The Mu3e and MuonEDM experiments at PSI

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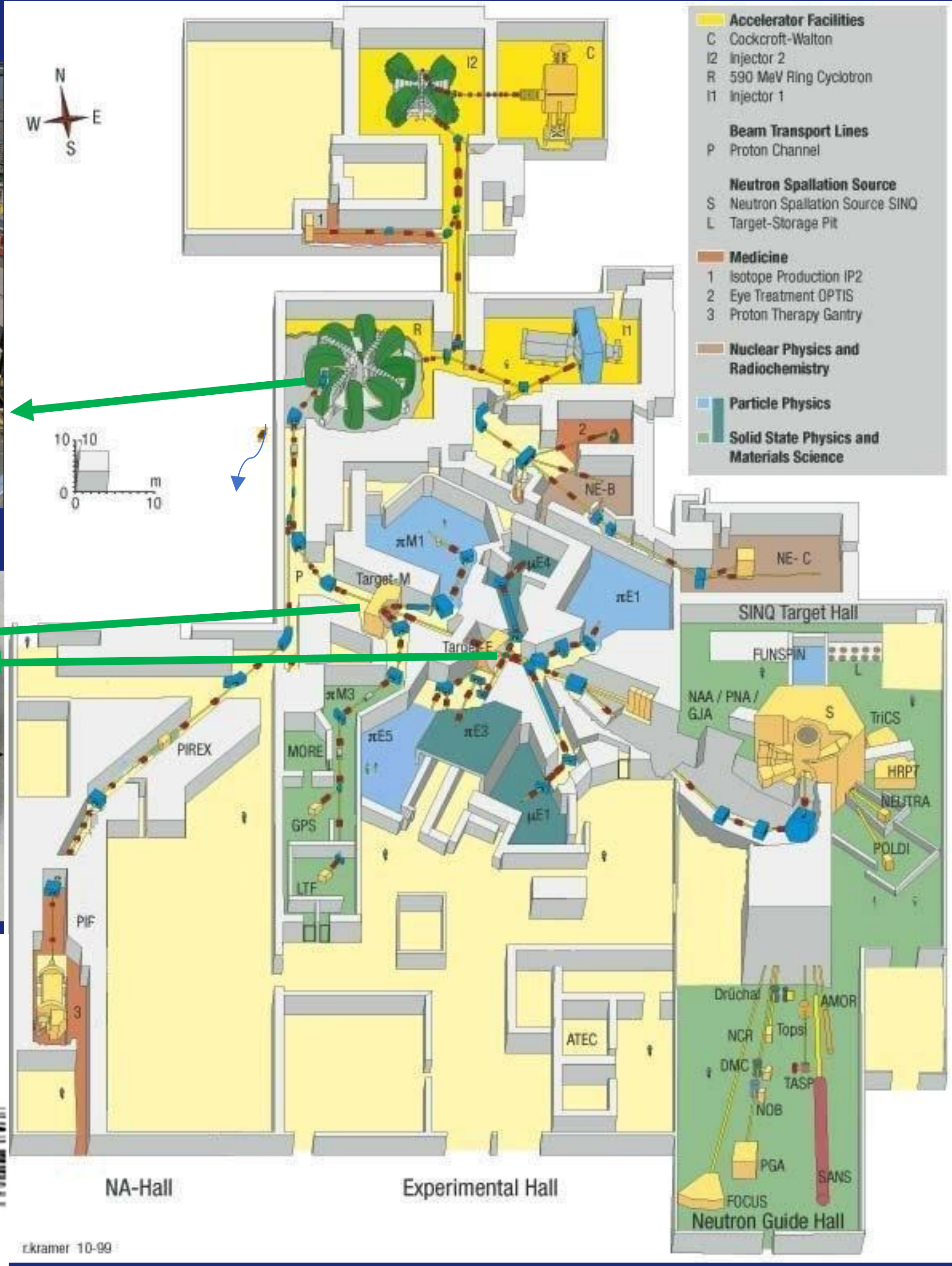
FCCP2025 Workshop, Capri

Muon beams at PSI

590MeV proton cyclotron 2.4 mA, 1.4 MW

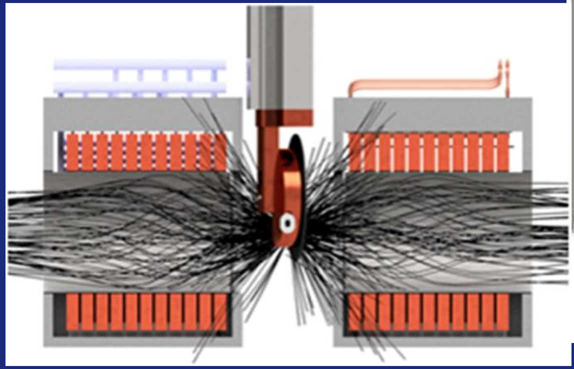
Muons produced from pion decay on two graphite target wheels provide to different muon experiments (MEG-II, Mu3e, MuEDM, MuSE, μSR,…)

World's highest intensity (> 1×10^{8} μ/s) DC beam of surface muons (~29 MeV) beam



High Intensity Muon Beam (HIMB) upgrade (27/28):

New target station and large aperture solenoids to deliver up to 1×10^{10} μ/s to future muon experiments.



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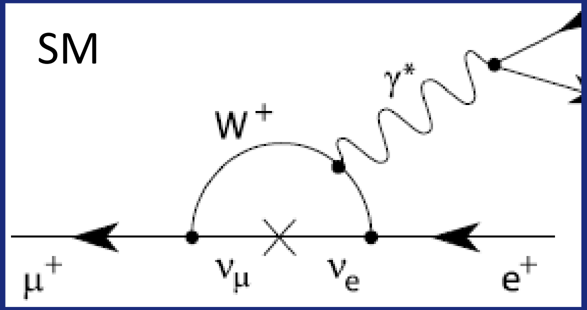
The mu3e experiment at PSI

Charged Lepton Flavour Violation in Muon decays

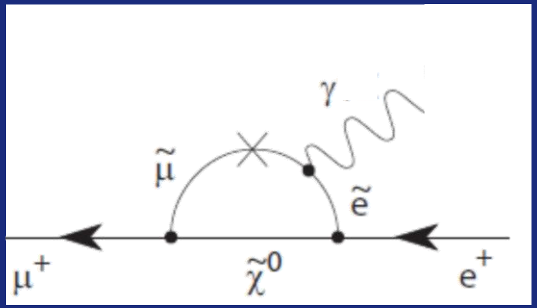
Heavily suppressed in the SM due to low neutrino mass.



$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W}\right|^2 < 10^{-54}$$

Any observation of CLFV is evidence of NP.

Charged lepton flavour violation can appear naturally in NP theories.



CLVF μ-decay status

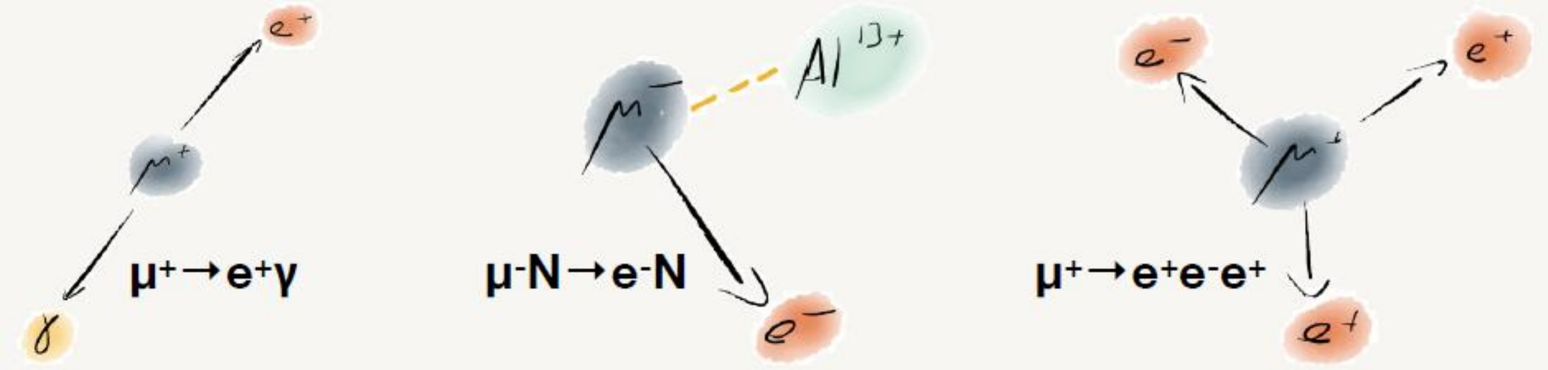
μ^- DECAY MODES

μ^+ modes are charge conjugates of the modes below.

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$e^-\overline{\nu}_e\nu_\mu$		$\approx 100\%$	
Γ_2	$e^-\overline{\nu}_e\nu_\mu\gamma$	[a]	$(6.0\pm0.5)\times10^{-8}$	
Γ_3	$e^-\overline{\nu}_e\nu_\mu e^+e^-$	[b]	$(3.4\pm0.4)\times10^{-5}$	

CLFV muon decays, thanks to simple SM decay modes and long lifetime, offer a sensitive probe for new physics.

If charged lepton flavour is violated, we can see the muon decays:



MEG-II (PSI)	SINDRUM II (PSI)	SINDRUM (PSI)
BR < 1.5×10^{-13}	BR(μ Au $\rightarrow$ e Au) < 7.0×10^{-13}	BR < 1.0×10^{-12}

New experiments will push the sensitivity for these branchings ratio by up to four orders of magnitude over the next 5-10 years.

Reach for NP up to O(PeV) mass scales.

	Projected sensitivities (90%CL)
$\mu\rightarrow e\gamma$	6×10^{-14} MEG II (PSI)
$\mu\rightarrow eee$	4×10^{-15} Mu3e I (PSI) 1×10^{-16} Mu3e II (PSI)
μAl$\rightarrow$eAl	6×10^{-17} Mu2e (FNAL) 7×10^{-15} COMET I (J-PARC) 6×10^{-17} COMET II (J-PARC)

The search for the μ → eee decay

Signal events

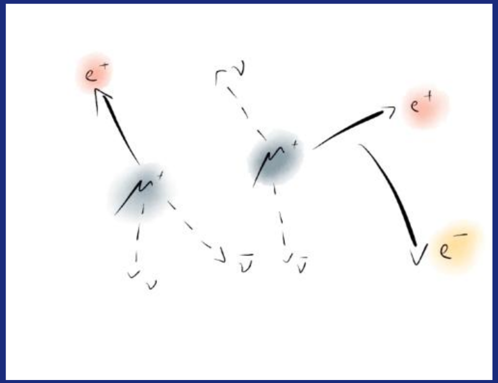
- 3 co-incident tracks from a single vertex ($e^+e^+e^-$)
- $\sum \vec{p} = 0, \sum E = m_\mu$

Backgrounds:

Michel decay with internal conversion

BR($\mu^+ \rightarrow e^+e^+e^-\nu\bar{\nu}$) = 3.4x10^{-5}

$\rightarrow \sum E < m_\mu$



Accidental backgrounds:

dominated by a Michel e^+ and an e^+e^- pair from a Bhabha scattering second Michel e^+ .

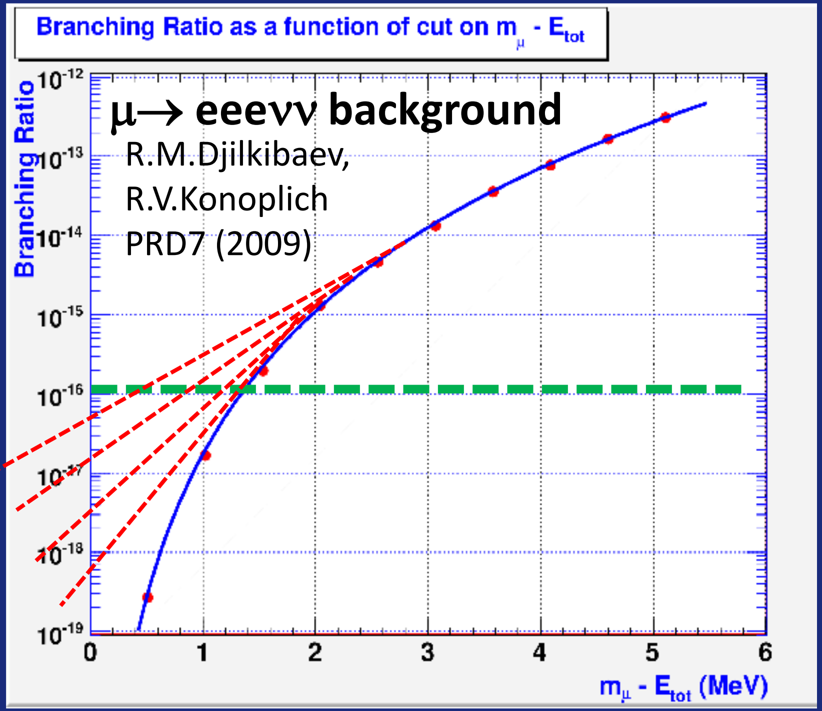
$\rightarrow \sum E \neq m_\mu$

→ not co-incident

→ no single vertex

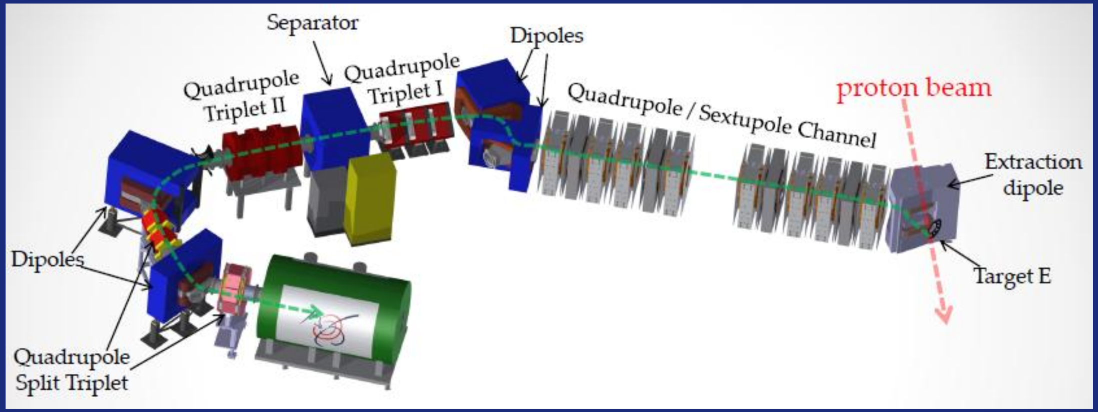
Experiment requirements:

- High intensity muon beam (1x10^8 – 2x10^9 μ/s)
- High rate capable detectors



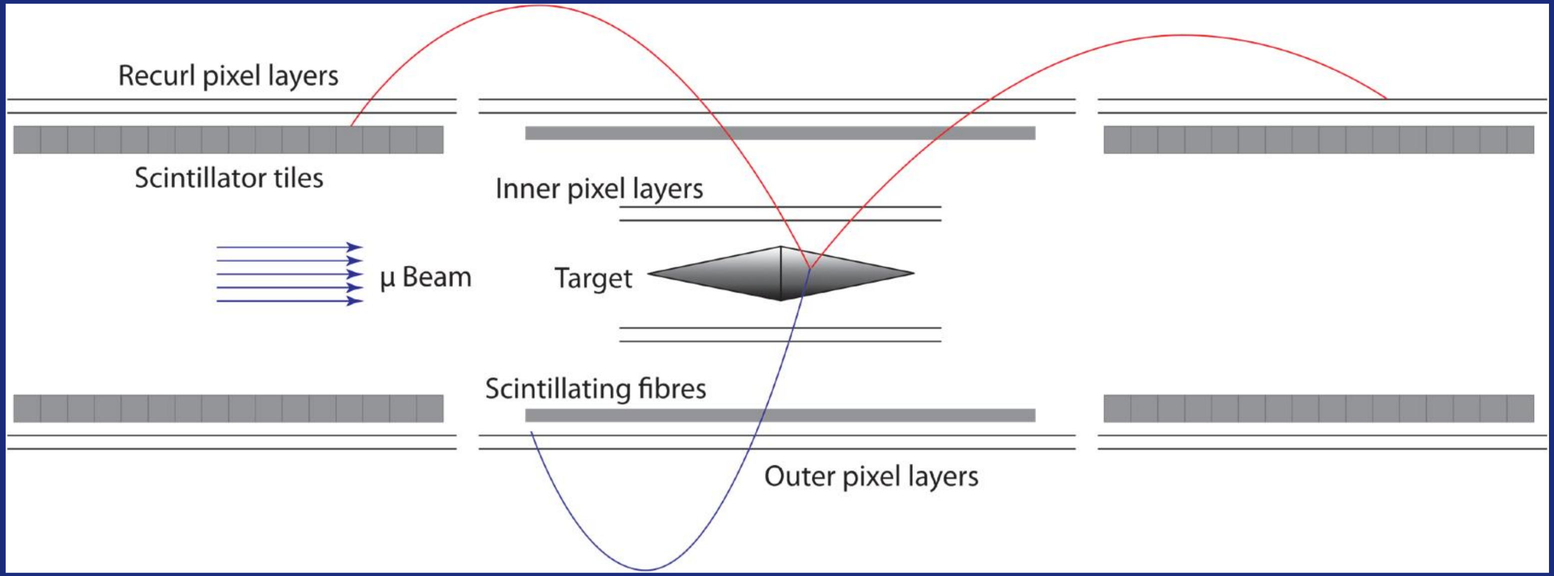
- Excellent momentum resolution for low momentum electrons (10^{-53} MeV) → σ(E$_{tot}$) < 1 MeV
- DC muon beam
- Excellent vertex and timing resolution

Mu3e: μ→eee at PSI



Mu3e shares the πe5 beamline with MEG-II

Inside the 1T magnet up to 2×10^9 μ/s are stopped on thin mylar target.

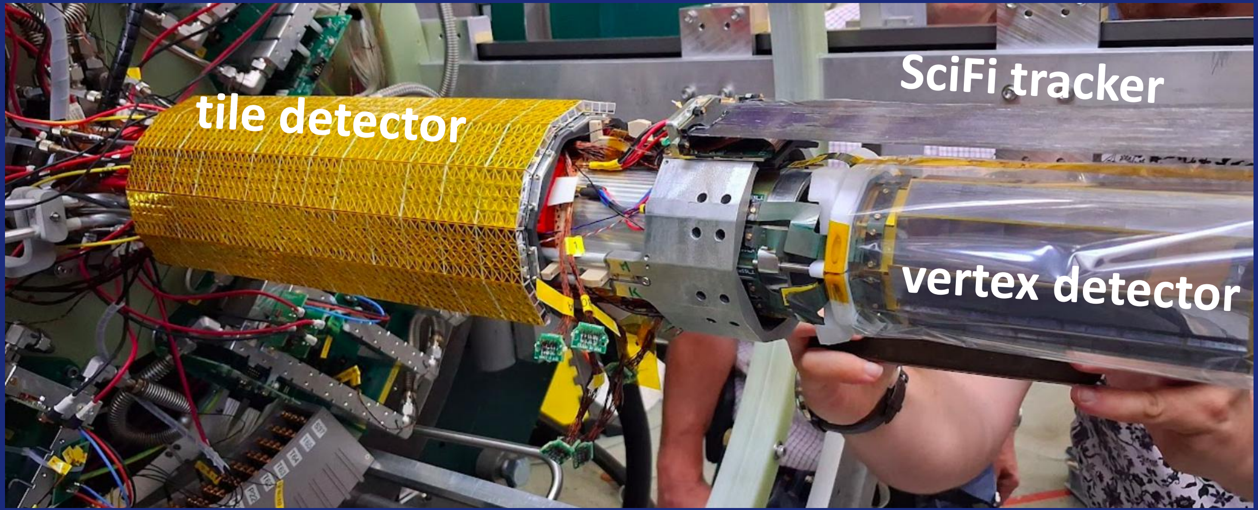


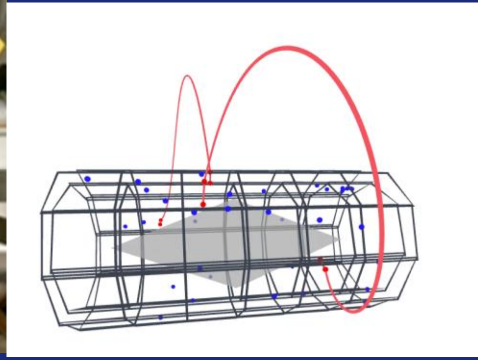
Electrons and positrons are tracked through the inner, outer and recurl layers of the HV-MAPS MuPix tracker
Ultra low mass tracker with ~0.1%X_0 per layer. (50-70 μm sensors, low mass supports, cooled with gaseous Helium)

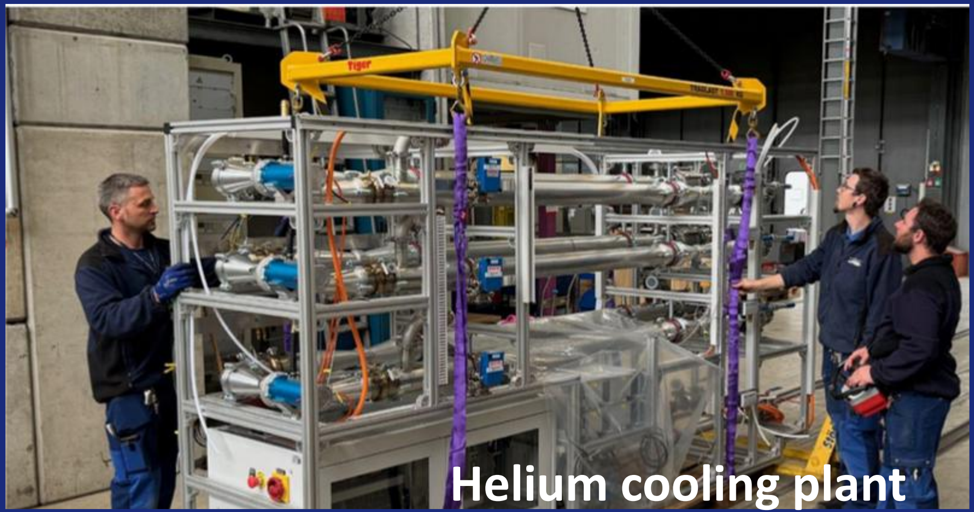
Electron and positron timing is measured
with the scintillating fiber and tile detectors, both with SiPM readout.

Mu3e status

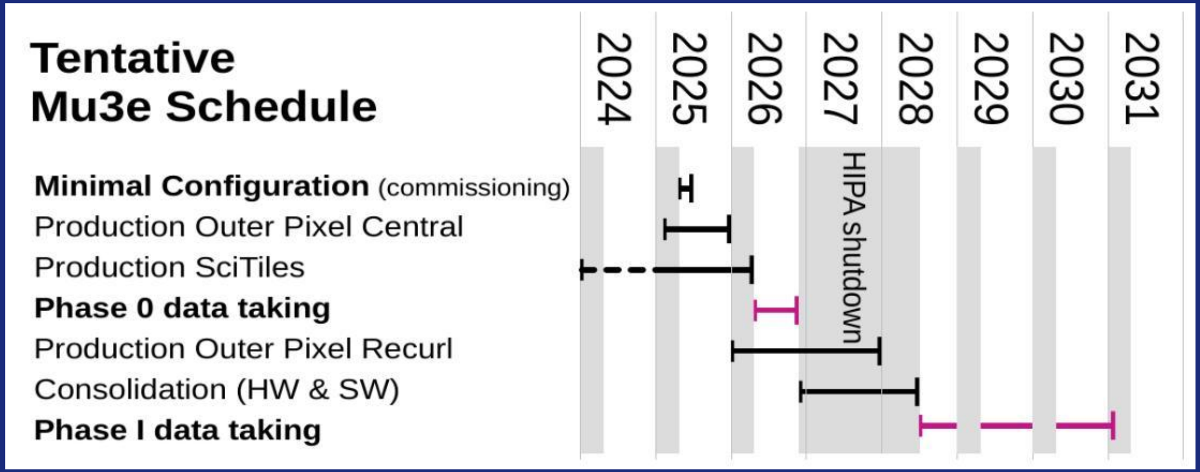
Construction of the mu3e experiment is ongoing. Cosmic and beam runs with a partial detector have taken place in 2024 and 2025.







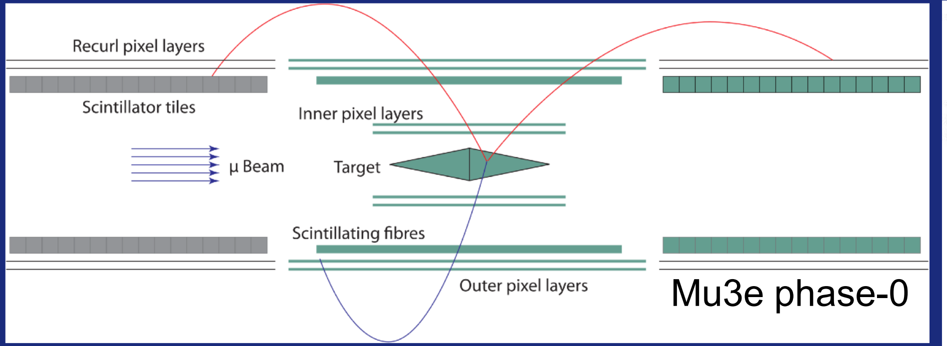
Mu3e Schedule

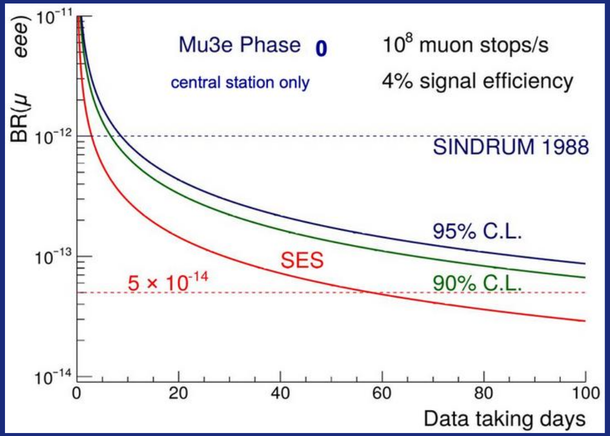


Phase-0 run 2026

First Mu3e physics operation in 2026.

- Full central detector + one tile station
- Substantial improvement on Sindrum limit (10^{-12}) based on weeks of data.





Phase-1 run 2028-2030

Complete phase 1 detector with recurl pixel layers and tiles

Sensitivity to BR($\mu \to eee$) ~ 2×10^{-15}

Phase-2 (>2031) experiment

- 2×10^{9} μ/s after PSI HIMB upgrade
- Upgraded detector with extended acceptance and fast silicon to control higher combinatoric backgrounds
- Sensitivity to BR($\mu \to eee$) ~10^{-16}

The MuEDM experiment at PSI

PSI Proposal No. R-21-02.1
Measurement of the Muon Electric Dipole Moment

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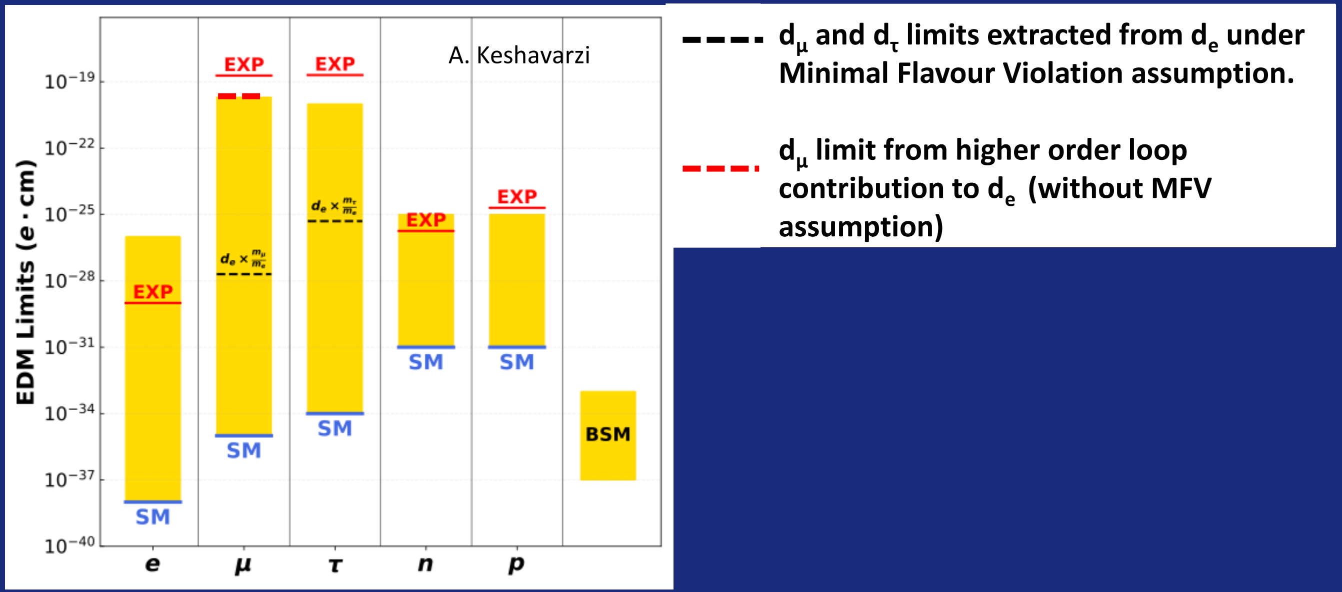
Motivation

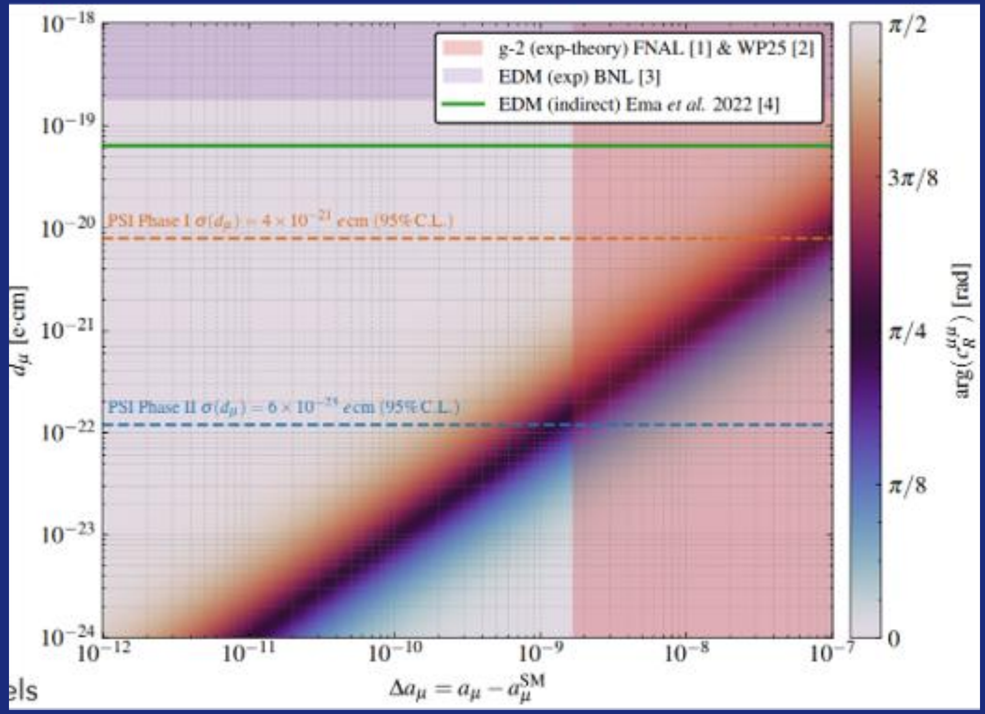
Fundamental particle electric dipole moments

- SM EDM value is small and out of reach of current experiments.
- non-zero EDM is direct evidence of NP (violation of CP)

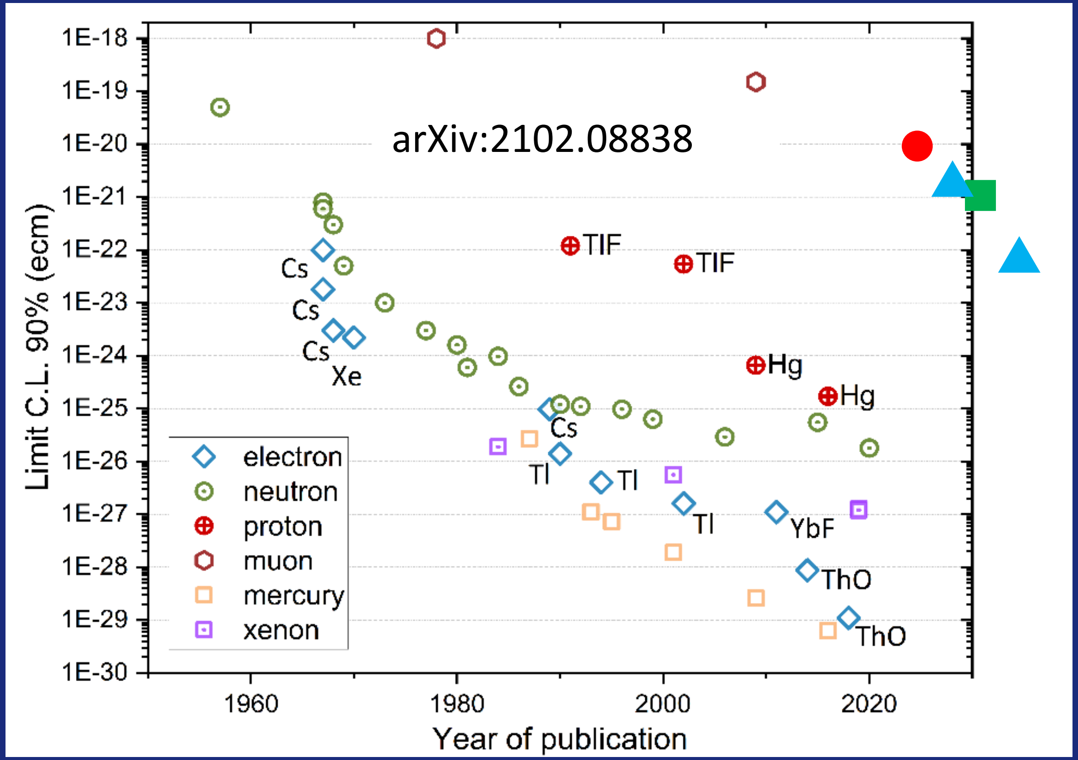
Why muons?

- Precision at which electron, proton and neutron EDMs have been studied is hard to reach, but a big improvement is possible and will cover substantial NP phase space.
- Non-zero muon EDM is evidence NP and violates both CP **and flavour universality**
- In EFT the electric dipole moment and an NP contribution to the anomalous magnetic moment are linked via the same Wilson coefficient.





Results / projections from g-2 experiments



- BNL g-2 experiment: $|d_\mu| < 1.9 \times 10^{-19}$ e.cm (95% C.L.)
- *FNAL g-2 experiment: $|d_\mu| < 1 \times 10^{-20}$ e.cm (95% C.L.)*
- *JPARC-E34 g-2 experiment: $|d_\mu| < 1.5 \times 10^{-21}$ e·cm (95% C.L.)*
- *PSI muEDM experiment (Phase 1): $|d_\mu| < 4 \times 10^{-21}$ e·cm (95% C.L.)*

  PSI muEDM experiment (Phase 2): $|d_\mu| < 6 \times 10^{-23}$ e·cm (95% C.L.)

Indirect muon edm limit from electron edm limits (without assuming minimal flavour violation!)
(Muon EDM induces electron EDM via higher order loop diagrams)
$|d_\mu| <$ few x 10^{-20} e·cm (depending on the calculation and e electron edm data used)

Muon electric dipole moment in g-2 experiments

General expression for the spin precession (Thomas-BMT equation):

$$\vec{\Omega} = -\frac{q}{m}\left[a\vec{B} - \frac{a\gamma}{(\gamma+1)}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] - \frac{\eta q}{2mc}\left[c\vec{\beta}\times\vec{B} + \vec{E} - \frac{\gamma\left(\vec{\beta}\cdot\vec{E}\right)\vec{\beta}}{(\gamma+1)}\right],$$

Anomalous Magnetic Moment term ($a = \frac{g-2}{2}$)

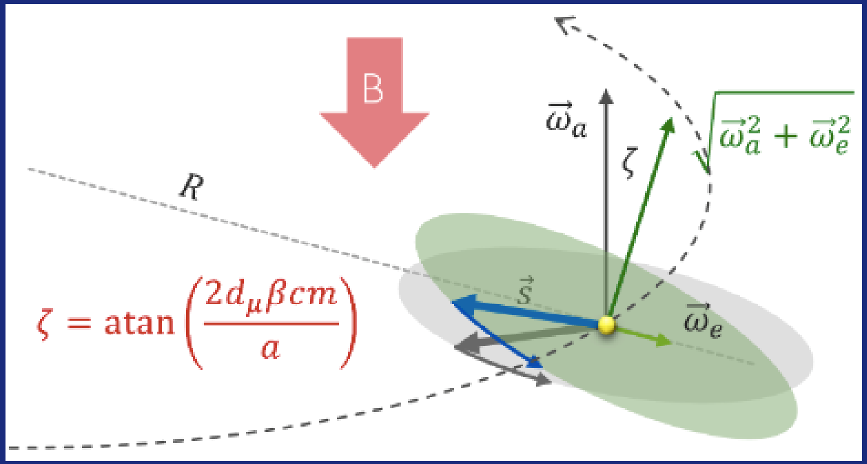
Electric Dipole Moment ($d = \frac{\eta q \hbar}{4m}$)

In g-2 experiments:

- $\vec{\beta} \perp \vec{B} \perp \vec{E} \quad (\vec{\beta}.\vec{B} = \vec{\beta}.\vec{E} = 0)$
- and also (FNAL and g-2) magic momentum ..(no focusing E-field in JPARC g-2)

To measure the muon EDM

- The g-2 precession causes the spin to rotate in the plane of the muon orbit.
- Al non-zero EDM causes an additional spin rotation out of the orbital plane.
- The combination of the two rotations causes tilt in the precession axis at a fixed (very small) angle with respect to the g-2 precession axis of the orbital plane.



A large enough tilt leads to an observable up-down fluctuation with frequency $\sim\omega_a$ (and phase shifted by 90°) in the rate of emitted positrons from the anti-muon decay. d_μ can be extracted from the amplitude of this asymmetry.

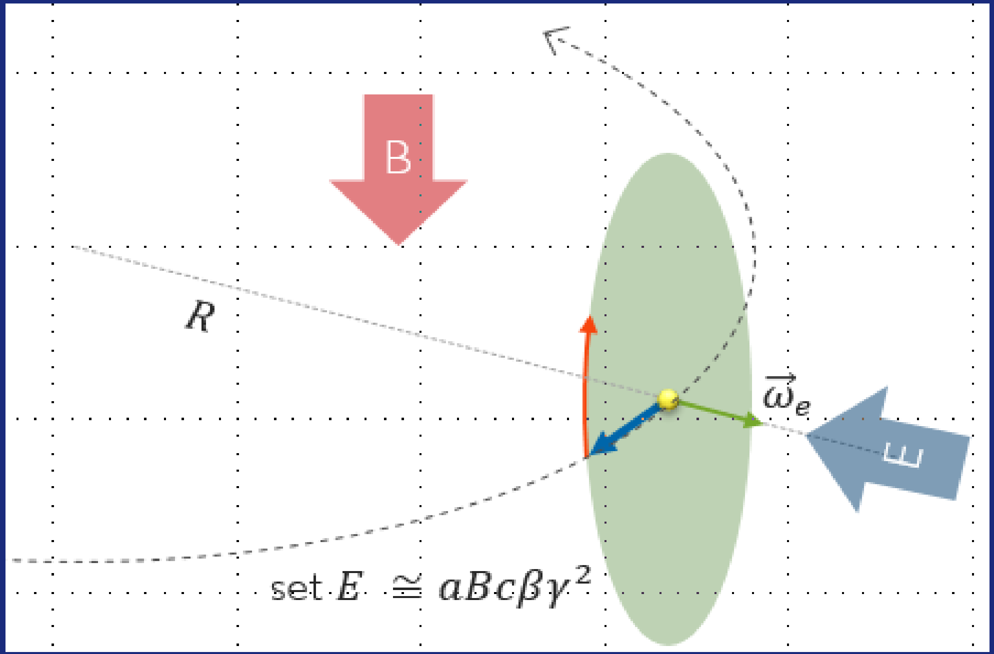
Muon e.d.m with the frozen spin method

$\vec{\beta} \perp \vec{B} \perp \vec{E} \quad (\vec{\beta}.\vec{B} = \vec{\beta}.\vec{E} = 0)$

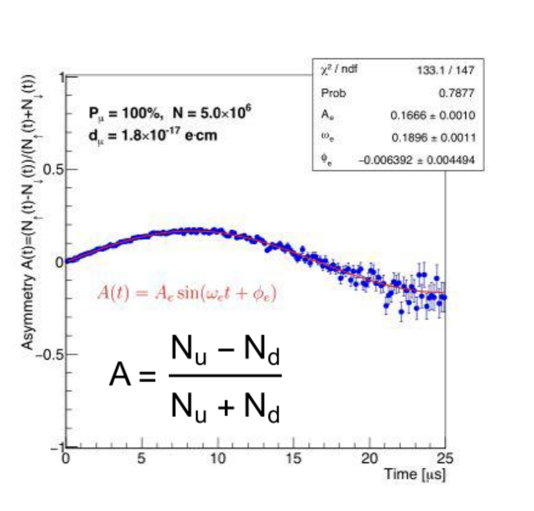
$$\vec{\Omega} = -\frac{q}{m}\left[a\vec{B} - \frac{a\gamma}{(\gamma+1)}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \left(a + \frac{1}{1-\gamma^2}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] - \frac{\eta q}{2mc}\left[c\vec{\beta}\times\vec{B} + \vec{E} - \frac{\gamma\left(\vec{\beta}\cdot\vec{E}\right)\vec{\beta}}{(\gamma+1)}\right],$$

With a radial electric field ($E \cong aBc\beta\gamma^2$) the g-2 precession can be removed, so spin stays aligned with the momentum (*frozen spin*)

This leaves only the EDM spin rotation out of the orbital plane. This now continues to build up over the entire lifetime of the muon.



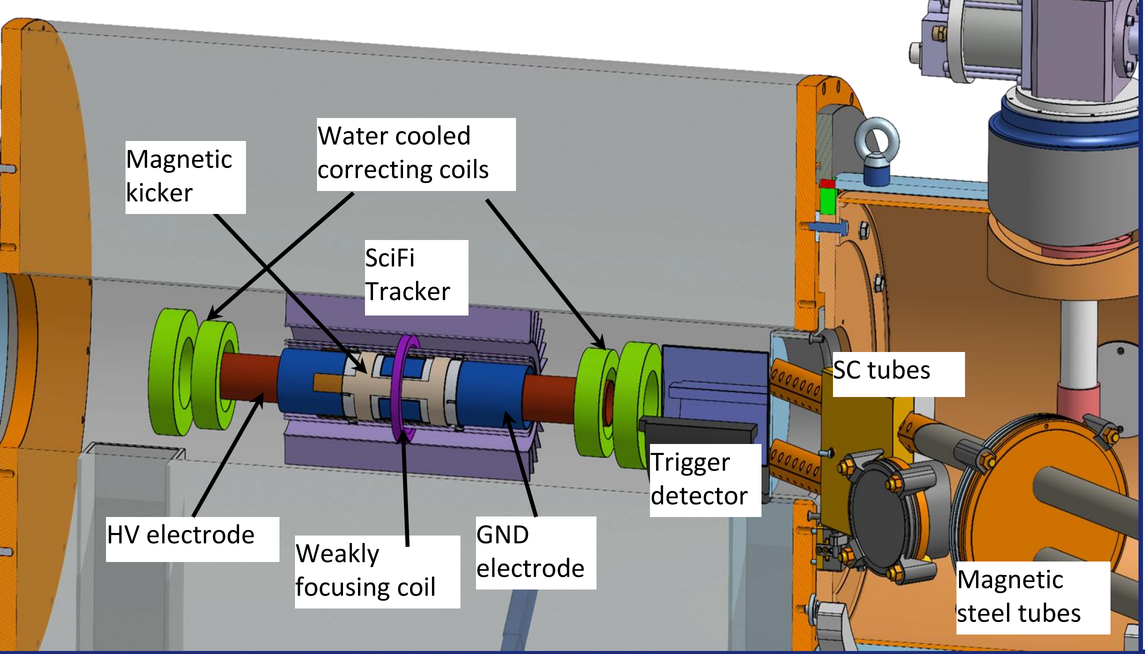
Note that for d_μ less than current limits We will see no oscillation, only a slow rise. (figure shows effect for d_μ =1.8x10^{-17} e.cm)



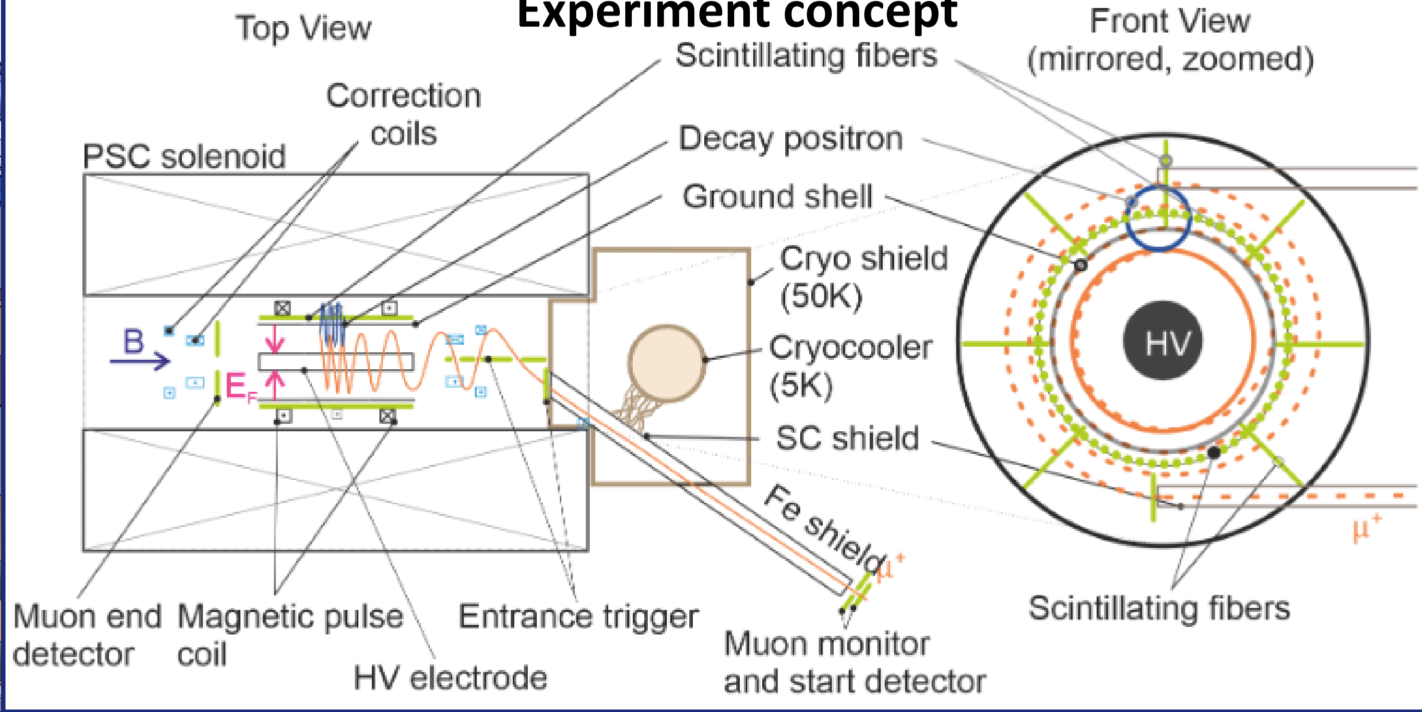
arXiv:2102.08838

The muon storage and detection cycle

Phase 1 experiment



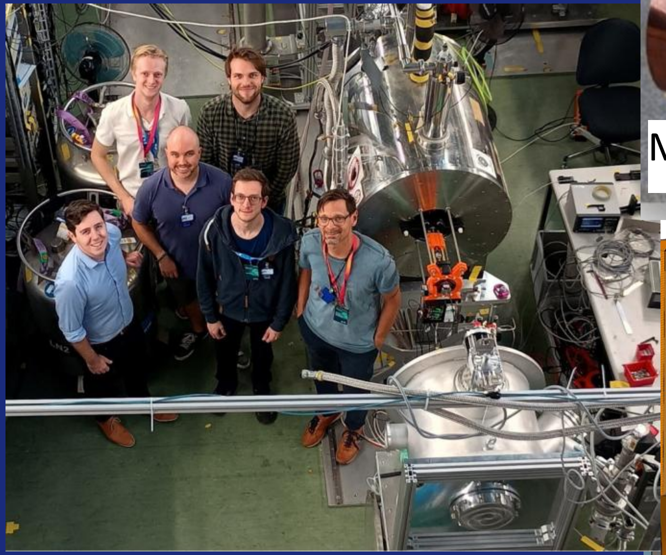
Experiment concept



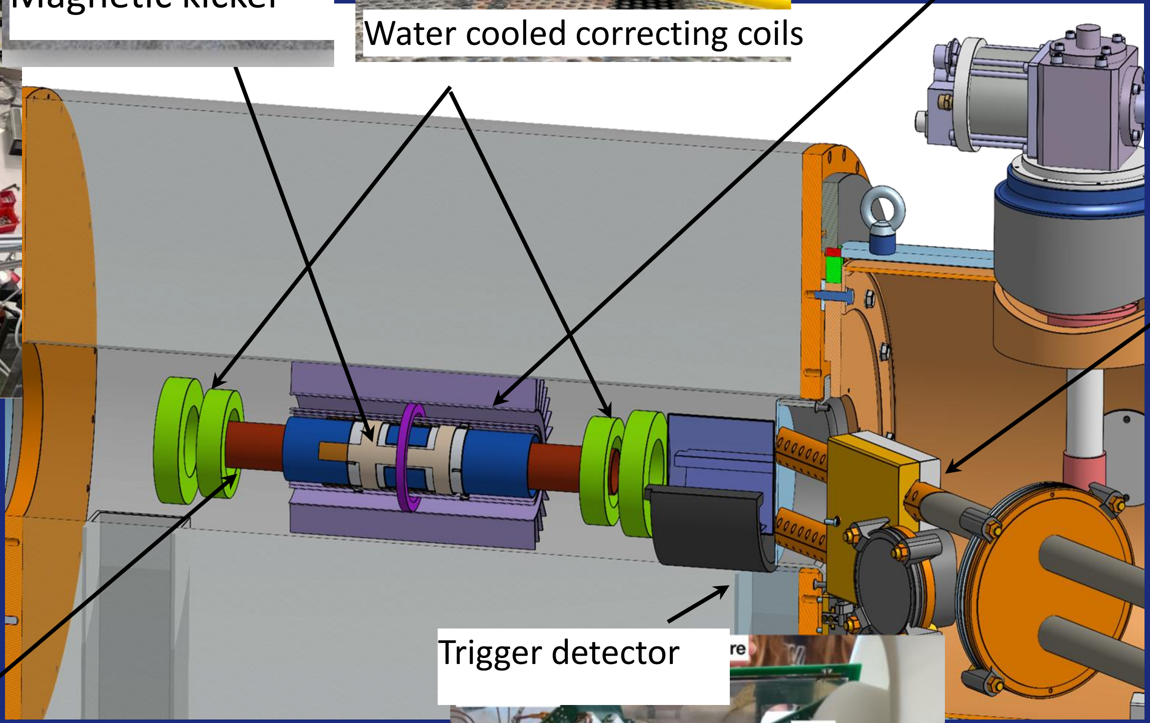
Storage and detection cycle

- Muons enter magnet through clockwise or anti-clockwise SC channel.
- Entrance trigger selects 23 MeV muons and triggers ..
- Kicker coils, remove longitudinal momentum
- Correction and focussing coils ensure muon is stored in central orbit
- Positron detectors measure in/out (AMM) and up/down (EDM) asymmetry

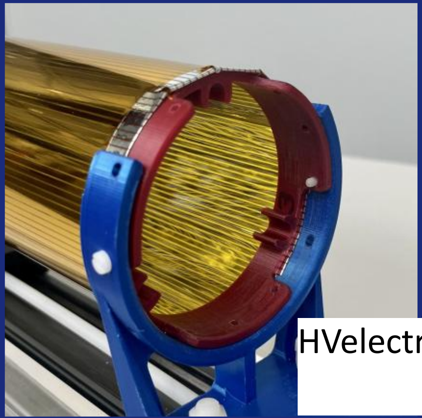
Development and construction progress



SciFi Tracker

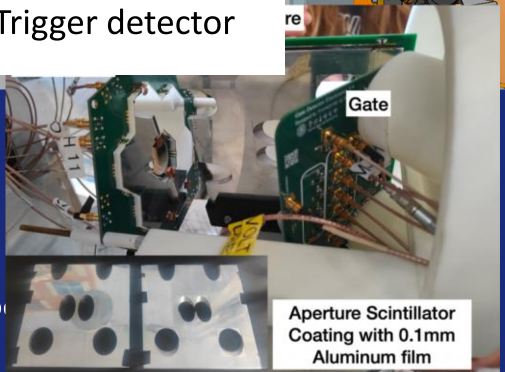


SC tubes



HVelectrode

Trigger detector



Experiment programme

Phase 1 (2025-2026) 23 MeV muons, B ~ 2.5 T,

$\vec{\sigma}.\vec{\beta} / |\vec{\sigma}| \left|\vec{\beta}\right| = +1$

2025 MuEDM testbeam

- Commission entrance detectors and demonstrate muon storage
- Verify positron detector performance

Beamtime programm 2025 in piE1

	hours	days
Initial mounting and alignement	48	
Beam tuning	12	
Measure spiral injection with TPC	72	5.5
remove TPC	12	
Measure sprial transmission	60	3
Modification to muSR stopping target	24	
Beam tuning	6	
Measure muSR spin orientation	108	5.8
Modification to magnetic pulse	36	
Measure stopping efficiency	108	6
modify to SciFi tests	120	
Measrue SciFi performance	72	8
Unmounting	6	
total days		**29**

Nov: 26 27 28 29 30 — December 2025: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23

2026 physics Run

- Frozen spin demonstration: measure g-2 and demonstrate it can be switched off with the appropriate electric field
- Possible first d_μ measurement with sensitivity $\sigma(d_\mu) \sim 3 \times 10^{-21}$ ***e.cm***

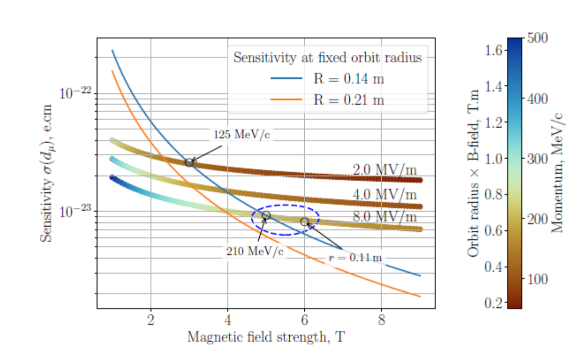
Phase 2: Dedicated high sensitivity experiment after PSI HIMB upgrade (>2030).

125 MeV muons, B ~ 5TeV, E ~ 8MV/m, $\vec{\sigma}.\vec{\beta} / |\vec{\sigma}| \left|\vec{\beta}\right| = -1$

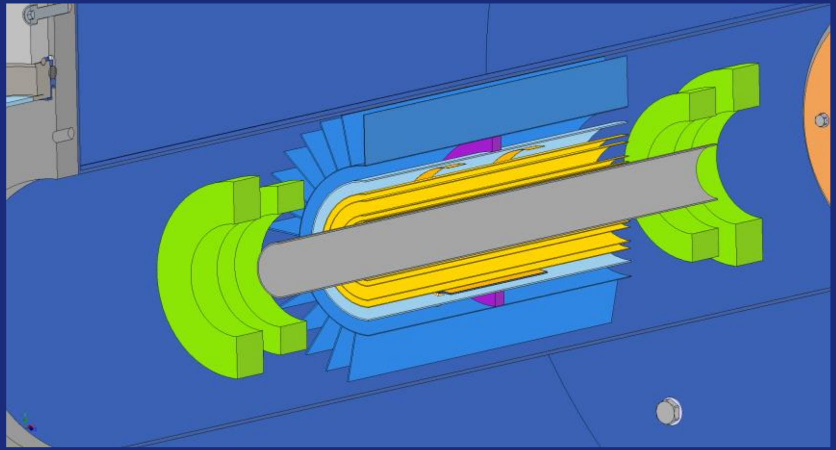
Upgrade of Phase 1 experiment based on R&D work and lessons from phase 1

A key limiting factor is the electric field (>8MV/m challenging in segmented thin electrodes)

Target sensitivity: $\sigma(d\mu) \sim 6 \times 10^{-23}$ ***e.cm***

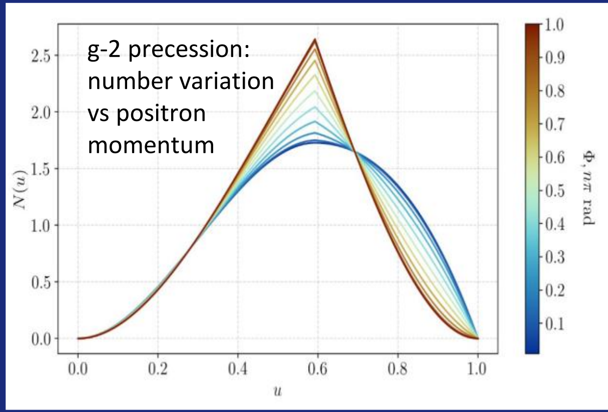


Optimizing the measurement



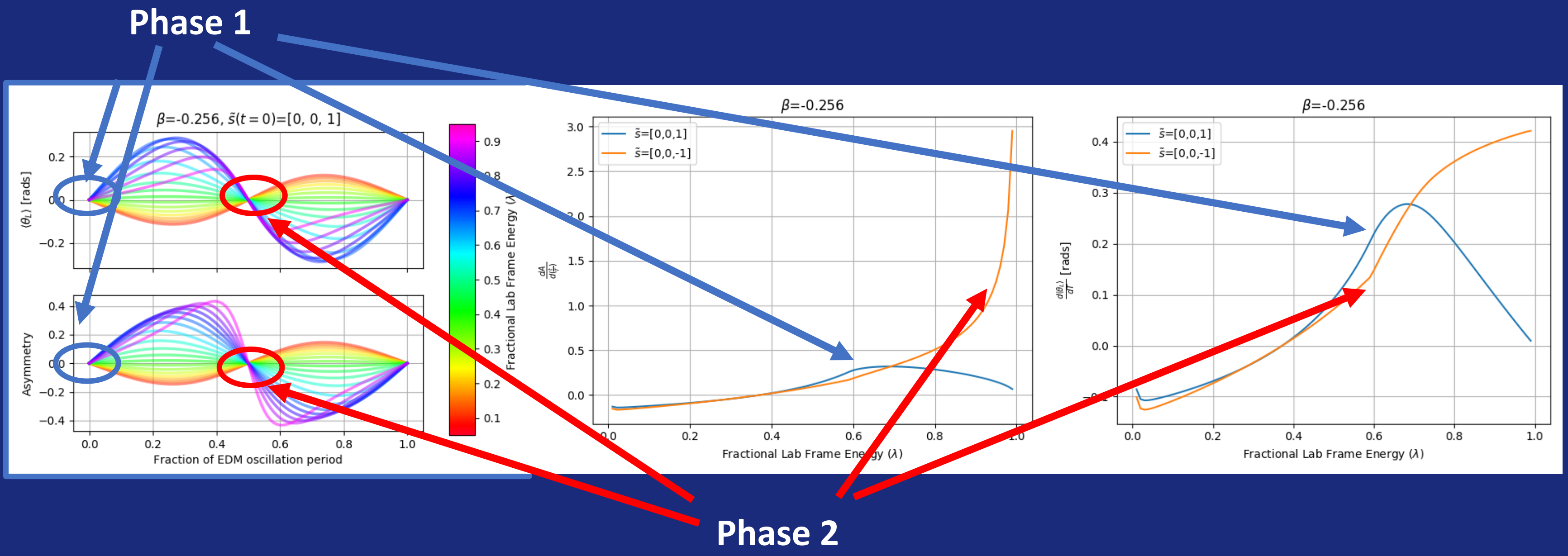
Scintillating fibre positron tracker measures the positron angle and momentum.

g-2 precession: optimization of the positron sample best use to tudy g-2 (and demonstrate the froze spin effect). number asymmetry depends on poritron momentum.



Demonstration frozen spin effect: exploit variation of rate as a function of positron momentum and angle to measure (and then remove) g-2 precession.

d_μ measurement: optimization of momentum and angle selection to maximize the slope of the up-down asymmetry.



Summary

Looking forward to the start of physic operation in 2026 for both the Mu3e and MuEDM experiments.

First physics results expected from 2026 operation.

Both will reach their full targeted sensitivities in the first half of the 2030's with sensitivity on the **Muon EDM** and the search for the **CLVF decay $\mu \rightarrow eee$** will be improved in steps with ultimate improvements of around four orders of magnitude compared to today's limits.

Summary

Exciting muon precision physics programme. I discussed only g-2, EDM and lepton flavour violation (there is more).

Sensitivity on the **Muon EDM** will be improved in steps with ultimate improvement of nearly four orders of magnitude possible from a dedicated experiment.

Current experiments and experiments under construction will improve sensitivity to **charged lepton flavour violation in muon decays** by up to four orders of magnitude.