Higgs Production via SUSY Decays at the LC

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based on collaboration with

A. Bharoucha, T. Fritzsche, F. v.d. Pahlen, H. Rzehak, C. Schappacher

1. Introduction

2. SUSY decays to Higgs bosons

3. Conclusions

1. Introduction

Production of SUSY particles at the ILC:

$$e^+e^- \to \tilde{t}_2\,\tilde{t}_1^\dagger \to h\,\tilde{t}_1\,\tilde{t}_1^\dagger \to h\,t\,\tilde{\chi}_1^0\,\bar{t}\,\tilde{\chi}_1^0$$

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$\Rightarrow$ precision prediction (at least) of BR's necessary

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Possible: production of Higgs bosons: $\tilde{t}_2 \to \tilde{t}_1 h_i$, ...

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⇒ important source for information on Higgs, LSP

⇒ precision prediction (at least) of BR's necessary

Focus here: h_i production

$\tilde{\chi}_1^0$ production ⇒ Federico's talk tomorrow 12.40pm

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)

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

Complex parameters:

- μ : Higgsino mass parameter
- $A_{t,b,\tau}$: trilinear couplings $\Rightarrow X_{t,b,\tau} = A_{t,b} - \mu^*\{\cot\beta\,, \tan\beta\}$ complex
- $M_{1,2}$: gaugino mass parameter (one phase can be eliminated)
- $m_{\tilde{g}}$: gluino mass

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

Effects of complex parameters in the Higgs sector:

Complex parameters enter via loop corrections:

Result:

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

with

$$M_{h_3} > M_{h_2} > M_{h_1}$$

More on complex phases: $\tilde{t}/\tilde{b}$ sector of the MSSM:

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

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

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

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

$SU(2)$ 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:

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

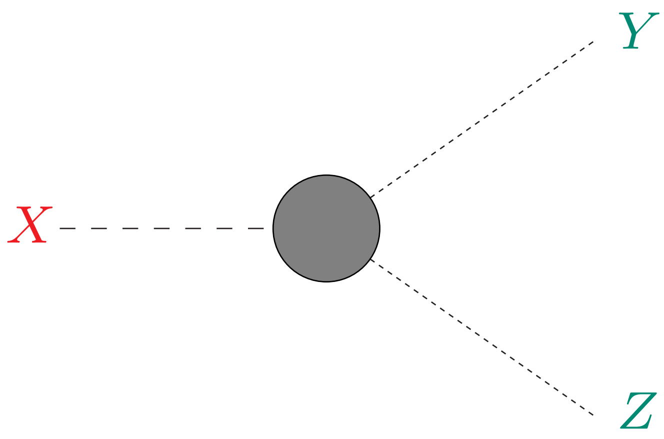
$\Rightarrow$ neutralinos: mass eigenstates

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

The bigger picture: SUSY decays in the cMSSM

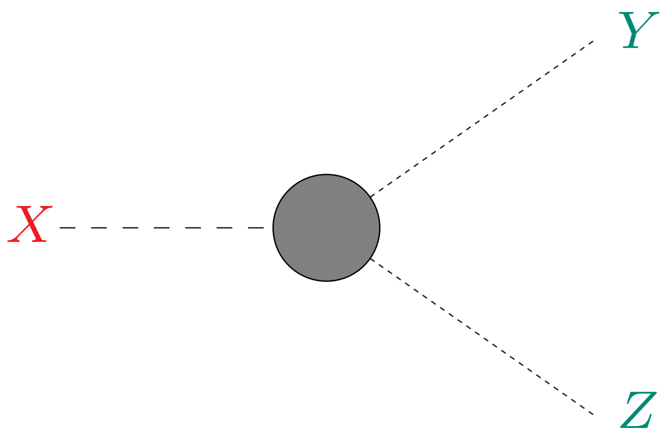


⇒ to get BRs right ⇒ all decays needed

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

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

The bigger picture: SUSY decays in the cMSSM



$\Rightarrow$ to get BRs right $\Rightarrow$ all decays needed

$\Rightarrow$ (nearly) all sectors of the cMSSM enter as external particles

$\Rightarrow$ (nearly) all sectors of the cMSSM have to be renormalized simultaneously

now ready:

– (heavy) stop, sbottom and stau decays $\Rightarrow$ relevant for Higgs, LSP
– gluino decays
– (non-hadronic) chargino decays $\Rightarrow$ relevant for Higgs, LSP
– (non-hadronic) neutralino decays $\Rightarrow$ relevant for Higgs, LSP

ILC 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

$$\mathrm{BR}^{\mathrm{full}} \equiv \frac{\Gamma^{\mathrm{full\ 1L}}(\tilde{g} \to \mathrm{xy})}{\Gamma^{\mathrm{full\ 1L}}_{\mathrm{tot}}}$$

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

close to the statistical uncertainty

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

2. SUSY decays to Higgs bosons

2A) Heavy Stop decays

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

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

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

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

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

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

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

Calculation of partial widths and branching ratios:

– all diagrams created with FeynArts → T

  → model file with all counterterms in the cMSSM

– including all soft/hard QED/QCD diagrams

– further evaluation with FormCalc

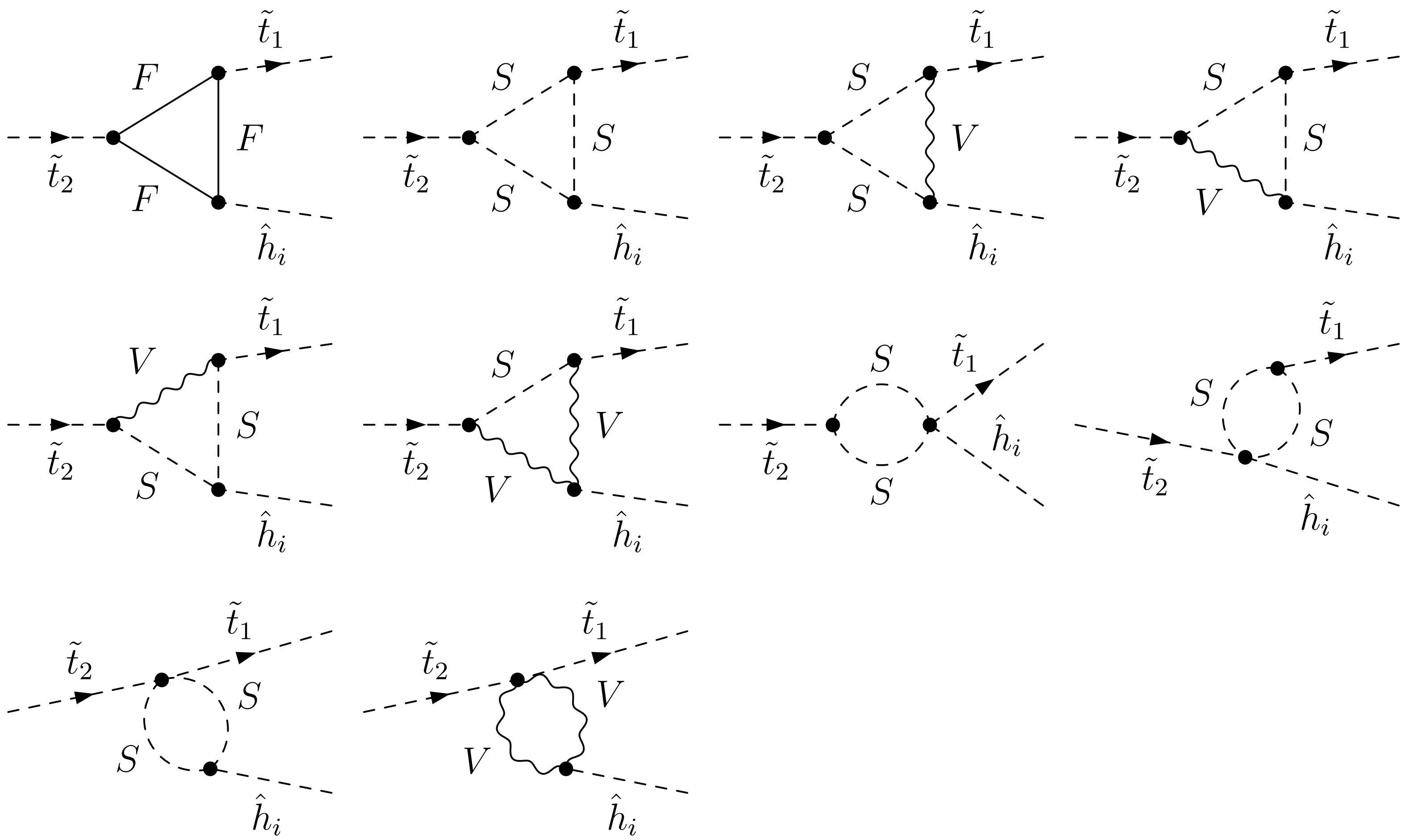
– Dimensional REDuction

– all UV and IR divergences cancel

– results will be included into FeynHiggs (www.feynhiggs.de)

→ example plots will focus on BR($\tilde{t}_2 \to \tilde{t}_1 h_1$)

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:

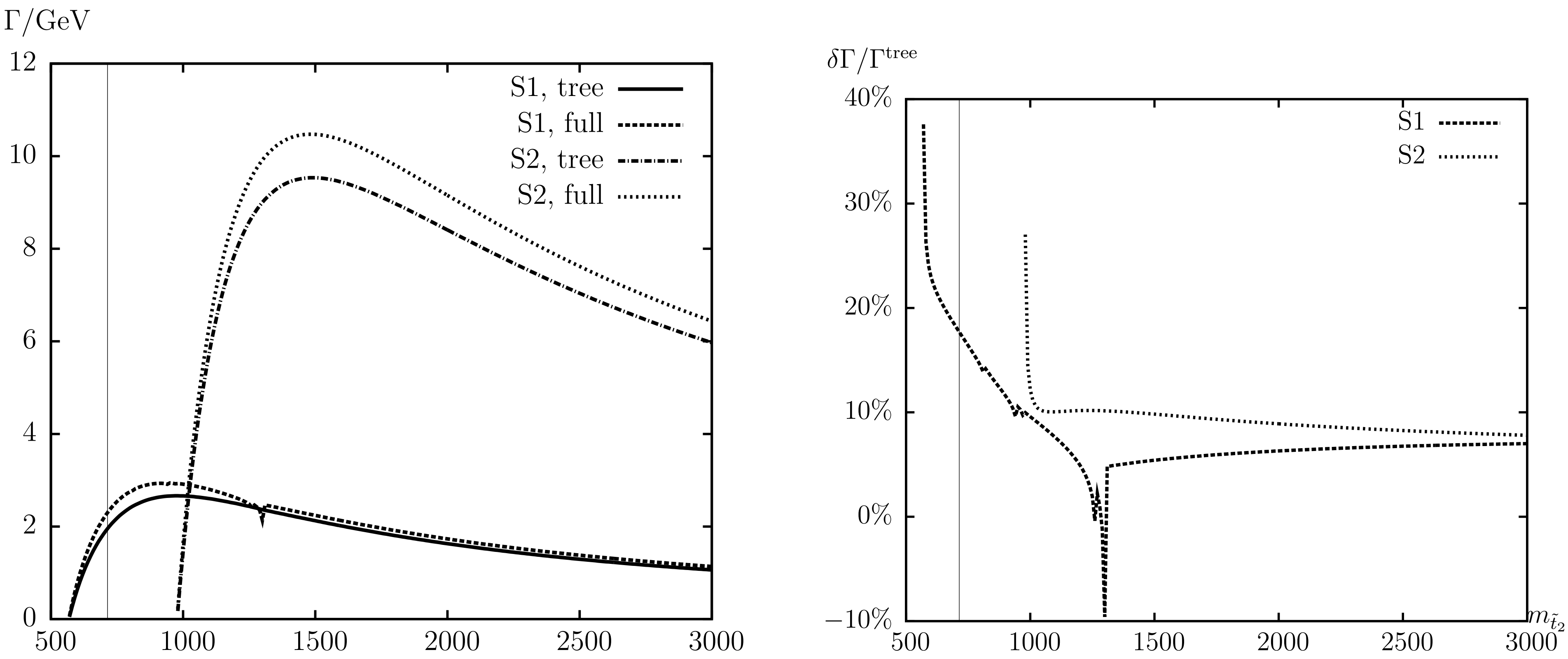
Scen.	$M_{H^\pm}$	$m_{\tilde{t}_2}$	$m_{\tilde{t}_1}$	$m_{\tilde{b}_2}$	μ	A_t	A_b	M_1	M_2	M_3
S1	150	650	$0.4\, m_{\tilde{t}_2}$	$0.7\, m_{\tilde{t}_2}$	200	900	400	200	300	800
S2	180	1200	$0.6\, m_{\tilde{t}_2}$	$0.8\, m_{\tilde{t}_2}$	300	1800	1600	150	200	400

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 '11]

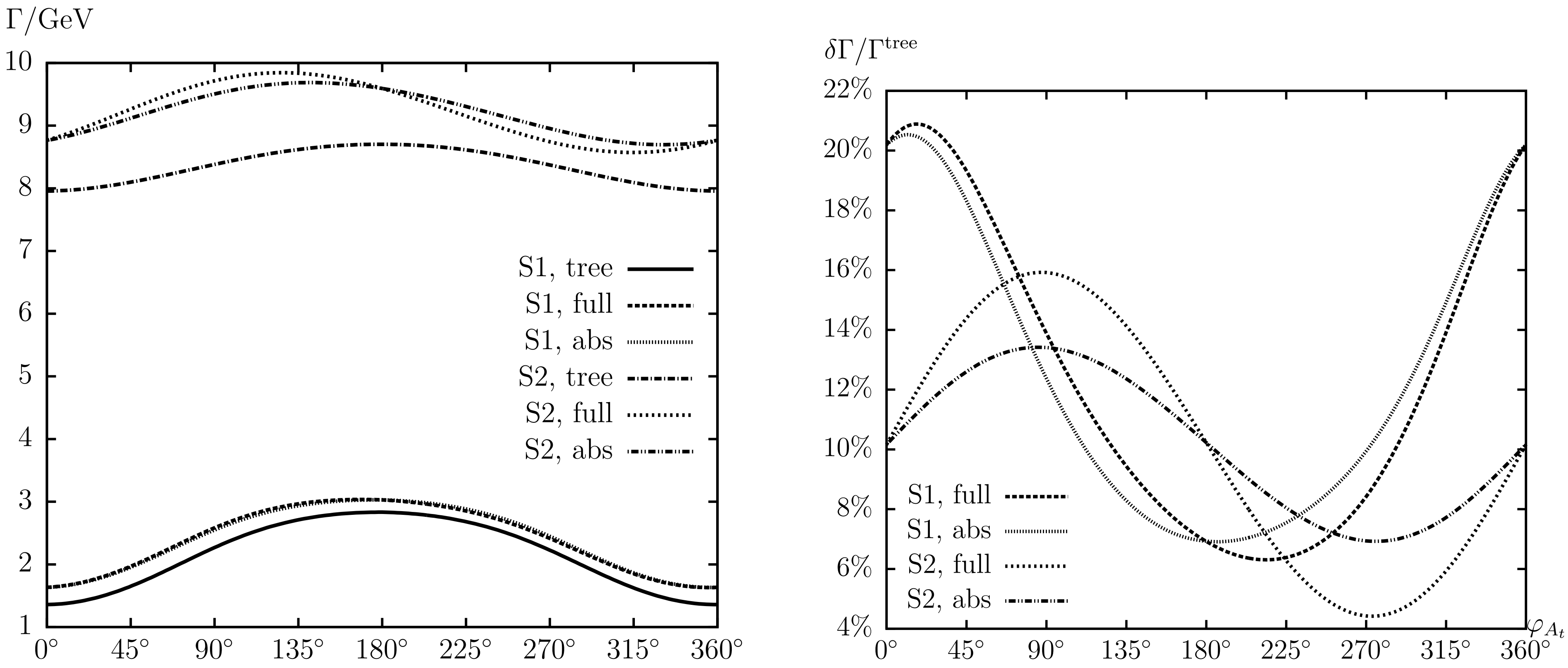


$\Rightarrow$ one-loop corrections under control and non-negligible

$\Rightarrow$ size of BR highly scenario dependent

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

[T. Fritzsche, S.H., H. Rzehak, C. Schappacher '11]



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2B) Heavy Stau decays

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

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

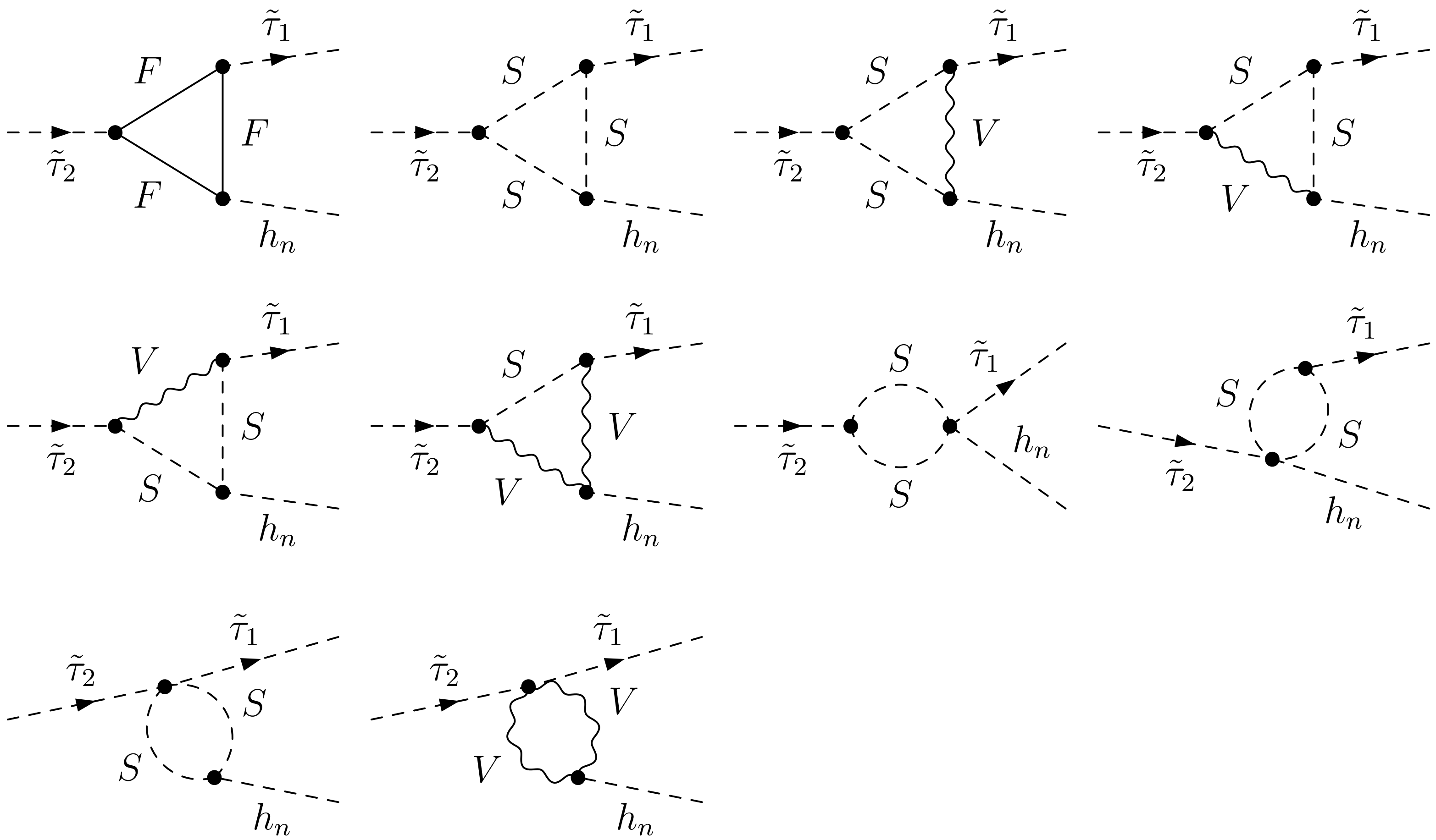
$$\Gamma(\tilde{\tau}_2 \to \tau \tilde{\chi}_k^0) \qquad (k = 1 \ldots 4) \ ,$$

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

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

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

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

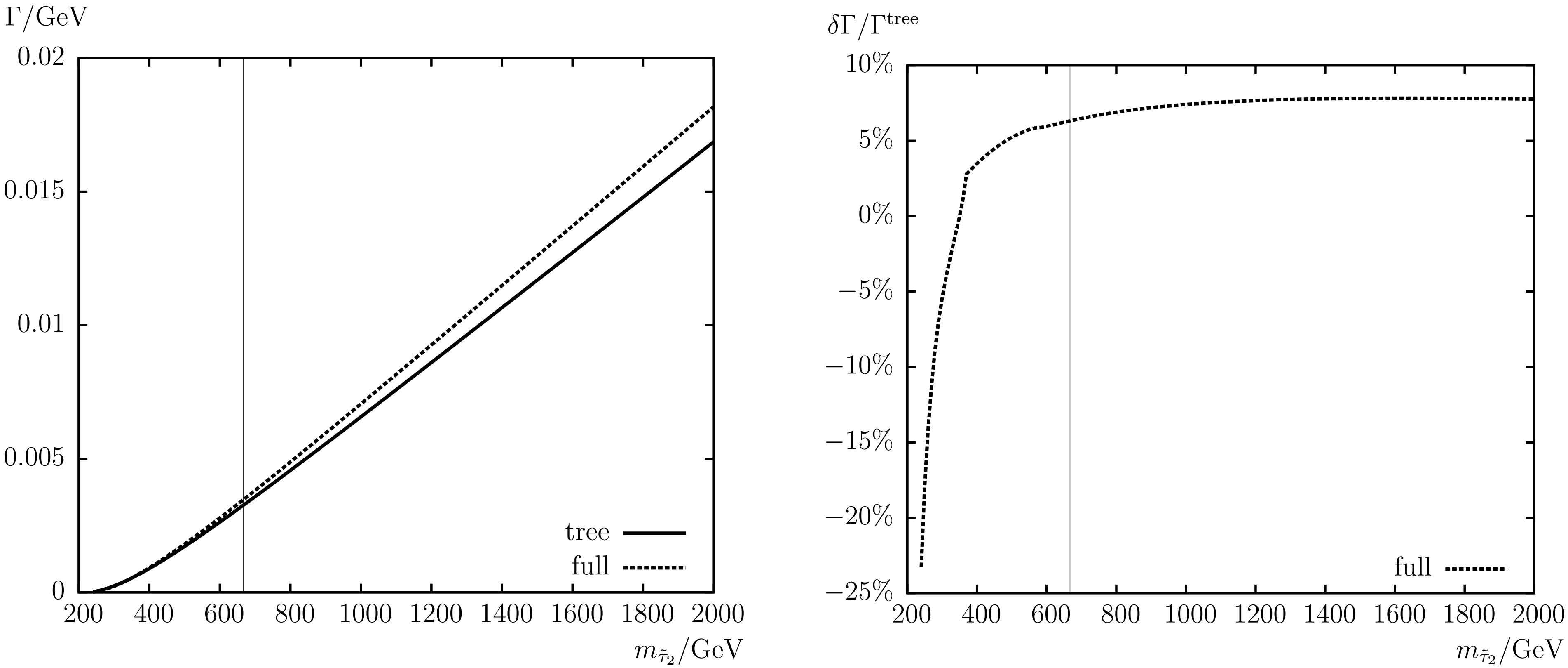
$m_{\tilde{\tau}_1}$	$m_{\tilde{\tau}_2}$	$m_{\tilde{\nu}_\tau}$
274.478	550.000	263.924

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 '12]



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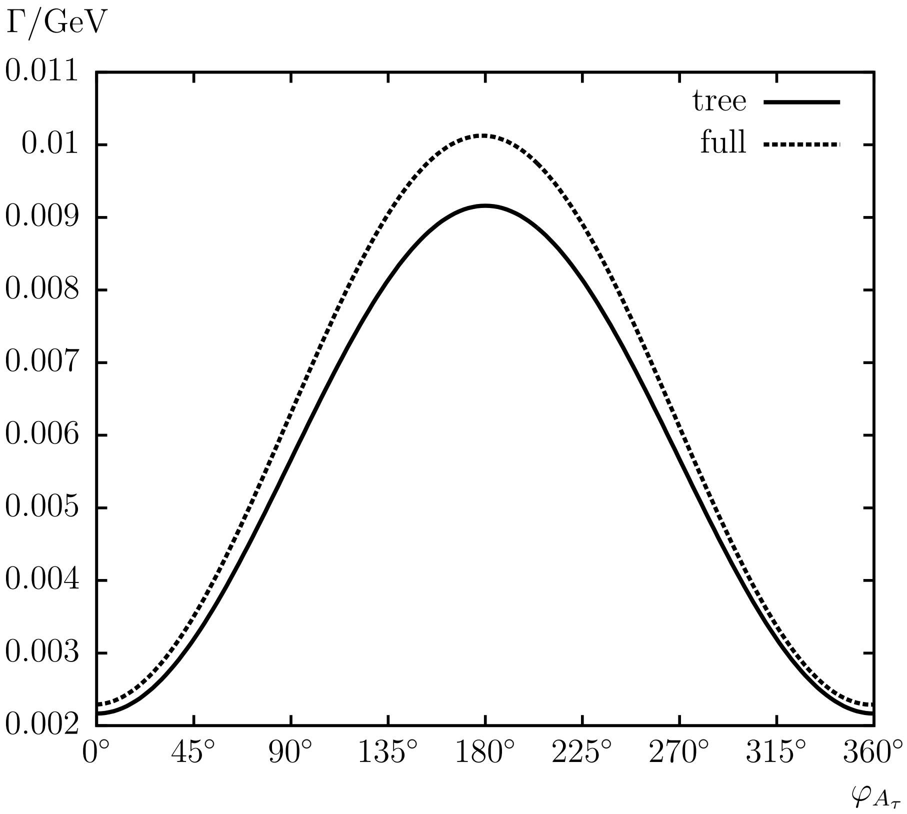
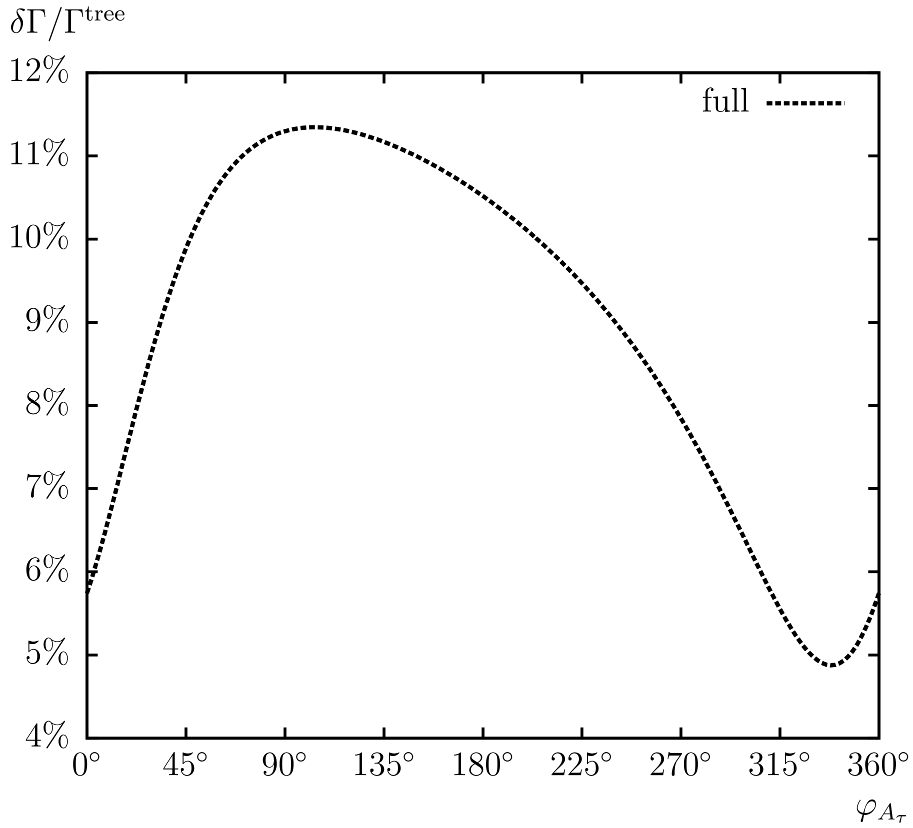
$\Gamma(\tilde{\tau}_2 \to \tilde{\tau}_1 h_1)$: dependence on ϕ_{A_τ}

[S.H., C. Schappacher '12]





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

$\Rightarrow$ size of BR highly scenario dependent

2C) Chargino decays

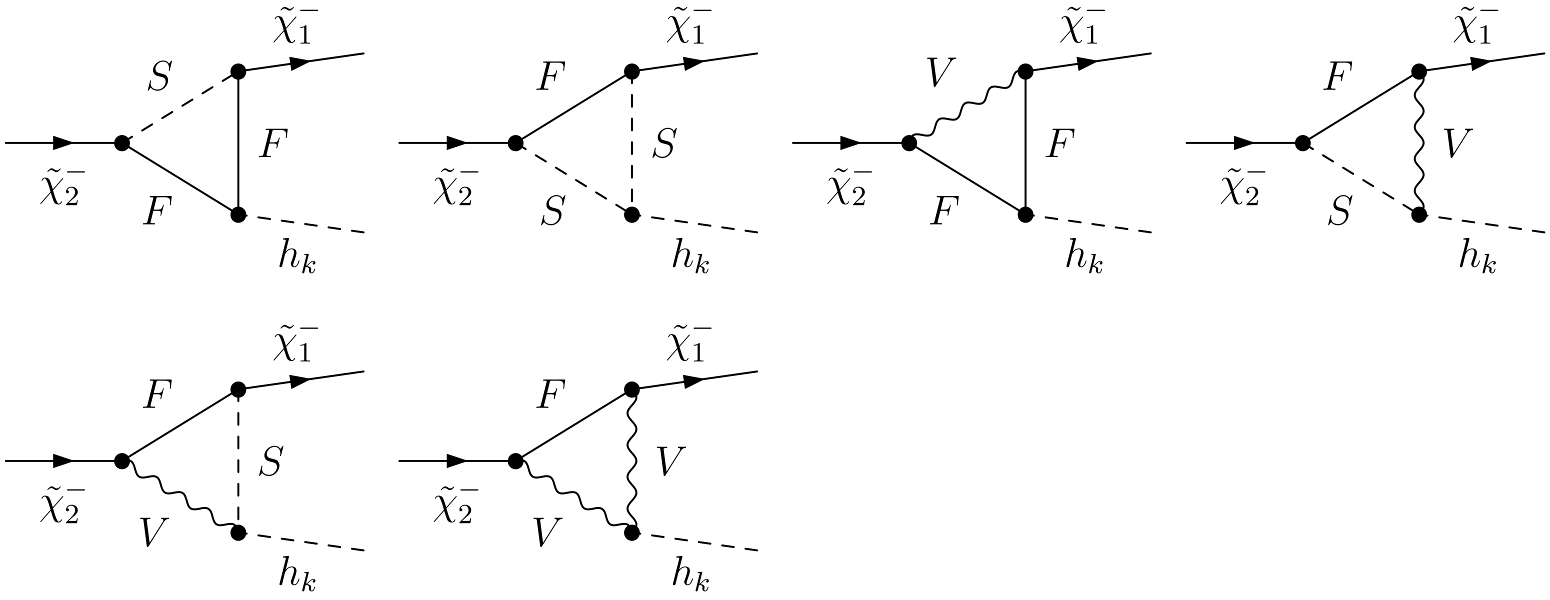
$$\Gamma(\tilde{\chi}_2^\pm \to \tilde{\chi}_1^\pm h_k) \qquad (k = 1,2,3) \;,$$
$$\Gamma(\tilde{\chi}_2^\pm \to \tilde{\chi}_1^\pm Z) \;,$$
$$\Gamma(\tilde{\chi}_i^\pm \to \tilde{\chi}_j^0 H^\pm) \qquad (i = 1,2,\; j = 1,2,3,4) \;,$$
$$\Gamma(\tilde{\chi}_i^\pm \to \tilde{\chi}_j^0 W^\pm) \qquad (i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

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)

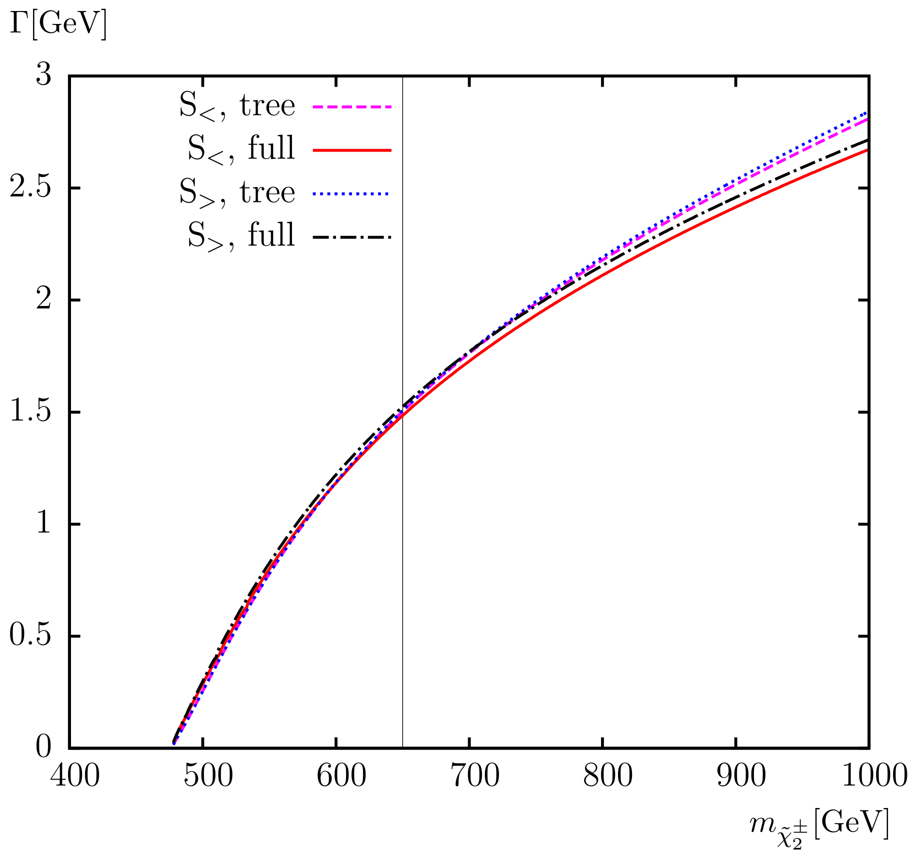
Feynman diagrams for $\tilde{\chi}_2^- \to \tilde{\chi}_1^- h_k$

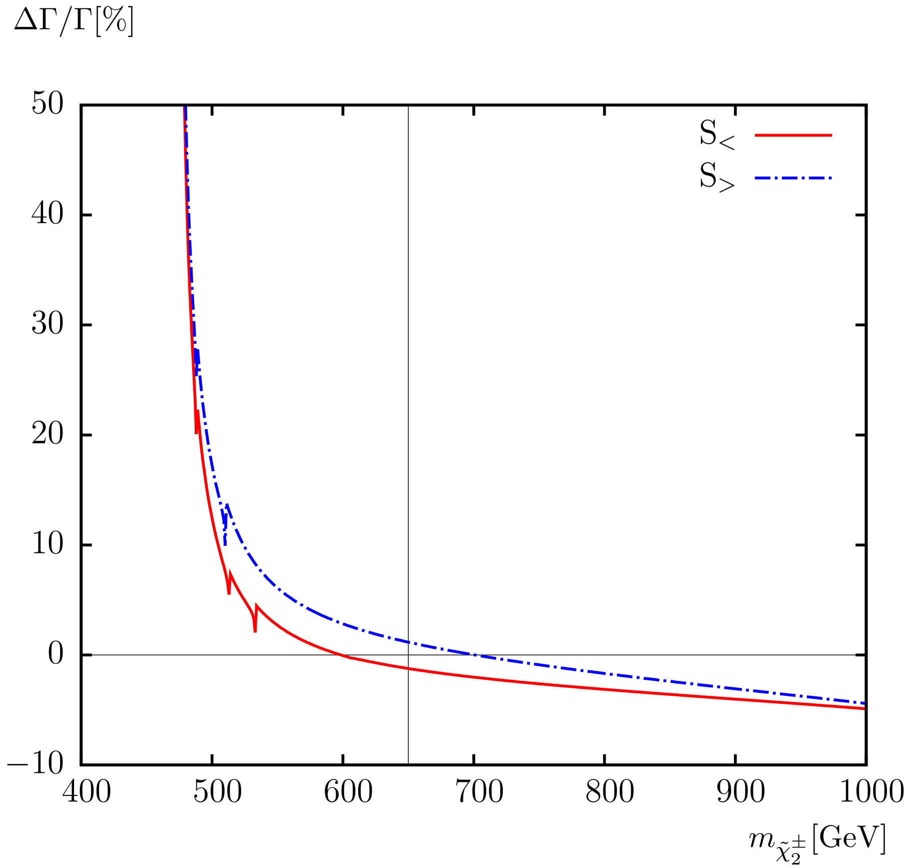


– including Z–A or G–A transition contribution on the external Higgs boson leg

– 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 '11]





⇒ one-loop corrections under control and non-negligible

⇒ size of BR highly scenario dependent

2D) Neutralino decays

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

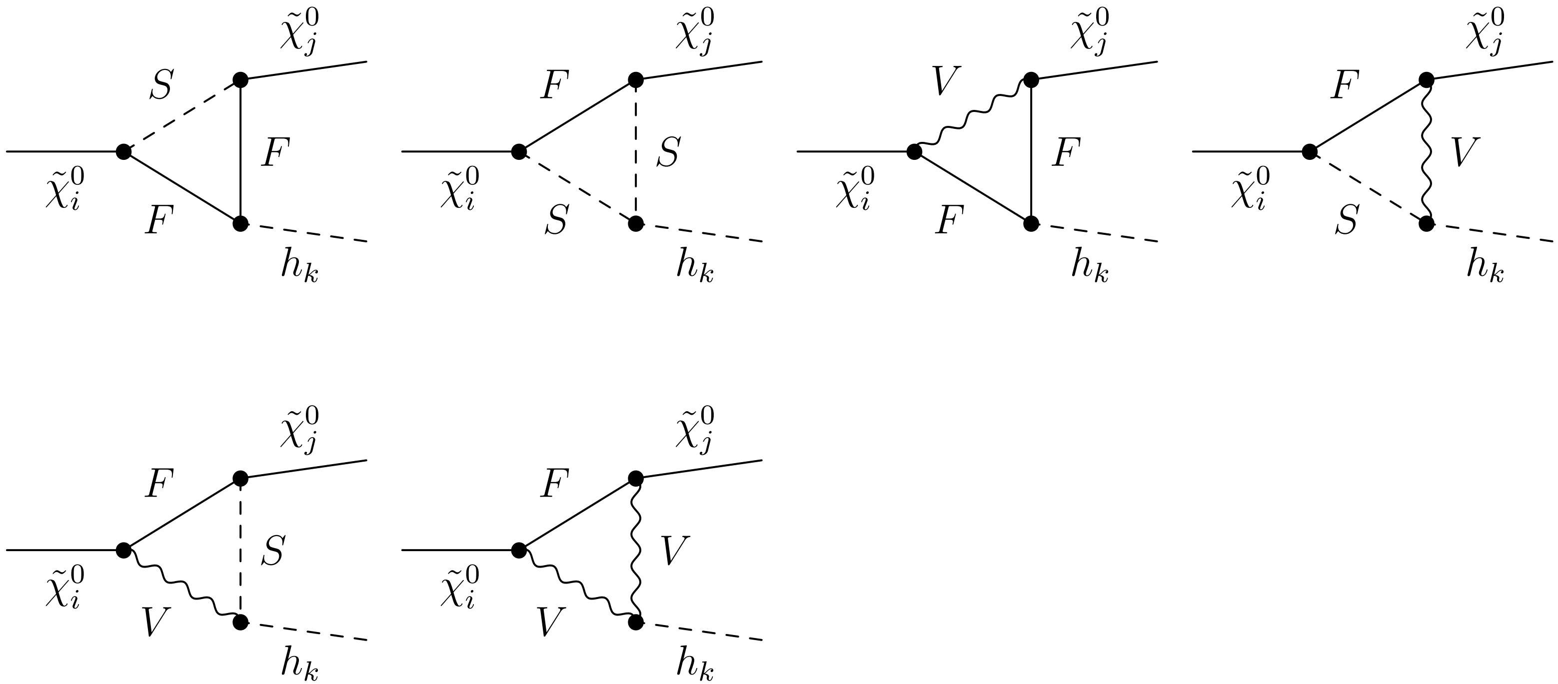
No hadronic decays yet . . .

$\tan\beta$	$M_{H^\pm}$	$m_{\tilde{\chi}_2^\pm}$	$m_{\tilde{\chi}_1^\pm}$	$M_{\tilde{l}_L}$	$M_{\tilde{l}_R}$	A_l	$M_{\tilde{q}_L}$	$M_{\tilde{q}_R}$	A_q
20	160	600	350	300	310	400	1300	1100	2000

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

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

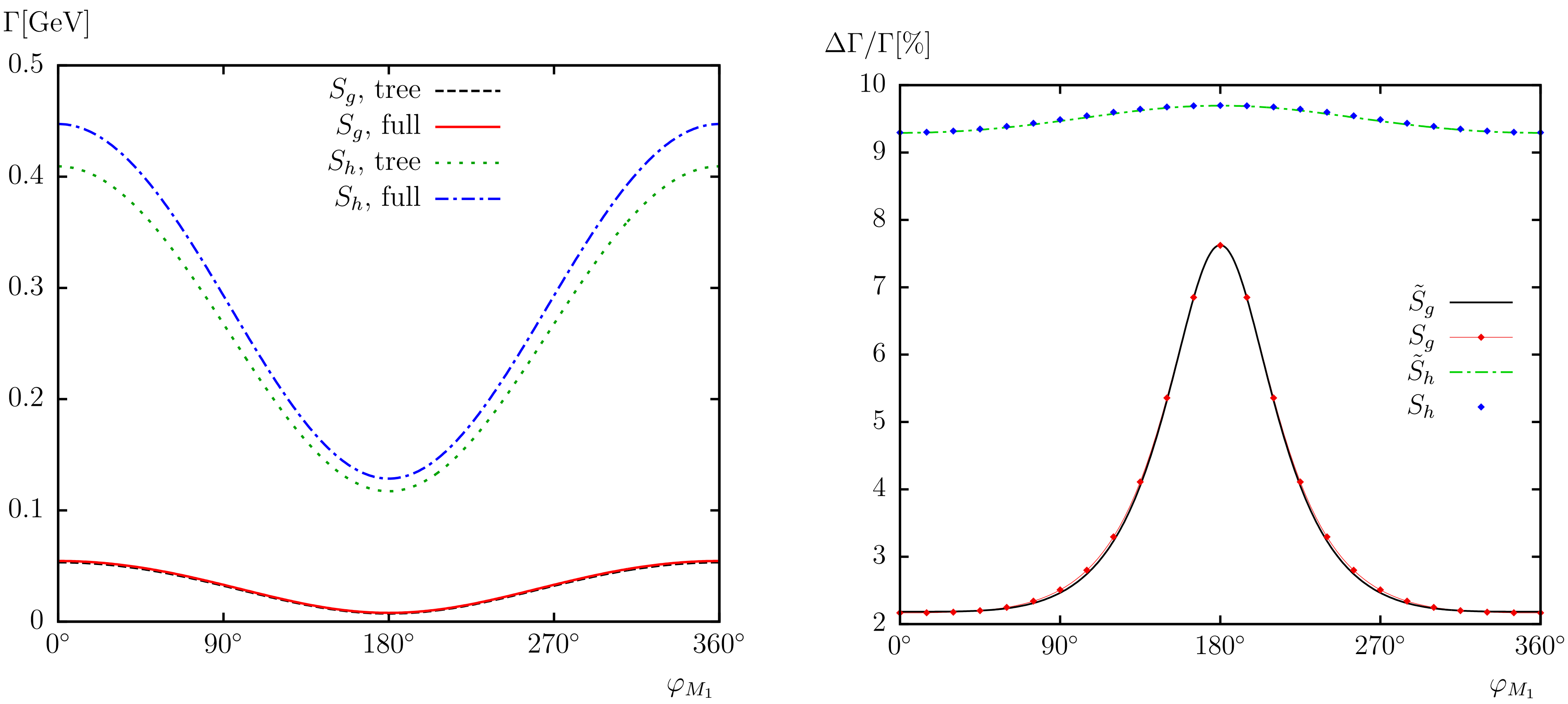
Feynman diagrams for $\tilde{\chi}^0_i \to \tilde{\chi}^0_j h_k$



- including Z–A or G–A transition contribution on the external Higgs boson leg
- including all soft/hard QED diagrams

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

[A. Bharoucha, S.H., F. v.d. Pahlen, C. Schappacher '12]



⇒ one-loop corrections under control and non-negligible

⇒ size of BR highly scenario dependent

3. Conclusinos

- Needed: reliable prediction for SUSY decays at the ILC

  Of special intrest: decays involving Higgs (or LSP)

- Our work:

  Calculation of decay widths and branching ratios

  – all two-body decays of
    scalar top, scalar bottom, scalar tau, gluino, chargino, neutralino
  – full one-loop (incl. hard QED/QCD radiation)
  – in the complex MSSM for arbirtrary parameters
  – renormalization of the full cMSSM!

- Heavy Stop decays: $\tilde{t}_2 \to \tilde{t}_1 h_1$: $\sim 20\%$, stong dep. on ϕ_{A_t}

- Heavy Sau decays: $\tilde{\tau}_2 \to \tilde{\tau}_1 h_1$: $\sim 10\%$, strong dep. on ϕ_{A_τ}

- Chargino decays: $\tilde{\chi}_2^- \to \tilde{\chi}_1^- h_1$: $\sim 10\%$

- Neutralino decays: $\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 h_1$: $\sim 10\%$, dep. on φ_{M_1}

- Full corrections must be taken into account in any LC analysis!