2HDMC – a calculator for two Higgs doublet models

Johan Rathsman, Lund University

BSM^{2}2022, Averiro, 2022-10-11

1. General two Higgs doublet models (2HDM)
2. Theoretical constraints
3. Yukawa sector
4. Experimental constraints
5. Usage/setting parameters/input-output

Executive summary

- General two Higgs Doublet Models – no CP-violation (yet)
- Choice of parameterisations of potential
- Tree-level Higgs masses
- Arbitrary Yukawa sector or Z_2- "types"
- Yukawa couplings with running quark masses
- Theoretical constraints (positivity, unitarity, perturbativity)
- Electroweak precision tests - oblique parameters, muon $g-2$
- mass-constraints from searches (HiggsBounds) and observed Higgs (HiggsSignals)
- Partial widths for two-body Higgs decays and non-standard top decays
- Les Houches style input/output
- Madgraph/MadEvent model

D. Eriksson, JR and O. Stål, Comp. Phys. Comm. **181** (2010) 189; 833

`https://2hdmc.hepforge.org`

General two Higgs doublet models (2HDM)

Why 2HDM?

- Simplest non-trivial extension of the SM Higgs sector
- Realized in the MSSM (and sometimes effectively in extensions of the MSSM)
- Interesting phenomenology:
  - non-minimal flavour violation (non-MFV)
  - flavour changing neutral currents (FCNC)
  - new charged current
  - dark matter candidates (inert doublet model)
  - CP-violation (explicit or spontaneous)

General two Higgs doublet model potential

- Two complex $SU(2)_L$ doublets with hypercharge Y=1: Φ_1 ,Φ_2
- Invariance under global $SU(2)$: $\Phi_a \to U_{ab}\Phi_b$

General potential

$$\begin{aligned}\mathcal{V} = & m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - \left[m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}\right] + \frac{1}{2}\lambda_1\left(\Phi_1^\dagger\Phi_1\right)^2 \\ & + \frac{1}{2}\lambda_2\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) \\ & + \left\{\frac{1}{2}\lambda_5\left(\Phi_1^\dagger\Phi_2\right)^2 + \left[\lambda_6\left(\Phi_1^\dagger\Phi_1\right) + \lambda_7\left(\Phi_2^\dagger\Phi_2\right)\right]\left(\Phi_1^\dagger\Phi_2\right) + \mathrm{h.c.}\right\}\end{aligned}$$

- Potential real $\Rightarrow$ m_{11}^2, m_{22}^2, λ_{1-4} real m_{12}^2, λ_{5-7} complex
- m_{12}^2, λ_{5-7} real $\Rightarrow$ no explicit CP-violation

Electroweak symmetry breaking

- EW symmetry broken by non-zero vev of Φ_1 and/or Φ_2
- Minimization conditions $\Rightarrow m_{11}^2,\ m_{22}^2$ traded for $v_1 = v\cos\beta$, $v_2 = ve^{i\xi}\sin\beta$ with $v = (\sqrt{2}G_F)^{-1/2} \approx 246$ GeV
- No spontaneous CP-violation $\Rightarrow \xi = 0$

$$\Phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}\left(G^+\cos\beta - H^+\sin\beta\right) \\ v\cos\beta - h\sin\alpha + H\cos\alpha + \mathrm{i}\left(G^0\cos\beta - A\sin\beta\right) \end{pmatrix}$$

$$\Phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}\left(G^+\sin\beta + H^+\cos\beta\right) \\ v\sin\beta + h\cos\alpha + H\sin\alpha + \mathrm{i}\left(G^0\sin\beta + A\cos\beta\right) \end{pmatrix}$$

- Three Goldstone bosons: $G^\pm$, $G^0 \Rightarrow$ masses to W and Z
- Five Higgs boson states: two CP-even, h, H with mixing angle α, one CP-odd A, and two charged $H^\pm$
- $\tan\beta$ defines basis in Φ space (Higgs basis: $\tan\beta = 0$)
- Higgs-gauge couplings from basis-invariant $s_{\beta-\alpha} \equiv \sin(\beta-\alpha)$
- Parameterisations of potential: $\{m_{12}^2,\ \lambda_{1-7},\ \tan\beta\}$ or $\{m_{12}^2,\ m_h,\ m_H,\ m_A,\ m_{H^\pm},\ s_{\beta-\alpha},\ \lambda_{6-7},\ \tan\beta\}$ or ...

Possible additional symmetries

Exact $U(1)_{PQ}$ symmetry

Demanding that the potential has additional $U(1)_{PQ}$ symmetry $\Rightarrow m_{12}^2 = 0$, $\lambda_{5-7} = 0$
(spontaneous breaking gives one more Goldstone boson which after explicit breaking by instanton effects could have given the axion solution to the strong CP-problem)

Exact Z_2 symmetry

Demanding that the potential is symmetric under $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2 \Rightarrow m_{12}^2 = 0$, $\lambda_{6-7} = 0$

Supersymmetry

Supersymmetry at tree-level $\Rightarrow$

$$\lambda_1 = \lambda_2 = \frac{g^2 + g'^2}{4}, \qquad \lambda_3 = \frac{g^2 - g'^2}{4}, \qquad \lambda_4 = -\frac{g^2}{2},$$
$$\lambda_5 = \lambda_6 = \lambda_7 = 0, \qquad m_{12}^2 = m_A^2 \cos\beta \sin\beta.$$

Theoretical constraints

Positivity of potential

Demanding that the potential is bounded from below $\Rightarrow$

$$\lambda_1 > 0, \qquad \lambda_2 > 0, \qquad \lambda_3 > -\sqrt{\lambda_1\lambda_2}$$

If $\lambda_6 = \lambda_7 = 0$: $\lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1\lambda_2}$

If $\lambda_6, \lambda_7 \neq 0$: $\lambda_3 + \lambda_4 - \lambda_5 > -\sqrt{\lambda_1\lambda_2}$
and more complicated constraints

Perturbativity

Cross-section for $2 \to 2$ Higgs scattering processes $\propto \dfrac{\lambda_{HHHH}^2}{16\pi^2}$
$\Rightarrow$ the quartic Higgs couplings λ_{HHHH} cannot be too large for the perturbative series to make sense

Tree-level unitarity

requiring tree-level unitarity for HH and HV_L scattering $\Rightarrow$ limits eigenvalues of scattering (S) matrices

$$16\pi S_{(2,1)} = \begin{pmatrix} \lambda_1 & \lambda_5 & \sqrt{2}\lambda_6 \\ \lambda_5 & \lambda_2 & \sqrt{2}\lambda_7 \\ \sqrt{2}\lambda_6 & \sqrt{2}\lambda_7 & \lambda_3+\lambda_4 \end{pmatrix}$$

$$16\pi S_{(2,0)} = \lambda_3 - \lambda_4$$

$$16\pi S_{(0,1)} = \begin{pmatrix} \lambda_1 & \lambda_4 & \lambda_6 & \lambda_6 \\ \lambda_4 & \lambda_2 & \lambda_7 & \lambda_7 \\ \lambda_6 & \lambda_7 & \lambda_3 & \lambda_5 \\ \lambda_6 & \lambda_7 & \lambda_5 & \lambda_3 \end{pmatrix}$$

$$16\pi S_{(0,0)} = \begin{pmatrix} 3\lambda_1 & 2\lambda_3+\lambda_4 & 3\lambda_6 & 3\lambda_6 \\ 2\lambda_3+\lambda_4 & 3\lambda_2 & 3\lambda_7 & 3\lambda_7 \\ 3\lambda_6 & 3\lambda_7 & \lambda_3+2\lambda_4 & 3\lambda_5 \\ 3\lambda_6 & 3\lambda_7 & 3\lambda_5 & \lambda_3+2\lambda_4 \end{pmatrix}$$

Yukawa sector

General Yukawa couplings for SM fermions with mass eigenstates in flavour vectors D, U, L and ν (neutrinos massless)

$$
\begin{aligned}
-\mathcal{L}_{\mathrm{Y}} =& \overline{D}\frac{\kappa^D s_{\beta-\alpha} + \rho^D c_{\beta-\alpha}}{\sqrt{2}} Dh + \overline{D}\frac{\kappa^D c_{\beta-\alpha} - \rho^D s_{\beta-\alpha}}{\sqrt{2}} DH + \mathrm{i}\overline{D}\gamma_5\frac{\rho^D}{\sqrt{2}} DA \\
&+ \overline{U}\frac{\kappa^U s_{\beta-\alpha} + \rho^U c_{\beta-\alpha}}{\sqrt{2}} Uh + \overline{U}\frac{\kappa^U c_{\beta-\alpha} - \rho^U s_{\beta-\alpha}}{\sqrt{2}} UH - \mathrm{i}\overline{U}\gamma_5\frac{\rho^U}{\sqrt{2}} UA \\
&+ \overline{L}\frac{\kappa^L s_{\beta-\alpha} + \rho^L c_{\beta-\alpha}}{\sqrt{2}} Lh + \overline{L}\frac{\kappa^L c_{\beta-\alpha} - \rho^L s_{\beta-\alpha}}{\sqrt{2}} LH + \mathrm{i}\overline{L}\gamma_5\frac{\rho^L}{\sqrt{2}} LA \\
&+ \left[\overline{U}\left\{V_{\mathrm{CKM}}\rho^D P_R - \rho^U V_{\mathrm{CKM}} P_L\right\} DH^+ + \overline{\nu}\rho^L P_R L H^+ + \mathrm{h.c.}\right]
\end{aligned}
$$

- κ^F and ρ^F 3×3 matrices: $\kappa^F \equiv \sqrt{2}\frac{M^F}{v}$, ρ^F free
- $P_{R/L} = (1 \pm \gamma_5)/2$
- Non-diagonal $\rho \Rightarrow$ non-MFV CC and FCNC
- Avoided (Glashow & Weinberg) by imposing Z_2 symmetry on Φ_1, Φ_2 and U_R, D_R, L_R such that each fermion type only couples to one Higgs doublet
  $\Rightarrow \rho^F = \kappa^F \cot\beta$ or $\rho^F = -\kappa^F \tan\beta$

Four different types of 2HDM

	Type			
	I	II	III	IV
ρ^D	$\kappa^D \cot\beta$	$-\kappa^D \tan\beta$	$-\kappa^D \tan\beta$	$\kappa^D \cot\beta$
ρ^U	$\kappa^U \cot\beta$	$\kappa^U \cot\beta$	$\kappa^U \cot\beta$	$\kappa^U \cot\beta$
ρ^L	$\kappa^L \cot\beta$	$-\kappa^L \tan\beta$	$\kappa^L \cot\beta$	$-\kappa^L \tan\beta$

- $\tan\beta$ promoted to physical parameter
- $\lambda_6, \lambda_7 \neq 0$ gives hard Z_2 violation
- $m_{12}^2 \neq 0$ gives soft Z_2 violation

Partial decay widths in 2HDMC

- $\mathcal{H} \to ff'$ with optional (N)LO QCD corrections
- $\mathcal{H} \to gg$ with optional LO QCD corrections
- $\mathcal{H} \to \mathcal{H}\mathcal{H}$
- $\mathcal{H} \to \mathcal{H}V^*$ including off-shell vector bosons
- $\mathcal{H} \to VV^*$ including off-shell vector bosons
- $\mathcal{H} \to \gamma\gamma$, $\mathcal{H} \to Z\gamma$
- $t \to H^+b$ and $H^+ \to tb$ including off-shell t, W

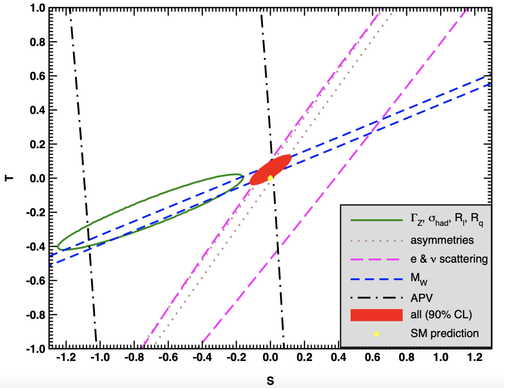
here $\mathcal{H} = \{h, H, A, H^\pm\}$, $V = \{Z, W\}$ as applicable

see also "Recommendations for evaluation of Higgs production cross sections and branching ratios at the LHC in the 2HDM", R. Harlander, M. Mühlleitner, JR, M. Spira, O. Stål [arXiv:1312.5571]

Experimental constraints

- Oblique parameters: contribution to S, T, U, V, W, X compared to SM with Higgs mass m_h^{ref}
- Muon anomalous magnetic moment: 2-loop Barr-Zee contribution
- Charged Higgs mass limits from LEP
- Additional Higgs mass and coupling limits via HiggsBounds and HiggsSignals (optional)

Example:
Combine with experimental limits on S and T with $U = 0$ from PDG [pdg.lbl.gov]



Usage/setting parameters/input-output

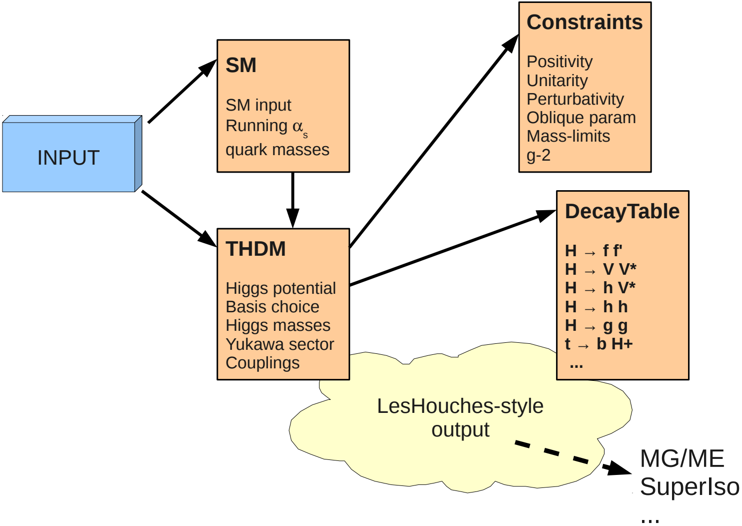
Programming features

- object oriented code (C++)
- modular structure
- “ready to compile” command line type programs
- library mode which can be called by user program

Getting started

- download code, manual, and full class documentation from `https://2hdmc.hepforge.org`
- system requirements
  - gcc compiler (preferably 9 or later)
  - GNU Scientific Library (GSL)
  - HiggsBounds (optional)
  - HiggsSignals (optional)
- adapt makefile and make
- test with `Demo`-program

Structure of 2HDMC code



rathsman — ssh herbert.thep.lu.se — 118×48

```
rathsman@herbert:~/private/div_programs/2HDMC/tmp/2HDMC-1.8.0$ ./CalcPhys 125 400 420 440 0.999 0 0 40000 3 2 outfile
****************************************************
*                                                  *
*    2HDMC - Two-Higgs-Doublet Model Calculator    *
*             http://2hdmc.hepforge.org            *
*                  Version 1.8.0                   *
*             Compiled on Oct  7 2022              *
*                                                  *
****************************************************

2HDM parameters in physical mass basis:
      m_h:    125.00000
      m_H:    400.00000
      m_A:    420.00000
     m_H+:    440.00000
 sin(b-a):      0.99900
 lambda_6:      0.00000
 lambda_7:      0.00000
    m12^2:  40000.00000
tan(beta):      3.00000

2HDM parameters in generic basis:
 lambda_1:      4.81665
 lambda_2:      0.23993
 lambda_3:      2.09923
 lambda_4:     -1.27781
 lambda_5:     -0.71038
 lambda_6:      0.00000
 lambda_7:      0.00000
    m12^2:  40000.00000
tan(beta):      3.00000

Constraints:
 Tree-level unitarity: 1
 Perturbativity:       1
 Stability:            1

Oblique parameters:
 S             -3.64026e-03
 T              1.41961e-02
 U              6.37471e-05
 V             -2.19814e-04
 W             -1.98745e-04
 X             -3.05952e-05
 Delta_rho     -3.94714e-05
 Delta_amu     -4.84754e-14

LesHouches output written to file outfile
```

rathsman — ssh herbert.thep.lu.se — 118×48

```
Decay table for h
Total width:   3.618e-03 GeV       BR
h  -> s  s     7.348e-07      2.031e-04
h  -> c  c     1.234e-04      3.411e-02
h  -> b  b     2.004e-03      5.538e-01
h  -> e  e     1.602e-11      4.429e-09
h  -> mu mu    6.851e-07      1.894e-04
h  -> ta ta    1.935e-04      5.349e-02
h  -> ga ga    8.985e-06      2.484e-03
h  -> Z  Z     1.053e-04      2.910e-02
h  -> W+ W-    8.427e-04      2.329e-01
h  -> Z  ga    6.147e-06      1.699e-03
h  -> g  g     3.328e-04      9.199e-02
---------------------------------------

Decay table for H
Total width:   5.326e-01 GeV       BR
H  -> s  s     2.247e-05      4.218e-05
H  -> c  c     2.562e-05      4.811e-05
H  -> b  b     6.338e-02      1.190e-01
H  -> t  t     3.478e-01      6.530e-01
H  -> e  e     6.342e-10      1.191e-09
H  -> mu mu    2.712e-05      5.091e-05
H  -> ta ta    7.667e-03      1.440e-02
H  -> ga ga    7.300e-06      1.371e-05
H  -> Z  Z     1.504e-02      2.824e-02
H  -> W+ W-    3.227e-02      6.060e-02
H  -> Z  ga    3.785e-06      7.107e-06
H  -> g  g     2.278e-03      4.277e-03
H  -> h  h     6.407e-02      1.203e-01
---------------------------------------

Decay table for A
Total width:   1.980e+00 GeV       BR
A  -> s  s     2.293e-05      1.158e-05
A  -> c  c     3.598e-05      1.817e-05
A  -> b  b     6.439e-02      3.252e-02
A  -> t  t     1.869e+00      9.440e-01
A  -> e  e     6.478e-10      3.272e-10
A  -> mu mu    2.770e-05      1.399e-05
A  -> ta ta    7.832e-03      3.956e-03
A  -> ga ga    2.349e-05      1.187e-05
A  -> Z  ga    6.162e-06      3.112e-06
A  -> g  g     8.170e-03      4.127e-03
A  -> Z  h     3.034e-02      1.532e-02
A  -> Z  H     1.645e-06      8.307e-07
---------------------------------------
```

Summary and outlook

Present status of 2HDMC

- general CP-conserving 2HDM with arbitrary Yukawa sector
- theoretical and experimental constraints
- object oriented program with modular structure
- specific and generic interfaces to other programs
- download from `https://2hdmc.hepforge.org`

Future possibilities

- renormalisation group evolution of parameters - integration with 2HDME
- CP-violation
- additional Higgs singlets (triplets)
- composite Higgs particles and vector like fermions
- integration to HiggsTools for latest exp results
- streamline installation