Introduction to SARAH

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Download & Documentation: http://sarah.hepforge.org
News, Feedback & Suggestions: Google+ Community 'SARAH'

Supersymmetry: Tools meet Models
Bonn, 29. June 2013

Steps to study a new SUSY model

collider phe-nomenology	dark matter	check constraints	...
↑	↑	↑	↑

Add loop corrections to masses

↑

Calculate the mass spectrum and parameters

↑

Embed model in GUT theory: **RGEs needed**

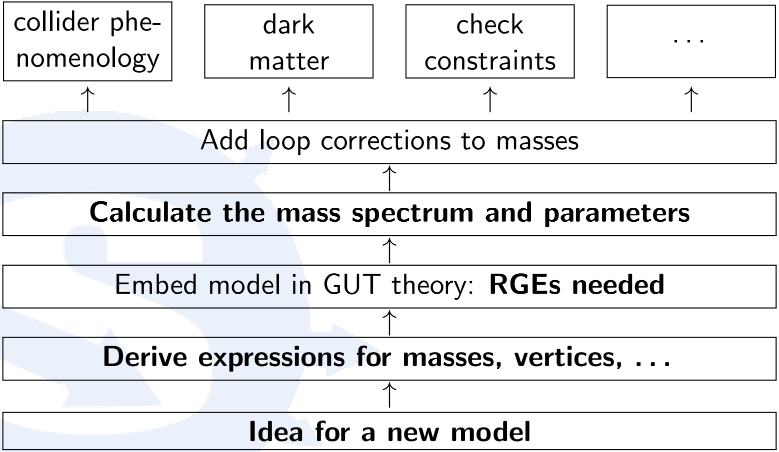
↑

Derive expressions for masses, vertices, ...

↑

Idea for a new model

Steps to study a new SUSY model



looks like a long and exhaustive way

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collider phenomenology | dark matter | check constraints | . . .

↑ ↑ ↑ ↑

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Derive expressions for masses, vertices, . . .

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Idea for a new model

is covered in a completely automatized way now!

Linking Model Building and Phenomenology using SARAH

1. Build and understand your model

Check model for consistency, get the Lagrangian, derive masses, vertices, RGEs.

$\rightarrow$ Strength of SARAH

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Calculate the mass spectrum based on GUT or SUSY-scale input
→ interface to SPheno

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2. Calculate the Mass spectrum

Calculate the mass spectrum based on GUT or SUSY-scale input
→ interface to SPheno

3. Constraints

Check constraints from dark matter, precision observables and vacuum stability.
→ interface to SPheno, MicrOmegas, Vevacious, HiggsBounds/HiggsSignals

Linking Model Building and Phenomenology using SARAH

4. Make your Collider study

Use your favorite MC tool and make some nice study.

$\rightarrow$ interface to CalcHep, CompHep, MadGraph, WHIZARD

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5. Other calculations

You might want to check loop corrections or do other calculations.
$\rightarrow$ interface to FeynArts/FormCalc

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Use your favorite MC tool and make some nice study.

→ interface to CalcHep, CompHep, MadGraph, WHIZARD

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You might want to check loop corrections or do other calculations.

→ interface to FeynArts/FormCalc

6. Save time and work

Combine all tools in an automatized way

→ try the SUSY Toolbox

SUSY Models and SARAH

Implement models in SARAH

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

SARAH is a Mathematica package to get from a minimal input all important properties of a model: SUSY models are easily defined by particle content & superpotential.

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- All gauge (and gaugino) interactions are automatically derived from quantum numbers
- Gauge fixing terms in R_ξ gauge are automatically derived
- SUSY Soft-breaking terms are added automatically ($m^2\phi\phi^*$, $M_\lambda\lambda\lambda$, $T\phi_i\phi_j\phi_k$, $B\phi_i\phi_j$, $L\phi_i$).

Supported models

Linking Susyno:

[Fonseca,1106.5016]

SARAH 4 links Susyno to support the following Gauge Groups:

$$SU(N),\ SO(N),\ SP(2N),\ E_{6,7,8},\ G_2,\ F_4.$$

Matter and gauge sector

The gauge sector can consist of an arbitrary number of groups and all irreducible representations can be used for matter fields.

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The gauge sector can consist of an arbitrary number of groups and all irreducible representations can be used for matter fields.

Full support of kinetic mixing for several Abelian gauge groups

(Q: charge-vector, G: coupling matrix, A_μ: vector bosons)

$$D_\mu = \partial_\mu - iQ^T G A_\mu$$

$\xi^{a,b} F^a_{\mu\nu} F^{\mu\nu,b}$ absorbed in off-diagonal elements of G

MSSM model file

```
Off[General::spell]

Model`Name = "MSSM";
Model`NameLaTeX ="MSSM";
Model`Authors = "F.Staub";
Model`Date = "2012-06-09";


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

(* Gauge Superfields *)

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


(* Chiral Superfields *)

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

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


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


SuperPotential = { {{1, Yu},{u,q,Hu}}, {{-1,Yd},{d,q,Hd}},
                   {{-1,Ye},{e,l,Hd}}, {{1,\[Mu]},{Hu,Hd}}};

(*-------------------------------------------*)
(* Integrate Out or Delete Particles         *)
(*-------------------------------------------*)

IntegrateOut={};
DeleteParticles={};
```

```
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]}}};


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

DEFINITION[EWSB][MatterSector]=
{    {{SdL, SdR}, {Sd, ZD}},
     {{SvL}, {Sv, ZV}},
     {{SuL, SuR}, {Su, ZU}},
     {{SeL, SeR}, {Se, ZE}},
     {{phid, phiu}, {hh, ZH}},
     {{sigmad, sigmau}, {Ah, ZA}},
     {{SHdm,conj[SHup]},{Hpm,ZP}},
     {{fB, fW0, FHd0, FHu0}, {L0, ZN}},
     {{{fWm, FHdm}, {fWp, FHup}}, {{Lm,UM}, {Lp,UP}}},
     {{{FeL},{conj[FeR]}},{{FEL,ZEL},{FER,ZER}}},
     {{{FdL},{conj[FdR]}},{{FDL,ZDL},{FDR,ZDR}}},
     {{{FuL},{conj[FuR]}},{{FUL,ZUL},{FUR,ZUR}}}
       };

DEFINITION[EWSB][Phases]=
{    {fG, PhaseGlu}    };


DEFINITION[EWSB][DiracSpinors]={
 Fd ->{  FDL, conj[FDR]},
 Fe ->{  FEL, conj[FER]},
 Fu ->{  FUL, conj[FUR]},
 Fv ->{  FvL, 0},
 Chi ->{ L0, conj[L0]},
 Cha ->{ Lm, conj[Lp]},
 Glu ->{ fG, conj[fG]}
};
```

Consistency check of a model

`CheckModel` performs several checks

Physical properties

- Check for gauge and Witten anomalies
- Check if all terms in the (super)potential are in agreement with charge conservation
- Check if other (renormalizable) terms allowed in the (super)potential by gauge invariance
- Check if other particles might mix
- ...

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Also formal checks take place: Are all particles/parameters defined? Do the number of PDGs for each particle fit to the number of generations? Do the dimensions fit for relations among parameters? ...

Implemented (public) models:

- MSSM: with/without FV or CPV
- Low scale extensions of the MSSM:
  - Singlet extensions: NMSSM, nMSSM, SMSSM (GNMSSM)
  - Triplet extensions: TMSSM, TNMSSM
  - RpV: bilinear RpV, Lepton/Baryon number violation, $\mu\nu$SSM
  - Additional $U(1)'s$: UMSSM, sMSSM, B-L-SSM, $U(1)_R \times U(1)_{B-L}$
  - inverse seesaw, linear seesaw
  - MSSM with color sextet
- Models with Dirac gauginos:
  - MDGSSM
  - MRSSM
- High scale extensions
  - Seesaw 1 - 3 ($SU(5)$ version)
  - Left/right model (ΩLR)
- Non SUSY models:
  - SM, SM+Color Octet
  - inert doublet model

Obtaining the analytical properties of the model

Tree-level Relations

During the initialization of model, SARAH calculates ...

- ...all Masses and Mass matrices
- ...all Tadpole equations

SARAH provides routines to calculate interactions:

- Specific vertices by defining the external fields
- All vertices present in the model

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One-loop corrections

[Pierce,Bagger,Matchev,Zhang,hep-ph/9606211]

One-loop tadpoles/self-energies ($\overline{\text{DR}}$-scheme, 't Hooft gauge)

$\rightarrow$ formulas for mass spectrum at one-loop

2-Loop Supersymmetric RGEs

Full CP and flavor structure [Martin,Vaughn,hep-ph/9311340]

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+ Support of kinetic mixing [Fonseca,Malinsky,Porod,FS,1107.2670]
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+ Running VEVs in R_ξ gauge [Sperling,Stöckinger,Voigt,1305.1548]

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2-Loop RGEs for a general gauge theory

[in coll. with Lyonnet, Schienbein, Wingerter]

Full support of non-SUSY RGEs in preparation [Luo,Wang,Xiao,hep-ph/0211440]

$\rightarrow$ Needed for split-SUSY scenarios

Linking SPheno and SARAH

Linking SARAH and SPheno

SPheno	SARAH
Restricted mostly to MSSM	Supports many models
RGEs, vertices, . . . hardcoded	Calculates everything by its own
Routines for loop integrals, phase space,. . .	Nothing like that
Numerically fast (Fortran)	Numerically slow (Mathematica)

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'Spectrum Generator Generator' MakeSPheno[]

SARAH writes source-code which can be compiled with SPheno.

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

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FlexibleSUSY: Coming SoftSusy-like 'spectrum generator generator' based on SARAH. [Athron,Park,Stöckinger,Voigt,flexiblesusy.hepforge.org]

SPheno by SARAH

All SPheno modules by SARAH provide the following features:

Precise mass spectrum calculation

- Full 2-loop running of all parameters and all masses at 1-loop
- MSSM 2-loop Higgs corrections can be linked

[Brignole,Degrassi,Dedes,Slavich,Zwirner]

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Models with threshold scales

- Heavy superfields can be integrated out during RGE evaluation (→ e.g. Seesaw models)
- Also threshold scales with gauge-symmetry breaking can be handled (→ e.g. GUT models, Quiver models)

Decay widths and branching ratios

SUSY / Heavy Gauge Boson Decays

- All 2-body decays of scalars, fermions and vector bosons
- 3-body decays of fermions into three fermions
- 3-body decays of scalars in prep. [Mitzka,Porod]

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Higgs decays

- All 2-body decays into SUSY particles and leptons at tree-level
- 2-body decays into quarks with gluonic NLO corrections
- 2-body decays in real and virtual vector boson included
- Loop induced decays in two photons and gluons including any possible contribution for given model at LO, dominant NLO corrections

Checking experimental constraints

SPheno modules calculate the following observables with (nearly) the same precision as SPheno does for the MSSM:

Precision observables calculated by SPheno

- LFV: $l_i \to l_j \gamma$, $l_i \to 3 l_j$, $Z \to l_i l_j$, μ–e conversion in nuclei
- $b \to s\gamma$
- $B^0_{s,d} \to l_i l_j$ (no NLO corrections) [Dreiner,Nickel,Porod,FS,1212.5074]
- $\delta\rho$, $g-2$, EMDs

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Automatized implementation of new observables using FeynArts/FormCalc under construction [Nickel,FS]

Checking Higgs constraints

SPheno modules write all necessary input files for HiggsBounds and HiggsSignals

HiggsBounds/HiggsSignals [Bechtle et al.,0905.2190,1102.1898,1305.1933]

HiggsBounds tests models against the exclusion bounds obtained by LEP, the Tevatron and the LHC.
HiggsSignals performs a χ^2 test of the Higgs sector predictions against the measured signal rates and masses.

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SLHA files written by SPheno include blocks with effective coupling ratios

- $\rightarrow$ Provide relative strength of Higgs couplings in a readable form
- $\rightarrow$ Can be used with HiggsBounds/HiggsSignals for models with up to 5 neutral scalars

MC Tools and SARAH

CalcHep

[Pukhov et al.,hep-ph/9908288,1207.6082]

CalcHep model files by SARAH MakeCHep[]

- Unitary and Feynman gauge; CP violation possible
- 4-scalar interactions are automatically split by introducing auxiliary fields
- Output in CompHep format possible
- Model files work also with MicrOmegas

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Full support of SLHA+ functionality

[Belanger et al., 1008.0181]]

- CalcHep can read spectrum files from SPheno
- SARAH writes also C-code to run SPheno via CalcHep
- Or mass matrices can be written to diagonalize them internally

MadGraph

[Degrande et al.,1108.2040], [Alwall et al.,1106.0522]

UFO output of SARAH MakeUFO[]

SARAH writes model files in the UFO format which can be used with MadGraph (and soon (?) also with Herwig): [FS,1207.0906]

Support of all color operators including triplets/octets as well sextets.

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Parameters

Spectrum files from SPheno can be given directly as param_card to MadGraph

WHIZARD

[Kilian,Ohl,Reuter,0708.4233],[Moretti,Ohl,Reuter,0102195]

WHIZARD interface of SARAH MakeWHIZARD[]

- Gauge can be chosen
- Output of generic couplings (e.g. SSSS,SSVV) can be suppressed to keep files shorter

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WHIZARD interface of SARAH MakeWHIZARD[]

- Gauge can be chosen
- Output of generic couplings (e.g. SSSS,SSVV) can be suppressed to keep files shorter

Input parameters

SPheno writes additional input file which can be used with WHIZARD.

SARAH + SPheno + MC tools

The implementation in SPheno as well as in CalcHep, WHIZARD or MadGraph are based on one implementation in SARAH

→ Spectrum calculator and Monte Carlo tool use for sure the same conventions

SPheno provides also the width of all particles.

Other output

Model files for FeynArts — MakeFeynArts[]

SARAH writes model files for FeynArts which can also be used with FormCalc.

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Vevacious input — MakeVevacious[]

- SARAH 4 can write the input file for Vevacious
- SARAH 4 includes examples for MSSM with Stau+Stop VEVs
- Works out of the box with spectrum files written by SARAH modules for SPheno

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LaTeX files — MakeTeX[]

Including all expressions for vertices, masses, RGEs, ...

The SUSY Toolbox

SUSY Toolbox
[FS,Ohl,Porod,Speckner,1109.5147]

. . . is a collection of scripts to create an environment including

- SARAH [FS,0806.0538],[FS,0909.2863],[FS,1002.0840]
- SPheno [Porod,hep-ph/0301101],[Porod,FS,1104.1573]
- WHIZARD [Kilian,Ohl,Reuter,0708.4233],[Moretti,Ohl,Reuter,0102195]
- HiggsBounds [Bechtle,Brein,Heinemeyer,Weiglein,Williams,1102.1898]
- HiggsSignals [Bechtle,Heinemeyer,Stal,Stefaniak,Weiglein,1305.1933]
- MadGraph [Alwall et. al,1106.0522]
- CalcHep [Pukhov et. al,hep-ph/9908288
- MicrOmegas [Belanger,Boudjema,Pukhov,Semenov,hep-ph/0405253]
- SSP [FS,Ohl,Porod,Speckner,1109.5147]

and to implement new models into the other tools based on the implementation in SARAH.

SUSY Toolbox

FS,Ohl,Porod,Speckner,1109.5147

The SUSY toolbox is a collection of scripts to create an environment including SARAH, SPheno, WHIZARD, HiggsBounds, HiggsSignals, CalcHep, MicrOmegas and SSP

http://projects.hepforge.org/sarah/Toolbox.html

All tools are downloaded, configured and installed just by:

```
> ./configure
> make
```

Afterwards, a model is implemented in all tools at once by:

```
> ./butler NMSSM
```

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SSP uses the provided infrastructure to perform parameter scans

collider pheno	dark matter	Higgs constraints	. . .	CalcHep, WHIZARD, HB, HS, MG5, MicrOmegas, FeynArts

↑ ↑ ↑ ↑

calculate observables; decays of sparticles and Higgs

↑

calculate running parameters and 1-loop corrected masses

SPheno

↑

create model files for MC tools and Fortran code for `SPheno`

↑

derive expressions for masses, vertices, RGEs, . . .

SARAH

↑

create `SARAH` **input file**

↑

Idea for a new model

User

Tutorial: Topics

Topics

- Using SARAH to get analytical information about your model
- Implementing new models in SARAH (from the MSSM to the SMSSM)
- SARAH and SPheno
- SARAH, SPheno and MicrOmegas
- SARAH, SPheno and HiggsBounds/HiggsSignals
- SARAH, SPheno and Vevacious
- SARAH, SPheno and MC-Tool (if there is time . . .)

All tar-files for the tools and additional material available at
sarah.hepforge.org/tutorial.tar.gz

For the installation of Vevacious, check the README. It needs HOM4PS, pyminuit, LHPC and CosmoTransitions. The other tools should work via the toolbox.