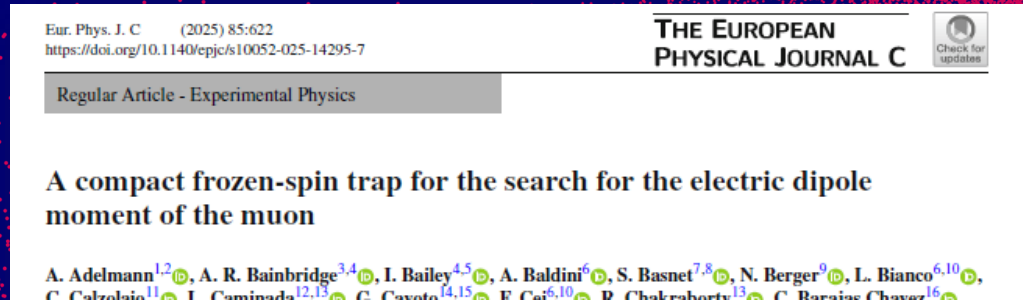


PSI Center for Neutron and Muon Sciences



Measurement of the EDM of the muon using the frozen-spin technique in a compact storage trap



- Philipp Schmidt-Wellenburg
- International Workshop on Muon Physics at the Intensity and Precision Frontiers | Shanghai | 23-24.04.2026

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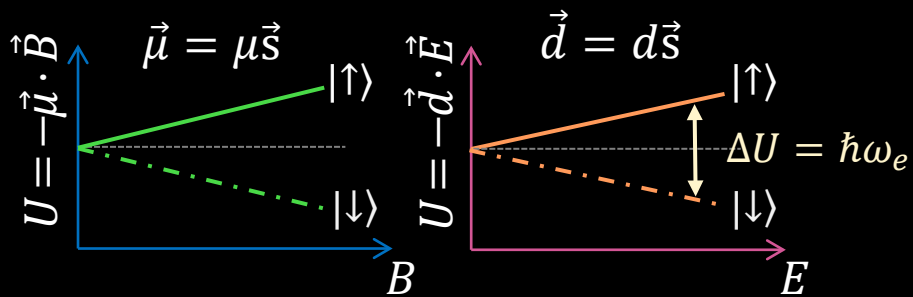
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SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
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This work is financed by the SNSF
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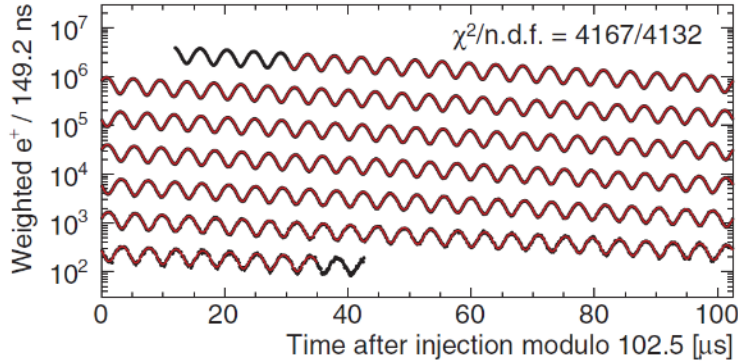
CP violation & edm



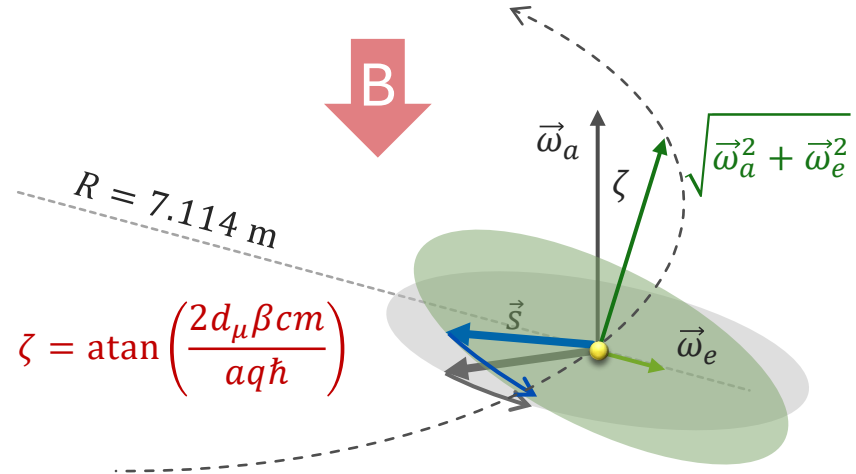


Muon dipole moments and frequencies

$$\vec{\omega} = \vec{\omega}_L - \vec{\omega}_c = -\frac{q}{m} \left[a\vec{B} + \underbrace{\left(\frac{1}{\gamma^2 - 1} - a \right) \frac{\vec{\beta} \times \vec{E}}{c}}_{\text{g-2 term } \omega_a} \right]$$



FNAL*: $\sigma(d_\mu) \approx 10^{-20} \text{ ecm}$
 JPARC**: $\sigma(d_\mu) \approx 10^{-21} \text{ ecm}$



[Abi et al., PRL126 141801(2021)]

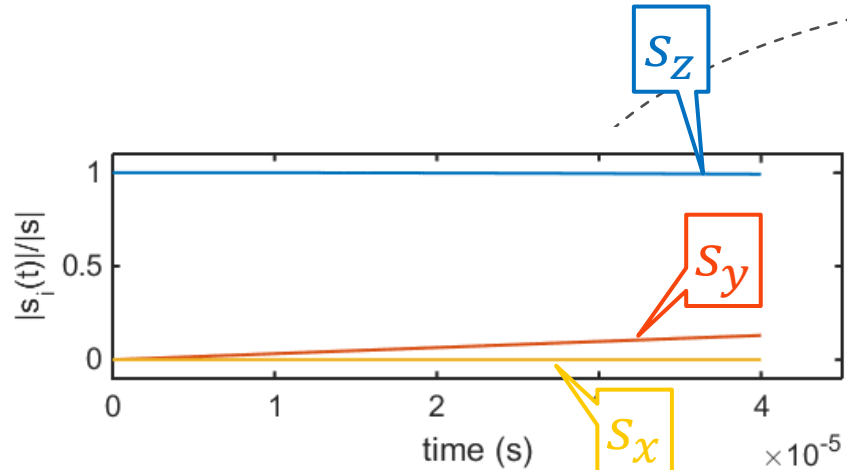
[*D. Vasikova (MPI2025), **Abe et al., PTEP053C02 (2019)]



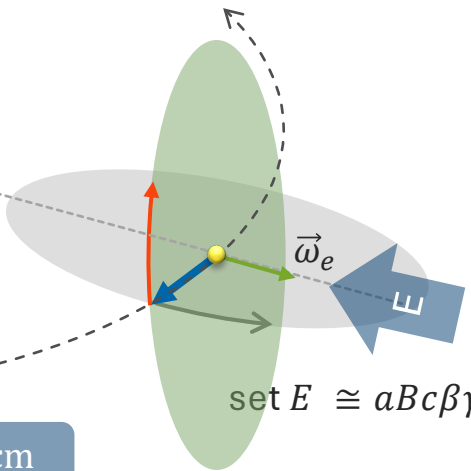
Muon dipole moments –freezing the spin at PSI PSI

$$\vec{\omega} = -\frac{q}{m} \left[\underbrace{a\vec{B} + \left(\frac{1}{1-\gamma^2} - a \right) \frac{\vec{\beta} \times \vec{E}}{c}}_{\text{g-2 term } \omega_a} + \underbrace{\frac{2d_\mu mc}{q\hbar} \left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right)}_{\text{EDM term } \omega_e} \right]$$

Frozen-spin potential at PSI: $\sigma(d_\mu) < 6 \cdot 10^{-23} \text{ ecm}$



$R = 31 \text{ mm}$

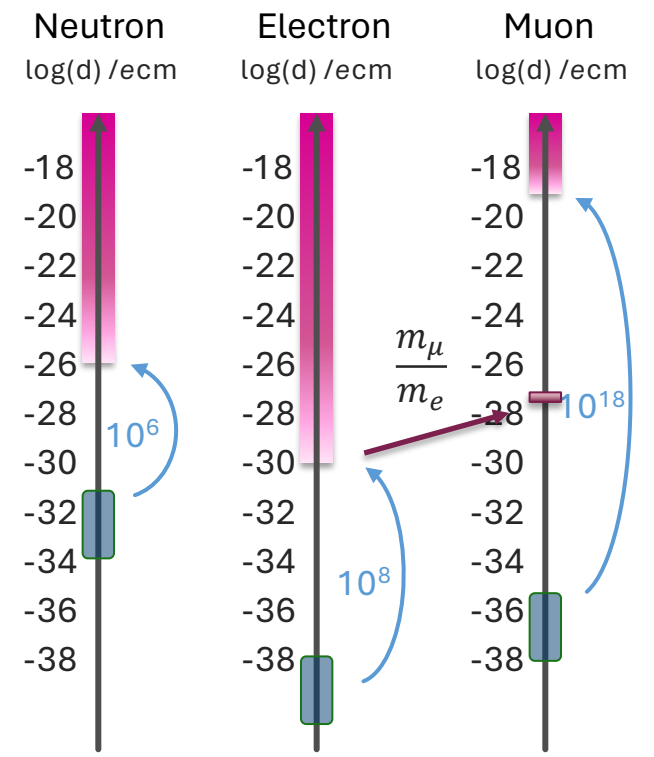
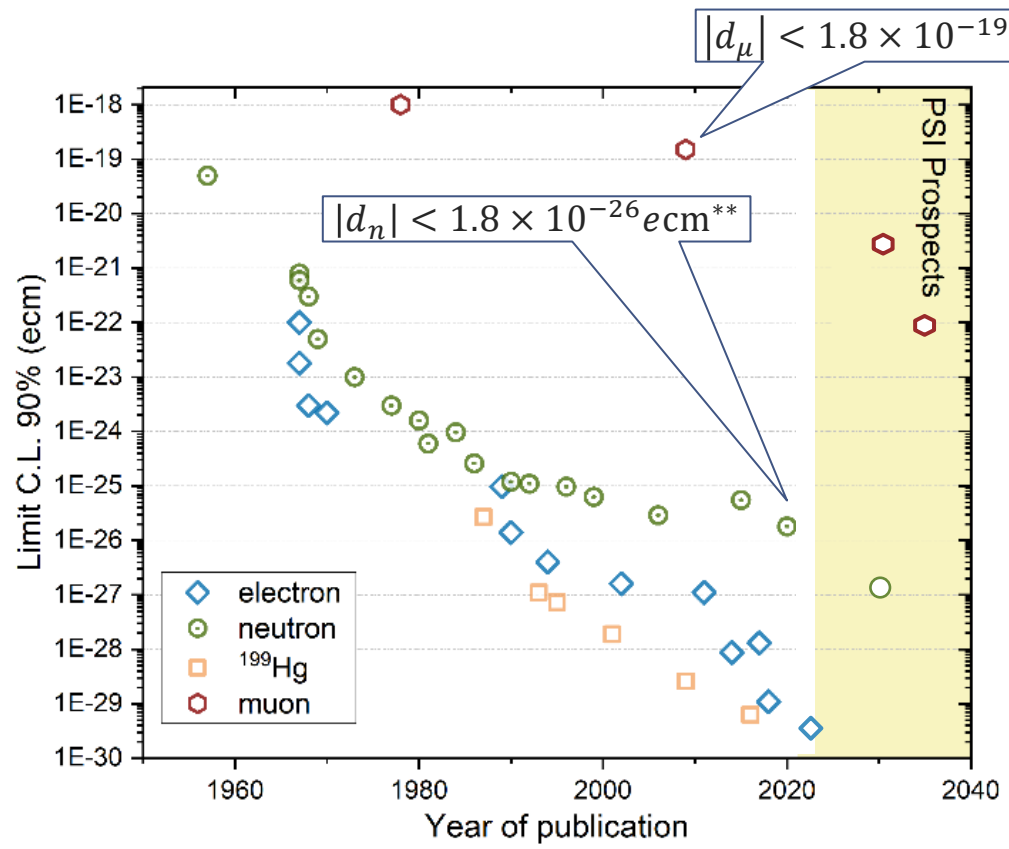


Phase I: $\sigma(d_\mu) < 4 \cdot 10^{-21} \text{ ecm}$

[*Farley et al., PRL93 042001 (2004)],



A not so brief history of EDM searches

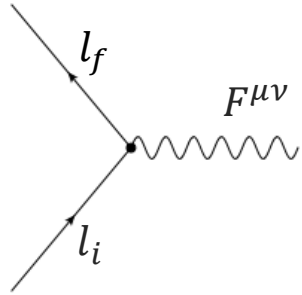


* Bennett et al., PRD80(2009)052008

** Abel et al., PRL124(2020)081803



Lepton form factors and dipole moments



$$\langle p' | J_{\mu}^{\text{EM}} | p \rangle = \bar{\Psi}(p') \left[F_1 \gamma_{\mu} + \overset{\text{magnetic-dipole}}{\frac{iF_2}{2M} \sigma_{\mu\nu} q^{\nu}} + \overset{\text{electric-dipole}}{\frac{iF_3}{2M} \sigma_{\mu\nu} \gamma_5 q^{\nu}} + \overset{\text{Anapole - moment}}{\frac{F_4}{M^2} (q^2 \gamma_{\mu} - \gamma^{\mu} q_{\mu} q_{\mu})} \right] \Psi(p)$$

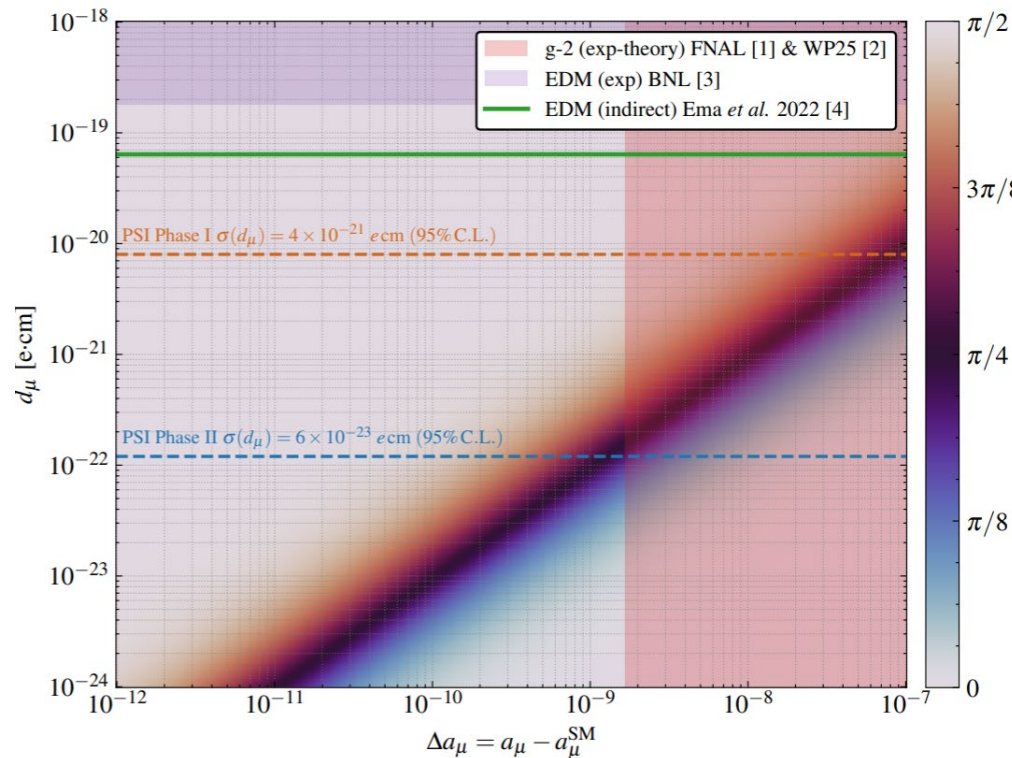
charge
magnetic-dipole
electric-dipole
Anapole - moment

$$\delta F_2 = a_{l_i} = -\frac{2m_{l_i}}{e} (c_R^{l_i l_i} + c_R^{l_i l_i^*}) = -\frac{4m_{l_i}}{e} \text{Re } c_R^{l_i l_i}$$

$$F_3 = d_{l_i} = i(c_R^{l_i l_i} - c_R^{l_i l_i^*}) = -2\text{Im } c_R^{l_i l_i}$$



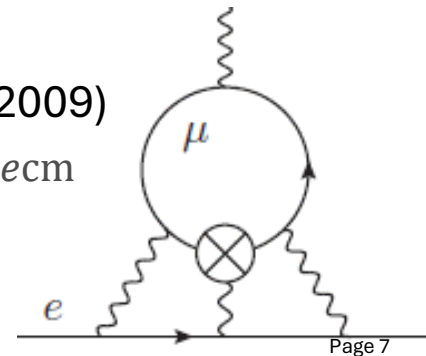
General limits on μ EDM



- MFV: $|d_{\mu \leftarrow e}^{\text{MFV}}| < 8.5 \times 10^{-28} \text{ ecm}$
- Contribution only starts at the 3-loop level* $|d_{\mu \leftarrow e}| < 4 \times 10^{-20} \text{ ecm}$

- Y. Ema et al., PRL **128**, 131801 (2022)
 $|d_{\mu}({}^{199}\text{Hg})| < 6 \times 10^{-20} \text{ ecm}$
 $|d_{\mu}(\text{ThO})| < 2 \times 10^{-20} \text{ ecm}$

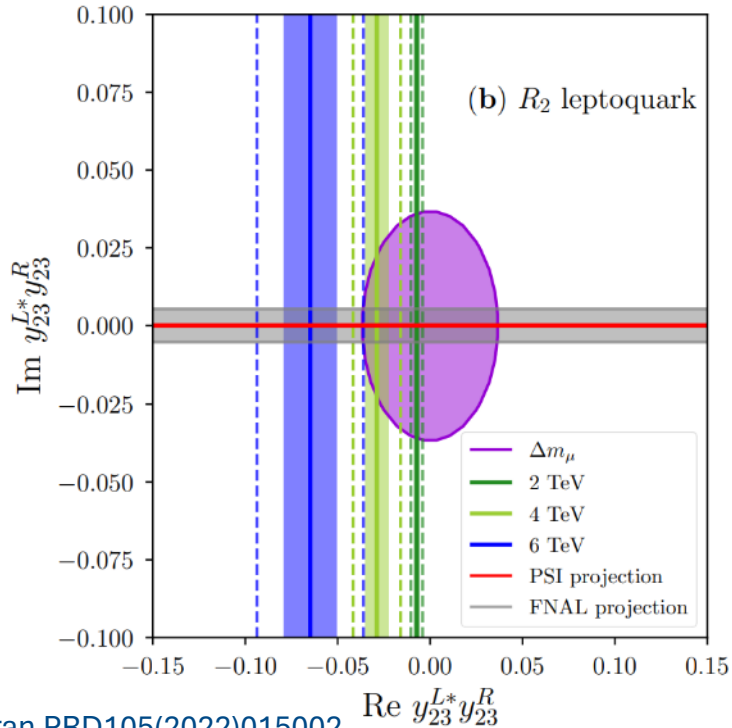
- Bennett et al., PRD80, 052008 (2009)
 $|d_{\mu}| < 1.5 \times 10^{-19} \text{ ecm}$



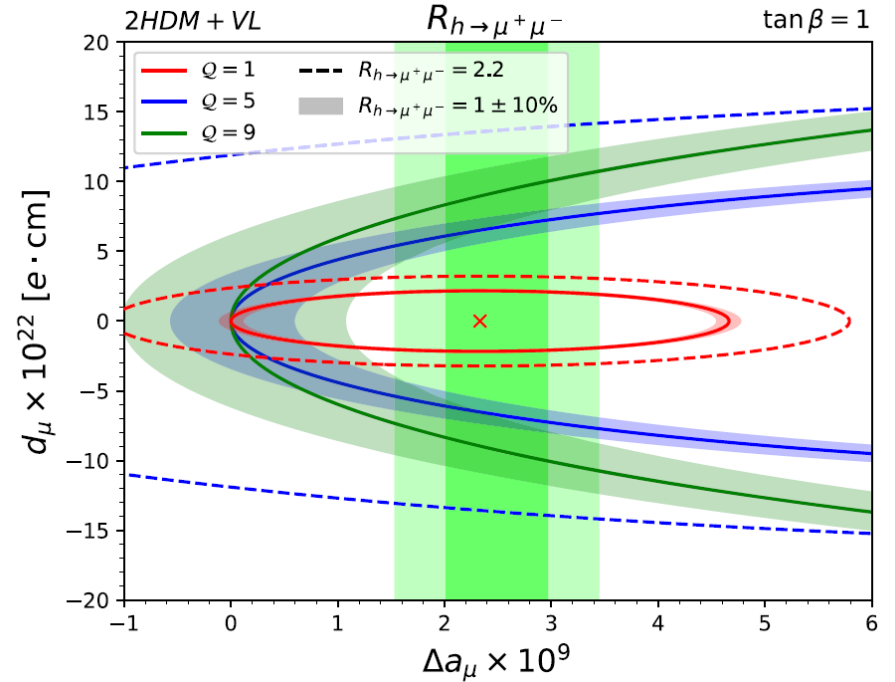
*A.Crivellin, M. Hoferichter, PSW PRD 98, 113002 (2018)



Leptoquark models with large muEDM



Bigaran PRD105(2022)015002



Dermisek PRD108(2023)055019

No significant tuning necessary

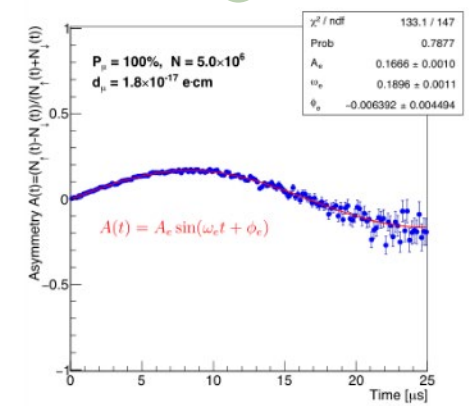
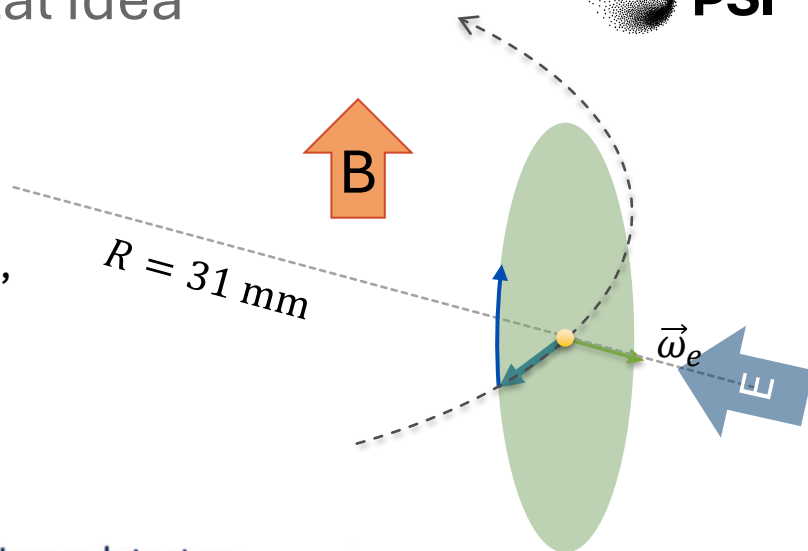
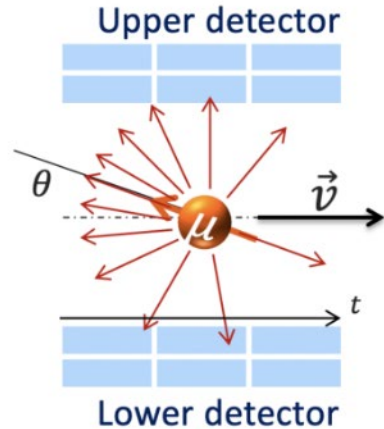


The general experimental idea

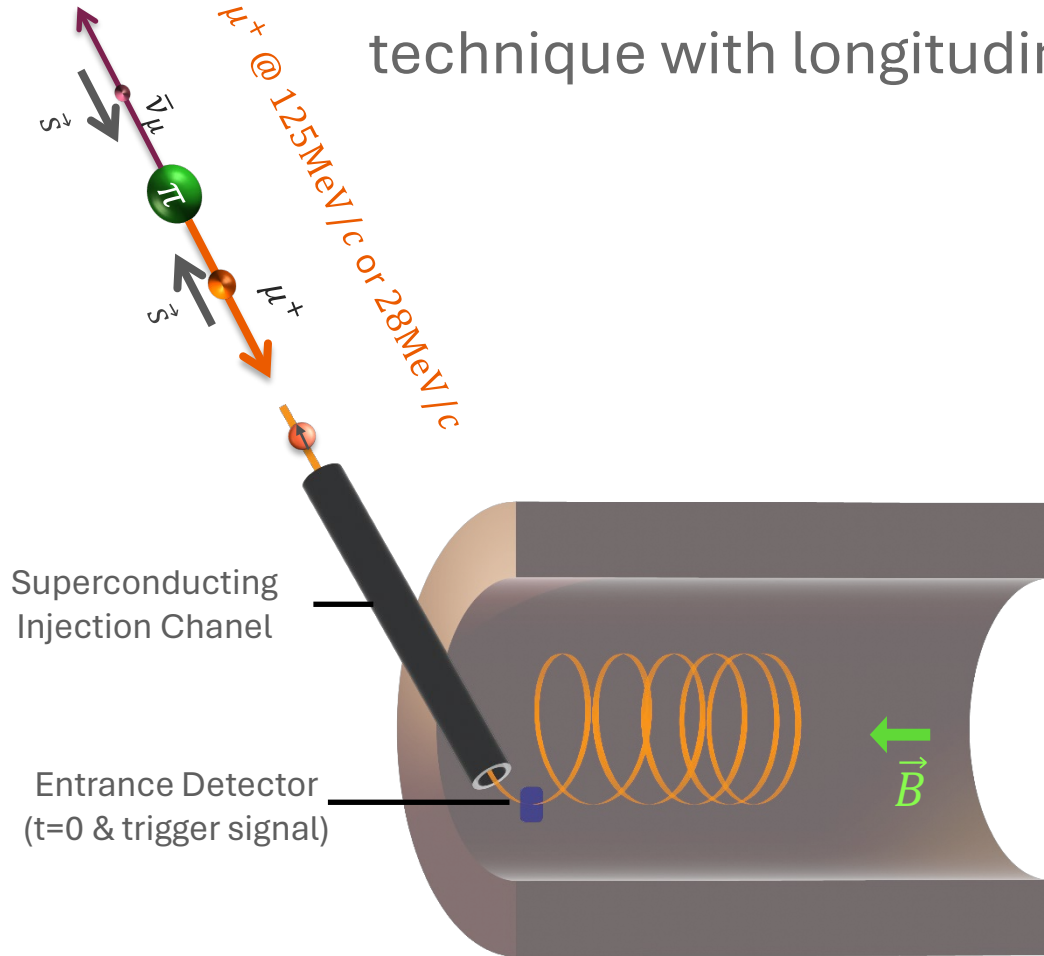


- EDM $\neq 0$ induces a vertical spin-precession out of the plane of the orbit.
- Build-up of longitudinal asymmetry with time, observed by recording decay positrons.
- If EDM = 0, spin “frozen” to the momentum change in asymmetry should be zero
- Some change in asymmetry could still be observed due to systematic effects

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

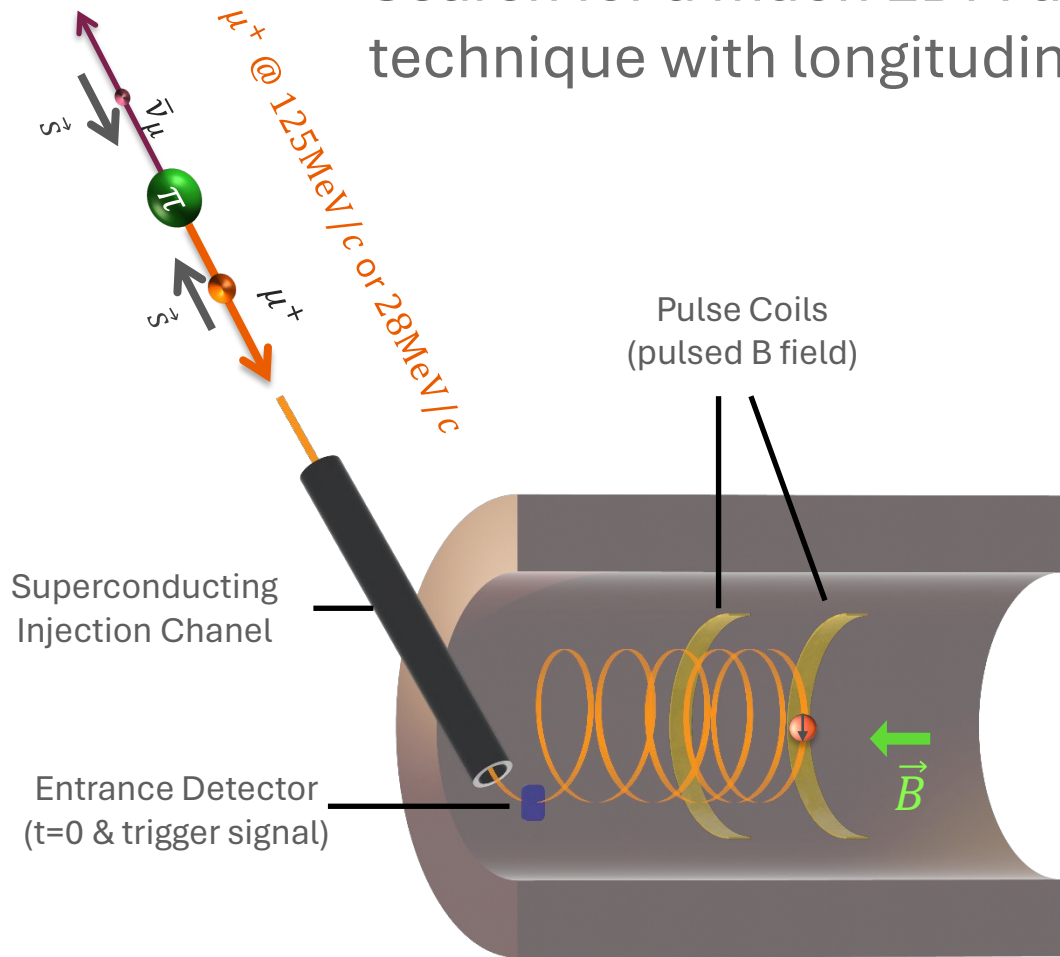


Search for a muon EDM using the frozen-spin technique with longitudinal injection



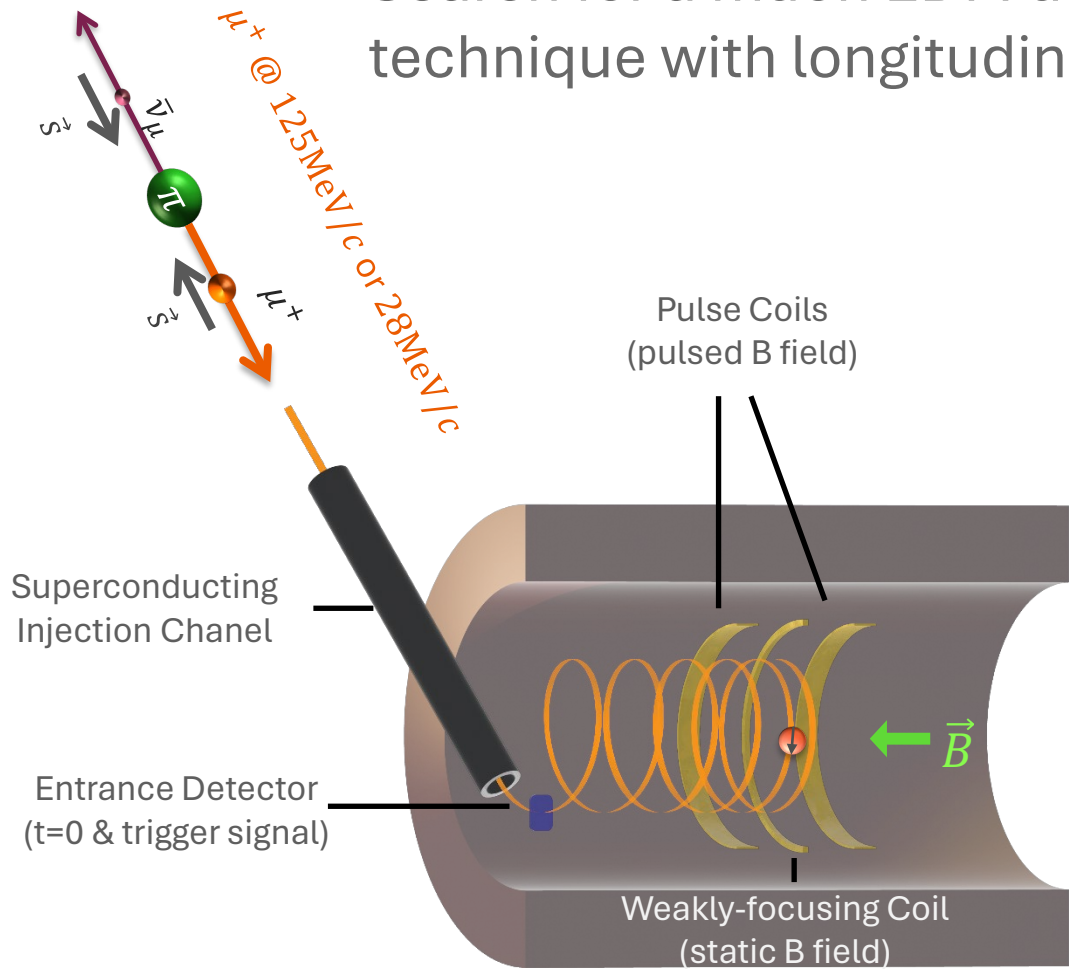
- μ^+ from Pion-decay \rightarrow high polarization $p \approx 95\%$
- Injection through superconducting channel
- Fast scintillator triggers pulse
- Magnetic pulse stops longitudinal motion of μ^+
- Weakly focusing field for storage
- Thin electrodes provide electric field for frozen spin
- Scintillating fiber detector (CHET) for e^+ -tracking

Search for a muon EDM using the frozen-spin technique with longitudinal injection



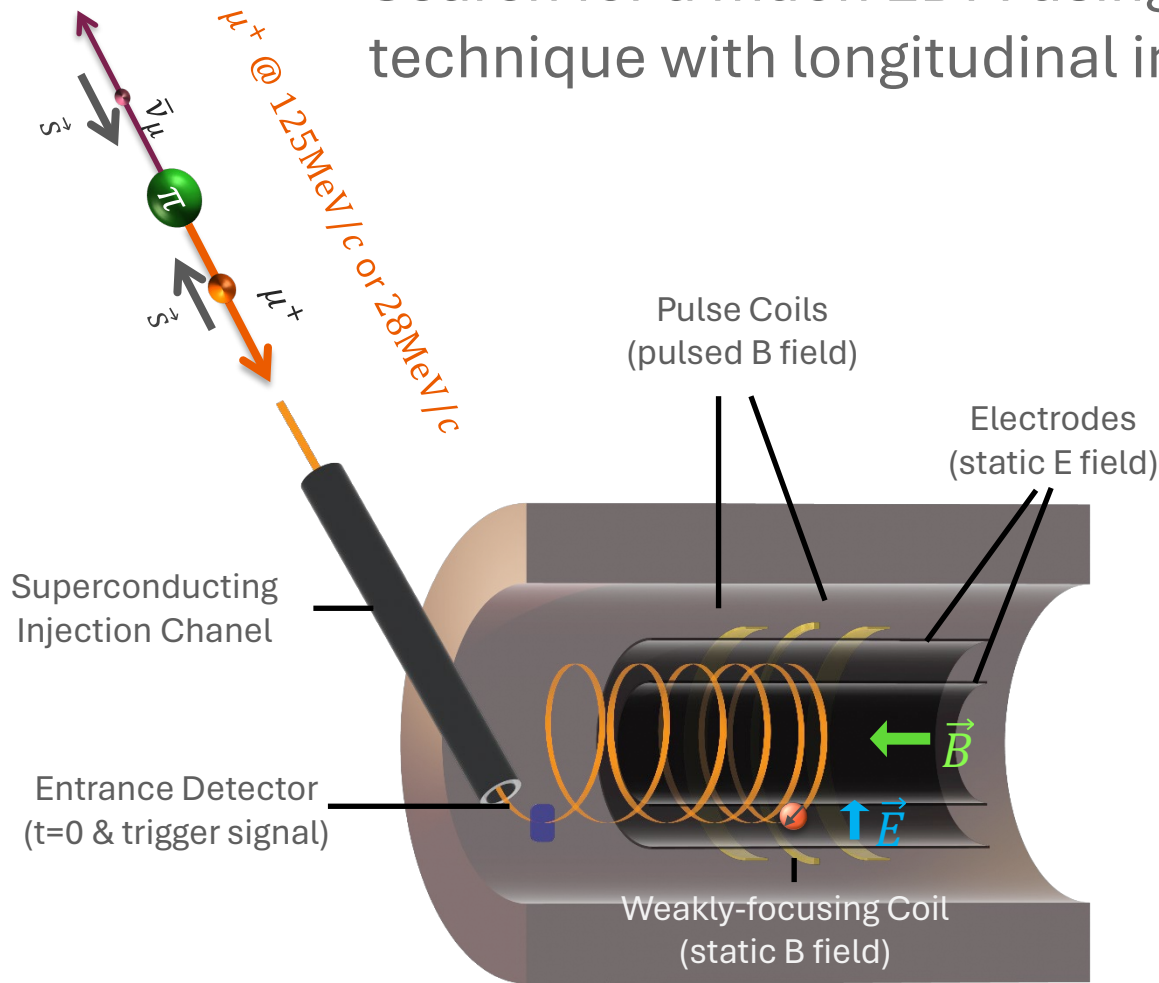
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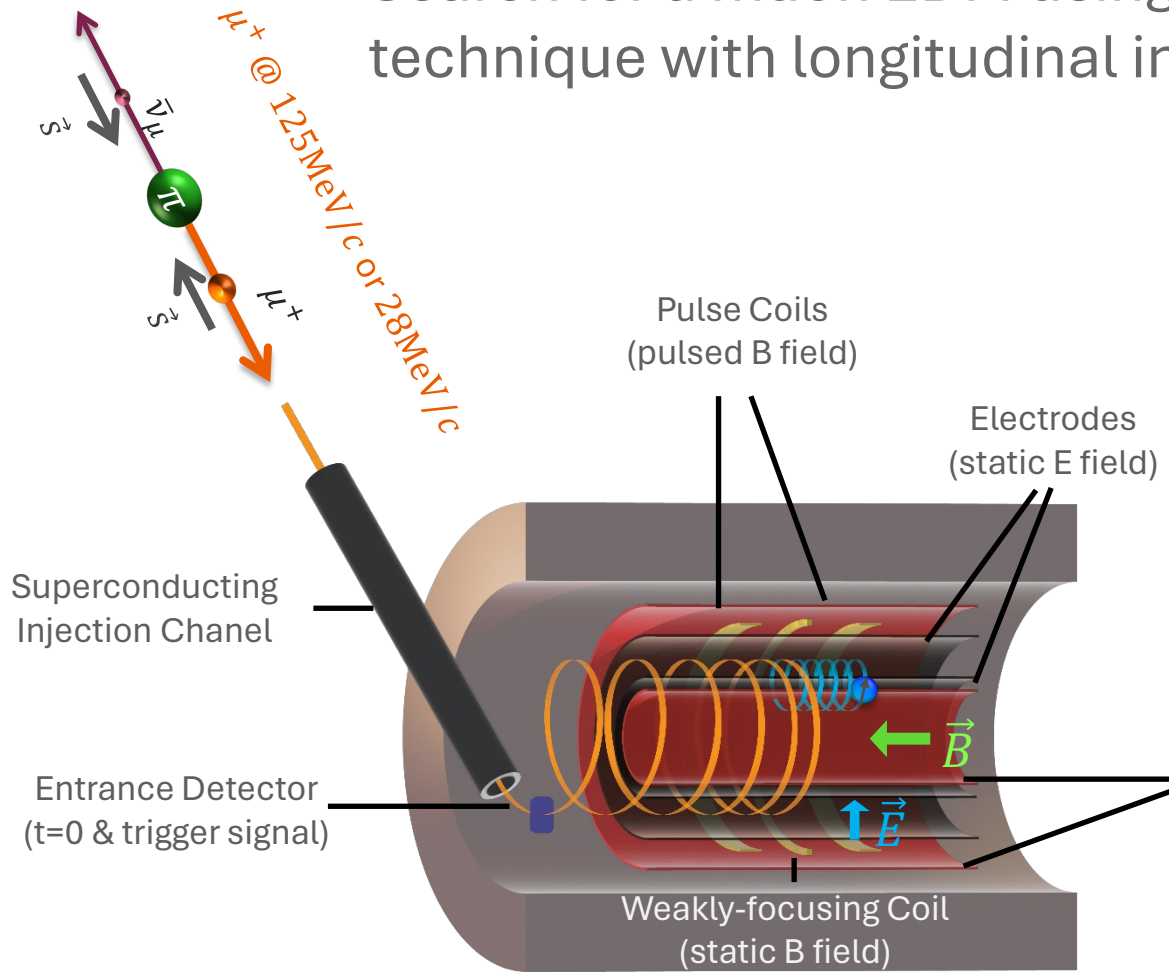
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A phased approach

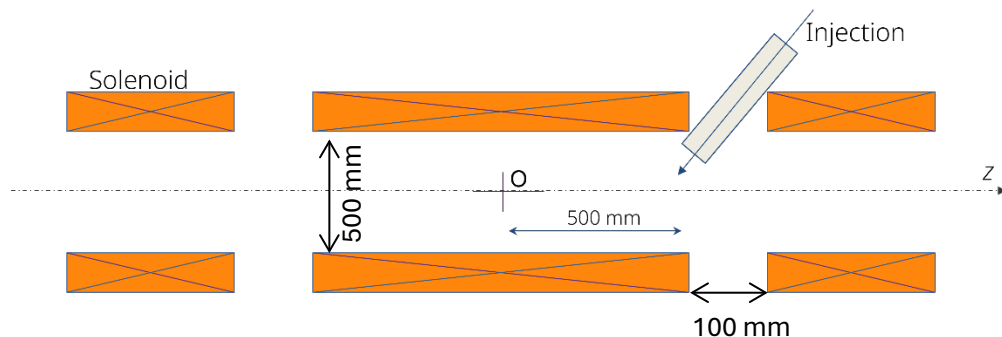


Phase I (small solenoid, surface muons)

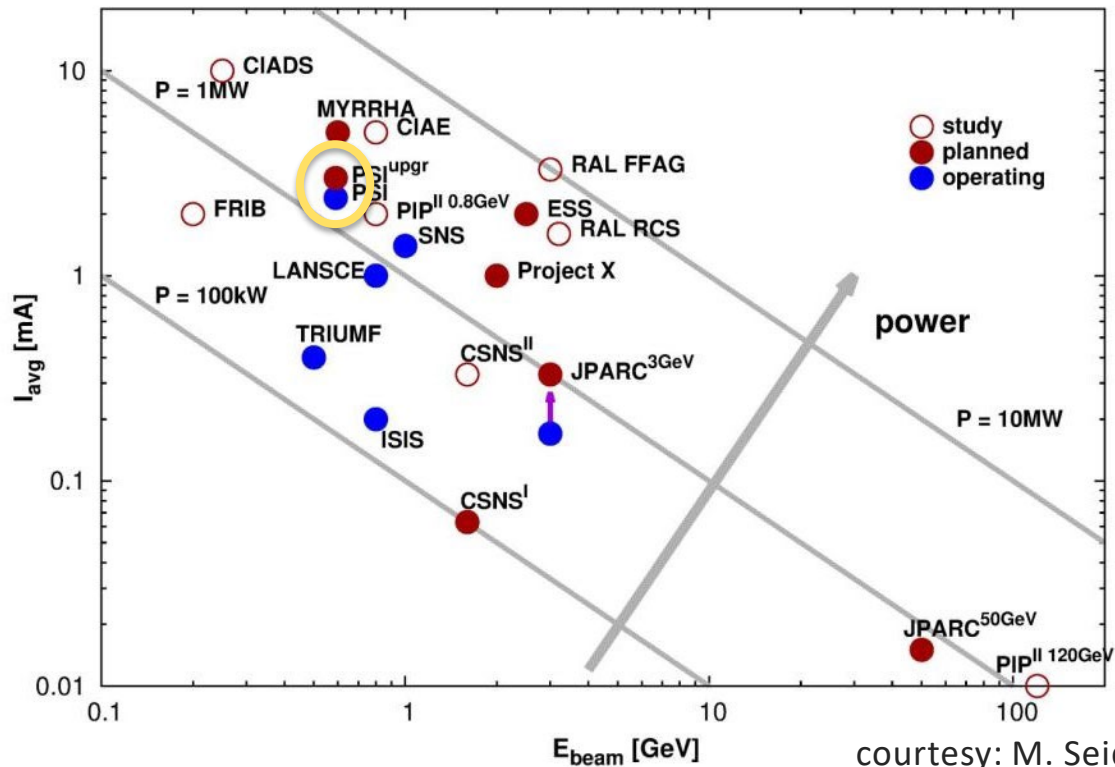
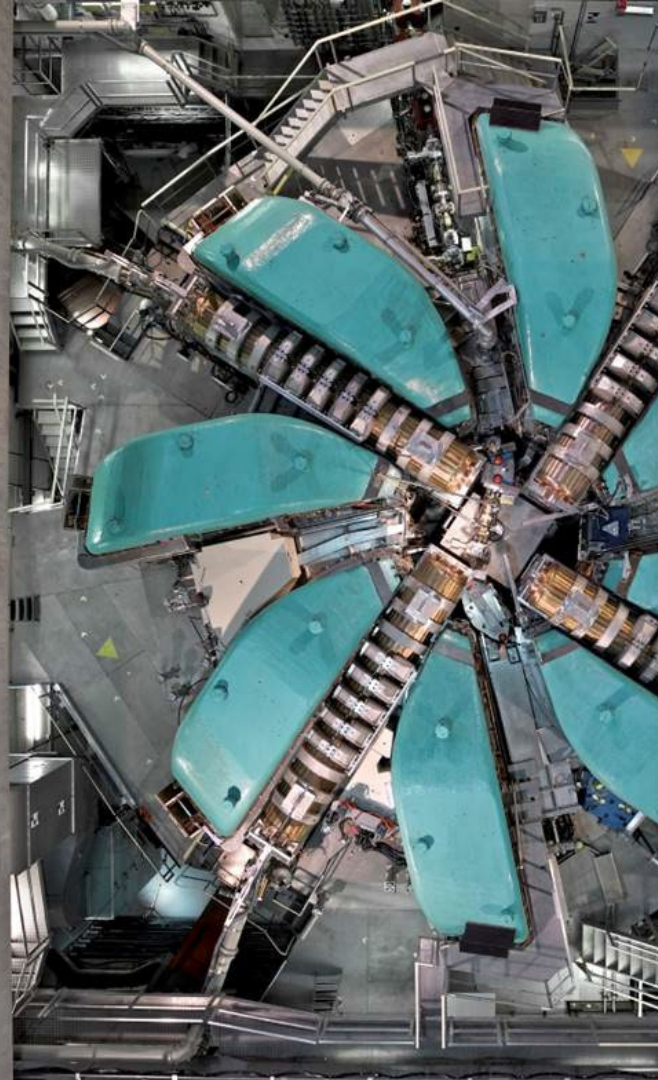


- Existing solenoid at PSI (max 5T)
- Bore diameters (200mm)
- Field was measured in 2022 (found suitable for injection)

Phase 2 (dedicated magnet
muon momentum $\geq 125\text{MeV}/c$)

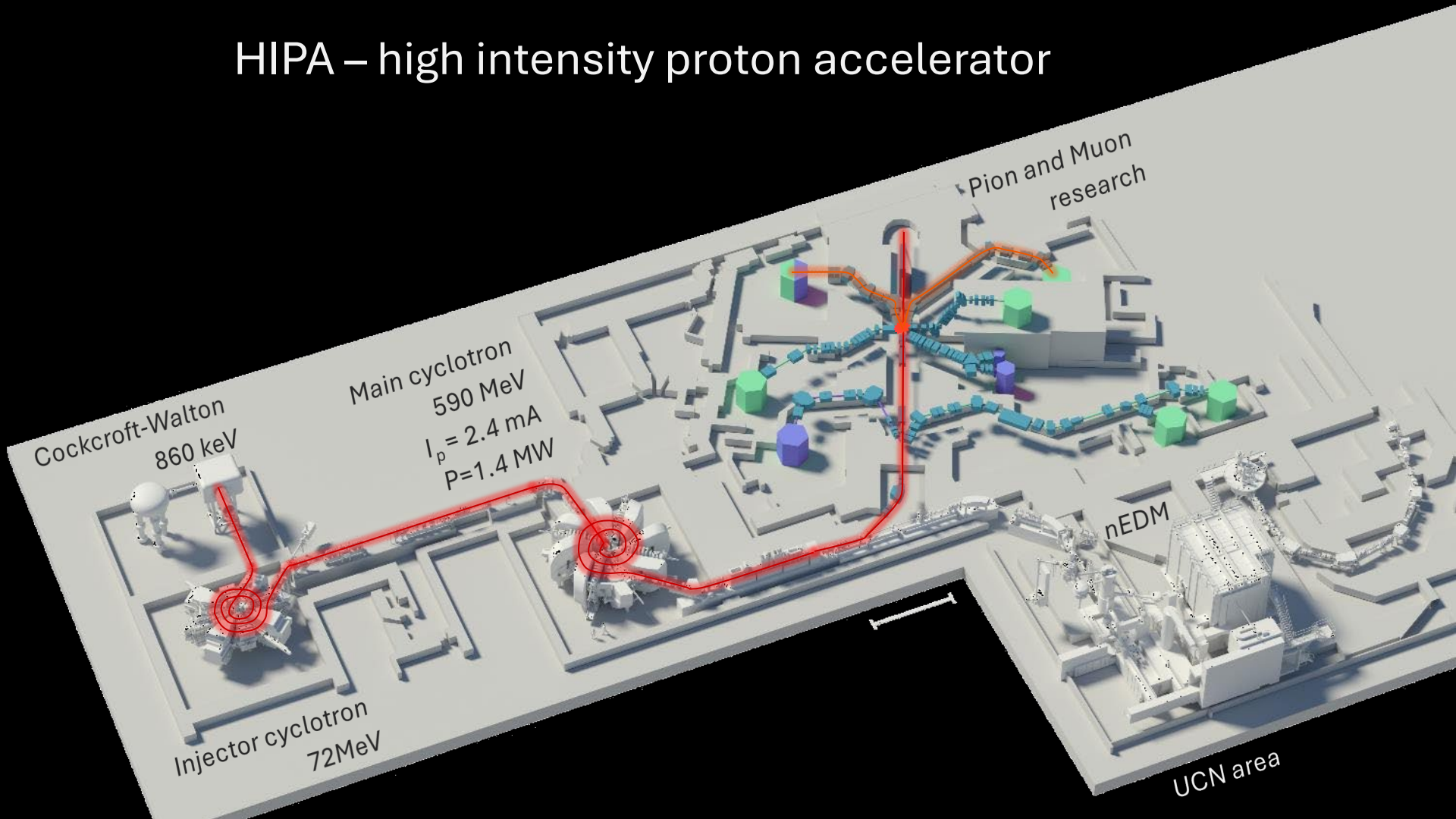


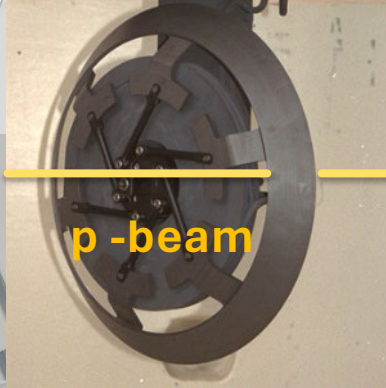
- Large bore (at least 500 mm diameter)
- Defined gradient $\Delta B/B = 1\text{ppt}$ at $R=140\text{mm}$, btw center and injection



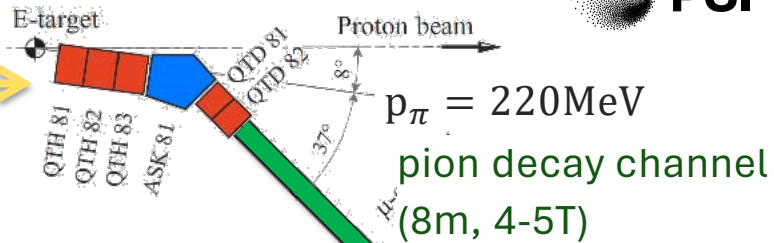
courtesy: M. Seidel

HIPA – high intensity proton accelerator

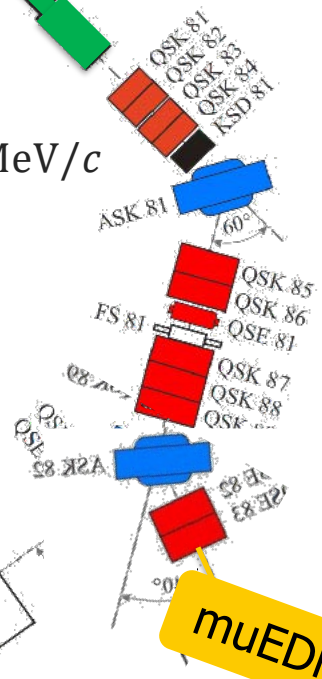
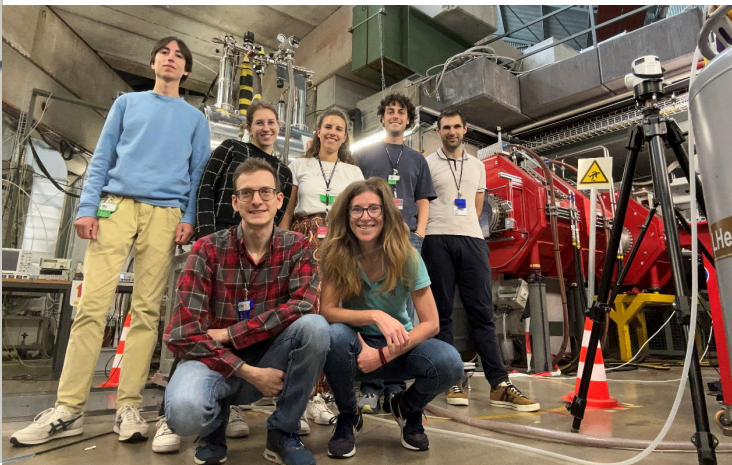




p-beam



$p_\mu = 125\text{MeV}/c$



$10^8 \mu^+ / s$

muEDM

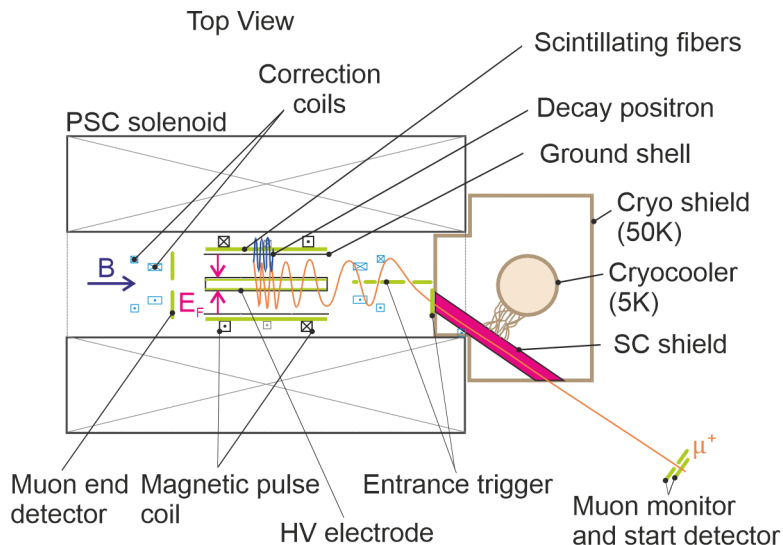


Injection and statistical sensitivity

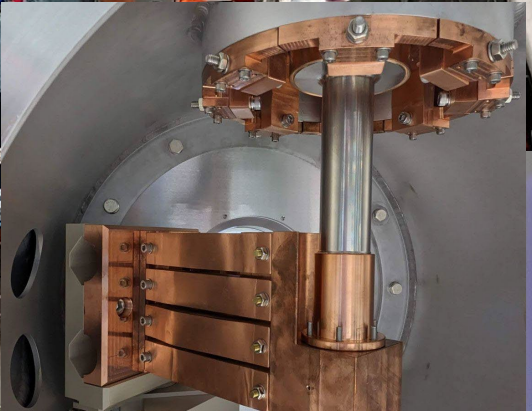
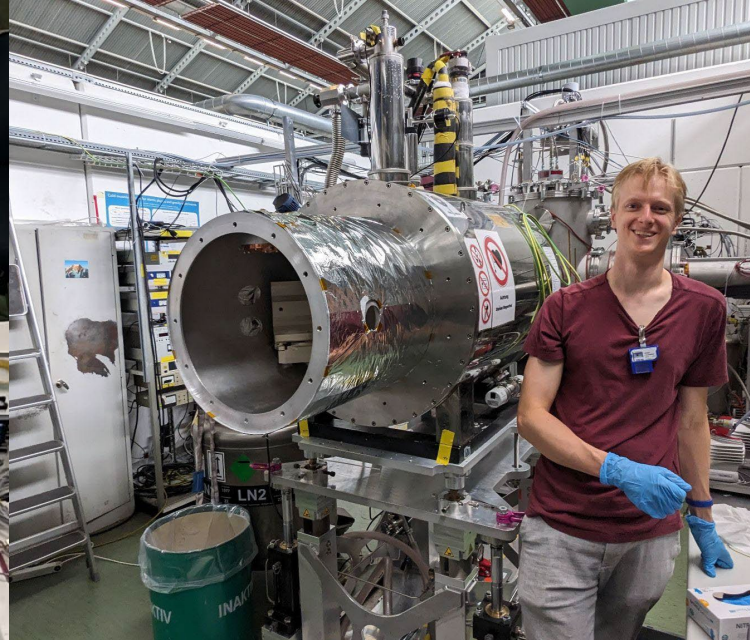


- Large phase space at exit of beam, collimated by passage through SC -shield
- Due to adiabatic magnetic collimation large part of transmitted μ^+ are reflected.
- Simulations show, only about 0.4×10^{-3} muons can be stored

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



	$\pi E1$ "28 MeV/c"	$\mu E1$ "125 MeV/c"
Muon flux (μ^+/s)	4×10^6	1.2×10^8
Channel transmission	0.03	0.005
Injection efficiency	0.004	0.60
Muon storage rate (1/s)	5×10^2	360×10^3
Gamma factor γ	1.024	1.56
e^+ detection rate (1/s)	400	90×10^3
Detections per 200 days	5.8×10^9	1.5×10^{12}
Mean decay asymmetry A	0.32	0.32
Initial polarization P_0	0.95	0.95
Sensitivity in one year ($e \cdot cm$)	$< 4 \times 10^{-21}$	$< 6 \times 10^{-23}$

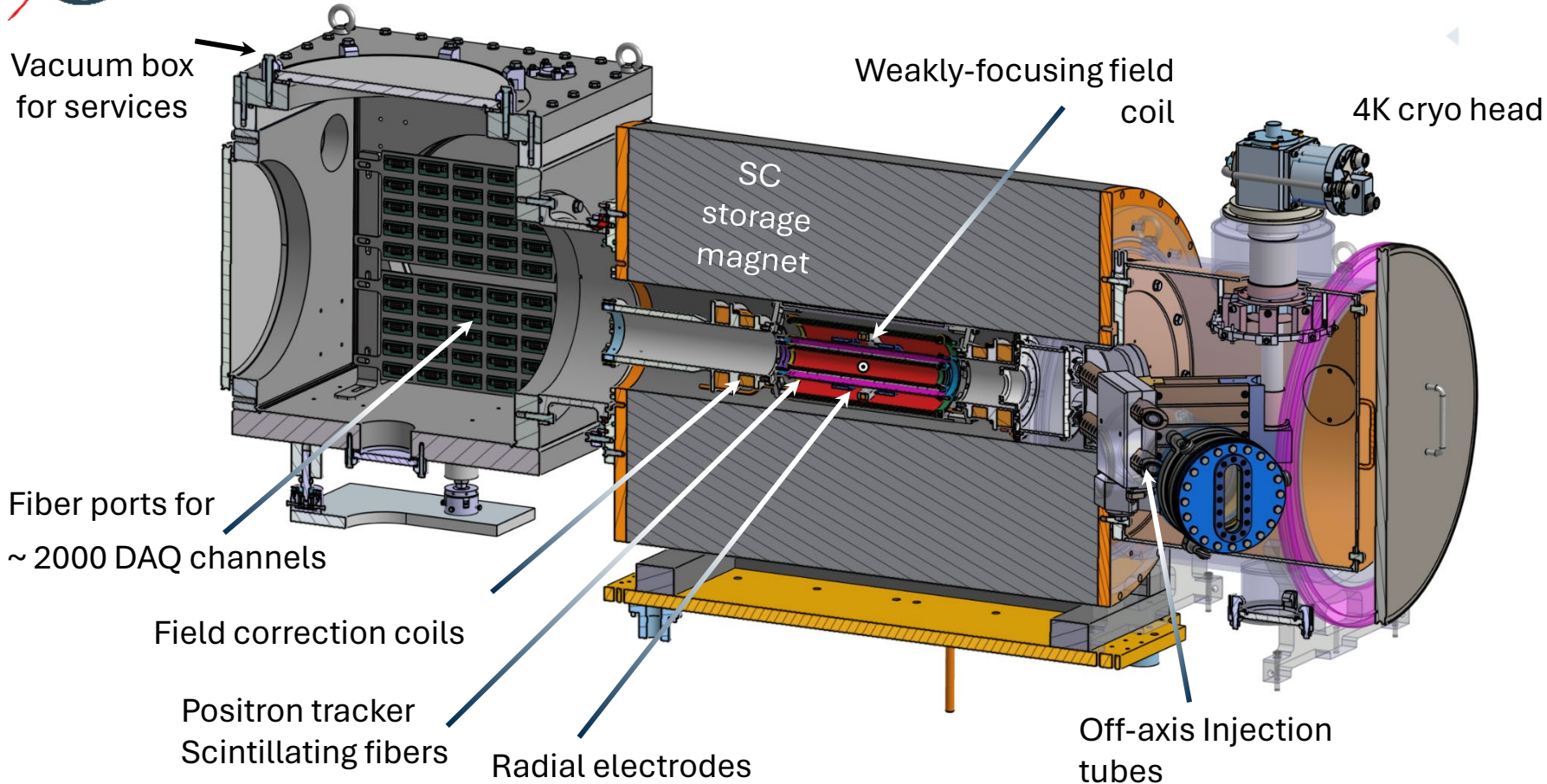


340 Temperature Controller





The Experiment - Technical overview

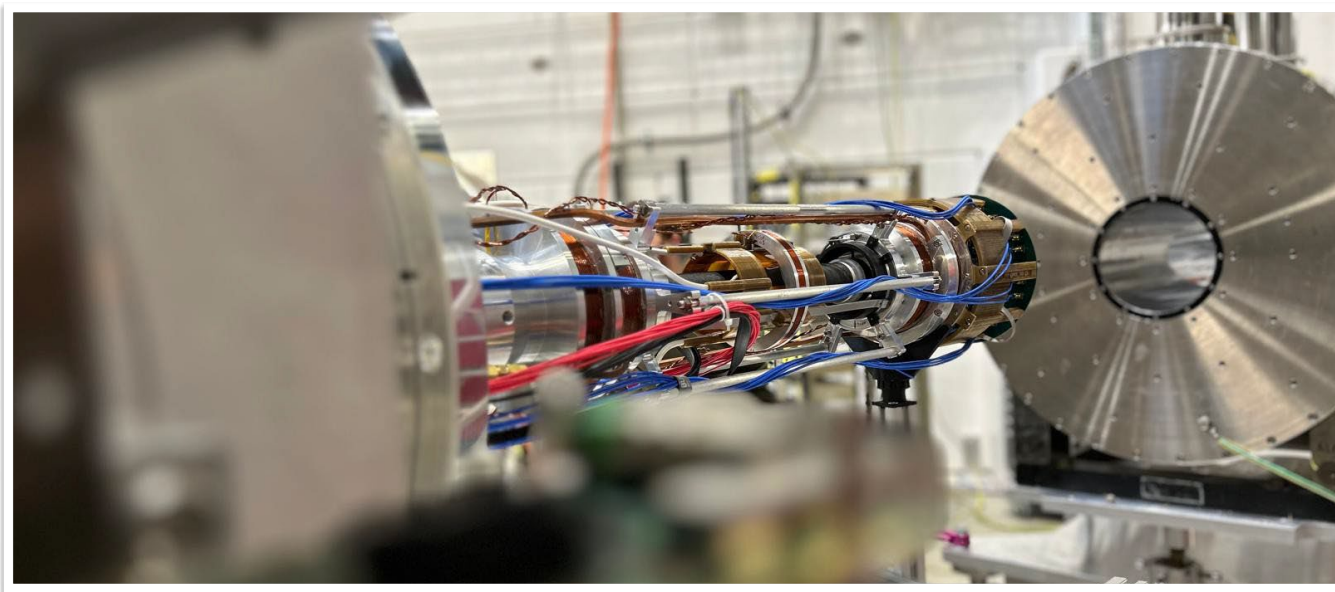




Current status



- The 2025 in a nutshell: Construction, assembly and integration of ALL items (whole/partially, prototype/final version)
 - A major milestone towards
 - the final assembly of the experimental setup, the proof of the frozen spin technique and base sensitivity (2026)
 - muEDM data taking (2027)

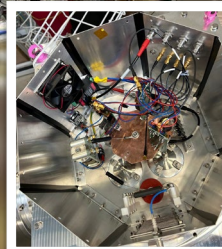
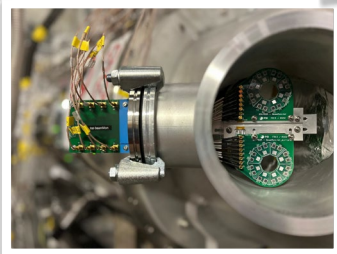
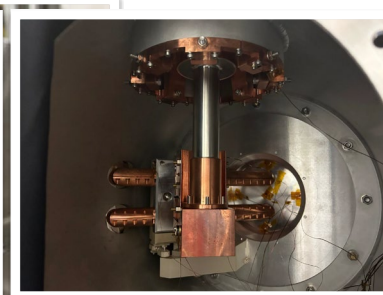
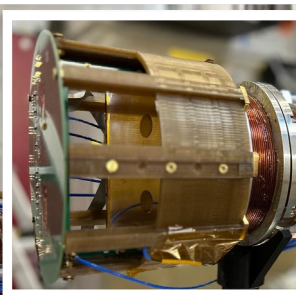
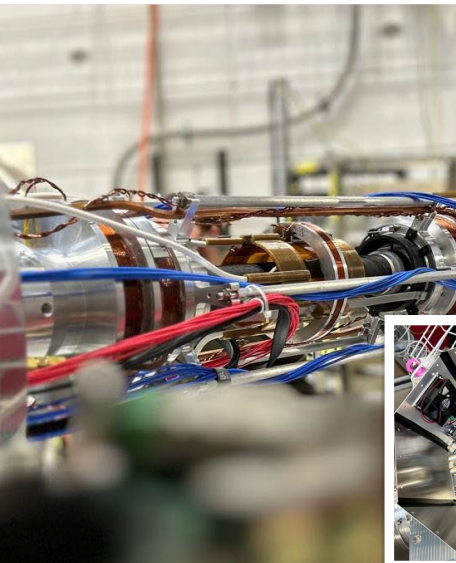




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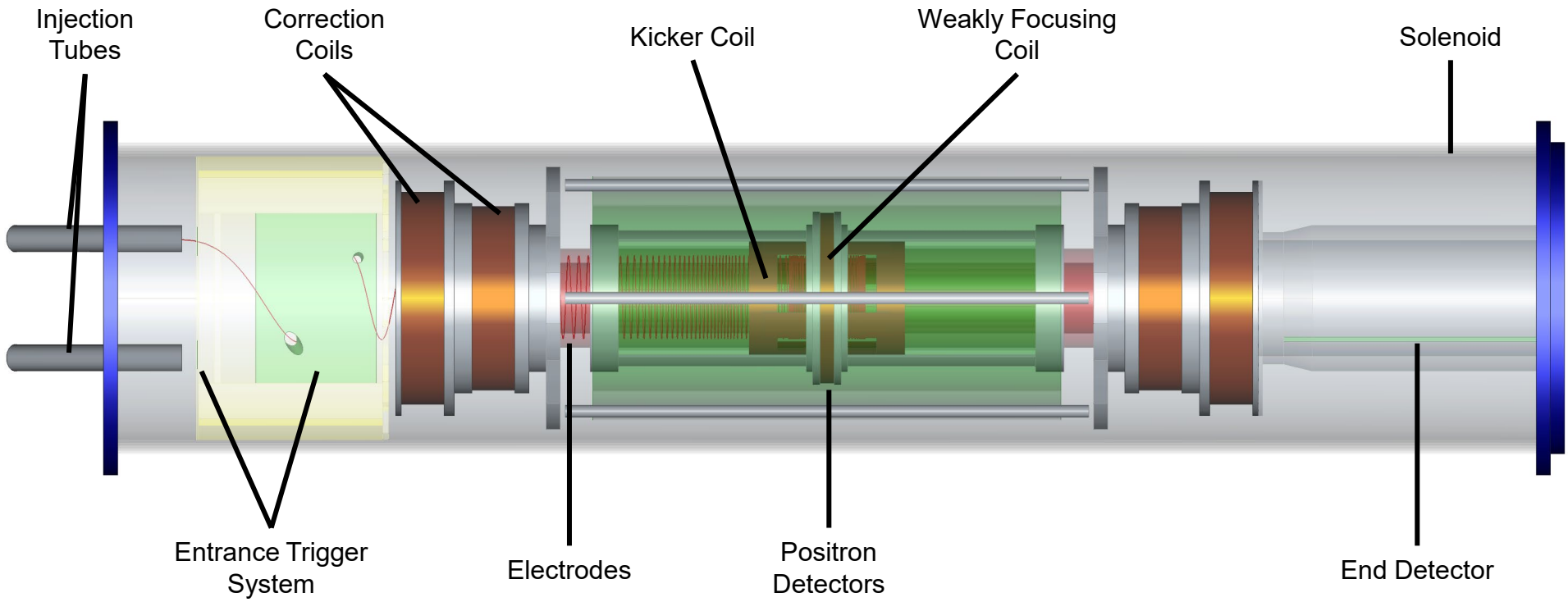


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Geant4 Implementation



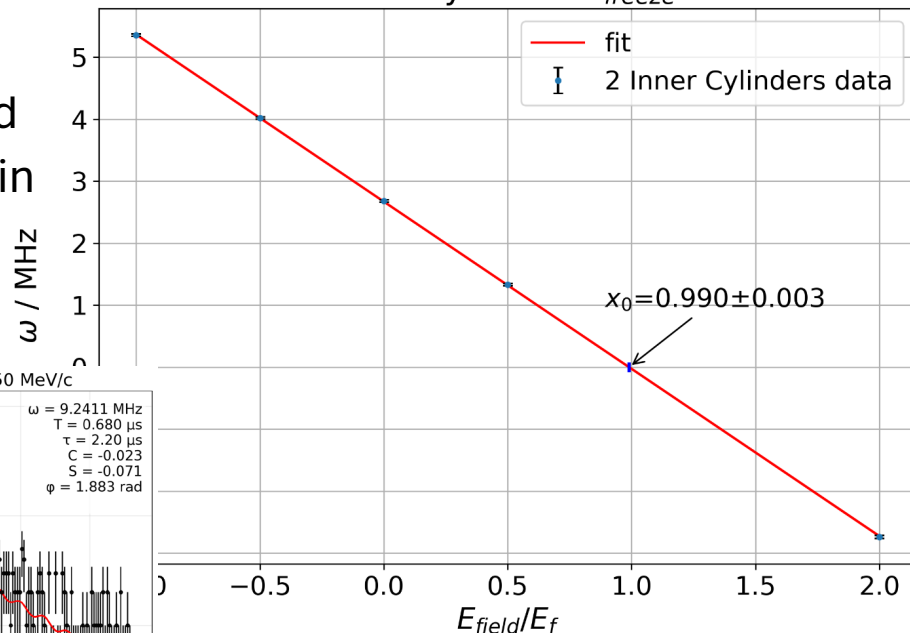


Adjusting the E –Field to freeze the spin

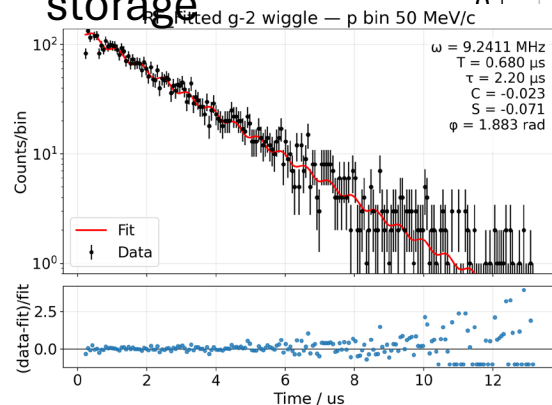
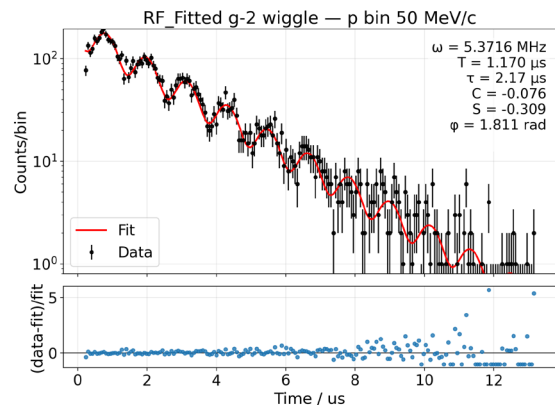
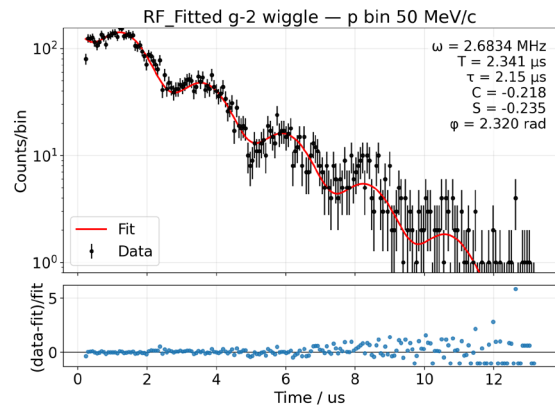


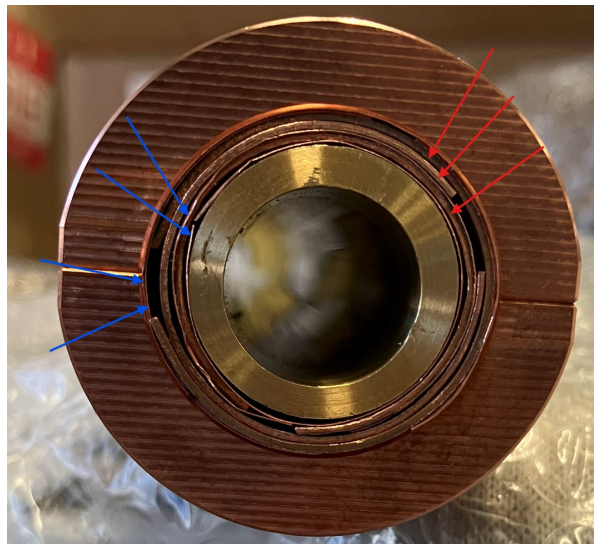
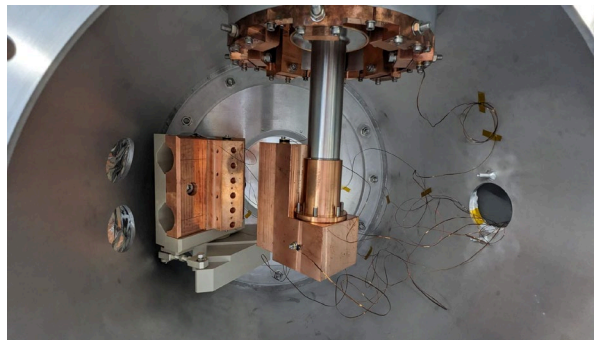
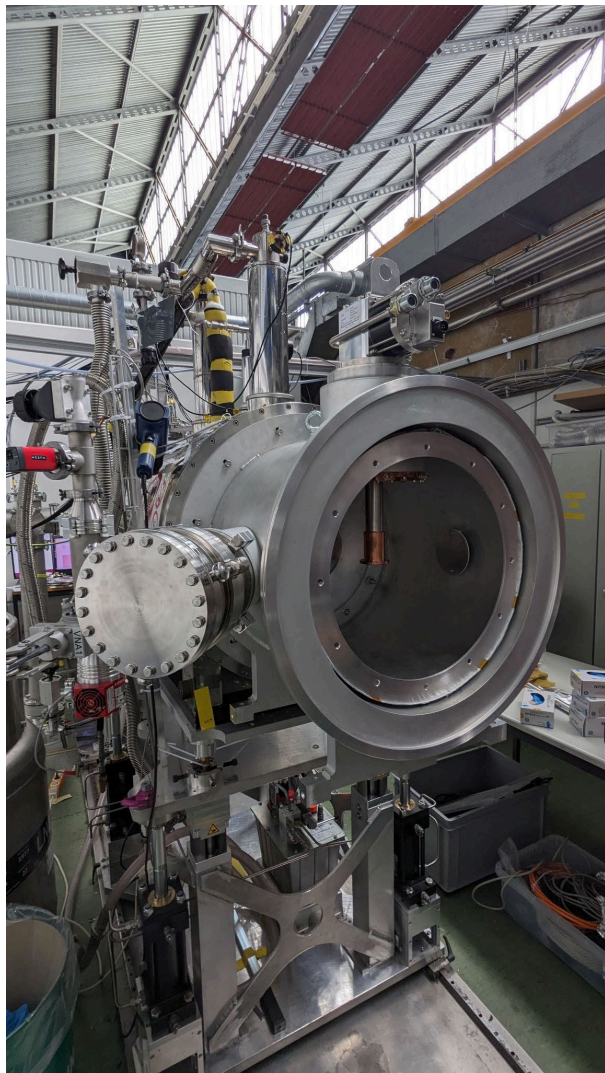
- Measure precession as function of E-Field
- Tune spin with spin rotator
- CW and CCW storage

2 Inner Cylinders E_{freeze} fit



- Measure ToF of each stored muon
- Momentum resolved measurement

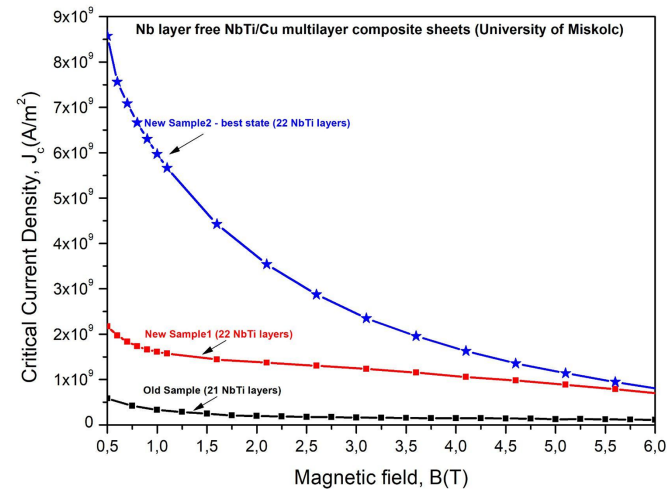




Cryostat setup

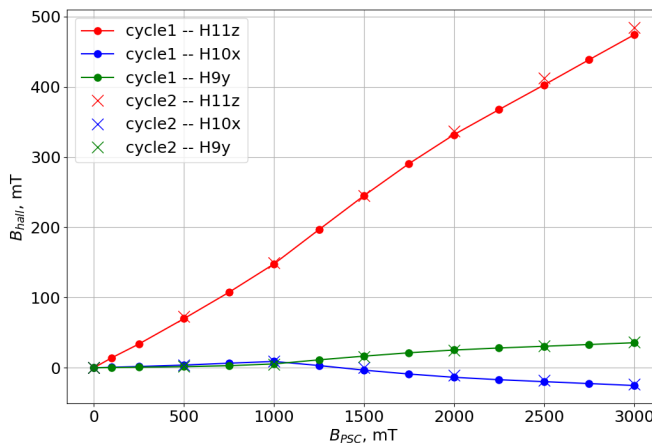
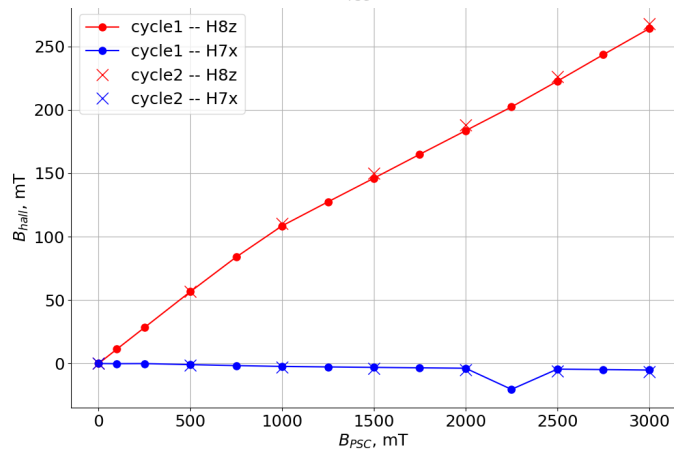
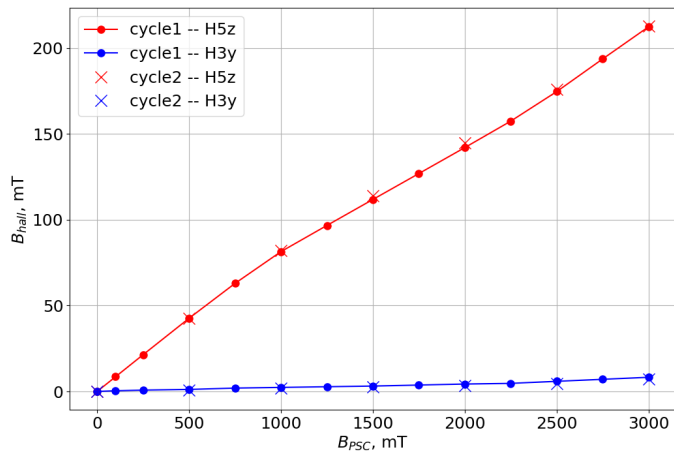
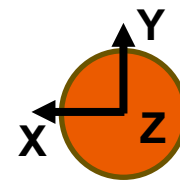


- Temperature monitoring system
 - 4 x ROX temperature sensors
 - 4 x PT-1000 temperature sensors
 - 1 x DT-670 sensor
 - 2 x Lakeshore model 340
- Reached $p \approx 1.7 \cdot 10^{-7}$ mBar
- Injection channel holder $T \approx 5.8$ K
- 9 x THS119 used to record mag.fields

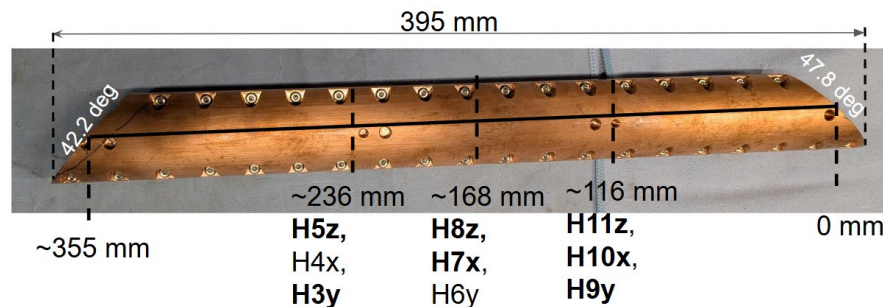




Shielding measurements



B, mT	H3y, mT (240mm)	H5z, mT (233mm)	H7x, mT (169mm)	H8z, mT (167mm)	H9y, mT (122mm)	H10x, mT (117mm)	H11z, mT (115mm)
COLD $T \approx 5.7K$ at 3T	7.1	212.8	-6.5	267.8	36.5	-23.5	484.4
HOT $T > 20K$ at 3T	26.7	186.2	-57.1	303.0	92.9	-141.2	459.9
$\frac{HOT}{COLD}$	3.8	0.9	8.8	1.1	2.5	6.0	0.9

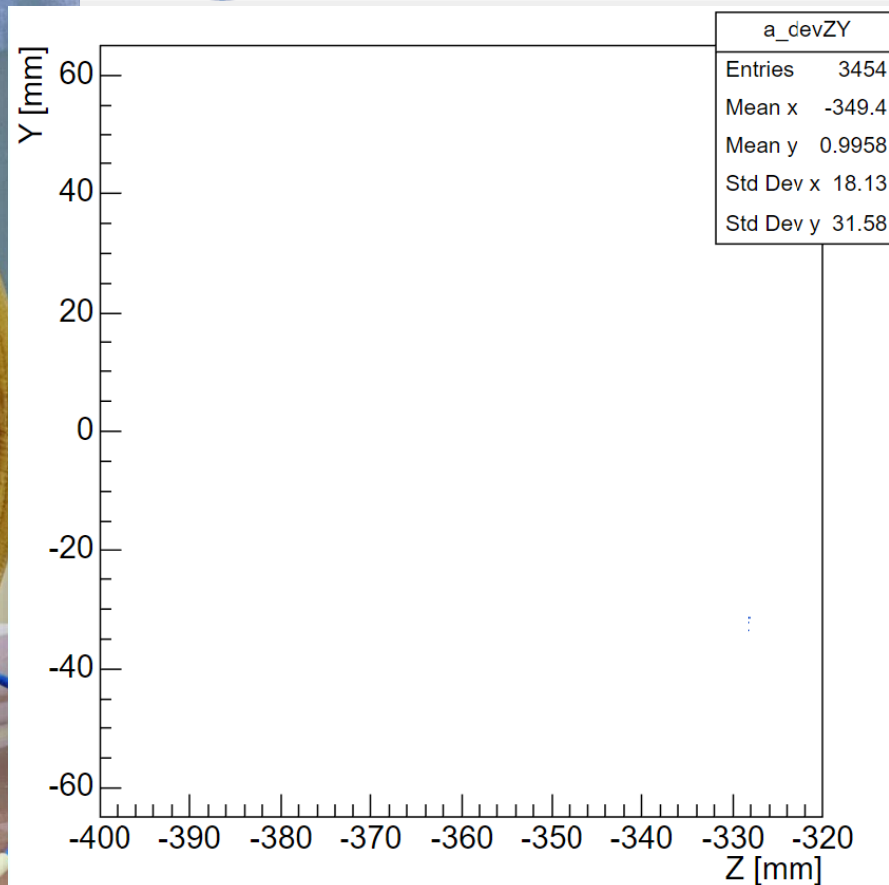
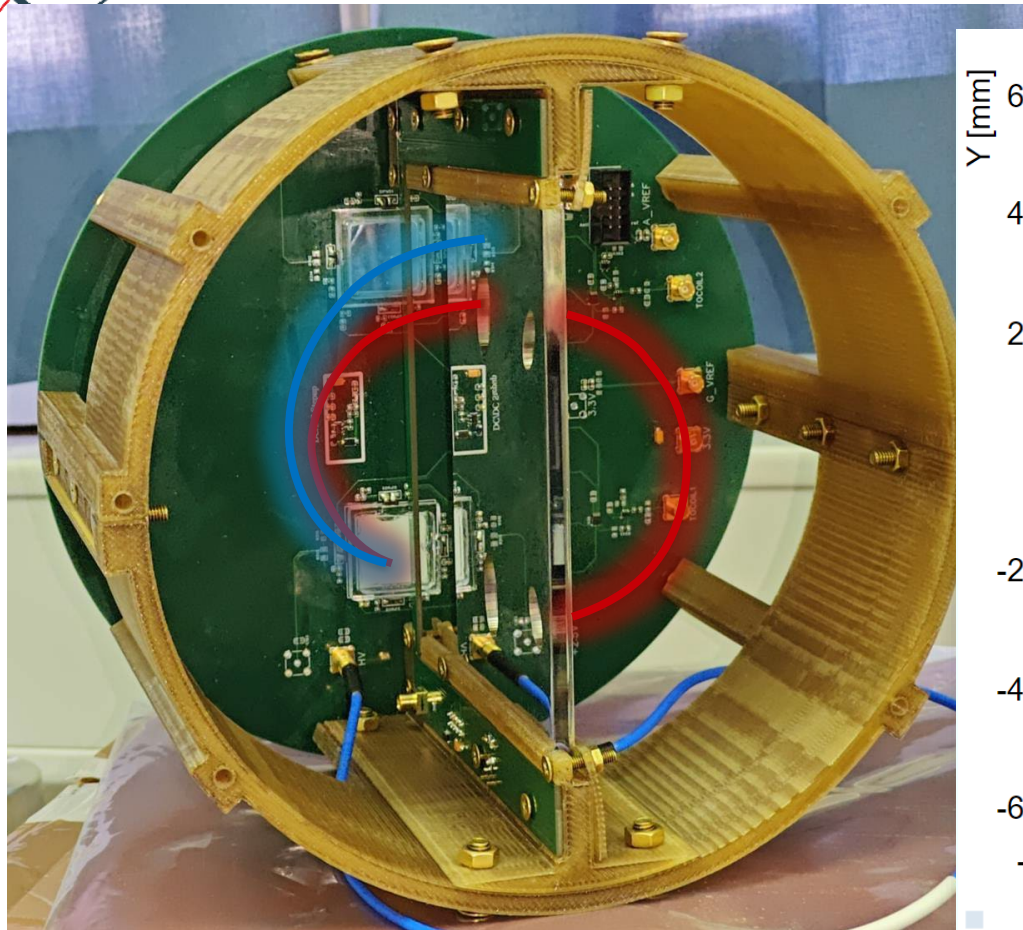




Muon trigger detector

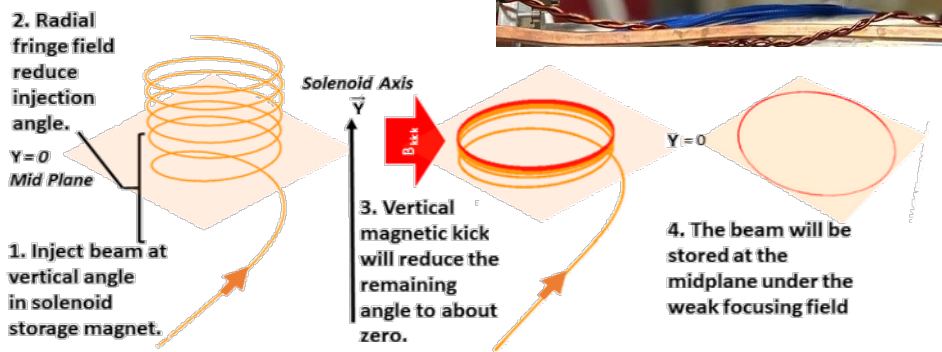
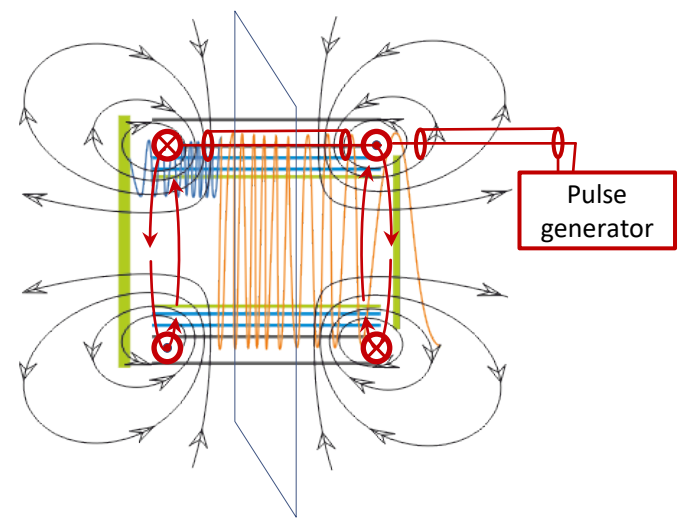
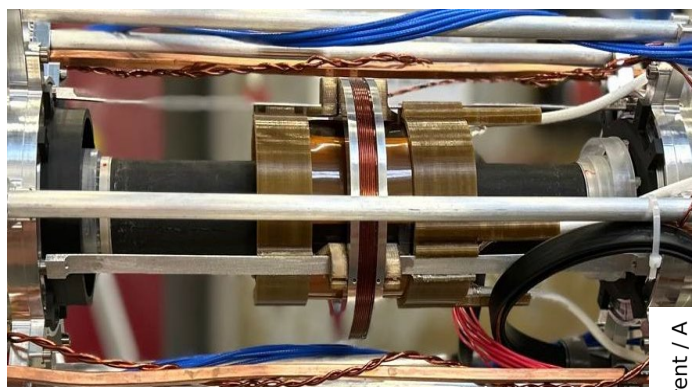
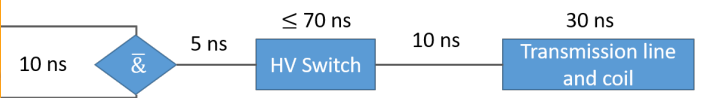
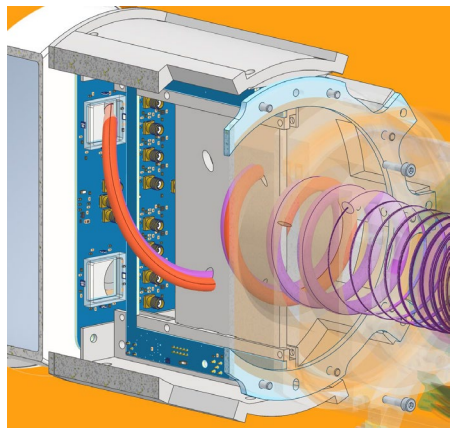


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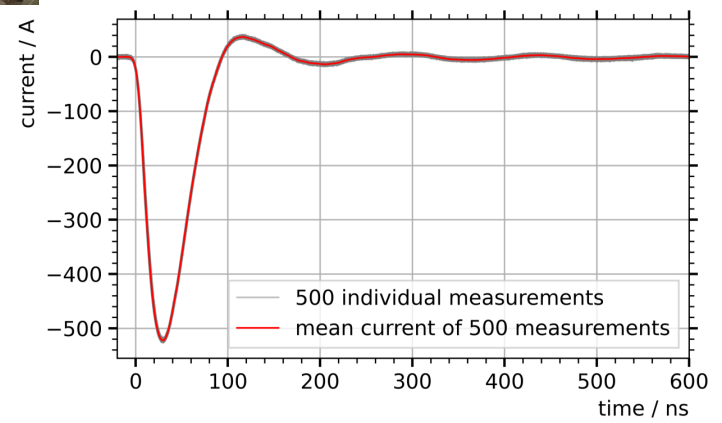




Radial magnetic field pulse to kick muons



courtesy A.M. Rehman

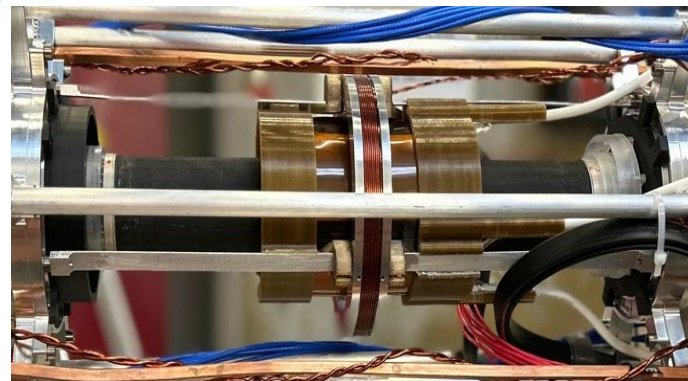
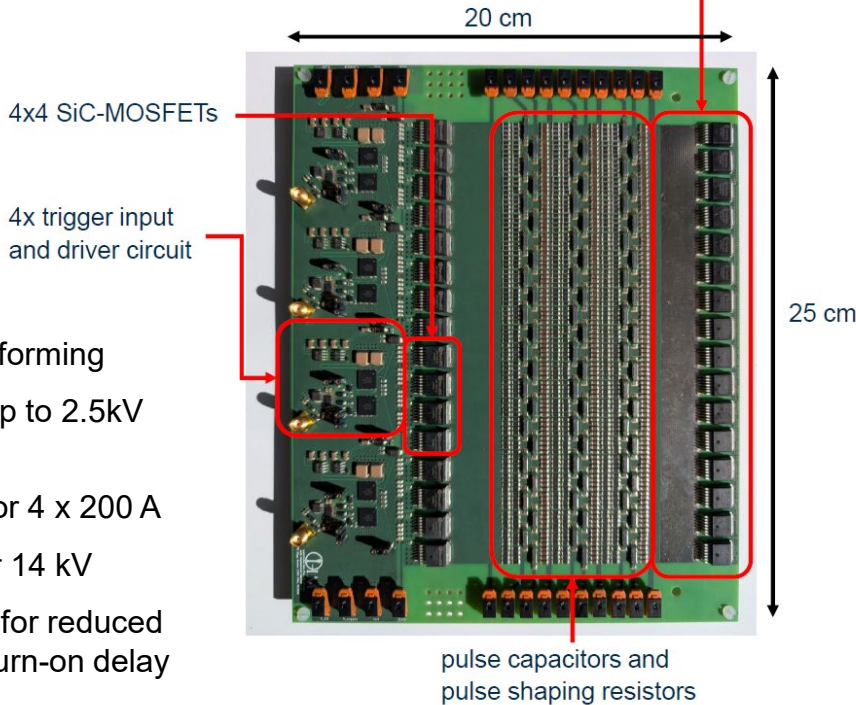




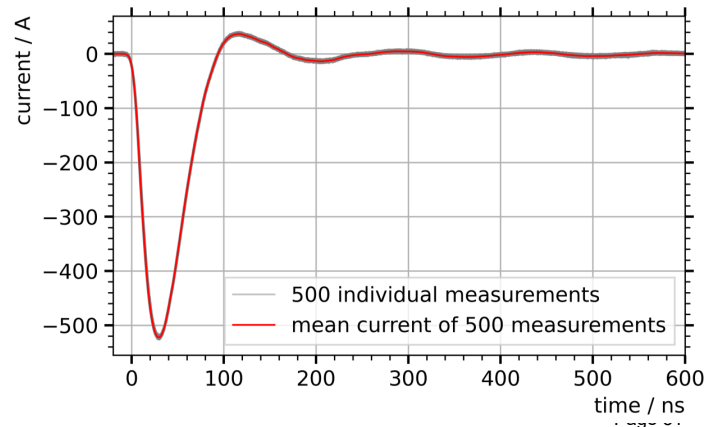
Pulse generator to kick muons



pad for load connection and diodes with damping resistors (backside)



- Passive pulse forming
- Designed for up to 2.5kV and 400 A
 - 2 in parallel for 4 x 200 A
 - 6 in series for 14 kV
- Gate-boosting for reduced rise-time and turn-on delay
- One optical fiber receiver per stage on-stage distribution via coaxial cables

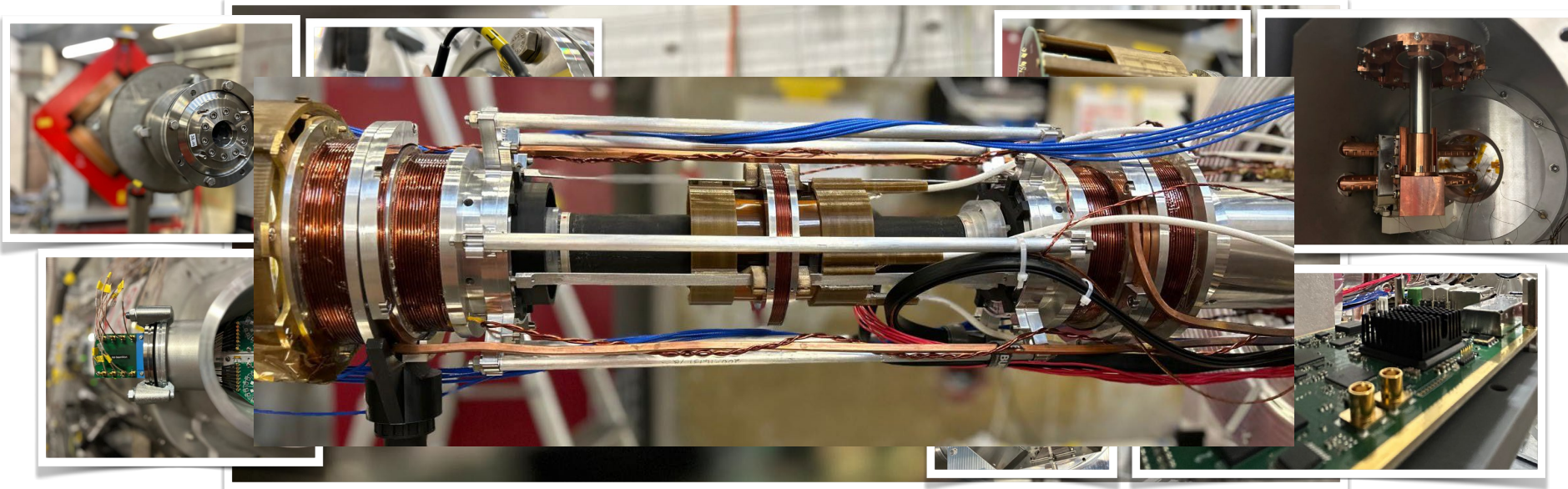




Current status



- The 2025 in a nutshell: Construction, assembly and integration of ALL items (whole/partially, prototype/final version)
 - A major milestone towards
 - the final assembly of the experimental setup, the proof of the frozen spin technique and base sensitivity (2026)
muEDM data taking (2027)

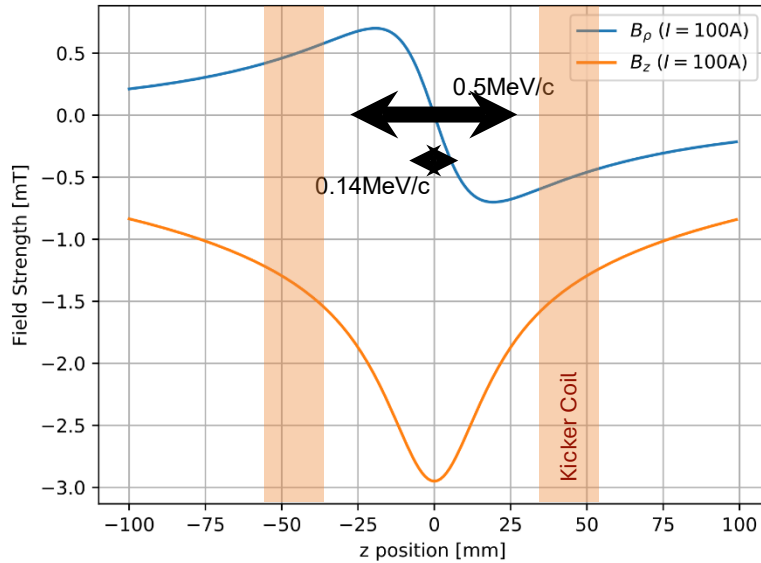




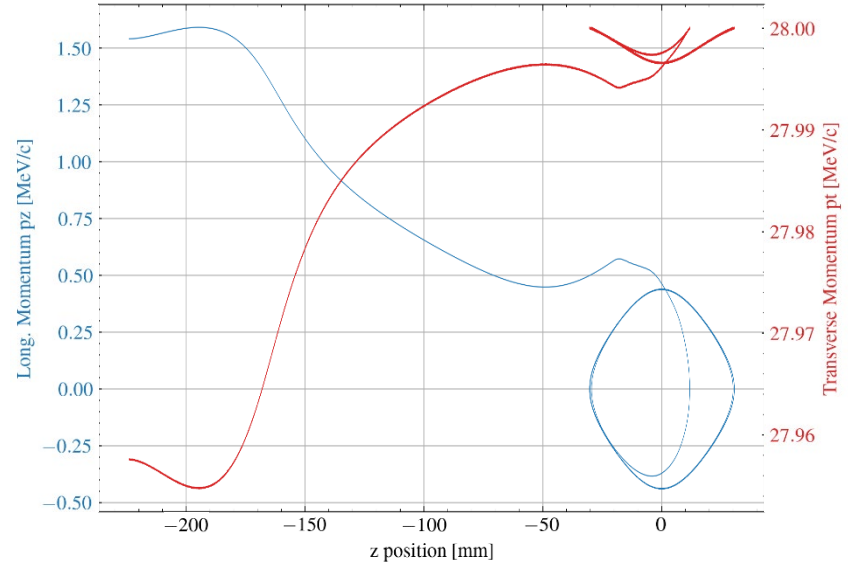
Longitudinal confinement



A **static weakly-focusing field** produced by a single circular coil will ensure confinement.

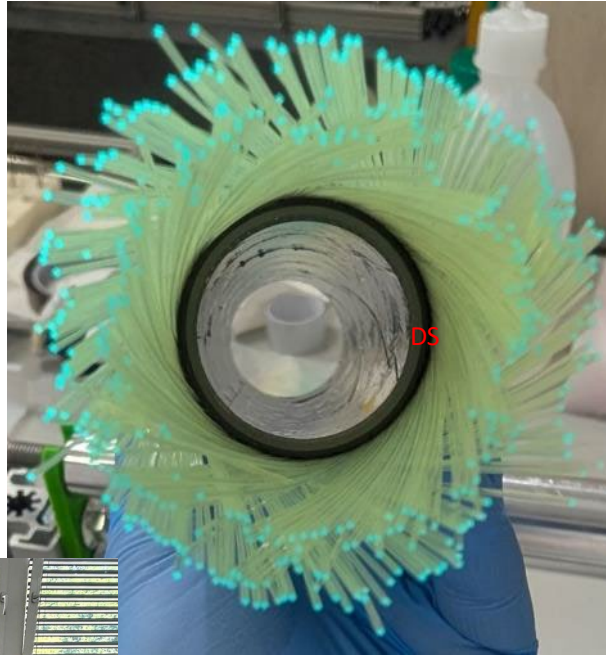
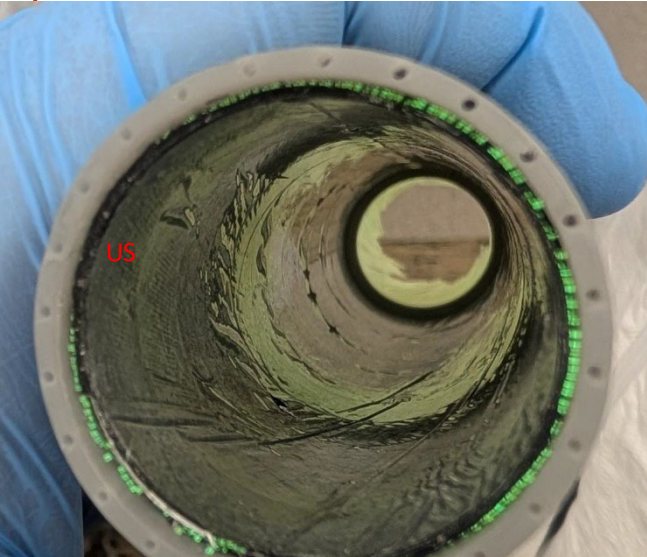


A longitudinal betatron oscillation of about 10MHz will persist during the measurement due to the remaining longitudinal momentum.

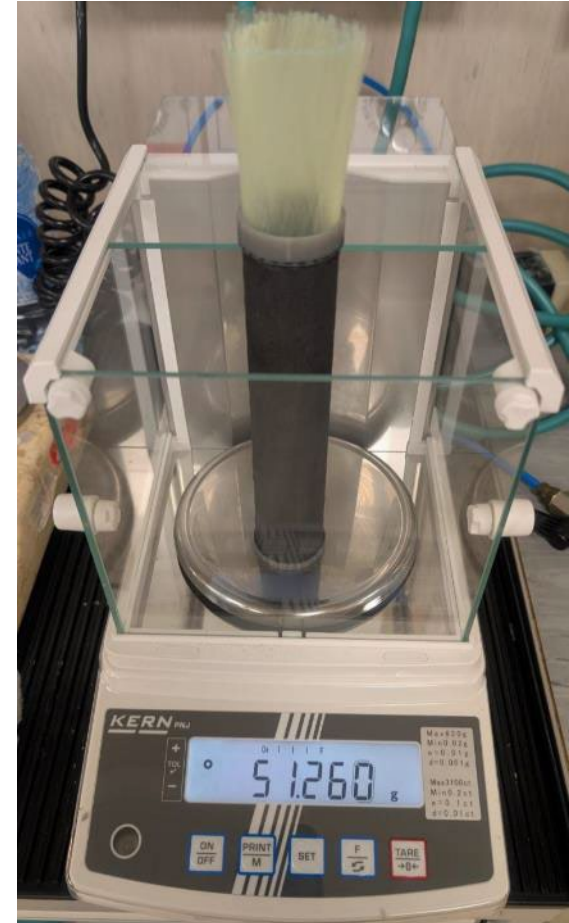




C1 demonstrator prototype: final details

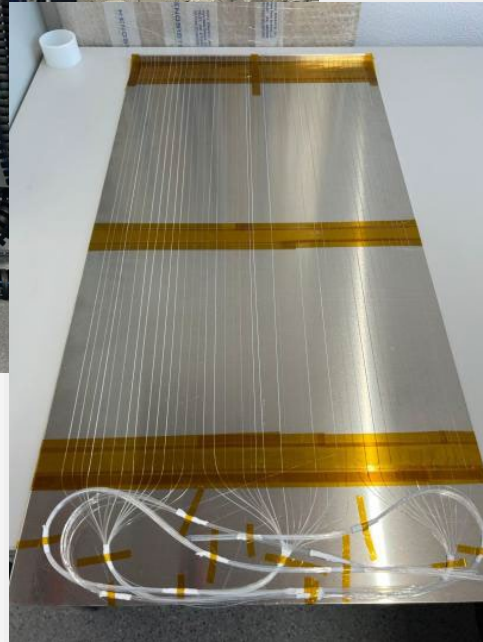
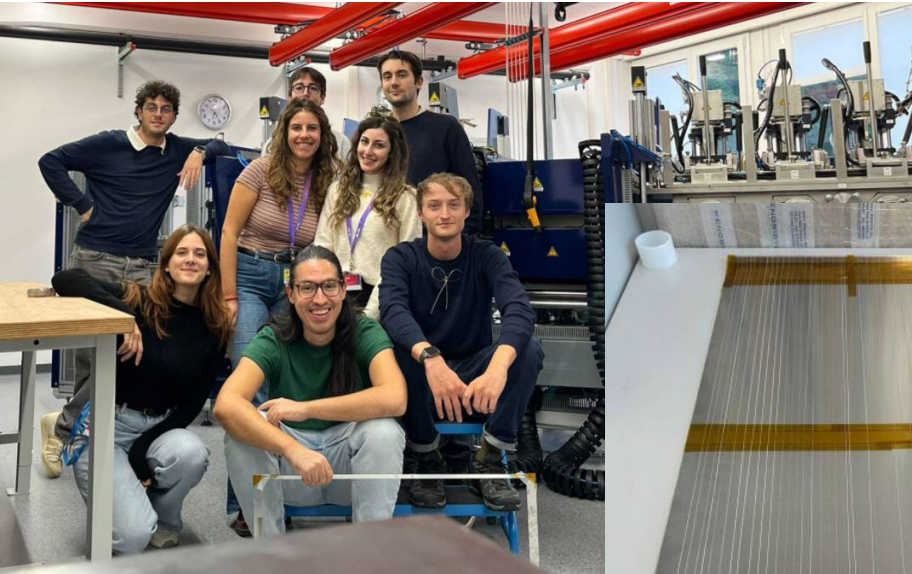


- Total weight of the demonstrator prototype is 51.3 g
- 420 fibers are 27.5 g carbon fiber mylar





Coating the fibers with AL for light transmission





open for participation

PSI proposal R-21-02.1

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CI: Cockcroft Institute, Daresbury, United Kingdom

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January 24, 2023



- The frozen-spin technique in a compact trap has a unique sensitivity for cp EDMs
- The PSI μ EDM search demonstrates all essential techniques in a step-by-step approach first storage this December
- In the first phase we will demonstrate a sensitivity to a μ EDM of better than $4 \times 10^{-21} ecm$
- Phase II welcomes collaborators and aims for a sensitivity of $6 \times 10^{-23} ecm$
- Possibility to measure $g-2$ with a sensitivity comparable to the current result
- Unique opportunity to explore hadronic CPV

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



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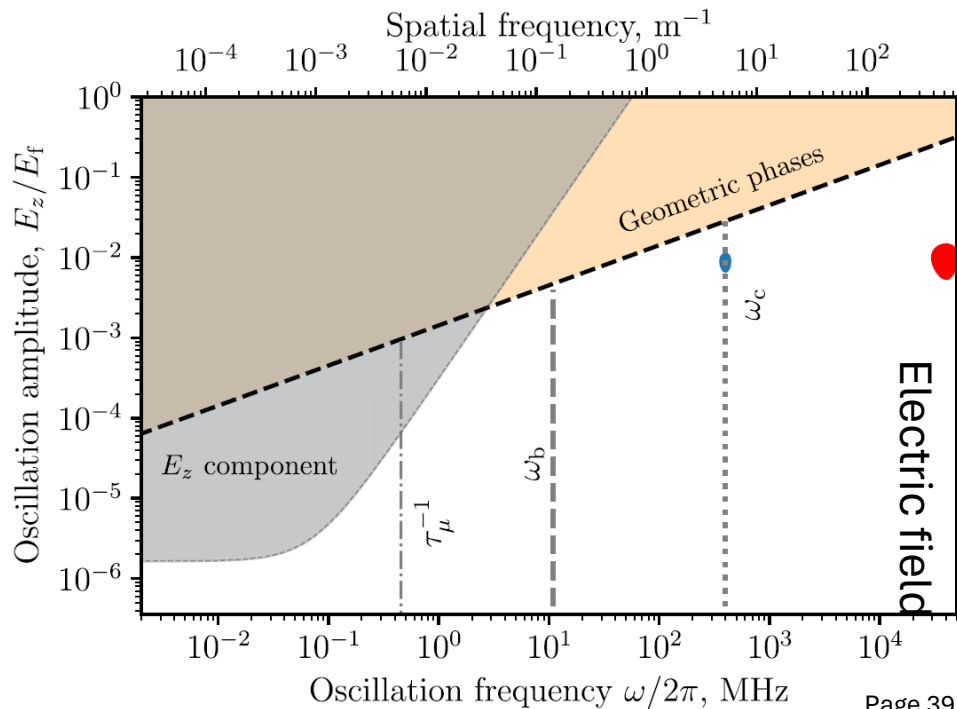
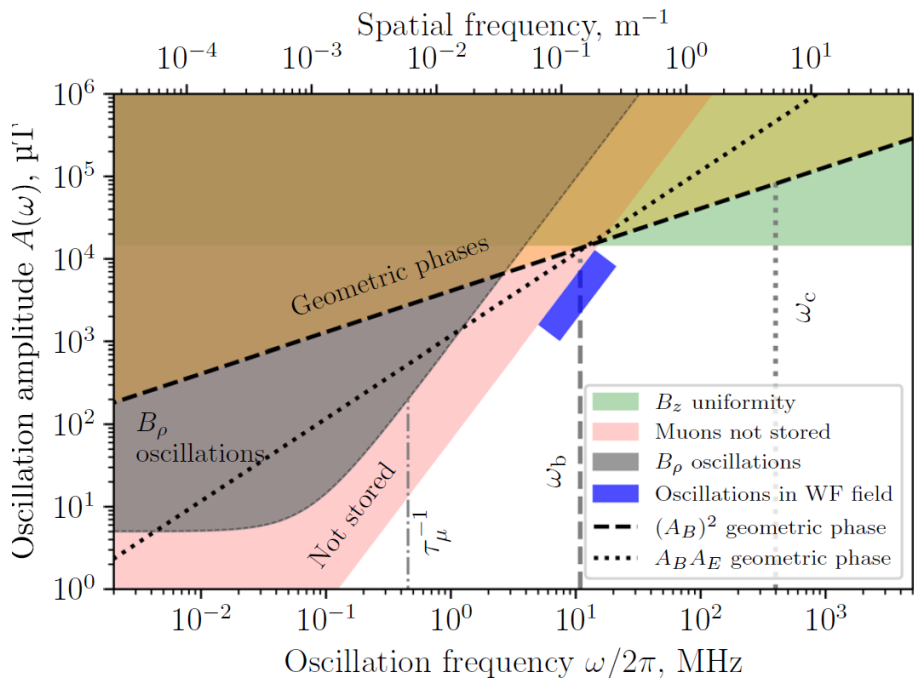
Backup



Geometric phases, and non-uniformities



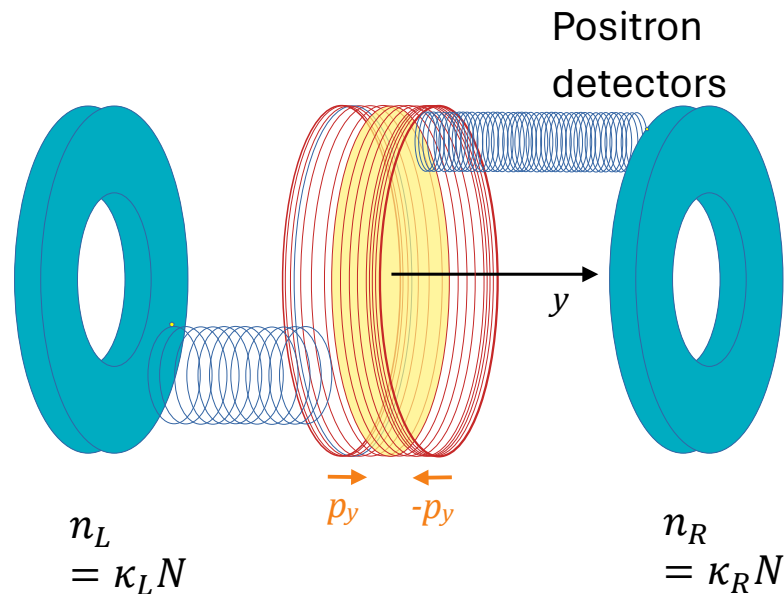
$$\frac{1}{4} \frac{\Omega_x \Omega_y}{\omega_x \omega_y} \left[\frac{\omega_x - \omega_y}{\omega_x + \omega_y} \cos((\omega_x + \omega_y)t + \beta_0) - \frac{\omega_x + \omega_y}{\omega_x - \omega_y} \cos((\omega_y - \omega_x)t + \beta_0) \right] \rightarrow -\frac{1}{2\omega} \Omega_x \Omega_y t \sin(\beta_0)$$





Detection efficiency asymmetry

- The EDM will be deduced from the accumulation of asymmetry between the upstream and downstream detectors that increases with time
- Static differences in the detection efficiency of one detector compared to the other is not a problem
- Change of the detection efficiency with time is a problem as it will introduce time dependent asymmetry





Constraints on the total detection efficiency PSI

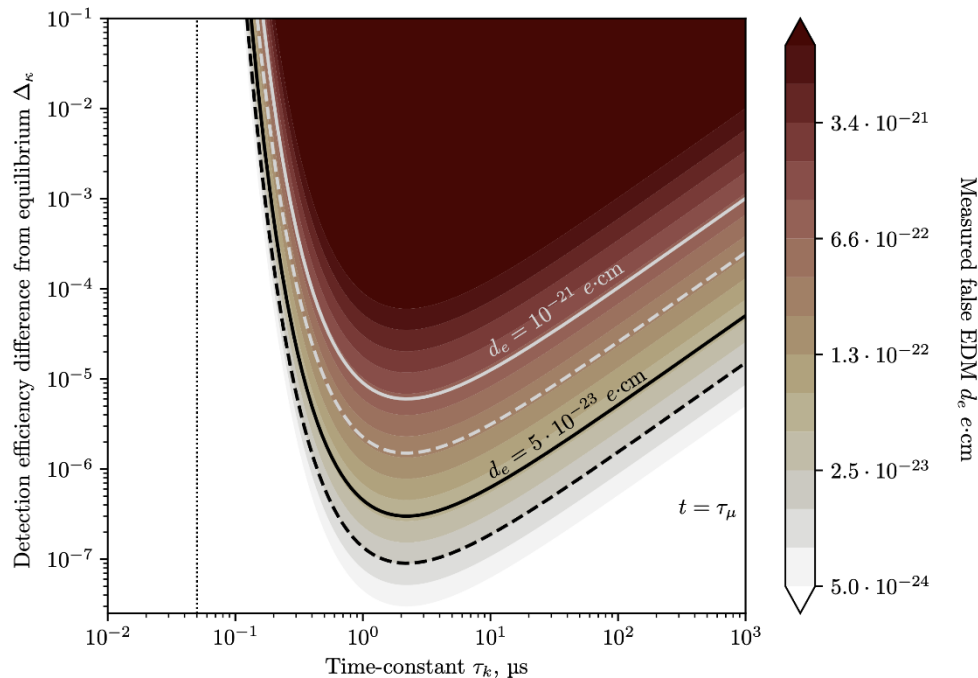
- Assumption: Change of detection efficiency triggered by pulse, exponential decay
- Detection efficiency of up and downstream detectors:

$$\kappa_u = \kappa_{u0} - \Delta_\kappa e^{-t/\tau_k},$$

$$\kappa_d = \kappa_{d0} + \Delta_\kappa e^{-t/\tau_k},$$

- Change in measured asymmetry with time:

$$\dot{A}_m = \frac{2}{\tau_k} \Delta_\kappa e^{-t/\tau_k}$$





Systematic study - overview



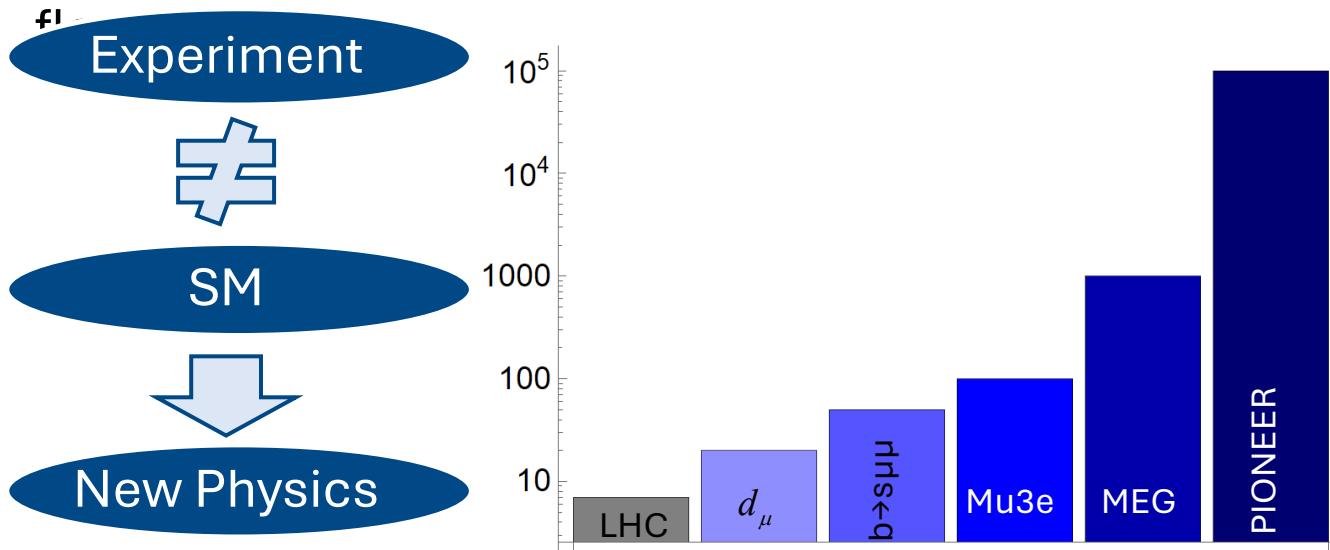
Systematic effect	Phase I		Phase II	
	Expected value	Syst.	Expected value	Syst.
	(Limit value)	$10^{-21} \text{ e}\cdot\text{cm}$	(Limit value)	$10^{-23} \text{ e}\cdot\text{cm}$
Radial B -field (ii) @100 kHz	5 μT (140 μT)	0.03	20 μT (40 μT)	0.75
Current flowing through orbit (iii)	< 10 mA (250 mA)	< 10^{-2}	< 10 mA (40 mA)	0.3
Longitudinal E -field E_z , (v)	< $10^{-4} E_f$	–	< $1.5 \times 10^{-5} E_f$	–
Mean momentum difference Δp , (vi)	0.2% (0.5%)	–	(0.1)%	–
Difference in initial polarisation, (vii)	25 mrad	–	5 mrad	–
Radial E -field adjustment, (viii)	0.1%	–	0.01%	–
Main B -field adjustment, (viii)	0.01%	–	0.001%	–
CW/CCW orbit displacement	1 mm	–	1 mm	–
$\partial_x E_z$, $\partial_y E_z$	(0.56 kV/m/m)	–	(0.15 kV/m/m)	–
E -field related systematics	–	0.75	–	1.5
Resonant geometrical phase accumulation (xi)	Pitch < 1 mrad Offset < 2 mm	2×10^{-2}	Pitch < 1 mrad Offset < 2 mm	0.15
TOTAL		0.75		1.70



Finding New Physics with Flavor



- At colliders one produces many (up to 10^{14}) heavy quarks or leptons and measures their decays into light



Flavor observables are sensitive to higher energy scales than collider searches