Hadronic uncertainties in EDM calculations

Martin Jung

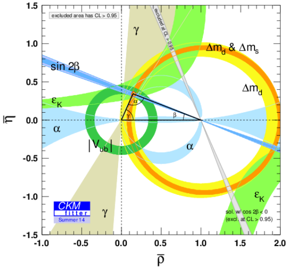
Deutsche Forschungsgemeinschaft

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 ($R_K, B \to K^* \ell\ell, B \to D^{(*)}\tau\nu, \ldots$)

➥ Works well!



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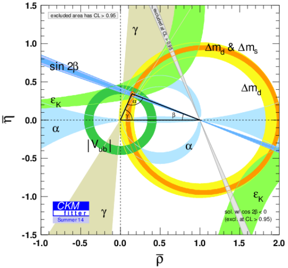
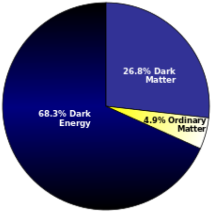


We expect new physics (ideally at the (few-)TeV scale):

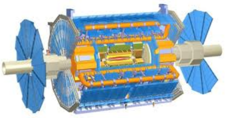
- Baryon asymmetry of the universe
- Hierarchy problem
- Dark matter and energy
- ...



➥ So where is it?

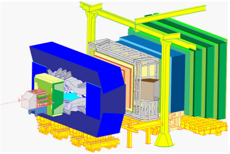
The Quest for New Physics

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



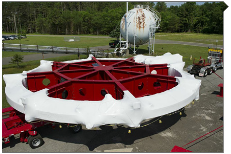
Direct search:

- Tevatron, LHC
- Maximal energy fixed



Indirect search, flavour violating:

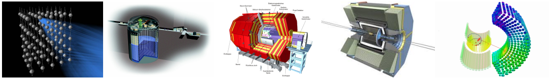
- LHCb, Belle II, BES III, NA62, MEG, ...
- Maximal reach flexible



Indirect search, flavour diagonal:

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

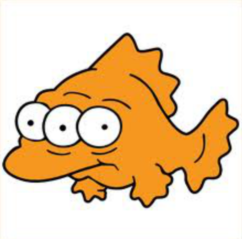
A new era in particle physics!



The curious case of the One-Higgs-Doublet Model

EDMs are finite in the SM...

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



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

EDMs are quasi-nulltests of the SM!

NP models typically do not exhibit such strong cancellations

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

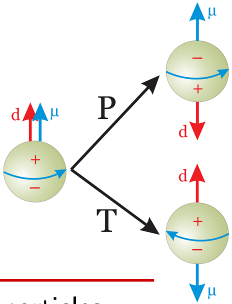
Here: focus as much as possible on model-independent statements

Back to basics: EDMs

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

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.* $d_A^{\rm para} \sim \mathcal{O}(100) \times d_e$!
[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

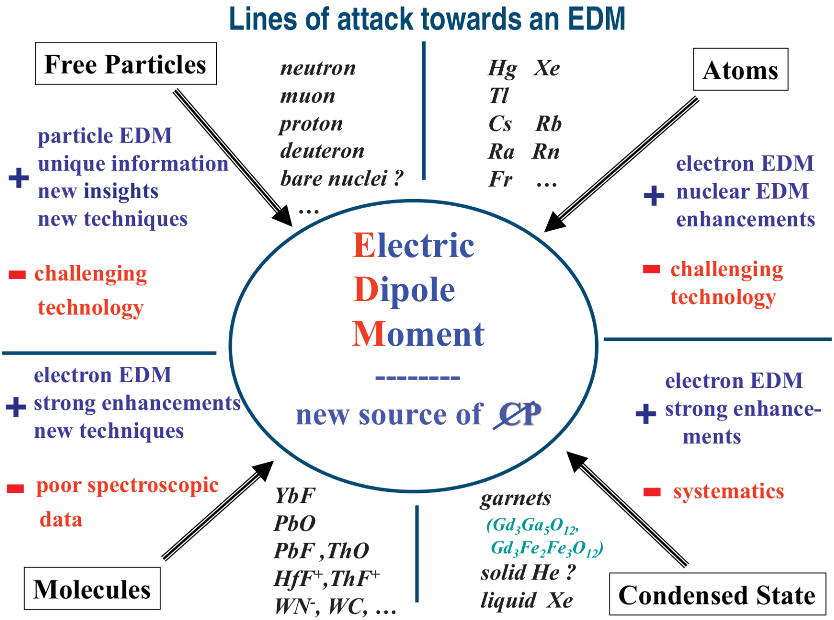
➥ Generic one-loop contributions excluded
($\rightarrow$ SUSY CP-problem)

➥ 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!

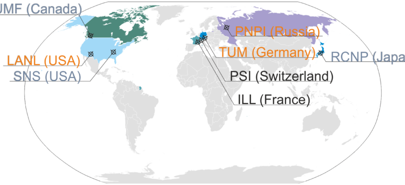
Experimental approaches [K. Jungmann'13 in Annalen der Physik]



Experimental status

Neutron EDM:

- $|d_n| \leq 3.6 \times 10^{-26} e\,\mathrm{cm}\,(95\%\mathrm{CL})$
  [Pendlebury+'15,Baker+'06]
- Worldwide effort aiming at $(10 \to 0.1) \times 10^{-27} e\,\mathrm{cm}$
- UCN sources critical problem



[P.Schmidt-Wellenburg'16]

Paramagnetic systems:

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

Diamagnetic systems:

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

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

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

Relating NP parameters and experiment

- Most stringent constraints from neutron, atoms and molecules
  - ➥ Shielding applies to some extent

Atomic level

$\Downarrow$

Nuclear Level

$\Downarrow$

Hadronic level

$\Downarrow$

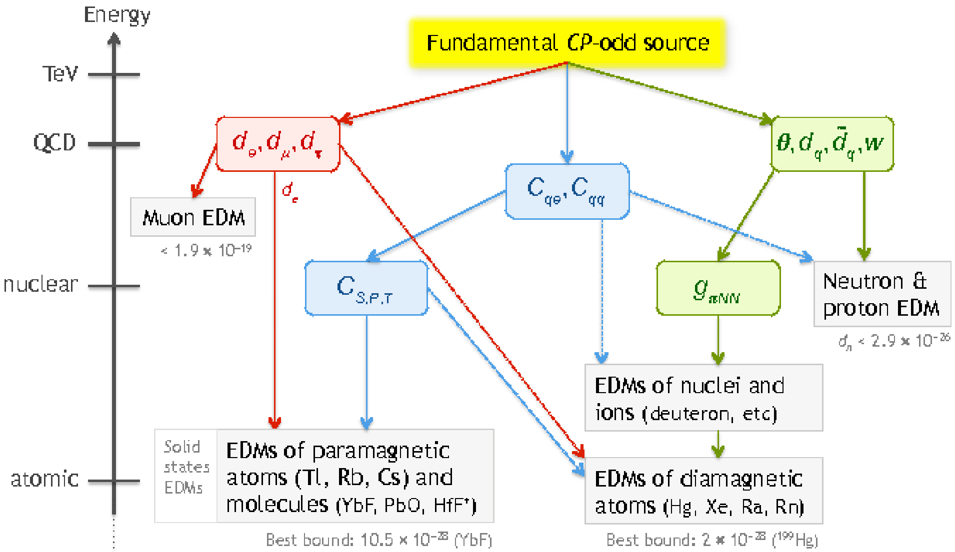
Effective Theory with (C)EDMs of fermions, $\mathcal{O}_W, \ldots$

$\Downarrow$

Parameters of your favourite NP model

- Each step potentially involves large uncertainties!
- 4/5 steps 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]



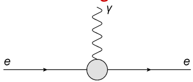
The EDM in heavy paramagnetic systems

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

d_e

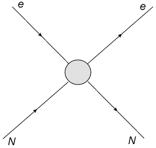


$\bar{e} F_{\mu\nu}\sigma^{\mu\nu}\gamma_5 e$

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

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

C_S



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

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

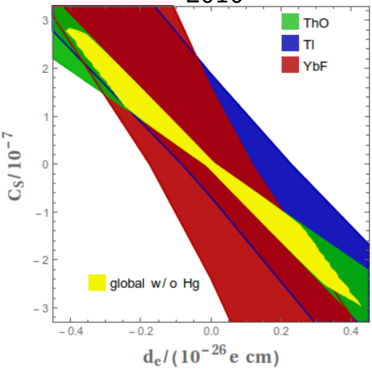
[Results entering: Nayak/Chaudhuri'07,'08,'09; Dzuba et al.'11, Meyer/Bohn'08, Skripnikov et al.'13, Fleig/Nayak'14; Averages: MJ'13, MJ/Pich'14]

Model-independent extraction of d_e and C_S

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

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

2016



Problem: Aligned constraints

Model-independent extraction of d_e and C_S

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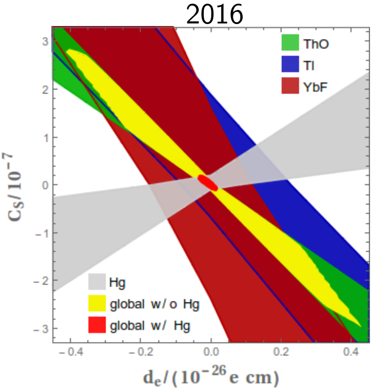


Problem: Aligned constraints

Mercury bound $\sim$ orthogonal!

Assumption: C_S, d_e saturate d_{Hg}

➥ Conservative!

$$d_e \leq 2.7 \times 10^{-28} e\text{ cm}$$
$$C_S \leq 1.5 \times 10^{-8}$$

Further atomic measurements:

Not competitive yet

➥ predicted from this fit!

Issue: C_S, d_e-coefficients for Hg less reliable (wip [Fleig/MJ('16)])

Relation to quark-electron operators involves scalar MEs $\langle N|\bar{q}q|N\rangle$:

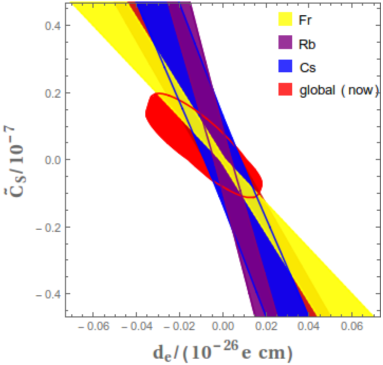
➥ e.g. important for strange-quark influence in EDMs

Model-independent extraction of d_e and C_S

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

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

$\sim$ 2020?



Problem: Aligned constraints

Mercury bound $\sim$ orthogonal!

Assumption: C_S, d_e saturate $d_{\rm Hg}$

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$$d_e \leq 2.7 \times 10^{-28} e\ \mathrm{cm}$$
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Further atomic measurements:

Not competitive yet

- predicted from this fit!

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: $\bar{\theta}$ ($\to$ 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
Multiple EDM measurements in various systems essential!

- $|d_{Hg}| \leq 7.4 \times 10^{-30} e\,\mathrm{cm}$ [Graner et al. '16] , very constraining
  Problem: QCD and nuclear theory uncertainties (x00%!)
  ➥ No conservative constraint on CEDMs left! [MJ/Pich'13]
- $|d_n| \leq 3.6 \times 10^{-26} e$ 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!

Chances and challenges for theory

- 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 (nuclear spin $\geq 3/2$)
  3. EDM: typically shielded, but relevant for ions
- Nuclear theory relates nuclear moments to hadronic operators
  1. EDMs of neutron and proton $d_{n,p}$
  2. CP-violating pion-nucleon interactions $\bar{g}_{\pi NN}$
  3. Four-nucleon contact terms (C_{4N})
  - Challenge: calculate $S, M, d_N(d_{n,p}, \bar{g}_{\pi NN}, C_{4N})$ for $A \sim 200$ Often (too?) simple models used, e.g. $S(d_{n,p})$
  - Hg: sign of $\bar{g}_{\pi NN}^{(1)}$ unclear $\rightarrow$ no constraint
- QCD relates hadronic operators to quark-level operators
  - Hg: sign of $\bar{g}_{\pi NN}^{0}/(\tilde{d}_u + \tilde{d}_d)$ unclear $\rightarrow$ no constraint

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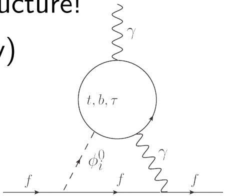
Hadronic uncertainties crucial *e.g.* for limits from Hg
Unique chance: orders of magnitude *without a new experiment!*

EDMs in NP Models

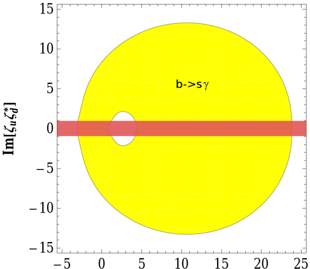
EDM constraints $\Rightarrow$ huge scales or highly specific structure!



- simple power-counting insufficient (UV sensitivity)
- ➥ EFT approach at EW scale seems problematic
- ➥ Model-independent analyses difficult
- strong model-dependent correlations

Example: 2HDMs (with non-trivial flavour-structure) [MJ/Pich'14]

- Two-loop graphs dominant [Weinberg'89,Dicus'90,Barr+'90,Gunion+'90,...]
- Tree-level can be relevant: $(m_q \times$ tree) vs. $(m_t \times$ two-loop)
- Electron EDM: $\mathrm{Im}(\varsigma_t^* \varsigma_e) \lesssim \mathcal{O}(0.05)$ $\sim 10^{-3} \times$ leptonic constraints ($\varsigma_t = \varsigma_c$)!
- Neutron EDM:
  - So far no fine-tuning necessary
  - Complementary to *e.g.* $b \to s\gamma$!
- Hg: potentially a few times stronger
  ➥ but different combination!



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.* $d_n, d_{\rm Hg}$ bottleneck! Chance for theory
- Robust, model-independent limit on electron EDM (C_S not model-independently negligible):

$$|d_e| \leq 2.7 \times 10^{-28} e\,\mathrm{cm} \quad (95\%\,\mathrm{CL}, \mathrm{Hg})$$

- General discussion of 2HDM constraints possible
- 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!

Mainz Institute for Theoretical Physics

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Low-Energy Probes of New Physics

May 2 - 24, 2017, JGU Campus Mainz

Selected Topics:

- Fundamental neutron physics
- Electric dipole moments
- "Exotics" (e.g. axion-like particles)
- Parity violation
- Fundamental muon physics

Organizers:

Peter Fierlinger (TU Munich)
Susan Gardner (University of Kentucky)
Martin Jung (Excellence Cluster Universe / TU Munich)

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

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

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

Options for matrix elements:

- Naive dimensional analysis[Georgi/Manohar '84] : 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:

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

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

$$\begin{aligned} \mathcal{L}_Y^{\varphi_i^0} &= -\frac{1}{v} \sum_{\varphi, f} \varphi_i^0 \, \bar{f} \, y_f^{\varphi_i^0} M_f \mathcal{P}_R f \; + \; \text{h.c.}\,, \\ y_f^{\varphi_i^0} &= \mathcal{R}_{i1} + (\mathcal{R}_{i2} \pm i\,\mathcal{R}_{i3}) \left(\varsigma_{F(f)}^{(*)} \right)_{ff} \quad \text{for} \quad F(f) = d, l(u)\,. \end{aligned}$$

For neutrals: additional CPV contributions from the potential!

Theory uncertainties and the EDM of Mercury

- Extremely precise atomic EDM limit:
  $|d_{Hg}| \leq 3.1 \times 10^{-29} e\,\mathrm{cm}$ [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]

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

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)]

$$\begin{aligned} d_n\left(d_q^\gamma, d_q^C\right)/e &= \left(1.0^{+0.5}_{-0.7}\right)\ \big[1.4\left(d_d^\gamma(\mu_h) - 0.25\, d_u^\gamma(\mu_h)\right) \\ &\quad + 1.1\ \left(d_d^C(\mu_h) + 0.5\, d_u^C(\mu_h)\right)\big]\ \frac{\langle \bar{q}q\rangle(\mu_h)}{(225\ \mathrm{MeV})^3}\,, \\ |d_n(C_W)/e| &= \left(1.0^{+1.0}_{-0.5}\right)\ 20\ \mathrm{MeV}\ C_W\,, \\ |d_n(C_{bd})/e| &= 2.6\ \left(1.0^{+1.0}_{-0.5}\right) \times 10^{-3}\ \mathrm{GeV}^2 \left(\frac{C_{bd}(\mu_b)}{m_b(\mu_b)} + 0.75\,\frac{C_{db}(\mu_b)}{m_b(\mu_b)}\right). \end{aligned}$$

Results for d_e and C_S from ThO [MJ/Pich'14]

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

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

Turning the argument around

Other limits not relevant to global fit

- Use results to conservatively bound their EDMs

System	Indirect bound(n=1/Hg)	Present/Expected limit
Cs	0.02/0.1	14 [Murthy+'89] /0.01
Rb	0.005/0.03	10^6 [Ensberg+'67] /0.001
	unpublished:	(12) [Huang-Hellinger'87]
Fr	0.2/0.6	—/0.01

Bounds on $|d_X|$ in $10^{-24}e$ 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:
  Cancellations (n=1), theory or experimental problem (Hg)

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]
- strong (model-dependent) constaints 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. $B \to D^{(*)}\tau\nu$)

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, ς_i complex matrices:

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

- 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
- $\varsigma_i \to$ numbers: Aligned 2HDM [Pich/Tuzon'09,MJ/Pich/Tuzon'10]
  - ➥ Comparisons with flavour data in this model

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

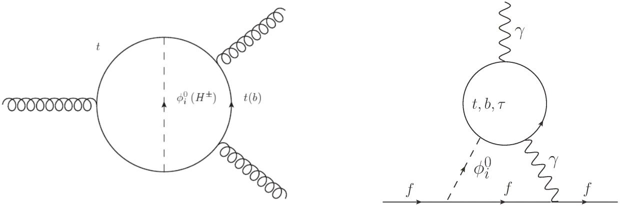
➥ Additional CPV contributions from the potential

➥ 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
  [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)

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

- 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

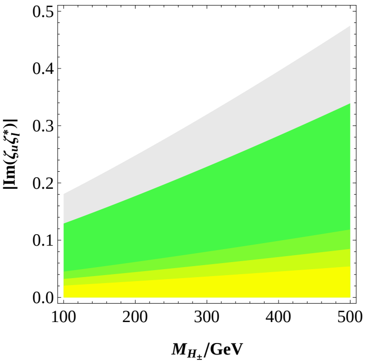
CPV in the potential tends to have smaller impact

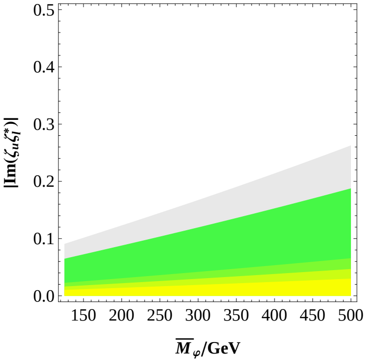
➥ Approximation for phenomenological analysis:

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

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 $\mathrm{Im}(\varsigma_u^* \varsigma_l) \lesssim \mathcal{O}(0.05)$
  - ➡ Strong despite two-loop suppression and mass factors
- Implies $\mathrm{Im}(\varsigma_l \varsigma_u^*)/M_{H^\pm}^2 \leq \times 10^{-5}\mathrm{GeV}^{-2}$ (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