Higgs and LSP Production via SUSY Decays at the ILC

Sven Heinemeyer, IFCA (CSIC, Santander)

Hamburg, 02/2012

based on collaboration with

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

1. Introduction
2. Decays to Higgs bosons
3. Decays to the LSP
4. Conclusions
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2. Decays to Higgs bosons
3. Decays to the LSP
4. Conclusions
5. Reminder of GigaZ   based on a collaboration with *G. Weiglein*

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

Always: production of the lightest SUSY particle: $\tilde{\chi}_1^0$

⇒ important source for information on Higgs, LSP

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

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:

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

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:

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

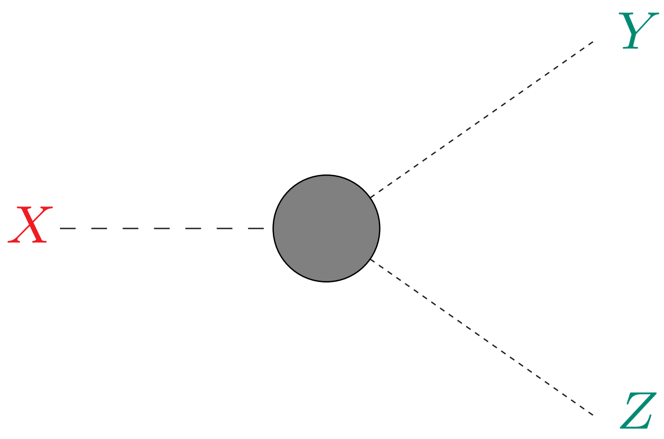
$\Rightarrow$ neutralinos: mass eigenstates

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

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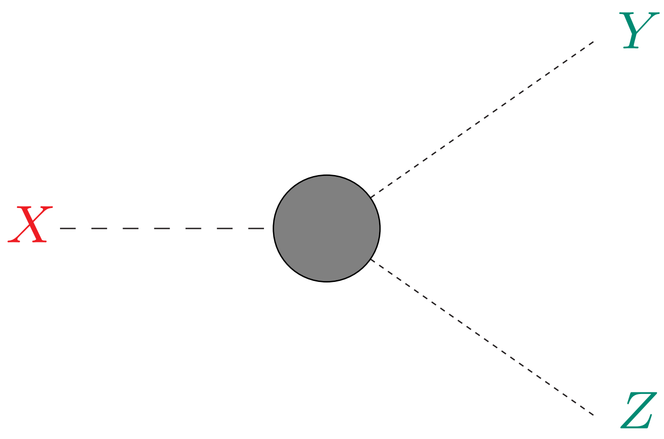


⇒ to get BRs right ⇒ all decays needed

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

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

now ready:

– (heavy) stop decays ⇒ relevant for Higgs, LSP
– gluino decays
– (non-hadronic) chargino decays ⇒ 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. 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

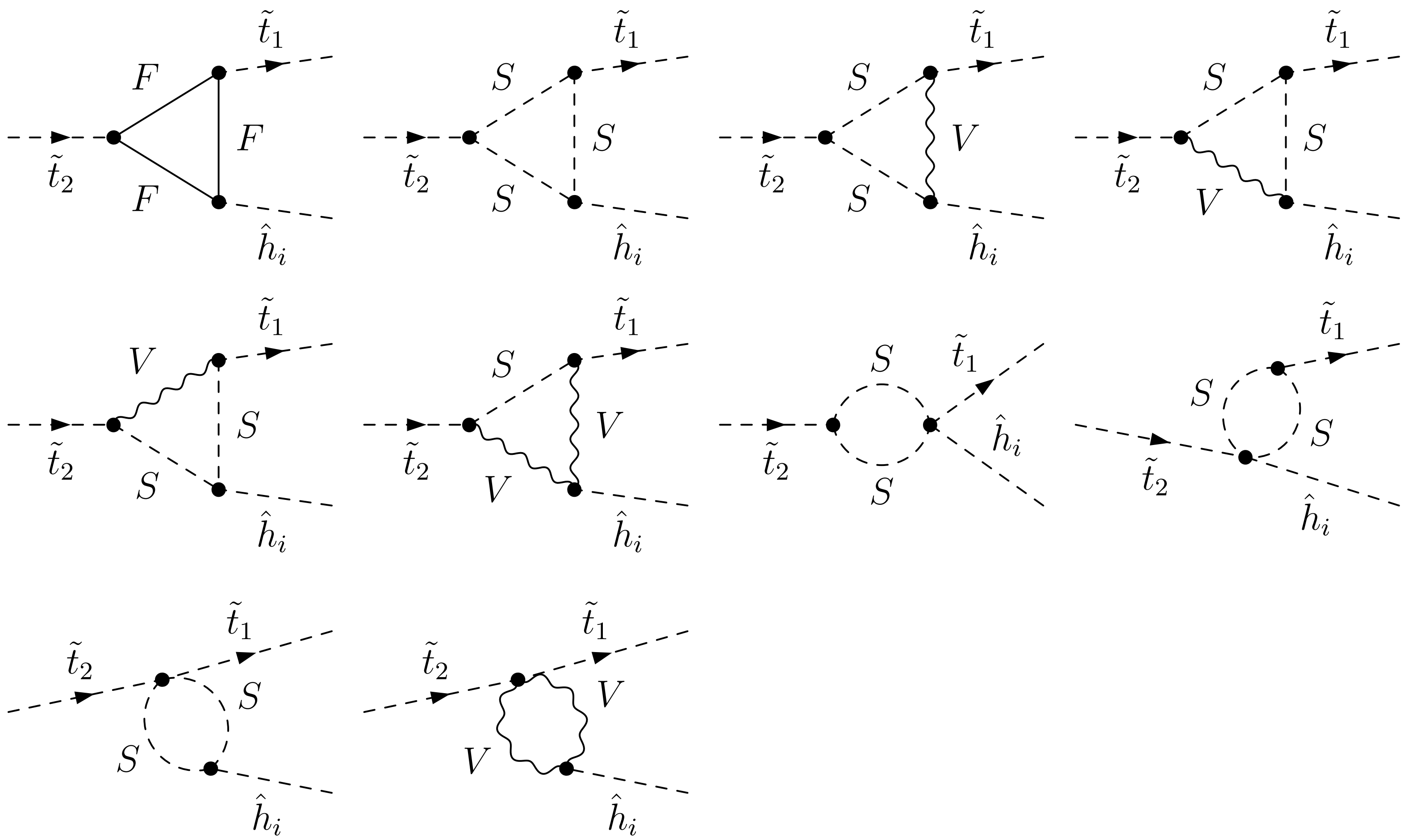
– Dimensional REDuction

– 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:

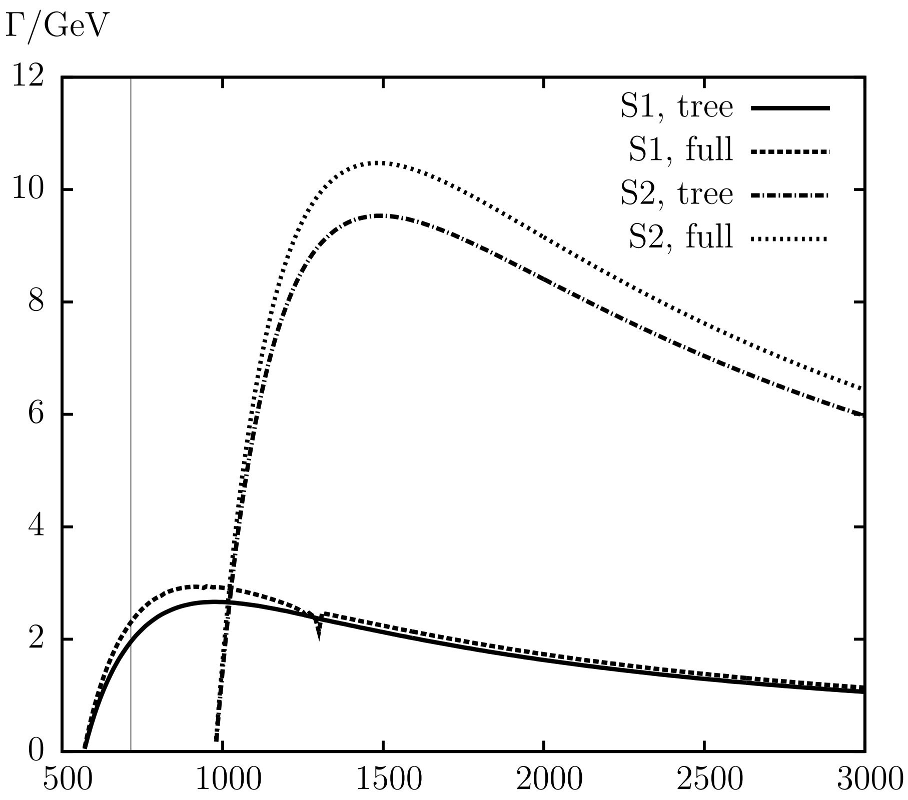
Scen.	$M_{H^\pm}$	$m_{\tilde{t}_2}$	$m_{\tilde{t}_1}$	$m_{\tilde{b}_2}$	μ	A_t	A_b	M_1	M_2	M_3
S1	150	650	$0.4\, m_{\tilde{t}_2}$	$0.7\, m_{\tilde{t}_2}$	200	900	400	200	300	800
S2	180	1200	$0.6\, m_{\tilde{t}_2}$	$0.8\, m_{\tilde{t}_2}$	300	1800	1600	150	200	400

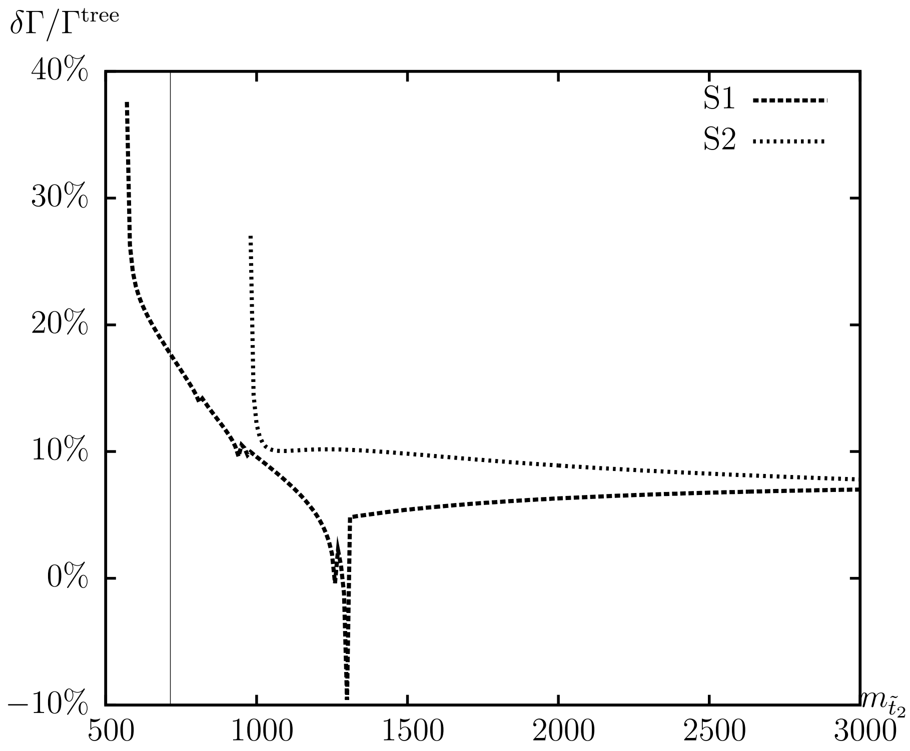
Scen.	$\tan\beta$	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	$m_{\tilde{b}_1}$	$m_{\tilde{b}_2}$
S1	2	260.000	650.000	305.436	455.000
	20	260.000	650.000	333.572	455.000
	50	260.000	650.000	329.755	455.000
S2	2	720.000	1200.000	769.801	960.000
	20	720.000	1200.000	783.300	960.000
	50	720.000	1200.000	783.094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





⇒ one-loop corrections under control and non-negligible

⇒ size of BR highly scenario dependent

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

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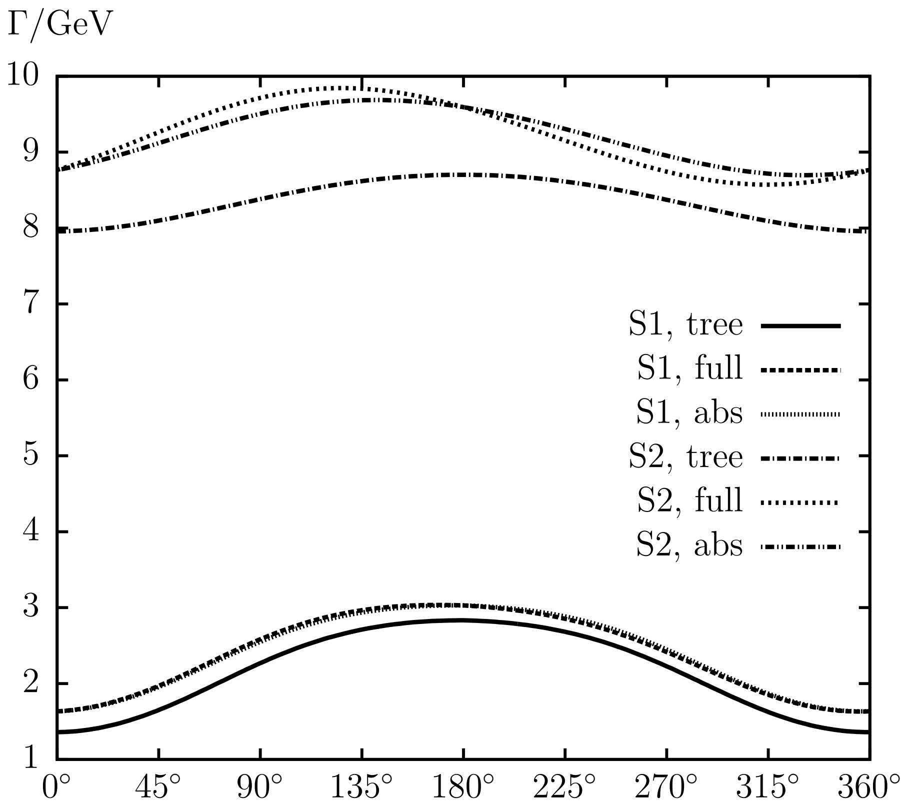

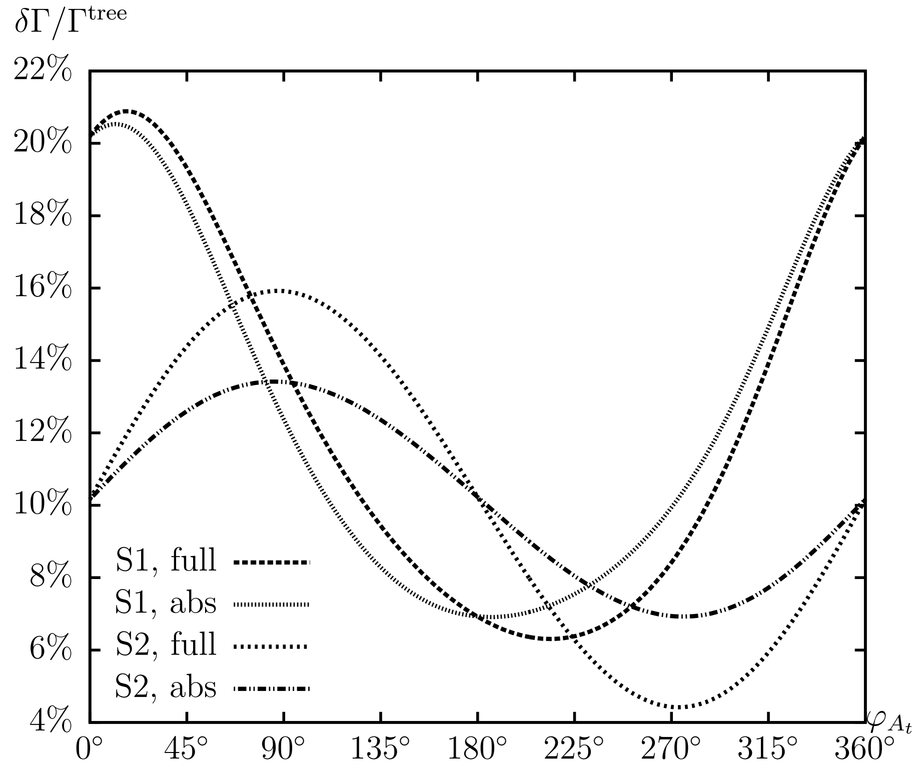

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2B) Chargino decays

$$\Gamma(\tilde{\chi}_2^\pm \to \tilde{\chi}_1^\pm h_k) \qquad (k = 1,2,3)\ ,$$

$$\Gamma(\tilde{\chi}_2^\pm \to \tilde{\chi}_1^\pm Z)\ ,$$

$$\Gamma(\tilde{\chi}_i^\pm \to \tilde{\chi}_j^0 H^\pm) \qquad (i = 1,2,\ j = 1,2,3,4)\ ,$$

$$\Gamma(\tilde{\chi}_i^\pm \to \tilde{\chi}_j^0 W^\pm) \qquad (i = 1,2,\ j = 1,2,3,4)\ ,$$

$$\Gamma(\tilde{\chi}_i^\pm \to \tilde{l}_k^\pm \nu_l) \qquad (i = 1,2,\ l = e,\mu,\tau,\ k = 1,2)\ ,$$

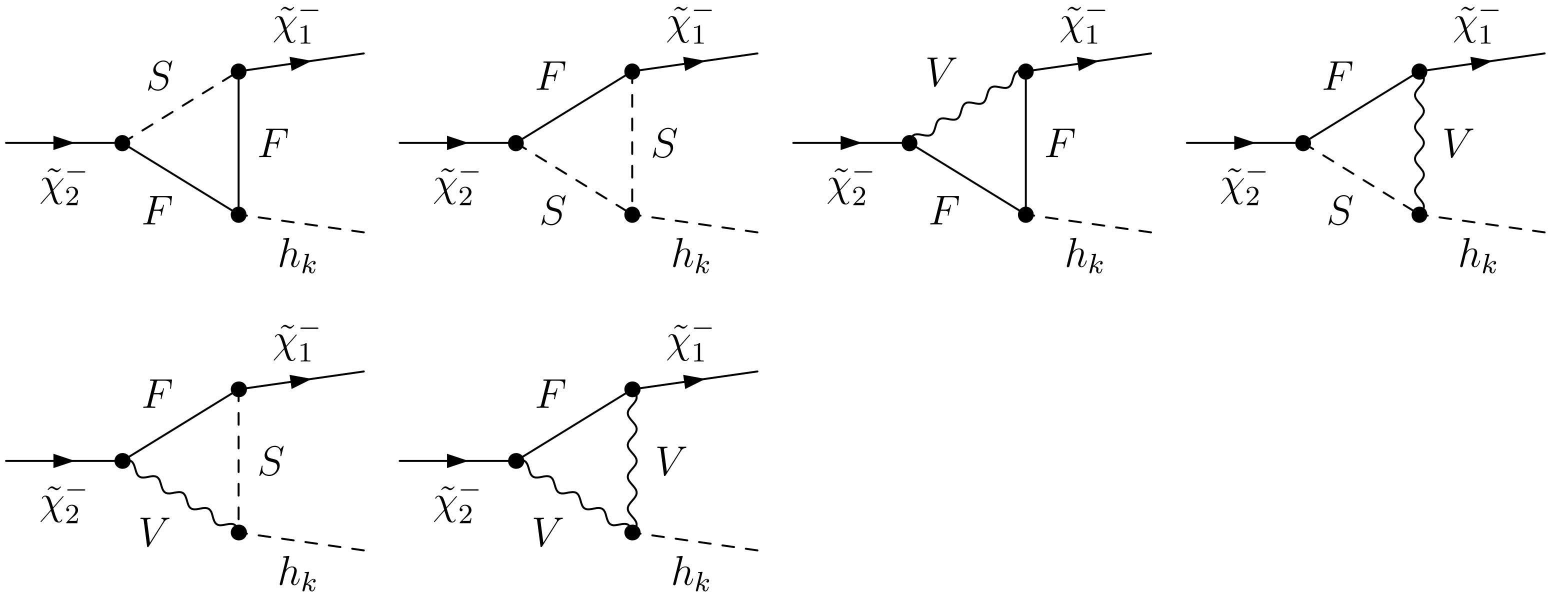
$$\Gamma(\tilde{\chi}_i^\pm \to \tilde{\nu}_l\, l^\pm) \qquad (i = 1,2,\ l = e,\mu,\tau)\ .$$

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

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

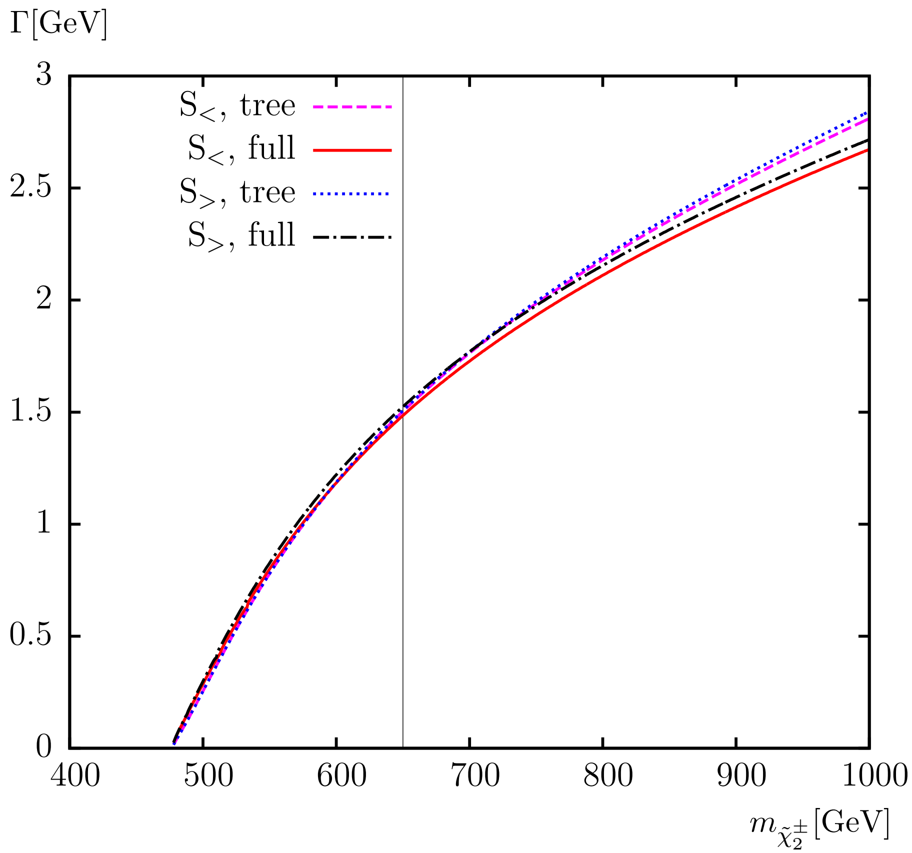
Feynman diagrams for $\tilde{\chi}_2^- \to \tilde{\chi}_1^- h_k$

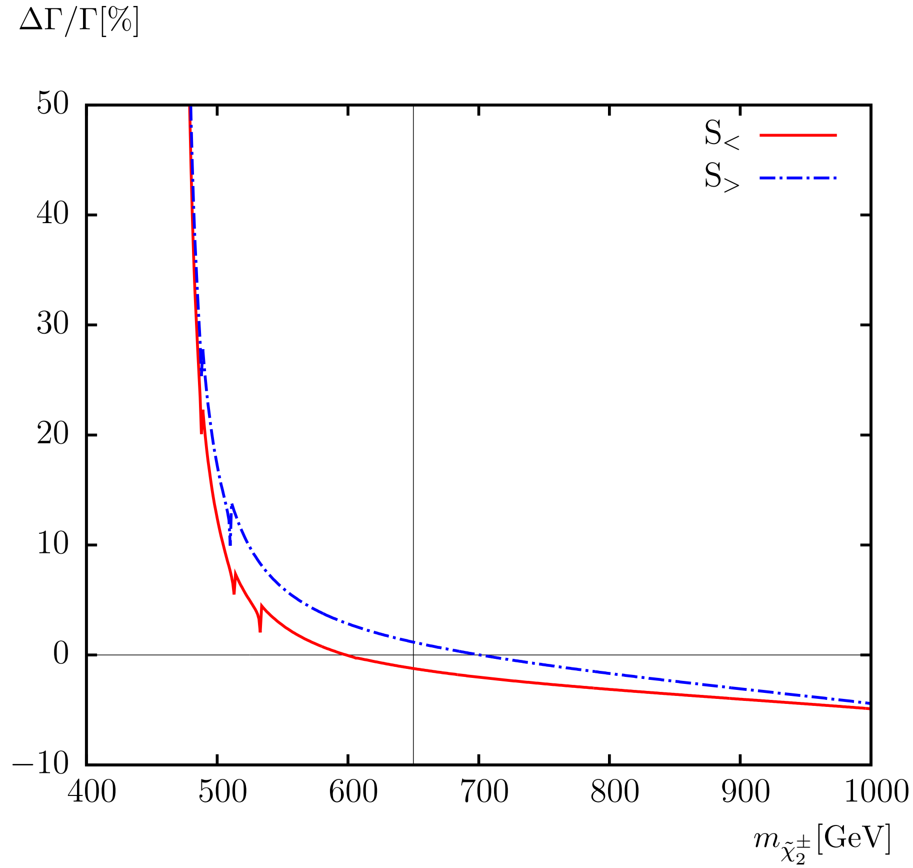


– including Z–A or G–A transition contribution on the external Higgs boson leg

– including all soft/hard QED/QCD 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]





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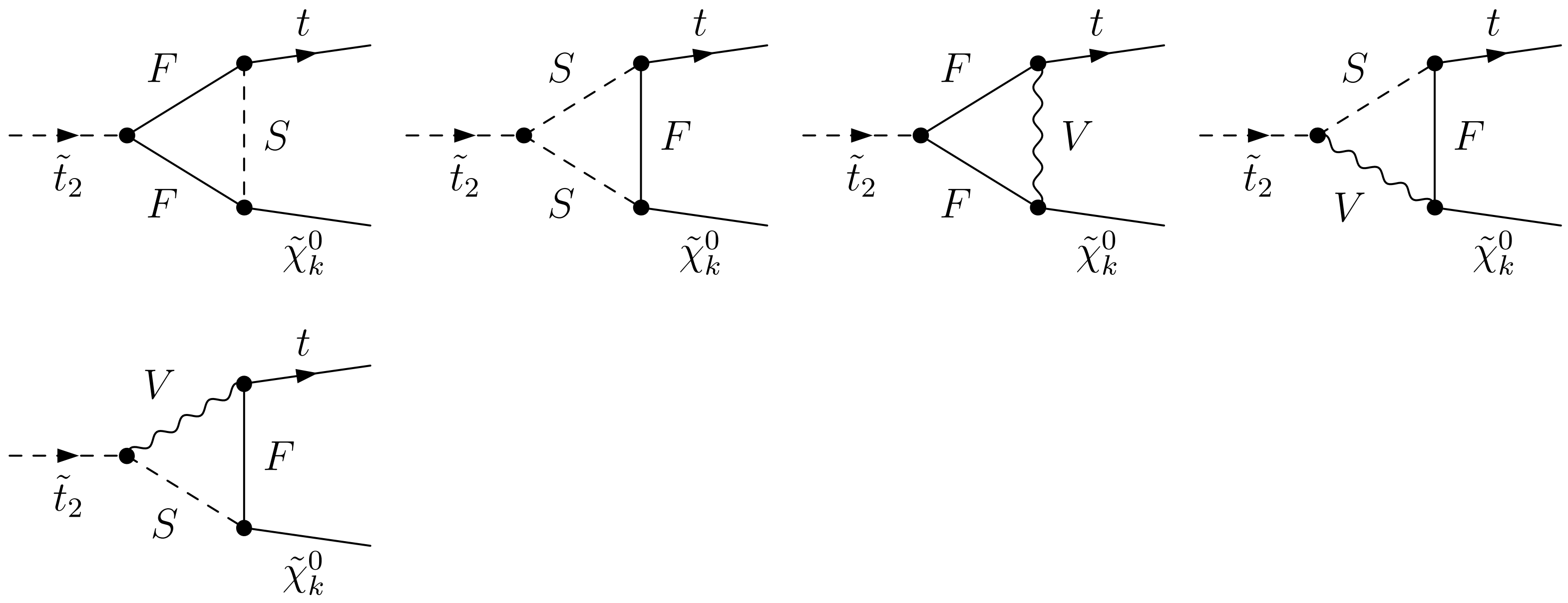
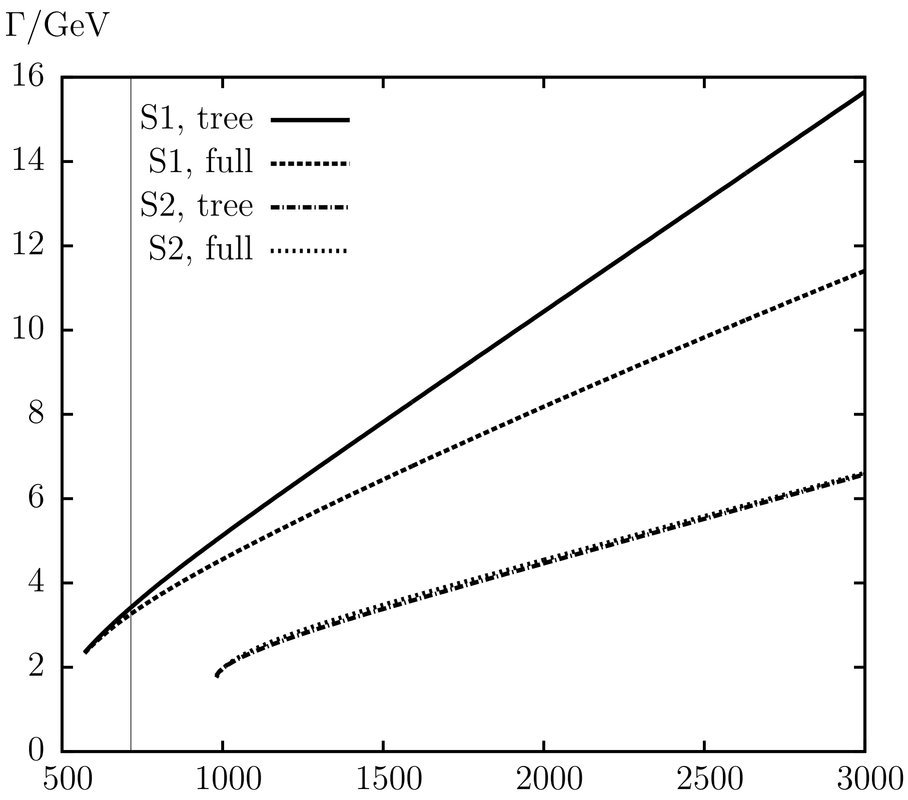
Feynman diagrams for $\tilde{t}_2 \to t\tilde{\chi}_1^0$

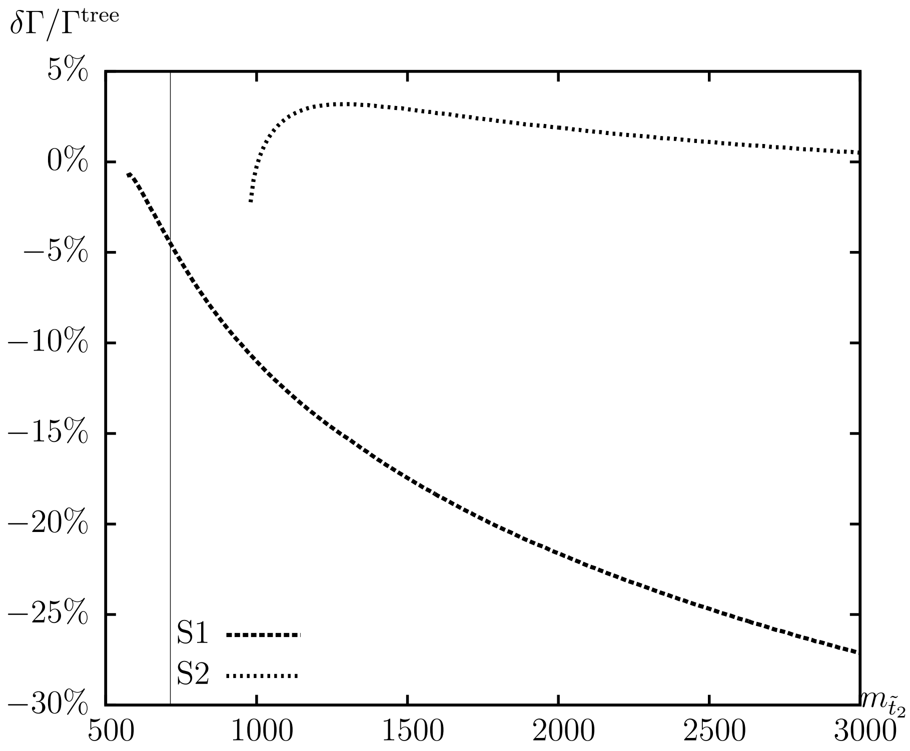


– including all soft/hard QED/QCD diagrams

$\Gamma(\tilde{t}_2 \to t\tilde{\chi}^0_1)$: dependence on $m_{\tilde{t}_2}$

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





⇒ one-loop corrections under control and non-negligible

⇒ size of BR highly scenario dependent

$\Gamma(\tilde{t}_2 \to t\tilde{\chi}_1^0)$: dependence on ϕ_{A_t}

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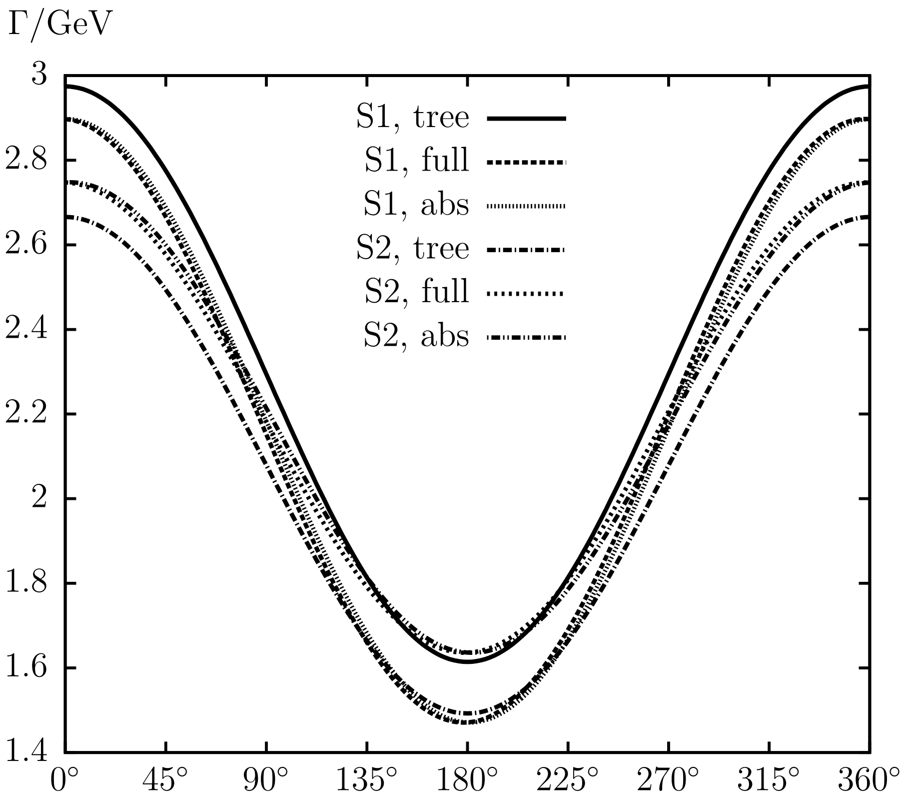

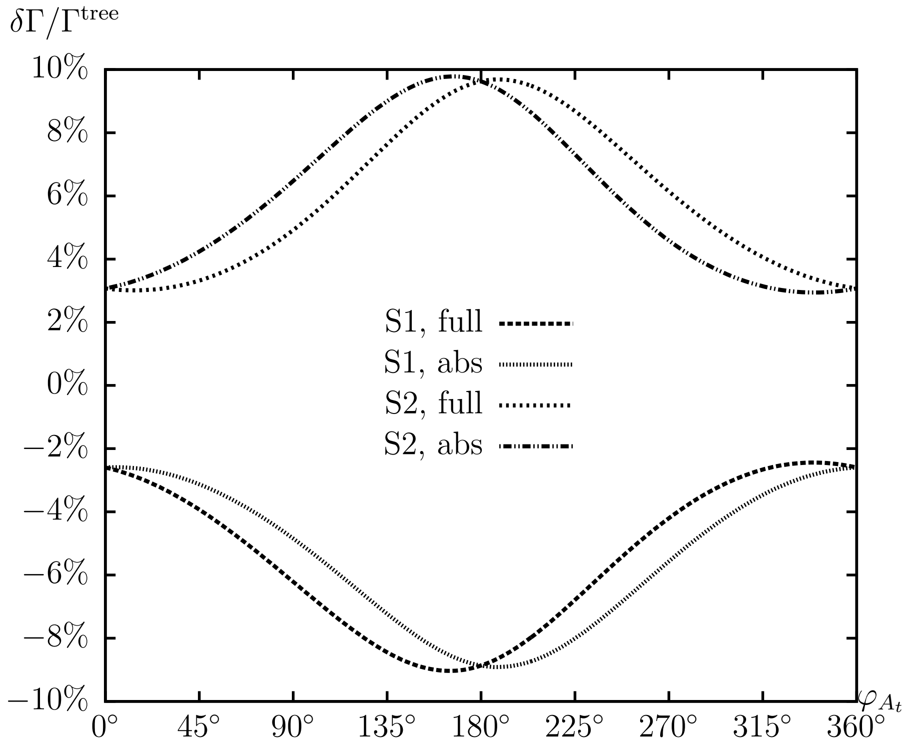

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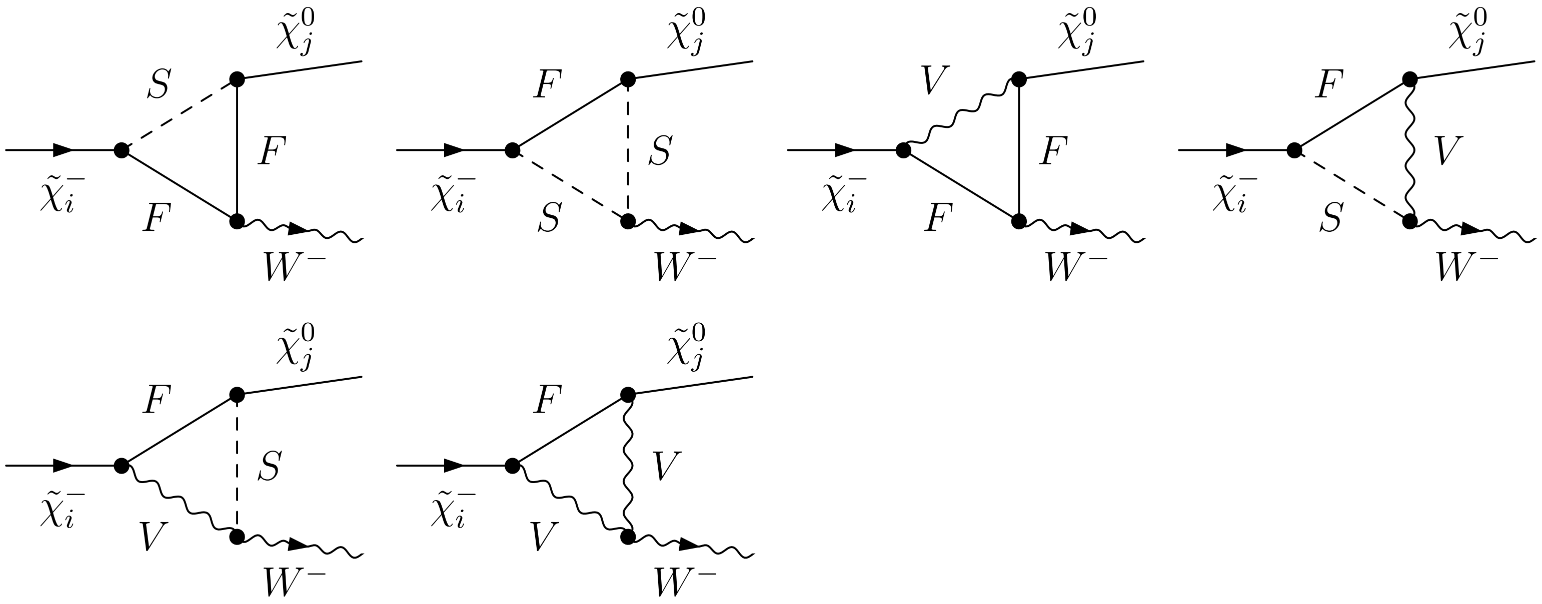
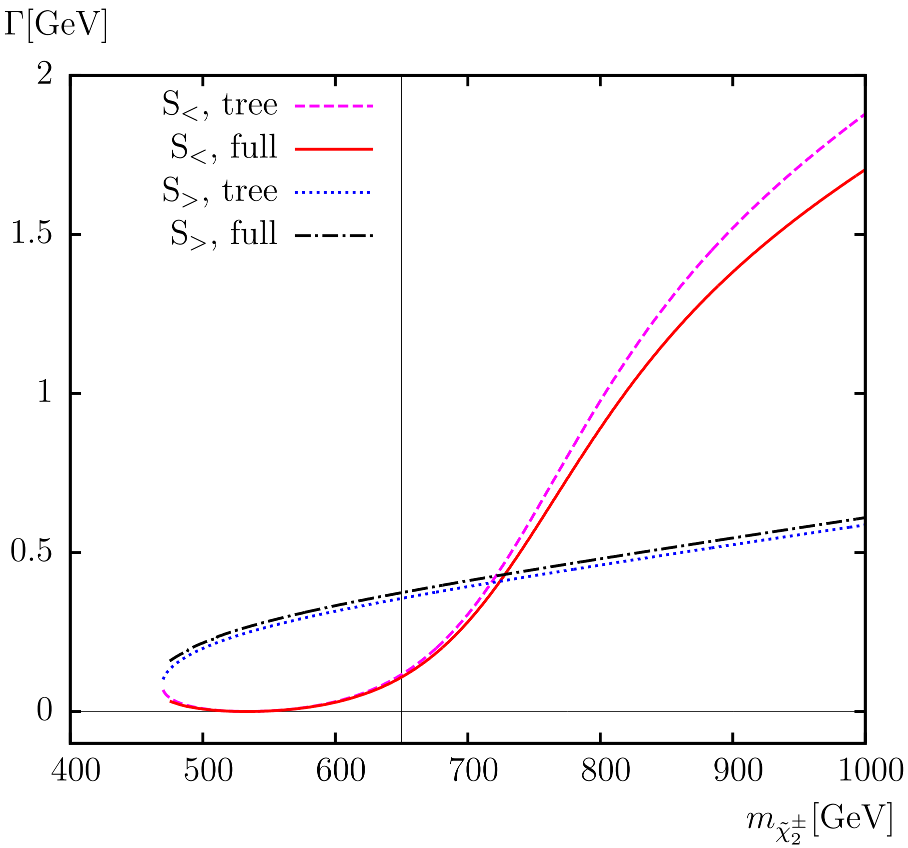
No hadronic decays yet . . .

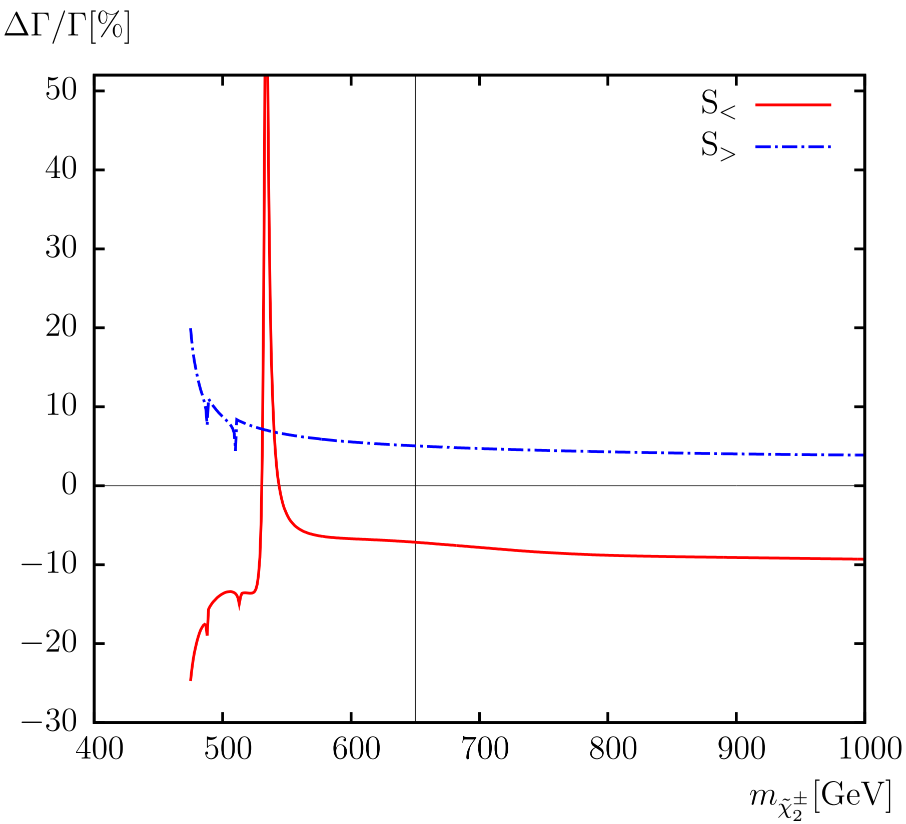
Feynman diagrams for $\tilde{\chi}_i^{\pm} \to \tilde{\chi}_j^0 W^{\pm}$



– including all soft/hard QED diagrams

$\Gamma(\tilde{\chi}_2^- \to \tilde{\chi}_1^0 W^-)$: dependence on $m_{\tilde{\chi}_2^\pm}$ [S.H., F. v.d. Pahlen, C. Schappacher '11]





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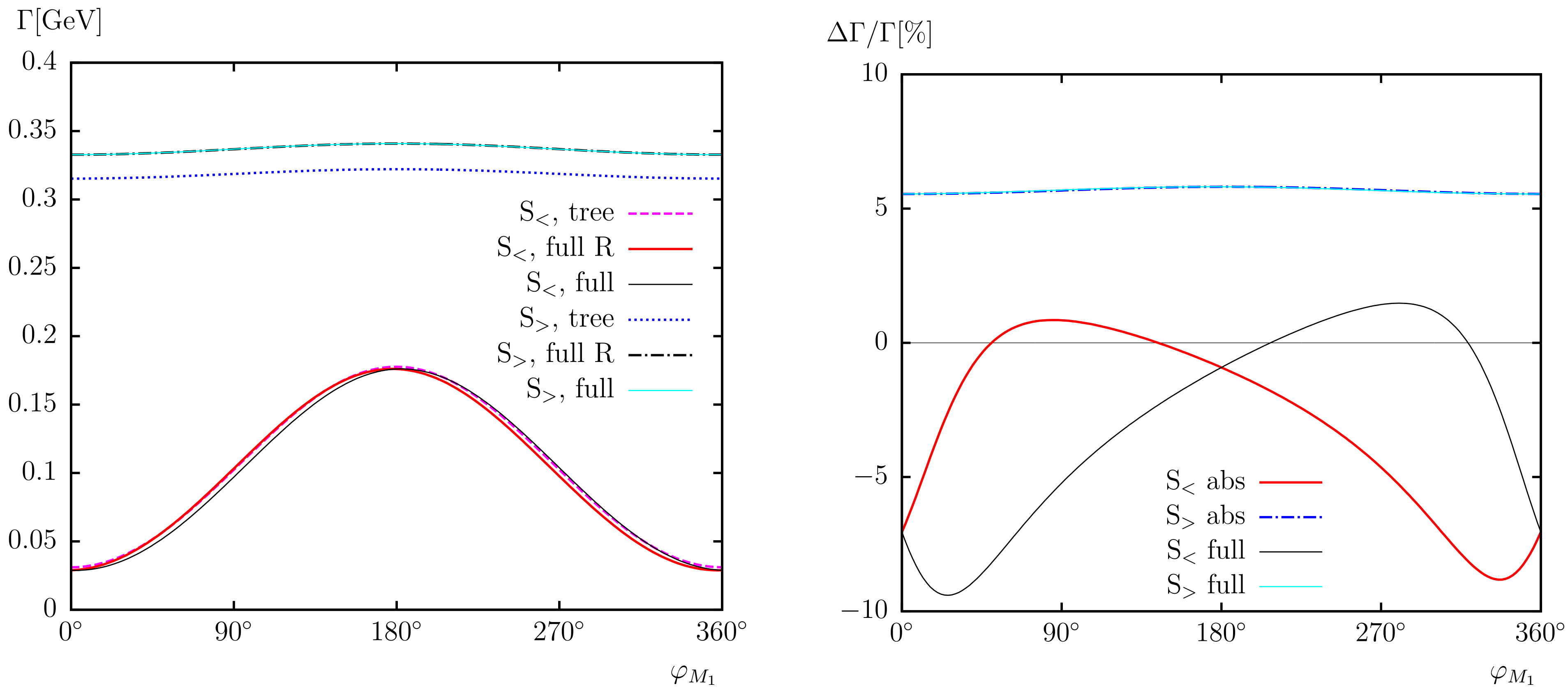
$\Gamma(\tilde{\chi}_2^- \to \tilde{\chi}_1^0 W^-)$: dependence on φ_{M_1} [S.H., F. v.d. Pahlen, C. Schappacher '11]



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4. 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
  – 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%, $\tilde{t}_2 \to t\tilde{\chi}_1^0$: $\sim \pm$10%

- Chargino decays:

  $\tilde{\chi}_2^- \to \tilde{\chi}_1^- h_1$: $\sim$ 10%, $\tilde{\chi}_2^- \to \tilde{\chi}_1^0 W^-$: $\sim$ 10%

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

5. Reminder of GigaZ

$\Rightarrow$ High-luminosity running at the Z pole and WW threshold

$\Rightarrow$ $\mathcal{O}\left(10^9\right)$ Z bosons

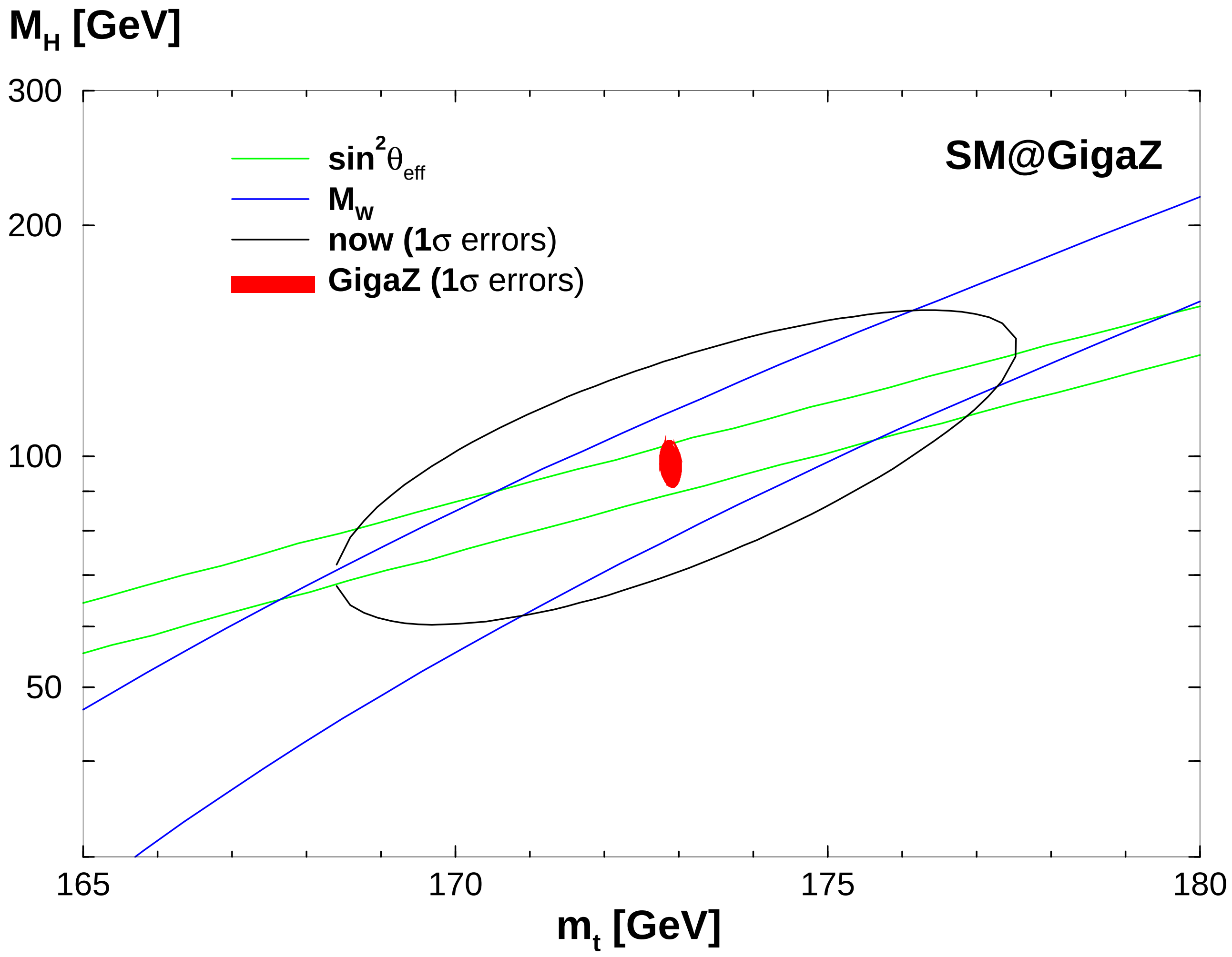
$\Rightarrow$ many high-precision measurements possible!

Experimental errors of the precision observables:

	today	Tev./LHC	ILC	GigaZ
$\delta \sin^2\theta_{\mathrm{eff}}(\times 10^5)$	16	16	–	1.3
δM_W [MeV]	23	15	10	7
δm_t [GeV]	0.9	~ 1	0.2	0.1

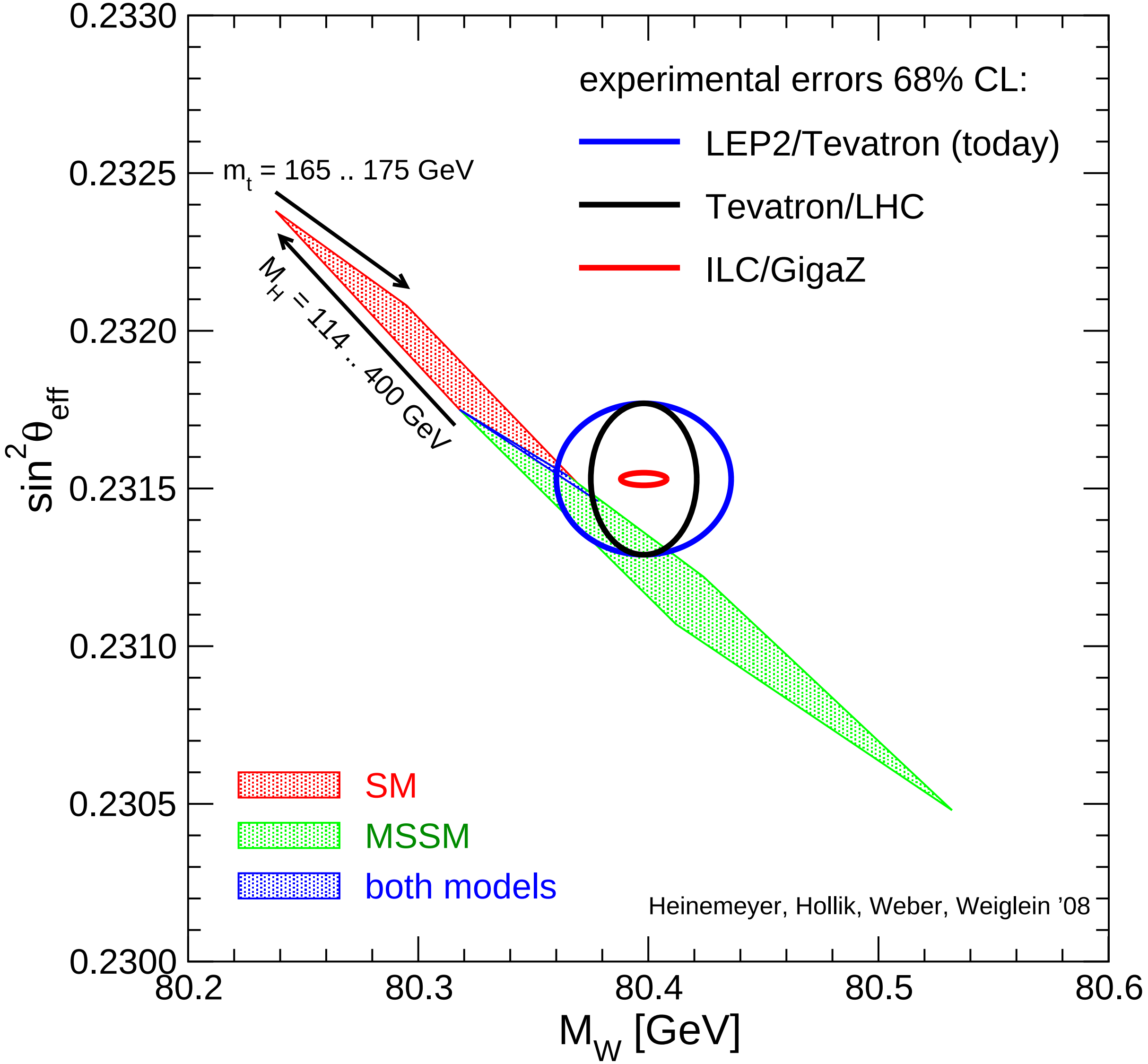
GigaZ: $\Rightarrow$ Improvement in M_H determination:

[J. Erler, S.H., W. Hollik, G. Weiglein, P. Zerwas '00]



Example: Prediction for M_W and $\sin^2\theta_{\rm eff}$ in the SM and the MSSM :

[S.H., W. Hollik, A. Weber, G. Weigleín '07]



MSSM band:
scan over
SUSY masses

overlap:
SM is MSSM-like
MSSM is SM-like

SM band:
variation of $M_H^{\rm SM}$

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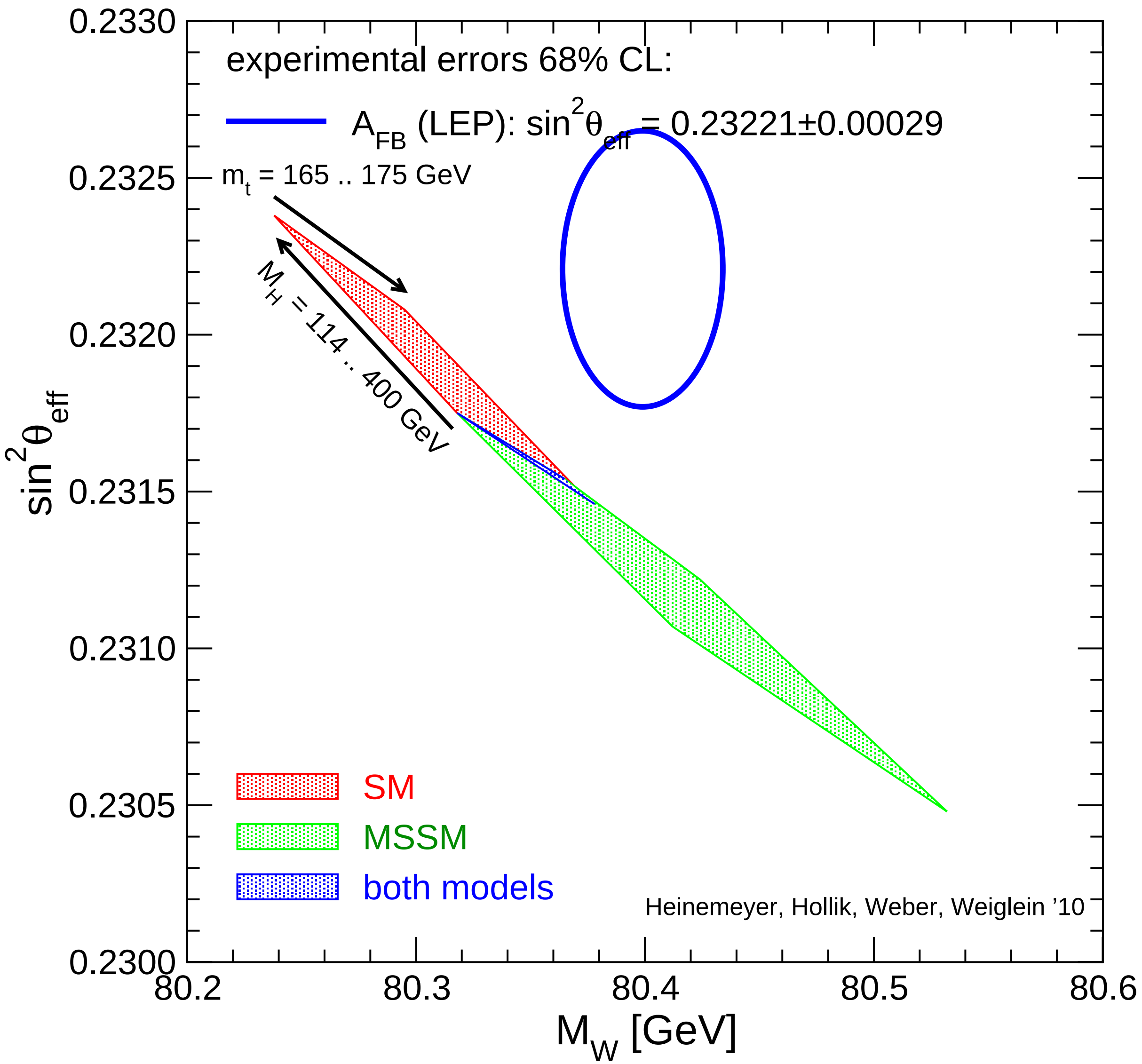

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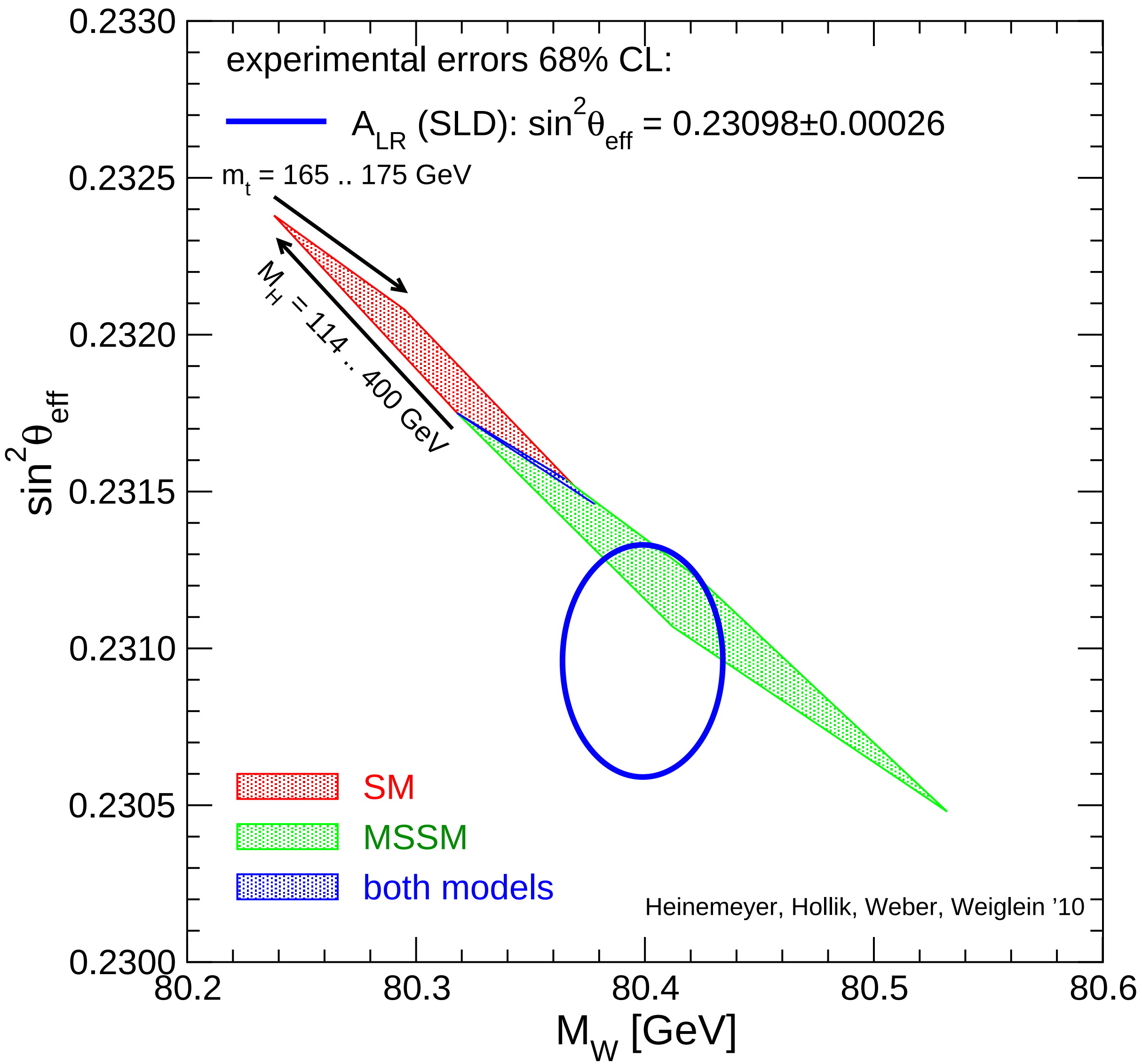
Example: Prediction for M_W and $\sin^2\theta_{\rm eff}$ in the SM and the MSSM :

[S.H., W. Hollik, A. Weber, G. Weiglein '07]



MSSM band:
scan over
SUSY masses

overlap:
SM is MSSM-like
MSSM is SM-like

SM band:
variation of $M_H^{\rm SM}$

Scenario with no SUSY particles at the LHC:

→ $\sin^2\theta_{\rm eff}$ investigation

→ SPS 1a with heavy scalars

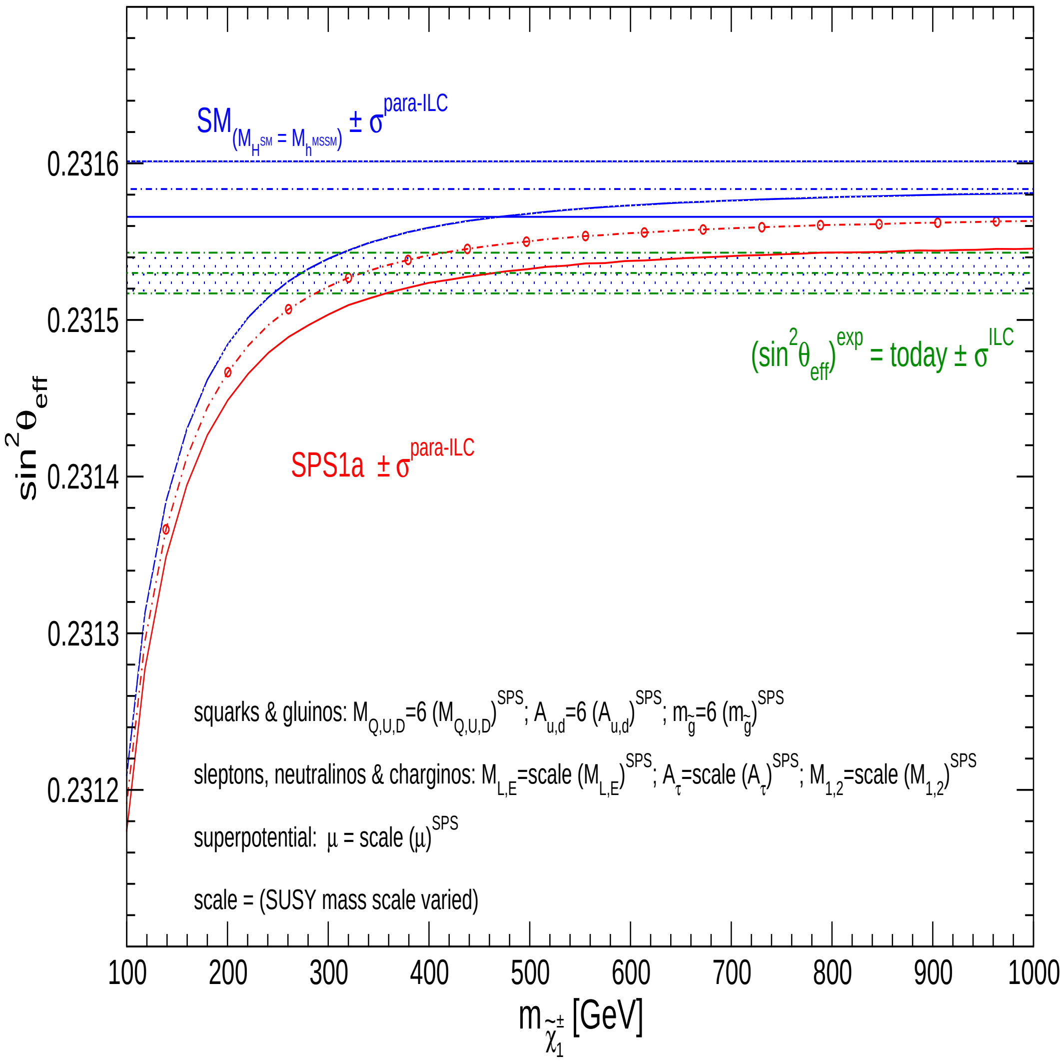
SM prediction

vs.

MSSM (SPS 1a) prediction

vs.

ILC resolution



⇒ the ILC(1000)/GigaZ could detect SUSY directly/indirectly

Tricky scenario:

The LHC finds only a SM-like Higgs and nothing else

Q: Do we still need the ILC with GigaZ?

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Q: Do we still need the ILC with GigaZ?

A: Of course! Or better: even more!

The ILC+GigaZ provides:

– precise Higgs coupling measurements (ILC)

– precision observable measurements (GigaZ)

⇒ Only the ILC+GigaZ can find deviations from the SM predictions via the various precision measurements

⇒ Only the ILC+GigaZ can point towards extensions of the SM