Status of EDM searches

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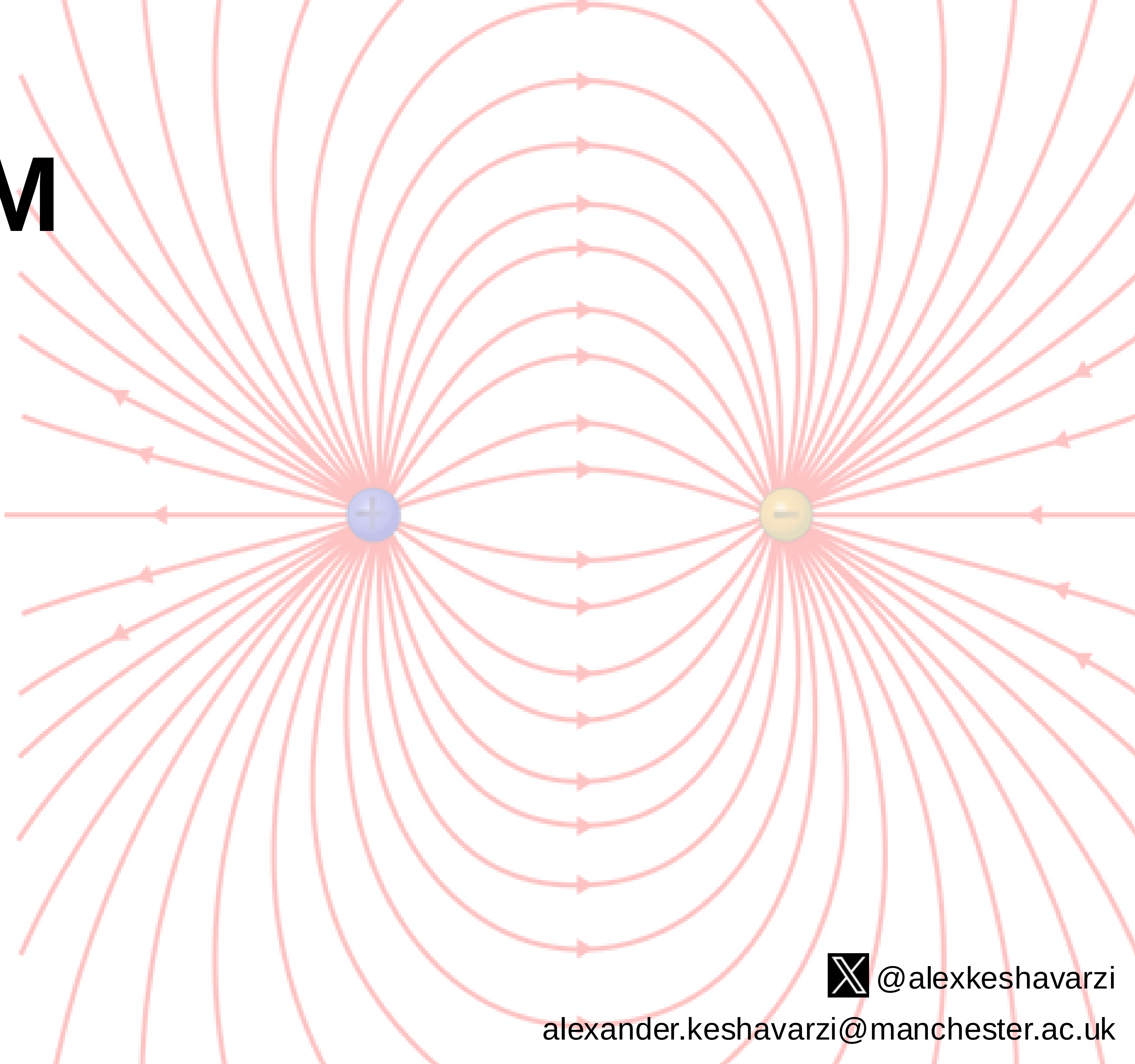
Workshop on Muon Precision Physics 2024

University of Liverpool

12th November 2024



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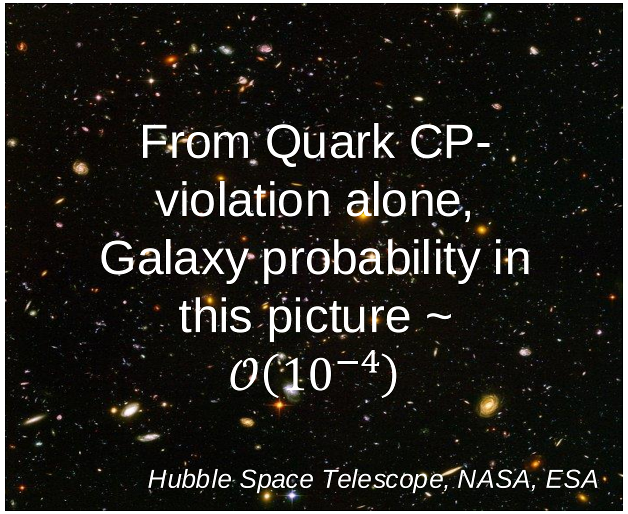
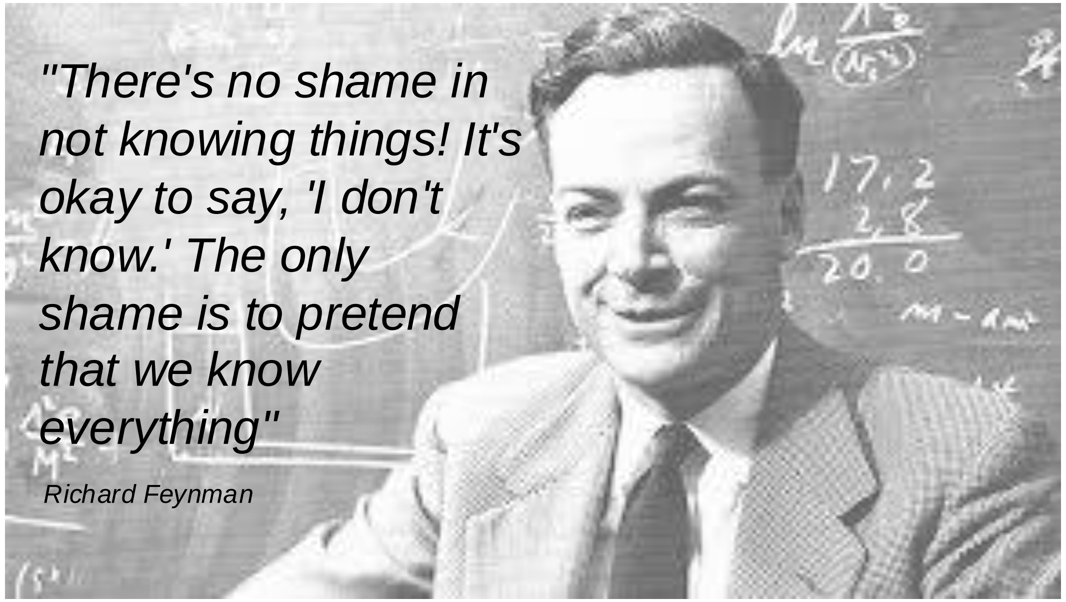
Some things that don't we know

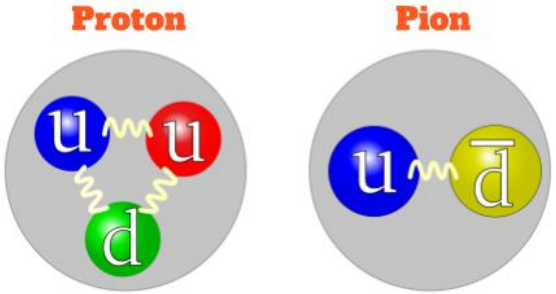
What is dark matter?
(What is 85% of the universe's matter?)

Where did all the antimatter go?
Need more CP violation!



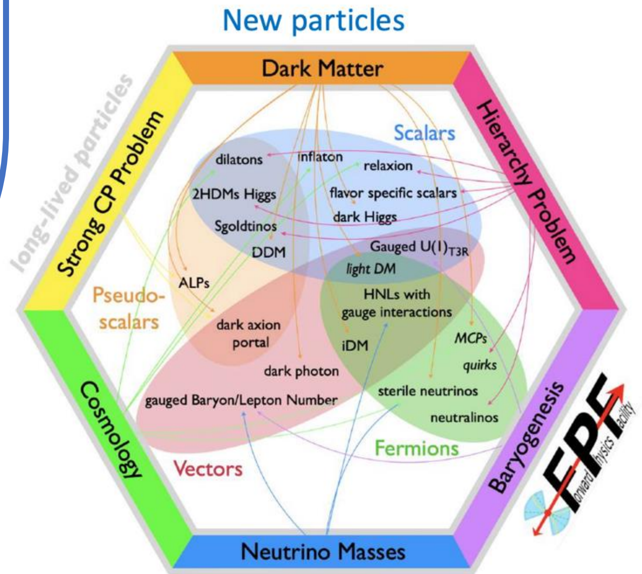


$$\mathcal{L} = \theta \frac{1}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu a}$$



The Strong CP Problem
We can't fully describe strong interactions

Is there BSM physics?
And if so, what/where is it?



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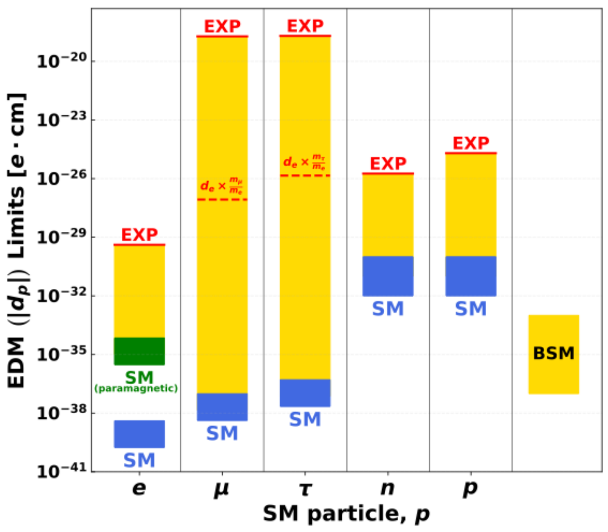
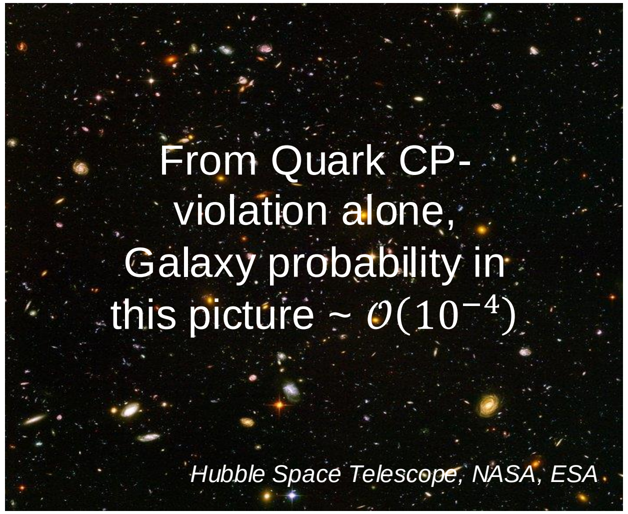
Robust precision test of the SM



Predicted values are immeasurably small in the SM.

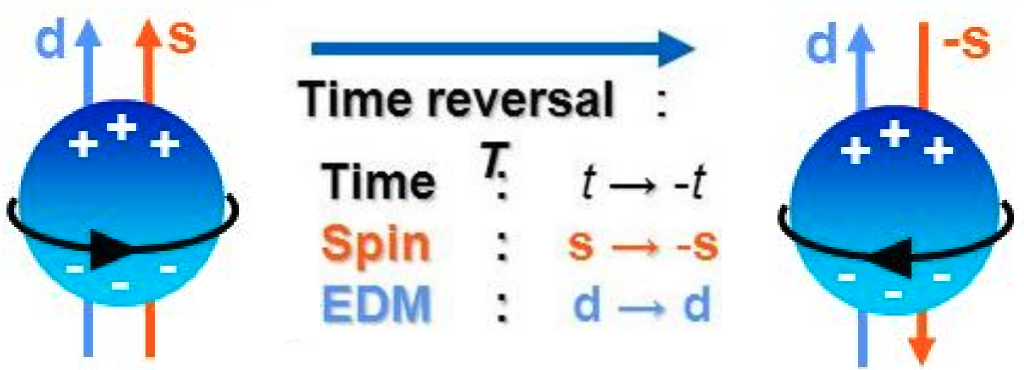
Universe's matter-antimatter asymmetry.

New CP violation.



Why EDMs?

Permanent EDM Violates both T & P Symmetries

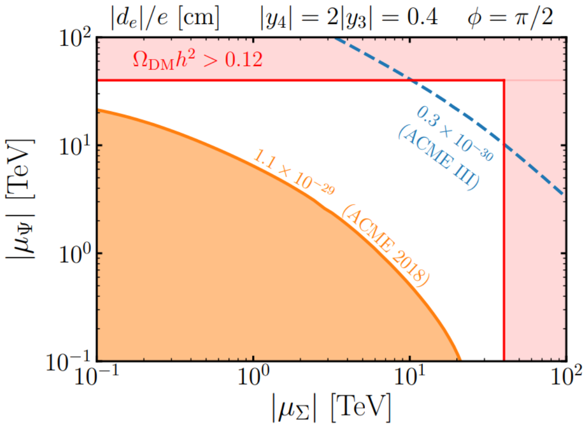


EDM, $d \neq 0$:
T-violation = CP-violation

Non-zero EDM = BSM physics + CP-violation.

Dark matter

DM models predict large EDMs.

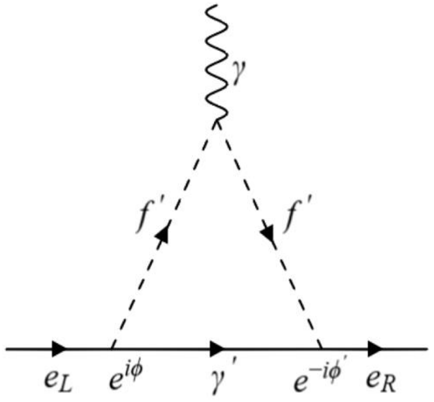


At minimum, can greatly constrain parameter space.

New physics sensitivity

BSM effects are loop-induced.

Sensitive to a wide range of interactions and energy scales.



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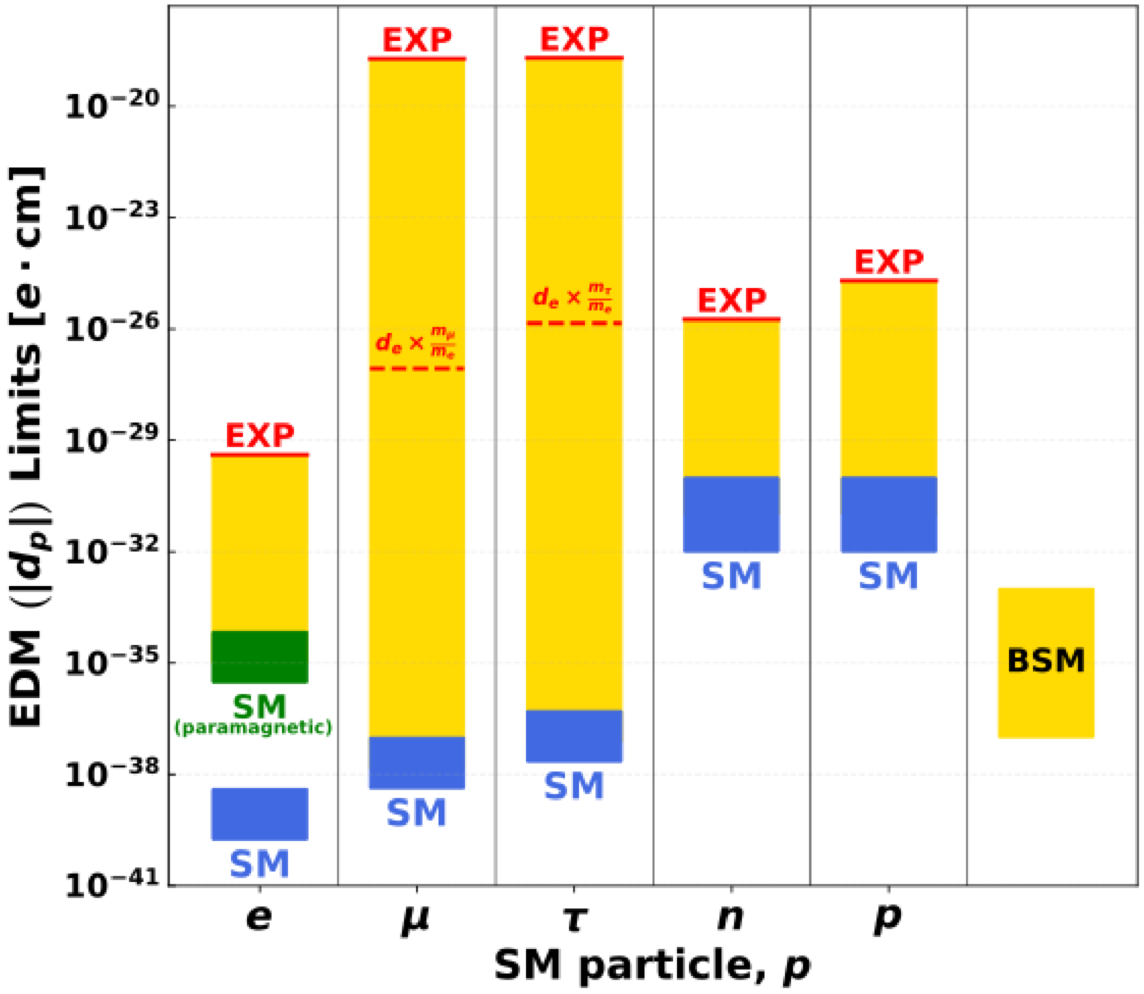
EDMs: Intro and Current Status

- Dirac equation in electric field yields EDM form factor, F_3:

$$\Gamma^\mu = -ie\left[\gamma^\mu F_1(q^2) + (F_2(q^2) + iF_3(q^2)\gamma_5)\frac{i\sigma^{\mu\nu}q_\nu}{2m}\right]$$

[For particle mass with m_p, EDM d_p $\rightarrow$ $F_3(0) \propto 2m_p d_p$]

- Measure of the overall polarity of the system:
  - i.e. the separation/distribution of positive (u) and negative (d) charge within the proton.
  - Charge asymmetry along the spin axis.
- External electric field + a non-zero, static EDM of the proton induces mechanical torque:
  - Uneven charge distribution + electric field = EDM-induced motion.
  - Not to be confused with magnetic dipole moment (g-2).
- A permanent EDM violates both P and T.
  - From CPT symmetry → model-independent CP violation.



Disclaimer: in this talk I was focus entirely on these particles and will not mention atomic EDMs.

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SM predictions of EDMs

Phys.Rev.Lett. 129 (2022) 23, 231801,
Phys.Rev.Lett. 129 (2022) 231801

SM predictions for paramagnetic EDMs (e.g. electron EDM in atoms, frequency of atomic transition) can be substantially enhanced (e.g. by K_s exchange parameterisation of CKM matrix) and can arise from EDM **OR** semi-leptonic operator:

Science 381 (2023) 6653,.

$$\left|d_e^{\text{equiv}}\right| < 4.1 \times 10^{-30}\ e \cdot \text{cm}$$

EDM operator

$$d_e^{\text{equiv}} = d_e + C_S \times 1.5 \times 10^{-20}\ e\,\text{cm}$$

Semi-leptonic operator

For "purely leptonic" CKM predictions…

Electron, Muon and Tau

- Ultimately transfers from quark EDMs.
- Long-distance, non-perturbative effects dominate.
- Errors are huge (~70%).

$$d_e^{(\text{SM})} = 5.8 \times 10^{-40} e\,\text{cm},$$
$$d_\mu^{(\text{SM})} = 1.4 \times 10^{-38} e\,\text{cm},$$
$$d_\tau^{(\text{SM})} = -7.3 \times 10^{-38} e\,\text{cm}.$$

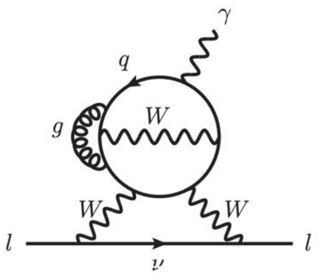

FIG. 1. Example of four-loop level diagram contributing to the EDM of charged leptons generated by the CKM matrix at the quark level.

Phys.Rev.Lett. 125 (2020) 241802

Neutron and Proton

- Induced by CKM matrix's CP-phase via hadronic loops.
- Again, huge uncertainties (order of magnitude).
- Long distance contributions calculated to be:

$$1 \times 10^{-32} e\,\text{cm} < \{|d_n|, |d_p|\} < 6 \times 10^{-32} e\,\text{cm}$$

Phys.Rev.C 91 (2015) 2, 025502

- Estimate of full contribution comes from P and CP conserving nuclear magnetic moment μ_N corrected for P-violating and CP violating phases:

$$d_N > \mu_N G_F f_\pi^2 \times 10^{-3} \times 10^{-7} \sim \mathbf{10^{-31}}\ \boldsymbol{e \cdot \text{cm}}$$

… ± an order of magnitude.

F. Abusaif et al. [CPEDM], arXiv:1912.07881 (2019).

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See Gerald Gabrielse's talk after this.

Electron EDM

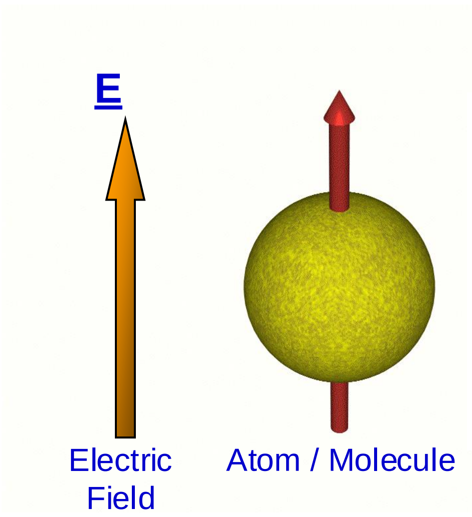
Using atoms or molecules to measure electron EDM, d_e:

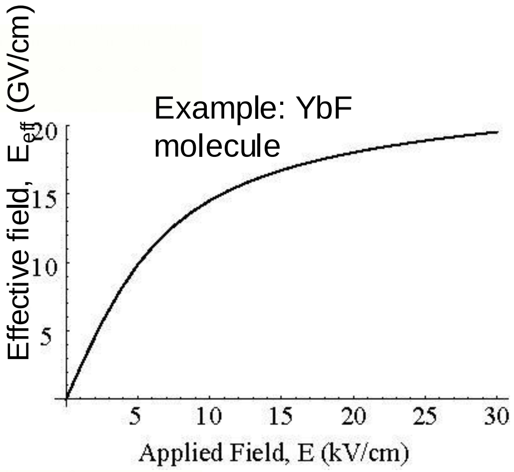
- For a free electron in an applied field **E**, expect an interaction energy $-\mathbf{d_e}.\mathbf{E}$
- For a bound electron, interaction energy = $-\mathbf{d_e}.\mathbf{E}_{eff}$

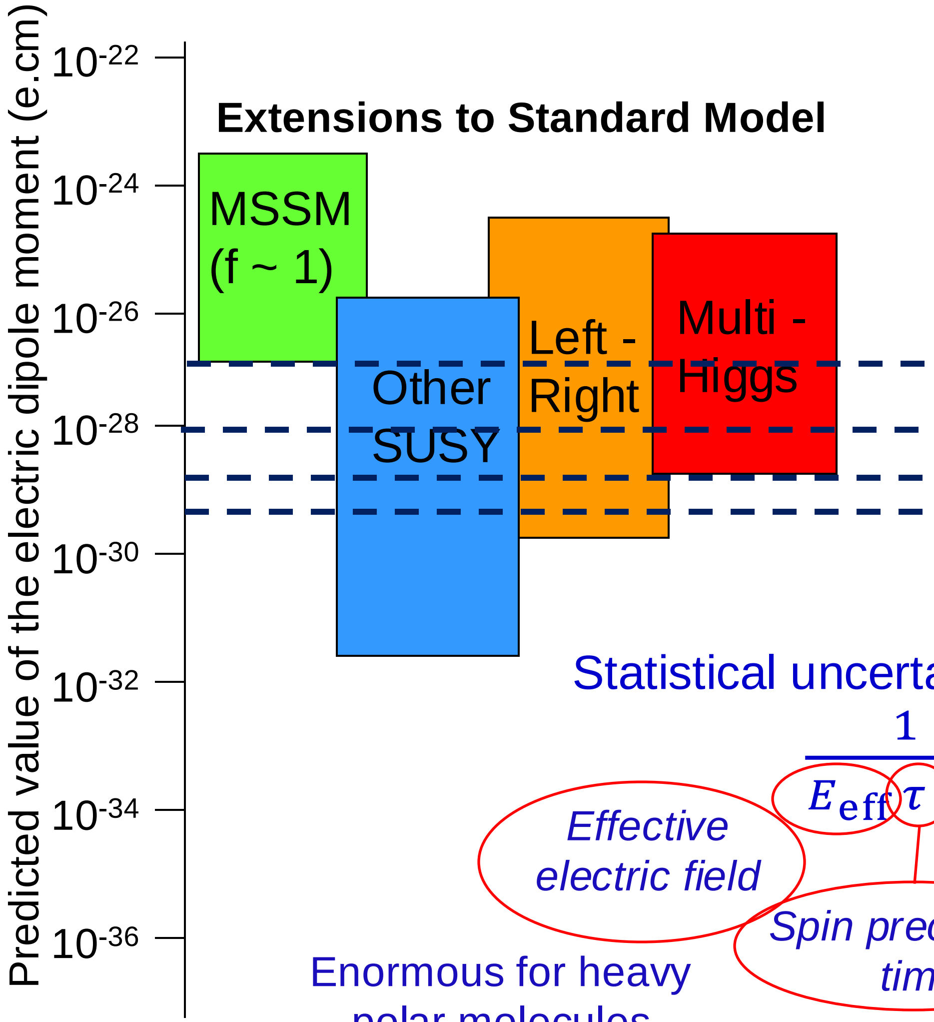
$$E_{eff} = F\,P$$

Structure dependent, ~10 $(Z/80)^3$ GV/cm

Polarization factor







YbF beam (Imperial, 2011, [1])
ThO beam (ACME, 2014, [2])
ThO beam (ACME, 2018, [3])
Trapped HfF^+ (JILA, 2023, [4])
$|d_e| < 4.1 \times 10^{-30}$ e.cm

[1] Nature 473, 493 (2011)
[2] Science 343, 269 (2014)
[3] Nature 562, 355 (2018)
[4] Science 381, 46 (2023)

Statistical uncertainty scales as

$$\frac{1}{E_{eff}\,\tau\,\sqrt{N}}$$

Effective electric field — Enormous for heavy polar molecules

Spin precession time — Can be long if particles are trapped

Number of particles — Can be large for neutral species

Mike Tarbutt, EDM Workshop, Trento, March 2024

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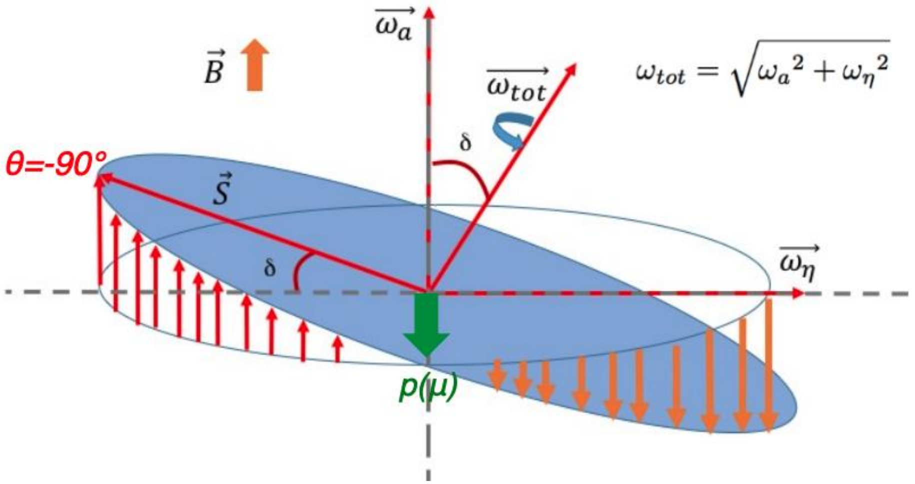
See Miko Sakurai's and Diego Becerra's talks on Thursday.

Muon EDM

$$\vec{\omega}_{a\eta} = \vec{\omega}_a + \vec{\omega}_\eta = -\frac{Qe}{m}\left[a\vec{B} - \left(a - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] - \eta\frac{Qe}{2m}\left[\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right] \qquad \vec{d} = \eta\left(\frac{Qe}{2mc}\right)\vec{s}$$

- Causes an increase in muon precession frequency
- Precession plane tilts towards center of ring
- Vertical oscillation is 90° out of phase with the a_μ oscillation



Both the Fermilab and J-PARC g-2 experiments will also search for a muon EDM in their storage ring experiments.

BNL: |dμ| ≈ 2.5 × 10-19 e.cm
FNAL: |dμ| ≈ 3.0 × 10-21 e.cm
J-PARC: |dμ| ≈ 1.0 × 10-21 e.cm

PSI – a dedicated muon EDM experiment

- Cancel anomalous precession with matched E-field:

$$E \cong aBc\beta\gamma^2$$

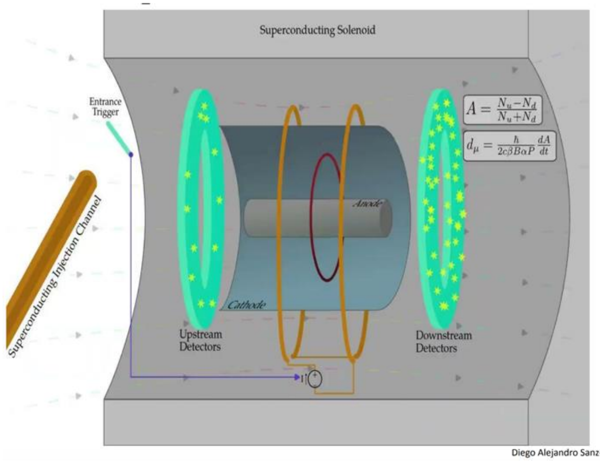
- Spin remains parallel to orbit
- No "contamination" from anomalous spin precession

$$s_z \propto \eta E^* \cdot t$$

$$\vec{\omega} = \frac{q}{m}\left[a\vec{B} + \left(\frac{1}{1-\gamma^2} - a\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta_d}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right]$$

PSI Sensitivity (1 year):
σ(dμ) < 5 × 10-23 e.cm

arXiv:2102.08838



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Tau EDM

- EDMs are chirality flipping with magnitude proportional to particle mass.
- BSM contributions to EDM may scale with lepton mass: $(m_\tau/m_e)^2 \sim 10^7$ and $\left(m_\tau/m_\mu\right)^2 \sim 300$.
- BUT, short tau lifetime: (2.903 ± 0.005) × 10−13 s, makes it impractical to store taus to search for EDM.
- PDG limits: $-1.85 \times 10^{-17}\ ecm < Re(d_\tau) < 6.1 \times 10^{-18}\ ecm,$ $-1.03 \times 10^{-17}\ ecm < Im(d_\tau) < 2.30 \times 10^{-18}\ ecm.$ (Belle)

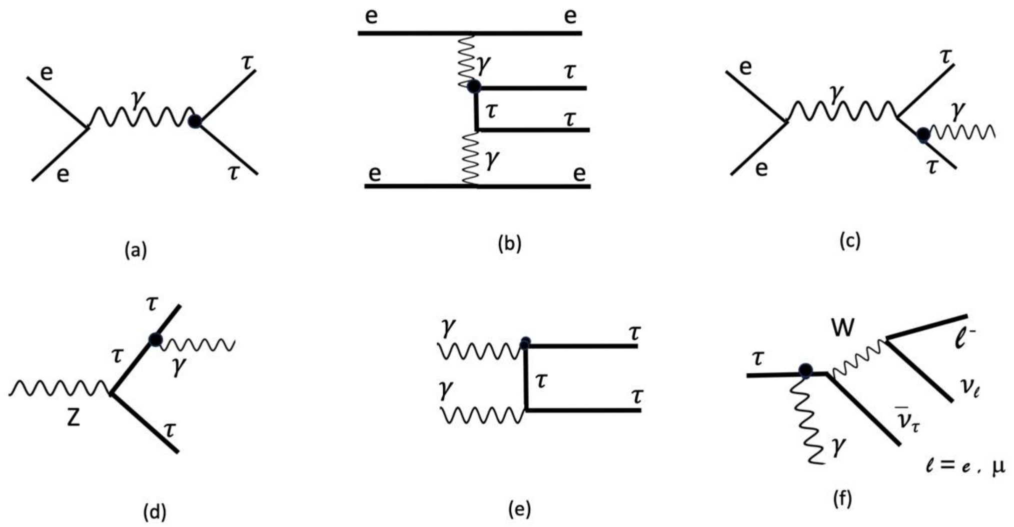

Figure 1: Some processes where the τ dipole moments may contribute.

GA González-Sprinberg, TAU2023, arXiv:2406.15286.

- Belle-II could probe $\sim 10^{-20}$
- Improved PID, tracking, MC, statistics, detector simulation.
- But restricted by beam BG.
  Needs run-by-run BG studies.
- Belle II aims to collect 50ab-1 ,
  - Around 10x more sensitive result can be expected for statistics
  - Luminosity increased by roughly x 8 on Belle.

Can also be probed by Pb-Pb collisions at LHC…

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Nucleon EDMs (d_N)

Nucleon (proton or neutron) are suppressed in the SM.

[Tiny CP violating phase in CKM matrix through higher-order loop processes involving quark interactions.]

The SM prediction for d_N is:

$$\left|d_N^{SM}\right| \sim 10^{-31}\ e \cdot cm$$

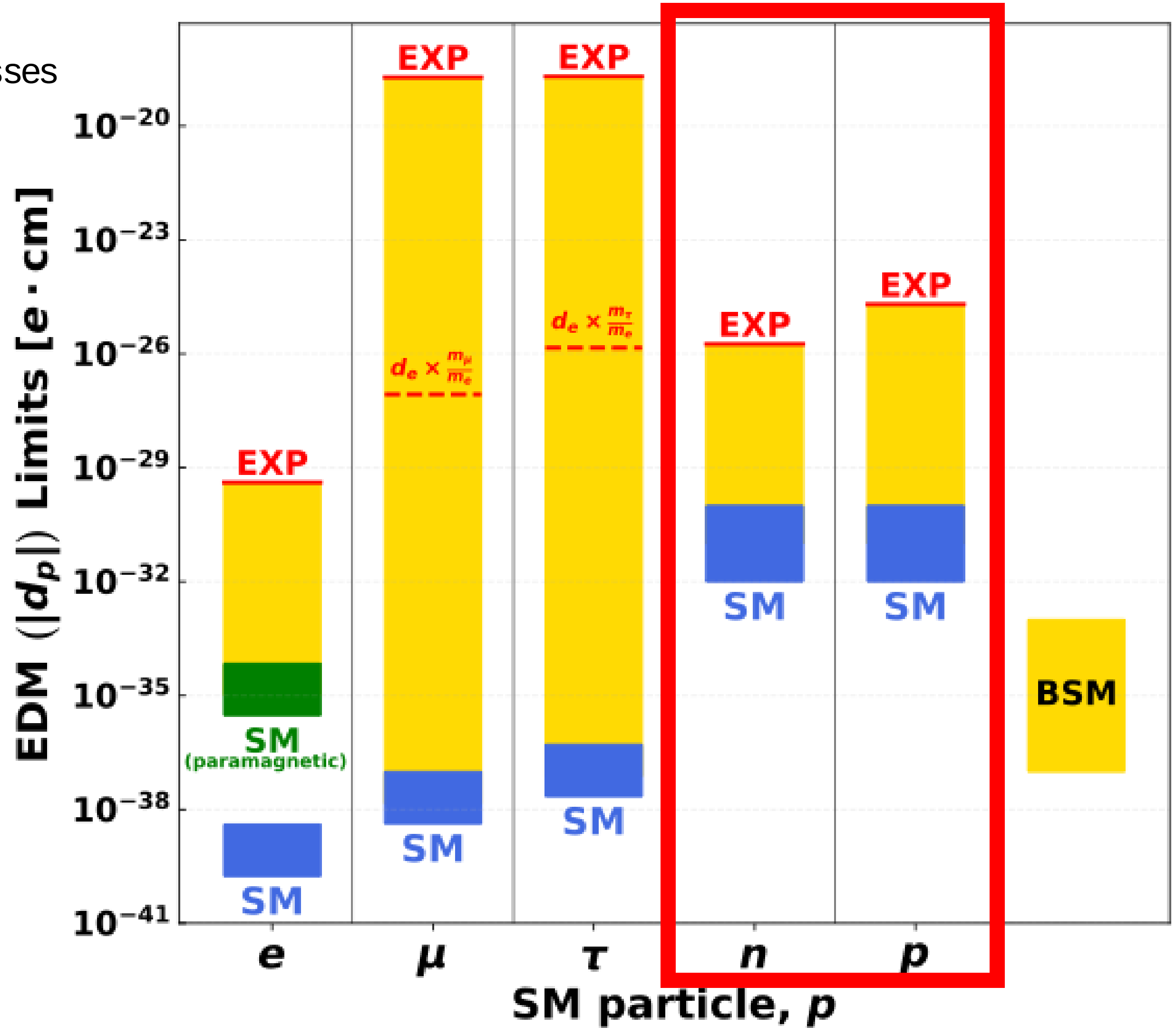
Larger EDMs can arise from:

- BSM models which generate new, CP-violating CKM matrix contributions (SUSY, 2HDM, dark Z, leptoquarks, Extra dimensions).
- The naturally arising QCD θ–term:

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \bar{q}(i\not{D} - m_q)q + \bar{\theta}\frac{g^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

leading to a non-zero d_N :

$$|d_N| \approx |\bar{\theta}| \frac{m_u m_d}{(m_u + m_d)} \frac{\mu_N}{\Lambda_{\text{QCD}}} \approx |\bar{\theta}| \times 10^{-16} e \cdot \text{cm}\,.$$



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Strong CP Problem

QCD (& The SM) has a glaring hole in it…

$$\mathcal{L}_{QCD} = (\ldots) + \boxed{\frac{g^2}{32\pi^2}\,\bar{\theta}\,\tilde{G}^a_{\mu\nu}G^{\mu\nu a}}$$

→ P-violating
→ T-violating
→ **CP-violating**
→ **Non-zero nucleon (N) Electric Dipole Moment (EDM) → $|\vec{d}_N| = \vartheta(\theta)$.**

BUT, no CP violation in strong interactions…

[$\bar{\theta} = \theta + \varphi$ = QCD θ -term + quark mass phase.]

→ No CP violation implies: $\bar{\boldsymbol{\theta}} = \boldsymbol{\theta} + \boldsymbol{\varphi} = \mathbf{0}$ **(Fine tuning!)**

→ No EDM implies $|\bar{\theta}| \lesssim 10^{-10} \rightarrow |\vec{d}_N^{SM}| \lesssim 10^{-31}\, e \cdot cm$ **(Fine tuning!)**

The Strong CP problem is a whole community problem…

Non-zero nucleon EDM, e.g.

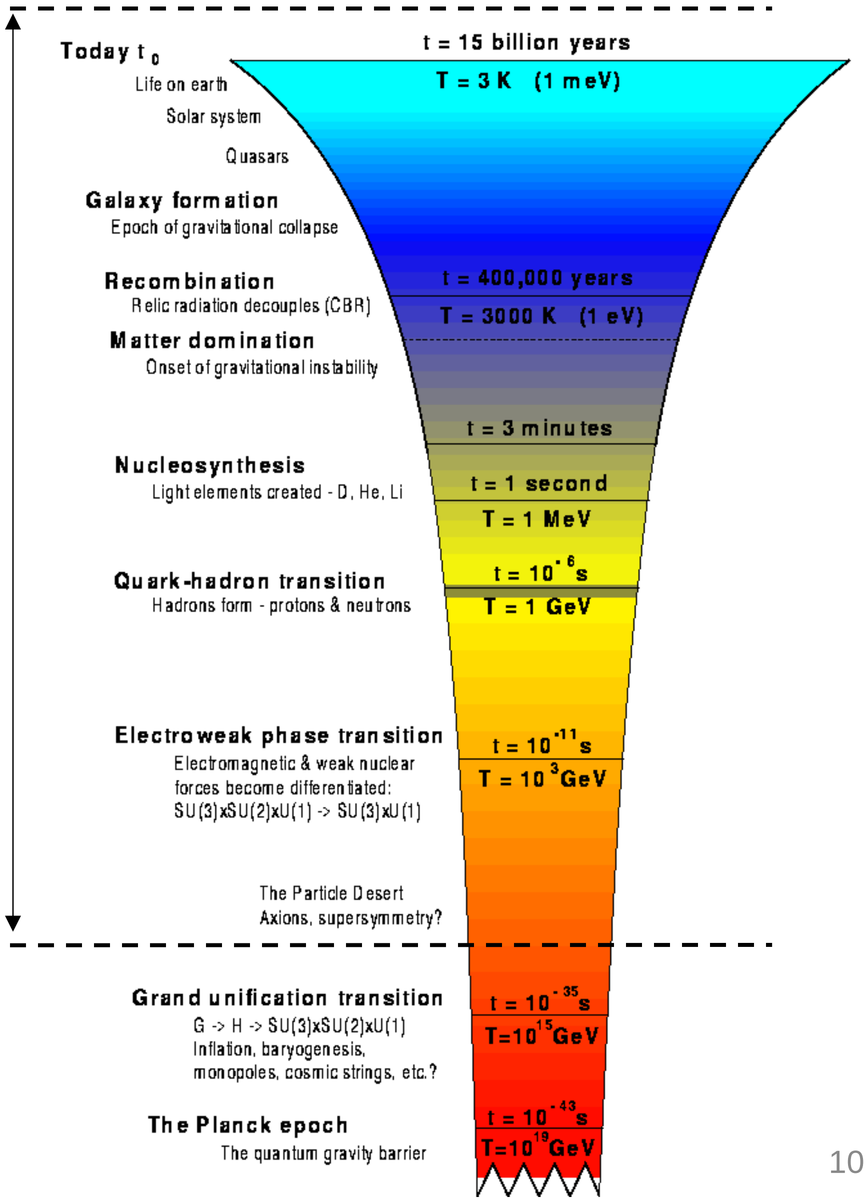
$10^{-26}\, e \cdot cm \gtrsim |\vec{d}_N| \gtrsim 10^{-30}\, e \cdot cm$:

= Understand the strong CP-problem!

= CP-violation source for Baryon Asymmetry!

= Unambiguous new physics!

Must understand the Strong CP Problem



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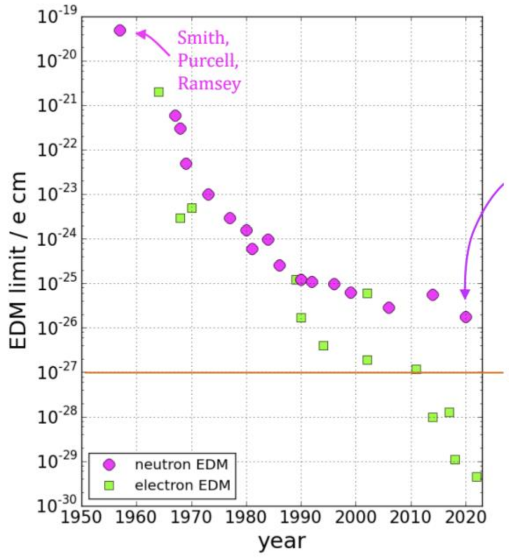
Neutron EDM

- Store ultra-cold neutrons (UCNs) at e.g. PSI.
- Few µT uniform magnetic along the trap axis sets baseline neutron spin precession frequency Zeeman effect.
- Strong electric Field (~ 10 kV/cm) applied across the neutron trap and periodically reversed.
- When an EDM exists, the precession frequency should slightly shift when the electric field is reversed relative to the magnetic field.
- Comagnetometer measurements and Magnetic Field Monitoring.



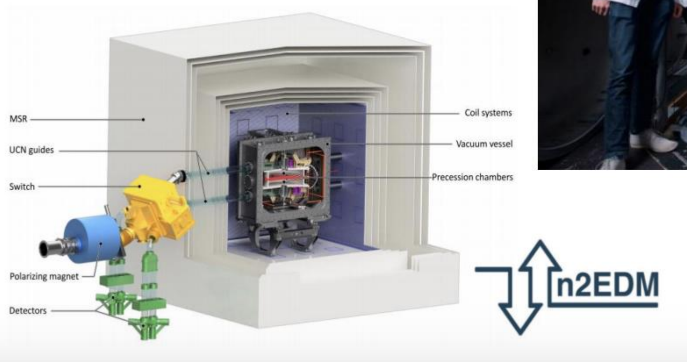
Neutron EDM measured by the nEDM collaboration (2020):

$$d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{sys}) \times 10^{-26}\ e\,cm$$

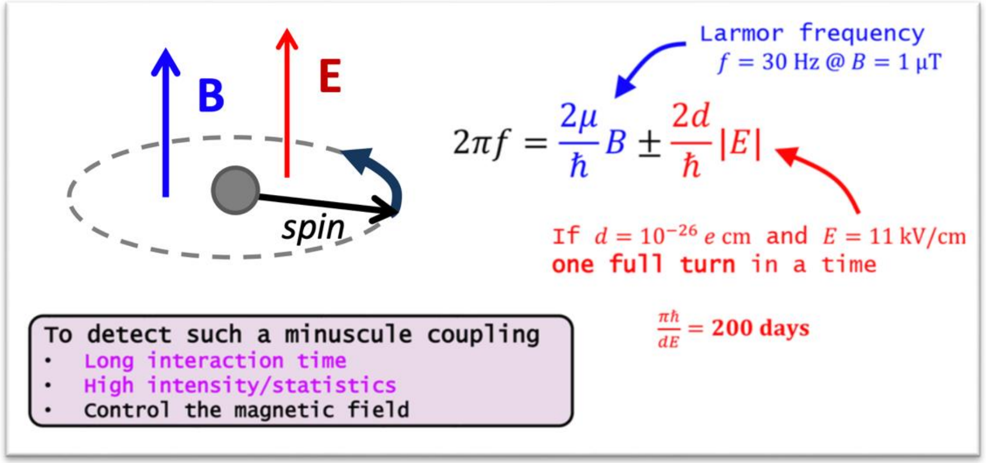
C. Abel *et al.*, Phys. Rev. Lett. 124 (2020), 081803

← The next goal:

n2EDM
PanEDM
LANL
TUCAN



nEDM measurement. The idea:



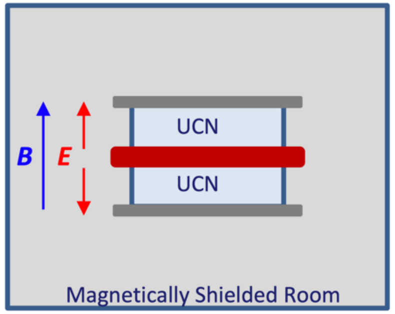
The actual upper limit (2020)

$|d_n| < 1.8 \times 10^{-26}\ e\,cm$ (90% C.L.)

C. Abel et al. Phys. Rev. Lett. 124, 081803

$$f(\uparrow\uparrow) - f(\uparrow\downarrow) = -\frac{2}{\pi\hbar} d\,E$$

$$d = \frac{\pi\hbar}{2|E|}\left(f(\uparrow\downarrow) - f(\uparrow\uparrow)\right)$$



Kseniia Svirina, EDM Workshop, Trento, March 2024

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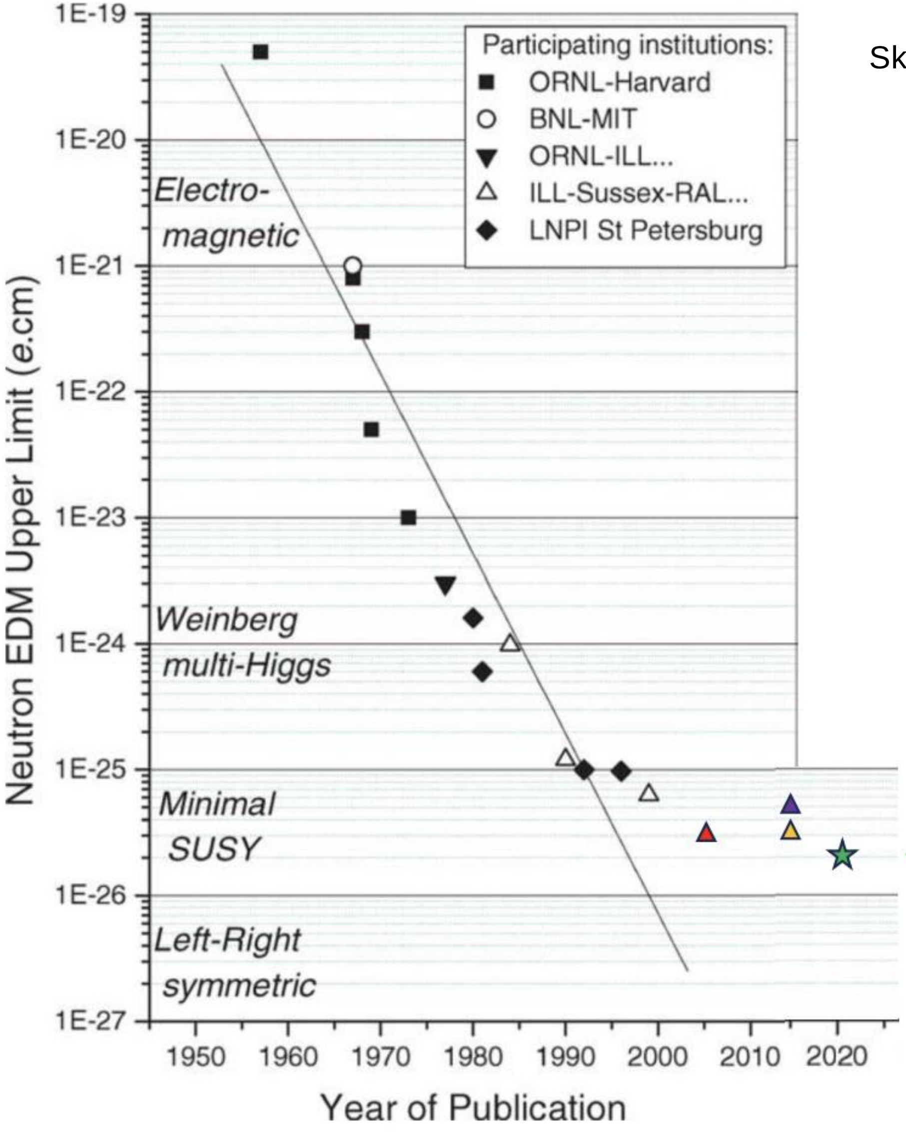
Neutron EDM: limitations



Skyler Degenkolb, DIS24 Grenoble, 2024.

Statistical sensitivity of the PSI experiment:

$$\sigma(d_n) \gtrsim \frac{\hbar}{2\alpha\,|\boldsymbol{E}|\,T\sqrt{N}}$$

Current limit (PSI): 2.2×10^{-26} e cm, 95% C.L.

Polarization contrast ≈ 0.8

11 kV/cm

180 s

$(54\times10^{3})\times(10^{4}/\text{shot})$

Now strongly limited by available neutrons

Future experiments working to develop technology for increased neutron intensity.

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Robust precision test of the SM

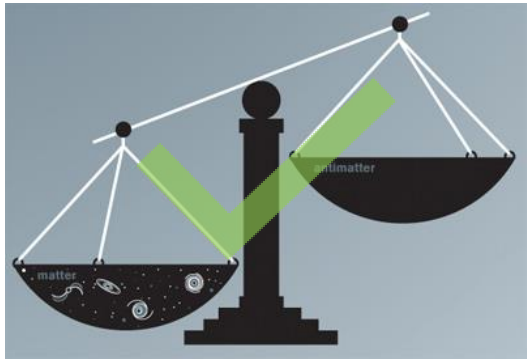
$$\mathcal{L}_{QCD} = (\dots) + \frac{g^2}{32\pi^2}\bar{\theta}\tilde{G}^a_{\mu\nu}G^{\mu\nu a}$$

Non-zero nucleon (N) Electric Dipole Moment (EDM) → $|\vec{d}_N| = \vartheta(\theta)$.

Understand the Strong CP problem.

Universe's matter-antimatter asymmetry.

CP-violating

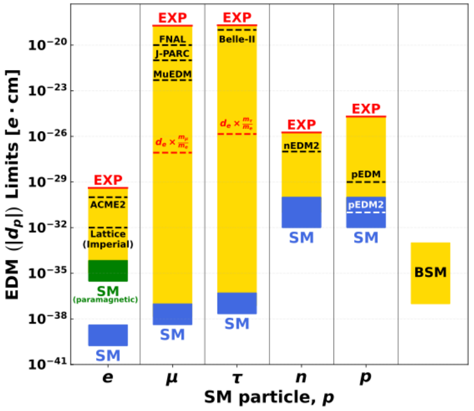


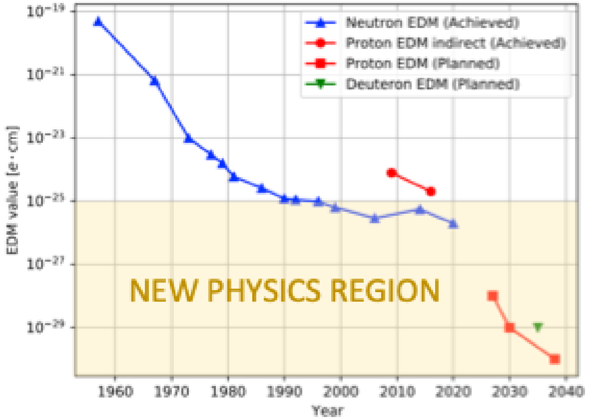
Confirmed proton EDM = model-independent CP violation.

Why Proton EDM?

First ever direct proton EDM measurement.

Improve on current (indirect) limit by at least $\mathcal{O}(10^4)$.

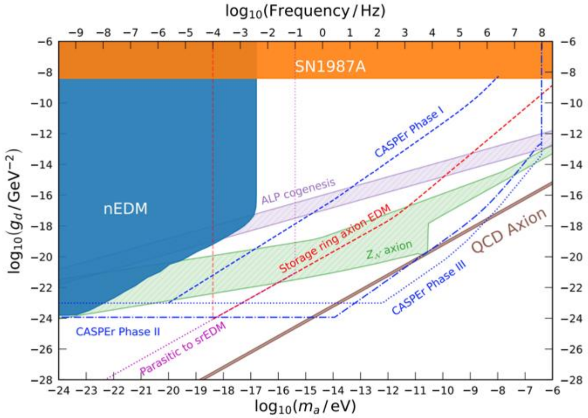




Only EDM measurement with current potential to probe SM limit.

Dark matter

Oscillating pEDM = axionic DM.



Probes axion field...

Freq: 1 mHz → 1MHz

Mass: 10^{-7} eV → 10^{-22} eV

New physics sensitivity

Far-reaching complimentary to wider programme.

$\mathcal{O}(\mathrm{PeV})$ mass scale:

$\phi^{\mathrm{NP}} \sim 1,\ \Lambda_{\mathrm{NP}} \sim 3 \times 10^3$ TeV.

[e.g. LHC/FCC.]

Light, weak new physics

$\Lambda_{\mathrm{NP}} \sim 1$ GeV, $g \lesssim 10^{-5}$, $\phi^{\mathrm{NP}} \sim 10^{-10}$.

[e.g. LZ, LDMX, FASER, SHiP.]

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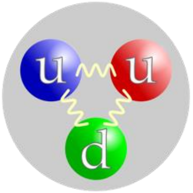
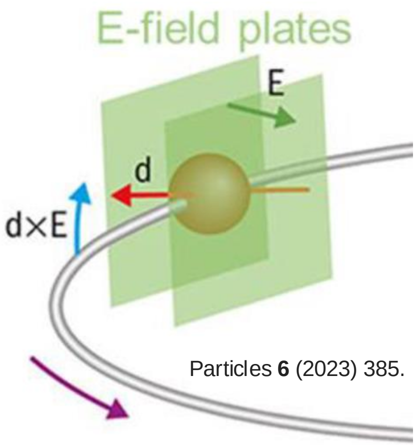
The Proton EDM

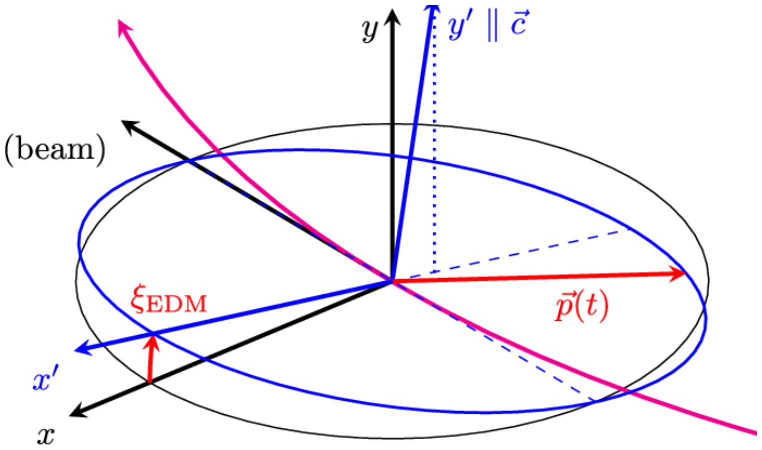
- Measure of charge separation of the system:
  - i.e. distribution of positive (u) and negative (d) charge within the proton.



- Uneven charge + electric field = EDM-induced torque.
- Results in vertical tilt the spin/polarisation:
  - We just need to measure an angle!



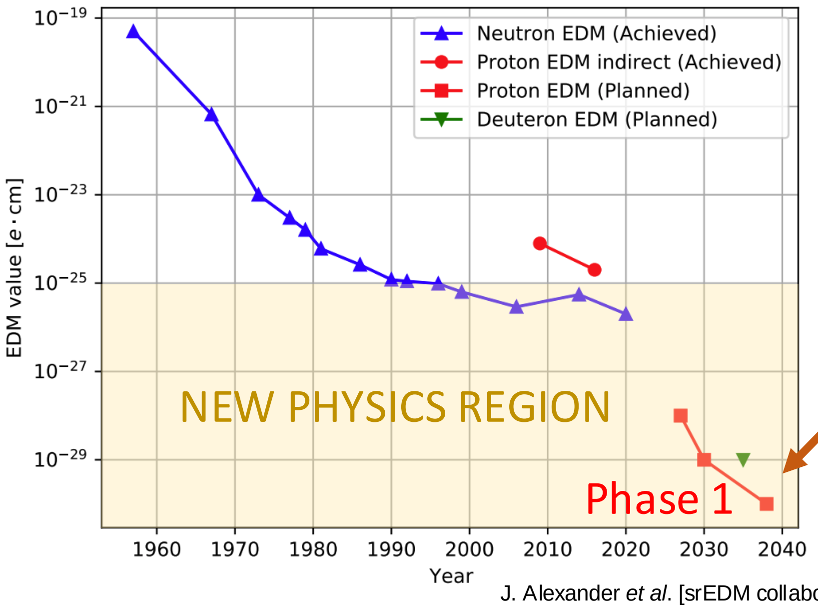
Particles **6** (2023) 385.



Phys. Rev. Accel. Beams **23** (2020) 024601.

- Requires:
  - Longitudinally polarised protons.
  - Electric storage ring (electric field bending).
  - Polarimeters to measure polarisation.

- Direct nEDM limit: $|\vec{d}_n| < 1.8 \times 10^{-26}\ e \cdot cm$.
- No direct limit on pEDM!
- Best indirect limit: $\left|d_p^{\downarrow 199\mathrm{Hg}}\right| < 2.0 \times 10^{-25}\ e \cdot cm$.



New paradigm of sensitivity

[Statistics > nEDM.]

J. Alexander *et al*. [srEDM collaboration], arXiv:2205.00830.

Proton EDM experiment phase 1 sensitivity ~ $10^{-29}\ e \cdot cm$!

[That's 0.00000000000000000000000000001 $e \cdot cm$]

→ **pEDM improved >** $\mathcal{O}(10^4)$.

→ θ_{QCD} **(strong CP problem) improved >** $\mathcal{O}(10^3)$.

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Storage ring EDM: a Muon g-2 spin-off

Consider Muon g-2 experiment: charged particle in magnetic ($\vec{B}$) and electric ($\vec{E}$) fields:

Measure a frequency →

$$\vec{\omega}_{spin} = \vec{\omega}_{MDM} \approx \frac{e}{m}\left[a\vec{B} + \left(a - \frac{1}{\gamma^2 - 1}\right)(\vec{\beta} \times \vec{E})\right].$$

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Storage ring EDM: a Muon g-2 spin-off

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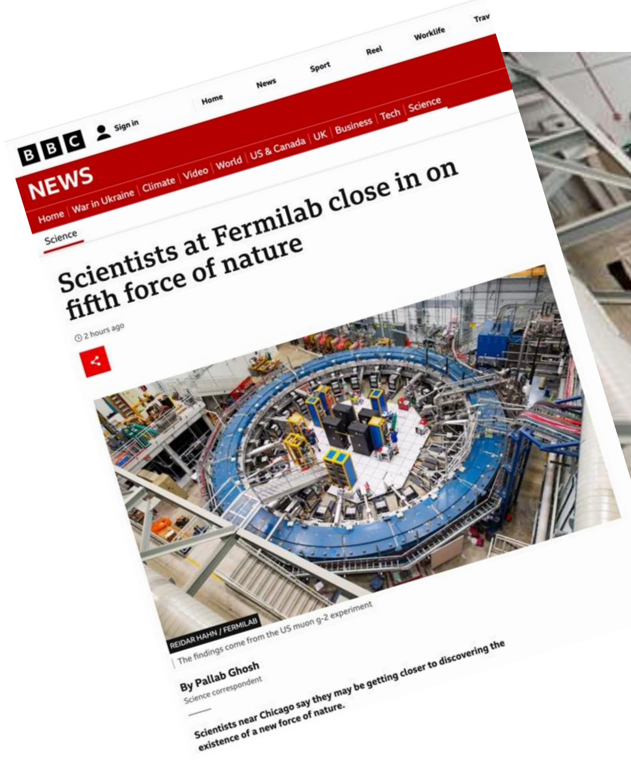
Muon → storage ring magnet $R_0 = 7.112\ \mathrm{m}$ and $B = 1.45\ \mathrm{T}$ ...

Choose muon g-2 magic-momentum, $\gamma_{\mathrm{magic}} = \sqrt{1 + 1/a} \rightarrow p = 3.094\ \mathrm{GeV/c}$.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Science

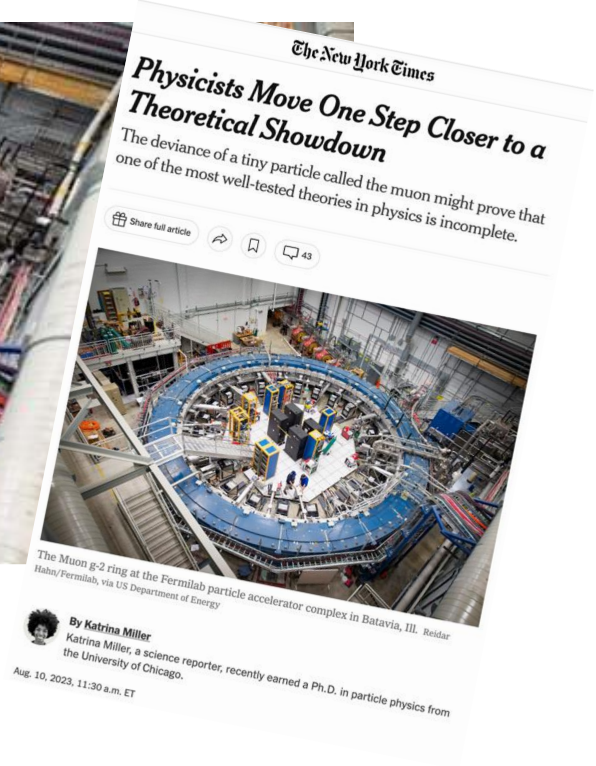
Scientists at Fermilab close in on fifth force of nature

2 hours ago

REIDAR HAHN / FERMILAB
The findings come from the US muon g-2 experiment

By Pallab Ghosh
Science correspondent

Scientists near Chicago say they may be getting closer to discovering the existence of a new force of nature.


The New York Times

Physicists Move One Step Closer to a Theoretical Showdown

The deviance of a tiny particle called the muon might prove that one of the most well-tested theories in physics is incomplete.

Share full article 43

The Muon g-2 ring at the Fermilab particle accelerator complex in Batavia, Ill. Reidar Hahn/Fermilab, via US Department of Energy

By Katrina Miller
Katrina Miller, a science reporter, recently earned a Ph.D. in particle physics from the University of Chicago.

Aug. 10, 2023, 11:30 a.m. ET

Major experimental and particle physics success!
Currently 200ppb precision!

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Storage ring EDM: a Muon g-2 spin-off

<u>Use</u> Muon g-2 principles: charged particle <u>with EDM</u> in magnetic ($\vec{B}$) and electric ($\vec{E}$) fields:

Measure a frequency → $\vec{\omega}_{spin} = \vec{\omega}_{MDM} + \vec{\omega}_{EDM} \approx \frac{e}{m}\left[a\vec{B} + \left(a - \frac{1}{\gamma^2-1}\right)(\vec{\beta} \times \vec{E}) + \frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B}\right)\right]$, $\vec{d} = \eta \frac{q\hbar}{2mc}\vec{S}$.

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(the $\vec{\omega}_{MDM}$ term and the $a\vec{B} + \left(a - \frac{1}{\gamma^2-1}\right)\left(\vec{\beta}\times\vec{E}\right)$ terms are crossed out)

Frozen-spin technique!

Proton → electric storage ring $R_0 = 800\ \mathrm{m}$ and $E = 4.4\ \mathrm{M/m}$ ...

Choose pEDM magic-momentum: $a\vec{B} + \left(a - \frac{1}{\gamma^2-1}\right)\left(\vec{\beta}\times\vec{E}\right) = 0 \rightarrow p = 0.7\ \mathrm{GeV/c}$.

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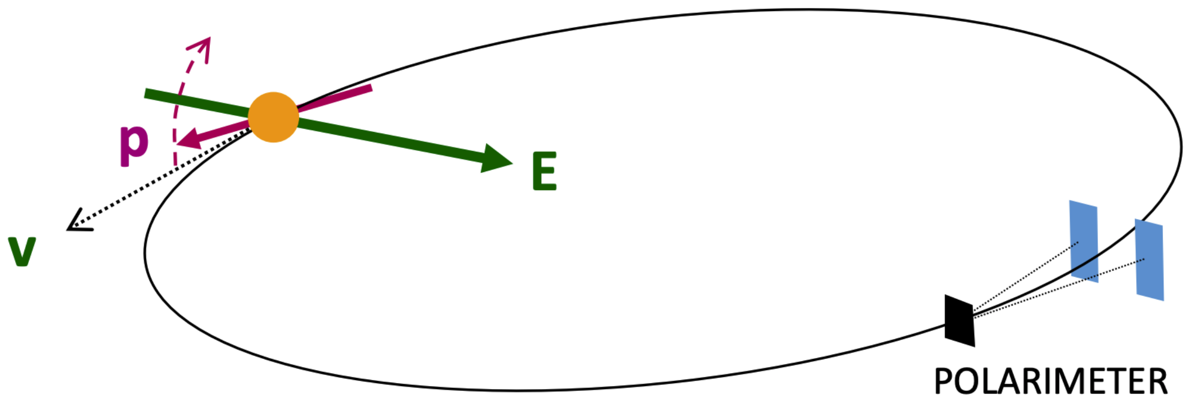

- Inject $\mathcal{O}(10^{10})$ polarized protons every twenty minutes.
- $\vec{E}$-field storage and bending.
- Vertical polarization in polarimeter = static EDM.

What about large, T-conserving systematics that mimic vertical, T-violating EDM, e.g. unwanted vertical electric fields?

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Storage ring EDM: a Muon g-2 spin-off

Use Muon g-2 principles: charged particle with EDM in magnetic ($\vec{B}$) and electric ($\vec{E}$) fields:

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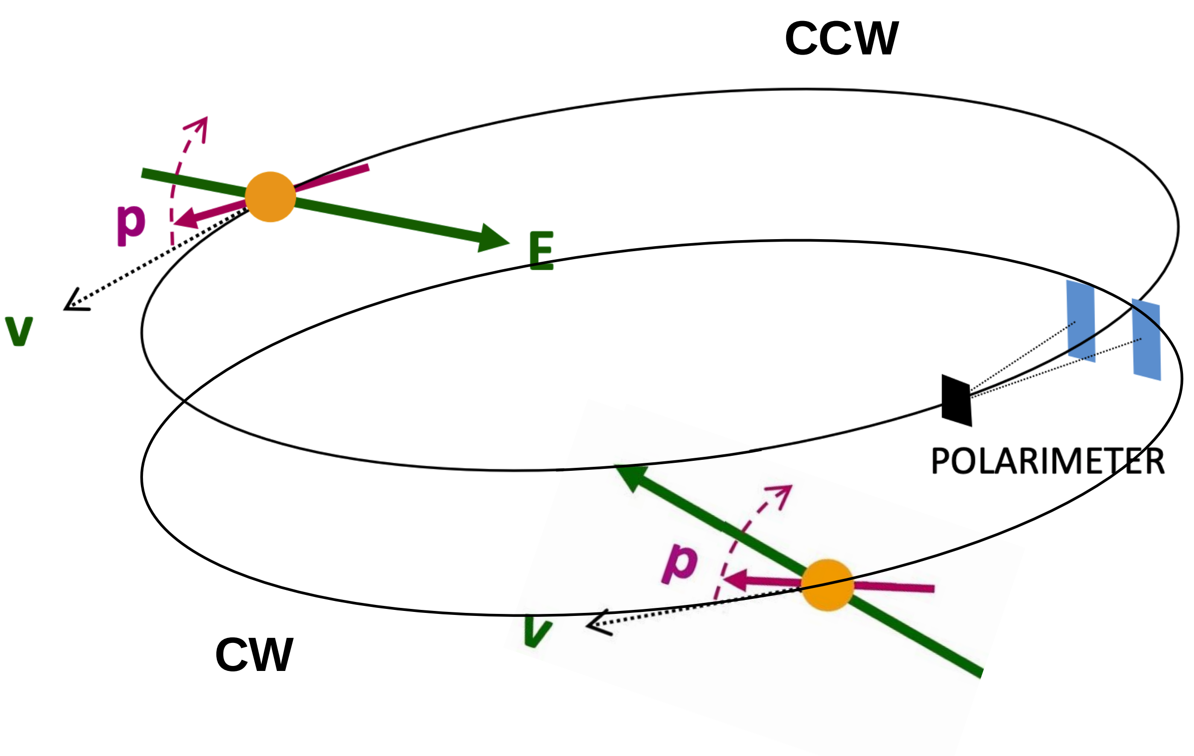

- Inject $\mathcal{O}(10^{10})$ polarized protons every twenty minutes.
- $\vec{E}$-field storage and bending.
- Vertical polarization in polarimeter = static EDM.

What about large, T-conserving systematics that mimic vertical, T-violating EDM, e.g. unwanted vertical electric fields?

→ Store CW and CCW beams (time reverse of each other) to cancel these effects!

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A Probe for Axionic Dark Matter (DM)

The Strong CP problem has a longstanding hypothesis solution:

- The Peccei-Quinn Mechanism (Phys. Rev. Lett. **38** (1977) 1440).
- Gives rise to the (undiscovered) axion → common DM candidate.

Axion DM field oscillates as background field in the universe:

- Frequency amplitude = universe's DM density.
- Axion frequency related to axion mass.

If axion exists, oscillating field = time-varying CP-violating interaction with Proton EDM.

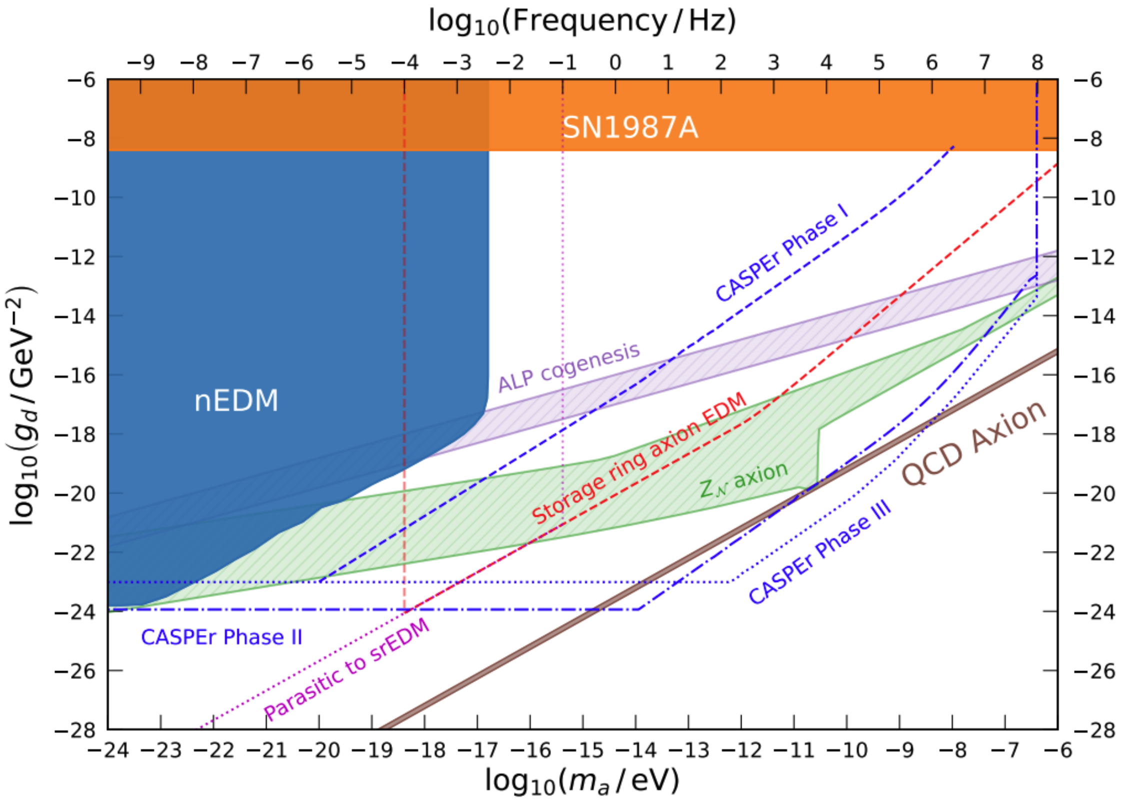
- Proton EDM would oscillate at the frequency of the axion field!

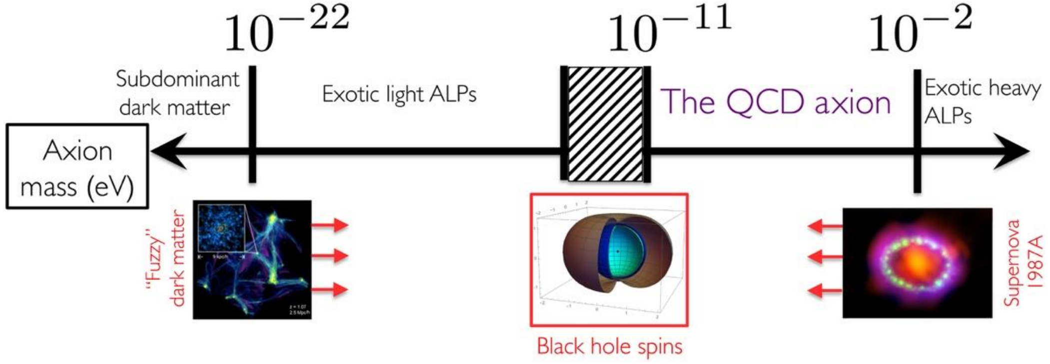
$$d_p(t) \approx \frac{a(t)}{f_a} \times 10^{16} \approx 5 \times 10^{-35} \cos\left(\frac{1}{\hbar} m_a c^2 (t - t_0) + \phi_0\right) \, e \cdot \text{cm}\,.$$

The Proton EDM Experiment is extremely sensitive to such time variations:

- Would stand out as a distinct signature from background.

Axion frequency / mass sensitivity:
Frequency: 1 mHz → 1MHz
Mass: 10^{-7} eV → 10^{-22} eV





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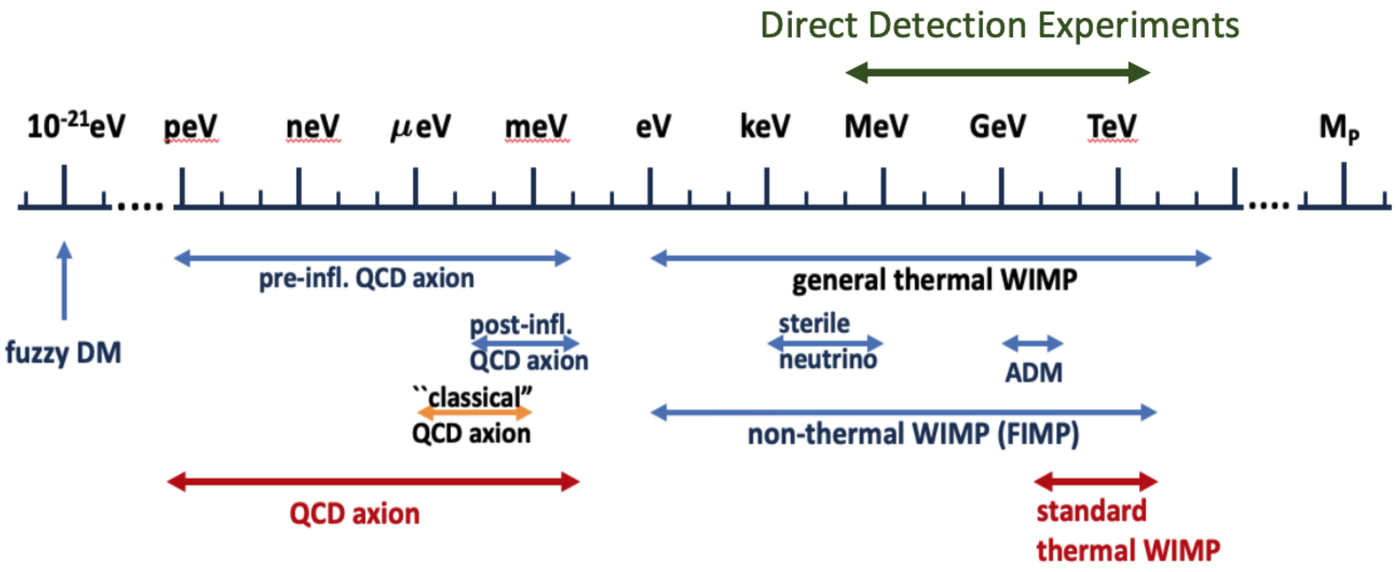
pEDM Experiment: New Physics Reach

Strong CP Problem	Matter-Antimatter Asymmetry	Dark Matter	EDM loop induced = wide range of interactions/energy scales $d_p \sim (g^2/16\pi^2)\,(e\,m_q)/\Lambda_{\rm NP}^2\ \sin\phi^{\rm NP}\ \ e\cdot cm$ m_q = mass of 1-loop quark, $\phi^{\rm NP}$ = complex CP violation phase of NP	
Solved!	Model-independent CP-violation.	Oscillating pEDM signature = **<u>axion</u>** [$\mathcal{O}(10^2)$ larger than nEDM!]. ERJC **84** (2024) 12, arXiv:2308.16135, PRD **99** (2019) 083002, PRD **104** (2021) 096006	Light, weak new physics: $\Lambda_{\rm NP}\sim 1$ GeV, $g \lesssim 10^{-5}$, $\phi^{\rm NP}\sim 10^{-10}$. [e.g. LZ, LDMX, FASER, SHiP.]	$\mathcal{O}$(PeV) mass scale: $\phi^{\rm NP}\sim 1$, $\Lambda_{\rm NP}\sim 3\times 10^3$ TeV. [e.g. LHC/FCC.]

Recent work suggests magnitude of d_N & BSM sensitivity are charge-dependent…

L. Di Luzio *et al.*, Phys. Rept. **870** (2020) 1; C. Smith, Eur. Phys. J. C **84** (2024) 12; L. Di Luzio *et al.*, JHEP **04** (2024) 076.

→ Proton potentially more sensitive probe than neutron.



Federica Petricca, Direct Dark Matter Detection Report Community Feedback Meeting (2021).

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pEDM Statistical Sensitivity

PRD **105** (2022) 032001, arxiv:2205.00830.

At BNL, circumference = 800 m for E = 4.4 MV/m. The signal accumulation is 10^{-9}rad/s for a sensitivity of $10^{-29}\ e \cdot cm$.

$$\sigma_d = \frac{2.33 s\hbar}{P_0 A E \sqrt{k N T_{\exp} \tau_p}}$$

P_0 = Beam polarisation = ~ 0.8

A = asymmetry = ~ 0.6

E = electric field strength = 4.4 MV/m

k = polarimetry efficiency = ~ 0.01

N = number of stored protons = ~ 2×10^{10}

$T_{\exp}$ = total experiment duration = ~ 10^8 s

τ_p = polarisation lifetime = ~ 2×10^3 s

pEDM2: Increase E and k = increase sensitivity to SM prediction – Work ongoing!

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(Short) path to readiness

Main message: no showstoppers! Due diligence, physics studies, moving to CDR/TDR phase…

Already completed…

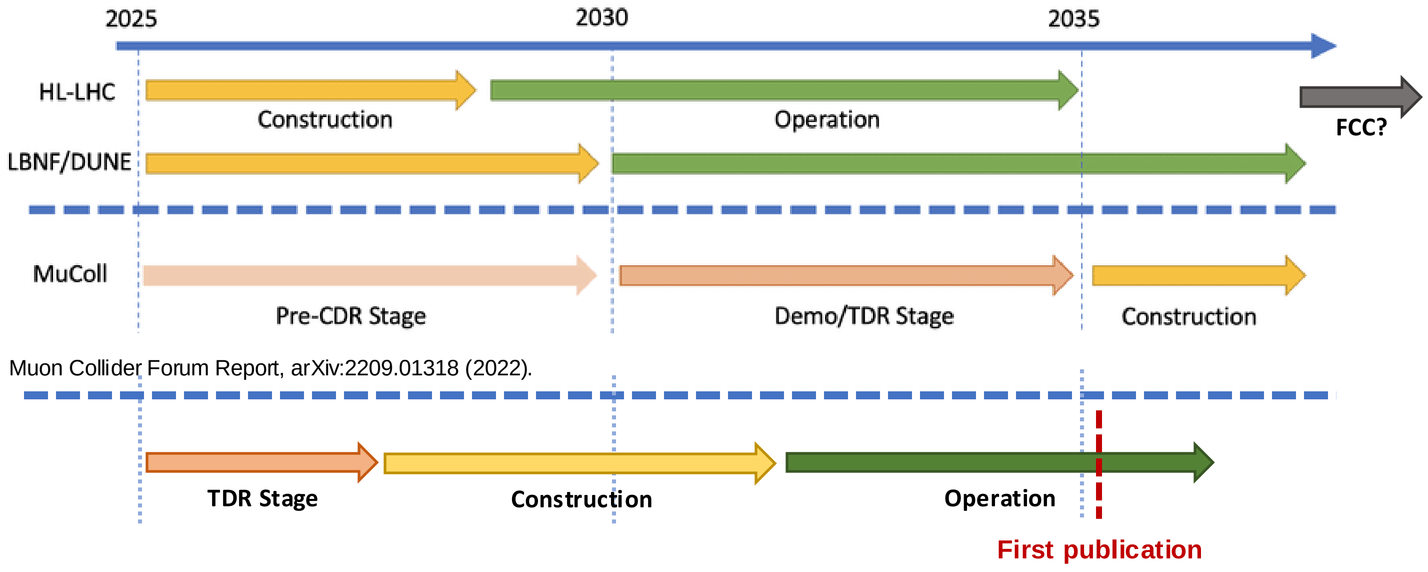
- Experiment design, engineering and modelling complete. ✅
- Prototype components under construction. ✅
- Measurement techniques understood. ✅
- Key systematics understood. ✅

Work to be done…

- Precision beams studies (Muon g-2 experts).
- Options for improved polarimetry (e.g. CMOS).
- Alignment system, methodology and studies.
- Simulate 10^3 particles for 10^3 seconds beam lifetime.
- More realistic costing (estimated $\mathcal{O}$(£100M)).

Build community/collaboration!

- Increased involvement (you are invited!).
- New generation to start and finish experiment.



- Cost O(£100M) and TDR to final publication in < 20 years.
- Can be started and finished by the new generation.
- Paramount physics drivers:
  - Solve strong CP problem.
  - Baryon asymmetry.
  - Dark matter.

Arguably one of the most low-cost/high-return proposals in particle physics today!

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(Short) path to readiness

<u>Main message:</u> no showstoppers! Due diligence, physics studies, moving to CDR/TDR phase…

- F. Abusaif *et al.* [CPEDM], arXiv:1912.07881 (2019).
- J. Alexander et al., arXiv:2205.00830 (2022).
- F. J. M. Farley *et al.*, Physical Review Letters **93** (2004) 052001.
- V. Anastassopoulos Mooser *et al.*, "*A proposal to measure the proton electric dipole moment with* $10^{-29}\, e \cdot cm$ *sensitivity*", by the Storage ring EDM collaboration (2011).
- N. Brantjes *et al.*, Nucl. Instrum. Meth. A **664** (2012) 49.
- W. M. Morse, Y. F. Orlov and Y. K. Semertzidis, Phys. Rev. ST Accel. Beams **16** (2013) 114001.
- E. M. Metodiev *et al.*, Phys. Rev. ST Accel. Beams **17** (2014) 074002.
- A. Mooser *et al.,* Nature **509** (2014) 596.
- D. Eversmann *et al.* [JEDI Collaboration], Phys. Rev. Lett. **115** (2015) 094801.
- E. M. Metodiev *et al.*, Nucl. Instrum. Meth. A **797** (2015) 311.
- G. Guidoboni *et al.* [JEDI Collaboration], Phys. Rev. Lett. **117** (2016) 054801.
- V. Anastassopoulos *et al.*, Rev. Sci. Instrum. **87** (2016) 115116.
- A. Saleev *et al.* [JEDI Collaboration], Phys. Rev. Accel. Beams **20** (2017) 072801.
- N. Hempelmann *et al.* [JEDI Collaboration], Phys. Rev. Lett. **119** (2017) 014801.
- N. Hempelmann *et al.* [JEDI Collaboration], Phys. Rev. Accel. Beams **21** (2018) 042002.
- G. Guidoboni *et al.* [JEDI Collaboration], Phys. Rev. Accel. Beams **21** (2018) 024201.
- S. Hacıömeroğlu and Yannis K. Semertzidis, Phys.Rev.Accel.Beams 22 (2019) 034001.
- Z. Omarov *et al.* Phys. Rev. D **105** (2022) 032001.
- JINST **17** (2022) C09010;.
- J. Gooding, PhD thesis, University of Liverpool

CDR is in preparation now!

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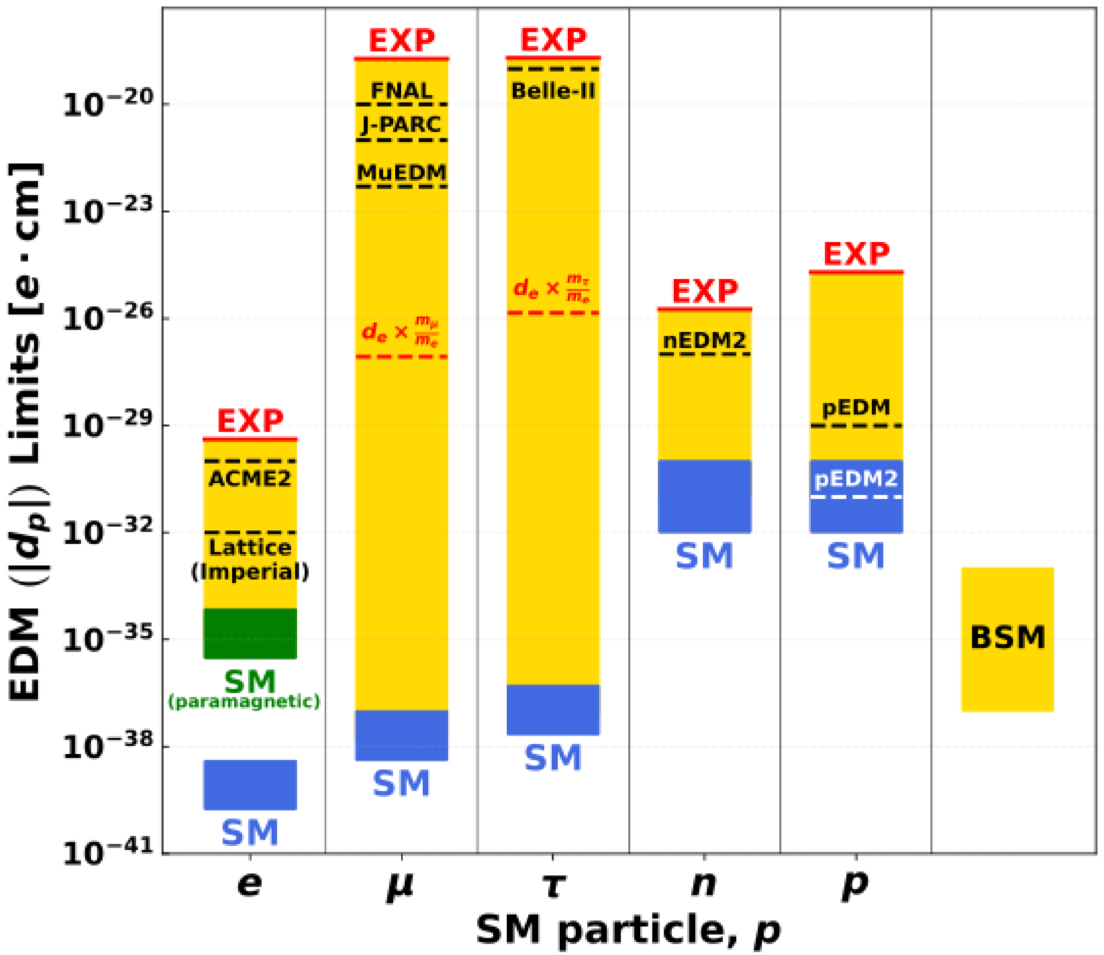
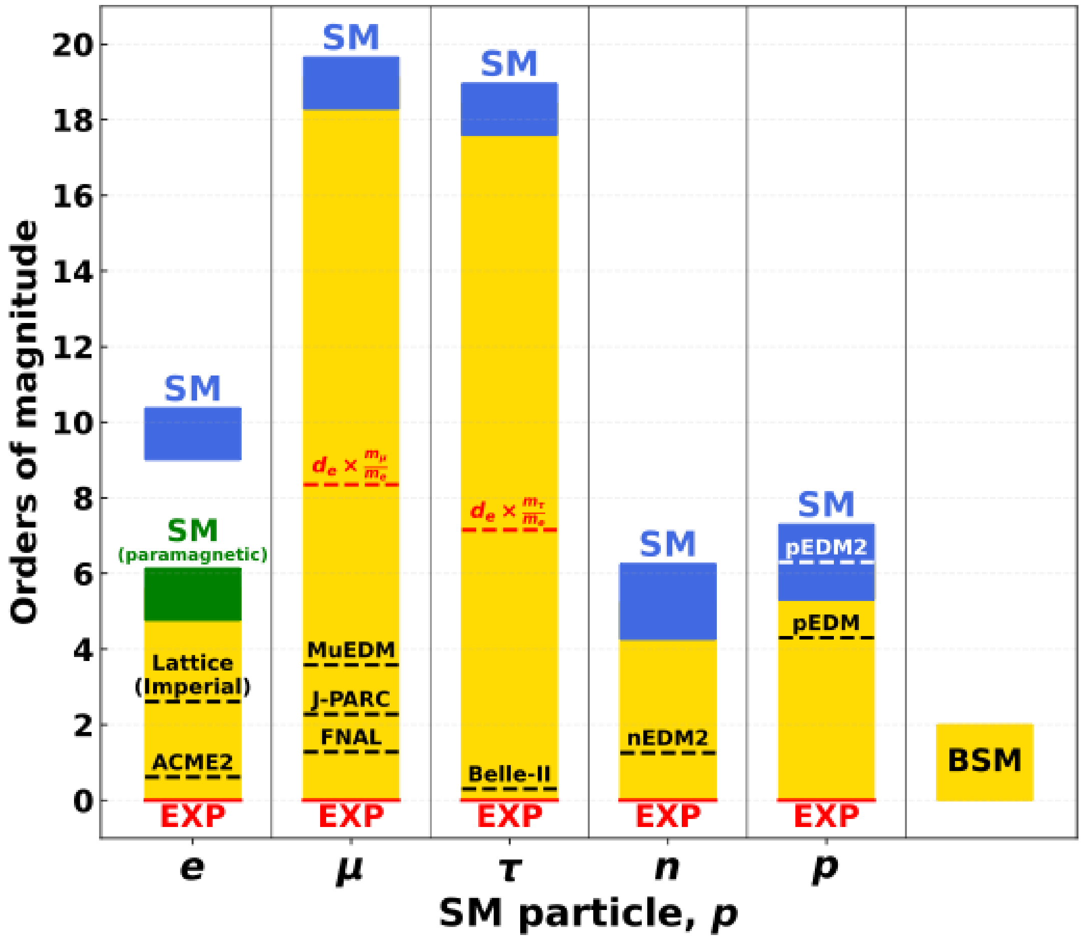
EDM Experiment Sensitivity





pEDM is the only experiment with immediate potential to measure a particle EDM down to its SM prediction

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Conclusions

- EDMs provide a tool to probe significant new physics drivers:
  - CP-violation source for Baryon Asymmetry.
  - Dark-matter.
  - Probe light-weak new particles → PeV-scale new physics.
  - No EDM would also be dramatic → at SM limit.
- SM predictions are difficult and have large uncertainties.
- Electron and muon EDM measurements to improve by 1-3 orders of magnitude in next 5 years.
- Nucleon EDMs probe strong CP problem and axionic DM.
- Next-generation neutron experiments will improve by x10.
- Proton EDM has never been directly measured.
- pEDM will improves on current (indirect) limit by $> \mathcal{O}(10^4)$.
- Has potential to to do $\mathcal{O}(10^6)$ and be sensitive to SM prediction.

Thank you

Backups

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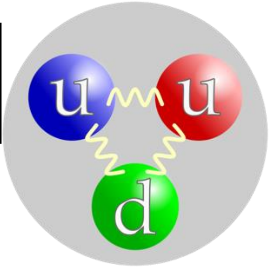
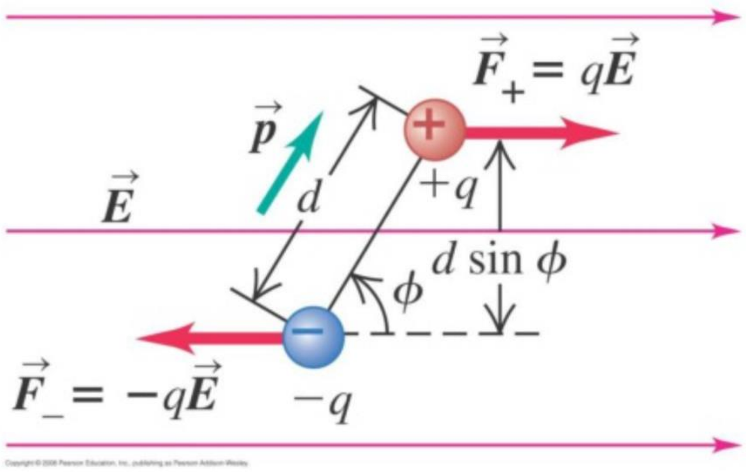
What is the proton EDM?

- The Dirac equation in an electric field gives rise to the EDM form factor, F_3:

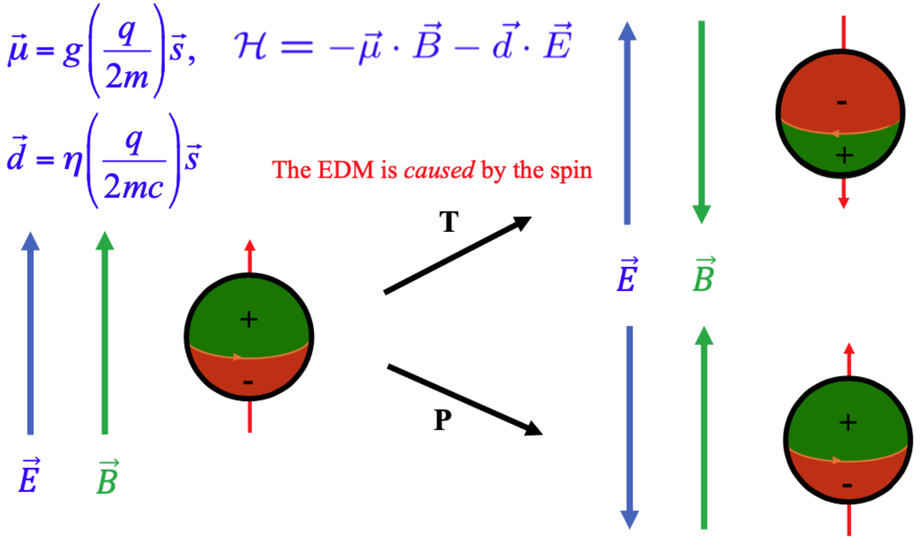
$$\Gamma^\mu = -ie\left[\gamma^\mu F_1(q^2) + (F_2(q^2) + iF_3(q^2)\gamma_5)\frac{i\sigma^{\mu\nu}q_\nu}{2m}\right]$$



For the Proton (mass m_p, EDM d_p) $\rightarrow$ $F_3(0) \propto 2m_p d_p$



- It is a measure of the overall polarity of the system:
  - i.e. the separation/distribution of positive (u) and negative (d) charge within the proton.
  - Charge asymmetry along the spin axis.
- External electric field + a non-zero, static EDM of the proton induces mechanical torque:
  - Uneven charge distribution + electric field = EDM-induced motion.
  - Not to be confused with magnetic dipole moment (g-2).
- A permanent EDM violates both P and T.
  - From CPT symmetry → model-independent CP violation.



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The SM Prediction of the Proton EDM

The allowed upper limit for for the nucleon EDM is given by

$$d_N < \mu_N G_F f_\pi^2 \times 10^{-3} \sim 10^{-24} e \cdot \mathrm{cm}$$

- μ_N is the P and CP conserving nuclear magnetic moment.
- Corrected P-violation scale in SM: $G_F f_\pi^2 \sim 10^{-7}$.
- Corrected for CP violation scale: ~ 10^{-3}

The lower limit of d_N is found by adjusting the upper bound of d_N in the SM.

- Should the Peccei-Quinn mechanism remove QCD θ-term…
- → SM's flavour-changing, CP-violating phase from the CKM-matrix corrects flavour-neutral nature of EDM upper limit by applying a further suppression factor of $G_F f_\pi^2 \sim 10^{-7}$:

$$d_N > \mu_N G_F f_\pi^2 \times 10^{-3} \times 10^{-7} \sim \mathbf{10^{-31}\, e \cdot cm}$$

More detailed calculations exist (e.g. Phys. Rev. C **91** (2015) 025502), but all similar order of magnitude and ALL have uncertainties of roughly ± an order of magnitude.

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Peccei-Quinn mechanism

- Basic idea: promote $\bar{\theta}$ to a field and make sure that it dynamically relaxes to zero

- How to get there: extend the SM with additional fields so that the model has an axial $U(1)_{PQ}$ global symmetry with these features:
  - $U(1)_{PQ}$ is broken spontaneously at some high scale → axion is the resulting Goldstone mode
  - $U(1)_{PQ}$ is broken by the axial anomaly → the axion acquires interactions with gluons, which generate an axion potential
  - Potential induces axion expectation value such that $\bar{\theta}=0$

- Salient features can be captured by effective theory analysis

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Strong CP Problem

$$\mathcal{L}_{QCD} = (\dots) + \frac{g^2}{32\pi^2}\bar{\theta}\tilde{G}^a_{\mu\nu}G^{\mu\nu a}$$

→ P-violating
→ T-violating
→ **CP-violating**

BUT, we do not overserve CP violation in strong interactions…

$$\bar{\theta} = \theta + \varphi$$

= QCD θ -term (non-perturbative) + quark mass phase.

→ No CP violation implies:

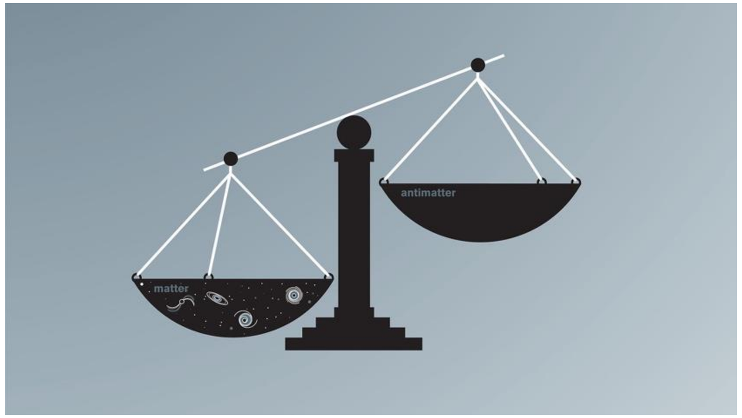
$$\bar{\boldsymbol{\theta}} = \boldsymbol{\theta} + \boldsymbol{\varphi} = \mathbf{0}$$ **(Fine tuning!)**

$\bar{\theta}\tilde{G}G$ leads to non-zero nucleon (N) EDM → $|\vec{d}_N| = \vartheta(\theta)$.

SM: $|\bar{\boldsymbol{\theta}}| \lesssim \mathbf{10^{-10}} \rightarrow |\vec{\boldsymbol{d}}_N^{SM}| \lesssim \mathbf{10^{-31}}\ \boldsymbol{e \cdot cm} \rightarrow$ **More fine tuning!** → **Strong CP problem**

A non-zero proton EDM (pEDM), e.g. $\mathbf{10^{-24}}\ \boldsymbol{e \cdot cm} \gtrsim |\vec{\boldsymbol{d}}_N| \gtrsim \mathbf{10^{-30}}\ \boldsymbol{e \cdot cm}$:

- Unambiguous evidence of new physics (with no SM theory needed!).
- Solves strong CP-problem!



- **Baryon asymmetry** - Model-independent source of CP-violation needed.
- **Dark matter -** new U(1) symmetry + SSB → pseudo-Goldstone boson, a = **axion**

$$\mathcal{L}_{QCD+a} = (\dots) + \frac{g^2}{32\pi^2}\bar{\theta}\tilde{G}^a_{\mu\nu}G^{\mu\nu a} - \frac{g^2}{32\pi^2}\frac{f_a\bar{\theta}}{f_a}\tilde{G}^a_{\mu\nu}G^{\mu\nu a}$$

→ Observed oscillating pEDM = possible signature of an axion-like DM particle**.**

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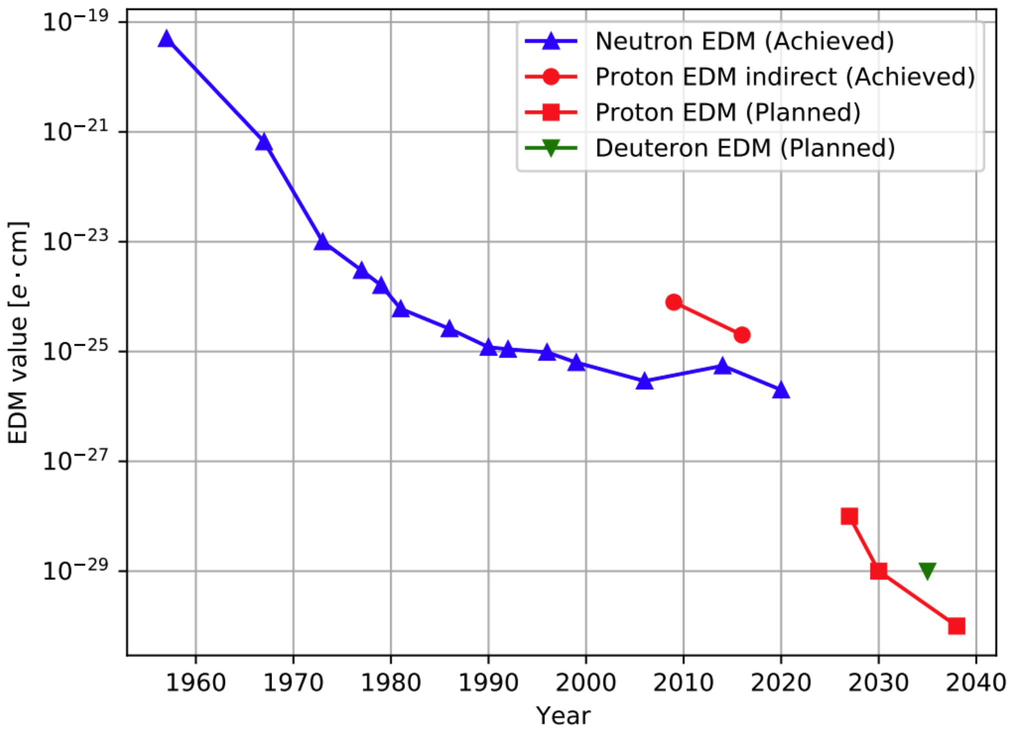
Proton EDM experiment sensitivity

- No current direct limit on pEDM! Best indirect limit from atomic physics is $\left|d_p^{\downarrow 199\text{Hg}}\right| < 2.0 \times 10^{-25}\, e \cdot cm$.
- Best current (direct) nEDM limit is $\left|\vec{d}_n\right| < 1.8 \times 10^{-26}\, e \cdot cm$.
- Remember, new physics in nucleon EDM range: $10^{-24}\, e \cdot cm \gtrsim \left|\vec{d}_N\right| \gtrsim 10^{-30}\, e \cdot cm$…

J. Alexander *et al.* [srEDM collaboration], arXiv:2205.00830.



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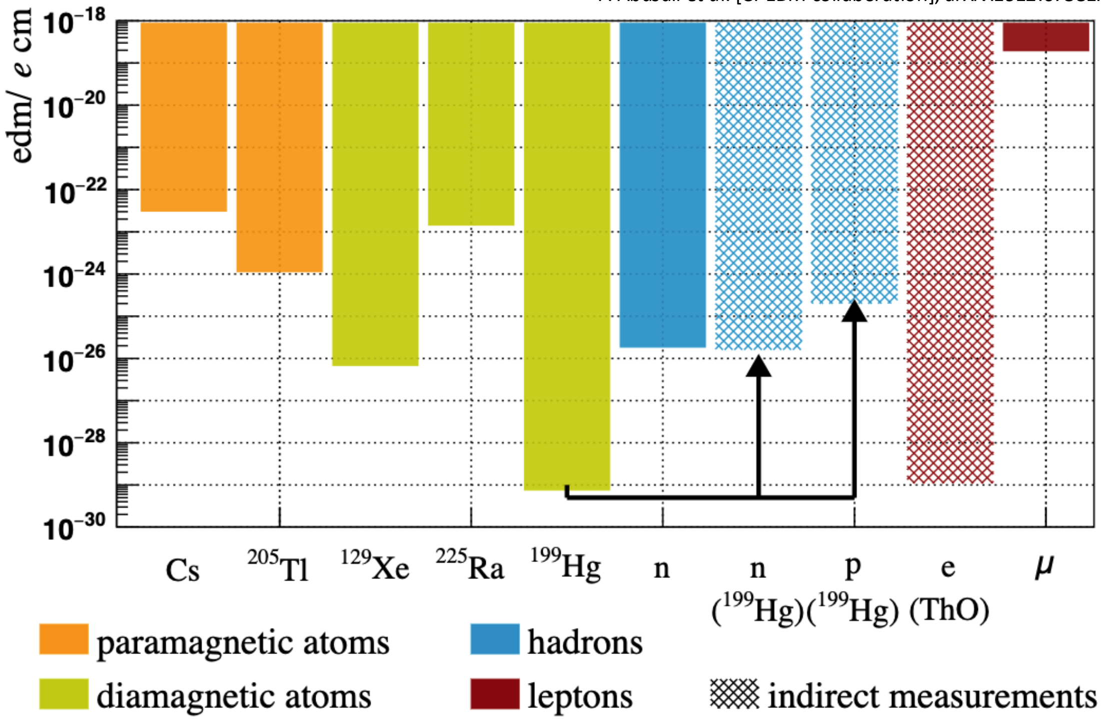

First-ever direct proton EDM measurement will have a sensitivity of $10^{-29}\, e \cdot cm$!

Take-home message: 4 orders of magnitude on pEDM, three orders of magnitude on θ_{QCD}.

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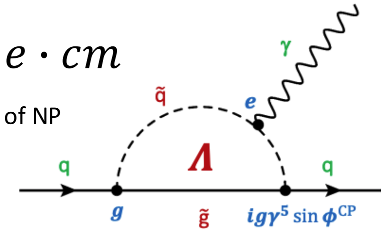
Physics complementarity

pEDM new physics (NP) with scale Λ_{NP} is quantum loop induced (by virtue of uncertainty principle):

$$d_p \sim (g^2/16\pi^2)\,(e\, m_q)/\Lambda_{\mathrm{NP}}^2 \,\sin\phi^{\mathrm{NP}} \;\; e\cdot cm$$

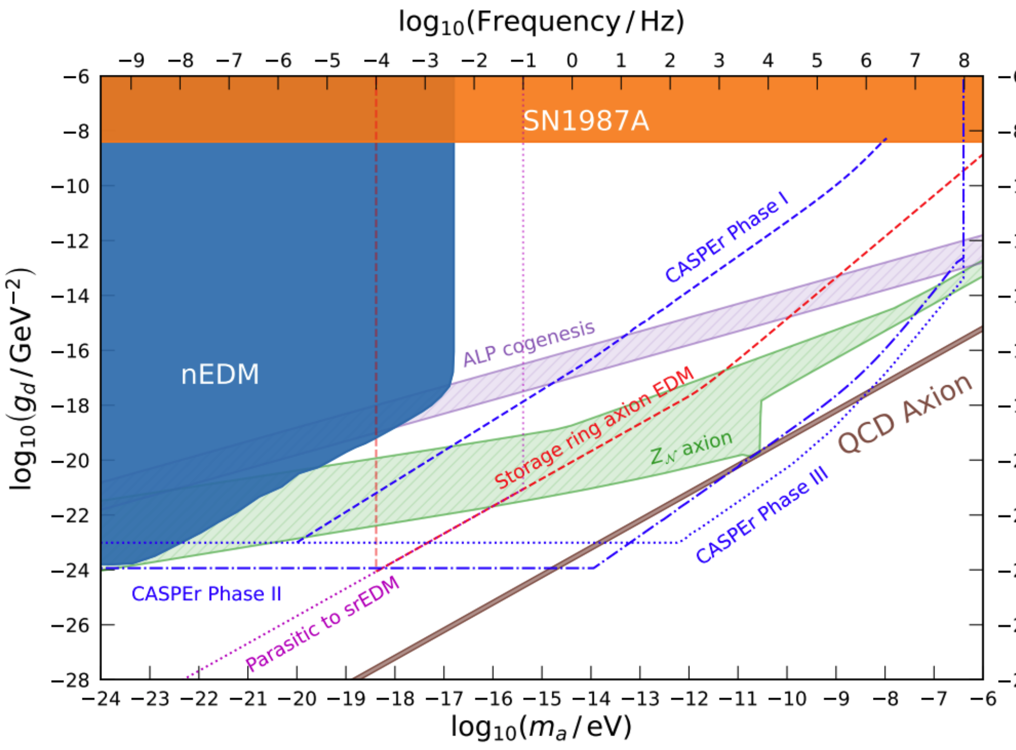
m_q = mass of 1-loop quark, ϕ^{NP} = complex CP violation phase of NP



[Pospelov & Ritz, 2005]

- Probe new physics of $\mathcal{O}(\mathrm{PeV})$ mass scale!
  - $\phi^{\mathrm{NP}} \sim 1,\ \Lambda_{\mathrm{NP}} \sim 3\times\ 10^3\ \mathrm{TeV}.$ W. Marciano (2020)
  - Complementary to e.g. LHC/FCC programme.
- Probe light, weakly-interacting new physics.
  - $\Lambda_{\mathrm{NP}} \sim 1\ \mathrm{GeV},\ \ g \lesssim 3\times\ 10^{-5},\ \ \phi^{\mathrm{NP}} \sim 10^{-10}.$ Z. Omarov *et al.*, PRD 105 (2022) 032001.
  - Complementary to e.g. LZ, LDMX, FASER, SHiP.
- Highly complementary to atomic/molecular EDM experiments.
  - Potential to also measure deuteron / ^{3}He EDMs.

J. Alexander *et al.* [srEDM collaboration], arXiv:2205.00830.



Importantly, pEDM will clearly be highly complementary to nEDM experiments…

→ **But, pEDM wins the statistics battle.**

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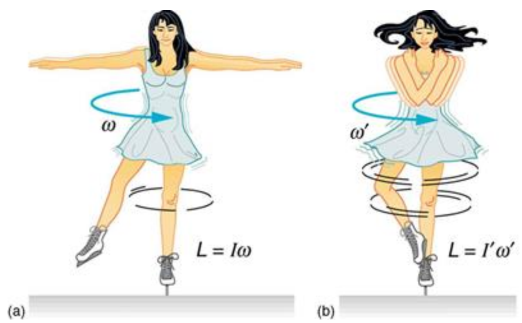
A Probe for Neutron Star Spin (maybe)

What is a neutron star?

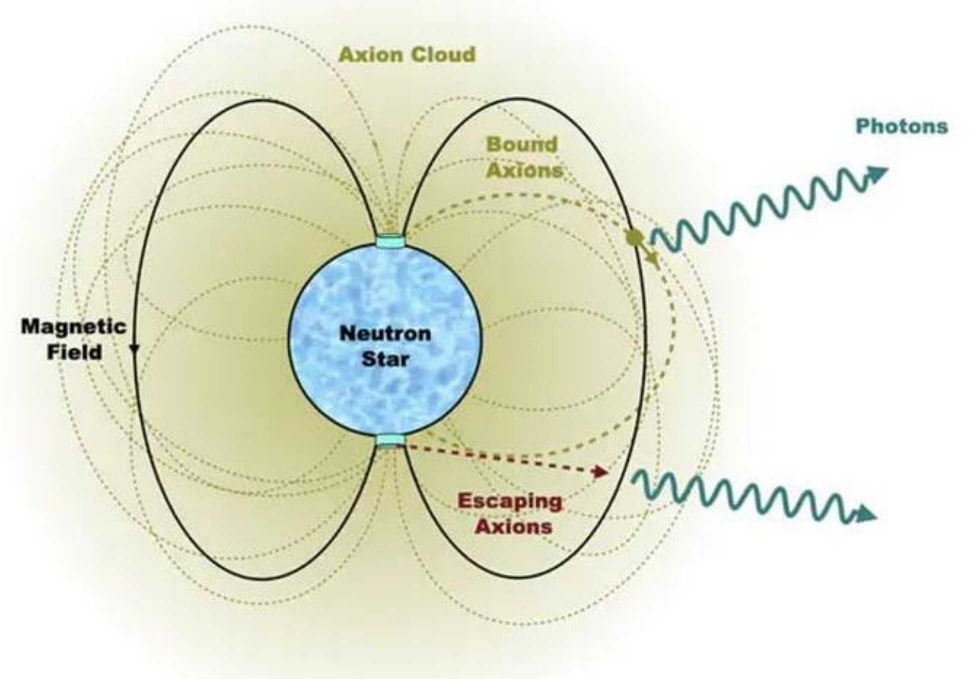
- Collapsed core of a massive, supergiant star not massive enough to produce black hole.
- Massive star supernova + gravity compresses star core (mostly neutrons) to atomic nucelli density: ~ 1.4 $M_\odot$ in ~ 10 km.

Neutron stars spin as fast as 60 times per second:

- As it collapses, its radius decreases with constant mass.
- Angular momentum causes the star to spin faster.
- Like how an ice skater spins faster when they pull in their arms.



PHYSICAL REVIEW X 14, 041015 (2024)



Neutron star spins are aligned…

- In presence of axionic DM field, θ_{QCD} oscillates at axion mass frequency.
- Whole spin (EDM) of neutron star would oscillate at same frequency.
- Resulting in strong radiation.
- Neuron star spin (EDM) potentially detectable by pEDM experiment:
  - Possible interactions with EDMs (e.g. proton, neutron) in lab on earth.
  - And EM radiation on earth that could be observed (e.g. with a resonant cavity).

Not yet proven, but work ongoing by theorists to understand this effect.

→ Could make pEDM a LIGO-like experiment...

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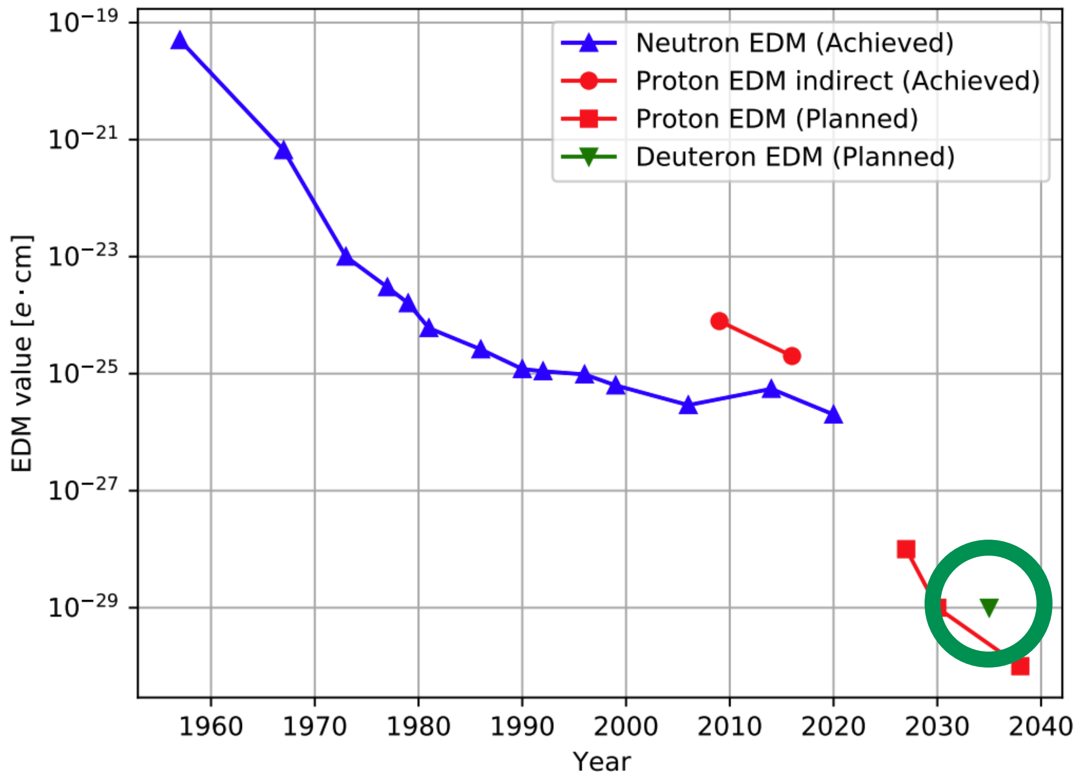
Deuteron and ^{3}He EDM

Proton EDM Experiment could also search for deuteron and ^{3}He nucleus EDM:

- No current limit on deuteron EDM.
- Could be up to 10^3 larger than neutron EDM if no axion mechanism is present.
- Complimentary physics to proton EDM.
- Theoretical relations between proton/deuterons EDM which will provide consistency checks.
- ^{3}He EDM will have similar sensitivity to deuteron.

Deuteron magnetic dipole moment is negative:

- Fields needed for storage are more complicated.
- All electric ring not possible.
- Requires combination of electric and magnetic fields for storage for frozen-spin.
- Corresponding uncertainties are larger than pEDM.
- Would require 1-year experimental alterations and extra 5 years data-taking on pEDM.



If any EDM is observed, is possible to decipher the CP-violating source by comparing the proton, deuteron, and neutron EDM values

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Ring lattice systematic studies

Table 8: Classification of systematic error sources

Source	Severity of effect; counter-measures	Risk level; Comments
Vertical electric field.	Primary effect, unavoidable when magnetic focusing is used. It cancels with clock-wise (CW) vs. counter-clock-wise (CCW) storage simultaneously.	Risk level: Low. If CW vs. CCW storage is not simultaneous it may become medium-high risk due to the unknown time-stability of vertical electric fields (not considered in present experiment).
Background radial magnetic fields.	They can be a systematic error source when electric focusing is present. Applying large radial magnetic fields around the ring can probe electric focusing in the ring (spin-based alignment).	Risk level: Low. No need for expensive magnetic field shielding, just Helmholtz wires mounted on the vacuum chambers. Time dependent small B-fields OK if their amplitude and direction are monitored. Applying appropriate electric focusing can also probe background magnetic fields.
Vertical velocity effect.	A major issue with non-symmetric lattices, not an issue here. Symmetry: Placing the magnetic quads at highly symmetric locations, greatly reduces their required placement accuracy.	Risk level: Low. Moving vertically in a radial E-field region, creates a longitudinal magnetic field in the particle's rest frame. The experiment will start with 0.1 mm accuracy in the quad placement. Eventually, we aim to achieve a placement accuracy better than 0.01 mm for each magnetic quad using spin-based alignment.
Geometrical phases, high-order vertical E-fields.	Under control with placement accuracy of lattice elements better than 0.1 mm and by flipping the current of the magnetic quadrupoles to better than 0.1% at each storage.	Risk level: Low. It's important to keep the beam planarity to within 0.1 mm and the beam separation between CW and CCW beams to below 0.01 mm. The risk comes from the time stability of the lattice elements if they move more than the 0.01 mm level per hour. Spin-based alignment can be used as needed to realign lattice.
Polarimeter related systematic errors.	Need paying attention to the relevant issues at design level. Storing beam with opposite polarization direction is critical in canceling rate related effects as well as effects related to beam-motion.	Risk level: Medium-low. Potentially serious issues can also come from beam-profile vertical polarization dependence. Prototype polarimeter-related systematic errors were studied first at KVI/The Netherlands and at COSY/Germany. Opposite polarizations were used to cancel the asymmetry systematic errors to 10^{-5} level, limited by statistics within a factor of ten to needed accuracy. It is not expected to be any issue improving the accuracy with more statistics available.

Table 9: Electric field alignment sequence including magnetic quad current flipping.

E-field direction alignment	Vertical spin precession rate	Comments
Mechanical, < 1 mrad average alignment. (It is also possible to mechanically align the electric field plates to better than $10\,\mu$rad with respect to gravity, which we will evaluate further later on, but here we assume much more relaxed alignment specs.)	< 2.5 krad/s.	Beam planarity of 0.1 mm out of specs; CW and CCW beam separation difference of 0.01 mm out of specs. We need to be able to align the plates of each section to better than 0.1 mrad to be able to store beam.
Beam-based alignment, to obtain an average electric field plate alignment of better than $2\,\mu$rad, with an average $E_V <$ 10 V/m. Aligning the plates to few μrad per section (12.5m) using trim electric field plates.	< 5 rad/s.	Compensate the average vertical E-field better than $E_V = 10$ V/m by keeping the beam planarity to better than $\pm 50\,\mu$m. Keep one beam direction (e.g., CW) at zero vertical spin precession rate within available statistics.
Spin-based alignment, to obtain an average vertical electric field alignment of $E_V < 20\,\mu$V/m every second.	$< 10\,\mu$rad/s.	Always keep one beam direction (e.g., CW) at zero vertical spin precession rate within available statistics by applying correction voltage on the trim electric field plates.
Spin-based alignment to reduce electric focusing below $m < 10^{-7}$ and align each magnetic quad better than $10\,\mu$m.	$< 1\,\mu$rad/s.	Always keep one beam direction (e.g., CW) at zero vertical spin precession rate within available statistics. Measure and reduce the CW and CCW beam separation to less than $\pm 5\,\mu$m. The ring is designed with stability of the electric focusing and quad offset parameters in mind.
Spin-based alignment, $E_V < 2\,\mu$V/m every second using the trim electric field plates.	$< 0.1\,\mu$rad/s.	Flip the magnetic quadrupole currents. Always keep one beam direction (e.g., CW) at zero vertical spin precession rate within available statistics. The EDM signal is the difference between the CW and CCW vertical precession rates while combining all quad current settings including information from radially polarized bunches.

Z. Omarov et al, Phys. Rev. D 105, 032001.

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pEDM Experiment: funding and timeline

Recent P5 report was not good for proton EDM at BNL

Report of the 2023 Particle Physics Project Prioritization Panel

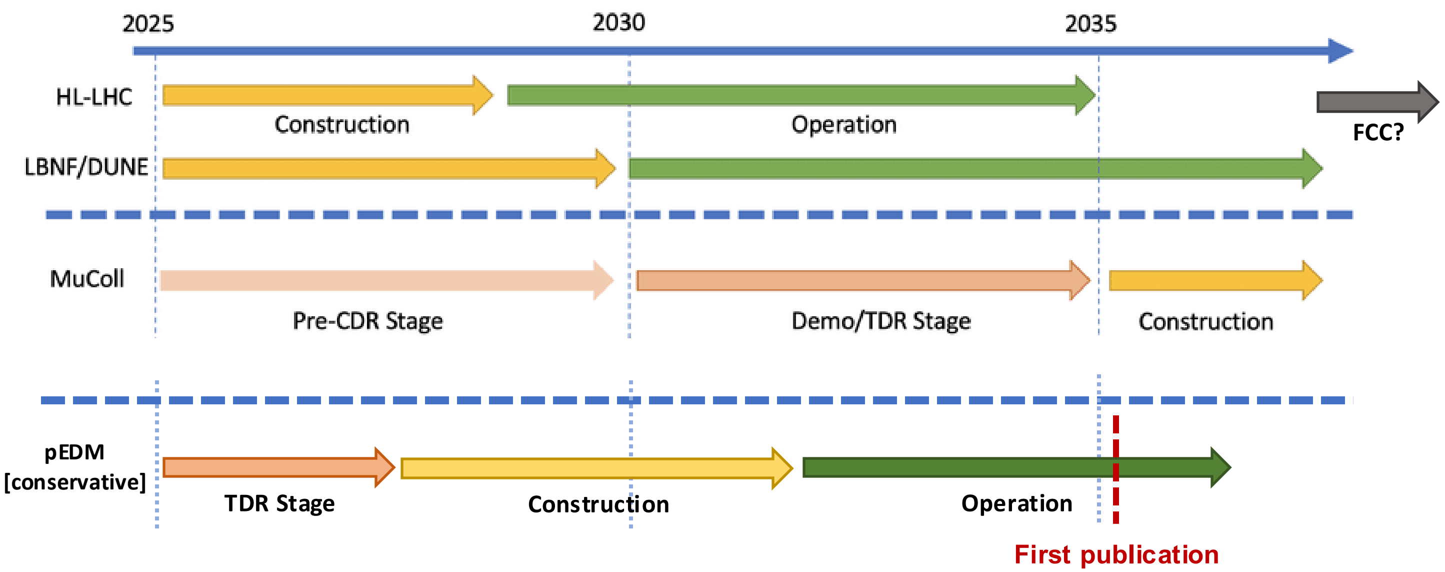
Figure 2 – Construction in Various Budget Scenarios

Index: N: No Y: Yes R&D: Recommend R&D but no funding for project C: Conditional yes based on review P: Primary S: Secondary
Delayed: Recommend construction but delayed to the next decade
Can be considered as part of ASTAE with reduced scope

Scenarios	Less	Baseline	More	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
US Construction Cost >$3B										
on-shore Higgs factory	N	N	N		P	S		P	P	
$1–3B										
off-shore Higgs factory	Delayed	Y	Y		P	S		P	P	
ACE-BR	R&D	R&D	C	P				P	P	
$400–1000M										
CMB-S4	Y	Y	Y	S		S	P			P
Spec-S5	R&D	R&D	Y	S		S	P			P
$100–400M										
IceCube-Gen2	Y	Y	Y	P		S				P
G3 Dark Matter 1	Y	Y	Y	S		P				
DUNE FD3	Y	Y	Y	P				S	S	S
test facilities & demonstrator	C	C	C		P	P		P	P	
ACE-MIRT	R&D	Y	Y	P						
DUNE FD4	R&D	R&D	Y	P				S	S	S
G3 Dark Matter 2	N	N	Y	S		P				
Mu2e-II	R&D	R&D	R&D						P	
srEDM	N	N	N			S?		S?	P	
$60–100M										
SURF Expansion	N	Y	Y	P		P				
DUNE MCND	N	Y	Y	P				S	S	
MATHUSLA #	N	N	N			P		P		
FPF #	N	N	N	P		P		P		

- *"… science case to enter this area needs to mature, especially relative to the cost of such a program"* → This talk!
- U.S. labour costs expensive. Realistic savings already identified!
- May be substantially cheaper if constructed in UK/Europe ($\mathcal{O}$(£100M)).

Muon Collider Forum Report, arXiv:2209.01318 (2022).



- From TDR to final publication in < 20 years.
- Can be started and finished by the new generation.
- Paramount physics drivers:
  - Solve strong CP problem.
  - Baryon asymmetry.
  - Dark matter.

Arguably one of the most low-cost/high-return proposals in particle physics today!

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pEDM potential locations

BNL

- R&D and planning done for 800m ring at AGS:
  - Well-understood polarised proton delivery.
  - Viable site with thought-out ring.
  - No major investment needed for new facility.
- Genesis of current g-2 team and expertise.
- Construction/engineering can be done in UK/EU.
- Least work to realisation but restricted by funding issues.

Fermilab

- Ambition to continue storage ring programme.
- High-intensity proton facility ready-to-go.
- Could borrow/use BNL polarised proton technology.
- Use substantial g-2/EDM expertise.
- Interplay with DUNE/neutrino programme.
- Continue Fermilab's wide-ranging particle physics output beyond just neutrinos in long-term.

CERN

- CERN is our national PP lab.
- Could make use of old ISR (CW/CCW beams).
- Could do polarised protons (or BNL polarisers).
- Cheaper than U.S. (but 950m ring = more expensive).
- Not tied to P5 report.
- More work to be done compared to BNL.
- Approved/balanced against CERN/LHC/FCC programme.

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- Cheaper than U.S. (but 950m ring = more expensive).
- Not tied to P5 report.
- More work to be done compared to BNL.
- Approved/balanced against CERN/LHC/FCC programme.

UK ???

- Ambition to have a UK-based experiment.
- Benefits to having a national facility (e.g. Boulby).
- Real UK infrastructure – multiple use facility.
- House it at e.g. Daresbury. Ring minimum 450m.
- Use UK engineering/experience (e.g. Cockcroft/JAI).
- Ring/polarimeter engineering and construction in UK.
- Substantial g-2/EDM expertise.

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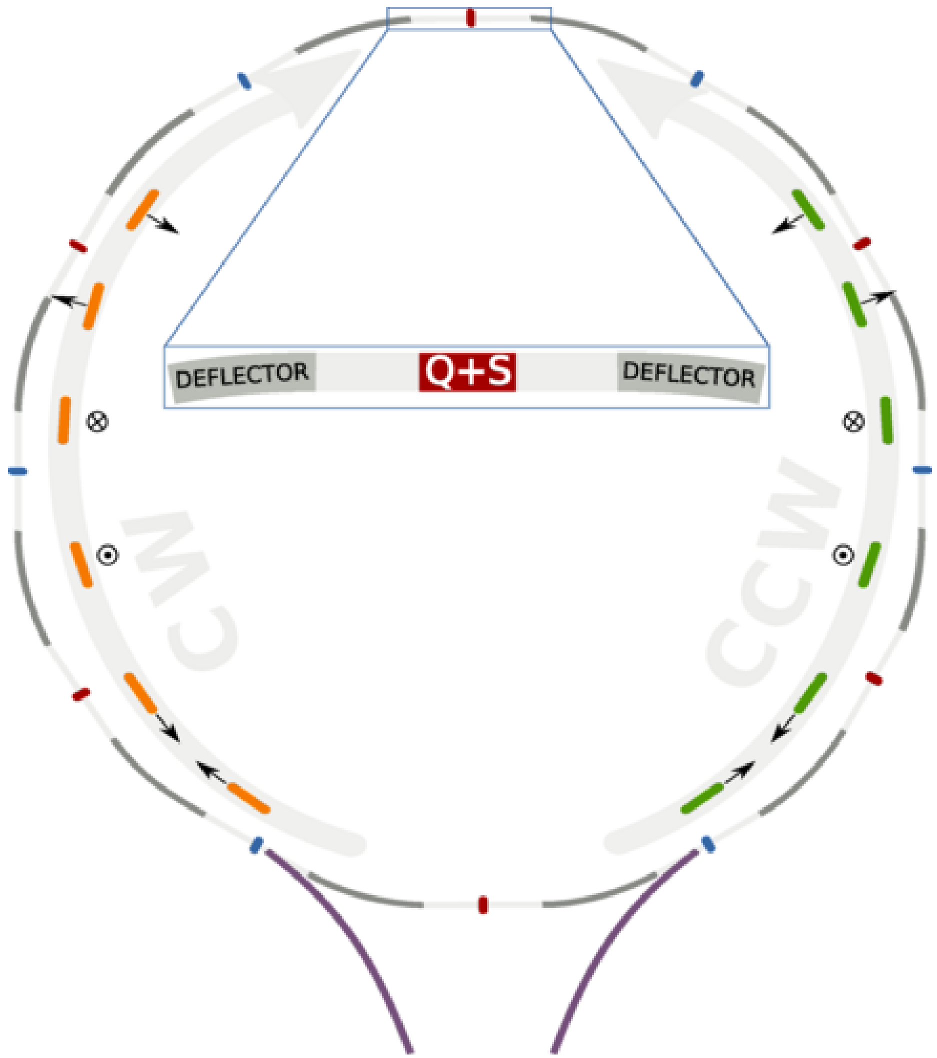
A Storage Ring EDM Experiment

Advanced design currently under consideration/construction at BNL:

- Highly symmetric, storage ring lattice to control systematics.
- Proton magic momentum = 0.7 GeV/c for frozen-spin.
- Proton polarimetry peak sensitivity at frozen-spin momentum.
- Optimal electric bending (and maybe magnetic focusing).
- 2×10^{10} polarized protons per fill. One fill every twenty minutes.
- Simultaneously store clockwise (CW) and counterclockwise (CCW) bunches.
- Simultaneously store longitudinally polarized bunches with positive and negative helicities as well as radially polarized bunches.
- 24-fold symmetric storage ring lattice.
- Closed orbit automatically compensates spin precession from radial magnetic fields.
- Circumference = 800 m with E = 4.4 MV/m, a conservative electric field strength.



PRD **105** (2022) 032001, arxiv:2205.00830.

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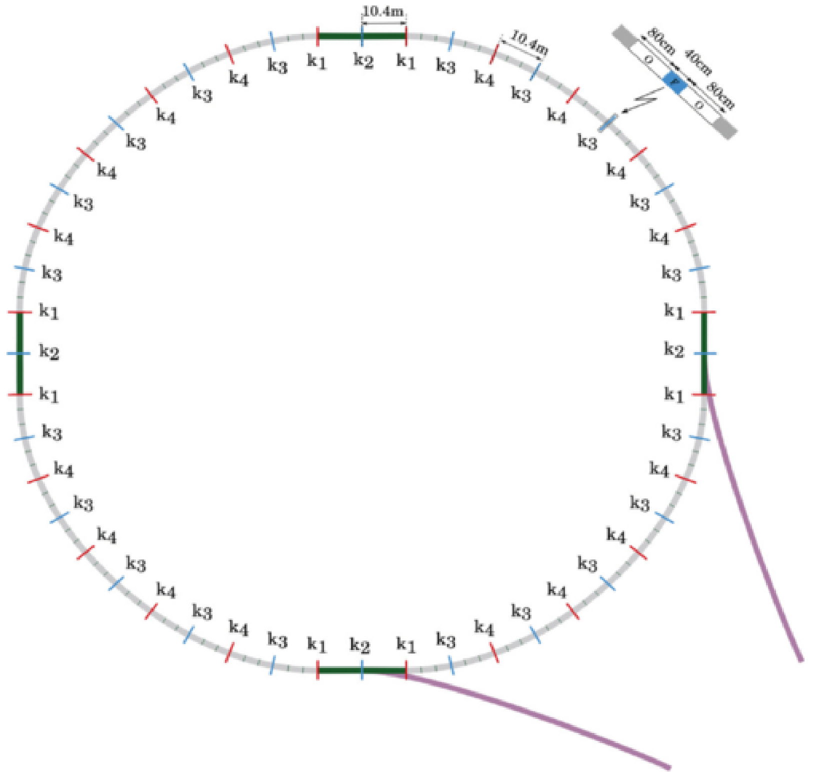
Storage Ring Options

Fields	Example	EDM signal term	Comments
Dipole magnetic field **B** (Parasitic).	Muon $(g-2)$ experiment.	Tilt of the spin precession plane. (Limited statistical sensitivity due to non-zero $(g-2)$ spin precession.)	Eventually limited by geometrical alignment. Requires consecutive CW and CCW injection to eliminate systematic errors.
Combination of electric and magnetic fields — **E**, **B**, (combined lattice).	Deuteron, ^{3}He, proton.	$\frac{d\boldsymbol{s}}{dt} \approx \boldsymbol{d} \times (\boldsymbol{v} \times \boldsymbol{B})$	High statistical sensitivity. Requires consecutive CW and CCW injection, with main fields flipping sign to eliminate systematic errors.
Radial Electric field (**E**) and Electric focusing (**E**) (All-electric lattice).	Proton.	$\frac{d\boldsymbol{s}}{dt} = \boldsymbol{d} \times \boldsymbol{E}$	Allows simultaneous CW and CCW storage. Requires demonstration of adequate sensitivity to radial $\boldsymbol{B}$-field systematic error source.
Radial Electric field (**E**) and Magnetic focusing (**B**) (Hybrid, symmetric lattice).	Proton.	$\frac{d\boldsymbol{s}}{dt} = \boldsymbol{d} \times \boldsymbol{E}$	Allows simultaneous CW and CCW storage. Only lattice to achieve direct cancellation of the main systematic error sources (its own "co-magnetometer").



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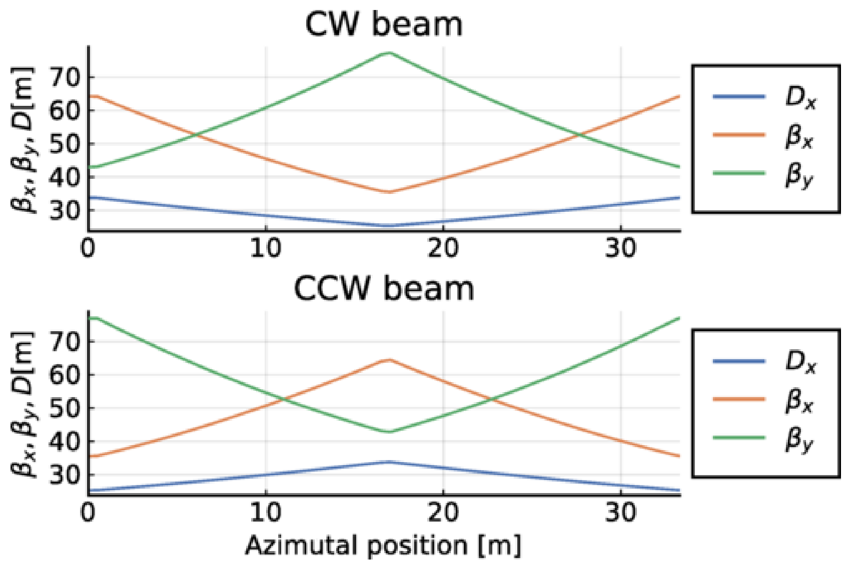
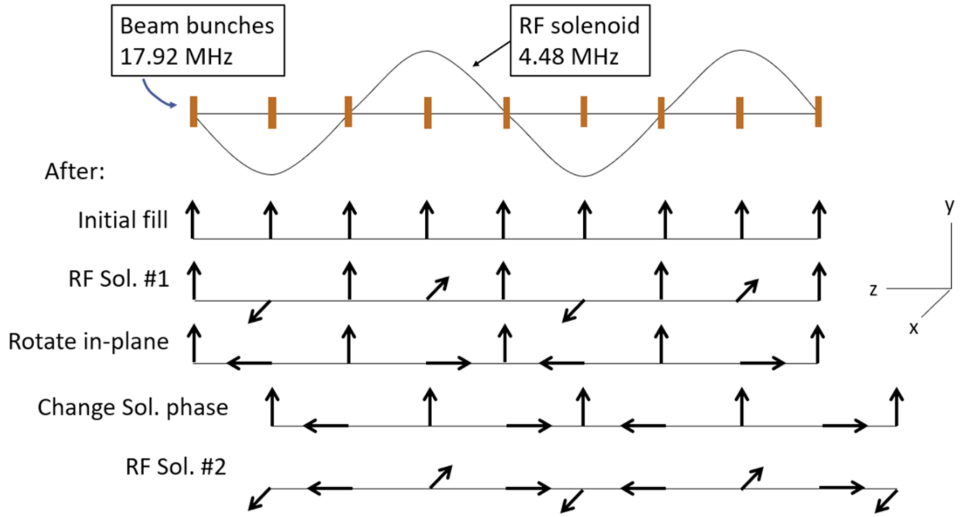
Storage Ring Systematics

Major systematic efforts from protons in storage ring mitigated/eliminated by enhanced ring symmetry:

Systematic Error Source	Ring Symmetry Mitigation
Unwanted (background) vertical electric fields, when magnetic focusing is used	CW vs. CCW storage
Unwanted (background) radial magnetic fields, when electric focusing exists	Spin based alignment to probe and cancel unwanted electric focusing
Unbalanced vertical velocity component of beam in a region with strong radial E-fields	Symmetric lattice; quad current flip; radial polarization
Geometrical phases originating from spin rotations in three dimensions	CW vs. CCW storage; magnetic quad current flip
Polarimeter related systematic errors	Storing simultaneously oppositely polarized bunches





PRD **105** (2022) 032001, arxiv:2205.00830.

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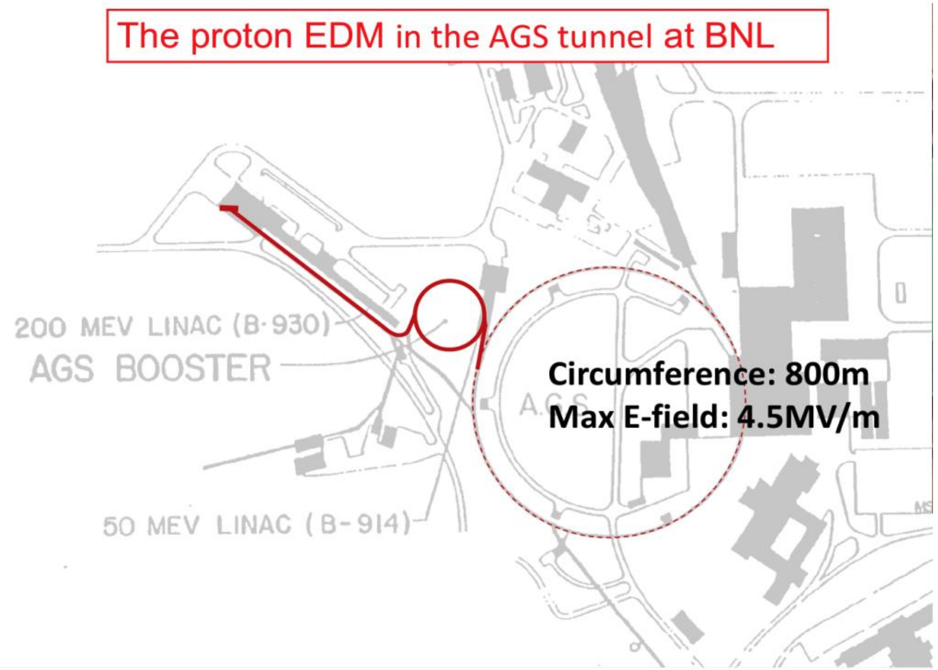
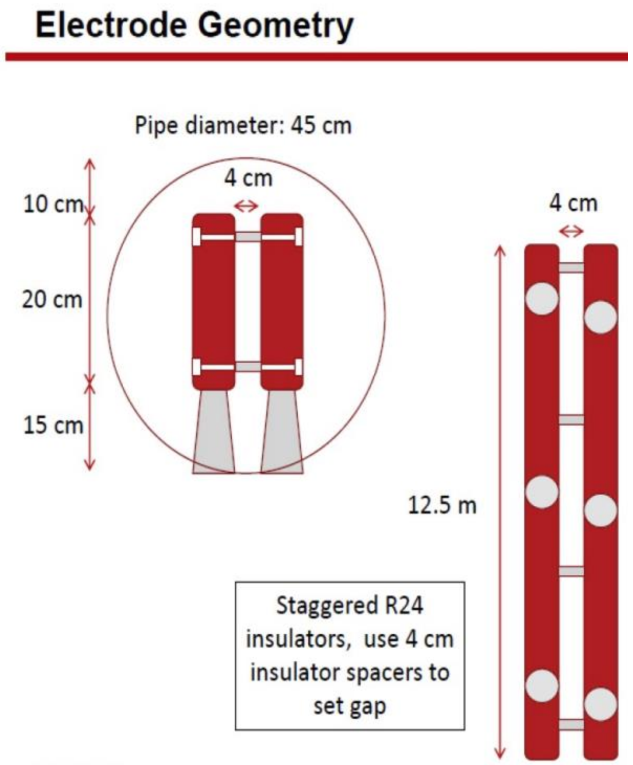
Ongoing Storage Ring Development

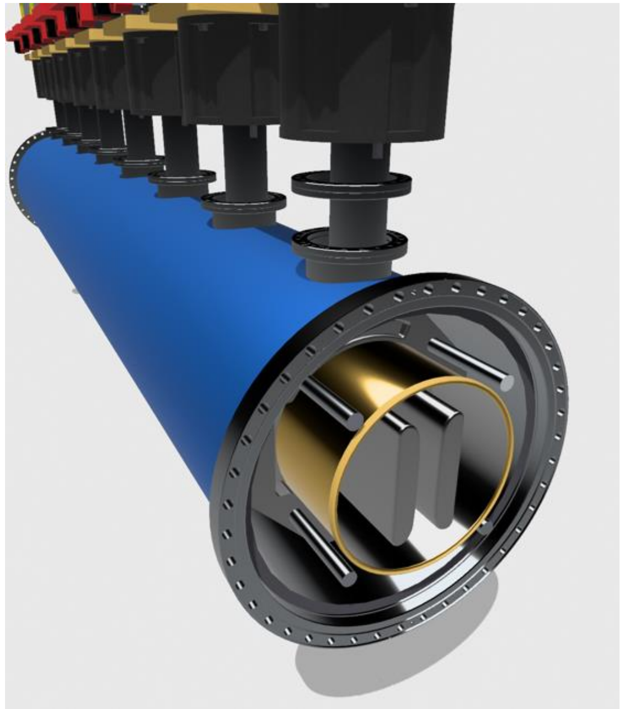
- BNL funded cost estimate of project ($140M - $190M) to build and commission the experiment in AGS tunnel for P5.



PRD **105** (2022) 032001, arxiv:2205.00830.

- Following P5, DOE + BNL approved 3-year LDRD to develop electric field plates at 4.4 MV/m and supporting study on stochastic cooling.





→ This in being done in collaboration with the UK.

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Polarimetry

Inject highly polarized (spin-aligned) protons with g - 2 nullified by the frozen-spin technique.

→ Electric field interaction with protons with non-zero EDM causes build-up of vertical polarisation component over time (~20 minutes).

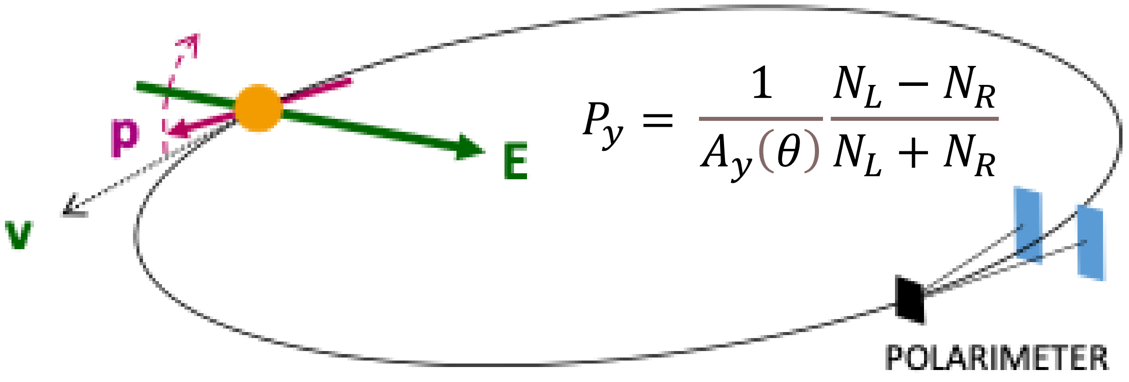
→ Electric field acts along radial direction (towards ring centre) and will induce vertical tilt in proton polarization.

→ Proton beam continuously elastically scattered off carbon target.

→ Downstream polarimeter measures the left-right (L-R) scattering asymmetry over the storage time.

→ Proton's vertical polarization, $p_y \propto (L - R)/(L + R)$, proportional to the L-R asymmetry rates of the scattered beam.

→ Measurable quantities are number of detected protons (L and R), scattering angle and scattered particle's energy (to exclude inelastic scattering or multiple scattering events).



$$P_y = \frac{1}{A_y(\theta)} \frac{N_L - N_R}{N_L + N_R}$$

Area for improvement

- Carbon target is located adjacent to the beam.
- Efficiency is limited by destructive extraction of beam.
- White noise is applied to beam to enlarge beam emittance until outer halo of the beam is incident on carbon target.
- Only 1% of the protons reach the carbon target and become part of the useful data stream. The rest are lost.

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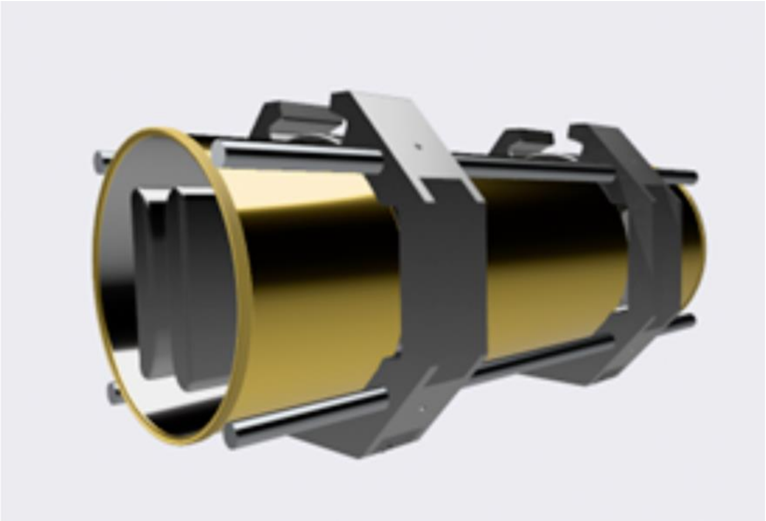
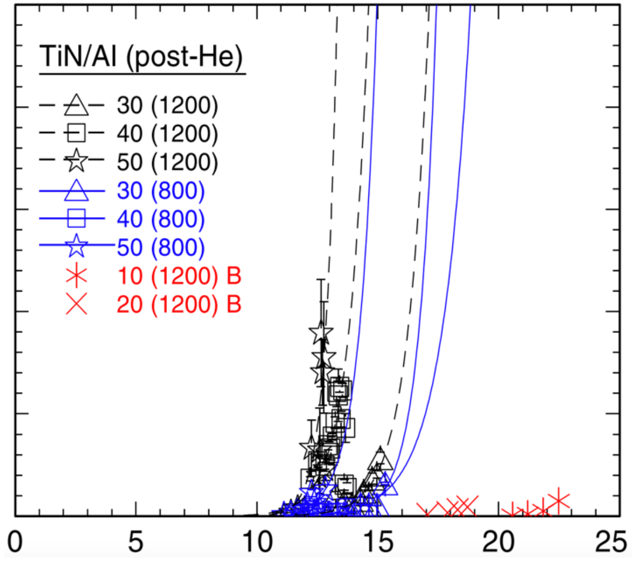
UK Electrostatic Deflector Work

PRD **105** (2022) 032001, arxiv:2205.00830.

- pEDM deflectors designed and are under construction in the UK.
- Stably maximising the electric field is potentially the key component to ensuring the success of the pEDM Experiment.
- Higher electric field = larger EDM effect and higher experimental sensitivity + potential for reduced cost from smaller ring size.
- Plans to extend HV performance by collaborating with industry to apply a 2-micron layer of titanium nitride (TiN) to electrodes.
- Technique pioneered by JLAB for smaller scale applications to provide a smoother and more robust surface.
- TiN layer improves breakdown voltage by reducing surface imperfections, minimizing the risk of sparking.
- Breakdown voltage for TiN-coated electrodes has been shown at JLAB to be ~ 3x higher than 4.4MV/m operating field for pEDM.
- 3x sensitivity + 3x reduction in storage ring size…





Work ongoing…

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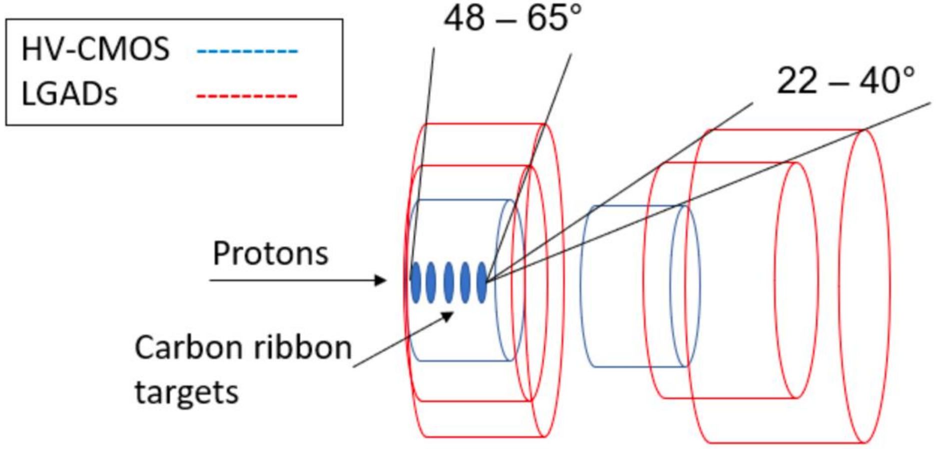
UK Polarimeter Work

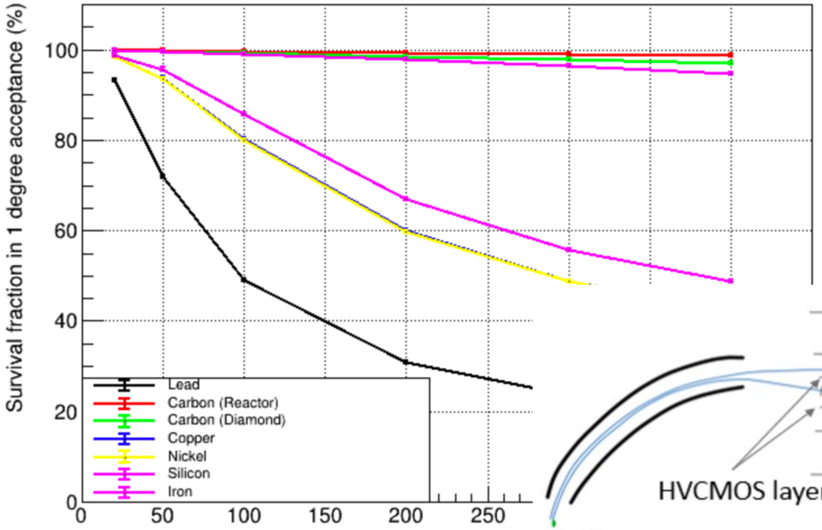
JINST **17** (2022) C09010; J. Gooding, PhD thesis, University of Liverpool

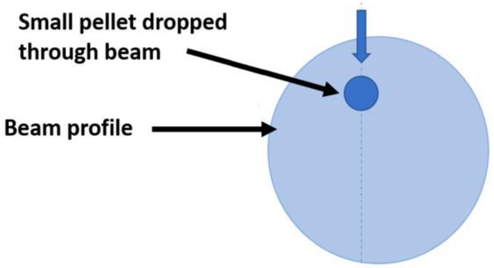
- State-of-the-art polarimeter designed and initially tested in the UK with proton beams.
- Measure proton's polarisation after elastic scattering off a carbon target.
- Inner silicon-based HV-CMOS sensors for precision position measurements (scattering angle).
- Outer Low Gain Avalanche Diodes (LGADs) for time-of-flight (ToF) measurements (energy).
- Intend to build and test full prototype soon.

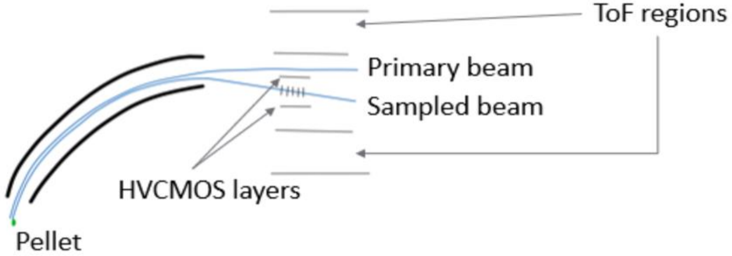


< 100 µm HV-CMOS layer. Pixel dimensions of 80 µm x 80 µm.

100 µm LGAD sub-layer ToF resolution ~ 30ps – 50ps.







- Proposal to use recyclable diamond pellet to non-destructively extract proton beam to polarimeter.
- Interacting protons lose energy and fall inwards to carbon target to be scattered.
- Remaining proton beam undisturbed and in continued.
- Initial simulation put proton beam survival at ~100%.

Work ongoing…

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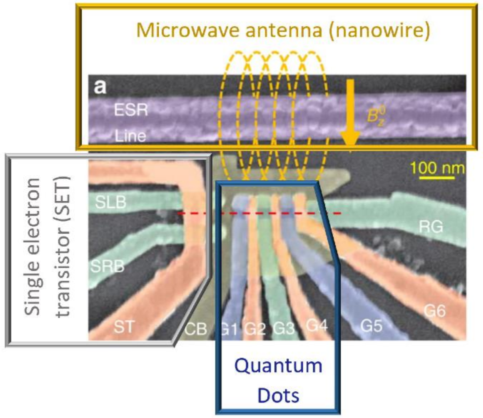
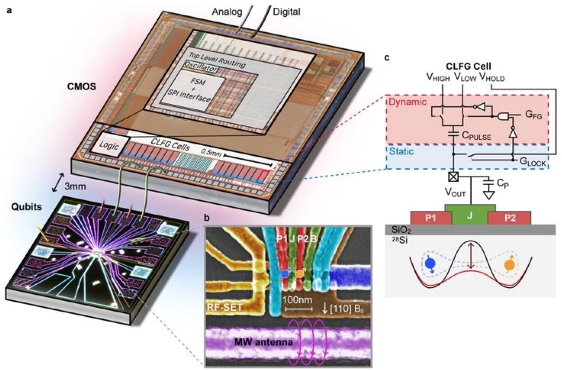
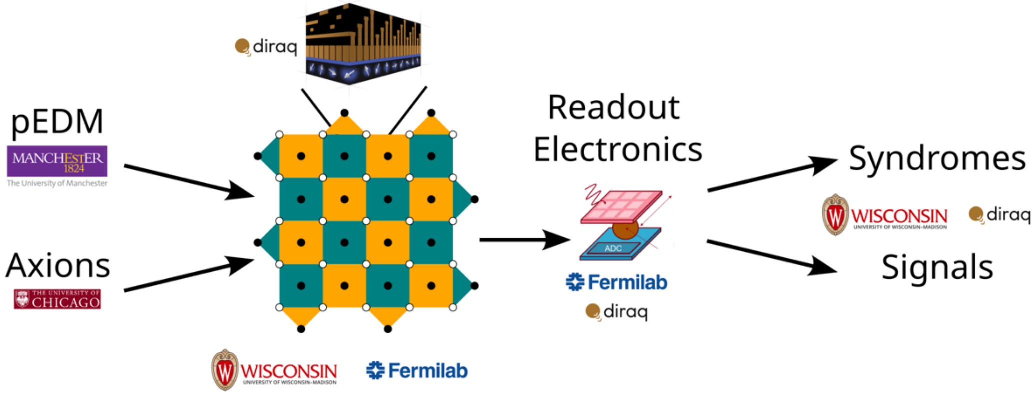
UK: Quantum Polarimeter

Can quantum detectors be used for and improve high-flux environments like pEDM $\mathcal{O}(100\ \mathrm{kHz})$?

- Silicon electron spin qubits + CMOS = significant promise in quantum sensing:
  - Long intrinsic coherence times.
  - Well-understood material environment.
  - Existing semiconductor infrastructure.
  - Small physical size
- Clear pathway to scale to 10^4 silicon spin qubits.
- Quantum error correction to maintain ensemble of qubits in superposition for extended periods.
- Sensitive measurements through spatio-temporal correlations of qubit disturbances.
- Partnered with Fermilab, University of Wisconsin-Madison, University of Chicago and Diraq (industry).
- R&D for spin qubit sensing elements and develop prototypes.
- Integrate with single-electron resolution cryoCMOS skipper readout electronics (cryogenic temperature readout is essential).
- Few-channel proof of concept and advance to a highly-scaled array with 10^4 elements.
- Study the prototypes EM characteristics to develop better models of the underlying technology.
- Develop models and algorithms to enable physics extraction from spin qubit ensembles (quantum polarimeters) for pEDM.







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UK involvement in proton EDM

<u>What the UK can provide</u>:

World class physicists, accelerator scientists and engineering.

- 50-100% of critical bending components.
- Engineering/construction for deflectors/adjustors.
- Developing/building polarimeters (Si, CMOS).
  - In-line with recent STFC investment.
- Project management.
- Alignment experience.
- Simulation + high-statistics modelling.
- Accelerator experience (e.g. Cockcroft/JAI) – UK experiment??
- Lower cost that U.S. estimates.
- Building a UK pEDM consortium/collaboration.
  - This experiment must happen, and UK can play a lead role.
  - Substantial UK expertise available.
  - Inspire a new generation of physicists.
  - Please get in touch if you would like to join.

Science & Technology Facilities Council Rutherford Appleton Laboratory

University of Liverpool

University of Sussex

The Cockcroft Institute of Accelerator Science and Technology

UCL

University of Oxford

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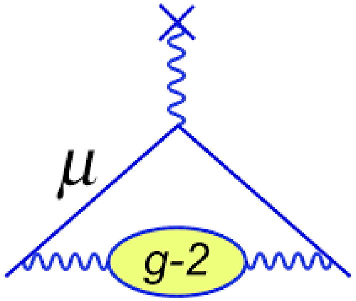

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European Strategy Update 2026

- Single statement for all “other essential scientific activities” in 2020 ESPPU:
  “Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported, as well as participation in such experiments in other regions of the world.”
- Contributing to UK and EU inputs/collaborations for 2026 update. Answer to questions asked for ESPPU:

Datasets and running/exposure time required:

- Five running years total.
- Year 1: Commissioning run, 10^{-27} e·cm, first publication.
- Shutdown improvements: 10^{-28} e·cm reached within one week of statistics in new configuration.
- Years 2 - 5: Four physics run years to reach 10^{-29} e·cm.
- Signal accumulation rate at 1E−29 e · cm is 10−9 rad/s for 1E8 s = 1158 days.

Project timeline:

- Phase I Proton EDM only:
  - R&D to TDR: 2030-2035, 5 years
  - Construction: 2035-2040, 5 years
  - Operations : 2040-2045, 5 years
  - Exploitation: 2045 - 2050, 5 years

[Proton EDM Phase II (SM prediction), extra 5 years.]
[Deuteron EDM, extra 5 years.]

Environmental cost of operation per year:

- Muon g-2 specific accelerator:
  - 3800 kW * 8760 hours * 2/3 year = 22.192E6 kWh
  - 22.192E6 kWh * 0.20707 kg CO2e per kWh = 4,595 tonnes of CO2 equivalent.
- FNAL remaining accelerator (shared):
  - ~250E3 MWh = 250E6 kWh [FNAL] - 22.2E6 kWh [Muon g-2] = 227.8 kWh [shared].
  - 250E6 kWh * 0.20707 kg CO2e per kWh = 47,171 tonnes of CO2 equivalent.
- Muon g-2 storage ring, detectors and building [2]:
  - 1E6 kWh * 0.20707 kg CO2e per kWh = 208 tonnes of CO2 equivalent.
- Muon g-2 emissions [3]:
  - (181703 [FNAL FY18] - 163818 [FNAL FY17]) *2/52 [2 weeks] * 2/3 year = 687 tonnes of CO2 equivalent
- **Muon g-2 only = 5,854 tonnes of CO2 equivalent per year**
- **Muon g-2 including shared FNAL accelerator = 53,025 tonnes of CO2 equivalent per year**

[pEDM storage ring power will be less as no superconducting magnet.]
[Accelerator costs likely reduced from no muon production / bunching.]

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Estimate of financial costs:

- Muon g-2
    - Accelerator cheaper for proton EDM.
    - Ring will be about the same
    - R&D: $5M
    - Construction: Muon g-2 $80M.
    - Operations: $5M per year.
- Adjust for pEDM:
    - R&D: £5M
    - Construction £100M
    - Operations: £5M per year

Preferred location for the project

- BNL (AGS).
- CERN (ISR) also considered. ISR used for FCC magnet R&D and CERN needs polarized protons.

Main risks/obstacles for realisation of physics goals:

- Location with high-intensity polarised proton source e.g. BNL.
- OR location with high-intensity proton source converted to polarised source.
- OR construction of new facility.

Anticipated area(s) of UK involvement:

- Electrostatic deflectors (electrodes)
- Polarimeters
- Alignment
- Simulation
- Analysis and physics exploitation

Total number of FTE /year required for construction/operation. Expected UK FTE?

Muon g-2: 96 FTE / year.
UK: 13 FTE / year

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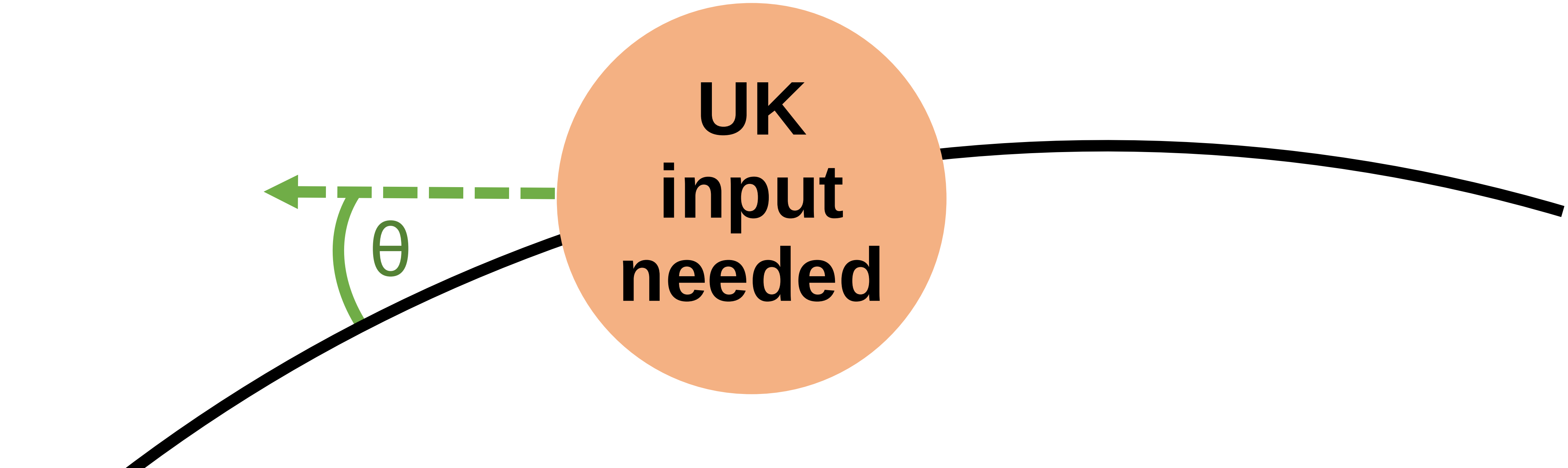
Call for collaborators

Please contact me if interested or just to learn more about the project. There’s a lot of interesting work to get involved in.



This is a beautiful experiment to precisely measure an angle… You can be a part of it.

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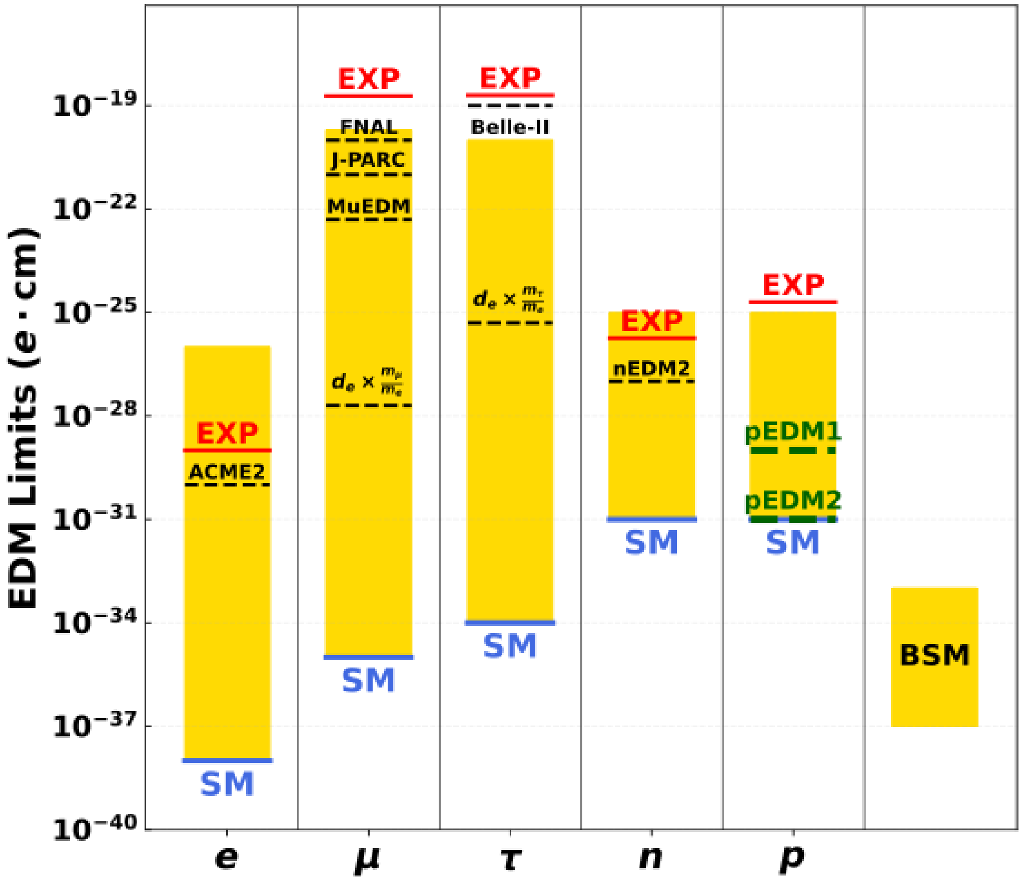
Impact and Importance of pEDM

- pEDM will be the state-of-the-art in experimental EDM searches for generations to come.
- First ever measurement of the proton EDM.
- Only experiment with the potential to measure a particle EDM down to its SM prediction (by improving on the current limit by $\mathcal{O}(10^6)$).
- Will either discover or rule out a particle EDM with a magnitude above the SM's highly suppressed value for the first time.
- Huge consequences for baryon asymmetry, DM and the Strong CP problem.
- Will expose or exclude many BSM models that predict large EDMs, e.g. supersymmetry, two-Higgs doublet models, extra dimensions with mass scale ranging from 1GeV – 1 PeV.



- Timely implications to inform the future international particle physics strategy and programme, e.g. FCC.
- New technology and novel experimental techniques with (hopefully) major UK involvement.

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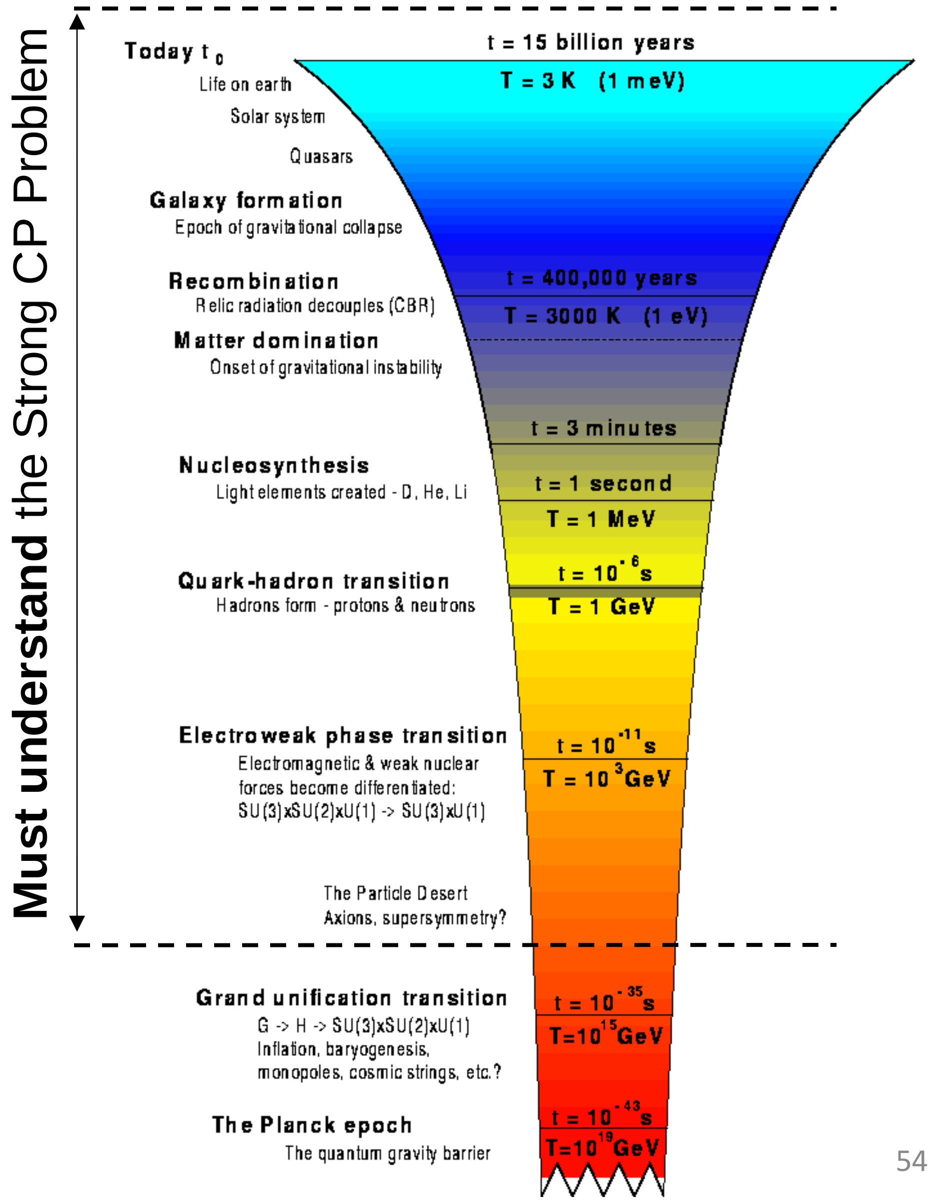
Conclusions

- pEDM experiment is the first direct search for the proton EDM.
- Improves on current (indirect) limit by $> \mathcal{O}(\mathbf{10^4})$.
- Has potential to to do $\mathcal{O}(\mathbf{10^6})$ and be sensitive to SM prediction.
- Directly address/solves the strong CP problem.
  - Strong CP/pEDM ↔ Astro + Particle + Nuclear.
- Significant new physics drivers:
  - CP-violation source for Baryon Asymmetry.
  - Sensitive probe for axionic dark-matter.
  - Probe light-weak new particles → PeV-scale new physics.
  - No EDM would also be dramatic → at SM limit.
- Major R&D completed / systematics understood.
- From TDR to final publication in < 20 years.
- One of the most low-cost/high-return proposals in particle physics today.



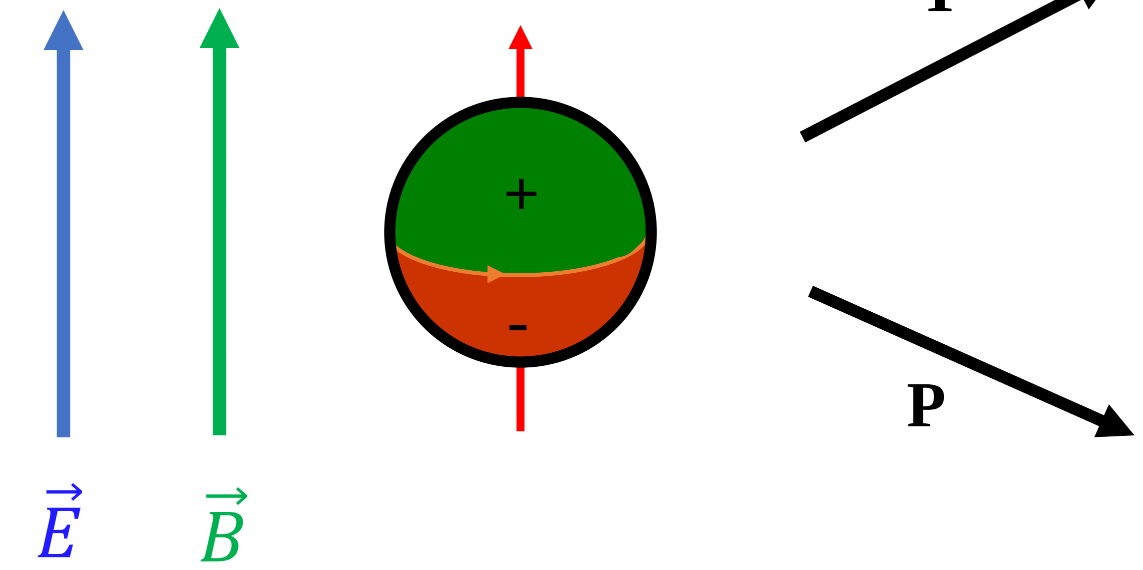
Thank you

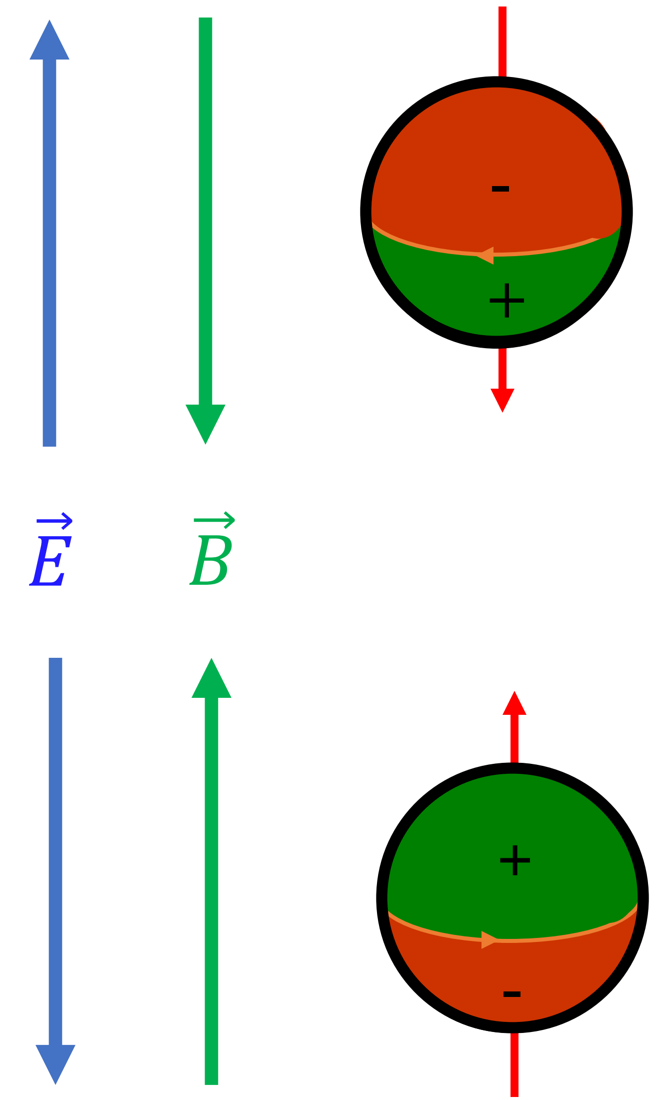
A Permanent EDM Violates both T & P Symmetries:

$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s}, \quad \mathcal{H} = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

$$\vec{d} = \eta\left(\frac{q}{2mc}\right)\vec{s}$$

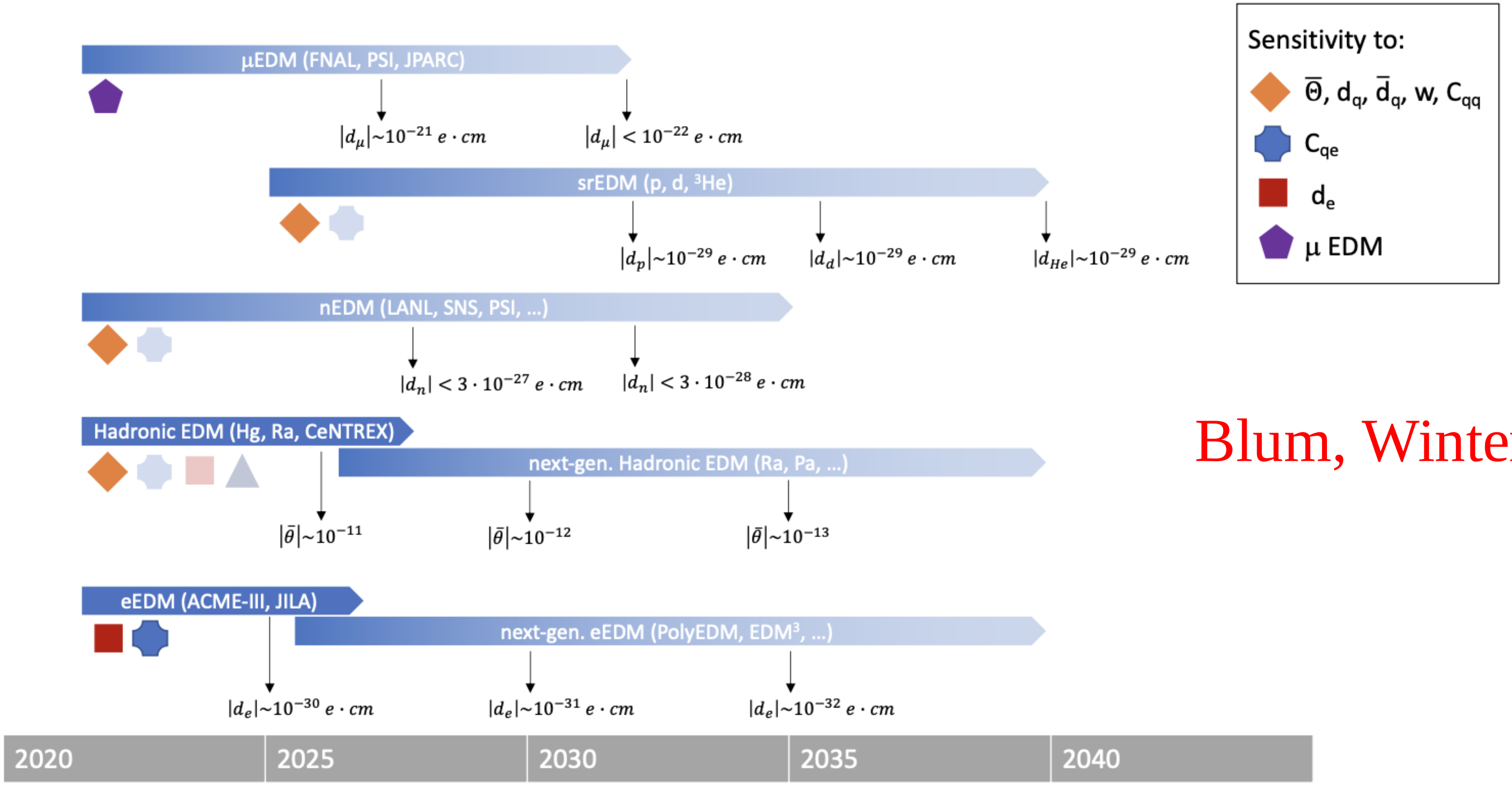
The EDM is *caused* by the spin





Reminder: batteries are allowed in the SM!

EDM timelines, from Snowmass 2021 (2022).



Blum, Winter *et al.*

Figure 3-1. *Timelines for the major current and planned EDM searches with their sensitivity to the important parameters of the effective field theory (see Fig. 3-2 for details). Solid (shaded) symbols indicate each experiment's primary (secondary) sensitivities. Measurement goals indicated by the black arrows are based on current plans of the various groups.*

Snowmass paper on EDMs

Neutron EDM

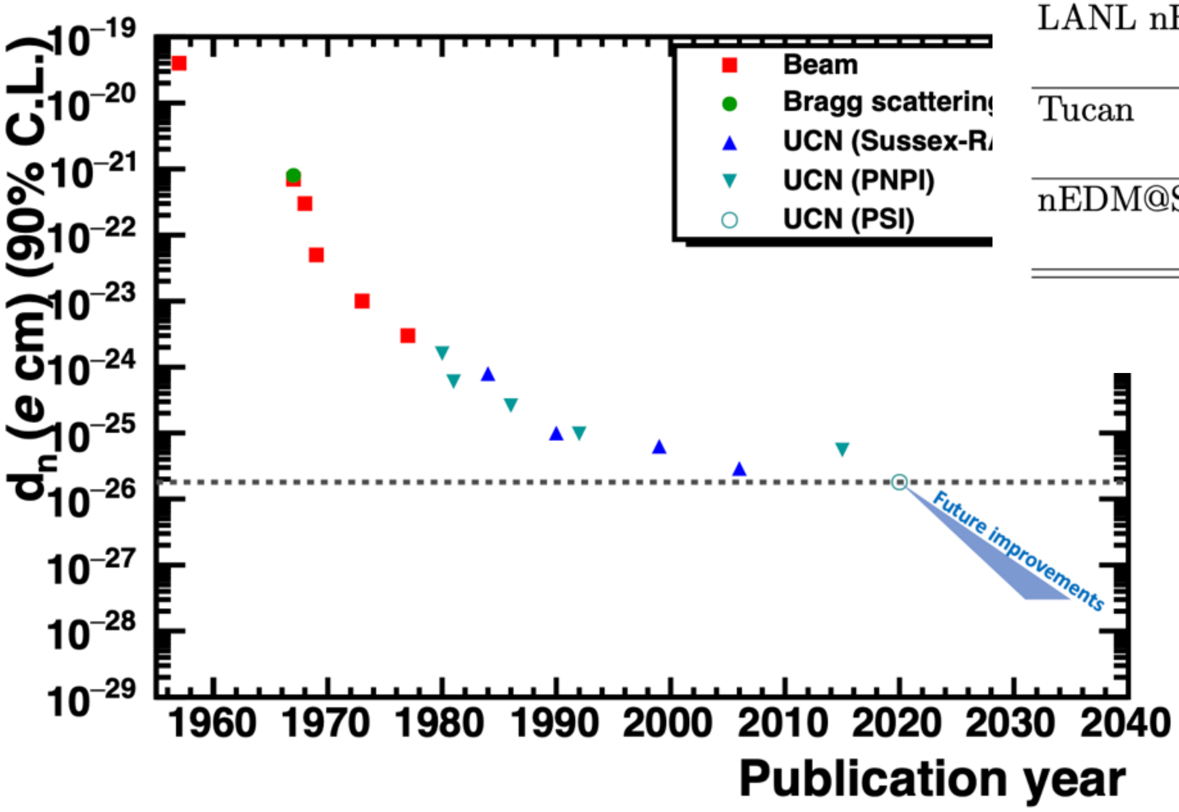


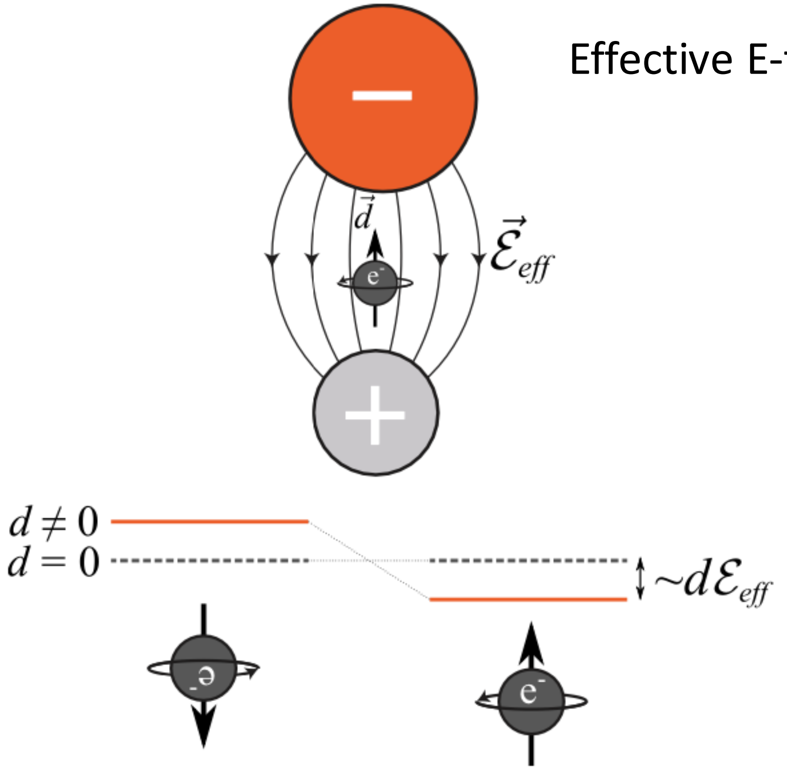
FIG. 3. Evolution of the nEDM results along with projected future results

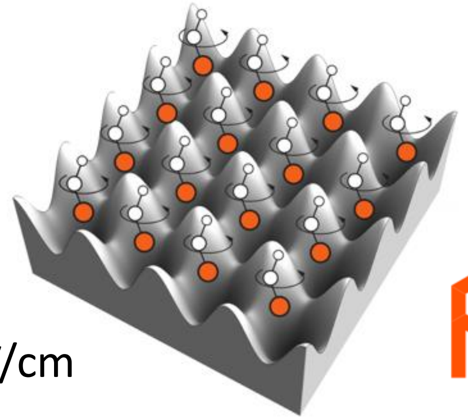
Experiment	Location	UCN source	Features	Ref.
n2EDM	PSI	Spallation, SD_2	Ramsey method, double cell, ^{199}Hg comagnetometer	[152]
PanEDM	ILL	Reactor, LHe	Ramsey method, double cell, ^{199}Hg comagnetometer	[153]
LANL nEDM	LANL	Spallation, SD_2	Ramsey method, double cell, ^{199}Hg comagnetometer	[135]
Tucan	TRIUMF	Spallation, LHe	Ramsey method, double cell, ^{129}Xe comagnetometer	[154]
nEDM@SNS	ORNL	In-situ production in LHe	Cryogenic, double cell, ^{3}He comagnetometer, ^{3}He as the spin analyzer	[139]

TABLE III. A list of the nEDM experiments that are being developed

Snowmass paper on EDMs

Effective E-field with polar molecules: order GV/cm





PolyEDM

Figure: Laser-cooled polyatomic molecules, optically trapped, with full quantum control. Such a platform can be used to access new physics at the PeV scale.

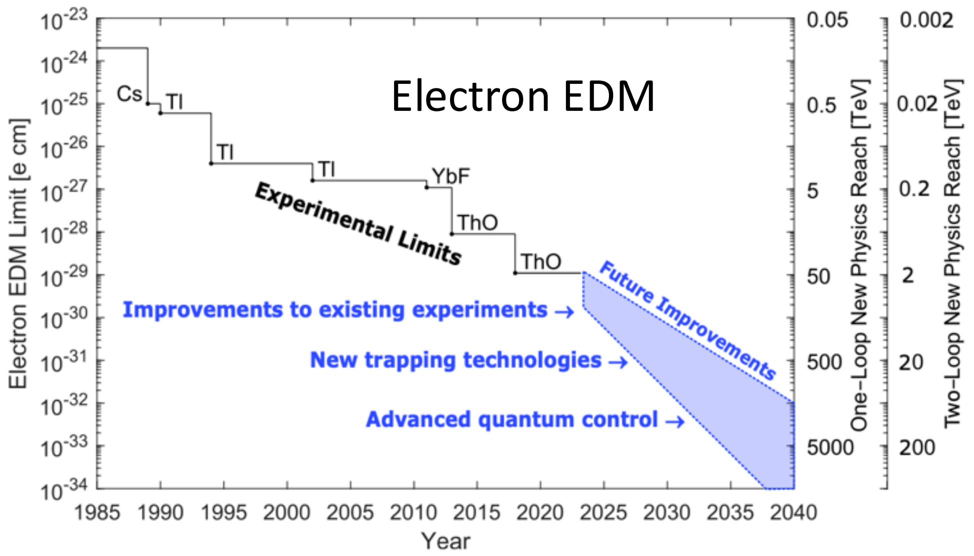
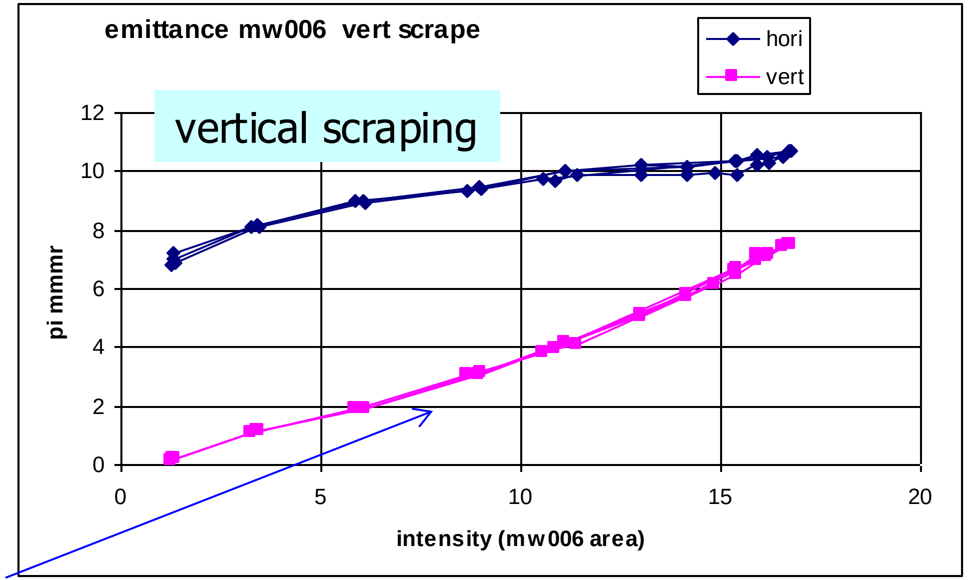


FIG. 5. Electron EDM limits versus time, along with new physics reach for one-loop and two-loop effects (see Eq. 2). All electron EDM experiments to date use AMO techniques. The solid line indicates the most sensitive experimental limit, including the species used. The shaded area indicates potential future improvements discussed in the text. Improvements in the next few years are driven largely by improvements to existing experiments and are quite likely, though as we go more into the future the projection becomes increasingly speculative and uncertain.

High intensity polarized proton Beam at BNL

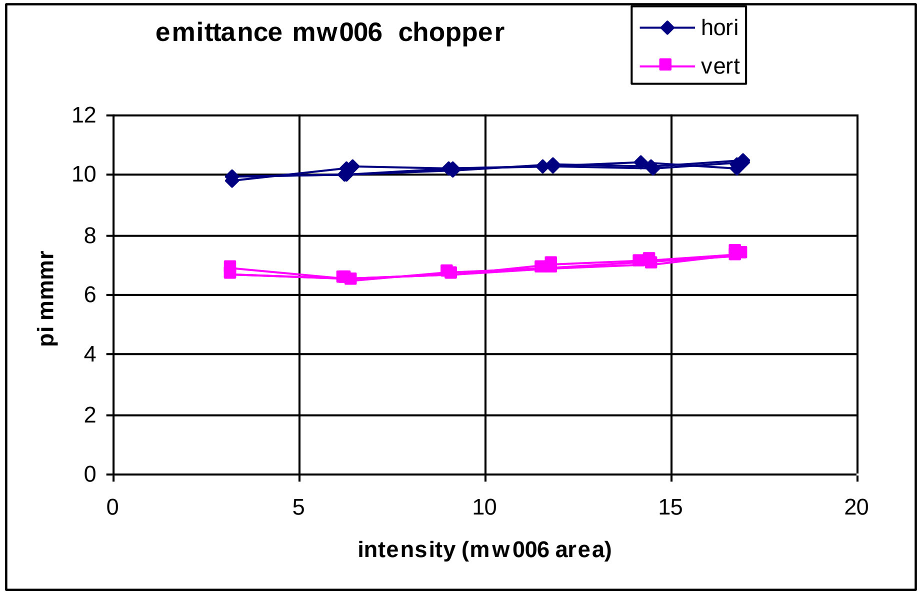
Proton intensity at Booster input $3*10^{11}$. The vertical scale is normalized 95% emittance.

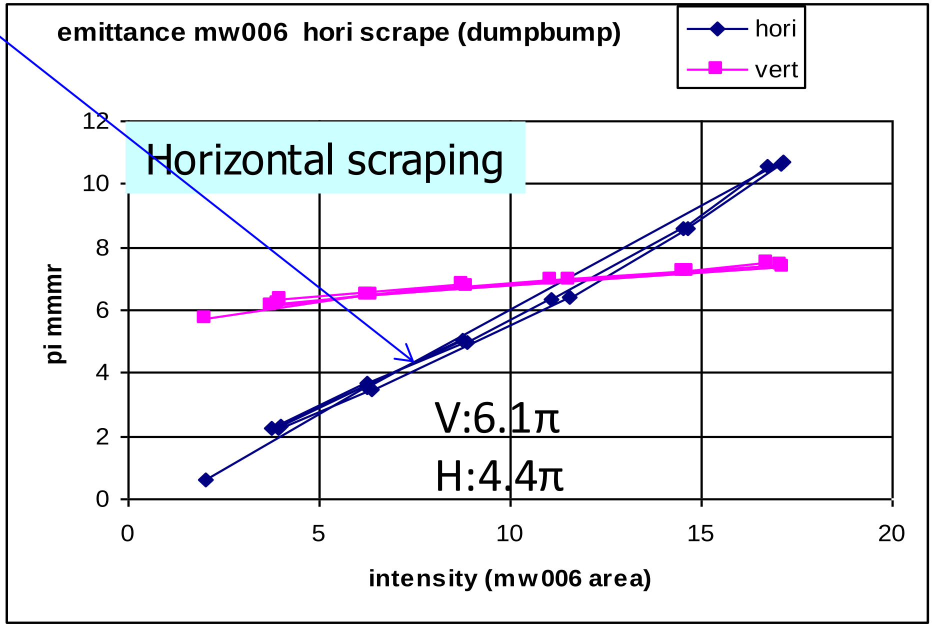
The corresponding normalized rms emittance at 10^{11} is 0.7π horizontal, 1.0π vertical for horizontal scraping.



@10^{11}

Intensity: 15~2e11 protons





Large statistics available, opportunity for great sensitivity improvement in EDMs

Hybrid, symmetric lattice storage ring, designed by Val. Lebedev (FNAL)

Z. Omarov *et al.*, PHYS. REV. D **105**, 032001 (2022)

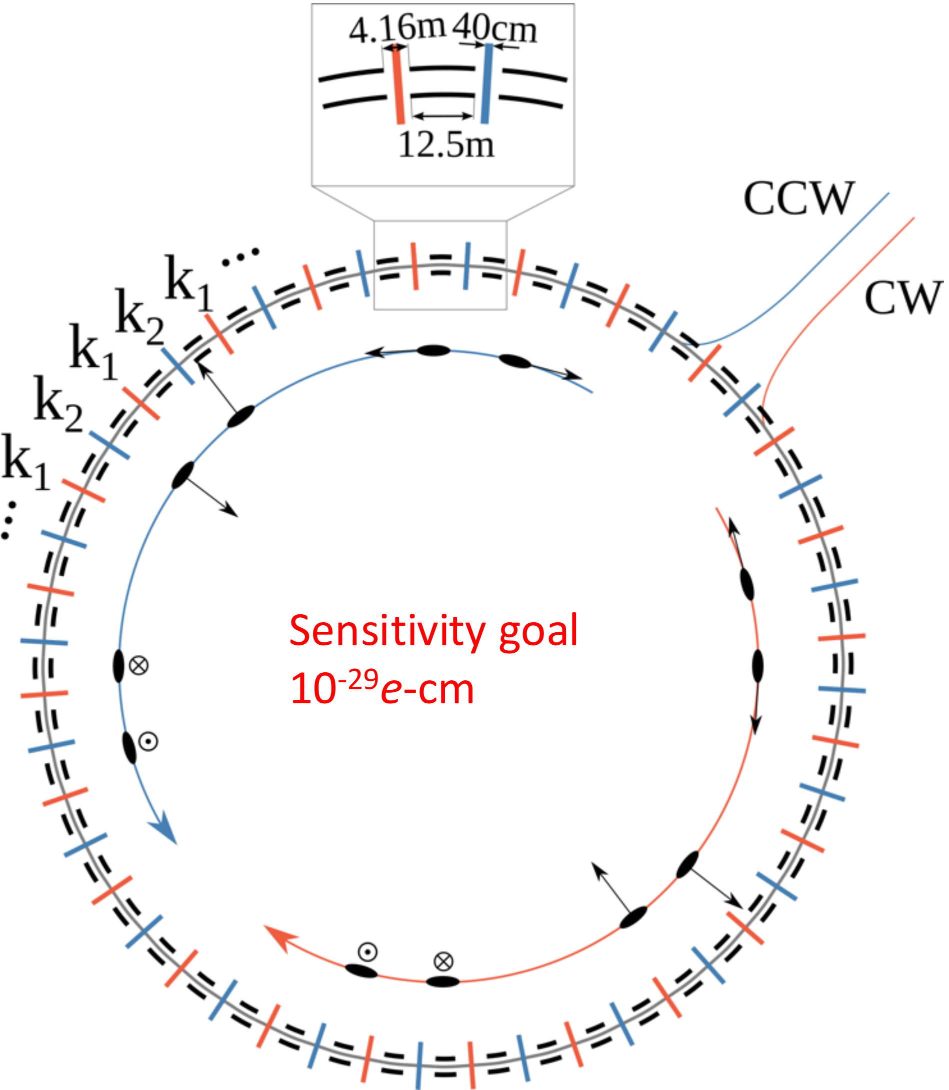


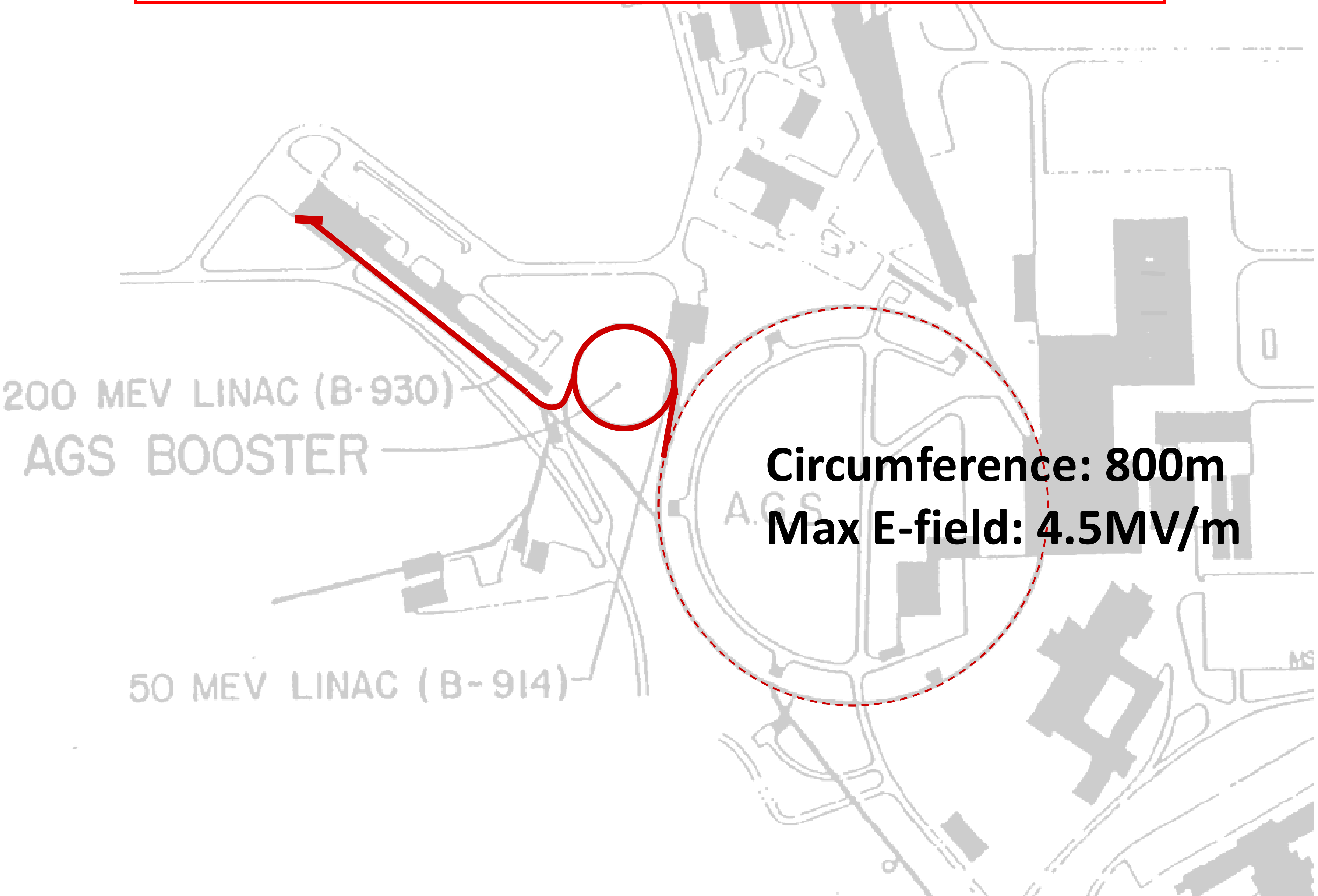
TABLE I. Ring and beam parameters for Symmetric Hybrid ring design

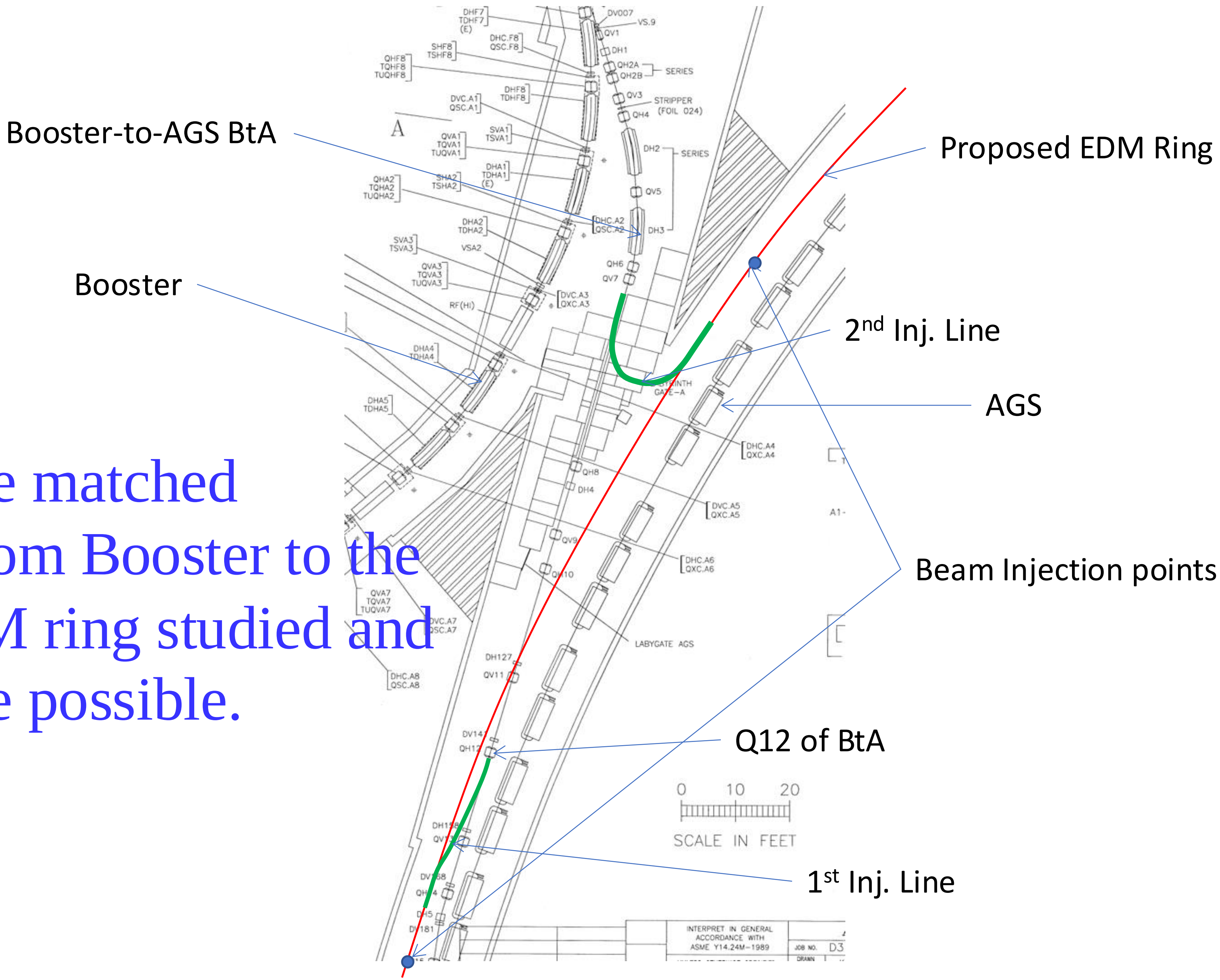
Quantity	Value
Bending Radius R_0	95.49 m
Number of periods	24
Electrode spacing	4 cm
Electrode height	20 cm
Deflector shape	cylindrical
Radial bending E-field	4.4 MV/m
Straight section length	4.16 m
Quadrupole length	0.4 m
Quadrupole strength	± 0.21 T/m
Bending section length	12.5 m
Bending section circumference	600 m
Total circumference	799.68 m
Cyclotron frequency	224 kHz
Revolution time	4.46 μs
β_x^{max}, β_y^{max}	64.54 m, 77.39 m
Dispersion, D_x^{max}	33.81 m
Tunes, Q_x, Q_y	2.699, 2.245
Slip factor, $\eta = \frac{dt}{t} / \frac{dp}{p}$	-0.253
Momentum acceptance, (dp/p)	5.2×10^{-4}
Horizontal acceptance [mm mrad]	4.8
RMS emittance [mm mrad], ϵ_x, ϵ_y	0.214, 0.250
RMS momentum spread	1.177×10^{-4}
Particles per bunch	1.17×10^{8}
RF voltage	1.89 kV
Harmonic number, h	80
Synchrotron tune, Q_s	3.81×10^{-3}
Bucket height, $\Delta p/p_{bucket}$	3.77×10^{-4}
Bucket length	10 m
RMS bunch length, σ_s	0.994 m

Low risk ← (Radial bending E-field)

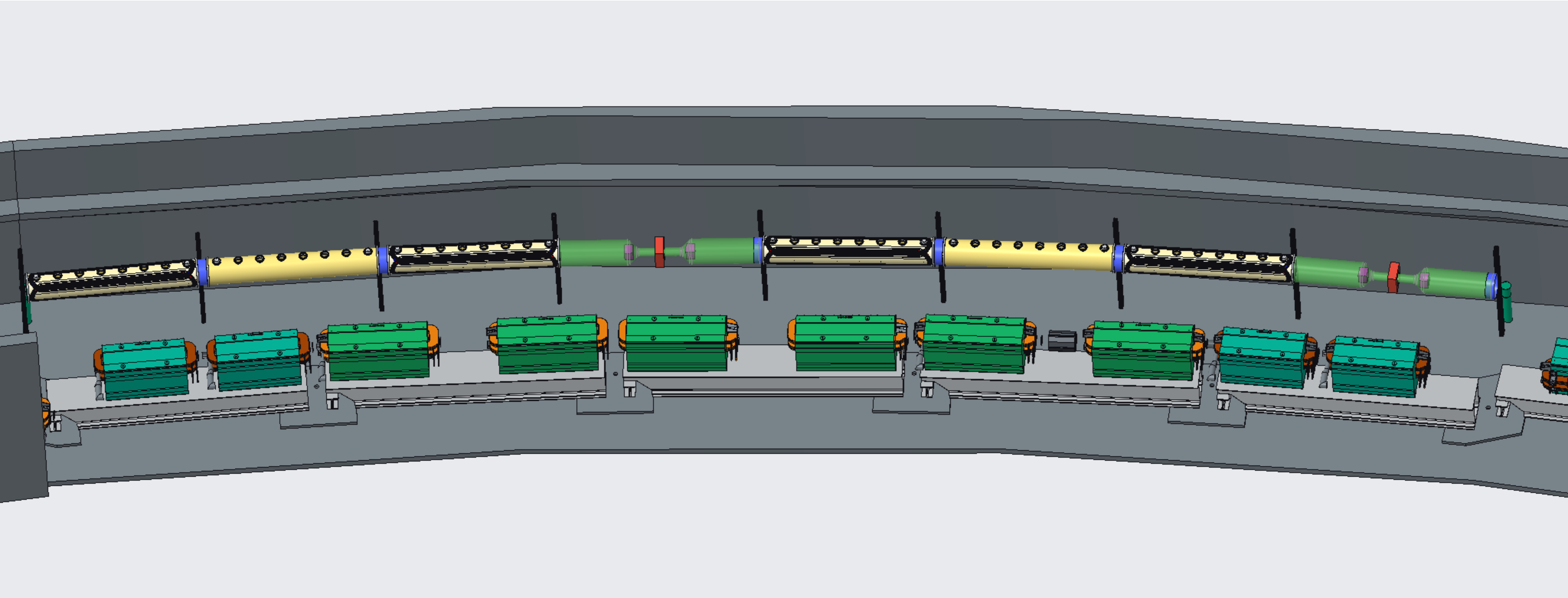
Strong focusing ← (Tunes)

The proton EDM in the AGS tunnel at BNL

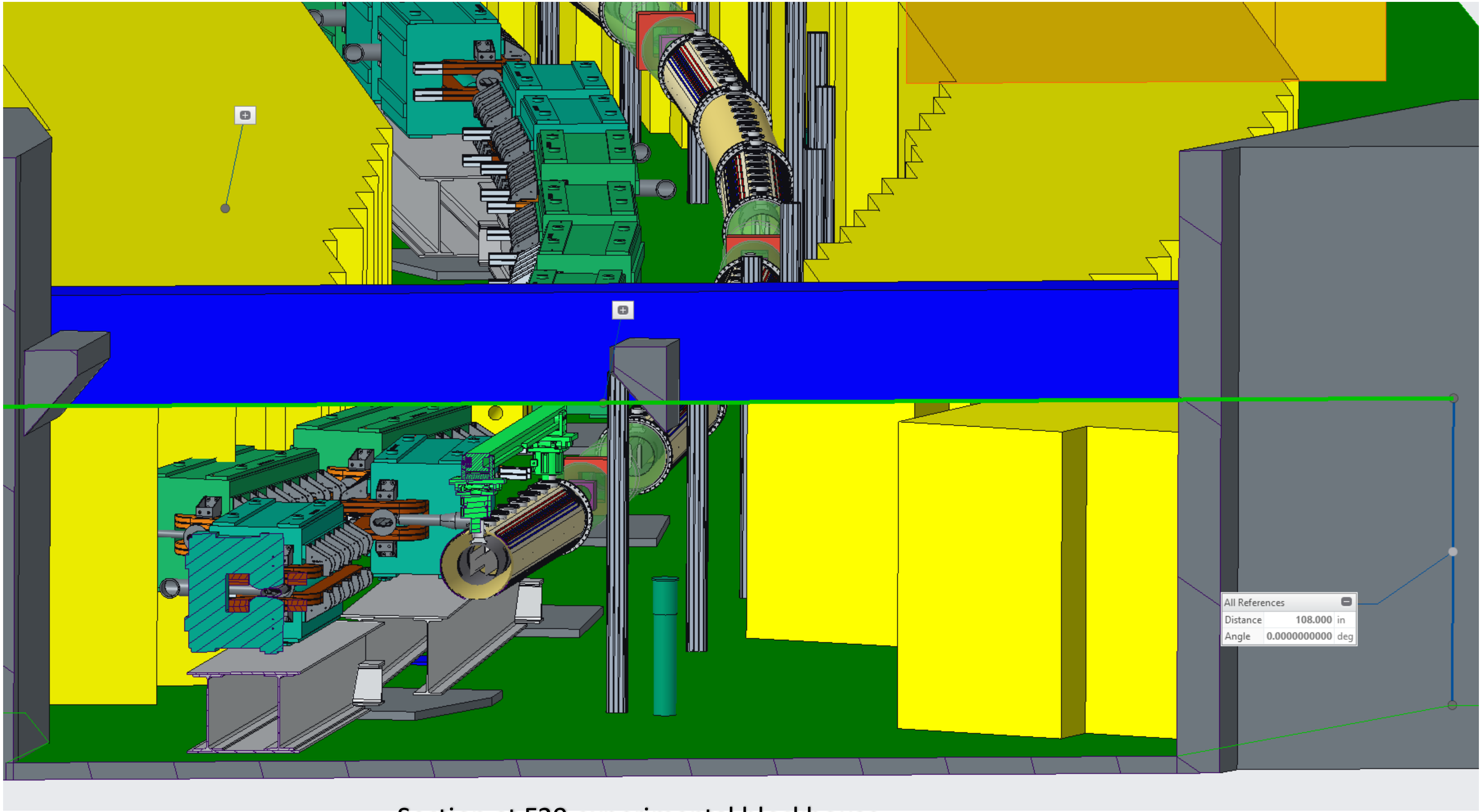




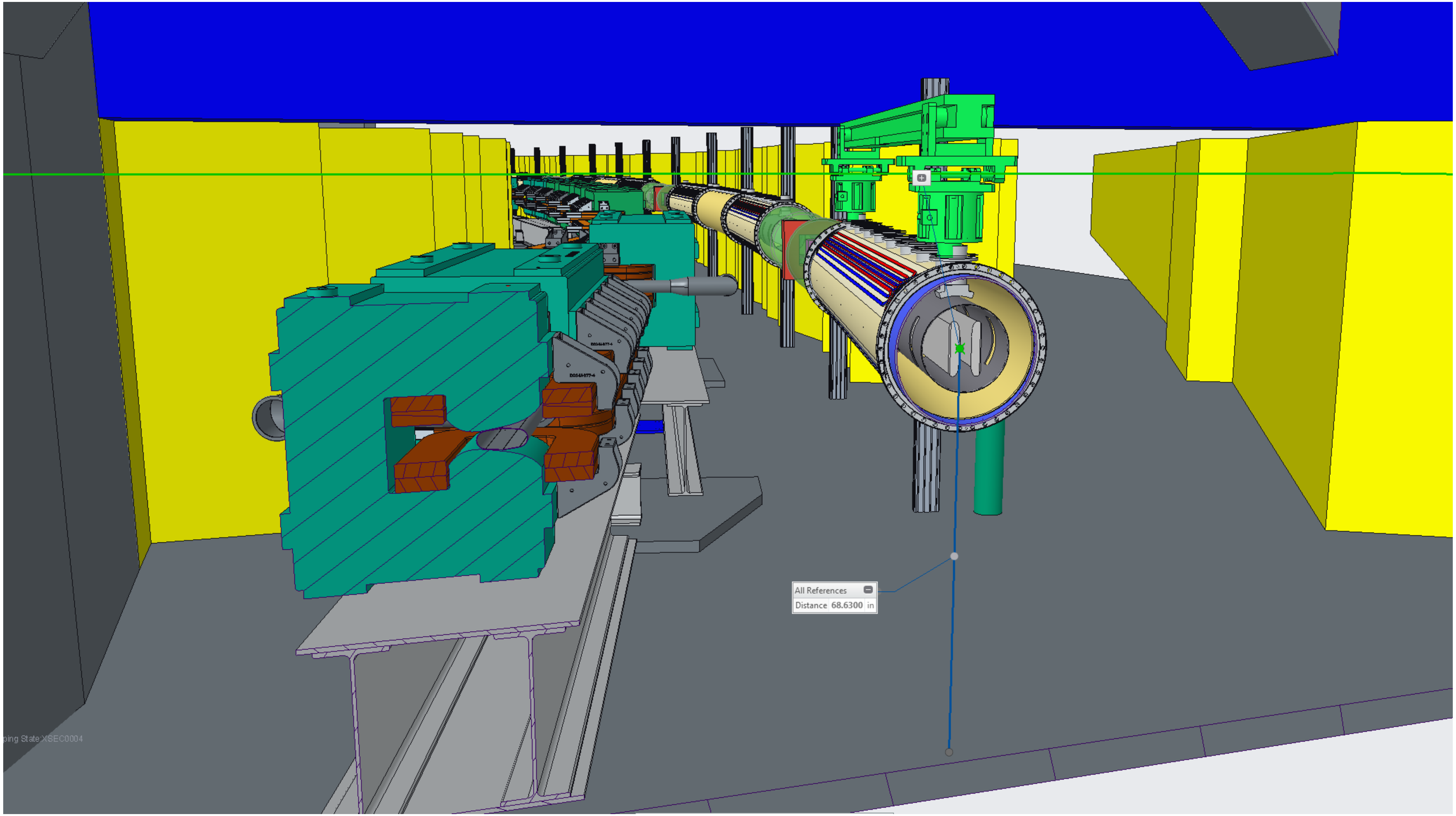
Phase-space matched injection from Booster to the proton EDM ring studied and shown to be possible.



1/24 section (15°) of pEDM ring



Section at F20 experimental blockhouse
Note: ceiling elevation = 108” (9’-0”)



Section at F20 experimental blockhouse

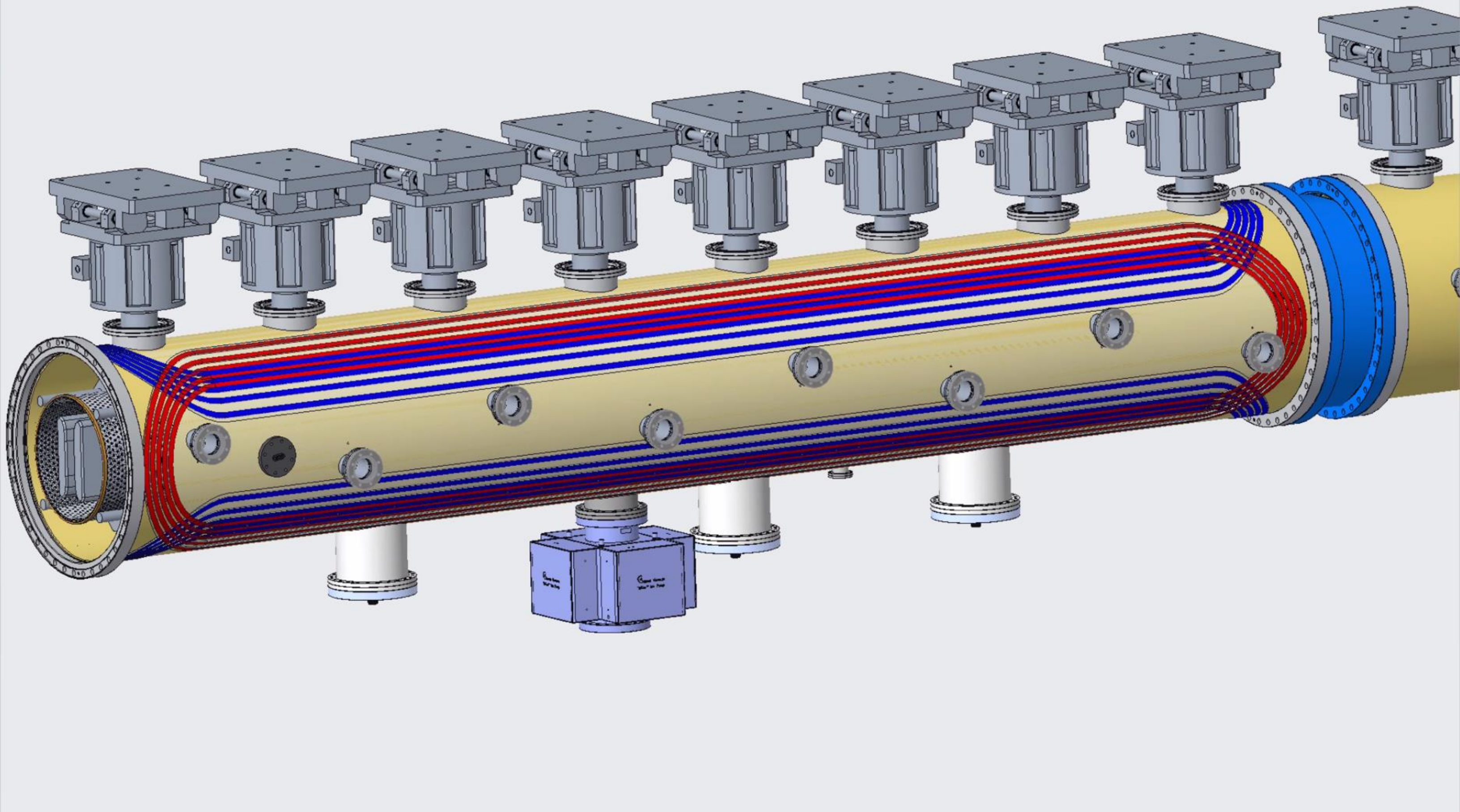
Note: preliminary ring elevation (centerline) = 68.63”

Magnetic field corrections/generation

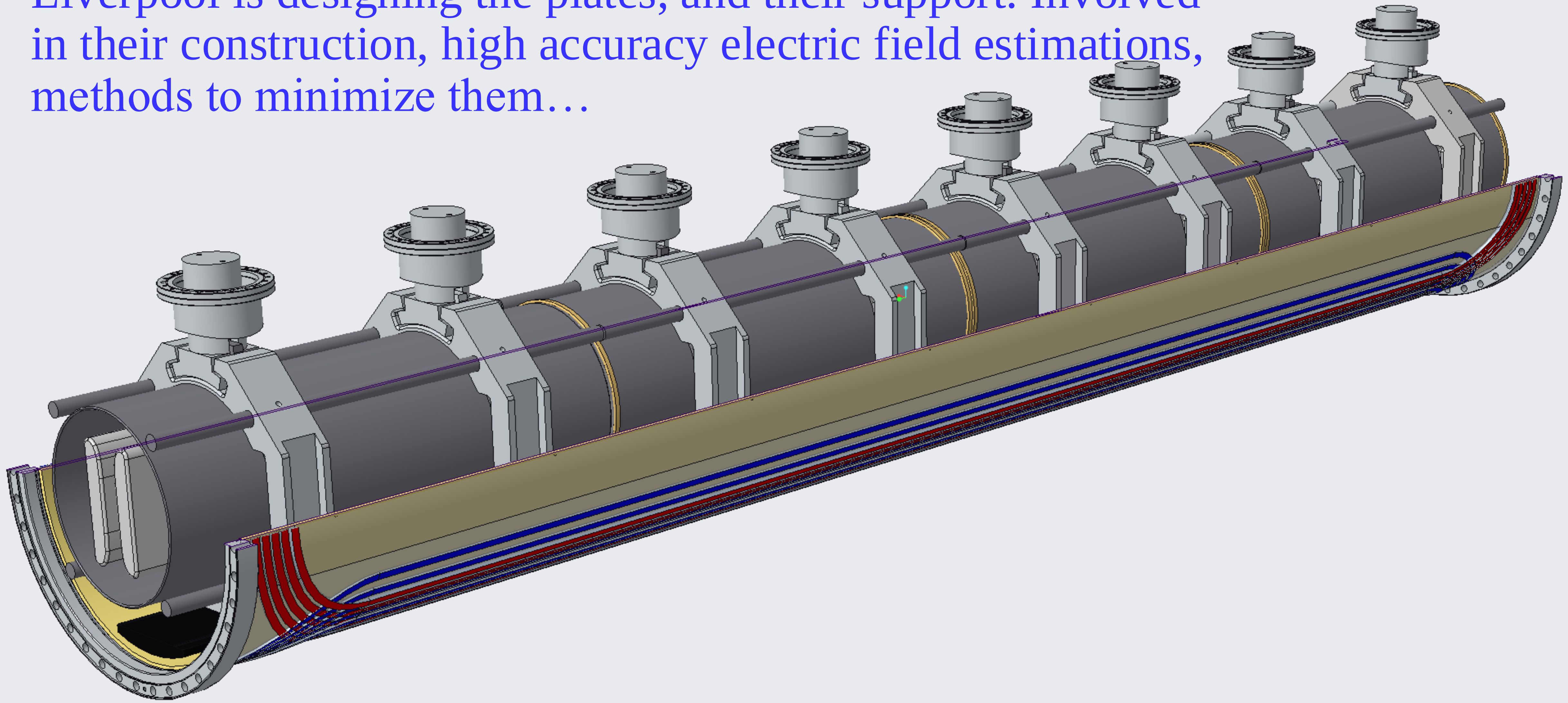
- Outside coils to generate vertical, and radial magnetic fields. Perhaps longitudinal B-fields too.

- Correction coils are used to
  - Eliminate outside B-fields
  - Probe electric field multipoles

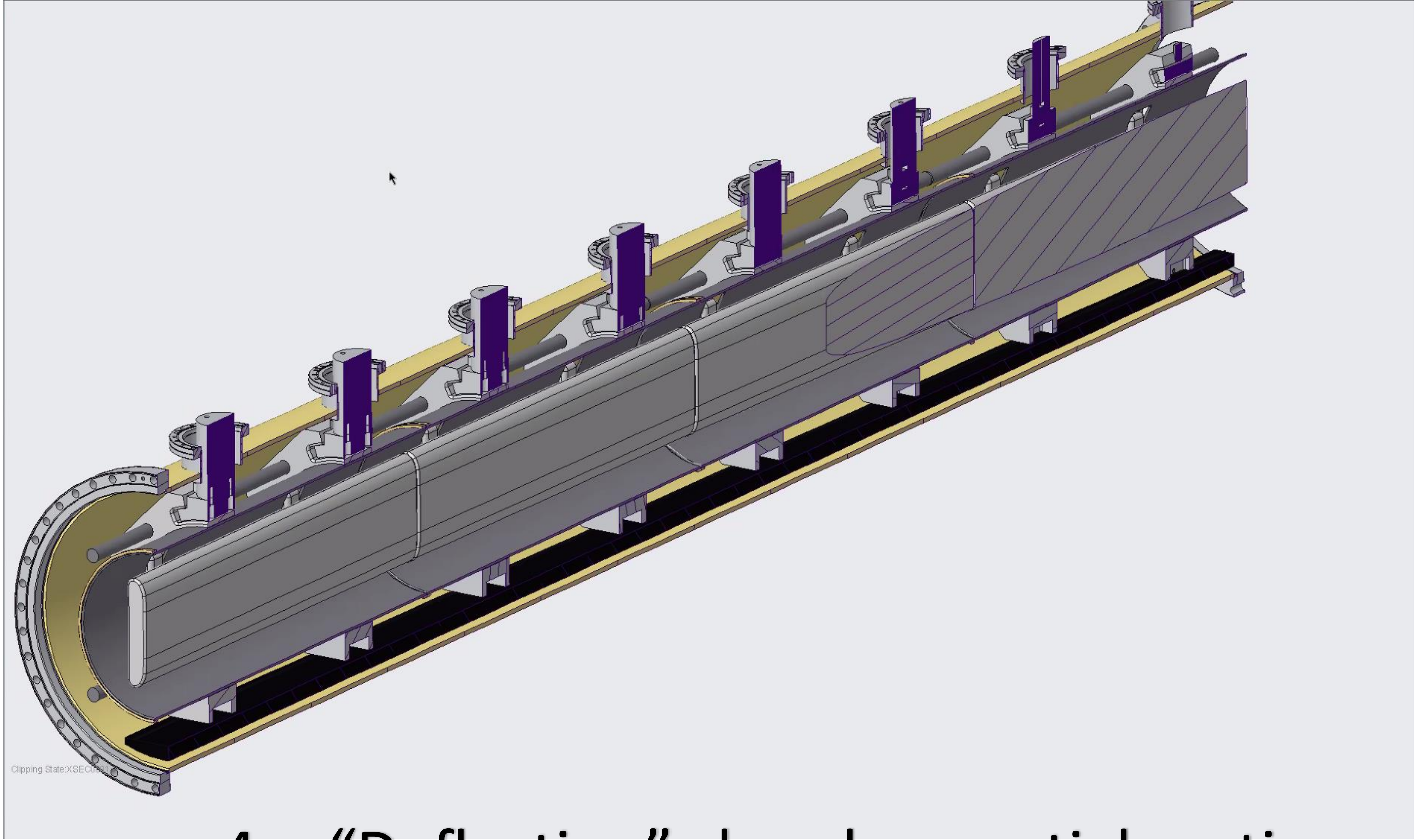
- Our correction coils should not generate unwanted longitudinal B-fields (needs to be specked)



- Liverpool is designing the plates, and their support. Involved in their construction, high accuracy electric field estimations, methods to minimize them…



4m "Deflection" chamber partial section



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