Computer tools in particle physics

- Lecture 1 : SARAH and SPheno -

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• **Name of the tool:** SARAH

• **Author:** Florian Staub (florian.staub@cern.ch)

• **Type of code:** Mathematica package

• **Website:** [http://sarah.hepforge.org/](http://sarah.hepforge.org/)
SARAH

- Lagrangian derivation: SUSY and non-SUSY models
- Mass matrices
- All vertices
- Tadpole equations
- 1-loop corrections for tadpoles and self-energies
- 2-loop renormalization group equations
- 1-loop Wilson coefficients for flavor observables
- Input files for other codes

Crucial for this course!
# Models already in SARAH

## Supersymmetric Models
- MSSM [in several versions]
- NMSSM
- Near-to-minimal SSM (near-MSSM)
- General singlet extended SSM (SMSSM)
- DiracNMSSM
- Triplet extended MSSM/NMSSM
- Several models with R-parity violation
- U(1)-extended MSSM (UMSSM)
- Secluded MSSM
- Several B-L extended models
- Inverse and linear seesaws [several embeddings]
- 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

## Non-Supersymmetric Models
- Standard Model
- Inert Higgs doublet model
- B-L extended SM
- B-L extended SM with inverse seesaw
- SM extended by a scalar color octet
- Two Higgs doublet model
- Singlet extended SM
- Singlet Scalar DM

[SARAH](http://sarah.hepforge.org/)
The scotogenic model

Also known as...

- The inert doublet model
- The radiative seesaw
- Ma's model
The scotogenic model

The scotogenic model is a theoretical framework in particle physics that introduces a new type of dark matter candidate, known as the scotogenic dark matter. The model is based on the concept of a dark matter particle, often referred to as a “scotus” or “skotos,” which is the Greek word for darkness.

In the scotogenic model, the dark matter candidate is a sterile neutrino, denoted by $N_i$, which is a Majorana fermion. The model also involves a new, inert doublet field $\phi$ and a scalar field $\eta$. The Lagrangian of the model is given by:

$$\mathcal{L}_N = \overline{N_i} \phi N_i - \frac{m_{N_i}}{2} \overline{N_i}^c N_i + y_i \alpha \eta \overline{N_i} \ell_\alpha + \text{h.c.}$$

where $\phi$ and $\eta$ are the fields for the inert doublet, $N_i$ is the sterile neutrino, $\ell_\alpha$ is the lepton, and $y_i$ is the Yukawa coupling.

The Lagrangian also includes the following terms for the kinetic and potential parts:

$$\mathcal{V} = m^2_\phi \phi^\dagger \phi + m^2_\eta \eta^\dagger \eta + \frac{\lambda_1}{2} (\phi^\dagger \phi)^2 + \frac{\lambda_2}{2} (\eta^\dagger \eta)^2 + \lambda_3 (\phi^\dagger \phi) (\eta^\dagger \eta)$$

$$+ \lambda_4 (\phi^\dagger \eta) (\eta^\dagger \phi) + \frac{\lambda_5}{2} \left[ (\phi^\dagger \eta)^2 + (\eta^\dagger \phi)^2 \right]$$

This Lagrangian includes terms that are responsible for the mass generation of the inert doublet and the dark matter sector. The model provides a new mechanism for dark matter production and interaction with the standard model particles.

[Ernest Ma, 2006]
The scotogenic model

[Ernest Ma, 2006]

\[
\mathcal{V} = m_\phi^2 \phi^\dagger \phi + m_\eta^2 \eta^\dagger \eta + \frac{\lambda_1}{2} (\phi^\dagger \phi)^2 + \frac{\lambda_2}{2} (\eta^\dagger \eta)^2 + \lambda_3 (\phi^\dagger \phi) (\eta^\dagger \eta) + \lambda_4 (\phi^\dagger \eta) (\eta^\dagger \phi) + \frac{\lambda_5}{2} \left[ (\phi^\dagger \eta)^2 + (\eta^\dagger \phi)^2 \right]
\]

Inert scalar sector: \[\eta^\pm \quad \eta^0 = (\eta_R + i\eta_I) / \sqrt{2}\]

\[
m_{\eta^+}^2 = m_\eta^2 + \lambda_3 \langle \phi^0 \rangle^2
\]

\[
m_R^2 = m_\eta^2 + (\lambda_3 + \lambda_4 + \lambda_5) \langle \phi^0 \rangle^2
\]

\[
m_I^2 = m_\eta^2 + (\lambda_3 + \lambda_4 - \lambda_5) \langle \phi^0 \rangle^2
\]

\[
m_R^2 - m_I^2 = 2\lambda_5 \langle \phi^0 \rangle^2
\]
Radiative neutrino masses

Tree-level: Forbidden by the $Z_2$ symmetry

Radiative generation of neutrino masses

Additional loop suppression

Dark particles in the loop

[Other variations in Restrepo et al, 2013]

1-loop neutrino masses:

[Ernest Ma, 2006]
Dark matter

The lightest particle charged under $Z_2$ is stable: dark matter candidate

**Fermion Dark Matter:** $\mathcal{N}_1$

- It can only be produced via Yukawa interactions
- Potential problems with lepton flavor violation: is it compatible with the current bounds?

J. Kubo, E. Ma, D. Suematsu, PLB 642 (2006) 18, D. Aristizabal Sierra, J. Kubo, D. Restrepo, D. Suematsu, O. Zapata, PRD 79 (2009) 013011, D. Suematsu, T. Toma, T. Yoshida, PRD 79 (2009) 093004, D. Schmidt, T. Schwetz, T. Toma, PRD 85 (2012) 073009, A. Vicente, C. E. Yaguna, JHEP 1502 (2015) 144, A. Ibarra, C. E. Yaguna, O. Zapata, arXiv:1601.01163, ...

**Scalar Dark Matter:** the lightest neutral $\eta$ scalar, $\eta_R$ or $\eta_I$

- It also has gauge interactions
- Not correlated to lepton flavor violation

R. Barbieri, L. J. Hall, V. S. Rychkov, PRD 74 (2006) 015007, M. Cirelli, N. Fornengo, A. Strumia, NPB 753 (2006) 178, L. L. Honorez, E. Nezri, J. F. Oliver, M. H. G. Tytgat, JCAP 0702 (2007) 028, Q.-H. Cao, E. Ma, PRD (2007) 095011, S. Andreas, M. H. G. Tytgat, Q. Swillens, JCAP 0904 (2009) 004, E. Nezri, M. H. G. Tytgat, G. Vertongen, JCAP 0904 (2009) 014, T. Hambye, F.-S. Ling, L. L. Honorez, J. Roche, JHEP 07 (2009) 090, L. L. Honorez, C. E. Yaguna, JHEP 1009 (2010) 046 and JCAP 1101 (2011) 002, S. Kashiwase, D. Suematsu, PRD 86 (2012) 053001, A. Goudelis, B. Herrman, O. Stål, JHEP 1309 (2013) 106, M. Klasen, C. E. Yaguna, J. D. Ruiz-Alvarez, D. Restrepo, O. Zapata, JCAP 1304 (2013) 044, J. Racker, JCAP 1403 (2014) 02, ...
Scotogenic: implementation

\[ \text{FermionFields}[[1]] = \{q, 3, uL, dL, 1/6, 2, 3, 1\}; \]

\[ q = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \]

Quark doublet
Scotogenic: implementation

Yukawa Lagrangian

\[ \text{LagFer} \equiv \mathcal{L}_Y = Y_d H^\dagger \bar{d} q + Y_e H^\dagger \bar{e} \ell + Y_u H \bar{u} q + Y_N \eta \bar{N} \ell \]
Scotogenic: implementation

Scalar decomposition

\[ H^0 = \frac{1}{\sqrt{2}} (\nu + h + iA) \]

\[ \eta^0 = \frac{1}{\sqrt{2}} (\eta_R + i\eta_I) \]
Scotogenic: exploration

Tadpole equations

\[ \frac{\partial V}{\partial v} = 0 \]
Scotogenic: exploration

Tadpole equations

\[ \frac{\partial V}{\partial v} = 0 \]

\[ \frac{1}{2} \lambda_1 v^3 - m_H^2 v = 0 \quad \Rightarrow \quad m_H^2 = \frac{1}{2} \lambda_1 v^2 \]
Scotogenic: exploration

Mass matrices

- Charged leptons

\[
\begin{pmatrix}
\frac{v(Y_e)_{11}}{\sqrt{2}} & \frac{v(Y_e)_{21}}{\sqrt{2}} & \frac{v(Y_e)_{31}}{\sqrt{2}} \\
\frac{v(Y_e)_{12}}{\sqrt{2}} & \frac{v(Y_e)_{22}}{\sqrt{2}} & \frac{v(Y_e)_{32}}{\sqrt{2}} \\
\frac{v(Y_e)_{13}}{\sqrt{2}} & \frac{v(Y_e)_{23}}{\sqrt{2}} & \frac{v(Y_e)_{33}}{\sqrt{2}}
\end{pmatrix}
\]

Chuck Norris fact of the day

*When Chuck Norris crosses the street, cars look both ways for Chuck Norris.*
Scotogenic: exploration

Mass matrices

- Right-handed neutrinos

\[
\begin{pmatrix}
- (M_N)_{11} & -\frac{1}{2} (M_N)_{12} - \frac{1}{2} (M_N)_{21} & -\frac{1}{2} (M_N)_{13} - \frac{1}{2} (M_N)_{31} \\
-\frac{1}{2} (M_N)_{12} - \frac{1}{2} (M_N)_{21} & - (M_N)_{22} & -\frac{1}{2} (M_N)_{23} - \frac{1}{2} (M_N)_{32} \\
-\frac{1}{2} (M_N)_{13} - \frac{1}{2} (M_N)_{31} & -\frac{1}{2} (M_N)_{23} - \frac{1}{2} (M_N)_{32} & -(M_N)_{33}
\end{pmatrix}
\]

\[
\begin{pmatrix}
- (M_N)_{11} & - (M_N)_{12} & - (M_N)_{13} \\
- (M_N)_{12} & - (M_N)_{22} & - (M_N)_{23} \\
- (M_N)_{13} & - (M_N)_{23} & - (M_N)_{33}
\end{pmatrix}
\]
Scotogenic: exploration

Higgs boson mass

\[ m_h^2 = \frac{3}{2} \lambda_1 v^2 - m_H^2 \quad \Rightarrow \quad m_h^2 = \lambda_1 v^2 \]

Tadpole equations
Scotogenic: exploration

\[ \ell_i^+ - \ell_j^- - h \]

\[ \frac{i}{\sqrt{2}} \sum_{m,n=1}^{3} (V_e)_{jn}^* (Y_e)_{mn} (U_e)_{im}^* P_L + \frac{i}{\sqrt{2}} \sum_{m,n=1}^{3} (V_e)_{in} (Y_e)_{mn}^* (U_e)_{jm} P_R \]

\[ \ell_i^+ - \nu_j^- - W^-_\mu \]

\[ -i \frac{g_2}{\sqrt{2}} \sum_{m=1}^{3} (V_e)_{im}^* (V_\nu)_{jm} \gamma_\mu P_L = i \frac{g_2}{\sqrt{2}} \sum_{m=1}^{3} K_{ij} \gamma_\mu P_L \]

\[ \nu_i - \chi_j^- - \eta_R \]

\[ -i \sum_{m,n=1}^{3} (V_\nu)_{in}^* (Y_N)_{mn} (Z_X)_{jm}^* P_L - \frac{i}{\sqrt{2}} \sum_{m,n=1}^{3} (V_\nu)_{in} (Y_N)_{mn}^* (Z_X)_{jm} P_R \]
Scotogenic: exploration

Renormalization group equations

\[ \frac{dc}{dt} = \beta_c = \frac{1}{16\pi^2} \beta^{(1)}_c + \frac{1}{(16\pi^2)^2} \beta^{(2)}_c + \cdots \]
Renormalization group equations

\[ \frac{dc}{dt} = \beta_c = \frac{1}{16\pi^2} \beta_c^{(1)} + \frac{1}{(16\pi^2)^2} \beta_c^{(2)} + \cdots \]

\[ \beta_{g_i}^{(1)} = \left( \frac{21}{5} g_1^3, -3g_2^3, -7g_3^3 \right) \]

\[ \beta_{m_\eta^2}^{(1)} = -\frac{9}{2} \left( \frac{1}{5} g_1^2 + g_2^2 \right) m_\eta^2 + 6\lambda_2 m_\eta^2 - 2 (2\lambda_3 + \lambda_4) m_H^2 \\
+ 2 m_\eta^2 \text{Tr} \left( Y_N Y_N^\dagger \right) - 4 \text{Tr} \left( M_N M_N^* Y_N Y_N^\dagger \right) \]
SARAH: Input for other codes

SPheno

SARAH

MicrOmegas

MadGraph
SPheno

- **Name of the tool:** SPheno
- **Authors:** Werner Porod (porod@physik.uni-wuerzburg.de) and Florian Staub (florian.staub@cern.ch)
- **Type of code:** Fortran
- **Website:** http://spheno.hepforge.org/
SPheno

SPheno is a Fortran code. It provides routines for the numerical evaluation of all vertices, masses and decay modes in a given model.

http://spheno.hepforge.org/

[Porod, Staub]
Scotogenic: benchmark point

**BS1 benchmark point**

\[
\begin{align*}
\lambda_1 &= 0.25 & \lambda_2 &= 0.5 & \lambda_3 &= 0.5 \\
\lambda_4 &= -0.5 & \lambda_5 &= 8 \cdot 10^{-11} & m_\eta^2 &= 1.85 \cdot 10^5 \text{ GeV}^2 \\

M_N &= \begin{pmatrix}
345 \text{ GeV} & 0 & 0 \\
0 & 4800 \text{ GeV} & 0 \\
0 & 0 & 6800 \text{ GeV}
\end{pmatrix} \\

Y_N &= \begin{pmatrix}
0.0172495 & 0.300325 & 0.558132 \\
-0.891595 & 1.00089 & 0.744033 \\
-1.39359 & 0.207173 & 0.253824
\end{pmatrix}
\]

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Backup
Radiative neutrino masses

\[ m_\nu = y^T \Lambda y \]

\[ \Lambda_{ij} = \frac{m_{N_i}}{2(4\pi)^2} \left[ \frac{m_R^2}{m_R^2 - m_{N_i}^2} \log \left( \frac{m_R^2}{m_{N_i}^2} \right) - \frac{m_I^2}{m_I^2 - m_{N_i}^2} \log \left( \frac{m_I^2}{m_{N_i}^2} \right) \right] \delta_{ij} \]

\[ y = \sqrt{\Lambda}^{-1} R \sqrt{\hat{m}_\nu} U_{PMNS}^\dagger \]

Modified Casas-Ibarra parameterization

\[ U_{PMNS}^T m_\nu U_{PMNS} = m_\nu^{\text{diag}} \]

Mixing angles \( \theta_{ij} \), \( m_{\nu_1}, \Delta m_{sol}^2, \Delta m_{atm}^2 \)

[Ernest Ma, 2006]
[See also Merle, Platscher, 2015]