
HAVE YOU HEARD? THEY DISCOVERED THE GOD PARTI...
IT'S CALLED THE HIGGS BOSON!

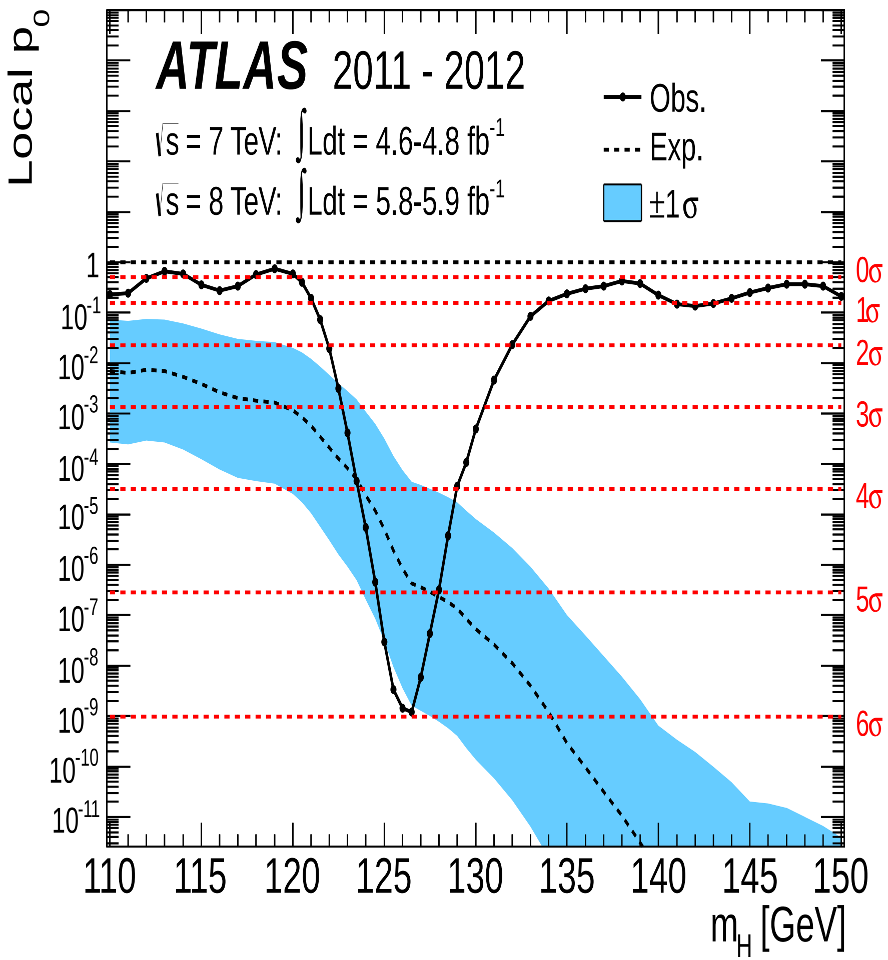
(N)MSSM Higgs Predictions for Production and Decay at the ILC and CLIC

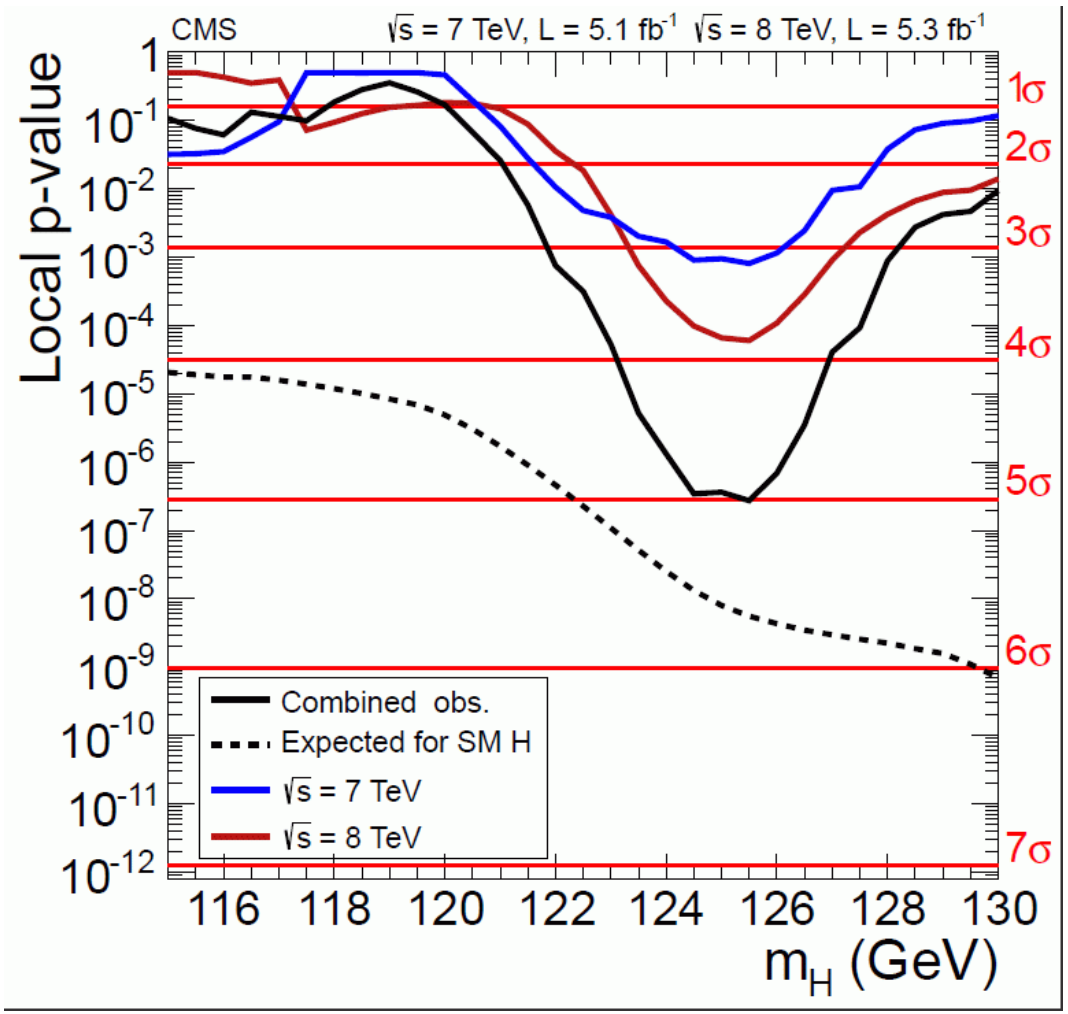
Sven Heinemeyer, IFT/IFCA (CSIC, Madrid/Santander)

Arlington, 10/2018

1. The Quest for Precision
2. MSSM Higgs production calculations for ILC/CLIC
3. (N)MSSM Higgs decays
4. Conclusions

1. The Quest for Precision





$\Rightarrow$ clear discovery at $\sim$ 125 GeV!

$\Rightarrow$ can be interpreted as the light(/heavy) $\mathcal{CP}$-even MSSM Higgs

The Higgs mass accuracy: experiment vs. theory:

Experiment:

ATLAS:	$M_h^{\text{exp}} = 125.36 \pm 0.37 \pm 0.18$ GeV
CMS:	$M_h^{\text{exp}} = 125.03 \pm 0.27 \pm 0.15$ GeV
combined:	$M_h^{\text{exp}} = 125.09 \pm 0.21 \pm 0.11$ GeV

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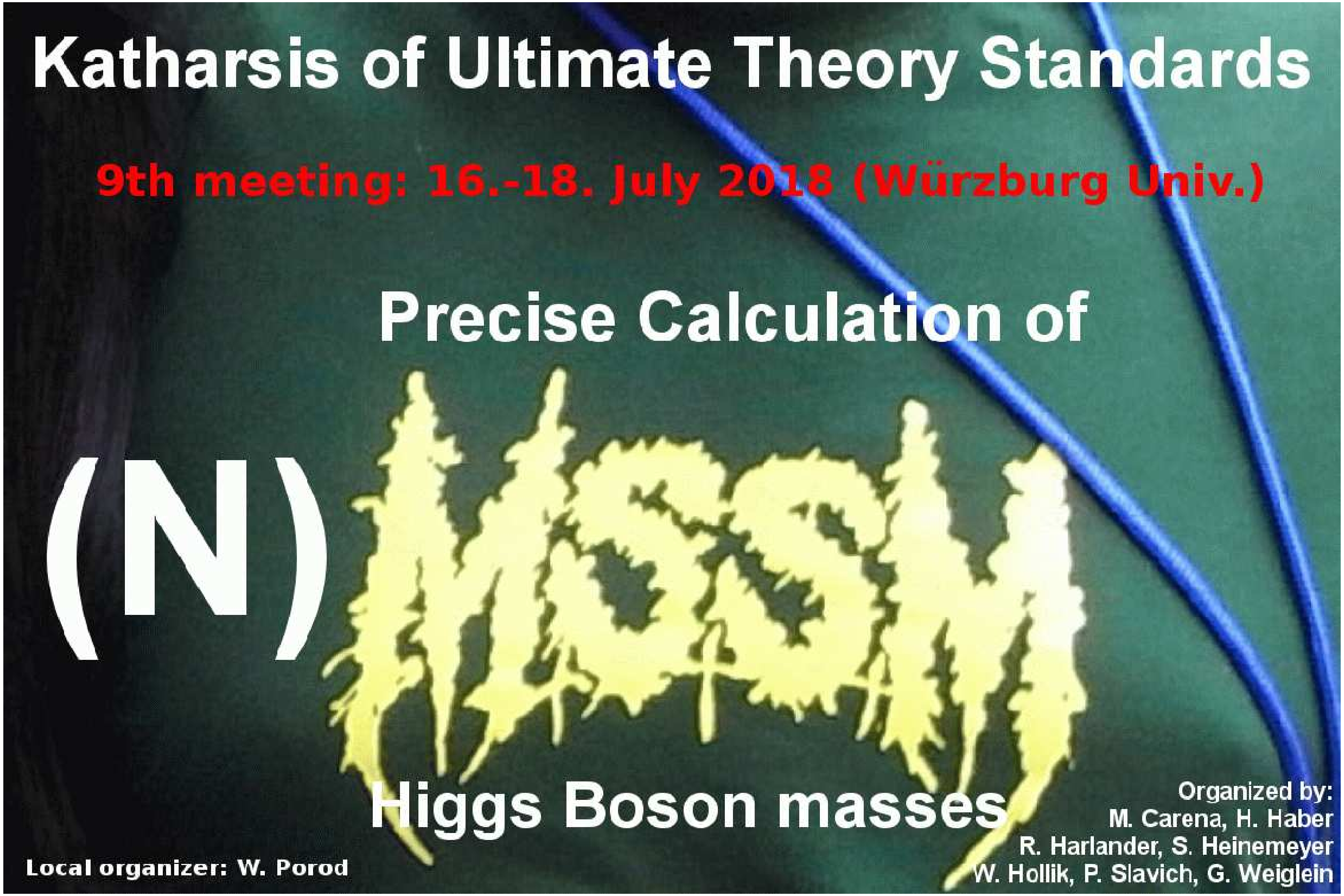
MSSM theory:

LHCHXSWG adopted FeynHiggs for the prediction of MSSM Higgs boson masses and mixings (considered to be the code containing the most complete implementation of higher-order corrections)

FeynHiggs: $\delta M_h^{\text{theo}} \sim 3$ GeV (now 2 GeV?)

$\to$ rough estimate, FeynHiggs contains algorithm to evaluate uncertainty, depending on parameter point

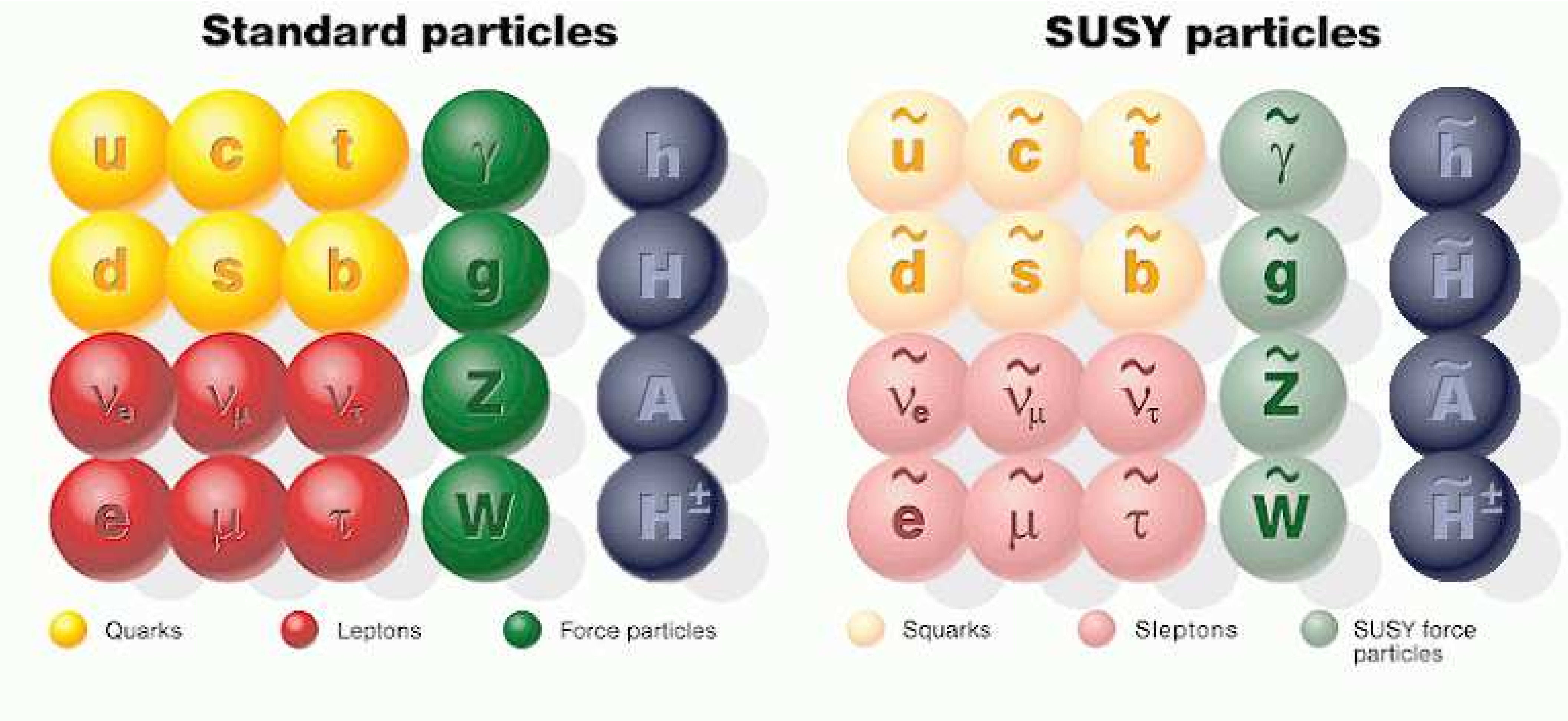
Working group on M_h predictions: sites.google.com/site/kutsmh



⇒ next meeting: 04/2019 in Dresden

The MSSM:

⇒ Superpartners for Standard Model particles



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

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

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

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

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

gauge couplings, in contrast to SM

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

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

Input parameters: (to be determined experimentally)

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

Z_3 invariant NMSSM

MSSM Higgs sector: Two Higgs doublets

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

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

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

Z_3 invariant NMSSM

NMSSM Higgs sector: Two Higgs doublets + one Higgs singlet

$$
\begin{aligned}
H_1 &= \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix} \\
H_2 &= \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix} \\
S &= v_s + S_R + I S_I
\end{aligned}
$$

$$
\begin{aligned}
V = {} & (\tilde{m}_1^2 + |\not{\mu}\lambda S|^2) H_1 \bar{H}_1 + (\tilde{m}_2^2 + |\not{\mu}\lambda S|^2) H_2 \bar{H}_2 - m_{12}^2(\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\
& + \frac{g'^2 + g^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2 \\
& + |\lambda(\epsilon_{ab} H_1^a H_2^b) + \kappa S^2|^2 + m_S^2 |S|^2 + (\lambda A_\lambda (\epsilon_{ab} H_1^a H_2^b) S + \frac{\kappa}{3} A_\kappa S^3 + \text{h.c.})
\end{aligned}
$$

Free parameters:

$$\lambda,\ \kappa,\ A_\kappa,\ M_{H^\pm},\ \tan\beta,\ \mu_{\text{eff}} = \lambda v_s$$

Higgs spectrum:

$$\begin{aligned} \mathcal{CP}\text{−even} &: h_1, h_2, h_3 \\ \mathcal{CP}\text{−odd} &: a_1, a_2 \\ \text{charged} &: H^+, H^- \\ \text{Goldstones} &: G^0, G^+, G^- \end{aligned}$$

Neutralinos:

$$\mu \to \mu_{\text{eff}}$$

compared to the MSSM: one singlino more

$$\to \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_5^0$$

Mass of the lightest $\mathcal{CP}$-even Higgs:

$$m^2_{h,\text{tree,NMSSM}} = m^2_{h,\text{tree,MSSM}} + M_Z^2 \frac{\lambda^2}{g^2} \sin^2 2\beta$$

Mass of the $\mathcal{CP}$-odd Higgs:

$$\text{MSSM} : M_A^2 = -m_{12}^2(\tan\beta + \cot\beta) = \mu B(\tan\beta + \cot\beta)$$

$$\text{NMSSM} : \text{"}M_A^2\text{"} = \mu_{\text{eff}} B_{\text{eff}}(\tan\beta + \cot\beta)$$

with $B_{\text{eff}} = A_\lambda + \kappa\, s,\ \mu_{\text{eff}} = \lambda\, s$ $\Rightarrow$ one very light a_1

Mass of the charged Higgs:

$$\text{MSSM} : M_{H^\pm}^2 = M_A^2 + M_W^2 = M_A^2 + \frac{1}{2} v^2 g^2$$

$$\text{NMSSM} : M_{H^\pm}^2 = M_A^2 + v^2 \left(\frac{g^2}{2} - \lambda^2 \right)$$

Mass of the lightest $\mathcal{CP}$-even Higgs:

$$m^2_{h,\text{tree,NMSSM}} = m^2_{h,\text{tree,MSSM}} + M_Z^2 \frac{\lambda^2}{g^2} \sin^2 2\beta$$

Mass of the $\mathcal{CP}$-odd Higgs:

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Mass of the charged Higgs:

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$$\text{NMSSM}: M^2_{H^\pm} = M_A^2 + v^2 \left(\frac{g^2}{2} - \lambda^2\right)$$

$\Rightarrow M_{h_1}^{\text{MSSM,tree}} \le M_{h_1}^{\text{NMSSM,tree}}$, one light a_1, $M_{H^\pm}^{\text{MSSM,tree}} \ge M_{H^\pm}^{\text{NMSSM,tree}}$

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

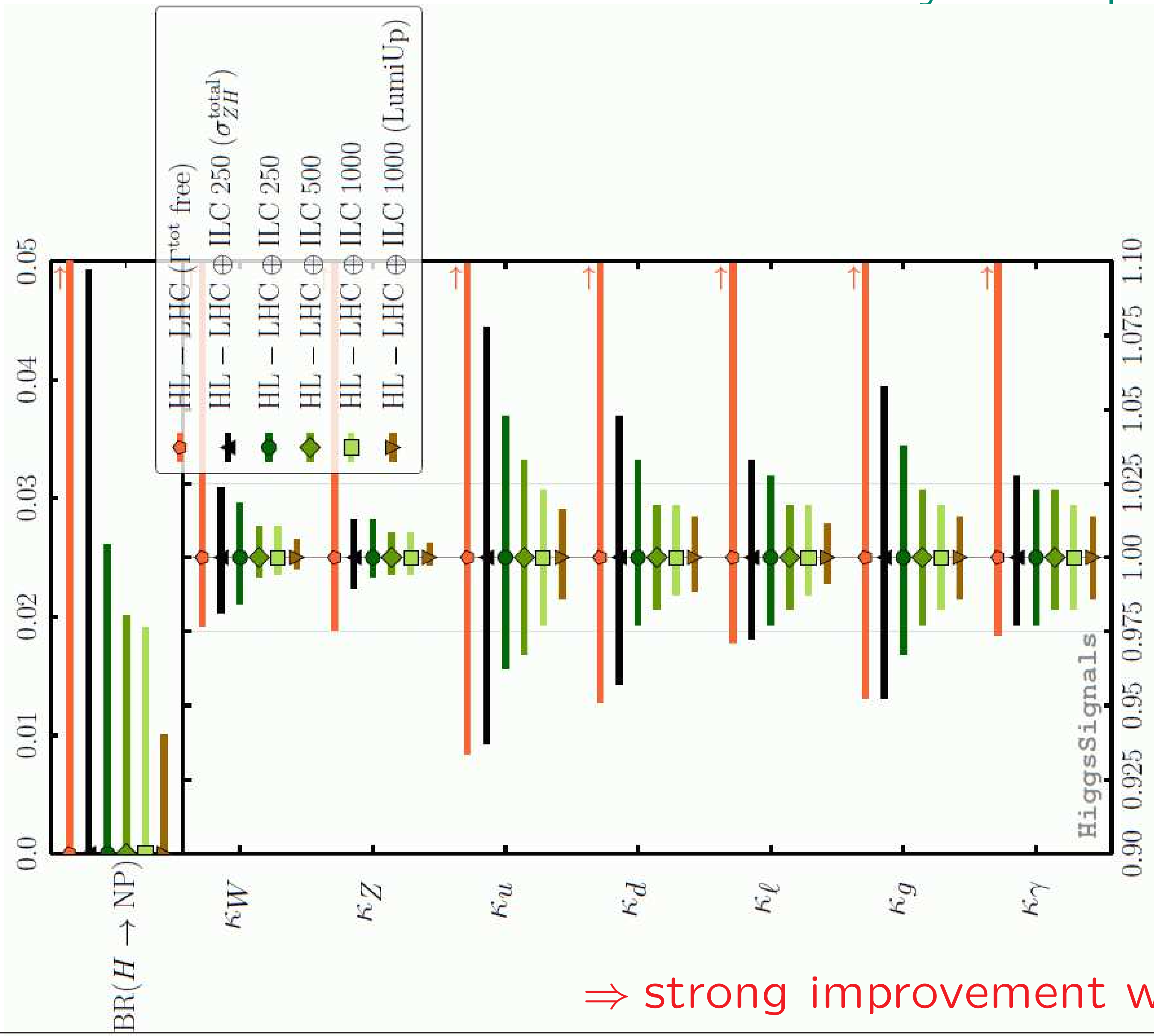
$\Rightarrow$ improvements necessary . . . full 2-loop calculations and more . . . ?!

$\Rightarrow$ 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*]

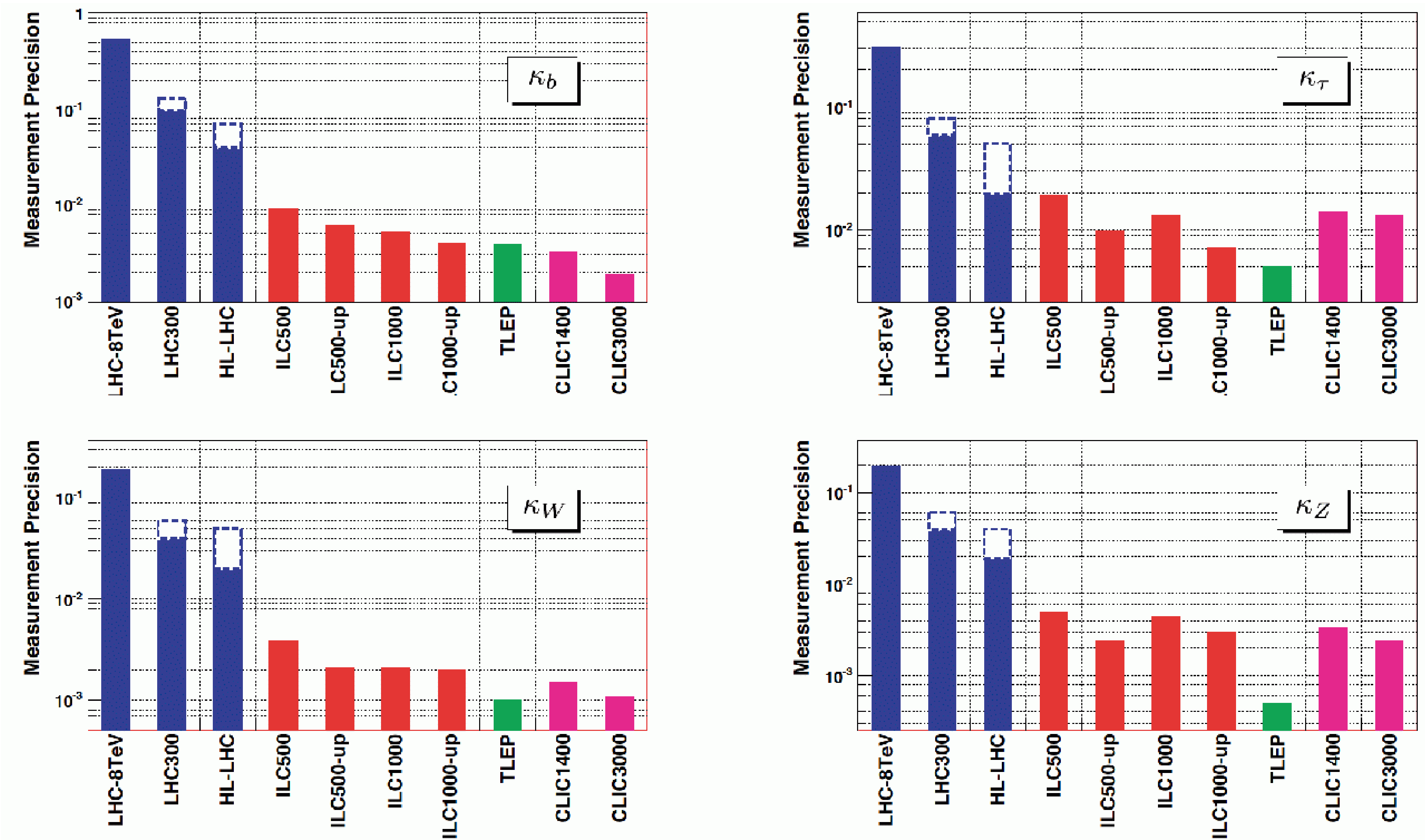
no theory assumptions, full fit



⇒ strong improvement with the ILC

ILC vs. TLEP/FCC-ee:

[*Snowmass Higgs Report '13*]



$\Rightarrow$ can the sub-percent/permille level be matched by theory?

Needed for LHC/ILC/CLIC/. . . physics:

Precise and consistent prediction of

- Higgs boson masses
- Higgs boson mixings
- Higgs boson couplings
- Higgs boson production cross sections $\Leftarrow$ focus here
- Higgs boson decay widths/branching ratios $\Leftarrow$ focus here
- . . .

$\Rightarrow$ (partially) provided by FeynHiggs

2. MSSM Higgs production calculations for ILC/CLIC

Neutral Higgs production:

$$e^+e^- \to h_i Z,\ h_i\gamma,\ h_i h_j,\ h_i\nu\bar{\nu},\ h_i e^+e^-,\ h_i t\bar{t},\ h_i b\bar{b},\ \ldots \qquad (i,j = 1,2,3)\,.$$

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

[*S.H., C. Schappacher '15*] [*F. Arco, S.H., C. Schappacher '18*]

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

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

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

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.

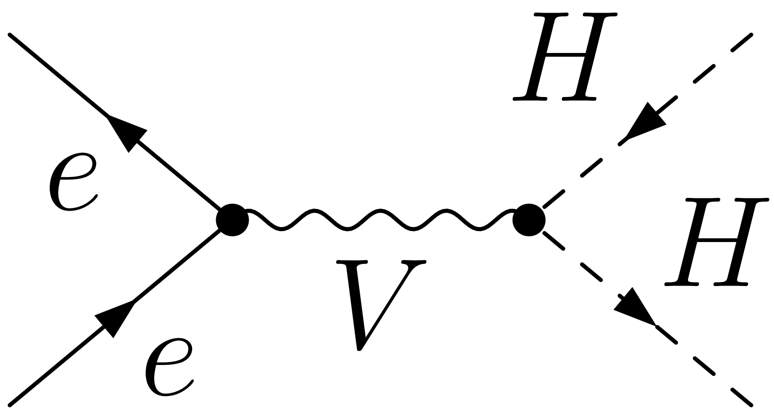
Scen.	$\sqrt{s}$	t_β	μ	$M_{H^\pm}$	$M_{\tilde{Q},\tilde{U},\tilde{D}}$	$M_{\tilde{L},\tilde{E}}$	$\lvert A_{t,b,\tau}\rvert$	M_1	M_2	M_3
$\mathcal{S}$	1000	7	200	300	1000	500	$1500 + \mu/t_\beta$	100	200	1500

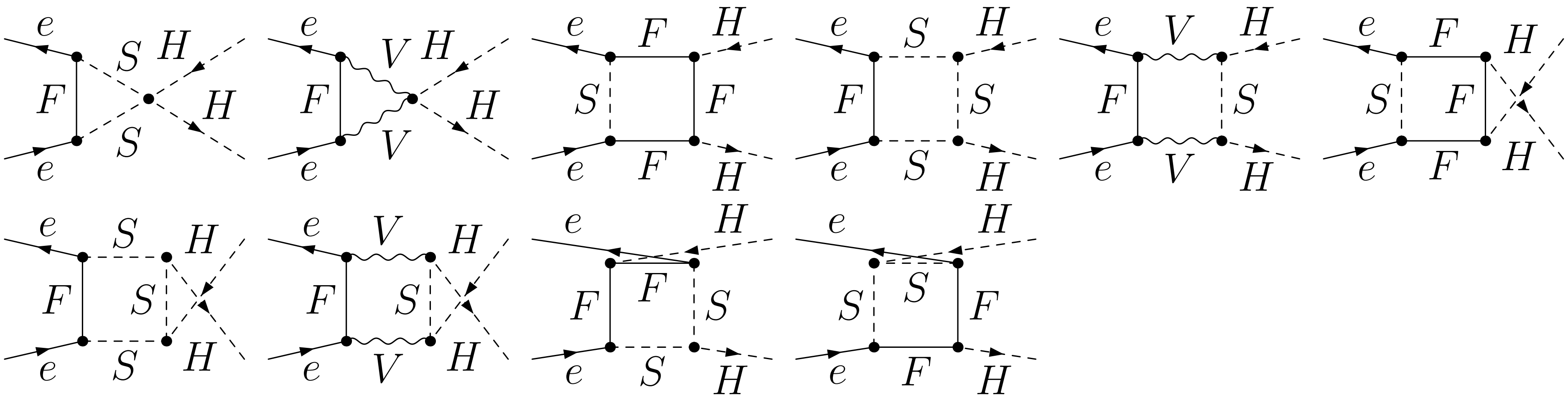
m_{h_1}	m_{h_2}	m_{h_3}
123.404	288.762	290.588

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

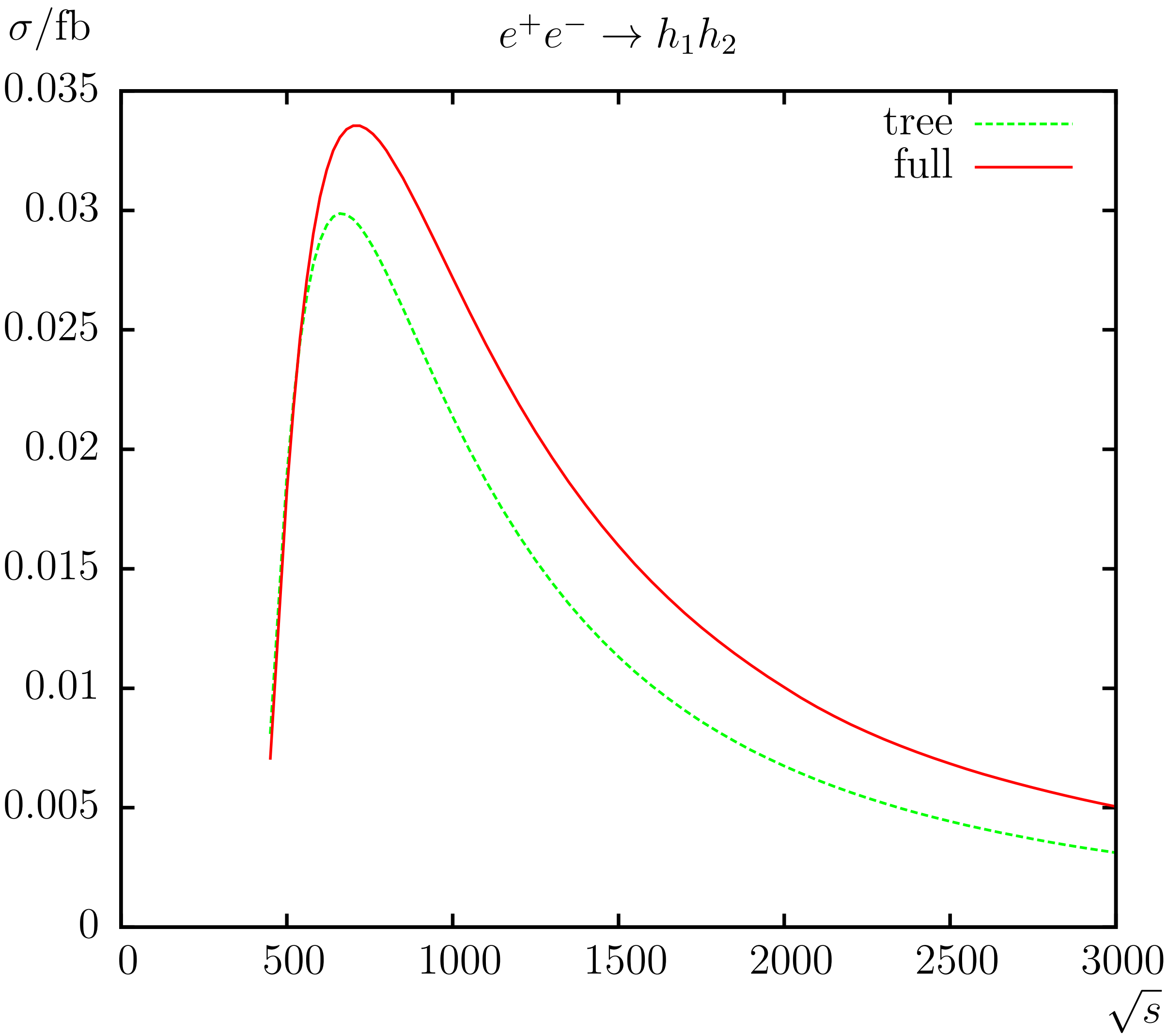
– Scenario chosen such that many processes are possible at the same time
– not chosen to maximize loop corrections

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


e
e
V
H
H

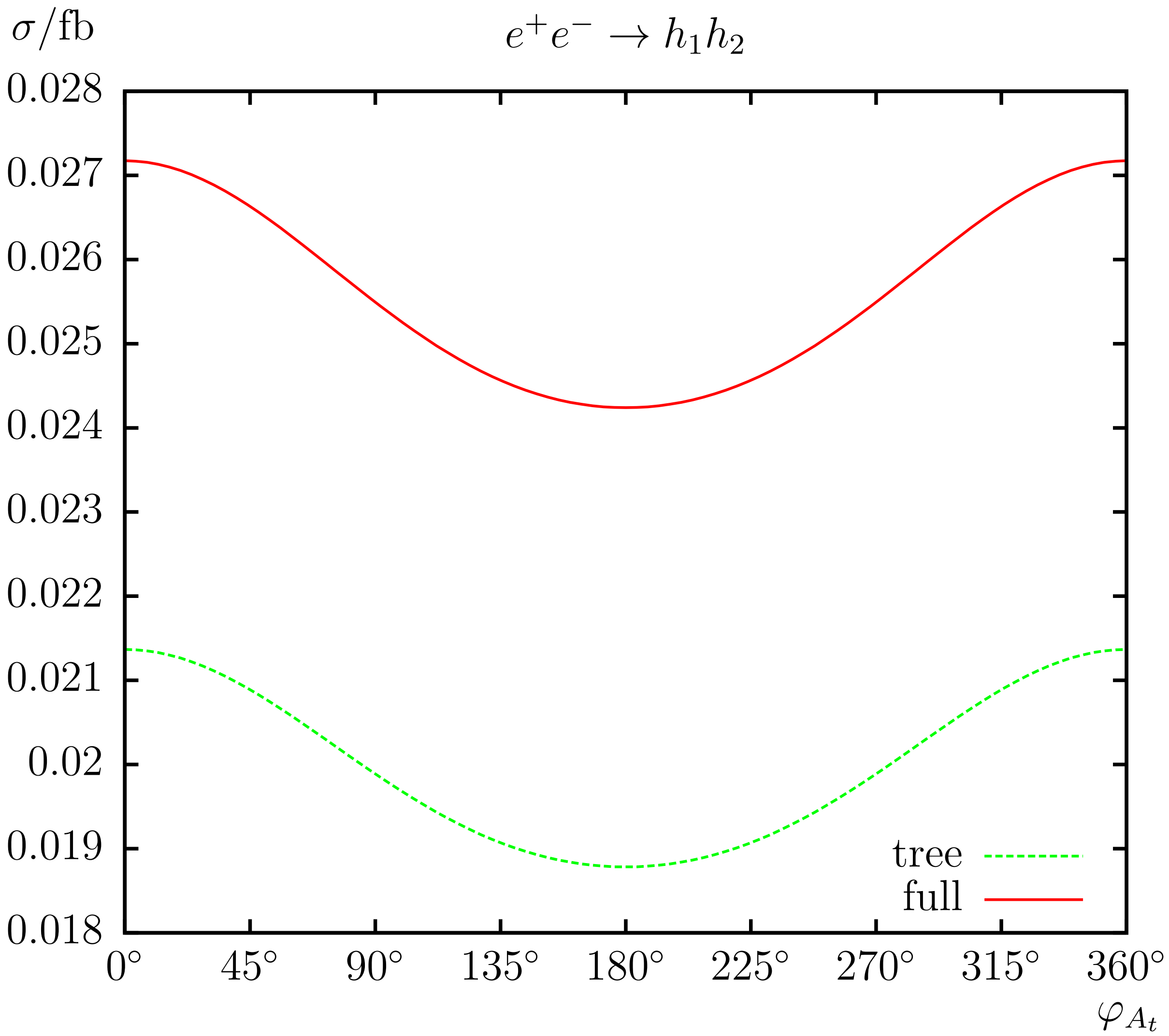

e S H F H S e
e V H F H V e
e F H S F F e H
e S H F S S e H
e V H F S V e H
e F H S F F e H
e S H F S S e H
e V H F S V e H
e H F F S S e H
e H S S F F e H

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



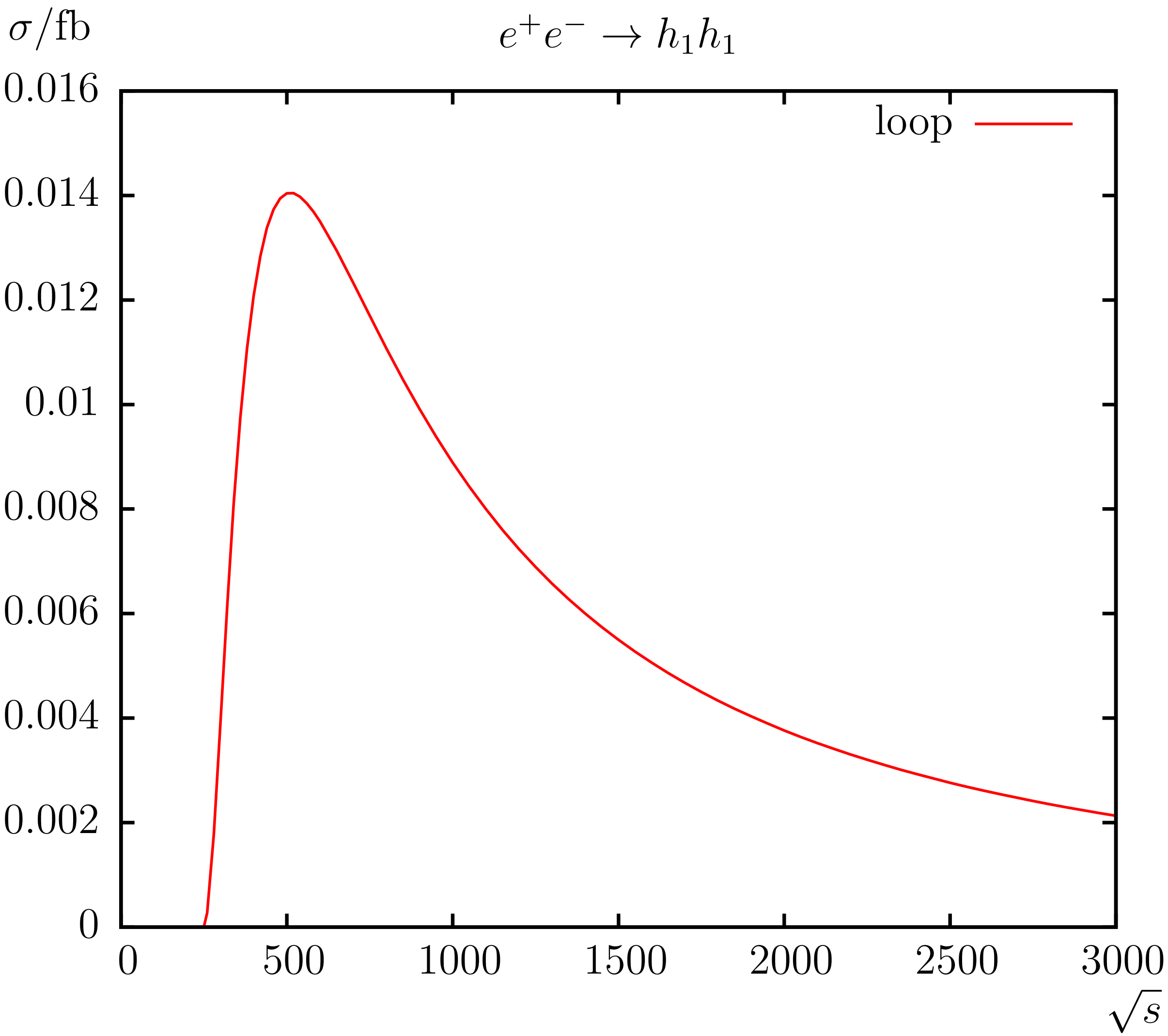
$\Rightarrow$ loop corrections crucial!

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



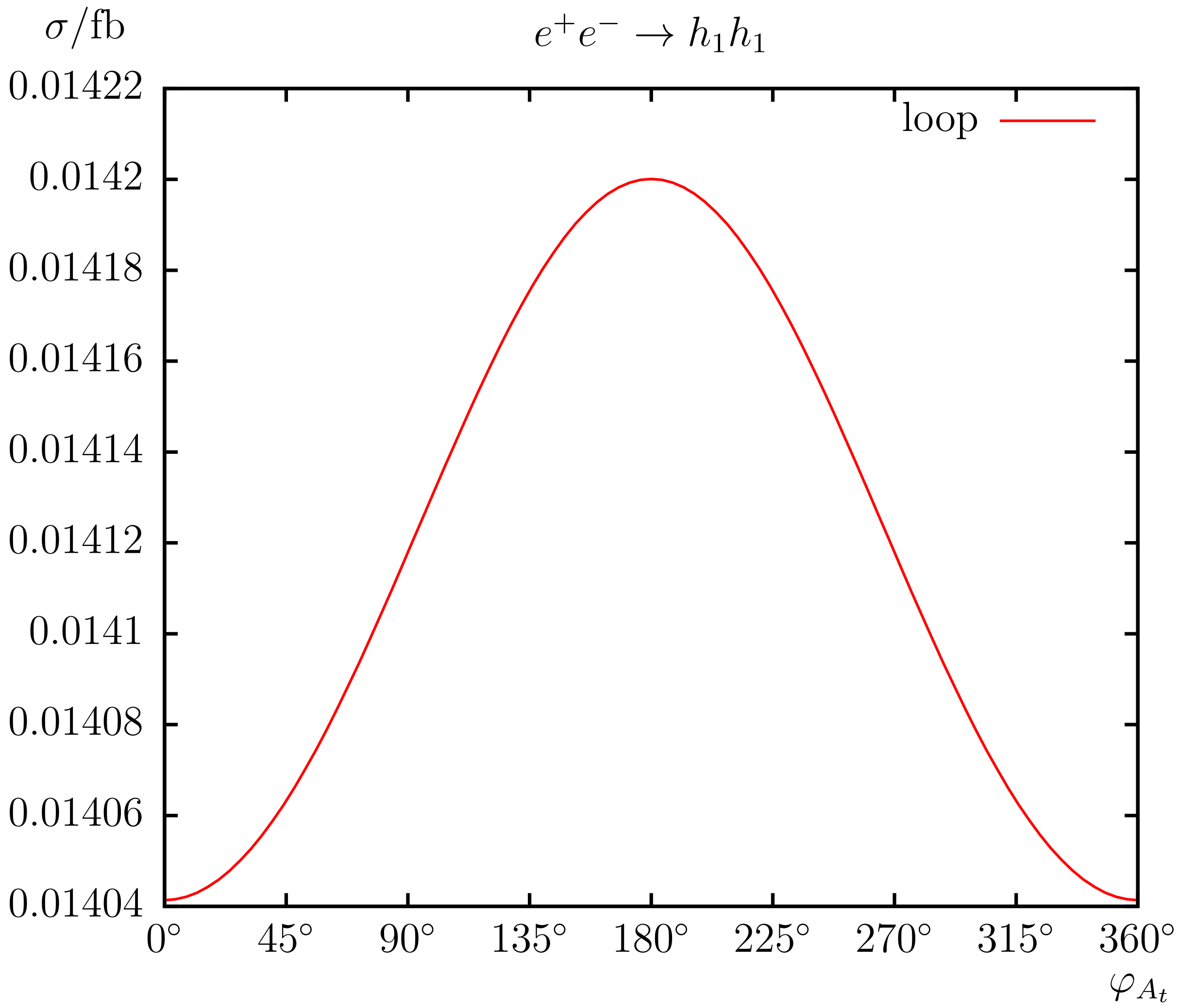
⇒ phase dependence more pronounced at loop-level

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



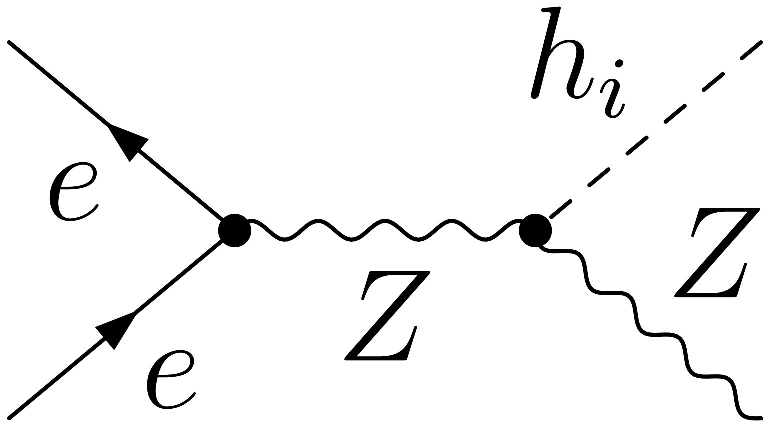
$\Rightarrow$ possibly observable!

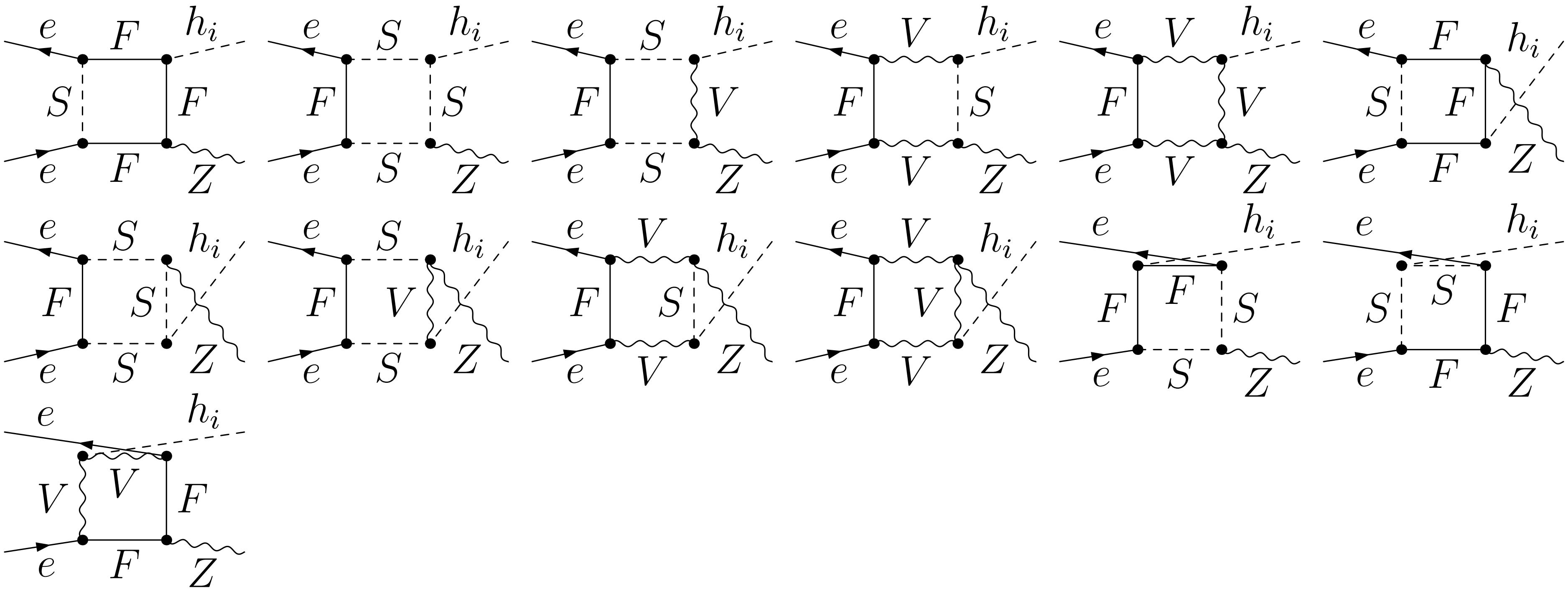
$e^+e^- \to h_1 h_1$ (purely loop induced):



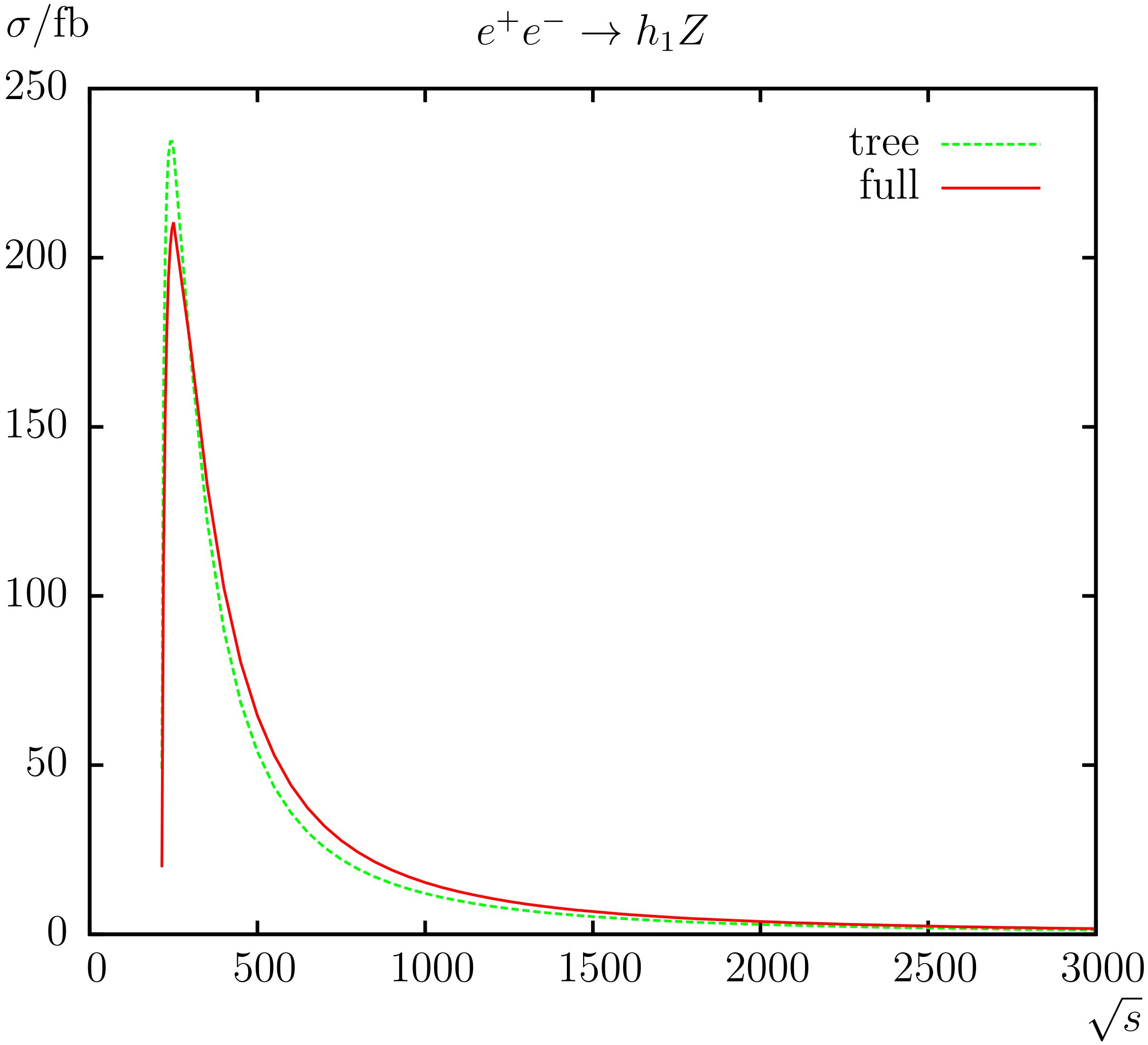
$\Rightarrow$ negligible ϕ_{A_t} dependence!

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


e
e
Z
h_i
Z

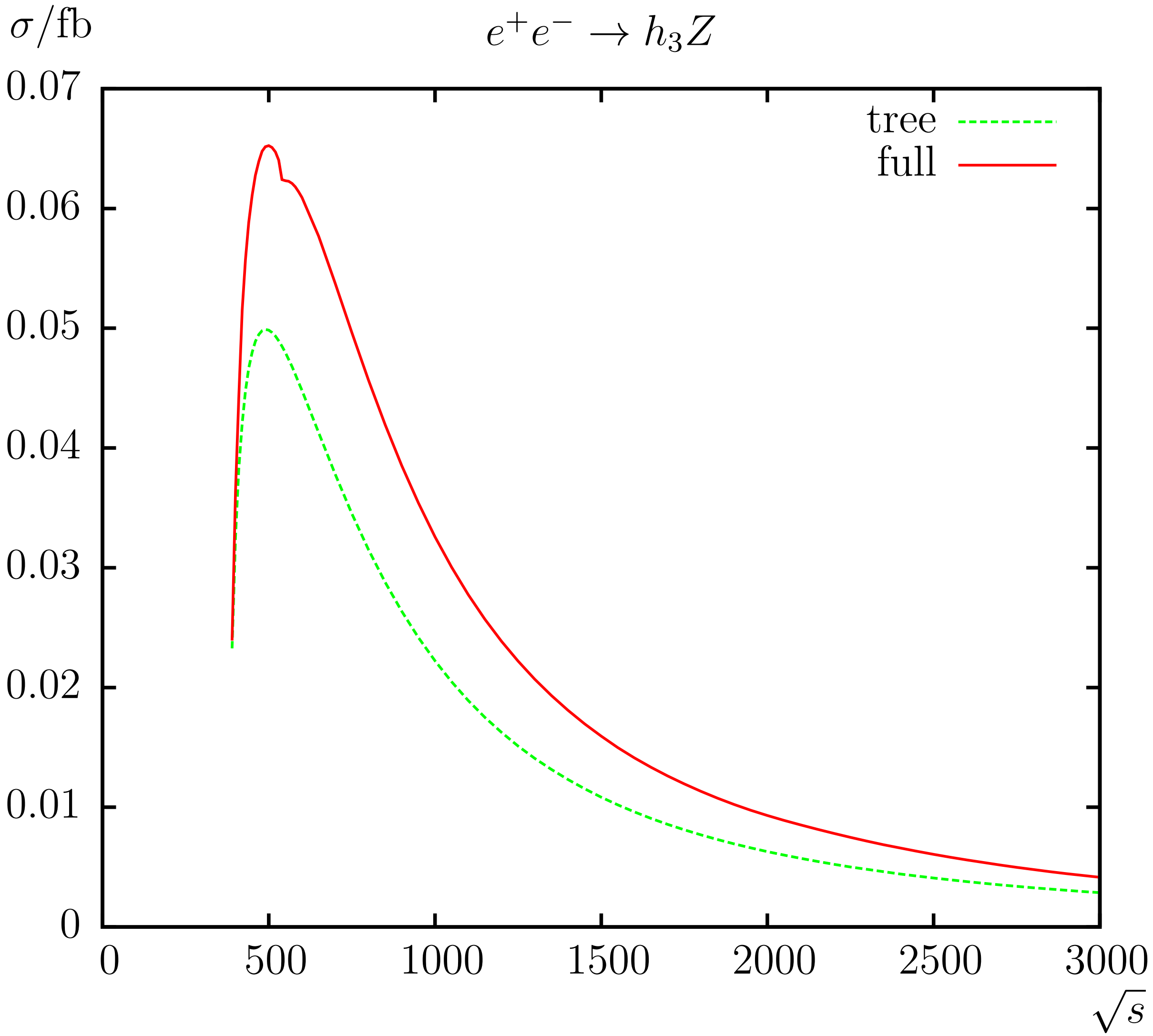

e F h_i S F e F Z
e S h_i F S e S Z
e S h_i F V e S Z
e V h_i F S e V Z
e V h_i F V e V Z
e F h_i S F e F Z
e S h_i F S e S Z
e S h_i F V e S Z
e V h_i F S e V Z
e V h_i F V e V Z
e h_i F F S e S Z
e h_i S S F e F Z
e h_i V V F e F Z

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



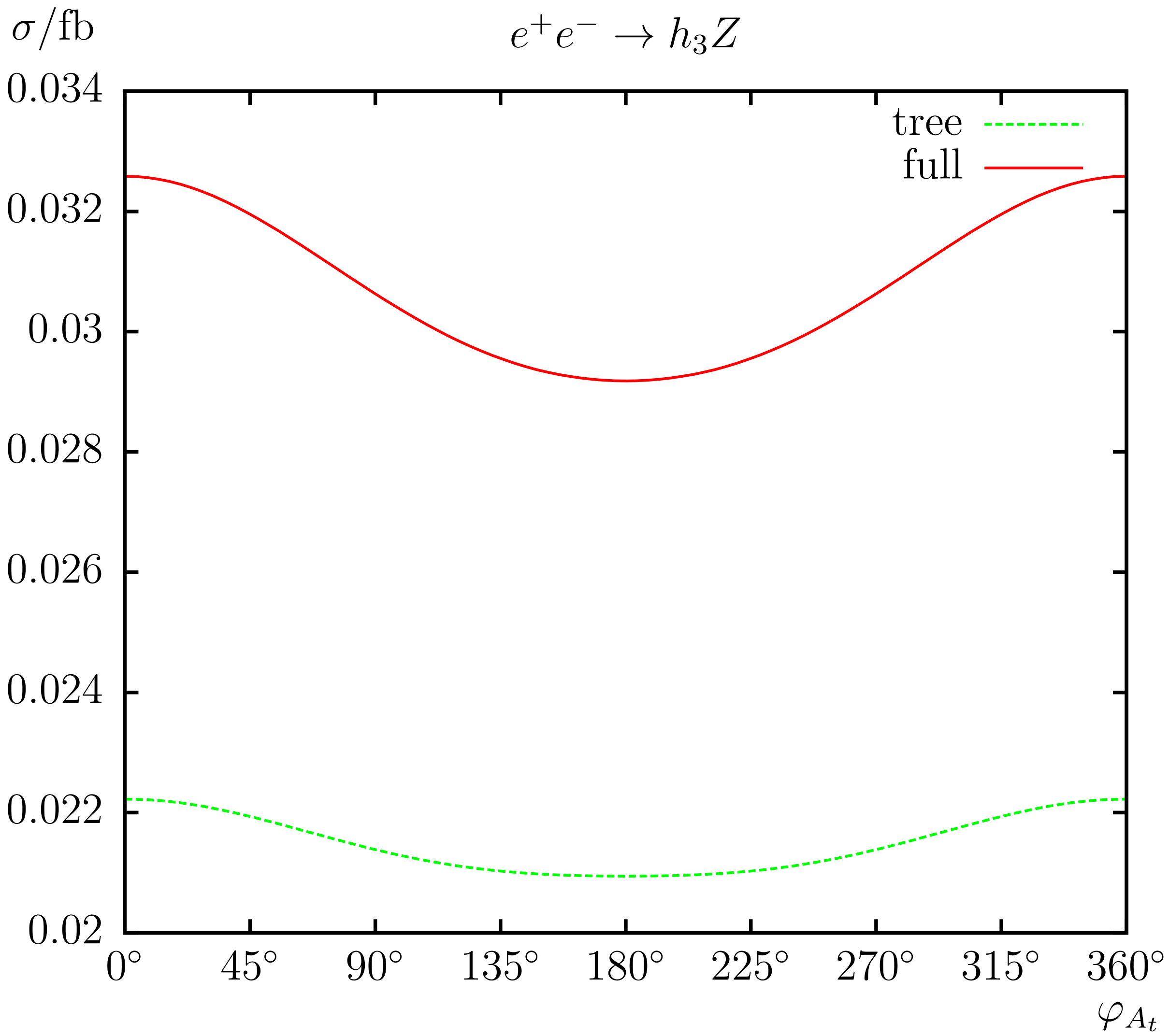
$\Rightarrow$ loop corrections crucial

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



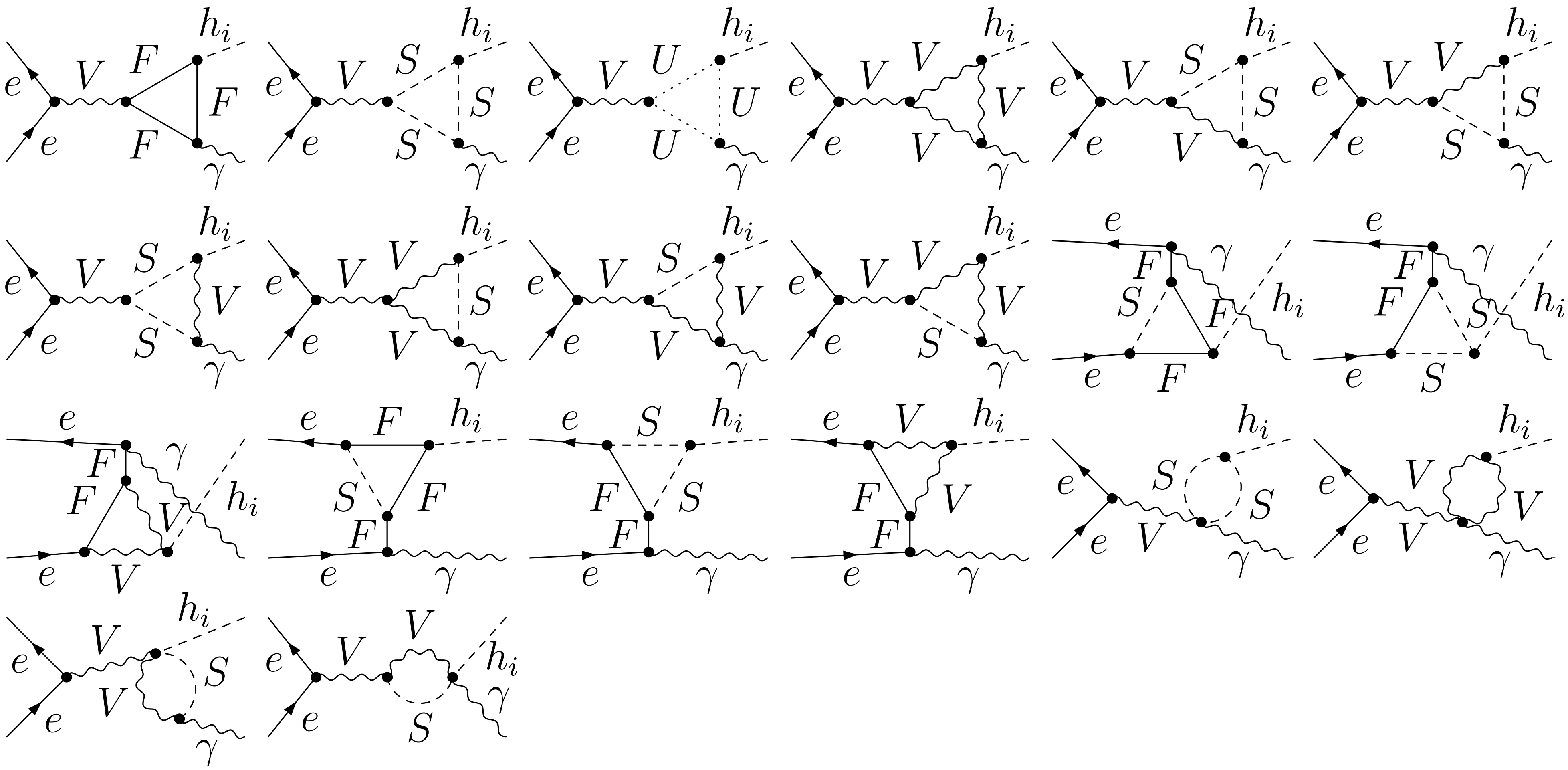
$\Rightarrow$ possibly observable, loop corrections crucial

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



$\Rightarrow$ pronounced phase dependence at the loop level

$e^+e^- \to h_i\gamma$: purely loop-induced!



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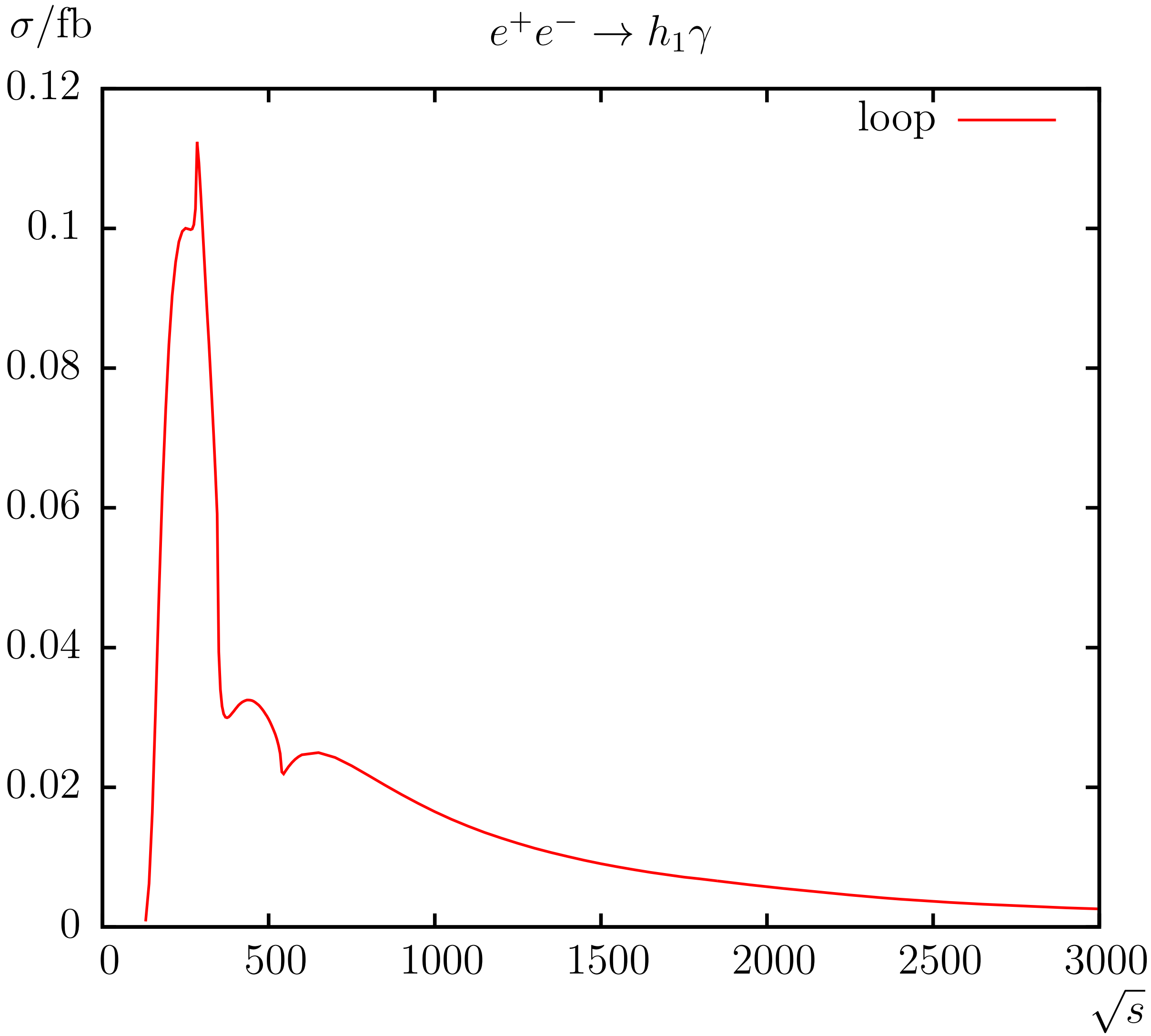

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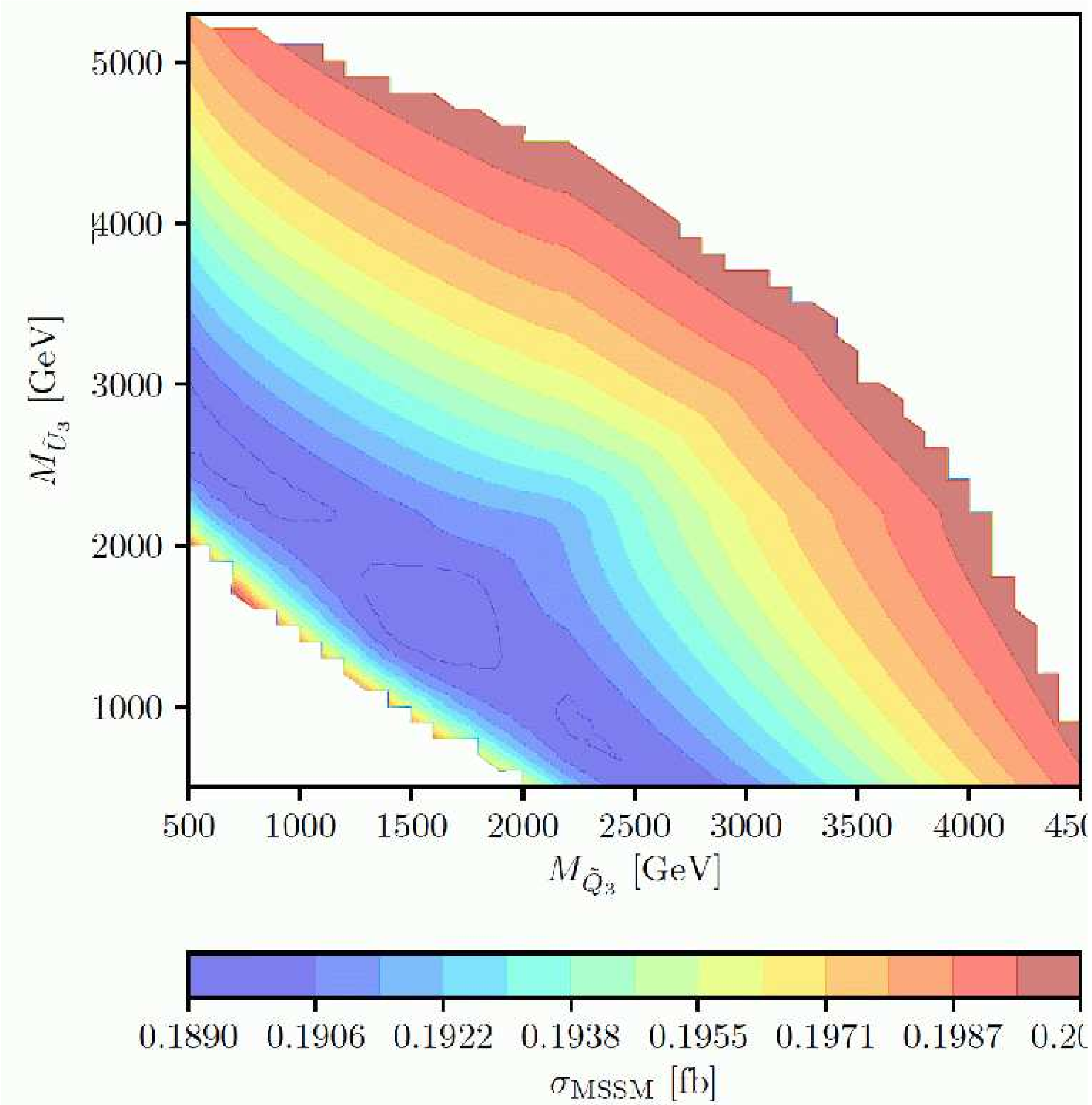
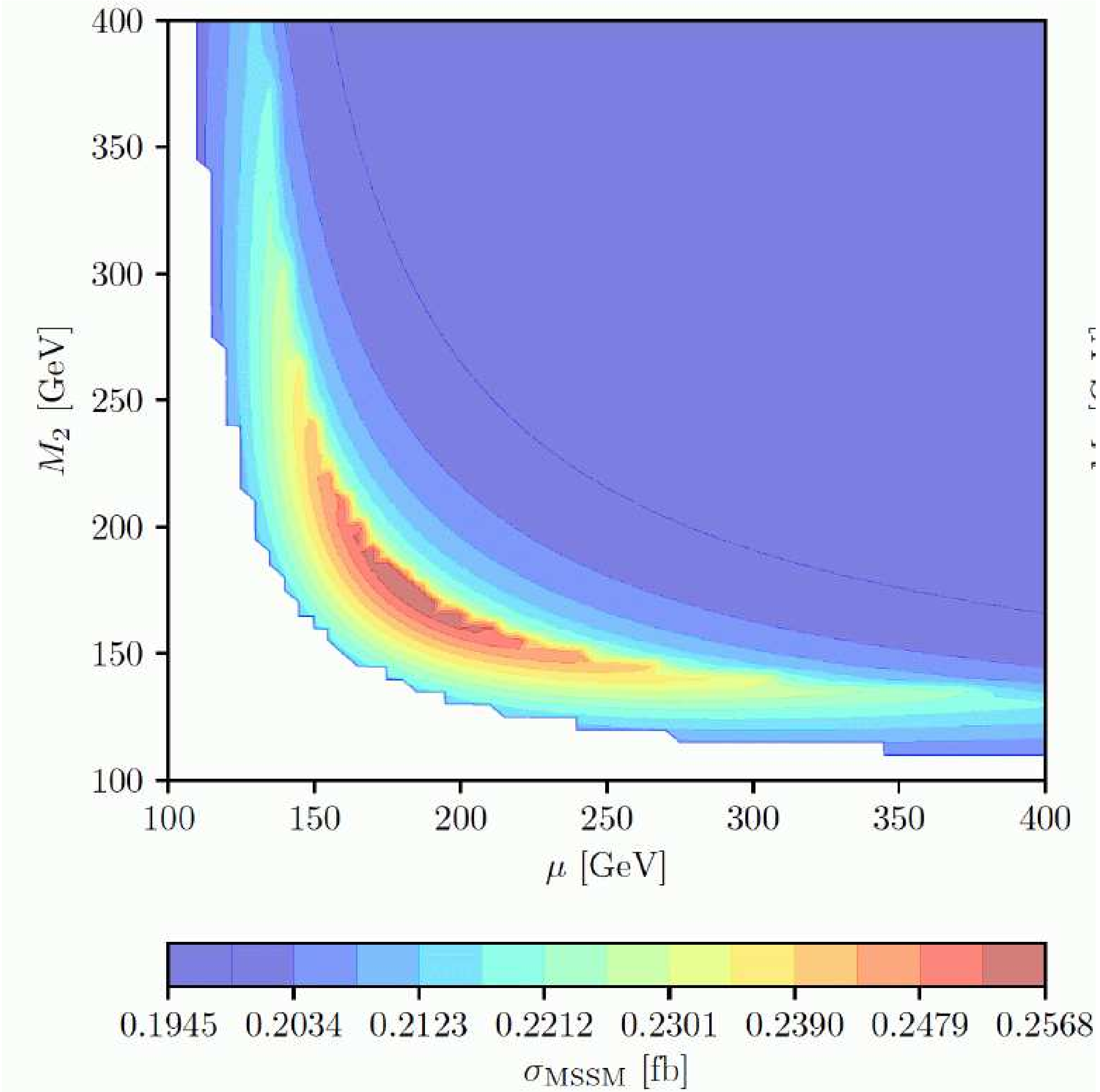
$e^+e^- \to h_1\gamma$ (purely loop induced):

[F. Arco, S.H., C. Schappacher '18]



$\Rightarrow$ relevant variation with scalar top sector

$e^+e^- \to h_1\gamma$ (purely loop induced): [*F. Arco, S.H., C. Schappacher '18*]



⇒ relevant variation with chargino sector

Charged MSSM Higgs Production at the LC

Charged Higgs production:

$$e^+e^- \to H^+H^-,\ H^\pm W^\mp,\ H^\pm e^\mp \nu,\ H^\pm tb, \ldots$$

Now available in the cMSSM at the full one-loop level:
[*S.H., C. Schappacher '17*]

$$\sigma(e^+e^- \to H^+H^-)$$

$$\sigma(e^+e^- \to H^\pm W^\mp)$$

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

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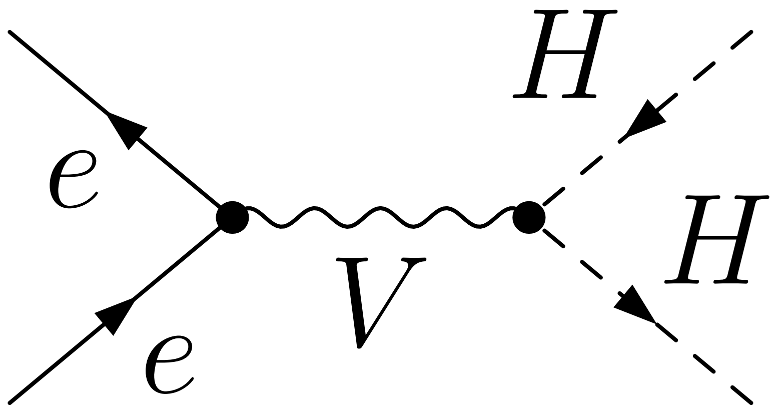
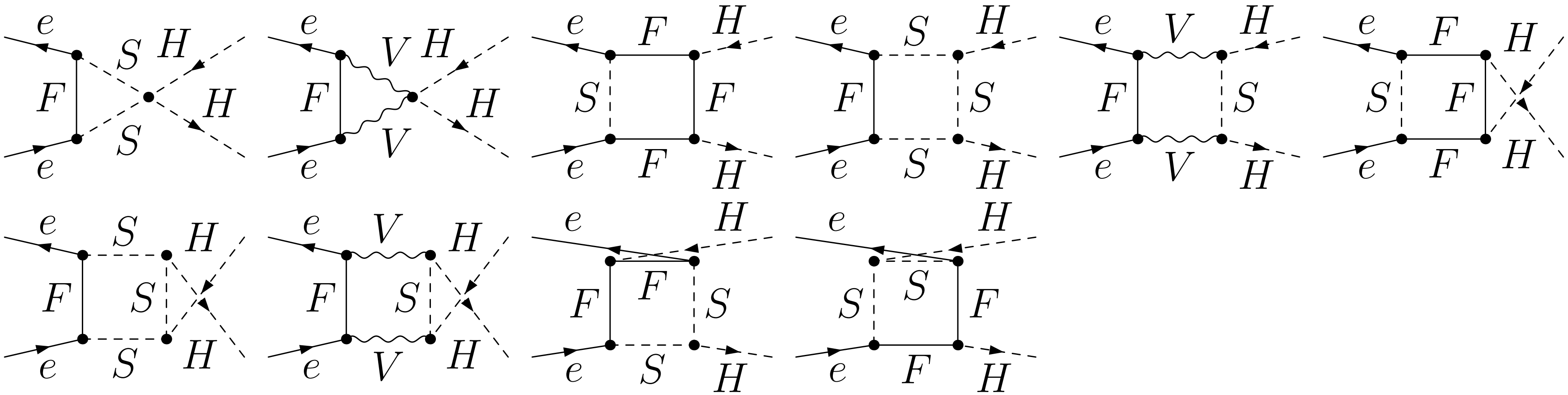
Scen.	$\sqrt{s}$	t_β	μ	$M_{H^\pm}$	$M_{\tilde{Q},\tilde{U},\tilde{D}}$	$M_{\tilde{L},\tilde{E}}$	$\lvert A_{t,b,\tau}\rvert$	M_1	M_2	M_3
S1	1000	7	200	300	1000	500	$1500 + \mu/t_\beta$	100	200	1500
S2	800	4	200	300	1000	500	$1500 + \mu/t_\beta$	100	200	1500

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

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


e
e
V
H
H


e S H F H S e
e V H F H V e
e F H S F S e F H
e S H F S e S H
e V H F S e V H
e F H S F e F H
e S H F S e S H
e V H F S e V H
e H F F S e S H
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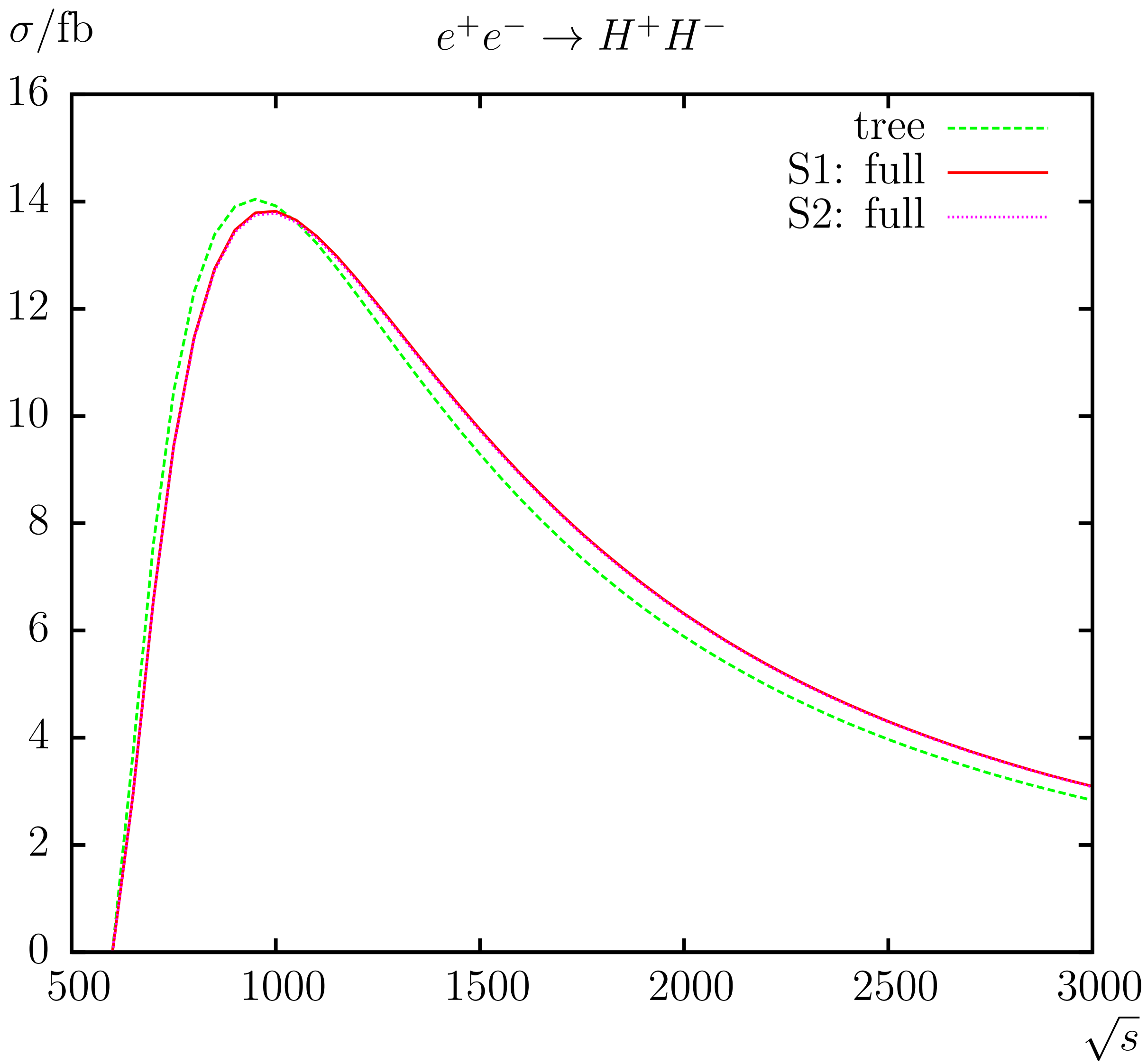

$\Rightarrow$ loop corrections non-negligible!

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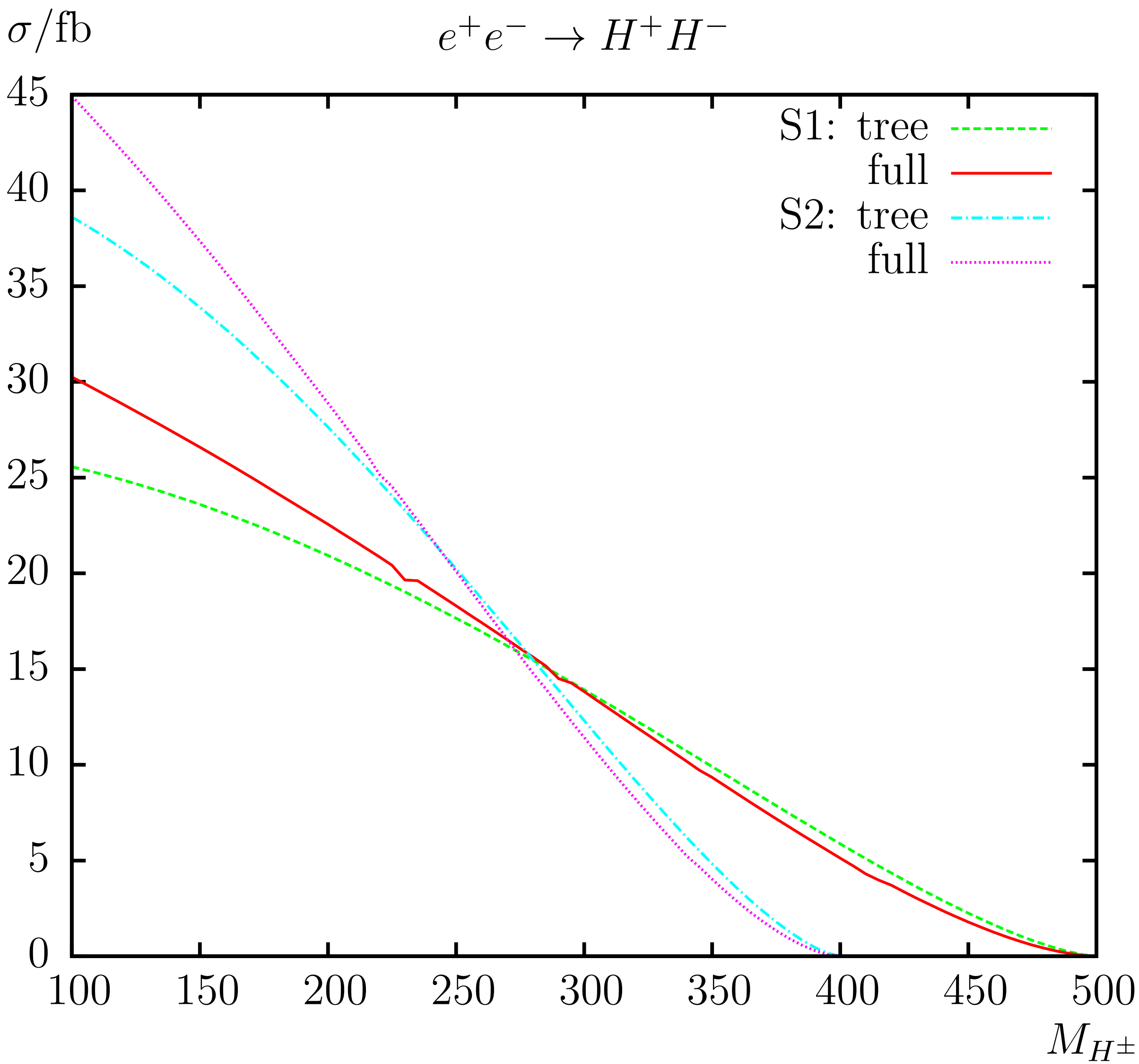

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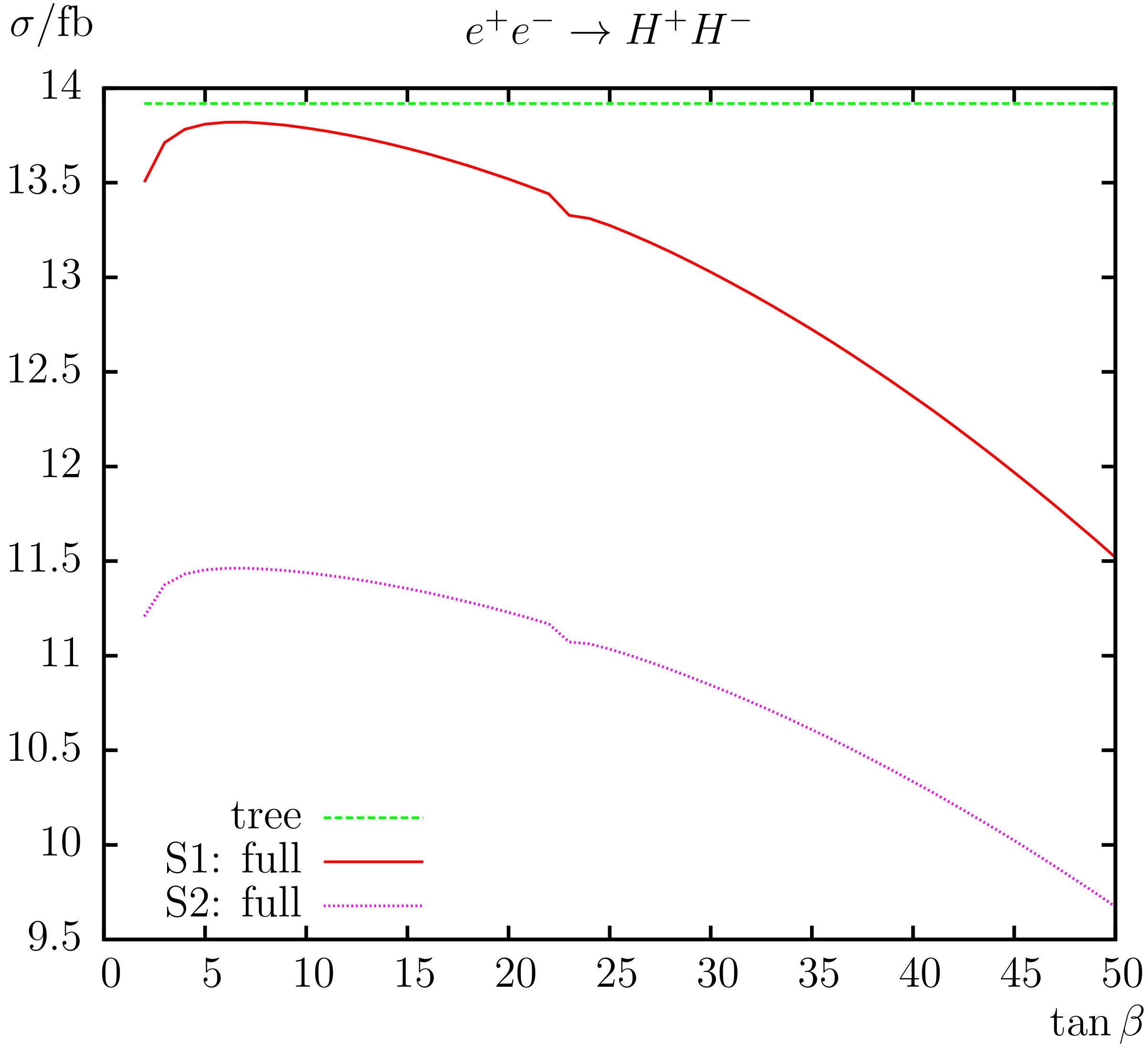
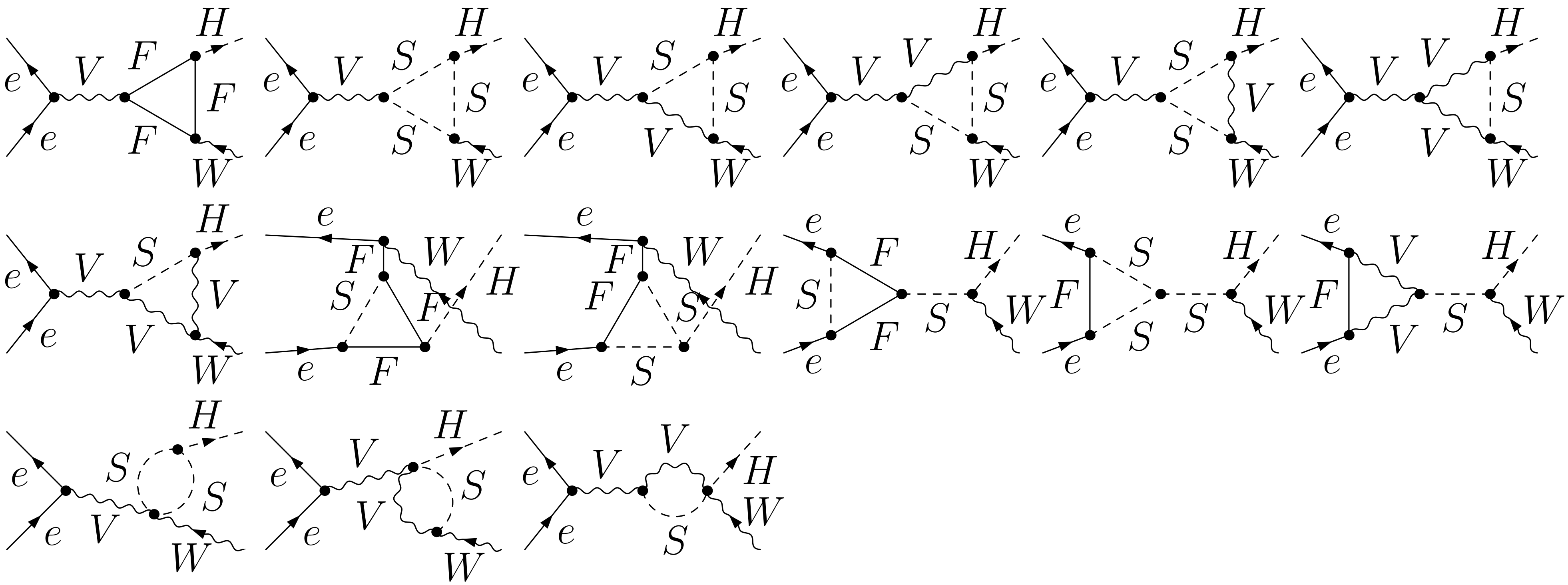


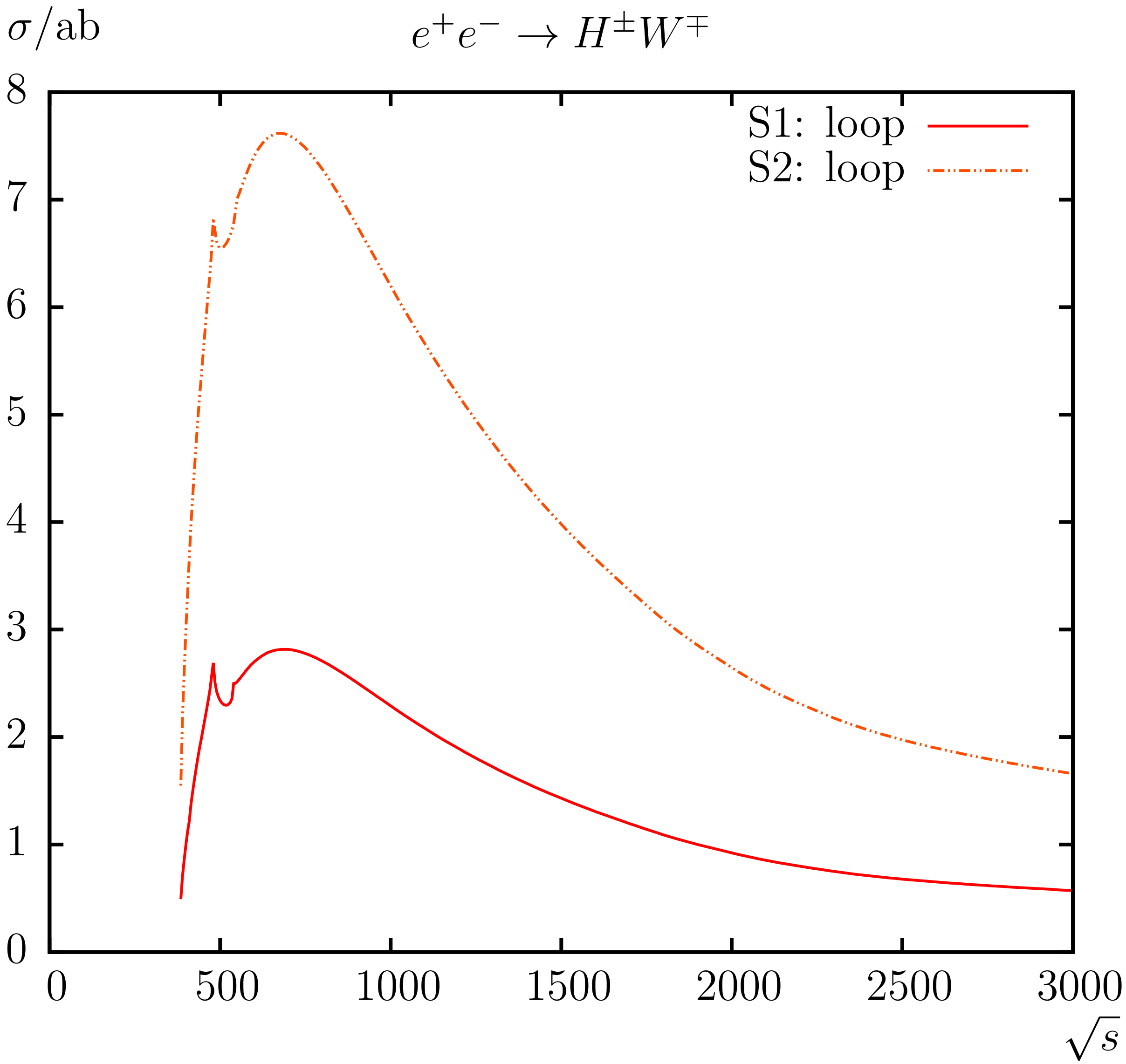
⇒ loop corrections sizable for large $\tan\beta$

⇒ no relevant complex phase dependence

$e^+e^- \to H^\pm W^\mp$: purely loop-induced!

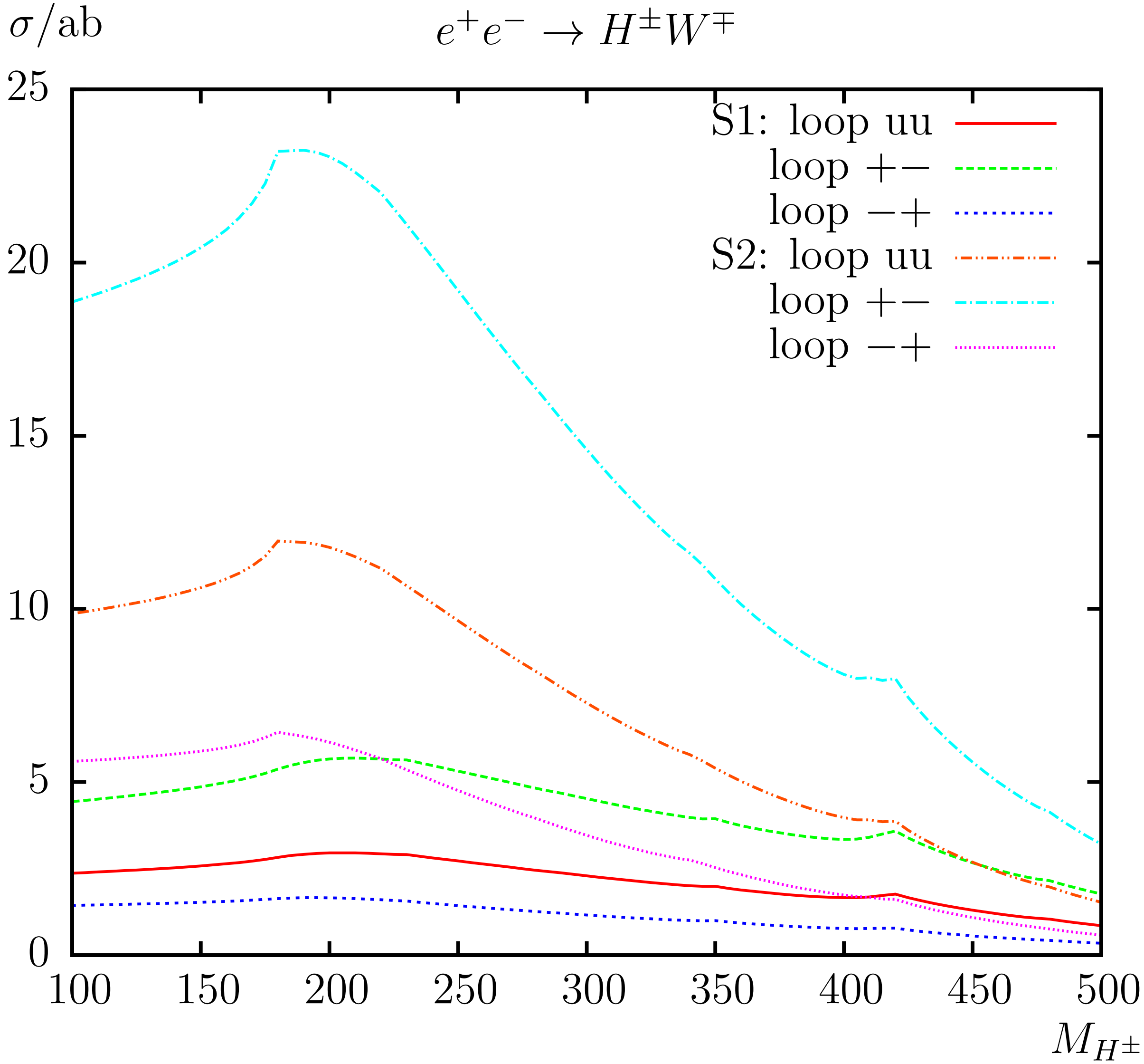


$e^+e^- \to H^\pm W^\mp$:



$\Rightarrow$ small loop-induced cross section . . .

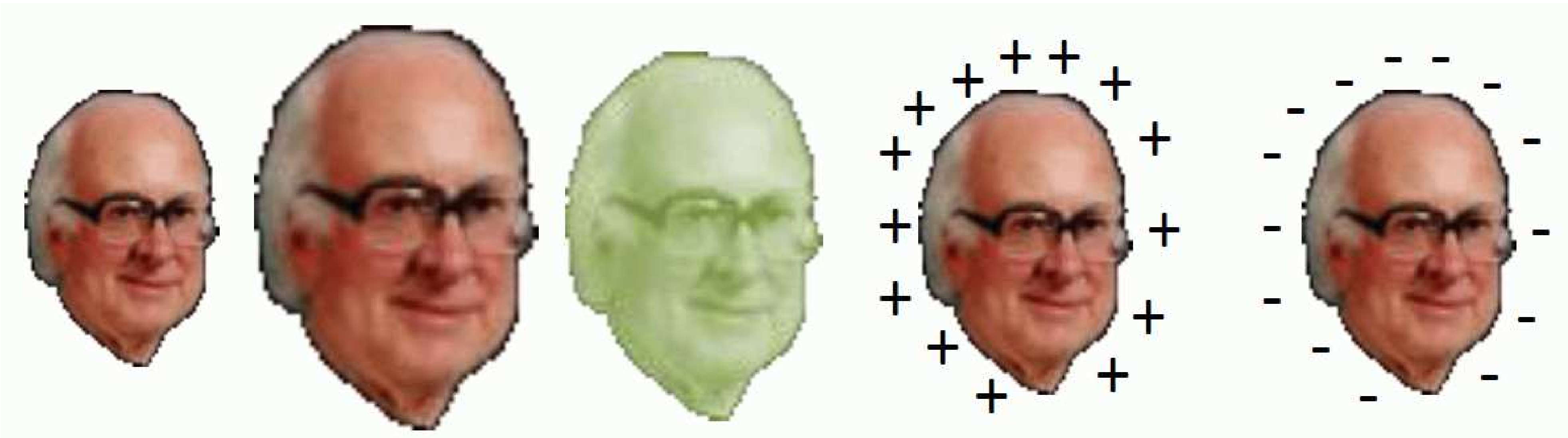
$e^+e^- \to H^\pm W^\mp$:



Polarization: $P(e^-) = +80\%$, $P(e^+) = -30\%$

$\Rightarrow$ crucial to yield detectable cross section!

3. Higgs boson decays in the (N)MSSM



The FeynHiggs Ansatz for masses (taken from talk by [P. Drechsel '16])

General idea: treat the MSSM part exactly as in the MSSM

- full inverse propagator in CP-even sector for mass determination

$$\Delta^{-1}\left(k^2\right) = \mathrm{i}\left[k^2\mathbb{1} - \underbrace{\mathcal{M}_{\phi\phi} + \hat{\Sigma}^{(1L)}_{\phi\phi}\left(k^2\right)}_{\text{NMSSM}} + \underbrace{\hat{\Sigma}^{(2L)}_{\phi\phi}\left(k^2=0\right)}_{\text{MSSM/FeynHiggs}}\right]$$

- included corrections from FeynHiggs at 2-loop order:
  - orders $\mathcal{O}\left(\alpha_s\alpha_t, \alpha_s\alpha_b, \alpha_t^2, \alpha_t\alpha_b\right)$
  - resummed large logarithms

⇒ any deviation from the MSSM can directly attributed to the extended model!

⇒ kind of obvious, but only FeynHiggs does it . . .

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- full inverse propagator in CP-even sector for mass determination

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⇒ any deviation from the MSSM can directly attributed to the extended model!

⇒ kind of obvious, but only FeynHiggs does it . . .

⇒ **same Ansatz for Higgs decays!**

What is included in FeynHiggs (so far):

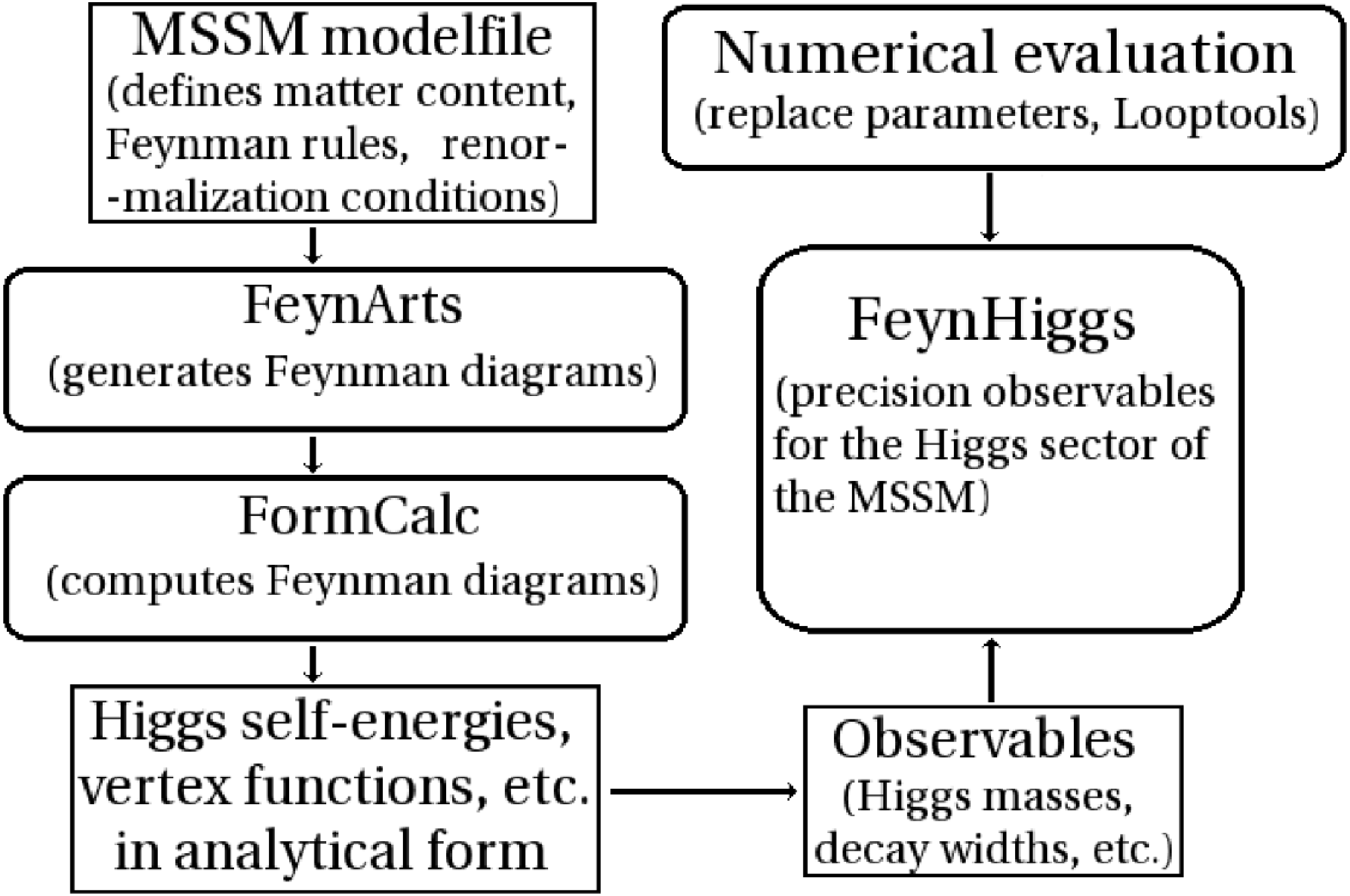
Evaluation of all MSSM Higgs boson masses and mixing angles

- $M_{h_1}, M_{h_2}, M_{h_3}, M_{H^\pm}$, α_{eff}, $\mathbf{Z}_{ij}$, $\mathbf{U}_{ij}$, . . . $\Rightarrow$ precision disussed before

Evaluation of all neutral MSSM Higgs boson decay channels (so far)

- total decay width Γ_{tot}
- BR($h_i \to f\bar{f}$): decay to SM fermions: full 1L, running m_q at 3L, $\mathbf{Z}_{ij}$
- BR($h_i \to Z^{(*)}Z^{(*)}, W^{(*)}W^{(*)}$): decay to massive SM gauge bosons: Prophecy4f $\oplus$ coupling factors, $\mathbf{U}_{ij}$
- BR($h_i \to \gamma\gamma, gg$): decay to massless SM gauge bosons: NLO QCD, gg: NNLO, NNLL from SM, $\mathbf{U}_{ij}$
- BR($h_i \to h_j Z^{(*)}, h_j h_k$): decay to gauge and Higgs bosons: $h_j Z^{(*)}$: $\mathbf{U}_{ij}$, $h_j h_k$: full 1L, log-resum, $\mathbf{Z}_{ij}$
- BR($h_i \to \tilde{f}_i \tilde{f}_j$): decay to sfermions: $\mathbf{U}_{ij}$
- BR($h_i \to \tilde{\chi}^\pm_i \tilde{\chi}^\mp_j, \tilde{\chi}^0_i \tilde{\chi}^0_j$): decay to charginos, neutralinos: $\mathbf{U}_{ij}$

FeynHiggs "workflow" :



Idea for this work:

[*slide from F. Domingo*]

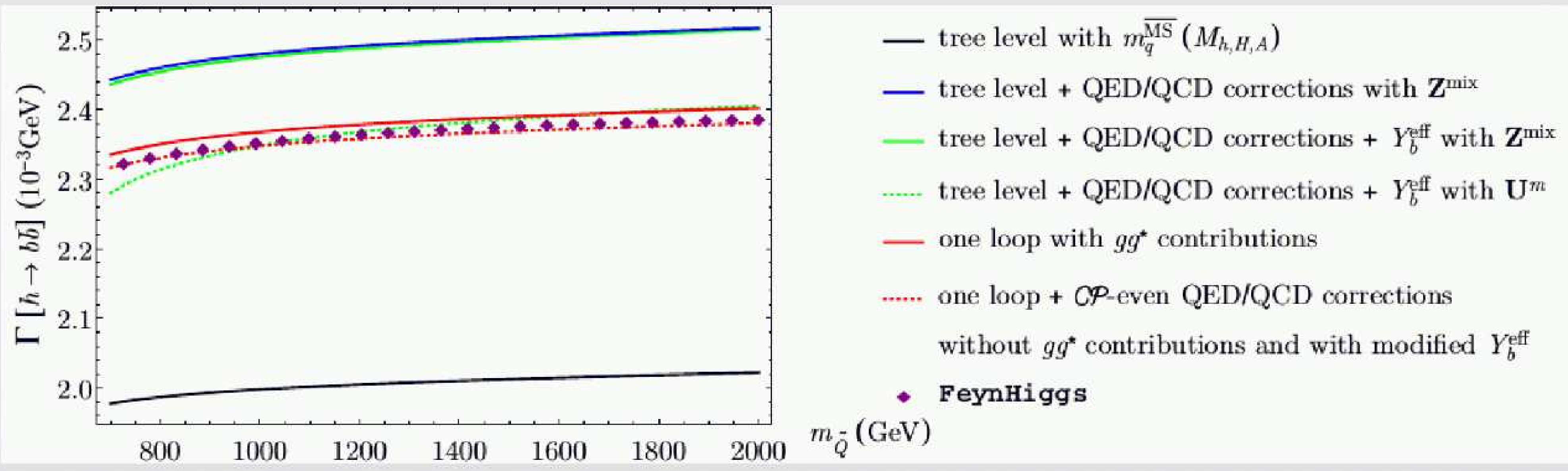
- Renormalization of the CP-conserving Higgs-sector
  [Drechsel, Galeta, Heinemeyer, Weiglein, (2016)];
- CP-violating NMSSM, on-shell neutral Higgs *[Drechsel, F.D., Paßehr (2017)]*;
- Neutral Higgs decays into SM particles at full one-loop order
  [F.D., Heinemeyer, Paßehr, Weiglein, (2018)];
- Higgs-to-Higgs + Higgs-to-SUSY on-going. . .
- Inclusion within FeynHiggs in an unforseeable future. . .

Learn from MSSM and adapt to the NMSSM.
+ Re-juvenate MSSM from NMSSM.

In the future: **FeynHiggs 3.0**

⇒ few numerical examples for the Higgs decays

[*slide from F. Domingo*]

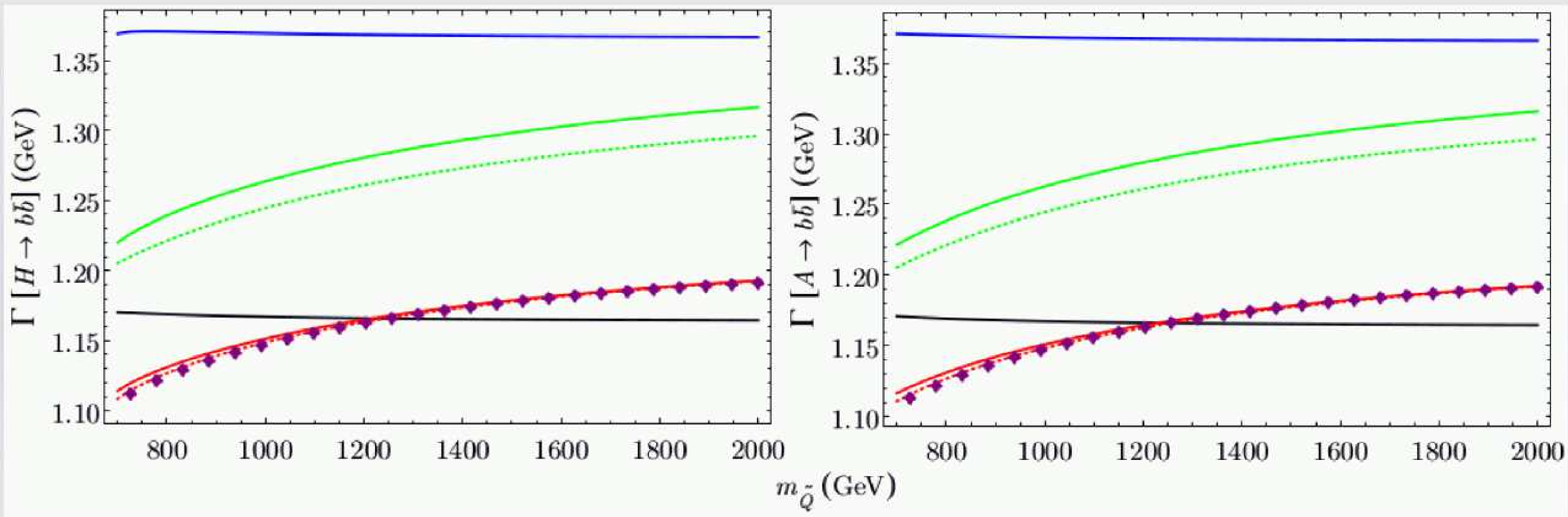


SM-like Higgs state

- Radiative corrections dominated by QCD-corrections;
- Unitary tree-level approximation works well;
- Difference wrt. FH (small): $h \to g(g^* \to b\bar{b})$
  (whether $h \to b\bar{b}$ or $h \to gg$ is an experimental question).

Bringing the NMSSM to the same level: NMSSM in the MSSM limit

[slide from F. Domingo]

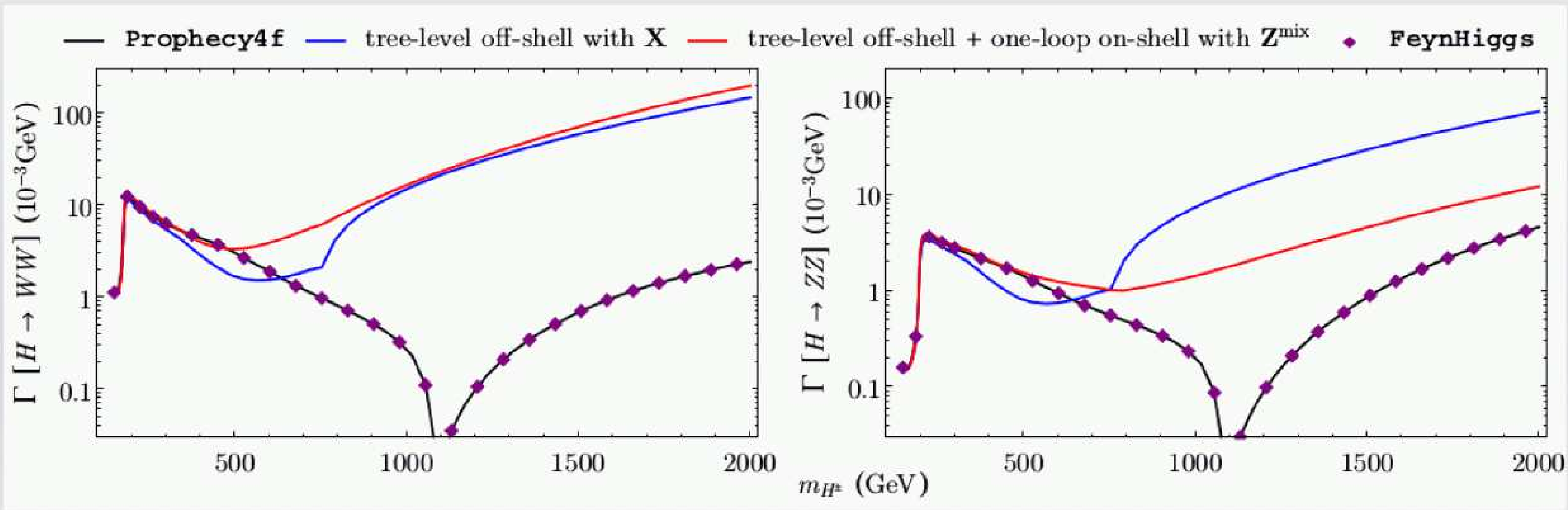


Heavy doublet Higgs states at ~ 1 TeV

- Sizable EW corrections due to Sudakov logarithms;
- Unitary tree-level approximation 'fails' ~ 10% off;
- Difference wrt. FH (minor): UV scale in Δ_b (higher-order).

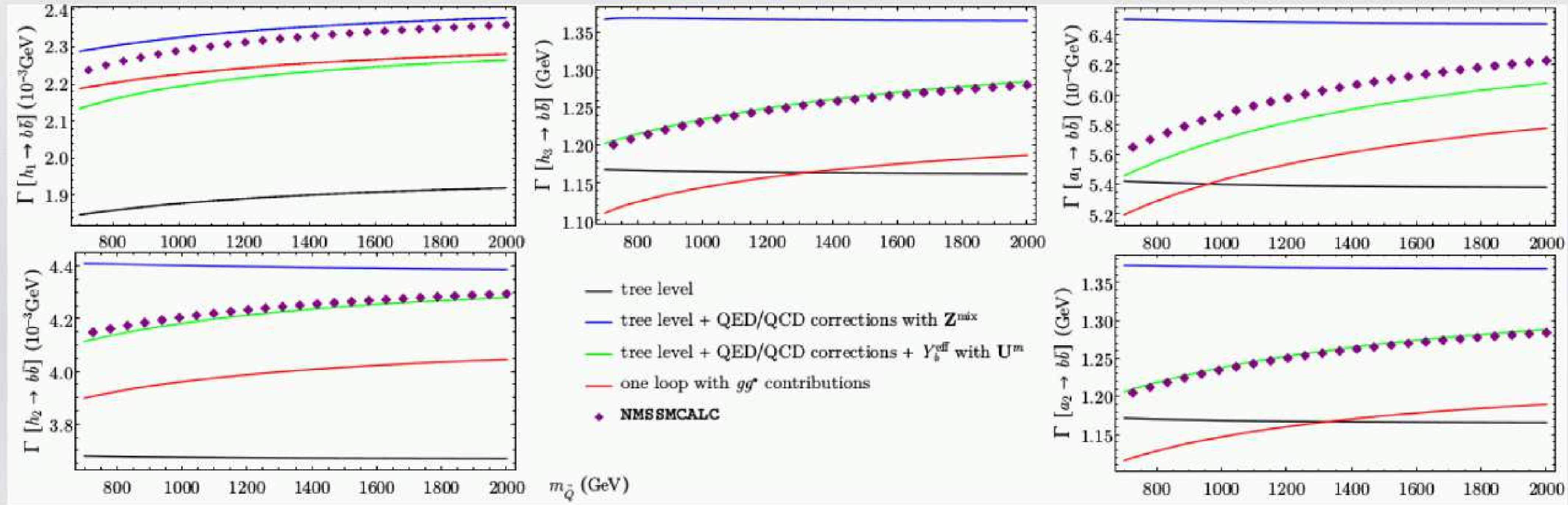
Bringing the NMSSM to the same level: NMSSM in the MSSM limit

[*slide from F. Domingo*]



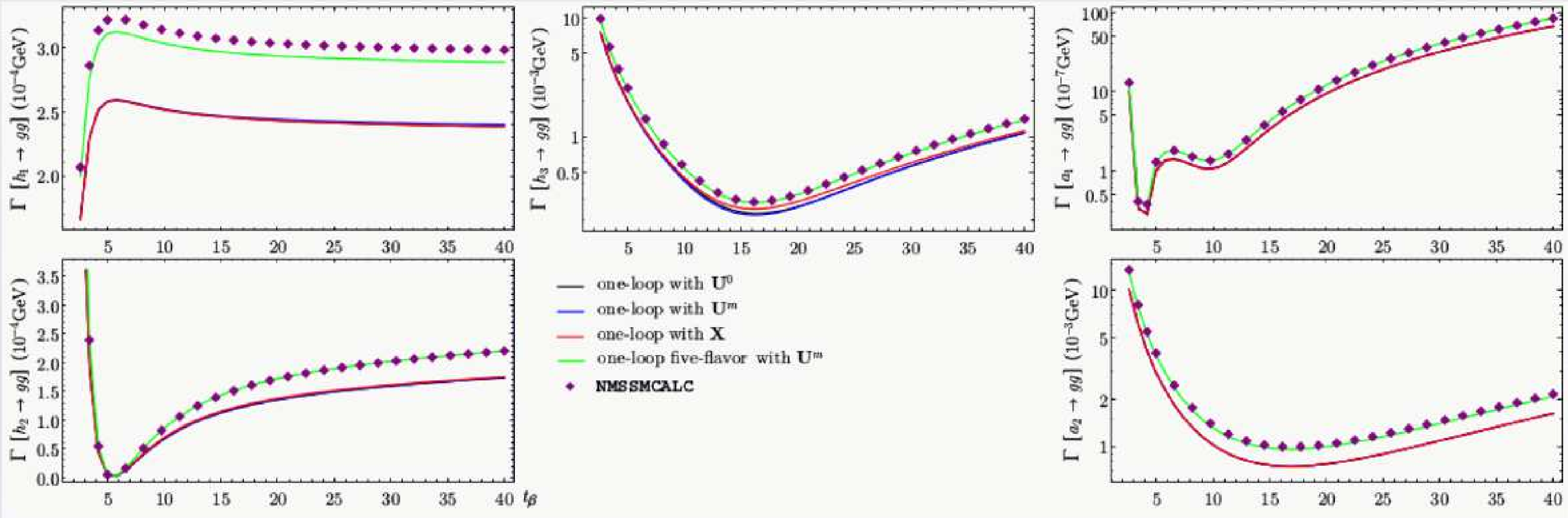
Heavy CP-even doublet Higgs state

- black curve: SM 1L prediction of Prophecy4f rescaled (as FH);
- Red curve: full one-loop (on-shell);
- Rescaling procedure fails for a decoupling state $g^{HVV}/g^{H_{\rm SM}VV} \simeq 0$.



- HDECAY provides a QCD/large $\tan\beta$-corrected width (including SQCD) $\simeq$ our green line;
- Full one-loop shows EW Sudakov logarithms for heavy states.

Here: h_1 SM-like; h_2 (640 GeV) and a_1 (320 GeV) singlet-like; h_3 and a_2 doublet-like (1 TeV).



- HDECAY performs at the same order as us with 5-flavor radiation;
- $\sim 4\%$ deviation due to normalization factor (difference of EW 2-loop and QCD 3-loop order).

Here: h_1 SM-like; h_2 (650 GeV) and a_1 (320 GeV) singlet-like; h_3 and a_2 doublet-like (1 TeV).

Overall (N)MSSM Higgs decay uncertainty estimates

- $h_i \to q\bar{q}$: SM-like: SM NNLO QCD, EW NNLO, SUSY 2L: $\sim 5\%$
  heavy: as SM-like, Sudakov logs: $\sim 5-10\%$
- $h_i \to \ell\bar{\ell}$: SM-like: $\lesssim 1\%$
  heavy: Sudakov logs for very heavy Higgses $\lesssim 10\%$
- $h_i \to WW^{(*)}, ZZ^{(*)}$: SM-like: $\lesssim 1\%$
  heavy: missing 2L (very small width): $\lesssim 50\%$
- $h_i \to \gamma\gamma, gg, \gamma Z$: $\gamma\gamma$: NNLO QCD, EW: $\lesssim 4\%$
  gg: NNLO QCD, EW: $\lesssim 4\%$
  γZ: NLO: $\sim 5\%$
- $h_i \to$ SUSY SUSY: [*S.H., C. Schappacher '14-'16*]
  1L effects $10-20\%$, 2L?
- all decays: $\mathbf{U}_{ij}$, $\mathbf{Z}_{ij}$: few %, effects close to threshold?

$\Rightarrow$ approaching LC precision for SM-like Higgs (not for heavy Higgses yet)

4. Conclusinos

- High precision prediction for cross sections and branching ratios 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:

$$\sigma(e^+e^- \to h_i h_j),\ \sigma(e^+e^- \to h_i Z),\ \sigma(e^+e^- \to h_i \gamma)$$
$$\sigma(e^+e^- \to H^+H^-),\ \sigma(e^+e^- \to H^\pm W^\mp)$$

- Tree-level processes: loop corrections crucial
  $(e^+e- \to h_1 h_2, h_1 Z, \ldots, H^+H^-)$

- Loop induced processes: possibly observable
  $(e^+e^- \to h_1 h_1, h_1 \gamma, \ldots, H^\pm W^\mp)$
  $\Rightarrow$ polarization could be crucial!
  $\Rightarrow$ possibly relevant MSSM parameter dependence

- (N)MSSM Higgs decays:
  approaching LC precision for SM-like Higgs (not for heavy Higgses yet)


Further Questions?