

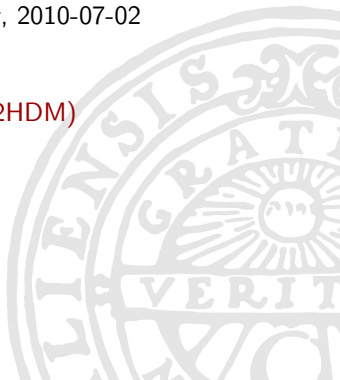


2HDMC – a calculator for two Higgs doublet models

Johan Rathsman, Uppsala University

TOOLS2010, Winchester, 2010-07-02

- 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 “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 $SU(2)$: $\Phi_a \rightarrow U_{ab}\Phi_b$

General potential

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

- Potential real $\Rightarrow m_{11}^2, m_{22}^2, \lambda_{1-4}$ real m_{12}^2, λ_{5-7} complex
- No explicit CP-violation $\Rightarrow m_{12}^2, \lambda_{5-7}$ 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 $v_1 = v \cos \beta$, $v_2 = v e^{i\xi} \sin \beta$ with $v = (\sqrt{2}G_F)^{-1/2} \approx 246$ GeV
- No spontaneous CP-violation $\Rightarrow \xi = 0$

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

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

- 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 $\Phi_1 \rightarrow \Phi_1,$
 $\Phi_2 \rightarrow -\Phi_2 \Rightarrow m_{12}^2 = 0, \lambda_{6-7} = 0$

Supersymmetry

Supersymmetry at tree-level \Rightarrow

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



Theoretical constraints

Positivity of potential

Demanding that the potential is bounded from below \Rightarrow

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

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 $2 \rightarrow 2$ Higgs scattering processes $\propto \frac{\lambda_{HHHH}^2}{16\pi^2}$
 \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)

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

- 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

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

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



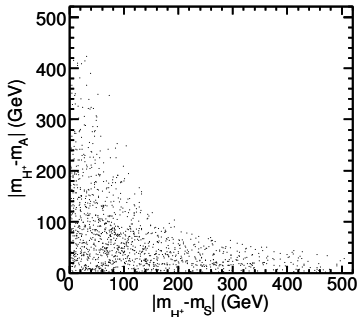
Experimental constraints

- 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

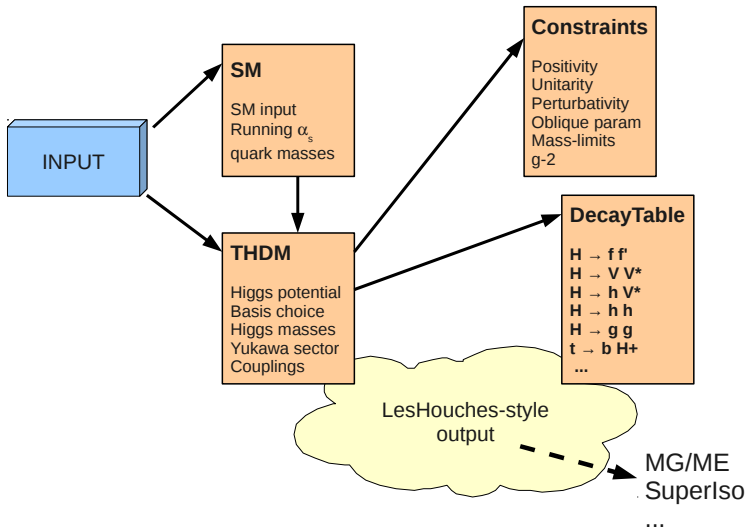
- object oriented code (C++)
- modular structure
- “ready to compile” commandline type programs
- library mode which can be called by user program

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





UPPSALA
UNIVERSITET

2HDMC

Johan Rathsmán

2HDM

TH constraints

Yukawa sector

EX constraints

Usage

Example

```
rathsmán@gungner: ~/private/div_programs/2hdmc
File Edit View Terminal Help
rathsmán@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

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



UPPSALA
UNIVERSITET

2HDMC

Johan Rathsman

2HDM

TH constraints

Yukawa sector

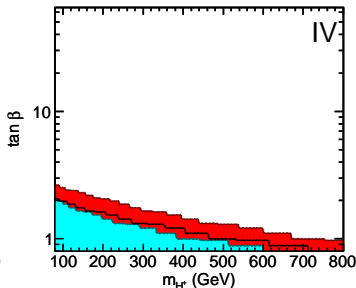
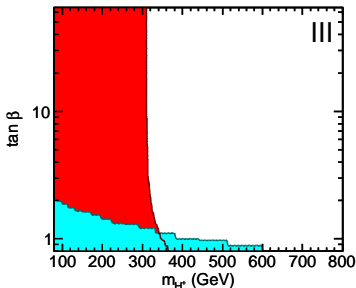
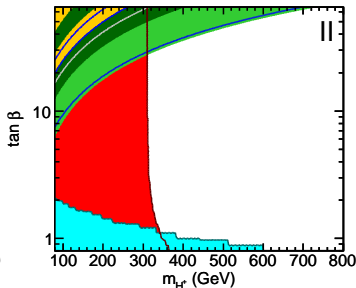
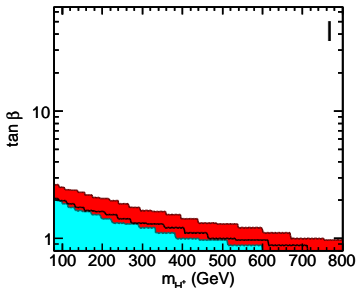
EX constraints

Usage

Example

Example: Flavour constraints on general 2HDMs

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

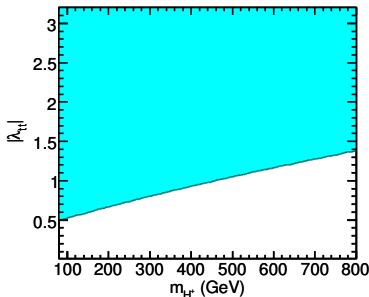




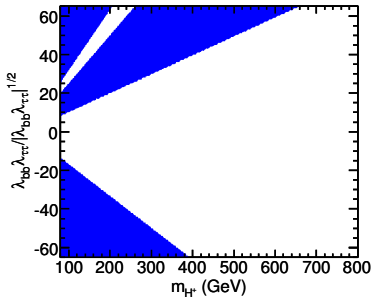
General flavour diagonal couplings

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

ΔM_{B_d} :



$B_u \rightarrow \tau \nu_\tau$:



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



UPPSALA
UNIVERSITET

2HDMC

Johan Rathsman

2HDM

TH constraints

Yukawa sector

EX constraints

Usage

Example

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

THIRD INTERNATIONAL WORKSHOP

cH[±]arged 2010

**Prospects for Charged Higgs
Discovery at Colliders**

Uppsala University, Sweden, 27-30 September 2010

International Scientific Advisory Committee:

- Wolfgang Assmann (JHU, USA)
- Olivier Breinl (University of Freiburg, Germany)
- Johann Collot (University of Grenoble, France)
- Dhiman Chakraborty (Northern Illinois University, USA)
- Sven Heinemann (University of Cantabria, Spain)
- Karl Johansson (University of Erlangen, Germany)
- Riitta Kinnunen (Finnish Institute of Physics, Finland)
- Sabine Kraml (University of Geneva, France)
- Stefano Moretti (University of Southampton, UK)
- Alexander Mikheyev (Imperial College London, UK)
- Per-Olof Nilsson-Almqvist (University of Hamburg, Germany)
- Tilman Plehn (University of Heidelberg, Germany)
- Steven Robertson (McGill University, Canada)
- Albert de Roeck (CERN, Switzerland)
- Peter Skands (CERN, Switzerland)

Local Organisation Committee:

- Camille Belanger-Champagne
- Richard Bremner, Claus Buszello
- Tord Elander (co-chair), MATEOS
- Ellert, Rikard Enberg, Ingar Ericson (secretary), Arnau Ferrarri, Gunnar Ingelman, Charlie Isaksson, Johan Rathsman (co-chair), Glenn Woouda

Topics:

- Theory and models
- Phenomenology and tools
- Analysis tools and backgrounds
- Search strategies and systematics

We welcome contributed talks

URL: www.grid.tsl.uu.se/chargedhiggs2010 **Email:** chargedhiggs2010@fysast.uu.se

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