2HDMC – a calculator for two Higgs doublet models

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TOOLS2010, Winchester, 2010-07-02

Executive summary

- General two Higgs Doublet Models – no CP-violation (yet)
- Choice of parameterisations of potential
- Tree-level Higgs masses
- Arbitrary Yukawa sector or “types”
- Yukawa coupling with running quark masses
- Theoretical constraints (positivity, unitarity, perturbativity)
- Electroweak precision tests - oblique parameters, muon $g-2$
- mass-limits (optionally from HiggsBounds, NMSSMTools)
- Flavour observables from SuperIso
- 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

`http://www.isv.uu.se/thep/MC/2HDMC`

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
  - flavour changing neutral currents
  - new charged current
  - dark matter candidates
  - CP-violation

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
- No explicit CP-violation $\Rightarrow$ m_{12}^2, λ_{5-7} real

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 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 on eigenvalues of the 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 (symmetric)
- $P_{R/L} = (1 \pm \gamma_5)/2$
- 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

- $H \to ff'$ with optional (N)LO QCD corrections
- $H \to gg$ with optional LO QCD corrections
- $H \to HH$
- $H \to HV^*$ including off-shell vector bosons
- $H \to VV^*$ including off-shell vector bosons
- $H \to \gamma\gamma$
- $t \to H^+ b$

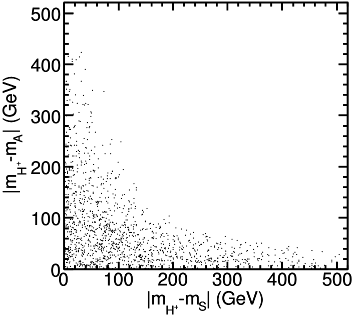
here $H = \{h, H, A, H^\pm\}$, $V = \{Z, W\}$

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: 2HDM contribution
- Charged Higgs mass limits from LEP
- Additional Higgs mass limits via HiggsBounds or NMSSMTools (optional)
- Flavour limits from SuperIso (optional)

Example:
2σ limits on Higgs mass differences from S, T, and U with $m_S^2 = m_H^2 s_{\beta-\alpha}^2 + m_h^2 c_{\beta-\alpha}^2$

F. Mahmoudi and O. Stål, Phys. Rev. D **81** (2010) 035016



Usage/setting parameters/input-output

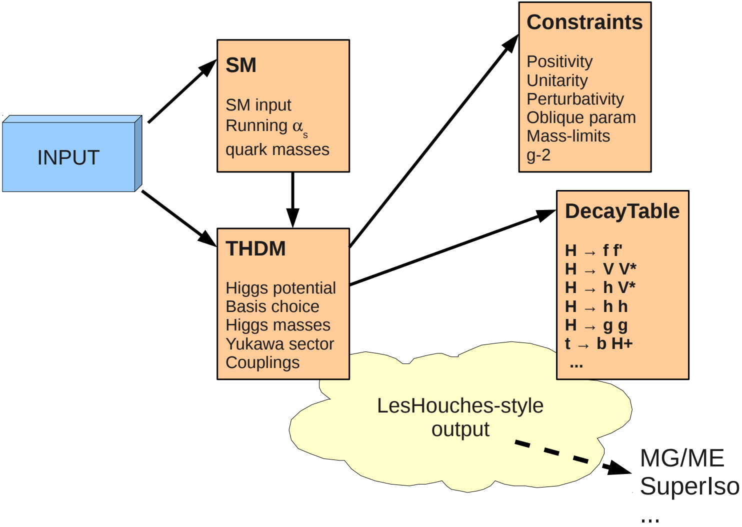
Programming features

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

Getting started

- download code, manual, and full class documentation from `http://www.isv.uu.se/thep/MC/2HDMC`
- system requirements
  - gcc compiler (3.4 and 4 tested)
  - GNU Scientific Library (GSL)
  - HiggsBounds (optional)
  - NMSSMTools (optional)
  - SuperIso (optional)
- adapt makefile and make
- test with `Demo`-program

Structure of 2HDMC code



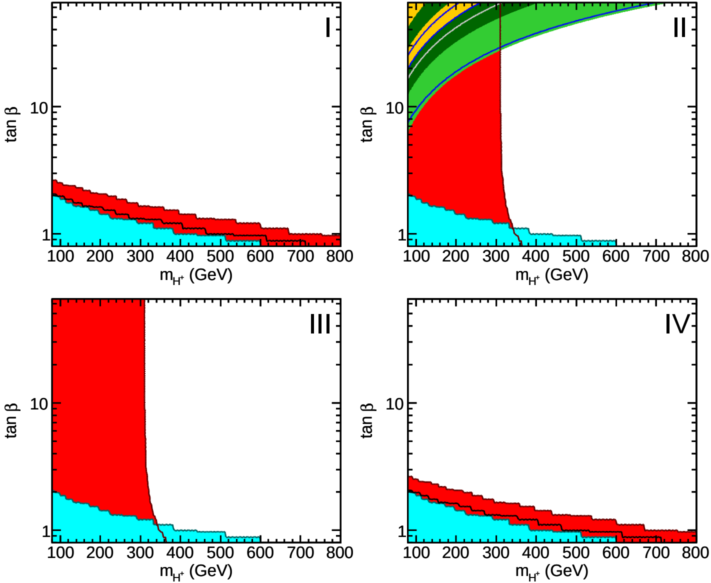
rathsman@gungner: ~/private/div_programs/2hdmc

File Edit View Terminal Help

```
rathsman@gungner:~/private/div_programs/2hdmc$ ./CalcPhys 115 250 220 300 0.5 0. 0. 5000 5 2 out_file

2HDM parameters in physical mass basis:
      m_h:    115.00000
      m_H:    250.00000
      m_A:    220.00000
     m_H+:    300.00000
 sin(b-a):      0.50000
 lambda_6:      0.00000
 lambda_7:      0.00000
    m12^2:   5000.00000
tan(beta):      5.00000

2HDM parameters in generic basis:
 lambda_1:      4.15907
 lambda_2:      0.68666
 lambda_3:      4.63597
 lambda_4:     -1.74187
 lambda_5:     -0.36949
 lambda_6:      0.00000
 lambda_7:      0.00000
    m12^2:   5000.00000
tan(beta):      5.00000

Tree-level unitarity  1
Perturbativity        1
Stability             1
Mass constraints      1
Charged Higgs         1 (HpHp:1 HpHptau:1 HpHpcs:1)
Oblique parameters:
  S                   1.86057e-02
  T                   1.56508e-01
  U                   2.80514e-03
  V                   4.16485e-03
  W                   2.39736e-03
  X                  -6.57052e-05
  Delta_rho           1.22358e-03
  Delta_amu           3.11201e-11

rathsman@gungner:~/private/div_programs/2hdmc$
```

Example: Flavour constraints on general 2HDMs

F. Mahmoudi and O. Stål, Phys. Rev. D **81** (2010) 035016

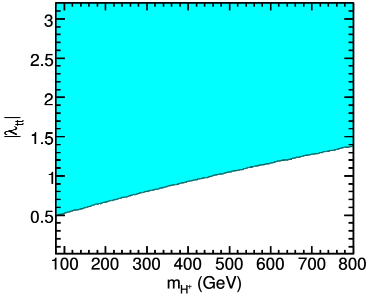


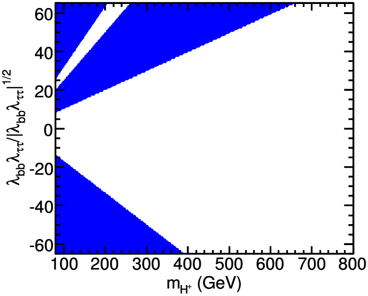
General flavour diagonal couplings

$$\rho^U = \frac{\sqrt{2}}{v} \begin{pmatrix} \lambda_{uu} m_u & 0 & 0 \\ 0 & \lambda_{cc} m_c & 0 \\ 0 & 0 & \lambda_{tt} m_t \end{pmatrix} \quad \text{etc}$$

ΔM_{B_d}:

$B_u \to \tau \nu_\tau$:





F. Mahmoudi and O. Stål, Phys. Rev. D **81** (2010) 035016

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 `http://www.isv.uu.se/thep/MC/2HDMC`

Future possibilities

- renormalisation group evolution of parameters
- CP-violation
- additional Higgs singlets (triplets)
- streamline installation

Charged Higgs 2010, Uppsala, Sweden, 27-30 September

http://www.grid.tsl.uu.se/chargedhiggs2010/