A robust limit on the EDM of the electron

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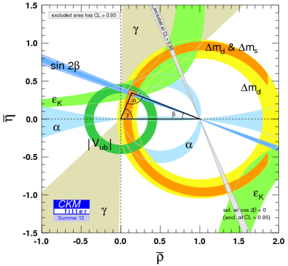
Outline

Motivation

Flavour and CP violation in the SM:

- CKM describes flavour and CP violation
- Extremely constraining, one phase
- Especially, K and B physics agree

➥ Works well!



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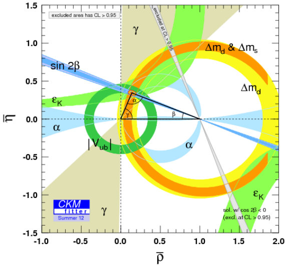

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- Baryon asymmetry of the universe
- Hierarchy problem
- Dark matter and energy
- . . .

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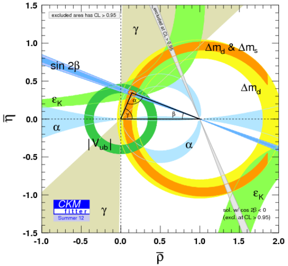

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➥So where is it?

The Quest for New Physics

We are living in interesting times! (Remember the curse?)

Three main paths to NP (also ν, astrophysics, ...):

- Tevatron results, LHC is running
  - Fantastic first three years at LHC
  - In layman's terms: We've got it!
  - New results just a week away

Direct search

- Flavour machines
  - B factories (!)
  - ΔA_{CP} in charm
  - Lots to come!
    Belle II, BES III, NA62, ...

Indirect search, flavour violating

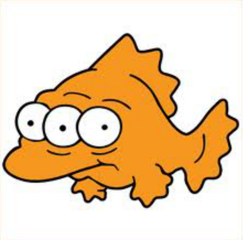
- EDM experiments, $g-2$,...
  - Qualitative progress in EDMs, new mechanisms and methods
  - Most recent results: YbF molecules
  - Many experiments ongoing/planned

Indirect search, flavour conserving

Particle physics is entering a new era!

The curious case of the One-Higgs-Doublet Model

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 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)

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

EDMs and NP

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

- In fact, generally (too) large EDMs ("EDMs just around the corner" always true)
- Highly non-trivial flavour- and CPV-structure

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

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

EDMs important on two levels:

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

Theory uncertainties - more than a nuisance

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: difficult diamagnetic system
  - Shielding efficient $\to$ sensitivity $\sim d_n, d_{Tl}$
  - All stages enter:

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

  - CEDMs typically dominant contribution
  - Uncertainties:
    Atomic$\sim 20\%$, Nuclear$\sim x00\%$, QCD sum rules$\sim 100-200\%$
  - ➥ No conservative constraint on CEDMs left!
    (MJ/Pich'13, in prep.)

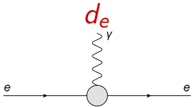
Progress in theory necessary to fully exploit precision measurements of diamagnetic EDMs

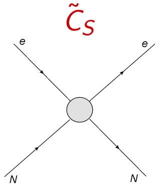
The EDM in paramagnetic systems

(Basics covered in talks by K. Jungmann, J. Hisano, Ed. Hinds, B.P. Das)

Two main contributions, enhanced by Z^3: (Sandars'65, Flambaum'76)

- Electron EDM d_e
- CP-odd Electron-Nucleon interaction $\tilde{C}_S$
- ➥ $d_X = C^X_{d_e} d_e + C^X_{\tilde{C}_S} \tilde{C}_S$
- Uncertainties in much better shape





System	C_{d_e}	$C_{\tilde{C}_S}/10^{-18} e\,\mathrm{cm}$
Tl	-573(20)	-7.0(3)
	-466(16)	-4.1(1)
Cs	123(4)	0.78(2)
Rb	25.7(8)	0.110(3)
Fr	903(45)	10.9(17)
YbF	$-1.3(1) \times 10^6$	-9740(960)

(Results entering: Burnes, Chaudhuri, Das, Dzuba, Flambaum, Harabati, Kozlov, Mukherjee, Murray, Nataraj, Nayak, Porsev, Safronova, Sahoo, Venugopal. Averages: MJ'13)

Theory uncertainties II - the EDM of Thallium

The EDM of Thallium:

- Often extracted via $d_{Tl} = -585 d_e$ (Mårtensson-Pendrill, Öster 1987)
- Calculations span $C_{d_e} \in [-1041, -179]$(!) (cancellations!)
- Recent results: $d_{Tl} \sim -582(20) d_e$, $\sim 466(10) d_e$, $\sim 573(20)$ (Dzuba/Flambaum '09, Nataraj et al.'10, Porsev et al.'12)
- Furthermore: Four-fermion operators relevant

➥ Above formula too simple!

➥ To obtain limit: constraint/assumption needed for $\tilde{C}_S$!

A model-independent limit on the electron EDM

Recent measurements for paramagnetic systems:

(Regan et al.'02, Hudson et al.'11)

$$d_{\rm Tl}^{\rm exp} = -(4.0 \pm 4.4) \times 10^{-25} e\,{\rm cm}, \quad d_{YbF} = (3.5 \pm 8.7) \times 10^{-22} e\,{\rm cm}$$

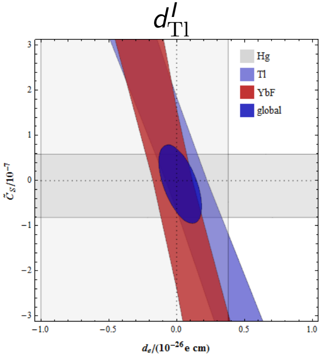
Assuming exact coefficients and $\tilde{C}_S = 0$ (90% CL):

$$\left| d_e^{\rm Tl} \right| \leq 1.6 \times 10^{-27} e\,{\rm cm} \quad \left| d_e^{\rm YbF} \right| \leq 1.05 \times 10^{-27} e\,{\rm cm}$$

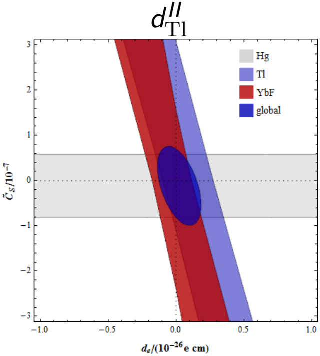
In principle: two unknowns, two similarly sensitive measurements

- Uncertainties estimated (see previous slide)
- Problem: $C_{d_e}^{\rm Tl} / C_{\tilde{C}_S}^{\rm Tl} \approx C_{d_e}^{\rm YbF} / C_{\tilde{C}_S}^{\rm YbF}$
  - ➥Bounds not independent in the $d_e - \tilde{C}_S$ plane!
  - ➥Large range / no bound on 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!)

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



$|\tilde{C}_S| \leq 0.72 \times 10^{-7}$



$|\tilde{C}_S| \leq 0.74 \times 10^{-7}$

$\mathbf{|d_e| \leq 1.4 \times 10^{-27}\,e\,cm}$ **(95% CL)** (MJ'13)

Without d_{Hg} (left): $|\tilde{C}_S| \leq 8.6 \times 10^{-7}$ and $|d_e| \leq 8.9 \times 10^{-27}\,e\,\mathrm{cm}$

(Compare the latter number also to Dzuba et al.'12)

Turning the argument around

Other limits not relevant to this plot

➡ Use results to bound their EDMs

System	Allowed range (theory)	Experimental bound on $\lvert d_X \rvert$
Cs	$[-1.6, 2.0] \times 10^{-25}$	1.4×10^{-23} (Murthy et al.'89)
Rb	$[-3.1, 4.1] \times 10^{-26}$	1×10^{-18} (Ensberg et al.'67)
	unpublished:	(1.2×10^{-23}) (Huang-Hellinger'87)
Fr	$[-1.3, 1.5] \times 10^{-24}$	—

➡ **Several orders of magnitude below present limits!**

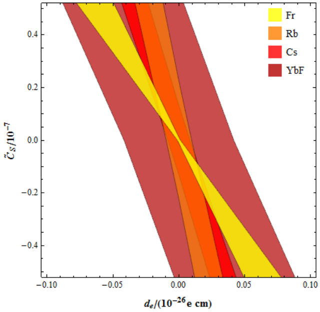
Experiments aiming at even better sensitivity:

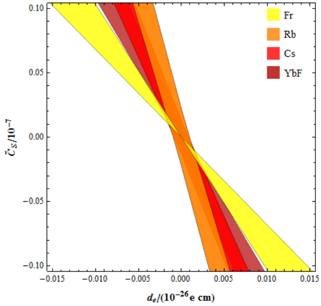
➡ Important progress to be expected

➡ Measurement larger than above limits would indicate a problem

Improving the method in the future

Projections for experiments with paramagnetic atoms:





- Left: in a few years (true? comments?)
- Right: longer term (> 5 years)
- Plot scale changes, area $\times\ 1/60$ and $1/2000$
- Constraints not shown fill the whole plots
- ➥ Large improvement, Hg not necessary anymore
- ➥ Measurements with varying $C_{d_e}/C_{\tilde{C}_S}$ important

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

Not an attempt at a complete theory!

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]

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

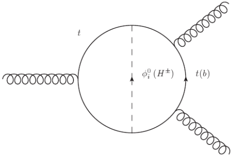
with complex, observable parameters $\varsigma_{u,d,l}$, implying:

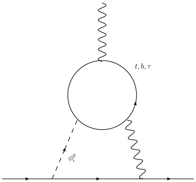
- No FCNCs at tree-level
- New sources for CP violation
- Only three complex new parameters (unlike Type III)
- $\mathcal{Z}_2$ models recovered for special values of $\varsigma_i' s$
- Radiative corrections symmetry-protected, of MFV-type (Cvetic et al. '98, Braeuninger et al. '10, MJ/Pich/Tuzón '10)
- 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 $\tan\beta^3$-enhancement
- ➥ Two-loop graphs dominant (Weinberg '89, Dicus '90, Barr/Zee '90, Gunion/Wyler '90,...)



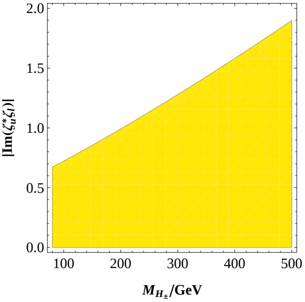


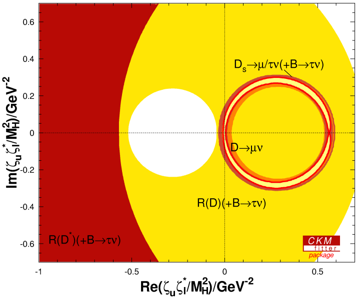
- ➥ Again sensitivity to UV-completion
- Largest $H^\pm$ contribution to neutron from Weinberg diagram
- Barr-Zee(-like) diagrams dominate neutral Higgs exchange
- For neutrals: sum includes cancellations in general

Charged Higgs contribution to the electron EDM

Constraining the $H^{\pm}$-Yukawa couplings: (MJ/Pich'13, in prep.)

- Enters via a Barr-Zee diagram (Bowser-Chao et al.'97)
- Results in structure $d_e \sim m_e\, G_F\, \mathrm{Im}(\varsigma_u^* \varsigma_l)\, f(M_H^2)$
- Assuming this contribution to saturate the limit:
  - Leads to $\mathrm{Im}(\varsigma_l \varsigma_u^*) \leq \mathcal{O}(1)$
    ➥Not very unnatural!
  - Implies $\mathrm{Im}(\varsigma_l \varsigma_u^*)/M_{H^\pm}^2 \leq 1 \times 10^{-4}\mathrm{GeV}^{-2}$
    ➥A factor 3000 stronger than (semi)leptonic constraints!





Conclusions and outlook

- We are entering a new era of particle physics
- Quantitative results require close look at theory uncertainties
  ➥Can be taken care of together with possible cancellations
- Robust, model-independent limit on electron EDM:

$$|d_e| \leq 1.4 \times 10^{-27} e\,\mathrm{cm} \quad (95\%\,\mathrm{CL})$$

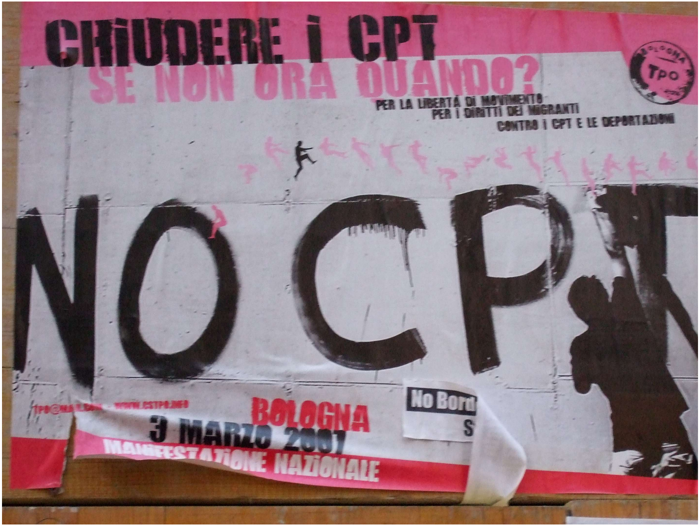
➥ Bounds on other systems

- 2HDMs active field, new developments
- A2HDM:
  - New CPV possible with sufficient FCNC suppression(!)
  - Rich phenomenology, only three new flavour-parameters
  - Very strong (but not "killing") constraints from EDMs

- Lots of new EDM-results to come (atoms and molecules), will make method independent of d_{Hg}

➥ Shortly we might see limits changing to determinations

Public protests about to change the picture?



Backupslides

- Expected limits from paramagnetic atoms
- Framework
- $\tilde{C}_S$ in the Mercury EDM

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.