hep-ph/9903229
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Testing Higgs self-couplings at the LC

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Outline

- Motivation
- Self-couplings of the SM Higgs particle
- Self-couplings of the MSSM Higgs particles
- Conclusions

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Motivation

Higgs mechanism production of masses via spontaneous symmetry breaking (SSB)

- particles acquire their masses through the interaction with a scalar field
- self-interaction of the scalar field $\rightsquigarrow$ non-zero field strength in the ground state $\rightsquigarrow$ SSB
- $v = 246\,\text{GeV} \neq 0$ induced by the typical form of the Higgs potential
- weak iso-doublet scalar field $\overset{\text{SSB}}{\rightsquigarrow}$ Higgs particle

How to establish the Higgs mechanism experimentally?

(I) Discovery of the Higgs particles

$\Downarrow$

(II) Yukawa and gauge couplings

$\Downarrow$

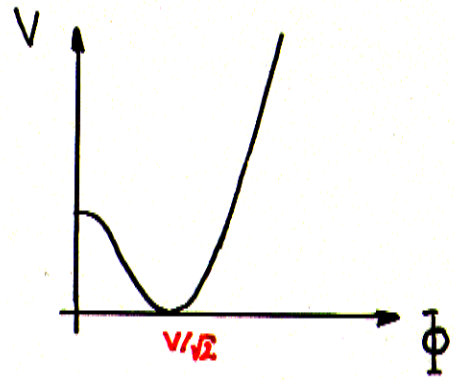
(III) Determination of the Higgs self-couplings

$\Downarrow$

Experimental verification of the creation of particle masses via the Higgs mechanism

Standard Model

$$\boxed{V(\Phi) = \lambda\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2}$$



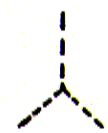
$v = 246$ GeV

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix} \rightsquigarrow$$

$$\boxed{V(H) = \frac{1}{2}M_H^2 H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4}$$

Higgs mass : $M_H = \sqrt{2\lambda}\, v$

trilinear Higg self-coupling : $\lambda_{HHH} = 3M_H^2/M_Z^2$



quadrilinear Higgs self-coupling : $\lambda_{HHHH} = 3M_H^2/M_Z^4$

(units $\lambda_0 = 33.8\,\mathrm{GeV}/\lambda_0^2$)

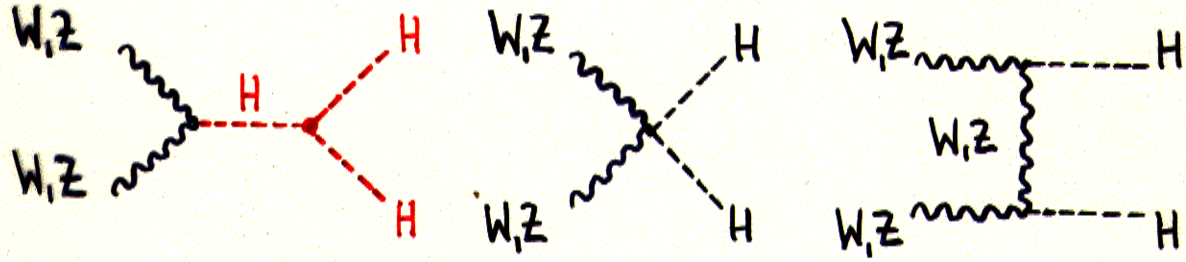
(a) trilinear coupling : via Higgs pair production

(b) quadrilinear coupling : via triple Higgs production

measurement of the Higgs self-couplings and reconstruction of the Higgs potential	$\Rightarrow$	establish the scalar sector of the Higgs mechanism experimentally

Determination of the trilinear Higgs coupling

WW-(ZZ-) fusion



Independent helicity amplitudes

$$\hat{\mathcal{M}}_{LL} = \frac{2\sqrt{2}G_F M_W^2}{(1-\beta_W^2)}\left\{(1+\beta_W^2)\frac{\lambda_{HHH}}{(\hat{s}-M_H^2)/M_Z^2} + (1+\beta_W^2) + \frac{1}{\beta_W\beta_H}\left[\frac{1-\beta_W^4+(\beta_W-\beta_H x)^2}{x-x_W} + (x\to -x)\right]\right\}$$

$$\hat{\mathcal{M}}_{LT} = \frac{G_F\sqrt{M_W^2(1-x^2)\hat{s}}}{\beta_W}\left[\frac{\beta_H x-\beta_W}{x-x_W} - (x\to -x)\right]$$

$$\hat{\mathcal{M}}_{+-} = \frac{\sqrt{2}G_F M_W^2\beta_H(1-x^2)}{\beta_W}\left[\frac{1}{x-x_W} + (x\to -x)\right]$$

$$\hat{\mathcal{M}}_{++} = 2\sqrt{2}G_F M_W^2\left\{\frac{\lambda_{HHH}}{(\hat{s}-M_H^2)/M_Z^2} + 1 + \frac{1}{2\beta_W\beta_H}\left[\frac{(1-x^2)\beta_H+8M_W^2/\hat{s}}{x-x_W} + (x\to -x)\right]\right\}$$

$x=\cos\theta$, $x_W=(1-2M_H^2/\hat{s})/\beta_H/\beta_W$, $\beta=(1-4M^2/\hat{s})^{1/2}$

high energy limit:

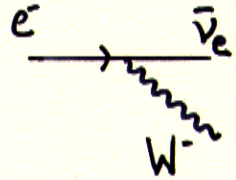
$$\hat{\sigma}_{LL} \to \hat{\sigma}_\infty = \frac{M_W^2 G_F^2}{2\pi} \qquad \sim \text{ constant}$$

$$\hat{\sigma}_{LT} \to \frac{M_W^2}{2\hat{s}}\,\frac{M_H^2-2M_W^2}{\hat{s}}\left[\ln\frac{\hat{s}}{M_W^2}-3\right] \qquad \sim \text{ scaling mod } \ln\hat{s}$$

$$\hat{\sigma}_{TT} \to \frac{M_W^2}{4\hat{s}}\,\hat{\sigma}_\infty \qquad \sim \text{ scaling}$$

Process $e^+e^- \to W^+W^- \to \bar{\nu}_e \nu_e HH$

Equivalent particle approximation: W bosons partons in e^-/e^+, W bosons on-shell



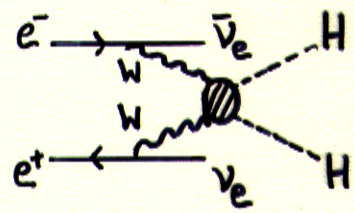
Kane,... Dawson

$$W_L\text{-spectrum} \quad : \quad f^L_{W/e}(x) = \frac{g^2}{16\pi^2}\,\frac{1-x}{x} \quad \text{high-energy limit}$$

$$x = E_W/E_e$$

Cross section for the process $e^+e^- \xrightarrow{WW} \bar{\nu}_e \nu_e HH$:

$$\sigma = \int_{4M_H^2/s_{ee}}^{1} d\tau \left(\frac{d\mathcal{L}}{d\tau}\right)_{WW/ee} \hat{\sigma}_{WW\to HH}(\hat{s} = \tau s_{ee})$$

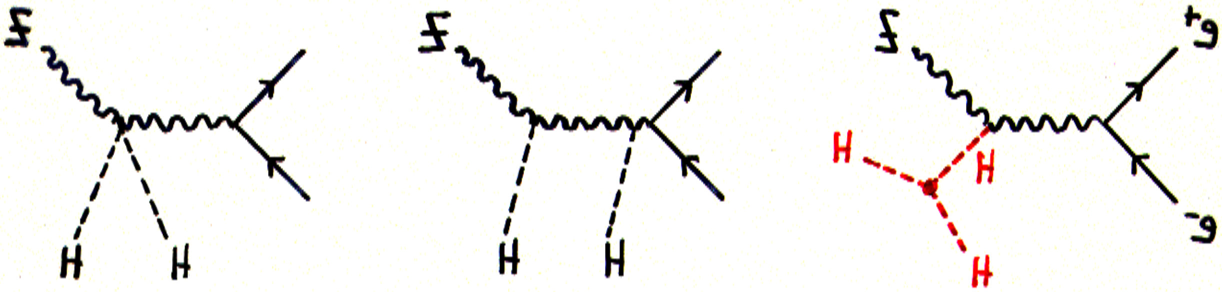


$$\left(\frac{d\mathcal{L}}{d\tau}\right)_{WW/ee} = \int_{\tau}^{1} \frac{dx_2}{x_2}\, f_{W/e}(x_2)\, f_{W/e}\left(\frac{\tau}{x_2}\right)$$

High energy limit:

$$\sigma_\infty(e^+e^- \xrightarrow{WW} \bar{\nu}_e \nu_e HH) \approx \left(\frac{\alpha}{4\pi \sin^2\theta_W}\right)^2 \left[\frac{1}{2}\ln^2\left(\frac{4M_H^2}{s_{ee}}\right) + 2\ln\left(\frac{4M_H^2}{s_{ee}}\right) + 3\right]\hat{\sigma}_\infty$$

Double Higgs-strahlung in e^+e^- collisions



$$\frac{d\sigma(e^+e^- \to ZHH)}{dx_1\,dx_2} = \frac{G_F^3 M_Z^6 (v_e^2+a_e^2)}{384\sqrt{2}\,\pi^3 s} \left\{ \frac{1}{(1-\mu_Z)^2} \, \frac{M_Z^2[(y_1+y_2)^2+8\mu_Z]}{4s[-1+x_1+x_2+\mu_Z-\mu_H]^2} \, \lambda_{HHH}^2 \right.$$

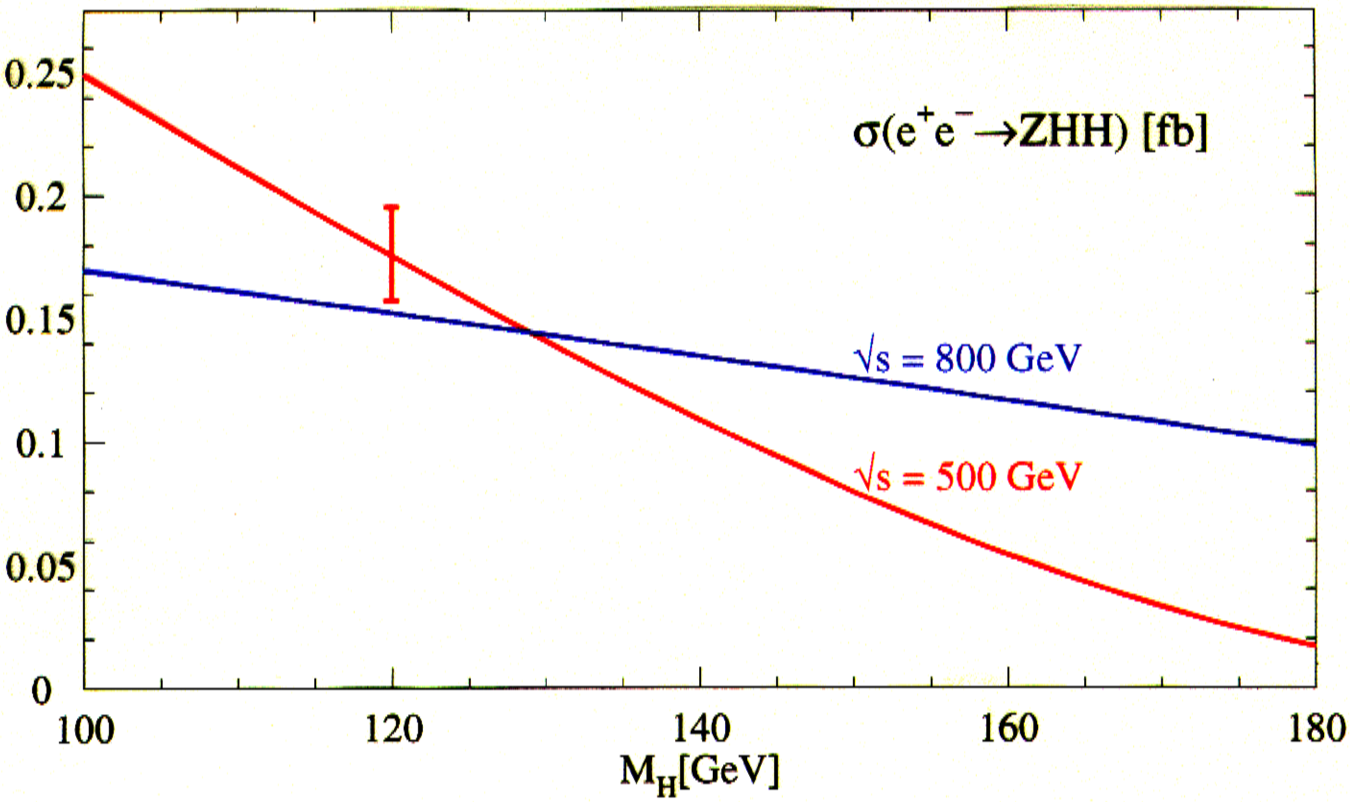
$$+ \text{ radiation contributions}$$

$$\left. + \text{ interference terms } (\sim \lambda_{HHH}) \right\}$$

$x_i = E_i/\sqrt{s}$, $i = 1,2$

$\mu_i = M_i^2/s$

SM double Higgs-strahlung : $\sqrt{s}$=500GeV, 800GeV



- $\sigma \sim 0.02 \ldots 0.25$ fb $\hat{=}$ 40...500 events for $\int \mathcal{L} = 2000\,fb^{-1}$
- polarized e^+, e^- beams $\rightsquigarrow \sigma^{pol} = 2\sigma^{unpol}$
- σ shows scaling behaviour
- I variation of σ(ZHH) for $\Delta\lambda/\lambda = 0.2$
- $\sqrt{s}$ = 500 GeV good choice for M_H=120 GeV : σ large
  sensitivity to λ_{HHH} large

Final states and background

Final states: (i) $M_H \lesssim 140$ GeV : $Zb\bar{b}b\bar{b}$

(ii) $M_H \gtrsim 140$ GeV : ZWW^*WW^*

For $M_H \lesssim 140$ GeV:

Miller, Moretti

- Parton level analysis : backgcound under control but signal rates are small.

  [$M_H = 110$ GeV , $\sqrt{s} = 500$ GeV , $\int \mathcal{L} = 1\,ab^{-1}$: $N_S = 26$, $N_B = 1$]

- Hadron level analysis $\longrightarrow$ talk by P. Gay

Quadrilinear coupling λ_{HHHH}

processes involving λ_{HHHH}

triple Higgs-strahlung : $e^+e^- \xrightarrow{Z^*} ZHHH$
WW triple Higgs fusion : $e^+e^- \xrightarrow{WW} \bar{\nu}_e \nu_e HHH$

however:

$\sigma_{HHH} \approx 10^{-3}\,\sigma_{HH}$ because

- quadrilinear coupling is suppressed with respect to the trilinear coupling
- one more particle in the final state

Quadrilinear coupling not measurable for the time being.

MSSM

supersymmetry + no anomaly $\Rightarrow$ 2 complex Higgs doublets

<u>5 physical states:</u>

$$h \quad : \quad M_h \lesssim 135 \text{ GeV}$$
$$H, A, H^\pm : \quad M_i = \mathcal{O}(v) \ldots 1 \text{TeV}$$

Haber...
Carena...
Zhang...
Heinemeyer...

6 CP-invariant neutral trilinear Higgs couplings

trilinear Born couplings — one-loop leading m_t^4-approximation

$$\lambda_{hhh} = 3\cos 2\alpha \sin(\beta+\alpha) + 3\frac{\varepsilon}{M_Z^2}\frac{\cos\alpha}{\sin\beta}\cos^2\alpha$$

$$\lambda_{Hhh} = 2\sin 2\alpha \sin(\beta+\alpha) - \cos 2\alpha \cos(\beta+\alpha) + 3\frac{\varepsilon}{M_Z^2}\frac{\sin\alpha}{\sin\beta}\cos^2\alpha$$

$$\lambda_{HHh} = -2\sin 2\alpha \cos(\beta+\alpha) - \cos 2\alpha \sin(\beta+\alpha) + 3\frac{\varepsilon}{M_Z^2}\frac{\cos\alpha}{\sin\beta}\sin^2\alpha$$

$$\lambda_{HHH} = 3\cos 2\alpha \cos(\beta+\alpha) + 3\frac{\varepsilon}{M_Z^2}\frac{\sin\alpha}{\sin\beta}\sin^2\alpha$$

$$\lambda_{hAA} = \cos 2\beta \sin(\beta+\alpha) + \frac{\varepsilon}{M_Z^2}\frac{\cos\alpha}{\sin\beta}\cos^2\beta$$

$$\lambda_{HAA} = -\cos 2\beta \cos(\beta+\alpha) + \frac{\varepsilon}{M_Z^2}\frac{\sin\alpha}{\sin\beta}\cos^2\beta$$

$\tan\beta = v_2/v_1$

<u>Radiative corrections</u> one-loop leading m_t^4 approximation parametrized by

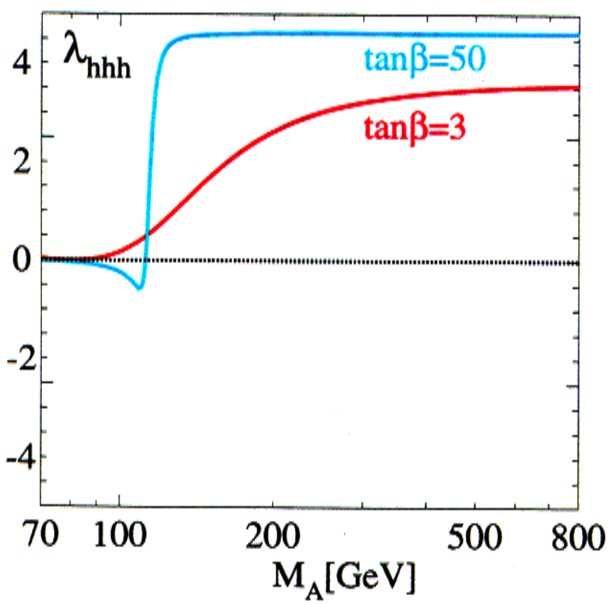
$$\varepsilon \approx \frac{3G_F m_t^4}{\sqrt{2}\pi^2 \sin^2\beta}\ln\left(1+\frac{M_S^2}{m_t^2}\right)$$

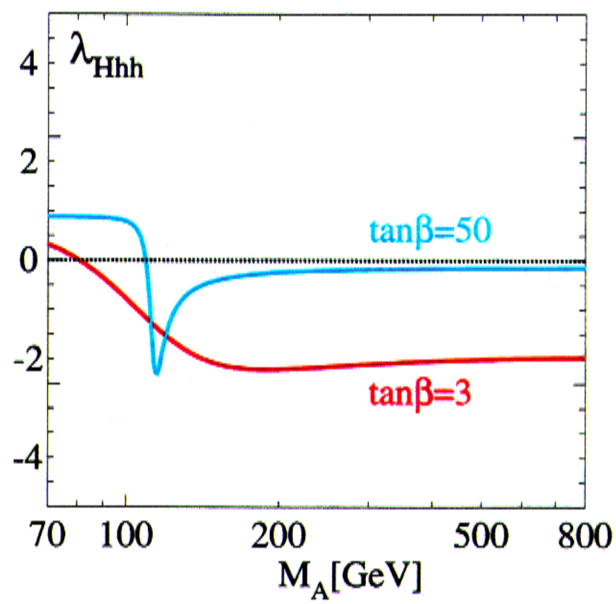
Trilinear couplings $\lambda_{hhh}, \lambda_{Hhh}$

Carena, Quiros, Wagner
Carena, Espinosa, Quiros, Wagner
Djouadi, Kalinowski, Spira

subsequent analysis: dominant one-loop and two-loop corrections to MSSM Higgs masses and couplings
corrections involve mixing parameters A and μ

$\lambda_{hhh}, \lambda_{Hhh}$ (no mixing):





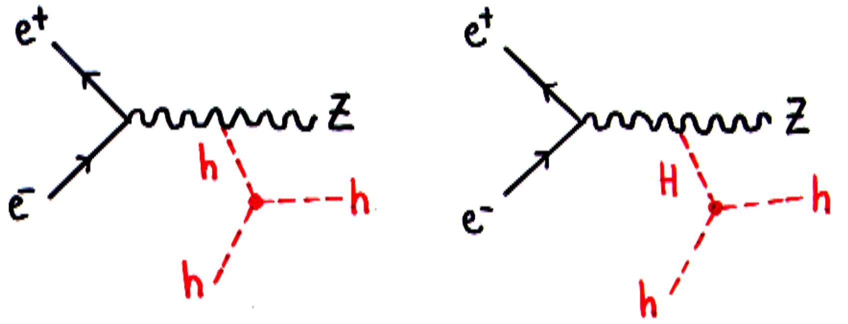
Note: $\lambda_{hhh}, \lambda_{Hhh}$ can become zero

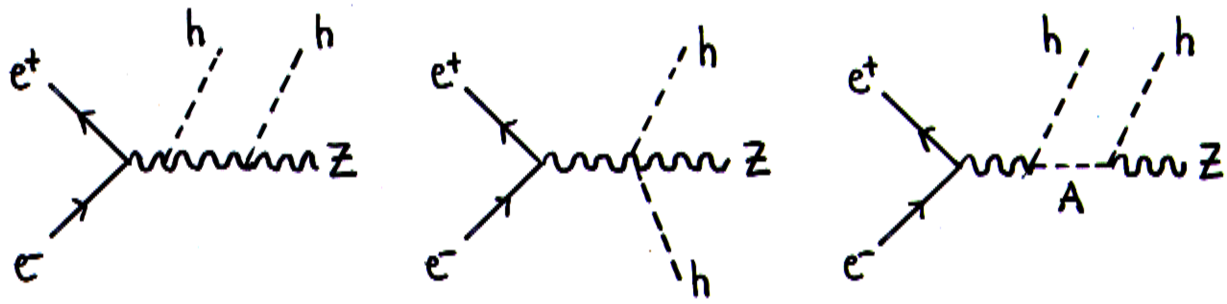
Determination of the trilinear Higgs couplings

Example: hh final state

(i) WW/ZZ fusion

(ii) double Higgs-strahlung $e^+e^- \to Zhh$:





$$\frac{d\sigma(e^+e^-\to Zhh)}{dx_1\,dx_2} = \frac{G_F^3 M_Z^6 (v_e^2+a_e^2)}{384\sqrt{2}\pi^3 s}\,\frac{1}{(1-\mu_Z)^2}\left\{\frac{M_Z^2[(y_1+y_2)^2+8\mu_Z]}{4s} * \right.$$

$$\left[\frac{\sin(\beta-\alpha)}{y_3+\mu_Z-\mu_h}\,\lambda_{hhh} + \frac{\cos(\beta-\alpha)}{y_3+\mu_Z-\mu_H}\,\lambda_{Hhh}\right]^2$$

$$+ \text{ radiation contributions}$$

$$\left. + \text{ interference terms} \right\}$$

sensitive to λ_{hhh} and λ_{Hhh}

(iii) triple Higgs production $e^+e^- \to Ahh$

Trilinear Higgs self-couplings in double and triple Higgs production

λ	double Higgs production				triple Higgs production			
	Zhh	ZHh	ZHH	ZAA	Ahh	AHh	AHH	AAA
hhh	x				x			
Hhh	x	x			x	x		
HHh		x	x			x	x	
HHH			x				x	
hAA				x	x	x		x
HAA				x		x	x	x

- combination of couplings in Higgs-strahlung isomorphic to WW fusion
- cross sections large enough $\Rightarrow$ system solvable for all λ's up to discrete ambiguities "bottom-up approach"
- in practice not all cross sections large enough $\Rightarrow$ compare the theoretical predictions of the cross sections with experimental results for the accessible channels "top-down approach"
- MSSM: $\lambda(hAA)$, $\lambda(HAA)$ are small $\Rightarrow$ can be left out of the analysis

Sensitivity areas

- sensitivity areas defined in the $[M_A, \tan\beta]$ plane

- sensitivity criteria

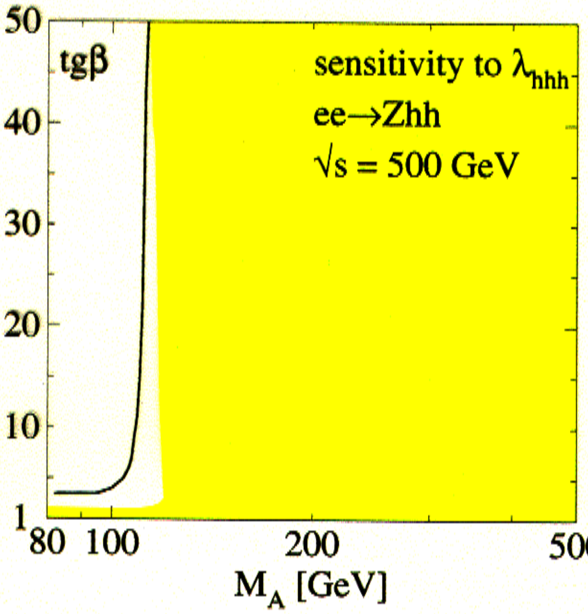
$$\boxed{\begin{array}{l} \text{(i)} \quad \sigma[\lambda] > 0.01\,\text{fb} \\ \text{(ii)} \quad \text{eff}\{\lambda \to 0\} > 2\ \text{st.dev.} \quad \text{for } \int \mathcal{L} = 2\,\text{ab}^{-1} \end{array}}$$

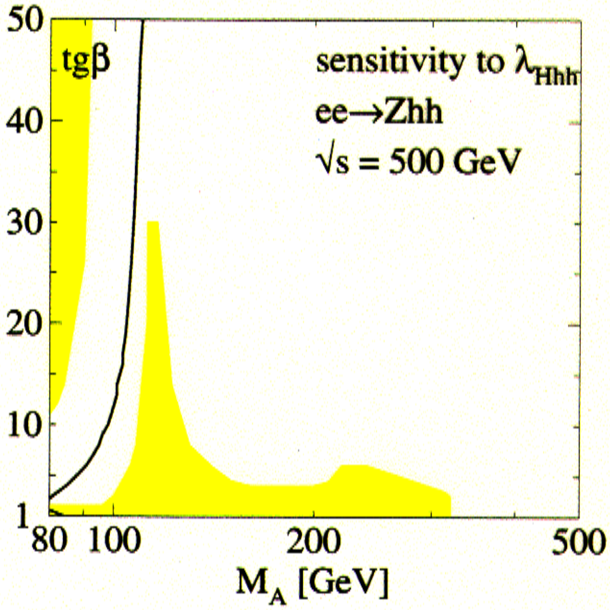
no mixing included

Sensitivity areas for $\lambda_{hhh}, \lambda_{Hhh}$

processes sensitive to λ_{hhh} : Zhh, Ahh

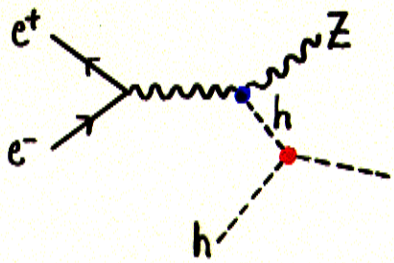
λ_{Hhh} : Zhh, ZHh, Ahh





<u>regions of no sensitivity</u>: couplings $\lambda \sin(\beta-\alpha)$, $\lambda \cos(\beta-\alpha)$ are small

for example:



$\sim \lambda_{hhh} \sin(\beta-\alpha)$

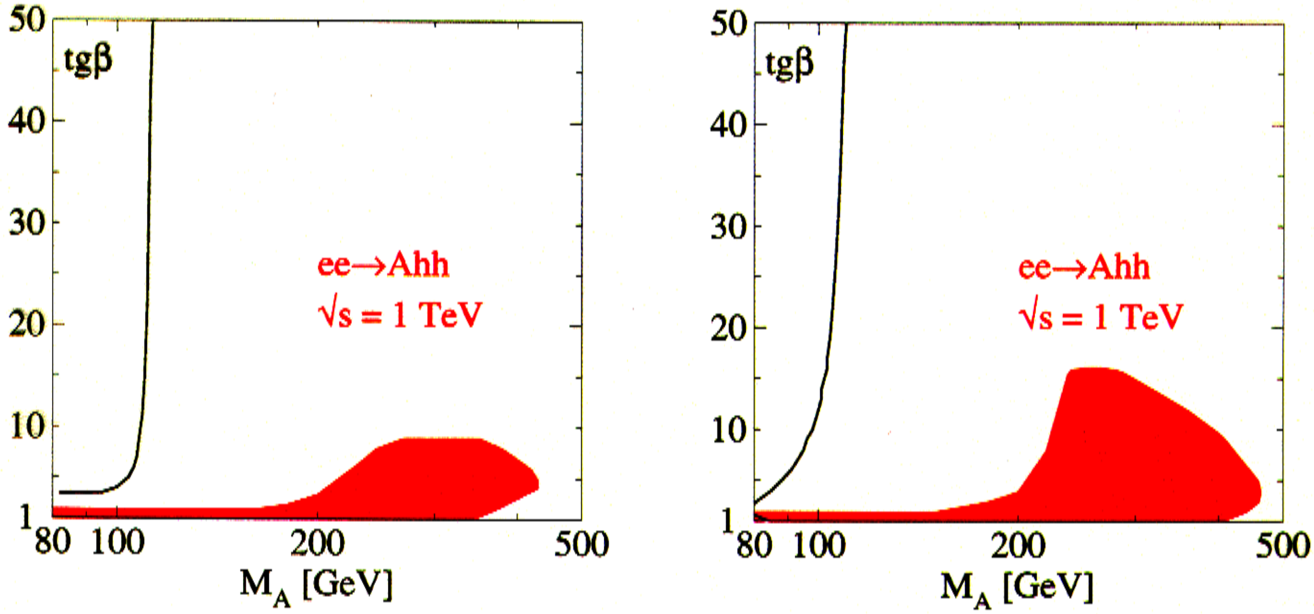
<u>large M_A</u>: sensitivity criteria not fulfilled due to

* phase space effects
* suppression of the H,A propagators for large masses

<u>sensitivity areas</u> for λ_{HHh} in ZHh, ZHH

λ_{HHH} in ZHH

are smaller



tgβ
50
40
30
20
10
1
80 100 200 500
M_A [GeV]
ee→Ahh
√s = 1 TeV
tgβ
50
40
30
20
10
1
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M_A [GeV]
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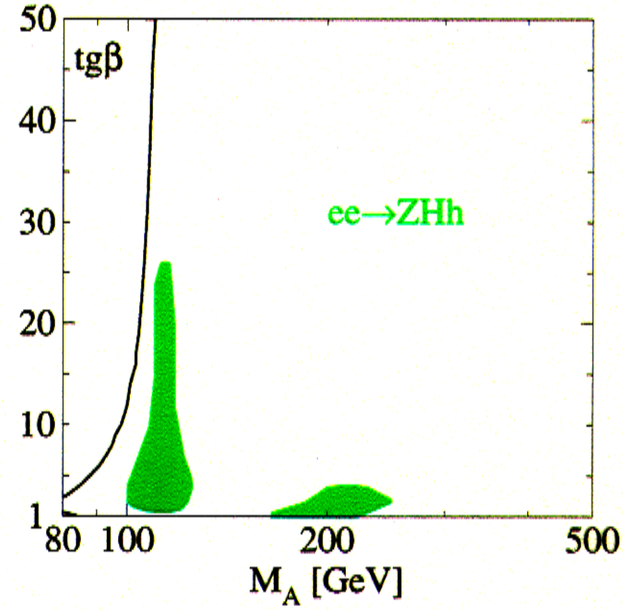
√s = 1 TeV



tgβ
ee→ZHh
50
40
30
20
10
1
80
100
200
500
M_A [GeV]

Conclusions

Standard Model:

* Double Higg-strahlung and WW double Higgs fusion are sensitive to λ_{HHH} in the intermediate Higgs mass region

* For $M_H = 120$ GeV $\sqrt{s} = 500$ GeV is a good choice: sensitivity to λ_{HHH} large (ZHH)

* Cross sections are small $\Rightarrow$ high $\mathcal{L}$ needed

* $\delta\lambda_{HHH}/\lambda_{HHH} \lesssim 20\%$

MSSM trilinear Higgs self-couplings

* The processes Zhh, ZHh, Ahh are sensitive to $\lambda(hhh)$, $\lambda(Hhh)$ in parts of the parameter space $\tan\beta - M_A$

* Sensitivity areas for $\lambda(HHh)$, $\lambda(HHH)$ are smaller.

$\Rightarrow$ Trilinear Higgs self-couplings are accessible at e^+e^- Linear colliders $\leadsto$ First step in order to establish the Higgs mechanism experimentally.