Electric Dipole Moment Measurement at Storage Rings

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on behalf of the JEDI & CPEDM collaboration

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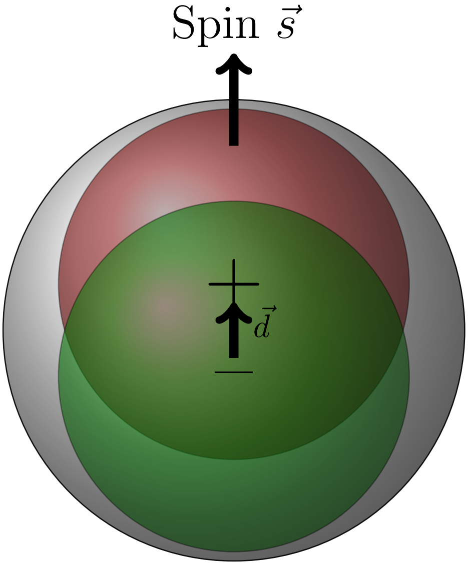
Outline

- Introduction & Motivation
  What are Electric Dipole Moments (EDMs)?, What do we know about EDMs?, Why are EDMs interesting?
- Experimental Methods
  How to measure **charged** particle EDMs?
- First Test Measurements (also on axion searches)

Introduction & Motivation

Electric Dipole Moments (EDM)

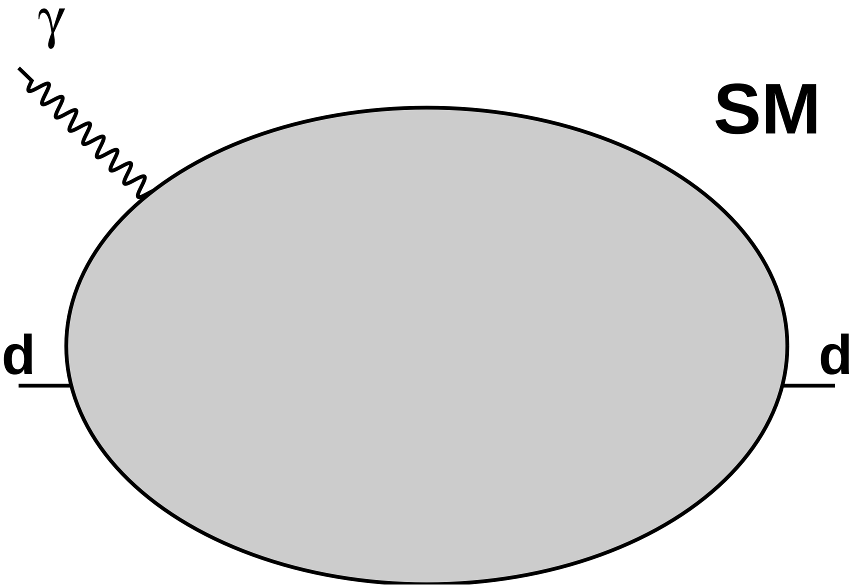


- permanent separation of positive and negative charge
- fundamental property of particles (like magnetic moment, mass, charge)
- existence of EDM only possible via violation of time reversal $\mathcal{T} \overset{\mathcal{CPT}}{=} \mathcal{CP}$ and parity $\mathcal{P}$ symmetry
- has nothing to do with electric dipole moments observed in some molecules (e.g. water molecule)
- close connection to “matter-antimatter” asymmetry
- **axion/ALP** field leads to oscillating EDM

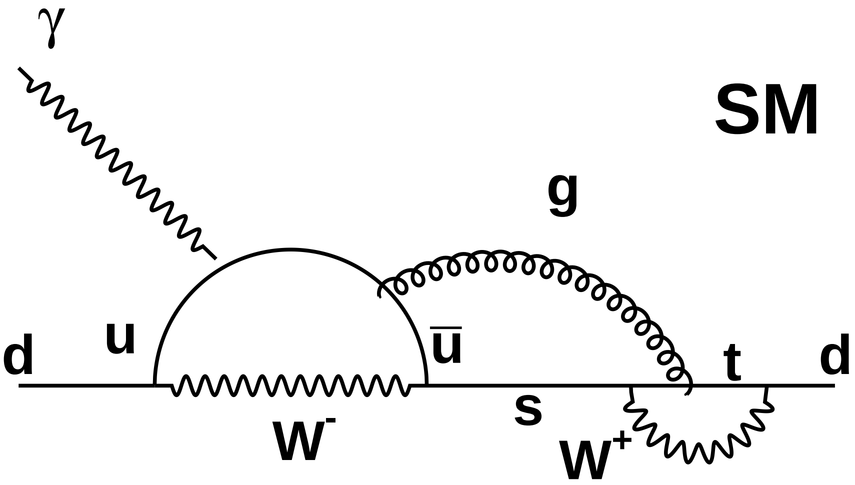
$\mathcal{CP}-$Violation & connection to EDMs

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

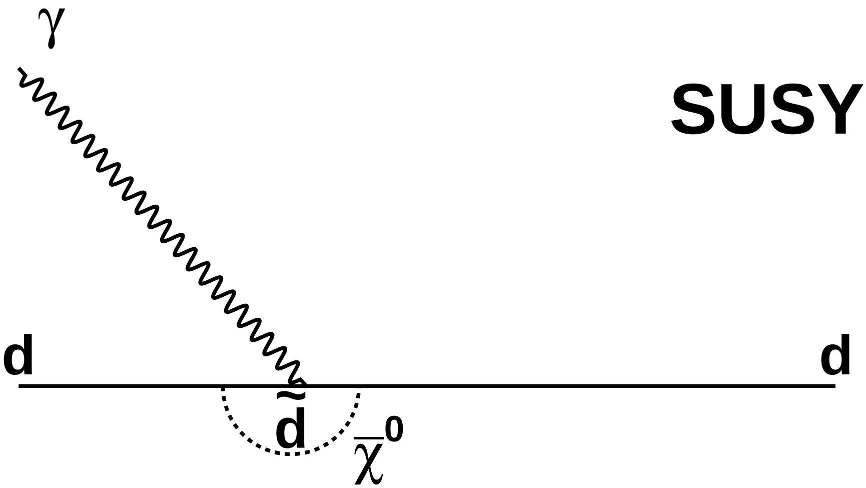
EDM in SM and SUSY



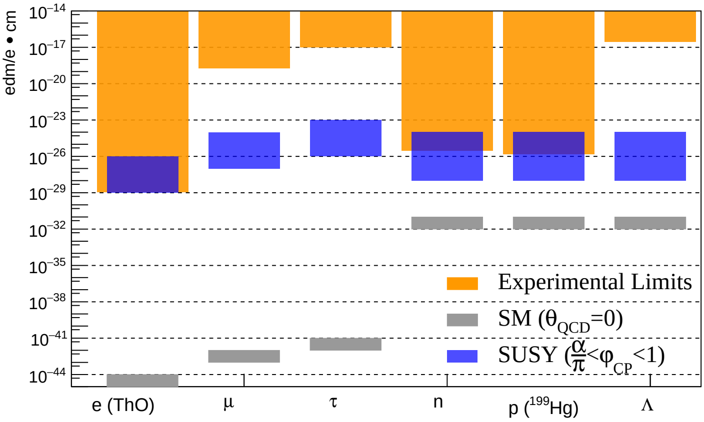
EDM in SM and SUSY



EDM in SM and SUSY



EDM: Current Upper Limits



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

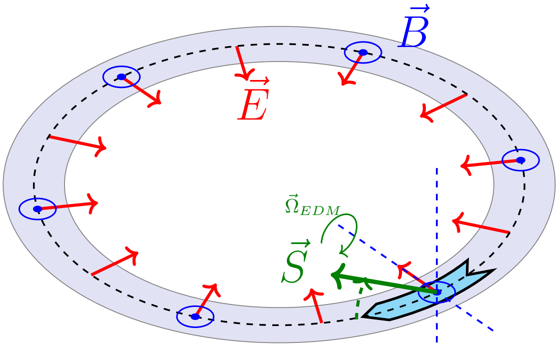
Experimental Method

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:



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

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

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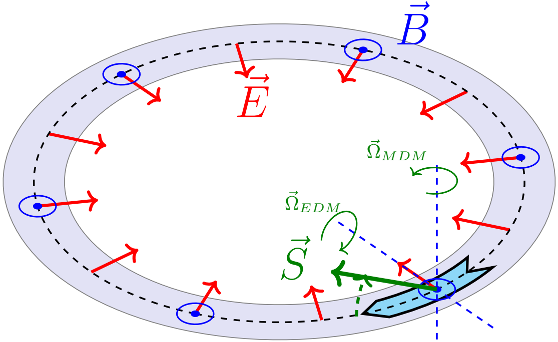


$$\frac{d\vec{s}}{dt} \propto d\vec{E}^* \times \vec{s}$$

In general:

$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s}$$

build-up of vertical polarization $s_\perp \propto d$, if $\vec{s}_{\mathrm{horz}} || \vec{p}$ (**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 $d = 10^{-29}e\mathrm{cm}$, $G \approx 1.79$ for protons

axion leads to oscillating EDM: $\eta = \eta_0 + \eta_1 \sin(m_a t + \varphi_a)$

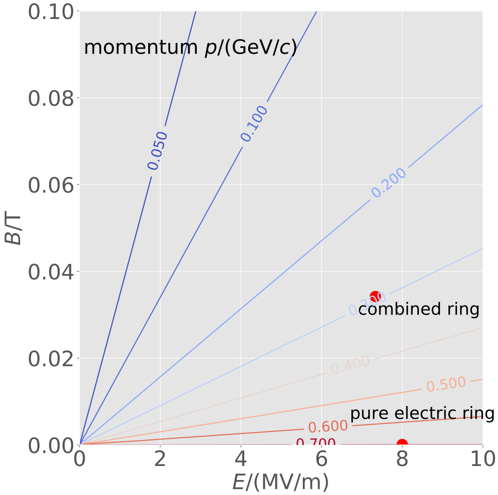
Spin Precession: Thomas-BMT Equation

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

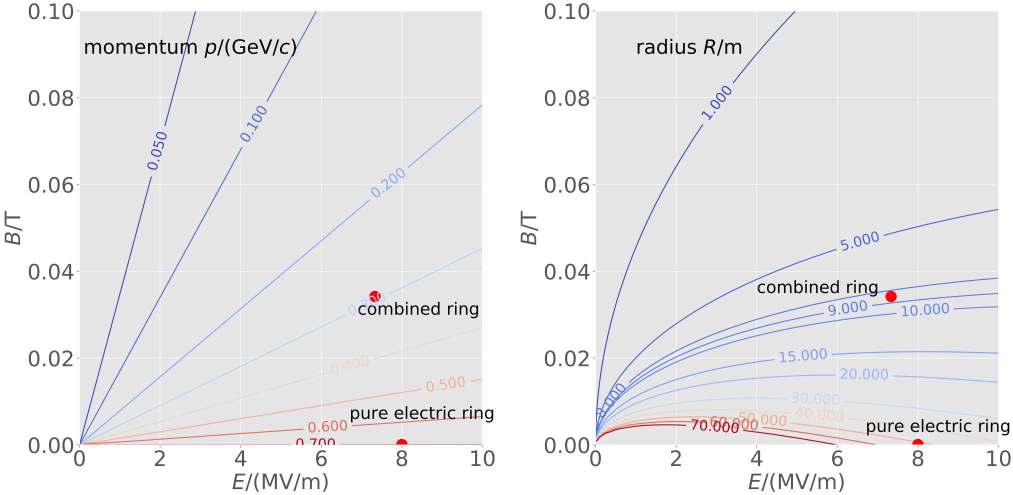
achievable with pure electric field if $G = \frac{1}{\gamma^2 - 1}$, works only for $G > 0$, e.g. proton

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

Momentum and ring radius for proton in frozen spin condition



Momentum and ring radius for proton in frozen spin condition



Different Options

time ↓

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

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

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	$f = 0.005$

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

challenge: get σ_{sys} to the same level

Systematic Sensitivity

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

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

Remedy:

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

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

Experimental Results

Test Measurements at COSY

COoler SYnchrotron COSY at Forschungszentrum Jülich provides (polarized) protons and deuterons with $p = 0.3 - 3.7\mathrm{GeV}/c$

$\Rightarrow$ **Ideal starting point for charged hadron EDM searches**

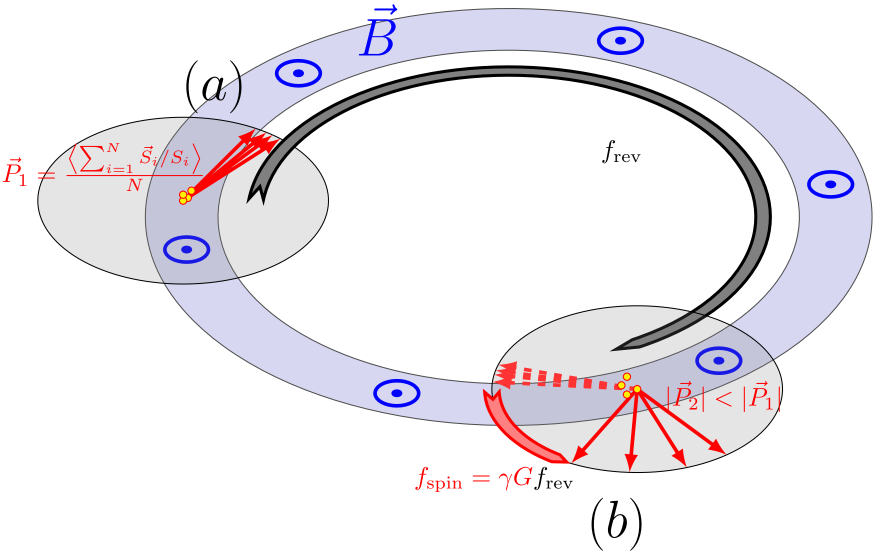
Recent achievements

1. **Spin coherence time:** $\tau > 1000$ s
   (PRL 117, 054801 (2016))
2. **Spin tune:** $\overline{\nu_s} = -0.16097\cdots \pm 10^{-10}$ in 100 s
   (PRL 115, 094801 (2015))
3. **Spin feedback:** polarisation vector kept within 12 degrees
   (PRL 119 (2017) no.1, 014801)

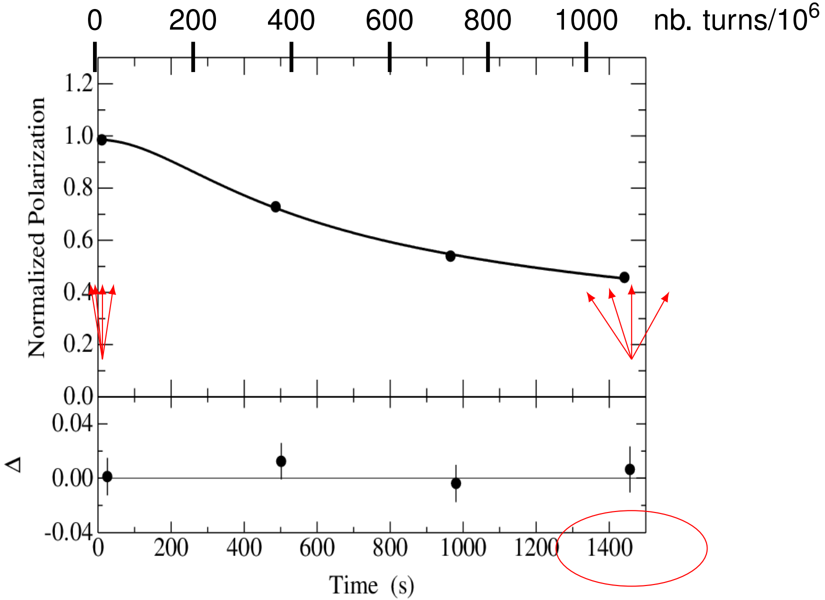
(all data shown were taken with deuterons, with $p \approx 1$ GeV/c)

① mandatory to reach statistical sensitivity
② & ③ shows that we can measure and manipulate polarisation vector with high accuracy

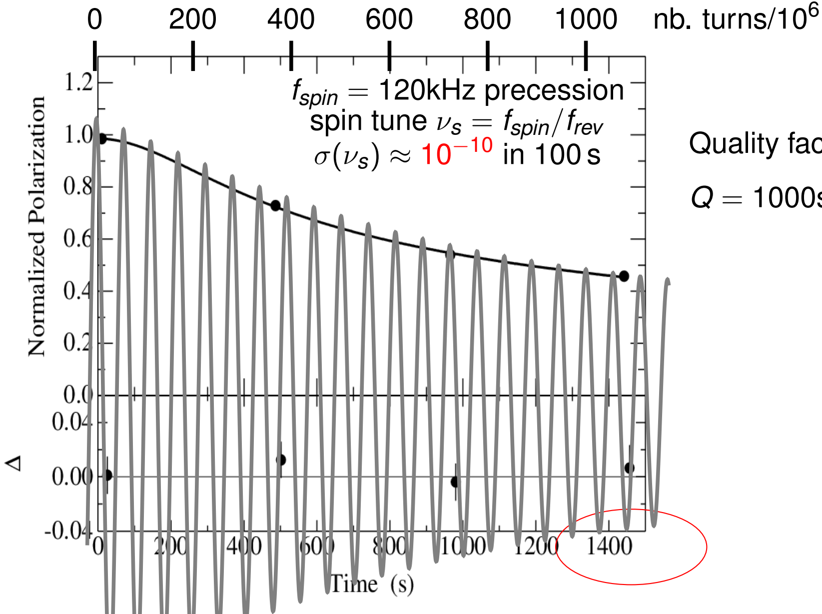
Spin Precession



Spin Coherence Time (SCT)



Spin Coherence Time (SCT)

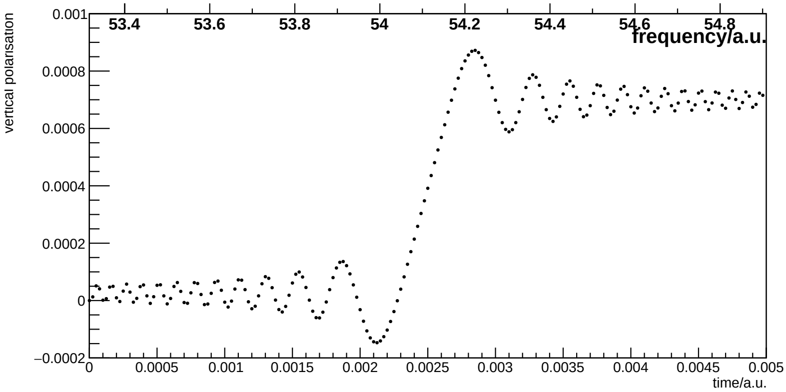


Quality factor:

$$Q = 1000\text{s}\, 2\pi\, 120\text{kHz} \approx 10^9$$

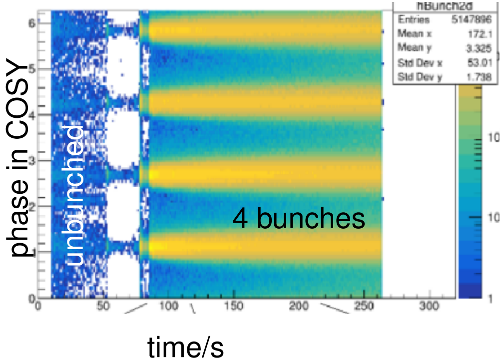
Axion Search at COSY

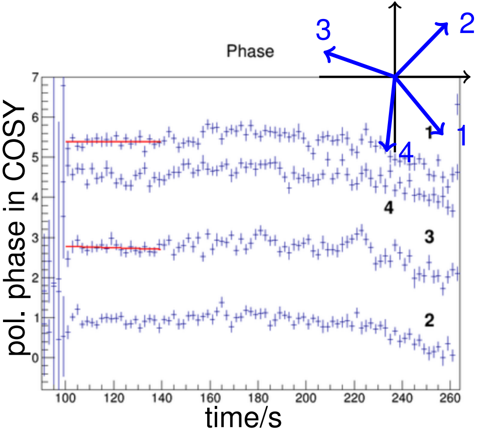
- if axion frequency (mass) equals $f_{spin} = \gamma G f_{rev}$
  $\Rightarrow$ resonance, vertical polarisation build-up observed



Axion Search at COSY

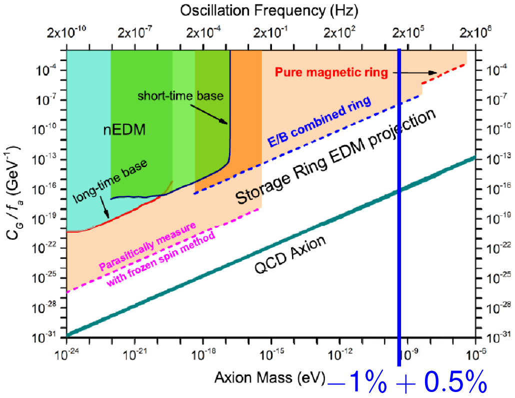
- problem: $d \propto \eta_0 + \eta_1 \sin(m_a t + \varphi_a)$, φ_a not known
  resonance only if phase relation between beam pol. and axion field “correct”
  solution: store at least two bunches with orthogonal polarisation





Axion Search at COSY

- test measurements performed with deuterons $p = 0.970\text{GeV}/c$
  $f_{spin} \approx \gamma G f_{rev} \approx$ 120kHz frequency range -1% to $+0.5\%$ around 120 kHz



S. P. Chang, S. Haciomeroglu, O. Kim, S. Lee, S. Park and Y. K. Semertzidis, Phys. Rev. D **99** (2019) no.8, 083002

- axion measurement much less sensitive to systematic effect than permanent EDM, (spin resonance would act the same way on every bunch)

Summary

- EDMs are unique probe to search for new CP-violating interactions
- axions/ALP lead to oscillating EDMs
- **charged** particle EDMs can be measured in storage rings
- proof of principle measurement performed at COSY/Forschungszentrum Jülich

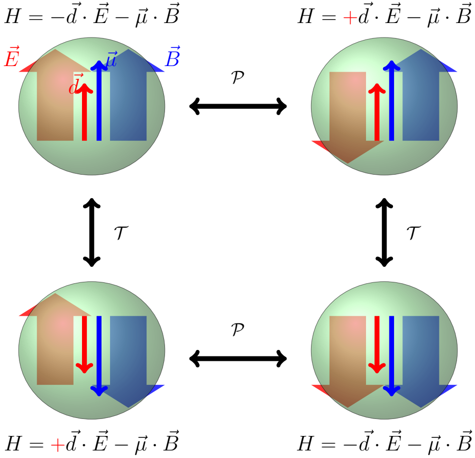
European Research Council

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 $\mathcal{T}(\overset{\mathcal{CPT}}{=}\mathcal{CP})$

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.)

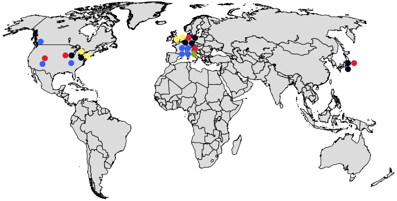
- CPEDM/JEDI
- muEDM @ PSI
- g-2 @ FNAL
- g-2 @ JPARC

High Energy Physics: (~ 20 ppl.)

- Λ-baryon @ LHCb

Atoms: (~ 60 ppl.)

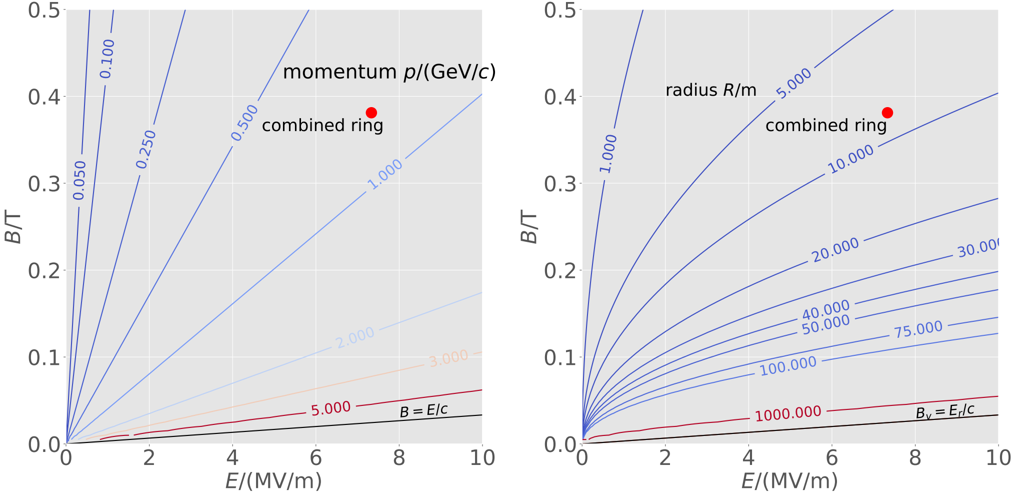
- Cs @ Penn State
- Fr @ Riken
- Hg @ Bonn
- Ra @ Argonne
- Xe @ Heidelberg
- Xe @ PTB
- Xe @ Riken



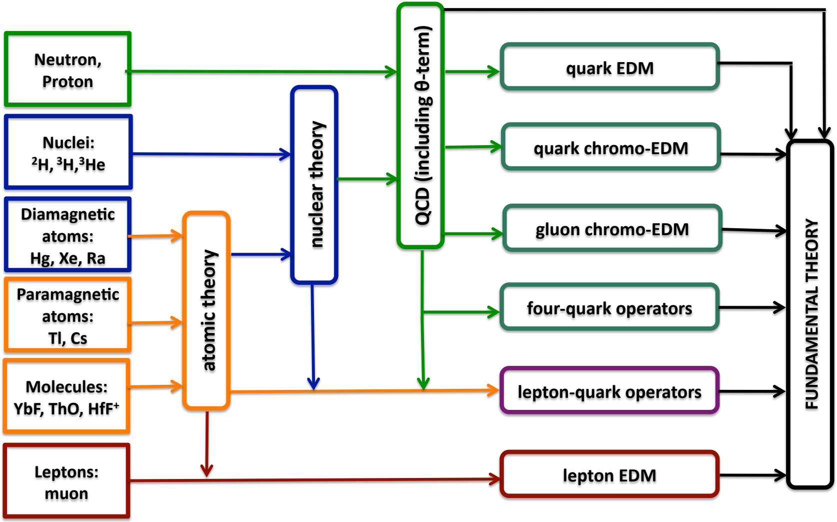
Molecules: (~ 55 ppl.)

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

Momentum and ring radius for deuteron in frozen spin condition



Why Charged Particle EDMs?



J. de Vries