The electron EDM and EDMs in Two-Higgs-Doublet Models

Martin Jung

technische universität dortmund

GEFÖRDERT VOM Bundesministerium für Bildung und Forschung

Recontres de Moriond EW 2014
March 21st 2014

Based on:

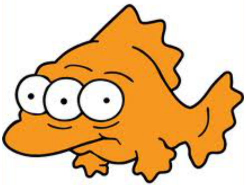
"A robust limit for the EDM of the electron", MJ, JHEP 1305 (2013) 168,

"EDMs in Two-Higgs-Doublet Models", MJ/Pich, JHEP 14xx (2014) xxx.

Outline

The Quest for New Physics

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



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

➥ $d_e^{SM} \lesssim 10^{-38} e\,\mathrm{cm}$ [Khriplovich/Pospelov '91]
Well below foreseeable tests!

EDMs extremely sensitive tests for new sources of CPV:

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

➥ Background-free precision-laboratory for NP
(For n assuming dynamical solution for strong CP)

➥ Probe of energy scales beyond the direct reach of LHC

EDMs and NP

Sakharov's conditions ('67):
NP models necessarily involve new sources of CPV!

- Typically over-fulfilled by NP models
  ("Significant EDMs just around the corner" always true)
- ➥ Generic one-loop contributions excluded
  ($\rightarrow$ e.g. SUSY CP-problem)
- ➥ Highly non-trivial flavour- and CPV-structure required
- ➥ Sensitivity to two-loop contributions

EDMs important on two levels:

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

Relating NP parameters and experiment

Most stringent constraints stem from neutral systems

➥ Shielding applies

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

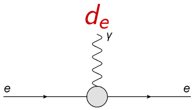
Each step potentially involves large uncertainties!

➥ E.g. sensitivity of Hg to Colour-EDMs questionable [MJ/Pich'14]

The EDM in heavy paramagnetic systems

Two main contributions, enhanced by Z^3: [Sandars'65, Flambaum'76]

- $\tilde{C}_S$: CP-odd Electron-Nucleon interaction
- Atoms: typically polarized in external field
- Molecules: aligned in external field

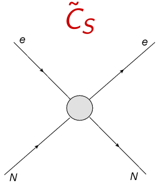


$\bar{e} F_{\mu\nu} \sigma^{\mu\nu} \gamma_5 e$

For molecules: energy shift $\Delta E = \hbar\omega$ with

$$\omega = 2\pi \left(\frac{W_d^M}{2} d_e + \frac{W_c^M}{2} \tilde{C}_S \right) .$$

Molecule	$W_d^M / 10^{25}\mathrm{Hz}/e\,\mathrm{cm}$	W_c^M/kHz
YbF	-1.3 ± 0.1	-92 ± 9
ThO	-3.67 ± 0.18	-598 ± 90



$(\bar{e} i \gamma_5 e)(\bar{N} N)$

[Results entering: Nayak/Chaudhuri'07,'08,'09; Dzuba et al.'11, Meyer/Bohn'08, Skripnikov et al.'13, Fleig/Nayak'14; Averages: MJ'13, MJ/Pich'14]

A model-independent limit on the electron EDM

Extracted limits for paramagnetic systems:

[Regan et al.'02, Hudson et al.'11, Baron et al.'14]

$$|d_e| \leq \left\{ \begin{array}{ll} 1.6 & (Tl) \\ 1.05 & (YbF) \\ 0.089 & (ThO) \end{array} \right\} \times 10^{-27} e\,\mathrm{cm}\,,$$

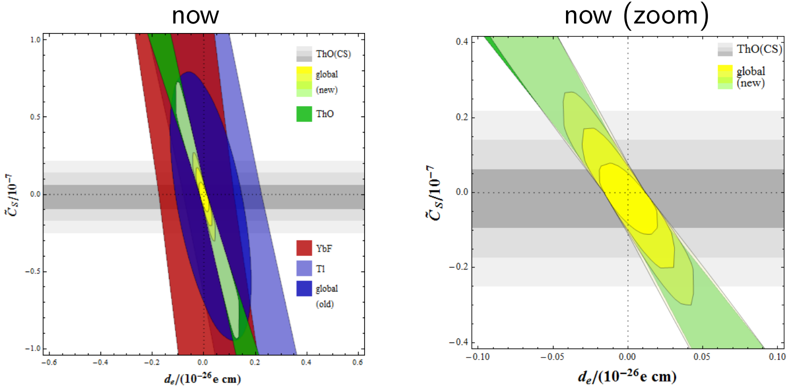
assuming exact coefficients and $\tilde{C}_S = 0$ (90% CL).

In principle: two unknowns, three measurements $\to d_e, \tilde{C}_S$

[Dzuba et al.'11,MJ'13]

- Coefficient uncertainties estimated, $(5-10)\%$
- Problem: W_d^M / W_c^M similar for all three systems
  - ➡ Bounds not independent in the $d_e - \tilde{C}_S$ plane
  - ➡ Large range for d_e and $\tilde{C}_S$ separately
- Idea for $\tilde{C}_S$: make assumption on a sub-leading level
  - ➡ Use bound on $\tilde{C}_S$ from Mercury (conservative!) [MJ'13]

Results for d_e and $\tilde{C}_S$

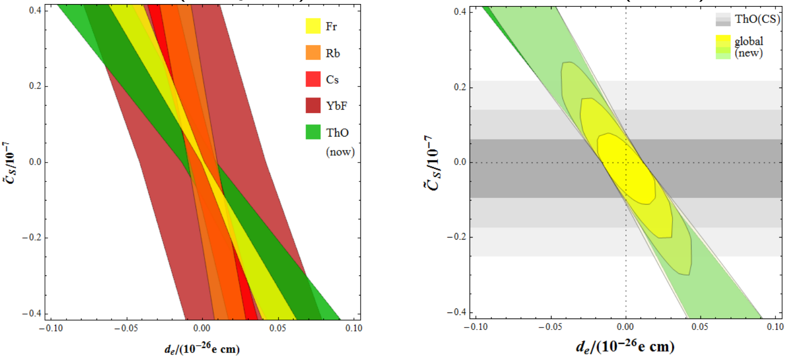


Problem: ThO first "new generation" experiment

- Cancellations possible in ThO, $|d_e| \leq 1.0 \times 10^{-27} e$ cm
- Option: impose $\omega_{\rm ThO}(\tilde{C}_S)|_{d_e=0} \leq n \times \omega_{\rm ThO}^{\rm exp}$, $n = 1, 2, 3 \ldots$
  - n=2 restriction: $|d_e| \leq 0.25 \times 10^{-27} e$ cm (95% CL)
- In the future: use additional measurements from *e.g.* Rb,Cs

Results for d_e and $\tilde{C}_S$

future (few years) now (zoom)



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  ➥ n=2 restriction: $|d_e| \leq 0.25 \times 10^{-27} e\,\mathrm{cm}$ (95% CL)
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Framework for 2HDM contributions

The CPV interactions of the 2nd doublet can generate EDMs

General parametrization for $H^\pm$ Yukawas, ς_i complex matrices:

$$\mathcal{L}_Y^{H^\pm} = -\frac{\sqrt{2}}{v} H^+ \left\{ \bar{u} \left[V \varsigma_d M_d \mathcal{P}_R - \varsigma_u M_u^\dagger V \mathcal{P}_L \right] d + \bar{\nu} \varsigma_l M_l \mathcal{P}_R l \right\} + \text{h.c.}$$

- Easily matched on your favourite model
  - ➥ M_i only choice of normalization
- $\varsigma_i \to$ numbers: Aligned 2HDM [Pich/Tuzon'09,MJ/Pich/Tuzon'10]
  - ➥ Comparisons with flavour data in this model

Neutral Higgs exchanges: couplings $y_i^0(\varsigma_i, V)$

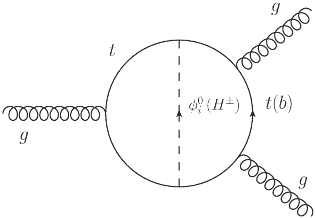
➥ Additional CPV contributions from the potential

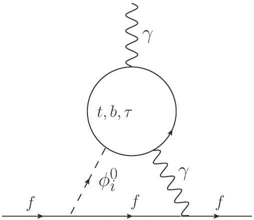
➥ Analysis depends on many unknown parameters

EDMs in 2HDMs

From necessary flavour suppression for a viable model:

- One-loop (C)EDMs: controlled (not tiny) [e.g. Buras et al. '10]
- 4-quark operators small (no $\tan^3\beta$-enhancement)
- ➥ Two-loop graphs dominant (plus eN-vertex) [Weinberg '89, Dicus '90, Barr/Zee '90, Gunion/Wyler '90,...]
  - Weinberg diagram important for neutron EDM
  - Barr-Zee(-like) diagrams dominate the other EDMs





➥ Mixed-up power counting, sensitivity to UV completion

Neutral Higgs contributions in general 2HDMs

Contributions typically involve the following sum:
(f,f': fermions, F(f): family of the fermion)

$$\sum_i \mathrm{Re}\left(y_f^{\varphi_i^0}\right)\mathrm{Im}\left(y_{f'}^{\varphi_i^0}\right) = \pm\,\mathrm{Im}\left[(\varsigma^*_{F(f)})_{ff}(\varsigma_{F(f')})_{f'f'}\right]$$

- R.h.s. independent of the Higgs potential
- Vanishes for equal fermions (universality: equal family)
- Modified by mass-dependent weight factors...
  - but holds for degenerate masses and decoupling limit

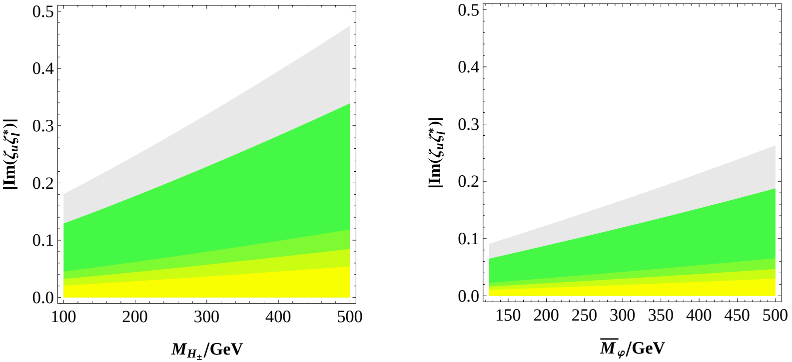
CPV in the potential tends to have smaller impact

Approximation for phenomenological analysis:

$$\sum_i f(M_{\varphi_i^0})\mathrm{Re}\left(y_f^{\varphi_i^0}\right)\mathrm{Im}\left(y_{f'}^{\varphi_i^0}\right) \to \pm\, f(\overline{M}_\varphi)\mathrm{Im}\left[(\varsigma^*_{F(f)})_{ff}(\varsigma_{F(f')})_{f'f'}\right] .$$

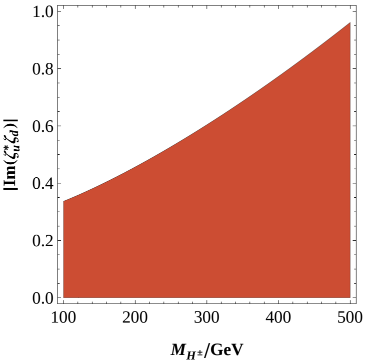
Bounds from the electron EDM

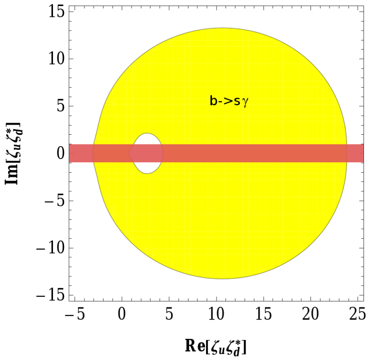
- Contributions via Barr-Zee diagrams [Bowser-Chao et al.'97]
- Sensitivity to $d_e \sim \mathrm{Im}(\varsigma^*_{u,33}\varsigma_{l,11})$
- Bounds $\mathrm{Im}(\varsigma^*_u \varsigma_l) \lesssim \mathcal{O}(0.1)$
  - ➥ Not too unnatural with mass normalization
- Implies $\mathrm{Im}(\varsigma_l \varsigma^*_u)/M^2_{H^\pm} \leq \times 10^{-5}\mathrm{GeV}^{-2}$ (universal ς_i's)
  - ➥ A factor 1000 stronger than (semi)leptonic constraints!



Bounds from the neutron EDM

- Size of Weinberg (charged) and Barr-Zee (neutral) similar
- So far no fine-tuning necessary
- Next-generation experiments will test critical parameter space
- Constraint from Hg potentially a few times stronger
- Comparison with $b \to s\gamma$: large impact! [MJ/Pich'14,MJ/Li/Pich'12]
  ➥ EDMs restrict CPV in other modes





Conclusions and outlook

- CPV-sector of NP models uniquely constrained by EDMs
- Quantitative results require close look at theory uncertainties
  - ➥ Use conservative limits, allowing for cancellations
- Robust, model-independent limit on electron EDM:

$$|d_e| \leq 1.0(0.25) \times 10^{-27} e\,\mathrm{cm} \quad (95\%\,\mathrm{CL}, Hg/n = 2)$$

  - ➥ Issue: 2nd competitive measurement missing

- General discussion of 2HDM constraints possible
  - ➥ ς_i key parameters, CPV from potential suppressed
- Very strong constraints from EDMs
  - ➥ Flavour suppression just sufficient
  - ➥ CPV in other observables strongly restricted

- Lots of new EDM-results to come (atoms and molecules)
  - ➥ Renders use of d_{Hg} or fine-tuning arguments unnecessary
  - ➥ Might turn limits into determinations


Thank you!
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Backup slides

- 2HDM Framework
- Limits on $|d_e|$ and $|\tilde{C}_S|$
- Expected limits from paramagnetic systems
- Theory uncertainties and the EDM of Mercury

Framework for 2HDM contributions

In 2HDMs, CPV in new interactions can generate EDMs!

Parametrization for $H^\pm$ Yukawas, ς_i complex:

$$\mathcal{L}_Y^{H^\pm} = -\frac{\sqrt{2}}{v} H^+ \left\{ \bar{u} \left[V \varsigma_d M_d \mathcal{P}_R - \varsigma_u M_u^\dagger V \mathcal{P}_L \right] d + \bar{\nu} \varsigma_l M_l \mathcal{P}_R l \right\} + \text{h.c.}$$

- General for coupling matrices ς_i (M_i choice of normalization)
- Numbers ς_i: Aligned 2HDM [Pich/Tuzon'09,MJ/Pich/Tuzon'10]
- Easily matched on your favourite model

For mass eigenstates $\varphi_i^0 = \{h, H, A\}$, $\mathcal{M}^2_{\rm diag} = \mathcal{R}\mathcal{M}^2\mathcal{R}^T$, we have

$$\mathcal{L}_Y^{\varphi_i^0} = -\frac{1}{v} \sum_{\varphi, f} \varphi_i^0 \, \bar{f} \, y_f^{\varphi_i^0} M_f \mathcal{P}_R f + \text{h.c.},$$

$$y_f^{\varphi_i^0} = \mathcal{R}_{i1} + (\mathcal{R}_{i2} \pm i \, \mathcal{R}_{i3}) \left(\varsigma_{F(f)}^{(*)} \right)_{ff} \quad \text{for} \quad F(f) = d, l(u) .$$

For neutrals: additional CPV contributions from the potential!

Results for d_e and $\tilde{C}_S$ from ThO [MJ/Pich'14]

Input	$\|d_e\|$ limit (95% CL)	$\|\tilde{C}_S\|$ limit (95% CL)
Result w/o ThO [MJ'13]	$1.4 \times 10^{-27} e\,\text{cm}$	7×10^{-8}
Including ThO, $\tilde{C}_S$ Hg	$1.0 \times 10^{-27} e\,\text{cm}$	7×10^{-8}
Including ThO, $\tilde{C}_S$ ThO ($n = 3$)	$0.35 \times 10^{-27} e\,\text{cm}$	2.3×10^{-8}
Including ThO, $\tilde{C}_S$ ThO ($n = 2$)	$0.25 \times 10^{-27} e\,\text{cm}$	1.6×10^{-8}
Including ThO, $\tilde{C}_S$ ThO ($n = 1$)	$0.16 \times 10^{-27} e\,\text{cm}$	0.8×10^{-8}
ThO only, $\tilde{C}_S = 0$, 90% CL	$0.089 \times 10^{-27} e\,\text{cm}^{\dagger,\ddagger}$	$0.6 \times 10^{-8,\ddagger}$

Table : New limits on the electron EDM and $\tilde{C}_S$, including the measurement in the ThO system [Baron et al,'13] . †: Using W_d from [Skripnikov et al.'13] . ‡: Theory errors neglected.

Expected limits from paramagnetic atoms

System	Expected limit (e cm)
^{133}Cs	$\mathcal{O}(10^{-26}/10^{-27})$ [Amini et al.'07,Kittle et al.'04,Weiss et al.'03]
^{85}Rb	$\mathcal{O}(10^{-27}/10^{-28})$ [Weiss et al.'03]
^{210}Fr	$\mathcal{O}(10^{-26}/10^{-29})$ [Sakemi et al.'11,Wundt et al.'12]
YbF	$\mathcal{O}(10^{-22}/10^{-23-24})$ [Kara et al.'12]

Table : Short-term/mid-term expected sensitivities for paramagnetic atoms.

Theory uncertainties and the EDM of Mercury

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

$$d_{Hg} \overset{Atomic}{=} d_{Hg}(S, C^N_{S,P}) \overset{Nuclear}{=} d_{Hg}(\bar{g}_{\pi NN}, C^{p,n}_{S,P}) \overset{QCD}{=} d_{Hg}(d^C_f, C_{qq'}, C^q_{S,P})$$

  - Uncertainties: Atomic$\sim$ 20%, Nuclear$\sim$ x00%, QCD sum rules$\sim$ 100 − 200%
  - ➡ No conservative constraint on CEDMs left! [MJ/Pich'13]

$$d_{\mathrm{Hg}} = \Big\{-(1.0 \pm 0.2)\left((1.0 \pm 0.9)\,\bar{g}^{(0)}_{\pi NN} + 1.1\,(1.0 \pm 1.8)\,\bar{g}^{(1)}_{\pi NN}\right) + (1.0 \pm 0.1) \times 10^{-5}\left[-4.7\,\tilde{C}_S + 0.49\,\tilde{C}_P\right]\Big\} \times 10^{-17}\; e\,\mathrm{cm}\,,$$

Progress in theory necessary to fully exploit precision measurements of diamagnetic EDMs