Precision experiments: Search for static Electric Dipole Moments

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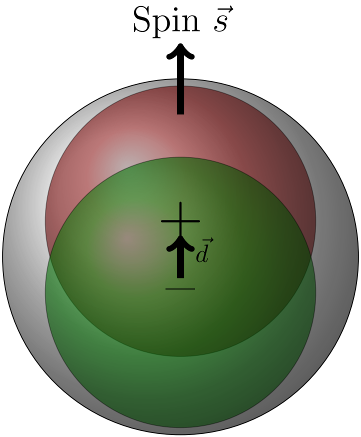
RWTH Aachen & FZ Jülich

Mainz, Future of Non-Collider-Physics, April 2017

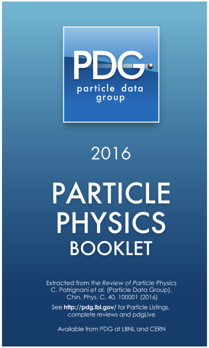
Outline

- Motivation for Electric Dipole Moment (EDM) Measurements
- **Charged** particle EDM measurements
  Principle & recent progress
- Activities around the world

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 $\mathcal{T}$ and parity $\mathcal{P}$ symmetry
- has nothing do due with electric dipole moments observed in some molecules (e.g. water molecule)



$\boxed{p}$

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

Mass $m = 1.00727646688 \pm 0.00000000009$ u

Mass $m = 938.272081 \pm 0.000006$ MeV [a]

$|m_p - m_{\overline{p}}|/m_p < 7 \times 10^{-10}$, CL = 90% [b]

$|\frac{q_{\overline{p}}}{m_{\overline{p}}}|/(\frac{q_p}{m_p}) = 0.99999999991 \pm 0.00000000009$

$|q_p + q_{\overline{p}}|/e < 7 \times 10^{-10}$, CL = 90% [b]

$|q_p + q_e|/e < 1 \times 10^{-21}$ [c]

Magnetic moment $\mu = 2.792847351 \pm 0.000000009\ \mu_N$

$(\mu_p + \mu_{\overline{p}}) / \mu_p = (0 \pm 5) \times 10^{-6}$

Electric dipole moment $d < 0.54 \times 10^{-23}$ 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 ± 0.00039 fm [d]

Charge radius, $e p$ CODATA value = 0.8751 ± 0.0061 fm [d]

Magnetic radius = 0.78 ± 0.04 fm [e]

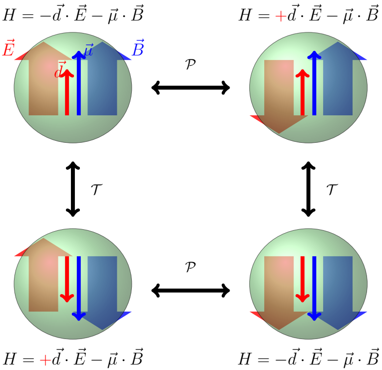
Mean life $\tau > 2.1 \times 10^{29}$ years, CL = 90% [f] ($p \to$ invisible mode)

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

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

$\vec{d}$: EDM
$\vec{\mu}$: magnetic moment
both || to spin

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

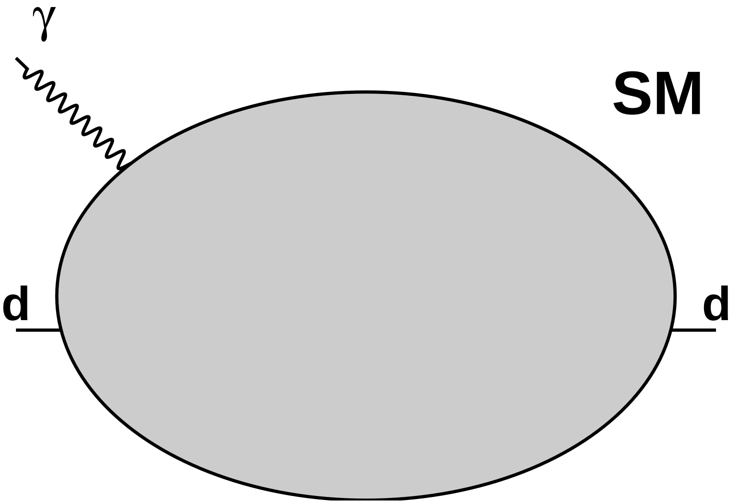


$\Rightarrow$ EDM measurement tests violation of fundamental symmetries $\mathcal{P}$ and $\mathcal{T}$($\stackrel{\mathcal{CPT}}{=}$ $\mathcal{CP}$)

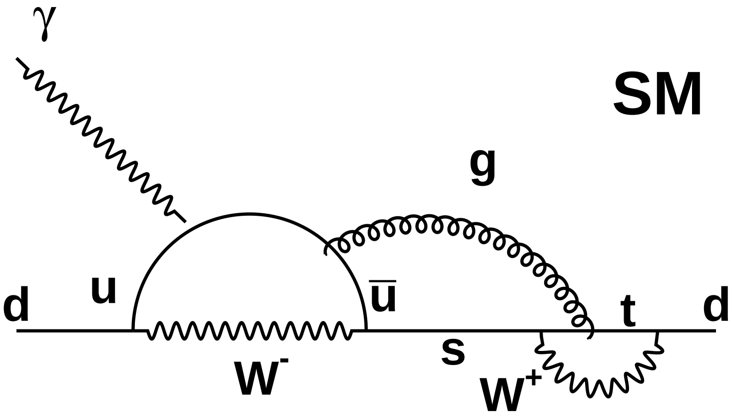
$\mathcal{CP}-$Violation & connection to EDMs

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

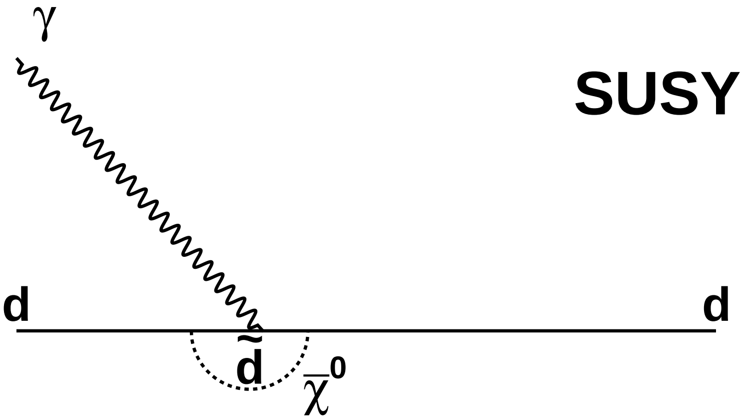
EDM in SM and SUSY



EDM in SM and SUSY



EDM in SM and SUSY



CP violation & Matter-Antimatter Asymmetry

Excess of matter in the universe:

	observed	SCM* prediction
$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$	$\mathbf{6 \times 10^{-10}}$	$\mathbf{10^{-18}}$

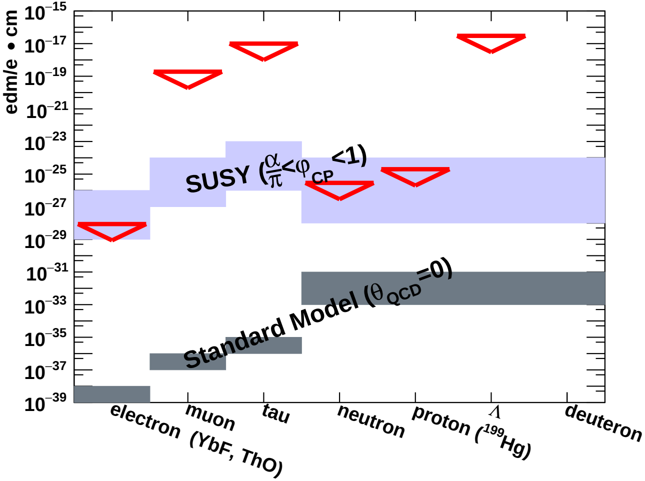
Sakharov (1967): $\mathcal{CP}$ violation needed for baryogenesis

⇒ New $\mathcal{CP}$ violating sources beyond SM needed to explain this discrepancy

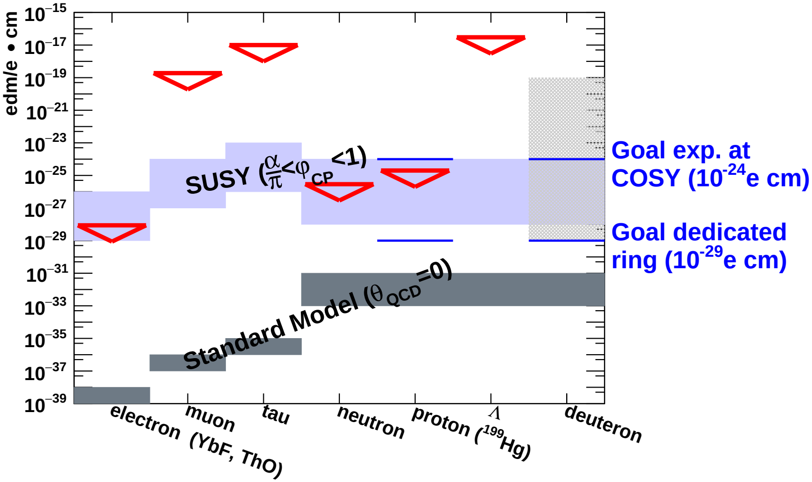
They could show up in EDMs of elementary particles

* SCM: Standard Cosmological Model

EDM: Current Upper Limits



EDM: Current Upper Limits



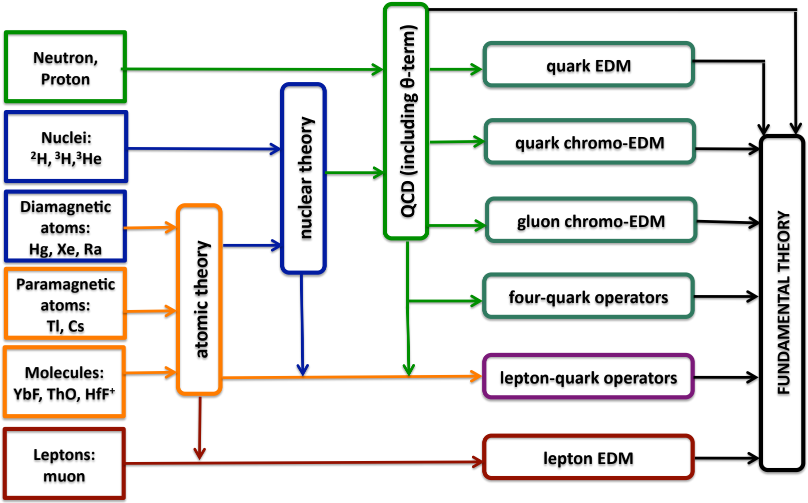
FZ Jülich: EDMs of **charged** hadrons: *p*, *d*, ^{3}He

Why Charged Particle EDMs?

- no direct measurements for charged hadrons exist
- potentially higher sensitivity (compared to neutrons):
  - longer life time,
  - more stored protons/deuterons
- complementary to neutron EDM:
  $d_d, d_p, d_n \Rightarrow$ access to θ_{QCD}

EDM of one particle alone not sufficient to identify $\mathcal{CP}-$violating source

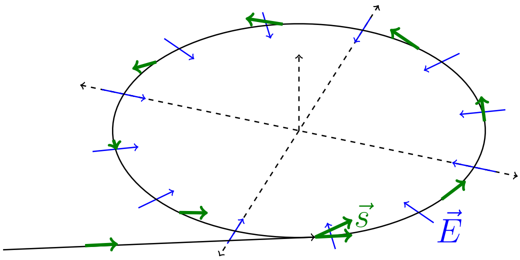
Sources of $\not{C}\not{P}$ Violation



J. de Vries

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/magnetic field in a storage ring:



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

In general:

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

build-up of vertical polarization $s_\perp \propto |d|$

Experimental Requirements

- high precision storage ring $\rightarrow$ **systematics** (alignment, stability, field homogeneity)
- high intensity beams ($N = 4 \cdot 10^{10}$ per fill)
- polarized hadron beams ($P = 0.8$)
- long spin coherence time ($\tau = 1000\,\mathrm{s}$),
- large electric fields ($E = 10\,\mathrm{MV/m}$)
- polarimetry (analyzing power $A = 0.6$, acc. $f = 0.005$)

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

challenge: get σ_{sys} to the same level

Test Measurements at COSY

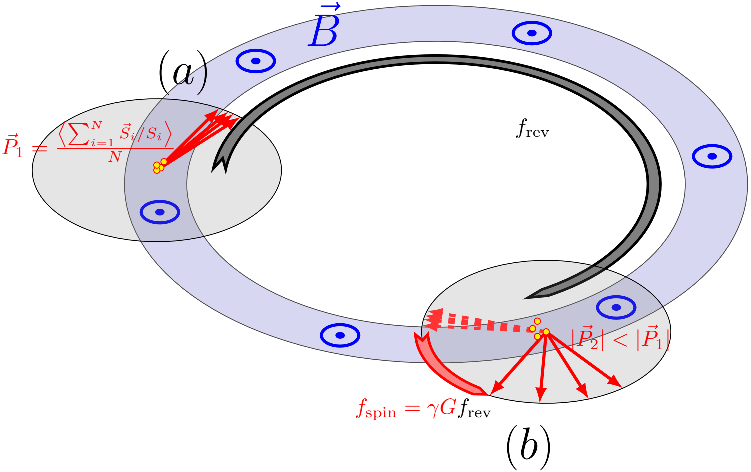
COSY provides (polarized) protons and deuterons with
$p = 0.3 - 3.7\mathrm{GeV}/c$
$\Rightarrow$ **Ideal starting point for charged hadron EDM searches**

Recent achievements

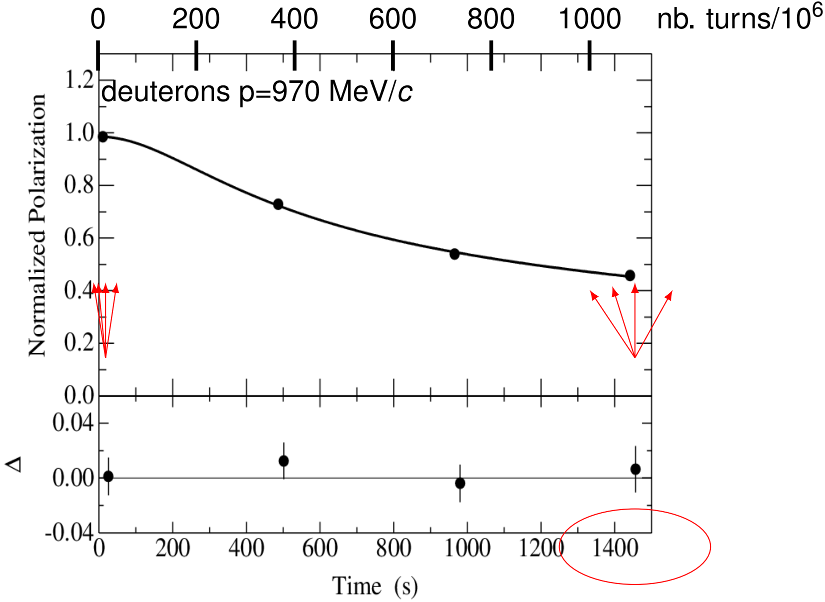
1. **Spin coherence time:** $\tau > 1000$ s
   (PRL 117, 054801 (2016))
2. **Spin tune:** $\overline{\nu_s} = -0.16097\cdots \pm 10^{-10}$ in 100 s
   (PRL 115, 094801 (2015))
3. **Spin feedback:** polarisation vector kept within 12 degrees
   (acc. for publication in PRL)

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

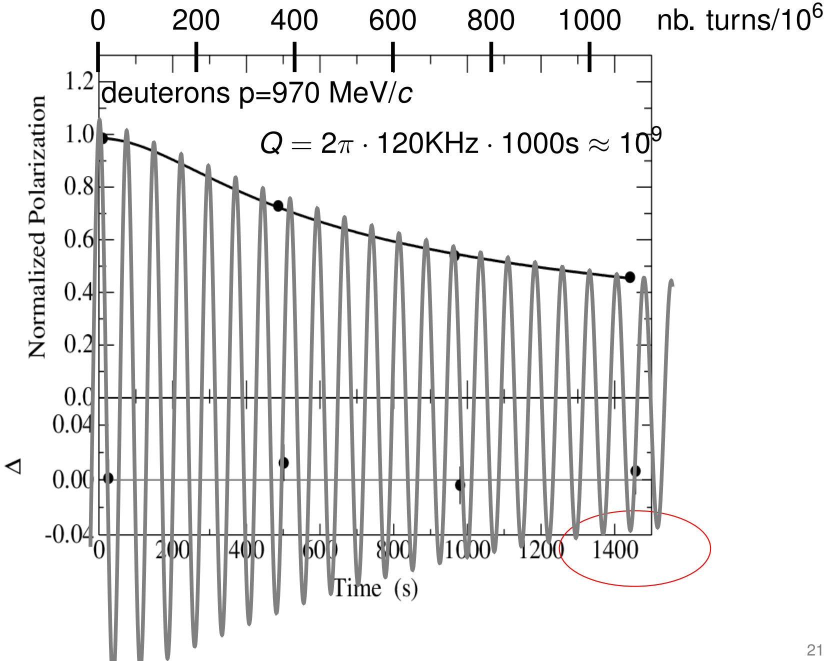
Spin Precession



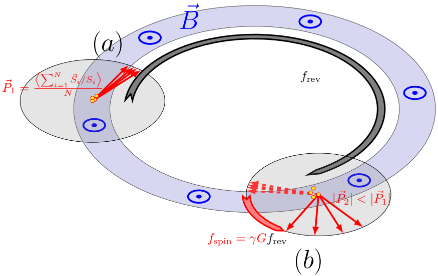
1.) Spin Coherence Time (SCT)

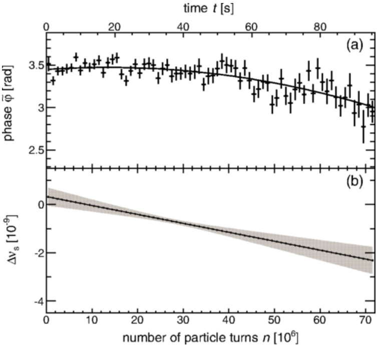


1.) Spin Coherence Time (SCT)



2.) Spin Tune ν_s

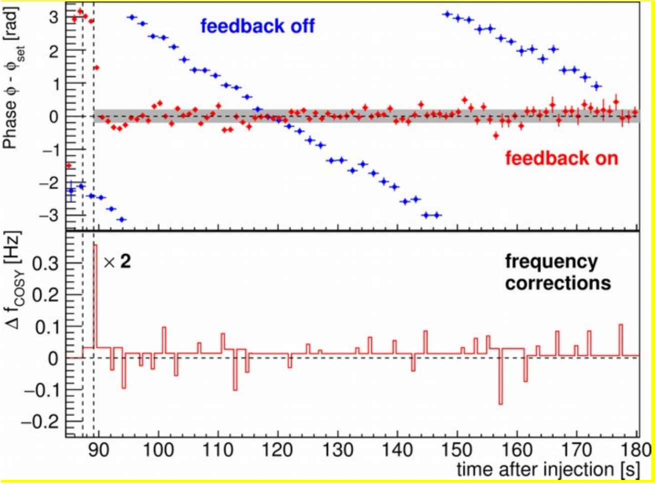




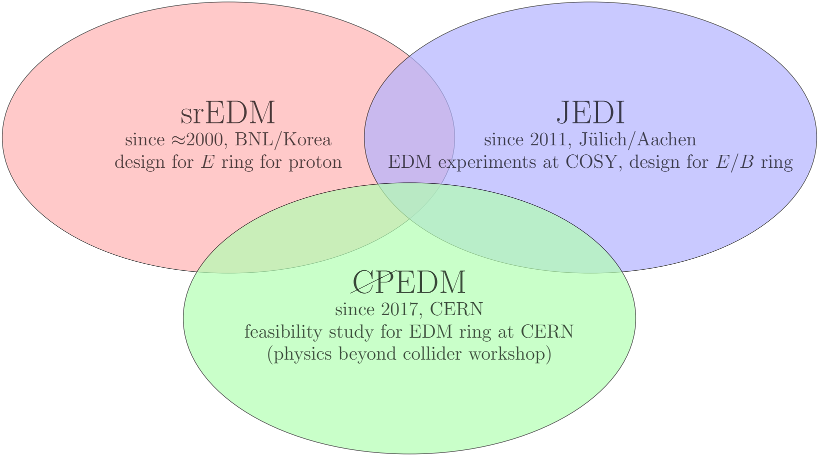
$\sigma(\nu_s = \gamma G) \approx 10^{-10}$ in 100 s
$\sigma(\nu_s = \gamma G) \approx 10^{-8}$ in 2 s

3.) Polarisation feedback

Controlling 120kHz precession



Charged hadron EDM activities



Route ARAGO
375
291
Route JENTSCHKE
Route SCHRÖDINGER
Route EINSTEIN
Route FERMI
Route GREGORY
100 m
Route COCKCROFT
Route PLATON
Route GREGORY

Electric dipole moment

Storage ring steps up search for electric dipole moments

The JEDI collaboration aims to use a storage ring to set the most stringent limits to date on the electric dipole moments of hadrons, describe **Paolo Lenisa**, **Jörg Pretz** and **Hans Ströher**.

Forschungszentrum Jülich

The fact that we and the world around us are made of matter and only

European Research Council

Search for electric dipole moments using storage rings

PI: H. Ströher, (FZ Jülich),

RWTH Aachen University,

University of Ferrara

Start: Oct, 1st, 2016

Summary

- EDMs are unique probe to search for new CP-violating interactions
- **charged** particle EDM searches require new high precision storage rings
- cooperation with CERN started: feasibility study end 2018