pm}$ ,  $M^2 (\equiv m_3^2/s_{\beta}c_{\beta})$

$\tan\beta$ ,  $s_{\beta-\alpha} (\geq 0)$ ,  $\text{Sign}(c_{\beta-\alpha})$

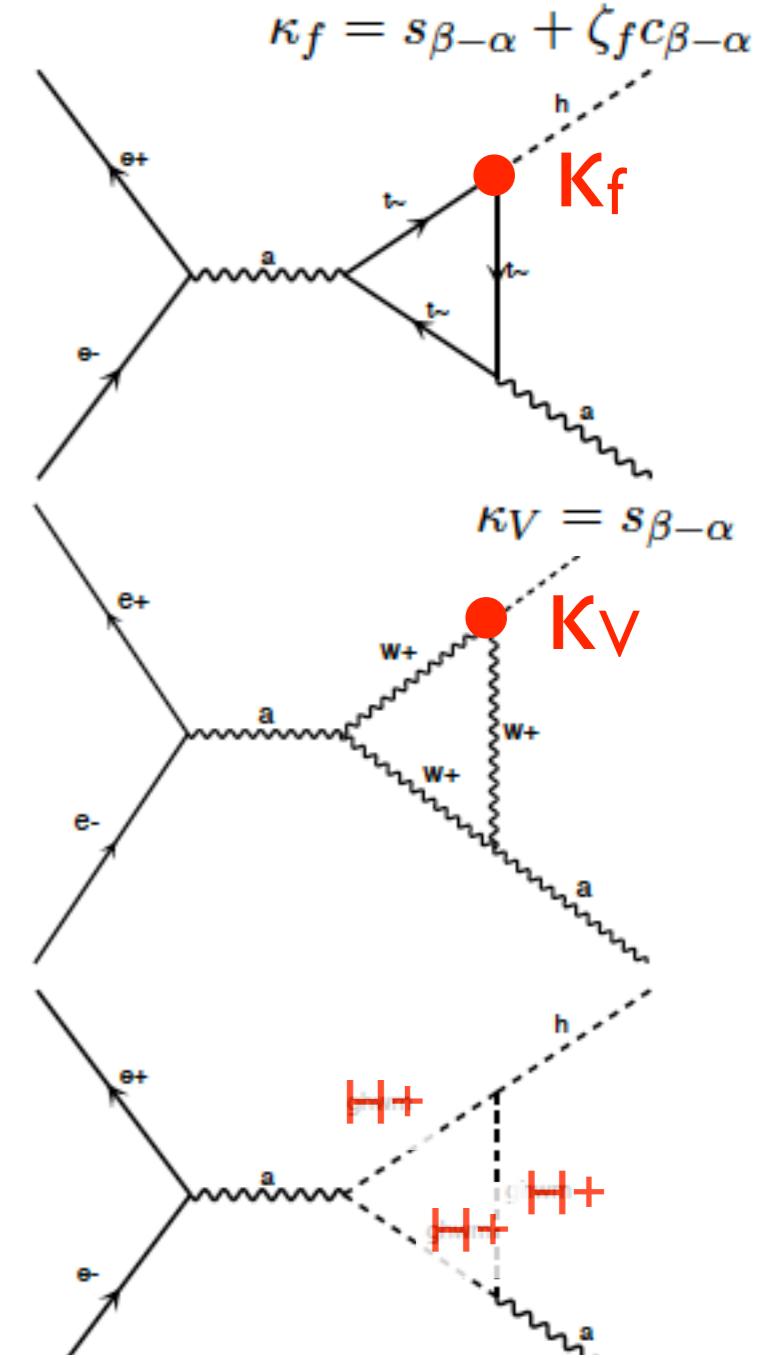
## TH Constraints:

- perturbative unitarity
- vacuum stability



$$\lambda_{hH^+H^-} = -v \lambda'_3$$

$$= -v \frac{2}{v^2} [(m_{H^+}^2 + \frac{1}{2}m_h^2 - M^2)s_{\beta-\alpha} + (m_h^2 - M^2)\cot 2\beta c_{\beta-\alpha}]$$



# Summary

- $h+\gamma$  production at ILC250 is an interesting channel, although the cross section is rather small,  $\sigma \sim \mathcal{O}(0.1 \text{ fb})$ , due to the loop-induced process.
  - ▶ The cross section is peaked at  $E=250\text{GeV}$ .
  - ▶ Beam polarization can enhance the cross section.
  - ▶ The signal is clean and very sensitive to New Physics.
- By using the H-COUP program, we have been studying the process in various extended Higgs models, such as IDM/ITM/THDM, systematically.
  - ▶ Light charged Higgs bosons can enhance the event rates by a factor of 2 at most under the theoretical (perturbative unitarity and vacuum stability) and experimental ( $h \rightarrow \gamma\gamma$ ) constraints.

