

Computer tools in particle physics

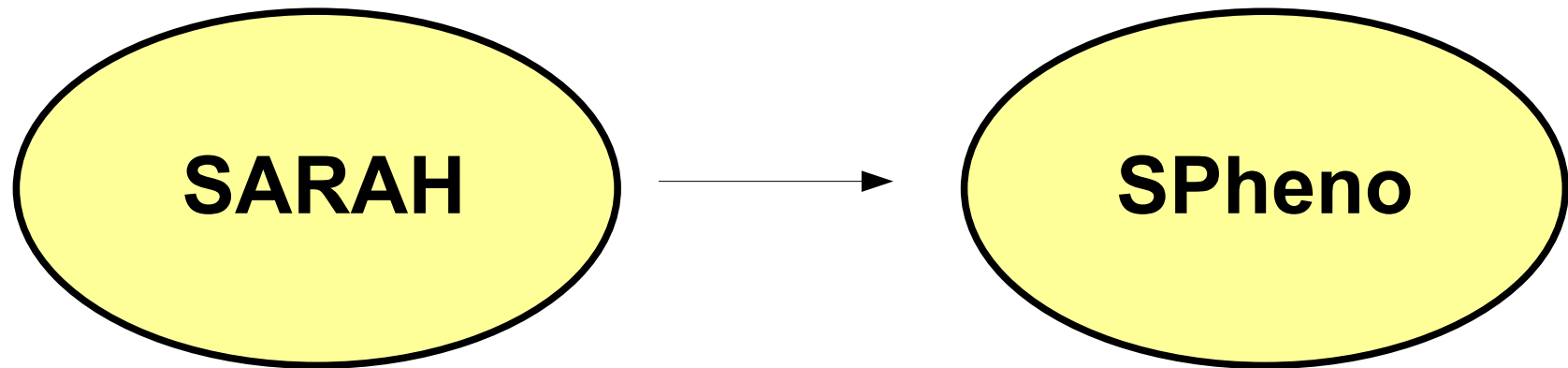
- Lecture 2 : SPheno -

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On-line course

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SARAH: Input for other codes



Chuck Norris fact of the day

*Chuck Norris counted to
infinity... twice*



SPheno

SPheno

[Porod, Staub]

- **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

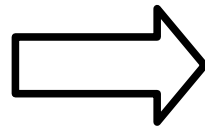
SPheno

[Porod, Staub]

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

SARAH

Analytics



SPheno

Numerics

<http://spheno.hepforge.org/>

Scotogenic: benchmark point

BS1 benchmark point

$$\lambda_1 = 0.26$$

$$\lambda_2 = 0.5$$

$$\lambda_3 = 0.5$$

$$\lambda_4 = -0.5$$

$$\lambda_5 = 8 \cdot 10^{-11}$$

$$m_\eta^2 = 1.85 \cdot 10^5 \text{ GeV}^2$$

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

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

Backup

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	$(2, -1/2)$	—

σκότος
skotos = darkness



← Inert (or dark) doublet

**Dark
Matter!**

$$\mathcal{L}_N = \overline{N_i} \not{\partial} N_i - \frac{m_{N_i}}{2} \overline{N_i^c} N_i + y_{i\alpha} \eta \overline{N_i} \ell_\alpha + \text{h.c.}$$

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

The scotogenic model

[Ernest Ma, 2006]

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

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

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

Radiative neutrino masses

[Ernest Ma, 2006]

Tree-level:

Forbidden by the Z_2 symmetry

Radiative generation of
neutrino masses

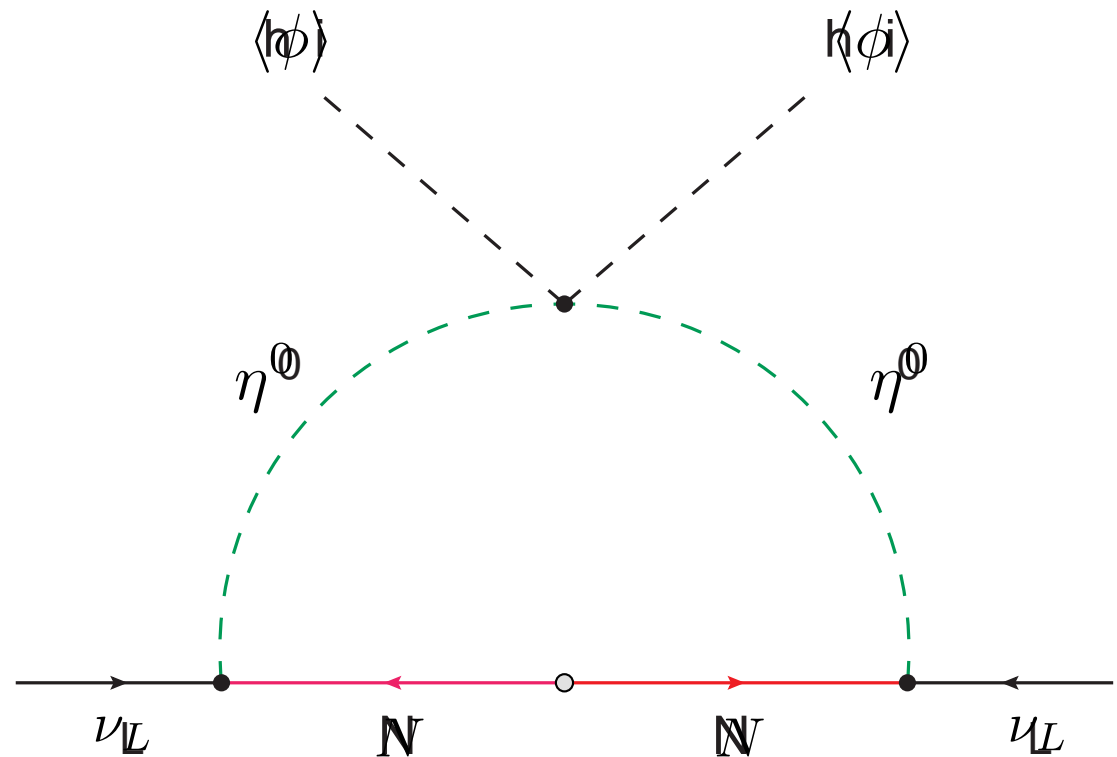


Additional
loop suppression

Dark particles in
the loop

[Other variations in
Restrepo et al, 2013]

1-loop neutrino masses:



Radiative neutrino masses

[Ernest Ma, 2006]

[See also Merle, Platscher, 2015]

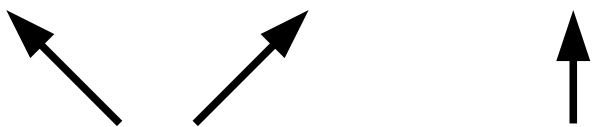
$$m_\nu = y^T \Lambda y$$

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

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

Modified
Casas-Ibarra parameterization
[Toma, Vicente, 2013]

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



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