Electric Dipole Moments and the Search for Physics Beyond the Standard Model

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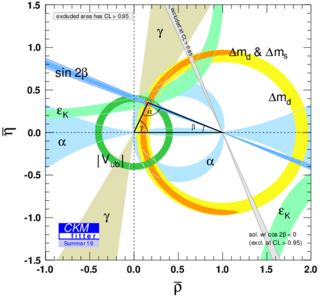
PSI Colloquium
25th of February 2021

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 ($R_{K,K^*}, P_5', B \to D^{(*)}\tau\nu, g_\mu - 2, \ldots$)

➥ Works well!



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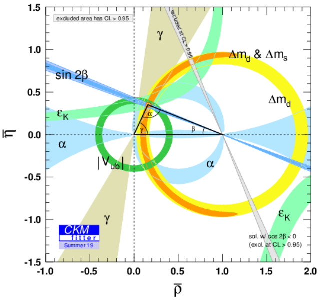
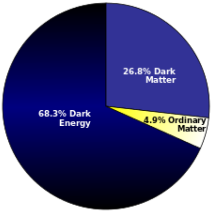


We expect new physics (ideally at the (few-)TeV scale):

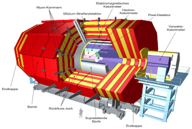
- Baryon asymmetry of the universe
- Hierarchy problem
- Dark matter and energy
- ...

➥ So where is it?



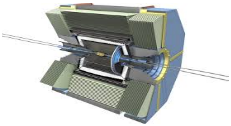
The Quest for New Physics

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



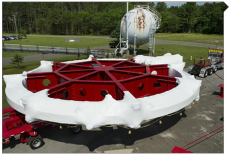
Direct search:

- Tevatron, LHC
- Maximal energy fixed



Indirect search, flavour violating:

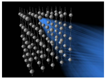
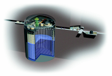
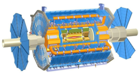
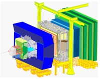
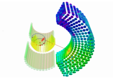
- LHCb, Belle II, BES III, NA62, MEG, ...
- Maximal reach flexible



Indirect search, flavour diagonal:

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

A new era in particle physics!

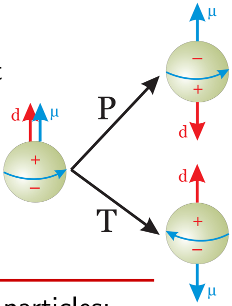
Back to basics: EDMs

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

But point-particle EDM vanishes! $\rightarrow$ QM effect

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

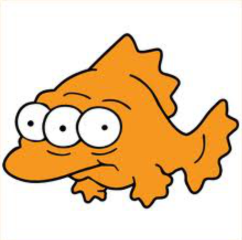
Shielding can be reversed, *e.g.* $d_A^{\mathrm{para}} \sim \mathcal{O}(100) \times d_e$!
[Sandars'65,'66]

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

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)

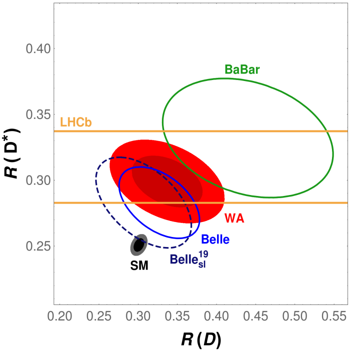
➥ EDMs test combination of flavour- and CPV-structure

EDMs important on two levels:

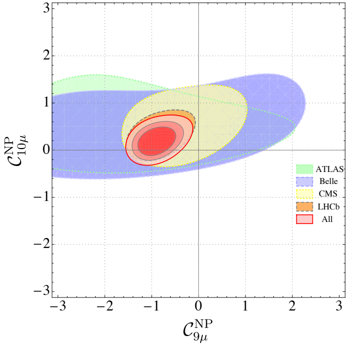
- "Smoking-gun-level": Visible EDMs proof for NP
- Quantitative level:
  Setting limits/determining parameters
  ➥ Theory uncertainties are important!

Flavour anomalies and EDMs

$b \to c\tau\nu$ [Murgui+'19]



$b \to s\ell^+\ell^-$ [Algueró+'19]



- Presently $\sim 3\sigma$ and $\sim 5\sigma$ from SM predictions
- No indication of CPV
  - ➥ Why is this relevant for EDMs?

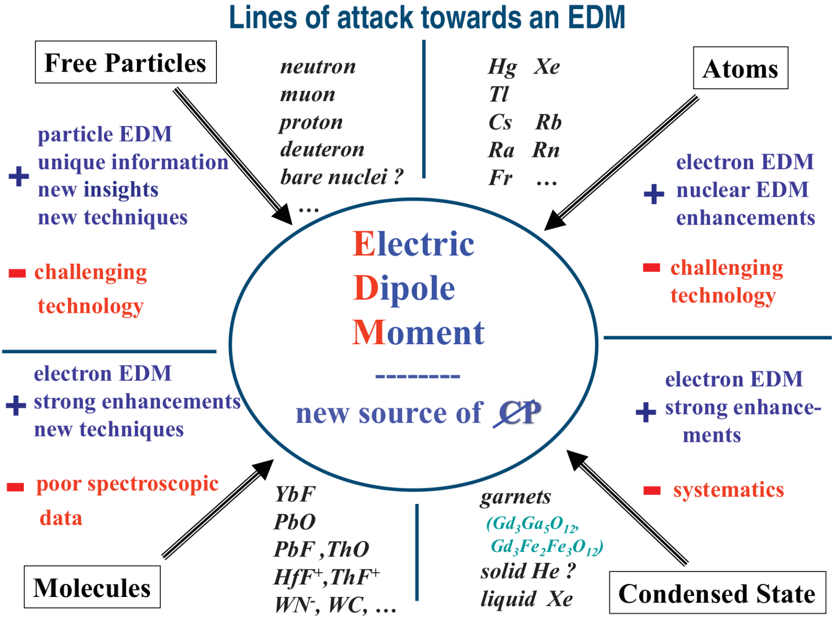
➥ Both imply lepton-flavour-non-universality (LFNU)!

➥ Often implicitly assumed in NP scenarios (at least in the past)

➥ Decouples e, μ, τ EDMs, no scaling with masses

- ➥ Increased importance of explicit μ, τ-EDM measurements!

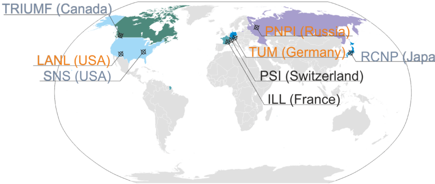
Experimental approaches [K. Jungmann'13 in Annalen der Physik]



Experimental status

Neutron EDM:

- $|d_n| \leq 1.8 \times 10^{-26} e\,\mathrm{cm}\,(90\%\mathrm{CL})$
  [PSI Abel'20]
- 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: $|\omega_{\mathrm{ThO}}| \leq 1.1\,\mathrm{mrad/s}\,(95\%\,\mathrm{CL})$ [ACME'18]
- Ionic: HfF^+, $|\omega_{\mathrm{HfF}}| \leq 7.9\,\mathrm{mrad/s}\,(90\%\,\mathrm{CL})$ [Cairncross+'17]

Diamagnetic systems:

- $|d_{\mathrm{Hg}}| \leq 7.4 \times 10^{-30} e\,\mathrm{cm}\,(95\%\,\mathrm{CL})$ [Graner+'16]
- Ongoing: Xe, Hg, 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]

Collider: $|d_\tau| \leq 3.4 \times 10^{-17} e\,\mathrm{cm}$ [Belle'03]

Relating NP parameters and experiment

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

Atomic level

$\Downarrow$

Nuclear Level

$\Downarrow$

Hadronic level

$\Downarrow$

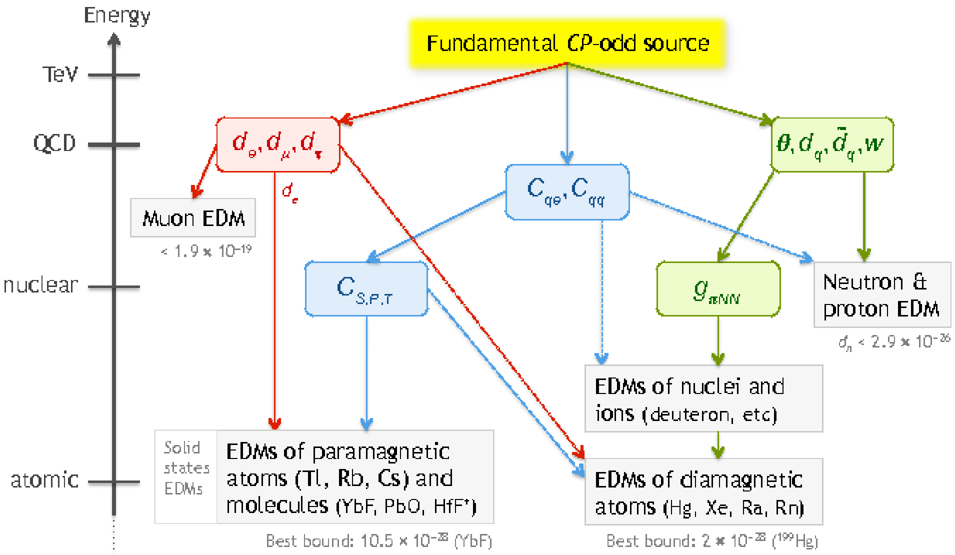
Effective Theory with (C)EDMs of fermions, $\mathcal{O}_W, \ldots$

$\Downarrow$

Parameters of your favourite NP model

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



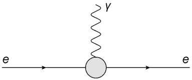
The EDM in heavy paramagnetic systems

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

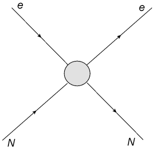


$\bar{e}F_{\mu\nu}\sigma^{\mu\nu}\gamma_5 e$

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

$$\omega_M[\mathrm{mrad/s}] = \alpha_{\mathrm{M}}^{\mathrm{d_e}}\mathrm{d_e} + \alpha_{\mathrm{M}}^{\mathrm{C_S}}\mathrm{C_S}\,.$$

C_S



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

Molecule	$\alpha_M^{d_e}/10^{-27}e\mathrm{cm}$	$\alpha_M^{C_S}/10^7$
HfF^+	34.9 ± 1.4	32.0 ± 1.3
ThO	120.6 ± 4.9	181.6 ± 7.3

[Results entering: Skripnikov'17,Fleig'17,Denis/Fleig'16,Skripnikov'16

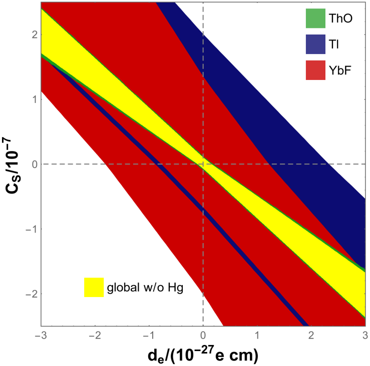
Averages: Fleig/MJ'18]

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

➥ weak limits

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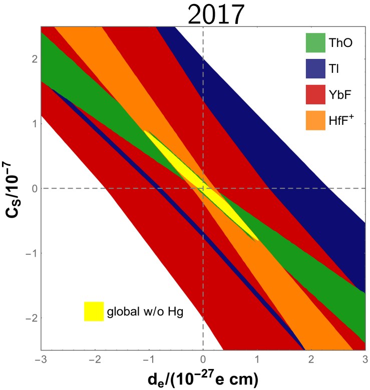

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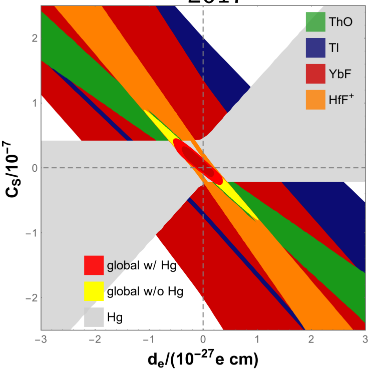

Problem: Aligned constraints

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Partial resolution: HfF^+ result

Mercury bound ∼ orthogonal!

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

➥ Conservative

[Fleig,MJ'18]

$d_e \leq 3.7 \times 10^{-28} e$ cm

$C_S \leq 2.6 \times 10^{-8}$

Yields model-independent limit on every paramagnetic system!

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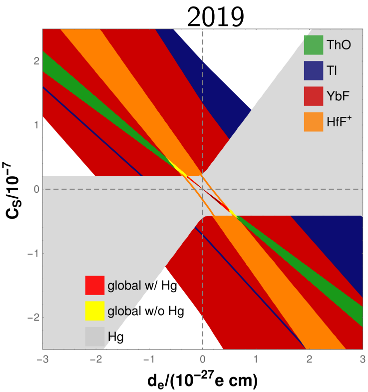

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Future measurements aim at precision beyond present constraints!

➥ 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

- $|d_{Hg}| \leq 7.4 \times 10^{-30} e\,\mathrm{cm}$ [Graner et al. '16] , very constraining
  Problem: QCD and nuclear theory uncertainties (x00%!)
  - ➥ No conservative constraint on CEDMs left! [MJ/Pich'13]
- $|d_n| \leq 1.8 \times 10^{-26} e$ cm [Abel'20]
  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'18]

LO contribution vanishes

➥ Triple perturbative expansion necessary:

1. External electric field (here: included in basis set)
2. Hyperfine splitting
3. d_e/C_S

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

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/baryons, light nuclei:

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

➥ 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)

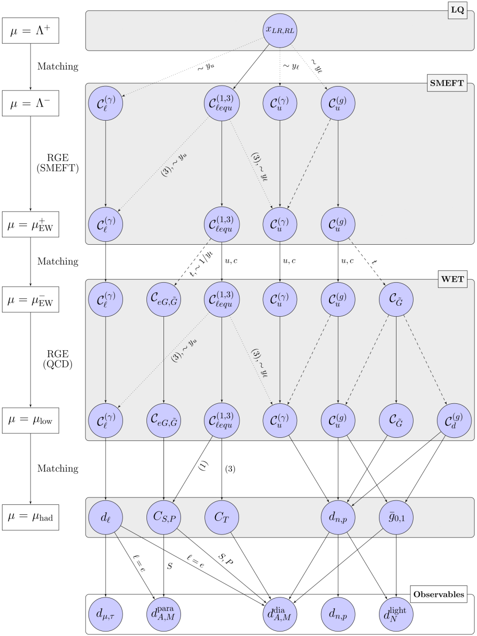
➥ Model-independent analyses difficult

EDMs unique, both blessing and curse

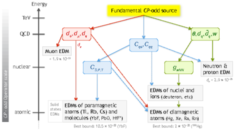
- some model-independent relations exist, *e.g.* to β decay [Khriplovich'91, see also e.g. Dekens/Vos'15]
- strong (model-dependent) constaints of related observables

➥ Consider models or subsets of model-independent framework

EDMs in sLQ models [Dekens/de Vries/MJ/Vos'18]



Cascade of EFTs:



Example: R_2 LQ

Tree-level: semileptonic operators

1-loop (matching + running):
Dipole operators are generated

Below $\mu_{\rm EW}$: gluonic operators added

$\mu_{\rm low} \sim 1$ GeV: $\rightarrow$ hadronic operators

- enter EDM calculations
  ($\rightarrow$ atomic + nuclear MEs)
- MEs have large uncertainties

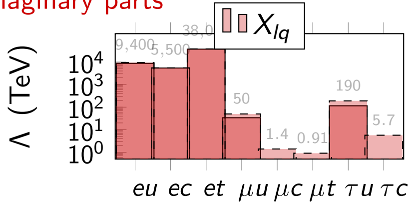
Phenomenological consequences

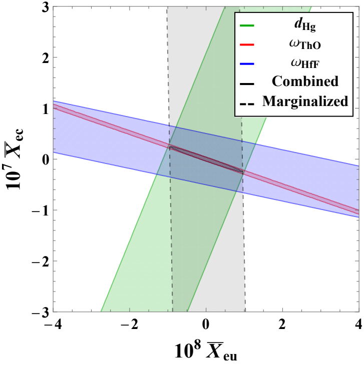
Most observables constrain (mainly) real parts

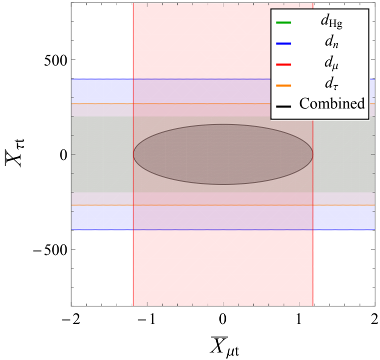
- EDMs constrain complementarily imaginary parts

Flavour-dependence of constraints

- Vastly different magnitudes
- Most relevant observables differ
- Complementarity of measurements!



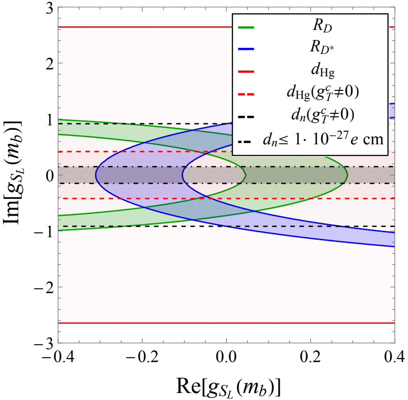




Relation to $R(D) - R(D^*)$ flavour anomaly

R_2 LQ part of NP model for flavour anomalies: [Bečirević+'18]

- Generates $C_{S_L} \sim 4C_T$ ($@\mu_{\rm LQ}$)
- Explanation of $R(D^{(*)})$ possible, but requires imaginary part
- The same coupling combination yields $(\bar{c}\sigma^{\mu\nu}\gamma_5 c)(\bar{\tau}\sigma_{\mu\nu}\tau)$
  - ➥ Generates charm ($+\ \tau$) EDMs + Weinberg operator
  - ➥ Bounds from neutron + Hg EDMs



2 main effects:

1. Weinberg operator: smaller effect (outer line)
2. Charm EDM: depends on charm tensor-current neutron ME

   1 calculation [Alexandrou+'17]

   ➥ compatible with 0

Future EDM experiments or lattice can improve this

Complementarity II: The Paradigm of LFU

What do we learn from this?

- Scalar LQs only one scenario, direct link to anomalies
- Our discussion is illustrative of something more general:

> The Paradigm of Lepton-Flavour-Universality has fallen!

- Motivated by LEP and low-energy data, LFU was assumed
- $b \to c\tau\nu$ and $b \to s\ell\ell$ anomalies non-universal
- ➥ Non-universal models compatible with LEP etc established
- Time will tell the fate of the anomalies (more at Moriond)
- ➥ Independently, LFU is only an assumption beyond the SM
- ➥ This decouples e.g. μ/τ EDMs from eEDM

> Independent experimental checks are crucial

Conclusions

- EDMs unique way to search for BSM physics
- 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 nuclear theory
- Robust, model-independent limit on electron EDM (C_S not model-independently negligible):

$$|d_e| \leq 3.7 \times 10^{-28} e\,\mathrm{cm} \quad (95\%\,\mathrm{CL})$$

- Flavour anomalies killed LFU paradigm
  - Increased importance of μ, τ EDM
- EDMs in scalar LQ models
  - Demonstrate this point
  - Every measurement important for at least one coupling!
- Plethora of new results to come
  - Might turn limits into determinations!