Complex NMSSM with NMSSMCALC: Present status and future prospects

NMSSM Workshop, **Université de Montpellier**

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INSTITUT FÜR THEORETISCHE PHYSIK

Outline

1. Introduction
2. Higher-order corrections in the NMSSM Higgs sector
3. `NMSSMCALC`: An implementation of the complex NMSSM for the Higgs sector
4. Outlook

From the MSSM to the (N)MSSM

- **SM Hierarchy problem:** Higgs mass corrections quadratically divergent in the SM $\Rightarrow$ Higgs mass stabilized by SUSY, MSSM minimal SM extension, **2** Higgs doublets
- **But μ–problem:** $\mu \hat{H}_u \cdot \hat{H}_d$ term in the superpotential, μ SUSY-invariant but of the order of EW scale $\Rightarrow$ naturalness problem!
- **Solution to the μ–problem:** effective μ–term generated dynamically $\Leftrightarrow$ **NMSSM**

NMSSM Superpotential

$$\mathcal{W} = \hat{u}_R^* y_u \left(\hat{Q} \cdot \hat{H}_u\right) - \hat{d}_R^* y_d \left(\hat{Q} \cdot \hat{H}_d\right) - \hat{e}_R^* y_e \left(\hat{L} \cdot \hat{H}_d\right) + \lambda \hat{S} \left(\hat{H}_u \cdot \hat{H}_d\right) + \frac{1}{3} \kappa \hat{S}^3$$

- **3+2 neutral Higgs** bosons, **2 charged Higgs** bosons, **4+1 neutralinos**
- Singlet field S gets a vacuum expectation value $\Rightarrow$ $\boldsymbol{\mu_{\mathrm{eff}} = \lambda v_s / \sqrt{2}}$
- Higgs sector less restricted in NMSSM compared to MSSM:

  upper bound on tree-level in the MSSM: $M_H \leq M_Z$
  $\Rightarrow$ large quantum corrections needed to get $M_H \simeq 125$ GeV

  Fine-tuning less important in the NMSSM, higher tree-level bound

  $$M_H^2 \leq M_Z^2 \left(\cos(2\beta)^2 + \frac{\lambda^2}{g^2}\sin(2\beta)^2\right),\ g^2 = \frac{g_1^2 + g_2^2}{2}$$ [see Ellwanger, Hugonie, Teixeira, (2010)]

From the real NMSSM to the complex NMSSM

- **CP violation:** CKM matrix can explain CP violation in $K - \bar{K}$ system but not the baryon asymmetry in the Universe:

  amount of CP violation (from CKM) in the SM too small

One solution

CP violation enhanced with complex parameters

- **Richer Higgs spectrum:** complex parameters in the NMSSM $\Rightarrow$ CP violation at tree–level, all the Higgs bosons mix:

$$H_i = \sum_k S_{ik}\phi_k, \quad \phi = (h_d, h_u, s, a, a_s)$$

$$(S_{ik})\ 5 \times 5 \text{ matrix}$$

The scalar potential in the NMSSM

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- From the superpotential to the scalar potential:

$$
\begin{aligned}
V = & |\lambda|^2|S|^2\left(H_u^\dagger H_u + H_d^\dagger H_d\right) + \left|\lambda\left(H_u^\intercal \epsilon H_d\right) + \kappa S^2\right|^2 + \frac{1}{2} g_2^2 |H_u^\dagger H_d|^2 \\
& + \frac{1}{8}(g_1^2 + g_2^2)\left(H_u^\dagger H_u - H_d^\dagger H_d\right)^2 + m_{H_u}^2 H_u^\dagger H_u + m_{H_d}^2 H_d^\dagger H_d + m_S^2 |S|^2 \\
& + \left(\lambda A_\lambda \left(H_u^\intercal \epsilon H_d\right) S + \frac{1}{3}\kappa A_\kappa S^3 + \text{c.c}\right)
\end{aligned}
$$

- Higgs fields with phases:

$$
H_d = \frac{1}{\sqrt{2}}\begin{pmatrix} v_d + h_d + \imath a_d \\ \sqrt{2}\, H_d^- \end{pmatrix} \qquad H_u = \frac{e^{\imath \phi_u}}{\sqrt{2}}\begin{pmatrix} \sqrt{2}\, H_u^+ \\ v_u + h_u + \imath a_u \end{pmatrix}
$$

$$
S = \frac{e^{\imath \phi_s}}{\sqrt{2}}\left(v_s + h_s + \imath a_s\right)
$$

$$
\tan\beta = \frac{v_u}{v_d} \tag{1}
$$

Higher-order corrections in the Higgs sector of the NMSSM

1-loop mass calculations: Ender, Graf, Mühlleitner, Rzehak, PRD 85 (2012) 075024; Graf, Gröber, Mühlleitner, Rzehak, Walz, JHEP 1210 (2012) 122

Higgs decays and NMSSMCALC: **J.B.**, Gröber, Mühlleitner, Nhung, Rzehak, Spira, Streicher, Walz, CPC 185 (2014) 12

2-loop mass calculation: Mühlleitner, Nhung, Rzehak, Walz, JHEP 1505 (2015) 128

Electron dipole moments: King, Mühlleitner, Nevzorov, Walz, Nucl.Phys.B 901 (2015) 526

NLO QCD+EW corrections: **J.B.**, Krauss, Mühlleitner, Walz, JHEP 1510 (2015) 024

Trilinear Higgs couplings: Nhung, Mühlleitner, Streicher, Walz, JHEP 1311 (2013) 181; Mühlleitner, Nhung, Ziesche, JHEP 1512 (2015) 034

1-loop corrections to Higgs masses in the real NMSSM

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- **LO Higgs masses:** diagonalizing the 3×3 CP-even $\mathcal{M}_S$ and the 3×3 CP-odd (+ Goldstone) $\mathcal{M}_A$ mass matrices give the LO masses $m_{H_1} < m_{H_2} < m_{H_3}$ and $m_{A_1} < m_{A_2}$
  sizable higher order corrections compulsory to obtain one SM-like H_i boson
- **1-loop corrections:** define input parameters, calculate renormalized self-energies in a mixed renormalization scheme [Graf, Ender, Graf, Mühlleitner, Rzehak, PRD 85 (2012) 075024]

  - 7 parameters renormalized on-shell: $e,\ M_W,\ M_Z,\ M_{H^\pm},\ t_{h_u},\ t_{h_d},\ t_s$
  - 5 parameters renormalized $\overline{\mathrm{DR}}$: $\tan\beta,\ \lambda,\ \kappa,\ A_k,\ v_s$

  - $\overline{\mathrm{DR}}$ field renormalization constants for the Higgs fields

$$H_d = \left(1 + \frac{1}{2}\delta Z_d\right)\hat{H}_d \qquad H_u = \left(1 + \frac{1}{2}\delta Z_u\right)\hat{H}_u \qquad S = \left(1 + \frac{1}{2}\delta Z_s\right)\hat{S}$$

  - $\delta M_V^2 = \mathrm{Re}\Sigma^T_{VV}(M_V^2)$, $\delta M^2_{H^\pm} = \mathrm{Re}\Sigma_{H^+H^+}(M^2_{H^\pm})$
  - δZ_e at the scale M_Z to absorb the dependence on light quark masses
  - Tadpole condition: $\hat{T}_{h_{u/d/s}} = 0 \Rightarrow \delta t_{h_{u/d/s}} = T_{h_{u/d/s}}$
    with $T_{h_i} = R_{ji} T_{H_j}, i = u, d, s$ and $j = 1, 2, 3$; (R_{ij}) tree-level mixing matrix

1-loop corrections to Higgs masses in the real NMSSM

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- **1-loop corrections:** with the renormalized self-energies calculate the zeros of the 1-loop 2-point vertex matrix

$$\Gamma^{11}(p^2) = i \begin{pmatrix} p^2 - m_{H_1}^2 + \hat{\Sigma}^{(1)}_{H_1H_1}(p^2) & \hat{\Sigma}^{(1)}_{H_1H_2}(p^2) & \hat{\Sigma}^{(1)}_{H_1H_3}(p^2) \\ \hat{\Sigma}^{(1)}_{H_2H_1}(p^2) & p^2 - m_{H_2}^2 + \hat{\Sigma}^{(1)}_{H_2H_2}(p^2) & \hat{\Sigma}^{(1)}_{H_2H_3}(p^2) \\ \hat{\Sigma}^{(1)}_{H_3H_1}(p^2) & \hat{\Sigma}^{(1)}_{H_3H_2}(p^2) & p^2 - m_{H_3}^2 + \hat{\Sigma}^{(1)}_{H_3H_3}(p^2) \end{pmatrix}$$

$$\hat{\Sigma}^{(1)}_{H_iH_j}(p^2) = \Sigma^{(1)}_{H_iH_j}(p^2) + \frac{1}{2}p^2(\delta Z_{H_jH_i} + \delta Z_{H_iH_j}) - \frac{1}{2}(\delta Z_{H_jH_i} m_{H_j}^2 - m_{H_i}^2 \delta Z_{H_iH_j}) - (R\delta\mathcal{M}_S R^\intercal)_{H_iH_j}$$

Algorithm to calculate the masses

1. Set $p^2 = m_{H_1}^2$ in the self-energies
2. Solve $\det\hat{\Gamma}(p^2) = 0$
3. Extract the smallest root obtained m^2_{tmp}
4. Set $p^2 = m^2_{\mathrm{tmp}}$ in the self-energies and back to 2 as long as $|m^2_{\mathrm{tmp},n} - m^2_{\mathrm{tmp},n-1}| > \epsilon$, n is the n^{th} iteration, ϵ the desired accuracy $\Rightarrow$ get the 1-loop mass M_{H_1}
5. Start again at 1 with the 2^{nd} Higgs mass, extract the next-to-smallest root, and so on

Complex parameters and renormalization

- **Many new phases in the complex NMSSM:** M_1, M_2, A_t, etc, all complex parameters with associated phases

  In the Higgs sector: 6 phases ϕ_u, ϕ_S, ϕ_λ, ϕ_κ, ϕ_{A_λ} and ϕ_{A_κ}

  At tree–level, only one relevant phase: only 3 combinations in the mass matrix

$$\Psi = \phi_\lambda - \phi_\kappa + \phi_u - 2\phi_s$$
$$\Psi_\lambda = \phi_\lambda + \phi_{A_\lambda} + \phi_u + \phi_s$$
$$\Psi_\kappa = \phi_\kappa + \phi_{A_\kappa} + 3\phi_s$$

  Ψ_λ, Ψ_κ fixed by two tadpole conditions

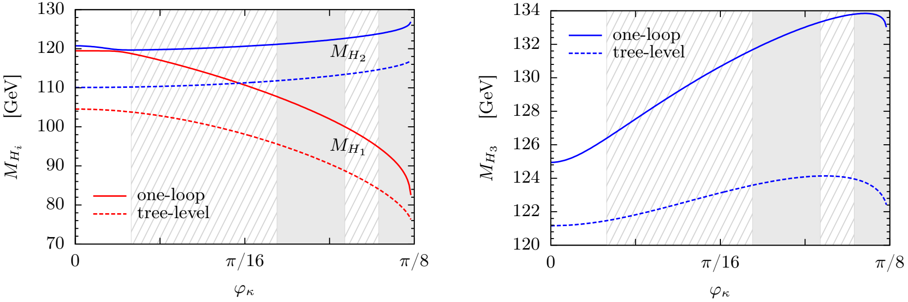
$$\frac{1}{\sqrt{2}}|A_\lambda| \sin\Psi_\lambda = -\frac{|\kappa| v_s}{2} \sin\Psi, \qquad \frac{1}{\sqrt{2}}|A_\kappa| \sin\Psi_\kappa = -\frac{3|\lambda| v_d v_u}{2 v_s} \sin\Psi$$

- **Renormalization in the Higgs sector:**
  - on–shell renormalization for e, M_W, M_Z, $M_{H^\pm}$
    $\overline{\mathrm{DR}}$ renormalization for $\tan\beta$, v_s, $|\lambda|$, $|\kappa|$, $|A_\kappa|$ and the phases
  - **vanishing phases counter–terms** but for two tadpole conditions t_a and t_{a_s}

Higgs masses at the one loop order

Complex phases have sizable effects [Graf, Gröber, Mühlleitner, Rzehak, Walz, JHEP 1210 (2012) 122]:

- **Tree–level CP violation ($\Psi \neq 0$):**



$$|\lambda| = 0.72, \quad |\kappa| = 0.2, \quad \tan\beta = 3, \quad v_s = 389\text{ GeV}, \quad |A_\kappa| = 27\text{ GeV},$$
$$|A_\lambda| = 928\text{ GeV}, \quad A_t = -875\text{ GeV}, \quad A_b = A_l = -963\text{ GeV}, \quad M_{\text{SUSY}} = 1\text{ TeV}$$
$$M_1 = 145\text{ GeV}, \quad M_2 = 200\text{ GeV}, \quad M_3 = 600\text{ GeV}, \quad Q = 300\text{ GeV}$$

Higgs masses at the one loop order

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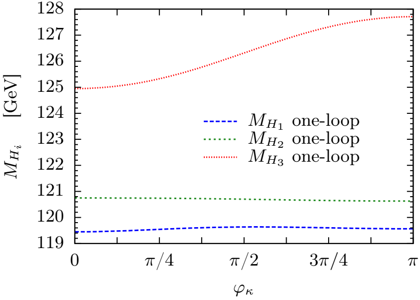
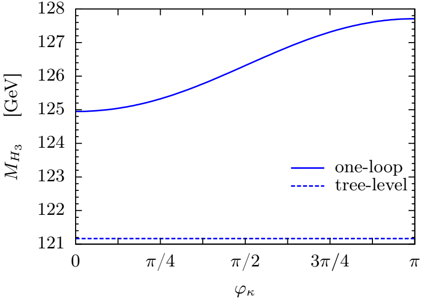
Complex phases have sizable effects [Graf, Gröber, Mühlleitner, Rzehak, Walz, JHEP 1210 (2012) 122]:

- **No tree–level CP violation ($\Psi = 0$), $\phi_\lambda = \phi_\kappa \neq 0$:**





- One loop corrections have a sizable impact (restore some scenarios)

- No tree-level *CP* violation scenario: still slight impact of ϕ_κ over H_3 through its coupling to stops

2-loop effects in Higgs mass calculation

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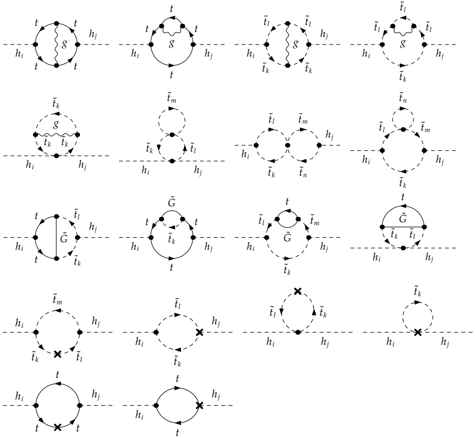
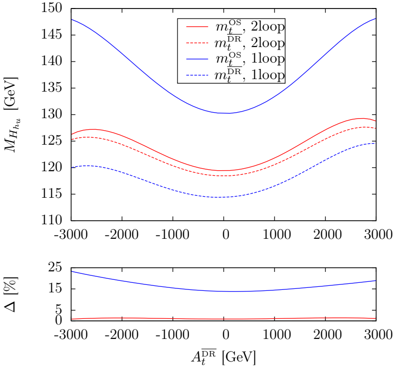
2-loop order $\mathcal{O}(\alpha_t\alpha_s)$ corrections in the effective potential approach using $\hat{\boldsymbol{\Sigma}}_{ij}(p^2=0)$

[Mühlleitner, Nhung, Rzehak, Walz, JHEP 1505 (2015) 128]





Presentation of NMSSMCALC

J.B., Gröber, Mühlleitner, Nhung, Rzehak, Spira, Streicher, Walz, CPC 185 (2014) 12

NMSSMCALC 2.0: calculate Higgs masses and decay widths in the NMSSM

2-loop Higgs boson masses in the NMSSM, allowing for complex parameters

+

new implementation to calculate the Higgs boson decay widths in the NMSSM based on the latest version of HDECAY

[Djouadi, Kalinowski, Spira, CPC 108 (1998) 56; Djouadi, Mühlleitner, Spira, Acta Phys.Polon. B38 (2007) 635]

- Real or complex parameters
- $\mathcal{O}(\alpha_t \alpha_s)$ 2-loop masses, electric dipole moments
- Decay widths and branching ratios including higher order corrections
- Off-shell decays into $VV^*, H_i V^*, tt^*, bt^*$
- Dominant SUSY corrections in the decays into quarks and leptons: implemented with two effective couplings Δ_b, Δ_1 calculated in the NMSSM

$$\mathcal{L} = -\lambda_b \overline{b_R}(1+\Delta_1)\left[H_d^0 + \frac{\lambda^* e^{i\phi_u}}{\mu_{\text{eff}}^*} \frac{\Delta_b}{\tan\beta} S^* H_u^{0*}\right] b_L + h.c.$$

$$\Delta_1 = -\frac{C_F}{2}\frac{\alpha_s}{\pi} M_3^* A_b I(m_{\tilde{b}_1}^2, m_{\tilde{b}_2}^2, m_{\tilde{g}}^2),\ \Delta_b = \frac{1}{1+\Delta_1}\left(\Delta_b^{\text{QCD}(1)} + \Delta_b^{\text{elw}(1)}\right)$$

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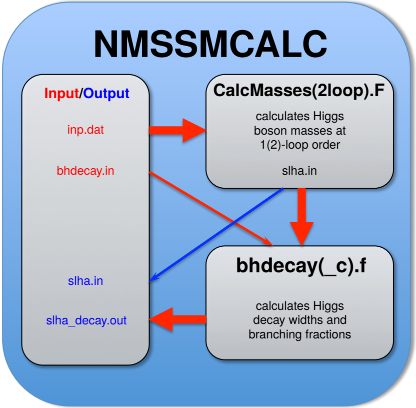

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Current status of mass calculation in NMSSMCALC:

- 2-point one-loop integrals with complex momentum
  $\Rightarrow$ no instabilities due to threshold singularities
- approximate 2-loop order for the calculation of the Higgs spectrum with $\mathcal{O}(\alpha_t \alpha_s)$ corrections in the effective potential approach ($\hat{\Sigma}_{ij}(p^2 = 0)$)

To download NMSSMCALC:
https://www.itp.kit.edu/~maggie/NMSSMCALC

NMSSMCALC input files

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- inp.dat: general input model file in the SLHA format

  MODSEL, SMINPUTS, MINPAR, EXTPAR block required

  SLHA convention extended to the complex NMSSM:
  - ⋆ new IMEXTPAR block: supply imaginary parts of the parameters in the block EXTPAR, the latter containing real parts
  - ⋆ new CMPLX block: supply the Higgs *CP* violating phase ϕ_u
  - ⋆ new NHMIX block: supply the 5×5 Higgs mixing matrix (in the output files slha.in and slha.out)
- bmhdecay.in: SM input file for bmhdecay.f with some HDECAY legacy parameters: which Higgs boson to be studied, value of $\alpha_s(M_Z)$, $\overline{m}_b(Q)$ ($Q = 2$ GeV), etc

An extract of a complex NMSSM inp.dat file:

```
Block MODSEL
  3  1   # NMSSM
  5  2   # CP violation
#
Block EXTPAR
         0     3.00000000e+02   # Input Scale
         1     1.08116260e+02   # M1
         2     1.67500000e+02   # M2
[...]
#
Block CMPLX
         3     3.92699080e-02   # phiu
#
Block IMEXTPAR  # gives the imaginary part of Block EXTRAPAR
         0     0.00000000e+00   # Input Scale
         1     5.20660490e+01   # M1
         2     2.90118510e+02   # M2
[...]
```

Inclusion of electric dipole moments

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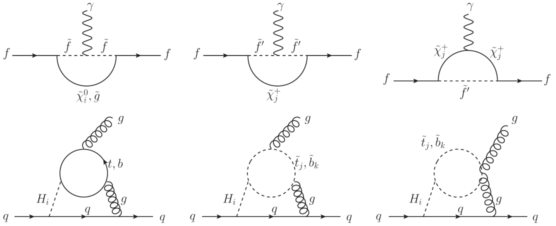
CP-violating effects enhance the (chromo-)electric dipole moments (EDM), predicted to be very small in the SM, and not yet observed



Exp upper bounds:

- Electron EDM $\lesssim 10^{-28} e$.cm [ACME, Science 343 (2014) 269]
- Thallium EDM $\lesssim 9 \times 10^{-25} e$.cm [Regan et al, PRL 88 (2002) 071805]
- Neutron EDM $\lesssim 3 \times 10^{-26} e$.cm [Baker et al, PRL 97 (2006) 131801]
- Mercury EDM $\lesssim 3.1 \times 10^{-29} e$.cm [Griffith et al, PRL 102 (2009) 101601]

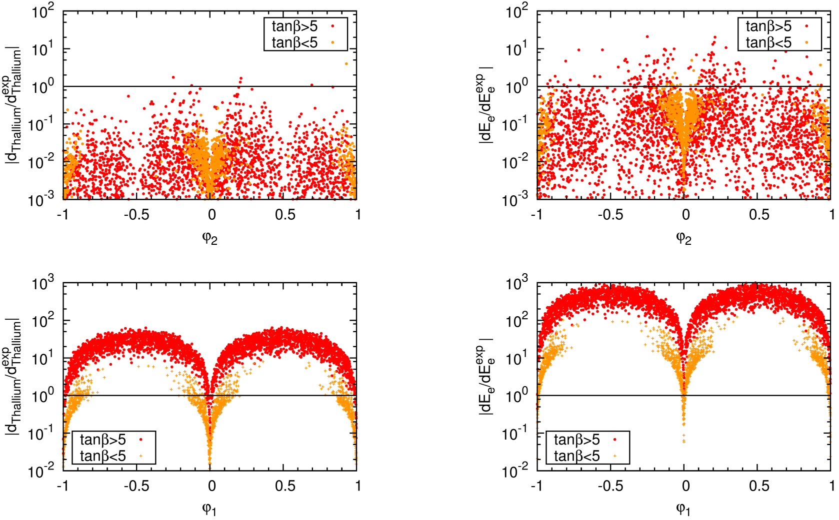
Implemented in `NMSSMCALC` at the 2-loop level, new switch in Block MODSEL [King, Mühlleitner, Nevzorov, Walz, Nucl.Phys.B 901 (2015) 526]

```
Block MODSEL
  3  1   # NMSSM
  5  2   # CP violation
  10 1   # EDMs: 0, no EDMs); 1, with EDMs); 2, EDMs individual contributions
```

Output with results rescaled to exp upper-bound

Impact of EDMs constraints

Still a sizable portion of NMSSM phases allowed by EDMs constraints



$\phi_2 = \phi_\kappa + 3\phi_s$, specific NMSSM phase $\quad \phi_1 = \phi_\lambda + \phi_s + \phi_u$, MSSM-like phase

Focus on one decay process: full NLO corrections to $A_k \to \tilde{t}_1\tilde{t}_2$ in the real NMSSM

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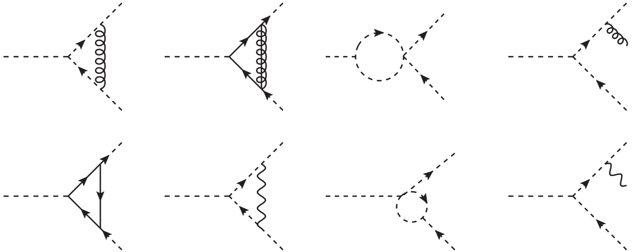
CP-odd Higgs decay into stops:

- NLO corrections known to be sizable in the MSSM [Bartl *et al*, Phys.Lett. B402 (1997) 303; Arhrib, Djouadi, Hollik, Jünger, PRD 75 (1998) 5860; Weber, Eberl, Majerotto, Phys. Lett. B572 (2003) 56, PRD 68 (2003) 093011]

  $\Rightarrow$ what about them in the NMSSM?
- Possible detection channel for stops given the exp limits on their mass or a discovery channel for the A_k bosons

Calculation strategy: complete NLO QCD and EW corrections:

- virtual corrections: vertex corrections, wave-function renormalization, counterterms diagrams, $A-Z$ mixing diagrams $\Rightarrow$ ultraviolet finite 1-loop amplitude
- real corrections: 1-loop amplitude infrared-divergent $\Rightarrow$ regularization with the gluon and photon real corrections in the the mass regularization scheme



Renormalization procedure

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Main framework for the calculation: the mixed renormalization scheme in `NMSSMCALC`

LO amplitude is the $A_k \tilde{t}_1 \tilde{t}_2^*$ coupling, with $(P)_{ij}$ the CP-odd mixing matrix:

$$G^{12}_{A_i} = -\frac{e m_t}{2}\sqrt{\frac{1}{M_W^2} - \frac{1}{M_Z^2}}\left[\left(\frac{A_t}{\tan\beta} + \mu_{\text{eff}}\right)P_{i1} + \frac{\lambda v}{\sqrt{2}}\frac{1}{\tan\beta}P_{i2}\right]$$

1. on-shell parameters: $M_Z,\ M_W,\ e$ + new parameters $m_t,\ m_{\tilde{t}_1},\ m_{\tilde{t}_2},\ \theta_t$ (stop mixing angle)
2. $\overline{\text{DR}}$ parameters: $\tan\beta,\ \lambda,\ v_s$

- **CP-odd mixing matrix for the EW corrections:** use finite $\mathcal{Z}$–factors to dress the LO mixing matrix [see e.g. Frank *et al*, JHEP 0702 (2007) 047; Nhung, Mühlleitner, Streicher, Walz, JHEP 1311 (2013) 181]

$$P^{(1)}_{i,j} = \mathcal{Z}_{ik} P^{(0)}_{kl},\, \mathcal{Z}_{ik} = \sqrt{\hat{Z}_i}\hat{Z}_{ik}$$

  with the factors $\hat{Z}_i, \hat{Z}_{ik}$ related to the effective self-energies
  $\Rightarrow$ full momentum dependence of the self-energies kept
- **Renormalization of the stop sector:** on-shell field renormalization and

$$\delta\theta_t = \frac{1}{2}\frac{\text{Re}\left(\Sigma_{12}(m^2_{\tilde{t}_2}) + \Sigma_{21}(m^2_{\tilde{t}_1})\right)}{m^2_{\tilde{t}_1} - m^2_{\tilde{t}_2}}$$

Scenarios for selected examples

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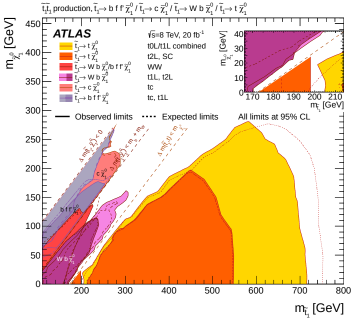
HEP 2015 ATLAS results for the direct stop search (arXiv:1506.08616)[1]:



- Select regions in the gap $m_{\tilde{t}_1} \in [250 - 350]$ GeV
- Check against current Higgs results with `HiggsBounds` and `HiggsSignal`

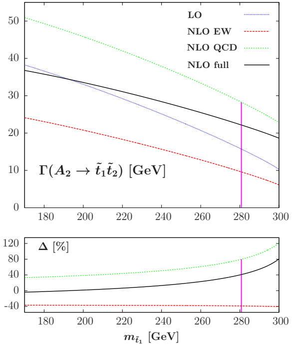
Two following scenarios extracted from a scan:

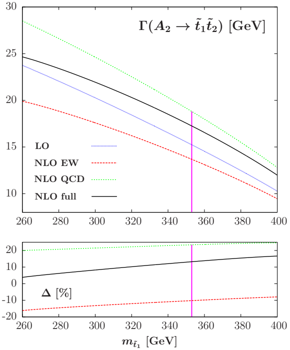
1. $m_{\tilde{t}_1} = 280.8$ GeV, $m_{\tilde{t}_2} = 709.1$ GeV, $M_{A_1} = 519.3$ GeV (singlet-like), $M_{A_2} = 1012$ GeV, $M_{H_1} = 126.2$ GeV (SM-like), $m_{\chi_1^0} = 106.7$ GeV
2. $m_{\tilde{t}_1} = 353.0$ GeV, $m_{\tilde{t}_2} = 927.6$ GeV, $M_{A_1} = 113.5$ GeV (singlet-like), $M_{A_2} = 1461$ GeV, $M_{H_2} = 124.8$ GeV (SM-like), $m_{\chi_1^0} = 57.45$ GeV

[1] Of course now outdated

Numerical results for $\Gamma(A_2 \to \tilde{t}_1\tilde{t}_2)$

SUSY-EW corrections compulsory for meaningful results, NLO corrections can be sizable





- Pink line: original scenarios 1 with $\mathrm{BR}^{\mathrm{NLO}} = 49.3\%$ (left) and 2 with $\mathrm{BR}^{\mathrm{NLO}} = 31.9\%$ (right)

Numerical results for $\Gamma(A_2 \to \tilde{t}_1\tilde{t}_2)$

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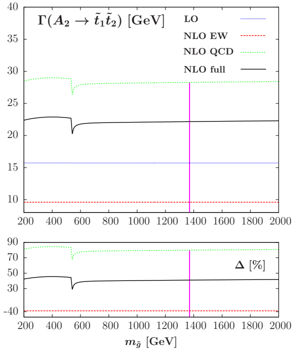
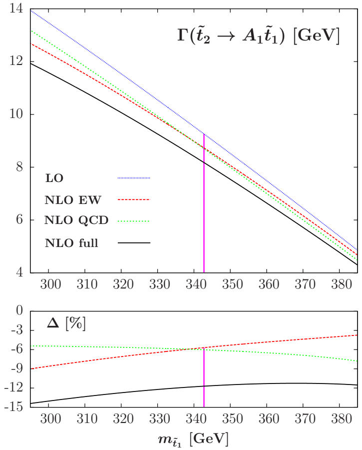


- Pink line: original scenarios 1 with $\mathrm{BR}^{\mathrm{NLO}} = 49.3\%$

- Kink from the threshold $m_{\tilde{t}_2} = m_t + m_{\tilde{g}}$ in the $\tilde{t}_2$ field renormalization

Reversed decay $\tilde{t}_2 \to \tilde{t}_1 A_k$

Same setup, reverse the kinematical relations: access to the stop decays into A_k



- **Spectrum parameters:** $m_{\tilde{t}_1} = 342.8$ GeV, $m_{\tilde{t}_2} = 1153$ GeV, $M_{A_1} = 637.4$ GeV (singlet-like), $M_{A_2} = 720.2$ GeV, $M_{H_1} = 125.2$ GeV (SM-like), $m_{\chi_1^0} = 230.9$ GeV

Prospects for NMSSMCALC

- **2-loop mass calculation:**
  - currently state-of-the-art in the mixed renormalization scheme; in agreement with other computer codes when taking into account $\neq$ input setup [see Staub et al, CPC 202 (2016) 113]
  - In the $\overline{\mathrm{DR}}$ scheme, 2-loop corrections known beyond $\mathcal{O}(\alpha_s\alpha_t)$ [Goodsell, Staub, EPJC 77 (2017) 46]
  - **Future implementation of 2-loop terms beyond $\mathcal{O}(\alpha_s\alpha_t)$ in progress**

- **NLO corrections in decay widths:** up to now EW corrections only calculated for the real NMSSM in $A \to \tilde{t}_1\tilde{t}_2$
  $\to$ **Inclusion of NLO (QCD+)EW corrections in the complex NMSSM for all Higgs decays in progress**

- **Package extension:**
  - Link to `Micromegas` to calculate the NMSSM LSP relic density planned.
  - Link to computation of flavor physics observables planned.
  - Test of S, T, U parameters planned.