Electric Dipole Moment Measurements at Storage Rings

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on behalf of the JEDI & CPEDM collaboration

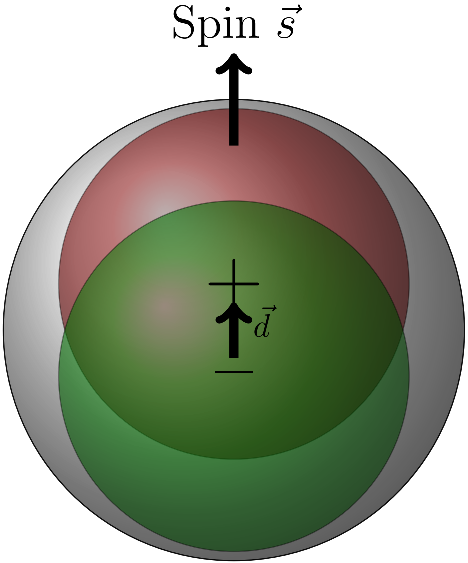
PhD School & Workshop Aspects of Symmetries, Nov. 2021

Outline

- **Motivation**
  EDMs and their relation to CP violation and Matter- Antimatter - asymmetry in the universe
- **Experimental Method**
  Spin Motion in Storage Rings
- **Experimental Results & Plans**
  activities at Cooler Synchrotron COSY, EDM prototype ring

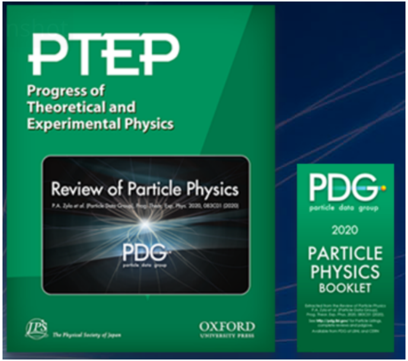
Motivation

Electric Dipole Moments (EDM)



- permanent separation of positive and negative charge
- fundamental property of particles (like magnetic moment, mass, charge)
- existence of EDM only possible via violation of time reversal $\mathcal{T} \stackrel{\mathcal{CPT}}{=} \mathcal{CP}$ and parity $\mathcal{P}$ symmetry
- close connection to matter-antimatter asymmetry
- axion field leads to oscillating EDM

Proton EDM



Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020) and 2021 update

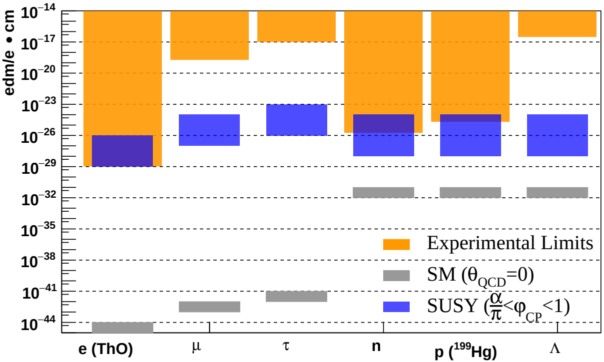
N BARYONS
($S = 0$, $I = 1/2$)

$p,\ N^+ = uud;\quad n,\ N^0 = udd$

p $\quad I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

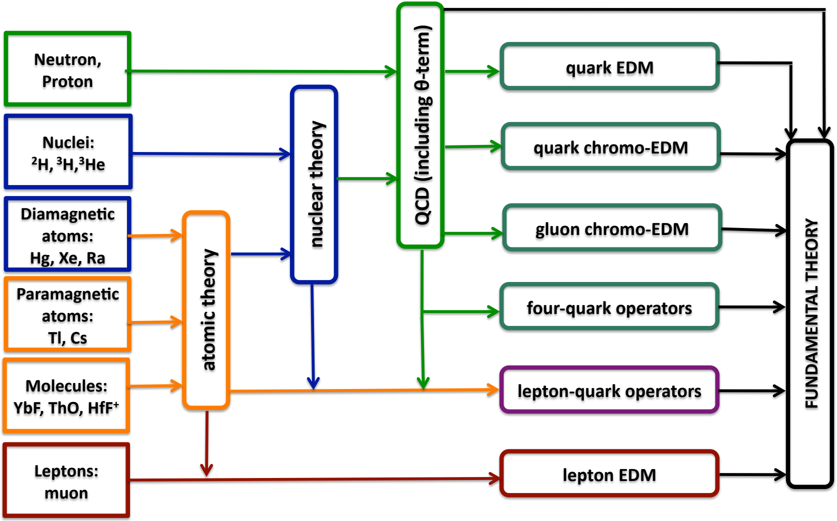
Mass $m = 1.00727646663 \pm 0.00000000009$ u (S = 2.9)
Mass $m = 938.272081 \pm 0.000006$ MeV [a]
$|m_p - m_{\overline{p}}|/m_p < 7 \times 10^{-10}$, CL = 90% [b]
$|\frac{q_{\overline{p}}}{m_{\overline{p}}}|/(\frac{q_p}{m_p}) = 1.00000000000 \pm 0.00000000007$
$|q_p + q_{\overline{p}}|/e < 7 \times 10^{-10}$, CL = 90% [b]
$|q_p + q_e|/e < 1 \times 10^{-21}$ [c]
Magnetic moment $\mu = 2.7928473446 \pm 0.0000000008\ \mu_N$
$(\mu_p + \mu_{\overline{p}}) / \mu_p = (0.002 \pm 0.004) \times 10^{-6}$
Electric dipole moment $d < 0.021 \times 10^{-23}$ e cm
Electric polarizability $\alpha = (11.2 \pm 0.4) \times 10^{-4}$ fm^3
Magnetic polarizability $\beta = (2.5 \pm 0.4) \times 10^{-4}$ fm^3 (S = 1.2)
Charge radius, μp Lamb shift $= 0.84087 \pm 0.00039$ fm [d]
Charge radius $= 0.8409 \pm 0.0004$ fm [d]
Magnetic radius $= 0.851 \pm 0.026$ fm [e]
Mean life $\tau > 3.6 \times 10^{29}$ years, CL = 90% [f] ($p \to$ invisible mode)
Mean life $\tau > 10^{31}$ to 10^{33} years [f] (mode dependent)

EDM: Current Upper Limits



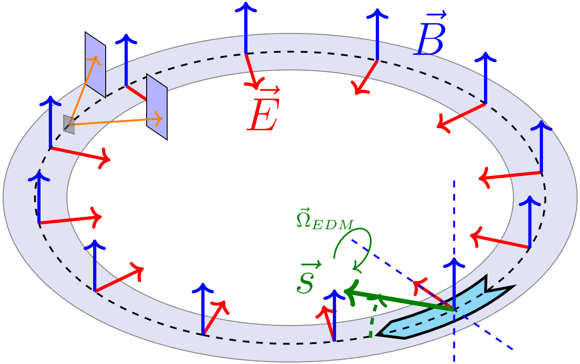
storage rings: EDMs of **charged** hadrons: p, d, ^{3}He, goal: $10^{-29}\,e\,$cm precision

Sources of $\mathcal{CP}$ Violation



Experimental Method

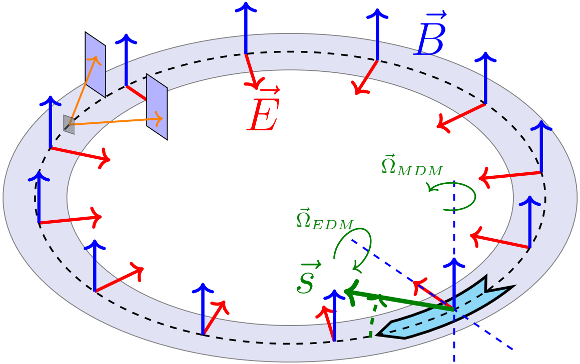
Experimental Method: Generic Idea



$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} \propto \underbrace{d(\vec{E} + \vec{v} \times \vec{B}) \times \vec{s}}_{= \vec{\Omega}_{\mathrm{EDM}}}$$

build-up of vertical polarization $s_\perp \propto d$, if $\vec{s}_{\mathrm{horz}} || \vec{p}$ (**frozen spin**)

Experimental Method: Generic Idea



$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} \propto \underbrace{d(\vec{E} + \vec{v} \times \vec{B})}_{= \vec{\Omega}_{\mathrm{EDM}}} \times \vec{s}$$

In general:

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = (\vec{\Omega}_{\mathrm{MDM}} + \vec{\Omega}_{\mathrm{EDM}}) \times \vec{s}$$

build-up of vertical polarization $s_\perp \propto d$, if $\vec{s}_{horz} || \vec{p}$ (**frozen spin**)

Spin Precession: Thomas-BMT Equation

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\Omega} \times \vec{s} = \frac{-q}{m} \Bigg[\underbrace{G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1} \right) \vec{v} \times \vec{E}}_{= \vec{\Omega}_{\mathrm{MDM}}} + \underbrace{\frac{\eta}{2} (\vec{E} + \vec{v} \times \vec{B})}_{= \vec{\Omega}_{\mathrm{EDM}}} \Bigg] \times \vec{s}$$

electric dipole moment (EDM): $\vec{d} = \eta \frac{q\hbar}{2mc} \vec{s}$,

magnetic dipole moment (MDM): $\vec{\mu} = 2(G + 1) \frac{q\hbar}{2m} \vec{s}$

Note: $\eta = 2 \cdot 10^{-15}$ for $d = 10^{-29}$ ecm, $G \approx 1.79$ for protons

Spin Precession: Thomas-BMT Equation

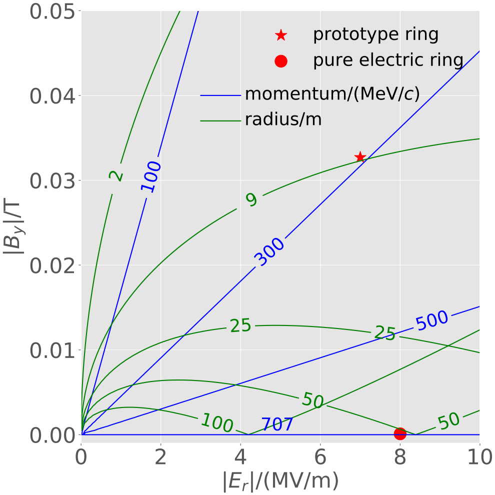
$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\Omega} \times \vec{s} = \frac{-q}{m}\left[G\vec{B} + \underbrace{\left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E}}_{\vec{\Omega}_{\mathrm{MDM}} = 0\,,\quad \textbf{frozen spin}} + \underbrace{\frac{\eta}{2}(\vec{E} + \vec{v} \times \vec{B})}_{= \vec{\Omega}_{\mathrm{EDM}}}\right] \times \vec{s}$$

frozen spin achievable with pure electric field if $G = \frac{1}{\gamma^2 - 1}$,

works only for $G > 0$, e.g. proton

or with special combination of E, B fields and γ, i.e. momentum

Momentum and ring radius for proton in frozen spin condition



Two options:

● Pure electric ring:
p = 707MeV, bending radius≈ 50 m at E=8 MV/m

⋆ combined prototype ring:
p = 300MeV, bending radius≈ 9 m at E=7 MV/m

Different Options

	☺	☹
3.) pure electric ring	no $\vec{B}$ field needed, ↺, ↻ beams simultaneously	works only for particles with $G > 0$ (e.g. e, p)
2.) combined ring	works for e, p, d, ^{3}He, smaller ring radius	both $\vec{E}$ and $\vec{B}$ B field reversal for ↺, ↻ required
1.) pure magnetic ring	existing (upgraded) COSY ring can be used, running now	lower sensitivity, precession due to G, i.e. no **frozen spin**

Statistical Sensitivity

beam intensity	$N = 4 \cdot 10^{10}$ per fill
polarization	$P = 0.8$
spin coherence time	$\tau = 1000\,\mathrm{s}$
electric fields	$E = 8\,\mathrm{MV/m}$
polarimeter analyzing power	$A = 0.6$
polarimeter efficiency	$f = 0.005$

$$\sigma_{\mathrm{stat}} \approx \frac{2\hbar}{\sqrt{Nf\tau}PAE} \quad \Rightarrow \sigma_{\mathrm{stat}}(1\mathrm{year}) = 2.4 \cdot 10^{-29}\; e\cdot\mathrm{cm}$$

challenge: get σ_{sys} to the same level

Systematic Sensitivity

signal: $\Omega_{\mathrm{EDM}} = \dfrac{dE}{s\hbar} = 2.4 \cdot 10^{-9}\,\mathrm{s}^{-1}$ for $d = 10^{-29}\,e\,\mathrm{cm}$

- radial B-field of $B_r = 10^{-17}\,\mathrm{T}$:
  $$\Omega_{B_r} = \frac{eGB_r}{m} = 1.7 \cdot 10^{-9}\,\mathrm{s}^{-1}$$
- geometric Phases (non-commutation of rotations), $B_{\mathrm{long}}, B_{\mathrm{vert}} \approx 1\,\mathrm{nT}$
  $$\Omega_{\mathrm{GP}} = \left(\frac{eGB}{16m}\right)^2 \frac{1}{f_{\mathrm{rev}}} = 3.7 \cdot 10^{-9}\,\mathrm{s}^{-1}$$
- General Relativity:
  $$\Omega_{\mathrm{GR}} = -\frac{\gamma}{\gamma^2+1}\frac{\beta g}{c} = -4.4 \cdot 10^{-8}\mathrm{s}^{-1}$$
- ...

Systematic Sensitivity

Remedy:

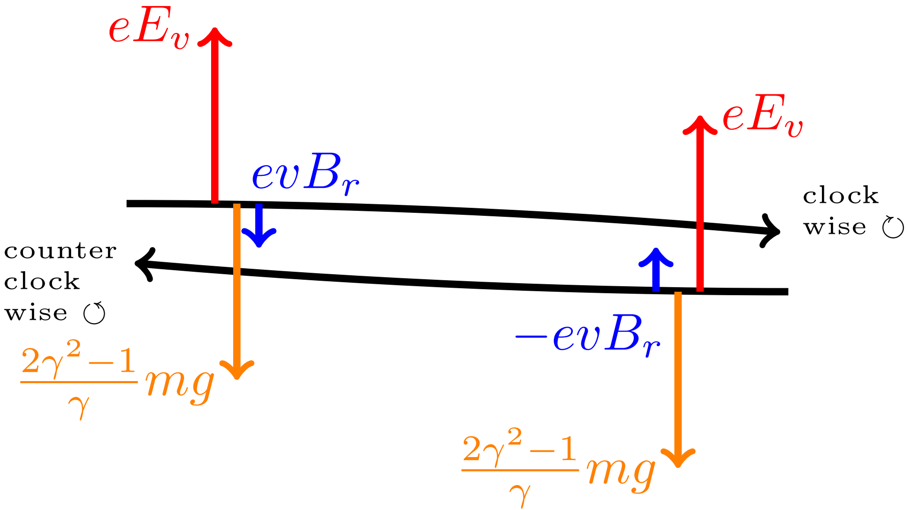
$$\circlearrowright: \quad \Omega_{\mathrm{CW}} = \Omega_{\mathrm{EDM}} + \Omega_{\mathrm{GP}} + \Omega_{\mathrm{GR}} + \Omega_{B_r} \,,$$
$$\circlearrowleft: \quad \Omega_{\mathrm{CCW}} = \Omega_{\mathrm{EDM}} - \Omega_{\mathrm{GP}} - \Omega_{\mathrm{GR}} + \Omega_{B_r} \,.$$

$\Omega_{\mathrm{GP}} + \Omega_{\mathrm{GR}}$ drops out in sum, $\Omega_{\mathrm{CW}} + \Omega_{\mathrm{CCW}}$, effect of B_r can be subtracted by observing displacement of the two beams.

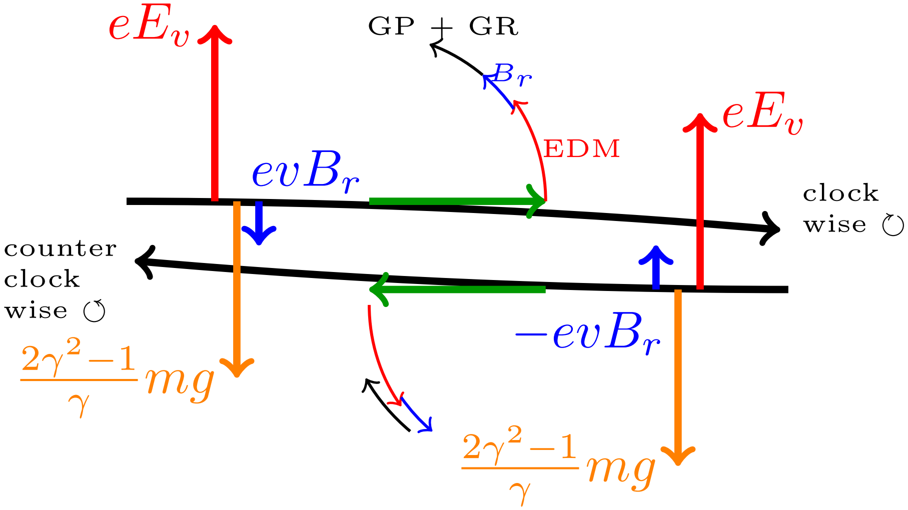
Conclusion:

Statistically one can reach sensitivity of $\approx 10^{-29}\, e\,\mathrm{cm}$, many systematic effects can be controlled using $\circlearrowleft$ and $\circlearrowright$ beams, needs further investigation
$\rightarrow$ **staged approach**

Systematics



Systematics



Staged approach

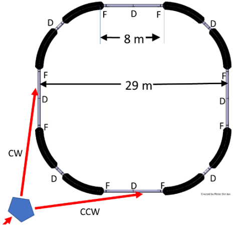
precursor experiment

at Cooler Synchrotron COSY

- magnetic storage ring

now

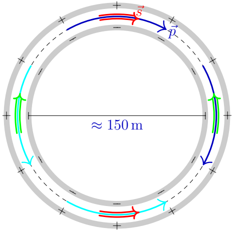
prototype ring



- initially electrostatic storage ring
- simultaneous ⟳ and ⟲ beams

5 years

dedicated storage ring



- magic momentum

(701 MeV/c)

10 years

$\sigma_{EDM}/(e \cdot \mathrm{cm})$

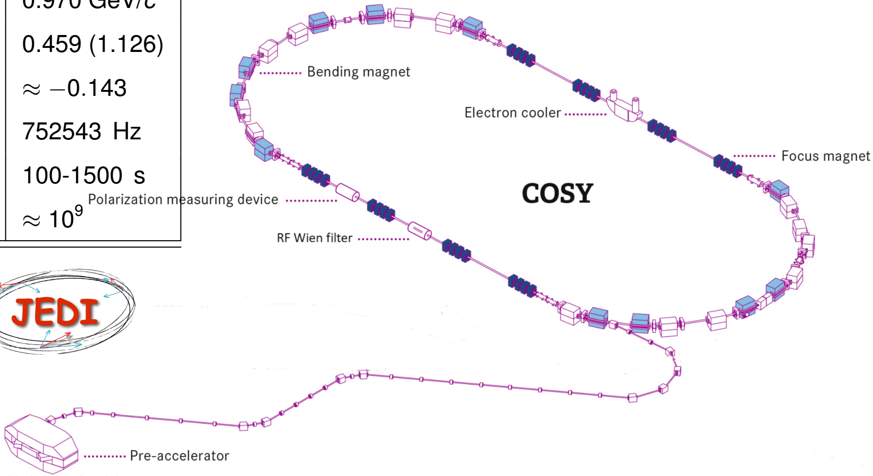
10^{-17} 10^{-18} 10^{-19} 10^{-20} 10^{-21} 10^{-22} 10^{-23} 10^{-24} 10^{-25} 10^{-26} 10^{-27} 10^{-28} 10^{-29}

Results & Plans

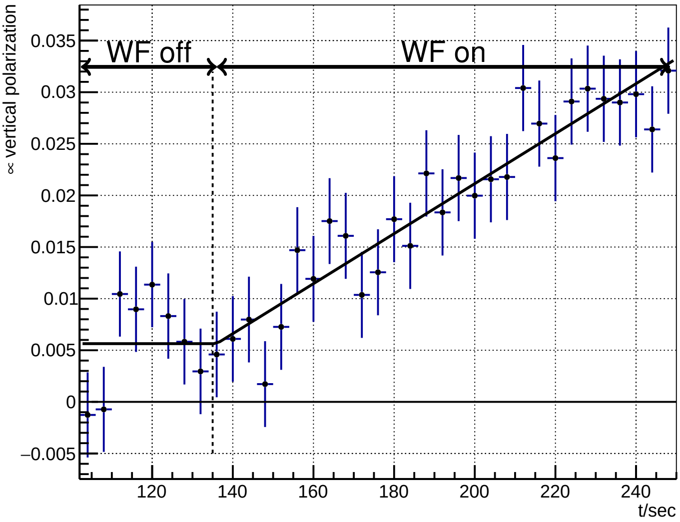
Precursor Experiment

COSY circumference	183 m
deuteron momentum	0.970 GeV/c
$\beta(\gamma)$	0.459 (1.126)
magnetic anomaly G	≈ -0.143
revolution frequency $f_{\rm rev}$	752543 Hz
cycle length	100-1500 s
nb. of stored particles/cycle	$\approx 10^9$

JEDI collaboration,



Observation of polarization build-up

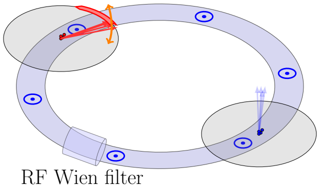


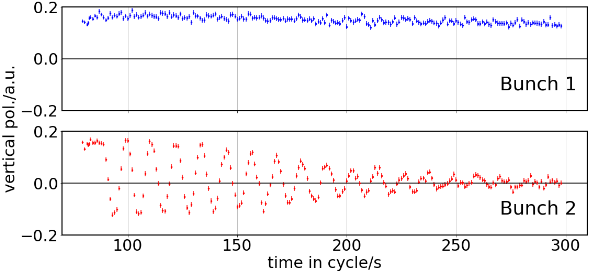
- radio-frequency Wien filter (WF) provides partially frozen spin
- polarization build-up proportional to EDM . . . and many perturbations
- perturbations are under investigation

Precursor Experiment at COSY

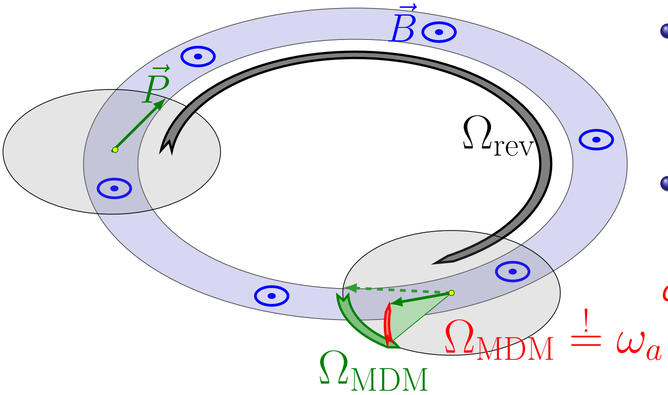
Tools developed to manipulate and measure beam polarization:

- reaching $>$ 1000 s spin coherence time
- measure 120 kHz spin tune precession in horizontal plane to 10^{-10} in 100 s
- development of polarization feed back system
- $\Rightarrow$ **Single bunch spin manipulation**





Principle of storage ring axion experiment

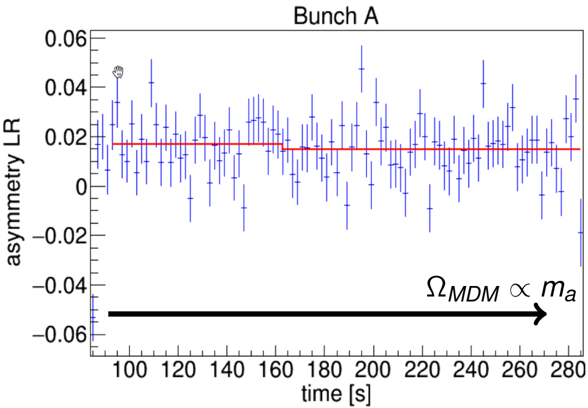


- Axion field gives rise to an effective time-dependent θ-QCD term
- This gives rise to an oscillating electric dipole moment EDM d.

$$d = d_{DC} + d_{AC}\sin(\omega_a t + \varphi_a)$$

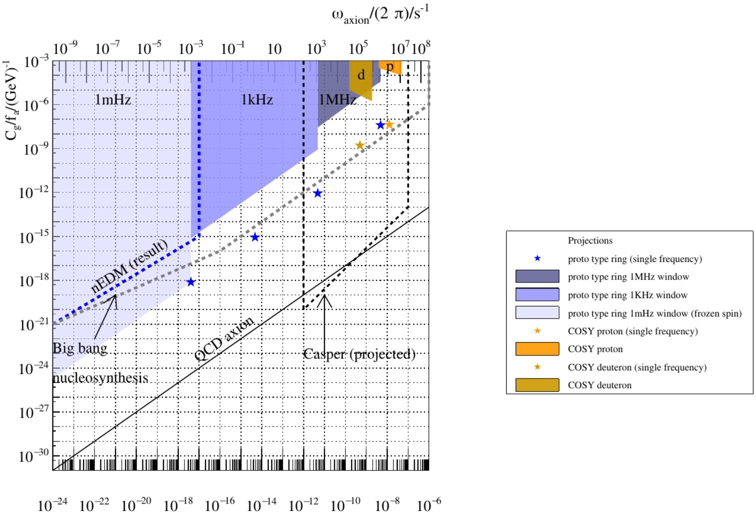
$$\omega_a = \frac{m_a c^2}{\hbar}$$

First Results



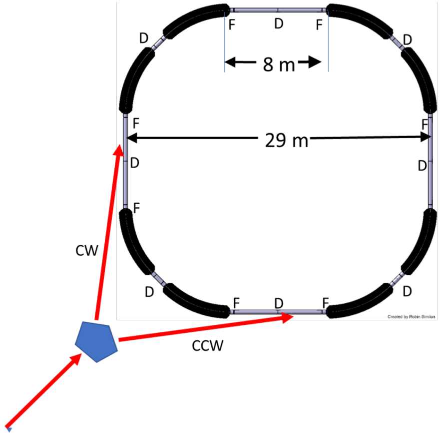
- Momentum scan $\rightarrow \Omega_{MDM}$ scan $\rightarrow$ axion mass scan
- mass range covered: $4.96 - 5.02 \cdot 10^{-9}$ eV
- axion would show up as jump in vertical polarisation
- allows to search at a given mass

Axion Searches at storage rings



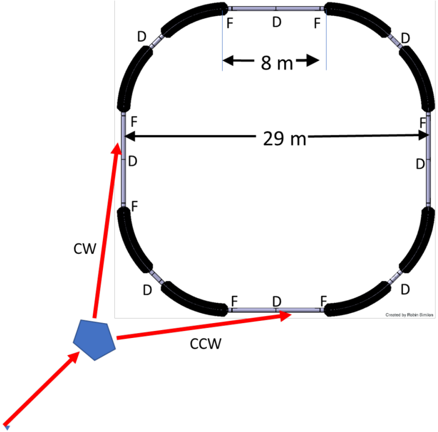
https://doi.org/10.1140/epjc/s10052-020-7664-9

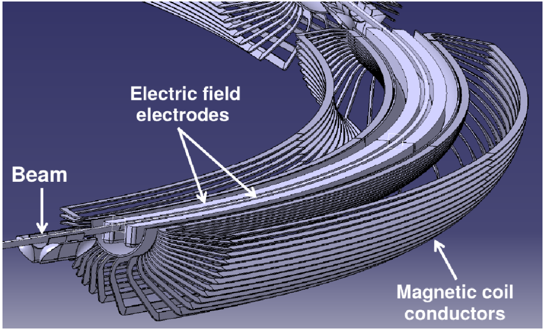
Prototype Ring: Lattice & Bending Element



- operate electrostatic ring
- store $10^9 - 10^{10}$ particles for 1000 s
- simultaneous ↻ and ↺ beams
- frozen spin (only possible with additional magnetic bending)
- develop and benchmark simulation tools
- develop key technologies:
  beam cooling, deflector, beam position monitors, shielding . . .
- perform EDM measurement

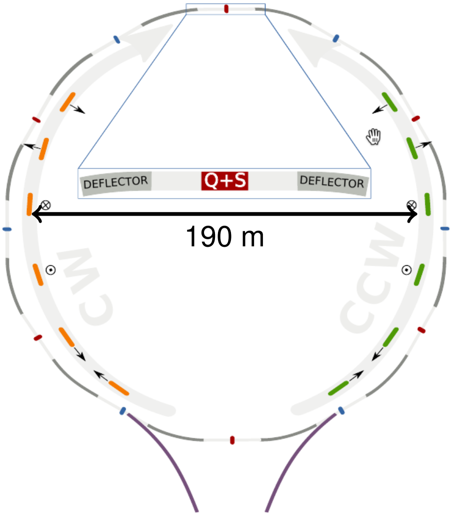
Prototype Ring: Lattice & Bending Element





CPEDM collaboration,
CERN Yellow report
https://doi.org/10.23731/CYRM-2021-003;

(Almost pure) Electric storage ring



- Electric bends
- Uses **magnetic** focusing
  $\rightarrow$ reduction of systematic error due to radial magnetic field
- bending radius = 95 m

US based storage ring EDM collaboration
arXiv:2007.10332v2

Summary

- EDMs are unique probe to search for new CP-violating interactions and contribute to axion searches
- **charged** particle EDMs can be measured in storage rings
- Several projects are ongoing on to search for e^-, μ, p, d EDM

erc European Research Council