LC Precision in the MSSM:
Getting It Under Control

Sven Heinemeyer, IFCA (CSIC, Santander)

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based on collaboration with *A. Bharoucha, T. Fritzsche, F. v.d. Pahlen, H. Rzehak, C. Schappacher, G. Weiglein*

1. Introduction & The bigger picture
2. Renormalization schemes for stops and sbottoms
3. Renormalization schemes for charginos and neutralinos
4. Some numerical examples
5. Conclusions & Outlook

1. The Grand Scheme

The LHC will run at 13-14 TeV . . .
→ discovery of BSM physics in 2015?

The ILC is 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 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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- masses
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- . . .

⇒ compare with theory calculations at the same level of accuracy

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

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

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

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

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

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: many scales

Problem in the MSSM: complex phases

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 $\phi_{\rm PQ}$

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

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

$\tilde{t}/\tilde{b}$ 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:

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

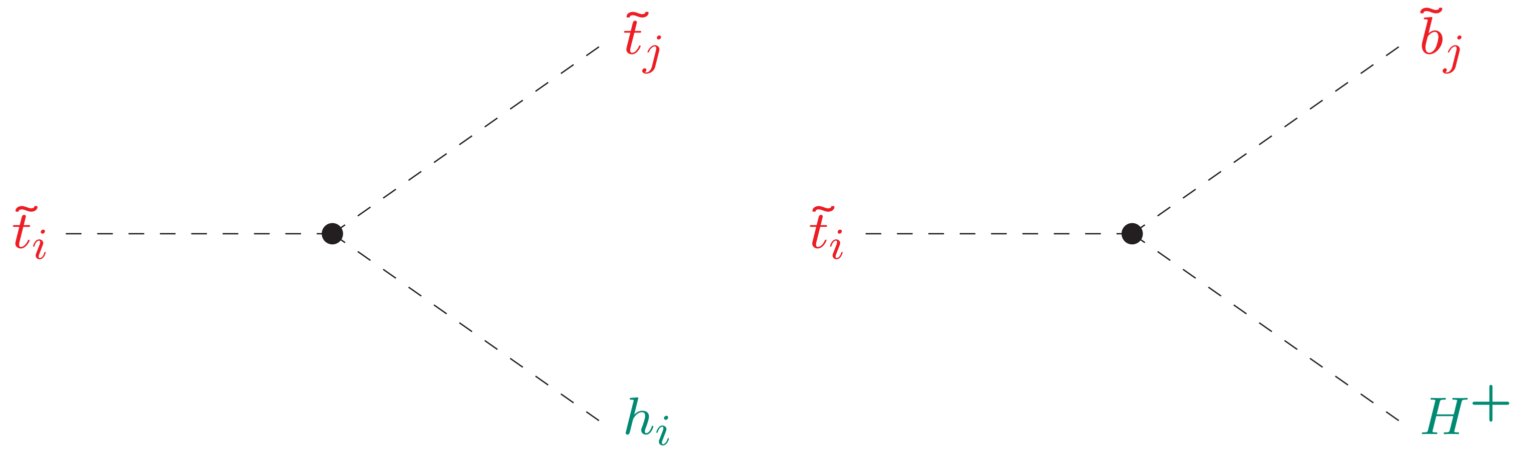
$\Rightarrow$ neutralinos: mass eigenstates

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

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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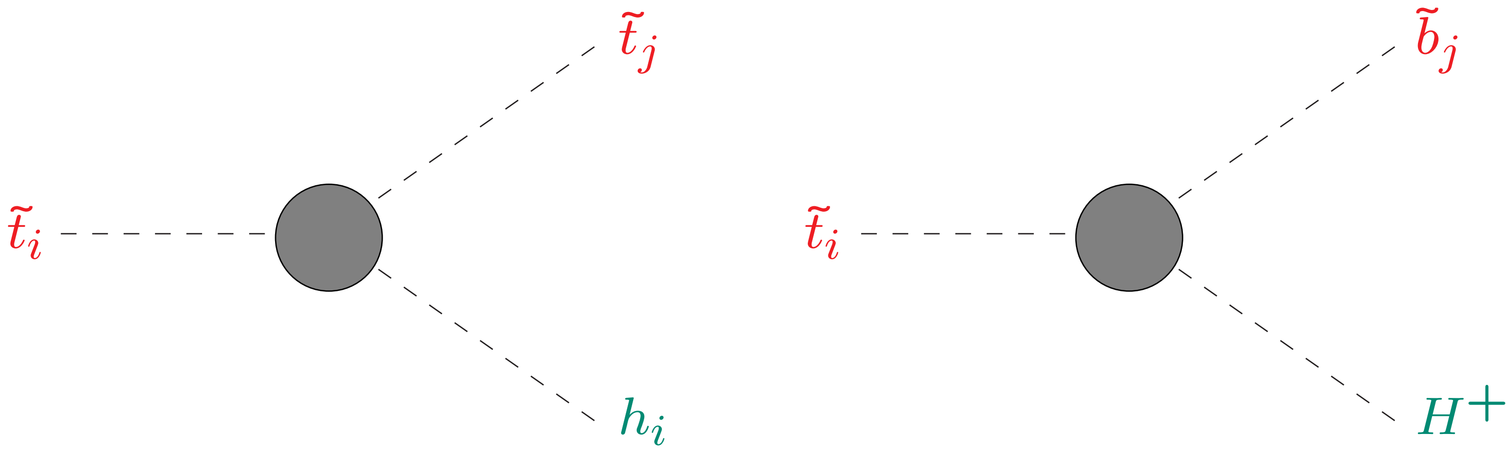

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⇒ higher-order corrections important!

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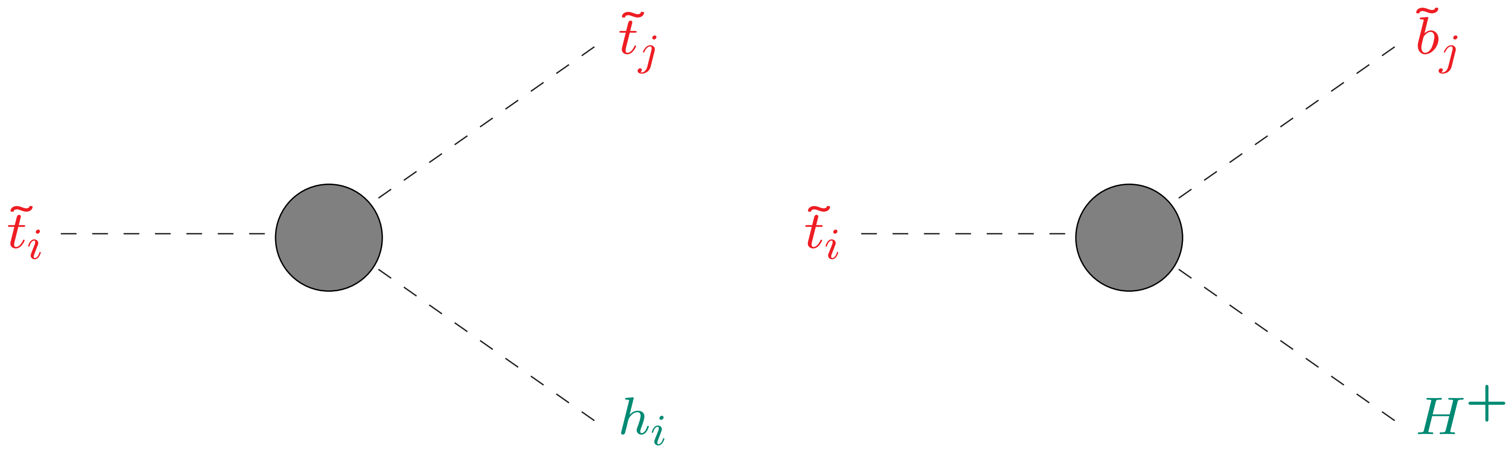

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$\Rightarrow$ simultaneous renormalization of stop and sbottom sector required!

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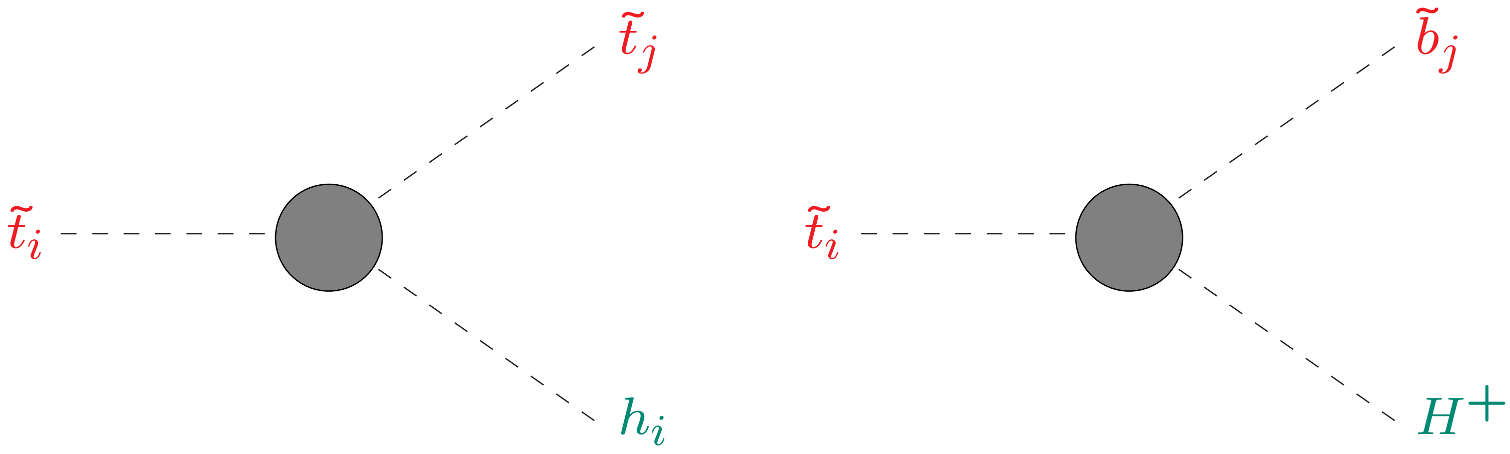

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⇒ higher-order corrections important!

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

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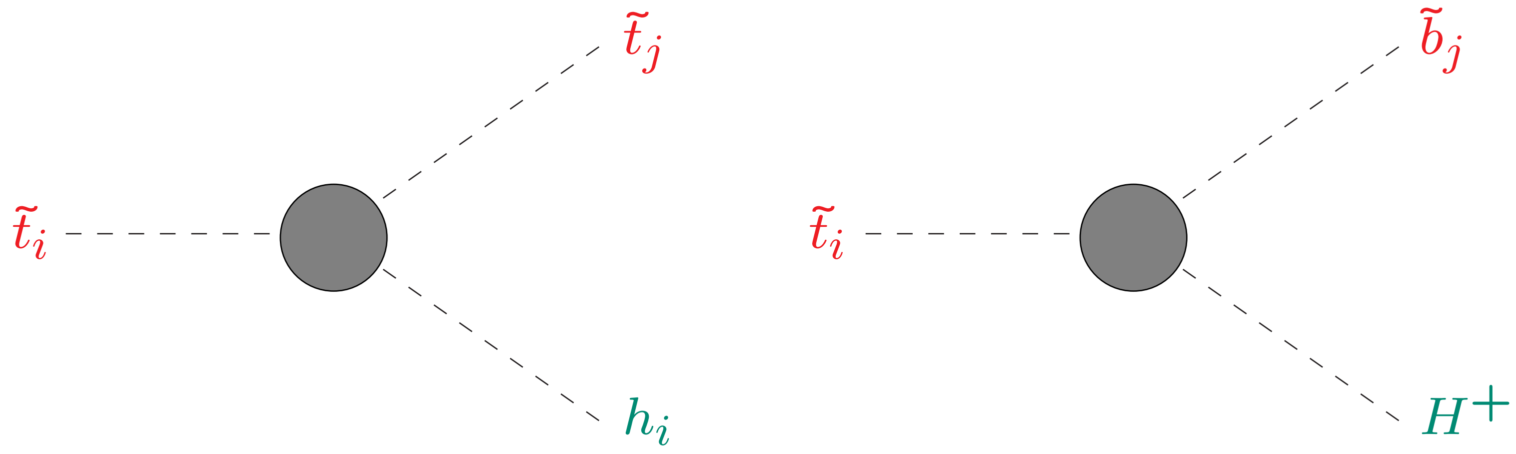
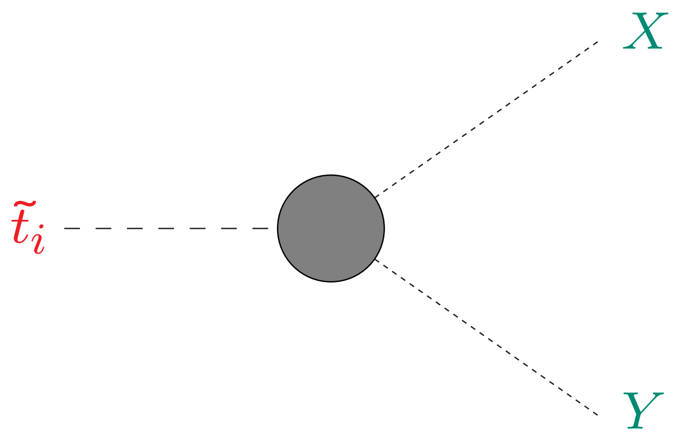


- important decay modes of stops
- A_t and A_b directly enter the vertex incl. complex phases!
- possible source of Higgs bosons at the LHC/ILC
- ...

⇒ higher-order corrections important!

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

The bigger picture: stop decays in the cMSSM

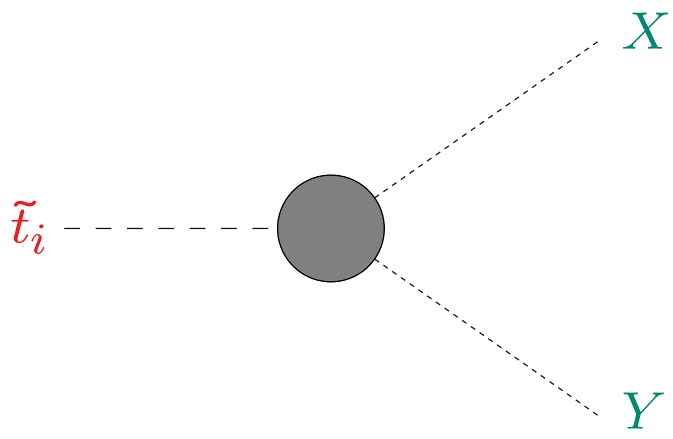


⇒ to get BRs right ⇒ all decays needed

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

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

The bigger picture: stop 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

⇒ combination of various tools and analyses:

– FeynArts/FormCalc for one-loop diagrams [*T. Hahn et al.*]

– MSSM counter term model file [*T. Fritzsche et al. '07*]

– LoopTools for numerical evaluation [*T. Hahn*]

– Renormalization: as usual the biggest issue
  * complex Higgs sector [*M. Frank et al. '06*]
  * (complex) stop/sbottom/stau sector [*H. Rzehak et al. '04, '07*][*S.H. et al. '10, '12*]
  * (complex) chargino/neutralino sector [*T. Fritzsche et al. '11*][*A. Fowler et al. '10*] [*M. Drees et al. '11*][*A. Bharoucha et al. '12*]
  * complex gluino sector

People used to choose the most convenient renormalization for their problem/sector

⇒ no longer possible

⇒ working FeynArts model file now ready!

[*T. Fritzsche, T. Hahn, S.H., H. Rzehak, C. Schappacher '13*]

– hard QED and QCD radiation

2. Renormalization schemes in the stop/sbottom sector

("analogously" in the slepton sector!)

Generic parameter and field renormalization for scalar quarks:

$$\mathbf{D}_{\tilde{q}} = \mathbf{U}_{\tilde{q}} \mathbf{M}_{\tilde{q}} \mathbf{U}_{\tilde{q}}^{\dagger} \quad (\tilde{q} = \tilde{t}, \tilde{b})$$

$$\mathbf{U}_{\tilde{q}} \mathbf{M}_{\tilde{q}} \mathbf{U}_{\tilde{q}}^{\dagger} \to \mathbf{U}_{\tilde{q}} \mathbf{M}_{\tilde{q}} \mathbf{U}_{\tilde{q}}^{\dagger} + \mathbf{U}_{\tilde{q}} \delta\mathbf{M}_{\tilde{q}} \mathbf{U}_{\tilde{q}}^{\dagger} = \begin{pmatrix} m_{\tilde{q}_1}^2 & Y_q \\ Y_q^* & m_{\tilde{q}_2}^2 \end{pmatrix} + \begin{pmatrix} \delta m_{\tilde{q}_1}^2 & \delta Y_q \\ \delta Y_q^* & \delta m_{\tilde{q}_2}^2 \end{pmatrix}$$

$$\delta\mathbf{M}_{\tilde{q}_{12}} = U_{\tilde{q}_{11}}^* U_{\tilde{q}_{12}} (\delta m_{\tilde{q}_1}^2 - \delta m_{\tilde{q}_2}^2) + U_{\tilde{q}_{11}}^* U_{\tilde{q}_{22}} \delta Y_q + U_{\tilde{q}_{12}} U_{\tilde{q}_{21}}^* \delta Y_q^*$$

$$\begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \end{pmatrix} \to \left(\mathbb{1} + \frac{1}{2} \delta\mathbf{Z}_{\tilde{q}} \right) \begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \end{pmatrix} \quad \text{with} \quad \delta\mathbf{Z}_{\tilde{q}} = \begin{pmatrix} \delta Z_{\tilde{q}_{11}} & \delta Z_{\tilde{q}_{12}} \\ \delta Z_{\tilde{q}_{21}} & \delta Z_{\tilde{q}_{22}} \end{pmatrix}$$

Renormalization of the $t/\tilde{t}$ sector

$\rightarrow$ employ the widely used on-shell renormalization

$$\delta m_t = \frac{1}{2}\widetilde{\text{Re}}\left\{m_t\left[\Sigma_t^L(m_t^2)+\Sigma_t^R(m_t^2)\right]+\left[\Sigma_t^{SL}(m_t^2)+\Sigma_t^{SR}(m_t^2)\right]\right\}$$

$$\delta m_{\tilde{t}_i}^2 = \widetilde{\text{Re}}\Sigma_{\tilde{t}_{ii}}(m_{\tilde{t}_i}^2) \qquad (i=1,2)$$

$$\delta Y_t = \frac{1}{2}\widetilde{\text{Re}}\left\{\Sigma_{\tilde{t}_{12}}(m_{\tilde{t}_1}^2)+\Sigma_{\tilde{t}_{12}}(m_{\tilde{t}_2}^2)\right\}$$

[*W. Hollik, H. Rzehak '03*]

This defines the counter term for A_t:

$$\delta A_t = \frac{1}{m_t}\Big[U_{\tilde{t}_{11}}U^*_{\tilde{t}_{12}}(\delta m_{\tilde{t}_1}^2-\delta m_{\tilde{t}_2}^2)+U_{\tilde{t}_{11}}U^*_{\tilde{t}_{22}}\delta Y_t^*+U^*_{\tilde{t}_{12}}U_{\tilde{t}_{21}}\delta Y_t - (A_t-\mu^*\cot\beta)\,\delta m_t\Big]+(\delta\mu^*\cot\beta-\mu^*\cot^2\beta\,\delta\tan\beta)$$

(with $\delta\mu$ from chargino/neutralino sector, $\delta\tan\beta$ from Higgs sector)

Field renormalization for on-shell squarks ($\tilde{t}$, $\tilde{b}$, ...):

Diagonal Z factors:

the real part of the residua of propagators is set to unity:

$$\widetilde{\mathrm{Re}} \frac{\partial \hat{\Sigma}_{\tilde{q}_{ii}}(k^2)}{\partial k^2}\Big|_{k^2=m^2_{\tilde{q}_i}} = 0 \qquad (i = 1, 2)$$

yielding

$$\mathrm{Re}\,\delta Z_{\tilde{q}_{ii}} = -\widetilde{\mathrm{Re}} \frac{\partial \Sigma_{\tilde{q}_{ii}}(k^2)}{\partial k^2}\Big|_{k^2=m^2_{\tilde{q}_i}} \qquad \mathrm{Im}\,\delta Z_{\tilde{q}_{ii}} = 0 \qquad (i = 1, 2)$$

Off-diagonal Z factors:

no transition from one squark to the other occurs:

$$\widetilde{\mathrm{Re}}\hat{\Sigma}_{\tilde{q}_{12}}(m^2_{\tilde{q}_1}) = 0 \qquad \widetilde{\mathrm{Re}}\hat{\Sigma}_{\tilde{q}_{12}}(m^2_{\tilde{q}_2}) = 0$$

yielding

$$\delta Z_{\tilde{q}_{12}} = +2\frac{\widetilde{\mathrm{Re}}\Sigma_{\tilde{q}_{12}}(m^2_{\tilde{q}_2}) - \delta Y_q}{(m^2_{\tilde{q}_1} - m^2_{\tilde{q}_2})} \qquad \delta Z_{\tilde{q}_{21}} = -2\frac{\widetilde{\mathrm{Re}}\Sigma_{\tilde{q}_{21}}(m^2_{\tilde{q}_1}) - \delta Y_q^*}{(m^2_{\tilde{q}_1} - m^2_{\tilde{q}_2})}$$

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

"LL" soft SUSY-breaking term for $\tilde{q} = \{\tilde{t}, \tilde{b}\}$:

$$M^2_{\tilde{Q}_L}(\tilde{q}) = |U_{\tilde{q}_{11}}|^2 m^2_{\tilde{q}_1} + |U_{\tilde{q}_{12}}|^2 m^2_{\tilde{q}_2} - M_Z^2 c_{2\beta}(T_q^3 - Q_q s_W^2) - m_q^2$$

Keeping $SU(2)$ relation at the one-loop level leads to a shift in the soft SUSY-breaking parameters

[A. Bartl, H. Eberl, K. Hidaka, S. Kraml, W. Majerotto, W. Porod, Y. Yamada '97, '98]

[A. Djouadi, P. Gambino, S.H., W. Hollik, C. Jünger, G. Weiglein '98]

$$M^2_{\tilde{Q}_L}(\tilde{b}) = M^2_{\tilde{Q}_L}(\tilde{t}) + \delta M^2_{\tilde{Q}_L}(\tilde{t}) - \delta M^2_{\tilde{Q}_L}(\tilde{b})$$

with

$$\delta M^2_{\tilde{Q}_L}(\tilde{q}) = |U_{\tilde{q}_{11}}|^2 \delta m^2_{\tilde{q}_1} + |U_{\tilde{q}_{12}}|^2 \delta m^2_{\tilde{q}_2} - U_{\tilde{q}_{22}} U^*_{\tilde{q}_{12}} \delta Y_q - U_{\tilde{q}_{12}} U^*_{\tilde{q}_{22}} \delta Y_q^* - 2 m_q \delta m_q$$
$$+ M_Z^2\, c_{2\beta}\, Q_q\, \delta s_W^2 - (T_q^3 - Q_q s_W^2)(c_{2\beta}\, \delta M_Z^2 + M_Z^2\, \delta c_{2\beta})$$

$\to$ under control

Renormalizations of the $b/\tilde{b}$ sector in the complex MSSM:

scheme	$m_{\tilde{b}_{1,2}}$	m_b	A_b	Y_b	name
analogous to the $t/\tilde{t}$ sector: "OS"	OS	OS	—	OS	RS1
"m_b, A_b $\overline{\text{DR}}$"	OS	$\overline{\text{DR}}$	$\overline{\text{DR}}$	—	RS2
"m_b, Y_b $\overline{\text{DR}}$"	OS	$\overline{\text{DR}}$	—	$\overline{\text{DR}}$	RS3
"m_b $\overline{\text{DR}}$, Y_b OS"	OS	$\overline{\text{DR}}$	—	OS	RS4
"A_b $\overline{\text{DR}}$, ReY_b OS"	OS	—	$\overline{\text{DR}}$	ReY_b: OS	RS5
"A_b vertex, ReY_b OS"	OS	—	vertex	ReY_b: OS	RS6

"— " = dependent parameter

$\Rightarrow$ often very involved analytical dependences

$\rightarrow$ more combinations possible

. . . also tested

. . . upcoming results remain unchanged

Renormalization of the sbottom masses:

OS renormalization:

$$\delta m^2_{\tilde{b}_i} = \widetilde{\mathrm{Re}}\Sigma_{\tilde{b}_{ii}}(m^2_{\tilde{b}_i}) \qquad (i = 1, 2)$$

Renormalization of the bottom mass:

OS renormalization:

$$\delta m_b = \frac{1}{2}\widetilde{\mathrm{Re}}\left\{m_b\left[\Sigma_b^L(m_b^2) + \Sigma_b^R(m_b^2)\right] + \left[\Sigma_b^{SL}(m_b^2) + \Sigma_b^{SL}(m_b^2)\right]\right\}$$

$\overline{\mathrm{DR}}$ renormalization:

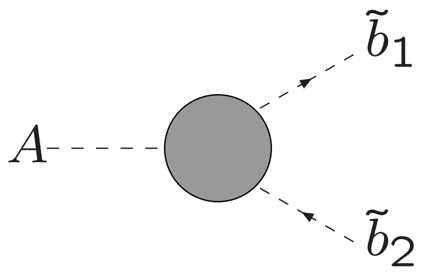
$$\delta m_b = \frac{1}{2}\widetilde{\mathrm{Re}}\left\{m_b\left[\Sigma_b^L(m_b^2) + \Sigma_b^R(m_b^2)\right]_{\mathrm{div}} + \left[\Sigma_b^{SL}(m_b^2) + \Sigma_b^{SL}(m_b^2)\right]_{\mathrm{div}}\right\}$$

Renormalization of A_b:

$\overline{\text{DR}}$ renormalization: analogous to A_t:

$$
\begin{aligned}
\delta A_b = \frac{1}{m_b}\Big[& U_{\tilde{b}_{11}} U^*_{\tilde{b}_{12}} \left(\widetilde{\text{Re}}\Sigma_{\tilde{b}_{11}}(m^2_{\tilde{b}_1})|_{\text{div}} - \widetilde{\text{Re}}\Sigma_{\tilde{b}_{22}}(m^2_{\tilde{b}_2})|_{\text{div}} \right) \\
& + \frac{1}{2} U^*_{\tilde{b}_{12}} U_{\tilde{b}_{21}} \left(\widetilde{\text{Re}}\Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_1})|_{\text{div}} + \widetilde{\text{Re}}\Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_2})|_{\text{div}} \right) \\
& + \frac{1}{2} U_{\tilde{b}_{11}} U^*_{\tilde{b}_{22}} \left(\widetilde{\text{Re}}\Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_1})|_{\text{div}} + \widetilde{\text{Re}}\Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_2})|_{\text{div}} \right)^* \\
& - \frac{1}{2}(A_b - \mu^* \tan\beta)\, \widetilde{\text{Re}}\Big\{ m_b \left[\Sigma^L_b(m^2_b) + \Sigma^R_b(m^2_b) \right]_{\text{div}} \\
& \quad + \left[\Sigma^{SL}_b(m^2_b) + \Sigma^{SR}_b(m^2_b) \right]_{\text{div}} \Big\} \Big] + \delta\mu^*|_{\text{div}} \tan\beta + \mu^*\, \delta\tan\beta
\end{aligned}
$$

Vertex renormalization:



$$\widehat{=} \quad i\,\hat{\Lambda}(p^2_A, p^2_{\tilde{b}_1}, p^2_{\tilde{b}_2})$$

$$\text{via} \quad \widetilde{\text{Re}}\hat{\Lambda}(0, m^2_{\tilde{b}_1}, m^2_{\tilde{b}_1}) + \widetilde{\text{Re}}\hat{\Lambda}(0, m^2_{\tilde{b}_2}, m^2_{\tilde{b}_2}) \stackrel{!}{=} 0$$

Renormalization of Y_b:

OS renormalization:

$$\delta Y_b = \frac{1}{2}\widetilde{\mathrm{Re}}\left\{\Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_1}) + \Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_2})\right\}$$

$\overline{\mathrm{DR}}$ renormalization:

$$\delta Y_b = \frac{1}{2}\widetilde{\mathrm{Re}}\left\{\Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_1})|_{\mathrm{div}} + \Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_2})|_{\mathrm{div}}\right\}$$

ReY_b OS renormalization

$$\mathrm{Re}\delta Y_b = \frac{1}{2}\mathrm{Re}\left\{\widetilde{\mathrm{Re}}\Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_1}) + \widetilde{\mathrm{Re}}\Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_2})\right\}$$

Existing analyses all in the real MSSM:

- [*A. Bartl et al. '98*] [*L. Jin, C. Li '01*]
  "OS" used for stop and sbottom decays
  ($\rightarrow$ implemented into SDecay)

- [*C. Weber, K. Kovarik, H. Eberl, W. Majerotto '07*]
  similar to "m_b, A_b $\overline{\text{DR}}$" used for Higgs decays to sfermions

- [*A. Arhrib, R. Benbrik '04*]
  an "OS" scheme used for $\tilde{f} \rightarrow \tilde{f}'V$

- [*Q. Li, L. Jin, C. Li '02*]
  an "OS" scheme with running m_t, m_b, A_t, A_b used for $\tilde{t}_2 \rightarrow \tilde{t}_1\phi$

- [*H. Eberl et al. '10*]
  pure $\overline{\text{DR}}$ scheme used for stop decays

- [*A. Brignole, G. Degrassi, P. Slavich and F. Zwirner '02*]
  [*S.H., W. Hollik, H. Rzehak, G. Weiglein '04*]
  real "A_b vertex, ReY_b OS" used for two-loop Higgs self-energies

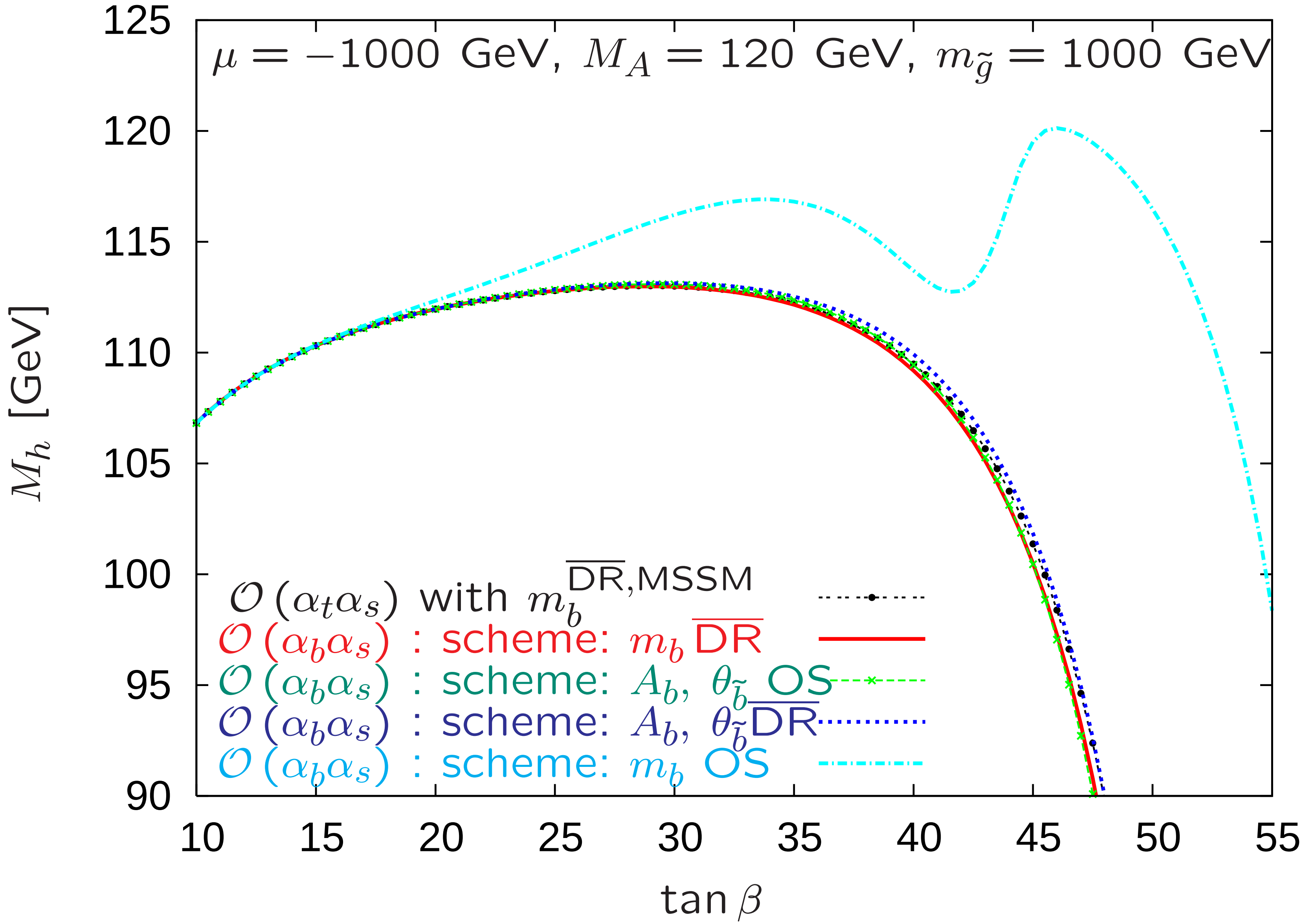
Analysis of the renormalization schemes

Numerical scenarios:

Scen.	$M_{H^\pm}$	$m_{\tilde{t}_2}$	μ	A_t	A_b	M_1	M_2	M_3
S1	150	600	200	900	400	200	300	800
S2	180	900	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	293.391	600.000	441.987	447.168
	20	235.073	600.000	418.824	439.226
	50	230.662	600.000	400.815	449.638
S2	2	495.014	900.000	702.522	707.598
	20	445.885	900.000	678.531	695.180
	50	442.416	900.000	628.615	697.202

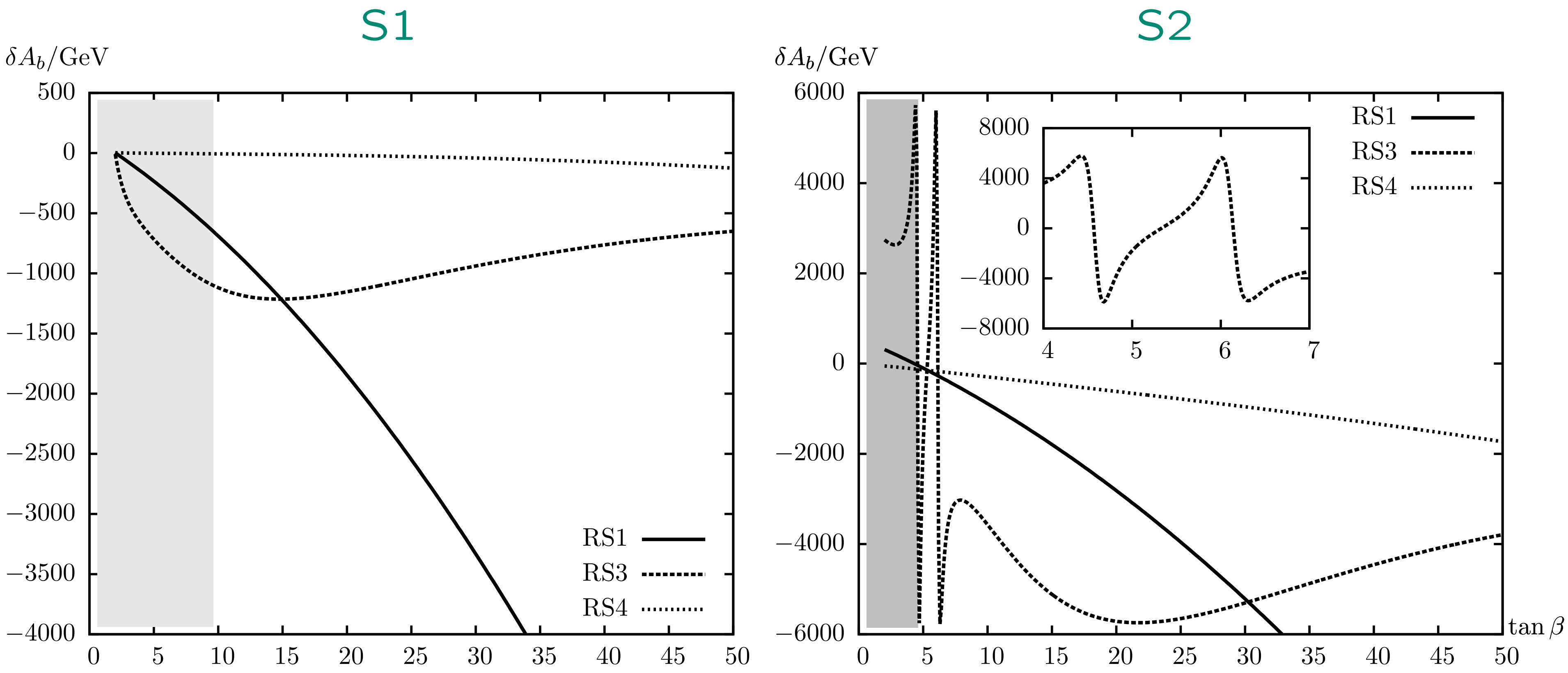
"OS" scheme: $\delta A_b = \frac{1}{m_b} [-(A_b - \mu^* \tan\beta)\, \delta m_b + \ldots]$



⇒ fails already for Higgs boson self-energies

Problems of non-A_b renormalizations:

$$\delta A_b|_{\text{fin}} = \frac{1}{m_b}\left[U_{\tilde{b}_{11}} U^*_{\tilde{b}_{12}} \left(\delta m^2_{\tilde{b}_1} - \delta m^2_{\tilde{b}_2}\right)\right]_{\text{fin}} + \dots$$

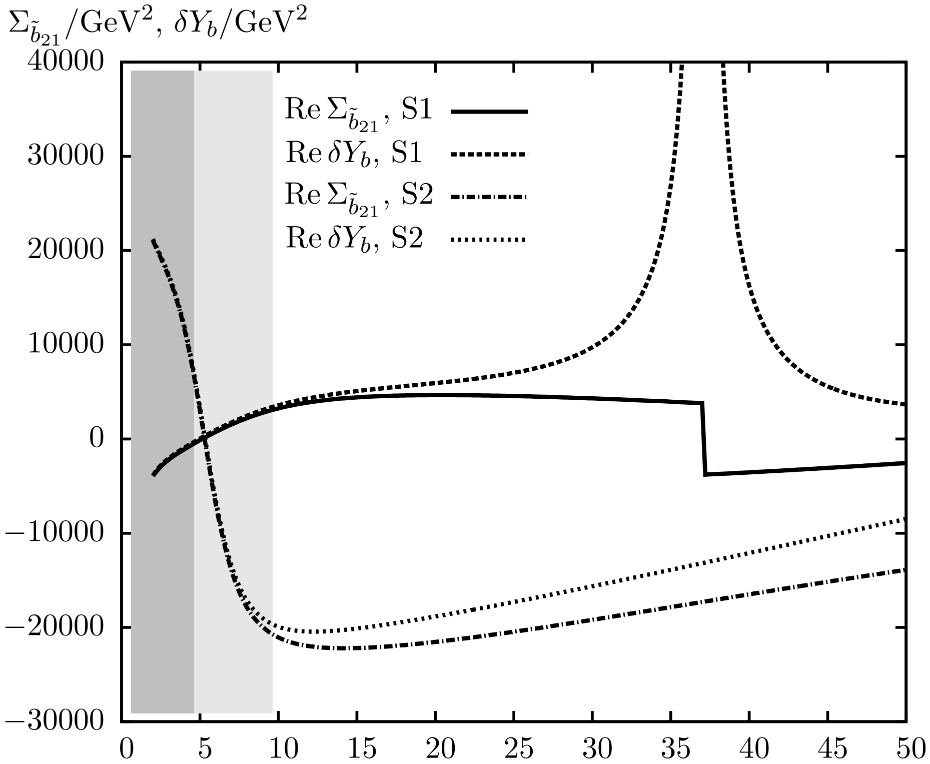


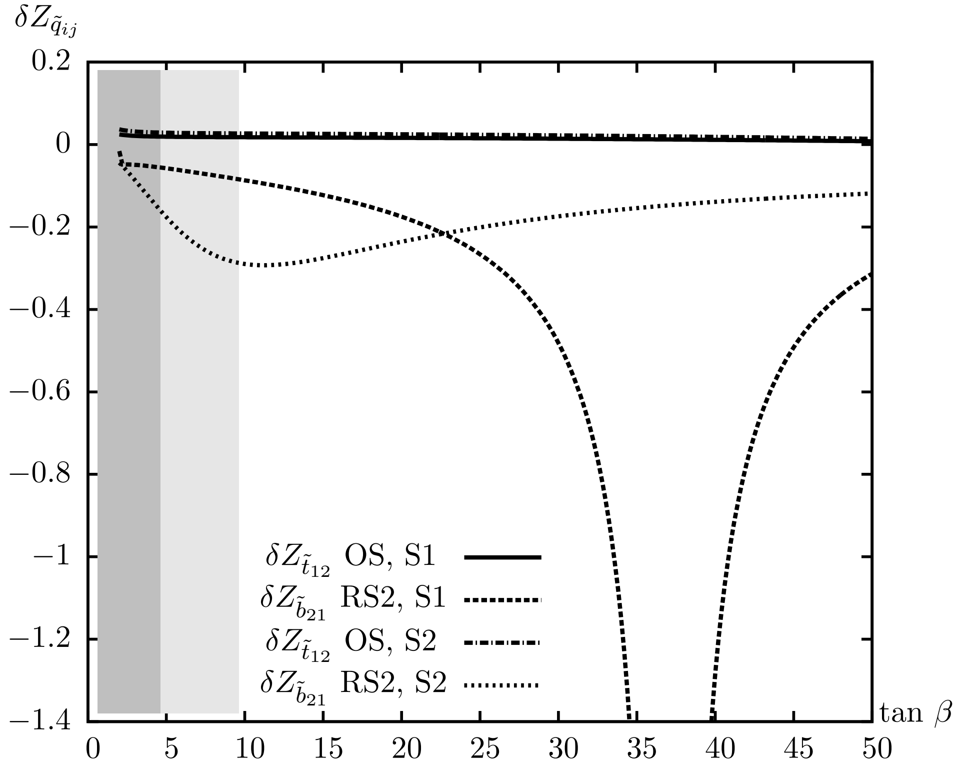
$\Rightarrow$ too large contributions to A_b are induced

Problems of m_b–A_b renormalizations:

$$\delta Y_b = \frac{U_{\tilde{b}_{11}} U_{\tilde{b}_{21}}}{|U_{\tilde{b}_{11}}|^2 - |U_{\tilde{b}_{12}}|^2} \left(\delta m^2_{\tilde{b}_1} - \delta m^2_{\tilde{b}_2} \right) + \ldots , \qquad \delta Z_{\tilde{b}_{21}} = -2 \frac{\mathrm{Re}\Sigma_{\tilde{b}_{21}}(m^2_{\tilde{b}_2}) - \delta Y_b}{m^2_{\tilde{b}_1} - m^2_{\tilde{b}_2}}$$

⇒ divergence for $|U_{\tilde{b}_{11}}| = |U_{\tilde{b}_{12}}|$ reached for $\tan\beta \approx 37$ in S1:





Problems of non-m_b renormalizations:

"A_b $\overline{\text{DR}}$, ReY_b OS" (RS5): (rMSSM)

$$\delta m_b = -\frac{m_b\,\delta A_b + \delta S}{(A_b - \mu \tan\beta)}$$

$\Rightarrow$ divergent for $A_b = \mu \tan\beta$

"A_b vertex, ReY_b OS" (RS6): (rMSSM)

$$\delta m_b = \frac{\delta S + F}{\mu\,(\tan\beta + 1/\tan\beta)}$$

$\Rightarrow$ no problem in the rMSSM!

"A_b vertex, ReY_b OS" (RS6): (cMSSM: $U_- = U_{\tilde{b}_{11}} U^*_{\tilde{b}_{22}} - U_{\tilde{b}_{12}} U^*_{\tilde{b}_{21}}$)

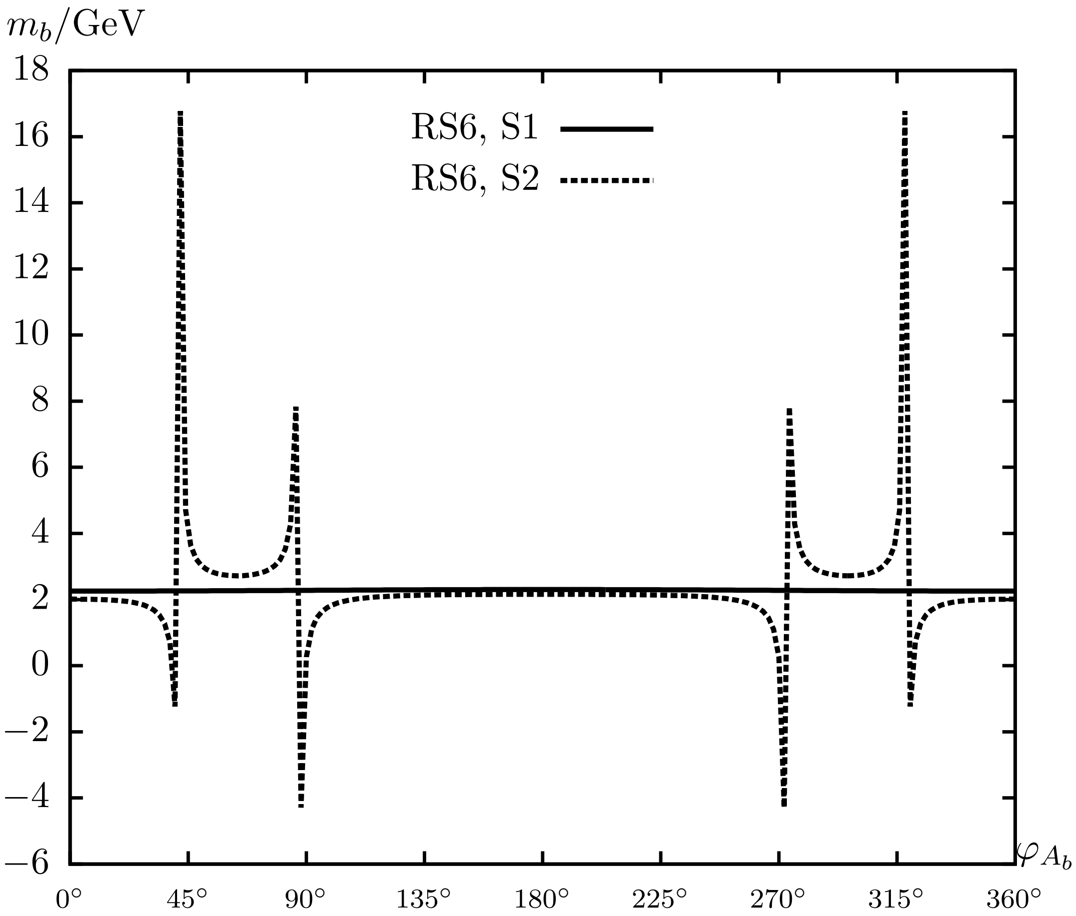
$$\frac{1}{\delta m_b} \sim 4\,\mu\,\tan^3\beta \left[\mathrm{Re} U_- \left(|U_{\tilde{b}_{11}}|^2 - |U_{\tilde{b}_{12}}|^2\right) + \mathrm{Im}\, U_- \frac{4\, m_b}{m^2_{\tilde{b}_1} - m^2_{\tilde{b}_2}} \mathrm{Im}\left(U^*_{\tilde{b}_{11}} U_{\tilde{b}_{12}} A_b\right)\right]$$

$\Rightarrow$ divergences appear depending on ϕ_{A_b}!

“A_b vertex, ReY_b OS” (RS6): (cMSSM: $U_- = U_{\tilde{b}_{11}} U^*_{\tilde{b}_{22}} - U_{\tilde{b}_{12}} U^*_{\tilde{b}_{21}}$)

$$\frac{1}{\delta m_b} \sim 4\,\mu\,\tan^3\beta \left[\mathrm{Re} U_- \left(|U_{\tilde{b}_{11}}|^2 - |U_{\tilde{b}_{12}}|^2 \right) + \mathrm{Im}\, U_- \frac{4\, m_b}{m^2_{\tilde{b}_1} - m^2_{\tilde{b}_2}} \mathrm{Im} \left(U^*_{\tilde{b}_{11}} U_{\tilde{b}_{12}} A_b \right) \right]$$

$\Rightarrow$ divergences appear depending on ϕ_{A_b}!



What is the "preferred" renormalization scheme?

one counterterm is a "dependent" quantity

$\Rightarrow$ no scheme can be identified that shows "good" behavior
over the full cMSSM parameter space

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Most "robust" behavior:

– RS2: "m_b, A_b $\overline{\mathrm{DR}}$"
  ⇒ problems only for maximal sbottom mixing
– RS6: "A_b vertex, ReY_b OS"
  ⇒ problems depending on ϕ_{A_b}

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All problems could be avoided in a pure $\overline{\text{DR}}$ scheme
$\Rightarrow$ not suited for external stops and sbottoms

$\Rightarrow$ we choose RS2: "m_b, A_b $\overline{\text{DR}}$" as our "preferred" scheme

3. Renormalization in the chargino/neutralino sector

$\Rightarrow$ Two "OS" schemes:

1. **Scheme I:**

   [*T. Fritzsche, S.H., H. Rzehak, C. Schappacher '11***][***S.H., F. v.d. Pahlen, C. Schappacher '12***]**

$$\left(\left[\widetilde{\mathbf{Re}} \hat{\Sigma}_{\tilde{\chi}^-}(p) \right]_{ii} \tilde{\chi}_i^-(p) \right) \Big|_{p^2 = m^2_{\tilde{\chi}_i^\pm}} = 0 \qquad (i = 1, 2) \; ,$$

$$\left(\left[\widetilde{\mathbf{Re}} \hat{\Sigma}_{\tilde{\chi}^0}(p) \right]_{11} \tilde{\chi}_1^0(p) \right) \Big|_{p^2 = m^2_{\tilde{\chi}_1^0}} = 0$$

2. **Scheme II:**

   [*A. Fowler, G. Weiglein '09***]**

$$\left(\left[\mathbf{Re} \hat{\Sigma}_{\tilde{\chi}^-}(p) \right]_{ii} \tilde{\chi}_i^-(p) \right) \Big|_{p^2 = m^2_{\tilde{\chi}_i^\pm}} = 0 \qquad (i = 1, 2) \; ,$$

$$\left(\left[\mathbf{Re} \hat{\Sigma}_{\tilde{\chi}^0}(p) \right]_{11} \tilde{\chi}_1^0(p) \right) \Big|_{p^2 = m^2_{\tilde{\chi}_1^0}} = 0$$

$\Rightarrow$ more details in Federico's talk, Thursday 12.40pm

Some comments:

– Scheme I and Scheme II agree for real parameters

– Both schemes can easily be extended to other variants, e.g.

$\mathrm{CCN}_i \ (i = 1, 2, 3, 4)$ or $\mathrm{CNN}_{ijk} \ (i = 1, 2; j, k = 1, 2, 3, 4)$

$\to$ relevant for $|\mu| \approx M_2$ [*F. v.d. Pahlen et al., in progress*]
(see also: [*Drees et al. '11*])

– Both schemes require a shift of three (neutralino) masses to their on-shell value:

$$\Delta m_{\tilde{\chi}_i^0} = -\frac{1}{2}\mathrm{Re}\Big\{ m_{\tilde{\chi}_i^0} \left(\hat{\Sigma}^L_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0}) + \hat{\Sigma}^R_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0}) \right) + \hat{\Sigma}^{SL}_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0}) + \hat{\Sigma}^{SR}_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0}) \Big\}$$

$$m^{\mathrm{OS}}_{\tilde{\chi}_i^0} = m_{\tilde{\chi}_i^0} + \Delta m_{\tilde{\chi}_i^0}$$

Comparison of the renormalization schemes

Parameters:

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

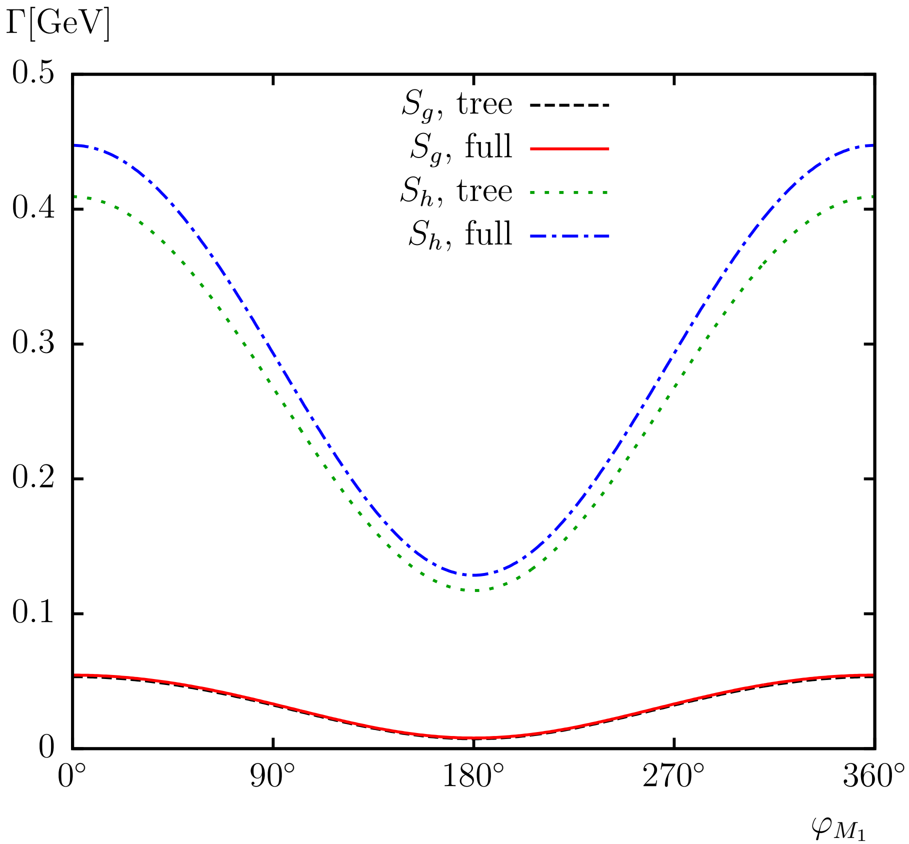
$$|M_1| = \frac{5}{3}\tan^2\theta_W M_2 \approx \frac{1}{2}M_2$$

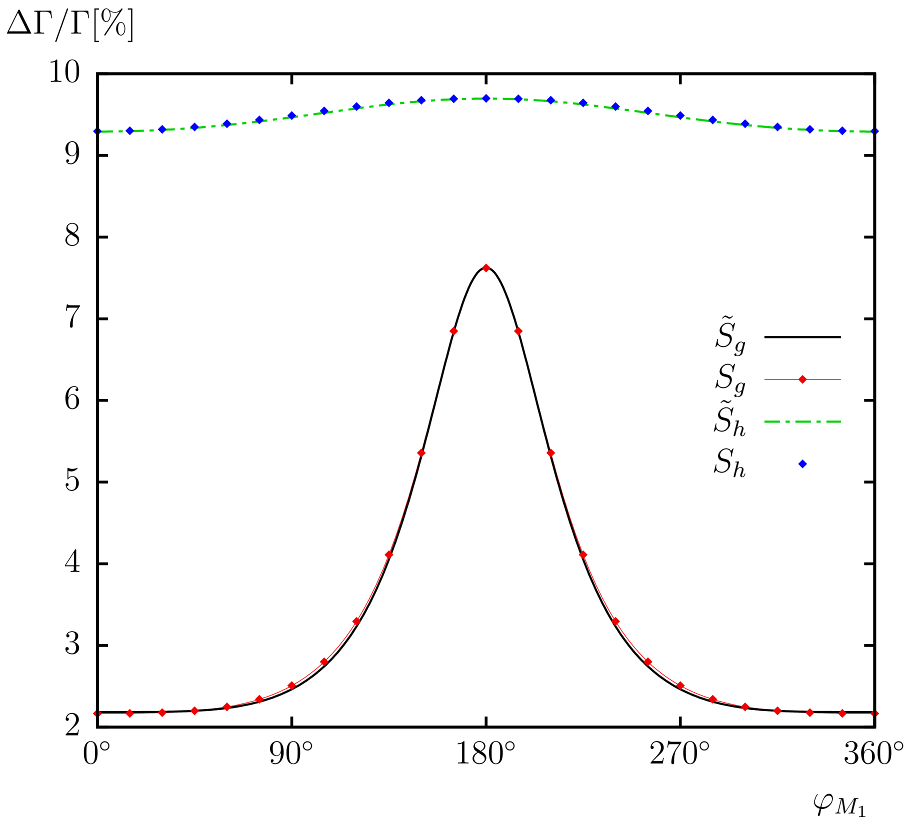
$$\mathcal{S}_g : \mu > M_2 \quad (\tilde{\chi}_4^0 \text{ more higgsino-like})$$
$$\mathcal{S}_h : \mu < M_2 \quad (\tilde{\chi}_4^0 \text{ more gaugino-like})$$

Scen.	$m_{\tilde{\chi}_2^\pm}$	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\chi}_4^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_1^0}$	μ	M_2	M_1
$\mathcal{S}_g$	600.0	350.0	600.0	364.2	359.6	267.2	362.1	581.8	277.7
$\mathcal{S}_h$	600.0	350.0	600.1	586.2	349.9	171.4	581.8	362.1	172.8

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

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



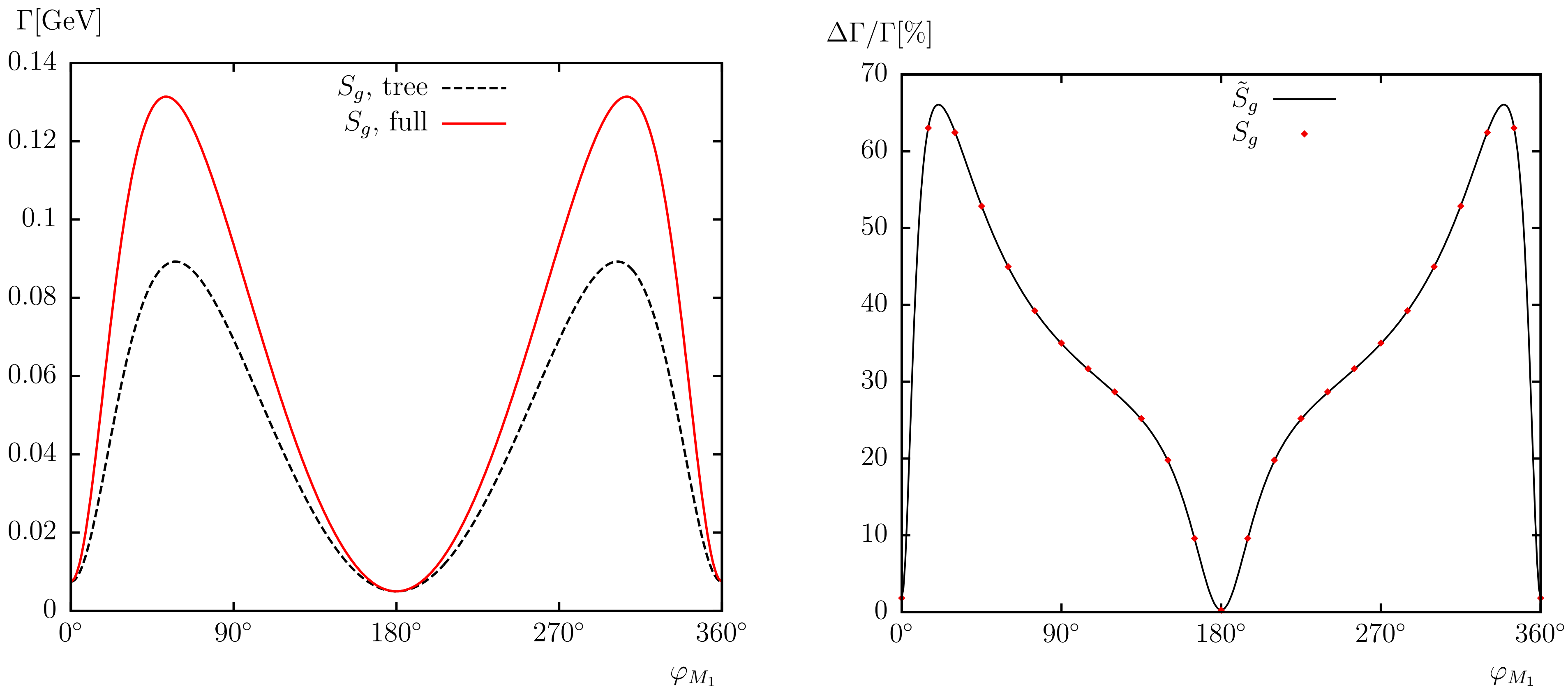


⇒ one-loop corrections under control and non-negligible

⇒ renormalization schemes agree (as expected)

$\Gamma(\tilde{\chi}^0_4 \to \tilde{\chi}^0_3 h_1)$: dependence on φ_{M_1}

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

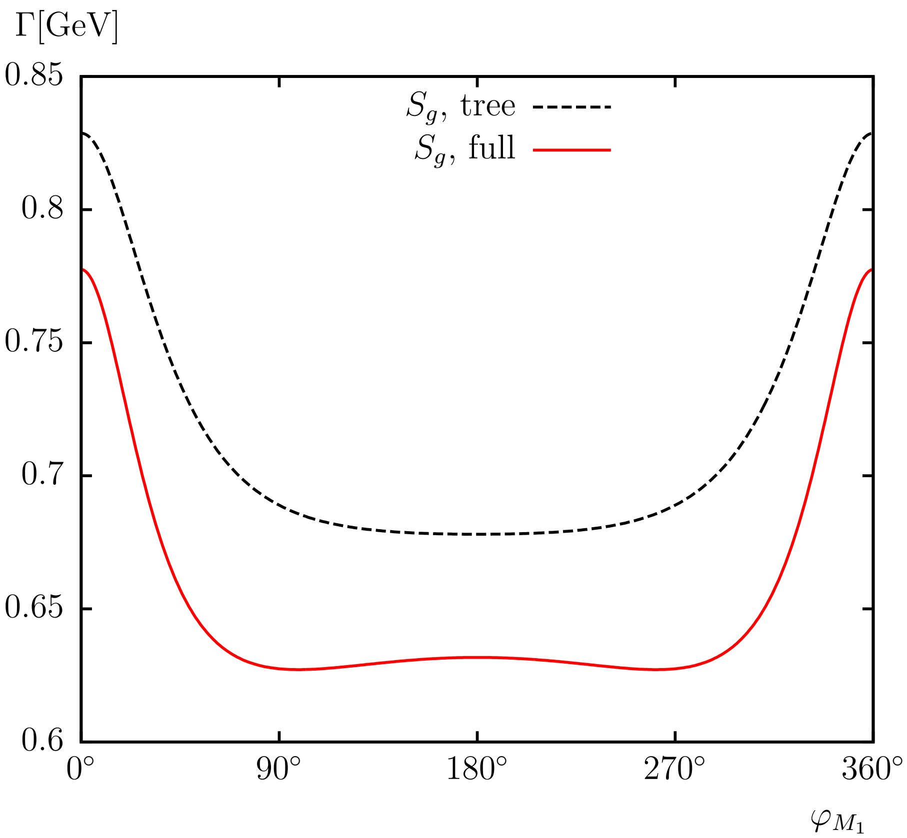


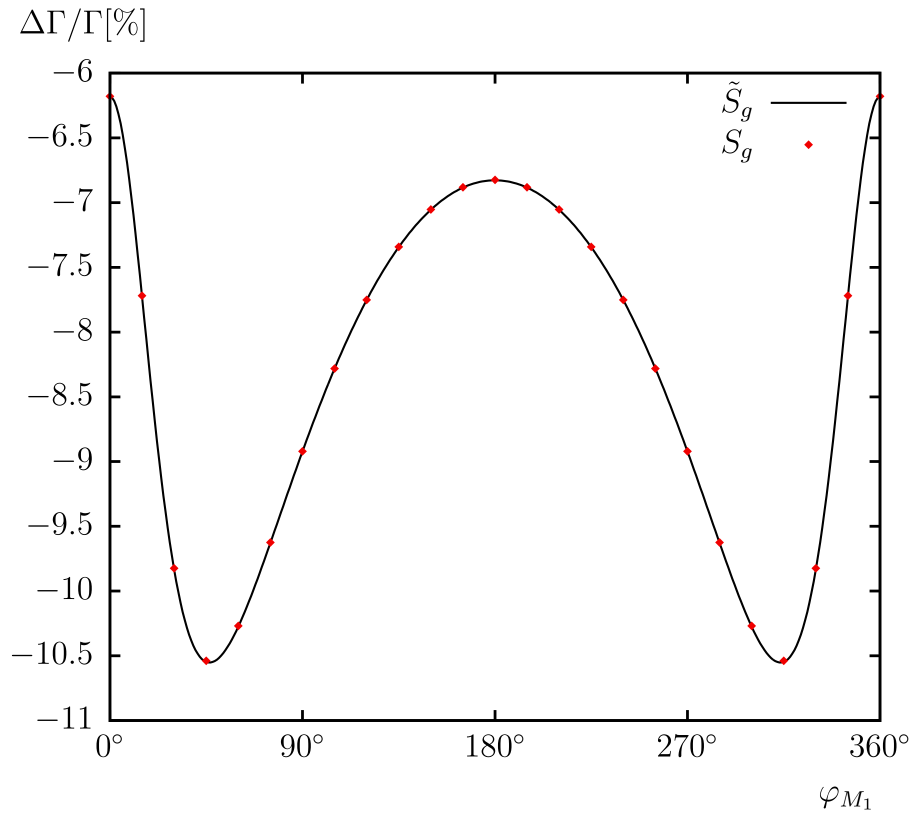
⇒ one-loop corrections under control and non-negligible

⇒ renormalization schemes agree (as expected)

$\Gamma(\tilde{\chi}^0_4 \to \tilde{\chi}^0_3 Z)$: dependence on φ_{M_1}

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





⇒ one-loop corrections under control and non-negligible

⇒ renormalization schemes agree (as expected)

4. Some numerical examples

4A) 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 $\rightarrow$ TT

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

– including all soft/hard QED/QCD diagrams

– further evaluation with FormCalc

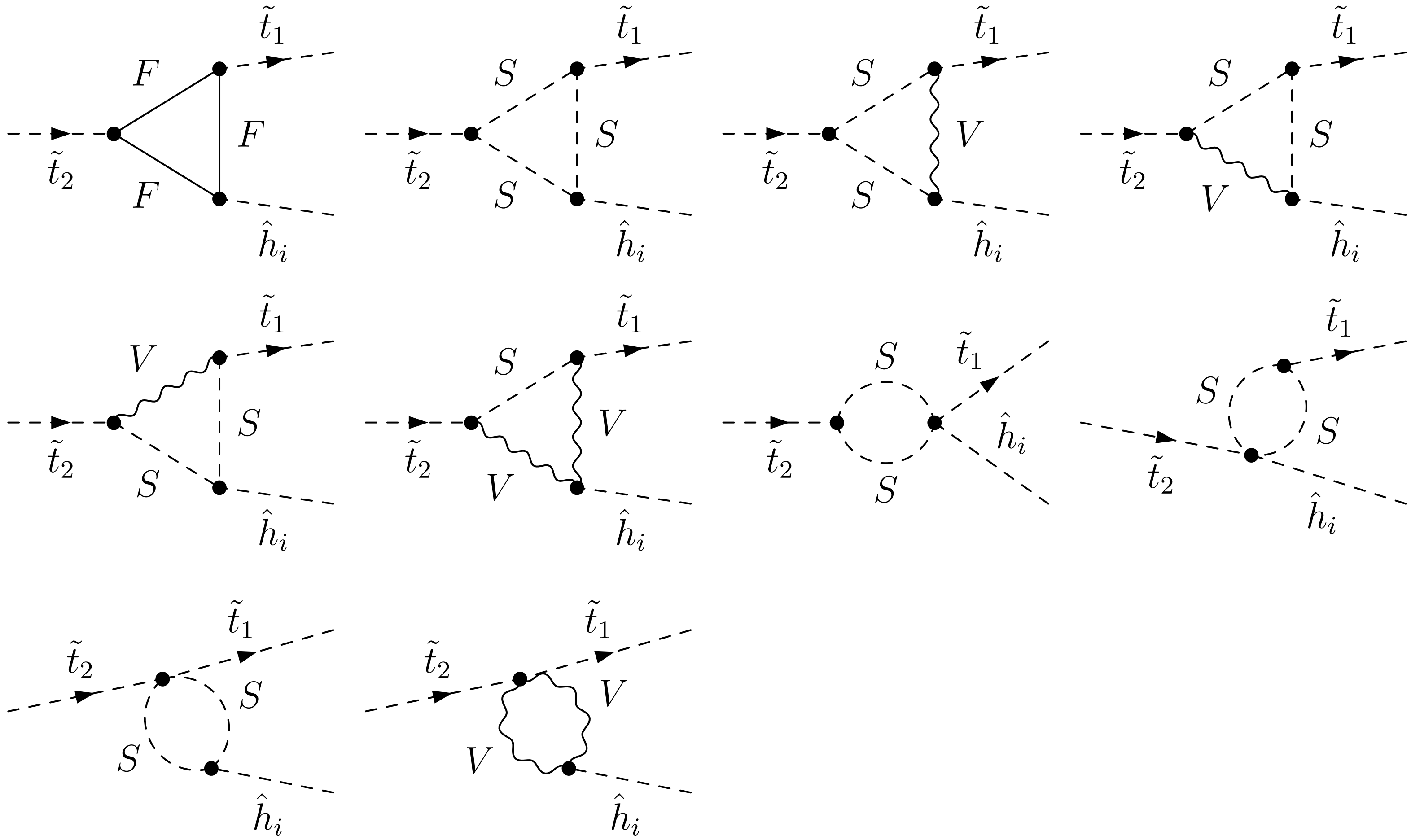
– Dimensional REDuction

– all UV and IR divergences cancel

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

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

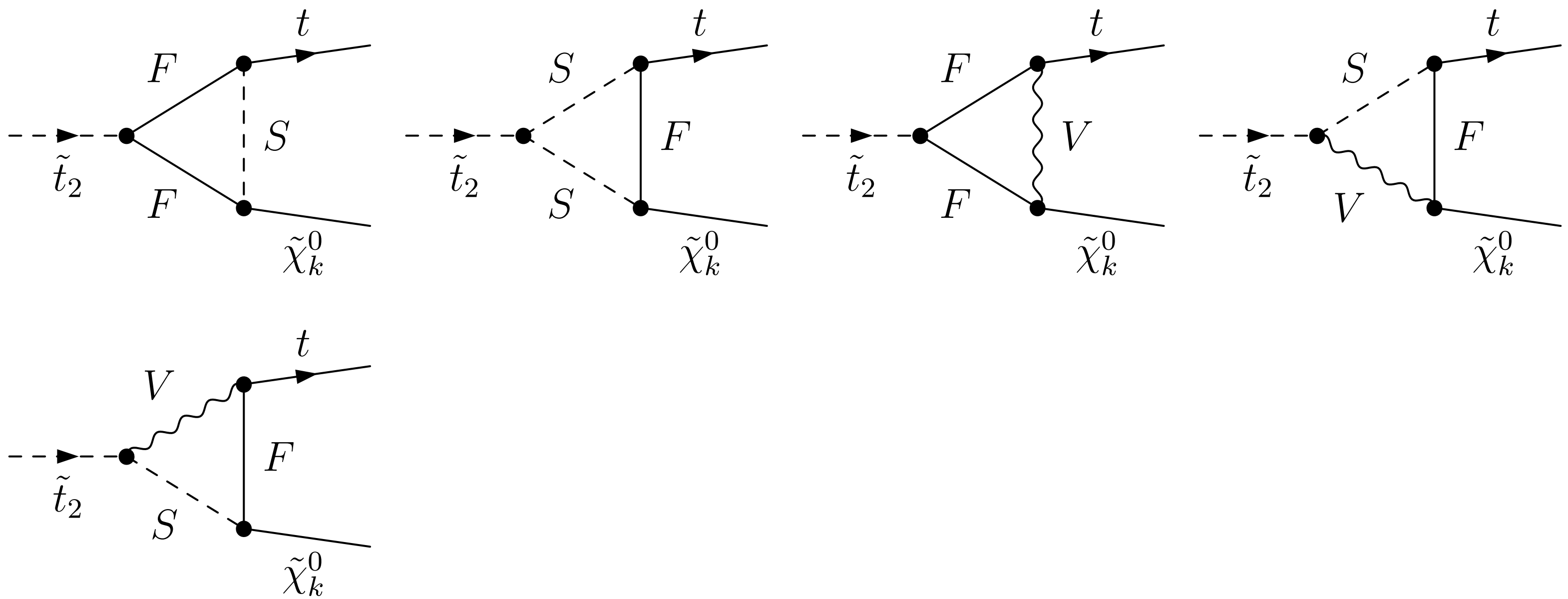
Feynman diagrams for $\tilde{t}_2 \to \tilde{t}_1 h_i$



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

– including all soft/hard QED/QCD diagrams

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



– including all soft/hard QED/QCD diagrams

Numerical scenarios:

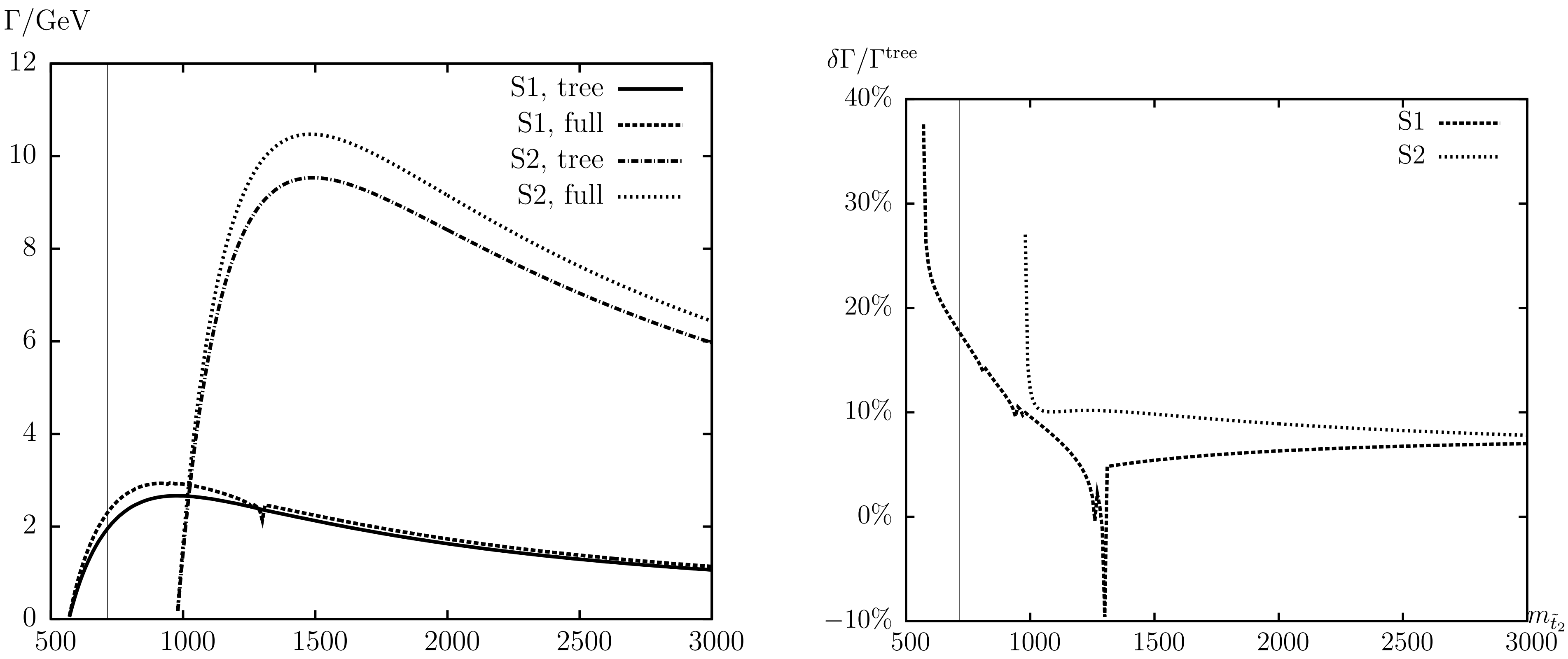
Scen.	$M_{H^\pm}$	$m_{\tilde{t}_2}$	$m_{\tilde{t}_1}$	$m_{\tilde{b}_2}$	μ	A_t	A_b	M_1	M_2	M_3
S1	150	650	$0.4\, m_{\tilde{t}_2}$	$0.7\, m_{\tilde{t}_2}$	200	900	400	200	300	800
S2	180	1200	$0.6\, m_{\tilde{t}_2}$	$0.8\, m_{\tilde{t}_2}$	300	1800	1600	150	200	400

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*]

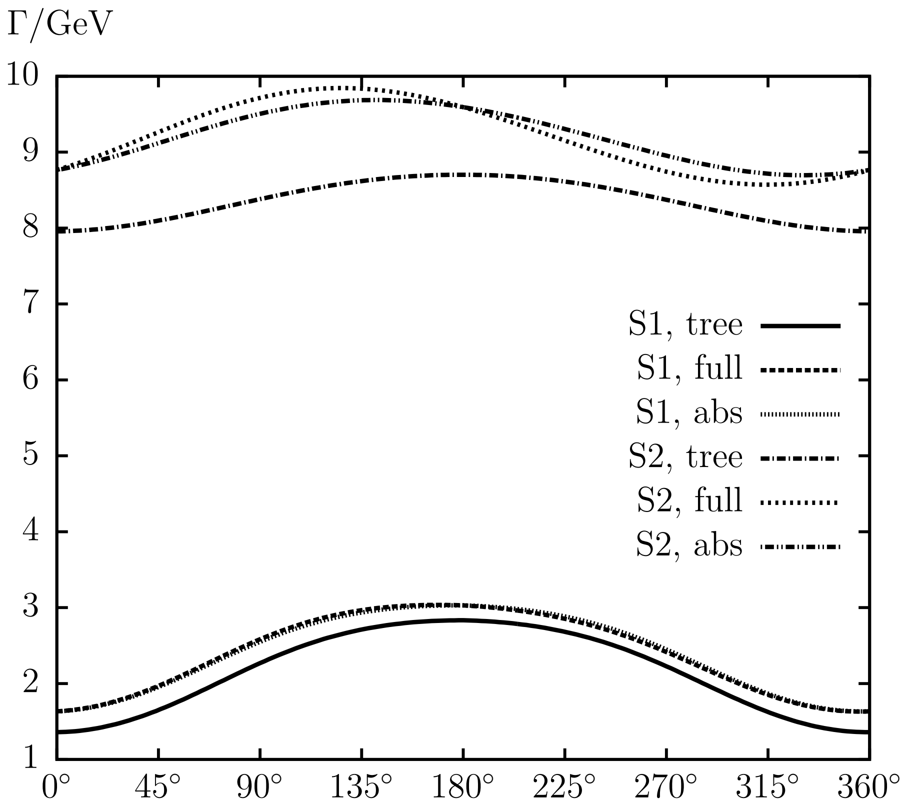


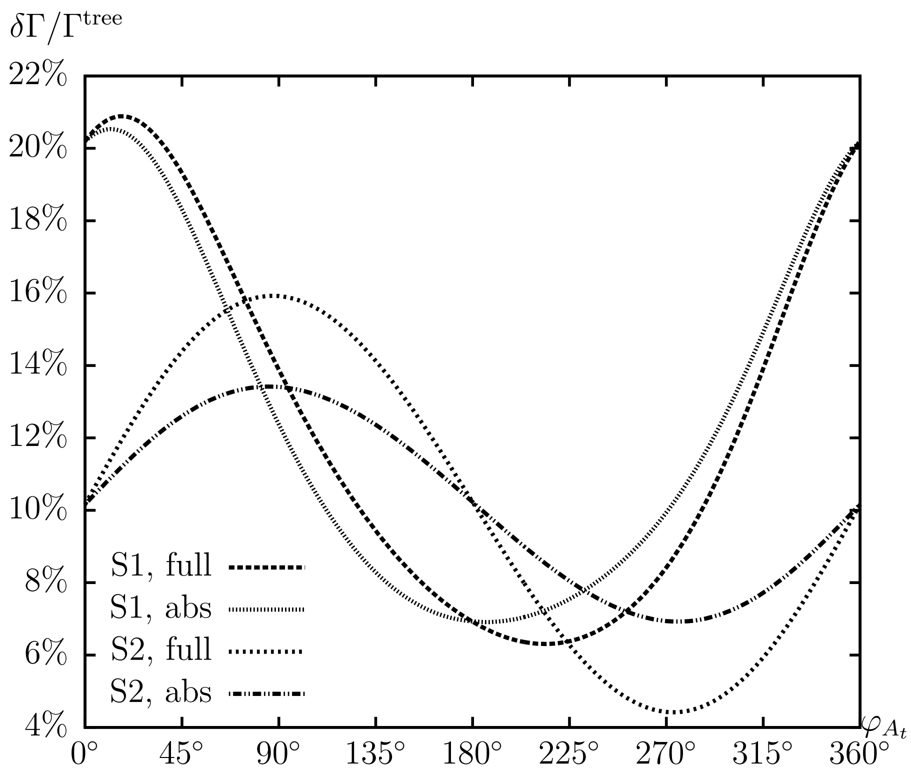
⇒ one-loop corrections under control and non-negligible

⇒ size of BR highly scenario dependent

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

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



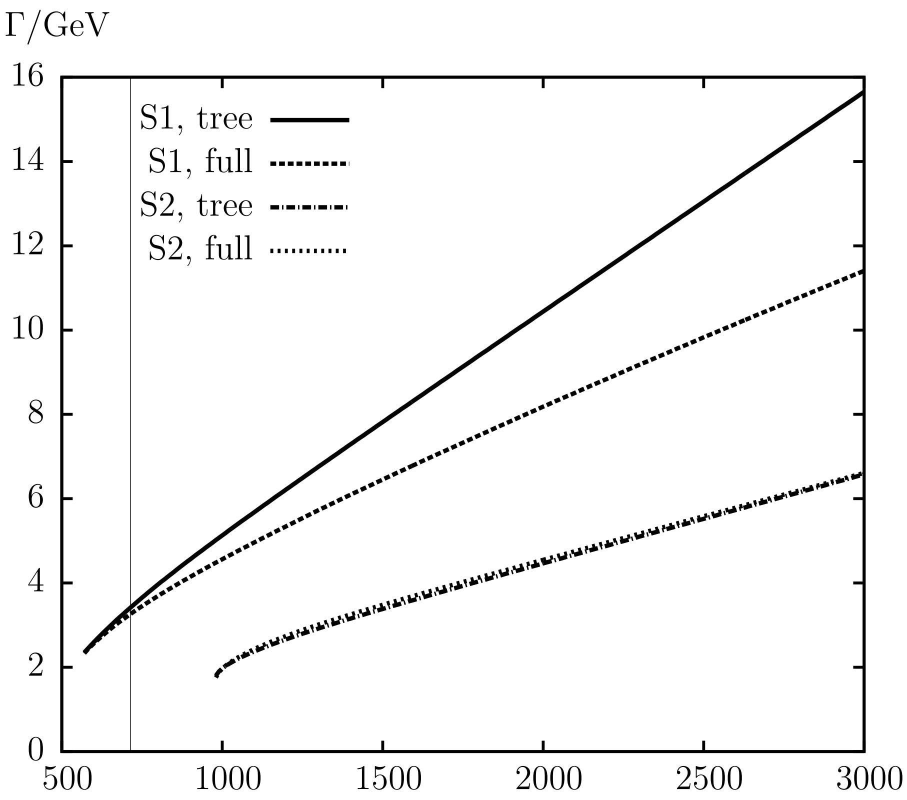


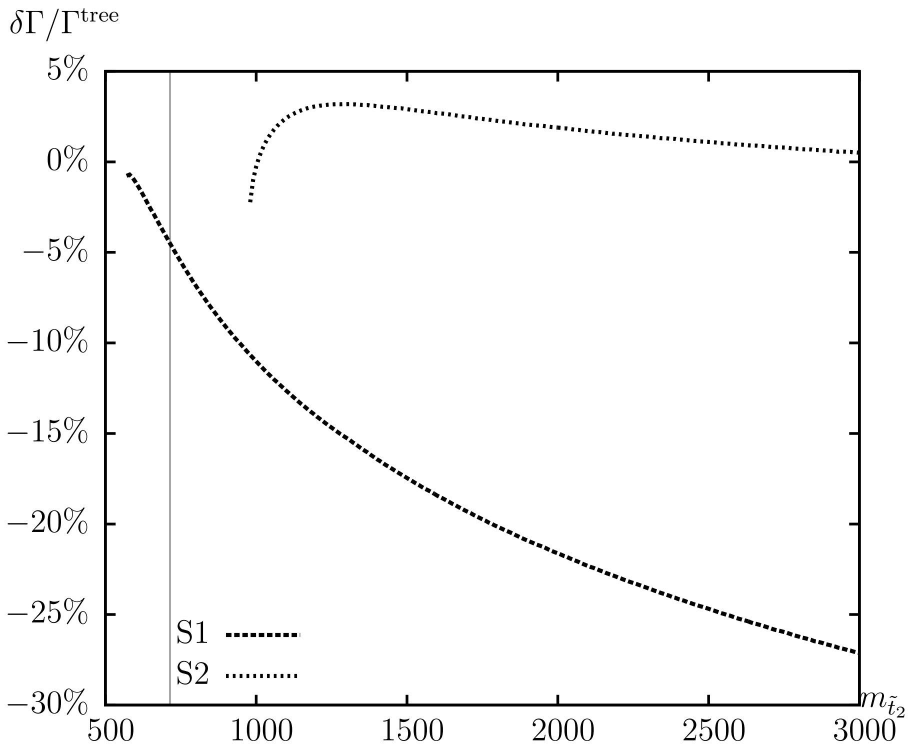
⇒ one-loop corrections under control and non-negligible

⇒ size of BR highly scenario dependent

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

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



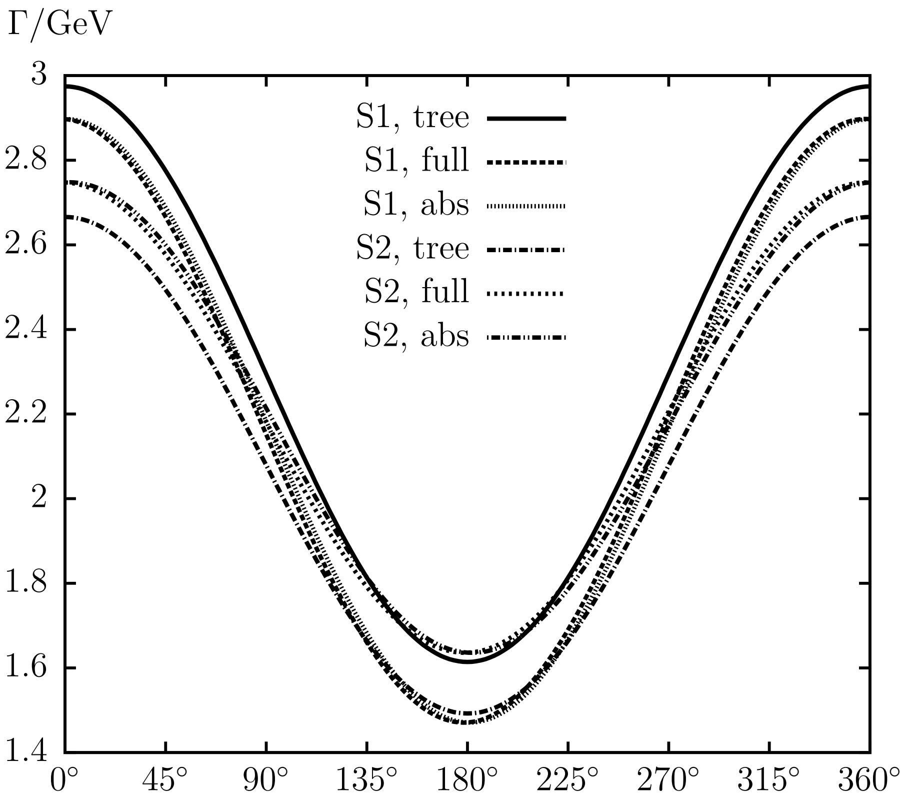


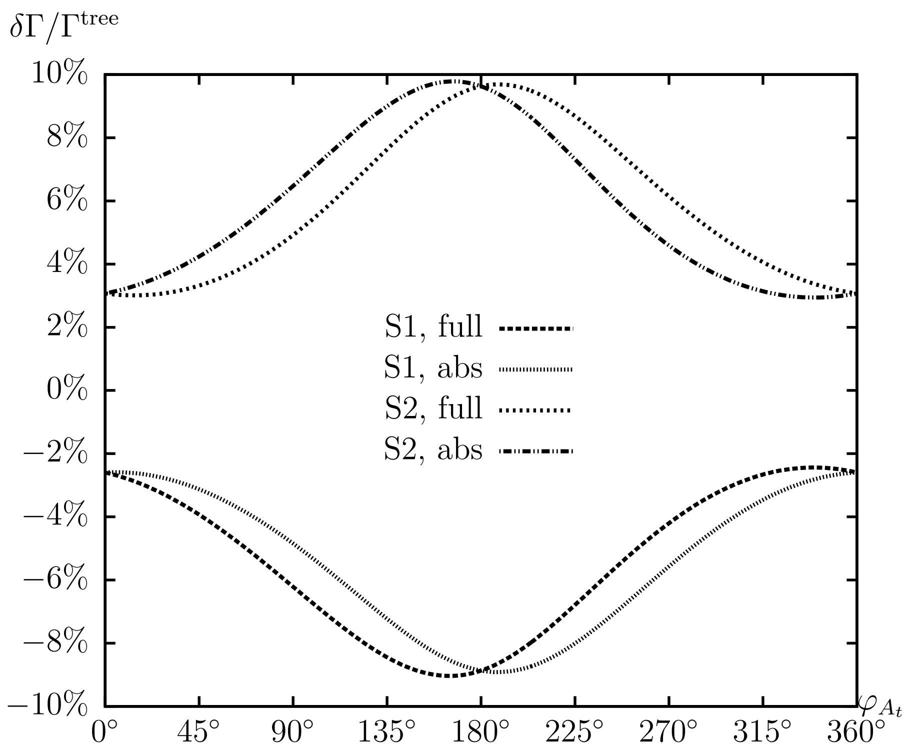
$\Rightarrow$ one-loop corrections under control and non-negligible

$\Rightarrow$ size of BR highly scenario dependent

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

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





⇒ one-loop corrections under control and non-negligible

⇒ size of BR highly scenario dependent

4B) Chargino decays

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

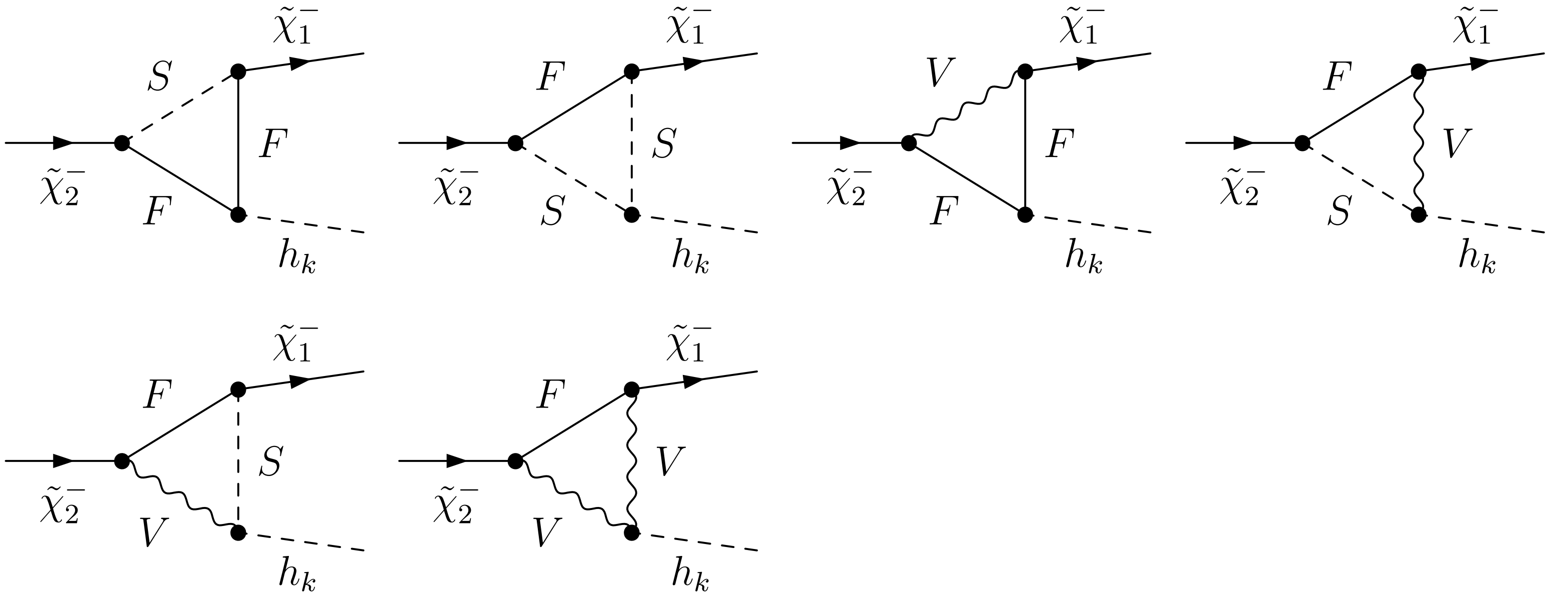
No hadronic decays yet . . .

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)

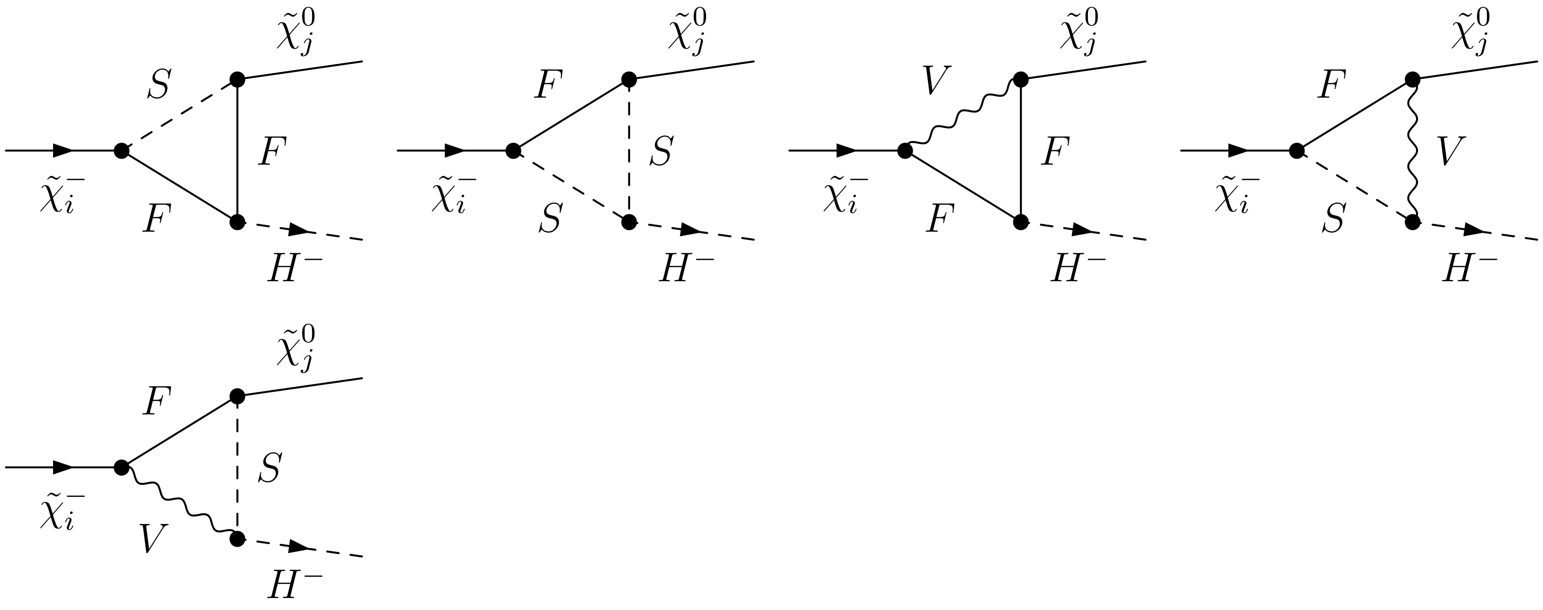
Feynman diagrams for $\tilde{\chi}_2^- \to \tilde{\chi}_1^- h_k$



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

– including all soft/hard QED/QCD diagrams

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

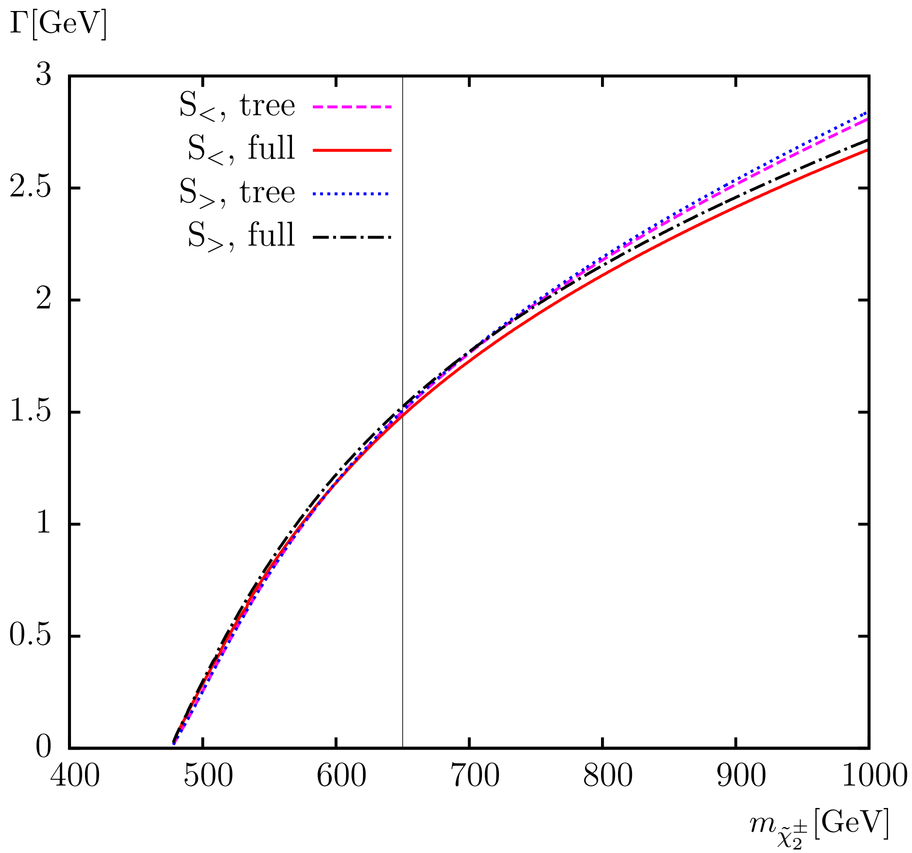


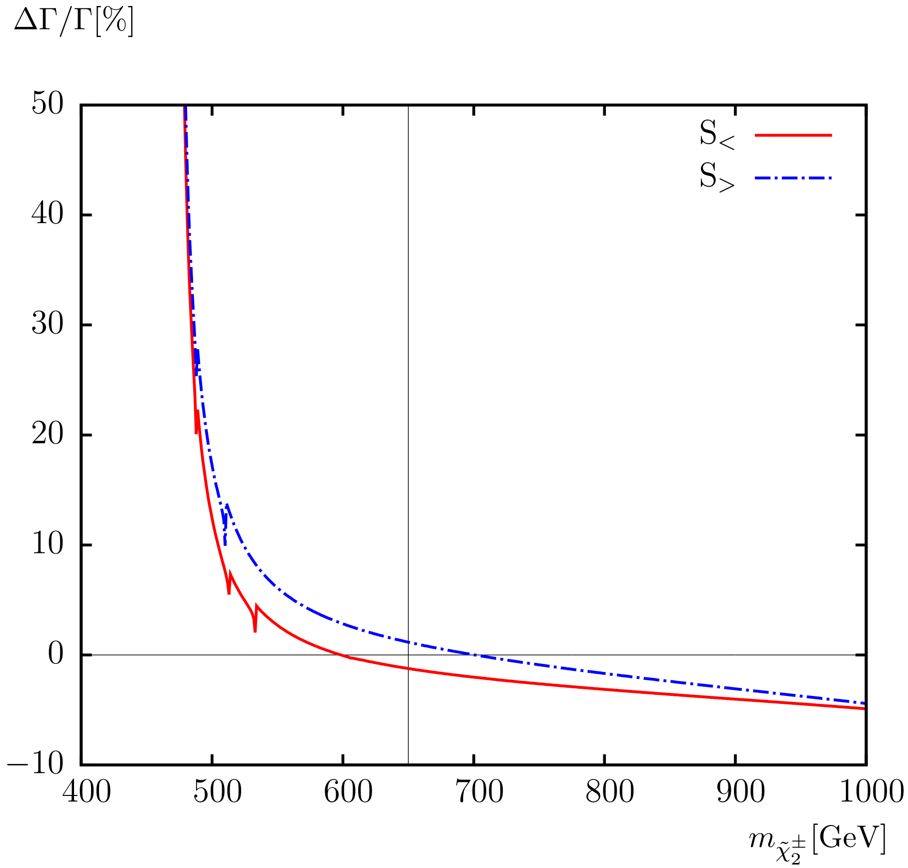
– including W^+–H^+ or G^+–H^+ transition contribution on the external Higgs boson leg

– including all soft/hard QED/QCD diagrams

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

[S.H., F. v.d. Pahlen, C. Schappacher '11]



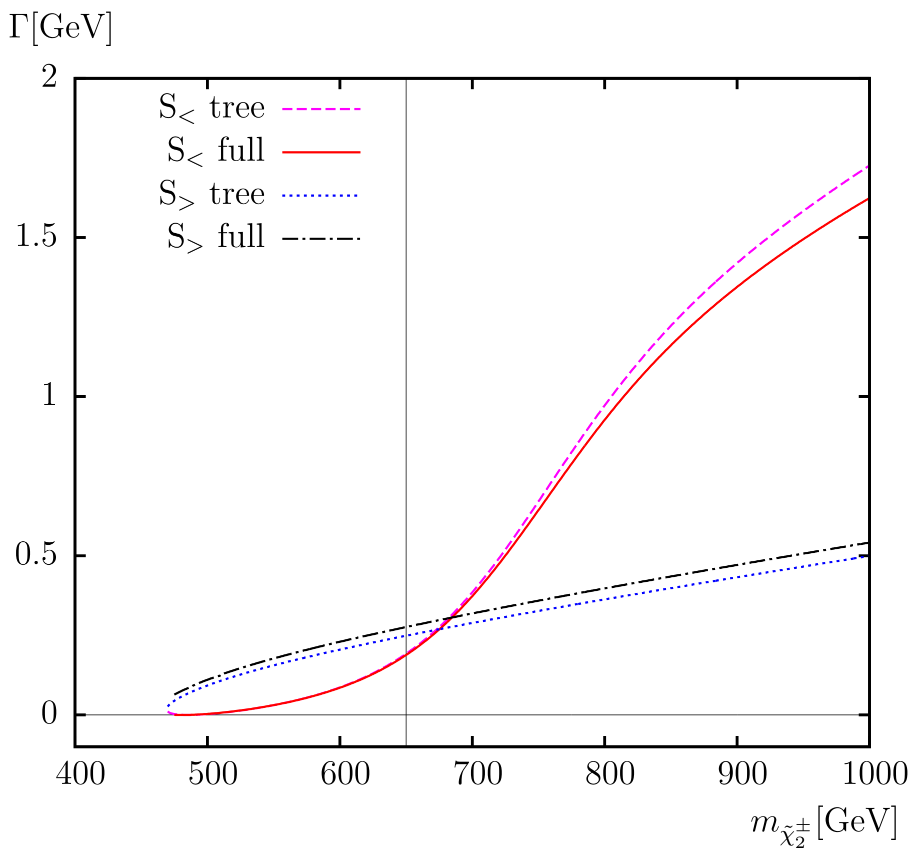


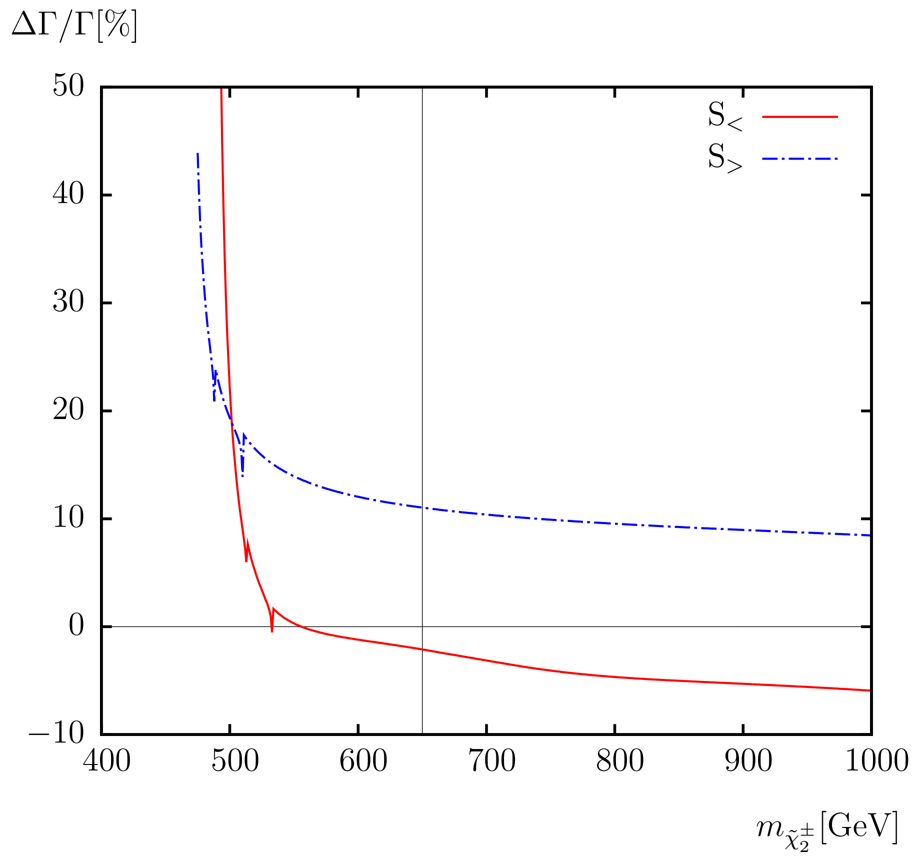
$\Rightarrow$ one-loop corrections under control and non-negligible

$\Rightarrow$ size of BR highly scenario dependent

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

[S.H., F. v.d. Pahlen, C. Schappacher '11]



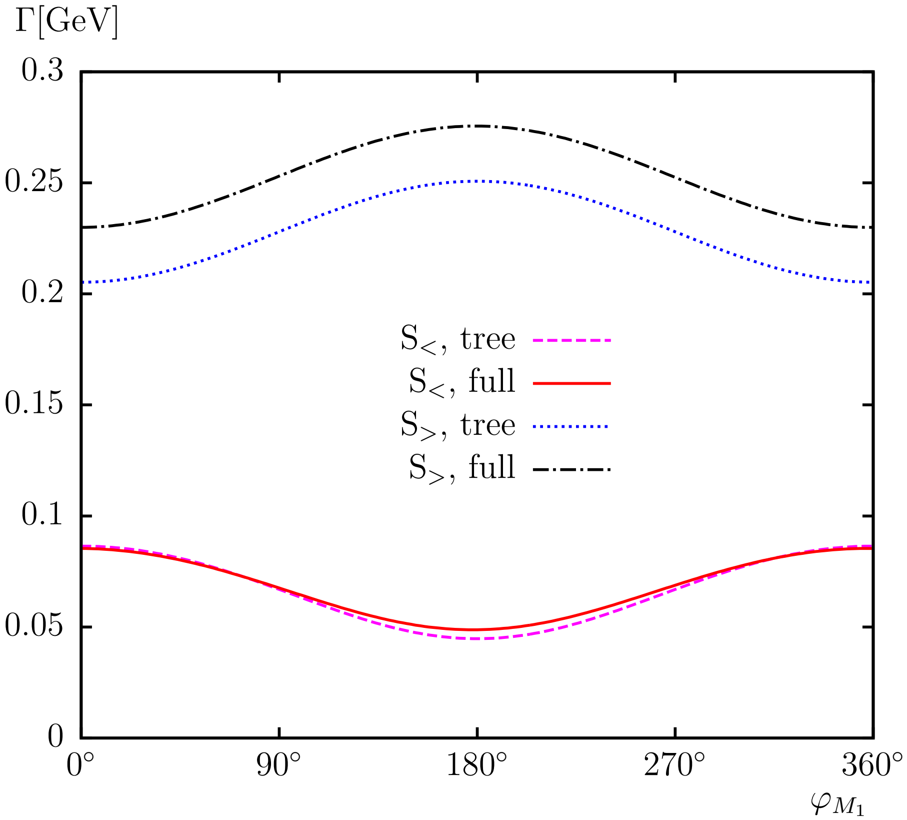


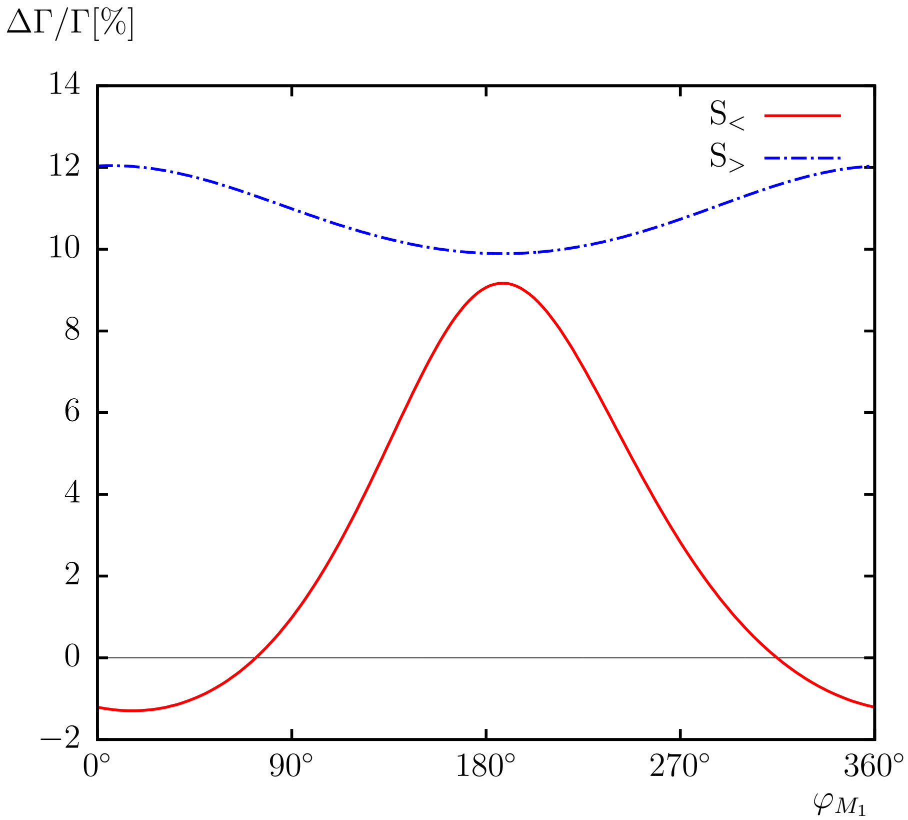
⇒ one-loop corrections under control and non-negligible

⇒ size of BR highly scenario dependent

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

[S.H., F. v.d. Pahlen, C. Schappacher '11]





⇒ one-loop corrections under control and non-negligible

⇒ size of BR highly scenario dependent

5. Conclusinos

- Needed: reliable prediction for SUSY cascades at the LHC

  Of special intrest: decays involving Higgs or LSP

- Our work: renormalization of the full cMSSM!

  $\Rightarrow$ 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

- Stop/Sbottom sector:
  – 6+ schemes compared
  – "m_b, A_b $\overline{\text{DR}}$" identified as preferred scheme

- Chargino/Neutralino sector:
  – 2 on-shell schemes compared
  – very good agreement found as expected

- FeynArts model file ready for cMSSM calculations

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