Electric Dipole Moment Measurements at Storage Rings

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on behalf of the JEDI & CPEDM collaboration

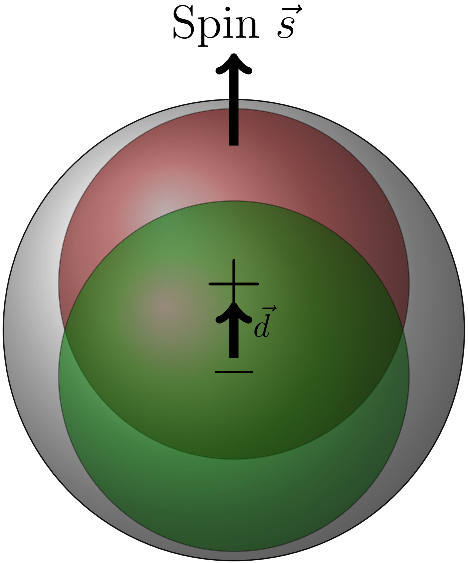
Spin 2021, October 2021

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**
  with focus on activities at Cooler Synchrotron COSY, Germany and EDM prototype ring

Motivation

Electric Dipole Moments (EDM)

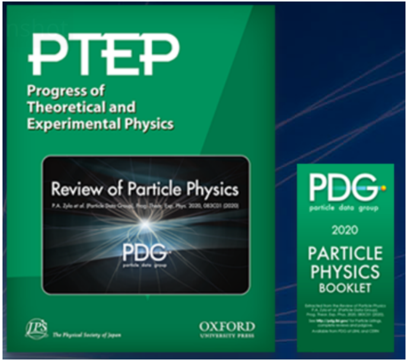


- permanent separation of positive and negative charge
- fundamental property of particles (like magnetic moment, mass, charge)
- existence of EDM only possible via violation of time reversal $\mathcal{T} \overset{\mathcal{CPT}}{=} \mathcal{CP}$ and parity $\mathcal{P}$ symmetry
- close connection to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

talks on EDM theory:

40 74 114 122 167

Proton EDM



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

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

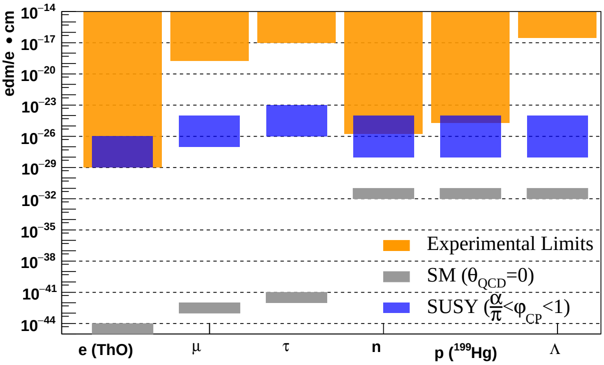
$p,\ N^+ = uud;\quad n,\ N^0 = udd$

p

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

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] ($p \rightarrow$ invisible mode)
Mean life $\tau > 10^{31}$ to 10^{33} years [f] (mode dependent)

EDM: Current Upper Limits



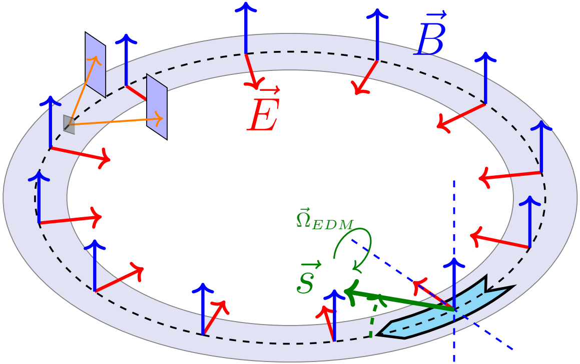
storage rings: EDMs of **charged** hadrons: p, d, ^{3}He, goal: $10^{-29}\,e\,$cm precision

more non-storage ring EDM talks:

nEDM: 33 60 62, atoms/molecules: 138, 179

Experimental Method

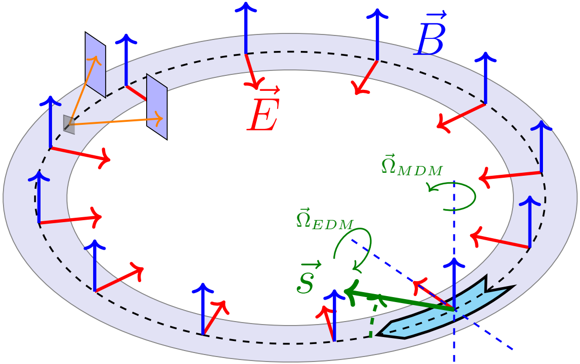
Experimental Method: Generic Idea



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

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

Experimental Method: Generic Idea



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

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

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

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

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

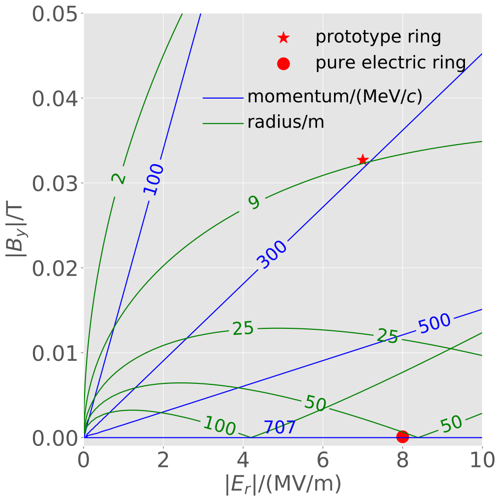
$$\underbrace{\left(G - \frac{1}{\gamma^2-1}\right)\vec{v}\times\vec{E}}_{\vec{\Omega}_{\mathrm{MDM}} = 0\,,\quad \textbf{frozen spin}} \qquad \underbrace{\frac{\eta}{2}(\vec{E}+\vec{v}\times\vec{B})}_{= \vec{\Omega}_{\mathrm{EDM}}}$$

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

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**

Staged approach

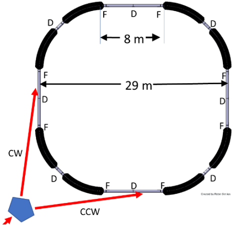
precursor experiment

at Cooler Synchrotron COSY

- magnetic storage ring

now

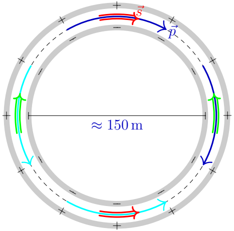
prototype ring



- initially electrostatic storage ring
- simultaneous ↻ and ↺ beams

5 years

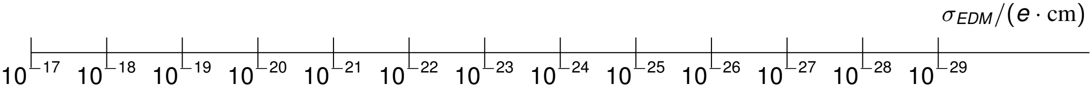
dedicated storage ring



- magic momentum

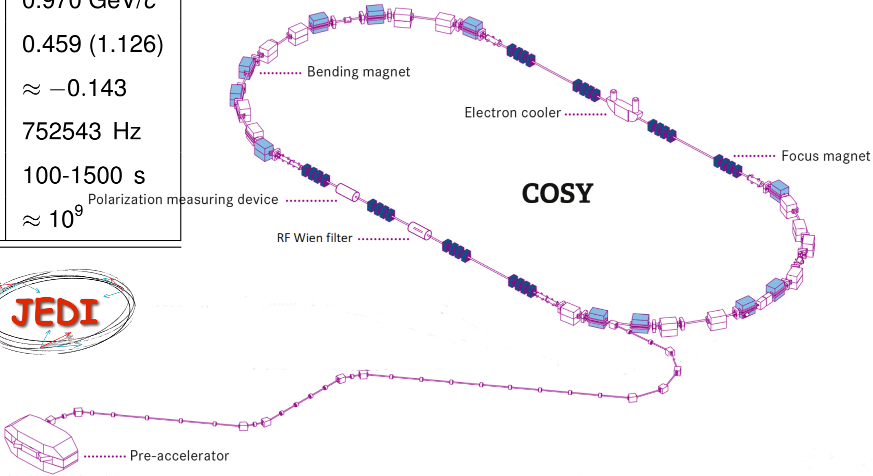
(701 MeV/c)

10 years



Precursor Experiment

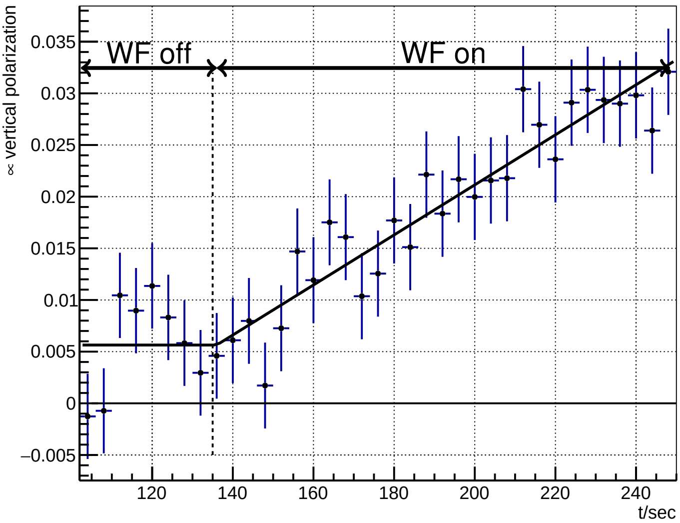
COSY circumference	183 m
deuteron momentum	0.970 GeV/c
$\beta(\gamma)$	0.459 (1.126)
magnetic anomaly G	≈ -0.143
revolution frequency f_{rev}	752543 Hz
cycle length	100-1500 s
nb. of stored particles/cycle	$\approx 10^9$



JEDI collaboration,

Results & Plans

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

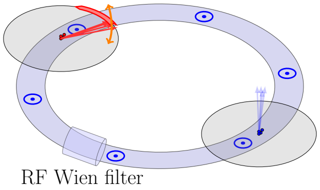
More details in:

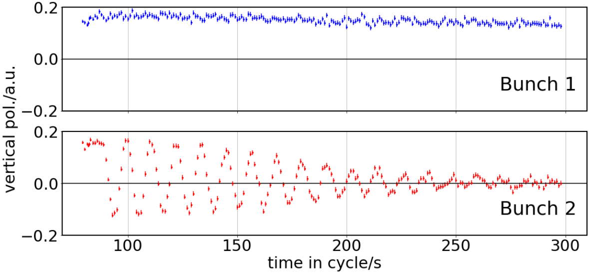
37 63 71 79 89

Precursor Experiment at COSY

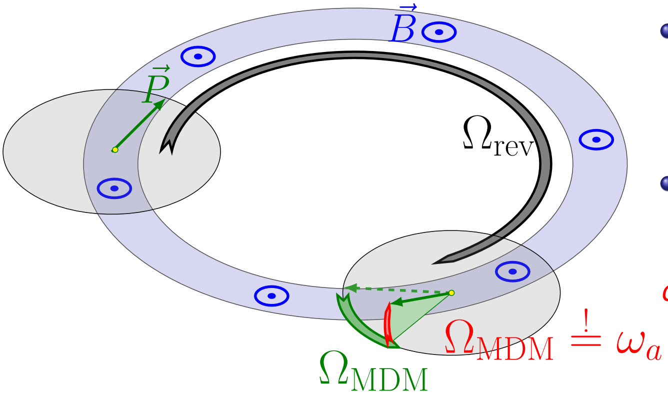
Tools developed to manipulate and measure beam polarization:

- 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

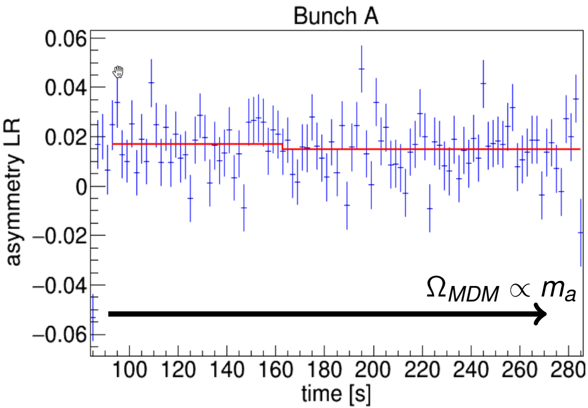


- Axion field gives rise to an effective time-dependent θ-QCD term
- This gives rise to an oscillating electric dipole moment EDM d.

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

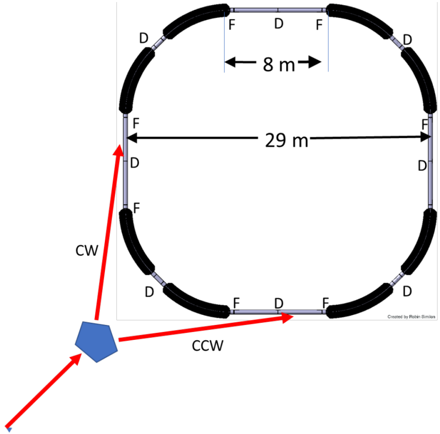
$$\omega_a = \frac{m_a c^2}{\hbar}$$

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

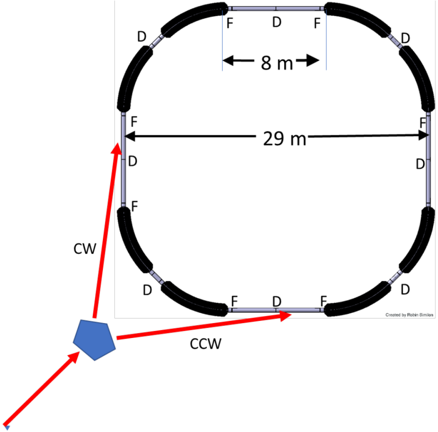
Prototype Ring: Lattice & Bending Element



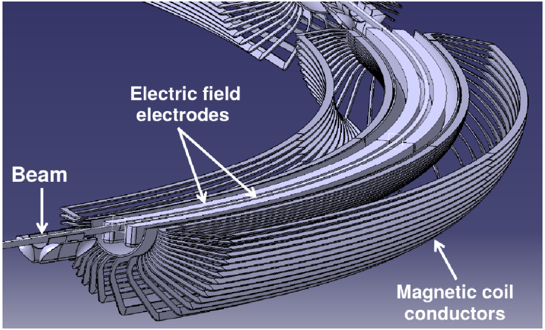
- operate electrostatic ring
- store $10^9 - 10^{10}$ particles for 1000 s
- simultaneous ⟳ and ⟲ beams
- frozen spin (only possible with additional magnetic bending)
- develop and benchmark simulation tools
- develop key technologies: beam cooling, deflector, beam position monitors, shielding . . .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

45 68 204

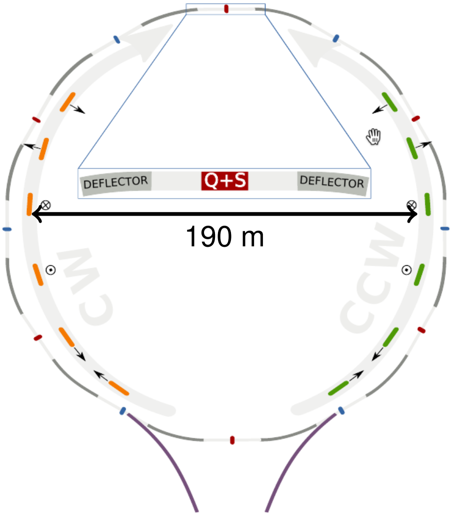
Prototype Ring: Lattice & Bending Element



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

Electron & muon EDM

50 **Electron EDM** @ Jefferson Lab
smaller ring size (few meters) using spin transparent mode
R. Suleiman, EDM in Small Rings, 21 Oct 2021, 08:10
see also:

81 Yury Filatov, Spin Transparency Method for High Precision Experiments with Polarized Beams, 19/10/2021, 20:30

41 **muon EDM** @ PSI
dedicated experiment to measure muon EDM
Mikio Sakurai: Towards a search for the muon electric dipole moment at PSI using the frozen-spin technique, 19/10/2021, 21:00

127 **muon EDM** @ JPARC
Yusuke Takeuchi, Muon g-2/EDM Experiment at J-PARC, 20/10/2021, 11:45

130 **muon EDM** @ FNAL muon EDM measurement parallel to muon $g-2$ measurement
V. Tishchenko, Measurement of muon $g-2$, 18 Oct 2021, 15:30

Other talks related to storage ring EDM I

- Experiments at COSY
  37. Max Vitz - Orbit Response Matrix Analysis for COSY - Model Optimization using LOCO, 18/10/2021, 21:20
  63. Artem Saleev - Spin tune response to vertical orbit correction at COSY
  71. Tim Wagner - Beam-based alignment at the Cooler Synchrotron (COSY), 19/10/2021, 21:20
  79. Vera Shmakova - The search for electric dipole moments of charged particles using storage rings, 19/10/2021, 20:30
  89. Jamal Slim - Towards a surrogate computational tool to quantify the systematic uncertainties in EDM experiments in storage rings, 19/10/2021, 21:20
- Prototype Ring
  45. Otari Javakhishvili - Pellet target development for storage ring EDM polarimetry 19/10/2021, 21:00
  68. Saad Siddique - Simulations of Beam Dynamics and Beam Lifetime for the Prototype EDM Ring 18/10/2021, 21:00
  204. Rahul Shankar - Optimisation of spin-coherence time in a prototype storage ring for electric dipole moment measurements

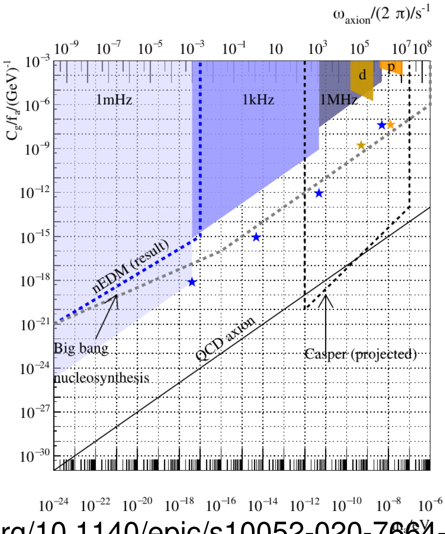
Summary

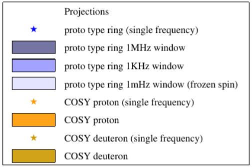
- EDMs are unique probe to search for new CP-violating interactions and contribute to axion searches
- **charged** particle EDMs can be measured in storage rings
- Several projects are ongoing on to search for e^-, μ, p, d EDM

erc European Research Council

Extra Slides

Axion Searches at storage rings

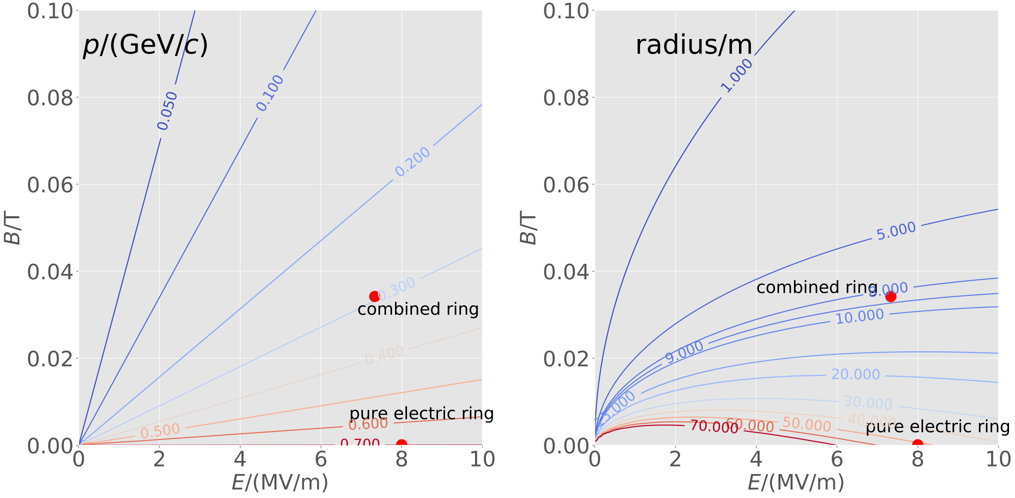




https://doi.org/10.1140/epjc/s10052-020-7664-9

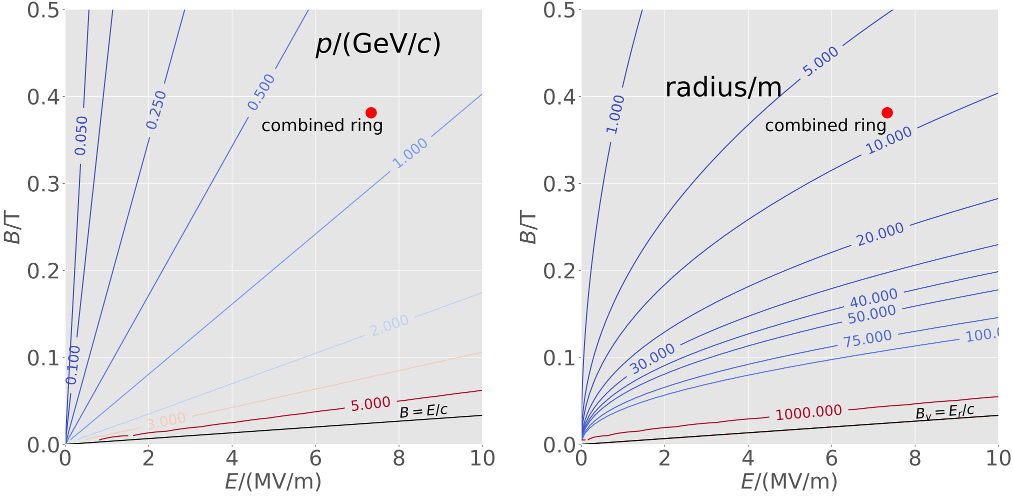
Momentum and ring radius for **proton** in frozen spin condition

$G = 1.7928474$



Momentum and ring radius for **deuteron** in frozen spin condition

$G = -0.1425617689$



Momentum and ring radius for **electron** in frozen spin condition

$G = 0.001159652$