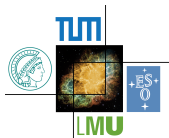


Bounds on new physics from EDMs

Martin Jung



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Forschungsgemeinschaft

Talk at the Workshop “Selected Topics in High Energy Physics”
Goriška Brda, Slovenia, 12th of October 2017

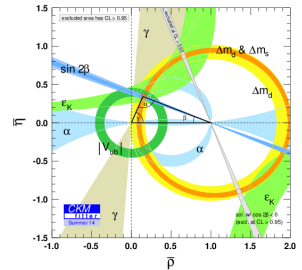


Motivation

Quark-flavour and CP violation in the SM:

- CKM describes flavour **and** CP violation
- Extremely constraining, one phase
- Especially, K and B physics agree
- Only tensions so far [see S.Jäger, O.Sumensari]
 $(R_{K,K^*}, P'_5, B \rightarrow D^{(*)} \tau \nu, g_\mu - 2, \dots)$

➔ Works well!

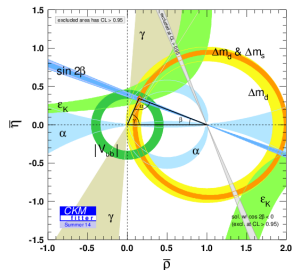


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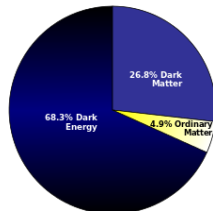
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 $(R_{K,K^*}, P'_5, B \rightarrow D^{(*)} \tau \nu, g_{\mu} - 2, \dots)$

➔ Works **too** well!



We expect new physics (ideally at the (few-)TeV scale):

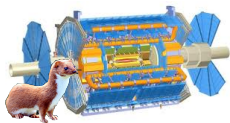
- Baryon asymmetry of the universe
- Hierarchy problem
- Dark matter and energy
- ...



➔ So where is it?

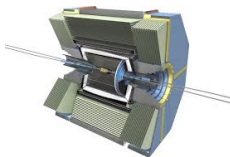
The Quest for New Physics

Three of the main strategies (missing are e.g. ν , DM, astro,...):



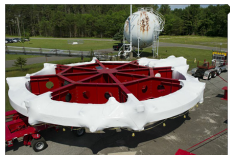
Direct search:

- Tevatron, LHC
- Maximal energy fixed



Indirect search, flavour violating:

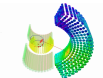
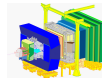
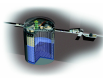
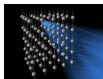
- LHCb, Belle II, BES III, NA62, MEG, ...
- Maximal reach flexible



Indirect search, flavour diagonal:

- **EDM experiments**, g-2, ...
- Maximal reach flexible, complementary to flavour-violating searches

**A new era in
particle physics!**

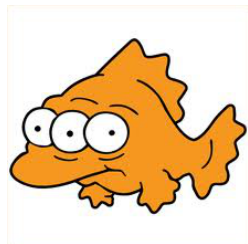


The curious case of the One-Higgs-Doublet Model

EDMs are finite in the SM...

...but flavour-sector of the SM is special (\rightarrow):

- Unique connection between Flavour- and CP-violation
- FCNCs highly suppressed, $\sim \Delta m^2/M_W^2$
 - $\rightarrow \Delta m^2/M_W^2 \sim 10^{-25}$ for ν in the loop!
- FC**onserving**NCs with CPV as well:
 - $\rightarrow d_e^{SM} \lesssim 10^{-38} e \text{ cm}$ [Khriplovich/Pospelov '91]



EDMs are quasi-nulltests of the SM!

NP models typically do **not** exhibit such strong cancellations

- \rightarrow Background-free precision-laboratories for NP (assuming dynamical solution for strong CP)
- \rightarrow EDMs $\sim CPV/\Lambda^2$ (interference with SM, e.g. LFV $\sim 1/\Lambda^4$)

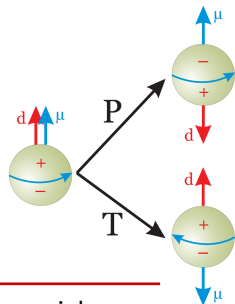
Here: focus as much as possible on model-independent statements

Back to basics: EDMs

Classically: $\mathbf{d} = \int d^3r \rho(\mathbf{r}) \mathbf{r}$, $U = \mathbf{d} \cdot \mathbf{E}$

QM: non-degenerate ground state implies $\mathbf{d} \sim \mathbf{j}$

- ➡ $\mathbf{d} \neq \mathbf{0}$ implies T- and P-violation!
- ➡ CP-violation for conserved CPT
- ➡ Search for linear shift $U = d \mathbf{j} \cdot \mathbf{E}$



Non-relativistic neutral system of **point-like** particles:
Potential EDMs of constituents are shielded! [Schiff'63]

- ➡ Sensitivity stems from violations of the assumptions
 - Paramagnetic systems: relativistic enhancement
 - Diamagnetic systems: finite-size effects

Shielding can be reversed, e.g. $d_A^{\text{para}} \sim \mathcal{O}(100) \times d_e!$

[Sandars'65,'66]

EDMs and New Physics: Generalities

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

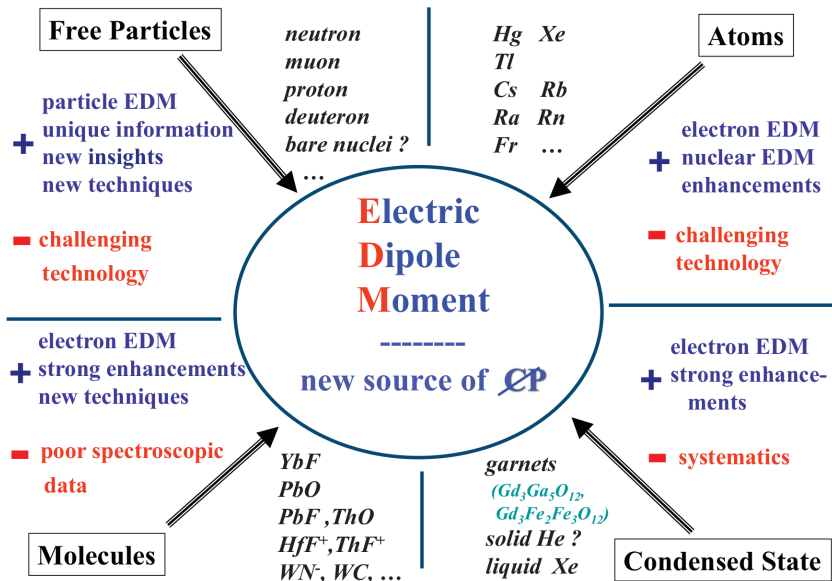
- This does not *imply* sizable EDMs
- However, typically (too) large EDMs in NP models
- ➔ Generic one-loop contributions excluded
(→ SUSY CP-problem)
- ➔ EDMs test combination of flavour- and CPV-structure

EDMs important on two levels:

- “Smoking-gun-level”: Visible EDMs proof for NP
- Quantitative level:
Setting limits/determining parameters
 - ➔ Theory uncertainties are important!

Experimental approaches [K. Jungmann'13 in Annalen der Physik]

Lines of attack towards an EDM



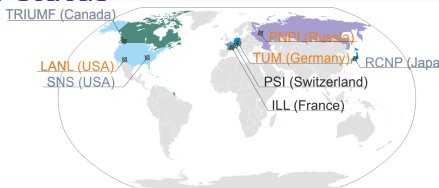
Experimental status

Neutron EDM:

- $|d_n| \leq 3.6 \times 10^{-26} e \text{ cm}$ (95%CL)

[Pendlebury+'15, Baker+'06]

- Worldwide effort aiming at $(10 \rightarrow 0.1) \times 10^{-27} e \text{ cm}$
- UCN sources critical problem



[P.Schmidt-Wellenburg'16]

Paramagnetic systems:

- Atomic: $|d_{\text{Tl}}| \leq 9.6 \times 10^{-25} e \text{ cm}$ (95% CL) [Regan+'02]
- Molecular: $|\omega_{\text{ThO}}| \leq 11.1 \text{ mrad/s}$ (90% CL) [Baron+'13]
- Naive interpretation: $|d_e| \leq 8.7 \times 10^{-29} e \text{ cm}$
- Ongoing: ThO, YbF, Cs, Fr, Rb, HfF⁺...

Diamagnetic systems:

- $|d_{\text{Hg}}| \leq 7.4 \times 10^{-30} e \text{ cm}$ (95% CL) [Graner+'16]
- Ongoing: exploit **octupole deformation**, e.g. Ra, Rn,...

Solid state systems: $|d_e| \leq 6.1 \times 10^{-24-25} e \text{ cm}$ [Eckel+'12, Kim+'15]

Storage rings: $|d_\mu| \leq 1.9 \times 10^{-19} e \text{ cm}$ [Bennett+'08]

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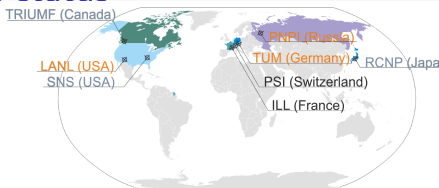
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- **New:** HfF⁺ measurement [Cairncross+'17, arXiv: 1704.07928]

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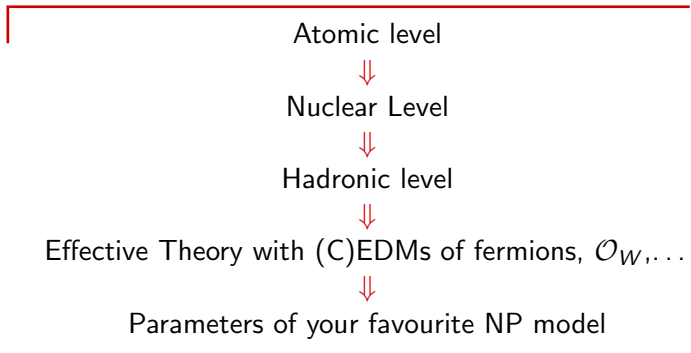
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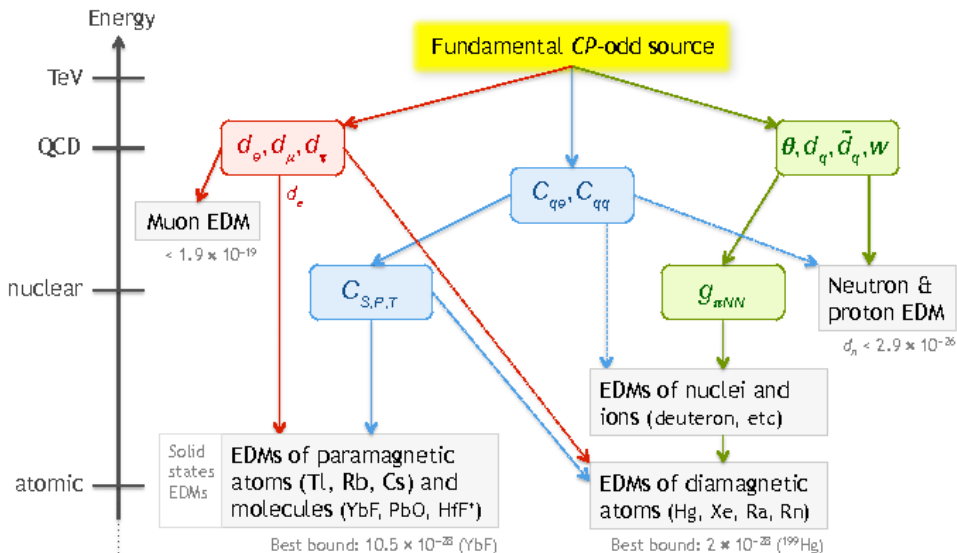
Relating NP parameters and experiment

- Most stringent constraints from neutron, atoms and molecules
 - ↳ Shielding typically applies



- Each step potentially involves large uncertainties!
- 4/5 model-independent \Rightarrow series of EFTs [e.g. deVries+'11]
- Limits usually displayed as allowed regions
 - ↳ Conservative uncertainty estimates important

Schematic EFT framework [Pospelov/Ritz'05,Hoecker'12]

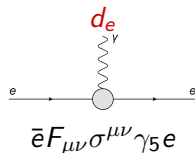


The EDM in heavy paramagnetic systems

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

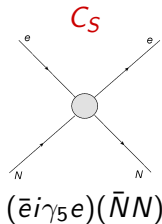
➡ A single measurement does **not** restrict d_e directly

- C_S : CP-odd electron-nucleon interaction
- Atoms: typically polarized in external field
- Molecules: aligned in external field
 - ➡ Exploit huge internal field



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

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



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

[Results entering: Nayak/Chaudhuri'07,'08,'09; Dzuba et al.'11, Meyer/Bohn'08,

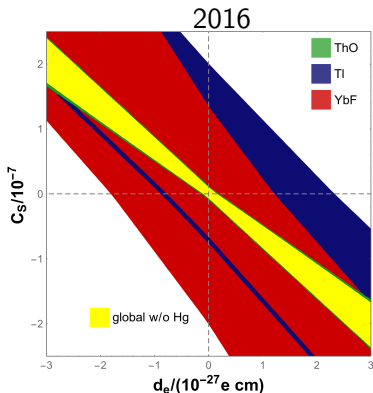
Skripnikov et al.'13, Fleig/Nayak'14;

Averages: MJ'13, MJ/Pich'14]

Model-independent extraction of d_e and C_S

In principle: two unknowns, three measurements (TI, YbF, ThO)

➔ Extract d_e , C_S model-independently [Dzuba et al.'11, MJ'13]



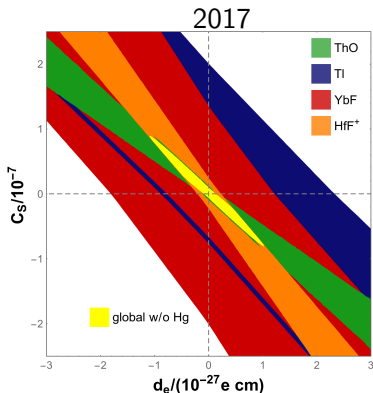
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➔ weak limits

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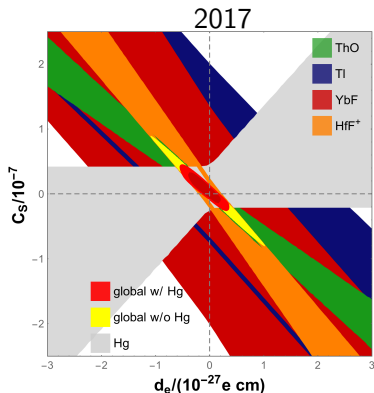
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Partial resolution: HfF⁺ result

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Mercury bound \sim orthogonal!

Assumption: C_S , d_e saturate d_{Hg}

➡ Conservative

[Fleig, MJ('17) preliminary]

$$d_e \leq 3.9 \times 10^{-28} e \text{ cm}$$

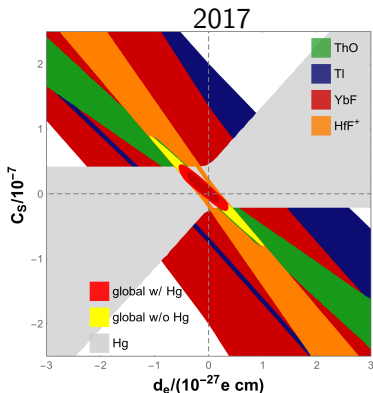
$$C_S \leq 3.2 \times 10^{-8}$$

Yields model-independent limit
on **every** paramagnetic system!

Model-independent extraction of d_e and C_S

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Yields model-independent limit
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Future measurements aim at precision beyond present constraints!

➡ Help to resolve the alignment problem

➡ Requires precision measurements of low-Z and high-Z elements

EDMs of diamagnetic systems and nucleons

Situation more complicated than for paramagnetic systems:

- Potential SM contribution: $\bar{\theta}$ (\rightarrow strong CP puzzle)
- Contributions from $\bar{\theta}$, d_q , \tilde{d}_q , w , $C_{S,P,T}$, C_{qq}
 - ➡ Interpretation usually model-dependent
 - (for model-independent prospects: [Chupp/Ramsey-Musolf'14])

Complementary measurements, different sources possible/likely

- $|d_{Hg}| \leq 7.4 \times 10^{-30} \text{ e cm}$ [Graner et al. '16] , very constraining
Problem: QCD and nuclear theory uncertainties ($\times 100\%$)
➡ No conservative constraint on CEDMs left! [MJ/Pich'13]
- $|d_n| \leq 3.6 \times 10^{-26} \text{ e cm}$ [Pendlebury'15]
Theory in better shape, still $\mathcal{O}(100\%)$ uncertainties
[Pospelov/Ritz'01, Hisano et al'12, Demir et al'03,'04, de Vries et al'11]

Progress in theory necessary to fully exploit these measurements
Unique: orders-of-magnitude improvement **w/o new measurement!**

The role of Mercury in determining the electron EDM

Mercury is a diamagnetic system, many contributions

- ➡ Why is it shown in the paramagnetic global fit? [MJ'13]
 - Shielding of C_S and d_e effective (even vanishing at LO)
 - ➡ Schiff moment contribution expected to be dominant
 - ➡ d_e , C_S only a fraction of the total EDM
 - ➡ Assuming d_e , C_S to saturate the exp. limit is **conservative**

New calculation of the C_S coefficient [Fleig/MJ('17),preliminary]

LO contribution vanishes

- ➡ Triple perturbative expansion necessary:
 1. External electric field (here: included in basis set)
 2. Hyperfine splitting
 3. d_e/C_S

$$\alpha_{C_S} = -2.8(6) \times 10^{-22} \text{ e cm}$$

α_{d_e} w.i.p., so far old calculation [Martensson-Pendrill/Oster'85] + conservative error estimate

The importance of multiple measurements

Only **pattern** of CPV observables allows for model-differentiation!

➡ There is no single “best” measurement!

Paramagnetic systems:

- 1 significant measurement NP
- 2 determine ideally d_e and C_S
- More for consistency (unless MQM is relevant)

Diamagnetic systems, nucleons, light nuclei:

- 1 significant measurement: $\bar{\theta}$ possible explanation
- 2 should tell $\bar{\theta}$ from other sources
- Many more to identify model-independently CPV structure

➡ We need as many measurement as possible!

➡ Ideally very different systems

➡ Try to find P-, T-odd measurements besides EDMs

EDMs in NP Models

EDM constraints forbid generic CPV contributions up to two loops

➡ huge scales or highly specific structure!

- hardly testable elsewhere
- simple power-counting insufficient (UV sensitivity)
- ➡ Model-independent analyses difficult

EDMs unique, both blessing and curse

- some model-independent relations exist, e.g. to β decay [Khriplovich'91, see also e.g. Dekens/Vos'15]
- strong (model-dependent) constraints of related observables



Remainder of this talk: 2HDMs as an example

Why 2HDM?

Model-independent NP analysis: Too many parameters in general

EW symmetry breaking mechanism still not completely fixed:

- 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
- Plethora of 2HDMs:
 - ➔ differ in their suppression mechanism for FCNCs

Could explain tensions in the flavour sector (e.g. $B \rightarrow D^{(*)} \tau \nu$)



Not an attempt at a complete theory!

Framework for 2HDM contributions

The CPV interactions of the 2nd doublet can generate EDMs

General parametrization for H^\pm Yukawas, ζ_i **complex matrices**:

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

- Induce couplings like W -exchange, just with a charged Higgs ($M_{H^\pm} \gtrsim m_t$)
- Easily matched on your favourite model
 - ➡ M_i only choice of normalization
- $\zeta_i \rightarrow$ **numbers**: Aligned 2HDM [Pich/Tuzon'09, MJ/Pich/Tuzon'10]
 - ➡ Comparisons with flavour data in this model

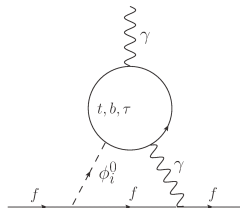
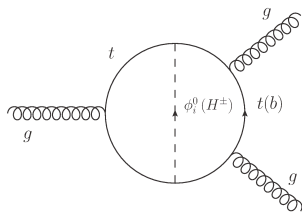
Neutral Higgs exchanges: couplings $y_i^0(\zeta_i, V)$

- ➡ 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
 - [Weinberg '89, Dicus '90, Barr/Zee '90, Gunion/Wyler '90, ...]
 - Weinberg diagram important for neutron EDM
 - Barr-Zee(-like) diagrams dominate other EDMs



Paramagnetic systems: tree-level can be relevant ($C_S \times Z^3$)
(light-quark mass \times tree) vs. (top mass \times two-loop)

Neutral Higgs contributions in general 2HDMs [MJ/Pich'13]

Contributions typically involve the following sum:

(f,f': fermions, F(f): family of the fermion)

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

- 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

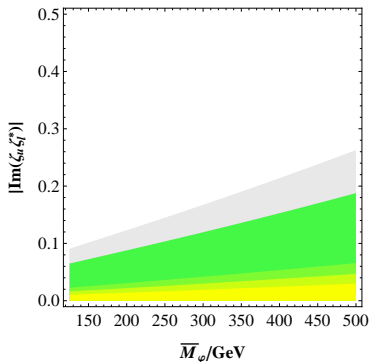
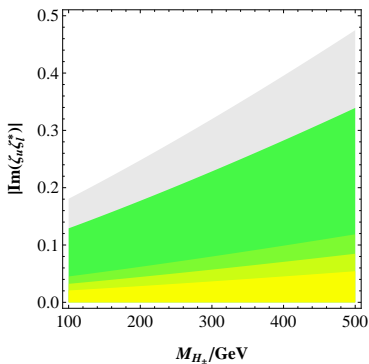
CPV in the potential tends to have smaller impact

➡ Approximation for phenomenological analysis:

$$\sum_i f(M_{\varphi_i^0}) \operatorname{Re} \left(y_f^{\varphi_i^0} \right) \operatorname{Im} \left(y_{f'}^{\varphi_i^0} \right) \rightarrow \pm f(\overline{M}_\varphi) \operatorname{Im} \left[(\zeta_{F(f)}^*)_{ff} (\zeta_{F(f')})_{f'f'} \right] .$$

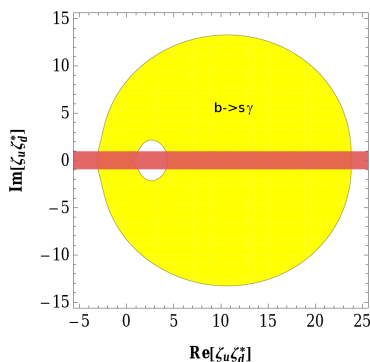
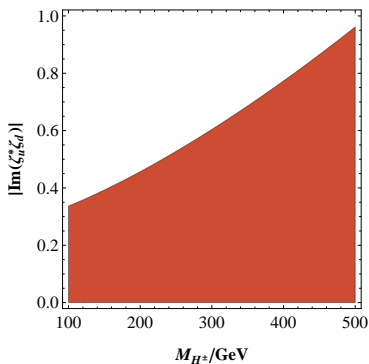
Bounds from the electron EDM

- Contributions via Barr-Zee diagrams [Bowser-Chao et al.'97]
- Sensitivity to $d_e \sim \text{Im}(\zeta_u^* \zeta_l)$
- Bounds $\text{Im}(\zeta_u^* \zeta_l) \lesssim \mathcal{O}(0.05)$
 - ➔ Strong despite two-loop suppression and mass factors
- Implies $\text{Im}(\zeta_l \zeta_u^*) / M_{H^\pm}^2 \leq \times 10^{-5} \text{GeV}^{-2}$ (universal ζ_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 $b \rightarrow s\gamma$: large impact! [MJ/Pich'14, MJ/Li/Pich'12]
- ➡ EDMs restrict CPV in other modes



Conclusions

- EDMs unique tests of NP models
- Model-independent constraints on NP parameters difficult
 - ➔ Need (at least) as many experiments as (eff.) parameters
- Quantitative results require close look at theory uncertainties
 - ➔ Use conservative limits, allowing for cancellations
 - ➔ For *e.g.* d_n, d_{Hg} bottleneck! **Chance for nuclear theory**
- Robust, model-independent limit on electron EDM (C_S not model-independently negligible):

$$|d_e| \leq 3.9 \times 10^{-28} e \text{ cm} \quad (95\% \text{ CL})$$

- General discussion of 2HDM constraints possible
 - ➔ ζ_j key parameters, CPV from potential suppressed
- Interplay of EDMs with flavour physics
 - ➔ Flavour suppression just sufficient
 - ➔ CPV in other observables strongly restricted
- Plethora of new results to come
 - ➔ Might turn limits into determinations!

Backup slides

- EDM EFT framework
- 2HDM Framework
- Limits on $|d_e|$ and $|C_S|$
- Expected limits from paramagnetic systems

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

$$\begin{aligned} \mathcal{O}_f^\gamma &= ie \bar{\psi}_f F^{\mu\nu} \sigma_{\mu\nu} \gamma_5 \psi_f, & \mathcal{O}_f^C &= ig_s \bar{\psi}_f G^{\mu\nu} \sigma_{\mu\nu} \gamma_5 \psi_f, \\ \mathcal{O}_W &= +\frac{1}{3} f^{abc} G_{\mu\nu}^a \tilde{G}^{\nu\beta,b} G_\beta^{\mu,c}, & \mathcal{O}_{ij}^{4f} &= (\bar{\psi}_i \psi_i) (\bar{\psi}_j i \gamma_5 \psi_j) \end{aligned}$$

Options for matrix elements:

- Naive dimensional analysis [Georgi/Manohar '84]: only order-of-magnitude estimates
- Baryon χPT : not applicable for all the operators
- QCD sum rules: used here [Pospelov et al.], uncertainties large

Framework for 2HDM contributions

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

Parametrization for H^\pm Yukawas, ς_i complex:

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

- 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 $\varphi_i^0 = \{h, H, A\}$, $\mathcal{M}_{\text{diag}}^2 = \mathcal{R} \mathcal{M}^2 \mathcal{R}^T$, we have

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

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

For neutrals: additional CPV contributions from the potential!

Theory uncertainties and the EDM of Mercury

- Extremely precise atomic EDM limit:

$$|d_{\text{Hg}}| \leq 3.1 \times 10^{-29} \text{ e cm} \text{ [Griffith et al. '09]}$$

- However: difficult diamagnetic system

- Shielding efficient \rightarrow sensitivity $\sim d_n, d_{TI}$

$$d_{\text{Hg}} \stackrel{\text{Atomic}}{=} d_{\text{Hg}}(S, C_{S,P}^N) \stackrel{\text{Nuclear}}{=} d_{\text{Hg}}(\bar{g}_{\pi NN}, C_{S,P}^{p,n})$$

$$\stackrel{\text{QCD}}{=} d_{\text{Hg}}(d_f^C, C_{qq'}, C_{S,P}^q)$$

- Uncertainties:

Atomic $\sim 20\%$, Nuclear $\sim \times 100\%$, QCD sum rules $\sim 100 - 200\%$

- \rightarrow No conservative constraint on CEDMs left! [MJ/Pich'13]

$$d_{\text{Hg}} = \left\{ -(1.0 \pm 0.2) \left((1.0 \pm 0.9) \bar{g}_{\pi NN}^{(0)} + 1.1 (1.0 \pm 1.8) \bar{g}_{\pi NN}^{(1)} \right) \right. \\ \left. + (1.0 \pm 0.1) \times 10^{-5} [-4.7 C_S + 0.49 C_P] \right\} \times 10^{-17} \text{ e cm},$$

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

The EDM of the Neutron

Explicit expressions for the neutron EDM [MJ/Pich'13 (refs therein)]

$$d_n(d_q^\gamma, d_q^C)/e = \left(1.0_{-0.7}^{+0.5}\right) \left[1.4 (d_d^\gamma(\mu_h) - 0.25 d_u^\gamma(\mu_h)) + 1.1 (d_d^C(\mu_h) + 0.5 d_u^C(\mu_h))\right] \frac{\langle \bar{q}q \rangle(\mu_h)}{(225 \text{ MeV})^3},$$

$$|d_n(C_W)/e| = \left(1.0_{-0.5}^{+1.0}\right) 20 \text{ MeV } C_W,$$

$$|d_n(C_{bd})/e| = 2.6 \left(1.0_{-0.5}^{+1.0}\right) \times 10^{-3} \text{ GeV}^2 \left(\frac{C_{bd}(\mu_b)}{m_b(\mu_b)} + 0.75 \frac{C_{db}(\mu_b)}{m_b(\mu_b)} \right).$$

Chances and challenges for nuclear theory

Some more detail:

- Measurements with neutral atoms (now) or ions (future)
- Atomic theory relates d_A to P-,T-odd **nuclear moments**
 1. Schiff moment: typically dominant in diamagnetic systems
 2. MQM: relevant in paramagnetic systems
 3. EDM: typically shielded, but relevant for ions

Nuclear theory relates nuclear moments to hadronic operators

- EDMs of neutron and proton $d_{n,p}$
- CP-violating pion-nucleon interactions $\bar{g}_{\pi NN}$
- Four-nucleon contact terms (C_{4N})
- QCD relates **hadronic operators** to quark-level operators
- Nuclear theory essential e.g. for world's best EDM limit (Hg)

Challenge: calculate $S, M, d_N(d_{n,p}, \bar{g}_{\pi NN}, C_{4N})$ for $A \sim 200$

Hg: **sign** of $\bar{g}_{\pi NN}^{(1)}$ unclear \rightarrow no constraint

$S(d_{n,p})$: 1. just d_n 2. shell model $\rightarrow S(d_{n,p})$ 3. can we do better?

Unique chance: orders of magnitude *without a new experiment!*

Turning the argument around

Other limits not relevant to global fit

➡ Use results to conservatively bound their EDMs

| System | Indirect bound | Present/Expected limit |
|--------|-------------------------------|------------------------------------|
| Cs | $[-3.1, 2.2]$ | 1400 [Murthy+'89] /1 |
| Rb | $[-0.8, 0.5]$ | 10^8 [Ensberg+'67] /0.1 |
| Fr | unpublished: $[-3.2, 4.2]$ | (1200) [Huang-Hellinger'87] —/1 |

Bounds on $|d_X|$ in $10^{-26} e \text{ cm}$

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

Experiments aiming at even better sensitivity:

➡ Important progress to be expected

➡ In case of a violation of the above limits:

Highly-tuned cancellations or experimental problem