

# Higgs Production via SUSY Decays at the LC

*Sven Heinemeyer, IFCA (CSIC, Santander)*

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based on collaboration with

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

1. Introduction & Renormalization of the cMSSM
2. Stop decays
3. Chargino decays
4. Conclusions

# 1. Introduction & Renormalization of the cMSSM

Production of SUSY particles at the LHC:

⇒ cascade decays:

$$\tilde{g} \rightarrow \bar{q}\tilde{q} \rightarrow \bar{q}q\tilde{\chi}_2^0 \rightarrow \bar{q}q\tilde{\tau}\tau \rightarrow \bar{q}q\tau\tau\tilde{\chi}_1^0$$

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

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

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

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

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\ + \underbrace{\frac{g'^2 + g^2}{8}}_{\text{gauge couplings, in contrast to SM}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{\text{gauge couplings, in contrast to SM}} |H_1 \bar{H}_2|^2$$

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

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

Input parameters: (to be determined experimentally)

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

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

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

Input parameters: (to be determined experimentally)

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

## Complex parameters:

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

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

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

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

$SU(2) \text{ relation} \Rightarrow M_{\tilde{t}_L} = M_{\tilde{b}_L}$

$\Rightarrow$  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:

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

⇒ charginos: mass eigenstates

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

neutral:

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

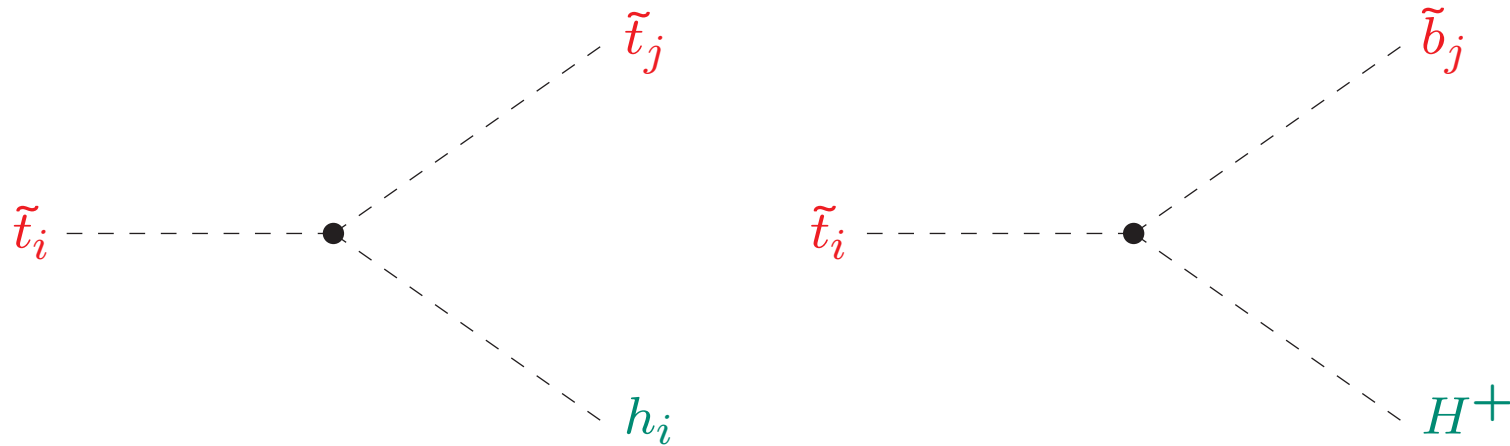
⇒ neutralinos: mass eigenstates

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

⇒ only one new parameter

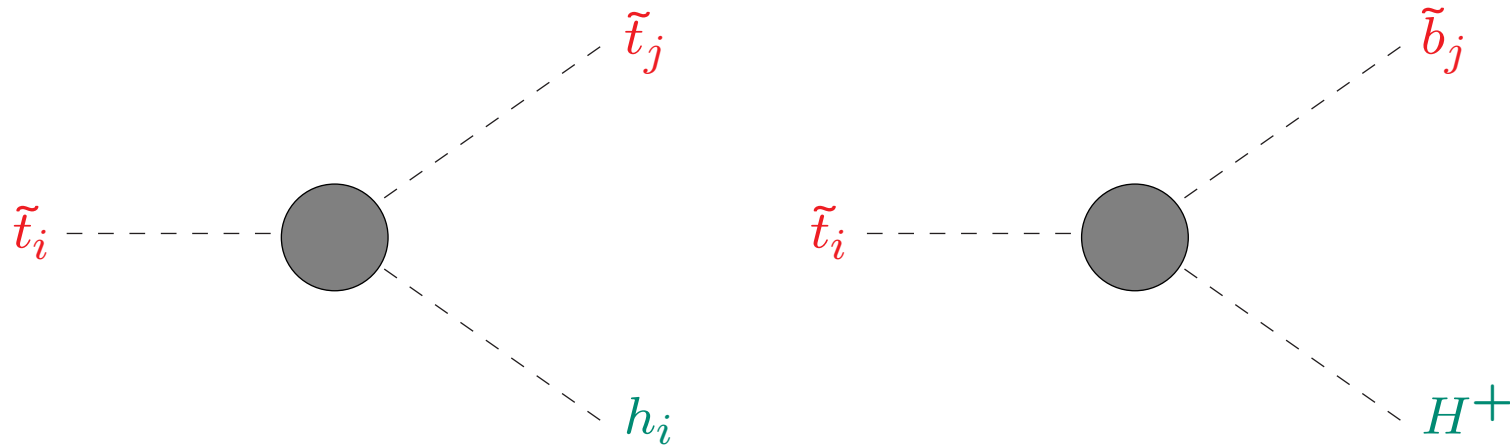
⇒ MSSM predicts mass relations between neutralinos and charginos

## 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
- . . .

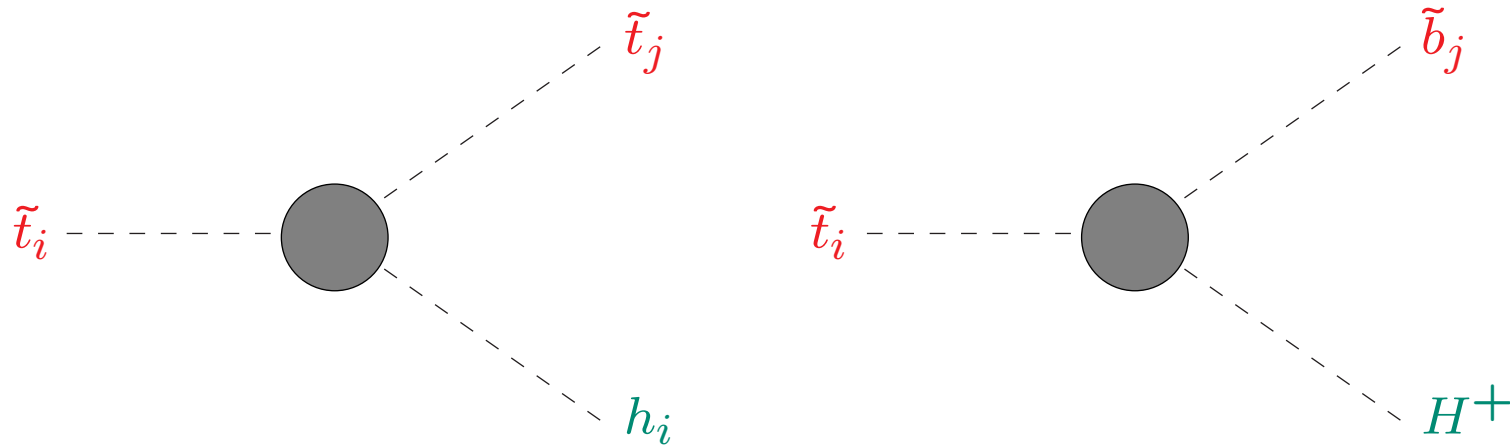
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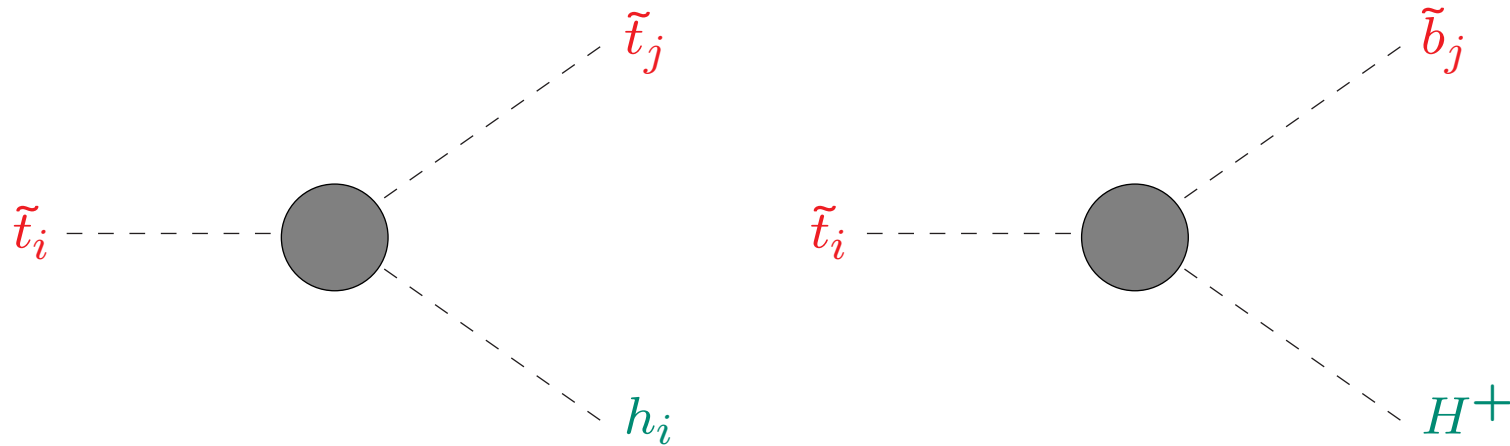


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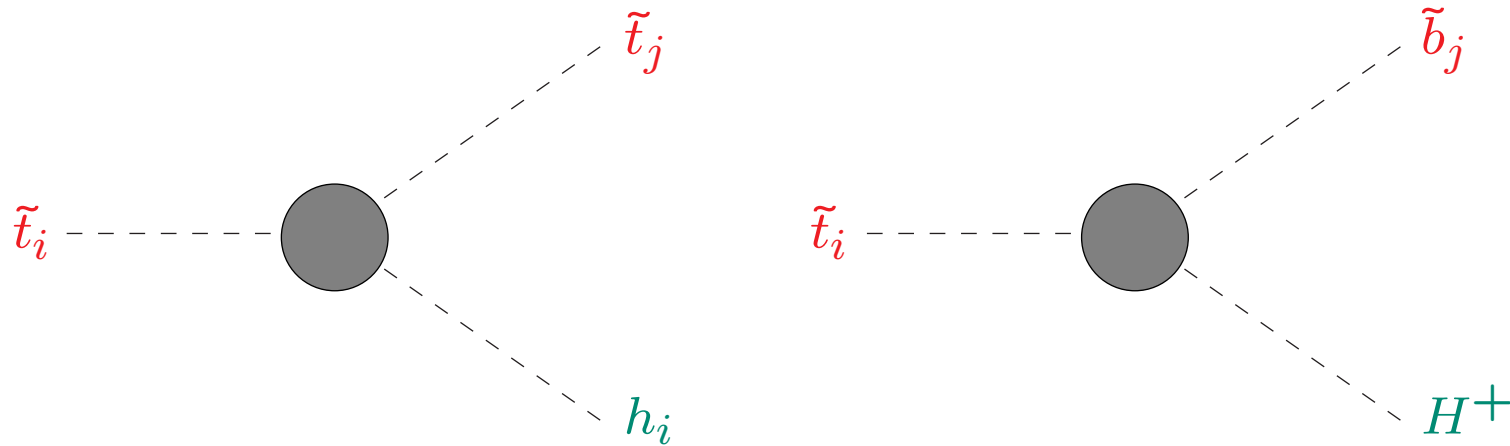
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⇒ with on-shell properties for external particles!

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



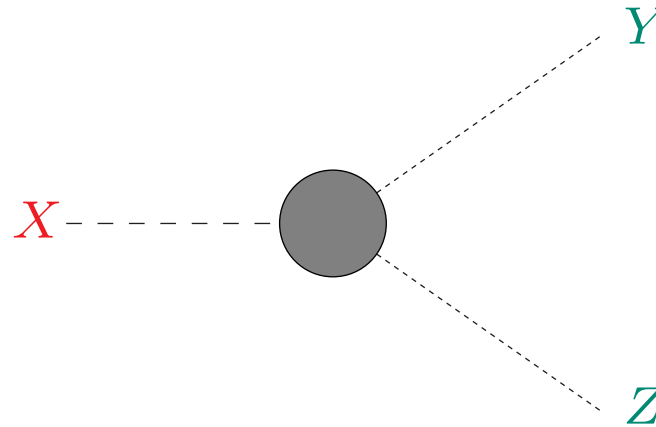
- important decay modes of stops
- $A_t$  and  $A_b$  directly enter the vertex **incl. complex phases!**
- possible source of Higgs bosons at the LHC/ILC
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⇒ higher-order corrections important!

⇒ simultaneous renormalization of stop and sbottom sector required!

⇒ including complex phases!

## The bigger picture: SUSY decays in the cMSSM



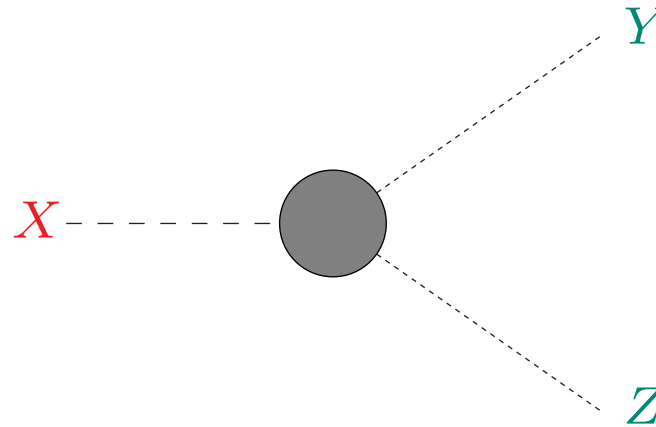
⇒ to get BRs right ⇒ all decays needed

⇒ (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



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

now ready:

- (heavy) stop decays ⇒ relevant for Higgs
- gluino decays
- (non-hadronic) chargino decays ⇒ relevant for Higgs

## 2. Heavy Stop Decays

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

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

$$\Gamma(\tilde{t}_2 \rightarrow t \tilde{\chi}_k^0) \quad (k = 1 \dots 4) ,$$

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

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

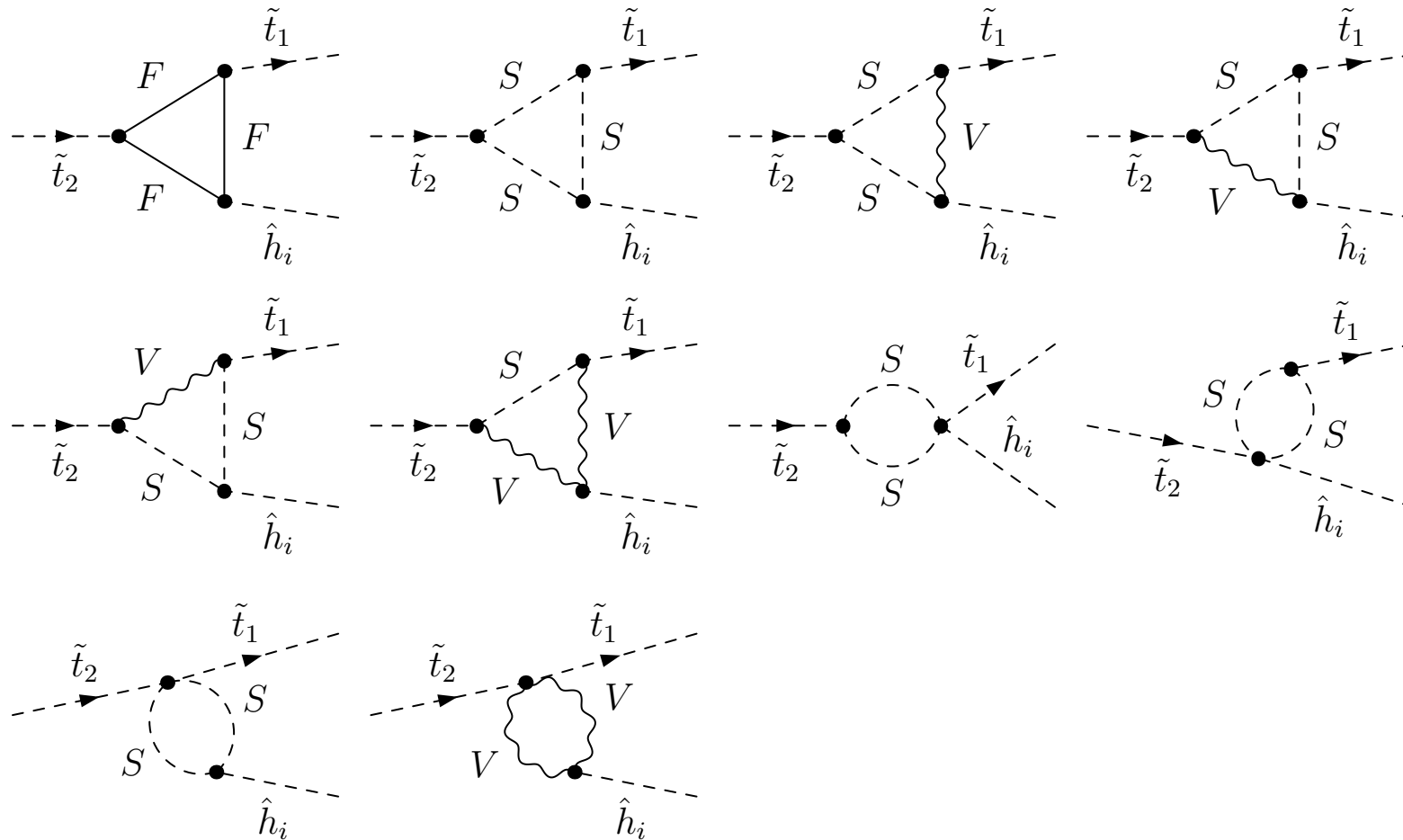
$$\Gamma(\tilde{t}_2 \rightarrow \tilde{b}_i W^+) \quad (i = 1, 2) ,$$

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

## Calculation of partial widths and branching ratios:

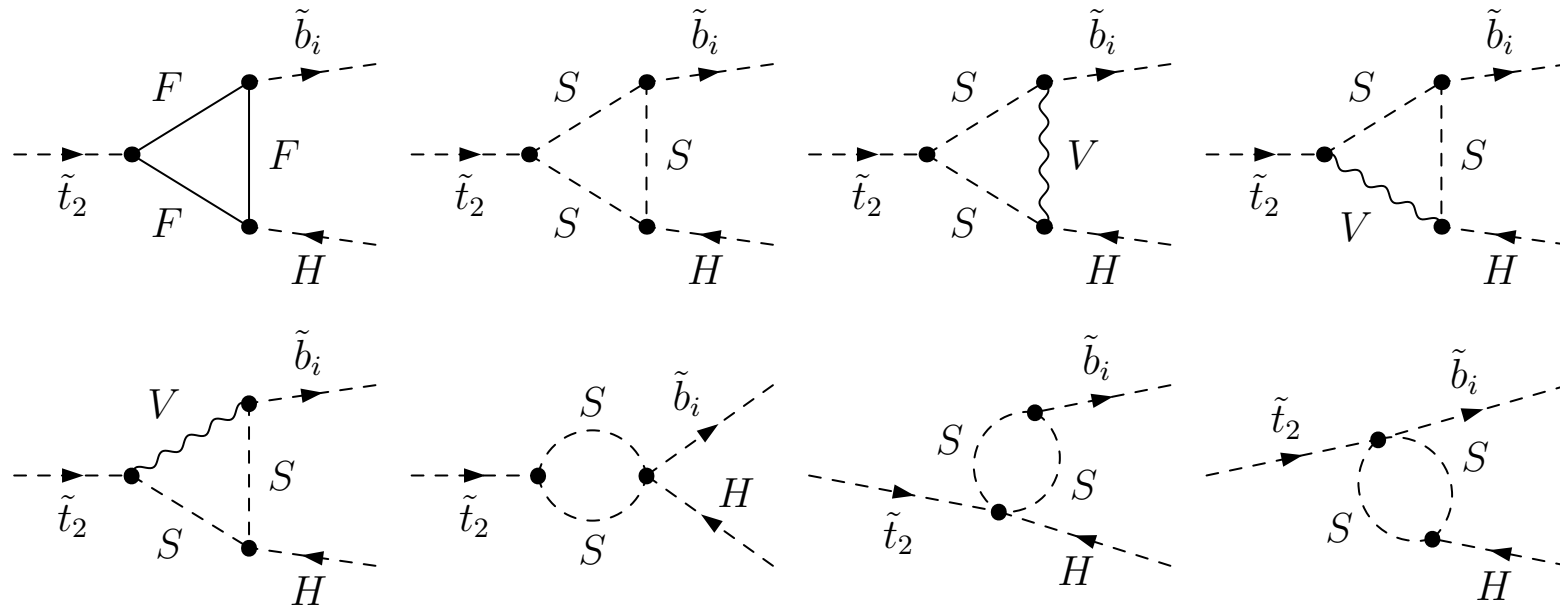
- all diagrams created with **FeynArts** → **TT**
  - model file with all counterterms in the cMSSM
- including all soft/hard QED/QCD diagrams
- further evaluation with **FormCalc**
- Dimensional **RED**uction
- all **UV** and **IR** divergences cancel
- results will be included into **FeynHiggs** ([www.feynhiggs.de](http://www.feynhiggs.de))
- example plots will focus on  $BR(\tilde{t}_2 \rightarrow \tilde{t}_1 h_1)$ ,  $BR(\tilde{t}_2 \rightarrow \tilde{b}_i H^+)$

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



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

## Feynman diagrams for $\tilde{t}_2 \rightarrow \tilde{b}_i H^+$



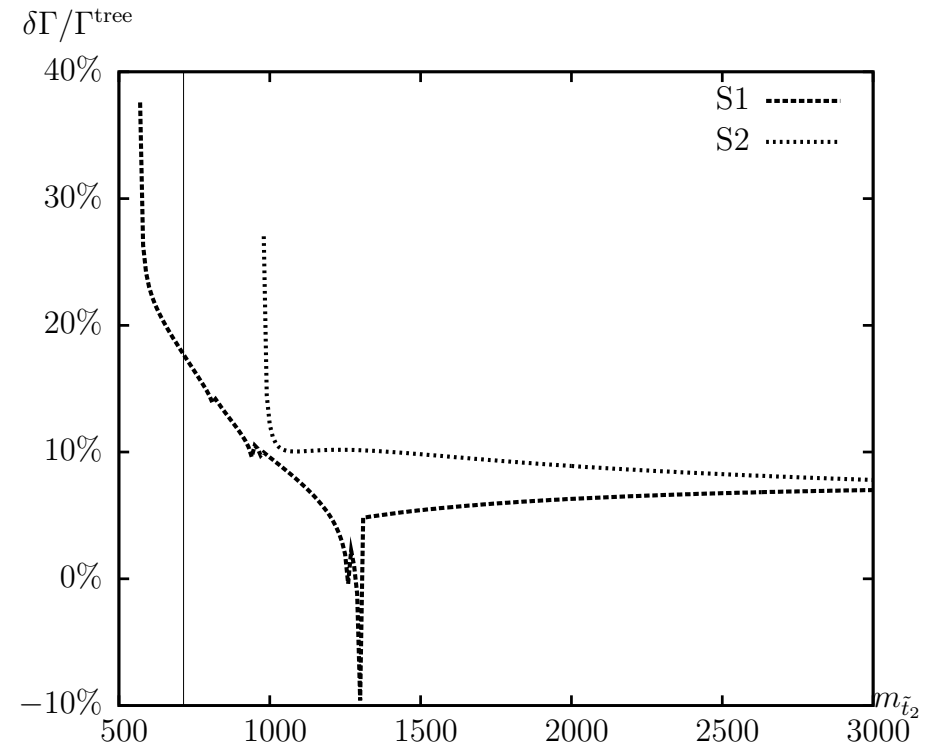
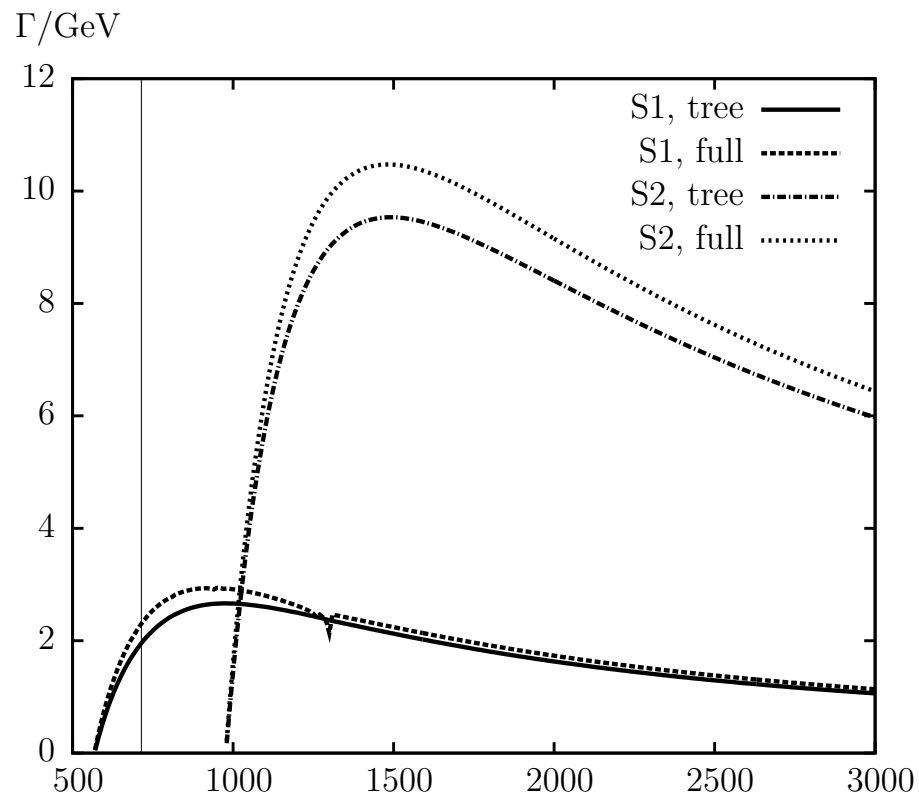
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## Numerical scenarios:

Scen.	$M_{H^\pm}$	$m_{\tilde{t}_2}$	$m_{\tilde{t}_1}$	$m_{\tilde{b}_2}$	$\mu$	$A_t$	$A_b$	$M_1$	$M_2$	$M_3$
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

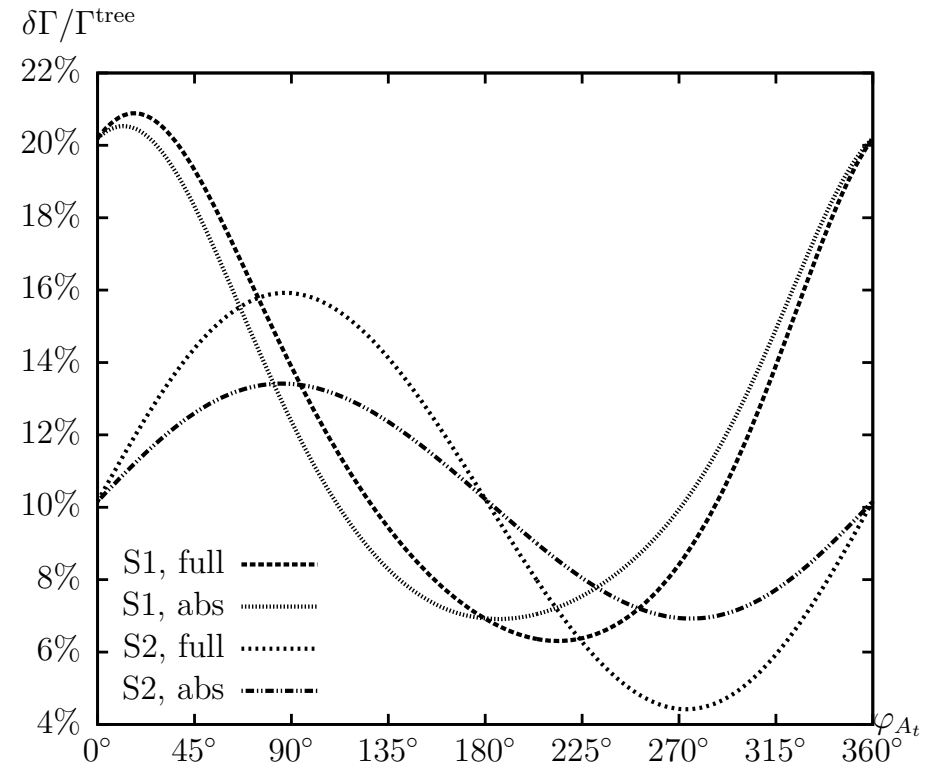
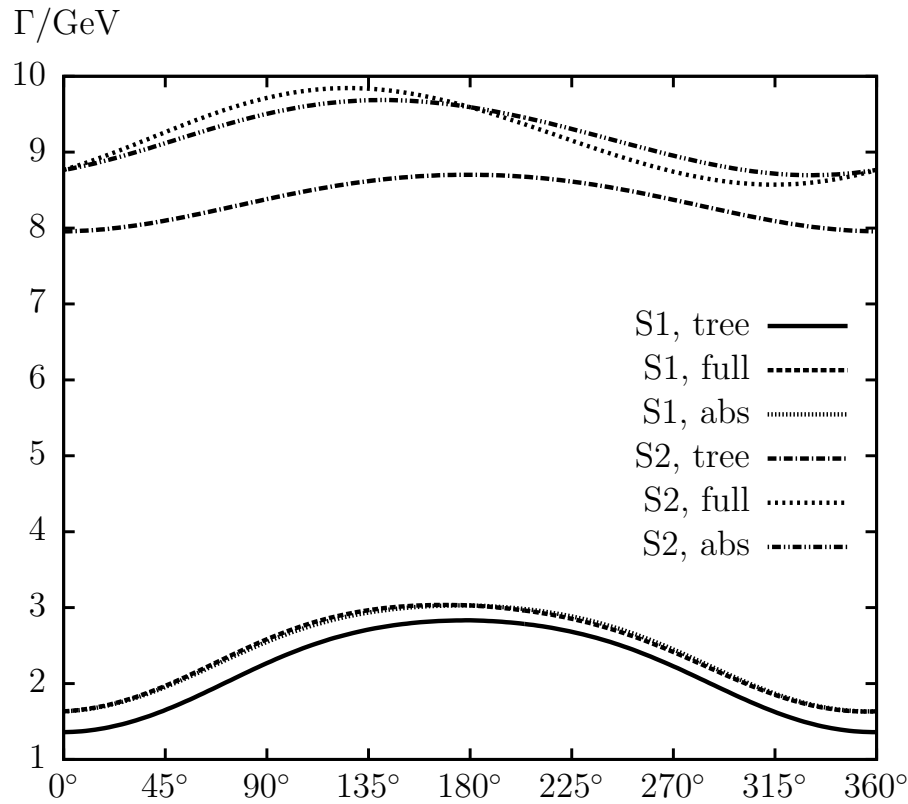
Scen.	$\tan \beta$	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	$m_{\tilde{b}_1}$	$m_{\tilde{b}_2}$
S1	2	260.000	650.000	305.436	455.000
	20	260.000	650.000	333.572	455.000
	50	260.000	650.000	329.755	455.000
S2	2	720.000	1200.000	769.801	960.000
	20	720.000	1200.000	783.300	960.000
	50	720.000	1200.000	783.094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

Scenarios chosen such that *all* decay channels are open



⇒ one-loop corrections under control and non-negligible

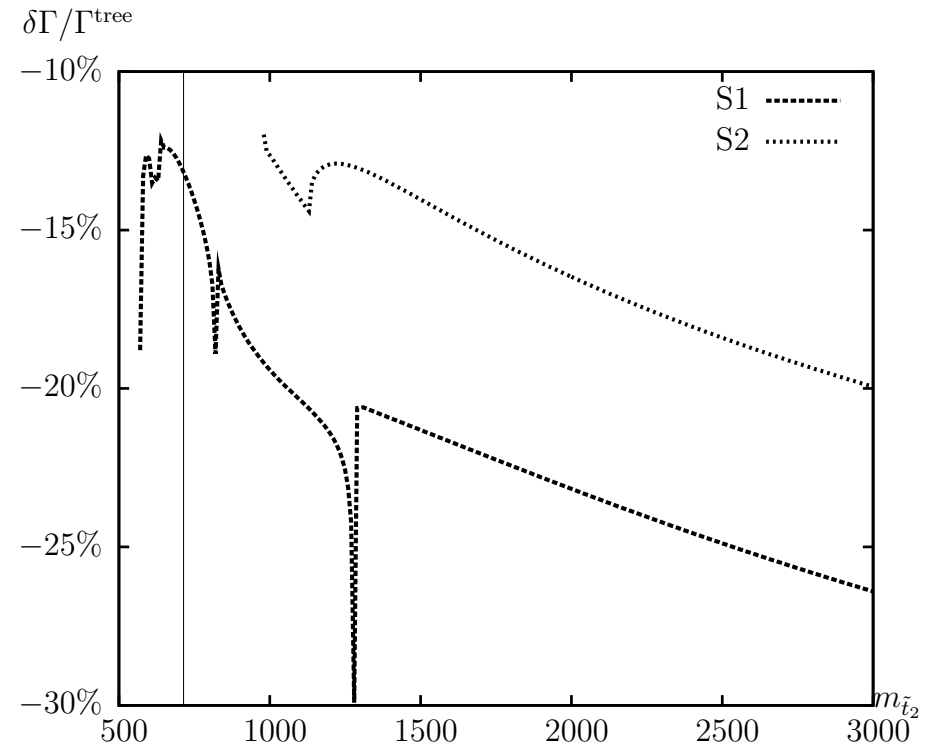
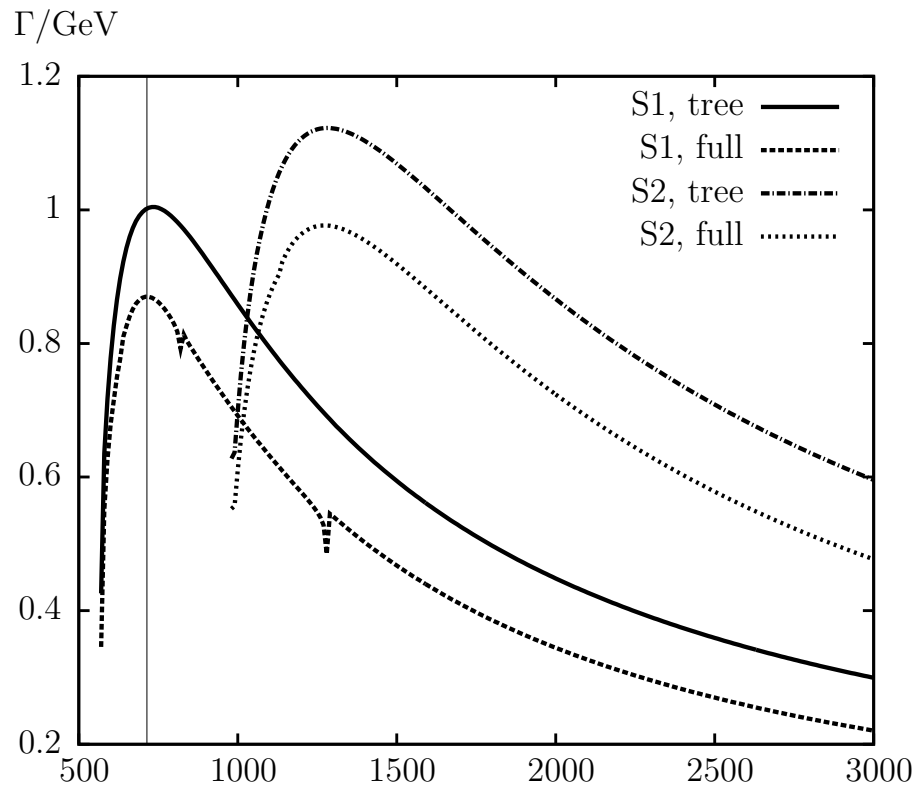
⇒ size of BR highly scenario dependent



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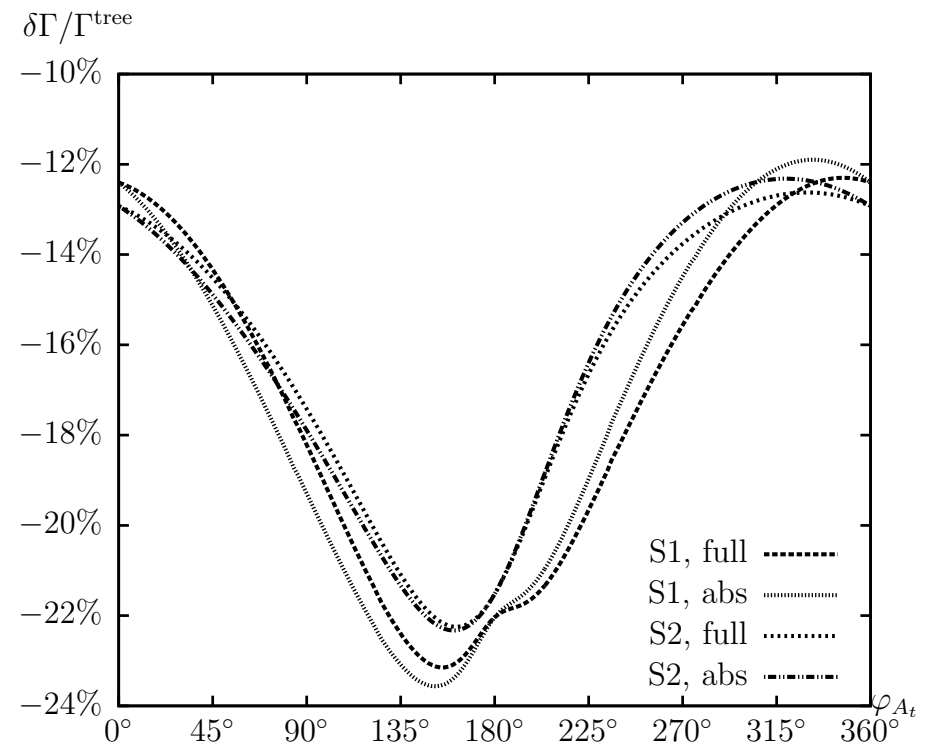
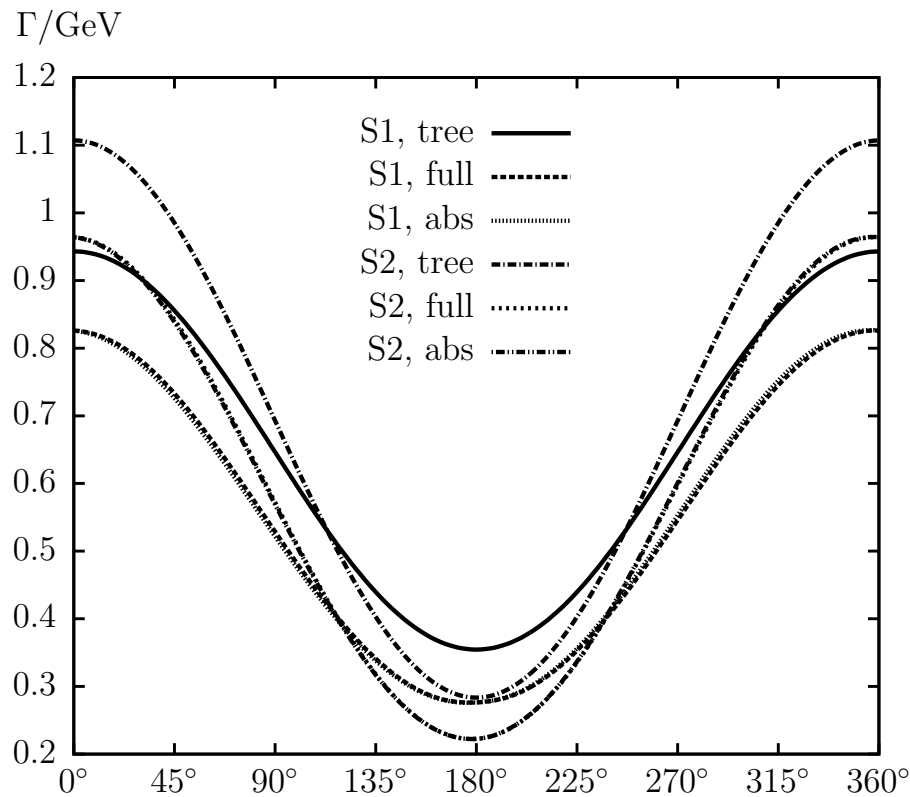
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### 3. Chargino decays

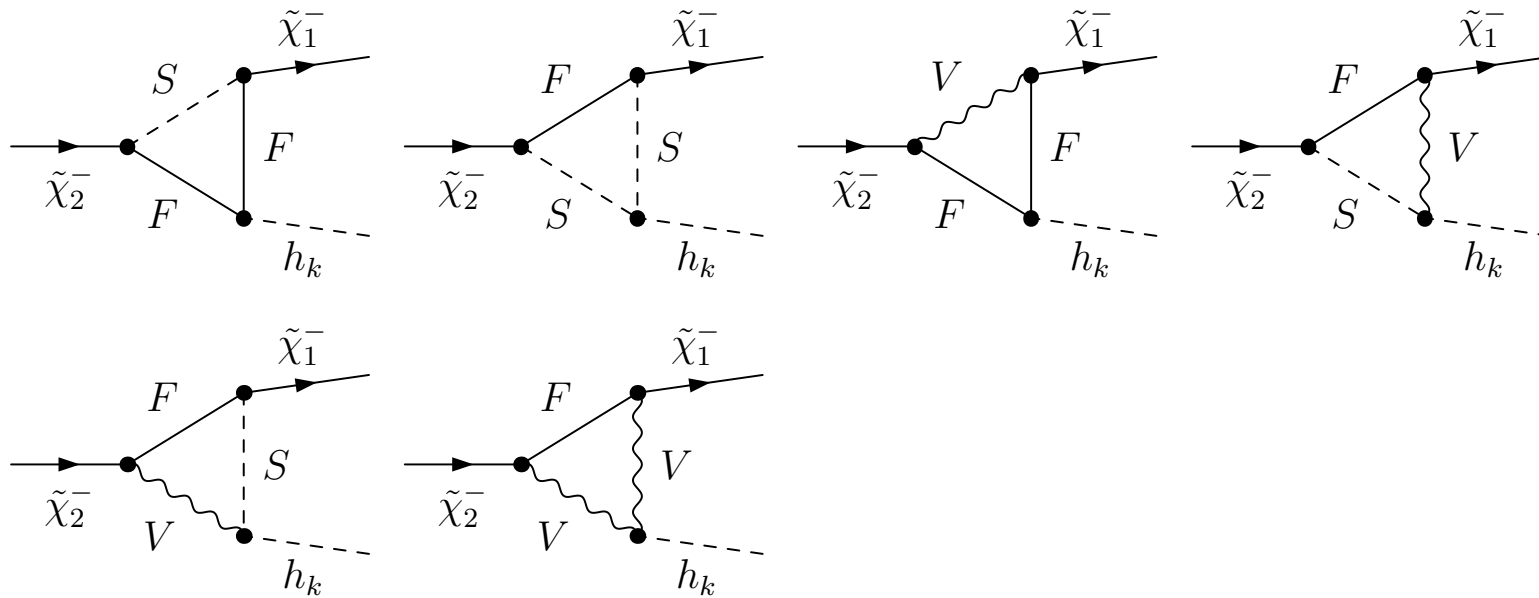
$$\begin{aligned}
 & \Gamma(\tilde{\chi}_2^\pm \rightarrow \tilde{\chi}_1^\pm h_k) && (k = 1, 2, 3) , \\
 & \Gamma(\tilde{\chi}_2^\pm \rightarrow \tilde{\chi}_1^\pm Z) , \\
 & \Gamma(\tilde{\chi}_i^\pm \rightarrow \tilde{\chi}_j^0 H^\pm) && (i = 1, 2, j = 1, 2, 3, 4) , \\
 & \Gamma(\tilde{\chi}_i^\pm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

No hadronic decays yet . . .

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

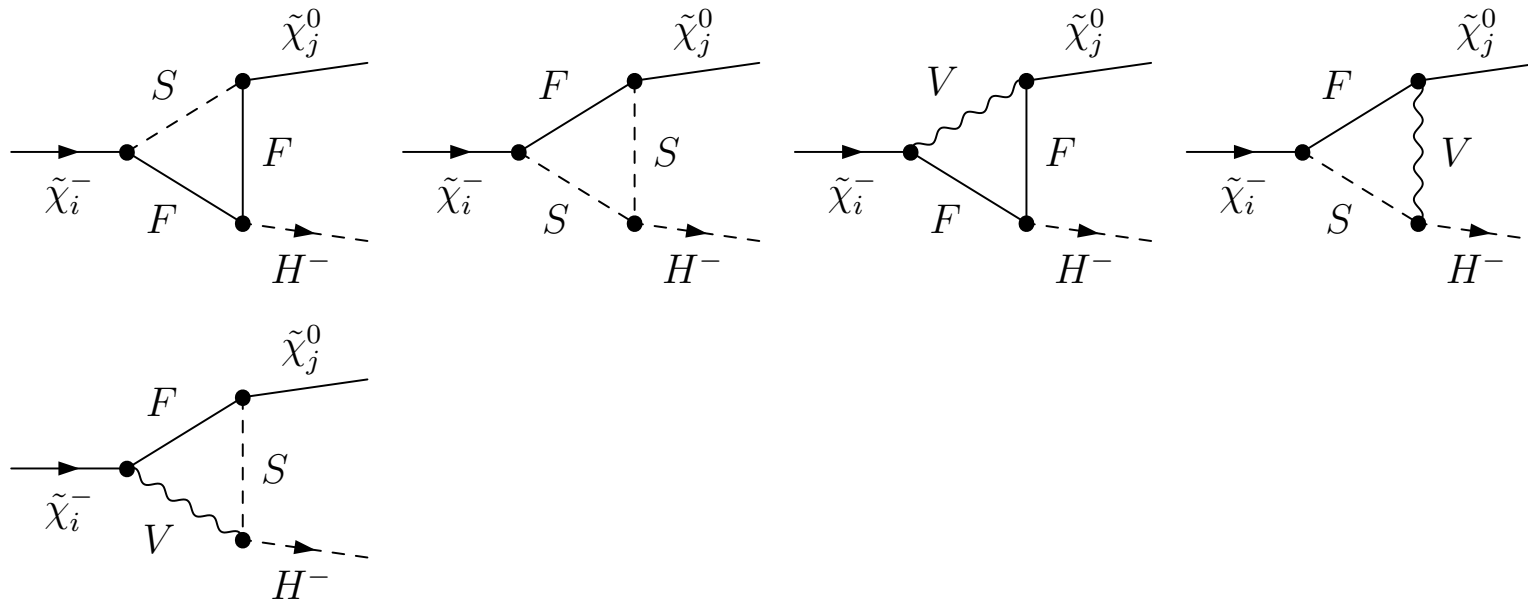
$$\begin{aligned}
 S_{>} & : \mu > M_2 && (\tilde{\chi}_2^\pm \text{ more higgsino-like}) \\
 S_{<} & : \mu < M_2 && (\tilde{\chi}_2^\pm \text{ more gaugino-like})
 \end{aligned}$$

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

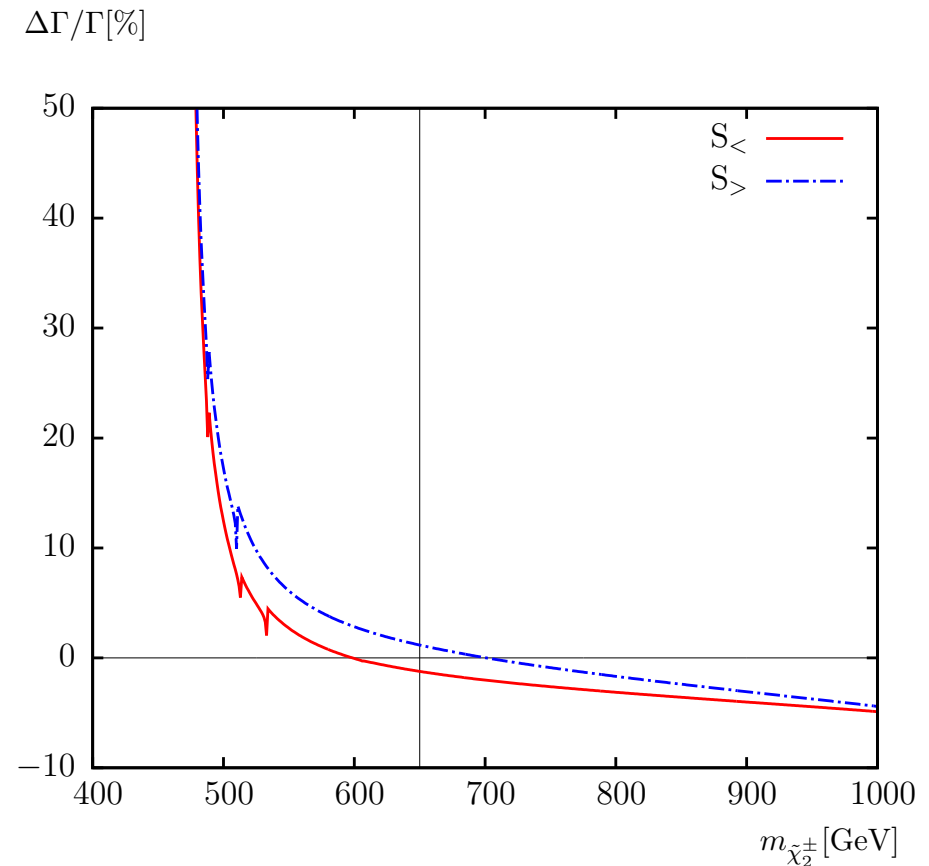
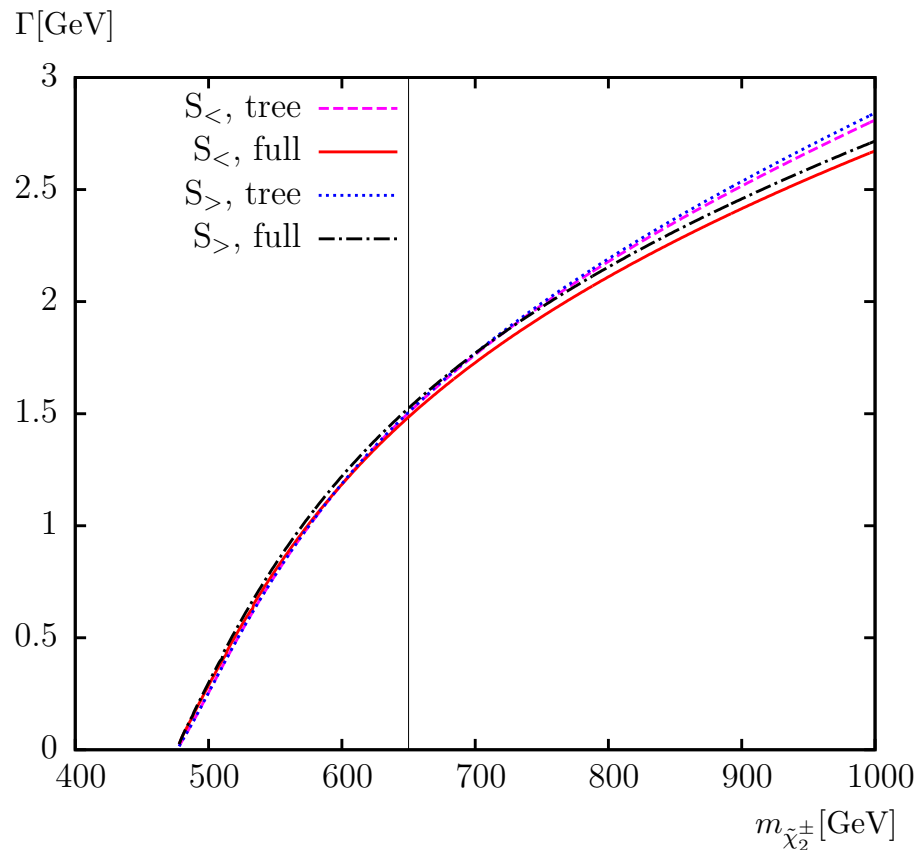


- including  $Z$ - $A$  or  $G$ - $A$  transition contribution on the external Higgs boson leg
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# Feynman diagrams for $\tilde{\chi}_i^- \rightarrow \tilde{\chi}_j^0 H^-$

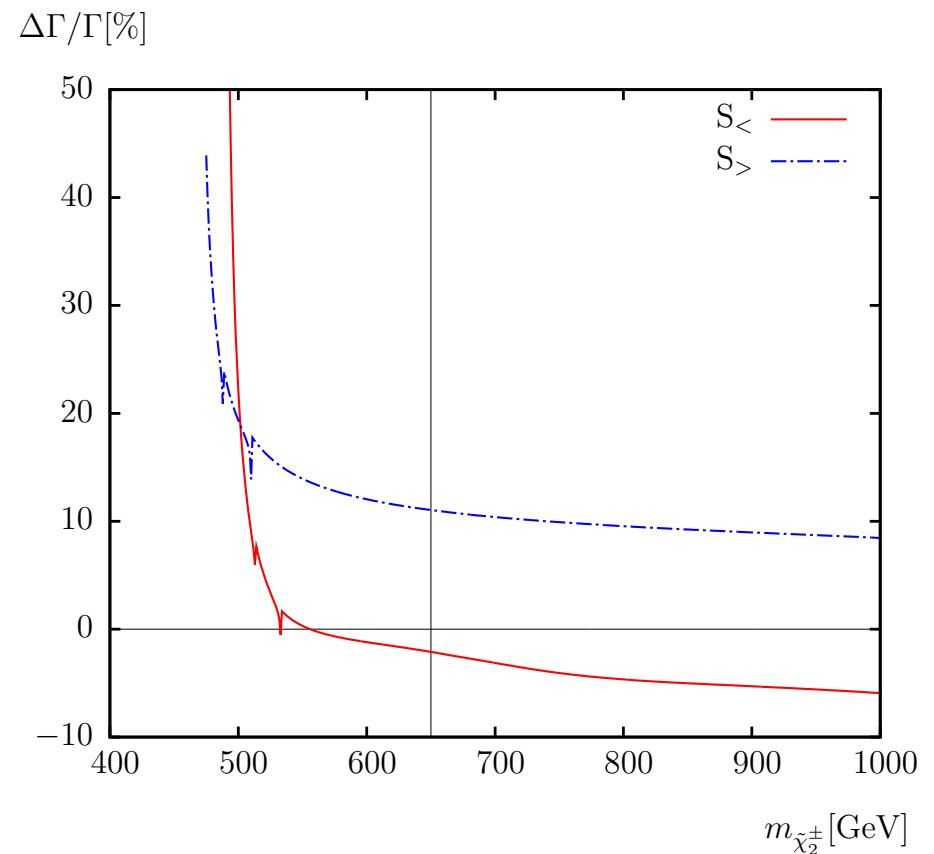
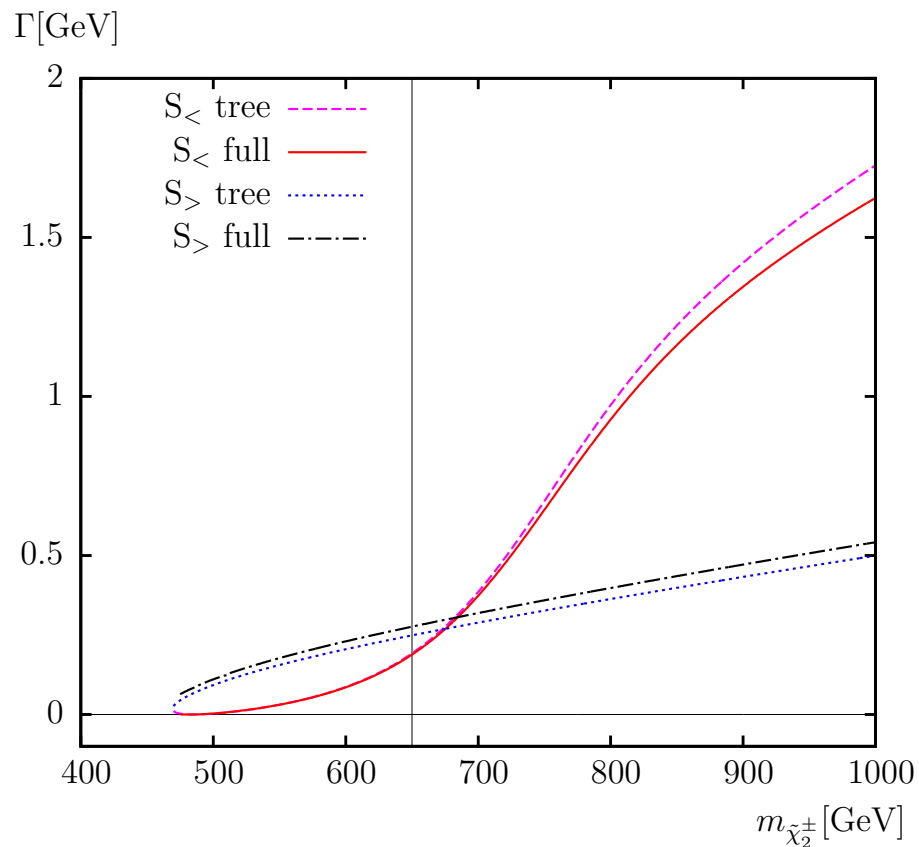


- including  $W^+-H^+$  or  $G^+-H^+$  transition contribution on the external Higgs boson leg
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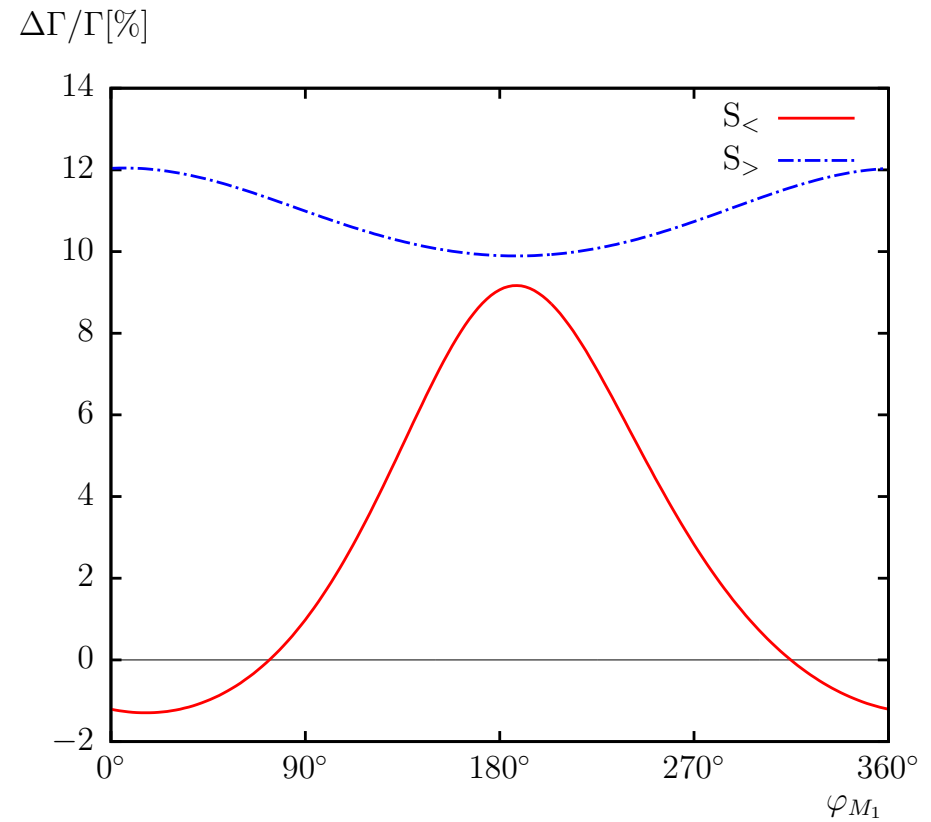
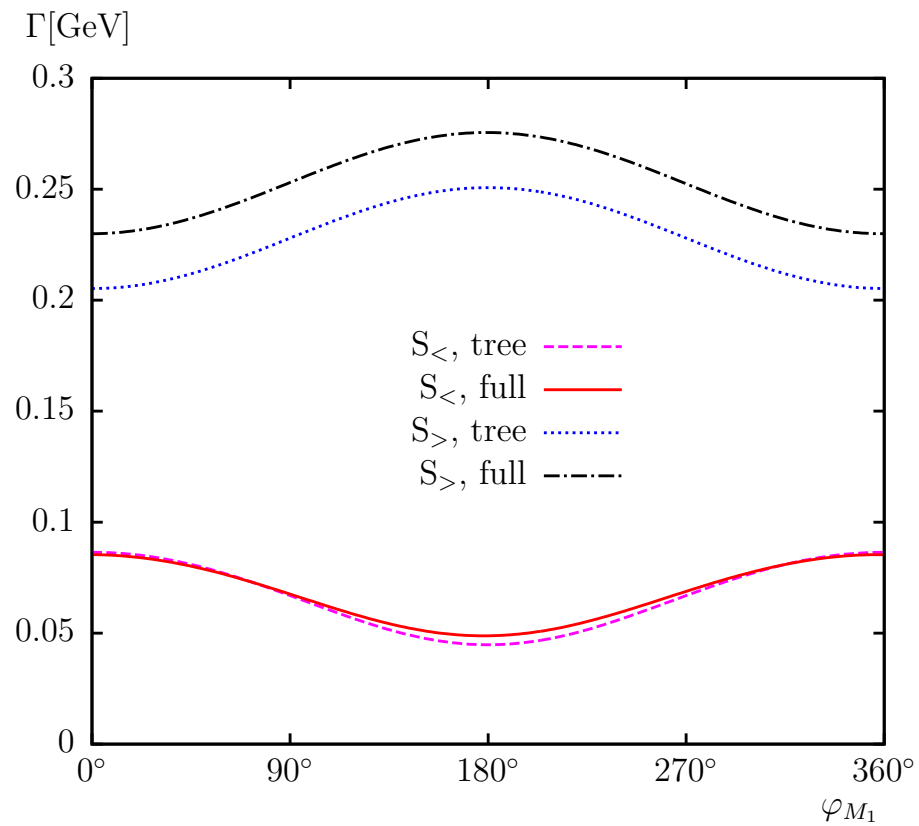
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## 4. Conclusinos

- Needed: reliable prediction for SUSY cascades at the LHC  
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 arbitrary parameters
  - renormalization of the full cMSSM!
- Heavy Stop decays:  
 $\tilde{t}_2 \rightarrow \tilde{t}_1 h_1: \sim 20\%$ ,     $\tilde{t}_2 \rightarrow \tilde{b}_1 H^+: \sim \pm 20\%$
- Chargino decays:  
 $\tilde{\chi}_2^- \rightarrow \tilde{\chi}_1^- h_1: \sim 10\%$ ,     $\tilde{\chi}_2^- \rightarrow \tilde{\chi}_1^0 H^-: \sim 10\%$
- Full corrections must be taken into account in any LC analysis!