Tackling SUSY beyond the MSSM

Florian Staub | (Re)interpreting the results of new physics searches at the LHC, 15th May 2018
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 is a Mathematica package to get from a minimal input all important properties of SUSY and non-SUSY models.
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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 $R\xi$ dependence of VEVs.
- Loop corrections to masses and precision observables

Interfaces to different tools exist to make use of this information
Example: MDGSSM mode file

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
2. ...the UFO model files with MadDM

[Belanger et al.]

[Ambrogi et al.]
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.
SPheno interface

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

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Necessary steps:

- Load Model in SARAH
- Run MakeSPheno[
- Copy code into a new SPheno subdirectory and compile it
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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:
  - $\text{Br}(l_i \rightarrow l_j \gamma)$, $\text{Br}(l \rightarrow 3l')$, $\text{Br}(Z \rightarrow ll')$
  - $\text{CR}(\mu \rightarrow e, N)$ (N=Al,Ti,Sr,Sb,Au,Pb), $\text{Br}(\tau \rightarrow l + P)$ (P=π, η, η')
- Quark flavour violation:
  - $\text{Br}(B \rightarrow X_s \gamma)$, $\text{Br}(B^0_{s,d} \rightarrow \bar{l}l)$, $\text{Br}(B \rightarrow s\bar{l}l)$, $\text{Br}(K \rightarrow \mu\nu)$
  - $\text{Br}(B \rightarrow q\nu\nu)$, $\text{Br}(K^+ \rightarrow \pi^+ \nu\nu)$, $\text{Br}(K_L \rightarrow \pi^0 \nu\nu)$
  - $\Delta M_{B_s,B_d}$, $\Delta M_K$, $\epsilon_K$, $\text{Br}(B \rightarrow K\mu\bar{\nu})$
  - $\text{Br}(B \rightarrow l\nu)$, $\text{Br}(D_s \rightarrow l\nu)$

There is even more 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, . . .
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There is even more

- The **FlavorKit** functionality can be used to add more observables
  
  [Porod, FS, Vicente, 1405.1434]

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  access to hundreds of (binned) BRs, angular observables, . . .
  
  [Straub, flav-io.github.io]
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]

...
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

- Full one-loop calculation including all contributions
- Nearly complete two-loop calculation neglecting only electroweak effects & momentum dependence
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**Two-loop masses with SARAH/SPheno**

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

→ **All available (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]
- ...
Improved handling of large scales

We can now deal also with large SUSY scales

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

\[ A_t = -M_{\text{SUSY}} \]

\[ \Delta m_h \text{[GeV]} \]

\[ M_{\text{SUSY}} \text{[GeV]} \]

→ Large changes in \( m_h \) for heavy SUSY
→ Good agreement with EFT codes.
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- The SM-Higgs mass prediction is improved by using EFT techniques

This works for all models if there is only one light Higgs
Testing numerically the **stability of the one-loop potential** including an arbitrary numbers of VEVs.

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

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