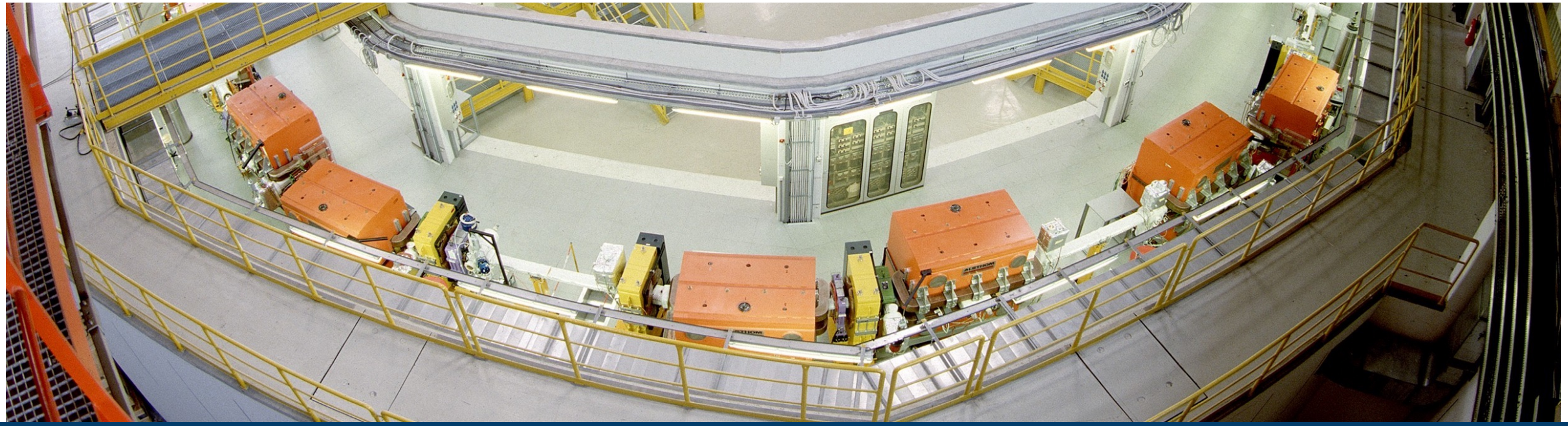

THE SEARCH FOR ELECTRIC DIPOLE MOMENTS OF CHARGED PARTICLES IN STORAGE RINGS

FPCP Conference 2022

25.05.2022 I ACHIM ANDRES ON BEHALF OF THE JEDI COLLABORATION

JEDI

Physics Institute III B | RWTH AACHEN UNIVERSITY

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COSY
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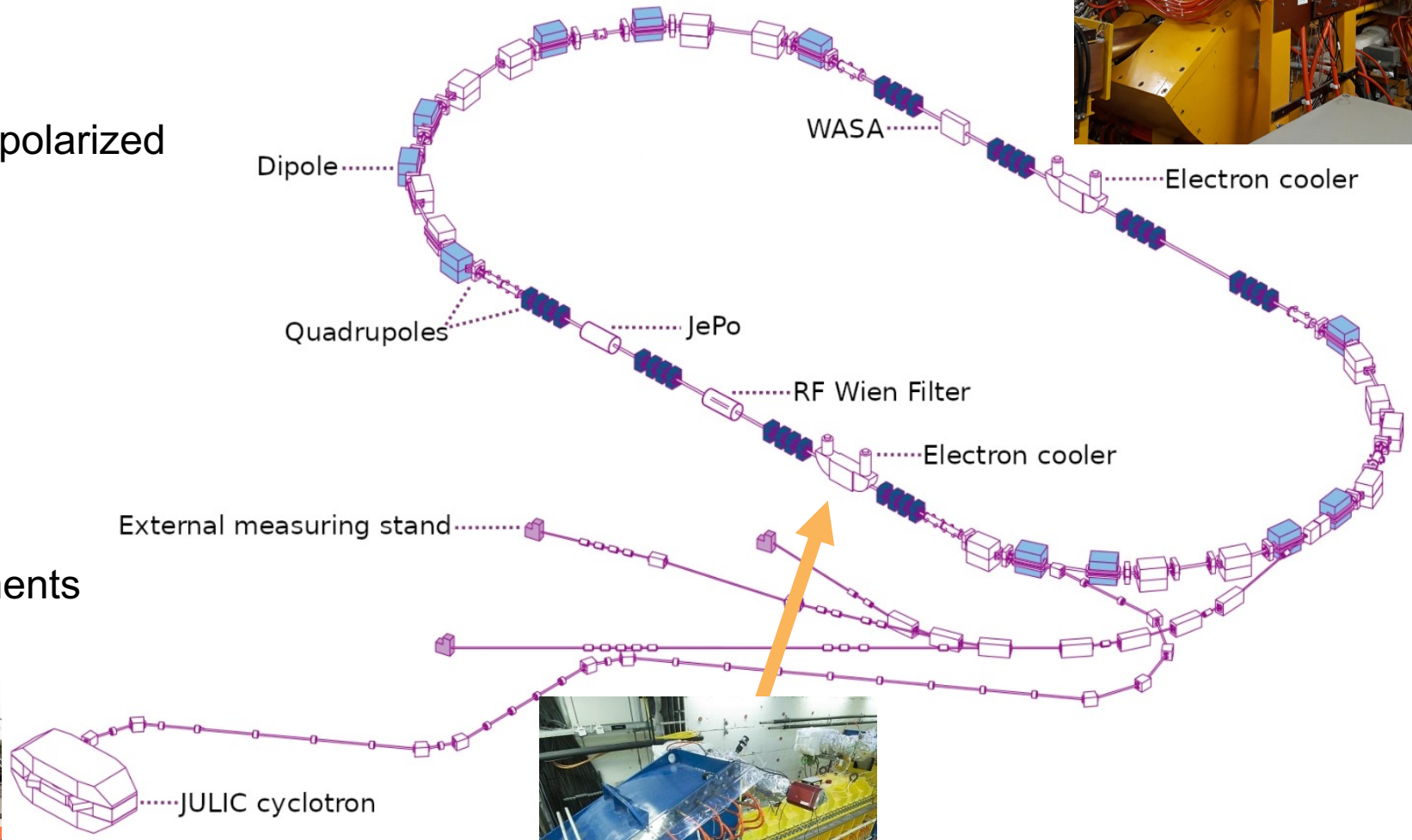
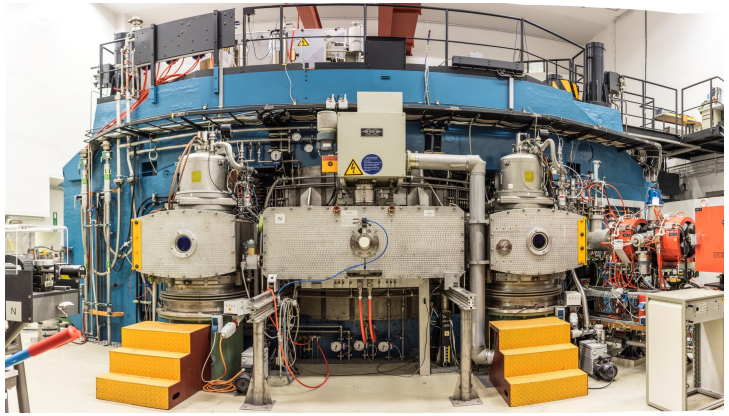
COSY - COOLER SYNCHROTRON

Overview

- Circumference 184 m
- Accelerate and Store **Polarized** / Unpolarized **Deuterons** and Protons
- $p = 0.3 - 3.7$ GeV/c
- **Internal** and **external** experiments
- 2 **Electron** Coolers
- 2 **Stochastic** Coolers
- Hadron Physics / **Precision** Experiments





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MATTER - ANTIMATTER ASYMMETRY

[1]

[2]

- Just After Big Bang

$$N_B = N_{\bar{B}}$$

- Universe cooled down below ~ 3000 K
- No Thermal Production

$$B + \bar{B} \rightarrow 2\gamma$$

- Baryon Asymmetry

$$\eta = \frac{N_B - N_{\bar{B}}}{N_\gamma} \approx \begin{cases} 10^{-10} & \text{measured} \\ 10^{-18} & \text{from SCM} \end{cases}$$

- According to A. Sakharov: **CP Violation** is needed

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ELECTRIC DIPOLE MOMENTS - EDM

- EDM Fundamental property of elementary particles

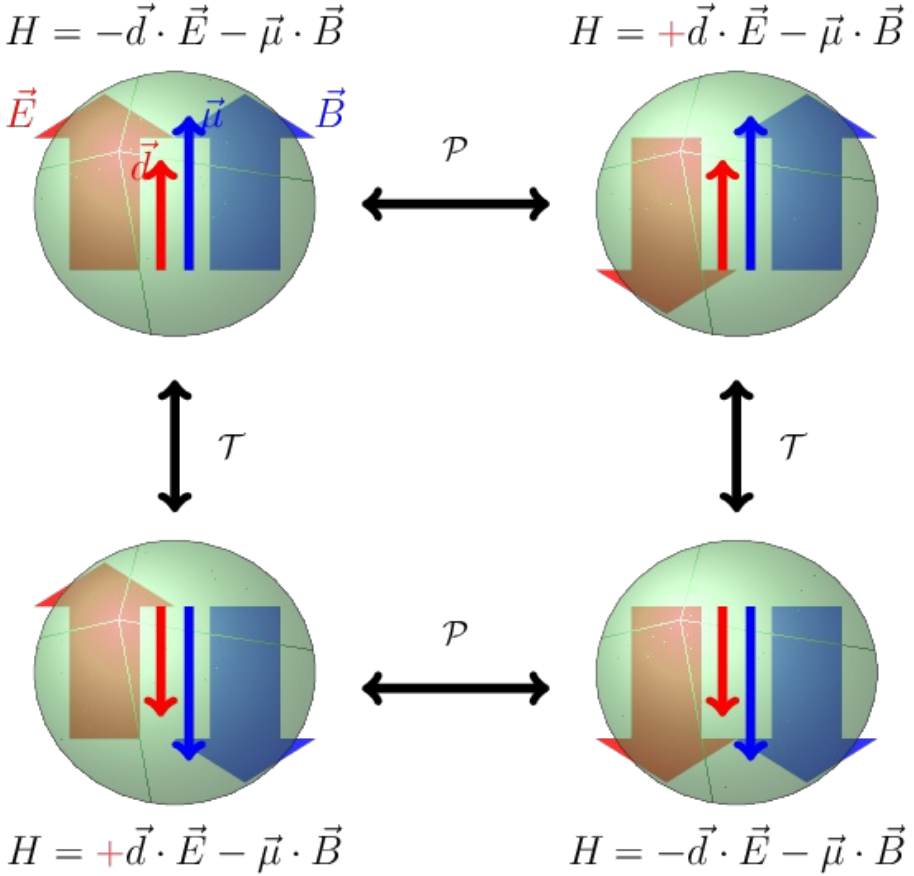
$$\vec{d} = d \cdot \vec{s}$$

- Magnetic Dipole Moment

$$\vec{\mu} = \mu \cdot \vec{s}$$

- Hamiltonian:

$$\hat{\mathcal{H}} = -d \cdot \vec{s} \cdot \vec{E} - \mu \cdot \vec{s} \cdot \vec{B}$$
$$\mathcal{P}(\hat{\mathcal{H}}) = +d \cdot \vec{s} \cdot \vec{E} - \mu \cdot \vec{s} \cdot \vec{B}$$
$$\mathcal{T}(\hat{\mathcal{H}}) = +d \cdot \vec{s} \cdot \vec{E} - \mu \cdot \vec{s} \cdot \vec{B}$$



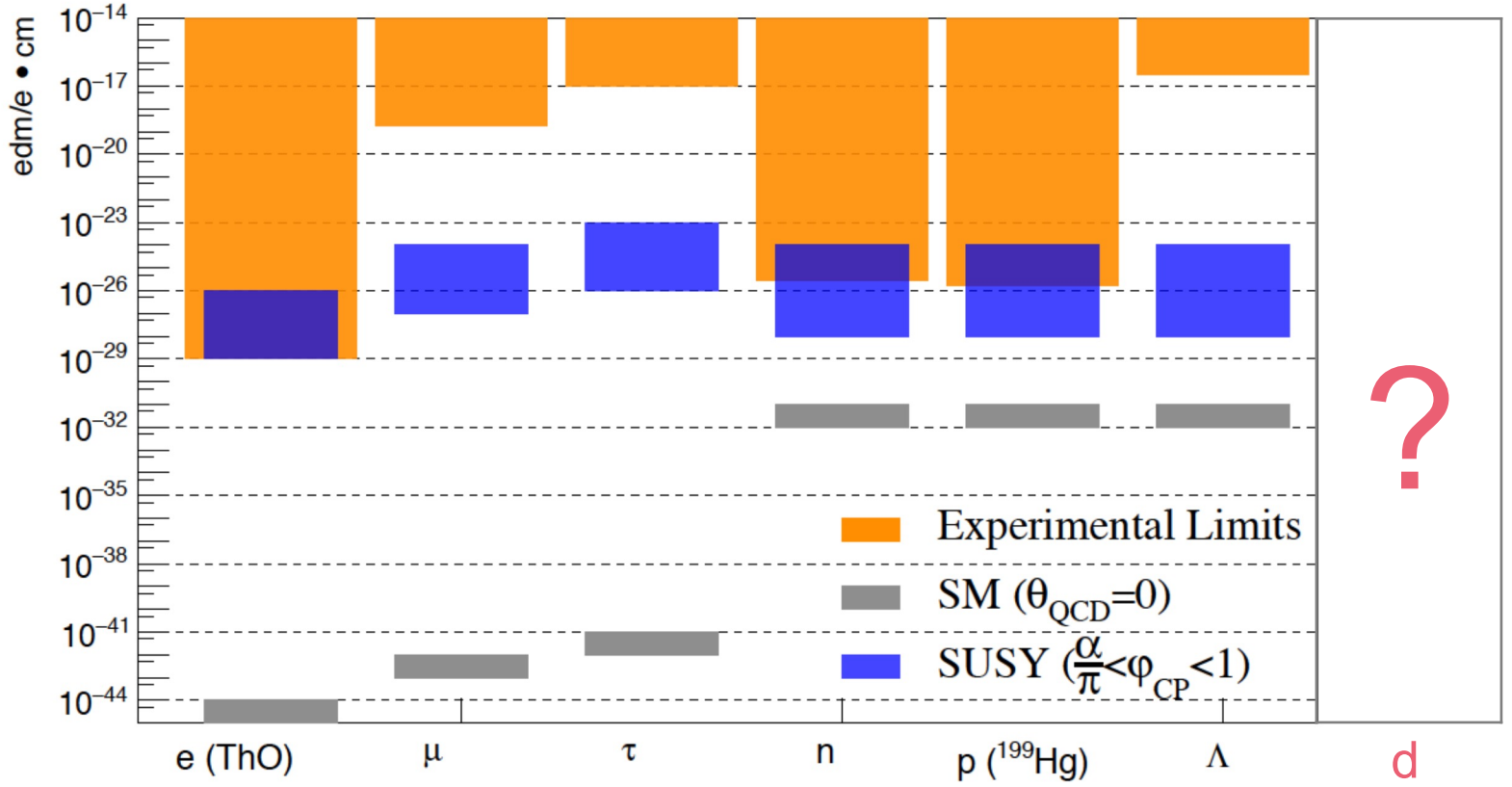
- According to CPT Theorem:

T Violation = CP Violation

- EDM violates both P and CP symmetry

EDM LIMITS

JEDI Collaboration (2011) – Juelich Electric Dipole Moment Investigations



- No direct measurements of **electron**: limit obtained from ThO molecule
- No direct measurements of **proton**: limit obtained from ^{199}Hg
- No measurement at all of deuteron

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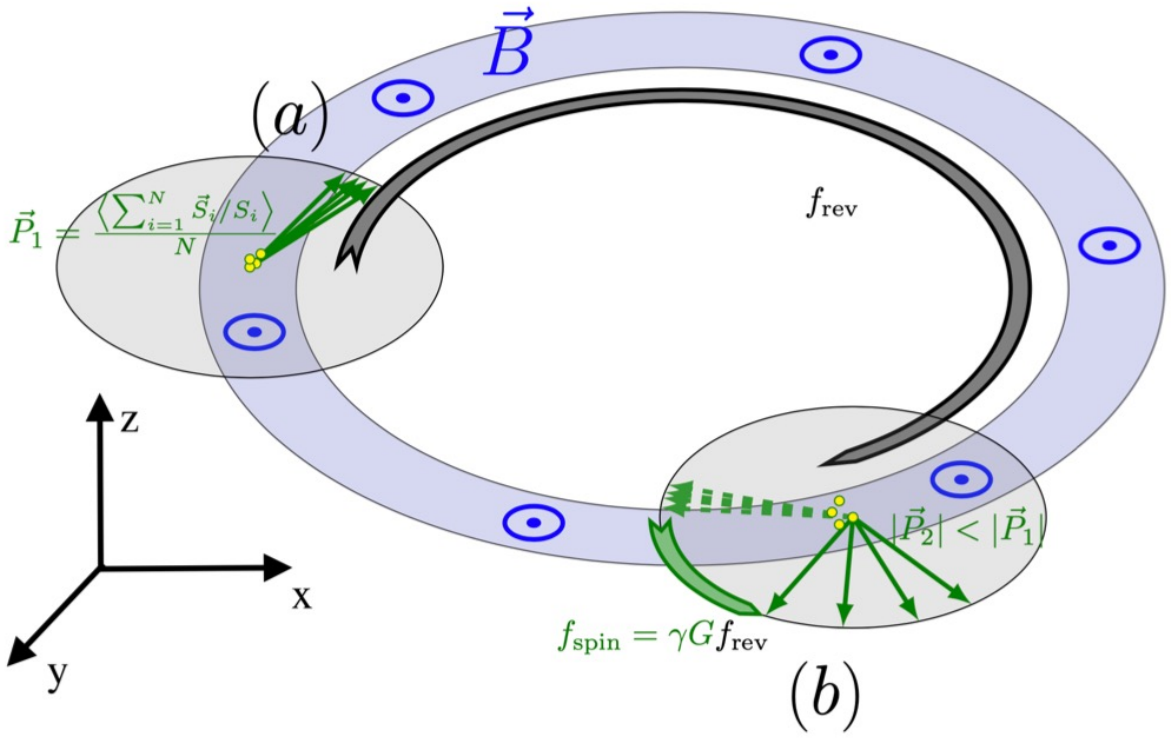
BEAM POLARIZATION

$$\text{Polarisation } \vec{P} = \frac{1}{N}\sum_{i=1}^{N}\vec{S}_i$$

$$\text{Vertical } p_V = p_z$$

$$\text{Radial } p_H = \sqrt{p_x^2 + p_y^2}$$



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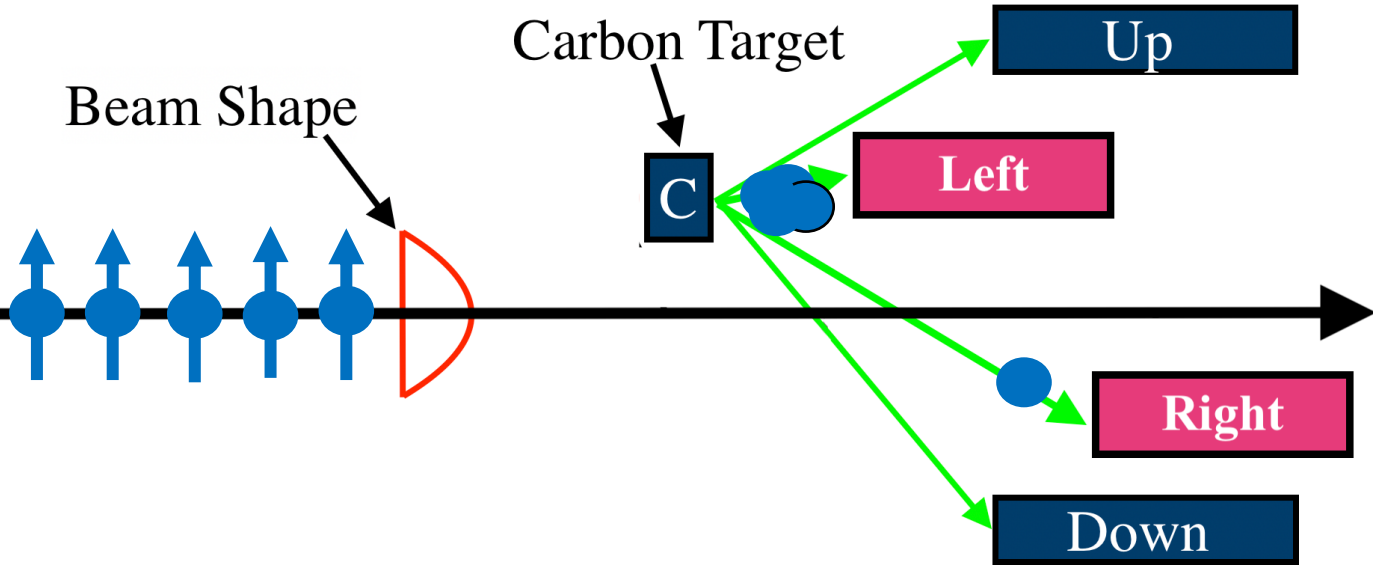
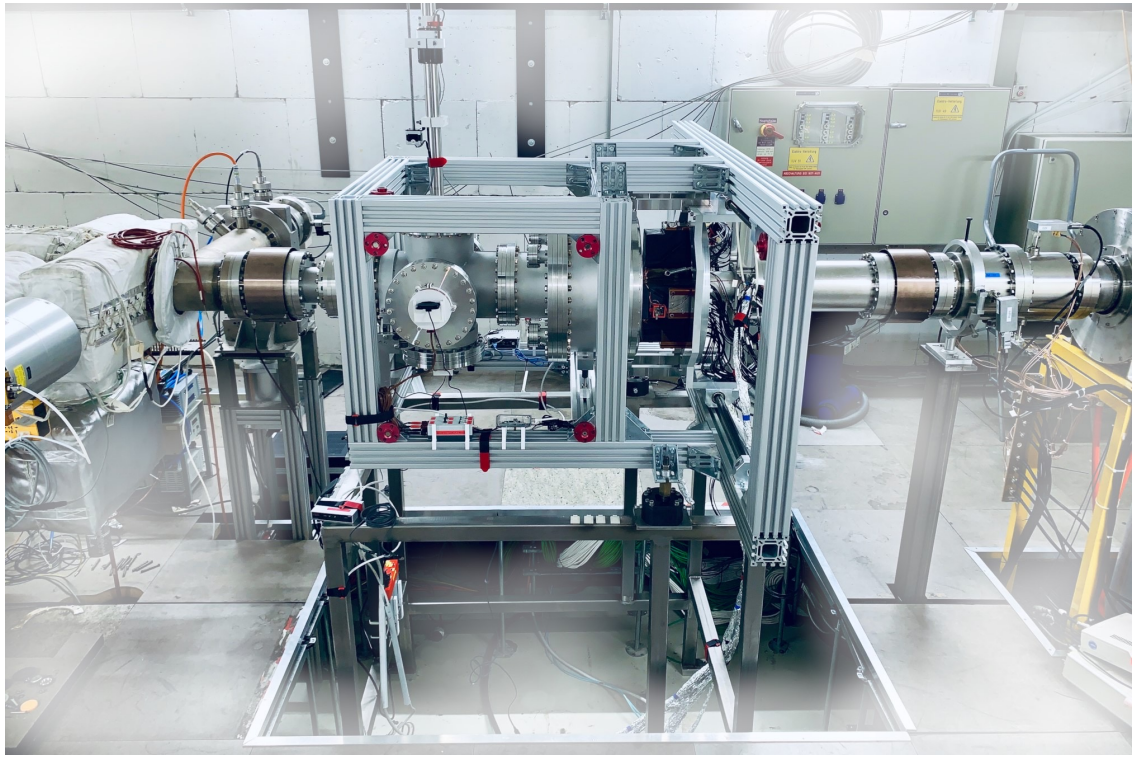
POLARIMETRY

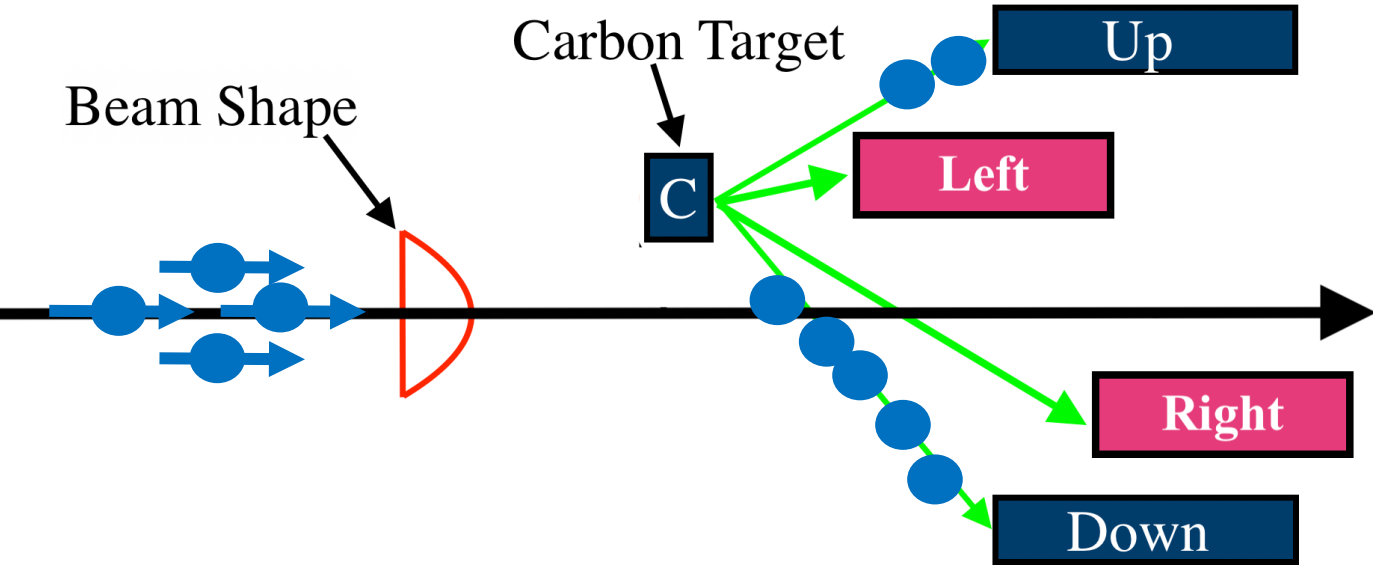


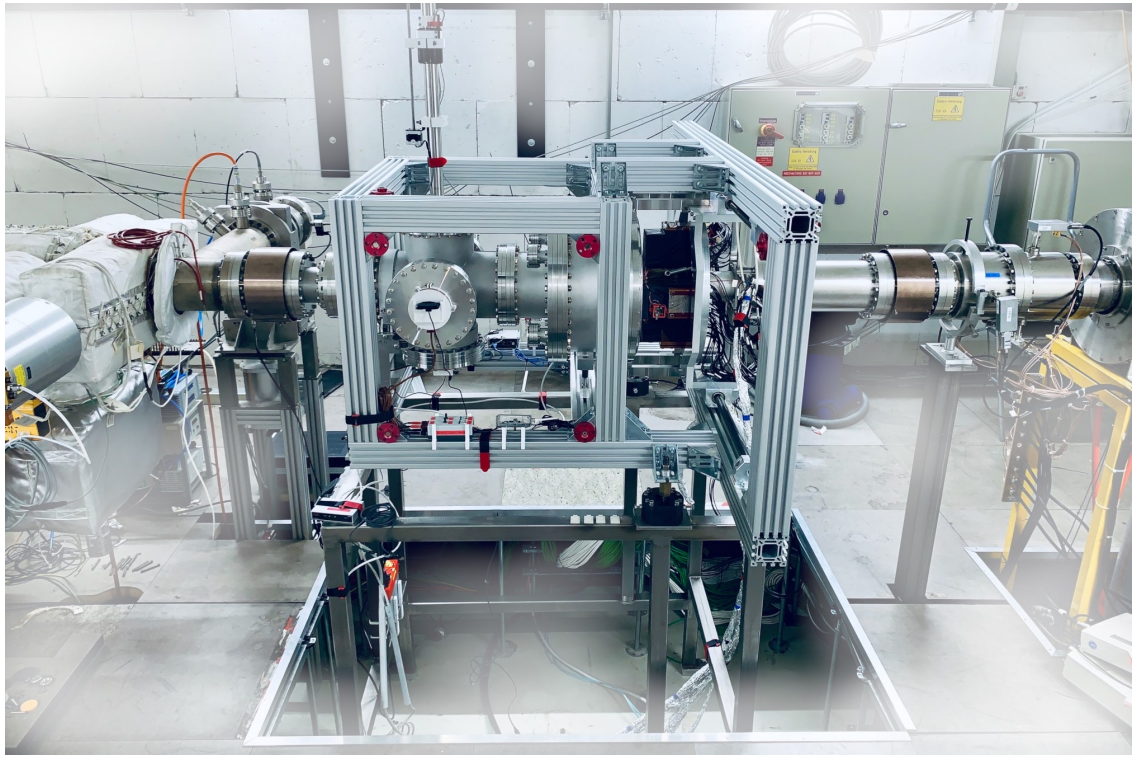


- **Determination of Beam Polarization**
  - **Vertical Polarization: Left – Right Asymmetry**
  - Radial Polarization: Up – Down Asymmetry

JePo (Jedi Polarimeter)

POLARIMETRY





- **Determination of Beam Polarization**
  - Vertical Polarization: Left – Right Asymmetry
  - **Radial Polarization: Up – Down Asymmetry**

JePo (Jedi Polarimeter)

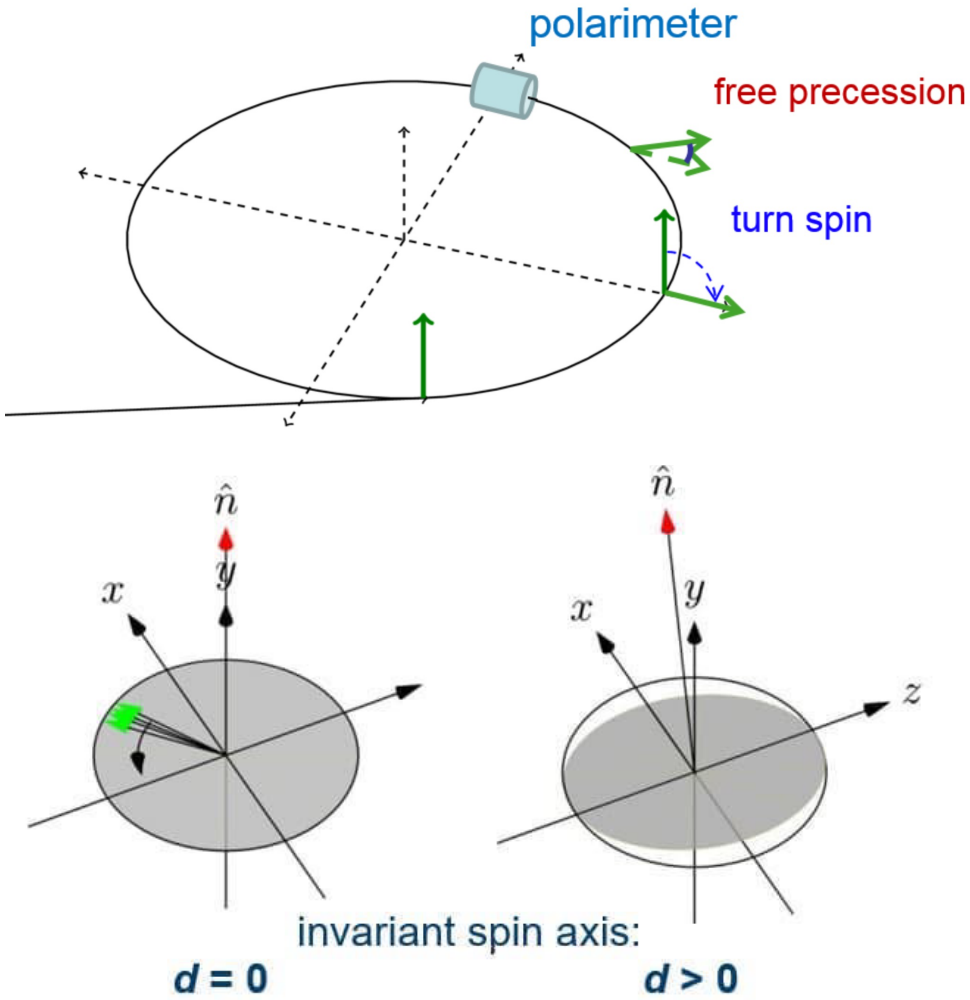
MEASUREMENT PRINCIPLE I

- Measure **influence** of **EDM** on beam **polarization**

- **Injection** of vertically **polarized** beam
- **Rotate** polarization into **accelerator plane**
- COSY: **Magnetic** Ring → Polarization Vector **precesses** around invariant spin axis $\hat{n}$

- $d > 0$: Tilts $\hat{n}$ in **radial** x direction

- **Goal**: Determination of the **orientation** of $\hat{n}$
- **Problem**: Ring **imperfections** (magnet misalignments,..) lead to rotations of $\hat{n}$ in **radial** (x) and **longitudinal** (z) direction



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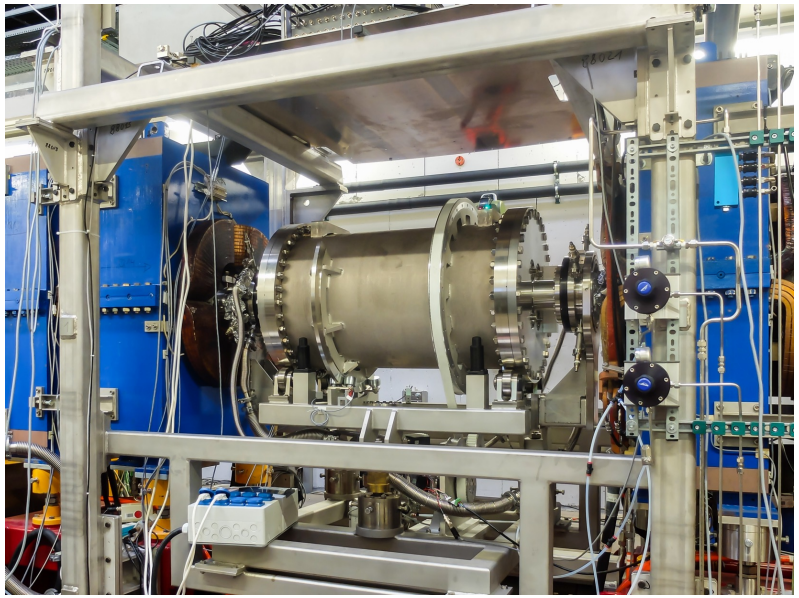
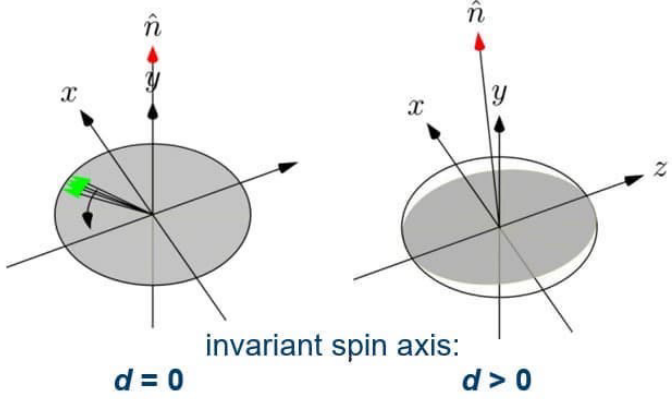
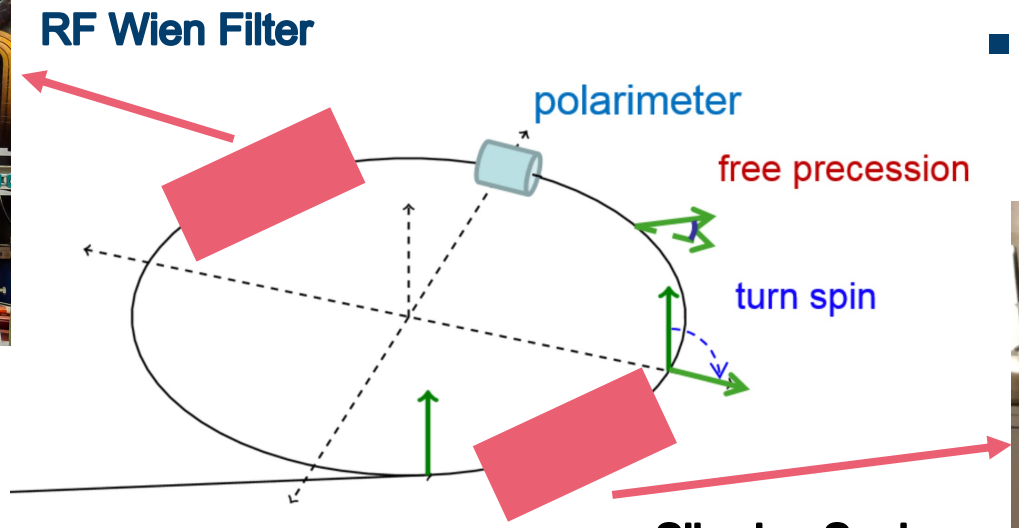
MEASUREMENT PRINCIPLE II

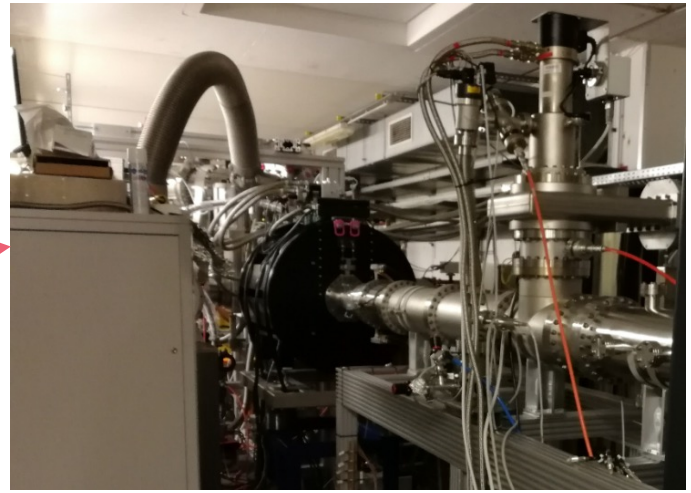
- **Goal**: Determination of the **orientation** of $\hat{n}$







- Longitudinal $\vec{B}$ field
- $\vec{B}$ - Field kicks $\hat{n}$ in **longitudinal** direction (z) by ξ^{SOL}



- $\vec{E} \perp \vec{B} \perp$ Beam $\rightarrow$ $\vec{F}_L = 0$
- $\vec{B}$ - Field kicks $\hat{n}$ in **radial** direction (x) at WF
- **Rotational** Device ϕ^{WF}

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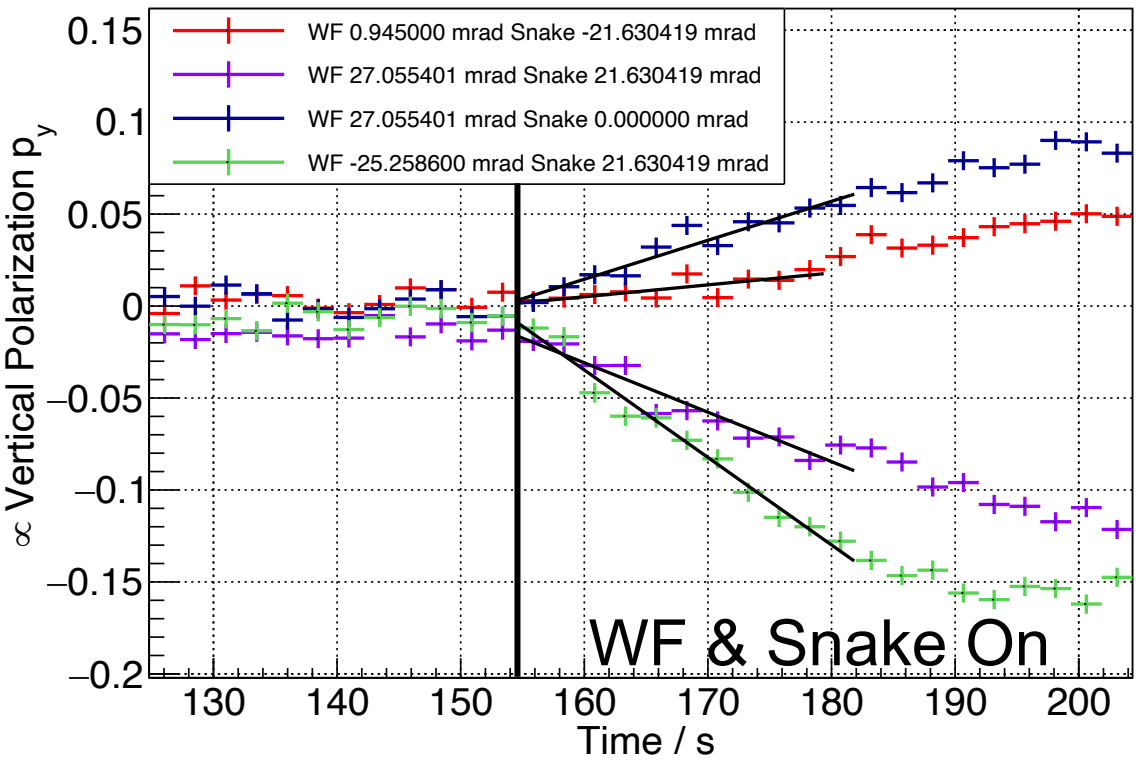
MEASUREMENT PRINCIPLE III

- Fix Wien Filter ϕ^{WF} and Siberian Snake (Solenoid) rotation angle ξ^{SOL}
- Measure **slope** of linear increasing vertical polarisation **after** turning on Wien Filter and Siberian Snake
- **Repeat** for different settings for **Wien Filter** and **Siberian Snake**
- **Resonance** Strength is given by

$$\epsilon(\phi^{WF}, \xi^{Sol}) \sim |\dot{p_y}|$$



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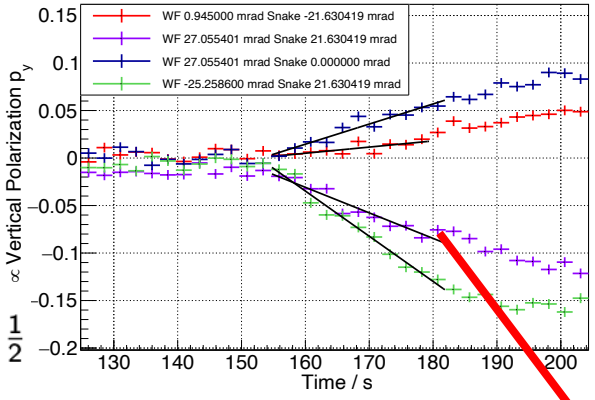
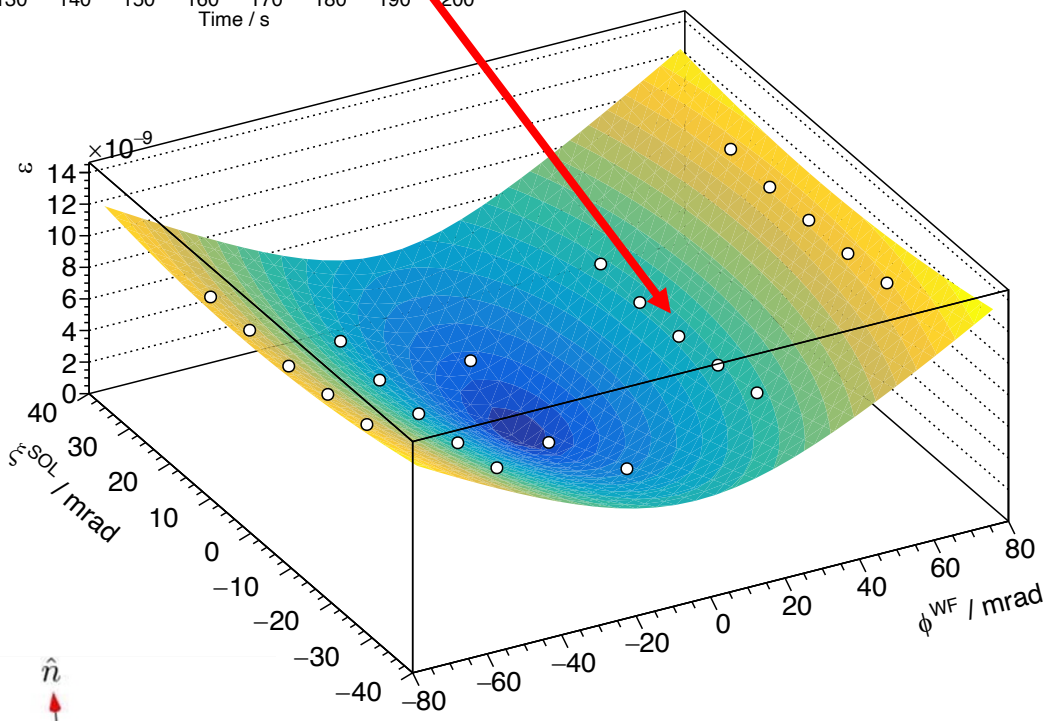
PRELIMINARY RESULTS

$$\epsilon(\phi^{WF}, \xi^{Sol}) = \left[A_{WF}^2 \left(\phi^{WF} - \phi_0^{WF} \right)^2 + \frac{A_{Sol}^2}{4 \sin^2(\pi \nu_s)} \left(\xi_0^{Sol} - \xi^{Sol} \right)^2 \right]$$



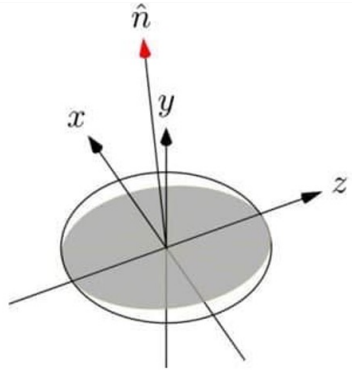
$$\epsilon(\phi^{WF}, \xi^{Sol}) \sim |\dot{p}_y|$$



Orientation of $\hat{n}$ including ring **imperfections** and **EDM** signal is:

$$\phi_0^{WF} = -2.91(8)\,\text{mrad}$$
$$\xi_0^{SOL} = -5.22(7)\,\text{mrad}$$

1) **Minimum** represents invariant spin axis orientation **including** EDM and ring imperfections
2) **Simulated** spin tracking shall determine orientation of stable spin axis **without** EDM
3) **EDM** is determined from difference of 1) and 2)



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ACHIEVEMENTS @ COSY

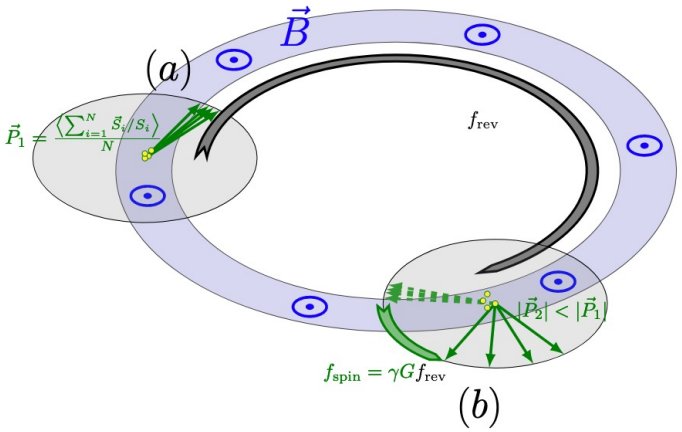
Spin Tune (PRL 115, 094801 2015)

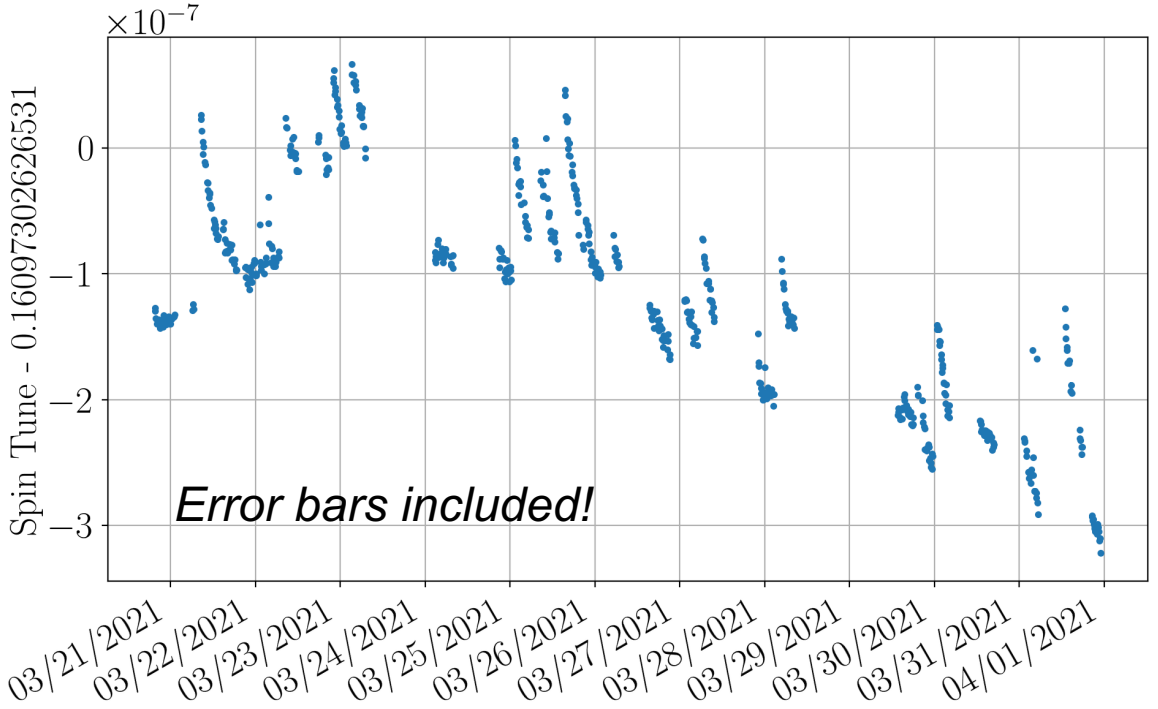
$$\Omega_{\mathrm{MDM}} = |\gamma G \Omega_{\mathrm{rev}}| \approx 121\ \mathrm{kHz}$$

$$\nu_s = \frac{\Omega_{\mathrm{MDM}}}{\Omega_{\mathrm{rev}}} = \gamma G \approx -0.161$$

$$\Delta\nu_s/\nu_s \approx 10^{-10}$$

- Spin Tune is crucial for:
  - Analysis of **Radial** Polarization
  - **Operation** of RF **Wien Filter**
  - **Calibration** of Siberian Snake
  - Understanding **Systematics**





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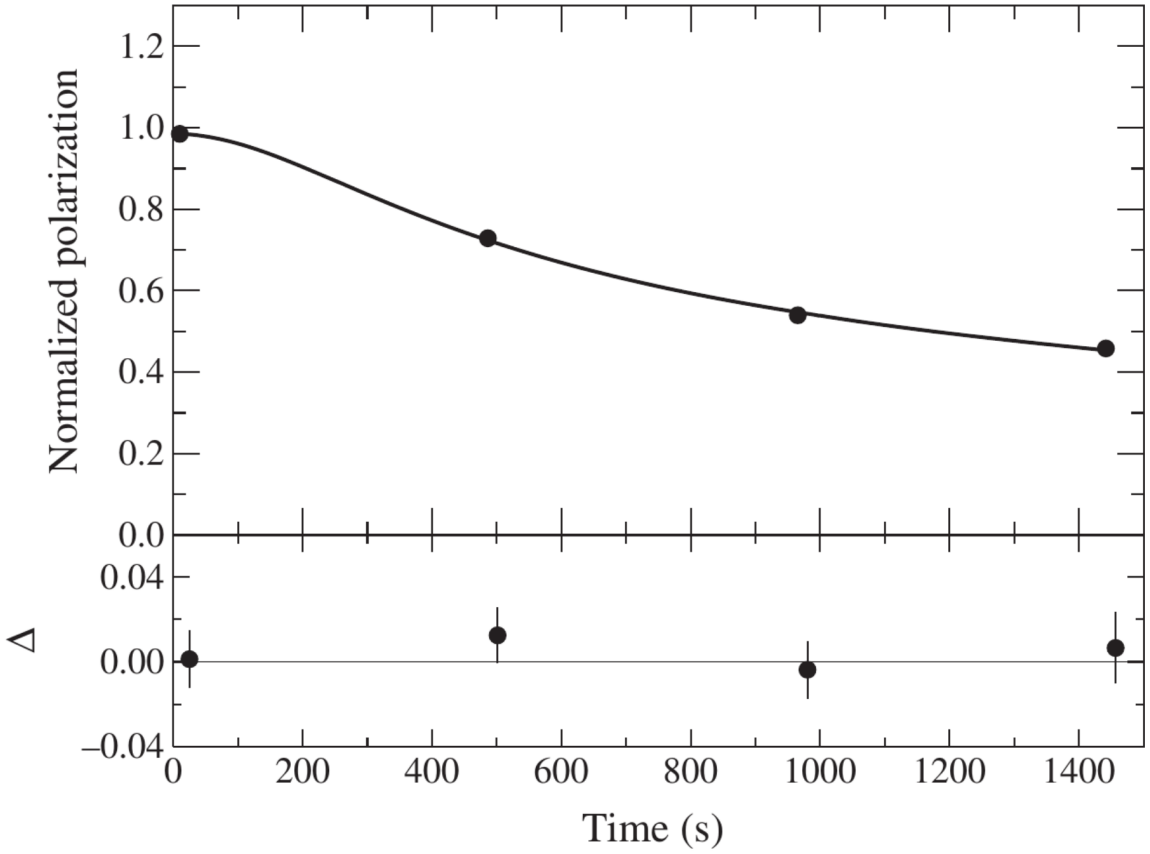
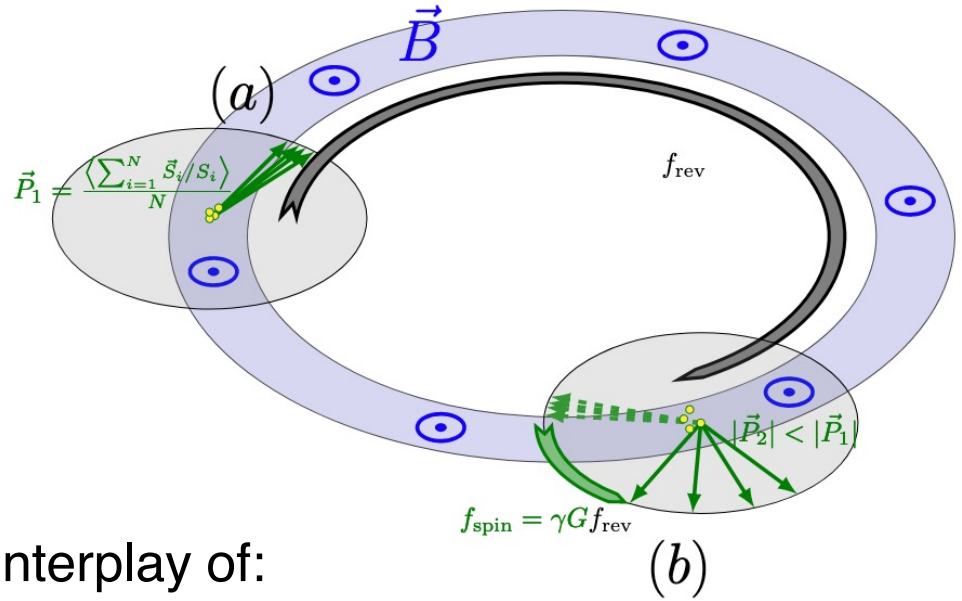
ACHIEVEMENTS @ COSY

Spin Coherence Time - Deuterons (PRL 117, 054801 2016)



Spring 2015: 1/*e* Lifetime = (2280 +/- 336) s



- Complex Interplay of:
  - Beam Emittance (Beam Cooling)
  - Beam Chromaticity
  - Orbit Deviations
  - Momentum Spread
  - …

$$\nu_s = \frac{\Omega_{\mathrm{MDM}}}{\Omega_{\mathrm{rev}}} = \gamma G \approx -0.161$$

$$\sigma_{\mathrm{stat}}^{\mathrm{EDM}} \propto 1/\mathrm{SCT}$$

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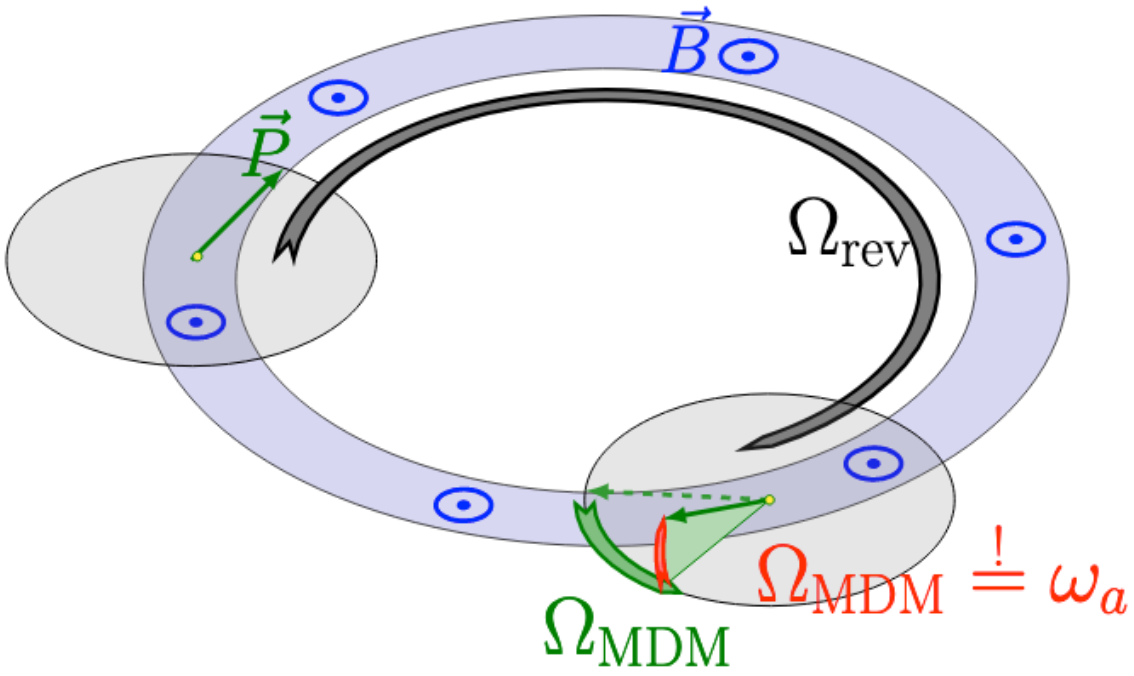
SEARCH FOR AXIONS / ALPS

PRINCIPLE OF STORAGE RING AXION/ALP EXPERIMENT

Swathi Karanth, Seung Pyo Chang



- Axions and ALPs:
  - Solution of strong CP Problem
  - Dark Matter Candidate
- From axion gluon coupling, a time **varying** EDM can be induced
- **Oscillating** EDM *d*
- Oscillation Frequency: axion **mass**

$$d = d_{\mathrm{DC}} + d_{\mathrm{AC}} \sin(\omega_a t + \varphi_a)$$

$$\omega_a = \frac{m_a c^2}{\hbar}$$

- Vertical Polarization **Build up** if

$$\Omega_{\mathrm{MDM}} = \gamma G \Omega_{\mathrm{rev}} \stackrel{!}{=} \omega_a$$

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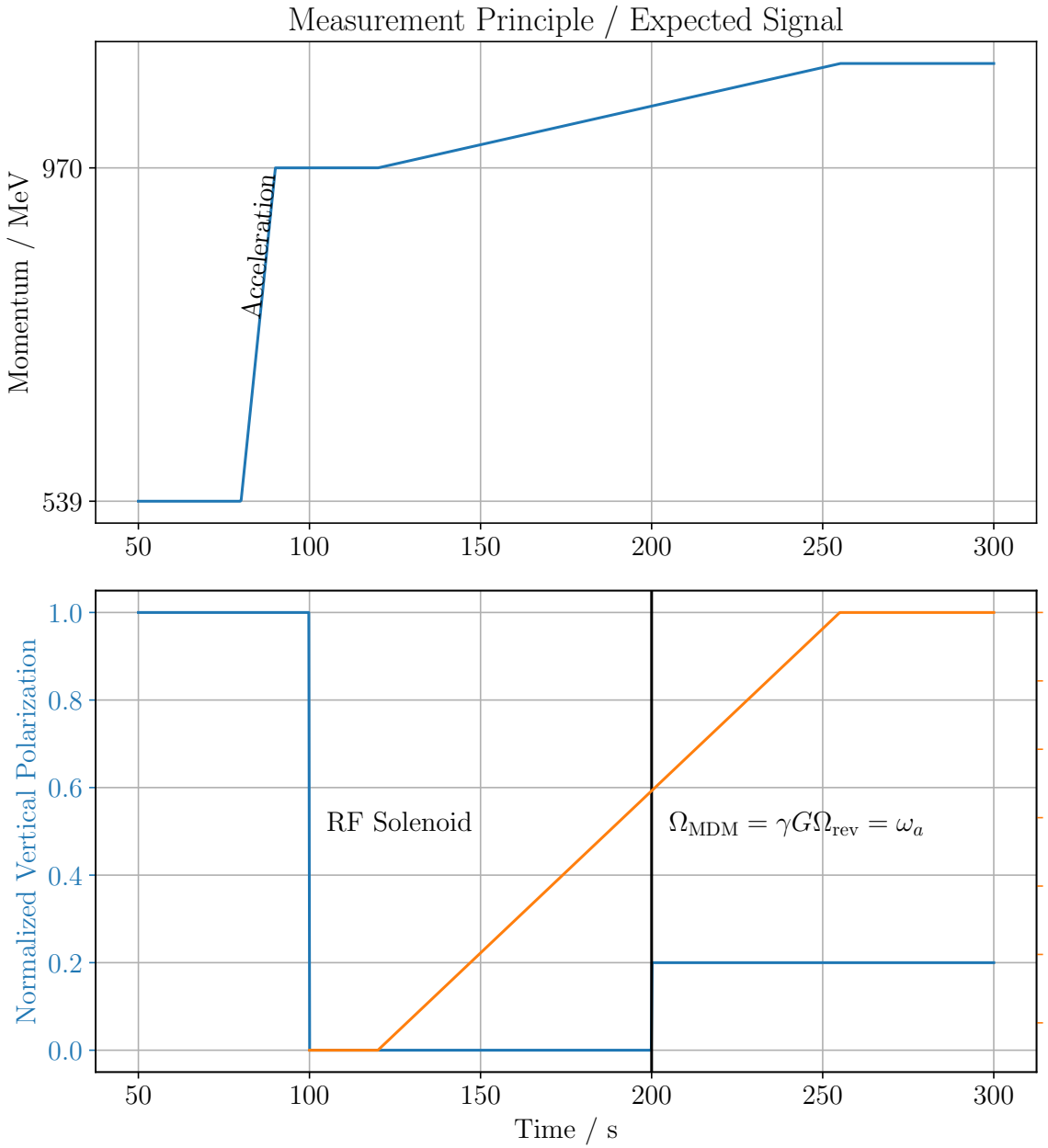
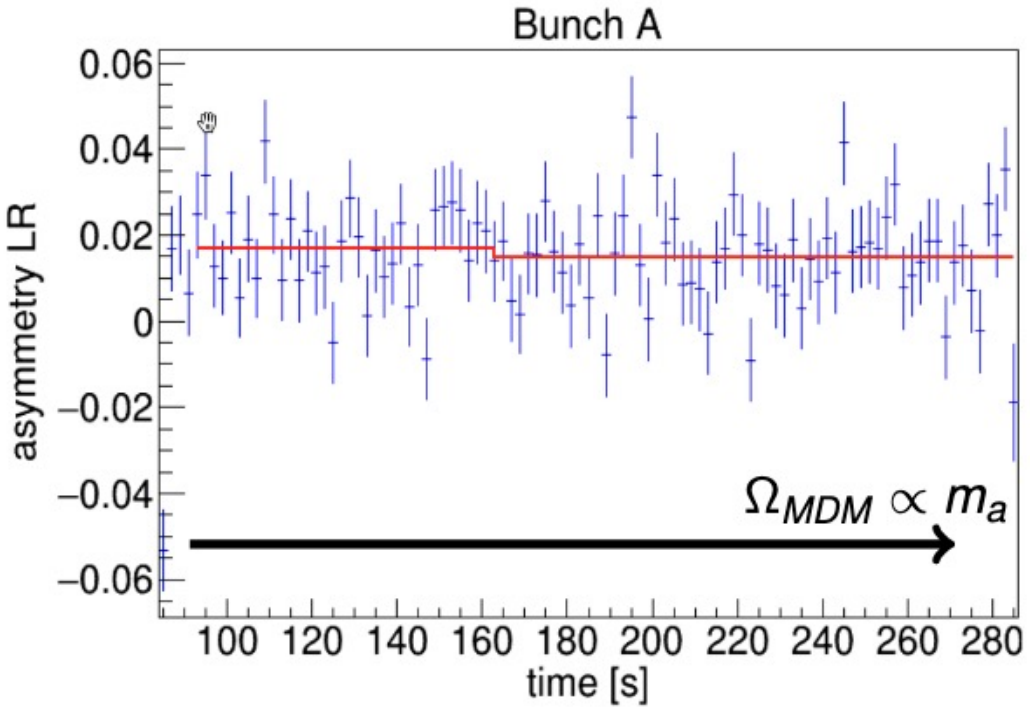
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.88.035023, **Graham and Rajendran** 2013

MEASUREMENT PRINCIPLE





- Momentum Scan
  = Ω_{MDM} Scan
  = Axion Mass Scan
- Scanned Frequency Range: 120.05 – 121.45 kHz
- Covered Axion Mass Range: (4.96 – 5.02) 10^{-10} eV

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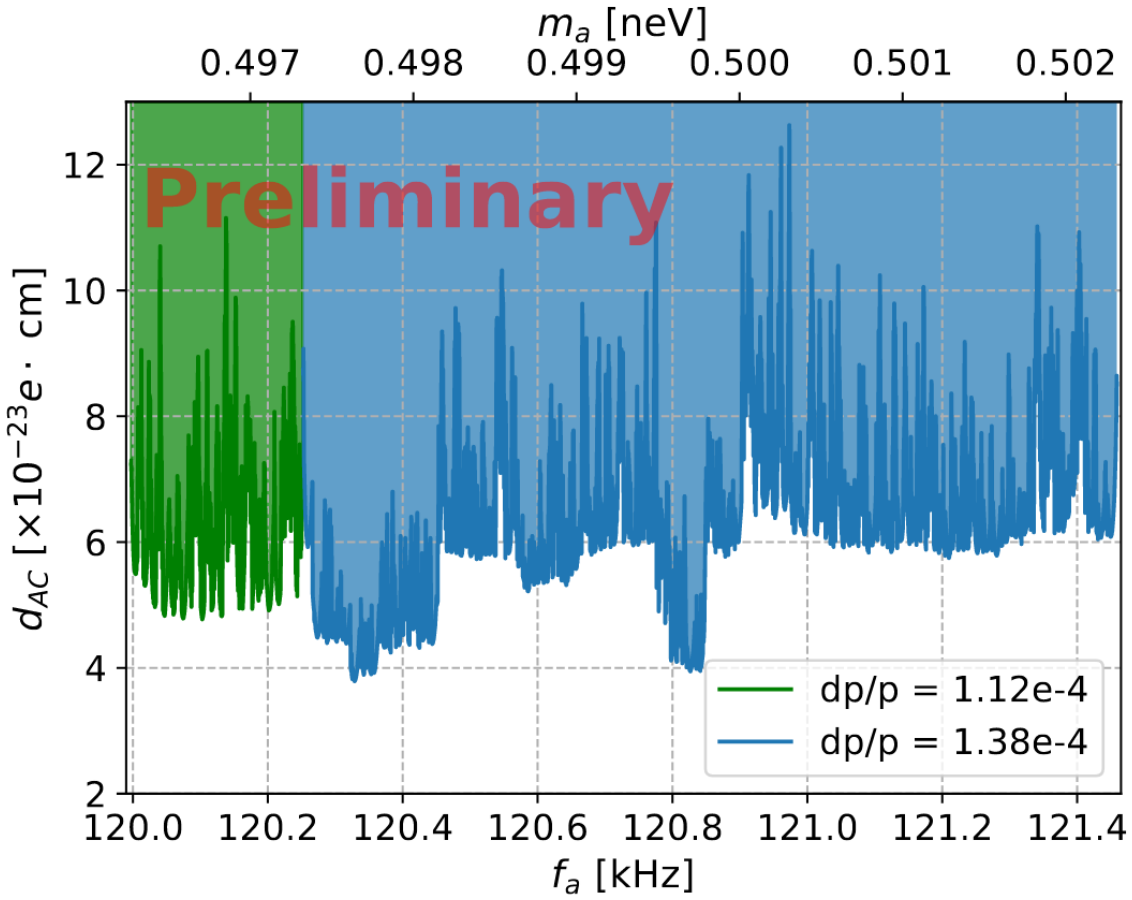
PRELIMINARY RESULTS



- Results from many scans
- 4 weeks of beam time in Spring 2019

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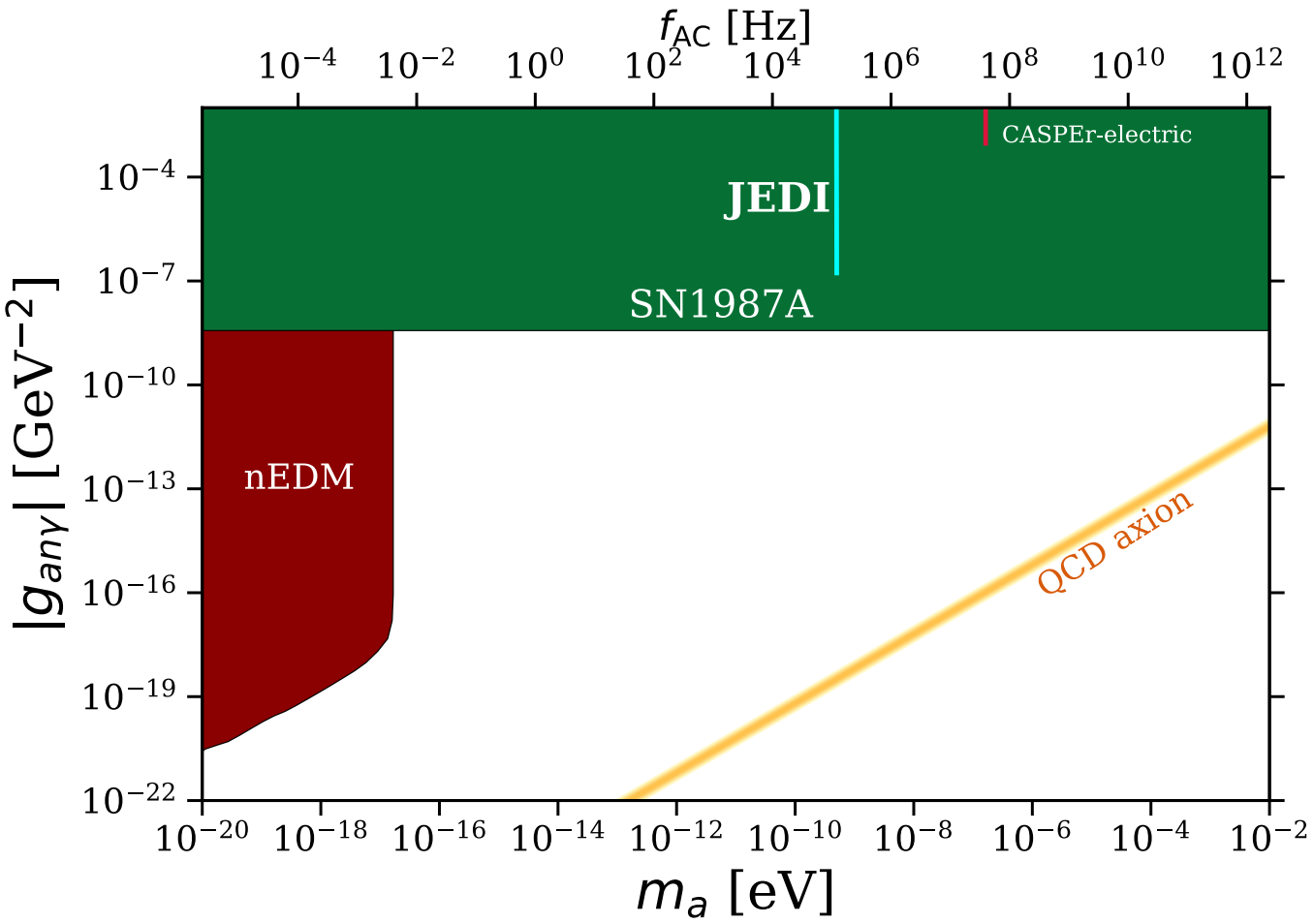
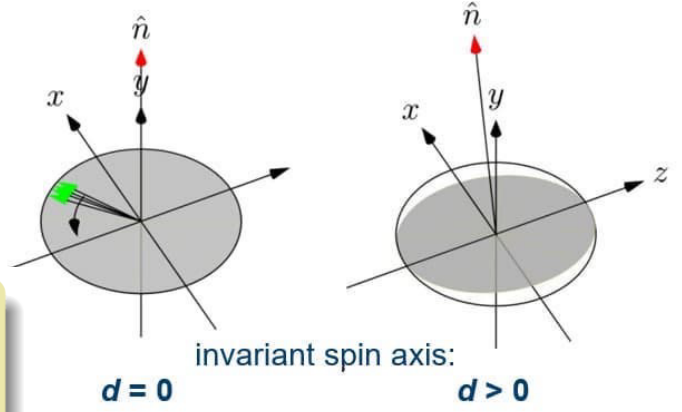
AXION ANOMALOUS COUPLING TO GLUONS



- Calculate upper limits for gluon langrangian axion coupling constant
- Blue „needle“ represents the result
- Could be longer (and thinner) if we spent more time measuring only one frequency
- Run at a given mass

WHAT COMES NEXT?

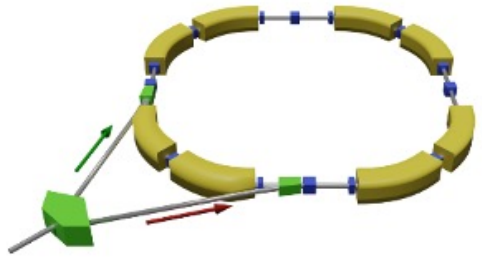
STAGED APPROACH // FROZEN SPIN



$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = \frac{-q}{m}\left[G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E} + \frac{\eta}{2}(\vec{E} + \vec{v} \times \vec{B})\right] \times \vec{s}$$

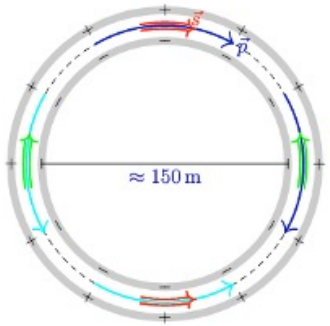
$$\vec{\Omega}_{\mathrm{MDM}} = 0\,, \quad \textbf{frozen spin} \qquad = \vec{\Omega}_{\mathrm{EDM}}$$

- Increase **sensitivity** and decrease **systematics**: $\vec{\Omega}_{\mathrm{MDM}} = 0$
- Combined E/B Ring (e, p, d, ^{3}He):



$$G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E} \stackrel{!}{=} \vec{0}$$

- Pure Electric Ring (only for protons / electrons):



$$G = \frac{1}{\gamma^2 - 1} \quad \longrightarrow \quad G > 0$$

- magic momentum

(701 MeV/c)

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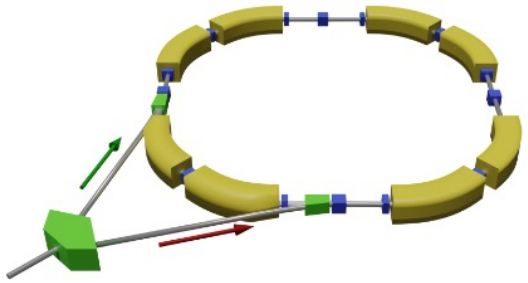
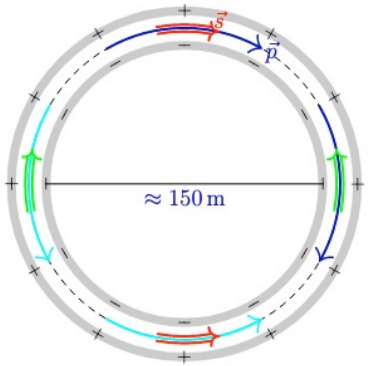
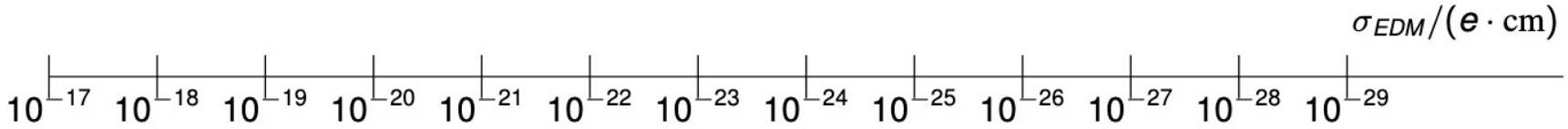
STAGED APPROACH

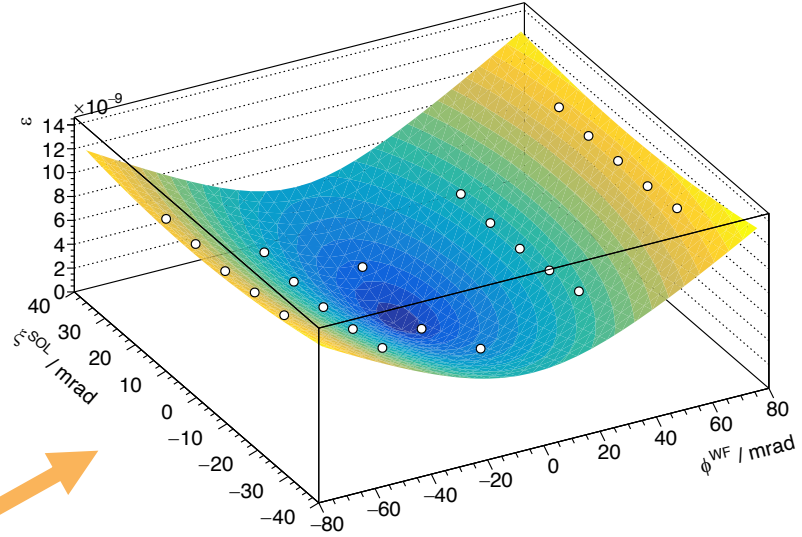
precursor experiment at Cooler Synchrotron COSY	prototype ring	dedicated storage ring
		
• magnetic storage ring	• initially electrostatic storage ring • simultaneous ↻ and ↺ beams	• magic momentum (701 MeV/c)

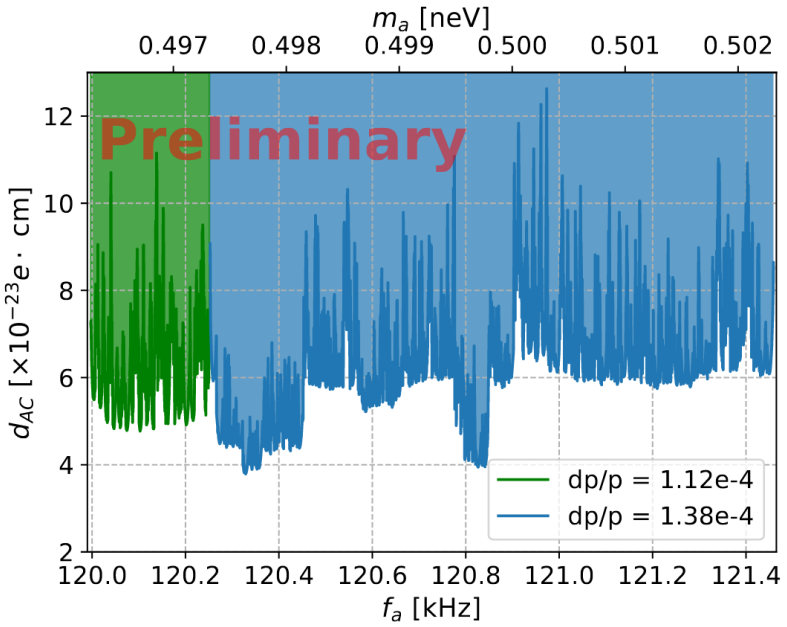


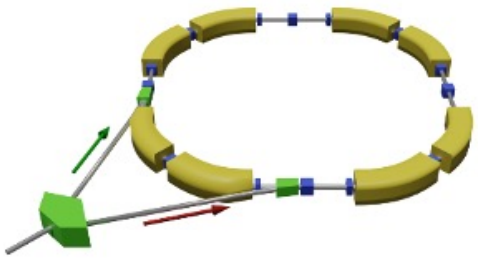
- Agreement within community on **staged** approach:
  - **First** direct **EDM** measurement (deuterons) and many **basics** studies with **COSY**
  - Next step: **prototype** ring to **gain experience** and better understand **limitations** and their **mitigations**

SUMMARY

- Introduction to COSY
- Spin Physics Program @ COSY
  - EDMs as a source for CP Violation
  - Observe EDM effect on beam polarization
  - Preliminary results
  - Search for **Axions/ALP** @ COSY
- Outlook: Staged Approach
  - Combined E/B Ring
  - Pure Electric Ring







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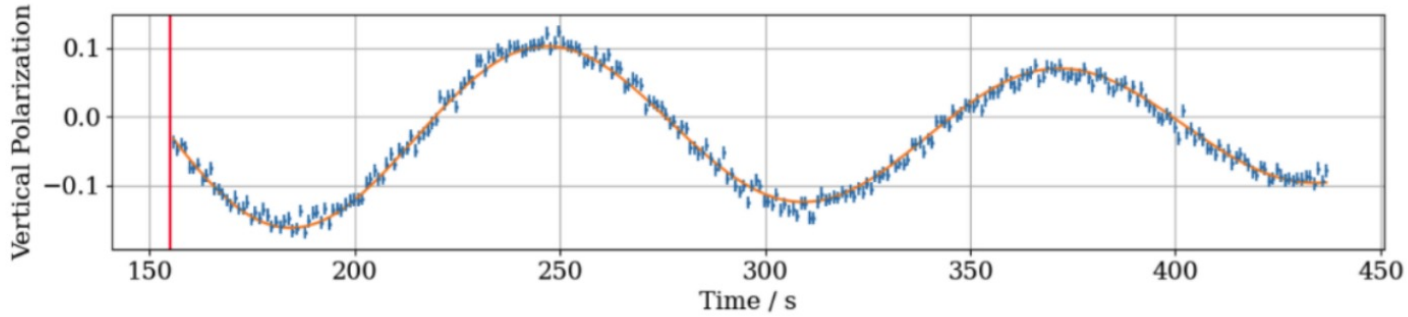
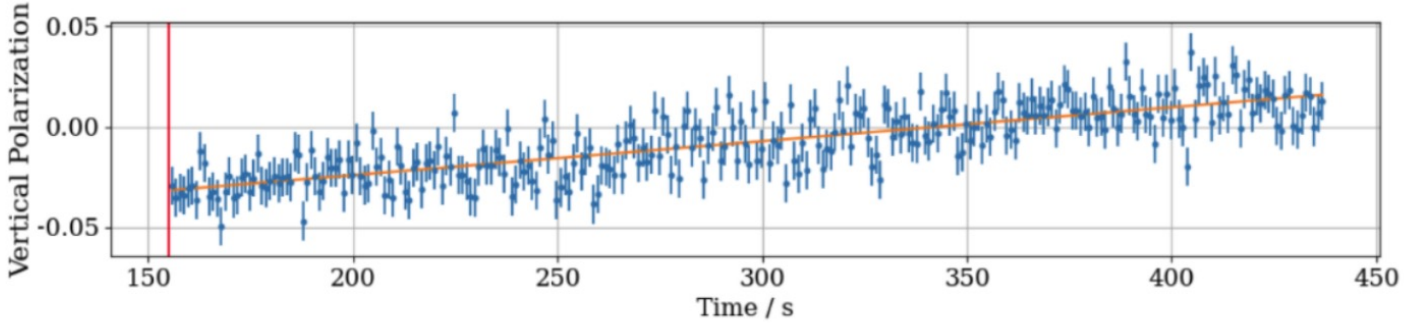
OUTLOOK

- Gate RF Wien Filter for an individual bunch
- Signal is an oscillation
- Similar Maps are measured as previously shown
- Polarization Decoherence is clearly visible

- Signal bunch



- Pilot bunch



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- http://www.phy.olemiss.edu/HEP/godang/Umiss_30Jan07.pdf (seen 22.05.2022) [1]
- https://collaborations.fz-juelich.de/ikp/jedi/public_files/usual_event/dpg19_vponcza.pdf (seen 24.05.2022) [2]

BACK UP

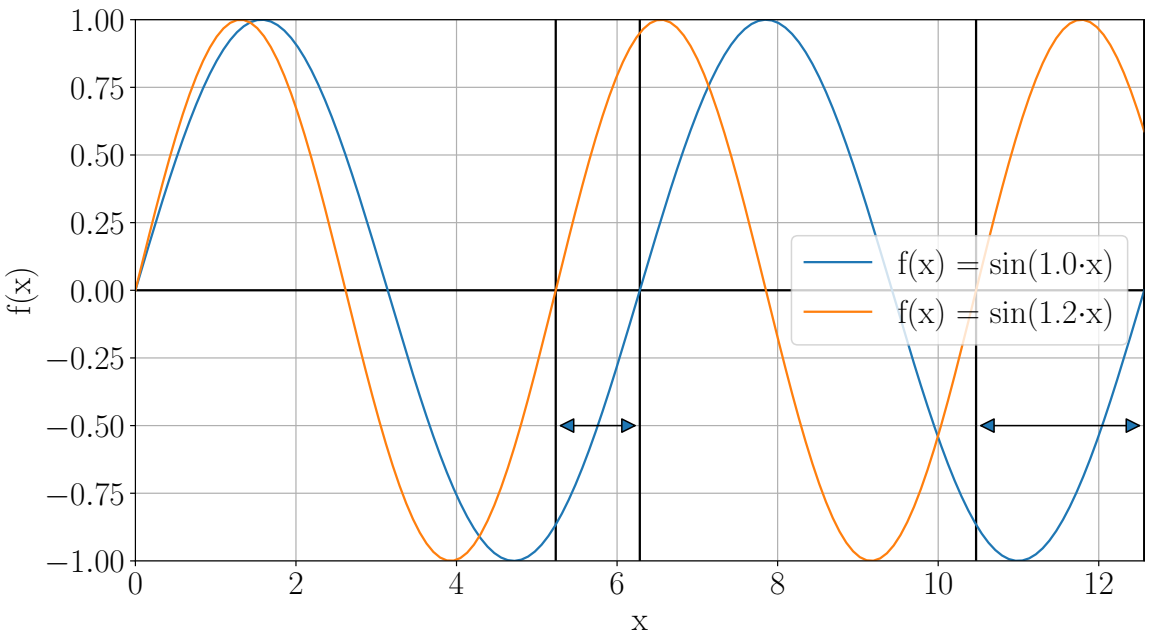
SPIN TUNE DETERMINATION

Spin-dependent differential cross section on unpolarized target:

$$N_{\mathrm{U,D}} \propto 1 \pm \frac{3}{2} p_x A_y \sin(\underbrace{\nu_s \cdot f_{\mathrm{rev}}}_{f_s = -120.7\,\mathrm{kHz}} \cdot t), \text{ where } f_{\mathrm{rev}} = 750.0\,\mathrm{kHz}$$

Problem: $\nu_s \approx 0.16 \hat{\approx} 120\,\mathrm{kHz}$ and Detector Rate $5000\,\mathrm{s}^{-1}$

$$\begin{aligned} \nu_s(n) &= \nu_s^{\mathrm{fix}} + \frac{1}{2\pi} \frac{\mathrm{d}\tilde{\phi}}{\mathrm{d}n} \\ &= \nu_s^{\mathrm{fix}} + \Delta\nu_s(n) \end{aligned}$$



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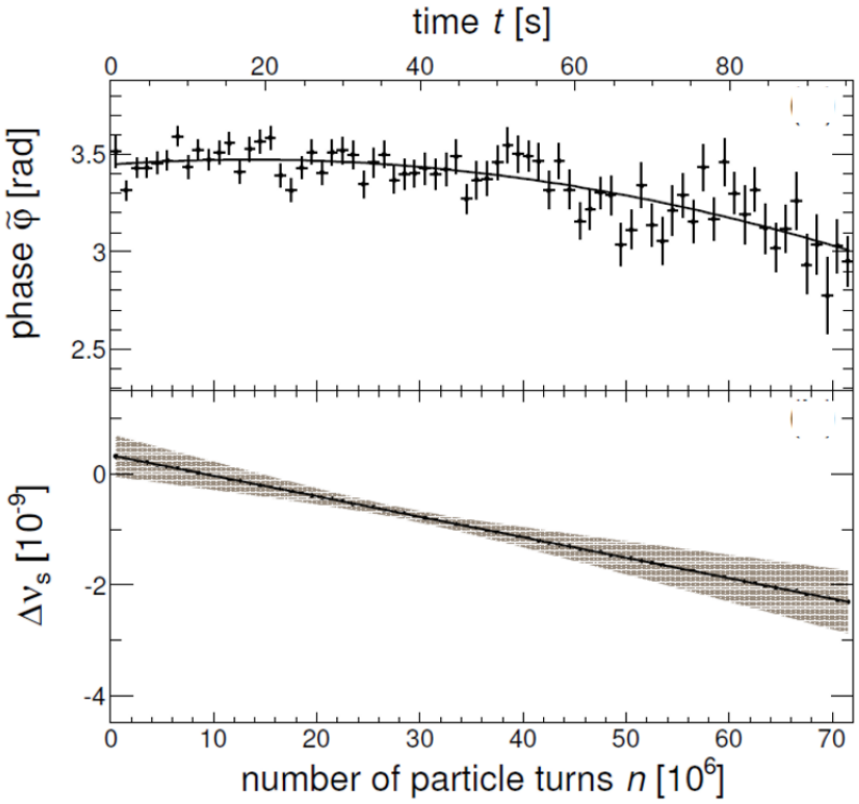

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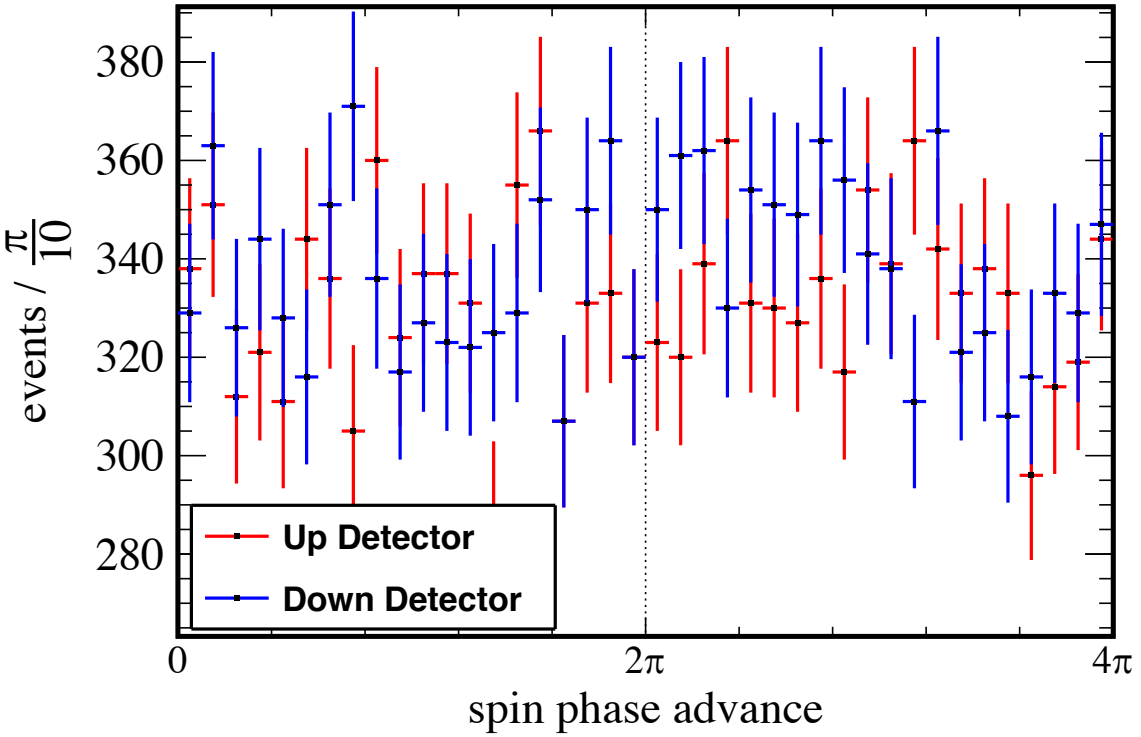
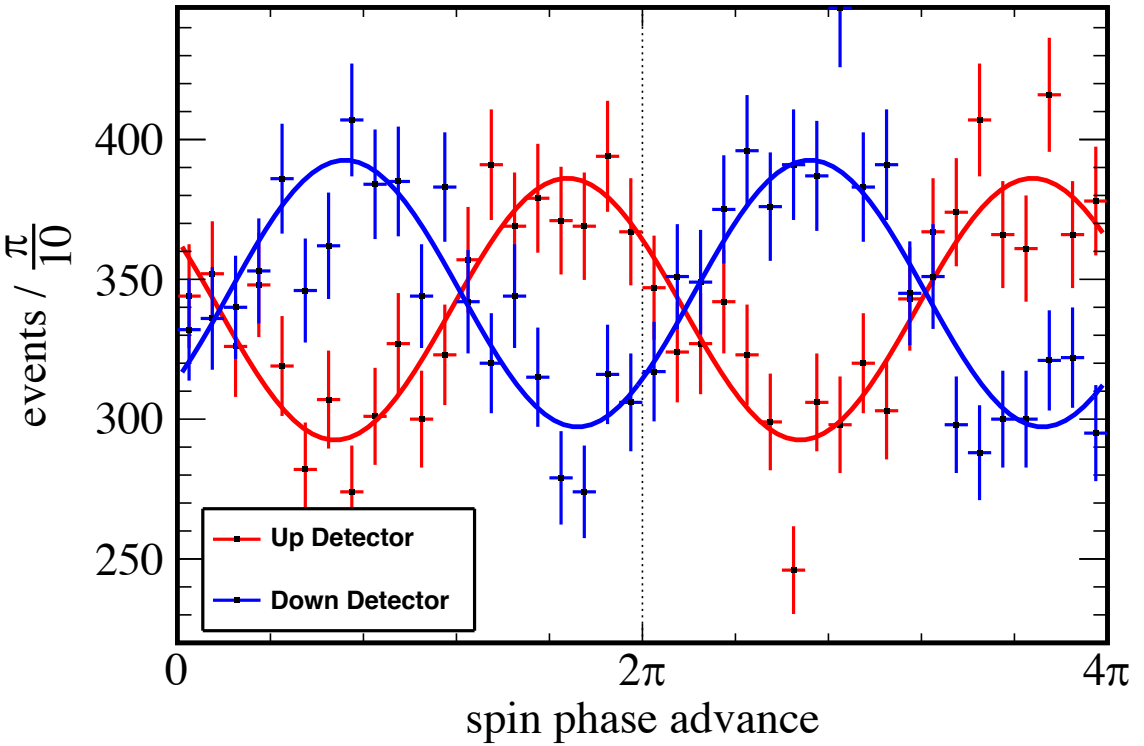
SPIN TUNE DETERMINATION



Scanning Frequency ≠ spin tune



Scanning Frequency = spin tune

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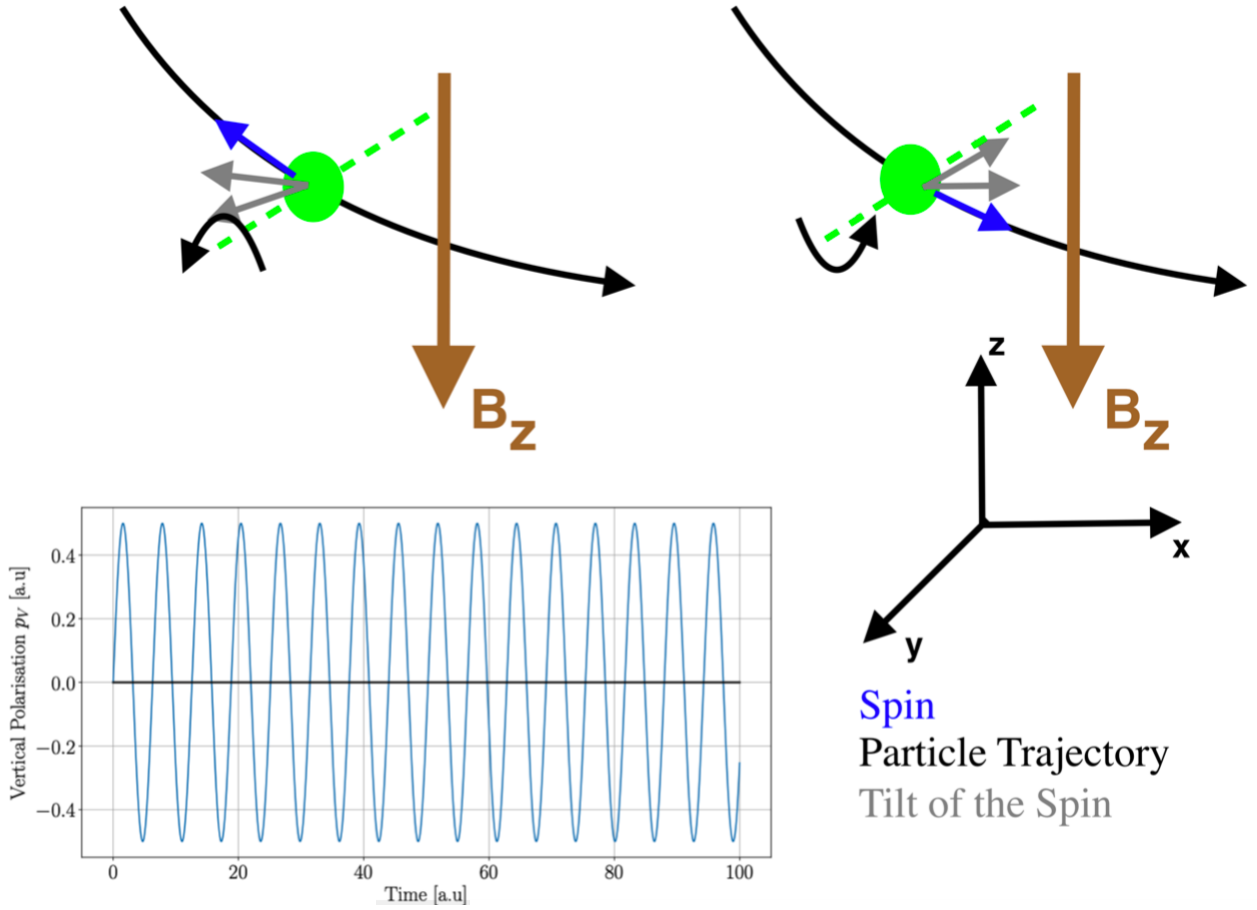
MEASURMENT PRINCIPLE I

- Uniform polarisation rotation
- Tilt of the polarisation due to the EDM: 50% up and 50% down
- No net signal measurable
- EDM $\propto$ Amplitude



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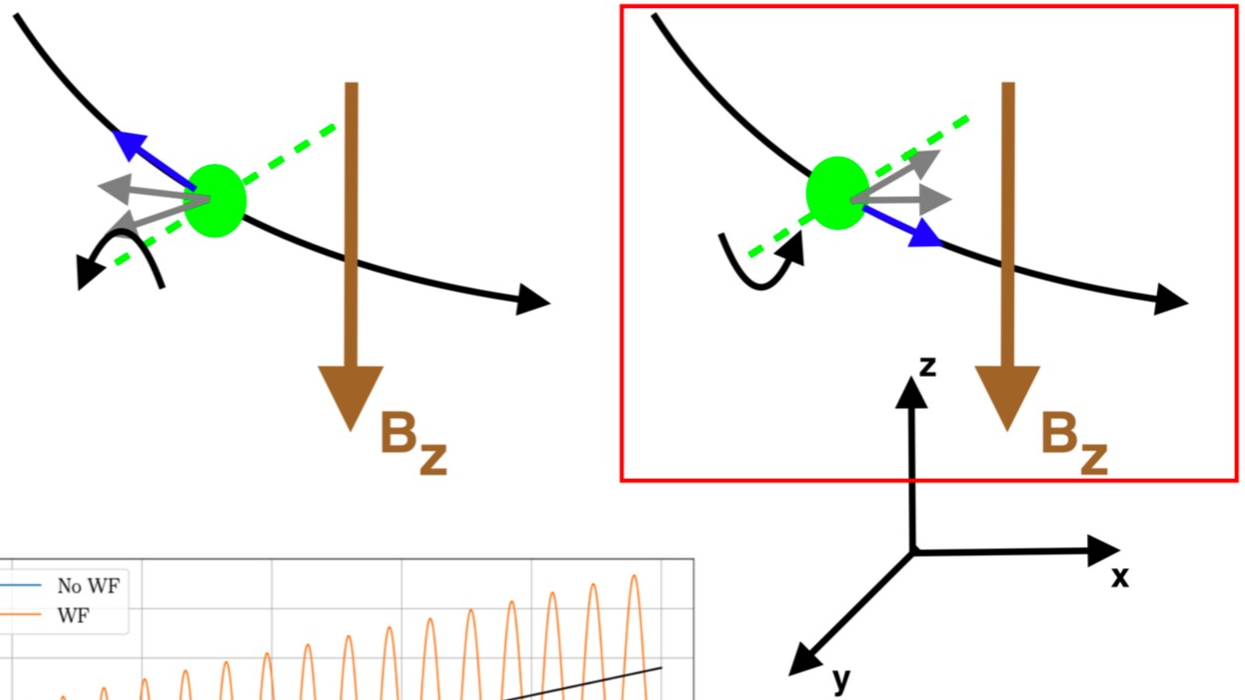
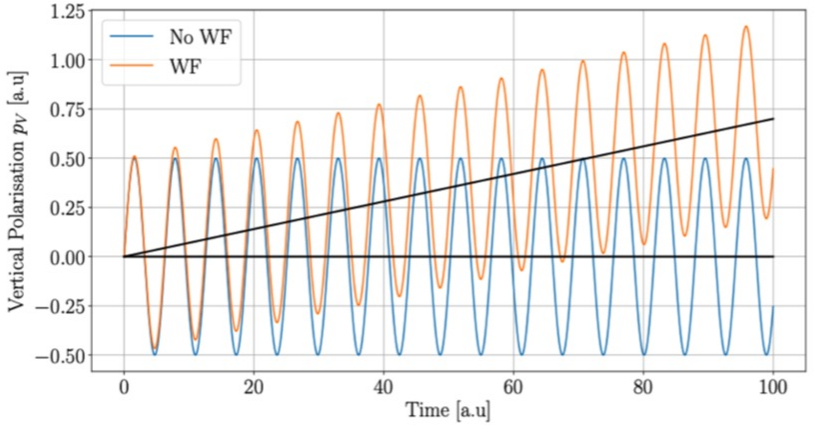
MEASUREMENT PRINCIPLE II

- RF WF rotates polarisation around the vertical axis
- Right (or left) scenario is preferential
- Vertical Polarisation accumulates





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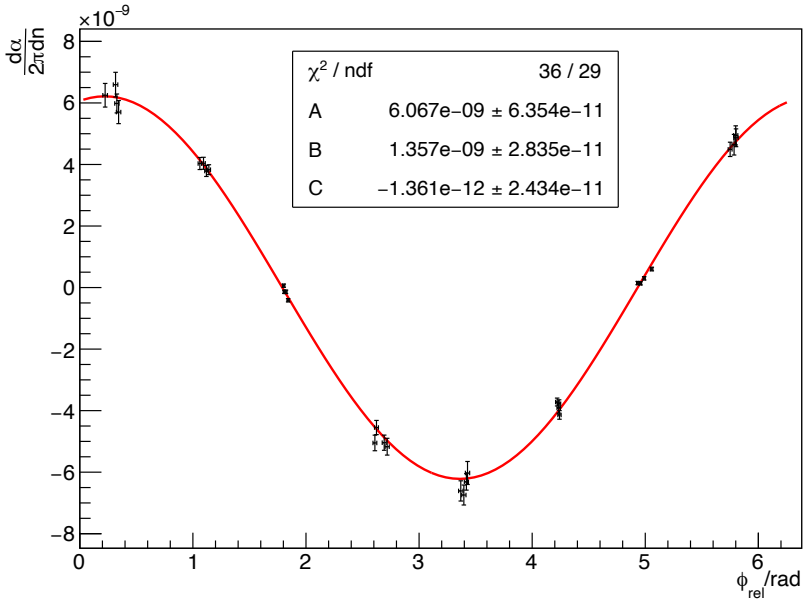
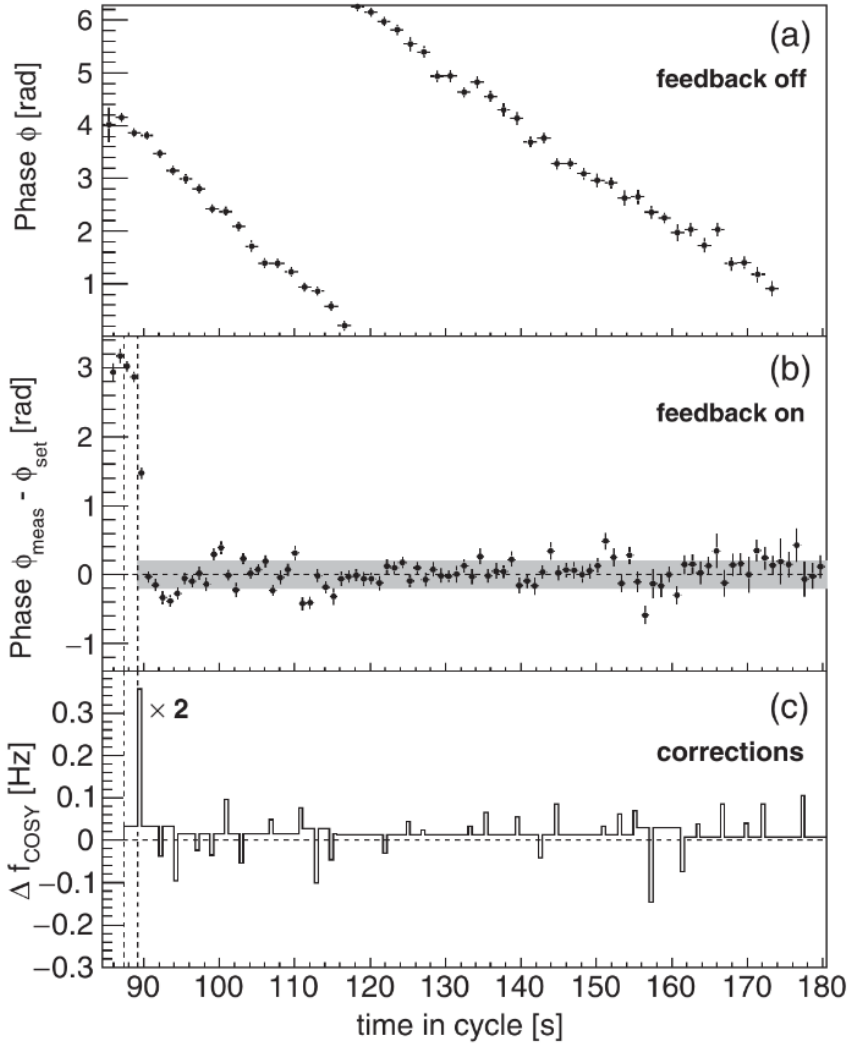
PHASE FEEDBACK / QUASI FROZEN SPIN

- Rotating Polarization
- RF Wien Filter
  - They both operate on the same frequency!
- Phase between both frequencies can be fixed!
  - By adjusting Wien Filter RF
- Polarization enters Wien Filter at the same angle
  - Asymmetry is broken → **Build Up**





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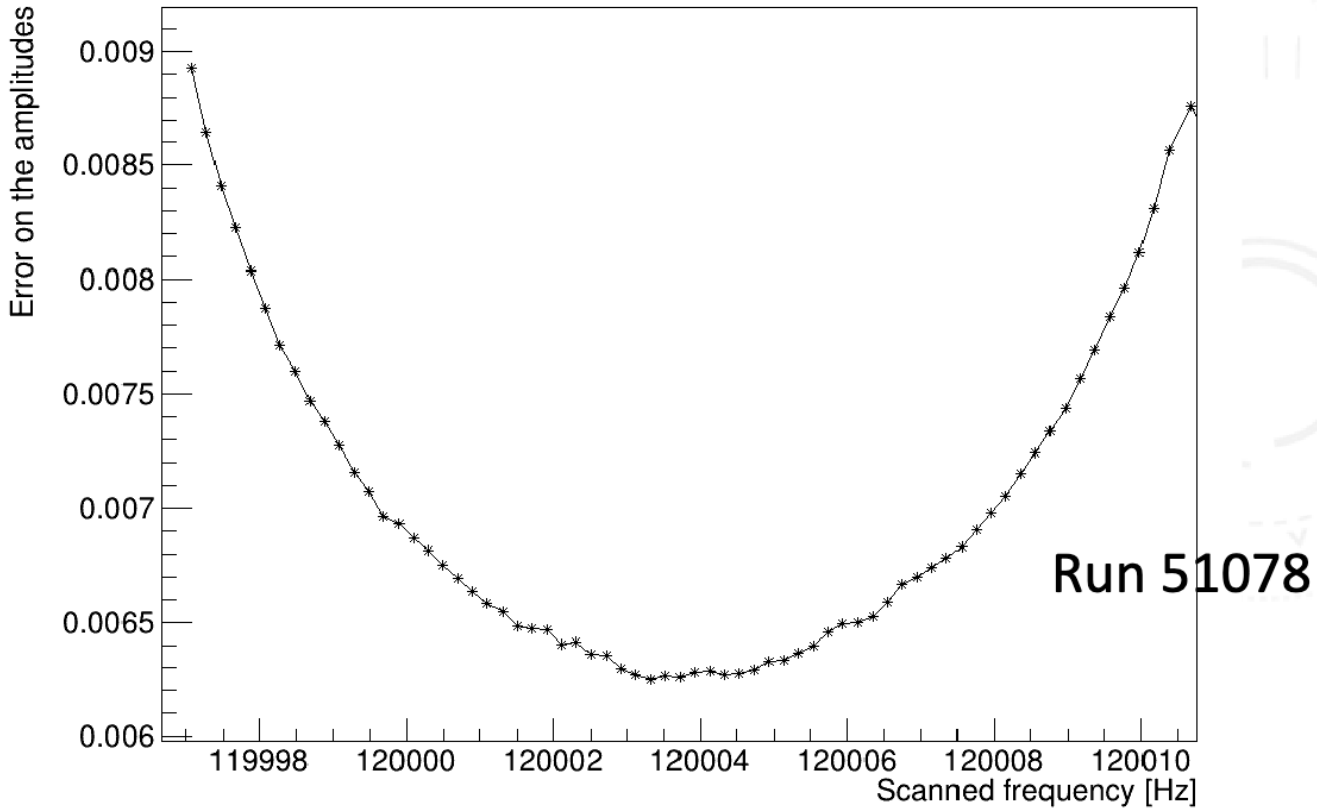
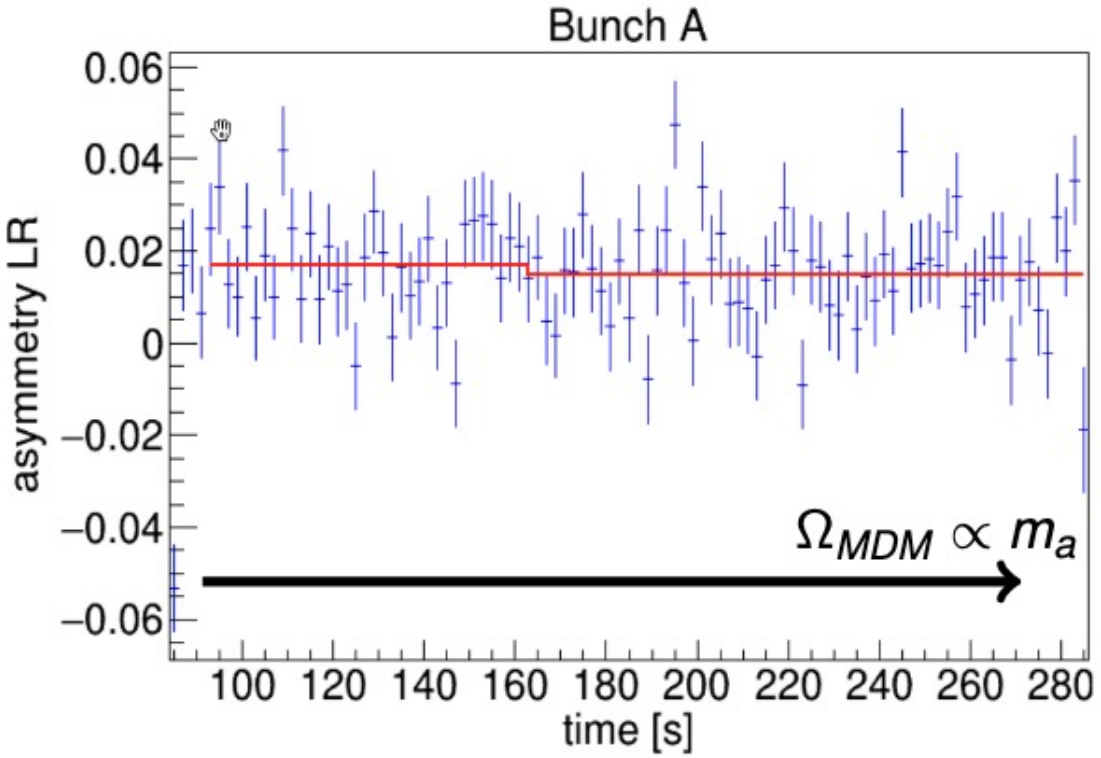
STATISTICAL UNCERTAINTIES AXION/ALP SEARCH





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