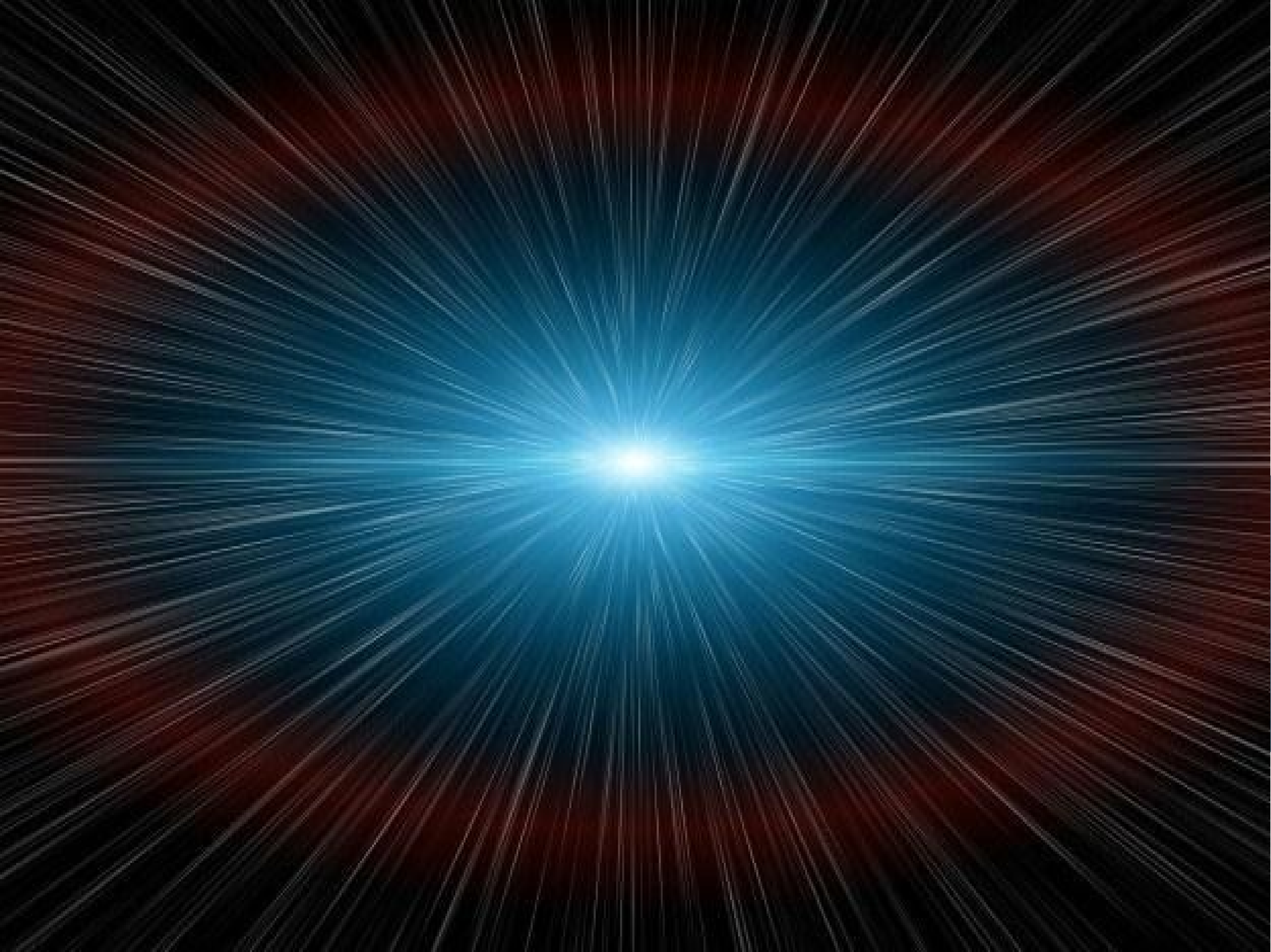
Recent Progress of the Storage Ring EDM Search with the JEDI Collaboration

28.02.2018 | Maria Żurek for JEDI Collaboration

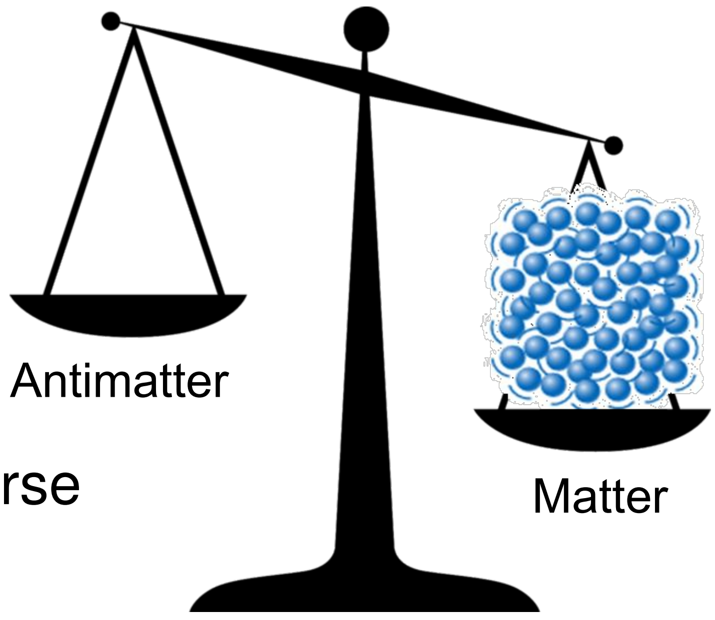
Forschungszentrum Jülich, Institut für Kernphysik



Motivation

Baryon Asymmetry Problem

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



Preconditions needed to explain it:

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

Sakharov (1967)

Motivation

Baryon Asymmetry Problem

- **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!

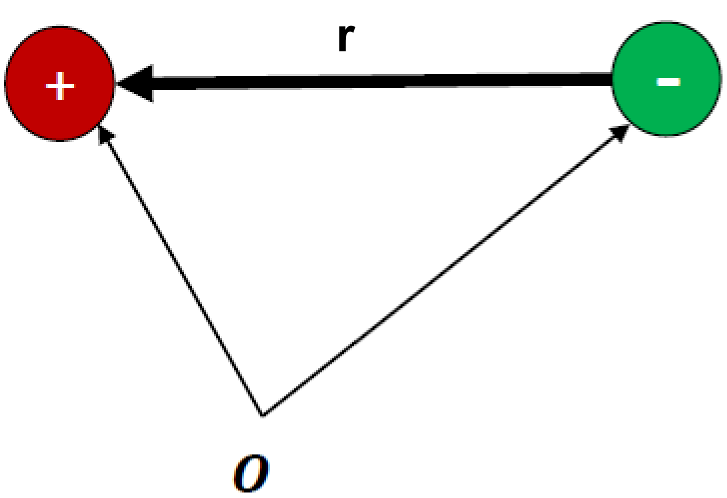
New sources of CP violation Beyond Standard Model needed!

They can manifest in **Electric Dipole Moments** of particles

Motivation

Electric Dipole Moment

Classically



- Charge × displacement

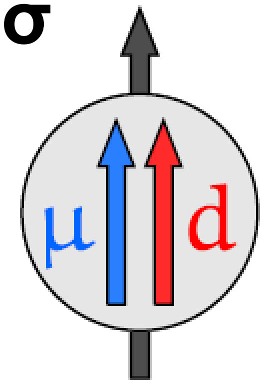
In Quantum Mechanics

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

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

$$\mathbf{d} = d\boldsymbol{\sigma}$$

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

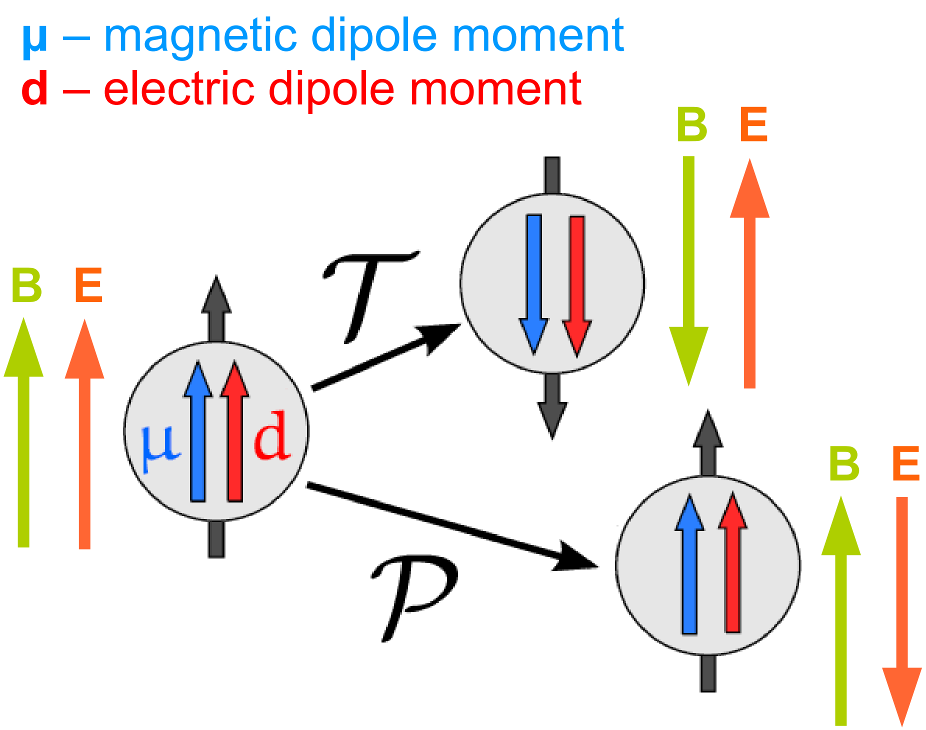


μ – magnetic dipole moment
d – electric dipole moment

EDM – CP violation

The observable quantity:

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

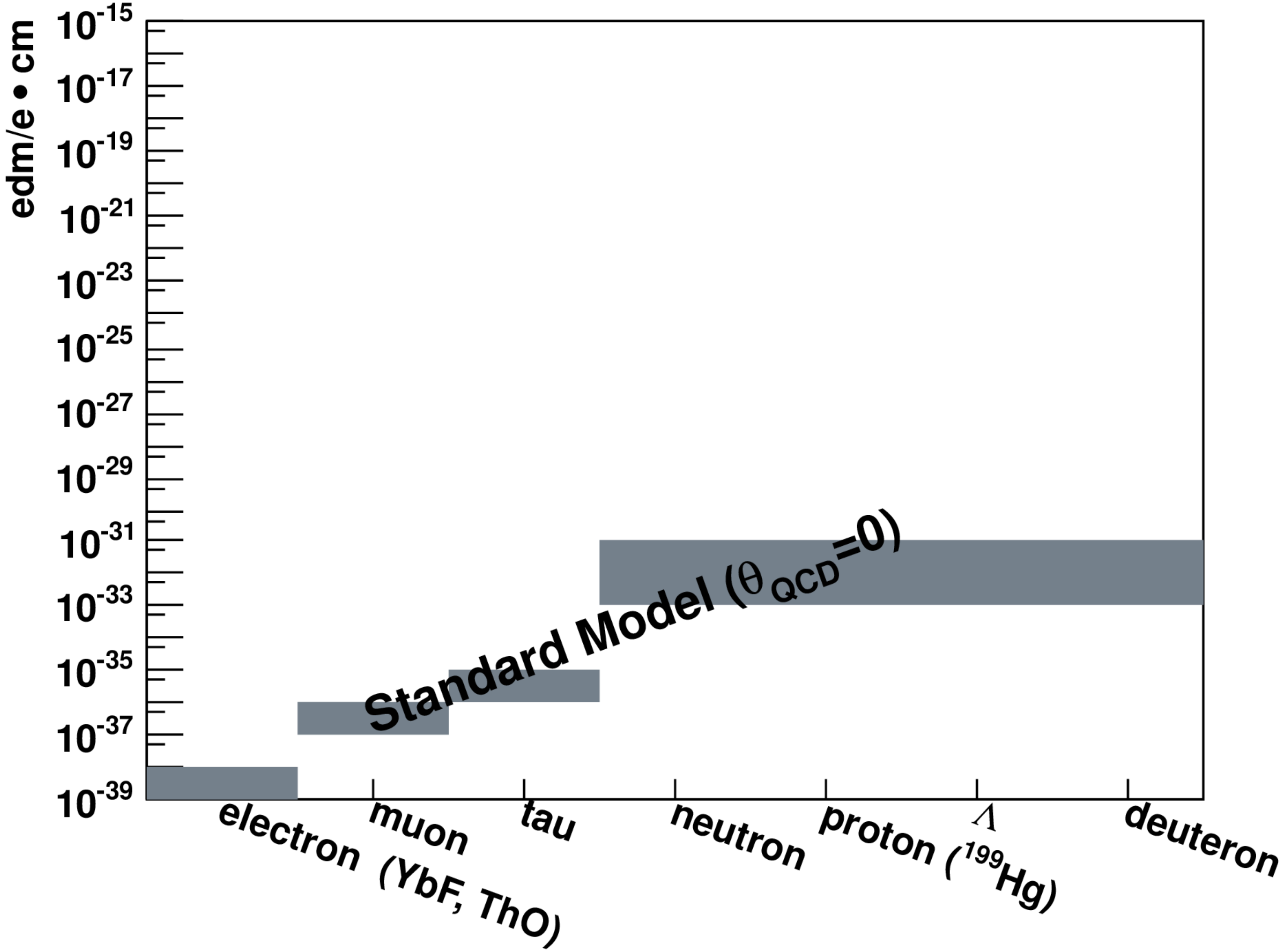


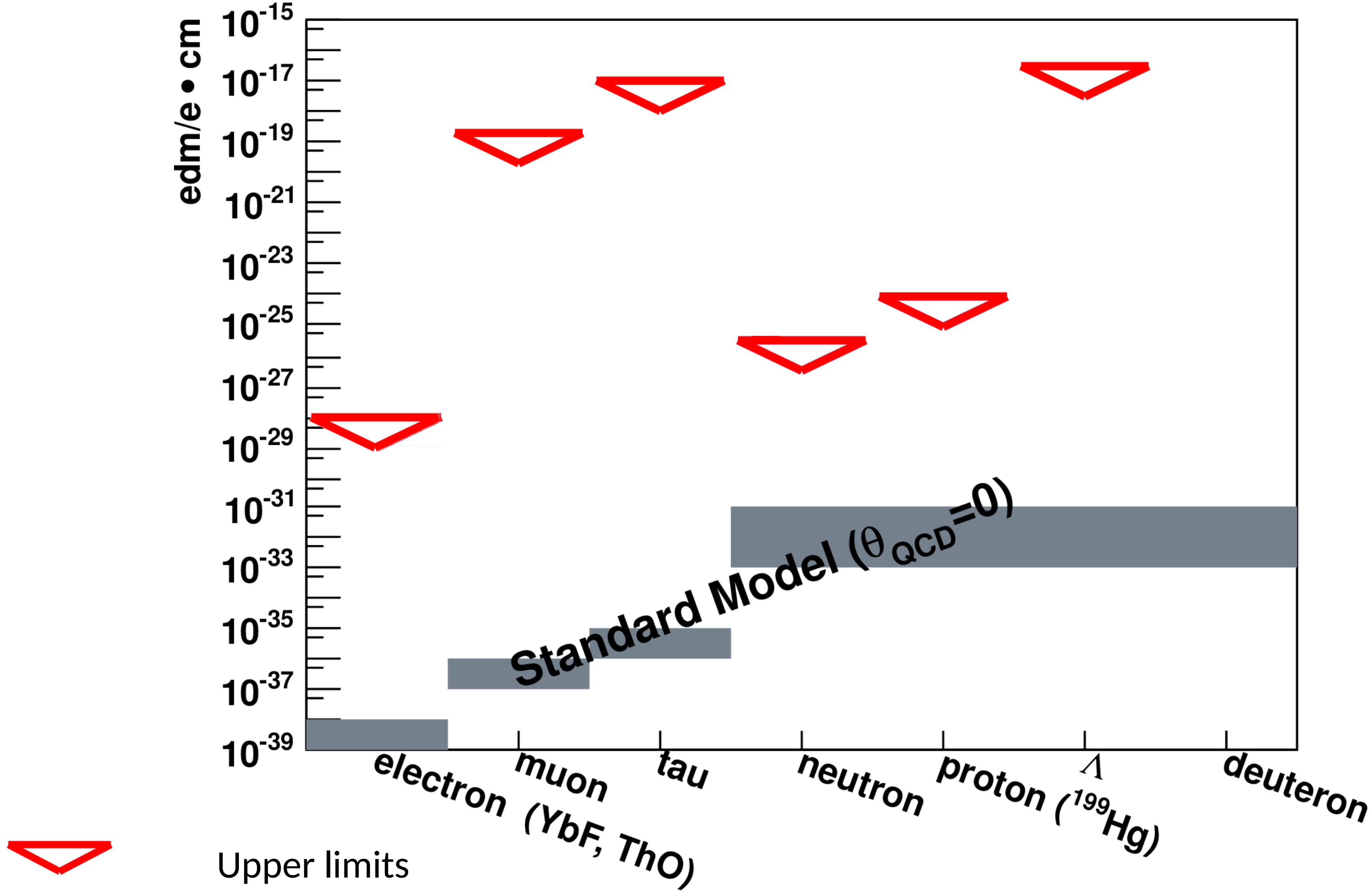
$$H = H_E + H_M = -\mu\boldsymbol{\sigma}\cdot\mathbf{B} - d\boldsymbol{\sigma}\cdot\mathbf{E}$$

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

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

T violation → CP violation (since CPT conserved)


edm/e • cm
10-15
10-17
10-19
10-21
10-23
10-25
10-27
10-29
10-31
10-33
10-35
10-37
10-39
Standard Model (θ QCD=0)
electron (YbF, ThO)
muon
tau
neutron
proton (199Hg)
Λ
deuteron


edm/e • cm
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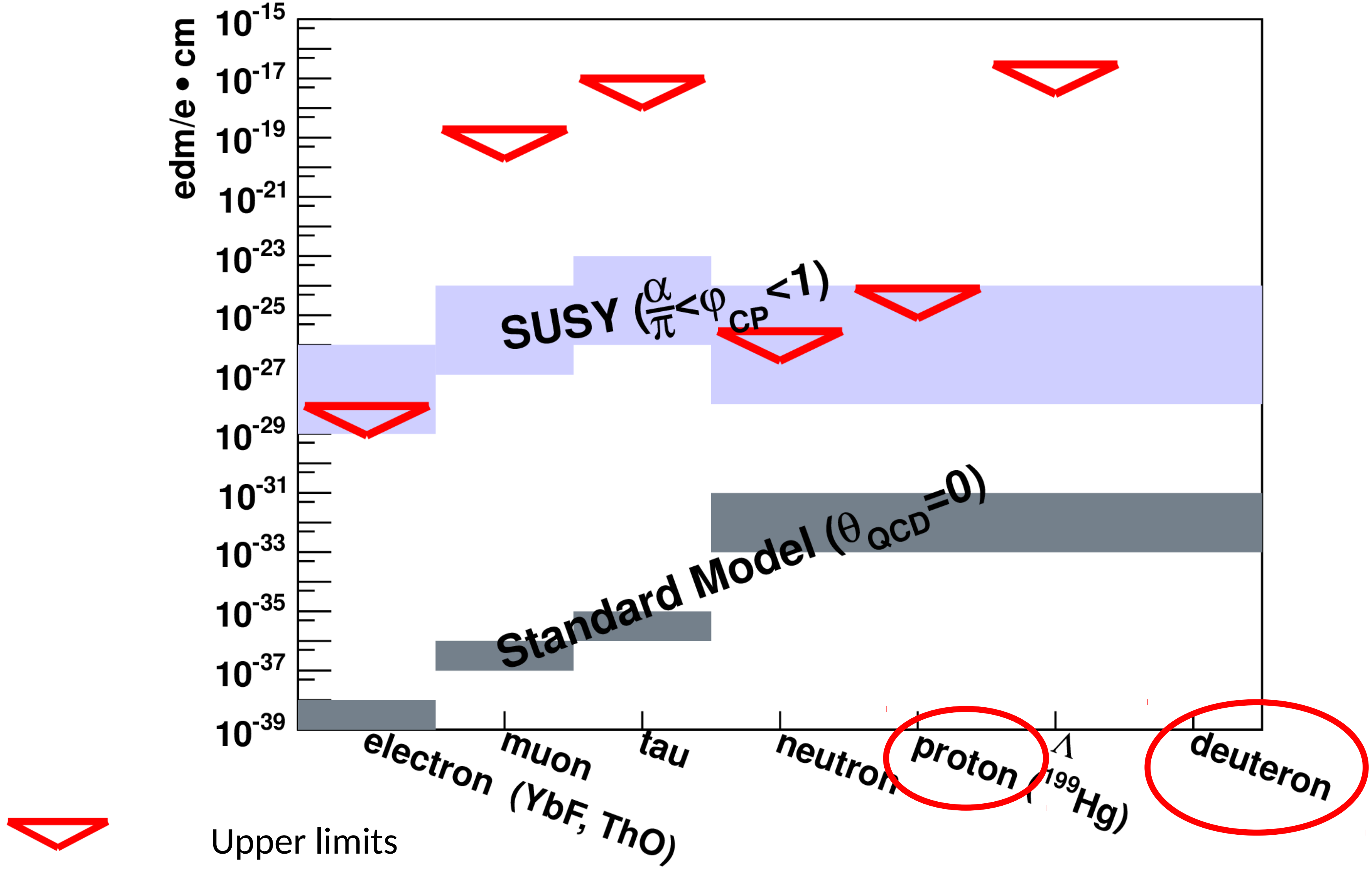
Standard Model (θ_{QCD}=0)
electron (YbF, ThO)
muon
tau
neutron
proton (^{199}Hg)
Λ
deuteron
Upper limits



edm/e • cm
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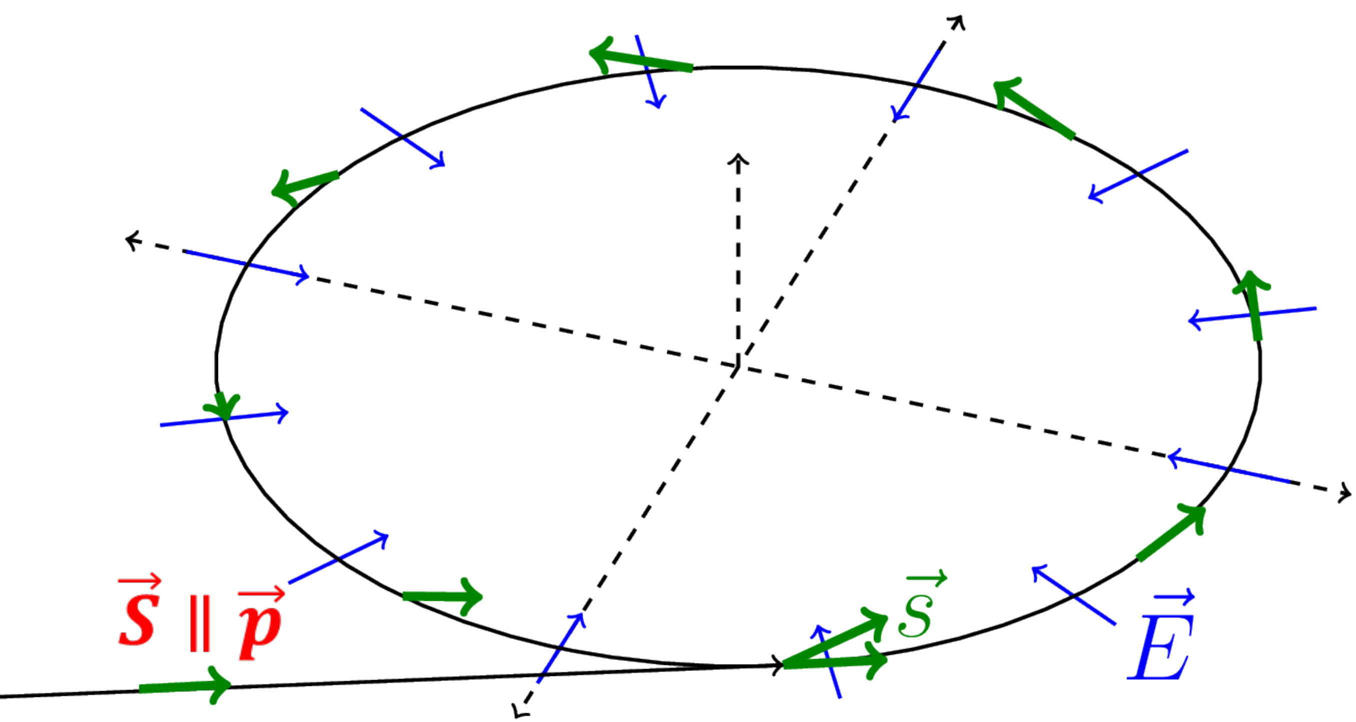
SUSY (α/π<φ_CP<1)
Standard Model (θ_QCD=0)
electron (YbF, ThO)
muon
tau
neutron
proton (199Hg)
Λ
deuteron
Upper limits

Measurement principle

For charged particles:

→ apply electric field in a storage ring

Simplified case:



"Frozen spin"

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

Build-up of vertical polarization by slow precession

Extremely small effects!

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

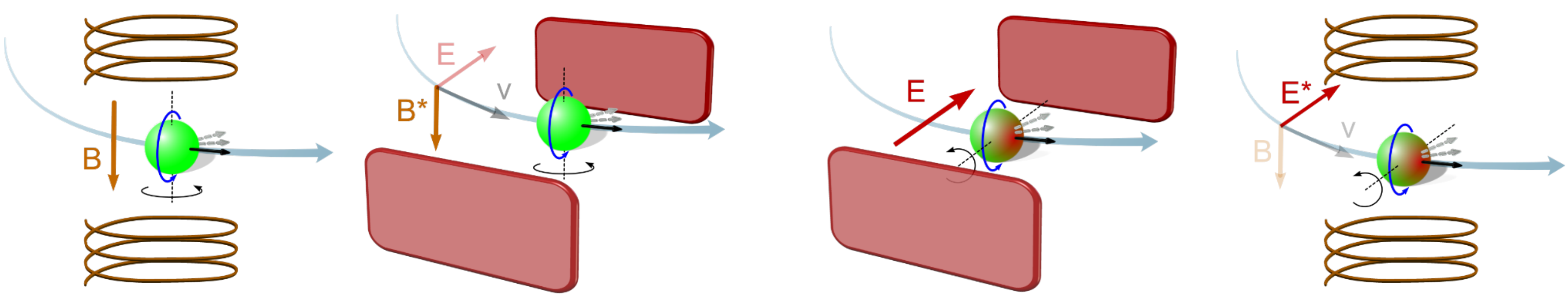
Measurement principle

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

Ω: angular precession frequency — d: electric dipole moment

G: anomalous magnetic moment — γ: Lorentz factor

Measurement

Pure 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

Research and Development at COSY

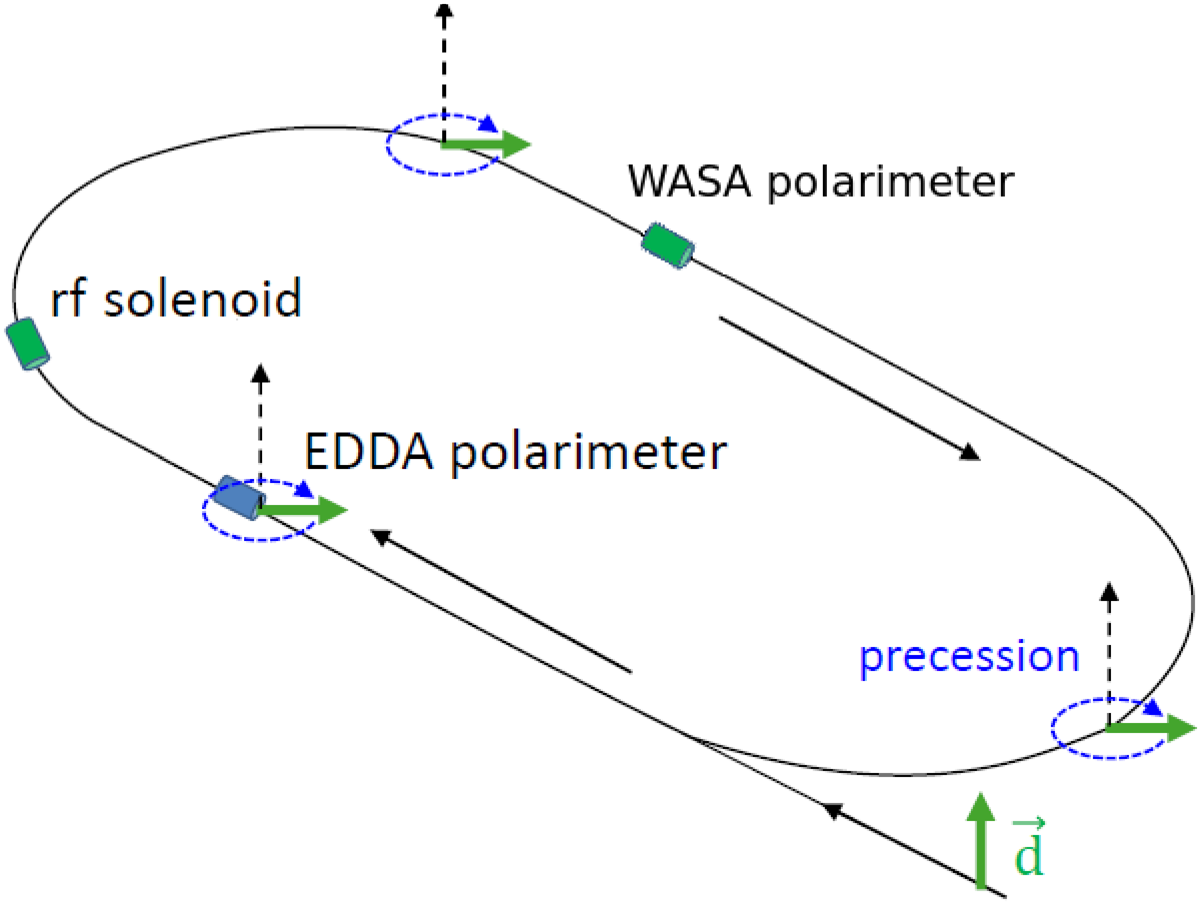
http://collaborations.fz-juelich.de/ikp/jedi/

EDMs of charged hadrons: p, **d**

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

study spin tune $\upsilon_s = \frac{|\vec{\Omega}|}{|\vec{\omega}_{\text{cycl}}|} = \gamma G$

→ phase advance per turn



Research and Development at COSY

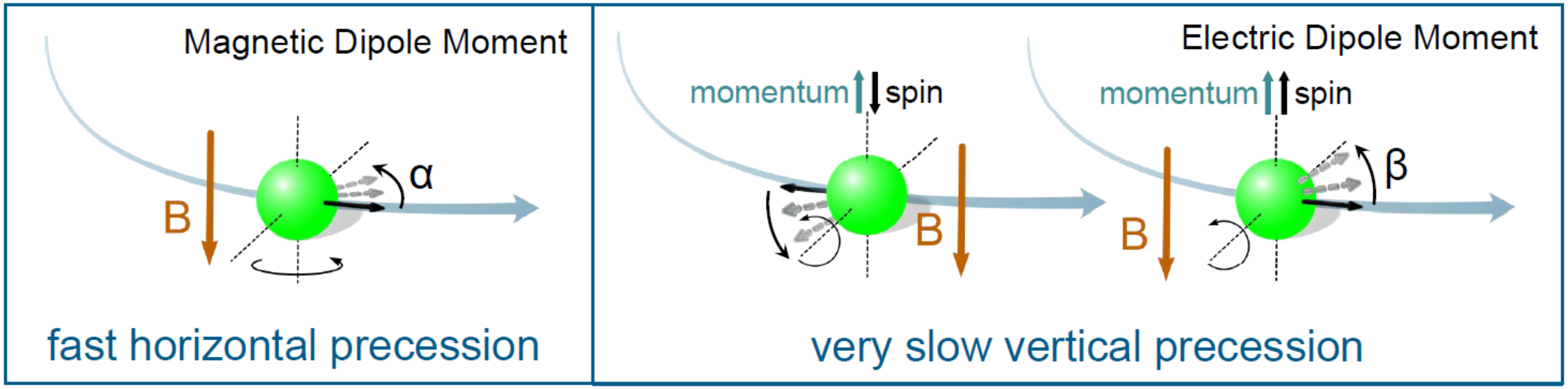
- Measurement of fast precessing polarization
  Phys. Rev. ST Accel. Beams 17, 052803 (2014)
- Precise determination of spin tune
  Phys. Rev. Lett. 115, 094801 (2015)
- Spin coherence time
  Phys. Rev. Lett. 117, 054801 (2016)
- Phase lock of spin precession
  Phys. Rev. Lett. 119, 014801 (2017)

- Dedicated polarimetry → D. Shergelashvili (HK 36.6) and F. Müller (HK 36.7) talks
- Beam instrumentation → F. Abusaif (HK 41.3) talk

- **Wien filter commissioning**
- **Database for future polarimetry**

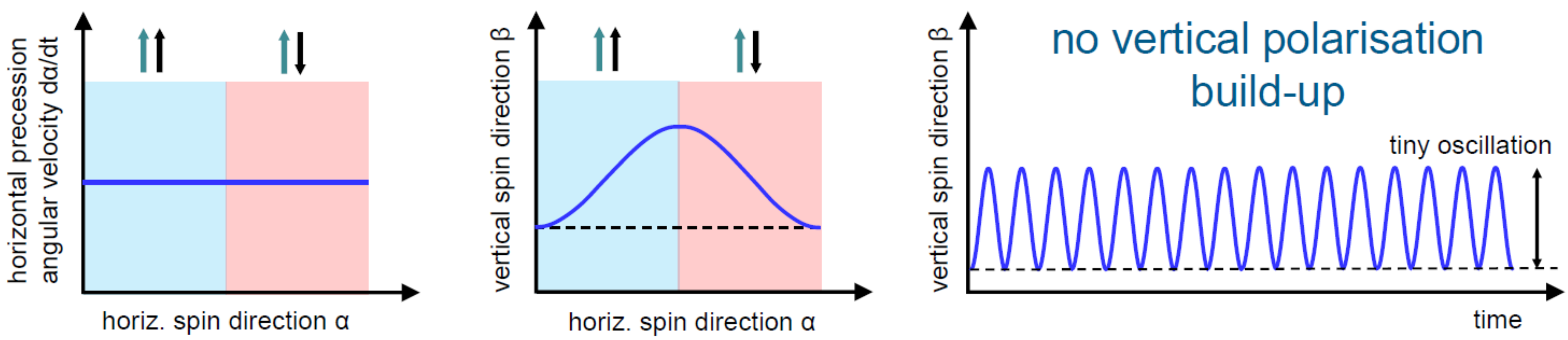
Measurement in COSY

Pure magnetic ring



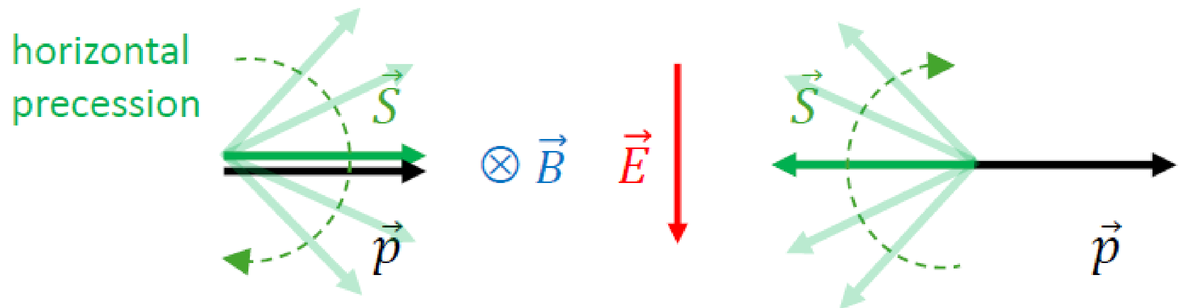
E* field tilts spin due to EDM
50% of time up
50% of time down

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



Measurement

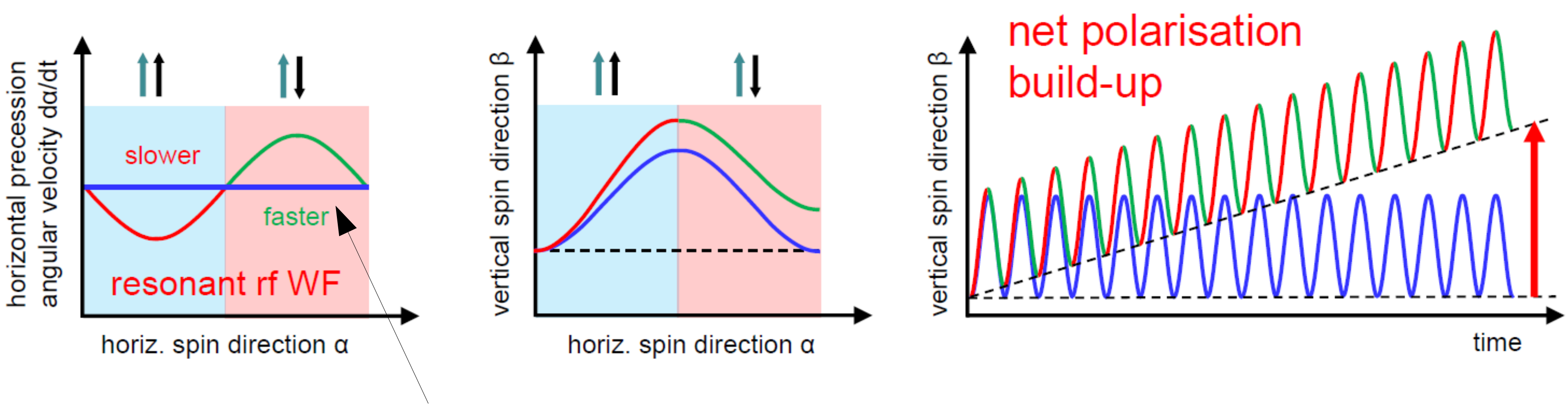
RF Wien Filter method



Wien Filter: introduces B and E field oscillating with radio frequency

Lorentz force vanishes: no effect on EDM rotation

Effect: Adds extra horizontal precession

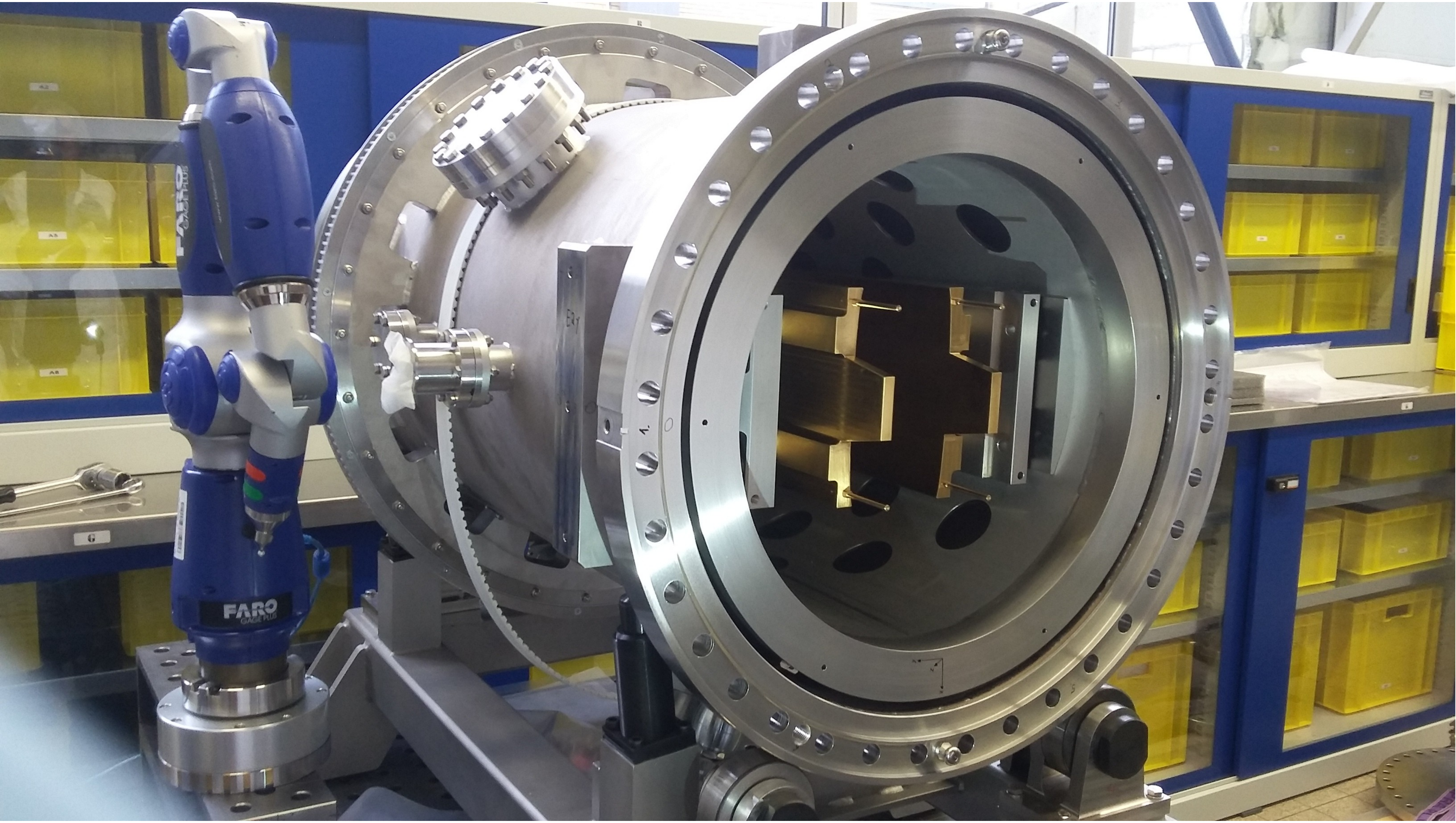


Wien Filter has to be always **in phase** with the horizontal spin precession!

Feedback system developed and tested: Phys. Rev. Lett., 119, 014801 (2017)

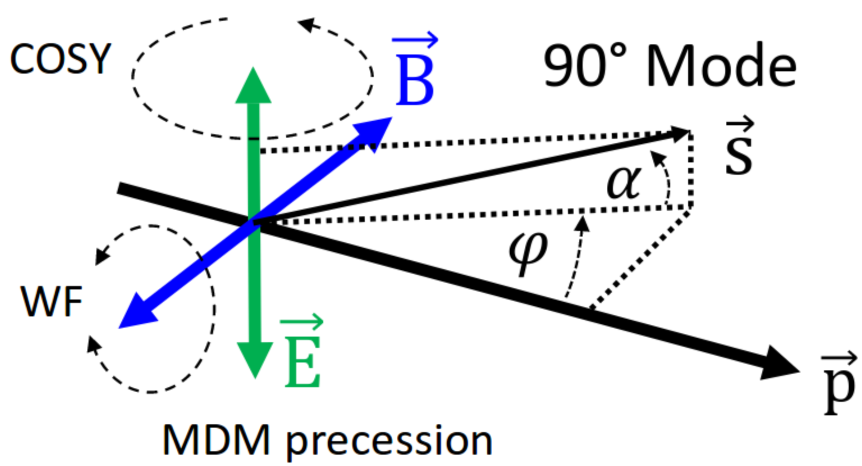
Resonant frequency controlled, precession of spin phase locked

Wien Filter Commissioning



Wien Filter Commissioning – 90° mode

Spin rotations with phase lock

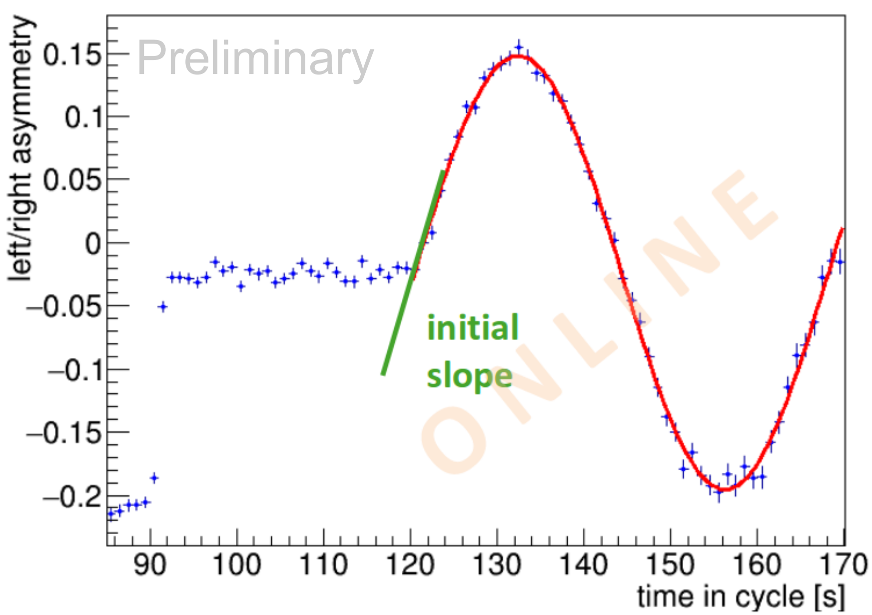


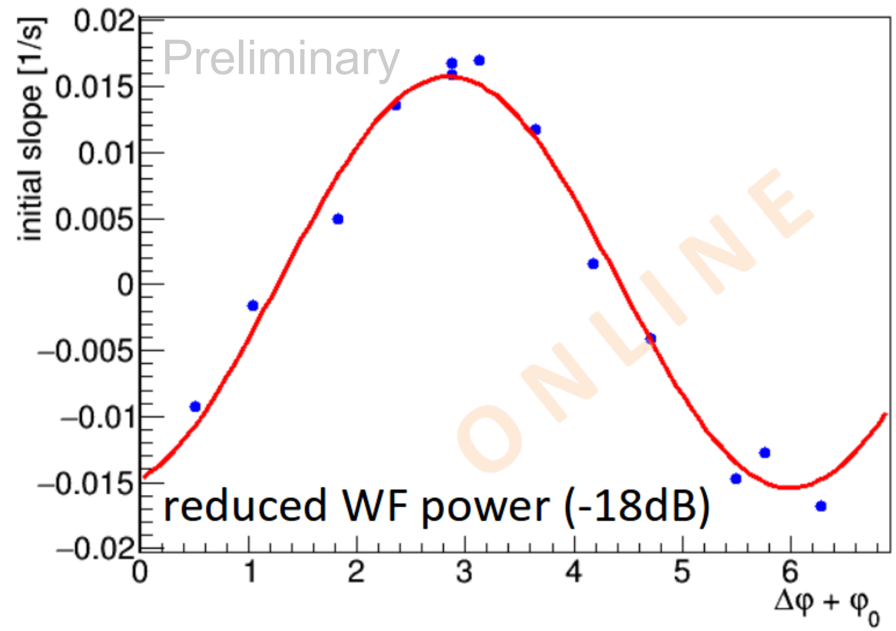
$\varphi(t) = 2\pi\, \nu_s f_C t$

$B_{WF}(t) = B_0 \sin(\omega t + \Delta\varphi)$

Task: maintain $\omega = 2\pi\, |k + \nu_s| f_C$ and fix $\Delta\varphi$

→ Controlled via WF frequency

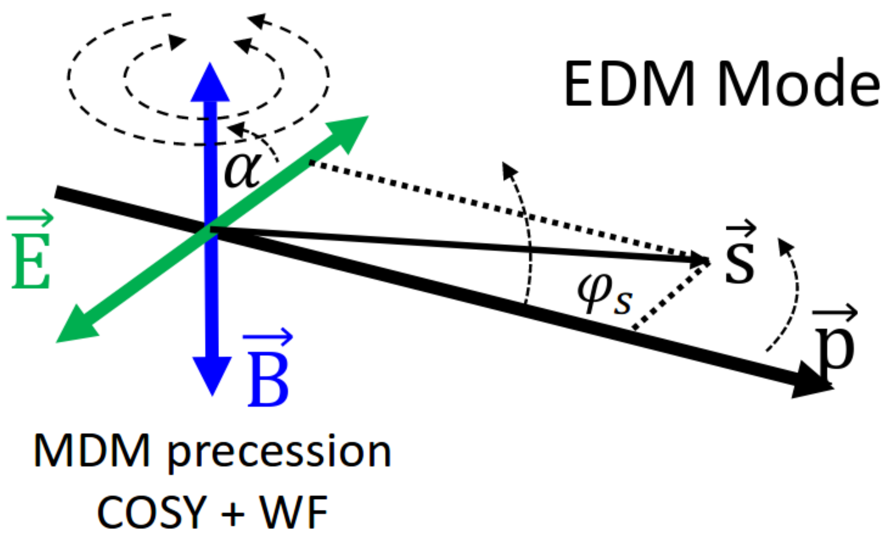


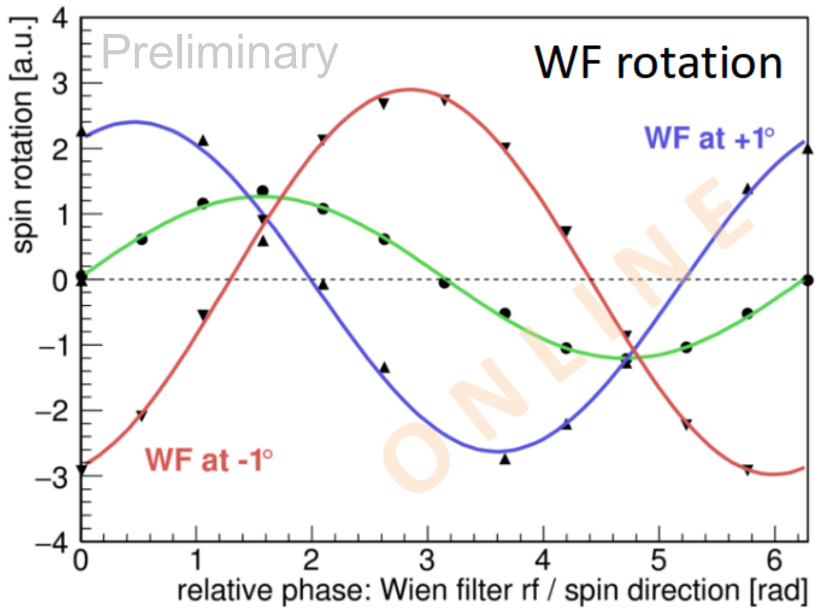


Spin build-up as a function of phase ~ sinΔφ → Feedback system works properly!

Wien Filter Commissioning – 0° mode

Spin rotations with phase lock





We see **vertical polarization buildup → EDM-like signal**

Two **systematic** contributions:

1. Residual, radial magnetic field from WF

→ effect equivalent to WF rotation

2. Field imperfections in COSY

→ transverse contribution: equivalent to WF rotation

→ longitudinal contribution: equivalent to additional static solenoid field

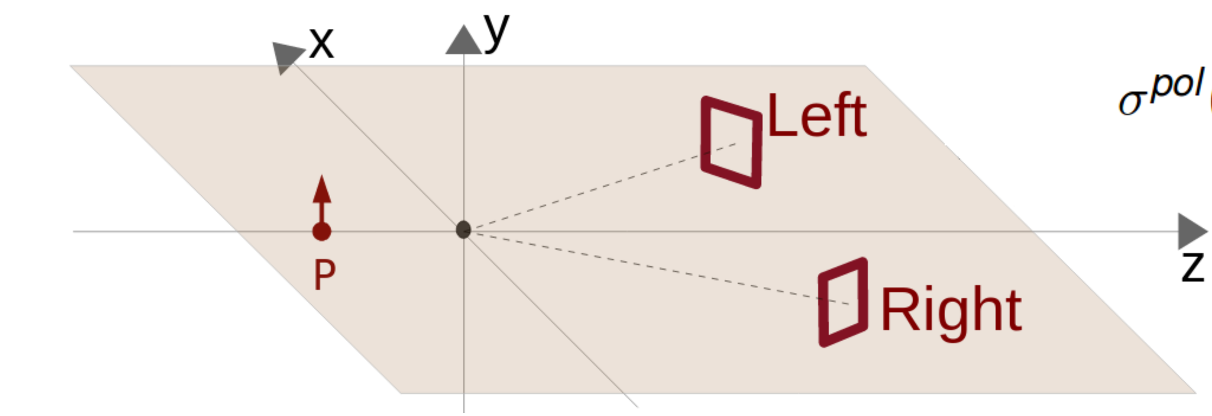
The measurement shows the stability of COSY conditions within 24 hours

Polarimetry – database experiment

Reaction: dC elastic scattering

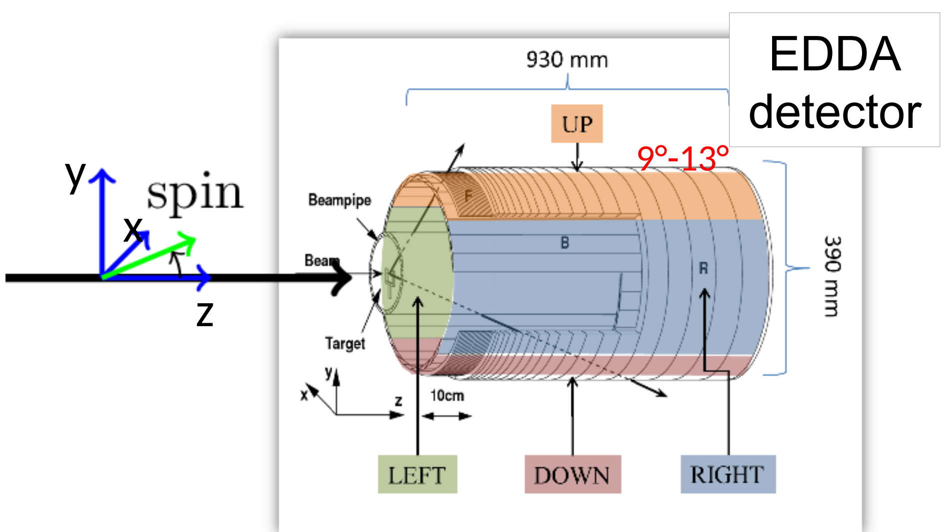
Up/Down asymmetry ∝ horizontal component of polarization P_x

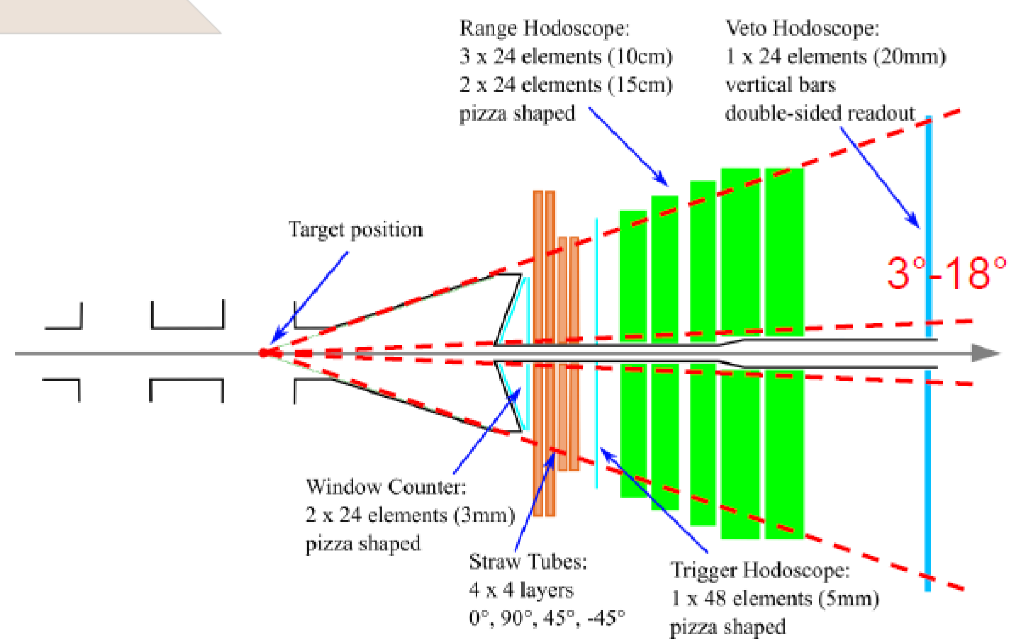
Right/Left asymmetry ∝ vertical component of polarization P_y



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

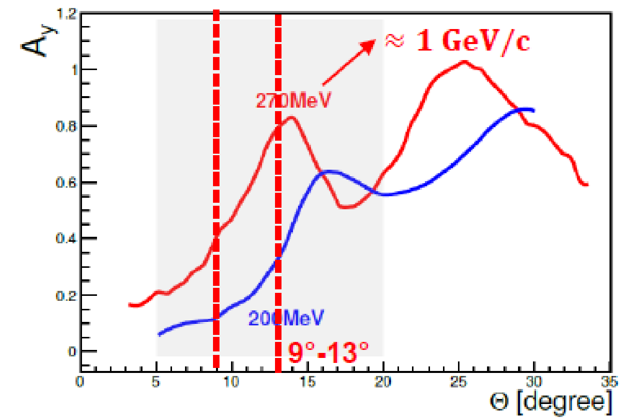
$$PA_y(\theta) = \frac{\sigma^L(\theta) - \sigma^R(\theta)}{\sigma^L(\theta) + \sigma^R(\theta)}$$





Polarimetry – database experiment

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



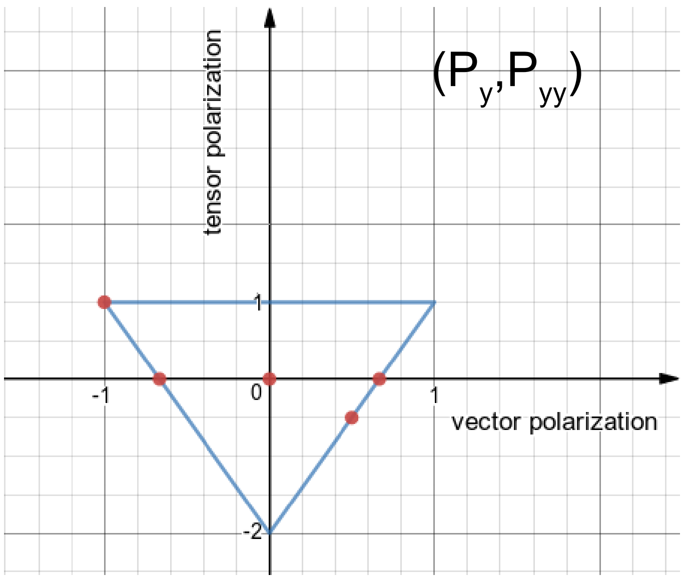
Goal: A_y, A_{yy}, $d\sigma/d\Omega$ for
→ dC elastic scattering
→ main background reactions (deuteron breakup)

Beamtime in November 2016 (2 weeks)

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

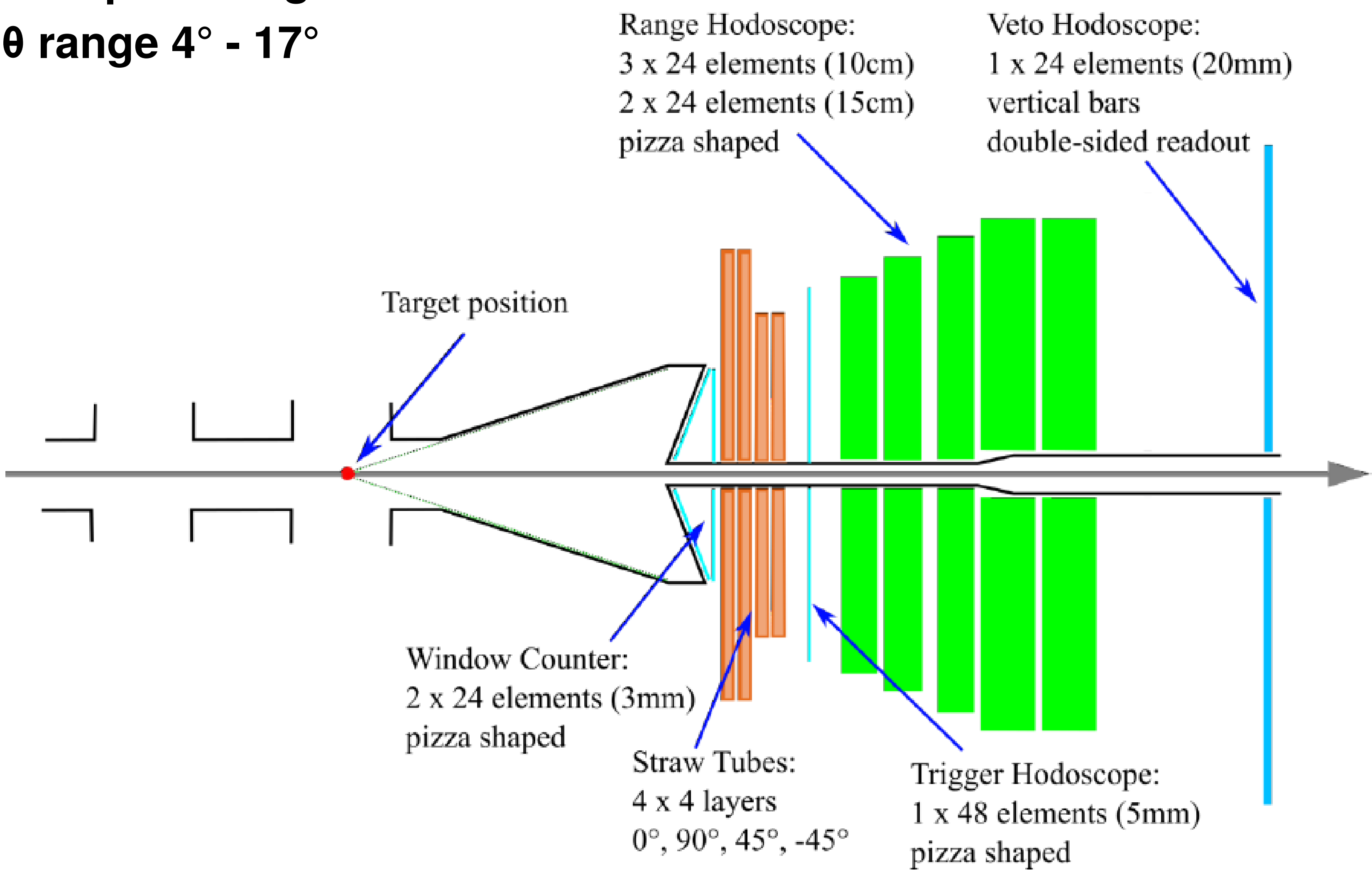
Beam polarization: 5 polarization states
(P_y,P_{yy}) = (0,0), (-⅔,0), (⅔,0), (½, -½), (-1, 1)

Setup: Modified WASA Forward Detector

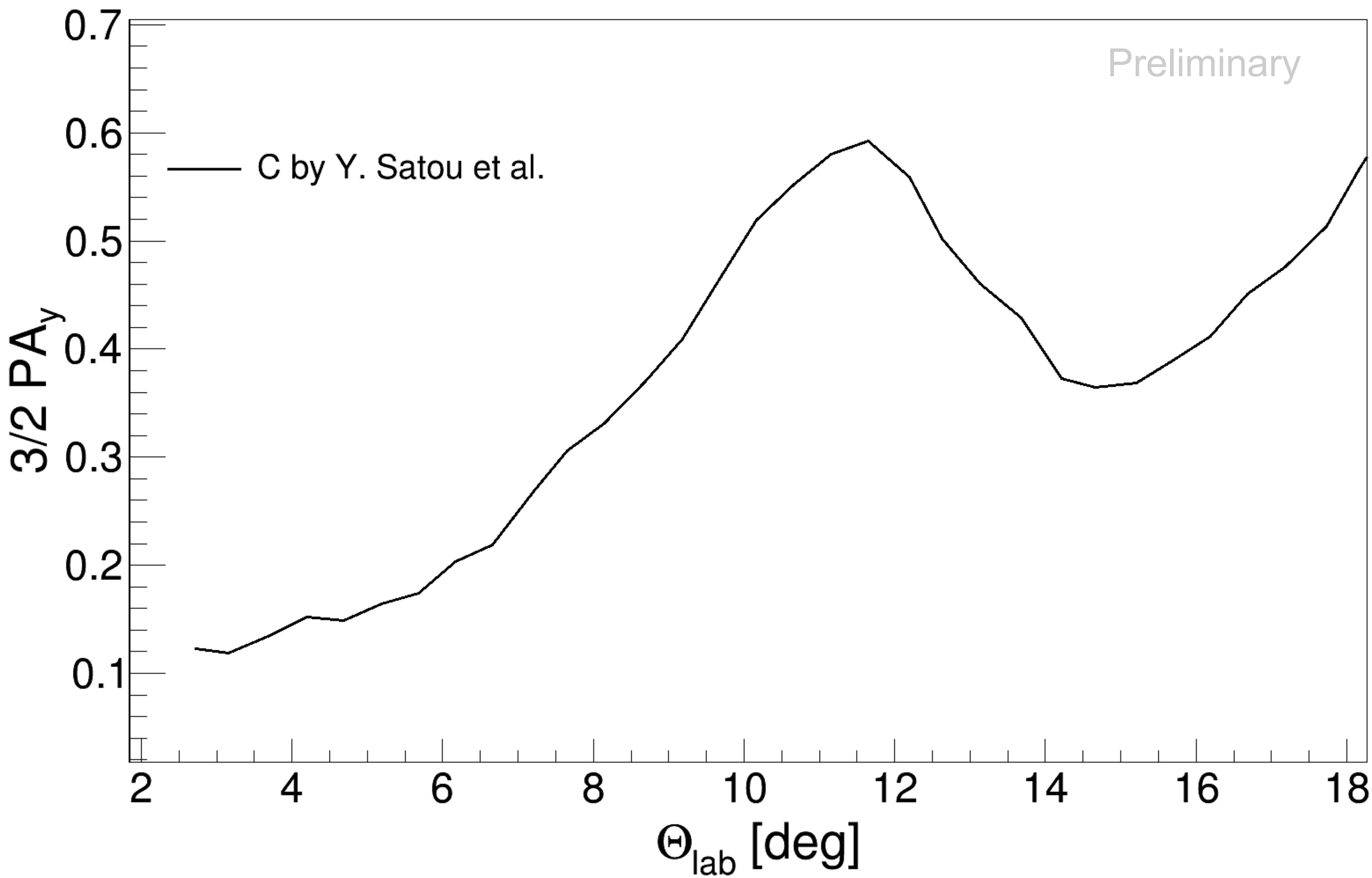


Polarimetry – database experiment

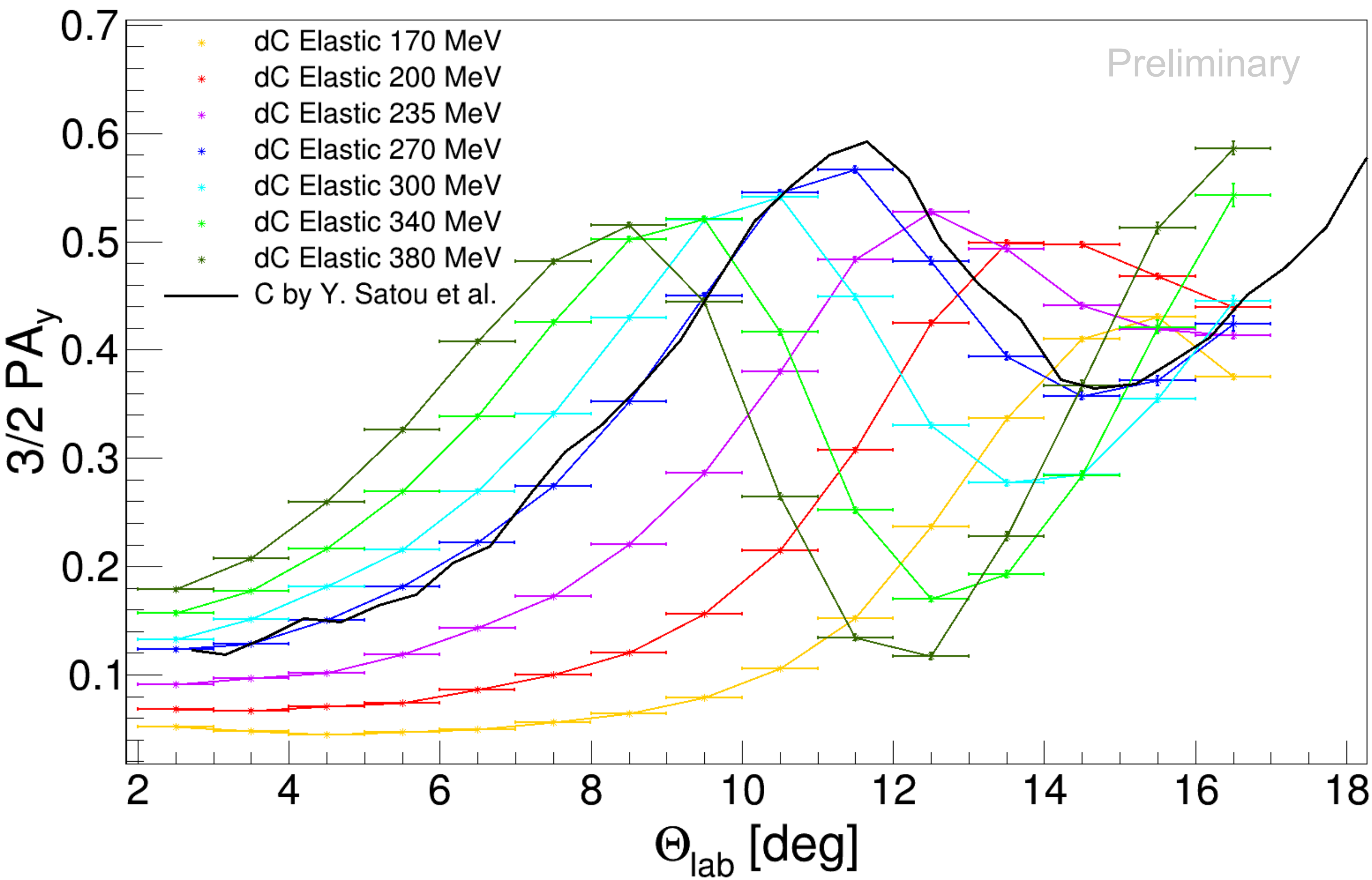
→ **Full φ coverage**
→ **θ range 4° - 17°**



Polarimetry – database experiment



Polarimetry – database experiment



Conclusions

- EDMs of elementary particles key for understanding sources of CP violation
  $\rightarrow$ 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

Backup

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

EDM – Orders of magnitude

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

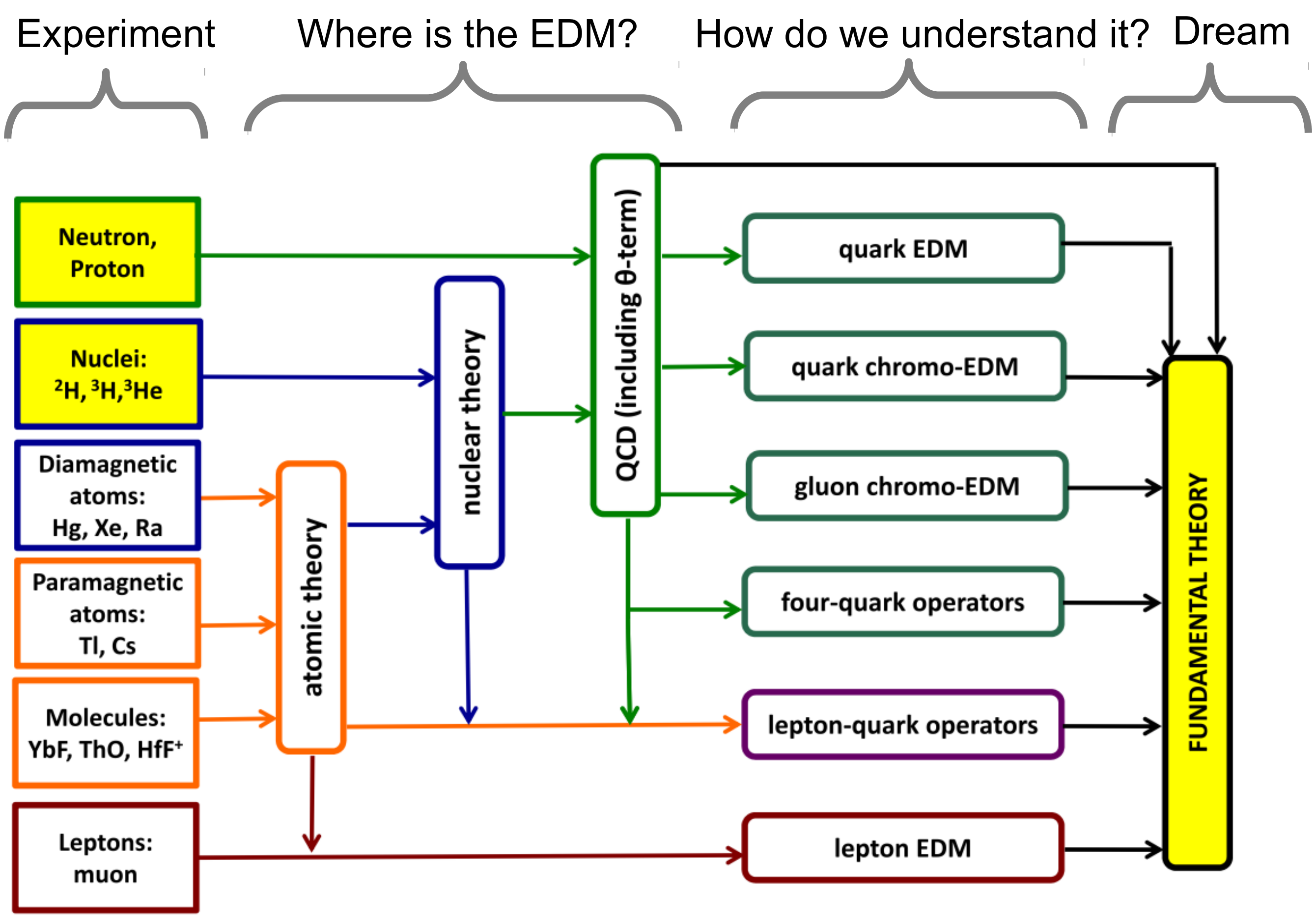
nEDM of 10^{-26} e · cm → separation of u from d quarks of ~ 5 · 10^{-26} cm

Motivation

Electric Dipole Moment of proton and deuteron

No direct measurement

Disentangle the fundamental source(s) of EDMs



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

$$\mu B_r \sim dE_r$$

Measurement

Pure 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

Storage rings: combined ring

magnetic moment EDM

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

„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

Polarimetry

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

- 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

Polarimetry

Detector signal

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

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Asymmetry

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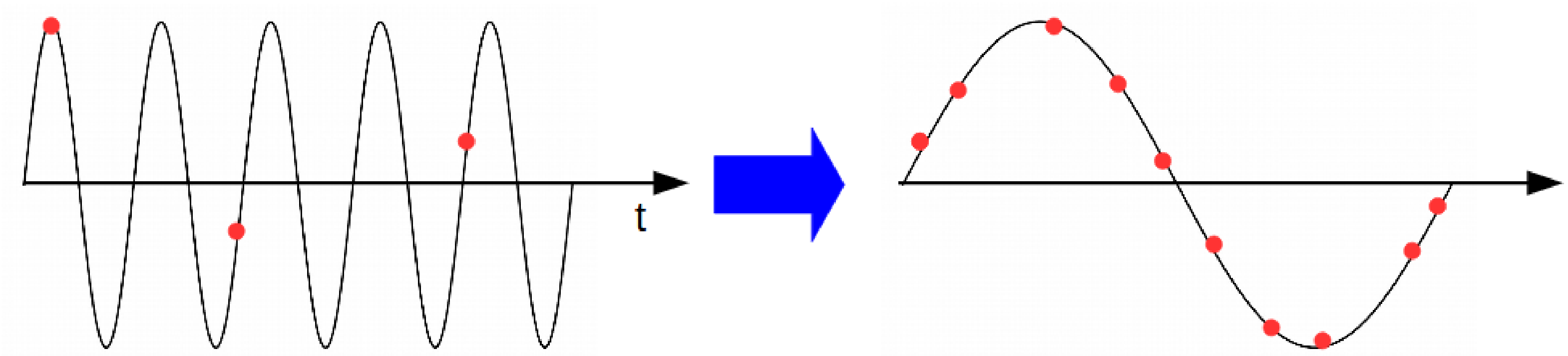


Too few polarimeter events to resolve oscillation directly!

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

Polarimetry

beam revolutions: counting turn number *n*

↓

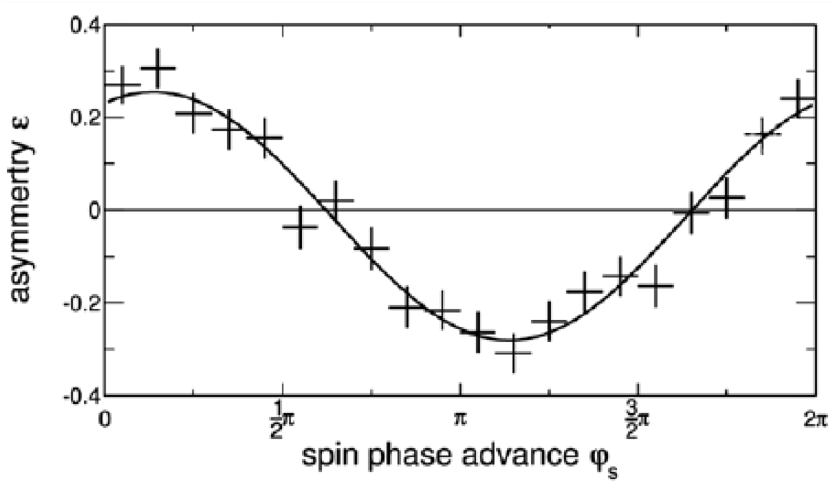
assign turn number *n* → phase advance $\varphi_s = 2\pi\nu_s n$

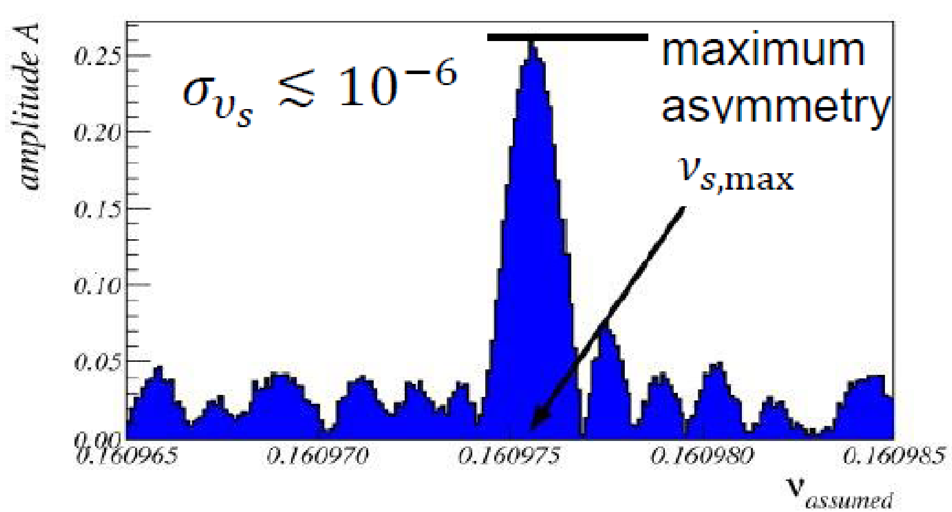
↓

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

↓

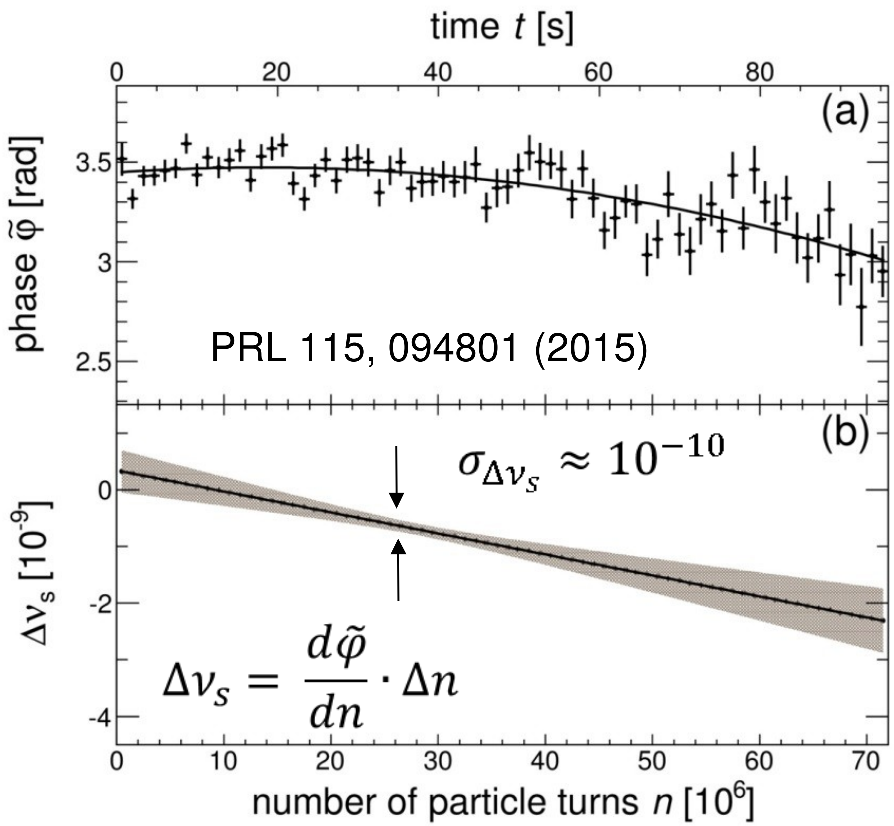
scan ν_s in some interval around $\nu_s = \gamma G$

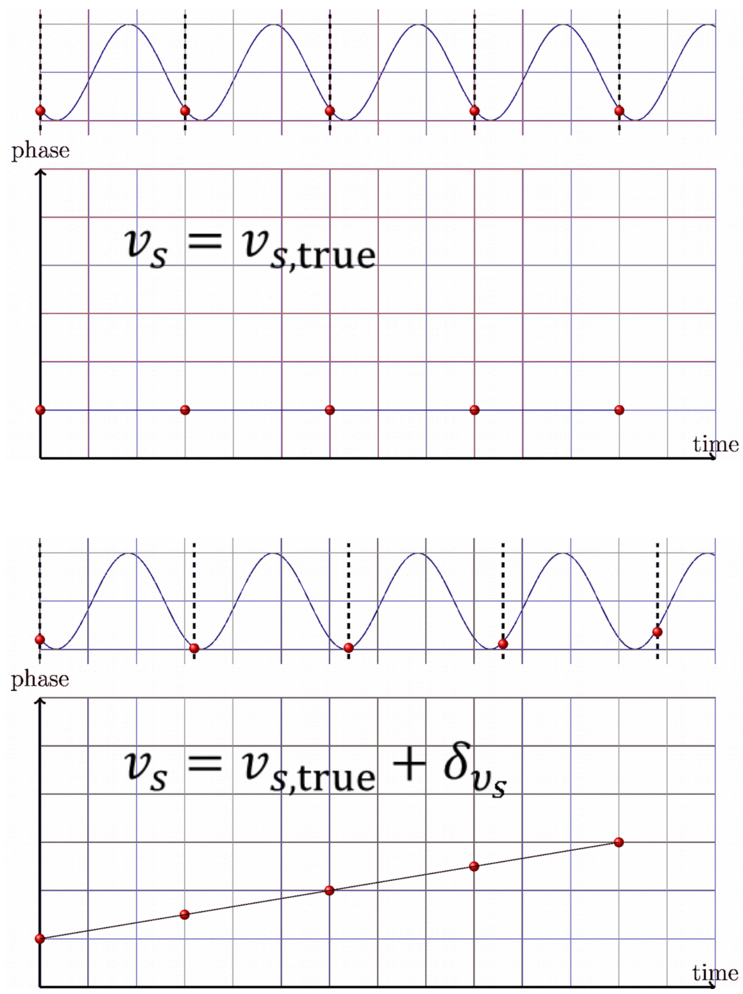




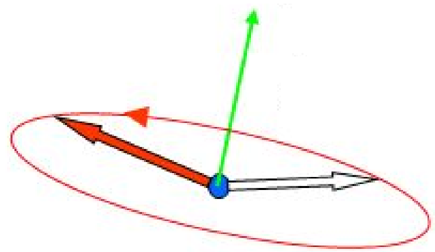
Spin tune measurement

Monitoring phase of asymmetry with fixed spin tune

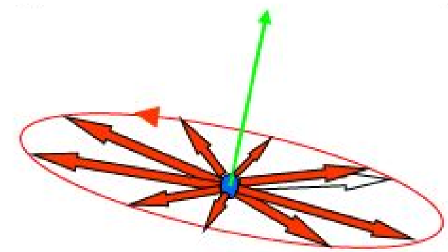




Spin coherence time



At the beginning all spin vectors aligned



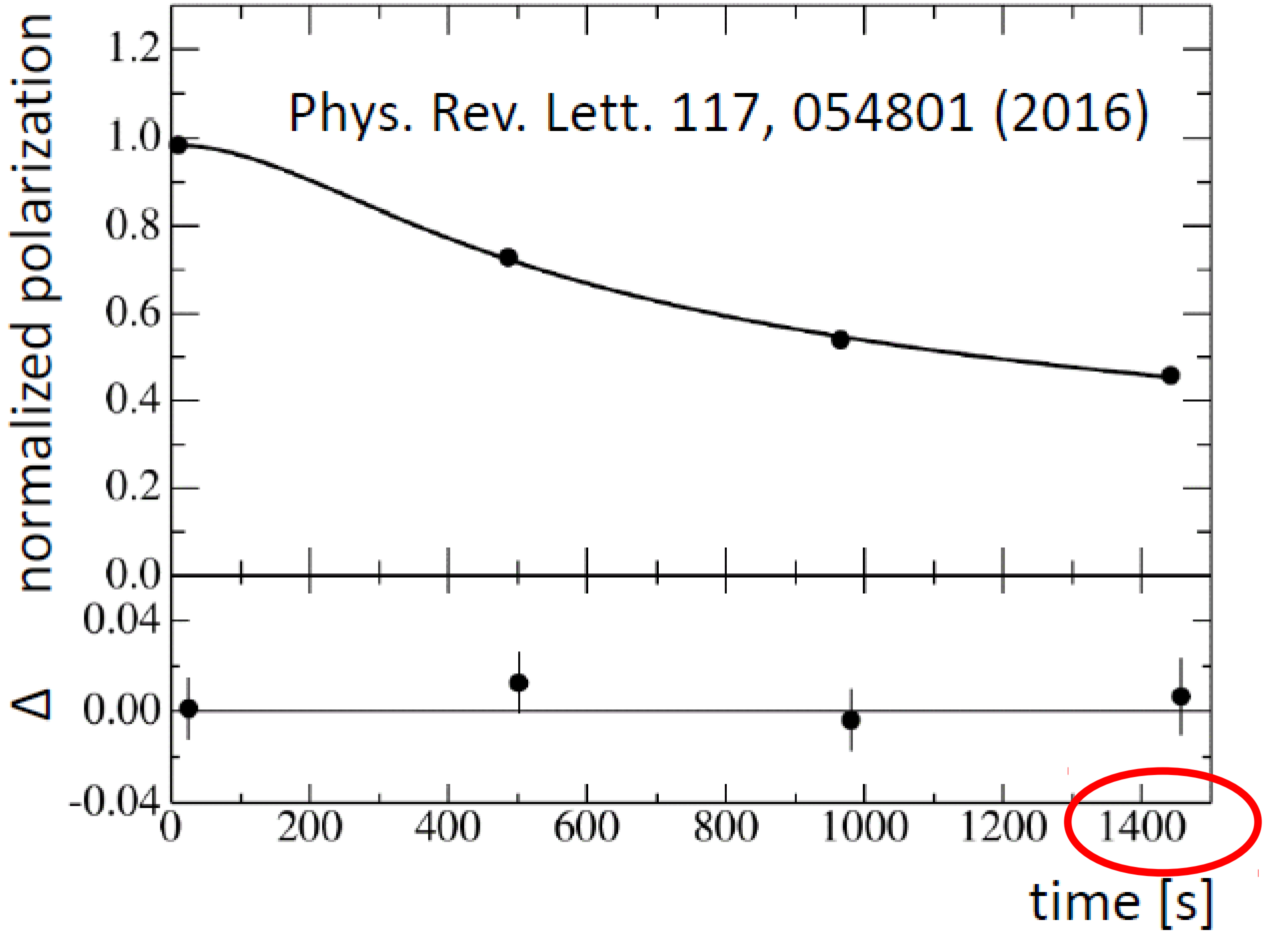
After some time spin vectors all out of phase

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



Controling spin direction

Feedback system

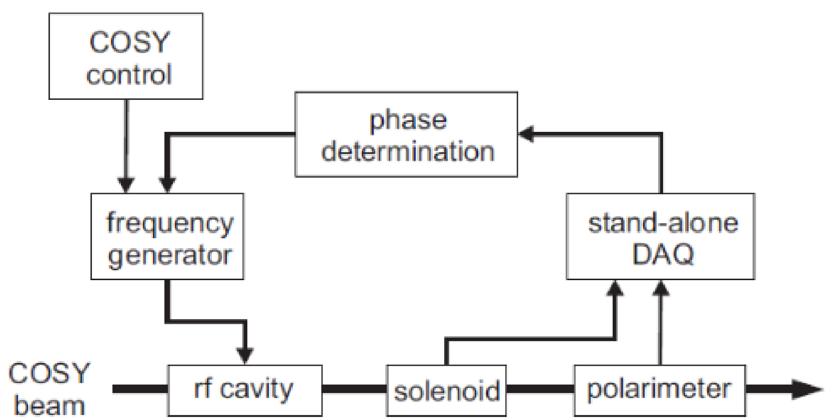
Goal: Maintain resonance frequency and phase between spin precession and Wien filter

→ 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



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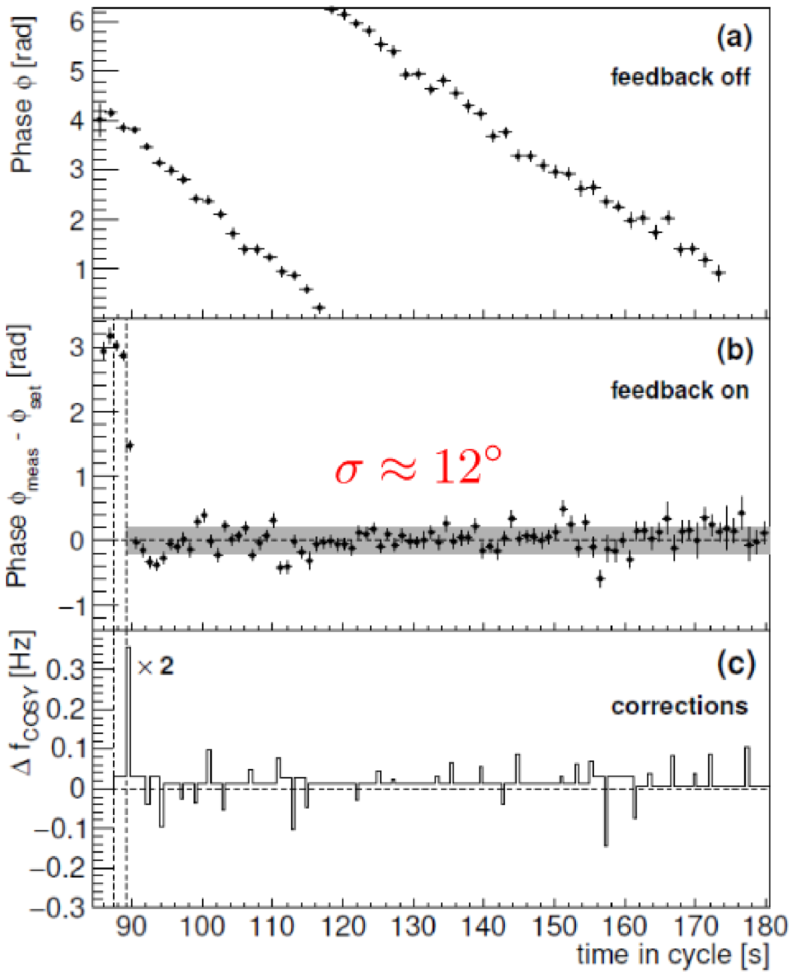

Wien Filter Commissioning

Detuned WF: residual Lorentz force

Tuned WF: Lorenz force vanishes

Detuned WF: residual Lorentz force excites beam at WF frequency
→ Lock-in amplifier connected to BPMs measures amplitude of beam oscillations