Axion Searches at Cooler Synchrotron COSY

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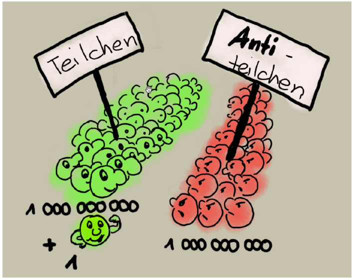
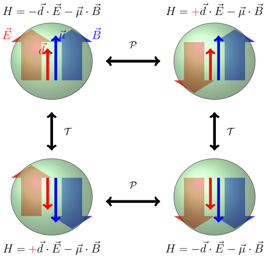
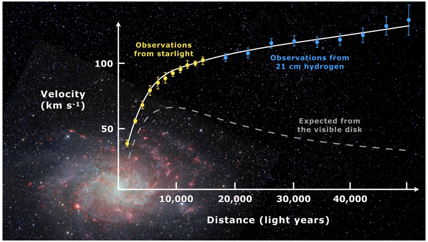
Motivation

Standard Model of Particle Physics successful but . . .

- Fails to explain matter-antimatter asymmetry in the universe
- Why is CP-violation in the strong sector not present (although allowed)?
- What does Dark Matter consists of?







source:M. De Leo, Wikipedia

Outline

- Introduction:
  Axions and Axion-like particles
- Experimental Method:
  How to search for axions/ALPs in storage rings
- Experiment:
  Analysis & Results
- Next steps

Axion/Axion Like Particle (ALPs)

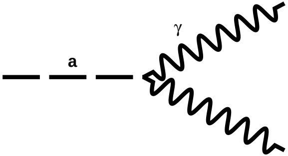
Axions/Axion Like Particles (ALPs)

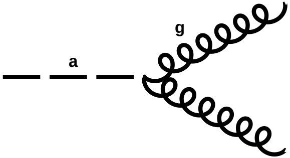
- hypothetical pseudoscalar elementary particle postulated by Peccei,Quinn,Wilczek,Weinberg to resolve the strong CP problem
- axion are also Dark Matter candidates
- axion like particles (ALP): similar properties as axions, (but ALPs don't solve the strong QCD problem)
- huge experimental effort to search for axion/ALPs (haloscopes, helioscopes, light shining through the wall, mainly coupling to photons)
- in storage rings with polarized beams axion-gluon/nucleon coupling can be studied

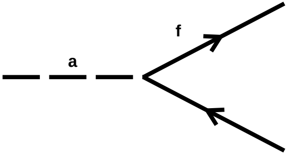
[1]

Axion Coupling

$$\mathcal{L}: -\frac{\alpha}{8\pi}\frac{C_\gamma}{f_a}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad -\frac{\alpha_s}{8\pi}\frac{C_G}{f_a}\, a\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} \qquad -\frac{1}{2}\frac{C_N}{f_a}\,\partial_\mu a\,\bar{\Psi}_f\gamma^\mu\gamma^5\Psi_f$$







Electric Dipole Moment (EDM) axion wind term

For low axion masses, if axions saturate dark matter they can be described by classical field: $a(t) = a_0 \cos(\omega_a t + \varphi_a)\,, \quad m_a c^2 = \hbar\omega_a\,, \quad \text{Coupling} \propto \frac{1}{f_a} \propto m_a$

Axion Coupling

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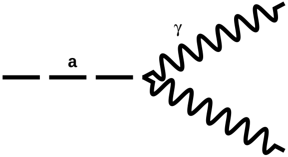
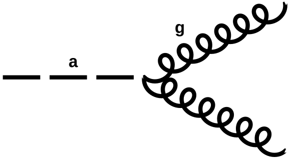
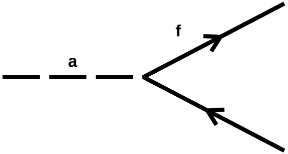




Electric Dipole Moment (EDM)



axion wind term

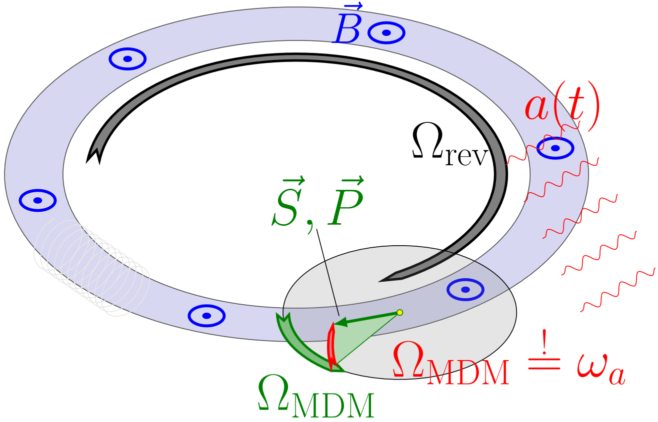
studied by many experiments

accessible in storage ring experiments with spin polarized beams

Experimental Method

How to search for axions/ALPs in storage rings

Principle of Experiment



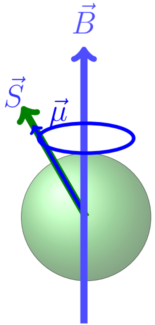
Observe polarization vector $\vec{P}$ in storage ring

Spin Motion in Storage Ring

with respect to momentum vector in magnetic field

$$\frac{d\vec{S}}{dt} = (\vec{\Omega}_{\mathrm{MDM}} \qquad\qquad) \times \vec{S}$$

$$\vec{\Omega}_{\mathrm{MDM}} = -\frac{q}{m} G\vec{B} \quad , \qquad \vec{\mu} = g\frac{q\hbar}{2m}\vec{S} = (1+G)\frac{q\hbar}{m}\vec{S}$$



S	spin
B	magnetic field
G	magnetic anomaly
g	g-factor
μ	magnetic moment
q, m	mass, charge
β	$=v/c$

[2, 3, 4]

Spin Motion in Storage Ring

with respect to momentum vector in magnetic field

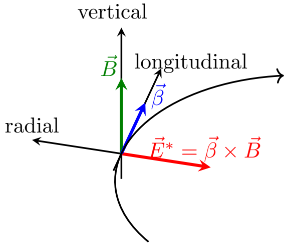
$$\frac{d\vec{S}}{dt} = (\vec{\Omega}_{\mathrm{MDM}} + \vec{\Omega}_{\mathrm{EDM}} + \vec{\Omega}_{\mathrm{wind}}) \times \vec{S}$$

$$\vec{\Omega}_{\mathrm{MDM}} = -\frac{q}{m}\, G\vec{B}$$

$$\vec{\Omega}_{\mathrm{EDM}} = -\frac{1}{S\hbar} d\, c\, \vec{\beta} \times \vec{B}$$

$$\vec{\Omega}_{\mathrm{wind}} = -\frac{1}{S\hbar}\frac{C_N}{2f_a}\left(\hbar\partial_0 a(t)\right)\vec{\beta}$$

$$|\vec{\Omega}_{\mathrm{MDM}}| \gg |\vec{\Omega}_{\mathrm{EDM}}|, |\vec{\Omega}_{\mathrm{wind}}|$$



EDM $d = d_{\mathrm{DC}} + g_{ad\gamma} a_0 \cos(\omega_a t + \varphi_0)$ (EDM)

[2, 3, 4]

Properties of Method

- AC measurement (i.e. systematics are under control)
- axion wind effect enhanced in storage rings ($v_{\text{particle}} \approx c$)
  $$\vec{\Omega}_{\text{wind}} = -\frac{1}{S\hbar}\frac{C_N}{2f_a}\left(\hbar\partial_0 a(t)\right)\vec{\beta}$$
- One can look for ALPs at a given mass given by Ω_{MDM} or scan a certain mass range by varying Ω_{MDM}

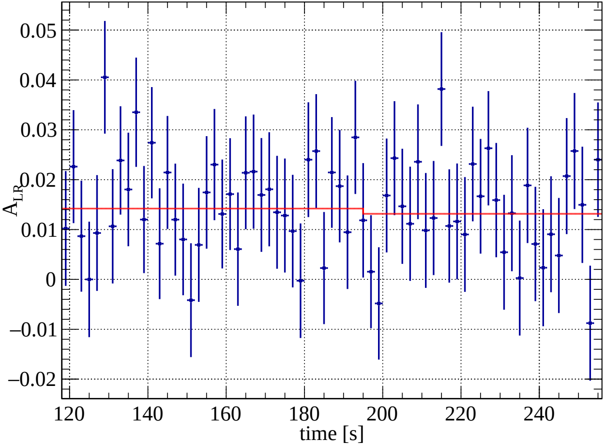
Experiment:
Analysis & Results

COoler SYnchrotron COSY

- pol. deuteron beam $p \approx 970\text{MeV}/c$
- polarization $P \approx 0.40$
- $\approx 10^9$ stored particles per 300 s cycle
- $\Omega_{\text{MDM}} \approx 2\pi \cdot 120\,\text{kHz}$
- JEDI (Jülich Electric Dipole moment Investigations) collaboration

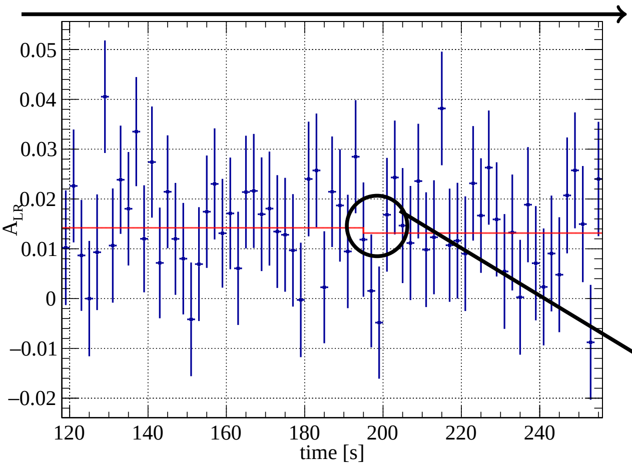
Left-Right Asymmetry $A_{LR} \propto P_V$ Scan

$|\vec{p}|, \Omega_{\mathrm{MDM}}, m_a$



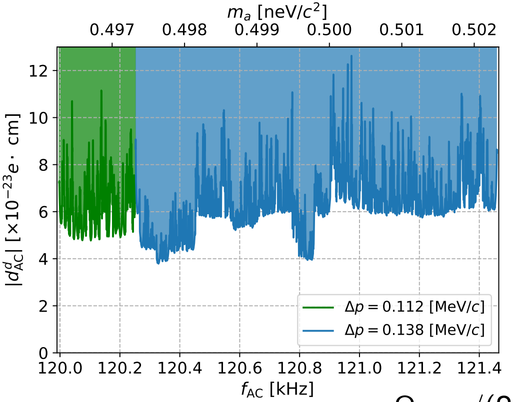
- axion signal $\propto$ accumulation of vertical poalrisation $\propto$ left-right counting rate asymmetry
- Axion signal would show up as jump in asymmetry at the corresponding frequency $\omega_a \propto m_a$

Left-Right Asymmetry $A_{LR} \propto P_V$ Scan



- axion signal $\propto$ accumulation of vertical poalrisation $\propto$ left-right counting rate asymmetry
- Axion signal would show up as jump in asymmetry at the corresponding frequency $\omega_a \propto m_a$
- determine jump ΔA_{LR} for every time bin

Results on Oscillating EDM d_{AC}, 90% CI

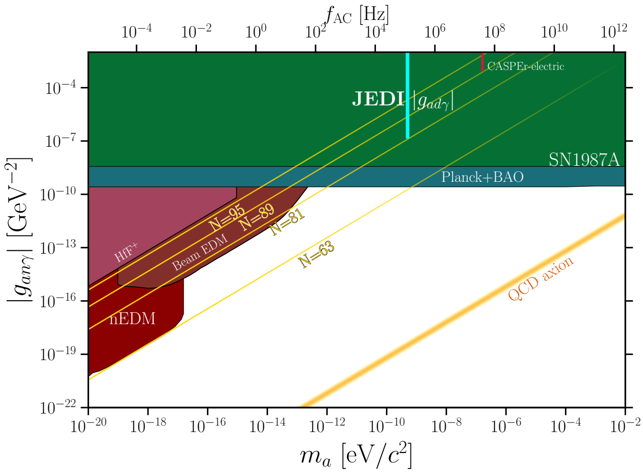


$\equiv \Omega_{\mathrm{MDM}}/(2\pi)$

- a few days of beam time
- $$\frac{\Omega_{\mathrm{MDM}}}{2\pi} = f_{AC} = \frac{1}{2\pi}\frac{m_a c^2}{\hbar} = \gamma G f_{\mathrm{rev}}$$

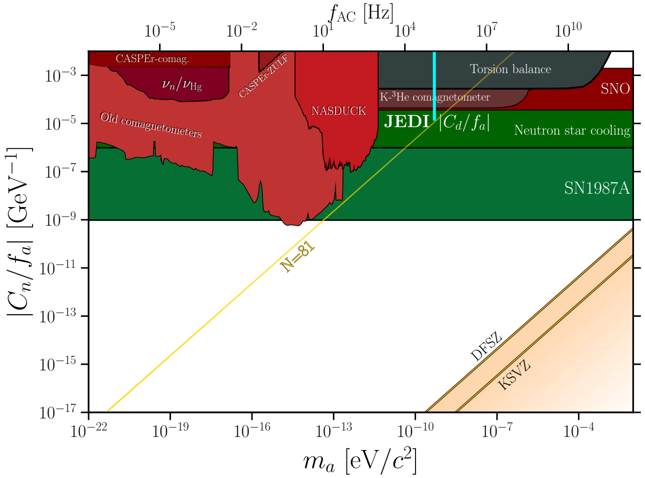
published in PRX: [5]

Axion Coupling to EDM operator $g_{ad\gamma}$ (Axion/Gluon Coupling))



- $g_{ad\gamma} = \dfrac{d_{AC}}{a_0}$
  $a_0 = 0.55$ GeV/cm^3
  (Dark Matter is saturated by ALPs)
- assume no axion wind effect
- yellow lines (parallel to QCD axion lines): models with light QCD axion
- JEDI limit comparable or even better compared to other experiments
- Limits from SN1987A, Planck+BAO have strong model dependence

Axion Wind Effect: Coupling to Nucleons C_N/f_a



- storage ring experiments particularly sensitive to axion wind effect ($\beta = \mathcal{O}(1)$)

Next steps?

How to Explore a Wider Mass Range m_a

Up to now experiment was performed in a very narrow frequency range. How to access wider mass range?

$$\Omega_{\mathrm{MDM}} = \gamma G \Omega_{rev}$$

1. modify beam energy (changes γ, Ω_{rev})
2. use different nuclei (changes G)
3. Use additional electric field
   $$\vec{\Omega}_{\mathrm{MDM}} = -\frac{q}{m}\left[G\vec{B} - \left(G - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right]$$
   allows to reduce $\vec{\Omega}_{\mathrm{MDM}}$ down to 0

Summary & Outlook

Summary & Outlook

- Axion/ALPs well motivated candidates for cold dark matter
- First storage ring experiment at COSY performed by JEDI collaboration to search for ALPs
- A new method to search for axion/ALPs using polarized hadrons beams was established
- In an engineering run (few days of data taking) limits reached which are comparable to other experiments
- POF IV milestone CML-12 (promised for 2024!)

Posters, related to EDM/axion searches:

Achim Andres, Max Vitz, Daoning Gu, Saad Siddique

Literature I

- R. L. Workman and Others, “Review of Particle Physics,” *PTEP*, vol. 2022, chapter 90, p. 083C01, 2022.
- S. P. Chang, S. m. c. Hacıömeroğlu, O. Kim, S. Lee, S. Park, and Y. K. Semertzidis, “Axionlike dark matter search using the storage ring edm method,” *Phys. Rev. D*, vol. 99, p. 083002, Apr 2019. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevD.99.083002
- N. N. Nikolaev, “Spin of protons in NICA and PTR storage rings as an axion antenna,” *Pisma Zh. Eksp. Teor. Fiz.*, vol. 115, no. 11, pp. 683–684, 2022.
- A. J. Silenko, “Relativistic spin dynamics conditioned by dark matter axions,” *Eur. Phys. J. C*, vol. 82, no. 10, p. 856, 2022.

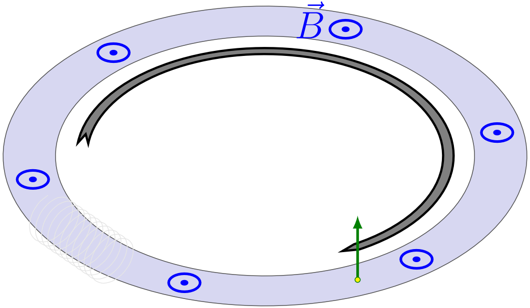
Literature II

S. Karanth, E. J. Stephenson, S. P. Chang, V. Hejny, S. Park, J. Pretz, Y. K. Semertzidis, A. Wirzba, A. Wrońska, F. Abusaif, A. Aggarwal, A. Aksentev, B. Alberdi, A. Andres, L. Barion, I. Bekman, M. Beyß, C. Böhme, B. Breitkreutz, C. von Byern, N. Canale, G. Ciullo, S. Dymov, N.-O. Fröhlich, R. Gebel, K. Grigoryev, D. Grzonka, J. Hetzel, O. Javakhishvili, H. Jeong, A. Kacharava, V. Kamerdzhiev, I. Keshelashvili, A. Kononov, K. Laihem, A. Lehrach, P. Lenisa, N. Lomidze, B. Lorentz, A. Magiera, D. Mchedlishvili, F. Müller, A. Nass, N. N. Nikolaev, A. Pesce, V. Poncza, D. Prasuhn, F. Rathmann, A. Saleev, D. Shergelashvili, V. Shmakova, N. Shurkhno, S. Siddique, J. Slim, H. Soltner, R. Stassen, H. Ströher, M. Tabidze, G. Tagliente, Y. Valdau, M. Vitz, T. Wagner, and P. Wüstner, "First search for axionlike particles in a storage ring using a polarized deuteron beam," *Phys. Rev. X*, vol. 13, p. 031004, Jul 2023. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevX.13.031004

Spare Slides

Principle of Experiment

- store polarized hadrons



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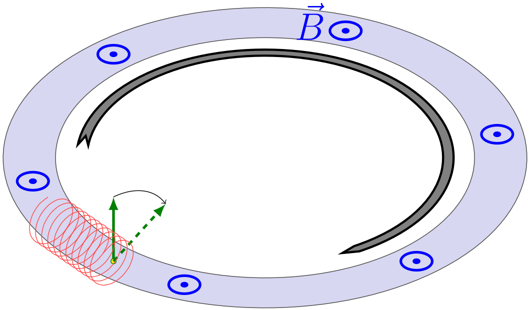
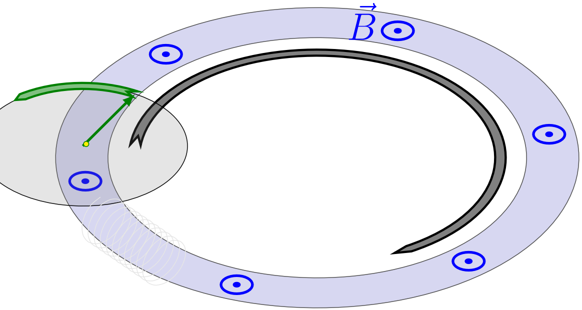


- store polarized hadrons
- flip polarization into horizontal plane,

Principle of Experiment



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- flip polarization into horizontal plane,
- maintain precession in horizontal plane for $\approx$ 100s

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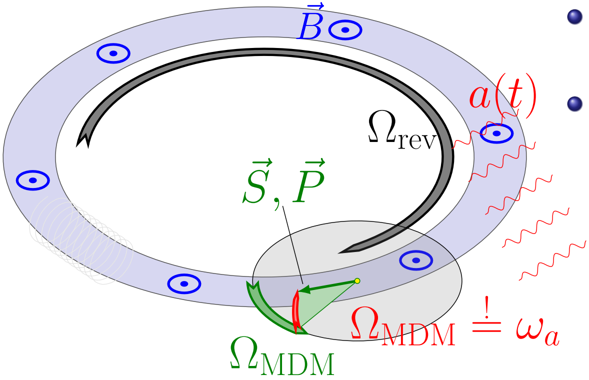

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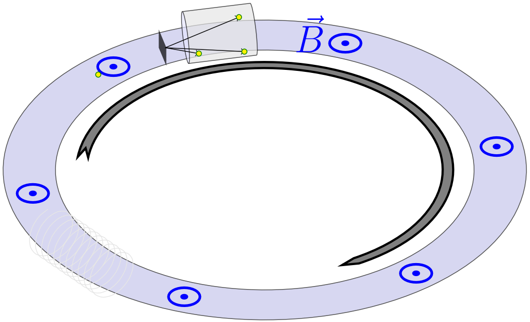
- if $m_a c^2 \equiv \hbar\omega_a \stackrel{!}{=} \Omega_{\mathrm{MDM}}\hbar$, polarization will turn out of the horizontal plane, resulting in a vertical polarization component, if the relative phase of axion field and a spin precession match.

Principle of Experiment



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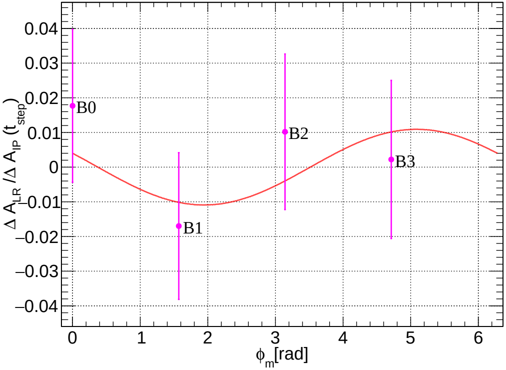
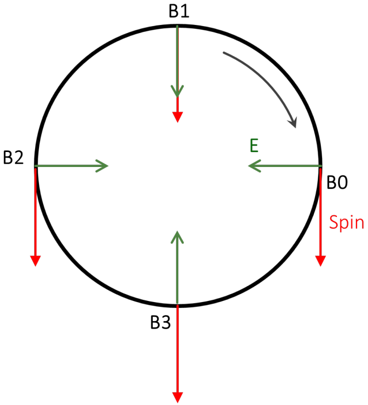
- Vertical polarization can be measured using a carbon target and a polarimeter.
  Left-right asymmetry A_{LR} is proportional to vertical polarization

Typical Asymmetry Measurement

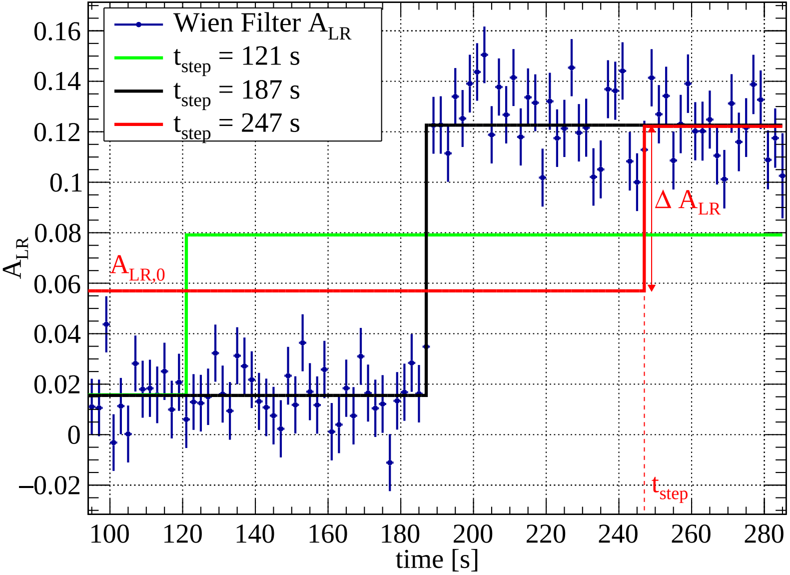




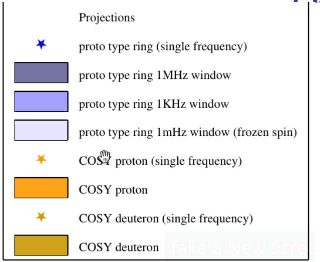
Fit: $f(\Phi_m) = C_1 \cos(\Phi_m) + C_2 \sin(\Phi_m)$

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

Artificial Signal Using RF Wien Filter



Axion Searches at Storage Rings



Estimate for one year (10^7 seconds) running time [**?**] for COSY and a prototype storage ring for EDM measurements