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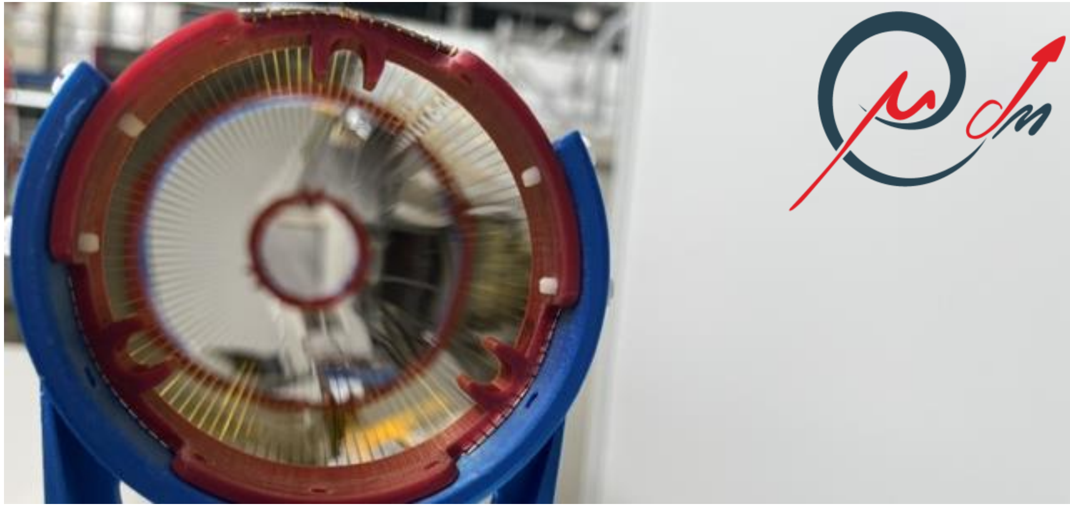


Chavdar Dutsov :: Postdoctoral Fellow :: Paul Scherrer Institute

# Search for the muon electric dipole moment using the frozen-spin technique

On behalf of the muonEDM collaboration

Ascona, 2-7 Jul 2023

Project funded by

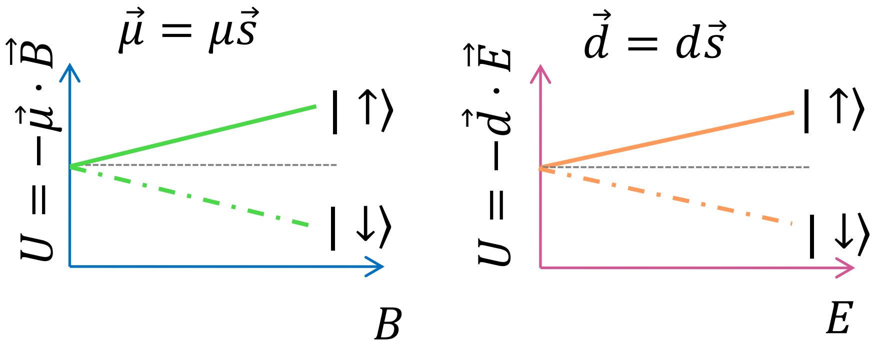
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

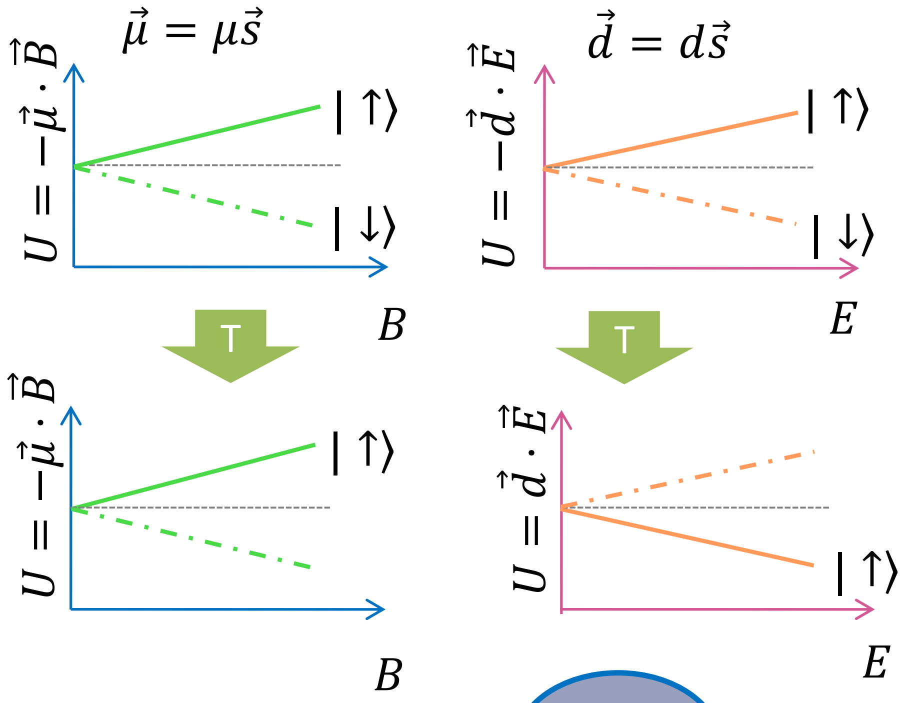
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

FNSNF
Swiss National Science Foundation

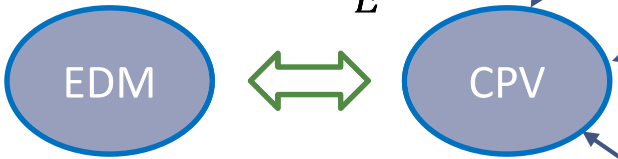
# CP violation and EDM



# CP violation and EDM




A non-zero particle EDM violates P, T and, assuming CPT conservation, also CP.



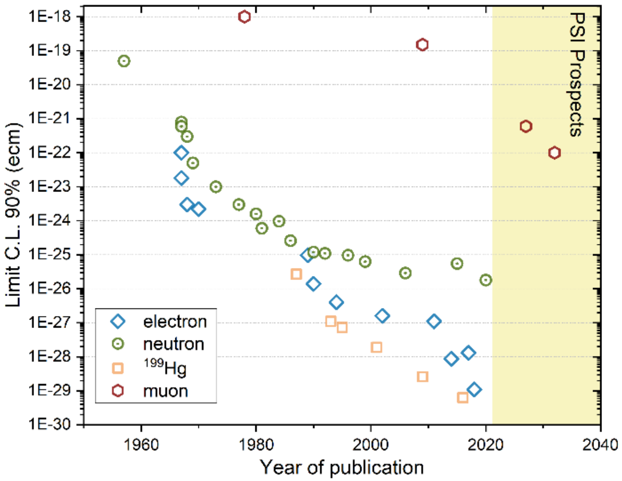

Baryon asymmetry of the Universe

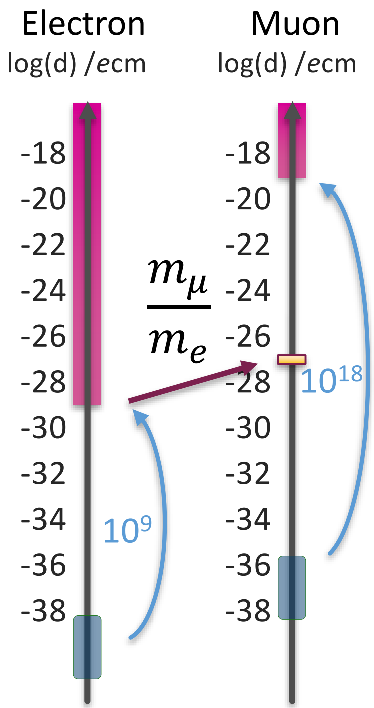
Arises “naturally” in beyond SM theories

Strong CP violation ($\Theta$-term)

# EDM of the muon

- Assuming minimal flavor violation (MFV) and naive mass scaling of the electron EDM one obtains O($10^{-26}$ e.cm), but does not hold for a flavor structure beyond MFV.
- The only EDM we can probe directly on the bare particle.
- The current experimental limit on the muon EDM is ~$10^{-19}$ $e$cm*.



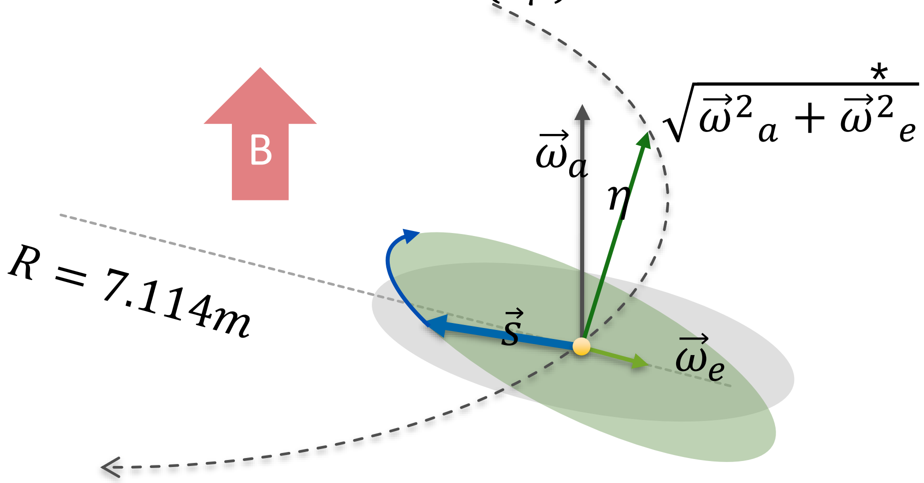



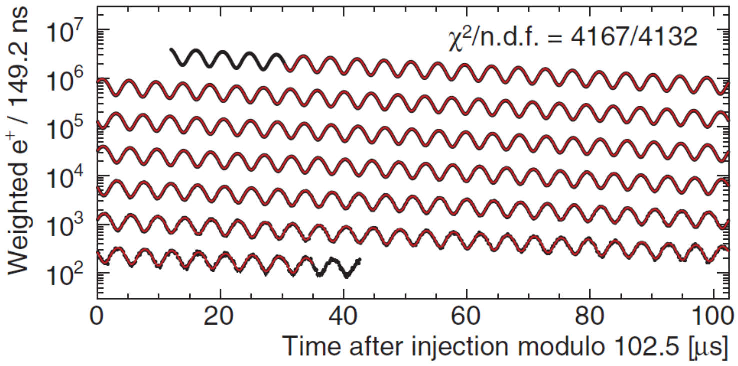

*Bennett et al.,PRD80(2009)052008

# Sensitivity from (g-2) experiments

$$\vec{\Omega} = -\frac{e}{m_0}\left[\underbrace{a\vec{B} + \left(\frac{1}{\gamma^2-1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}}_{\text{g-2 term}} + \underbrace{\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)}_{\text{EDM term}}\right]$$

FNAL* & JPARC** $\sigma(d_\mu) \approx 10^{-21} ecm$




Here the direction of precession due to EDM changes sign every half g-2 period.

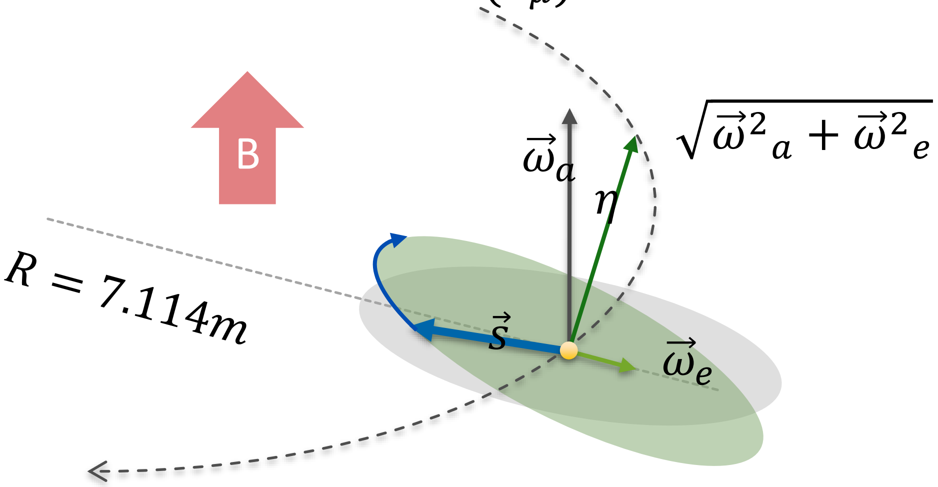
*Chislett, R.EPJ Web Conf., (2016) 118, 01005, **Abe et al., PTEP053C02 (2019)

# The frozen spin technique*

$$\vec{\Omega} = -\frac{e}{m_0}\left[\underbrace{a\vec{B} + \left(\frac{1}{\gamma^2-1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}}_{\text{g-2 term}} + \underbrace{\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)}_{\text{EDM term}}\right]$$

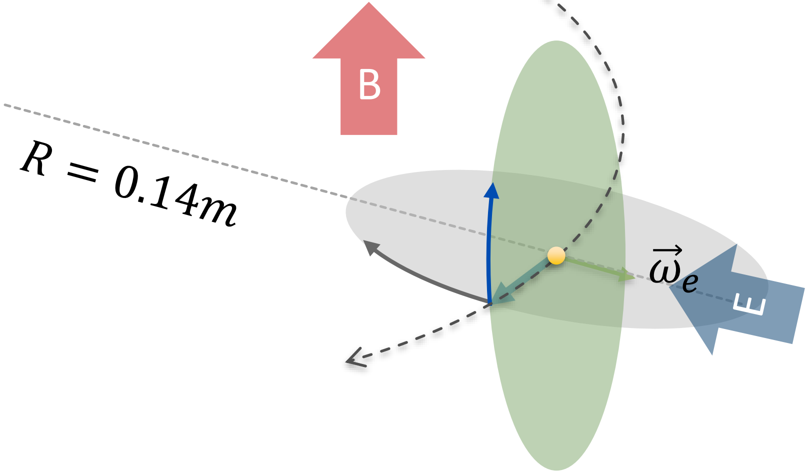
FNAL & JPARC

$\sigma(d_\mu) \approx 10^{-21} ecm$




Frozen spin at PSI:

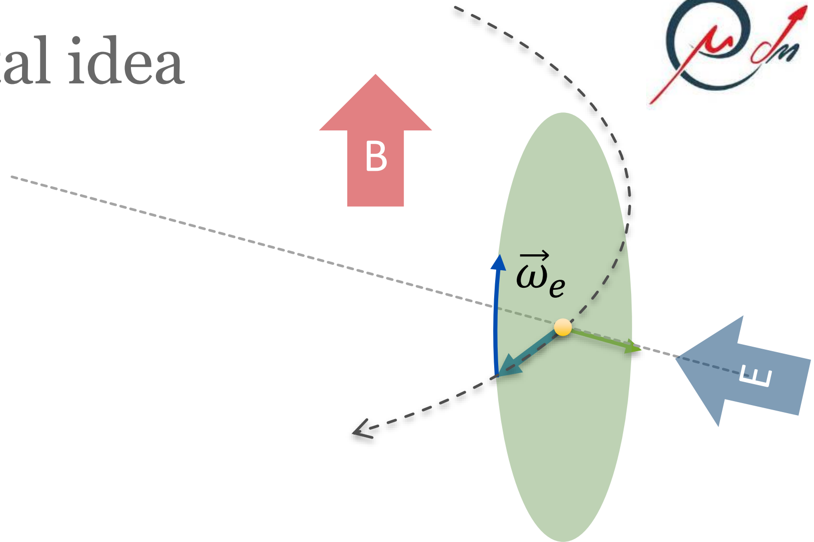
- precursor: $d_\mu = 3\text{x}10^{-21}$ e.cm
  final: $d_\mu = 6\text{x}10^{-23}$ e.cm



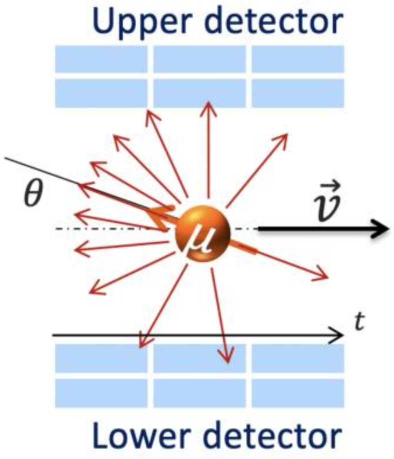

*Farley et al, PRL93 042001 (2004)

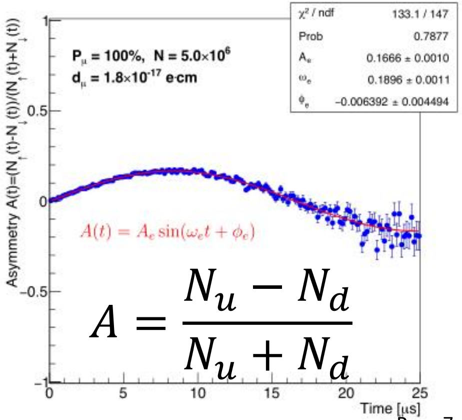
# The general experimental idea

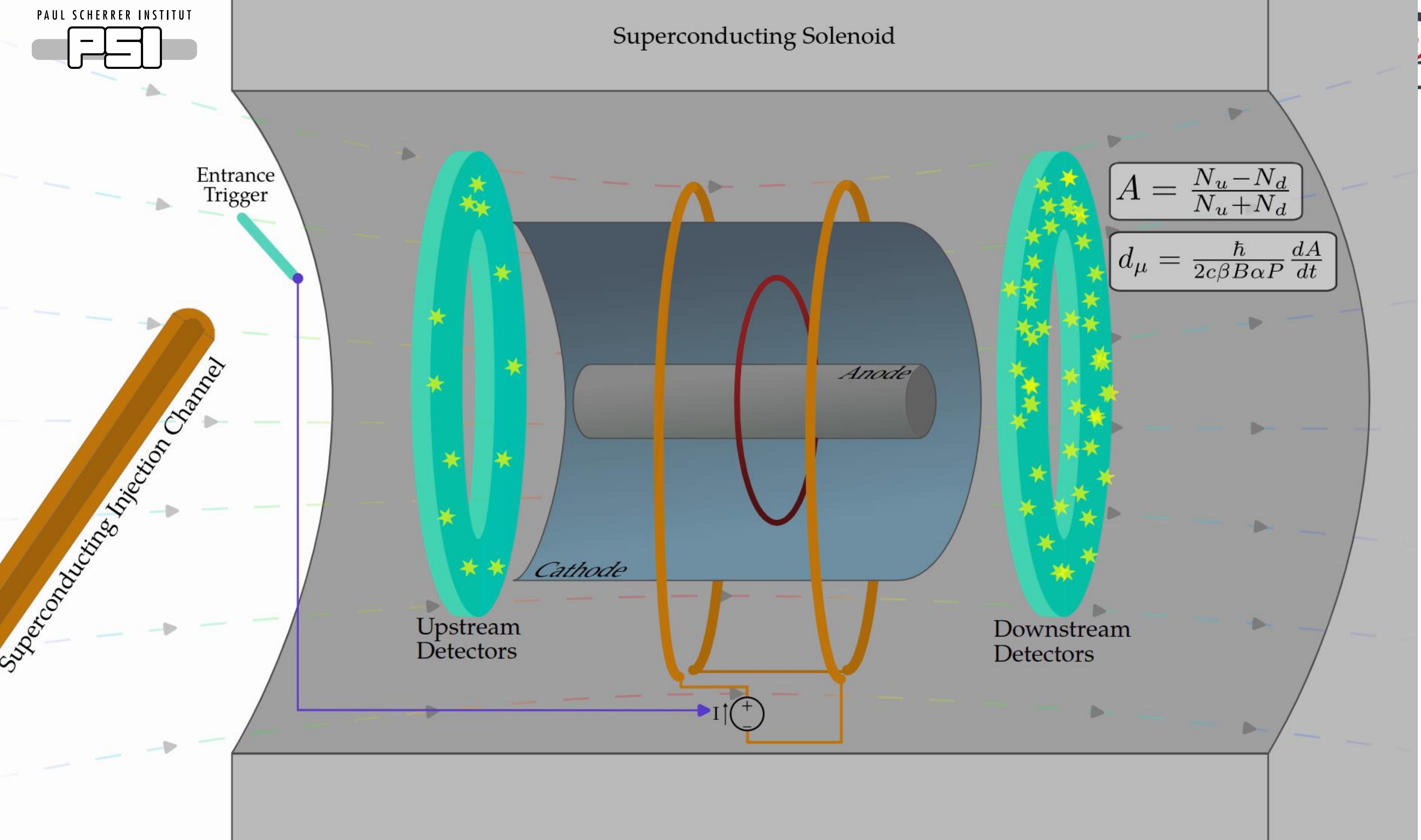
- If the EDM ≠ 0, then there will be a vertical precession out of the plane of the orbit
  - An asymmetry increasing with time will be observed recording decay positrons




- If the EDM = 0, then the spin should always be parallel to the momentum asymmetry should be zero




Superconducting Solenoid
Entrance Trigger
Superconducting Injection Channel
Anode
Cathode
Upstream Detectors
Downstream Detectors
$A = \frac{N_u - N_d}{N_u + N_d}$
$d_\mu = \frac{\hbar}{2c\beta B\alpha P}\frac{dA}{dt}$
I

# A phased approached

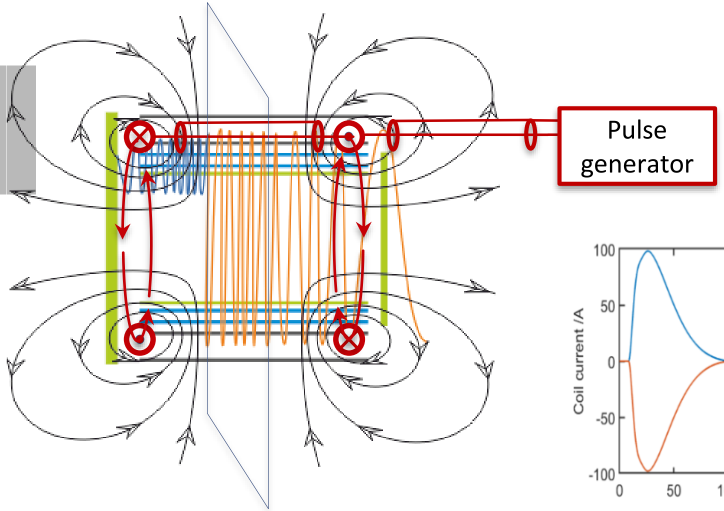
**Phase I** (small solenoid, 28 MeV/c muons)

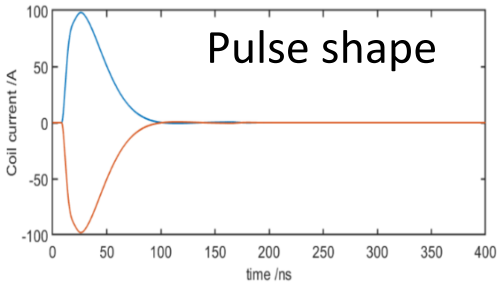

- Existing solenoid at PSI, max 5 tesla
- Bore diameter 200 mm
- Field was measured in 2022 (found suitable for injection)

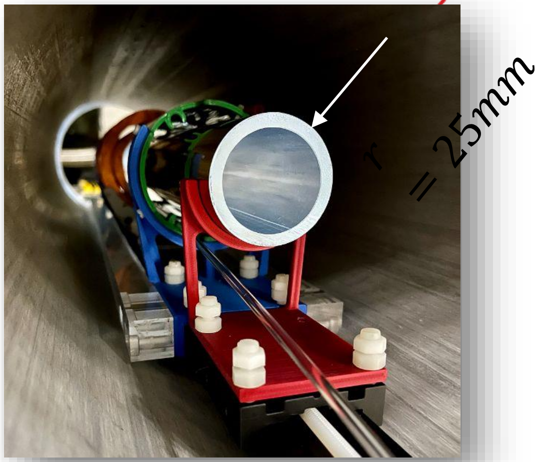
**Phase II** (dedicated magnet, 125 MeV/c muons)

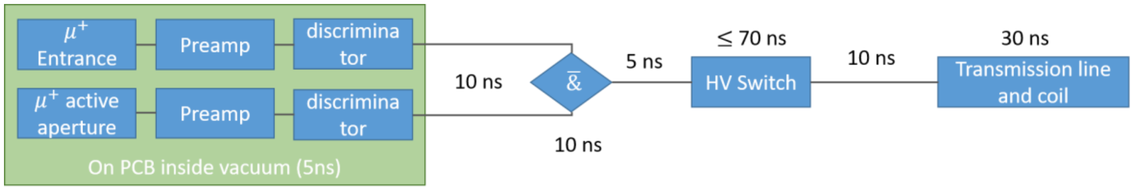

- Large bore (up to 900 mm diameter)
- High Temporal field stability (10ppb/h)
- Excellent spatial field uniformity (<1 ppb/mm)

# Radial magnetic field pulse to kick muons



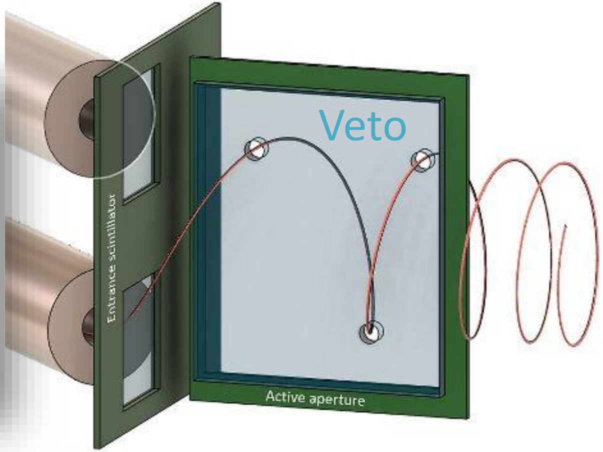



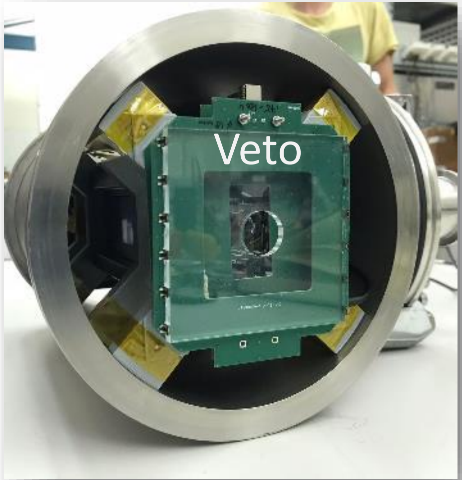

- PS delay input → output < 60 ns
- Pulse FWHM ≈ 40 ns
- Peak current per coil $I_{max}$ ≈ 170 A
  - Includes damping effect (factor 2) by Eddy currents
- Suppression of oscillation in tail < 1 A (corresponds to B ≈ 5 μT)

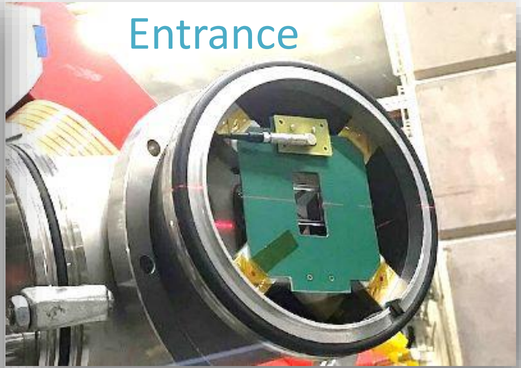
# Muon entrance trigger

- Magnetic pulse needs to be triggered within ~100 ns by incident muon
- Only about 1% of muons passing through the collimation channel are within the acceptance phase space
- Scattering in scintillators increase beam divergence

- Combin in (entrance scintillator with an active aperture as veto)



# Frozen spin technique in a nutshell

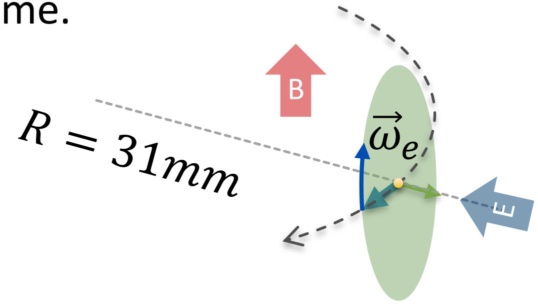
- The angular velocity of the spin precession is given by the Thomas-BMT equation →

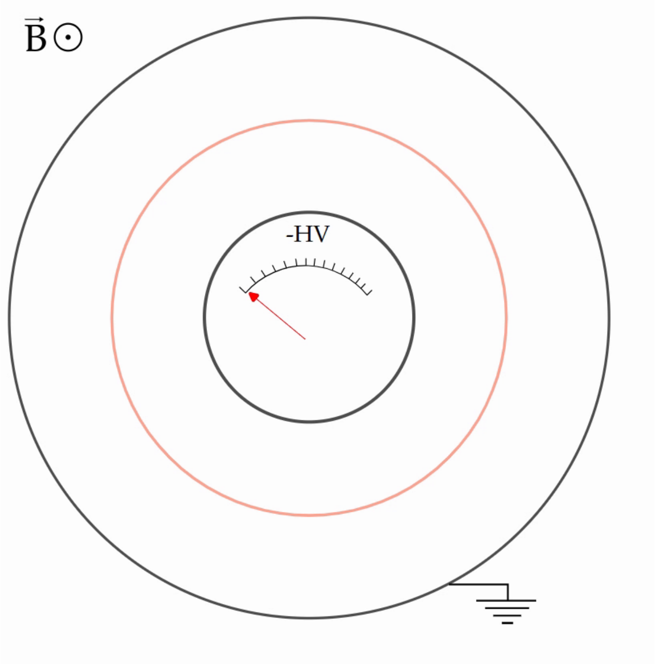
$$\vec{\Omega} = -\frac{e}{m_0}\left[\underbrace{a\vec{B} + \left(\frac{1}{\gamma^2-1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}}_{\text{g-2 term}} + \underbrace{\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)}_{\text{EDM term}}\right]$$

- By applying an appropriate radial E-field to the muon we negate the *aB* term.

- **EDM is proportional to angular velocity of the spin around the β×B axis *(radial)*.**

- To measure the muon EDM we need to measure the spin direction as a function of time.

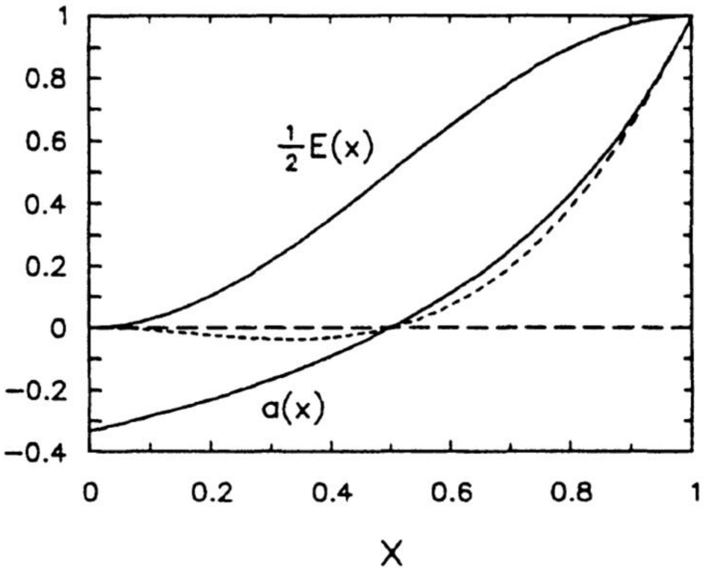


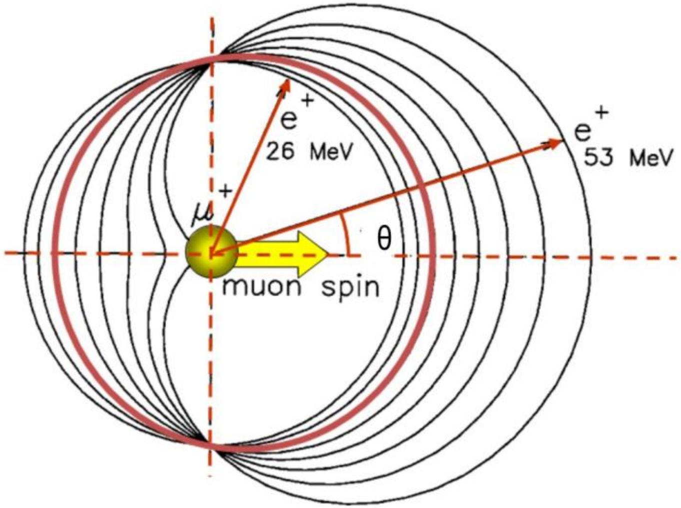



# Angular distribution – muon rest frame

- For high positron energies – preferentially emitted in the direction of the muon spin

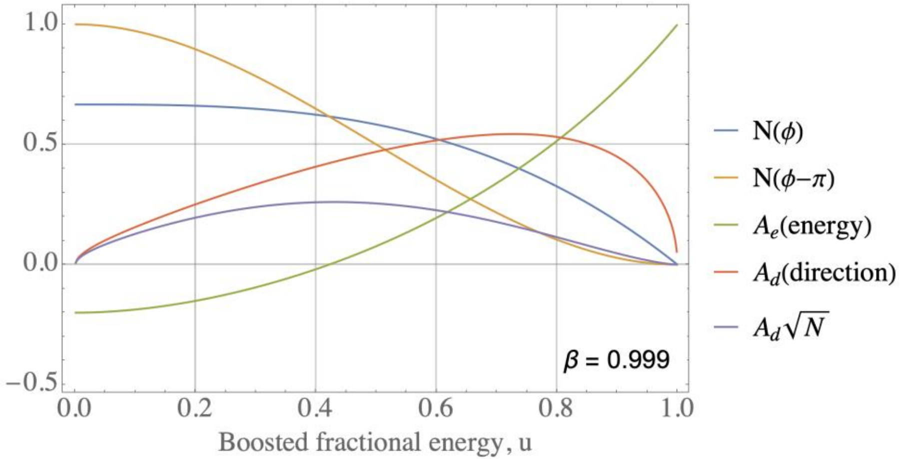
- Energy spectrum and **directional** asymmetry as a function of the fractional energy $x = E/E_{max}$:

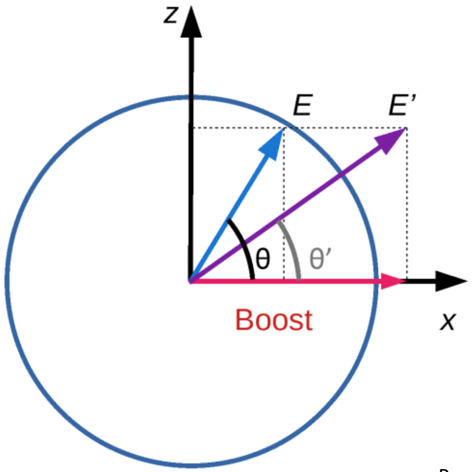


# Angular distribution – g-2 experiments

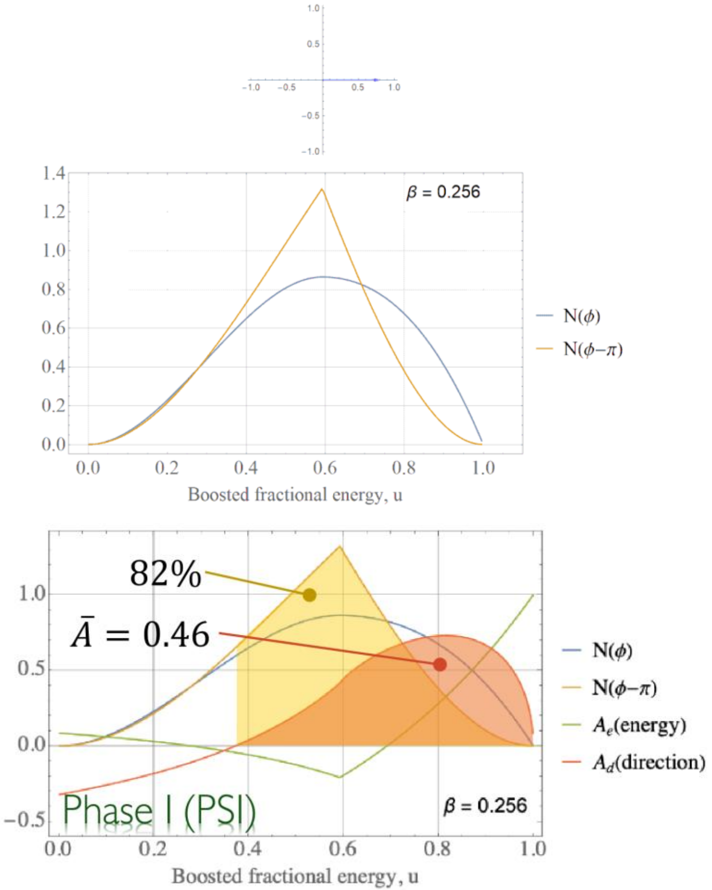
- For high momentum muons the angular distribution is Lorentz boosted along the momentum.
- For large boosts practically all decay positrons are emitted in the forward direction – no directional asymmetry.
- Dependence of the number of decay positrons at a given enrgy on the spin.



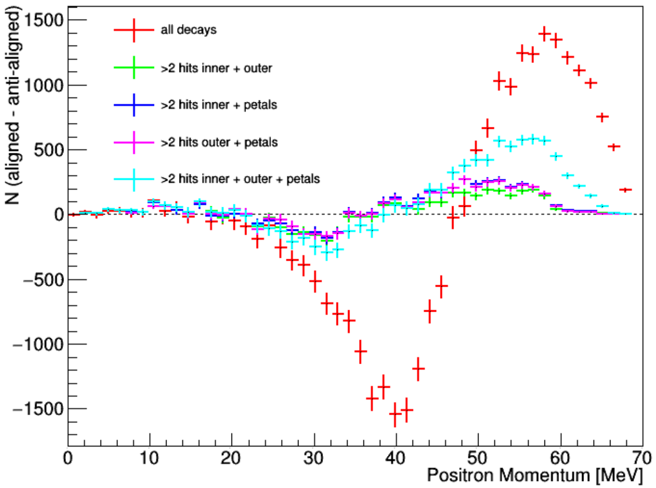
# Angular distribution – Phase I @ 28 MeV/c

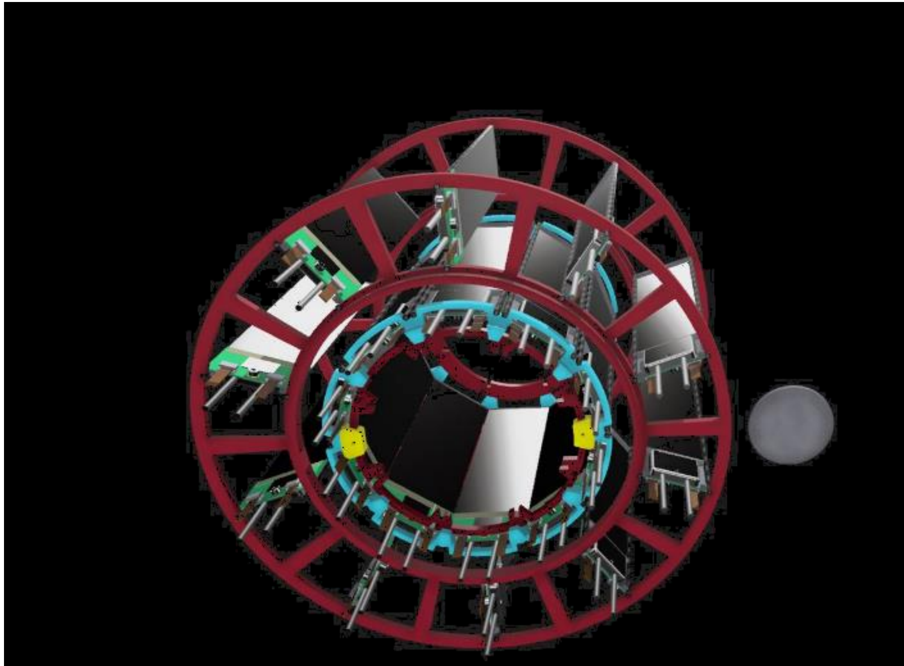
- Detection of g-2 precession $\boldsymbol{\omega_a}$. Needed for:
  - Measurement of the mean magnetic field
  - Measure $\boldsymbol{\omega_a}$ to tune electric field to frozen-spin condition
    **(requires momentum resolution)**
- Detection of EDM polarization
  - Measurement of the asymmetry as a function of time A(t)
    **(requires spatial resolution along the bore axis)**



## Silicon strip detector for g-2 detection

- Reconstruction of transverse positron momentum (Δp ≈ 5 MeV/c)
- Timing t ≈ 2 ns
- Lateral spatial resolution ≈ 0.1 mm

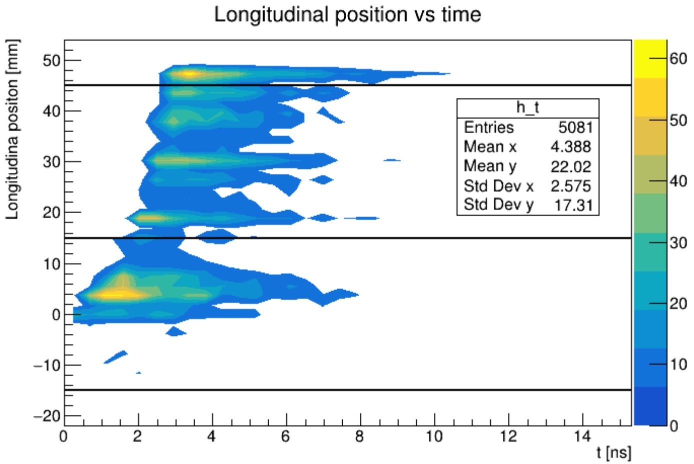


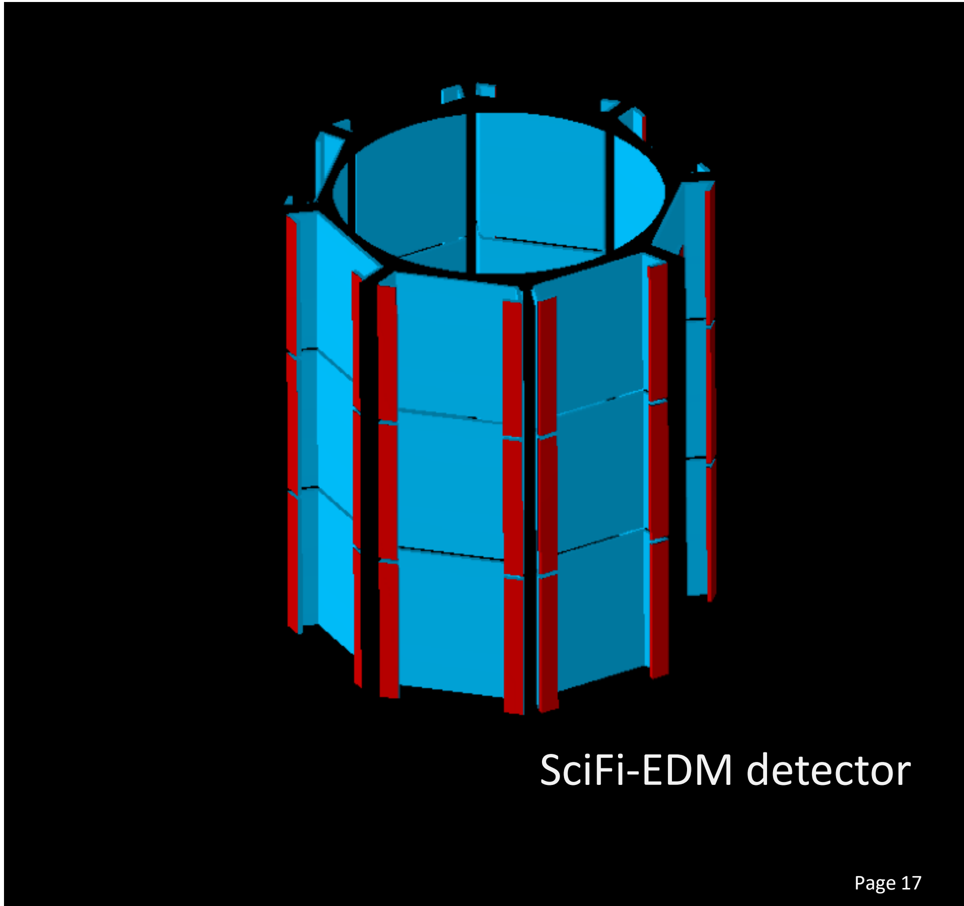



Si-Petal detector

**Scintillating fiber detector for EDM asymmetry measurement and timing**

- Horizontal fiber ribbons with 250 µm pitch and 100 µm resolution
- Timing resolution < 2 ns
- Reconstruction of longitudinal



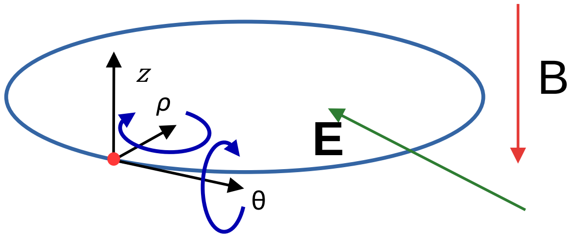



# Systematic studies (example)

- Even in the absence EDM one might observe a signal due to systematic effects
- Systematic effects: all effects that lead to a ***real*** or ***apparent*** precession of the spin around the radial axis that are not related to the EDM
  - Coupling of the magnetic moment with the EM fields of the experimental setup ***(real)***
  - Early to late variation of detection efficiency of the EDM detectors (***apparent***)

- Rotations that could mimic the EDM:
  - Radial around ρ
  - Azimutal around θ

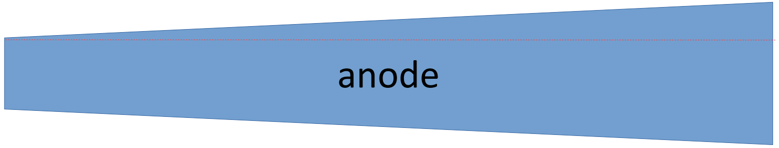
$$\vec{\Omega}_{\mathrm{MDM}} = -\frac{e}{m_0}\left[a\vec{B} - a\frac{\gamma-1}{\gamma}\frac{(\vec{\beta}\cdot\vec{B})\vec{\beta}}{\beta^2} + \left(\frac{1}{\gamma^2-1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$



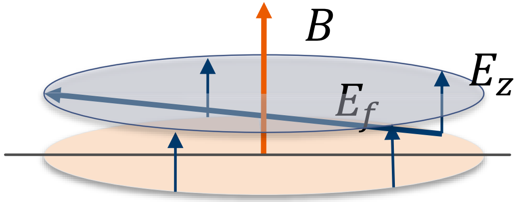
# Sources of $E_z$ field: conical central electrode

- Non-constant radius of cylindrical anode (cone)

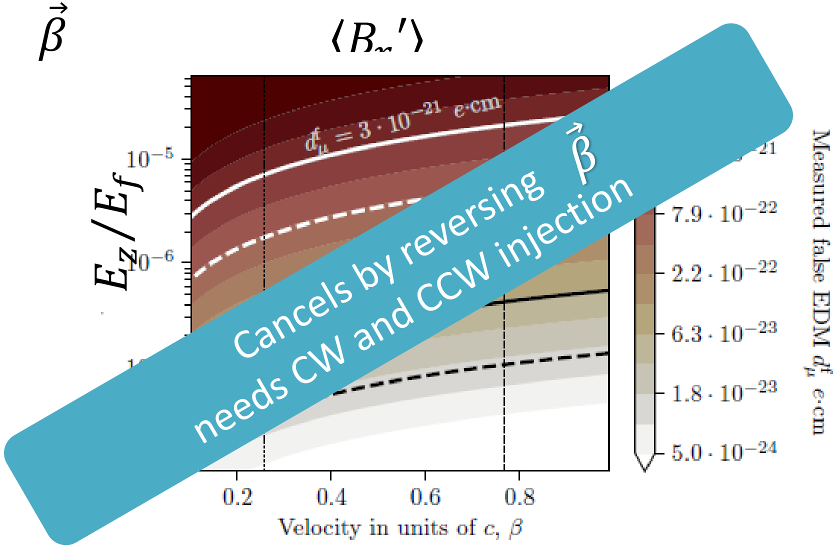
$$E_z \approx E_\mathrm{f}\frac{\Delta_R}{L} \approx E_\mathrm{f}\alpha_\mathrm{R}$$




- Cylindricity on the order of 50 nm is measurable even on large samples and possible to machine.
- Ground electrode made of thin foil more difficult to keep deviations from cylindricity below 30 µm.



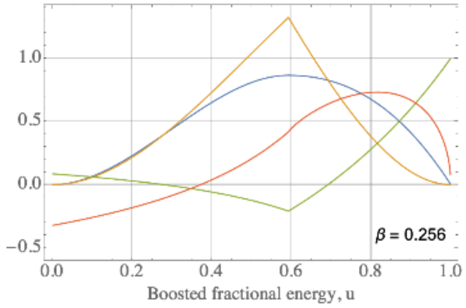

Will move orbit out of central plane until:

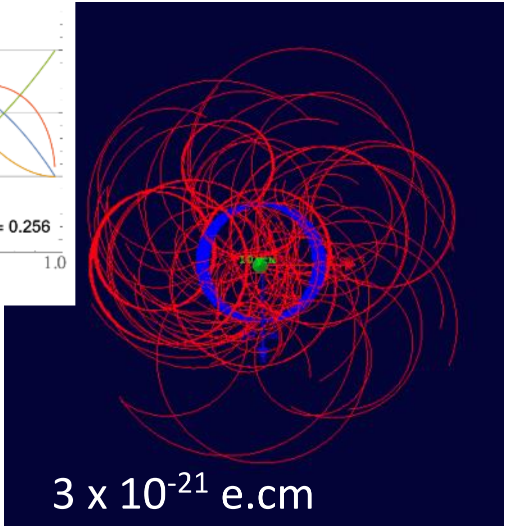


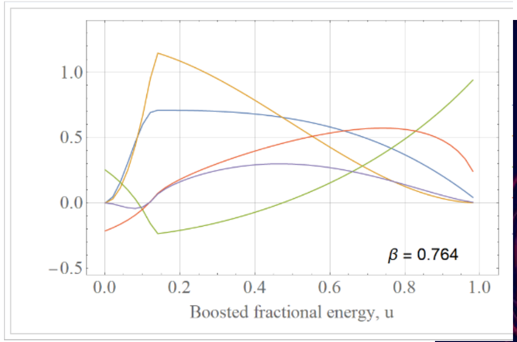
# Going from Phase I to Phase II

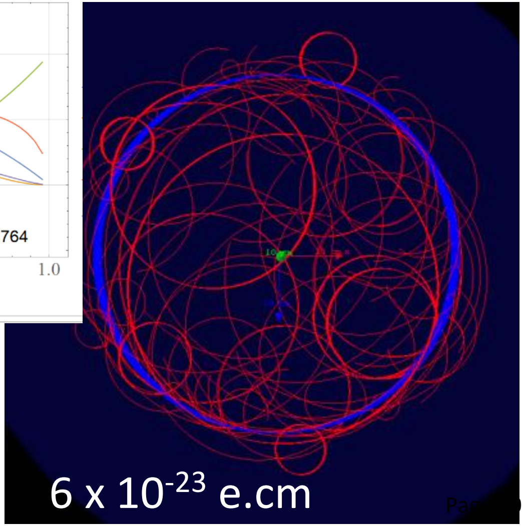
**Phase I**
- B-Field 3T
- Momentum 28 MeV/c
- Muon radius 31mm
- Most positrons outside

**Phase II**
- B-Field 3T
- Momentum 125 MeV/c
- Muon radius 141 mm
- Most positrons inside



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# Conclusions and Outlook

- Setup of a demonstration experiment to prove the high sensitivity for a search for muon EDM using the frozen-spin method.

- By exploiting existing muon beams at PSI we will eventually improve the current experimental upper limit by 3 orders of magnitude to better than 6 x $10^{-23}$.

- The experiment will take place in two phases:
  - **Phase I:** Demonstration of the frozen-spin method and all required techniques.
  - **Phase II:** Dedicated high uniformity NMR magnet exploiting PSI's beam with highest muon flux at a momentum of 125 MeV/c.

# The collaboration *open for participation*

## PSI proposal R-21-02.1


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A. Baldini, F Cei, L. Galli, M. Grassi, D. Nicolò, A. Papa, G. Signorelli, B. Vitali
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C. Chen, T. Hu[1], K.S. Khaw, J.K. Ng[1], G.M. Wong[1], Y. Zeng[1]
**SJTU:** Shanghai Jiao Tong University and Tsung-Dao Lee Institute, Shanghai, China

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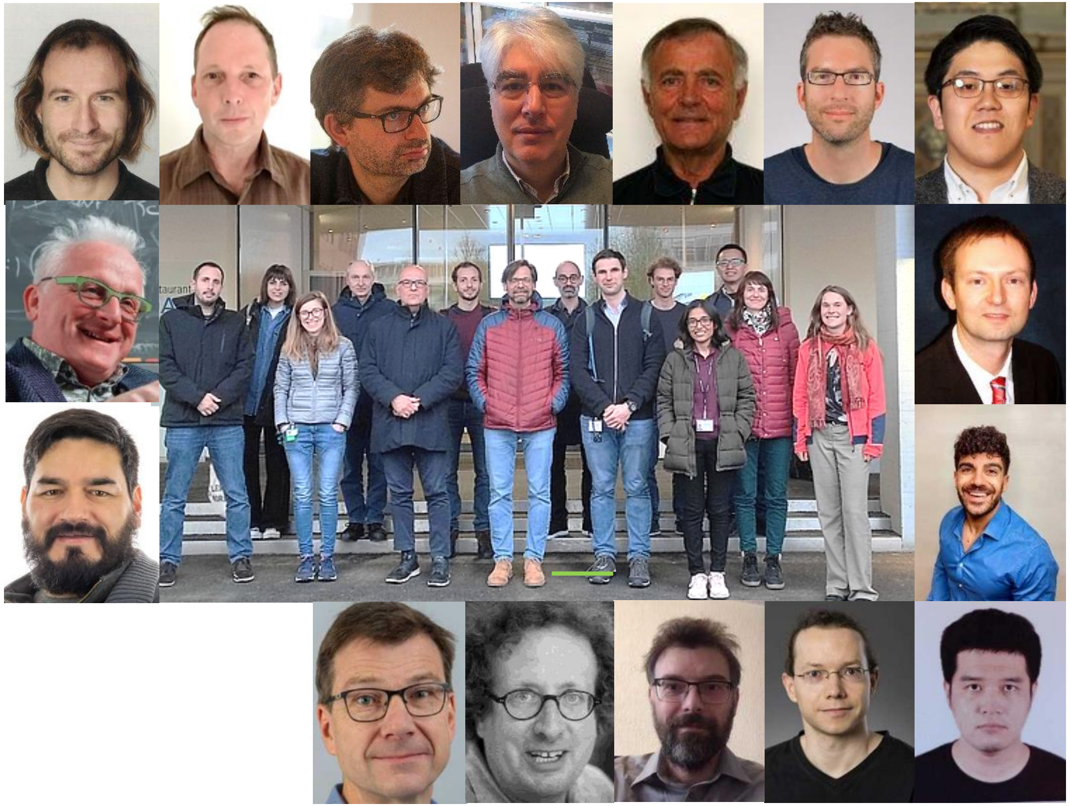
**PSI:** Paul Scherrer Institut, Villigen, Switzerland

K. Kirch[3], M. Sakurai[1,5]
**ETHZ:** ETH Zürich, Switzerland

L. Caminada[5], A. Crivellin[5]
**UZ:** University of Zürich, Zürich, Switzerland


January 24, 2023



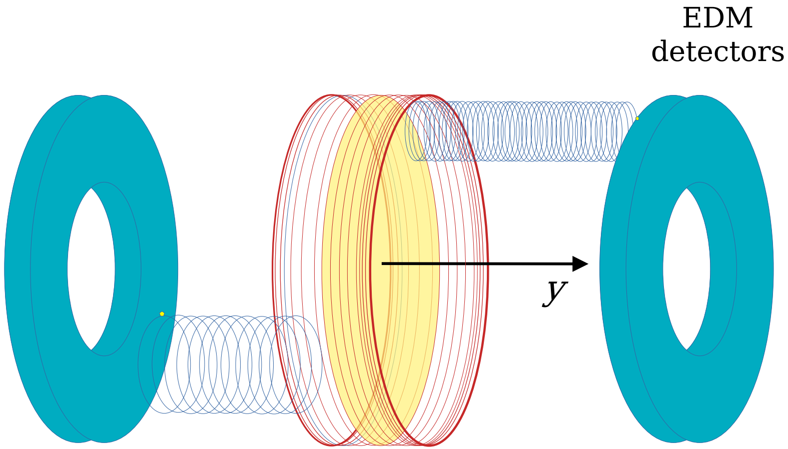
# Systematic effects

- **Some asymmetry could still be observed due to systematic effects**
  - effects that lead to a *real* or *apparent* precession of the spin around the radial axis that are not related to the EDM

- Types of systematic effects:
  - Early to late variation of detection efficiency of the EDM detectors ***(apparent)***
  - Coupling of the anomalous magnetic moment with the EM fields of the experimental setup ***(real)***
    - Dynamical phase $$\vec{\Omega}_{\mathrm{MDM}} = -\frac{e}{m_0}\left[a\vec{B} - a\frac{\gamma-1}{\gamma}\frac{\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta}}{\beta^2} + \left(\frac{1}{\gamma^2-1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$
    - Geometric phase $$\gamma_n[C] = i\oint_C \langle n,t|\left(\nabla_R|n,t\rangle\right)dR$$

# Early-to-late detection efficiency changes

- Strong pulsed magnetic field → eddy currents, noise, heat in detectors and associated electronics.
- **Time-dependent changes in the detection efficiency of a set of detectors will be seen as a false EDM signal.**
- Systematics can be studied by decoupling the pulse time from the stopping time.
  *(stop muons in a target and study the detector response)*



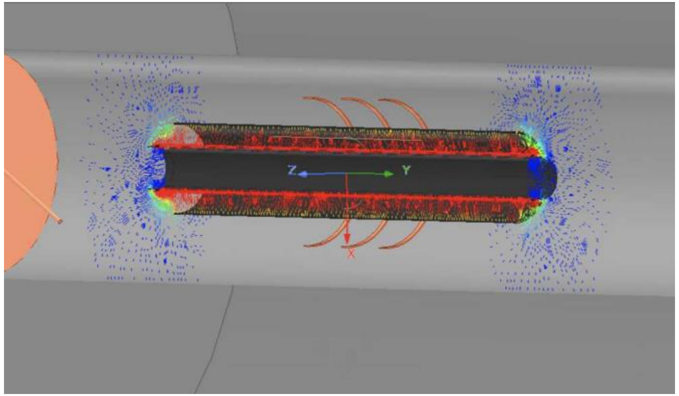

$N_u = \varepsilon_u N$

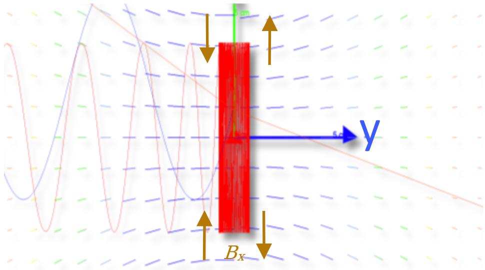
$\varepsilon = \varepsilon(t)$

$N_d = \varepsilon_d N$

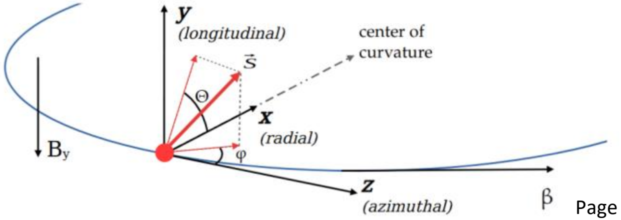
# Coupling of the MDM to EM fields

- Main EM fields in the experiment:
  - Main solenoid
  - Coaxial electric freeze field
  - Weakly focusing field
  - Magnetic kick (time varying)
- Rotations that could mimic the EDM:
  - Radial around *x*
  - Azimutal around *z*






$$\vec{\Omega}_{\text{MDM}} = -\frac{e}{m_0}\left[a\vec{B} - a\frac{\gamma-1}{\gamma}\frac{(\vec{\beta}\cdot\vec{B})\vec{\beta}}{\beta^2} + \left(\frac{1}{\gamma^2-1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

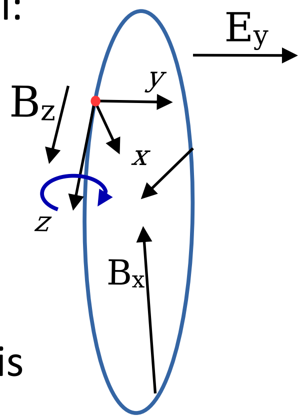


# Average over all orbits

- If we take the average over all muon orbits the periodic oscillations disappear and we are left with three terms that could lead to a false EDM signal:

$$\langle \Omega_{\hat{z}} \rangle = -\frac{ea}{m_0} \langle B_z \rangle \qquad \langle \Omega_{\hat{x}} \rangle = -\frac{ea}{m_0} \langle B_x \rangle$$

$$\langle \Omega_{\hat{z}\times\hat{y}} \rangle = -\frac{ea}{m_0 c} \left( \frac{1}{a(\gamma^2 - 1)} - 1 + \frac{1}{\beta_z^2} \right) \langle \beta_z E_y \rangle$$



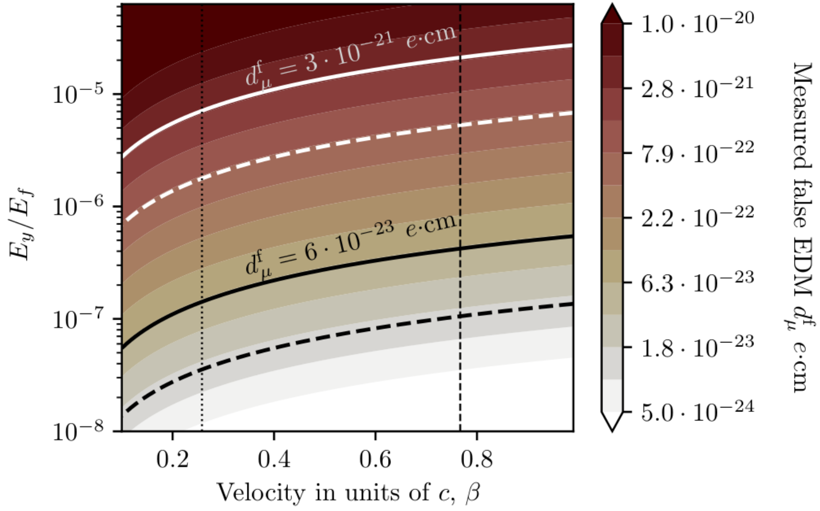

- Net *B*-field component along the momentum $B_z$ → non-zero if there is current flowing through the muon orbit

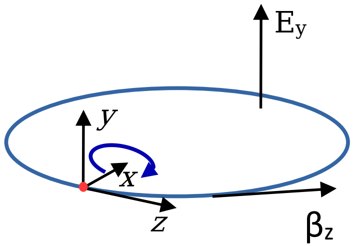
- Net radial *B*-field component $B_x$ → can be non-zero due to residual fields from the magnetic kick

- Radial magnetic field in the reference frame of the muon due to a ***β×E*** term → non-zero if there is E-field prependicular to the muon orbit

# Constraints on the average horizontal E-field

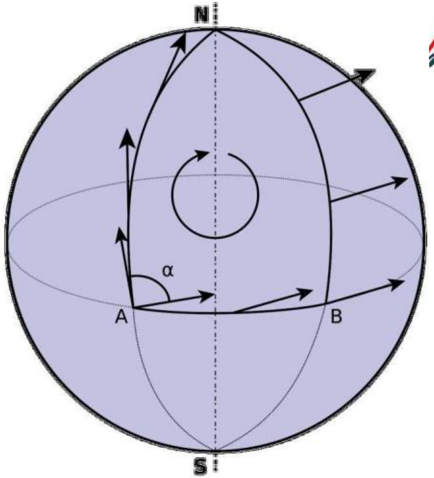
- Limit on the average $E_y$ field as a function of the muon velocity shown as a fraction of the radial component
- **Effect cancels if particles are injected alternatively CW and CCW and subtracting counts in the detectors**
- CW and CCW orbit directions are done by switching the B-field direction.




$$\langle \Omega_{\hat{z}\times\hat{y}} \rangle = -\frac{ea}{m_0 c}\left(\frac{1}{a(\gamma^2-1)} - 1 + \frac{1}{\beta_z^2}\right)\langle \beta_z E_y \rangle$$

# Geometric (Berry) phase



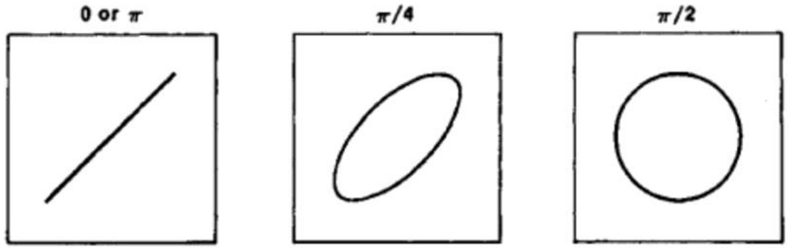

- The geometric phase is a phase difference acquired over the course of a cycle in parameter space.
- Parallel transport of a vector around a closed loop.
- The angle by which it twists is proportional to the area inside the loop:
  - In classical parallel transport it's equal.
  - In quantum mechanics it's -½ (fermions).
- If oscillations around two axes are combined we can observe a phase shift (false EDM)
  **even if the average of the oscillations is zero.**

# Calculation of Berry phases

- For two oscillations have the same frequency the Berry phase is:

$$\frac{1}{2}\int (\Omega\cos(\Omega t+\beta_0)\sin(\Omega t)-\Omega\cos(\Omega t)\sin(\Omega t+\beta_0))\,dt=\frac{1}{2}\Omega t\sin(\beta_0).$$

- The motion of the spin in this case is an ellipse with eccentricity defined by the phase difference $\beta_0$ between oscillations
  - no phase difference: ellipse looks like a line
  - π/2 phase difference: ellipse is a circle and maximum area



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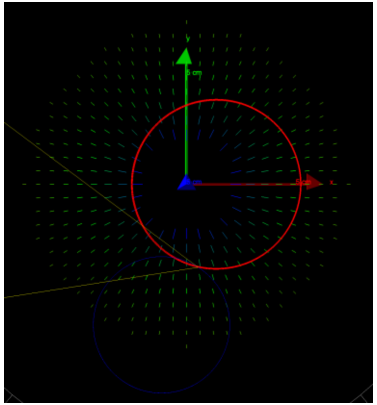
# Example of Berry phases

- Spin precession due to misalignment of the radial E-field:
  - longitudinal oscillations due to stronger and weaker freeze field *(cyclotron frequency)*
  - radial oscillations due to longitudinal E-field oscillating between upstream and downstream directions *(cyclotron frequency)*



Tilted and shifted E-field with respect to the center of the muon orbit