



The muEDM Experiment at PSI

Search for the Muon Electric Dipole Moment

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on behalf of the muEDM collaboration

University of Pisa & INFN Pisa

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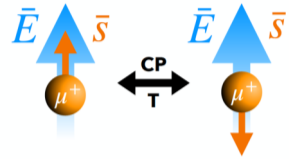


Physics Motivation: Why Muon EDM?

Searching for the Muon Electric Dipole Moment (d_μ) is a powerful and clean probe for Beyond Standard Model (BSM) physics:

- **Symmetry Violation:** EDMs are intimately connected to the violation of time invariance T and charge-parity CP symmetries (assuming CPT)
- **Signature of New Physics:** Many BSM models predict enhanced CP -violating phases. Any observation above the tiny SM prediction is a clear, background-free signature of New Physics
- **Complementarity:** Strongly complementary to direct searches at colliders, probing energy scales otherwise unreachable (up to the **PeV** scale)

A permanent EDM requires T violation, equivalently CP violation by the CPT Theorem.



$$H_\mu^{EDM} \stackrel{\beta \rightarrow 0}{\propto} d_\mu \bar{\sigma} \cdot \bar{E}$$

Hamiltonian EDM term is CP violating

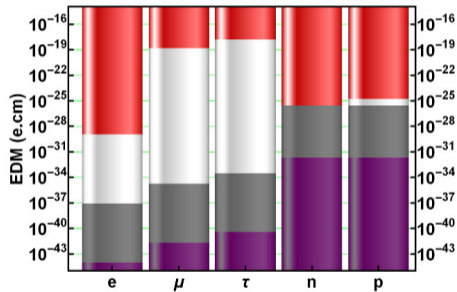
Standard Model Prediction

$$d_\mu^{SM} \approx 1.4 \times 10^{-38} \text{ e} \cdot \text{cm}$$

[Yamaguchi & Yamanaka, 2020]

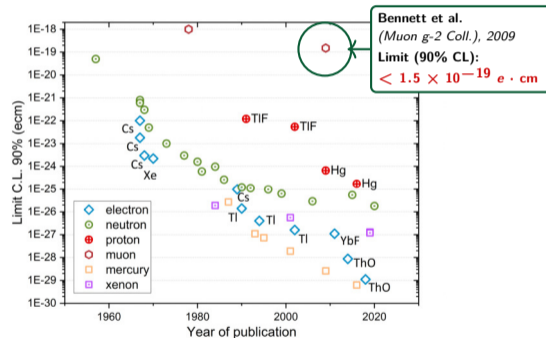
Current Experimental Limits: The Muon Gap

While electron and neutron EDMs are severely constrained, the muon exhibits a massive, unexplored gap between the experimental limit and the SM background



Current limits (red) vs SM weak sector background (violet) and possible strong CP-violation (grey)

[K. Kirch, P. Schmidt-Wellenburg, EPJ Web Conf. (2020)]

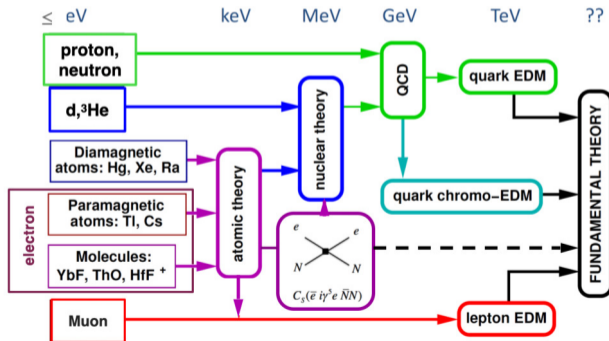


History of EDM upper limits

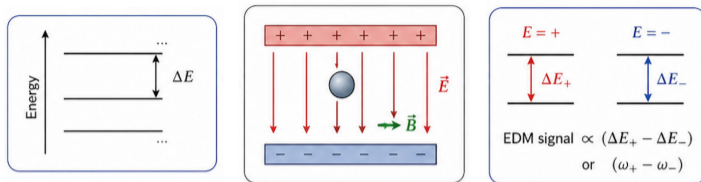
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Why a Dedicated Direct Search for the Muon?

- **"Naked" Lepton:** A fundamental particle free from complex atomic or nuclear shielding
 - **Mass Scaling:** Linear scaling implies $d_\mu \sim 1 \times 10^{-28} \text{ e} \cdot \text{cm}$, but BSM models can heavily violate this, making a direct probe crucial
- ⇒ **PSI muEDM Project:** A staged search to cover the unexplored region, aiming at 3×10^{-21} (Precursor) and $6 \times 10^{-23} \text{ e} \cdot \text{cm}$ (Final)



How to Measure an EDM: Observable & Challenges



The simplest observable for an EDM is the energy splitting in an external field:

$$|\Delta\omega| = \frac{|dE|}{\hbar J}$$

To optimize the statistical sensitivity σ_d , the experiment must address **key experimental challenges...**

- ⚡ **Maximize Electric Field E**
- ⌚ **Maximize Measurement Time τ**
- 📊 **Maximize Statistics N**
- 🛑 **Control Magnetic Field B**

Ensure small, stable B to suppress fluctuations from spurious $\mu \cdot B$ precession

$$\sigma_d \gtrsim \frac{\hbar J}{E} \frac{1}{\sqrt{2N\tau}}$$

The Relativistic Precession: Thomas-BMT Equation

Under the simplified condition of particle velocity perpendicular to \vec{B} and \vec{E} , the spin precession relative to momentum is:

$$\vec{\omega} = -\frac{e}{m} \left[a_{\mu} \vec{B} - \left(a_{\mu} - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2} \left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right]$$

Standard $g - 2$ experimental approaches:

BNL / FNAL Approach

$$\gamma \approx 29.3 \quad (p \approx 3 \text{ GeV}/c)$$

The "magic momentum" cancels the electric field term in the main brackets:

$$\vec{\omega}_a \approx -\frac{e}{m} \left[a_{\mu} \vec{B} + \frac{\eta}{2} (\dots) \right]$$

J-PARC Approach

$$E = 0 \text{ at any } \gamma$$

Uses ultra-cold muons injected into a uniform B field with **no** electric field:

$$\vec{\omega}_a \approx -\frac{e}{m} \left[a_{\mu} \vec{B} + \frac{\eta}{2} (\vec{\beta} \times \vec{B}) \right]$$

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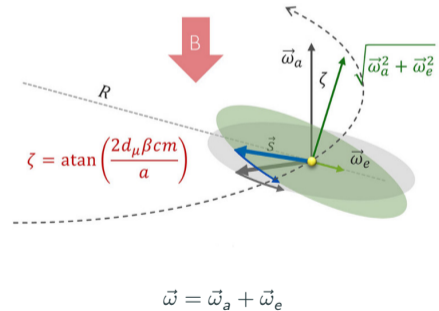
Limitations of the Precession "Frequency" Approach

In classic $g - 2$ experiments, the EDM sensitivity is extracted from the tilt angle (ζ) of the precession plane:

$$\zeta = \text{atan} \left(\frac{2d_\mu \beta c m}{a_\mu} \right)$$

Systematic Limitation

- The tilt angle ζ produces a vertical oscillation of the spin relative to the storage plane
- The final sensitivity to a muon EDM is strictly **limited by the resolution of the vertical amplitude**



The Solution: The Frozen-Spin Technique

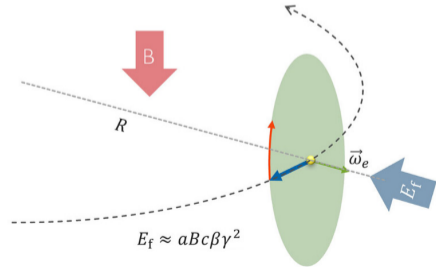
To overcome the vertical amplitude limitation, the **frozen-spin technique** applies a radial electric field \vec{E}_f to cancel the entire $g - 2$ precession part of the Thomas-BMT equation:

$$\vec{\omega} = -\frac{e}{m} \left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}_f}{c} + \frac{\eta}{2} \left(\vec{\beta} \times \vec{B} + \frac{\vec{E}_f}{c} \right) \right]$$

This cancellation is achieved by:

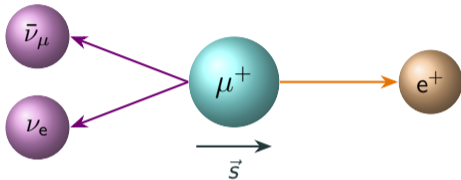
$$a_\mu \vec{B} = \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}_f}{c} \implies \mathbf{E}_f \approx \mathbf{a}_\mu \mathbf{B} c \beta \gamma^2$$

- **Without EDM ($d_\mu = 0$):** Spin remains locked along the momentum direction ($\vec{\omega} = 0$)
- **With EDM ($d_\mu \neq 0$):** Spin precesses out of the orbital plane ($\vec{\omega}_e \parallel \vec{E}$), leading to a linear growth of vertical polarization



Signal Signature: Positron Decay Asymmetry

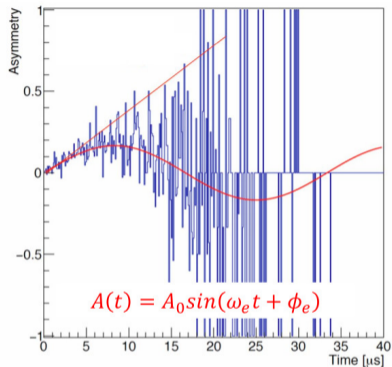
Decay positrons ($\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$) are emitted preferentially along the muon spin direction:



The Observable

An EDM generates a time-dependent **Up/Down asymmetry**:

$$A(t) = \frac{N_{\uparrow}(t) - N_{\downarrow}(t)}{N_{\uparrow}(t) + N_{\downarrow}(t)} \approx \frac{2P_0 E \alpha |d_\mu|}{\hbar \gamma^2} \cdot t$$

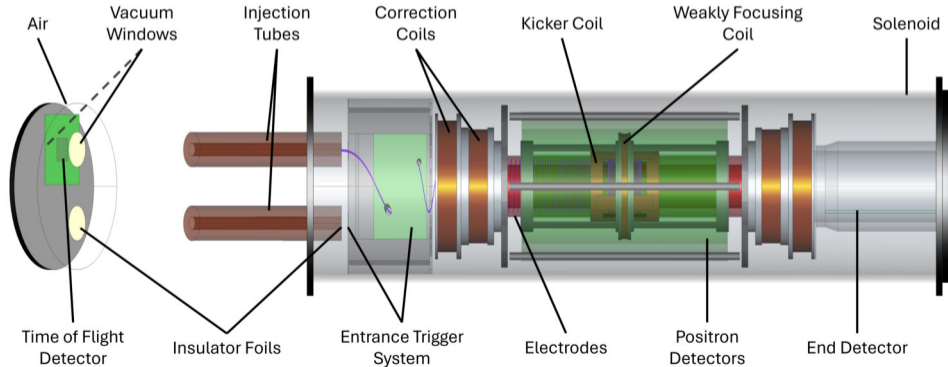


Expected statistical uncertainty on the EDM:

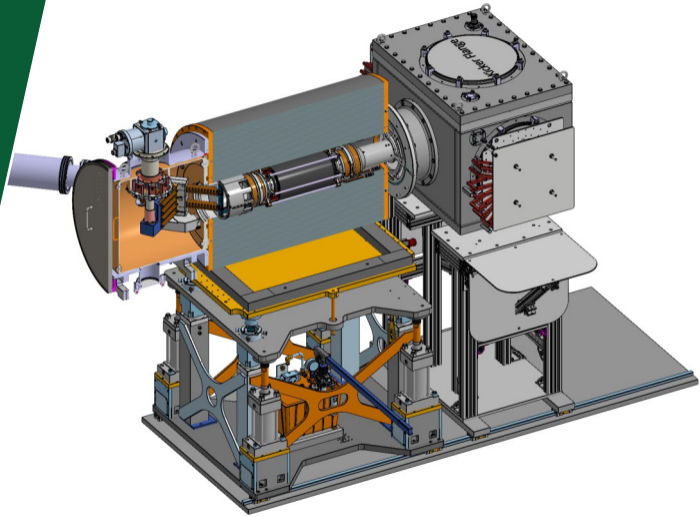
$$\sigma(|d_\mu|) \sim \frac{a \hbar \gamma}{2P_0 E \sqrt{N} \tau_\mu \alpha}$$

The Experimental Setup Concept at PSI

1. **Injection:** Muons enter the uniform magnetic field region via superconducting (SC) lines
2. **Storage:** A fast radial magnetic pulse (*kicker*) stops the longitudinal motion for storage
3. **Spin Freezing:** A radial electric field \vec{E}_f cancels the $g - 2$ precession
4. **Detection:** The tracker detects the decayed positron

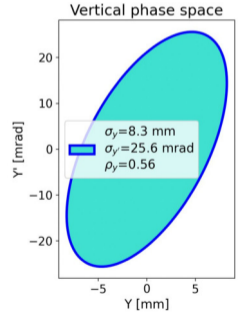
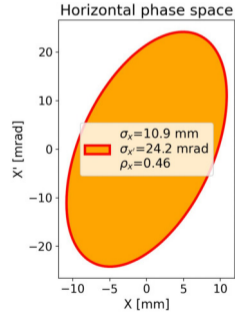
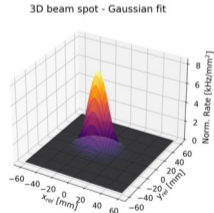
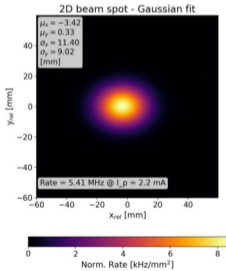


muEDM Phase 1



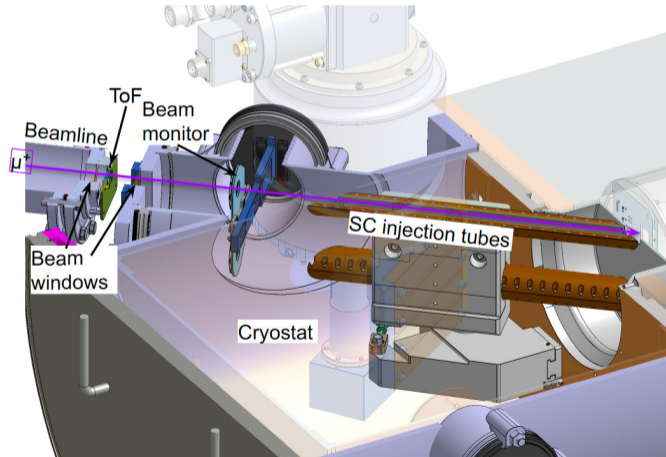
Muon Beam

- **Surface muons** at $28 \text{ MeV } c^{-1}$ with minimal divergence
- Polarization: $\sim 95 \%$
- Intensity: $\sim 5 \times 10^6$ muons/s



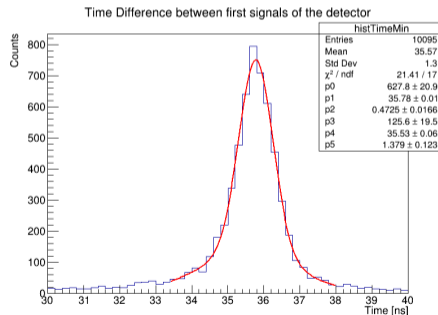
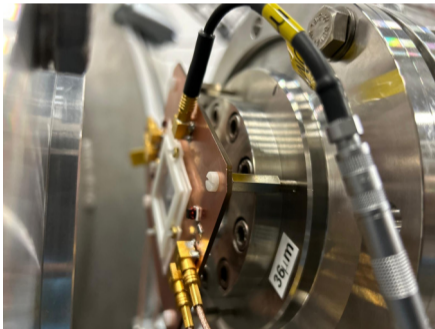
Injection: ToF, Beam Monitoring and SC Line

Following the muon path...



Time of Flight (ToF) detector used to measure **muon momentum**:

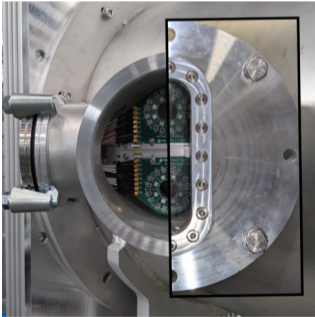
- Essential to control **systematic uncertainties**
- Time resolution: $\sigma_t \simeq 500$ ps using FERS5203 ($\simeq 473$ ps using WaveDreamDAQ)
- **50 μm scintillating foil** coupled to Hamamatsu **MPPC** for minimal multiple scattering



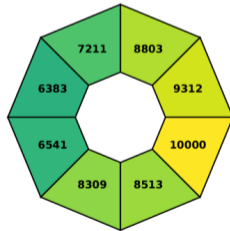
Injection - Beam Monitor

Non-invasive beam detector for **beam alignment** and **monitoring**:

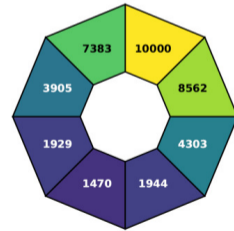
- 2 mm thick plastic scintillators coupled to Hamamatsu MPPC
- Particle Identification (PID) capability



Top Beam Monitor Measurement
"muEDM_2025_27.5_Gate_V3.sp"
B = 0 T



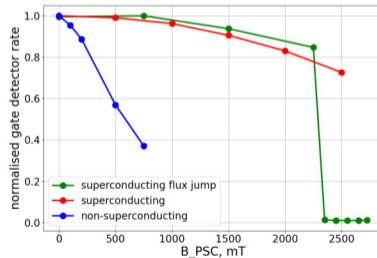
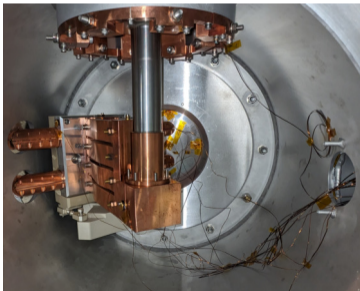
Top Beam Monitor Simulation
"muEDM_2025_27.5_Gate_V3.sp"
B = -2.726 T



Injection - SC Line

Muon transport into the solenoid bore through **superconducting (SC) injection tubes**:

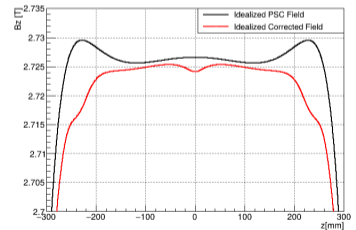
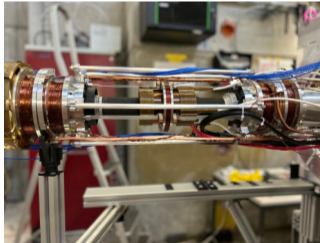
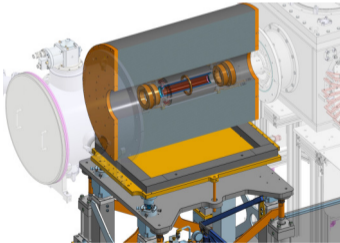
- **Shielding** from the fringe magnetic field to **minimize deflection** ($B_{\perp} < 10$ mT, $B_{\parallel} < 1$ T)
- **Transmission efficiency** $\approx 3\%$
- **4 types of SC**: BSCCO2223, NbTi, HTS REBCO, NbTi/Nb/Cu sheets



Muon Storing Acceptance - Correction and Weakly Focusing Coils

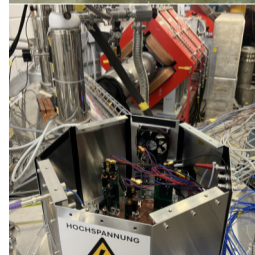
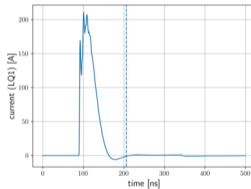
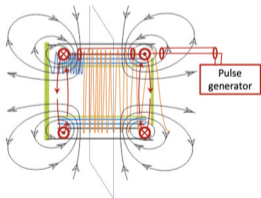
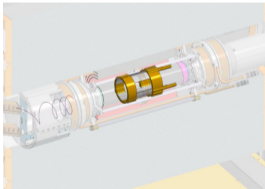
Correction and weakly focusing coils setup:

- Improve **muon acceptance** and **storage** within the solenoid
- Power dissipation: **1 W to 4 W**. With a water flow $\geq 10 \text{ mL s}^{-1}$, the **temperature is kept stable** below 30°C



Magnetic pulse (kicker) to stop the **longitudinal (z) motion** of muons and store them:

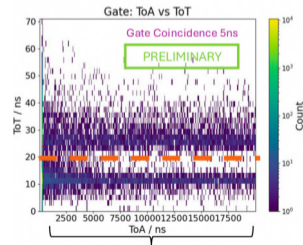
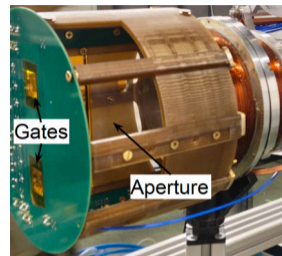
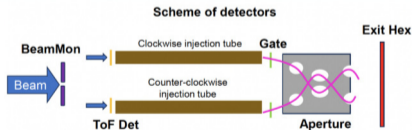
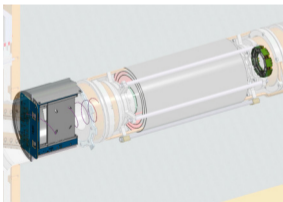
- **4-quadrant anti-Helmholtz coil** made of **100 μm Cu foil**
- Requires **200 A current pulse** for a duration of \sim **100 ns** after a \sim 100 ns trigger delay



Trigger detector

The **trigger detector** provides the signal that a **good muon** is reaching the storage region:

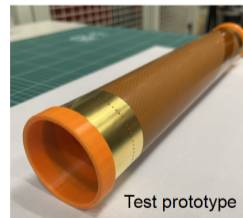
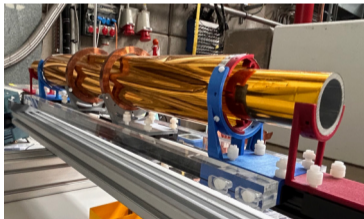
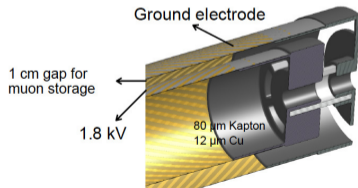
- Made of the **gate** and the **aperture** detectors
- **Fast detector and logic** to release the signal for activating the kicker



Frozen-spin electrodes

Tuning of \vec{E}_f such that it **freezes the spin** to the \vec{p}_μ :

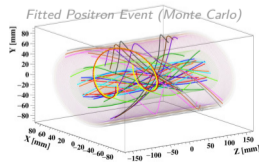
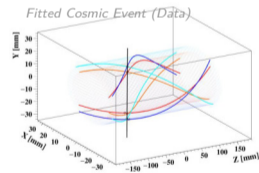
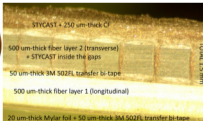
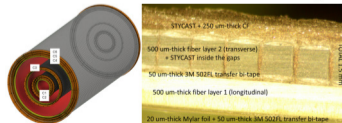
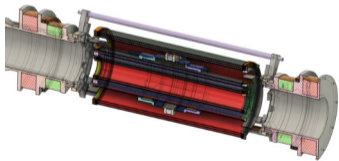
- **Very thin** ($< 100 \mu\text{m}$) to **reduce multiple scattering**
- **Striped Cu segmentation** to reduce the **shielding of the magnetic kick** due to **eddy currents**



Positron tracker: the CHeT

Measure the **direction and momentum** of decay positrons:

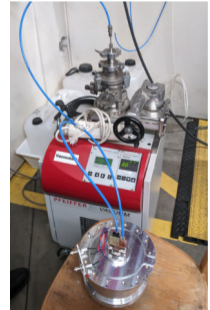
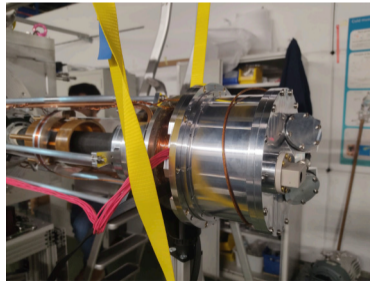
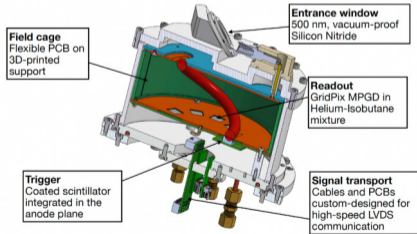
- **Position resolution:** $\mathcal{O}(1)$ mm, **Timing resolution:** < 1 ns
- **Cylindrical detector:** 6 cylinders, each with two **stereo layers of fibres**. Preliminary MC resolutions: $\sigma_p \approx 0.1 \text{ MeV} \cdot p$, $\sigma_\phi \approx 50 - 100 \text{ mrad}$, $\sigma_\theta \approx 10 - 50 \text{ mrad}$
- **500 μm fibres** in 2x/4x, coupled to **MPPCs** (Hamamatsu S13360-50PE)
- **C1 + C2 installed** for the BT2025



Muon TPC

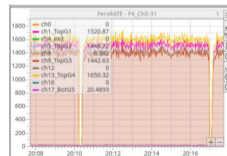
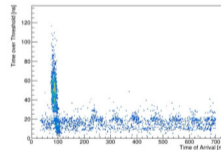
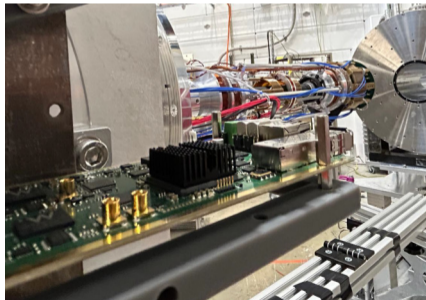
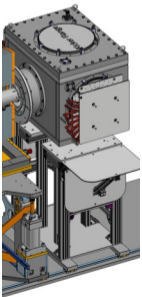
Small **Time Projection Chamber (TPC)** with **5 cm drift** and **GridPix** readout for a **muon trajectory** measurement:

- Muon **momentum difference** between CW and CCW injection within **0.5 % precision**
- **Phase space** at the entrance of the magnet: cross-check the **alignment** of beam, injection channels and magnet
- Extremely **light material budget: 500 nm silicon**



DAQ: CAEN FERS 5200 + FERS 5203

- **Modular** (A520x FERS units - 64/128 channels) + **DT5215 Concentrator Board**.
Scalability: from a single FERS unit up to **8192 channels**. **Easy-synch:** up to 128 FERS units synchronized by a single board
- **ToA** (timing @200 ps level), **Time Over Threshold**, read out up to **100 kHz**



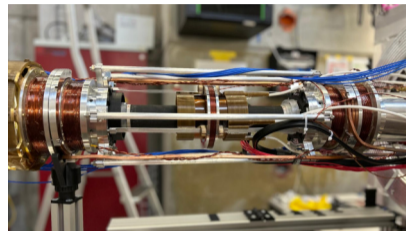
Conclusions & Outlook

Outlook & Goals

- **EDMs** are a **major focus** of modern research to test both **SM & BSM physics**
- **muEDM** aims to improve the current limit by **two orders of magnitude**, paving the way for future measurements using the **frozen spin technique**

Road to muEDM

- 2025 – Test Beam:** Assembly, integration, and characterization of key components
- 2026 – Test Beam:** Final setup assembly, proof of the frozen spin technique, and base sensitivity
- 2027:** muEDM Phase 1 production runs and data taking



Backup

Introduction to EDMs: Symmetries and Lagrangian

If a permanent EDM \vec{d} exists, it must be aligned with the spin direction \vec{J} (average angular momentum):

$$H = -(\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}) = -(\mu\vec{J} \cdot \vec{B} + d\vec{J} \cdot \vec{E})/J$$

Symmetry Properties

Quantity	P	T
Spin \vec{J} , Field \vec{B}	Even	Odd
Field \vec{E}	Odd	Even
Term $\vec{E} \cdot \vec{J}$ (EDM)	Odd	Odd

Parity (P) and time-reversal (T) violation are introduced in the EM Lagrangian density via the EDM term:

$$\mathcal{L}_{\text{EM}} = -\frac{\mu}{2}\bar{\Psi}\sigma^{\mu\nu}F_{\mu\nu}\Psi - i\frac{d}{2}\bar{\Psi}\sigma^{\mu\nu}\gamma^5F_{\mu\nu}\Psi$$

The Dirac matrix γ^5 and the imaginary unit i introduce P and T violation respectively.

muEDM Sensitivity: Statistical Formulation

The statistical uncertainty on d_μ is derived directly from the time-dependent decay asymmetry:

$$A_m(t) = \frac{N_\uparrow(t) - N_\downarrow(t)}{N_\uparrow(t) + N_\downarrow(t)} \approx P(t) \cdot \tilde{\alpha}$$

Assuming a linear growth of the tilt angle $\Theta(t) = \omega_e t$:

$$P(t) \approx 2P_0 \frac{d_\mu}{\hbar} \beta c B t$$

The slope $b = \dot{A}_m$ has an uncertainty of:

$$\sigma_b = \frac{1}{\gamma \tau \sqrt{N}}$$

Integrating over the dilated muon lifetime yields the standard sensitivity formula:

$$\sigma(d_\mu) = \frac{\hbar}{2P_0 \beta c B \sqrt{N} \gamma \tau_\mu \tilde{\alpha}}$$

Primary parameters for optimization:

- **N**: Total number of tracked decay positrons
- **B**: Stronger storage magnetic field
- $\tilde{\alpha}$: Effective parity-violating asymmetry

muEDM Sensitivity: Projected Parameters

Parameter	$\pi E1$ (Phase I)	$\mu E1$ (Phase II)
Muon flux (μ^+ /s)	4×10^6	1.2×10^8
Channel transmission	0.03	0.005
Injection efficiency	0.003	0.60
Muon storage rate (1/s)	400	360×10^3
Gamma factor γ	1.04	1.56
e^+ detection rate (1/s)	300	90×10^3
Detections per 200 days	8.64×10^9	1.5×10^{12}
Mean decay asymmetry A	0.45	0.3
Initial polarization P_0	0.95	0.95
Sensitivity in one year ($e \cdot \text{cm}$)	$< 3 \times 10^{-21}$	$< 6 \times 10^{-23}$

T-Method (Energy Cut)

- Applies a simple lower threshold u_0 to the positron energy spectrum in the LAB frame
- Extracts a single global asymmetry value $\tilde{\alpha}$ above the threshold u_0
- Simple, but discards low-energy positrons with opposite asymmetry sign

W-Method (Binned Information)

- Retains the full (u, θ, ϕ) phase space information
- Bins are weighted dynamically by their local statistical sensitivity:

$$W_{ijk}^2 = \frac{S_{ijk}^2}{N_{ijk}} \propto I(\Theta)_{ijk}$$

- Captures and exploits the asymmetry sign flip

muEDM Analysis: Fisher Information and Figure of Merit

Continuous Formulation:

- The PDF with a small EDM perturbation is modeled as:

$$p(\Omega, \Theta) = p_0(\Omega) [1 + \Theta \cdot \partial_{\Theta} A(\Omega)]$$

- Evaluating the Fisher Information $I(\Theta)$ at the null hypothesis $\Theta = 0$:

$$I(0) = \int \frac{1}{p_0(\Omega)} \left(\frac{\partial p}{\partial \Theta} \right)^2 d\Omega$$

- Substituting the derivative yields:

$$I(0) = \int p_0(\Omega) [\partial_{\Theta} A(\Omega)]^2 d\Omega$$

Binned Discretization:

- In a binned phase space $\Delta\Omega_{ijk}$, the background and signal estimators are:

$$N_{ijk} \approx N_{\text{tot}} p_0(\Omega_{ijk}) \Delta\Omega$$

$$S_{ijk} \approx N_{\text{tot}} p_0(\Omega_{ijk}) \partial_{\Theta} A(\Omega_{ijk}) \Delta\Omega$$

- The global Figure of Merit \mathcal{W}^2 directly measures the discrete Fisher Information:

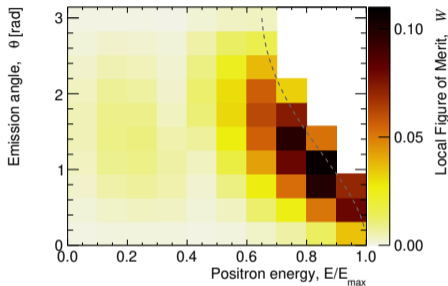
$$\mathcal{W}^2 = \frac{1}{N_{\text{tot}}} \sum_{ijk} \frac{S_{ijk}^2}{N_{ijk}} \equiv I(0)$$

- Since $\sigma^2(\Theta) \geq 1/I(0)$, the W-method mathematically saturates the sensitivity limit

Effect of the Tracker on Sensitivity

- **Binned analysis** optimizes the sensitivity (the Figure of Merit F is nearly doubled)
- \Rightarrow The positron tracker must reconstruct **all kinematic variables** (E, θ, ϕ) of the decay positron

Method	Thres.	Phase I ($E_{\max} = 68.9$ MeV)			Phase II ($E_{\max} = 140.2$ MeV)			
		$\bar{\alpha}$	N_{e^+}/N_{μ^+}	FoM (F)	Thres.	$\bar{\alpha}$	N_{e^+}/N_{μ^+}	FoM (F)
Simple	None	0.166	1.000	0.166	None	0.166	1.000	0.166
T-method	0.626	0.345	0.397	0.217	0.183	0.195	0.835	0.178
W-method (1D)	None	0.251	1.000	0.251	None	0.183	1.000	0.183
(20 energy bins)	0.400	0.280	0.800	0.250	0.150	0.194	0.876	0.183
W-method (3D)	None	0.292	1.000	0.292	None	0.280	1.000	0.280
(20x20x20 bins)	0.400	0.326	0.800	0.291	0.150	0.299	0.876	0.280



Local sensitivity distribution in (E, θ) space. The dashed line marks the kinematic limit of the boost.

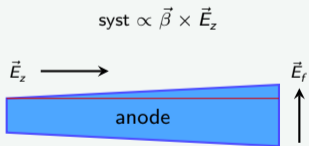
Systematics - Main sources

All effects leading to a real or apparent spin precession around the radial axis mimic an EDM:

- **Real:** Coupling of a_μ with the EM fields of the experimental setup
- **Apparent:** Early-to-late variation of detection efficiency of the EDM detectors

Geometric Imperfection

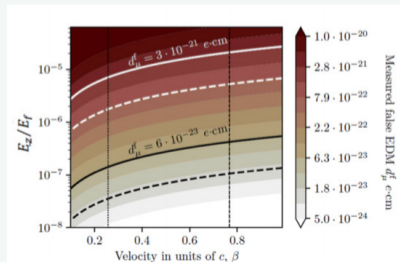
Non-constant radius of the cylindrical anode induces a spurious longitudinal field \vec{E}_z :



Cancellation Mechanism

Reversing $\vec{\beta}$ (and \vec{B}) isolates the true EDM signal ($\vec{\beta} \times \vec{B}$):

- Requires alternating **CW** and **CCW** injection runs



Systematics summary

Systematic Effect	Phase I ($10^{-21} \text{ e} \cdot \text{cm}$)		Phase II ($10^{-23} \text{ e} \cdot \text{cm}$)	
	Expected Value	Syst. Contribution	Expected Value	Syst. Contribution
Radial B -field (ω_a coupling)	$5 \mu\text{T}$	0.03	$20 \mu\text{T}$	0.75
Current flowing through orbit	$< 10 \text{ mA}$	$< 10^{-2}$	$< 10 \text{ mA}$	0.30
E -field related systematics (gradients)	–	0.75	–	1.50
Resonant geometrical phase	Pitch $< 1 \text{ mrad}$	2×10^{-2}	Pitch $< 1 \text{ mrad}$	0.15
TOTAL		0.75		1.70

- The systematic budget is strictly controlled to match the target sensitivity of each phase: $\approx 1 \times 10^{-21} \text{ e} \cdot \text{cm}$ (Phase I) and $\approx 6 \times 10^{-23} \text{ e} \cdot \text{cm}$ (Phase II)
- The dominant systematic contributions arise from electric field gradients and radial magnetic field couplings

Beam Time 2026: Expected Outcomes

Technical & Trap Commissioning

- **Efficient Injection:** Mapping and imaging the magnetic field via muon trajectories and beam spot propagation
- **Kicker Tuning:** Optimizing the new KIT kicker parameters for highly efficient trapping
- **First Muon Storage:** Successful trapping of muons inside a compact magnetic trap
- **Positron Tracking:** Demonstration of CHET tracker performance using the cylindrical scintillating fiber detector

Physics & Sensitivity Milestones

- **Frozen-Spin Application:** First experimental implementation of the frozen-spin technique for stored muons
- **$g-2$ vs. Electric Field:** Measurement of the $g - 2$ precession frequency as a function of the applied E -field
- **EDM Sensitivity:** Measurement at the exact frozen-spin condition, demonstrating sensitivity to the EDM
- **Ready for 2027:** Commissioning finalized and setup ready for production data taking

CHeT: Positron Reconstruction Pipeline

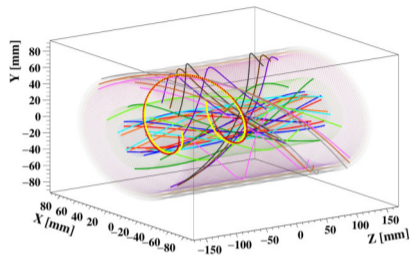
1. Pattern Recognition (Hough Transform)

▪ XY Circular Hough:

- Triplet-logic voting scheme to find the circle center (x_c, y_c) and track radius R in the transverse plane
- Uses random sampling for high-occupancy events

▪ SZ Linear Hough:

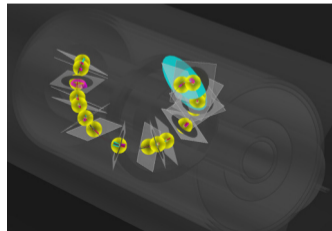
- Once (x_c, y_c, R) is fixed, the helix unrolls to a line in the s - z plane ($s = R \cdot \phi$)
- Solves multi-turn ambiguities in ϕ space



2. Track Fitting (Kalman Refinement)

▪ GenFit Engine Integration:

- Runge-Kutta numerical propagation (RKTrackRep) inside the magnetic field
- Fully integrates multiple scattering and energy loss (dE/dx) corrections

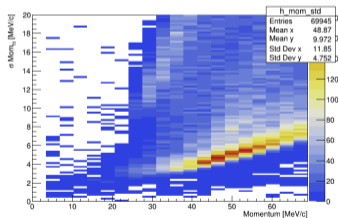


Reconstructed helix visual representation (GenFit)

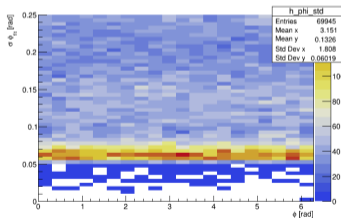
CHeT: Reconstructed Track Resolutions

Typical track parameter resolutions obtained from Monte Carlo simulation (estimated using the **mode** of the residual distributions to suppress the tails of badly reconstructed tracks):

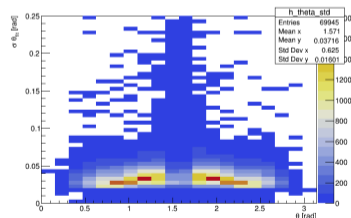
- **Momentum resolution:** $\sigma_p \approx 0.1 \text{ MeV} \times p$
- **Polar angle resolution:** $\sigma_\theta \approx 50 - 100 \text{ mrad}$
- **Azimuthal angle resolution:** $\sigma_\phi \approx 10 - 50 \text{ mrad}$



Momentum resolution σ_p vs. p



Azimuthal resolution σ_ϕ vs. ϕ



Polar resolution σ_θ vs. θ

CHeT: Cosmic Run & Efficiency Study (TB2025)

Direct Helical Fitting on 1D Bundles

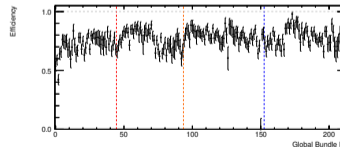
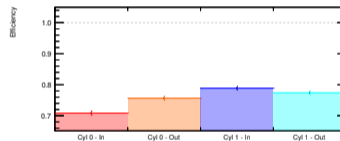
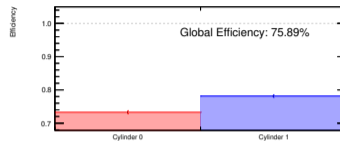
- The TB2025 setup consisted of only 2 cylinders, making standard 3D point-reconstruction fragile
- **Paradigm Shift:** Each fired fiber is treated as a 1D helical bundle constraint
- Direct track χ^2 minimization of 3D distances:

$$\chi^2 = \sum \frac{\Delta x_i^2 + \Delta z_i^2}{\sigma^2}$$

- Highly robust against single-layer inefficiencies.

Preliminary Detection Efficiency

- **Methodology:** Extrapolating the 3D reconstructed track to the cylinder radius and searching for a matching hit within $\pm N$ neighboring fibers
- **Results:** Estimated single-bundle detection efficiency of **75%** – **80%** (dependent on the search window tolerance)



Experimental cosmic track reconstructed (TB2025)