Renormalization of the Complex MSSM in FeynArts/FormCalc

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in collaboration with

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SUSY 2014

Aim

Precision calculations must match experiemtal precision

Exampes:

- m_h @ 2-Loop requires 1-Loop subrenormalization
- 1-Loop Branching ratios: renormalization of all sectors

We need:

- Consistent renormalization of the full cMSSM
- Implementation in FA/FC for fully automated calculations

Renormalization Scheme:

- Mostly on-shell:

  All processes with on-shell external particles

Renormalization of the Complex MSSM in FA/FC

- Introduction
- Fully Automated Calculations in the cMSSM:
  Implement Renormalization in FA/FC
- Applications
- Conclusions

Introduction

The Big Question: which Lagrangian describes the world?

- The LHC may discover BSM physics soon
- $\Rightarrow$ precise measurements at the ILC

Introduction

The Big Question: which Lagrangian describes the world?

- The LHC may discover BSM physics soon
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- Theory calculations must match experiemental precision:
  —masses
  —cross sections
  —branching ratios
  —angular distributions
  —etc.

We focus on the MSSM

- Enlarged Higgs sector: two Higgs doublets
- Many scales
- complex phases

Where are we? (a selection!)

1. Neutral Higgs boson masses
   - $\mathcal{O}(\alpha_t\alpha_s)$ in the cMSSM [Heinemeyer, Hollik, Rzehak, Weiglein '07]
   - $\mathcal{O}(\alpha_t\alpha_s^2)$, $\mathcal{O}(\alpha_t^2\alpha_s)$, rMSSM [Martin '07]
   - $\mathcal{O}(\alpha_t\alpha_s^2)$, rMSSM (incl. fin. terms) [Harlander, Kant, Mihaila, Steinhauser '08]
   - FD $\oplus$ log resummation [Hahn, Heinemeyer, Hollik, Rzehak, Weiglein '13]
2. Charged Higgs mass
   - full 1-loop [M. Frank et al. '06]
   - $\mathcal{O}(\alpha_t\alpha_s)$ [Frank et al. '13]

Where are we? (a selection!) II

3. Production cross sections at the LHC

– $gg \to h$ at 2-loop [Anastasiou et al. '08] [Mühlleitner et al. '08] [Slavich et al. '11]
  [Harlander et al. '12 (SusHi)] [Bagnaschi et al. '14]

– WBF at 1-loop [Ciccolini et al. '07] [Hollik et al. '08] [Palmer, Weiglein '11]

– $bb \to h$: 4FS vs. 5FS, Santander matching
  [Dittmaier et al. '06] [Dawson et al. '06] [Harlander et al. '11] [Maltoni et al. '12]

– Z-factors at 2-loop [Frank, Hahn,Heinemeyer, Hollik, Rzehak, G. Weiglein '06]

Where are we? (a selection!) III

4. Higgs decays to SM
   - full 1-loop, leading 2-loop, . . . (depending on final state) [. . .]
   - Z-factors at 2-loop [Frank, Hahn, Heinemeyer, Hollik, Rzehak, Weiglein '06]
5. Higgs decays to SUSY
   - full 1-loop (depending on final state) [. . .]
   - Z-factors at 2-loop [Frank, Hahn, Heinemeyer, Hollik, Rzehak, G. Weiglein '06]
6. SUSY decays to Higgs bosons
   - (partial) 1-loop, rMSSM [. . .]
   - (partial) 1-loop, cMSSM [Rzehak, Weiglein, Williams] [Bharucha, Fritzsche, Heinemeyer, FP, Rzehak, 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
   - improved log resummations
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

$\Rightarrow$ provide corresponding codes!

Fully Automated cMSSM Calculations

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!

Renormalization of the cMSSM

Example: Chargino and neutralino sector

On-shell renormalization

- renormalize 3 (complex) parameters: $M_1,\ M_2,\ \mu$
- chargino-neutralino sector $\Rightarrow$ 6 mass paramters:

$$m_{\tilde{\chi}_i^\pm},\ i = 1, 2,\ m_{\tilde{\chi}_j^0},\ j = 1, \ldots, 4$$

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$$m_{\tilde{\chi}_i^\pm},\ i = 1, 2,\ m_{\tilde{\chi}_j^0},\ j = 1, \ldots, 4$$

CCN_j scheme: choose $m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^\pm}, m_{\tilde{\chi}_j^0}$ on-shell $\Rightarrow$ $\delta M_1,\ \delta M_2,\ \delta\mu$

remaining masses receive finite mass shifts

Q: why $m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^\pm}, m_{\tilde{\chi}_j^0}$?

Chargino and neutralino sectors: renormalization

CCN$_j$ scheme: choose $m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^\pm}, m_{\tilde{\chi}_j^0}$ on-shell $\Rightarrow$ $\delta M_1,\ \delta M_2,\ \delta\mu$

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

$$\left[\widetilde{\text{Re}}\hat{\Sigma}_{\tilde{\chi}_j^0}(p)\right]_{jj}\tilde{\chi}_j^0(p)\Big|_{p^2=m^2_{\tilde{\chi}_j^0}} = 0,$$

3 eqs. define 3 complex parameters & field renormalization const.

Mass shifts (in CCN$_1$ scheme)

$$m_{\tilde{\chi}_k^0} = m^{(0)}_{\tilde{\chi}_k^0} + \Delta m_{\tilde{\chi}_k^0}, \qquad (k=2,3,4)$$

$$\Delta m_{\tilde{\chi}_j^0} = -\tfrac{1}{2}\text{Re}\Big\{\widetilde{\text{Re}}\Big[m_{\tilde{\chi}_k^0}\hat{\Sigma}^L_{\tilde{\chi}_k^0}(m^2_{\tilde{\chi}_k^0}) + \hat{\Sigma}^{SL}_{\tilde{\chi}_k^0}(m^2_{\tilde{\chi}_k^0}) + (L \leftrightarrow R)\Big]\Big\}$$

Choose masses of charged particles as input to avoid IR divergencies

Chargino and neutralino sectors: renormalization

On-Shell schemes have numerical instabilities for some parameters!
$\Rightarrow$ no fundamental problem, need alternative RS conditions

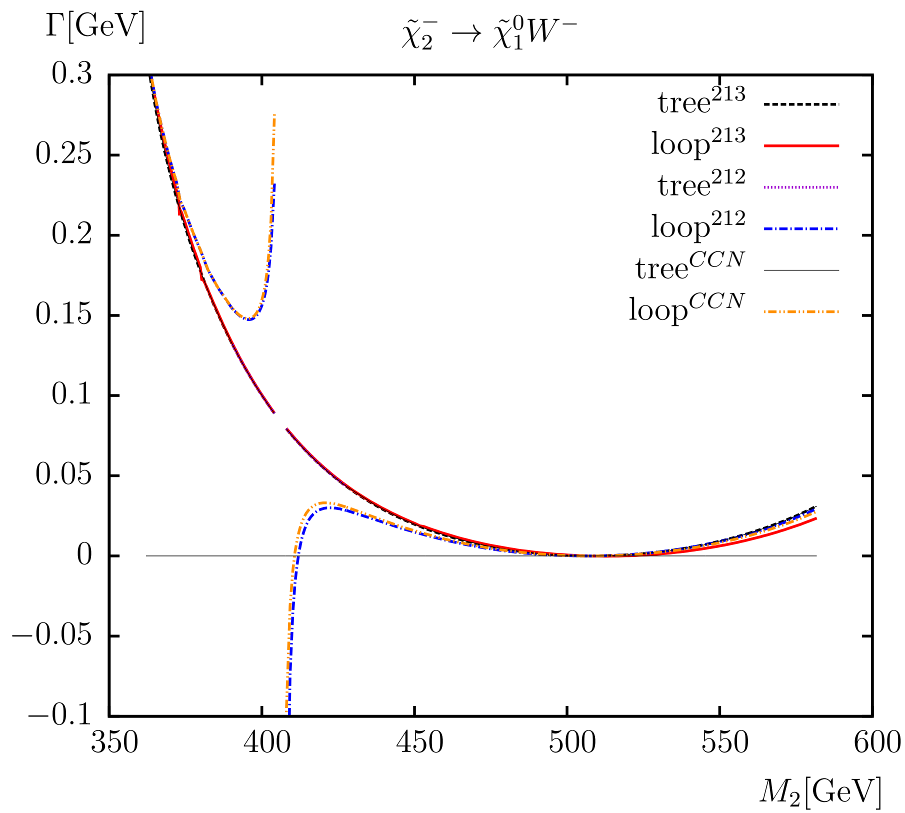
CCN$_j$ scheme: ($m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^\pm}, m_{\tilde{\chi}_j^0}$ on-shell)

CNN$_{i,j,k}$ scheme: ($m_{\tilde{\chi}_i^\pm}, m_{\tilde{\chi}_j^0}, m_{\tilde{\chi}_k^0}$ on-shell)

Shift mass of chargino only if not an external particle!

Renormalization schemes: matching

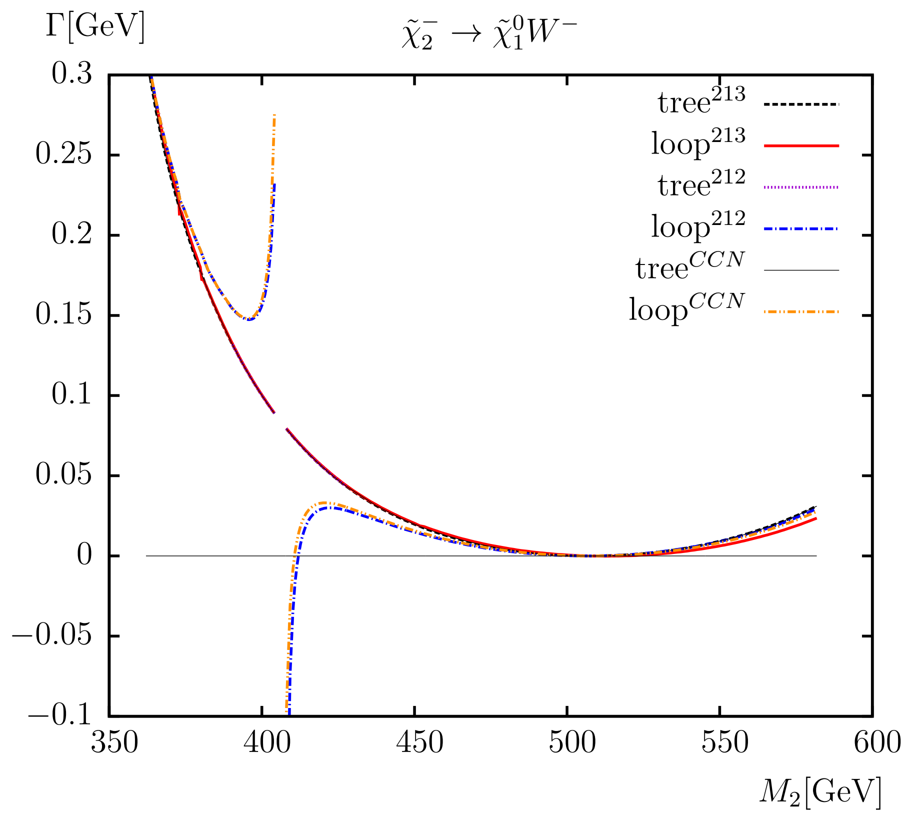
no on-shell scheme works everywhere: here $|\mu| \simeq |M_2|$ region



Renormalization schemes: matching

no on-shell scheme works everywhere: here $|\mu| \simeq |M_2|$ region

- "good RS"
  $\Rightarrow$ smaller rad. corrections
- different schemes
  $\Rightarrow$ theory uncertainty
- implement results in FA/FC:
  matching of RSs



cMSSM @ one-loop: overview

- Higgs wave function renormalization and $\tan\beta$: $\overline{\mathrm{DR}}$
- Higgs masses: on-shell.
  Z_H-matrix: $h, H, A \to h_1, h_2, h_3$ [FeynHiggs]
- electroweak gauge bosons: on-shell
- quark sector: internal m_b $\overline{\mathrm{DR}}$, external m_b on-shell,
  other quarks on-shell
- squark sector: A_b $\overline{\mathrm{DR}}$, squarks on-shell
- lepton/slepton sector: on-shell
- chargino-neutralino sector: on-shell

Fully Automated cMSSM Calculations: Higgs sector

- Higher-order corrections phenomenologically very important
- But: including these corrections on propagators and vertices mixes orders of perturbartion theory
- $\Rightarrow$ no cancellation of UV and IR divergencies
- Masses of Higgs propagators should be consistent with mixing angle α parametrizing the vertices

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- Recipe:
  - Vertices with tree-level α
  - Loop propagators with tree-level Higgs masses
  - tree propagators with loop-correctied masses

Automated cMSSM Calculations Automatic Diagram Evaluation

- FeynArts: Diagram generation: $\Rightarrow$ Amplitudes
  - create topologies
  - insert fields
  - apply Feynman rules
  - paint diagrams
- FormCalc: Algebraic simplification
  - contract indices
  - calculate traces
  - reduce tensor integrals
  - introduce abbrevations
- FormCalc: numerical evaluation
  - convert Mathematica output to Fortran code
  - supply driver integrals
  - link LoopTools: implement integrals
- $\rightarrow$ Squared amplitudes

Fully Automated cMSSM Calculations Modelfile

- Modelfile `MSSMCT` :
  complex MSSM including all one-loop counterterms

Fully Automated cMSSM Calculations: Higgs sector

- Recipe:
  - Vertices with tree-level α
  - Loop propagators with tree-level Higgs masses
  - tree propagators with loop-correctied masses
- Implementation in FeynArts:

```
S[1] == {
 Mass -> Mh0,
 Mass[Loop] -> Mh0tree, ...  }
```

Fully Automated cMSSM Calculations: CKM and NMFV

- MSSMCT presently limited to minimal flavor violation (MFV) in the Sfermion Sector
  (Onlt mixing within each generation)
- for non-trivial CKM matrix:
  $\Rightarrow$ imbalance between fermions and sfermions
- CKM mixing turned off by default
  may be switched on: `$CKM == True`

Run-time Renormalization Scheme selection

- Choice of RS conditions dependent on parameter: (e.g. Chargino/Neutralino sector)
- Schemes require different computation of a set of Renormalization Constant, e.g. `dMino11, dMino21, dMUE1`
- Solution1: `dMUE1 = IndexIf[`$cond$`, `$\delta\mu^A, \delta\mu^B$`]`
- However: dependences cannot be resolved with individual `IndexIfs` f.i.:
  Scheme A: $\delta\mu = f(\delta M_1)$
  Scheme B: $\delta M_1 = f(\delta\mu)$
- Solution2: One-pass ordering collects & recurses on `IndexIfs`

Run-time RS selection: One-pass ordering

dMUE1 = IndexIf[$cond$, $\delta\mu^A(\delta M_1^A), \delta\mu^B$];
dMino11 = IndexIf[$cond$, δM_1^A, $\delta M_1^B(\delta\mu^B)$];
dMino21 = IndexIf[$cond$, δM_2^A, δM_2^B];

$\rightarrow$

IndexIf[$cond$,
  dMino11 = $\delta\mu^A(\delta M_1^A)$;
  dMUE1 = $\delta\mu^A(\delta M_1^A)$;
  dMino21 = δM_2^B ,
(* else *)
  dMUE1 = $\delta\mu^B$;
  dMino11 = $\delta M_1^B(\delta\mu^B)$;
  dMino21 = δM_2^B];

Run-time RS selection

Scheme switching selected as

- `$InoScheme = IndexIf[`$cond$`, CNN[2,1,3], CNN[1]]`
  where $cond$ might be `Abs[Abs[MUE]] - Abs[Mino2]] < 50`
  to chose most stable RS for $\mu \approx M_2$
- `$InoScheme = CCN[1]`
  where `nbino` is determined at run-time to be the most bino-like neutralino

Warning:
note that a renormalization-scheme switch in principle requires a corresponding transition of the affected parameters from one scheme to the other for a fully consistent interpretation of the results

Further developements

- FormCalc 8.4
  - Automated vectorization of helicity loop
  - suppression of negligibble helicity combinations
  - Ninja inteface

Applications

FeynArts/FormCalc with the new cMSSM-CT model file are ready

Calculations have been performed for

–Stop decays at one-loop

–Sbottom decays at one-loop

–Stau decays at one-loop

–Gluino decays at one-loop

–Chargino decays at one-loop

–Neutralino decays at one-loop

–Higgs masses at two-loop [$\rightarrow$ see S.Borowkas talk]

Neutralino decays

$$\Gamma(\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 h_k), \quad i,j = 1,...,4,\ k = 1,...,3,$$

$$\Gamma(\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 Z), \quad i,j = 1,...,4,$$

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

$$\Gamma(\tilde{\chi}_i^0 \to \tilde{\chi}_j^\pm W^\mp),$$

$$\Gamma(\tilde{\chi}_i^0 \to \ell^\mp \, \tilde{\ell}_k^\pm), \quad i = 1,...,4,\ \ell = \tau, \mu, e,\ k = 1,2$$

$$\Gamma(\tilde{\chi}_i^0 \to \nu_\ell \, \tilde{\nu}_\ell), \quad i = 1,...,4,\ \ell = \tau, \mu, e$$

No hadronic decays yet:

$$\Gamma(\tilde{\chi}_i^\pm \to q \, \tilde{q}_k), \quad k = 1,2$$

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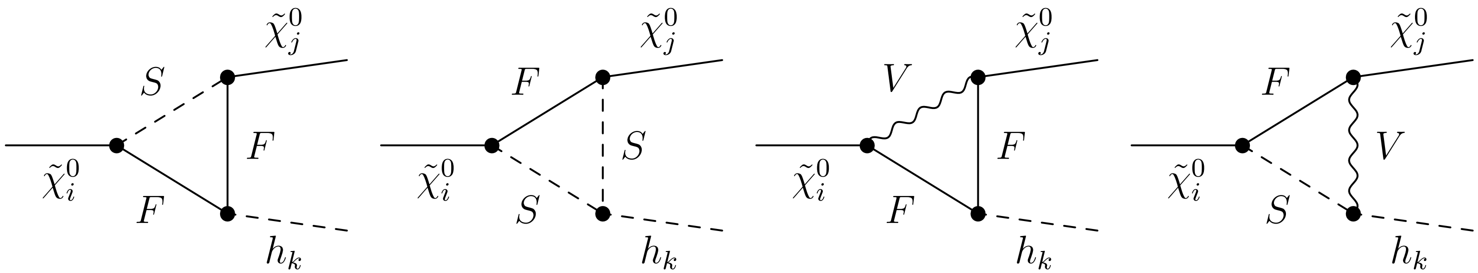
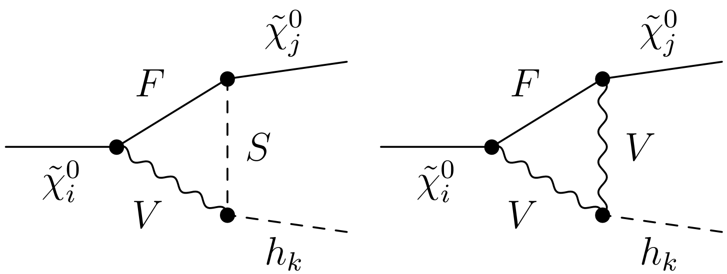
No hadronic decays yet:

$$\Gamma(\tilde{\chi}_i^\pm \to q \tilde{q}_k), \quad k = 1,2$$

- Numerical comparison of all decay channels in both RS

One loop diagrams: $\tilde{\chi}_4^0 \to \tilde{\chi}_1^0 h_k$





F : EW-inos/leptons/quarks
S : sfermions/Higgs bosons
V : gauge bosons

- evaluate with FeynArts/FormCalc/LoopTools/FeynHiggs
- for charged processes: include all hard QED diagrams

Numerical analysis

Parameters for numerical evaluation

- $m_{\tilde{\chi}_1^\pm} = 350$ GeV, $m_{\tilde{\chi}_2^\pm} = 600$ GeV, $\varphi_\mu = 0$ and $\mu > 0$
- μ and M_2 as a function of the chargino masses:

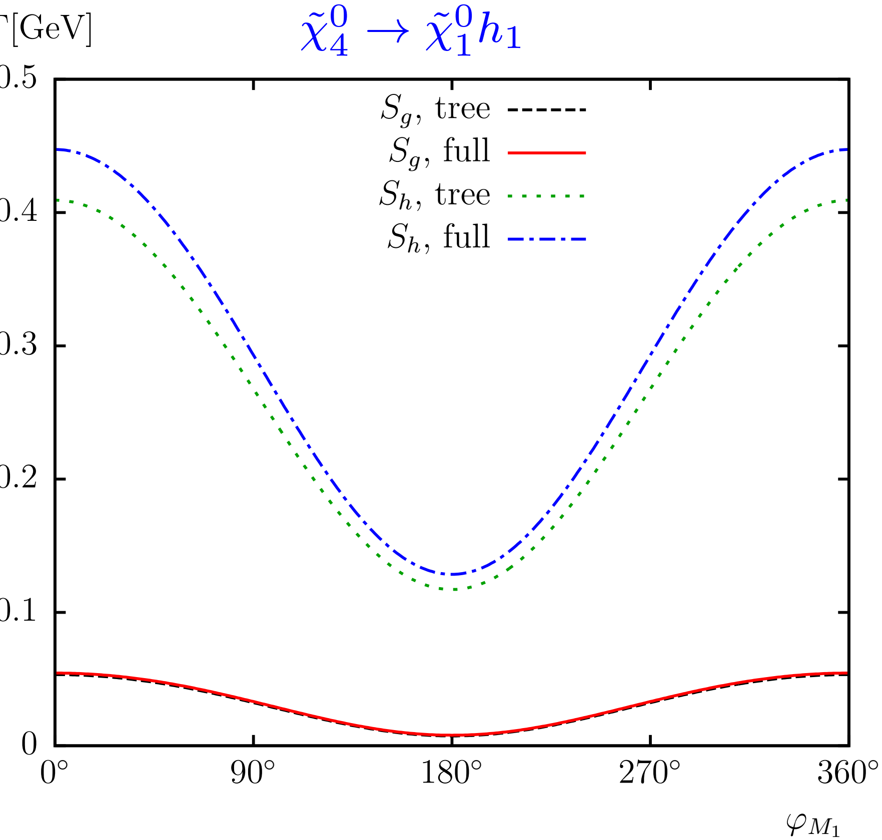
$$S_> := \{\mu > M_2\} \quad \tilde{\chi}_2^\pm \sim \mathrm{Higgsino-like}$$

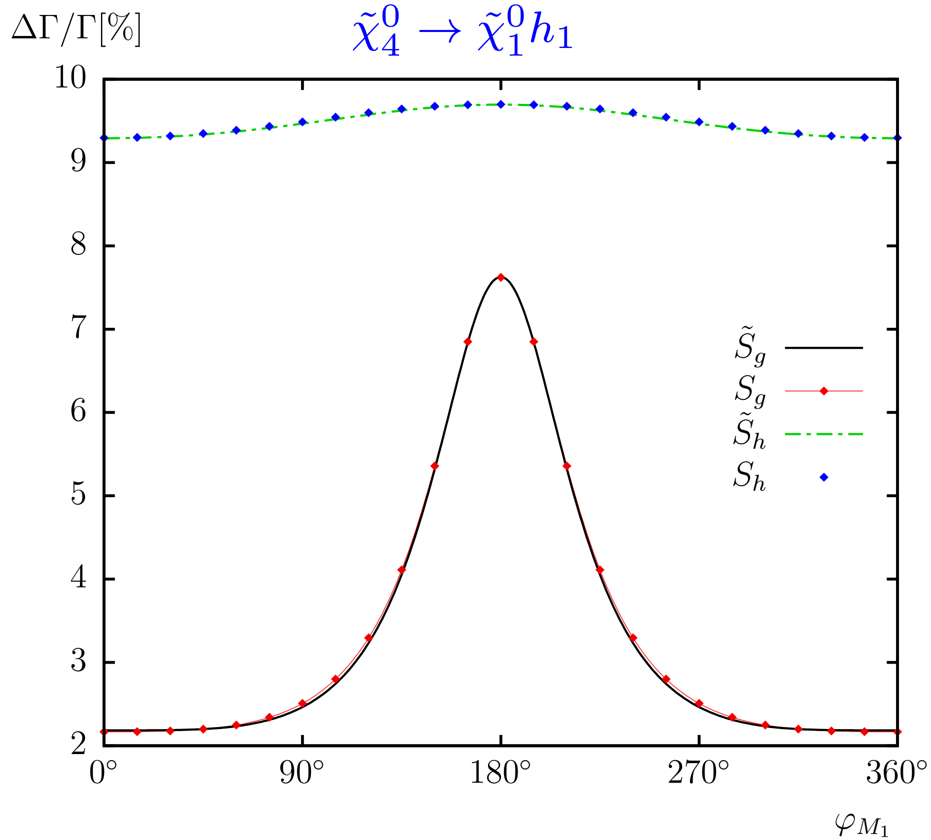
$$S_< := \{\mu < M_2\} \quad \tilde{\chi}_2^\pm \sim \mathrm{wino-like}$$

- $|M_1|$ fixed by GUT relation: $|M_1|/M_2 = 5/3\tan^2\theta_W \simeq 0.5$
- $\tan\beta = 20$, $\varphi_{M_1} = 0$

Choice of scenario: so that most neutralino decay channels are open

Neutralino decays: φ_{M_1}-dependence



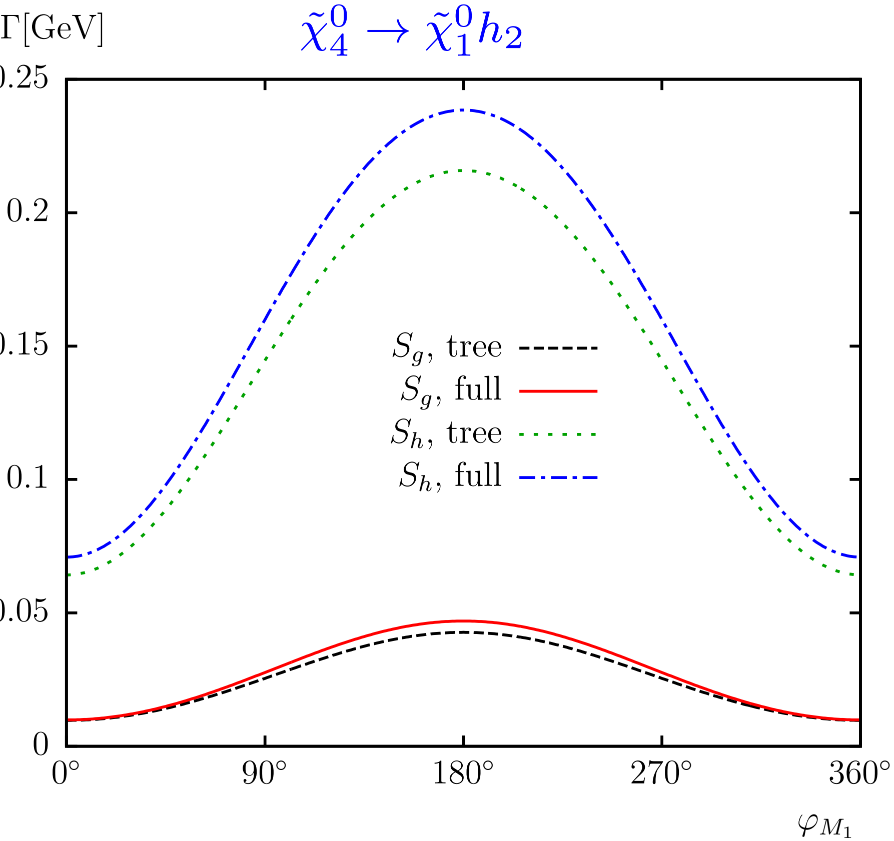


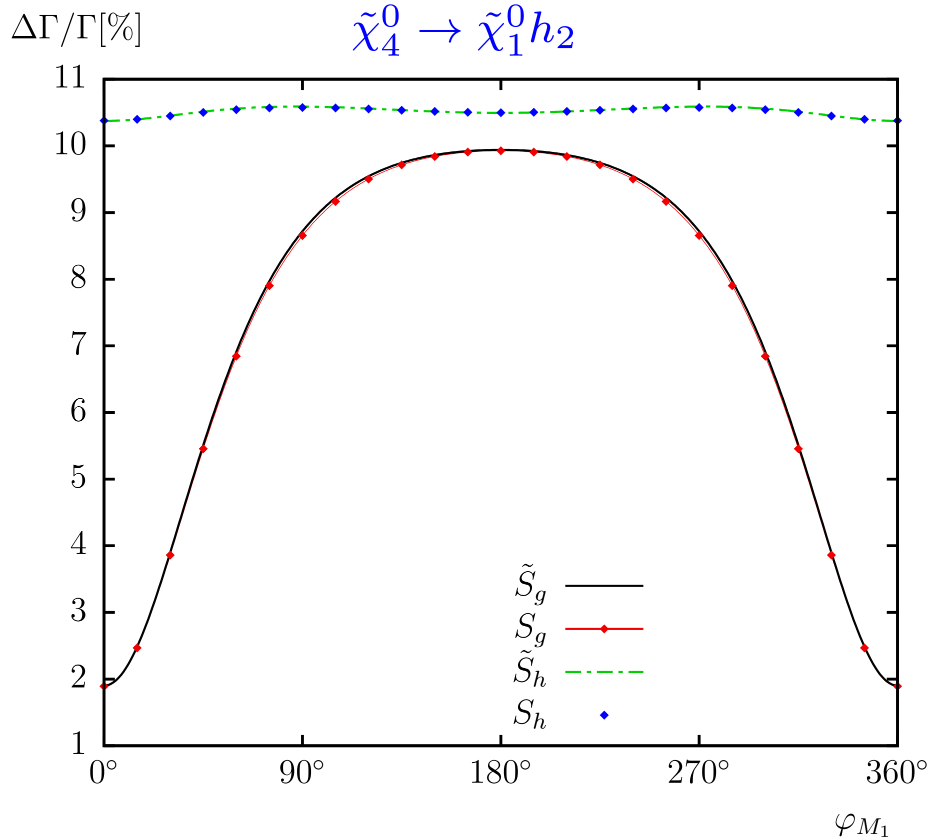
⇒ one-loop corrections under control and non-negligible

⇒ size of BR highly scenario dependent

Very good agreement between RS

Neutralino decays: φ_{M_1}-dependence



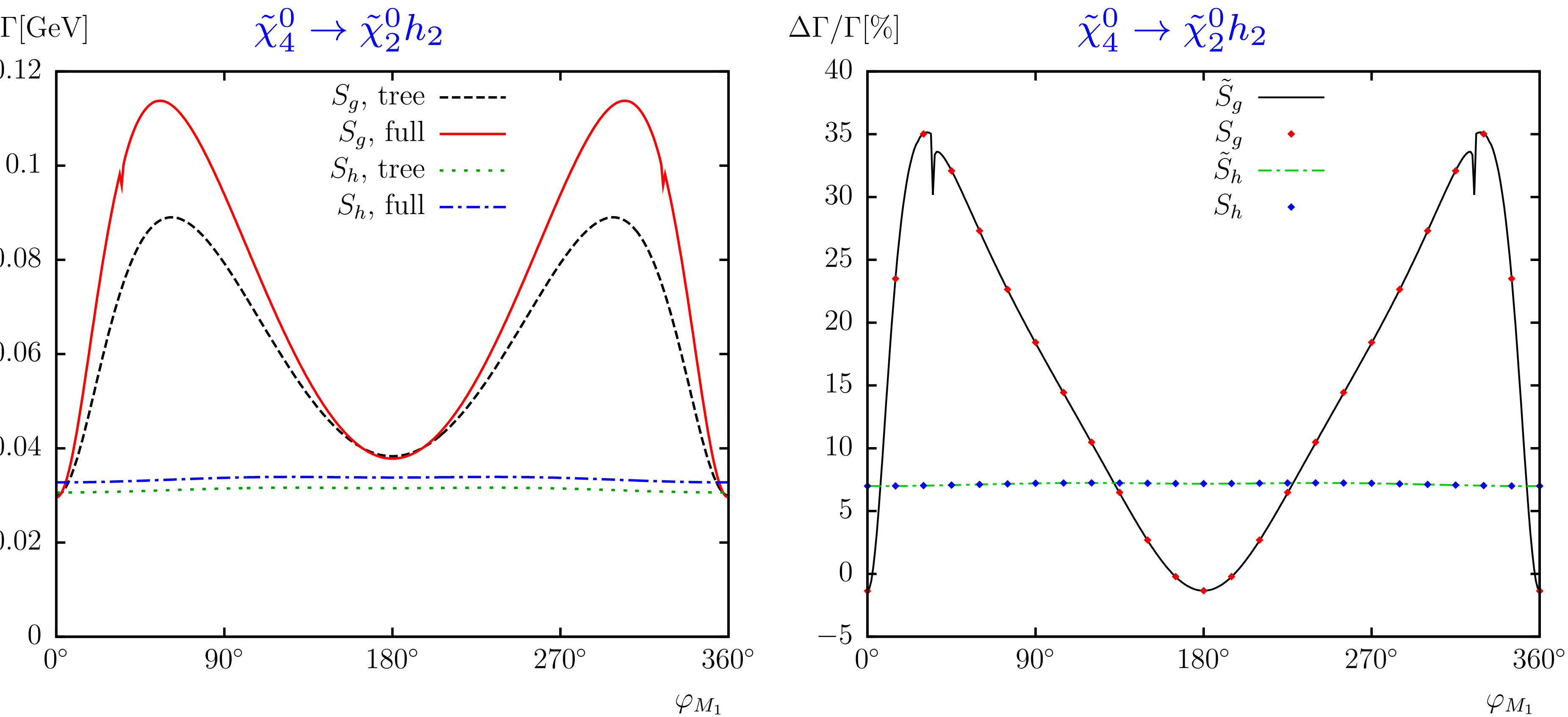


Very good agreement between RS

φ_{M_1}-dependence opposite for h_1 $(\sim h)$ and h_2 $(\sim A)$!

here $\varphi_{M_1} = 0 \Rightarrow$ p-wave suppressed!

Neutralino decays: φ_{M_1}-dependence

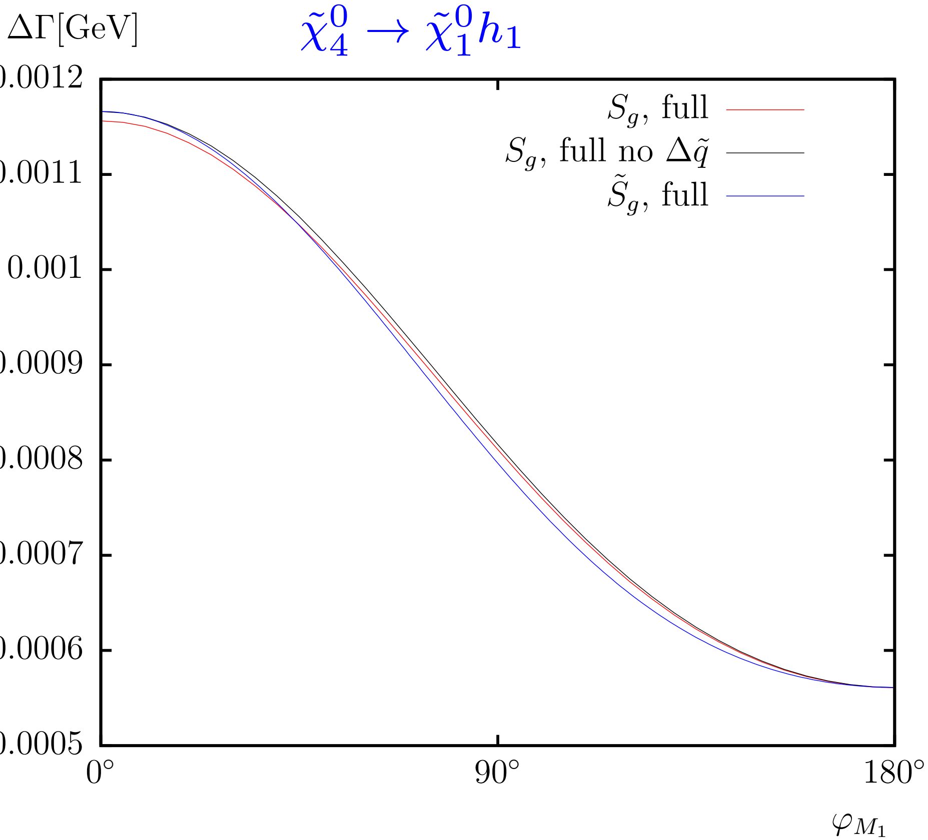


$\Rightarrow$ one-loop corrections under control and non-negligible

large corrections to neutralino mixing!

Very good agreement between RS

Neutralino decays: comparison of the schemes



Difference of two-loop order

In CP-conserving limit ($\varphi_{M_1} = 0, \pi$), schemes identical

Summary

- Renormalization of the full complex MSSM under control
- FeynArts 3.9: MSSMCT model file including complete 1-loop renormalization
- FormCalc 8.4
  - Support run-time renormalization scheme selection
  - Additional improvementes (not discussed here):
    Automated vectorization of helicity loop
    suppression of negligibble helicity combinations
    Ninja inteface
- Applications

backup transparencies

$\tilde{t}/\tilde{b}$ sector of the MSSM:

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

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

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

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

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

$\Rightarrow$ 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 $m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}, \theta_{\tilde{b}}$

Renormalization schemes in the stop/sbottom sector

nalogously" in the slepton sector!)

neric parameter and field renormalization for scalar quarks:

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

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

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

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

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

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

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

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

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

This defines the counter term for A_t:

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

(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:

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

yielding

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

Off-diagonal Z factors:

no transition from one squark to the other occurs:

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

yielding

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

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

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

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

Keeping $SU(2)$ relation at the one-loop level leads to a shift in the soft SUSY-breaking parameters
[Bartl, Eberl, Hidaka, Kraml, Majerotto, Porod, Yamada '97, '98]
[Djouadi, Gambino, Heinemeyer, Hollik, Jünger, 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

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

$\rightarrow$ under control

Complex renormalization in $t/\tilde{t}$ sector:

1) A_t complex

$\Rightarrow$ renormalization of $|A_t|$ and ϕ_{A_t}: $\delta A_t = e^{i\,\phi_{A_t}}\delta|A_t| \;+\; i\,A_t\,\delta\phi_{A_t}$

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

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

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

$\Rightarrow$ On-shell renormalization via

$$\widetilde{\mathrm{Re}}\hat{\Sigma}_{\tilde{t}_{12}}(m^2_{\tilde{t}_1}) + \widetilde{\mathrm{Re}}\hat{\Sigma}_{\tilde{t}_{12}}(m^2_{\tilde{t}_2}) \stackrel{!}{=} 0$$

$$\Rightarrow \widetilde{\mathrm{Re}}\Sigma_{\tilde{t}_{12}}(m^2_{\tilde{t}_1}) + \widetilde{\mathrm{Re}}\Sigma_{\tilde{t}_{12}}(m^2_{\tilde{t}_2}) = e^{i\phi_{\tilde{t}}}(m^2_{\tilde{t}_1} - m^2_{\tilde{t}_2}) \times (\delta\theta_{\tilde{t}} + i\,s_{\tilde{t}}\,c_{\tilde{t}}\,\delta\phi_{\tilde{t}})$$

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

$\Rightarrow$ preferred scheme

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 $\overline{\mathrm{DR}}$"	OS	$\overline{\mathrm{DR}}$	$\overline{\mathrm{DR}}$	—	RS2
"m_b, Y_b $\overline{\mathrm{DR}}$"	OS	$\overline{\mathrm{DR}}$	—	$\overline{\mathrm{DR}}$	RS3
"m_b $\overline{\mathrm{DR}}$, Y_b OS"	OS	$\overline{\mathrm{DR}}$	—	OS	RS4
"A_b $\overline{\mathrm{DR}}$, ReY_b OS"	OS	—	$\overline{\mathrm{DR}}$	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:

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

Renormalization of the bottom mass:

OS renormalization:

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

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

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

Renormalization of A_b:

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

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

Vertex renormalization:

$\tilde{b}$

Renormalization of Y_b:

OS renormalization:

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

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

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

ReY_b OS renormalization

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