Precision experiments: Search for static Electric Dipole Moments

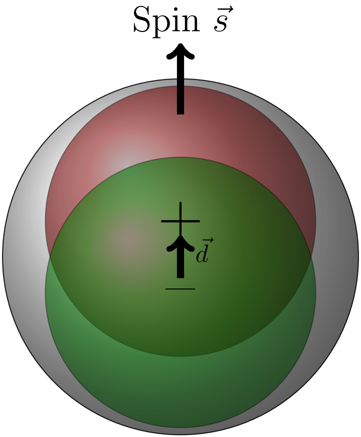
J. Pretz
RWTH Aachen & FZ Jülich

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

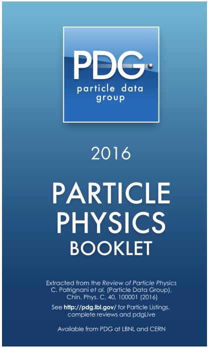
Outline

- 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)



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]

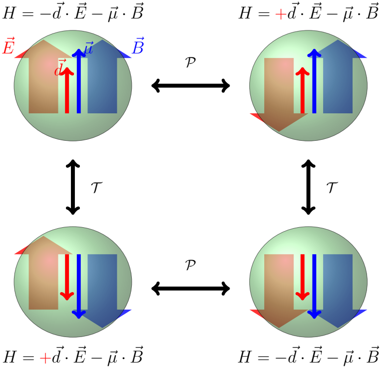
Mean life $\tau > 2.1 \times 10^{29}$ years, CL = 90% [f] ($p \rightarrow$ invisible mode)

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

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

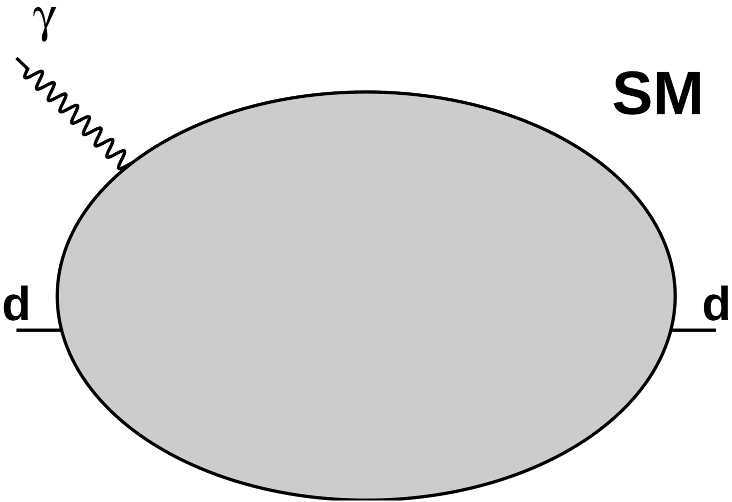


$\Rightarrow$ EDM measurement tests violation of fundamental symmetries $\mathcal{P}$ and $\mathcal{T}(\overset{\mathcal{CPT}}{=}\mathcal{CP})$

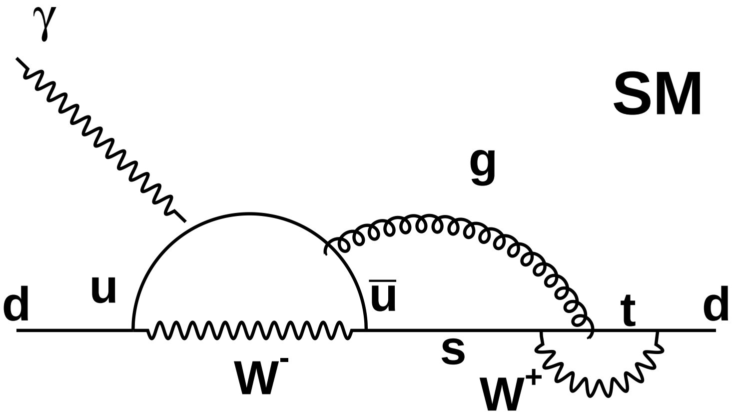
$\mathcal{CP}-$Violation & connection to EDMs

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

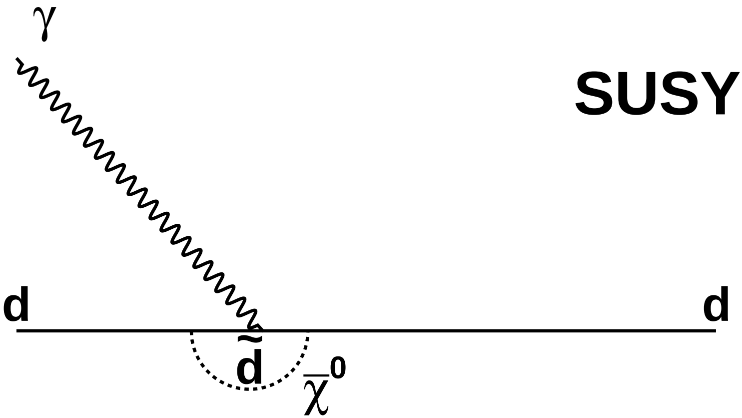
EDM in SM and SUSY



EDM in SM and SUSY



EDM in SM and SUSY



CP violation & Matter-Antimatter Asymmetry

Excess of matter in the universe:

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

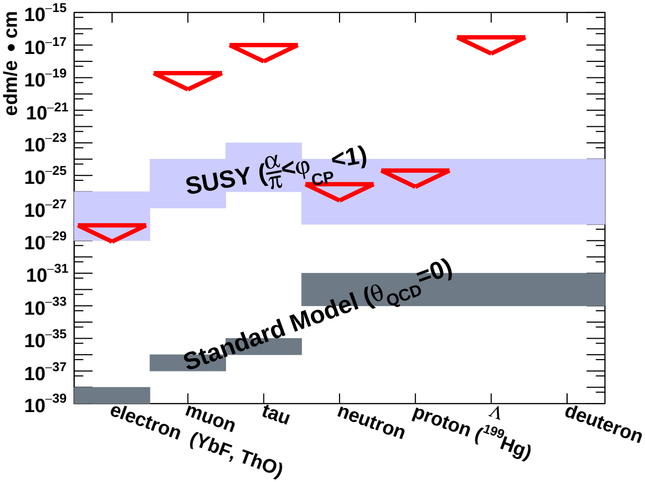
Sakharov (1967): $\mathcal{CP}$ violation needed for baryogenesis

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

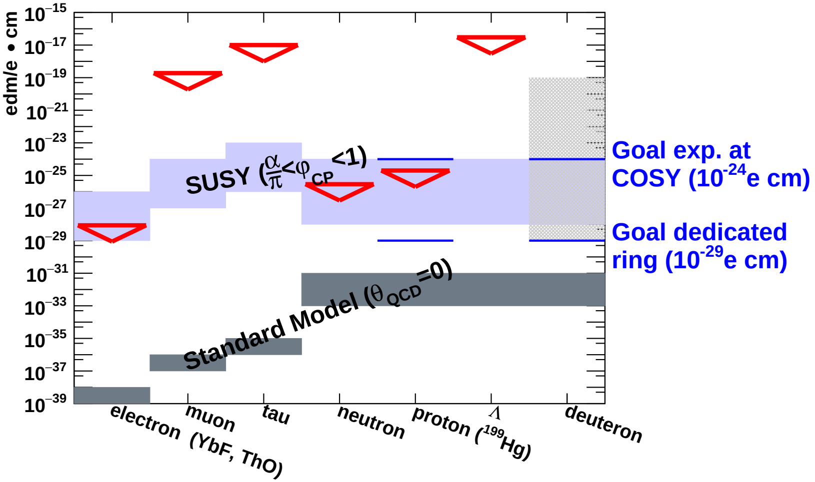
They could show up in EDMs of elementary particles

* SCM: Standard Cosmological Model

EDM: Current Upper Limits



EDM: Current Upper Limits



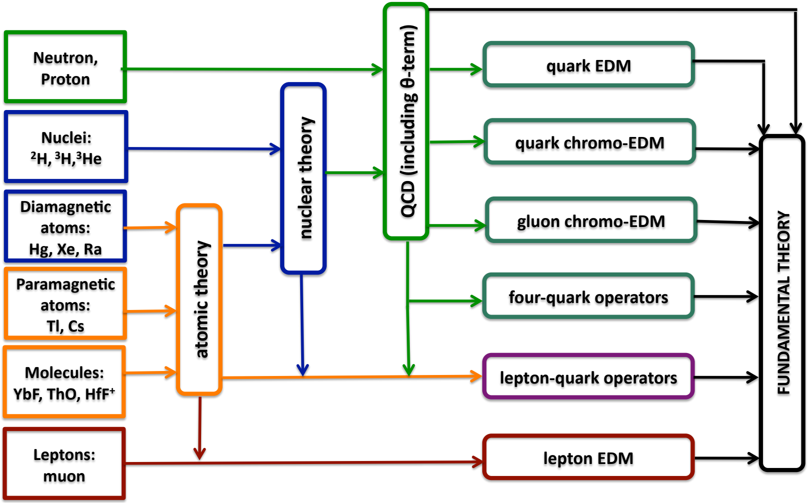
FZ Jülich: EDMs of **charged** hadrons: p, d, ^{3}He

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

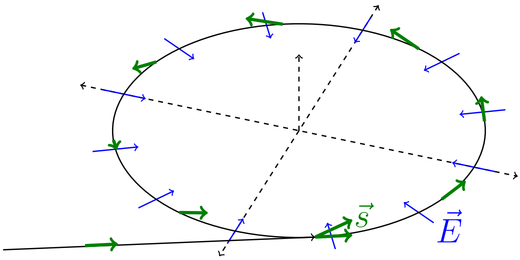
Sources of $\mathcal{CP}$ Violation



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:

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

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. $f = 0.005$)

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

challenge: get σ_{sys} to the same level

Test Measurements at COSY

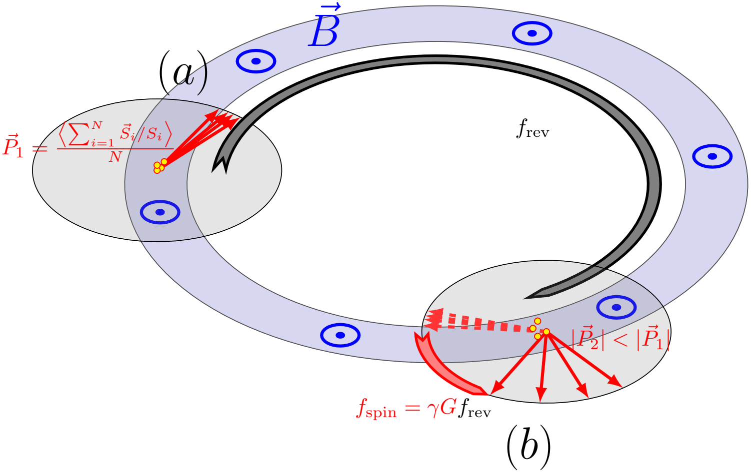
COSY provides (polarized) protons and deuterons with
$p = 0.3 - 3.7\text{GeV}/c$
⇒ **Ideal starting point for charged hadron EDM searches**

Recent achievements

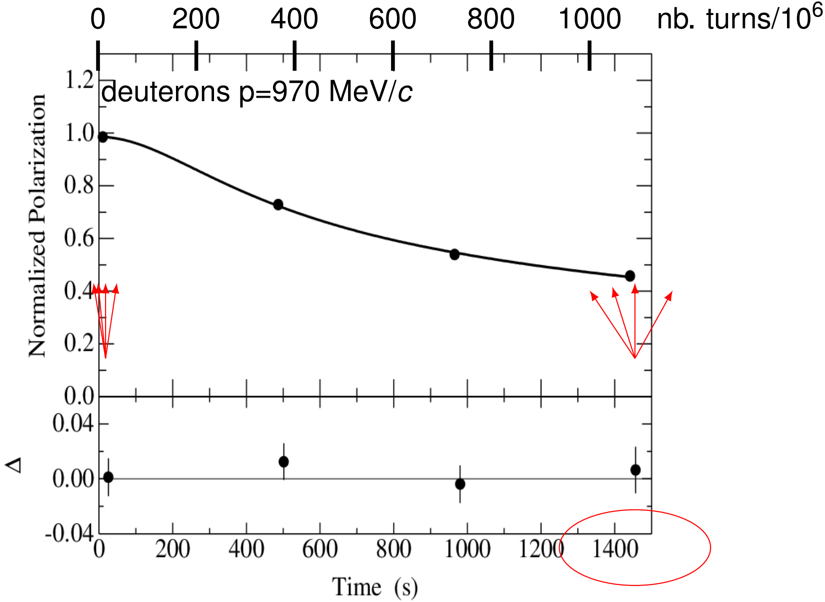
1. **Spin coherence time:** $\tau > 1000$ s
   (PRL 117, 054801 (2016))
2. **Spin tune:** $\overline{\nu_s} = -0.16097 \cdots \pm 10^{-10}$ in 100 s
   (PRL 115, 094801 (2015))
3. **Spin feedback:** polarisation vector kept within 12 degrees
   (acc. for publication in PRL)

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

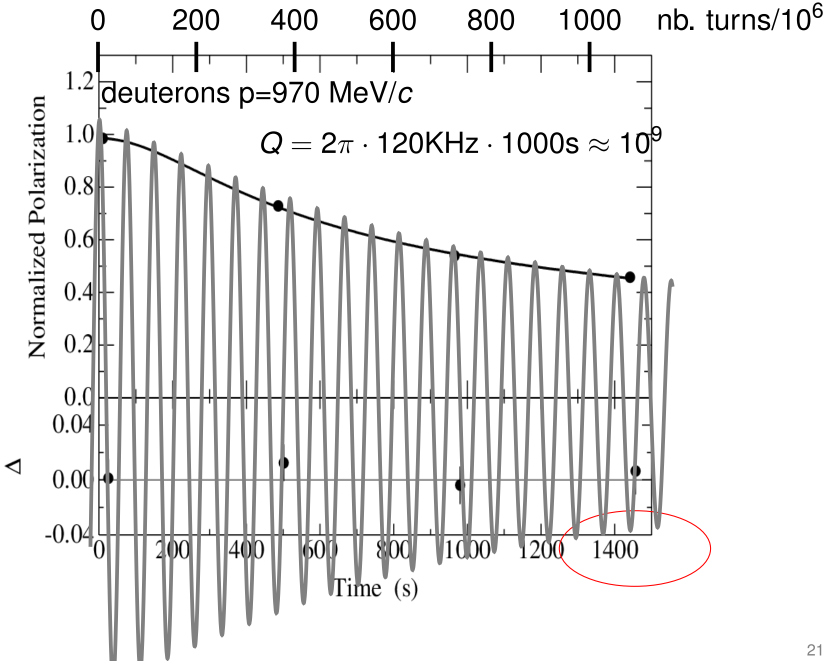
Spin Precession



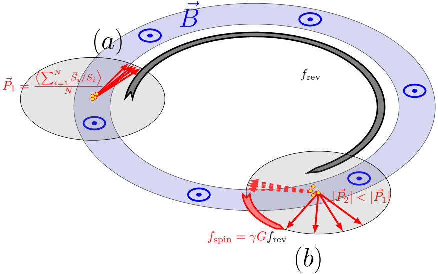
1.) Spin Coherence Time (SCT)

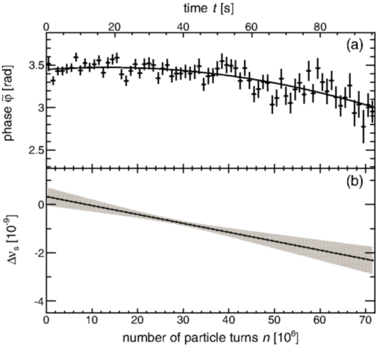


1.) Spin Coherence Time (SCT)



2.) Spin Tune ν_s

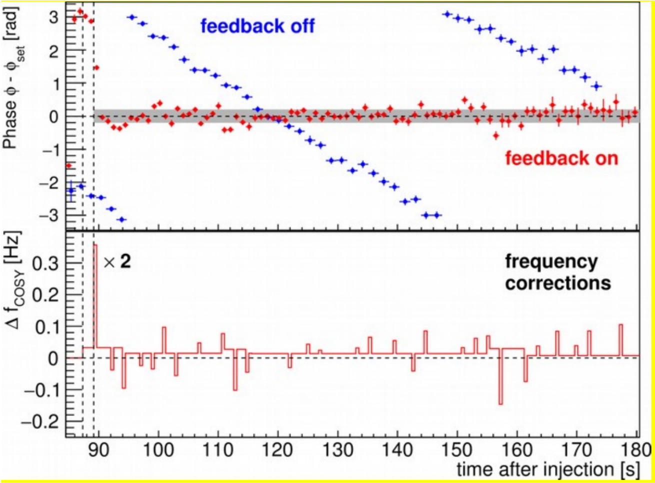




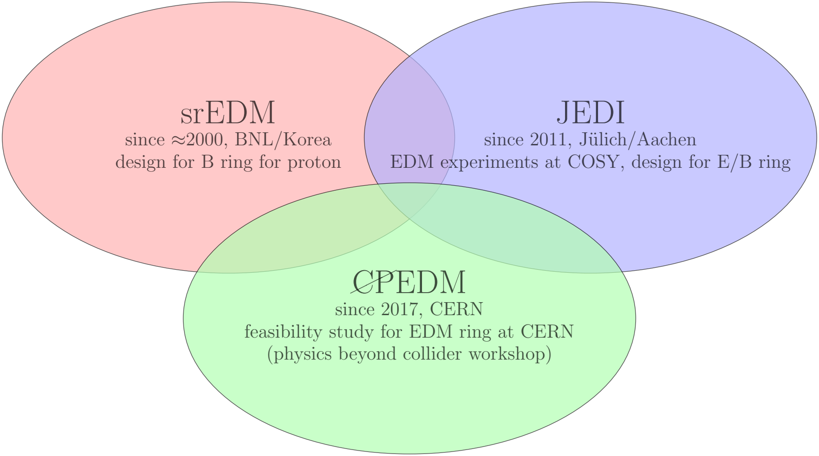
$\sigma(\nu_s = \gamma G) \approx 10^{-10}$ in 100 s
$\sigma(\nu_s = \gamma G) \approx 10^{-8}$ in 2 s

3.) Polarisation feedback

Controlling 120kHz precession



Charged hadron EDM activities




375
291
100 m
Route ARAGO
Route FERMI
Route GREGORY
Route COCKCROFT
802
(TT2A)

CERN Courier September 2016

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