Nigel finds the Higgs boson.

Higgs Boson Production Cross Sections in the complex MSSM

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Whistler, 11/2015

based on collaboration with *C. Schappacher*

1. Motivation
2. The thrilling technical details
3. Results for the neutral MSSM Higgs Production Cross Sections
4. Conclusions

1. Motivation: Model choice

Some "recent" measurements:

– top quark mass
– Higgs boson mass
– Higgs boson "couplings"
– Dark Matter (properties)

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⇒ good motivation to look at SUSY! :-)

1. Motivation: Higgs coupling determination

LHC always measures $\sigma \times$ BR

$\Rightarrow$ Total width $\Gamma_{H,\text{tot}}$ cannot be measured without further theory assumptions.

Recommendation of the LHCHXSWG:

$\Rightarrow$ Higgs coupling strength scale factors: κ_i
For each benchmark (except overall coupling strength) various versions are proposed:
with and without additinal theory assumptions

– no additional theory assumptions:

$\Rightarrow$ Determination of ratios of scaling factors, e.g. $\kappa_i \kappa_j / \kappa_H$

– additional theory assumptions (on $\Gamma_{H,\text{tot}}$ or $\kappa_{W,Z}$ or $H \to$ NP)

$\Rightarrow$ Determination of κ_i (evaluated to NLO QCD accuracy)

Higgs coupling determination at e^+e^- collider:

recoil method: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$

$\Rightarrow$ total measurement of Higgs production cross section

$\Rightarrow$ NO additional theoretical assumptions needed for absolute determination of partial widths

$\Rightarrow$ all observable channels can be measured with high accuracy

$\Rightarrow$ Cross section needed with high precision, better than $\sim 1\%$

Available: SM cross section predictions at the 1% accuracy level

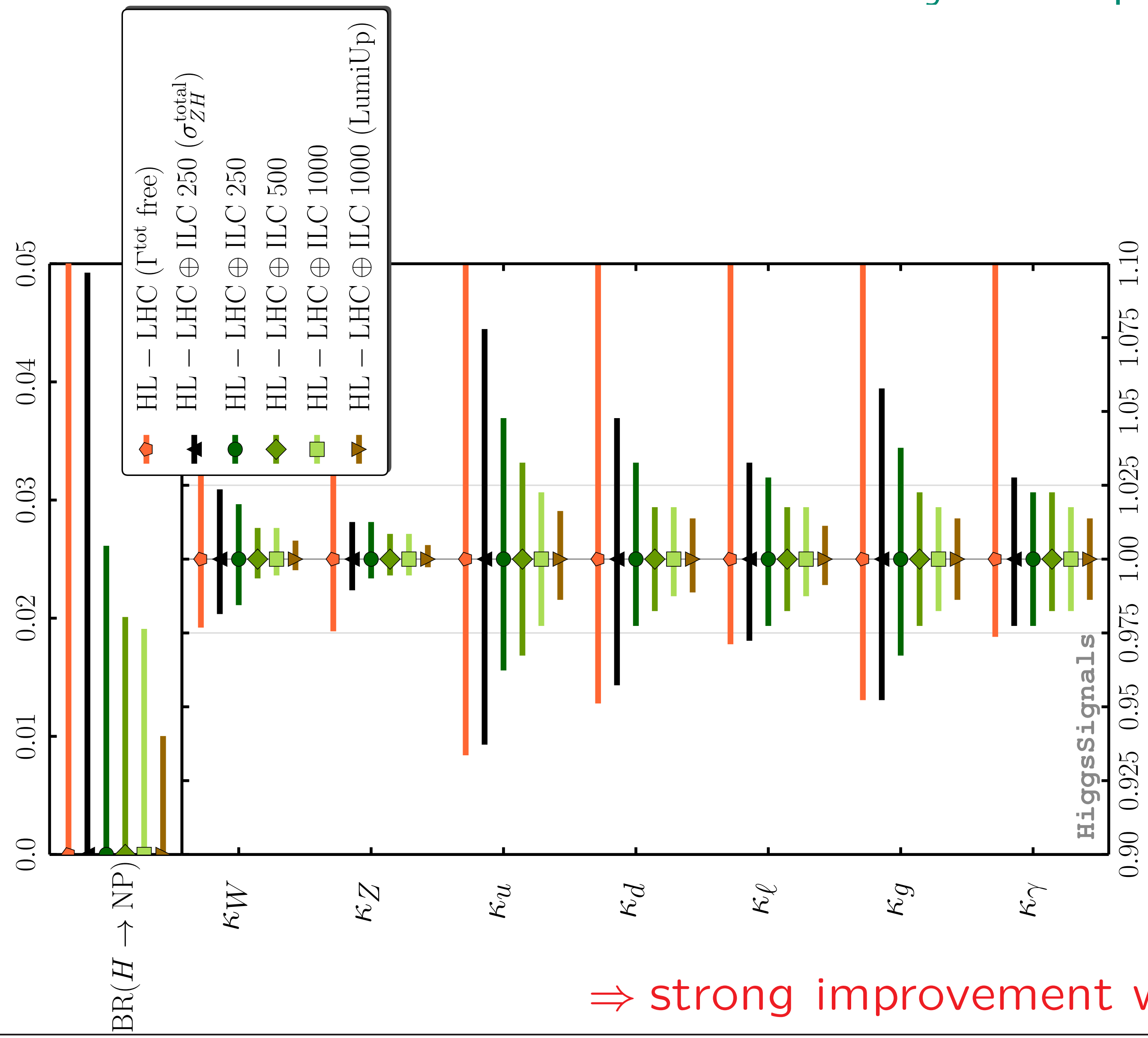
$\Rightarrow$ improvements necessary . . . full 2-loop calculations and more . . . ?!

$\Rightarrow$ What about the MSSM cross sections?

HL-LHC vs. ILC in the most general κ framework:

[*P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '14*]

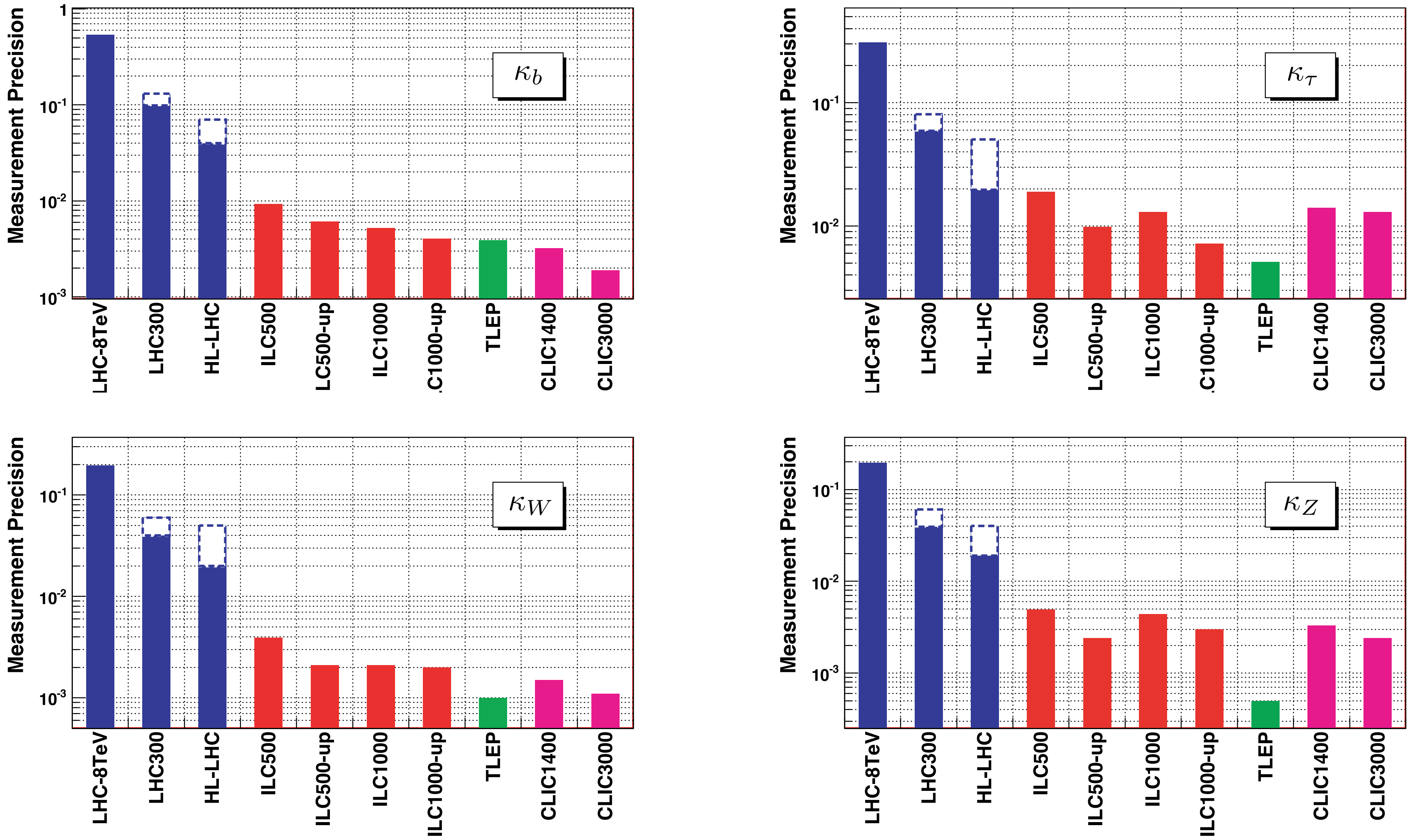
no theory assumptions, full fit



⇒ strong improvement with the ILC

ILC vs. TLEP/FCC-ee:

[*Snowmass Higgs Report '13*]



⇒ can the sub-percent/permille level be matched by theory?

2. The thrilling technical details

The Minimal Supersymmetric Standard Model (MSSM)

$$\left[u, d, c, s, t, b\right]_{L,R} \quad \left[e, \mu, \tau\right]_{L,R} \quad \left[\nu_{e,\mu,\tau}\right]_{L} \qquad \text{Spin } \tfrac{1}{2}$$

$$\left[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\right]_{L,R} \quad \left[\tilde{e}, \tilde{\mu}, \tilde{\tau}\right]_{L,R} \quad \left[\tilde{\nu}_{e,\mu,\tau}\right]_{L} \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^{\pm}, H^{\pm}} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin 1 / Spin 0}$$

$$\tilde{g} \quad \tilde{\chi}^{\pm}_{1,2} \quad \tilde{\chi}^{0}_{1,2,3,4} \qquad \text{Spin } \frac{1}{2}$$

Enlarged Higgs sector: Two Higgs doublets $\Leftarrow$ for obvious reasons some focus here!

Problem in the MSSM: many scales

Problem in the MSSM: complex phases

Enlarged Higgs sector: Two Higgs doublets

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

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

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

$$+ \underbrace{\frac{g'^2 + g^2}{8}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

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

Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

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

Enlarged Higgs sector: Two Higgs doublets with $\mathcal{CP}$ violation

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

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

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gauge couplings, in contrast to SM

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

2 $\mathcal{CP}$-violating phases: ξ, $\arg(m_{12})$ $\Rightarrow$ can be set/rotated to zero

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_{H^\pm}^2$$

The Higgs sector of the cMSSM at tree-level:

- phase of m_{12} :

  $m_{12} = 0$ and $\mu = 0 \Rightarrow$ additional $U(1)$ (PQ) symmetry

  reality: $m_{12} \neq 0$, $\mu \neq 0$

  $\Rightarrow$ perform PQ transformation with $\phi_{\rm PQ}$

$$
\begin{aligned}
m_{12}^{2\prime} &= |m_{12}^2| e^{i(\phi_{m_{12}} - \phi_{\rm PQ})} \\
\mu' &= |\mu| e^{i(\phi_\mu - \phi_{\rm PQ})}
\end{aligned}
$$

  $\Rightarrow$ m_{12} can always be chosen real

- phase of H_2: ξ :

  mixing between $\mathcal{CP}$-even and $\mathcal{CP}$-odd states:

$$
\mathcal{M}_{\mathcal{CP}-\text{even},\mathcal{CP}-\text{odd}} = \begin{pmatrix} 0 & m_{12}^2 \sin\xi \\ -m_{12}^2 \sin\xi & 0 \end{pmatrix}
$$

  Tadpoles have to vanish: $T_A^{\rm tree} \propto \sin\xi \, m_{12}^2 \stackrel{!}{=} 0$
  $\Rightarrow \xi = 0 \Rightarrow$ no $\mathcal{CP}$V at tree-level

The Higgs sector of the cMSSM at the loop-level:

Complex parameters enter via loop corrections:

– μ : Higgsino mass parameter

– $A_{t,b,\tau}$: trilinear couplings $\Rightarrow X_{t,b,\tau} = A_{t,b,\tau} - \mu^*\{\cot\beta\,, \tan\beta\}$ complex

– $M_{1,2}$: gaugino mass parameter (one phase can be eliminated)

– M_3 : gluino mass parameter

$\Rightarrow$ can induce $\mathcal{CP}$-violating effects

Result:

$$(A, H, h) \to (h_3, h_2, h_1)$$

with

$$m_{h_3} > m_{h_2} > m_{h_1}$$

$\Rightarrow$ strong changes in Higgs couplings to SM gauge bosons and fermions

Generic problems for SUSY loop calculations: renormalization

- SUSY has to be preserved in the calculation
- Many different mass scales
- Many more mass scales than free parameters
- Even more parameters: mixing angles, complex phases
- Renormalization is much more involved than in the SM
  - much less explored than in the SM
  - has to preserve/respect mass relations
  - depend on mass scales realized in Nature
  - sometimes no really good solution exist (e.g. $\tan\beta$)
  - many sectors enter at the same time

  $\Rightarrow$ this is the biggest issue!

Renormalization status:

– LC precision requires all calculations at the per-cent level

– full complex MSSM renormalized

[*A. Bharucha, T. Fritzsche, T. Hahn, S.H., F.v.d. Pahlen, H. Rzehak, C. Schappacher '11 - '13*]

– stable and well behaved results over nearly complete parameter space

– available as FeynArts model file

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$\Rightarrow$ **go and make your prediction!**

$\Rightarrow$ and so we did :-)

3. Results for the MSSM Higgs Production Cross Sections at the LC

Neutral Higgs production:

$$e^+e^- \to h_iZ,\ h_i\gamma,\ h_ih_j,\ h_i\nu\bar{\nu},\ h_ie^+e^-,\ h_it\bar{t},\ h_ib\bar{b},\ \ldots \qquad (i,j = 1,2,3)\,.$$

Now available in the cMSSM at the full one-loop level:
[*S.H., C. Schappacher '15*]

$$\sigma(e^+e^- \to h_ih_j)$$
$$\sigma(e^+e^- \to h_iZ)$$
$$\sigma(e^+e^- \to h_i\gamma)$$

In the following:
few examples of each process, relevance of loop corrections

cMSSM parameters:

Table 2: MSSM default parameters for the numerical investigation; all parameters (except of t_β) are in GeV (calculated masses are rounded to 1 MeV). The values for the trilinear sfermion Higgs couplings, $A_{t,b,\tau}$ are chosen such that charge- and/or color-breaking minima are avoided [76], and $A_{b,\tau}$ are chosen to be real. It should be noted that for the first and second generation of sfermions we chose instead $A_f = 0$, $M_{\tilde{Q},\tilde{U},\tilde{D}} = 1500$ GeV and $M_{\tilde{L},\tilde{E}} = 500$ GeV.

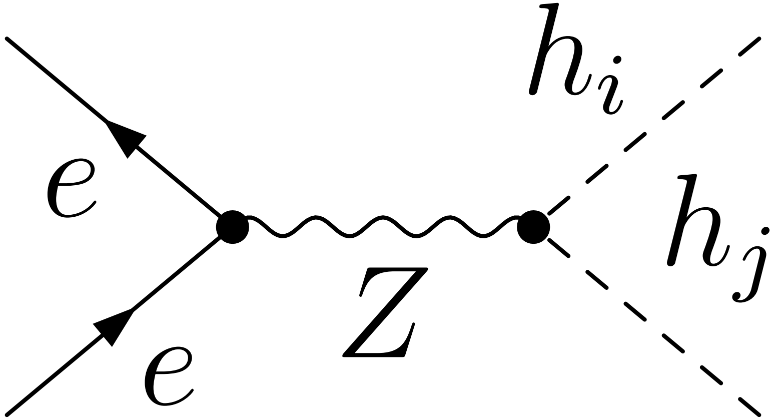
Scen.	$\sqrt{s}$	t_β	μ	$M_{H^\pm}$	$M_{\tilde{Q},\tilde{U},\tilde{D}}$	$M_{\tilde{L},\tilde{E}}$	$\lvert A_{t,b,\tau}\rvert$	M_1	M_2	M_3
$\mathcal{S}$	1000	7	200	300	1000	500	$1500 + \mu/t_\beta$	100	200	1500

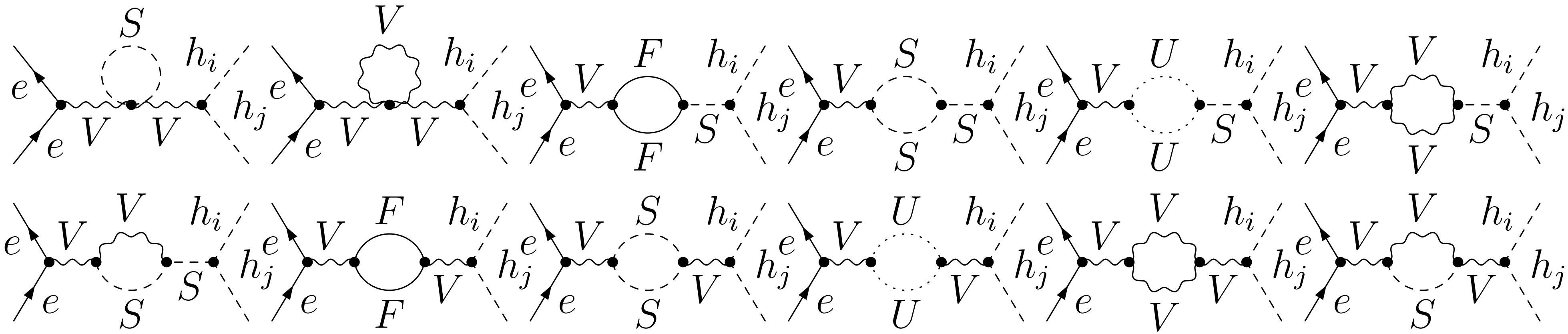
m_{h_1}	m_{h_2}	m_{h_3}
123.404	288.762	290.588

with $\sqrt{s}$, $M_{H^\pm}$, $\tan\beta$, ϕ_{A_t} varied

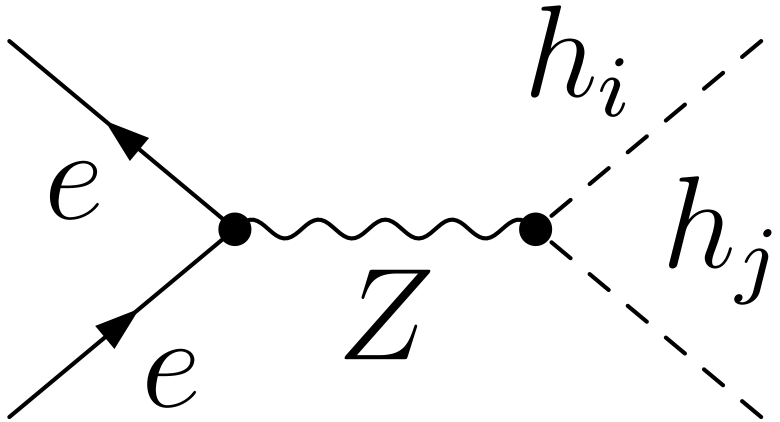
– Scenario chosen such that many processes are possible at the same time
– not chosen to maximize loop corrections

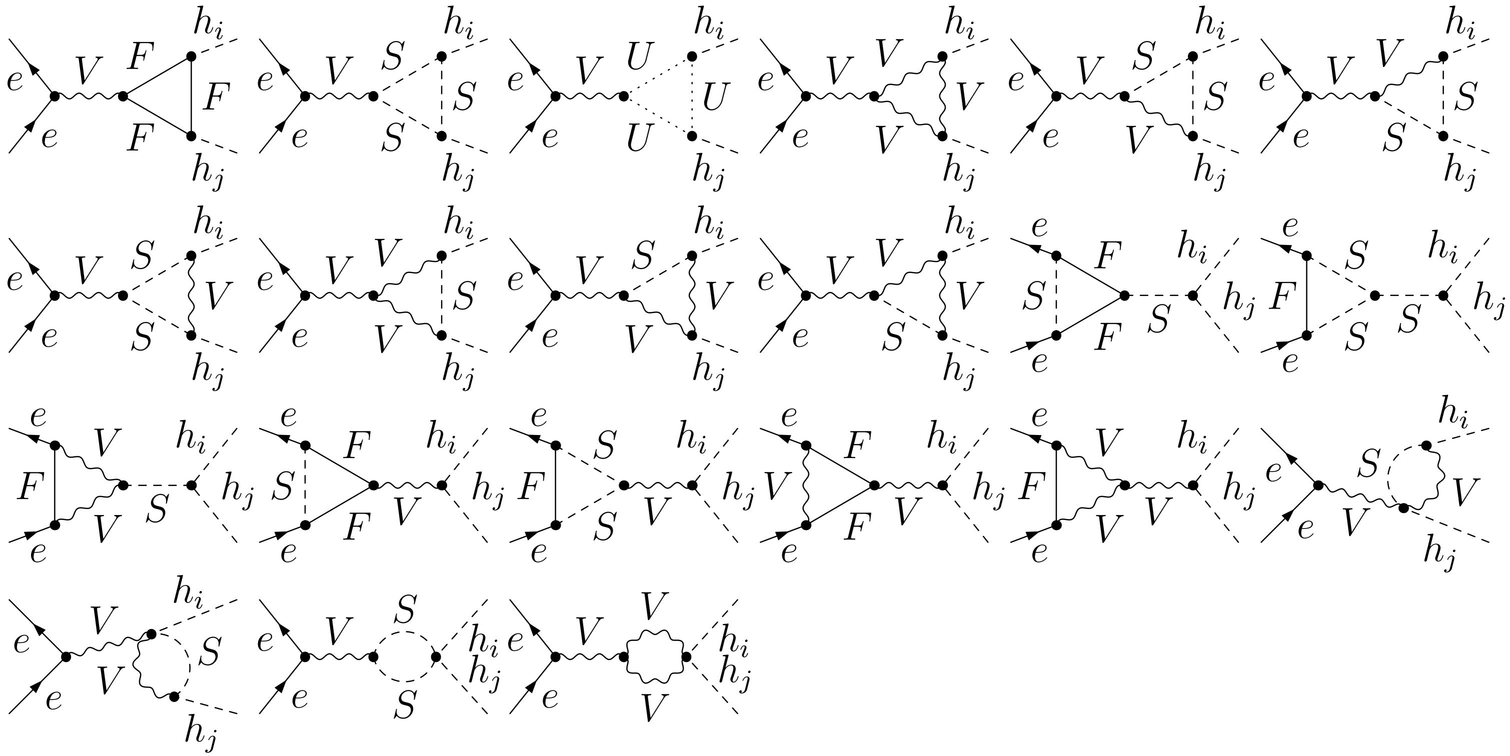
$e^+e^- \to h_i h_j$:



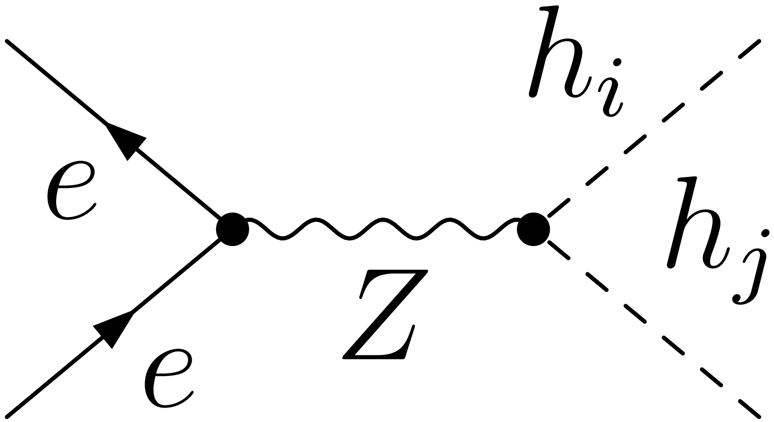


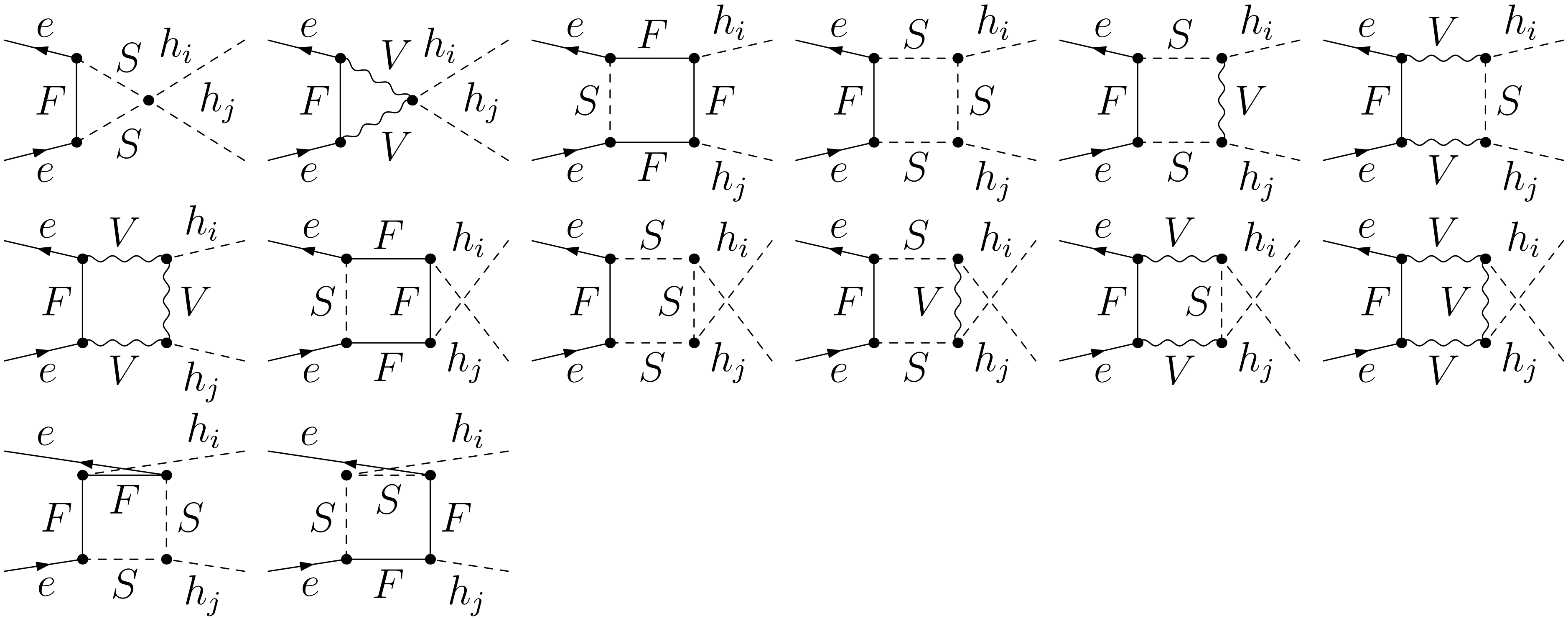
$e^+e^- \to h_i h_j$:





$e^+e^- \to h_ih_j$:


e
e
Z
h_i
h_j


e S h_i F h_j S e
e V h_i F h_j V e
e F h_i S F e F h_j
e S h_i F S e S h_j
e S h_i F V e S h_j
e V h_i F S e V h_j
e V h_i F V e V h_j
e F h_i S F e F h_j
e S h_i F S e S h_j
e S h_i F V e S h_j
e V h_i F S e V h_j
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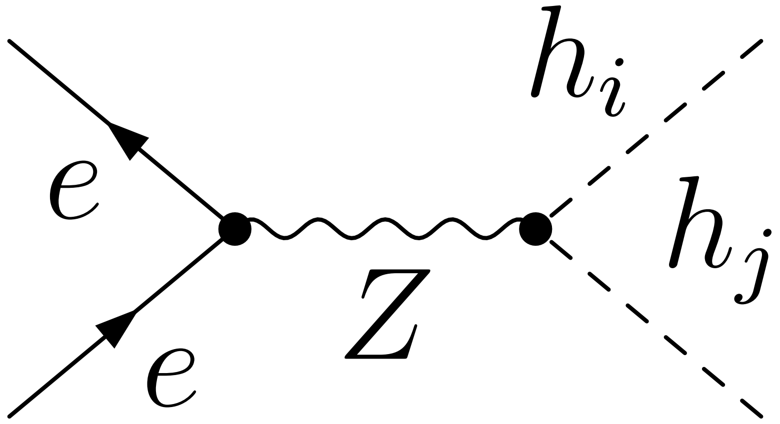
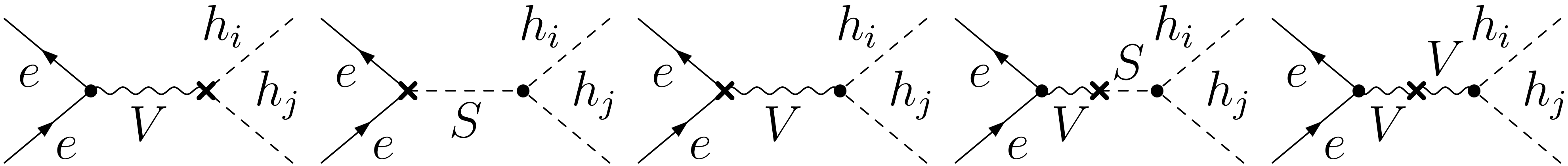
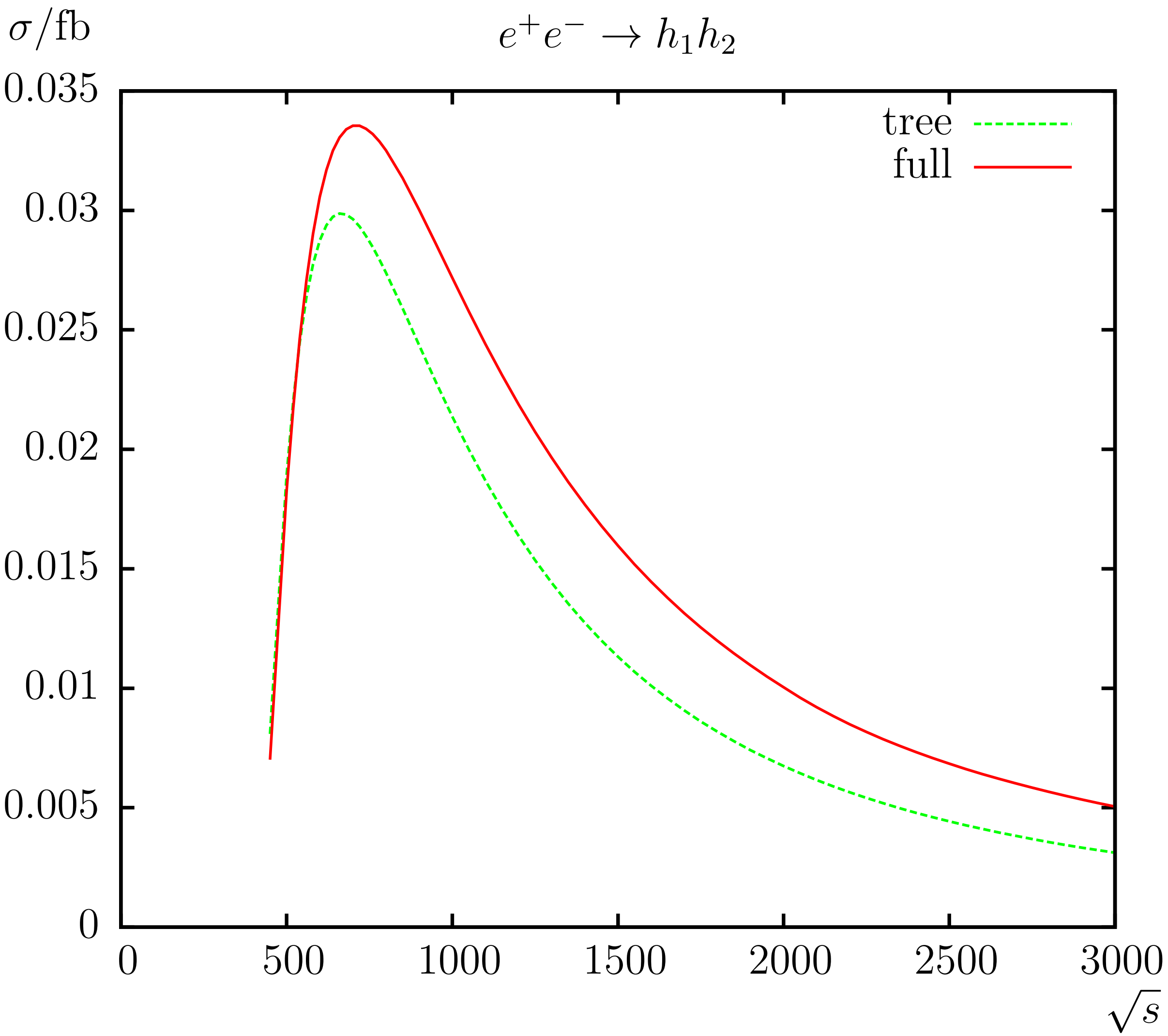




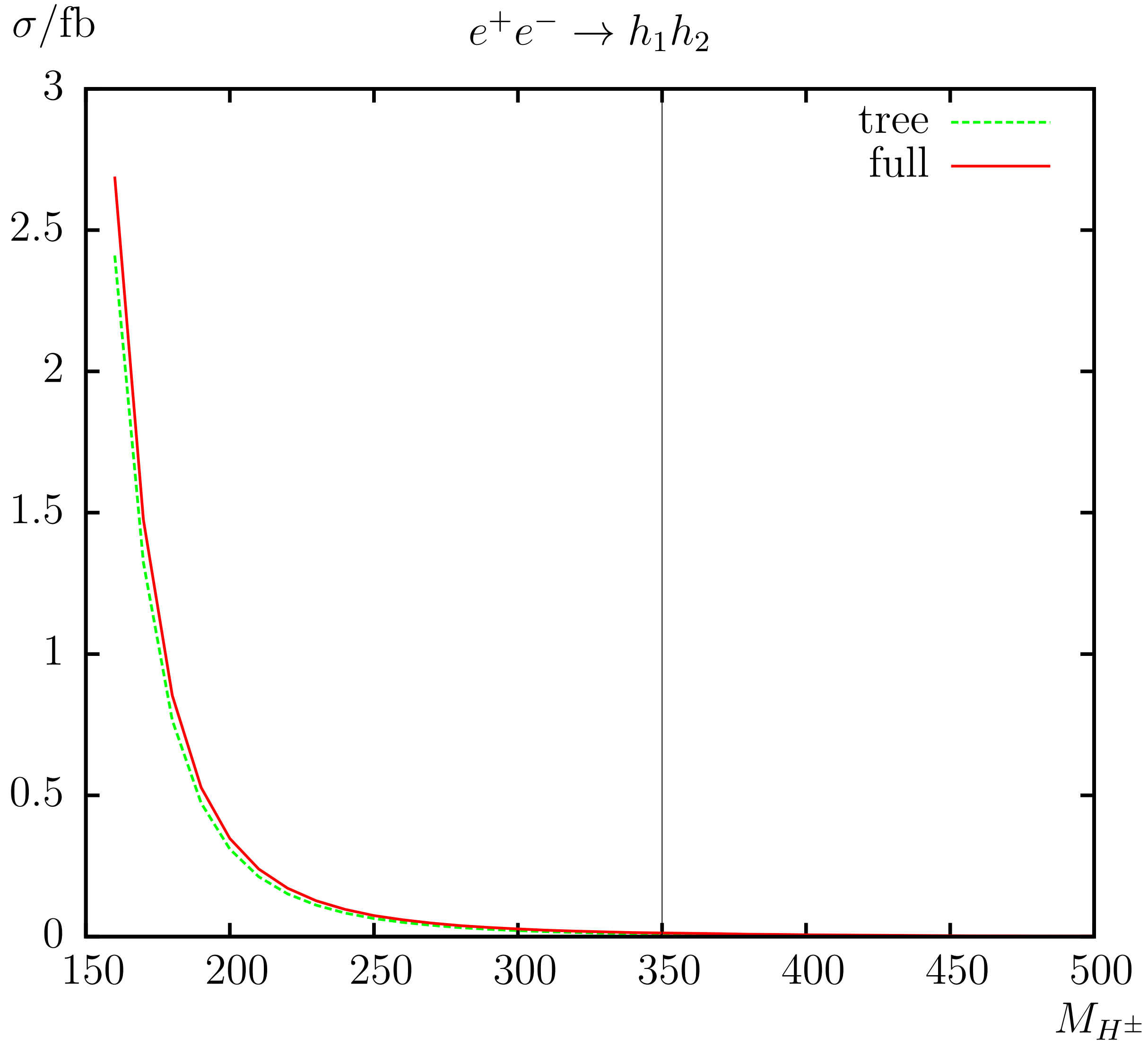
+ soft and hard QED radiation

$e^+e^- \to h_1 h_2$:



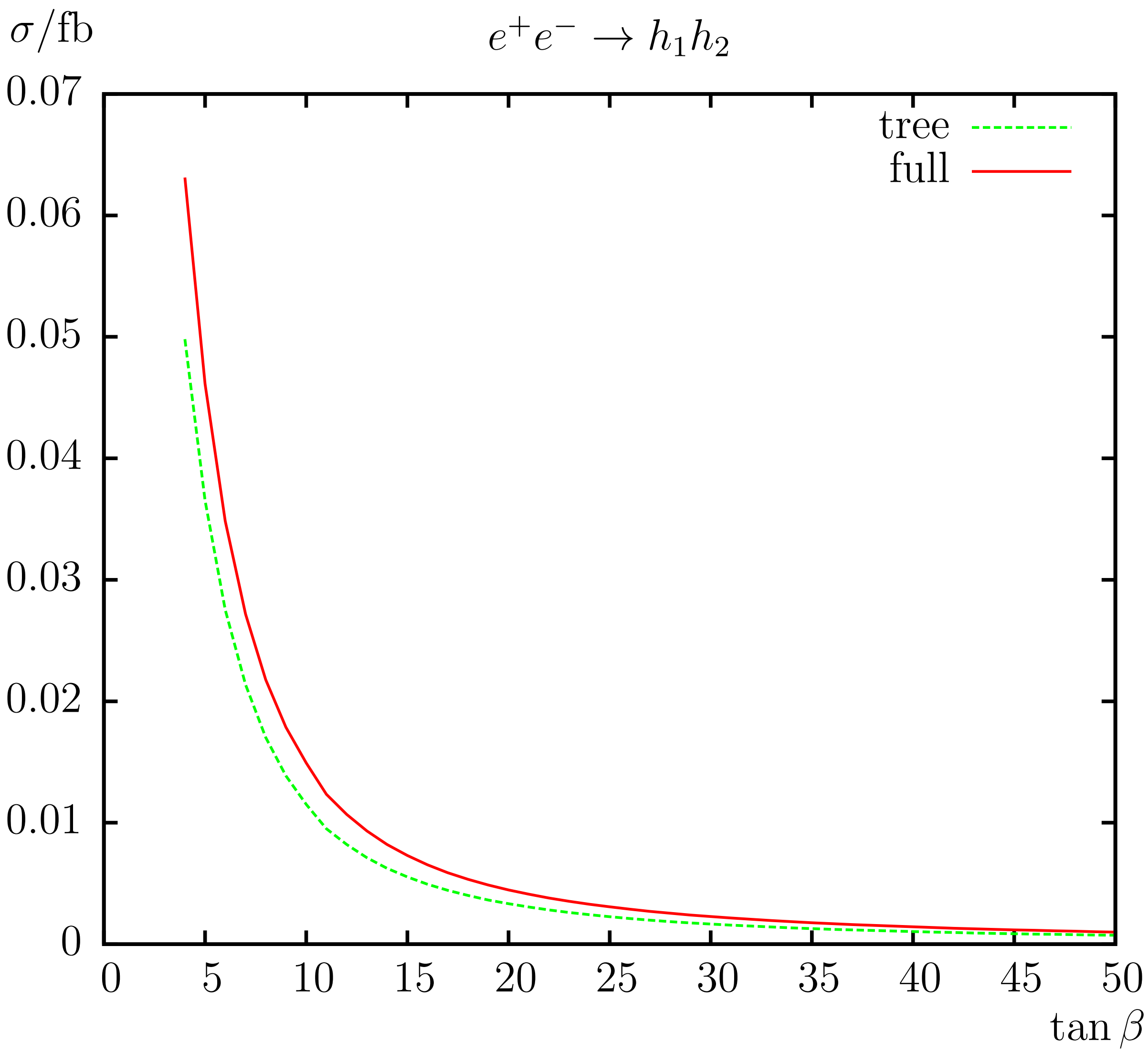
$\Rightarrow$ loop corrections crucial!

$e^+e^- \to h_1 h_2$:



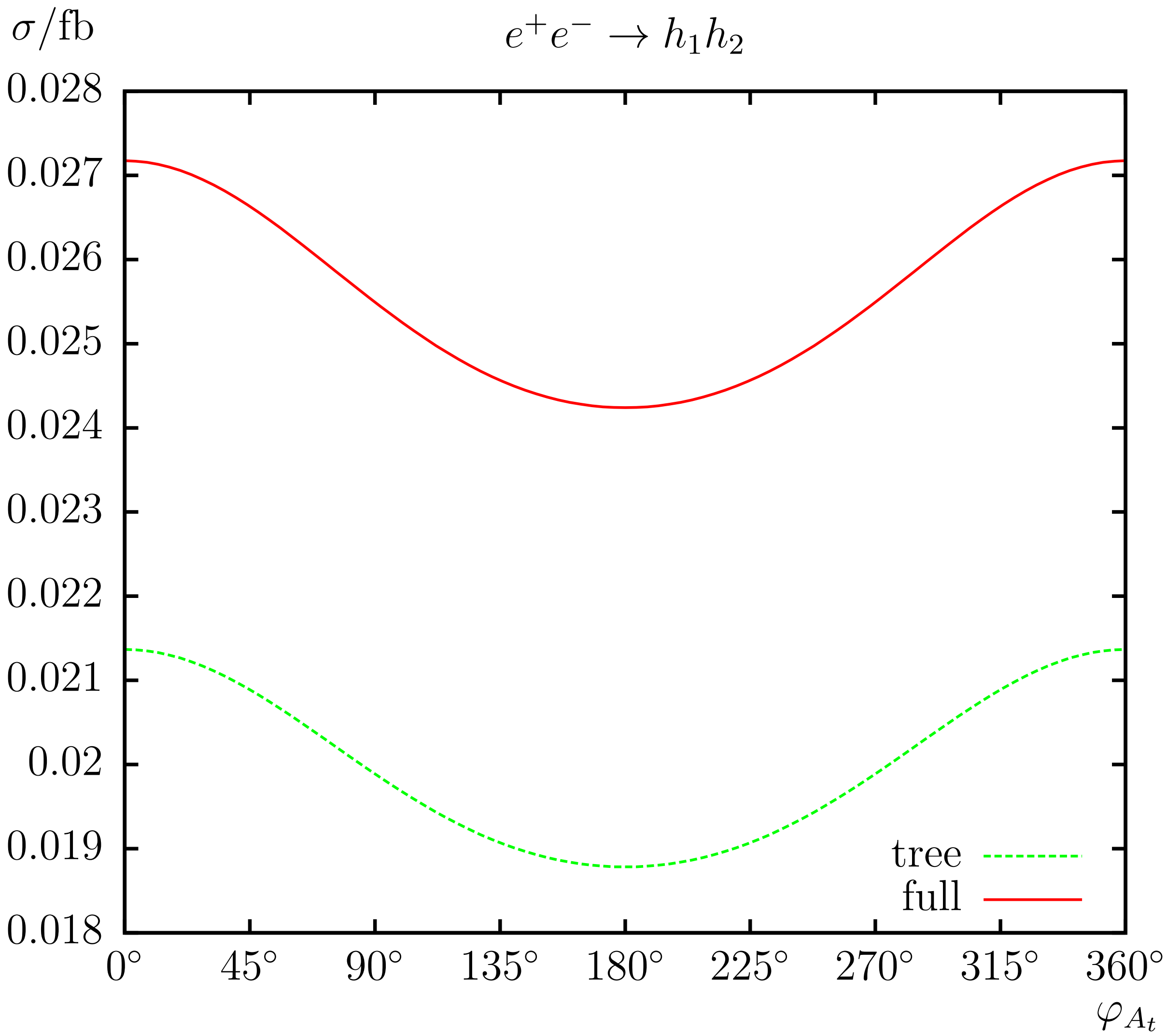
σ/fb
$e^+e^- \to h_1 h_2$
tree
full
3
2.5
2
1.5
1
0.5
0
150
200
250
300
350
400
450
500
$M_{H^\pm}$

$e^+e^- \to h_1 h_2$:



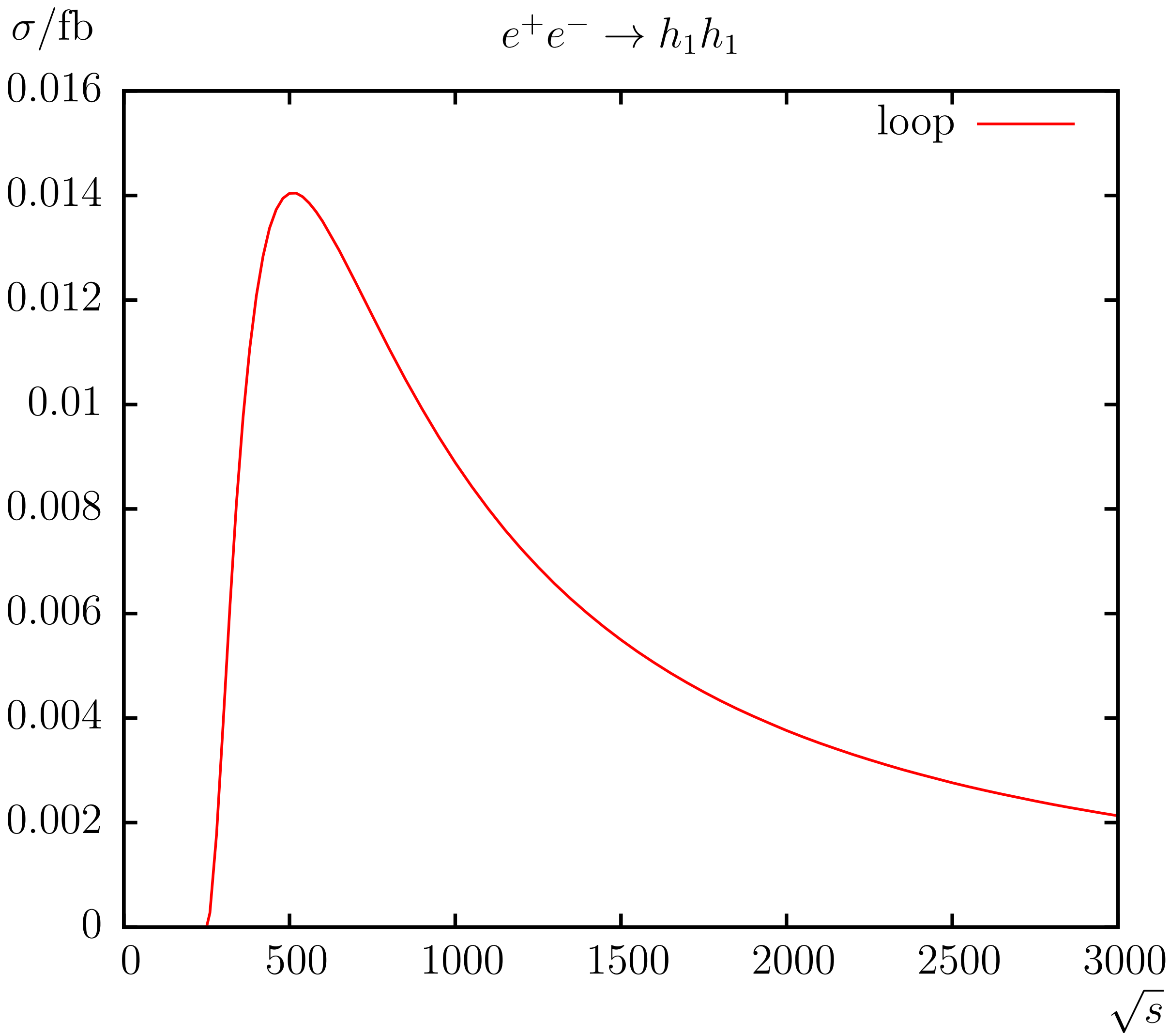
σ/fb
e+e− → h1h2
tree
full
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0 5 10 15 20 25 30 35 40 45 50
tan β

$e^+e^- \to h_1 h_2$:



$\Rightarrow$ phase dependence more pronounced at loop-level

$e^+e^- \to h_1 h_1$ (purely loop induced):



$\Rightarrow$ possibly observable!

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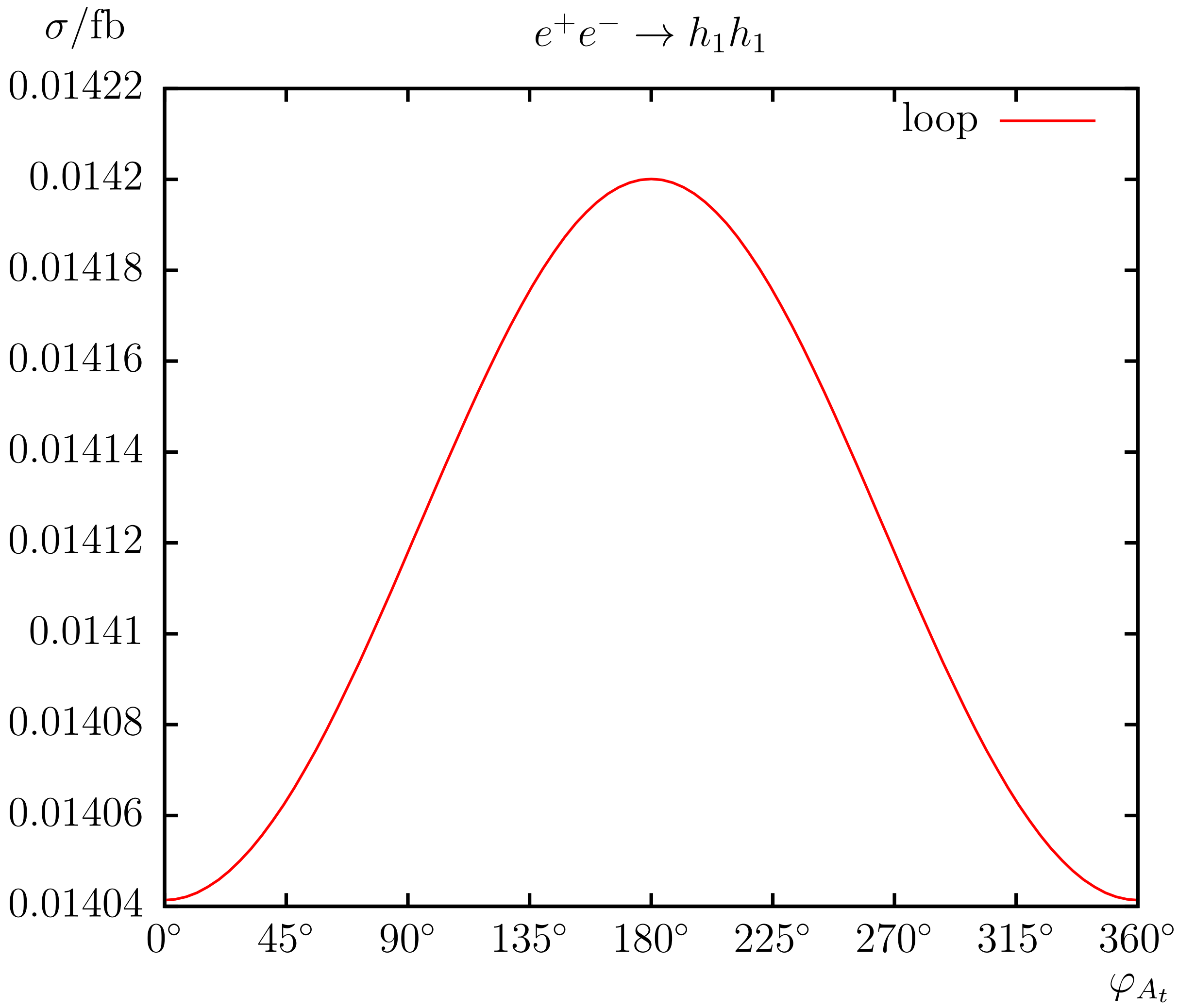
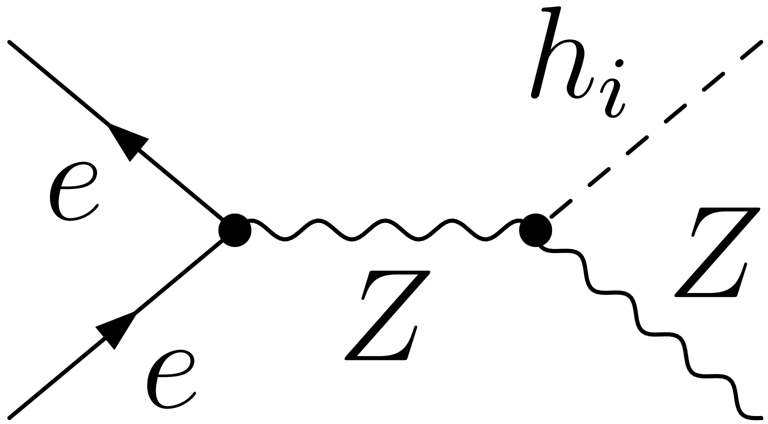
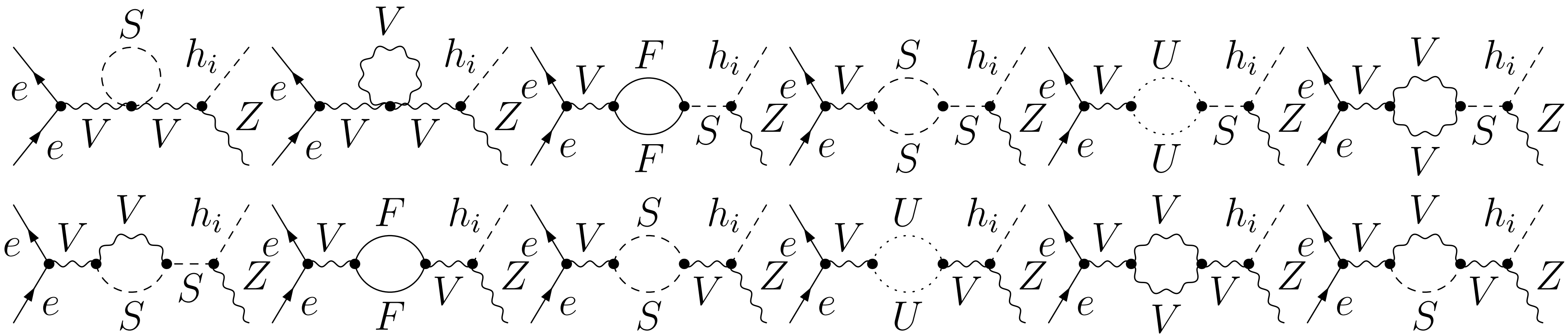


$\Rightarrow$ negligible ϕ_{A_t} dependence!

$e^+e^- \to h_i Z$:





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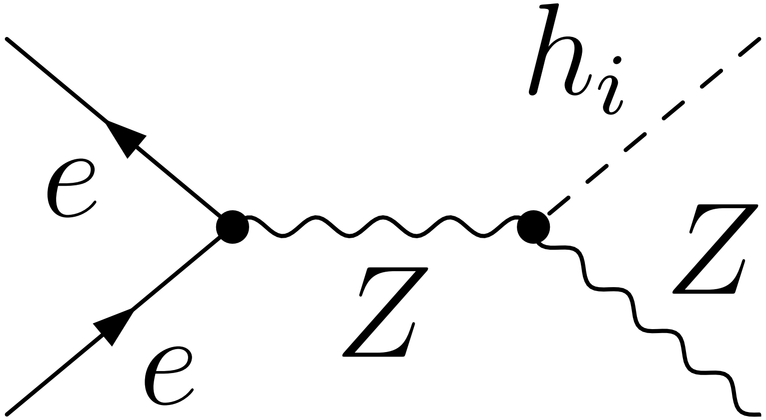

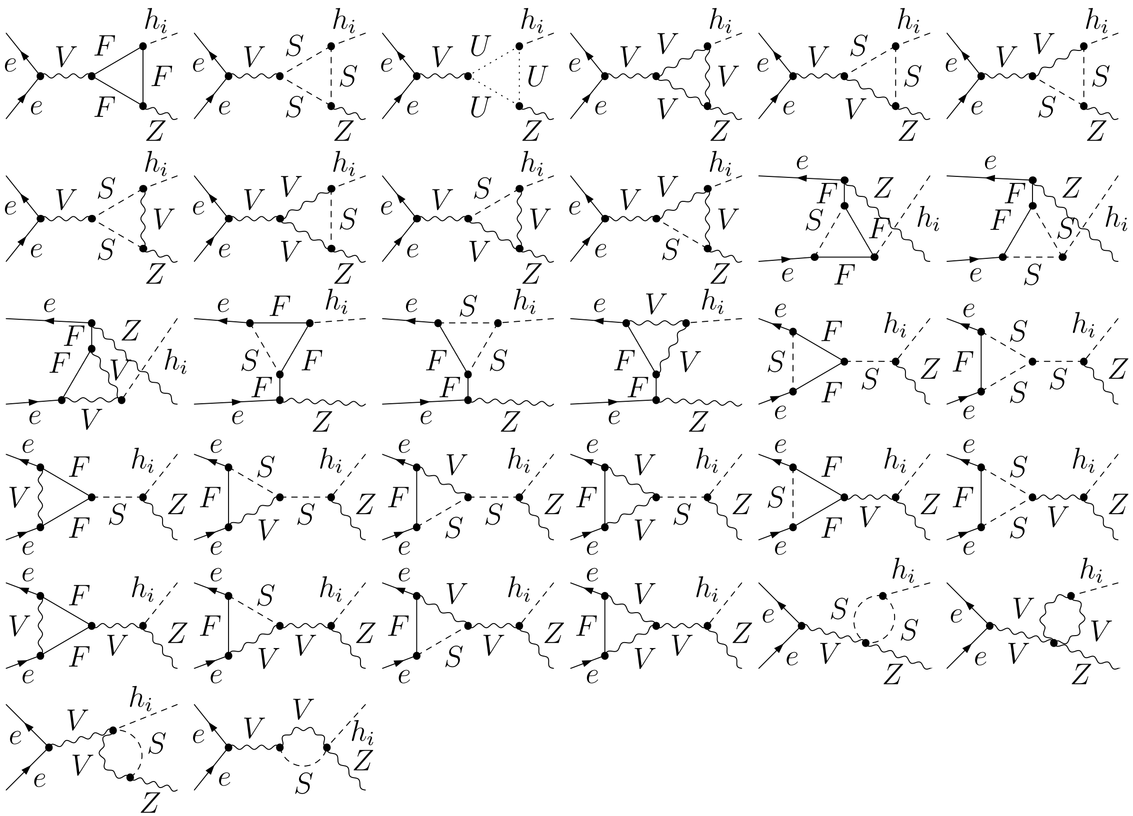

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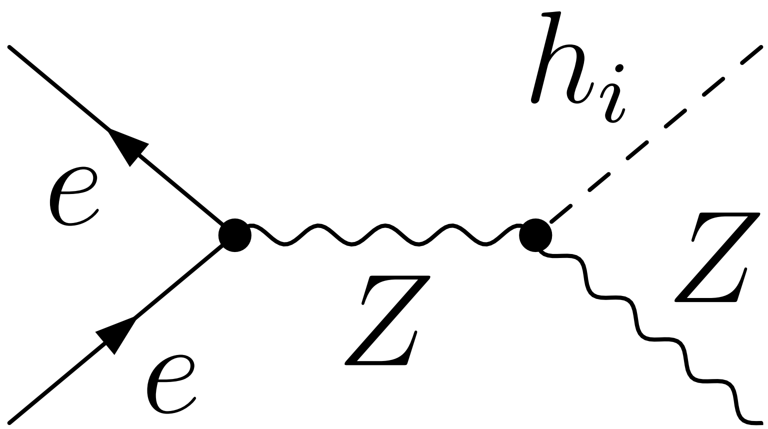
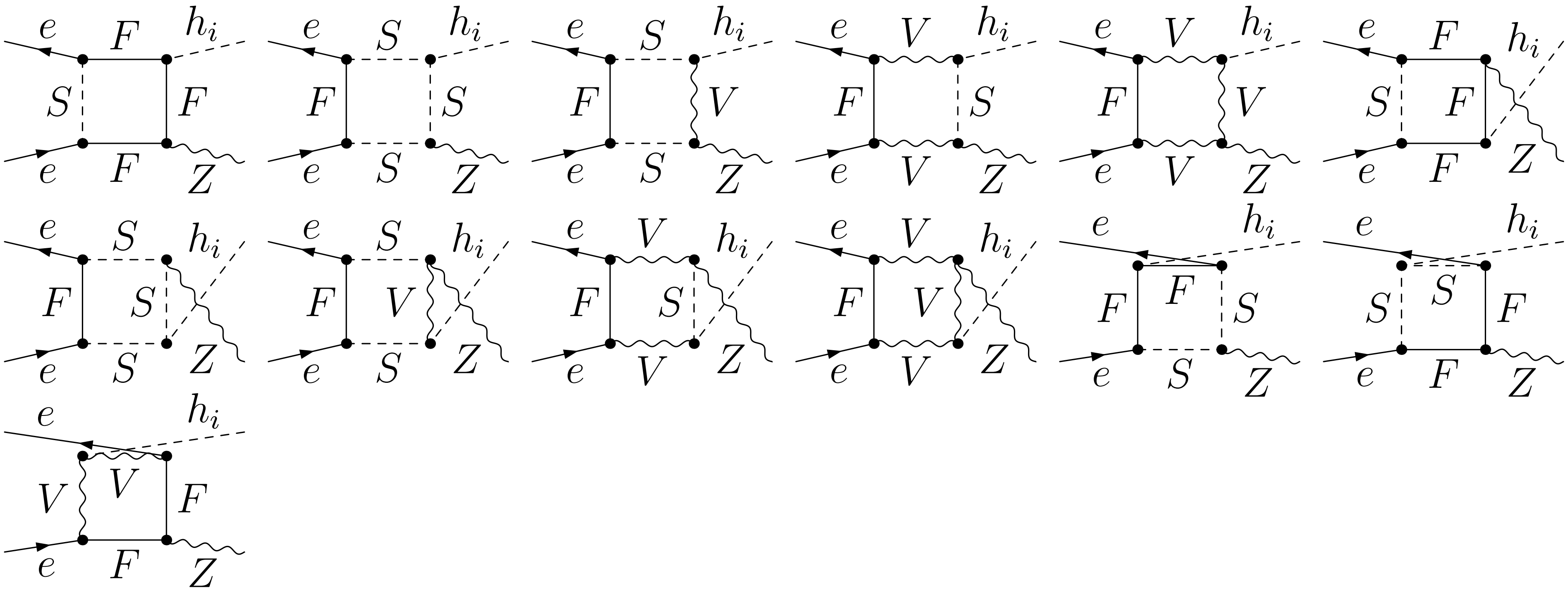


e
e
Z
h_i
Z



e F h_i S F e F Z
e S h_i F S e S Z
e S h_i F V e S Z
e V h_i F S e V Z
e V h_i F V e V Z
e F h_i S F e F Z
e S h_i F S e S Z
e S h_i F V e S Z
e V h_i F S e V Z
e V h_i F V e V Z
e h_i F F S e S Z
e h_i S S F e F Z
e h_i V V F e F Z

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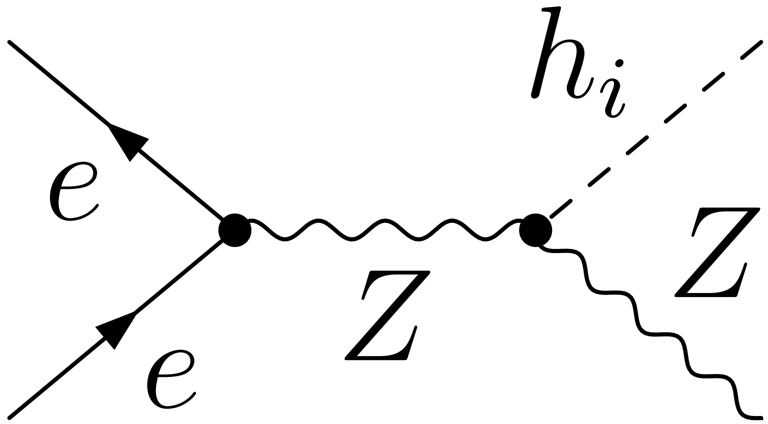

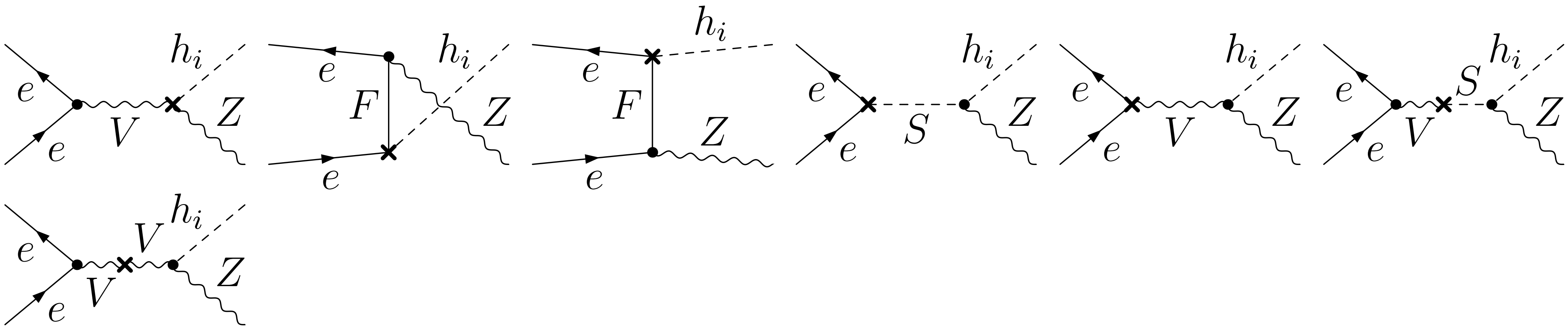

+ soft and hard QED radiation

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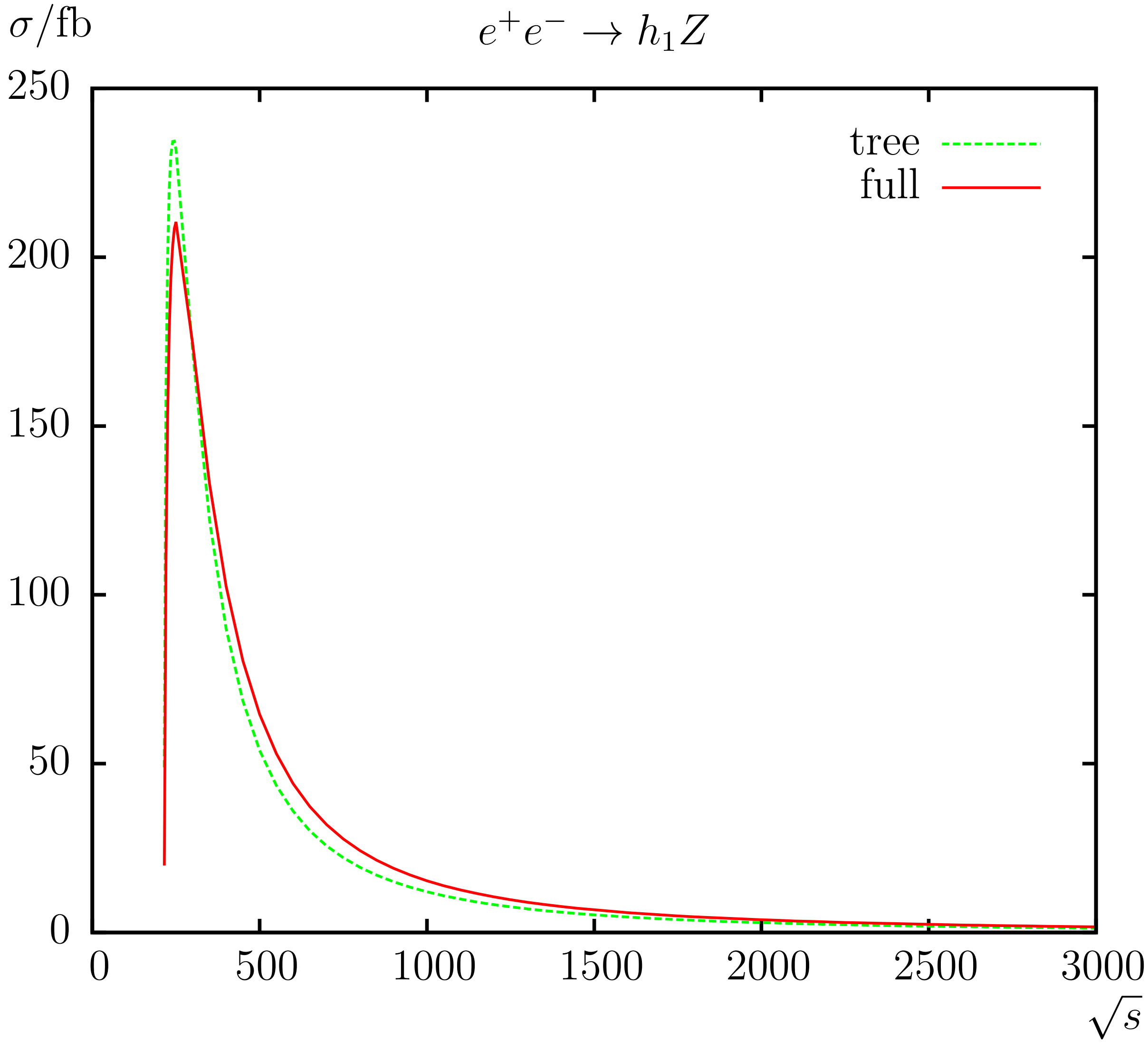
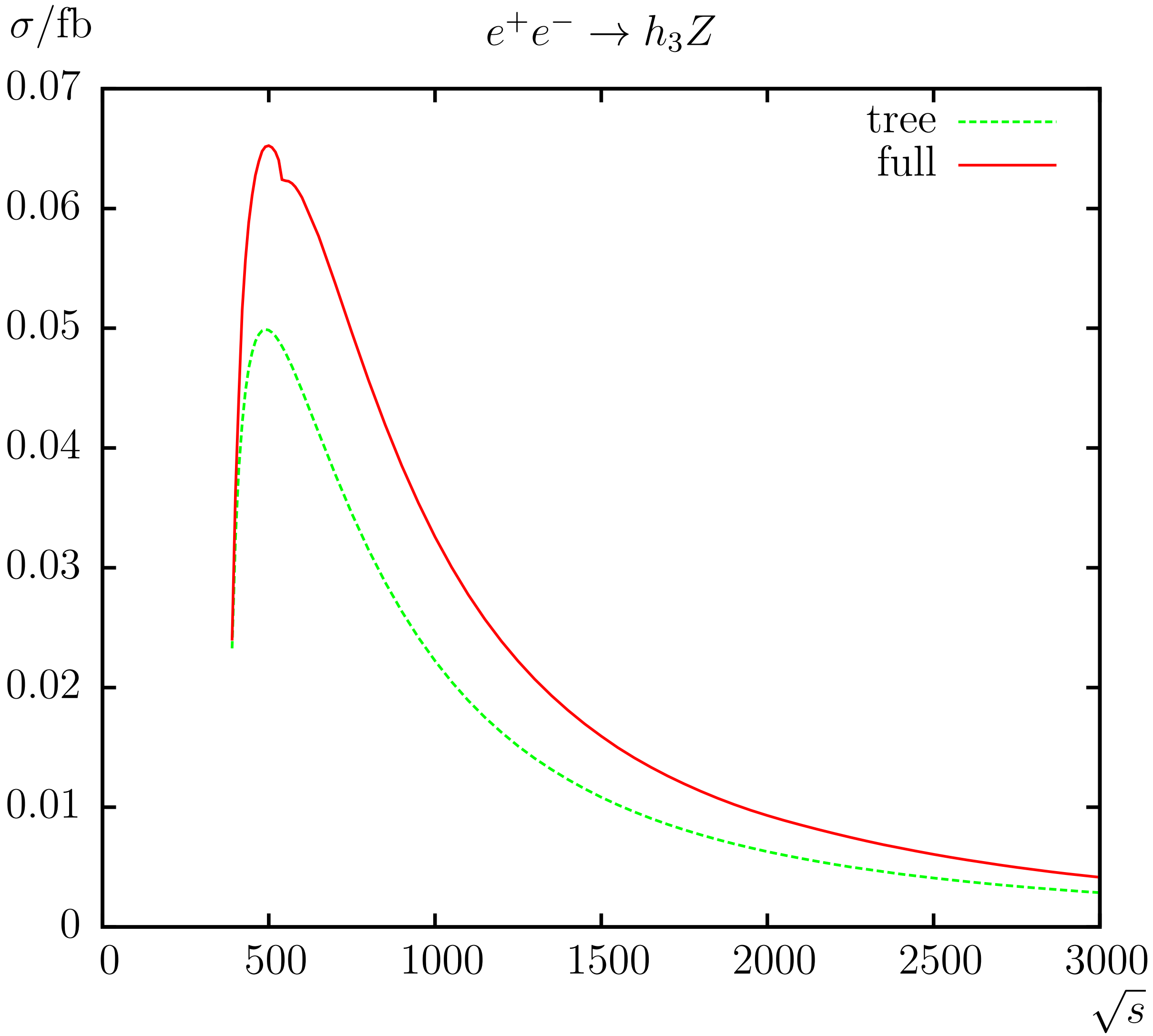


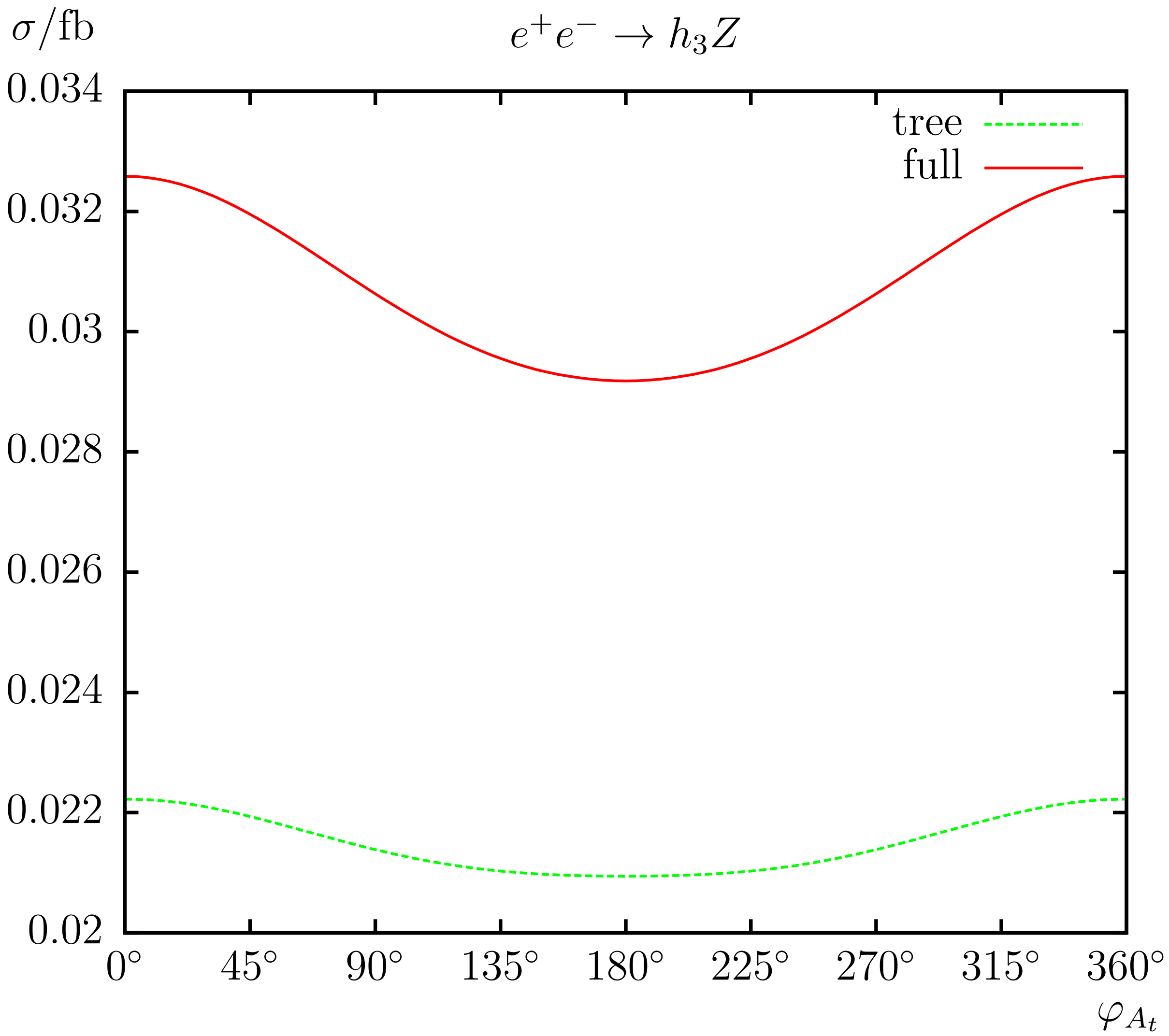
$\Rightarrow$ loop corrections crucial

$e^+e^- \to h_3 Z$:



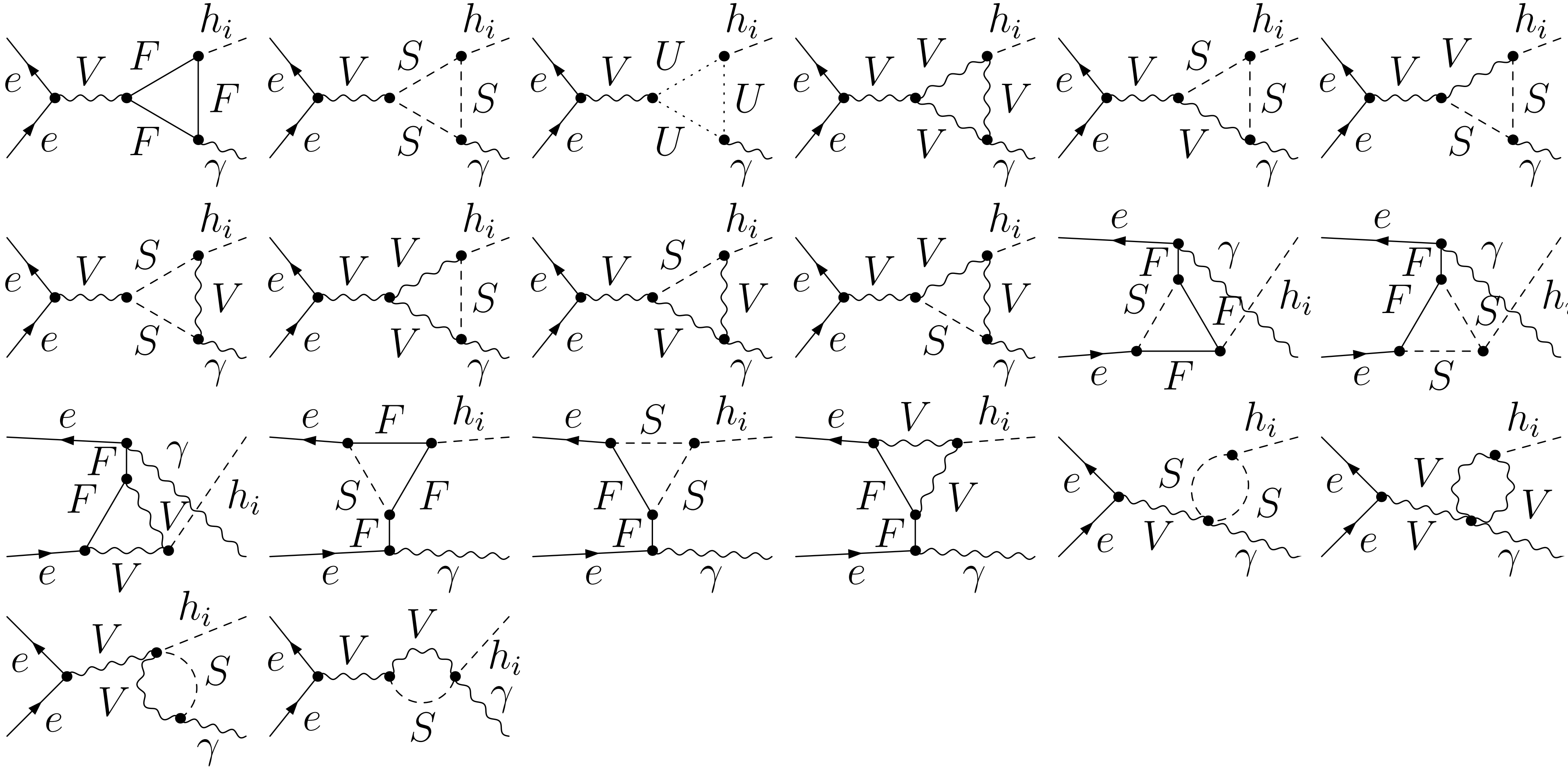
$\Rightarrow$ possibly observable, loop corrections crucial

$e^+e^- \to h_3 Z$:

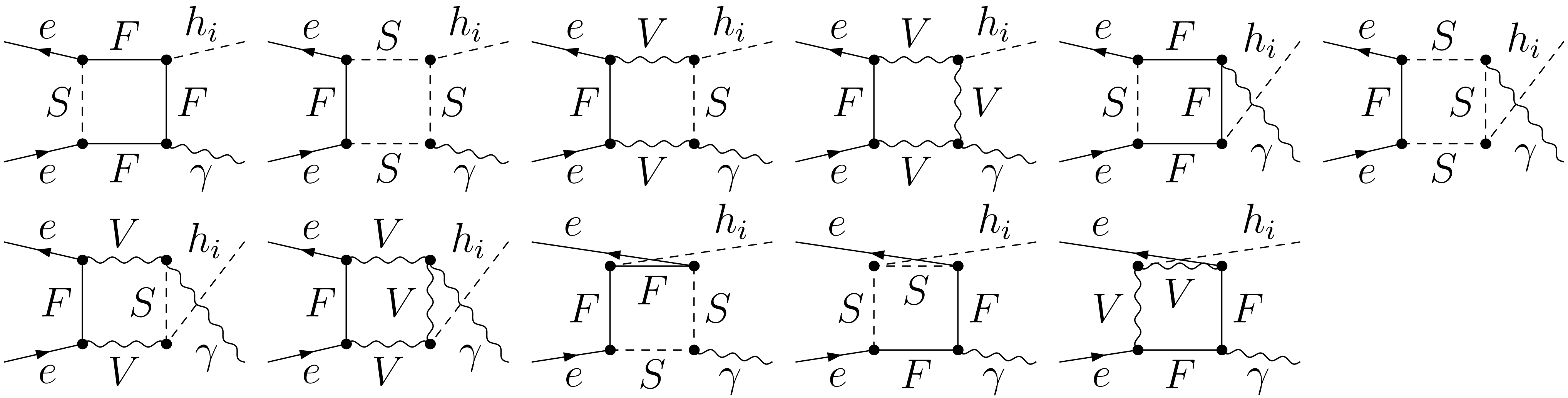


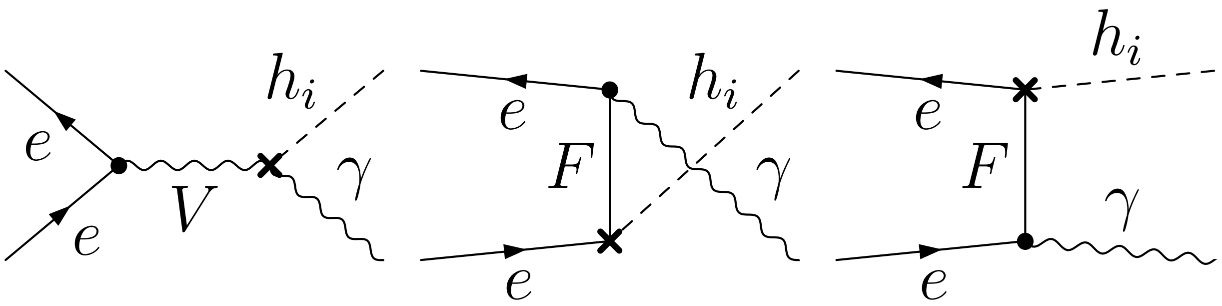
$\Rightarrow$ pronounced phase dependence at the loop level

$e^+e^- \to h_i\gamma$:



$e^+e^- \to h_i\gamma$:





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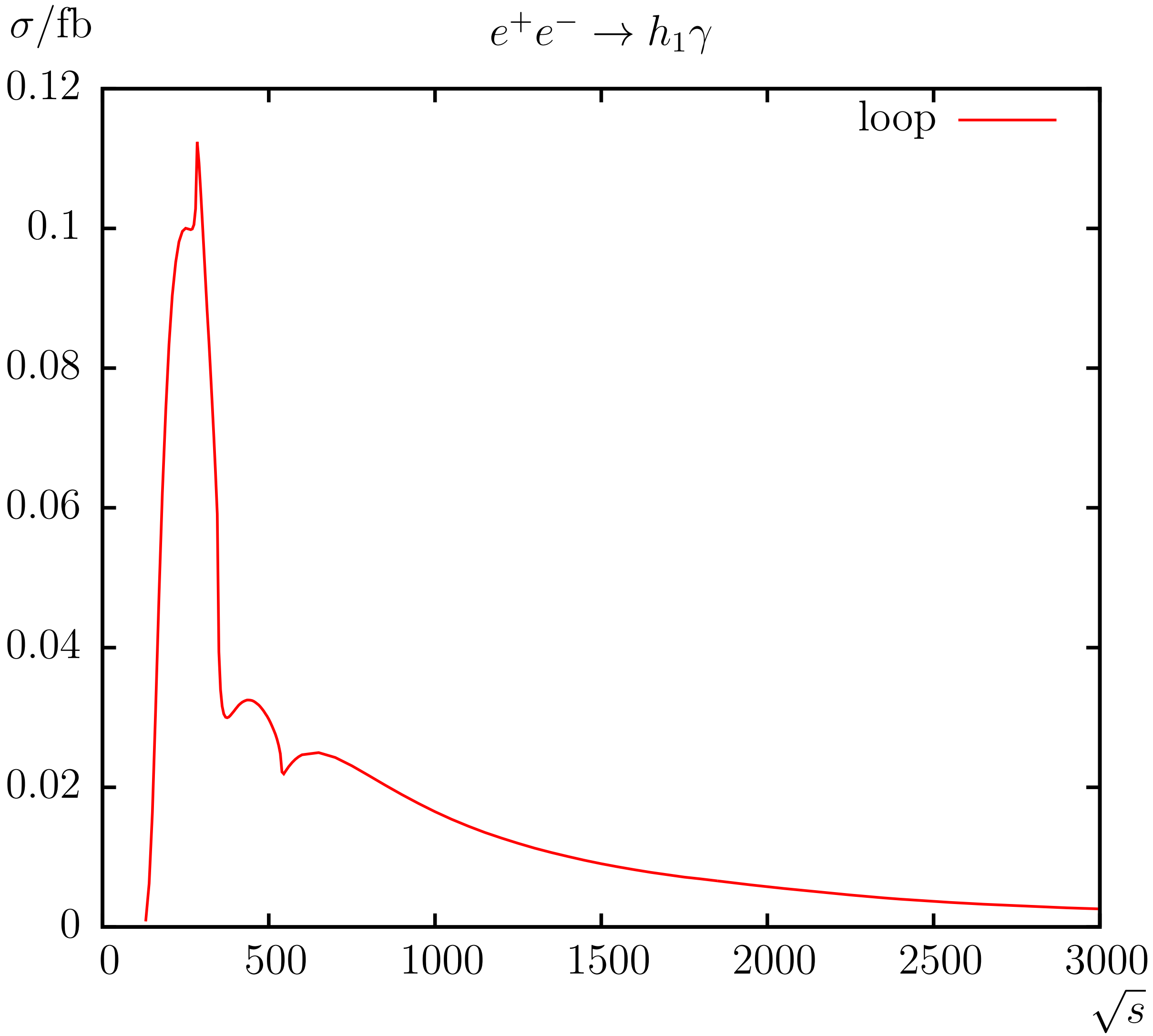

$\Rightarrow$ possibly observable!

4. Conclusinos

- High precision prediction for cross sections are crucial for coupling constant determination

- Prediction (in the SM and MSSM) needed at/below the per-cent level!

- Now available in the cMSSM at the full one-loop level:

$$\sigma(e^+e^- \to h_i h_j)$$
$$\sigma(e^+e^- \to h_i Z)$$
$$\sigma(e^+e^- \to h_i \gamma)$$

- Tree-level processes: loop corrections crucial
  $(e^+e- \to h_1h_2, h_1Z, \ldots)$

- Loop induced processes: possibly observable
  $(e^+e^- \to h_1h_1, h_1\gamma, \ldots)$