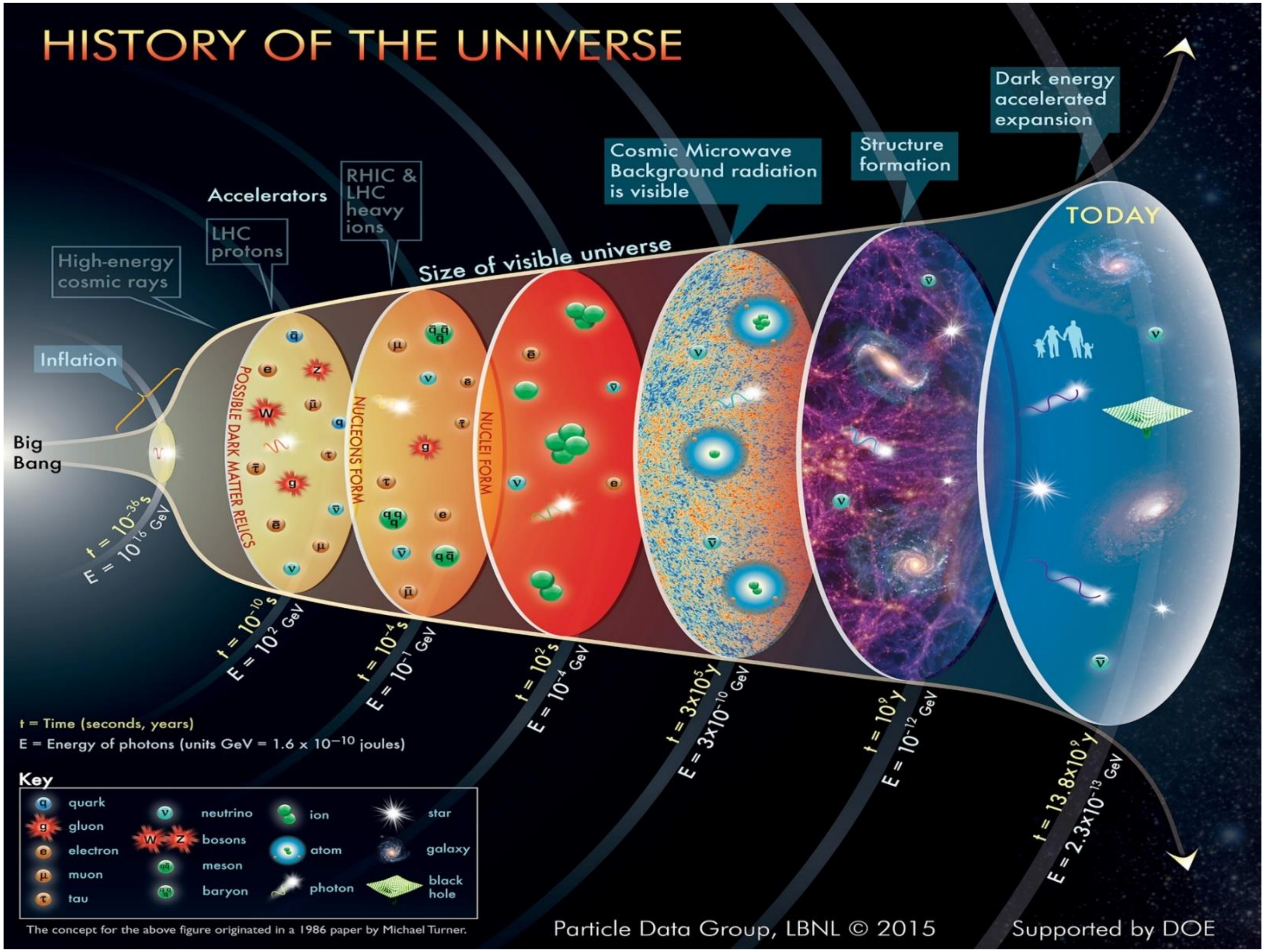
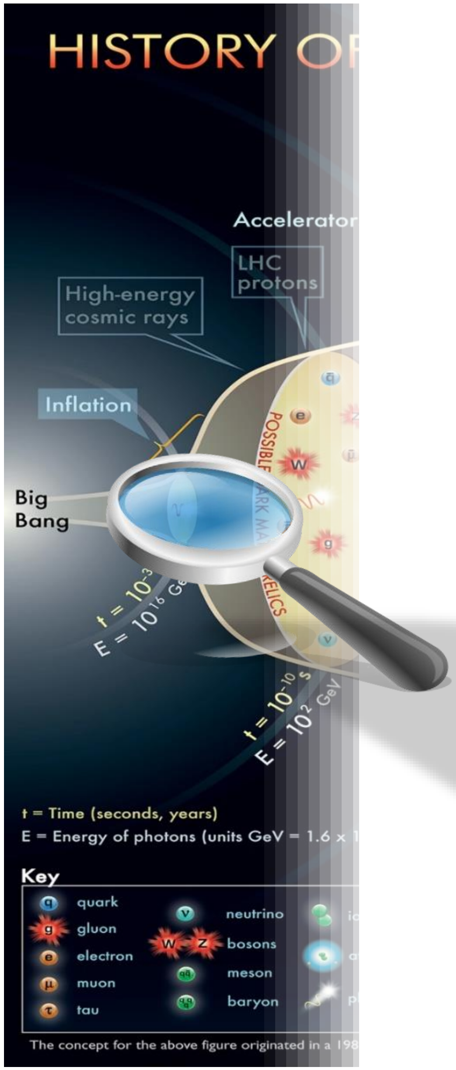
Why are we here?



Why are we here?



Big Bang

energy
⇩
matter & antimatter

symmetrie between matter & antimatter

Early Universe

preference of matter

Sakharov criteria:
- baryon number violation
- no thermic equilibrium
- $\mathcal{C}, \mathcal{CP}$ violation

matter-antimatter annihilation

Today

ratio

$$\frac{\text{matter - antimatter}}{\text{radiation}}$$

observed
(WMAP 2003)
$(6.14 \pm 0.25)10^{-10}$

galaxies, stars, planets

⇕

Standard Model
10^{-18}

“empty” universe

Search for $\mathcal{CP}$ violation beyond the Standard Model

Mitglied der Helmholtz-Gemeinschaft

Measurement of Electric Dipole Moments at Storage Rings

Volker Hejny
Forschungszentrum Jülich

HPSS2016, September 5 - 9, 2016, Jülich

Outline

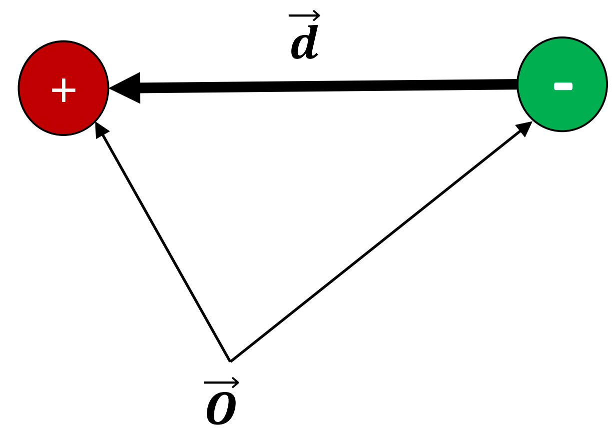
- Electric Dipole Moments
  - What are those?
  - How can they help?
- EDM measurements using storage rings
  - Basic principles
  - Options
- R&D and first measurements at COSY

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

Electric Dipole Moments (EDM)

Classical definition: $\vec{d} = \sum q_i \vec{r}_i$

charge x distance



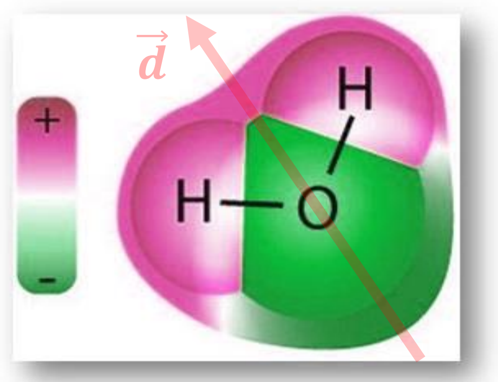
Example: water molecule

charge separation

⇩

electric dipole moment

d ≈ 4 x 10^{-9} *e* cm



EDMs of elementary particles

$\vec{s}$ spin

$\vec{d}$ electric dipole moment

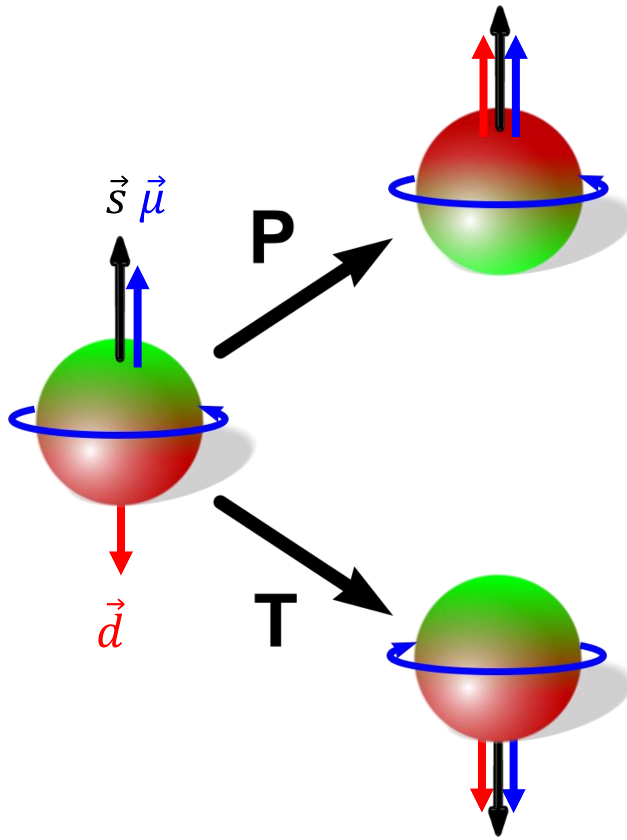
$\vec{\mu}$ magnetic moment

Transformations w.r.t. $\mathcal{P}, \mathcal{T}$

$$H = -\mu\vec{\sigma}\cdot\vec{B} - d\vec{\sigma}\cdot\vec{E}$$

$$\mathcal{P}:\quad H = -\mu\vec{\sigma}\cdot\vec{B} + d\vec{\sigma}\cdot\vec{E}$$

$$\mathcal{T}:\quad H = -\mu\vec{\sigma}\cdot\vec{B} + d\vec{\sigma}\cdot\vec{E}$$



EDM measurements test violation of fundamental symmetries $\mathcal{P}, \mathcal{T}$ and $\mathcal{CP}$ (via $\mathcal{CPT}$)

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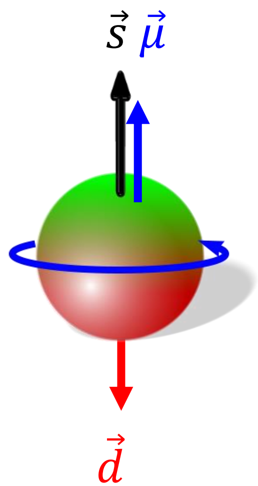
So what is the difference?

elementary particle

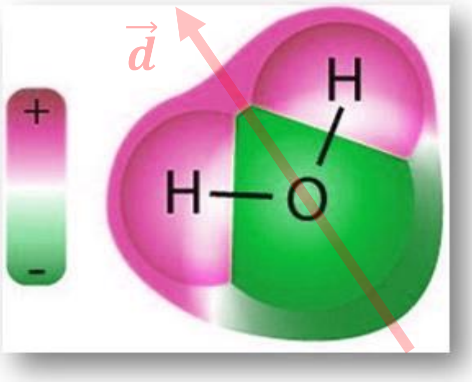
EDM violates $\mathcal{P}$, $\mathcal{T}$



defined parity!

water molecule

EDM allowed



degenerated
ground state
with mixed parity!

How can that help?

Reminder: excess of matter in the universe

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

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

⇩

New sources of $\mathcal{CP}$ violation needed
to explain this mismatch

⇩

EDMs as a probe for $\mathcal{CP}$ violation beyond the SM

Symmetries in the Standard Model

	electro-magnetic	weak	strong
$\mathcal{C}$	✓	×	✓
$\mathcal{P}$	✓	×	✓
$\mathcal{T}\,/\,\mathcal{CP}$	✓	×	(✓)

$\mathcal{C}$ and $\mathcal{P}$ are maximally violated in weak interactions

(Lee, Yang, Wu)

$\mathcal{CP}$ violation discovered in kaon decays described by CKM-matrix in Standard Model (Cronin,Fitch)

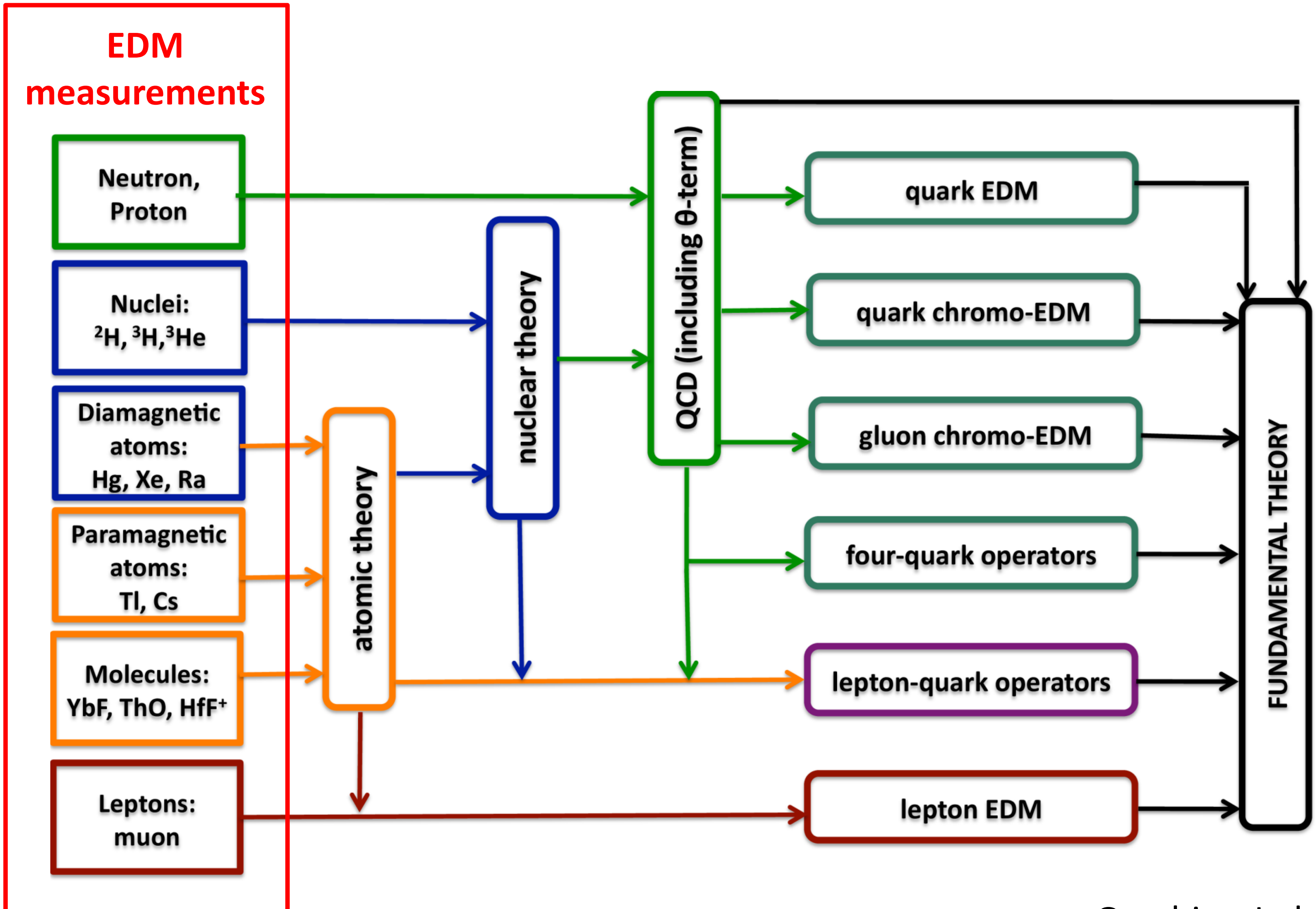
$\mathcal{CP}$ violation allowed in strong interaction but corresponding parameter $\theta_{QCD} \lesssim 10^{-10}$ (strong $\mathcal{CP}$-problem)

Sources of $\mathcal{CP}$ violation

Standard Model		
weak interaction	CKM matrix	unobservably small EDMs
strong interaction	θ_{QCD}	best limit from neutron EDM ($\lesssim 10^{-10}$) "strong CP problem"
beyond Standard Model		
e.g. SUSY	?	accessible by EDM measurements

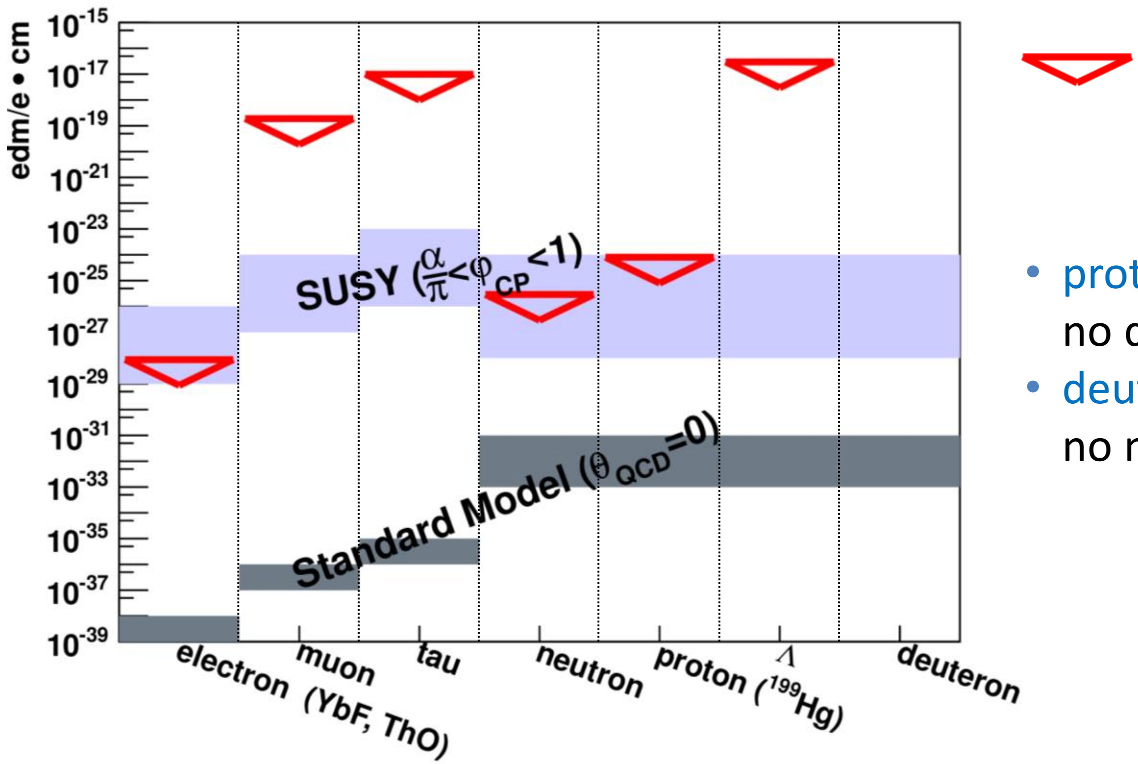
Different sources of $\mathcal{CP}$ violation result in a different EDM for different particle types

Disentangling $\mathcal{CP}$ violation ...



Graphics: J. de Vries

Current EDM limits



- proton
  no direct measurement
- deuteron
  no measurement

Here: EDMs of charged particles

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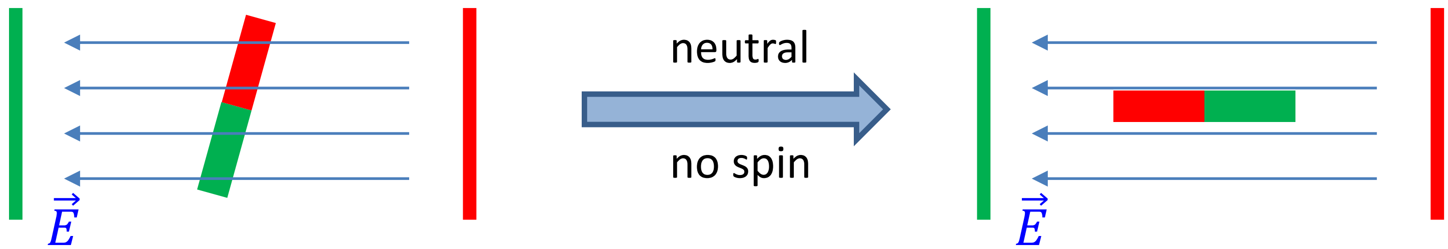
How to measure EDMs?

Common strategy for all EDM measurements:

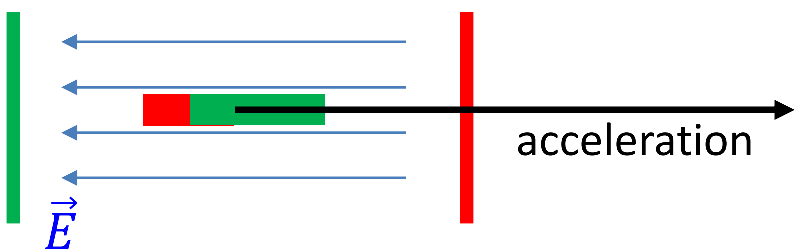
$\rightarrow$ measure interaction of $\vec{d}$ with electric field $\vec{E}$



With spin:

$\rightarrow$ precession

For charged particles:



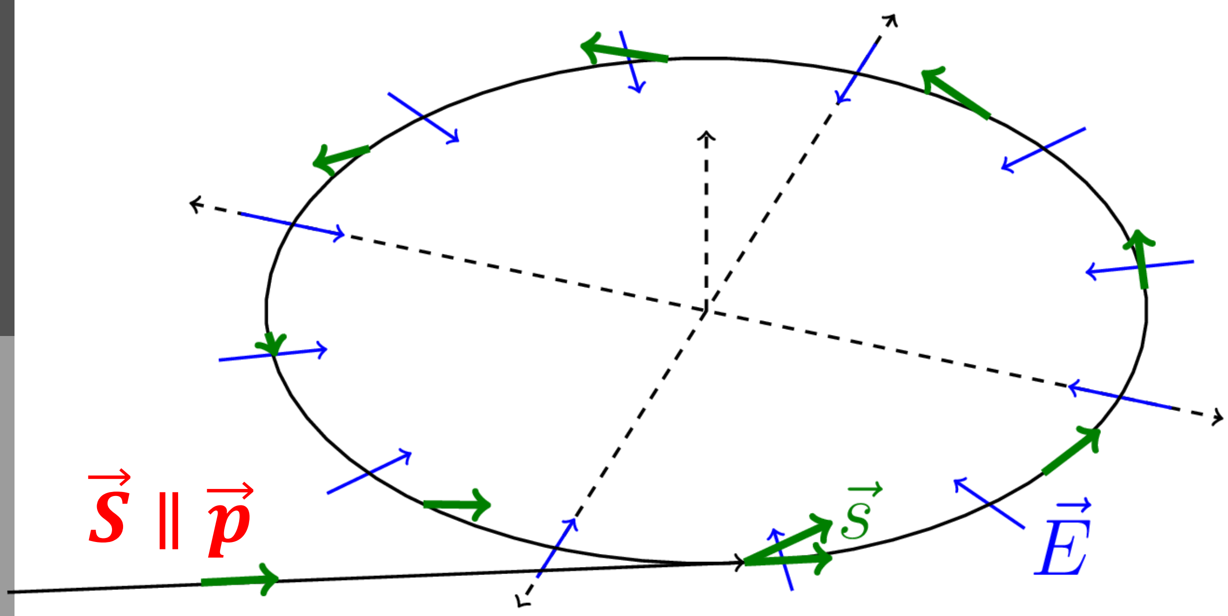
https://www.youtube.com/watch?v=qwM4ensIA_k
by Tales Of a Musing Gator

How to measure EDMs of charged particles?

Electric field accelerates particles

$\longrightarrow$ use a storage ring

Ideal case:



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

⇩

Build-up of vertical polarisation by slow precession $s_{\perp} \propto |d|$

"Ad-hoc" boundary conditions

Very slow spin precession	Long measurement times ($t \approx 1000$ s) High electric fields ($E \approx 10$ MV/m) High degree of polarization ($P \approx 0.8$) Precise polarisation measurement (analysing power $A \approx 0.6$, acc. $f \approx 0.005$)
Particle ensemble ($N \approx 4 \times 10^{10}$ per fill)	All particles must act identically All spins need to be aligned ("spin coherence time")
Horizontal polarisation ǁ momentum	Control spin motion at high precision
Magnetic moment causes fake rotations	High field quality Magnetic shielding Precise geometrical alignment Fringe fields under control

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

Major challenge:
get systematic uncertainties
to the same level!

Spin motion

Thomas-BMT equation:

magnetic moment

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

EDM

Ω: angular precession frequency

G: anomalous magnetic moment

d: electric dipole moment

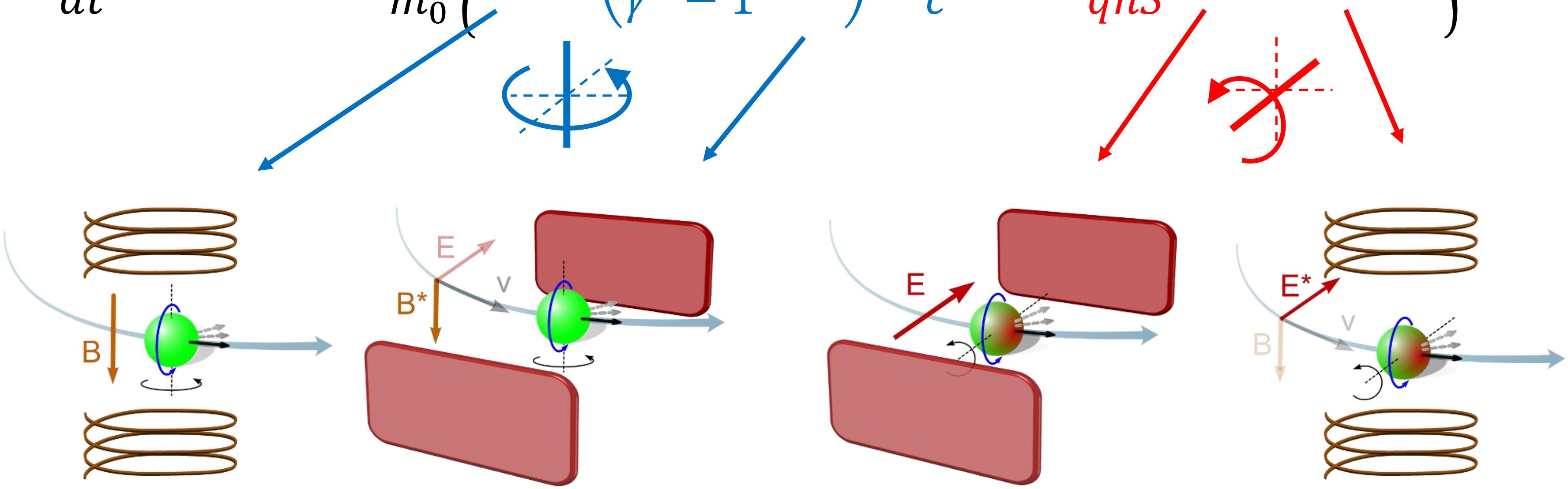
γ: Lorentz factor

Storage rings: $\vec{B}$ vertical, $\vec{E}$ radial

Storage rings: general case

magnetic moment — EDM — Lorentz force

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



magnetic moment causes
fast spin precession: $\vec{s}_H \nparallel \vec{p}$

Ω: angular precession frequency
G: anomalous magnetic moment
d: electric dipole moment
γ: Lorentz factor

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

Storage rings: combined ring

magnetic moment — EDM

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

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

All-in-one ring for protons, deuterons, ^{3}He

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 $\vec{\beta} \times \vec{B}$

Ideal starting place for R&D and a proof-of-principle experiment

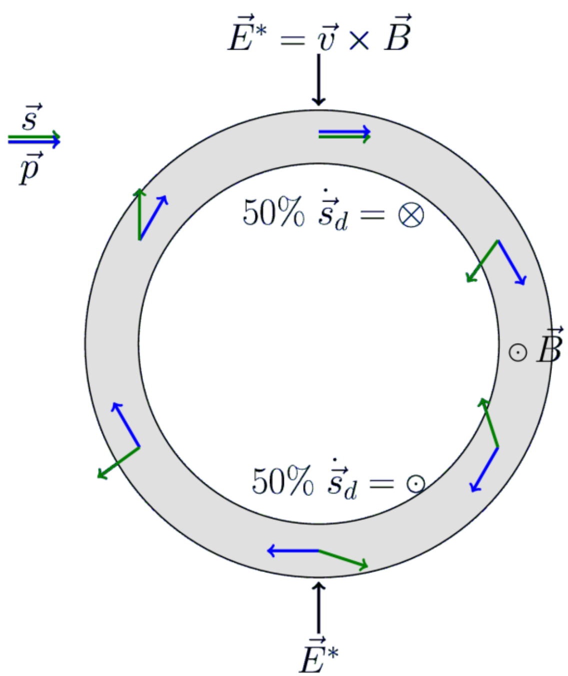
Pure magnetic ring

Due to fast precession longitudinal polarization component is

50% of time parallel

50% of time anti-parallel

to momentum



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

E* field in the particle rest frame tilts spin due to EDM

50% of time up and

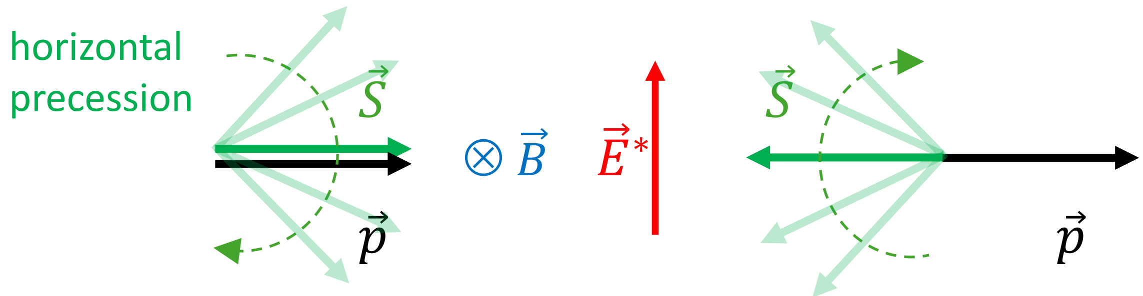
50% of time down

$\rightarrow$ no net EDM effect

Resonant rf Wien filter

Wien filter: Lorentz force vanishes ⟶ no effect on EDM rotation

Effect on horizontal precession:



Without WF	50 %	50 %
Static WF	50 %	50 %
(precession just faster or slower)		
Resonant rf WF	speed up prec.	slow down prec.
(resonant on precession frequency)	<50 %	>50%

net EDM effect

R&D at COSY

Thomas-BMT equation:

magnetic moment — neglect EDM

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

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

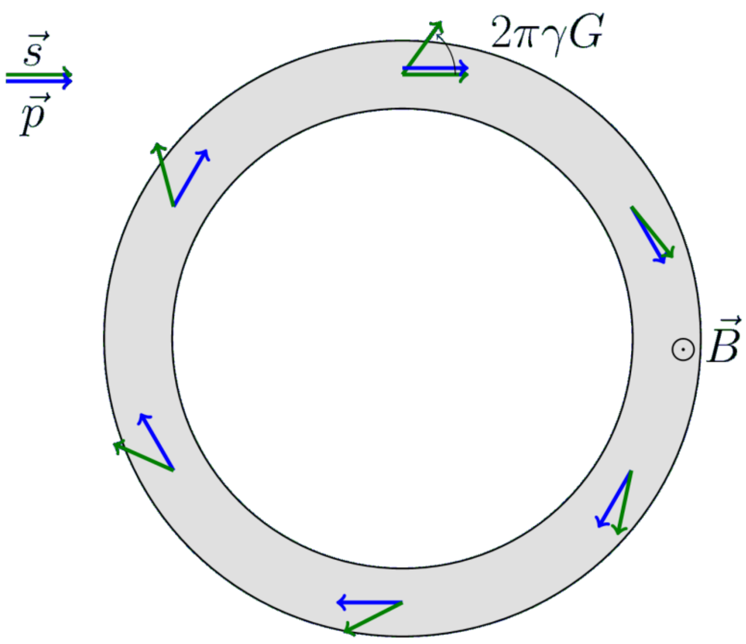
$\longrightarrow$ phase advance per turn

R&D with deuterons

p = 1 GeV/c

G = -0.14256177(72)

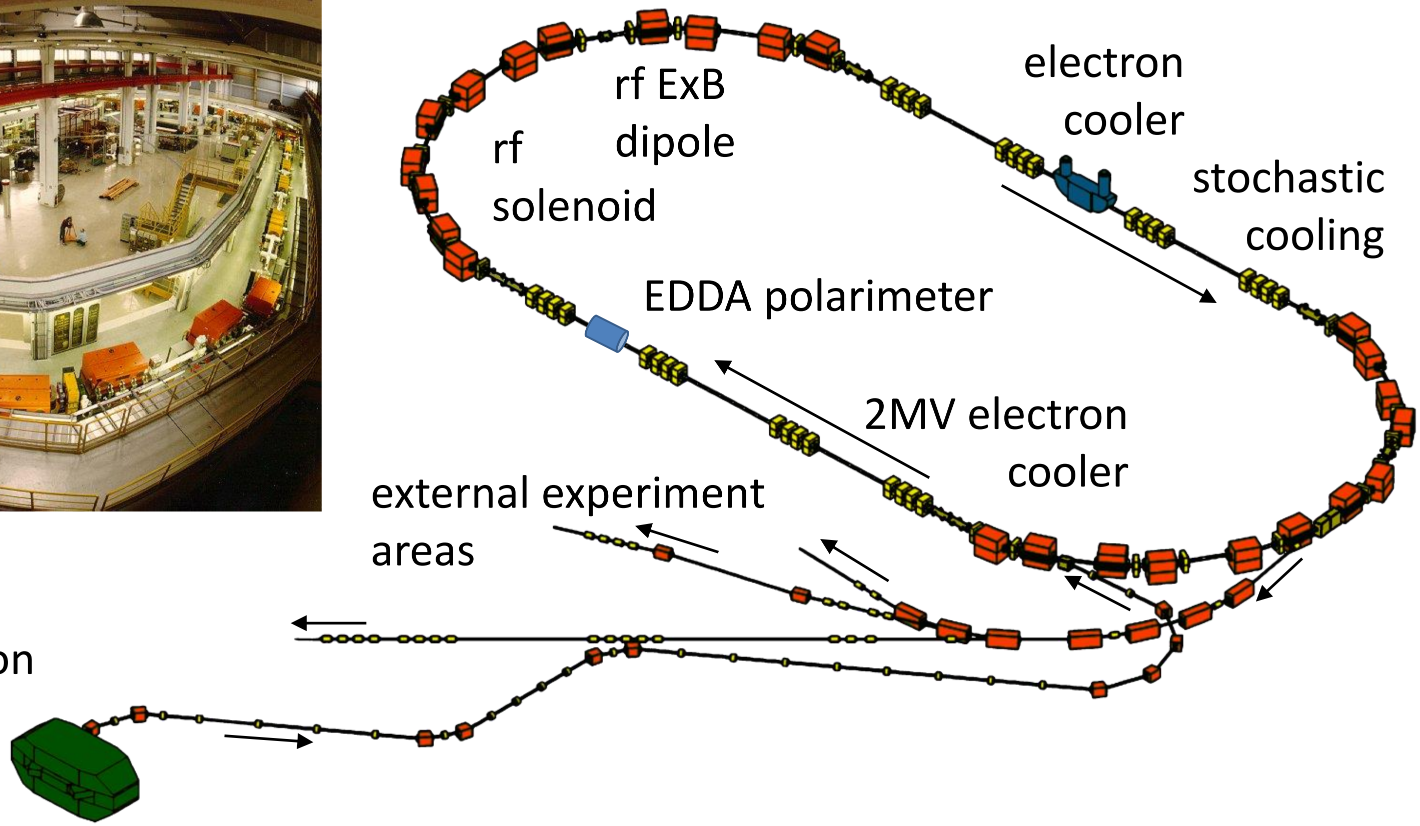
ν_s ≈ -0.161 $\longrightarrow$ f ≈ 120 kHz



(Some) Questions to be addressed

- Precise measurement of the precession frequency (spin tune)
  $\longrightarrow$ also time dependent within one cycle
- Maximizing the spin coherence time (goal: ≈1000 s)
- Maintaining the spin direction
  $\longrightarrow$ keep precession frequency stable
  $\longrightarrow$ match frequency and phase to Wien filter radio frequency
- Study effects of field misalignments, orbit distortions, etc.

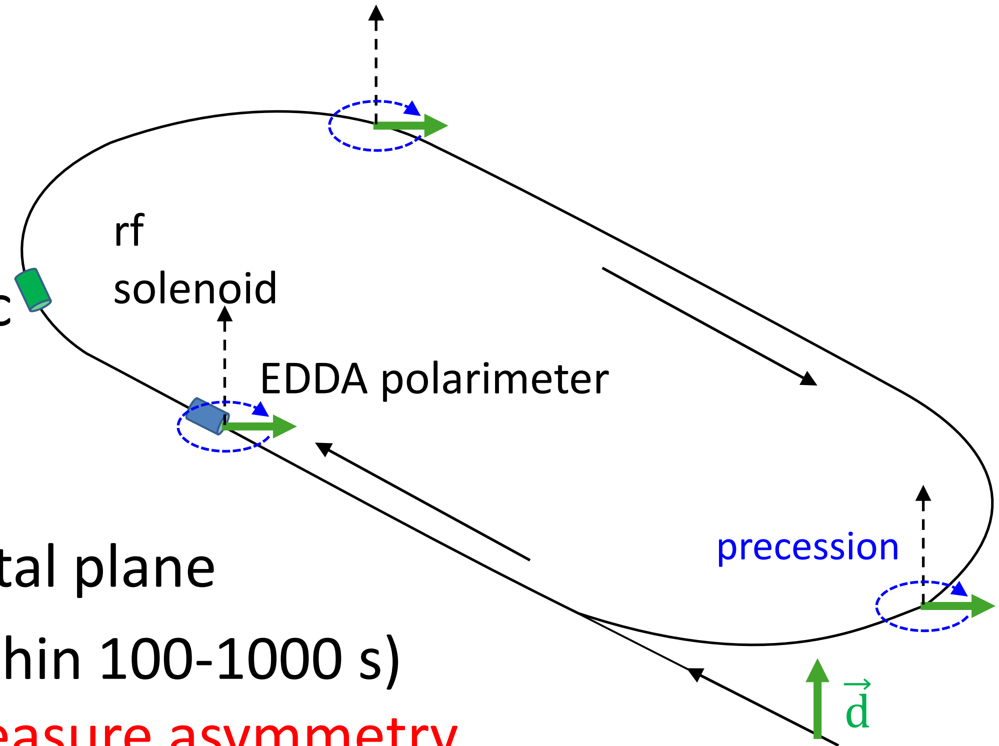
Cooler Synchrotron COSY



COSY provides cooled & polarized protons and deuterons with p = 0.3 – 3.7 GeV/c

Experimental setup

1. inject and accelerate vertically polarized deuterons to p = 1 GeV/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

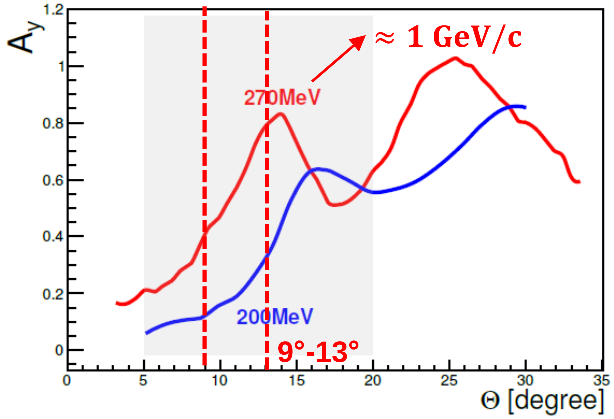


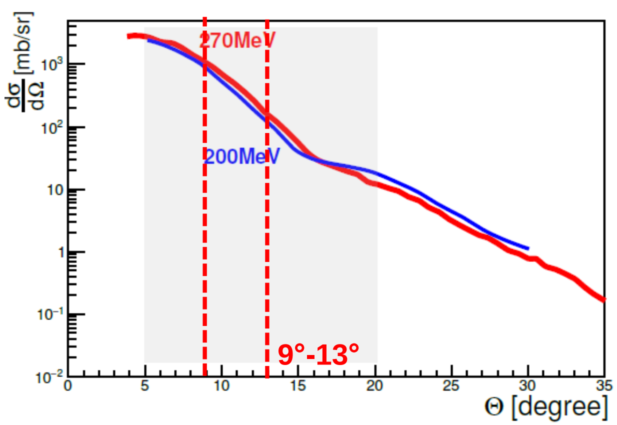
spin tune:

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

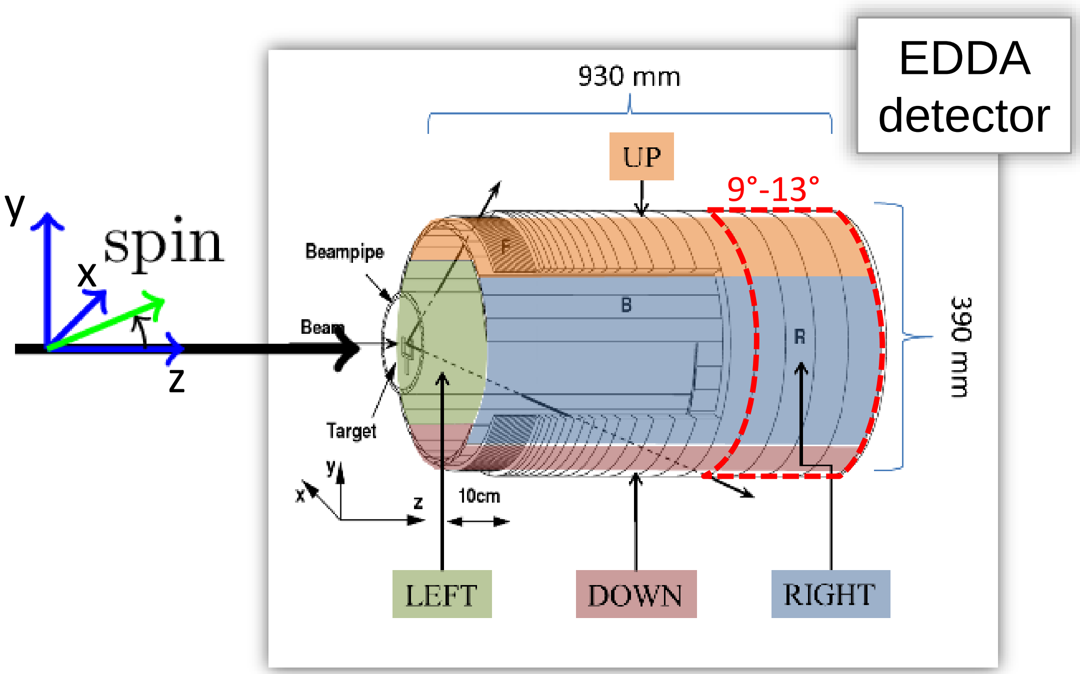
Polarimetry

- reaction: elastic d+C scattering
- up/down asymmetry $\propto P_x$ projection on x-axis
- left/right asymmetry $\propto P_y$ projection on y-axis





Y. Satou et al., Phys. Lett. B 549, 307 (2002)



Asymmetry 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

- 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

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Asymmetry measurement

„time stamping"

single reference clock

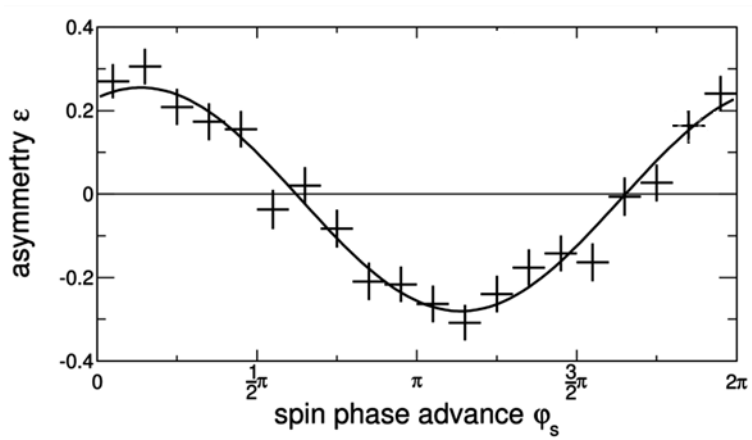
COSY rf → **TDC** → beam revolutions: counting turn number n

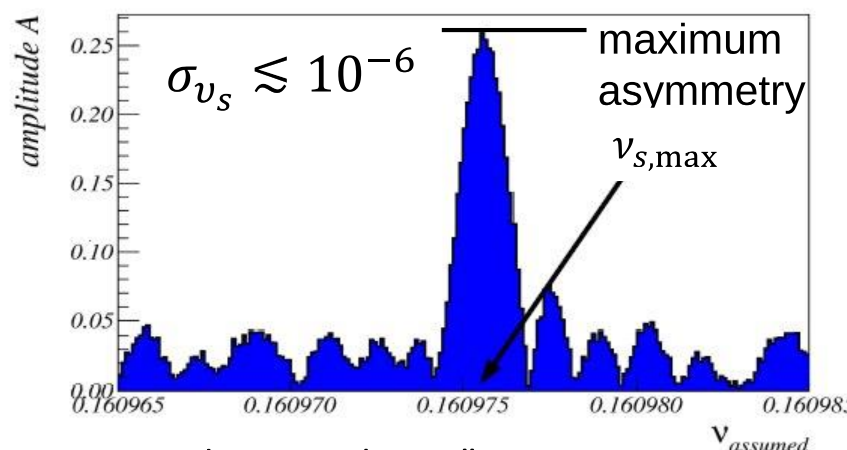
detector events → **TDC** → assign turn number n → phase advance $\varphi_s = 2\pi\nu_s n$

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

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

true ν_s *a priori* not known





see: "Measuring the polarization of a rapidly precessing deuteron beam" Phys.Rev. STAB 17, 052803 (2014)

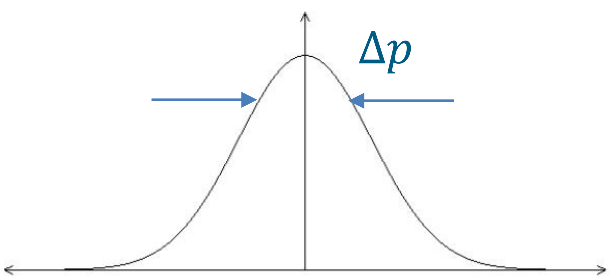
Spin Coherence Time (SCT)

Ensemble of ≈ 10^9 deuterons: coherent precession needed!

Ideal case:

- all particles have exactly the same momentum — no
- all particles travel the same path (orbit) in the ring — no
- all particles see the same fields — no

Example:



$$\frac{\Delta\gamma}{\gamma} = \beta^2 \frac{\Delta p}{p} \approx 10^{-4} = \frac{\Delta\nu}{\nu}$$

(β^2: 0.2; $\frac{\Delta p}{p}$: 10^{-3})

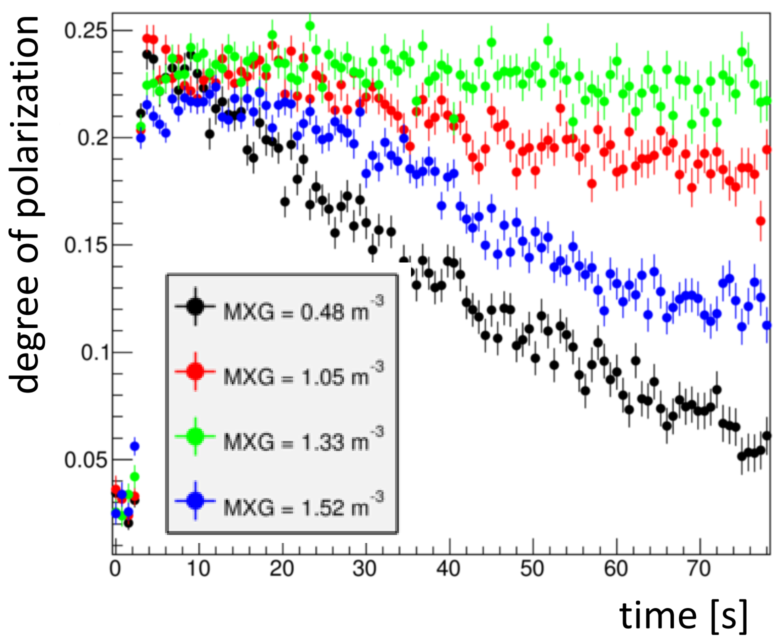
$$\Delta\nu \approx 10^{-4} \cdot 0.16 \approx 10^{-5}$$

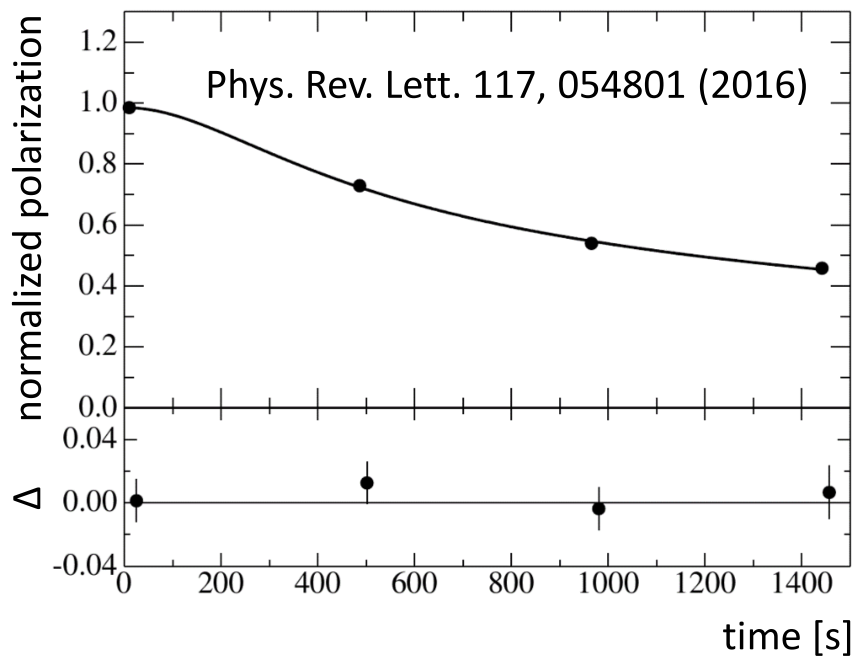
$$\Delta\varphi = 2\pi \cdot 10^{-5} \cdot 10^6 s^{-1} \approx 60\ {}^{\text{rad}}/_{\text{s}}$$

($10^6 s^{-1}$: revolution frequency)

Spin Coherence Time (SCT)

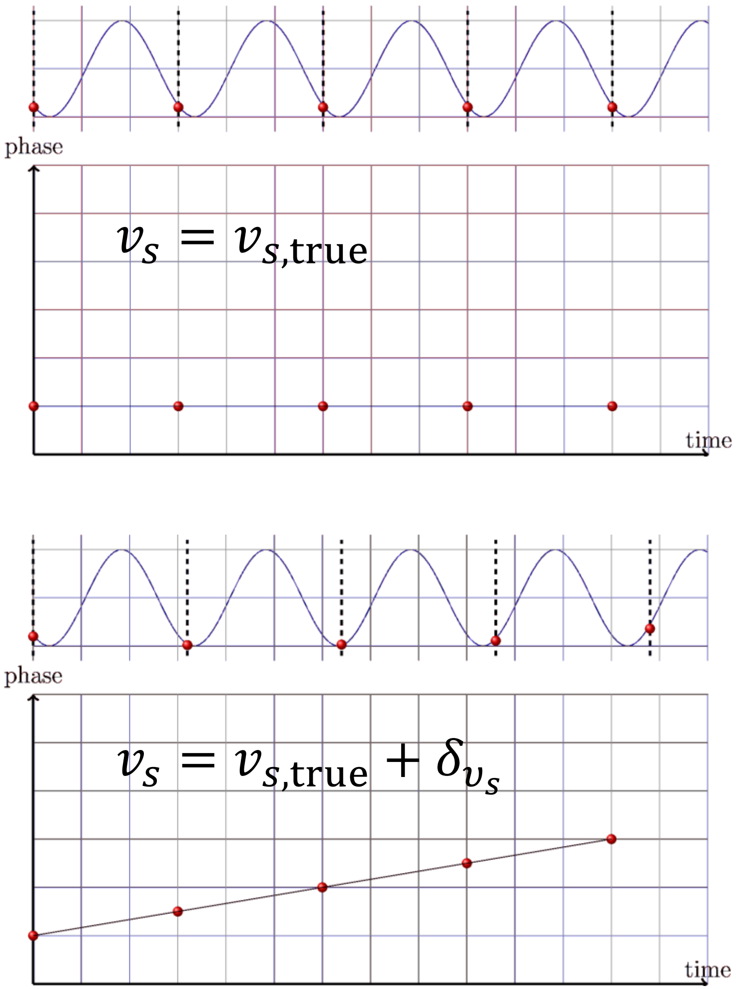
- unbunched beam: $\frac{\Delta\gamma}{\gamma} \approx 10^{-5} \implies$ decoherence in < 1s
- bunching: eliminate effects on $\frac{\Delta p}{p}$ in 1st order → $\tau \approx 20$ s
- correcting higher order effects using sextupoles and (pre-) cooling → $\tau \approx 1000$ s

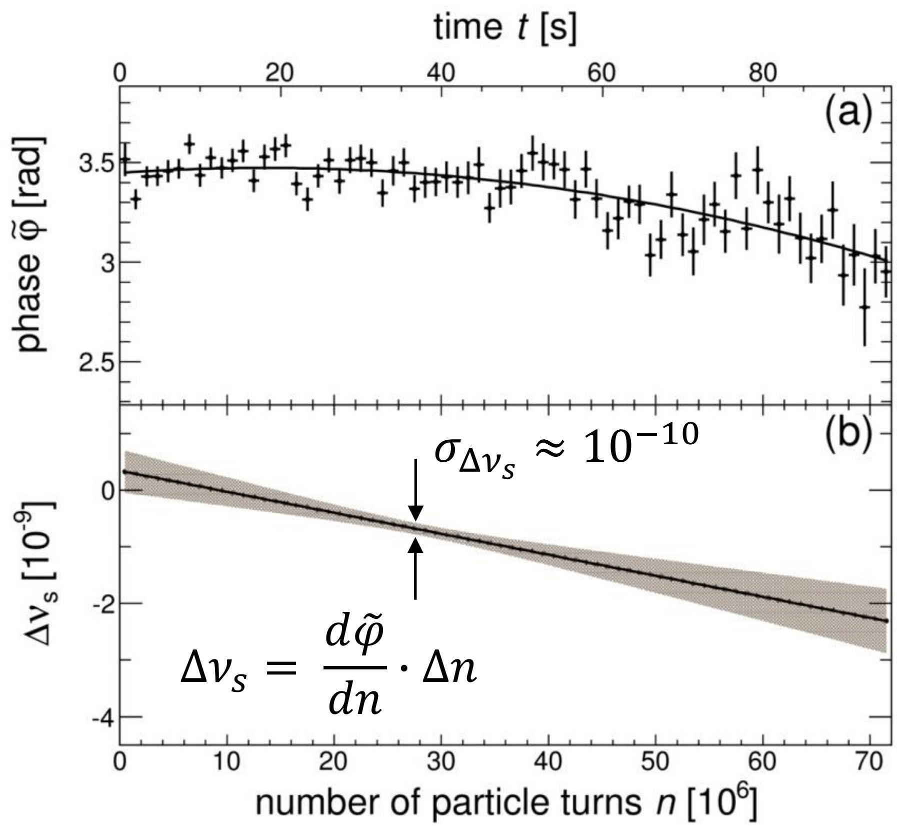




Precise determination of spin tune

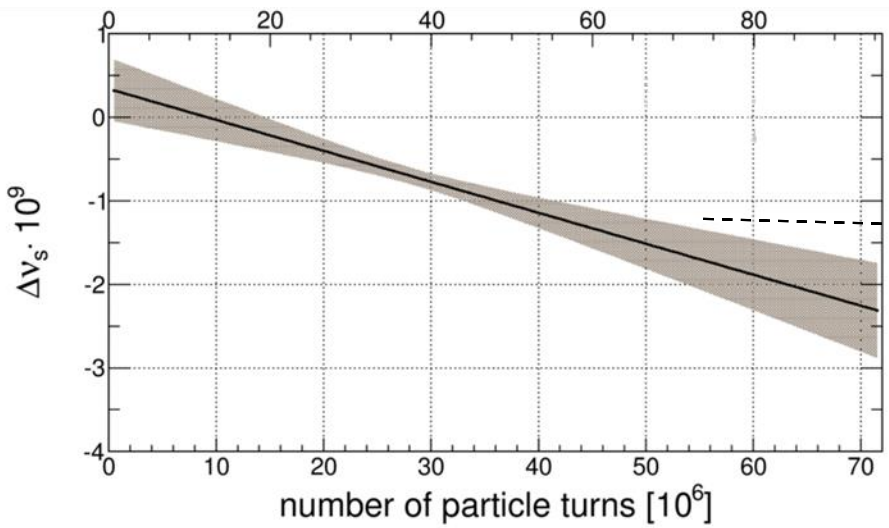
Monitoring phase of asymmetry (ν_s fixed):

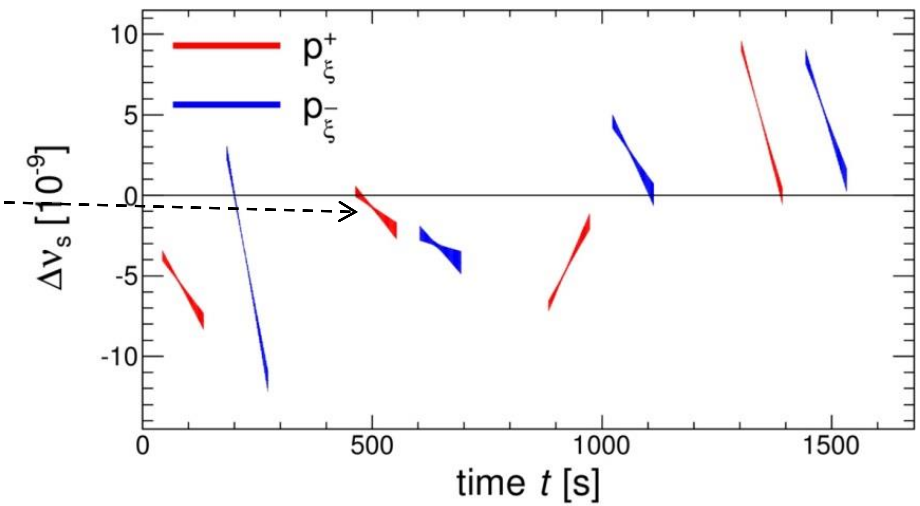




see: Phys.Rev.Lett. 115, 094801 (2015)

Application: precise determination of ν_s





- spin tune ν_s can be determined to $\sigma_{\nu_s} \approx 10^{-8}$ in $\Delta t \approx 2s$
- average $\overline{\nu_s}$ in 1 cycle ($\approx$ 100s) determined to $\sigma_{\nu_s} \approx 10^{-10}$
- tool for: study long term stability of the ring
  dedicated online feedback systems
  probing ring/field imperfections

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

Spin tune: feedback system

Challenges:

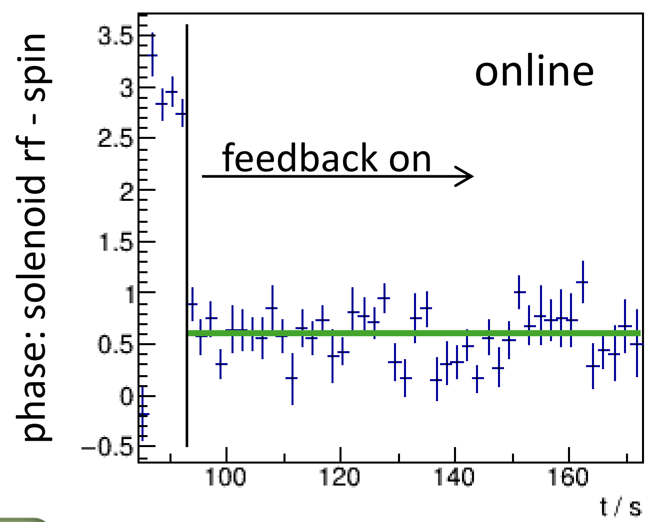
- maintain resonance frequency and phase between spin precession and Wien filter
- maintain frozen spin condition in a future dedicated ring

Test at COSY:

- control spin tune via COSY rf:

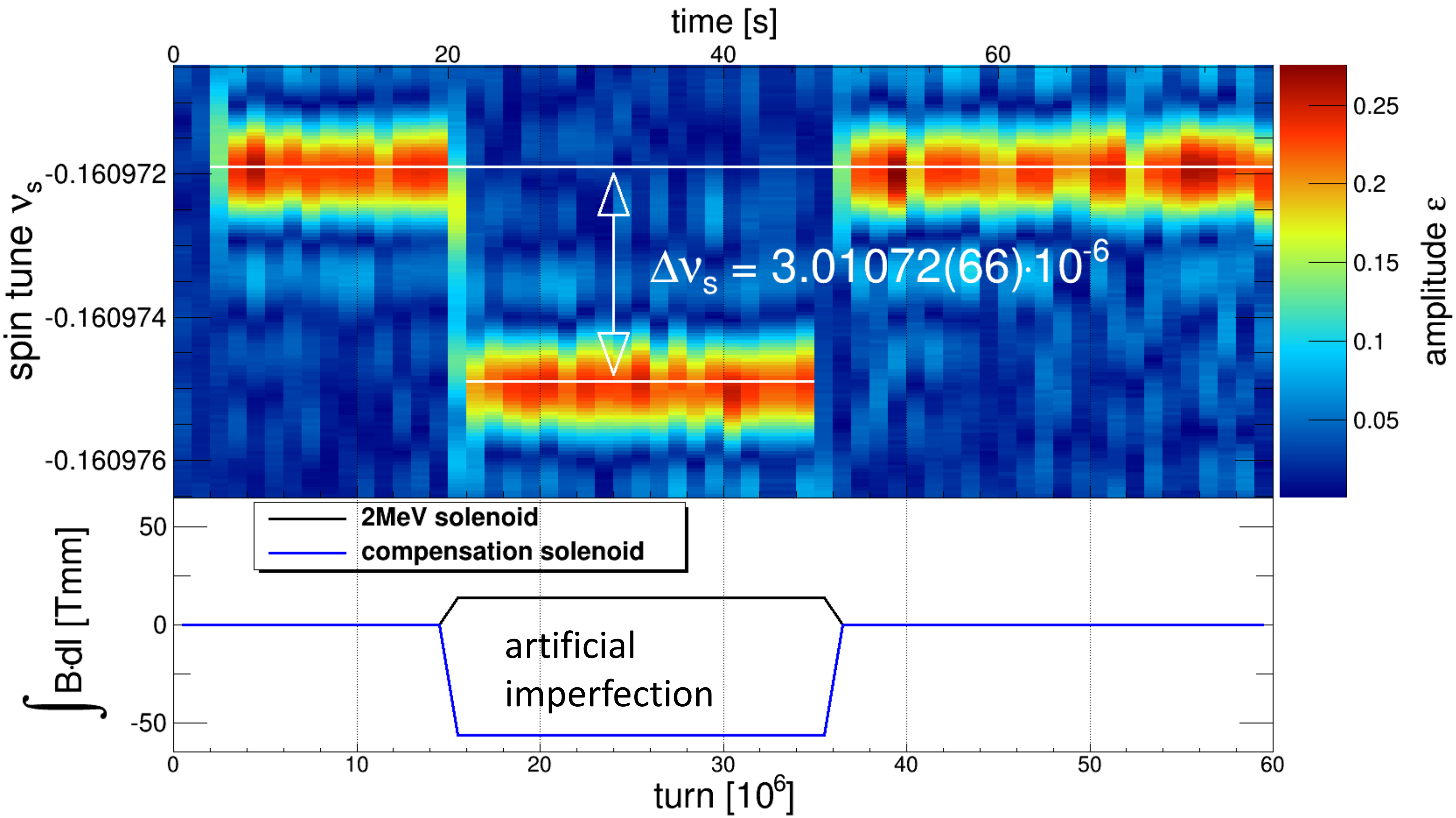
$$\frac{\Delta\nu_s}{\nu_s} = \frac{\Delta\gamma}{\gamma} = \beta^2 \frac{\Delta p}{p} = \frac{\beta^2}{\eta}\frac{\Delta f}{f}$$

- control phase to external frequency
- by accelerating/decelerating spin precession



Success!

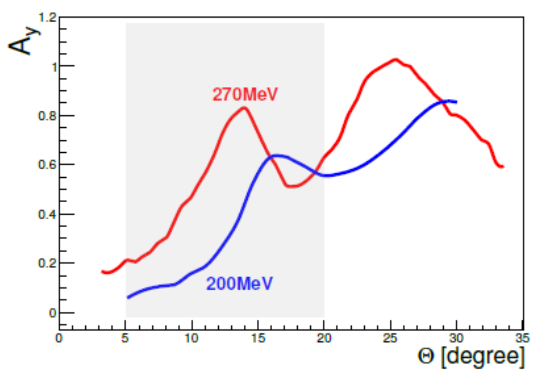
Spin tune: probing field imperfections

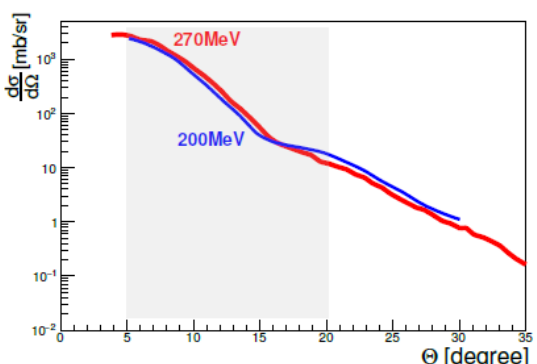


Outlook: Polarimeter development

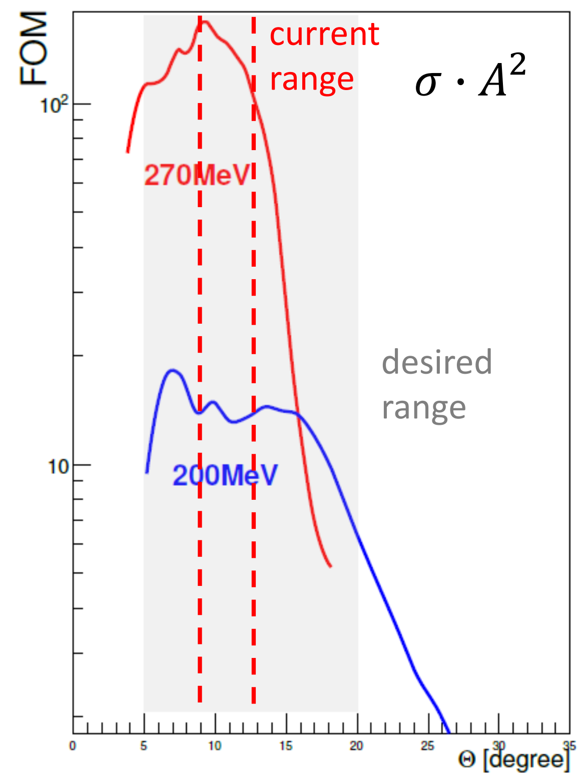
Status:

- EDDA is in operation since about 20 years
- acceptance limits polarimeter efficiency → crucial for feedback system



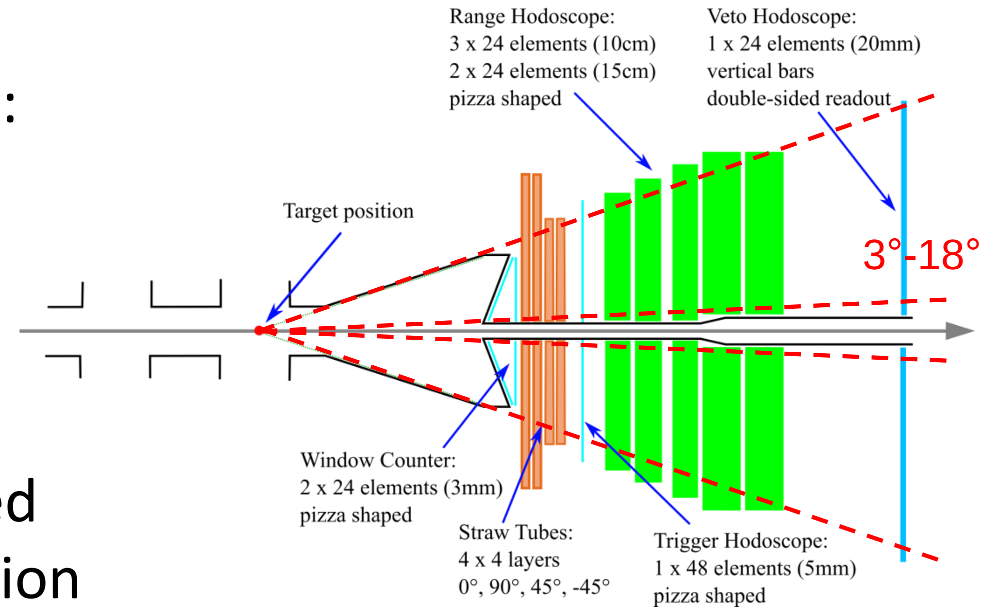


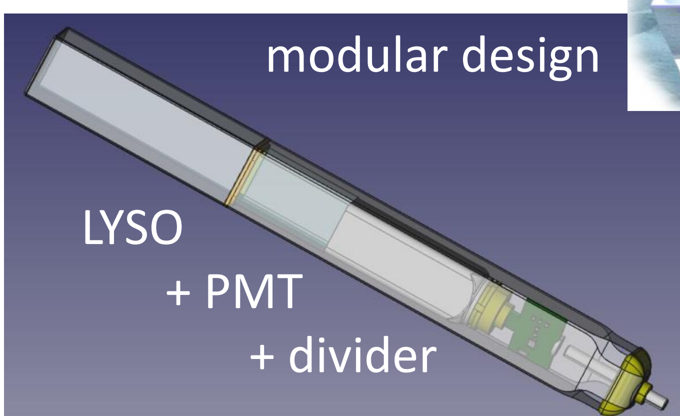
data: PLB 549, 307 (2002)

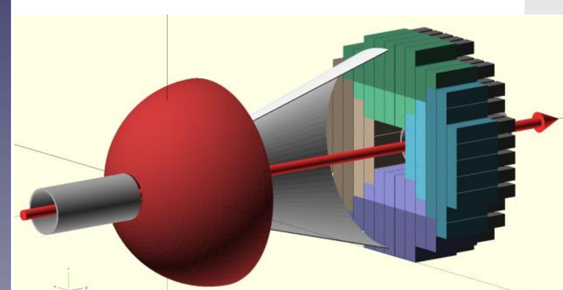


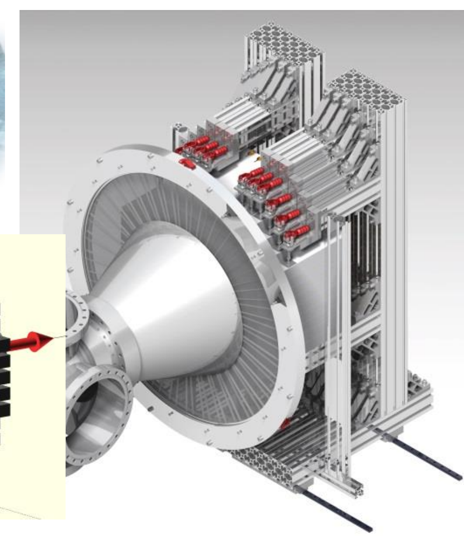
Outlook: Polarimeter development

- „database“ measurements: pC, dC analyzing powers at various beam momenta using the WASA-at-COSY forward detector
- development of a dedicated polarimeter for high precision EDM measurements









Summary

- EDMs sensitive to new sources of $\mathcal{CP}$ violation
- Mechanism for $\mathcal{CP}$ violation: EDMs of charged hadrons needed
- Observable: spin precession in electric fields in storage rings
- COSY: ideal starting point for R&D and a pre-cursor experiment

Outlook

- pre-cursor experiment at COSY:
  proof of principle with lower sensitivity
- dedicated storage ring:
  different option are currently under investigation
  goal: conceptual design report

Jülich Electric Dipole Moment Investigations:

- ≈ 100 members:
  Aachen, Daejeon, Dubna, Ferrara, Grenoble, Indiana, Ithaca, Jülich, Krakau, Michigan, Minsk, Novosibirsk, St. Petersburg, Stockholm, Tbilisi, …
- see
  http://collaborations.fz-juelich.de/ikp/jedi