Flavour Physics in the Aligned
Two-Higgs-Doublet Model

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Outline

Introduction

Tensions
The Aligned Two-Higgs-Doublet Model

Phenomenology

(Semi-)Leptonic Decays
Loop-induced processes

Conclusions and Outlook
Tensions

Present tensions in the global CKM fit:
- $\sin 2\beta_{B \to \tau\nu}$ vs. $\sin 2\beta_{B \to J/\psi K}$
- $(\epsilon_K$, depending on inputs and statistical treatment $)$

Tensions in the neutral $B$ systems:
- Phase in $B_s \to J/\psi \phi$
  (however: $2.3\sigma \to \sim 1\sigma$ 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?

Model-independent analysis: Too many parameters in general

Electroweak symmetry breaking mechanism unknown yet:

- 1HDM minimal and elegant, but unlikely (SUSY, GUTs, . . .)
- 2HDM “next-to-minimal”:
  - $\rho$-parameter “implies” doublets
  - low-energy limit of more complete NP models
  - Model-independent element
  - simple structure, but interesting phenomenology
  - affects the aforementioned tensions (with new CPV present)
Lots of 2HDMs...

General 2HDM:

\[-\mathcal{L}_{\bar{Y}}^q = \bar{Q}_L^\prime (\Gamma_1 \phi_1 + \Gamma_2 \phi_2) d_R' + \bar{Q}_L^\prime (\Delta_1 \tilde{\phi}_1 + \Delta_2 \tilde{\phi}_2) u_R' + \text{h.c.}\]

\(\Gamma_i, \Delta_i\): Independent 3 × 3 coupling matrices

Flavour problem: generic couplings imply huge NP scale

Most common solution: Applying a discrete \(\mathbb{Z}_2\) 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
Beyond $\mathcal{Z}_2$

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

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

- **2HDM with MFV** (D’Ambrosio et al. ’02):
  - EFT framework, unknown couplings
  - Yukawa matrices remain only source of flavour and CP violation
  - 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, …
The Aligned two-Higgs-doublet model

Alignment condition: $\Gamma_2 = \xi_d e^{-i\theta} \Gamma_1$, $\Delta_2 = \xi_u^* e^{i\theta} \Delta_1$

leads to [Pich/Tuzón '09]

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

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)
- $\mathbb{Z}_2$ models recovered for special values of $\varsigma_i's$
- Radiative corrections symmetry-protected, of MFV-type (Cvetic et al. '98, Braeuninger et al. '10, MJ/Pich/Tuzón '10)
- Recently: Proposals towards UV-completion (Medeiros Varzielas '11, Serôdio '11)
Combination of (semi-)leptonic constraints

Joining these constraints with semi-leptonic decays:

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

High sensitivity for NP in general:
- SM-process suppressed by loop and CKM-factors
- Internal heavy particles can contribute
  - Large Higgs-couplings
  - Sensitivity to UV-completion as well

Here only examples, for full analyses see [JM/Pich/Tuzón '10,'11,'11 (in prep.)]
Famous example for this NP-sensitivity:

- Inclusive process, theoretically well under control (but affected by non-local effects, see Benzke et al. ’10)
- $BR \sim \text{NNLO (NLO)}$ in the SM (2HDM) (community effort)
- Experimental accuracy $\sim 7\%$, thanks to B-factories
- Type II: $\zeta_u \zeta_d^* = -1$: mainly limit on $M_H$
- A2HDM: $\zeta_{u,d}$ independent $\rightarrow$ more freedom

Correlations are extremely important:
Projections

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

- Additional correlations
- All models: $\tan \beta \gtrsim 1$
- Type II/Y: $M_{H^\pm} \gtrsim 277$ GeV
- Type II: Upper limit on $\tan \beta$

<table>
<thead>
<tr>
<th>Type</th>
<th>$\varsigma_d$</th>
<th>$\varsigma_u$</th>
<th>$\varsigma_l$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$\cot \beta$</td>
<td>$\cot \beta$</td>
<td>$\cot \beta$</td>
</tr>
<tr>
<td>II</td>
<td>$- \tan \beta$</td>
<td>$\cot \beta$</td>
<td>$- \tan \beta$</td>
</tr>
<tr>
<td>X</td>
<td>$\cot \beta$</td>
<td>$\cot \beta$</td>
<td>$- \tan \beta$</td>
</tr>
<tr>
<td>Y</td>
<td>$- \tan \beta$</td>
<td>$\cot \beta$</td>
<td>$\cot \beta$</td>
</tr>
</tbody>
</table>

Type I

Type II
Electric dipole moments

- Highly sensitive to new CPV sources (SM tiny)
- In the A2HDM:
  - One-loop (C)EDMs: not tiny, but under control
  - 4-fermion operators: small, no \( \tan \beta^3 \)-enhancement
  - Two-loop graphs dominant (Weinberg '89, Dicus '90, Barr/Zee '90, Gunion/Wyler '90)
  - Again sensitivity to UV-completion

- Largest charged Higgs contribution from Weinberg diagram
- Barr-Zee(-like) diagrams dominate neutral Higgs exchange
- For neutrals: sum includes cancellations in general
Charged Higgs in the neutron EDM

- Two-step matching (Boyd et al. ’90): $b$-CEDM at $\mu_{EW} \rightarrow O_{W}$ at $\mu_{b}$
- QCD sum rule estimate for matrix element

$$d_n \sim d_n^{\exp} \frac{500 \text{ GeV}}{M_{H^{\pm}}} \text{Im}[\zeta_d \zeta_u^+]$$
Charged Higgs in the neutron EDM

- Two-step matching (Boyd et al. ’90): $b$-CEDM at $\mu_{EW} \rightarrow O_W$ at $\mu_b$
- QCD sum rule estimate for matrix element

\[
d_n \sim d_n^{\text{exp}} \frac{500 \text{ GeV}}{M_{H^\pm}} \text{Im}[\zeta_d \zeta_u^*]
\]

Constraint from neutron EDM on charged Higgs contribution:
Charged Higgs in the neutron EDM

- Two-step matching (Boyd et al. '90): $b$-CEDM at $\mu_{EW} \rightarrow \mathcal{O}_{W}$ at $\mu_b$
- QCD sum rule estimate for matrix element

$$d_n \sim d_n^{\exp} \frac{500 \text{ GeV}}{M_{H^\pm}} \text{Im}[\zeta_d \zeta_u^*]$$

Combination of $BR(b \rightarrow s\gamma)$ and neutron EDM:

- orange: $M_{H^\pm} = 500 \text{ GeV}$
- brown: $M_{H^\pm} = 80 \text{ GeV}$

$\text{Im}(\zeta_d \zeta_u^*)$ strongly constrained, but not tiny
Neutral Higgs in EDMs

- Effect dominated by Barr-Zee(-like) diagrams
- Non-trivial constraints for all combinations apart from $\text{Im}(y_u^2)$
- Here: only results for Thallium, one neutral Higgs

Paramagnetic atom, EDM dominated by $d_e$: $d_{\text{Tl}} \approx -585 \, d_e$

Again $\mathcal{O}(1)$ imaginary parts remain allowed

The A2HDM passes the EDM-test
Conclusions and outlook

Conclusions:

- 2HDMs active field, new developments
- Type II: best constrained, but no effect on present tensions
- A2HDM:
  - New CPV possible with sufficient FCNC suppression (!)
  - Rich phenomenology, only three new flavour-parameters
  - Strong (but not “killing”) constraints from EDMs

Outlook:

- A2HDM: Additional analyses in progress:
  - neutral Higgs effects
  - combined electroweak and radiative decays
  - EDMs continued
- Interesting times! Measurements to come from LHC, SuperB/BelleII, BES-III, NA-62, ...
- Shortly we might see limits changing to determinations
Public protests about to change the picture?
Backup slides

- 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/Tuzón ’10, Cvetic et al. ’98]

\[
\mathcal{L}_{\text{FCNC}} = \frac{C(\mu)}{4\pi^2 v^3} (1 + \varsigma_u^* \varsigma_d) \times \\
\times \sum_i \varphi_i^0(x) \left\{ (\mathcal{R}_{i2} + i \mathcal{R}_{i3}) (\varsigma_d - \varsigma_u) \right. \\
\left. - (\mathcal{R}_{i2} - i \mathcal{R}_{i3}) (\varsigma_d^* - \varsigma_u^*) \right\} + \text{h.c.}
\]

- Vanish for \(\mathbb{Z}_2\) symmetry
- FCNCs still strongly suppressed
- See also Braeuninger et al. ’10, Ferreira et al. ’10
### Observables

<table>
<thead>
<tr>
<th>Observable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(</td>
<td>g^{s}_{RR}</td>
</tr>
<tr>
<td>(\text{Br}(\tau \rightarrow \mu \nu_{\tau} \bar{\nu}_{\mu}))</td>
<td>((17.36 \pm 0.05) \times 10^{-2})</td>
</tr>
<tr>
<td>(\text{Br}(\tau \rightarrow e \nu_{\tau} \bar{\nu}_{e}))</td>
<td>((17.85 \pm 0.05) \times 10^{-2})</td>
</tr>
<tr>
<td>(\text{Br}(\tau \rightarrow \mu \nu_{\tau} \bar{\nu}<em>{\mu}) / \text{Br}(\tau \rightarrow e \nu</em>{\tau} \bar{\nu}_{e}))</td>
<td>(0.9796 \pm 0.0039)</td>
</tr>
<tr>
<td>(\text{Br}(B \rightarrow \tau \nu))</td>
<td>((1.73 \pm 0.35) \times 10^{-4})</td>
</tr>
<tr>
<td>(\text{Br}(D \rightarrow \mu \nu))</td>
<td>((3.82 \pm 0.33) \times 10^{-4})</td>
</tr>
<tr>
<td>(\text{Br}(D \rightarrow \tau \nu))</td>
<td>(\leq 1.3 \times 10^{-3} \text{ (95% CL)})</td>
</tr>
<tr>
<td>(\text{Br}(D_{s} \rightarrow \tau \nu))</td>
<td>((5.58 \pm 0.35) \times 10^{-2})</td>
</tr>
<tr>
<td>(\text{Br}(D_{s} \rightarrow \mu \nu))</td>
<td>((5.80 \pm 0.43) \times 10^{-3})</td>
</tr>
<tr>
<td>(\Gamma(K \rightarrow \mu \nu) / \Gamma(\pi \rightarrow \mu \nu))</td>
<td>(1.334 \pm 0.004)</td>
</tr>
<tr>
<td>(\Gamma(\tau \rightarrow K \nu) / \Gamma(\tau \rightarrow \pi \nu))</td>
<td>((6.50 \pm 0.10) \times 10^{-2})</td>
</tr>
<tr>
<td>(\log C)</td>
<td>(0.194 \pm 0.011)</td>
</tr>
<tr>
<td>(\text{Br}(B \rightarrow D \tau \nu) / \text{BR}(B \rightarrow D \ell \nu))</td>
<td>(0.392 \pm 0.079)</td>
</tr>
<tr>
<td>(\Gamma(Z \rightarrow b \bar{b}) / \Gamma(Z \rightarrow \text{hadrons}))</td>
<td>(0.21629 \pm 0.00066)</td>
</tr>
<tr>
<td>(\text{Br}(B \rightarrow X_{s} \gamma)<em>{E</em>{\gamma} &gt; 1.6 \text{GeV}})</td>
<td>((3.55 \pm 0.26) \times 10^{-4})</td>
</tr>
<tr>
<td>(\text{Br}(B \rightarrow X_{c} \ell \bar{\nu}_{\ell}))</td>
<td>((10.74 \pm 0.16) \times 10^{-2})</td>
</tr>
<tr>
<td>(\Delta m_{B_{d}})</td>
<td>((0.507 \pm 0.005) \text{ ps}^{-1})</td>
</tr>
<tr>
<td>(\Delta m_{B_{s}})</td>
<td>((17.77 \pm 0.12) \text{ ps}^{-1})</td>
</tr>
<tr>
<td>(</td>
<td>\epsilon_{K}</td>
</tr>
</tbody>
</table>
## Hadronic Inputs I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{B_s}$</td>
<td>$(0.242 \pm 0.003 \pm 0.022)$ GeV</td>
<td>Our average</td>
</tr>
<tr>
<td>$f_{B_s}/f_{B_d}$</td>
<td>$1.232 \pm 0.016 \pm 0.033$</td>
<td>Our average</td>
</tr>
<tr>
<td>$f_{D_s}$</td>
<td>$(0.2417 \pm 0.0012 \pm 0.0053)$ GeV</td>
<td>Our average</td>
</tr>
<tr>
<td>$f_{D_s}/f_{D_d}$</td>
<td>$1.171 \pm 0.005 \pm 0.02$</td>
<td>Our average</td>
</tr>
<tr>
<td>$f_K/f_{\pi}$</td>
<td>$1.192 \pm 0.002 \pm 0.013$</td>
<td>Our average</td>
</tr>
<tr>
<td>$f_{B_s}\sqrt{\hat{B}_{B_s}}$</td>
<td>$(0.266 \pm 0.007 \pm 0.032)$ GeV</td>
<td></td>
</tr>
<tr>
<td>$f_{B_d}\sqrt{\hat{B}<em>{B_s}}/(f</em>{B_s}\sqrt{\hat{B}_{B_s}})$</td>
<td>$1.258 \pm 0.025 \pm 0.043$</td>
<td></td>
</tr>
<tr>
<td>$\hat{B}_K$</td>
<td>$0.732 \pm 0.006 \pm 0.043$</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>V_{ud}</td>
<td>$</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>$0.2255 \pm 0.0010$</td>
<td>$(1 -</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>$</td>
</tr>
<tr>
<td>$A$</td>
<td>$0.80 \pm 0.01 \pm 0.01$</td>
<td>$b \rightarrow cl\nu$ (excl. + incl.)</td>
</tr>
<tr>
<td>$\bar{\rho}$</td>
<td>$0.15 \pm 0.02 \pm 0.05$</td>
<td>Our fit</td>
</tr>
<tr>
<td>$\bar{\eta}$</td>
<td>$0.38 \pm 0.01 \pm 0.06$</td>
<td>Our fit</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{m}_u(2 \text{ GeV})$</td>
<td>$(0.00255 \pm 0.00075$ $\pm 0.00105$) GeV</td>
<td></td>
</tr>
<tr>
<td>$\bar{m}_d(2 \text{ GeV})$</td>
<td>$(0.00504 \pm 0.00096$ $\pm 0.00154$) GeV</td>
<td></td>
</tr>
<tr>
<td>$\bar{m}_s(2 \text{ GeV})$</td>
<td>$(0.105 \pm 0.025$ $\pm 0.035$) GeV</td>
<td></td>
</tr>
<tr>
<td>$\bar{m}_c(2 \text{ GeV})$</td>
<td>$(1.27 \pm 0.07$$ \pm 0.11$) GeV</td>
<td></td>
</tr>
<tr>
<td>$\bar{m}_b(m_b)$</td>
<td>$(4.20 \pm 0.17$$ \pm 0.07$) GeV</td>
<td></td>
</tr>
<tr>
<td>$\bar{m}_t(m_t)$</td>
<td>$(165.1 \pm 0.6 \pm 2.1$) GeV</td>
<td></td>
</tr>
<tr>
<td>$\delta^K_{\ell2}/\pi\ell2_{em}$</td>
<td>$-0.0070 \pm 0.0018$</td>
<td></td>
</tr>
<tr>
<td>$\delta^{\tau K2}/K\ell2_{em}$</td>
<td>$0.0090 \pm 0.0022$</td>
<td></td>
</tr>
<tr>
<td>$\delta^{\tau \pi 2}/\pi\ell2_{em}$</td>
<td>$0.0016 \pm 0.0014$</td>
<td></td>
</tr>
<tr>
<td>$\rho^2</td>
<td>B \to D\ell\nu$</td>
<td>$1.18 \pm 0.04 \pm 0.04$</td>
</tr>
<tr>
<td>$\Delta</td>
<td>B \to D\ell\nu$</td>
<td>$0.46 \pm 0.02$</td>
</tr>
<tr>
<td>$f^K_{\pi}(0)$</td>
<td>$0.965 \pm 0.010$</td>
<td></td>
</tr>
<tr>
<td>$\bar{g}_{b,SM}$</td>
<td>$-0.42112 \pm 0.00035$</td>
<td></td>
</tr>
<tr>
<td>$\kappa_{\epsilon}$</td>
<td>$0.94 \pm 0.02$</td>
<td></td>
</tr>
<tr>
<td>$\bar{g}_{R,SM}$</td>
<td>$0.07744 \pm 0.00006$</td>
<td></td>
</tr>
</tbody>
</table>

**Table:** Input values for the hadronic parameters. The first error denotes statistical uncertainty, the second systematic/theoretical.
CKM-fit within the A2HDM

In the A2HDM, the CKM-parameters are determined as follows:

- Only the constraints from $|V_{ub}/V_{cb}|$ and $\Delta m_s/\Delta m_d$ survive.
- $\gamma$ from tree-level decays not competitive yet, but excludes 2nd solution.
- $\Delta m_s/\Delta m_d = \Delta m_s/\Delta m_d|_{SM} + \mathcal{O}\left(\frac{m_s-m_d}{M_W}s_d\right)$
Statistical Treatment

In this work, the RFit-scheme is used: [Höcker et al., 2001]

- Philosophy: distance from central value has no statistical meaning for theory errors / large systematics
- This implies that the statistical problem is not well-defined

**Assumption:** Within a range no contribution to $\chi^2$, outside increase corresponding to statistical error
- Choose range conservatively
- Theory errors add linearly

Averaging different theory-results even less well-defined...
- Theory error at least that of best single result
- Statistical errors treated “normally”
- Here additionally: Criteria from FLAG (where available)
**$b \rightarrow s\gamma$: Results**

However: Correlations are extremely important:

\[
|\varsigma_u^* \varsigma_d| \text{ vs. } M_H
\]

\[
|\varsigma_u^* \varsigma_d| \text{ vs. } \text{Arg}(\varsigma_u^* \varsigma_d)
\]

- Constraint much stronger for small Higgs masses
- For $\phi \sim \pi$ constructive, $\phi \sim 0$ destructive interference
- Implies small effect to LCDA from charged Higgs
  (neutral sector effects might be large: see Buras et al. ’10)
Direct CP-asymmetry in $b \rightarrow s\gamma$

- Potentially large in 2HDMs with new CPV (Borzumati/Greub ’98)
- However, $BR(b \rightarrow s\gamma)$ constrains the asymmetry strongly:

Compatible with measurement, but enhancement possible

More precise measurement interesting (→ SuperB)
Constraints from mixing

Mixing in the SM induced by box-graphs:

- **B-system**: internal top-quark dominant for $\Delta m_{d,s}$
- **K-system**: charm-loop dominant in $\Delta m_K$, but top in $\epsilon_K$

⚠️ Short-distance calculations possible

Large Higgs-effects expected in top loops: $m_t/M_H \sim 1$ possible

⚠️ Effects in $\Delta m_{d,s}, \phi_{d,s}, \epsilon_K$

However: main effect real, $\sim |s_u|^2$, CPV suppressed as $\left(s_d s_u^* \frac{m_b m_t}{M_H^2}\right)^2$
Kaon mixing

- Two SM amplitudes relevant $\rightarrow$ no NP phase needed
- Recent updates: improved non-perturbative corrections [Buras et al. ’08,’10] and NNLO in $\eta_{ct}$ [Brod/Gorbahn ’10]
- In $Z_2$-models $\sim \tan^{-2} \beta$
- In the A2HDM: constraint on general parameter $|\varsigma_u|$
- At 68% preference for non-vanishing NP-contribution
  - automatically right direction for mini-tension
Mixing in the B system

- In the SM completely dominated by the top-loop
- Complex NP-contributions necessary to change the mixing-phase
- Below only charged Higgs discussed, but neutral Higgs effects can be sizable [Buras et al. '10]

A2HDM: large (sizable) effect in $\Delta m_{d,s}$ ($\phi_{d,s}$) possible:

- $O(1)$ effect to SM-contribution w/o phase $\rightarrow \Delta_{d,s}$
- Up to $10 - 40\%$ effect for $O_{SLL}$ with weak phase $\rightarrow \phi_{d,s}$
- Both contributions universal for $q = d, s : \Delta_d \simeq \Delta_s$
- $\Delta m_s / \Delta m_d$ still usable in UT fit
The Like-sign dimuon charge asymmetry

Difference of $\mu^+\mu^+$ and $\mu^-\mu^-$ pairs from a $B - \bar{B}$-system

Measure for $CP$-violation in mixing

- For $B_d$ measured at the B-factories
- At D0: Measurement for sum $B_d, B_s$
- Effect in $B_s$-mixing

Characteristic measure: $\frac{a_{sl}^s|_{\text{full}}}{a_{sl}^s|_{\text{SM}}} = \frac{\sin \phi_{s}^{\text{full}}}{\Delta_s \sin \phi_{s}^{\text{SM}}}$

- Central value unphysical ($a_{sl}^s|_{\text{full}} \sim 400a_{sl}^s|_{\text{SM}}$), but error still large
- Correlations from $b \rightarrow s\gamma$ important!
- Effect of $H^{\pm}$ too small
- Neutrals contribute