

Two component Dark Matter

with neutrino masses

Diego Restrepo

Sep 6, 2019 - IPP - Natal [PDF: <http://bit.ly/SARAHIPP>]

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

Focus on

[arXiv:1811.11927](https://arxiv.org/abs/1811.11927) [PRD]

In collaboration with

N. Bernal (UAN), C. Yaguna (UPTC), Ó. Zapata, (UdeA)



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
V4.14.2 (Transferred to W.Porod)

- [SARAH](#)
- [SPheno](#)
- [McrOMEGAs](#)
- [MadGraph](#)
- [MadAnalysis](#)
- [FlavorKit](#)

Contact

Avelino Vicente
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Office B-6-0

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 programas 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](#).

References

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

About

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

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Input/Output Code

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

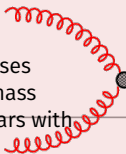
Also in SARAH

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



Ready to be computed in your favourite model!

Computer tools in particle physics

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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

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

- Minimal Supersymmetric Standard Model (MSSM)
- NMSSM (in several versions)
- Near-minimal SSM (near-MSSM)
- General singlet extended SSM (SMSSM)
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Standard Model

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

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

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

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

```
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	Y	$SU(2)_L$	$SU(3)_c$	Z_2
Q	3	$(u_L d_L)^T$	1/6	2	3	+
L	3	$(\nu_L e_L)^T$	-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}};
```

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

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

$$d_L = V_d D_L, \quad (d_R)^\dagger = D_R^c U_d,$$

$$V_d \rightarrow N_F \times N_F, \dots$$

Chuck Norris fact of the day

*Chuck Norris lost his virginity
before his dad*



(* 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}};
```



```
...
{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"}},

...
```

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

```
...
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" }},

  ...
}
...
```

```
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};
```

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=SPheno # 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=MICROMEGAS
...
#-----
# 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				

```
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    # Lambda1IN
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
10 2               # Matching order ( 0:automatic, 1:scale, 2: tree, 3: one, 4: two loop)
-:--- LesHouches.in.SSDM Top L16 (Fundamental)

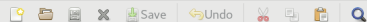
```



```
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
10 2              # Matching order ( 2:automatic, 1:scale, 0:2: tree, one, 5: 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
```



```
# 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 mass 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 MODESEL # Input parameters
1 1 # GUT scale input
2 1 # Boundary conditions
6 1 # switching on flavour violation
Block MINPAR # Input parameters
1 2.80000000E-01 # Lambda1IN
2 1.00000000E-02 # LamSHIN
3 0.00000000E+00 # LamSIN
4 2.00000000E+02 # MSinput
Block gaugeGUT Q= -1.00000000E+00 # (GUT scale)
1 0.00000000E+00 # g1(Q)
2 0.00000000E+00 # g2(Q)
3 0.00000000E+00 # g3(Q)
Block SMINPUTS # SM parameters
-:--- SPheno.spc.SSDM Top L39 (Fundamental)
Beginning of buffer
```

```

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

```

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

```

Block UDL MIX 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)
-:--- SPheno.spc.SSDM 9% L75 (Fundamental)

```

```

52 0.00000000E+00 # Ignore negative masses
53 0.00000000E+00 # Ignore negative masses at MZ
55 0.00000000E+00 # Calculate one loop masses
56 1.00000000E+00 # Calculate two-loop Higgs masses
57 1.00000000E+00 # Calculate low energy
60 1.00000000E+00 # Include kinetic mixing
65 1.00000000E+00 # Solution of tadpole equation
Block HiggsBoundsInputHiggsCouplingsFermions #
1.00000000E+00 0.00000000E+00 3 25 5 5 # h_1 b b coupling
1.00000000E+00 0.00000000E+00 3 25 3 3 # h_1 s s coupling
1.00000000E+00 0.00000000E+00 3 25 6 6 # h_1 t t coupling
1.00000000E+00 0.00000000E+00 3 25 4 4 # h_1 c c coupling
1.00000000E+00 0.00000000E+00 3 25 15 15 # h_1 tau tau coupling
1.00000000E+00 0.00000000E+00 3 25 13 13 # h_1 mu mu coupling
Block HiggsBoundsInputHiggsCouplingsBosons #
1.00000000E+00 3 25 24 24 # h_1 W W coupling
1.00000000E+00 3 25 23 23 # h_1 Z Z coupling
0.00000000E+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
0.00000000E+00 4 25 21 23 # h_1 g g Z coupling
0.00000000E+00 3 25 25 23 # h_1 h_1 Z coupling
Block EFFHIGGSCOUPPLINGS # 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 0.00000000E+00 # H-Photon-Z (not yet calculated by SPheno)
Block SPhenoLowEnergy # low energy observables
1 -0.00000000E+00 # T-parameter (1-loop BSM)
2 0.00000000E+00 # S-parameter (1-loop BSM)
3 0.00000000E+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 0.00000000E+00 # EDM(e)
24 0.00000000E+00 # EDM(mu)
25 0.00000000E+00 # EDM(tau)
39 -3.57242562E-04 # delta(rho)
Block FlavorKitQFV # quark flavor violating observables
200 3.15000000E-04 # BR(B->X_s gamma)
201 1.00000000E+00 # BR(B->X_s gamma)/BR(B->X s gamma) SM
-:--- SPheno.spc.SSDM 22% L186 (Fundamental)

```




```

Block FlavorKitFV # 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
300 5.89291589E-04 # BR(D->nu nu)
301 9.8895696E-01 # BR(D->nu nu)/BR(D->nu nu)_SM
400 5.57245359E-03 # BR(Ds->nu nu)
401 9.98893051E-01 # BR(Ds->nu nu)/BR(Ds->nu nu)_SM
402 5.44600031E-02 # BR(Ds->tau nu)
403 9.08836361E-01 # BR(Ds->tau nu)/BR(Ds->tau nu)_SM
500 5.0580381E-07 # BR(B->nu nu)
501 9.91642649E-01 # BR(B->nu nu)/BR(B->nu nu)_SM
502 1.12505751E-04 # BR(B->tau nu)
503 0.01645648E-01 # BR(B->tau nu)/BR(B->tau nu)_SM
600 6.32329548E-01 # BR(K->nu nu)
601 9.99293701E-01 # BR(K->nu nu)/BR(K->nu nu)_SM
602 2.47647734E-05 # R K s BR(K->nu nu)/(K->nu nu)
603 2.47614752E-05 # R K* s BR(K->nu nu)_SM/(K->nu nu)_SM
1900 1.09803077E-01 # Delta(M Bs)
1901 1.00057030E+00 # Delta(M Bs)/Delta(M Bs)_SM
1902 4.25535576E-01 # Delta(M Bd)
1903 1.000185173E+00 # Delta(M Bd)/Delta(M Bd)_SM
4000 1.00152020E-15 # BR(B^0 d->e e)
4001 1.00000468E+00 # BR(B^0 d->e e)/BR(B^0 d->e e)_SM
4002 7.18091179E-14 # BR(B^0 s->e e)
4003 1.00000430E+00 # BR(B^0 s->e e)/BR(B^0 s->e e)_SM
4004 4.53409508E-11 # BR(B^0 d->nu nu)
4005 1.00000616E+00 # BR(B^0 d->nu nu)/BR(B^0 d->nu nu)_SM
4006 3.07110166E-09 # BR(B^0 s->nu nu)
4007 1.00000052E+00 # BR(B^0 s->nu nu)/BR(B^0 s->nu nu)_SM
4008 9.49161541E-09 # BR(B^0 d->tau tau)
4009 1.00000355E+00 # BR(B^0 d->tau tau)/BR(B^0 d->tau tau)_SM
4010 6.51328066E-07 # BR(B^0 s->tau tau)
4011 1.00000057E+00 # BR(B^0 s->tau tau)/BR(B^0 s->tau tau)_SM
5000 1.64141441E-06 # BR(B-> s e e)
5001 0.00116250E-01 # BR(B-> s e e)/BR(B-> s e e)_SM
5002 1.59101057E-00 # BR(B-> s nu nu)
5003 9.91417398E-01 # BR(B-> s nu nu)/BR(B-> s nu nu)_SM
6000 1.10904181E-07 # BR(B-> K nu nu)
6001 9.09130779E-01 # BR(B-> K nu nu)/BR(B-> K nu nu)_SM
6002 1.10904181E-07 # BR(B-> K nu nu)
6003 9.99130779E-01 # BR(B-> K nu nu)/BR(B-> K nu nu)_SM
7000 3.08642094E-05 # BR(B-> nu nu)
7001 1.00000000E+00 # BR(B-> nu nu)/BR(B-> nu nu)_SM
7002 8.07379292E-07 # BR(B->0 nu nu)
7003 1.00000000E+00 # BR(B->0 nu nu)/BR(B->0 nu nu)_SM
8000 1.30845848E-10 # BR(K*+ -> pi*+ nu nu)
8001 1.00000000E+00 # BR(K*+ -> pi*+ nu nu)/BR(K*+ -> pi*+ nu nu)_SM
8002 1.62288731E-43 # BR(K L -> pi^0 nu nu)
8003 1.00000000E+00 # BR(K L -> pi^0 nu nu)/BR(K L -> pi^0 nu nu)_SM
8004 0.00000000E+00 # BR(K*0 L -> e nu)
8005 0.00000000E+00 # BR(K*0 L -> e nu)/BR(K*0 L -> e nu)_SM
9100 1.04643051E-15 # Delta(M K)
9102 9.99993421E-01 # Delta(M K)/Delta(M K)_SM
9103 1.64370744E-03 # epsilon_L K
9104 1.00000000E+00 # epsilon_L K/epsilon_L K_SM

Block FlavorKitLV # lepton flavor violating observables
701 0.00000000E+00 # BR(mu-> gamma)
702 0.00000000E+00 # BR(tau-> gamma)
703 0.00000000E+00 # BR(tau->nu gamma)
800 0.00000000E+00 # CR(mu-> A)
801 0.00000000E+00 # CR(mu-> T)
802 0.00000000E+00 # CR(mu-> S)
803 0.00000000E+00 # CR(mu-> Sb)
804 0.00000000E+00 # CR(mu-> Au)
805 0.00000000E+00 # CR(mu-> Pb)
901 0.00000000E+00 # CR(mu->3e)
902 0.00000000E+00 # BR(tau->3e)
903 0.00000000E+00 # BR(tau->3mu)
904 0.00000000E+00 # BR(tau -> e- mu- nu-)
905 0.00000000E+00 # BR(tau -> mu- e- e-)
906 0.00000000E+00 # BR(tau -> nu- mu- nu-)
907 0.00000000E+00 # BR(tau -> mu- e- e-)
1001 0.00000000E+00 # BR(Z-> nu nu)
1002 0.00000000E+00 # BR(Z->e tau)
1003 0.00000000E+00 # BR(Z->mu tau)
1101 0.00000000E+00 # BR(h->nu nu)
1102 0.00000000E+00 # BR(h->tau tau)
1103 0.00000000E+00 # BR(h->mu tau)
2001 0.00000000E+00 # BR(tau->nu pi)
2002 0.00000000E+00 # BR(tau->nu eta)
2003 0.00000000E+00 # BR(tau->nu eta')
2004 0.00000000E+00 # BR(tau->nu pi)
2005 0.00000000E+00 # BR(tau->nu eta)
2006 0.00000000E+00 # BR(tau->nu eta')

Block FACIEF Q= 1.60000000E+02 # Wilson coefficients at scale 0
0300 4422 00 0 -0.16461706E-00 # coeffCTm
0300 4422 00 2 -0.16461706E-00 # coeffCT
0300 4322 00 2 -0.37370893E-10 # coeffCTp
0300 4422 00 1 0.00000000E+00 # coeffCTNP
0300 4322 00 1 -0.37370893E-10 # coeffCTpNP
0300 6421 00 0 -0.82476738E-09 # coeffCBm
0300 6421 00 2 -0.82476738E-09 # coeffCB
0300 6321 00 2 -0.19309485E-10 # coeffCTp
0300 6421 00 1 0.00000000E+00 # coeffCBNP
0300 6321 00 1 -0.19309485E-10 # coeffCBNP
03051111 4133 00 0 -0.10103545E-00 # coeffCbmSM
03051111 4133 00 2 0.10103545E-00 # coeffCbm
03051111 4233 00 0 -0.21615055E-14 # coeffCbmW
03051111 4135 00 1 0.00000000E+00 # coeffCbmW

new bar options new.pdf Font

```

```

Block PMDFE-0 1.609090909E+02 # Wilson coefficients at scale 0
0305 4422 0 0 -0.164617108E-06 # coeffC7m
0305 4422 0 0 -0.164617108E-06 # coeffC7
0305 4322 0 0 -0.37378693E-10 # coeffC7p
0305 4422 0 0 -0.8904691E-09 # coeffC7CP
0305 4322 0 0 -0.37378693E-10 # coeffC7NP
0305 6421 0 0 -0.854767128E-09 # coeffC8a
0305 6421 0 0 -0.854767128E-09 # coeffC8
0305 6321 0 0 -0.19394845E-10 # coeffC8p
0305 6421 0 0 -0.8904691E-09 # coeffC8CP
0305 6321 0 0 -0.19394845E-10 # coeffC8NP
03051111 4133 0 0 0.10163545E-06 # coeffC9mS
03051111 4133 0 0 0.10163545E-06 # coeffC9c
03051111 4233 0 0 -0.2163565E-14 # coeffC9pS
03051111 4233 0 0 -0.2163565E-14 # coeffC9p

```

```
Block FlavorKitLFV # lepton flavor violating observables
701      0.00000000E+00 # BR(mu->e gamma)
702      0.00000000E+00 # BR(tau->e gamma)
703      0.00000000E+00 # BR(tau->mu gamma)
```

```

01050105 3232 00 0 0.00000000E+00 # coeffBB_SRRSM
01050105 3132 00 0 0.00000000E+00 # coeffBB_SLRSM
01050105 4141 00 0 0.00000000E+00 # coeffBB_VLLSM
01050105 4242 00 0 0.00000000E+00 # coeffBB_VRRSM
01050105 4142 00 0 0.00000000E+00 # coeffBB_VLRSM
01050105 4343 00 0 0.00000000E+00 # coeffBB_TLLSM
01050105 4444 00 0 0.00000000E+00 # coeffBB_TRRSM
03050305 3131 00 0 0.00000000E+00 # coeffBsBs_SLLSM
03050305 3232 00 0 0.00000000E+00 # coeffBsBs_SRRSM
03050305 3132 00 0 0.00000000E+00 # coeffBsBs_SLRSM
03050305 4141 00 0 0.00000000E+00 # coeffBsBs_VLLSM
03050305 4242 00 0 0.00000000E+00 # coeffBsBs_VRRSM
03050305 4142 00 0 0.00000000E+00 # coeffBsBs_VLRSM
03050305 4343 00 0 0.00000000E+00 # coeffBsBs_TLLSM
03050305 4444 00 0 0.00000000E+00 # coeffBsBs_TRRSM

```

Block TREELEVELUNITARITY #

```

0 1.00000000E+00 # Tree-level unitarity limits fulfilled or not
1 1.67207372E-02 # Maximal scattering eigenvalue

```

Block TREELEVELUNITARITYwTRILINEARS #

```

0 1.00000000E+00 # Tree-level unitarity limits fulfilled or not
1 1.61576897E-02 # Maximal scattering eigenvalue
2 2.00000000E+03 # best scattering energy
11 1.00000000E+03 # min scattering energy
12 2.00000000E+03 # max scattering energy
13 5.00000000E+00 # steps

```

DECAY 4 3.82261015E-13 # Fu_2

#	BR	NDA	ID1	ID2	ID3	
#	BR	NDA	ID1	ID2		
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	
1.67597777E-03	2	3	24	# BR(Fu_3 -> Fd_2 Vwp)	
9.98288583E-01	2	5	24	# BR(Fu_3 -> Fd_3 Vwp)	

```

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 21 21 # BR(Fu_2 -> Fu_1 VG )
1.94211179E-02 2 22 22 # BR(Fu_2 -> Fu_1 VP )

```

```

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

```

```

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

```

```

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

```

→ $BR(h \rightarrow SS) = 26\%$

Run micrOMEGAs

micromegas/SSDM/CalcOmega_with_DDetection_MOv5 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 =====

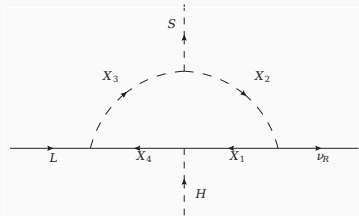
73Ge: Total number of events=1.29E-03 /day/kg

Number of events in 10 - 50 KeV region=4.19E-04 /day/kg

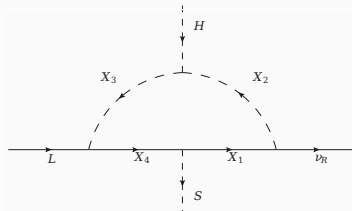
131Xe: Total number of events=2.66E-03 /day/kg

Dirac neutrino masses

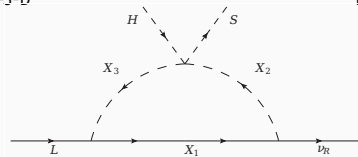
One loop topologies $U(1)_{B-L} \oplus Z_2 \oplus Z_2$



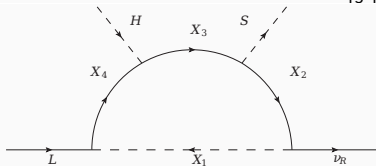
T1-3-D



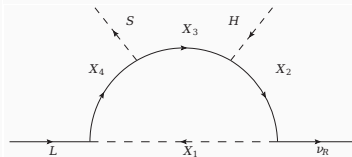
T1-3-E



T3-1-A



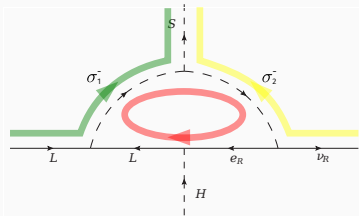
T1-2-A



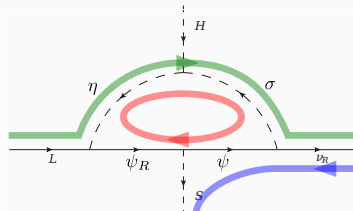
T1-2-B

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

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



T1-3-D

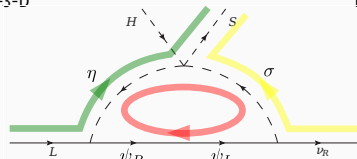


T1-3-E

$\psi_{L,R} \rightarrow$ Singlet fermions

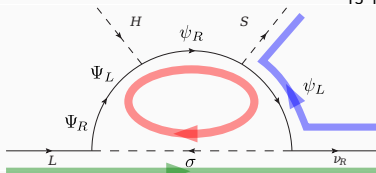
$\Psi_{L,R} \rightarrow$ Vector-like doublet fermions

$\sigma \rightarrow$ Singlet scalar

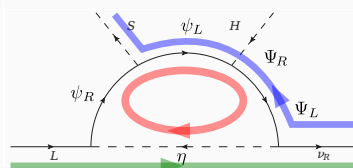


T3-1-A

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

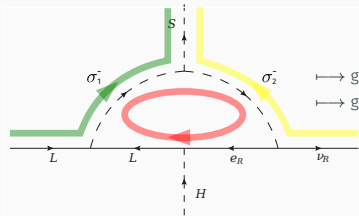


T1-2-A



T1-2-B

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

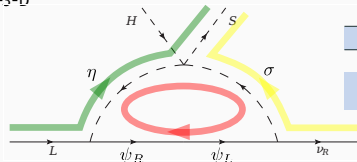


→ generalization to two and three loops: S. Saad arXiv:1902.07259 [NPB]
 → generalization to $U(1)_R$: et al, S. Saad arXiv:1904.07407

T1-3-D

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

$\sigma \rightarrow$ Singlet scalar



T3-1-A

Fields: f_i	$(\nu_{R3})^\dagger$	$(\nu_{R2})^\dagger$	$(\nu_{R1})^\dagger$	ψ_L	$(\psi_R)^\dagger$	S
(A)	+4	+4	-5	-r	r	+3

Anomaly cancellation conditions

$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$

EXTRA

2nd Chuck Norris fact of the day

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