PAUL SCHERRER INSTITUT

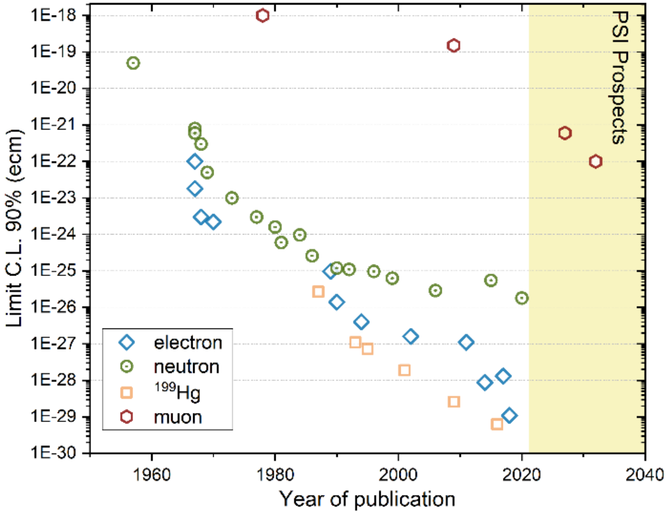
Chavdar Dutsov :: Postdoctoral Fellow :: Paul Scherrer Institute

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

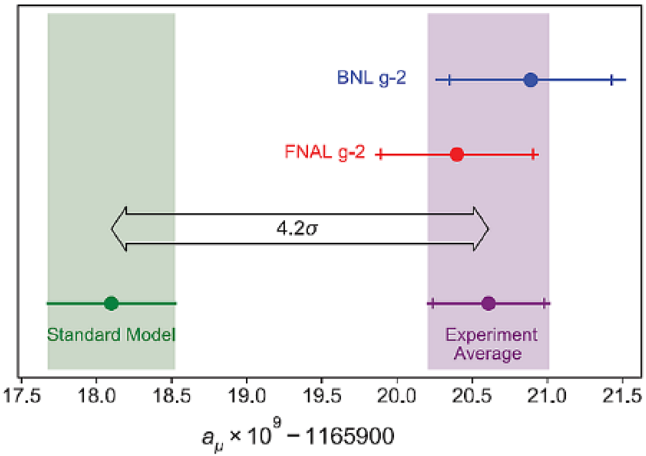
On behalf of the muonEDM collaboration

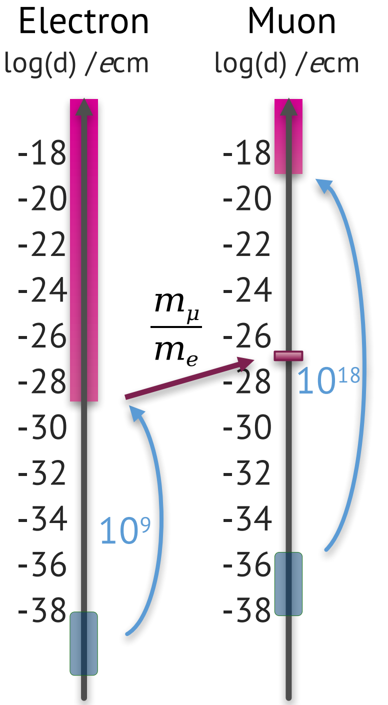
EDM of the muon

- Assuming MFV, LFU and naive mass scaling of the electron EDM →
- Long-standing muon (g-2) tension → hints of New Physics involving the muon.
- The only EDM we can probe on the bare fundamental particle.
- The current experimental limit on the muon EDM is ~10^{-19} $e$cm*.



*arXiv:2103.11769 [hep-ex]



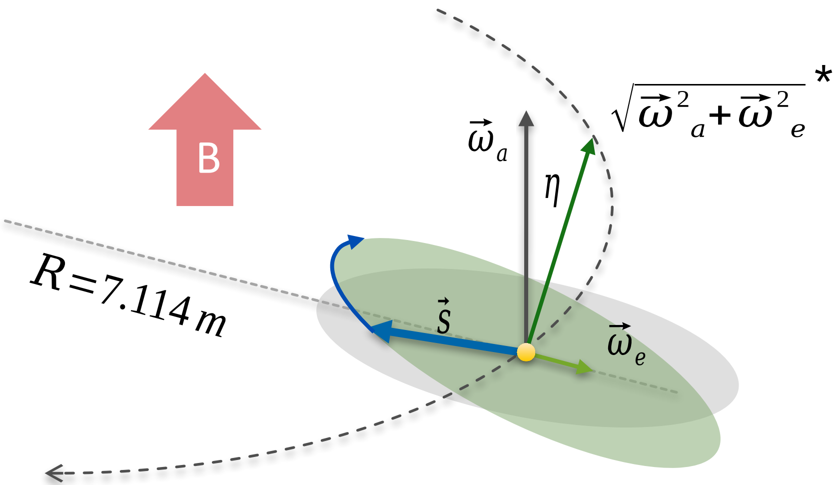


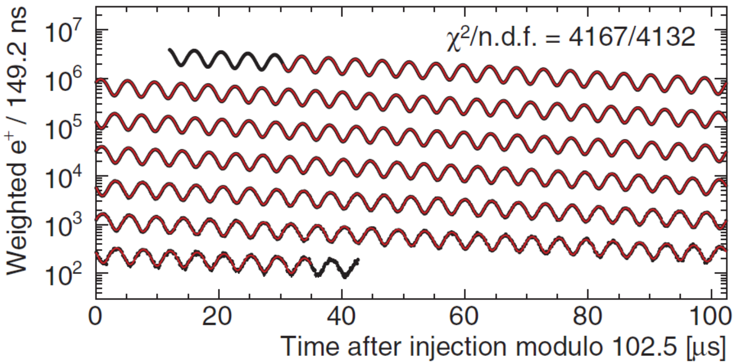
*Bennet et al. PhysRevD.73.072003 (2006)

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** $\sigma\left(d_\mu\right) \approx 10^{-21}\, e\, cm$





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

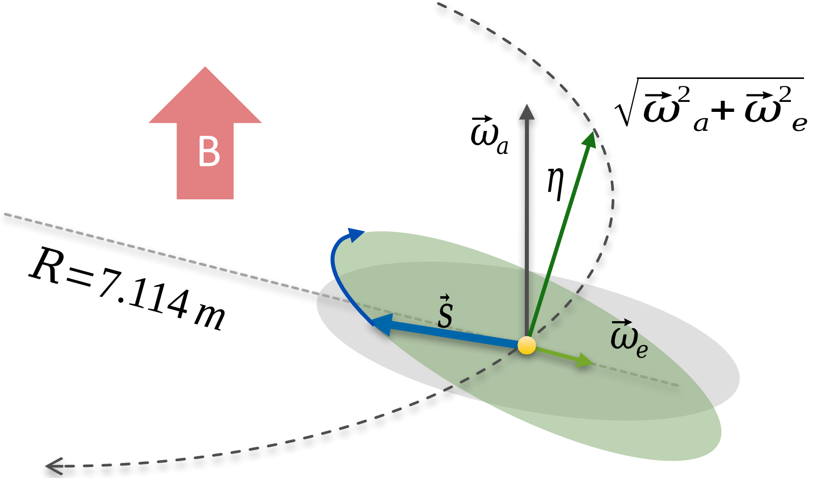
The frozen spin technique*

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

g-2 term   EDM term

FNAL & JPARC

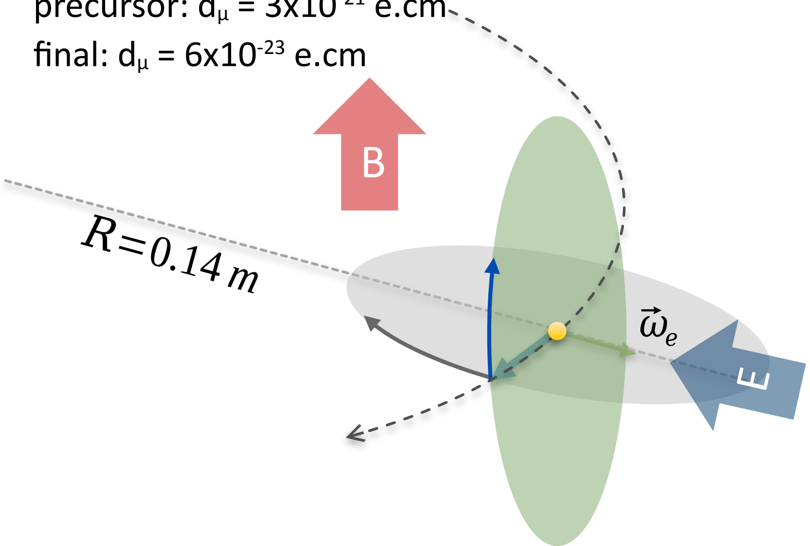
$\sigma(d_\mu) \approx 10^{-21}\, ecm$



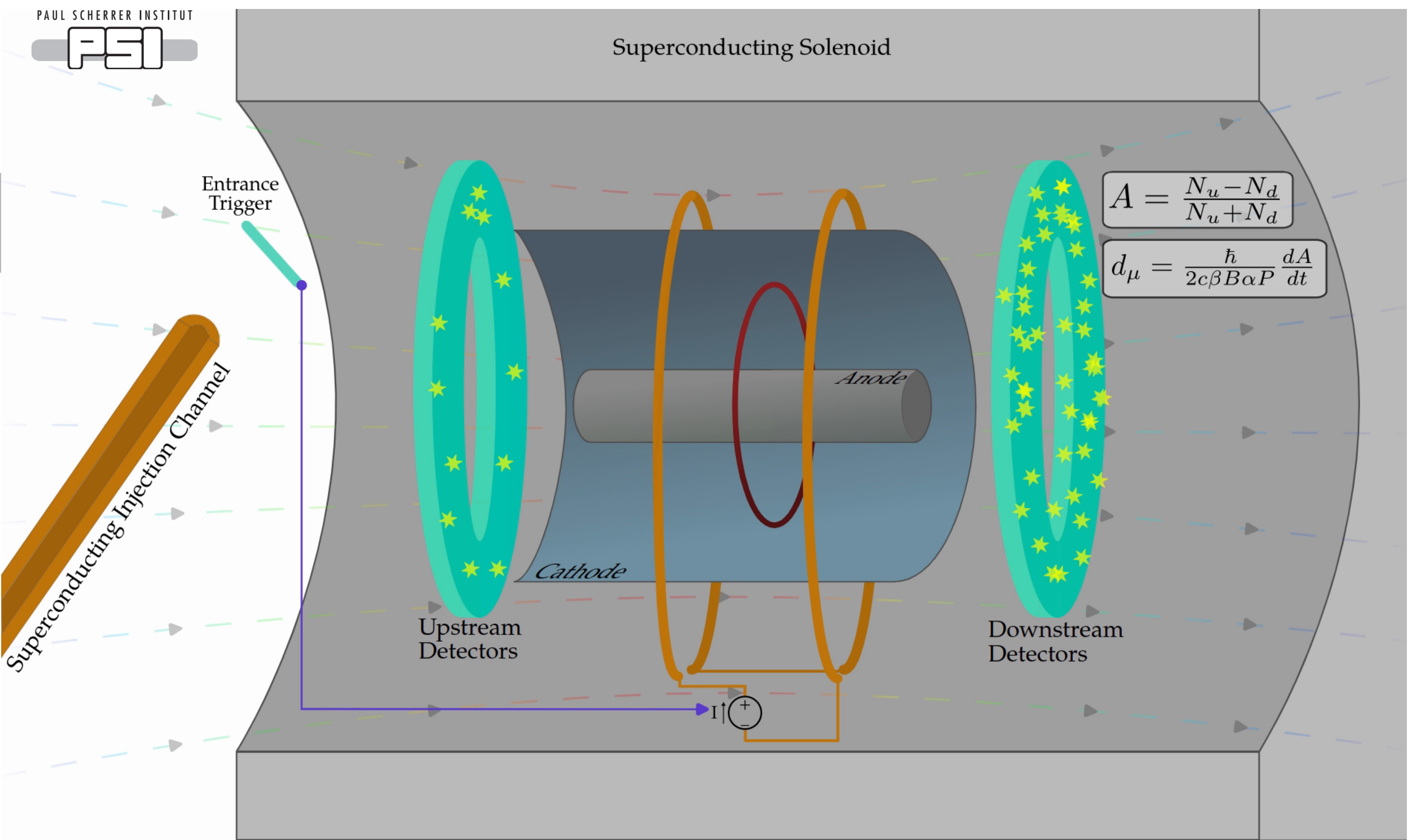
Frozen spin at PSI:

precursor: d_μ = 3x10^{-21} e.cm

final: d_μ = 6x10^{-23} e.cm



*Farley et al, PRL93 042001 (2004)

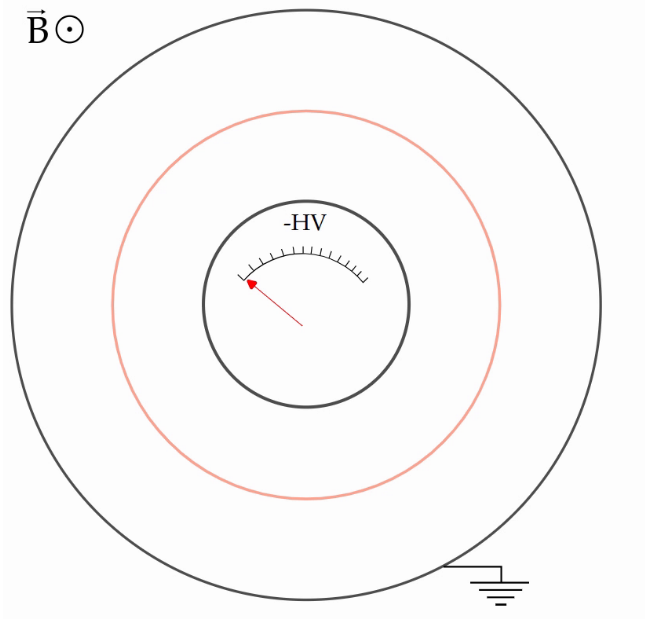


PAUL SCHERRER INSTITUT
PSI
Superconducting Solenoid
Entrance Trigger
Superconducting Injection Channel
Upstream Detectors
Anode
Cathode
I
Downstream Detectors
$A = \frac{N_u - N_d}{N_u + N_d}$
$d_\mu = \frac{\hbar}{2c\beta B\alpha P}\frac{dA}{dt}$

Frozen spin technique in a nutshell

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

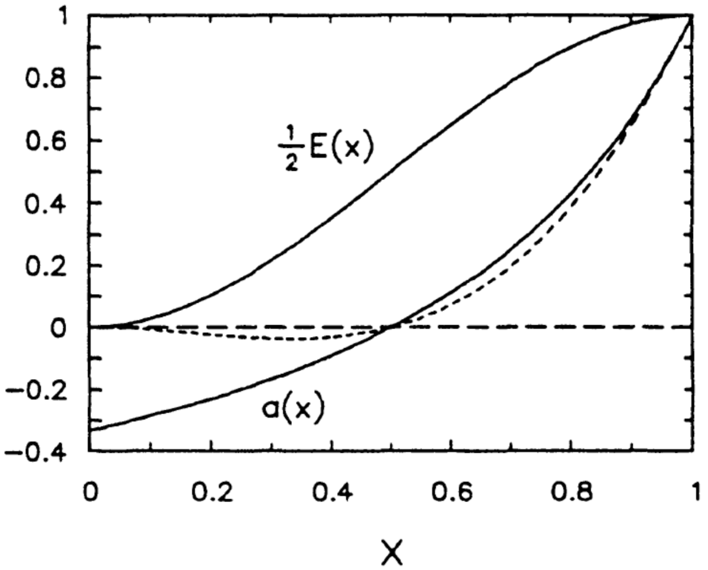
$$\vec{\Omega} = -\frac{e}{m_0}\left[\underbrace{a\vec{B} + \left(\frac{1}{\gamma^2-1}-a\right)\frac{\vec{\beta}\times\vec{E}}{c}}_{\text{g-2 term}} + \underbrace{\frac{\eta}{2}\left(\frac{\vec{E}}{c}+\vec{\beta}\times\vec{B}\right)}_{\text{EDM term}}\right]$$

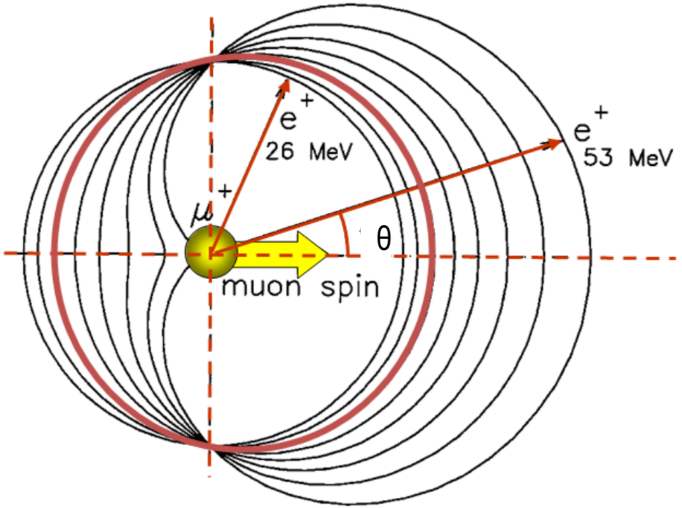


Angular distribution – muon rest frame

- 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 $x = E/E_{max}$:

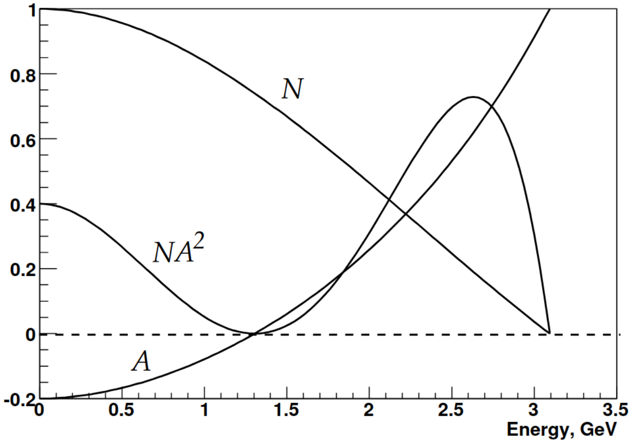


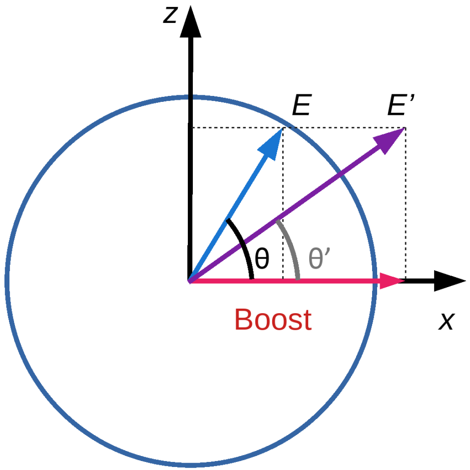


Angular distribution – g-2 experiments

- 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.

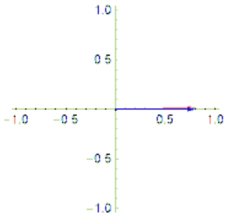
FNAL g-2 experiment design document page 81:

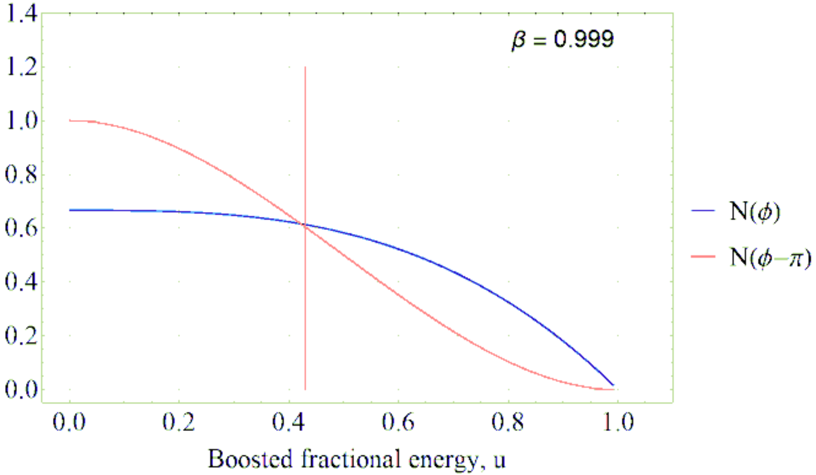


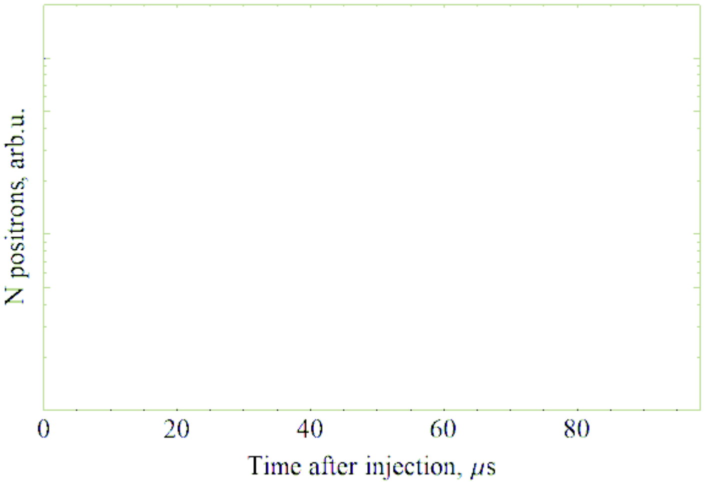


Angular distribution – g-2 experiments

- Detecting the number of positrons with energy above a threshold leads to the ‘wiggle plot’:

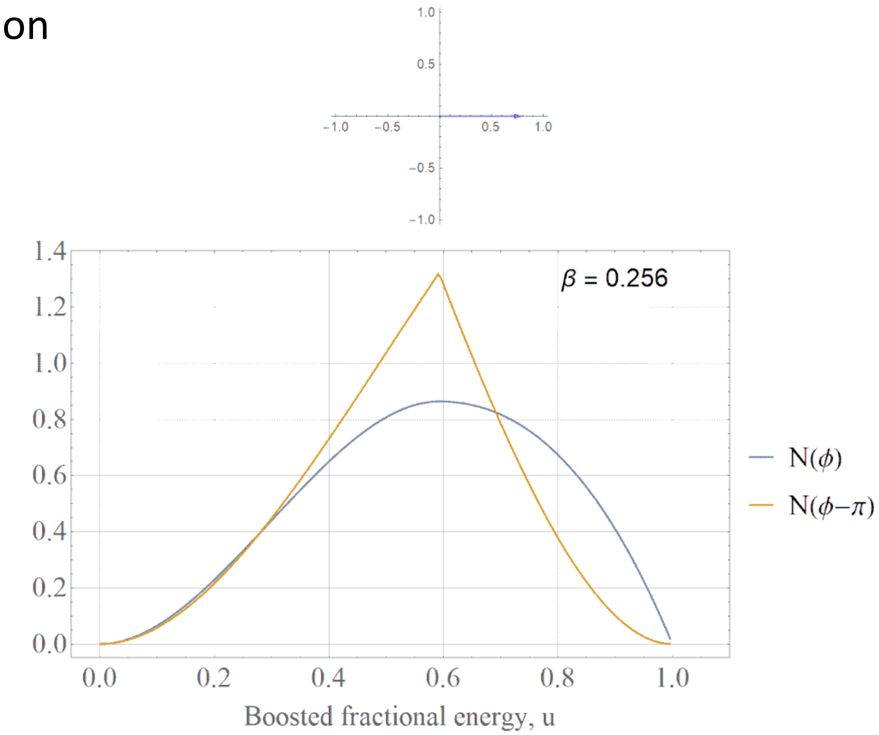






Angular distribution – muon EDM experiment

- The first stage muon EDM – 28 MeV/c surface muons.
- Both directional and energy dependence on the spin direction.
- Precession due to the AMM can be measured using intensity asymmetry.
  - used to tune the frozen spin.
- Precession due to EDM can be measured from the direction of emitted positrons:
  - up-down asymmetry.



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

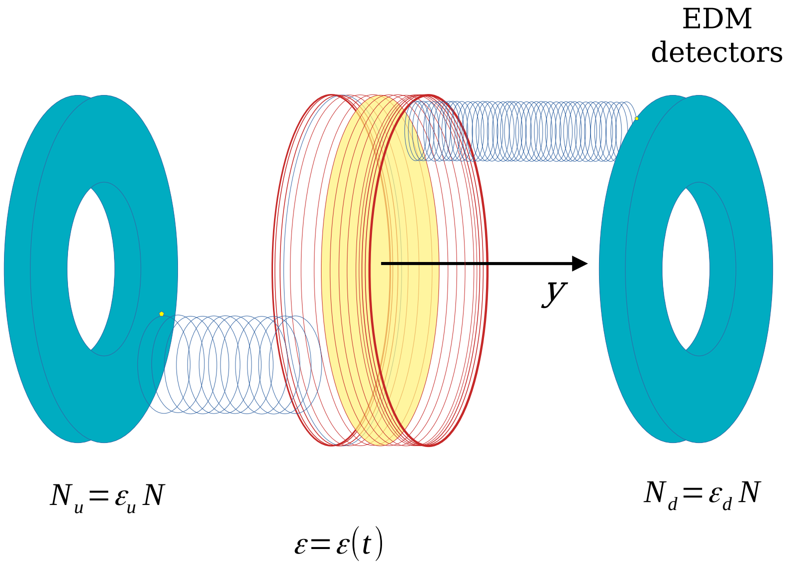
$$\vec{\Omega}_{\mathrm{MDM}} = -\frac{e}{m_0}\left[a\vec{B} - a\frac{\gamma-1}{\gamma}\frac{\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta}}{\beta^2} + \left(\frac{1}{\gamma^2-1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

    - Geometric phase

$$\gamma_n[C] = i\oint_C \langle n,t|\left(\nabla_R|n,t\rangle\right)dR$$

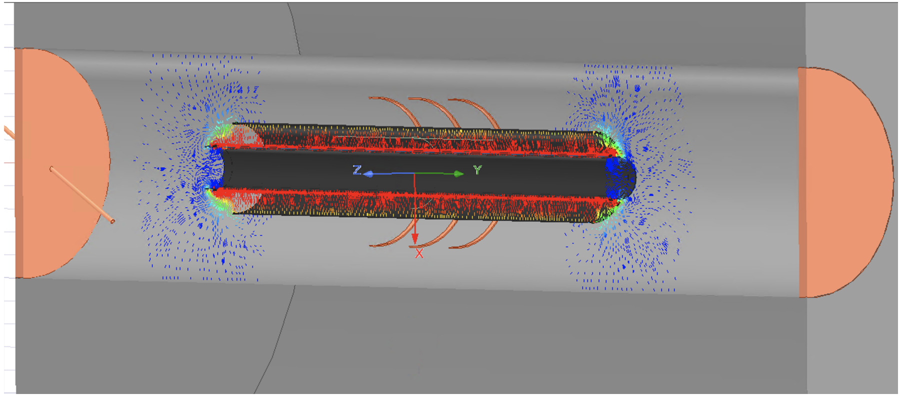
Early-to-late detection efficiency changes

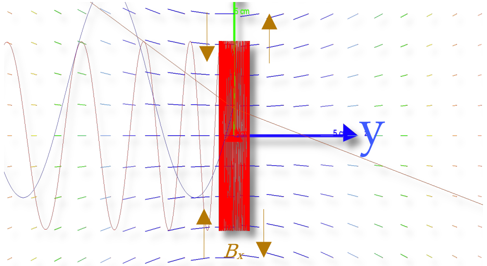
- Strong pulsed magnetic field → eddy currents, noise, heat in detectors and associated electronics.
- **Time-dependent changes in the detection efficiency of a set of detectors will be seen as a false EDM signal.**
- Systematics can be studied by decoupling the pulse time from the stopping time.
  (stop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



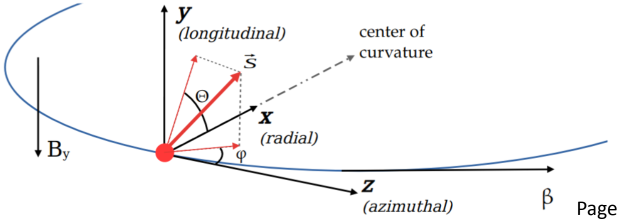
Coupling of the MDM to EM fields

- 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*





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

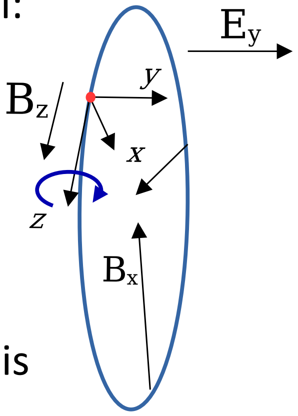


Average over all orbits

- 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:

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

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



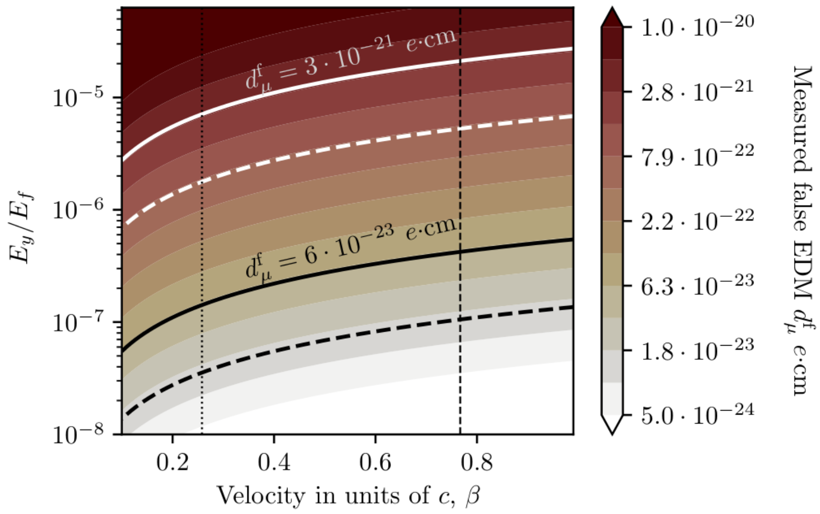
- Net B-field component along the momentum B_z → non-zero if there is current flowing through the muon orbit

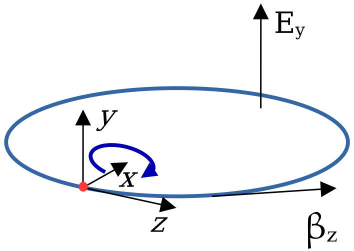
- Net radial B-field component B_x → can be non-zero due to residual fields from the magnetic kick

- Radial magnetic field in the reference frame of the muon due to a $\boldsymbol{\beta}\times\boldsymbol{E}$ 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.

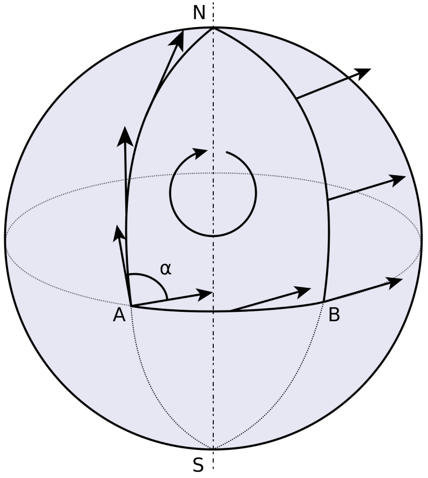




$$\langle \Omega_{\hat{z}\times\hat{y}} \rangle = -\frac{ea}{m_0 c}\left(\frac{1}{a(\gamma^2-1)} - 1 + \frac{1}{\beta_z^2}\right)\langle \beta_z E_y \rangle$$

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.

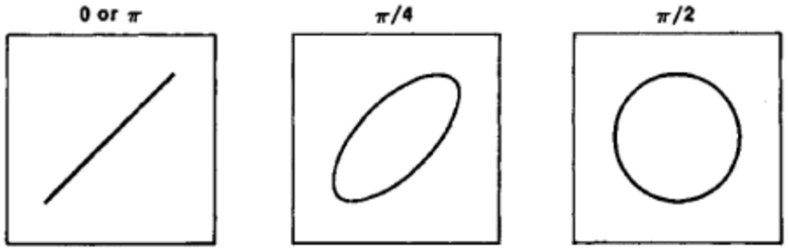


Calculation of Berry phases

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

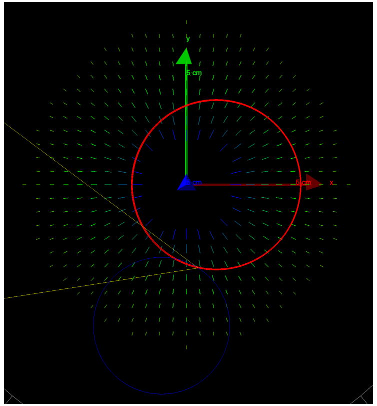
$$\frac{1}{2}\int (\Omega\cos(\Omega t+\beta_0)\sin(\Omega t)-\Omega\cos(\Omega t)\sin(\Omega t+\beta_0))\,dt=\frac{1}{2}\Omega t\sin(\beta_0).$$

- The motion of the spin in this case is an ellipse with eccentricity defined by the phase difference β_0 between oscillations
  - no phase difference: ellipse looks like a line
  - π/2 phase difference: ellipse is a circle and maximum area

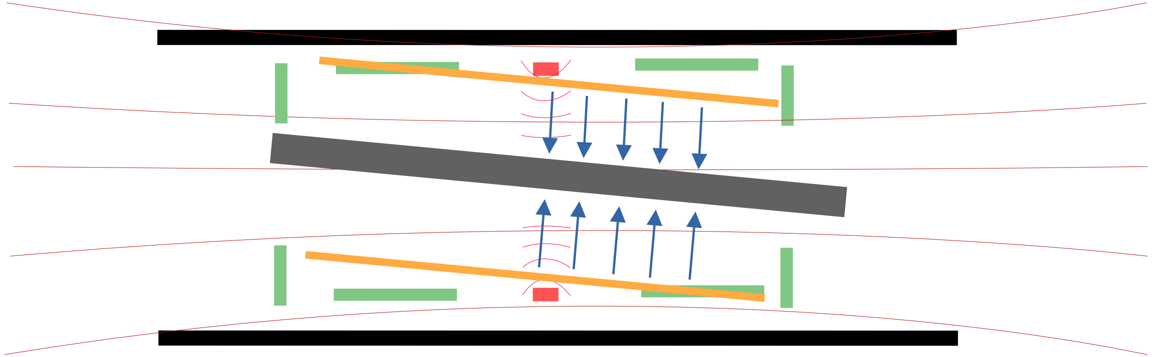


Example of Berry phases

- 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



Conclusions

- Plans to demonstrate the operation of all critical components and go to $3x10^{-21}$ e.cm until 2026.
- Final target $6x10^{-23}$ e.cm – large improvement over the current limits due to the frozen spin technique.
- Groundwork for the analysis of systematic effects in the experiment has been laid.

Thank you for the attention!

muonEDM collaboration kick-off meeting May 2022 (Pisa, Italy) →

Calculation of Berry phases

- Spin precesses around axis **x** with amplitude C_1 and frequency Ω_x, and around **y** with amplitude C_2 and frequency Ω_y. Phase difference between the two β_0.

$$x = C_1 \sin(\Omega_x t), \quad y = C_2 \sin(\Omega_y t + \beta_0)$$

- The movement of the spin encloses an area A on some abstract surface. The area can be calculated from Green's theorem:

$$A = \frac{1}{2}\int_{t_0}^{t_1} (xy' - yx')dt$$

- The Berry phase as a function time is then:

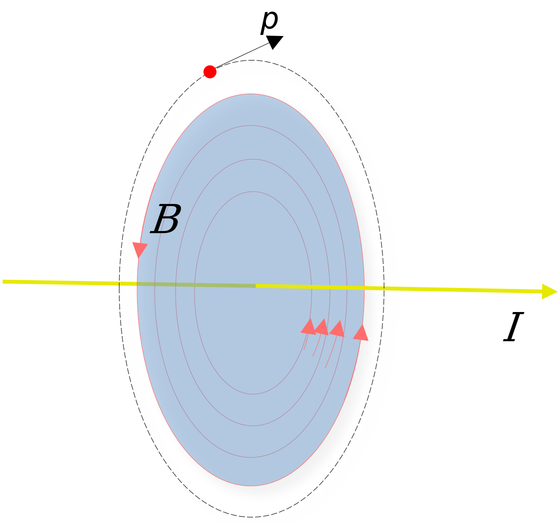
$$\alpha(t;\omega_x,\omega_y,\beta_0) = \frac{1}{2}\frac{\Omega_x\Omega_y}{\omega_x\omega_y}\int \left(\omega_y\cos(\omega_y t+\beta_0)\sin(\omega_x t) - \omega_x\cos(\omega_x t)\sin(\omega_y t+\beta_0)\right)dt =$$

$$= \frac{1}{4}\frac{\Omega_x\Omega_y}{\omega_x\omega_y}\left[\frac{\omega_x-\omega_y}{\omega_x+\omega_y}\cos((\omega_x+\omega_y)t+\beta_0) - \frac{\omega_x+\omega_y}{\omega_x-\omega_y}\cos((\omega_y-\omega_x)t+\beta_0)\right]$$

Limit on the *B*-field parallel to the momentum

- Non-zero average B_z field if there is electric current flowing through the area enclosed by the muon orbit
- Write net current!
- From Biot-Savart's law we can give a limit on the systematics due to such current
- Assuming non-insulated wire at the center of the orbit:
  - Precursor: I < 250 mA
  - Final experiment: I < 40 mA

$$\langle \Theta_{\hat{z}} \rangle = -\frac{ea}{m_0} \langle B_z \rangle t$$



Limit on the radial B-field

- Limit on the kicker field decay time with relation to the injection angle

- Assumptions:
  - half-sine kicker field intensity
  - end of the kick is considered to be at the 10% from maximum livel
  - exponential decay of the ringing signal with time constant τ_B
  - the limit is such that the influence of the residual field is less than a given d_e at ~400 ns time

- *Note: the constraint is lower for later times and stronger for earlier times*