

# Towards Fully Automatized (N)MSSM Calculations

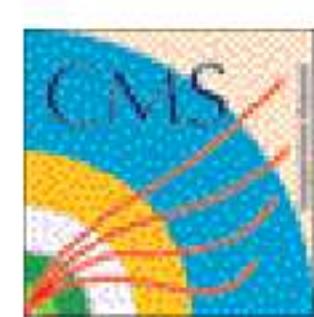
*Sven Heinemeyer, IFCA (CSIC, Santander)*

Wernigerode, 04/2012

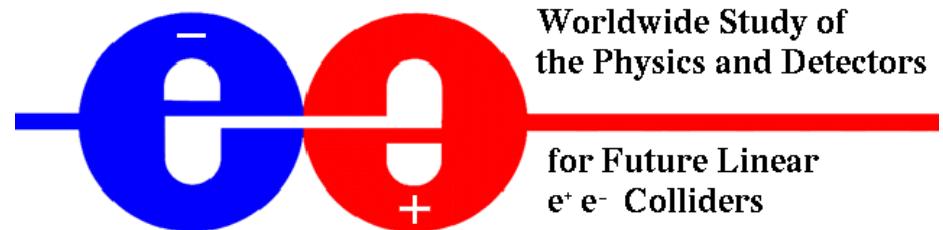
1. The Grand Scheme
2. Towards Fully Automatized MSSM Calculations
3. Towards Fully Automatized NMSSM Calculations  
→ connection to the real world!
4. Conclusions

## 1. The Grand Scheme

The LHC up and running . . .  
→ discovery of BSM physics this year?



The ILC is still coming . . .  
. . . a bit later than anticipated  
→ to investigate BSM physics



⇒ 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

⇒ concentrate on the (N)MSSM from now on

(other people ⇒ other guesses ⇒ other priorities . . . )

In any case:

⇒ we have to measure as many observables as possible

- masses
- branching ratios
- angular distributions
- cross sections
- . . .

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In any case:

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- masses
- branching ratios
- angular distributions
- cross sections
- . . .

⇒ compare with theory calculations at the same level of accuracy

## 2. Towards fully automatized MSSM Calculations

Superpartners for Standard Model particles

$$\begin{array}{lll} [u, d, c, s, t, b]_{L,R} & [e, \mu, \tau]_{L,R} & [\nu_{e,\mu,\tau}]_L \\ & & \text{Spin } \frac{1}{2} \\ [ \tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b} ]_{L,R} & [ \tilde{e}, \tilde{\mu}, \tilde{\tau} ]_{L,R} & [ \tilde{\nu}_{e,\mu,\tau} ]_L \\ & & \text{Spin } 0 \\ g \underbrace{W^\pm, \textcolor{orange}{H}^\pm}_{\tilde{g}} & \underbrace{\gamma, Z, H_1^0, H_2^0}_{\tilde{\chi}_{1,2}^\pm} & \text{Spin 1 / Spin 0} \\ & & \\ \tilde{g} & \tilde{\chi}_{1,2}^\pm & \text{Spin } \frac{1}{2} \\ & & \end{array}$$

Enlarged Higgs sector: Two Higgs doublets  $\Leftarrow$  focus here!

Problem in the MSSM: many scales

Problem in the MSSM: complex phases

## Where are we? (a selection!)

1. Neutral Higgs boson masses
  - $\mathcal{O}(\alpha_t \alpha_s)$  in the cMSSM [S.H., W. Hollik, H. Rzehak, G. Weiglein '07]
  - $\mathcal{O}(\alpha_t \alpha_s^2)$ ,  $\mathcal{O}(\alpha_t^2 \alpha_s)$ , rMSSM [S. Martin '07]
  - $\mathcal{O}(\alpha_t \alpha_s^2)$ , rMSSM (incl. fin. terms) [Haarlander, Kant, Mihaila, Steinhauser '08]
2. Charged Higgs mass full 1-loop [M. Frank et al. '06]
3. Production cross sections at the LHC [R. Haarlander et al. '12]
  - $gg \rightarrow h$  at 2-loop [C. Anastasiou et al. '08][M. Mühlleitner et al. '08][P. Slavich et al. '11]
  - WBF at 1-loop [M. Ciccolini et al. '07][W. Hollik et al. '08][S. Palmer, G. Weiglein '11]
  - $bb \rightarrow h$ : 4FS vs. 5FS, Santander matching  
[S. Dittmaier et al. '06][S. Dawson et al. '06][R. Haarlander et al. '11]
  - Z-factors at 2-loop [M. Frank, T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '06]
4. Higgs decays
  - full 1-loop (depending on final state) [...]
  - Z-factors at 2-loop [M. Frank, T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '06]
5. Decays to Higgs bosons
  - (partial) 1-loop, rMSSM [...]
  - (partial) 1-loop, cMSSM [H. Rzehak, G. Weiglein, K. Williams]  
[T. Fritzsche, S.H., F. v.d. Pahlen, H. Rzehak, C. Schappacher]

## What is missing? (a selection!)

1. Neutral Higgs boson masses
  - full 2-loop
  - more 3-loop (and in “easier accessible” scheme?)
  - leading 4-loop
2. Charged Higgs boson mass
  - leading 2-loop
3. Higgs decays
  - full 1-loop in the r/cMSSM (some final states)
  - leading 2-loop
4. Decays to Higgs bosons
  - full 1-loop in the rMSSM
  - full 1-loop in the cMSSM

⇒ provide corresponding codes!

## 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
- ⇒ this is the biggest issue!

## Enlarged Higgs sector: Two Higgs doublets

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

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

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{\text{gauge couplings, in contrast to SM}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{\text{gauge couplings, in contrast to SM}} |H_1 \bar{H}_2|^2$$

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)

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

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

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

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

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

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gauge couplings, in contrast to SM

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

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

Input parameters: (to be determined experimentally)

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

## 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  $\phi_{\text{PQ}}$

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

$\Rightarrow m_{12}$  can always be chosen real

- phase of  $H_2$ :  $\xi$ :

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

$\Rightarrow \xi = 0 \Rightarrow$  no  $\mathcal{CPV}$  at tree-level

## The Higgs sector of the cMSSM at the loop-level:

Complex parameters enter via loop corrections:

- $\mu$  : 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:

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

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

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

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

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

soft SUSY-breaking parameters  $A_t, A_b$  also appear in  $\phi$ - $\tilde{t}/\tilde{b}$  couplings

$$m_{\tilde{t}_{1,2}}^2 = m_t^2 + \frac{1}{2} \left( M_{\tilde{t}_L}^2 + M_{\tilde{t}_R}^2 \mp \sqrt{(M_{\tilde{t}_L}^2 - M_{\tilde{t}_R}^2)^2 + 4m_t^2 |X_t|^2} \right)$$

$\Rightarrow$  independent of  $\phi_{X_t}$   
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:

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

⇒ charginos: mass eigenstates

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

neutral:

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

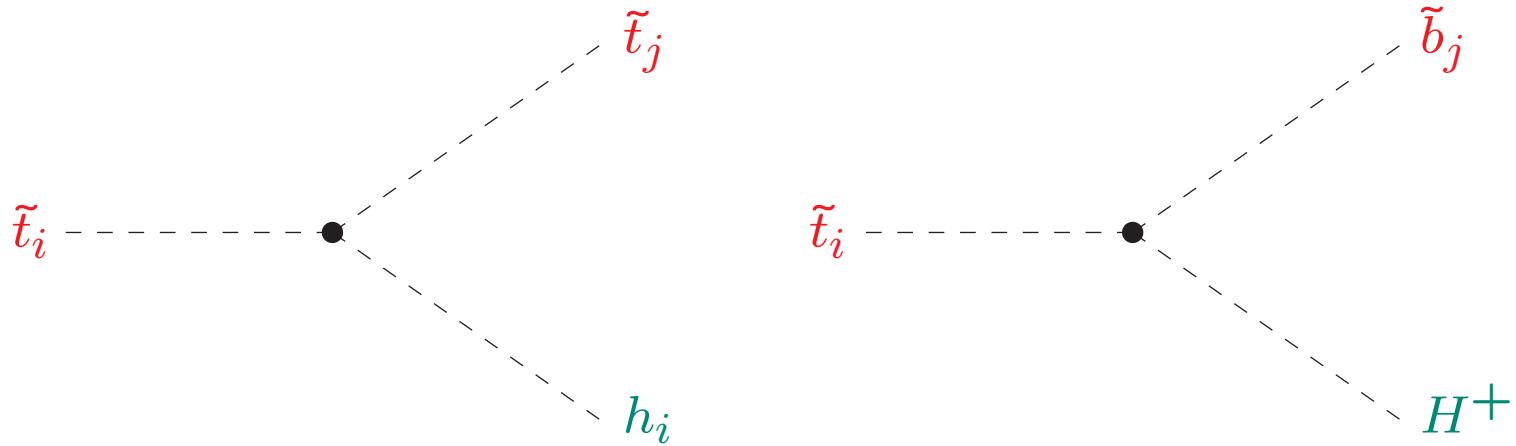
⇒ neutralinos: mass eigenstates

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

⇒ only one new parameter

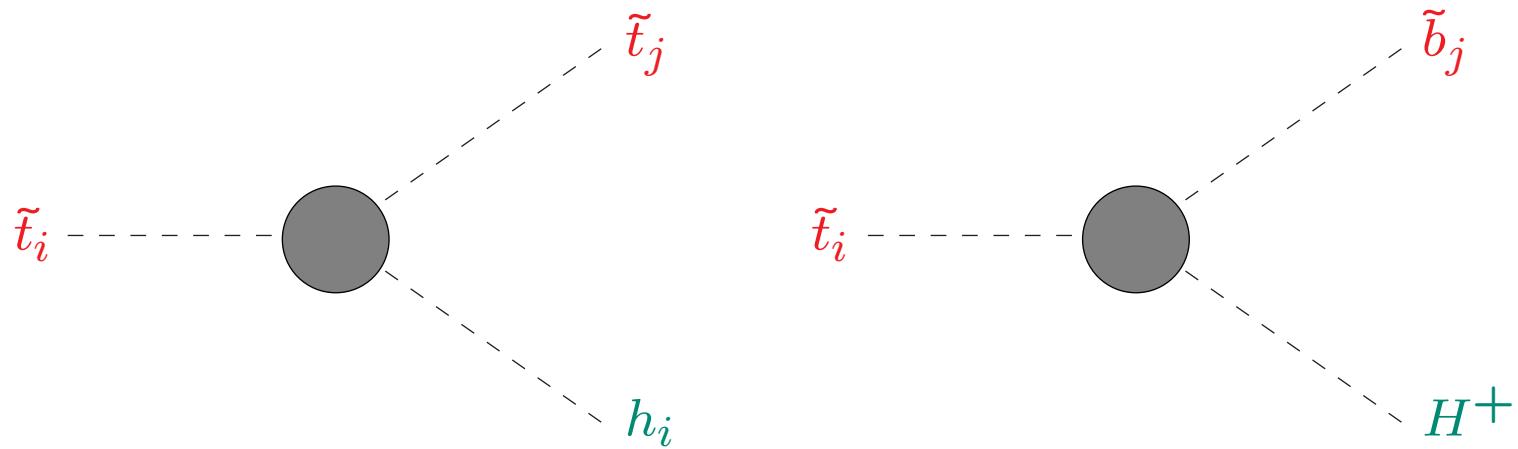
⇒ MSSM predicts mass relations between neutralinos and charginos

## 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
- ...

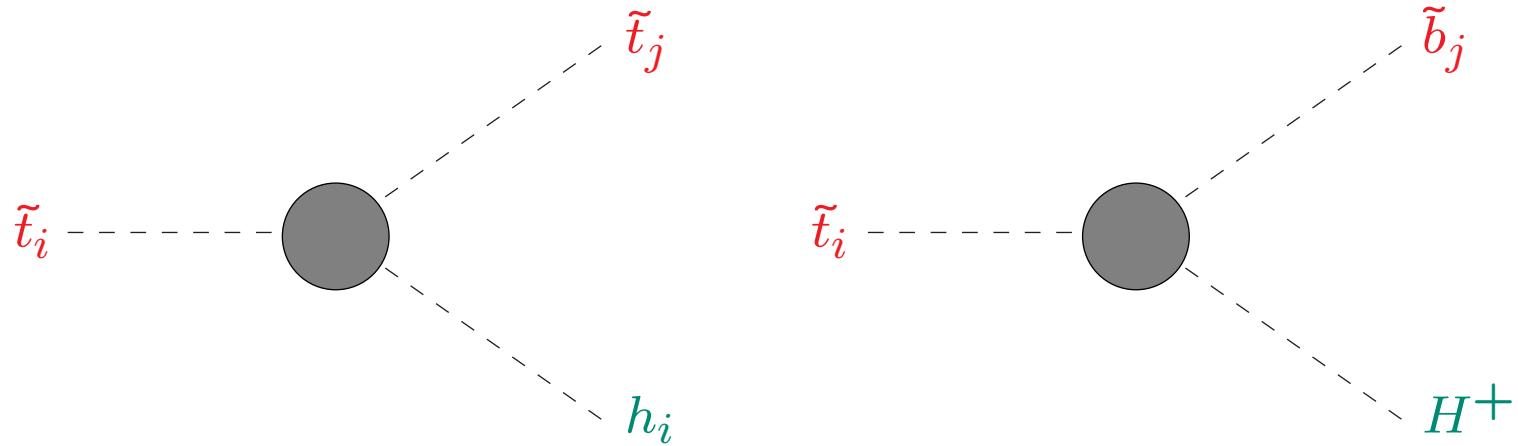
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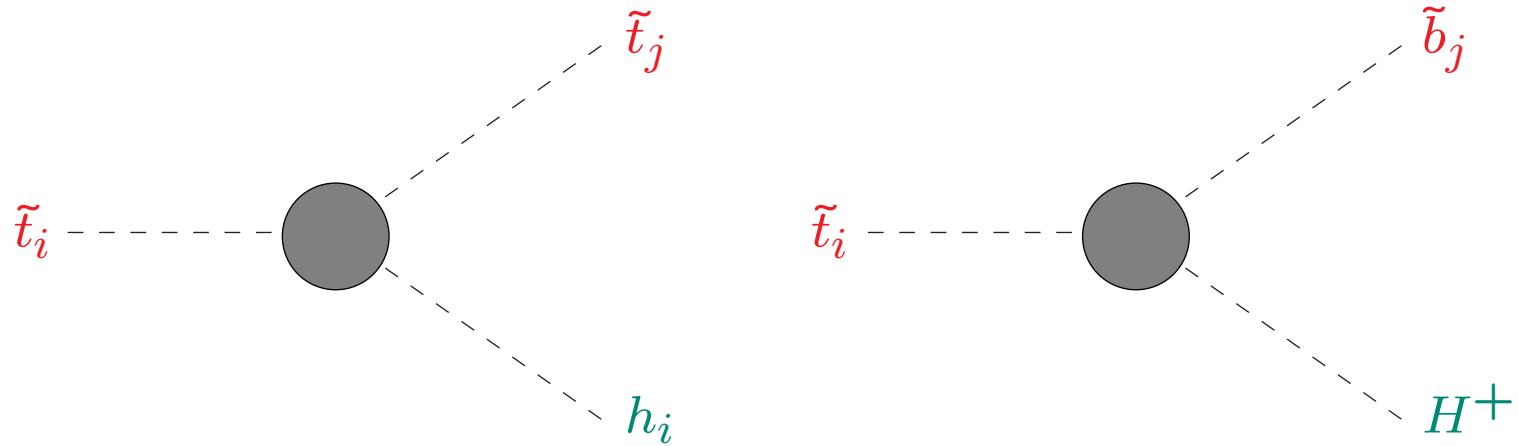


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⇒ simultaneous renormalization of stop and sbottom sector required!

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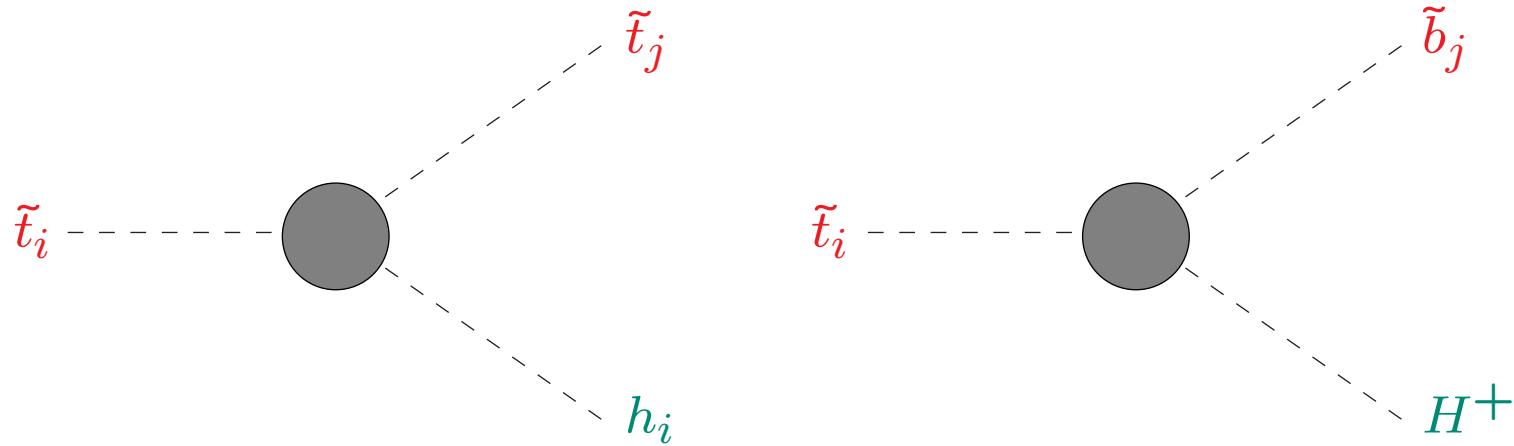


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⇒ higher-order corrections important!

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

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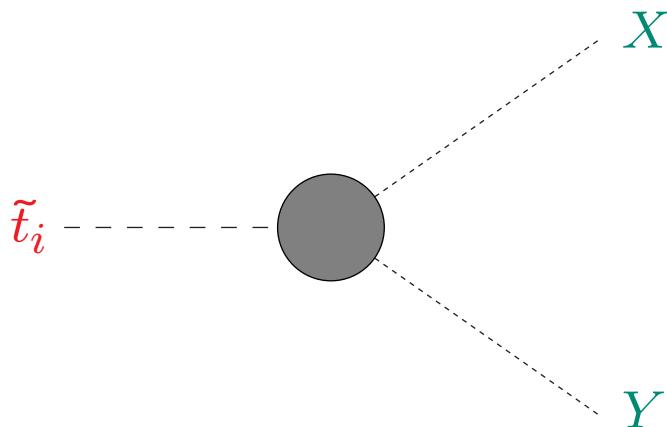


- important decay modes of stops
- $A_t$  and  $A_b$  directly enter the vertex incl. complex phases!
- possible source of Higgs bosons at the LHC/ILC
- ...

⇒ higher-order corrections important!

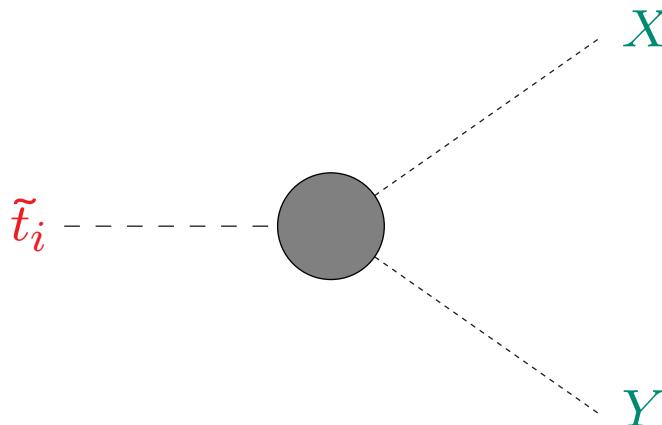
⇒ simultaneous renormalization of stop and sbottom sector required!  
⇒ including complex phases!

## 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



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

now ready:

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

⇒ 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 sector [*H. Rzehak et al. '04, '07*]
  - \* complex chargino/neutralino sector [*T. Fritzsche et al. '11*][*A. Fowler et al. '10*]  
[*M. Drees et al. '11*]
  - \* complex gluino sector

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

⇒ no longer possible

⇒ working FeynArts model file now ready!

- hard QED and QCD radiation

## Complex renormalization:

- 1)  $A_t$  complex

⇒ renormalization of  $|A_t|$  and  $\phi_{A_t}$ :  $\delta A_t = e^{i\phi_{A_t}} \delta |A_t| + i |A_t| \delta \phi_{A_t}$

⇒  $\overline{\text{DR}}$  renormalization

- 2) alternatively  $\theta_{\tilde{t}}$  complex

⇒ renormalization of  $|\theta_{\tilde{t}}|$  and  $\phi_{\tilde{t}}$ :

⇒ On-shell renormalization via

$$\widetilde{\text{Re}}\hat{\Sigma}_{\tilde{t}12}(m_{\tilde{t}1}^2) + \widetilde{\text{Re}}\hat{\Sigma}_{\tilde{t}12}(m_{\tilde{t}2}^2) \stackrel{!}{=} 0$$

$$\Rightarrow \widetilde{\text{Re}}\Sigma_{\tilde{t}12}(m_{\tilde{t}1}^2) + \widetilde{\text{Re}}\Sigma_{\tilde{t}12}(m_{\tilde{t}2}^2) = e^{i\phi_{\tilde{t}}}(m_{\tilde{t}1}^2 - m_{\tilde{t}2}^2) \times (\delta\theta_{\tilde{t}} + i s_{\tilde{t}} c_{\tilde{t}} \delta\phi_{\tilde{t}})$$

⇒ evaluate  $\delta|A_t|$  and  $\delta\phi_{A_t}$  as dependent parameters

- 3)  $A_b, \theta_{\tilde{b}}$  complex

→ like for  $A_t, \theta_{\tilde{t}}$

Note:  $\delta m_{\tilde{b}_1}^2$  cannot be fixed via on-shell condition anymore

⇒ dependent parameter, enters  $\delta A_b, \delta\phi_{A_b}$

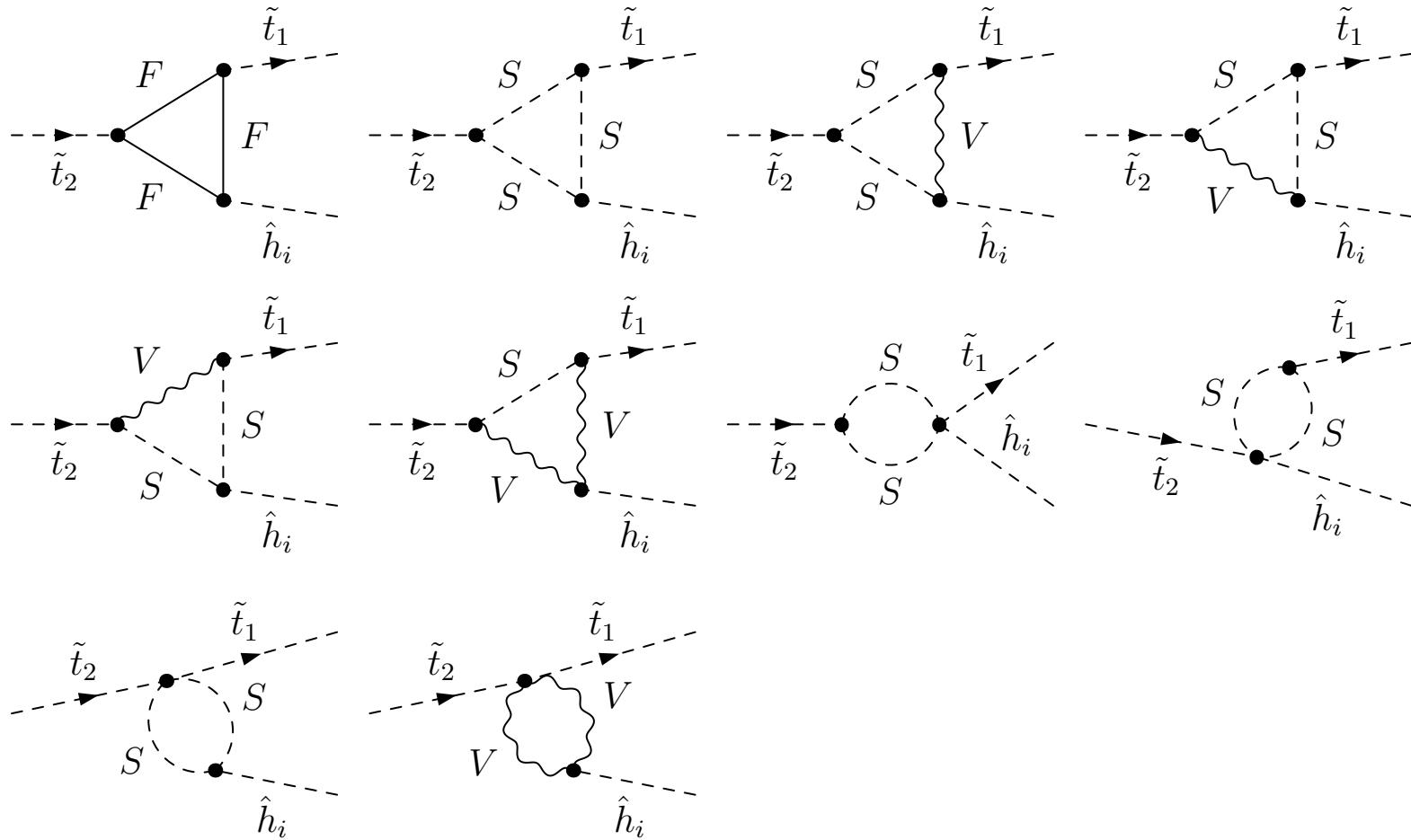
- 4)  $M_1, M_2, \mu$  complex

⇒ On-shell conditions for  $m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^\pm}, m_{\tilde{\chi}_1^0}$

## Calculation of partial widths and branching ratios:

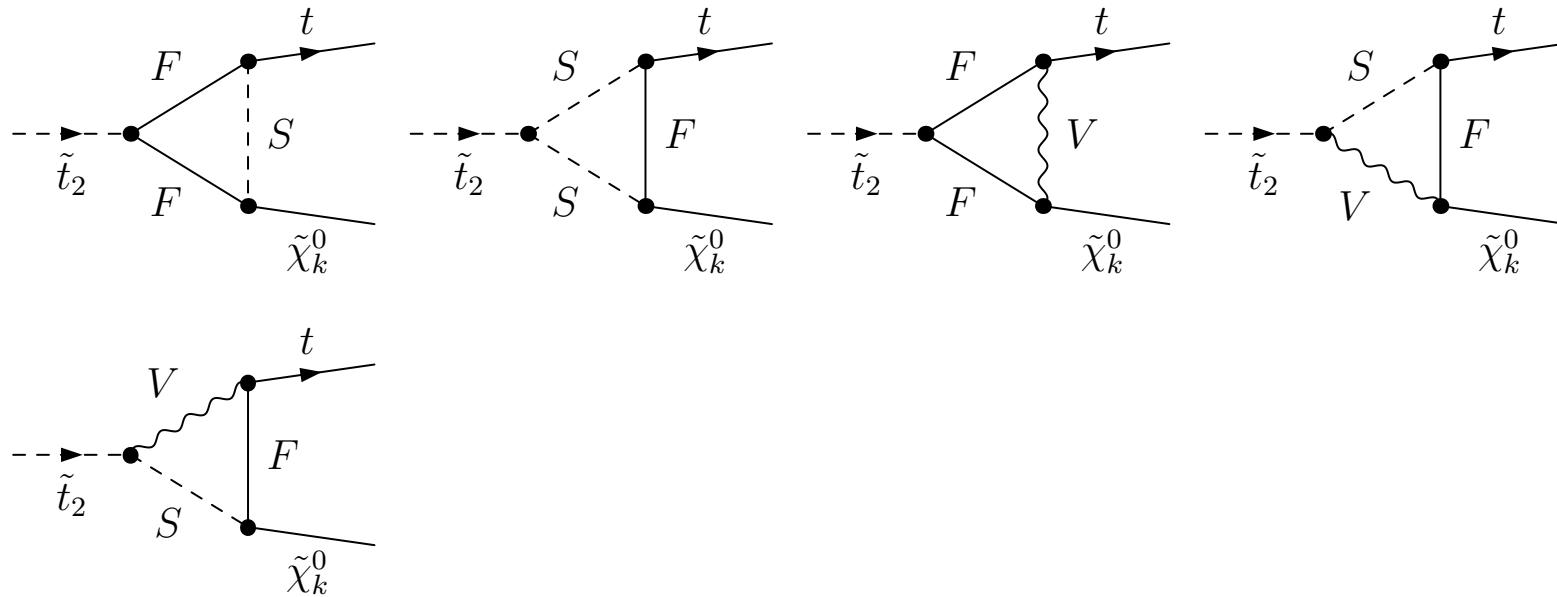
- all diagrams created with **FeynArts** →  $T\bar{T}$   
⇒ model file with all counterterms in the cMSSM
  - including all soft/hard QED/QCD diagrams
  - further evaluation with **FormCalc**
  - Dimensional **RED**uction
  - all **UV** and **IR** divergences cancel
  - results will be included into **FeynHiggs** ([www.feynhiggs.de](http://www.feynhiggs.de))
- example plots will focus on  $\text{BR}(\tilde{t}_2 \rightarrow \tilde{t}_1 h_1)$ ,  $\text{BR}(\tilde{t}_2 \rightarrow t \tilde{\chi}_1^0)$

## 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 $\tilde{t}_2 \rightarrow t \tilde{\chi}_1^0$



– including all soft/hard QED/QCD diagrams

## Numerical scenarios:

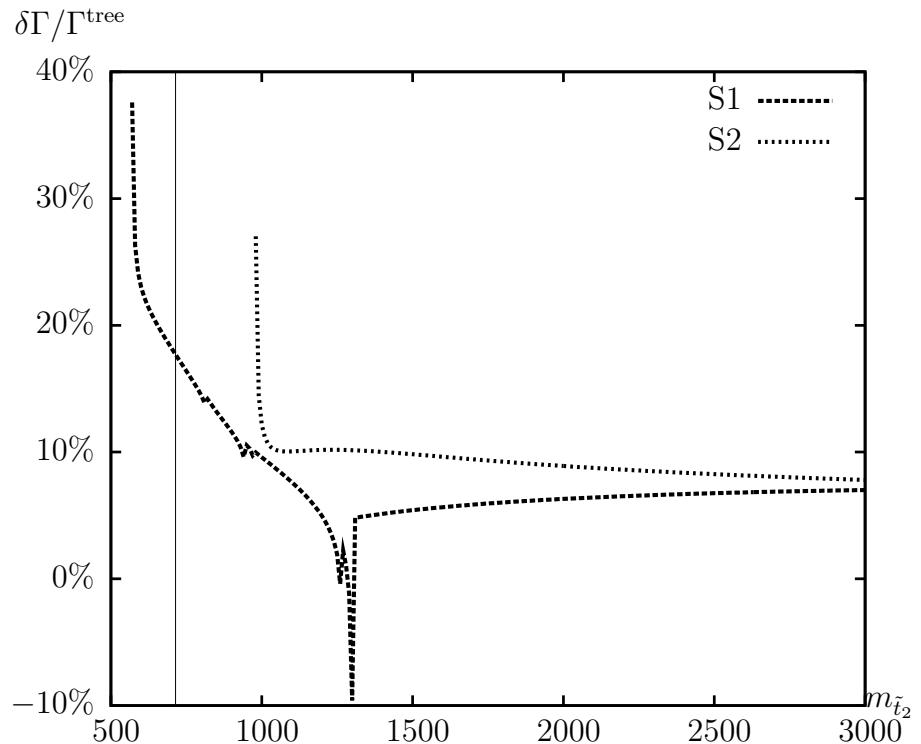
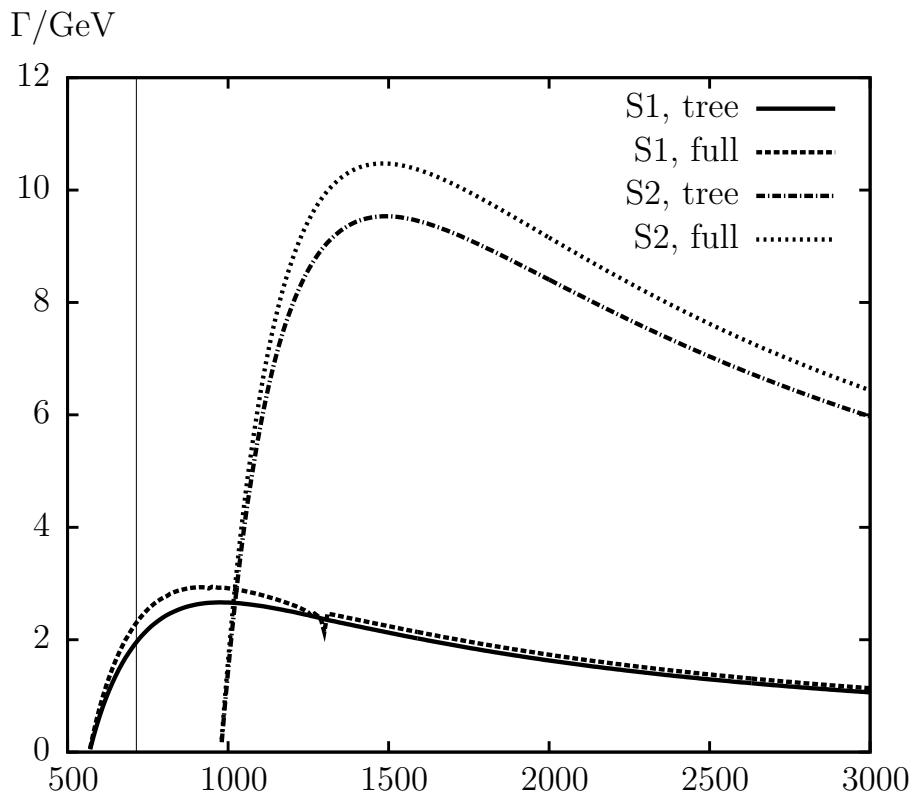
Scen.	$M_{H^\pm}$	$m_{\tilde{t}_2}$	$m_{\tilde{t}_1}$	$m_{\tilde{b}_2}$	$\mu$	$A_t$	$A_b$	$M_1$	$M_2$	$M_3$
S1	150	650	$0.4 m_{\tilde{t}_2}$	$0.7 m_{\tilde{t}_2}$	200	900	400	200	300	800
S2	180	1200	$0.6 m_{\tilde{t}_2}$	$0.8 m_{\tilde{t}_2}$	300	1800	1600	150	200	400

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

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

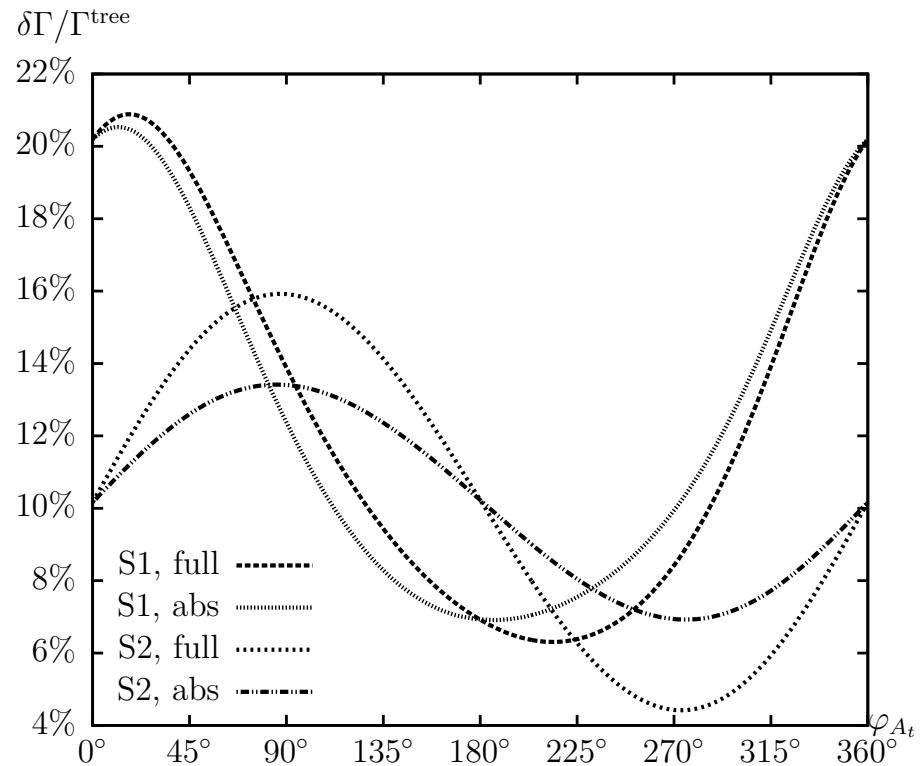
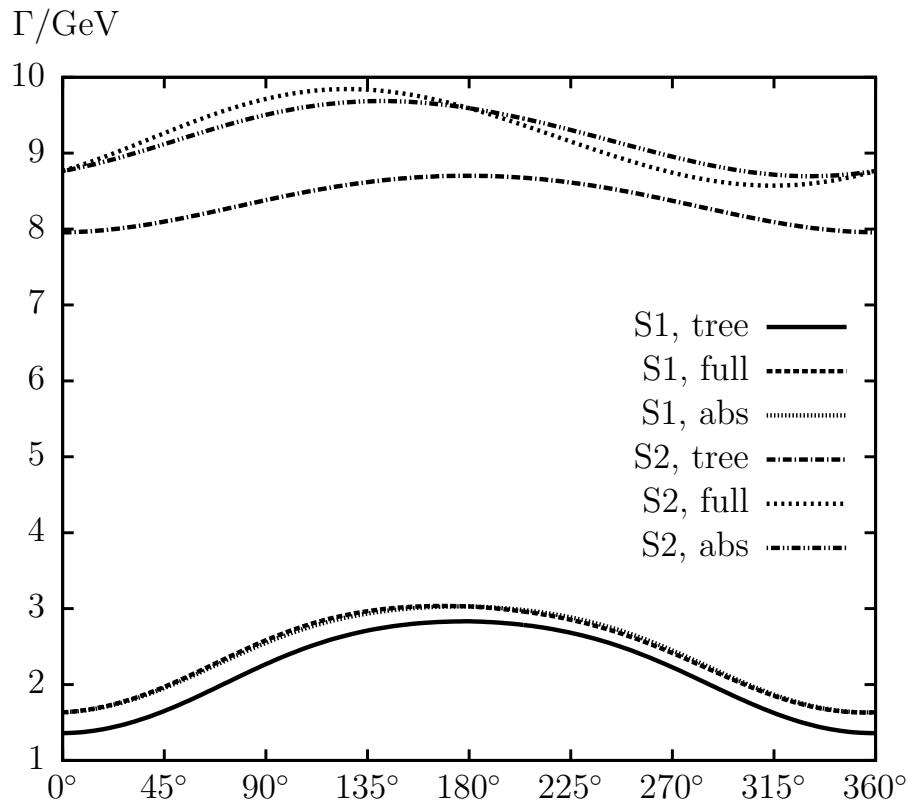
[T. Fritzsch, S.H., H. Rzehak, C. Schappacher '11]



- ⇒ one-loop corrections under control and non-negligible
- ⇒ size of BR **highly** scenario dependent

## $\Gamma(\tilde{t}_2 \rightarrow \tilde{t}_1 h_1)$ : dependence on $\phi_{A_t}$

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

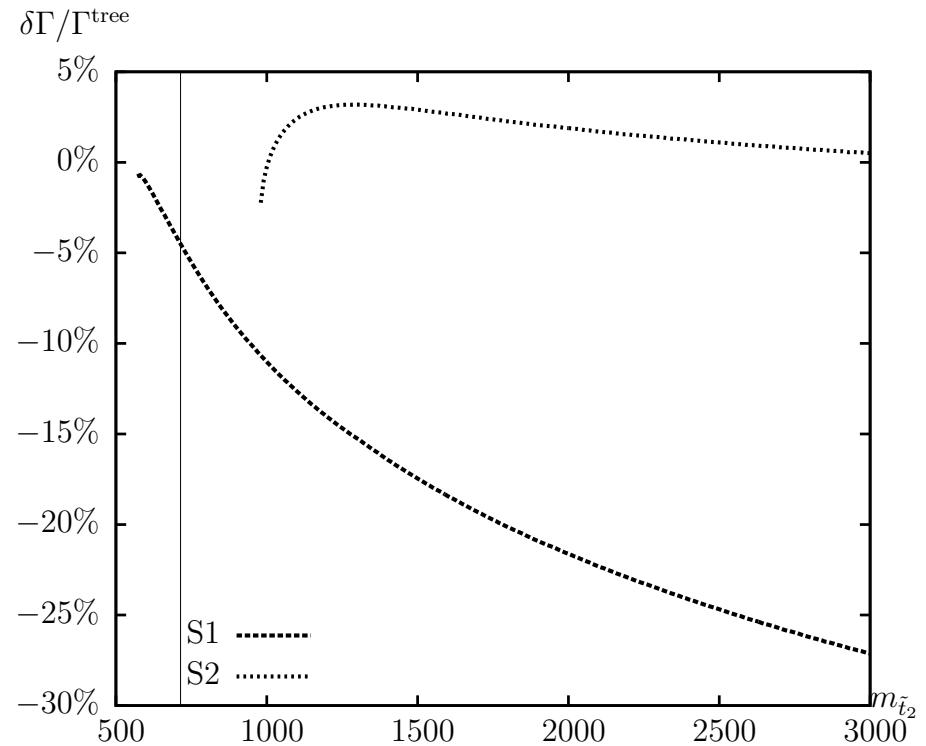
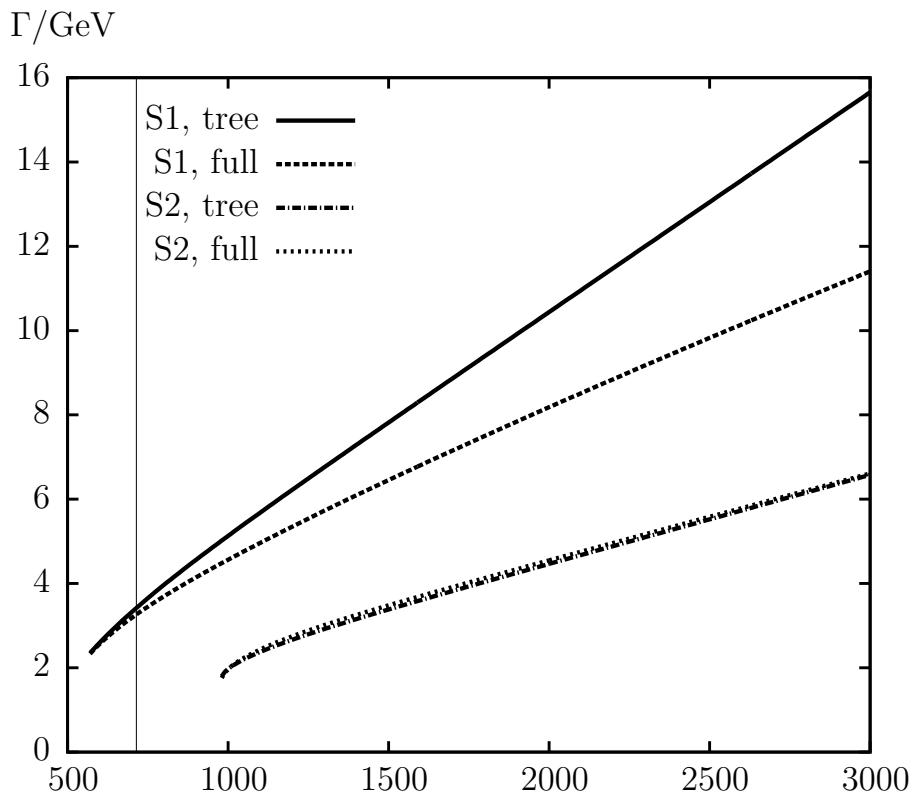


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# $\Gamma(\tilde{t}_2 \rightarrow t\tilde{\chi}_1^0)$ : dependence on $m_{\tilde{t}_2}$

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

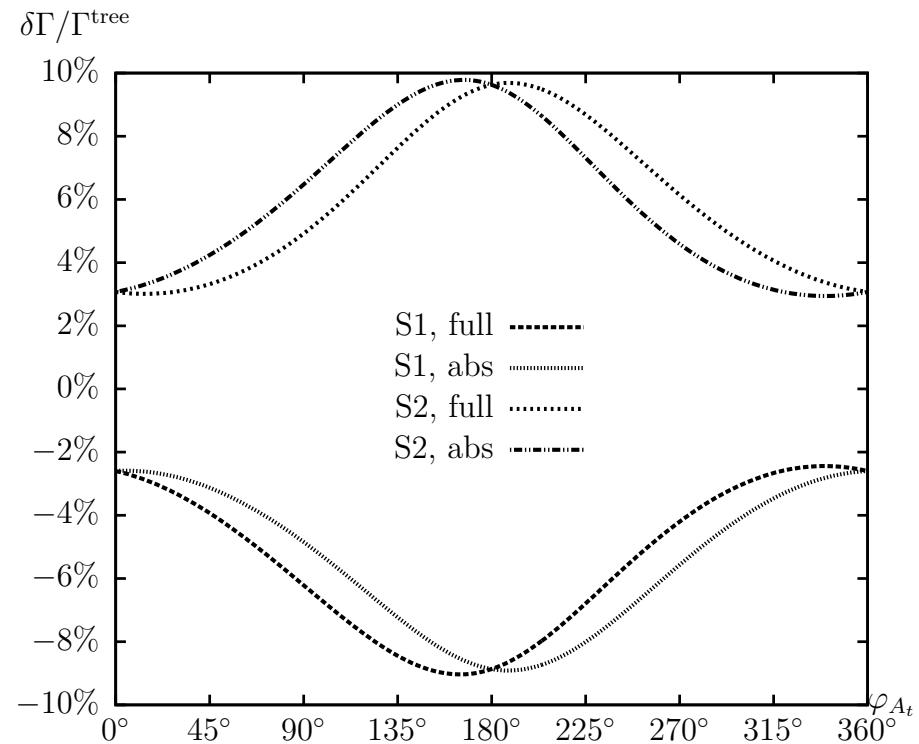
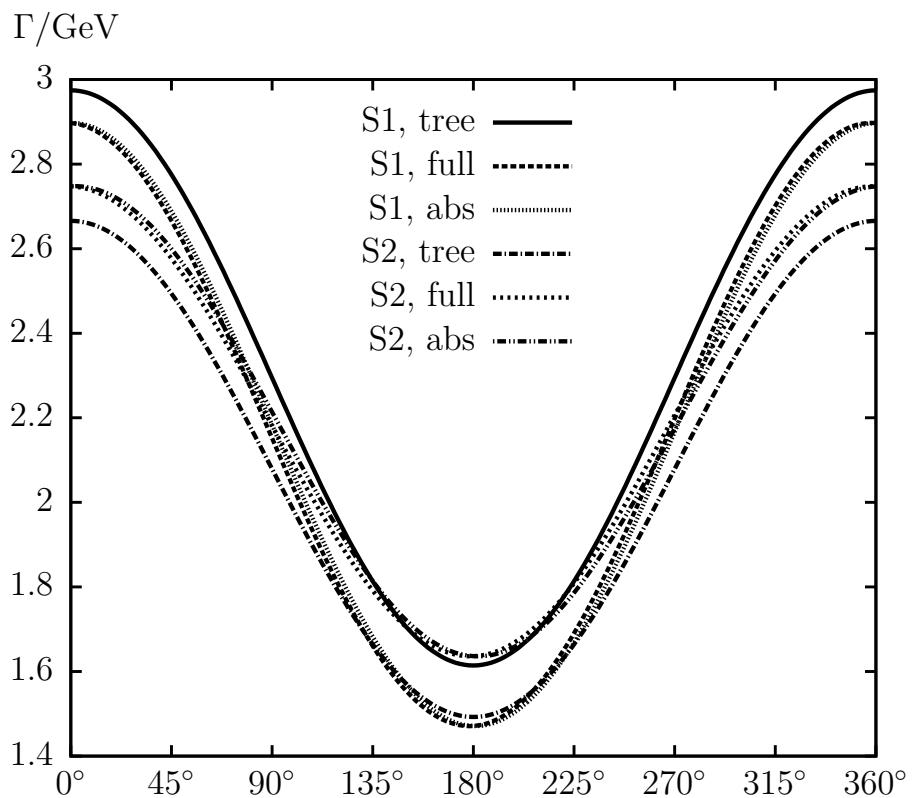


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# $\Gamma(\tilde{t}_2 \rightarrow t\tilde{\chi}_1^0)$ : dependence on $\phi_{A_t}$

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⇒ one-loop corrections under control and non-negligible

⇒ size of BR **highly** scenario dependent

### 3. Towards fully automatized NMSSM calculations ( $Z_3$ invariant NMSSM)

MSSM Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} \textcolor{brown}{v}_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$
$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ \textcolor{brown}{v}_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$\begin{aligned} V = & (\tilde{m}_1^2 + |\mu^-|^2) H_1 \bar{H}_1 + (\tilde{m}_2^2 + |\mu^-|^2) H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\ & + \frac{g'^2 + g^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2 \end{aligned}$$

### 3. Towards fully automatized NMSSM calculations ( $Z_3$ invariant NMSSM)

NMSSM Higgs sector: Two Higgs doublets + one Higgs singlet

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

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

$$S = v_s + S_R + IS_I$$

$$V = (\tilde{m}_1^2 + |\mu \lambda S|^2) H_1 \bar{H}_1 + (\tilde{m}_2^2 + |\mu \lambda S|^2) H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \frac{g'^2 + g^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2$$

$$+ |\lambda(\epsilon_{ab} H_1^a H_2^b) + \kappa S^2|^2 + m_S^2 |S|^2 + (\lambda A_\lambda (\epsilon_{ab} H_1^a H_2^b) S + \frac{\kappa}{3} A_\kappa S^3 + \text{h.c.})$$

Free parameters:

$$\lambda, \kappa, A_\kappa, M_{H^\pm}, \tan \beta, \mu_{\text{eff}} = \lambda v_s$$

## Higgs spectrum:

$\mathcal{CP}$ -even :  $H_1, H_2, H_3$

$\mathcal{CP}$ -odd :  $A_1, A_2$

charged :  $H^+, H^-$

Goldstones :  $G^0, G^+, G^-$

## Neutralinos:

$$\mu \rightarrow \mu_{\text{eff}}$$

compared to the MSSM: one singlino more

$$\rightarrow \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_5^0$$

Needed for a fully automatized NMSSM calculation:

[R. Benbrik, M. Gomez Bock, S.H., O. Stal, G. Weiglein, L. Zeune]

## 1. NMSSM model file for FeynArts

- mostly done employing SARAH and FeynRules
- extensive comparisons / simplifications
- extensive checks:  $\mathcal{O}(50)$   $1 \rightarrow 2$  processes (loop only!)  
 $\mathcal{O}(100)$   $2 \rightarrow 2$  processes (loop only!)

## 2. NMSSM model file with counterterms

- most existing calculations do pure  $\overline{\text{DR}}$
- mostly as in the MSSM
- Higgs sector: work in progress  
→ not yet as settled as in the MSSM  
(competitors did it . . . [M. Mühlleitner et al. '11] )
- ready for L&L 2014 :-)

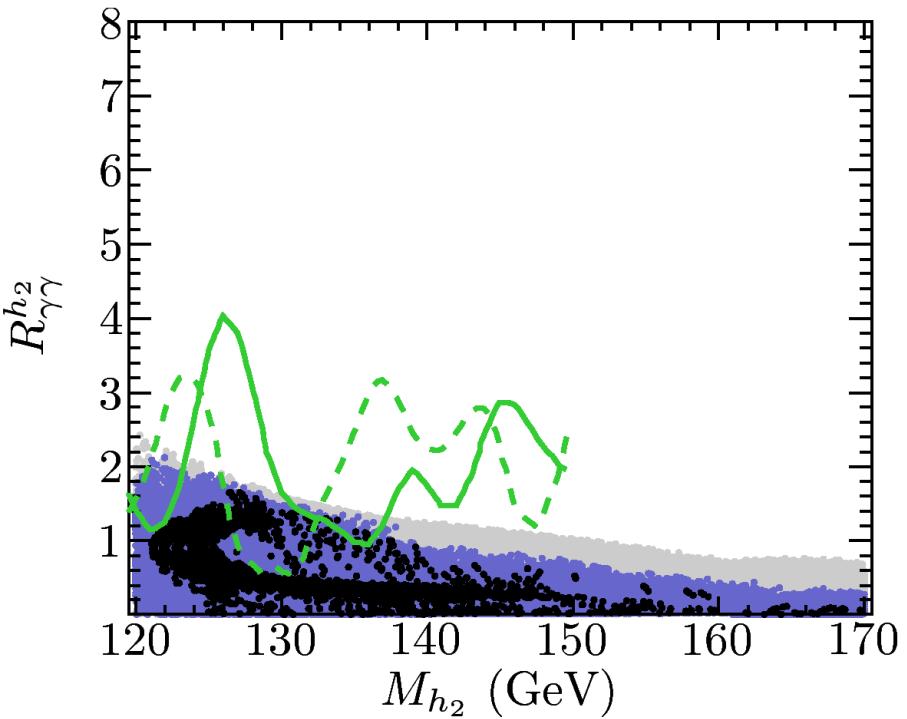
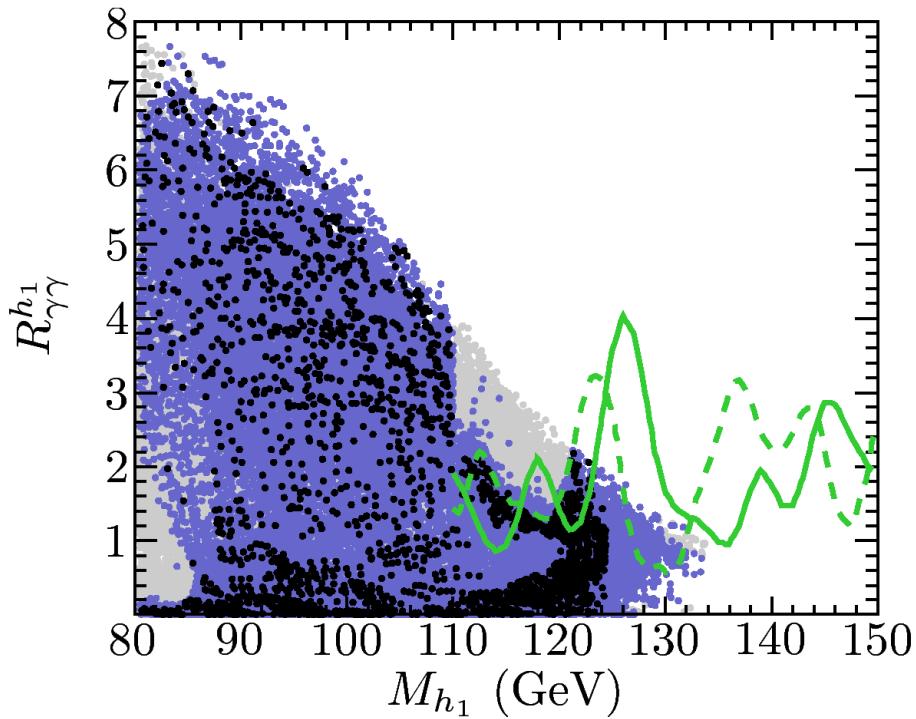
## Contact to real world:

⇒ calculate  $\Gamma(h_i \rightarrow gg)$  and  $\Gamma(h_i \rightarrow \gamma\gamma)$

$$\begin{aligned} R_{\gamma\gamma}^{h_i} &\simeq \frac{\Gamma(h_i \rightarrow gg) \times \text{BR}(h_i \rightarrow \gamma\gamma)}{\Gamma(H_{\text{SM}} \rightarrow gg) \times \text{BR}(H_{\text{SM}} \rightarrow \gamma\gamma)} \\ &= \frac{\Gamma(h_i \rightarrow gg) \times \Gamma(h_i \rightarrow \gamma\gamma) \times \Gamma_{\text{tot}}(H_{\text{SM}})}{\Gamma(H_{\text{SM}} \rightarrow gg) \times \Gamma(H_{\text{SM}} \rightarrow \gamma\gamma) \times \Gamma_{\text{tot}}(h_i)} \end{aligned}$$

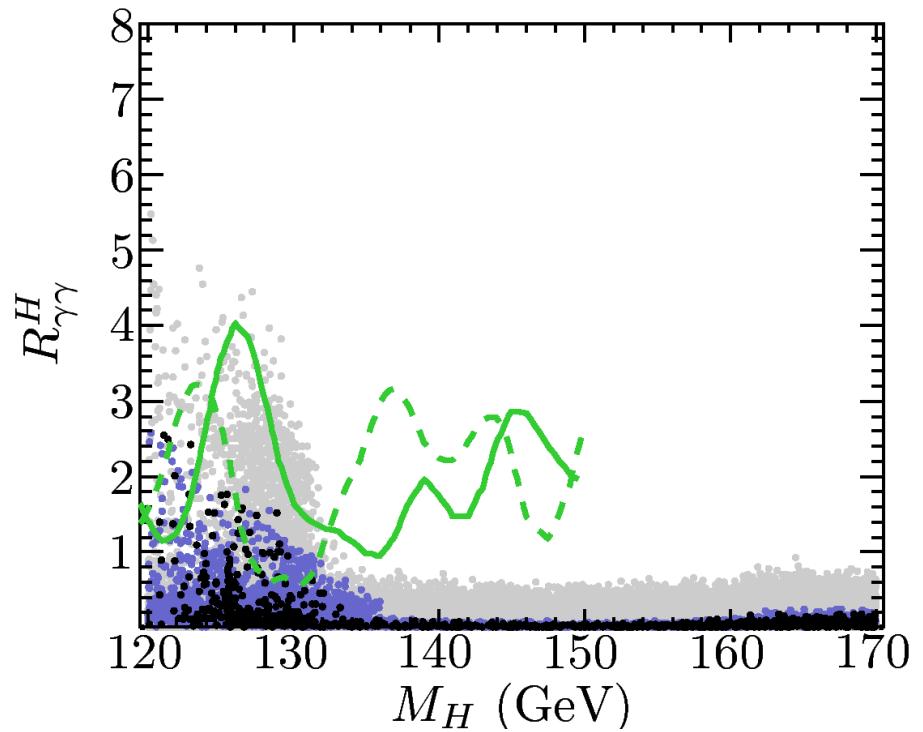
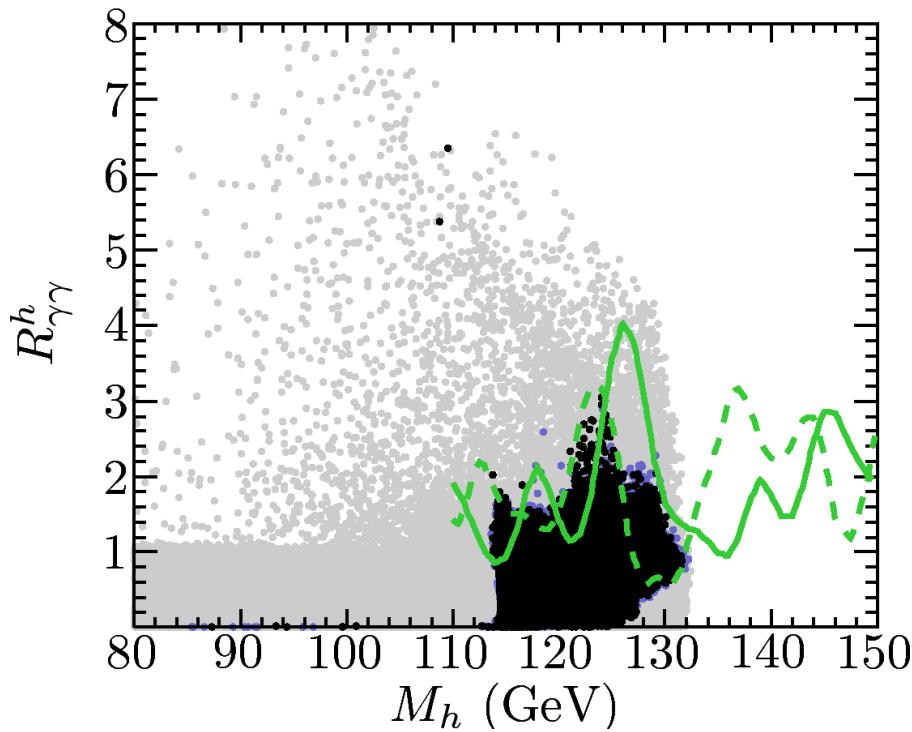
⇒ scan the NMSSM parameter space  
(scan part of the NMSSM parameter space . . . )

⇒ compare to experimental results



solid: ATLAS;    dashed: CMS

⇒ fits the data,  $h_1$  and  $h_2$  can accomodate slightly larger rates than SM



solid: ATLAS; dashed: CMS

⇒ fits the data,  $h$  and  $H$  can accomodate slightly larger rates than SM

## 4. Conclusions

- Loop corrections in BSM models are clearly important now
- MSSM: renormalization is still a (the) big(gest) issue
- FeynArts, FormCalc: model file incl. renormalization ready including complex phases
- Calculated: decays of stops, staus, charginos, gluinos including complex phases (+ hard/soft QED/QCD, . . .)  
→ corrections relevant for LHC/LC
- NMSSM: tree-level model file ready  
renormalization: work in progress
- Connection to real world:  $gg \rightarrow h_i \rightarrow \gamma\gamma$   
agreement with data found for the two lightest Higgses in both, NMSSM and MSSM

# Higgs Days at Santander 2012

Theory meets Experiment

17.-21. September



contact: [Sven.Heinemeyer@cern.ch](mailto:Sven.Heinemeyer@cern.ch)  
<http://www.ifca.es/HDays12>

Back-up

## 5. Renormalization schemes

Generic parameter and field renormalization for scalar quarks:

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

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

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

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

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

→ employ the widely used **on-shell renormalization**

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

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

$$\delta Y_t = \frac{1}{2} \widetilde{\text{Re}} \left\{ \Sigma_{\tilde{t}_{12}}(m_{\tilde{t}_1}^2) + \Sigma_{\tilde{t}_{12}}(m_{\tilde{t}_2}^2) \right\} \quad [\text{W. Hollik, H. Rzehak '03}]$$

This defines the counter term for  $A_t$ :

$$\begin{aligned} \delta A_t = & \frac{1}{m_t} \left[ U_{\tilde{t}_{11}} U_{\tilde{t}_{12}}^* (\delta m_{\tilde{t}_1}^2 - \delta m_{\tilde{t}_2}^2) + U_{\tilde{t}_{11}} U_{\tilde{t}_{22}}^* \delta Y_t^* + U_{\tilde{t}_{12}}^* U_{\tilde{t}_{21}} \delta Y_t \right. \\ & \left. - (A_t - \mu^* \cot \beta) \delta m_t \right] + (\delta \mu^* \cot \beta - \mu^* \cot^2 \beta \delta \tan \beta) \end{aligned}$$

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

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

Diagonal  $Z$  factors:

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

$$\widetilde{\text{Re}} \frac{\partial \widehat{\Sigma}_{\tilde{q}ii}(k^2)}{\partial k^2} \Big|_{k^2=m_{\tilde{q}_i}^2} = 0 \quad (i = 1, 2)$$

yielding

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

Off-diagonal  $Z$  factors:

no transition from one squark to the other occurs:

$$\widetilde{\text{Re}} \widehat{\Sigma}_{\tilde{q}12}(m_{\tilde{q}_1}^2) = 0 \quad \widetilde{\text{Re}} \widehat{\Sigma}_{\tilde{q}12}(m_{\tilde{q}_2}^2) = 0$$

yielding

$$\delta Z_{\tilde{q}12} = +2 \frac{\widetilde{\text{Re}} \Sigma_{\tilde{q}12}(m_{\tilde{q}_2}^2) - \delta Y_q}{(m_{\tilde{q}_1}^2 - m_{\tilde{q}_2}^2)} \quad \delta Z_{\tilde{q}21} = -2 \frac{\widetilde{\text{Re}} \Sigma_{\tilde{q}21}(m_{\tilde{q}_1}^2) - \delta Y_q^*}{(m_{\tilde{q}_1}^2 - m_{\tilde{q}_2}^2)}$$

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

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

$$M_{\tilde{Q}_L}^2(\tilde{q}) = |U_{\tilde{q}11}|^2 m_{\tilde{q}1}^2 + |U_{\tilde{q}12}|^2 m_{\tilde{q}2}^2 - M_Z^2 c_{2\beta} (T_q^3 - Q_q s_W^2) - m_q^2$$

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]

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

with

$$\begin{aligned} \delta M_{\tilde{Q}_L}^2(\tilde{q}) &= |U_{\tilde{q}11}|^2 \delta m_{\tilde{q}1}^2 + |U_{\tilde{q}12}|^2 \delta m_{\tilde{q}2}^2 - U_{\tilde{q}22} U_{\tilde{q}12}^* \delta Y_q - U_{\tilde{q}12} U_{\tilde{q}22}^* \delta Y_q^* - 2m_q \delta m_q \\ &\quad + M_Z^2 c_{2\beta} Q_q \delta s_W^2 - (T_q^3 - Q_q s_W^2)(c_{2\beta} \delta M_Z^2 + M_Z^2 \delta c_{2\beta}) \end{aligned}$$

→ 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
“ $m_b \overline{\text{DR}}, Y_b \text{ OS}$ ”	OS	$\overline{\text{DR}}$	—	OS	RS4
“ $A_b \overline{\text{DR}}, \text{Re}Y_b \text{ OS}$ ”	OS	—	$\overline{\text{DR}}$	$\text{Re}Y_b: \text{OS}$	RS5
“ $A_b$ vertex, $\text{Re}Y_b \text{ OS}$ ”	OS	—	vertex	$\text{Re}Y_b: \text{OS}$	RS6

“—” = dependent parameter

⇒ often very involved analytical dependences

→ more combinations possible

... also tested

... upcoming results remain unchanged

## Renormalization of the sbottom masses:

OS renormalization:

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

## Renormalization of the bottom mass:

OS renormalization:

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

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

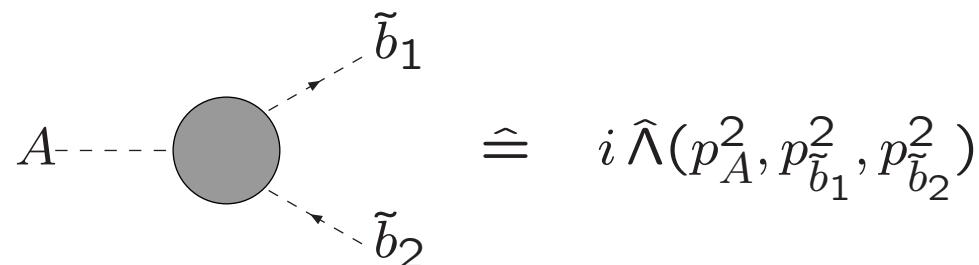
$$\delta m_b = \frac{1}{2}\widetilde{\text{Re}}\left\{m_b\left[\Sigma_b^L(m_b^2) + \Sigma_b^R(m_b^2)\right]_{\text{div}} + \left[\Sigma_b^{SL}(m_b^2) + \Sigma_b^{RL}(m_b^2)\right]_{\text{div}}\right\}$$

## Renormalization of $A_b$ :

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

$$\begin{aligned}\delta A_b = & \frac{1}{m_b} \left[ U_{\tilde{b}11} U_{\tilde{b}12}^* \left( \widetilde{\text{Re}}\Sigma_{\tilde{b}11}(m_{\tilde{b}1}^2)|_{\text{div}} - \widetilde{\text{Re}}\Sigma_{\tilde{b}22}(m_{\tilde{b}2}^2)|_{\text{div}} \right) \right. \\ & + \frac{1}{2} U_{\tilde{b}12}^* U_{\tilde{b}21} \left( \widetilde{\text{Re}}\Sigma_{\tilde{b}12}(m_{\tilde{b}1}^2)|_{\text{div}} + \widetilde{\text{Re}}\Sigma_{\tilde{b}12}(m_{\tilde{b}2}^2)|_{\text{div}} \right) \\ & + \frac{1}{2} U_{\tilde{b}11} U_{\tilde{b}22}^* \left( \widetilde{\text{Re}}\Sigma_{\tilde{b}12}(m_{\tilde{b}1}^2)|_{\text{div}} + \widetilde{\text{Re}}\Sigma_{\tilde{b}12}(m_{\tilde{b}2}^2)|_{\text{div}} \right)^* \\ & - \frac{1}{2} (A_b - \mu^* \tan \beta) \widetilde{\text{Re}} \left\{ m_b \left[ \Sigma_b^L(m_b^2) + \Sigma_b^R(m_b^2) \right]_{\text{div}} \right. \\ & \left. \left. + \left[ \Sigma_b^{SL}(m_b^2) + \Sigma_b^{SR}(m_b^2) \right]_{\text{div}} \right\} \right] + \delta \mu^*|_{\text{div}} \tan \beta + \mu^* \delta \tan \beta\end{aligned}$$

Vertex renormalization:



via  $\widetilde{\text{Re}}\hat{\Lambda}(0, m_{\tilde{b}1}^2, m_{\tilde{b}1}^2) + \widetilde{\text{Re}}\hat{\Lambda}(0, m_{\tilde{b}2}^2, m_{\tilde{b}2}^2) \stackrel{!}{=} 0$

## Renormalization of $Y_b$ :

OS renormalization:

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

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

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

$\text{Re} Y_b$  OS renormalization

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