THDM + CS in SARAH[1]

PROGRESS REPORT

[1]https://sarah.hepforge.org/

First step: N2HDM [1612.01309]

- THDM + RS Potential:

$$
\begin{aligned}
V &= m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\
&+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.] \\
&+\frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2 \,.
\end{aligned}
$$

- Z_2 Symmetries:

$$\Phi_1 \to \Phi_1\,, \quad \Phi_2 \to -\Phi_2\,, \quad \Phi_S \to \Phi_S$$

$$\Phi_1 \to \Phi_1\,, \quad \Phi_2 \to \Phi_2\,, \quad \Phi_S \to -\Phi_S$$

Implementation in SARAH

- Lagrangian:

```
LagNoHC = -(M112 conj[H1].H1 + M222 conj[H2].H2 + Lambda1/2 conj[H1].H1.conj[H1].H1 + \
      Lambda2/2 conj[H2].H2.conj[H2].H2 + Lambda3 conj[H1].H1.conj[H2].H2 + Lambda4 conj[H1].H2.conj[H2].H1 + \
      MS2/2 S.S + Lambda6/8 S.S.S.S + Lambda7/2 conj[H1].H1.S.S + Lambda8/2 conj[H2].H2.S.S);

LagHC = - (M12 conj[H1].H2 + Lambda5/2 conj[H1].H2.conj[H1].H2) ;
LagYuk =        -(- Yd conj[H1].d.q - Ye conj[H1].e.l + Yu H2.u.q) ;
```

- VEVs:

```
DEFINITION[EWSB][VEVs]=
{    {H10, {v1, 1/Sqrt[2]}, {sigma1, I/Sqrt[2]},{phi1, 1/Sqrt[2]}},
     {H20, {v2, 1/Sqrt[2]}, {sigma2, I/Sqrt[2]},{phi2, 1/Sqrt[2]}},
     {sR,  {vS, 1}, {sigmaS, I},{phiS, 1}}     };
```

Output (outline)

- Matrix Elements:

$$m_h^2 = \begin{pmatrix} m_{\phi_1\phi_1} & m_{\phi_2\phi_1} & \lambda_7 v_1 v_S \\ m_{\phi_1\phi_2} & m_{\phi_2\phi_2} & \lambda_8 v_2 v_S \\ \lambda_7 v_1 v_S & \lambda_8 v_2 v_S & m_{\phi_S\phi_S} \end{pmatrix}$$

$$m_{\phi_1\phi_1} = \frac{1}{2}\Big(3\lambda_1 v_1^2 + \lambda_7 v_S^2 + v_2^2\Big(\lambda_3 + \lambda_4 + \Re\Big(\lambda_5\Big)\Big)\Big) + m_1^2$$

$$m_{\phi_1\phi_2} = \frac{1}{2} v_1 v_2 \Big(2\Big(\lambda_3 + \lambda_4\Big) + 2\Re\Big(\lambda_5\Big)\Big) + \Re\Big(m_{12}\Big)$$

$$m_{\phi_2\phi_2} = \frac{1}{2}\Big(3\lambda_2 v_2^2 + \lambda_8 v_S^2 + v_1^2\Big(\lambda_3 + \lambda_4 + \Re\Big(\lambda_5\Big)\Big)\Big) + m_2^2$$

$$m_{\phi_S\phi_S} = \frac{1}{2}\Big(3\lambda_6 v_S^2 + \lambda_7 v_1^2 + \lambda_8 v_2^2\Big) + m_S^2$$

Matrix Elements

- Using from minimization conditions:

$$\frac{v_2}{v_1}m_{12}^2 - m_{11}^2 = \frac{1}{2}(v_1^2\lambda_1 + v_2^2\lambda_{345} + v_S^2\lambda_7)$$
$$\frac{v_1}{v_2}m_{12}^2 - m_{22}^2 = \frac{1}{2}(v_1^2\lambda_{345} + v_2^2\lambda_2 + v_S^2\lambda_8)$$
$$-m_S^2 = \frac{1}{2}(v_1^2\lambda_7 + v_2^2\lambda_8 + v_S^2\lambda_6)$$

- And:

$$v^2 = v_1^2 + v_2^2$$
$$t_\beta = \frac{v_2}{v_1}$$
$$\lambda_{345} \equiv \lambda_3 + \lambda_4 + \lambda_5$$

Matrix Elements

- One obtains:

$$M^2_{\text{scalar}} = \begin{pmatrix} \lambda_1 c_\beta^2 v^2 + t_\beta m_{12}^2 & \lambda_{345} c_\beta s_\beta v^2 - m_{12}^2 & \lambda_7 c_\beta v v_S \\ \lambda_{345} c_\beta s_\beta v^2 - m_{12}^2 & \lambda_2 s_\beta^2 v^2 + m_{12}^2 / t_\beta & \lambda_8 s_\beta v v_S \\ \lambda_7 c_\beta v v_S & \lambda_8 s_\beta v v_S & \lambda_6 v_S^2 \end{pmatrix}$$

THDM + CS

- Inspiration and template from Baum and Shah [1808.02667]

$$
\begin{aligned}
V_{2\mathrm{HDM}} = {} & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left(m_{12}^2 \Phi_1^\dagger \Phi_2 + \mathrm{h.c.} \right) \\
& + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2 \right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) \\
& + \left[\frac{\lambda_5}{2} \left(\Phi_1^\dagger \Phi_2 \right)^2 + \lambda_6 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_1^\dagger \Phi_2 \right) + \lambda_7 \left(\Phi_2^\dagger \Phi_2 \right) \left(\Phi_1^\dagger \Phi_2 \right) + \mathrm{h.c.} \right]
\end{aligned}
$$

$$
\mathcal{L}_{\mathrm{Yuk}} = -Y_u \bar{Q} \cdot \Phi_1 u_R - Y_d \bar{Q} \cdot \widetilde{\Phi}_2 d_R - Y_e \bar{L} \cdot \widetilde{\Phi}_2 e_R
$$

THDM + CS

- Most general Singlet terms:

$$
\begin{aligned}
V_S = & (\xi S + \text{h.c.}) + m_S^2 S^\dagger S + \left(\frac{m_S'^2}{2} S^2 + \text{h.c.}\right) \\
& + \left(\frac{\mu_{S1}}{6} S^3 + \text{h.c.}\right) + \left(\frac{\mu_{S2}}{2} S S^\dagger S + \text{h.c.}\right) \\
& + \left(\frac{\lambda_1''}{24} S^4 + \text{h.c.}\right) + \left(\frac{\lambda_2''}{6} S^2 S^\dagger S + \text{h.c.}\right) + \frac{\lambda_3''}{4}\left(S^\dagger S\right)^2 \\
& + \left[S\left(\mu_{11}\Phi_1^\dagger\Phi_1 + \mu_{22}\Phi_2^\dagger\Phi_2 + \mu_{12}\Phi_1^\dagger\Phi_2 + \mu_{21}\Phi_2^\dagger\Phi_1\right) + \text{h.c.}\right] \\
& + S^\dagger S\left[\lambda_1'\Phi_1^\dagger\Phi_1 + \lambda_2'\Phi_2^\dagger\Phi_2 + \left(\lambda_3'\Phi_1^\dagger\Phi_2 + \text{h.c.}\right)\right] \\
& + \left[S^2\left(\lambda_4'\Phi_1^\dagger\Phi_1 + \lambda_5'\Phi_2^\dagger\Phi_2 + \lambda_6'\Phi_1^\dagger\Phi_2 + \lambda_7'\Phi_2^\dagger\Phi_1\right) + \text{h.c.}\right].
\end{aligned}
$$

Mapping to NMSSM [1808.02667]

- Use mapping to NMSSM for Z_3-violating parameters and check

2HDM+S	m_{11}^2	m_{22}^2	m_{12}^2	M^4			
NMSSM	$m_{H_u}^2 + \mu^2$	$m_{H_d}^2 + \mu^2$	$m_3^2 - \lambda\xi_F$	ξ_F^2			
2HDM+S	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7
NMSSM	$\frac{g_1^2+g_2^2}{4}$	$\frac{g_1^2+g_2^2}{4}$	$-\frac{g_1^2-g_2^2}{4}$	$\lambda^2 - \frac{g_2^2}{2}$	0	0	0
2HDM+S	ξ	m_S^2	$m_S'^2$				
NMSSM	$\xi_S + \xi_F\mu'$	$m_S^2 + \mu'^2$	$m_S'^2 + 2\kappa\xi_F$				
2HDM+S	μ_{S1}	μ_{S2}	μ_{11}	μ_{22}	μ_{12}	μ_{21}	
NMSSM	$2\kappa A_\kappa$	$2\kappa\mu'$	$\lambda\mu$	$\lambda\mu$	$-\lambda\mu'$	$-\lambda A_\lambda$	
2HDM+S	λ_1''	λ_2''	λ_3''				
NMSSM	0	0	$4\kappa^2$				
2HDM+S	λ_1'	λ_2'	λ_3'	λ_4'	λ_5'	λ_6'	λ_7'
NMSSM	λ^2	λ^2	0	0	0	$-\kappa\lambda$	0

Z_3-Symmetry:

$$e^{\frac{2\pi i n}{3}}$$

$$\mu = \mu' = m_3^2 = m_S'^2 = \xi_F = \xi_S = 0$$

THDM + CS with Z_2- and Z_3 -Symmetry

```
LagNoHC = -(M112 conj[H1].H1 + M222 conj[H2].H2 + Lambda1/2 conj[H1].H1.conj[H1].H1 + \
        Lambda2/2 conj[H2].H2.conj[H2].H2 + Lambda3 conj[H2].H2.conj[H1].H1 + Lambda4 conj[H2].H1.conj[H1].H2 + \
        MS2 conj[S].S + Lambda3pp/4 conj[S].S.conj[S].S + Lambda1p conj[S].S.conj[H1].H1 + Lambda2p conj[S].S.conj[H2].H2);

LagHC = -(M12 conj[H1].H2 + Lambda5/2 conj[H2].H1.conj[H2].H1 + MUS1/6 S.S.S + MU21 S.conj[H2].H1);

LagYuk = -(Yd conj[H1].d.q + Ye conj[H1].e.l + Yu H2.u.q);
```

Matrix Elements

$$m_h^2 = \begin{pmatrix} m_{\phi_1\phi_1} & m_{\phi_2\phi_1} & \frac{1}{\sqrt{2}} v_2 \Re\left(\mu_{21}\right) + \lambda_1' v_1 v_S \\ m_{\phi_1\phi_2} & m_{\phi_2\phi_2} & \frac{1}{\sqrt{2}} v_1 \Re\left(\mu_{21}\right) + \lambda_2' v_2 v_S \\ \frac{1}{\sqrt{2}} v_2 \Re\left(\mu_{21}\right) + \lambda_1' v_1 v_S & \frac{1}{\sqrt{2}} v_1 \Re\left(\mu_{21}\right) + \lambda_2' v_2 v_S & m_{\phi_S\phi_S} \end{pmatrix}$$

$$m_{\phi_1\phi_1} = \frac{1}{2}\left(3\lambda_1 v_1^2 + \lambda_1' v_S^2 + v_2^2\left(\lambda_3 + \lambda_4 + \Re\left(\lambda_5\right)\right)\right) + m_{11}^2$$

$$m_{\phi_1\phi_2} = \frac{1}{4}\left(2\sqrt{2} v_S \Re\left(\mu_{21}\right) + 2 v_1 v_2 \left(2\left(\lambda_3 + \lambda_4\right) + 2\Re\left(\lambda_5\right)\right) - 4\Re\left(m_{12}\right)\right)$$

$$m_{\phi_2\phi_2} = \frac{1}{2}\left(3\lambda_2 v_2^2 + \lambda_2' v_S^2 + v_1^2\left(\lambda_3 + \lambda_4 + \Re\left(\lambda_5\right)\right)\right) + m_{22}^2$$

$$m_{\phi_S\phi_S} = \frac{1}{4}\left(2\left(\lambda_1' v_1^2 + \lambda_2' v_2^2 + \sqrt{2} v_S \Re\left(\mu_{S1}\right)\right) + 3\lambda_3'' v_S^2\right) + m_S^2$$

Consistency Checks

- Check limit to THDM by decoupling/ turning-off mixing of Singlet with Higss doublets and generate spectra in Spheno ✓
- Make Singlet mass heavy ✓
- Check N2HDM with SARAH model or scanners

SPheno.m

- Uses slha in- and output
- Allows Matching Conditions / parametrization
- Allows to pick parameters to solve Tadpoles

```
MINPAR={{1,Lambda1Input},
        {2,Lambda2Input},
        {3,Lambda3Input},
        {4,Lambda4Input},
        {5,Lambda5Input},
        {6,Lambda1pInput},
        {7,Lambda2pInput},
        {8,Lambda3ppInput},
        {9,MUS1Input},
        {10,MU21Input},
        {11,M12Input},
        {12,vsInput},
        {13,TanBeta} };
```

```
ParametersToSolveTadpoles = {M112,M222,MS2};
```

SPheno[1]

- S(upersymmetric) Pheno(menology)
- Calculates SUSY spectra with low energy data and a high scale model as input
- Calculates cross sections for e^+e^- annihilation
- Creates output usable by Madgraph, etc.

[1] https://spheno.hepforge.org/

SPheno

- Already calculated first test spectra with SPheno

```
Block MASS  # Mass spectrum
#   PDG code      mass          particle
        25     1.32902589E+02  # hh_1
        35     1.84977312E+02  # hh_2
        45     3.10808293E+02  # hh_3
        36     1.45572383E+02  # Ah_2
        46     2.63229795E+02  # Ah_3
        37     2.63109903E+02  # Hm_2
        23     9.11887000E+01  # VZ
        24     8.03497269E+01  # VWm
         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
```

```
Block SCALARMIX Q=  1.73500000E+02  # ()
  1  1    -8.30581672E-02   # ZH(1,1)
  1  2    -9.57378431E-01   # ZH(1,2)
  1  3     2.76636731E-01   # ZH(1,3)
  2  1    -4.26300641E-02   # ZH(2,1)
  2  2    -2.73928389E-01   # ZH(2,2)
  2  3    -9.60804827E-01   # ZH(2,3)
  3  1    -9.95632472E-01   # ZH(3,1)
  3  2     9.15957295E-02   # ZH(3,2)
  3  3     1.80611139E-02   # ZH(3,3)
Block PSEUDOSCALARMIX Q=  1.73500000E+02  # ()
  1  1     1.96116135E-01   # ZA(1,1)
  1  2     9.80580676E-01   # ZA(1,2)
  1  3     4.13463131E-17   # ZA(1,3)
  2  1     3.55177340E-02   # ZA(2,1)
  2  2    -7.10354680E-03   # ZA(2,2)
  2  3    -9.99343800E-01   # ZA(2,3)
  3  1    -9.79937218E-01   # ZA(3,1)
  3  2     1.95987444E-01   # ZA(3,2)
  3  3    -3.62211238E-02   # ZA(3,3)
```

Next-up

- Implementation of actual complex parameters
- Finding intial parameter space
- Phenomenological analysis with Spheno
- Check limit to N2HDM
- Scanners?