Results from the first search for axion-like particles in storage rings

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30 march 2022

DPG Spring Meeting - Hadronic and Nuclear Physics

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Axion / axion-like particle (ALPs)

- Proposed to explain the lack of CP violation in the strong interaction.
- Candidates for dark-matter in the universe.
- Axion/ALPs – gluon coupling induces an oscillating Electric Dipole Moment (EDM)

$$d = d_{DC} + \boldsymbol{d_{AC}\,cos(\omega_a t + \phi_a)}$$

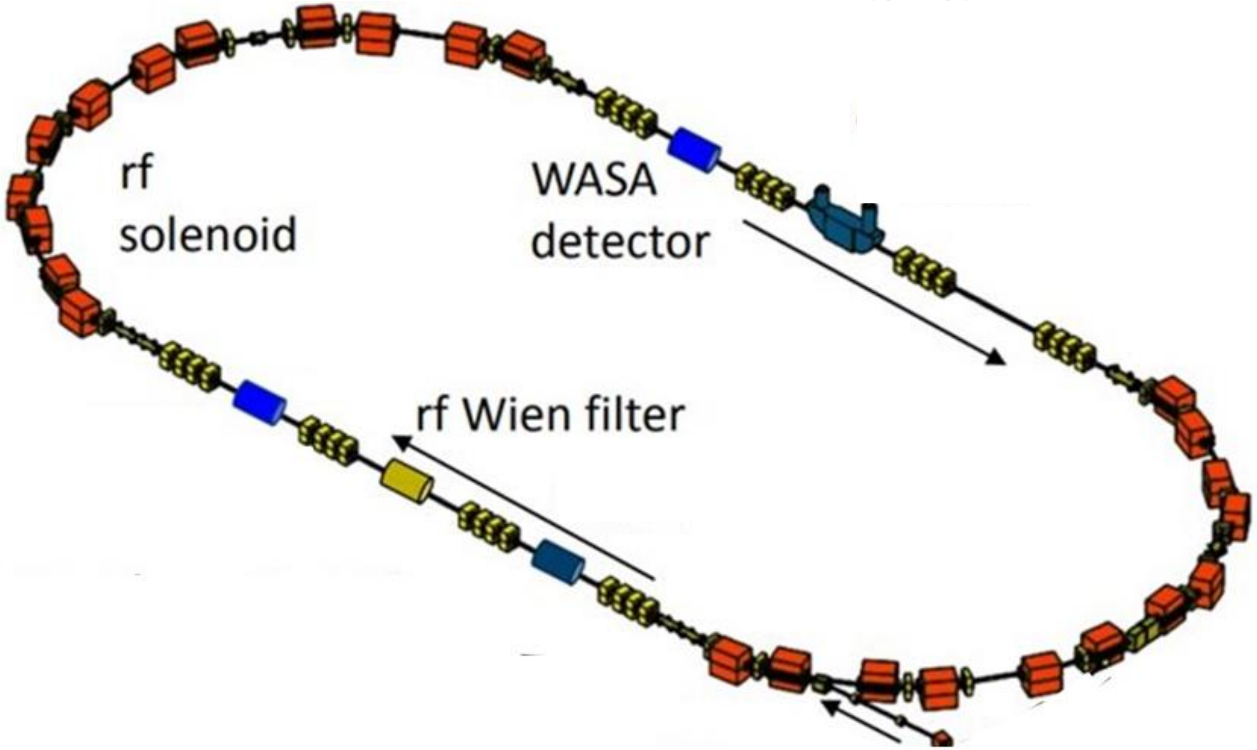
Oscillation frequency connected to axion mass $\omega_a = \frac{m_a c^2}{\hbar}$

Phase of the oscillating EDM is unknown.

See: P. W. Graham et al., PRD 84, 055013 (2011)

Cooler Synchrotron (COSY)

- A proof-of-principle experiment to search for ALPs
- Polarized and cooled deuteron beam
- WASA detector as the polarimeter



How to search for ALPs in a storage ring?

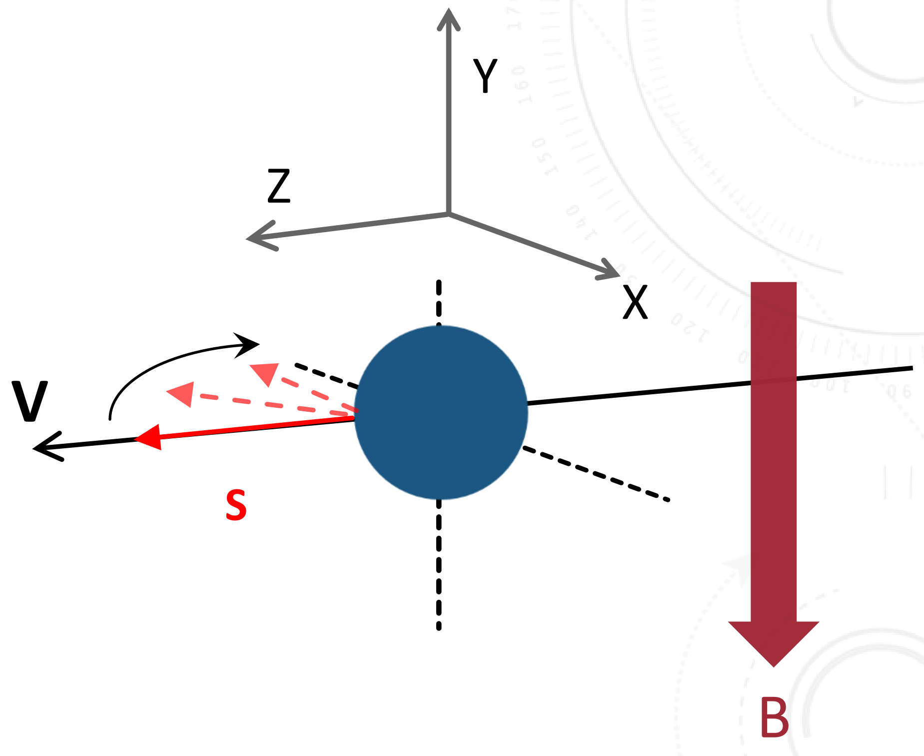
- Horizontally polarized beam
- Spin tune $(\nu_s) = \frac{\#\text{spin rotations}}{\#\text{particle revolutions}}$

$$\nu_s = G\gamma$$

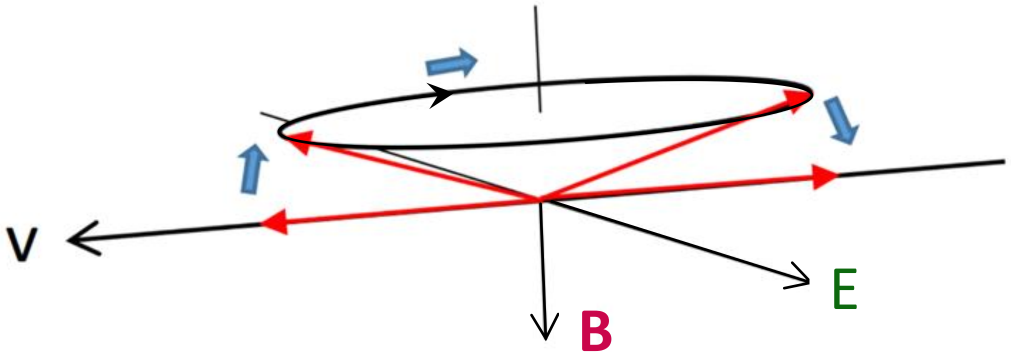
G: anomalous magnetic moment

γ: Lorentz factor

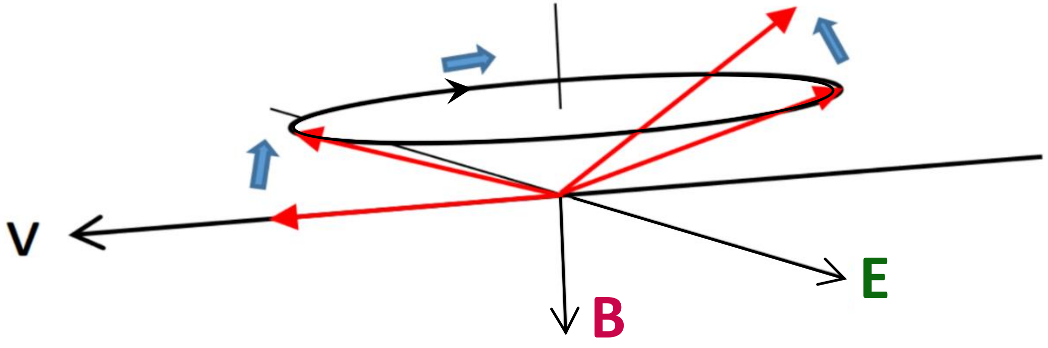
- $f_{\text{spin}} = \nu_s f_{\text{rev}}$



How to search ALPs in a storage ring?



Static EDM

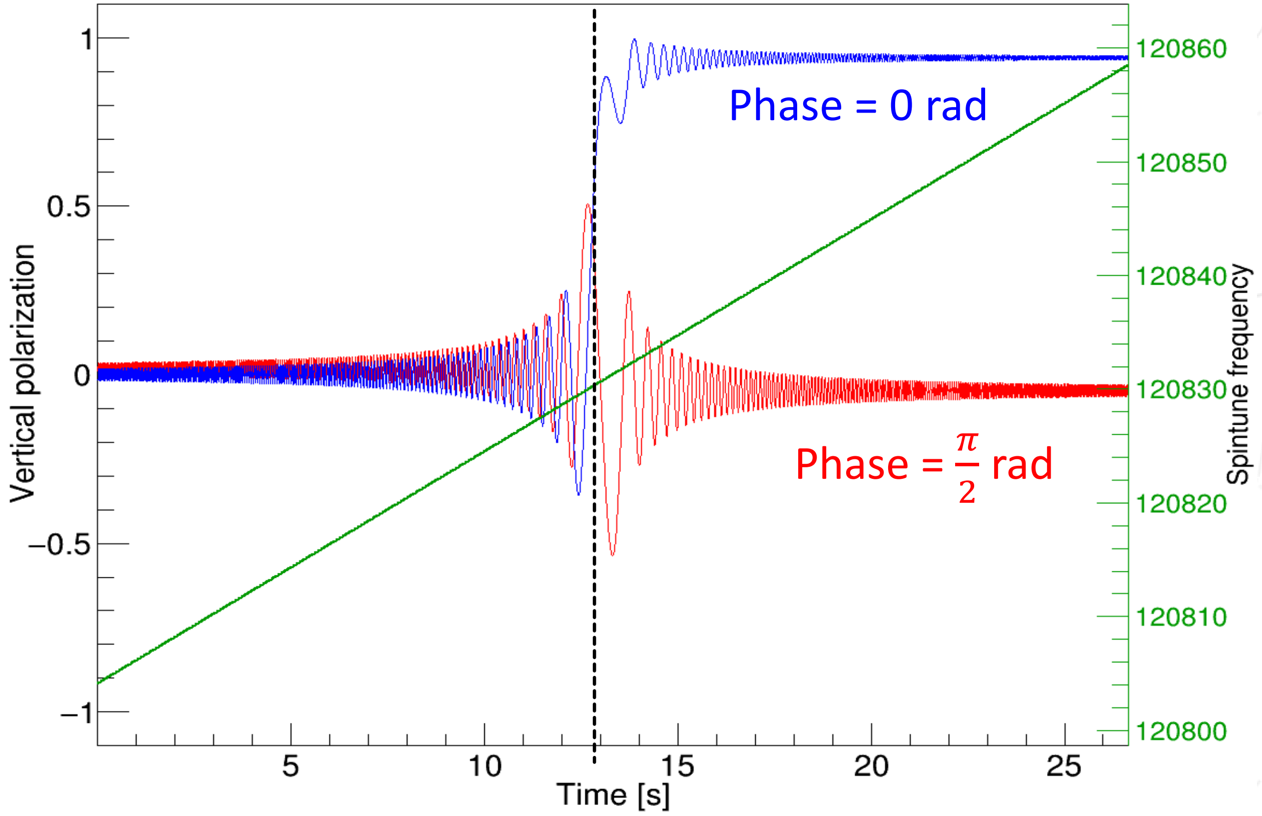


Oscillating EDM

Axion oscillation frequency (f_{AC}) = Spin tune frequency (f_{spin}) ⇒ Accumulation of vertical polarization

Model calculations

- Ramp frequency in search of resonance
- Describe the polarization jump at resonance crossing.
- Phase plays an important role in determining the jump.

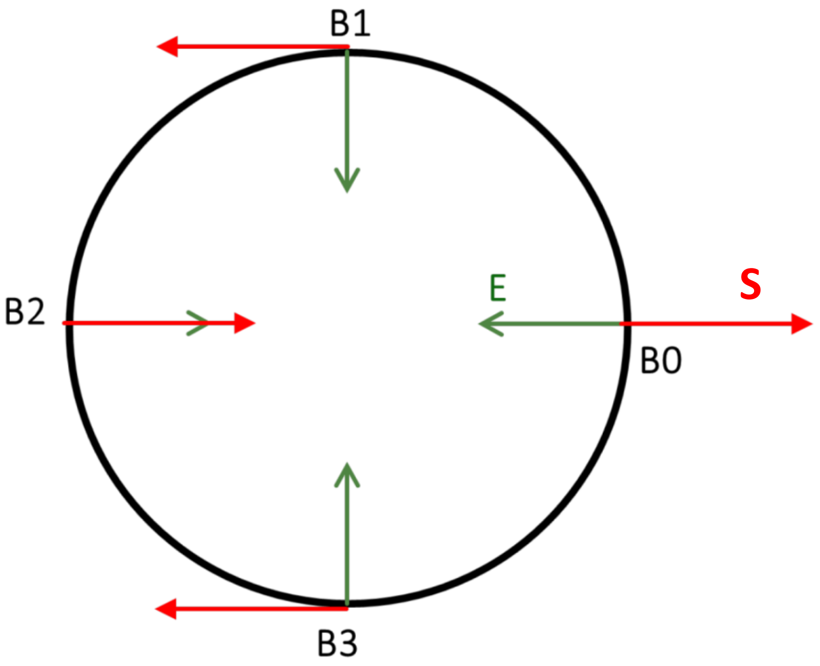


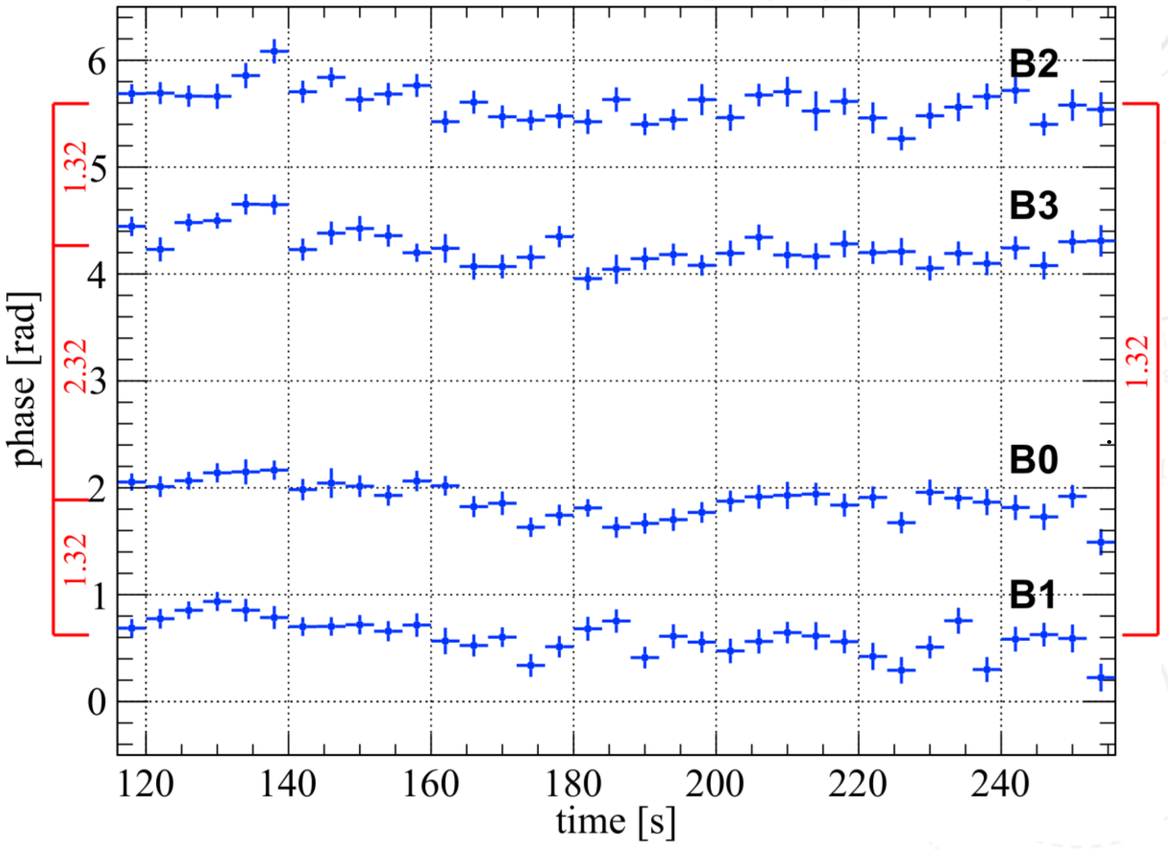
Unknowns of the experiment: frequency and phase

Phase problem and 4 bunches

- Simultaneous searches with perpendicular beam polarization using 4 bunches.
- RF solenoid run at $f_{rev}(1 + G\gamma)$

A top-down view of the ring.

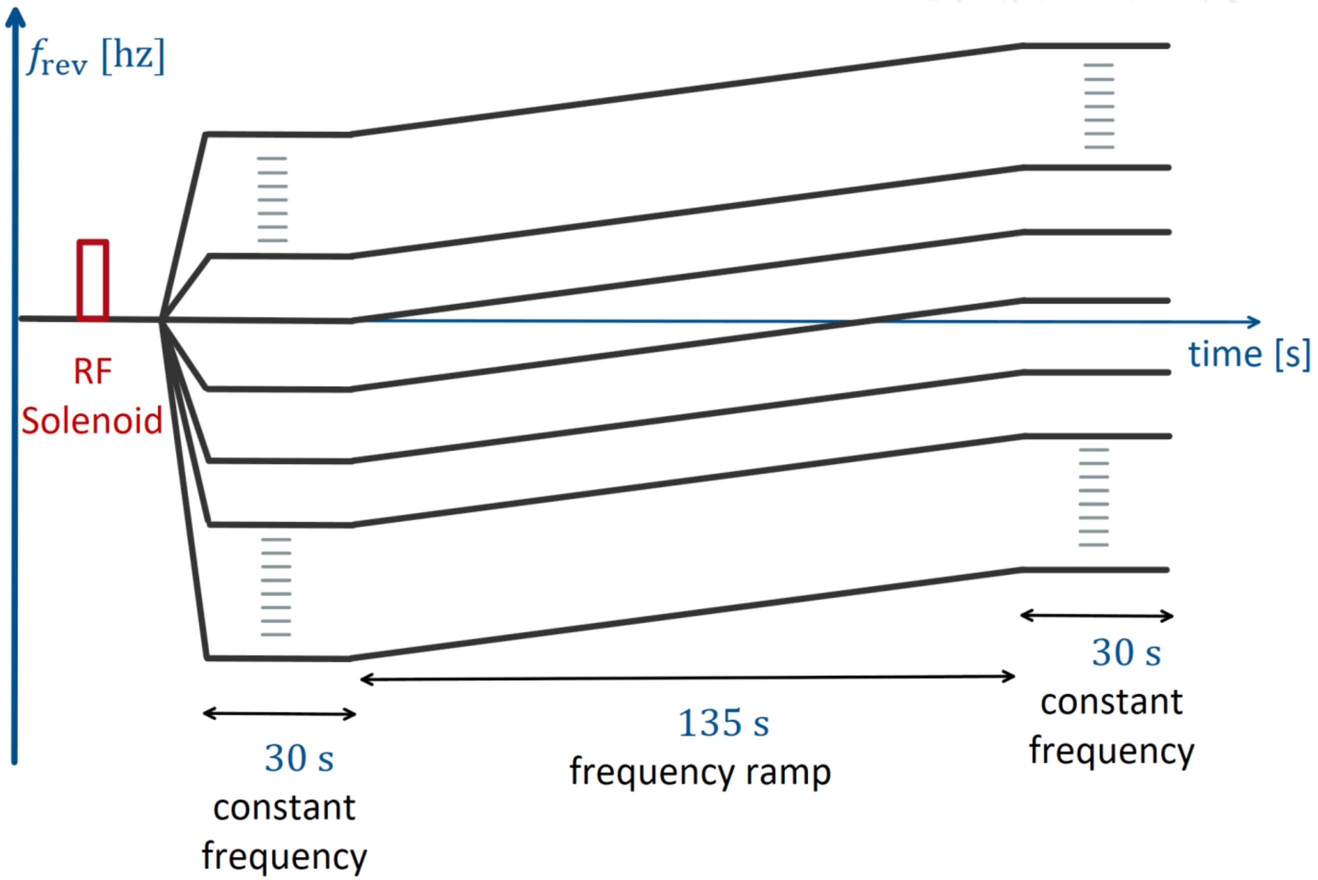




At the detector

Scan management

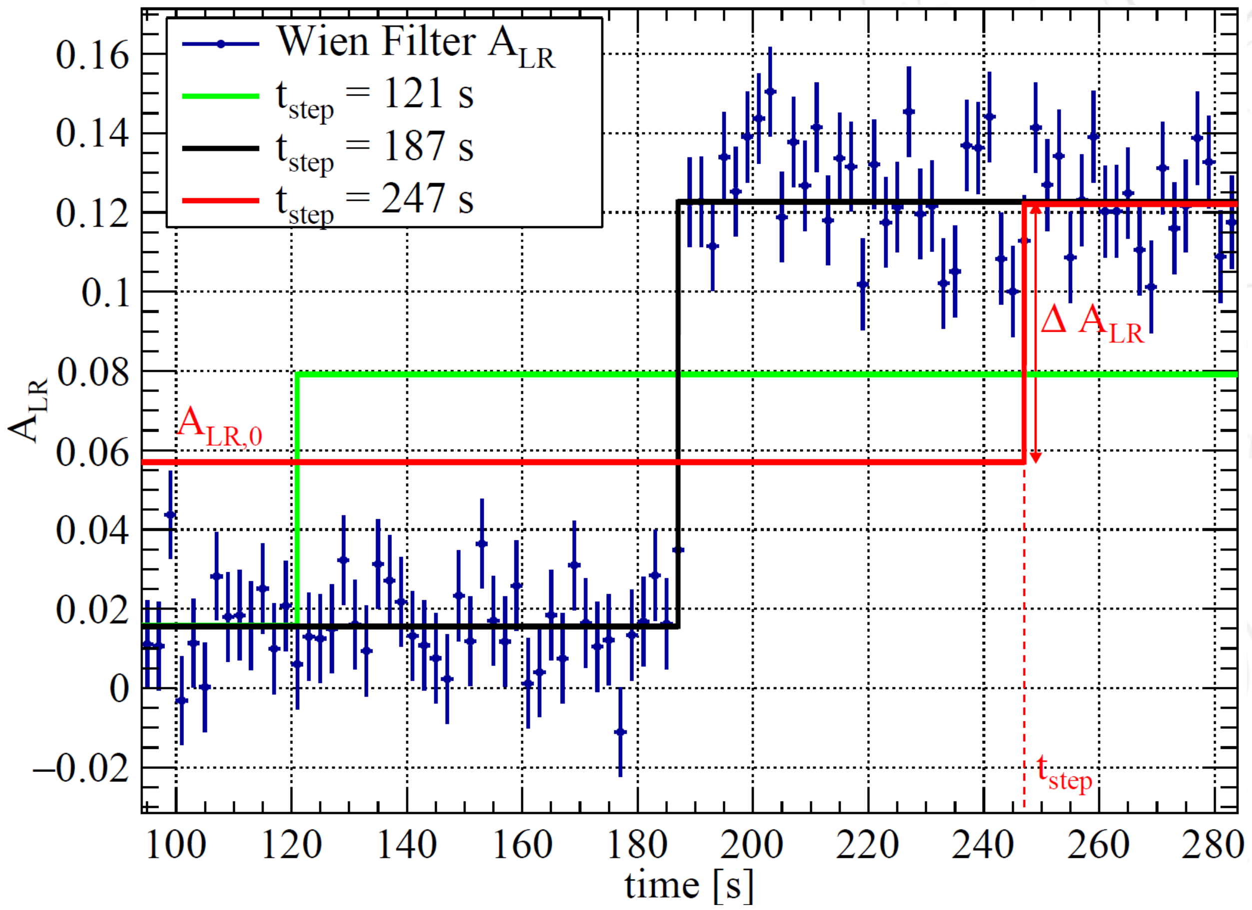
- Vary the spintune frequency in search of resonance.
- Measure polarization as a function of time.
- About 100 scans
  - Frequency Range
    $119997\ \text{Hz} - 121457\ \text{Hz}$
  - Total width $\approx 1500\ \text{Hz}$
  - ALP mass range
    $0.496\ \text{neV} - 0.502\ \text{neV}$



$$\text{ramp rate} = \begin{cases} 0.1 \\ 0.124 \end{cases} \text{Hz/s}$$

Wien filter test and analysis of data

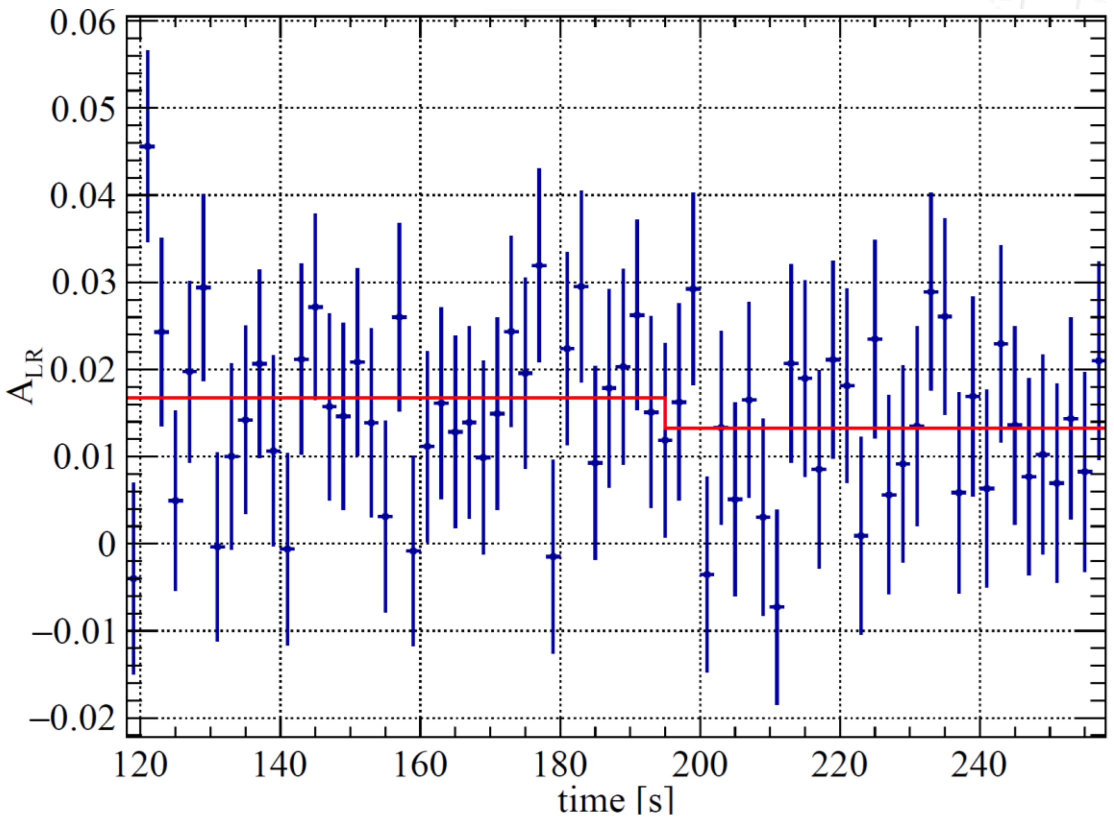
- A test of methodology.
- Scans to cross a fixed f_{WF}
- A check for the calibration used to calculate the d_{AC} from data.



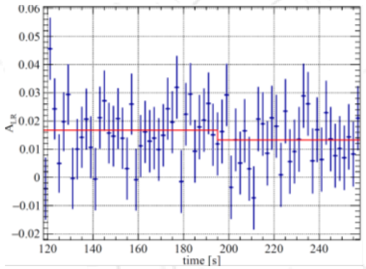
Experimental data from WF

Axion scan - example

Data from a single bunch with a step function fit



Axion scan – calculate amplitude

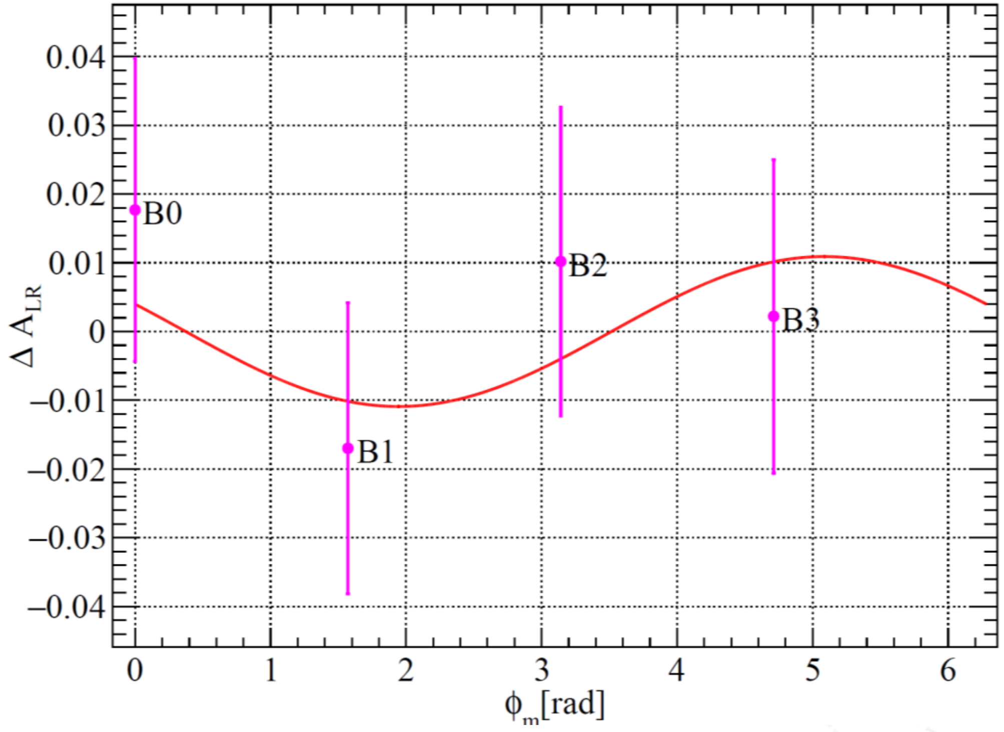


- The amplitude $\widehat{A}$ is calculated from the sinusoidal fit.

$$f(\phi_m) = C_1 \sin\phi_m + C_2 \cos\phi_m$$

$$\hat{A} = \sqrt{C_1^2 + C_2^2}$$

  - ϕ_m - angle between **E** and **S**



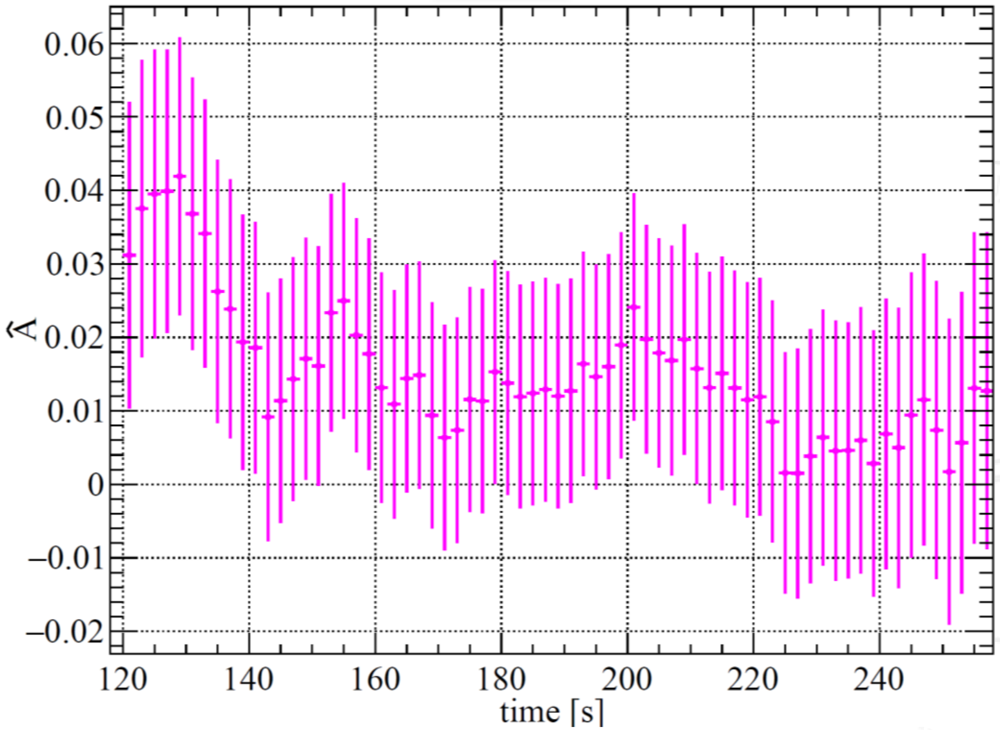
Jumps from all bunches at a single time bin.

Systematics - $\hat{A}$ positive bias

$$\hat{A} = \sqrt{c_1^2 + c_2^2}$$

Feldman Cousins method – use of probability density function

- Deal with the systematics
- Construct confidence intervals
  - Calculate true value A for an estimated $\hat{A}$ at 90% confidence level.



Gary J. Feldman and Robert D. Cousins Phys. Rev. D 57, 3873 (1998)

90 % oscillating EDM d_{AC}

- Thomas-BMT equation gives spin rotation ω_a caused by d_{AC}

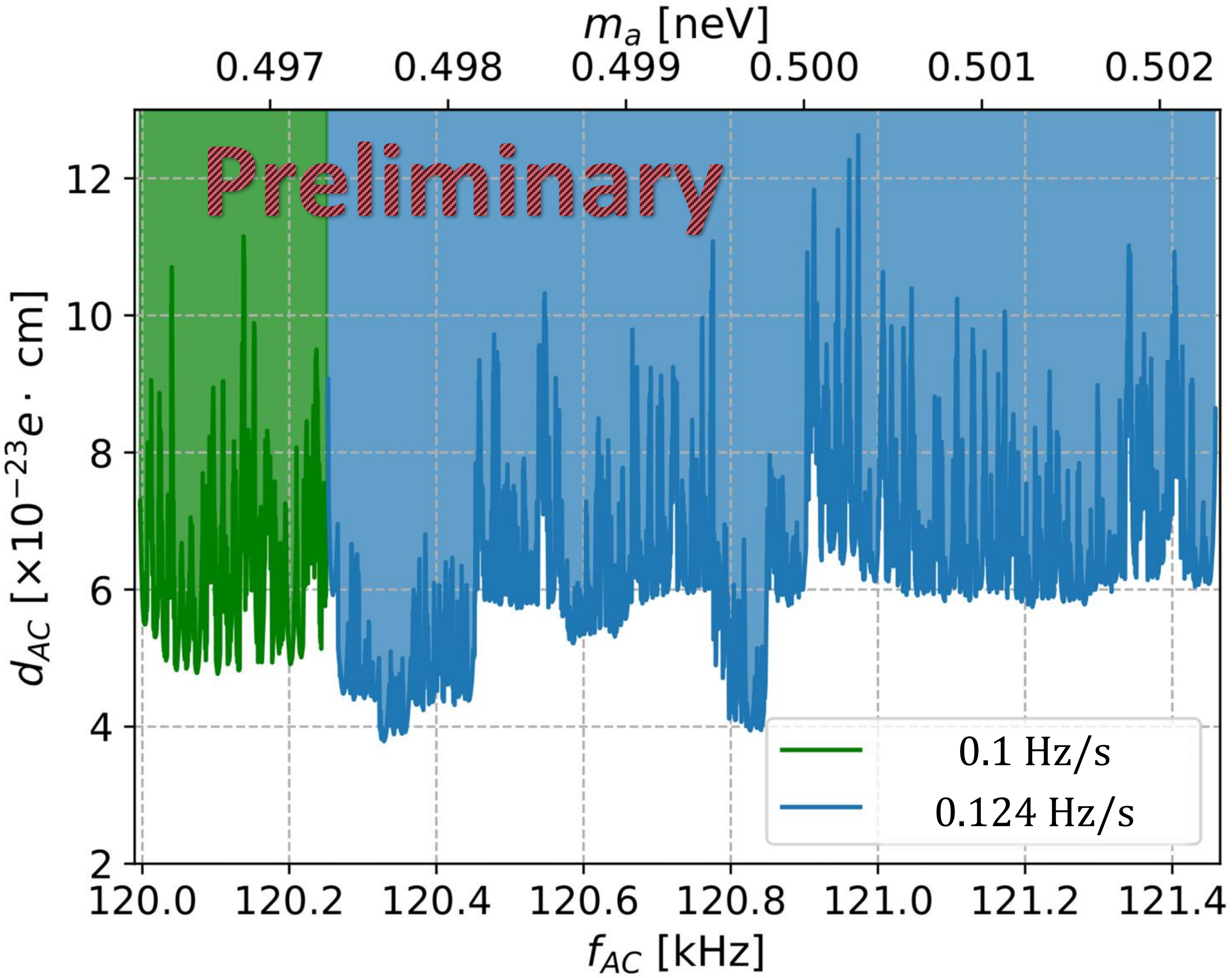
$$\mathrm{d}_{\mathrm{AC}}[e \cdot \mathrm{cm}] = \frac{\hbar}{B\rho} \kappa\, A$$

- $\omega_a = \kappa\, A$
  - Calibration factor $\kappa = \begin{cases} 5.28 \times 10^{14} \\ 5.84 \times 10^{14} \end{cases}$ for ramp rate $= \begin{cases} 0.1 \\ 0.124 \end{cases} \mathrm{Hz/s}$
  - $B\rho$: describes momentum of the beam

Preliminary result - bound on oscillating EDM

90 % CL upper limit on the ALPs induced oscillating EDM

Average of individual points
$|d_{\mathrm{AC}}| < 6.4 \times 10^{-23} e \cdot \mathrm{cm}$

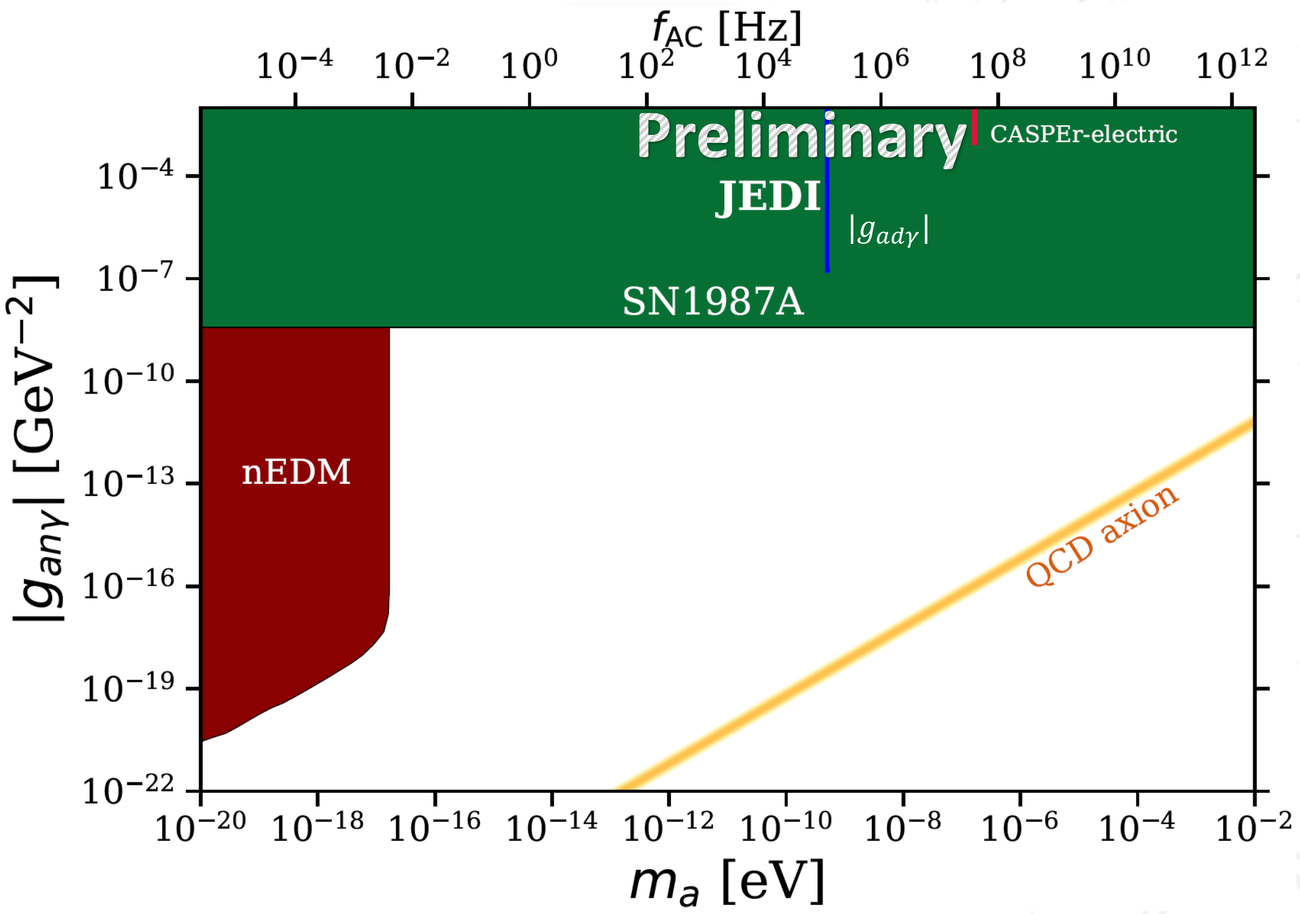


See: P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020) and 2021 update

Preliminary result - bound on ALP-EDM coupling

Model independent coupling of axion to deuteron EDM

$$\left|g_{ad\gamma}\right| < 1.7 \times 10^{-7}\,\mathrm{GeV}^{-2}$$



P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020) and 2021 update

C. O'Hare, "cajohare/axionlimits: Axionlimits," (2020), URL https://doi.org/10.5281/zenodo.3932430

C. Abel et al. Phys. Rev. X 7, 041034 – Published 14 November 2017

D. Avbas et al. Phys. Rev. Lett. 126, 141802 (2021)

P. W. Graham et al. Phys. Rev. D 88, 035023 (2013)

Summary

- ALP induces an oscillating EDM (d_{AC}), allows searching for ALPs in a storage ring.
- Polarized deuteron beam to search for resonance between the oscillating EDM frequency and the spin tune frequency.
  - Frequency range $119997\ \mathrm{Hz} - 121457\ \mathrm{Hz}$. Total width $\approx 1500\ \mathrm{Hz}$.
  - ALP mass range $0.496\ \mathrm{neV} - 0.502\mathrm{neV}$
- Wien filter used as a test to observe a signal at resonance crossing.
- $|d_{\mathrm{AC}}| < 6.4 \times 10^{-23} e \cdot \mathrm{cm}$
- $|g_{ad\gamma}| < 1.7 \times 10^{-7} \mathrm{GeV}^{-2}$

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Thank You

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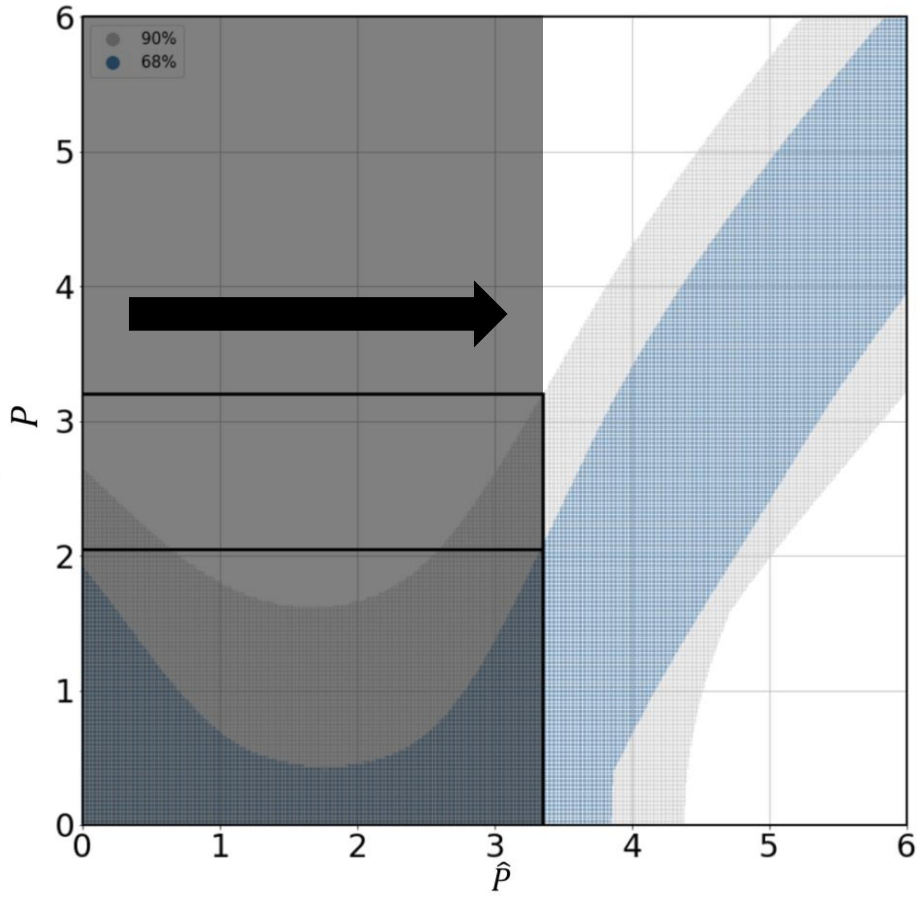
Confidence interval

- Feldman Cousins [ref] using the probability density function PDF
  - Deal with the systematics
  - Construct confidence intervals
- Modified to include the average of multiple cycles.
- $\hat{P} = \hat{A}/\sigma$
- $\hat{P}$ denote the estimated value
- P denote the true value
- For $\hat{P}$ < 3.42 i.e., $< \hat{P} >$ interval is calculated at the expectation value $P = 3.3$



68% (blue)and 90% (grey) confidence interval for analysis of 8 cycles.

Equate ΔP_y, oscillating EDM and coupling strength

From T-BMT equation,

$$\mathrm{d_{osc}} = \frac{\hbar\, \omega_{\mathrm{EDM}}}{c\, \beta\, \mathrm{B}}$$

- ω_{EDM} - rotation of spin $\propto \Delta \mathrm{P_y}$
- B - Magnetic field

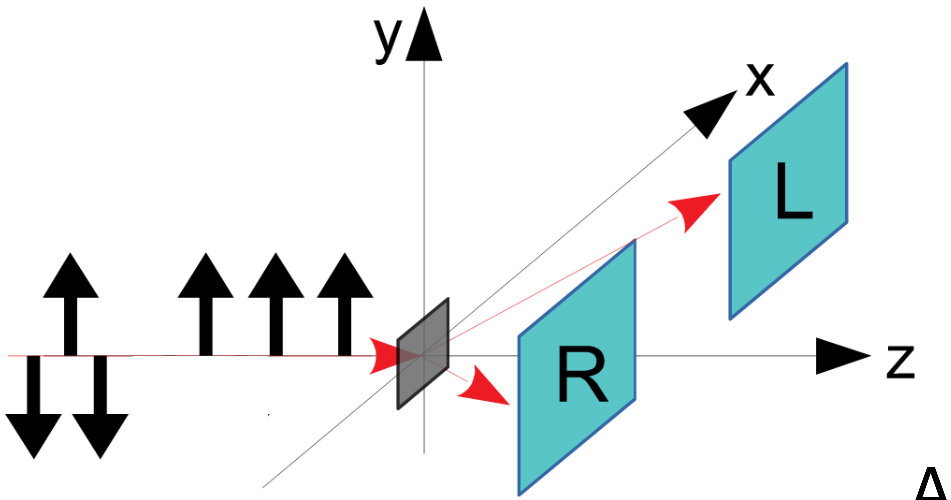
- $\mathrm{d_{osc}} = 10^{-16} \theta_{\mathrm{QCD}}$

$$= 10^{-16} a_0 \frac{C_G}{f_a}$$

- a_0 - dependent on local axion density
- $\frac{C_G}{f_a}$ - axion-gluon coupling strength

See: arXiv:1902.03254 (2019)

Polarimetry



$$\epsilon = \frac{N_L - N_R}{N_L + N_R} = AP_y$$

Asymmetry

Analysing power

Polarization

Sinusoidal fit to get amplitude