Towards a Storage Ring Electric Dipole Moment Measurement

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on behalf of the JEDI & CPEDM collaboration

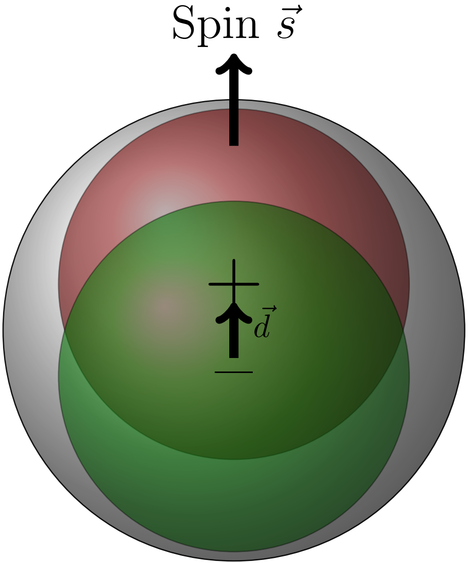
Aachen, DPG meeting, March 2019

Outline

- Introduction & Motivation
  What are EDMs?, What do we know about EDMs?,
  Why are EDMs interesting?
- Experimental Methods
  How to measure **charged** particle EDMs?
- Strategy towards a storage ring EDM measurement

Introduction & Motivation

Electric Dipole Moments (EDM)

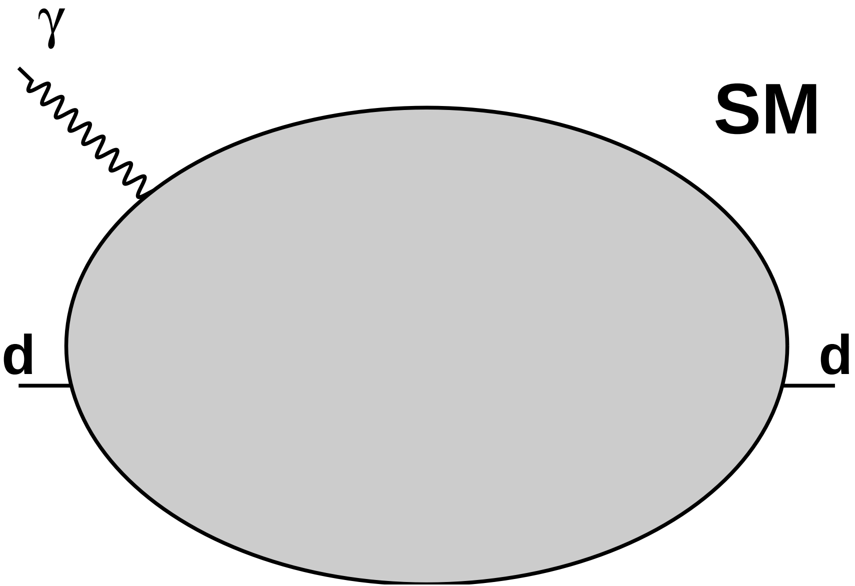


- permanent separation of positive and negative charge
- fundamental property of particles (like magnetic moment, mass, charge)
- existence of EDM only possible via violation of time reversal $\mathcal{T} \stackrel{\mathcal{CPT}}{=} \mathcal{CP}$ and parity $\mathcal{P}$ symmetry
- close connection to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

$\mathcal{CP}-$Violation & connection to EDMs

Standard Model	
Weak interaction	
CKM matrix	$\rightarrow$ unobservably small EDMs
Strong interaction	
θ_{QCD}	$\rightarrow$ best limit from neutron EDM
beyond Standard Model	
e.g. SUSY	$\rightarrow$ accessible by EDM measurements

EDM in SM and SUSY



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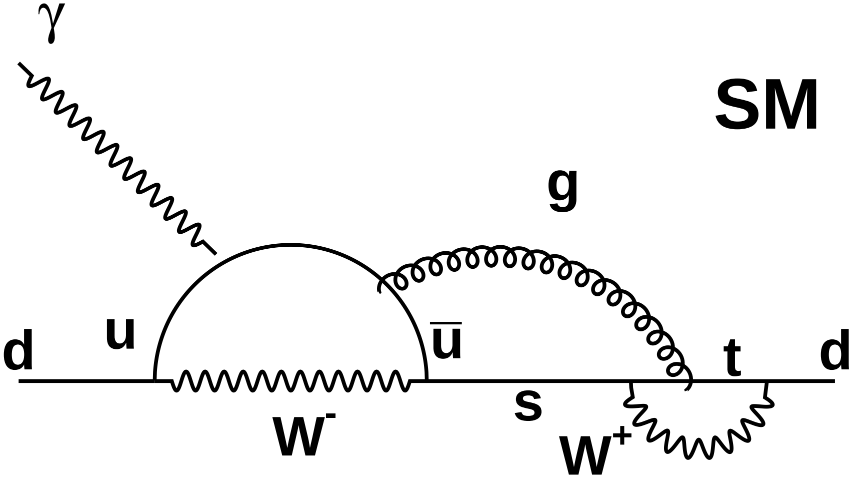

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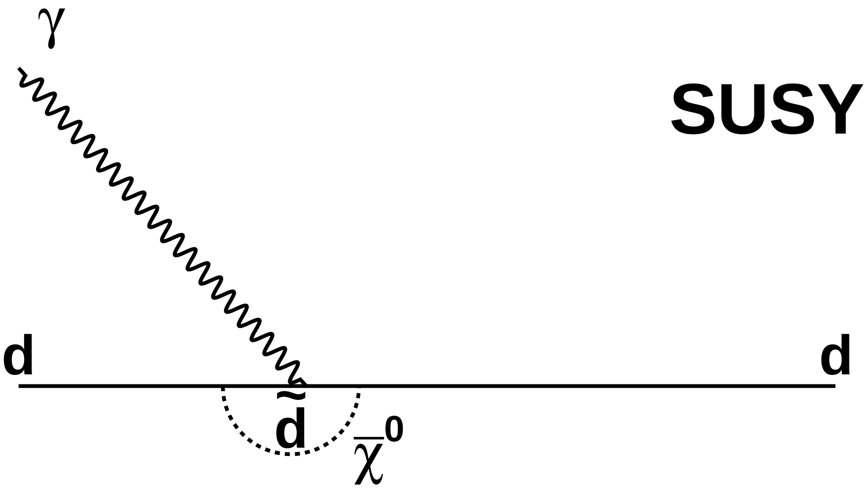
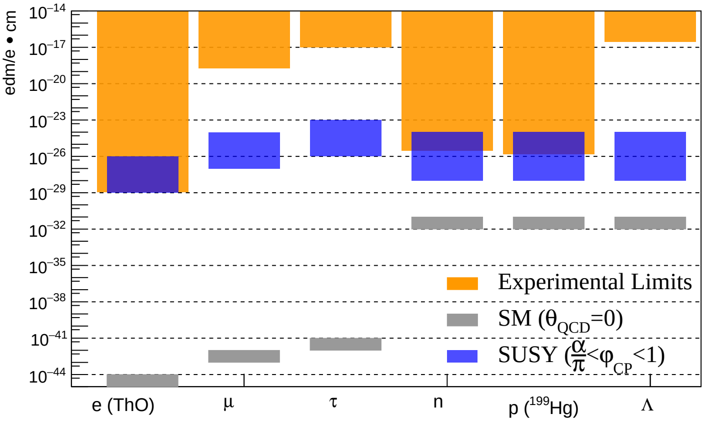


EDM: Current Upper Limits



storage rings: EDMs of **charged** hadrons: p, d, ^{3}He

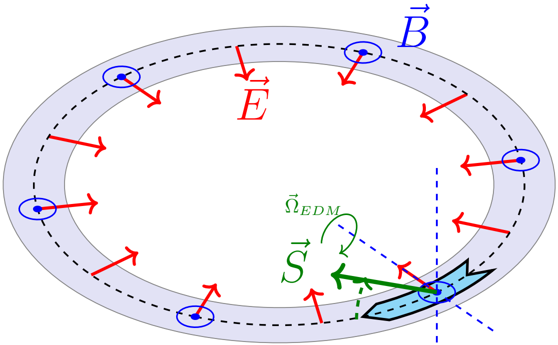
Experimental Method

Experimental Method: Generic Idea

For **all** EDM experiments (neutron, proton, atoms, . . .):

Interaction of $\vec{d}$ with electric field $\vec{E}$

For charged particles: apply electric field in a storage ring:



$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} \propto d\vec{E} \times \vec{s}$$

In general:

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\Omega} \times \vec{s}$$

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

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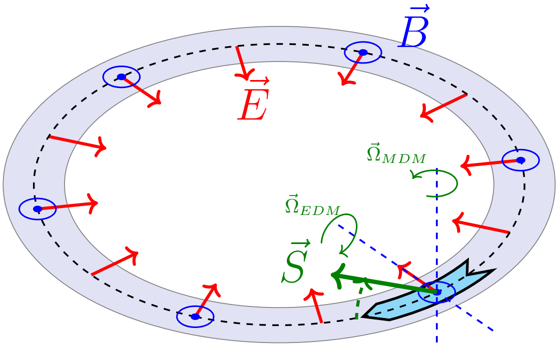

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Spin Precession: Thomas-BMT Equation

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

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

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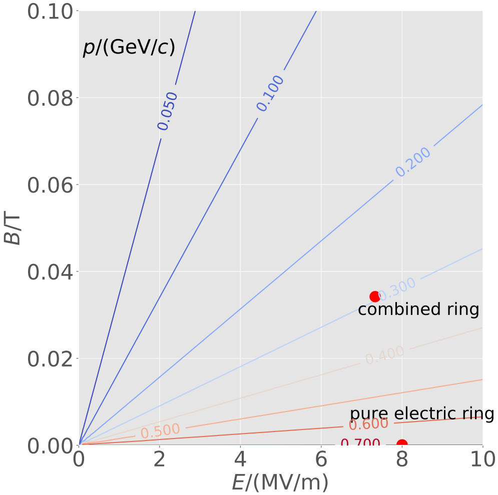
achievable with pure electric field if $G = \frac{1}{\gamma^2 - 1}$, works only for $G > 0$, e.g. proton

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

Momentum and ring radius for proton in frozen spin condition



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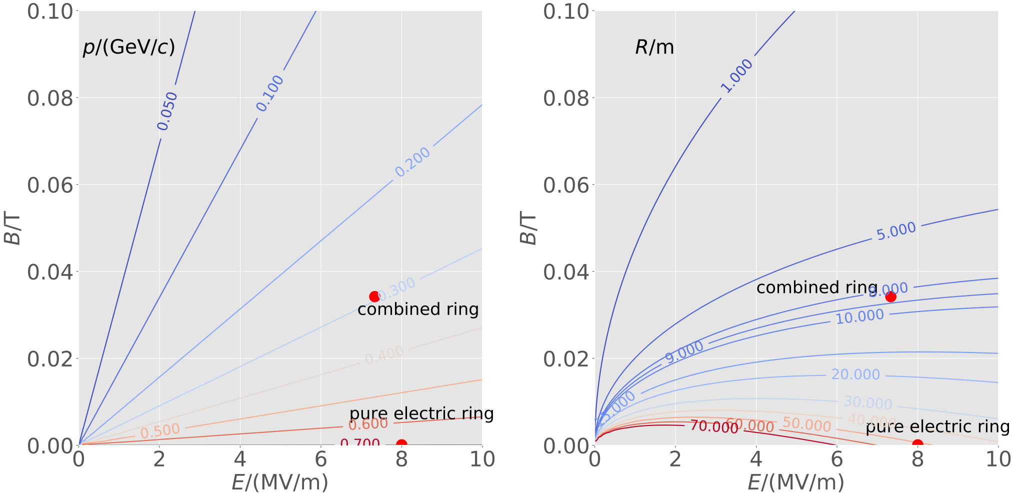


Different Options

	☺	☹
1.) pure electric ring	no $\vec{B}$ field needed, $\circlearrowleft$, $\circlearrowright$ beams simultaneously	works only for particles with $G > 0$ (e.g. p)
2.) combined ring	works for p, d, ^{3}He, smaller ring radius	both $\vec{E}$ and $\vec{B}$ B field reversal for $\circlearrowleft$, $\circlearrowright$ required
3.) pure magnetic ring	existing (upgraded) COSY ring can be used, shorter time scale	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	$\tau = 1000\,\text{s}$
electric fields	$E = 8\,\text{MV/m}$
polarimeter analyzing power	$A = 0.6$
polarimeter efficiency	$f = 0.005$

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

challenge: get σ_{sys} to the same level

Systematic Sensitivity

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

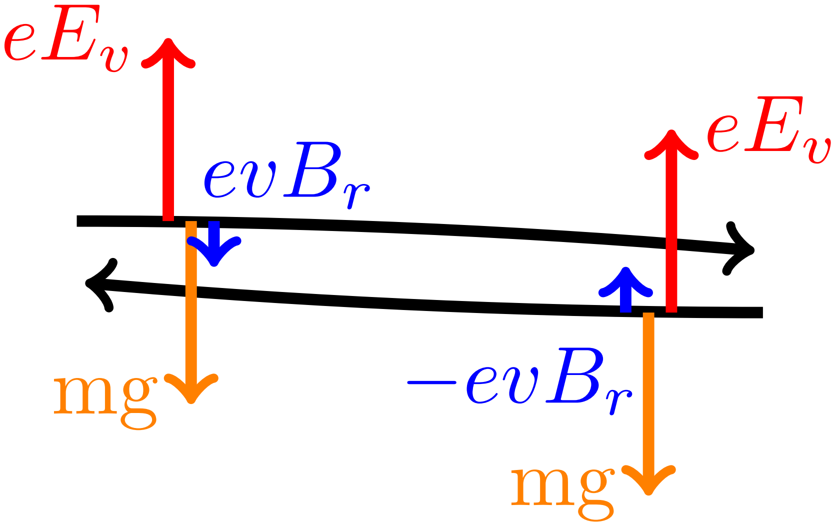
- radial B-field of $B_r = 10^{-17}\,\mathrm{T}$:
  $\Omega_{B_r} = \frac{eGB_r}{m} = 1.7 \cdot 10^{-9}\,\mathrm{s}^{-1}$
- geometric Phases (non-commutation of rotations), $B_{\mathrm{long}}, B_{\mathrm{vert}} \approx 1\,\mathrm{nT}$
  $\Omega_{\mathrm{GP}} = \left(\frac{eGB}{16m}\right)^2 \frac{1}{f_{\mathrm{rev}}}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

Remedy:

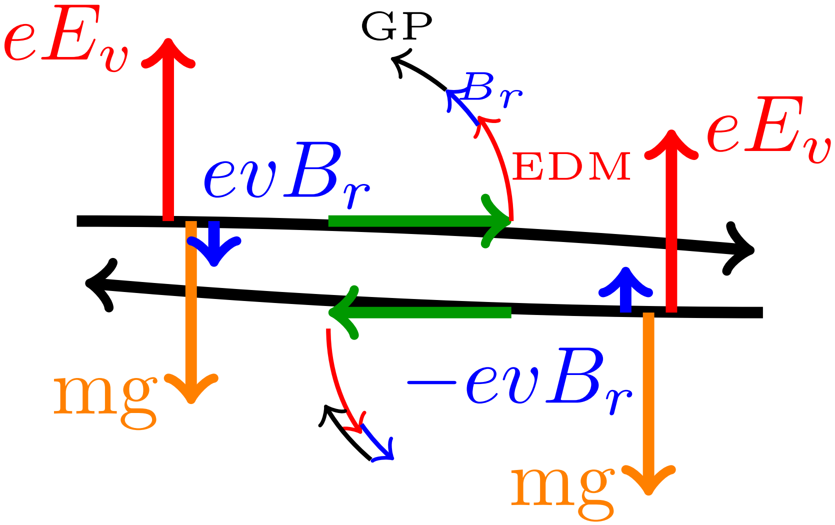
$$\begin{aligned} \circlearrowright:\quad \Omega_{\mathrm{CW}} &= \Omega_{\mathrm{EDM}} + \Omega_{\mathrm{GP}} + \Omega_{B_r}\,, \\ \circlearrowleft:\quad \Omega_{\mathrm{CCW}} &= \Omega_{\mathrm{EDM}} - \Omega_{\mathrm{GP}} + \Omega_{B_r}\,. \end{aligned}$$

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

Systematics



Systematics



Systematics

Gravity:

$$\Omega_{\mathrm{grav}} = \frac{2\gamma + 1}{\gamma + 1} \frac{\beta g}{c} = 3 \cdot 10^{-8}\,\mathrm{s}^{-1}$$

$g = 9.81\mathrm{m}/\mathrm{s}^2$
second effect: vertival electric (E_V) and radial magnetic (B_r) field needed to counteract force due to gravity $\left(F_{\mathrm{grav}} = \frac{2\gamma^2 - 1}{\gamma} mg\right)$

Conclusion:

Statistically one can reach sensitivity of $\approx 10^{-29}\,e\,\mathrm{cm}$, many systematic effects can be controlled using ↺ and ↻ beams, needs further investigation

$\rightarrow$ **staged approach**

Towards a storage ring EDM measurement

Staged approach

Stage 1

precursor experiment

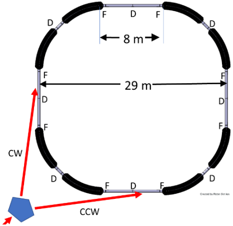
at COSY (FZ Jülich)

- magnetic storage ring

now

Stage 2

prototype ring

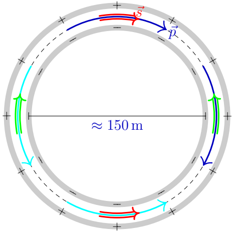


- initially electrostatic storage ring
- simultaneous ↻ and ↺ beams

5 years

Stage 3

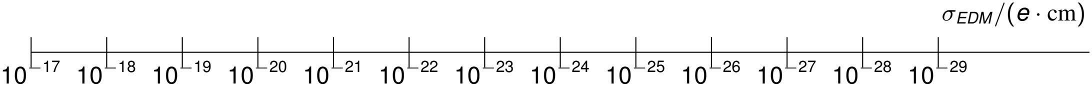
dedicated storage ring



- magic momentum

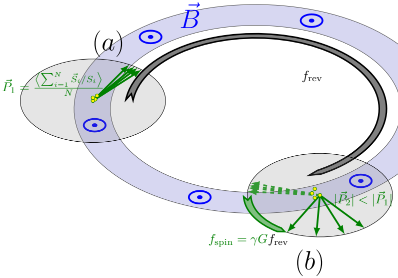
(701 MeV/c)

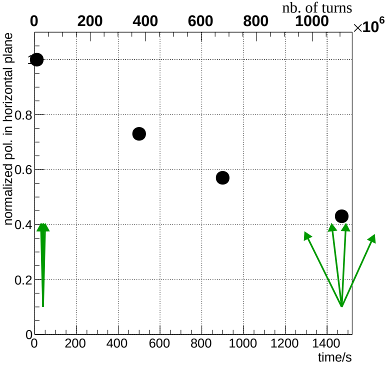
10 years



Stage 1: Precursor Experiment

- Ongoing at COSY/ Forschungszentrum Jülich
- Achievements:
  - Long Spin Coherence time > 1000 s ✓



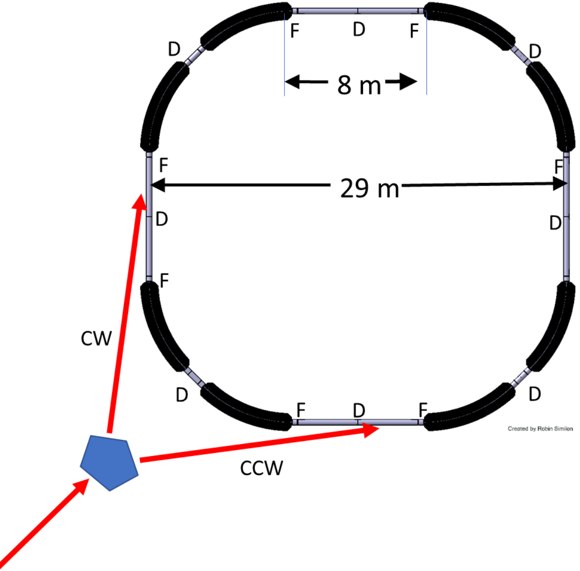


  - measurement and manipulation and polarisation vector ✓
- First deuteron EDM measurement underway → V. Shmakova

Step 2: Prototype Ring

- operate electrostatic ring
- store $10^9 - 10^{10}$ particles for 1000 s
- simultaneous $\circlearrowright$ and $\circlearrowleft$ 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

Ring Lattice & Bending Element



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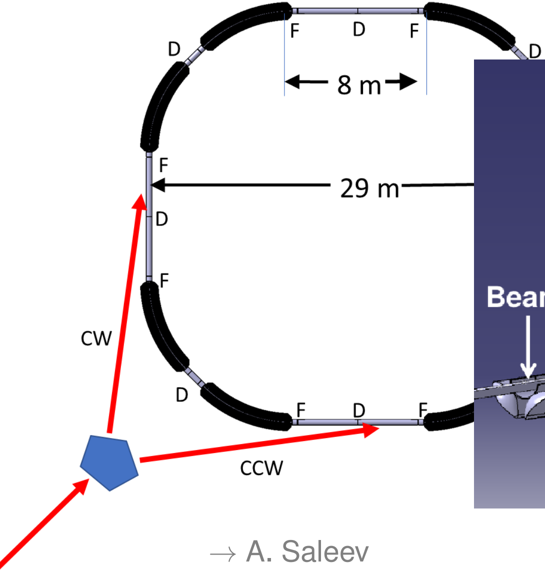
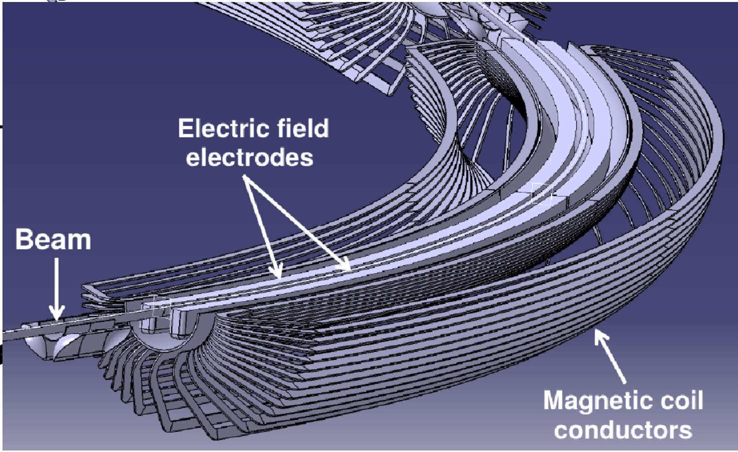
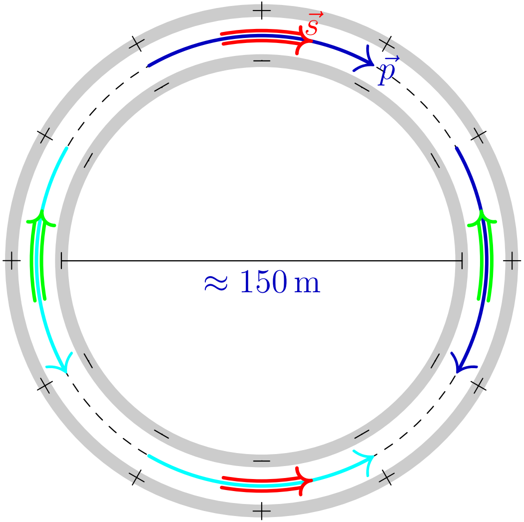




→ A. Saleev

Step 3: Dedicated Ring

- pure electric ring:
  frozen spin ($p = 701$ MeV/c E_{kin}=233 MeV):



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
- staged approach:
  precursor at COSY $\rightarrow$ prototype (100 m) $\rightarrow$ dedicated ring (500 m)

Document submitted to ESPP in Dec. 2018 (arXiv:1812.08535, CERN yellow report CERN-PBC-REPORT-2019-002 in preparation)

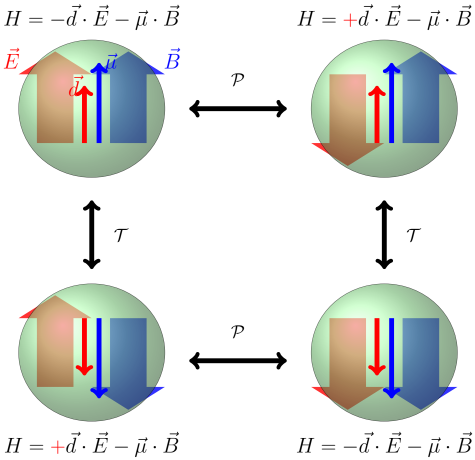
erc European Research Council

Spare

$\mathcal{T}$ and $\mathcal{P}$ violation of EDM

$\vec{d}$: EDM
$\vec{\mu}$: magnetic moment (MDM)
both || to spin $\vec{s}$

	H	$=$	$-\mu\frac{\vec{s}}{s}\cdot\vec{B}-d\frac{\vec{s}}{s}\cdot\vec{E}$
$\mathcal{T}$:	H	$=$	$-\mu\frac{\vec{s}}{s}\cdot\vec{B}+d\frac{\vec{s}}{s}\cdot\vec{E}$
$\mathcal{P}$:	H	$=$	$-\mu\frac{\vec{s}}{s}\cdot\vec{B}+d\frac{\vec{s}}{s}\cdot\vec{E}$



$\Rightarrow$ EDM measurement tests violation of fundamental symmetries $\mathcal{P}$ and $\mathcal{T}(\stackrel{\mathcal{CPT}}{=}\mathcal{CP})$

EDM activities around the world

Neutrons: (~ 200 ppl.)

- Beam EDM @ Bern
- LANL nEDM @ LANL
- nEDM @ PSI
- nEDM @ SNS
- PanEDM @ ILL
- PNPI/FTI/ILL @ ILL
- TUCAN @ TRIUMF

Storage rings: (~ 400 ppl.)

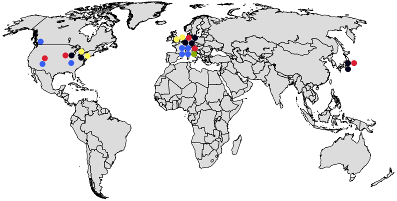
- CPEDM/JEDI
- muEDM @ PSI
- g-2 @ FNAL
- g-2 @ JPARC

High Energy Physics: (~ 20 ppl.)

- Λ-baryon @ LHCb

Atoms: (~ 60 ppl.)

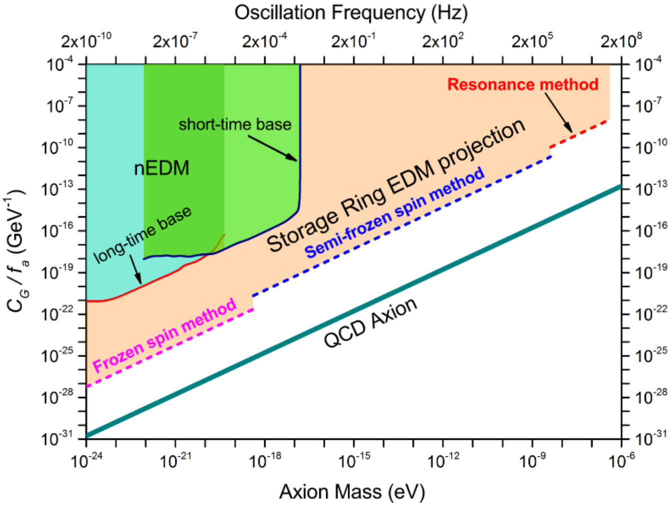
- Cs @ Penn State
- Fr @ Riken
- Hg @ Bonn
- Ra @ Argonne
- Xe @ Heidelberg
- Xe @ PTB
- Xe @ Riken



Molecules: (~ 55 ppl.)

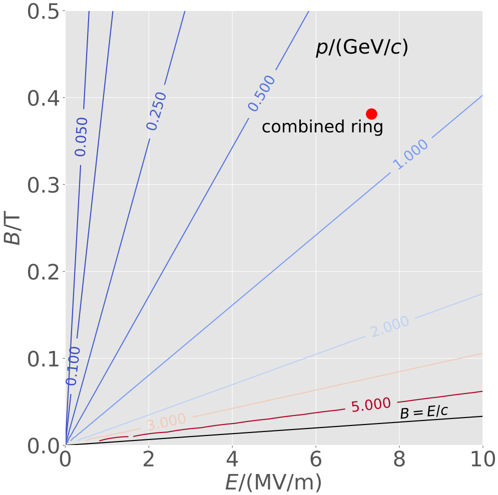
- BaF (EDM^3) @ Toronto
- BaF (NLeEDM) @ Groningen/Nikhef
- HfF+ @ JILA
- ThO (ACME) @ Yale
- YBF @ Imperial

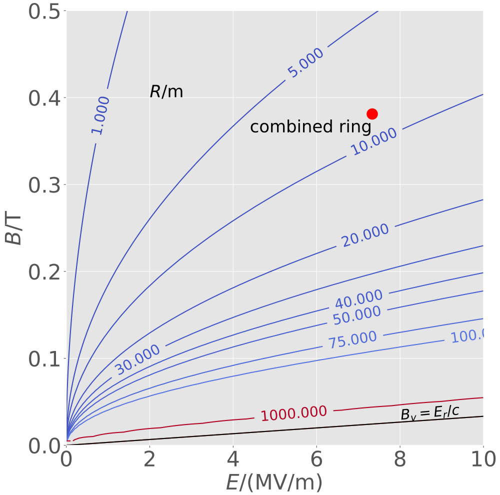
Axion Searches



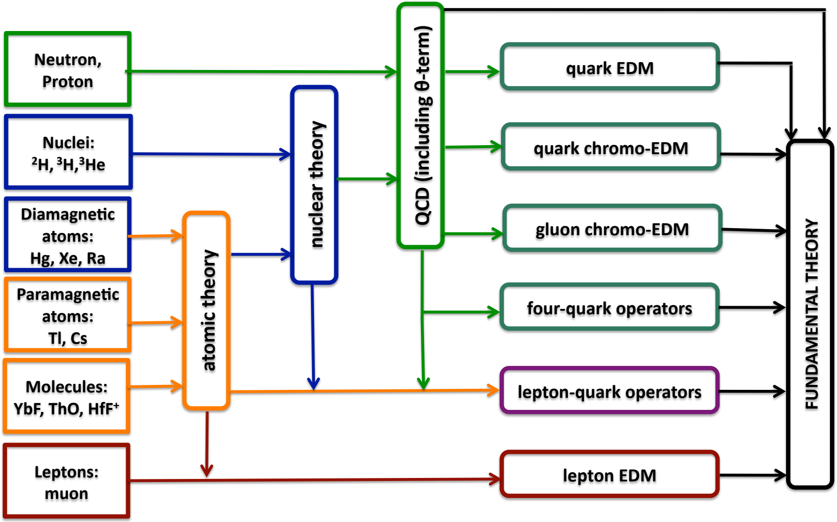
S. P. Chang, S. Haciomeroglu, O. Kim, S. Lee, S. Park and Y. K. Semertzidis, PoS PSTP **2017** (2018) 036 [arXiv:1710.05271 [hep-ex]].

Momentum and ring radius for deuteron in frozen spin condition





Why Charged Particle EDMs?



J. de Vries