Recent Progress of the JEDI Collaboration

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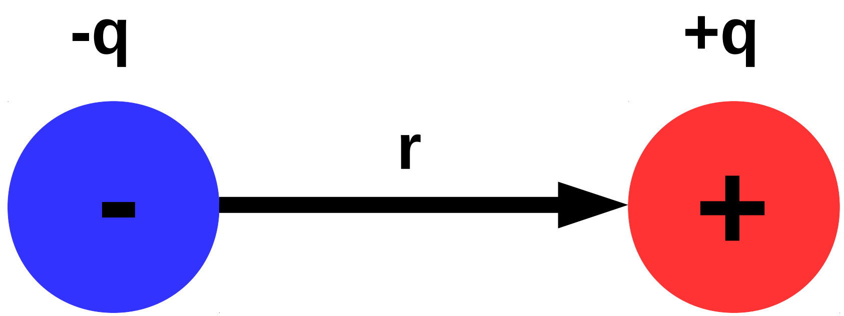
Electric Dipole Moment (EDM)



$$\vec{d} = q\vec{r}$$

This talk: **Permanent** EDM **along spin** direction
(of charged particles, e.g. electron, proton, ...)

Talk about tiny EDMs: $|\vec{d}| \approx \mathcal{O}(10^{-29})\,\mathrm{e}\cdot\mathrm{cm}$

Planck length: $l_P \approx 1.6 \cdot 10^{-33}\,\mathrm{cm}$

Proton ↔ Sun

$|\mathbf{r_{EDM}}| \approx \mathbf{10}\,\mu\mathrm{m}$

Matter-Antimatter Asymmetry

$$\eta_{BAU} = \frac{n_B - n_{\bar{B}}}{n_\gamma} = \begin{cases} 6 \cdot 10^{-10} & \text{observed} \\ 10^{-18} & \text{Standard Model Expectation} \end{cases}$$

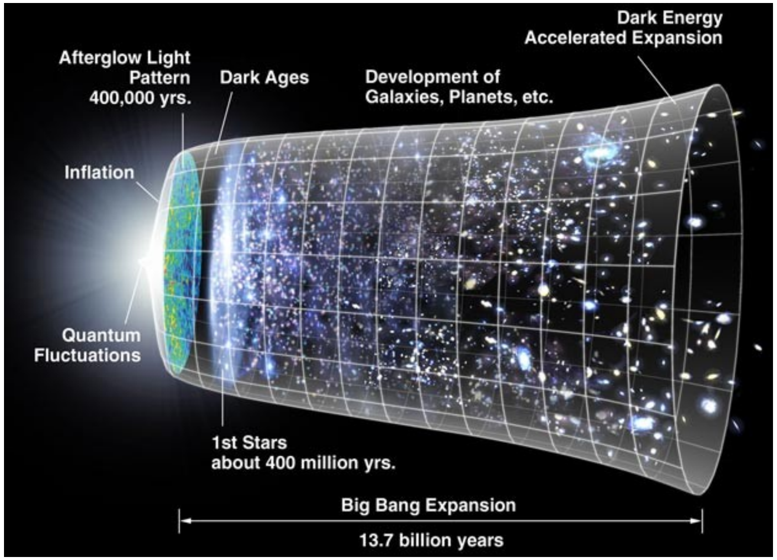
Either they were created in different amounts or antimatter was lost along the way

Matter

10.000.000.001

Antimatter

10.000.000.000



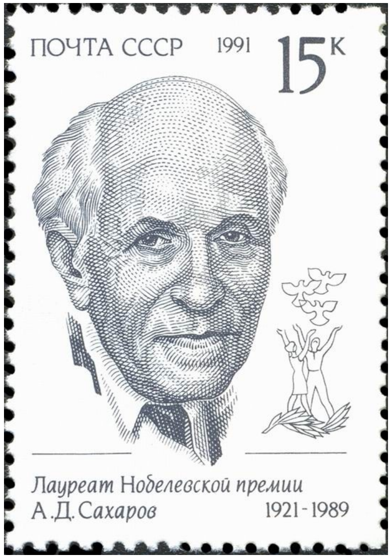
Sakharov Conditions

Sakharov (1967): Need 3 conditions for baryon asymmetry

1.) Baryon number violation

2.) C and CP violation

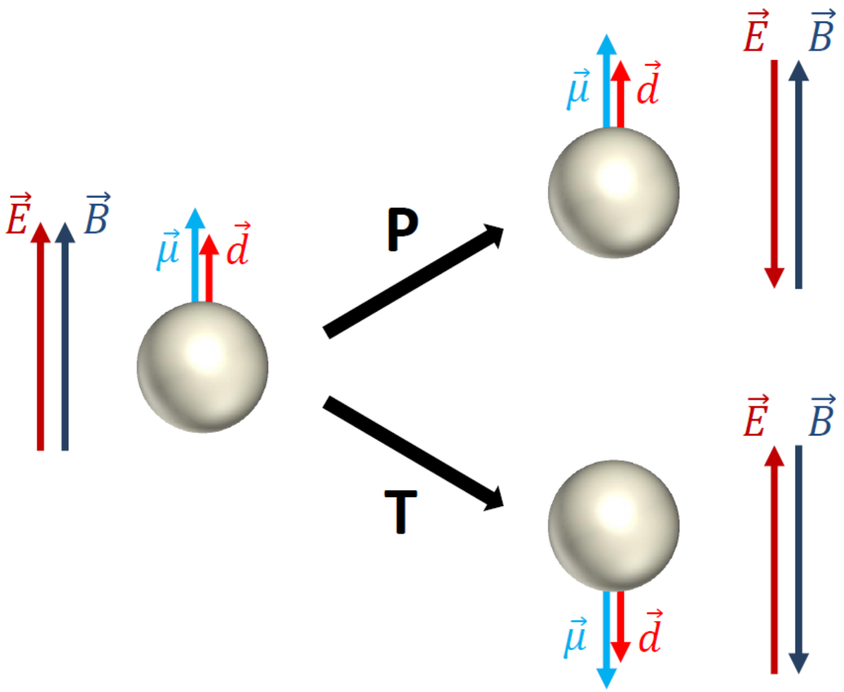
3.) Non-equilibrium interactions



Currently: **CP violation observed in weak interaction**

Plan: **Search for CP violation in QCD, SUSY, etc.**

EDMs and CP Violation



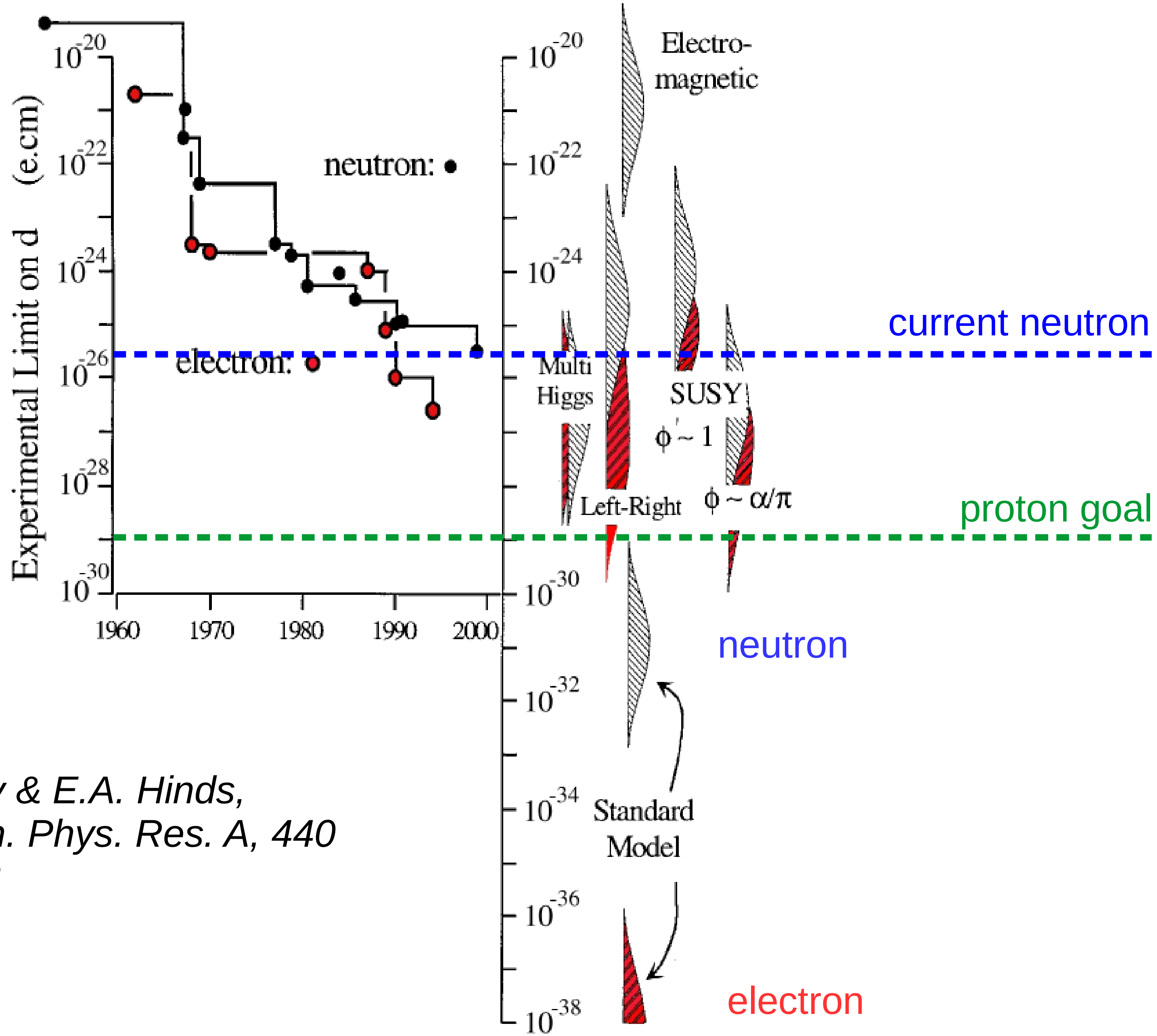
$$H = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

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

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

CPT theorem: T violation → CP violation

Current Upper Limits



J.M. Pendlebury & E.A. Hinds, Nucl. Instr. Meth. Phys. Res. A, 440 (2000), 471-478

Behavior of Spin

In rest frame: $$\frac{d\vec{S}}{d\tau} = \vec{\mu} \times \vec{B}^* + \vec{d} \times \vec{E}^*$$

Transform fields into rest frame, use equation of motion
→ get T-BMT Equation, $G = \frac{g-2}{2},\ \eta \approx 10^{-15}$ for $|\vec{d}| = 10^{-29}\, e \cdot \mathrm{cm}$

$$\begin{aligned}
\frac{d\vec{S}}{dt} &= \vec{S} \times (\vec{\Omega}_{MDM} + \vec{\Omega}_{EDM}) \\
\vec{\Omega}_{MDM} &= \frac{q}{m}\left(G\vec{B} - \frac{\gamma G}{\gamma+1}\vec{\beta}(\vec{\beta}\cdot\vec{B}) - \left(G - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right) \\
\vec{\Omega}_{EDM} &= \frac{\eta q}{2mc}\left(\vec{E} - \frac{\gamma}{\gamma+1}\vec{\beta}(\vec{\beta}\cdot\vec{E}) + c\vec{\beta}\times\vec{B}\right)
\end{aligned}$$

small, neglect for now

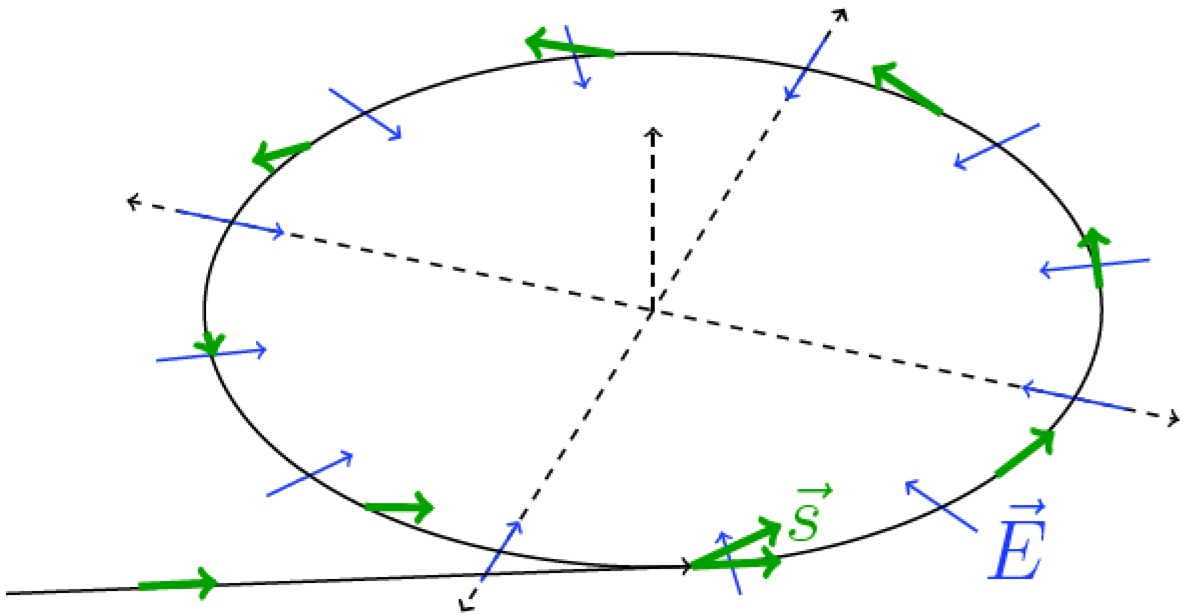
Frozen Spin Concept

$$\vec{\Omega}_{MDM} = \frac{q}{m}\left(G\vec{B} - \left(G - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right)$$

$$\vec{\Omega}_{EDM} = \frac{\eta q}{2mc}\left(\vec{E} + c\vec{\beta}\times\vec{B}\right)$$

Option 1: All-Electric Ring	**Option 2:** Combined E- and B-Fields
$\vec{B} = 0, \ |\vec{p}| = \frac{mc}{\sqrt{G}}$	$\vec{\Omega}_{MDM} = 0, \ \vec{\Omega}_{EDM} \propto \vec{F}_L$
"magic momentum"	
$\vec{\Omega}_{MDM} = 0, \ \vec{\Omega}_{EDM} \propto \vec{E}$	• **Can vary momentum** • **Works for all particles** • **B-Fields difficult for systematics**
Only if G>0 (protons, electrons)	

Frozen Spin Concept



- Inject longitudinal polarized beam
- Run in frozen spin mode
- Observe build-up of vertical polarization

$$(|\vec{E}| = 10\,\mathrm{MV/m},\ \eta = 10^{-15})$$

Expected build-up rate for protons (all electric ring): $|\vec{\Omega}_{EDM}| \approx 1.6 \cdot 10^{-9}\,\mathrm{rad/s}$

Bending radius (beam) $R \approx 42\,\mathrm{m}$

Activities at COSY

COoler SYnchrotron in Jülich

- Circumference: 183m
- All-magnetic → no frozen spin runs possible
- Use a third concept for EDM measurement: run RF-Wienfilter on spin resonance
- Systematics not great, don’t expect very stringent EDM limits
- Great to study systematic errors, learn to design a dedicated EDM ring
- Test and benchmark equipment and simulations

Challenge 1: Spin Coherence Time

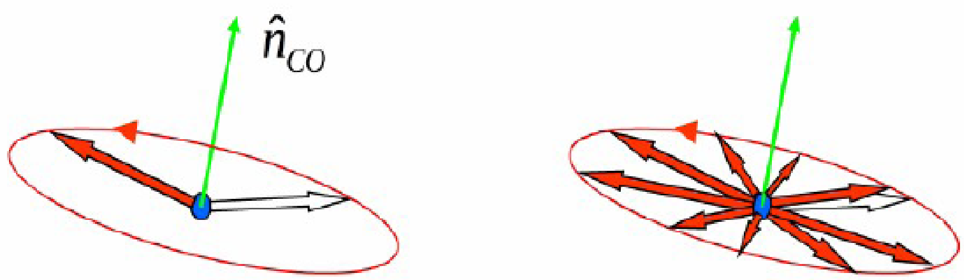
Typically: Don't worry about SCT:

At injection all spin vectors aligned (coherent)

After some time, spin vectors get out of phase and fully populate the cone

Polarization not affected!

Problem with frozen Spin:



At injection all spin vectors aligned

Later, spin vectors are out of phase in the horizontal plane

Longitudinal polarization vanishes!

Problem Solved!

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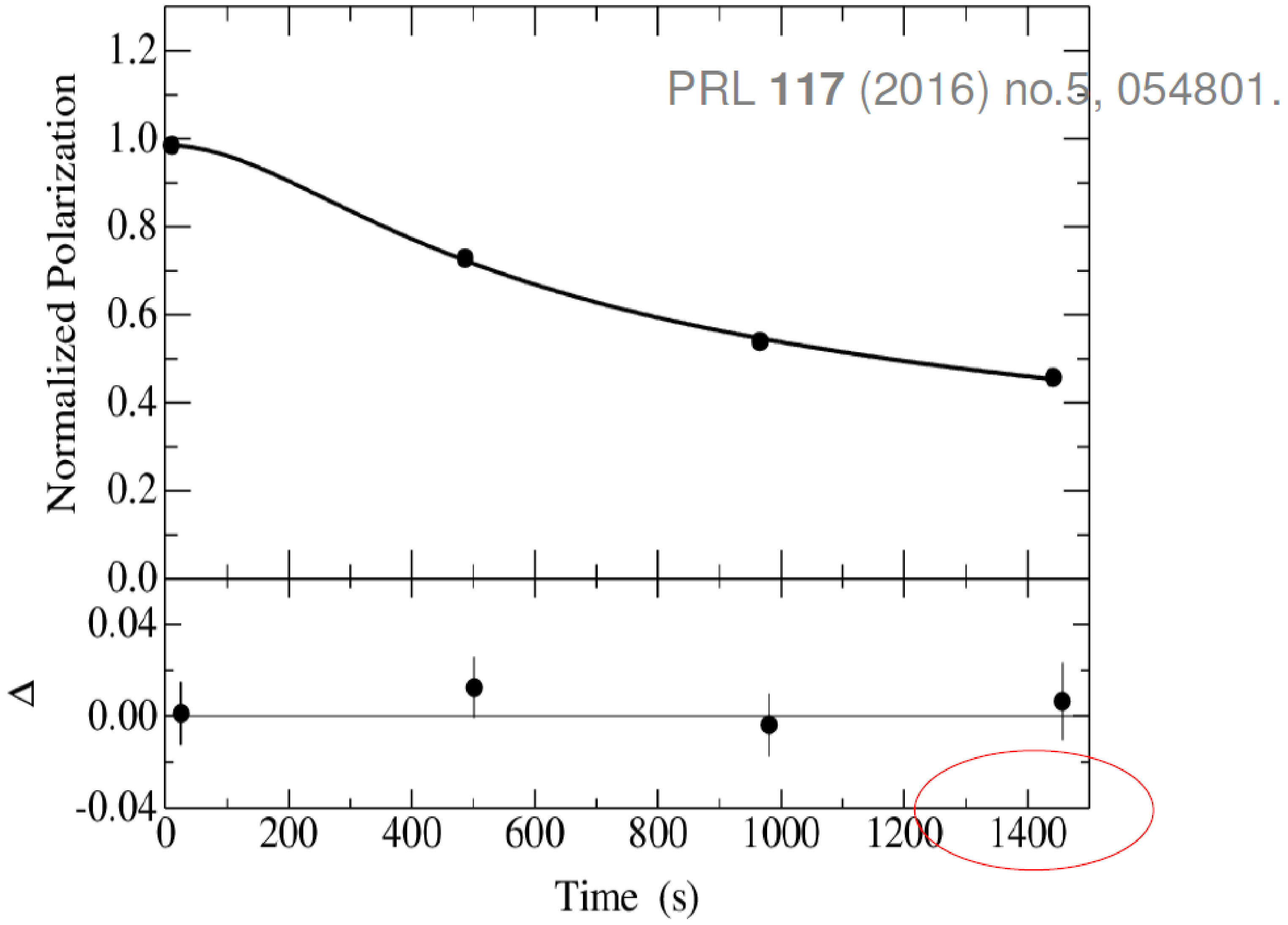
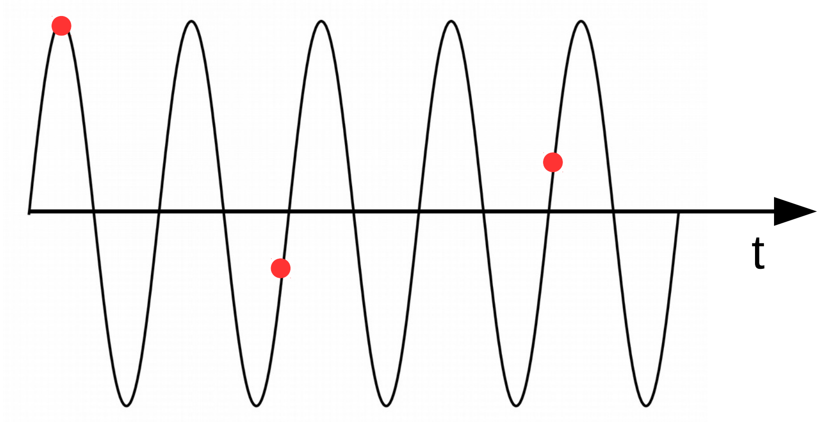


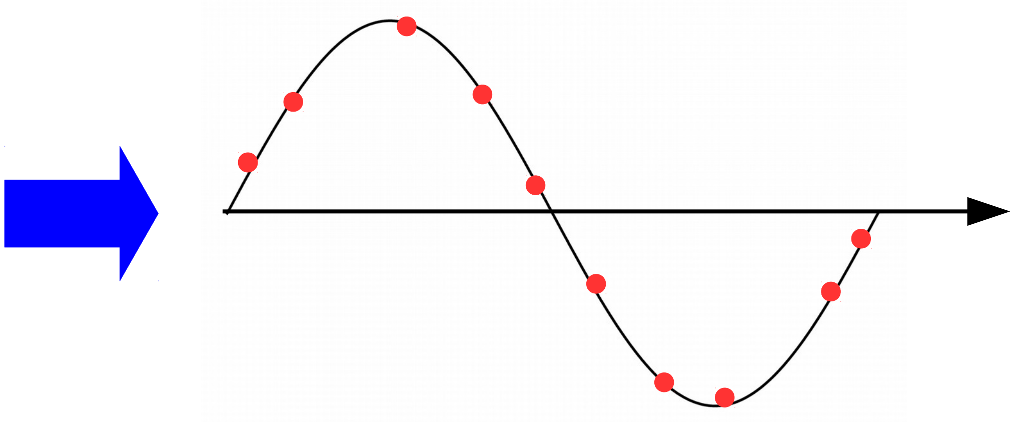
Challenge 2: Measure Precessing Polarization

$$\nu_s = \frac{\text{spin revolutions}}{\text{turn}} \approx G\gamma \approx -0.16$$

→ (Deuteron) Spin precesses at ca. 120 kHz!

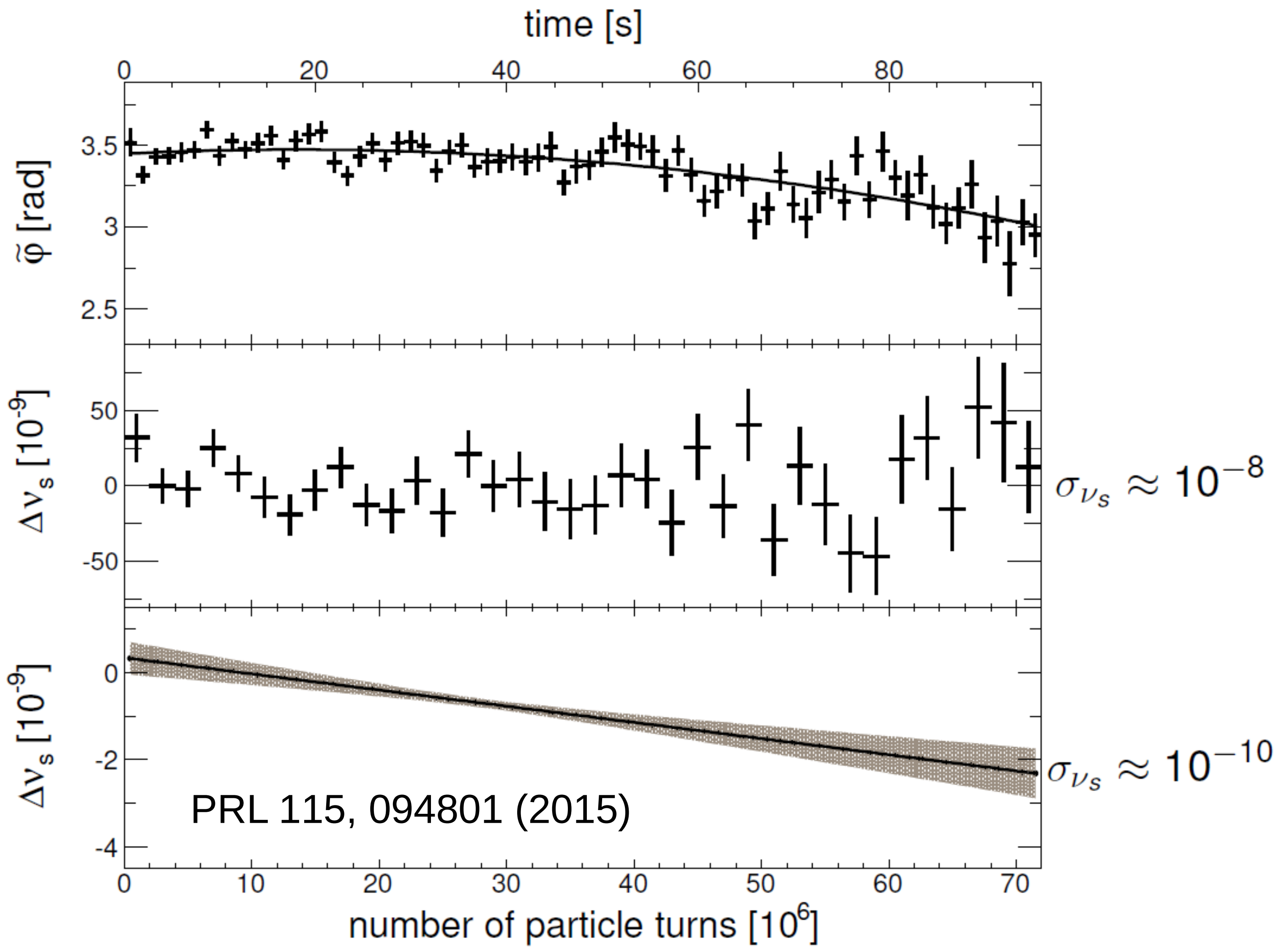


Too few polarimeter events to resolve oscillation directly!

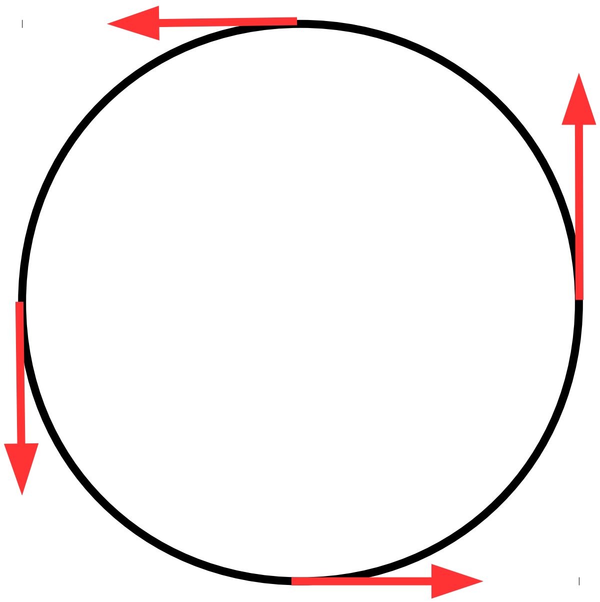


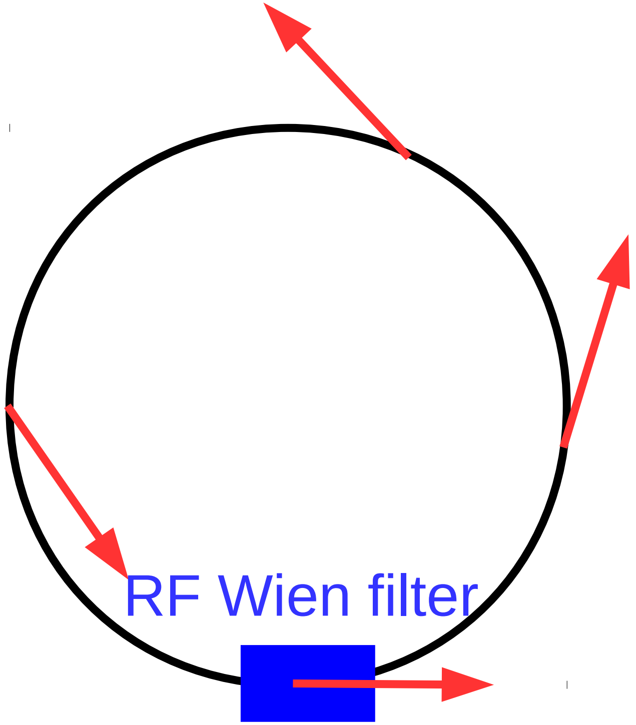
Map many events to one cycle
Phys. Rev. ST Accel. Beams 17, 052803 (2014)

Precise Measurement of Spin Tune



Challenge 3: Controlling Spin Direction





Frozen spin concept: Keep spin in forward direction

RF Wien filter method: Keep RF Wien filter in phase with spin rotation

Solution: Use Feedback System

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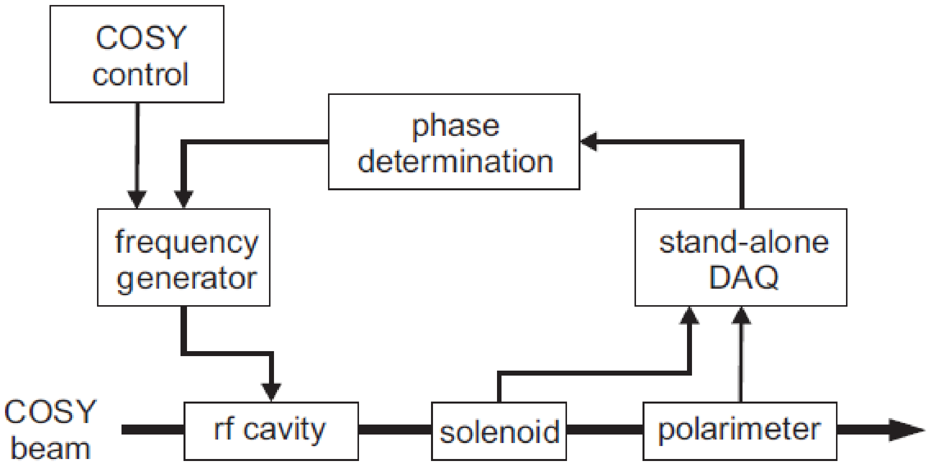
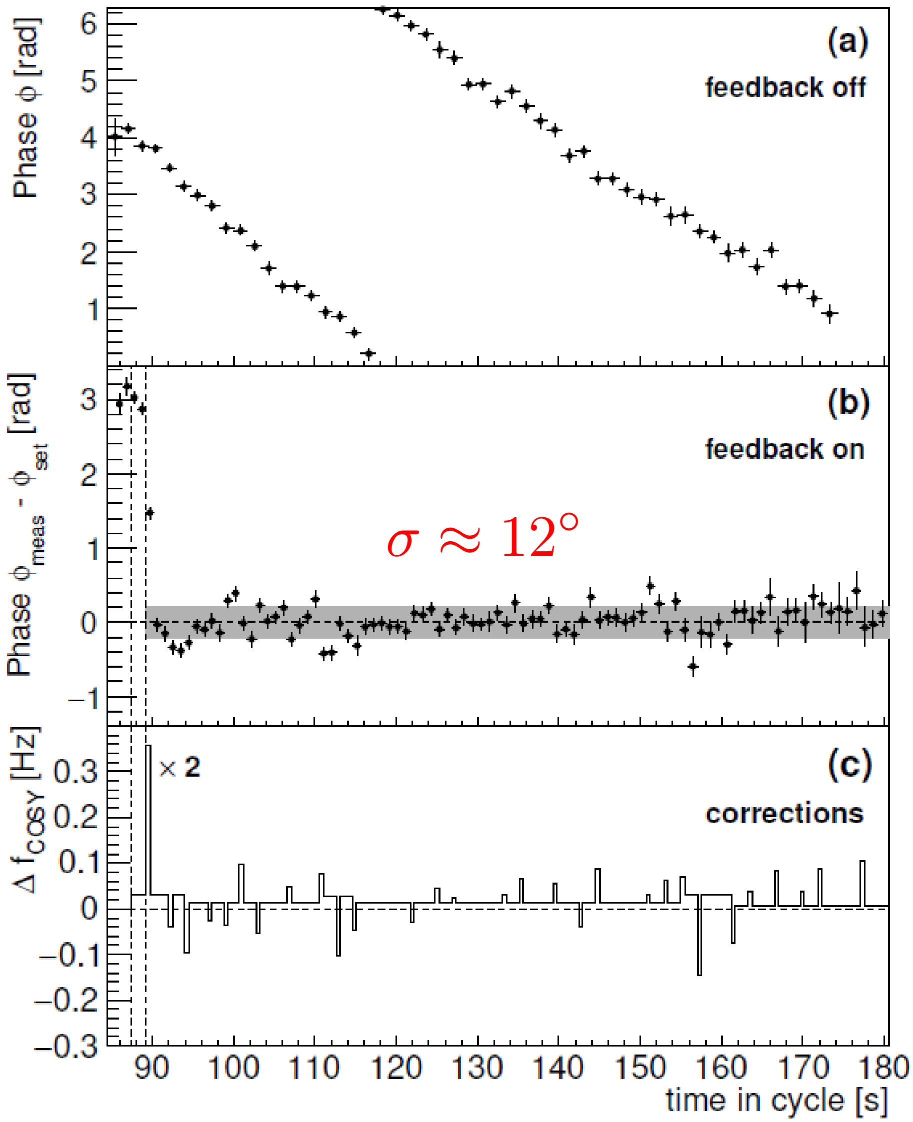


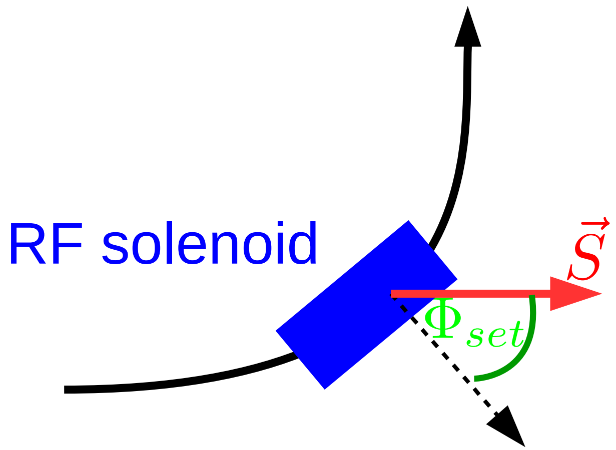


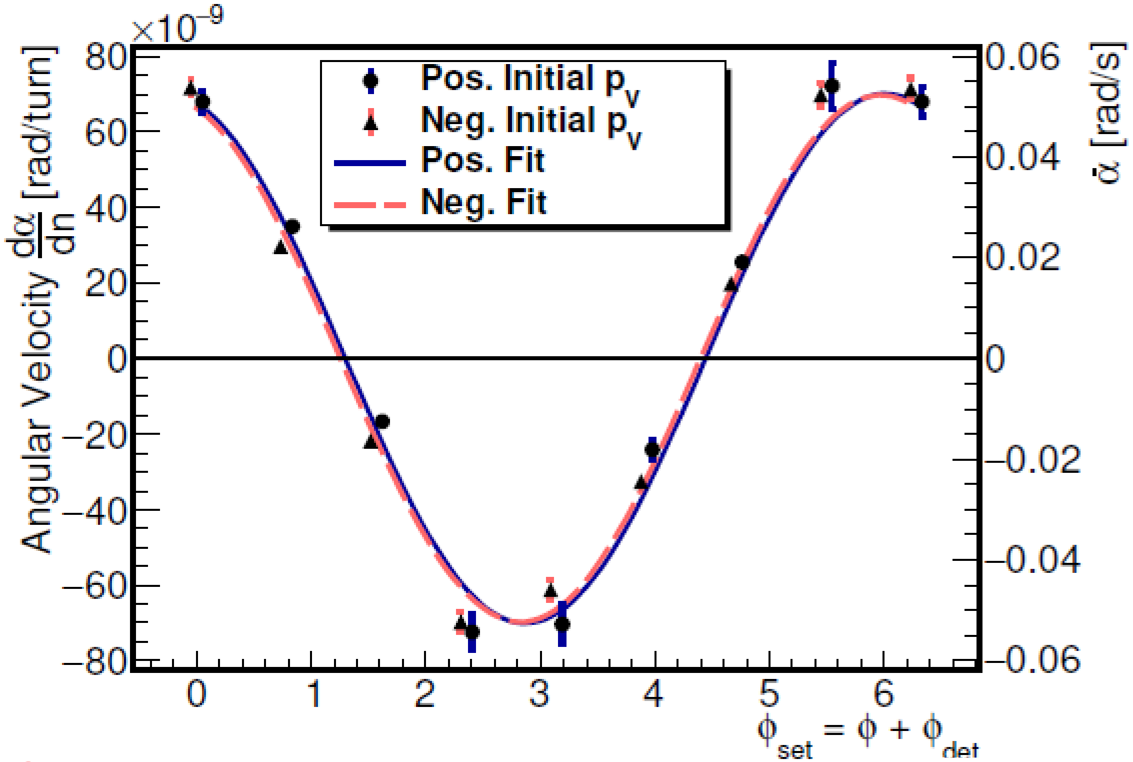
Use RF cavity to change spin tune via $\nu_s = G\gamma$

Courtesy: Nils Hempelmann

Solution: Use Feedback System

Feedback system allows to set arbitrary phase relations between spin and RF elements
→ Rotate spin back into vertical direction using RF solenoid, rate depends on phase between spin and solenoid





Courtesy: Nils Hempelmann

Summary

- EDMs are possible source of CP violation
- JEDI Collaboration is developing highly precise methods to measure and control the spin of charged particles
- Results put us on a good way for a first EDM measurement of the deuteron at COSY in 2018