Tutorial to SARAH

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Getting Started

Requirements: Mathmatica 7.0 or higher

1. Download `SARAH` from

   `http://sarah.hepforge.org/`

   (Choose either version 3.3.1 or the 4b.0.0.1)

2. Copy the tar-file to

   `/home/[USER]/.Mathematica/Applications/`

3. Extract the tar file via

   `tar -xf SARAH-3.3.1.tar.gz`

4. Do load `SARAH` in Mathematica use

First part: SARAH commands

Important Commands

- ShowModels: Returns a list with installed models
- Start[''Model'']: Starts the given model
- CheckModel: Performs checks of a model implementation
- MassMatrix[Particle]: Returns the mass matrix
- TadpoleEquation[Particle]: Returns the tadpole equation
- Vertex[Particles]: Calculates the vertex for given states
- MakeVertexList[Options]: Calculates all vertices
- CalcRGEs[Options]: Calculates the RGEs
- MakeFeynArts[Options]: Writes FeynArts model files
- MakeCHep[Options]: Writes CalcHep/CompHep model files
- MakeWHIZARD[Options]: Writes WHIZARD model files
- MakeUFO[Options]: Writes model files in the UFO format
- MakeTeX[Options]: Writes LaTeX files
- MakeSPheno[Options]: Writes source code for SPheno

In the first part of the tutorial we use the MSSM and test those commands in SARAH.

See Playing_with_the_MSSM.nb

Second part: SARAH model files

In this part of the tutorial we extend the MSSM model file to implement another model. We have to choices:

1. Easy: we want to get the NMSSM
2. Advanced: we go for the B-L-SSM

The NMSSM in SARAH

From MSSM to NMSSM in SARAH

- The gauge sector hasn't to be changed

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

From MSSM to NMSSM in SARAH

- The gauge sector hasn't to be changed
- Add singlet superfield

```
Fields[[1]] = {{uL,dL}, 3, q, 1/6, 2, 3};
...
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};
```

From MSSM to NMSSM in SARAH

- The gauge sector hasn't to be changed
- Add singlet superfield

```
Fields[[1]] = {{uL,dL}, 3, q, 1/6, 2, 3};
...
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};
Fields[[8]] = {Sing, 1, S, 0, 1, 1};
```

From MSSM to NMSSM in SARAH

- The gauge sector hasn't to be changed
- Add singlet superfield
- Change superpotential

```
SuperPotential = {{{Yu,1},{q, Hu, u}},
        {{Yd,-1},{q, Hd, d}},{{Ye,-1},{l, Hd, e}},
        {{μ,1},{Hu, Hd}}};
```

From MSSM to NMSSM in SARAH

- The gauge sector hasn't to be changed
- Add singlet superfield
- Change superpotential

```
SuperPotential = {{{Yu,1},{q, Hu, u}},
          {{Yd,-1},{q, Hd, d}},{{Ye,-1},{l, Hd, e}},
          {{λ,1},{Hu, Hd, S}},
          {{κ,1/3},{S,S,S}}};
```

From MSSM to NMSSM in SARAH

- The gauge sector hasn't to be changed
- Add singlet superfield
- Change superpotential
- Give VEV to scalar singlet

```
DEFINITION[EWSB][VEVs]=
{{SHd0, {vd, 1/√2}, {sigmad, I/√2},{phid, 1/√2}},
{SHu0, {vu, 1/√2}, {sigmau, I/√2},{phiu, 1/√2}}};
```

From MSSM to NMSSM in SARAH

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{SSing, {vS,1/√2},{sigmaS,I/√2},{phiS,1/√2}}};
```

From MSSM to NMSSM in SARAH

- The gauge sector hasn't to be changed
- Add singlet superfield
- Change superpotential
- Give VEV to scalar singlet
- Change particle mixings

```
DEFINITION[EWSB][MatterSector]=
{{{SdL, SdR}, {Sd, ZD}},
...
{{phiu, phid}, {h, ZH}},
{{sigmau, sigmad}, {Ah, ZA}},
{{fB, fW0, FHd0, FHu0}, {L0, ZN}},
{{{fWm, FHdm}, {fWp, FHup}}, {{Lm,Um}, {Lp,Up}}}}
```

From MSSM to NMSSM in SARAH

- The gauge sector hasn't to be changed
- Add singlet superfield
- Change superpotential
- Give VEV to scalar singlet
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```
DEFINITION[EWSB][MatterSector]=
{{{SdL, SdR}, {Sd, ZD}},
...
{{phiu, phid,phiS}, {h, ZH}},
{{sigmau, sigmad,sigmaS}, {Ah, ZA}},
{{fB, fW0, FHd0, FHu0,FSing}, {L0, ZN}},
{{{fWm, FHdm}, {fWp, FHup}}, {{Lm,Um}, {Lp,Up}}}}
```

From MSSM to NMSSM in SARAH

- The gauge sector hasn't to be changed
- Add singlet superfield
- Change superpotential
- Give VEV to scalar singlet
- Change particle mixings
- Define properties of parameters

```
{κ,{LaTeX -> "\\kappa",
    Real -> True,
    LesHouches -> {EXTPAR,62} }}
```

The B-L-SSM and SARAH

The Model

[Khalil,Masiero (0710.3525); Perez, Spinner (0812.3661)]

Particle content

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(U(1)_Y \otimes SU(2)_L \otimes SU(3)_C \otimes U(1)_{B-L})$
$\hat{Q}$	$\tilde{Q}$	Q	3	$(\frac{1}{6}, \mathbf{2}, \mathbf{3}, \frac{1}{6})$
$\hat{D}$	$\tilde{d}^c$	d^c	3	$(\frac{1}{3}, \mathbf{1}, \overline{\mathbf{3}}, -\frac{1}{6})$
$\hat{U}$	$\tilde{u}^c$	u^c	3	$(-\frac{2}{3}, \mathbf{1}, \overline{\mathbf{3}}, -\frac{1}{6})$
$\hat{L}$	$\tilde{L}$	L	3	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1}, -\frac{1}{2})$
$\hat{E}$	$\tilde{e}^c$	e^c	3	$(1, \mathbf{1}, \mathbf{1}, \frac{1}{2})$
$\hat{\nu}$	$\tilde{\nu}^c$	ν^c	3	$(0, \mathbf{1}, \mathbf{1}, \frac{1}{2})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1}, 0)$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2}, \mathbf{2}, \mathbf{1}, 0)$
$\hat{\eta}$	η	$\tilde{\eta}$	1	$(0, \mathbf{1}, \mathbf{1}, -1)$
$\hat{\bar{\eta}}$	$\bar{\eta}$	$\tilde{\bar{\eta}}$	1	$(0, \mathbf{1}, \mathbf{1}, 1)$

The superpotential is given by

$$W = Y_u^{ij}\,\hat{U}_i\,\hat{Q}_j\,\hat{H}_u - Y_d^{ij}\,\hat{D}_i\,\hat{Q}_j\,\hat{H}_d - Y_e^{ij}\,\hat{E}_i\,\hat{L}_j\,\hat{H}_d + \mu\,\hat{H}_u\,\hat{H}_d$$
$$+ Y_\nu^{ij}\,\hat{L}_i\,\hat{H}_u\,\hat{\nu}_j - \mu'\,\hat{\eta}\,\hat{\bar{\eta}} + Y_x^{ij}\,\hat{\nu}_i\,\hat{\eta}\,\hat{\nu}_j$$

$U(1)_Y \times U(1)_{B-L}$

The anomalous dimension matrix is not diagonal

$$\gamma = \frac{1}{16\pi^2}\begin{pmatrix} \frac{33}{5} & 6\sqrt{\frac{2}{5}} \\ 6\sqrt{\frac{2}{5}} & 9 \end{pmatrix}$$

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Induces in general non-vanishing $F^Y_{\mu\nu} F^{B-L,\mu\nu}$

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Induces in general non-vanishing $F^{Y}_{\mu\nu}F^{B-L,\mu\nu}$

Kinetic mixing

Both Abelian gauge groups mix. $\kappa F^{Y}_{\mu\nu}F^{B-L,\mu\nu}$ can be absorbed in a non canonical covariant derivative

$$D_\mu = \partial_\mu - i(Q^Y, Q^{B-L})\begin{pmatrix} g_{YY} & g_{YB} \\ g_{BY} & g_{BB} \end{pmatrix}\begin{pmatrix} A^Y_\mu \\ A^B_\mu \end{pmatrix}$$

$U(1)_Y \times U(1)_{B-L}$

The anomalous dimension matrix is not diagonal

$$\gamma = \frac{1}{16\pi^2}\begin{pmatrix} \frac{33}{5} & 6\sqrt{\frac{2}{5}} \\ 6\sqrt{\frac{2}{5}} & 9 \end{pmatrix} \quad \rightarrow$$

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We choose $g_{BY} = 0$ and $g_{YB} = \tilde{g}$ and

$$g1 = \frac{g_{YY}g_{BB} - g_{YB}g_{BY}}{\ldots}, g_{BL} = \sqrt{g^2_{BB} + g^2_{BY}} = , \tilde{g} = \frac{g_{YB}g_{BB} + g_{BY}g_{YY}}{\ldots}$$

Gauge symmetry breaking and physical states

The gauge symmetry is broken by

$$\langle H_d^0 \rangle = v_d, \; \langle H_u^0 \rangle = v_u, \; \langle \bar{\eta} \rangle = v_{\bar{\eta}}, \; \langle \eta \rangle = v_\eta$$

with $\tan\beta = \frac{v_u}{v_d}$ and $\tan\beta' = \frac{v_\eta}{v_{\bar{\eta}}}$

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with $\tan\beta = \frac{v_u}{v_d}$ and $\tan\beta' = \frac{v_\eta}{v_{\bar{\eta}}}$

The gauge bosons (B, B', W^3) mix to (γ, Z, Z')

The CP even and CP odd sneutrinos split because of $Y_x^{ij} \hat{\nu}_i \eta \hat{\nu}_j$

$$\tilde{\nu}_L^i = \frac{1}{\sqrt{2}} \left(\sigma_L^i + i\phi_L^i \right) \qquad \tilde{\nu}_R^i = \frac{1}{\sqrt{2}} \left(\sigma_R^i + i\phi_R^i \right)$$

Summary of mass eigenstates

- 4 CP even Higgs fields
- 2 CP odd Higgs fields, 2 neutral Goldstones
- 7 neutralinos
- 6 CP even sneutrinos, 6 CP odd sneutrinos
- 6 neutrinos
- 3 neutral gauge bosons
- (s)quarks, charges (s)leptons as in the MSSM
- charged Higgs and gauge bosons as in the MSSM

Summary of mass eigenstates

- 4 CP even Higgs fields
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- 6 CP even sneutrinos, 6 CP odd sneutrinos
- 6 neutrinos
- 3 neutral gauge bosons
- (s)quarks, charges (s)leptons as in the MSSM
- charged Higgs and gauge bosons as in the MSSM

$\rightarrow$ Getting all vertices and RGEs would be a tedious work

From MSSM to B-L-SSM in SARAH

- Adding the new gauge group

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

From MSSM to B-L-SSM in SARAH

- Adding the new gauge group

```
Gauge[[1]]={B, U[1], hypercharge, g1,False};
Gauge[[2]]={WB, SU[2], left, g2,True};
Gauge[[3]]={G, SU[3], color, g3,False};
Gauge[[4]]={Bp, U[1], BminusL, g1p,False};
```

From MSSM to B-L-SSM in SARAH

- Adding the new gauge group
- Add the new quantum numbers and superfields

```
Fields[[1]] = {{uL,dL}, 3, q, 1/6, 2, 3};
...
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};
```

From MSSM to B-L-SSM in SARAH

- Adding the new gauge group
- Add the new quantum numbers and superfields

```
Fields[[1]] = {{uL,dL}, 3, q, 1/6, 2, 3, 1/6};
...
Fields[[5]] = {conj[dR], 3, d, 1/3, 1, -3, -1/6};
Fields[[6]] = {conj[uR], 3, u, -2/3, 1, -3, -1/6};
Fields[[7]] = {conj[eR], 3, e, 1, 1, 1, 1/2};
Fields[[8]] = {conj[vR], 3, vR, 0, 1, 1, 1/2};
Fields[[9]] = {et, 1, eta, 0, 1, 1, -1};
Fields[[10]] = {etb, 1, etaB, 0, 1, 1, 1};
```

From MSSM to B-L-SSM in SARAH

- Adding the new gauge group
- Add the new quantum numbers and superfields
- Change superpotential

```
SuperPotential = {{{1,Yu},{q, Hu, u}},
        {{-1,Yd,},{q, Hd, d}},{{-1,Ye},{l, Hd, e}},
        {{1,μ},{Hu, Hd}}};
```

From MSSM to B-L-SSM in SARAH

- Adding the new gauge group
- Add the new quantum numbers and superfields
- Change superpotential

```
SuperPotential = {{{1, Yu},{q, Hu, u}},
        {{-1, Yd,},{q, Hd, d}},{{-1, Ye,},{l, Hd, e}},
        {{1,μ},{Hu, Hd}}, {{1, Yv},{l,Hu,vR}}
        {{-1, MuP},{eta, etaB}}, {{1, Yx},{vR, eta,vR}}
};
```

From MSSM to B-L-SSM in SARAH

- Adding the new gauge group
- Add the new quantum numbers and superfields
- Change superpotential
- Decompose Higgs fields and sneutrinos

```
DEFINITION[EWSB][VEVs]=
{{SHd0, {vd, 1/√2}, {sigmad, I/√2},{phid, 1/√2}},
{SHu0, {vu, 1/√2}, {sigmau, I/√2},{phiu, 1/√2}}};
```

From MSSM to B-L-SSM in SARAH

- Adding the new gauge group
- Add the new quantum numbers and superfields
- Change superpotential
- Decompose Higgs fields and sneutrinos

```
DEFINITION[EWSB][VEVs]=
{{SHd0, {vd, 1/Sqrt[2]}, {sigmad, I/Sqrt[2]},{phid,1/Sqrt[2]}},
{SHu0, {vu, 1/Sqrt[2]}, {sigmau, I/Sqrt[2]},{phiu,1/Sqrt[2]}},
{Set,{vEta,1/Sqrt[2]},{sigmaEta,I/Sqrt[2]},{phiEta,1/Sqrt[2]}},
{Setb,{vEtaB,1/Sqrt[2]},{sigmaEtaB,I/Sqrt[2]},{phiEtaB,1/Sqrt[2]}},
{SvR,{0 ,0 },{sigmaR,I/Sqrt[2]},{phiR,1/Sqrt[2]}},
{SvL,{0, 0},{sigmaL,I/Sqrt[2]},{phiL,1/Sqrt[2]}} ;
```

From MSSM to B-L-SSM in SARAH

- Adding the new gauge group
- Add the new quantum numbers and superfields
- Change superpotential
- Decompose Higgs fields and sneutrinos
- Mixing of gauge bosons

```
DEFINITION[EWSB][GaugeSector] = {
{{VB,VWB[3]},{VP,VZ},ZZ},
...  };
```

From MSSM to B-L-SSM in SARAH

- Adding the new gauge group
- Add the new quantum numbers and superfields
- Change superpotential
- Decompose Higgs fields and sneutrinos
- Mixing of gauge bosons

```
DEFINITION[EWSB][GaugeSector] = {
{{VB,VWB[3],VBp},{VP,VZ,VZp},ZZ},
...  };
```

From MSSM to B-L-SSM in SARAH

- Adding the new gauge group
- Add the new quantum numbers and superfields
- Change superpotential
- Decompose Higgs fields and sneutrinos
- Mixing of gauge bosons
- Change particle mixings

```
DEFINITION[EWSB][MatterSector]=
{{{SdL, SdR}, {Sd, ZD}},
...
{{phiu, phid}, {h, ZH}},
{{sigmau, sigmad}, {Ah, ZA}},
{{fB, fW0, FHd0, FHu0}, {L0, ZN}},
...
```

From MSSM to B-L-SSM in SARAH

- Adding the new gauge group
- Add the new quantum numbers and superfields
- Change superpotential
- Decompose Higgs fields and sneutrinos
- Mixing of gauge bosons
- Change particle mixings

```
DEFINITION[EWSB][MatterSector]=
{{{SdL, SdR}, {Sd, ZD}},
...
{{phiu, phid,phiEta,phiEtaB}, {h, ZH}},
{{sigmau, sigmad,sigmaEta,sigmaEtaB}, {Ah, ZA}},
{{fB, fW0, FHd0, FHu0,fBp,Fet,Fetb}, {L0, ZN}},
...
```

From MSSM to B-L-SSM in SARAH

- Adding the new gauge group
- Add the new quantum numbers and superfields
- Change superpotential
- Decompose Higgs fields and sneutrinos
- Mixing of gauge bosons
- Change particle mixings
- Possibility go give additional information: new PDGs, LaTeXcode, properties of parameter, ...

From MSSM to B-L-SSM in SARAH

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```
{Yx,{LaTeX -> "Y_x",
     Real -> False,
     LesHouches -> YX }}
```

From MSSM to B-L-SSM in SARAH

- Adding the new gauge group
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Initializing the model in Mathematica

```
<< $PATH/SARAH.m;
Start[‘‘B-L-SSM’’];
```

SARAH and SPheno

Seven steps to get a new spectrum generator

Run in Mathematica:

1. `<< [SARAH]/SARAH.m''`
2. `Start[''B-L-SSM''];`
3. `MakeSPheno[];`

and in the terminal

4. `mkdir [SPHENO]/BLSSM/`
5. `cp [SARAH]/Output/EWSB/SPheno/* [SPHENO]/BLSSM/`
6. `cd [SPHENO]`
7. `make Model=BLSSM`

([SPHENO] and [SARAH] are the paths to your local SPheno and SARAH installations)

This creates a new executable `bin/SPhenoBLSSM` which can be fed by `LesHouches.in.BLSSM`

Setting up the SPheno properties

The basic properties of SPheno are defined in a separate input file

Setting up the SPheno properties

The basic properties of SPheno are defined in a separate input file

- The input parameters

```
MINPAR={ {1,m0},
         {2,m12},
         {3,TanBeta},
         {4,SignumMu},
         {5,Azero},
         {6,TanBetaP},
         {7,SignumMuP},
         {8,MZp}   };
```

Setting up the SPheno properties

The basic properties of SPheno are defined in a separate input file

- The input parameters
- Definition for GUT scale

```
ConditionGUTscale =
(g1*g1p-g1g1p*g1pg1)/Sqrt[g1p^2+g1pg1^2] == g2;
```

Setting up the SPheno properties

The basic properties of SPheno are defined in a separate input file

- The input parameters
- Definition for GUT scale
- The boundary conditions

```
BoundaryHighScale= {
        {g1g1p, 0}, {g1pg1, 0},
        {MassB, m12},..., {MassBp, m12}, {MassBBp, 0},
        {mq2, DIAGONAL m0^2}, ...
        {mEta2, m0^2}, {mEtaB2, m0^2},
        {T[Ye], Azero*Ye}, ...
        {T[Yx], Azero*Yx}, {T[Yv],Azero*Yv}};
```

Setting up the SPheno properties

The basic properties of SPheno are defined in a separate input file

- The input parameters
- Definition for GUT scale
- The boundary conditions
- The parameters fixed by the tadpole equations

```
ParametersToSolveTadpoles = {B[Mu],Mu,B[MuP], MuP};
```

Setting up the SPheno properties

The basic properties of SPheno are defined in a separate input file

- The input parameters
- Definition for GUT scale
- The boundary conditions
- The parameters fixed by the tadpole equations
- The renormalization scale

```
RenormalizationScale = MSu[1]*MSu[6];
```

Setting up the SPheno properties

The basic properties of SPheno are defined in a separate input file

- The input parameters
- Definition for GUT scale
- The boundary conditions
- The parameters fixed by the tadpole equations
- The renormalization scale
- Particles, for which the decays should be calculated

```
ListDecayParticles = Automatic;
ListDecayParticles3B = Automatic;
```

(Automatic: All Non-SM fields)

Setting up the SPheno properties

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- The input parameters
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- The boundary conditions
- The parameters fixed by the tadpole equations
- The renormalization scale
- Particles, for which the decays should be calculated

MakeSPheno[]

Starts all necessary calculations (masses, RGEs, vertices,...) and writes the source code.