Bounds on New Physics from EDMs

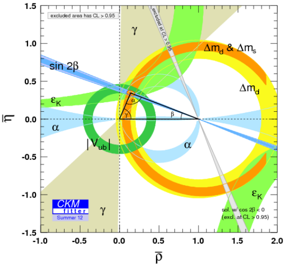
Martin Jung

Motivation

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 ($R_K, P_5', B \to D^{(*)}\tau\nu, h \to \tau\mu, \ldots$)

➥ Works well!



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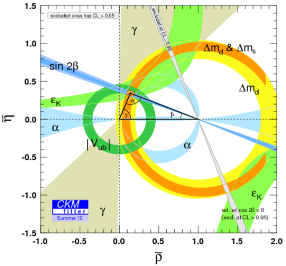
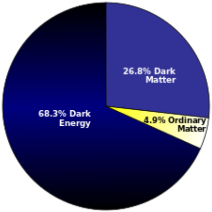
➥ Works **too** well!



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

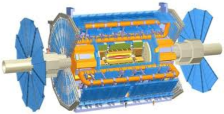
- Baryon asymmetry of the universe
- Hierarchy problem
- Dark matter and energy
- ...

➥ So where is it?



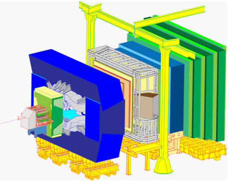
The Quest for New Physics

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



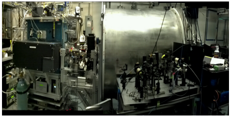
Direct search:

- Tevatron, LHC (Run 2 is coming!)
- Maximal energy fixed



Indirect search, flavour violating:

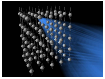
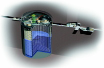
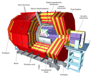
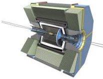
- LHCb, Belle II, BES III, NA62, MEG, ...
- Maximal reach flexible



Indirect search, flavour diagonal:

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

A new era in particle physics!


Back to basics: EDMs

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

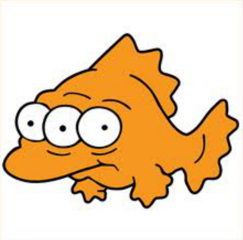
QM: non-degenerate ground state implies $\mathbf{d} \sim \mathbf{j}$

- $\mathbf{d} \neq \mathbf{0}$ 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! [Sandars'65]
- Sensitivity stems from violations of the assumptions
  - Paramagnetic systems: relativistic enhancement
  - Diamagnetic systems: finite-size effects

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 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 energy scales beyond the reach of LHC!

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!

Relating NP parameters and experiment

- Most stringent constraints from neutron, atoms and molecules
- ➥ shielding applies
- Limits usually displayed as allowed regions
- ➥ Conservative uncertainty-estimates important

Atomic level

$\Downarrow$

Nuclear Level

$\Downarrow$

QCD level

$\Downarrow$

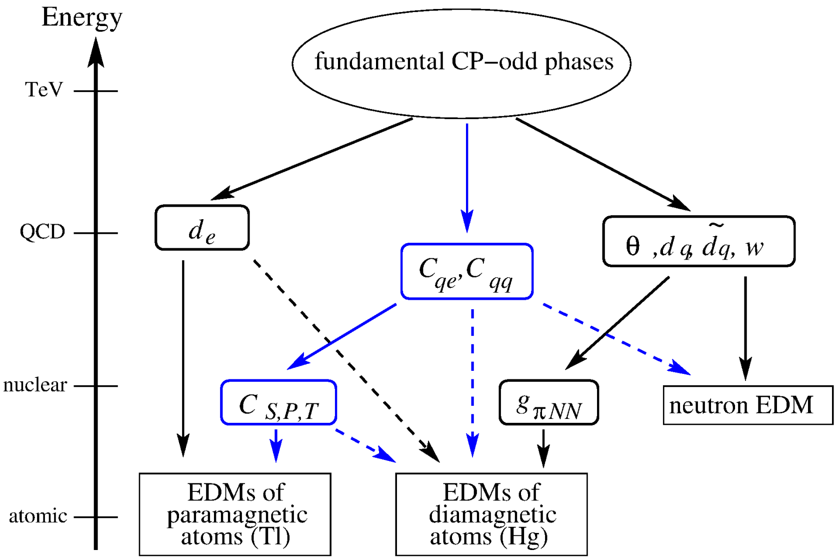
Effective Theory with (C)EDMs of fermions, $\mathcal{O}_W, \ldots$

$\Downarrow$

Parameters of your favourite NP model

- Each step potentially involves large uncertainties!
- $4/5$ steps model-independent $\Rightarrow$ series of EFTs

Schematic EFT framework [Pospelov/Ritz'05]

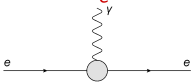


The EDM in heavy paramagnetic systems

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
  - ➥ Exploit huge internal field

d_e

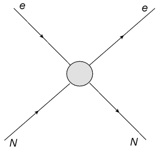


$\bar{e} F_{\mu\nu} \sigma^{\mu\nu} \gamma_5 e$

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

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

$\tilde{C}_S$



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

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

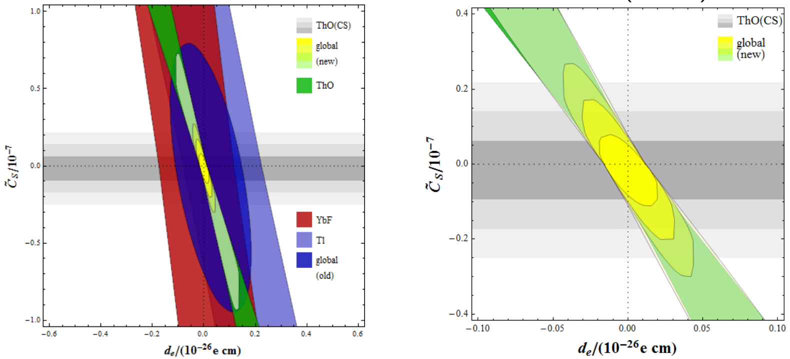
[Results entering: Nayak/Chaudhuri'07,'08,'09; Dzuba et al.'11, Meyer/Bohn'08, Skripnikov et al.'13, Fleig/Nayak'14; Averages: MJ'13, MJ/Pich'14]

Model-independent extraction of d_e and $\tilde{C}_S$

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

➥ Extract d_e, $\tilde{C}_S$ model-independently [Dzuba et al.'11,MJ'13]

now   now (zoom)



Problems: Aligned theory bounds, ThO precision unmatched

- Option: impose $\omega_{\text{ThO}}(\tilde{C}_S)|_{d_e=0} \leq n \times \omega_{\text{ThO}}^{\text{exp}}$, $n = 1, 2, 3 \ldots$
  ➥ n=1 restriction: $|d_e| \leq 0.16 \times 10^{-27} e$ cm (95% CL)
- In the future: use additional measurements

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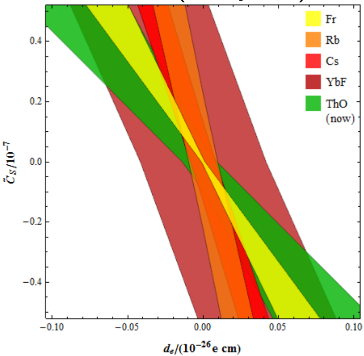
future (few years)



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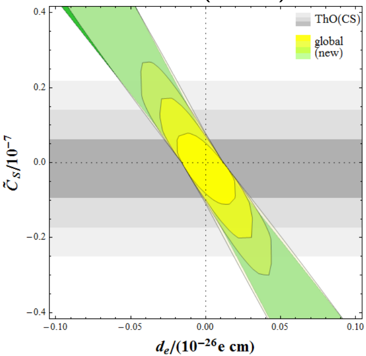

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EDMs of Mercury and the neutron

Situation more complicated than for paramagnetic systems:

- Potential SM contribution: $\bar{\theta}$ ($\rightarrow$ strong CP puzzle)
  - ➥ Several measurements necessary
- 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])
- $|d_{Hg}| \leq 3.1 \times 10^{-29} e\,\mathrm{cm}$ [Griffith et al. '09] very constraining
  Problem: QCD and nuclear theory uncertainties (x00%!)
  - ➥ No conservative constraint on CEDMs left! [MJ/Pich'13]
- $|d_n| \leq 3.3 \times 10^{-26} e$ cm [Baker et al.'06] (prospects: next talk)
  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!
➥ Several measurements necessary to extract different contributions

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

- strong (model-dependent) constaints of related observables

EDMs unique, both blessing and curse

Remainder of this talk: 2HDMs as an example

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 $y_i^0(\varsigma_i, V)$

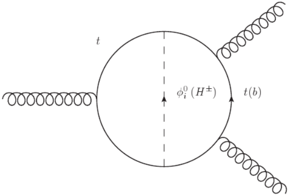
➥ Additional CPV contributions from the potential

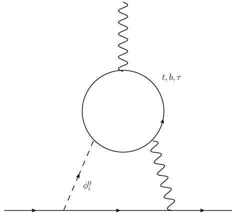
➥ Analysis depends on many unknown parameters

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
  [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

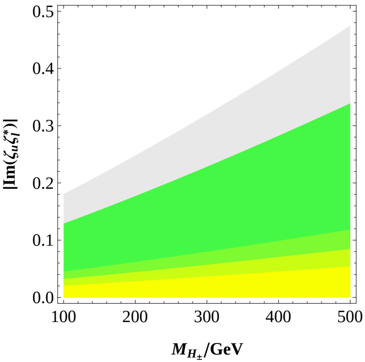
CPV in the potential tends to have smaller impact

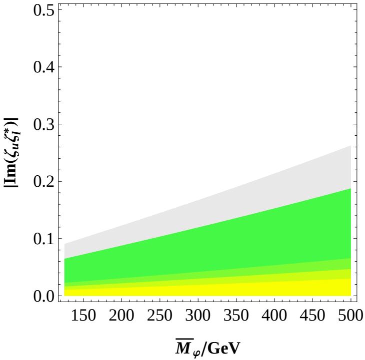
➥ Approximation for phenomenological analysis:

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

Bounds from the electron EDM

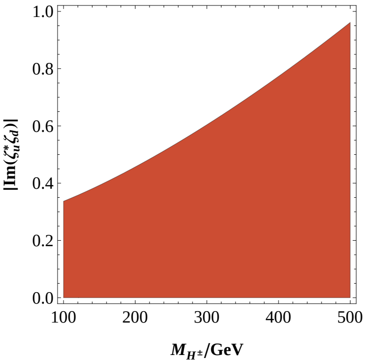
- Contributions via Barr-Zee diagrams [Bowser-Chao et al.'97]
- Sensitivity to $d_e \sim \mathrm{Im}(\varsigma_{u,33}^* \varsigma_{l,11})$
- Bounds $\mathrm{Im}(\varsigma_u^* \varsigma_l) \lesssim \mathcal{O}(0.05)$
  - ➥ Strong despite two-loop suppression and mass factors
- Implies $\mathrm{Im}(\varsigma_l \varsigma_u^*)/M_{H^\pm}^2 \leq \times 10^{-5} \mathrm{GeV}^{-2}$ (universal ς_i's)
  - ➥ A factor 1000 stronger than (semi)leptonic constraints!

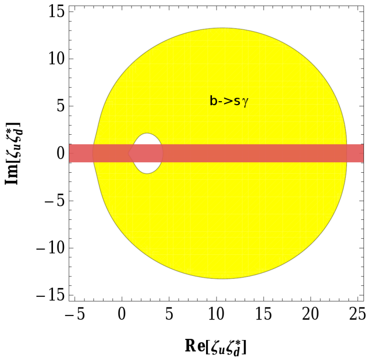




Bounds from the neutron EDM

- 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





Conclusions and outlook

- CPV-sector of NP models uniquely constrained by EDMs
- Difficult to set model-independent constrains
- Quantitative results require close look at theory uncertainties
  - ➥ Use conservative limits, allowing for cancellations
- Robust, model-independent limit on electron EDM ($\tilde{C}_S$ not model-independently negligible):

$$|d_e| \leq 1.0(0.16) \times 10^{-27} e\,\mathrm{cm} \quad (95\%\,\mathrm{CL}, Hg/n = 1)$$

  - ➥ 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)
  - ➥ Might turn limits into determinations!

Backup slides

- EDM EFT framework
- 2HDM Framework
- Limits on $|d_e|$ and $|\tilde{C}_S|$
- 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

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

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

For neutrals: additional CPV contributions from the potential!

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]

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

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

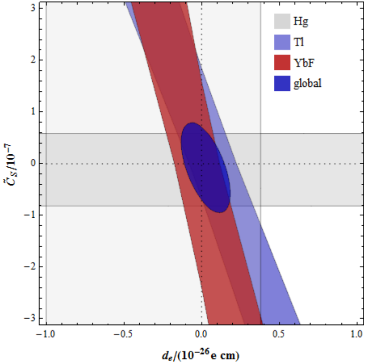
The EDM of the Neutron

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

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

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

pre-ThO



Competitive with naive extraction:

- Model-independent bounds:
  $|d_e| \leq 1.4 \times 10^{-27} e$ cm @95% CL
  $|\tilde{C}_S| \leq 0.72 \times 10^{-7}$

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

Input	$\lvert d_e \rvert$ limit (95% CL)	$\lvert \tilde{C}_S \rvert$ limit (95% CL)
Result w/o ThO [MJ'13]	$1.4 \times 10^{-27} e\,\mathrm{cm}$	7×10^{-8}
Including ThO, $\tilde{C}_S$ Hg	$1.0 \times 10^{-27} e\,\mathrm{cm}$	7×10^{-8}
Including ThO, $\tilde{C}_S$ ThO ($n=3$)	$0.35 \times 10^{-27} e\,\mathrm{cm}$	2.3×10^{-8}
Including ThO, $\tilde{C}_S$ ThO ($n=2$)	$0.25 \times 10^{-27} e\,\mathrm{cm}$	1.6×10^{-8}
Including ThO, $\tilde{C}_S$ ThO ($n=1$)	$0.16 \times 10^{-27} e\,\mathrm{cm}$	0.8×10^{-8}
ThO only, $\tilde{C}_S = 0$, 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 $\tilde{C}_S$, including the measurement in the ThO system [Baron et al,'13] . †: Using W_d from [Skripnikov et al.'13] . ‡: Theory errors neglected.

Turning the argument around

Other limits not relevant to global fit

➥ Use results to conservatively bound their EDMs
(ThO not yet included)

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

➥ Above limits "sanity check" for future measurements