Precise Predictions for MSSM Higgs boson production at e^+e^- colliders

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2. Higgs Production at e^+e^- colliders
3. Numerical results for $e^+e^- \to hZ$, hA
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1. Introduction:

Higgs sector of the MSSM:

MSSM: Enlarged Higgs sector:

Two Higgs doublets

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

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

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_h, m_H:

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

$\Rightarrow$ $m_h \le M_Z$ at tree level

Large radiative corrections:

Yukawa couplings: $\frac{e\, m_t}{2 M_W s_w}$, $\frac{e\, m_t^2}{M_W s_w}$, ...

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

$\tilde{t}$ sector:

$$M^2_{\tilde{t}} = \begin{pmatrix} M^2_{\tilde{t}_L} + m_t^2 + DT_1 & m_t X_t \\ m_t X_t & M^2_{\tilde{t}_R} + m_t^2 + DT_2 \end{pmatrix}$$

$X_t = A_t - \mu \cot\beta$; large mixing possible

Input parameters: $M_{\tilde{t}_L}$, $M_{\tilde{t}_R}$, X_t
often used: $M_{\text{SUSY}} \equiv M_{\tilde{t}_L} = M_{\tilde{t}_R}$

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

At LC with $\sqrt{s} = 500 - 1000$ GeV:

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

Electroweak corrections at LEP $\leftrightarrow$ LC:

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

$\rightarrow$ $2 \rightarrow 4$, $2 \rightarrow 6$, . . . processes

Remaining theoretical uncertainties in MSSM Higgs calculations:

→ From unknown higher-order corrections

Present estimate: $\Delta m_h^{\text{theo}} \approx 3$ GeV

→ From uncertainties in input parameters

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

Present situation:

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

At LC:

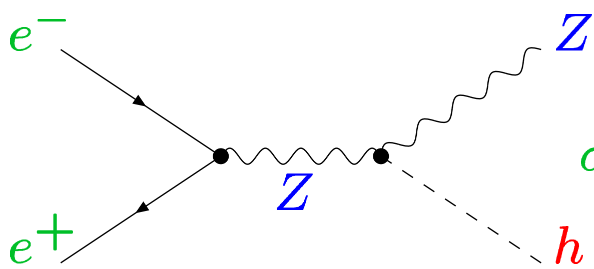
$$\Delta m_t = 0.2 \text{ GeV} \Rightarrow \Delta m_h^{\text{theo}} \approx 0.2 \text{ GeV}$$

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

⇒ High-precision measurement of m_t important!

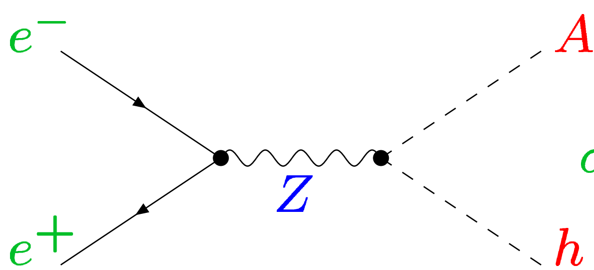
2. Higgs production at e^+e^- colliders:

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



$$\sigma_{\rm hZ} \approx \sin^2(\beta - \alpha)\, \sigma_{\rm hZ}^{\rm SM}$$

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

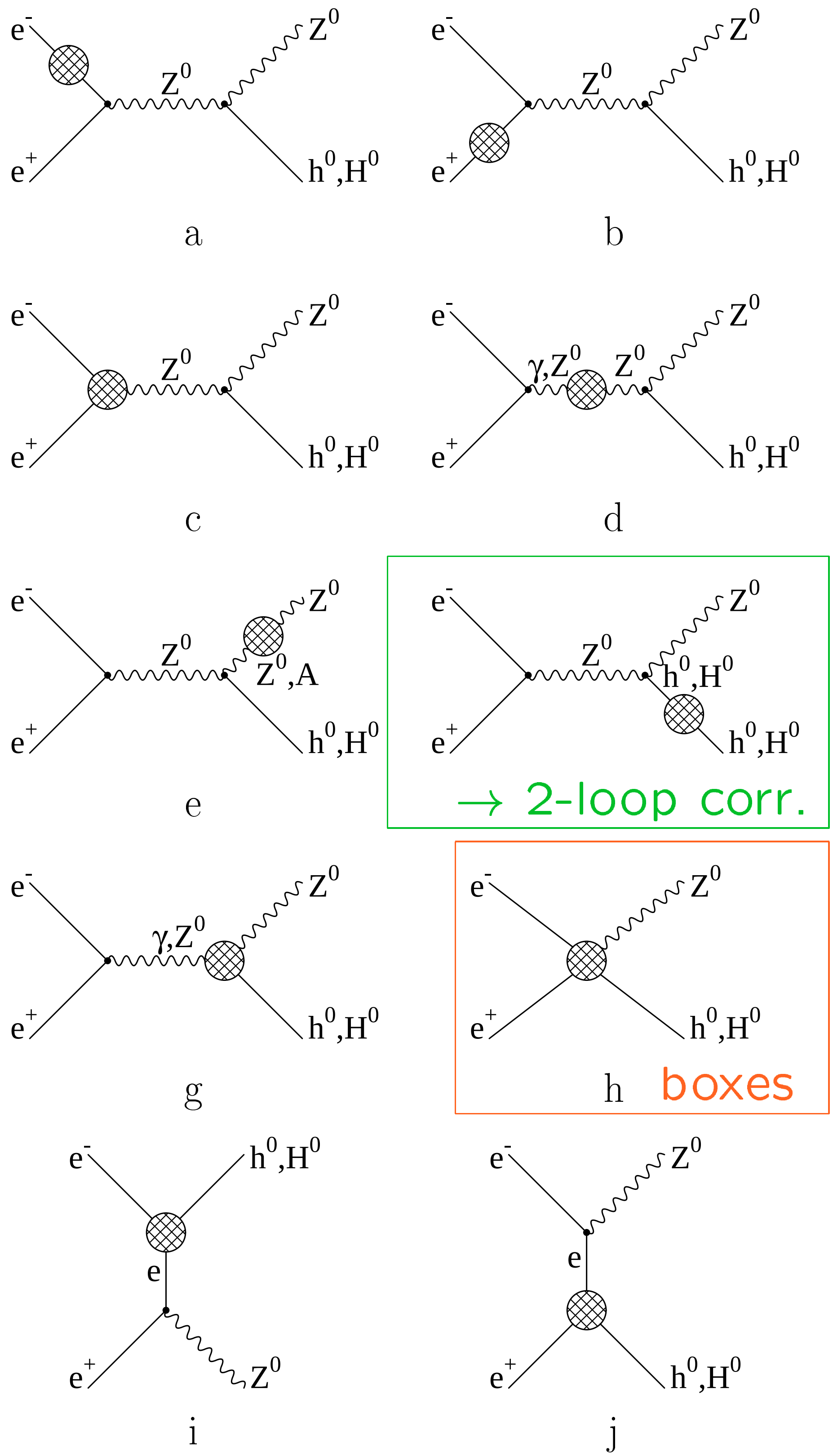


$$\sigma_{\rm hA} \sim \cos^2(\beta - \alpha)\, \sigma_{\rm hZ}^{\rm SM}$$

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

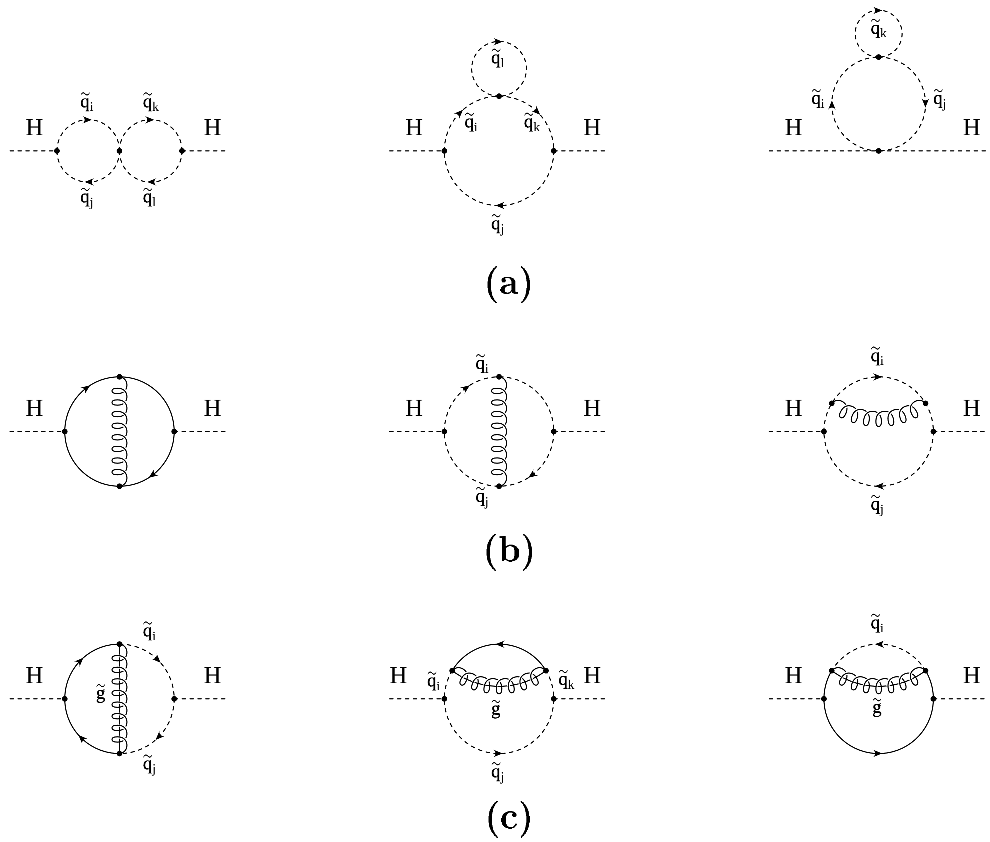
– Dominant two-loop contributions $\mathcal{O}(G_\mu \alpha_s m_t^4)$ incorporation via propagator corrections
  [*S.H., W. Hollik, J. Rosiek, G. Weiglein '00*] $\to$ FF

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



Leading two-loop corrections:

$\mathcal{O}(\alpha\alpha_s)$ contribution from $t-\tilde{t}$-sector
(Yukawa contribution, $p^2 = 0$)
[*S.H., W. Hollik, G. Weiglein '98*]



Complete result for

$$m_h, \quad \sigma(e^+e^- \to hZ,\, hA), \quad \mathrm{BR}(h \to f\bar{f})$$

included in:

FeynHiggs, *FeynHiggsXS*

available from: www.feynhiggs.de

Alternative approach:

Renormalization group α_{eff} approximation:

Higgs mass matrix: (in $\phi_1 - \phi_2$ basis)
incl. dominant higher-order corrections:

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

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

$$\begin{pmatrix} M_H^2 & 0 \\ 0 & M_h^2 \end{pmatrix}$$

$\Rightarrow$ M_h, M_H, mixing angle α_{eff} at higher order

α_{eff} contains dominant higher order corrections

$\rightarrow$ production $\rightarrow$ $\sin(\beta - \alpha_{\text{eff}}), \cos(\beta - \alpha_{\text{eff}})$

$\rightarrow$ decay

$\Rightarrow$ Deviations from other approaches:

- different accuracies for $\hat{\Sigma}_s(0)$
- momentum dependence
- vertex, box corrections

3. Numerical results

Comparison:

FD (1-loop, 2-loop) $\longleftrightarrow$ RG-α_{eff} (2-loop)
[*S.H., W. Hollik, J, Rosiek, G. Weiglein '01*]

FD:

– Fortran code
including all FD corrections ($\to$ *FeynHiggsXS*)
[*V. Driesen, S.H., J. Rosiek '95/'01*]

RG-α_{eff}:

– Fortran code subhpole
[*M. Carena, M. Quiros, C. Wagner '95*]

– $m_t(M_S)$ corrections included
[*M. Carena, H. Haber, S.H., W. Hollik, C. Wagner, G. Weiglein '00*]

– On-shell $\overline{\text{MS}}$ transition (M_{SUSY}, Xt) included
[*M. Carena, H. Haber, S.H., W. Hollik, C. Wagner, G. Weiglein '00*]

– $\to$ α_{eff} approximation

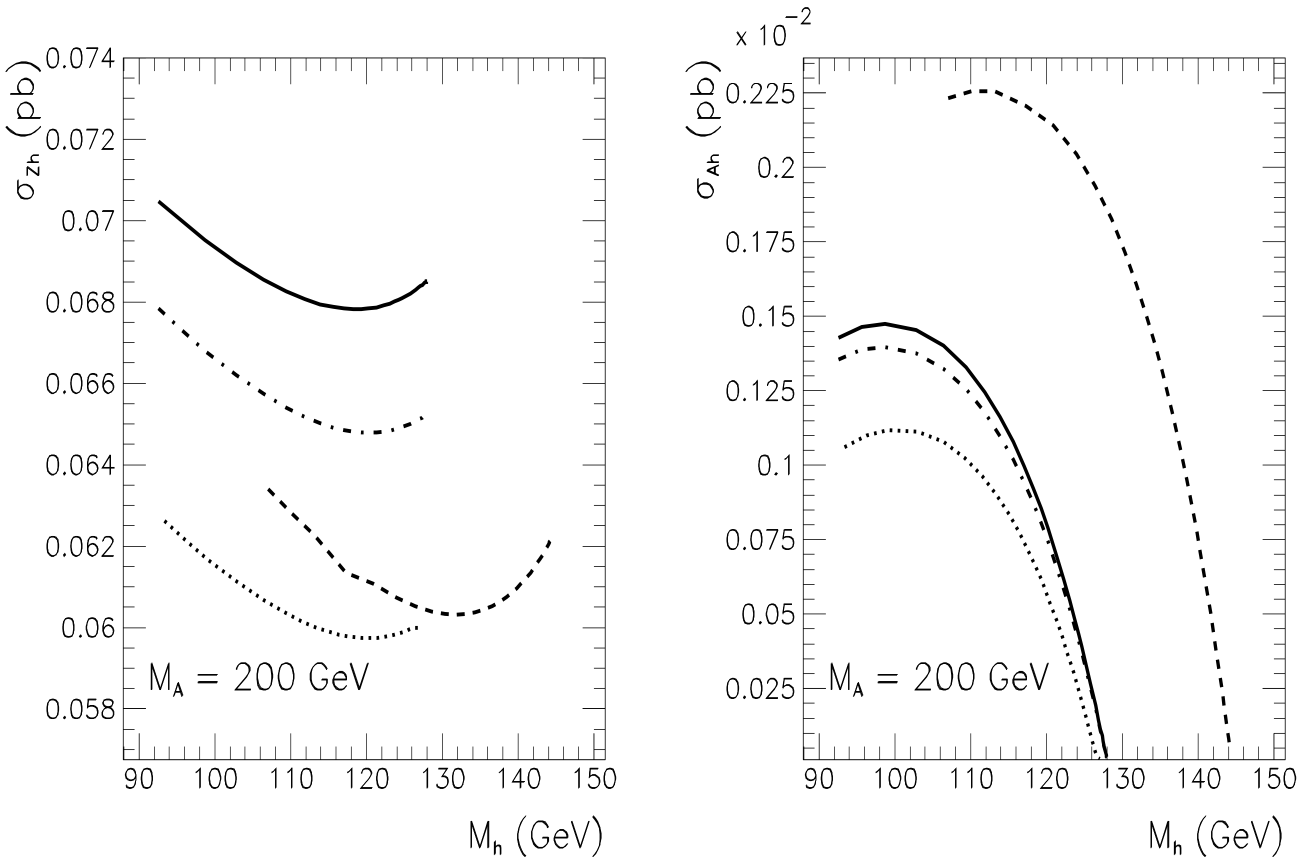
$e^+e^- \to hZ, hA$, $\sqrt{s} = 500$ GeV:

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

$X_t = 2M_{\tilde{q}}$, $M_A = 200$ GeV

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

dashed: FD 1L , dotted: RG 2L



Diff. FD 2L – RG-α_{eff} result: $\sigma_{Zh} \approx$ 10–15%

$\sigma_{Ah} \approx$ 25%

Effect of 2L corrections: $\sim$ 20%

Effects of box contributions: 5–10%

larger effects in differential cross sections

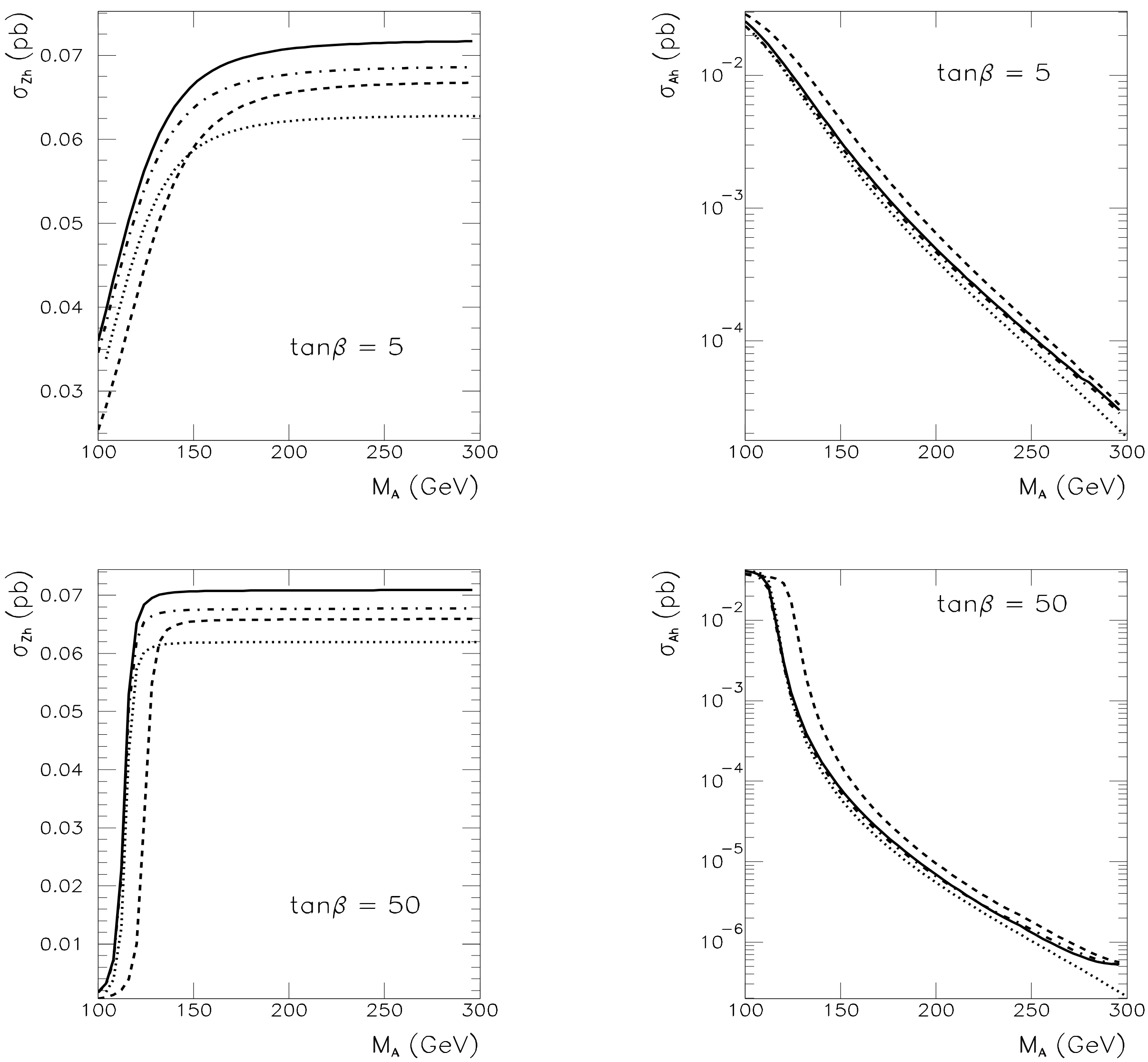
$e^+e^- \to hZ, hA,\ \sqrt{s} = 500$ GeV

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

$X_t = 0$, $\tan\beta = 5, 50$:

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

dashed: FD 1L , dotted: RG 2L



⇒ Sizable deviations between FD and RG-$\alpha_{\rm eff}$ result for large M_A

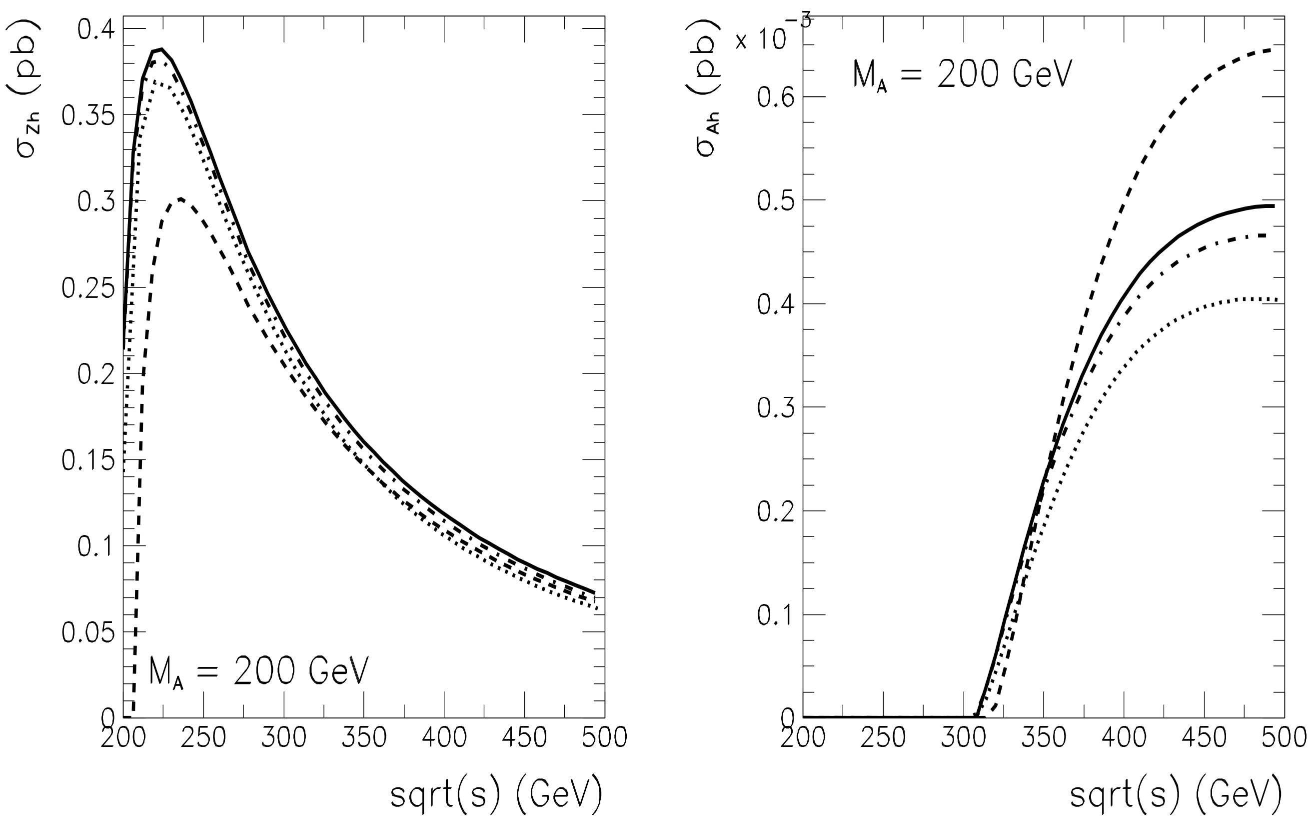
$e^+e^- \to hZ, hA$ as a function of $\sqrt{s}$:

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

$X_t = 0$, $M_A = 200$ 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 $\sqrt{s}$

Code currently used for the LEP2 analysis: HZHA

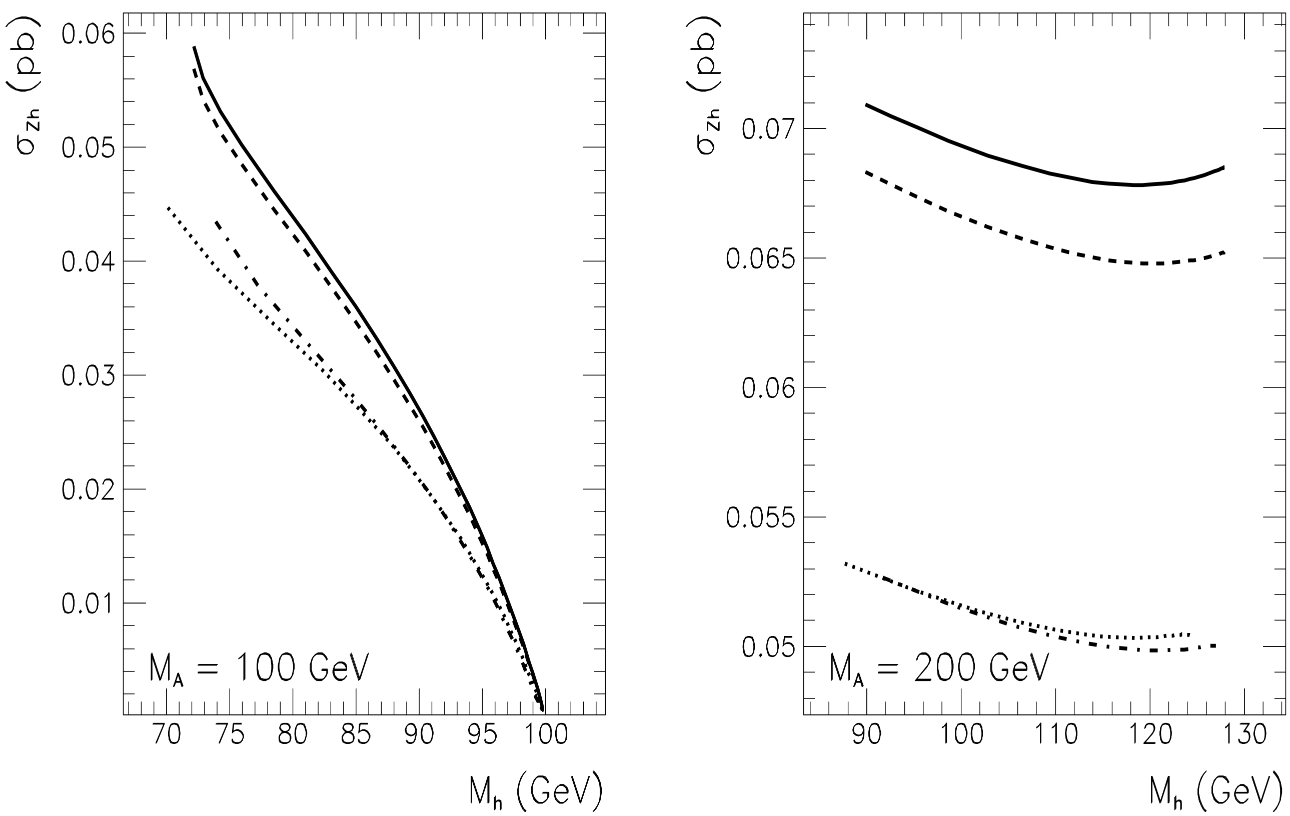
[*P. Janot '96-'00*]

$e^+e^- \to hZ$, comparison with HZHA: $M_{\tilde{q}} = 1$ TeV, $M_{\tilde{l}} = 300$ GeV, $M_2 = \mu = 200$ GeV

$X_t = 2M_{\tilde{q}}$, $M_A = 100, 200$ GeV

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

dotted: HZHA (*FeynHiggs*), dot-dashed: HZHA (*subhpole*)



⇒ sizable deviations for large M_A

Outlook:

- Further comparison with HZHA
  $\rightarrow$ full effect of FD calculation

- Implementation of *FeynHiggsXS*
  into existing codes ?

  $\rightarrow$ Pythia
  $\rightarrow$ HZHA

- leading two-loop (process specific) vertex corrections?
  $\Rightarrow$ needed for 1% accuracy

4. Conclusinos

- Calculation for Higgs production:

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

  Higgs propagator correction combined with complete one-loop on-shell result (→ vertices, boxes)

  $\Rightarrow$ *FeynHiggsXS*

- Comparison of FD and RG-α_{eff} :
  - σ_{Zh} : @ $\sqrt{s} = 500$ GeV

    box corrections up to 7%

    two-loop corrections $\sim$ 10%

    FD larger than RG up to 15%
  - σ_{Ah} : @ $\sqrt{s} = 500$ GeV

    box contributions up to 10%

    two-loop corrections $\sim$ 20%

    FD larger than RG up to 25%

- Improvement factor of 10 needed in theoretical prediction to match the experimental precision