SUSY Decays in the Complex MSSM:

A Full One-Loop Analysis

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. Gluino decays
4. Chargino decays
5. Conclusions

1. Introduction & Renormalization of the cMSSM

Production of SUSY particles at the LHC:

$\Rightarrow$ cascade decays:

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

Production of uncolored particles via cascade decays often dominates over direct production

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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: $\tilde{\chi}_1^0$

$\Rightarrow$ important source for information on Higgs, LSP

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

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:

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

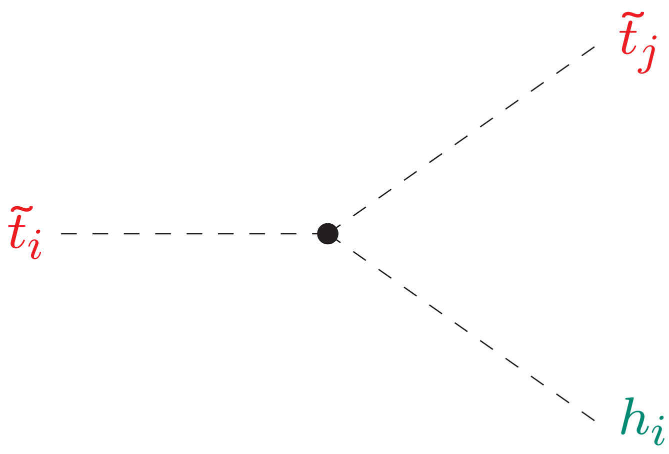
$\Rightarrow$ neutralinos: mass eigenstates

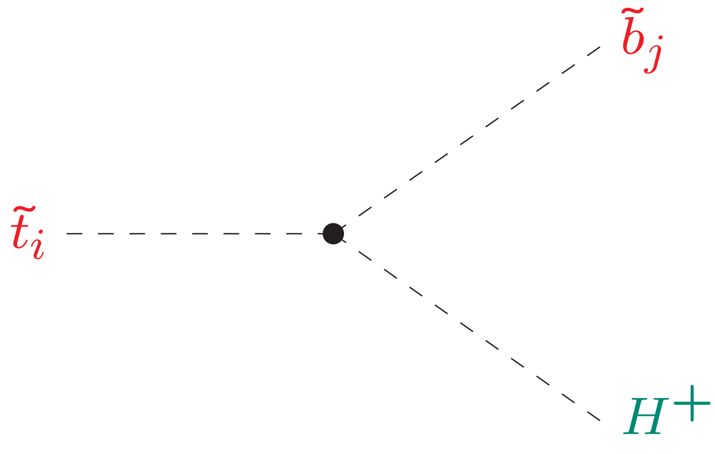
mass matrix given in terms of M_1, M_2, μ, $\tan\beta$

$\Rightarrow$ only one new parameter

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

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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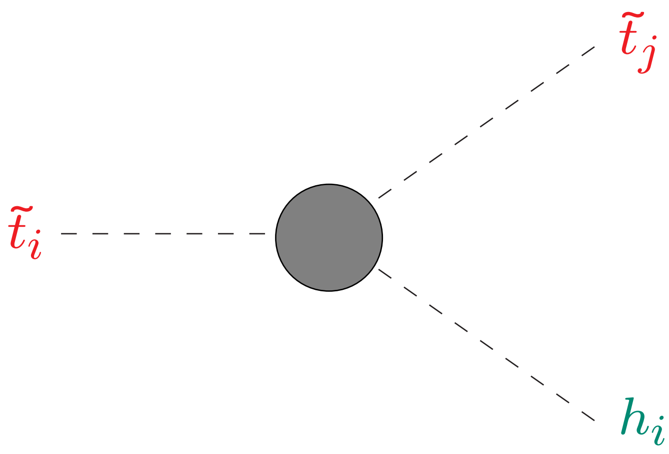

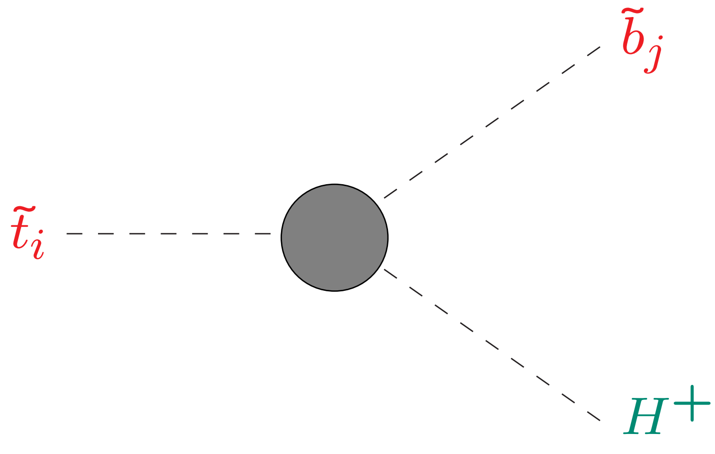

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⇒ higher-order corrections important!

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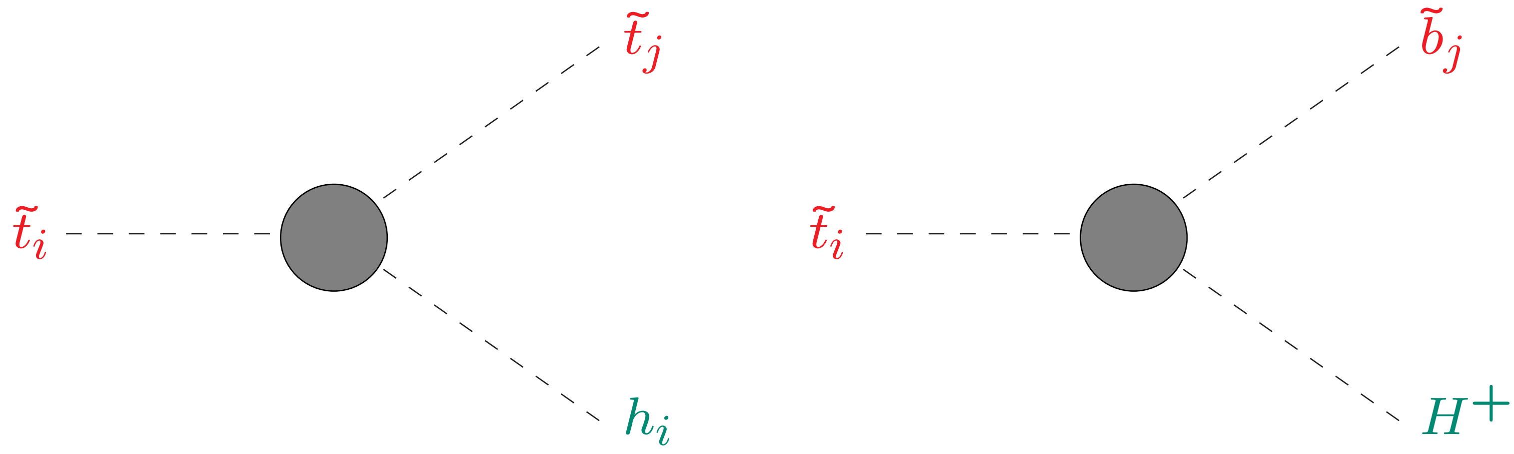

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⇒ simultaneous renormalization of stop and sbottom sector required!

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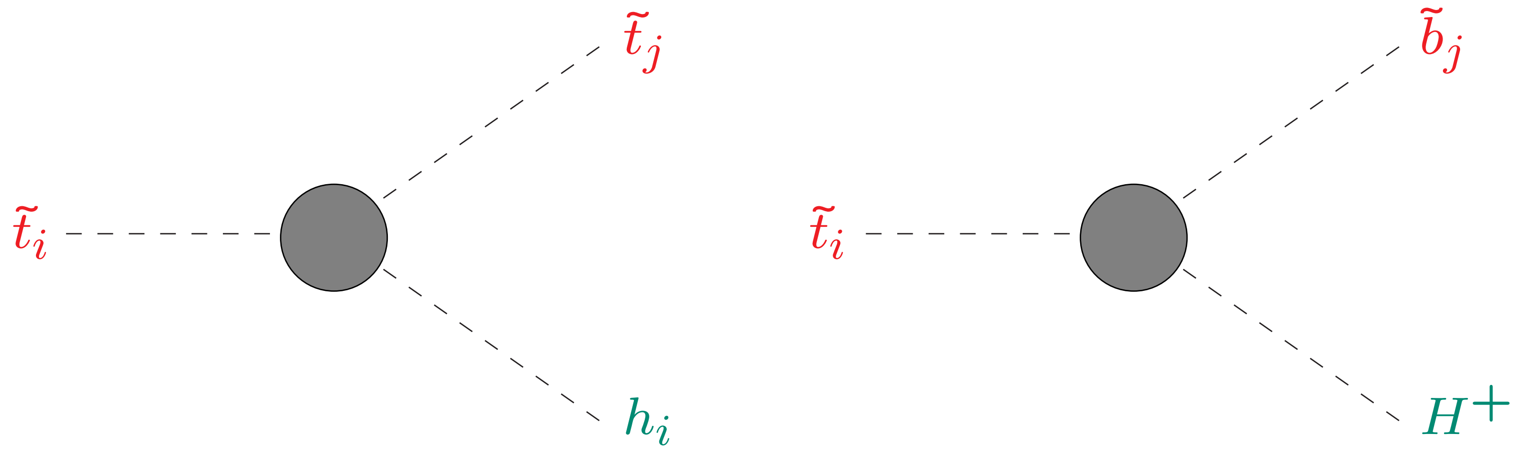

– important decay modes of stops

– A_t and A_b directly enter the vertex

– possible source of Higgs bosons at the LHC/ILC

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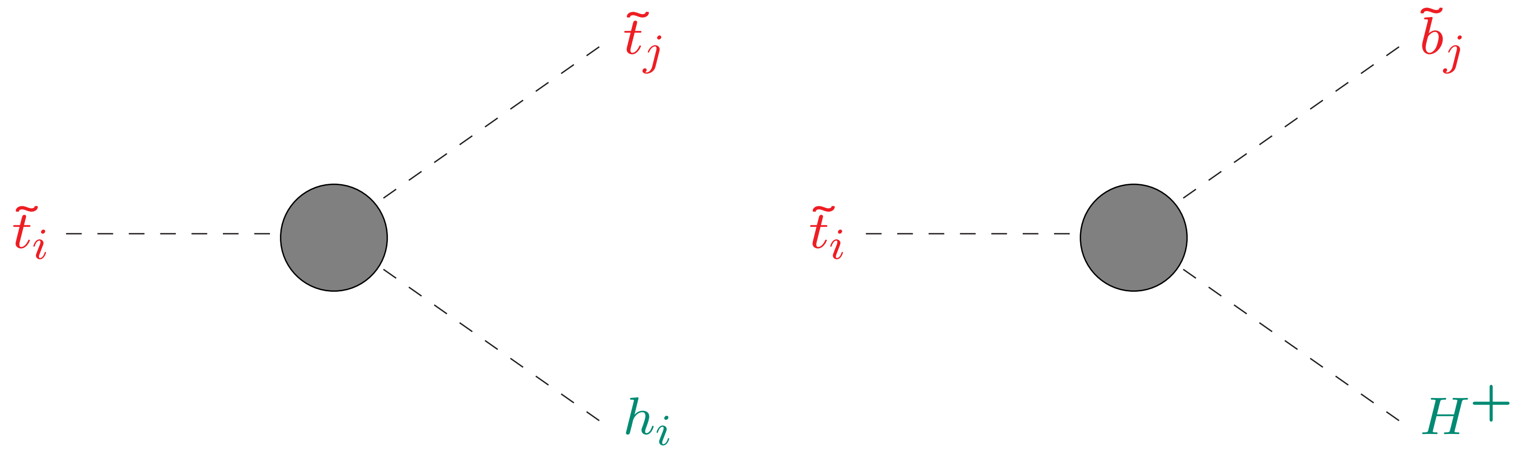
⇒ higher-order corrections important!

⇒ 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

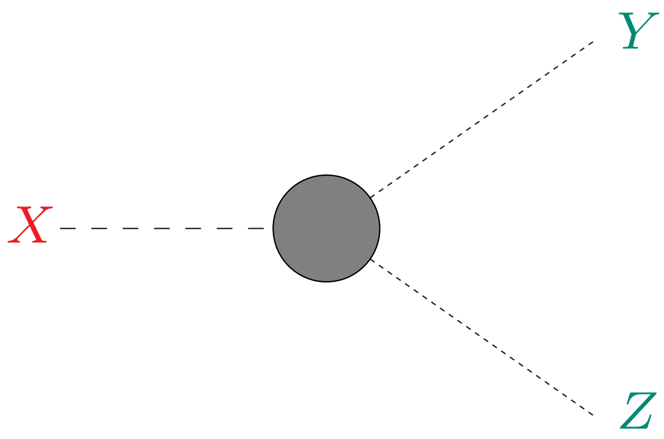
– . . .

⇒ higher-order corrections important!

⇒ simultaneous renormalization of stop and sbottom sector required!

⇒ including complex phases!

The bigger picture: 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

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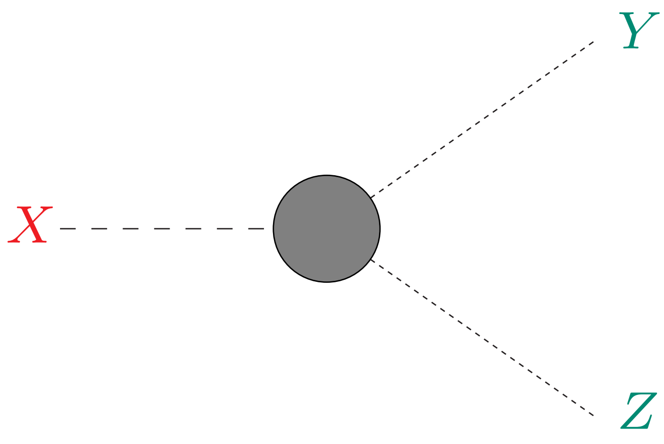

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now ready:

– (heavy) stop decays
– gluino decays
– (non-hadronic) chargino decays

2. 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 $\to$ TT

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

– including all soft/hard QED/QCD diagrams

– further evaluation with FormCalc

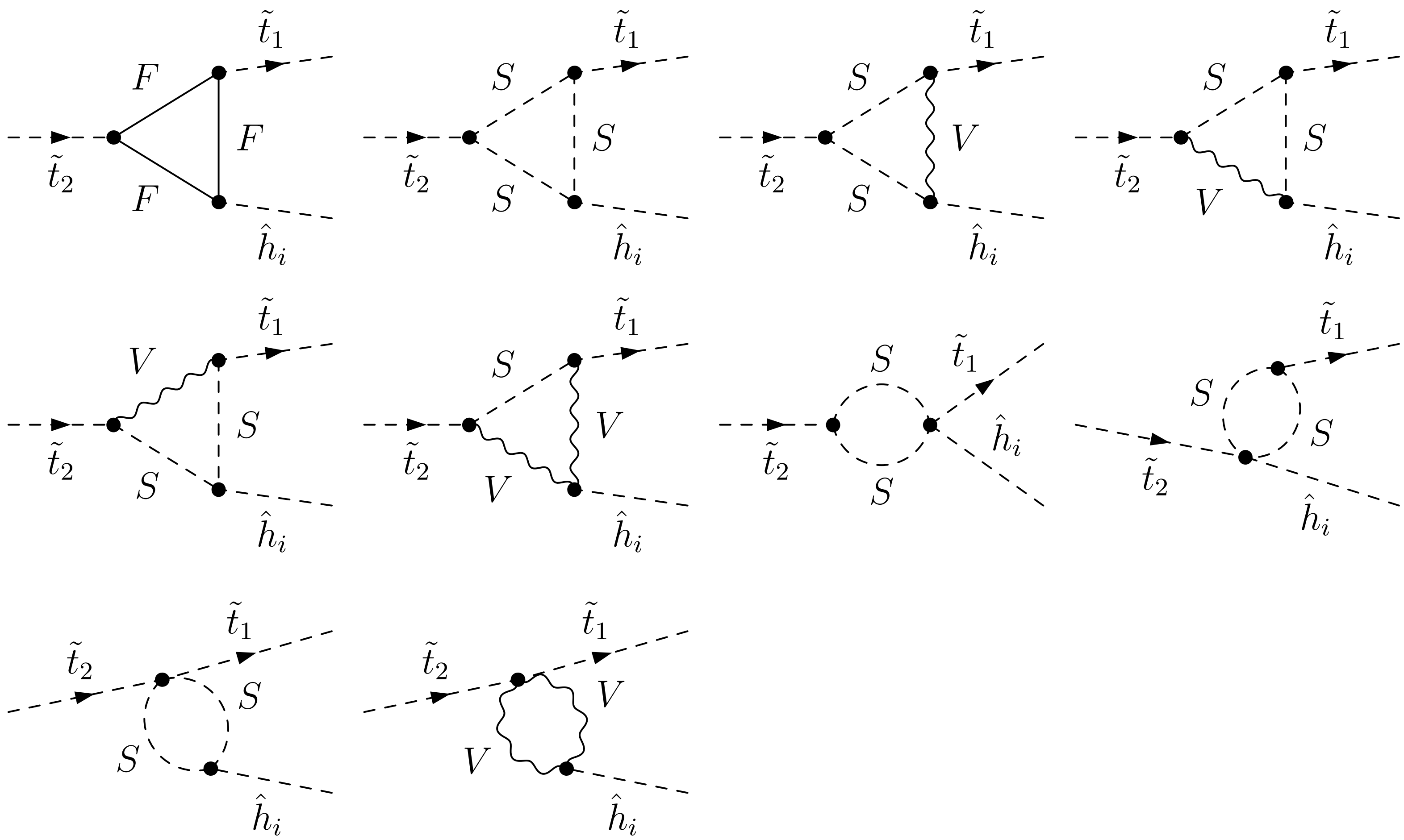
– Dimensional REDuction

– all UV and IR divergences cancel

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

$\to$ example plots will focus on BR($\tilde{t}_2 \to \tilde{t}_1 h_1$), BR($\tilde{t}_2 \to t\tilde{\chi}^0_1$)

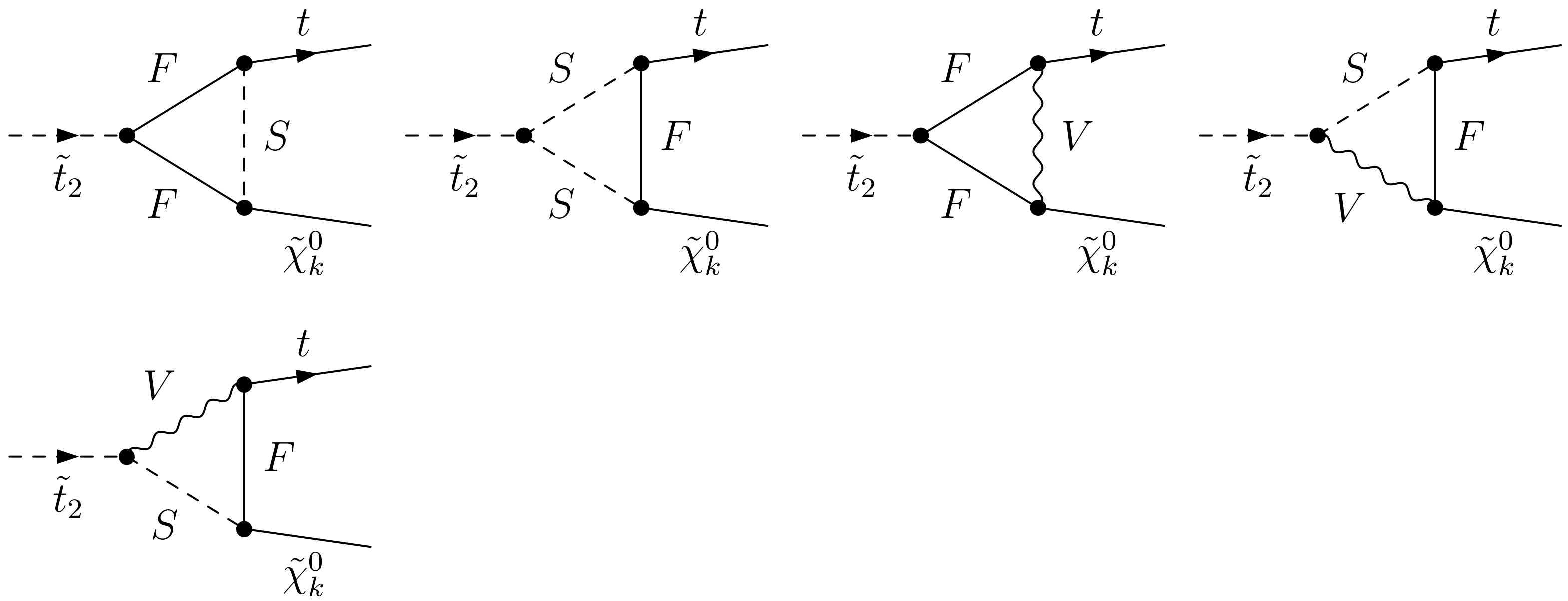
Feynman diagrams for $\tilde{t}_2 \to \tilde{t}_1 h_i$



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

– including all soft/hard QED/QCD diagrams

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



– including all soft/hard QED/QCD diagrams

Numerical scenarios:

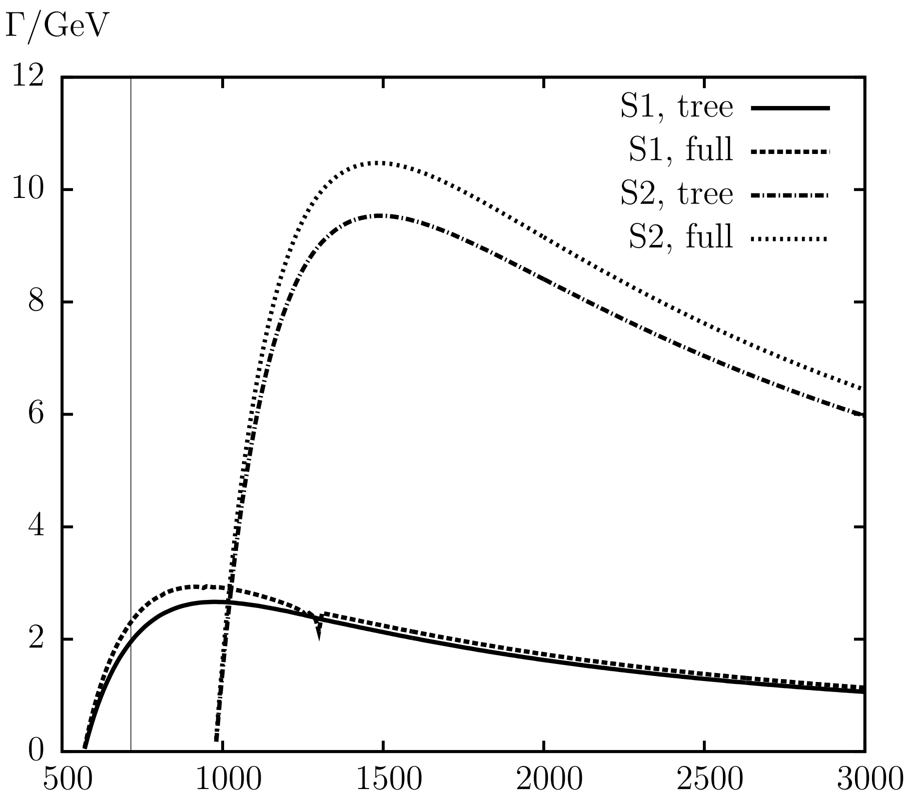
Scen.	$M_{H^\pm}$	$m_{\tilde{t}_2}$	$m_{\tilde{t}_1}$	$m_{\tilde{b}_2}$	μ	A_t	A_b	M_1	M_2	M_3
S1	150	650	$0.4\, m_{\tilde{t}_2}$	$0.7\, m_{\tilde{t}_2}$	200	900	400	200	300	800
S2	180	1200	$0.6\, m_{\tilde{t}_2}$	$0.8\, m_{\tilde{t}_2}$	300	1800	1600	150	200	400

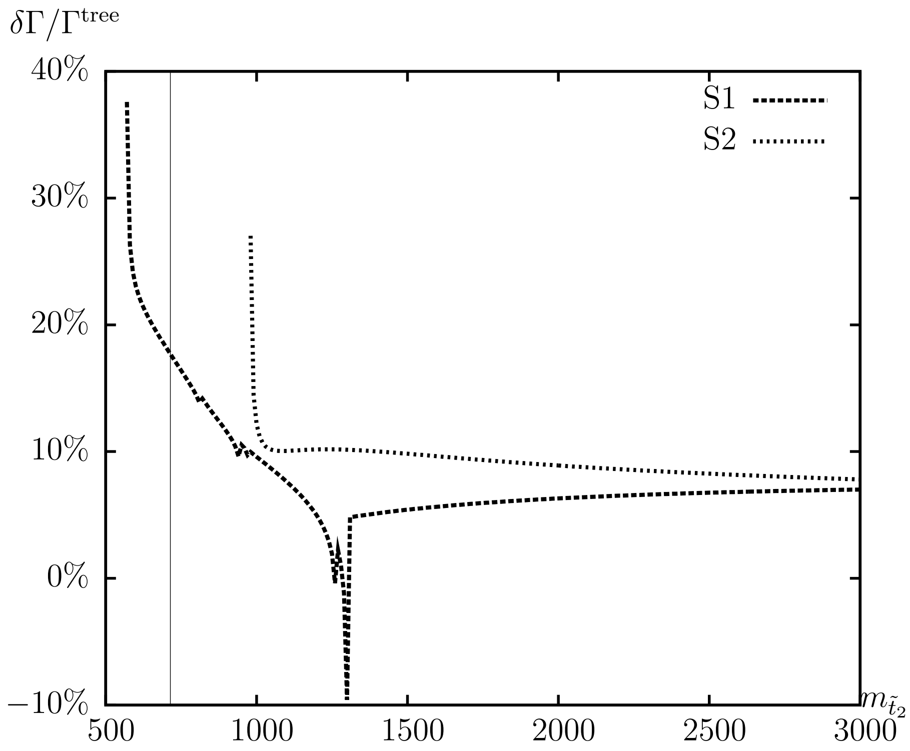
Scen.	$\tan\beta$	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	$m_{\tilde{b}_1}$	$m_{\tilde{b}_2}$
S1	2	260.000	650.000	305.436	455.000
	20	260.000	650.000	333.572	455.000
	50	260.000	650.000	329.755	455.000
S2	2	720.000	1200.000	769.801	960.000
	20	720.000	1200.000	783.300	960.000
	50	720.000	1200.000	783.094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

Scenarios chosen such that *all* decay channels are open

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

[PRELIMINARY]





⇒ 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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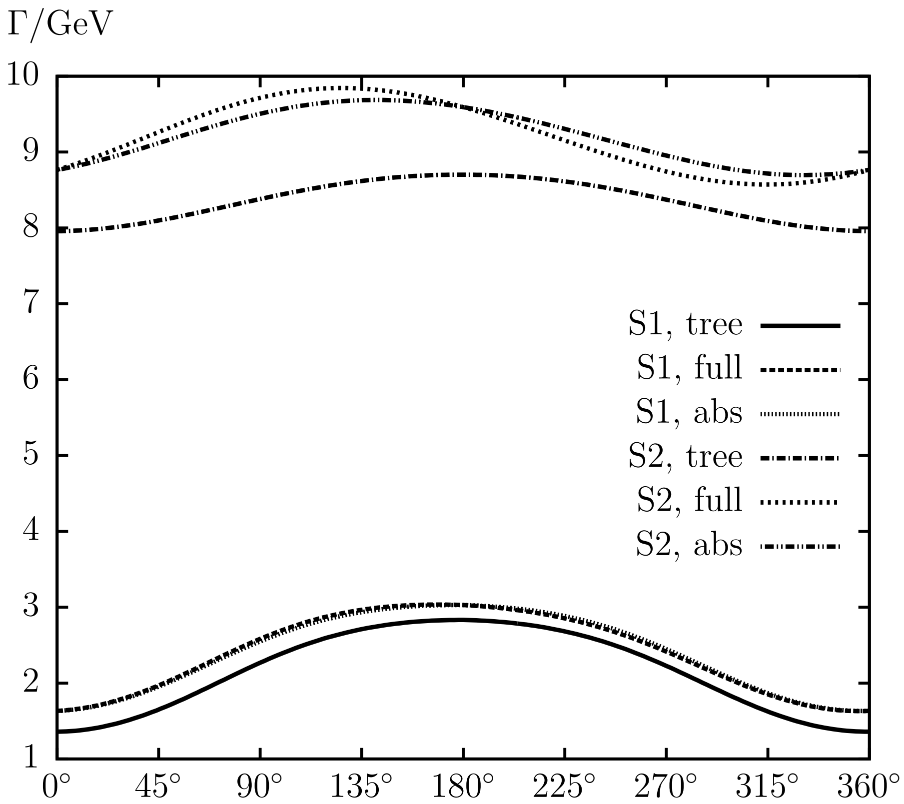

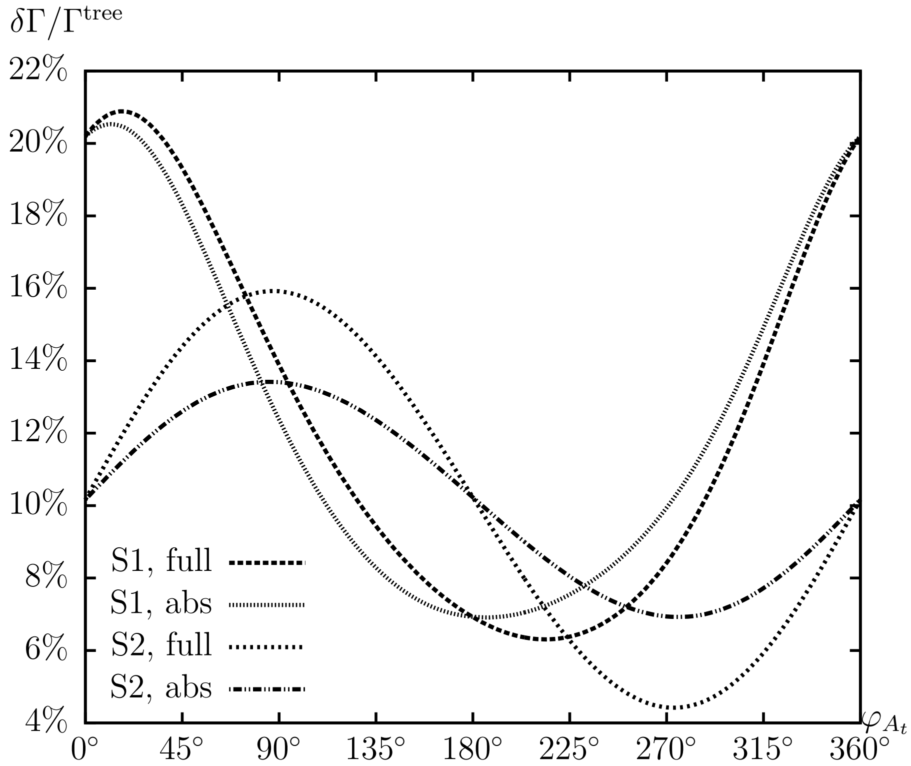

$\Rightarrow$ one-loop corrections under control and non-negligible

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

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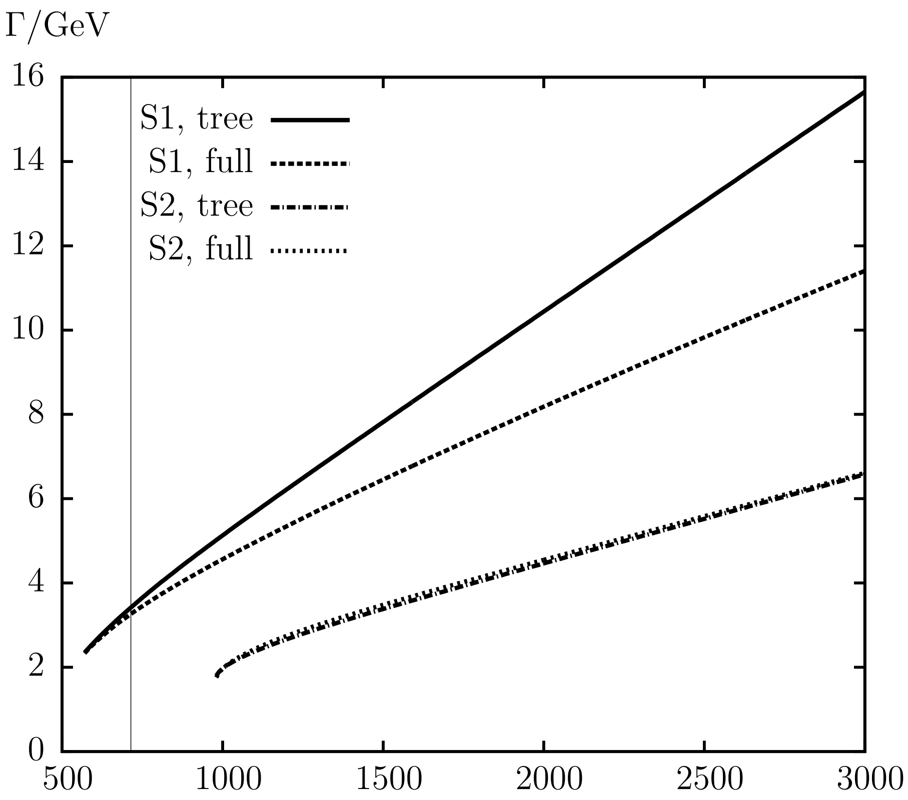

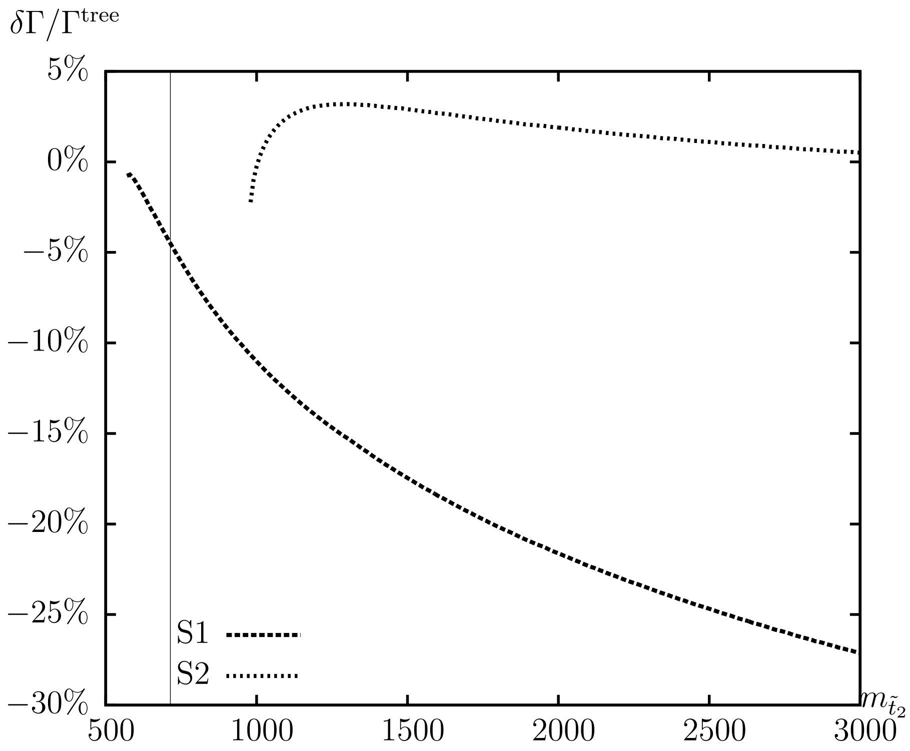

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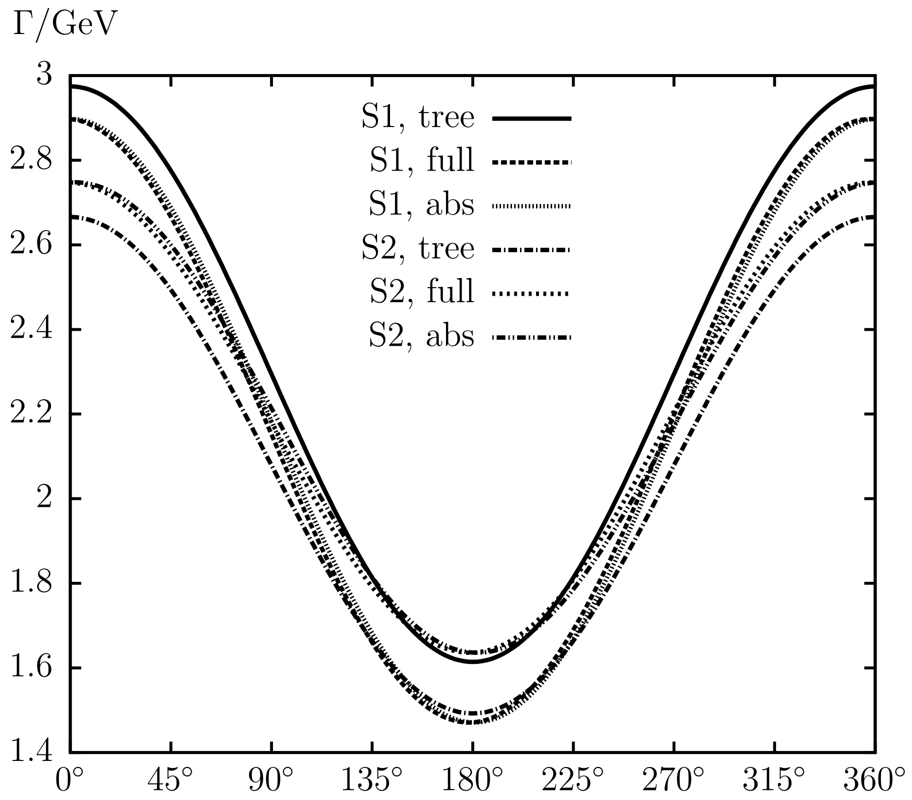
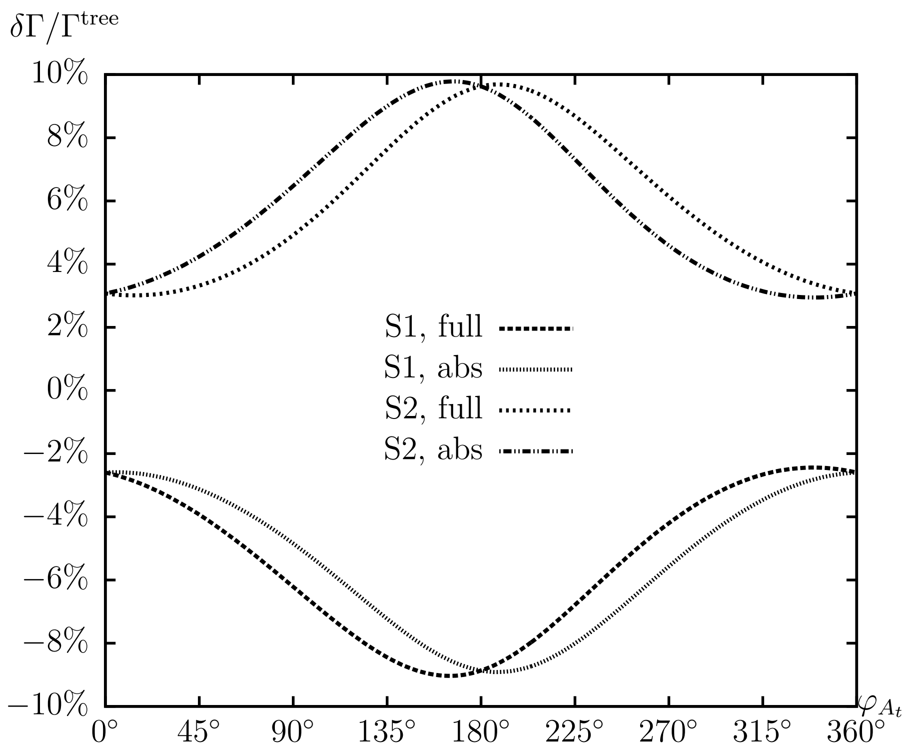




$\Rightarrow$ one-loop corrections under control and non-negligible

$\Rightarrow$ size of BR highly scenario dependent

3. Gluino decays

$$\Gamma(\tilde{g} \to \bar{\tilde{q}}_i \, q) \qquad (i = 1, 2, \; q = t, b, c, s, u, d) \; ,$$

$$\Gamma(\tilde{g} \to \tilde{q}_i \, \bar{q}) \qquad (i = 1, 2, \; q = t, b, c, s, u, d) \; ,$$

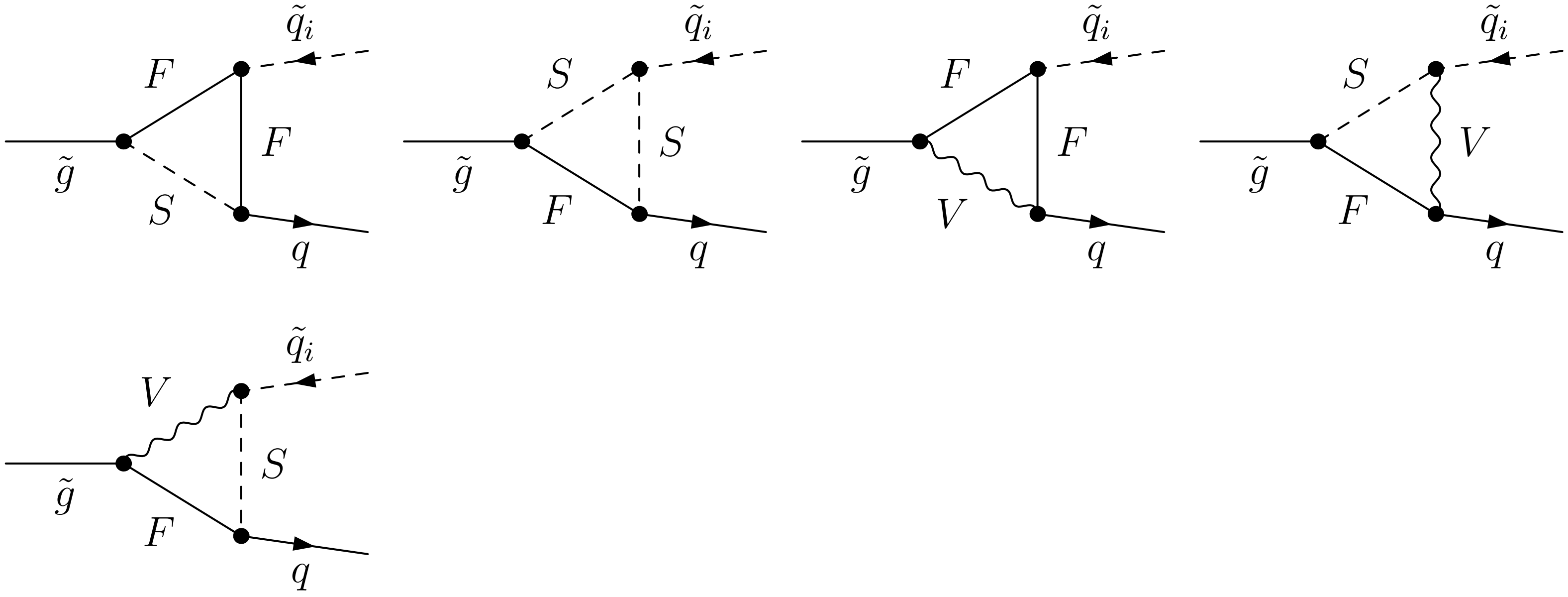
$$\Gamma(\tilde{g} \to \tilde{\chi}^0_k \, g) \qquad (k = 1, 2, 3, 4) \; .$$

No tree-level three-body decays included . . .

⇒ focus on decays involving Stops!
(see previous section)

Scen.	$\tan\beta$	$M_{H^\pm}$	$M_{\tilde{Q}_L}$	$M_{\tilde{q}_R}$	μ	A_t	A_b	M_1	M_2	M_3
S1	20	200	700	800	200	1000	800	200	300	1200

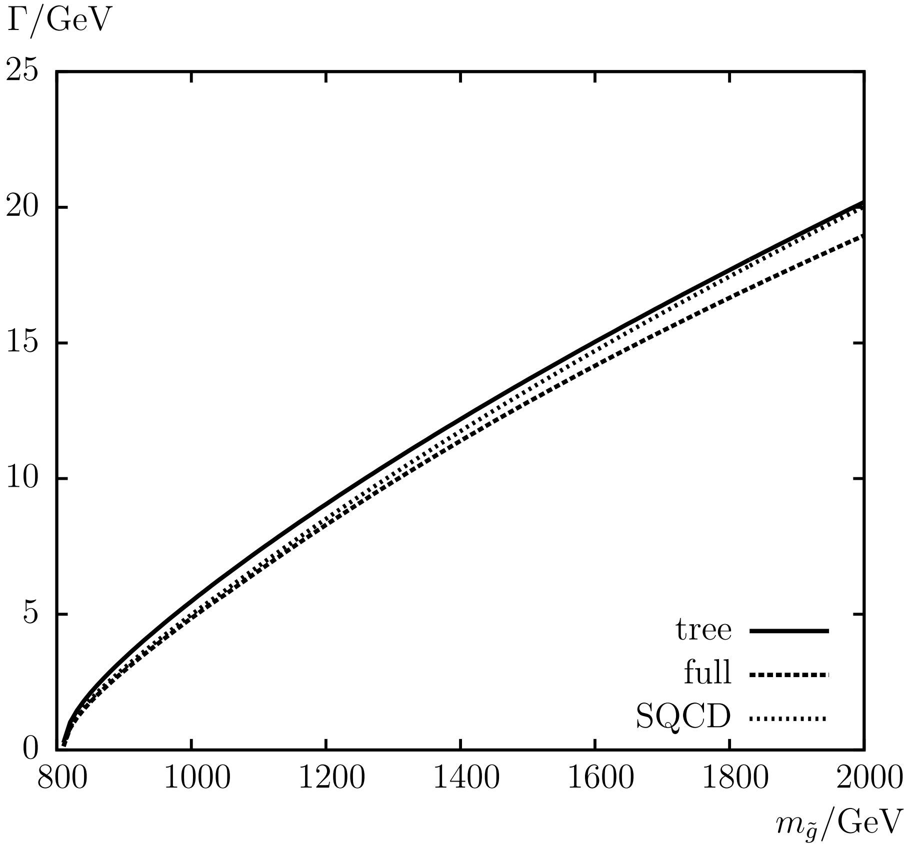
Feynman diagrams for $\tilde{g} \to \tilde{q}_i \, q$

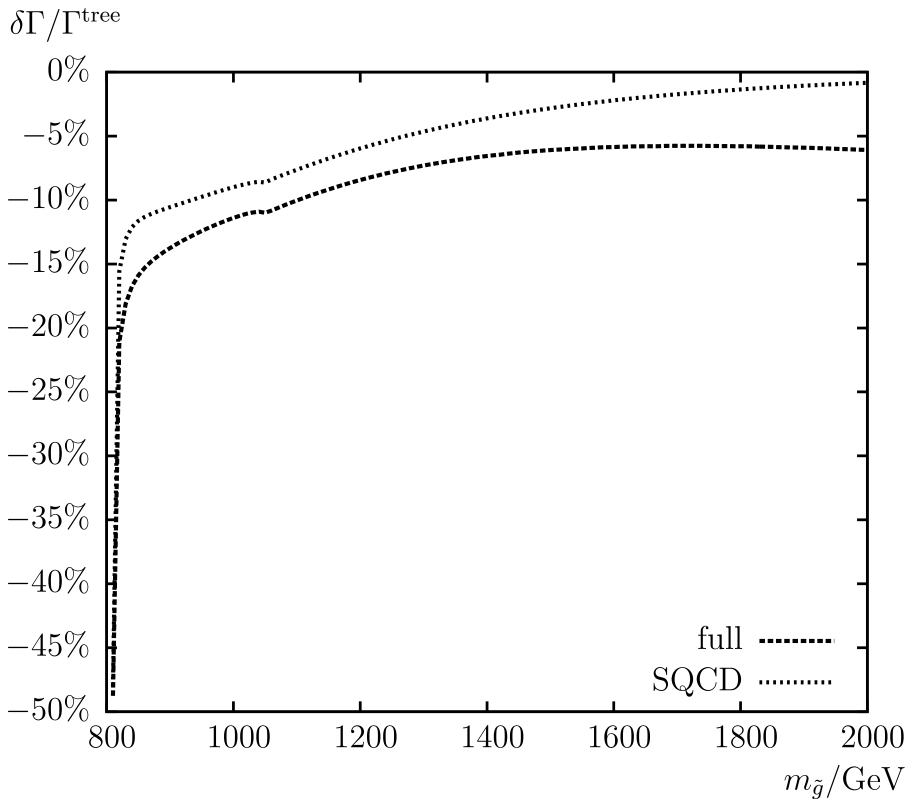


– including all soft/hard QED/QCD diagrams

$\Gamma(\tilde{g} \to \tilde{t}_1\, t)$: dependence on $m_{\tilde{g}}$

[PRELIMINARY]





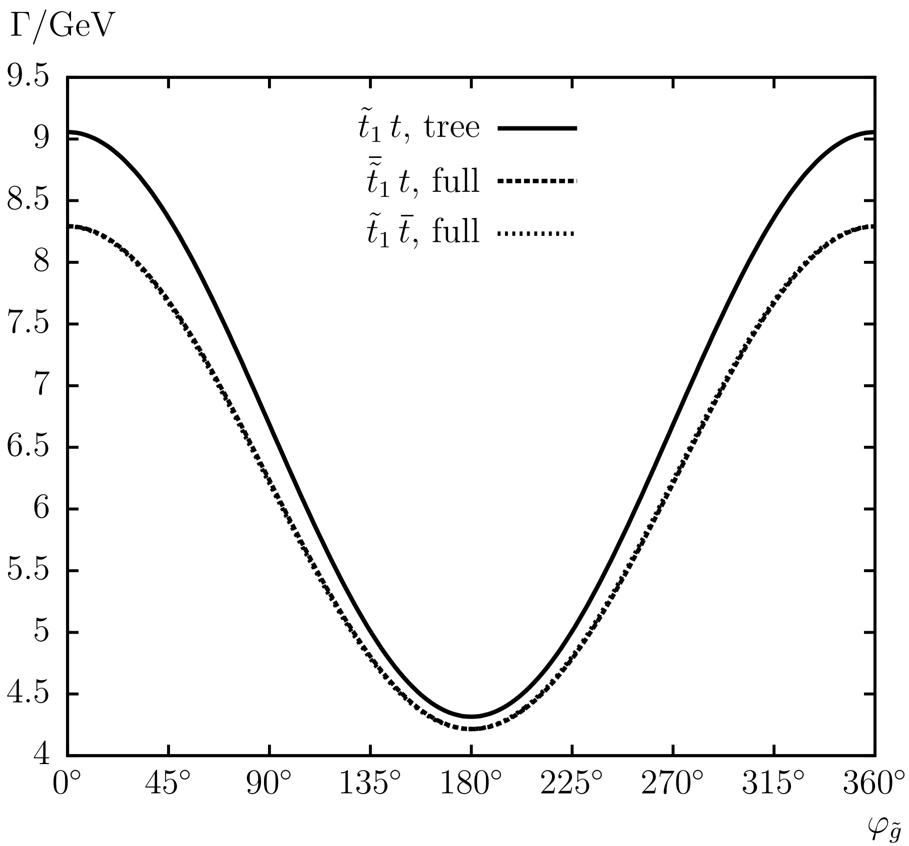
⇒ one-loop corrections under control and non-negligible

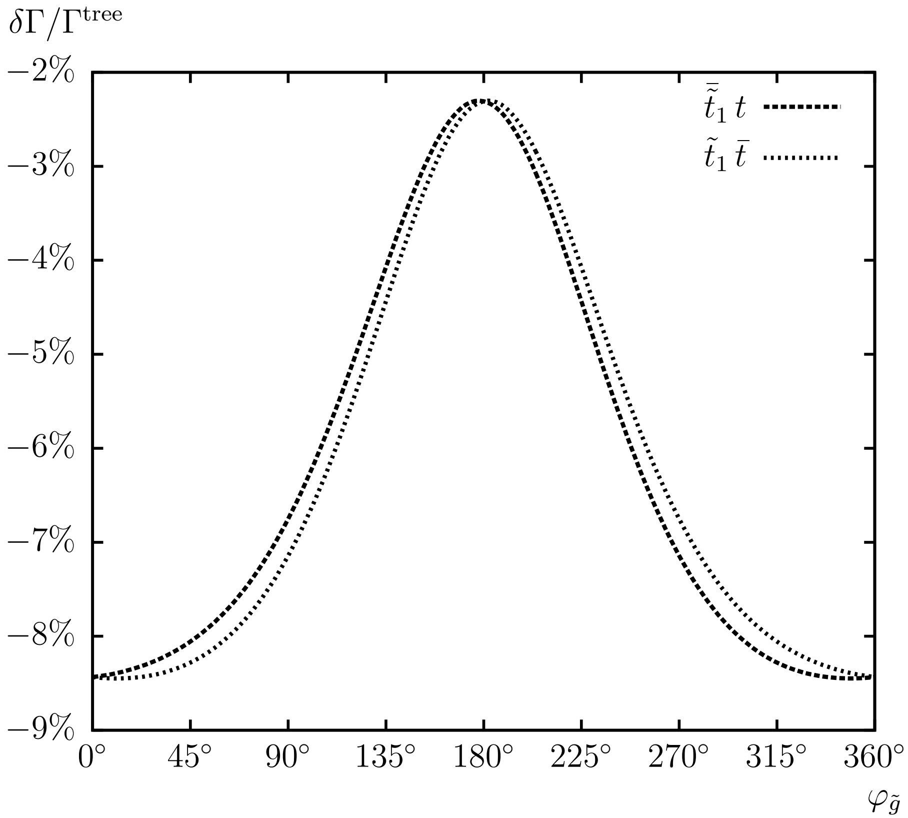
⇒ SQCD not sufficient (rMSSM: EW calculated for the first time)

⇒ size of BR highly scenario dependent

$\Gamma(\tilde{g} \to \tilde{t}_1\, t)$: dependence on $\varphi_{\tilde{g}}$

[PRELIMINARY]





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4. Chargino decays

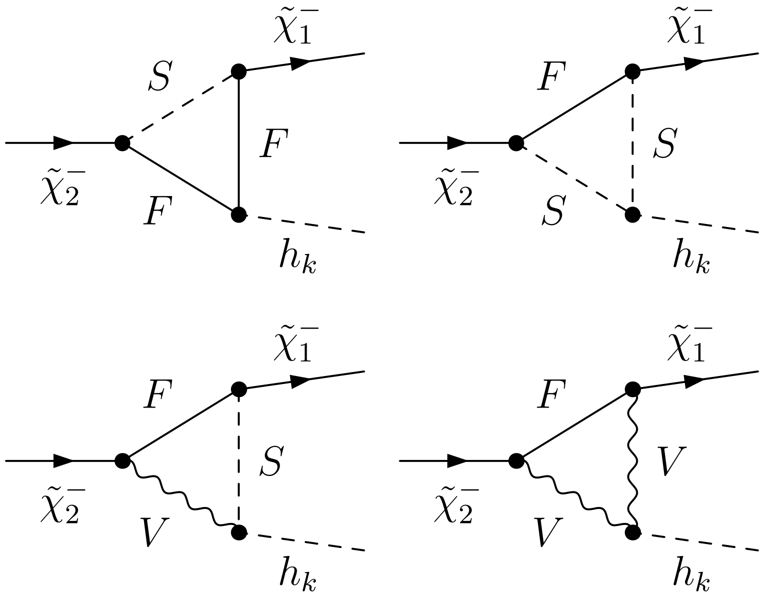
$$\Gamma(\tilde{\chi}_2^\pm \to \tilde{\chi}_1^\pm h_k) \qquad (k = 1, 2, 3)\ ,$$
$$\Gamma(\tilde{\chi}_2^\pm \to \tilde{\chi}_1^\pm Z)\ ,$$
$$\Gamma(\tilde{\chi}_i^\pm \to \tilde{\chi}_j^0 H^\pm) \qquad (i = 1, 2,\ j = 1, 2, 3, 4)\ ,$$
$$\Gamma(\tilde{\chi}_i^\pm \to \tilde{\chi}_j^0 W^\pm) \qquad (i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

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

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

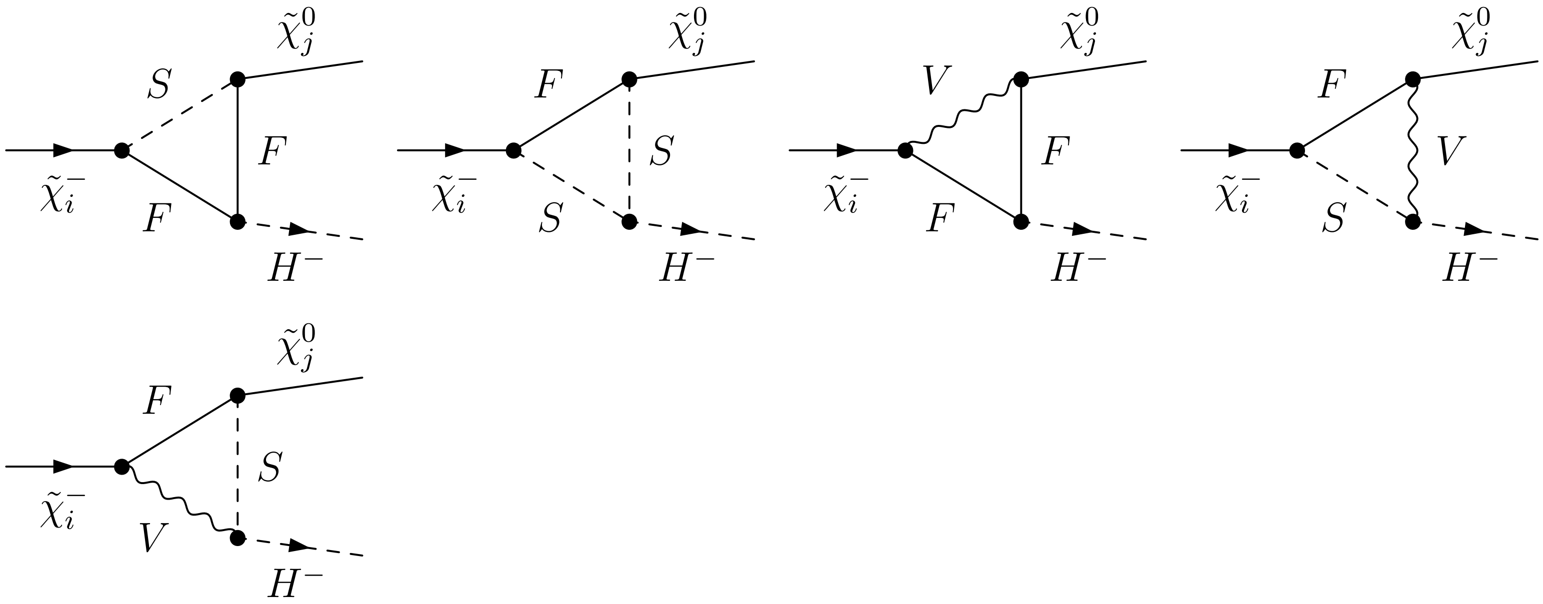
Feynman diagrams for $\tilde{\chi}_2^- \to \tilde{\chi}_1^- h_k$



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

– including all soft/hard QED/QCD diagrams

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

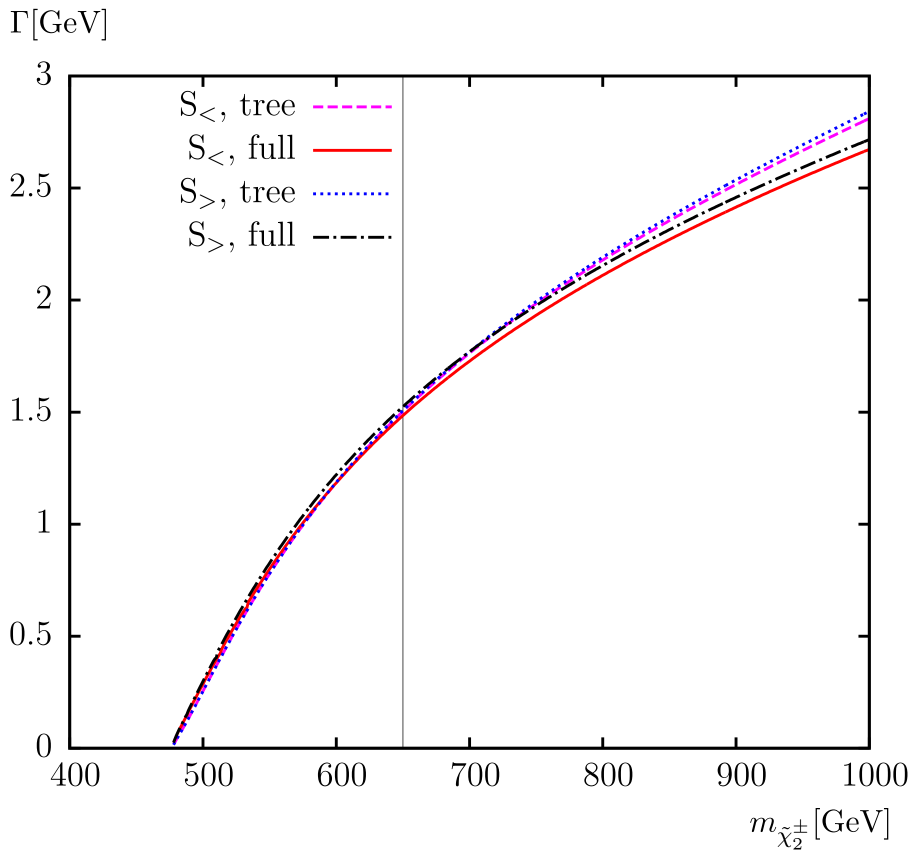


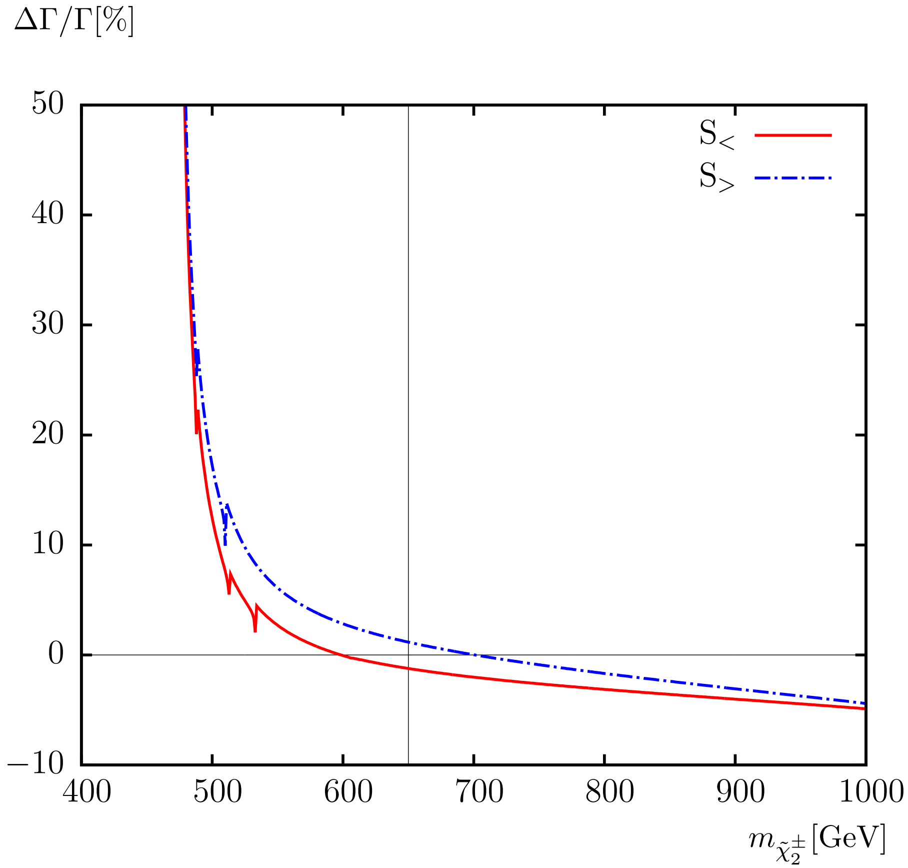
– including W^+–H^+ or G^+–H^+ transition contribution on the external Higgs boson leg

– including all soft/hard QED/QCD diagrams

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

[PRELIMINARY]



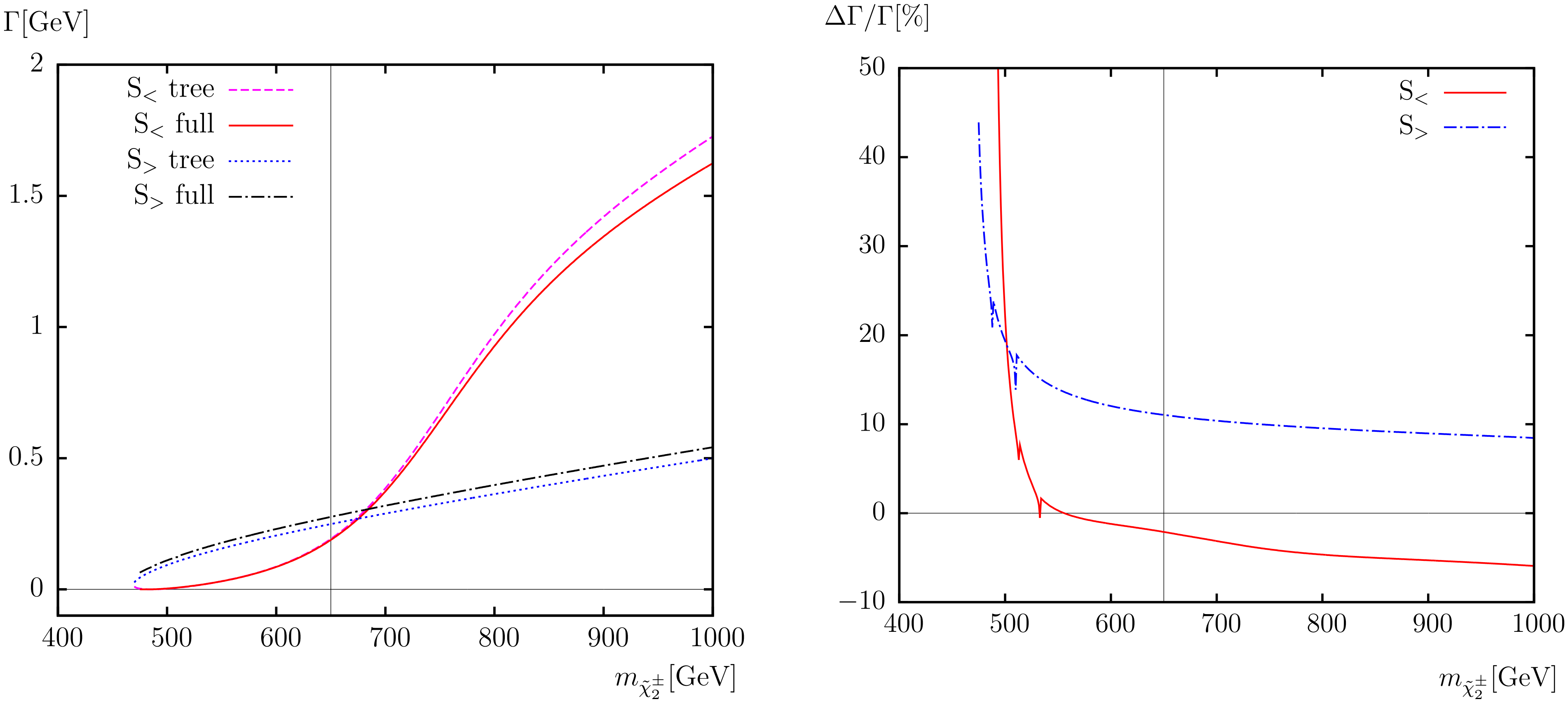


⇒ one-loop corrections under control and non-negligible

⇒ size of BR highly scenario dependent

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

[PRELIMINARY]



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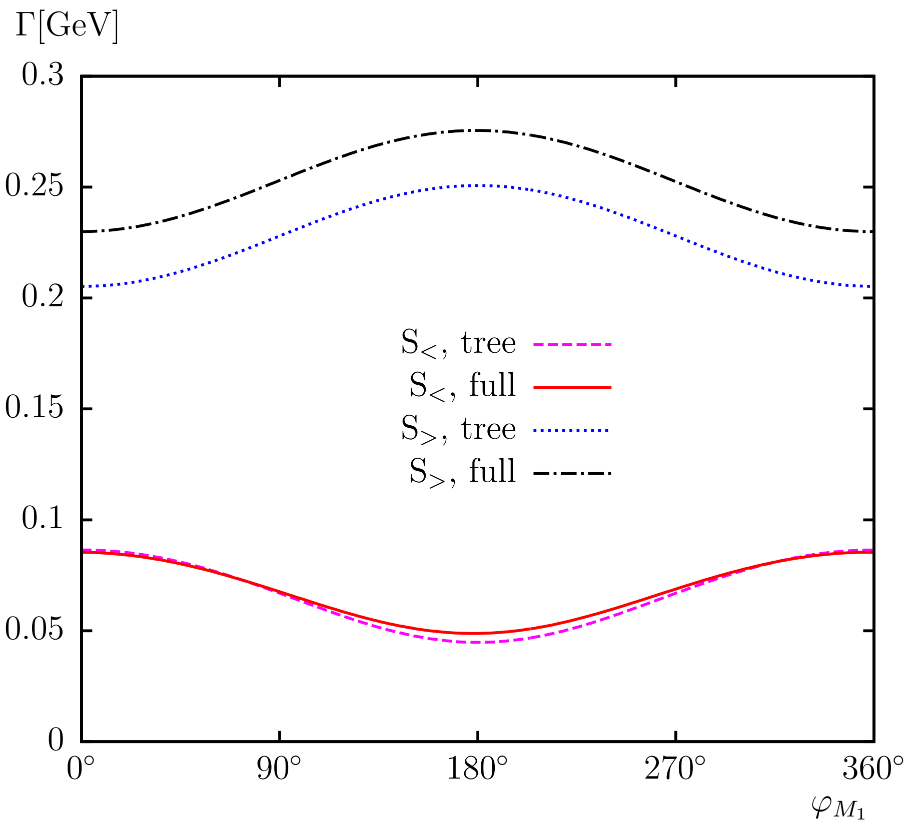
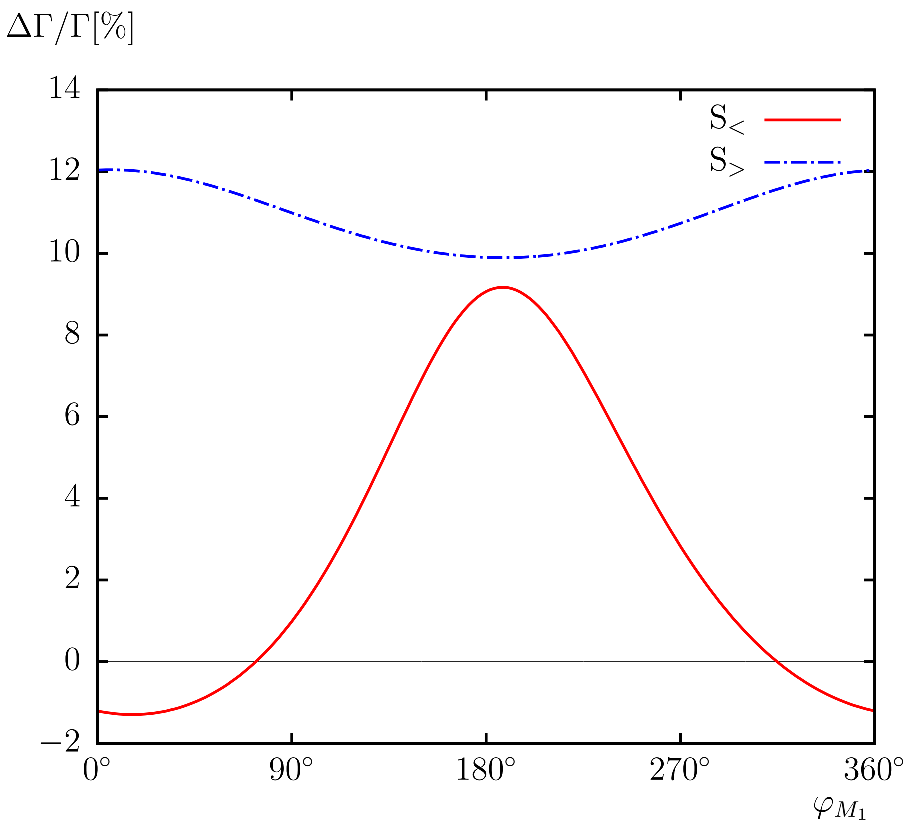
$\Gamma(\tilde{\chi}_2^- \to \tilde{\chi}_1^0 H^-)$: dependence on φ_{M_2}

[PRELIMINARY]





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5. 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 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%

- Gluino decays:

  $\tilde{g} \to \tilde{t}_1\, t$: $\sim$ 10%, SQCD not sufficient

- Chargino decays:

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


Higgs Days at Santander 2011
Theory meets Experiment
19.-23. September
Instituto de Física de Cantabria
CSIC
UC
UNIVERSIDAD DE CANTABRIA
contact:Sven.Heinemeyer@cern.ch
http://www.ifca.es/HDays11