Computer tools in particle physics

- Lecture 1 : SARAH and SPheno -

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SARAH

SARAH [Staub]

- **Name of the tool:** `SARAH`
- **Author:** Florian Staub (florian.staub@cern.ch)
- **Type of code:** `Mathematica` package
- **Website:** http://sarah.hepforge.org/

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 <u>other codes</u>

↑

Crucial for this course!

Picture taken in Valencia (Spain)

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!

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

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

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

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

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

Radiative neutrino masses

[Ernest Ma, 2006]

Tree-level:
Forbidden by the Z_2 symmetry

Radiative generation of neutrino masses

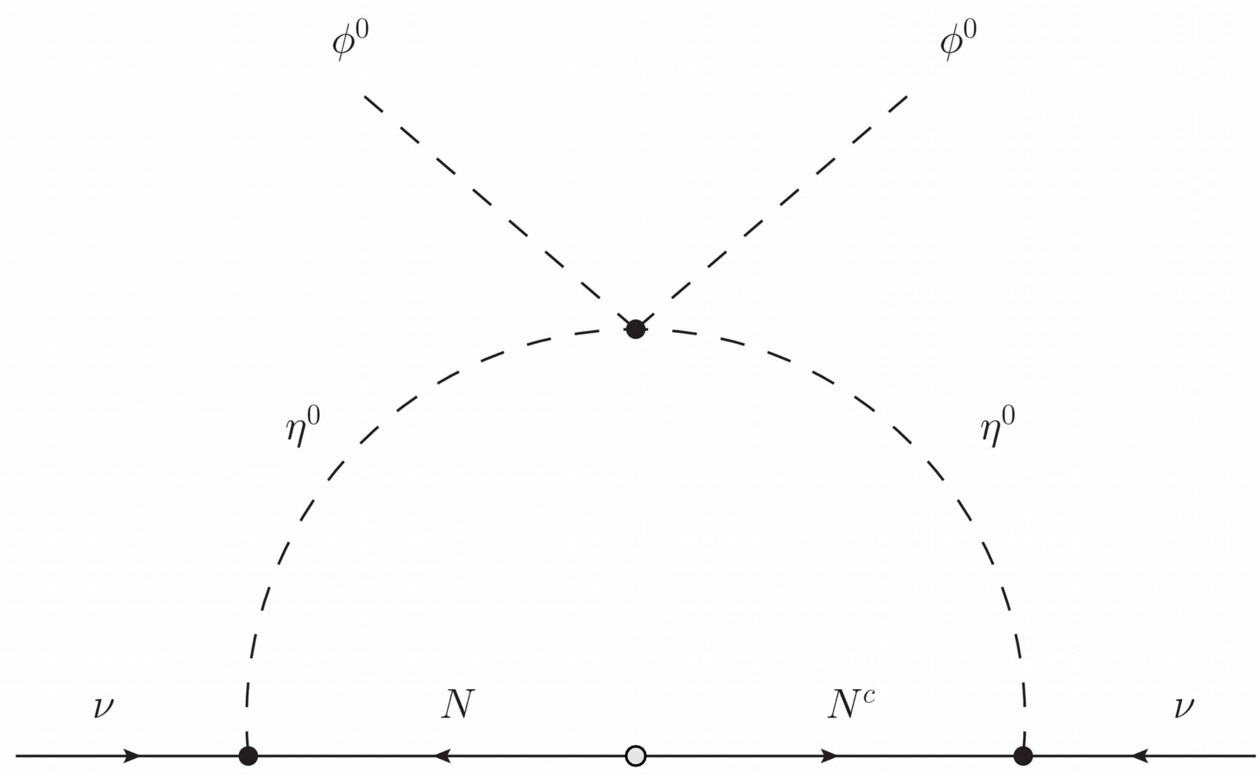
↓

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?

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 η scalar, η_R or η_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

```
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

$$q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

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

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

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.

Mass matrices

- Right-handed neutrinos

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

$$\begin{pmatrix} -\left(M_N\right)_{11} & -\left(M_N\right)_{12} & -\left(M_N\right)_{13} \\ -\left(M_N\right)_{12} & -\left(M_N\right)_{22} & -\left(M_N\right)_{23} \\ -\left(M_N\right)_{13} & -\left(M_N\right)_{23} & -\left(M_N\right)_{33} \end{pmatrix}$$

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

Vertices

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

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

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

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

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

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

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

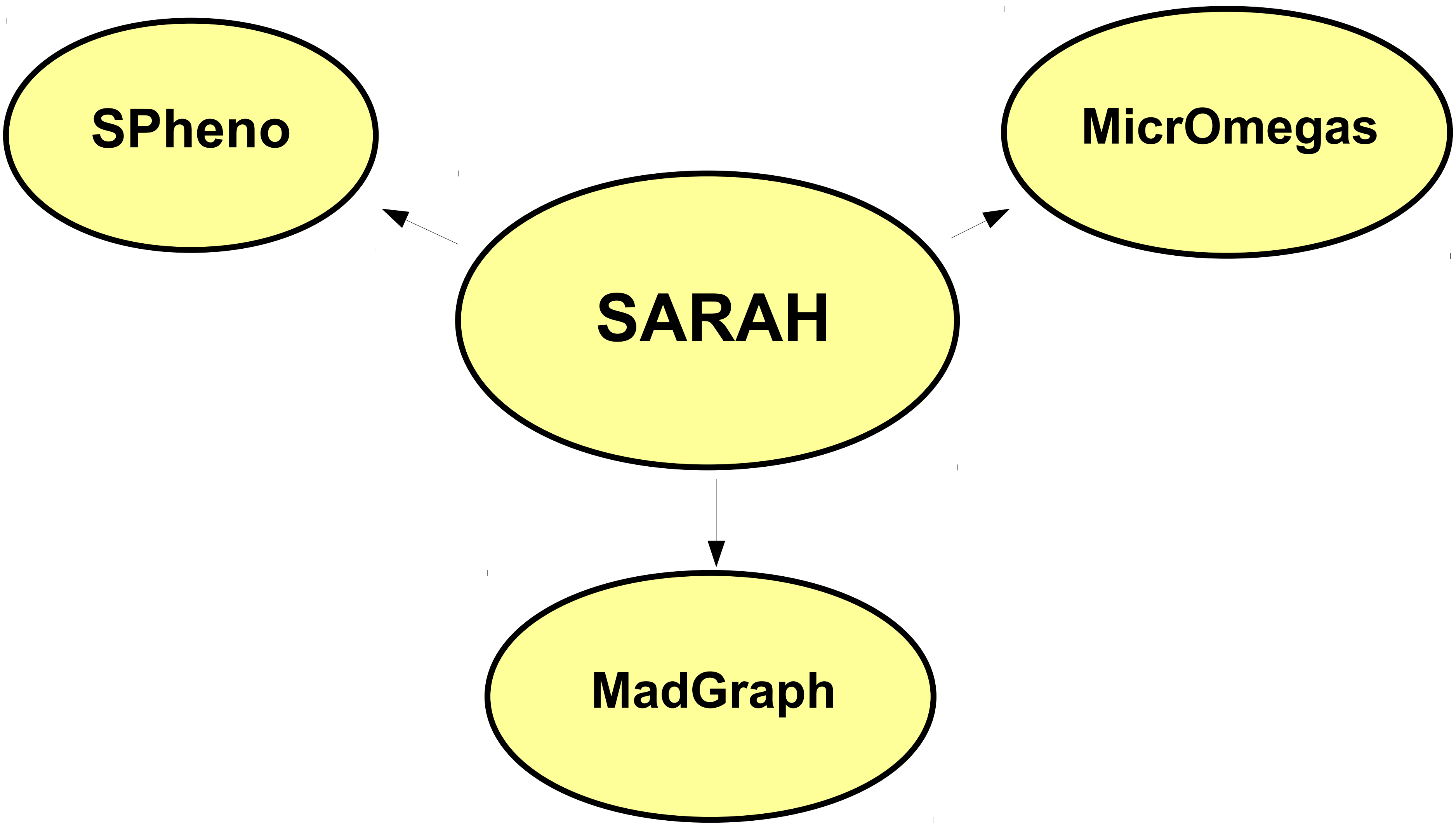
Renormalization group equations

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

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

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

SARAH: Input for other codes



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	→	SPheno
Analytics		Numerics

http://spheno.hepforge.org/

Scotogenic: benchmark point

BS1 benchmark point

$$\lambda_1 = 0.26 \qquad \lambda_2 = 0.5 \qquad \lambda_3 = 0.5$$

$$\lambda_4 = -0.5 \qquad \lambda_5 = 8 \cdot 10^{-11} \qquad m_\eta^2 = 1.85 \cdot 10^5 \, \mathrm{GeV}^2$$

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

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

Backup

Radiative neutrino masses

[Ernest Ma, 2006]

[See also Merle, Platscher, 2015]

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

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

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

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

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

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