

# Two component Dark Matter

## with neutrino masses

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Diego Restrepo

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

Instituto de Física  
Universidad de Antioquia  
Phenomenology Group  
<http://gfif.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

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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.

- [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](#)
- [MicrOMEGAs](#)
- [MadGraph](#)
- [MadAnalysis](#)
- [FlavorKit](#)

## Contact

Avelino Vicente  
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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 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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## 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	$\bar{B} \rightarrow X_s \ell^+ \ell^-$
$\tau \rightarrow P \ell$	$\bar{B} \rightarrow X_{d,s} \nu \bar{\nu}$
$h \rightarrow \ell_\alpha \ell_\beta$	$B \rightarrow K \ell^+ \ell^-$
$Z \rightarrow \ell_\alpha \ell_\beta$	$K \rightarrow \pi \nu \bar{\nu}$
	$\Delta M_{B_{s,d}}$
	$\Delta M_K$ and $\varepsilon_K$
	$P \rightarrow \ell \nu$

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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	$P \rightarrow \ell \nu$

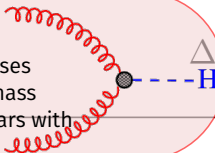
Also in SARAH

$S, T, U$

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!

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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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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
```

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

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

```
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};
```

```

(* 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}}
};

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

```

```

(* 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}};

```

```

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};

```



```

...
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" }},

  ...
}
...

```

```
...
{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 -> "Hypercharge-Coupling",  
      LaTeX -> "g_1",  
      DependenceOptional -> e/Cos[ThetaW],  
      DependenceNum -> e/Cos[ThetaW],  
      LesHouches -> {gauge,1},  
      GUTnormalization -> Sqrt[3/5],  
      OutputName-> g1 } },  
...
```

# 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
18 2              # Matching order ( 1:automatic, 1:scale, 0 2: tree, one, 5: two loop)
-:--- LesHouches.in.SSDM Top L16 (Fundamental)

```



```
Block MODSEL      #
1 1               # 1/0: High/low scale input
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1 2.8000000E-01   # LambdaLIN
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16 1              # One-loop decays
18 2              # Matching order ( 2: automatic, 1: pole, 0: 2: tree, -1: 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 1.12505752E-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 9.99263701E-01 # BR(K->nu nu)/BR(K->nu nu)_SM
602 2.47647734E-05 # R_K = BR(K->nu nu)/(K->nu nu)
603 2.47612475E-05 # R_K* = BR(K->nu nu)_SM/(K->nu nu)_SM
1900 1.09803077E-01 # Delta(M_B)
1901 1.00057030E+00 # Delta(M_B)/Delta(M_B)_SM
1902 4.25535576E-01 # Delta(M_B)
1903 1.000185173E+00 # Delta(M_B)/Delta(M_B)_SM
4000 1.00152002E-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 mu)
4005 1.00000616E+00 # BR(B^0 d->nu mu)/BR(B^0 d->nu mu)_SM
4006 3.07110166E-09 # BR(B^0 s->nu mu)
4007 1.00000052E+00 # BR(B^0 s->nu mu)/BR(B^0 s->nu mu)_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 mu)
5003 9.91417398E-01 # BR(B-> s nu mu)/BR(B-> s nu mu)_SM
6000 1.10904181E-07 # BR(B-> K mu mu)
6001 9.09130779E-01 # BR(B-> K mu mu)/BR(B-> K mu mu)_SM
6002 1.10904181E-07 # BR(B-> K mu mu)
6003 9.99130779E-01 # BR(B-> K mu mu)/BR(B-> K mu mu)_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 mu)
8001 1.00000000E+00 # BR(K*+ -> pi*+ nu mu)/BR(K*+ -> pi*+ nu mu)_SM
8002 1.62288731E-43 # BR(K_L -> pi^0 nu mu)
8003 1.00000000E+00 # BR(K_L -> pi^0 nu mu)/BR(K_L -> pi^0 nu mu)_SM
8004 0.00000000E+00 # BR(K^0_L -> e mu)
8005 0.00000000E+00 # BR(K^0_L -> e mu)/BR(K^0_L -> e mu)_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

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```





```
Block FlavorKitQV # quark flavor violating observables
200 3.1500000E-04 # BR(B->L gamma)
201 1.0000000E+00 # BR(B->L gamma)/BR(B->L gamma)_SM
300 5.89291589E-04 # BR(D->nu nu)
301 9.8925696E-01 # BR(D->nu nu)/BR(D->nu nu)_SM
400 5.57245359E-03 # BR(Ds->nu nu)
401 9.9883031E-01 # BR(Ds->nu nu)/BR(Ds->nu nu)_SM
402 5.4460003E-02 # BR(D->tau nu)
403 9.08836361E-01 # BR(Ds->tau nu)/BR(Ds->tau nu)_SM
500 5.0582801E-07 # BR(B->nu nu)
501 9.91645649E-01 # BR(B->nu nu)/BR(B->nu nu)_SM
502 1.1250575E-04 # BR(B->tau nu)
503 0.01645649E-01 # BR(B->tau nu)/BR(B->tau nu)_SM
600 6.32329548E-01 # BR(K->nu nu)
601 9.9925793E-01 # BR(K->nu nu)/BR(K->nu nu)_SM
602 2.47647734E-05 # R_K = BR(K->nu nu)/(K->nu nu)
603 2.4761475E-05 # R_K^SM = BR(K->nu nu)_SM/(K->nu nu)_SM
1900 1.00003077E+01 # Delta(M_B)
1901 1.00057030E+00 # Delta(M_B)/Delta(M_B)_SM
1902 2.2553573E-01 # Delta(M_B)
1903 1.00031573E+00 # Delta(M_B)/Delta(M_B)_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 mu)
4005 1.00000616E+00 # BR(B^0_d->nu mu)/BR(B^0_d->nu mu)_SM
4006 3.07110160E-09 # BR(B^0_s->nu mu)
4007 1.00000032E+00 # BR(B^0_d->tau tau)/BR(B^0_d->tau tau)_SM
4008 9.49161541E-09 # BR(B^0_s->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 1.00000595E+00 # BR(B^0_s->tau tau)/BR(B^0_s->tau tau)_SM
5000 1.64141441E-06 # BR(B->e e)
5001 0.00116250E-01 # BR(B->e e)/BR(B->e e)_SM
5002 1.59101057E-00 # BR(B->e nu mu)
5003 9.91417398E-01 # BR(B->e nu mu)/BR(B->e nu mu)_SM
6000 1.10904183E-07 # BR(B->K mu mu)
6001 9.99130779E-01 # BR(B->K mu mu)/BR(B->K mu mu)_SM
6002 1.10904183E-07 # BR(B->K mu mu)
6003 9.99130779E-01 # BR(B->K mu mu)/BR(B->K mu mu)_SM
7000 3.08620946E-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 mu)
8001 1.00000000E+00 # BR(K^+->pi^+ nu mu)/BR(K^+->pi^+ nu mu)_SM
8002 1.62288731E-43 # BR(K_L->pi^0 nu mu)
8003 1.00000000E+00 # BR(K_L->pi^0 nu mu)/BR(K_L->pi^0 nu mu)_SM
8004 0.00000000E+00 # BR(K^0_L->e mu)
8005 0.00000000E+00 # BR(K^0_L->e mu)/BR(K^0_L->e mu)_SM
1900 1.04613051E-15 # Delta(M_K)/Delta(M_K)_SM
9102 9.99993421E-01 # Delta(M_K)
9103 1.64370744E-03 # epsilon_K
1904 1.00000000E+00 # Delta(M_K)/Delta(M_K)_SM

Block FlavorKitLV # 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(mu->tau 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->B)
804 0.00000000E+00 # CR(mu->A)
805 0.00000000E+00 # CR(mu->B)
901 0.00000000E+00 # BR(mu->3e)
902 0.00000000E+00 # BR(tau->3e)
903 0.00000000E+00 # BR(tau->3mu)
904 0.00000000E+00 # BR(tau->e mu mu)
905 0.00000000E+00 # BR(tau->mu mu e)
906 0.00000000E+00 # BR(tau->nu mu mu)
907 0.00000000E+00 # BR(tau->nu mu 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->mu tau)
1102 0.00000000E+00 # BR(h->tau tau)
1103 0.00000000E+00 # BR(h->nu 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 FACIEP Q= 1.00000000E+02 # Wilson coefficients at scale 0
```

```
0305 4422 00 0 -0.16461706E-00 # coeffCTm
0305 4422 00 2 -0.16461706E-00 # coeffCT
0305 4322 00 2 -0.37370893E-10 # coeffCTp
0305 4422 00 1 0.00000000E+00 # coeffCTNP
0305 4322 00 1 -0.37370893E-10 # coeffCTpNP
0305 6421 00 0 -0.82476738E-09 # coeffCBm
0305 6421 00 2 -0.82476738E-09 # coeffCB
0305 6321 00 2 -0.19399485E-10 # coeffCBp
0305 6421 00 1 0.00000000E+00 # coeffCBNP
0305 6321 00 1 -0.19399485E-10 # coeffCBpNP
03051111 4133 00 0 -0.10103545E-00 # coeffCDeSM
03051111 4133 00 2 0.10103545E-00 # coeffCDe
03051111 4233 00 0 -0.21615055E-14 # coeffCDeW
03051111 4135 00 1 0.00000000E+00 # coeffCDeW
```

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```

Block FlavorKitLV # lepton flavor violating observables

```
701 0.000000000E+00 # BR(mu->e gamma)
702 0.000000000E+00 # BR(tau->e gamma)
703 0.000000000E+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 )

```

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

# 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