Computer tools in particle physics

- Lecture 1 : SARAH -

Avelino Vicente
IFIC – CSIC / U. Valencia

On-line course

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SARAH

SARAH

[Staub]

- **Name of the tool:** `SARAH`
- **Author:** Florian Staub
- **Type of code:** `Mathematica` package
- **Website:** http://sarah.hepforge.org/

Currently maintained by
Mark Goodsell & Werner Porod

SARAH

SARAH [Staub]

- 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

↑

SPheno, MicrOmegas, MadGraph, ...

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/

The scotogenic model

Also known as...

The inert doublet model

The radiative seesaw

Ma's model

The scotogenic model

[Ernest Ma, 2006]

Field	$SU(2)_L \times U(1)_Y$	Z_2
L_i	$(2,-1/2)$	$+$
e_i	$(1,1)$	$+$
ϕ	$(2,-1/2)$	$+$
N_i	$(1,0)$	$-$
η	$(2,-1/2)$	$-$

← Inert (or dark) doublet

σκότος

skotos = darkness

Dark Matter!

$$\mathcal{L}_N = \overline{N_i} \partial\!\!\!/ N_i - \frac{m_{N_i}}{2} \overline{N_i^c} N_i + y_{i\alpha} \eta \overline{N_i} \ell_\alpha + \text{h.c.}$$

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

The scotogenic model

[Ernest Ma, 2006]

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

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

$$\begin{aligned} m_{\eta^+}^2 &= m_\eta^2 + \lambda_3 \langle \phi^0 \rangle^2 \\ m_R^2 &= m_\eta^2 + (\lambda_3 + \lambda_4 + \lambda_5) \langle \phi^0 \rangle^2 \\ m_I^2 &= m_\eta^2 + (\lambda_3 + \lambda_4 - \lambda_5) \langle \phi^0 \rangle^2 \end{aligned}$$

$$\Rightarrow \quad \mathrm{m}_R^2 - m_I^2 = 2 \lambda_5 \langle \phi^0 \rangle^2$$

Radiative neutrino masses

[Ernest Ma, 2006]

Tree-level:
Forbidden by the Z_2 symmetry

Radiative generation of neutrino masses

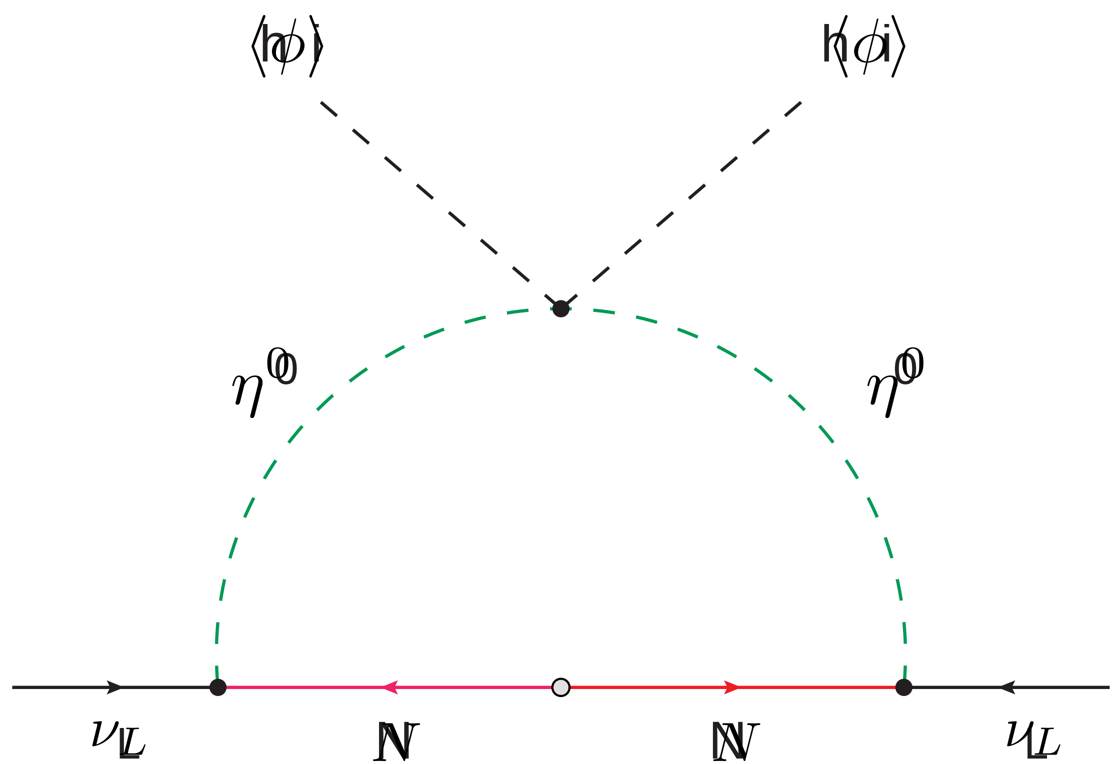
↓

Additional loop suppression

Dark particles in the loop

[Other variations in Restrepo et al, 2013]

1-loop neutrino masses:



Dark matter

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

Fermion Dark Matter: N_1

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

Scalar Dark Matter: the lightest neutral η scalar, η_R or η_I

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

Scotogenic: implementation

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

- generations → 3
- $U(1)_Y$ → 1/6
- $SU(2)_L$ → 2
- $SU(3)_c$ → 3
- $\mathbb{Z}_2$ → 1

$$q = \left(\begin{array}{c} u_L \\ d_L \end{array} \right)$$

Quark doublet

Scotogenic: implementation

Yukawa Lagrangian

$$\texttt{LagFer} \equiv \mathcal{L}_Y = Y_d H^\dagger \, \bar{d} \, q + Y_e H^\dagger \, \bar{e} \, \ell + Y_u H \, \bar{u} \, q + Y_N \, \eta \, \overline{N} \, \ell$$

Scotogenic: implementation

Scalar decomposition

$$
\begin{aligned}
H^0 &= \frac{1}{\sqrt{2}}\left(v + h + iA\right) \\
\eta^0 &= \frac{1}{\sqrt{2}}\left(\eta_R + i\eta_I\right)
\end{aligned}
$$

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

Chuck Norris can kill two stones with one bird

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

Tadpole equations

$$\frac{\partial \mathcal{V}}{\partial v} = 0$$

Scotogenic: exploration

Tadpole equations

$$\frac{\partial \mathcal{V}}{\partial v} = 0$$

$$\boxed{\frac{1}{2}\lambda_1 v^3 - m_H^2 v = 0 \quad \Rightarrow \quad m_H^2 = \frac{1}{2}\lambda_1 v^2}$$

Scotogenic: exploration

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

Vertices

$$\ell_i^+ - \ell_j^- - h$$

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

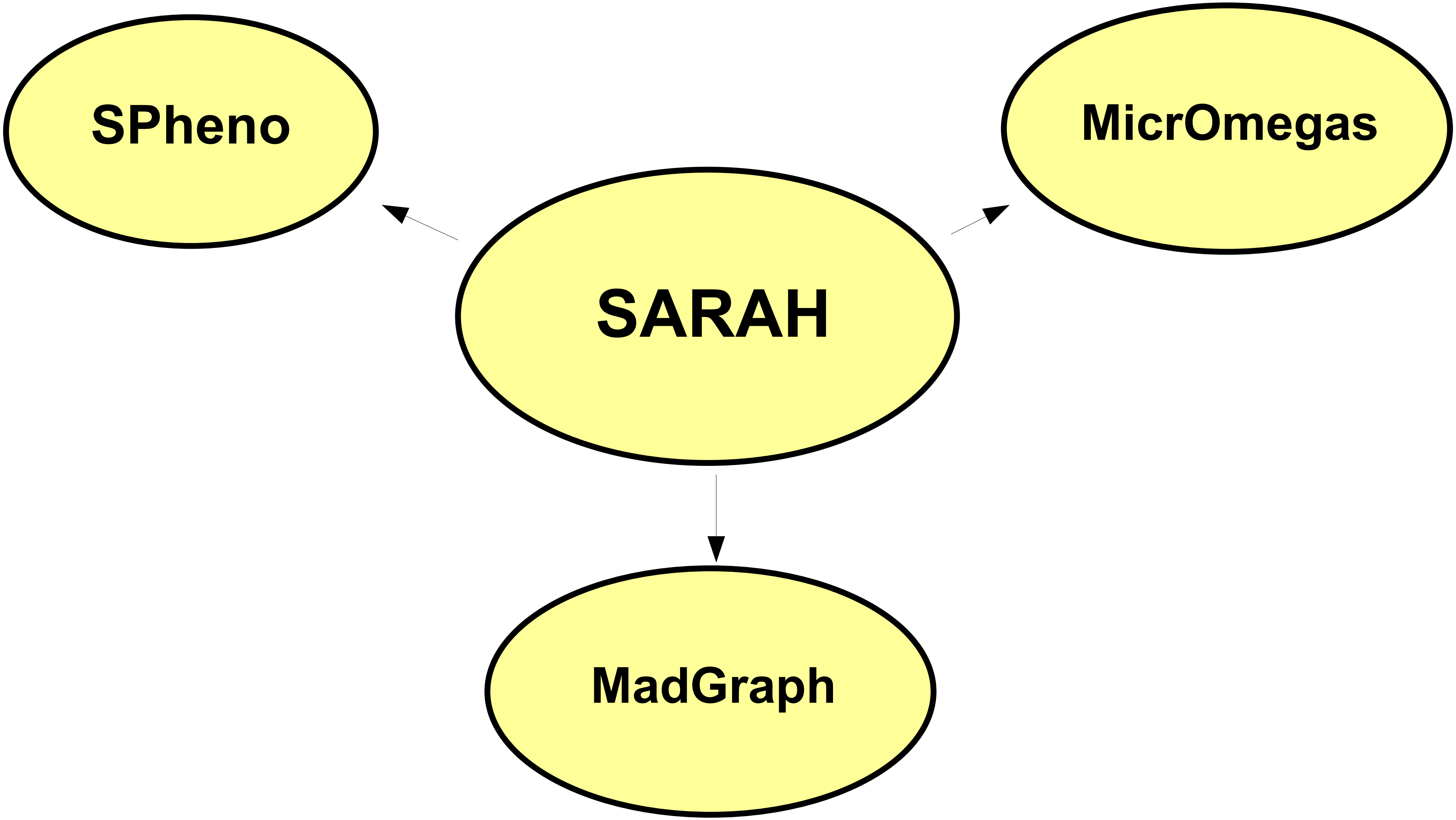
$$\ell_i^+ - \nu_j - W_\mu^-$$

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

$$\nu_i - \chi_j - \eta_R$$

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

SARAH: Input for other codes



Backup

Radiative neutrino masses

[Ernest Ma, 2006]

[See also Merle, Platscher, 2015]

$$m_\nu = y^T \Lambda \, y$$

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

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

Modified

Casas-Ibarra parameterization

[Toma, Vicente, 2013]

$$U_{\text{PMNS}}^T \, m_\nu \, U_{\text{PMNS}} = m_\nu^{\text{diag}}$$

Mixing angles θ_{ij} $\quad m_{\nu_1}, \Delta m_{sol}^2, \Delta m_{atm}^2$

Scotogenic: exploration

Renormalization group equations

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

Scotogenic: exploration

Renormalization group equations

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

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

$$\begin{aligned}\beta_{m_\eta^2}^{(1)} \quad = \quad & -\frac{9}{2}\left(\frac{1}{5}g_1^2 + g_2^2\right)m_\eta^2 + 6\lambda_2 m_\eta^2 - 2\left(2\lambda_3 + \lambda_4\right)m_H^2 \\ & +2\,m_\eta^2 \mathrm{Tr}\left(Y_N Y_N^\dagger\right) - 4\mathrm{Tr}\left(M_N M_N^* Y_N Y_N^\dagger\right)\end{aligned}$$