Flavour Physics in two-Higgs-doublet models

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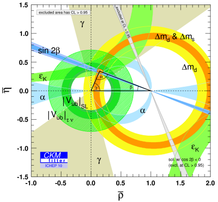
Outline

Motivation

Last few years shift of focus:
CKM mechanism main source of (low energy) CP violation ✔

➥ Concentration on new physics



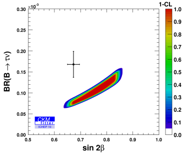
- NP expected at the TeV-scale
- Direct search is being performed at the LHC
- Flavour physics complementary tool
  - High sensitivity, even beyond LHC reach
  - But: Flavour data still compatible with SM

    ➥ Flavour Puzzzle

Tensions

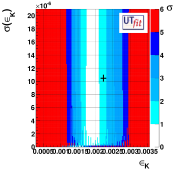
Present tensions in the global CKM fit:

- $\sin 2\beta_{B\to\tau\nu}$ vs. $\sin 2\beta|_{B\to J/\psi K^{(*)}}$
- (ϵ_K, depending on inputs and statistical treatment)



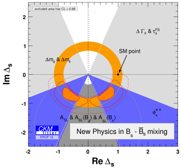
Tensions in the neutral B systems:

- Phase in $B_s \to J/\psi\phi$
  (however: $2.x\sigma \to\sim 1\sigma$ recently)
- Like-sign dimuon charge asymmetry



Not discussed here:

- $|V_{ub}|$ exclusive vs. inclusive
- Pattern of $B\to\pi K$ CP asymmetries
- Neutrino physics
- Astrophysical constraints
- . . .



Why 2HDM?

EW symmetry breaking mechanism unknown yet:

- 1HDM minimal and elegant, but unlikely (SUSY,GUTs,. . .)
- 2HDM:
  - "next-to-minimal"
  - ρ-parameter "implies" doublets
  - simple structure, but interesting phenomenology
  - low-energy limit of more complete NP models

affects all of the mentioned tensions (if new CPV sources present)

Lots of 2HDMs...

General 2HDM:

$$-\mathcal{L}_Y^q = \bar{Q}_L'(\Gamma_1\phi_1 + \Gamma_2\phi_2)\, d_R' + \bar{Q}_L'(\Delta_1\widetilde{\phi}_1 + \Delta_2\widetilde{\phi}_2)\, u_R' + \text{h.c.}$$

Γ_i, Δ_i: Independent 3×3 coupling matrices

Flavour problem: generic couplings imply huge NP scale

Most common solution: Applying a discrete $\mathcal{Z}_2$ symmetry:

- Eliminates two couplings, hence tree-level FCNCs
- Different charge assignments lead to "Type I,II,X,Y"
- Only one new parameter in the flavour sector: $\tan\beta$
- Type II SUSY-motivated: Bulk of analyses (Recently: El Kaffas et al. '07, GFitter '08, CKMfitter '09, UTfit '09)
- However: no new source of CP violation

Models/frameworks without $\mathcal{Z}_2$ symmetry:

- Type III: $Y_{ij}' \sim \sqrt{\frac{m_i m_j}{v^2}}$, e.g. Mahmoudi/Stål '09

Beyond $\mathcal{Z}_2$

- Aligned two-Higgs-doublet model (Pich/Tuzón '09): Alignment $\Gamma_2 = \xi_d\, e^{-i\theta}\,\Gamma_1$, $\Delta_2 = \xi_u^*\, e^{i\theta}\Delta_1$ leads to

$$-\mathcal{L}^q_{Y,H^\pm} = \frac{\sqrt{2}}{v}\, H^+(x)\bar{u}(x)\left[\varsigma_d\, VM_d\mathcal{P}_R - \varsigma_u\, M_u^\dagger V\mathcal{P}_L\right] d(x) + \mathrm{h.c.}$$

  with complex, observable parameters $\varsigma_{u,d,l}$, implying:
  - No FCNCs at tree-level
  - New sources for CP violation
  - Only three complex new parameters (unlike Type III)
  - $\mathcal{Z}_2$ models recovered for special values of $\varsigma_i's$
  - Radiative corrections symmetry-protected, of MFV-type
- 2HDM with MFV (D'Ambrosio et al. '02):
  - EFT framework, unknown couplings
  - Spurion formalism with flavour-blind phases: can be used to arrive at the A2HDM (1st term in series)
  - Recently: Expansion around Type II (as '02 as well) with phases and decoupling (Buras et al. '10). See also Paradisi/Straub, Kagan et al., Botella et al., Feldmann/MJ/Mannel, Colangelo et al., all '09
- BGL models (Branco et al. '96), Ferreira/Silva '10, ...

General Strategy

Problem twofold:

- Understand SM hadronic process
- Determine NP influence

In the process:

- Perform UT analysis independent of NP considered
- Choose statistical treatment (RFit in CKMfitter, GFitter and A2HDM plots)
- Determine hadronic inputs
  ➥Theory input (Lattice, QCD sum rules, χPT,...)
- Determine overall compatibility and parameter ranges for scenario considered

Usually publications differ in all these steps

In the following: Mostly A2HDM, comments on differences

Leptonic decays

Leptonic decays affected on tree-level by charged Higgs:

$$\frac{\Gamma(P_{ij}^+ \to l^+\nu_l)_{\rm full}}{\Gamma(P_{ij}^+ \to l^+\nu_l)_{\rm SM}} = |1-\Delta_{ij}|^2$$

i,j: valence quarks of the meson under consideration and

$$\Delta_{ij} = \left(\frac{m_{P_{ij}^\pm}}{M_{H^\pm}}\right)^2 \varsigma_l^* \frac{\varsigma_u m_{u_i} + \varsigma_d m_{d_j}}{m_{u_i} + m_{d_j}}$$

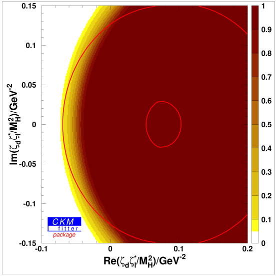
- Impact large due to helicity suppression in SM
- Results in circles in the complex Δ_{ij}-plane
- NP influence decreases for lighter mesons
- Comparison:
  - Type II: $\Delta > 0$ or $\sim 0 \to \Gamma_{\rm full} \lesssim \Gamma_{SM}$ ($\Delta \sim 2$ excluded)
  - Assuming decoupling: $\Delta \sim 0$, $B \to \tau\nu$ used in UT fit
  - Type III, A2HDM: $\Gamma_{\rm NP} > \Gamma_{SM}$ possible w/o large $|\Delta|$

Semileptonic decays of pseudoscalar mesons

- Helicity suppression absent in SM
  ➡Smaller relative influence of NP (m_ℓ suppression)
- Extraction of CKM elements unaffected
- Form-factor dependence, hence more involved
- Scalar form-factor affected through

$$\tilde{f}_0(t) = f_0(t)\ (1 + \delta_{ij}\, t)\ , \quad \delta_{ij} \equiv -\frac{\varsigma_l^*}{M_{H^\pm}^2}\,\frac{\varsigma_u m_{u_i} - \varsigma_d m_{d_j}}{m_{u_i} - m_{d_j}}$$

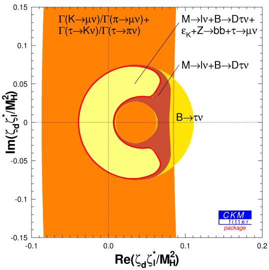
Example $B \to D\tau\nu$:

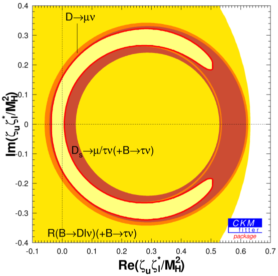


- Type II: m_s term dominant ($\tan\beta^2$ enhanced)
- A2HDM: Both terms relevant
- In both cases: Helps excluding second (real) solution
- For details, here and in the following: MJ/Pich/Tuzón '10

Combination of (semi-)leptonic constraints

Putting these constraints together:



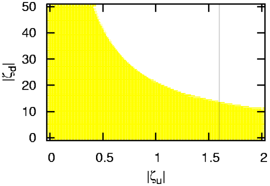


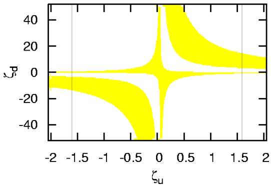
- Only combinations $\delta_{u/dl} = \varsigma_{u,d}\varsigma_l^* / M_{H^\pm}^2$ constrained
- Resulting "bananas" exclude the second real solution (with δ_{dl} help needed)
- $\delta_{dl} \lesssim 0.1$, δ_{ul} constraint weaker (but see later)
- Projection on Type II: δ_{dl} translates to $\tan\beta \lesssim 0.1 \frac{M_{H^\pm}}{GeV}$

$b \to s\gamma$

Famous for NP-sensitivity:

- FCNC process, loop-induced already in the SM
- $H^{\pm}$ effects expected to be large (tops in the loop)
- BR calculated to $\sim$NNLO (NLO) in the SM (2HDM) (Misiak et al.(many!) '07, Ciuchini et al. '97, Ciafaloni et al. '97, Borzumati/Greub '98, Degrassi/Slavich '10)
- Experimental accuracy $\sim 7\%$, thanks to B-factories
- Type II: $\varsigma_u \varsigma_d^* = -1$: mainly limit on M_H
- A2HDM: $\zeta_{u,d}$ independent $\to$ more freedom
  $|\zeta_u \zeta_d| \lesssim 20$ limit, but locally much stronger





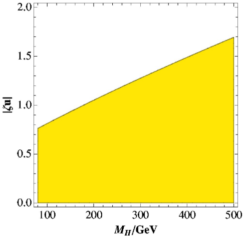
Constraints from mixing

Large effects expected in top loops:
➥Effects in $\Delta m_{d,s}, \phi_{d,s}, \epsilon_K$

Also: Possible effects in $b \to s$ with new phase (A2HDM)
➥$B_s \to J/\psi\phi$, $B_d \to J/\psi K$ not necessarily "golden"

Kaon mixing:

- Two SM amplitudes relevant $\to$ no NP phase needed
- Recent updates: improved non-perturbative corrections [Buras et al. '08,'10] and NNLO in η_{ct} [Brod/Gorbahn '10]



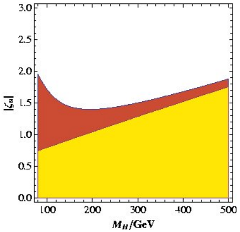
Completely different phenomenology:

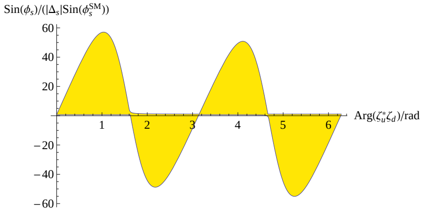
- Type II: Basically no effect
- MFVfb: dito, tiny effect from $\mathcal{O}^2_{LR}$
- A2HDM: Releatively strong limit on $|\zeta_u|$ through $\mathcal{O}_{VLL}$

Mixing in the B system

Effects are again very different for the different scenarios:

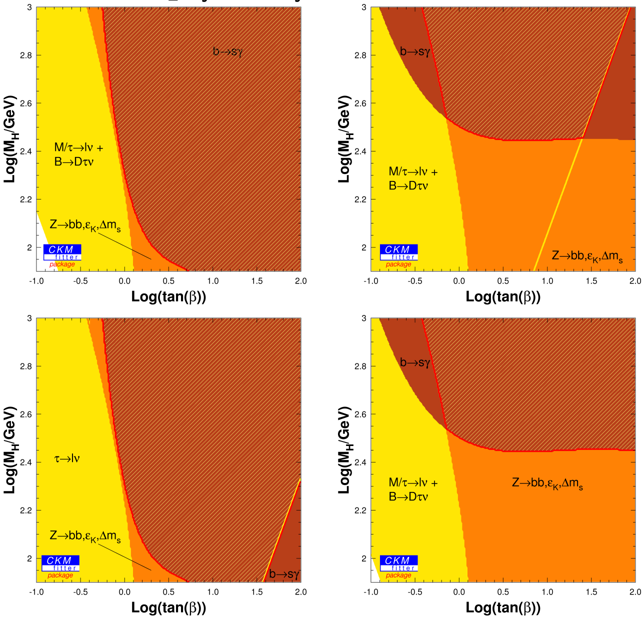
- In Type II neither $\phi_{d,s}$ nor $\Delta m_{d,s}$ affected (sizably)
- In MFVfb large effects expected, again via $\mathcal{O}_{LR}^2$:
  $S_q = S_0(x_t) - T_q$ with $T_q \sim 64\pi^2 m_b m_q / M_H^2$
  - $S_{\psi\phi}$ can take any value with $\mathcal{O}(1)$ coefficient
  - $T_d/T_s = m_d/m_s \sim \%$ → small effect (right direction)
- A2HDM: large (sizable) effect in $\Delta m_{d,s}$ ($\phi_{d,s}$) possible:
  - $\mathcal{O}(1)$ effect for $\mathcal{O}_{VLL}$ w/o phase → $\Delta_{d,s}$
  - $10 - 40\%$ effect for $\mathcal{O}_{SLL}$ with weak phase → $\phi_{d,s}$
  - Both contributions universal for $q = d, s$: $\Delta_d \simeq \Delta_s$
    ➥ $\Delta m_s / \Delta m_d$ still usable in UT fit





Projections

Models with $\mathcal{Z}_2$ symmetry are limits of the A2HDM:



Conclusions and outlook

Conclusions:

- 2HDMs active field, new developments
- Type II: best constrained, but no effect in $\phi_{d,s}$
- MFVfb:
  - EFT framework, systematic expansion
  - Buras et al. '10: Expansion around Type II, decoupling
  - $S_{J/\psi\phi}(A_{sl}^b)$ can be explained, softens tension $\epsilon_K - S_{J/\psi K}$
- A2HDM:
  - New CPV possible with sufficient FCNC suppression(!)
  - Rich phenomenology, only three new flavour-parameters
  - Present tensions can be addressed; moderate enhancement of A_{sl}^b possible

Outlook:

- Interesting times (as Guy put it: Here comes the sun!) Observables for LHC(b), SuperB (!), BES-III, NA-62,...
- A2HDM: Analysis of neutral Higgs effects in progress...
- Next CKM might see limits changing to determinations

Public protests about to change the picture?

Backupslides

- Radiative corrections in the A2HDM
- Neutron EDM in the A2HDM
- Experimental data used
- Hadronic inputs

Radiative corrections in the A2HDM

Symmetry structure forces the (one-loop) corrections to be of the form [MJ/Pich/Tuzon '10, Cvetic et al. '98]

$$\begin{aligned}
\mathcal{L}_{\mathrm{FCNC}} &= \frac{C(\mu)}{4\pi^2 v^3}\,(1+\varsigma_u^*\varsigma_d)\,\times \\
&\times \sum_i \varphi_i^0(x)\,\Big\{(\mathcal{R}_{i2}+i\,\mathcal{R}_{i3})\,(\varsigma_d-\varsigma_u)\,\Big[\bar{d}_L\,V^\dagger M_u M_u^\dagger\,V M_d\,d_R\Big] - \\
&-(\mathcal{R}_{i2}-i\,\mathcal{R}_{i3})\,(\varsigma_d^*-\varsigma_u^*)\,\Big[\bar{u}_L\,V M_d M_d^\dagger\,V^\dagger M_u\,u_R\Big]\Big\} + \mathrm{h.c.}
\end{aligned}$$

- Vanish for $\mathcal{Z}_2$ symmetry
- FCNCs still strongly suppressed
- See also Braeuninger et al. '10, Ferreira et al. '10

Neutron EDM in the A2HDM

One-loop contributions to neutron EDM have the structure

$$d_u \propto e\,(m_u/(4\pi v)^2)|V_{ui}|^2(m_i/M_{H^\pm})^2$$
$$d_d \propto e\,(m_d/(4\pi v)^2)|V_{id}|^2(m_i/M_{H^\pm})^2$$

➥Under control (see also Buras et al. '10, Batell/Pospelov '10,…(incomplete list))

Two-loop diagrams important (Barr-Zee diagrams), but also sensitive to UV-completion

➥Work in progress

Observables

Observable	Value
$\lvert g^S_{RR}\rvert_{\tau\to\mu}$	< 0.72 (95% CL)
$\mathrm{Br}(\tau \to \mu\nu_\tau\bar{\nu}_\mu)$	$(17.36 \pm 0.05) \times 10^{-2}$
$\mathrm{Br}(\tau \to e\nu_\tau\bar{\nu}_e)$	$(17.85 \pm 0.05) \times 10^{-2}$
$\mathrm{Br}(\tau \to \mu\nu_\tau\bar{\nu}_\mu)/\mathrm{Br}(\tau \to e\nu_\tau\bar{\nu}_e)$	0.9796 ± 0.0039
$\mathrm{Br}(B \to \tau\nu)$	$(1.73 \pm 0.35) \times 10^{-4}$
$\mathrm{Br}(D \to \mu\nu)$	$(3.82 \pm 0.33) \times 10^{-4}$
$\mathrm{Br}(D \to \tau\nu)$	$\leq 1.3 \times 10^{-3}$ (95% CL)
$\mathrm{Br}(D_s \to \tau\nu)$	$(5.58 \pm 0.35) \times 10^{-2}$
$\mathrm{Br}(D_s \to \mu\nu)$	$(5.80 \pm 0.43) \times 10^{-3}$
$\Gamma(K \to \mu\nu)/\Gamma(\pi \to \mu\nu)$	1.334 ± 0.004
$\Gamma(\tau \to K\nu)/\Gamma(\tau \to \pi\nu)$	$(6.50 \pm 0.10) \times 10^{-2}$
$\log C$	0.194 ± 0.011
$\mathrm{Br}(B \to D\tau\nu)/BR(B \to D\ell\nu)$	0.392 ± 0.079
$\Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$	0.21629 ± 0.00066
$\mathrm{Br}(\bar{B} \to X_s\gamma)_{E_\gamma > 1.6\mathrm{GeV}}$	$(3.55 \pm 0.26) \times 10^{-4}$
$\mathrm{Br}(\bar{B} \to X_c e\bar{\nu}_e)$	$(10.74 \pm 0.16) \times 10^{-2}$
$\Delta m_{B^0_d}$	$(0.507 \pm 0.005)\ \mathrm{ps}^{-1}$
$\Delta m_{B^0_s}$	$(17.77 \pm 0.12)\ \mathrm{ps}^{-1}$
$\lvert\epsilon_K\rvert$	$(2.228 \pm 0.011) \times 10^{-3}$

Hadronic Inputs I

Parameter	Value	Comment
f_{B_s}	$(0.242 \pm 0.003 \pm 0.022)$ GeV	Our average
f_{B_s}/f_{B_d}	$1.232 \pm 0.016 \pm 0.033$	Our average
f_{D_s}	$(0.2417 \pm 0.0012 \pm 0.0053)$ GeV	Our average
f_{D_s}/f_{D_d}	$1.171 \pm 0.005 \pm 0.02$	Our average
f_K/f_π	$1.192 \pm 0.002 \pm 0.013$	Our average
$f_{B_s}\sqrt{\hat{B}_{B_s^0}}$	$(0.266 \pm 0.007 \pm 0.032)$ GeV	
$f_{B_d}\sqrt{\hat{B}_{B_s^0}}/(f_{B_s}\sqrt{\hat{B}_{B_s^0}})$	$1.258 \pm 0.025 \pm 0.043$	
$\hat{B}_K$	$0.732 \pm 0.006 \pm 0.043$	
$\lvert V_{ud}\rvert$	0.97425 ± 0.00022	
λ	0.2255 ± 0.0010	$\left(1 - \lvert V_{ud}\rvert^2\right)^{1/2}$
$\lvert V_{ub}\rvert$	$(3.8 \pm 0.1 \pm 0.4) \cdot 10^{-3}$	$b \to ul\nu$ (excl. + incl.)
A	$0.80 \pm 0.01 \pm 0.01$	$b \to cl\nu$ (excl. + incl.)
$\bar{\rho}$	$0.15 \pm 0.02 \pm 0.05$	Our fit
$\bar{\eta}$	$0.38 \pm 0.01 \pm 0.06$	Our fit

Table: *Input values for the hadronic parameters. The first error denotes statistical uncertainty, the second systematic/theoretical.*

Hadronic Inputs II

Parameter	Value	Comment
$\bar{m}_u(2\ \mathrm{GeV})$	$(0.00255\,^{+\,0.00075}_{-\,0.00105})$ GeV	
$\bar{m}_d(2\ \mathrm{GeV})$	$(0.00504\,^{+\,0.00096}_{-\,0.00154})$ GeV	
$\bar{m}_s(2\ \mathrm{GeV})$	$(0.105\,^{+\,0.025}_{-\,0.035})$ GeV	
$\bar{m}_c(2\ \mathrm{GeV})$	$(1.27\,^{+\,0.07}_{-\,0.11})$ GeV	
$\bar{m}_b(m_b)$	$(4.20\,^{+\,0.17}_{-\,0.07})$ GeV	
$\bar{m}_t(m_t)$	$(165.1 \pm 0.6 \pm 2.1)$ GeV	
$\delta_{\mathrm{em}}^{K\ell 2/\pi\ell 2}$	-0.0070 ± 0.0018	
$\delta_{\mathrm{em}}^{\tau K2/K\ell 2}$	0.0090 ± 0.0022	
$\delta_{\mathrm{em}}^{\tau\pi 2/\pi\ell 2}$	0.0016 ± 0.0014	
$\rho^2\vert_{B\to Dl\nu}$	$1.18 \pm 0.04 \pm 0.04$	
$\Delta\vert_{B\to Dl\nu}$	0.46 ± 0.02	
$f_+^{K\pi}(0)$	0.965 ± 0.010	
$\bar{g}_{b,SM}^L$	$-0.42112\,^{+\,0.00035}_{-\,0.00018}$	
κ_ϵ	0.94 ± 0.02	
$\bar{g}_{b,SM}^R$	$0.07744\,^{+\,0.00006}_{-\,0.00008}$	

Table: *Input values for the hadronic parameters. The first error denotes statistical uncertainty, the second systematic/theoretical.*