EDMs and the search for new physics

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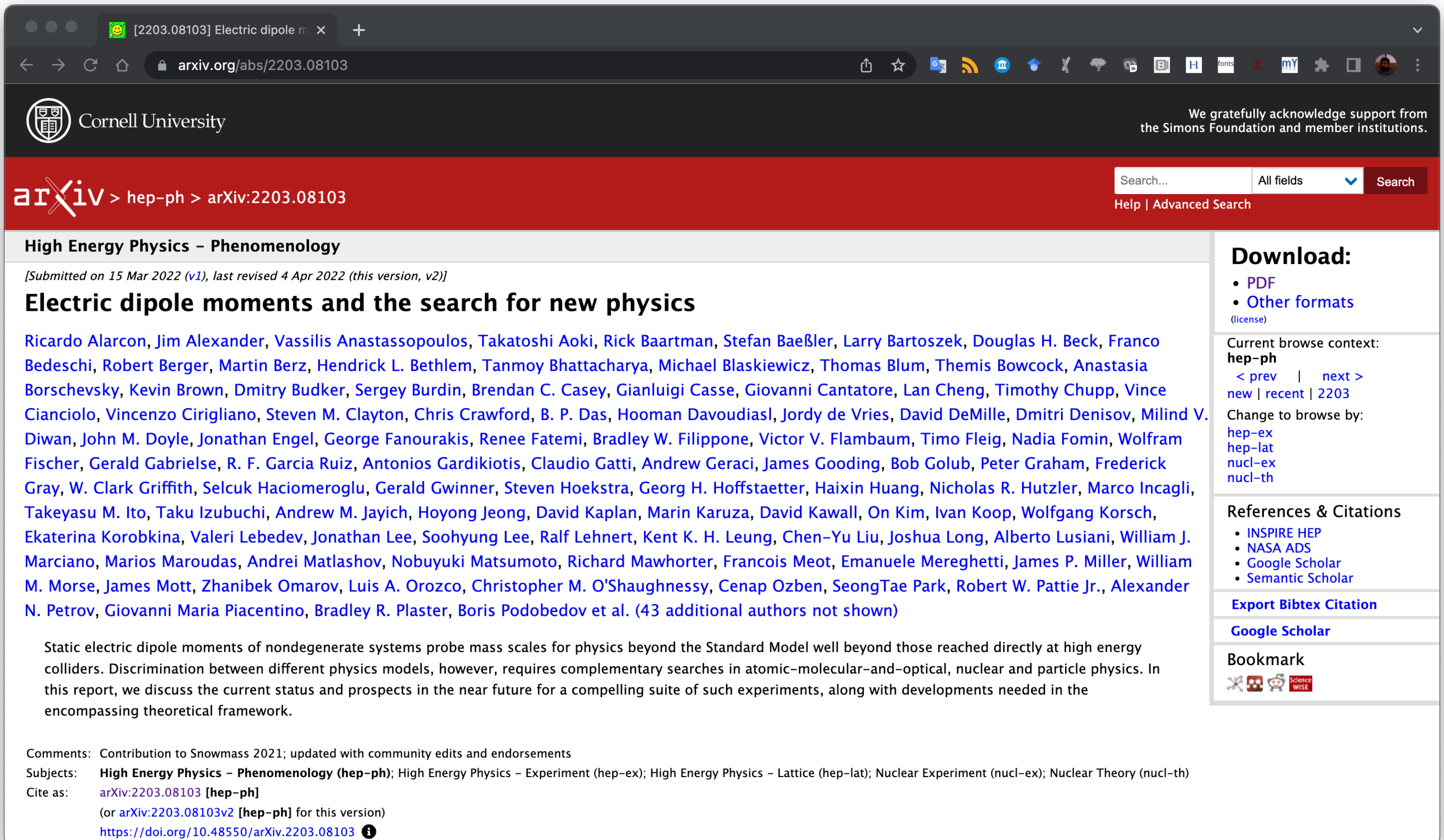
The Whitepaper


[2203.08103] Electric dipole m

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High Energy Physics – Phenomenology

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Electric dipole moments and the search for new physics

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Static electric dipole moments of nondegenerate systems probe mass scales for physics beyond the Standard Model well beyond those reached directly at high energy colliders. Discrimination between different physics models, however, requires complementary searches in atomic-molecular-and-optical, nuclear and particle physics. In this report, we discuss the current status and prospects in the near future for a compelling suite of such experiments, along with developments needed in the encompassing theoretical framework.

Comments: Contribution to Snowmass 2021; updated with community edits and endorsements

Subjects: **High Energy Physics – Phenomenology (hep-ph)**; High Energy Physics – Experiment (hep-ex); High Energy Physics – Lattice (hep-lat); Nuclear Experiment (nucl-ex); Nuclear Theory (nucl-th)

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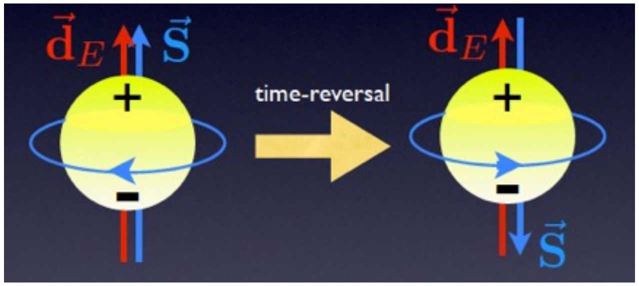
Why EDMs?

- CP violation in excess of Standard Model contribution must exist.
  - Too much matter in the universe.
  - Can't be present initially.
  - SM CP-violation too small to create it.
- If BSM CP-violation couples to the baryonic or charged leptonic sector
  - Typically gives rise to EDMs,
  - Much larger than the tiny SM contribution.
- Observation of EDMs starting point for investigation into
  - Nature of CP-violation,
  - Whether spontaneous or explicit.
- Opportunity for rapid improvement in the next decade.



Effective Field Theory

Use the framework of EFT:

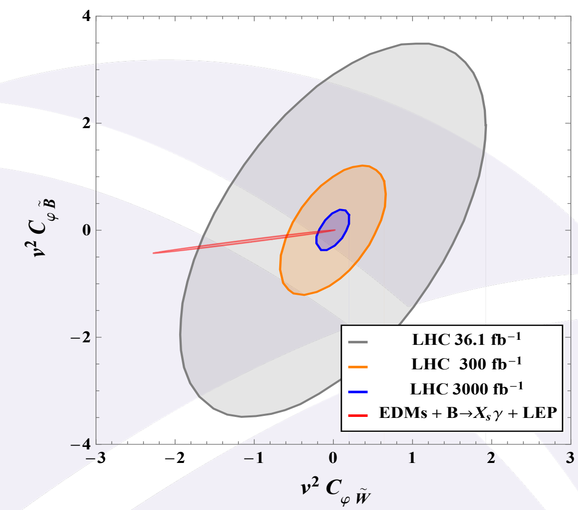
- Assume a single large energy scale of new physics
  - Use (naïve) dimensional analysis to make things dimensionless
- Like Taylor series in theory space
  - Drop high-order terms because they are small
- Use symmetries of the problem
  - Assume all terms allowed by symmetry are “equally” big
  - Can incorporate soft symmetry-breaking through spurions
- Assume all remaining dimensionless constants O(1)

Low energy description

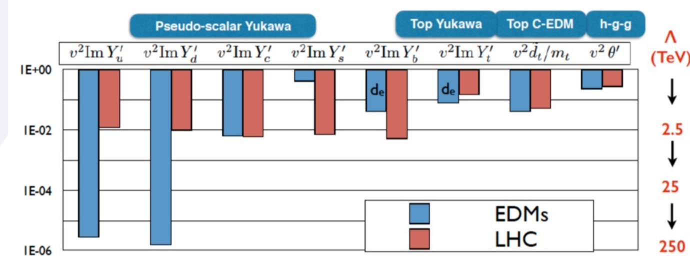
- At low energies, EDMs primarily arise from:
  - EDMs of elementary particles
    - Electrons (and neutrinos)
    - Neutrons
    - Protons
  - CP-violation in electron-nucleus interactions
  - CP-violation in pion-nucleon interactions
- Above the hadronic scale, these come from:
  - QCD topological term
  - EDMs of quarks and electrons
  - Chromo-EDMs of quarks and gluons
  - Four-fermi interactions (not all equal: organized by the broken weak symmetry)

Probes high scales

- Arise at a very high scale if at one-loop
  - Electron EDM 10^{-29} *e* cm 48 TeV
  - Quark EDM 10^{-29} *e* cm 130 TeV
  - Quark cEDM 10^{-29} cm 250 TeV
  - Gluon cEDM 10^{-29} cm/100 MeV 260 TeV
- One order of magnitude lower reach
  - If further loop-suppressed,
  - Has other suppression (e.g., flavor)
  - Has small phases
- Often complementary to accelerator searches.



Cirigliano *et al.*,
PRL 123, 051801 (2019)



Pseudo-scalar Yukawas in units of SM Yukawa m_q/v

$$\mathcal{L} = \frac{m_q}{v}\,\tilde{\kappa}_q\,\bar{q} i\gamma_5 q\,h$$

$\tilde{\kappa}_u$	$\tilde{\kappa}_d$	$\tilde{\kappa}_s$	$\tilde{\kappa}_c$	$\tilde{\kappa}_b$	$\tilde{\kappa}_t$
0.45	0.11	58	2.3	3.6	0.01

Cirigliano *et al.*,
PRD 94 (2016) 016002

Needs combination of theory and experiments

- Most coefficients very poorly known
- Lattice calculations provide precision
- Currently available for
  - u and d Quark EDM contribution to nucleon EDM
  - Semileptonic 4-fermion (u and d with lepton) contribution to electron-nucleon coupling

$$d_n = -(0.0015 \pm 0.0007)\ e\,\vartheta\,\mathrm{fm}$$
$$-(0.20 \pm 0.01)d_u + (0.78 \pm 0.03)d_d + (0.0027 \pm 0.016)d_s$$
$$-(0.55 \pm 0.28)e\tilde{d}_u - (1.1 \pm 0.55)e\tilde{d}_d \pm (50 \pm 40)e\,w\ \mathrm{MeV}$$

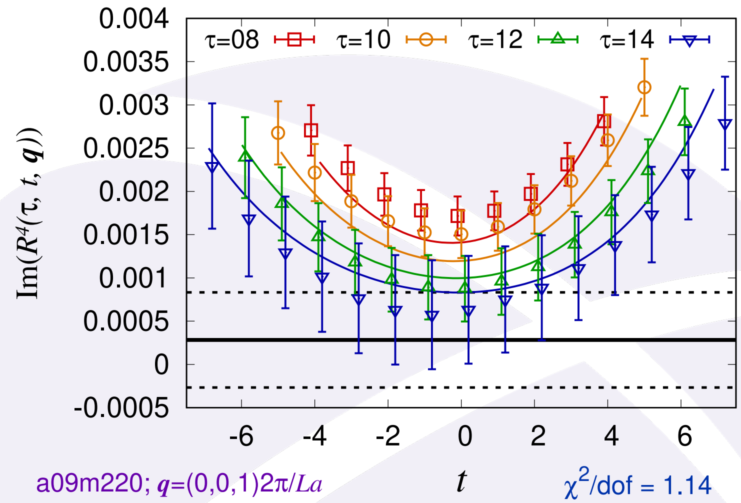
$$\bar{g}_0 = (5 \pm 10)\left(\tilde{d}_u + \tilde{d}_d\right)\mathrm{fm}^{-1}$$

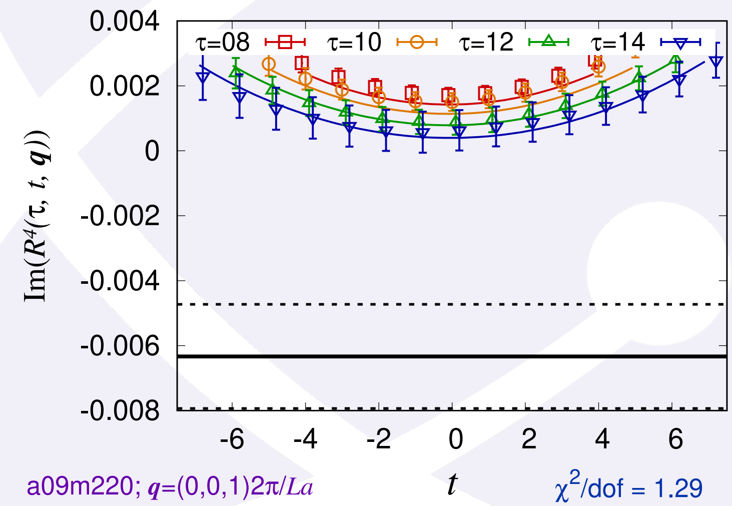
Green indicates lattice results

$$\bar{g}_1 = (24^{+40}_{-10})\left(\tilde{d}_u - \tilde{d}_d\right)\mathrm{fm}^{-1}$$

Lattice calculations

- Lattice calculations provide precision
- Have to control systematics: finite spacing, volume, unphysical parameters, matching, …
- Plagued by systematic effects peculiar to baryons
  - CP violation often sensitive to low-lying pion excitations
  - Local nucleon sources also couple to Nπ states
  - Difficult to isolate for light pion masses
  - Seen to be important in many places
- Expensive calculations needed to control these.
  - May need innovative solutions
- Chiral perturbation theory can provide guidance.

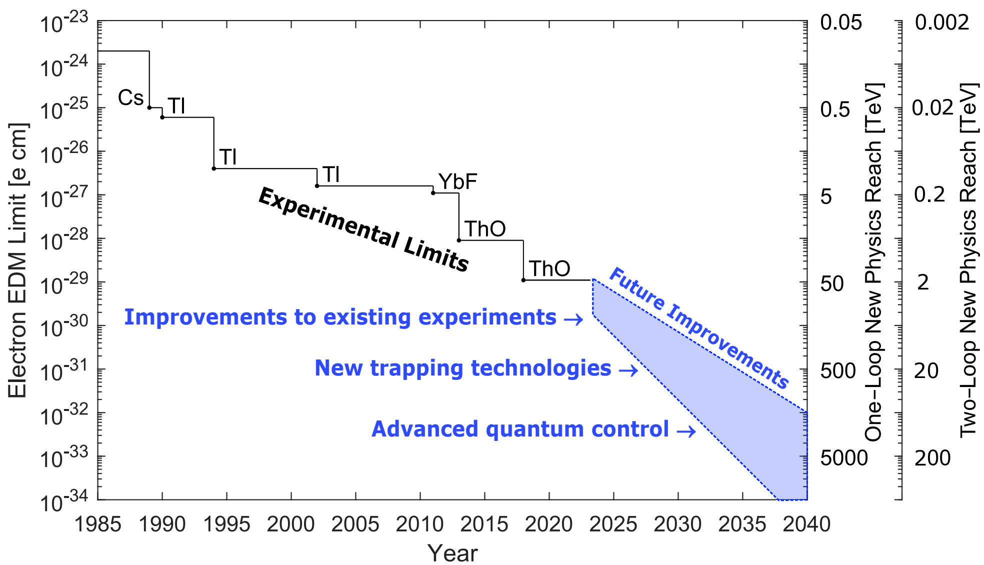




Need multiple systems

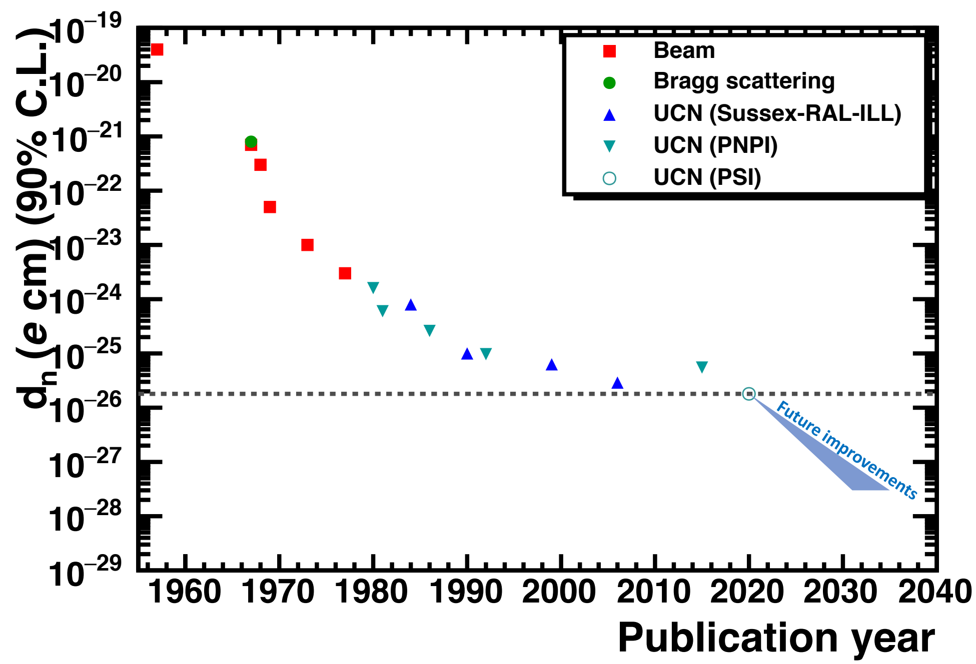
- More than one low-energy CPV quantity: d_n, d_p, g_0, g_1, d_e, C_S, C_P, C_T, …
- Need EDM of more than one system
  - Neutron EDM: d_n
  - Proton EDM: d_p
  - Nuclear/Diamagnetic atoms/molecules EDM (^{199}Hg, ^{129}Xe, ^{225}Ra): d_n, d_p, g_0, g_1
  - Paramagnetic atoms and molecules (ThO, HfF^+) EDM: d_e, C_S, C_P, C_T, …
- Currently
  - n and Hg most constraining (assuming single term) for d_n, d_p, g_0
  - TlF best for g_1
  - Molecules, in general, can have large internal fields (but, Schiff's theorem)
- Interest and expertise among the HEP, NP, and AMO communities; as well as in quantum sensing and other disciplines.

Improvement Over Time



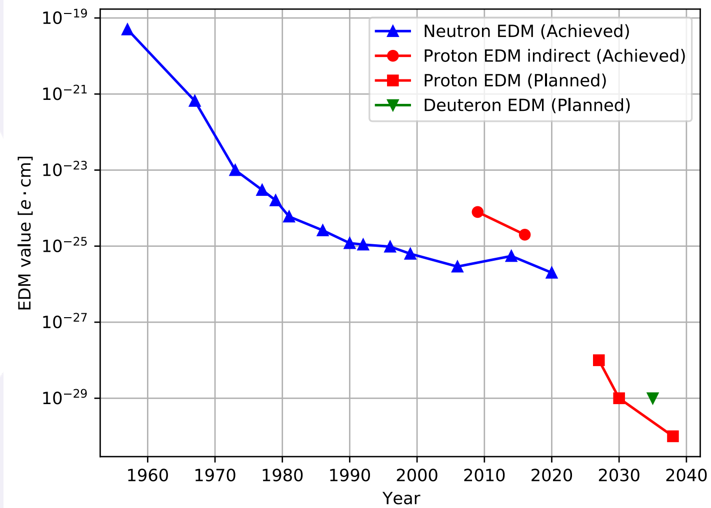
AMO

Neutron



Opportunity: Storage Rings

- Useful for charged particles.
  - Highly polarized and along beam axis
  - At magic momentum (in-plane precession frozen)
- Early systems: p, ^{2}H, ^{3}He (and μ)
  - Can reach $d_p < 10^{-29}$ *e* cm in five years of data taking
- Also sensitive to dark matter



Snowmass

- EDMs one of the best short-term insight into BSM theories
- Needs multiple systems and interdisciplinary science
  - Input from nuclear and AMO physics needed
  - Needs synergistic experimental and theory progress
  - Needs various theoretical advances
    - Effective field theories to see correlations in particular BSM models
    - Chiral perturbation theory to organize low-energy observations
    - AMO and Nuclear structure calculations
    - Lattice QCD to handle string interactions
- Proton storage ring a window of opportunity