NMSSM: Tools

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The NMSSM in a nutshell

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Possible features: enhanced tree-level Higgs mass ($\rightarrow$ Naturalness), Z_3 invariant version solves μ problem, new dark matter candidate (singlino), rich phenomenology, . . .

Public tools for the NMSSM

1. Codes to calculate the **mass spectrum** of the NMSSM:
   - `FlexibleSUSY & SARAH`: @HepForge
   - `NMSSMCALC`: www.itp.kit.edu/∼maggie/NMSSMCALC/
   - `NMSSMTools`: www.th.u-psud.fr/NMHDECAY/nmssmtools.html
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2. Code to check the **vacuum stability**:
   - Vevacious: @HepForge
3. Code to calculate the neutral Higgs **cross section**
   - SusHi: @HepForge

Spectrum generators I: supported variants of the NMSSM

Following **variants of the real NMSSM** can be studied :

- with and without Z_3; SUSY and GUT input:
  `NMSSMTools`, `FlexibleSUSY`, `SoftSUSY`, `SPheno`
- only Z_3 invariant NMSSM with SUSY input:
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CP violation is implemented at different level in the tools

- `NMSSMCALC`: CPV included at one- and two-loop
- `SPheno`: CPV included at one-loop; two-loop in preparation
- `FlexibleSUSY`: CPV included at one-loop
- `NMSSMTools`: CPV at one-loop in preparation
- `SoftSUSY`: no CPV included

Spectrum generators II: Higgs mass calculation

The main differences in the Higgs mass calculation are

- **Renormalization scheme:**
  - NMSSMCALC: $\overline{\text{DR}}$ and on-shell calculation
  - all other codes just $\overline{\text{DR}}$

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- **Included two-loop corrections:** (all tools have full 1-loop)
  - $\alpha_S \alpha_t$: NMSSMCALC
  - $\alpha_S(\alpha_t + \alpha_b)$ & MSSM approx. for $\alpha_t(\alpha_t + \alpha_b)$, $(\alpha_b + \alpha_\tau)^2$: NMSSMTools, FlexibleSUSY, SoftSUSY
  - $\alpha_s(\alpha_b + \alpha_t)$, $(\alpha_t + \alpha_b + \alpha_\lambda)^2$, $\alpha_\tau(\alpha_\tau + \alpha_b)$, $\alpha_\kappa(\alpha_\kappa + \alpha_\lambda)$: SPheno

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- **Different approaches to obtain $\overline{\text{DR}}$ parameters**: sizeable differences in $Y_t^{\overline{\text{DR}}}(M_{SUSY})$

Spectrum generators III: Higgs mass prediction

Differences using a $\overline{\text{DR}}$ calculation are larger than in the MSSM:

	Q	$\tan\beta$	λ	κ	A_λ	A_κ	μ_{eff}	M_1	M_2	M_3	A_t	A_b	$m_{\tilde{t}_L}$	$m_{\tilde{t}_R}$
TP1	1500.	10.	0.1	0.1	-10.	-10.	900.	500.	1000.	3000.	3000.	0.	1500.	1500.
TP2	1500.	10.	0.05	0.1	-200.	-200.	1500.	1000.	2000.	2500.	-2900.	0.	2500.	500.
TP3	1000.	3.	0.67	0.1	650.	-10.	200.	200.	400.	2000.	1000.	1000.	1000.	1000.
TP4	750.	2.	0.67	0.2	405.	0.	200.	120.	200.	1500.	1000.	1000.	750.	750.
TP5	1500.	3.	0.67	0.2	570.	-25.	200.	135.	200.	1400.	0.	0.	1500.	1500.
TP6	1500.	3.	1.6	1.61	375.	-1605.	614.	200.	400.	2000.	0.	0.	1500.	1500.

SM-like Higgs mass:

	TP1	TP2	TP3	TP4	TP5	TP6
FlexibleSUSY	123.55	122.83	126.58	127.62	125.08	126.46
NMSSMCalc	120.34	118.57	124.86	126.37	123.14	123.45
NMSSMTOOLS	123.91	121.38	128.00	128.12	126.94	126.60
SOFTSUSY	123.84	123.08	126.59	127.52	125.12	126.67
SPHENO	124.84	124.74	126.77	126.62	125.61	131.29

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- All differences are fully understood: discussion to appear soon
- Next step: comparison with **OS calculation** including also upcoming `FeynHiggs` version

Spectrum generators IV: other calculations

Decays of the Higgs bosons

- NMSSMCALC, NMSSMTools, SPheno perform independent calculations of the decays
- NMSSMCALC adapts HDECAY: many radiative corrections included
- SoftSUSY can be interfaced with NMHDECAY and NMSDECAY
- Calculation of decays in FlexibleSUSY under construction

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Flavour and precision observables

- NMSSMTools: B decays, $\Delta M_{B_{d,s}}$, $(g-2)_\mu$
- SPheno: B and K decays, $\Delta M_{B_{d,s}}/\Delta M_K$, ϵ_K, $(g-2)_l$, $\delta\rho$, EDMs
- Superiso supports also the NMSSM

Overview spectrum generators

	FlexibleSUSY	NMSSM-CALC	NMSSM-Tools	SoftSUSY	SPheno
General					
	using SARAH	stand alone	stand alone	stand alone	using SARAH
No Z_3	✓	✗	✓	✓	✓
GUT model	✓	✗	✓	✓	✓
CPV	1-loop	✓	in prep.	✗	1-loop
Higgs corrections					
scheme	$\overline{\text{DR}}$	OS, $\overline{\text{DR}}$	$\overline{\text{DR}}$	$\overline{\text{DR}}$	$\overline{\text{DR}}$
1-loop from	SARAH	1206.6806	0907.4682	0907.4682	SARAH
2-loop	$\alpha_s(\alpha_b+\alpha_t)$ + MSSM	$\alpha_s\alpha_t$	$\alpha_s(\alpha_b+\alpha_t)$ + MSSM	$\alpha_s(\alpha_b+\alpha_t)$ + MSSM	all but ew
Other calculations					
1-loop SUSY	✓	✗	✓	✓	✓
Decays	in prep.	✓	✓	(✓)	✓
Flavour observables	✗	✗	✓	✗	✓

Check for the vacuum stability

The **vacuum with correct EWSB is not necessarily the global minimum** of the scalar potential:

- Large stop mixing: charge and colour breaking minima with stop VEVs can appear
- Large A_κ, A_λ: deeper minima with other combinations of v_d,v_u,v_S more likely

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The code Vevacious checks the vacuum stability

- Needs SLHA file as input
- Global minimum of the one-loop effective potential of the NMSSM found numerically (including stau and stop VEVs)
- Finite temperature effects included
- Life-time of metastable vacua calculated using CosmoTransitions

Higgs cross section I

Gluon fusion and bottom-quark annihilation for the real NMSSM supported by SusHi v1.5.0

Included corrections for gluon fusion in SusHi

- Third generation quarks and squarks at LO QCD
- Full massive quark contributions at NLO QCD; NLO QCD squark contributions expanded in heavy SUSY masses
- NNLO top quark corrections in heavy top limit
- $\tan\beta$ resummation included
- NLO electroweak corrections for CP-even Higgs bosons

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- Private version of HiGlu for quark induced contributions.
- Kinematic distributions with MoRe-SusHi and aMCSusHi

Higgs cross section II

Theoretical uncertainties for gluon fusion (see MSSM):

- Scale uncertainty: Renormalization and factorization scale taken at $m_\phi/2 \to$ similar to MSSM
- PDF uncertainty: can be taken from SM Higgs with same mass
- Δ_b uncertainty: small for $\tan\beta$ values often considered in the NMSSM
- Uncertainty due to heavy SUSY masses expansion: relevant for heavy Higgs bosons
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Other production rates can be estimated with a good accuracy by reweighting the effective couplings to Z, W and t