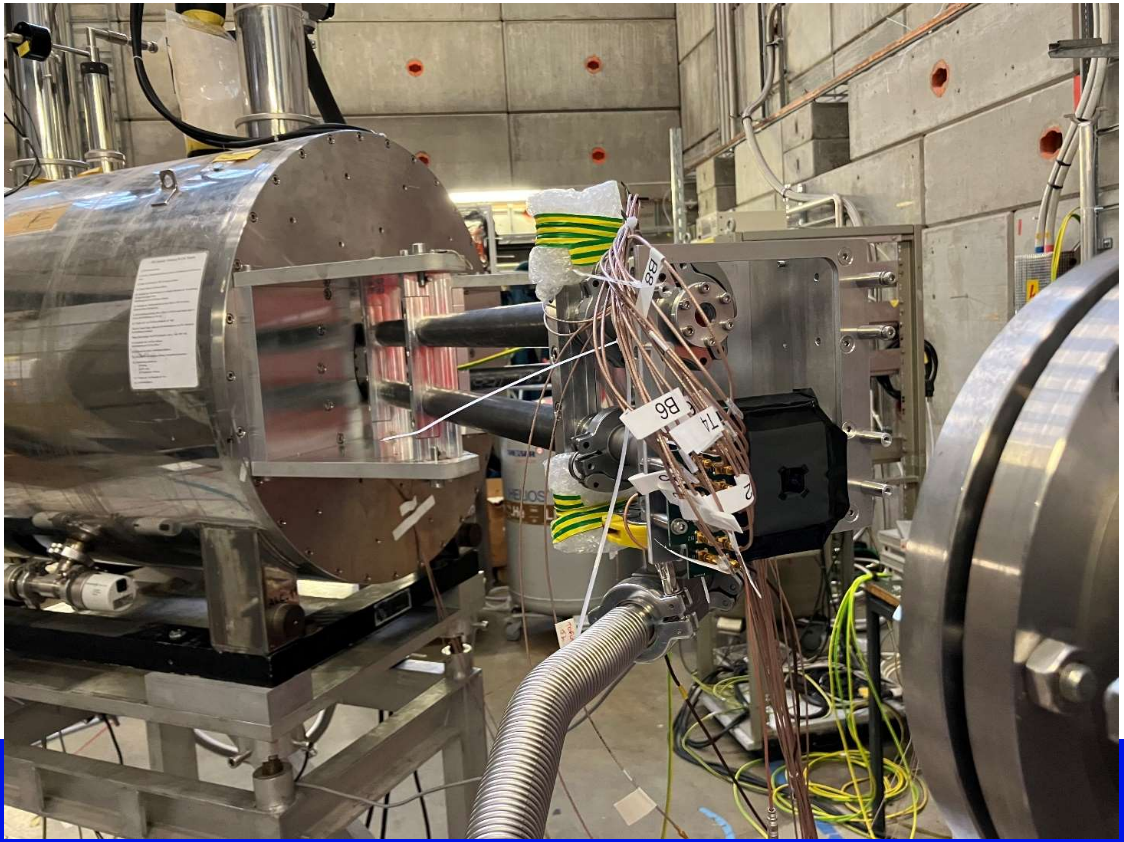
PSI Center for Neutron and Muon Sciences

# The muEDM experiment at PSI



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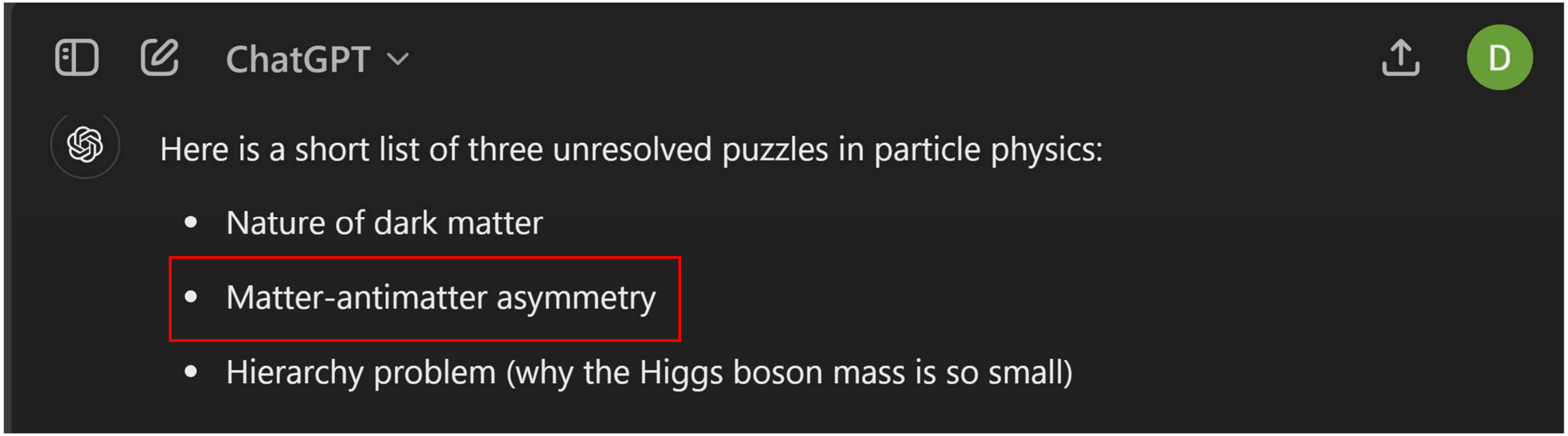
# Why the muon electric dipole moment?

# Puzzles in Particle Physics?



Here is a short list of three unresolved puzzles in particle physics:

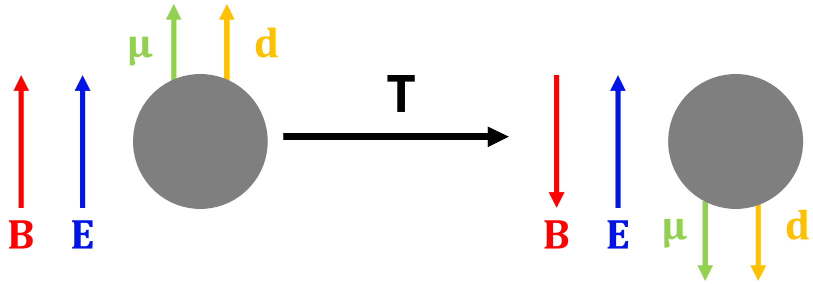
- Nature of dark matter
- Matter-antimatter asymmetry
- Hierarchy problem (why the Higgs boson mass is so small)

Sakharov conditions:

- Baryon number violation
- **C and CP violation**
- Departure from thermal equilibrium

# CP Violation

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



$\xrightarrow[\text{theorem}]{\text{CPT}}$ electric dipole moments (EDM) of fundamental particles are CP violating

Standard Model sources:

- phase of CKM matrix $d_\mu \sim O\left(10^{-42}\right)\ \mathrm{e} \cdot \mathrm{cm}$[1]
- strong CP angle $\overline{\boldsymbol{\theta}}$ (QCD) $d_\mu \lesssim 1.8 \times 10^{-35}\ \mathrm{e} \cdot \mathrm{cm}$[1]

→ insufficient to explain excess of matter

→ EDMs good probes for new physics

# Muon EDM

**In effective field theory**

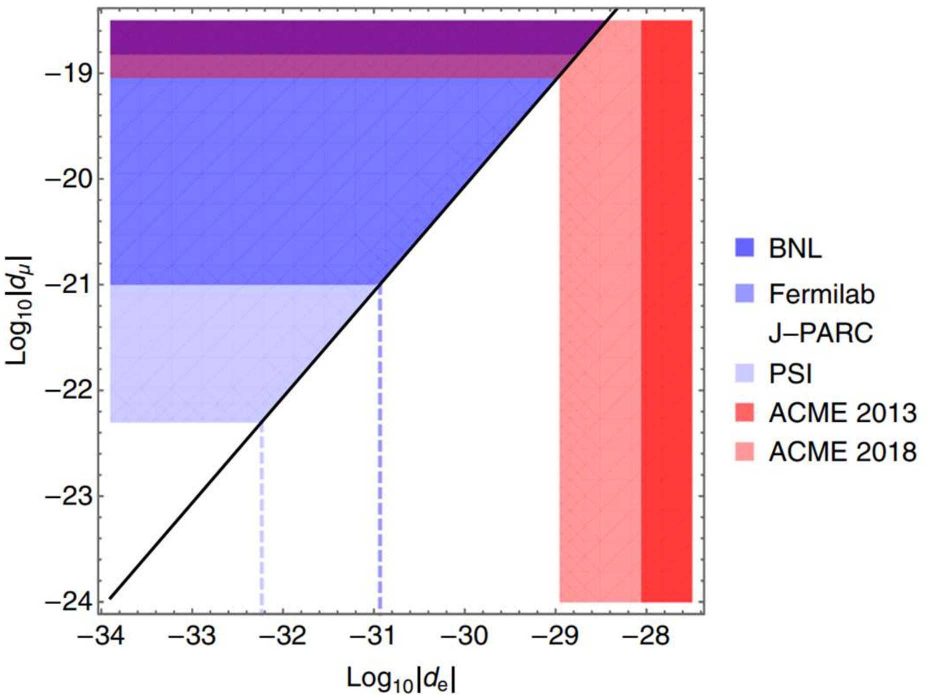
$$\mathcal{H}_{eff} = c_R^{\ell_f\ell_i}\bar{\ell}_{\mathrm{f}}\sigma_{\mu\nu}P_R\ell_iF^{\mu\nu} \ + \ h.c.$$

Wilson coefficient $c_R^{\ell_f\ell_i}$, $\ell \in \{e, \mu, \tau\}$

$$a_{\ell_i} \sim \mathrm{Re}\ c_R^{\ell_i\ell_i} \text{ and } d_{\ell_i} \sim \mathrm{Im}\ c_R^{\ell_i\ell_i}$$ [2]

muon EDM measurement on bare lepton and constraining $c_R^{\ell_f\ell_i}$

Current best direct limit $\boldsymbol{d_\mu < 1.8 \times 10^{-19}\mathrm{e}\cdot\mathrm{cm}}$[3]



Present and future limits on $|d_\mu|$ [2]

At PSI measure muEDM in a storage ring using the frozen-spin technique

- $\boldsymbol{d_\mu < 3 \times 10^{-21}\mathrm{e}\cdot\mathrm{cm}}$
- $\boldsymbol{d_\mu < 6 \times 10^{-23}\mathrm{e}\cdot\mathrm{cm}}$

# Measuring MDM and EDM in a storage ring

# Magnetic Dipole Moment

$$\vec{\mu} = g\,\frac{q}{2m_\mu}\vec{s}$$

Larmor precession with Thomas precession

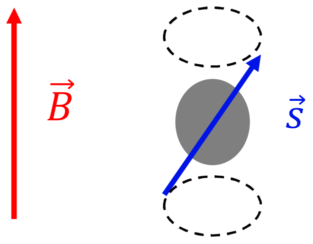
$$\vec{\omega}_0 = -\frac{q\,a}{m}\left(\left(1+\frac{1}{\gamma\,a}\right)\vec{B} - \frac{\gamma}{\gamma+1}\left(\vec{B}\cdot\vec{\beta}\right)\vec{\beta}\right)$$

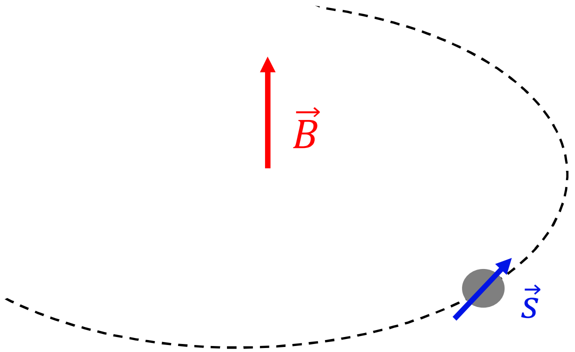
Cyclotron frequency

$$\vec{\omega}_c = -\frac{q\,a}{m}\left(\frac{\vec{B}}{\gamma\,a}\right)$$

Spin precession due to anomalous magnetic moment

$$\vec{\omega}_a = \vec{\omega}_0 - \vec{\omega}_c = -\frac{q\,a}{m}\left(\vec{B} - \frac{\gamma}{\gamma+1}\left(\vec{B}\cdot\vec{\beta}\right)\vec{\beta}\right)$$





# Electric Dipole Moment

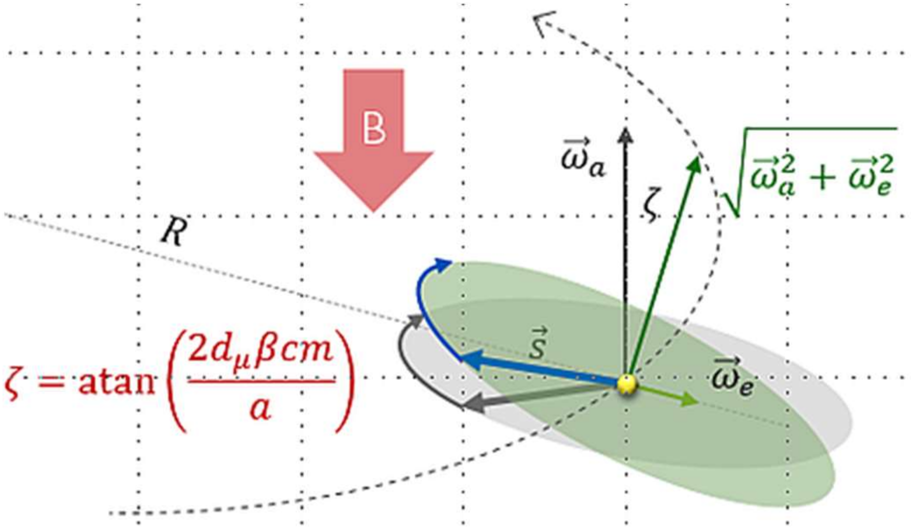
$$\vec{d} = \eta\,\frac{q}{2m_\mu c}\,\vec{s}$$

Additional precession

$$\vec{\omega} = \overrightarrow{\omega_a} + \overrightarrow{\omega_e} = \frac{q\,a}{m}\left(\vec{B} - \cancel{\frac{\gamma}{\gamma+1}\left(\vec{B}\cdot\vec{\beta}\right)\vec{\beta}} - \left(1+\frac{1}{a(1-\gamma^2)}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right)$$

$$+\frac{q\,\eta}{2m}\left(\frac{\vec{E}}{c} - \cancel{\frac{\gamma c}{\gamma+1}\left(\vec{E}\cdot\vec{\beta}\right)\vec{\beta}} + \vec{\beta}\times\vec{B}\right)$$

$$\boxed{\vec{B}\perp\vec{\beta}\perp\vec{E}}$$



# Frozen-Spin Technique

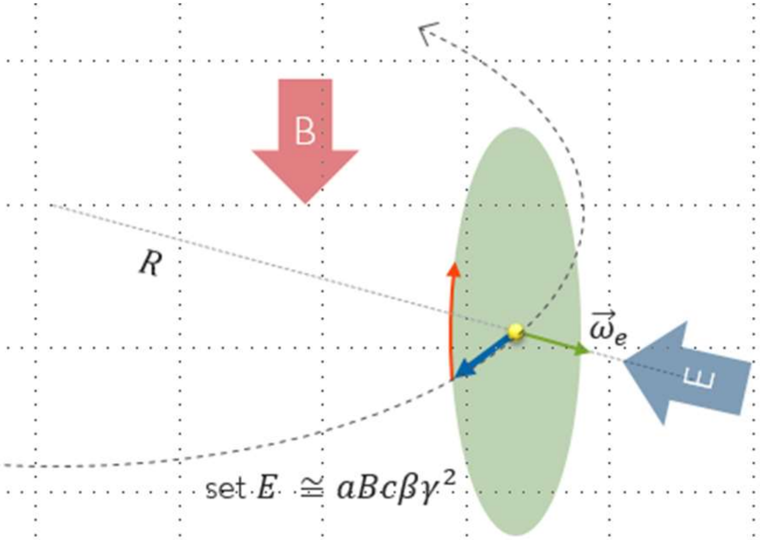
Tuning the electric field

$$\vec{\omega} = \overrightarrow{\omega_a} + \overrightarrow{\omega_e} = \frac{q\,a}{m}\left(\cancel{\vec{B}} - \cancel{\frac{\gamma}{\gamma+1}\left(\vec{B}\cdot\vec{\beta}\right)}\vec{\beta} - \cancel{\left(1+\frac{1}{a(1-\gamma^2)}\right)\frac{\vec{\beta}\times\vec{E}}{c}}\right)$$

$$+\frac{q\,\eta}{2m}\left(\frac{\vec{E}}{c} - \cancel{\frac{\gamma c}{\gamma+1}\left(\vec{E}\cdot\vec{\beta}\right)}\vec{\beta} + \vec{\beta}\times\vec{B}\right)$$

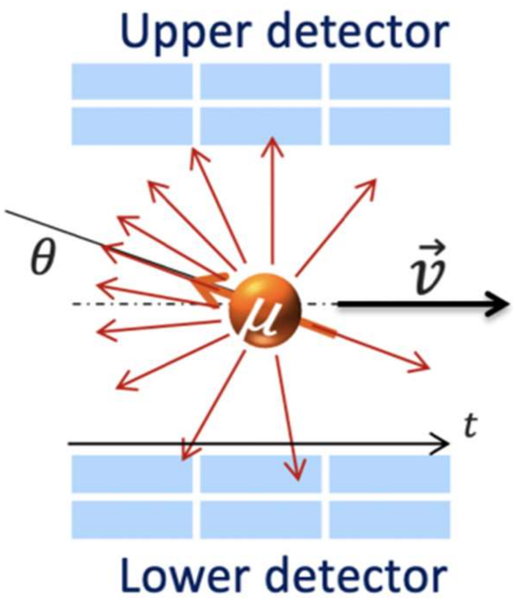
$$\boxed{E \simeq aBc\beta\gamma^2}$$

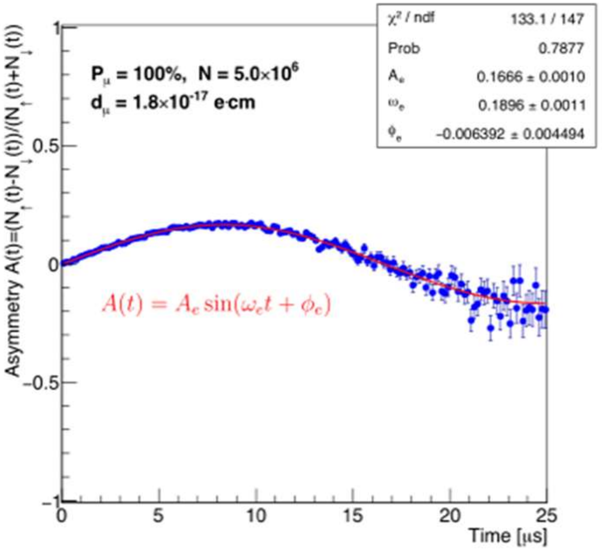
$$\boxed{\vec{B} \perp \vec{\beta} \perp \vec{E}}$$



→ Spin precession only due to EDM

# Measuring the muEDM





$$A = \frac{N_u - N_d}{N_u + N_d}$$

$$\dot{A}(\Psi_0, t) = \frac{\partial A}{\partial \Psi}\frac{\partial \Psi}{\partial t}\bigg|_{\Psi_0} = \alpha(\Psi_0)\dot{\Psi}(t)$$

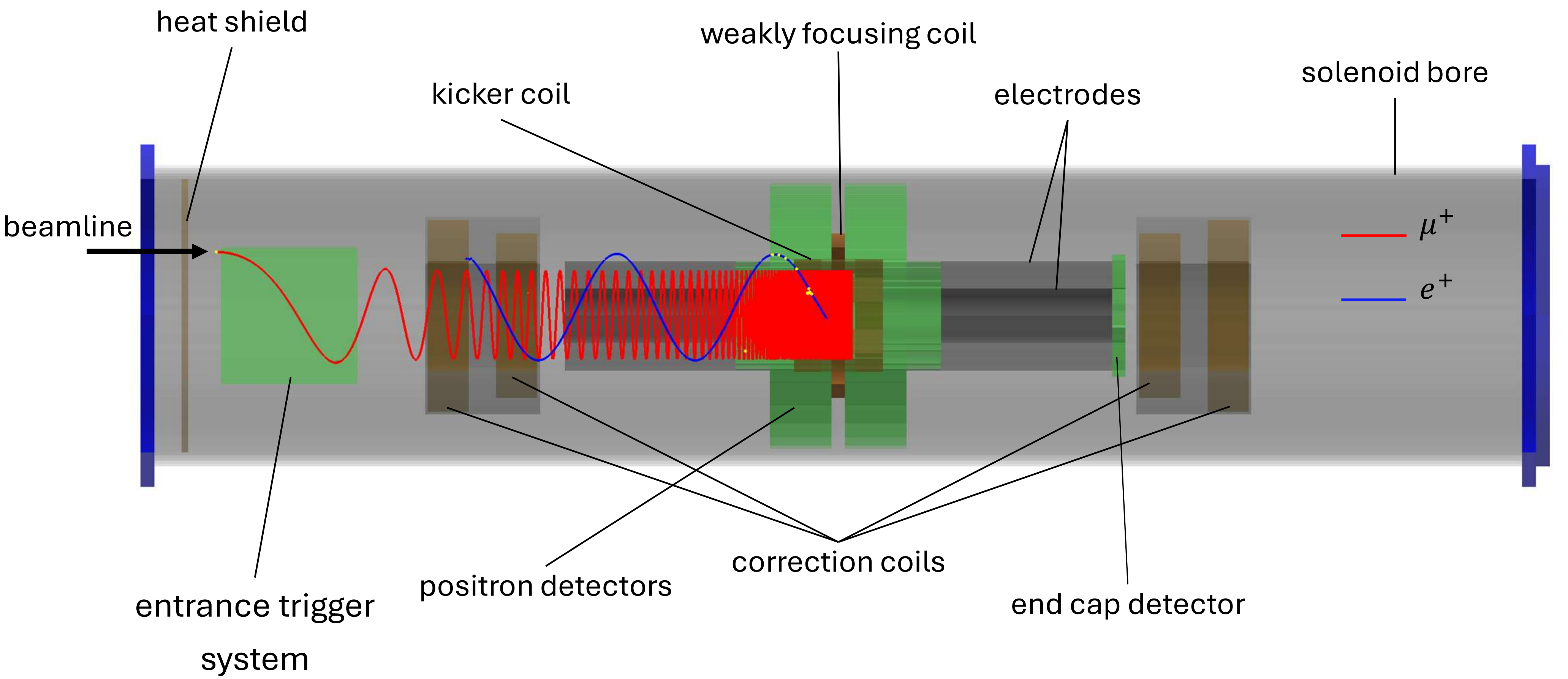
$$\sigma_\mu = \frac{\hbar}{2c\beta B\alpha P}\frac{1}{\gamma\tau\sqrt{N}}$$

$P$: initial polarization
$E'_B = c\beta B\gamma$: Boosted B
$N$: detected e$^+$
$\tau$: μ life-time
$\alpha$: analysis parameter

- asymmetry precession too slow
- change of asymmetry with respect to time
- optimize sensitivity by maximizing $\alpha\sqrt{N}$

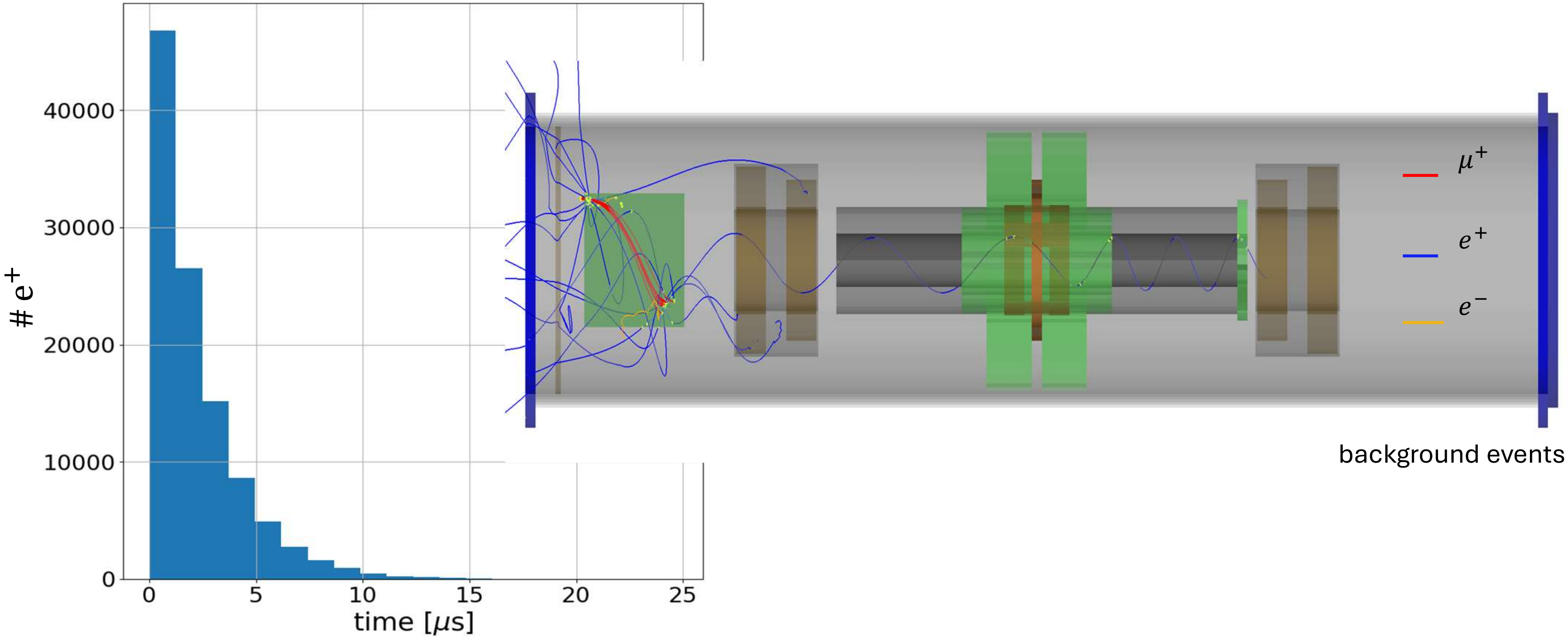
# The muEDM experiment

# muEDM setup in Geant4[4-6]



# Background Signals

storage efficiency 0.4% → rest background events



background events

# Outlook

# Outlook

- *Preliminary Results for the Injection Studies at Low Magnetic Fields for the muEDM Experiment* by Diego Alejandro Sanz Becerra
- future measurement campaigns
  - study possible effects on detector signals due to kicker pulse
  - characterize muons trajectory
  - injection through superconducting channels
  - store muons on stable orbit
- first muEDM measurement in 2026

- Posters
  - *Detector system to study early-to-late stability of the muEDM experiment* by Chavdar Dutsov
  - *Electric and magnetic field studies towards muon storage in the search for a muon electric dipole moment* by Timothy Hume

# Thank you!

# References

[1] Diptimoy Ghosh and Ryosuke Sato. Lepton electric dipole moment and strong CP violation. In: Physics Letters B 777 (Feb. 2018), 335–339. doi: 10.1016/j.physletb.2017.12.052

[2] Andreas Crivellin, Martin Hoferichter, and Philipp Schmidt-Wellenburg. Combined explanations of $(g-2)_{\mu,e}$ and implications for a large muon EDM. In: Physical Review D 98.11 (Dec. 2018), p. 113002.

[3] G. W. Bennett et al. Improved limit on the muon electric dipole moment. In: Phys. Rev. D 80 (5 2009), p. 052008. url: https://link.aps.org/doi/10.1103/PhysRevD.80.052008.

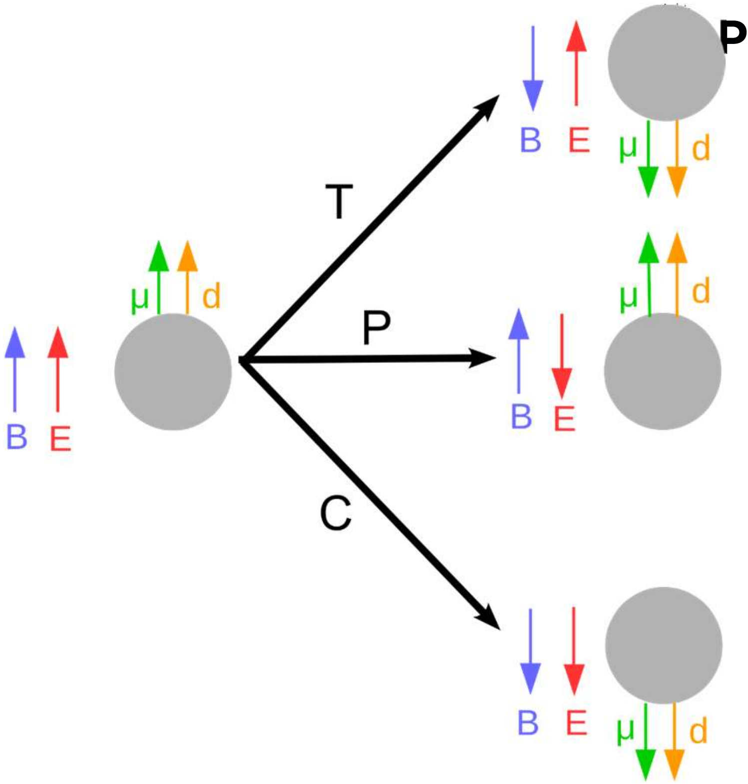
[4] S. Agostinelli et al. Geant4—a simulation toolkit. In: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 506.3 (July 2003), pp. 250–303. doi: 10.1016/s0168-9002(03)01368-8.

[5] J. Allison et al. Geant4 developments and applications. In: IEEE Transactions on Nuclear Science 53.1 (Feb. 2006), pp. 270–278. doi: 10.1109/tns.2006.869826.

[6] J. Allison et al. Recent developments in Geant4. In: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 835 (Nov. 2016), pp. 186–225. doi: 10.1016/j.nima.2016.06.125.

# Backup

# CP Violation



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

→ electric dipole moments (EDM) of fundamental particles are CP violating

Standard Model contributions:

- phase of CKM matrix $d_e \sim O(10^{-44})\ \mathrm{e \cdot cm}$
- strong CP angle $\boldsymbol{\bar{\theta}}$ (QCD) $d_e \lesssim 8.6 \times 10^{-38}\ \mathrm{e \cdot cm}$

→ insufficient to explain excess of matter

→ EDMs good probes for new physics

# $\theta$-term in QCD

$$\mathcal{L}_\theta = \theta \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} \qquad \tilde{G}^{a,\mu\nu} = \frac{1}{2} \epsilon^{\mu\nu\rho\sigma} G^a_{\rho\sigma}$$

possible term due to QCD topological structure

- $\bar{\theta} = \theta + \mathrm{Arg\,Det}\, M_q$ (chiral transformation $\psi' = e^{i\alpha\gamma_5/2}\psi$)
- Induces a neutron electric dipole moment
$$d_n \sim (2.50 \pm 1.25) \times 10^{-16}\, \bar{\theta}\ \mathrm{e \cdot cm}$$
- With experimental limit on $d_n$ giving $\bar{\theta} \lesssim 10^{-1}$

- Hadronic light-by-light diagrams give dominant contribution to lepton EDMs[1]

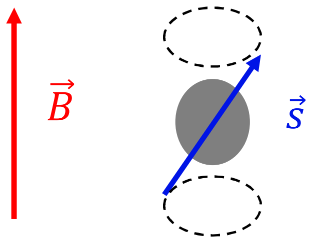
*Tanmoy Bhattacharya, Vincenzo Cirigliano, Rajan Gupta, Emanuele Mereghetti, and Boram Yoon.Contribution of the QCD $\theta$-term to the nucleon electric dipole moment. In: Physical Review D 103.11 (June 2021)

# Magnetic Dipole Moment

$$\vec{\mu} = g\,\frac{q}{2m_\mu}\,\vec{s}$$

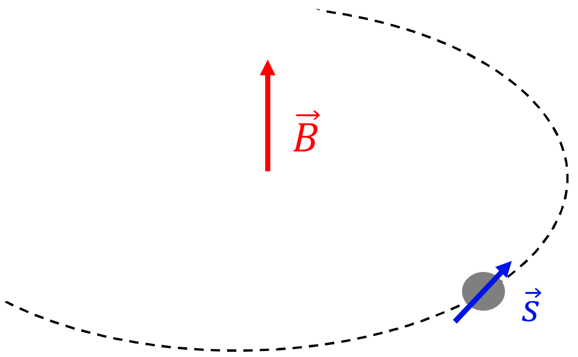
Larmor precession Thomas prec relativistic

$$\vec{\omega}_0 = -\frac{q\,a}{m}\left(\left(1+\frac{1}{\gamma\,a}\right)\vec{B} - \frac{\gamma}{\gamma+1}\left(\vec{B}\cdot\vec{\beta}\right)\vec{\beta} - \left(1+\frac{1}{a\,(1+\gamma)}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right)$$



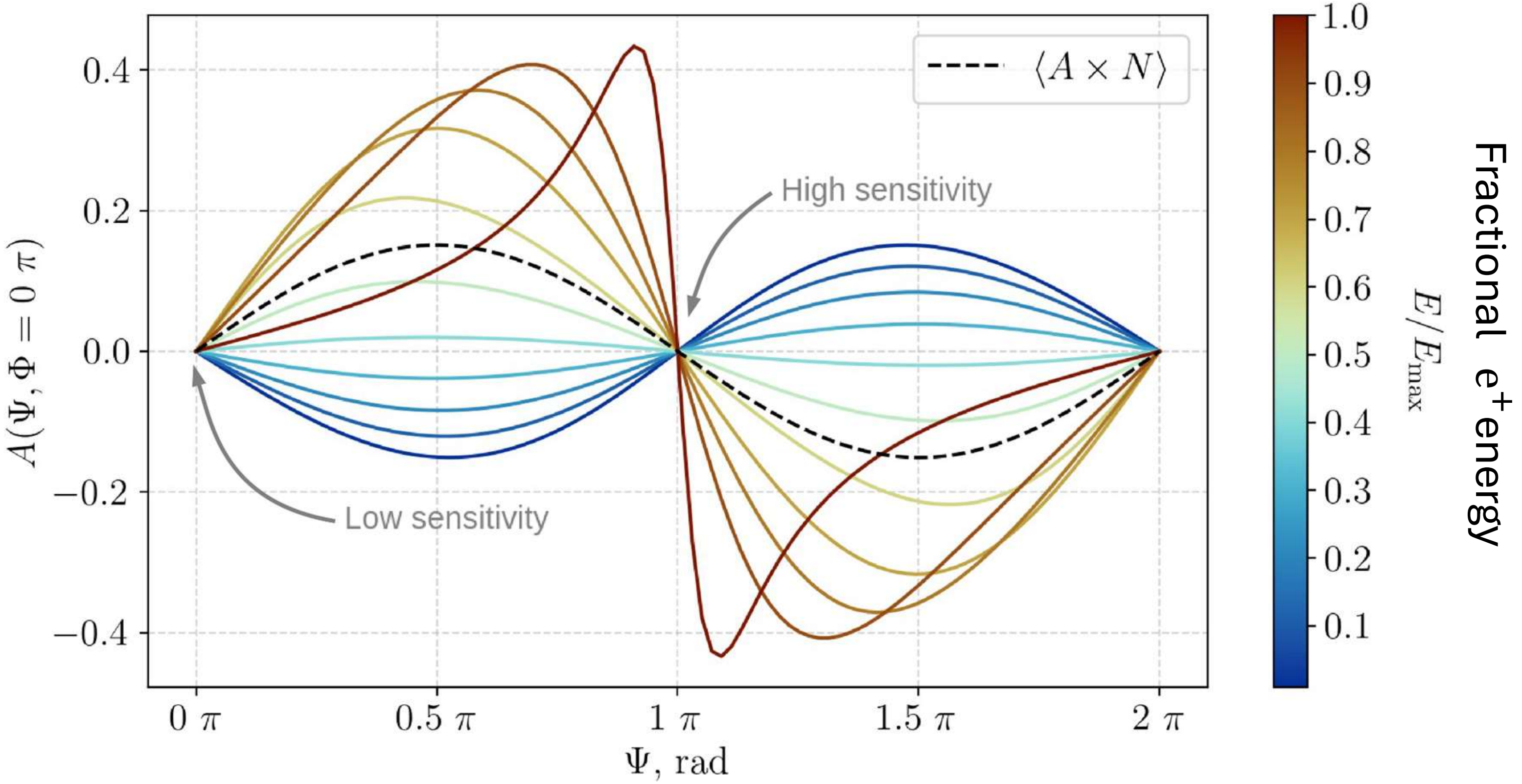
Cyclotron frequency

$$\vec{\omega}_c = -\frac{q\,a}{m}\left(\frac{\vec{B}}{\gamma\,a} - \frac{\gamma}{a\,(\gamma^2-1)}\,\frac{\vec{\beta}\times\vec{E}}{c}\right)$$



Spin precession due to anomalous magnetic moment

$$\vec{\omega}_a = \vec{\omega}_0 - \vec{\omega}_c = \frac{q\,a}{m}\left(\vec{B} - \frac{\gamma}{\gamma+1}\left(\vec{B}\cdot\vec{\beta}\right)\vec{\beta} - \left(1+\frac{1}{a\,(1-\gamma^2)}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right)$$



Angle due to EDM precesseion

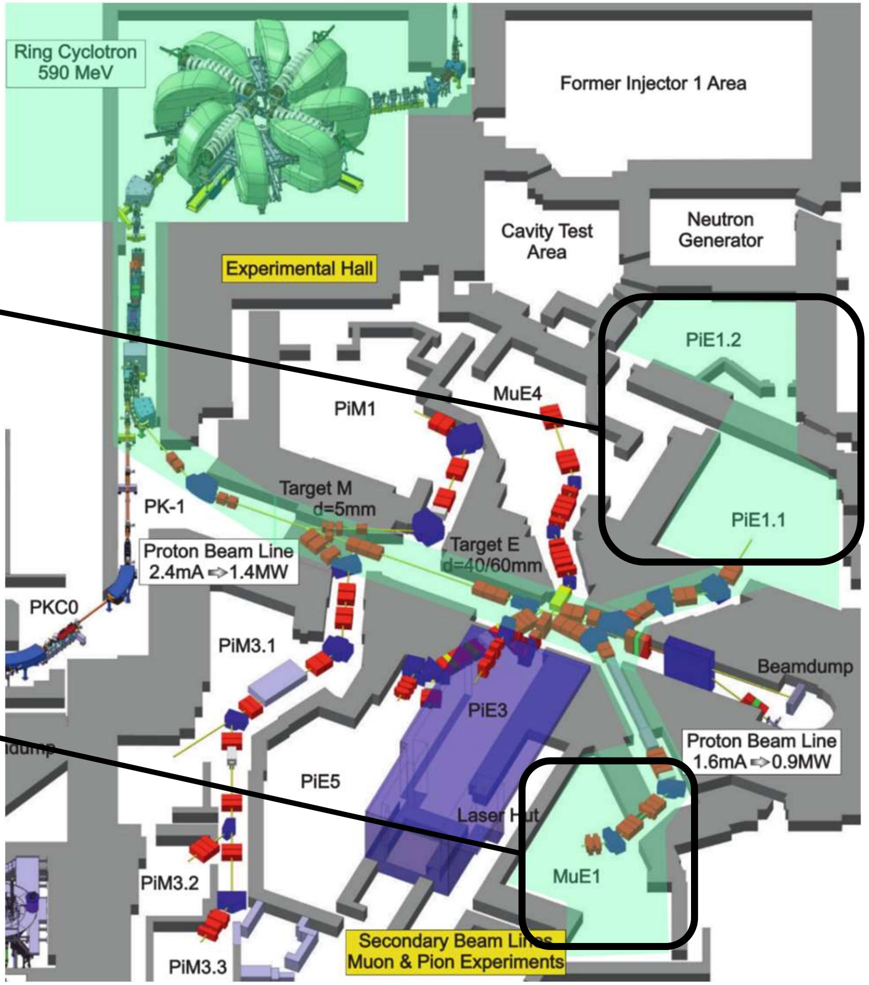
# Muon Beamlines

Phase I

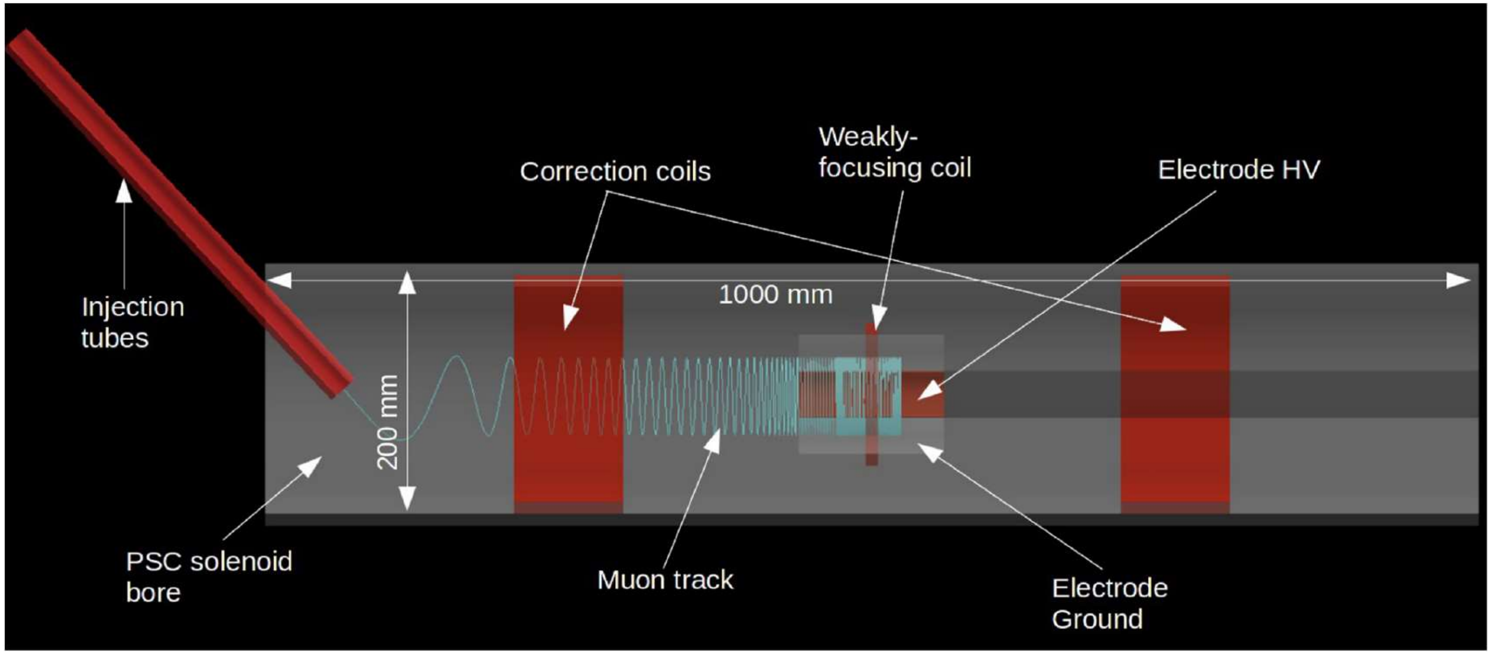
- $p_\mu = 28\,\frac{\mathrm{MeV}}{c}$
- Flux $O(10^6\ \mu^+/s)$
- $d_\mu < 3 \cdot 10^{-21}\ e \cdot \mathrm{cm}$

Phase II

- $p_\mu = 125\,\frac{\mathrm{MeV}}{c}$
- Flux $O(10^8\ \mu^+/s)$
- $d_\mu < 6 \cdot 10^{-23}\ e \cdot \mathrm{cm}$



# G4beamline Optimization



- simulation runs for different sets in the parameter space
- surrogate model to optimize for storage efficiency and heat output
- for optimized parameters achieved $0.4\%$ storage efficiency

# Talks and Posters

## Talks

- *Preliminary Results for the Injection Studies at Low Magnetic Fields for the muEDM Experiment* by Diego Alejandro Sanz Becerra

## Posters

- *Detector system to study early-to-late stability of the muEDM experiment* by Chavdar Dustsov
- *Electric and magnetic field studies towards muon storage in the search for a muon electric dipole moment* by Timothy Hume