Probing New Physics with Muons

>> Muon g-2 and EDM <<

Kim Siang Khaw

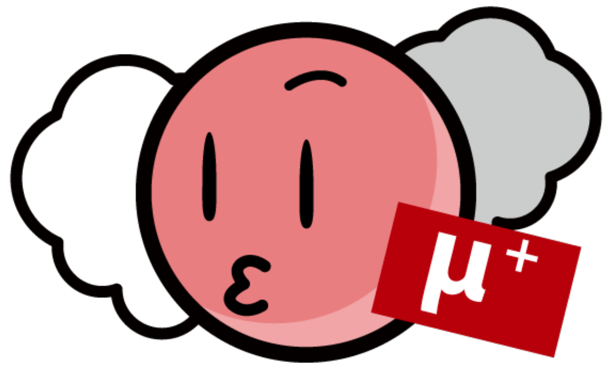
Tsung-Dao Lee Institute, SJTU

KMI 2025, 2025.03.05

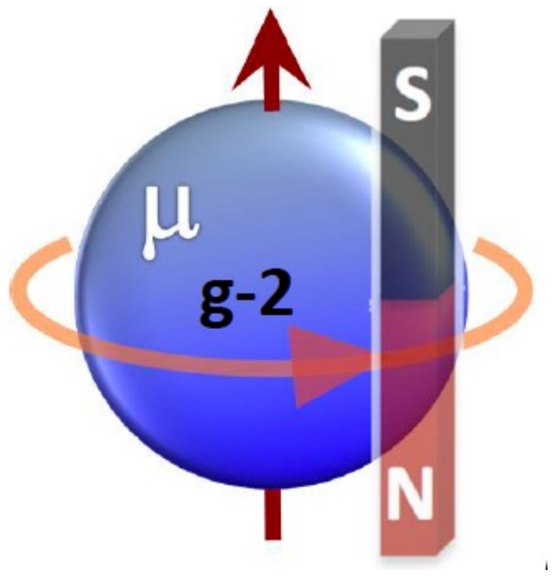
李政道研究所
TSUNG-DAO LEE INSTITUTE

Muon g-2 and EDM

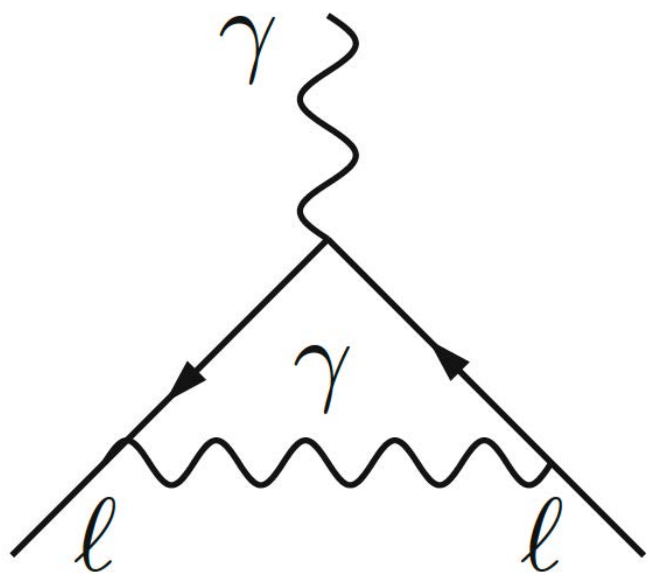
- The muon is an excellent probe for New Physics due to its enhanced sensitivity to quantum loop effects ("heavier electron", longer lifetime than tau)

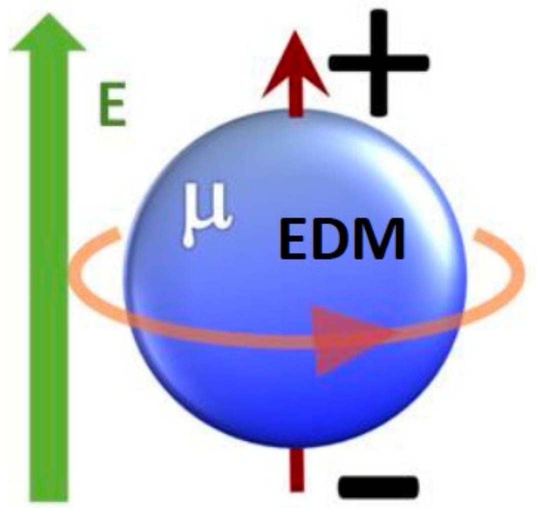


- Both g-2 and EDM experiments test different fundamental properties of the muon:
  - Muon g-2: Anomalous magnetic moment → tests loop corrections from SM and new physics.
  - Muon EDM: Electric dipole moment → tests CP violation.

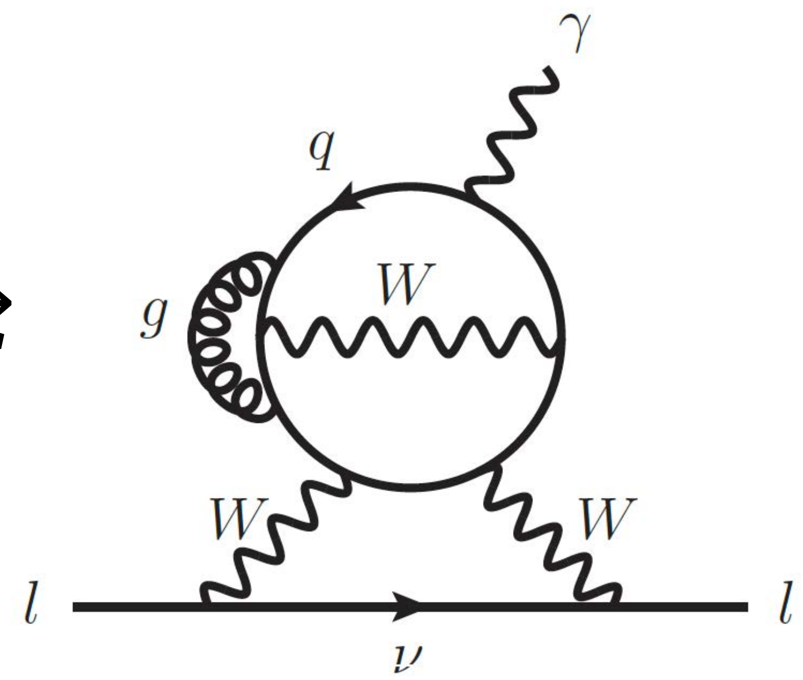


$$\vec{\mu} = g\frac{e}{2m}\vec{s}$$





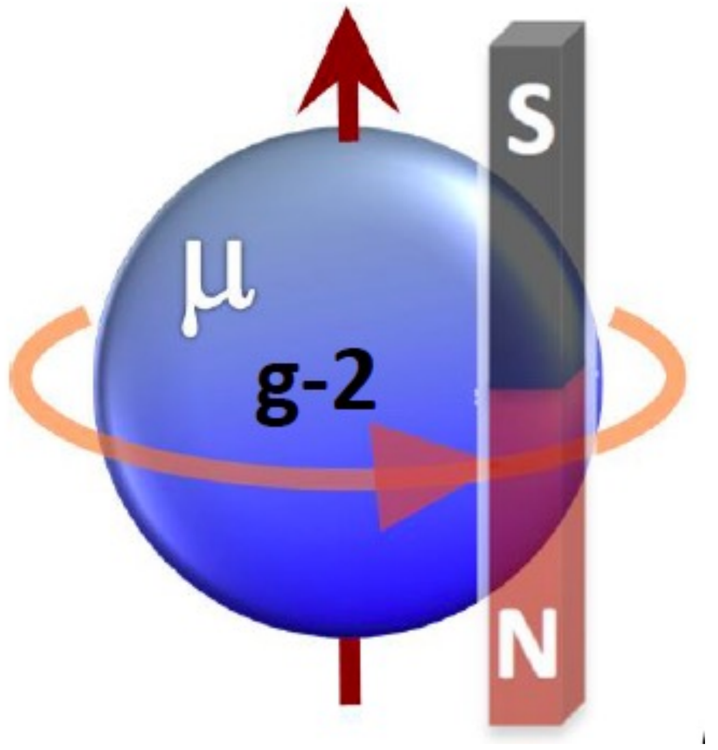
$$\vec{d} = \eta\frac{e}{2mc}\vec{s}$$



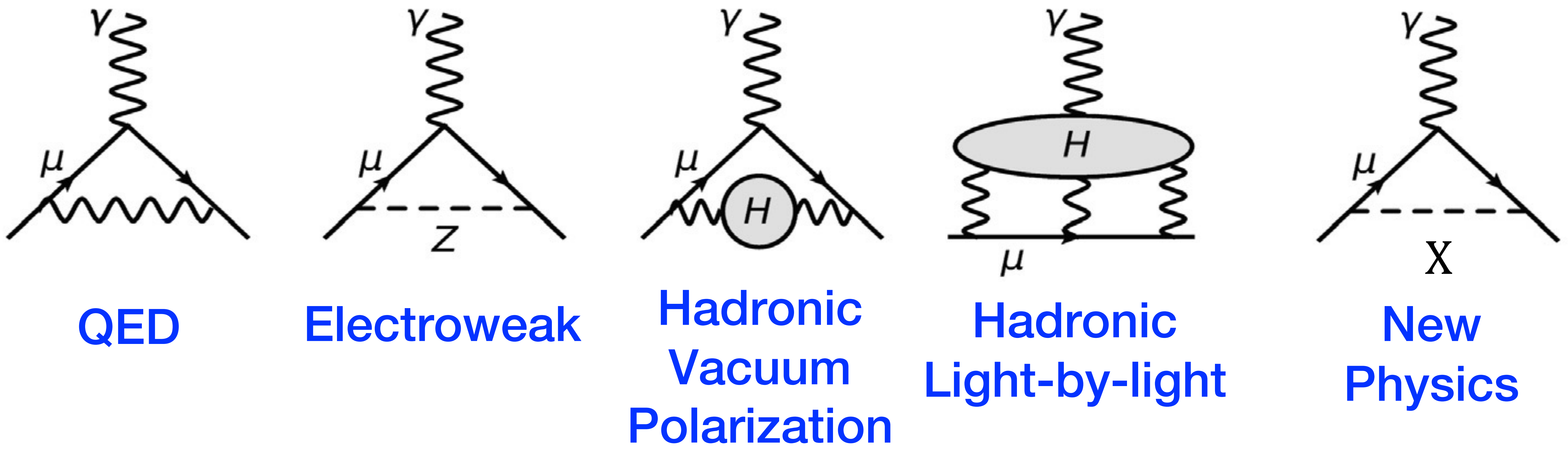
Probing New Physics with Muon g-2

magnetic moment and spin

$a_\mu = \frac{g-2}{2}$, $g = 2$ at the tree level



$$\vec{\mu} = g\frac{e}{2m}\vec{s}$$

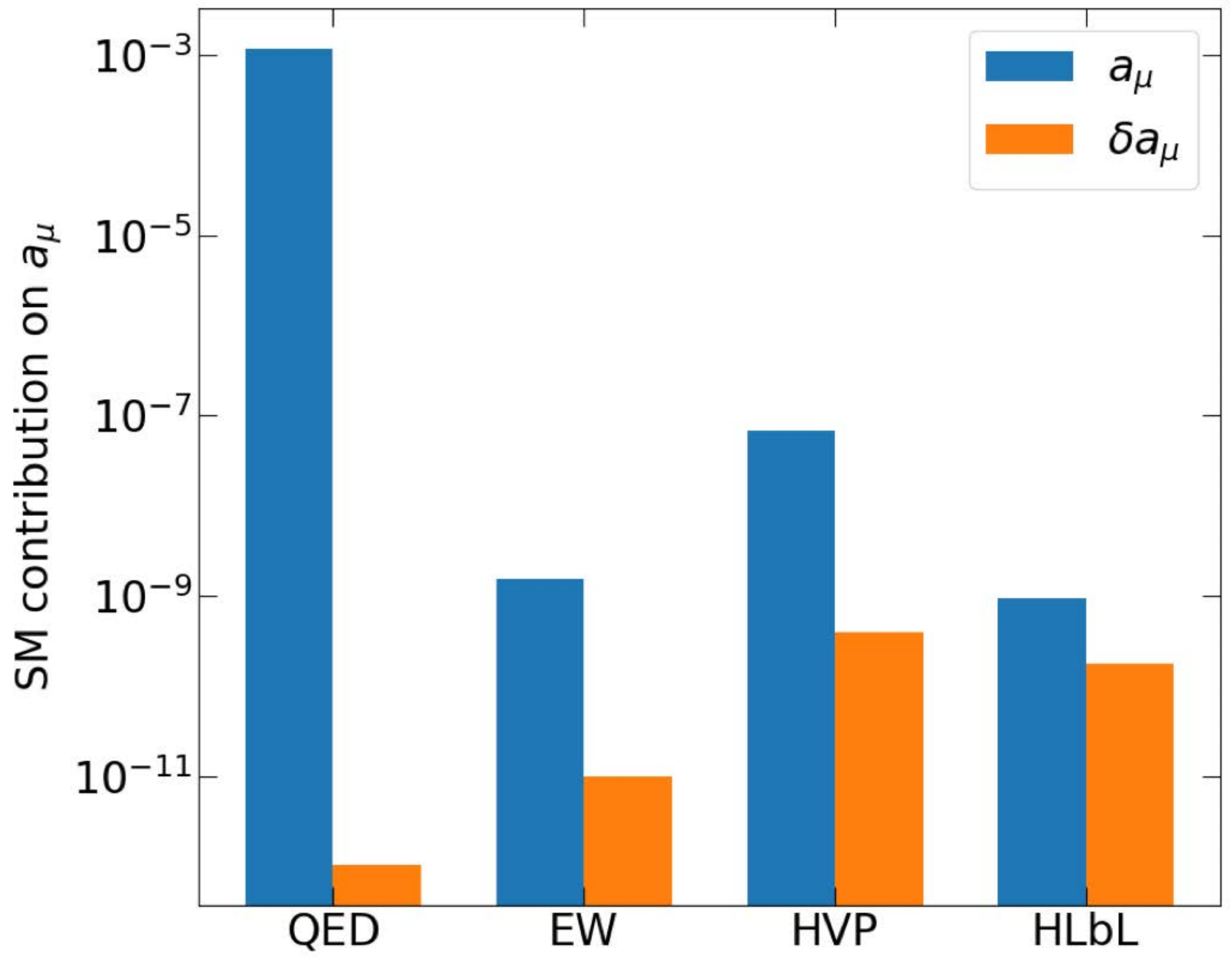


- Can be calculated and measured to high precision (sub-ppm)
- Precision test of SM calculations (at 4-loop QED, EW, and QCD)

$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{HVP,\ LO}} + a_\mu^{\mathrm{HVP,\ NLO}} + a_\mu^{\mathrm{HVP,\ NNLO}} + a_\mu^{\mathrm{HLbL}} + a_\mu^{\mathrm{HLbL,\ NLO}}$$
$$= 116\,591\,810(43) \times 10^{-11}\,.$$

Theory Initiative White Paper
T. Aoyama et al. Phys. Rept. **887** (2020)

- Powerful discriminant for BSM physics models



Muon g-2 Collaboration

(181 collaborators, 33 institutes, 7 countries)

USA
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central
- Northern Illinois
- Regis
- Virginia
- Washington

USA National Labs
- Argonne
- Brookhaven
- Fermilab

China
- Shanghai Jiao Tong

Germany
- Dresden
- Mainz

Italy
- Frascati
- Molise
- Naples
- Pisa
- Roma Tor Vergata
- Trieste
- Udine

Korea
- CAPP/IBS
- KAIST

Russia

Budker/Novosibirsk
JINR Dubna

United Kingdom

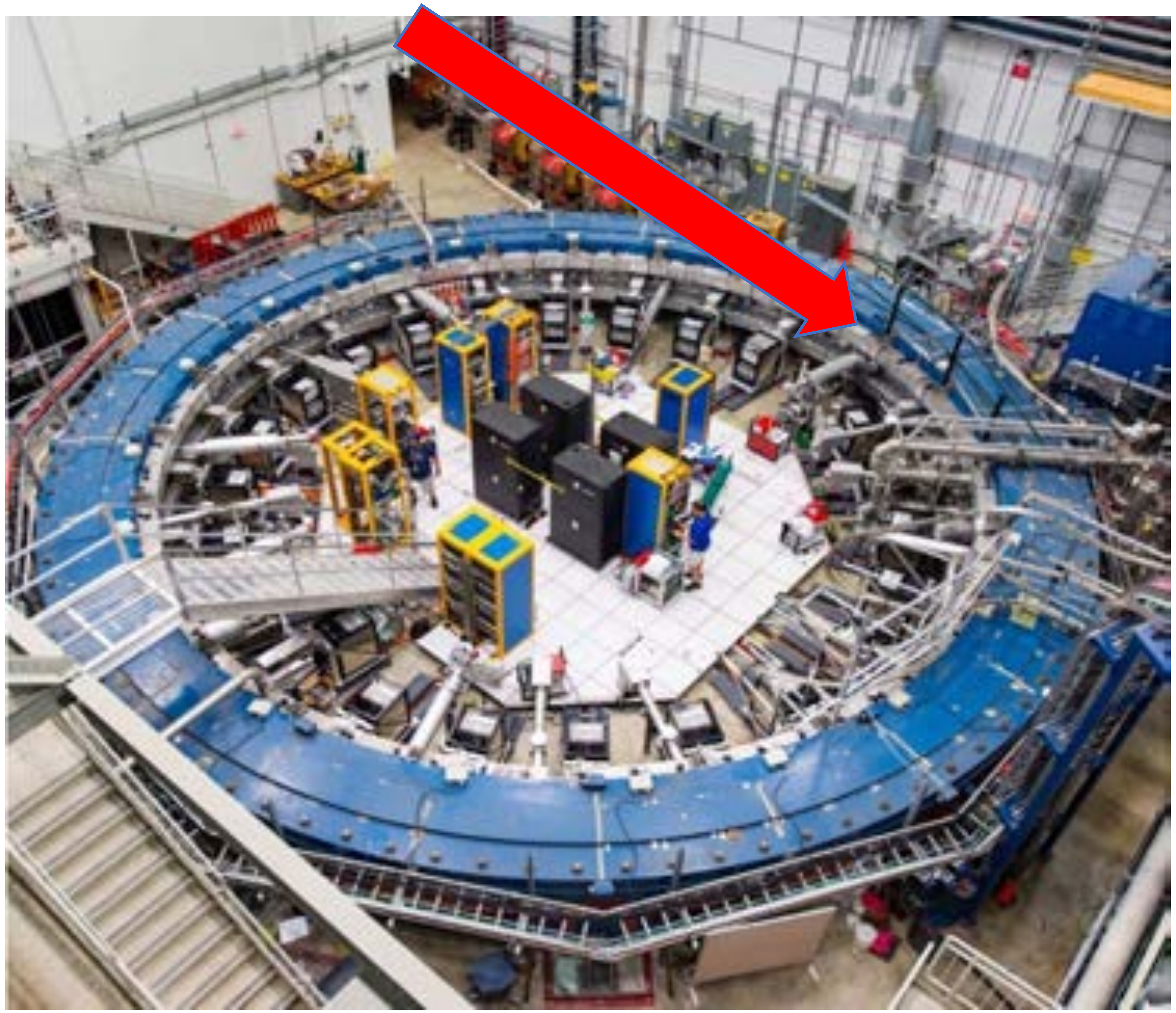
Lancaster/Cockcroft
Liverpool
Manchester
University College London

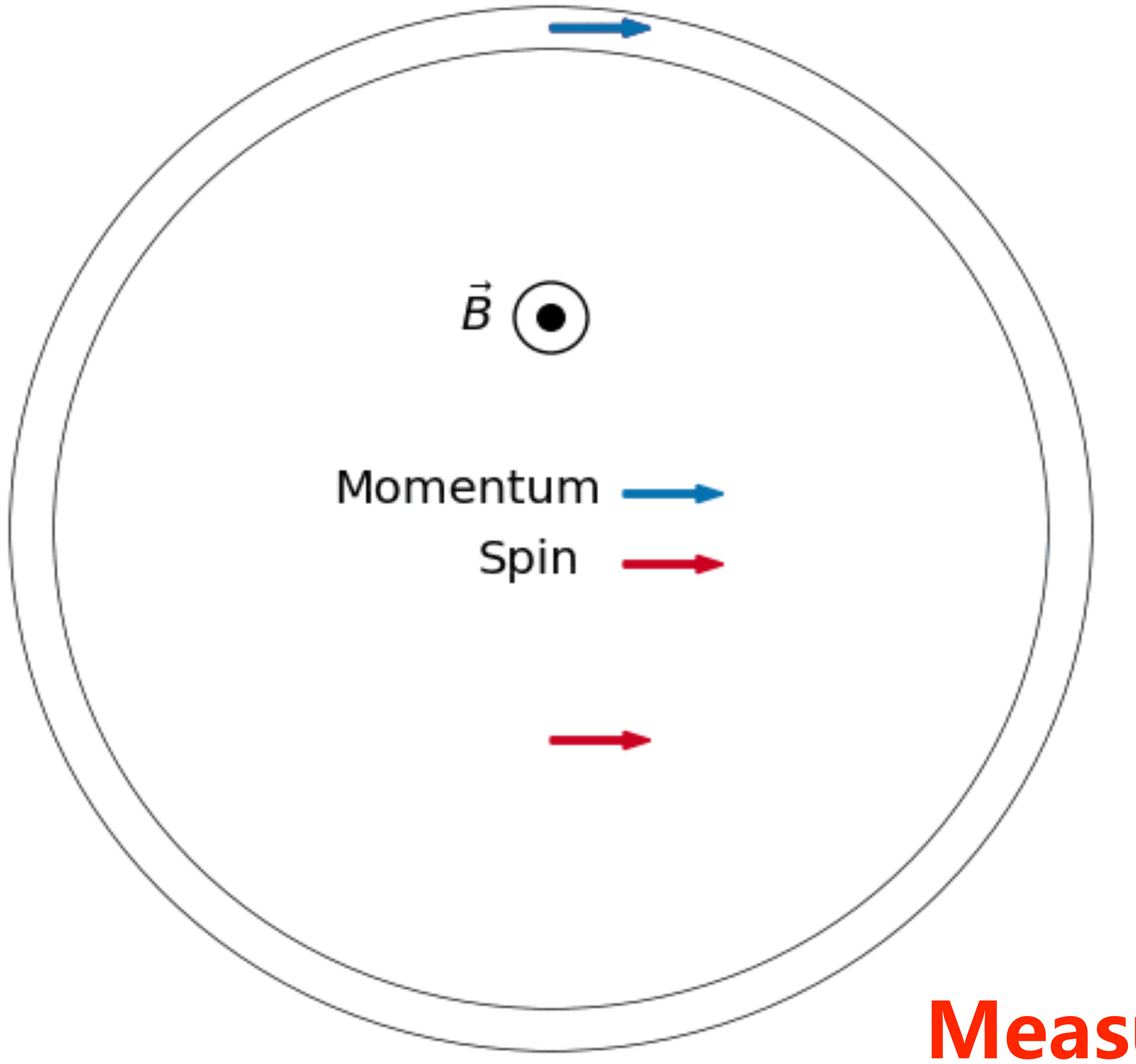
We include: Particle-, Nuclear-, Atomic-, Optical-, Accelerator-, and Theoretical Physicists and we combine our effort to measure a single value, g-2, to 140 ppb (BNL - 540 ppb)!

Muon g-2 collaboration meeting at Elba, Summer 2019

Principle of g-2 measurement

Inject a spin-polarized muon beam into a magnetic storage ring





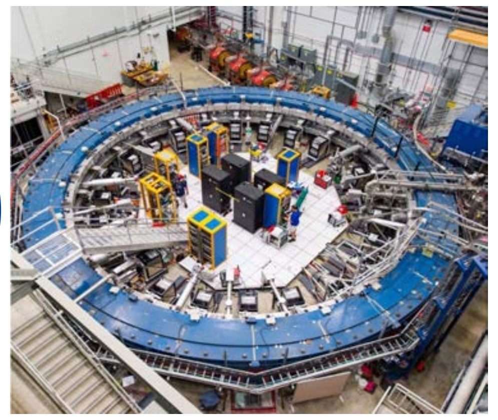
Measure the difference in frequency

Measure the magnetic field of the storage ring

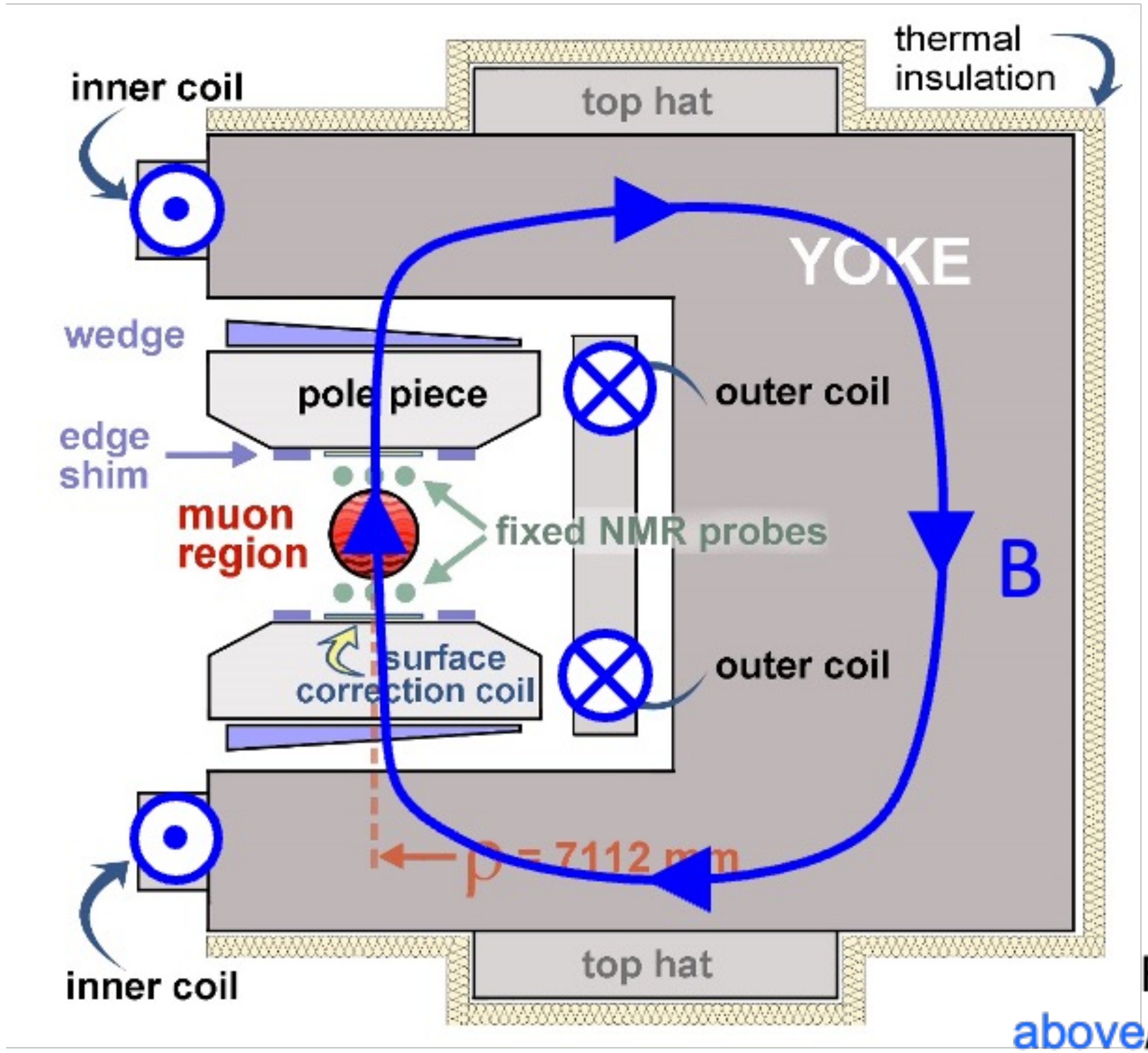
$$\omega_a = \omega_s - \omega_c = a_\mu \frac{eB}{m_\mu}$$

Obtain g-2

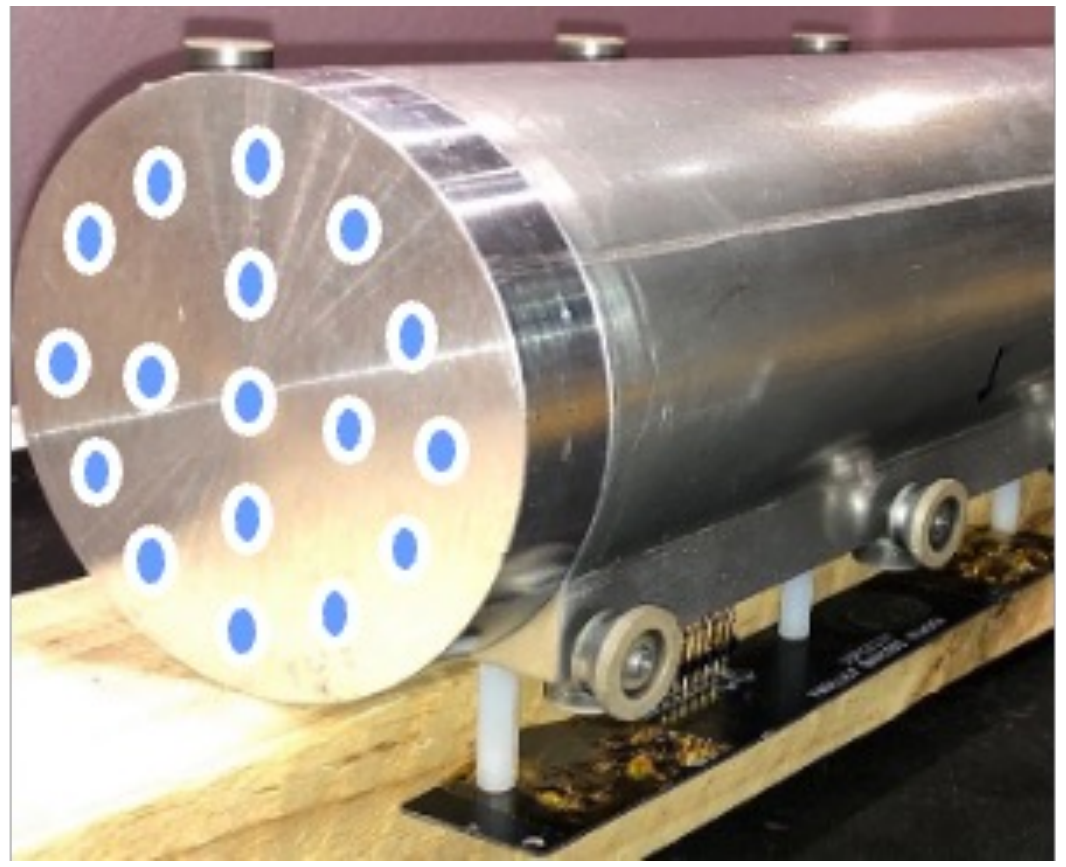
Muon g-2 superconducting storage ring



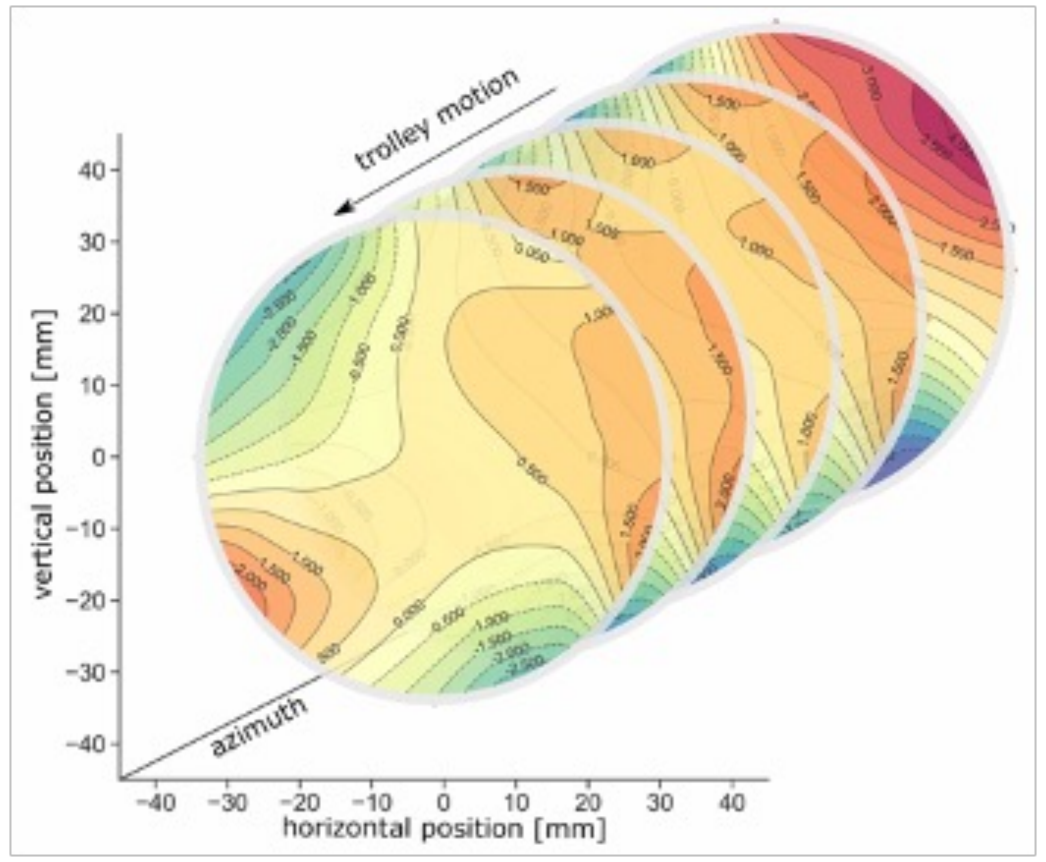
- 14 m diameter, 1.45 T
- C-shaped SC magnet



- In-vacuum NMR trolley maps field every ~3 days



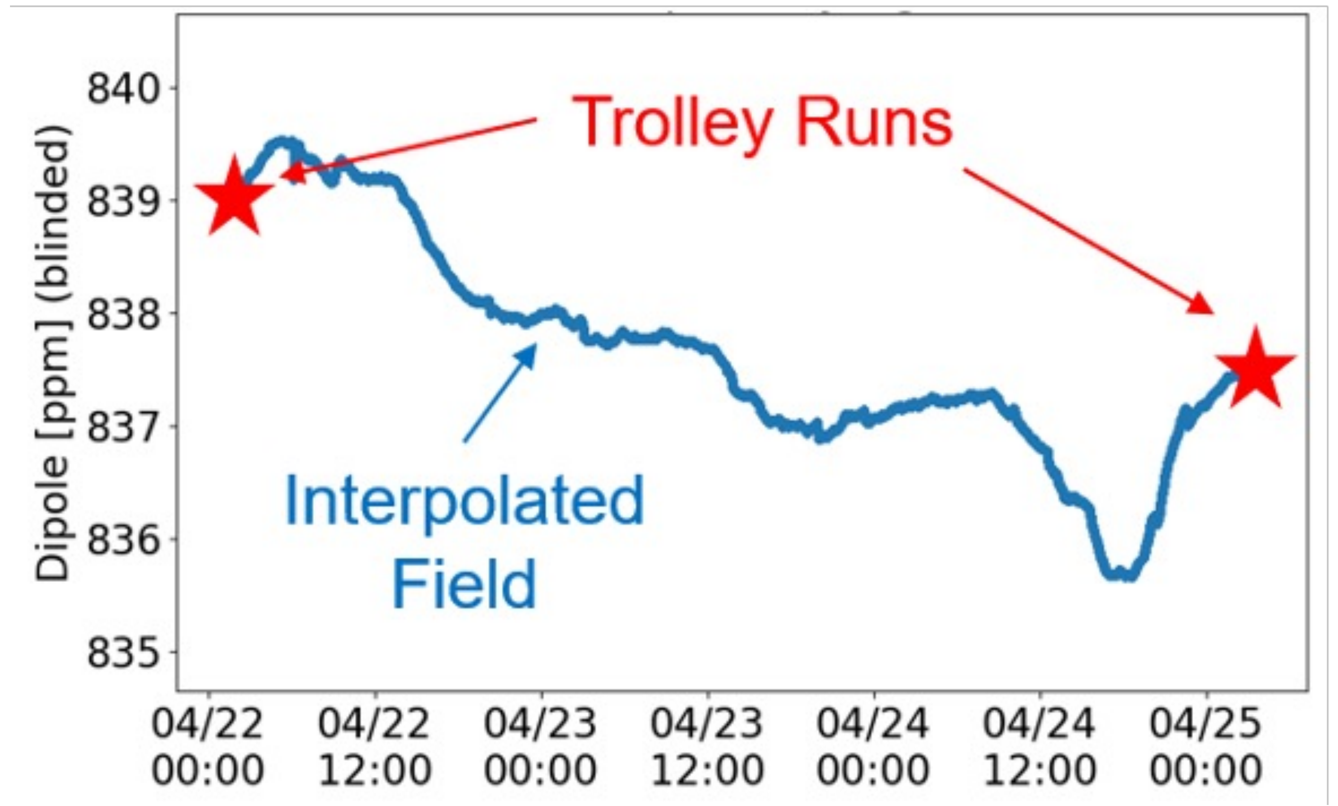
17 petroleum jelly NMR probes



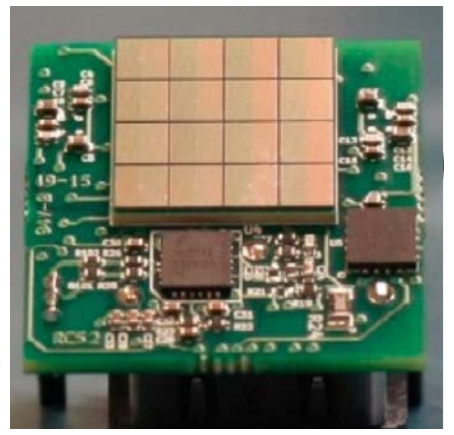
2D field maps (~8000 points)

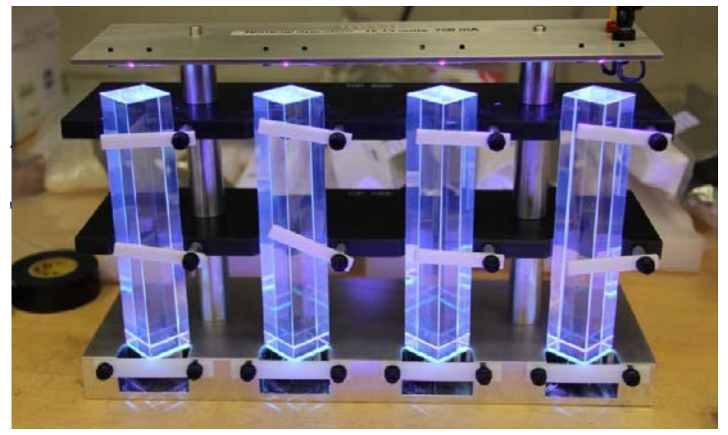
- 378 fixed NMR probes monitor field during muon storage at 72 locations

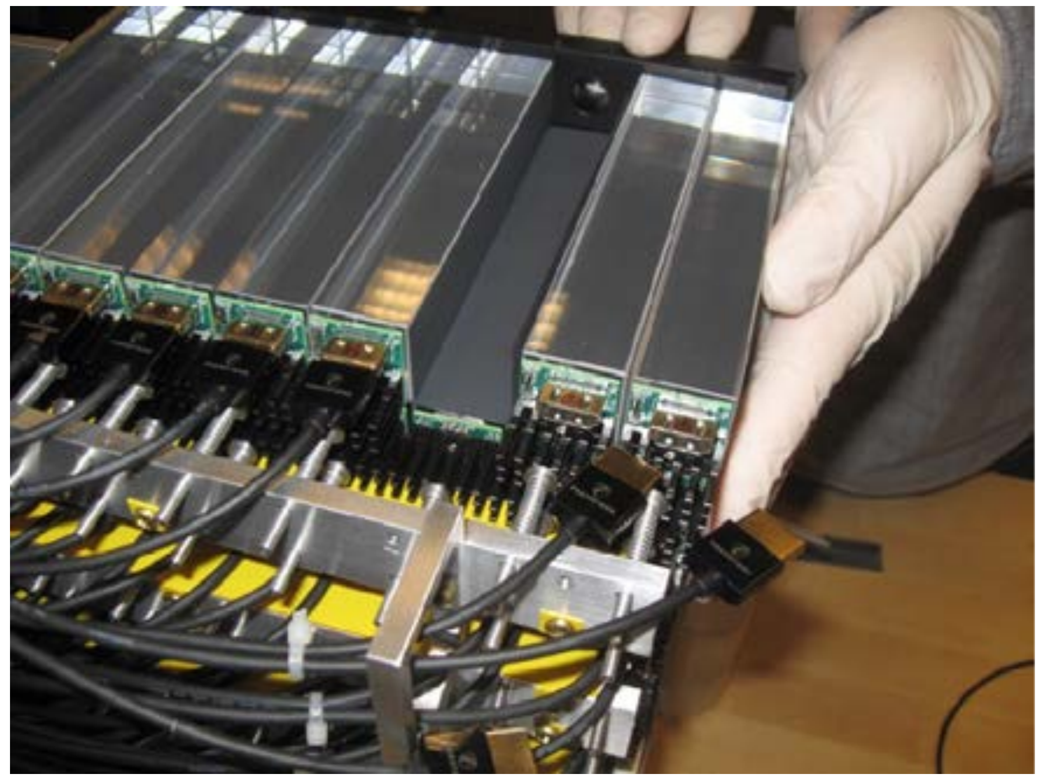
Fixed probes above/below muon storage region

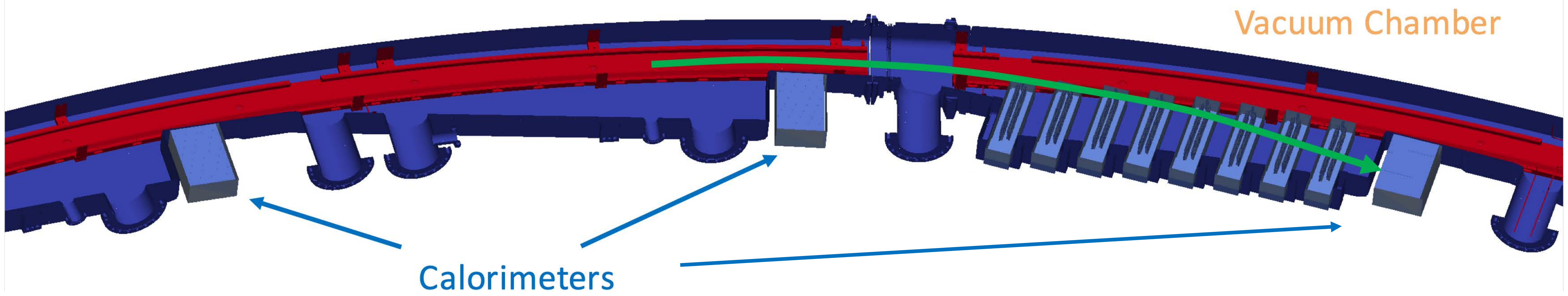


Precession frequency measurement



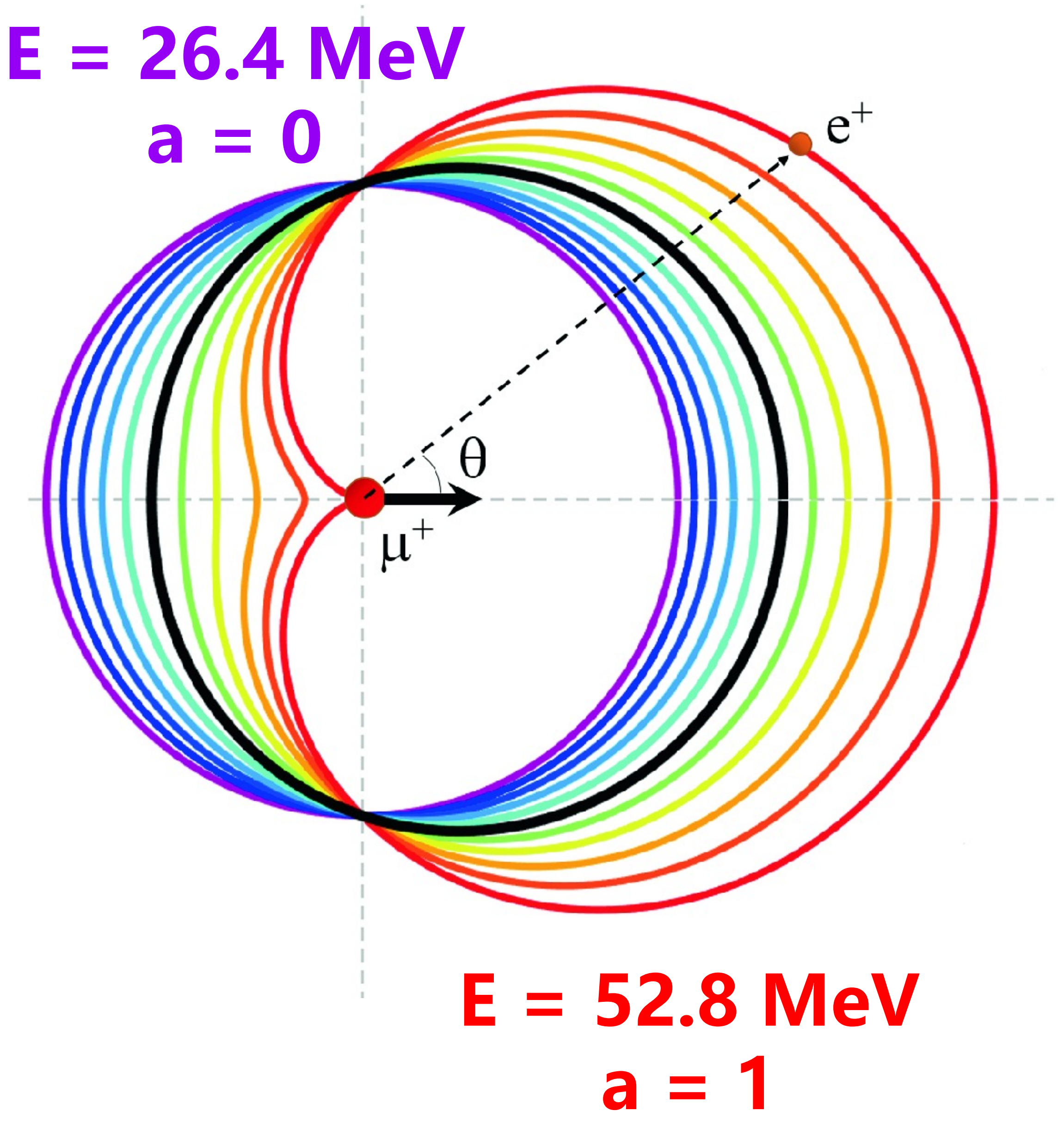


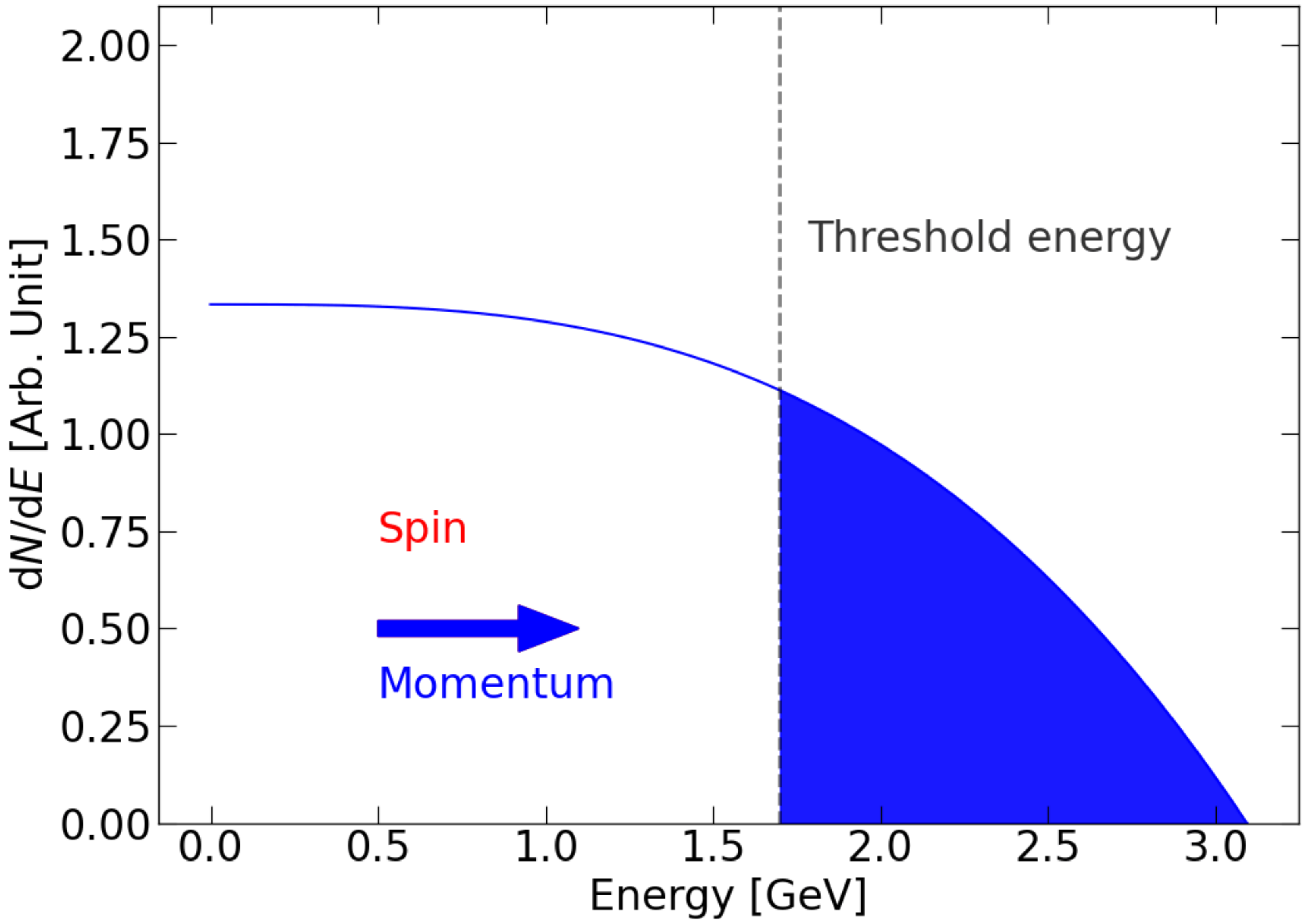




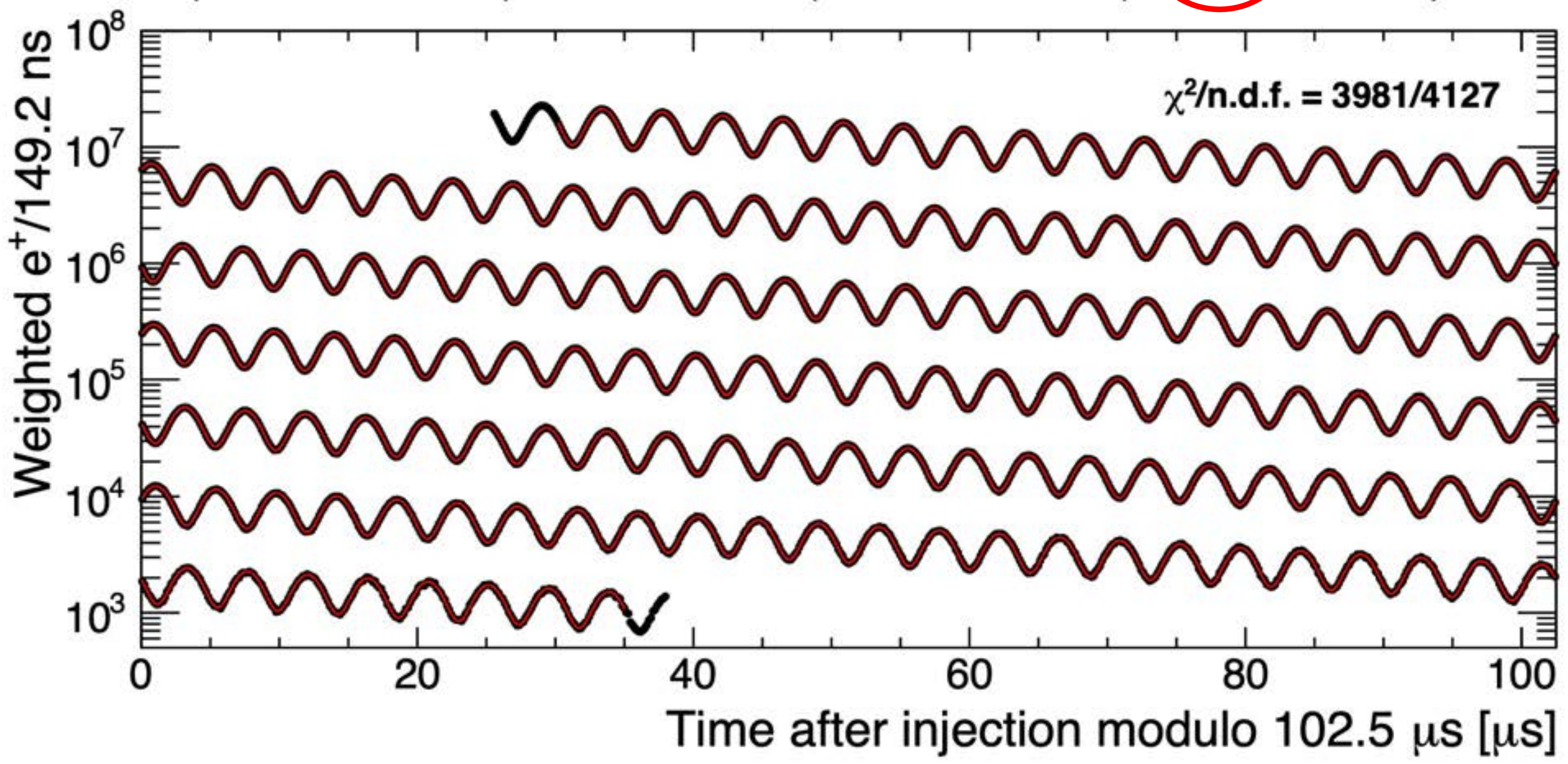
PbF_2 calorimeter

high energy e^+ is emitted preferentially in the muon spin direction due to parity-violating weak decay

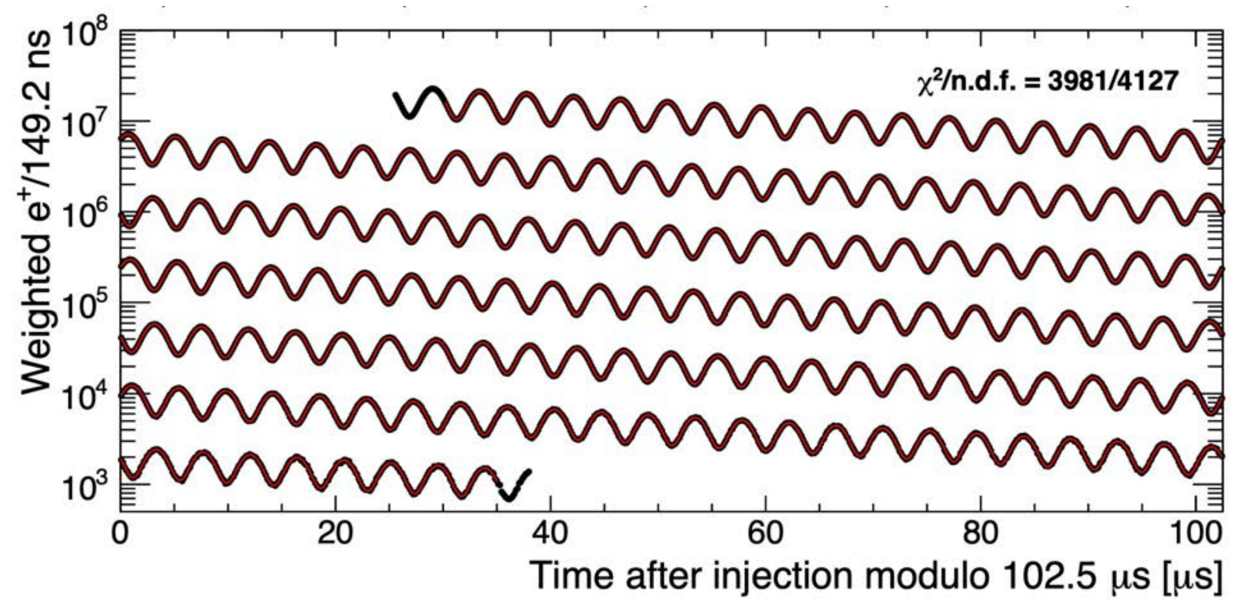




$$N(t) = N_0 e^{-t/\tau}\left[1 + A_\mu \cos(\omega_a t + \phi)\right]$$



Additional corrections



$$N(t) = N_0 e^{-t/\tau}\left[1 + A_\mu \cos(\omega_a t + \phi)\right]$$

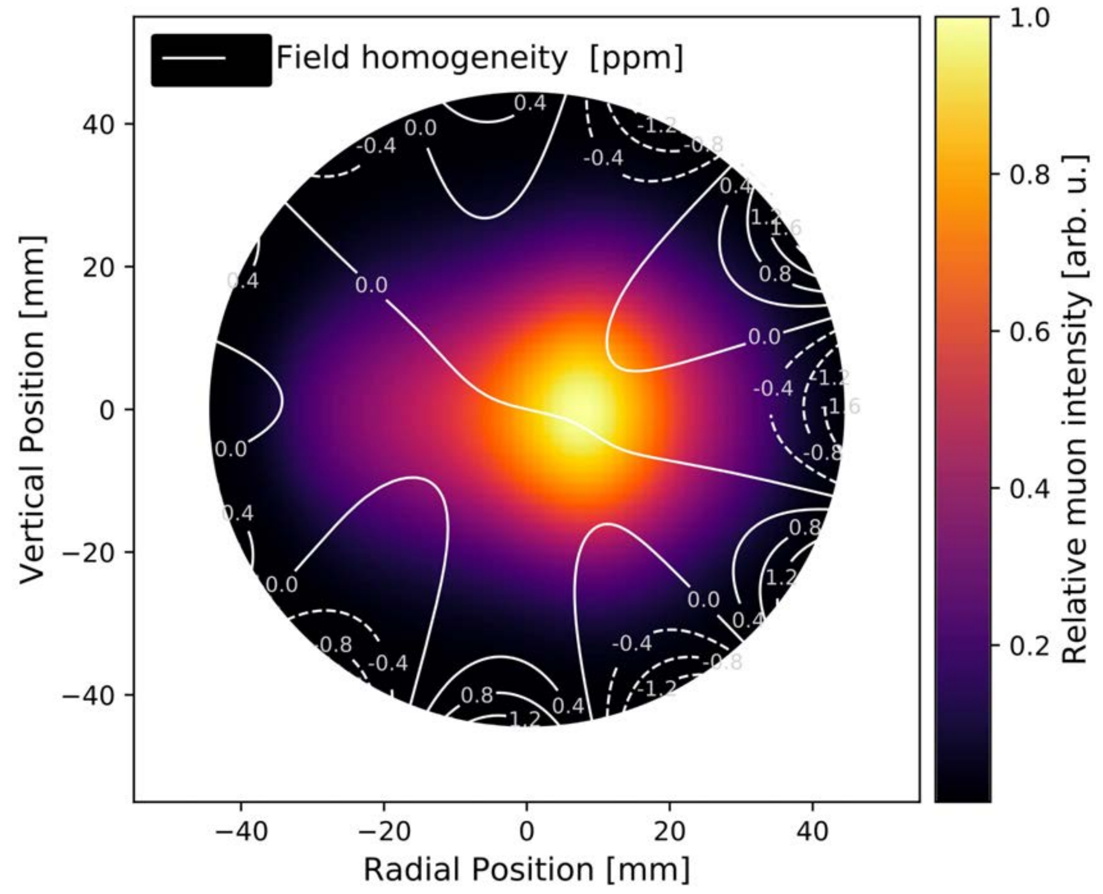
Beam Dynamics Corrections

E-field & vertical motion: Spin precesses slower than in basic equation

Phase changes over each muon fill: Phase acceptance, differential decay, and muon losses

$$a_\mu \sim \frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m}\frac{1+C_e+C_p+C_{pa}+C_{dd}+C_{ml}}{1+B_k+B_q}$$

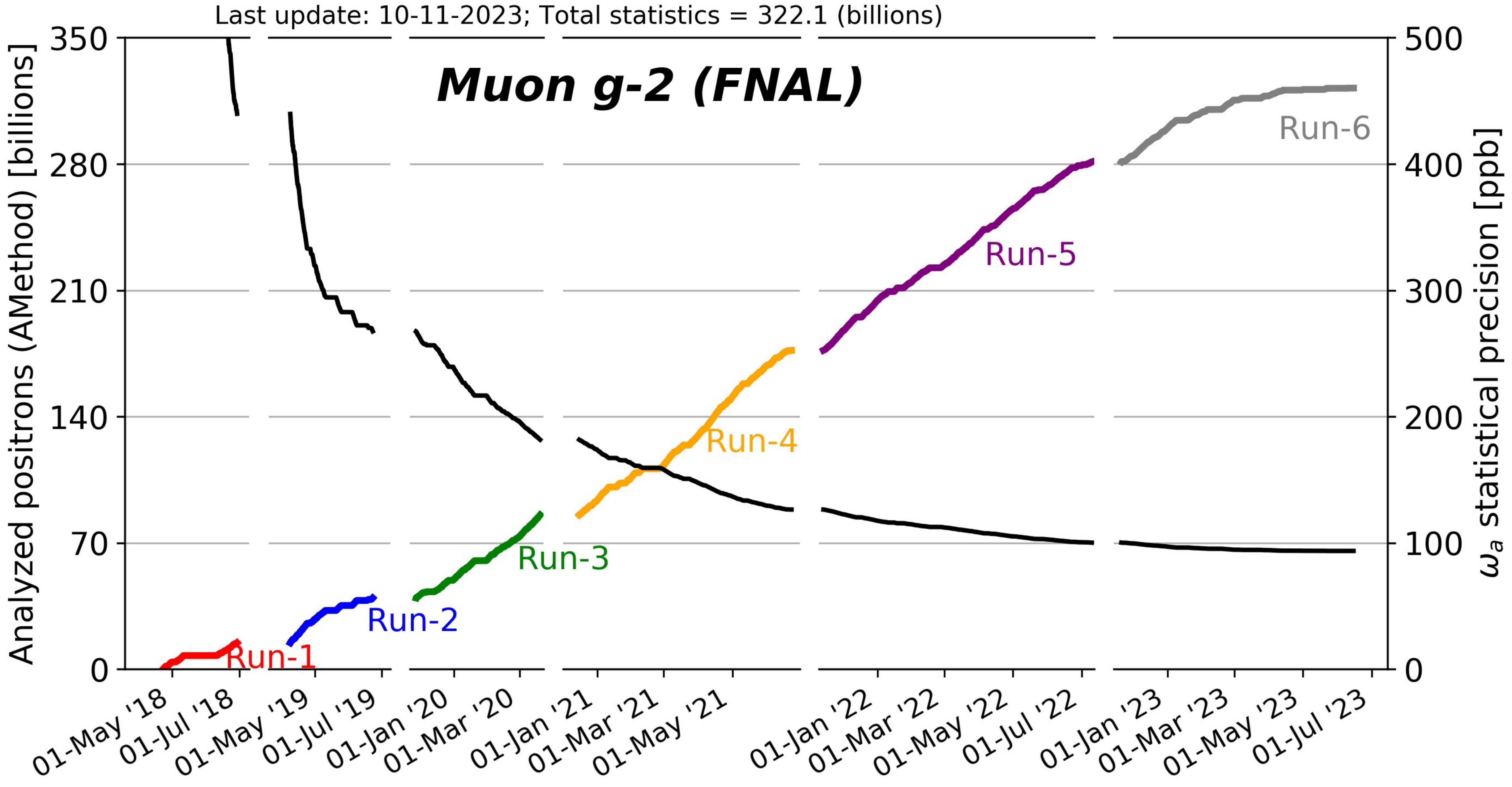
Transient magnetic fields: Quad vibrations and kicker eddy current

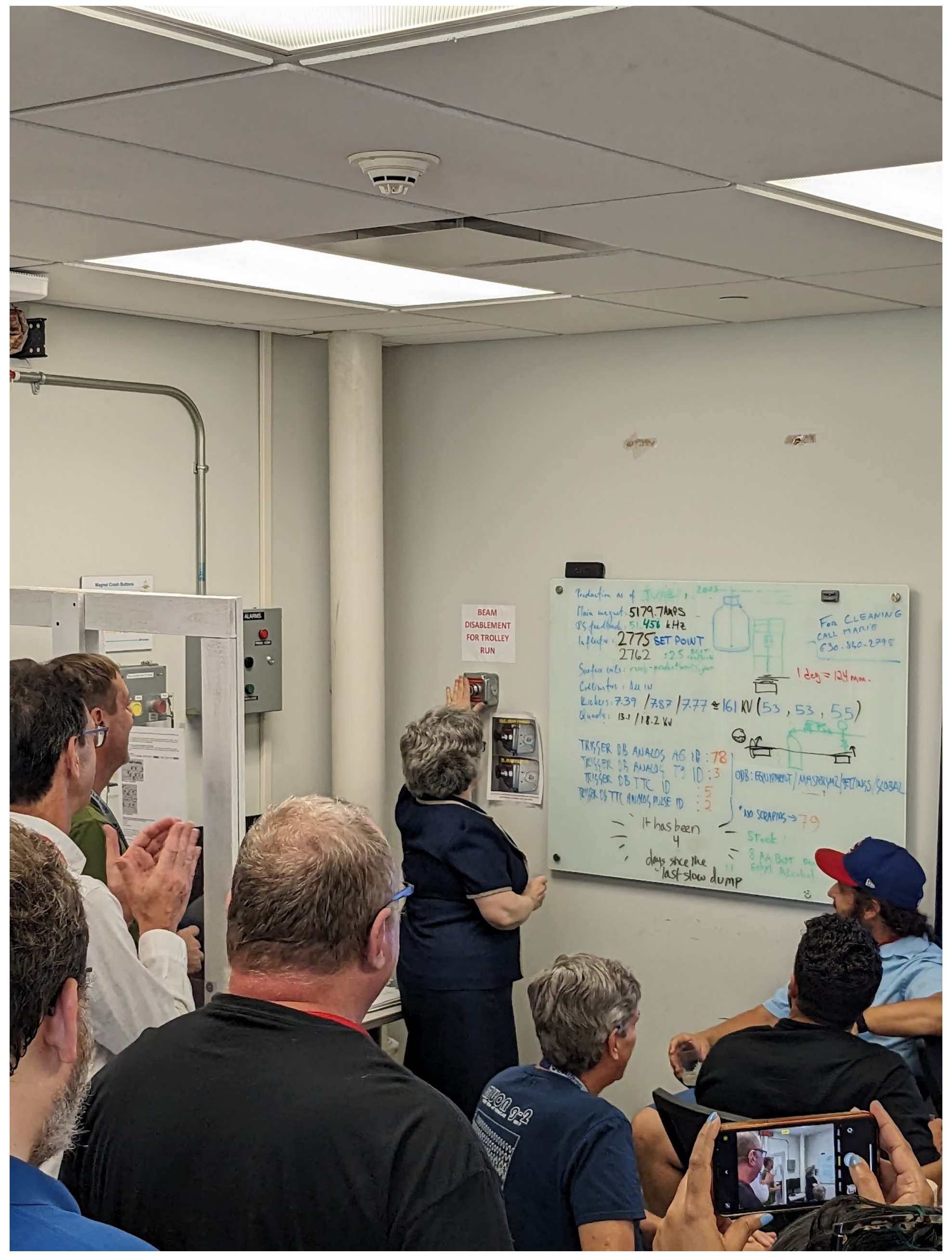


Status of the Muon g-2 experiment

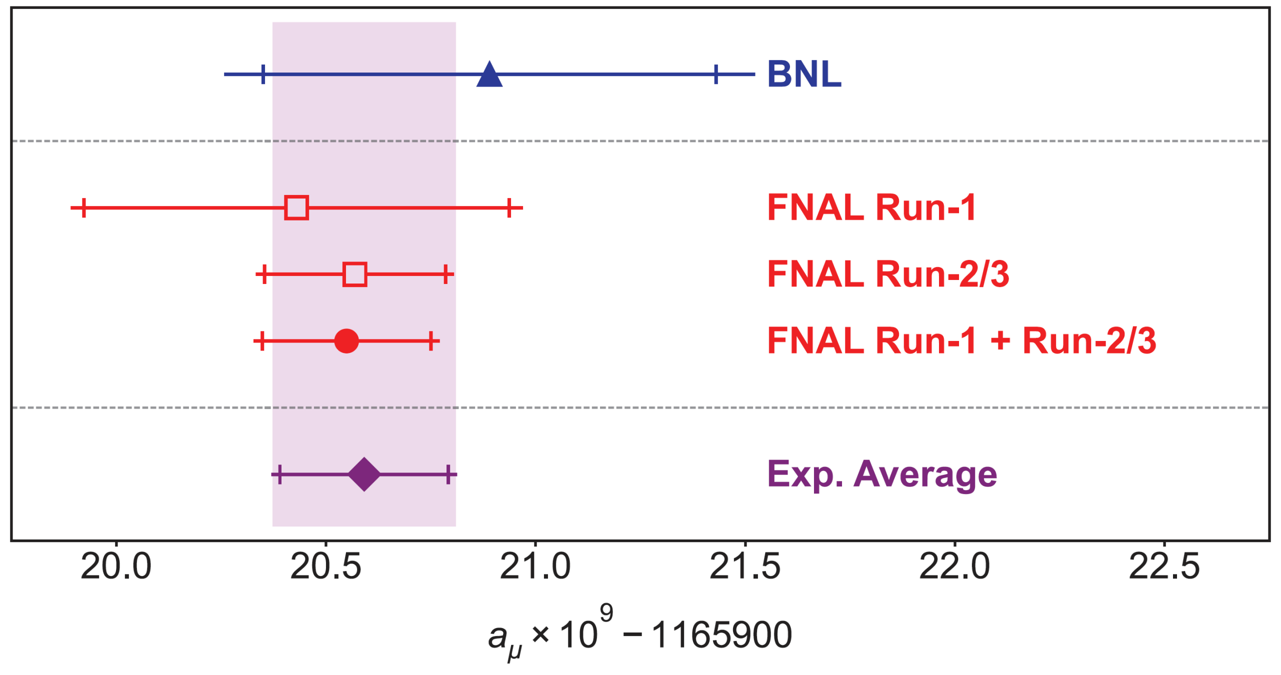
李政道研究所 TSUNG-DAO LEE INSTITUTE

Celebrating first beam at MC1 (Summer 2017)



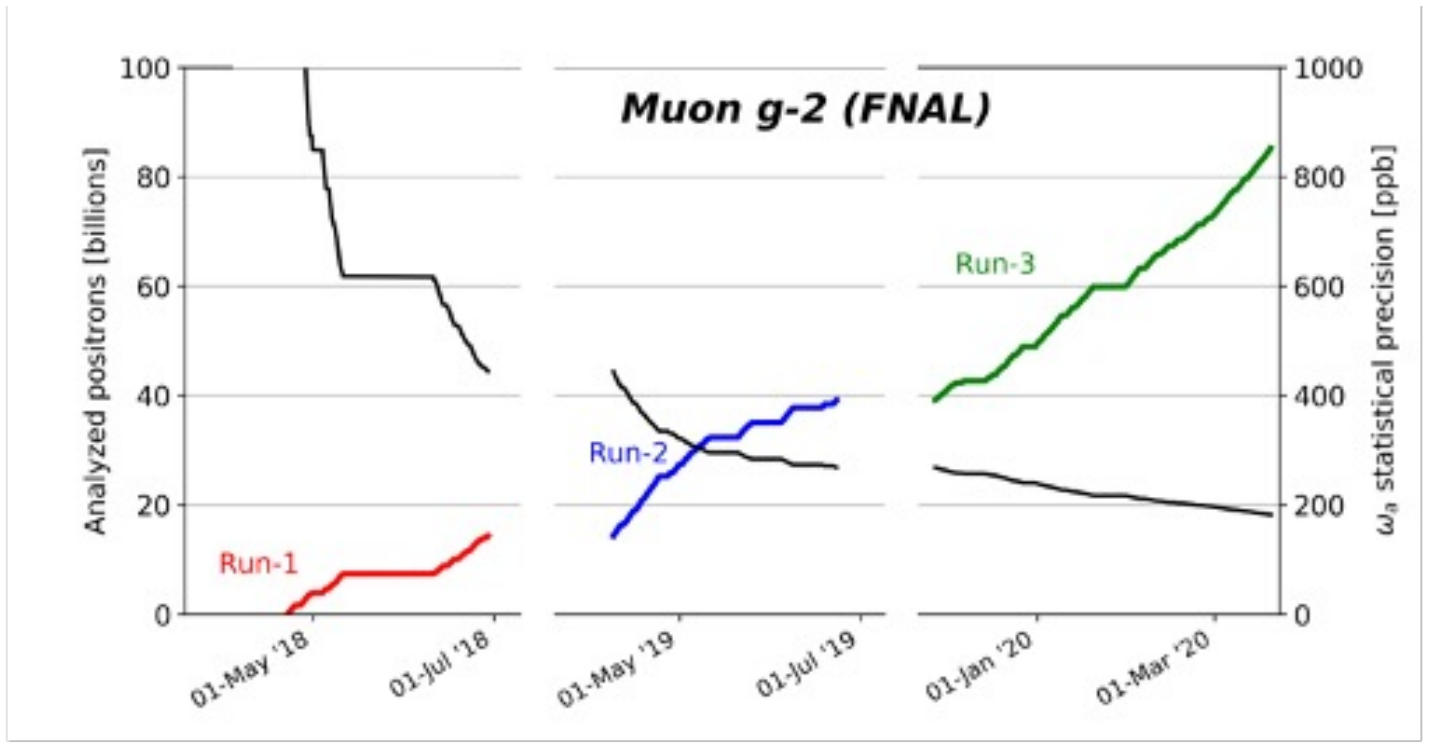


Fermilab director Lia Merminga pushed the red button to shut the beam down (Jul 10, 2023)

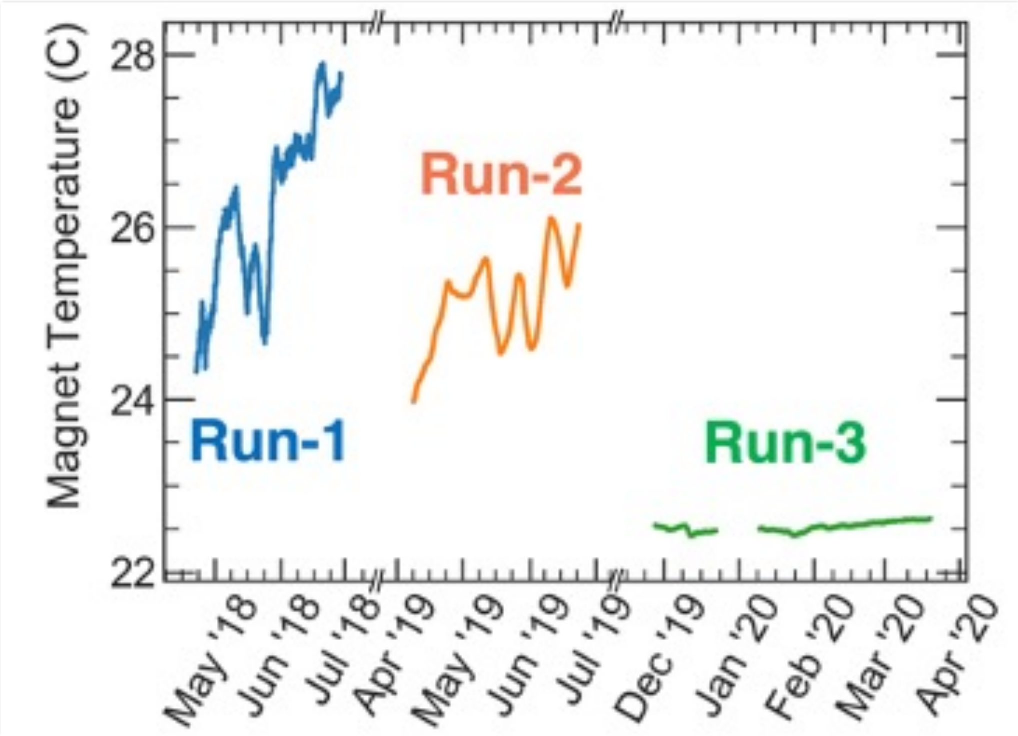


- Apr 2021: **Run-1** Result (2018 data)
- Aug 2023: **Run-2/3** Result (2019-20 data)
- ~2025: **Run-4/5/6** Result (2021-23 data)
- Reached our proposal goal for statistics (~4x Run-1/2/3)

Run-1 to Run-2/3 improvements

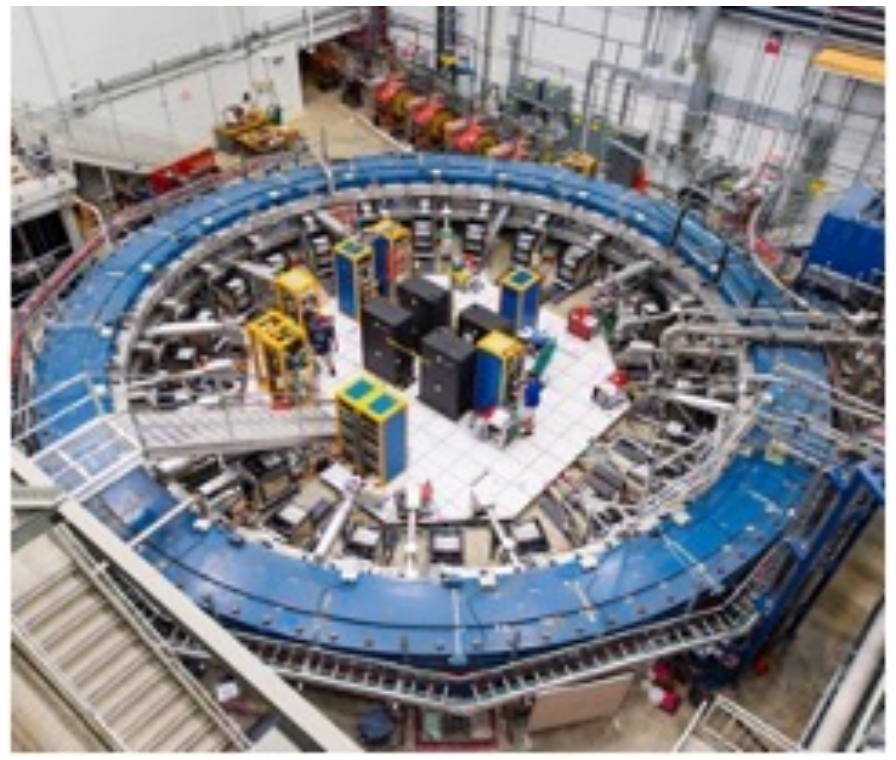


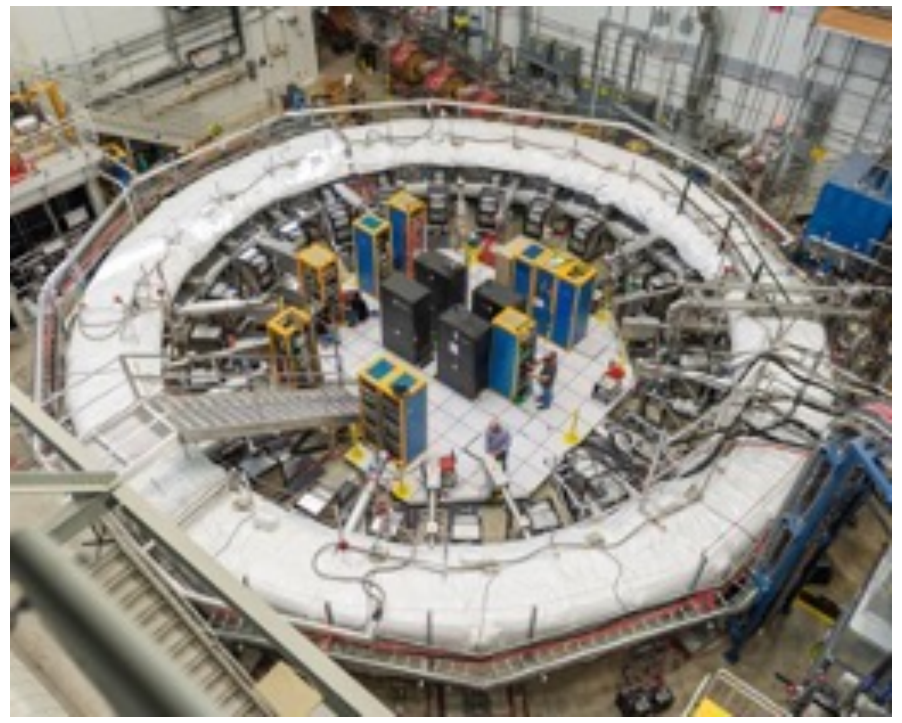
Statistics

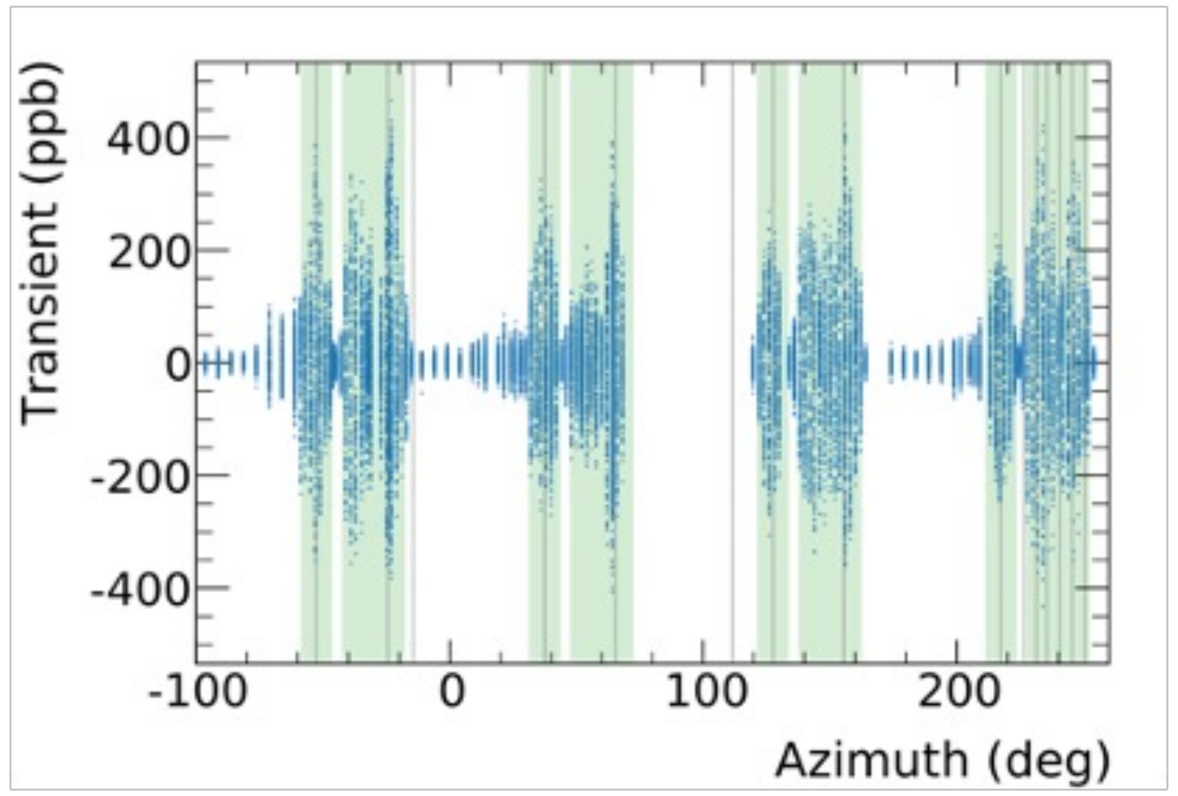


Running Conditions

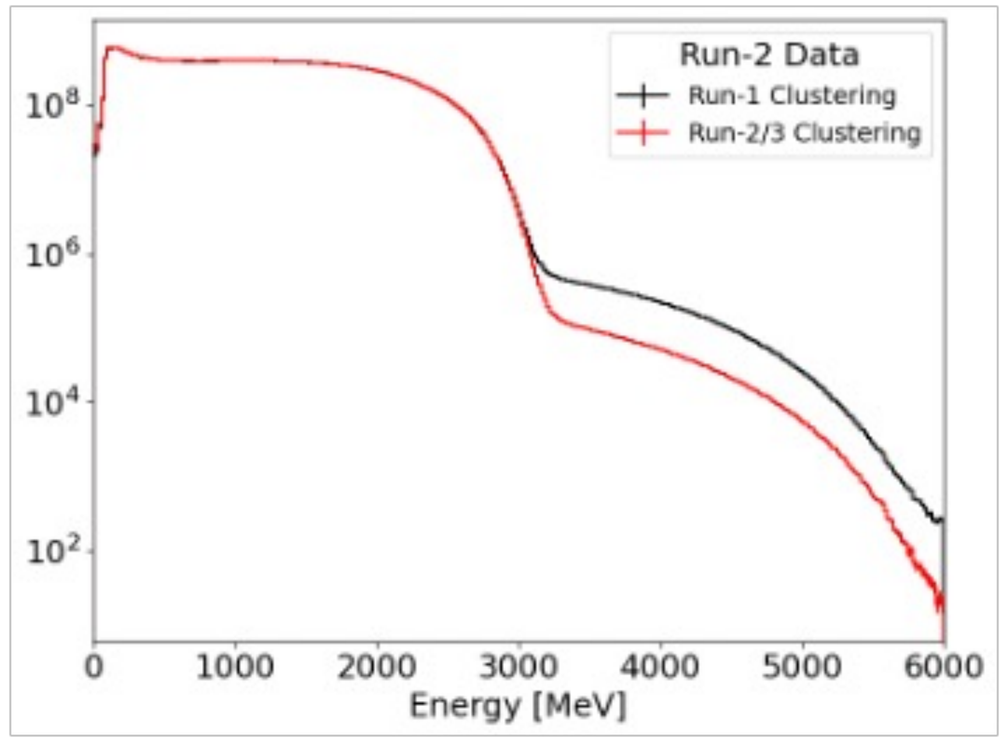
- Damaged quad resistors fixed
- Hall/Ring temperature stabilized
- Kicker strength improved







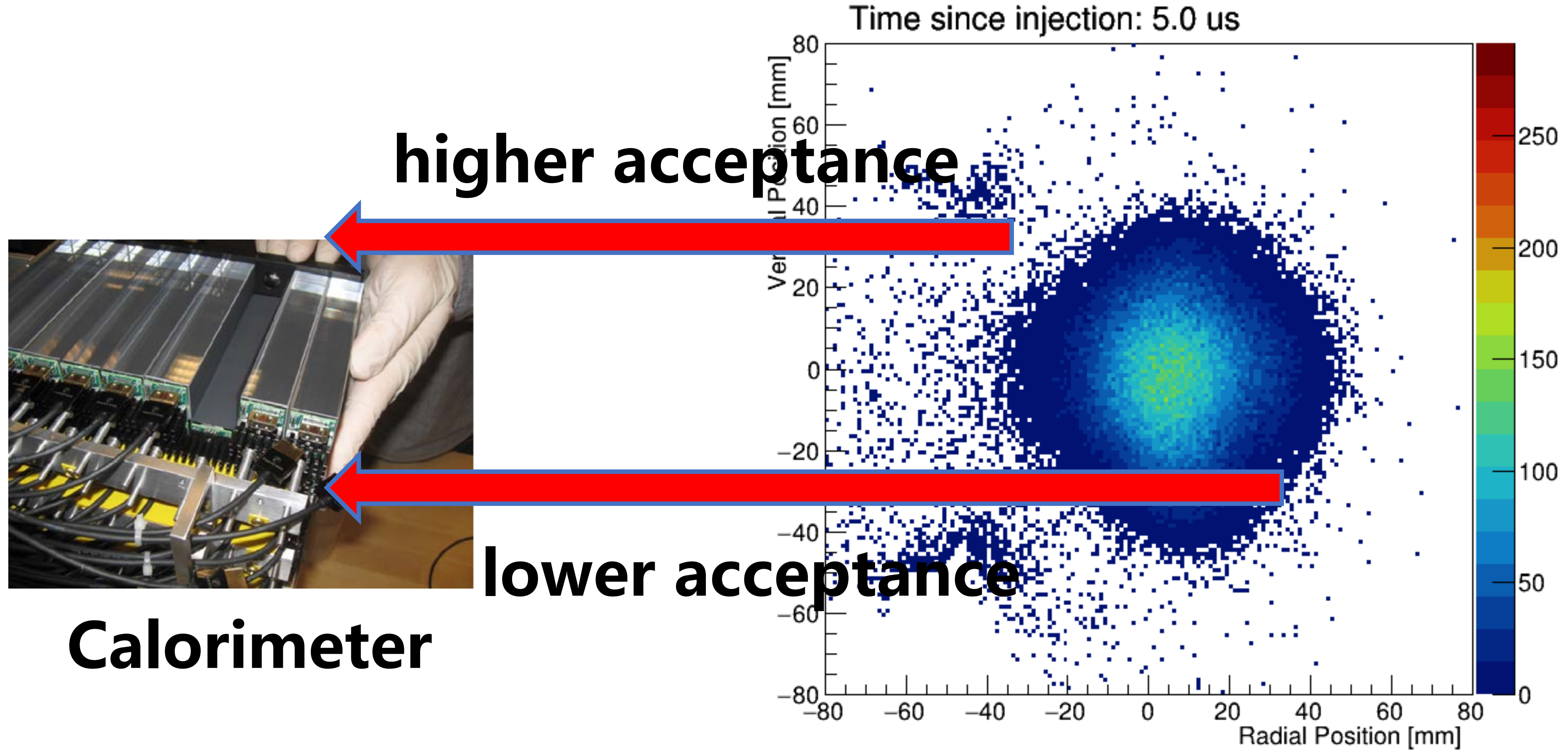
Systematic Measurements & Studies

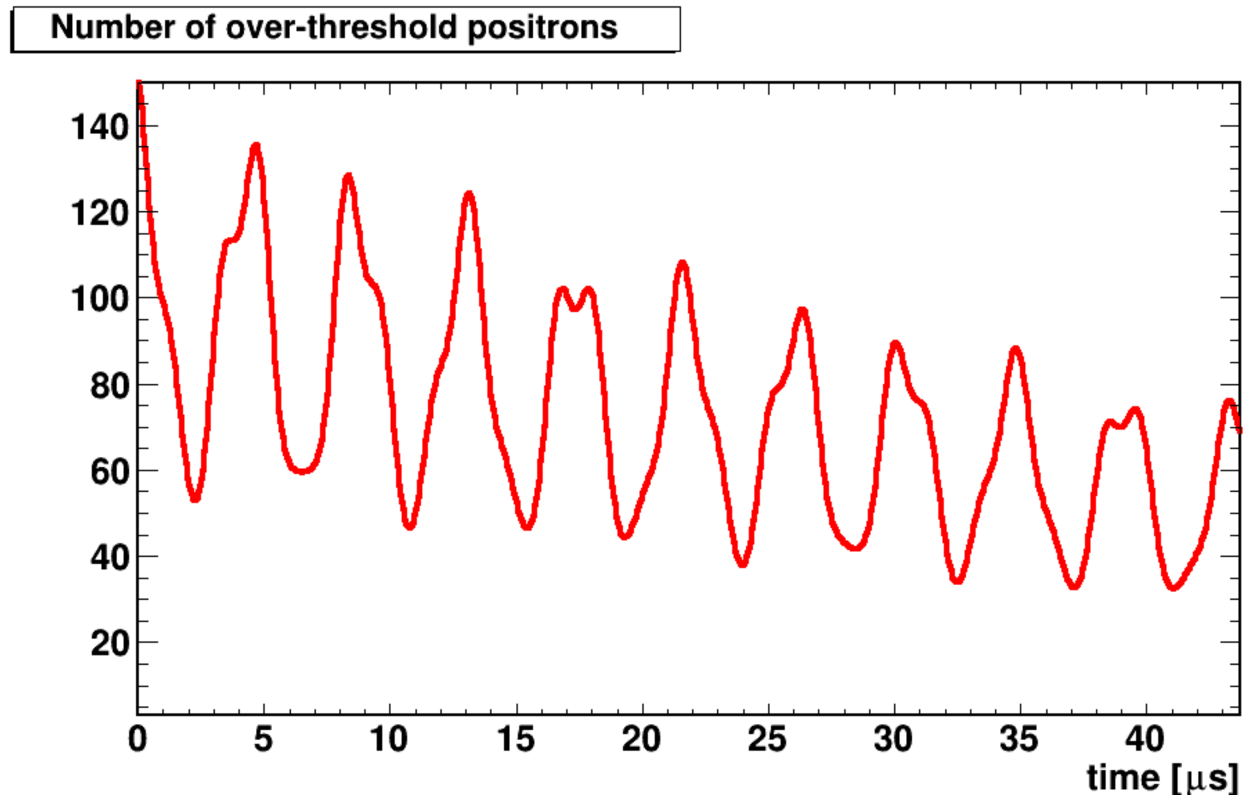


Analysis Improvements

Run-2/3 to Run-4/5/6 improvements

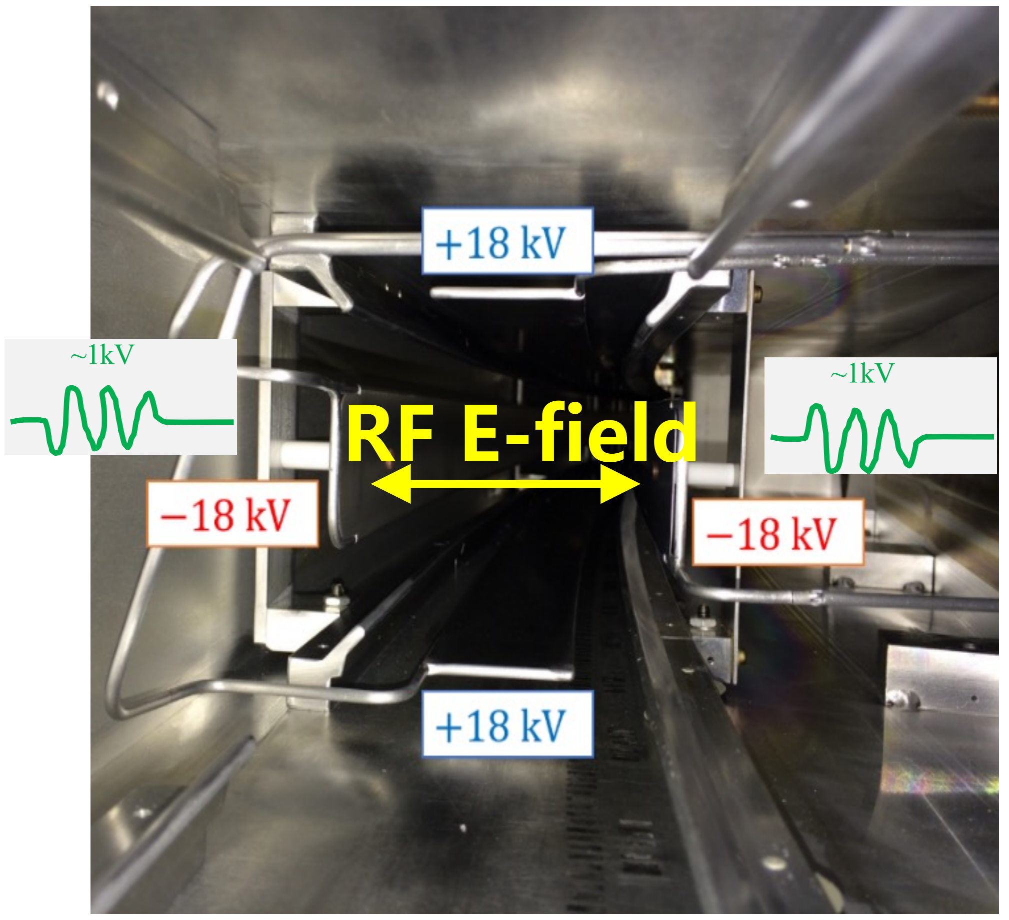
- Stored muon beam exhibits coherent betatron oscillation (CBO)
- Coupled with the calorimeter acceptance, it distorts the time spectrum



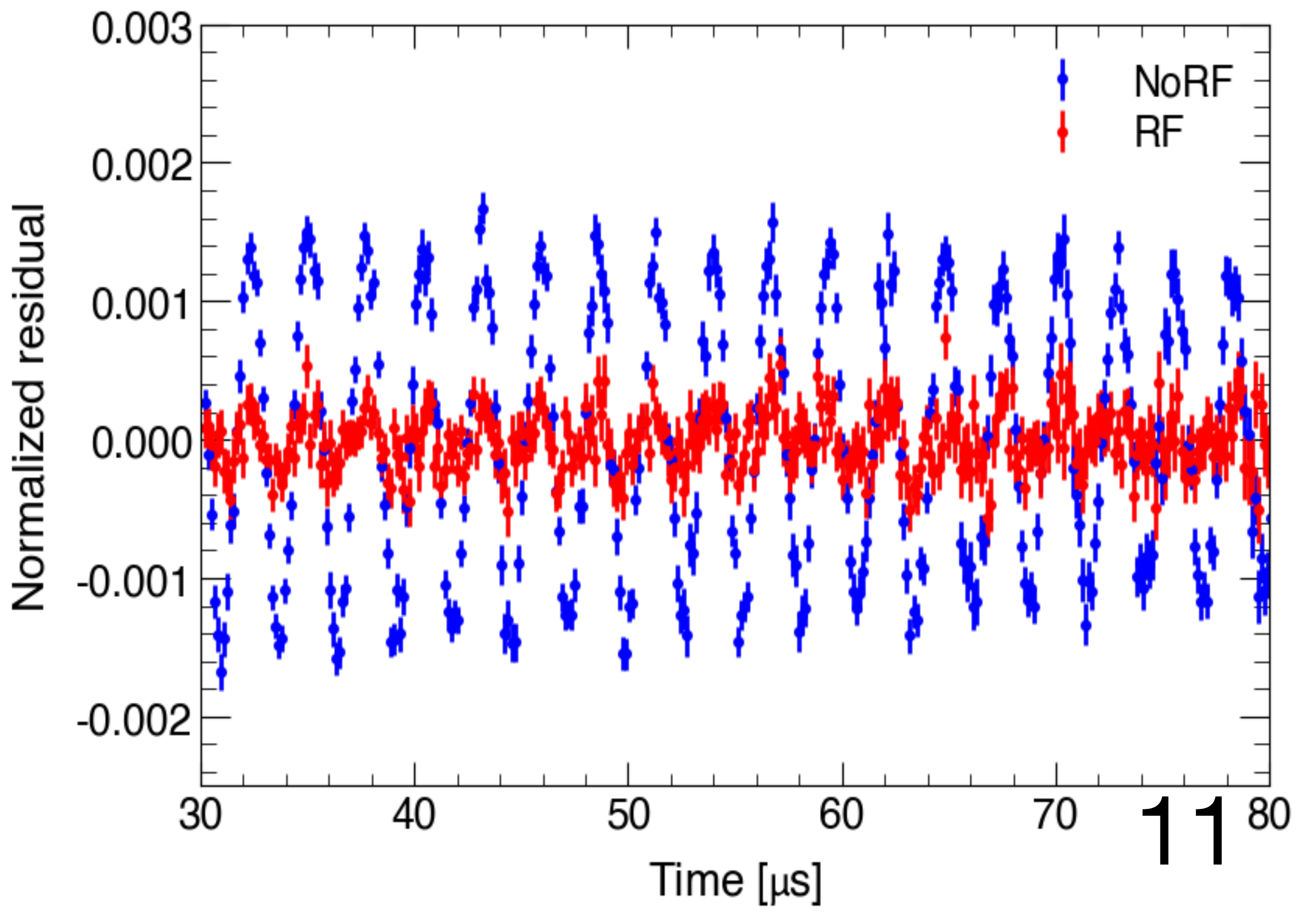


- Implemented a RF system to reduce the CBO significantly.
- Run-5/6 data (almost half of the entire data) was taken with the RF system.

Electrostatic Quadrupole + RF



CBO



Run-4/5/6 expected improvements

李政道研究所 Tsung-Dao Lee Institute

Run-2/3 Result: PRL **131**, 161802 (2023)

TABLE I. Values and uncertainties of the $\mathcal{R}'_\mu$ terms in Eq. (2), and uncertainties due to the external parameters in Eq. (1) for a_μ. Positive C_i increases a_μ; positive B_i decreases a_μ [see Eq. (2)]. The ω_a^m uncertainties are decomposed into statistical and systematic contributions. All values are computed with full precision and then rounded to the reported digits.

	Quantity	Correction (ppb)	Uncertainty (ppb)
ω_a	ω_a^m (statistical)	⋯	201
	ω_a^m (systematic)	⋯	25
BD	C_e	451	32
	C_p	170	10
	C_{pa}	−27	13
	C_{dd}	−15	17
	C_{ml}	0	3
ω_p	$f_{\text{calib}} \cdot \langle \omega'_p(\vec{r}) \times M(\vec{r}) \rangle$	⋯	46
	B_k	−21	13
	B_q	−21	20
	$\mu'_p(34.7°)/\mu_e$	⋯	11
	m_μ/m_e	⋯	22
	$g_e/2$	⋯	0
	Total systematic for $\mathcal{R}'_\mu$	⋯	70
	Total external parameters	⋯	25
	Total for a_μ	622	215

$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\ \omega_a^m\,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle \omega_p(x,y,\phi) \times M(x,y,\phi)\rangle (1 + B_k + B_q)}$$

Expected Run-4/5/6 improvements
(Estimation for systematics on-going)

~100 (in total Runs 1-6), ~x4 stats

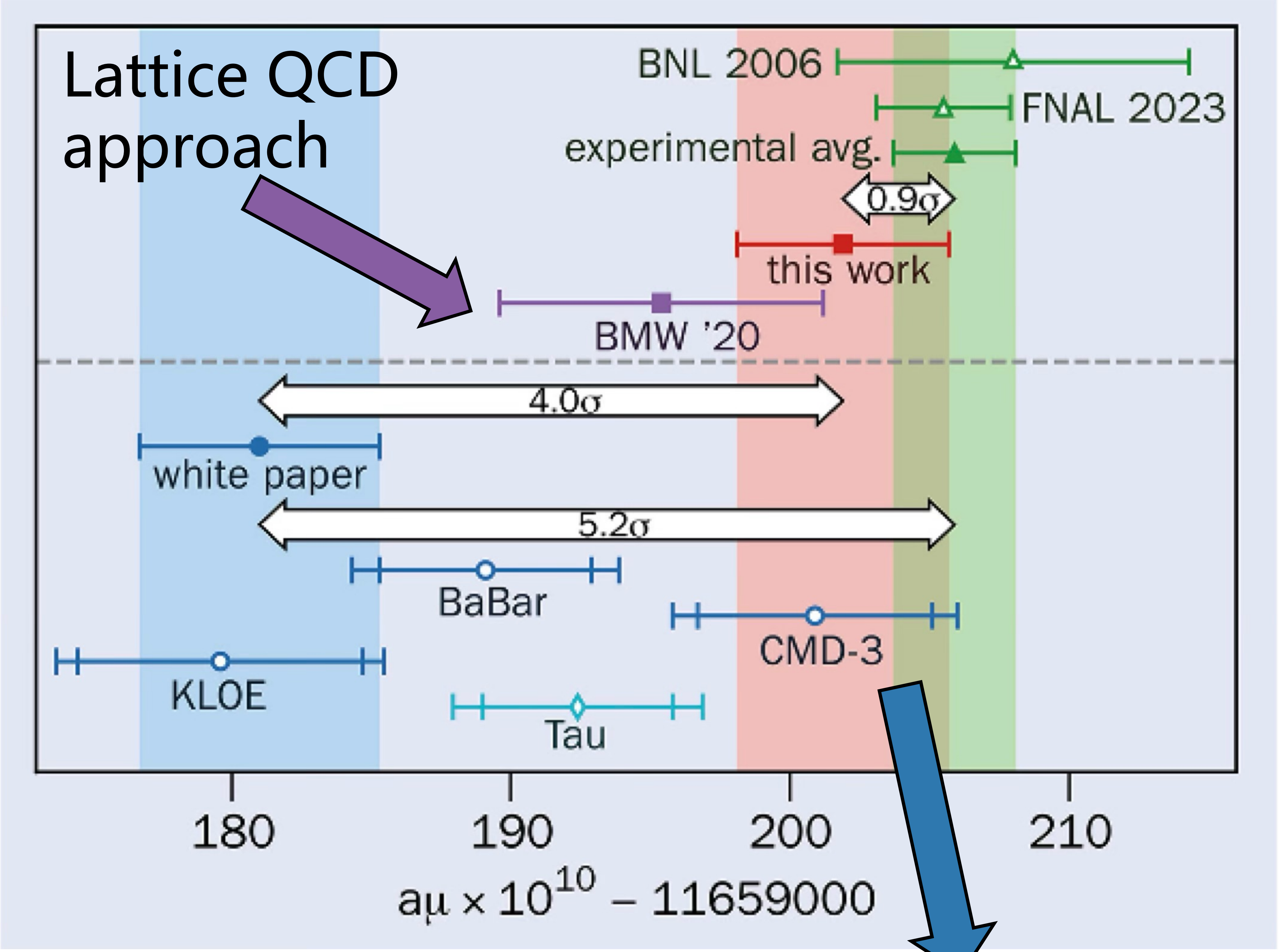
~x10 reduction of CBO with the RF system (Run-5/6)

New signal processing algorithm
New beam-monitoring system (miniSciFi)
New tracker-based analysis method

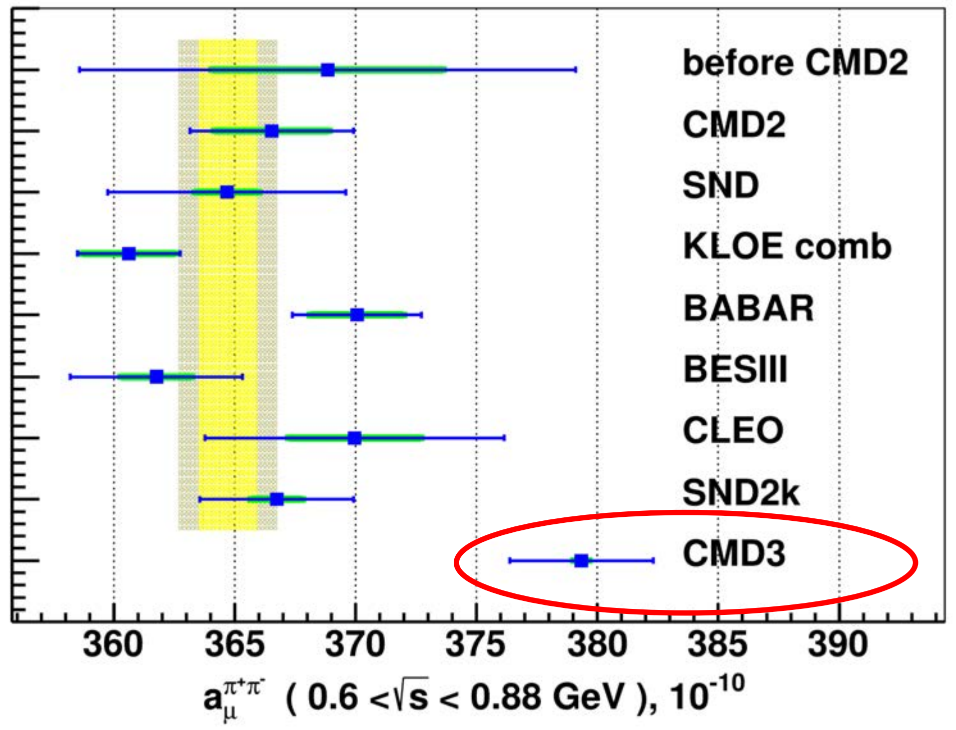
More calibrations + cross-calibrations.
Better understanding and handling of magnet drift.
More and better measurements

Surpassed the TDR systematics goal of 100 ppb.
And possibly even smaller for Run-4/5/6!

Theory vs Experiment for g-2



Data-driven approach

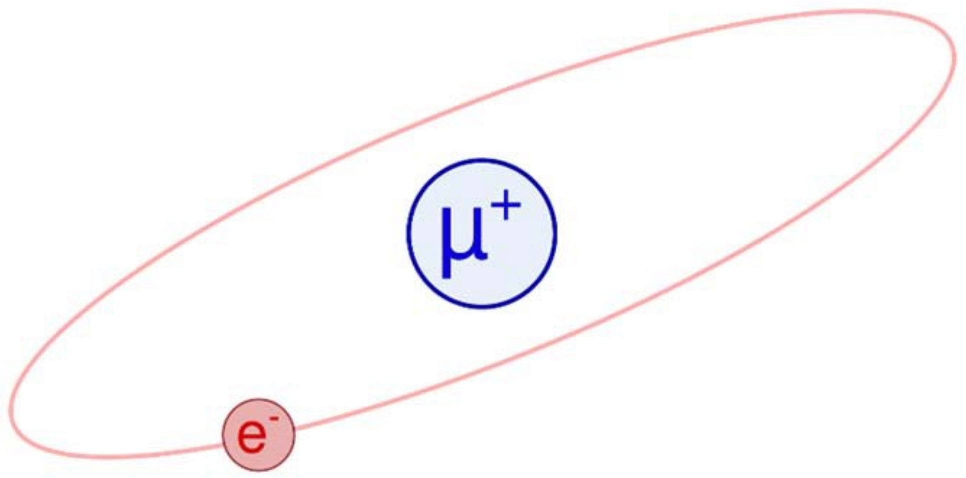


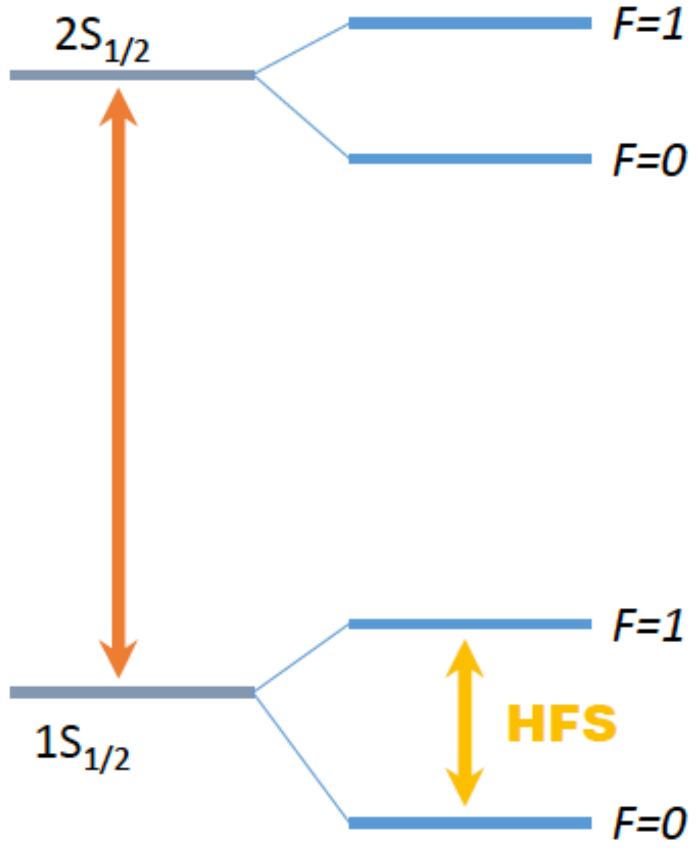
- Large discrepancy between experiment and WP (2020)
- New results since WP 2020
  - **BMW** (swapping HVP from WP with their value) falls **in between** WP (2020) and experiment
  - **CMD-3** in tension with other e^+e^- machine data (data-driven approach)
- Many **parallel efforts are underway** to resolve the theoretical ambiguity
  "The muon g-2 theory puzzle".
- An update is expected in 2025, many more years to resolve this new puzzle
- **An independent experiment at J-PARC** to provide another experimental input (Suzuki-san)

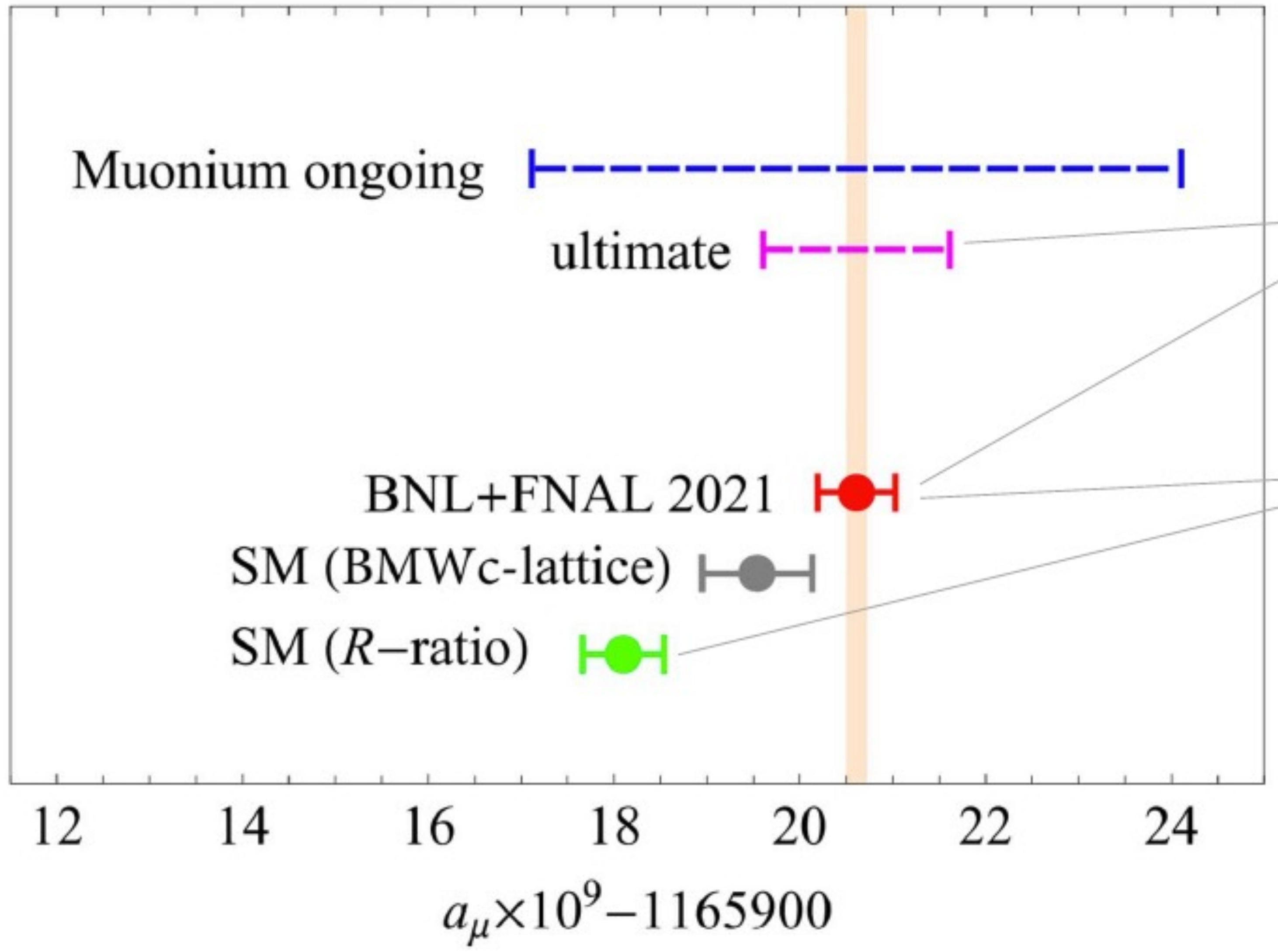
Muon g-2 from muonium spectroscopy

李政道研究所 TSUNG-DAO LEE INSTITUTE

Phys. Rev. Lett. 127 (2021) 25, 251801







A value of $a_\mu^{\rm Mu}$ at $\mathcal{O}(1\mathrm{ppm})$ is not competitive to current spin-precession measurements

However, it may help to understand the origin of the $\sim 2\mathrm{ppm}$ difference between (R-ratio) SM and experiment

Ground-state HFS theory

Rydberg constant $R_\infty \equiv \alpha^2 m_e c/(2h)$

fine-structure constant

nonrelativistic **Fermi energy** from $H_{\rm HFS}$

$$\nu_{\rm HFS} = \frac{16}{3}(1+a_\mu)\frac{m_e}{m_\mu}\frac{R_\infty c\alpha^2}{(1+m_e/m_\mu)^3}[1+\delta_{\rm HFS}]$$

electron-muon mass ratio

$\mathcal{O}(\alpha)$ correction [CODATA 2018 + refs therein]

Z-exchange $-65\,\mathrm{Hz}$

$$\delta_{\rm HFS} = \delta_{\rm Dirac} + \delta_{\rm rad} + \delta_{\rm rec} + \delta_{\rm rad-rec} + \delta_{\rm weak} + \delta_{\rm had}$$

hadronic vacuum pol. $= 237.7(1.5)\,\mathrm{Hz}$

relativistic (exact)

antimuon charge $Z=1$

radiative known up to $\mathcal{O}(Z\alpha^4)$ including a_e

recoil known up to $\mathcal{O}[(m_e/m_\mu)(Z\alpha)^3]$ $\sim 60\,\mathrm{Hz}$ uncertainty

radiative-recoil known up to $\mathcal{O}[(m_e/m_\mu)\alpha^3]$ $\sim 10\,\mathrm{Hz}$ uncertainty

Total TH uncertainty $\sim 70\,\mathrm{Hz}\,(16\mathrm{ppb})$ dominanted by (yet) uncalculated QED corrections at three-loop order

[Eides-Shelyuto IJMPA 2016]

1S-2S theory

nonrelativistic energy (including recoil)

$\mathcal{O}(\alpha^2)$ correction [CODATA 2018 + refs therein] rescaling hydrogen formulae with the muon mass and removing nuclear finite size and pol. effects

$$\nu_{\rm 1S-2S} = \frac{3}{4}\frac{R_\infty c}{(1+m_e/m_\mu)}[1+\delta_{\rm 1S-2S}]$$

vacuum pol. known up to $\mathcal{O}[\alpha(Z\alpha)^4]$

2+3 photon exchange known up to $\mathcal{O}[\alpha^3(Z\alpha)^4]$

muon self-E

$$\delta_{\rm 1S-2S} = \delta_{\rm Dirac} + \delta_{\rm rel-rec} + \delta_{e\rm SE} + \delta_{\rm VP} + \delta_{2\gamma} + \delta_{3\gamma} + \delta_{\rm rad-rec} + \delta_{\mu\rm SE}$$

relativistic (exact)

relativistic-recoil known up to $\mathcal{O}[(m_e/m_\mu)(Z\alpha)^4]$

electron self-E $\mathcal{O}[\alpha(Z\alpha)^4]$ known

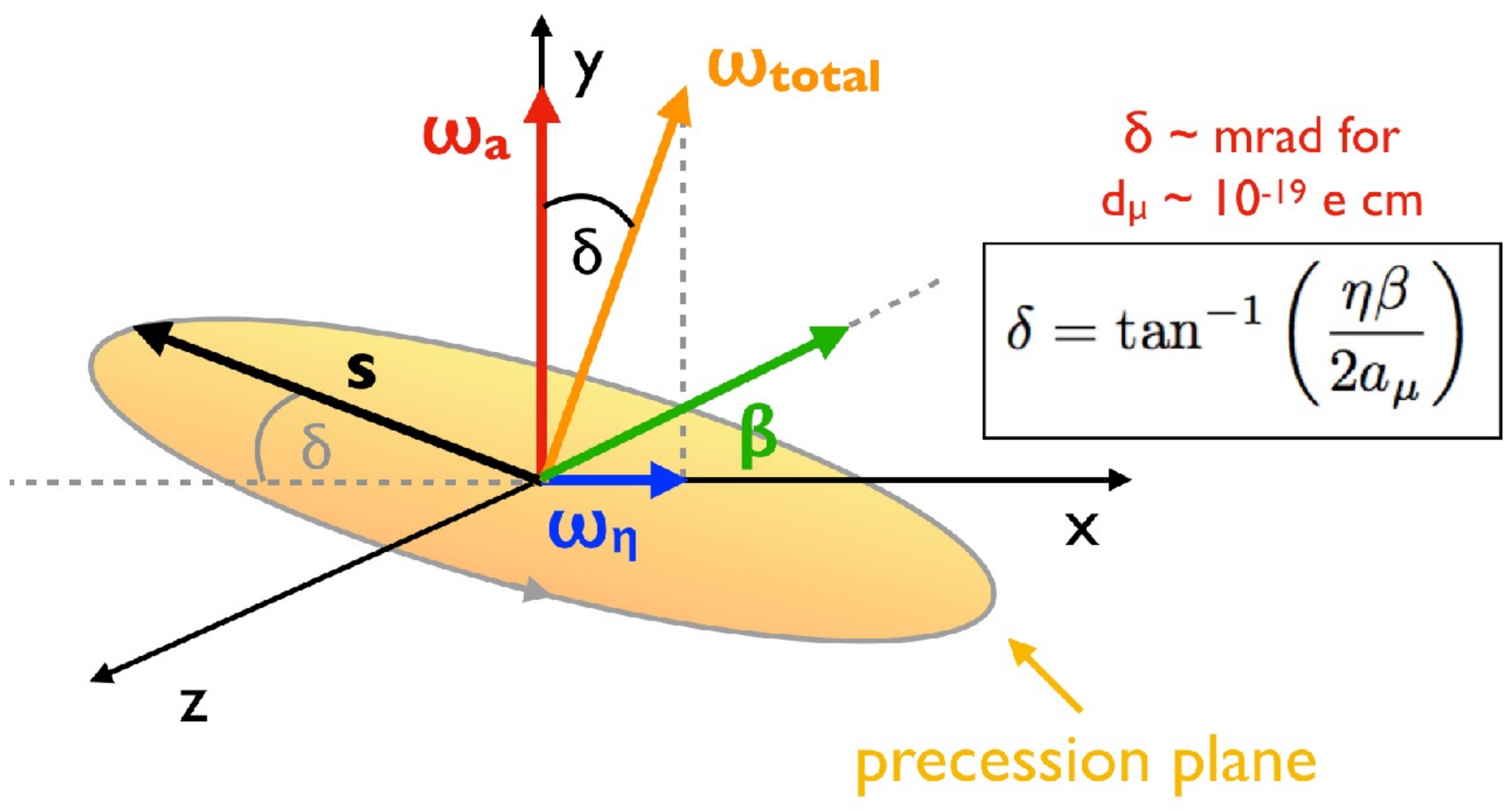
radiative-recoil known up to $\mathcal{O}[(m_e/m_\mu)\alpha(Z\alpha)^3]$

Total TH uncertainty $\sim 20\,\mathrm{kHz}\,(8\mathrm{ppt})$ from (yet) uncalculated QED (rad-rec) corrections at three-loop order

[Karshenboim et al. PLB 2019]

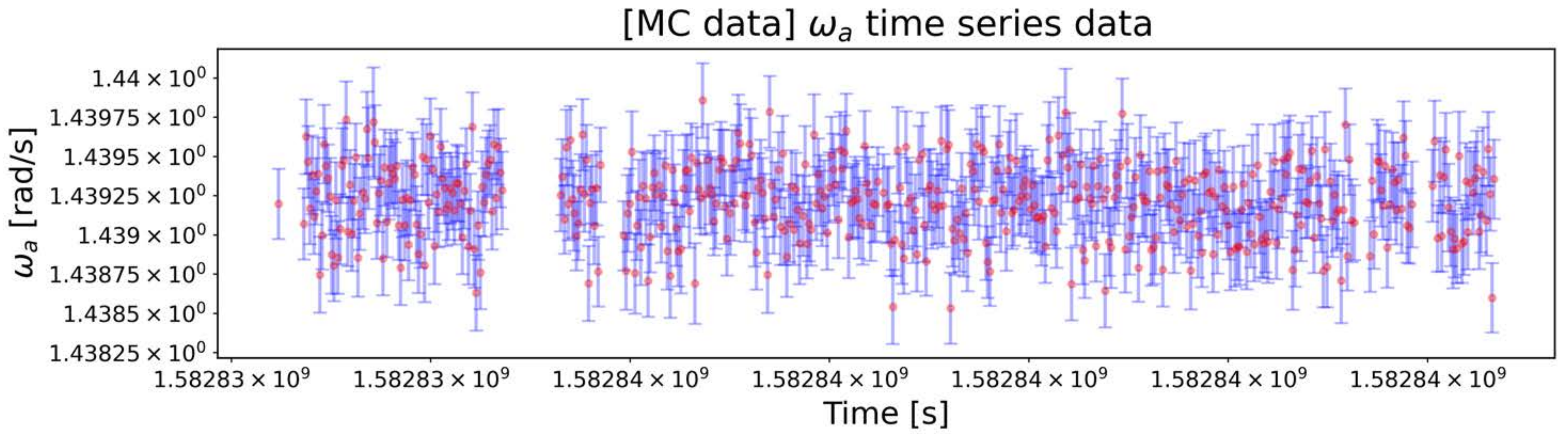
BSM searches (EDM, CPT/LI, DM)

- **Muon Electric Dipole Moment (EDM)**
  - ➢ The spin precession plane is tilted in the presence of the EDM.
  - ➢ Run-1 analysis in review, Run-2/3 analysis in progress
  - ➢ Current limit (BNL): 1.8×10^{-19} e · cm → Projected limit: $\lesssim 3 \times 10^{-20}$ e · cm



- **CPT and Lorentz Invariance Violation**
  - ➢ ω_a modulated at the sidereal motion freq.
  - ➢ Run-2/3 analysis in review.
  - ➢ Current limit (BNL): 1.4×10^{-24} GeV → Projected limit (FNAL Run-2/3): $\mathcal{O}(10^{-25})$ GeV

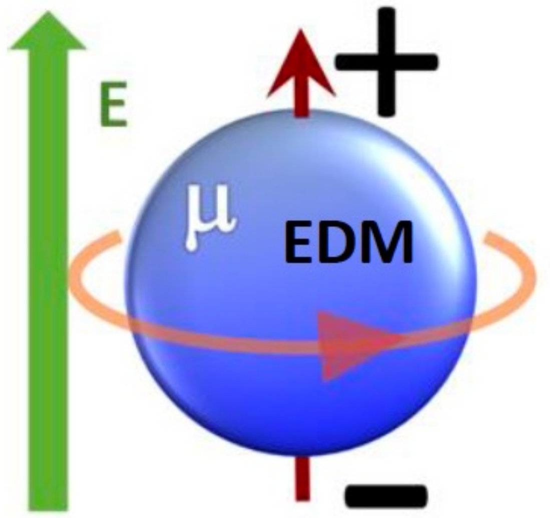
- **Ultralight Muonic Dark Matter (scalar)**
  - ➢ ω_a modulated at the DM Compton frequency.
  - ➢ Run-2/3 analysis in progress.



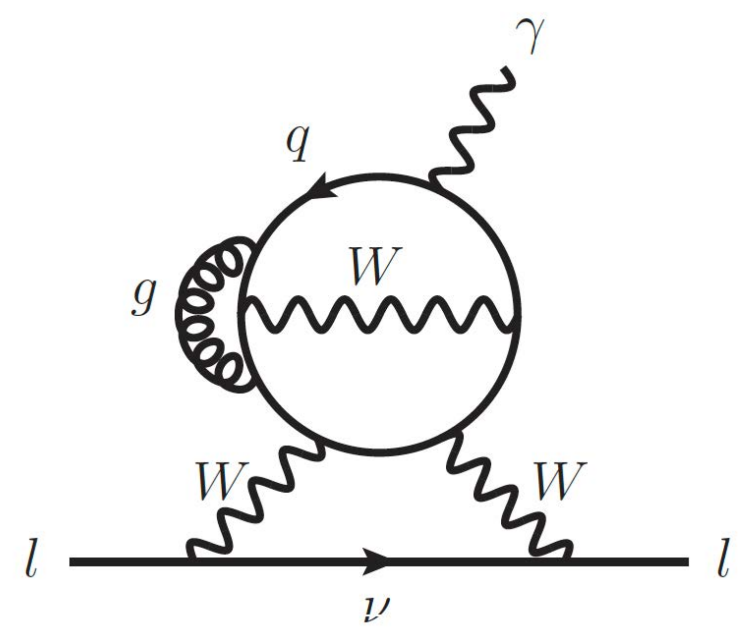
Motivation for EDM searches

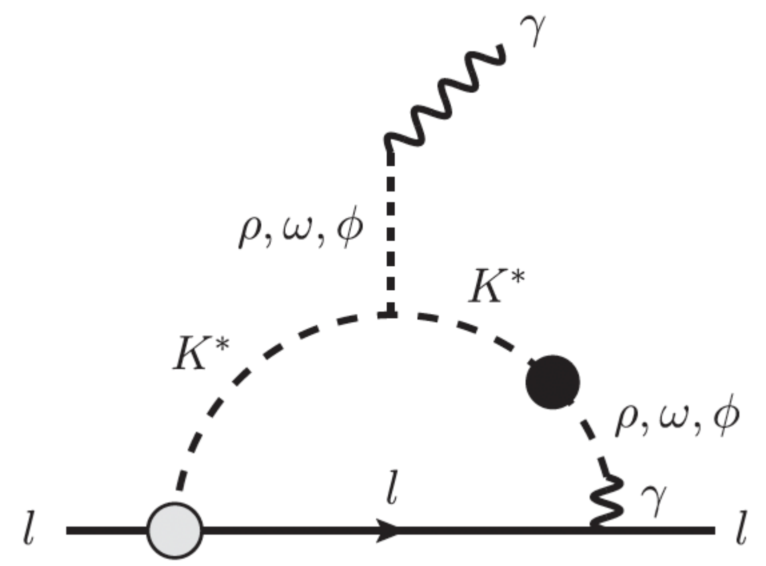
Tsung-Dao Lee Institute

- Electric dipole moment (EDM) violates time-reversal symmetry and charge-parity (CP) symmetry, assuming CPT invariance.



$$\vec{d} = \eta \frac{e}{2mc} \vec{s}$$





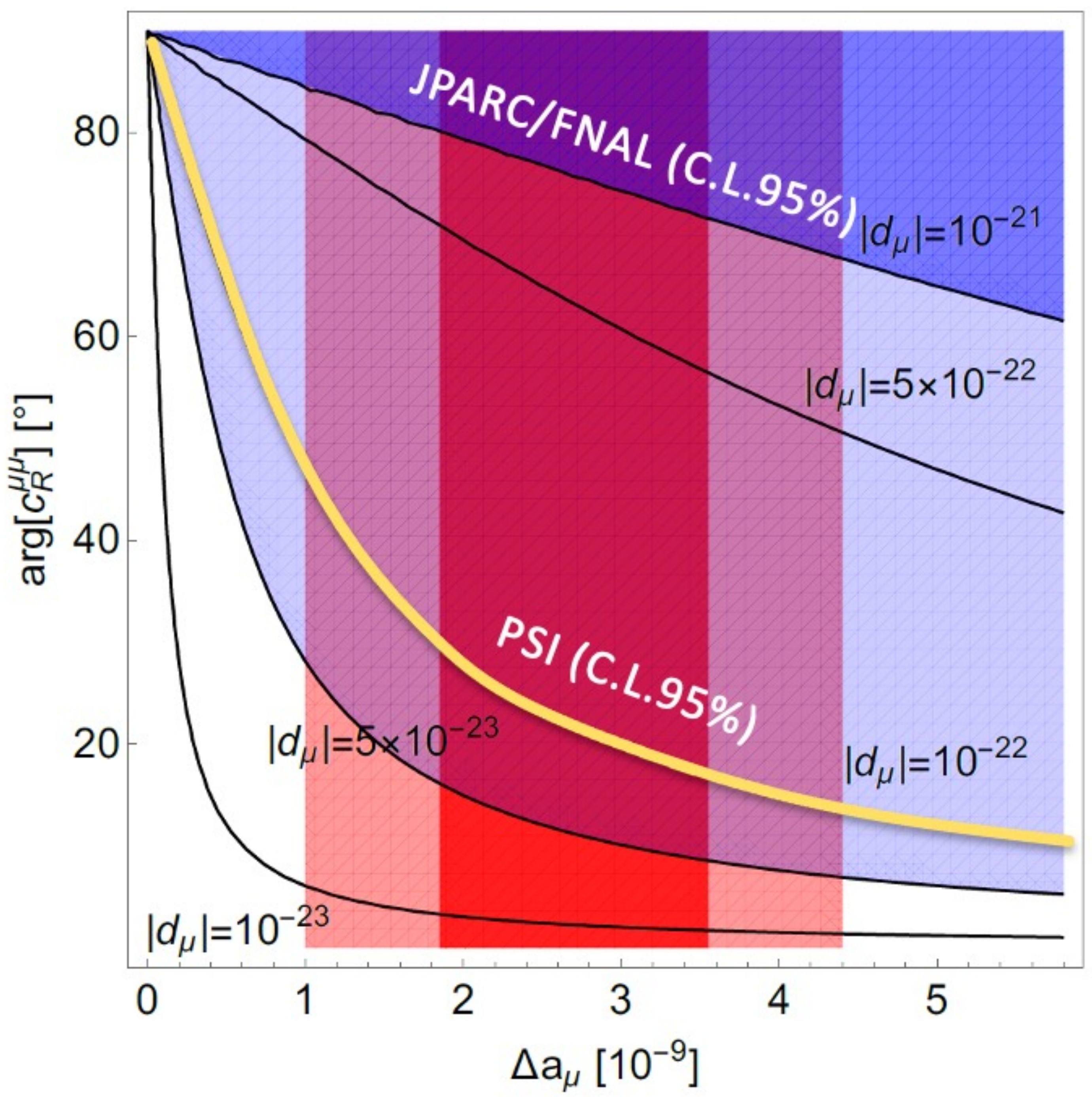
- Standard Model predicts small EDMs for fundamental particles
  - CKM contribution: $d_\mu^{CKM} \sim 10^{-42}\ \mathrm{e \cdot cm}$, hadronic long-range effect: $d_\mu^{HLR} \sim 10^{-38}\ \mathrm{e \cdot cm}$ PRD 89 (2014) 056006 PRL 125 (2020) 241802
  - Current experimental limit $d_\mu^{\mathrm{BNL}} < 1.8 \times 10^{-19}\ \mathrm{e \cdot cm}\ (95\%\ \mathrm{C.L.})$ PRD 80 (2009) 052008
  - Indirect limit from heavy atom EDM searches $|d_\mu| < 2{\times}10^{-20}\ \mathrm{e \cdot cm}$ PRL 128 (2022) 131803
  - Excellent probes for new physics since it is essentially “background-free”
- Any observed EDM signal is for sure BSM physics!
  - May shed light on the baryon asymmetry in the universe as new sources of CPV are required

A.D. Sakharov, JETP Lett. 5, 24 (1967)

BSM/EFT models with large EDMs

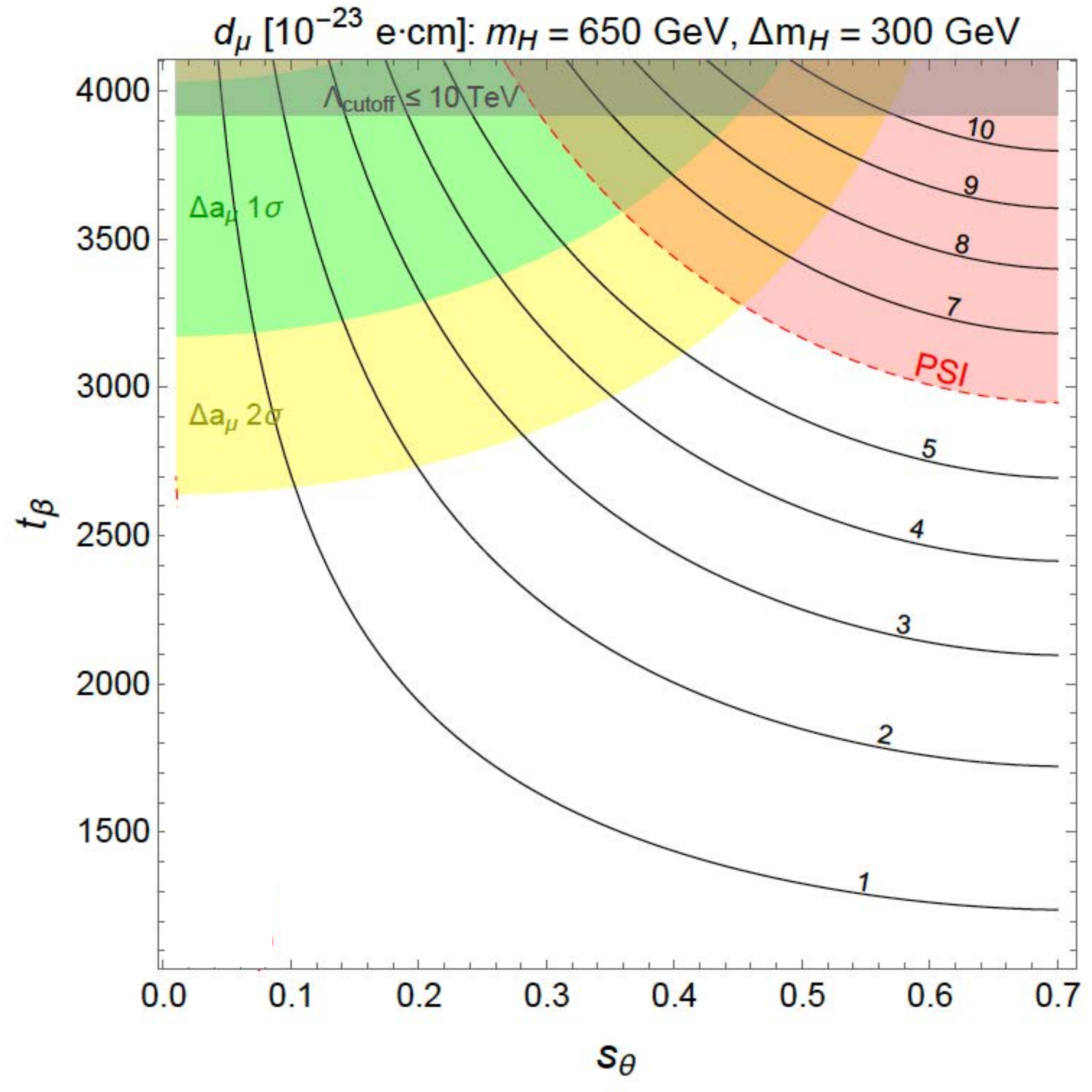
TSUNG-DAO LEE INSTITUTE

EFT Analysis



PRD 98 (2018) 113002

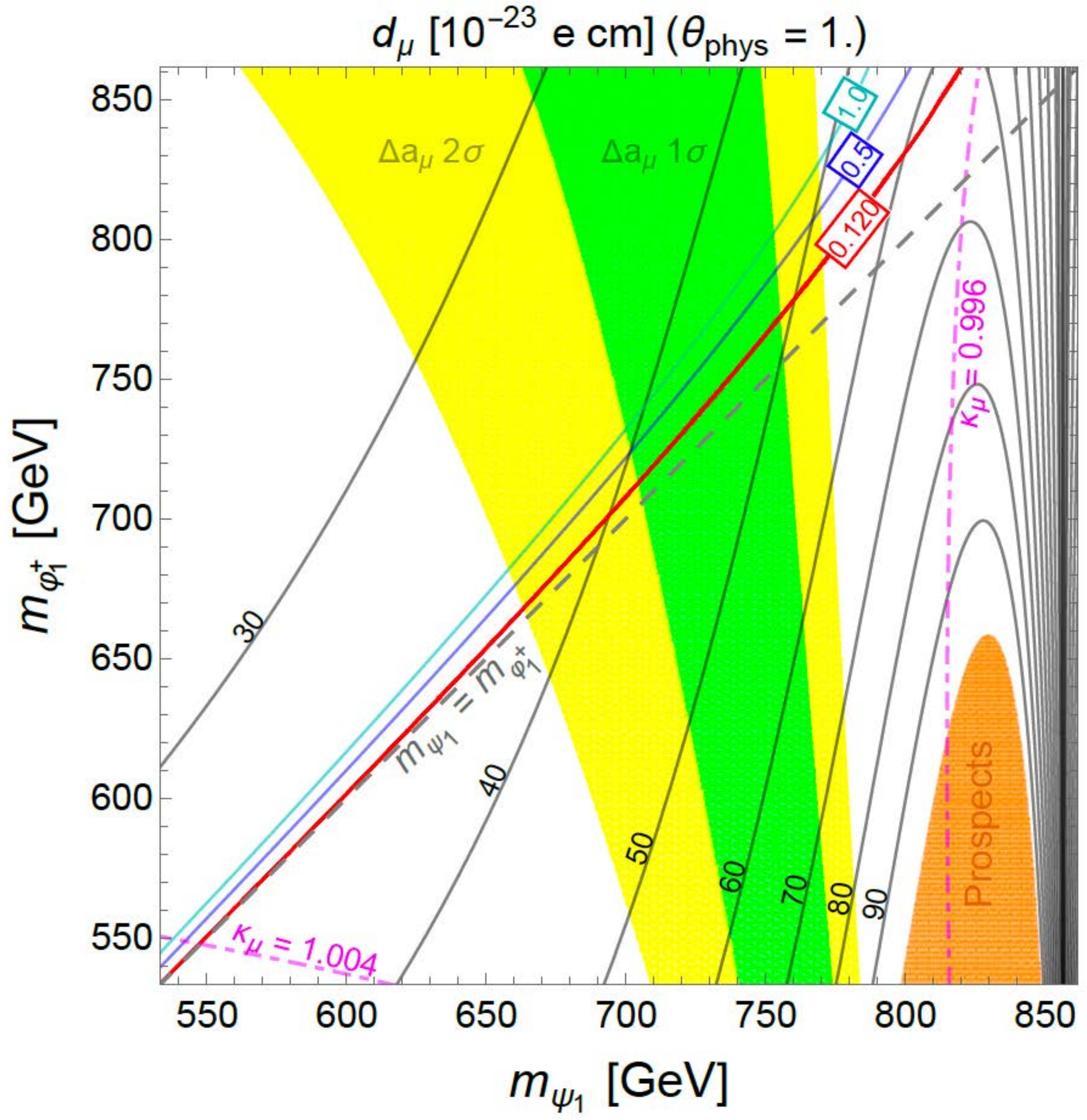
Muon specific 2HDM



Interesting parameter space: $s_\theta \sim 0.35$, tanβ ~ 3700

PLB 831 (2022) 137194

Radiative muon mass model

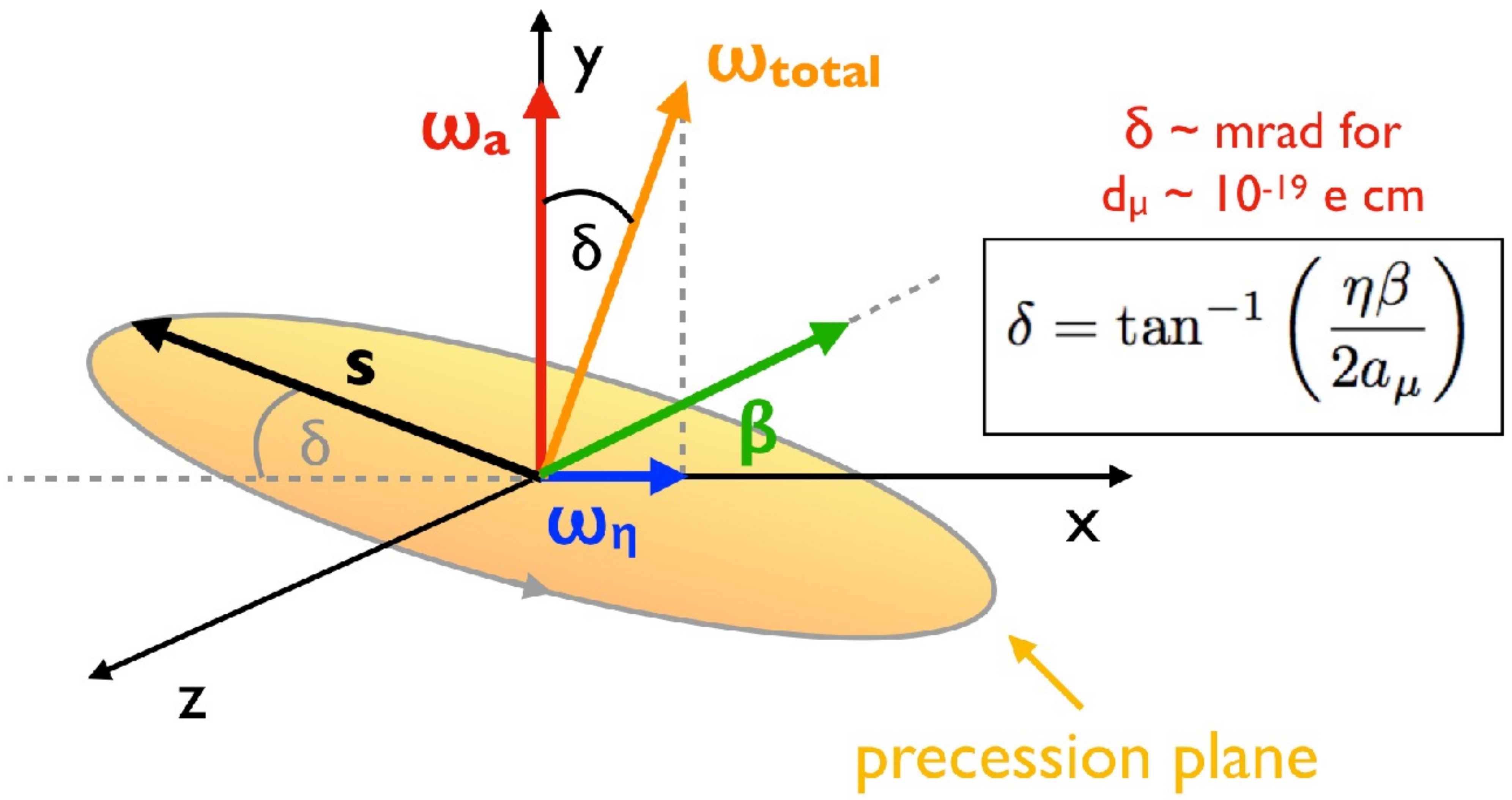


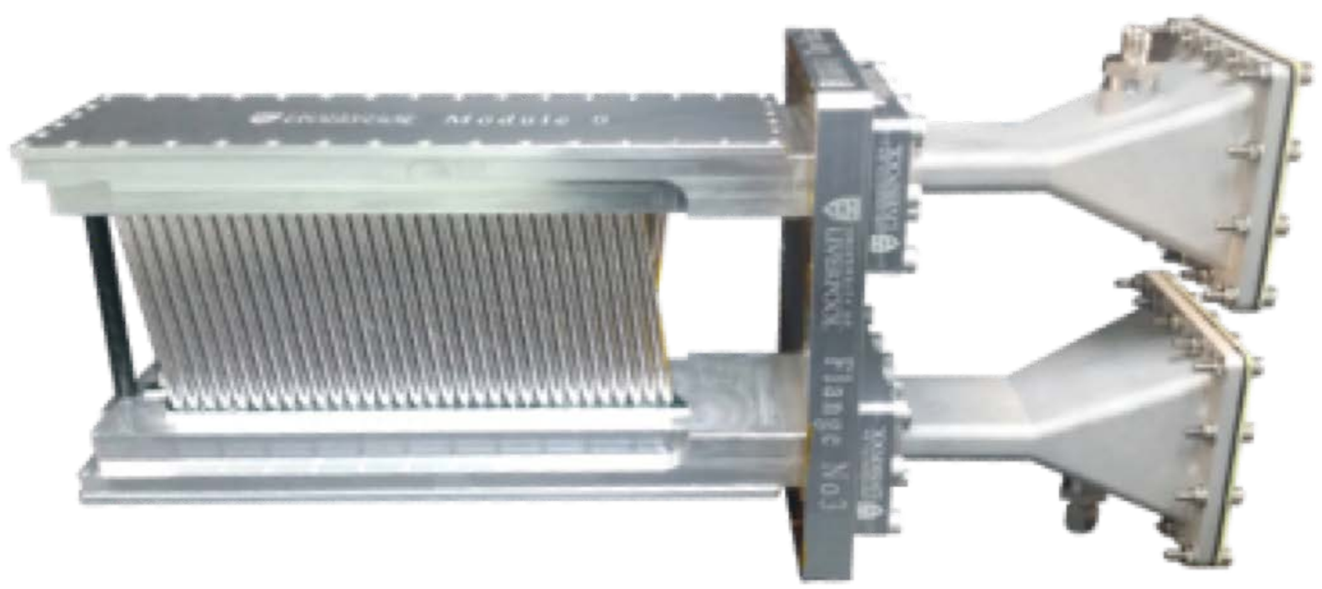
JHEP02 (2023) 234 (4)

Strong motivation to go beyond FNAL/J-PARC goal of 10^{-21} e cm!

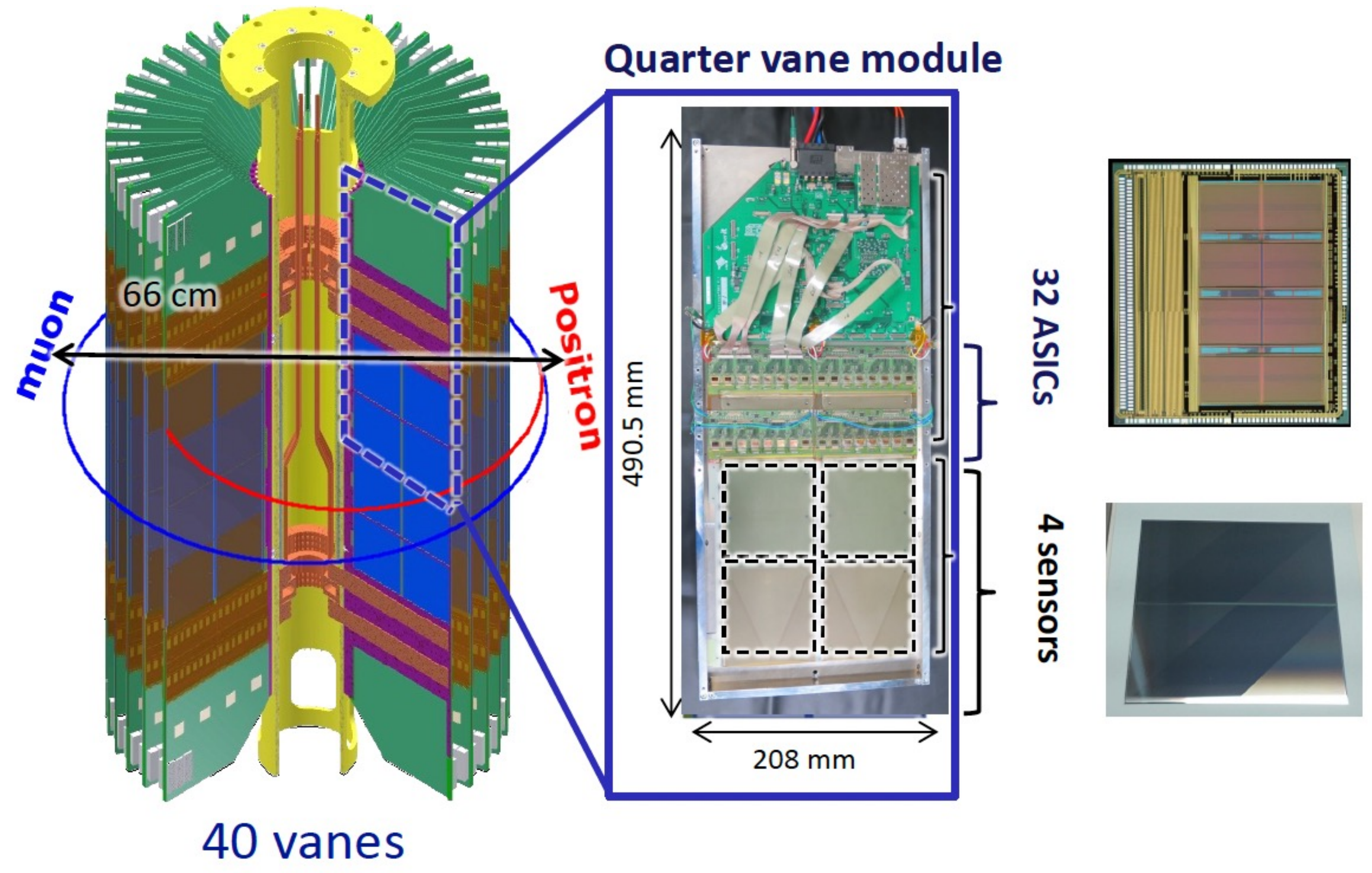
Going beyond 10^{-21} e cm?

- How can we improve the sensitivity of the muon EDM search?
- In the parasitic g-2 approach, the tilt angle is the limiting factor
- For an EDM below 10^{-21} e cm, it will be very challenging to measure this small angle < μrad (multiple scattering effect + systematic effects like mis-alignment)





Straw trackers
FNAL Muon g-2



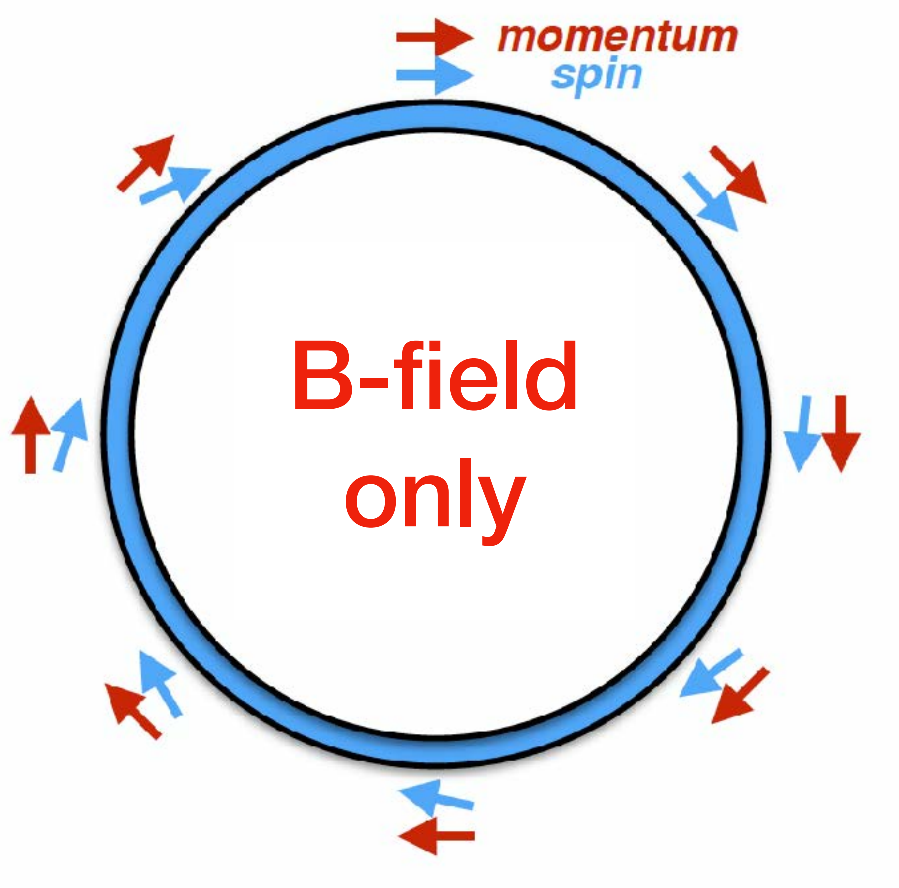
Silicon Strip Detector
J-PARC Muon g-2/EDM

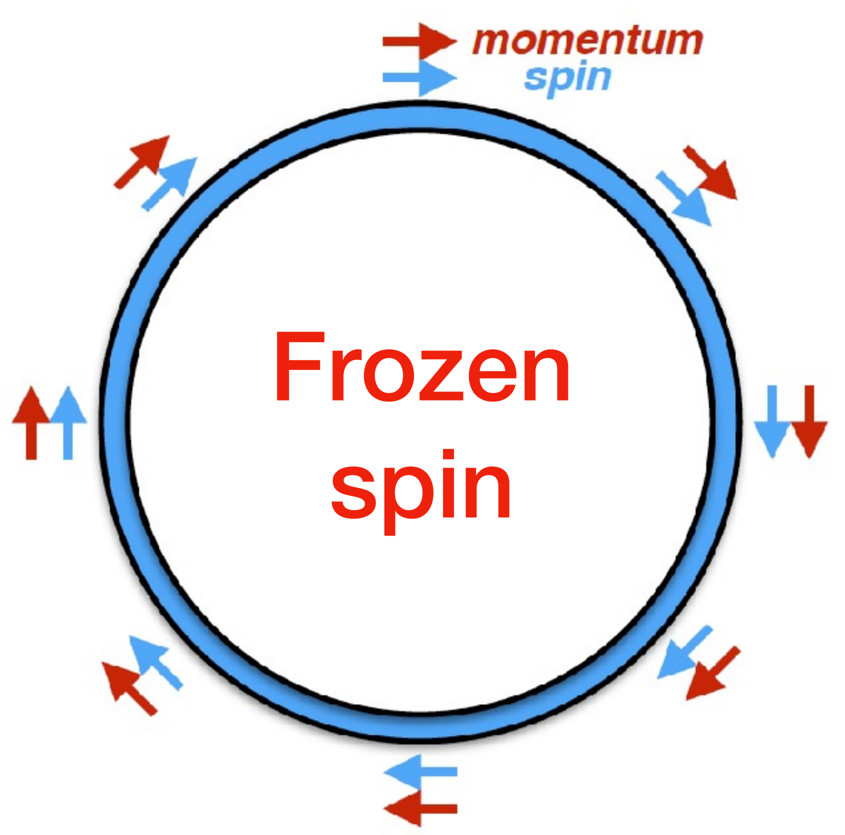
The “frozen-spin” technique

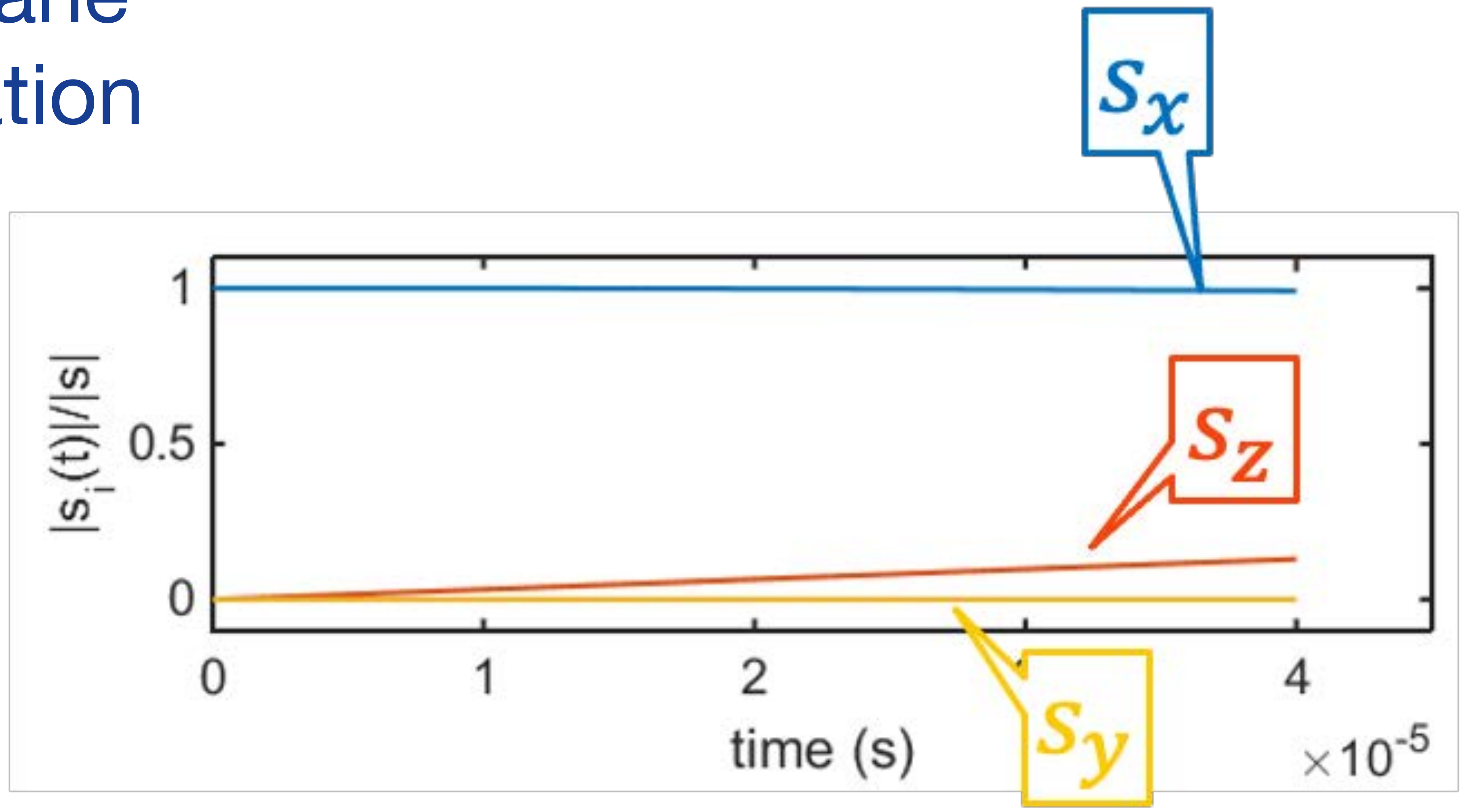
$$\vec{\omega}_s - \vec{\omega}_c = -\frac{e}{m}\{\boxed{\cancel{a\vec{B} + \left(\frac{1}{\gamma^2 - 1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}}} + \frac{\eta}{2}\boxed{\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)}\}$$

ω_a : g-2 $\qquad$ ω_η: EDM

- Developed in 2004 for the muon EDM search PRL 93 (2004) 052001
- Freeze g-2 component by applying a radial E-field of ~ **$aBc\beta\gamma^2$**
  → no anomalous precession in the storage plane
  → EDM causes an increasing vertical polarization

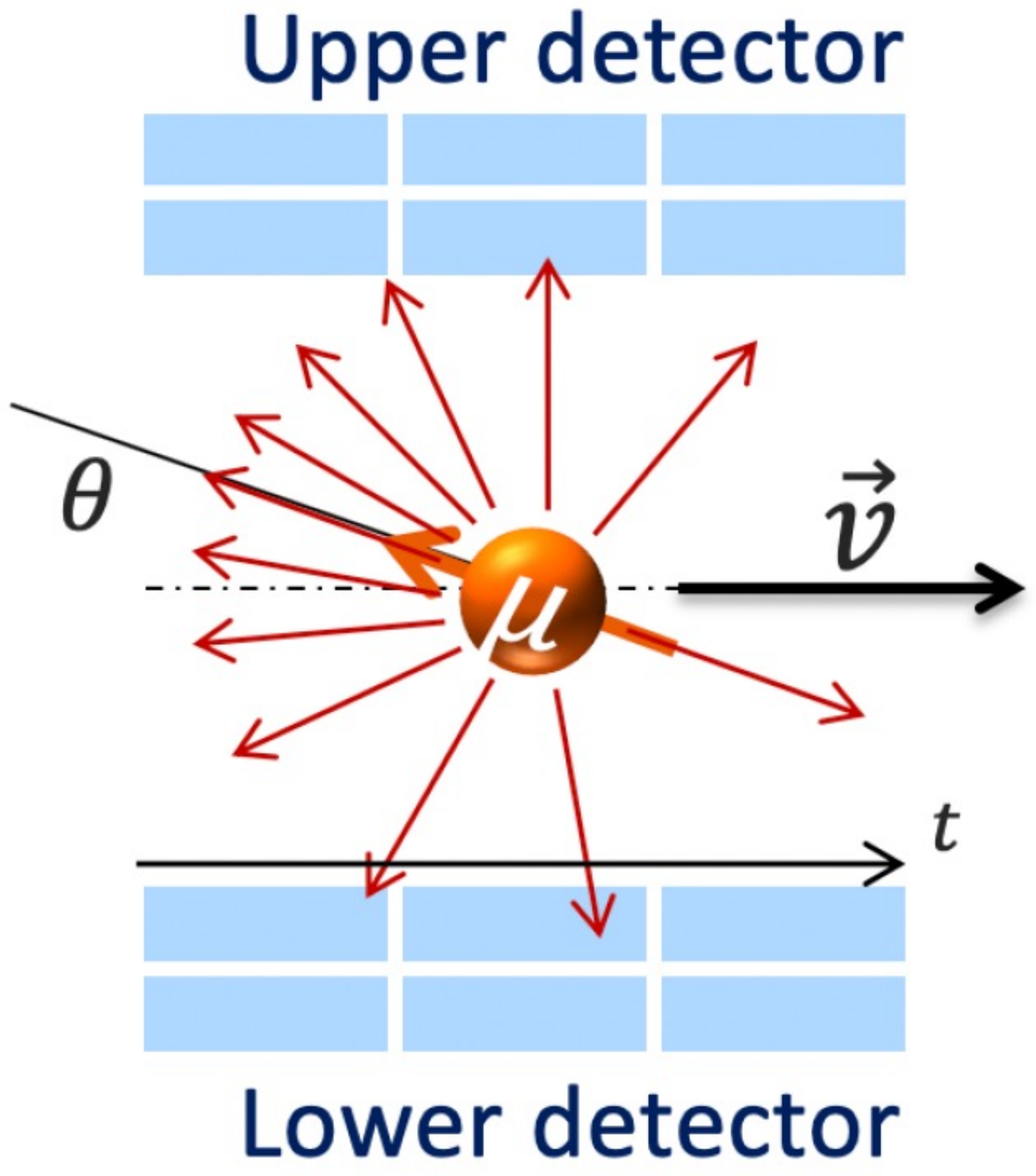


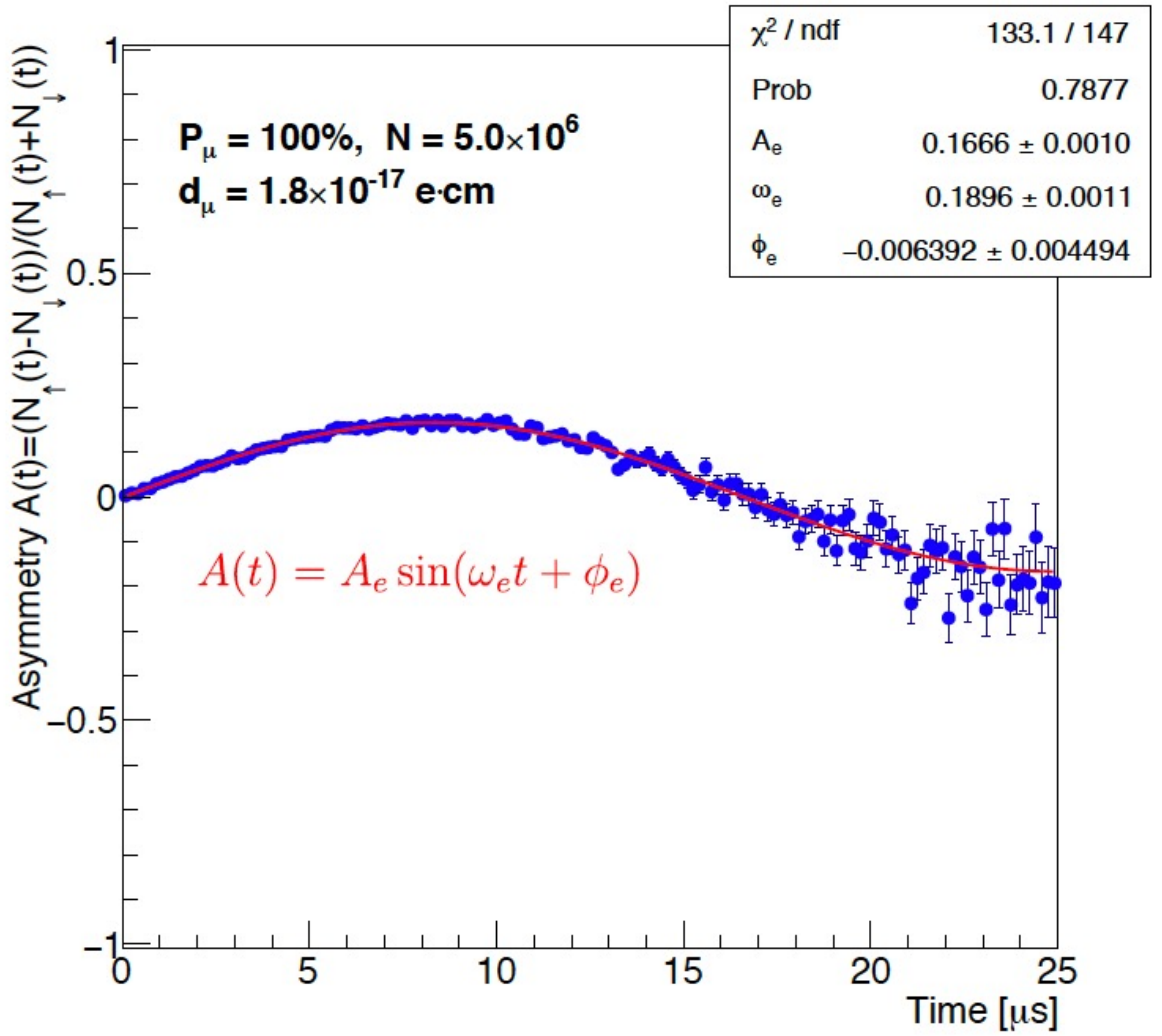




Principle of the FS-EDM measurement

- Up-down asymmetry measured using upper and lower detectors





$$\sigma(d_\mu) = \frac{\hbar\gamma^2 a_\mu}{2PE_f\sqrt{N}\,\gamma\tau_\mu\,\alpha}$$

P := initial polarization

E_f := Electric field in lab

$\sqrt{N}$:= number of positrons

τ_μ := lifetime of muon

α := mean decay asymmetry

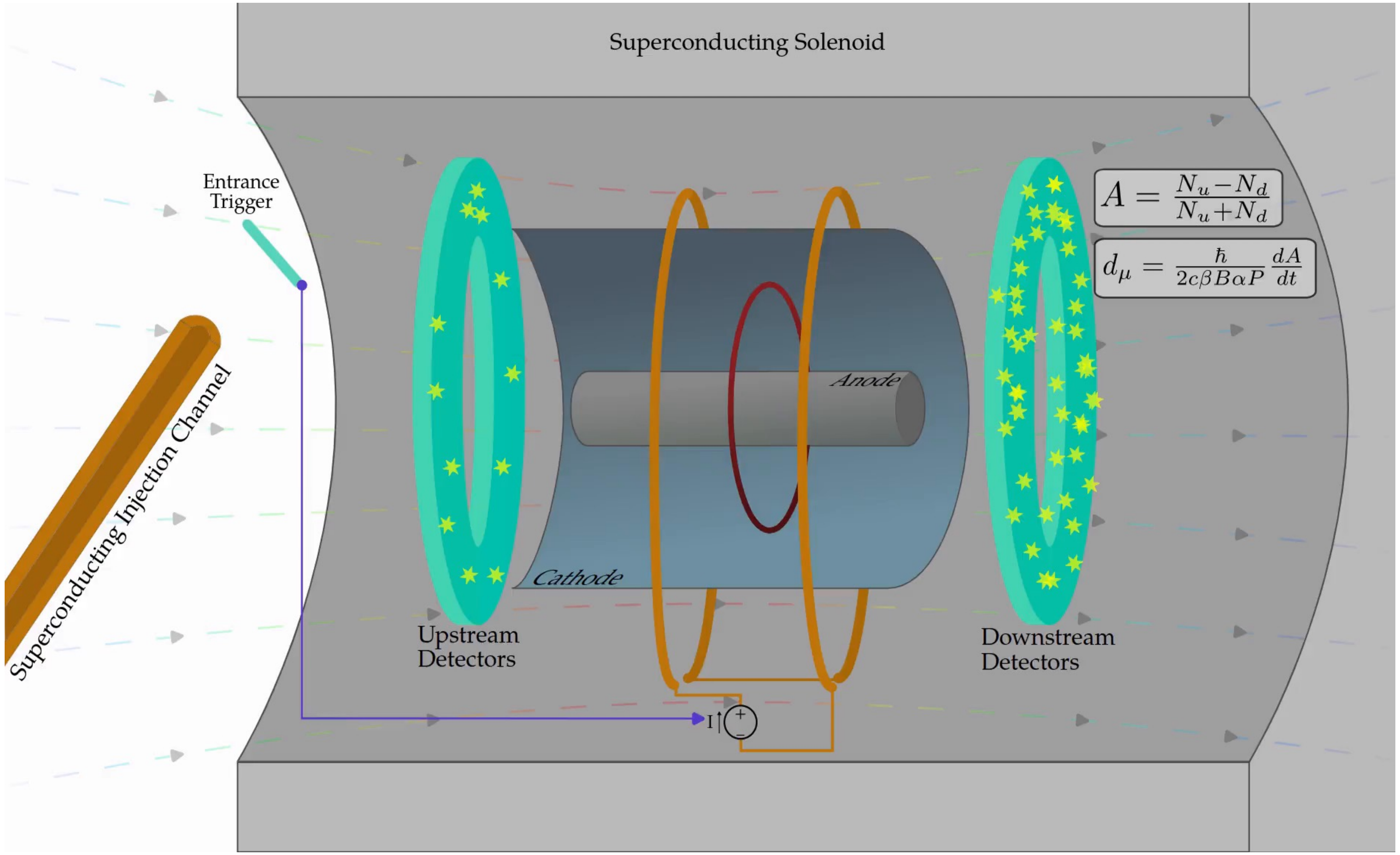
The PSI muEDM collaboration

李政道研究所
Tsung-Dao Lee Institute

~ 30 active members from 6 countries

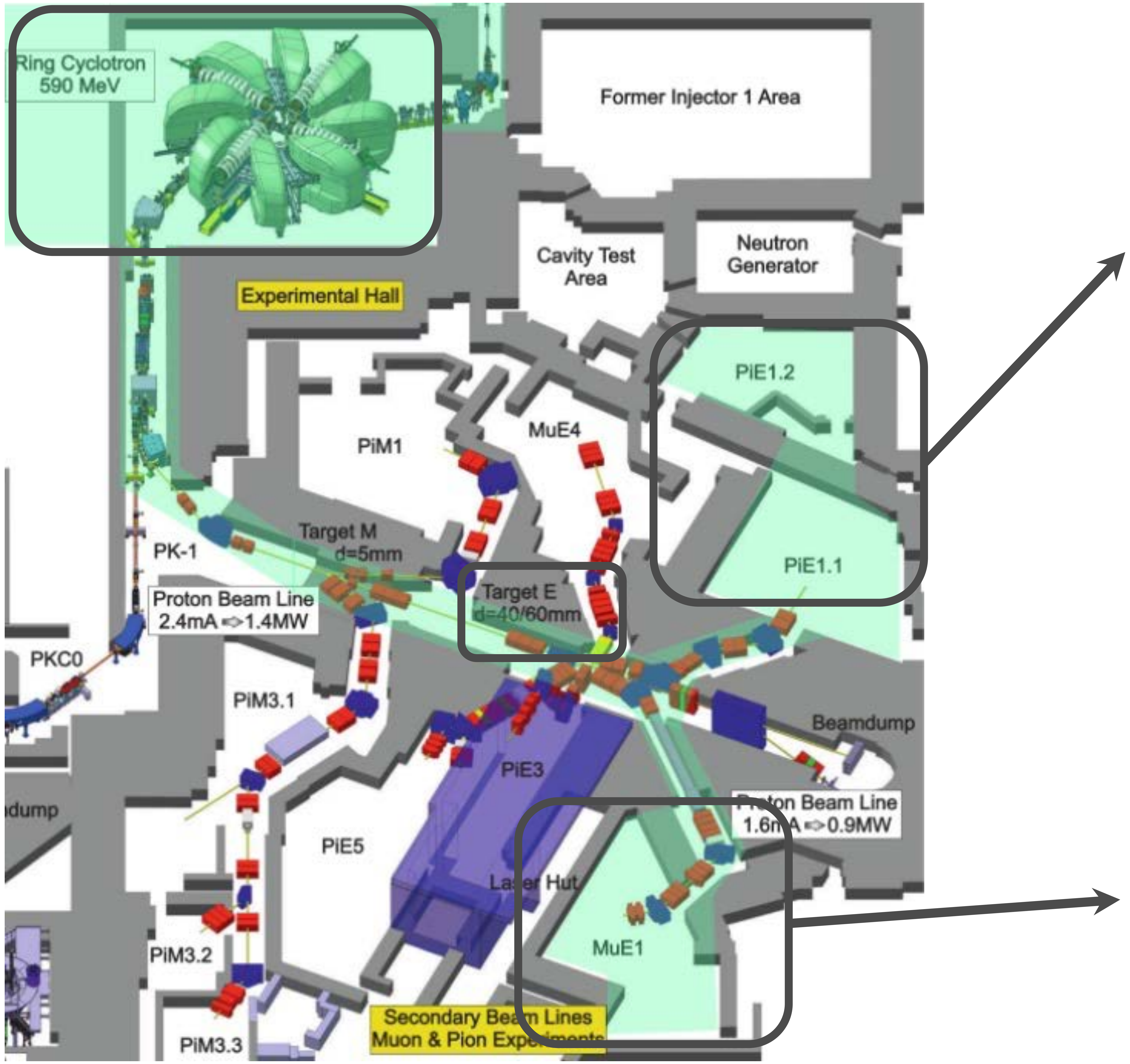
CERN
u^b Universität Bern
tu technische universität dortmund
The Cockcroft Institute of Accelerator Science and Technology
University of Liverpool
UCL
Johannes Gutenberg Universität Mainz JG|U
Manchester 1824 The University of Manchester
Universidad Nacional Autónoma de México
Technical University of Munich TUM
INFN
Università di Pisa
Sapienza Università di Roma
李政道研究所 Tsung-Dao Lee Institute
PSI
ETH zürich
Universität Zürich UZH

Principle of the FS-EDM measurement



- Muon enters the solenoid through a SC injection channel
- Magnetic pulse kicker stops the muon's longitudinal motion within a weakly focusing field where it is stored
- Radial electric field 'freezes' the spin so that the precession due to the g-2 is cancelled
- Up-down detectors measure the asymmetry of the muon decay

muEDM Phase I and Phase II



Phase 1:

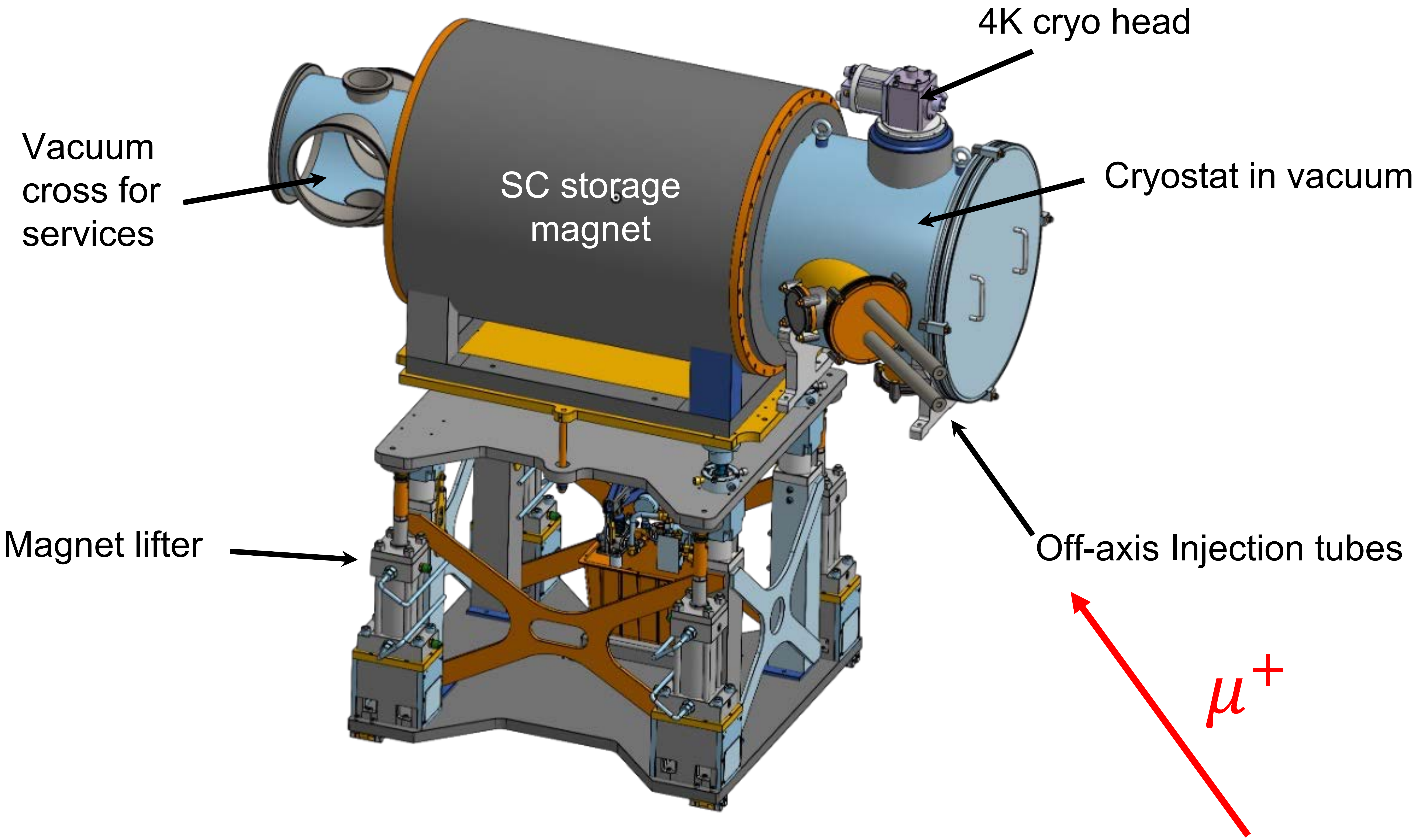
- Negative helicity (95%)
- p=28 MeV/c
- B=3T
- Flux: O(10^6 μ^+/s)
- Storage rate: O(10^2 μ^+/s)
- γ=1.04
- Sensitivity/year < 3×10^{-21} e·cm

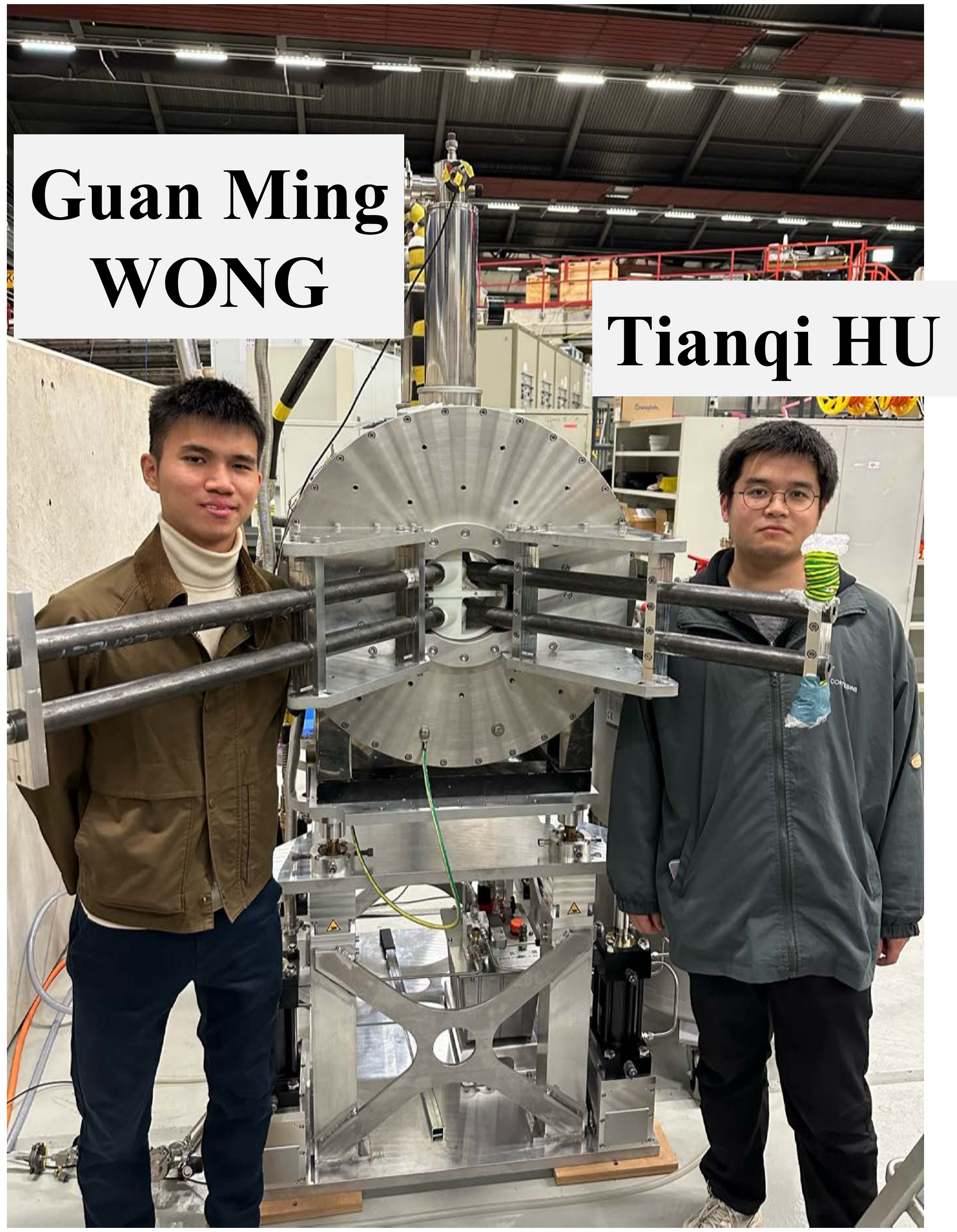
$$\boxed{\sigma_{d_\mu} = \frac{\hbar}{2\,c\,\beta\,B\,\alpha\,P}\,\frac{1}{\gamma\,\tau\,\sqrt{N}}}$$

Phase 2:

- Positive helicity (95%)
- p=125 MeV/c
- B=3T
- Flux: O(10^8 μ^+/s)
- Storage rate: O(100×10^3 μ^+/s)
- γ=1.56
- Sensitivity/year < 6×10^{-23} e·cm

Overview of muEDM Phase I

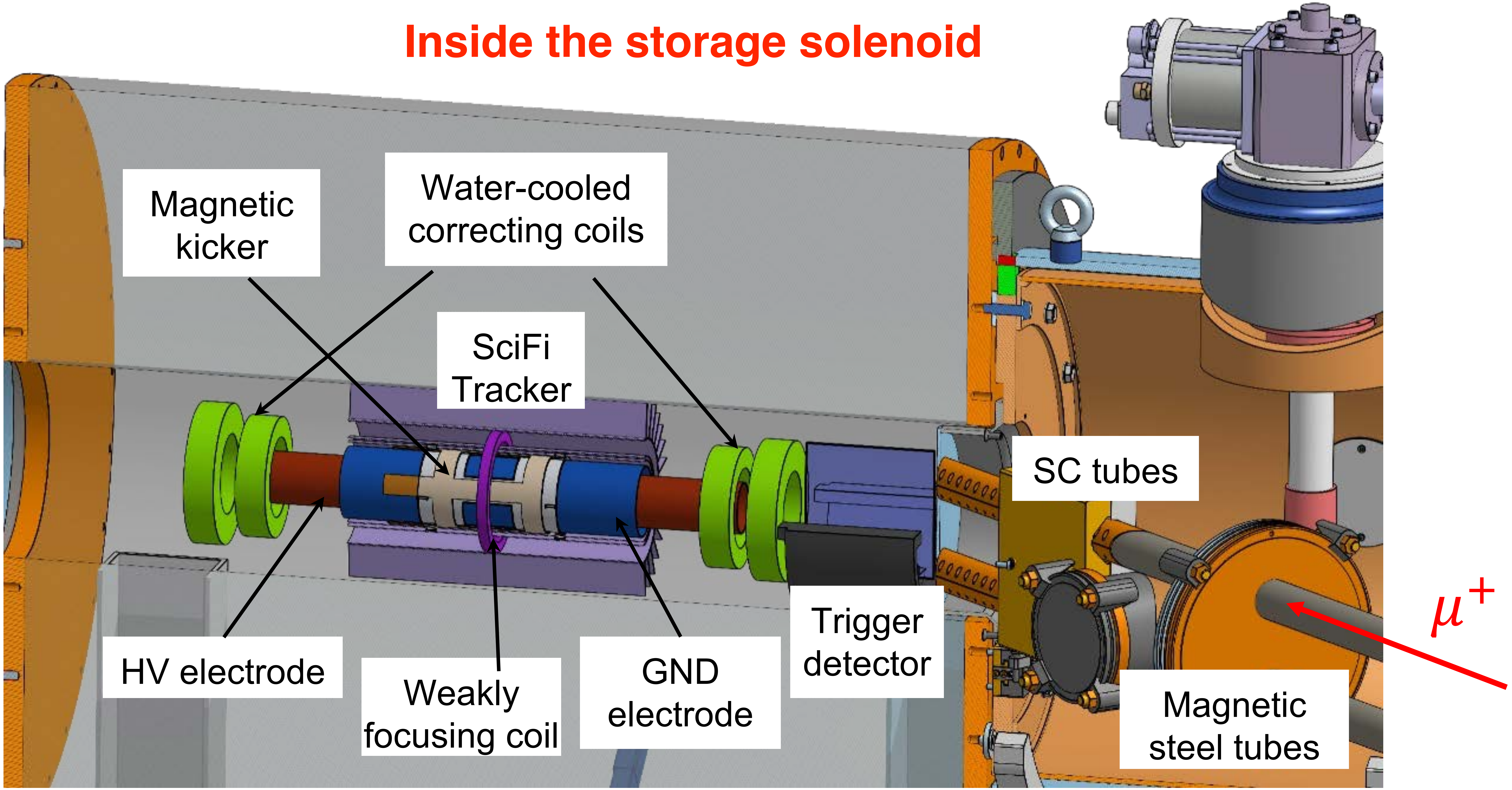




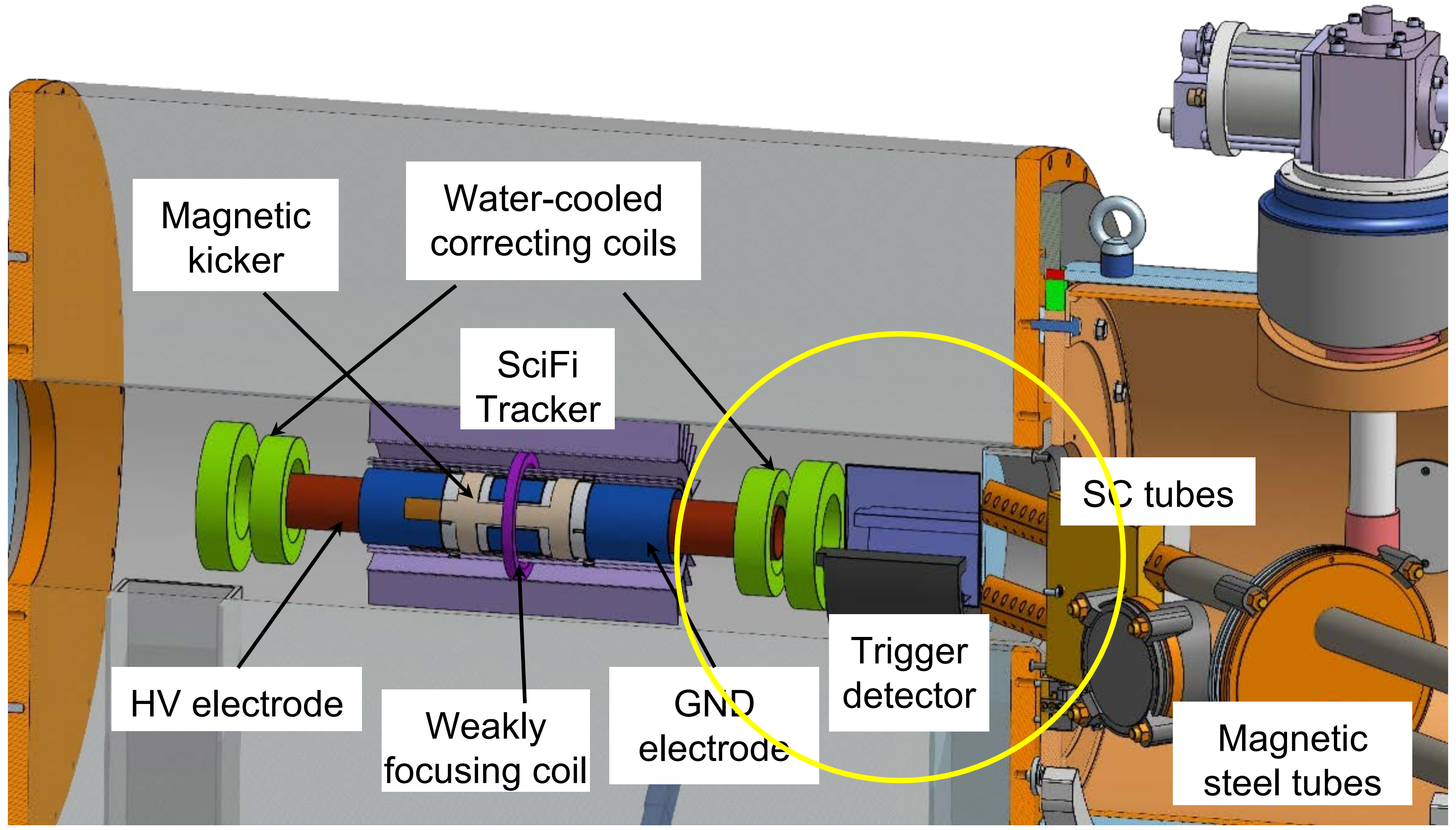
A "tabletop" experiment

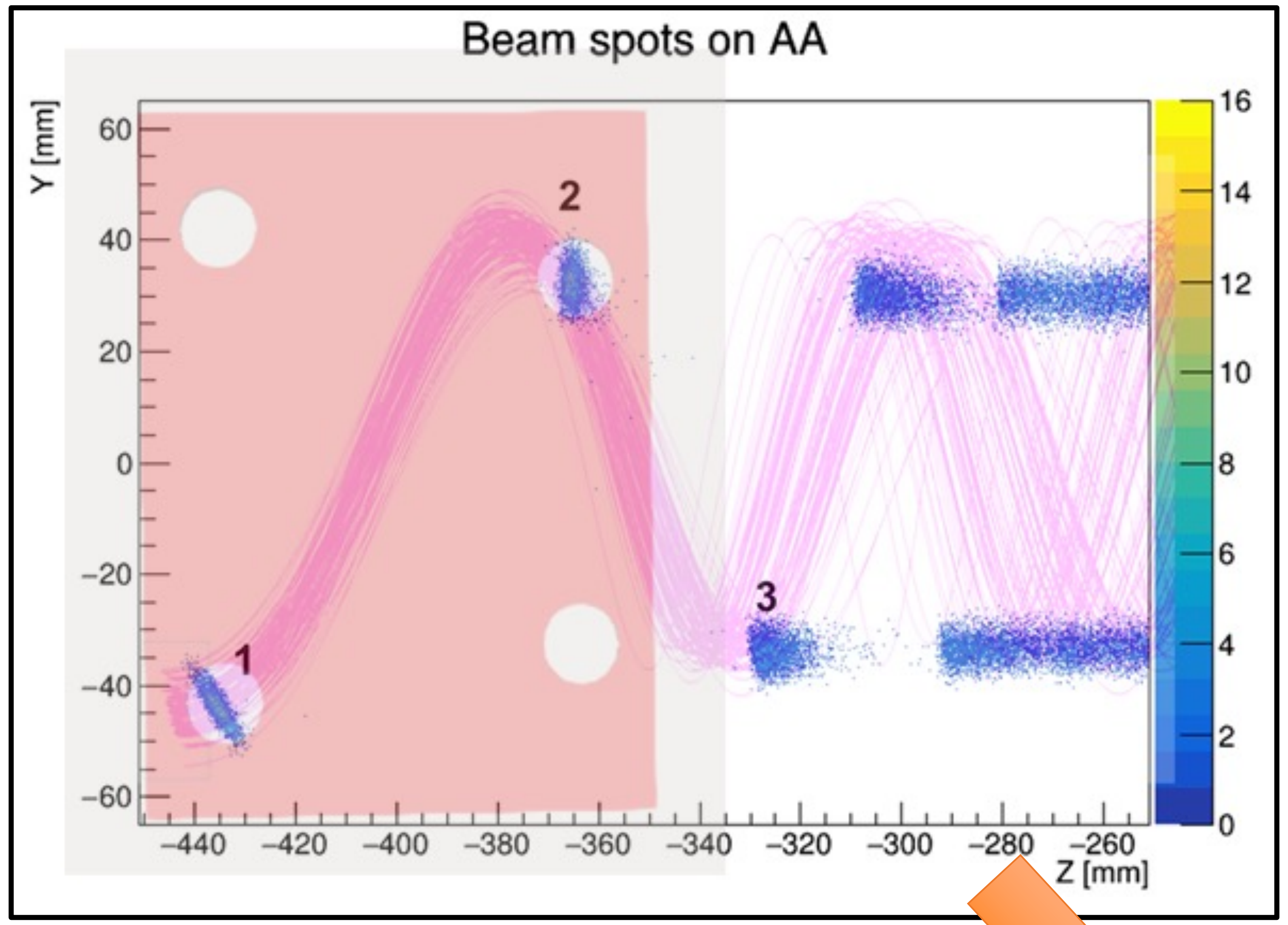
Overview of muEDM Phase I

Inside the storage solenoid

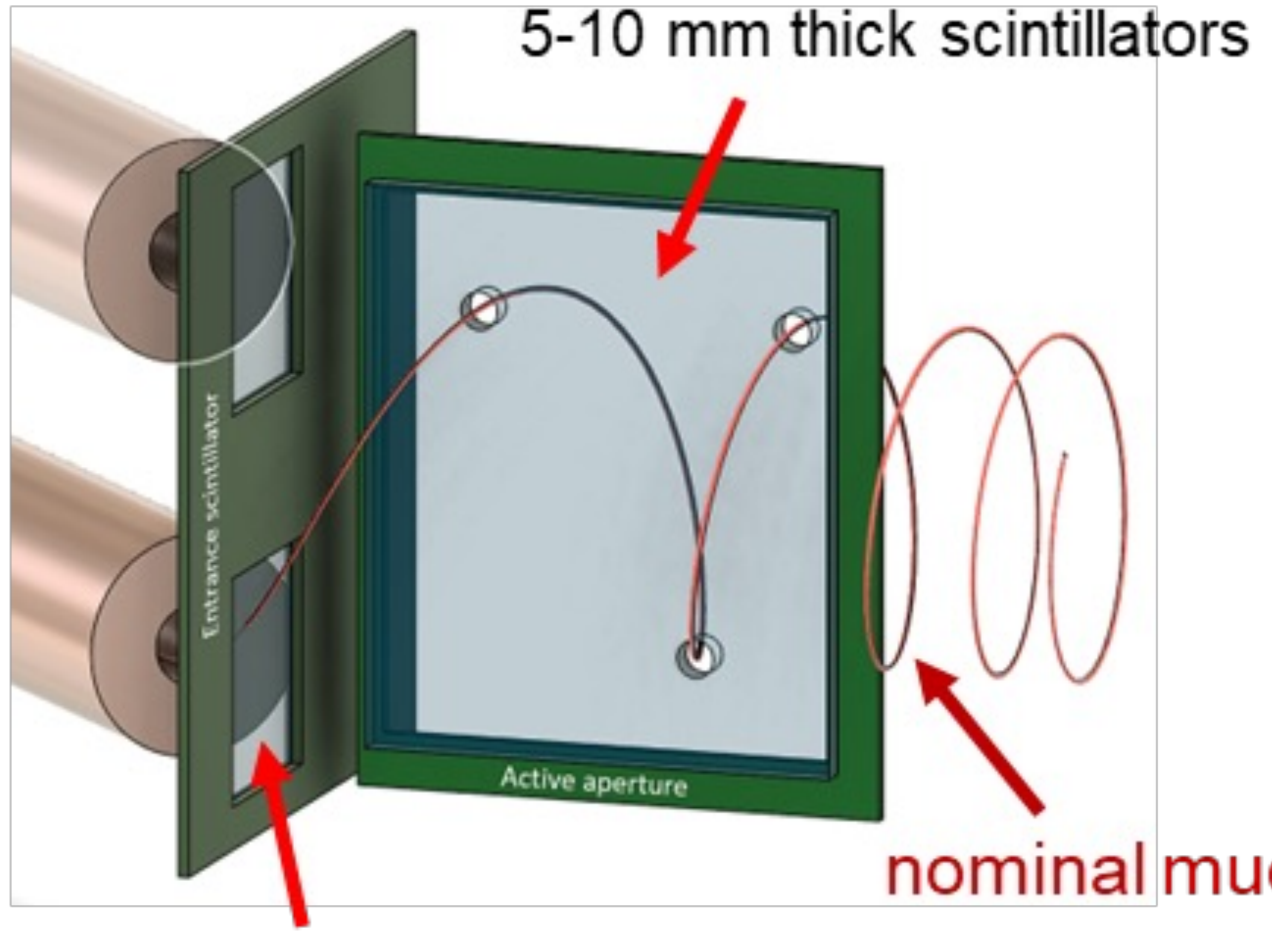


Muon trigger detector



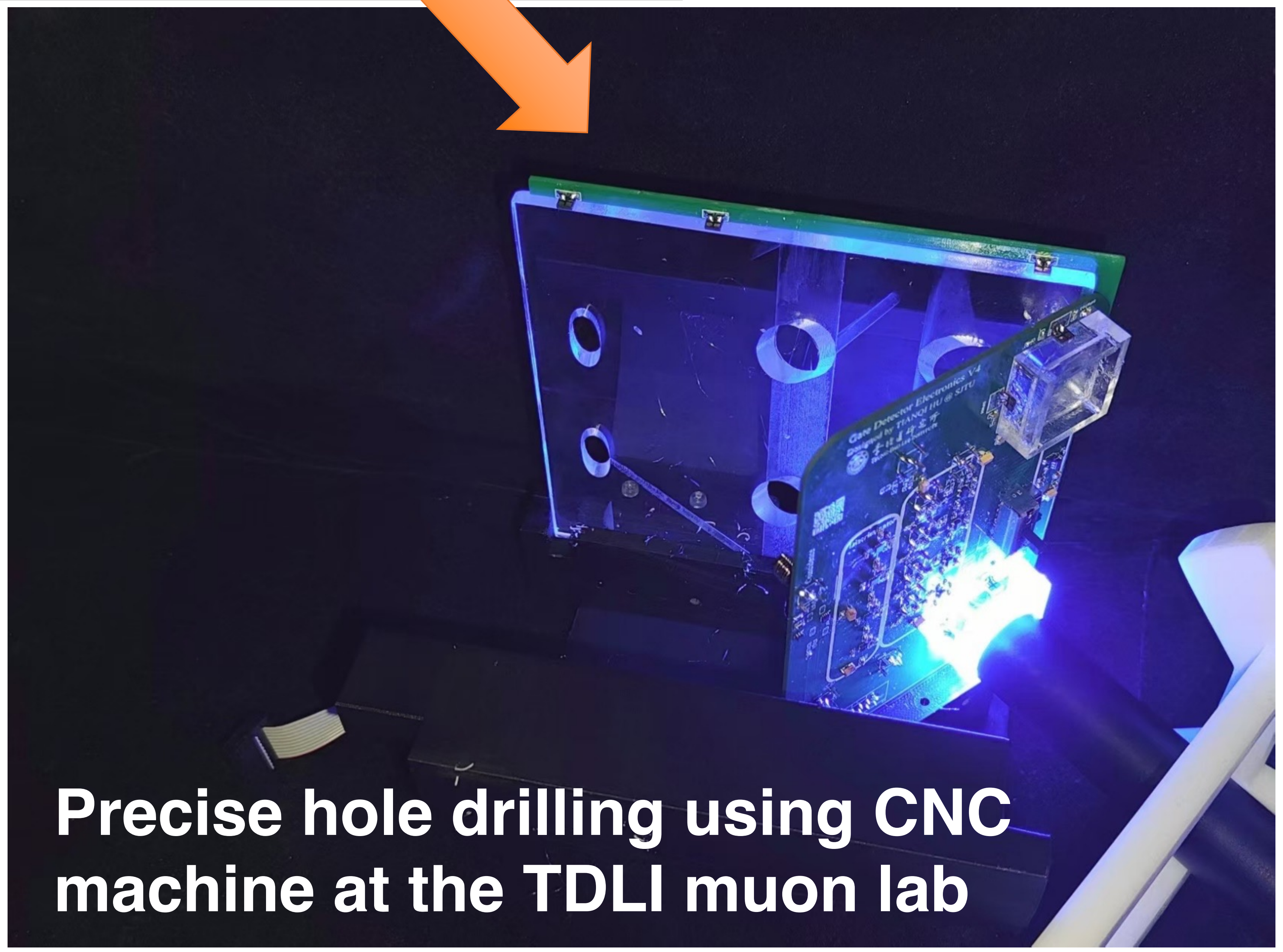


Optimized detector geometry to maximize storage muons

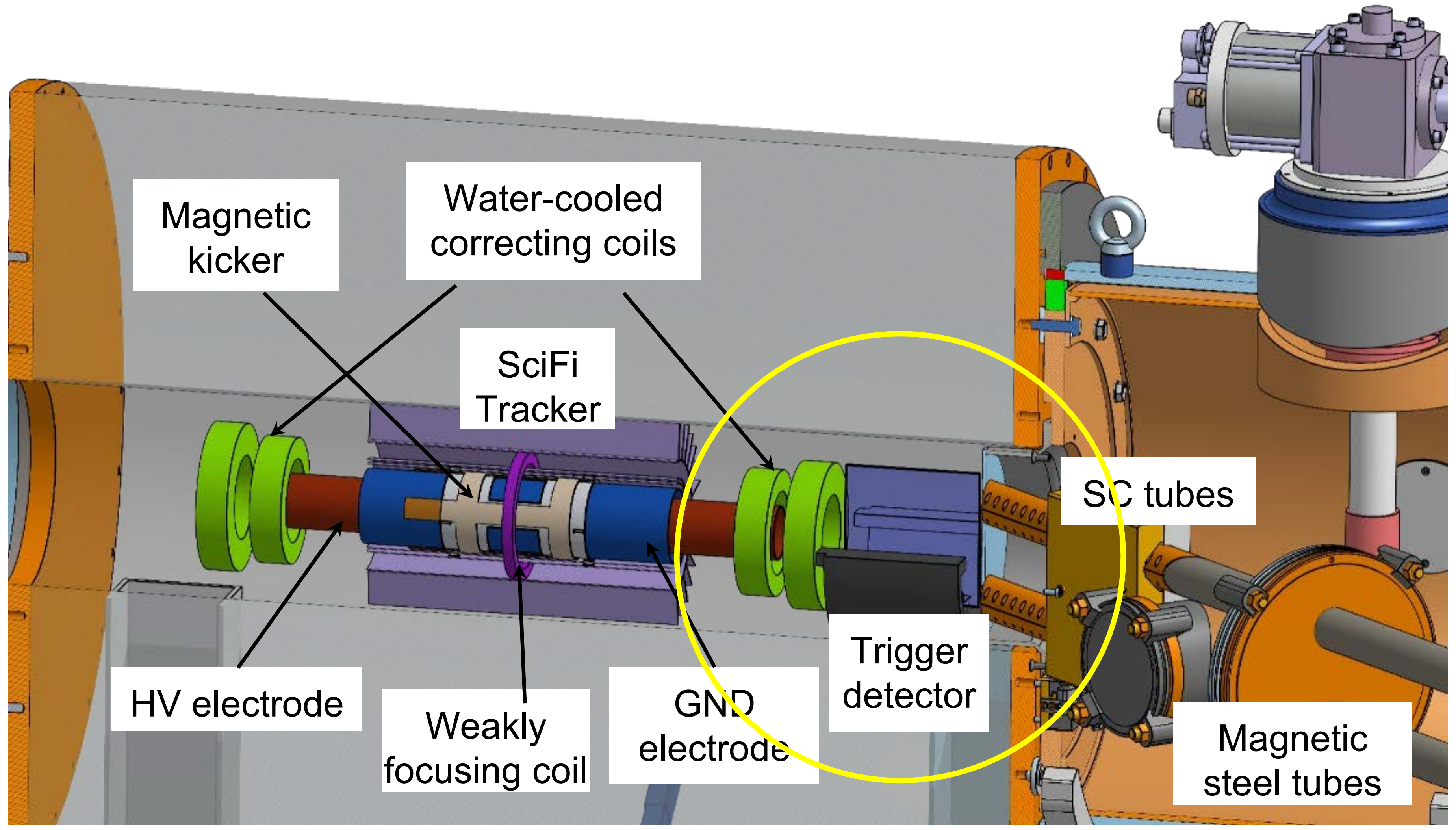


Provides trigger signal of storage pulse kick

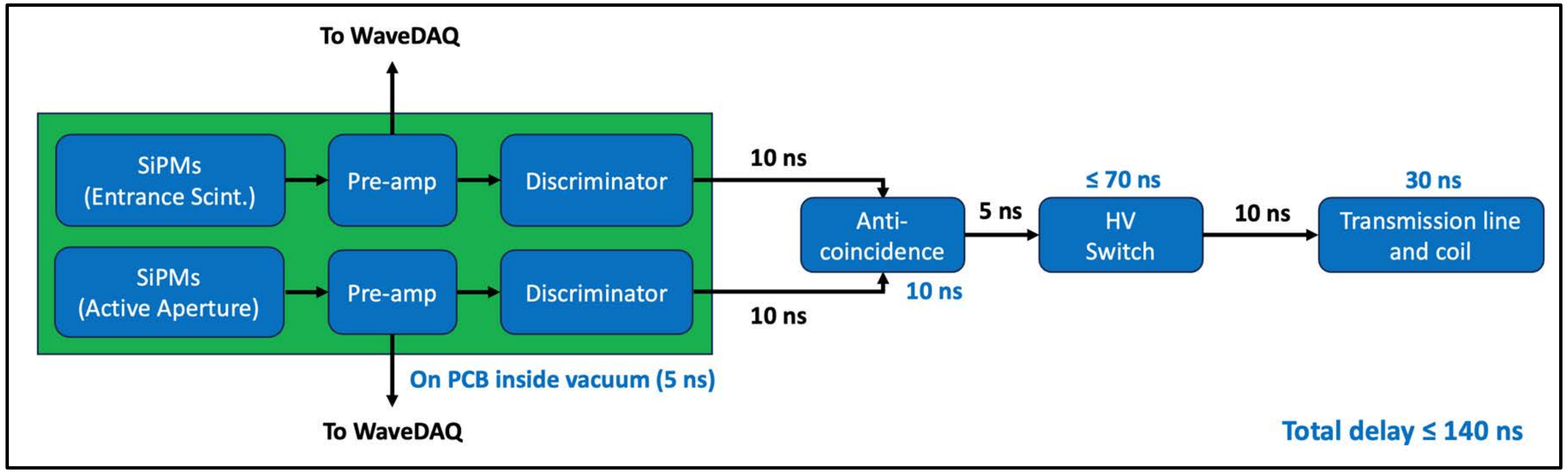
- Fast detector
- Only does so for *storable muons*
- Rejects out-of-acceptance muons

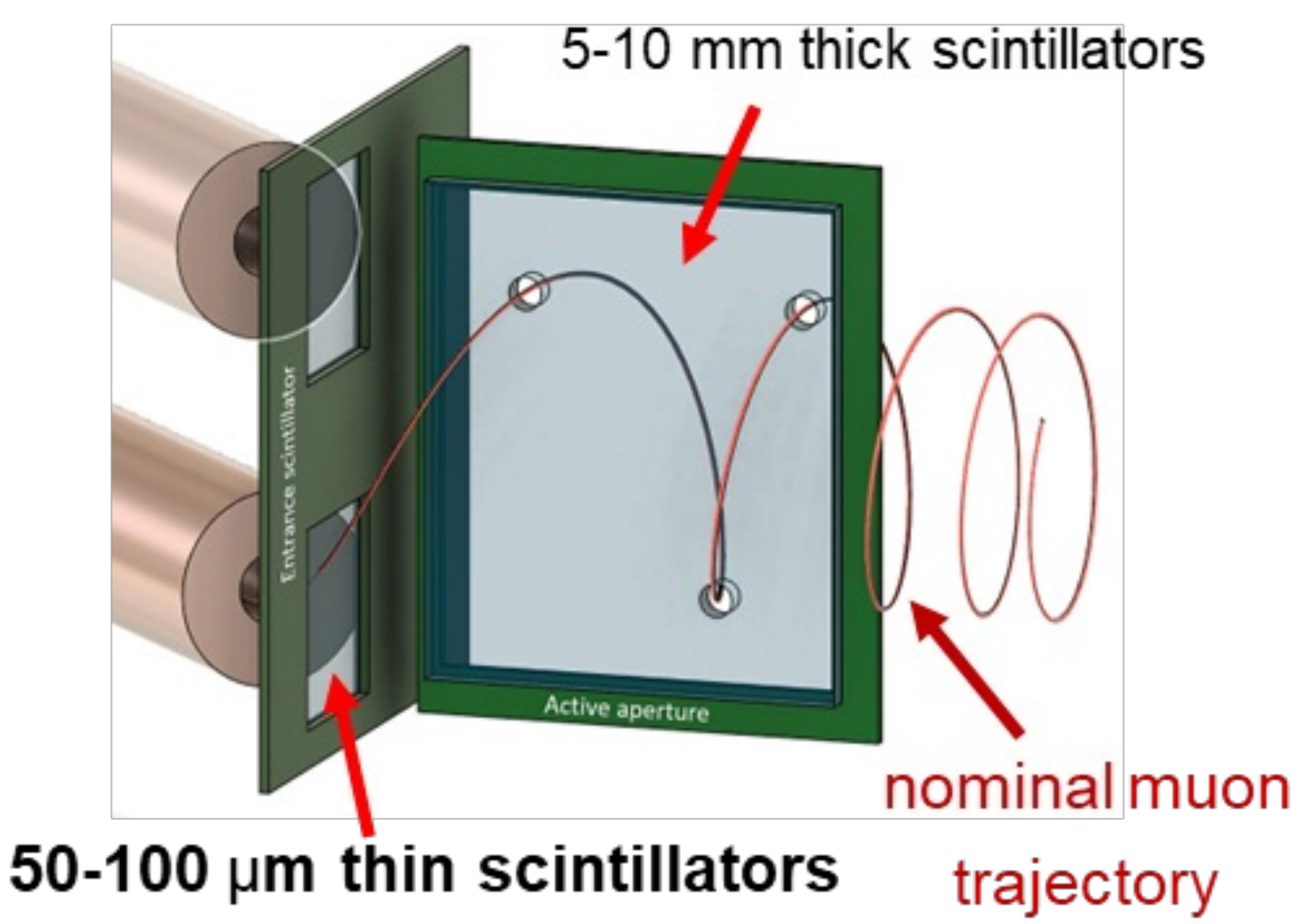


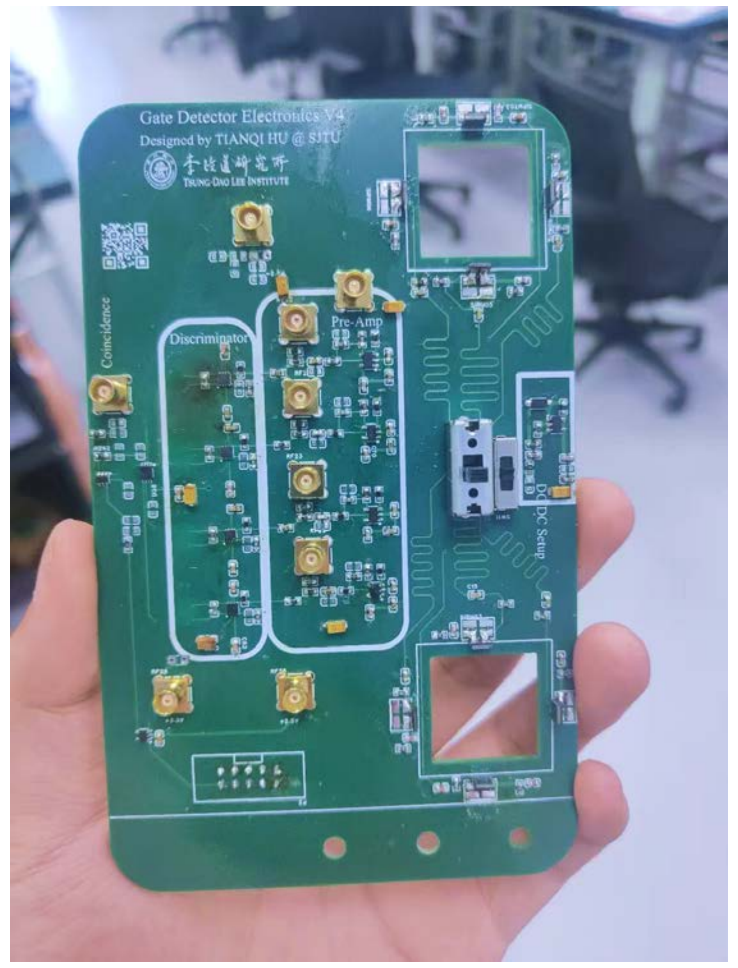
Fast trigger for kicker coils

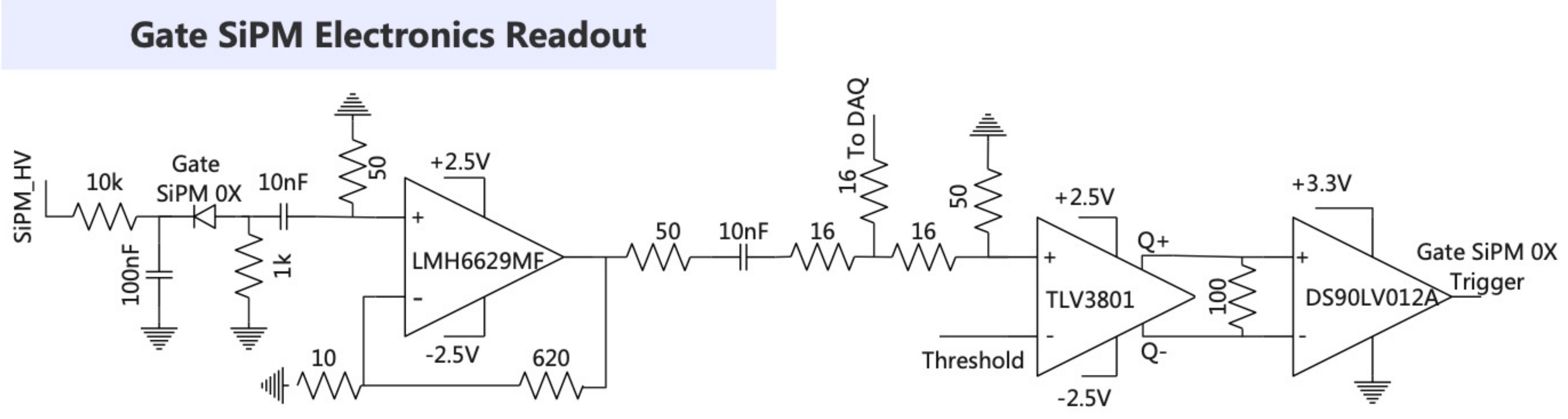


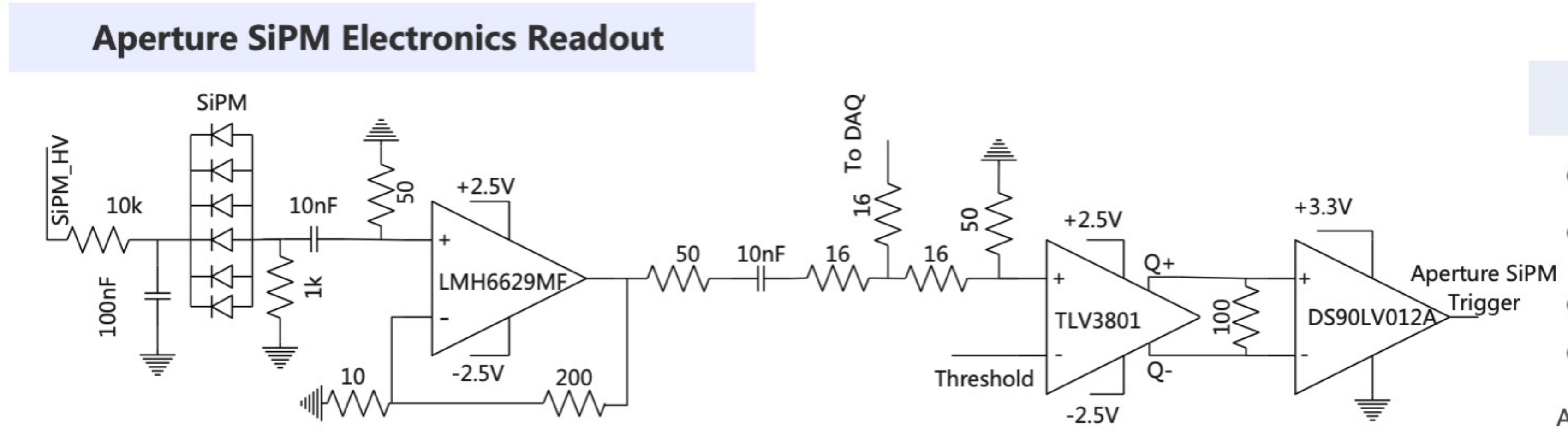
Fast electronics design to satisfy stringent timing requirements

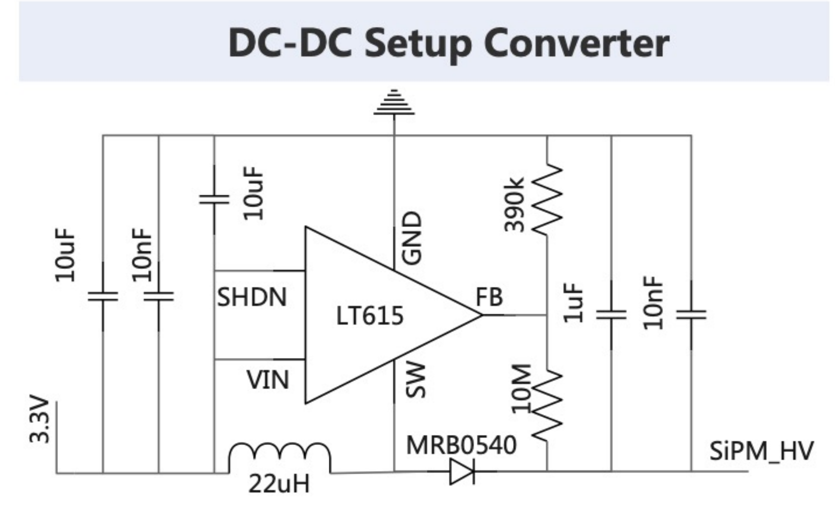


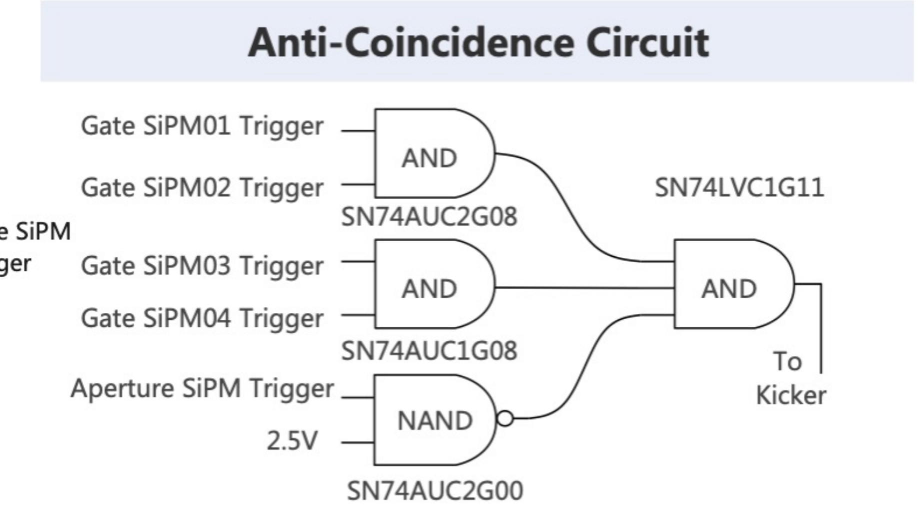




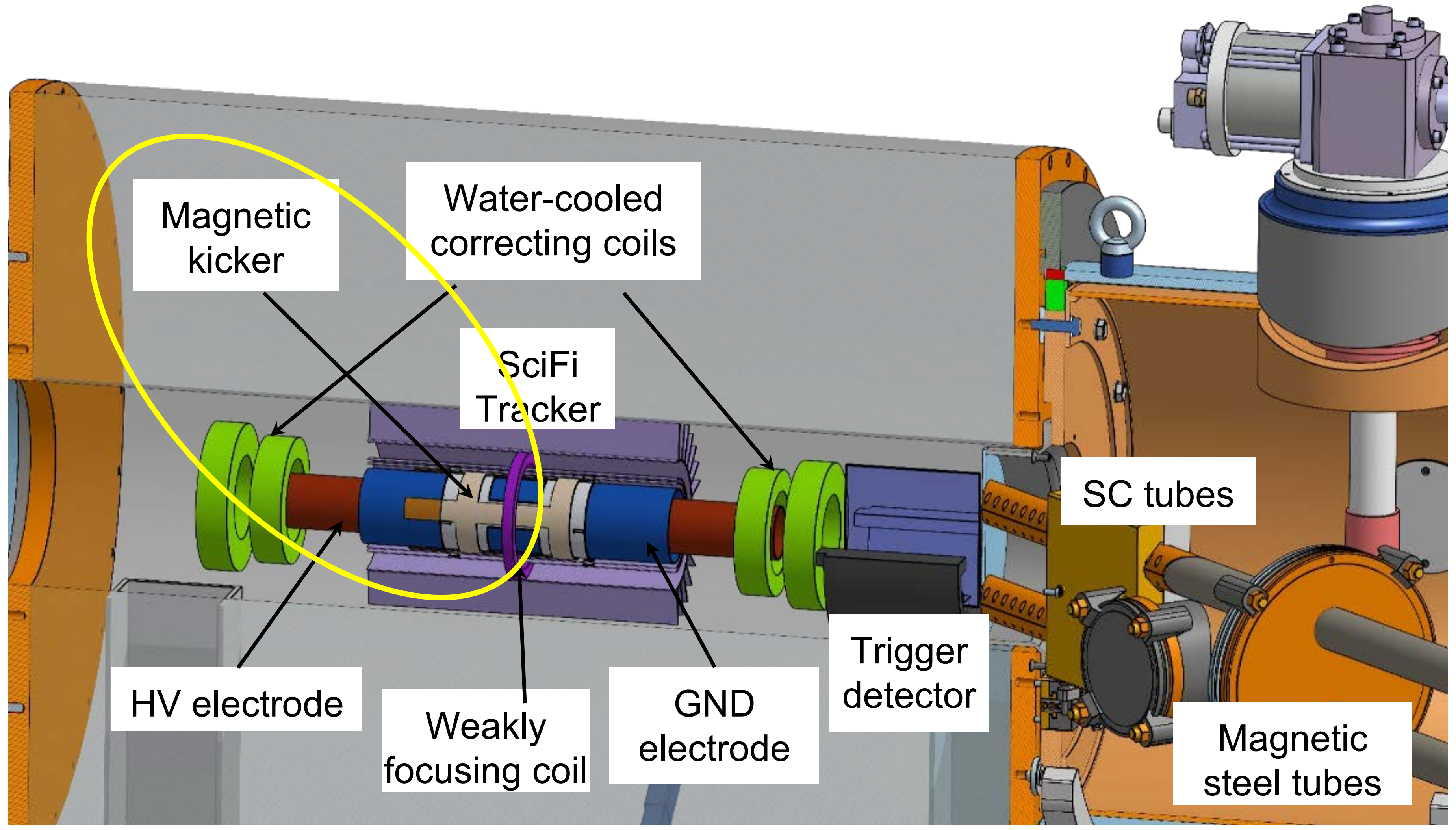




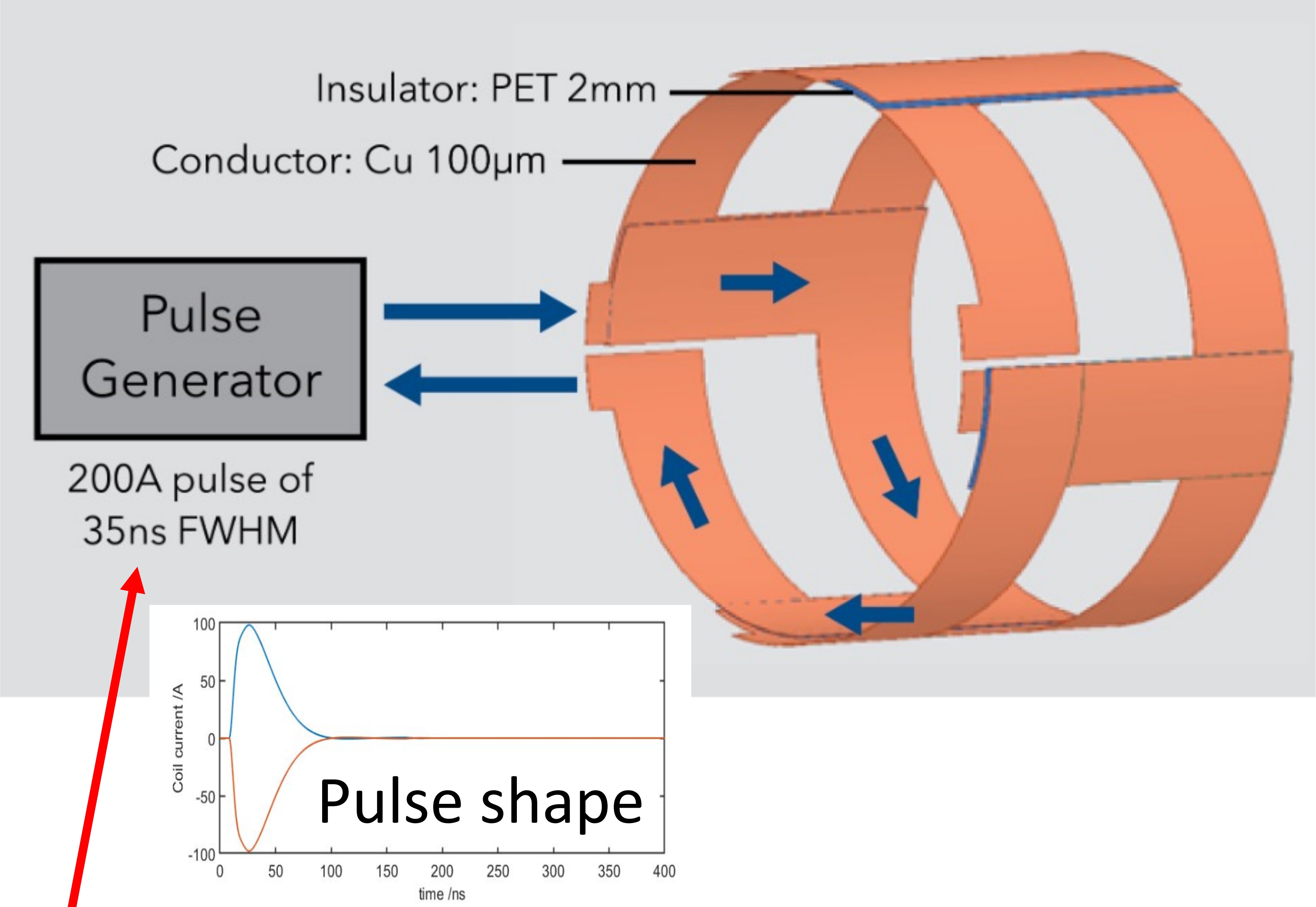


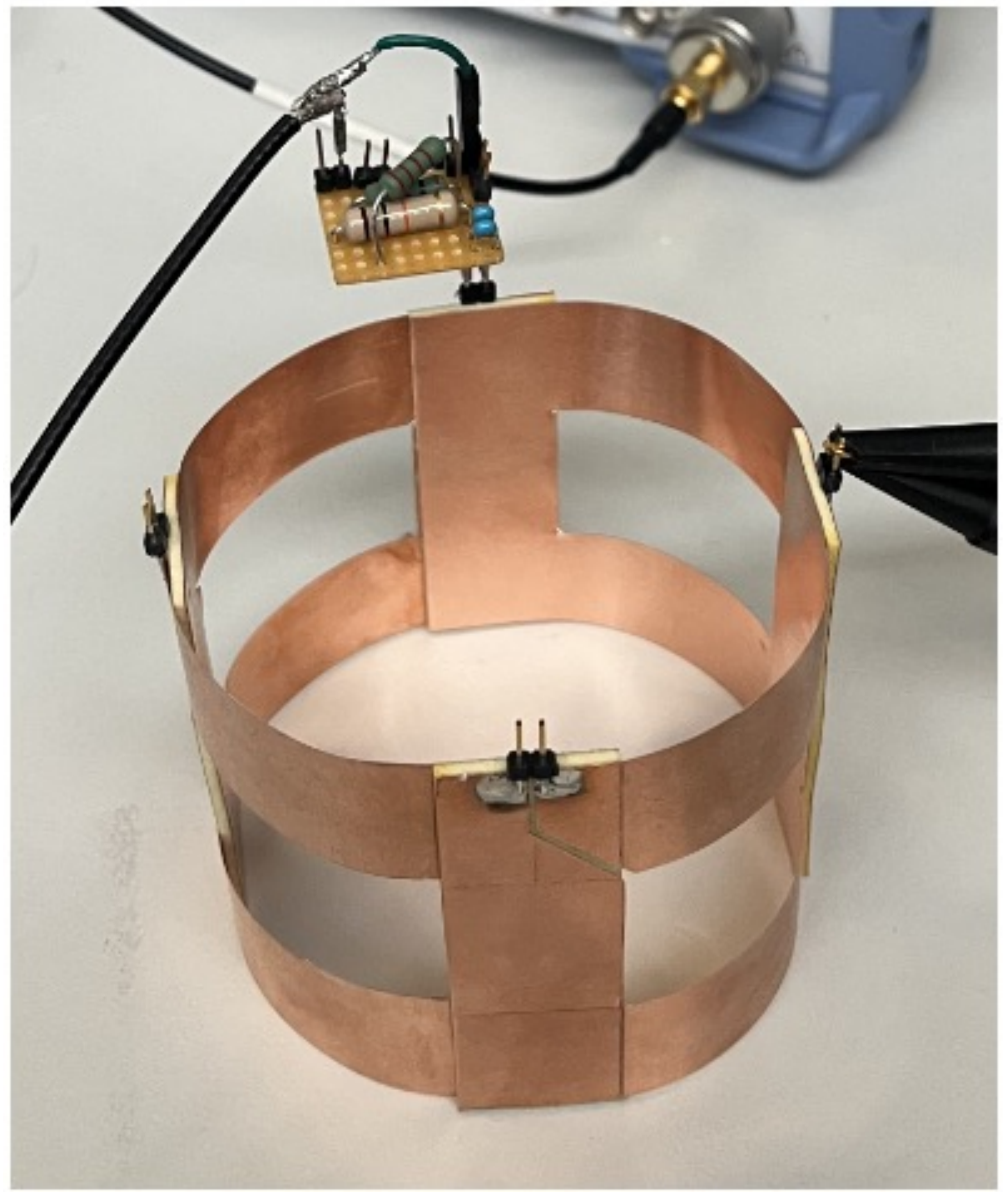


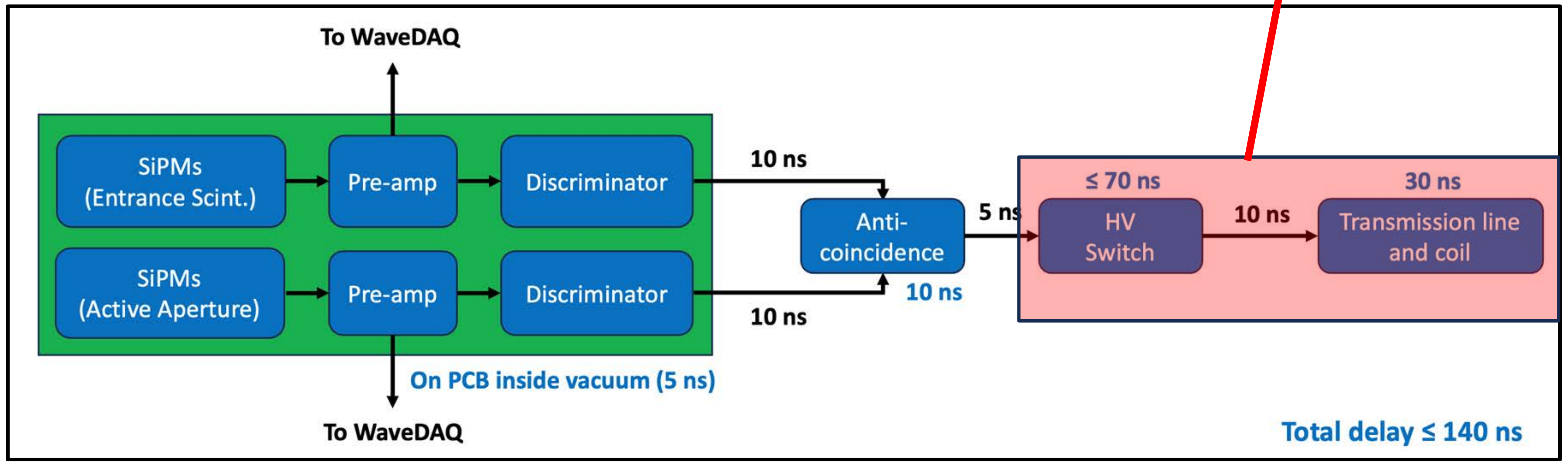
Storage pulse kicker



First prototype





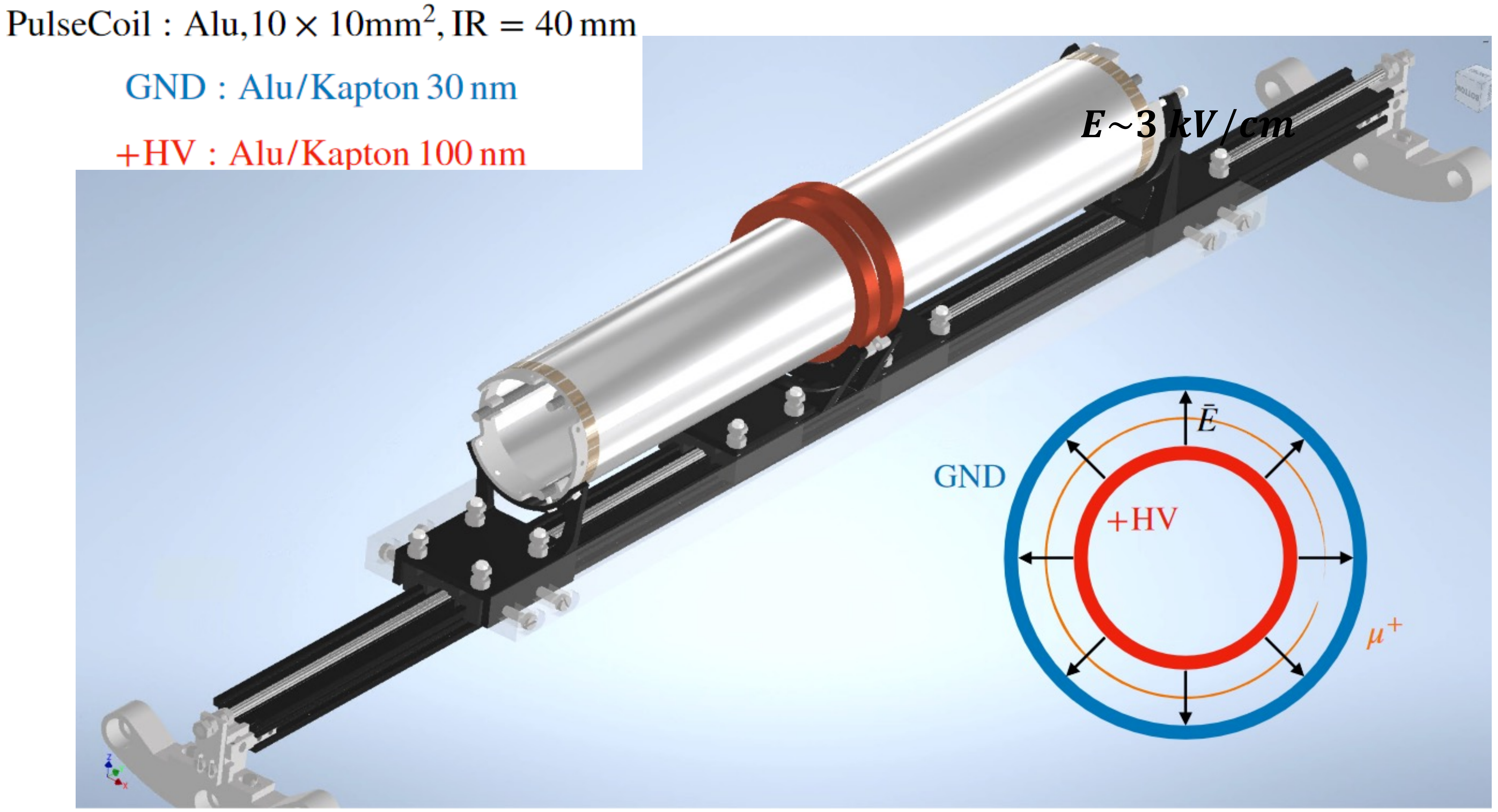


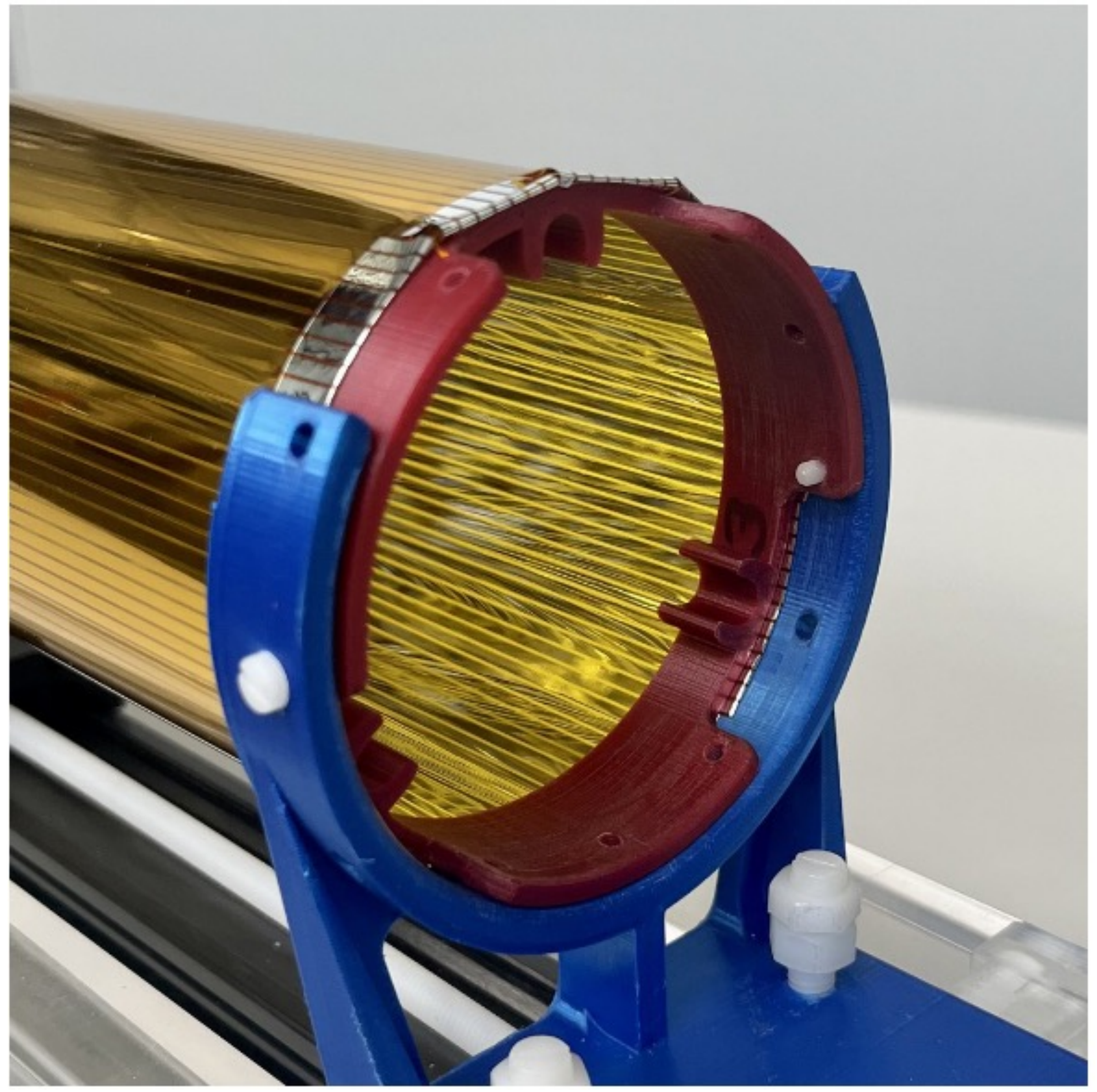
Short trigger delay necessitates internal latency of pulse generator to < *60 ns*

- Coil quadrants generating pulsed longitudinal kick to store muons
- Technical requirements:
  - large amplitude
  - rapid triggering of short-duration pulsed magnetic field, with strong tail suppression

Frozen-spin electrodes

Radial electric field applied by two concentric electrodes enclosing muon orbit





Current solution:

- 25 μm Kapton films
- Strip-segmented ~30 nm Al coating
- 2.2 mm pitch

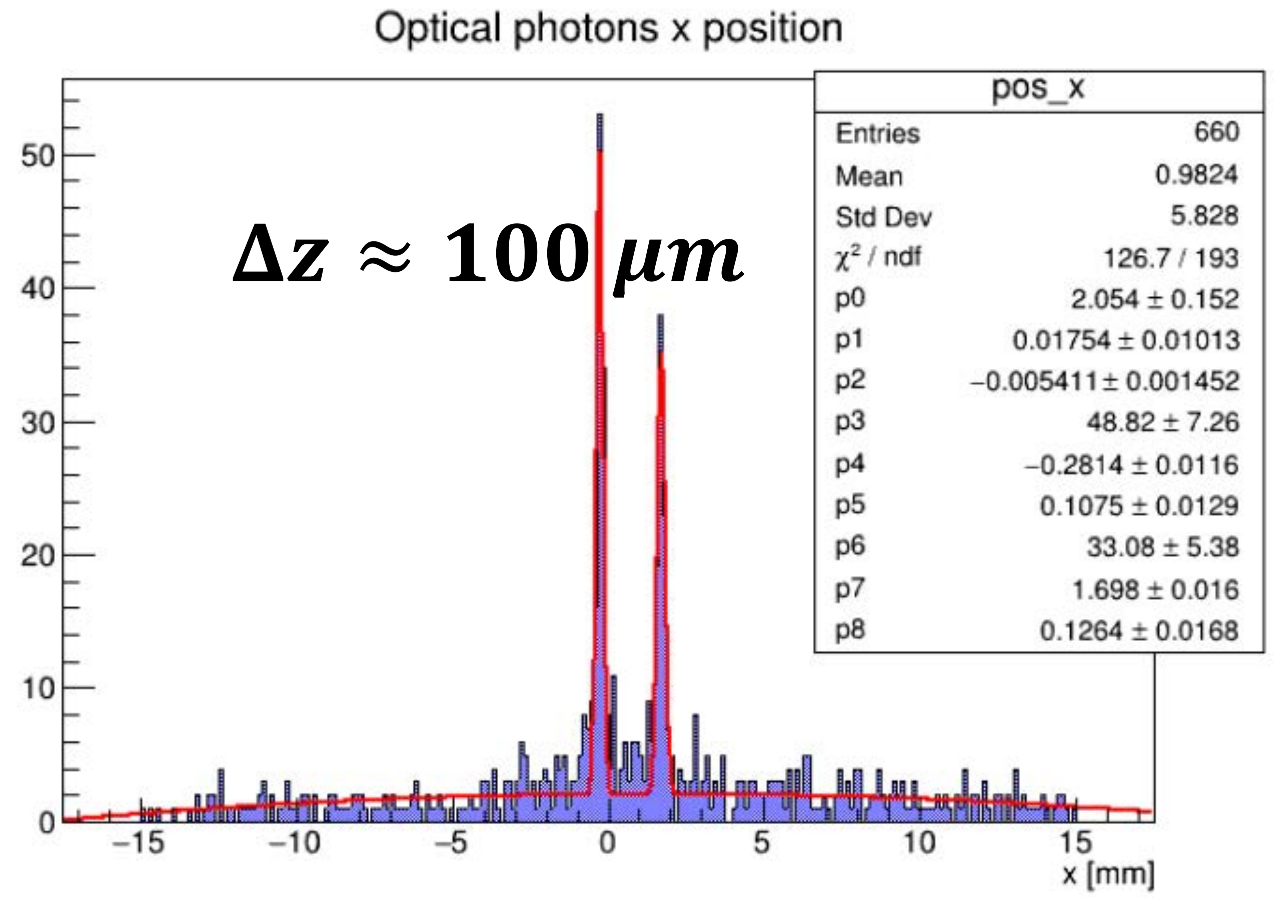
Technical requirements:

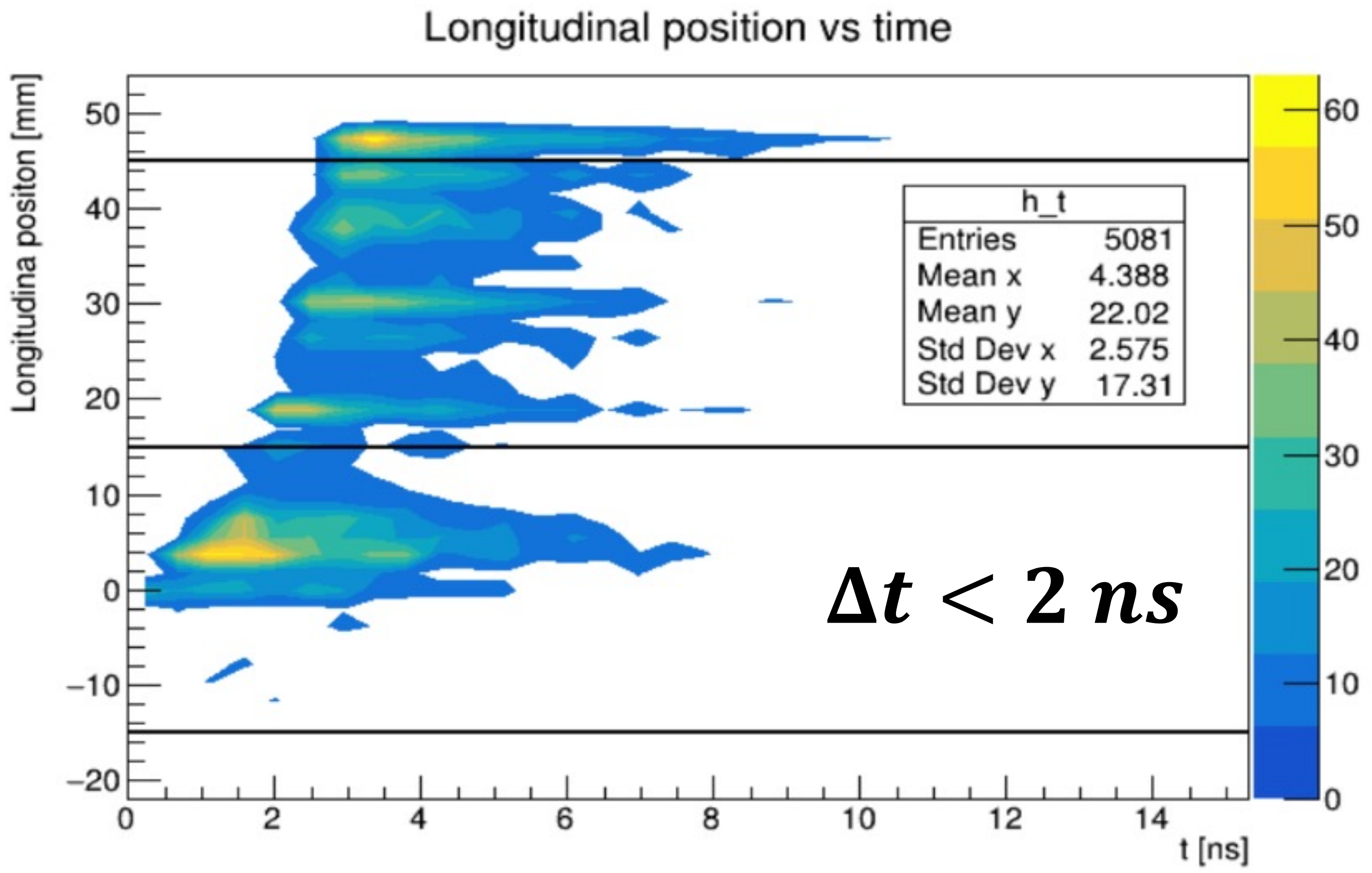
- Precise alignment with muon storage plane
- Heat dissipation
- Minimal multiple scattering for positrons
- Suppress Eddy current

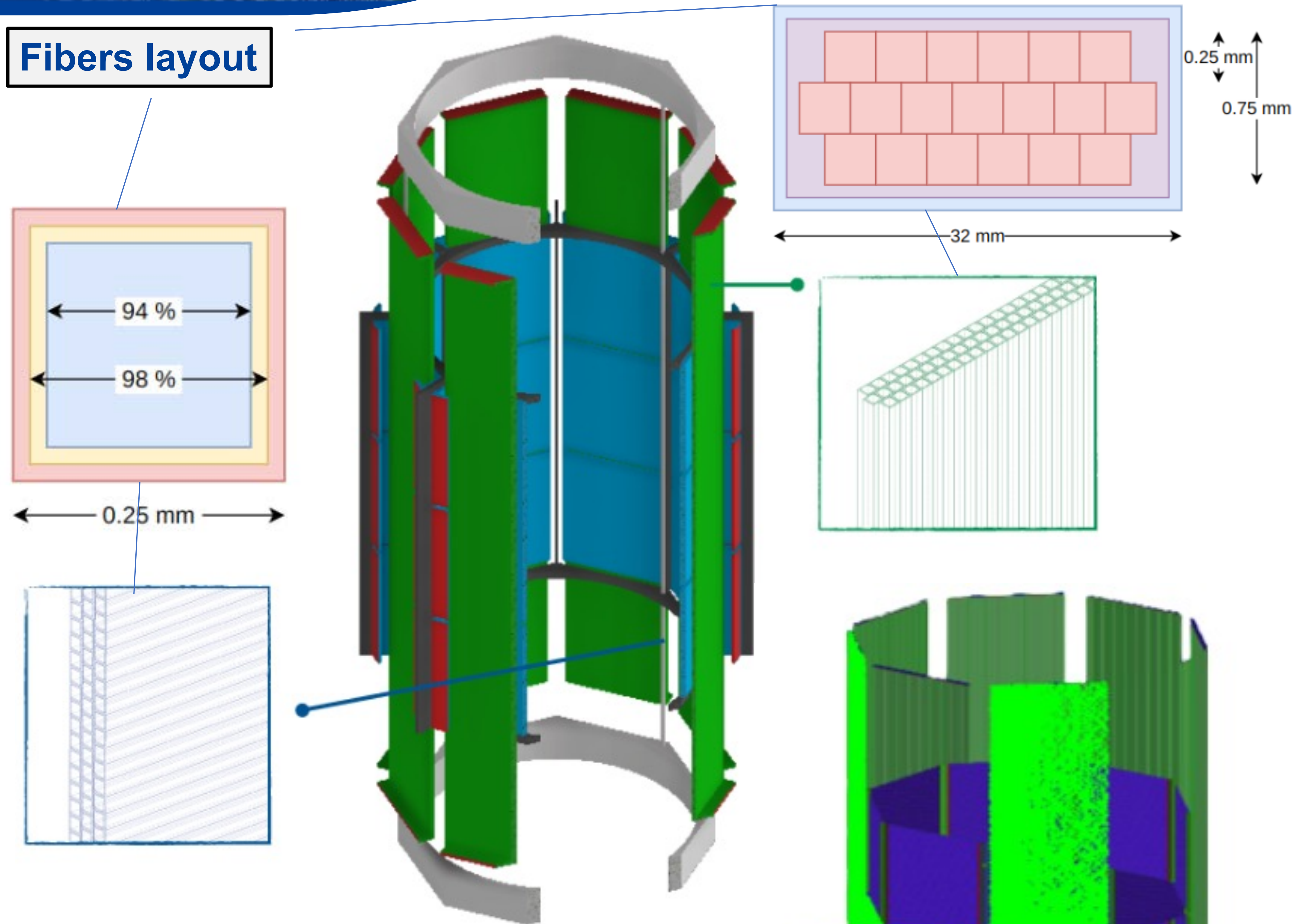
Strip-segmented Alu-Kapton film approach **suppresses Eddy current damping**, without compromising **electric field uniformity**.

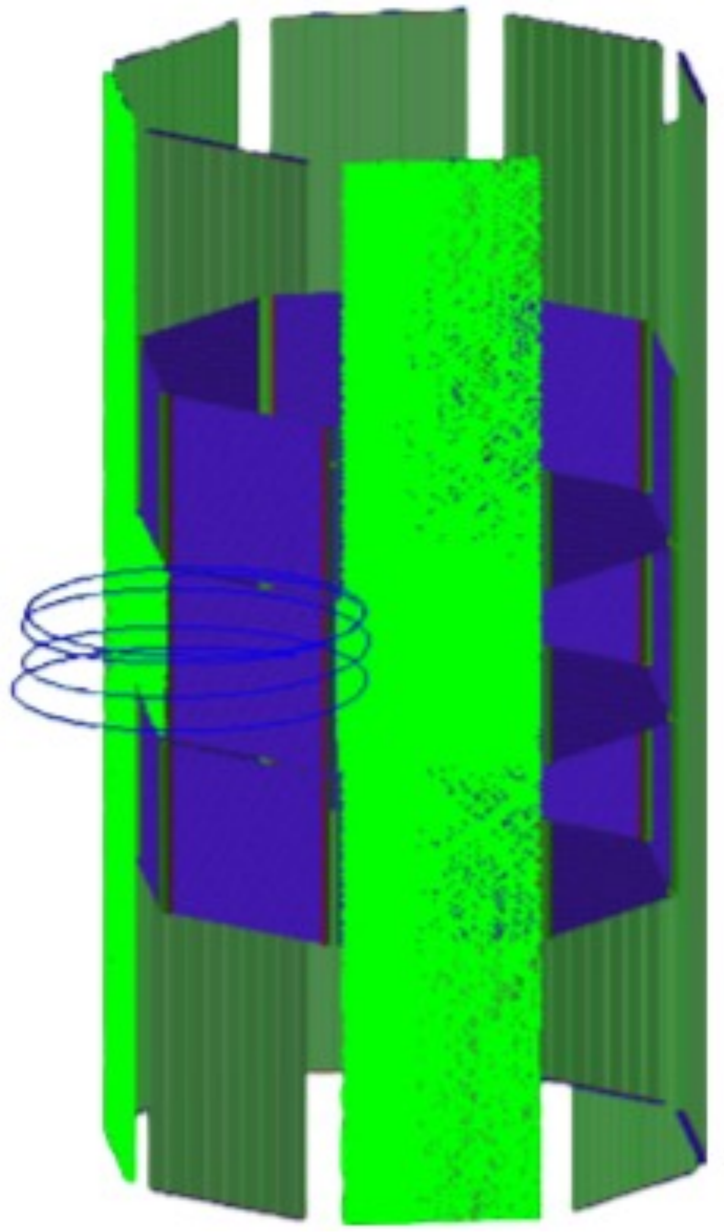
Positron detectors for EDM signal

- Double barrel SciFi tracker
- Measures longitudinal asymmetry of positron
- Bundles of fibers with good timing and position resolutions
  - transverse and longitudinal fibers







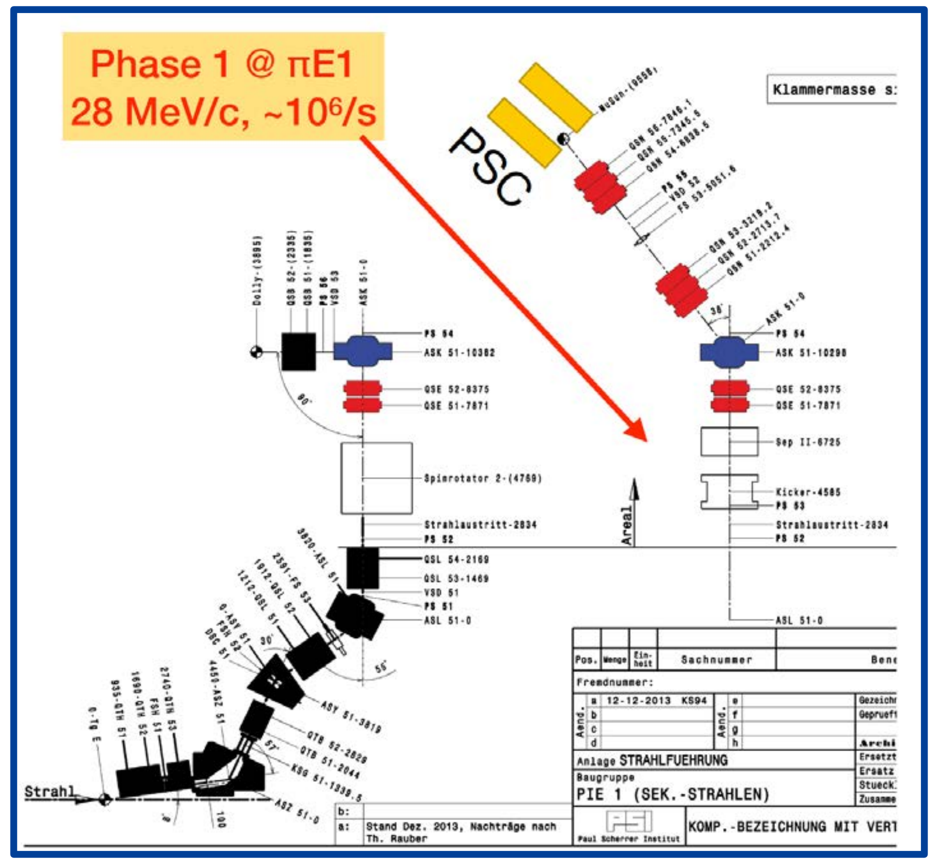


- Photon time and position (longitudinal info on internal barrel)
- Large number of readout channel a challenge
- Considering other possible geometries

Annual beam tests at PSI

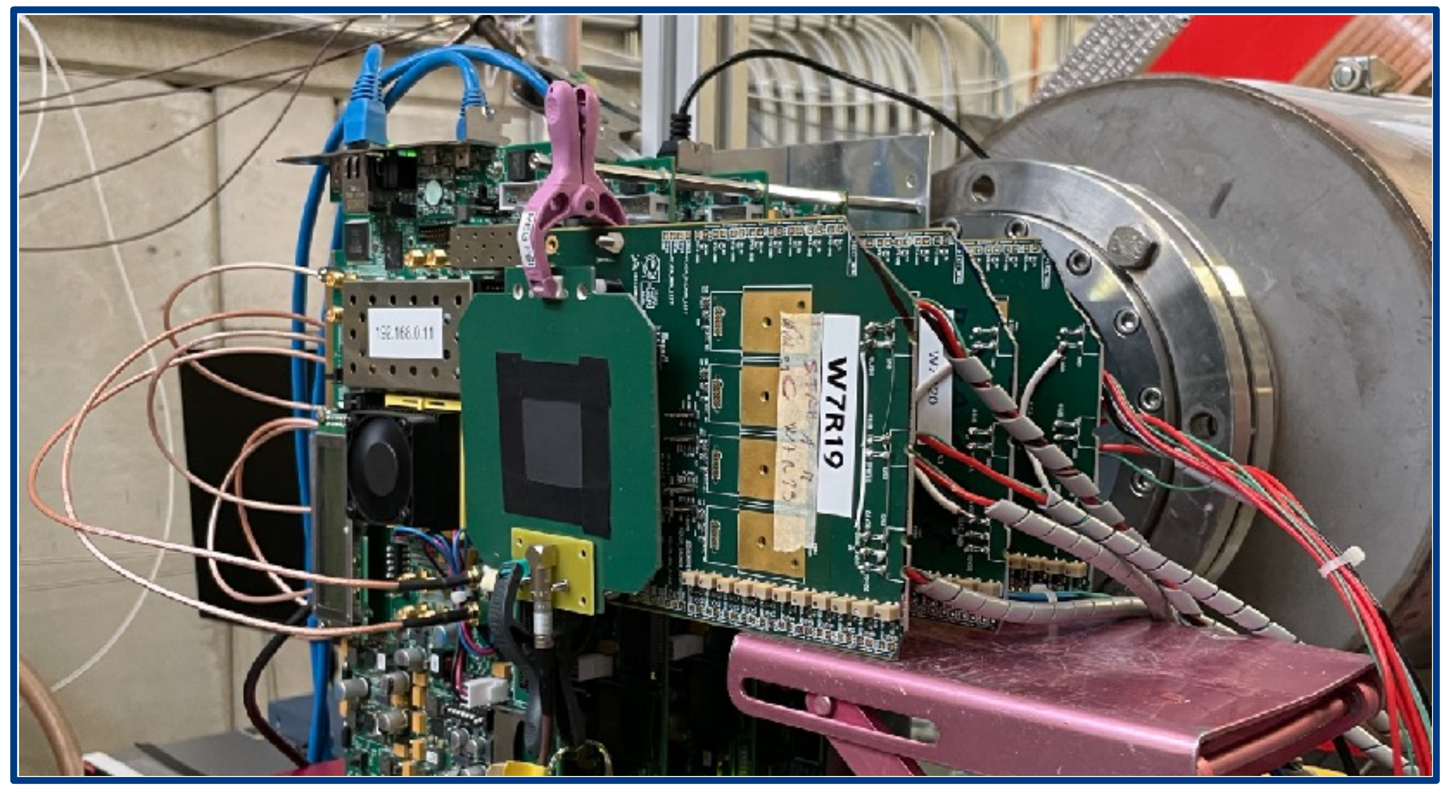
李政道研究所
TSUNG-DAO LEE INSTITUTE

2019



Characterisation of potential beam lines

2020

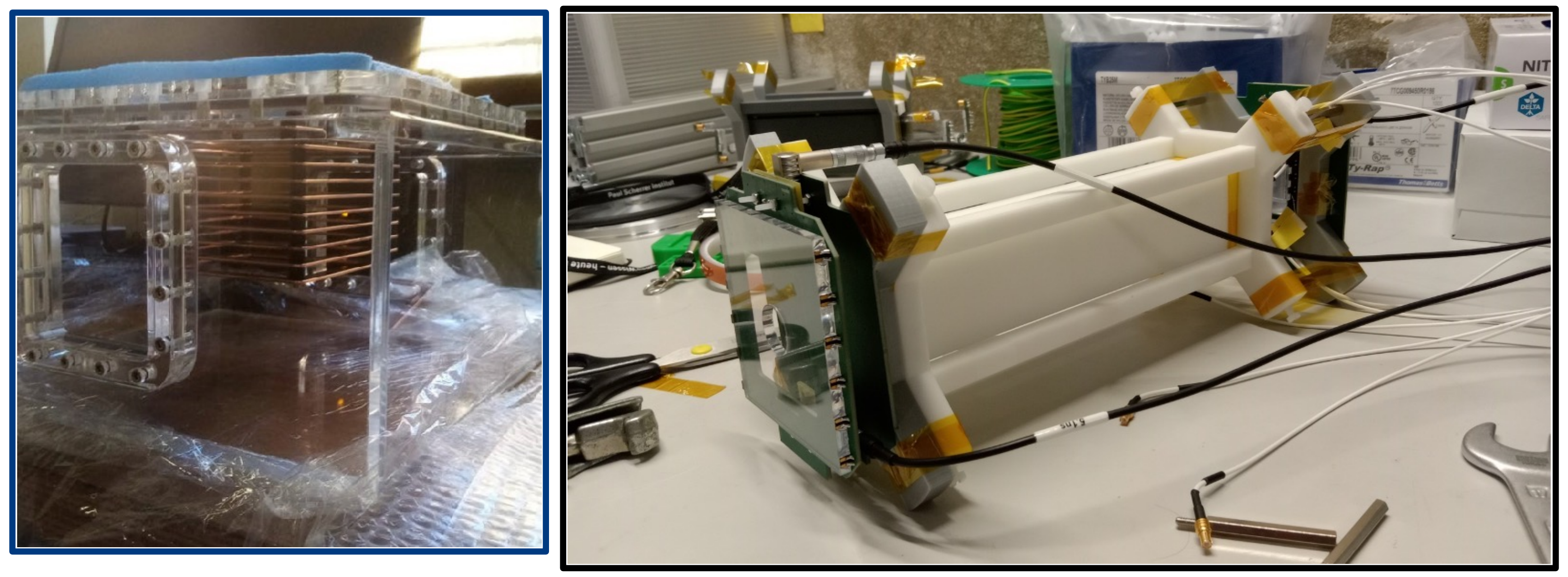


Study multiple scattering of e^+ at low momenta

2021

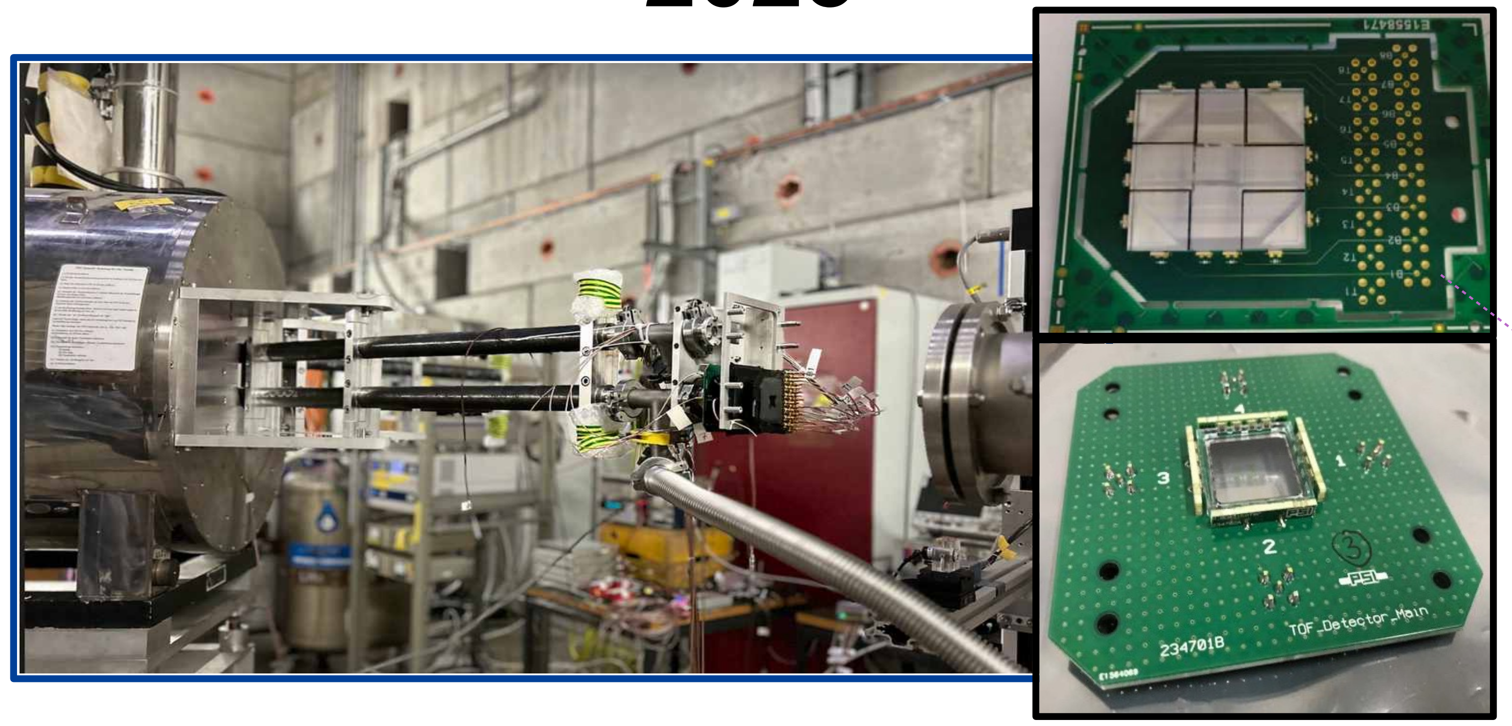
Characterization of potential electrode material with e^+ and μ^+

2022



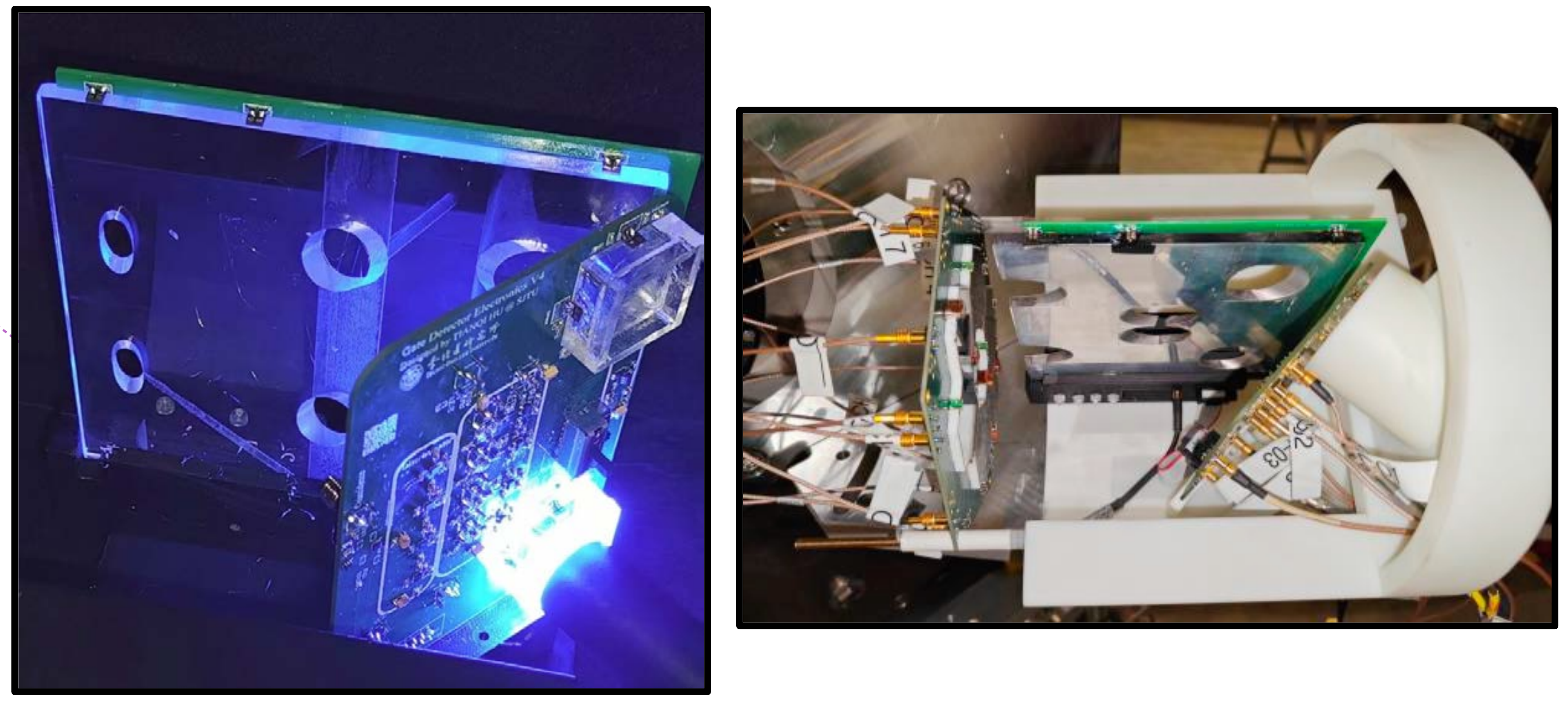
Performance test of prototype entrance detector and TPC tracker

2023



Aligning muon beam with centre axis of injection channel

2024



Positron detection efficiency, muon trigger detector

muEDM Phase-I timeline

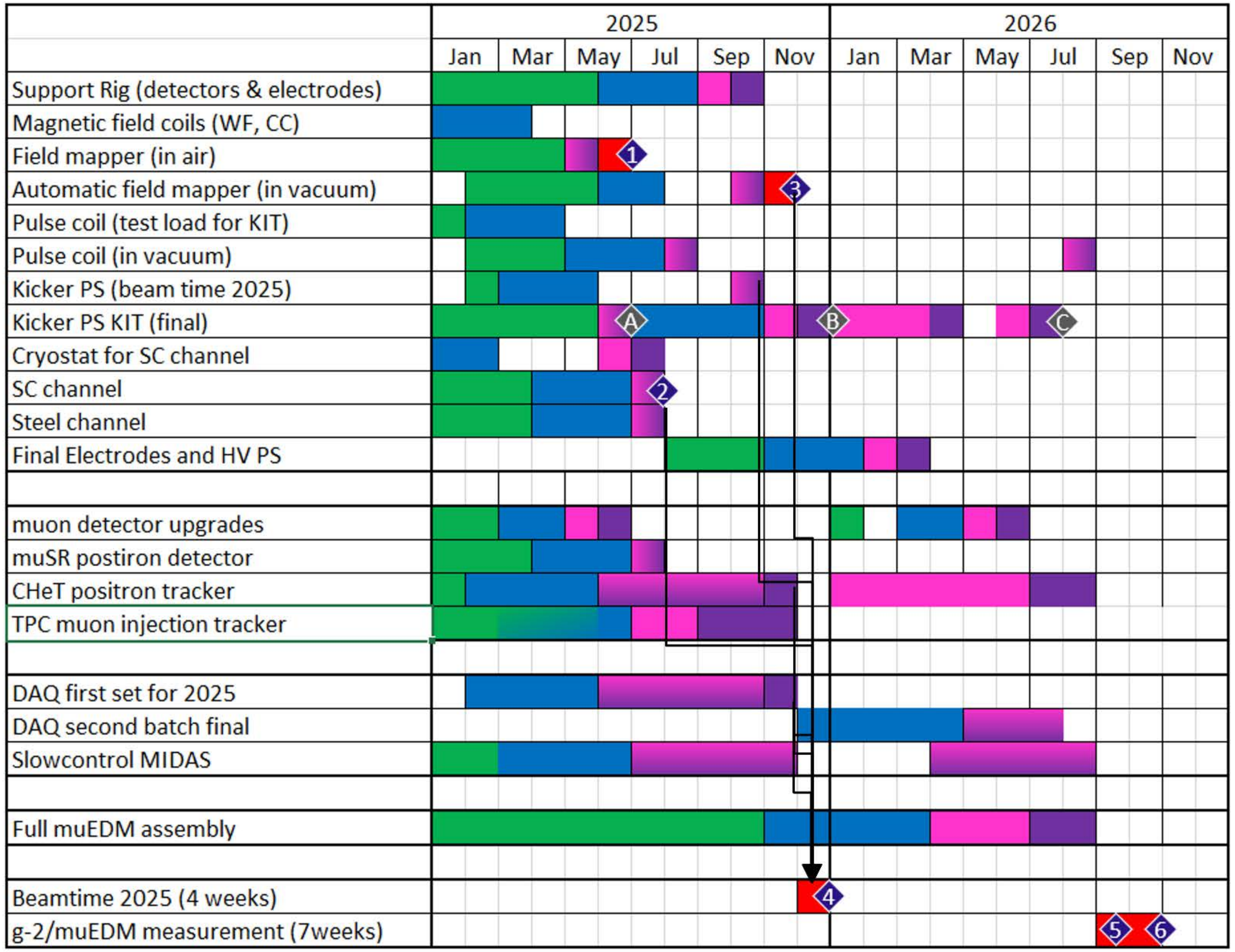
李政道研究所
TSUNG-DAO LEE INSTITUTE

2025: Demonstration of critical methods and techniques

- Preparation of magnetic field
- Preparation of kicker field (preliminary)
- Preparation of cryogenic injection
- Preparation of positron detection
- Preparation of TPC injection tracker
- Preparation of FRES DAQ system

2026: Prepapartion and demonstration of g-2/muEDM measurement

Design (Concept and technical)
Procurement and manufacturing
Assembly
Commissioning
Measurements



Summary and outlook

李政道研究所 TSUNG-DAO LEE INSTITUTE

- **Muon g-2 at Fermilab**
  - Data-taking completed in 2023, Run-2/3 results published, Run-4/5/6 analysis ongoing.
  - Met TDR statistical and systematics goal, final uncertainty goal: < 140 ppb by 2025
  - BSM searches ongoing: EDM, CPT/LV, Dark Matter
- **Muon EDM at PSI**
  - Aiming for sensitivity 10^{-23} e·cm using the frozen-spin technique.
  - Phase I progressing well: Beam tests since 2019, first measurement expected by 2026.
  - Sensitive to new CP-violation sources, complementary to Muon g-2

📌 **Muon experiments continue to be a powerful probe for new physics—testing quantum corrections (g-2) and CP violation (EDM).**