Electric Dipole Moments in Two-Higgs-Doublet Models

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Outline

Importance of EDMs

Flavour-sector of the SM is special ($\rightarrow$):

- Unique connection between Flavour- and CP-violation
- FCNCs highly suppressed
- FConservingNCs with CPV as well!

➥ $d_n^{SM,CKM} \lesssim 10^{-32} e\,\mathrm{cm}$ (Pospelov/Ritz '05), well below foreseeable tests

EDMs test sources for CPV to extremely high precision:

- Experimentally e.g. $d_n^{\mathrm{exp}} \lesssim 3 \times 10^{-26} e\,\mathrm{cm}$ (Baker et al. '06)

➥ Strong CP problem; below some dynamical solution assumed

➥ Background-free precision-laboratory for NP!

EDMs and NP

NP models necessarily involve new sources of CPV:

- Generally (too) large EDMs ("NP models predict EDMs just below the present limits" always true)
- Limits on FCNCs and EDMs imply highly non-trivial flavour- and CPV-structure

➥ Generic one-loop contributions excluded ($\rightarrow$ SUSY CP-problem)

➥ Sensitivity to two-loop contributions $\rightarrow$ UV-completion

EDMs important on two levels:

- "Smoking-Gun-level": Visible EDMs prove for NP
- Quantitative level: Setting limits/determining parameters
  ➥Theory uncertainties are important!

Flavour meets Colour

- Most stringent constraints stem from neutron and atoms
- ➥ QCD essential
- Limits usually displayed as allowed regions
- ➥ Conservative uncertainty-estimates important

Atomic level

$\Downarrow$

Nuclear Level

$\Downarrow$

QCD level

$\Downarrow$

Effective Theory with (C)EDMs of fermions, $\mathcal{O}_W, \ldots$

$\Downarrow$

Parameters of your favourite NP model

Each step might involve uncertainties of orders of magnitude!

Framework

Effective Lagrangian at a hadronic scale:

$$\mathcal{L} = -\sum_{f=u,d,e}\left[\frac{d_f^\gamma}{2}\mathcal{O}_f^\gamma + \frac{d_f^C}{2}\mathcal{O}_f^C\right] + C_W\mathcal{O}_W + \sum_{i,j=(q,l)} C_{ij}\mathcal{O}_{ij}^{4f} \,,$$

in the operator basis

$$\mathcal{O}_f^\gamma = ie\bar{\psi}_f F^{\mu\nu}\sigma_{\mu\nu}\gamma_5\psi_f \,, \qquad \mathcal{O}_f^C = ig_s\bar{\psi}_f G^{\mu\nu}\sigma_{\mu\nu}\gamma_5\psi_f \,,$$

$$\mathcal{O}_W = +\frac{1}{3}f^{abc}G^a_{\mu\nu}\tilde{G}^{\nu\beta,b}G_\beta{}^{\mu,c} \,, \qquad \mathcal{O}_{ij}^{4f} = (\bar{\psi}_i\psi_i)(\bar{\psi}_j i\gamma_5\psi_j)$$

Options for matrix elements:

- Naive dimensional analysis (Georgi/Manohar '84): a.o. arbitrary factos of 4π (e.g. Bigi/Uraltsev '91)
- Baryon χPT: not applicable for all the operators
- QCD sum rules: used here (Pospelov et al.), uncertainties large
- Ideas, anyone?

Theory uncertainties I

Example: The electron EDM

- Often extracted using $d_{Tl} = C_e d_e$ with $C_e = -585$
  (Mårtensson-Pendrill, Öster 1987)
- Calculations span $C_e \in [-1041, -179](!)$ (cancellations)
- Recent results: $d_{Tl} \sim -582(20) d_e$ and $\sim 466(10) d_e$
  (Dzuba/Flambaum '09, Nataraj et al.'10)
- Furthermore: Four-fermion operators relevant

$$\Rightarrow d_{Tl} = -(529 \pm 73) d_e - (34 \pm 10)\ \mathrm{GeV}\ e\, C_S$$

- To obtain limit: constraint/assumption needed for C_S!

Theory uncertainties II

Example: The EDM of Mercury

- The most precise EDM-limit so far: $|d_{Hg}| \leq 3.1 \times 10^{-29} e\,\mathrm{cm}$ (Griffith et al. '09)
- However: diamagnetic system
  - Shielding efficient $\rightarrow$ sensitivity $\sim d_n, d_{Tl}$
  - All stages enter:

$$d_{Hg} \overset{Atomic}{=} d_{Hg}(S, C_{S,P}) \overset{Nuclear}{=} d_{Hg}(\tilde{g}_{\pi NN}, C_{S,P})$$
$$\overset{QCD}{=} d_{Hg}(d_f^C, C_{qq'}, C_{S,P})$$

  - Uncertainties: Atomic$\sim$ 30%, Nuclear$\sim$ x00%, QCD sum rules$\sim$ $100 - 200\%$
  - ➥ Constraint on CEDMs not very reliable $(1_{CV} \rightarrow 1/30_{rc} \rightarrow 0_c)$

Progress in theory needed to fully exploit precision measurements of EDMs

A model-independent limit on the electron EDM

In general: Too many parameters for model-independent analysis

➥ Bounds usually obtained by assuming vanishing cancellations

Electron EDM:

- Bound in (Regan et al. '02): $|d_e| \leq 1.6 \times 10^{-27}$ (90% CL)
- Two shortcomings: $C_e = -585$ chosen and C_S ignored
- First issue addressed already
- Idea for C_S: make assumption on a sub-leading level
    1. Use bound on C_S from Mercury
    2. Use that bound and range for C_e to obtain limit on d_e
- This procedure results in

$$\begin{aligned} |C_S| &\leq 2.2 \times 10^{-13}\ \mathrm{GeV}^{-2} \quad \text{and} \\ |d_e| &\leq 2.8 \times 10^{-27} e\,\mathrm{cm} \quad (95\%\,\mathrm{CL}) \end{aligned}$$

- Robust, model-independent limt, can be used for NP-bounds

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":
  - ρ-parameter "implies" doublets
  - low-energy limit of more complete NP models
    ➥Model-independent element
  - simple structure, but interesting phenomenology
  - important effects in flavour observables

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

Some of the many approaches:

- $\mathcal{Z}_2$ (SUSY-motivated, 1 flavour-parameter, no CPV)
- Type III: $Y_{ij}' \sim \sqrt{\frac{m_i m_j}{v^2}}$ (Cheng/Sher '87)
- 2HDM with MFV (D'Ambrosio et al. '02):
    - EFT framework, unknown couplings
    - Yukawas remain only source of flavour and CP violation
    - 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]

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

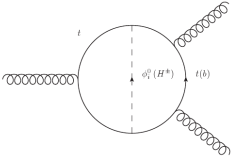
with complex, observable parameters $\varsigma_{u,d,l}$, implying:

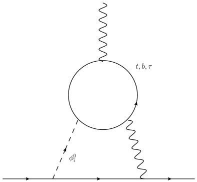
- No FCNCs at tree-level
- New sources for CP violation
- Only three complex new parameters (unlike Type III)
- $\mathcal{Z}_2$ models recovered for special values of ς_i's
- Radiative corrections symmetry-protected, of MFV-type (Cvetic et al. '98, Braeuninger et al. '10, MJ/Pich/Tuzón '10)
- Proposals towards UV-completion (Medeiros Varzielas'11, Serôdio'11)
- 1st term in spurion formalism with flavour-blind phases, w/o series around type II

EDMs in 2HDMs

In A2HDM, and most models with effective flavour-suppression:

- One-loop (C)EDMs: controlled (not tiny) (e.g. Buras et al. '10)
- 4-quark operators: small, no tan β^3-enhancement
- ➥ Two-loop graphs dominant (Weinberg '89, Dicus '90, Barr/Zee '90, Gunion/Wyler '90)
- ➥ Again sensitivity to UV-completion





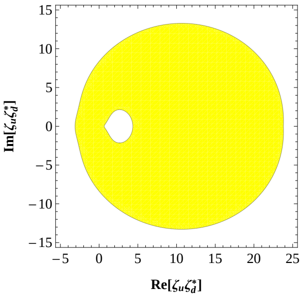
- Largest charged Higgs contribution from Weinberg diagram
- Barr-Zee(-like) diagrams dominate neutral Higgs exchange
- For neutrals: sum includes cancellations in general

Charged Higgs in the neutron EDM

- Two-step matching (Braaten et al., Boyd et al. '90):
  b-CEDM at $\mu_{EW} \to \mathcal{O}_W$ at μ_b
  ➥Absence of strong RGE-suppression for $\mathcal{O}_W$
- QCD sum rule estimate for matrix element

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

From $BR(b \to s\gamma)$ in complex $\zeta_d \zeta_u^*$-plane:



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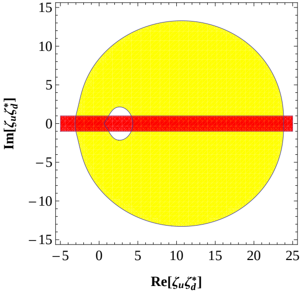
Constraint from neutron EDM on charged Higgs contribution:



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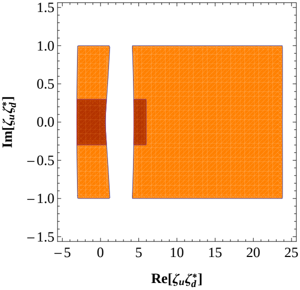
Combination of $BR(b \rightarrow s\gamma)$ and neutron EDM:



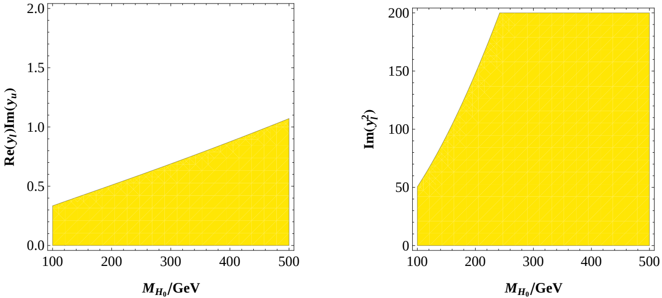
orange: $M_{H^\pm} = 500$ GeV
brown: $M_{H^\pm} = 80$ GeV

➥$Im(\zeta_d \zeta_u^*)$ strongly constrained, but not tiny

Neutral Higgs in EDMs

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

➜ Paramagnetic atom, EDM dominated by d_e (as shown)



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

➜ The A2HDM passes the EDM-test ✓

Conclusions and outlook

Conclusions:

- CPV-sector of NP models uniquely constrained by EDMs
- Quantitative results require close look at theory uncertainties
- Robust, model-independent limit on electron EDM:

$$|d_e| \leq 2.8 \times 10^{-27} e\,\mathrm{cm} \quad (95\%\,\mathrm{CL})$$

- 2HDMs active field, new developments
- 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
- Lots of new EDM-results to come, $1-3$ orders of magnitude expected within 1-few years

➥ Shortly we might see limits changing to determinations

Backupslides

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

Mercury EDM

$$
\begin{aligned}
d_{Hg} \quad = \quad & -(1.0 \pm 0.3) \times 10^{-17}\ e\,\mathrm{cm} \Big((1.0 \pm 0.8) 0.7\, \bar{g}_{\pi NN}^{(0)} + \\
& (1.0 \pm 0.9) 2.1\, \bar{g}_{\pi NN}^{(1)} \Big) + (1.0 \pm 0.1) \times 10^{-2}\ e\,\mathrm{GeV} \times \\
& \left[-1.48\, C_S + 0.09 \left(C_P + \frac{Z-N}{A} C_P' \right) \right] . \qquad (1)
\end{aligned}
$$

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]

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

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

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	
$\rho^2\|_{B\to Dl\nu}$	$1.18 \pm 0.04 \pm 0.04$	
$\Delta\|_{B\to Dl\nu}$	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	
$\bar{g}_{b,SM}^R$	$0.07744\,^{+\,0.00006}_{-\,0.00008}$	

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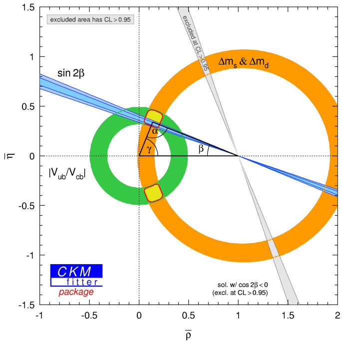
CKM-fit within the A2HDM

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



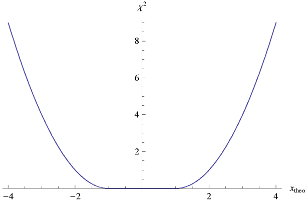
- Only the constraints from $|V_{ub}/V_{cb}|$ and $\Delta m_s/\Delta m_d$ survive.
- γ from tree-level decays not competitive yet, but excludes 2nd solution.
- $\Delta m_s/\Delta m_d = \Delta m_s/\Delta m_d|_{SM} + \mathcal{O}\left(\frac{m_s - m_d}{M_W}\varsigma_d\right)$

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 χ^2, outside increase corresponding to statistical error
➥Choose range conservatively
➥Theory errors add linearly

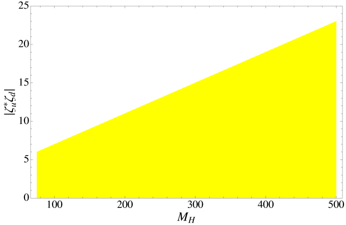


Averaging different theory-results even less well-defined...
➥Theory error at least that of best single result
➥Statistical errors treated "normally"
➥Here additionally: Criteria from FLAG (where available)

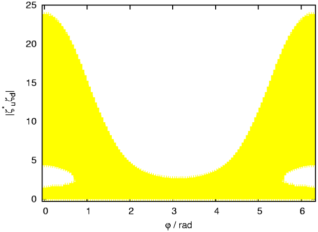
$b \to s\gamma$: Results

However: Correlations are extremely important:

$|\varsigma_u^* \varsigma_d|$ vs. M_H



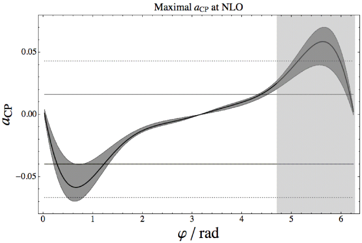
$|\varsigma_u^* \varsigma_d|$ vs. $\mathrm{Arg}(\varsigma_u^* \varsigma_d)$



- 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 $b \to s\gamma$

- Small in the SM (Ali et al.'98, Kagan/Neubert '98, Hurth et al.'05). See however again Benzke et al. '11.
- Potentially large in 2HDMs with new CPV (Borzumati/Greub '98)
- However, $BR(b \to s\gamma)$ constrains the asymmetry strongly:



➡ Compatible with measurement, but enhancement possible

➡ More precise measurement interesting ($\mapsto$ SuperB)