2HDMC
Two-Higgs-Doublet Model Calculator

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Interplay of Collider and Flavour Physics
2nd general meeting
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1. 2HDM physics
2. 2HDMC code
3. Examples

Why 2HDM?

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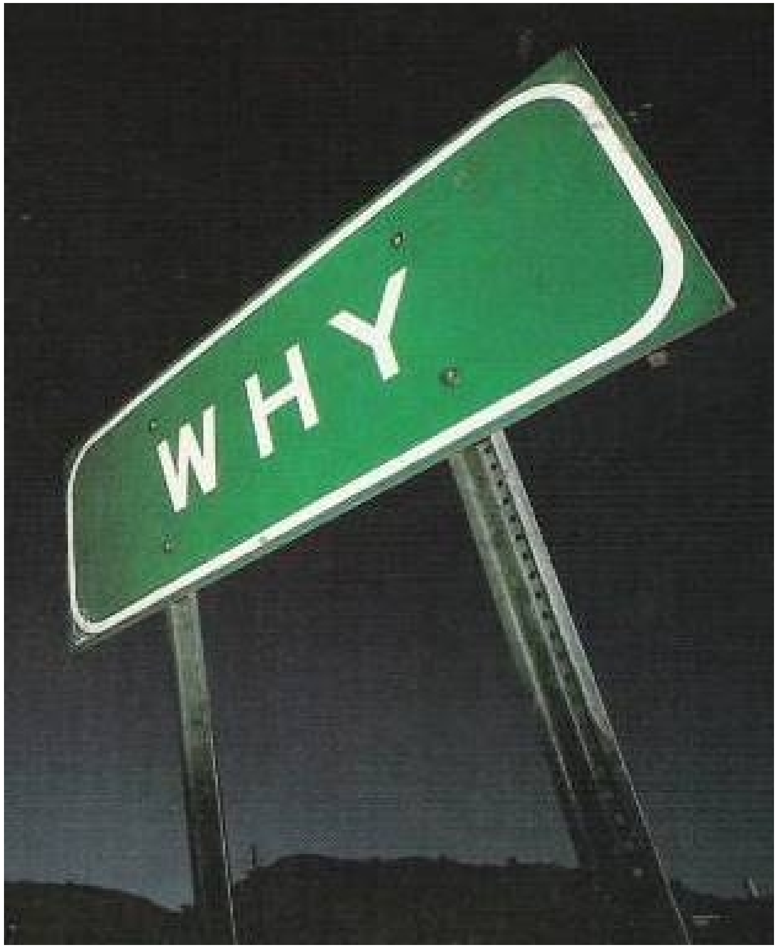
- Simplest non-trivial extension of SM Higgs sector

- Realized in the MSSM, effectively in extensions of the MSSM

- Interesting phenomenology:
  nMFV, FCNC, CP-violation, new cc, dark matter ...

  --> Flavour physics constraints
  important for 2HDM ...

  Talks by F. Mescia, T. Jones (yesterday)
  S. Heinemeyer, N. Mahmoudi (this session)



2HDM Potential

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Two complex $SU(2)_L$ doublets: Φ_1 and Φ_2 (Y=+1)

Invariance under unitary transformation: $\Phi_a \to \Phi_a' = U_{ab}\Phi_b$

General potential:

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

Explicit CP-violation from complex parameters

Tree-level MSSM: $\lambda_1 = \lambda_2 = \frac{g^2+(g')^2}{4}$ $\quad\lambda_3 = \frac{g^2-(g')^2}{4}$

$\lambda_4 = -\frac{g^2}{2}$ $\quad\lambda_5 = \lambda_6 = \lambda_7 = 0$ $\quad m_{12}^2 = m_A^2\cos\beta\sin\beta$

Theoretical constraints

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The Higgs potential must be bounded from below (positivity)
Translates into conditions on the λ_i:

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

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

$\exists$ (longer) expressions also for the case when $\lambda_6, \lambda_7 \neq 0$

Requiring tree-level unitarity for HH and HV_L scattering sets upper limits on the λ_i parameters: $\quad |\Lambda^{Z_2}_{Y\sigma}| \leq 16\pi$

with $\lambda_6 = \lambda_7 = 0$

$$\Lambda^{+}_{21\pm} = \frac{1}{2}\left(\lambda_1 + \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4|\lambda_5|^2}\right)$$

$$\Lambda^{+}_{01\pm} = \frac{1}{2}\left(\lambda_1 + \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_4^2}\right)$$

$$\Lambda^{+}_{00\pm} = \frac{1}{2}\left(3(\lambda_1 + \lambda_2) \pm \sqrt{9(\lambda_1 - \lambda_2)^2 + 4(2\lambda_3 + \lambda_4)^2}\right)$$

$$\Lambda^{-}_{00\pm} = \lambda_3 + 2\lambda_4 \pm 3|\lambda_5|$$

$$\Lambda^{-}_{01\pm} = \lambda_3 \pm |\lambda_5|$$

$$\Lambda^{-}_{20} = \lambda_3 - \lambda_4$$

$$\Lambda^{-}_{21} = \lambda_3 + \lambda_4$$

Ginzburg and Ivanov, PRD72, 115010 (2005) [hep-ph/0508020]

EW symmetry breaking

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EW symmetry broken by non-zero vev of Φ_1 and/or Φ_2

Spectrum contains three neutral Higgses H_i and a charged pair $H^\pm$

If $\mathcal{CP}$ conserved $\Rightarrow$ h, H (CP-even, $m_h \leq m_H$) and A (CP-odd)

Parameters m_{11}^2 and m_{22}^2 traded for $v_1 \equiv v\cos\beta, \quad v_2 \equiv v\sin\beta$

$$\Phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}\left(G^+\cos\beta - H^+\sin\beta\right) \\ v\cos\beta - h\sin\alpha + H\cos\alpha + \mathrm{i}\left(G^0\cos\beta - A\sin\beta\right)\end{pmatrix} \qquad v \simeq 246 \text{ GeV}$$

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

$\tan\beta \equiv v_2/v_1$ defines basis in Φ space. Higgs basis: $\tan\beta = 0$

Higgs-Gauge couplings determined by invariant $s_{\beta-\alpha} \equiv \sin(\beta-\alpha)$

Parametrization: $m_h,\ m_H,\ m_A,\ m_{H^+},\ s_{\beta-\alpha},\ \lambda_6,\ \lambda_7,\ m_{12}^2$

Yukawa sector

Quark Yukawa interactions:

$$-\mathcal{L}_{\mathrm{Y}} = \bar{Q}_L^0 \tilde{\Phi}_1 \eta_1^{U,0} U_R^0 + \bar{Q}_L^0 \Phi_1 \eta_1^{D,0} D_R^0 + \bar{Q}_L^0 \tilde{\Phi}_2 \eta_2^{U,0} U_R^0 + \bar{Q}_L^0 \Phi_2 \eta_2^{D,0} D_R^0 + \mathrm{h.c.}$$

Q_L^0, U_R^0 etc. weak ineraction eigenstates. $\tilde{\Phi} \equiv i\sigma_2 \Phi^*$

In Higgs basis (only $H_1 \equiv \Phi_1$ has vev):

$$-\mathcal{L}_{\mathrm{Y}} = \bar{Q}_L^0 \tilde{H}_1 \kappa^{U,0} U_R^0 + \bar{Q}_L^0 H_1 \kappa^{D,0} D_R^0 + \bar{Q}_L^0 \tilde{H}_2 \rho^{U,0} U_R^0 + \bar{Q}_L^0 H_2 \rho^{D,0} D_R^0 + \mathrm{h.c.}$$

$$\begin{pmatrix} \kappa^{Q,0} \\ \rho^{Q,0} \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \eta_1^{Q,0} \\ \eta_2^{Q,0} \end{pmatrix}$$

Mass eigenstates: $U_R = V_R^U U_R^0,\ D_R = V_R^D D_R^0$ $\quad V_{\mathrm{CKM}} = V_L^U (V_R^D)^\dagger$

$$U_L = V_L^U U_L^0,\ D_L = V_L^D D_L^0$$

Transformed couplings: $\kappa^Q = V_L^Q \kappa^{Q,0} (V_R^Q)^\dagger \quad \rho^Q = V_L^Q \rho^{Q,0} (V_R^Q)^\dagger$

$$\Rightarrow \kappa^Q = \sqrt{2}\frac{m^Q}{v}$$

Davidson and Haber, PRD72, 035004 (2005) [hep-ph/0504050]

Couplings of physical Higgs states

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Basis-independent Yukawa couplings (no $\mathcal{CP}$-violation):

$$
\begin{aligned}
-\mathcal{L}_{\mathrm{Y}} = & \frac{1}{\sqrt{2}}\overline{D}\Big\{\kappa^D s_{\beta-\alpha} + \rho^D c_{\beta-\alpha}\Big\}Dh + \frac{1}{\sqrt{2}}\overline{D}\Big\{\kappa^D c_{\beta-\alpha} - \rho^D s_{\beta-\alpha}\Big\}DH + \frac{\mathrm{i}}{\sqrt{2}}\overline{D}\gamma_5\rho^D DA \\
& + \frac{1}{\sqrt{2}}\overline{U}\Big\{\kappa^U s_{\beta-\alpha} + \rho^U c_{\beta-\alpha}\Big\}Uh + \frac{1}{\sqrt{2}}\overline{U}\Big\{\kappa^U c_{\beta-\alpha} - \rho^U s_{\beta-\alpha}\Big\}UH - \frac{\mathrm{i}}{\sqrt{2}}\overline{U}\gamma_5\rho^U UA \\
& + \frac{1}{\sqrt{2}}\overline{L}\Big\{\kappa^L s_{\beta-\alpha} + \rho^L c_{\beta-\alpha}\Big\}Lh + \frac{1}{\sqrt{2}}\overline{L}\Big\{\kappa^L c_{\beta-\alpha} - \rho^L s_{\beta-\alpha}\Big\}LH + \frac{\mathrm{i}}{\sqrt{2}}\overline{L}\gamma_5\rho^L LA \\
& + \Big[\overline{U}\big\{V_{\mathrm{CKM}}\rho^D P_R - \rho^U V_{\mathrm{CKM}} P_L\big\}DH^+ + \overline{\nu}\rho^L P_R L H^+ + \mathrm{h.c.}\Big].
\end{aligned}
$$

Free couplings: 3×3 symmetric Yukawa matrices ρ^D, ρ^U, ρ^L

Diagonal $\rho^Q \Rightarrow H^\pm$ flavour structure given by CKM

Off-diagonal ρ^Q elements $\Rightarrow$ Both non-MFV $H^\pm$ and FCNC

Davidson and Haber, PRD72, 035004 (2005) [hep-ph/0504050]

Discrete Yukawa symmetry

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FCNC problem naturally solved by GW mechanism

Introduce Z_2 under which e.g. D_R, Φ_1 are even, while U_R, Φ_2 odd:

$$-\mathcal{L}_{\mathrm{Y}} = \cancel{\bar{Q}_L^0 \tilde{\Phi}_1 \eta_1^{U,0} U_R^0} + \bar{Q}_L^0 \Phi_1 \eta_1^{D,0} D_R^0 + \bar{Q}_L^0 \tilde{\Phi}_2 \eta_2^{U,0} U_R^0 + \cancel{\bar{Q}_L^0 \Phi_2 \eta_2^{D,0} D_R^0} + \mathrm{h.c.}$$

$$\Rightarrow \rho^U = \kappa^U \cot\beta,\ \rho^D = -\kappa^D \tan\beta \quad \text{(Type-II)}$$

$\tan\beta$ promoted to physical parameter through Yukawa couplings

	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	$\kappa^L \cot\beta$	$-\kappa^L \tan\beta$	$\kappa^L \cot\beta$	$-\kappa^L \tan\beta$

Barger, Hewitt, Philips, PRD41 (1990)

Non-zero λ_6 or λ_7 in the potential gives hard violation of Z_2

2HDMC: Calculator for the 2HDM

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Features version 1.01

- General 2HDM (currently without CP-violation)
- Different parametrizations – including physical masses
- Tree-level mass calculation
- Arbitrary Yukawa sector or “types”
- Theoretical constraints (positivity, unitarity)
- LEP mass limits (NMSSMTools)
- Oblique parameters, muon g-2
- Yukawa couplings with running quark masses
- All two-body Higgs decays at tree-level (incl. FCNC)
- Non-standard top decays
- H -> VV* and H -> HV* off-shell decays
- H -> gg and H -> $\gamma\gamma$
- LesHouches-style interface
- MadGraph/MadEvent model

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

Structure of 2HDMC code

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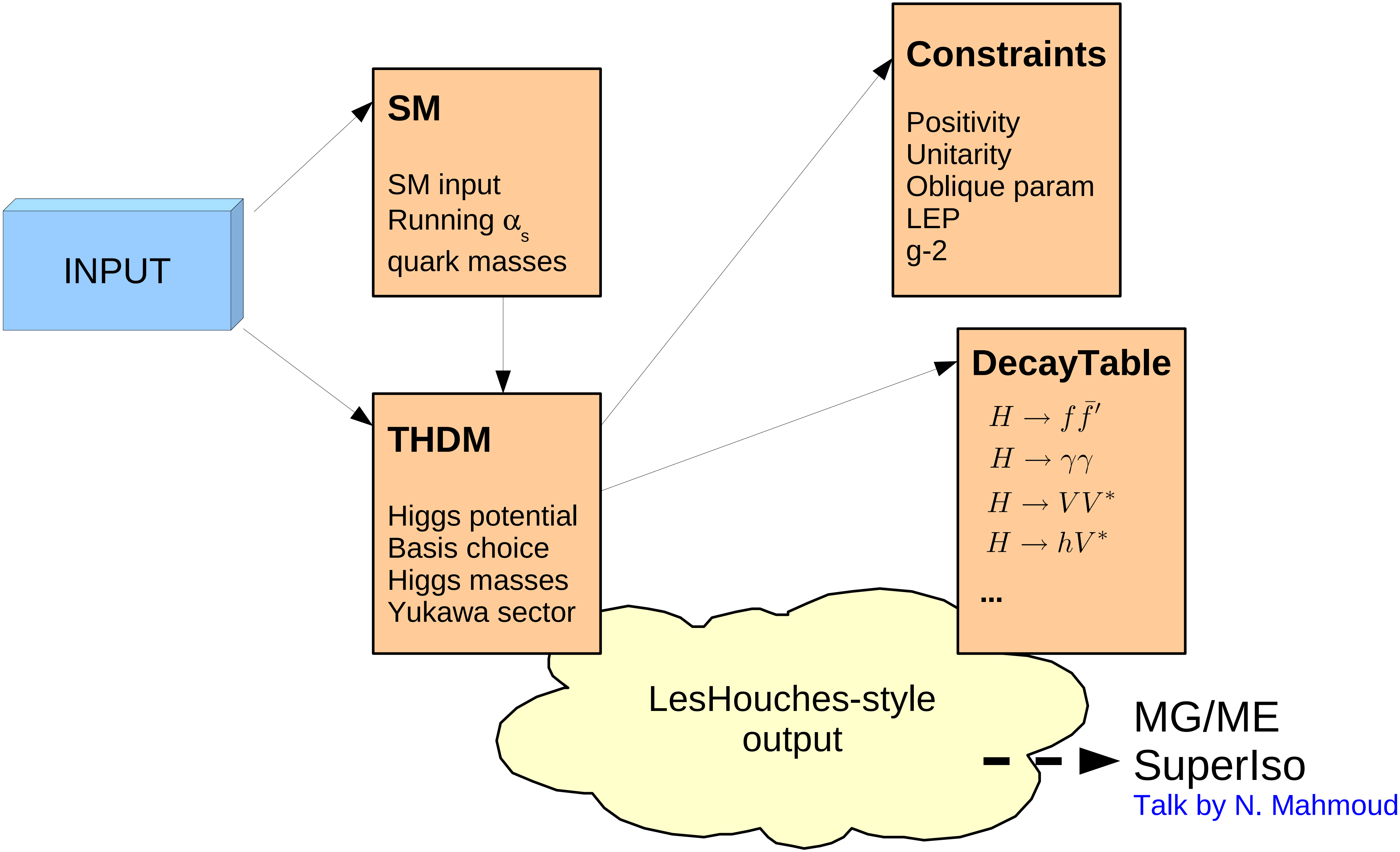

Sample run

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oscar@amos: ~/projects/2hdmcalc

File Edit View Terminal Tabs Help

```
oscar@amos:~/projects/2hdmcalc$ ./CalcPhys 50 120 150 160 0.5 0. 0. 0. 10 2 output_file

2HDM parameters in physical mass basis:
      m_h:     50.00000
      m_H:    120.00000
      m_A:    150.00000
     m_H+:    160.00000
 sin(b-a):      0.50000
 lambda_6:      0.00000
 lambda_7:      0.00000
    m12^2:     -0.00000
tan(beta):     10.00000

2HDM parameters in generic basis:
 lambda_1:     10.91937
 lambda_2:      0.17236
 lambda_3:      1.78415
 lambda_4:     -0.47341
 lambda_5:     -0.37114
 lambda_6:      0.00000
 lambda_7:      0.00000
    m12^2:     -0.00000
tan(beta):     10.00000
Tree-level unitarity  1
Stability             1
LEP constraints       0 (hZ:1 hZ2b:0 hZ2tau:1 hZinv:1 hZ2j:0 hZ2gamma:1 hZ4b:1 hZ4tau:1 hZ2b2
tau:1 hA:1 hA4b:1 hA4tau:1 hA2b2tau:1 hA6b:1 hA6tau:1 ZhZjj:1 HpHp:1 HpHptau:1 HpHpcs:1)
S                    -5.36266e-02
T                     8.39449e-03
U                     2.56652e-03
V                    -1.88629e-02
W                    -3.96246e-03
X                     7.70645e-04
Delta_rho             6.56281e-05
Delta_amu             4.44178e-11

oscar@amos:~/projects/2hdmcalc$ 
```

Example 1: SM-like Higgs

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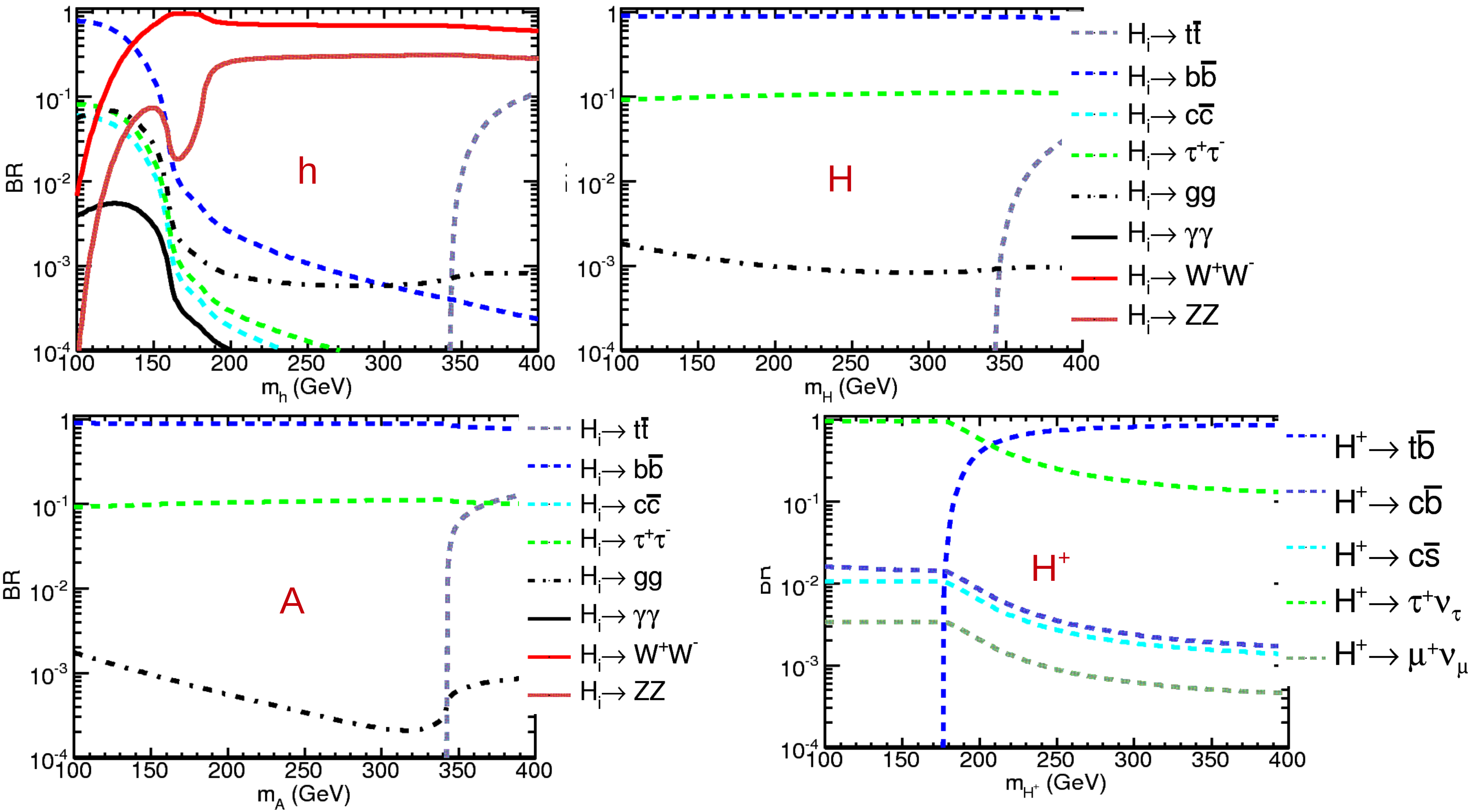
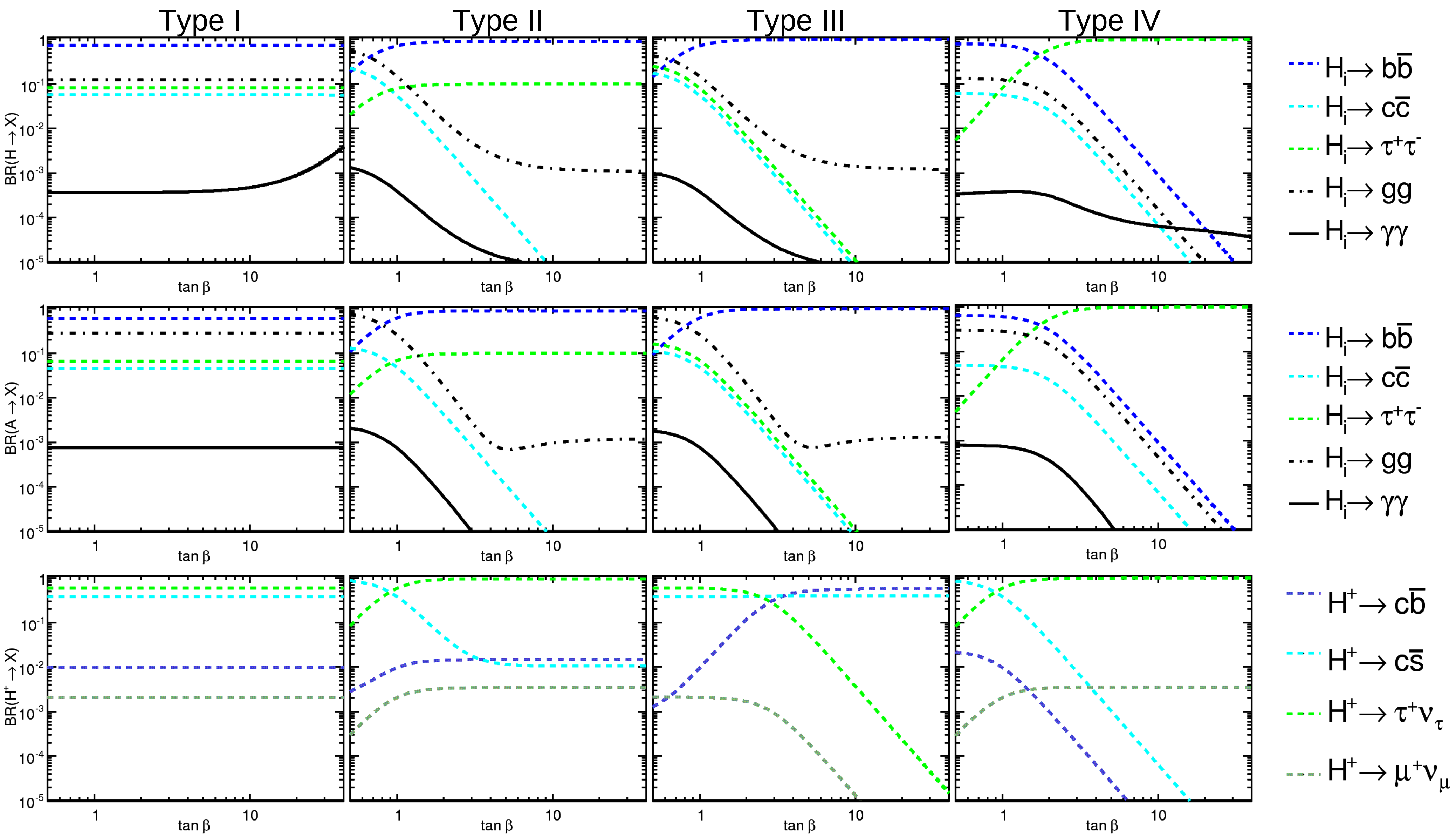
$\sin(\beta-\alpha)=1$ (SM-like h) $\lambda_6=\lambda_7=0$ $m_{12}^2=0$

$\tan\beta=10$ Type II Yukawas $m_h=m_H=m_A=m_{H^+}$ scan



Example 2: Different Yukawa sectors

$$m_H = m_A = m_{H^+} = 150 \text{ GeV} \qquad \sin(\beta - \alpha) = 1 \qquad m_{12} = M\sqrt{\sin\beta\cos\beta}$$



Aoki et al, arXiv:0902.4665
Su, Thomas, arXiv:0903.0667

Example 3: Flavour-violating decays

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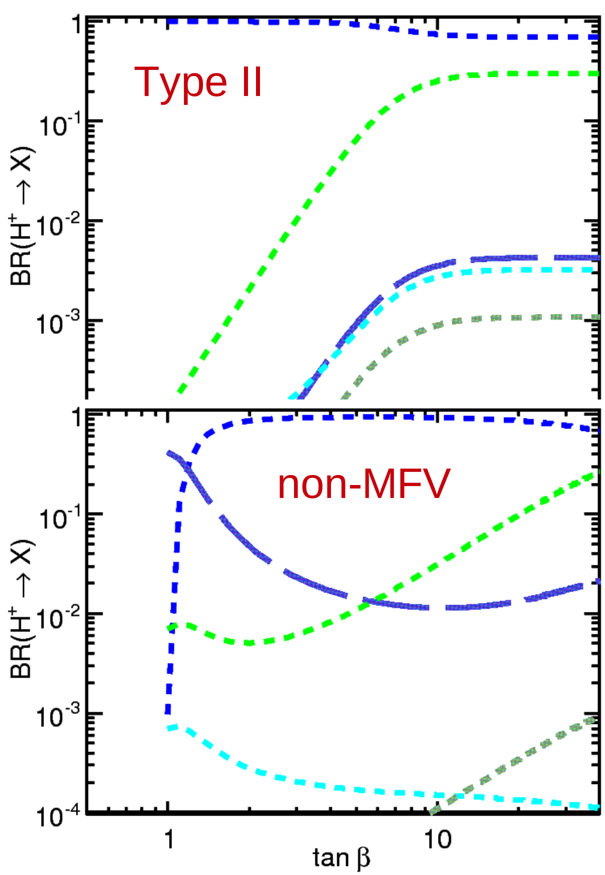
Diaz-Cruz, Hernandez-Sanchez, Moretti, Noriega-Papaqui, Rosado, arxiv:0902.4490

Four-texture Yukawa matrices $\Rightarrow$

$$[\rho^D]_{ij} = -[\kappa^D]_{ij}\tan\beta - \frac{\sqrt{m_{d_i}m_{d_j}}}{v\cos\beta}\chi_{ij} \qquad [\rho^U]_{ij} = [\kappa^U]_{ij}\cot\beta - \frac{\sqrt{m_{u_i}m_{u_j}}}{v\sin\beta}\chi_{ij}$$

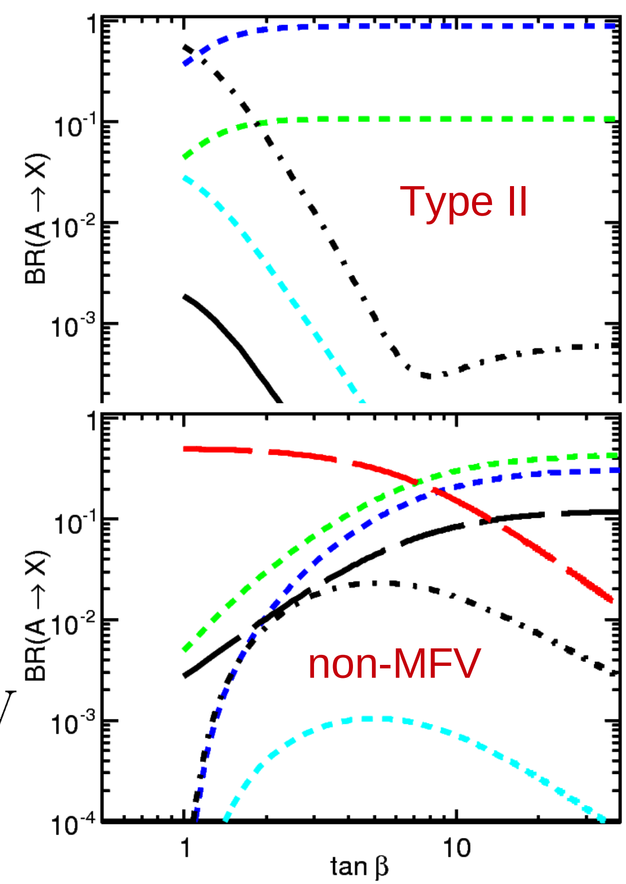
$$\text{Type II:} \quad \chi_{ij} = 0 \quad \forall i,j \qquad \text{Scenario A:} \quad \chi_{ij} = 1 \quad \forall i,j$$



$$\sin(\beta-\alpha) = 0$$

$$m_h = m_H = m_A = m_{H^+} = 250 \text{ GeV}$$

$$\lambda_6 = \lambda_7 = 0, \quad m_{12}^2 = 0$$



Summary

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- The 2HDM has interesting phenomenology,
  both for high-energy colliders and flavour physics.

- Some aspects of the 2HDM have perhaps been somewhat overlooked (MSSMania?).

- 2HDMC is a new tool to facilitate studies in the general 2HDM, currently for the CP-conserving case.

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

Physics and Manual: D. Eriksson, J. Rathsman, O. Stål
arXiv:0902.0851