Leading Two-Loop Corrections to MSSM Higgs Production at e^+e^- colliders

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based on collaboration with
W. Hollik, J. Rosiek and *G. Weiglein*

1. Introduction
2. Leading two-loop corrections to Higgs production in e^+e^- colliders
3. Numerical results
4. Outlook
5. Conclusions

m_h calculable from MSSM parameters:

Stringent direct test of SUSY:

Light Higgs boson h required

Tree level: $m_h < M_Z$

Large radiative corrections: $\Rightarrow m_h \lesssim$ 135 GeV

$\Rightarrow$ Precise prediction needed for Higgs search:

- Higgs masses ($m_h, m_H, \ldots$)

- Higgs decay ($\Gamma(h \to f\bar{f}), BR(h \to f\bar{f})$)

- Higgs production ($e^+e^- \to hZ,\ hA$)

production in e^+e^- colliders

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 , $A^0, H^\pm$

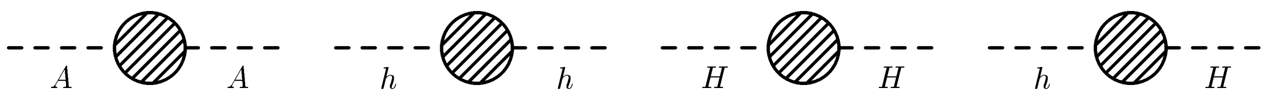
Input parameters:

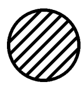
$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2(\tan\beta + \cot\beta)$$

Higgs sector:

$\rightarrow \mathcal{O}(G_\mu\, m_t^4)$, $\mathcal{O}(G_\mu\, \alpha_s\, m_t^4)$

(via Higgs propagators)




: Complete MSSM in 1-loop order

[*A. Dabelstein '95*]

$+\ \mathcal{O}(\alpha\alpha_s)$ contributions from $t-\tilde{t}$-sector

(Yukawa contribution, $p^2 = 0$) $\rightarrow$ F

[*S. H., W. Hollik, G. Weiglein '98*]

$+$ subdominant terms $\mathcal{O}(G_\mu^2 m_t^6)$

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

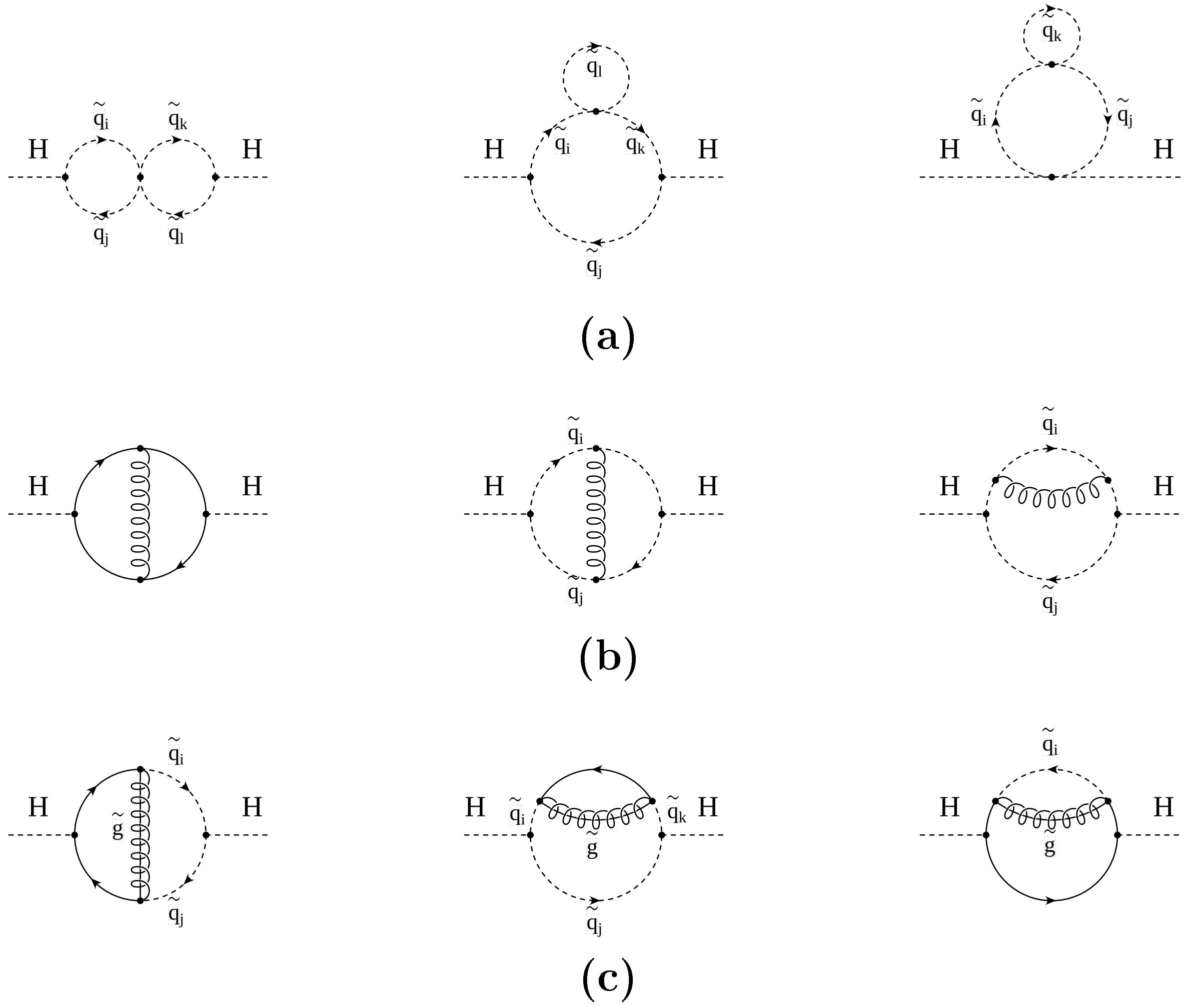
Full self-energy:

$$\hat{\Sigma}_s(q^2) = \hat{\Sigma}_s^{(1)}(q^2) + \hat{\Sigma}_s^{(2)}(0)$$

Approximation:

$$\hat{\Sigma}_s(q^2) \rightarrow \hat{\Sigma}_s^{(1)}(0) + \hat{\Sigma}_s^{(2)}(0)$$

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



$\tilde{t}$ sector:

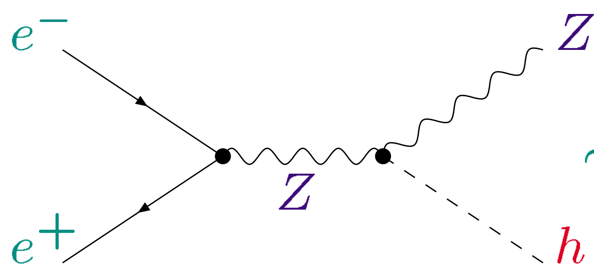
$$M_{\tilde{t}}^2 = \begin{pmatrix} M_S^2 + DT_1 & m_t X_t \\ m_t X_t & M_S^2 + DT_2 \end{pmatrix}$$

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

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

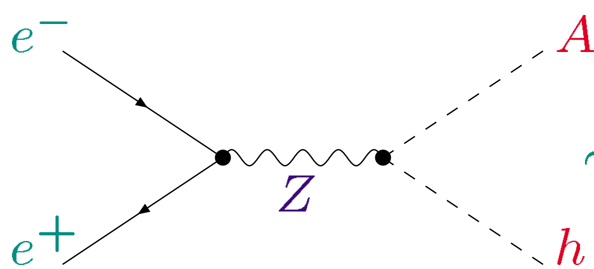
$X_t/M_{\text{SUSY}} \approx 0$: no mixing
$X_t/M_{\text{SUSY}} \approx \pm 2$: maximal mixing

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



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

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

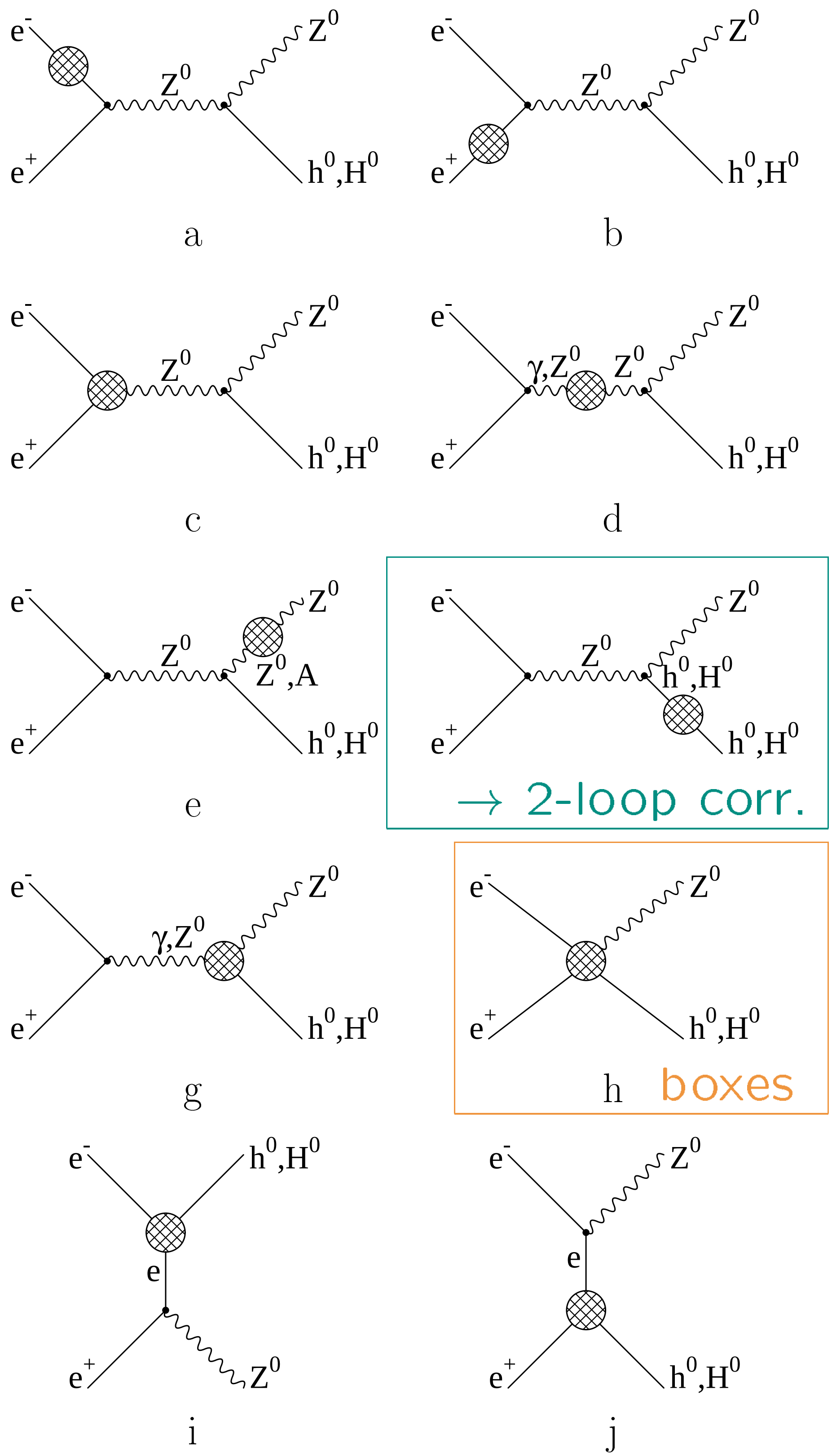


$\sim \cos(\beta - \alpha)$

– 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*]

$\to$ F

– 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 '99*]


a
b
c
d
e
→ 2-loop corr.
g
h
boxes
i
j
e-
e+
Z0
h0,H0
γ,Z0
Z0,A
e

effective potential approach:

mainly rely on α_{eff} approximation :

Tree-level:

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

$$M^{2,\text{tree}}_{\text{Higgs}} = \begin{pmatrix} m^2_{\phi_1} & m^2_{\phi_1\phi_2} \\ m^2_{\phi_1\phi_2} & m^2_{\phi_2} \end{pmatrix} =$$

$$\begin{pmatrix} M_A^2 \sin^2\beta + M_Z^2 \cos^2\beta & -(M_A^2 + M_Z^2) \sin\beta \cos\beta \\ -(M_A^2 + M_Z^2) \sin\beta \cos\beta & M_A^2 \cos^2\beta + M_Z^2 \sin^2\beta \end{pmatrix}$$

$$\Big\Downarrow \quad \leftarrow \text{ Diagonalization } , \alpha$$

$$\begin{pmatrix} m_H^{2,\text{tree}} & 0 \\ 0 & m_h^{2,\text{tree}} \end{pmatrix}$$

$\Rightarrow$ m_h, m_H, mixing angle α at tree level

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

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

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

$$\begin{pmatrix} M^2_H & 0 \\ 0 & M^2_h \end{pmatrix}$$

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

α_{eff} contains dominant higher order corrections

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

$\to$ decay

$\Rightarrow$ Deviations from other approaches:

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

Comparison:

FD (1-loop, 2-loop) $\longleftrightarrow$ RG (2-loop)

[*all preliminary*]

FD:

– Fortran code
  including all FD corrections
  [*V. Driesen, S. H., J. Rosiek '95/'99*]

RG:

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

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

– $\rightarrow$ α_{eff} approximation

M_A = 100 GeV (fixed)

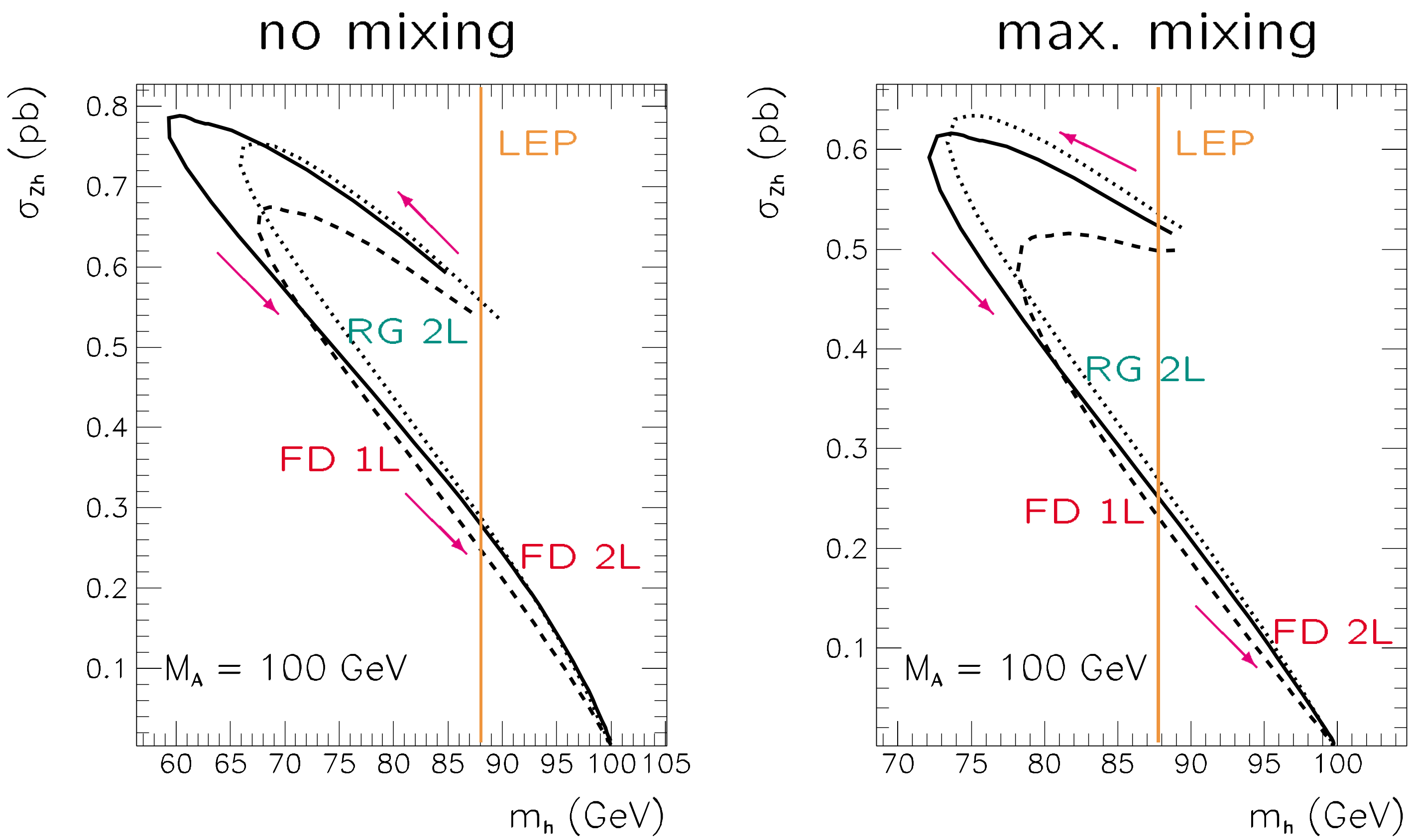
$\tan\beta$ = 0.5 .. 50 (varied) ($\rightarrow\rightarrow\rightarrow$)

$\rightarrow$ calculation of m_h

Other parameters:

$M_{\text{SUSY}} = 1$ TeV, $M_2 = \mu = 200$ GeV

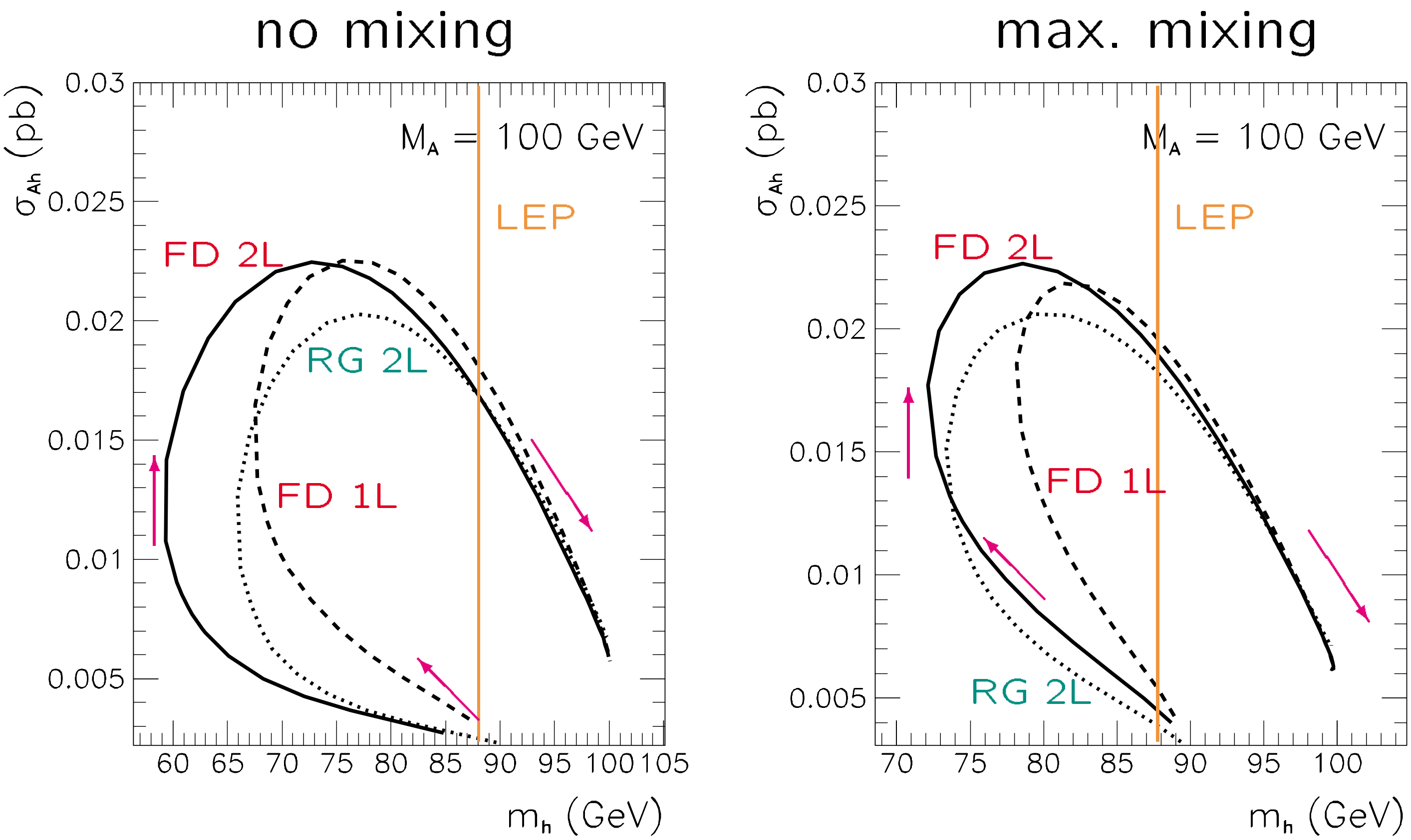
σ_{Zh} @ $\sqrt{s}$ = 206 GeV



$\rightarrow$ two-loop up to 10% larger than one-loop

$\rightarrow$ FD up to 7% smaller than RG (max. mix.)

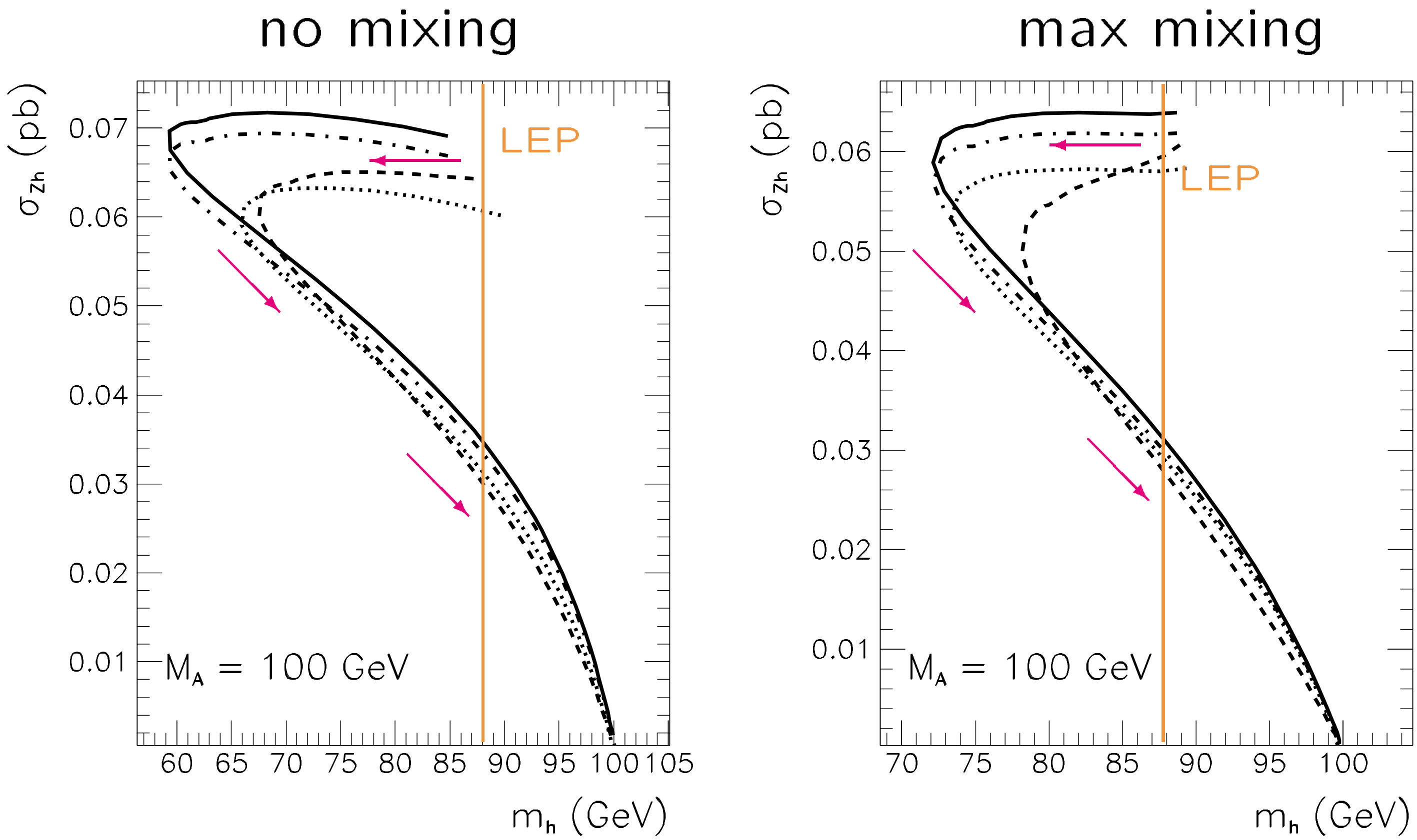
σ_{Ah} @ $\sqrt{s}$ = 206 GeV



→ two-loop up to 10% smaller than one-loop

→ FD up to 4% smaller than RG (max. mix.)

σ_{Zh} @ $\sqrt{s} = 500$ GeV, $M_A = 100$ GeV



solid: FD 2L (with box) [$M_{\rm SUSY} = 300$ GeV for sleptons]

dot-dashed: FD 2L (no box)

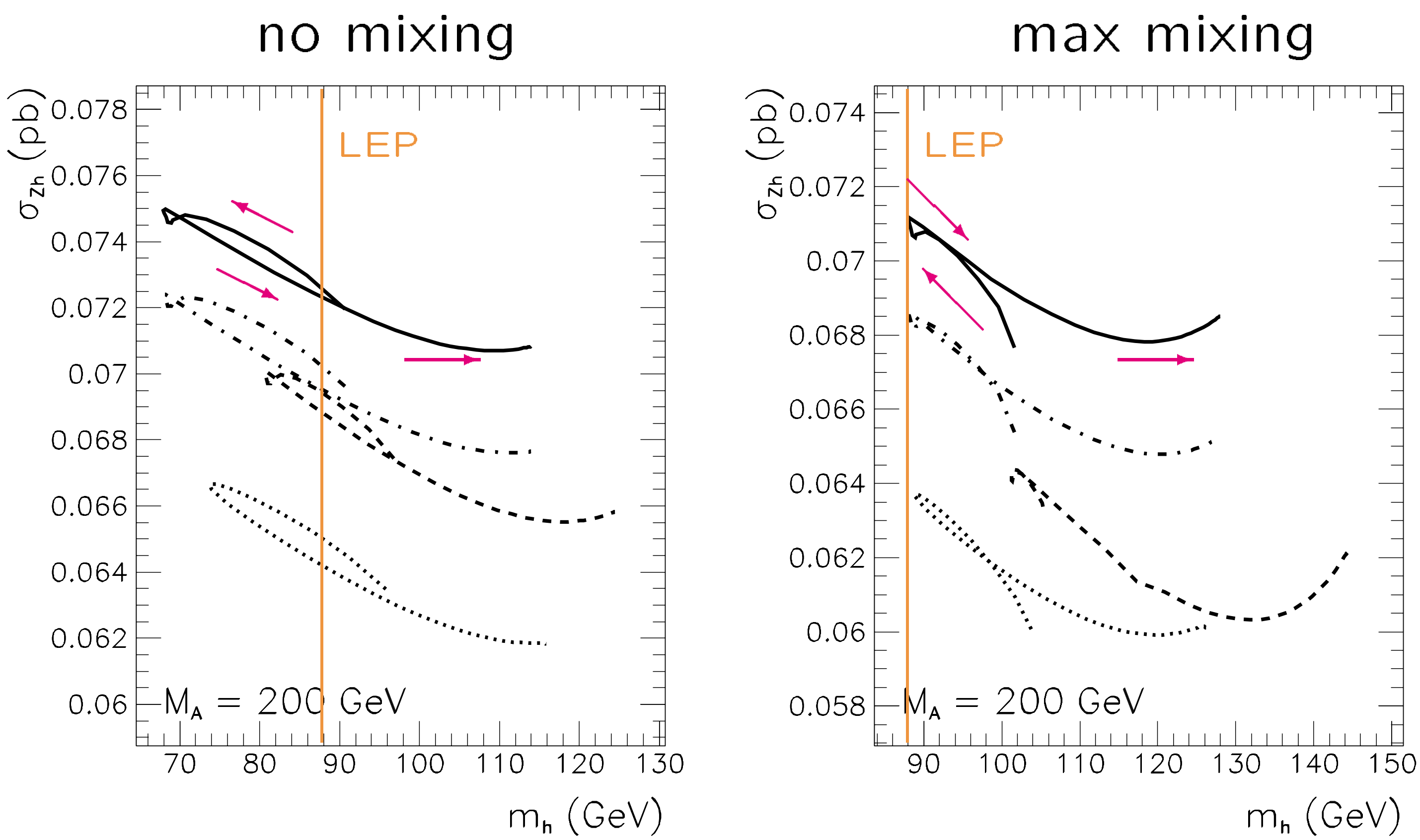
dashed: FD 1L

dotted: RG 2L

→ small two-loop effect

→ box effects below 7%

→ FD up to 15%/10% larger than RG



solid: FD 2L (with box) [$M_{\mathrm{SUSY}} = 300$ GeV for sleptons]

dot-dashed: FD 2L (no box)

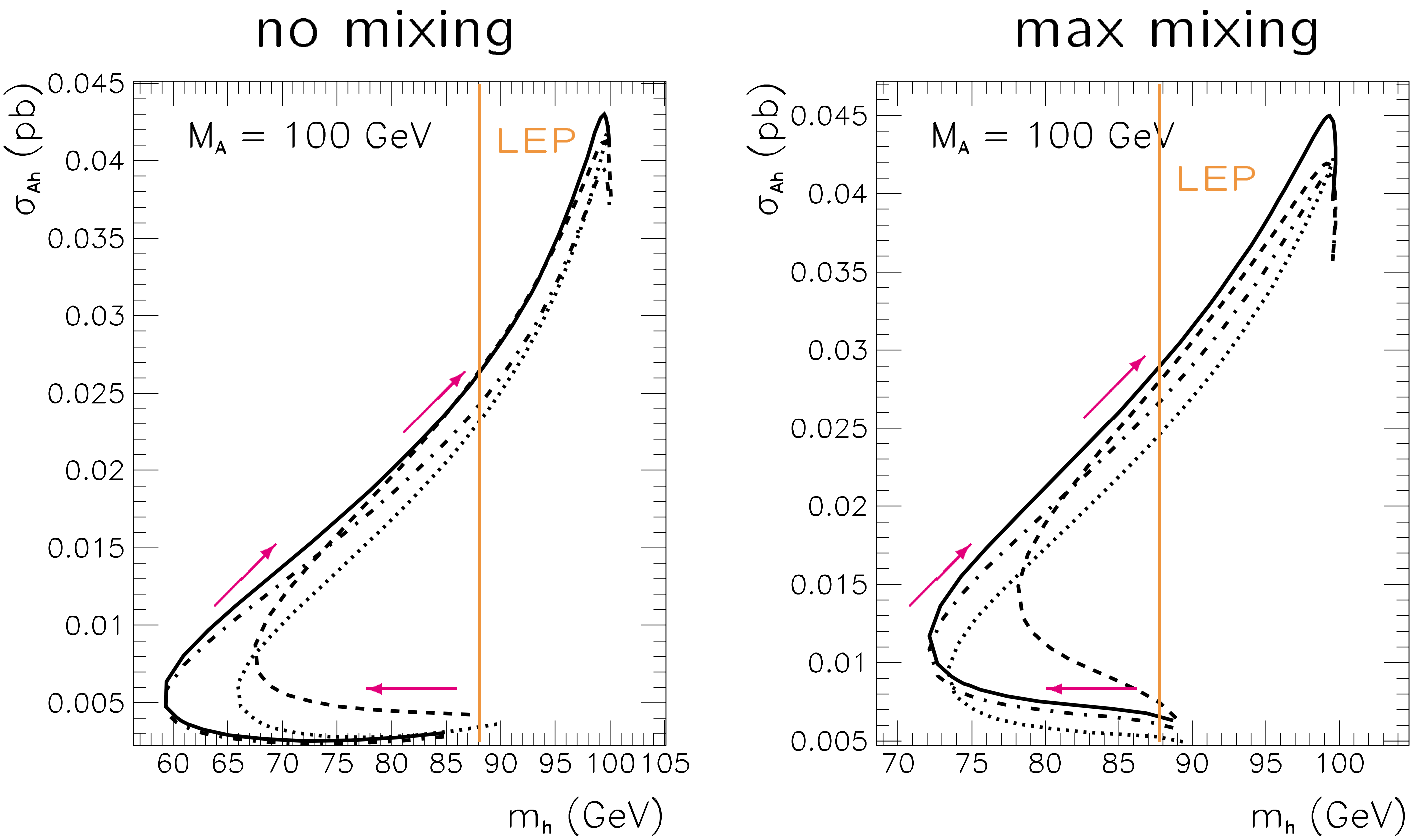
dashed: FD 1L

dotted: RG 2L

→ moderate two-loop effect

→ box effects up to 5%

→ FD up to 12%/15% larger than RG



solid: FD 2L (with box) [$M_{\text{SUSY}} = 300$ GeV for sleptons]

dot-dashed: FD 2L (no box)

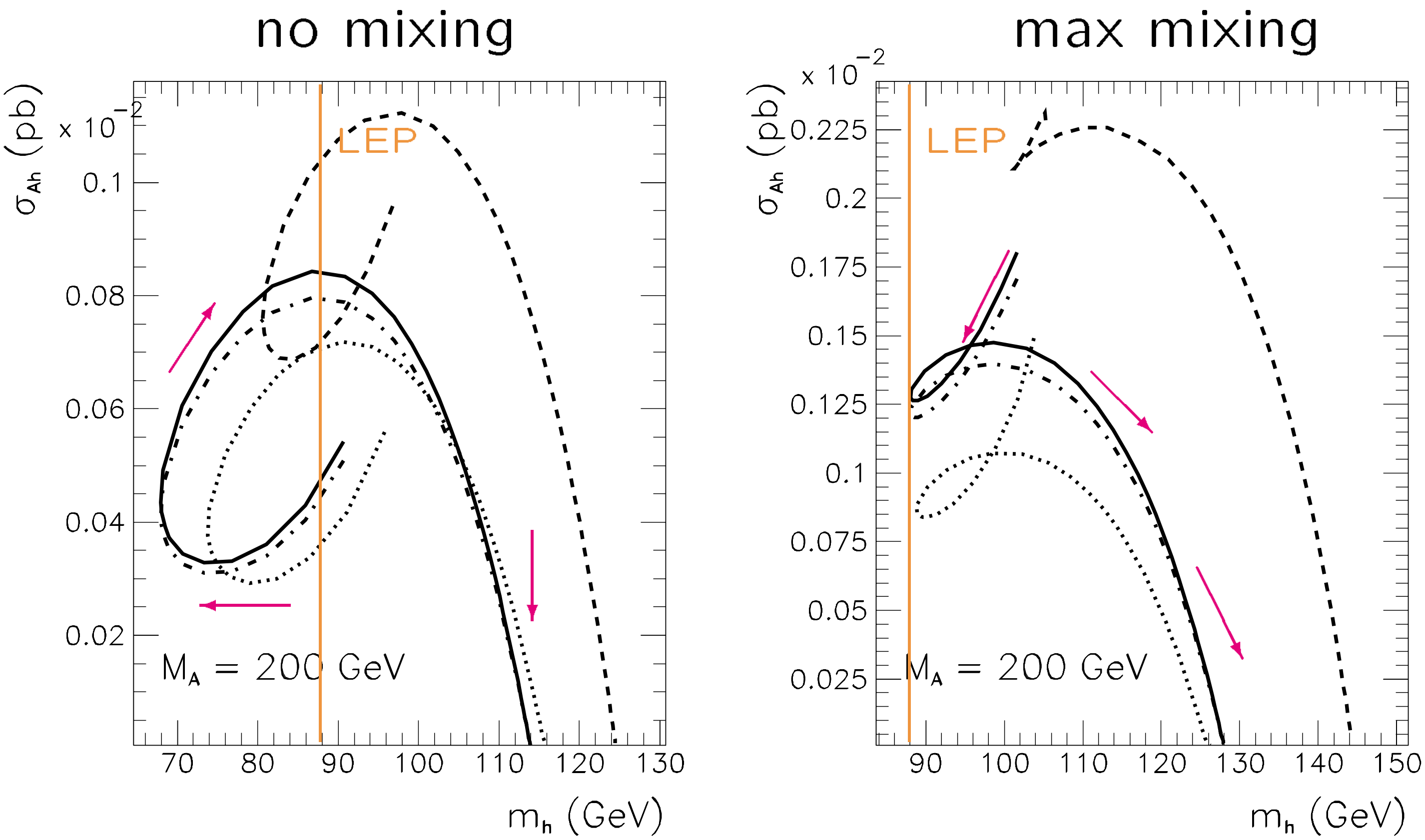
dashed: FD 1L

dotted: RG 2L

→ two-loop effect up to 7%

→ box effects up to 10%

→ FD up to 15%/20% larger than RG



solid: FD 2L (with box) [$M_{\rm SUSY} = 300$ GeV for sleptons]

dot-dashed: FD 2L (no box)

dashed: FD 1L

dotted: RG 2L

$\to$ large two-loop effect

$\to$ box effects up to 7%

$\to$ FD up to 20%/30% larger than RG

- Comparison with HZHA
  $\rightarrow$ full effect of FD calculation

- public Fortran code
  ($\rightarrow$ implementation into existing code?)

- leading two-loop (process specific) vertex corrections?

- Dominant corrections in MSSM Higgs sector $\mathcal{O}(G_\mu m_t^4)$, $\mathcal{O}(G_\mu \alpha_s m_t^4)$ via Higgs propagator corrections

  $\rightarrow$ Leading two-loop result combined with complete one-loop on-shell result

- Calculation for Higgs production:

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

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

- Comparison of FD and RG :
  - σ_{Zh} : @ $\sqrt{s} = 500$ GeV
    box corrections up to 7%
    FD larger than RG up to 15%
  - σ_{Ah} : @ $\sqrt{s} = 500$ GeV
    box contributions up to 10%
    FD larger than RG up to 30%

- More detailed studies and public Fortran code in progress