Searching for the Muon's Electric Dipole Moment by A Compact Frozen-Spin Trap

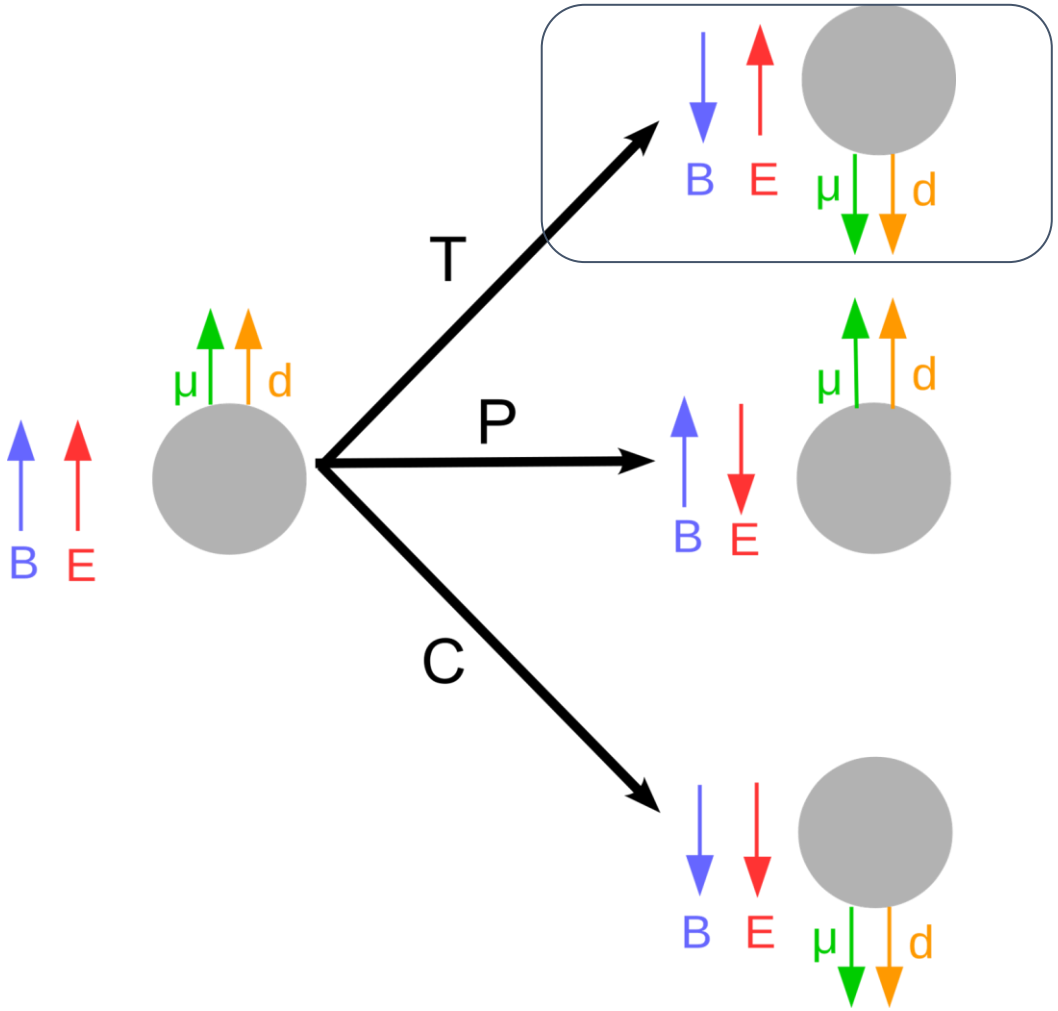
Tianqi Hu

June 10, 2025

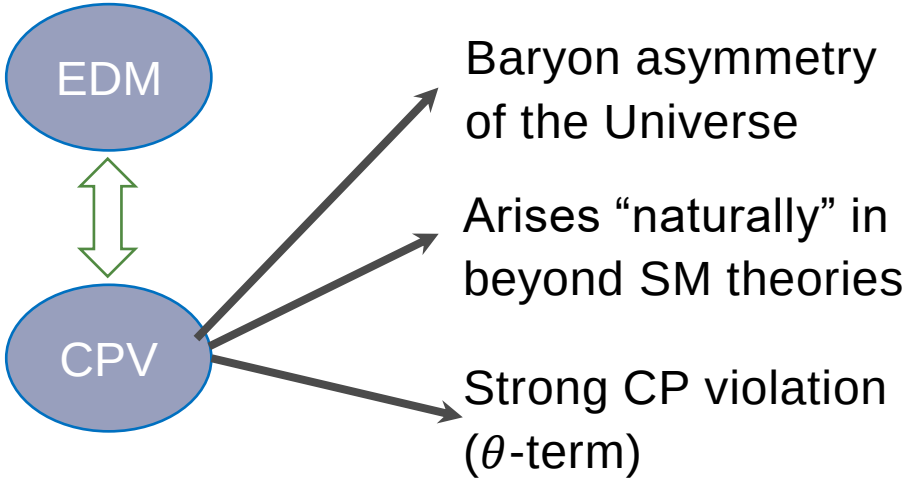
WIN 2025

李政道研究所
TSUNG-DAO LEE INSTITUTE

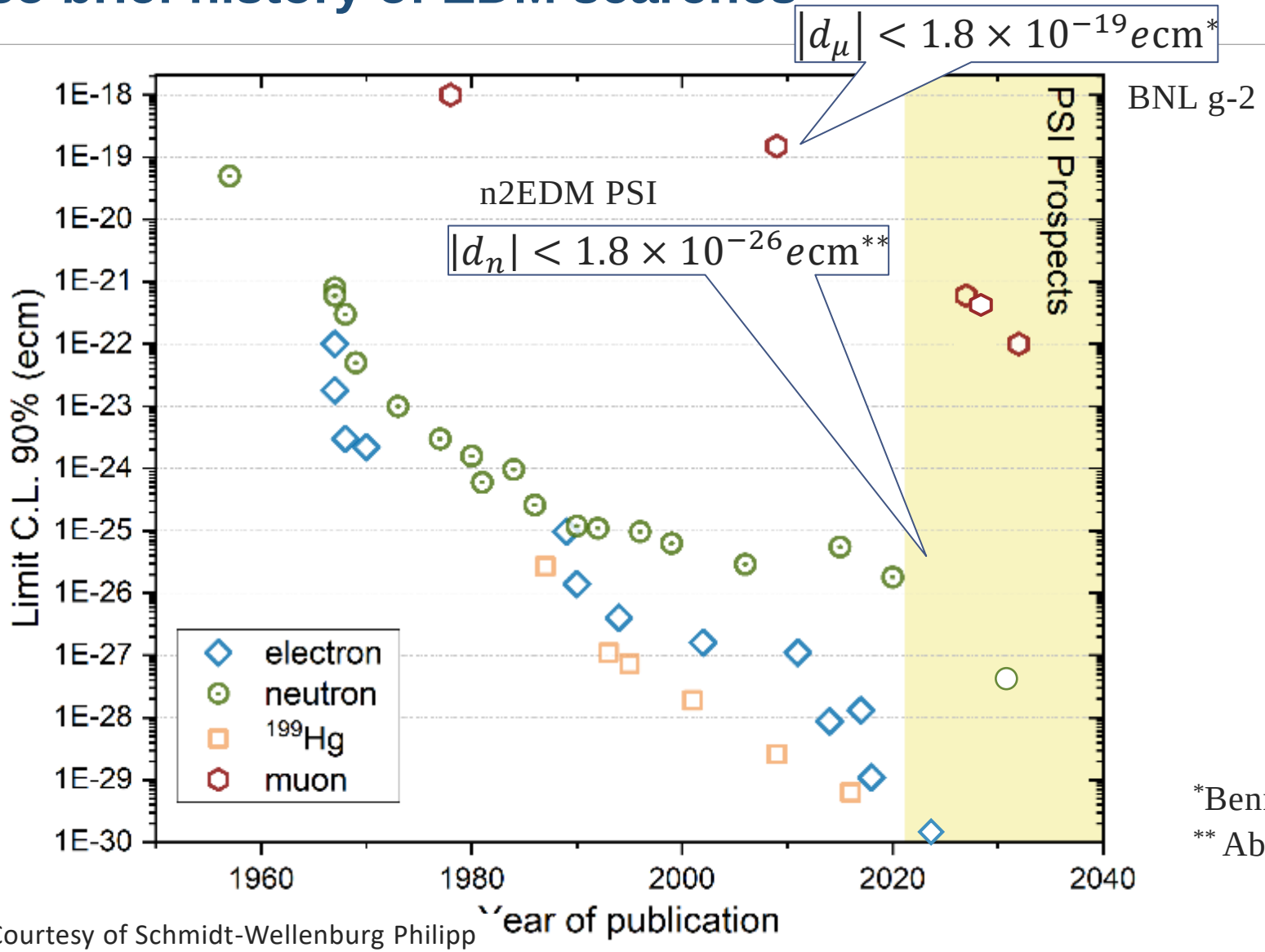
The Basics - CP violation in EM



A non-zero particle EDM violates P, T and, assuming CPT conservation, also CP.



A not so brief history of EDM searches



Courtesy of Schmidt-Wellenburg Philipp

*Bennett et al.,PRD80(2009)052008

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

The Basics - General limits on muon EDM

- MFV:

$$\left|d_{\mu\leftarrow e}^{\mathrm{MFV}}\right| < 8.5 \times 10^{-28} e\mathrm{cm}$$

- Contribution only starts at the 3-loop level*

$$\left|d_{\mu\leftarrow e}\right| < 4 \times 10^{-20}\ e\ \mathrm{cm}$$

- Y. Ema et al., PRL128, 131801 (2022)

$$\left|d_{\mu}\left({}^{199}\mathrm{Hg}\right)\right| < 6 \times 10^{-20}\ e\ \mathrm{cm}$$

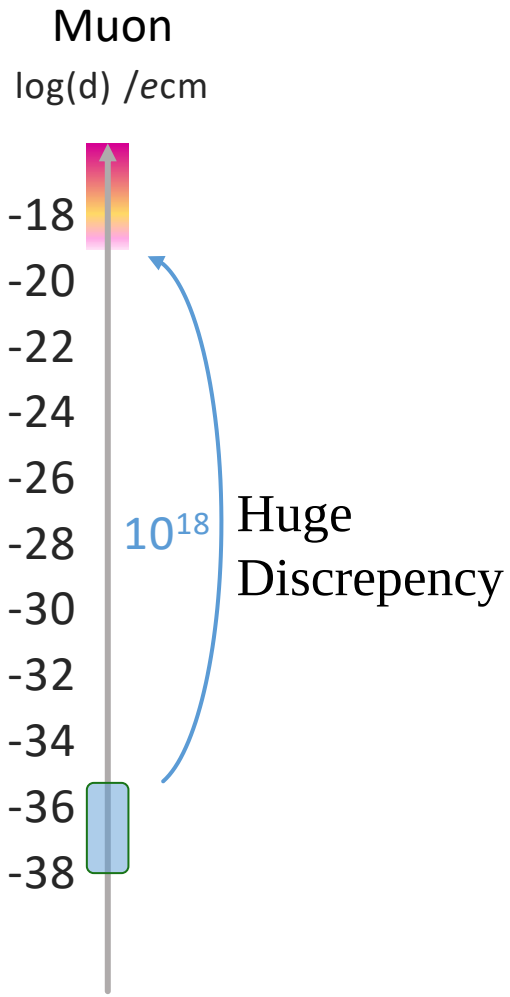
$$\left|d_{\mu}(\mathrm{ThO})\right| < 2 \times 10^{-20}\ e\ \mathrm{cm}$$

- A relatively large limitation within SM, from the hadronic long-distance contributions:

$$\left|d_{\mu}\right| < 1.38 \times 10^{-38} e\ \mathrm{cm}$$

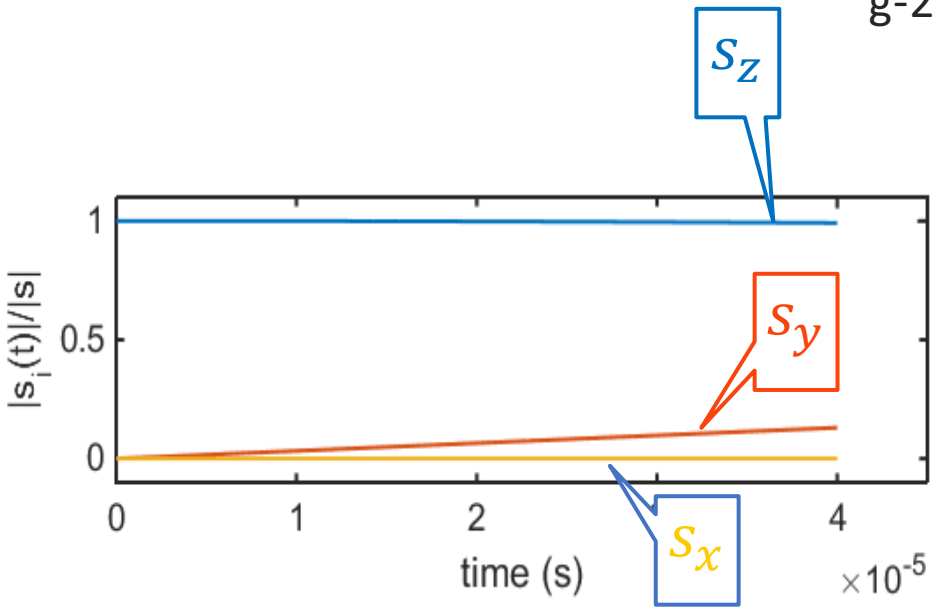
- Bennett et al., PRD80, 052008 (2009)

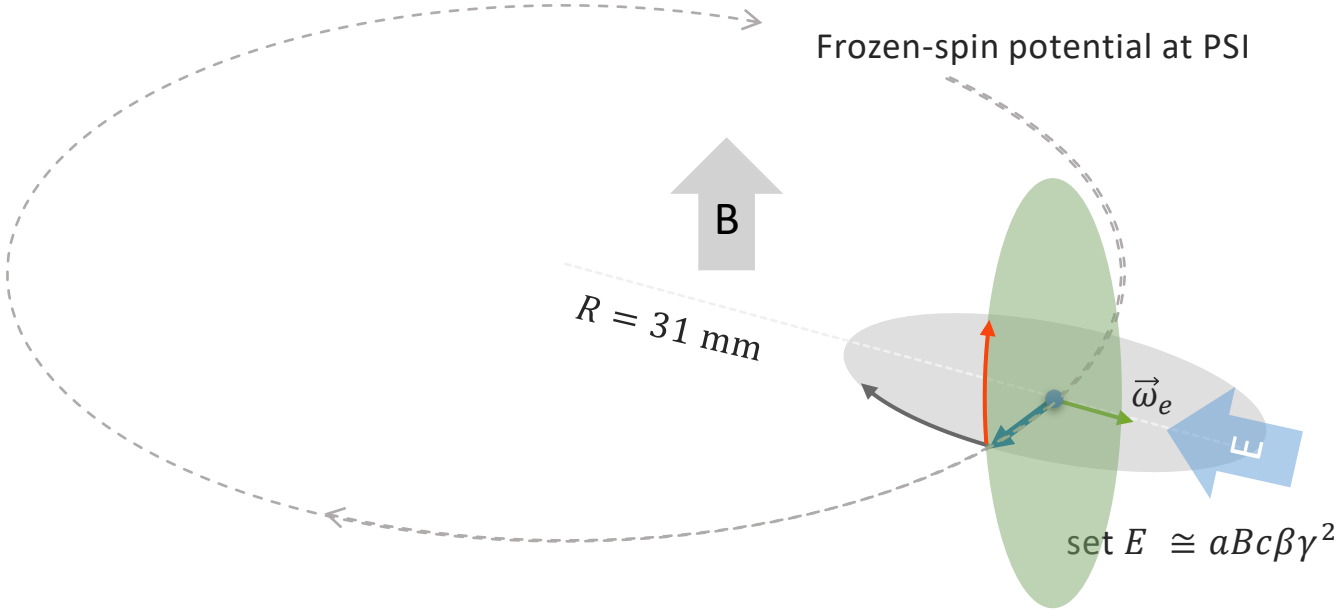
$$\left|d_{\mu}\right| < 1.5 \times 10^{-19}\ e\ \mathrm{cm}$$



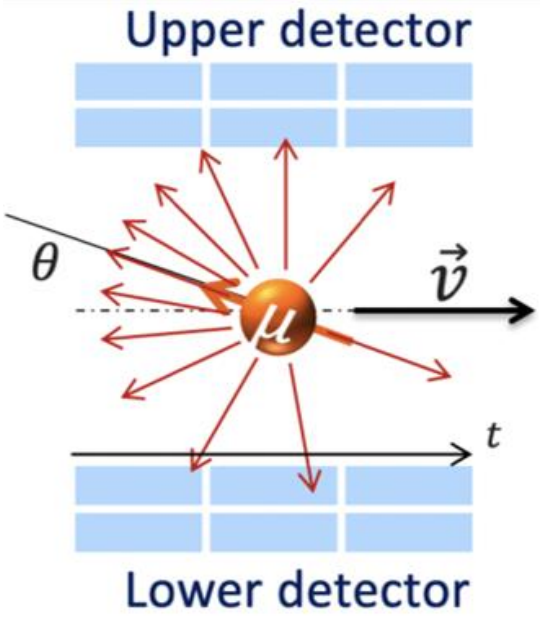
Muon dipole moments – freezing the spin at PSI

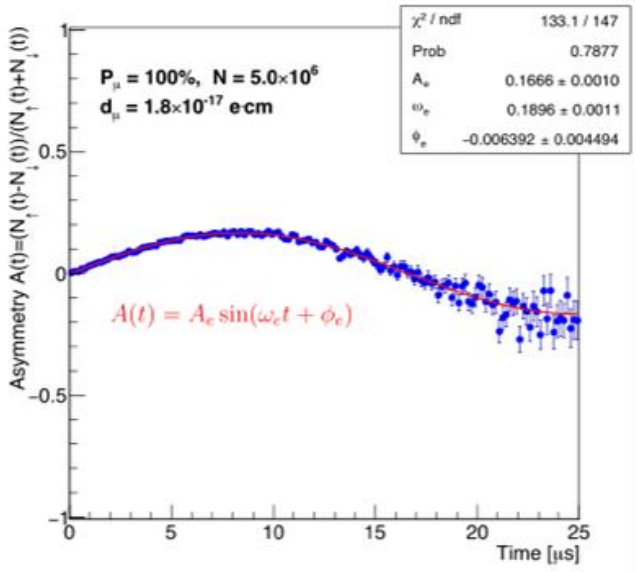
$$\vec{\omega} = -\frac{q}{m}\left[a\vec{B} + \underbrace{\left(\frac{1}{1-\gamma^2} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}}_{\text{g-2 term } \omega_a} + \underbrace{\frac{2d_\mu mc}{q\hbar}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)}_{\text{EDM term } \omega_e}\right]$$





The Experiment - The Signal





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

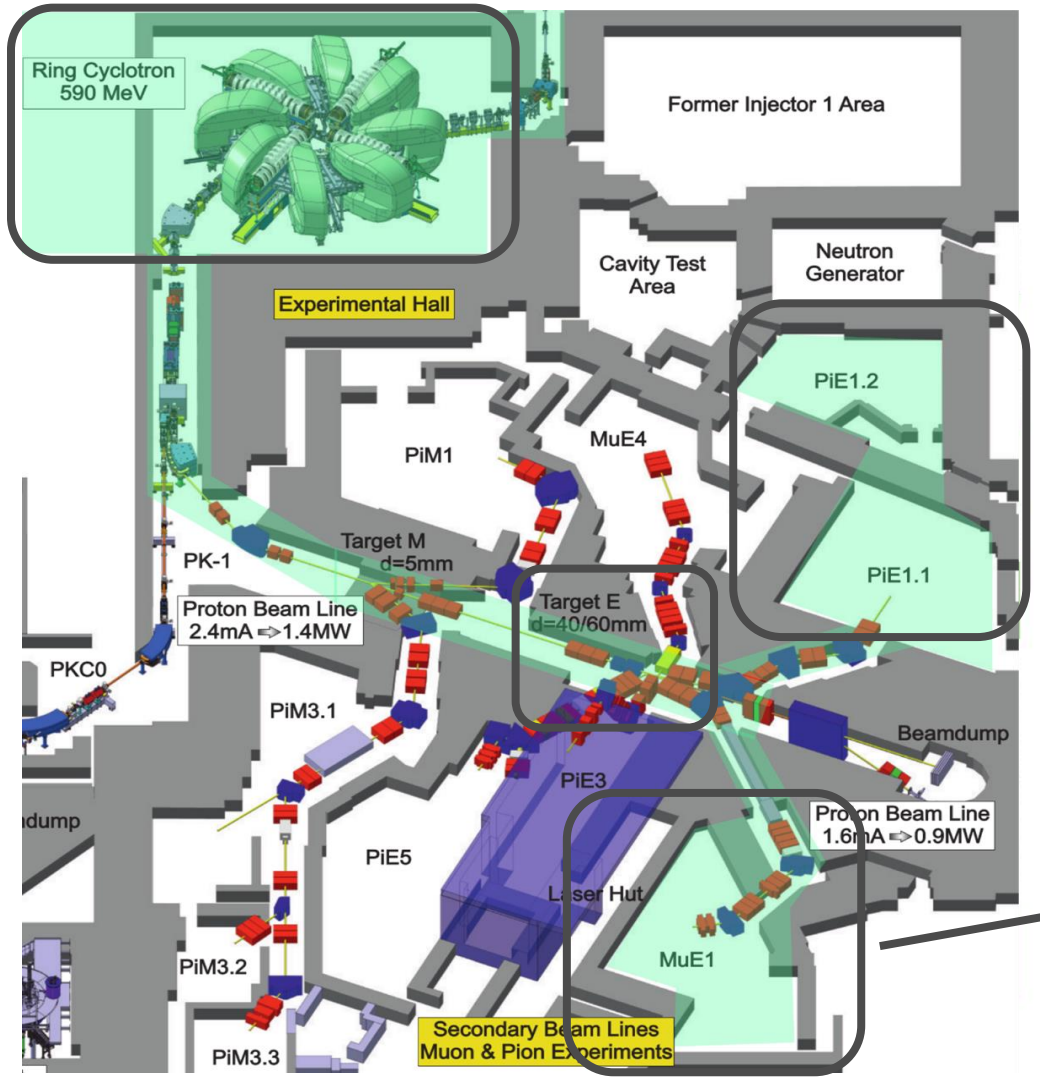
$$\dot{A}(\Psi_0, t) = \frac{\partial A}{\partial \Psi}\frac{\partial \Psi}{\partial t}\bigg|_{\Psi_0} = \alpha(\Psi_0)\,\dot{\Psi}(t)$$

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

- P: Initial polarization
- E_B': cβBγ (Boosted B)
- N: Detected positrons
- τ: Muon life-time
- α: Analysis parameter

- Asymmetry precession due to EDM is too slow.
- The change of asymmetry with respect to time is relevant.
- The sensitivity is optimized by maximizing α√N: (Figure-of-merit)

The Experiment - The Muons



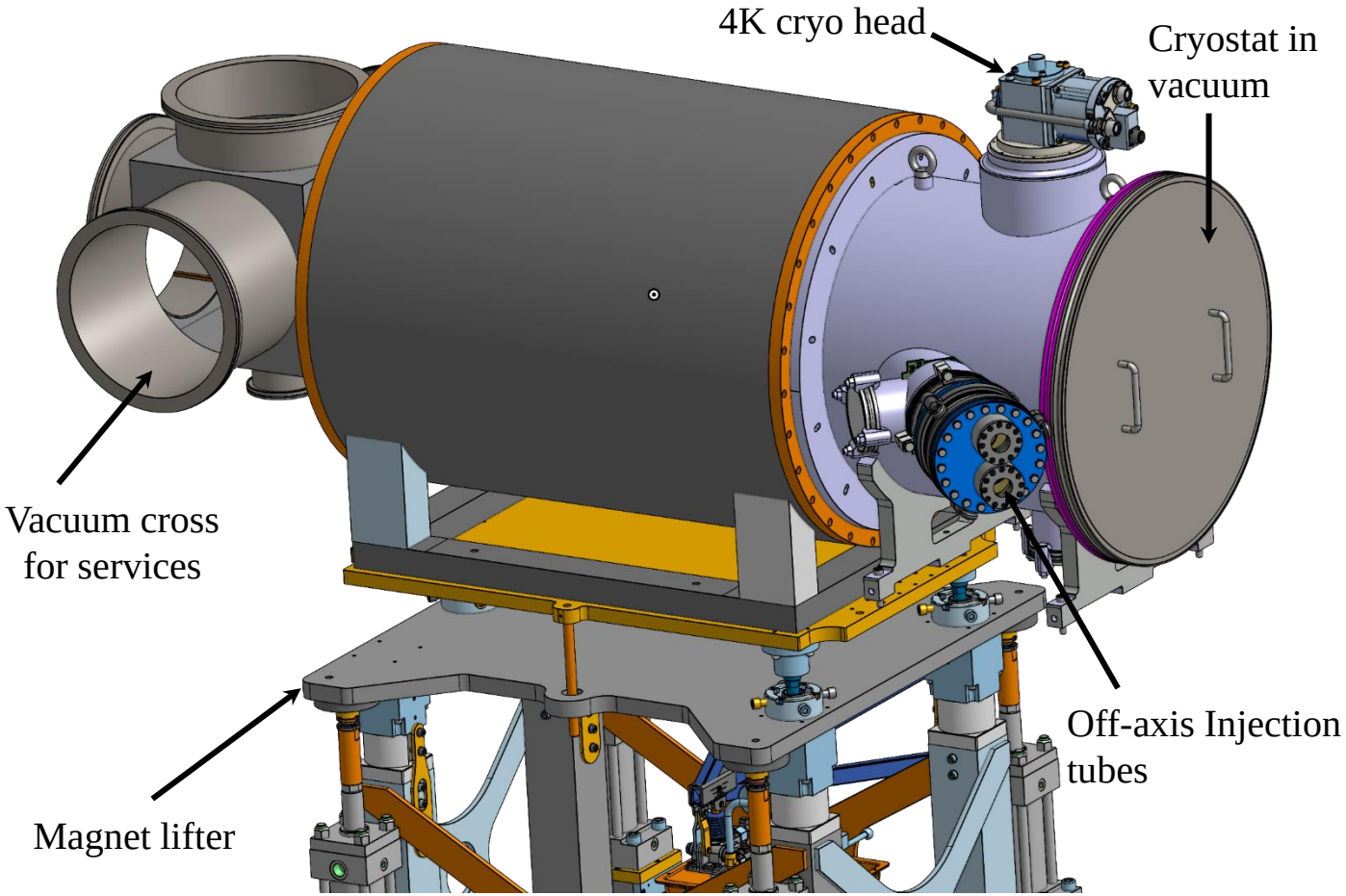
Phase I

- **p=28 MeV** muons
- Existing solenoid at PSI, max 5 T
- Bore diameter 200 mm
- Length 1 m
- Field measured in 2022 & found suitable for injection

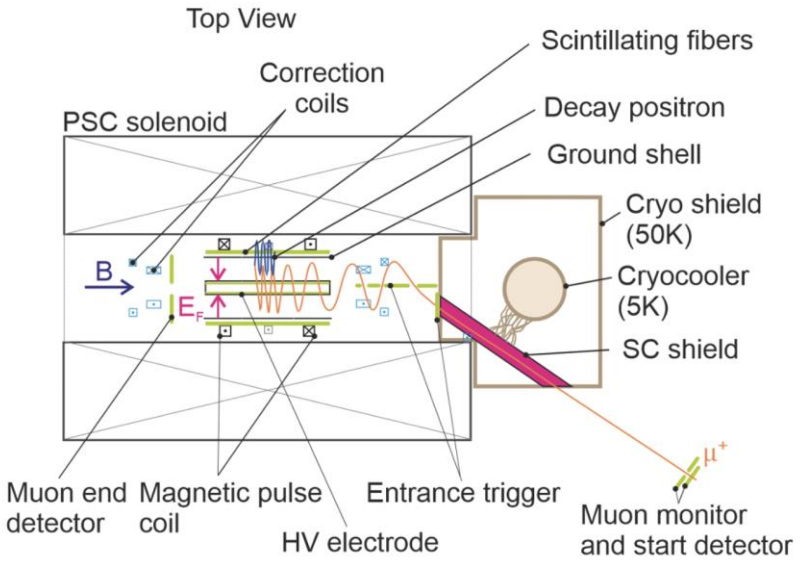
Phase II

- **p=125 MeV** muons
- Larger bore (up to 900 mm diameter)
- Better spatial and temporal stability

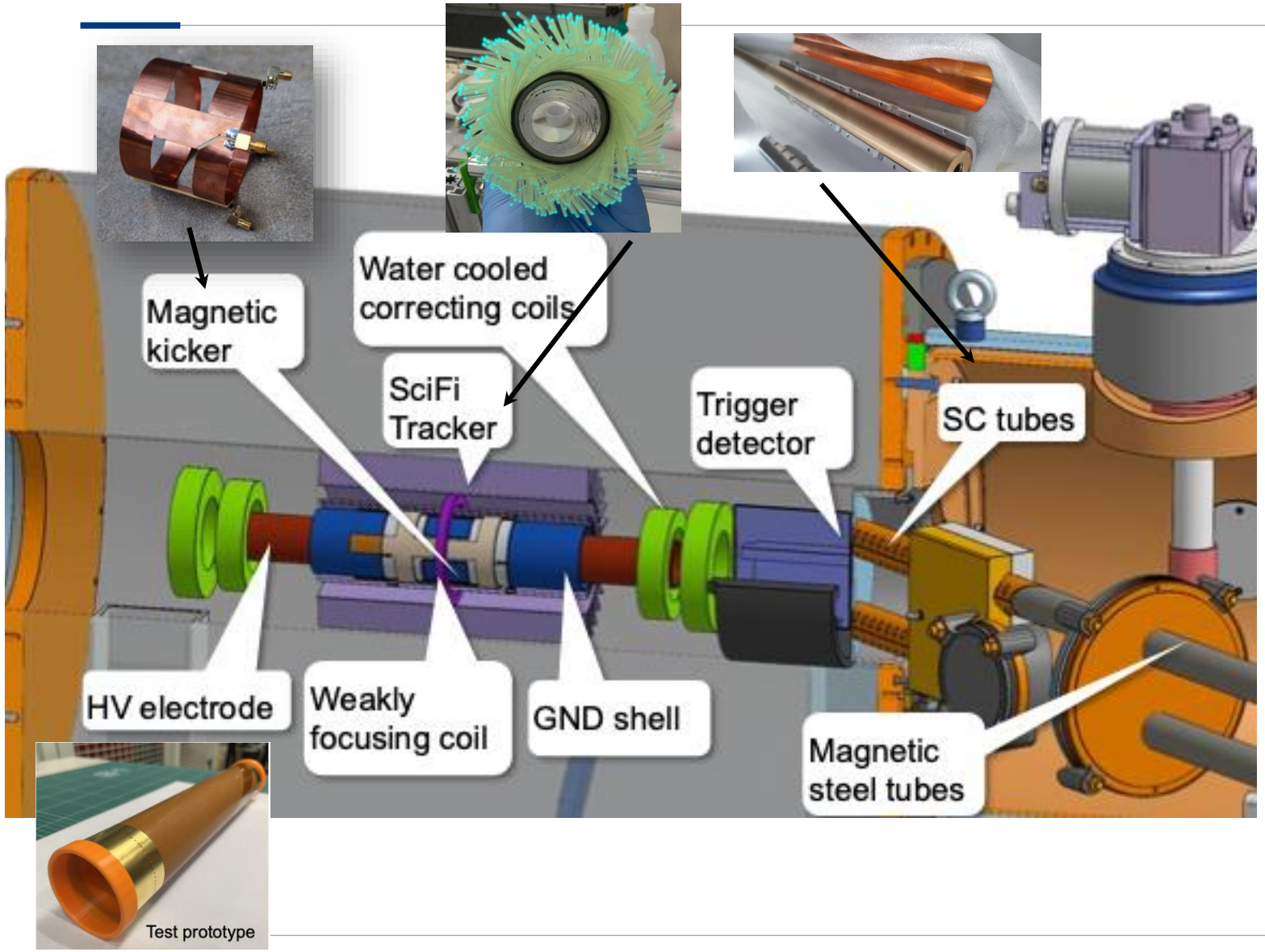
The Experiment - Technical overview

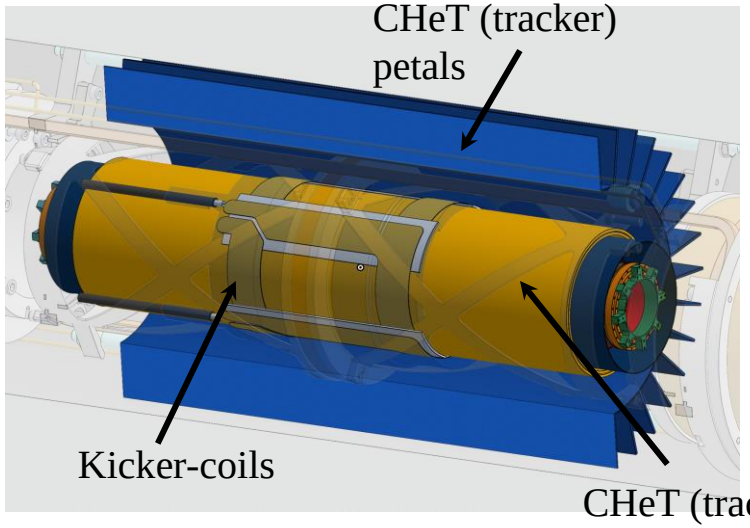


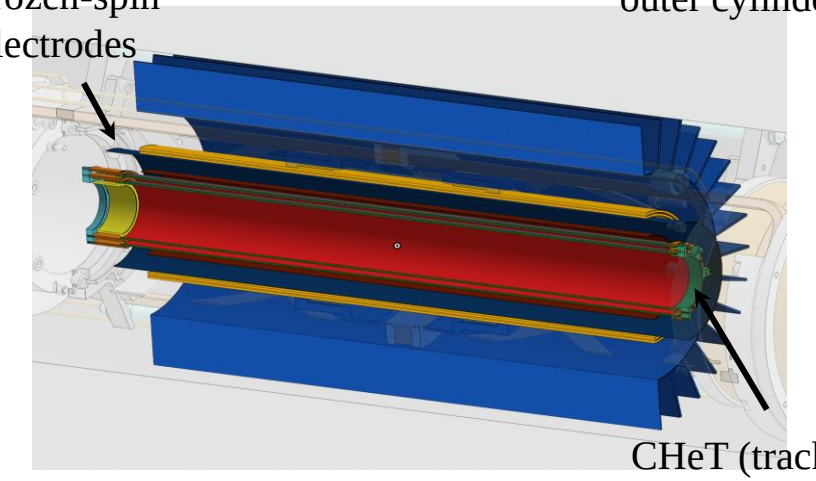
- Muons injected through a superconducting (SC) channel
- Fast entrance scintillator triggers magnetic pulse that stops the longitudinal μ+ motion
- Weakly focusing field for storage
- Thin electrodes provide an electric field for the frozen spin
- Scintillator detectors for decay e+ tracking



The Experiment - Layout

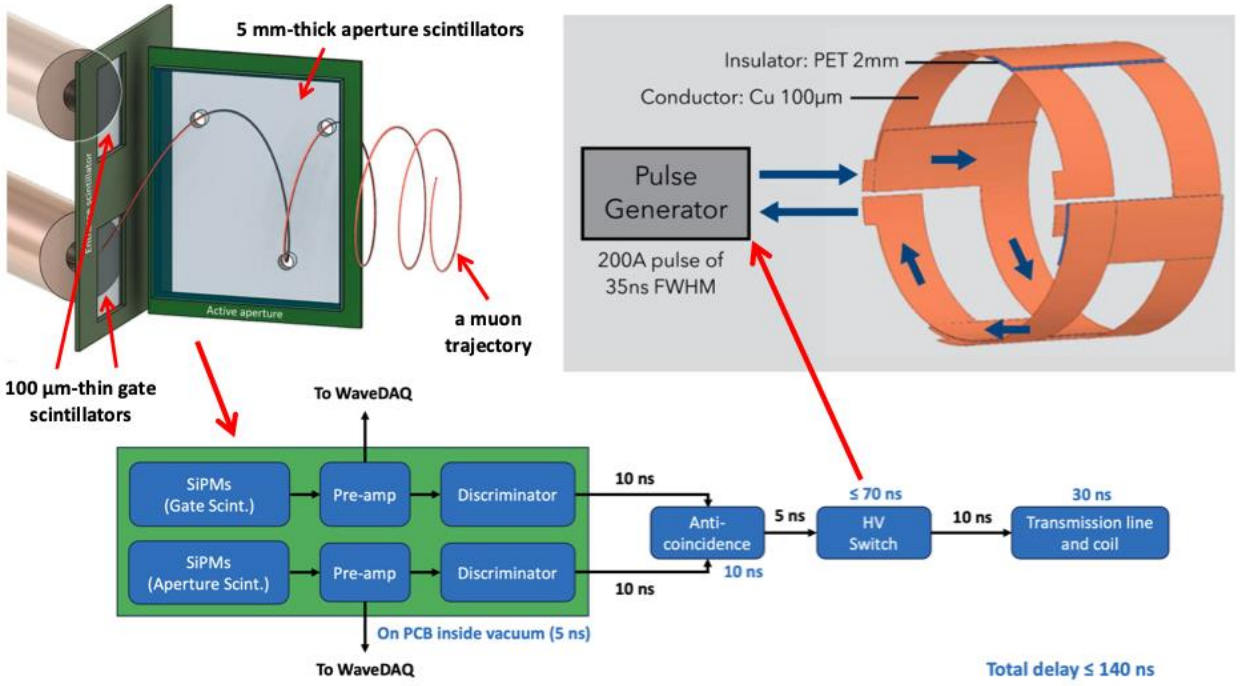






The Experiment - The Trigger detector

- **Developed by Shanghai Jiao Tong University**
- Trigger the kicker for storable muons
- ~0.4% of the incoming μ are in the acceptance phase space
- Thin gate scintillator with active aperture as veto
- Good performance in the 2024 beam test
- Anti-coincidence efficiency: > 99%, Propagation delay < 5 ns



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Development of Fast Front-End Electronics for the Muon Trigger Detector in the PSI muEDM Experiment

Tianqi Hu, Guan Ming Wong, Chavdar Dutsov, Siew Yan Hoh, Kim Siang Khaw, Diego Alejandro Sanz Becerra, Philipp Schmidt-Wellenburg, Yuzhi Shang, and Yusuke Takeuchi

Check for updates

Beam test performance of a prototype muon trigger detector for the PSI muEDM experiment

Tianqi Hu[1,2] · Jun Kai Ng[1,2] · Guan Ming Wong[1,2] · Cheng Chen[1,2] · Kim Siang Khaw[1,2] · Meng Lyu[1,3] · Angela Papa[4,5,6] · Philipp Schmidt-Wellenburg[6] · David Staeger[6] · Bastiano Vitali[5,7]

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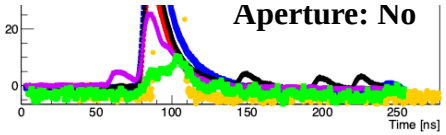
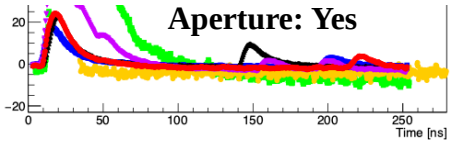
Bayesian optimization of beam injection and storage in the PSI muEDM Experiment*

Siew Yan Hoh,[1] Yuzhi Shang,[1] Ritwika Chakraborty,[2] Tianqi Hu,[1] Kim Siang Khaw,[1,†] Philipp Schmidt-Wellenburg,[2] Yusuke Takeuchi,[1] and Guan Ming Wong[1]
[1]*Tsung-Dao Lee Institute and School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 201210, China*
[2]*Paul Scherrer Institut, Forschungsstrasse 111, 5232 Villigen PSI, Switzerland*



A good muon (With LVTTL)

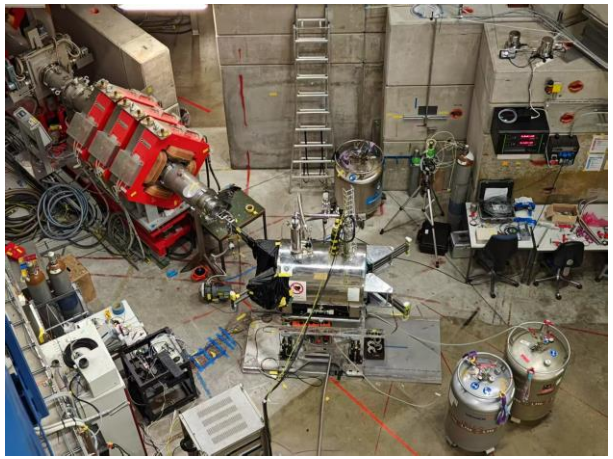


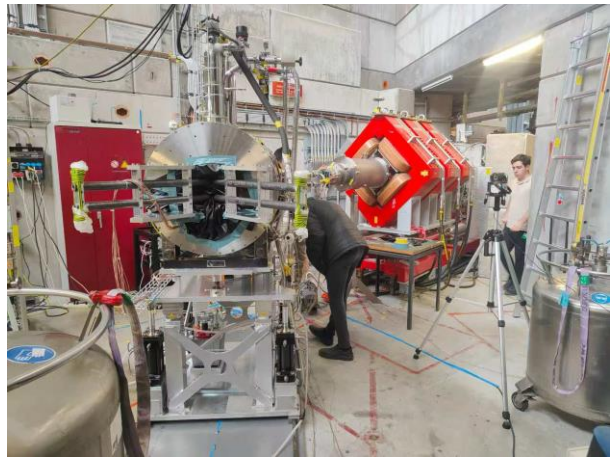
A bad muon (Without LVTTL)

The Experiment - Current status & plans

PSI muEDM Collaboration Group

- Dec 2025 beam-time: test (preliminary) components and assembly
  - Cryogenic injection
  - Magnetic kick - can we store muons?
  - Positron detection in the fiber detector prototype
  - Characterization of muon trajectory with TPC
  - DAQ
- 2026: Demonstration of the frozen spin techniques and first measurement of muEDM



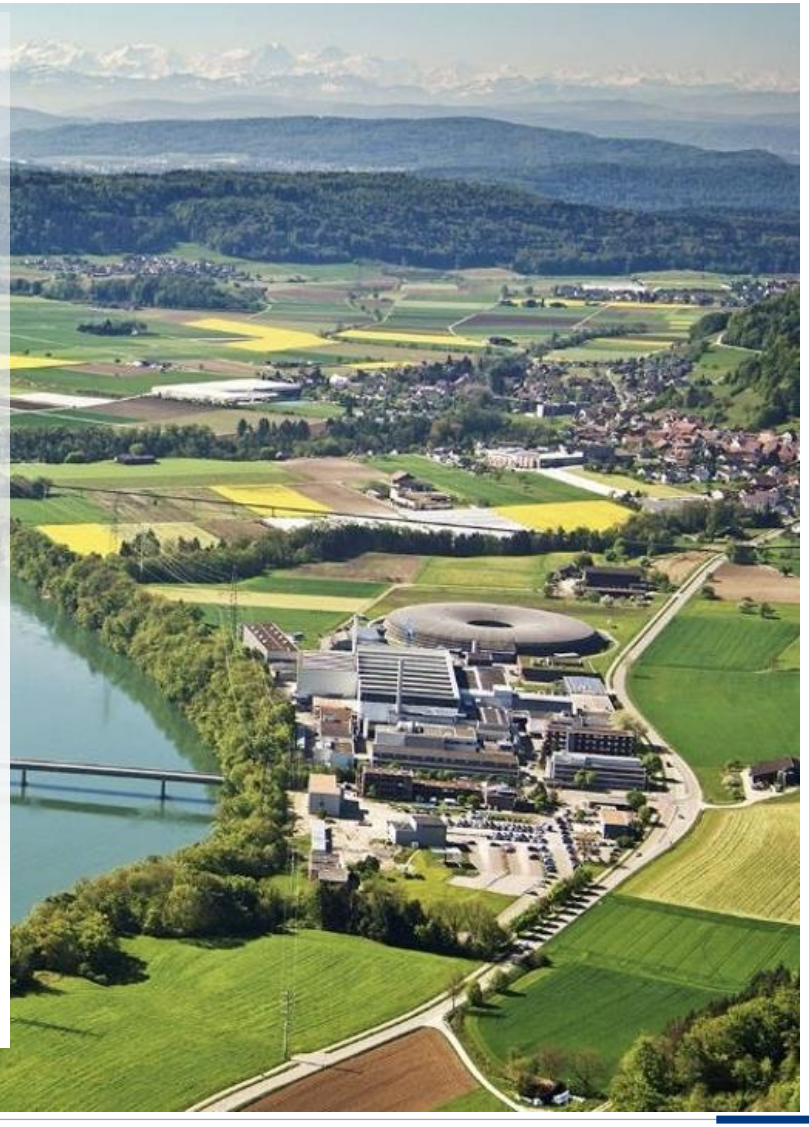


A compact frozen-spin trap for the search for the electric dipole moment of the muon

A. Adelmann,[1,2] A.R. Bainbridge,[3,4] I. Bailey,[4,5] A. Baldini,[6] S. Basnet,[7,8] N. Berger,[9] C. Calzolaio,[10] L. Caminada,[11,12] G. Cavoto,[13,14] F. Cei,[6] R. Chakraborty,[12] C. Chavez Barajas,[15] M. Chiappini,[6] A. Crivellin,[11] C. Dutsov,[12] A. Ebrahimi,[12] M. Francesconi,[6] L. Galli,[6] G. Gallucci,[6] M. Giovannozzi,[16] H. Goyal,[12] M. Grassi,[6] A. Gurgone,[6] M. Hildebrandt,[12] M. Hoferichter,[17] D. Höhl,[12] T. Hu,[7,8] T. Hume,[12] J.A. Jaeger,[12] P. Juknevicius,[12] H.C. Kästli,[12] A. Keshavarzi,[18] K.S. Khaw,[7,8] K. Kirch,[1,12] A. Kozlinskiy,[9] M. Lancaster,[18] B. Märkisch,[19] L. Morvaj,[12] A. Papa,[6,12] M. Paraliev,[10] D. Pasciuto,[14] J. Price,[15] F. Renga,[14] M. Sakurai,[20] D. Sanz-Becerra,[12] P. Schmidt-Wellenburg,[12,*] Y. Z. Shang,[7,8] Y. Takeuchi,[7,8] M. E. Tegano,[6] T. Teubner,[15] F. Trillaud,[21] D. Uglietti,[22] D. Vasilkova,[15] A. Venturini,[6] B. Vitali,[6] C. Voena,[14] J. Vossebeld,[15] F. Wauters,[9] G. M. Wong,[7,8] and Y. Zeng[7,8]

Conclusion and outlook

- Searches of EDMs are sensitive to BSM and complementary to HEP
- The muon EDM search is the only search using a bare particle
- The PSI muEDM search demonstrates all essential techniques in a step-by-step approach
- In the first phase we will demonstrate a sensitivity to a muEDM of better than $4 \times 10^{-21} e\mathrm{cm}$
- Phase II welcomes collaborators and aims for a sensitivity of $6 \times 10^{-23} e\mathrm{cm}$



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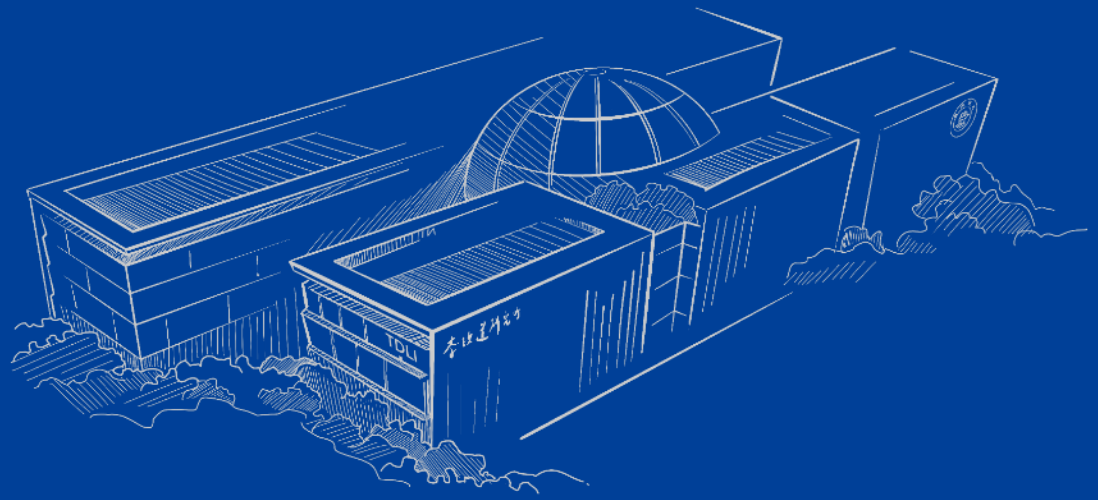
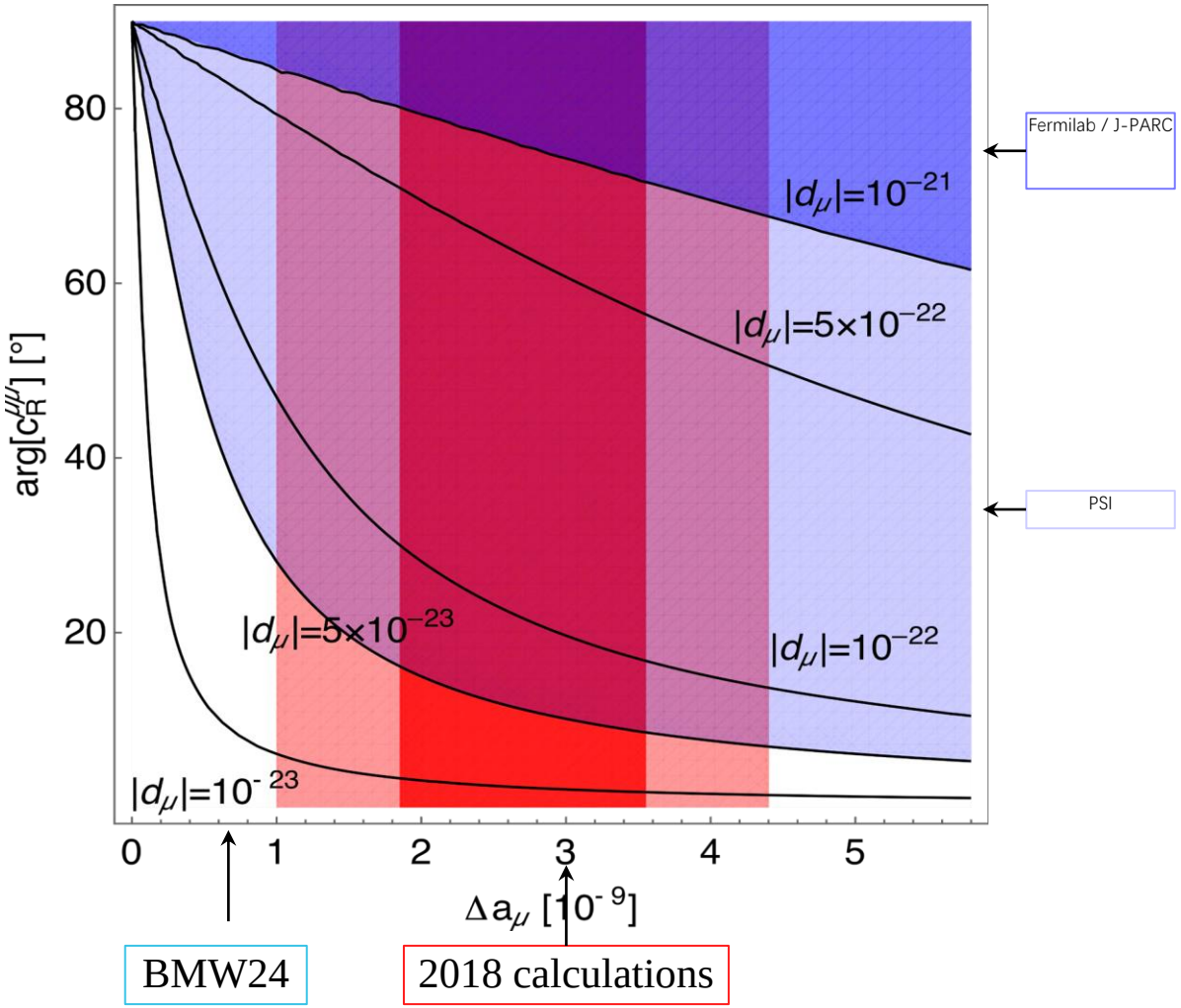


The Basics - General limits



- MFV: $\left|d_{\mu\leftarrow e}^{\mathrm{MFV}}\right| < 8.5\times10^{-28} e\mathrm{cm}$
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- Y. Ema et al., PRL128, 131801 (2022)

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- A relatively large limitation within SM, from the hadronic long-distance contributions:

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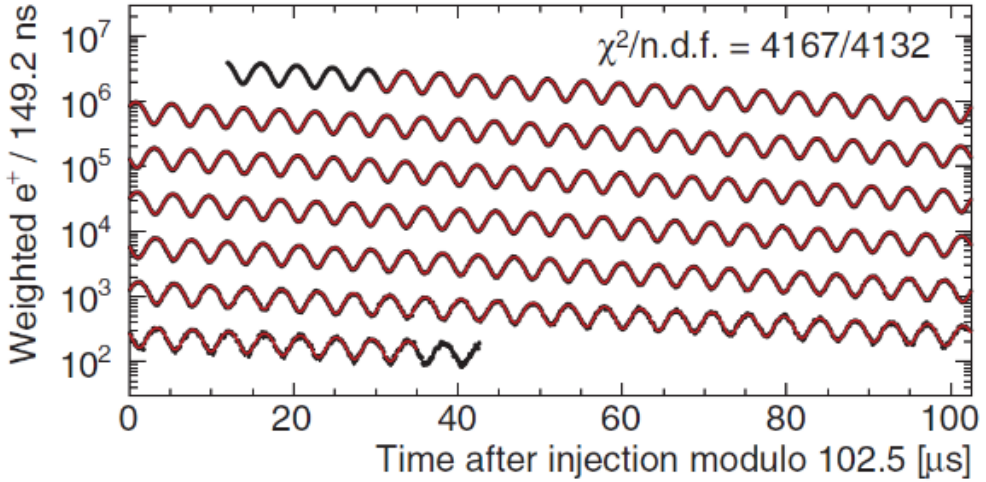
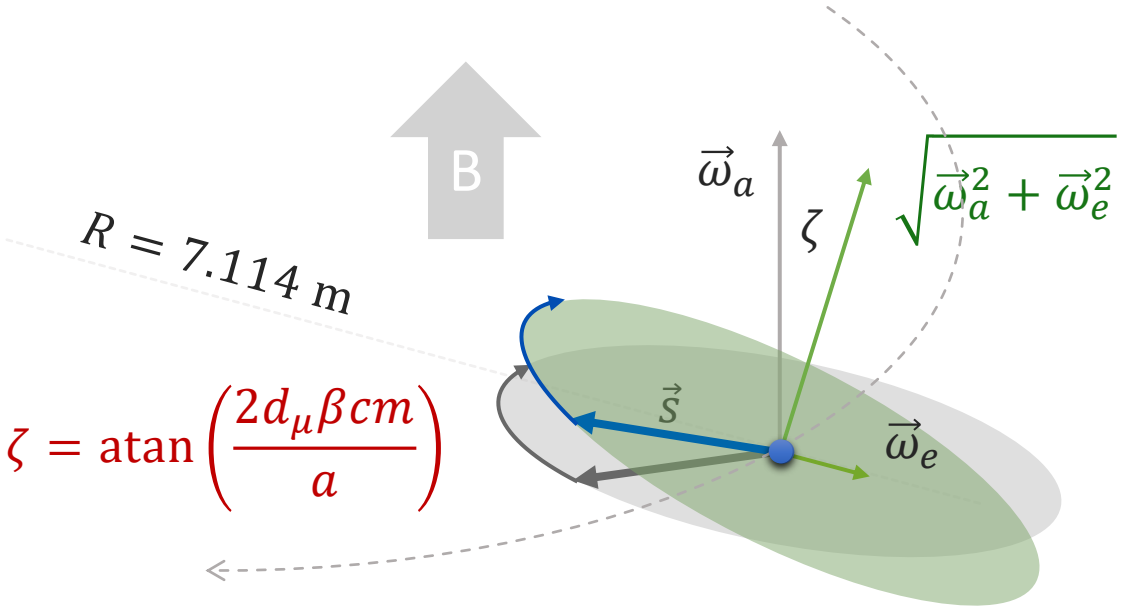
- Bennett et al., PRD80, 052008 (2009)

$$\left|d_\mu\right| < 1.5\times10^{-19}\ e\ \mathrm{cm}$$

Muon dipole moments and frequencies

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





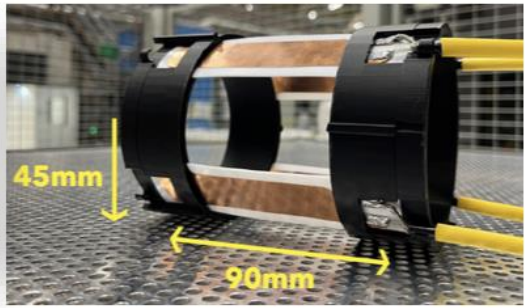
FNAL* & JPARC**: $\sigma(d_\mu) \approx 10^{-21} e\mathrm{cm}$

[Abi et al., PRL**126** 141801(2021)]

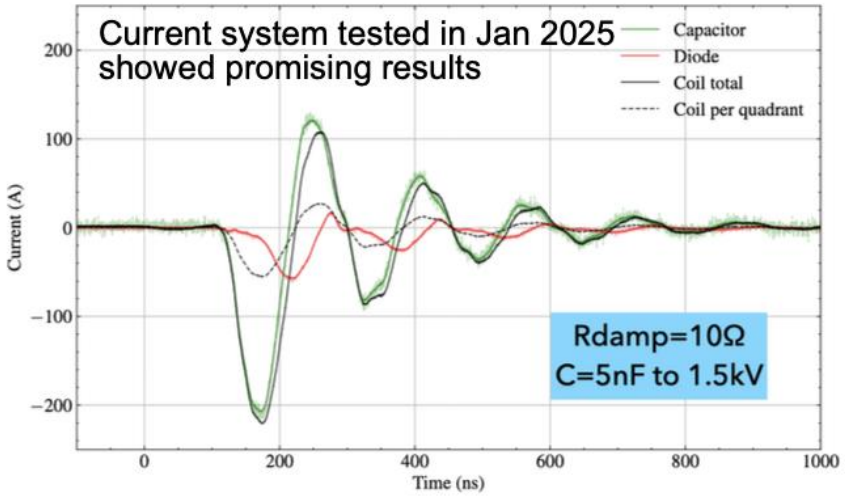
[*Chislett et al., EPJConf.**118** 01005(2016), Abi et al., PRL**126** 141801(2021), **Abe et al., PTEP053C02 (2019)]

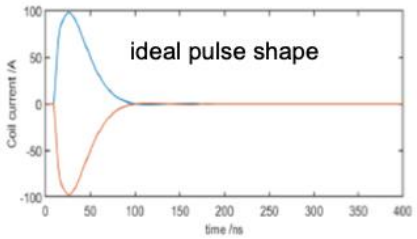
The Experiment – Magnetic Kicker

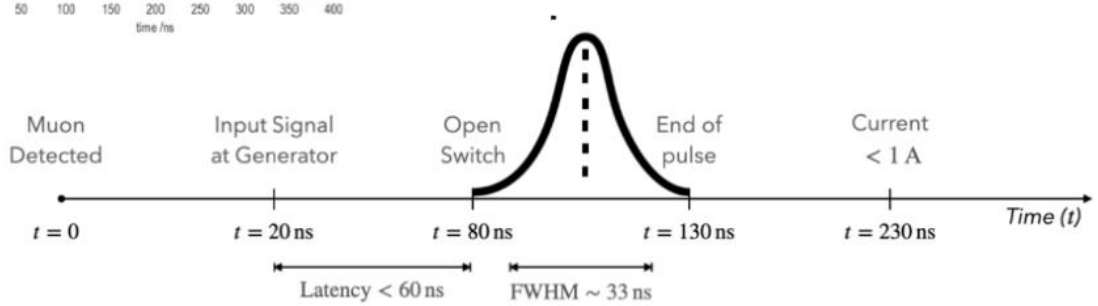
- **Magnetic pulse to stop the z-motion of muons and store them in the centre of the solenoid**
- Kicker coil:
  - 4-quadrant anti-Helmholtz made of 100 μm Cu
- Kicker power supply under development
  - With very strict requirements



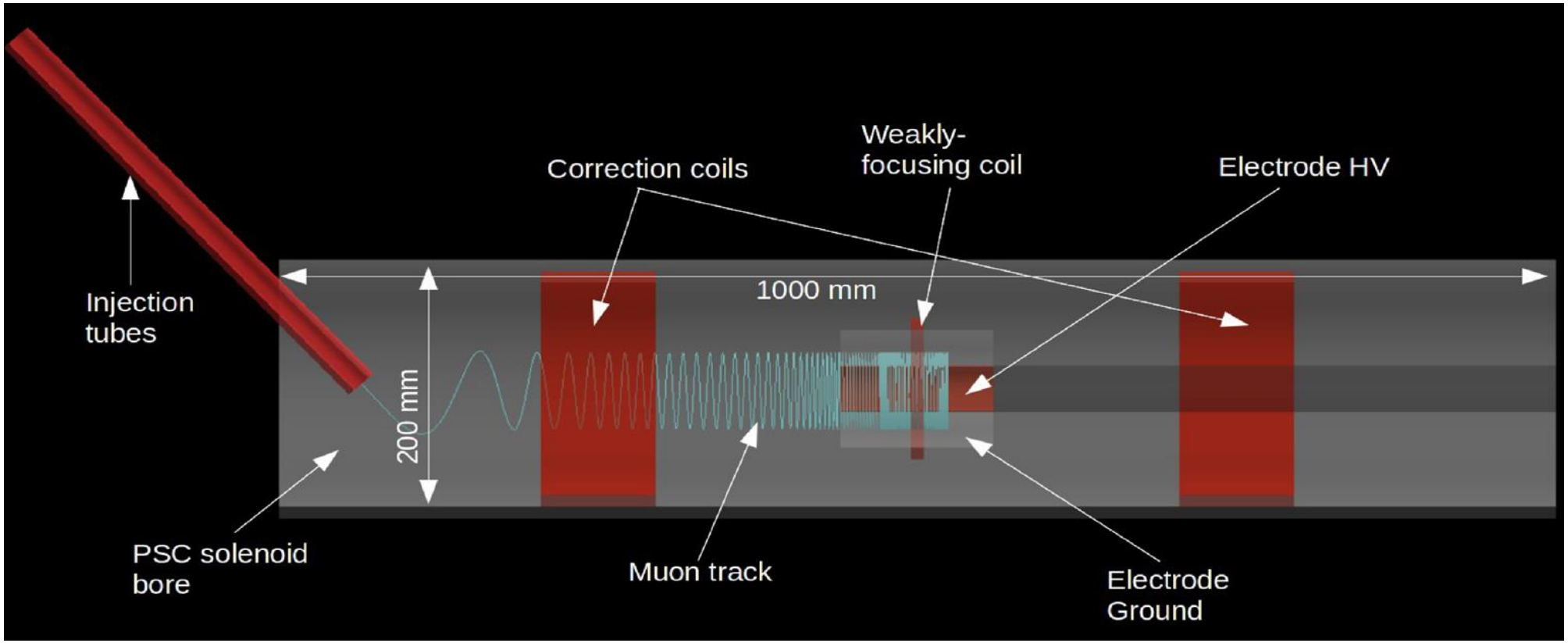
pulse start delay	< 70ns (ideally < 60ns)
FWHM	33ns – 66ns
peak current amplitude	4 x 200A
current oscillations after >150ns	< 10A (ideally < 1A)
repetition rate	2000/s
recovery time	< 20μs







The Experiment – Storage Parameters



- Using G4beamline and surrogate models, we optimized the storage efficiency of muons up to ~0.4 %.

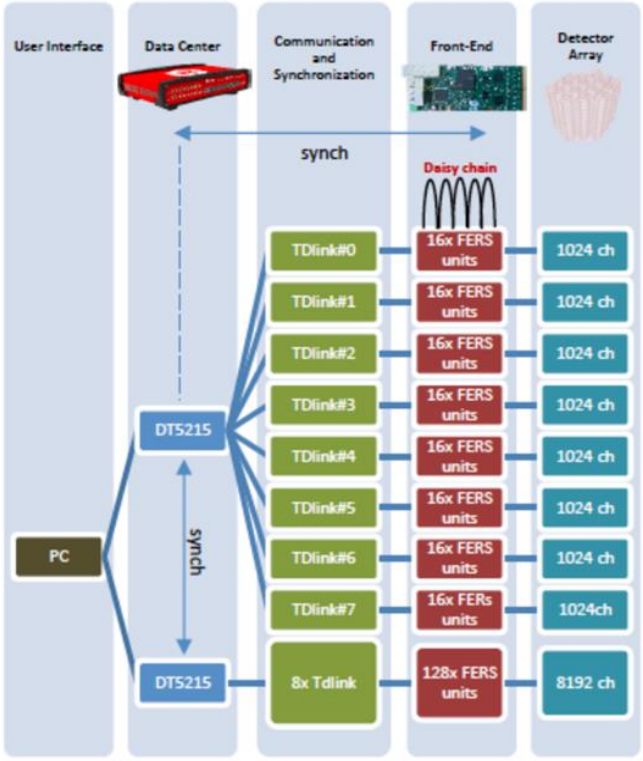
The Experiment – Systematics

Summary of systematic effects for both phases of the experiment

Systematic effect	Constraints	Phase-I		Phase-II	
		Expected value	Syst. ($\times 10^{-21} e\cdot$cm)	Expected value	Syst. ($\times 10^{-23} e\cdot$cm)
Cone shaped electrodes (longitudinal E-field)	Up-down asymmetry in the electrode shape	$\Delta_R < 30$ μm	0.75	$\Delta_R < 7$ μm	1.5
Electrode local smoothness (longitudinal E-field)	Local longitudinal electrode smoothness	$\delta_R < 3$ μm	0.75	$\delta_R < 0.7$ μm	1.5
Residual B-field from kick	Decay time of kicker field	< 50 ns	$< 10^{-2}$	< 50 ns	0.5
Net current flowing muon orbit area	Wiring of electronics inside the orbit	< 10 mA	$< 10^{-2}$	< 10 mA	0.3
Early-to-late detection efficiency change	Shielding and cooling of detectors	–		–	
Resonant geometrical phase accumulation	Misalignment of central axes	Pitch < 1 mrad Offset < 2 mm	2×10^{-2}	Pitch < 1 mrad Offset < 2 mm	0.15
TOTAL			1.1		2.2

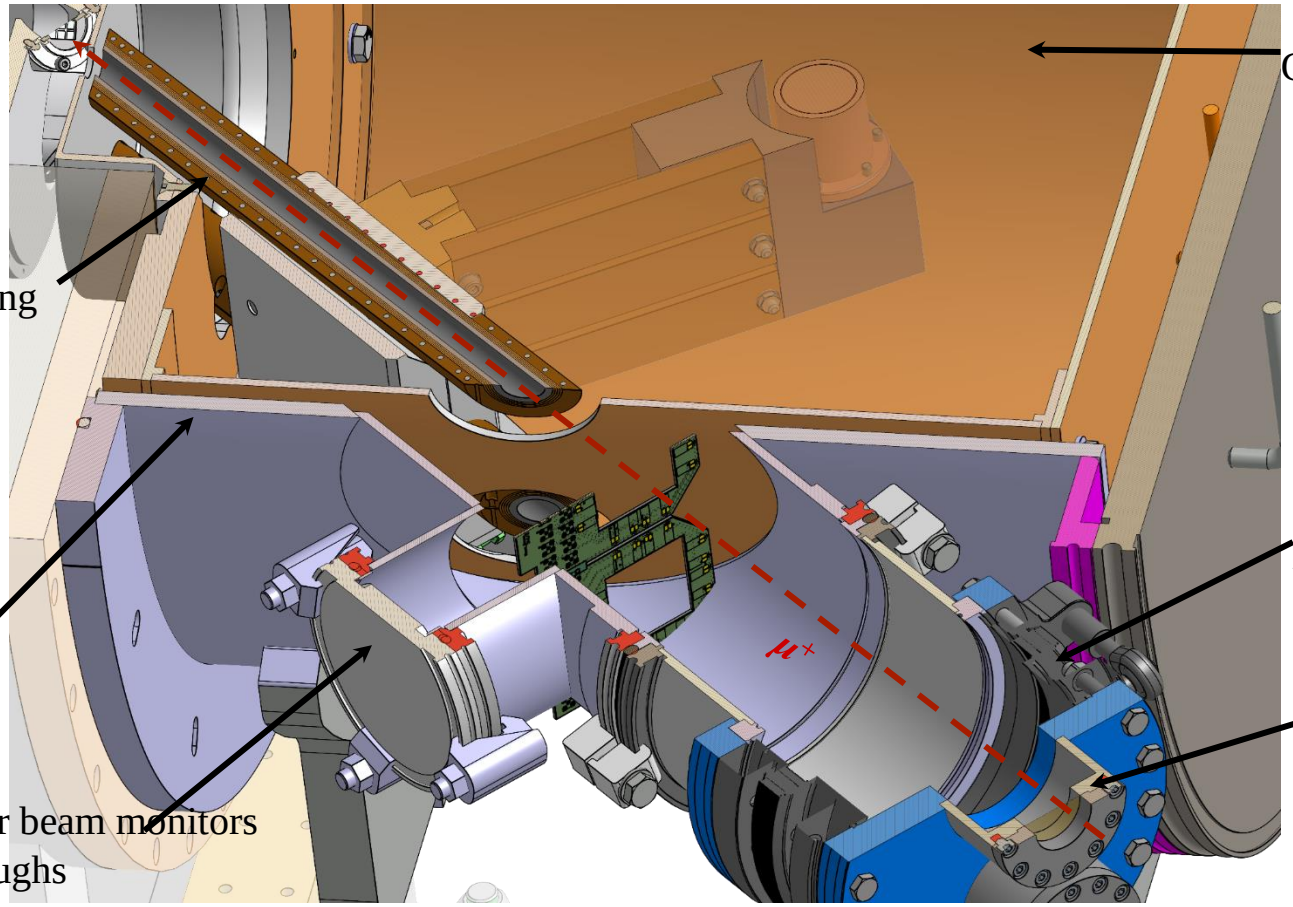
CAEN A5202 board

- Extendible up to 8192 channels
  - *SiPM bias and front end amplification included*
  - *synchronisation circuit developed by CAEN*
- Timing @200ps level
  - *Time Over Threshold available*
- Read out up > 100 kHz
- One board ordered for September test beam
  - *refer to Giovanni Gallucci's slide for preliminary tests*



Pisa, 04-04-2024 3 L. Galli, INFN Pisa

The Experiment – Injection Channel



The Experiment – Super Conducting Channel

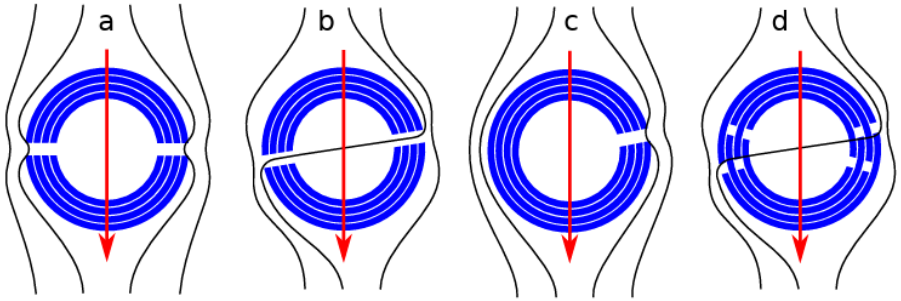
Bending the NbTi/Nb/Cu sheets

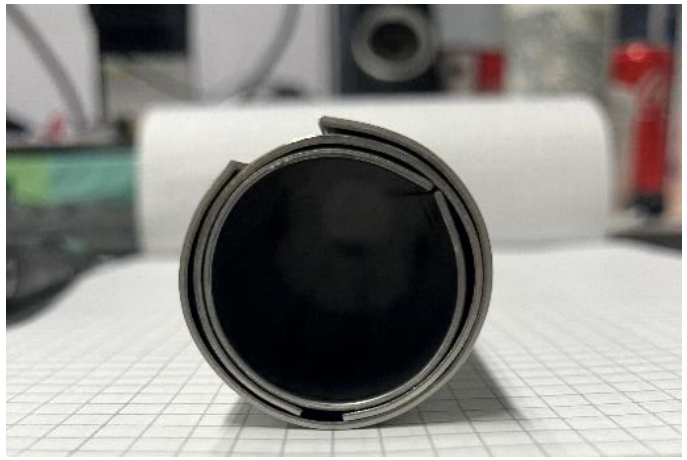
- ✓ Sheets @PSI
- ✓ Initial tests with steel sheets
- ✓ Tested to shield up to ~3.1T @CERN

  NbTi/Nb/Cu multilayer shield for the superconducting shield (SuShi) septum

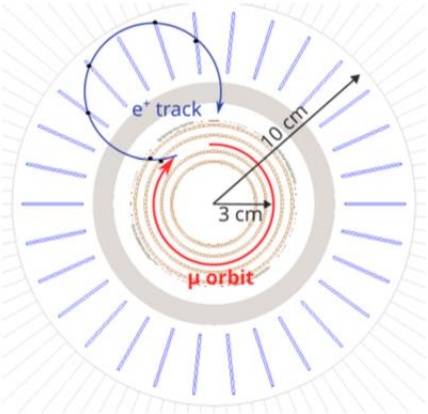
  D. Barna et al.

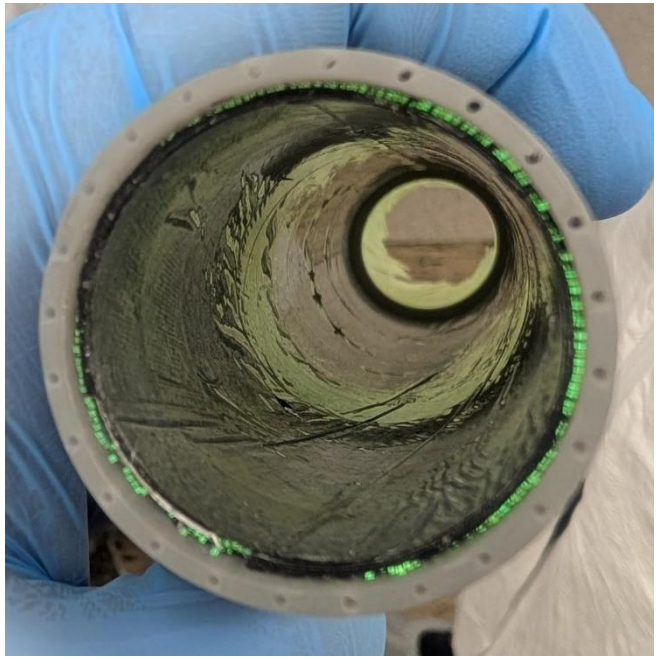
  https://arxiv.org/abs/1809.04330
- ✓ / ✗ Holder design
- ✗ Formed sheets

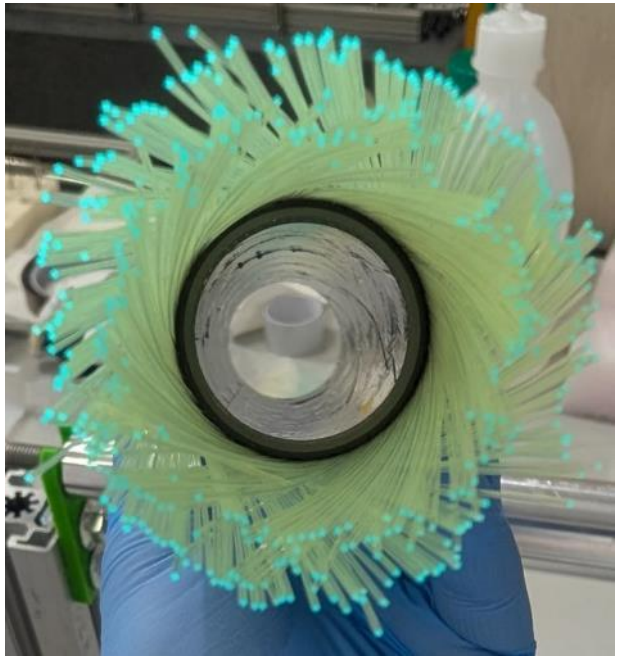


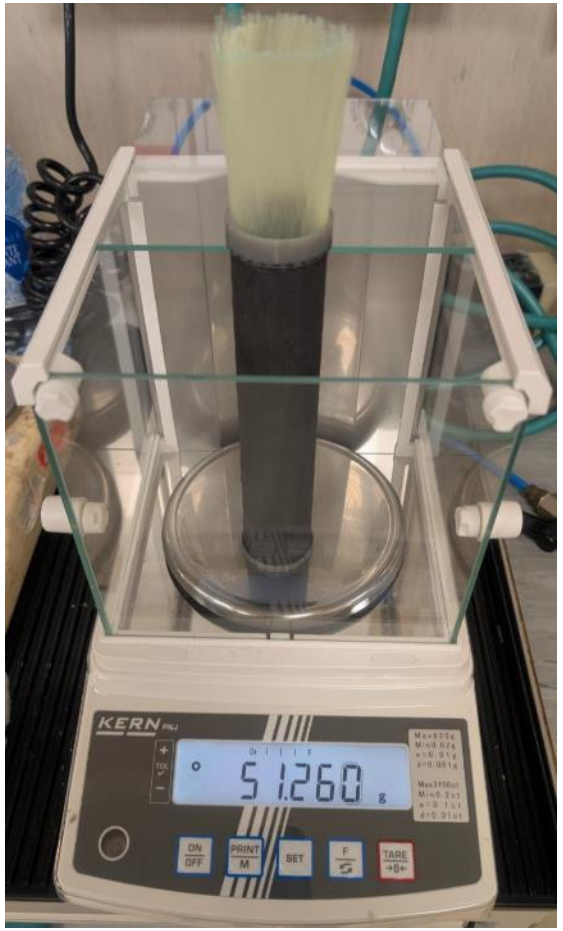


The Experiment - CHeT (tracker) cylinders prototype









- **Developed by INFN PISA**
- **Measure the direction and momentum of decay positrons**
- Requirements
  - Momentum resolution: a **few MeV**
  - Single hit resolution in transverse plane: **~ 1 mm**
  - Timing resolution: **<1 ns** (1 circle in the transverse plane takes ≥0.6 ns)

The Experiment - Sensitivity

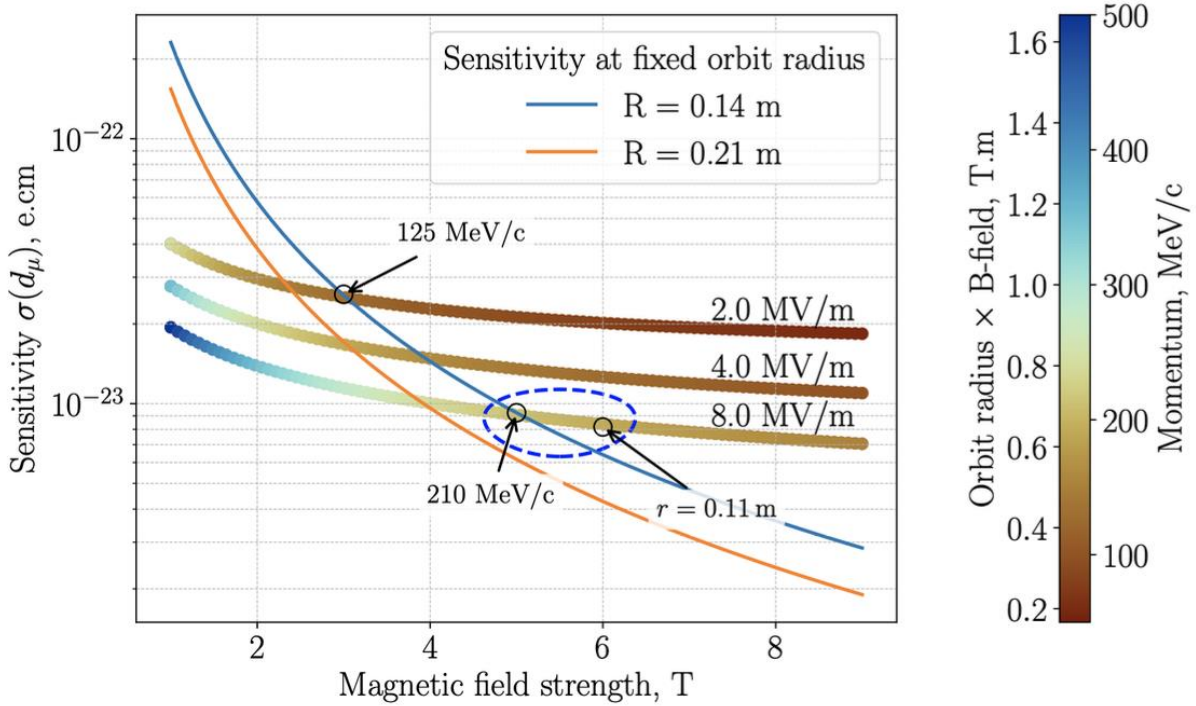


Figure 4: Statistical sensitivity for muon EDM searches over 200 days of data taking, assuming a single-muon "on request." Sensitivity increases with magnetic field strength keeping the radius constant. Electric fields above 8 MV/m are very difficult to obtain for large, stripped electrodes with extremely thin material thickness, required for positron transmission. The region within the circle indicates the possible parameter space for a muon EDM search using muons with momentum up to 210 MeV/c.

The Experiment – Magnetic field

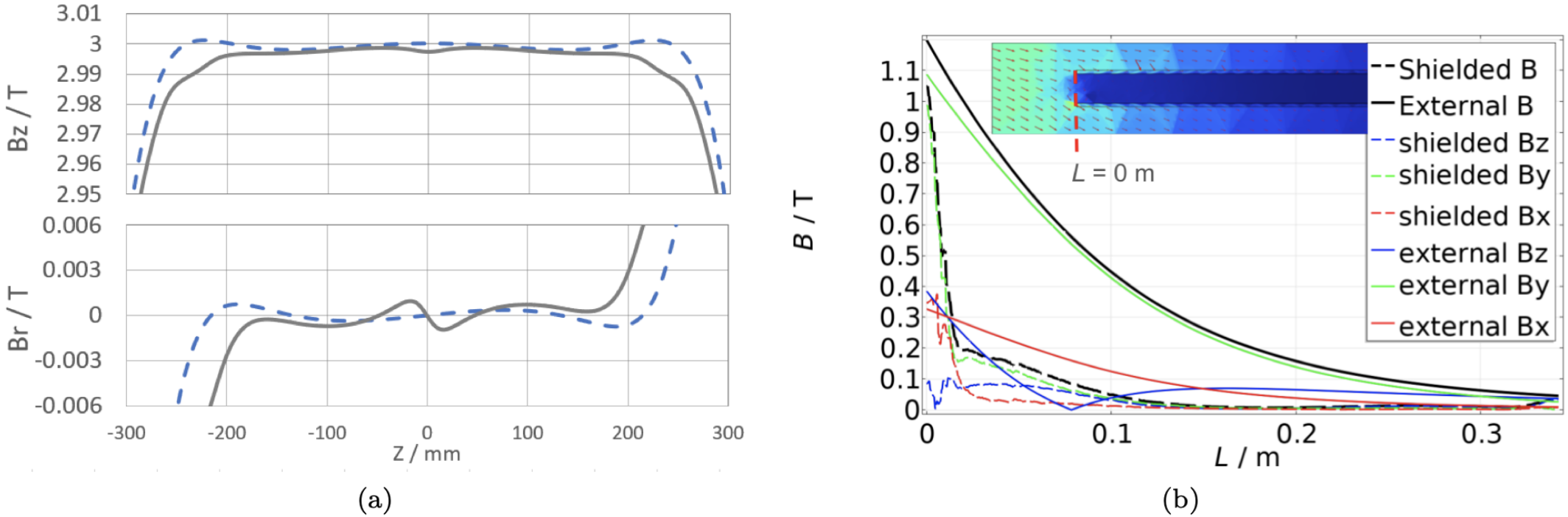


Figure 12: (a) Longitudinal (upper), B_z, and radial (lower), B_r, magnetic field for $r = 30\,\mathrm{mm}$. Continuous gray (dashed blue) line shows magnetic field with(out) weakly focusing and correction coils. (b) Magnetic field, $\vec{B}$, along the injection tube with (dashed lines) and without (continuous lines) magnetic shield in local right-handed coordinates with y pointing along the axis of the tube. The insert shows the a slice of the COMSOL FEM calculation along the injection tube. All transverse components remain below 0.1 T.