Karlsruher Institut für Technologie

Tackling SUSY beyond the MSSM

Florian Staub | (Re)interpreting the results of new physics searches at the LHC, 15th May 2018

KARLSRUHE INSTITUTE OF TECHNOLOGY, ITP & IKP

Consequences of BSM physics

- Today, we are interested in less minimal SUSY models.
- Of course, we need for these models predictions for **production rates and decays**
- However, also **many other things need to be checked**:
  1. Impact on flavour observables?
  2. Impact on $g-2$, $\Delta\rho$, EDMs?
  3. Dark matter abundance and direct detection?
  4. Predictions for the Higgs mass & couplings?
  5. Impact on vacuum stability?

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`SARAH` provides a fully automatised framework to perform all these studies

SARAH [FS,0806.0538,0909.2863,1002.0840,1207.0906,1309.7223,1503.04200]

SARAH is a Mathematica package to get from **a minimal input** all important properties of **SUSY** and **non-SUSY models**.

SARAH

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Calculated information:

- all **Vertices**, **Tadpole equations**, **Masses** and **Mass matrices**
- **Two-loop RGEs** including the **full CP and flavour** structure, effects of **gauge kinetic mixing**, and R_ξ **dependence of VEVs**.
- **Loop corrections** to masses and precision observables

Interfaces to different tools exist to make use of this information

Included Models

- 331
  - v1
  - v2
- BLRinvSeesaw
- B-L-SM
- B-L-SM-IS
- B-L-SSM
- B-L-SSM-IS
- brokenMRSSM
- BxL-SSM
- CCB-MSSM
  - SfermionVEVs
  - StauStopVEVs
  - StauVEVs
  - StopVEVs
- DiracGauginos
- DiracNMSSM
- E6SSMalt3I
- Georgi-Machacek
- GTHDM
- Inert
- inverse-Seesaw
- inverse-Seesaw-NMSSM
- Leptoquarks
  - ScalarLeptoquarks
  - TwoScalarLeptoquarks
- LinSeesaw
- LRmodels
  - darkLR
  - LRLR
  - LR-VL
  - tripletLR
- MDGSSM
- MRSSM
- MSSM
  - CKM
  - CPV
  - LeptonFV
  - NoFV
  - NoFV2
- MSSM6C
- MSSM-RpV
  - Bi
  - Bi_NoFV
  - BnV
  - LnV
  - TriLnV
  - TriRpV
- MSSM+U1prime-VL
- munuSSM
  - 3G
- N-B-L-SSM
- near-MSSM
- NHSSM
- NMSSM
  - CKM
  - CPV
  - NoFV
  - NoFV2
  - Two_Rotations
- NMSSM+VL
  - 10plets
  - 5+10plets
  - 5plets
  - 5plets+RpV
  - VLtop
- Omega
- Omega_Short
- QEW12
- QEWmld2L3
- SDDM
- secluded-MSSM
- Seesaw1
- Seesaw2
- Seesaw3
- SM
  - CKM
- SM-8C
- SM-S-Octet
- SMSSM
- SM+Triplet
  - Complex
  - Real
- SM+VL
  - complexS
  - CPevenS
  - CPoddS
  - PortalDM
  - TripletQuarks
- SSDM
- SSM
- THDM
  - ScalarSeptuplet
  - ScalarTriplet
- THDM-CPV
- THDM-Flipped
- THDM-II
- THDM-III
- THDM-LS
- THDM+VL
  - min-3
  - min-8
  - Type-II-SM-like-VL
  - Type-II-VL
  - Type-I-SM-like-VL
  - Type-I-VL
- TMSSM
- TNMSSM
- U1Extensions
  - BL-VL
  - darkU1
  - hiddenU1
  - nonUniversalU1
  - scotoU1
  - simpleU1
  - trickingLY
  - U1Leptophobic
  - VLsample
- U1xMSSM
- U1xMSSM3G
  - Vevacious
- UMSSM
- Vectorlike
  - BottomR
  - BottomY
  - SusyTop
  - SusyTopSpectator
  - TopBottomL
  - TopR
  - TopX

Models

Example: MDGSSM mode file

```
Off[General::spell]

Model`Name = "MDGSSM";
Model`NameLaTeX ="Minimal-Dirac-Gaugino-SSM with UV completion";
Model`Authors = "M.D. Goodsell, F.Staub";
Model`Date = "2013-03-27";

(*-------------------------------------------*)
(*   Particle Content*)
(*-------------------------------------------*)

(* Global symmetries *)

Global[[1]] = {Z[2],RParity};
RpM = {-1,-1,1};
RpP = {1,1,-1};

(* Gauge Superfields *)

Gauge[[1]]={B,   U[1], hypercharge, g1,False, RpM};
Gauge[[2]]={WB, SU[2], left,        g2,True,  RpM};
Gauge[[3]]={G,  SU[3], color,       g3,False, RpM};


(* Chiral Superfields *)

SuperFields[[1]] = {q,  3, {uL,  dL},    1/6, 2, 3, RpM};
SuperFields[[2]] = {l,  3, {vL,  eL},   -1/2, 2, 1, RpM};
SuperFields[[3]] = {Hd, 1, {Hd0, Hdm},  -1/2, 2, 1, RpP};
SuperFields[[4]] = {Hu, 1, {Hup, Hu0},   1/2, 2, 1, RpP};

SuperFields[[5]] = {d,   3, conj[dR],  1/3, 1, -3, RpM};
SuperFields[[6]] = {u,   3, conj[uR], -2/3, 1, -3, RpM};
SuperFields[[7]] = {e,   3, conj[eR],    1, 1,  1, RpM};

SuperFields[[8]] = {S,   1, s, 0, 1, 1, RpP};
SuperFields[[9]] = {T,   1, {{T0/Sqrt[2],Tp},{Tm, -T0/Sqrt[2]}},  0, 3, 1, RpP};
SuperFields[[10]] = {oc, 1, Oc, 0, 1, 8, RpP};

SuperFields[[11]] = {ru,  1, {Ru0,Rum}, -1/2, 2, 1, RpM};
SuperFields[[12]] = {rd,  1, {Rdp,Rd0},  1/2, 2, 1, RpM};
SuperFields[[13]] = {er1, 2, conj[ER1],    1, 1, 1, RpM};
SuperFields[[14]] = {er2, 2, conj[ER2],   -1, 1, 1, RpM};


AddDiracGauginos = True;
AddMixedSofts = False;

(*-----------------------------------------------------*)
(* Superpotential *)
(*-----------------------------------------------------*)


SuperPotential = Yu u.q.Hu - Yd d.q.Hd - Ye e.l.Hd + \[Mu] Hu.Hd + MS/2 S.S \
                + \[Lambda] S.Hd.Hu + LT Hd.T.Hu  + LS/2 S.T.T \
                + LambdaSR S.ru.rd + MuR ru.rd + LambdaTR ru.T.rd + LambdaSE S.er1.er2 \
                +  MuE er1.er2 + YE1 ru.Hd.er1 + YE2 rd.Hu.er2 + YL l.Hd.er1;

AddSoftGauginoMasses = False;
AddTterms = False;
```

```
(*-------------------------------------------*)
(*   DEFINITION                              *)
(*-------------------------------------------*)

NameOfStates={GaugeES, EWSB};

(* ----- After EWSB ----- *)


(* Gauge Sector *)

DEFINITION[EWSB][GaugeSector] =
{
  {{VB,VWB[3]},{VP,VZ},ZZ},
  {{VWB[1],VWB[2]},{VWm,conj[VWm]},ZW},
  {{fWB[1],fWB[2],fWB[3]},{fWm,fWp,fW0},ZfW}
};


(* ----- VEVs ---- *)

DEFINITION[EWSB][VEVs]=
  {{SHd0, {vd, 1/Sqrt[2]}, {sigmad, \[ImaginaryI]/Sqrt[2]},{phid,1/Sqrt[2]}},
   {SHu0, {vu, 1/Sqrt[2]}, {sigmau, \[ImaginaryI]/Sqrt[2]},{phiu,1/Sqrt[2]}},
   {ST0, {vT, 1/Sqrt[2]}, {sigmaT, \[ImaginaryI]/Sqrt[2]},{phiT,1/Sqrt[2]}},
   {Ss, {vS, 1/Sqrt[2]}, {sigmaS, \[ImaginaryI]/Sqrt[2]},{phiS,1/Sqrt[2]}},
  {SOc, {0,0}, {sigmaO, \[ImaginaryI]/Sqrt[2]},{phiO,1/Sqrt[2]}}
 };



(* ---- Mixings ---- *)

DEFINITION[EWSB][MatterSector]=
{    {{SdL, SdR}, {Sd, ZD}},
     {{SvL, SRu0, conj[SRd0]}, {Sv, ZV}},
     {{SuL, SuR}, {Su, ZU}},
     {{SeL, SeR, SRum, conj[SRdp],SER1,conj[SER2]}, {Se, ZE}},
     {{phid, phiu, phiS, phiT}, {hh, ZH}},
     {{sigmad, sigmau, sigmaS, sigmaT}, {Ah, ZA}},
     {{SHdm,conj[SHup],STm,conj[STp]},{Hpm,ZP}},
     {{fB, fW0, FHd0, FHu0, Fs, FT0}, {L0, ZN}},
     {{{fWm, FHdm,FTm}, {fWp, FHup,FTp}}, {{Lm,UM}, {Lp,UP}}},
     {{FvL,FRu0, FRd0}, {RN, UV}},
     {{{FeL,FRum,conj[FER2]},{conj[FeR],FRdp,conj[FER1]}},{{FEL,ZEL},{FER,ZER}}},
     {{{FdL},{conj[FdR]}},{{FDL,ZDL},{FDR,ZDR}}},
     {{{FuL},{conj[FuR]}},{{FUL,ZUL},{FUR,ZUR}}},
     {{fG,FOc},{Gl,ZG}}
       };

DEFINITION[EWSB][DiracSpinors]={
 Fd ->{  FDL, conj[FDR]},
 Fe ->{  FEL, conj[FER]},
 Fu ->{  FUL, conj[FUR]},
 Fv ->{  RN, conj[RN]},
 Chi ->{ L0, conj[L0]},
 Cha ->{ Lm, conj[Lp]},
 Glu ->{ Gl, conj[Gl]}
};
```

This defines a rather complicated model with extra singlet, triplet, octet, vector-like states and Dirac gaugino masses!

Monte-Carlo tools

SARAH writes model files for

- CalcHep/CompHep [Pukhov et al.],[Boos et al.]
- WHIZARD [Kilian,Ohl,Reuter,0708.4233],[Moretti,Ohl,Reuter,0102195]
- MadGraph, Herwig++, (WHIZARD) via UFO [Alwall et al.,1106.0522], [Bellm et al.,1310.6877]

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Input for MC Tools

There is a **direct link between SPheno version generated by SARAH and the MC model files**:

→ no issue with convention between spectrum generator and MC tools

→ also widths (including one-loop corrections) are provided

[Goodsell,Liebler,FS,1703.09237]

Dark matter constraints

Dark matter properties can be obtained from ...

1. ...`CalcHep` model files with `MicrOmegas` [Belanger et al.]
2. ...the UFO model files with `MadDM` [Ambrogi et al.]

SPheno interface

'Spectrum Generator Generator' [FS,0909.2863,1002.0840,1207.0906,1309.7223,1503.04200]

SARAH **writes Fortran code** which can be **compiled with** SPheno.

→ **Implementation of new models in** SPheno in a modular way **without** the need to write **source code by hand**.

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Necessary steps:

- Load Model in SARAH
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Running time and lines of SPheno source code:

- MSSM: ~20min, ~520k lines
- NMSSM: ~25min, ~570k lines
- B-L-SSM: ~60min, ~980k lines

Precision Observables

`SPheno` calculates many observables out-of-the-box at **full one-loop:**

- S,T,U parameter
- EDMs, $g-2$
- Lepton flavour violation:
  - Br($l_i \to l_j \gamma$), Br($l \to 3l'$), Br($Z \to ll'$)
  - CR($\mu - e, N$) (N=Al,Ti,Sr,Sb,Au,Pb), Br($\tau \to l + P$) (P=π, η,η')
- Quark flavour violation:
  - Br($B \to X_s \gamma$), Br($B^0_{s,d} \to l\bar{l}$), Br($B \to s l\bar{l}$), Br($K \to \mu\nu$)
  - Br($B \to q\nu\nu$), Br($K^+ \to \pi^+ \nu\nu$), Br($K_L \to \pi^0 \nu\nu$)
  - $\Delta M_{B_s,B_d}$, ΔM_K, ϵ_K, Br($B \to K\mu\bar{\mu}$)
  - Br($B \to l\nu$), Br($D_s \to l\nu$)

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There is even more

- The `FlavorKit` functionality can be used to add more observables

  [Porod,FS,Vicente,1405.1434]

- **New Interface to `flav-io`:** [Straub, flav-io.github.io]

  access to hundreds of (binned) BRs, angular observables, . . .

SPheno

Many new results

Many new predictions were made possible by this framework:

- RpV loop-contributions to B-decays [Dreiner,Nickel,FS,1309.1735]
- LFV in inverse seesaw [Abada et al.,1408.0138]
- LFV in left-right models [Bonilla et al., 1611.07025,]
- $g-2$ in vector-like extensions of the MSSM [Choudhury,1701.08778]
- Flavour violating Higgs decays [Phang, Hung, Hue, 1605.07164]
- LFV in scotogenic model [Rocha-Moran,Vicente,1605.01915]
- Different ideas to explain B-anomalies [1503.06077,1604.03416 ,1706.07337,1803.04703]
- ...

SPheno

Higgs constraints

- The Higgs mass became a precision observable
  → **One-loop calculations no longer sufficient!**
- The combination `SARAH/SPheno` provides a **fully automatised two-loop calculation** of the Higgs mass in BSM models

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Two-loop masses with `SARAH/SPheno` [Goodsell,Nickel,FS,1411.0675,1503.03098]

- **Full one-loop calculation** including *all* contributions
- **Nearly complete two-loop calculation** neglecting only electroweak effects & momentum dependence

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- **Full one-loop calculation** including *all* contributions
- **Nearly complete two-loop calculation** neglecting only electroweak effects & momentum dependence

→ All available ($\overline{\text{DR}}$) **two-loop results** are **exactly reproduced!**

→ SARAH/SPheno **is the only combination which provides MSSM-like accuracy for other BSM models!**

→ see [Goodsell,Nickel,FS,1411.4665] for new two-loop results in the NMSSM obtained with SARAH/SPheno

→ Also **new results for the MSSM** could be obtained

→ see [Goodsell,Nickel,FS,1511.01904] for the impact of large flavour mixing at two-loop

Other new two-loop results

The machinery was applied to many different models, e.g.

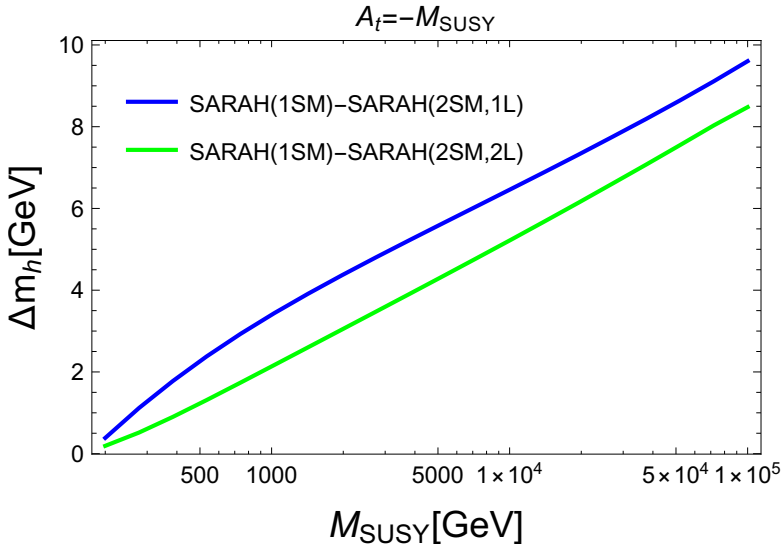
- Contributions from trilinear RpV [Dreiner,Nickel,FS,1411.3731]
- CP violating NMSSM beyond $O(\alpha_s \alpha_t)$ [Goodsell,FS, 1604.05335]
- Contributions from non-holomorphic soft-terms [Ün et al.,1412.1440]
- MRSSM [Diessner,Kalinoswki,Kotlarski,Stöckinger,1504.05386]
- Contributions from vectorlike (s)tops [Nickel,FS,1505.06077]
- The MSSM beyond MFV [Goodsell,Nickel,FS,1511.01904]
- 'Dark Sector' VL states [Basirnia, Macaluso, Shih, 1605.08442]
- SUSY $B-L$ [Rose,Khalil,King,Marzo,Moretti,Un,1702.01808]
- NMSSM with right-handed sneutrinos [Cerdeno et al.,1707.03990]
- ...

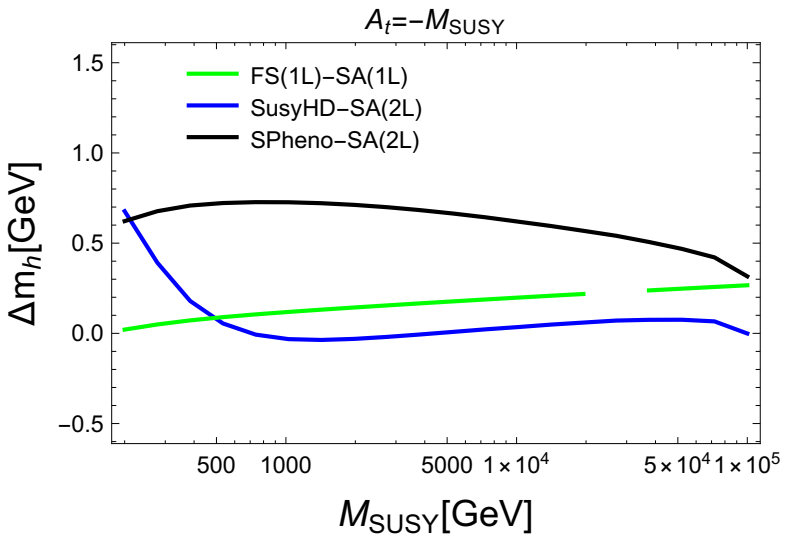
SPheno

Improved handling of large scales

We can now deal also with large SUSY scales [Porod,FS,1703.03267]

- New two-scale matching, i.e. SUSY particles are properly decoupled
- The SM-Higgs mass prediction is improved by using EFT techniques





→ Large changes in m_h for heavy SUSY

→ Good agreement with EFT codes.

SPheno

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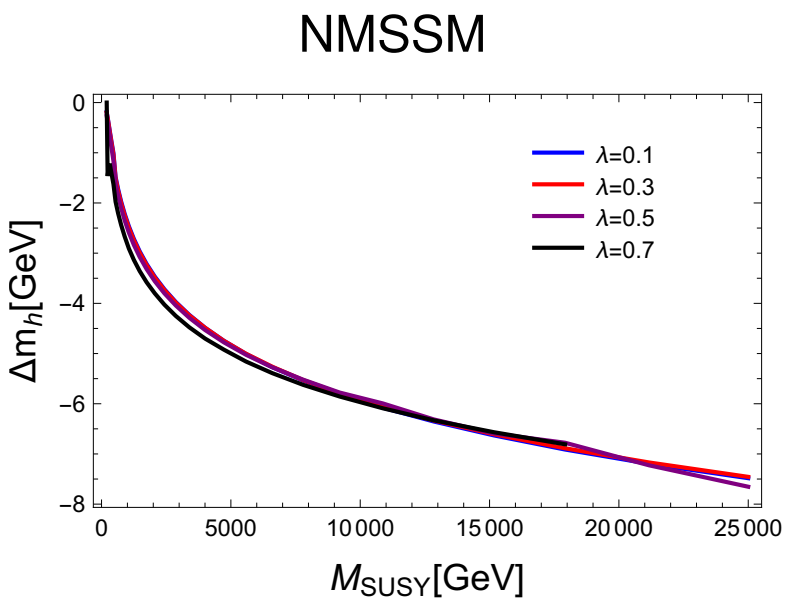


This works for all models if there is only one light Higgs

SPheno

Vacuum Stability

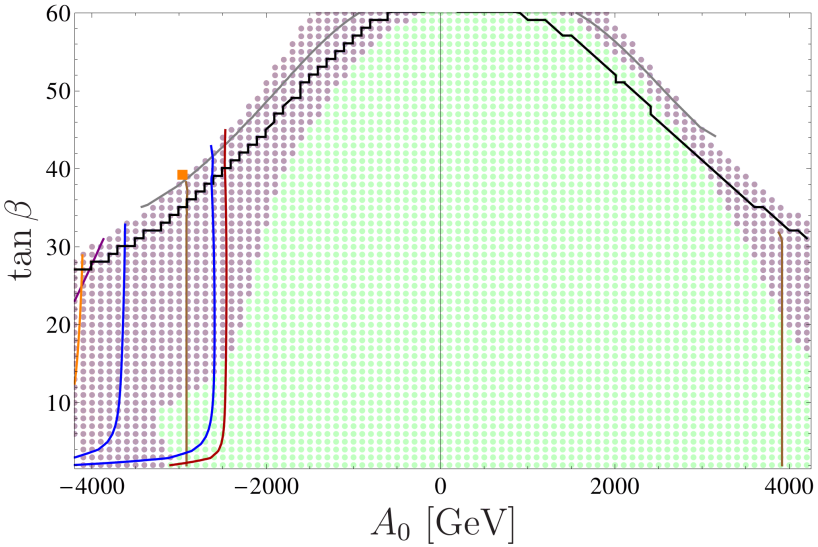
Vevacious

[Camargo-Molina,O'Leary,Porod,FS,1307.1477]

Testing numerically the **stability of the one-loop potential** including an arbitrary numbers of VEVs

CCB in the MSSM

[Camargo-Molina,O'Leary,Porod,FS,1309.7212]

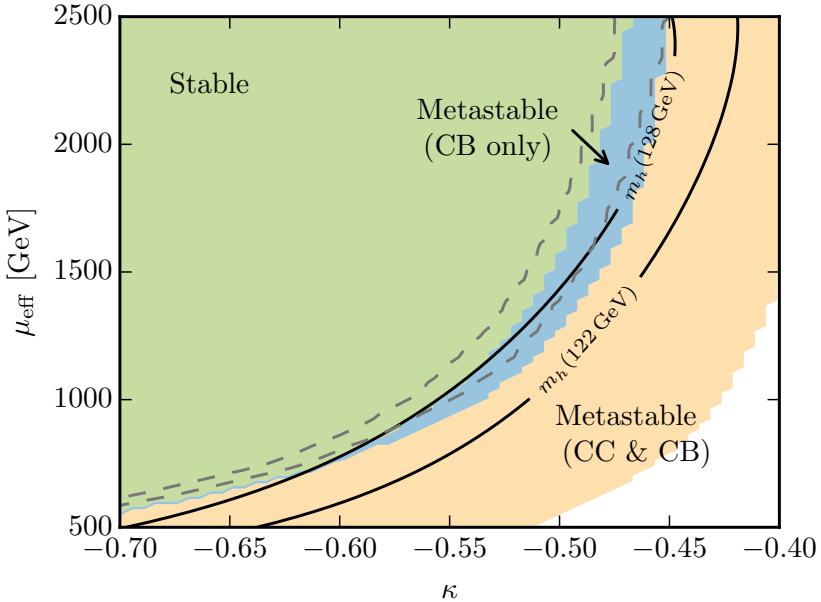


Points: stable/unstable
Lines: Simplified, analytical conditions

→ **Analytical conditions miss many unstable points!**

H^+ VEVs in the NMSSM

[Krauss,Opferkuch,FS,1703.05329]



→ **Charged Higgs VEV can play some role!**

Summary

- SARAH became an established and comprehensive **framework to study non-minimal SUSY models**
- Large efforts have been put in a precise **prediction of the Higgs mass**:
  - Model dependent two-loop calculations
  - EFT approach to handle large SUSY scales
- Many **other observables are directly available** by combining SARAH with other tools

All of that is true also for non-supersymmetric models!