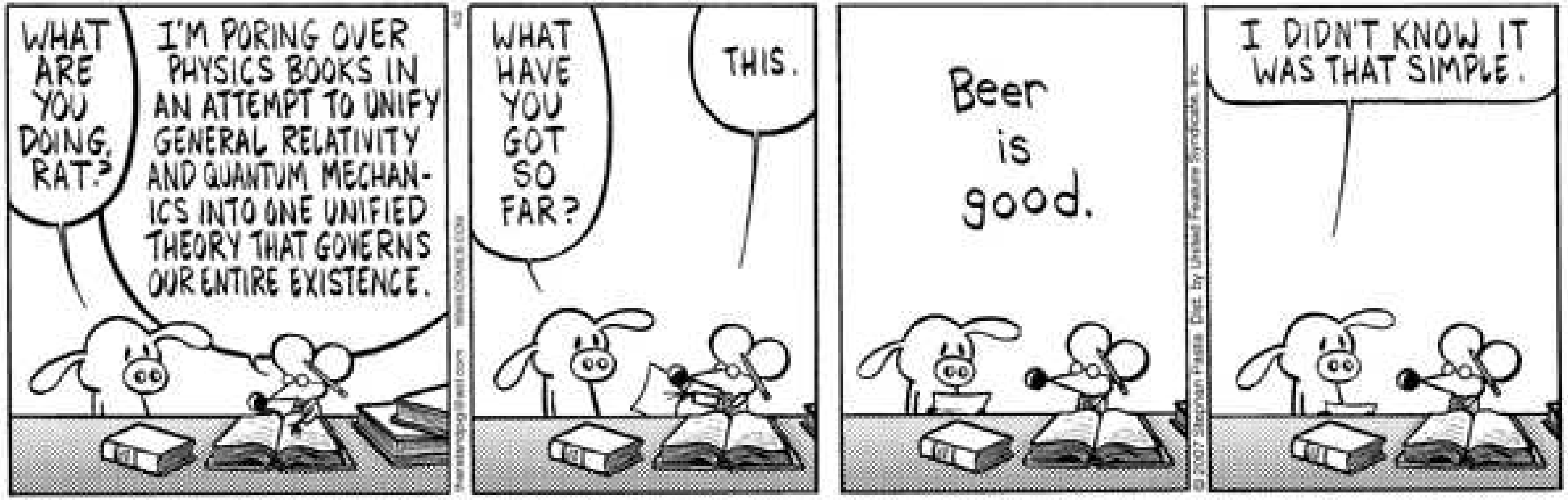
WHAT ARE YOU DOING, RAT?
I'M PORING OVER PHYSICS BOOKS IN AN ATTEMPT TO UNIFY GENERAL RELATIVITY AND QUANTUM MECHANICS INTO ONE UNIFIED THEORY THAT GOVERNS OUR ENTIRE EXISTENCE.
WHAT HAVE YOU GOT SO FAR?
THIS.
Beer is good.
I DIDN'T KNOW IT WAS THAT SIMPLE.
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Higgs production from SUSY decays at the LHC – Higgs production at ILC/CLIC in the cMSSM at NLO

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

Granada, 04/2016

1. The Grand Scheme
2. Renormalizing the MSSM with complex parameters (cMSSM)
3. Higgs Production from SUSY decays
4. Direct Higgs Production at the e^+e^- LC
5. Conclusions

1. The Grand Scheme

The LHC up and running . . .
→ discovery of BSM physics in 2016?

The ILC (and CLIC?) still coming . . .
. . . a bit later than anticipated
→ to investigate BSM physics

Worldwide Study of the Physics and Detectors for Future Linear $e^+ e^-$ Colliders

⇒ New Physics is certainly around the corner

⇒ Time to get ready for BSM physics

The big question:

Which Lagrangian describes the world?

My guess:

It is a supersymmetric one

$\Rightarrow$ concentrate on the (N)MSSM from now on

(other people $\Rightarrow$ other guesses $\Rightarrow$ other priorities . . .)

In any case:

$\Rightarrow$ we have to measure as many observables as possible

– masses
– branching ratios
– angular distributions
– cross sections
– . . .

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In any case:

$\Rightarrow$ we have to measure as many observables as possible

– masses
– branching ratios
– angular distributions
– cross sections
– . . .

$\Rightarrow$ compare with theory calculations at the same level of accuracy

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

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

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

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

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

Enlarged Higgs sector: Two Higgs doublets $\Leftarrow$ focus here!

Problem in the MSSM: many scales

Problem in the MSSM: complex phases

Where are we? (a selection!)

1. Neutral Higgs boson masses
   - $\mathcal{O}(\alpha_t\alpha_s)$, $\mathcal{O}\left(\alpha_t^2\right)$ in the cMSSM [S.H., W. Hollik, H. Rzehak, G. Weiglein '07]
   - $\mathcal{O}\left(\alpha_t\alpha_s^2\right)$, $\mathcal{O}\left(\alpha_t^2\alpha_s\right)$, rMSSM [S. Martin '07] [W. Hollik, S. Passehr '14]
   - $\mathcal{O}\left(\alpha_t\alpha_s^2\right)$, rMSSM (incl. fin. terms) [Haarlander, Kant, Mihaila, Steinhauser '08]
   - log-resummation, 2L/3L [Hahn et al. '13][Draper et al. '13][E. Bagnaschi et al. '14] [J. Pardo Vega et al. '14][Lee et al. '15]
2. Charged Higgs mass
   - 1-loop [M. Frank et al. '06] $\mathcal{O}(\alpha_t\alpha_s)$ [M. Frank et al. '13] $\mathcal{O}\left(\alpha_t^2\right)$ [Hollik, Passehr '14]
3. Production cross sections at the LC
   - $e^+e^- \to h_ih_j, Zh_i, \gamma h_i$, full one-looop, cMSSM [S.H., C. Schappacher '15]
   - $e^+e^- \to H^\pm e^\mp \nu$ at one-loop, rMSSM [O. Brein, T. Figy '07][T. Farris et al. '04]
   - Z-factors at 2-loop [M. Frank, T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '06]
4. Higgs decays
   - full 1-loop (depending on final state) [. . .]
   - Z-factors at 2-loop [M. Frank, T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '06]
5. Decays to Higgs bosons
   - full 1-loop, cMSSM [K. Williams et al. '11][S.H., C. Schappacher '14, 15] [A. Bharucha, T. Fritzsche, S.H., F. v.d. Pahlen, H. Rzehak, C. Schappacer '11 - '13]

What is missing? (a selection!)

1. Neutral Higgs boson masses
   - full 2-loop
   - more 3-loop (and in "easier accessible" scheme?)
   - leading 4-loop
   - Improved combinatin of LL, NLL, . . . resummation with diag. calc.
2. Charged Higgs boson mass
   - (sub)leading 2-loop
3. LC Higgs boson production
   - full 1-loop in the cMSSM (some initial states)
   - leading 2-loop
4. Higgs decays
   - full 1-loop in the r/cMSSM (few final states)
   - leading 2-loop
5. Decays to Higgs bosons probably ok now

$\Rightarrow$ provide corresponding codes!

2. Renormalization of the cMSSM

Generic problems for SUSY loop calculations:

- 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!

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)

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

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 ϕ_{PQ}

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

  $\Rightarrow$ 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: $T_A^{\text{tree}} \propto \sin\xi \, m_{12}^2 \stackrel{!}{=} 0$
  $\Rightarrow \xi = 0 \Rightarrow$ 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:

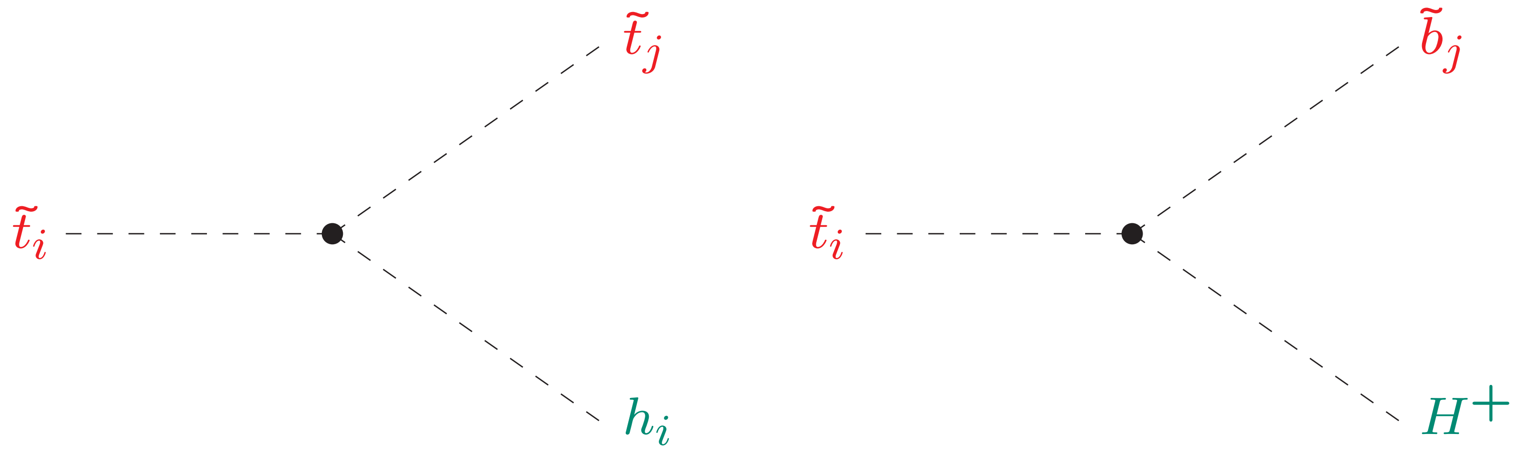
$$(A, H, h) \to (h_3, h_2, h_1)$$

with

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

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

Examples for processes with (external) stops and Higgs bosons:



- important decay modes of stops
- A_t and A_b directly enter the vertex
- possible source of Higgs bosons at the LHC/ILC
- ...

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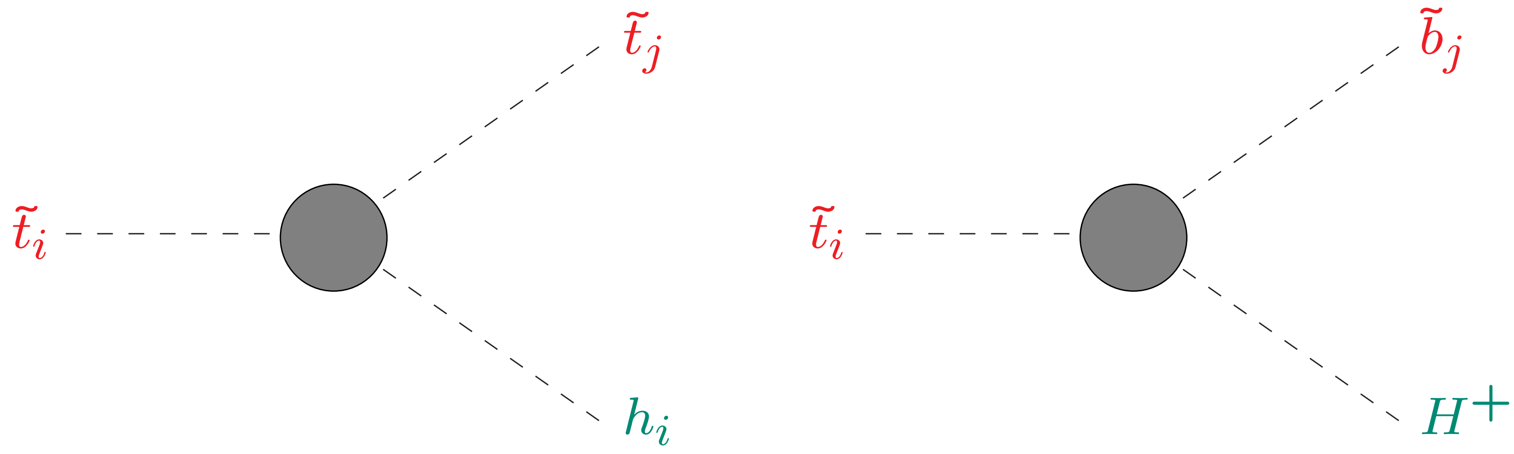

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⇒ higher-order corrections important!

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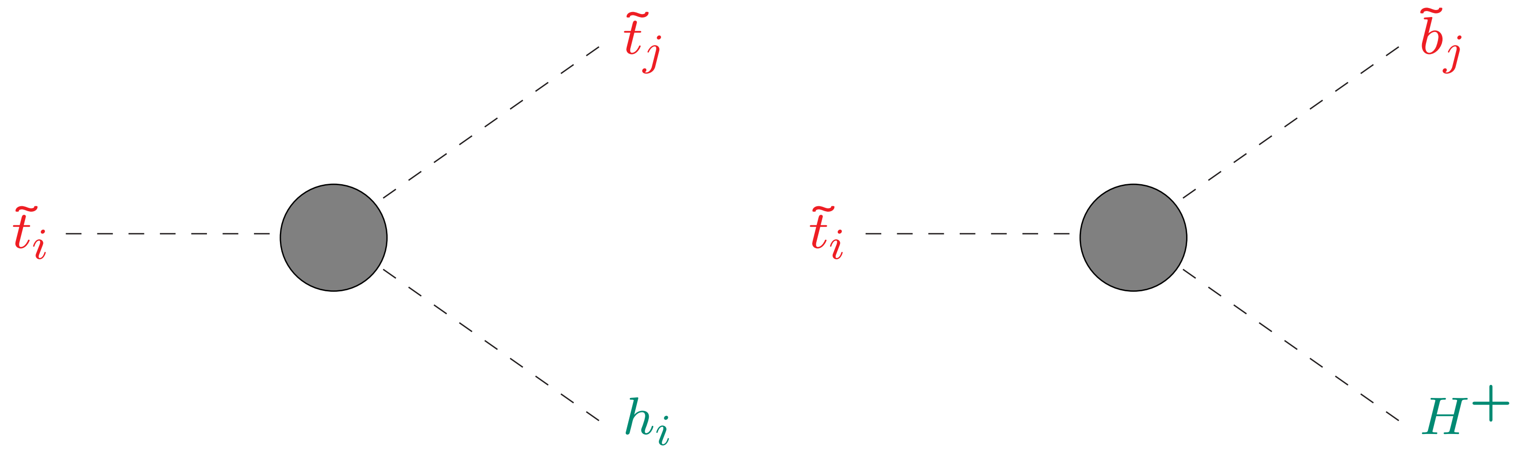

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⇒ simultaneous renormalization of stop and sbottom sector required!

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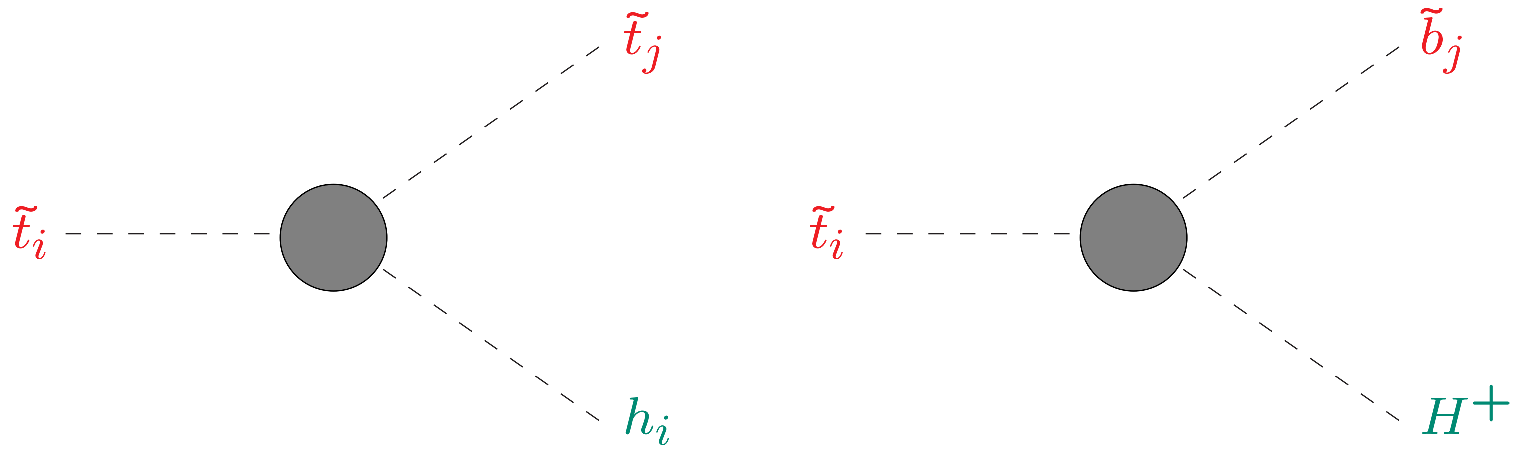
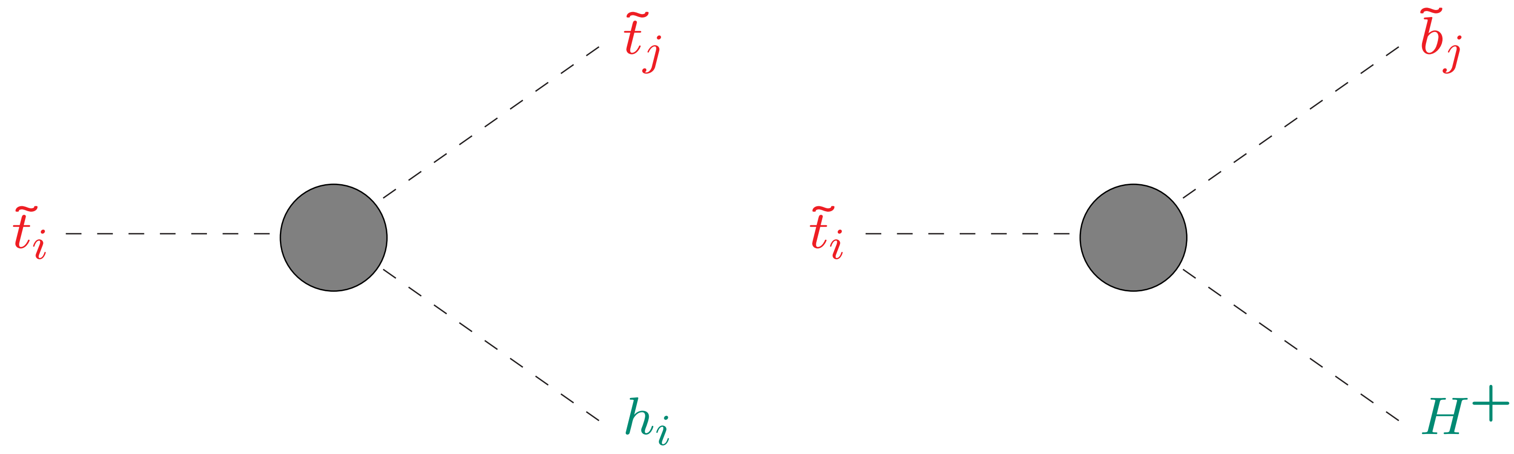


– important decay modes of stops
– A_t and A_b directly enter the vertex
– possible source of Higgs bosons at the LHC/ILC
– . . .

⇒ higher-order corrections important!

⇒ simultaneous renormalization of stop and sbottom sector required!
⇒ with on-shell properties for external particles!

Examples for processes with (external) stops and Higgs bosons:

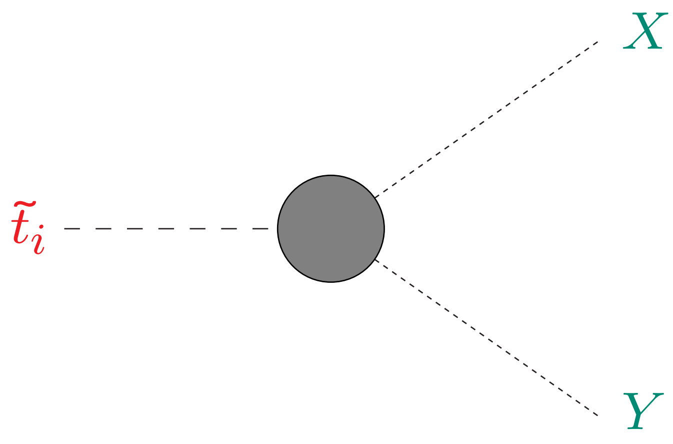


- important decay modes of stops
- A_t and A_b directly enter the vertex incl. complex phases!
- possible source of Higgs bosons at the LHC/ILC
- . . .

⇒ higher-order corrections important!

⇒ simultaneous renormalization of stop and sbottom sector required!
⇒ including complex phases!

The bigger picture: stop decays in the cMSSM



– important for cascade decays at the LHC

– source of uncolored particles at the LHC

. . . especially for Higgs bosons and Dark Matter

⇒ to get BRs right ⇒ all decays needed

⇒ (nearly) all sectors of the cMSSM enter as external particles

⇒ (nearly) all sectors of the cMSSM have to be renormalized simultaneously

LC potential:

The clean environment of the ILC would permit a detailed study of the SUSY decays

The ILC environment would result in an accuracy of the relative branching ratio

$$\mathrm{BR}^{\mathrm{full}} \equiv \frac{\Gamma^{\mathrm{full\ 1L}}(\mathrm{SUSY} \to \mathrm{xy})}{\Gamma_{\mathrm{tot}}^{\mathrm{full\ 1L}}}$$

$$\frac{\delta\mathrm{BR}}{\mathrm{BR}} \equiv \frac{\mathrm{BR}^{\mathrm{full}} - \mathrm{BR}^{\mathrm{tree}}}{\mathrm{BR}^{\mathrm{full}}}$$

close to the statistical uncertainty

$\Rightarrow$ Precision at the per-cent level possible!

$\Rightarrow$ theory precision at the per-cent level required!

Renormalization status:

– LHC/LC precision requires all calculations at the $\mathcal{O}(5\%)/\mathcal{O}(1\%)$ level

– full complex MSSM renormalized

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

[*S.H., C. Schappacher '13 - '15*]

– stable and well behaved results over nearly complete parameter space

– available as FeynArts model file

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

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

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

$\Rightarrow$ and so we did :-)

Results for the MSSM Higgs at the LC

A. Status and latest results for M_h prediction
$\Rightarrow$ still far away from LC precision!

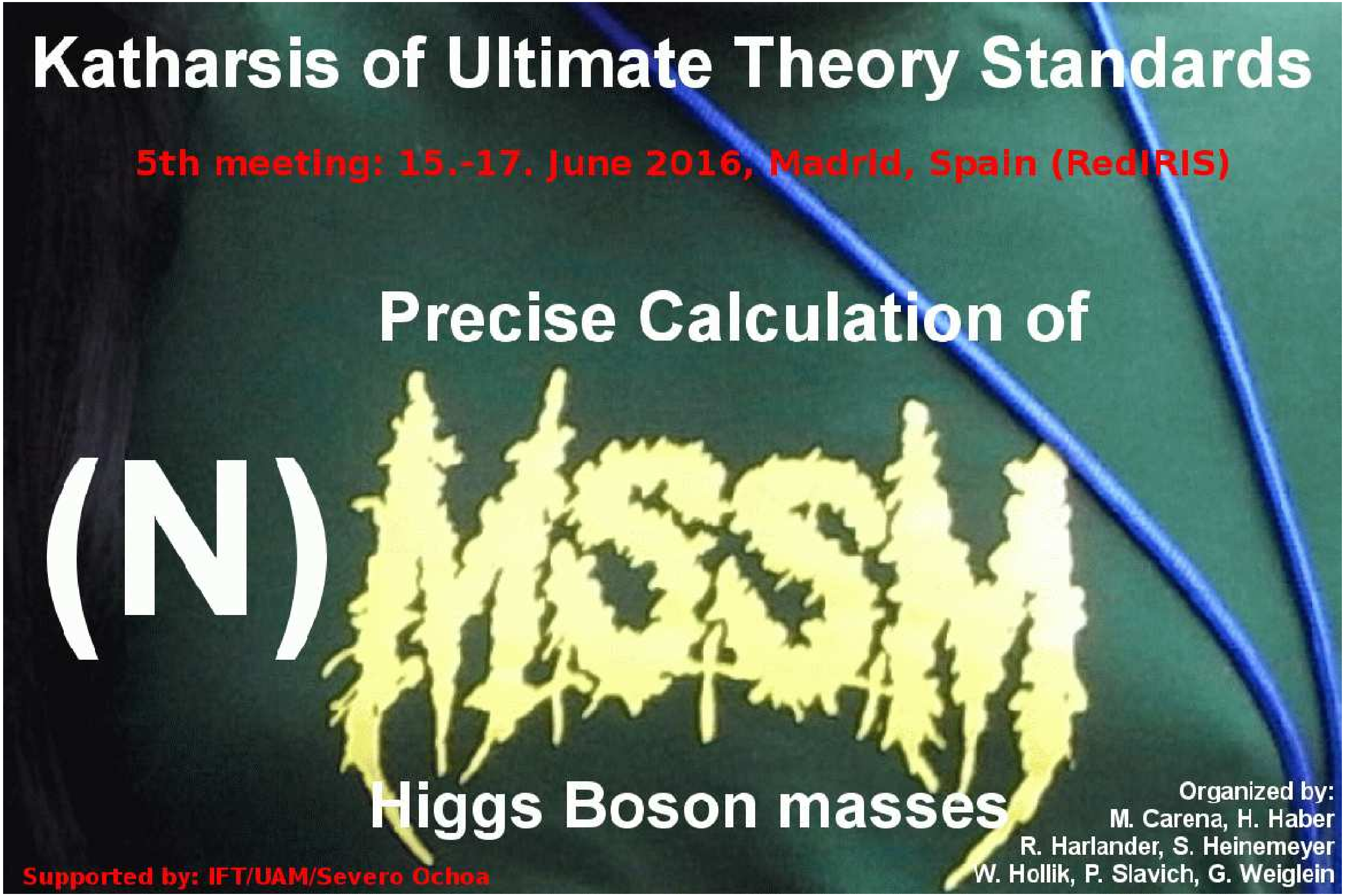
B. Status for the charged Higgs boson mass predictions

C. Recent results for Higgs boson decays

D. Recent results for decays to Higgs bosons

E. Status of $e^+e^- \to h_i h_j, Z h_i, \gamma h_i$

Covered here: D and E


Katharsis of Ultimate Theory Standards
5th meeting: 15.-17. June 2016, Madrid, Spain (RedIRIS)
Precise Calculation of
(N)
MSSM
Higgs Boson masses
Supported by: IFT/UAM/Severo Ochoa
Organized by:
M. Carena, H. Haber
R. Harlander, S. Heinemeyer
W. Hollik, P. Slavich, G. Weiglein

3. Higgs Production from SUSY decays

Calculated in the cMSSM full one-loop:

[A. Bharucha, S.H., F. v.d. Pahlen, H. Rzehak, C. Schappacher '11 - '15]

- stop/sbottom decays
- stau decays
- chargino decays
- neutralino decays
- gluino decays

Anything relevant missing?

Calculation of partial widths and branching ratios:

- all diagrams created with FeynArts

  $\to$ model file with all counterterms in the cMSSM

- including all soft/hard QED/QCD diagrams

- further evaluation with FormCalc

- Dimensional REDuction

- all UV and IR divergences cancel

- planned to include results into FeynHiggs (www.feynhiggs.de)

3A) Heavy Stop decays

$$\Gamma(\tilde{t}_2 \to \tilde{t}_1 h_i) \qquad (i = 1, 2, 3) \ ,$$

$$\Gamma(\tilde{t}_2 \to \tilde{t}_1 Z) \ ,$$

$$\Gamma(\tilde{t}_2 \to t \tilde{\chi}^0_k) \qquad (k = 1 \ldots 4) \ ,$$

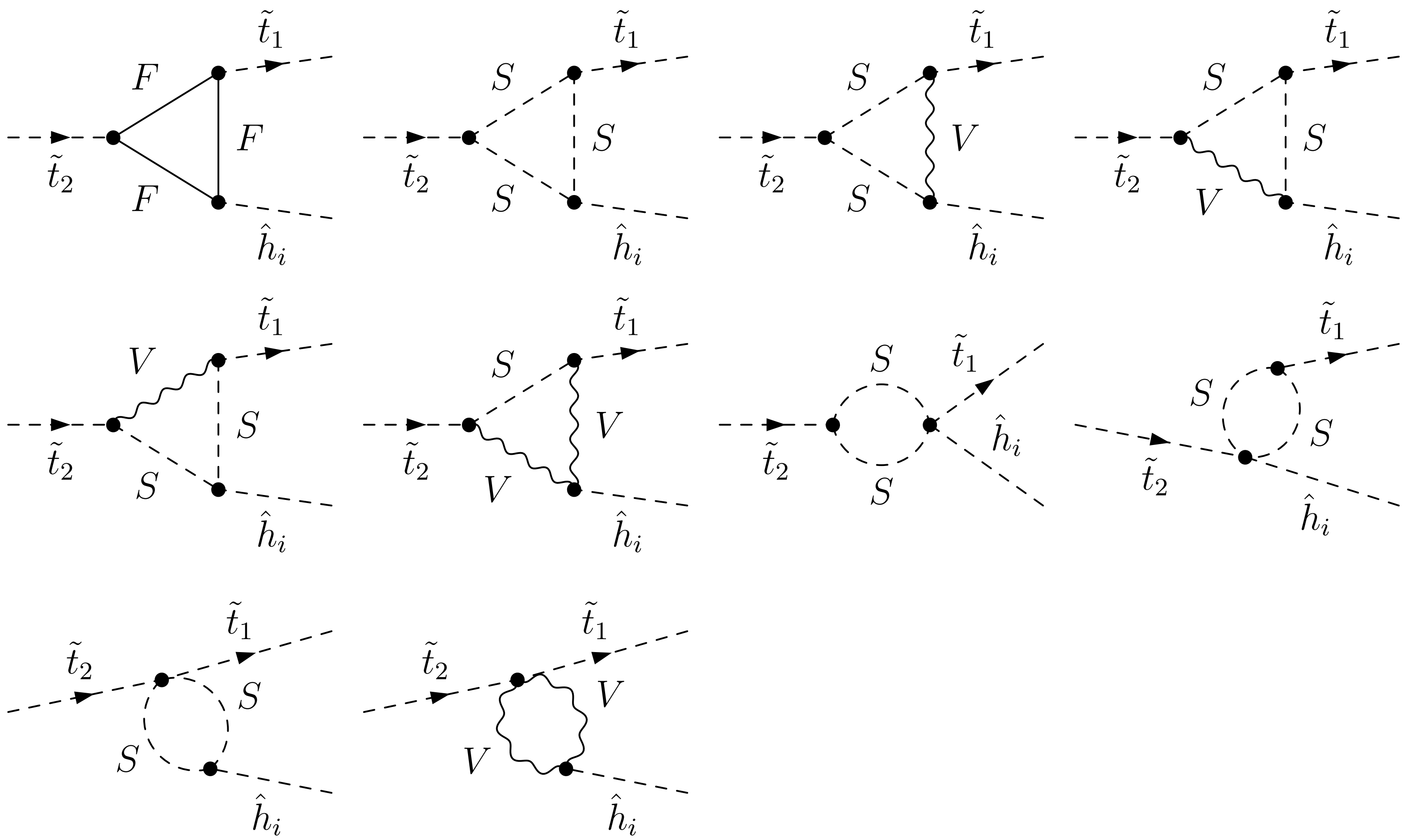
$$\Gamma(\tilde{t}_2 \to t \tilde{g}) \ ,$$

$$\Gamma(\tilde{t}_2 \to \tilde{b}_i H^+) \qquad (i = 1, 2) \ ,$$

$$\Gamma(\tilde{t}_2 \to \tilde{b}_i W^+) \qquad (i = 1, 2) \ ,$$

$$\Gamma(\tilde{t}_2 \to b \tilde{\chi}^+_k) \qquad (k = 1, 2) \ .$$

Feynman diagrams for $\tilde{t}_2 \to \tilde{t}_1 h_i$



– including Z–A or G–A transition contribution on the external Higgs boson leg

– including all soft/hard QED/QCD diagrams

Numerical scenarios:

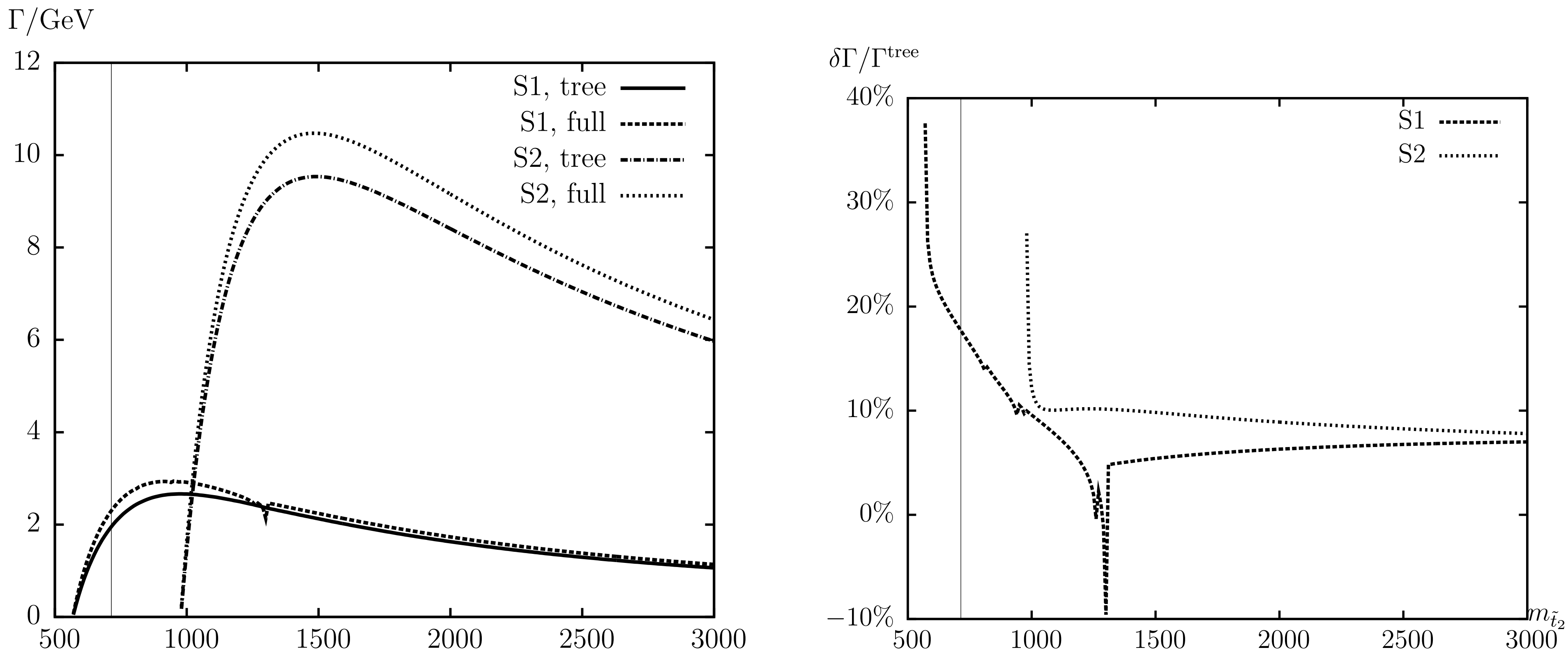
Scen.	$M_{H^\pm}$	$m_{\tilde{t}_2}$	$m_{\tilde{t}_1}$	$m_{\tilde{b}_2}$	μ	A_t	A_b	M_1	M_2	M_3
S1	150	650	$0.4\, m_{\tilde{t}_2}$	$0.7\, m_{\tilde{t}_2}$	200	900	400	200	300	800
S2	180	1200	$0.6\, m_{\tilde{t}_2}$	$0.8\, m_{\tilde{t}_2}$	300	1800	1600	150	200	400

Scen.	$\tan\beta$	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	$m_{\tilde{b}_1}$	$m_{\tilde{b}_2}$
S1	2	260.000	650.000	305.436	455.000
	20	260.000	650.000	333.572	455.000
	50	260.000	650.000	329.755	455.000
S2	2	720.000	1200.000	769.801	960.000
	20	720.000	1200.000	783.300	960.000
	50	720.000	1200.000	783.094	960.000

Scenarios chosen such that *all* decay channels are open

$\Gamma(\tilde{t}_2 \to \tilde{t}_1 h_1)$: dependence on $m_{\tilde{t}_2}$

[*T. Fritzsche, S.H., H. Rzehak, C. Schappacher*]



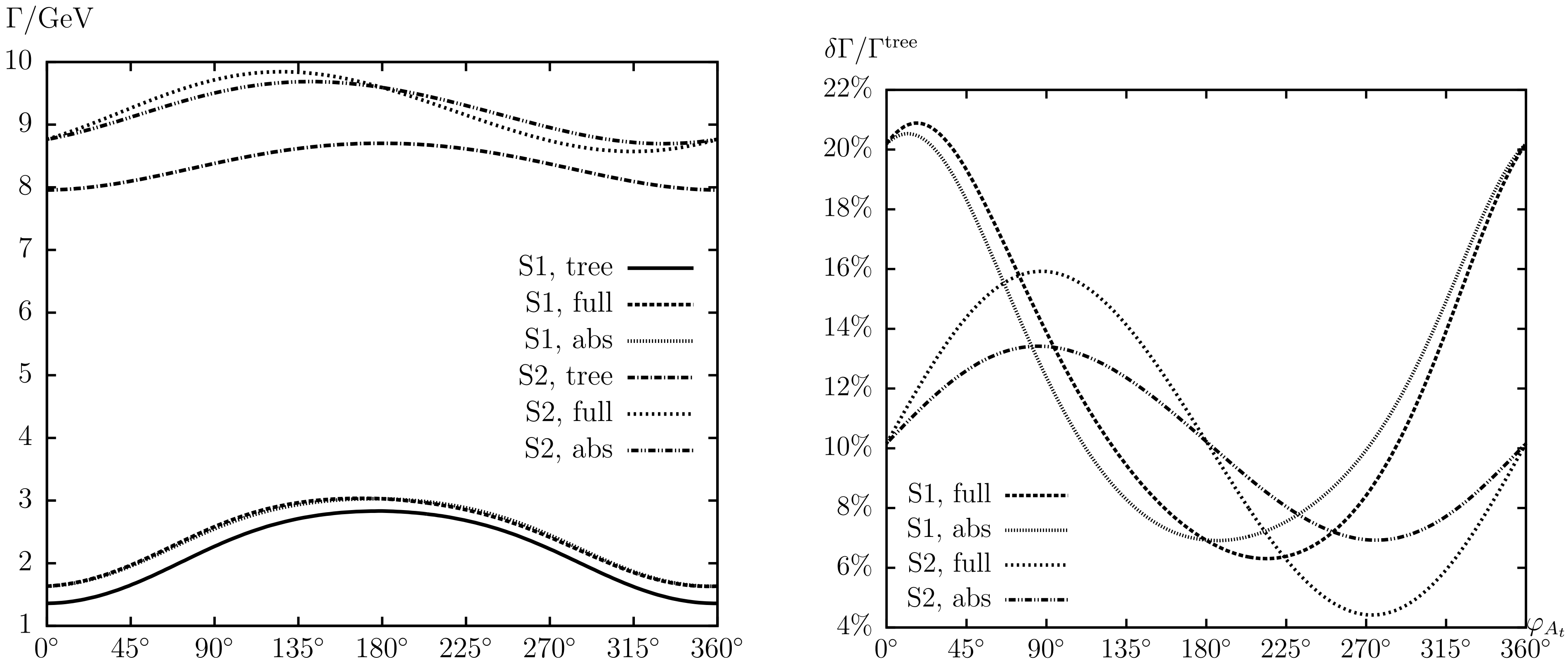
⇒ one-loop corrections under control and non-negligible

⇒ size of BR highly scenario dependent

⇒ EW and QCD corrections can be of similar size!

$\Gamma(\tilde{t}_2 \to \tilde{t}_1 h_1)$: dependence on ϕ_{A_t}

[*T. Fritzsche, S.H., H. Rzehak, C. Schappacher*]



⇒ one-loop corrections under control and non-negligible

⇒ size of BR highly scenario dependent

⇒ EW and QCD corrections can be of similar size!

3B) Heavy Stau decays

$$\Gamma(\tilde{\tau}_2 \to \tilde{\tau}_1 h_i) \qquad (i = 1, 2, 3) \ ,$$

$$\Gamma(\tilde{\tau}_2 \to \tilde{\tau}_1 Z) \ ,$$

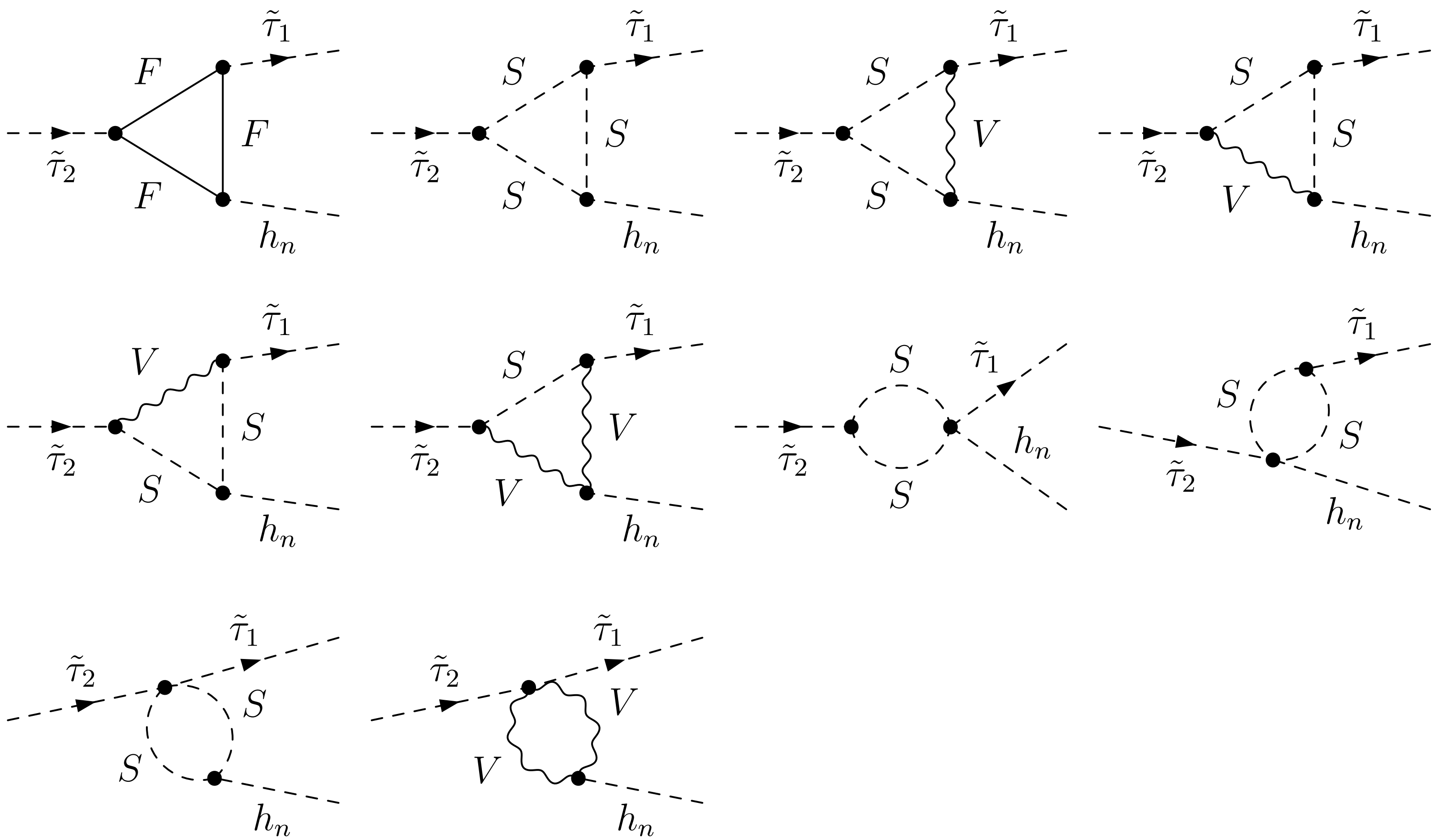
$$\Gamma(\tilde{\tau}_2 \to \tau \tilde{\chi}_k^0) \qquad (k = 1 \ldots 4) \ ,$$

$$\Gamma(\tilde{\tau}_2 \to \tilde{\nu}_\tau H^+) \ ,$$

$$\Gamma(\tilde{\tau}_2 \to \tilde{\nu}_\tau W^+) \ ,$$

$$\Gamma(\tilde{\tau}_2 \to \nu_\tau \tilde{\chi}_k^+) \qquad (k = 1, 2) \ .$$

Feynman diagrams for $\tilde{\tau}_2 \to \tilde{\tau}_1 h_n$



– including Z–A or G–A transition contribution on the external Higgs boson leg

– including all soft/hard QED diagrams

Numerical scenario:

Scen.	$\tan\beta$	$M_{H^\pm}$	$m_{\tilde{\tau}_2}$	$m_{\tilde{\tau}_1}$	$M_{\tilde{q}_{L,R}}$	μ
S1	5	200	550	$\frac{1}{2}m_{\tilde{\tau}_2}$	1000	150
		A_l	A_q	M_1	M_2	M_3
		$\frac{9}{5}m_{\tilde{\tau}_2}$	2000	$\sim \frac{1}{2}M_2$	250	1500

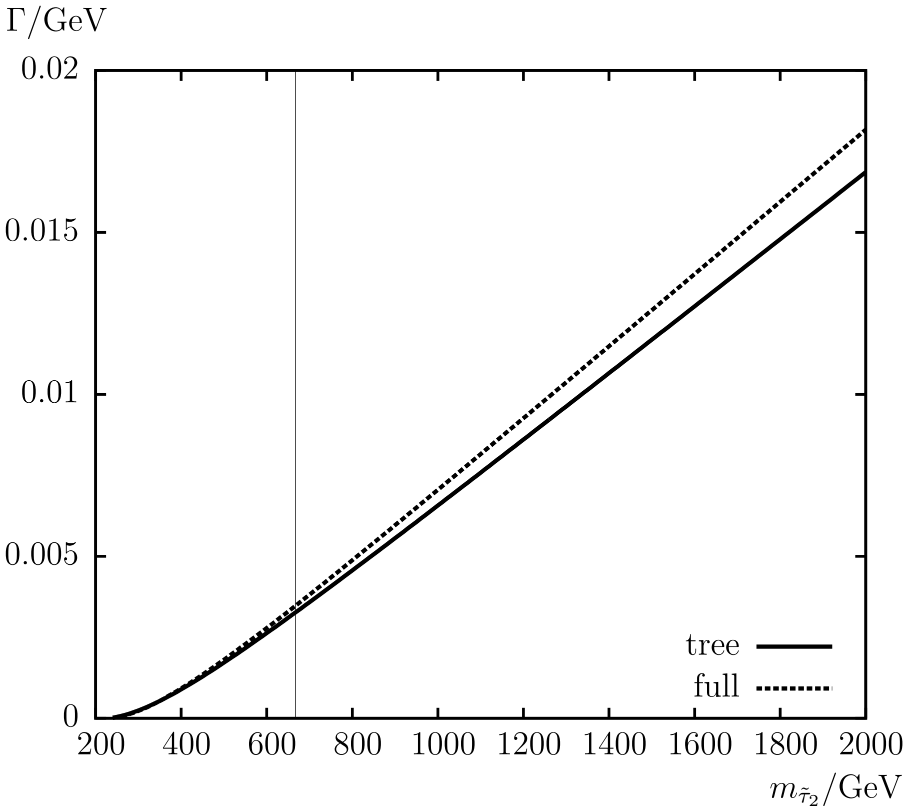
$m_{\tilde{\tau}_1}$	$m_{\tilde{\tau}_2}$	$m_{\tilde{\nu}_\tau}$
274.478	550.000	263.924

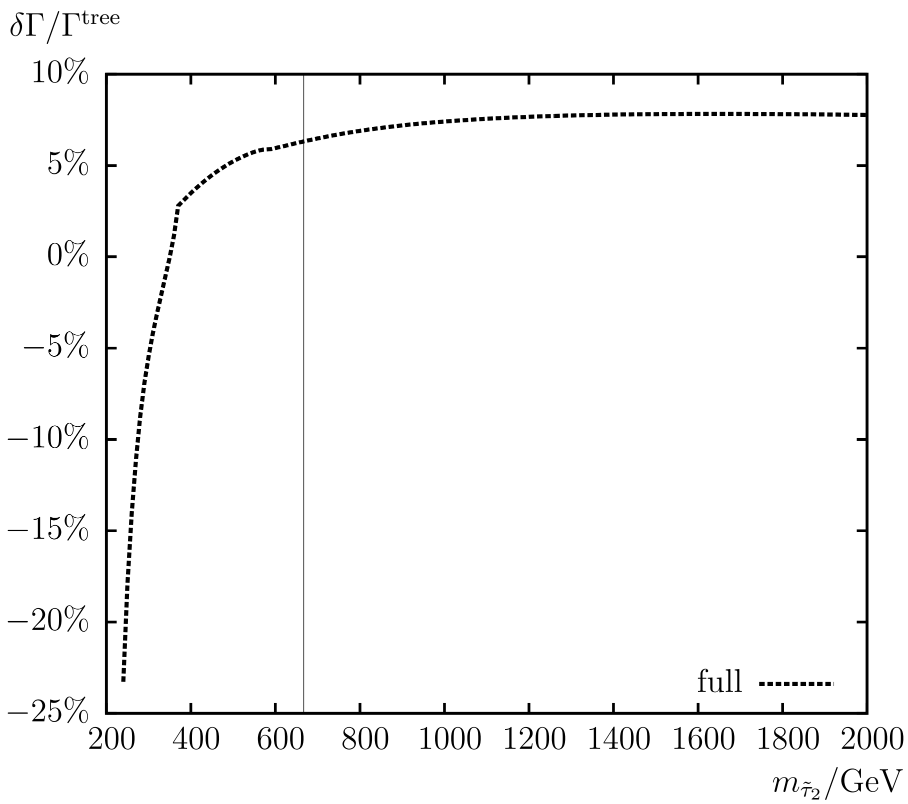
S1: $e^+e^- \to \tilde{\tau}_2\tilde{\tau}_1 \to \tilde{\tau}_1 h_n\, \tilde{\tau}_1$ possible at the ILC(1000)

Scenario chosen such that *all* decay channels are open

$\Gamma(\tilde{\tau}_2 \to \tilde{\tau}_1 h_1)$: dependence on $m_{\tilde{\tau}_2}$

[S.H., C. Schappacher]



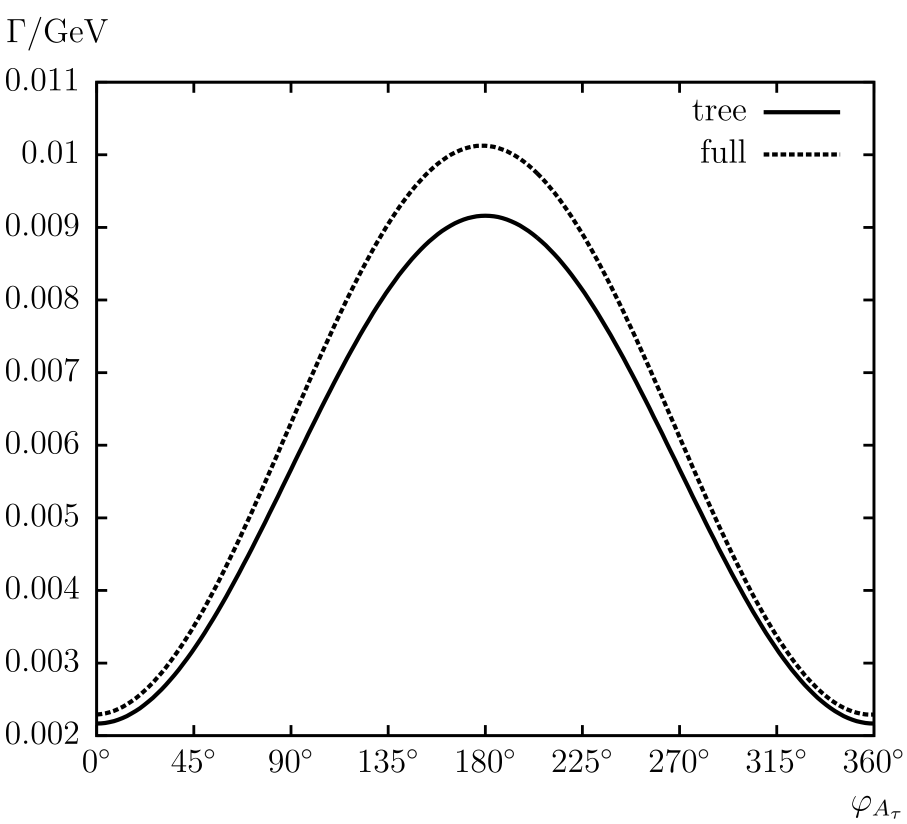


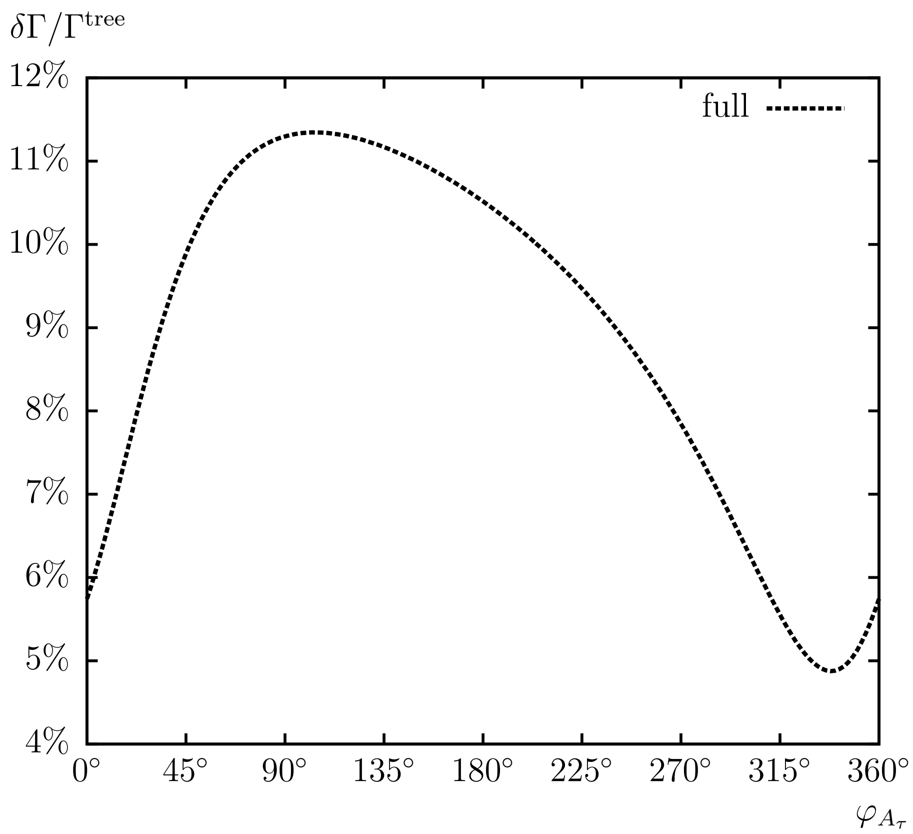
$\Rightarrow$ one-loop corrections under control and non-negligible

$\Rightarrow$ size of BR highly scenario dependent

$\Gamma(\tilde{\tau}_2 \to \tilde{\tau}_1 h_1)$: dependence on ϕ_{A_τ}

[S.H., C. Schappacher]





$\Rightarrow$ one-loop corrections under control and non-negligible

$\Rightarrow$ size of BR highly scenario dependent

3C) Chargino decays

$$\Gamma(\tilde{\chi}_2^\pm \to \tilde{\chi}_1^\pm h_k) \qquad (k = 1, 2, 3) \ ,$$
$$\Gamma(\tilde{\chi}_2^\pm \to \tilde{\chi}_1^\pm Z) \ ,$$
$$\Gamma(\tilde{\chi}_i^\pm \to \tilde{\chi}_j^0 H^\pm) \qquad (i = 1, 2, \ j = 1, 2, 3, 4) \ ,$$
$$\Gamma(\tilde{\chi}_i^\pm \to \tilde{\chi}_j^0 W^\pm) \qquad (i = 1, 2, \ j = 1, 2, 3, 4) \ ,$$
$$\Gamma(\tilde{\chi}_i^\pm \to \tilde{l}_k^\pm \nu_l) \qquad (i = 1, 2, \ l = e, \mu, \tau, \ k = 1, 2) \ ,$$
$$\Gamma(\tilde{\chi}_i^\pm \to \tilde{\nu}_l \, l^\pm) \qquad (i = 1, 2, \ l = e, \mu, \tau) \ .$$

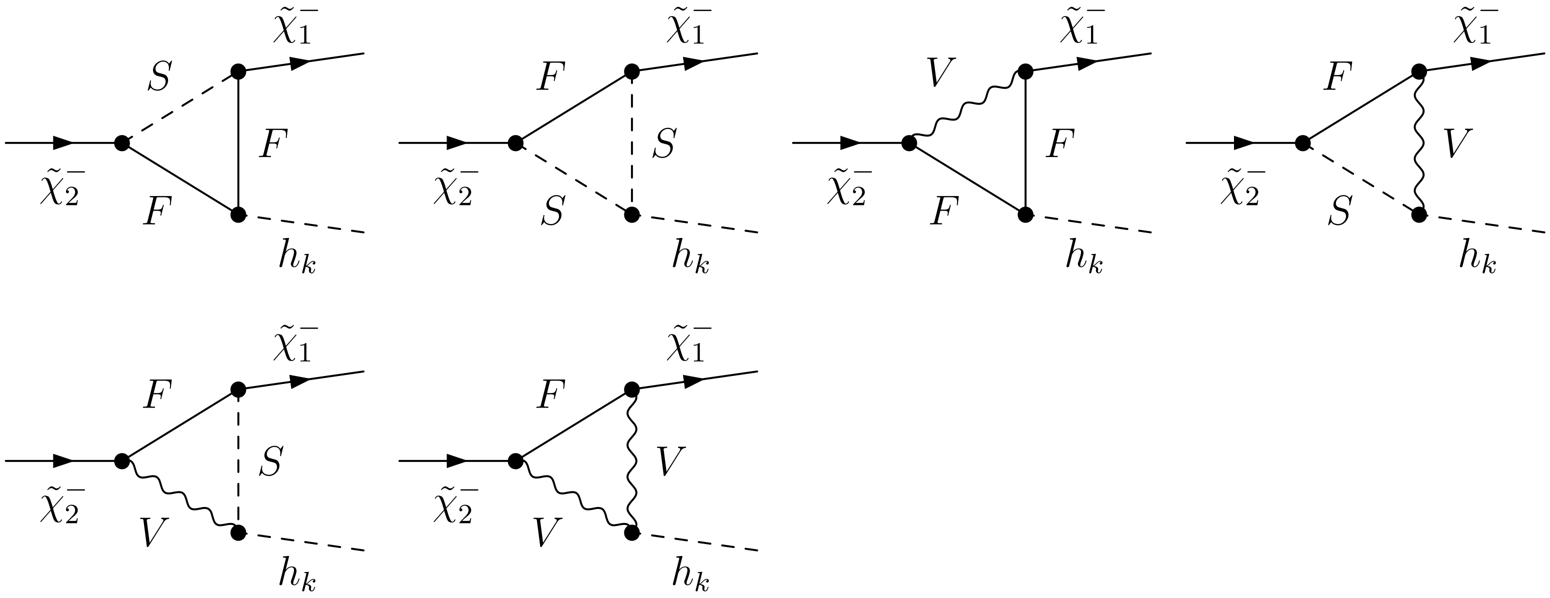
No hadronic decays yet . . .

Scen.	$\tan\beta$	$M_{H^\pm}$	$m_{\tilde{\chi}_2^\pm}$	$m_{\tilde{\chi}_1^\pm}$	$M_{\tilde{l}_L}$	$M_{\tilde{l}_R}$	A_l
$\mathcal{S}$	20	160	650	350	300	310	400

$\mathcal{S}_> : \mu > M_2$ ($\tilde{\chi}_2^\pm$ more higgsino-like)

$\mathcal{S}_< : \mu < M_2$ ($\tilde{\chi}_2^\pm$ more gaugino-like)

Feynman diagrams for $\tilde{\chi}_2^- \to \tilde{\chi}_1^- h_k$

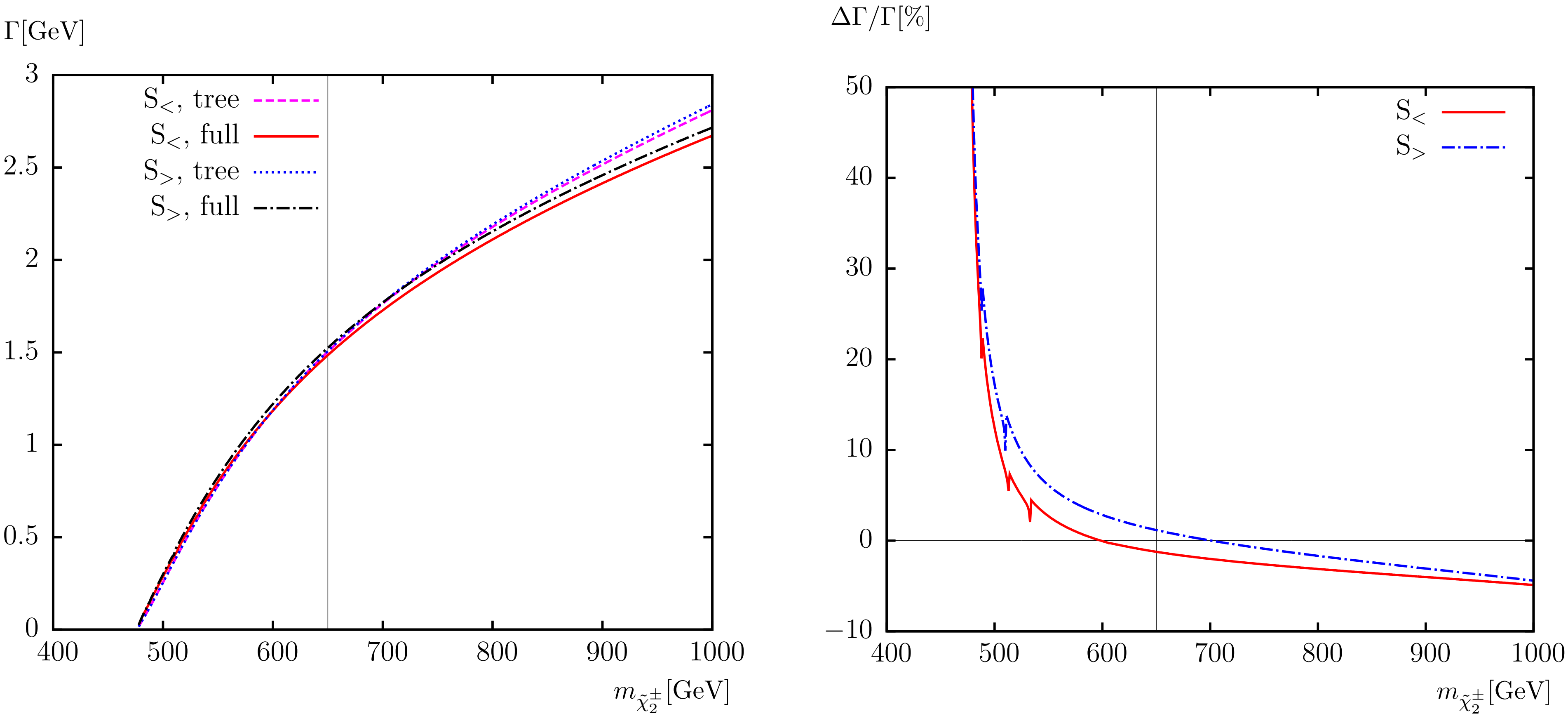


– including Z–A or G–A transition contribution on the external Higgs boson leg

– including all soft/hard QED diagrams

$\Gamma(\tilde{\chi}_2^- \to \tilde{\chi}_1^- h_1)$: dependence on $m_{\tilde{\chi}_2^\pm}$

[S.H., F. v.d. Pahlen, C. Schappacher]



⇒ one-loop corrections under control and non-negligible

⇒ size of BR highly scenario dependent

3D) Neutralino decays

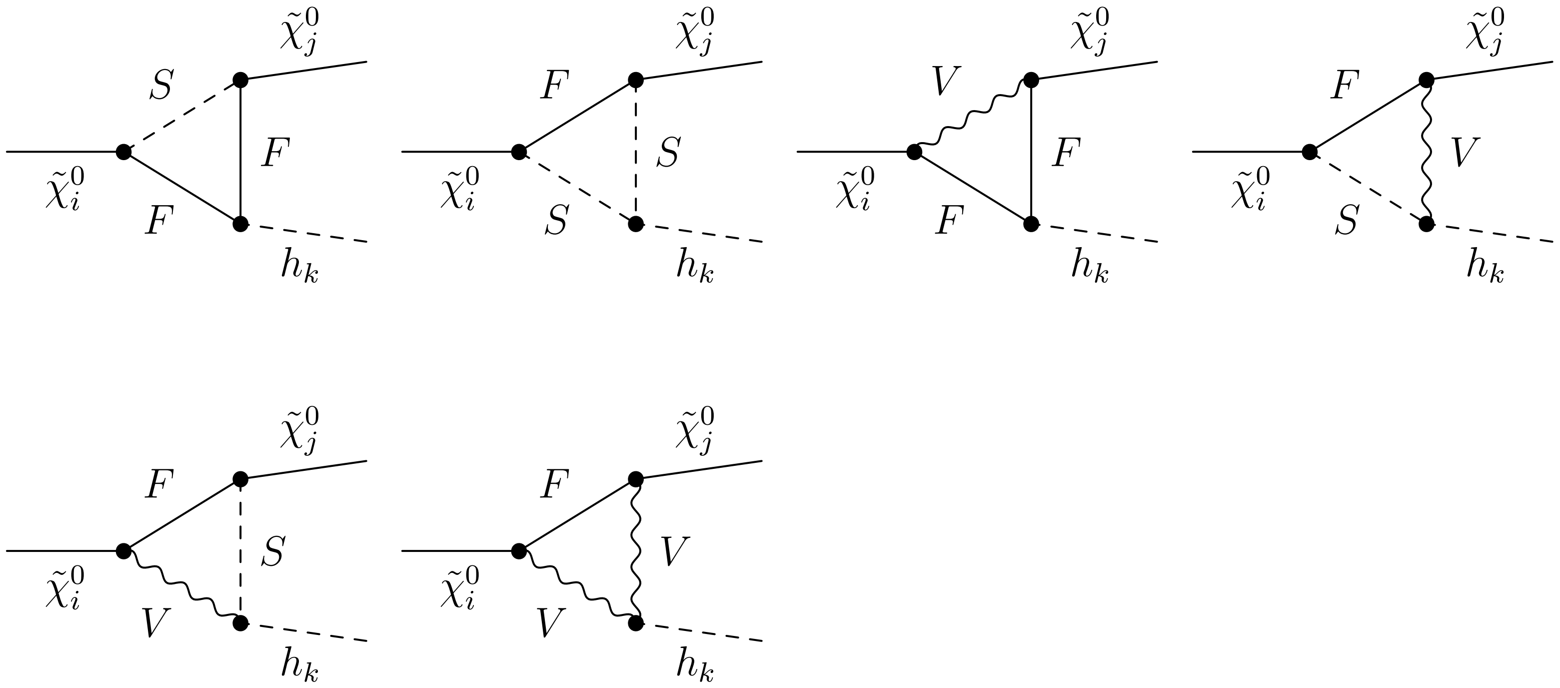
$$\Gamma(\tilde{\chi}^0_i \to \tilde{\chi}^0_j h_k) \qquad (i = 2,3,4;\ j < i;\ k = 1,2,3)\ ,$$
$$\Gamma(\tilde{\chi}^0_i \to \tilde{\chi}^{\mp}_j H^{\pm}) \qquad (i = 2,3,4;\ j = 1,2)\ ,$$
$$\Gamma(\tilde{\chi}^0_i \to \tilde{\chi}^{\mp}_j W^{\pm}) \qquad (i = 2,3,4;\ j = 1,2)\ ,$$
$$\Gamma(\tilde{\chi}^0_i \to \tilde{\chi}^0_j Z) \qquad (i = 2,3,4;\ j < i)\ ,$$
$$\Gamma(\tilde{\chi}^0_i \to \ell^{\mp}\,\tilde{\ell}^{\pm}_k) \qquad (i = 2,3,4;\ \ell = e,\mu,\tau;\ k = 1,2)\ ,$$
$$\Gamma(\tilde{\chi}^0_i \to \bar{\nu}_\ell\,\tilde{\nu}_\ell / \nu_\ell\,\tilde{\nu}^{\dagger}_\ell) \qquad (i = 2,3,4;\ \ell = e,\mu,\tau)\ .$$

No hadronic decays yet . . .

$\tan\beta$	$M_{H^\pm}$	$m_{\tilde{\chi}^\pm_2}$	$m_{\tilde{\chi}^\pm_1}$	$M_{\tilde{l}_L}$	$M_{\tilde{l}_R}$	A_l	$M_{\tilde{q}_L}$	$M_{\tilde{q}_R}$	A_q
20	160	600	350	300	310	400	1300	1100	2000

$$\mathcal{S}_h : \mu > M_2 \quad (\tilde{\chi}^0_4 \text{ more higgsino-like})$$
$$\mathcal{S}_g : \mu < M_2 \quad (\tilde{\chi}^0_4 \text{ more gaugino-like})$$

Feynman diagrams for $\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 h_k$

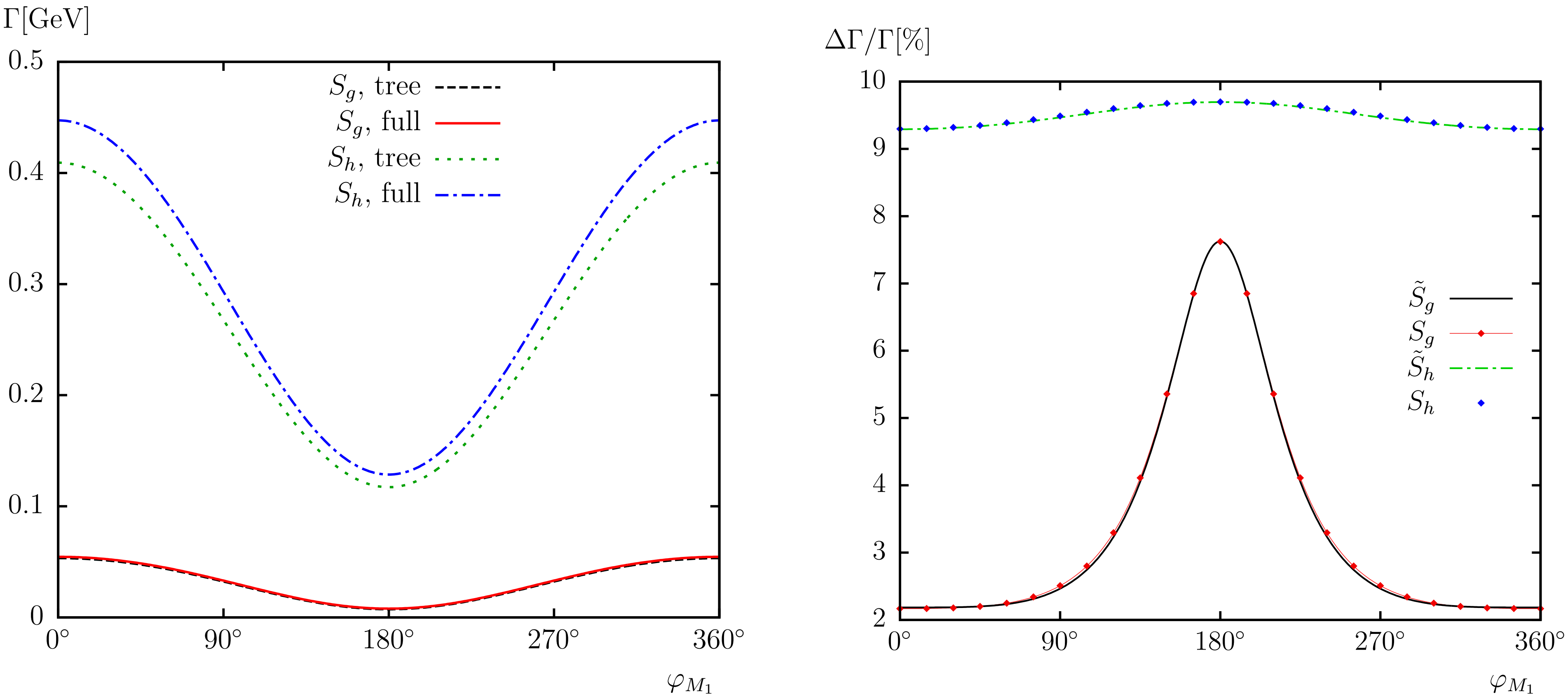


– including Z–A or G–A transition contribution on the external Higgs boson leg

– including all soft/hard QED diagrams

$\Gamma(\tilde{\chi}^0_4 \to \tilde{\chi}^0_1 h_1)$: dependence on φ_{M_1}

[*A. Bharoucha, S.H., F. v.d. Pahlen, C. Schappacher*]



⇒ one-loop corrections under control and non-negligible

⇒ size of BR highly scenario dependent

4. Direct Higgs Production at the e^+e^- LC

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*]

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

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

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

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

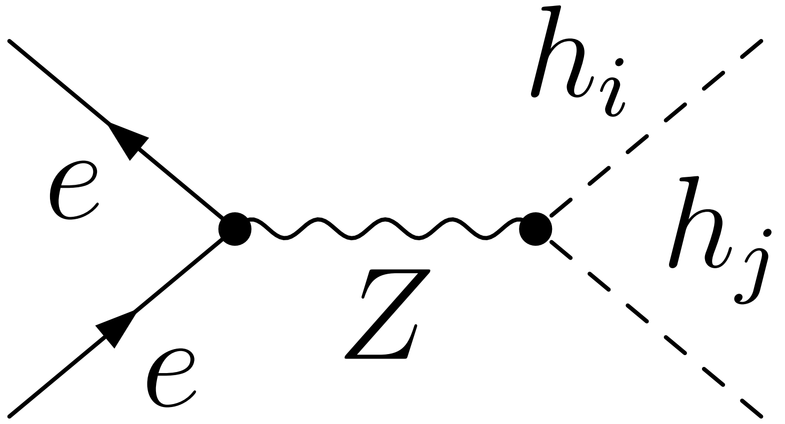
m_{h_1}	m_{h_2}	m_{h_3}
123.404	288.762	290.588

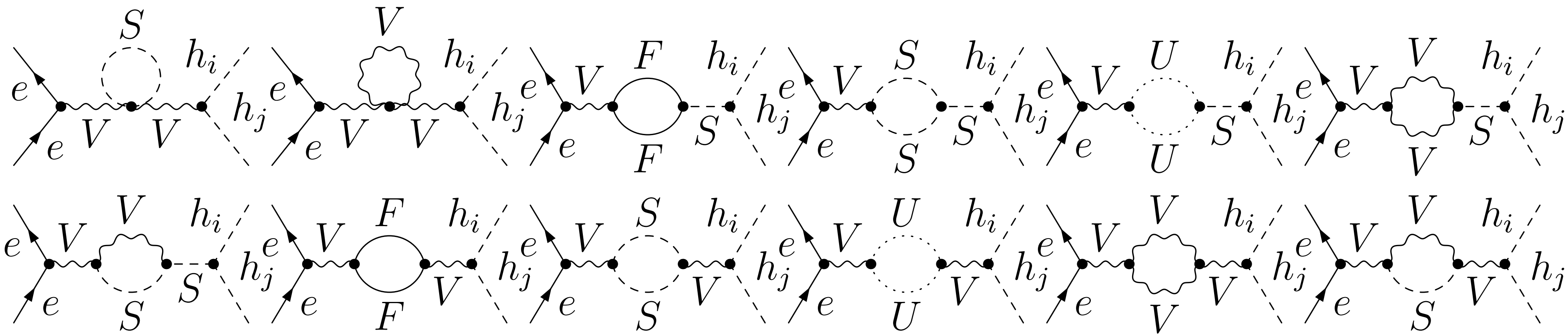
with $\sqrt{s}$, $M_{H^\pm}$, $\tan\beta$, ϕ_{A_t} varied

– Scenario chosen such that many processes are possible at the same time

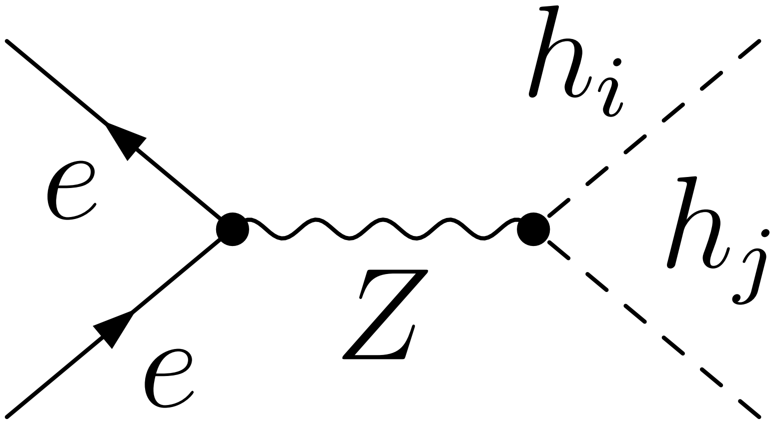
– not chosen to maximize loop corrections

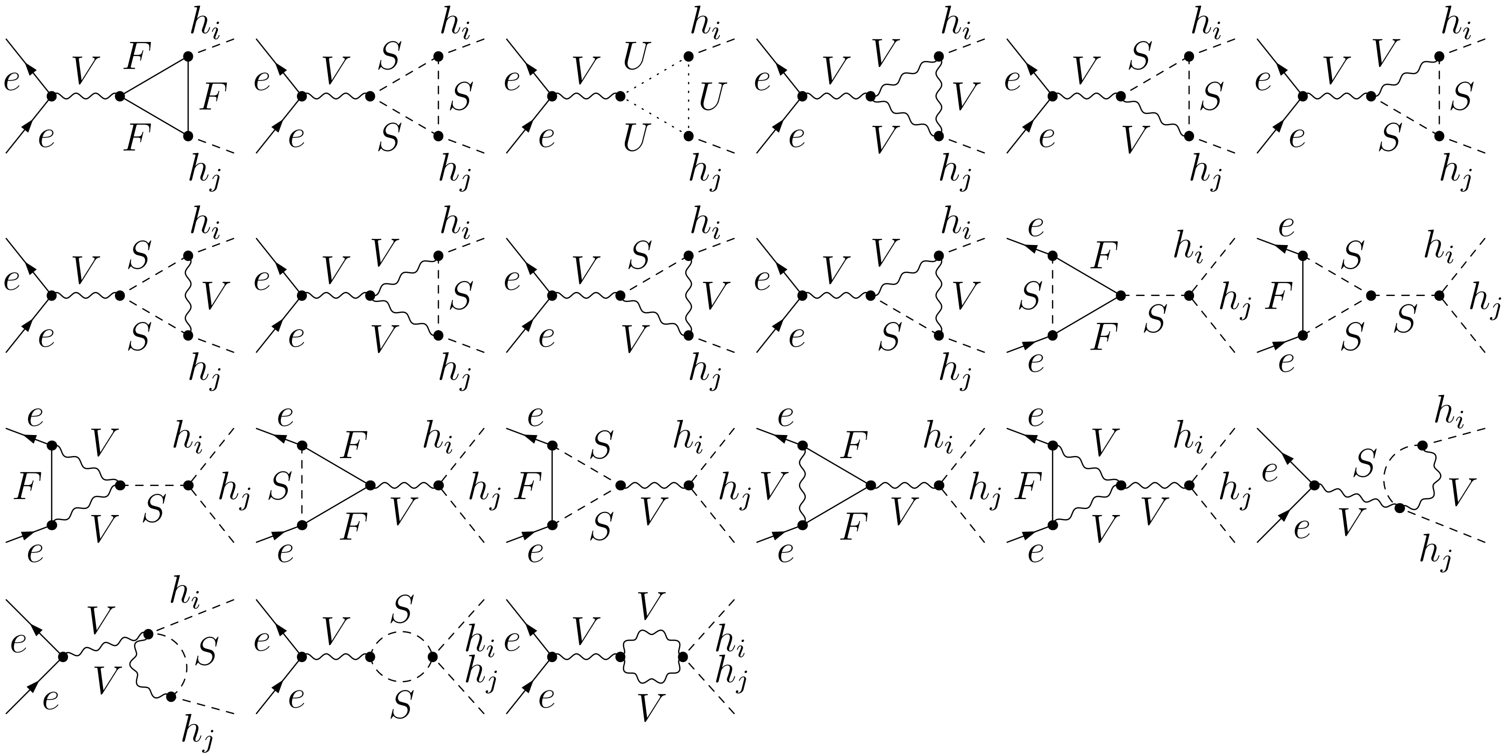
$e^+e^- \to h_i h_j$:



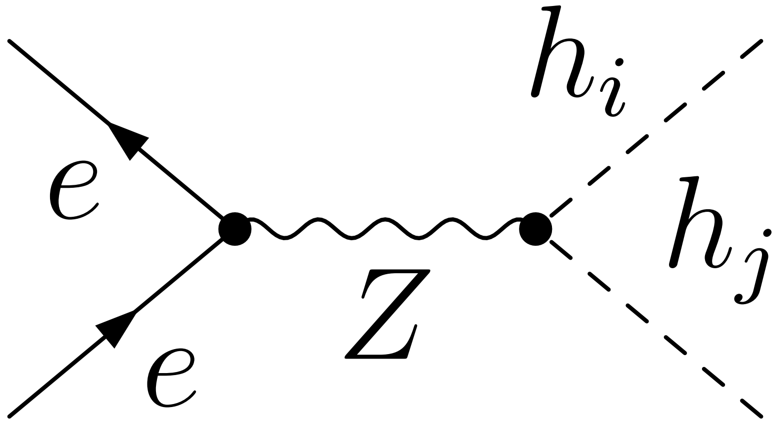


$e^+e^- \to h_i h_j$:

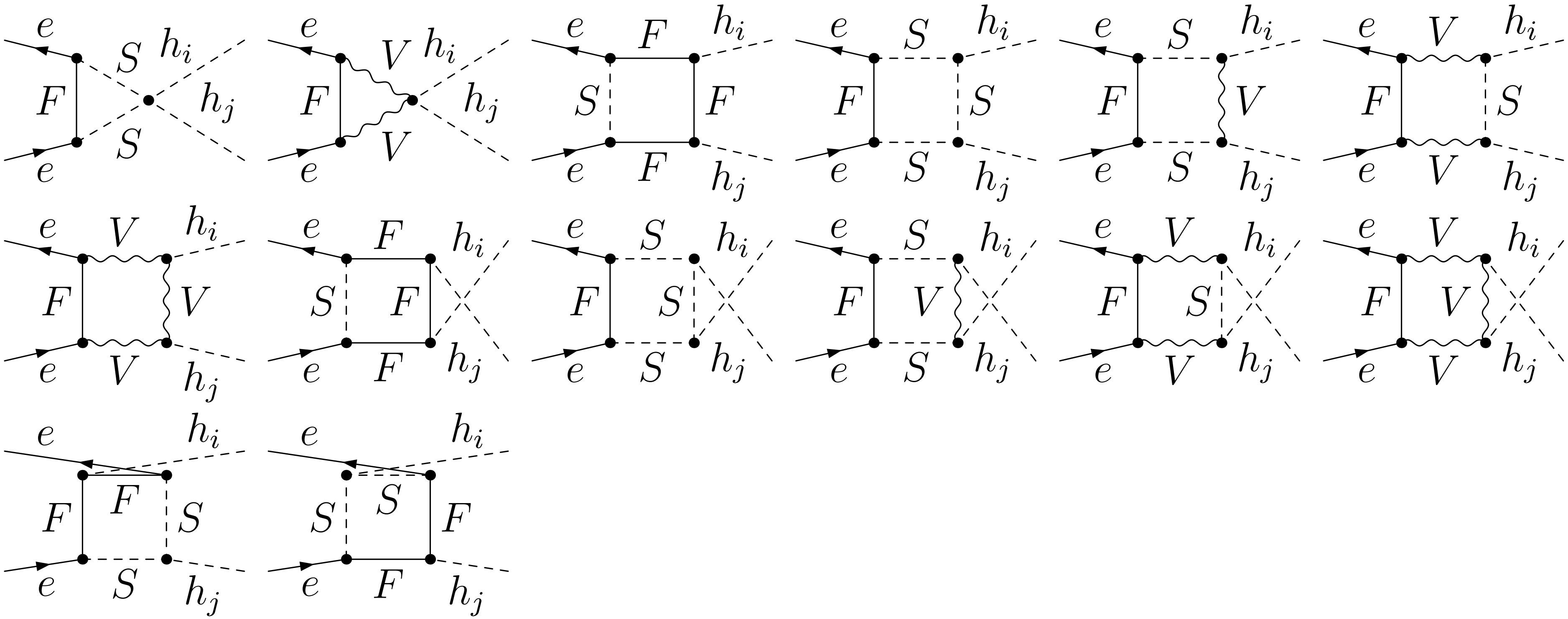




$e^+e^- \to h_ih_j$:

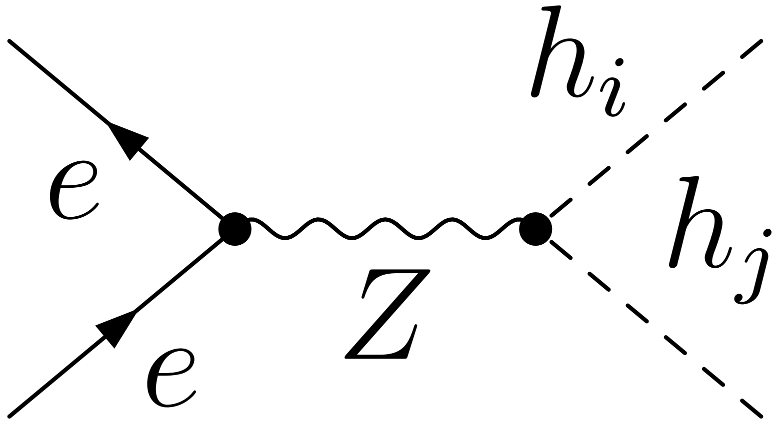


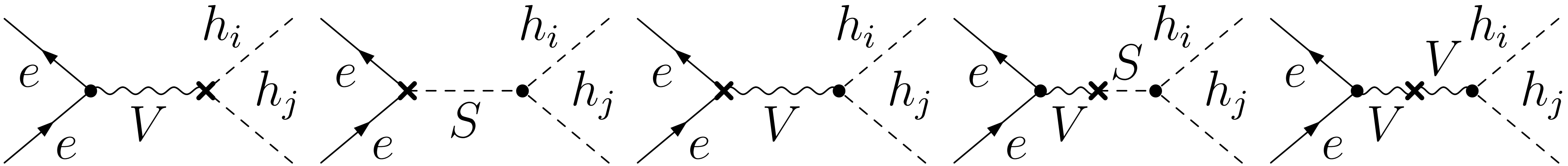
e
e
Z
h_i
h_j



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

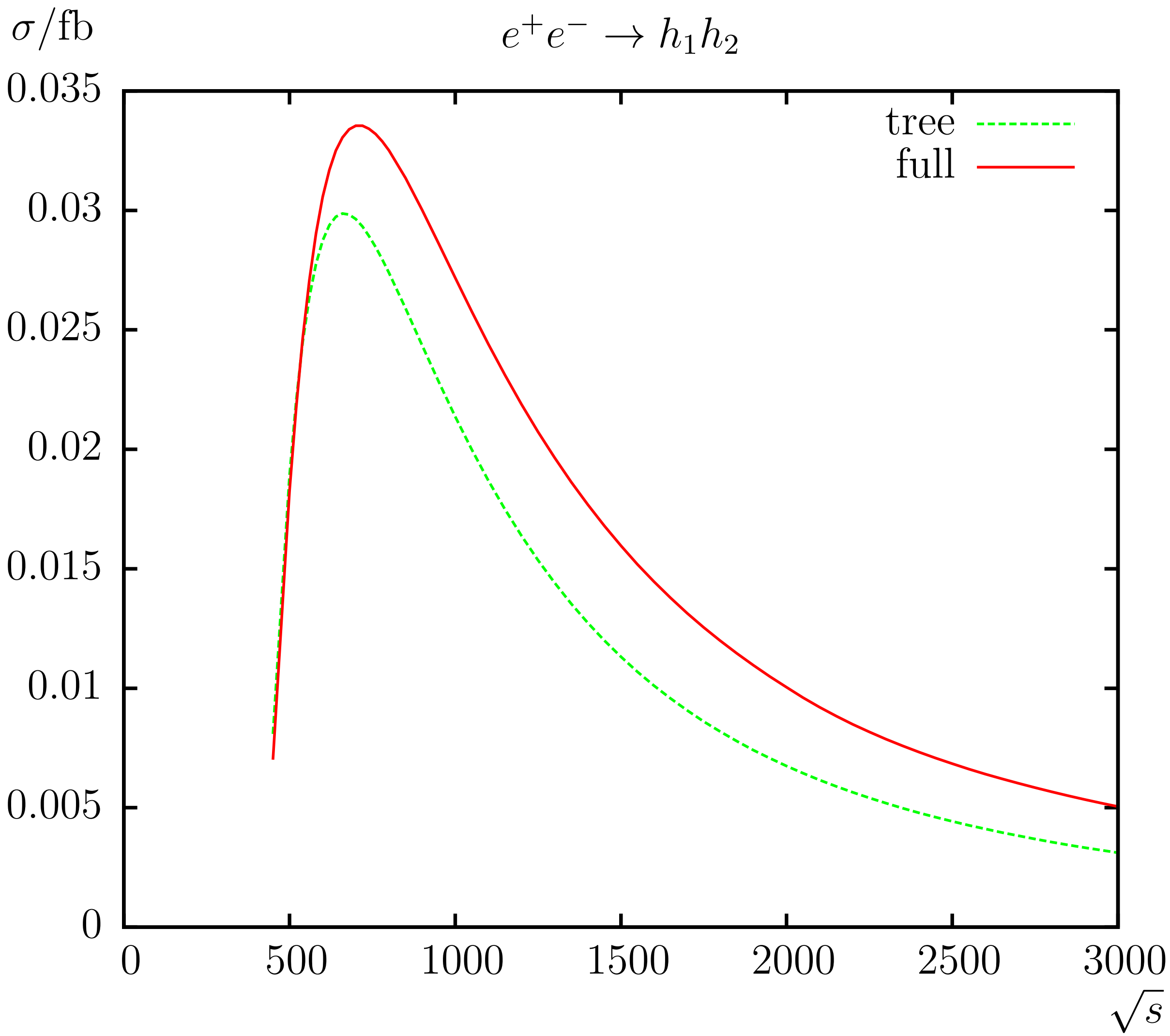
<u>$e^+e^- \to h_i h_j$:</u>





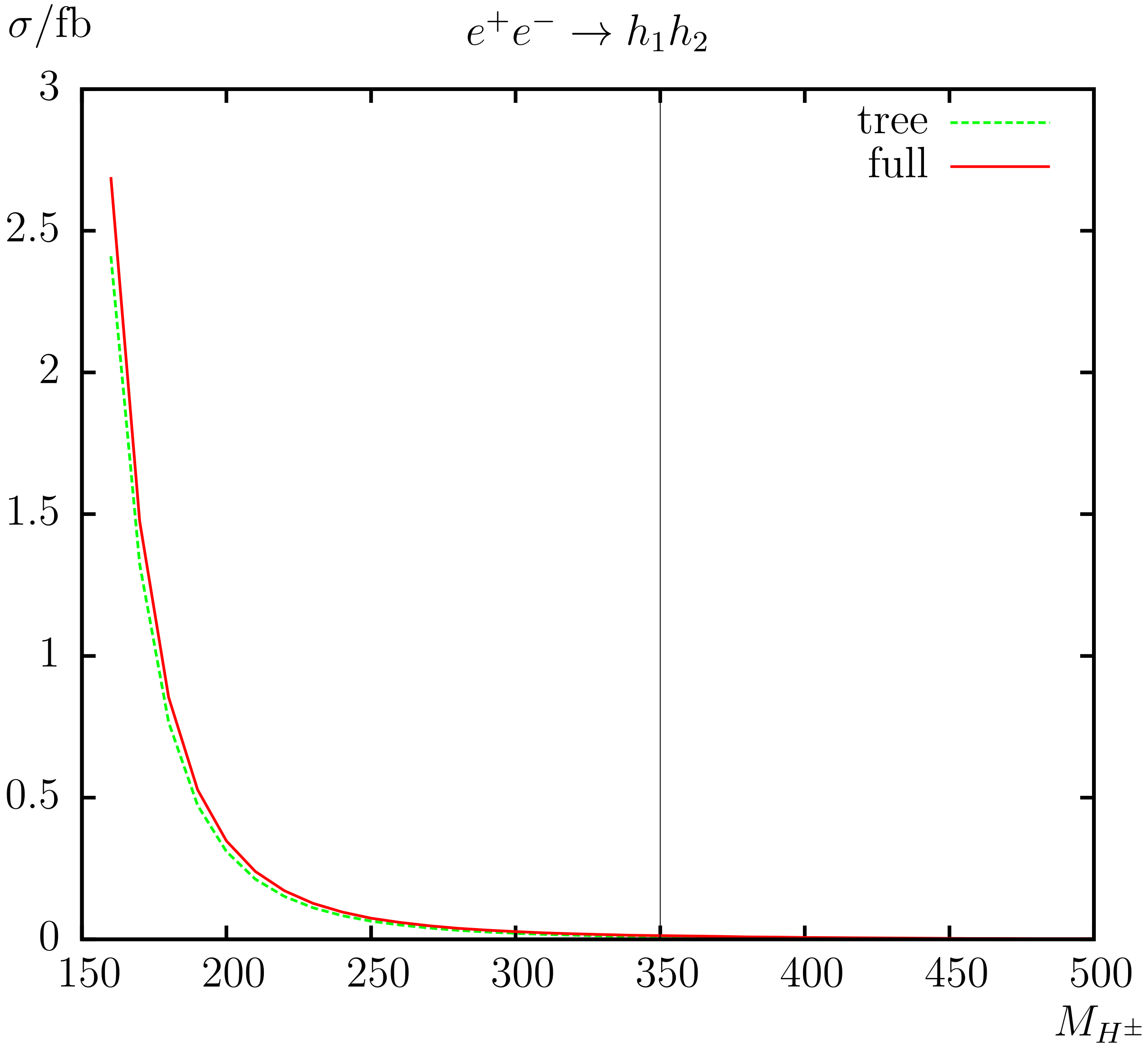
+ soft and hard QED radiation

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



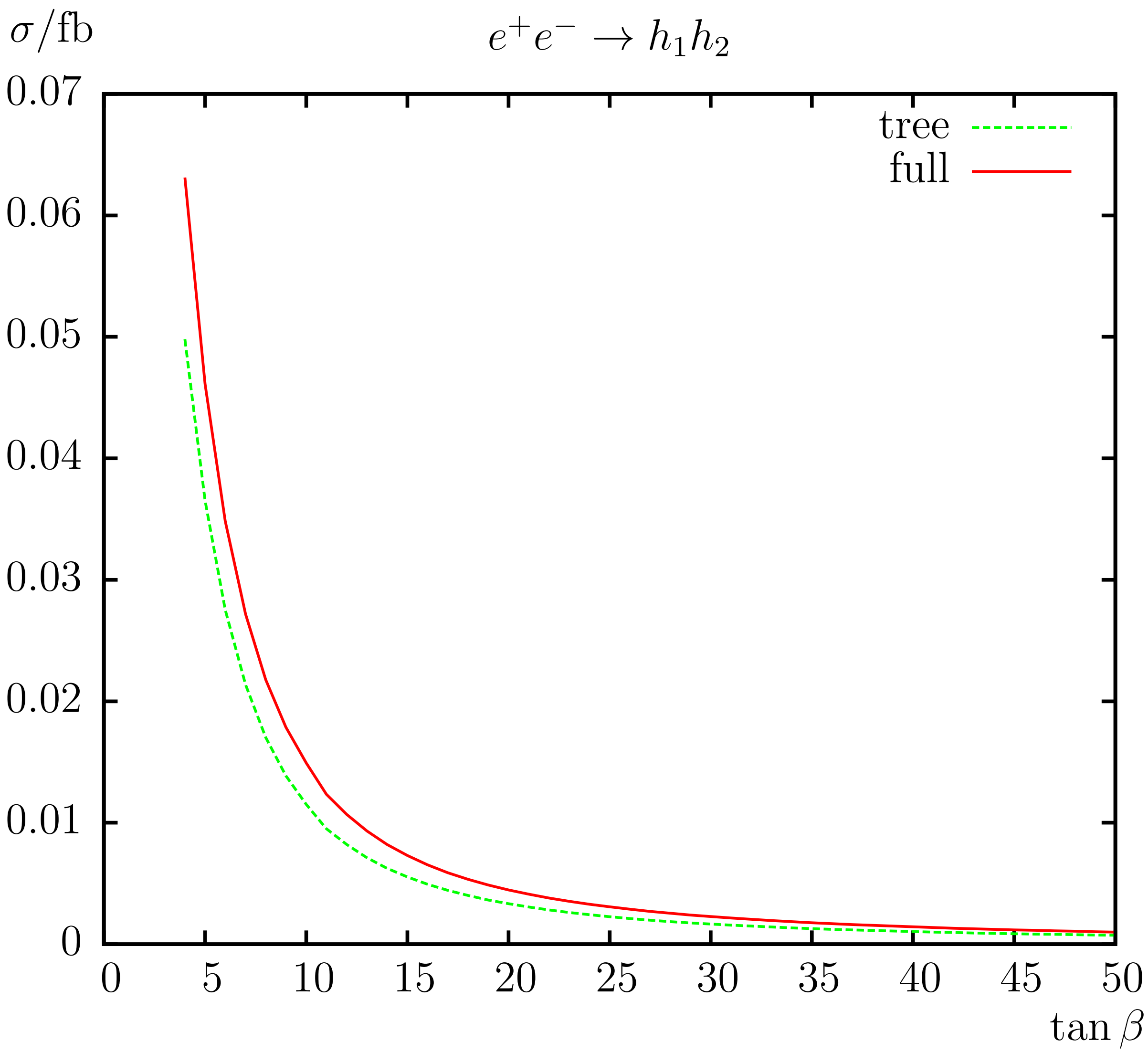
$\Rightarrow$ loop corrections crucial!

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



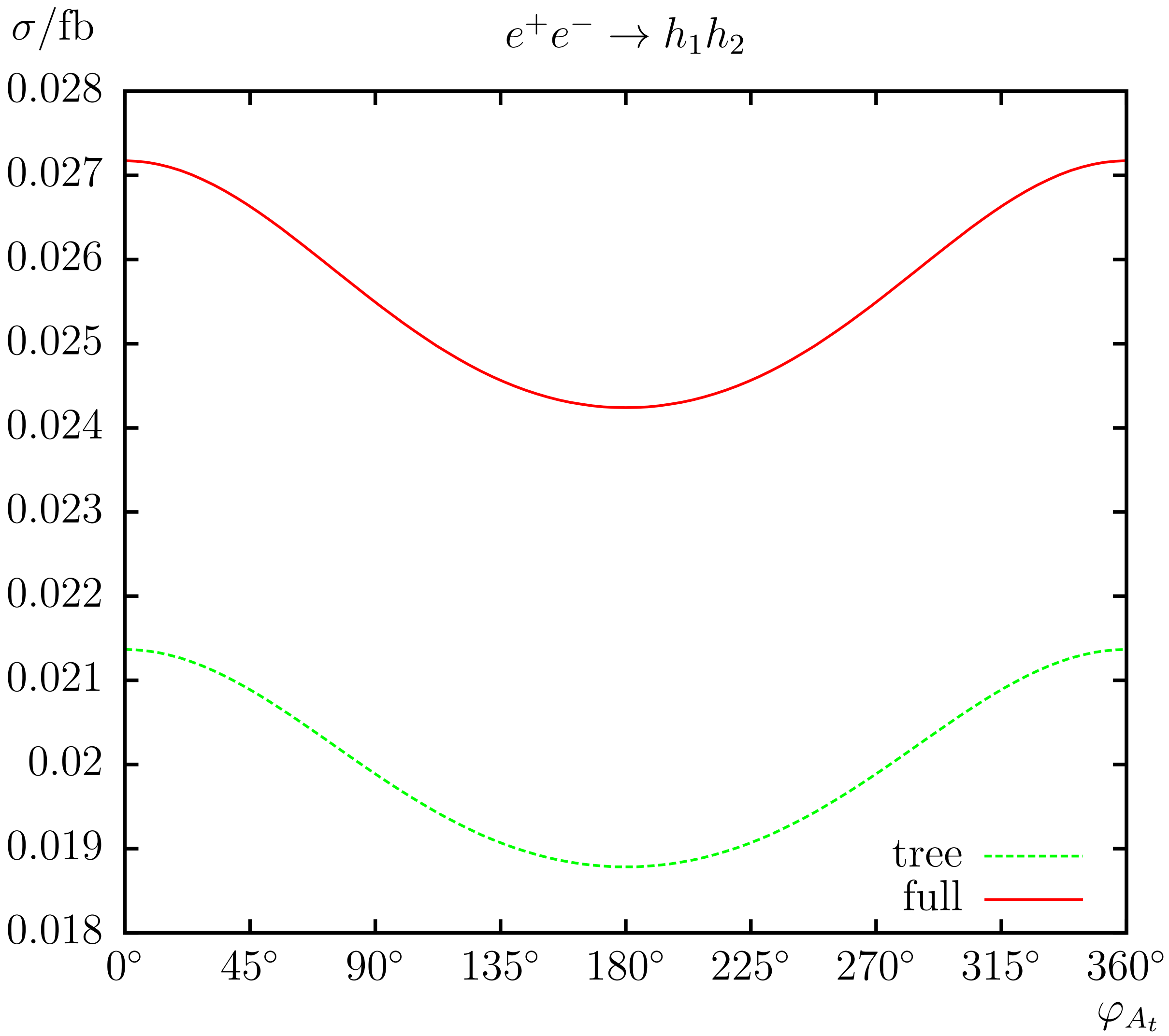
σ/fb
$e^+e^- \to h_1h_2$
3
2.5
2
1.5
1
0.5
0
tree
full
150
200
250
300
350
400
450
500
$M_{H^\pm}$

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



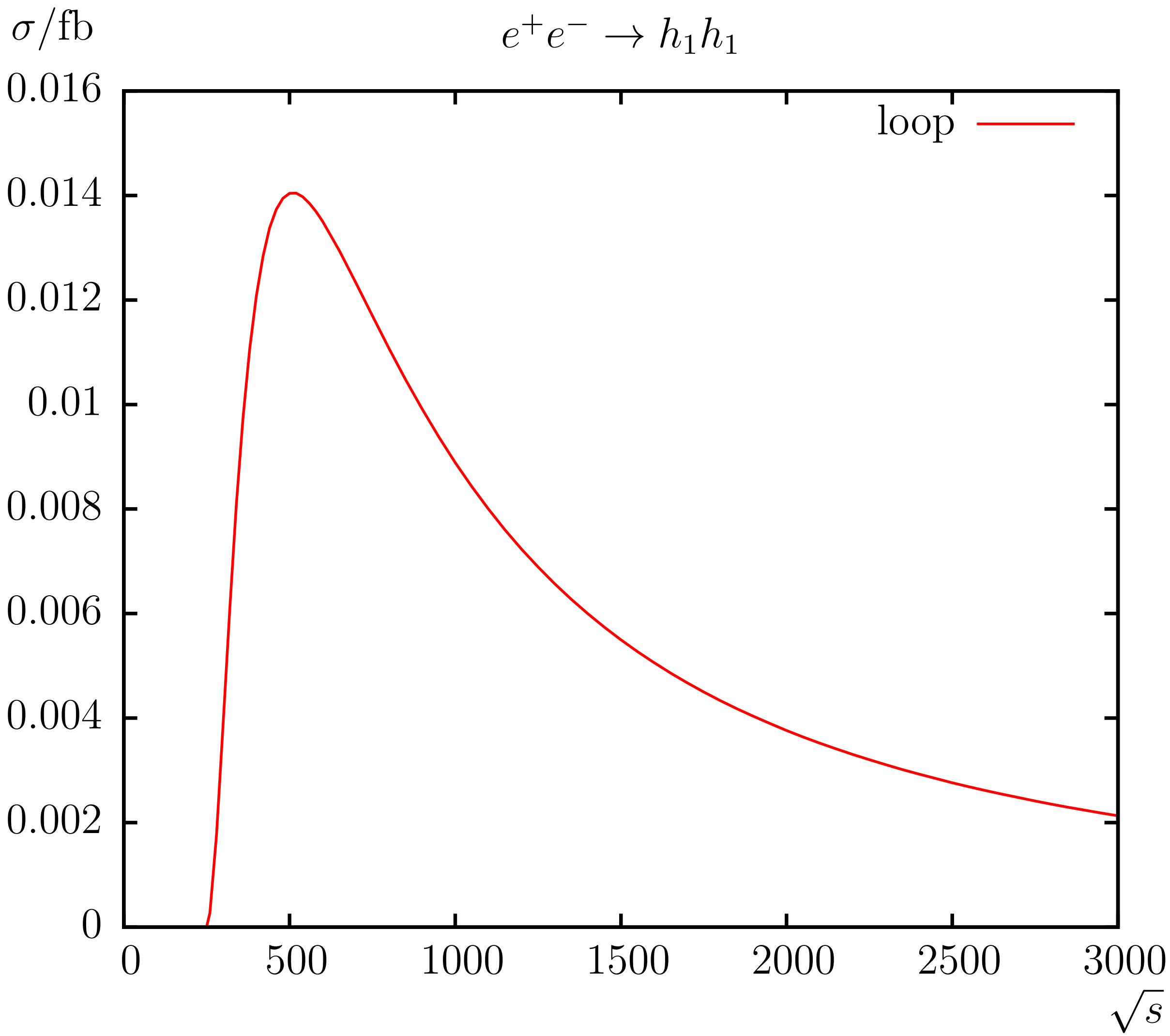
σ/fb
$e^+e^- \to h_1h_2$
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
tree
full
0
5
10
15
20
25
30
35
40
45
50
$\tan\beta$

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



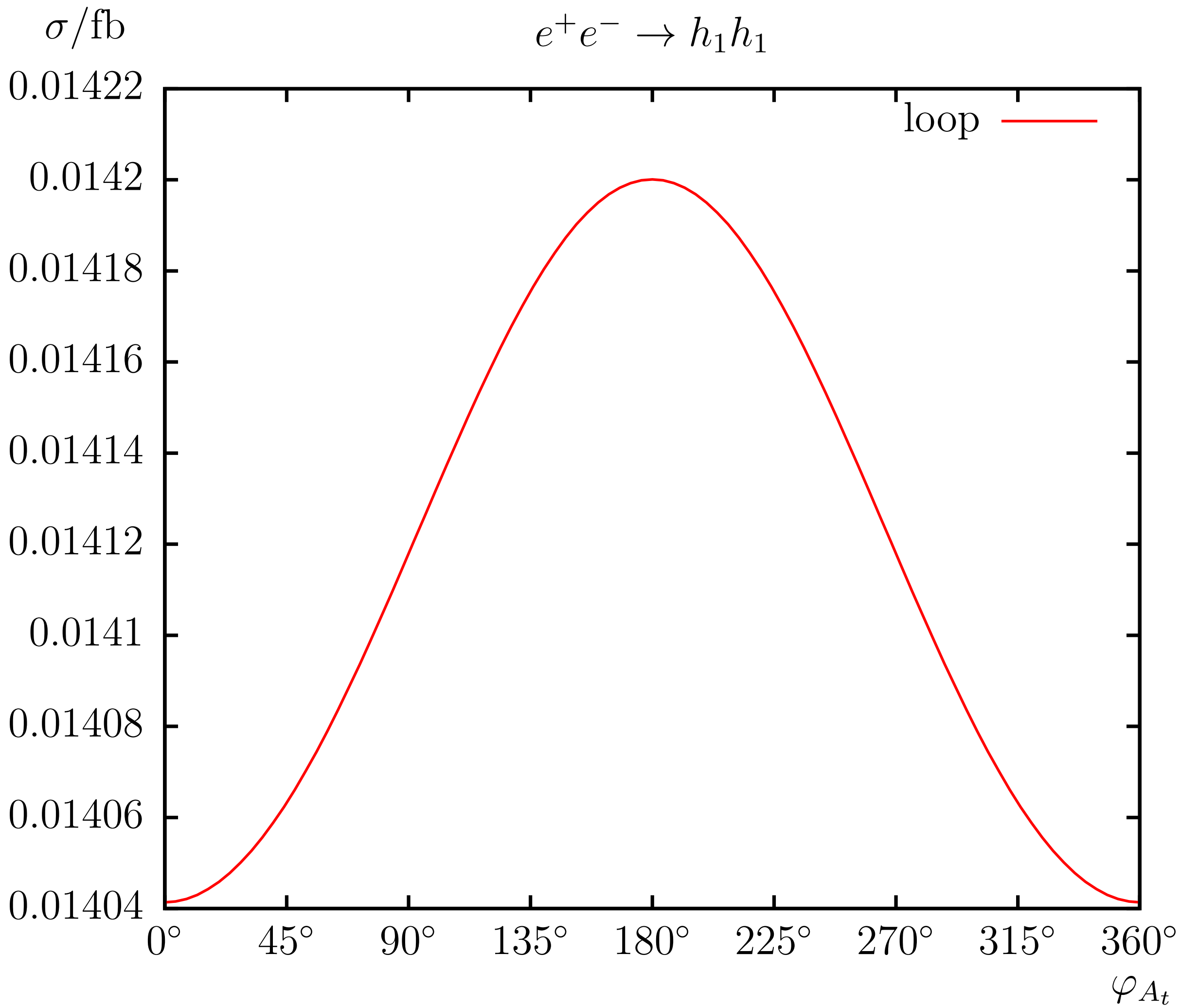
$\Rightarrow$ phase dependence more pronounced at loop-level

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



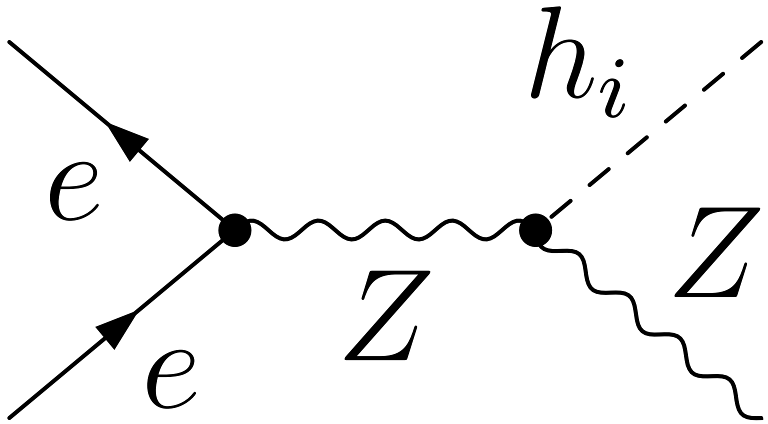
$\Rightarrow$ possibly observable!

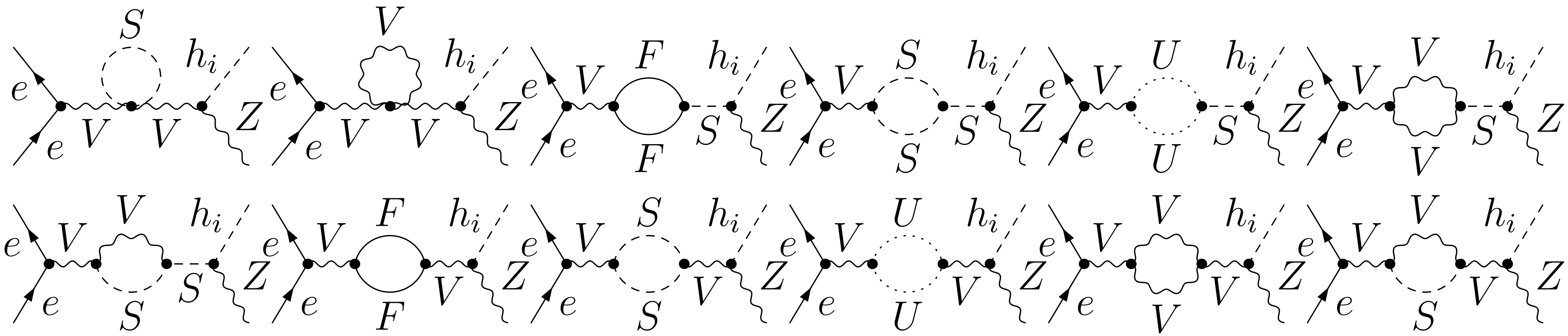
$e^+e^- \to h_1 h_1$ (purely loop induced):



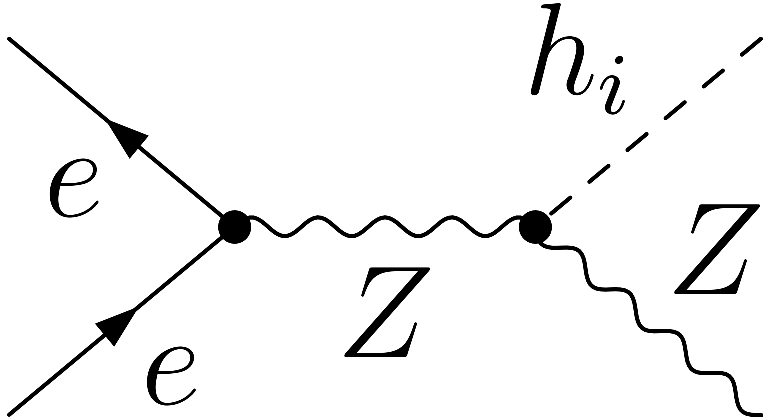
$\Rightarrow$ negligible ϕ_{A_t} dependence!

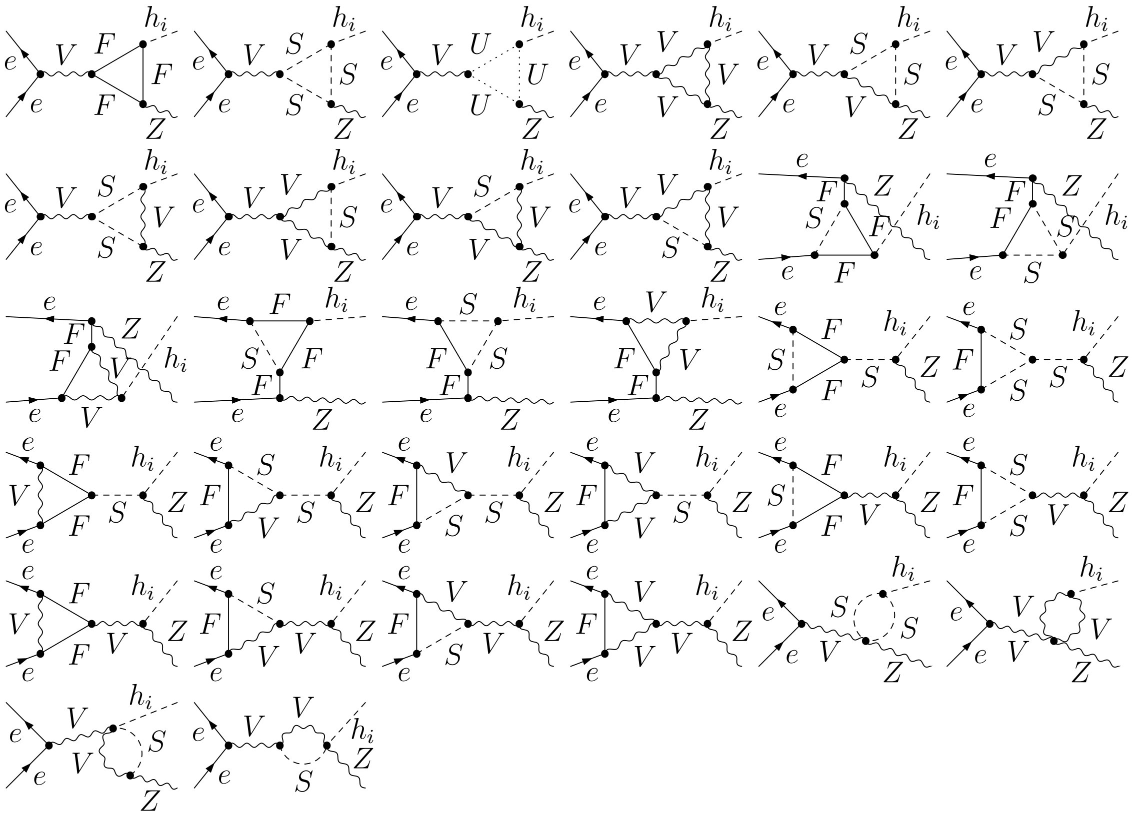
$e^+e^- \to h_i Z$:



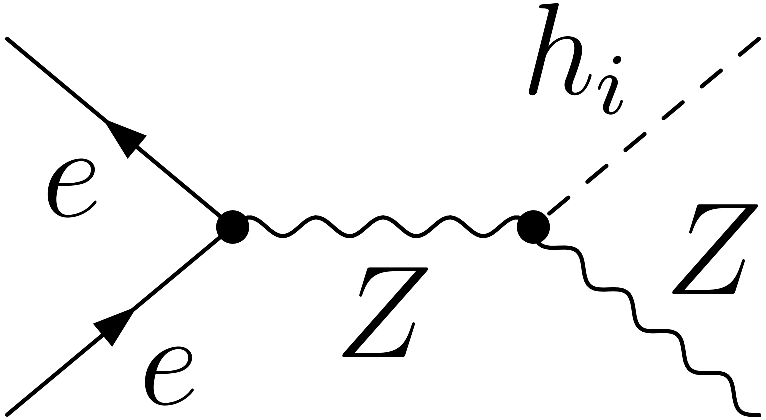


$e^+e^- \to h_i Z$:

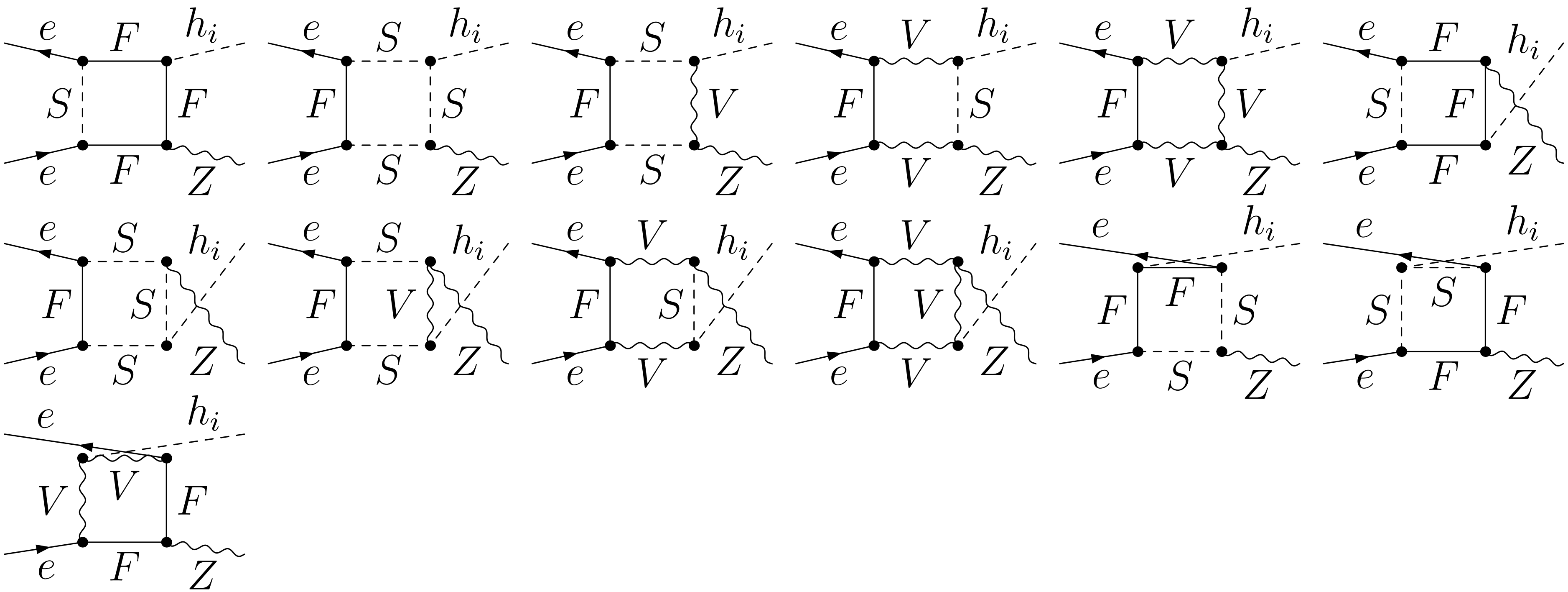




$e^+e^- \to h_i Z$:

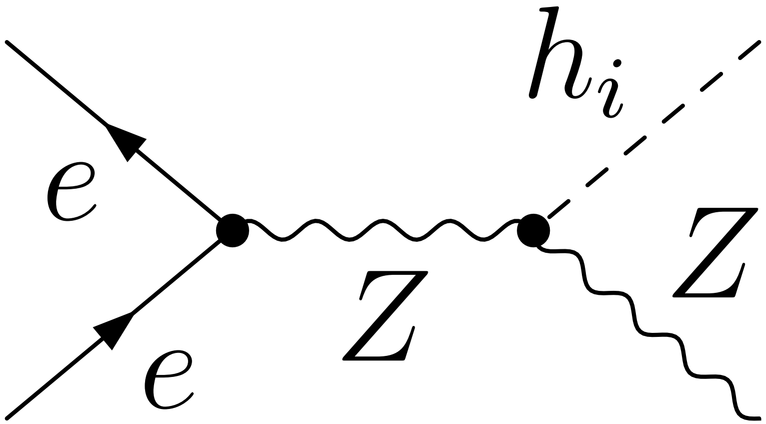


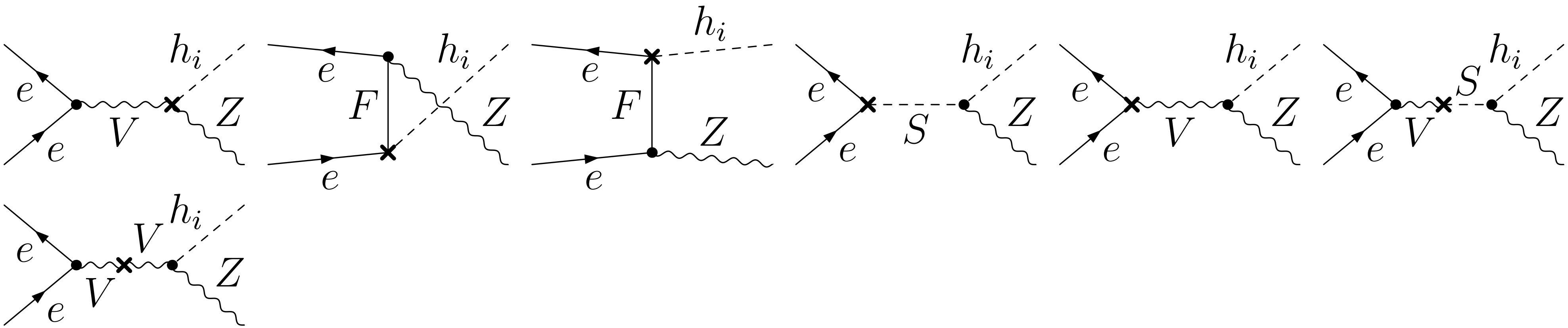
e
e
Z
h_i
Z



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

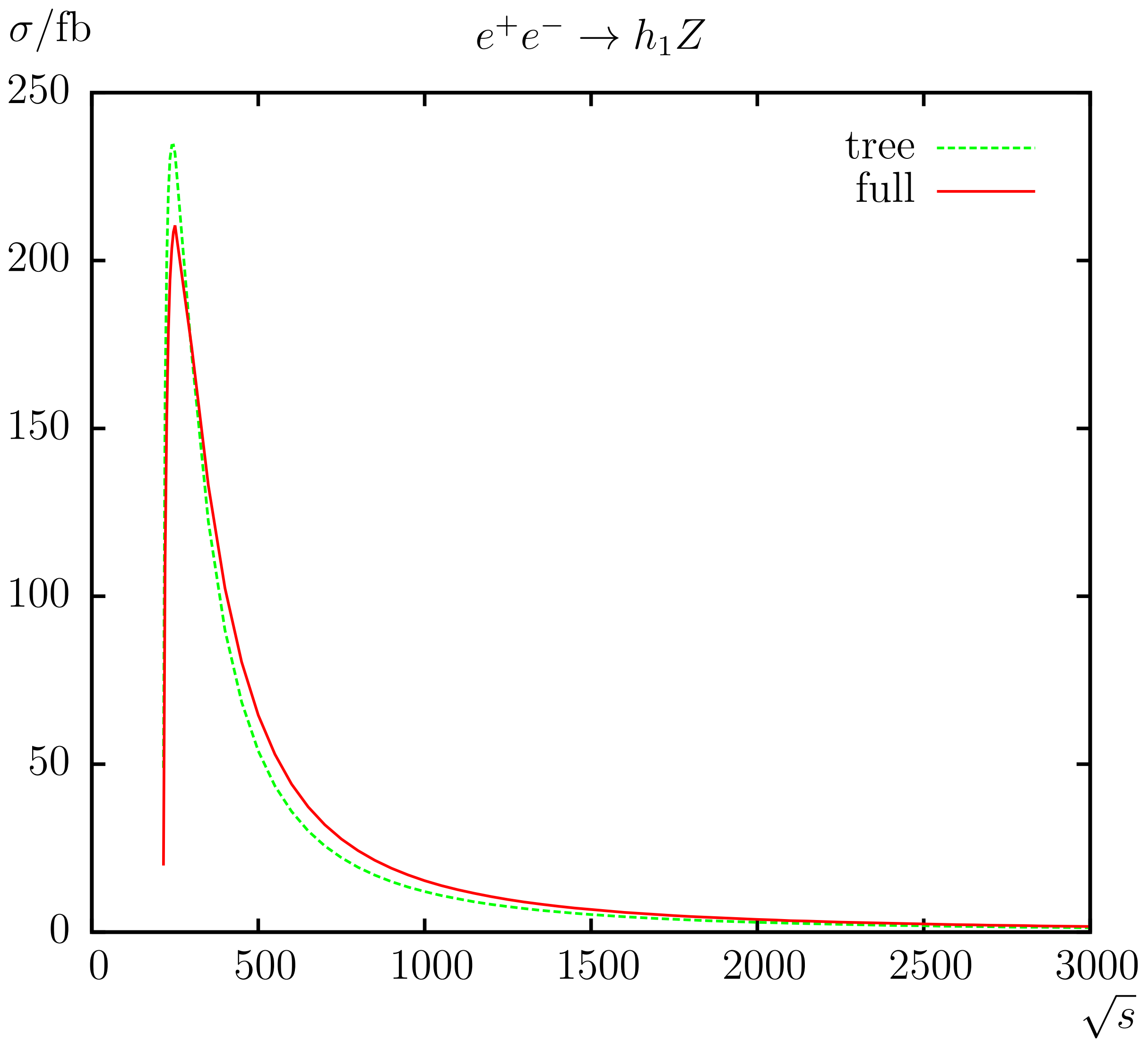
$e^+e^- \to h_i Z$:





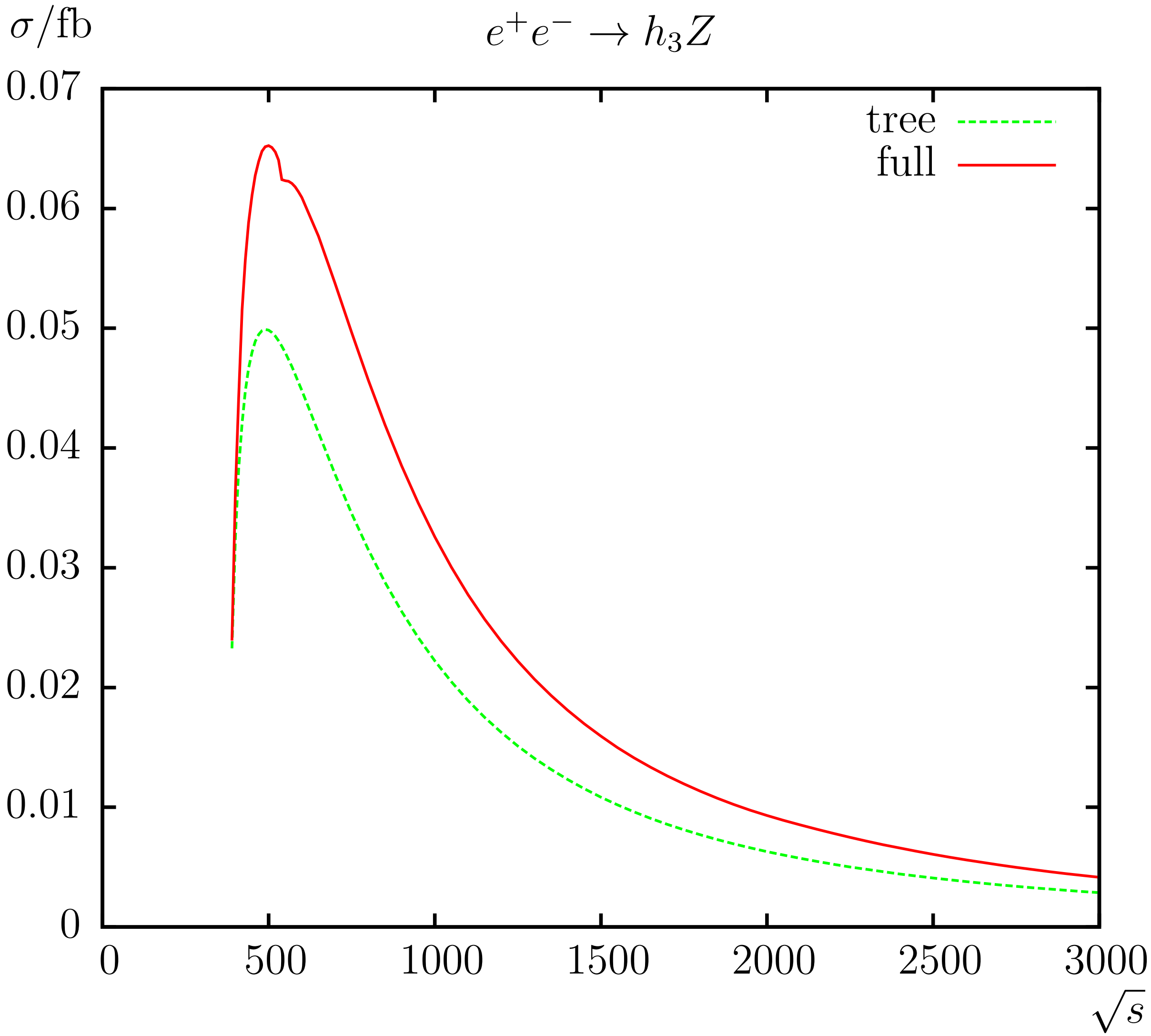
+ soft and hard QED radiation

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



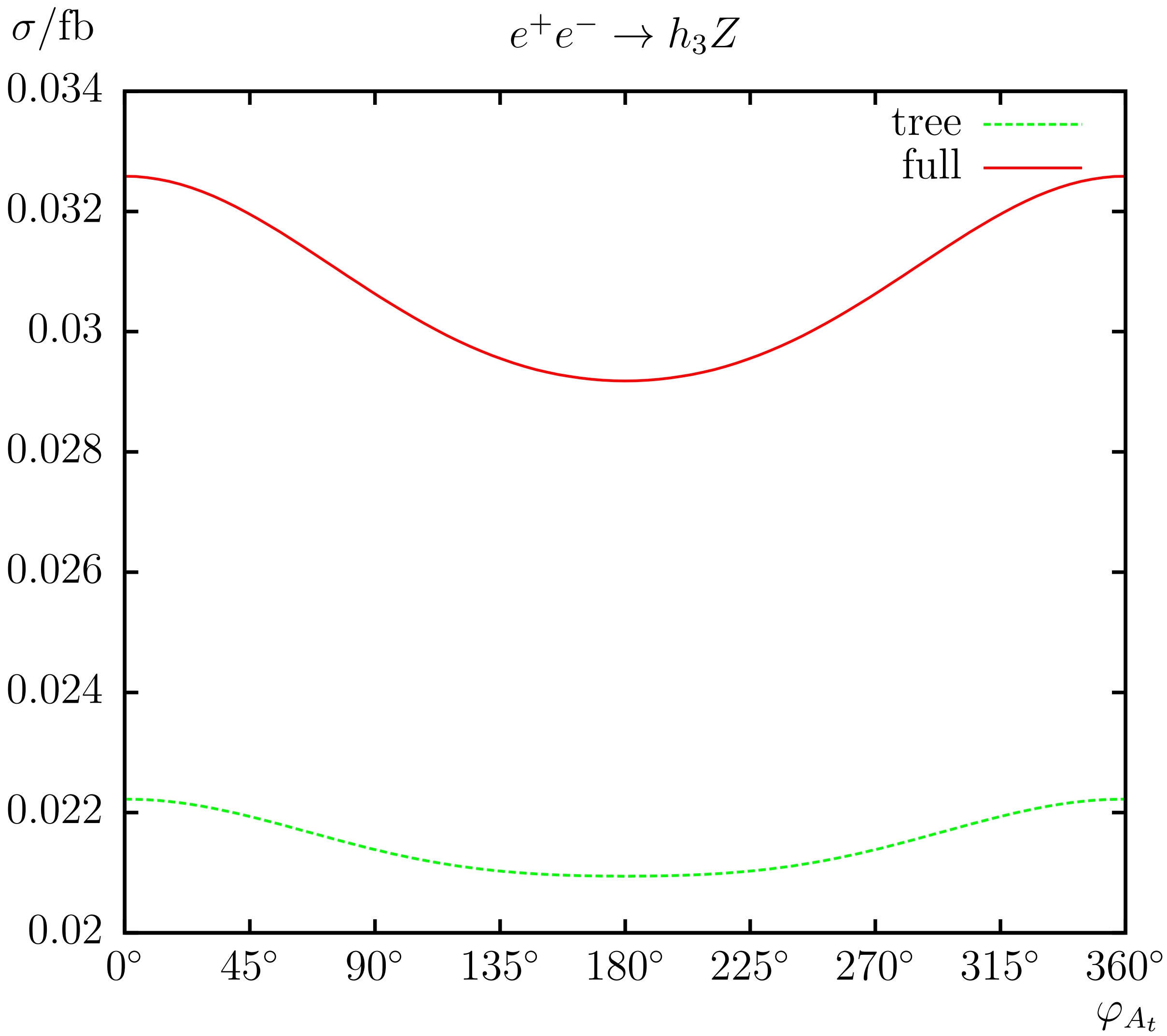
$\Rightarrow$ loop corrections crucial

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



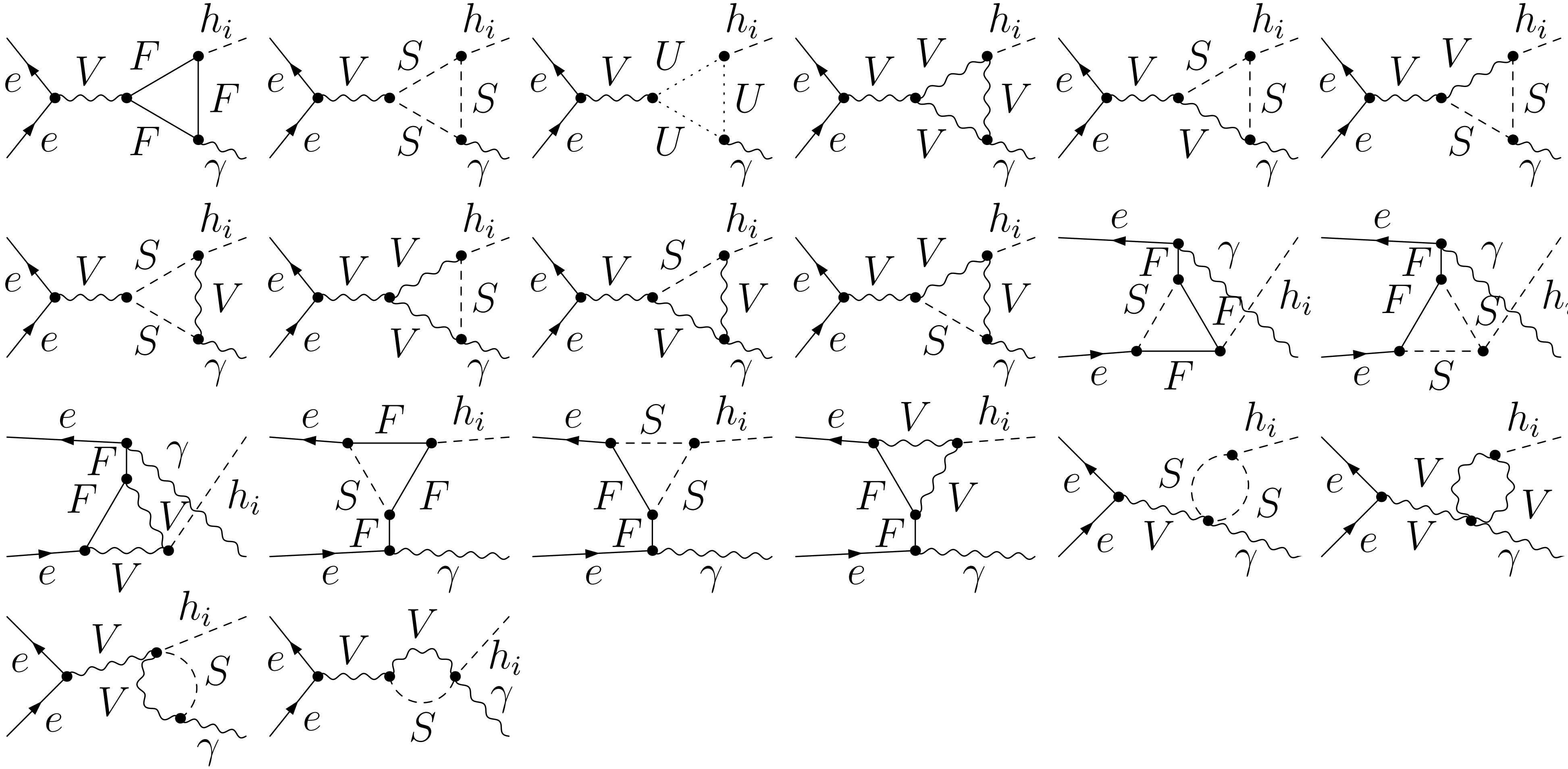
$\Rightarrow$ possibly observable, loop corrections crucial

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

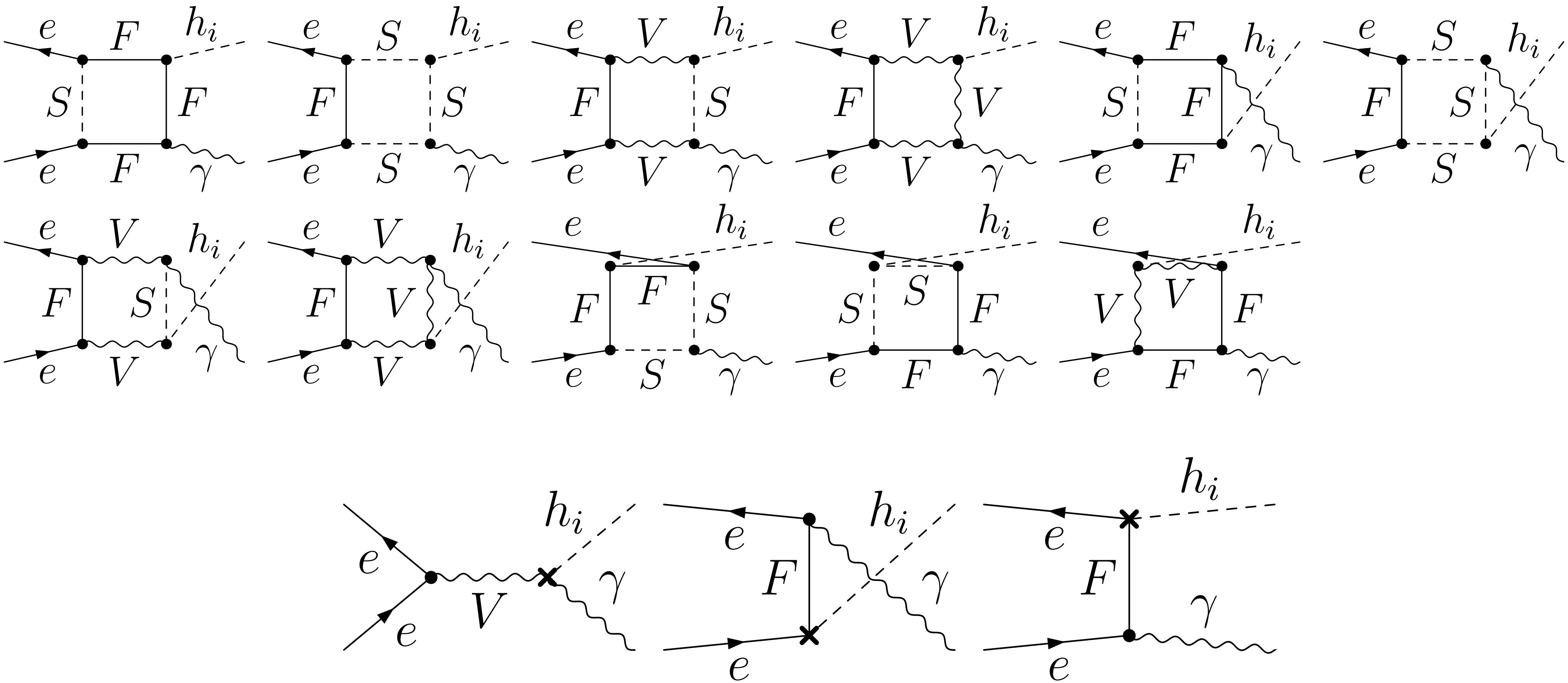


$\Rightarrow$ pronounced phase dependence at the loop level

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



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



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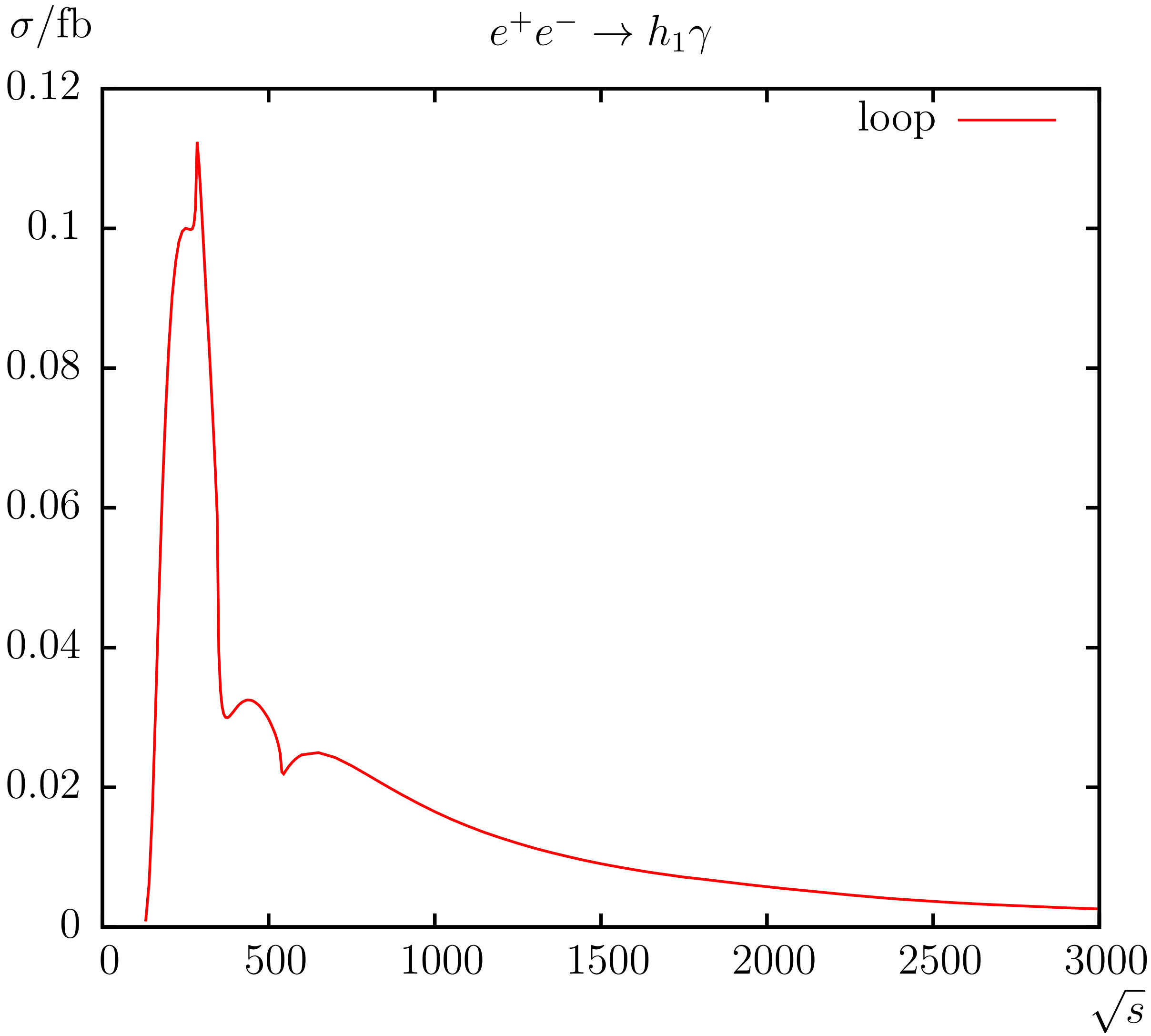
$e^+e^- \to h_1\gamma$ (purely loop induced):



$\Rightarrow$ possibly observable!

5. Conclusinos

- The Higgs will be explored at the LHC/LC
  SUSY will be explored at the LHC/LC

- Problem in the MSSM, in particular with complex parameters:
  consistent renormalization of the whole model (simultaneously)

  $\Rightarrow$ now solved!
  $\Rightarrow$ model file available for FeynArts/FormCalc/LoopTools

  $\Rightarrow$ full one-loop calculations of any SUSY process possible

- Calculation of decay widths and branching ratios
  - all two-body decays of
    scalar top, scalar bottom, scalar tau, gluino, chargino, neutralino
  - corrections between 10% and 20%
  - EW and QCD corrections can be of similar size

- Higgs production at the LC in the cMSSM at the full one-loop level:

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

  Tree-level processes: loop corrections crucial

  Loop induced processes: possibly observable


Further Questions?

$\tilde{t}/\tilde{b}$ sector of the MSSM: (scalar partner of the top/bottom quark)

Stop, sbottom mass matrices ($X_t = A_t - \mu^*/\tan\beta$, $X_b = A_b - \mu^* \tan\beta$):

$$\mathcal{M}^2_{\tilde{t}} = \begin{pmatrix} M^2_{\tilde{t}_L} + m_t^2 + DT_{t_1} & m_t X_t^* \\ m_t X_t & M^2_{\tilde{t}_R} + m_t^2 + DT_{t_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m^2_{\tilde{t}_1} & 0 \\ 0 & m^2_{\tilde{t}_2} \end{pmatrix}$$

$$\mathcal{M}^2_{\tilde{b}} = \begin{pmatrix} M^2_{\tilde{b}_L} + m_b^2 + DT_{b_1} & m_b X_b^* \\ m_b X_b & M^2_{\tilde{b}_R} + m_b^2 + DT_{b_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{b}}} \begin{pmatrix} m^2_{\tilde{b}_1} & 0 \\ 0 & m^2_{\tilde{b}_2} \end{pmatrix}$$

mixing important in stop sector (also in sbottom sector for large $\tan\beta$)

soft SUSY-breaking parameters A_t, A_b also appear in ϕ-$\tilde{t}/\tilde{b}$ couplings

$$m^2_{\tilde{t}_{1,2}} = m_t^2 + \frac{1}{2}\left(M^2_{\tilde{t}_L} + M^2_{\tilde{t}_R} \mp \sqrt{(M^2_{\tilde{t}_L} - M^2_{\tilde{t}_R})^2 + 4 m_t^2 |X_t|^2}\right)$$

$\Rightarrow$ independent of ϕ_{X_t}

but $\theta_{\tilde{t}}$ is now complex

$SU(2)$ relation $\Rightarrow M_{\tilde{t}_L} = M_{\tilde{b}_L}$ $\Rightarrow$ relation between $m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}, \theta_{\tilde{b}}$

More on complex phases: Neutralinos and charginos:

Higgsinos and electroweak gauginos mix

charged:

$$\tilde{W}^+, \tilde{h}_u^+ \to \tilde{\chi}_1^+, \tilde{\chi}_2^+, \qquad \tilde{W}^-, \tilde{h}_d^- \to \tilde{\chi}_1^-, \tilde{\chi}_2^-$$

$\Rightarrow$ charginos: mass eigenstates

mass matrix given in terms of M_2, μ, $\tan\beta$

neutral:

$$\underbrace{\tilde{\gamma}, \tilde{Z},}_{\tilde{W}^0, \tilde{B}^0} \tilde{h}_u^0, \tilde{h}_d^0 \to \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$$

$\Rightarrow$ neutralinos: mass eigenstates

mass matrix given in terms of M_1, M_2, μ, $\tan\beta$

$\Rightarrow$ only one new parameter

$\Rightarrow$ MSSM predicts mass relations between neutralinos and charginos

A/B) MSSM Higgs mass prediction: The embarrasing situation

The light $\mathcal{CP}$-even Higgs mass accuracy in the MSSM:

A/B) MSSM Higgs mass prediction: The embarrasing situation

The light $\mathcal{CP}$-even Higgs mass accuracy in the MSSM:

Experiment:

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

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Theory:

$$\delta M_h^{\rm theo} \sim 3 \text{ GeV}$$

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to match the experimental accuracy!

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Theory:

$$\delta M_h^{\text{theo}} \sim 3 \text{ GeV}$$

$\Rightarrow$ Theory prediction must be improved
to match the experimental accuracy!

$\Rightarrow$ dedicated working group has been formed to take care . . . (KUTS)

C) Higgs to SUSY decays

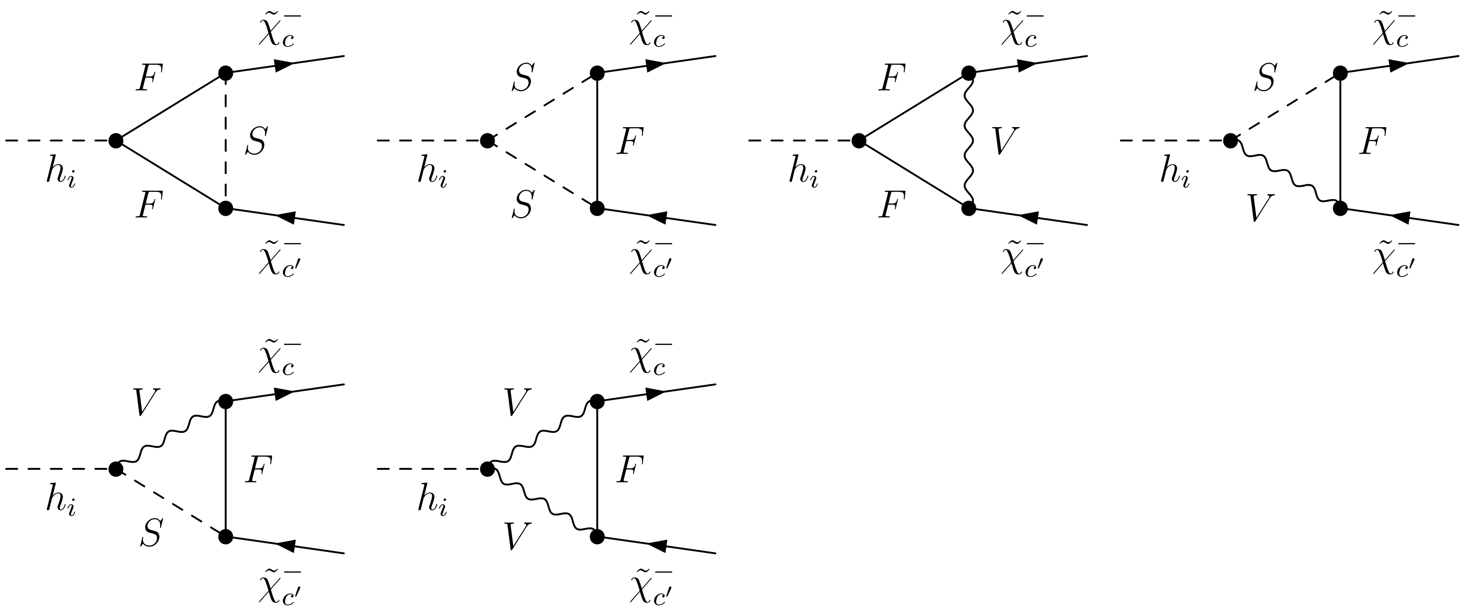
C-1) Higgs decays to charginos/neutralinos

[arXiv:1503.02996]

$$\Gamma(h_i \to \tilde{\chi}_c^- \tilde{\chi}_{c'}^+) \quad (i = 1, 2, 3;\ c, c' = 1, 2)$$

$$\Gamma(h_i \to \tilde{\chi}_n^0 \tilde{\chi}_{n'}^0) \quad (i = 1, 2, 3;\ n, n' = 1, 2, 3, 4)$$

$$\Gamma(H^\pm \to \tilde{\chi}_n^0 \tilde{\chi}_c^\pm) \quad (n = 1, 2, 3, 4;\ c = 1, 2)$$



Numerical example scenario:

$\tan\beta$	μ	A_{u_g}	A_{d_g}	A_{e_g}	$\lvert M_1\rvert$	M_2	M_3	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	$m_{\tilde{b}_2}$	$m_{\tilde{\nu}_\tau}$	$m_{\tilde{\tau}_1}$
10	500	1200	600	1000	300	600	1500	394	771	582	280	309

Parameters varied: $M_{H^\pm}$, M_1, φ_{M_1}

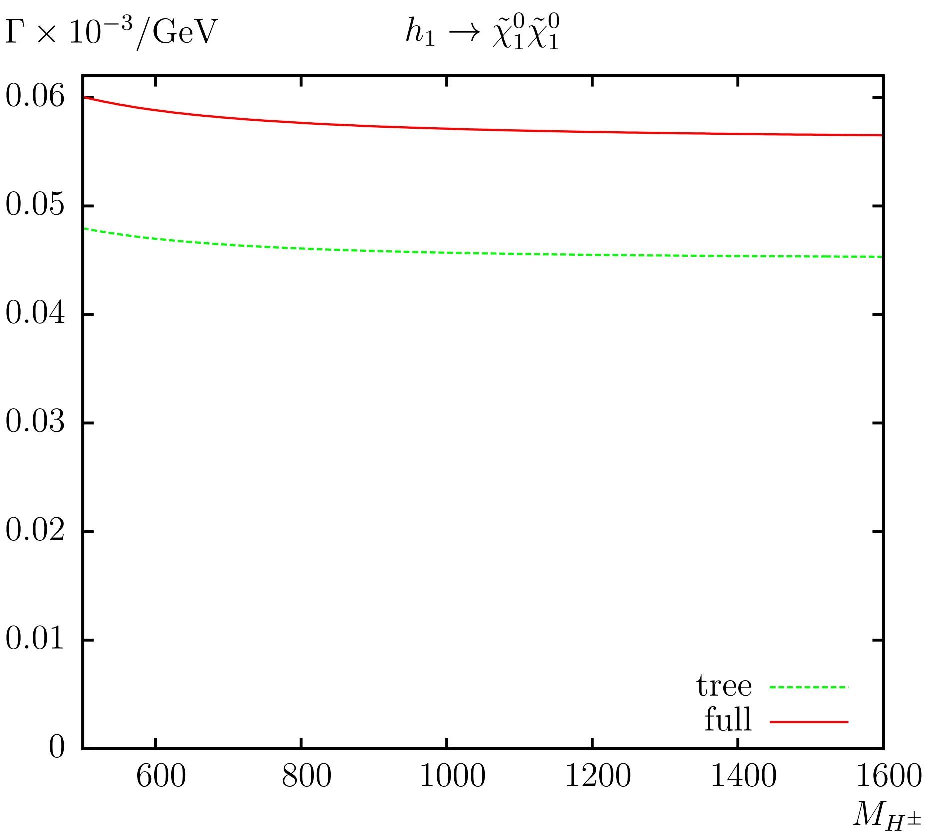
– in agreement with exp. data

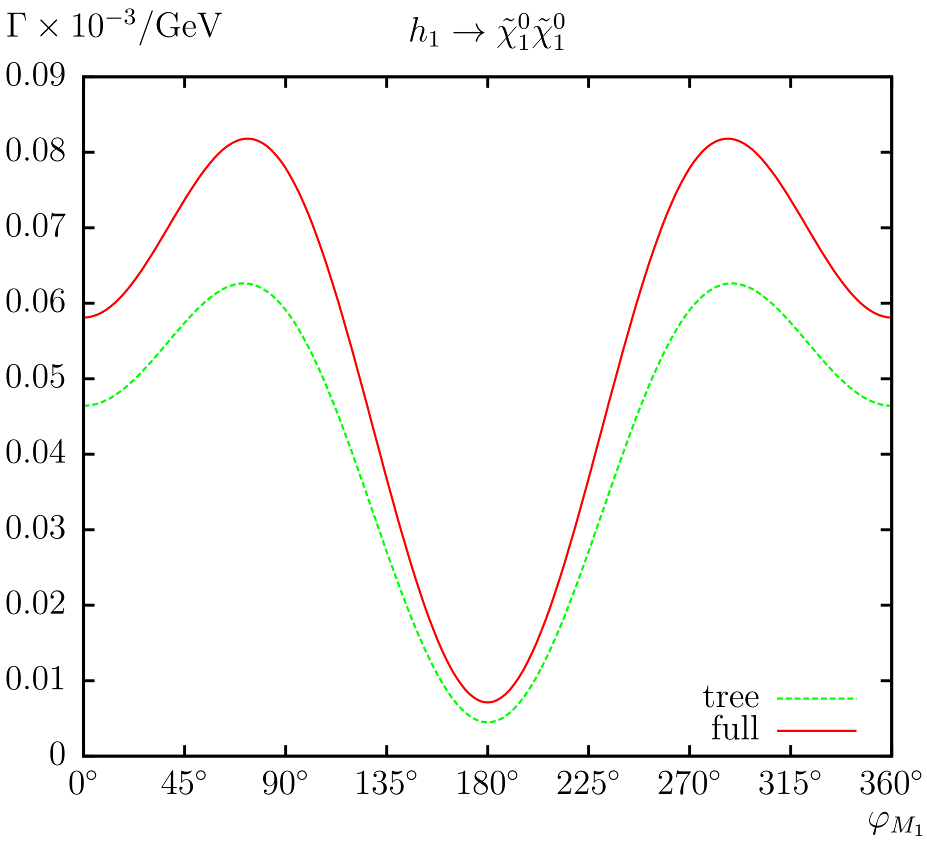
– opens up many (all) decay channels

– relevant parameters varied

– ...

Light Higgs decay to Dark Matter (I):

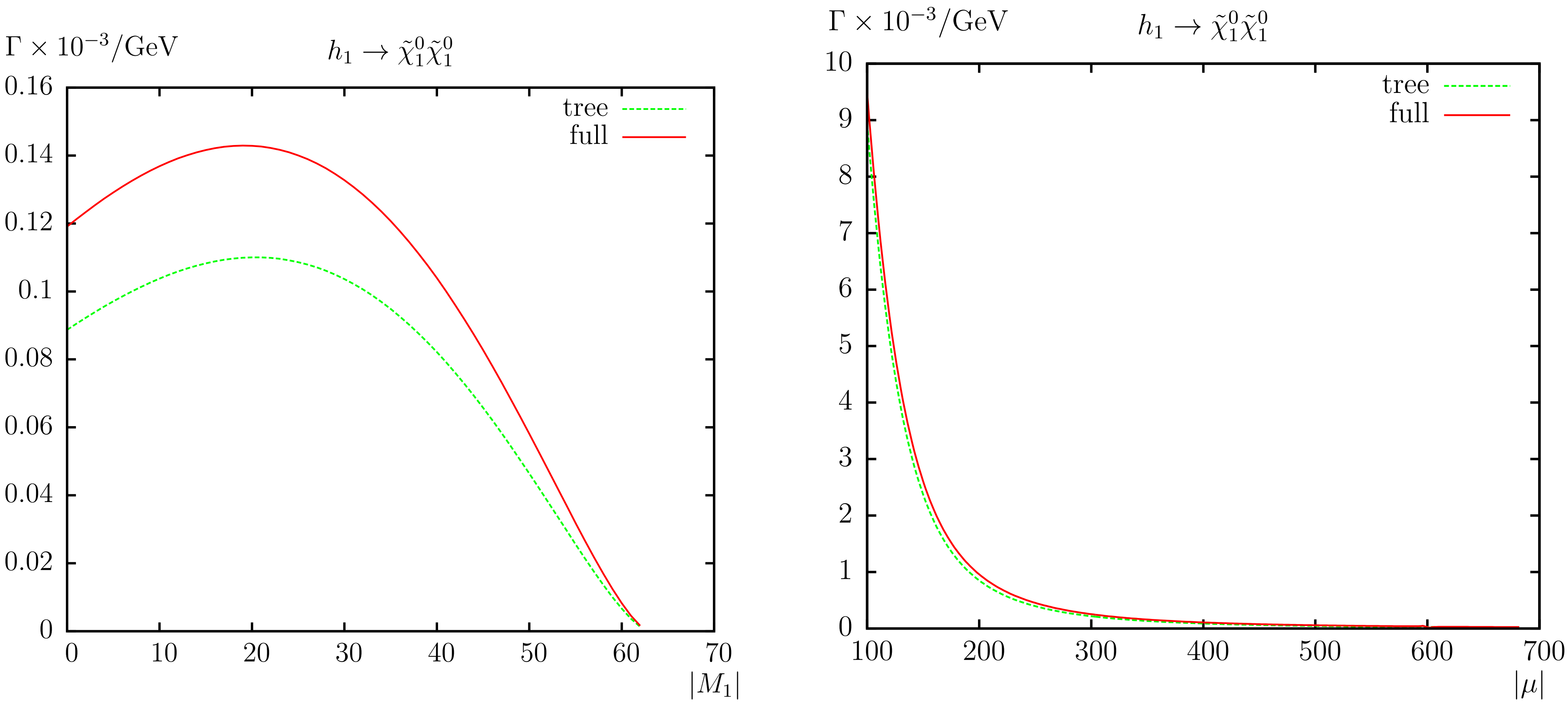




$\Rightarrow$ loop corrections $\sim$ 20%

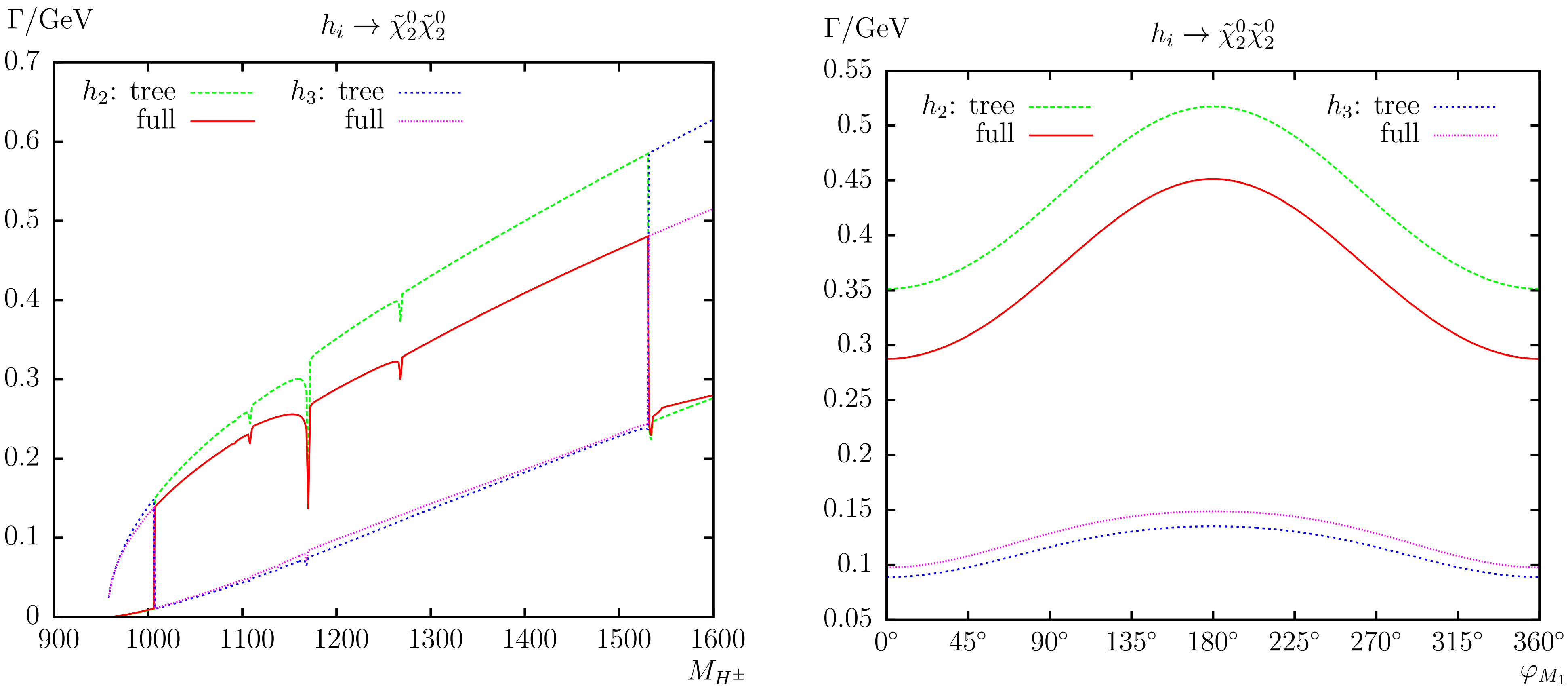
$\Rightarrow$ strong phase dependence

Light Higgs decay to Dark Matter (II):



$\Rightarrow$ strong dependence on $|M_1|$, μ

Heavy Higgs decay to heavier neutralinos:

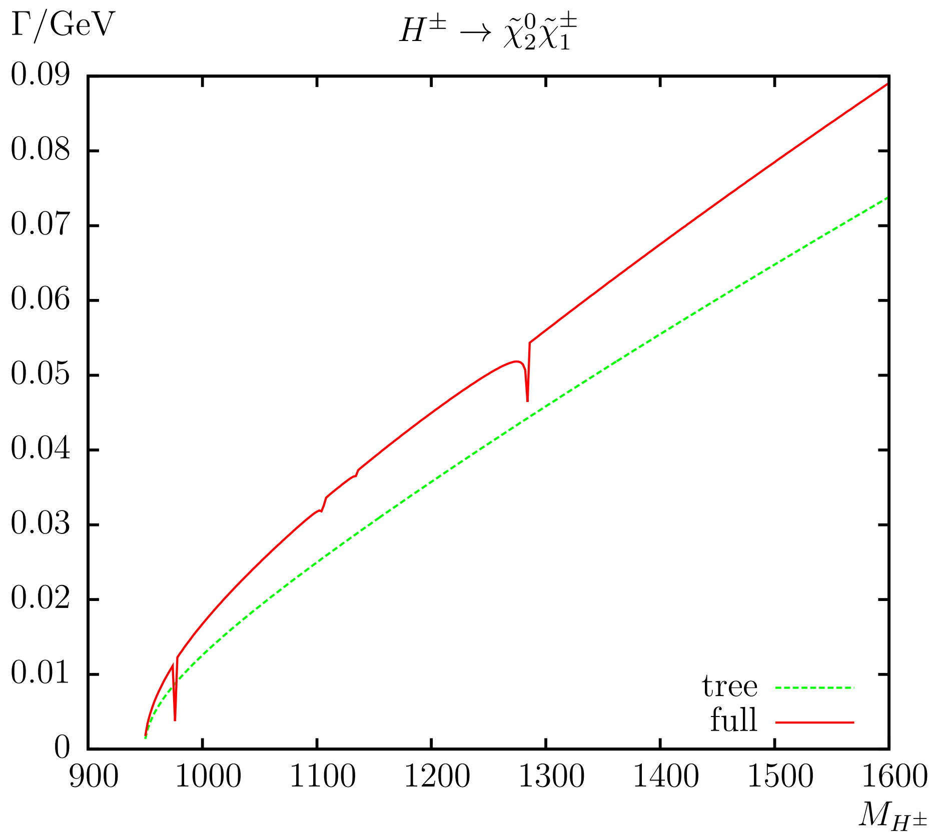


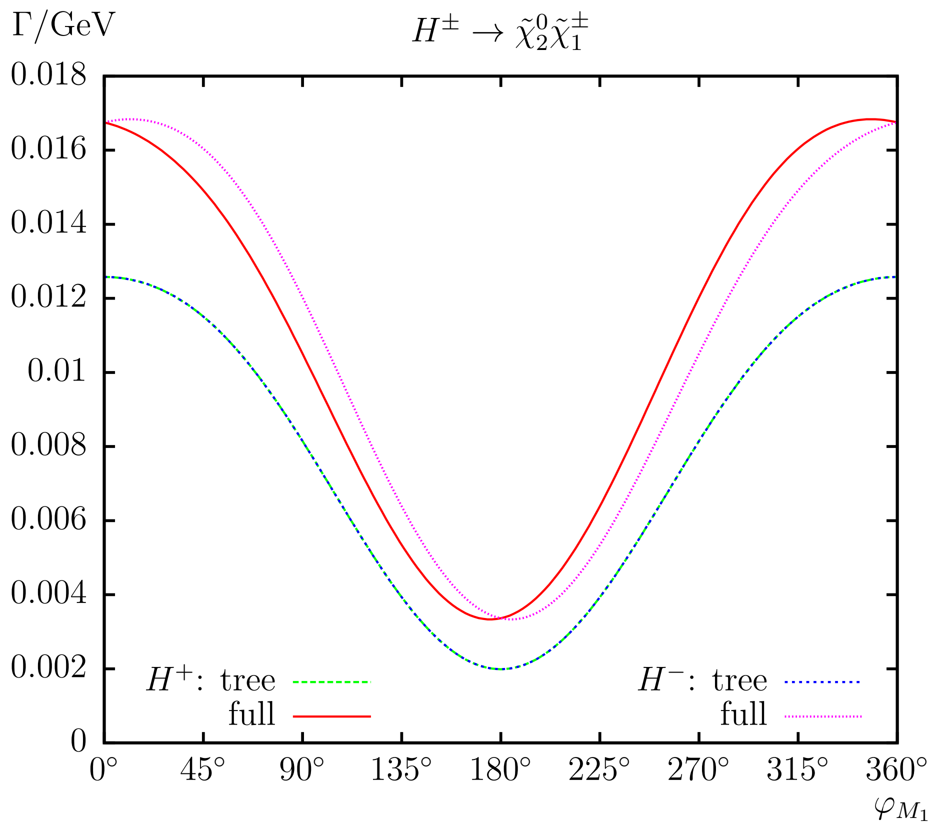
⇒ loop corrections up to ∼ 20%

⇒ strong phase dependence

⇒ level crossing, thresholds, . . .

Charged Higgs decay:





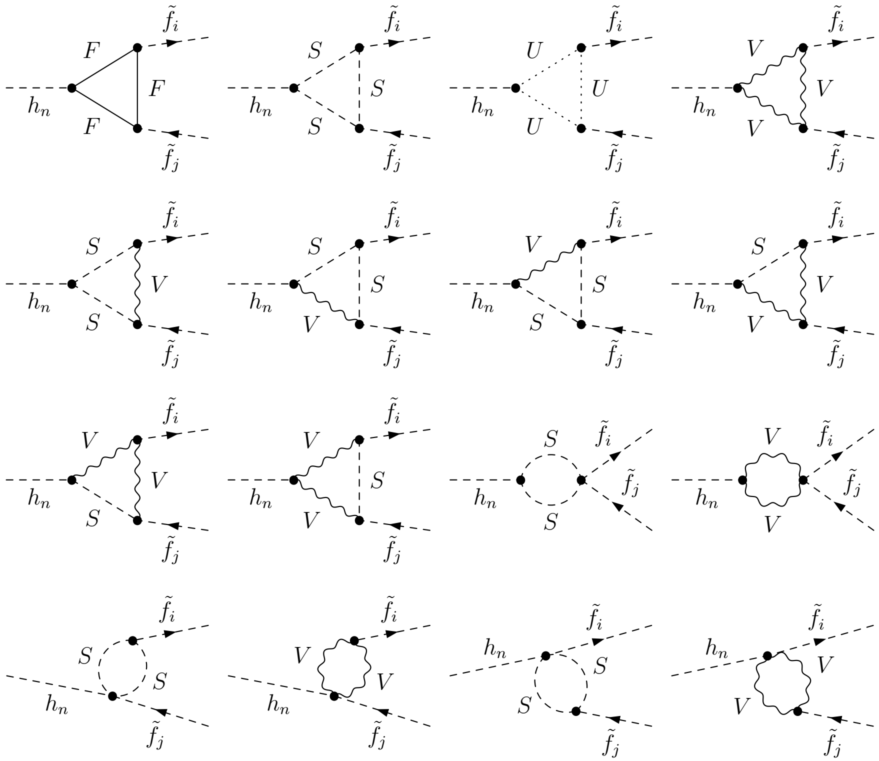
⇒ loop corrections up to ~ 20%

⇒ strong phase dependence

⇒ small difference between H^+ and H^- decay

$$\Gamma(h_n \to \tilde{f}_i \tilde{f}_j^\dagger) \quad (n = 2, 3;\ i, j = 1, 2)$$

$$\Gamma(H^\pm \to \tilde{f}_i \tilde{f}_j'^\dagger) \quad (i, j = 1, 2)$$



Numerical example scenario:

$\tan\beta$	μ	$\lvert A_t\rvert$	$\lvert A_b\rvert$	$\lvert A_\tau\rvert$	M_1	M_2	M_3	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	$m_{\tilde{b}_2}$	$m_{\tilde{\nu}_\tau}$	$m_{\tilde{\tau}_2}$
10	500	1200	600	1000	300	600	1500	394	771	582	280	309

Parameters varied: $M_{H^\pm}$, ϕ_{A_t}, ϕ_{A_b}, ϕ_{A_τ}

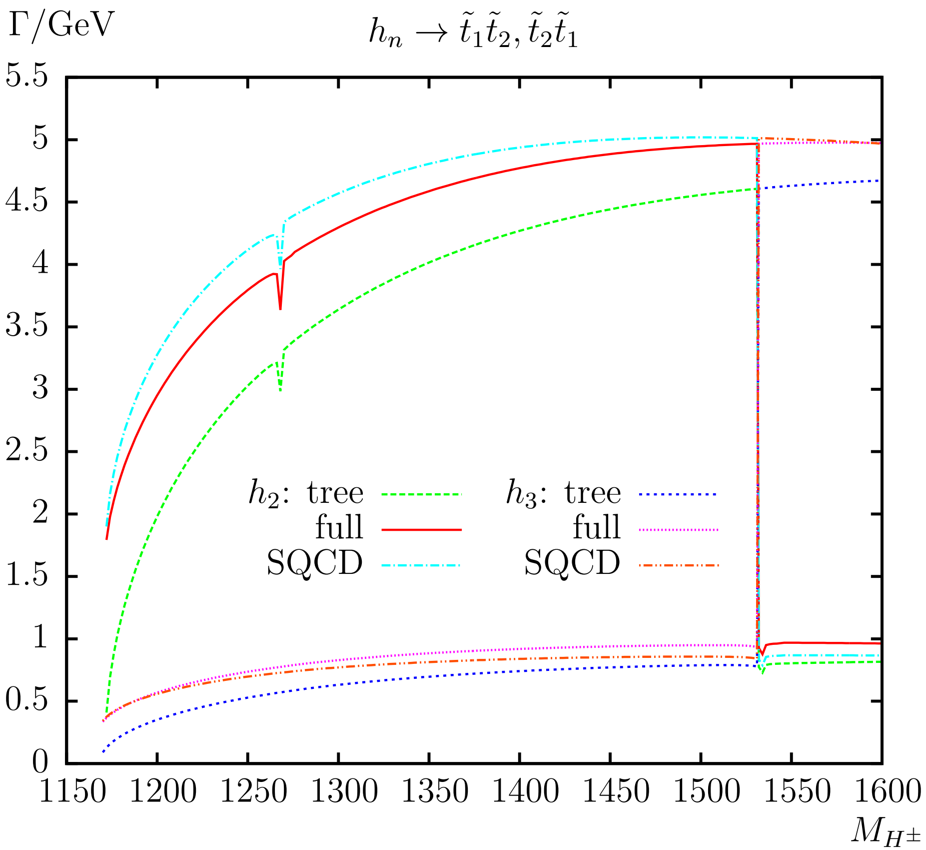
– in agreement with exp. data

– opens up many (all) decay channels

– relevant parameters varied

– ...

Heavy Higgs decay to stops:

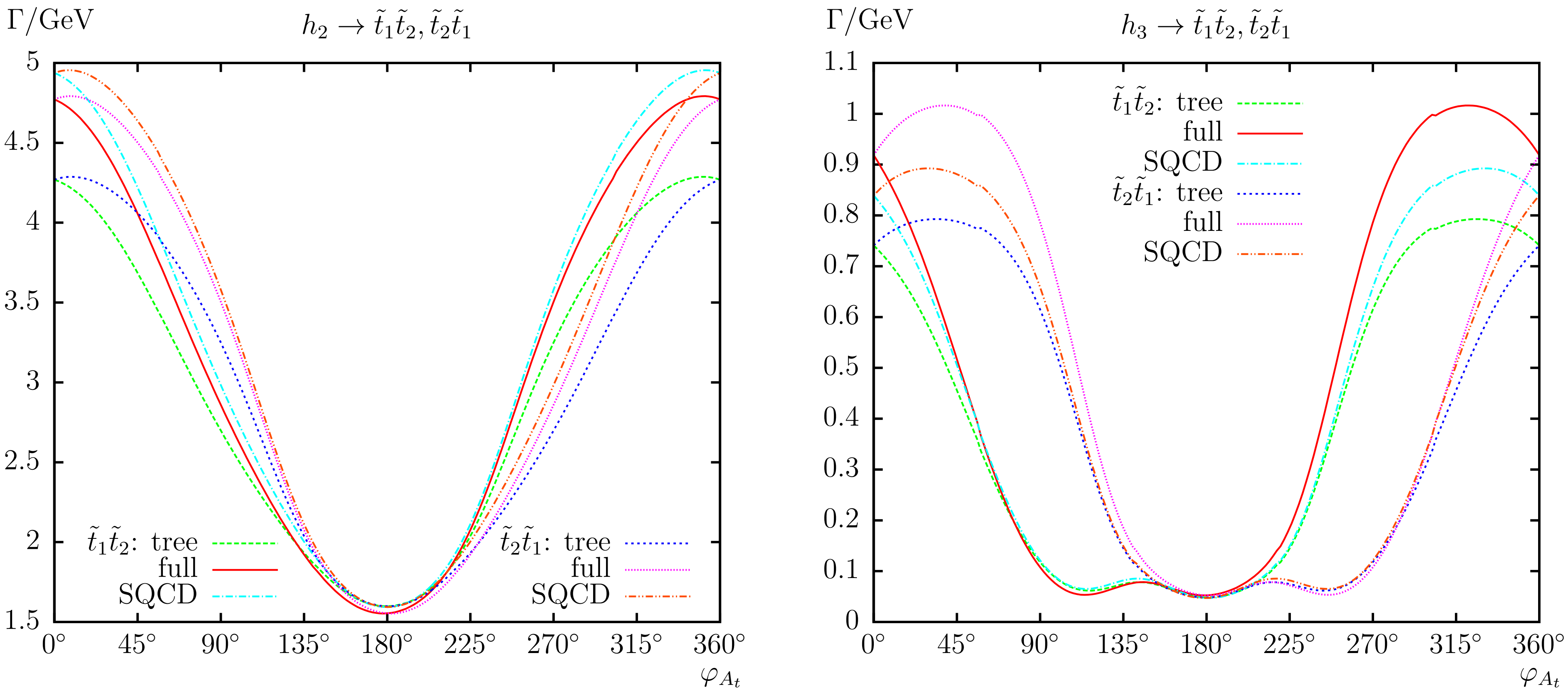


⇒ loop corrections up to ∼ 30%

⇒ SUSY QCD not sufficient

⇒ level crossing, thresholds, . . .

Heavy Higgs decay to stops:

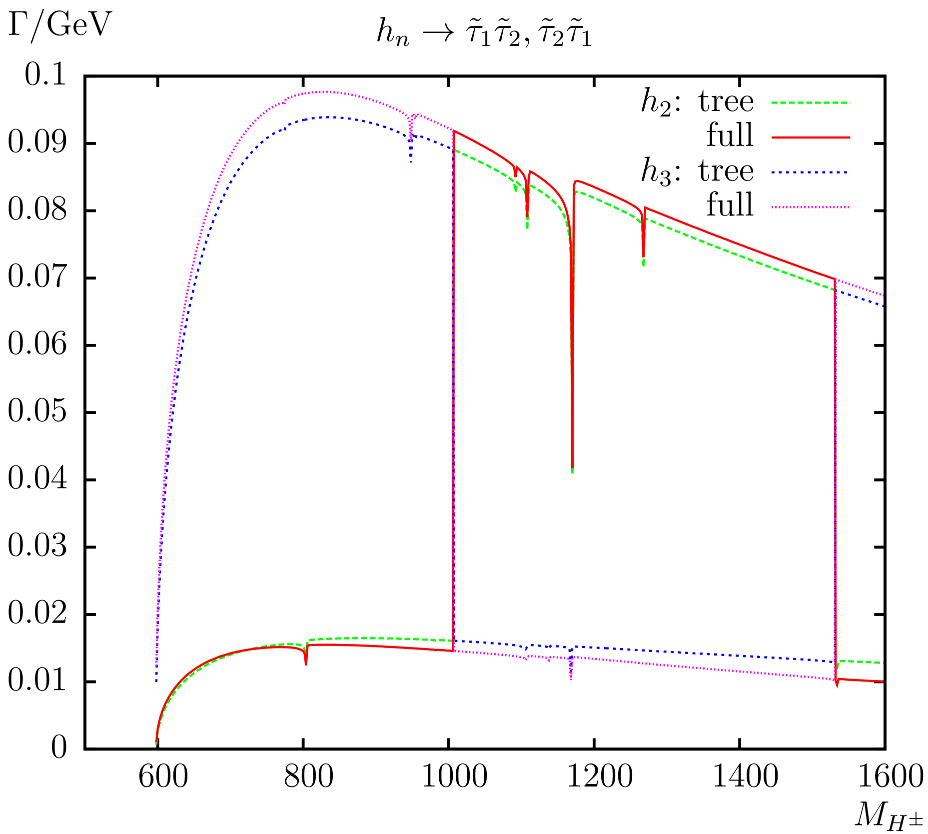


⇒ loop corrections up to ∼ 30%, SUSY EW important

⇒ strong phase dependence

⇒ difference between charge conjugated decays

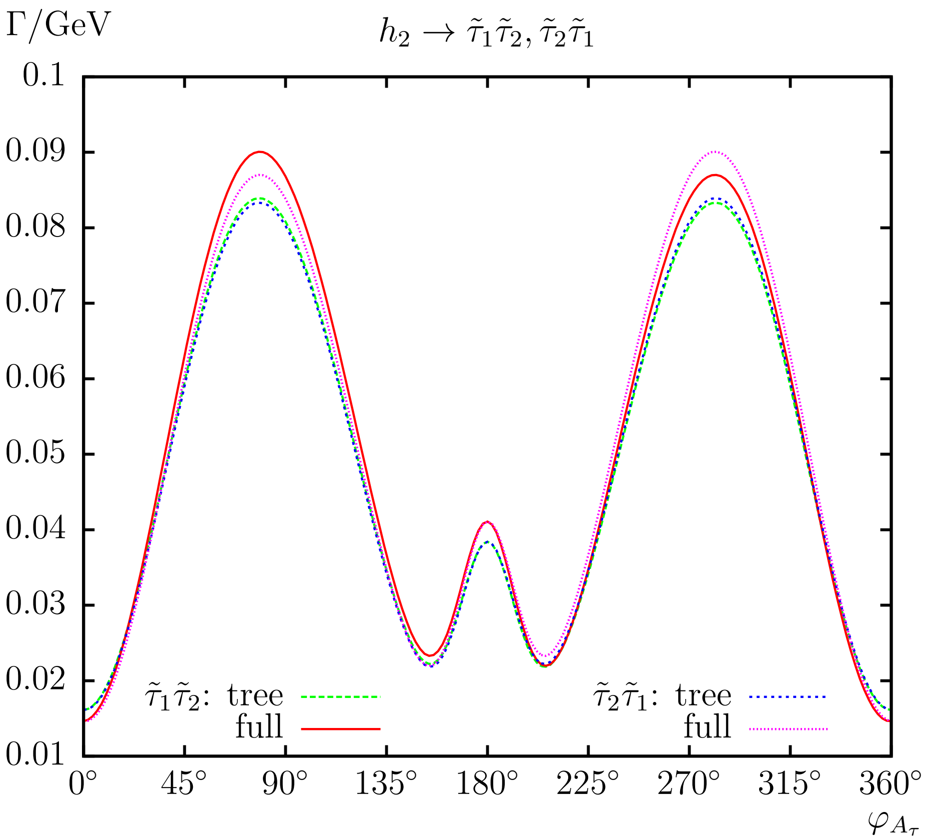
Heavy Higgs decay to staus:

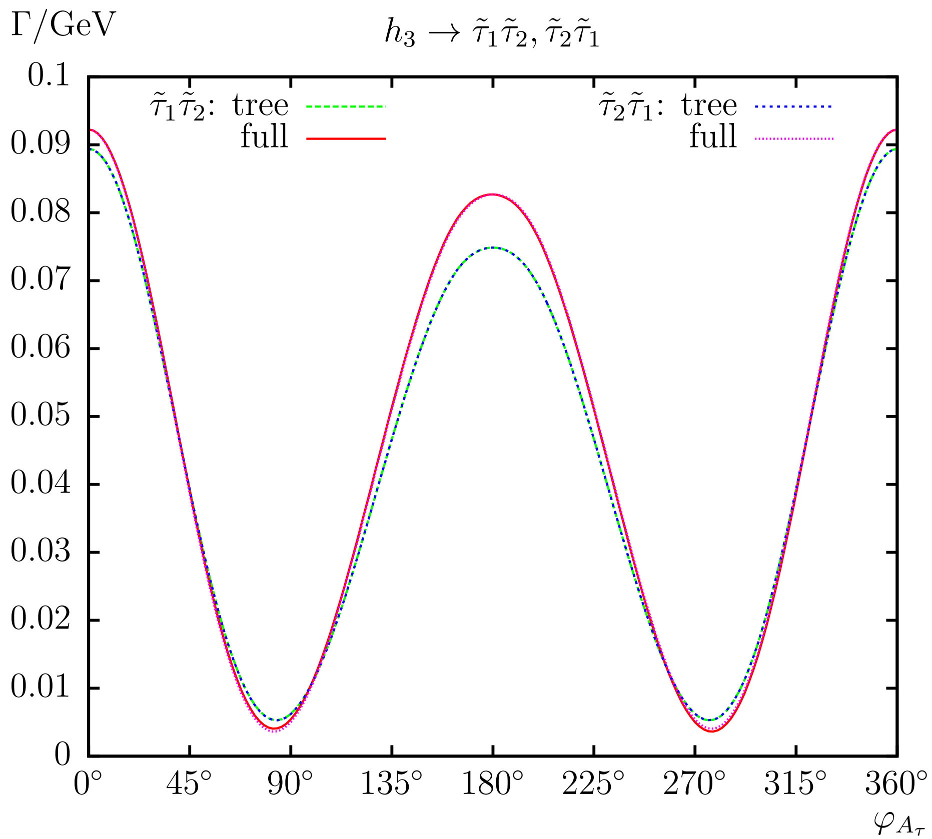


⇒ loop corrections up to $\sim 10\%$, purely EW

⇒ level crossing, thresholds, . . .

Heavy Higgs decay to staus:



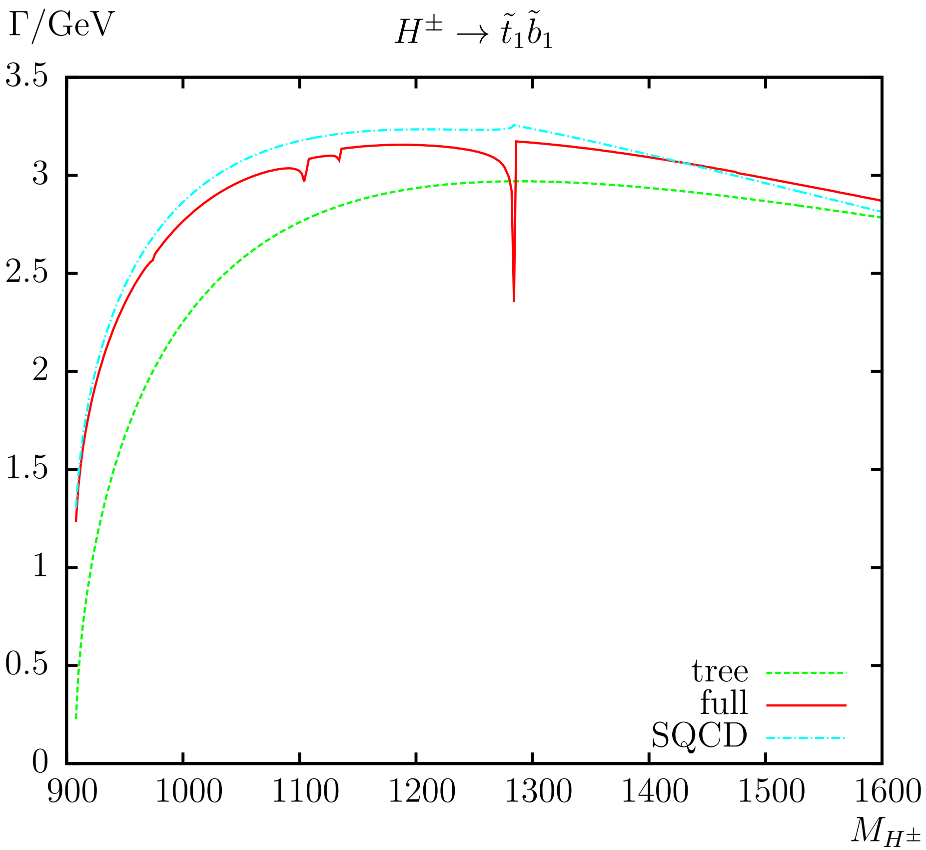


$\Rightarrow$ loop corrections up to $\sim$ 10%, purely EW

$\Rightarrow$ strong phase dependence

$\Rightarrow$ small difference between charge conjugated decays

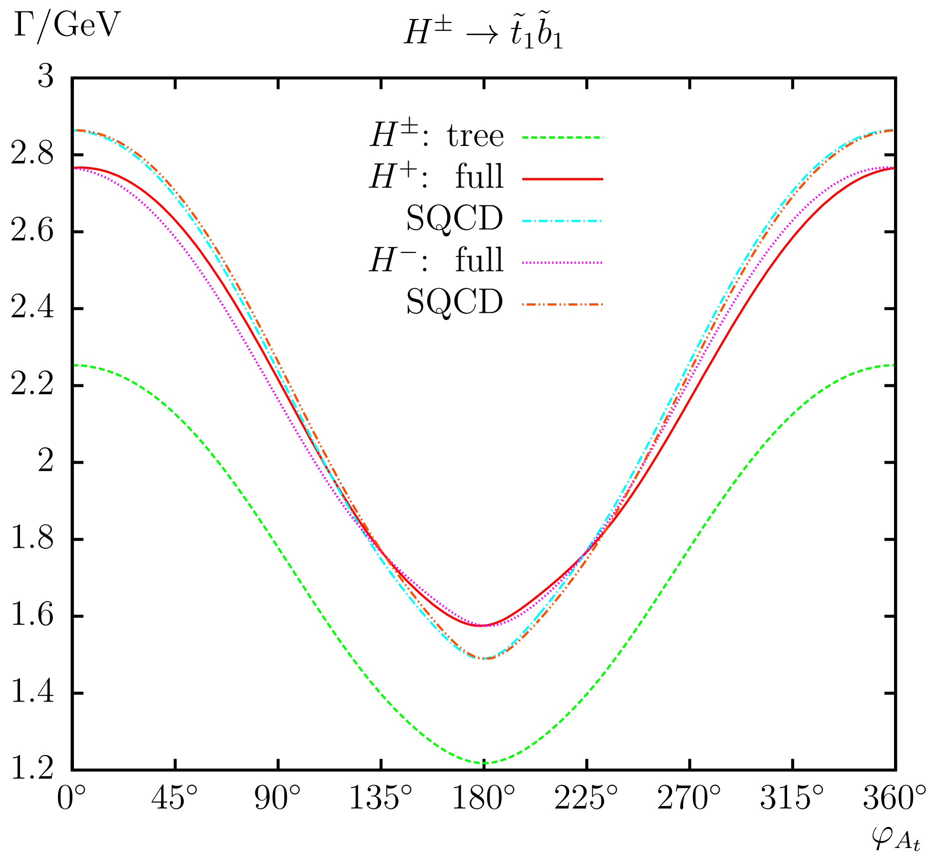
Charged Higgs decay to stop/sbottom:

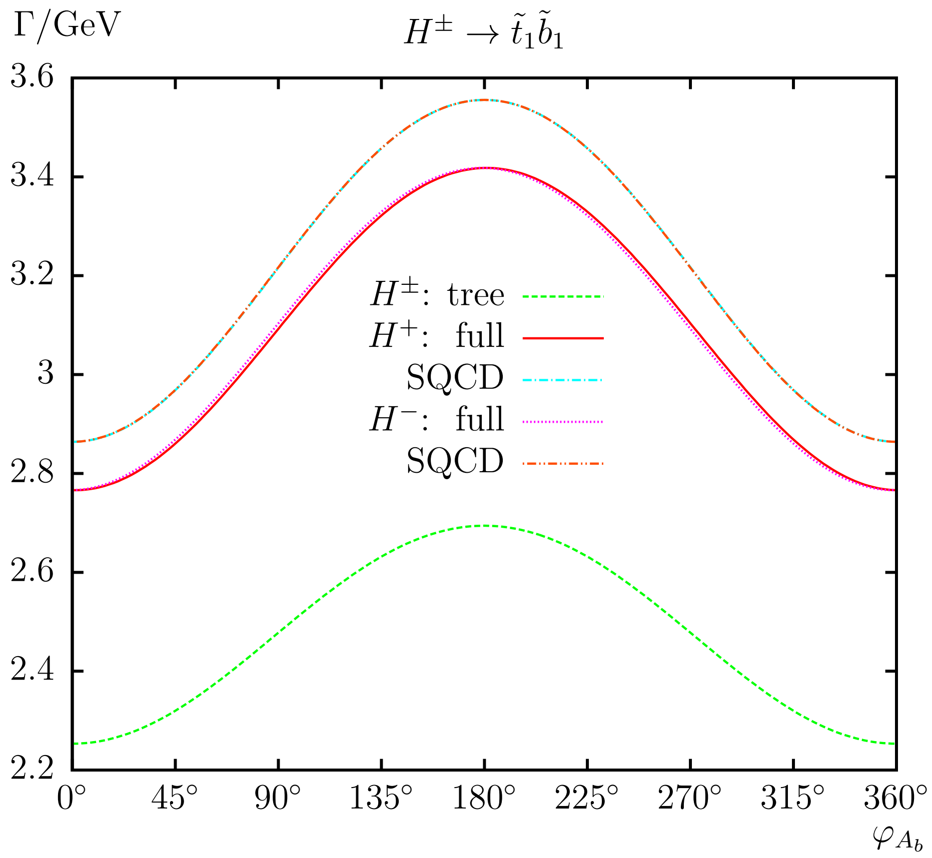


$\Rightarrow$ loop corrections up to $\sim$ 30%

$\Rightarrow$ SUSY QCD not sufficient

Charged Higgs decay to stop/sbottom:





⇒ loop corrections up to ∼ 30%, SUSY EW important

⇒ strong phase dependence

⇒ small difference between charge conjugated decays