



UNIVERSIDAD DE ANTIOQUIA
1803

HEP computer tools

from SARAH and beyond

Diego Restrepo

Oct 8, 2019 - IFGW-UNICAMP : [PDF: <http://bit.ly/SARAHIFGW>]

Instituto de Física
Universidad de Antioquia
Phenomenology Group
<http://gfif.udea.edu.co>



Preliminars

✿ Computer tools in particle physics

Information

This is the website for the course 'Computer tools in particle physics' by Avelino Vicente.

- [CINVESTAV, México City \(México\) 2015](#)
- [IFIC, Valencia \(Spain\) 2016](#)
- [Universidad de Antioquia, Medellín \(Colombia\) 2016](#)
- [IFIC, Valencia \(Spain\) 2017](#)

References

The course focuses on the material contained in the following notes:

[Computer tools in particle physics, A. Vicente, arXiv:1507.06349 \[PDF\]](#)

For two-loops RGEs see also:

"[Exploring new models in all detail with SARAH](#)", Florian Staub, arXiv:1503.04200 [PDF]

SARAH:

"[SARAH 4: A tool for \(not only SUSY\) model builders](#)", Florian Staub, arXiv:1309.7223 [PDF]

About

This is the website for the course 'Computer tools in particle physics'.

- Links V1.0 August 2009: Susy Only
 V4.0 September 2013: non-Susy
- [SARAH](#) V4.14.2 (Transferred to W.Porod)
 - [SPheno](#)
 - [MicrOMEGAS](#)
 - [MadGraph](#)
 - [MadAnalysis](#)
 - [FlavorKit](#)

Contact

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For questions and comments, you can send me an [e-mail](#).

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Computer tools in particle physics

Information

This is the website for the course [Computer tools in particle physics](#) by Avelino Vicente, to take place at [Instituto de Física Corpuscular](#) (CSIC/Universidad de Valencia).

Dates: Monday 22/05/2017 - Friday 26/05/2017

Place: IFIC - Sala de Audiovisuales (Nave experimental)

Time: 15:00

Duration: 1.5 h for the first session and 1 h for the rest

Material and required programs

This will be a hands-on course, where all participants are encouraged to run all codes in their own laptops. The only required programs are [Mathematica](#), a [LaTeX](#) compiler and [Fortran 90](#) and [C++](#) compilers. If you wish to fully participate please download the following files:

- For lecture 1: [run_sarah_Scotogenic.nb](#) and [Scotogenic.tar.gz](#)
- For lecture 2: [micromegas_4.2.5.tgz](#)
- For lecture 4: [run_sarah_DarkBS.nb](#), [DarkBS.tar.gz](#) and [plotDarkBS.txt](#)

You should also download the latest versions of the codes we are going to use (exception: for lecture 2 we will use an old version of MicrOMEGAs, see above). You can find them in their official websites (links on your right). Finally, the slides of the course are available here: [introduction](#), [lecture 1](#), [lecture 2](#), [lecture 3](#), [lecture 4](#) and [lecture 5](#).

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About

This is the website for the course [Computer tools in particle physics](#). IFIC (CSIC/U. Valencia), May 22nd - 26th, 2017.

Links

• [SARAH](#)

• [SPheno](#)

• [MicrOMEGAs](#)

• [MadGraph](#)

• [MadAnalysis](#)

• [FlavorKit](#)

Input/Output

Code



Contact

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Observables already in FlavorKit

Lepton flavor	Quark flavor
$\ell_\alpha \rightarrow \ell_\beta \gamma$	$B_{s,d}^0 \rightarrow \ell^+ \ell^-$
$\ell_\alpha \rightarrow 3\ell_\beta$	$\bar{B} \rightarrow X_s \gamma$
$\mu - e$ conversion in nuclei	$\bar{B} \rightarrow X_s \ell^+ \ell^-$
$\tau \rightarrow P \ell$	$\bar{B} \rightarrow X_{d,s} \nu \bar{\nu}$
$h \rightarrow \ell_\alpha \ell_\beta$	$B \rightarrow K \ell^+ \ell^-$
$Z \rightarrow \ell_\alpha \ell_\beta$	$K \rightarrow \pi \nu \bar{\nu}$
	$\Delta M_{B_{s,d}}$
	ΔM_K and ε_K
	$P \rightarrow \ell \nu$

Ready to be computed in your favourite model!

Observables already in FlavorKit

Lepton flavor	Quark flavor
$\ell_\alpha \rightarrow \ell_\beta \gamma$	$B_{s,d}^0 \rightarrow \ell^+ \ell^-$
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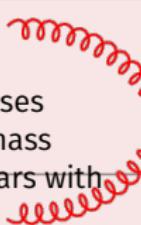
Also in SARAH

S,T,U

One-loop corrections to All masses

Two-loop corrections to Higgs mass

Gluon fusion production of scalars with
proper output for MadGraph



$\Delta M_{B_{s,d}}$
 ΔM_K and ε_K
 $P \rightarrow \ell \nu$

Ready to be computed in your favourite model!

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Models already in SARAH

Supersymmetric Models

- MSSM [in several versions]
- NMSSM [in several versions]
- Near-to-minimal SSM (near-MSSM)
- General singlet extended SSM (SMSSM)
- DiracNMSSM
- Triplet extended MSSM/NMSSM
- Several models with R-parity violation
- Several U(1)-extended models
- Secluded MSSM
- Several B-L extended models
- Inverse and linear seesaws
- MSSM/NMSSM with Dirac Gauginos
- Minimal R-Symmetric SSM
- Minimal Dirac Gaugino SSM
- Seesaws I-II-III [SU(5) versions]
- Left-right symmetric model
- Quiver model
- Models with vector-like superfields

Non-Supersymmetric Models

- Standard Model
- Two Higgs doublet models (including inert)
- Singlet extensions
- Triplet extensions
- U(1) extensions
- SM extended by a scalar color octet
- Gauged Two Higgs doublet model
- Singlet extended SM
- Singlet Scalar DM
- Singlet-Doublet DM
- Models with vector-like fermions
- Model with a scalar SU(2) 7-plet
- Leptoquark models
- Left-right models
- 331 models (with and without exotics)
- Georgi-Machacek model

More info: <http://sarah.hepforge.org/>

Models already in SARAH

Supersymmetric Models

- Minimal supersymmetric SM
- NMSSM (in several versions)
- Minimal R-minimal SSM (near-MSM_{inv})
- General singlet extended SSM (GMSM)
- DiracNMSM
- Triplet extended MSSM/NMSSM
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- Models with vector-like superfields

Always check any version of
SARAH and SPheno with this one!

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- Standard Model
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More info: <http://sarah.hepforge.org/>

BSM-Submodules

```
git clone --recursive https://github.com/restrepo/BSM-Submodules.git  
cd BSM-Submodules/  
emacs SARAH/Models/SSDM/SSDM.m
```

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times Z_2$$

$$\begin{aligned}\mathcal{D}_\mu &= \partial_\mu - i g_1 Y B_\mu \\ &\quad - i g_2 T W_\mu^B \\ &\quad - i g_3 \Lambda G_\mu.\end{aligned}$$

```

Off[General::spell]

Model`Name = "SSDM";
Model`NameLaTeX ="Singlet scalar Dark Matter";
Model`Authors = "Diego Restrepo ...";
Model`Date = "2015-11-16";

(* 2013-01-24: ...)

(* Global Symmetries *)

Global[[1]] = {Z[2], Z2};

(* Gauge Groups *)

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

```

	N_F	Lorentz	γ	$SU(2)_L$	$SU(3)_c$	Z_2
Q	3	$(u_L d_L)^\top$	1/6	2	3	+
L	3	$(\nu_L e_L)^\top$	-1/2	2	1	+
d^c	3	$(d_R)^\dagger$	1/3	1	$\bar{3}$	+
u^c	3	$(u_R)^\dagger$	-2/3	1	$\bar{3}$	+
e^c	3	$(e_R)^\dagger$	1	1	1	+
H	1	$(H^+ H^0)$	1/2	2	1	+
S	1	S	0	1	1	-

$$\mathcal{L} = (\mathcal{L}_C + \text{h.c})$$

$$+ \mathcal{L}_R,$$

$$\mathcal{L}_C = - Y_e e^c \tilde{H} \cdot L - Y_d d^c \tilde{H} \cdot Q - Y_u u^c H \cdot Q,$$

$$\begin{aligned} \mathcal{L}_R = & - \mu^2 \tilde{H} \cdot H - \lambda_1 (\tilde{H} \cdot H)^2 \\ & - M_S^2 S^2 - \lambda_{SH} S^2 \tilde{H} \cdot H - \lambda_S S^4. \end{aligned}$$

$$Y_e \rightarrow N_F \times N_F, \dots$$

(* Matter Fields *)

```
FermionFields[[1]] = {q, 3, {uL, dL},      1/6, 2, 3, 1};
FermionFields[[2]] = {l, 3, {vL, eL},      -1/2, 2, 1, 1};
FermionFields[[3]] = {d, 3, conj[dR],      1/3, 1, -3, 1};
FermionFields[[4]] = {u, 3, conj[uR],      -2/3, 1, -3, 1};
FermionFields[[5]] = {e, 3, conj[eR],      1, 1, 1, 1};
```

```
ScalarFields[[1]] = {H, 1, {Hp, H0},      1/2, 2, 1, 1};
ScalarFields[[2]] = {S, 1, ss,            0, 1, 1, -1};
RealScalars = {S};
```

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

```
NameOfStates={GaugeES, EWSB};
```

(* ----- Before EWSB ----- *)

```
DEFINITION[GaugeES][LagrangianInput]= {
  {LagHC, {AddHC->True}},
  {LagNoHC,{AddHC->False}}
};
```

```
LagHC = -(Ye e.conj[H].l + Yd d.conj[H].q + Yu u.H.q);
```

```
LagNoHC = -(mu2 conj[H].H + Lambda1/2 conj[H].H.conj[H].H
           + MS2/2 S.S + LamSH S.S.conj[H].H + LamS/2 S.S.S.S);
```

$$\begin{pmatrix} B^\mu \\ W_3^\mu \end{pmatrix} = Z^{\gamma Z} \begin{pmatrix} A^\mu \\ Z^\mu \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} A^\mu \\ Z^\mu \end{pmatrix}$$

$$H^0 = \frac{iA + (h + v)}{\sqrt{2}}.$$

$$d_L = V_d D_L, \quad (d_R)^\dagger = D_R^C U_d, \\ V_d \rightarrow N_F \times N_F, \dots$$

$$\Psi_d = \begin{pmatrix} D_L \\ D_R \end{pmatrix}$$

```
(* Gauge Sector *)
DEFINITION[EWSB][GaugeSector] =
{{VB,VWB[3]},{VP,VZ},ZZ},
{{VWB[1],VWB[2]},{VWp,conj[VWp]},ZW};
};

(* ----- VEVs ----- *)
DEFINITION[EWSB][VEVs]=
{{H0,{v,1/Sqrt[2]}}, {Ah,\ImaginaryI/Sqrt[2]}, {hh,1/Sqrt[2]}} };

DEFINITION[EWSB][MatterSector]=
{{{dL}, {conj[dR]}}, {{DL,Vd}, {DR,Ud}}},
{{{uL}, {conj[uR]}}, {{UL,Vu}, {UR,Uu}}},
{{{eL}, {conj[eR]}}, {{EL,Ve}, {ER,Ue}}}};
(*-----*)
(* Dirac-Spinors *)
(*-----*)

DEFINITION[EWSB][DiracSpinors]={
Fd ->{ DL, conj[DR]},
Fe ->{ EL, conj[ER]},
Fu ->{ UL, conj[UR]},
Fv ->{ vL, 0}};
```

$$\begin{pmatrix} B^\mu \\ W_3^\mu \end{pmatrix} = Z^{\gamma Z} \begin{pmatrix} A^\mu \\ Z^\mu \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} A^\mu \\ Z^\mu \end{pmatrix}$$

$$H^0 = \frac{iA + (h + v)}{\sqrt{2}}.$$

$$d_L = V_d D_L, \quad (d_R)^\dagger = D_R^C U_d, \\ V_d \rightarrow N_F \times N_F, \dots$$

(* Gauge Sector *)

```
DEFINITION[EWSB][GaugeSector] =
{{VB,VWB[3]},{VP,VZ},zz},
{{VWB[1],VWB[2]},{VWp,conj[VWp]},zw}
};
```

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

```
DEFINITION[EWSB][VEVs]=
{{H0,{v,1/Sqrt[2]}}, {Ah,\ImaginaryI/Sqrt[2]}, {hh,1/Sqrt[2]}} };
```

```
DEFINITION[EWSB][MatterSector]=
{{{dL}, {conj[dR]}}, {{DL,Vd}, {DR,Ud}}},
{{{uL}, {conj[uR]}}, {{UL,Vu}, {UR,Uu}}},
{{{eL}, {conj[eR]}}, {{EL,Ve}, {ER,Ue}}}}};
```

(*-----*)

(* Dirac-Spinors *)

(*-----*)

```
DEFINITION[EWSB][DiracSpinors]={
Fd ->{ DL, conj[DR]},
Fe ->{ EL, conj[ER]},
Fu ->{ UL, conj[UR]},
Fv ->{ VL, 0}}};
```



Chuck Norris fact of the day

Chuck Norris lost his virginity before his dad

From A. Vicente

./parameters.m

```
...
{g1,          { Description -> "Hypercharge-Coupling"}},
{g2,          { Description -> "Left-Coupling"}},
{g3,          { Description -> "Strong-Coupling"}},
...
{v,           { Description -> "EW-VEV",
               DependenceNum -> Sqrt[4*Mass[vWp]^2/(g2^2)],
               DependenceSPheno -> None   }},
{ThetaW,      { Description -> "Weinberg-Angle",
               DependenceNum -> ArcSin[Sqrt[1 - Mass[vWp]^2/Mass[vZ]^2]]}},
{ZZ, {Description -> "Photon-Z Mixing Matrix"}},
...
...
```

./parameters.m

```
...
{Description -> "Photon-Z Mixing Matrix",
 Dependence -> {{Cos[ThetaW],-Sin[ThetaW]},
                  {Sin[ThetaW],Cos[ThetaW]}},
 Real ->True,
 LaTeX -> "Z^{\gamma Z}",
 LesHouches -> None,
 OutputName -> ZZ },
...
...
```

./particles.m

```
...
ParticleDefinitions[EWSB] = {

{hh , { Description -> "Higgs",
        PDG -> {25},
        PDG.IX -> {101000001},
        Mass -> LesHouches,
        FeynArtsNr -> 1,
        LaTeX -> "h",
        ElectricCharge -> 0,
        LHPC -> {1},
        OutputName -> "h" }},

{ss , { Description -> "Singlet",
        PDG -> {6666635},
        PDG.IX -> {101000002},
        FeynArtsNr -> 10,
        Mass -> LesHouches,
        LaTeX -> "S",
        ElectricCharge -> 0,
        LHPC -> {"gold"},
        OutputName -> "Ss" }},

...
}
```

./SPheno.m

```
OnlyLowEnergySPheno = True;

MINPAR={{1,Lambda1IN},
        {2,LamSHIN},
        {3,LamSIN},
        {4,MSinput}
      };

...
ListDecayParticles = {Fu,Fe,Fd,hh};
ListDecayParticles3B = {{Fu,"Fu.f90"},{Fe,"Fe.f90"},{Fd,"Fd.f90"}};

.....

DefaultInputValues ={Lambda1IN -> 0.28, LamSHIN -> 0.01, LamSIN -> 0,
                    MSinput -> 200};
```

Implicit files without editors

```
cat << EOF > kk.txt
Hello world
EOF
```

Listing 1: Creates kk.txt file

```
math << EOF
2+2
EOF
```

Listing 2: commands expecting input files

```
Mathematica 11.0.0 for Linux x86 (64-bit)
Copyright 1988-2016 Wolfram Research, Inc.
```

```
In[1]:= 
Out[1]= 4

In[2]:=
```

Check SARAH

```
math << EOF
<<./SARAH/SARAH.m
Start["SSDM"]
MakeSPheno[]
EOF
```

```
Mathematica 11.0.0 for Linux x86 (64-bit)
...
In[1]:= SARAH 4.14.1
by Florian Staub, 2018
...
In[2]:= Preparing arrays
...
Model files loaded
  Model      : SSDM
  Author(s): Diego Restrepo (based on SM model by F.Staub)
  Date       : 2015-11-16
*****
Loading Susyno functions for the handling of Lie Groups
Based on Susyno v.2.0 by Renato Fonseca (1106.5016)
webpage: web.ist.utl.pt/renato.fonseca/susyno.html
*****
...
Finished! SPheno code generated in 170.872s
...
The following steps are now necessary to implement the model in SPheno:
```

Check SPheno

```
cp -r SARAH/Output/SSDM/EWSB/SPheno SPheno/SSDM  
cd SPheno  
make Model=SSDM # Be sure that Makefile use gfortran!
```

```
cd SSDM ; make F90=gfortran version=400.00  
make[1]: Entering directory '****/BSM-Submodules/SPHENO/SSDM'  
.  
. .  
make[2]: Leaving directory '****/BSM-Submodules/SPHENO/SSDM'  
gfortran -o SPhenoSSDM -g SPhenoSSDM.o ..//lib/libSPhenoSSDM.a ..//lib/libSPheno.a  
mv SPhenoSSDM ..//bin  
rm SPhenoSSDM.o  
make[1]: Leaving directory '****/BSM-Submodules/SPHENO/SSDM'
```

```
# Return to parent directory: BSM-Submodules  
cd ../
```

Check micrOMEGAs

```
cd micromegas  
make # Recompile everything!  
make # twice
```

```
make -C CalcHEP_src MICROMEGAS=MICROMEGRAS  
...  
#-----  
# CalcHEP has compiled successfully and can be started.  
# The manual can be found on the CalcHEP website:  
#      http://theory.sinp.msu.ru/~pukhov/calchep.html  
# The next step is typically to run  
#      ./mkWORKdir <new_dir>  
# where <new_dir> is the new directory where you will do  
# your calculations. After creating this directory, you  
# should cd into it and run calchep or calchep_batch.  
# Please see the manual for further details.  
#-----"  
...  
make[1]: Leaving directory '****/BSM-Submodules/micromegas/sources'
```

Build micrOMEGAs model

```
./newProject SSDM  
cd .. # return to parent directory
```

Check micrOMEGAs II

```
math << EOF
<<./SARAH/SARAH.m
Start["SSDM"]
MakeCHep[]
EOF
```

```
Mathematica 11.0.0 for Linux x86 (64-bit)
...
Write main file for MicrOmegas
Done. Model files generated in 31.044s
Output is saved in ****/BSM-Submodules/SARAH/Output/SSDM/EWSB/CHep/
```

```
cp SARAH/Output/SSDM/EWSB/CHep/* micromegas/SSDM/work/models/
cd micromegas/SSDM/
cp work/models/*.cpp .
# check your micrOMEGAs version
make main=CalcOmega_with_DDetection_M0v5.cpp
```

```
make -C work
...
g++ -g -fPIC -o CalcOmega_with_DDetection_M0v5 CalcOmega_with_DDetection_M0v5.cpp ... -lpthread
cd ../../ #Return to parent directory
```

Check Madgraph

```
math << EOF
<<./SARAH/SARAH.m
Start["SSDM"]
MakeUFO[]
EOF
```

```
Mathematica 11.0.0 for Linux x86 (64-bit)
...
Writing effective diphoton and digluon vertices

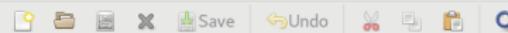
Done. UFO files generated in 30.716s
Output is saved in ****/BSM-Submodules/SARAH/Output/SSDM/EWSB/UFO/
```

```
cp -r SARAH/Output/SSDM/EWSB/UFO/ madgraph/models/SSDM
madgraph/bin/mg5_aMC << EOF
import model SSDM
check u u~ > mu+ mu-
EOF
```

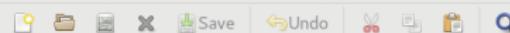
Process	Min element	Max element	Relative diff.	Result
u u~ > mu+ mu-	4.9949890843e-03	4.9949890843e-03	5.2093911919e-15	Passed
Summary:	1/1 passed,	0/1 failed		

Benchmark point

```
cp SPheno/SSDM/Input_Files/LesHouches.in.SSDM .
emacs LesHouches.in.SSDM
```



```
Block MODSEL      #
1 1              # 1/0: High/low scale input
2 1              # Boundary Condition
6 1              # Generation Mixing
Block SMINPUTS   # Standard Model inputs
2 1.166370E-05 # G_F, Fermi constant
3 1.187000E-01 # alpha_s(MZ) SM MSbar
4 9.118870E+01 # Z-boson pole mass
5 4.180000E+00 # m_b(mb) SM MSbar
6 1.735000E+02 # m_top(pole)
7 1.776690E+00 # m_tau(pole)
Block MINPAR     # Input parameters
1 2.8000000E-01 # LambdaLIN
2 1.0000000E-02 # LamSHIN
3 0.0000000E+00 # LamSIN
4 2.0000000E+02 # MSinput
Block SPhenoInput # SPheno specific input
1 -1             # error level
2 0              # SPA conventions
7 0              # Skip 2-loop Higgs corrections
8 3              # Method used for two-loop calculation
9 1              # Gaugeless limit used at two-loop
10 0             # safe-mode used at two-loop
11 1             # calculate branching ratios
13 1             # 3-Body decays: none (0), fermion (1), scalar (2), both (3)
14 0             # Run couplings to scale of decaying particle
12 1.000E-04    # write only branching ratios larger than this value
15 1.000E-30    # write only decay if width larger than this value
16 1             # One-loop decays
19 2             # Matching order / ?; automatic, 1-loop, 0.2, tree, one, 5-loop
:-... LesHouches.in.SSDM  Top L16  (Fundamental)
```



```
Block MODSEL      #
1 1              # 1/0: High/low scale input
2 1              # Boundary Condition
6 1              # Generation Mixing
Block SMINPUTS   # Standard Model inputs
2 1.166370E-05 # G_F, Fermi constant
3 1.187000E-01 # alpha_s(MZ) SM MSbar
4 9.118870E+01 # Z-boson pole mass
5 4.180000E+00 # m_b(mb) SM MSbar
6 1.735000E+02 # m_top(pole)
7 1.776690E+00 # m_tau(pole)
Block MINPAR     # Input parameters
1 2.8000000E-01 # LambdaLIN
2 1.0000000E-02 # LamSHIN
3 0.0000000E+00 # LamSIN
4 2.0000000E+02 # MSinput
Block SPhenoInput # SPheno specific input
1 -1             # error level
2 0              # SPA conventions
7 0              # Skip 2-loop Higgs corrections
8 3              # Method used for two-loop calculation
9 1              # Gaugeless limit used at two-loop
10 0             # safe-mode used at two-loop
11 1             # calculate branching ratios
13 1             # 3-Body decays: none (0), fermion (1), scalar (2), both (3)
14 0             # Run couplings to scale of decaying particle
12 1.000E-04    # write only branching ratios larger than this value
15 1.000E-30    # write only decay if width larger than this value
16 1             # One-loop decays
19 2             # Matching order / 2: automatic, 1-loop, 0.2; tree, one, or two loop
:-... LesHouches.in.SSDM  Top L16  (Fundamental)
```

Run SPheno

```
BSM-Submodules$ SPheno/bin/SPhenoSSDM LesHouches.in.SSDM
Calculating branching ratios and decay widths
Calculating one loop decays
Loop masses not calculated: tree-level masses used for kinematics
Loop masses not calculated: no U-factors are applied
Calculating one-loop decays of Fu
Calculating one-loop decays of Fe
Calculating one-loop decays of Fd
Calculating one-loop decays of hh
Calculating low energy constraints
Calculating unitarity constraints
Writing output files
Finished!
BSM-Submodules$ emacs SPheno.spc.SSDM
```



Save

Undo



```
# SUSY Les Houches Accord 2 - SSDM Spectrum + Decays + Flavor Observables
# SPheno module generated by SARAH
# -----
# SPheno v4.0.3
# W. Porod, Comput. Phys. Commun. 153 (2003) 275-315, hep-ph/0301101
# W. Porod, F.Staub, Comput.Phys.Commun.183 (2012) 2458-2469, arXiv:1104.1573
# SARAH: 4.14.1
#   F. Staub; arXiv:0806.0538 (online manual)
#   F. Staub; Comput. Phys. Commun. 181 (2010) 1077-1086; arXiv:0909.2863
#   F. Staub; Comput. Phys. Commun. 182 (2011) 808-833; arXiv:1002.0840
#   F. Staub; Comput. Phys. Commun. 184 (2013) 1792-1809; arXiv:1207.0906
#   F. Staub; Comput. Phys. Commun. 185 (2014) 1773-1790; arXiv:1309.7223
# Including the calculation of flavor observables based on the FlavorKit
# W. Porod, F. Staub, A. Vicente; Eur.Phys.J. C74 (2014) 8, 2992; arXiv:1405.1434
# Two-loop masss corrections to Higgs fields based on
# M. D. Goodsell, K. Nickel, F. Staub; Eur.Phys.J. C75 (2015) no.6, 290; arXiv:1411.0675
# M. D. Goodsell, K. Nickel, F. Staub; Eur.Phys.J. C75 (2015) no.1, 32; arXiv:1503.03098
# M. D. Goodsell, F. Staub; arXiv:1511.01904
#
# in case of problems send email to florian.staub@kit.edu and goodsell@lpthe.jussieu.fr
# -----
# Created: 19.09.2019, 22:47
Block SPINFO # Program information
  1 SPhenoSARAH      # spectrum calculator
  2 v4.0.3            # version number of SPheno
  9 4.14.1            # version number of SARAH
Block MODSEL # Input parameters
  1 1    # GUT scale input
  2 1    # Boundary conditions
  6 1    # switching on flavour violation
Block MINPAR # Input parameters
  1 2.8000000E-01 # Lambda1IN
  2 1.0000000E-02 # LamSHIN
  3 0.0000000E+00 # LamSIN
  4 2.0000000E+02 # MSinput
Block gaugeGUT Q= -1.0000000E+00 # (GUT scale)
  1 0.0000000E+00 # g1(Q)
  2 0.0000000E+00 # g2(Q)
  3 0.0000000E+00 # g3(Q)
Block SMINPUTS # SM parameters
----- SPheno.spc.SSDM Top L39 (Fundamental)
Beginning of buffer
```



Undo



```
3 3 9.95678124E-01 # Real(Yu(3,3),dp)
Block Yd Q= 1.60000000E+02 # (Renormalization Scale)
1 1 2.87184285E-05 # Real(Yd(1,1),dp)
1 2 0.00000000E+00 # Real(Yd(1,2),dp)
1 3 0.00000000E+00 # Real(Yd(1,3),dp)
2 1 0.00000000E+00 # Real(Yd(2,1),dp)
2 2 5.45650142E-04 # Real(Yd(2,2),dp)
2 3 0.00000000E+00 # Real(Yd(2,3),dp)
3 1 0.00000000E+00 # Real(Yd(3,1),dp)
3 2 0.00000000E+00 # Real(Yd(3,2),dp)
3 3 2.40086062E-02 # Real(Yd(3,3),dp)
Block Ye Q= 1.60000000E+02 # (Renormalization Scale)
1 1 2.93501725E-06 # Real(Ye(1,1),dp)
1 2 0.00000000E+00 # Real(Ye(1,2),dp)
1 3 0.00000000E+00 # Real(Ye(1,3),dp)
2 1 0.00000000E+00 # Real(Ye(2,1),dp)
2 2 6.06868478E-04 # Real(Ye(2,2),dp)
2 3 0.00000000E+00 # Real(Ye(2,3),dp)
3 1 0.00000000E+00 # Real(Ye(3,1),dp)
3 2 0.00000000E+00 # Real(Ye(3,2),dp)
3 3 1.02047490E-02 # Real(Ye(3,3),dp)
```

Block MASS # Mass spectrum

# PDG code	mass	particle
25	1.30287679E+02	# hh
6666635	2.83944658E+01	# ss
23	9.11887000E+01	# VZ
24	8.03497269E+01	# VWP
1	5.00000000E-03	# Fd_1
3	9.50000000E-02	# Fd_2
5	4.18000000E+00	# Fd_3
2	2.50000000E-03	# Fu_1
4	1.27000000E+00	# Fu_2
6	1.73500000E+02	# Fu_3
11	5.10998930E-04	# Fe_1
13	1.05658372E-01	# Fe_2
15	1.77669000E+00	# Fe_3

Block UDLMIX Q= 1.60000000E+02 # ()

```
1 1 1.00000000E+00 # Real(ZDL(1,1),dp)
1 2 0.00000000E+00 # Real(ZDL(1,2),dp)
1 3 0.00000000E+00 # Real(ZDL(1,3),dp)
```

$$M_S = 28 \text{ GeV}$$

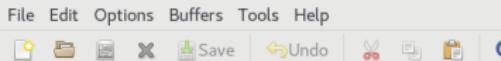
File Edit Options Buffers Tools Help

Save Undo

```

52  0.0000000E+00 # Ignore negative masses
53  0.0000000E+00 # Ignore negative masses at MZ
55  0.0000000E+00 # Calculate one loop masses
56  1.0000000E+00 # Calculate two-loop Higgs masses
57  1.0000000E+00 # Calculate low energy
60  1.0000000E+00 # Include kinetic mixing
65  1.0000000E+00 # Solution of tadpole equation
Block HiggsBoundsInputHiggsCouplingsFermions #
 1.0000000E+00  0.0000000E+00    3      25      5      5 # h_1 b b coupling
 1.0000000E+00  0.0000000E+00    3      25      3      3 # h_1 s s coupling
 1.0000000E+00  0.0000000E+00    3      25      6      6 # h_1 t t coupling
 1.0000000E+00  0.0000000E+00    3      25      4      4 # h_1 c c coupling
 1.0000000E+00  0.0000000E+00    3      25     15     15 # h_1 tau tau coupling
 1.0000000E+00  0.0000000E+00    3      25     13     13 # h_1 mu mu coupling
Block HiggsBoundsInputHiggsCouplingsBosons #
 1.0000000E+00    3      25      24      24 # h_1 W W coupling
 1.0000000E+00    3      25      23      23 # h_1 Z Z coupling
 0.0000000E+00    3      25      23      22 # h_1 Z gamma coupling
 1.04284942E+00   3      25      22      22 # h_1 gamma gamma coupling
 1.02186767E+00   3      25      21      21 # h_1 g g coupling
 0.0000000E+00    4      25      21      21     23 # h_1 g g Z coupling
 0.0000000E+00    3      25      25      23 # h_1 h_1 Z coupling
Block EFFHIGGSCOUPLEDINGS # values of loop-induced couplings
 25      22      22      0.33598689E-04 # H-Photon-Photon
 25      21      21      0.65965686E-04 # H-Gluon-Gluon
 25      22      23      0.0000000E+00 # H-Photon-Z (not yet calculated by SPheno)
Block SPhenoLowEnergy # low energy observables
 1  -0.0000000E+00 # T-parameter (1-loop BSM)
 2  0.0000000E+00 # S-parameter (1-loop BSM)
 3  0.0000000E+00 # U-parameter (1-loop BSM)
 20  1.99137438E-23 # (g-2)_e
 21  2.00436756E-14 # (g-2)_mu
 22  9.10708358E-10 # (g-2)_tau
 23  0.0000000E+00 # EDM(e)
 24  0.0000000E+00 # EDM(mu)
 25  0.0000000E+00 # EDM(tau)
 39  -3.57242562E-04 # delta(rho)
Block FlavorKitQFV # quark flavor violating observables
 200  3.1500000E-04 # BR(B->X_s gamma)
 201  1.0000000E+00 # BR(B->X_s gamma)/BR(B->X_s gamma) SM
-:--- SPheno.spc.SSDM 22% L186 (Fundamental)

```

```

Block FlavorFlavor #夸克 flavor violating observables
280 3.156950960e-04 #BR(B+ x s gamma)
281 1.00000000e-09 #BR(B+ x s gamma)/BR(B- x s gamma)_SM
282 1.00000000e-09 #BR(B+ x s gamma)/BR(B- x s gamma)_NLO
301 9.99950696e-01 #BR(B+ x u mu)/BR(B- x u mu)_SM
493 5.7245359e-03 #BR(B+ x u mu)/BR(B- x u mu)_NLO
494 9.99950696e-01 #BR(B+ x d mu)/BR(B- x d mu)_SM
495 9.99950696e-01 #BR(B+ x d mu)/BR(B- x d mu)_NLO
496 9.9836361e-01 #BR(B+ x tau mu)/BR(B- x tau mu)_SM
497 9.9836361e-01 #BR(B+ x tau mu)/BR(B- x tau mu)_NLO
500 9.9836361e-01 #BR(B+ x tau mu)/BR(B- x tau mu)_SM
501 9.9836361e-01 #BR(B+ x tau mu)/BR(B- x tau mu)_NLO
502 1.1265752e-04 #BR(B+ x tau mu)/BR(B- x tau mu)_SM
503 0.01455464e-01 #BR(B+ x tau mu)/BR(B- x tau mu)_NLO
691 9.9992793e-01 #BR(K+ x u mu)/BR(K- x u mu)_SM
692 4.2767734e-05 #K = BR(K+ x u mu)/BR(K- x u mu)_SM
693 9.9992793e-01 #BR(K+ x d mu)/BR(K- x d mu)_SM
694 9.9992793e-01 #BR(K+ x d mu)/BR(K- x d mu)_NLO
1990 8.9983877e+01 #Delta(B)SM
1991 0.00057800e-01 #Delta(B)NLO/Delta(B)SM_SM
1992 0.00057800e-01 #Delta(B)NLO/Delta(B)SM_NLO
1993 0.00135275e-06 #Delta(B)NLO/Delta(B)SM_SM
4000 0.01652251e-05 #BR(B0 -> d e e)
4001 0.0001652251e-05 #BR(B0 -> d e e)
4002 7.1889117e-14 #BR(B0 -> d e e)
4003 0.000093630e-05 #BR(B0 -> s e e)
4004 4.534959e-11 #BR(B0 -> d mu mu)
4005 0.000093630e-05 #BR(B0 -> s mu mu)/BR(B0 -> d mu mu)_SM
4006 0.07116046e-09 #BR(B0 -> s mu mu)
4007 0.000093630e-05 #BR(B0 -> s mu mu)/BR(B0 -> s mu mu)_NLO
4008 0.000093630e-05 #BR(B0 -> s mu mu)/BR(B0 -> s mu mu)_SM
4009 0.000093556e-06 #BR(B0 -> tau tau)/BR(B0 -> tau tau)
4010 0.51329690e-07 #BR(B0 -> tau tau)
4011 0.000093630e-05 #BR(B0 -> tau tau)/BR(B0 -> tau tau)
4012 0.000093630e-05 #BR(B0 -> tau tau)/BR(B0 -> tau tau)
5000 0.64141414e-06 #BR(B0 -> s + e)
5001 0.9161724e-01 #BR(B0 -> s + e)
5002 0.000093630e-05 #BR(B0 -> s + e)/BR(B0 -> s mu mu)
5003 0.00147179e-01 #BR(B0 -> s + e)/BR(B0 -> s mu mu)_SM
6000 1.00004181e-07 #K = BR(K+ -> K mu mu)
6001 1.00004181e-07 #BR(K+ -> K mu mu)/BR(K- -> K mu mu)_SM
6002 1.00004181e-07 #BR(K+ -> K mu mu)/BR(K- -> K mu mu)_NLO
6003 9.9913776e-01 #K = BR(K+ -> K mu mu)/BR(K- -> K mu mu)_SM
7000 0.00061099e-05 #BR(K+ -> K mu mu)/BR(K- -> K mu mu)_NLO
7001 0.00061099e-05 #BR(K+ -> K mu mu)/BR(K- -> K mu mu)_SM
7002 0.8737939e-07 #BR(K+ -> mu mu)/BR(K- -> mu mu)_SM
7003 0.00000000e+00 #BR(K+ -> mu mu)/BR(K- -> mu mu)_NLO
8000 0.00000000e+00 #BR(K+ -> pi+ pi-)/BR(K- -> pi+ pi-)
8001 0.00000000e+00 #BR(K+ -> pi+ pi-)/BR(K- -> pi+ pi-)_SM
8002 0.12287511e-13 #BR(K+ -> pi+ pi-)/BR(K- -> pi+ pi-)_NLO
8003 0.00000000e+00 #BR(K+ -> pi+ pi-)/BR(K- -> pi+ pi-)_SM
8004 0.00000000e+00 #BR(K+ -> pi0 pi0)/BR(K- -> pi0 pi0)
8005 0.00000000e+00 #BR(K+ -> pi0 pi0)/BR(K- -> pi0 pi0)_SM

```

Block: FlavorKitEV # lepton flavor violating observables

```

701 0.0000000E+00 # BR(mu->e gamma)
702 0.0000000E+00 # BR(tau->e gamma)
703 0.0000000E+00 # BR(tau->mu gamma)

```

```

1801 0.00000000e+00 # BR(Z->mu)
1802 0.00000000e+00 # BR(Z->tau)
1803 0.00000000e+00 # BR(Z->mu)
1181 0.00000000e+00 # BR(h->mu)
1182 0.00000000e+00 # BR(h->tau)
1183 0.00000000e+00 # BR(h->mu)
2001 0.00000000e+00 # BR(tau-mu-pi)
2002 0.00000000e+00 # BR(tau-mu-eta)
2003 0.00000000e+00 # BR(tau-mu-eta)
2004 0.00000000e+00 # BR(tau-mu-pi)
2005 0.00000000e+00 # BR(tau-mu-eta)
2006 0.00000000e+00 # BR(tau-mu-eta)
Block  $\Delta_{\text{FC}}^{\text{FC}}$ : 1.00000000e+00 # Wilson coefficients at scale 0
0365 4421 0 0 -1.64701690 # coeffCf'm
0365 4422 0 0 0.00000000 # coeffCf'p
0365 4322 0 2 0.37708923 # coeffCTp
0365 4423 0 0 0.00000000 # coeffCTm
0365 4424 0 0 0.00000000 # coeffCTp

```

0305	6421	00	00	-8.8547618E-09	#	cofTCBall
0305	6421	00	2	-8.8547618E-09	#	cofTCB8
0305	6321	00	2	-0.1930484E-10	#	cofTCBp
0305	6421	00	1	-0.1930484E-10	#	cofTCBpp
0305	6421	00	0	-0.3860968E-10	#	cofTCBppP
03051111	4133	00	00	-8.1615354E-06	#	cofTCBallSM
03051111	4133	00	2	-8.1615354E-06	#	cofTCBee
03051111	4233	00	2	-2.2161505E-14	#	cofTCBppEE
03051111	4133	00	1	-2.2161505E-14	#	cofTCBppSM



```

01050105 3232 00 0 0.0000000E+00 # coeffBB_SRRSM
01050105 3132 00 0 0.0000000E+00 # coeffBB_SLRSM
01050105 4141 00 0 0.0000000E+00 # coeffBB_VLLSM
01050105 4242 00 0 0.0000000E+00 # coeffBB_VRRSM
01050105 4142 00 0 0.0000000E+00 # coeffBB_VLRSM
01050105 4343 00 0 0.0000000E+00 # coeffBB_TLLSM
01050105 4444 00 0 0.0000000E+00 # coeffBB_TRRSM
03050305 3131 00 0 0.0000000E+00 # coeffBsBs_SLLSM
03050305 3232 00 0 0.0000000E+00 # coeffBsBs_SRRSM
03050305 3132 00 0 0.0000000E+00 # coeffBsBs_SLRSM
03050305 4141 00 0 0.0000000E+00 # coeffBsBs_VLLSM
03050305 4242 00 0 0.0000000E+00 # coeffBsBs_VRRSM
03050305 4142 00 0 0.0000000E+00 # coeffBsBs_VLRSM
03050305 4343 00 0 0.0000000E+00 # coeffBsBs_TLLSM
03050305 4444 00 0 0.0000000E+00 # coeffBsBs_TRRSM

Block TREELEVELUNITARITY #
  0 1.0000000E+00 # Tree-level unitarity limits fulfilled or not
  1 1.67207372E-02 # Maximal scattering eigenvalue

Block TREELEVELUNITARITYwTRILINEARS #
  0 1.0000000E+00 # Tree-level unitarity limits fulfilled or not
  1 1.61576897E-02 # Maximal scattering eigenvalue
  2 2.0000000E+03 # best scattering energy
  11 1.0000000E+03 # min scattering energy
  12 2.0000000E+03 # max scattering energy
  13 5.0000000E+00 # steps

DECAY      4 3.82261015E-13 # Fu_2
#   BR          NDA     ID1     ID2
#   BR          NDA     ID1     ID2     ID3
  3.05502575E-02 3       2       -1      1 # BR(Fu_2 -> Fu_1 Fd_1^* Fd_1 )
  5.45954987E-01 3       2       -1      3 # BR(Fu_2 -> Fu_1 Fd_1^* Fd_2 )
  1.56486313E-03 3       2       -3      1 # BR(Fu_2 -> Fu_1 Fd_2^* Fd_1 )
  2.79270154E-02 3       2       -3      3 # BR(Fu_2 -> Fu_1 Fd_2^* Fd_2 )
  1.07295183E-02 3       1       -11     12 # BR(Fu_2 -> Fd_1 Fe_1^* Fv_1 )
  1.01645236E-02 3       1       -13     14 # BR(Fu_2 -> Fd_1 Fe_2^* Fv_2 )
  1.91744771E-01 3       3       -11     12 # BR(Fu_2 -> Fd_2 Fe_1^* Fv_1 )
  1.81364064E-01 3       3       -13     14 # BR(Fu_2 -> Fd_2 Fe_2^* Fv_2 )

DECAY      6 1.55526925E+00 # Fu_3
#   BR          NDA     ID1     ID2
  1.6759777E-03 2       3       24    # BR(Fu_3 -> Fd_2 VWP )
  9.98288583E-01 2       5       24    # BR(Fu_3 -> Fd_3 VWP )

----- SPheNo.spc.SSDM 80% L558 (Fundamental)

```

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```

2.15252618E-03 3 2 -12 11 # BR(Fd_3 -> Fu_1 Fv_1^* Fe_1 )
2.14490780E-03 3 2 -14 13 # BR(Fd_3 -> Fu_1 Fv_2^* Fe_2 )
5.83957751E-04 3 2 -16 15 # BR(Fd_3 -> Fu_1 Fv_3^* Fe_3 )
1.59069889E-01 3 4 -12 11 # BR(Fd_3 -> Fu_2 Fv_1^* Fe_1 )
1.58104211E-01 3 4 -14 13 # BR(Fd_3 -> Fu_2 Fv_2^* Fe_2 )
1.96896118E-02 3 4 -16 15 # BR(Fd_3 -> Fu_2 Fv_3^* Fe_3 )

DECAY 25 6.42252863E-03 # hh
# BR NDA ID1 ID2
  1.93338706E-03 2 22 22 # BR(hh -> VP VP )
  5.96211424E-02 2 21 21 # BR(hh -> VG VG )
  2.82490956E-02 2 23 23 # BR(hh -> VZ VZ )
  2.33261695E-01 2 -24 24 # BR(hh -> VWP^* VWP_virt )
  1.33790716E-04 2 -3 3 # BR(hh -> Fd_2^* Fd_2 )
  3.58433068E-01 2 -5 5 # BR(hh -> Fd_3^* Fd_3 )
  1.45065926E-04 2 -13 13 # BR(hh -> Fe_2^* Fe_2 )
  4.18774507E-02 2 -15 15 # BR(hh -> Fe_3^* Fe_3 )
  1.68995783E-02 2 -4 4 # BR(hh -> Fu_2^* Fu_2 )
  2.59445280E-01 2 6666635 6666635 # BR(hh -> SS SS )

DECAY1L 4 1.11448989E-23 # Fu_2
# BR NDA ID1 ID2
  9.80578882E-01 2 2 21 # BR(Fu_2 -> Fu_1 VG )
  1.94211179E-02 2 2 22 # BR(Fu_2 -> Fu_1 VP )

DECAY1L 6 1.40218346E+00 # Fu_3
# BR NDA ID1 ID2
  1.67434891E-03 2 3 24 # BR(Fu_3 -> Fd_2 VWP )
  9.98290247E-01 2 5 24 # BR(Fu_3 -> Fd_3 VWP )

DECAY1L 3 1.38160366E-20 # Fd_2
# BR NDA ID1 ID2
  9.93677595E-01 2 1 21 # BR(Fd_2 -> Fd_1 VG )
  6.32240539E-03 2 1 22 # BR(Fd_2 -> Fd_1 VP )

DECAY1L 5 4.50364203E-14 # Fd_3
# BR NDA ID1 ID2
  2.05693613E-02 2 1 21 # BR(Fd_3 -> Fd_1 VG )
  9.74708472E-01 2 3 21 # BR(Fd_3 -> Fd_2 VG )
  4.62332156E-03 2 3 22 # BR(Fd_3 -> Fd_2 VP )

DECAY1L 25 8.26580363E-03 # hh
# BR NDA ID1 ID2
  3.55304437E-04 2 -3 3 # BR(hh -> Fd_2^* Fd_2 )
  6.75629528E-01 2 -5 5 # BR(hh -> Fd_3^* Fd_3 )
  1.19436199E-04 2 -13 13 # BR(hh -> Fe_2^* Fe_2 )

```

The highlighted section of the code lists the branching ratios for the decay of the scalar particle h into various final states. The total branching ratio for $h \rightarrow S S$ is 26%.

$\text{BR}(h \rightarrow S S) = 26\%$

- : --- SPheNo.spc.SSDM 93% L632 (Fundamental)

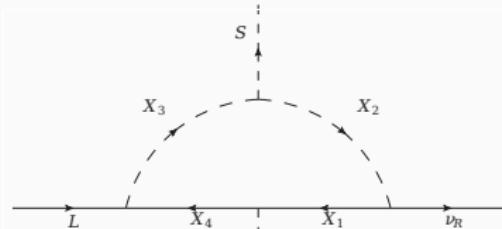
Run micrOMEGAs

```
micromegas/SSDM/CalcOmega_with_Detection_M0v5 SPheno.spc.SSDM
```

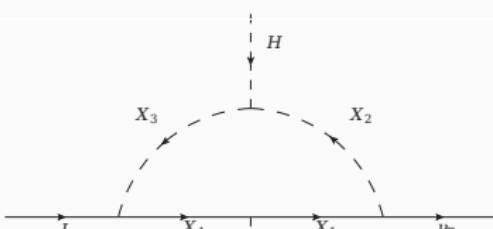
```
Masses of odd sector Particles:  
~Ss : MSs = 28.4 ||  
PROCESS: ~Ss,~Ss->AllEven,1*x{h,g,A,Z,Wp,Wm,nu1,Nu1,nu2,Nu2,nu3,Nu3,d1,D1,d2,D2,d3,D3,u1,U1,u2,U2,u3,U3,e1,E1,e2,E2,e3,  
E3  
Xf=1.64e+01 Omega h^2=2.28e+01  
  
# Channels which contribute to 1/(omega) more than 1%.  
# Relative contributions in % are displayed  
85% ~Ss ~Ss ->d3 D3  
8% ~Ss ~Ss ->e3 E3  
4% ~Ss ~Ss ->u2 U2  
2% ~Ss ~Ss ->g g  
  
===== Calculation of CDM-nucleons amplitudes =====  
TREE LEVEL  
PROCESS: QUARKS,~Ss->QUARKS,~Ss{d1,D1,d2,D2,d3,D3,u1,U1,u2,U2,u3,U3  
Delete diagrams with _S0_!=1,_V5_,A  
....  
CDM-nucleon cross sections[pb]:  
proton SI 2.407E-09 SD 0.000E+00  
neutron SI 2.471E-09 SD 0.000E+00  
  
===== Direct Detection =====  
73Ge: Total number of events=1.29E-03 /day/kg  
Number of events in 10 - 50 KeV region=4.19E-04 /day/kg  
131Xe: Total number of events=2.66E-03 /day/kg
```

Dirac neutrino masses

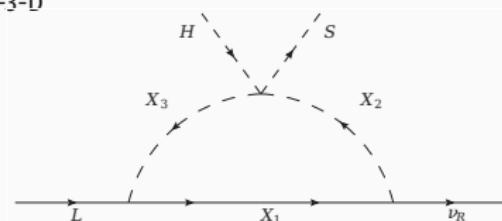
One loop topologies $U(1)_{B-L} \oplus Z_2 \oplus Z_2$



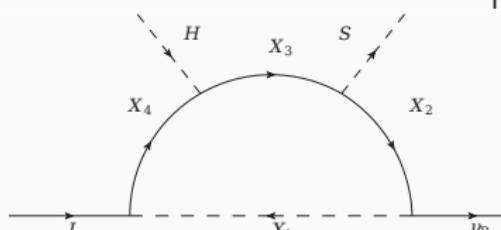
T1-3-D



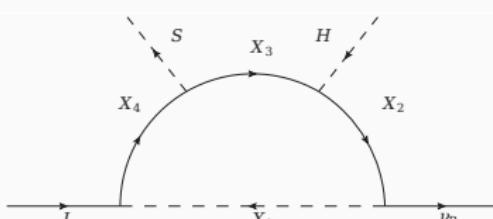
T1-3-E



T3-1-A



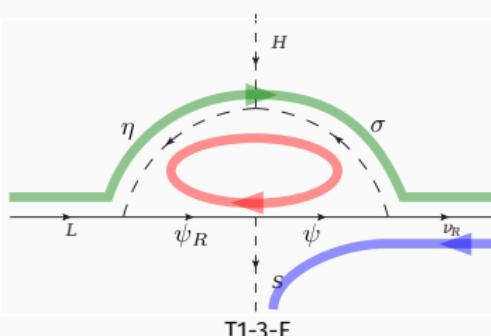
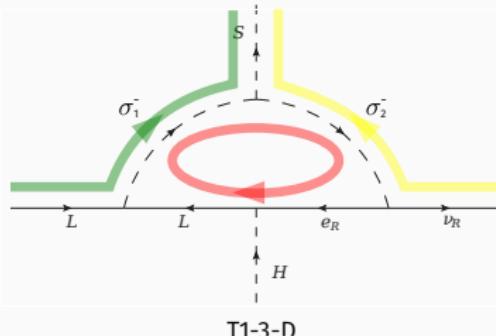
T1-2-A



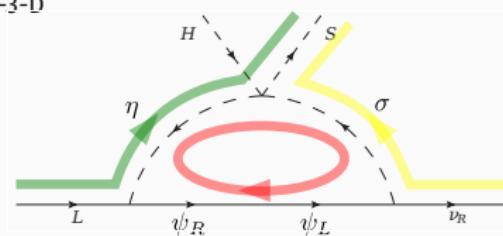
T1-2-B

Chang-Yuan Yao and Gui-Jun Ding, arXiv:1802.05231 [PRD]

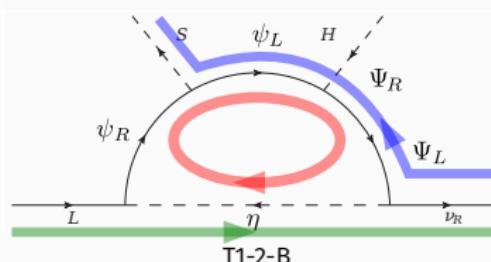
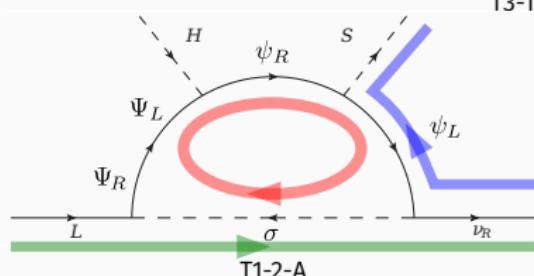
One loop topologies $U(1)_{B-L}$ only!



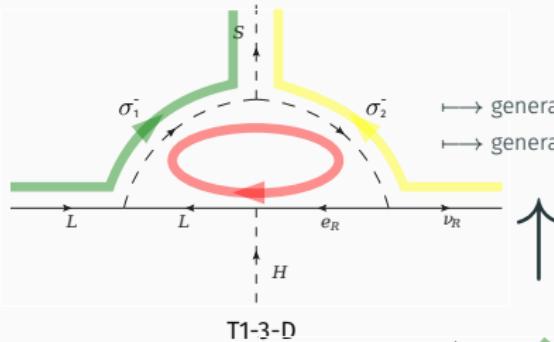
$\psi_{L,R} \rightarrow$ Singlet fermions (vector-like)
 $\sigma \rightarrow$ Singlet scalar



with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]



One loop topologies $U(1)_{B-L}$ only! with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]

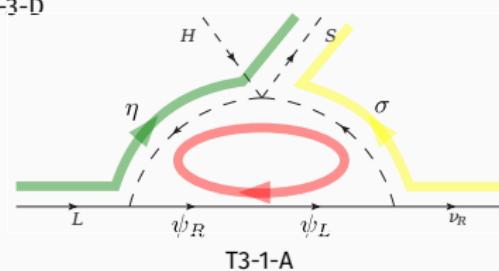


→ generalization to two and three loops: S. Saad arXiv:1902.07259 [NPB]
 → generalization to $U(1)_R$: et al, S. Saad arXiv:1904.07407

Fields: f_i	L, e_R	ν_{R3}	ν_{R2}	ν_{R1}	S	H
$U(1)_{B-L}$	-1	-4	-4	+5	+3	0

T1-3-D

$\psi_{L,R} \rightarrow$ Singlet fermions (vector-like)
 $\sigma \rightarrow$ Singlet scalar



T3-1-A

Anomaly cancellation conditions

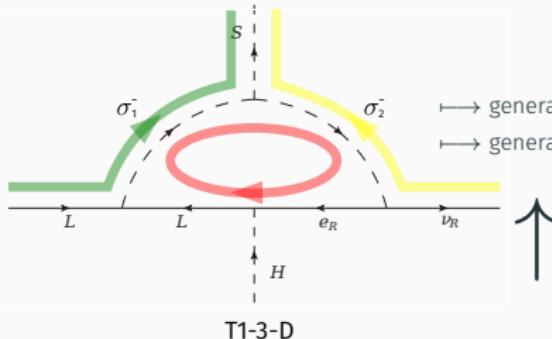
$$\sum_i \nu_{Ri} = -3$$

$$\sum_i \nu_{Ri}^3 = -3$$

Three-level cancellation conditions

$$\frac{\nu_R \nu_R}{(\nu_R)^\dagger L \cdot H}$$

One loop topologies $U(1)_{B-L}$ only! with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]



→ generalization to two and three loops: S. Saad arXiv:1902.07259 [NPB]
 → generalization to $U(1)_R$: et al, S. Saad arXiv:1904.07407

Fields: f_i	L, e_R	ν_{R3}	ν_{R2}	ν_{R1}	σ_1^-	σ_2^-	S	H
$U(1)_{B-L}$	-1	-4	-4	+5	-2	-5	+3	0

Anomaly cancellation conditions

$\psi_{L,R} \rightarrow$ Singlet fermions (vector-like)

$\sigma \rightarrow$ Singlet scalar

$$\sum_i \nu_{Ri} = -3$$

$$\sum_i \nu_{Ri}^3 = -3$$

Three-level cancellation conditions

$$\cancel{(\nu_R)^\dagger L \cdot H}$$

```
cp -r BSM/SARAH/Models/B-L/ SARAH/Models/  
math << EOF  
<<./SARAH/SARAH.m  
Start["B-L/DZ"]  
MakeSPheno[]  
EOF
```

```
cp -r SARAH/Output/B-L-DZ/EWSB/SPheno SPheno/BLDZ  
cd SPheno  
make Model=BLDZ  
cd .. # Return to parent directory
```

```
cp BSM/Input_Files/LesHouches.in.BLDZ .
```

SPHENO/bin/SPHENO2BLDZ LesHouches.in.BLDZ

```
55 1      # Calculate loop corrected masses  
50 0      # Majorana phases: use only positive masses  
520 0     # Write effective Higgs couplings
```

```
cp -r BSM/SARAH/Models/B-L/ SARAH/Models/
math << EOF
<<./SARAH/SARAH.m
Start["B-L/DZ"]
MakeSPheno[]
EOF
```

```
cp -r SARAH/Output/B-L-DZ/EWSB/SPheno SPheno/BLDZ
cd SPheno
make Model=BLDZ
cd .. # Return to parent directory
```

```
cp BSM/Input_Files/LesHouches.in.BLDZ .
```

```
SPheno/bin/SPhenoBLDZ LesHouches.in.BLDZ
```

```
cat SPheno.spc.BLDZ
```

```
Block MASS # Mass spectrum
#   PDG code      mass      particle
    25      1.24861947E+02 # hh_1
    35      1.71464282E+03 # hh_2
  900037      2.00000000E+03 # Hm_2
  900038      3.00000000E+03 # Hm_3
    22      0.00000000E+00 # VP
    23      9.11887000E+01 # VZ
    21      0.00000000E+00 # VG
    24      7.96796394E+01 # VWm
    31      2.57196423E+03 # VZp
    1      5.00000000E-03 # Fd_1
    .
    .
    .
  15      1.77669000E+00 # Fe_3
  12      0.00000000E+00 # Fv_1
  14     -1.61994502E-31 # Fv_2
  16      4.42048291E-14 # Fv_3
 8810012     -4.42048291E-14 # Fv_4
 8810014      2.08300541E-10 # Fv_5
 8810016     -2.08300541E-10 # Fv_6
```

EXTRA

2nd Chuck Norris fact of the day

*Chuck Norris can run collider
simulations with MadGraph on
an abacus*

From A. Vicente