Loop Corrections to MSSM Higgs Production in the WW Fusion channel (LC)

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Kloster Banz, 09/02

based on collaboration with
T. Hahn and *G. Weiglein*

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   and Higgs-strahlung channel
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1. Introduction

Higgs sector of the MSSM:

Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1^0 + i\chi_1^0)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$
$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2^0 + i\chi_2^0)/\sqrt{2} \end{pmatrix}$$

Higgs potential:

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$
$$+ \frac{g'^2 + g^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2$$

Physical states: $h^0, H^0, A^0, H^\pm$

Goldstones: $G^0, G^\pm$

Input parameters:

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2 (\tan\beta + \cot\beta)$$

Tree-level predictions:

$$m^2_{H,h} = \frac{1}{2}\left[M_A^2 + M_Z^2 \pm \sqrt{(M_A^2+M_Z^2)^2 - 4M_Z^2 M_A^2 \cos^2 2\beta}\right]$$

$$\Rightarrow m_h \le M_Z \;, \qquad M_A \approx m_H \approx m_{H^\pm}$$

$$M^2_\Phi = \begin{pmatrix} m^2_{\phi_1} & m^2_{\phi_1\phi_2} \\ m^2_{\phi_1\phi_2} & m^2_{\phi_2} \end{pmatrix} \xrightarrow{\alpha} \begin{pmatrix} m^2_H & 0 \\ 0 & m^2_h \end{pmatrix}$$

Two-loop predictions:

$\Rightarrow M_h \lesssim 135$ GeV ($m_t = 175$ GeV$, M_{\mathrm{SUSY}} \lesssim 1$ TeV)
[S.H., W. Hollik, G. Weiglein '02]

$$M_A \approx M_H \approx M_{H^\pm}$$

$$M^2_\Phi - \begin{pmatrix} \hat\Sigma_{11}(0) & \hat\Sigma_{12}(0) \\ \hat\Sigma_{12}(0) & \hat\Sigma_{22}(0) \end{pmatrix} \xrightarrow{\alpha_{\mathrm{eff}}} \begin{pmatrix} M_H^{2,\alpha_{\mathrm{eff}}} & 0 \\ 0 & M_h^{2,\alpha_{\mathrm{eff}}} \end{pmatrix} \approx \begin{pmatrix} M^2_H & 0 \\ 0 & M^2_h \end{pmatrix}$$

α_{eff} incorporates leading corrections (Higgs prop.)

$$M_A \gtrsim 200 \text{ GeV} \;\Rightarrow\; \sin^2(\beta - \alpha_{\mathrm{eff}}) \approx 1$$
$$\cos^2(\beta - \alpha_{\mathrm{eff}}) \approx 0$$

Dominant corrections in the MSSM Higgs sector from $t - \tilde{t}$-sector :

Yukawa couplings: $\frac{e\, y_t}{2 s_w \sin\beta}$, $\frac{e\, y_t^2\, M_W}{s_w \sin\beta}$, ...

$$\Delta m_h^2 \;\sim\; \frac{m_t^4}{M_W^2 \sin^2\beta} \log\left(\frac{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}{m_t^4}\right)$$

$$\approx\; \frac{m_t^4}{M_W^2 \sin^2\beta} \log\left(\frac{(M_{\mathrm{SUSY}}^2 + m_t^2)^2 - m_t^2 X_t^2}{m_t^4}\right)$$

$\tilde{t}$ -masses:

$$(\tilde{t}_L, \tilde{t}_R) \begin{pmatrix} M_{\mathrm{SUSY}}^2 + m_t^2 + DT_1 & m_t X_t \\ m_t X_t & M_{\mathrm{SUSY}}^2 + m_t^2 + DT_2 \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

M_{SUSY}: soft SUSY-breaking parameter

$X_t = A_t - \mu/\tan\beta$

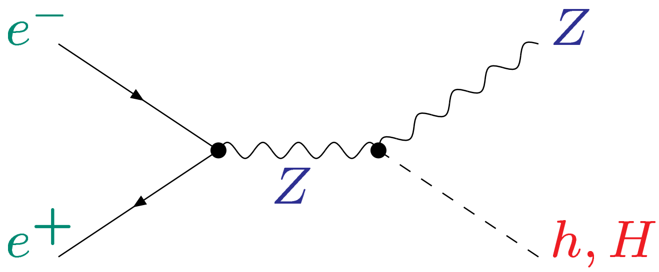
Similar expressions for $\tilde{b}, \tilde{\tau}, \ldots$

Yukawa couplings: $\frac{e\, y_b}{2 s_w \cos\beta}$, $\frac{e\, y_\tau}{2 s_w \cos\beta}$, ...

$\Rightarrow$ non-negligible contributions for large $\tan\beta$

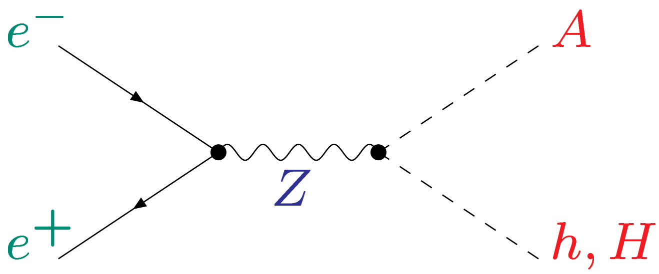
Production of neutral MSSM Higgs bosons at LC:

SM like: $e^+e^- \to Zh, ZH$



$$\sigma_{\mathrm{hZ}} \approx \sin^2(\beta-\alpha)\sigma^{\mathrm{SM}}_{\mathrm{HZ}}$$
$$\sigma_{\mathrm{HZ}} \approx \cos^2(\beta-\alpha)\sigma^{\mathrm{SM}}_{\mathrm{HZ}}$$

Complementary: $e^+e^- \to Ah, AH$



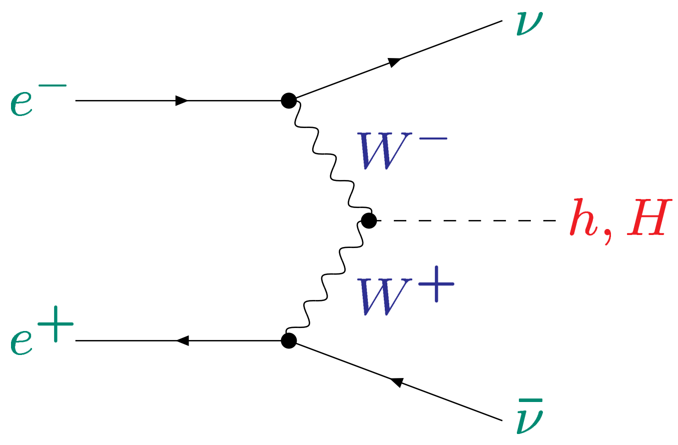
$$\sigma_{\mathrm{hA}} \propto \cos^2(\beta-\alpha)\sigma^{\mathrm{SM}}_{\mathrm{HZ}}$$
$$\sigma_{\mathrm{HA}} \propto \sin^2(\beta-\alpha)\sigma^{\mathrm{SM}}_{\mathrm{HZ}}$$

$\Rightarrow$ large radiative corrections, up to two-loop
see e.g. [*S.H., talk at L&L2000*]

$\Rightarrow$ production of heavy Higgs boson: $M_{H,A} \lesssim \sqrt{s}/2$
(and suppressed with $1/s$)

Better for high energies: WW fusion

$e^+e^- \to \nu\bar{\nu}\ h, H$:



SM Higgs mass reach: $M_H \lesssim 0.8\sqrt{s}$

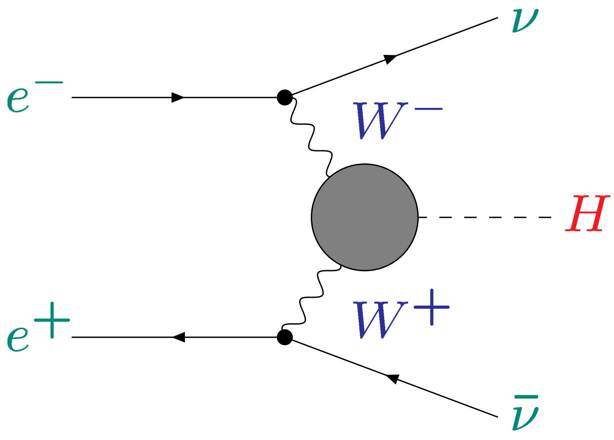
$$\sigma_h \propto \sin^2(\beta-\alpha)\sigma_H^{\mathrm{SM}}$$
$$\sigma_H \propto \cos^2(\beta-\alpha)\sigma_H^{\mathrm{SM}}$$

h: $\tilde{t}/\tilde{b}$ one-loop corrections exist
[*H. Eberl, W. Majerotto, V. Spanos '02*]

H: decouples at tree-level: $\sim \cos^2(\beta-\alpha)$
decouples for leading higher-order corr.:
$\sim \cos^2(\beta-\alpha_{\mathrm{eff}})$

A: no WWA tree-level coupling
one-loop result tiny
[*A. Arhrib '02*]

However, non-decoupling loop effects possible, e.g.:



$\Rightarrow$ evaluate leading corrections for h, H production

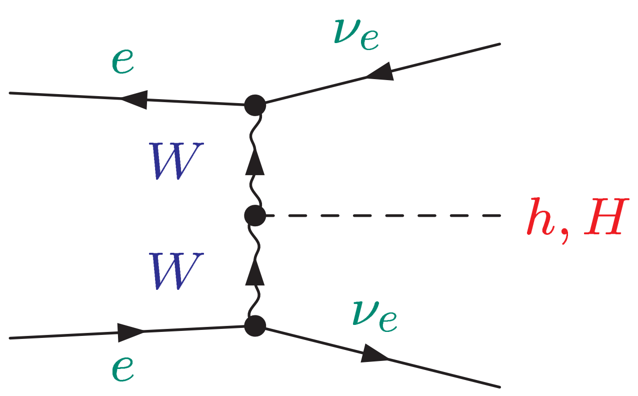
$\Rightarrow$ concentrate on corrections from third familiy fermions and scalar fermions :

$$t, b, \tau, \nu_\tau, \quad \tilde{t}, \tilde{b}, \tilde{\tau}, \tilde{\nu}_\tau$$

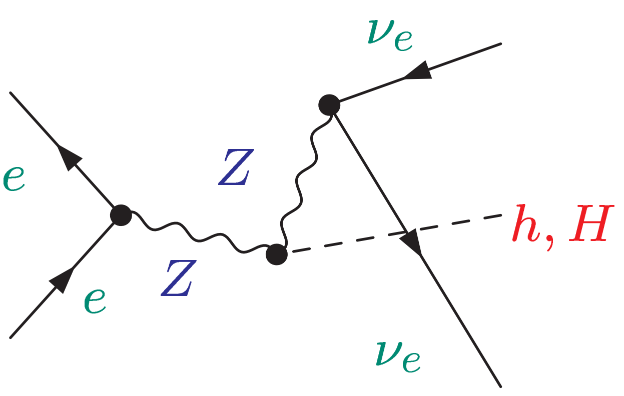
$\Rightarrow$ leading corrections expected: y_t^2, $y_b \tan\beta$, ...

2. Loop corrections to the WW fusion and Higgs-strahlung channel

Main process: WW fusion



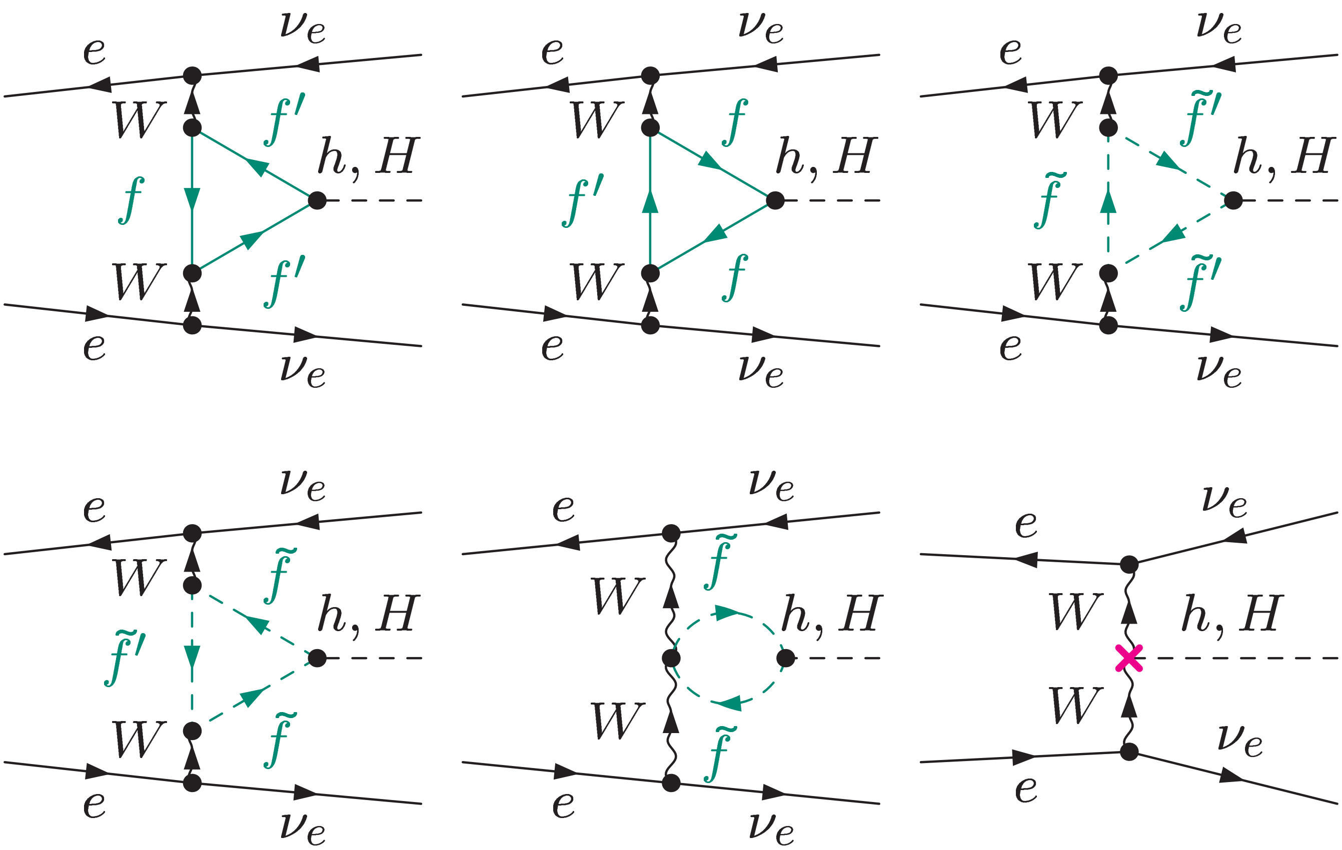
same final state: Higgs-strahlung



$\Rightarrow$ describe corrections to WW fusion

$\Rightarrow$ loop corrections to Higgs-strahlung taken into account in the same way

Vertex corrections:



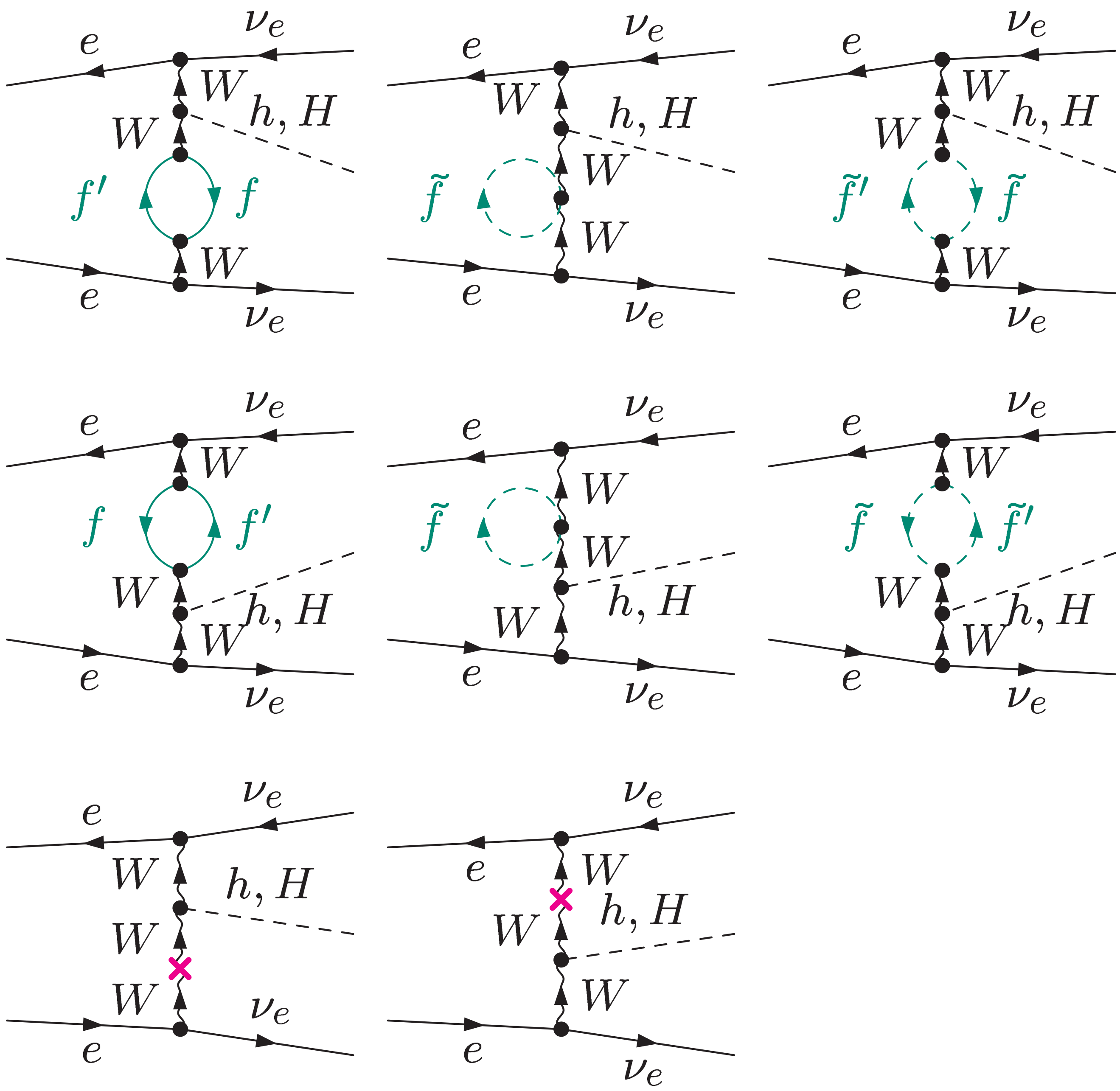
$\rightarrow$ loop diagrams

$\rightarrow$ CT diagrams

WWH CT:

$$\frac{ieM_W}{s_w}\cos(\beta-\alpha) \quad \times \quad \Big[\delta\tilde{Z}_e + \frac{1}{2}\frac{\delta M_W^2}{M_W^2} + \delta Z_W + \frac{\delta s_w}{s_w}$$
$$+\sin\beta\,\cos\beta\,\frac{\sin(\beta-\alpha)}{\cos(\beta-\alpha)}\delta\tan\beta$$
$$+\frac{1}{2}\delta Z_h + \frac{1}{2}\frac{\sin(\beta-\alpha)}{\cos(\beta-\alpha)}\delta Z_{hH}\Big]$$

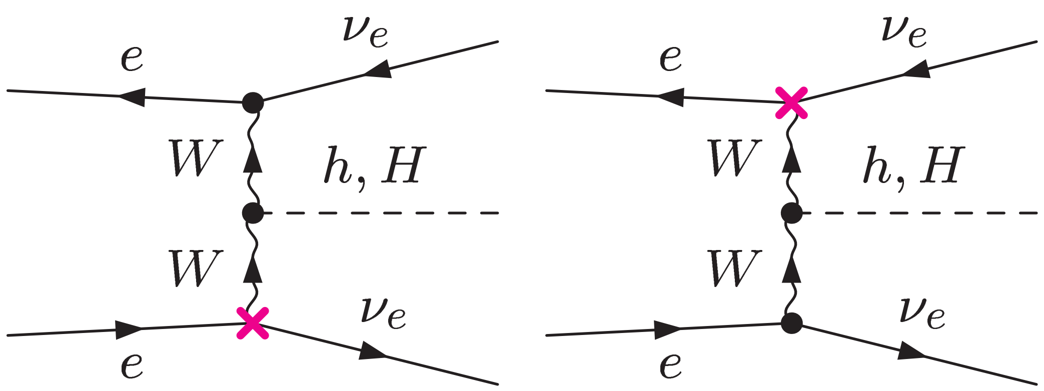
Self-energy corrections:



$\rightarrow$ loop diagrams

$\rightarrow$ CT diagrams

Pure CT contritubions:



Renormalization:

- Electroweak sector: OS

$$\delta M_{W,Z} = \mathrm{Re}\,\Sigma_V(M^2_{W,Z}) \ , \ \ldots$$

- Higgs sector: $\overline{\mathrm{MS}}$ or OS

$$\begin{aligned} \overline{\mathrm{MS}} \ &: \ \delta Z_{h,H} = -\left[\mathrm{Re}\,\Sigma'_{h,H}(m^2_{h,H})\right]^{\mathrm{div}} \ , \ \ldots \\ \mathrm{OS} \ &: \ \delta Z_{h,H} = -\mathrm{Re}\,\Sigma'_{h,H}(m^2_{h,H}) \ , \ \ldots \end{aligned}$$

$\Rightarrow$ comparison of schemes

- $\tan\beta$: $\overline{\mathrm{MS}}$

$$\delta\tan\beta = \frac{1}{2\cos 2\alpha}\left[\mathrm{Re}\,\Sigma'_h(m^2_h) - \mathrm{Re}\,\Sigma'_H(m^2_H)\right]^{\mathrm{div}}$$

Ensure:

On-shell properties of outgoing Higgs boson:

$\to$ finite wave function renormalization

$$\Gamma^{0,\mathrm{WF}}_{WWh} = \sqrt{\hat{Z}_h}\left(\Gamma^{(0)}_h + \frac{1}{2}\hat{Z}_{Hh}\,\Gamma^{(0)}_H\right)$$

$$\Gamma^{0,\mathrm{WF}}_{WWH} = \sqrt{\hat{Z}_H}\left(\Gamma^{(0)}_H + \frac{1}{2}\hat{Z}_{hH}\,\Gamma^{(0)}_h\right)$$

$\Gamma^{(0)}_h, \Gamma^{(0)}_H$: WWh, H vertex, $\sim \sin(\beta - \alpha)$,

$\sim \cos(\beta - \alpha)$

$\hat{Z}_h, \hat{Z}_H$: finite residue of Higgs propagators

$\hat{Z}_{hH}, \hat{Z}_{Hh}$: finite Higgs mixing contribution

large Higgs propagator corrections enter

$\Rightarrow$ all availabel used (up to two-loop)

Limit of external momentum $\to 0$: α_{eff} approx.

$$\Gamma^{0,\mathrm{WF}}_{WWh} \;\widetilde{\longrightarrow}\; \sin(\beta - \alpha_{\mathrm{eff}})$$

$$\Gamma^{0,\mathrm{WF}}_{WWH} \;\widetilde{\longrightarrow}\; \cos(\beta - \alpha_{\mathrm{eff}})$$

Good approximation for h

Bad approximation for H

Outgoing Higgs boson no longer on-shell

Cross section evaluation:

amplitude for $e^+e^- \to \nu_e \bar{\nu}_e \; h, H$

$$\mathcal{M}^{(i)}_{\Phi,e} \quad (\Phi = h, H), \; (i = 0, 1)$$

$i = 0$: lowest order:
WW fusion + Higgs-strahlung
$i = 1$: one-loop corrections to both

lowest order:

$$\mathcal{M}^{(0)}_{\Phi,e} = \mathcal{M}^{\rm tree}_{\Phi,e} + \mathcal{M}^{\rm WF}_{\Phi,e}$$

with

$$e = 2\, s_w \, M_W \left[\frac{\sqrt{2}\, G_F}{1 + \Delta r} \right]^{1/2}$$

to absorb the pure shift in the coupling constant in the lowest order result

amplitude for $e^+e^- \to \nu_f \bar{\nu}_f \; h, H$

$$\mathcal{M}^{(0)}_{\Phi,f} \quad (\Phi = h, H), \; (f = \mu, \tau)$$

(experimentally undistinguishable final state)

$$\begin{aligned} \sigma^1_h \;&\propto\; |\mathcal{M}^{(0)}_{h,e}|^2 + 2\,{\rm Re}\,[(\mathcal{M}^{(0)}_{h,e})^* \, \mathcal{M}^{(1)}_{h,e}] \\ &\quad + |\mathcal{M}^{(0)}_{h,\mu}|^2 + |\mathcal{M}^{(0)}_{h,\tau}|^2 \\ \sigma^1_H \;&\propto\; |\mathcal{M}^{(0)}_{H,e} + \mathcal{M}^{(1)}_{H,e}|^2 + |\mathcal{M}^{(0)}_{H,\mu}|^2 + |\mathcal{M}^{(0)}_{H,\tau}|^2 \end{aligned}$$

Our tools (I):

- Automatic generation of Feynman diagrams and amplitudes: *FeynArts*

  [*J. Küblbeck, A. Denner, M. Böhm '90*]

  [*H. Eck '95*]

  [*T. Hahn '98, '00*]

  $\rightarrow$ MSSM model file complete

  [*T. Hahn, C. Schappacher '01*]

  Only WWh, H CTs had to be added

- Further evaluation with *FormCalc*

  [*T. Hahn, M. Pérez-Victoria '99*]

- Automatic generation of Fortran code, using *LoopTools* for numerical evaluation

  [*T. Hahn, M. Pérez-Victoria '99*]

  $\Rightarrow$ numbers, plots

  For tools and (other) Fortran packages, see

  www.feynarts.de
  www.hep-processes.de

Our tools (II):

Evaluation of the Higgs sector: *FeynHiggs*2.0

[*M. Frank, S.H., W. Hollik, G. Weiglein '02*]

www.feynhiggs.de

$\rightarrow$ automatically linked to *FormCalc* output

*FeynHiggs*2.0 includes:

– evaluation of the Higgs sector of the (c)MSSM:
 * full 1-loop, $q^2 \neq 0$
 * leading/subleading 2-loop
 [*M. Frank, S.H., W. Hollik, G. Weiglein '02*]

– full 1-loop corrections for charged Higgs sector

– New renormalization ($\overline{\text{MS}}$/OS)
 for 1-loop result
 [*M. Frank, S.H., W. Hollik, G. Weiglein '02*]

– subleading non-log $\mathcal{O}\left(\alpha_t^2\right)$ terms
 [*A. Brignole, G. Degrassi, P. Slavich, F. Zwirner '01*]
 [*J. Espinosa, R. Zhang '01*]

– "Δm_b" corrections for Higgs masses
 $\Rightarrow$ leading $\mathcal{O}\left(\alpha_b \alpha_s\right)$ terms included
 [*M. Carena, D. Garcia, U. Nierste, C. Wagner '00*]

3. Numerical examples

Reach of a 1 TeV LC ?

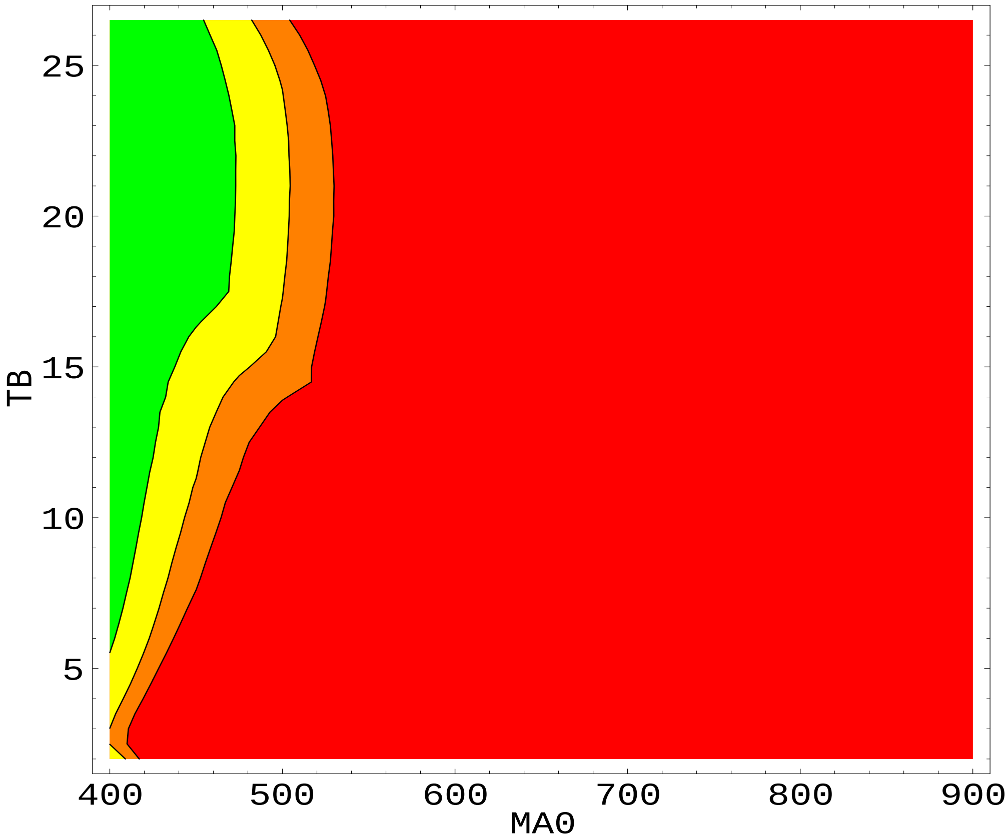
Example parameters:

$m_t = 175$ GeV, $M_{\text{SUSY}} = 300$ GeV, $X_t = 2\,M_{\text{SUSY}}$

$\mu = 1000$ GeV, $M_2 = 200$ GeV, $m_{\tilde{g}} = 0.8 M_{\text{SUSY}}$

$\Rightarrow$ Scan over $M_A - \tan\beta$-plane

tree-level:

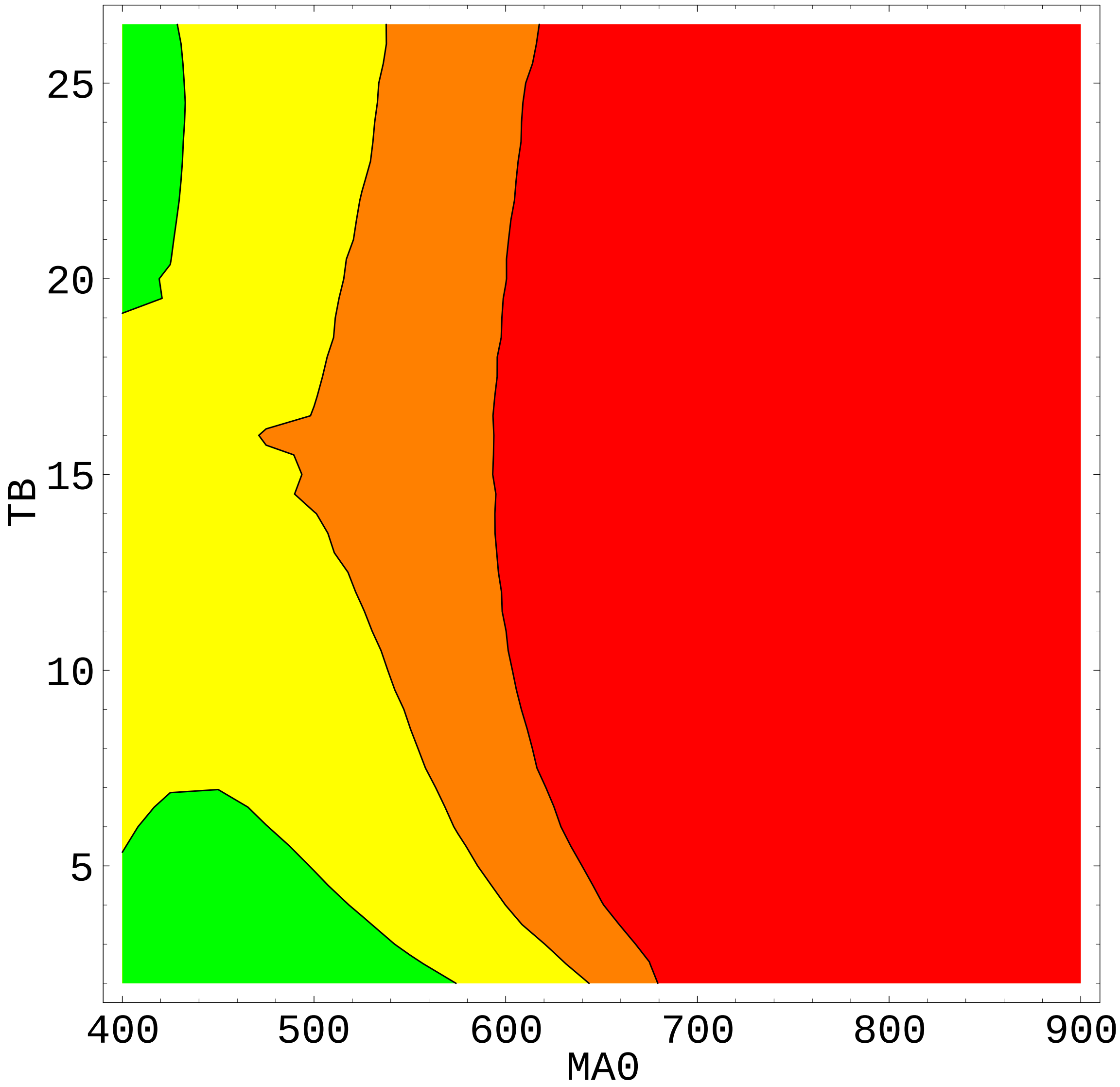


$\sigma_H^0 < 0.01$ fb , $0.01 - 0.02$ fb
$0.02 - 0.05$ fb , $\sigma_H^0 > 0.05$ fb

one-loop corrected:

$m_t = 175$ GeV, $M_{\text{SUSY}} = 300$ GeV, $X_t = 2\, M_{\text{SUSY}}$

$\mu = 1000$ GeV, $M_2 = 200$ GeV, $m_{\tilde{g}} = 0.8 M_{\text{SUSY}}$



$\sigma_H^1 < 0.01\,\text{fb}$, $0.01 - 0.02\,\text{fb}$

$0.02 - 0.05\,\text{fb}$, $\sigma_H^1 > 0.05\,\text{fb}$

$\Rightarrow$ Enlarged reach for LC
(for favorable parameters)

4. Conclusinos

- WW fusion is an interesting process also for heavy Higgs boson production at the LC

- Loop corrections to $e^+e^- \to \nu\bar{\nu}\, h, H$
  - Leading corrections from fermions and sfermions of the third family
  - vertex, self-energy and CT contributions
  - same for Higgs-strahlung contribution

- Ensure on-shell properties for outgoing Higgs
  - small numerical effects for h
  - large numerical effects for H

- Tools:
  - *FeynArts* (complete MSSM model file)
  - *FormCalc*, *LoopTools*
  - *FeynHiggs* (new version 2.0)

- Results for H production
  Enlarged reach (for favorable parameters)