Towards axion searches with polarized hadron beams and targets at the GSI/FAIR storage rings

14 MARCH 2024 GIESSEN

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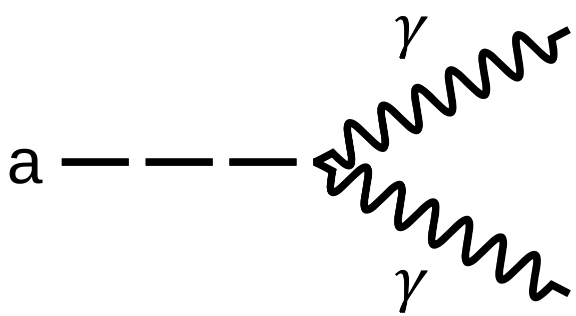
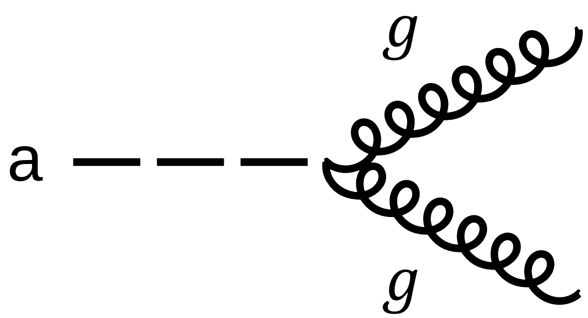
INTRODUCTION

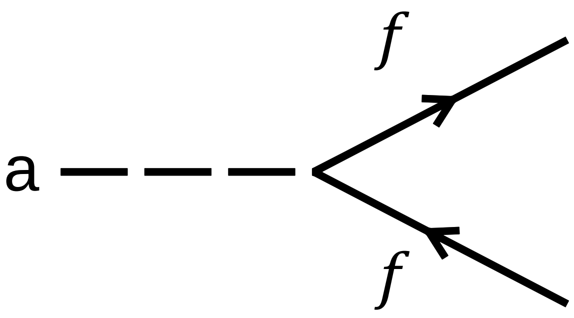
Axions/Axion Like Particles (ALPs)

- Axions are leading particle candidates for dark matter.
- Possible couplings to standard model particles:

$$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad \frac{a}{f_a}G_{\mu\nu}\tilde{G}^{\mu\nu} \qquad \frac{\partial_\mu a}{f_a}\bar{\Psi}_f\gamma^\mu\gamma_5\Psi_f$$







storage ring experiments

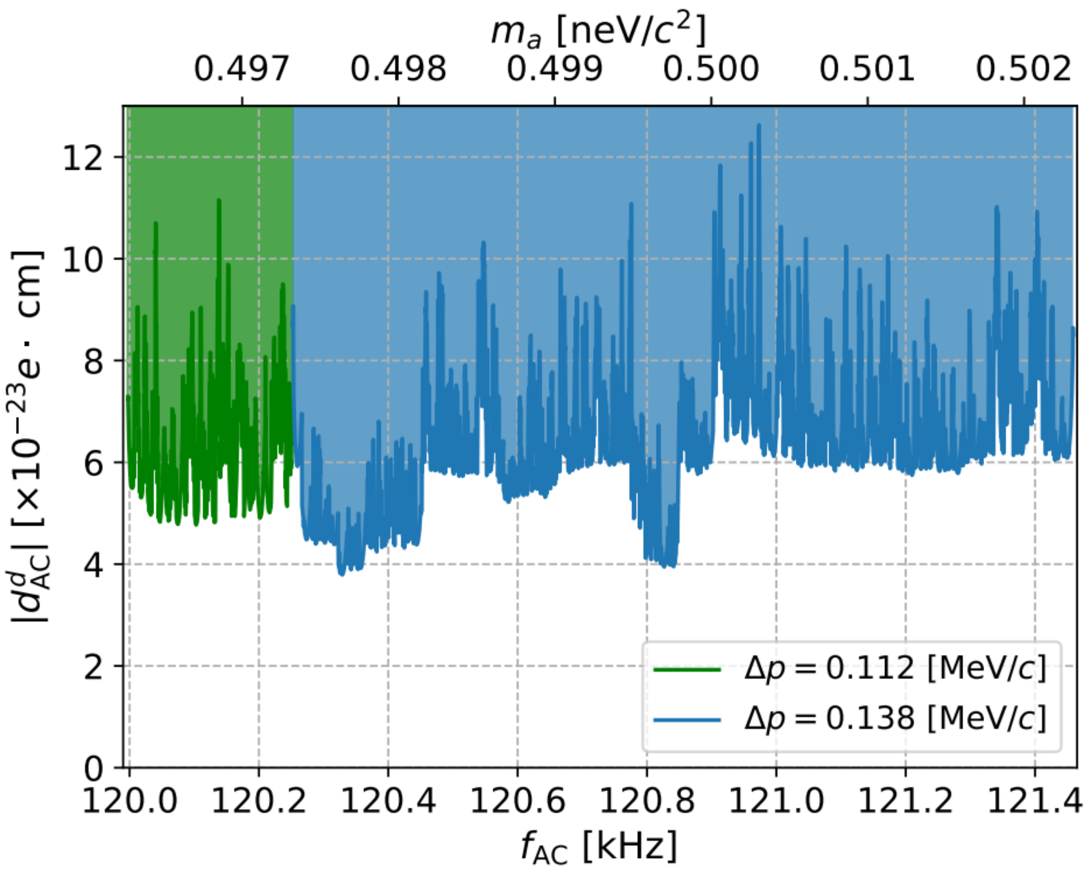
- For low axion mass ($<10^{-7}\,\mathrm{eV}/c^2$), ALPs dark matter can be expressed as a classical field:

$$a(\mathrm{t}) = a_o\cos(\omega_a t + \varphi_o).$$

AXION SEARCH AT COSY

- First proof-of-principle experiment was performed at COSY, FZ Jülich.
- Polarized deuteron beam: 970 MeV/c
- Only a few days of data taking.

- 90% CL upper limit on the ALPs induced oscillating EDM.



[Phys. Rev. X 13, 031004. (2023)]

SPIN MOTION IN STORAGE RINGS

- Spin motion in a purely magnetic ring:

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

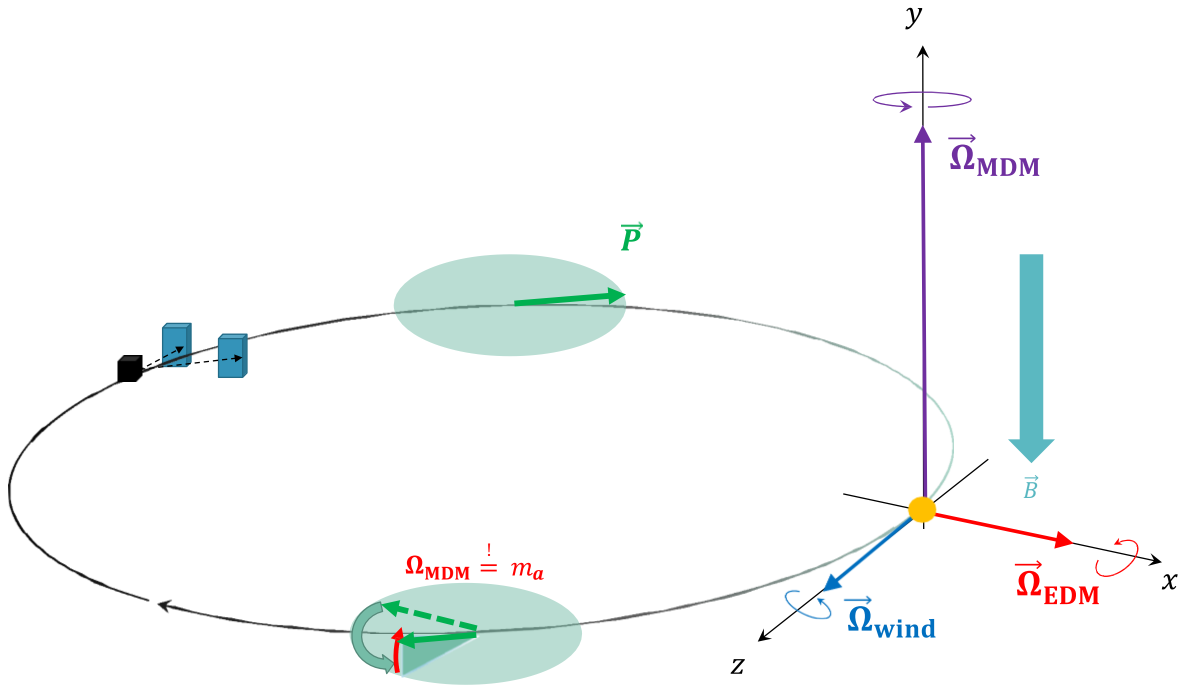
$$\vec{\Omega}_{MDM} = -\frac{q}{m} G\vec{B}, \qquad \vec{\Omega}_{EDM} = -\frac{1}{S\hbar} dc\vec{\beta} \times \vec{B},$$

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

- Axion/ALPs – gluon coupling induces an oscillating electric dipole moment (oEDM):

$$d = d_{DC} + d_{AC}\cos(\omega_a t + \varphi_o).$$

- If $m_a c^2 \equiv \hbar\omega_a = \Omega_{MDM}\hbar$, polarization will turn out of the horizontal plane, resulting in a vertical polarization.

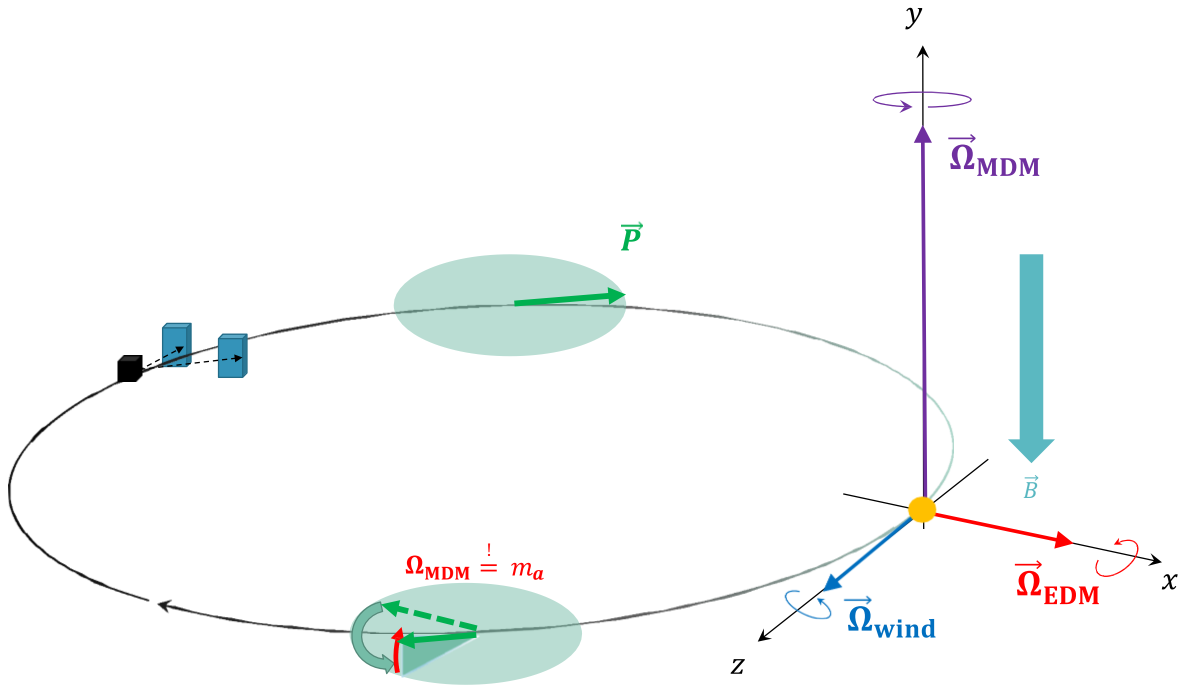


EXPERIMENT METHOD

- Advantages:

1. scanning a large mass region.
2. verifying a narrow mass region for a given claim.

- Store polarized particles in a storage ring.
- Maintain precession in horizontal plane (long Spin Coherence Time).
- Frequency ramps for ALPs scans.
- Vertical polarization can be measured using a carbon target and a polarimeter.



SPIN TUNE

- Spin tune: number of spin precessions per turn.

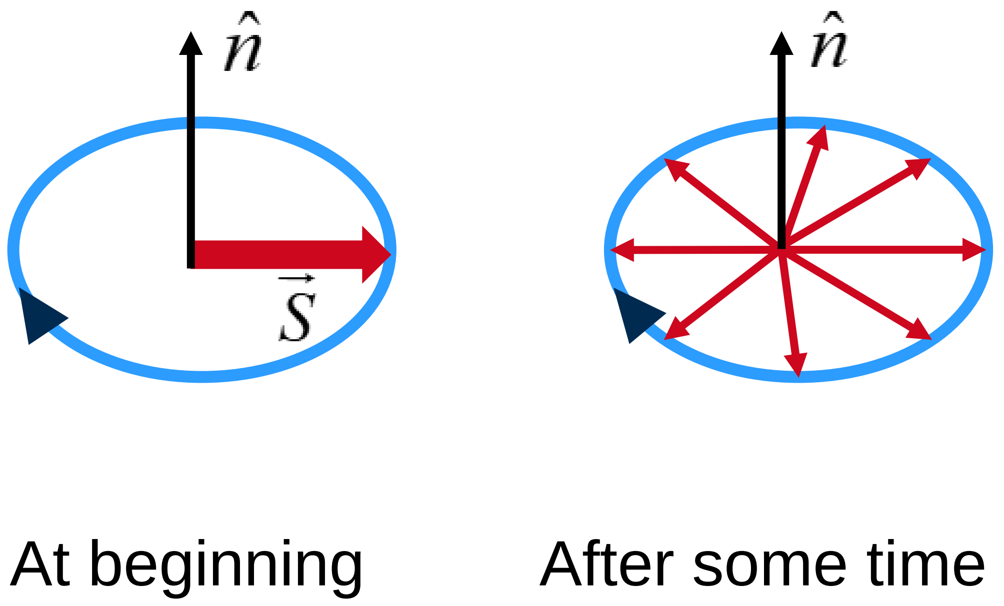
  $$\nu_s = \gamma G$$

  Sensitive to orbital motions.

  G: the gyromagnetic anomaly.

- Spin Coherence Time (SCT)

  = time after total polarization drops to 1/e.



SCT OPTIMIZATION

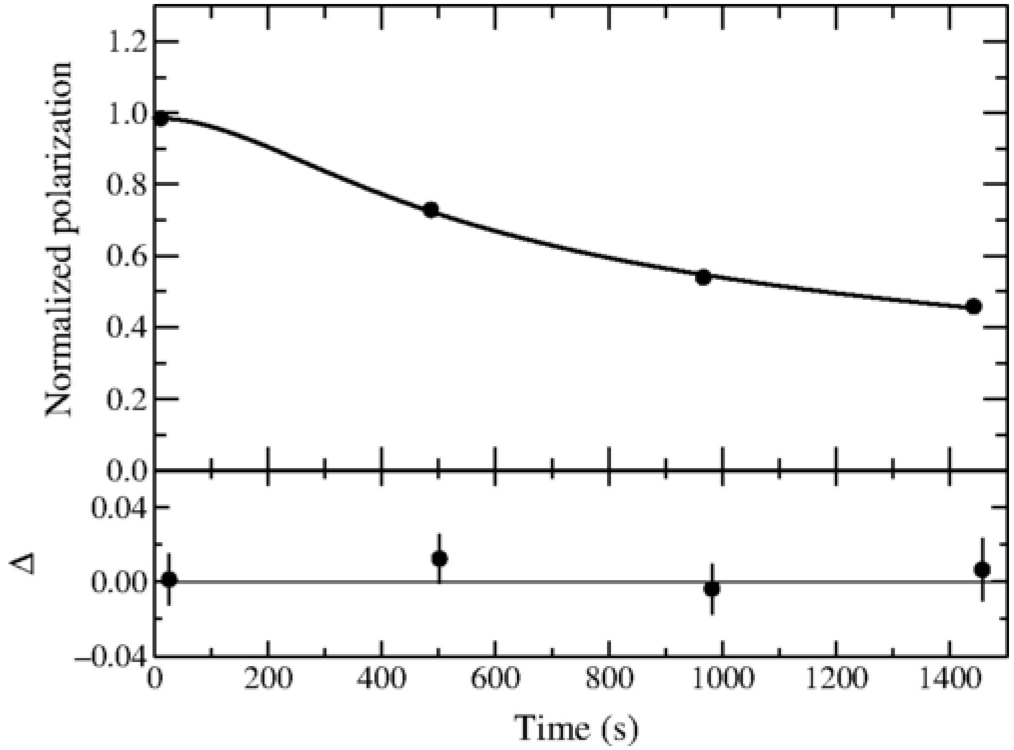
Depolarization:

- Beam emittance.
- Momentum spread.
- 1st-order effect.
- 2nd-order effect.
- Orbit deviation.

Optimization:

- Electron cooling.
- Beam bunching.
- Sextupole correction.

- SCT > 1000 *s* achieved at COSY for deuterons. (2016)



[Phys. Rev. Lett. 117, 054801 (2016)]

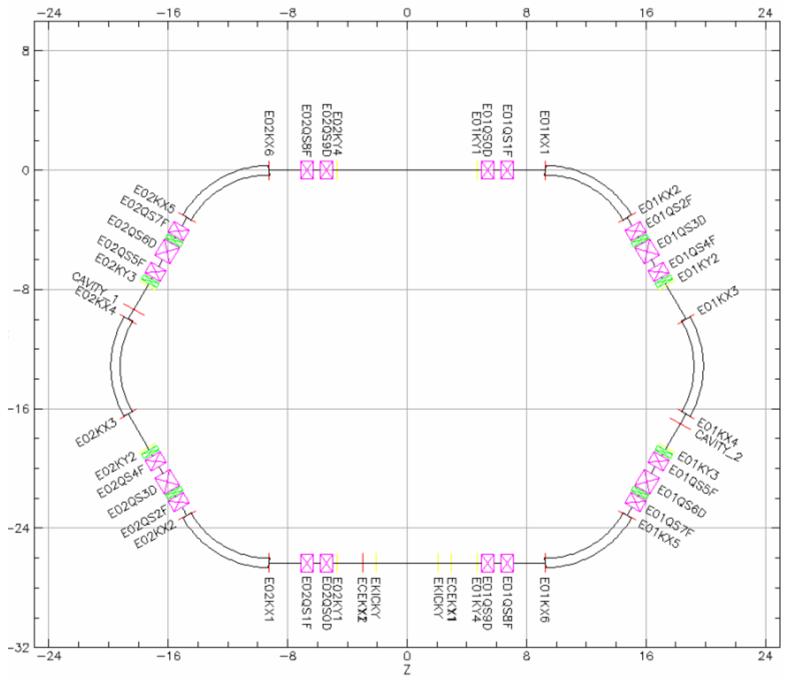
ESR at GSI/FAIR

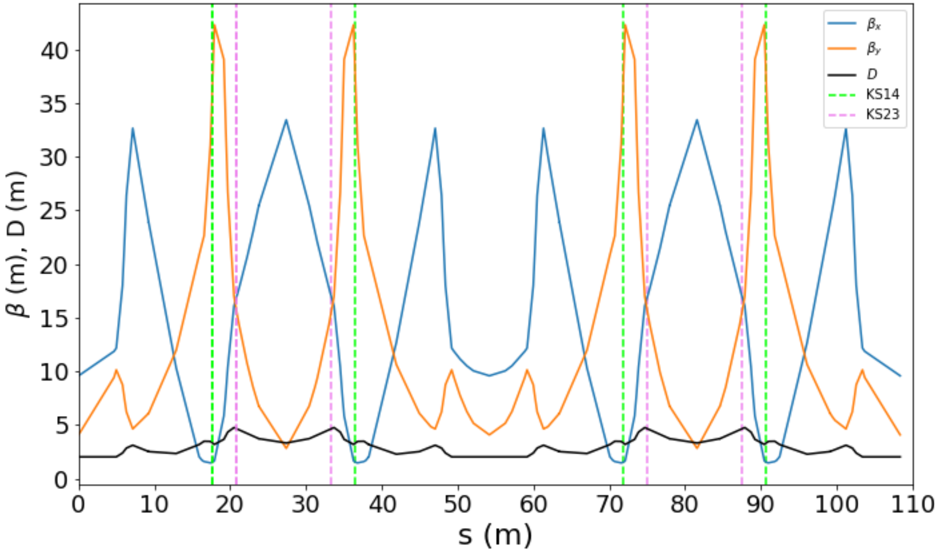
The Experimental Storage Ring ESR

- Circumference: 108.36 m
- Maximum magnetic rigidity: 10 Tm.
- Energy range:

  30 - 2200 MeV/u (proton)

  3 - 556 MeV/u (Uranium)
- Intensity: 10e9.
- 6 dipoles, 20 quadrupoles, 8 sextupoles.
- Currently, no polarized beam is available.
- Software library BMAD with idealized lattice.
- Betatron tune: $Q_x = 2.36,\ Q_y = 2.28$.





[PoS, PSTP2022 (2023), 028]

SEXTUPOLE'S CORRECTION

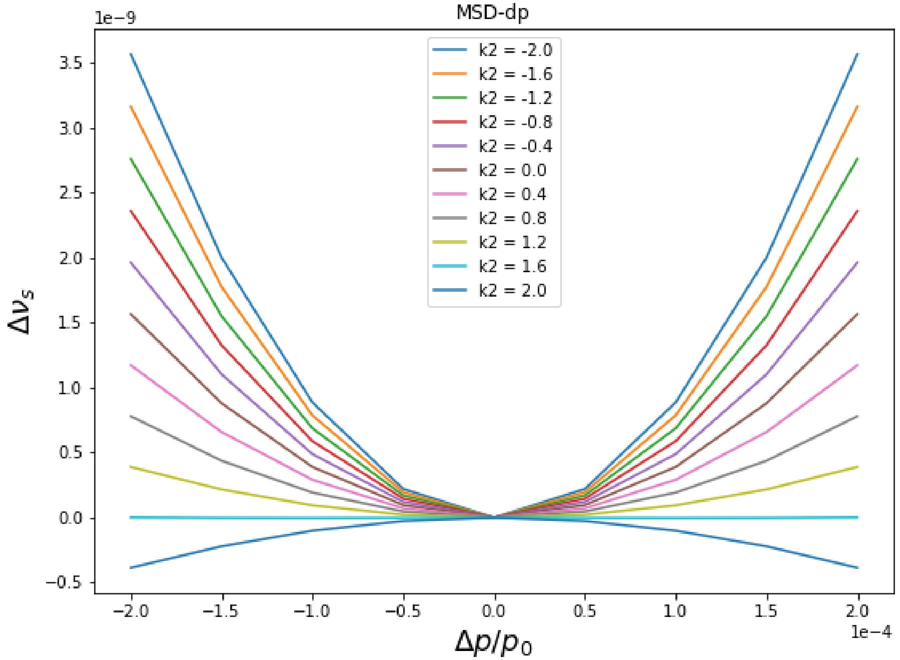
$$\frac{1}{SCT} \propto \Delta\nu_s = |A + a_i k_{2i}| \cdot (\Delta x^2) + |B + b_i k_{2i}| \cdot (\Delta y^2) + |C + c_i k_{2i}| \cdot \left(\frac{\Delta p}{p}\right)^2$$

- Second-order effects.
- Long SCT can be obtained by flattening these parabolas.
- Hardly correctable at low energies.

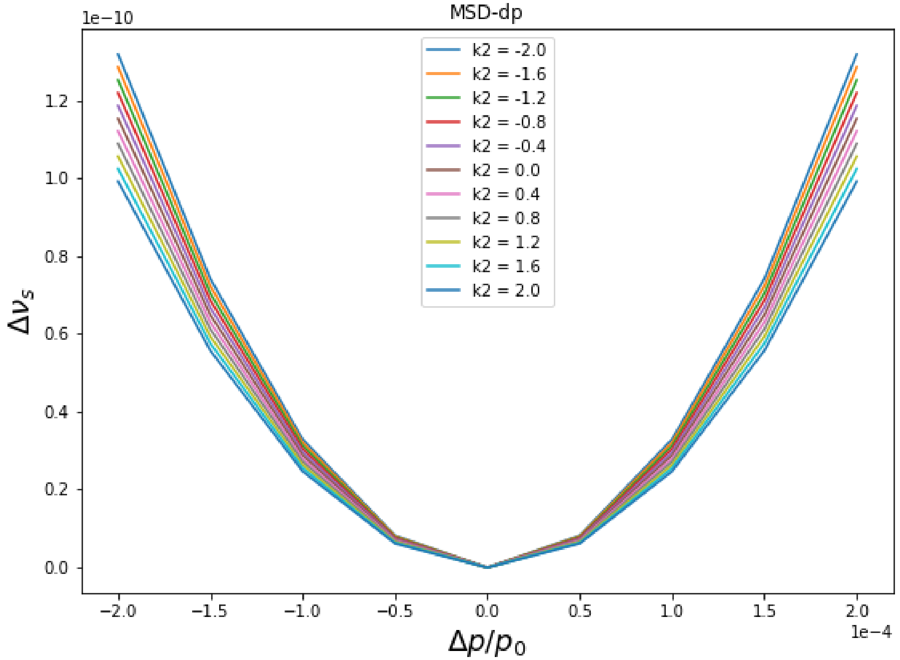
$$\gamma_{2nd} = \gamma_0 + \gamma_0 \beta_0^2 \Delta\delta_{eq}.$$

limited by energy!

p = 1000 MeV/c



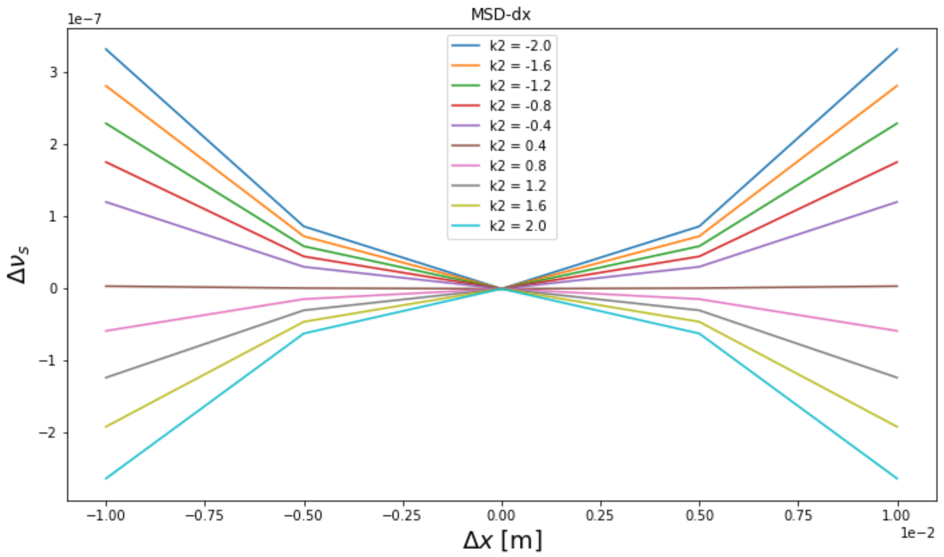
p = 100 MeV/c

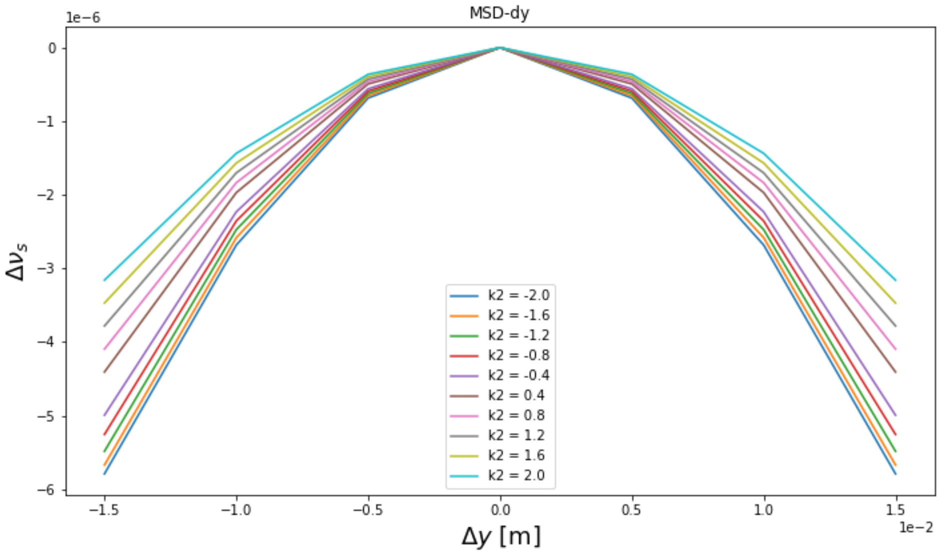


SEXTUPOLE'S CORRECTION

- Correction effects of the sextupole:
  - Betatron motion: $\left(\frac{\Delta L}{L}\right)_\beta = \mp \frac{k_2 D_0 \beta_{x,y} \varepsilon_{x,y}}{L}$
  - Momentum compaction: $\Delta\alpha_1 = -\frac{k_2 {D_0}^3}{L}$
- 3 or more groups of sextupoles are needed.

  (located at large β_x , β_y and dispersion D)
- ESR has 6 dipoles of 6.657 meter length.
- Large β_x are found in the center of the long bending magnets.
- Currently, no space for the 3rd group of sextupoles.



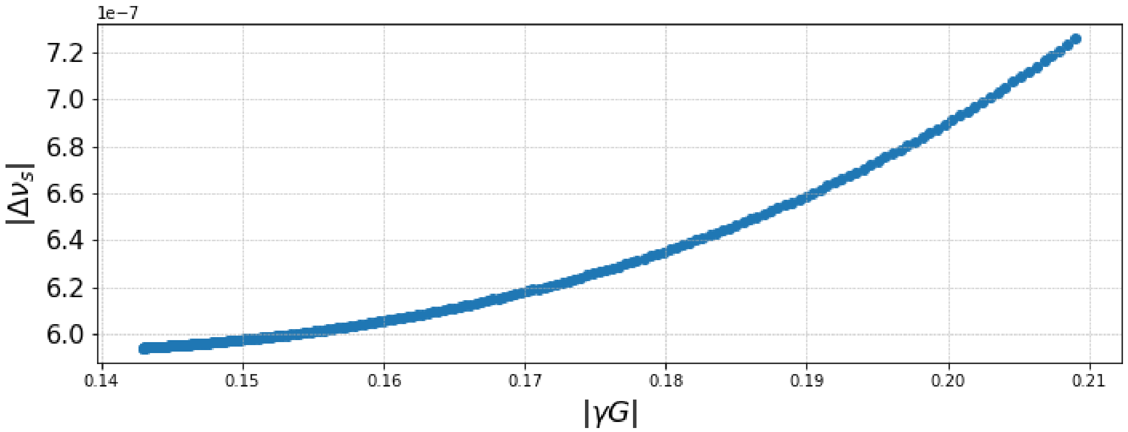


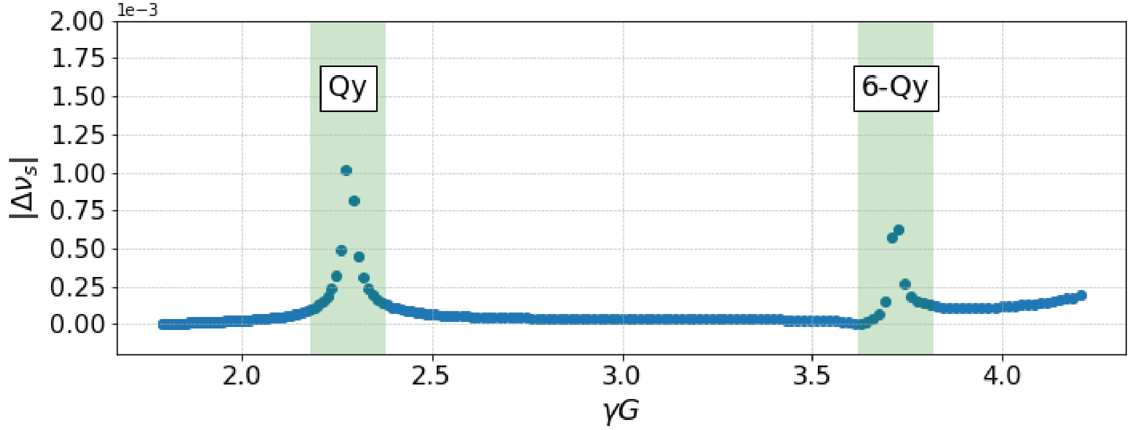
SPIN RESONANCES

- Intrinsic resonance : $\gamma G = nP \pm Q_y$.
- Resonance strength: $\varepsilon \propto \gamma G \sqrt{\frac{\varepsilon_y}{\beta\gamma}}$.
- Deuterons (top): far from resonances.
- Strong impact on protons (bottom) :

$$\gamma G = Q_y, \qquad \gamma G = 6 - Q_y$$

- Half-integer spin tune.
- Multi-parameter optimization is needed.





SUMMARY & OUTLOOK

- Storage ring experiments offer new possibilities for searching the Axions / ALPs.
- Maintaining a long Spin Coherence Time (SCT) is a prerequisite for the experiment.
- Sextupole magnets can only effectively correct spin tune spread at higher energies.

Future:

- The 3rd group of sextupoles needs to be implemented in the simulation.
- A new multi-parameter optimization method is still under investigation.

Thank You!

- $\Omega_{MDM} = \gamma G \Omega_{rev}$, a wide mass range can be covered by:

1) vary the three parameters γ, G and Ω_{rev},
2) use an additional electric field (frozen spin method).

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

G: the gyromagnetic anomaly.