Search for Electric Dipole Moments and Axions/ALPs of charged particles using storage rings

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Present and Future Perspectives in Hadron Physics
LNF, June 17^{th}, 2024

Motivation

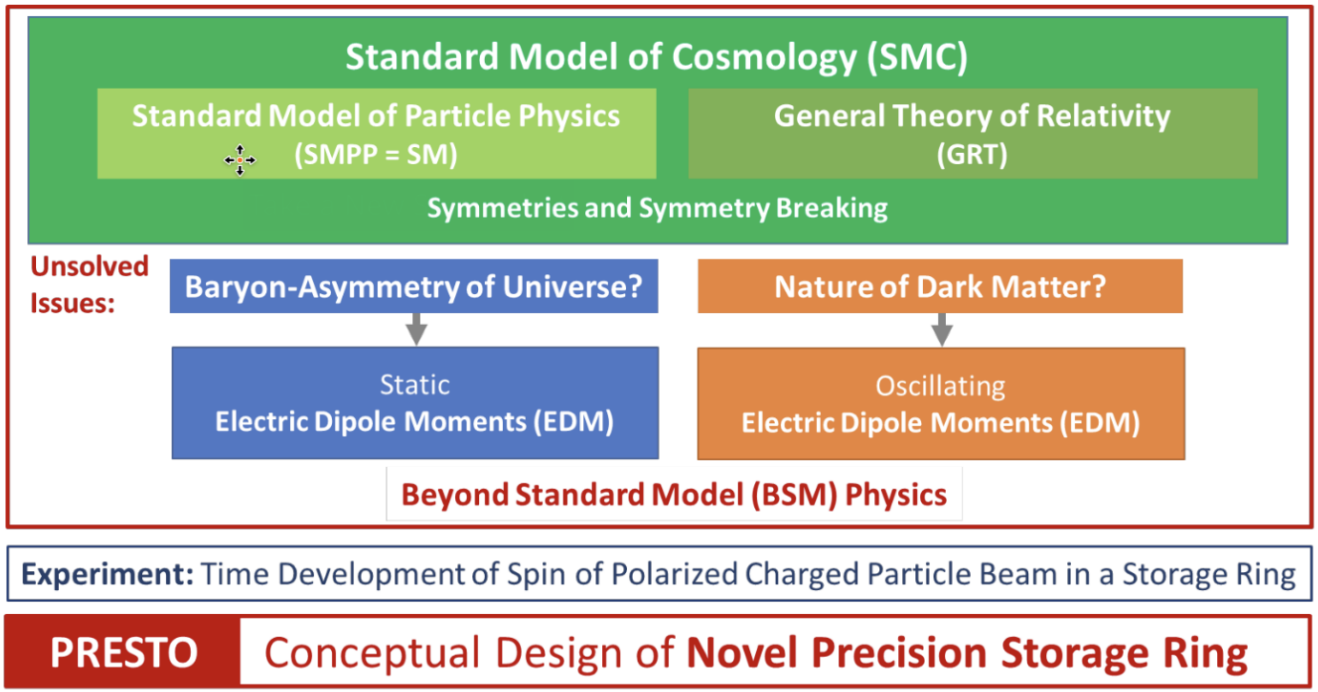
Physics case

Problems

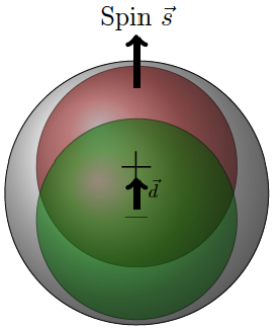
- Preponderance of matter over antimatter
- Nature of Dark Matter (DM)

Approach

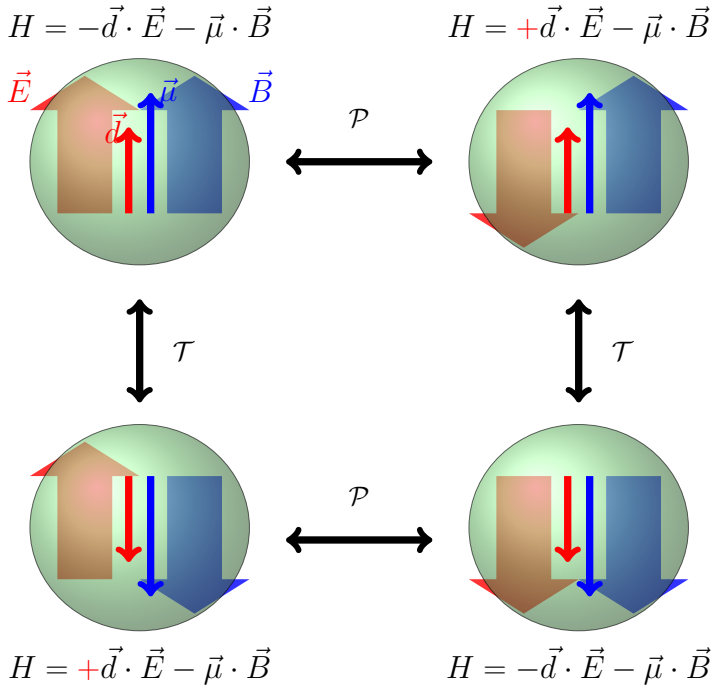
- Measurements of static Electric Dipole Moments (EDM) of fundamental particles.
- Searches for axion-like particles as DM candidates through oscillating EDM



Electric Dipole Moment (EDM)



- Permanent separation of + and - charge
- Fund. property of particles (like mag. moment, mass, charge)
- Possible via violation of time-reversal (T) and parity (P)



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

- T: $H = -\mu \frac{\vec{s}}{s}\cdot\vec{B} + d\frac{\vec{s}}{s}\cdot\vec{E}$
- P: $H = -\mu \frac{\vec{s}}{s}\cdot\vec{B} + d\frac{\vec{s}}{s}\cdot\vec{E}$

EDM meas. test violation of P and T symmetries ($\overset{CPT}{=}$CP)

CP-violation & Matter-Antimatter Asymmetry

Matter dominance:

- Excess of Matter in the Universe:

$\eta = \frac{n_B - n_{\overline{B}}}{n_\gamma}$	observed	SM prediction
	6×10^{-10}	10^{-18}

- Sacharov (1967): CP-violation needed for baryogenesis

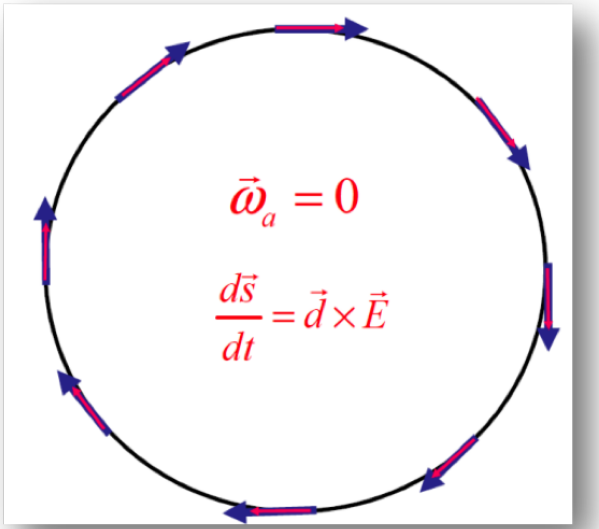
- $\Rightarrow$ New CP-V sources beyond SM needed
- Could show up in EDMs of elementary particles

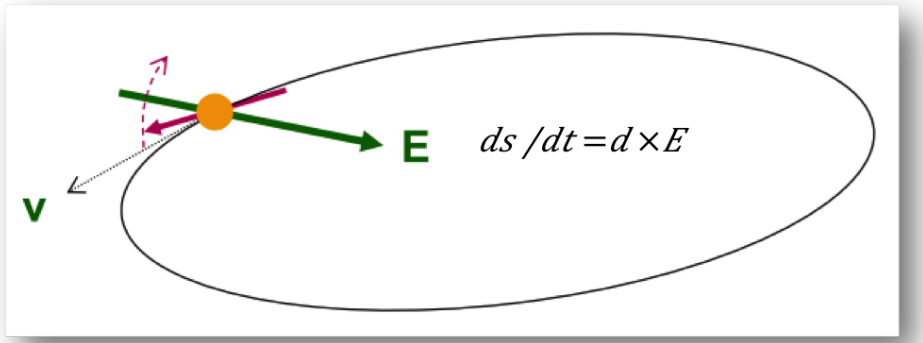
Experimental method

Search for static EDM in storage rings

Measurement concept

1. Inject particles in storage ring
2. Align spin along momentum ($\rightarrow$ freeze horiz. spin-precession)
3. Search for time development of vertical polarization

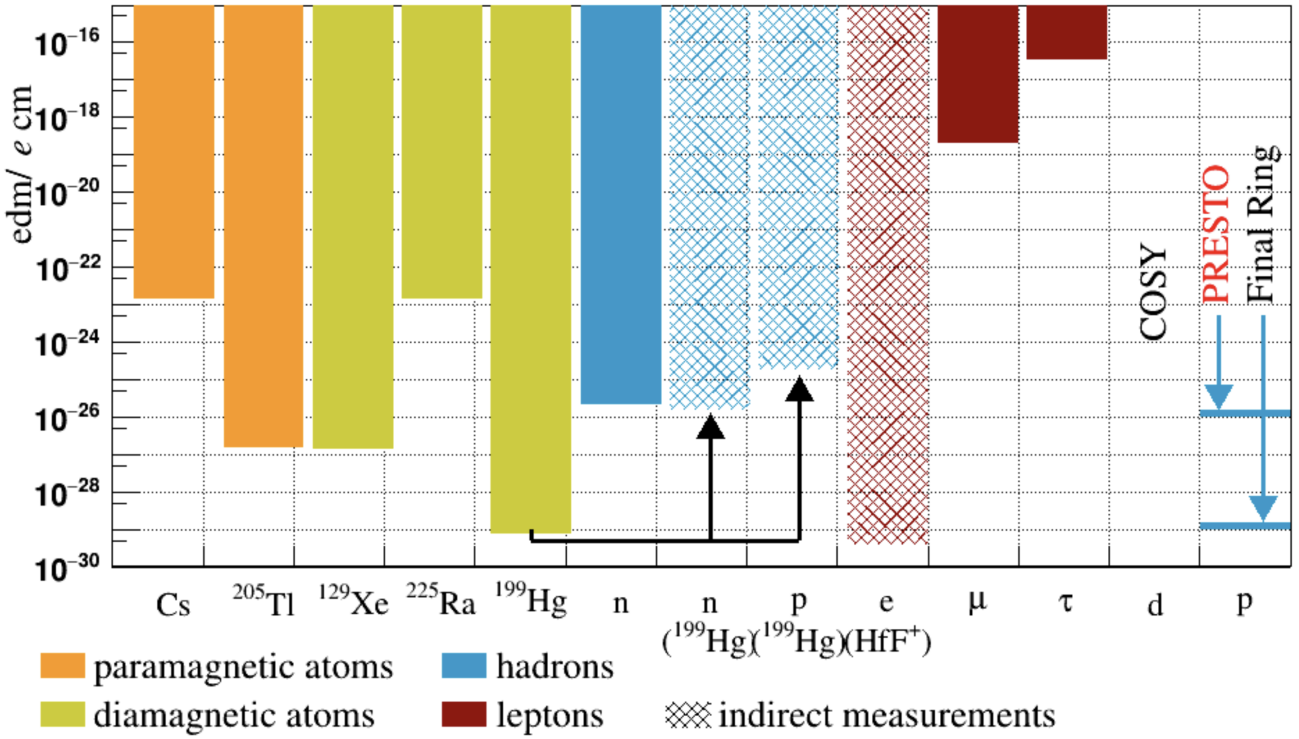




Frozen-spin condition:

- Pure E ring for *p*
- Combined E/B ring for *d* and ^{3}He

Static EDM upper limits



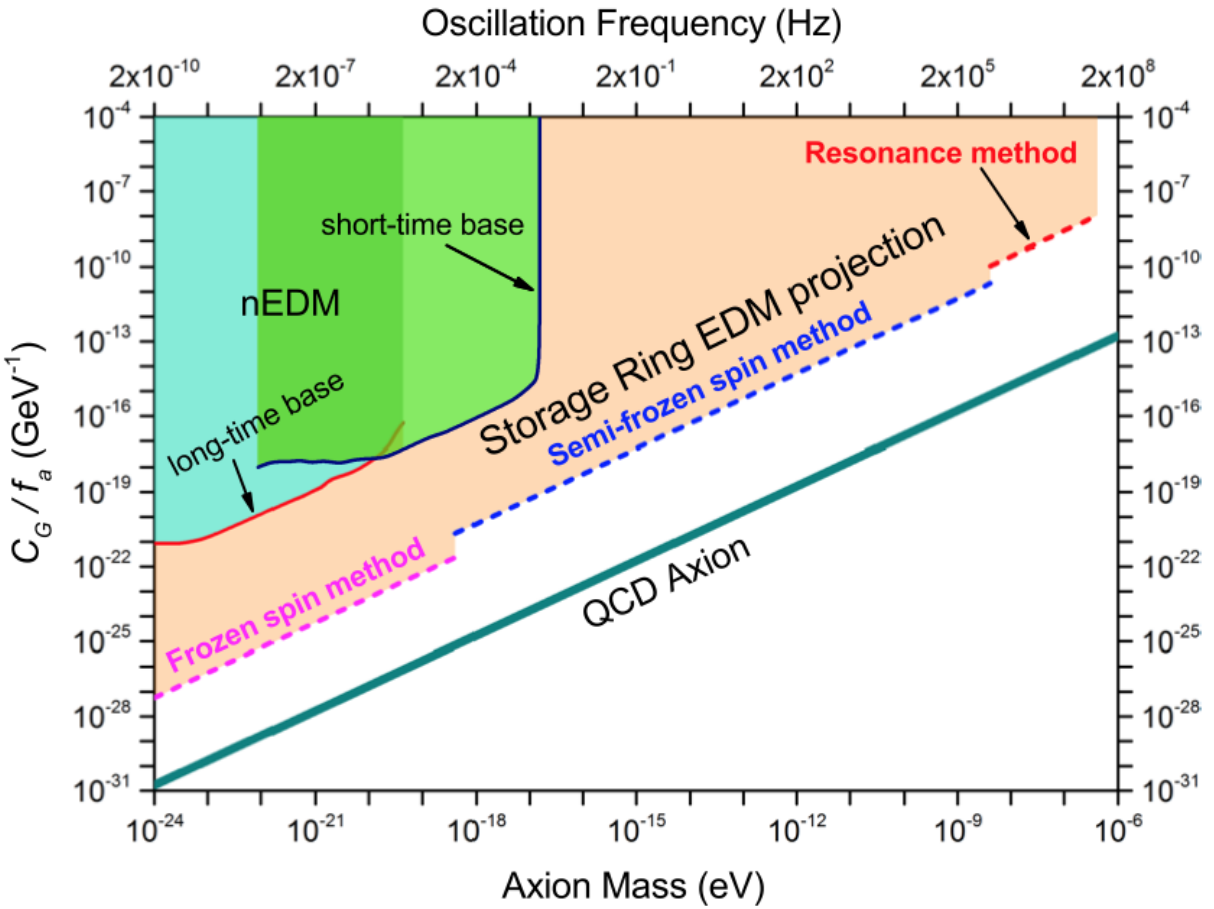
Direct EDM measurements missing

- No direct measurements of electron: limit obtained from HF molecule.
- No direct measurements of proton: limit obtained from $^{199}_{80}Hg$.
- No measurement yet of deuteron EDM.

Theory:

- EDM of single particle not suffcient to identify CP violating source

Axion Dark Matter search with Storage Ring EDM method



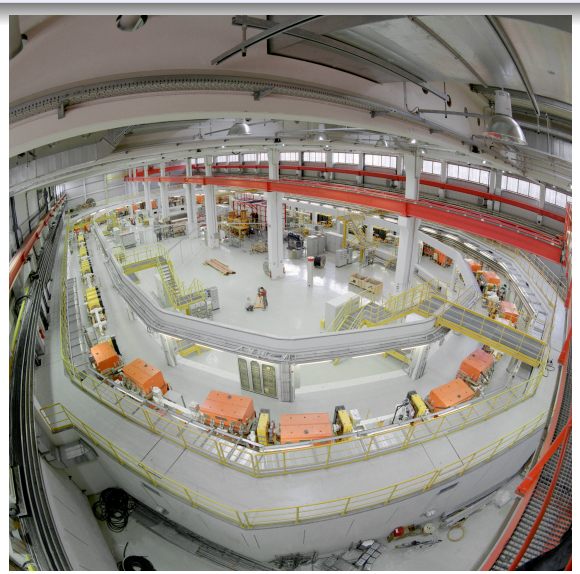
- Experimental limits for axion-gluon coupled oscillating EDM measurements

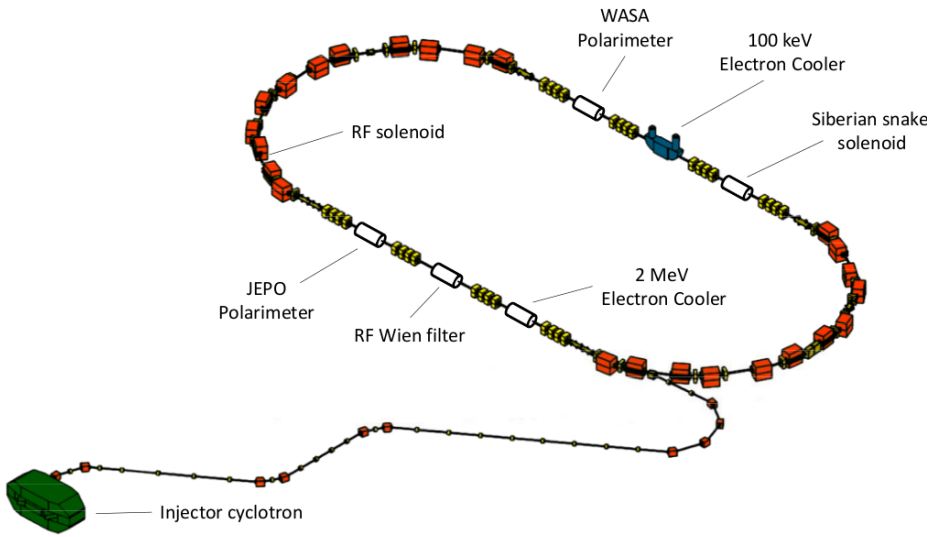
Achievements at COSY

The COSY storage ring at FZ-Jülich (Germany)

COoler SYnchrotron COSY

- Cooler and storage ring for (pol.) protons and deuterons.
- Momenta p= 0.3-3.7 GeV/c
- Phase-space cooled internal and extracted beams



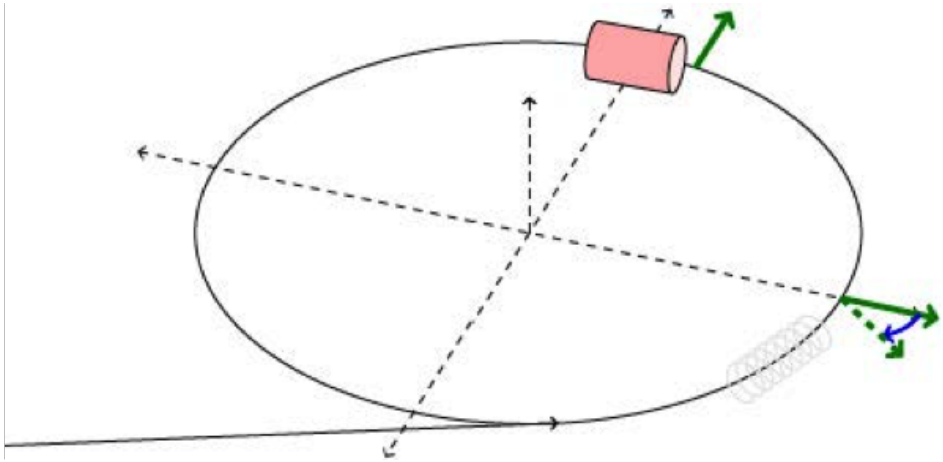


Previously used as spin-physics machine for hadron physics:

- Ideal starting point for Storage Ring EDM related R&D
- Dedicated and unique experimental effort worldwide
- Closed end 2023: essential R&D/expts. with MAGNETIC ring successfully done.

Experiment preparation

1. Inject and accelerate vertically pol. deut. to p $\approx$ 1 GeV/c
2. Flip spin with solenoid into horizontal plane
3. Extract beam slowly (100 s) on Carbon target
4. Measure asymmetry and determine spin precession



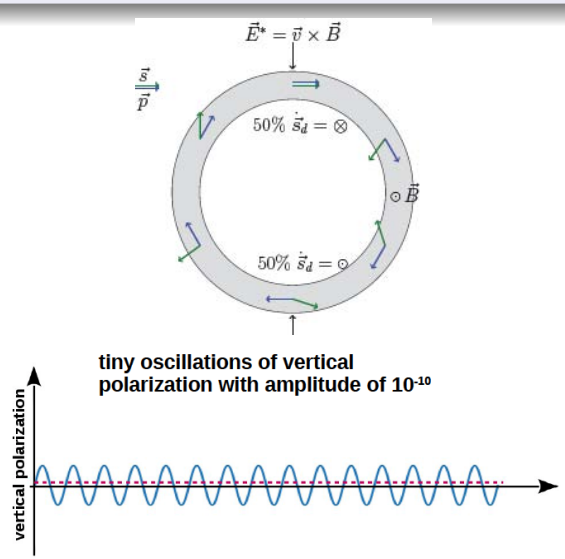
Measurement of EDM in a magnetic ring

First-ever direct EDM measurement using this method

- If external E fields = 0 spin motion is driven by radial field $\vec{E} = c\vec{\beta} \times \vec{B}$ induced by relativistic motion in the vertical $\vec{B}$ field, so that $\frac{d\vec{S}}{dt} \propto \vec{d} \times \vec{E}$
- But this yields only small oscillation of vertical component p_y due to EDM.

Problem

- Momentum $\uparrow\uparrow$ spin
  spin $\Rightarrow$ spin kicked up
- Momentum $\uparrow\downarrow$ spin
  $\Rightarrow$ spin kicked down
- $\Rightarrow$ no accumulation of vert. asymmetry



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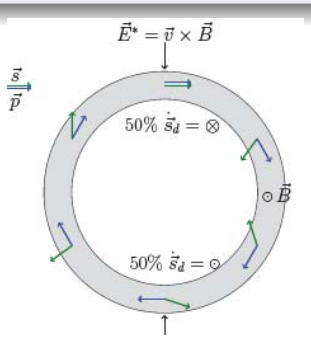
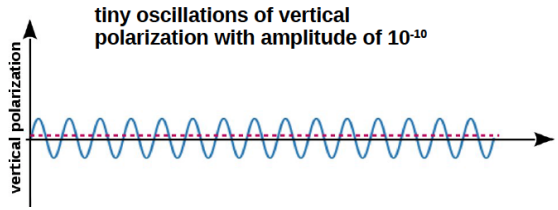


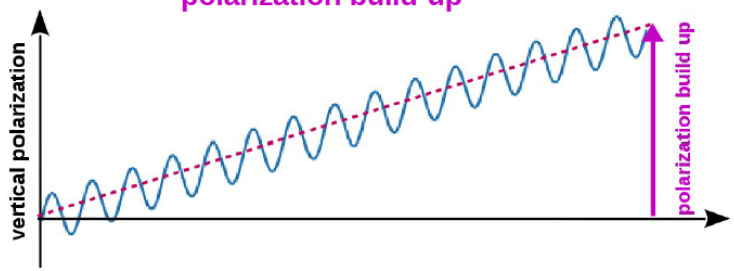


Solution: RF-Wien filter

- Lorentz force: $\vec{F}_L = q(\vec{E} + \vec{v} \times \vec{B}) = 0$
- $\vec{B} = (0, B_y, 0)$ and $\vec{E} = (E_x, 0, 0)$

phase lock between spin precession and RF Wien filter

polarization build-up



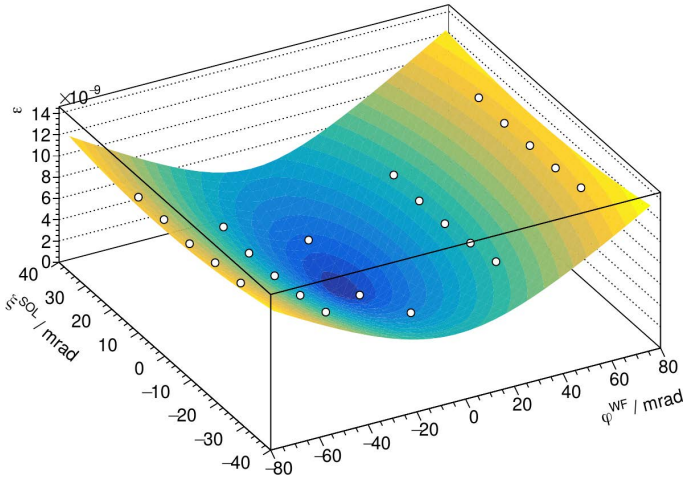
Results from dEDM precursor experiment

Search for EDM $\equiv$ search for spin-invariant axis

- Includes tilts of invariant spin axis due to EDM and magnetic ring imperfections.

Preliminary result on static EDM

- Determination of minimum via fit with theoretical surface function yields:
  - ϕ_0^{WF} (mrad) = - 2.05 $\pm$0.02
  - ψ_0^{sol} (mrad) = + 4.32 $\pm$0.06



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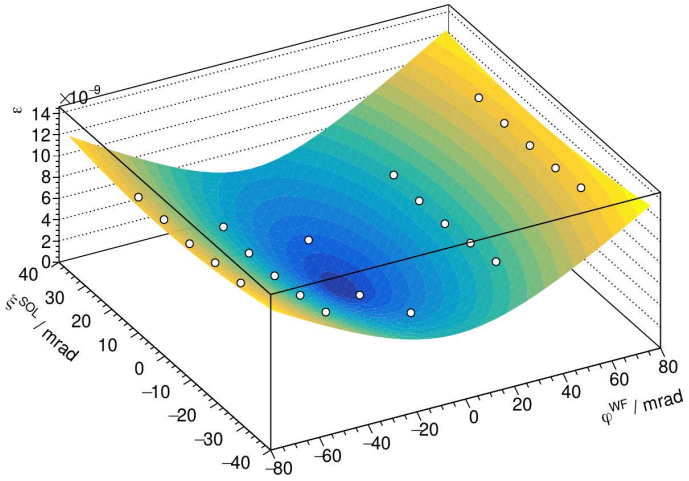

Extraction of EDM

1. Minimum determines spin rotation axis (3-vector) at RF WF, including EDM
2. Spin tracking in COSY lattice $\rightarrow$ orientation of stable spin axis w/o EDM
3. EDM is obtained from the difference of 1. and 2.

EDM analysis presently focused on systematics

- Data analysis close to final & EDM results in preparation.
- Goal: Describe observed tilts of stable spin axis by spin tracking

Measurement of axion-like particle in storage ring

First-ever search for axion-like particles using this method

Axions and oscillating EDM

- Axion: candidates for light dark matter ($m_a < 10^{-6}$ eV)
- Axion interaction with ordinary matter: $\frac{a}{f_0} F_{\mu\nu}\tilde{F}_{\mu\nu}$, $\frac{a}{f_0} G_{\mu\nu}\tilde{G}_{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\bar{\Psi}\gamma^\mu\gamma_5\Psi$
- $\frac{a}{f_0} G_{\mu\nu}\tilde{G}_{\mu\nu} \rightarrow$ coupling to gluons with same structure as QCD-θ term
- Generation of an oscillating EDM with freq. related to mass: $\hbar\omega_a = m_a c^2$

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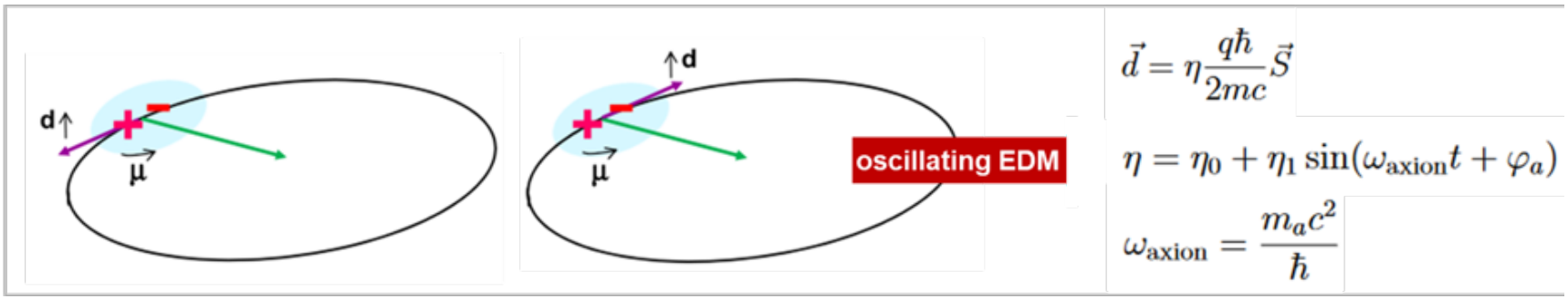
Experimental approach

- Mag. dipole moment (MDM) $\rightarrow$ spin prec. in B field $\rightarrow$ nullifies static EDM effect
- Osc. EDM resonant condition ($\omega_a = \omega_s$) $\rightarrow$ buildup of out-of-plane spin rotation

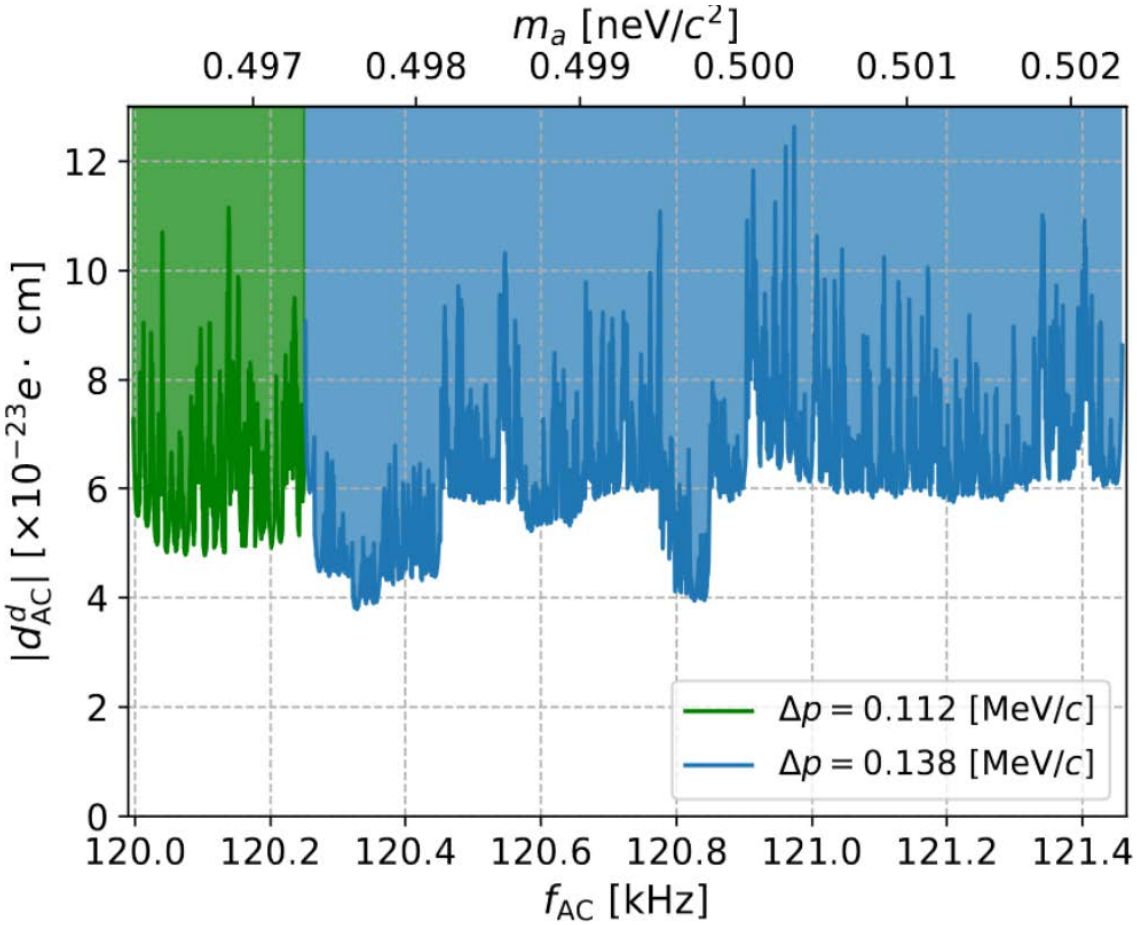


$$\vec{d} = \eta \frac{q\hbar}{2mc}\vec{S}$$

$$\eta = \eta_0 + \eta_1 \sin(\omega_{\text{axion}} t + \varphi_a)$$

$$\omega_{\text{axion}} = \frac{m_a c^2}{\hbar}$$

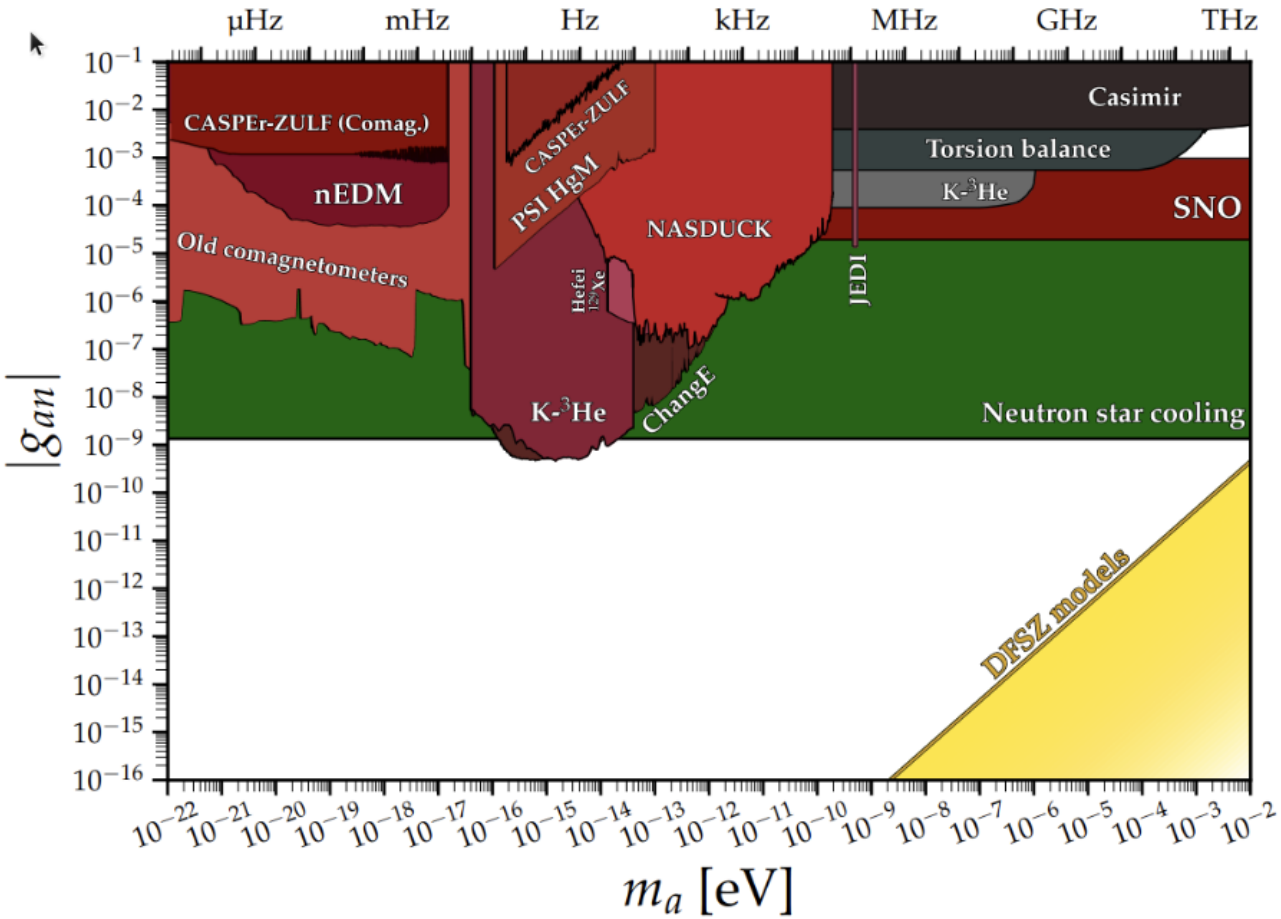
Bound on oscillating EDM of deuteron



Observed oscillation amplitudes from 4 bunches

- Variation of m_A via f_{AC}
- 90 % CL upper limit on the ALPs induced oscillating EDM
- Average of individual measured points $d_{AC} < 6.4 \times 10^{-23}$ e cm

Bound on axion-nucleon coupling



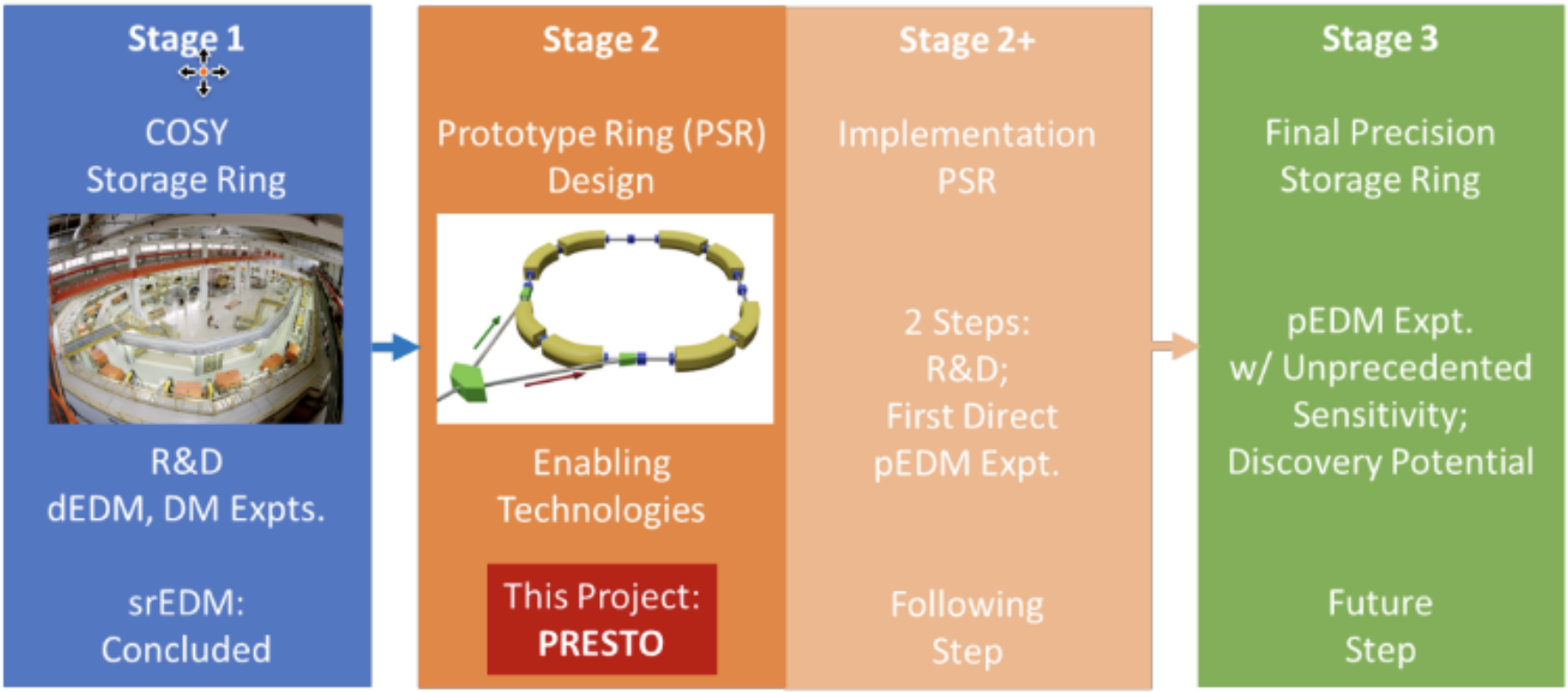
Limits on axion/ALP neutron coupling from the Particle Data Group

- It includes the result from the JEDI collaboration
  - S. Karanth et al., Phys. Rev. X 13 (2023) 031004

Next steps

Strategy: staged approach to a storage ring for precision physics

On the basis of the preparedness of the required technological developments

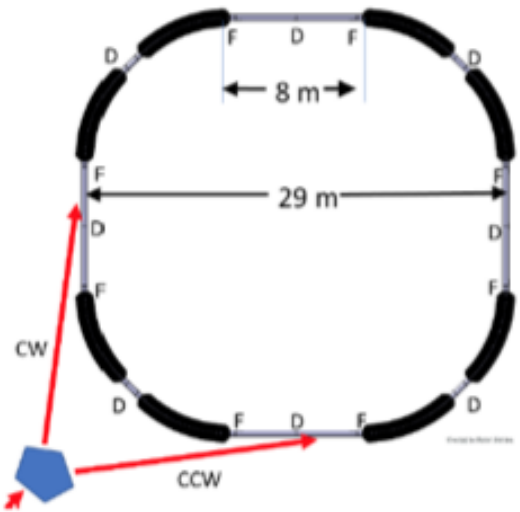


PRESTO: Pathfinder facility for a new class of PREcision Physics STOrage rings

Stage 2: prototype EDM storage ring

100 m circumference

- p at 30 MeV all-electric CW-CCW beams operation
- Frozen spin including additional vertical magnetic fields



Challenges

- All electric & E-B combined deflection
- Storage time
- CW-CCW operation
  - Orbit control
  - Control of orbit difference
- Polarimetry
- Spin-coherence time
- Magnetic moment effects
- Stochastic cooling

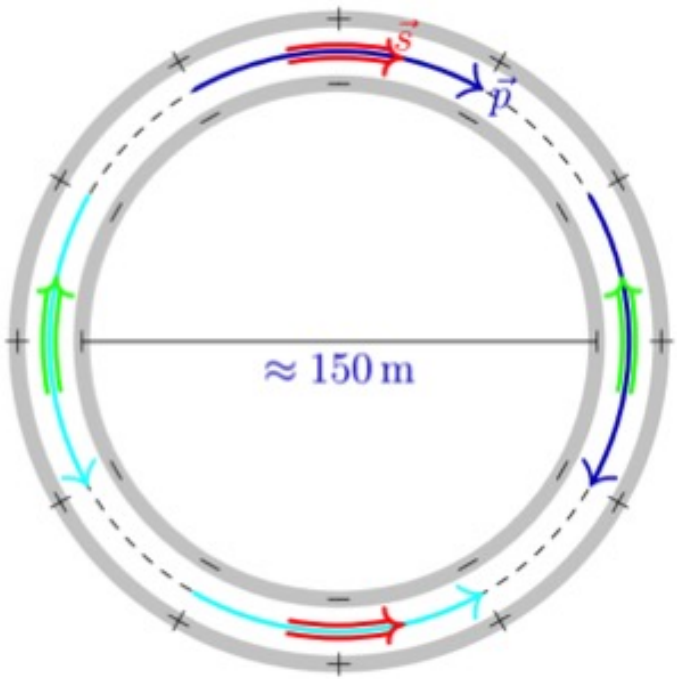
Objectives of PTR

- Study open issues.
- First direct proton EDM measurement.

Stage 3: precision EDM ring

500 m circumference (with E = 8 MV/m)

- All-electric deflection
- Magic momentum for protons (p = 707 MeV/c)

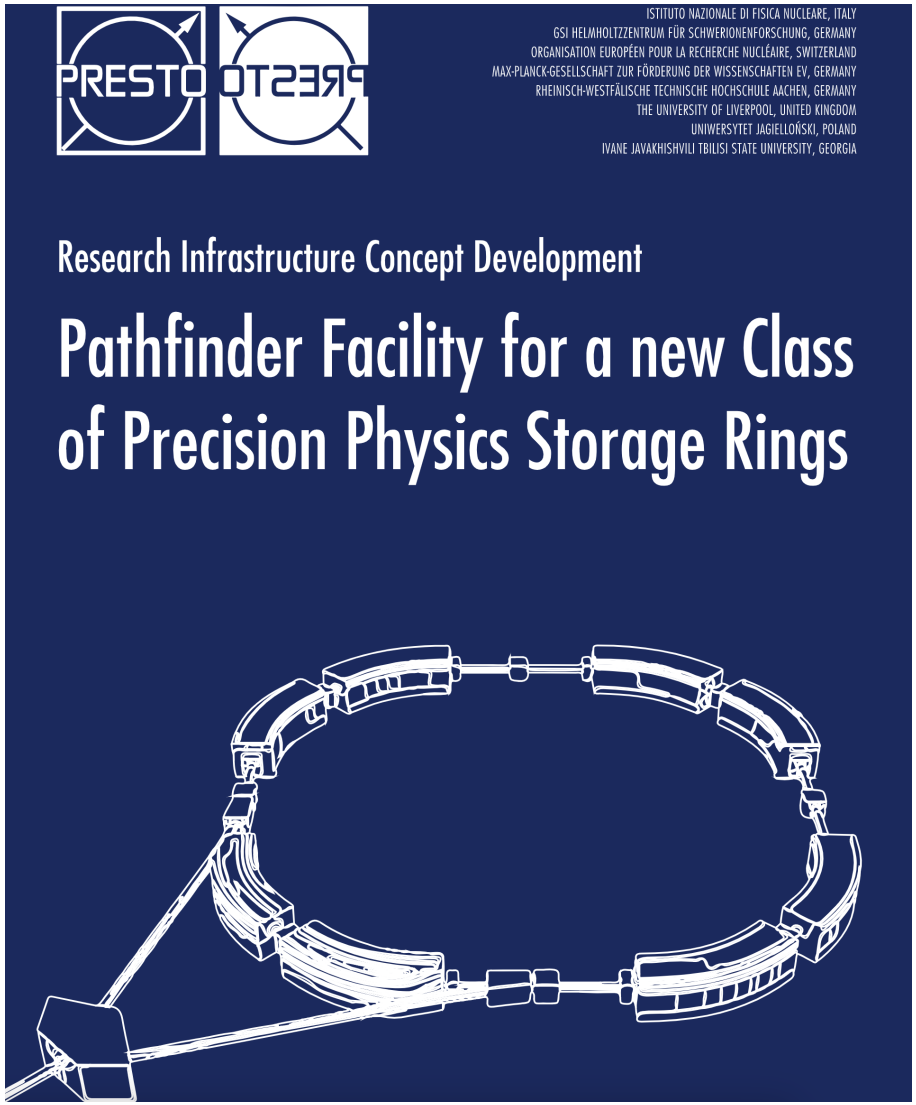


Challenges

- All-electric deflection
- Simultaneous CW/CCW beams
- Phase-space cooled beams
- Long spin coherence time ($>$ 1000 s)
- Non-destructive precision polarimetry
- Optimum orbit control
- Optimum shielding of external fields
- Control of residual B_r fields

"Holy Grail" storage ring (largest electrostatic ever conceived)

Research Infrastructure Concept Development:
PRESTO:
Pathfinder facility for a new class of PREcision-physics STOrage rings "



Hint for a possible STRONG2020 successor
New Aspect: Spin Physics for the Precision Frontier

Could be either a JRA or a Network

- Design Study of a Prototype Storage Ring
  - Study of both static and oscillating EDMs
- Development of simulation codes for beam and spin-tracking
  - Application of Artificial Intelligence and Machine Learning
- Possible partners
  - INFN, CERN, MPI, RWTH, Georgia, Poland, BNL, KAIST and open to other institutions ...

Possible hardware developments

- Low energy proton polarimetry
- High-precision beam position monitors
- Electrostatic deflectors

Conclusions

EDM searches in Storage Rings

- Outstanding scientific case with high discovery potential
- Key developments in accelerator technology

Fundamental achievements at COSY

- Spin-control tools
- First measurement of (static and oscillating) deuteron EDM

Staged approach to face challenges in accelerator technology

- Feasibility study of a *pure electrostatic* EDM proton ring

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Perspective for the *hadron community*

- Keep EU leading competence
- Sustainment of expertise and continuation of the activity
  - Interdisciplinary impact
    - Fundamental and particle physics
    - Astroparticle and hadron physics
    - Accelerator and data science
- Consistent with JRA or Networking Activity

Selected publications

- D. Eversmann et al (JEDI Collaboration): New method for a continuous determination of the spin tune in storage rings and implications for precision experiments - Phys. Rev. Lett. 115, 094801 (2015)
- J. Slim, et al.:Electromagnetic simulation and design of a novel waveguide rf-Wien filter for electric dipole moment measurements of protons and deuterons - Nucl. Instr. and Meth. A: 828, 116 (2016), ISSN 0168-9002
- G. Guidoboni et al. (JEDI Collaboration): How to reach a thousand-second in-plane polarization lifetime with 0:97 Gev/c deuterons in a storage ring - Phys. Rev. Lett. 117, 054801 (2016)
- N. Hempelmann et al. (JEDI Collaboration): Phase locking the spin precession in a storage ring - Phys. Rev. Lett. 119, 014801 (2017)
- F. Abusaif (CPEDM Collaboration): Storage Ring to Search for Electric Dipole Moments of Charged Particles - Feasibility Study - (CERN, Geneva, 2021)
- S. Karanth et al. (JEDI Collaboration): First Search for Axion-Like Particles in a Storage Ring Using a Polarized Deuteron Beam - S. Karanth et al., Phys. Rev. X 13 (2023) 031004.
- J. Slim, et al. (JEDI Collaboration): Proof-of-principle demonstration of a pilot bunch comagnetometer in a stored beam - J. Slim et al., submitted to Phys. Rev. Lett.