Higgs production and decay in the MSSM: status and perspectives

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

Input parameters:

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

Diagonalization of tree-level mass matrix

$\Rightarrow m_h$, m_H, mixing angle α

Tree-level result for $m_{\rm h}$, $m_{\rm H}$:

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

$\Rightarrow m_{\rm h} \leq M_{\rm Z}$ at tree level

Large radiative corrections:

Yukawa couplings: $\frac{e\, m_{\rm t}}{2 M_{\rm W} s_{\rm W}}$, $\frac{e\, m_{\rm t}^2}{M_{\rm W} s_{\rm W}}$, ...

$\Rightarrow$ Dominant one-loop corrections: $G_\mu m_{\rm t}^4 \ln\left(\frac{m_{\tilde{\rm t}_1} m_{\tilde{\rm t}_2}}{m_{\rm t}^2}\right)$

$\tilde{\rm t}$ sector:

$$M^2_{\tilde{\rm t}} = \begin{pmatrix} M_{\tilde{t}_L}^2 + m_{\rm t}^2 + DT_1 & m_{\rm t} X_{\rm t} \\ m_{\rm t} X_{\rm t} & M_{\tilde{t}_R}^2 + m_{\rm t}^2 + DT_2 \end{pmatrix}$$

$X_{\rm t} = A_{\rm t} - \mu \cot\beta$; large mixing possible

Input parameters: $M_{\tilde{t}_L}$, $M_{\tilde{t}_R}$, $X_{\rm t}$

often used: $M_{\rm SUSY} \equiv M_{\tilde{t}_L} = M_{\tilde{t}_R}$, $M_{\rm S}^2 \equiv M_{\rm SUSY}^2 + m_{\rm t}^2$

$\Rightarrow$ Physical parameters: $m_{\tilde{\rm t}_1}$, $m_{\tilde{\rm t}_2}$, $\theta_{\tilde{\rm t}}$

At LC with $\sqrt{s} = 500$–1000 GeV:

$\Rightarrow$ Need prediction for Higgs production cross sections and branching ratios at 1% level or better

Difficult goal, several possible sources of large corrections/uncertainties:

- Large Yukawa corrections to Higgs masses and mixing angles: $\mathcal{O}(G_\mu m_t^4/M_W^2)$, $\mathcal{O}(G_\mu \alpha_s m_t^4/M_W^2)$
- Large corrections in b–$\tilde{\text{b}}$ sector for large $\tan\beta$, μ
- Large electroweak contributions from vertex and box diagrams
- Large effects from complex phases
- Uncertainties from experimental error of m_t

...

Electroweak corrections

At LEP1:

Z-boson resonance $\Rightarrow$ description in terms of universal corrections ($\Delta\alpha$, $\Delta\rho$, ...), effective couplings (propagator-type corrections)

$\Rightarrow$ Born-type structure

Genuine box contributions negligible

Partially still true at LEP2 energies

At LC with $\sqrt{s} = 500$–1000 GeV:

Propagator-type corrections no longer dominant

$\Rightarrow$ potentially large box corrections,

Sudakov-logs, ...

Finite width effects:

$\Rightarrow$ need to include non-resonant contributions

$\Rightarrow$ $2 \to 4$, $2 \to 6$, ... processes

2. Higgs mass and $\alpha_{\rm eff}$

Present status of $m_{\rm h}$ prediction in the MSSM:

Previously used for LEP analyses:

RG improved one-loop effective potential result

$\Rightarrow$ Leading logs at two-loop level

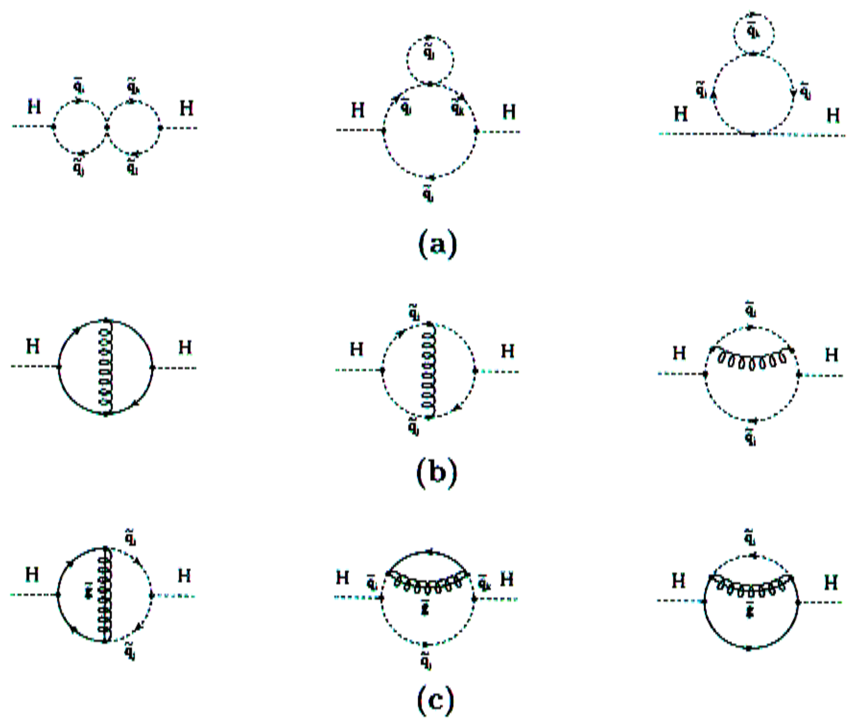
program: *subhpole*

[*M. Carena, M. Quirós, C. Wagner '95*]

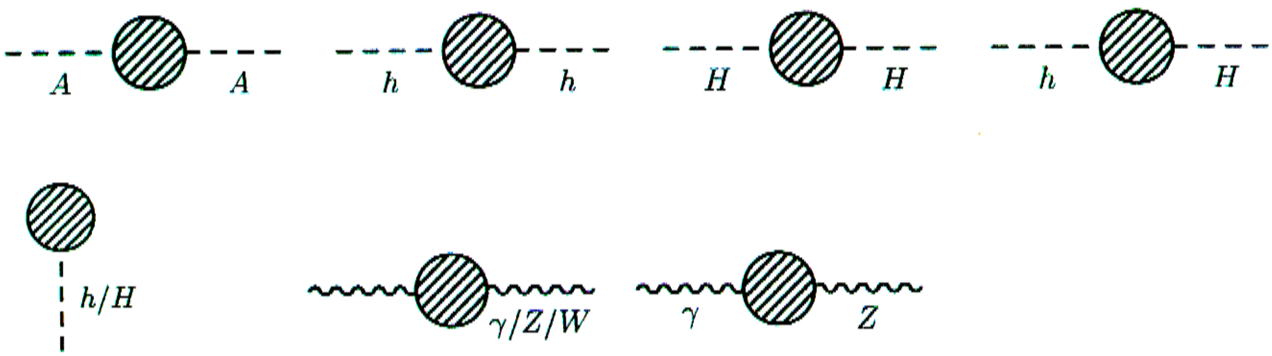
New result:

Feynman-diagrammatic two-loop result

Dominant two-loop corrections:



Explicit Feynman-diagrammatic calculation,
Higgs mass: pole of propagator



⇒ solution of

$$\left[q^2 - m_{\rm h}^2 + \hat{\Sigma}_{\rm hh}(q^2)\right]\left[q^2 - m_{\rm H}^2 + \hat{\Sigma}_{\rm HH}(q^2)\right] - \left(\hat{\Sigma}_{\rm hH}(q^2)\right)^2 = 0$$

Complete one-loop + dominant two-loop corrections

program: *FeynHiggs*

[*S. Heinemeyer, W. Hollik, G. W. '98, '00*]

`http://www.feynhiggs.de`

Approximate calculation of masses and mixing angle:

Mass matrix (in $\phi_1 - \phi_2$ basis):

$$M^2_{\text{Higgs}} = \begin{pmatrix} m^2_{\phi_1} - \hat{\Sigma}_{\phi_1}(0) & m^2_{\phi_1\phi_2} - \hat{\Sigma}_{\phi_1\phi_2}(0) \\ m^2_{\phi_1\phi_2} - \hat{\Sigma}_{\phi_1\phi_2}(0) & m^2_{\phi_2} - \hat{\Sigma}_{\phi_2}(0) \end{pmatrix}$$

$$\Big\Downarrow \leftarrow \text{ Diag. }, \alpha_{\text{eff}}$$

$$\begin{pmatrix} m^2_{\text{H}} & 0 \\ 0 & m^2_{\text{h}} \end{pmatrix}$$

$\Rightarrow$ m_{h}, m_{H}, effective mixing angle α_{eff}

α_{eff} approximation for production and decay:

tree-level formulas, $\alpha_{\text{tree}} \longrightarrow \alpha_{\text{eff}}$

$\Rightarrow$ dominant $\mathcal{O}(G_\mu m_{\text{t}}^4/M_{\text{W}}^2)$, $\mathcal{O}(G_\mu \alpha_{\text{s}} m_{\text{t}}^4/M_{\text{W}}^2)$
Yukawa corrections

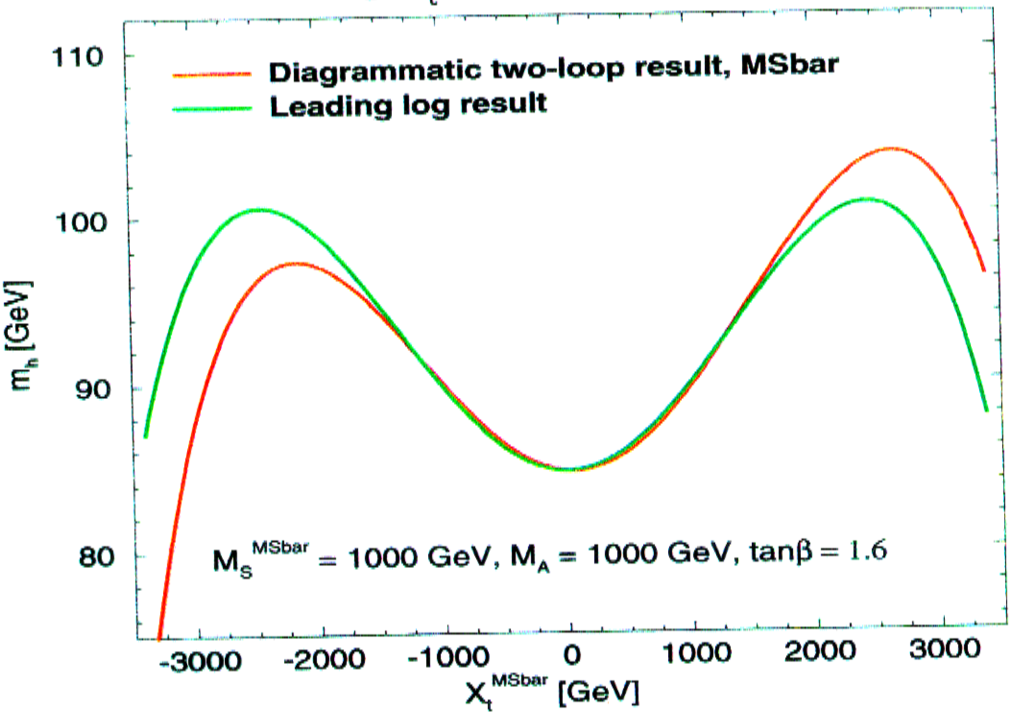
neglected: momentum dependence,
vertex and box corrections, ...

Comparison of Feynman-diagrammatic two-loop result for $m_{\rm h}$ with RG result:

– Agreement in leading logs at two-loop order
[*M. Carena, H. Haber, S. Heinemeyer, W. Hollik, C. Wagner, G. W. '00*]

– Diagrammatic result contains new genuine two-loop contributions:

Leading m_t^4 approximation at $\mathcal{O}(\alpha\alpha_s)$



$\Rightarrow$ Sizable numerical effect

result is asymmetric in $\pm X_t$

Increase in $m_{\rm h}^{\rm max}$ by up to 4 GeV

Non-leading one-loop terms, variation of $m_{\tilde{g}}$, ...
$\Rightarrow$ further deviations

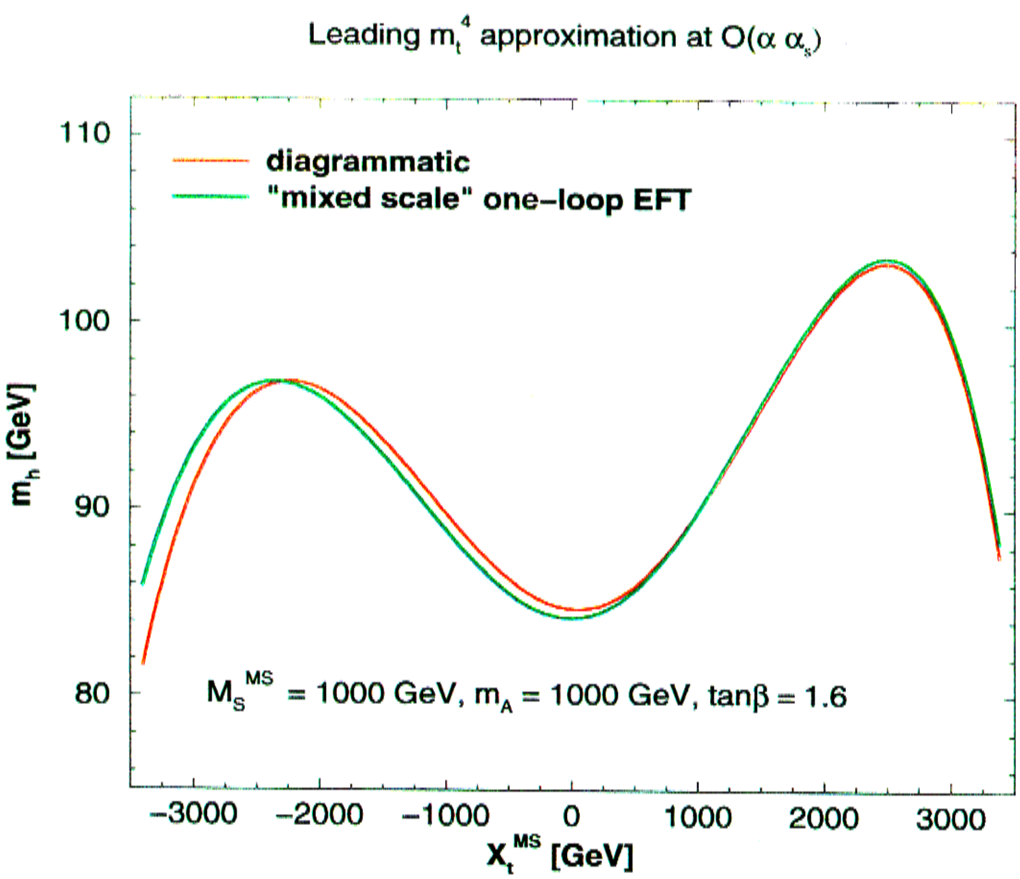
New genuine two-loop terms confirmed by independent calculation

[*R. Zhang '99*] [*J. Espinosa, R. Zhang '00*]

Parameterization of one-loop result with $m_t(\mu)$, mixing contribution: $m_t(M_S)$, includes SUSY corr.

⇒ Dominant numerical effect of two-loop terms can be absorbed into effective one-loop result

[*M. Carena, H. Haber, S. Heinemeyer, W. Hollik, C. Wagner, G. W. '00*]



Remaining theoretical uncertainties in prediction for m_h:

– From unknown higher-order corrections

– From uncertainties in input parameters

$m_t, \ldots, M_A, \tan\beta, m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{g}}, \ldots$

Present situation:

Higher-order corrections: $\Delta m_h^{\text{theo}} \approx 3$ GeV

Input parameters: $\Delta m_t \approx 5$ GeV $\Rightarrow$ $\Delta m_h^{\text{theo}} \approx 5$ GeV

At LC:

$\Delta m_t = 0.2$ GeV $\Rightarrow$ $\Delta m_h^{\text{theo}} = 0.2$ GeV

$\Delta m_h^{\text{exp}} = 0.05$ GeV

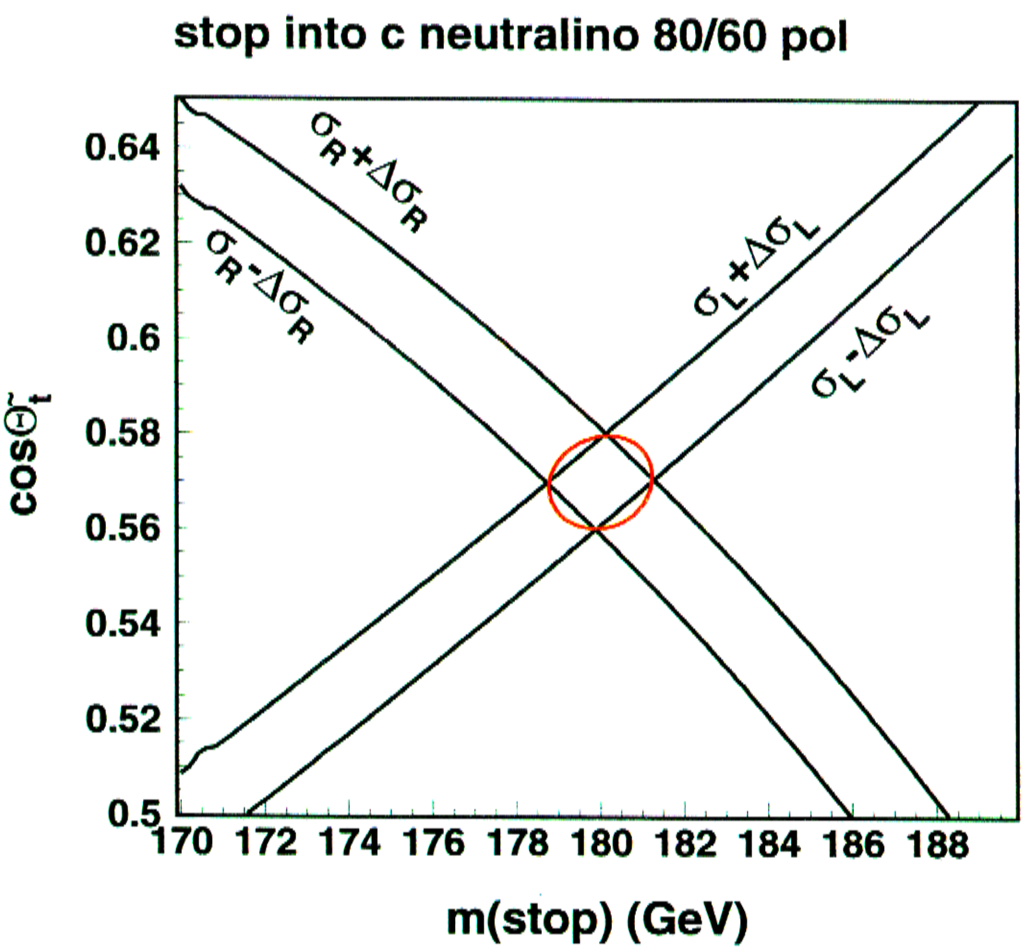
$\Rightarrow$ High-precision measurement of m_t important!

The Higgs mass as a precision observable

Combination of direct and indirect information on $\tilde{t}$ sector parameters:

$e^+e^- \to \tilde{t}_1\tilde{t}_1$ at high luminosity LC:

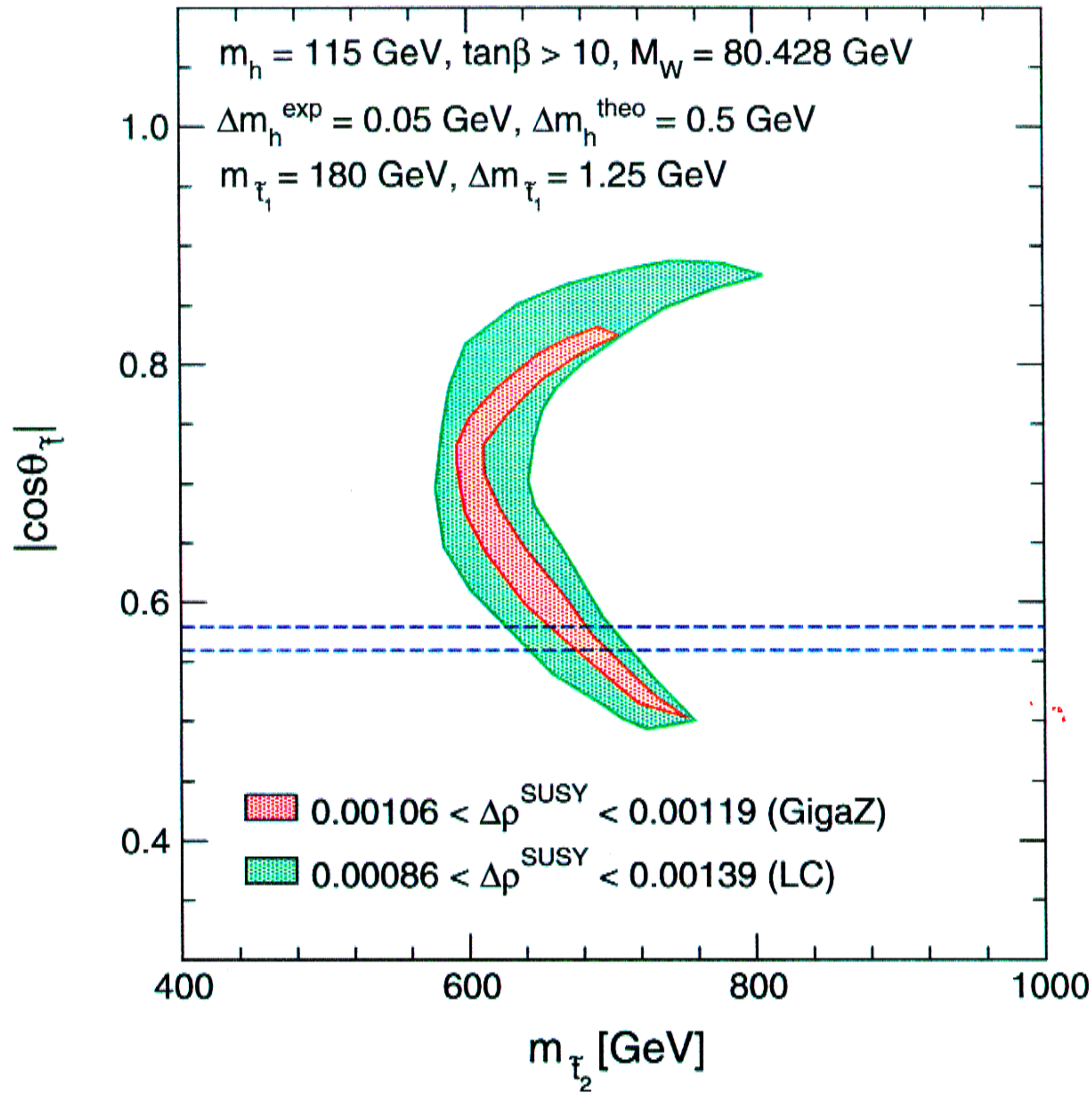
80% pol. e^- beam, 60% pol. e^+ beam,
$\sqrt{s} = 500$ GeV, $\mathcal{L} = 500$ fb^{-1}
[R. Keränen, H. Nowak, A. Sopczak '00]



$\Rightarrow$ Precise determination of $m_{\tilde{t}_1}$, $\theta_{\tilde{t}}$

Indirect constraints on $m_{\tilde{t}_2}$, $\theta_{\tilde{t}}$ from precise measurement of m_h, M_W, $\sin^2\theta_{\rm eff}$ at LC/GigaZ:
[*S. Heinemeyer, G.W. '00*]

Allowed region in $m_{\tilde{t}_2}$–$\theta_{\tilde{t}}$ plane:

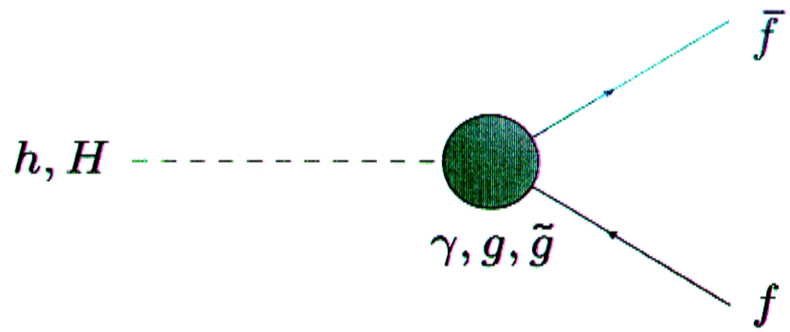


$\Rightarrow$ Direct/indirect information is complementary

Indirect determination of $m_{\tilde{t}_2}$ with high precision

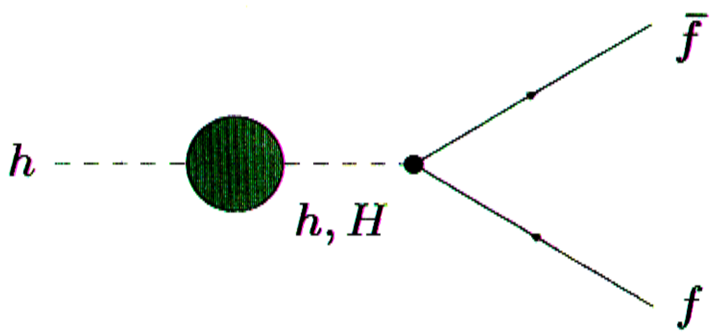
3. Higgs decays into fermions

One-loop QED and QCD $(g + \tilde{g})$ corrections:



[A. Dabelstein '95]

Leading Yukawa corrections: $\mathcal{O}(\alpha)$, $\mathcal{O}(\alpha\alpha_s)$



$\Rightarrow$ Incorporation of dominant FD 2-loop contrib.

$$A(h \to f\bar{f}) = \sqrt{Z_h}\left(\Gamma_h - \frac{\hat{\Sigma}_{hH}(m_h^2)}{m_h^2 - m_H^2 + \hat{\Sigma}_{HH}(m_h^2)}\Gamma_H\right)$$

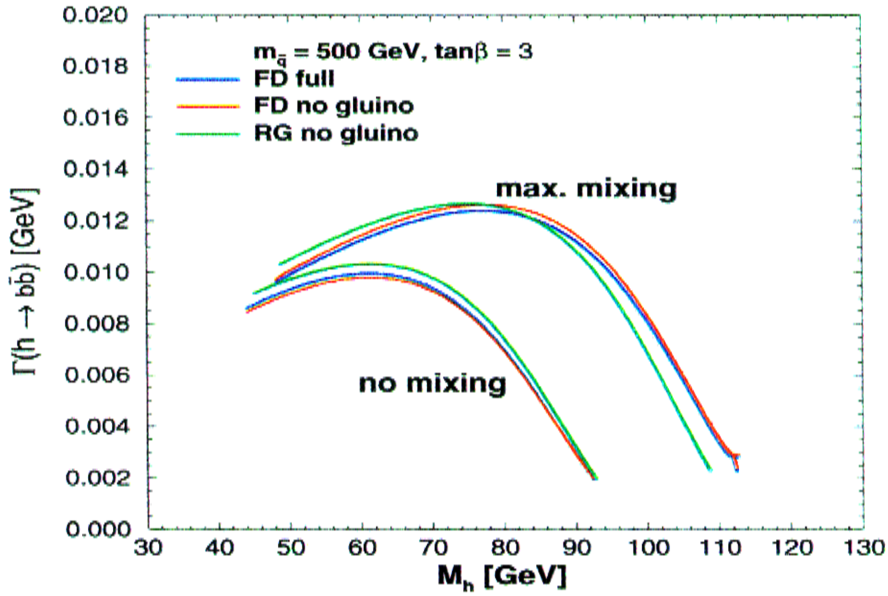
For $\hat{\Sigma}(q^2) \approx \hat{\Sigma}(0)$:

$\Rightarrow$ $A(h \to f\bar{f}) \approx C_f \sin\alpha_{\text{eff}}$, $C_f \sim \frac{1}{\cos\beta}$, $f = b, \tau, \ldots$

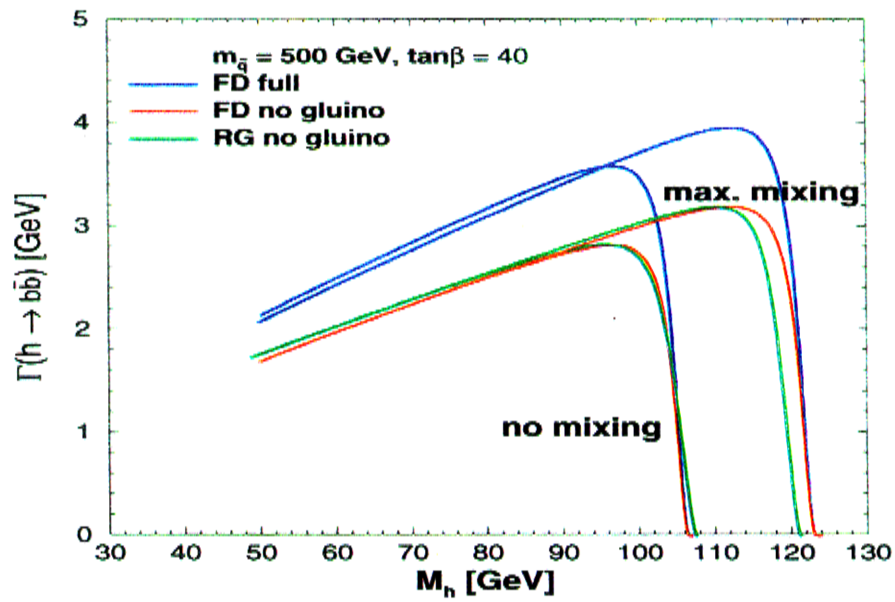
Comparison between FD result (*FeynHiggs*) and RG calculation (HDECAY):

[*S. Heinemeyer, W. Hollik, G. W. '00*]

$h \to b\bar{b}$, $\tan\beta = 3$:



$h \to b\bar{b}$, $\tan\beta = 40$:



$\Rightarrow$ Deviations up to $10 - 15\%$ (main effect: $\overset{m_h,}{\alpha_{\text{eff}}}$)

Gluino contributions important

Effective $hf\bar{f}$ coupling can go to zero for large $\hat{\Sigma}_{\mathrm{hH}}$

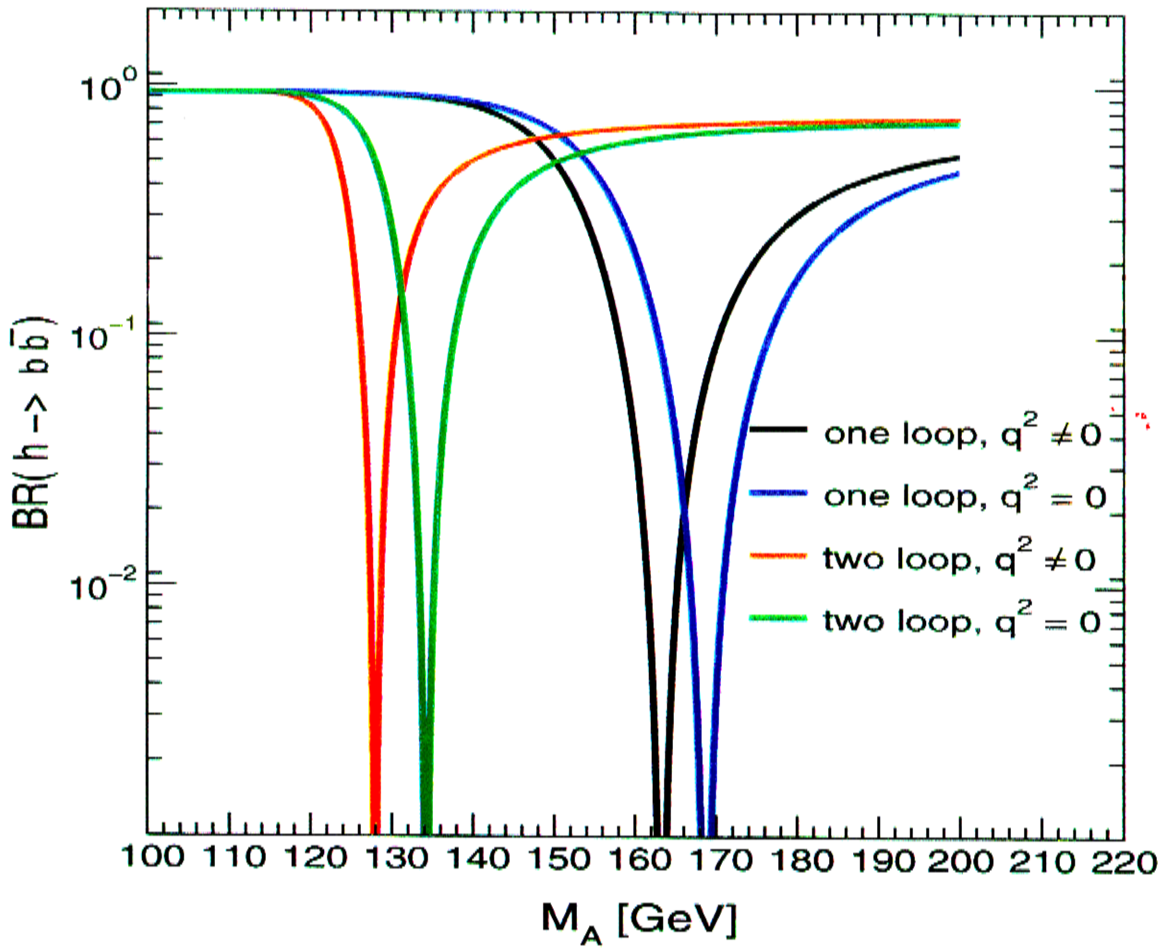
[*W. Loinaz, J. Wells '98*]

[*M. Carena, S. Mrenna, C. Wagner '99*]

$\Rightarrow$ "Pathological regions"

$\Rightarrow$ Suppression of $\mathrm{BR}(h \to b\bar{b})$, $\mathrm{BR}(h \to \tau\tau)$, ...

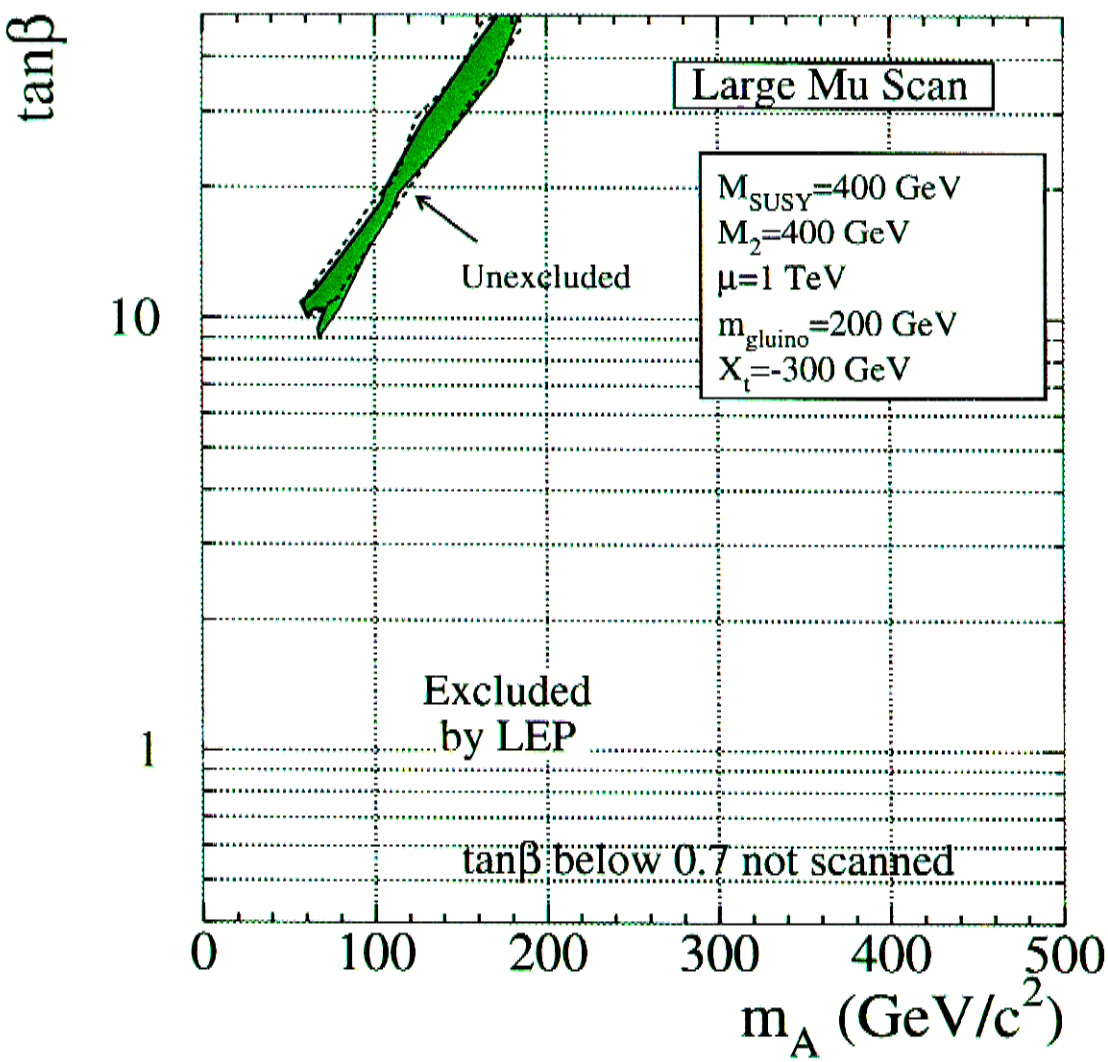
Suppression of $\mathrm{BR}(h \to f\bar{f})$:
$M_{\mathrm{SUSY}} = X_{\mathrm{t}} = 500$ GeV, $\tan\beta = 25$



[*S. Heinemeyer, W. Hollik, G. W. '00*]

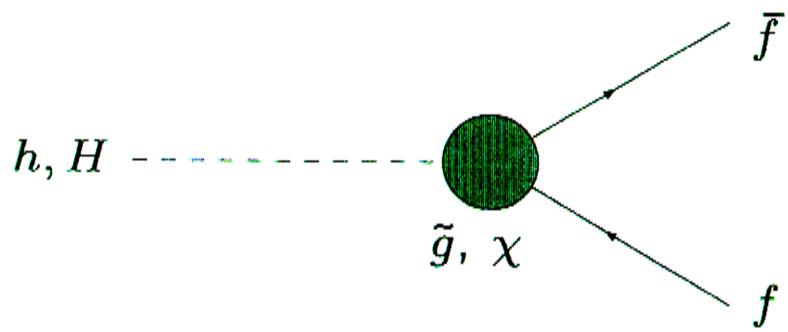
Unexcluded region in large μ scenario:

[*LEP Higgs Working Group '00*]



$hq\bar{q}$ coupling:

large gluino/higgsino corrections possible for large $\tan\beta$



Gluino vertex corrections to $h \to q\bar{q}$:

$\Rightarrow$ ratio $\Gamma(h \to \tau^+\tau^-)/\Gamma(h \to b\bar{b})$ can significantly differ from SM value

Resummation of leading corrections for large $\tan\beta$ to all orders

[*M. Carena, S. Mrenna, C. Wagner '99*]

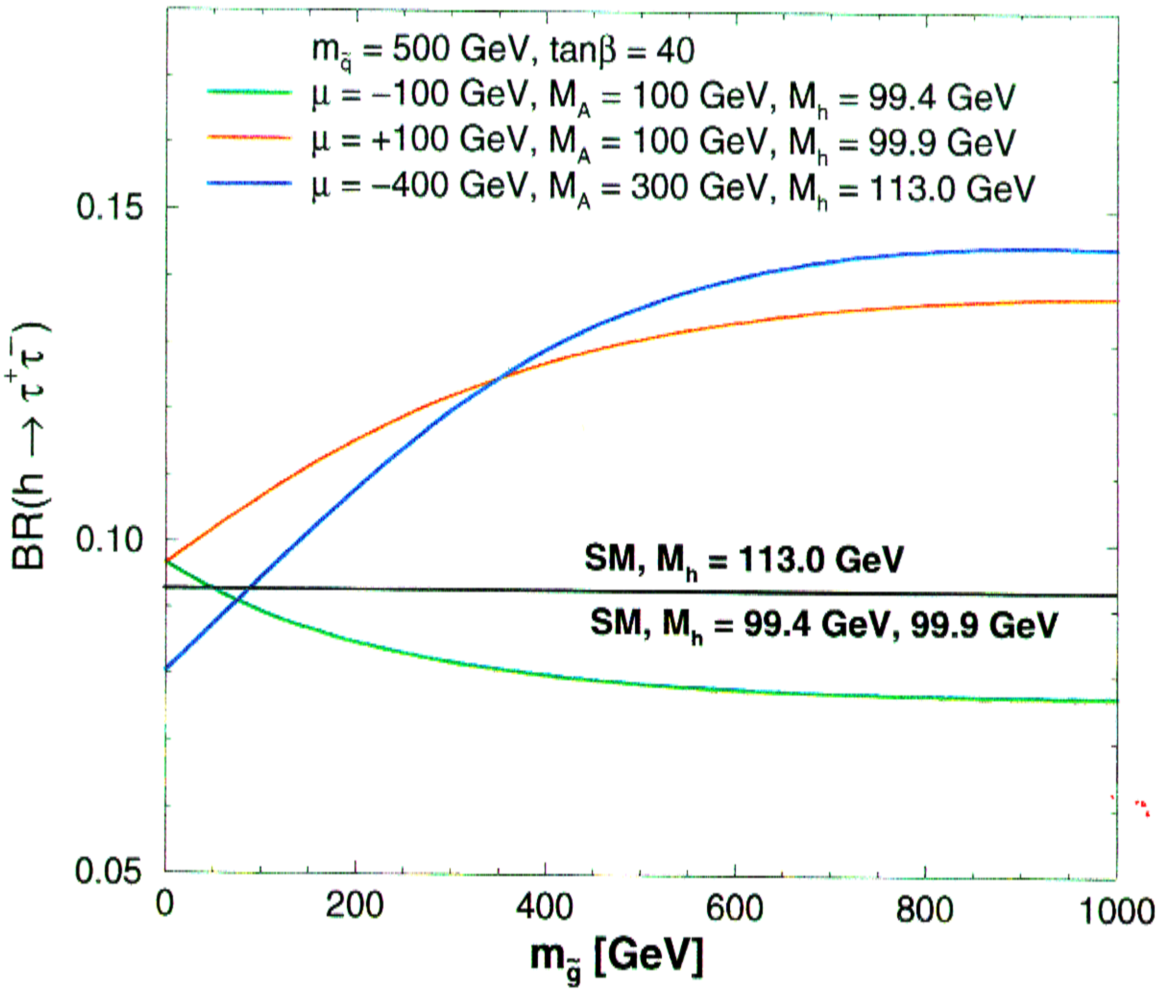
[*M. Carena, D. Garcia, U. Nierste, C. Wagner '00*]

Absorption of the dominant $\mathcal{O}(\alpha_s)$ corrections into effective tree-level couplings

[*H. Eberl, K. Hidaka, S. Kraml, W. Majerotto, Y. Yamada '99*]

Effect of gluino vertex corrections to $h \to q\bar{q}$ on $\mathrm{BR}(h \to \tau^+\tau^-)$:

[S. Heinemeyer, W. Hollik, G. W. '00]

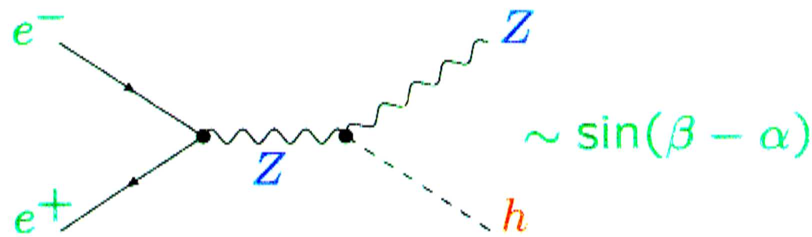


⇒ Large effects possible for large $\tan\beta$,

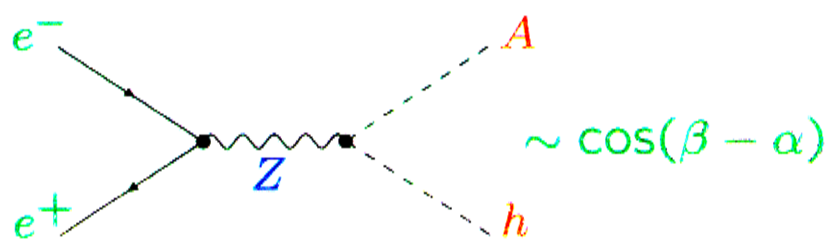
even for relatively large M_A

4. Higgs production: $e^+e^- \to hZ, hA$

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



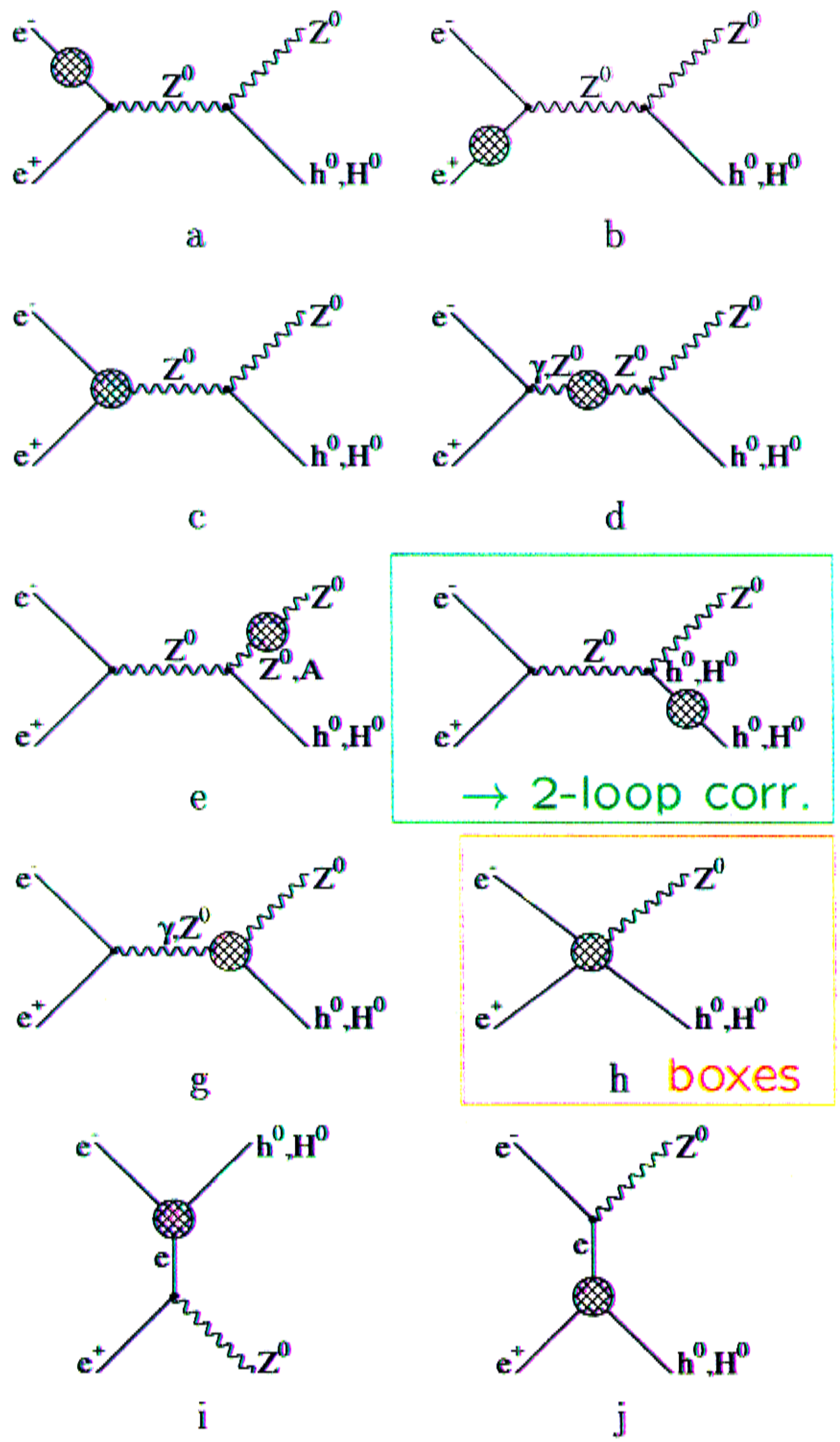
Complementary: $e^+e^- \to hA$



– Complete Feynman-diagrammatic
 one-loop result in on-shell scheme
 $\to$ vertex and box corrections included
 $\to$ full momentum dependence included
 [*V. Driesen, W. Hollik, J. Rosiek '95*]

– Dominant two-loop contributions of $\mathcal{O}(G_\mu \alpha_s m_t^4)$
 incorporation via propagator corrections
 [*S. Heinemeyer, W. Hollik, J. Rosiek, G. W. '00*]

Diagrams for $e^+e^- \to Zh$:



Comparison of FD and RG result

FD result:

Complete FD one-loop result +
dominant two-loop corrections (*FeynHiggs*)
[S. Heinemeyer, W. Hollik, J. Rosiek, G. W. '00]

RG result:

$m_t(M_S)$ parameterization included (*subhpoledm*)
[M. Carena, M. Quiros, C. Wagner '95]
[M. Carena, H. Haber, S. Heinemeyer, W. Hollik, C. Wagner, G. W. '00]

On-shell $\overline{\mathrm{MS}}$ transition (M_{SUSY}, X_t) included

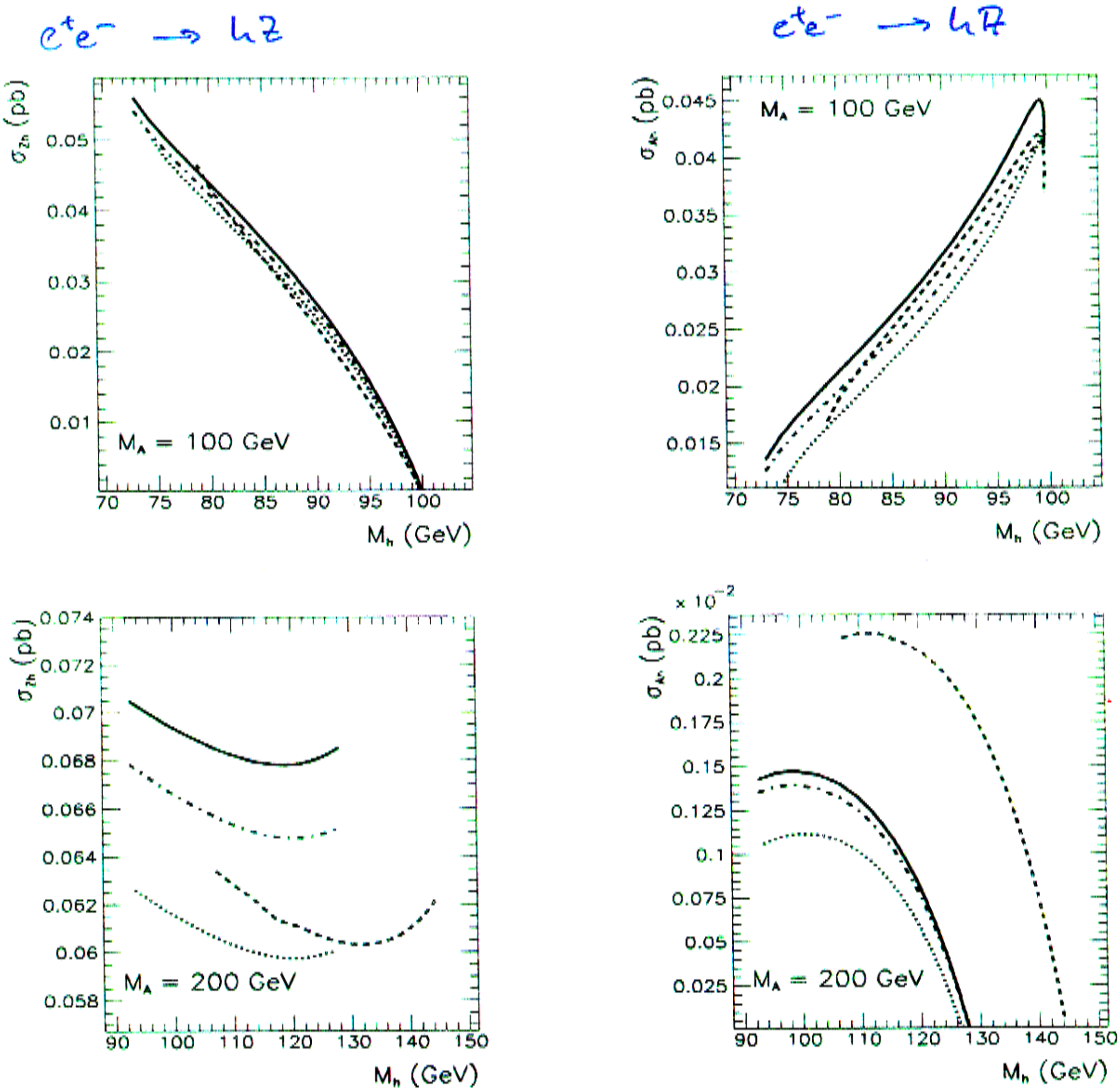
α_{eff} approximation

$e^+e^- \to hZ, hA$, $\sqrt{s} = 500$ GeV, maximal $\tilde{t}$ mixing:

$M_{\tilde{q}} = 1$ TeV, $M_{\tilde{l}} = 300$ GeV, $M_2 = \mu = 200$ GeV

solid: FD 2L (with box), dot-dashed: FD 2L (no box)

dashed: FD 1L, dotted: RG 2L



Diff. FD 2L − RG result: $\sigma_{Zh} \approx$ 10–15%, $\sigma_{Ah} \approx$ 25%

Effects of box contributions:

5–10%, large effects in differential cross sections

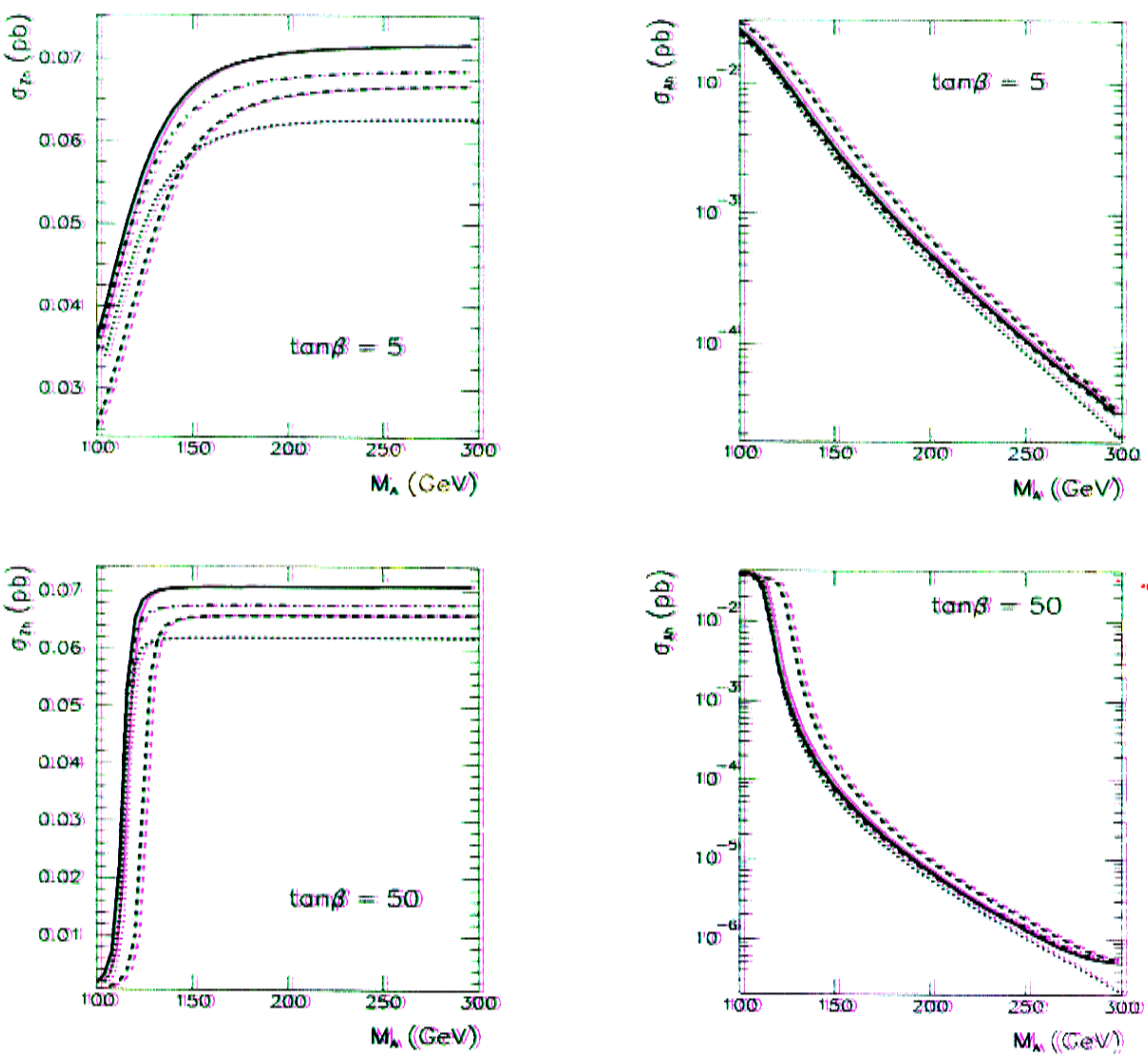
$e^+e^- \to hZ, hA$, $\tan\beta = 5, 50$, no $\tilde{t}$ mixing:

$M_{\tilde{q}} = 1$ TeV, $M_{\tilde{l}} = 300$ GeV, $M_2 = \mu = 200$ GeV

solid: FD 2L (with box), dot-dashed: FD 2L (no box)

dashed: FD 1L, dotted: RG 2L

$e^+e^- \to hZ$ $\qquad\qquad$ $e^+e^- \to hA$



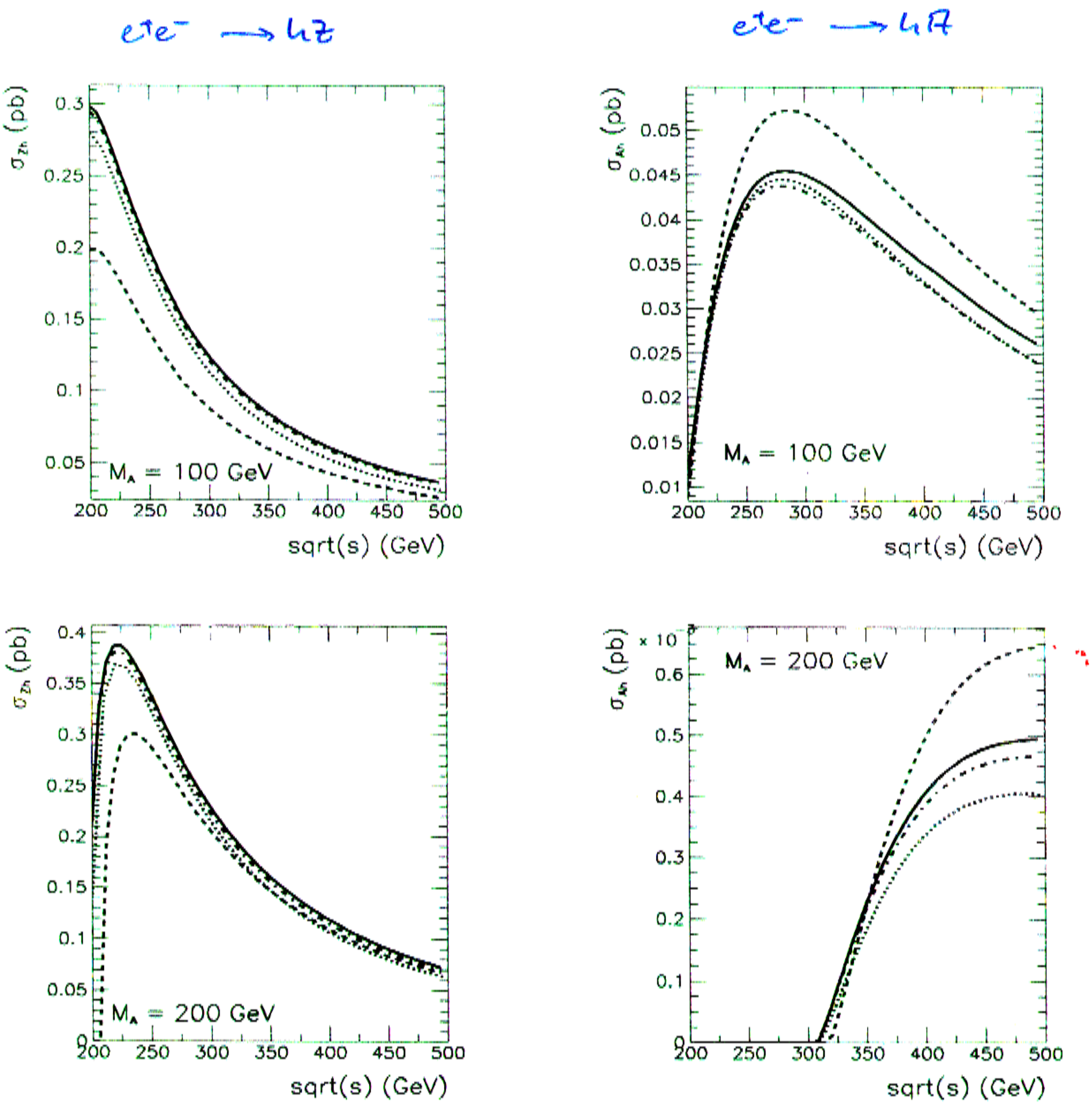
$\Rightarrow$ Sizable deviations between FD and RG result for large M_A

$e^+e^- \to hZ, hA$, $M_A = 100, 200$ GeV, no $\tilde{t}$ mixing:

$M_{\tilde{q}} = 1$ TeV, $M_{\tilde{l}} = 300$ GeV, $M_2 = \mu = 200$ GeV

solid: FD 2L (with box), dot-dashed: FD 2L (no box)

dashed: FD 1L, dotted: RG 2L



⇒ Relative difference between FD and RG result grows with increasing $\sqrt{s}$

5. Conclusions and outlook

- Dominant Feynman-diagrammatic two-loop corrections combined with one-loop on-shell result

  $\Rightarrow$ prediction for m_h, $h \to f\bar{f}$, $e^+e^- \to hZ, hA$

- Large SUSY corrections possible in BR($h \to b\bar{b}$), BR($h \to \tau^+\tau^-$), ...

- Comparison with RG results ($m_\mathrm{t}(\overline{\mathrm{MS}})$ parameterization included)

  $\Rightarrow$ Good agreement for $h \to f\bar{f}$

  Sizable deviations for $e^+e^- \to hZ, hA$ (box corrections, ...)

- m_h, Higgs couplings, Higgs production cross sections as precision observables at the LC

  $\Rightarrow$ Highly sensitive test of SUSY

- Considerable progress of theoretical predictions in Higgs sector of the MSSM

  Still a long way to go to reach accuracies needed for the LC