Searches for Electric Dipole Moments (EDM) at Storage Rings

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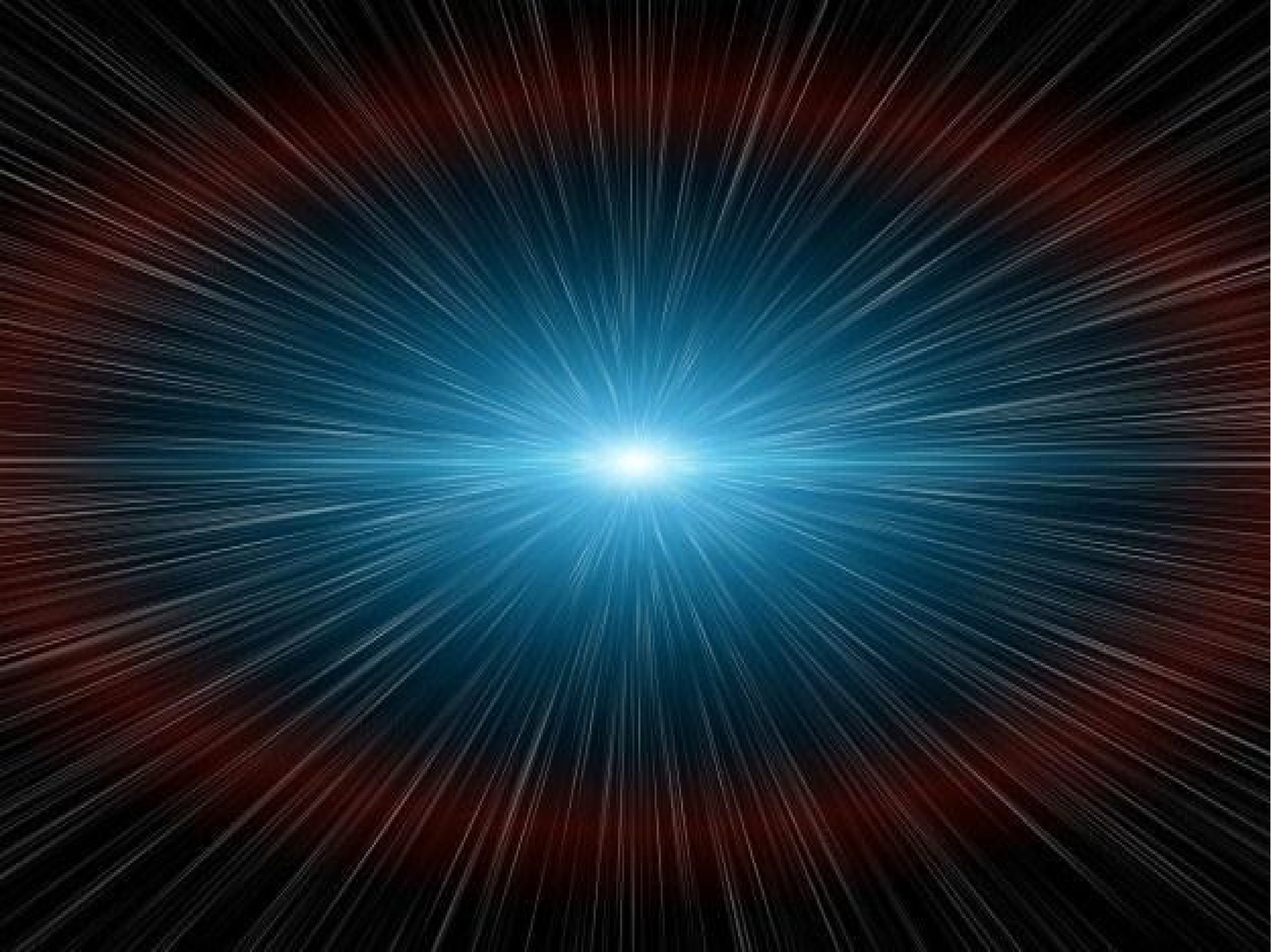
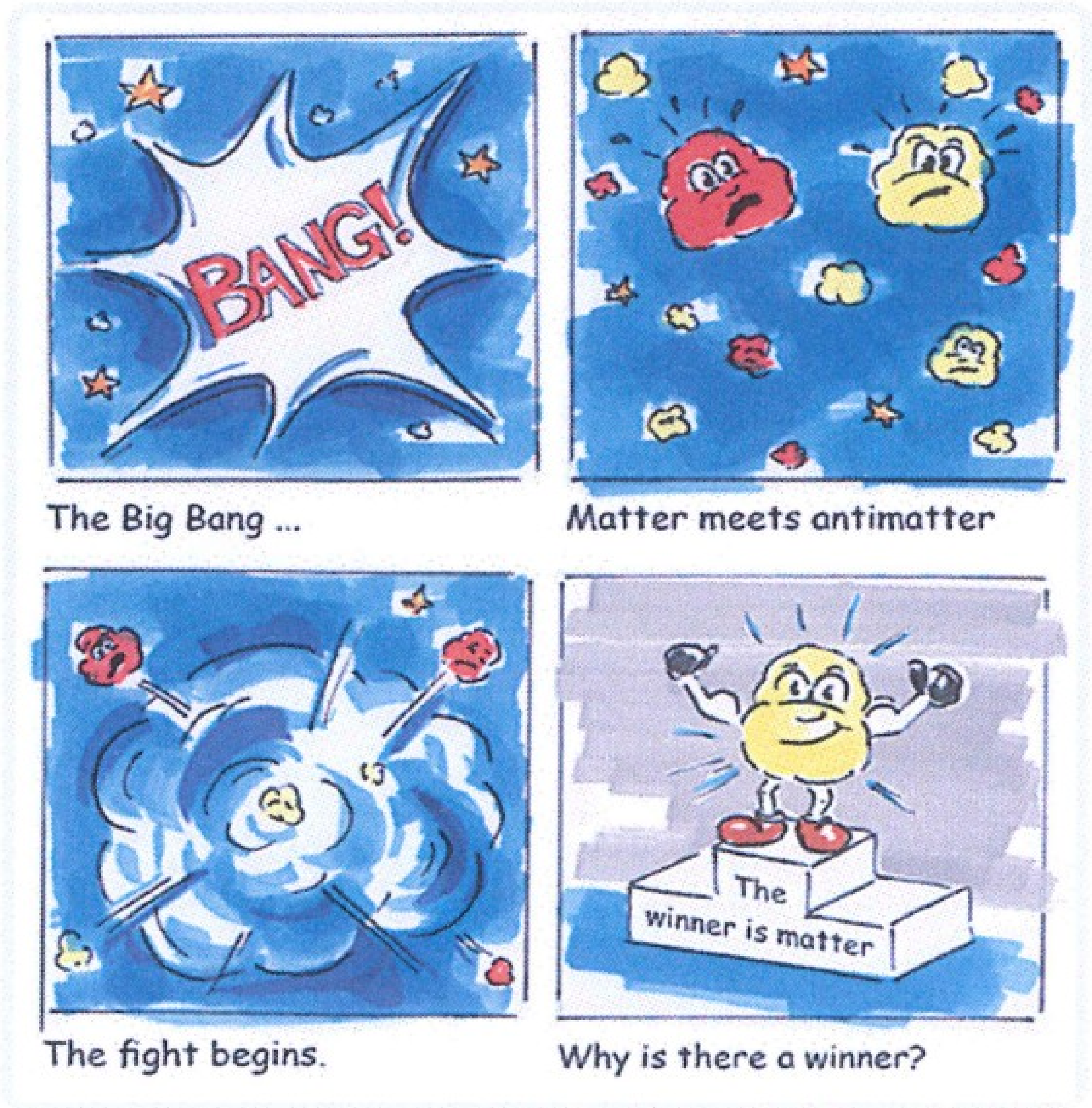
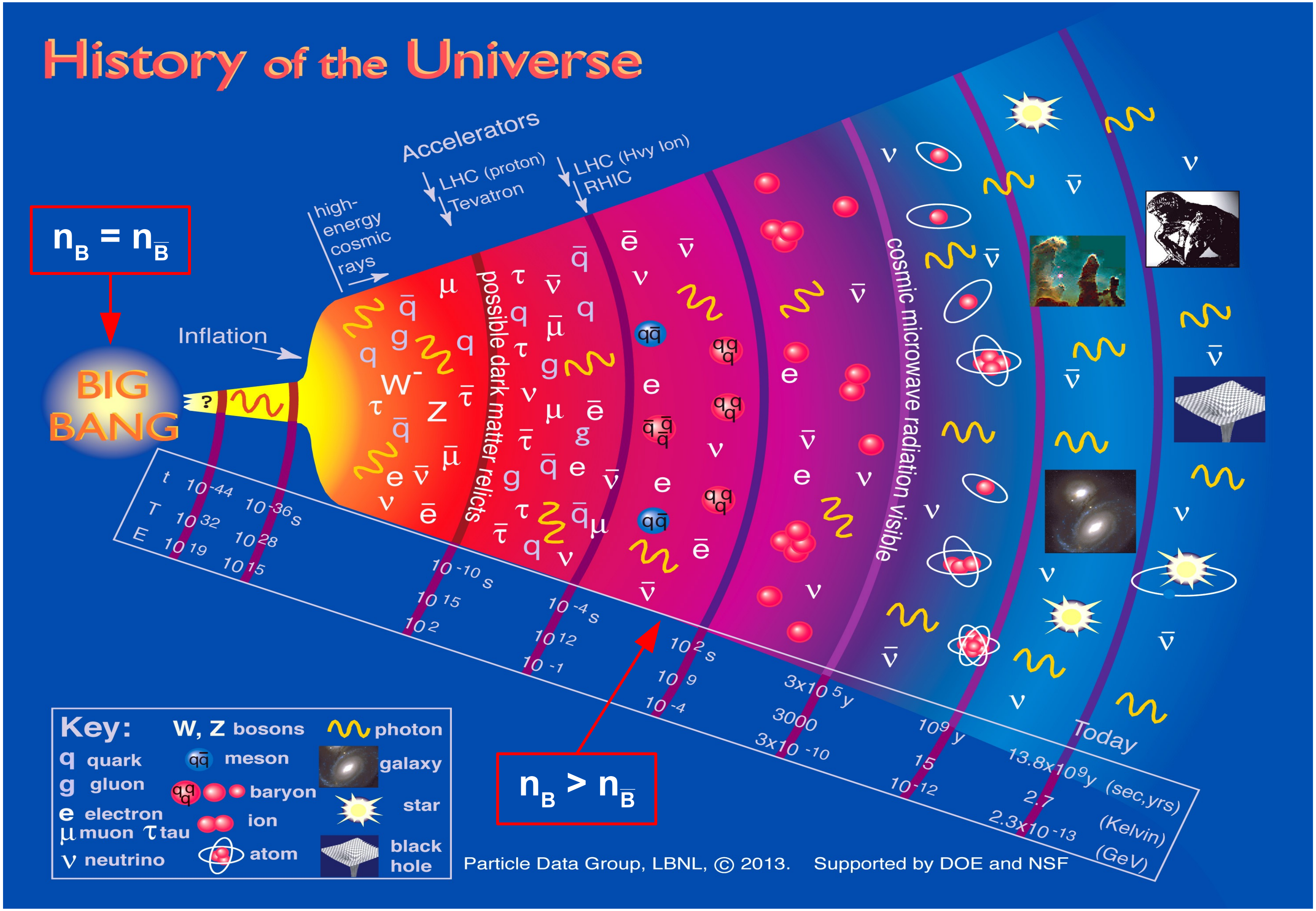



BANG!
The Big Bang ...
Matter meets antimatter
The fight begins.
The winner is matter
Why is there a winner?

Outline

- **Motivation** Cosmic Baryon Asymmetry Problem
- **Background** CP symmetry violation
- **Solution?** EDM of particles
- **New approach** Storage ring EDM measurement

Evolution of Universe



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Baryon Asymmetry Problem

	Standard Model	Observed
$\frac{n_B - n_{\bar{B}}}{n_\gamma}$	$\approx 10^{-18}$	6×10^{-10}

Preconditions needed to explain this imbalance:

- Baryon number violation
- **C and CP violation**
- Thermal non-equilibrium in the early Universe

Sakharov (1967)

Fundamental Discrete Symmetries

A physical model is symmetric under a certain operation
→ if its properties are invariant under this operation

- T-symmetry: t → -t
- P-symmetry: **r** → -**r**
- C-symmetry: particle-antiparticle interchange
- CPT conserved

	C	P	T	CP
Electric field **E**	**-E**	**-E**	**E**	**E**
Magnetic field **B**	**-B**	**B**	**-B**	**-B**
Momentum **p**	**p**	**-p**	**-p**	**-p**
Angular momentum **l**	**l**	**l**	**-l**	**l**
Charge density q	-q	q	q	-q

CP Violation in the Standard Model

- **Electroweak sector** (CKM matrix well established)
  → First observation: 1964 - decay of the neutral K meson

- **Strong Interactions** (so called θ-term)
  → Not observed experimentally yet (it is very small)
  → Strong CP puzzle

↓

Predictions orders of magnitude too small to explain the observed matter-antimatter asymmetry!

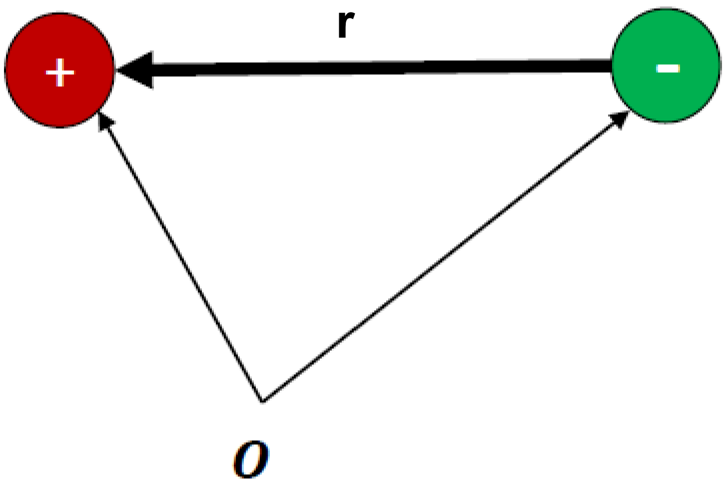
New sources of CP violation Beyond Standard Model needed!

They can manifest in **EDM** of particles

Electric Dipole Moment

Electric Dipole Moment

Classically



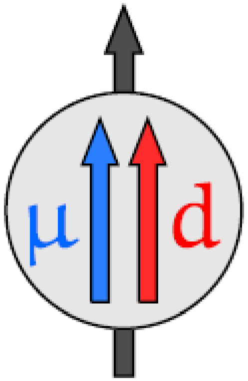
- Charge × displacement

In Quantum Mechanics

Operator **d** = q**r**

Only available quantization axis is the spin **s** = s**σ**
(there can be only one vector in a quantum system)

d = d**σ**

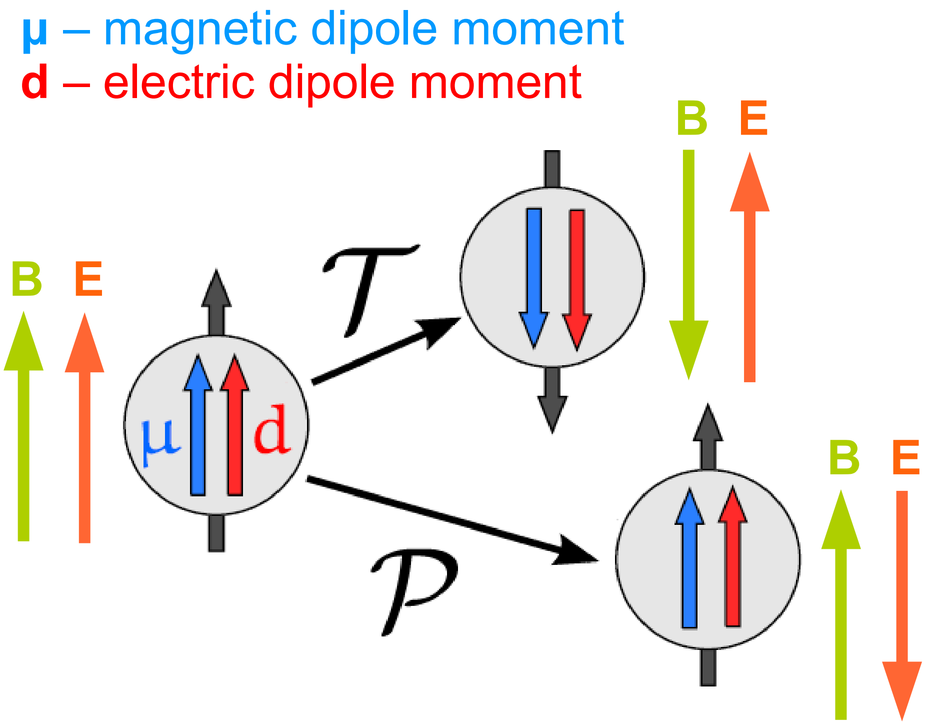


- **d** || **σ** and **μ** || **σ** (magnetic moment)

Electric Dipole Moment – CP violation

The observable quantity:

- Energy of electric dipole in electric field
- Energy of magnetic dipole in magnetic field



$$H = H_E + H_M = -\mu\boldsymbol{\sigma}\cdot\mathbf{B} - d\boldsymbol{\sigma}\cdot\mathbf{E}$$

$$T: H = -\mu\boldsymbol{\sigma}\cdot\mathbf{B} + d\boldsymbol{\sigma}\cdot\mathbf{E}$$
$$P: H = -\mu\boldsymbol{\sigma}\cdot\mathbf{B} + d\boldsymbol{\sigma}\cdot\mathbf{E}$$

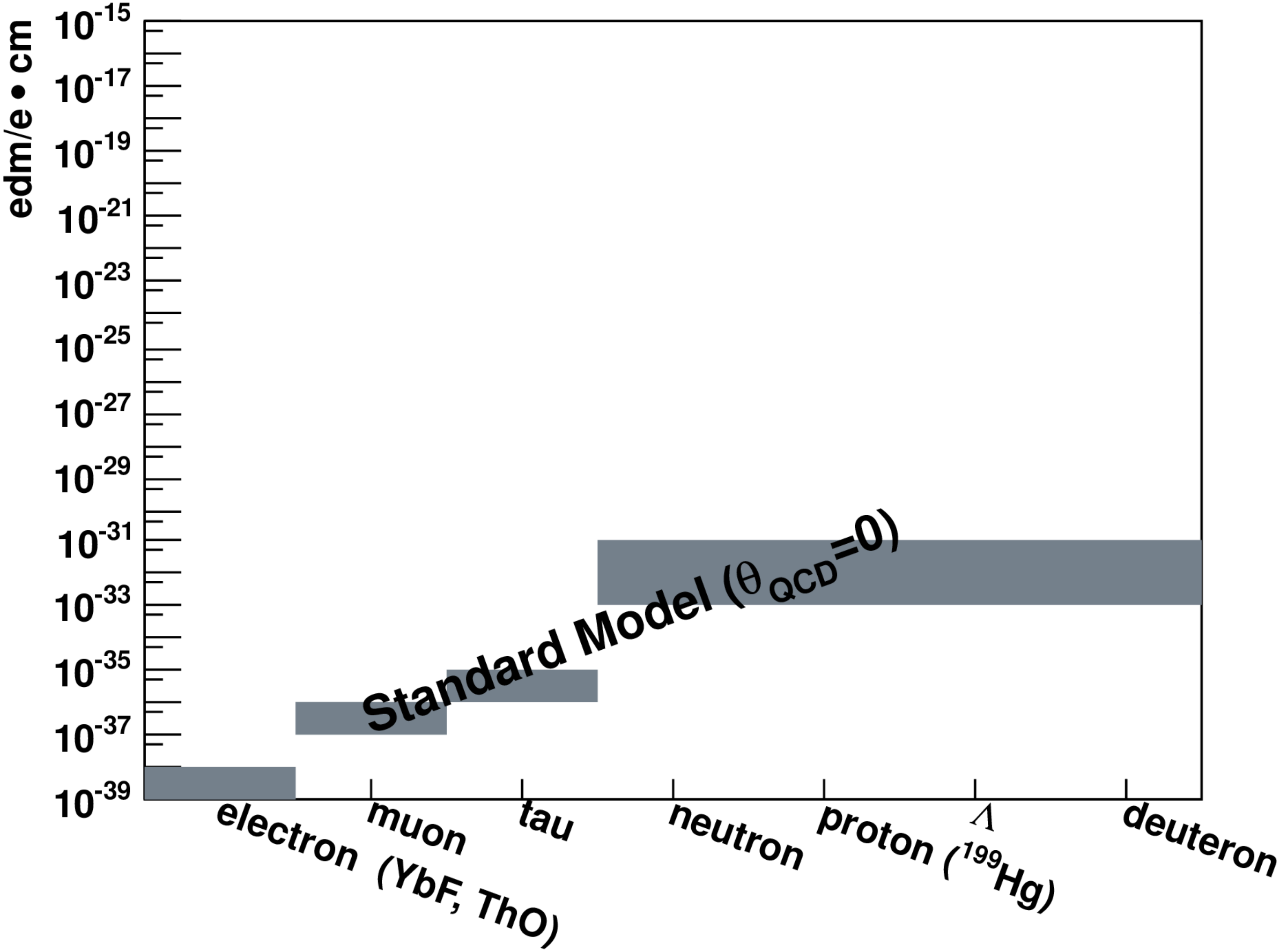
H violates T and P symmetry if **$d \neq 0$**

T violation → CP violation (since CPT conserved)

EDM – Orders of magnitude

Neutron (udd)	
Charge	e
$\lvert \mathbf{r}_1 - \mathbf{r}_2 \rvert$	1 fm = 10^{-13} cm
EDM	
Naive expectation	10^{-13} e · cm
Observed (upper limit)	$< 3 \cdot 10^{-26}$ e · cm
SM prediction - Parity violation - CP electroweak violation	~ 10^{-32} e · cm

nEDM of 10^{-26} e · cm → separation of u from d quarks of ~ $5 \cdot 10^{-26}$ cm


edm/e • cm
10^{-15}
10^{-17}
10^{-19}
10^{-21}
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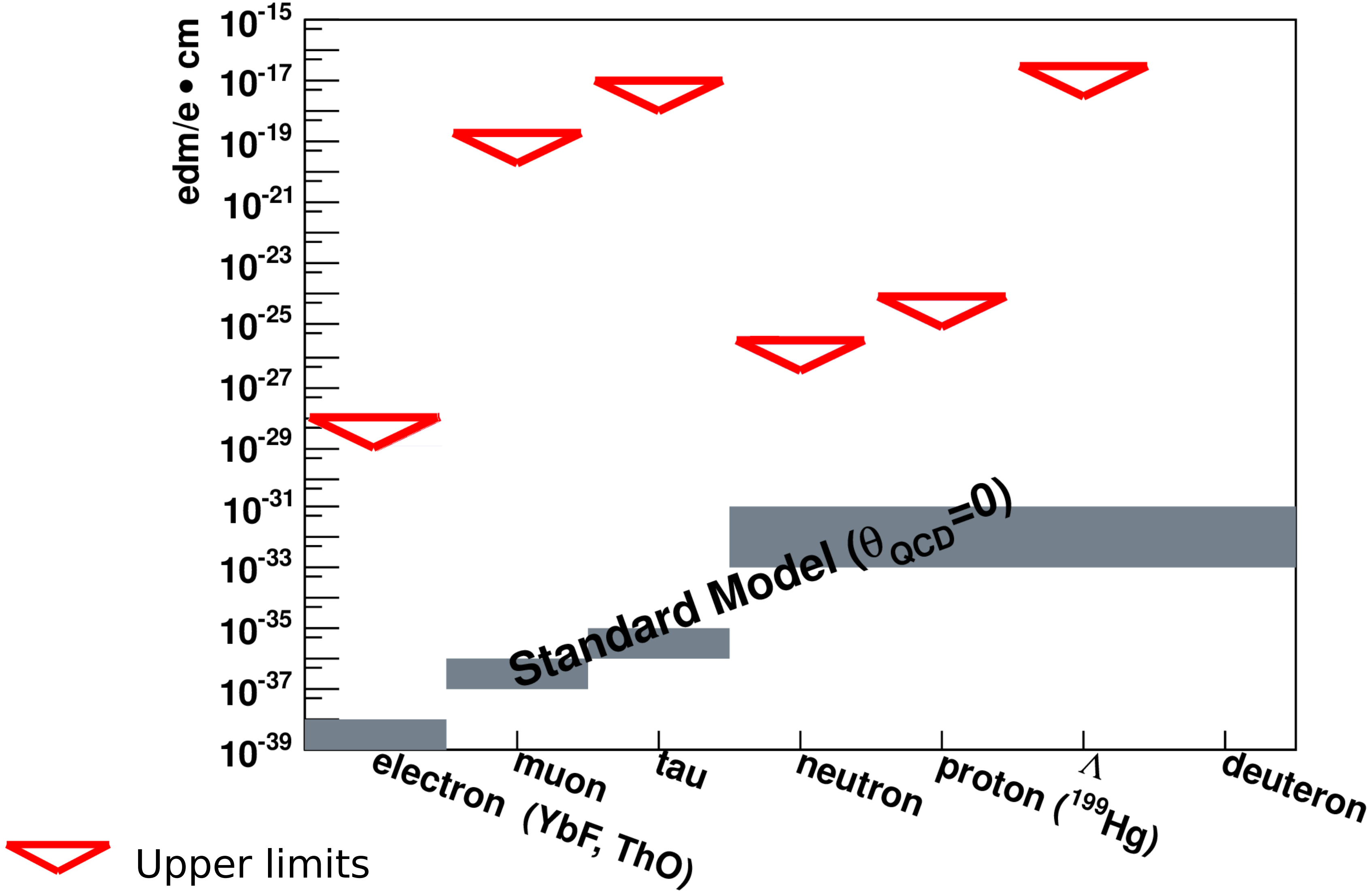
10^{-35}
10^{-37}
10^{-39}
Standard Model (θ_{QCD}=0)
electron (YbF, ThO)
muon
tau
neutron
proton (^{199}Hg)
Λ
deuteron


edm/e • cm
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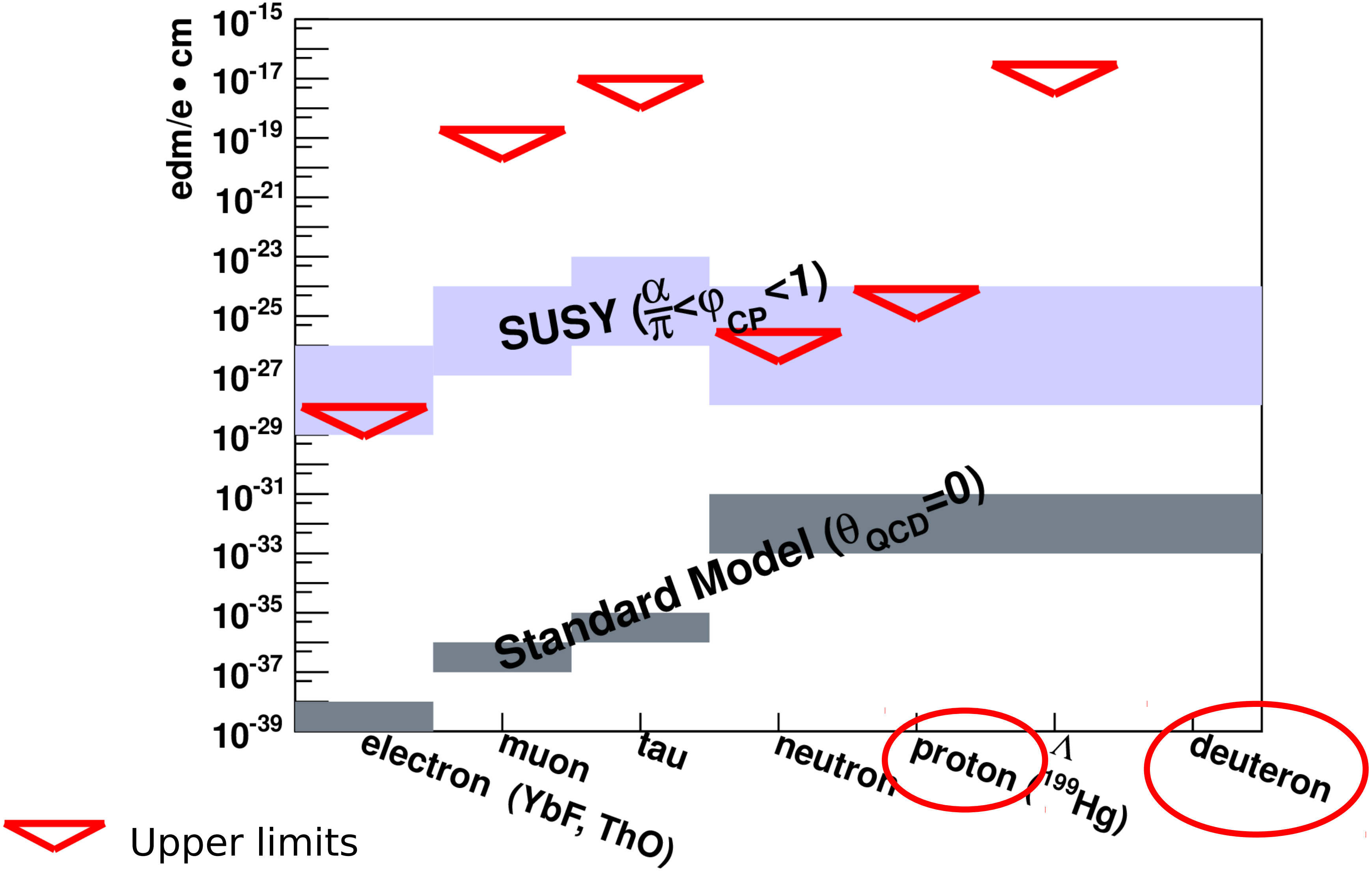
Upper limits


edm/e • cm
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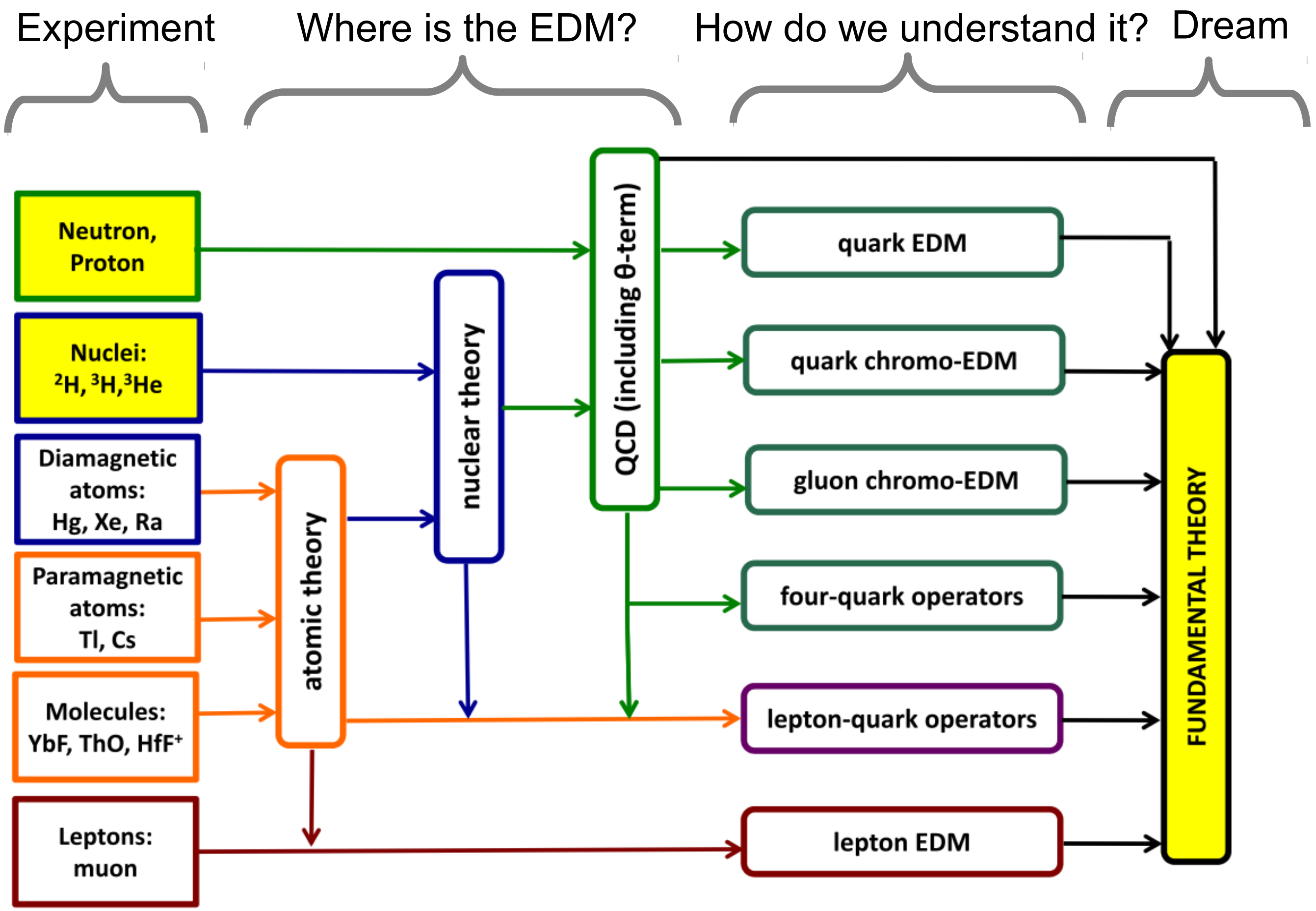
10^{-39}
SUSY ($\frac{\alpha}{\pi}<\varphi_{CP}<1$)
Standard Model ($\theta_{QCD}=0$)
electron (YbF, ThO)
muon
tau
neutron
proton (^{199}Hg)
Λ
deuteron
Upper limits

Why protons and deuterons?

- No direct measurement
- **disentangle the fundamental source(s)** of EDMs



Measurement of Electric Dipole Moments

Measurement of charged particle EDM

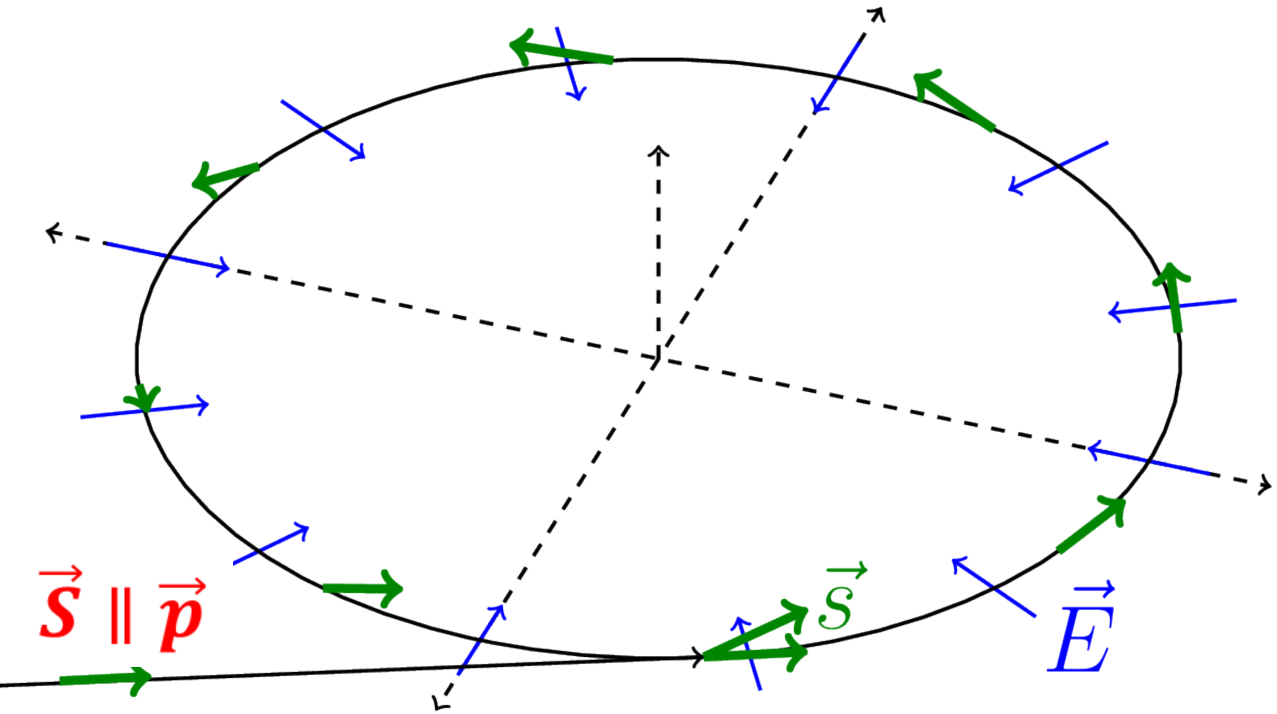
For charged particles:
→ apply electric field in a storage ring

simplified case:

$$\frac{d\vec{S}}{dt} \propto d\vec{E} \times \vec{S}$$

⇓

Build-up of vertical polarization by slow precession



"Frozen spin"

Extremely small effects!

With edm ~ 10^{-29} e·cm
we talk about the effect
of the order of **µdeg/hour**

Spin motion

Thomas-BMT equation:

In storage rings (magnetic field – vertical, electric field - radial)

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{q}{m_0}\left\{ \overset{\text{magnetic moment}}{G\vec{B} + \left(\frac{1}{\gamma^2 - 1} - G\right)\frac{\vec{\beta} \times \vec{E}}{c}} + \overset{\text{EDM}}{d\frac{m_0}{q\hbar S}\left(\vec{E} + c\vec{\beta} \times \vec{B}\right)} \right\} \times \vec{S}$$

Ω: angular precession frequency

G: anomalous magnetic moment

d: electric dipole moment

γ: Lorentz factor

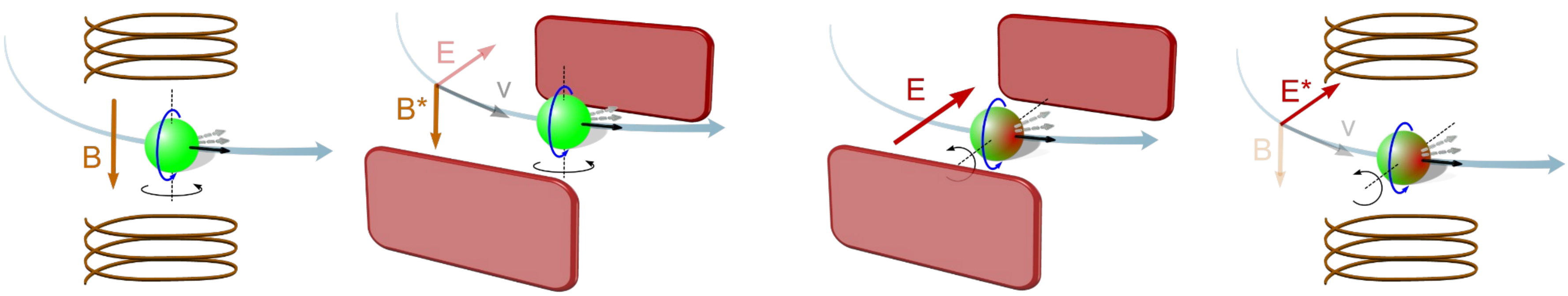
Spin motion

Thomas-BMT equation:

In storage rings (magnetic field – vertical, electric field - radial)

magnetic moment EDM

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{q}{m_0}\left\{ G\vec{B} + \left(\frac{1}{\gamma^2 - 1} - G\right)\frac{\vec{\beta} \times \vec{E}}{c} + d\,\frac{m_0}{q\hbar S}\left(\vec{E} + c\vec{\beta} \times \vec{B}\right)\right\} \times \vec{S}$$



Magnetic moment causes fast spin precession in horizontal plane

Storage rings: electric ring

magnetic moment EDM

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{q}{m_0}\left\{ G\vec{B} + \underbrace{\left(\frac{1}{\gamma^2 - 1} - G\right)}_{\equiv 0!}\frac{\vec{\beta} \times \vec{E}}{c} + d\,\frac{m_0}{q\hbar S}\left(\vec{E} + c\vec{\beta} \times \vec{B}\right)\right\} \times \vec{S}$$

„frozen spin“ : precession vanishes at magic momentum

$$G = \frac{1}{\gamma^2 - 1} \Rightarrow p = \frac{m}{\sqrt{G}}$$

only possible for $G > 0$

Dedicated ring for protons

Experimental requirements

High precision storage ring	alignment, stability, field homogeneity
High intensity beams	N = 4 x 10^{10} per fill
Polarized hadron beams	P = 0.8
Large electric fields	E = 10 MV/m
Long spin coherence time	τ = 1000 s
Polarimetry	analyzing power A = 0.6, acc. f = 0.005

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

Challenge: systematic uncertainties on the same level!

Even in Pure Electric Ring – lots of sources of syst. uncertainties
→ Very small radial B field can mimic an EDM effect

$$\mu B_r \sim dE_r$$

Storage rings: combined ring

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{q}{m_0}\left\{\overset{\text{magnetic moment}}{\underbrace{G\vec{B} + \left(\frac{1}{\gamma^2 - 1} - G\right)\frac{\vec{\beta} \times \vec{E}}{c}}_{\equiv 0!}} + \overset{\text{EDM}}{d\,\frac{m_0}{q\hbar S}\left(\vec{E} + c\vec{\beta} \times \vec{B}\right)}\right\} \times \vec{S}$$

„frozen spin“: proper combination of $\vec{B}$, $\vec{E}$ and γ
also for $G < 0$ (i.e. deuterons, ^{3}He)

Combined ring both for protons and deuterons

Storage rings: magnetic ring

magnetic moment

EDM

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{q}{m_0}\left\{G\vec{B} + \left(\frac{1}{\gamma^2 - 1} - G\right)\frac{\vec{\beta} \times \vec{E}}{c} + d\,\frac{m_0}{q\hbar S}\left(\vec{E} + c\vec{\beta} \times \vec{B}\right)\right\} \times \vec{S}$$

COSY: pure magnetic ring, polarized protons and deuterons

access to EDM via motional electric field $\vec{\beta} \times \vec{B}$

Starting point for a proof-of-principle experiment

EDM in Forschungszentrum Jülich

JEDI

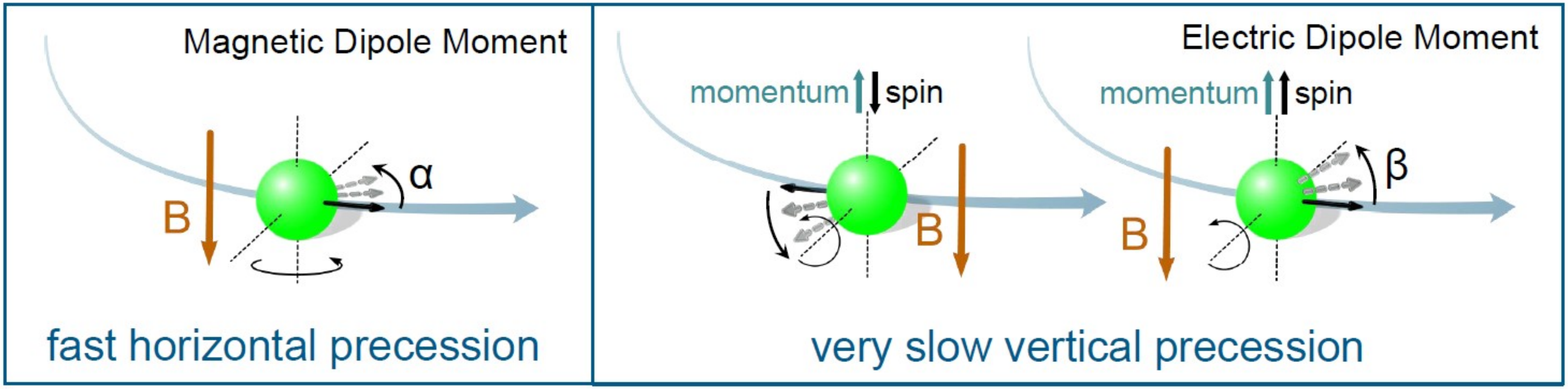
http://collaborations.fz-juelich.de/ikp/jedi/

EDMs of charged hadrons: p, d

COSY: polarized protons and deuterons with p = 0.3 – 3.7 GeV/c

Pure Magnetic Ring

Spin motion in magnetic ring

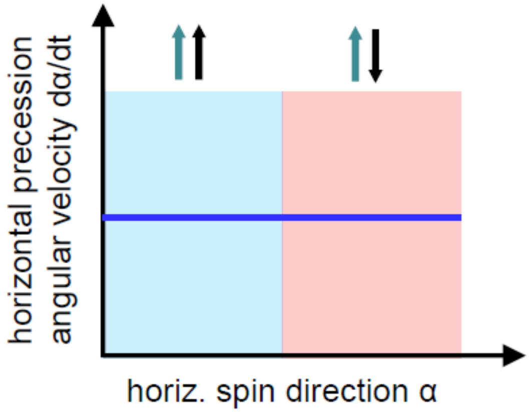


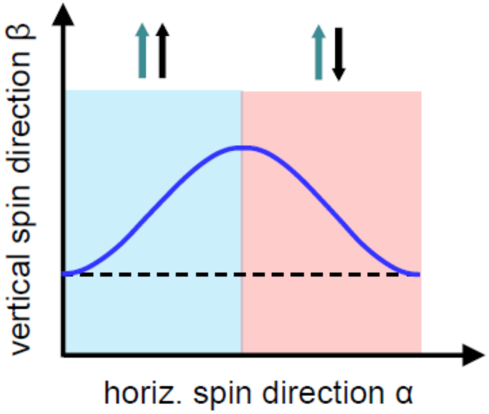
E* field tilts spin due to EDM

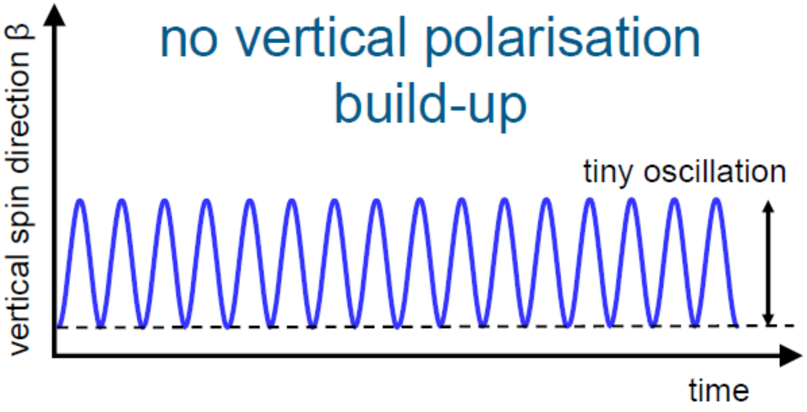
50% of time up and

50% of time down

$$\frac{d\vec{S}}{dt} \propto \left(G\vec{B} + d\frac{m_0 c}{q\hbar S}\vec{\beta} \times \vec{B} \right) \times \vec{S}$$



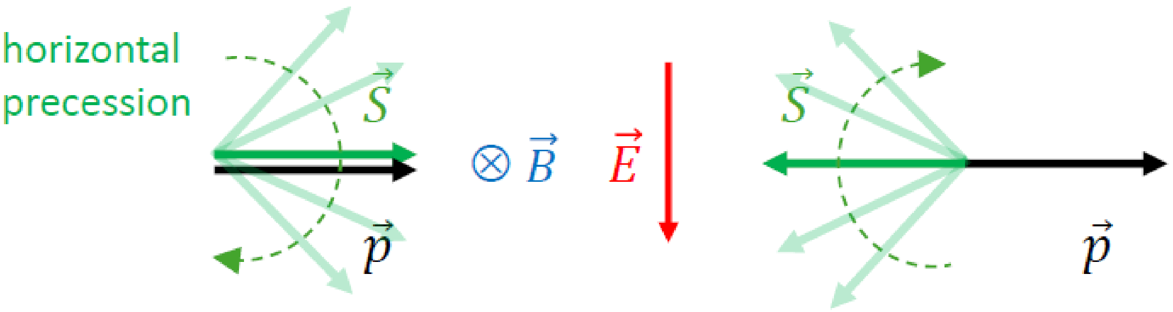


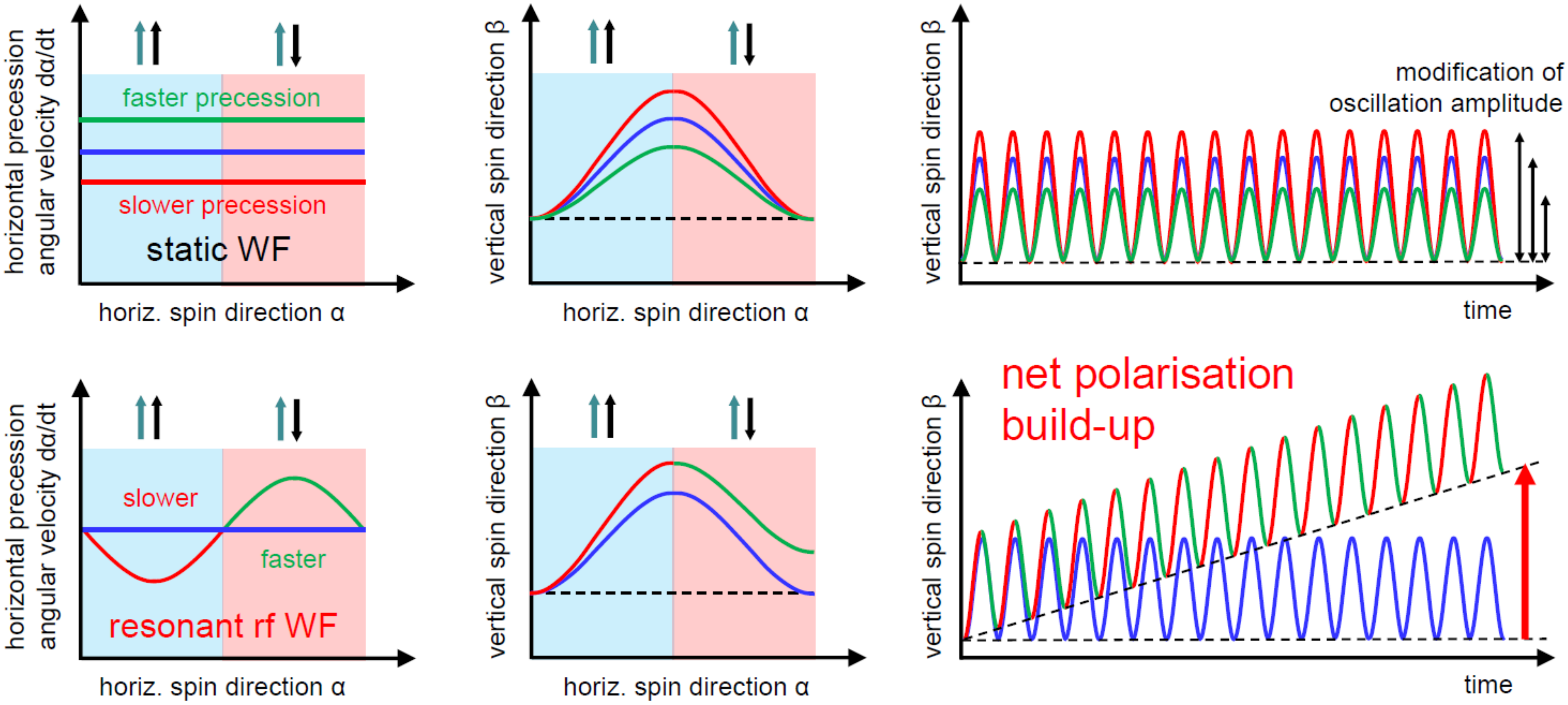


RF Wien Filter

Lorentz force vanishes:
no effect on EDM rotation

Effect: Adds extra horizontal precession





COSY Research and Development

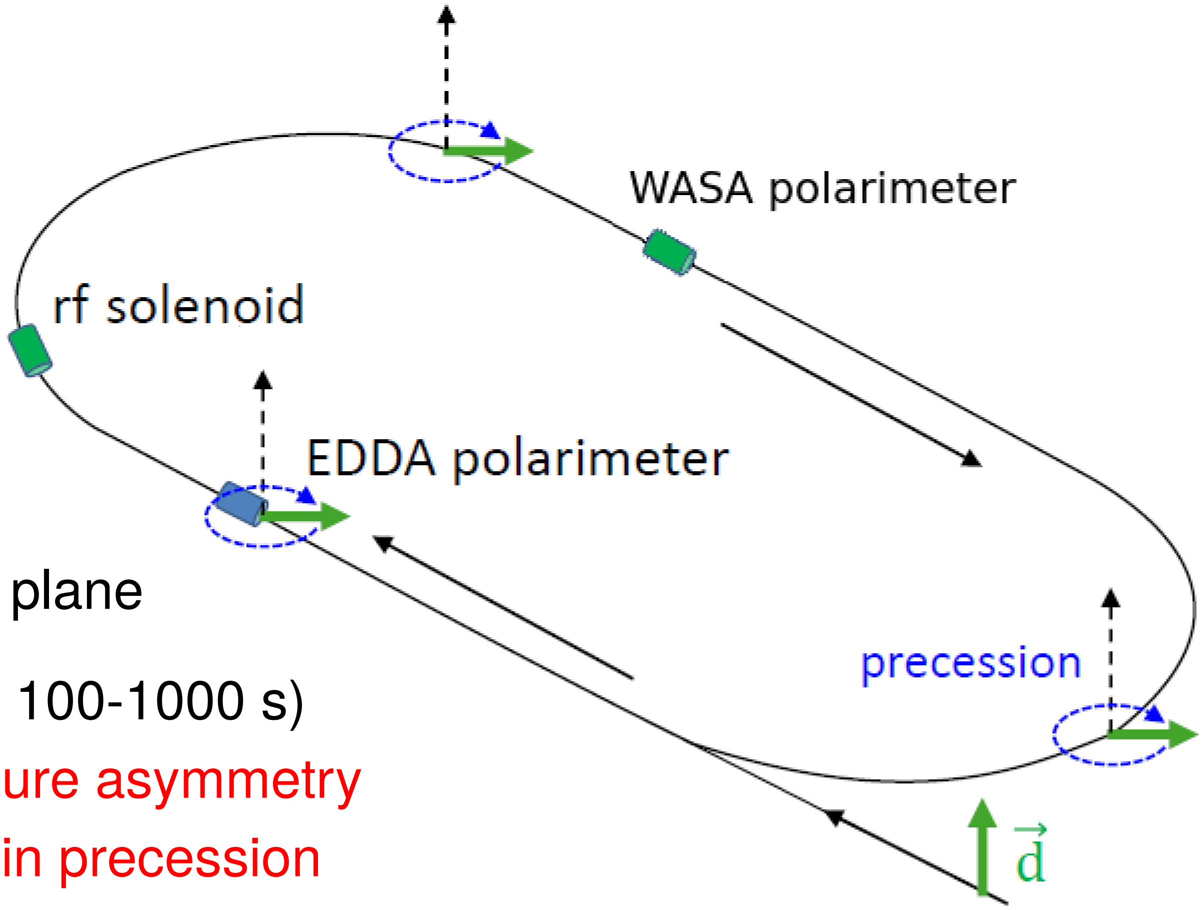
R&D with deuterons
p = 1 GeV/c
G = -0.14256177(72)
ν_s ≈ -0.161 → f ≈ 120 kHz

study spin tune $\upsilon_s = \frac{|\vec{\Omega}|}{|\vec{\omega}_{\mathrm{cycl}}|} = \gamma G$
→ phase advance per turn

- Precise measurement of the precession frequency (spin tune)
  → also time dependent within one cycle
- Maximizing the spin coherence time (goal: ≈1000 s)
- Maintaining the spin direction
  → keep precession frequency stable
  → match frequency and phase to Wien filter radio frequency
- **Developing and finding optimal working conditions for EDM polarimetry**

Experimental Setup

1. inject and accelerate vertically polarized deuterons to p=1GeV/c
2. bunch and (pre-)cool
3. turn spin by means of a RF solenoid into horizontal plane
4. extract beam slowly (within 100-1000 s) onto a carbon target, measure asymmetry and precisely determine spin precession



spin tune:

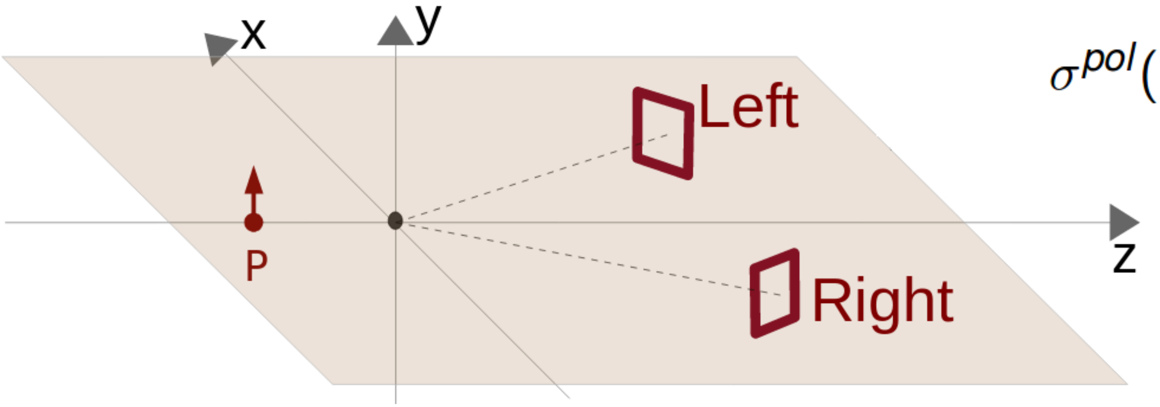
$$|\nu_s| = |\gamma G| = \frac{\text{spin precessions}}{\text{particle turn}} = \frac{f_{\text{prec}}}{f_{\text{rev}}} \approx \frac{120\ \text{kHz}}{750\ \text{kHz}} \approx 0.16$$

Polarization measurement

1. Reaction: dC elastic scattering

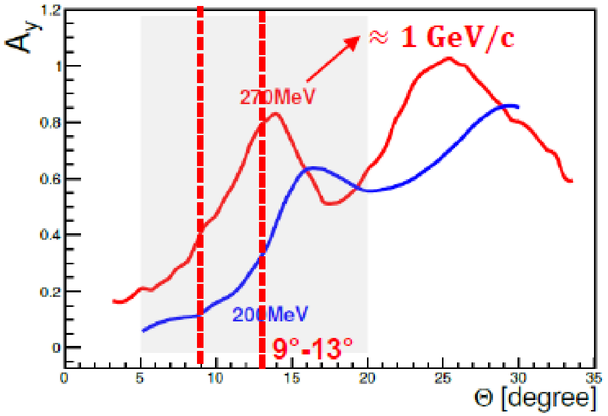
Up/Down asymmetry $\propto$ horizontal component of polarization P_x

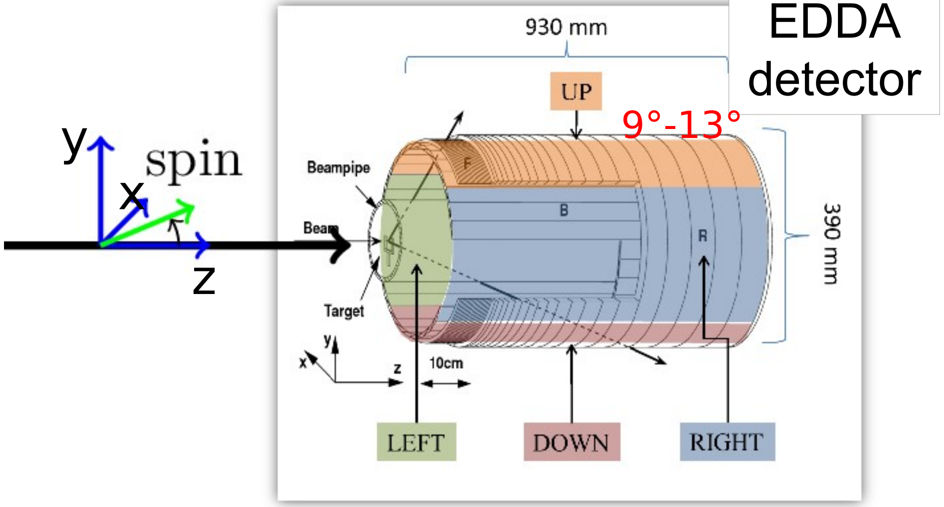
Right/Left asymmetry $\propto$ vertical component of polarization P_y



$$\sigma^{pol}(\theta,\phi) = \sigma_0(\theta)[1 + \tfrac{3}{2} PA_y(\theta)\cos\phi\,]$$

$$PA_y(\theta) = \frac{\sigma^L(\theta) - \sigma^R(\theta)}{\sigma^L(\theta) + \sigma^R(\theta)}$$





EDDA detector

Polarization measurement

Detector signal

$$N^{up,down} = 1 \pm PA\sin\left(2\pi \cdot f_{\text{prec}} t\right)$$
$$= 1 \pm PA\sin\left(2\pi \cdot \nu_s\, n_{\text{turns}}\right)$$

P: polarisation, A: analysing power

Asymmetry

$$\varepsilon = \frac{N^{up} - N^{down}}{N^{up} + N^{down}} = PA\sin(2\pi \cdot \nu_s\, n_{\text{turns}})$$

Challenges

- precession frequency $f_{\text{prec}} \approx 120$ kHz
- $\nu_s \approx -0.16$ → 6 turns / precession
- event rate ≈ 5000 s^{-1} → 1 hit / 25 precessions

→ no direct fit of the rates

Polarization measurement

Detector signal

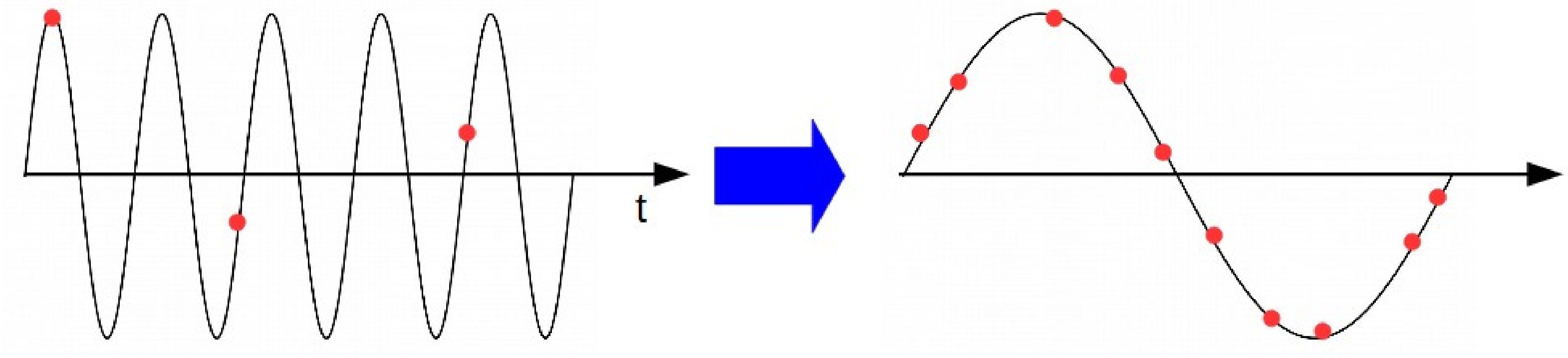
$$N^{up,down} = 1 \pm PA\sin\left(2\pi \cdot f_{\text{prec}} t\right)$$
$$= 1 \pm PA\sin(2\pi \cdot \nu_s \, n_{\text{turns}})$$

P: polarisation, A: analysing power

Asymmetry

$$\varepsilon = \frac{N^{up} - N^{down}}{N^{up} + N^{down}} = PA\sin(2\pi \cdot \nu_s \, n_{\text{turns}})$$

Challenges



Too few polarimeter events to resolve oscillation directly!

Map many events to one cycle
Phys. Rev. ST Accel. Beams 17, 052803 (2014)

Polarization measurement

beam revolutions: counting turn number *n*

↓

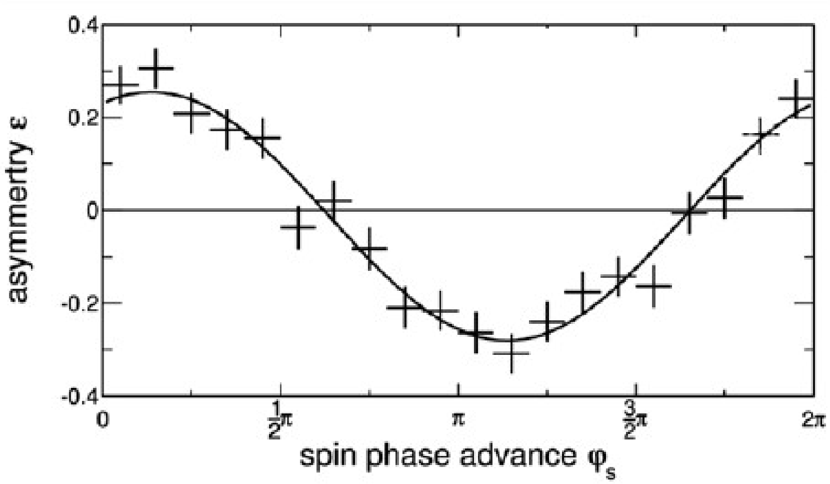
assign turn number *n* → phase advance $\varphi_s = 2\pi\nu_s n$

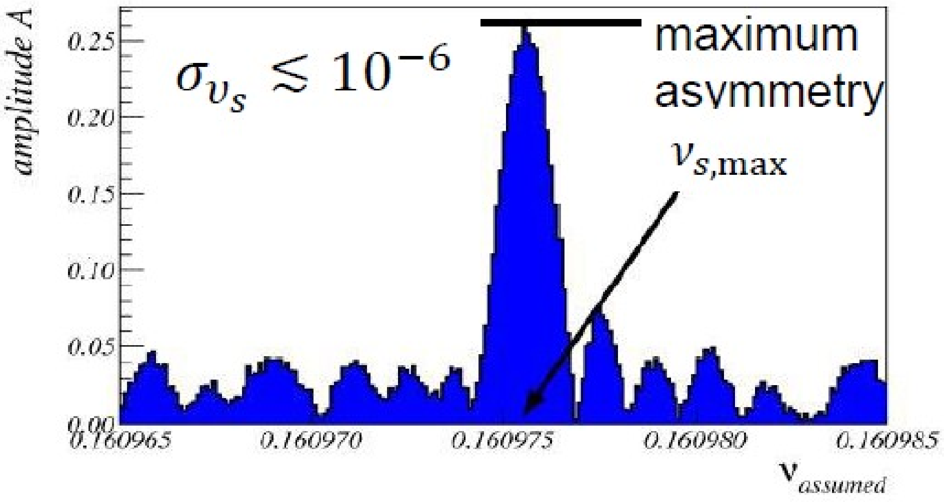
↓

for intervals of $\Delta n = 10^6$ turns: $\varphi_s \rightarrow \varphi_s \bmod 2\pi$

↓

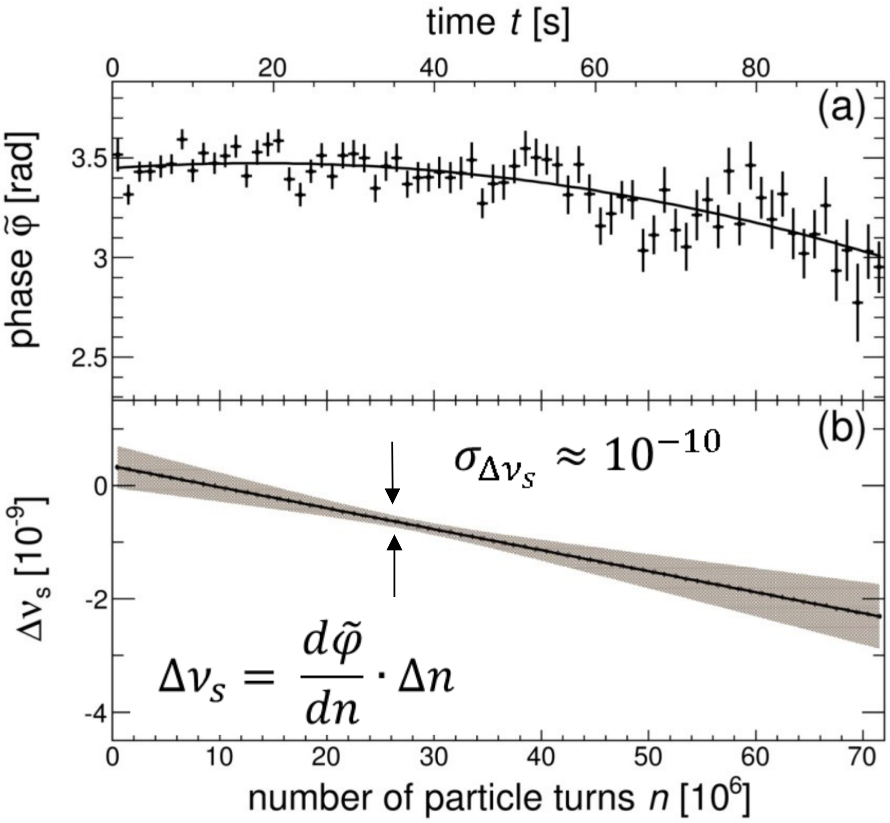
scan ν_s in some interval around $\nu_s = \gamma G$



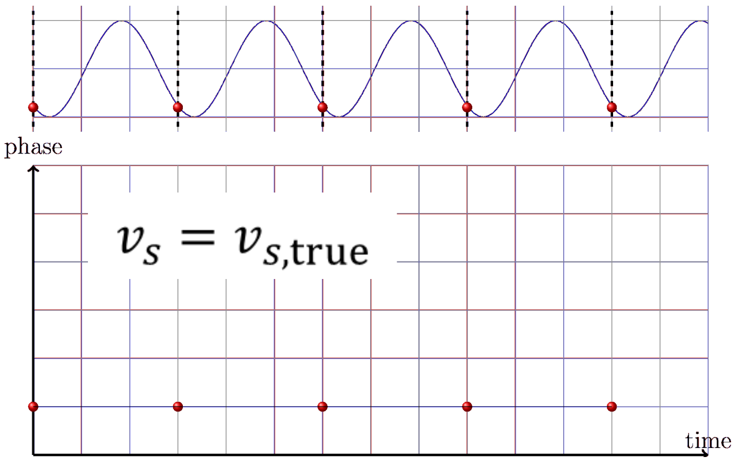


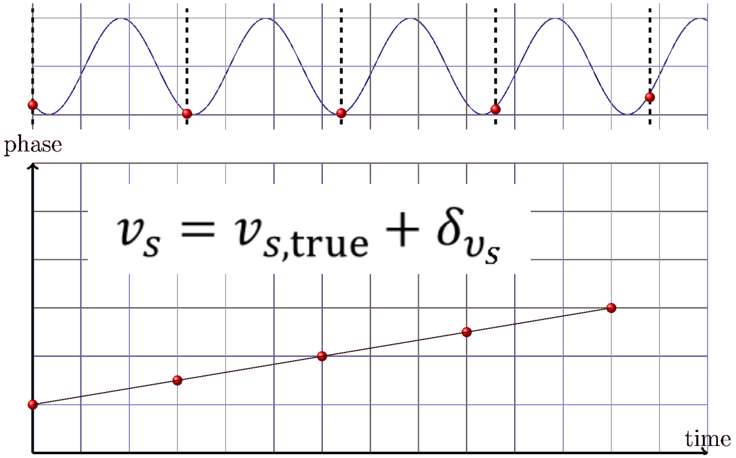
Precise spin tune measurement

Monitoring phase of asymmetry with fixed spin tune

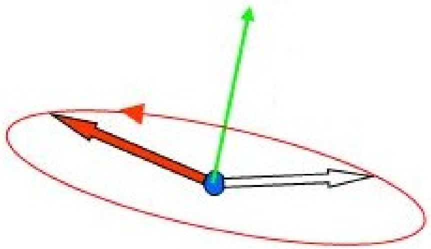


Phys.Rev.Lett. 115, 094801 (2015)

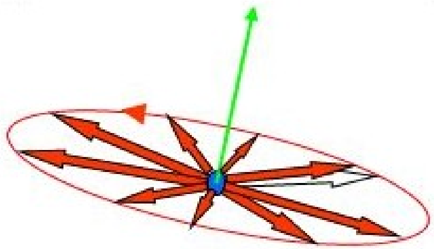




Spin coherence time



At the beginning all spin vectors aligned



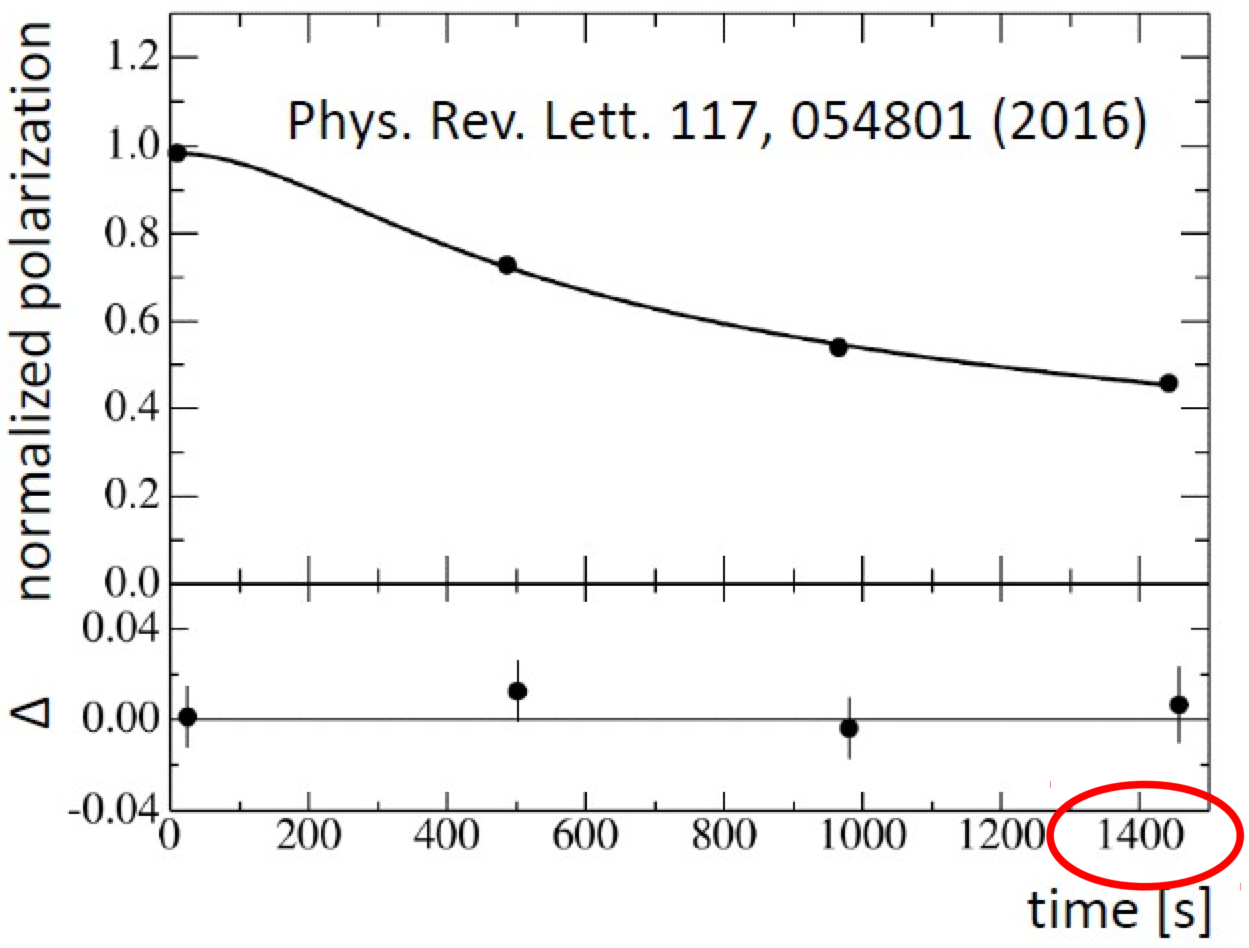
After some time spin vectors all out of phase

Polarization vanishes → measurement time limited

$$\frac{\Delta\gamma}{\gamma} = \beta^2 \frac{\Delta p}{p} \approx 10^{-4} = \frac{\Delta\nu}{\nu} \quad \Longrightarrow \quad \Delta\varphi \approx 60\, {}^{\mathrm{rad}}/_{\mathrm{s}}$$

- unbunched beam: $\frac{\Delta\gamma}{\gamma} \approx 10^{-5} \;\; \Longrightarrow$ decoherence in < 1s
- bunching: eliminate effects on $\frac{\Delta p}{p}$ in 1st order → $\tau \approx 20$ s
- correcting higher order effects using sextupoles and (pre-) cooling → $\tau \approx 1000$ s

Spin coherence time



Controlling spin direction

Maintain resonance frequency and phase between spin precession and Wien filter

→ keep precession frequency stable
→ match frequency and phase to Wien filter

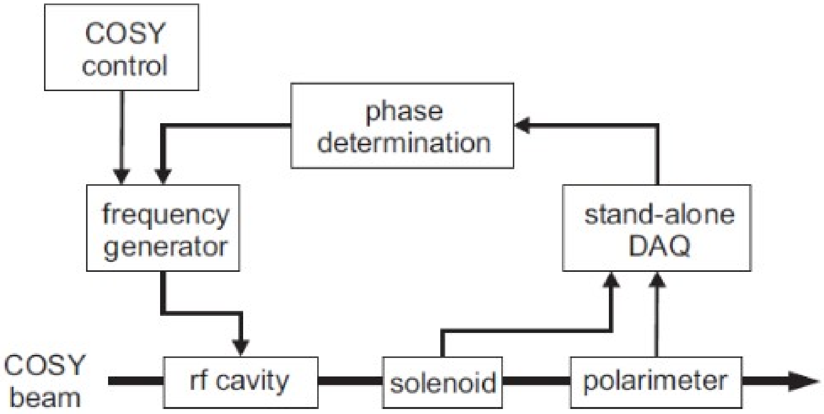
Test at COSY:

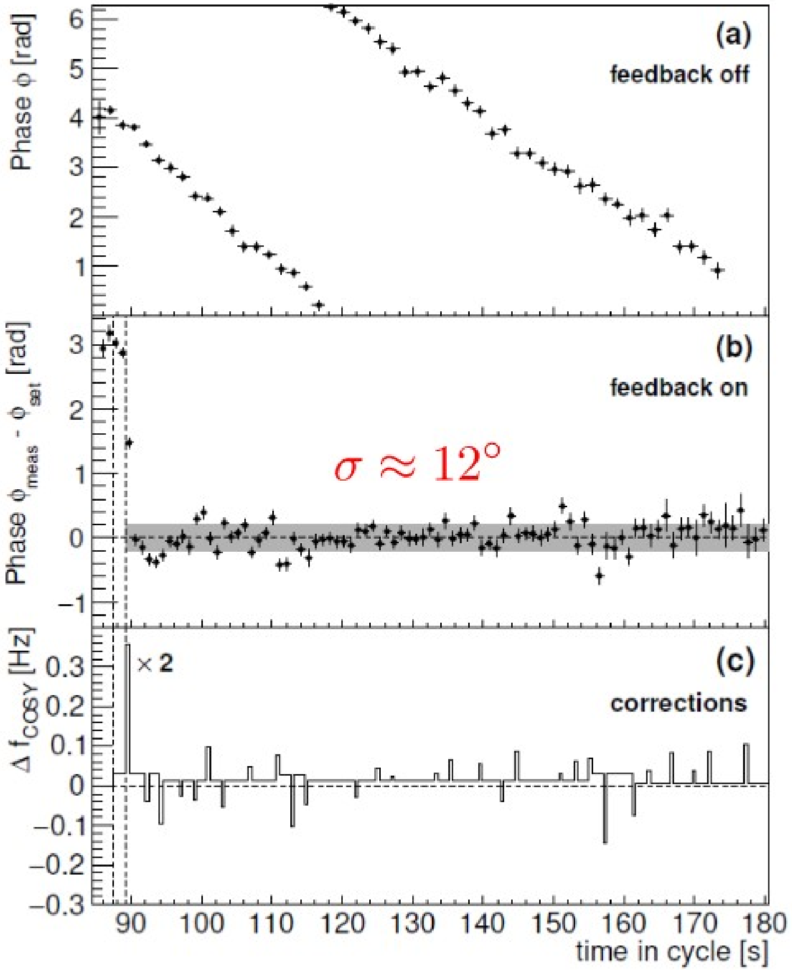
control spin tune via COSY rf:

$$\nu_s = G\gamma$$

control phase to external frequency

by accelerating/decelerating spin precession





PRL, 119, 014801 (2017)

JEDI Polarimetry – Database experiment

Motivation: database to produce realistic Monte Carlo simulations of detector responses for a polarimeter designed for EDM

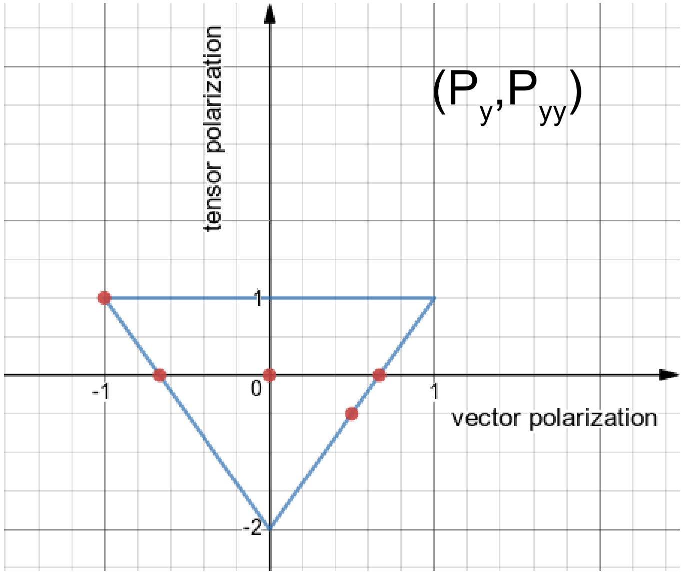
Goal: A_y, A_{yy}, dσ/dΩ for
→ dC elastic scattering
→ main background reactions (deuteron breakup)

Beamtime in November 2016 (2 weeks)

d energies: 170, 200, 235, 270, 300, 340, 380 MeV
Targets: C and CH_2

Beam polarization: 5 polarization states
(P_y,P_{yy}) = (0,0), (-⅔,0), (⅔,0), (½, -½), (-1, 1)

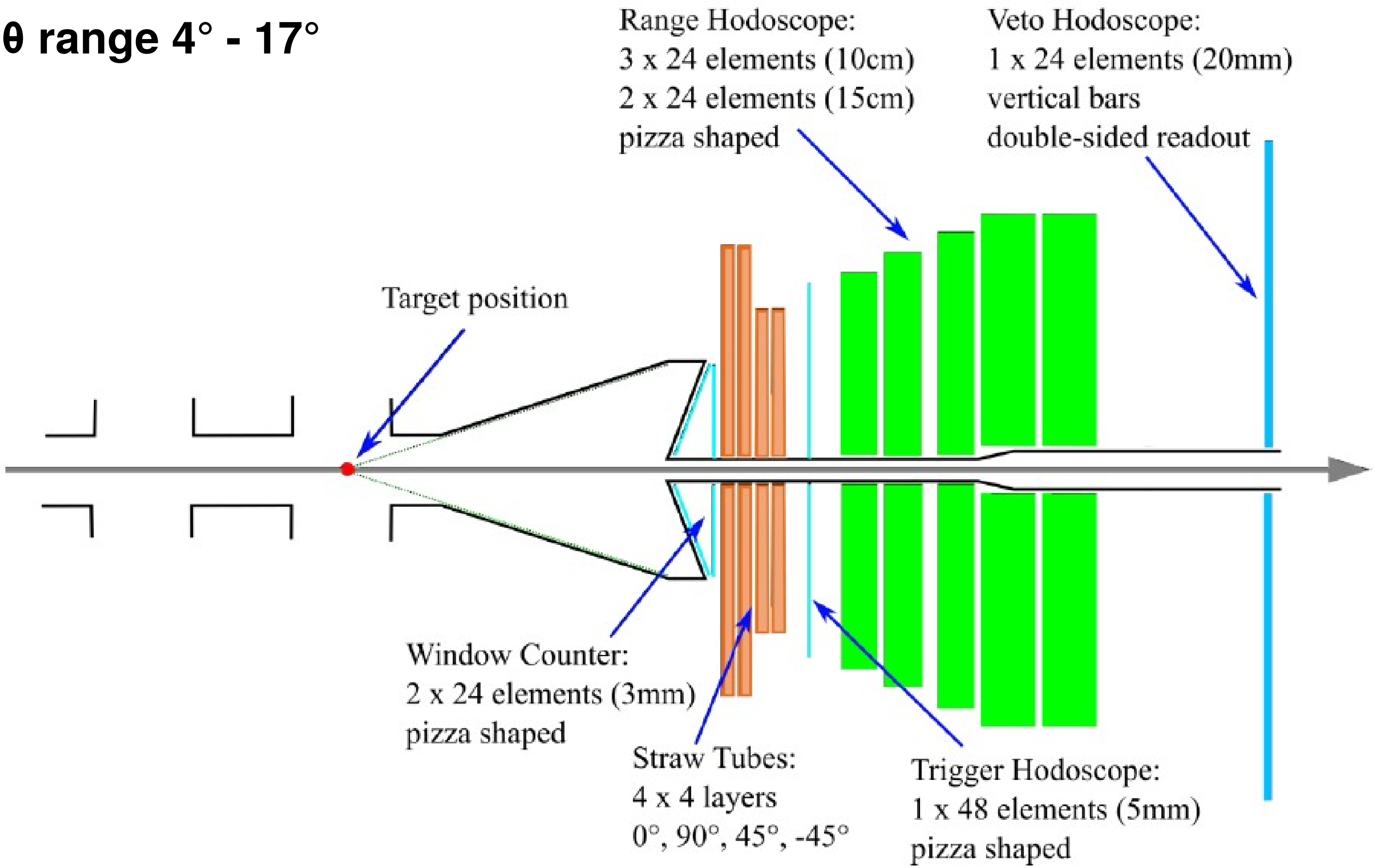
Setup: Modified WASA Forward Detector



Experiment Overview

→ **Full φ coverage**

→ **θ range 4° - 17°**



Range Hodoscope:
3 x 24 elements (10cm)
2 x 24 elements (15cm)
pizza shaped

Veto Hodoscope:
1 x 24 elements (20mm)
vertical bars
double-sided readout

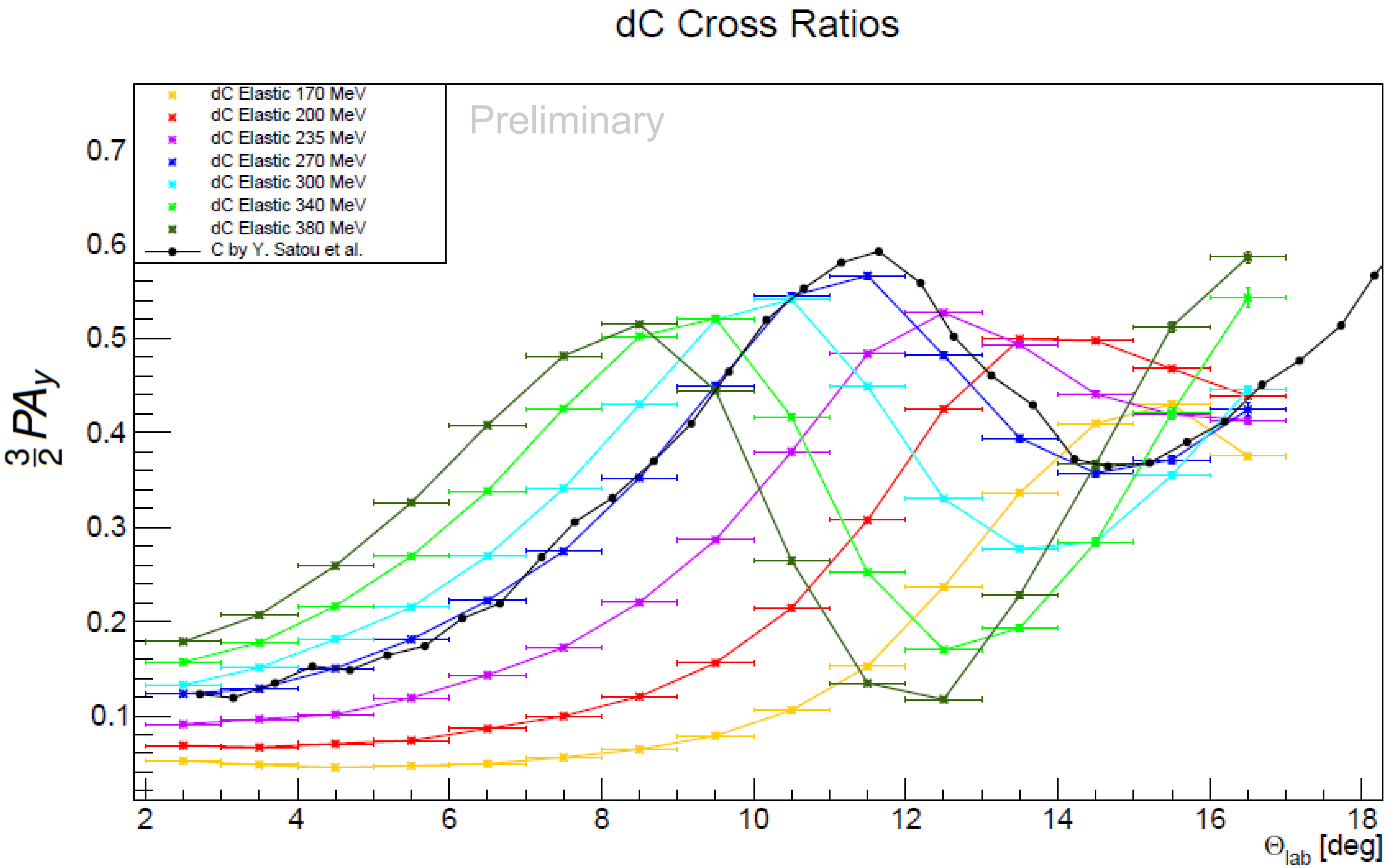
Target position

Window Counter:
2 x 24 elements (3mm)
pizza shaped

Straw Tubes:
4 x 4 layers
0°, 90°, 45°, -45°

Trigger Hodoscope:
1 x 48 elements (5mm)
pizza shaped

JEDI Polarimetry – Database experiment



Cross rations for all energies and angles. Satou et al. data scaled for comparison.

Conclusions

- EDMs of elementary particles key for understanding sources of CP violation
  → explanation of matter – antimatter imbalance

- Principle of experiments – measurements of spin precession in magnetic field
- EDM of charged particles measured in storage rings

- COSY: ideal starting point for R&D and a pre-cursor experiment with Wien Filter method