Storage Rings for the Search of Charged-Particle Electric Dipole Moments

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on behalf of the JEDI & CPEDM collaboration

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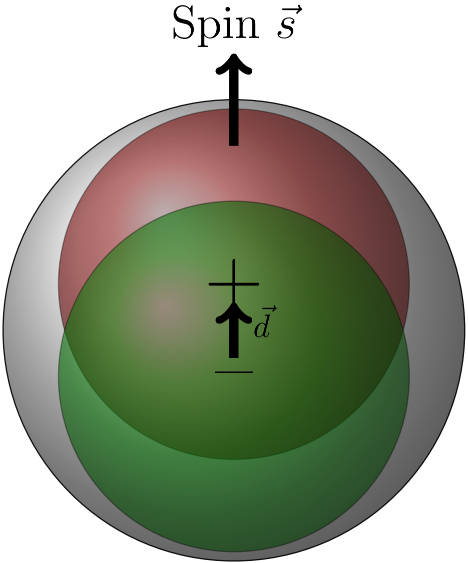
Outline

- **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 storage ring

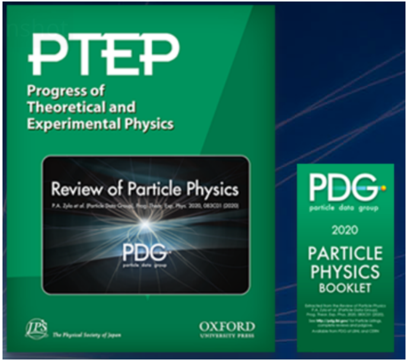
Motivation

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

Proton EDM



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

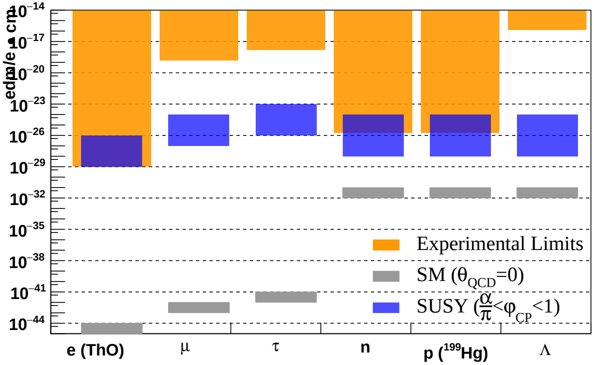
N BARYONS ($S = 0$, $I = 1/2$)

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

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

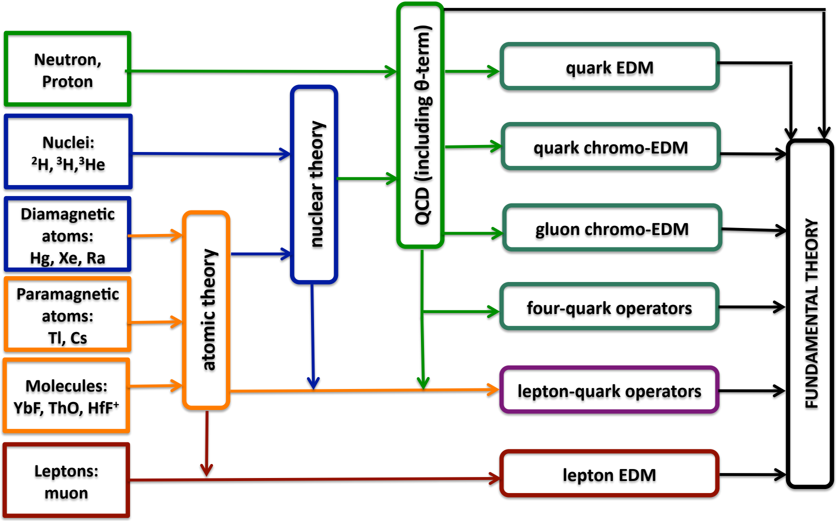
Mass $m = 1.00727646663 \pm 0.00000000009$ u (S = 2.9)
Mass $m = 938.272081 \pm 0.000006$ MeV [a]
$|m_p - m_{\overline{p}}|/m_p < 7 \times 10^{-10}$, CL = 90% [b]
$|\frac{q_{\overline{p}}}{m_{\overline{p}}}|/(\frac{q_p}{m_p}) = 1.00000000000 \pm 0.00000000007$
$|q_p + q_{\overline{p}}|/e < 7 \times 10^{-10}$, 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 90% Upper Limits



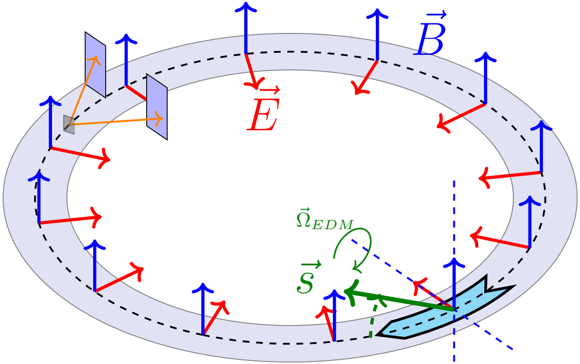
storage rings: EDMs of **charged** hadrons: p, d, ^{3}He, goal: $10^{-29}\,e\,$cm precision

Sources of $\mathcal{CP}$ Violation



Experimental Method

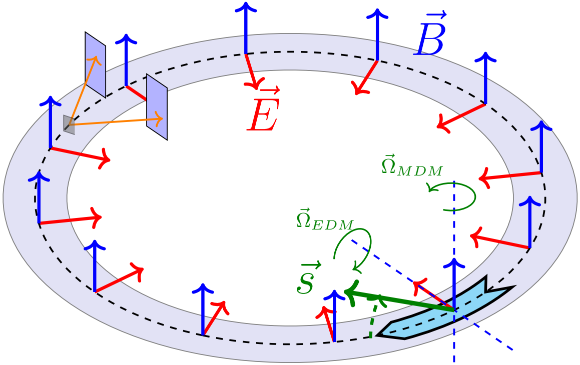
Experimental Method: Generic Idea



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

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

Experimental Method: Generic Idea



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

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

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

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 $d = 10^{-29}\,e\mathrm{cm}$, $G \approx 1.79$ for protons

Spin Precession: Thomas-BMT Equation

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

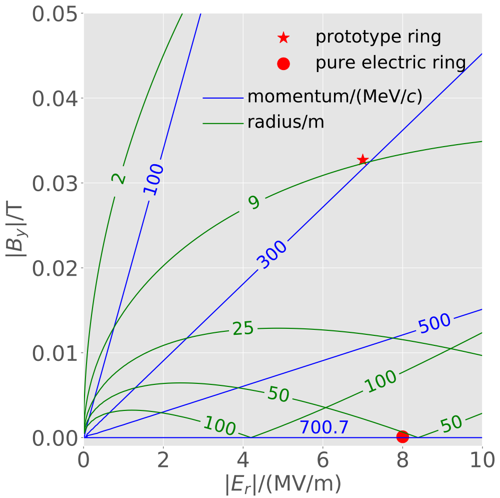
$\vec{\Omega}_{\mathrm{MDM}} = 0\,,$ **frozen spin** $\qquad = \vec{\Omega}_{\mathrm{EDM}}$

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 = 701MeV, 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	$f = 0.005$

$$\sigma_{\mathrm{stat}} \approx \frac{2\hbar}{\sqrt{N f \tau} P A E} \quad \Rightarrow \sigma_{\mathrm{stat}}(1\mathrm{year}) = 2.4 \cdot 10^{-29}\ e\cdot\mathrm{cm}$$

challenge: get σ_{sys} to the same level

Systematic Sensitivity

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

- radial B-field of $B_r = 10^{-17}$ 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:

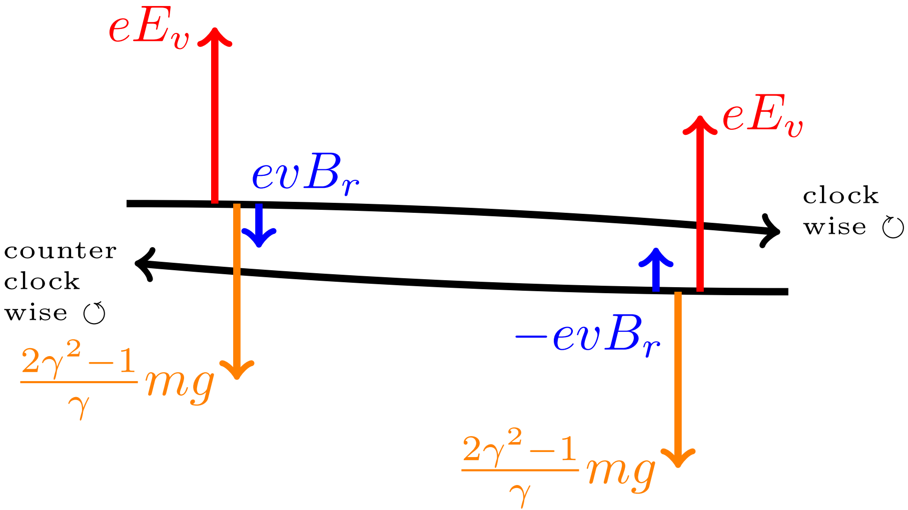
$$\circlearrowright: \quad \Omega_{\mathrm{CW}} = \Omega_{\mathrm{EDM}} + \Omega_{\mathrm{GP}} + \Omega_{\mathrm{GR}} + \Omega_{B_r} \,,$$
$$\circlearrowleft: \quad \Omega_{\mathrm{CCW}} = \Omega_{\mathrm{EDM}} - \Omega_{\mathrm{GP}} - \Omega_{\mathrm{GR}} + \Omega_{B_r} \,.$$

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

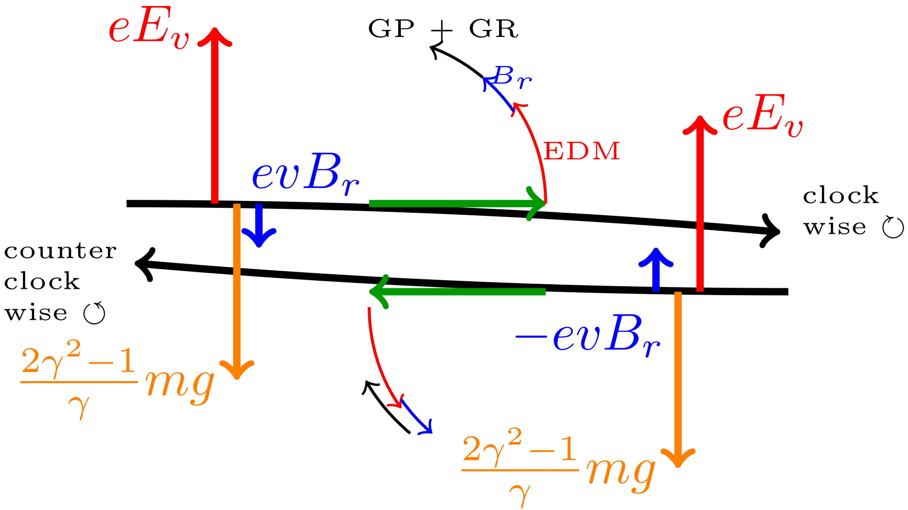
Conclusion:

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



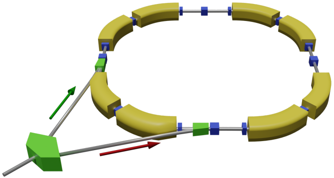
Staged approach

precursor experiment

at Cooler Synchrotron COSY

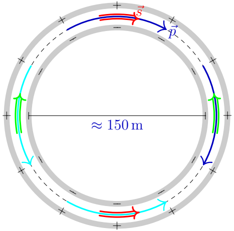
- magnetic storage ring

prototype ring



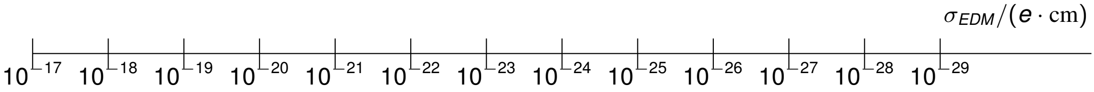
- initially electrostatic storage ring
- simultaneous ↻ and ↺ beams

dedicated storage ring



- magic momentum

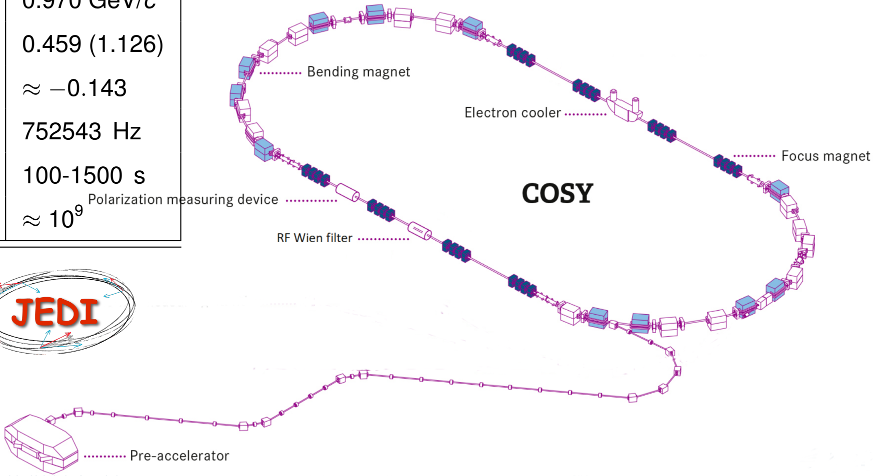
(701 MeV/c)



Results & Plans

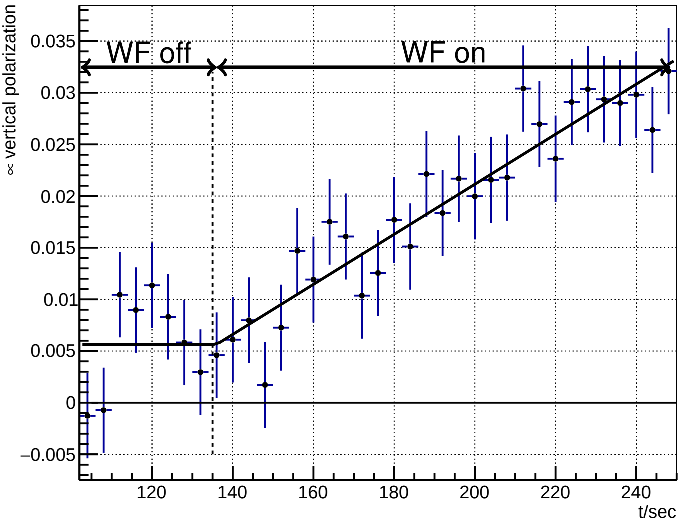
Precursor Experiment

COSY circumference	183 m
deuteron momentum	0.970 GeV/c
$\beta(\gamma)$	0.459 (1.126)
magnetic anomaly G	≈ -0.143
revolution frequency f_{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

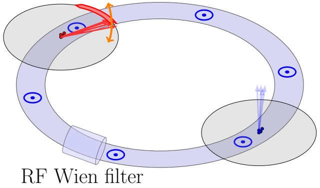
Poster: V. Shmakova, M. Vitz

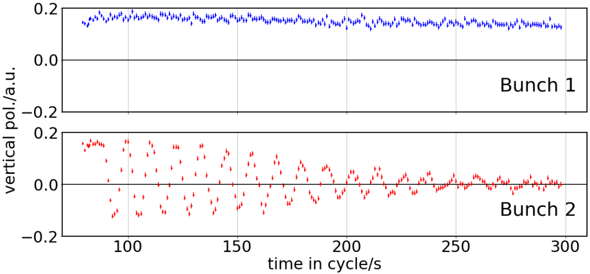
Precursor Experiment at COSY

Tools developed to manipulate and measure beam polarization:

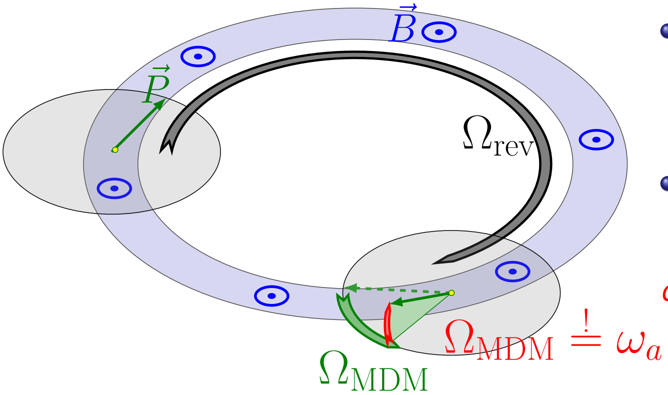
- reaching $>$ 1000 s spin coherence time
- measure 120 kHz spin tune precession in horizontal plane to 10^{-10} in 100 s
- development of polarization feed back system
- $\Rightarrow$ **Single bunch spin manipulation**

} 3 PRLs





Principle of storage ring axion/ALP experiment

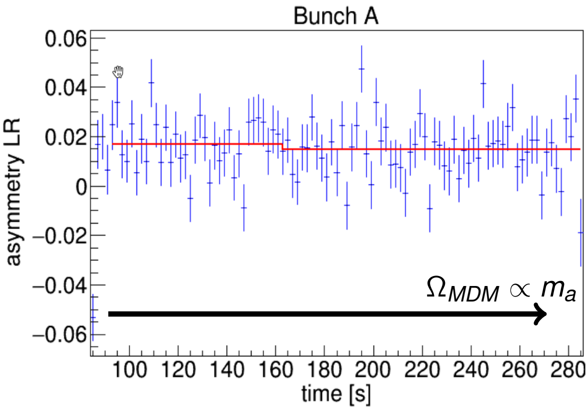


- Axion field gives rise to an effective time-dependent θ-QCD term
- This gives rise to an oscillating electric dipole moment EDM d.

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

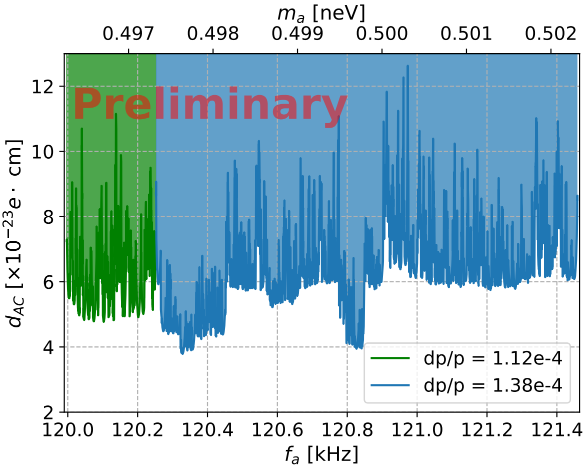
$$\omega_a = \frac{m_a c^2}{\hbar}$$

First Results



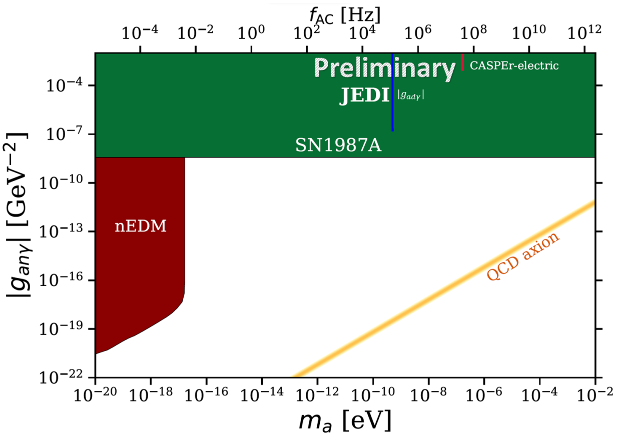
- Momentum scan $\rightarrow \Omega_{MDM}$ scan $\rightarrow$ axion mass scan
- mass range covered: $4.96 - 5.02 \cdot 10^{-10}$ eV
- axion would show up as jump in vertical polarisation
- allows to search at a given mass

Axion Analysis: d_{AC}



- Result from many scans from previous page
- a few days of beam time
- $f_a = \frac{1}{2\pi}\frac{m_a c^2}{\hbar} = \gamma G f_{\mathrm{rev}}$

Axion Analysis: axion anomalous coupling to gluons $g_{aN\gamma}$



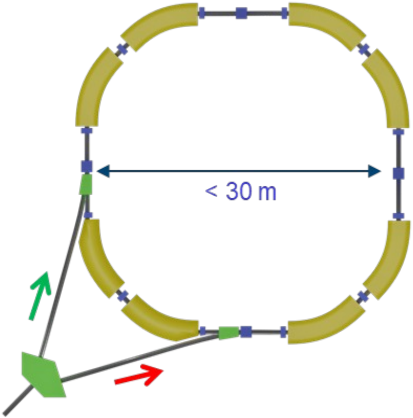
- blue "needle" could be longer (and thinner) if we had spent the measurment time on a single frequency.
- For couplings to fermions, effect at storage rings ($v \approx c$) creatly enhanced compared to NMR or cold neutrons ($v \approx 0$)

(A. Silenko https://arxiv.org/abs/2109.05576

K. Nikolaev https://arxiv.org/abs/2204.13448)

Plans for a dedicated EDM ring

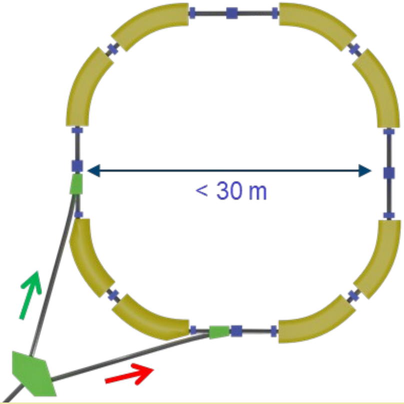
Prototype Ring: Lattice & Bending Element

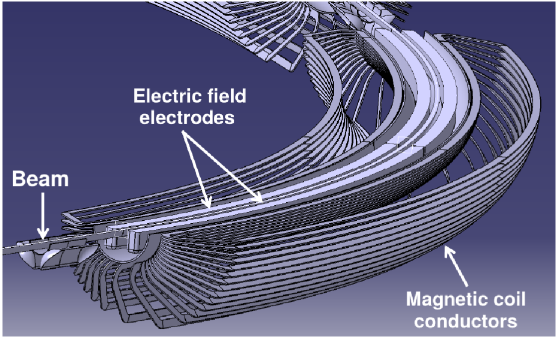


- operate electrostatic ring
- store $10^9 - 10^{10}$ particles for 1000 s
- simultaneous ↻ and ↺ beams
- frozen spin (only possible with additional magnetic bending)
- develop and benchmark simulation tools
- develop key technologies:
  beam cooling, deflector, beam position monitors, shielding . .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

Poster: R. Shankar, S Siddique

Prototype Ring: Lattice & Bending Element





Research Infrastructure Concept Development:
Pathfinder Facility for a new Class of **Pre**cision Physics **Sto**rage Rings (PRESTO) proposal submitted to EU
Partner: INFN, GSI/FZJ, CERN, MPG, RWTH, LIV, JAG, TSU

Summary

- EDMs are unique probe to search for new CP-violating interactions and contribute to axion/ALP searches
- **charged** particle EDMs can be measured in storage rings
- First steps done at Cooler Synchrotron COSY at Forschungszentrum Jülich, Germany
- Next step:

Construct a new type of accelerator in the MeV momentum range to answer fundamental questions of particle physics and cosmology.

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ECFA
European Committee for Future Accelerators

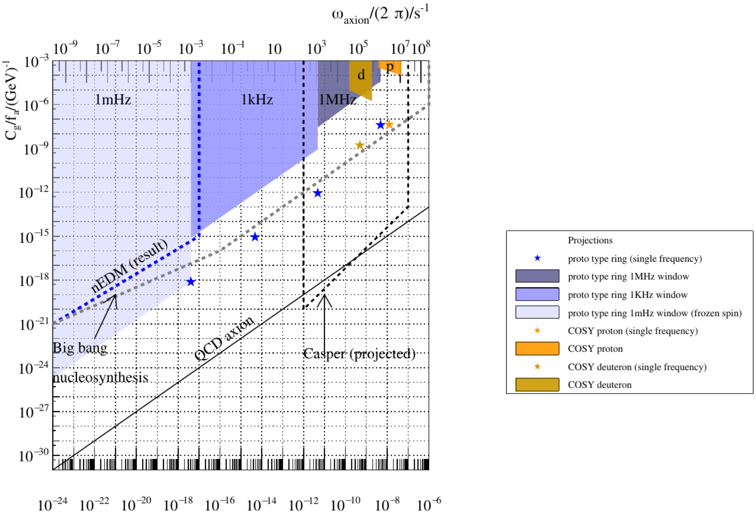
NuPECC

APPEC

Jenas EOI: https://indico.ph.tum.de/event/4482/

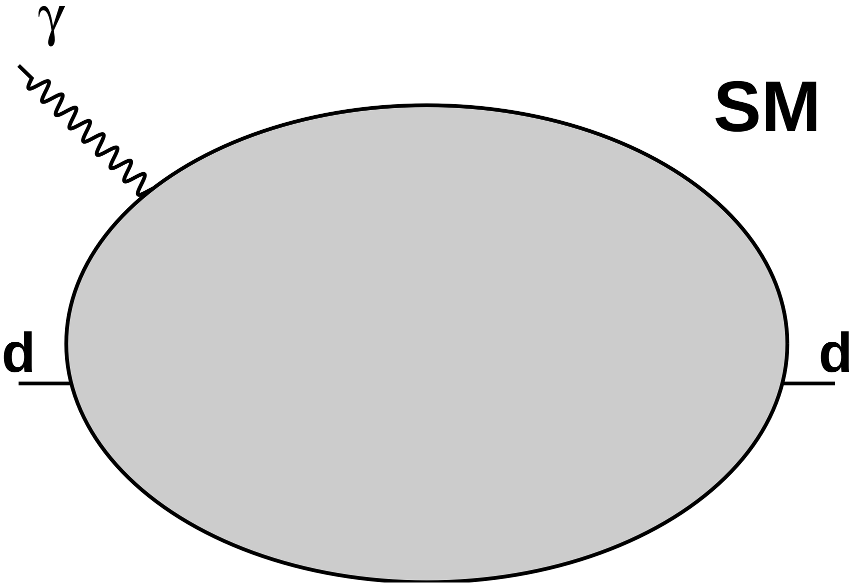
Extra Slides

Axion Searches at storage rings



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

EDM in SM and SUSY



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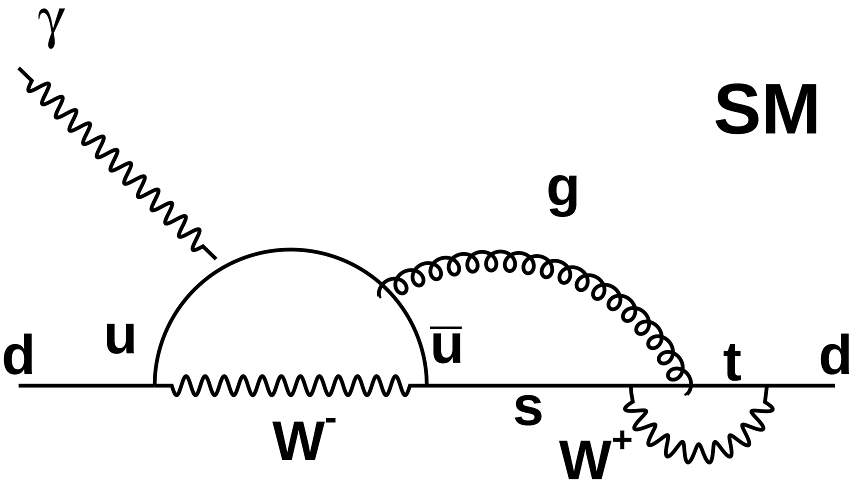

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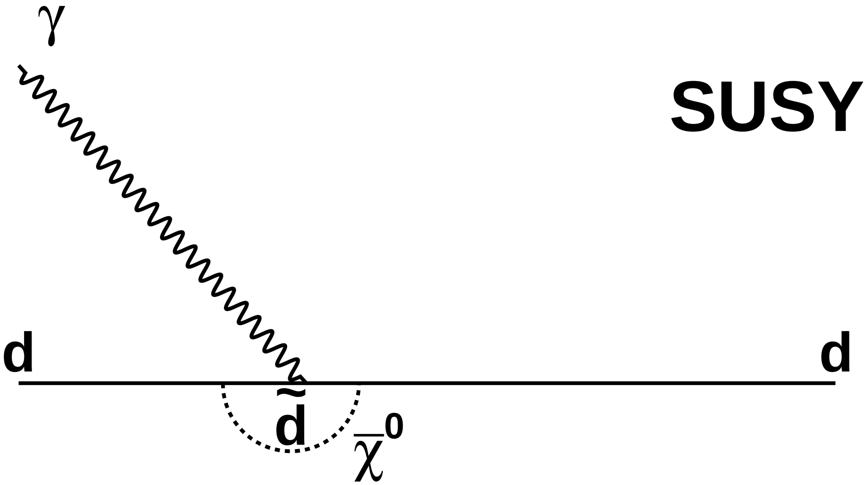
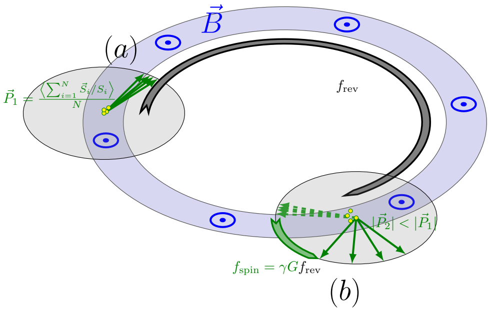
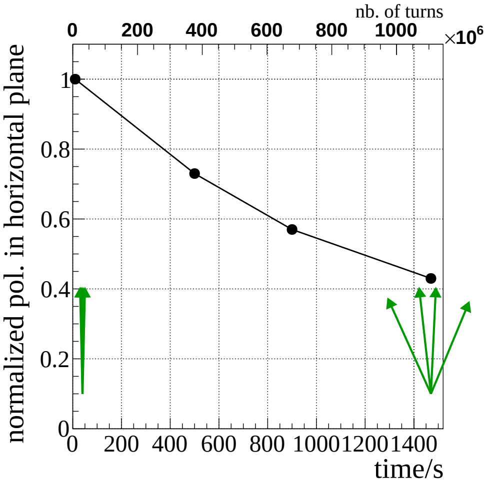


Long Spin Coherence Time (SCT)

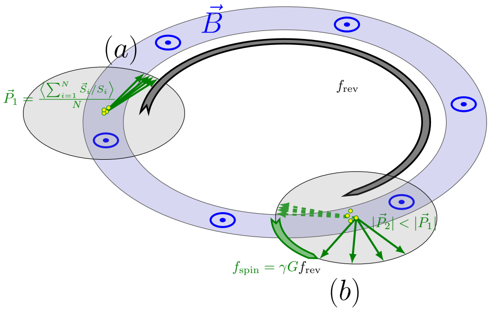
Long Spin Coherence time $>$ 1000 s reached

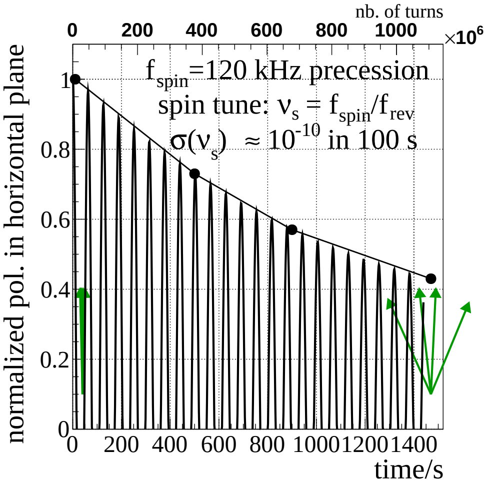




Long Spin Coherence Time (SCT)

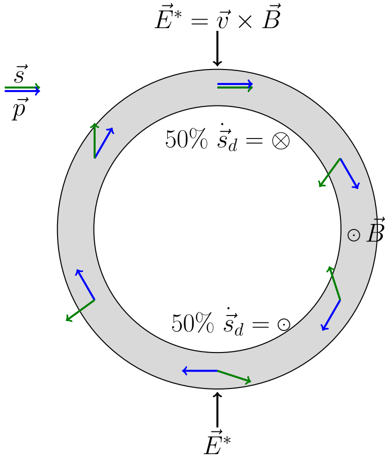
Long Spin Coherence time > 1000 s reached





Principle of EDM measurement at magnetic storage ring

Problem:
Due to precession caused by magnetic moment, 50% of time longitudinal polarization component is || to momentum, 50% of the time it is anti-||.



E^* field in the particle rest frame tilts spin due to EDM up and down $\Rightarrow$ **no net EDM effect**

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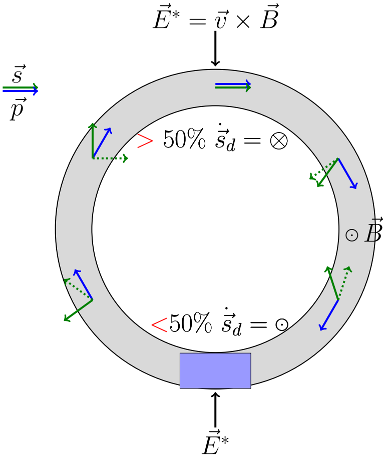
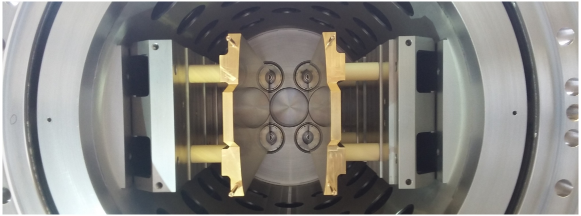
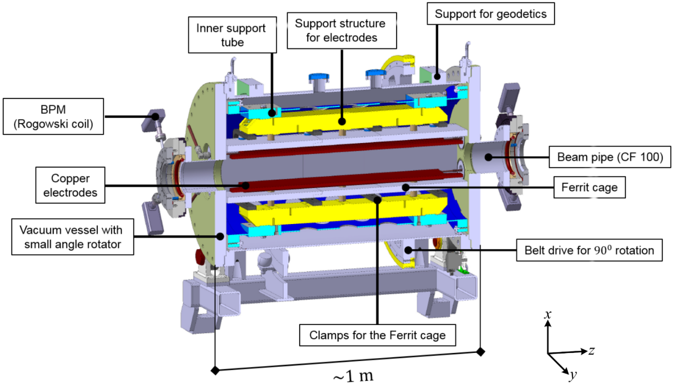


E^* field in the particle rest frame tilts spin due to EDM up and down $\Rightarrow$ **no net EDM effect**

Use resonant "magic Wien-Filter" in ring ($\vec{E}_W + \vec{v} \times \vec{B}_W = 0$):
$E^*_W = 0 \rightarrow$ part. trajectory is not affected but
$B^*_W \neq 0 \rightarrow$ mag. mom. is influenced
$\Rightarrow$ **net EDM effect can be observed!**

Wien filter





- field: $2.7 \cdot 10^{-2}$Tmm for 1kW input power
- frequency range: 100 kHz-2MHz