Physics potential of Higgs pair production at a $\gamma\gamma$ collider

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On behalf of
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Higgs

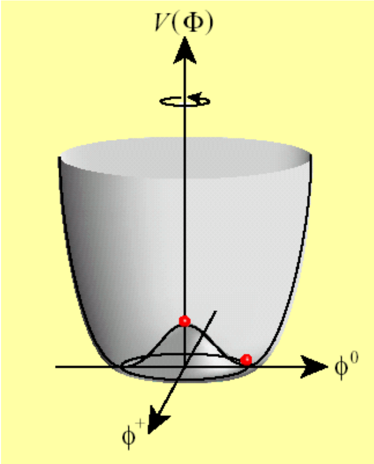
- Picture for the origin of Mass= Spontaneous EWSB

- Higgs sector remains unknown.
  - No Higgs found yet
  - Mass and couplings are unknown yet
- SM Higgs: a scalar iso-doublet
  - Problematic
  - Motivation for various new physics models

Identify Higgs sector = Determination of New Physics

Higgs potential

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



- SM Higgs potential
  - Electroweak Symmetry Breaking

$$V(\Phi) = -\mu^2 |\Phi|^2 + \lambda |\Phi|^4$$

  - Free parameter of the SM λ

$$m_h^2 = \lambda v^2, \quad \lambda_{hhh} = \lambda v, \quad \lambda_{hhhh} = \lambda$$

- It is important to measure both the mass m_h and hhh (and hhhh) coupling
  - Test for the SM Higgs potential
  - Nature of the EWSB
  - New physics determination

New Physics effect on HHH

- Non-decoupling effects

hhh **coupling**

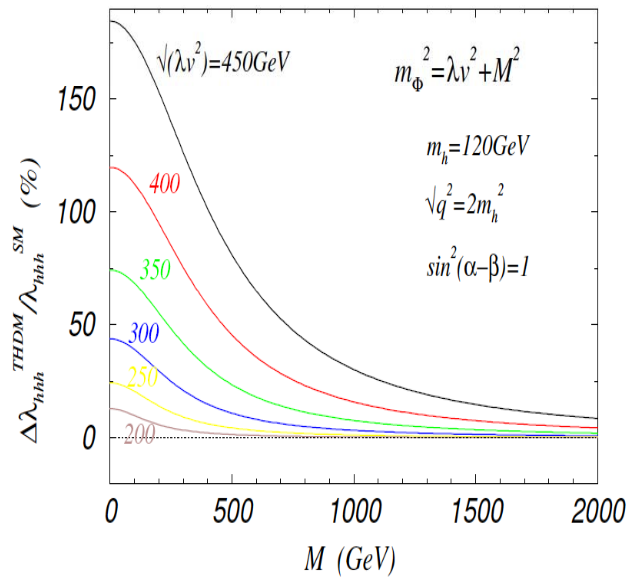
$$\lambda_{hhh} \simeq \frac{3m_h^2}{v}\left(1 - \frac{N_c m_t^4}{3\pi^2 v^2 m_h^2} + \cdots\right)$$

A m_t^4 term appears in the 1-loop correction.

loop effect $\sim$ 10%

Similarly, by new physics loops, HHH can easily receive large deviation from the SM value.

2HDM



SK, Kiyoura, Okada, Senaha, Yuan

- Pure dim-6 operators

$$\mathcal{L}' = \sum_i^2 \frac{f_i}{\Lambda^2}\mathcal{O}_i$$

$$\mathcal{O}_1 = \frac{1}{2}\partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi) \quad \mathcal{O}_2 = -\frac{1}{3}(\Phi^\dagger\Phi)^3$$

$$\mathcal{L}_{H^3} = -\frac{m_H^2}{2v}\left((1 - \frac{a_1}{2} + \frac{2a_2}{3}\frac{v^2}{m_H^2})H^3 - \frac{2a_1 H\partial_\mu H\partial^\mu H}{m_H^2}\right)$$

Tsumura's talk

Cosmological Connections

- Higgs Effective Potential
- Electroweak Phase Transition at Early Universe

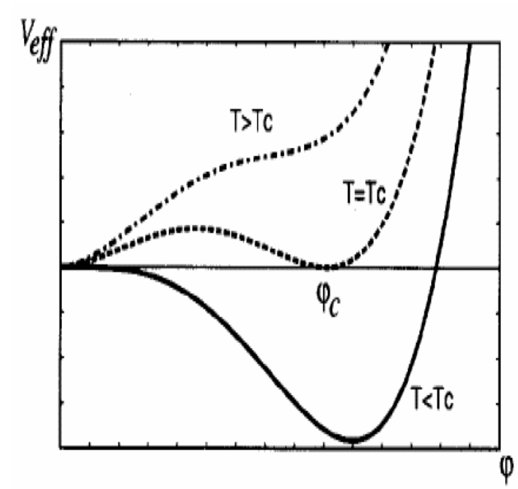
SM λ_{HHH} 2nd Order	$\Leftrightarrow$	A large $\delta\lambda_{HHH}$ Strong 1st Order

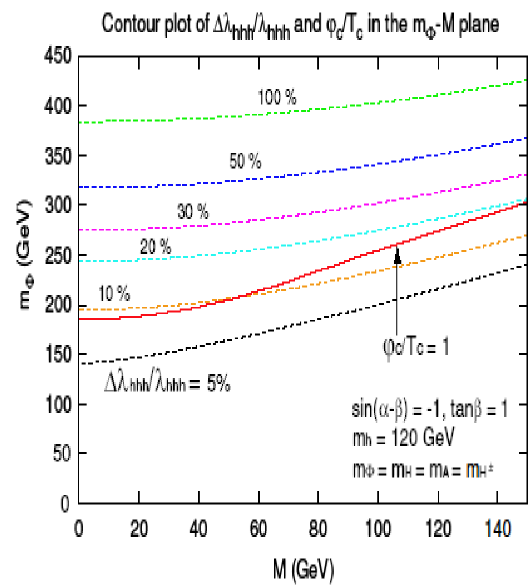
  - Electroweak Baryogenesis requires a strong 1st Order PT (For avoiding sphaleron smearing in broken phase)

$$\frac{\varphi_c}{T_c} > 1 \quad \Rightarrow \quad \frac{\Delta\lambda_{hhh}}{\lambda_{hhh}^{SM}} > \mathcal{O}(10)\%$$

  - 2HDM
  - Dim-6 Operator (Grogean, Sevant, Wells)
  - MSSM (Nelson et al; Carena et al, …..)

Noble, Pelestein





SK, Okada, Senaha

In this talk

- We discuss a possibility to measure the Higgs tri-linear coupling via the process of

$$\gamma\gamma \rightarrow HH$$

  at the ILC photon collider option.
  - Alternative or better as compared to e+e- collision?
    Jikia, Jikia and Belusevic HHZ, HH$\nu\nu$
  - Can new physics effects drastically change SM predictions?
  - Valuable for a simulation study?

Measurement of the HHH coupling

- Higgs self-coupling (HHH)
  - Direct information to the Higgs potential
  - Effect on the New Physics
  - Cosmological Connection

Required accuracy $\frac{\Delta\lambda_{hhh}}{\lambda_{hhh}^{\mathrm{SM}}} < \mathcal{O}(10)\%$

- Measurement at collider experiments
  - LHC $gg \to HH$
  - ILC $e^+e^- \to ZHH$ $e^+e^- \to HH\bar{\nu}\nu$
  - ILC ($\gamma\gamma$ collider)

$$\gamma\gamma \to HH$$

This is our subject.

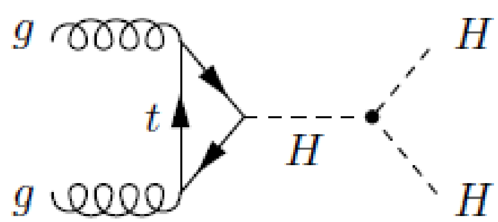
- Sensitivity to anomalous deviations of λ

$$\lambda=\lambda_{SM} + \delta\lambda = \lambda_{SM}\,(1+ \delta\kappa)$$

HHH measurement at LHC

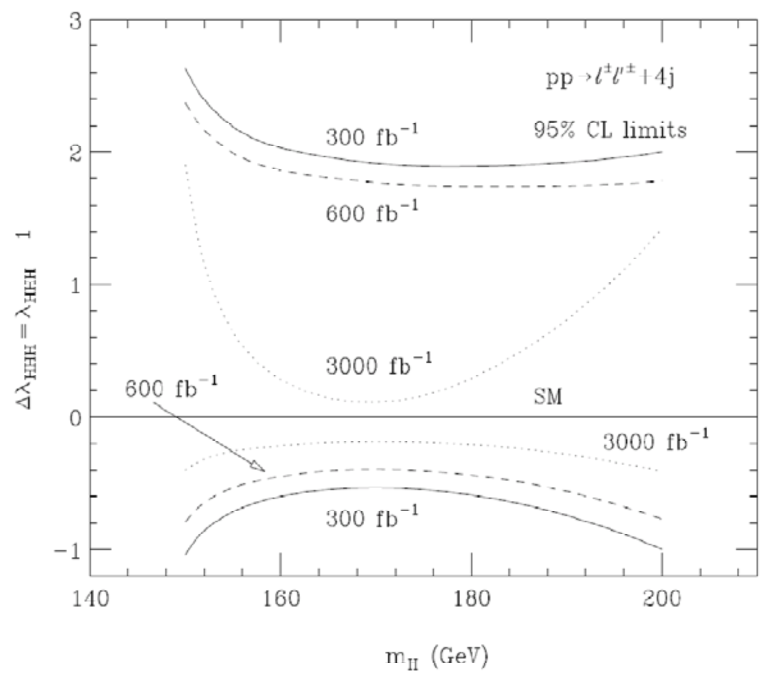
- Decays into gauge boson pairs
- Hopeless for a light H
- Intermediate masses:

  Non-vanishing of λ can be established at the LHC.



Precision measurement of the HHH coupling is business of the ILC.

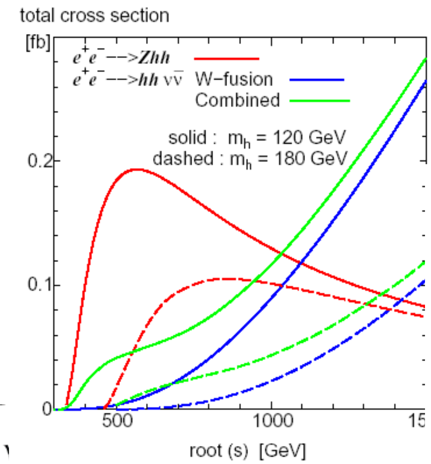
$$pp \to HH \to W^+W^-W^+W^- \to \ell^\pm \ell'^\pm + 4j$$

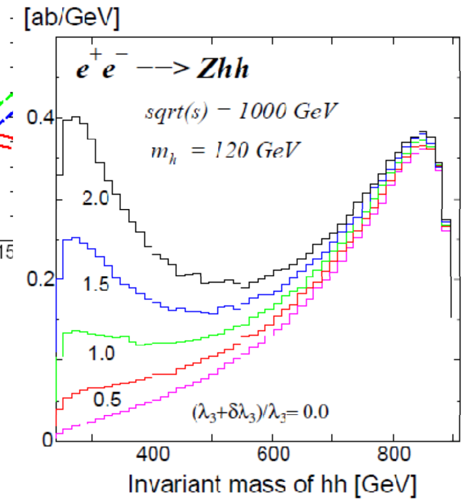


Bauer, Plehn, Rainwater

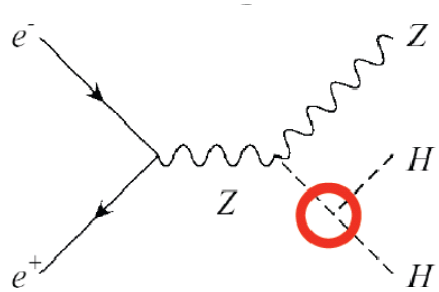
Measurement at the ILC

1st stage $\sqrt{s} = 500$ GeV
2nd stage $\sqrt{s} = 1$ TeV
$\int \mathcal{L} = 0.5 - 1\ \mathrm{ab}^{-1}$

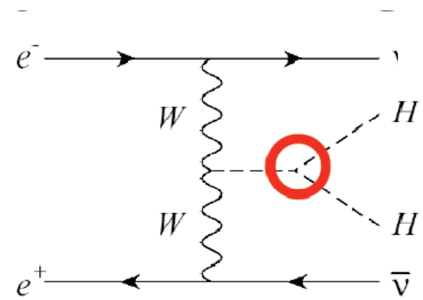


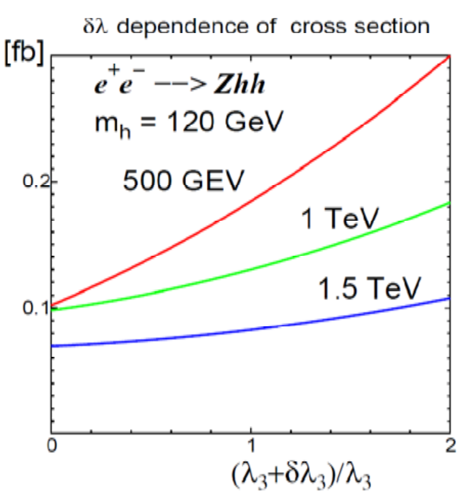


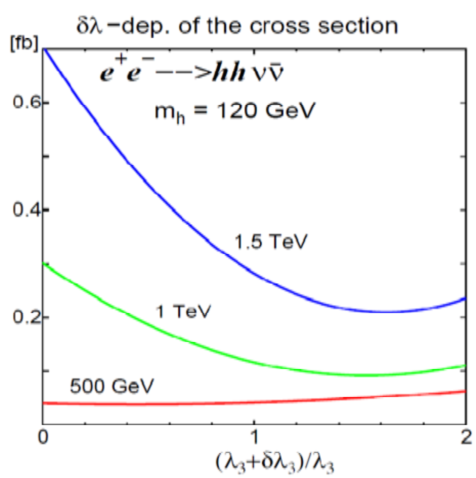
HH-strahlung

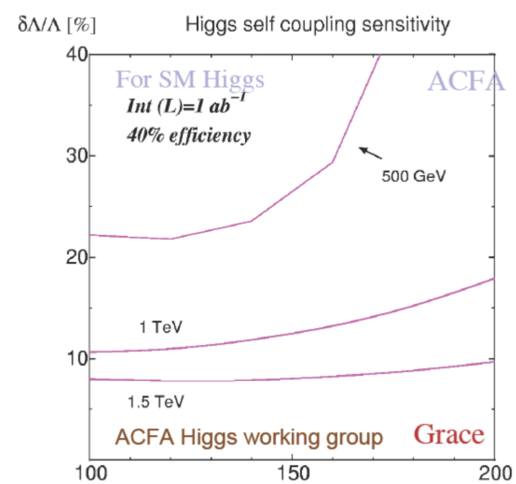


HH-fusion









ACFA Higgs Working Group 2002

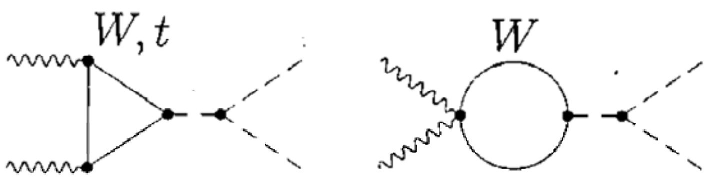
$\mathcal{O}(10-20)\%$

Study HHH at a photon collider

$$\gamma\gamma \to HH$$

Difference from ZHH and HH$\nu\nu$ production at ILC

– Two body final state
  - There is kinematical advantage, even though a loop suppression and also even though $L\gamma\gamma \sim L_{e+e-}/3$



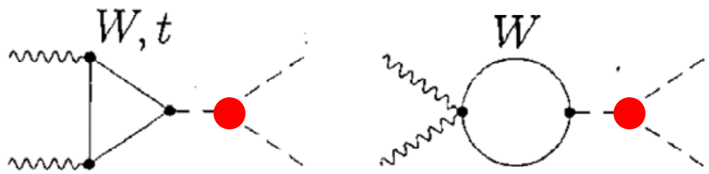
– Loop induced process
  - New physics loop correction to the $\gamma\gamma$H (loop induced) couplings can be O(1).
  - Different $\delta\lambda$ dependences from e^+e^- collision
    $\Rightarrow$ different sensitivity property

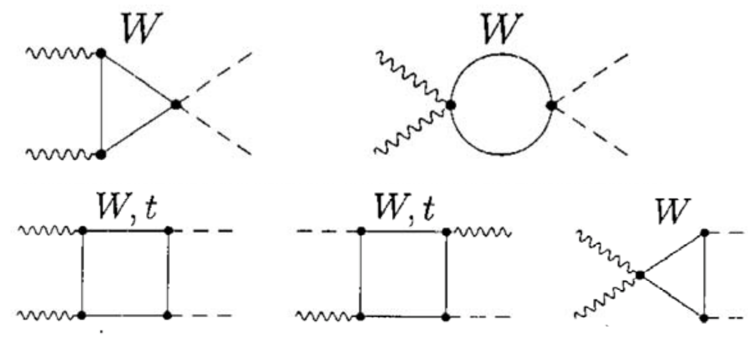
– Helicity amplitude

We can select a best helicity set to measure HHH.

Process $\gamma\gamma \to HH$

SM diagrams





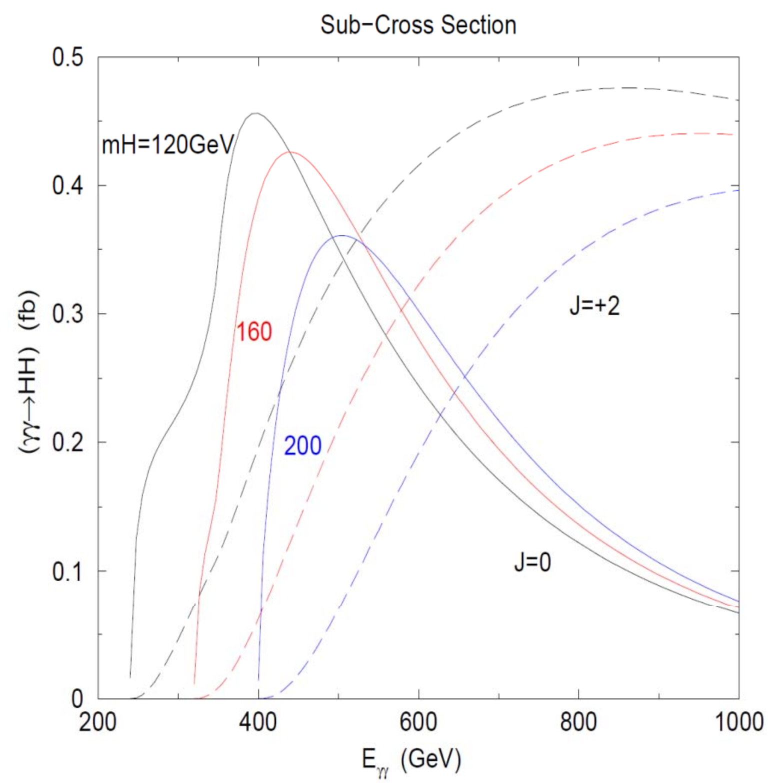
Helicity amplitudes

$$\mathcal{M}(\lambda_1, \lambda_2) = \mathcal{M}(-\lambda_1, -\lambda_2)$$

$$\mathcal{M}(+,+) = \text{pole} + \text{box}(+,+) \qquad J_z = 0$$

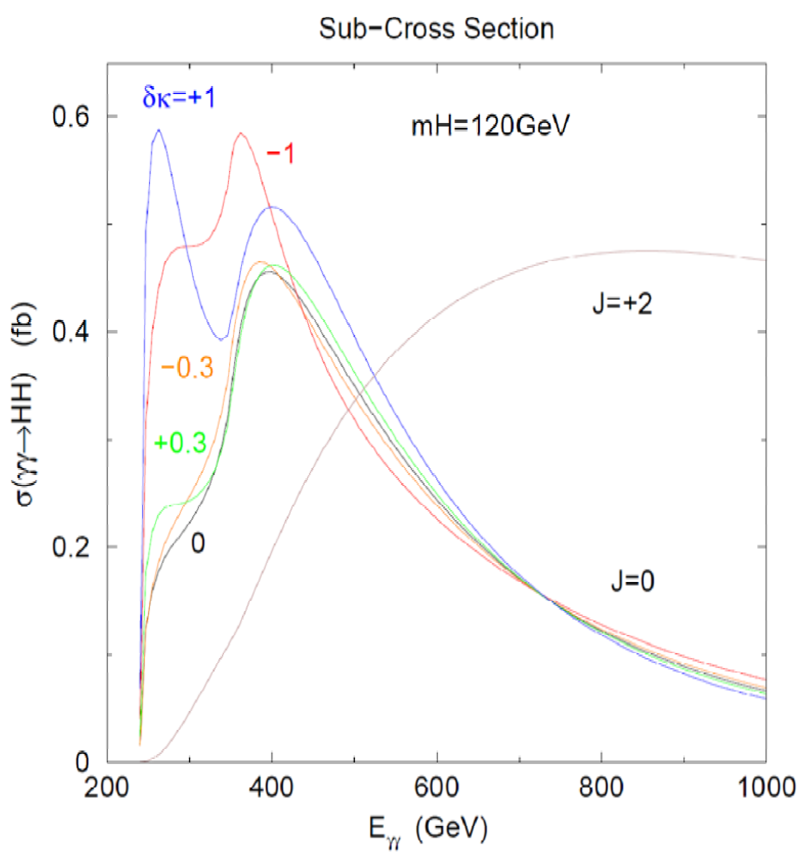
$$\mathcal{M}(+,-) = \text{box}(+,-) \qquad J_z = +2$$

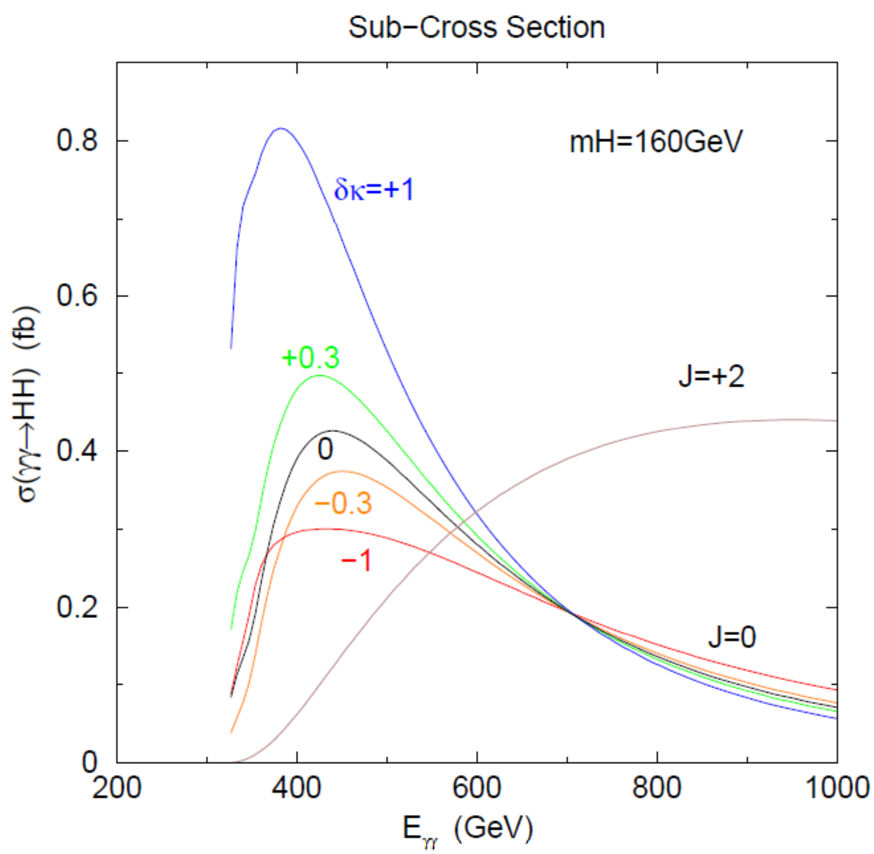
$$\frac{d\sigma(\lambda_1, \lambda_2)}{dt} = \frac{\alpha^2 \alpha_W^2}{32\pi s^2} |\mathcal{M}(\lambda_1, \lambda_2)|^2$$



Anomalous HHH coupling

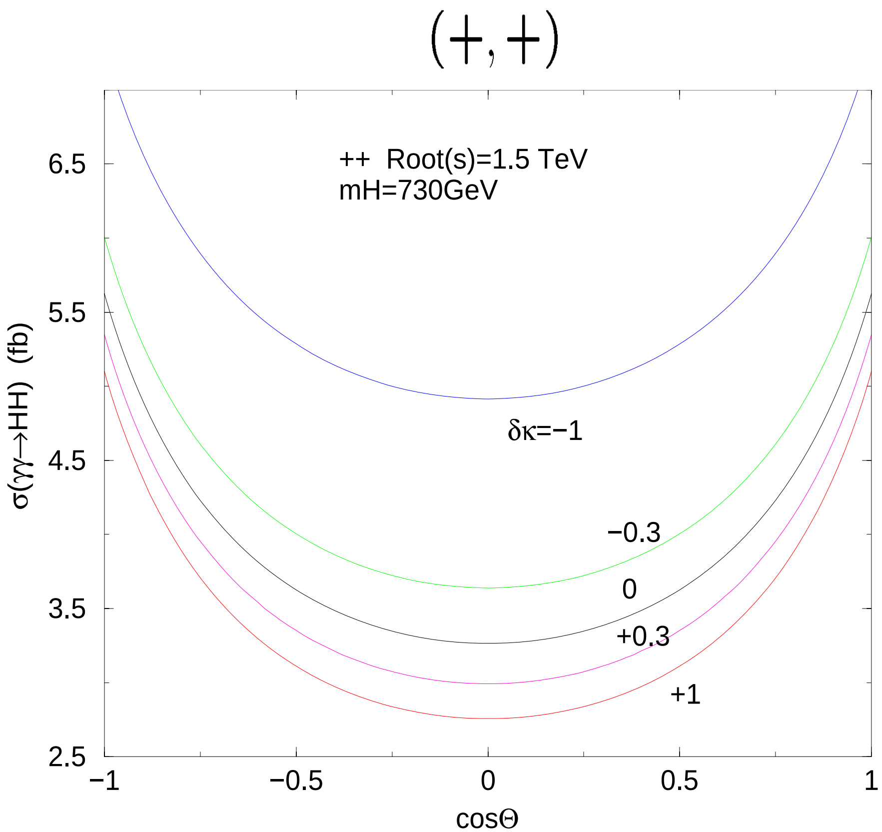
$$\lambda = \lambda^{\mathrm{SM}}(1 + \delta\kappa)$$

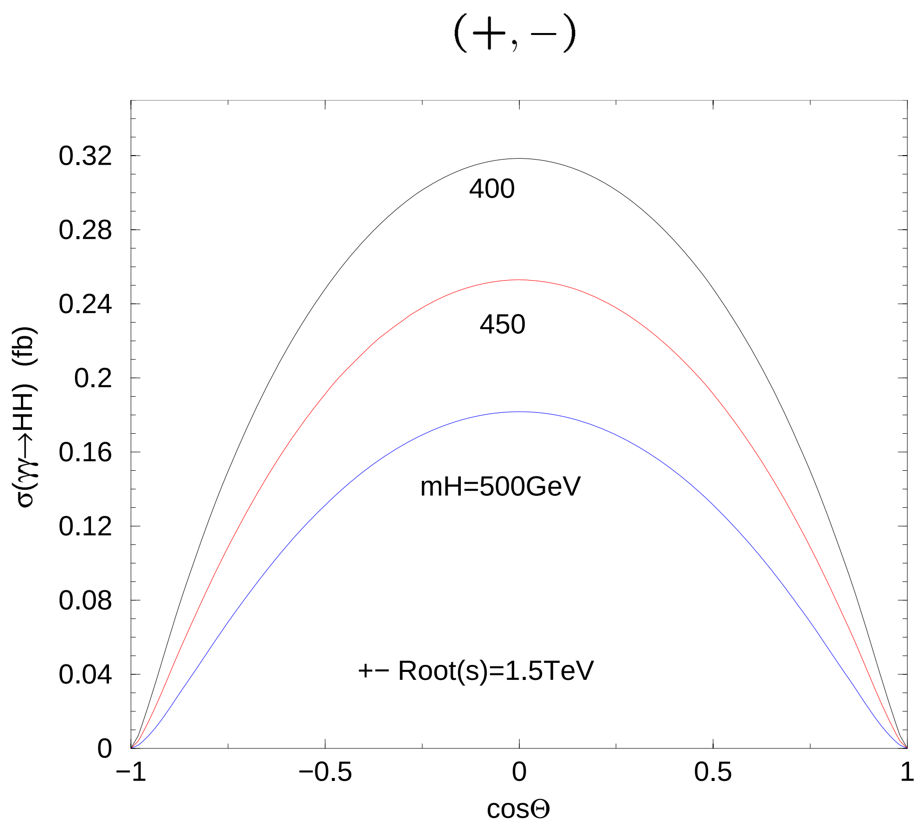




Sub cross section is more sensitive to $\delta\kappa$ for heavier H.

Sub-Process





Anomalous coupling parameter δκ

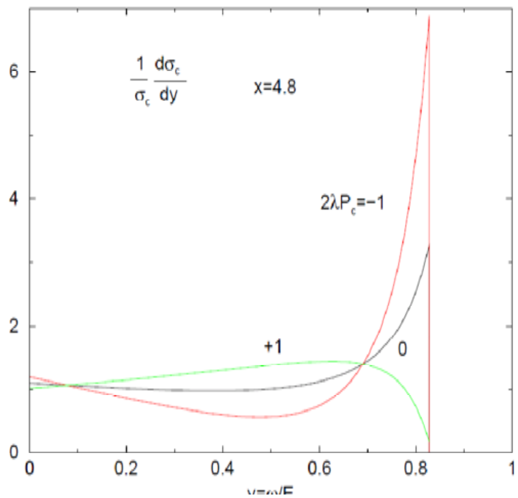
$$\lambda = \lambda^{SM}(1 + \delta\kappa)$$

δκ changes cross sections, but does not affect angular distribution

Full Cross Section

Photon structure function

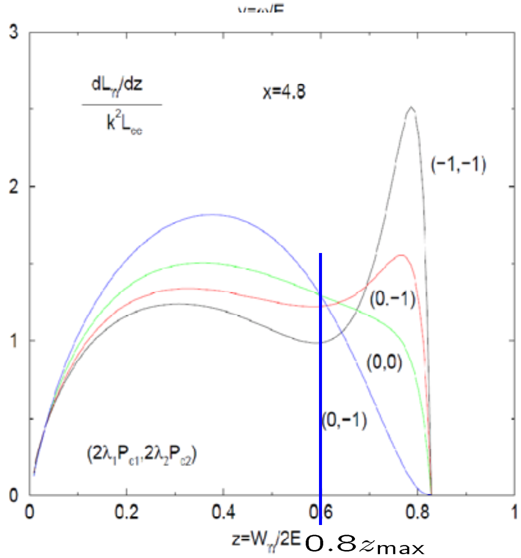
Ginzburg, et. al

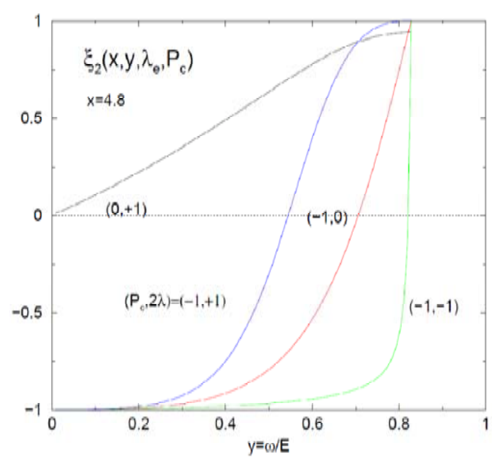


$$d\sigma = \int_{\frac{4m_H^2}{s}}^{y_m^2} d\tau \frac{dL_{\gamma\gamma}}{d\tau}\left(\frac{1+\langle\xi_2^{(1)}\xi_2^{(2)}\rangle}{2} d\hat{\sigma}(+,+) + \frac{1-\langle\xi_2^{(1)}\xi_2^{(2)}\rangle}{2} d\hat{\sigma}(+,-)\right)$$

$$\frac{L_{\gamma\gamma}}{d\tau} = \int_{\tau/y_m}^{y_m} \frac{dy}{y} f_\gamma(x,y) f_\gamma(x,\tau/y)$$

$$\tau = \hat{s}/s, y = E_\gamma/E_e \qquad y_m = \frac{x}{1+x}, x = \frac{4E_e\omega_0}{m_e^2}$$





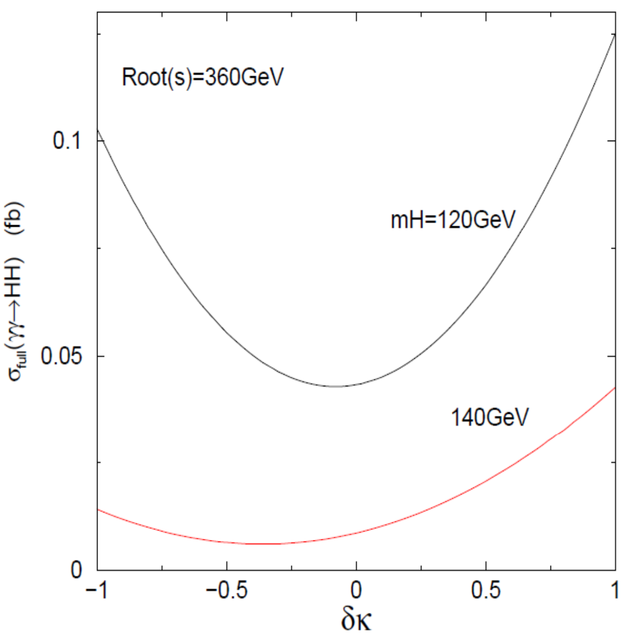
$\langle\xi_2\rangle$: mean polarzation of the γ beam

λ_e:electron helicity

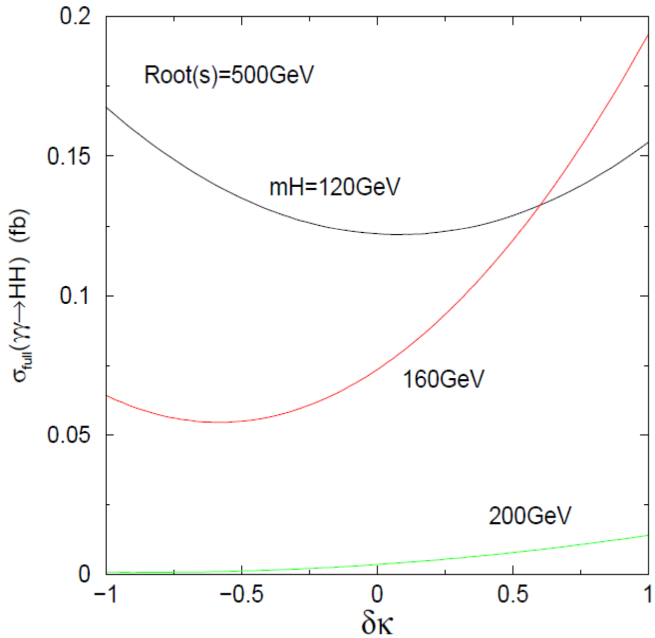
P_c:laser photon mean helicity

Full cross section (δκ dependences)

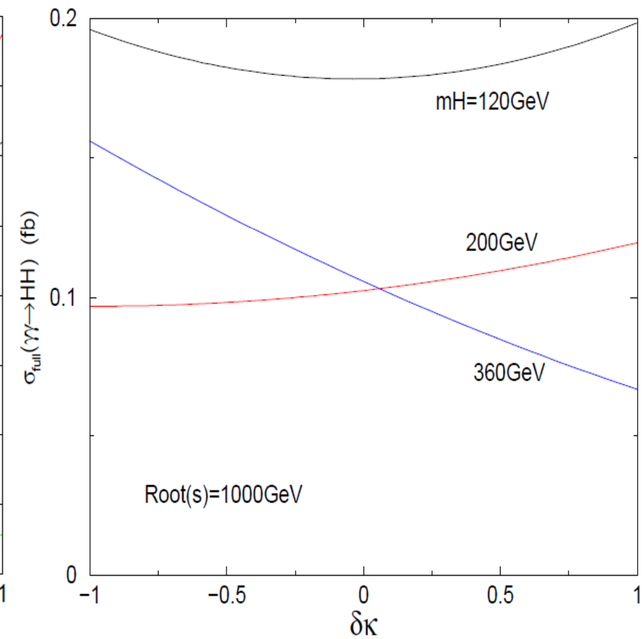
$\sqrt{s_{ee}} = 360\text{GeV}$



$\sqrt{s_{ee}} = 500\text{GeV}$



$\sqrt{s_{ee}} = 1000\text{GeV}$



pole > box

pole < box

Anomalous coupling parameter δκ

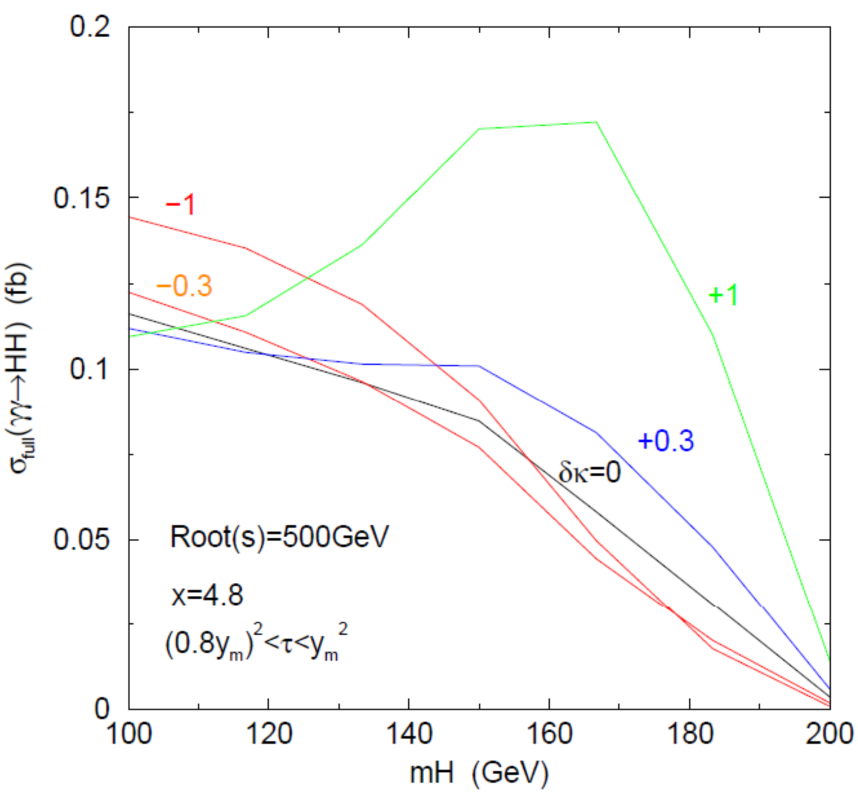
$$\lambda = \lambda^{SM}(1 + \delta\kappa)$$

Sensitivity to δκ can be large depending on parameters

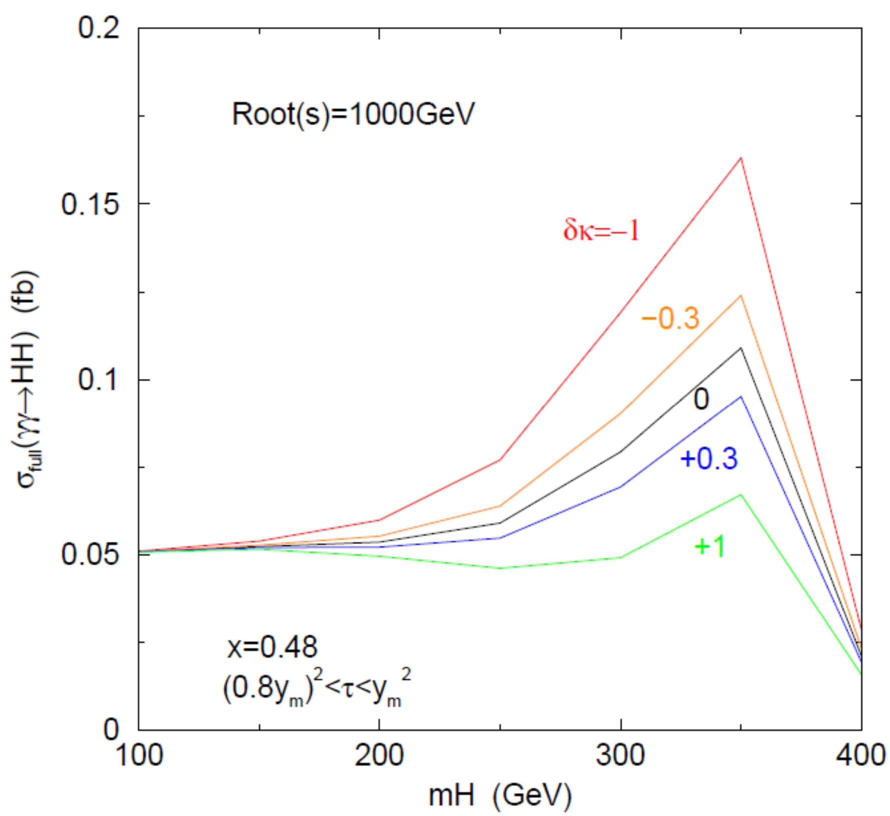
$$\lambda_{e_1} = \lambda_{e_2} = 0.45$$
$$\lambda_{\gamma_1} = \lambda_{\gamma_2} = -1$$

Full Cross Section 2

$\sqrt{s_{ee}} = 500\text{GeV}$

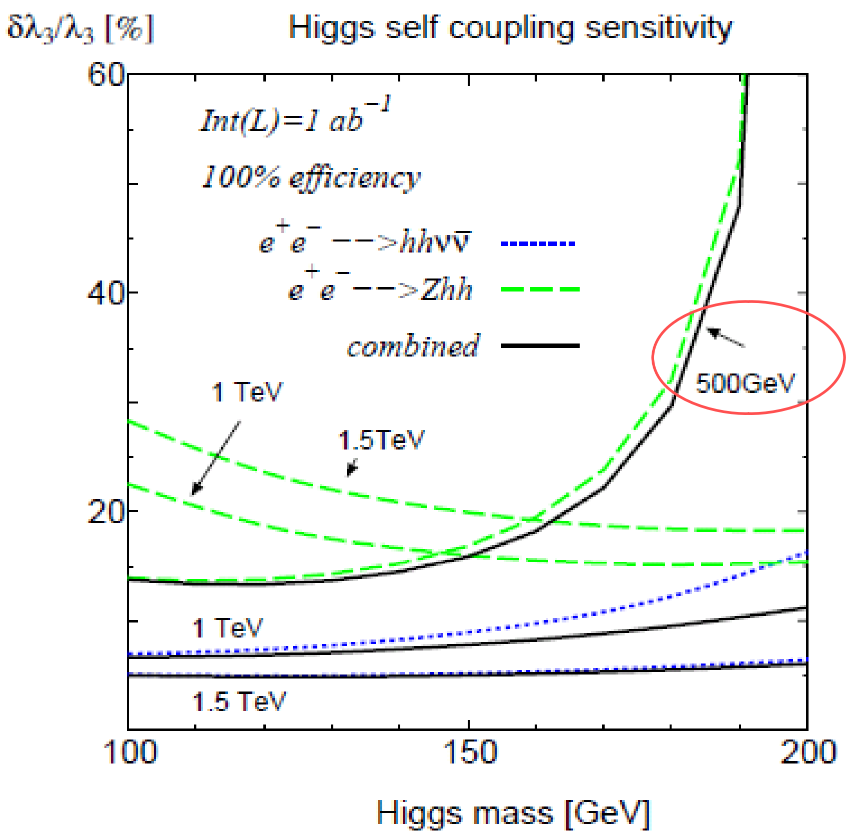


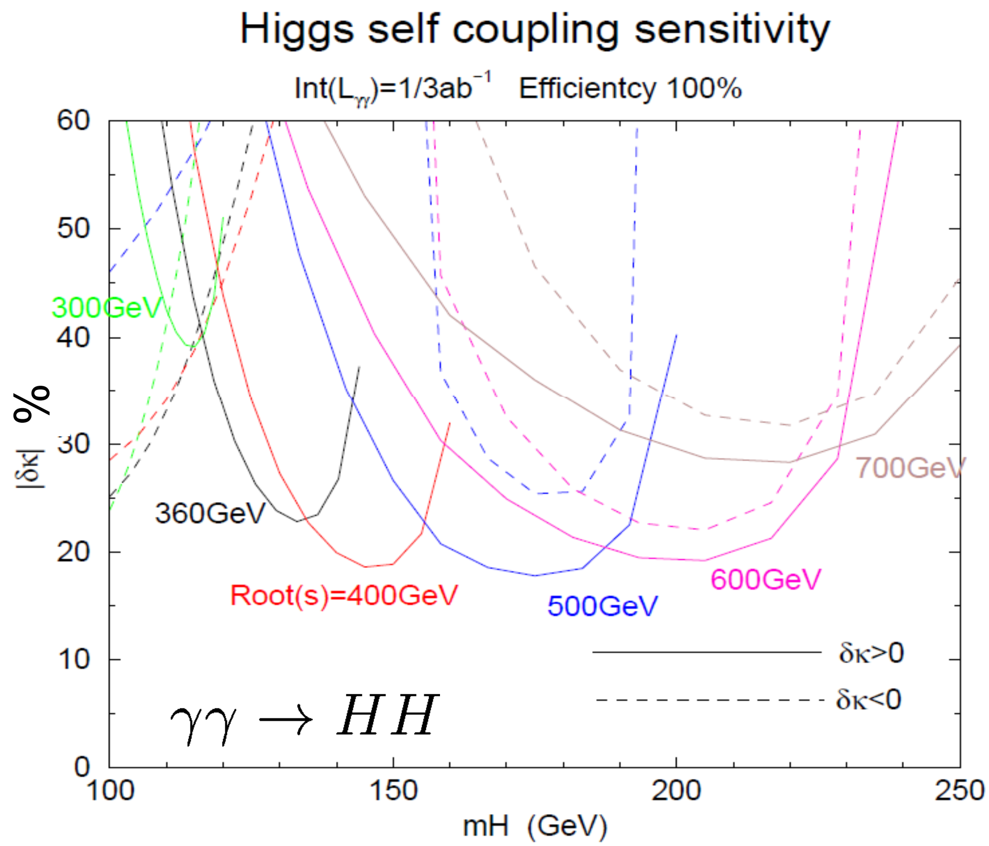
$\sqrt{s_{ee}} = 1000\text{GeV}$



$$\lambda_{e_1} = \lambda_{e_2} = 0.45$$
$$\lambda_{\gamma_1} = \lambda_{\gamma_2} = -1$$

Estimation of HHH sensitivity





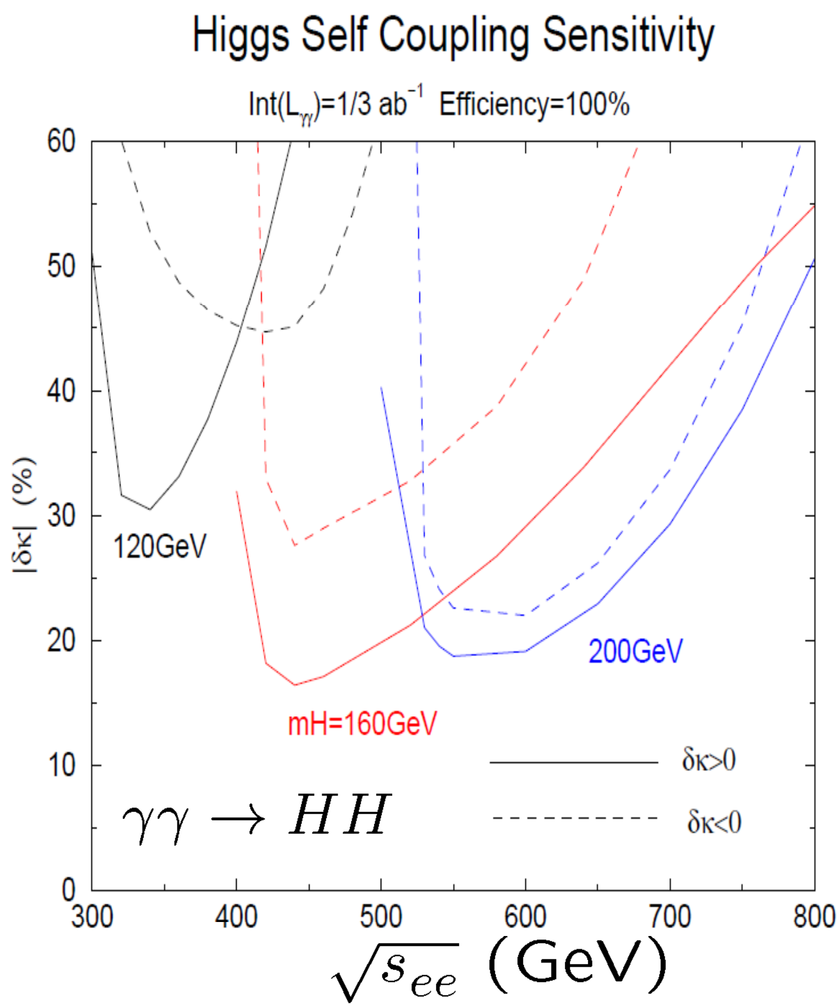
$$\lambda_{e_1} = \lambda_{e_2} = 0.45$$
$$\lambda_{\gamma_1} = \lambda_{\gamma_2} = -1$$

For relatively low e^+e^- (e^-e^-) energies ($\sqrt{s} <$ 500 GeV), sensitivity is larger in e^+e^- process for $m_H <$ 150 GeV, but $\gamma\gamma \to HH$ can be useful for higher values of m_H.

Estimation of HHH sensitivity

- At the ILC, energies of initial electron and laser can be changed.
- After H is found, mH is known. Then we can examine the HHH coupling by selecting the best E_{ee}.

$$m_H \approx \frac{\frac{x}{x+1}\sqrt{s_{ee}}\times 0.8}{2} = 0.33\times\sqrt{s_{ee}}$$



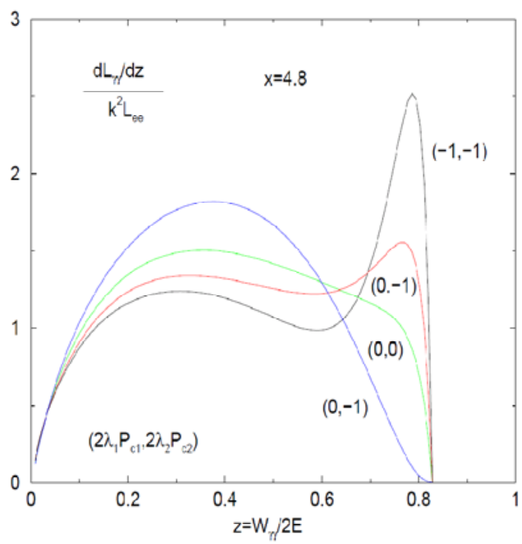
Summary

- Higgs self-coupling (HHH)
  - Nature of SSB (Higgs potential)
  - Probe of new physics, EWPT
- HHH measurements
  - LHC: Difficult
  - ILC: ZHH (better for lighter H), $\nu\nu$HH (better for lighter E)
- HHH at $\gamma\gamma$ collider $\gamma\gamma \to HH$
  - Result is consistent with previous works in the SM. Jikia, Belusevic
  - Sensitivity study
  - A $\gamma\gamma$ collider (Eee<500GeV) may be useful to measure the HHH coupling especially for mH=150-200GeV.
  - Simulation

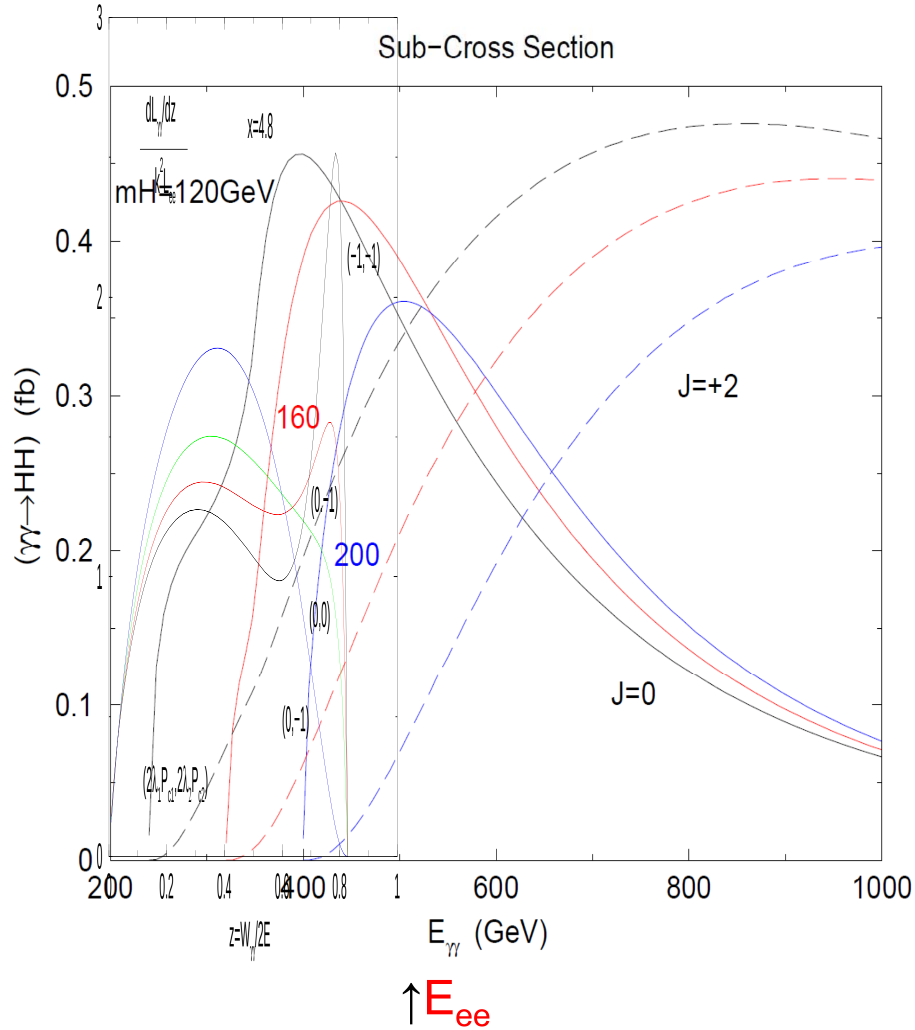
The best E_{ee} for each m_H

mH=160 GeV

Full Cross Section becomes large for Eee=450-500 GeV



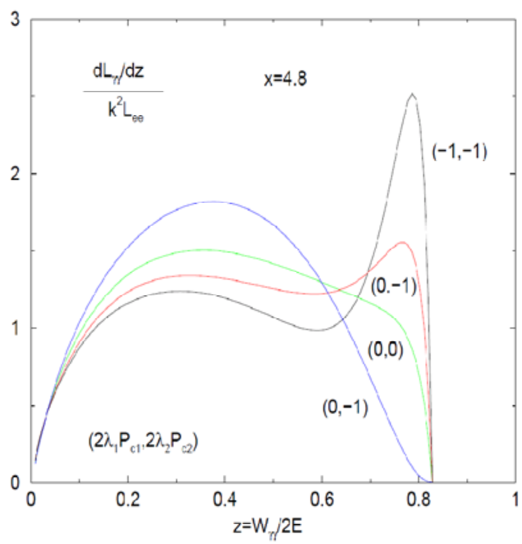
Photon Structure Funciton



The best E_{ee} for each m_H

mH=200GeV

Full Cross Section becomes large for Eee=550-600 GeV



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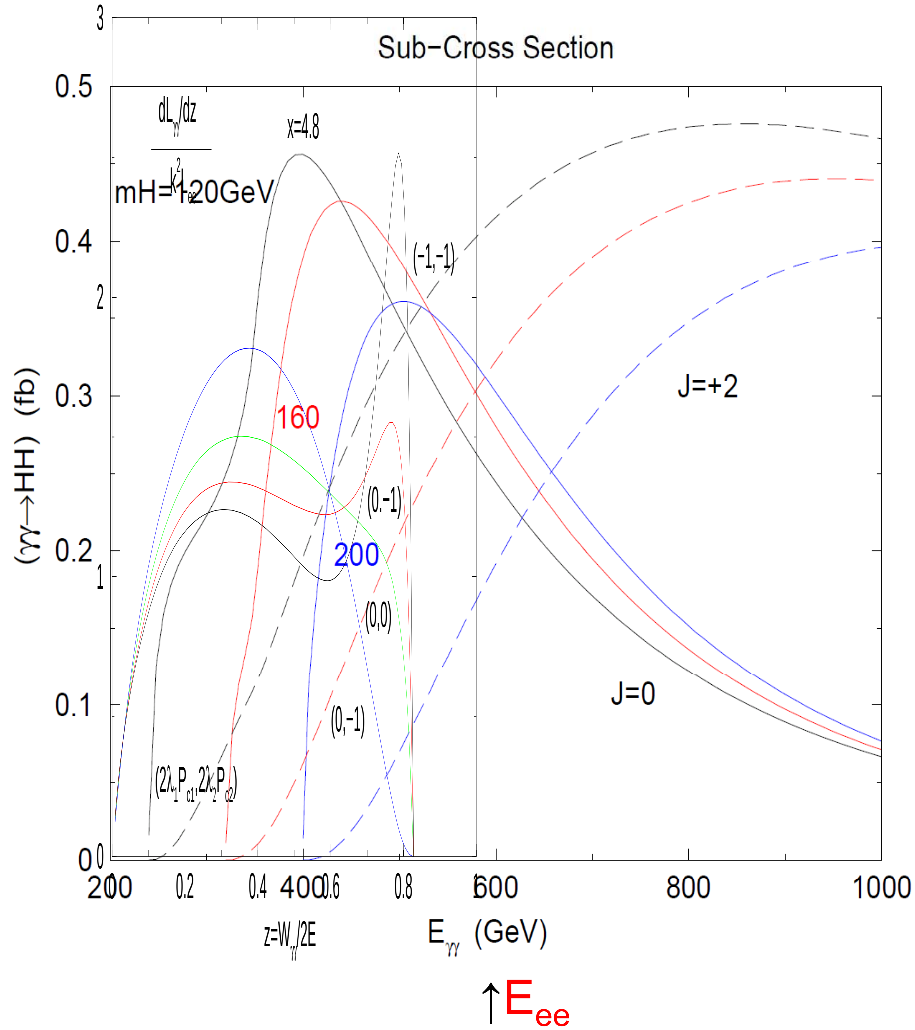
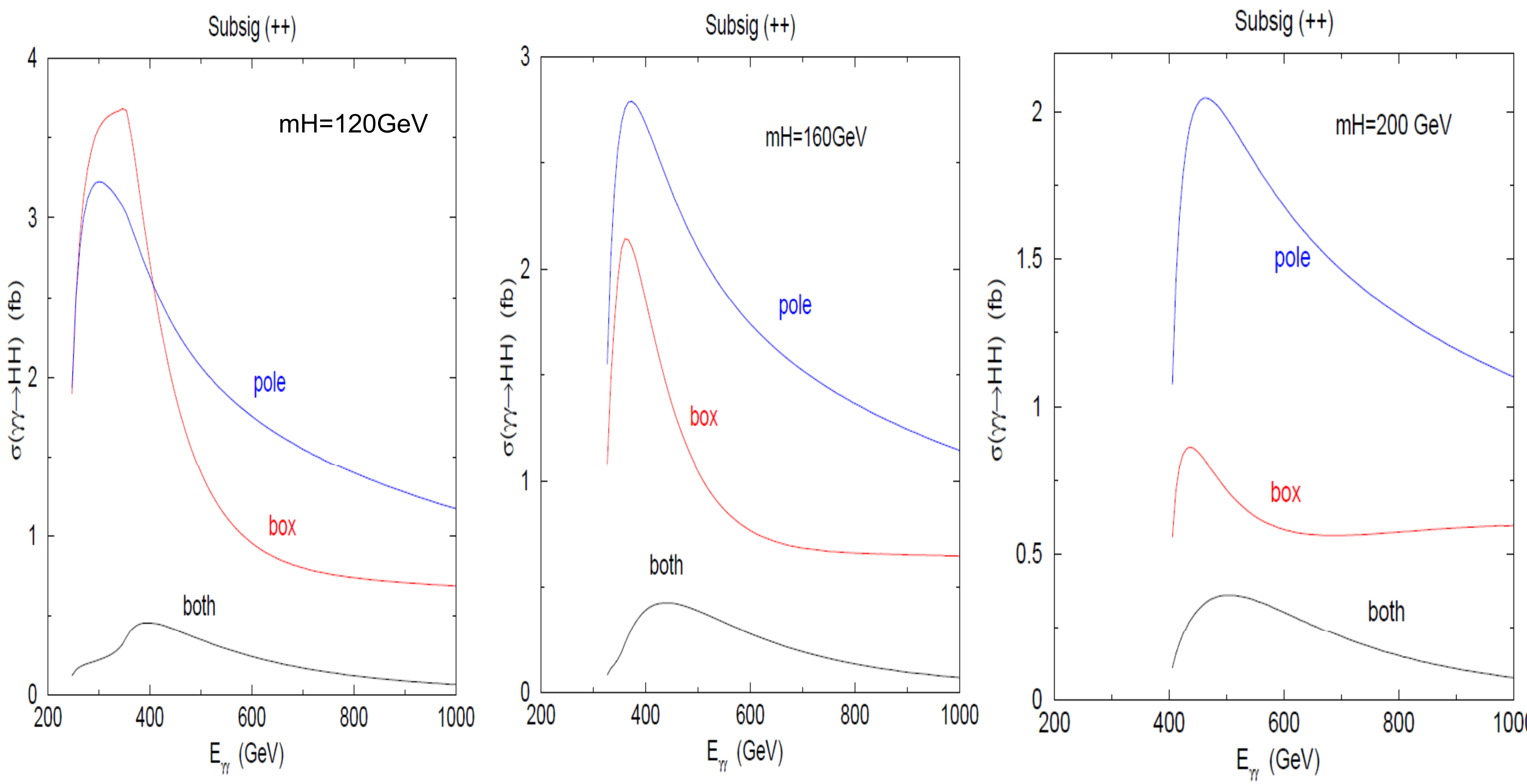


Pole vs Box (J=0)



Large destructive cancellation between pole and box contributions.
Pole contribution becomes dominant for larger MH values.

New Physics effects on $\gamma\gamma \to HH$

- New physics loop effect can be large, because the SM contributions are also loop-induced.

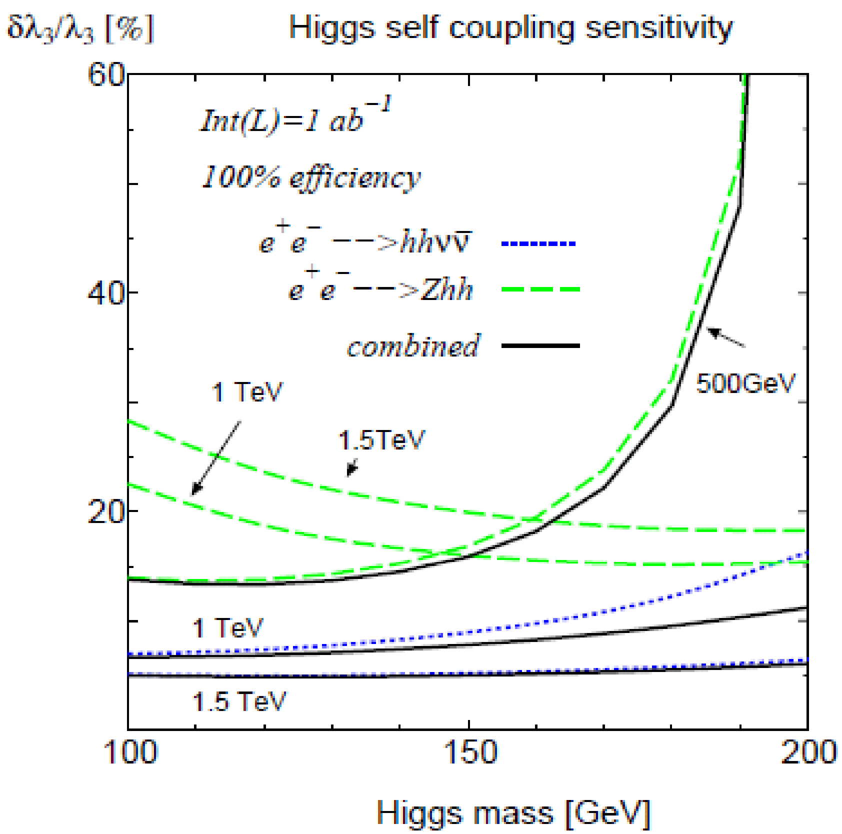
$$\mathcal{M}(\text{pole}) = (\mathcal{M}_{\text{SM}}^{\text{loop}} + \mathcal{M}_{\text{NEW}}^{\text{loop}})\frac{1}{\hat{s} - m_H^2}(\lambda + \delta\lambda)$$

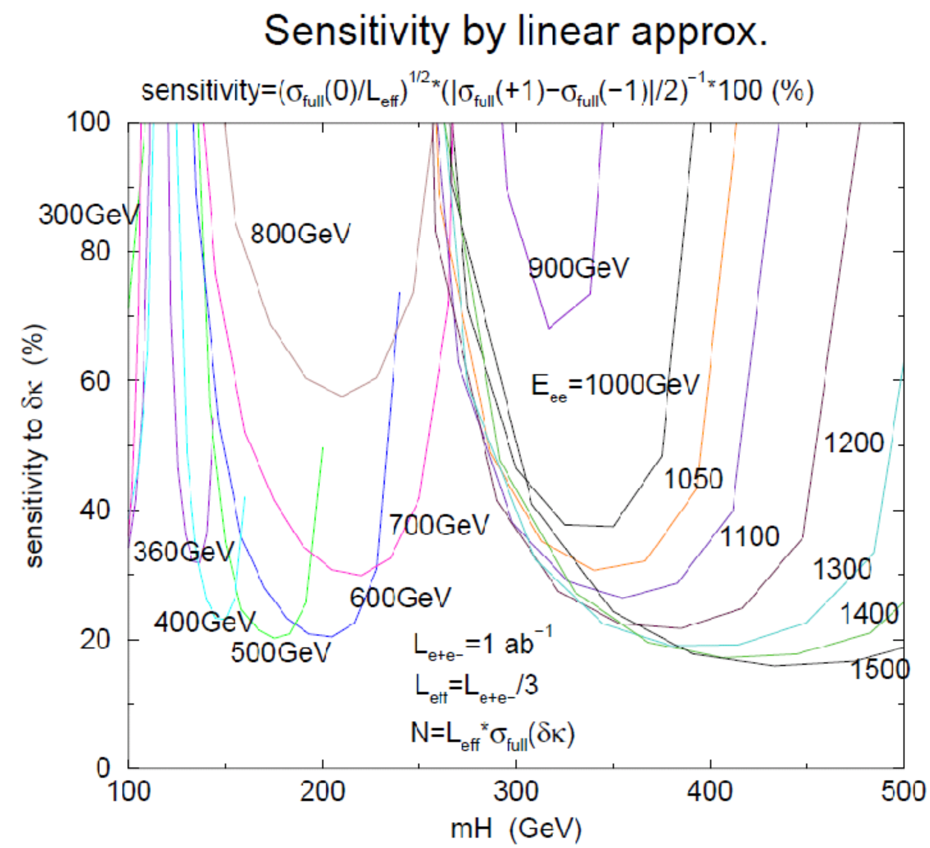
- New Physics contribution changes not only the size of the cross section but also (delicate) balance between the pole and the box diagrams.

$$|\mathcal{M}(+,+)|^2 = |A(\lambda + \delta\lambda) + B|^2$$
$$= |A|\,\delta\lambda^2 + 2|A|\,|A\lambda + B|\,\delta\lambda + |A\lambda + B|^2$$

HHH sensitivity could greatly depend on the model

Backup Slide 1





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Backup Slide 2

- Sensitivity

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

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