# Magnetic moment and *g*-factor
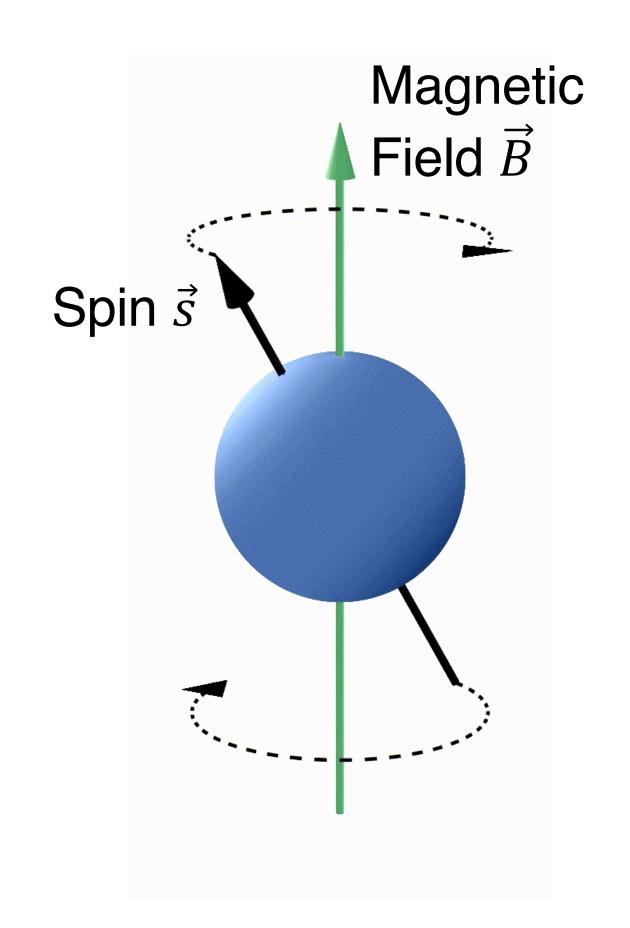
- ***g*-factor** connects the **spin** ($\vec{s}$) of a particle to its **magnetic moment** ($\vec{\mu}$)

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

- **Spin precesses** in a magnetic field; larger g-factor, higher spin precession frequency ($\omega_s$)

$$\omega_s = \frac{\textcolor{red}{g}}{2}\frac{e}{m}\,B$$

Magnetic Field $\vec{B}$

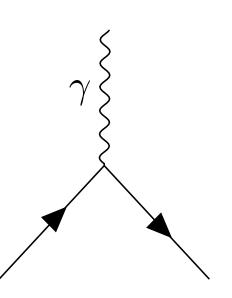Spin $\vec{s}$

# 100 years of g-factor

***Studies on the g-factor have laid the foundation of the Standard Model***

**g = 1** for classical current loop

- Stern-Gerlach (1922) and atomic spectroscopy found $g_e \approx 2$

**g = 2** for a "free" spin-1/2 Dirac particle

- A prediction of Dirac's equation (1928)

**g > 2** due to interactions with virtual particles (quantum fluctuations)

- Kusch and Forley (1947) studied Zeeman effect in Ga atom and found g ~ 2.002

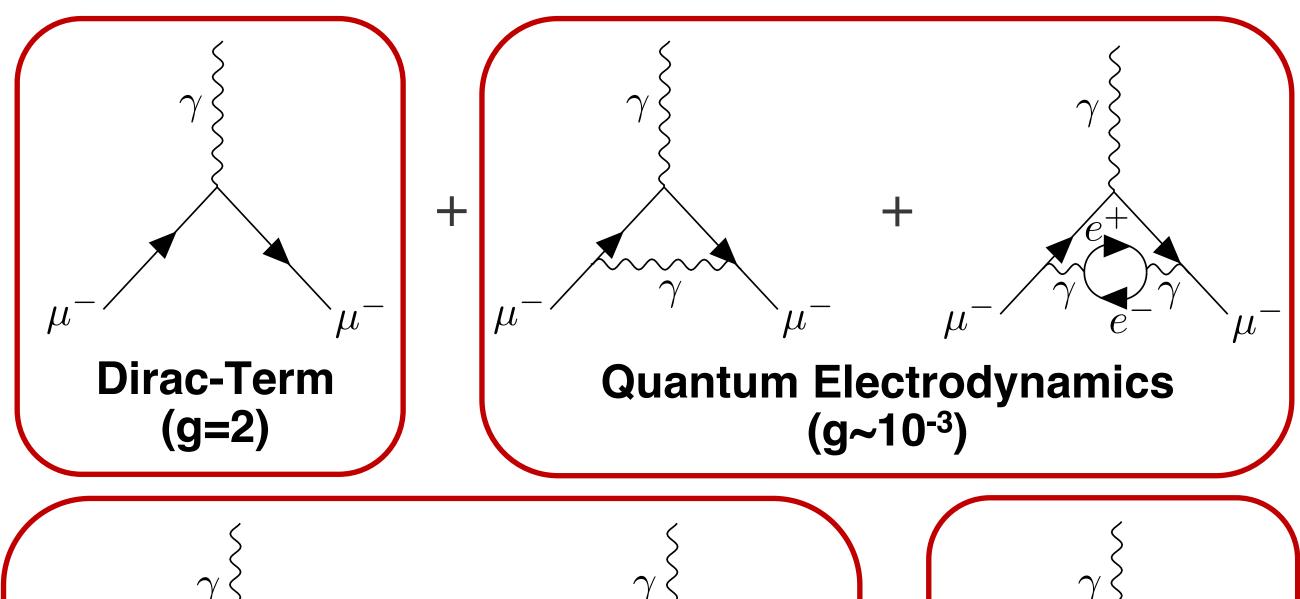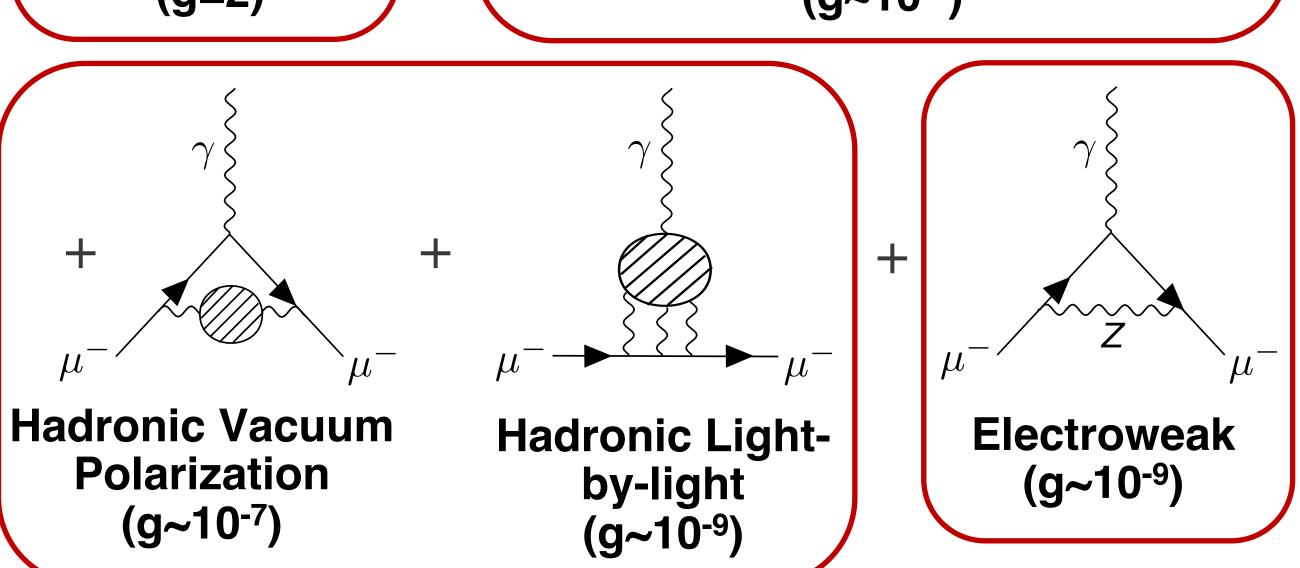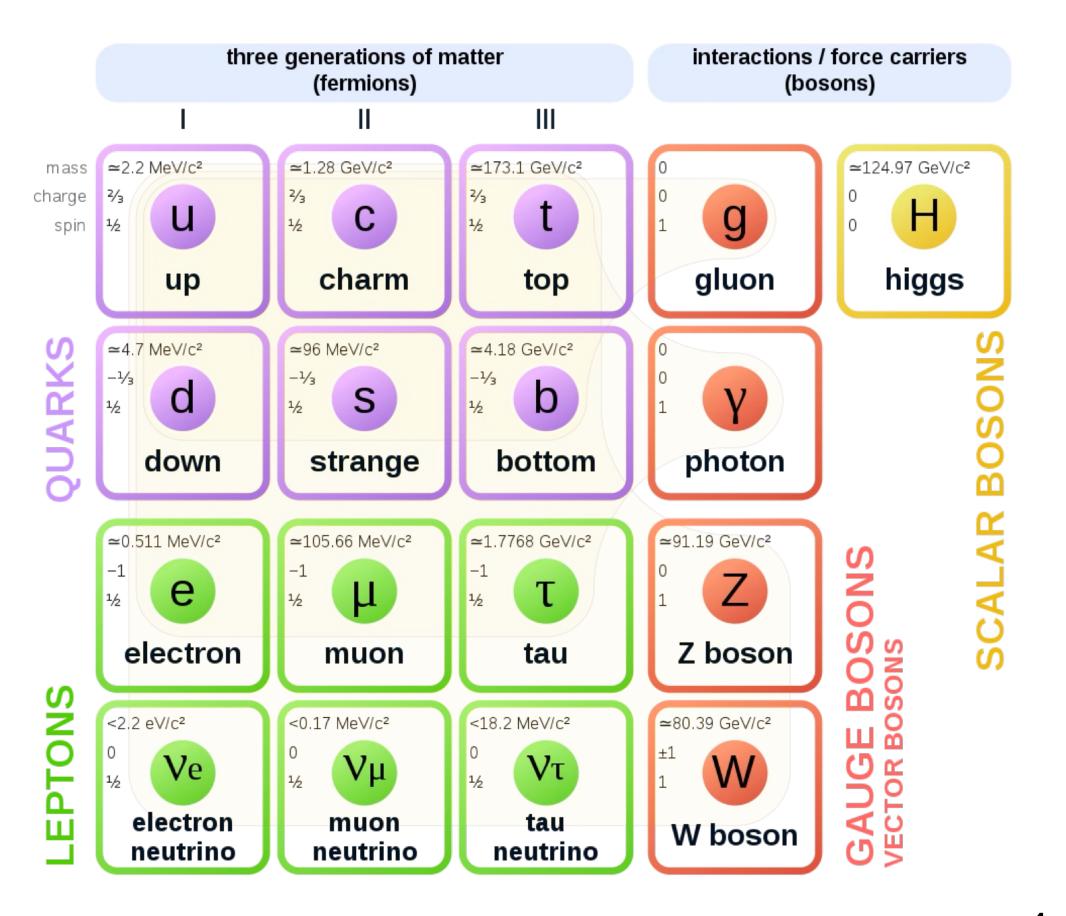- J. Schwinger (1947) calculated the 1st order QED correction

**Quantum Electrodynamics**

**Measuring the size of quantum fluctuations reveals the particle and force content of the universe**



**Dirac-Term**
**(g=2)**

**Quantum Electrodynamics**
**(g~$10^{-3}$)**

**Hadronic Vacuum Polarization**
**(g~$10^{-7}$)**

**Hadronic Light-by-light**
**(g~$10^{-9}$)**

**Electroweak**
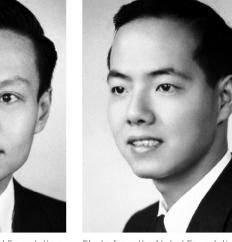**(g~$10^{-9}$)**



Source: Wikipedia/Cush

# Probing New Physics with Muon g-2



**Parity violation in weak decay (1956)**
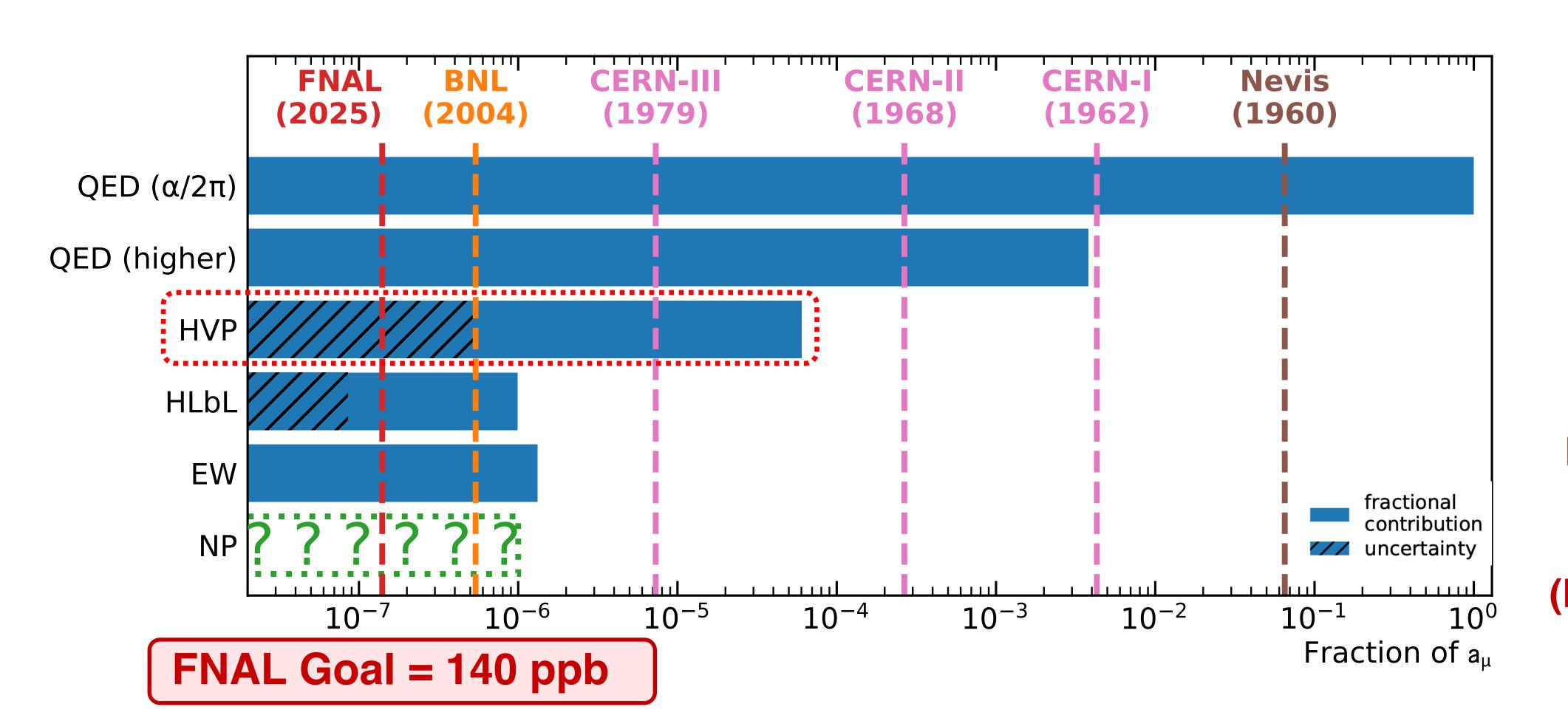
Chen Ning Yang

Tsung-Dao (T.D.) Lee
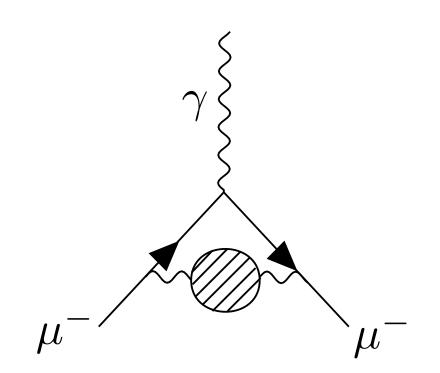
**Parity violation in muon decay and g~2 (Lederman,1957)**

**FNAL Goal = 140 ppb**

Is there any **new physics** (in the experiment) that is not in the Standard Model (calculation)?

# Muon g-2 Collaboration
## (176 collaborators, 34 institutes, 7 countries)

**US Universities**
- Boston
- Cornell
- UIUC
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central College
- Regis
- Trinity
- Virginia
- Washington
- York CUNY

**US 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

**United Kingdom**
- Lancaster/Cockcroft
- Liverpool
- Manchester
- University College London

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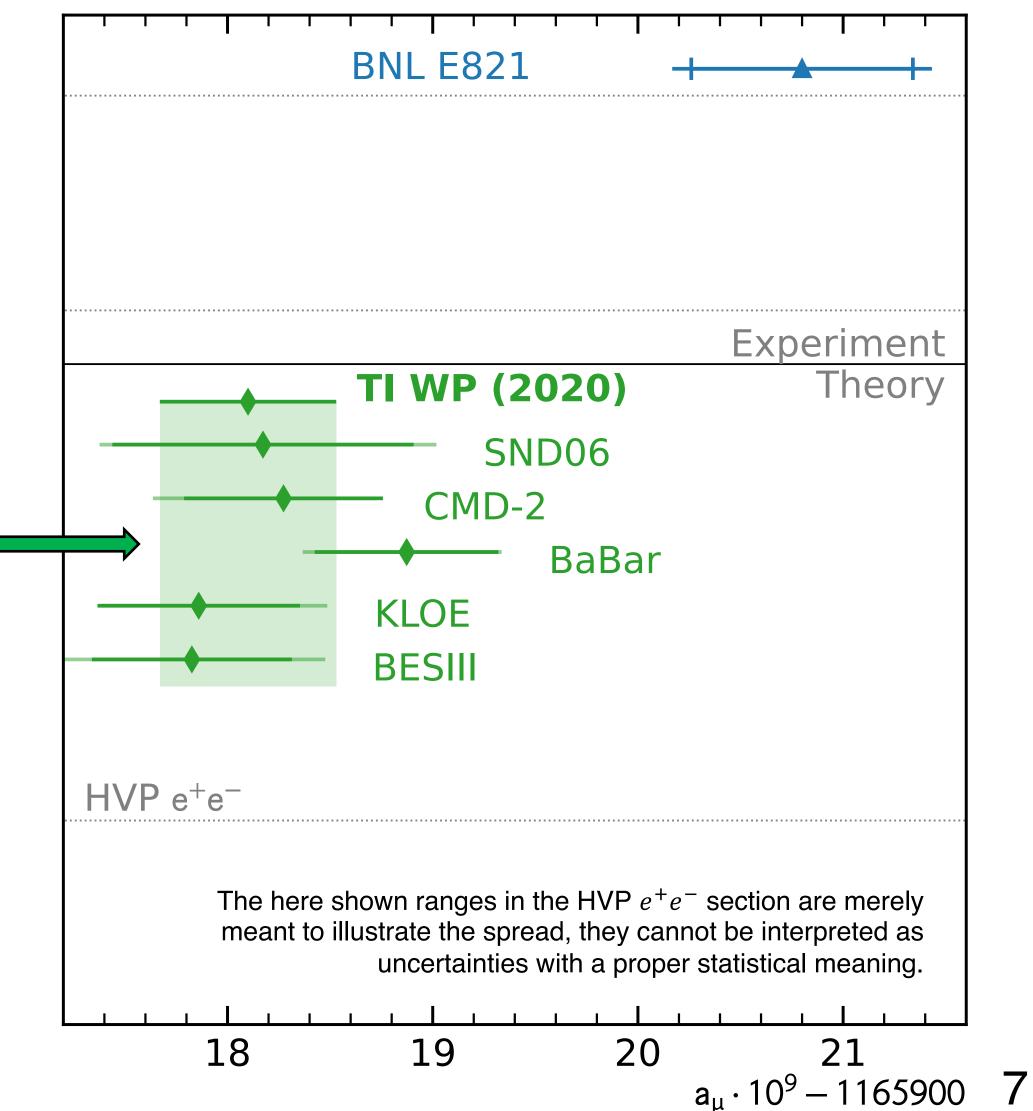
μ

g-2

- 100+ theorist compile the theoretical input and provide recommendations (*muon-gm2-theory.illinois.edu*)

- **TI White Paper 2020**
  Physics Reports 887 (2020) 1-166

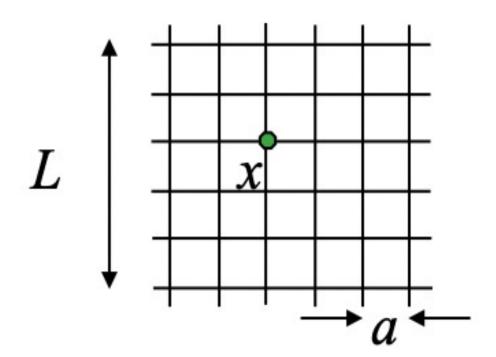- **data-driven** dispersive approach from $\sigma(e^+e^- \to hadrons)$ data from different experiments over 20+ years



BNL E821

Experiment
Theory
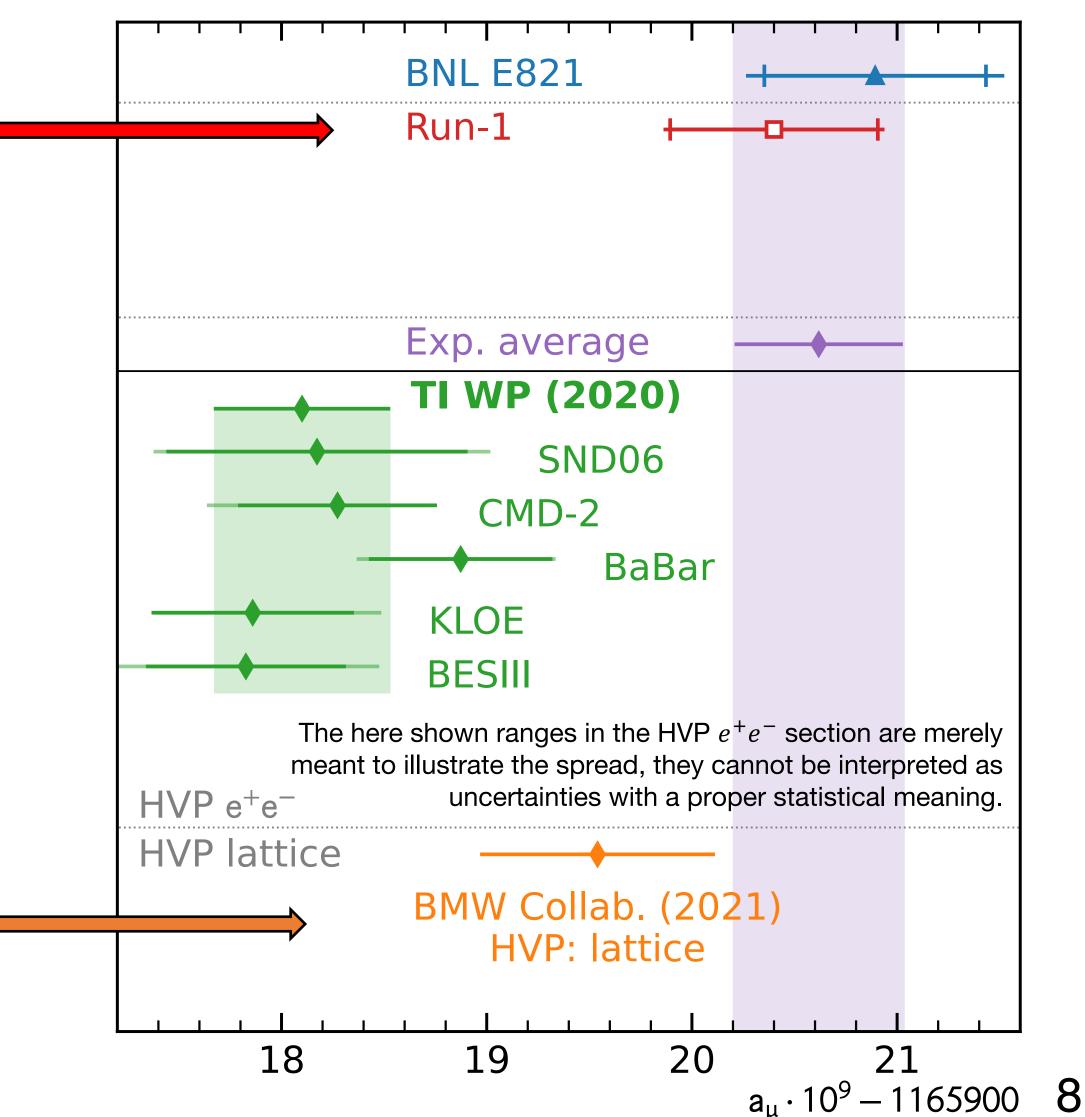
TI WP (2020)
SND06
CMD-2
BaBar
KLOE
BESIII

HVP $e^+e^-$

The here shown ranges in the HVP $e^+e^-$ section are merely meant to illustrate the spread, they cannot be interpreted as uncertainties with a proper statistical meaning.

18    19    20    21

$a_\mu \cdot 10^9 - 1165900$    7

- First result using 5% of our full dataset (Run-1 in 2018)

- In good agreement with previous results

- First high-precision *ab-initio* calculations of HVP on QCD-lattice

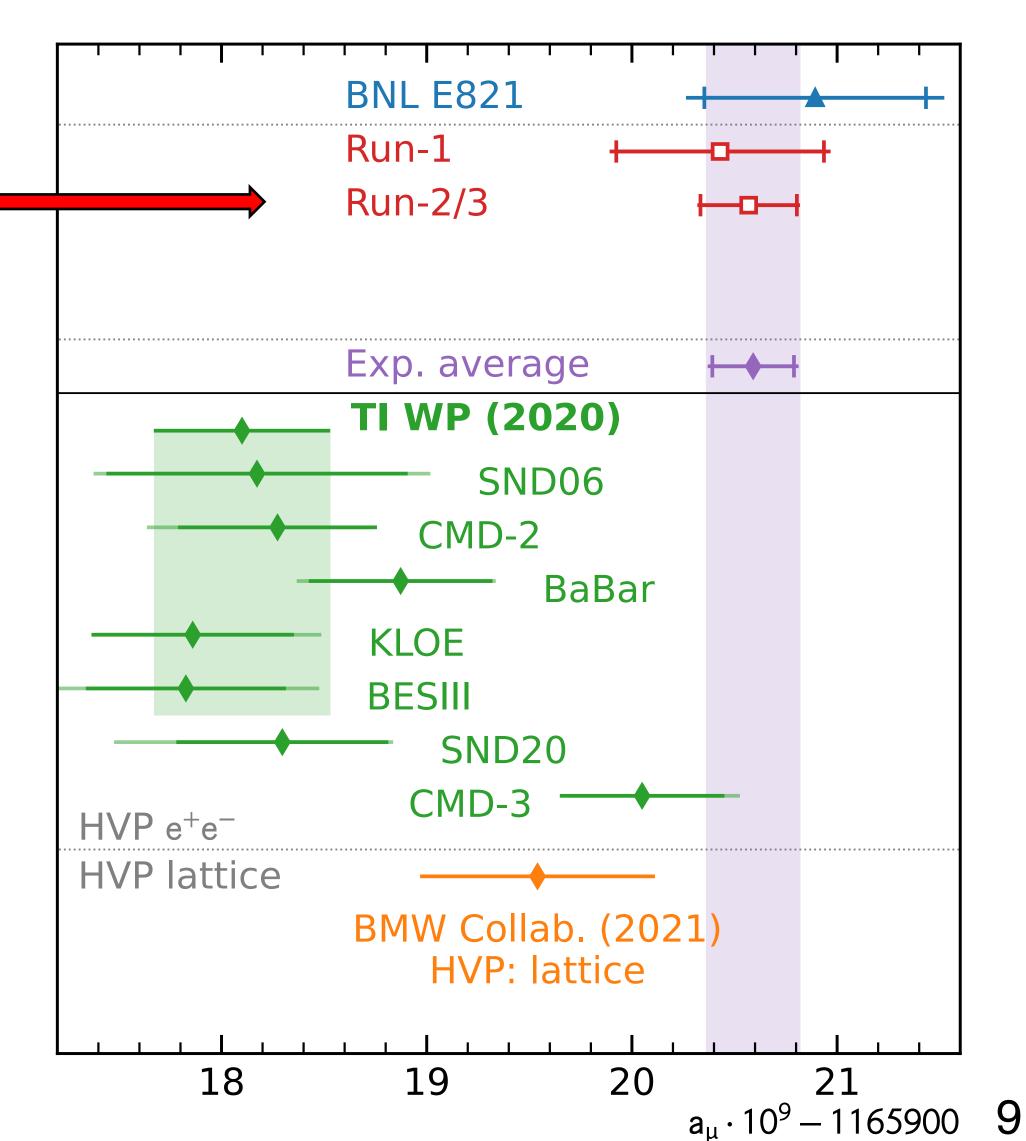- in tension with the data-driven approach ($e^+e^- \rightarrow hadrons$)



BNL E821

Run-1

Exp. average

**TI WP (2020)**

SND06

CMD-2

BaBar

KLOE

BESIII

The here shown ranges in the HVP $e^+e^-$ section are merely meant to illustrate the spread, they cannot be interpreted as uncertainties with a proper statistical meaning.

HVP $e^+e^-$

HVP lattice

BMW Collab. (2021)
HVP: lattice

18    19    20    21

$a_\mu \cdot 10^9 - 1165900$

8

- Second result using 4.6 times more data (Run-2/3 in 2019 and 2020)

- More than a two-fold increase in precision



**Muon g-2 collaboration @ Liverpool in 2023**



BNL E821
Run-1
Run-2/3

Exp. average

**TI WP (2020)**
SND06
CMD-2
BaBar
KLOE
BESIII
SND20
CMD-3

HVP $e^+e^-$
HVP lattice

BMW Collab. (2021)
HVP: lattice

18    19    20    21

$a_\mu \cdot 10^9 - 1165900$    9
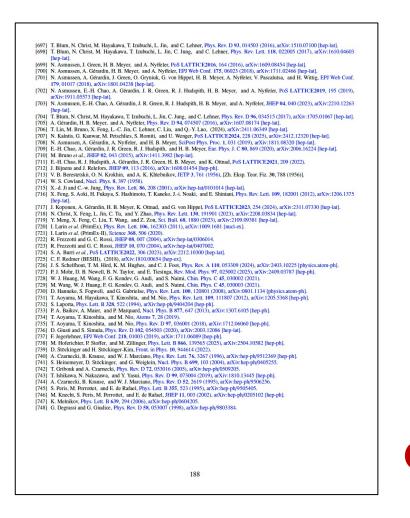
**Two months ago:**
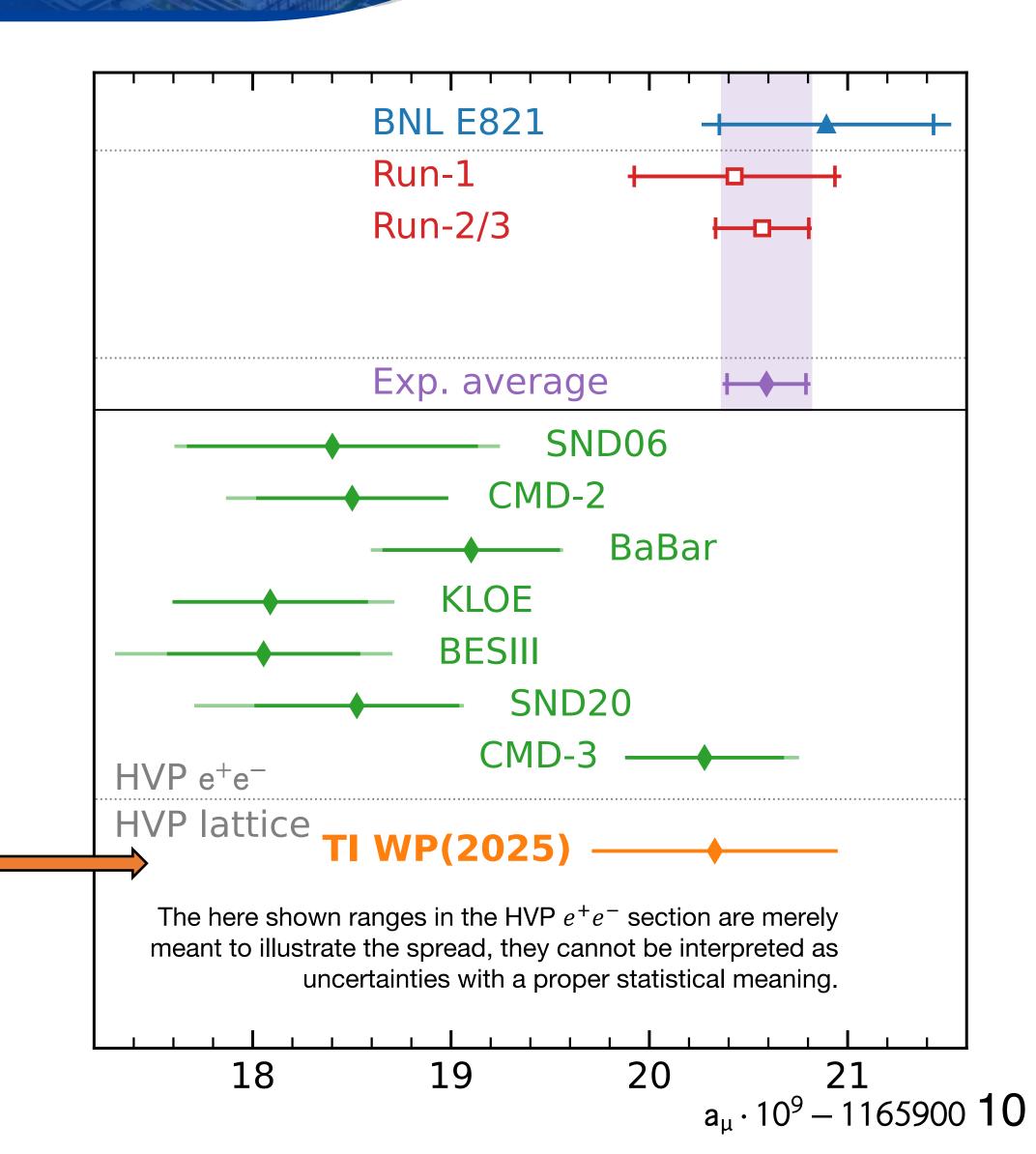
New **TI White Paper (2025)** using only

QCD-lattice based (LO-)HVP determination

All the details in **TI White Paper 2025**

arXiv:2505.21476
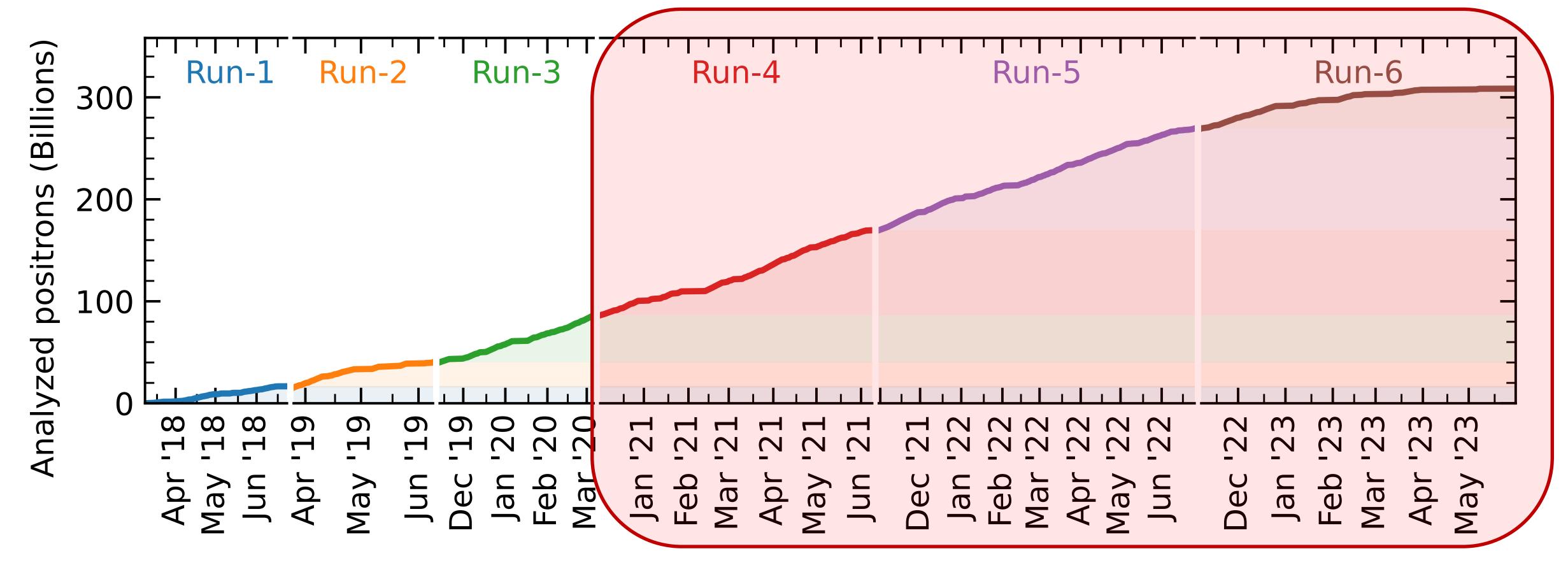
~ 100 authors
only 188 pages



The here shown ranges in the HVP $e^+e^-$ section are merely meant to illustrate the spread, they cannot be interpreted as uncertainties with a proper statistical meaning.

$a_\mu \cdot 10^9 - 1165900$

10

# Data Collection – 6 Runs over 7 Years
## (2017-2023)



April 2021: **Run-1** results
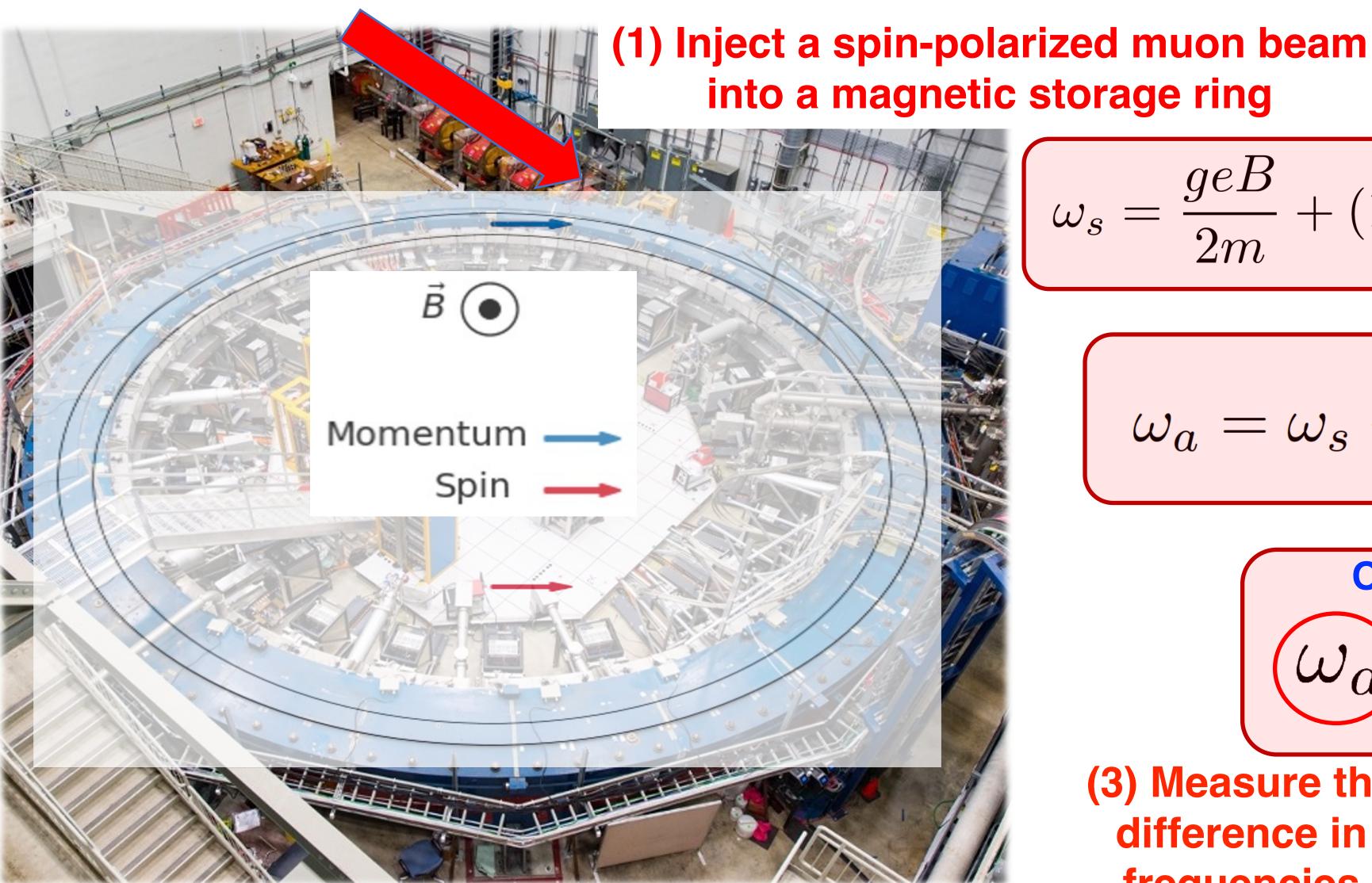
August 2023: **Run-2/3** results

Today: **Run-4/5/6** results    **2.6 times more data**
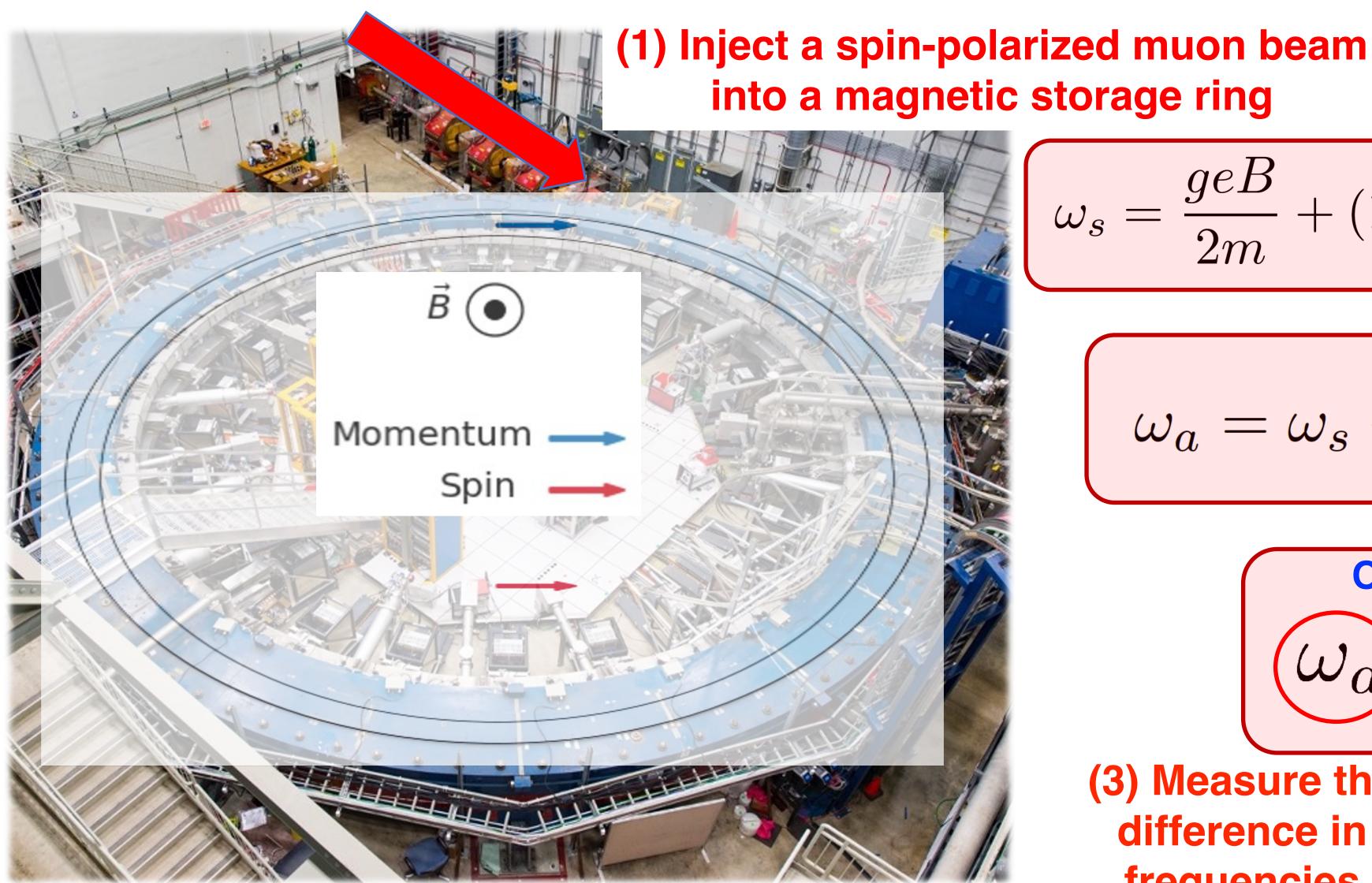
11

# Principle of g-2 measurement

**(1) Inject a spin-polarized muon beam into a magnetic storage ring**

$\vec{B}$ ⊙

Momentum →

Spin →

$$\omega_s = \frac{geB}{2m} + (1-\gamma)\frac{eB}{\gamma m}$$

$$\omega_c = \frac{eB}{\gamma m}$$

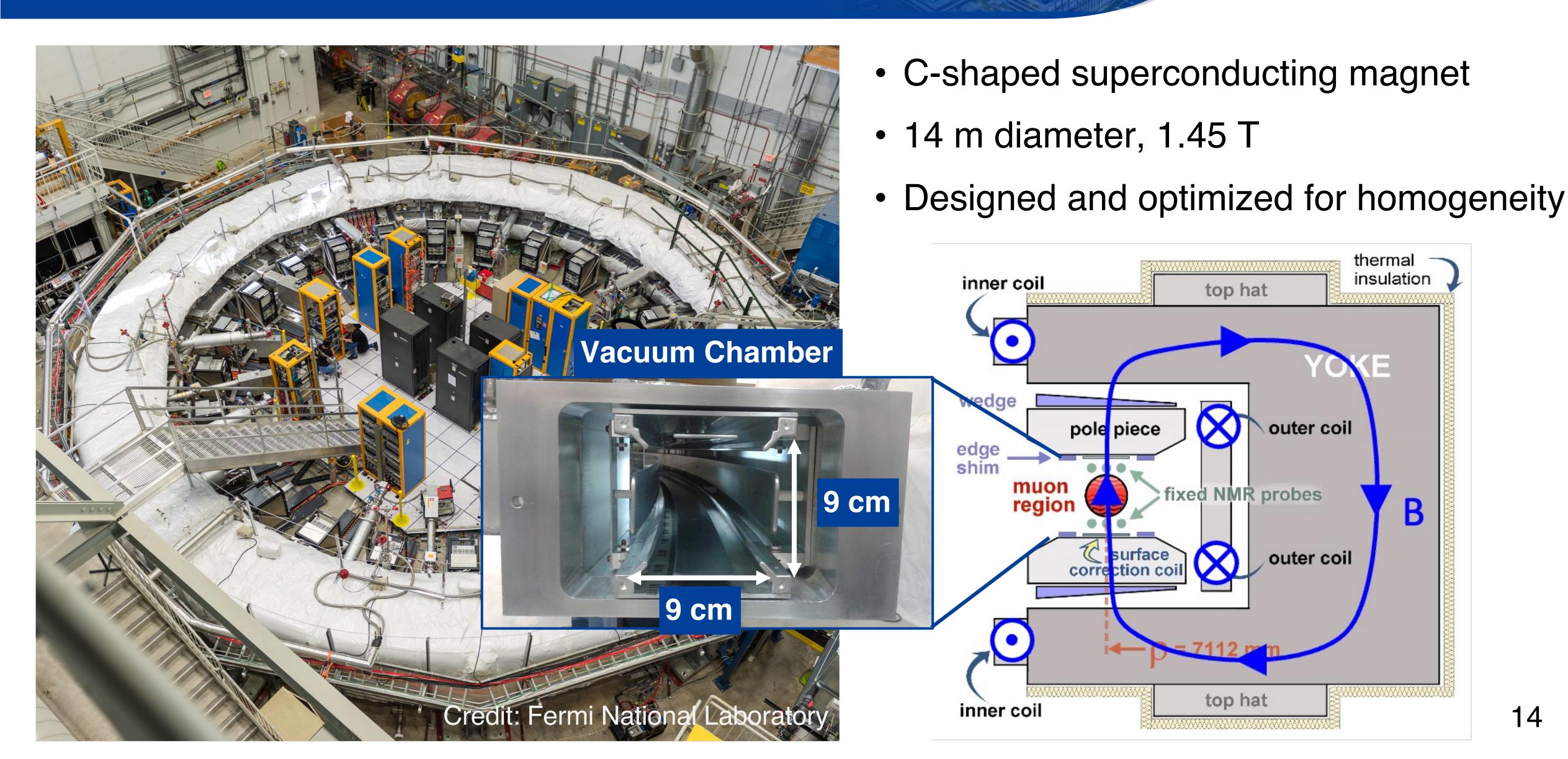$$\omega_a = \omega_s - \omega_c = \left(\frac{g-2}{2}\right)\frac{eB}{m}$$

**Obtain g-2**

$$\boxed{\omega_a = a_\mu \frac{eB}{m}}$$

**(3) Measure the difference in frequencies**

**(2) Measure the storage ring magnetic field**

# Principle of g-2 measurement



**(1) Inject a spin-polarized muon beam into a magnetic storage ring**

$$\omega_s = \frac{geB}{2m} + (1-\gamma)\frac{eB}{\gamma m}$$

$$\omega_c = \frac{eB}{\gamma m}$$

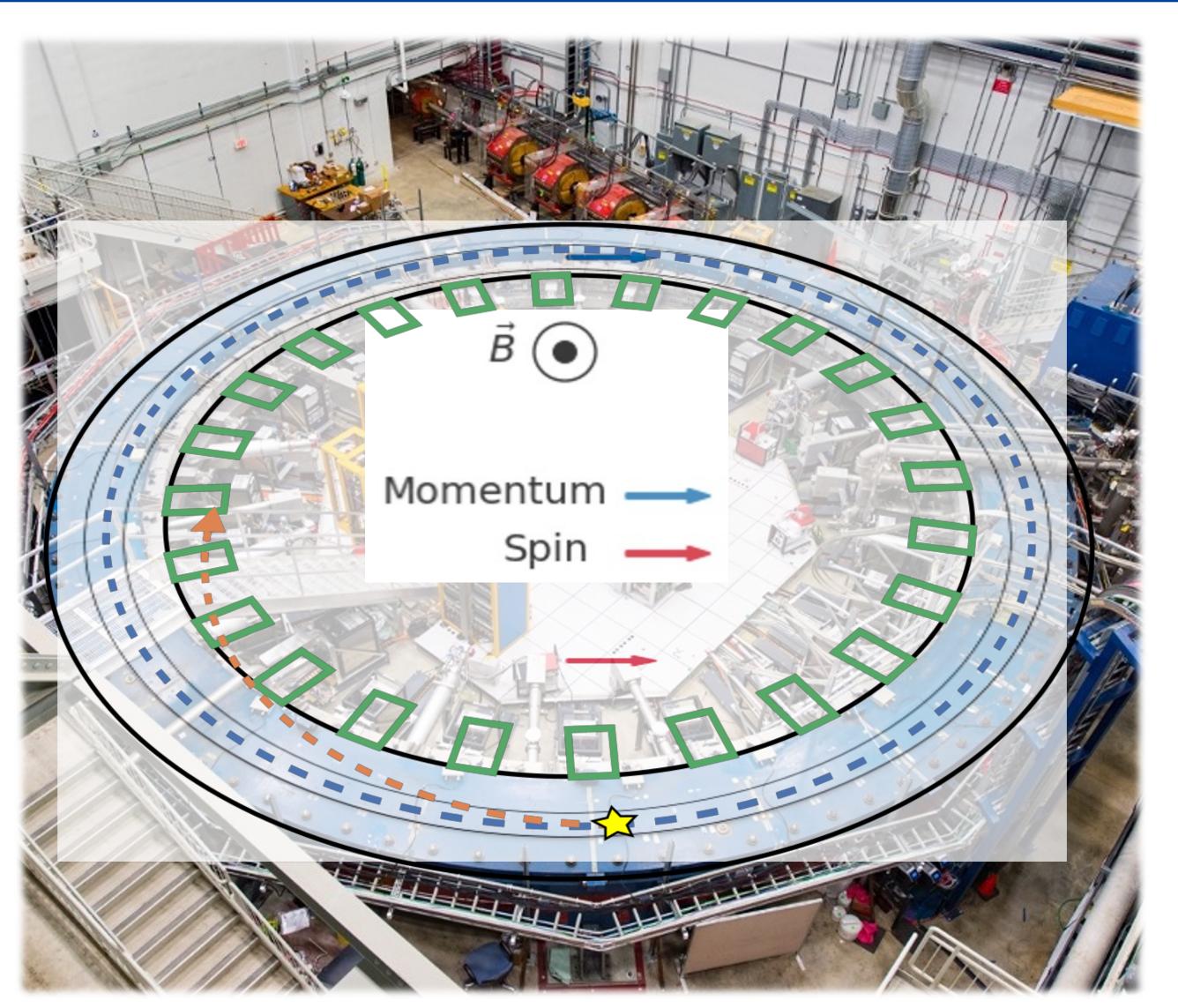$$\omega_a = \omega_s - \omega_c = \left(\frac{g-2}{2}\right)\frac{eB}{m}$$

**Obtain g-2**

$$\omega_a = a_\mu \frac{eB}{m}$$

**(3) Measure the difference in frequencies**

**(2) Measure the storage ring magnetic field**

# Muon g-2 storage ring



**Vacuum Chamber**

9 cm
9 cm

Credit: Fermi National Laboratory

- C-shaped superconducting magnet
- 14 m diameter, 1.45 T
- Designed and optimized for homogeneity
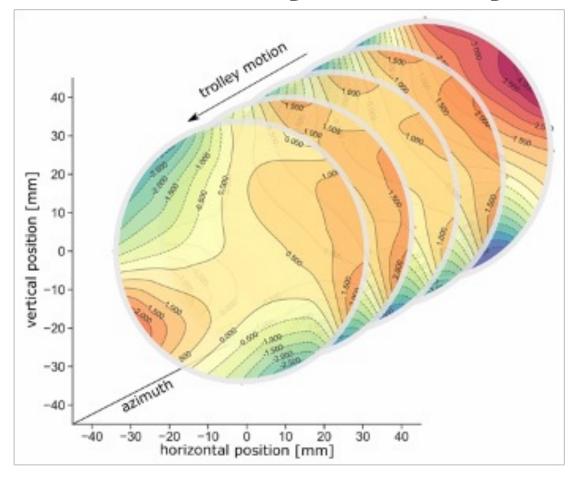
**In-vacuum NMR trolley maps field every ~3 days**
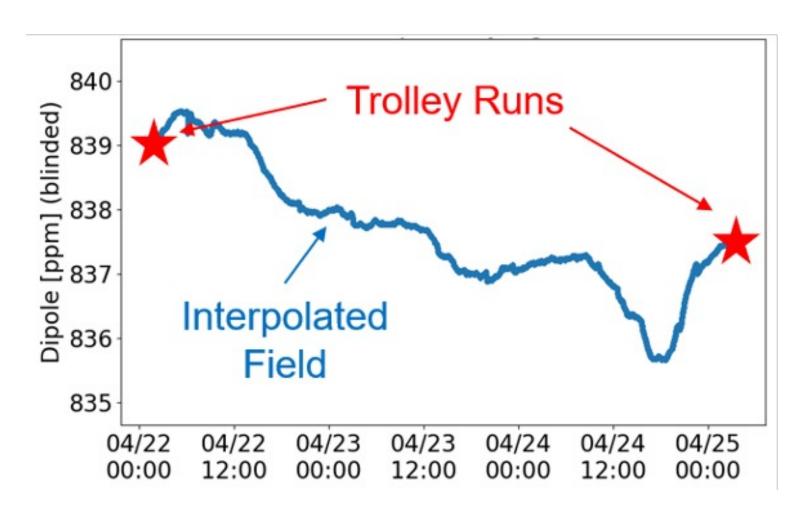


17 petroleum jelly NMR probes

2D field maps (~9000 slides per scan)

**378 fixed NMR probes monitor the field during muon storage at 72 azimuthal locations**

Fixed probes above/below muon storage region

# Principle of g-2 measurement

**(1) Inject a spin-polarized muon beam into a magnetic storage ring**

$\vec{B}$ ⊙

Momentum →

Spin →

$$\omega_s = \frac{geB}{2m} + (1-\gamma)\frac{eB}{\gamma m}$$

$$\omega_c = \frac{eB}{\gamma m}$$

$$\omega_a = \omega_s - \omega_c = \left(\frac{g-2}{2}\right)\frac{eB}{m}$$

**Obtain g-2**

$$\omega_a = a_\mu \frac{eB}{m}$$

**(3) Measure the difference in frequencies**

**(2) Measure the storage ring magnetic field**

16
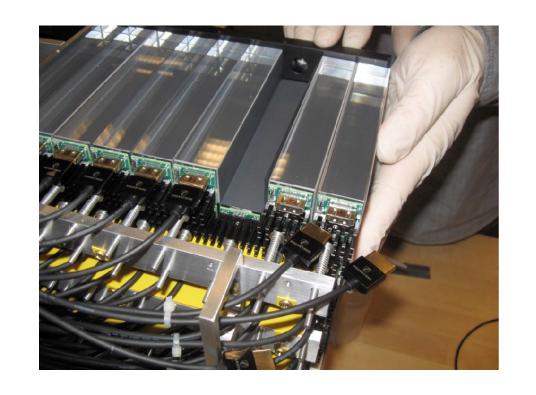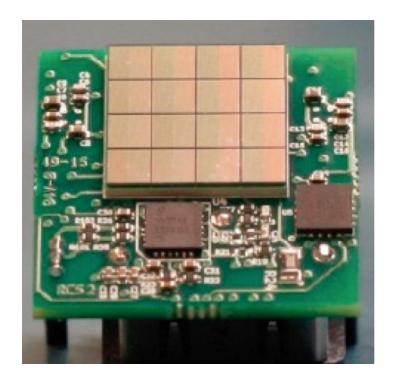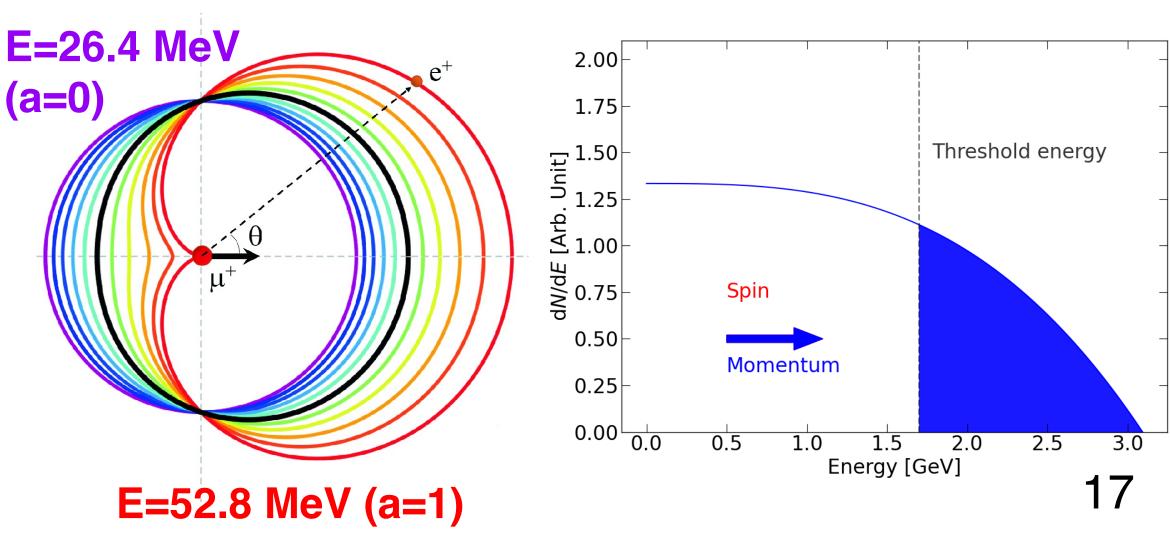
**1,296 Lead Fluoride crystals readout by SiPM**
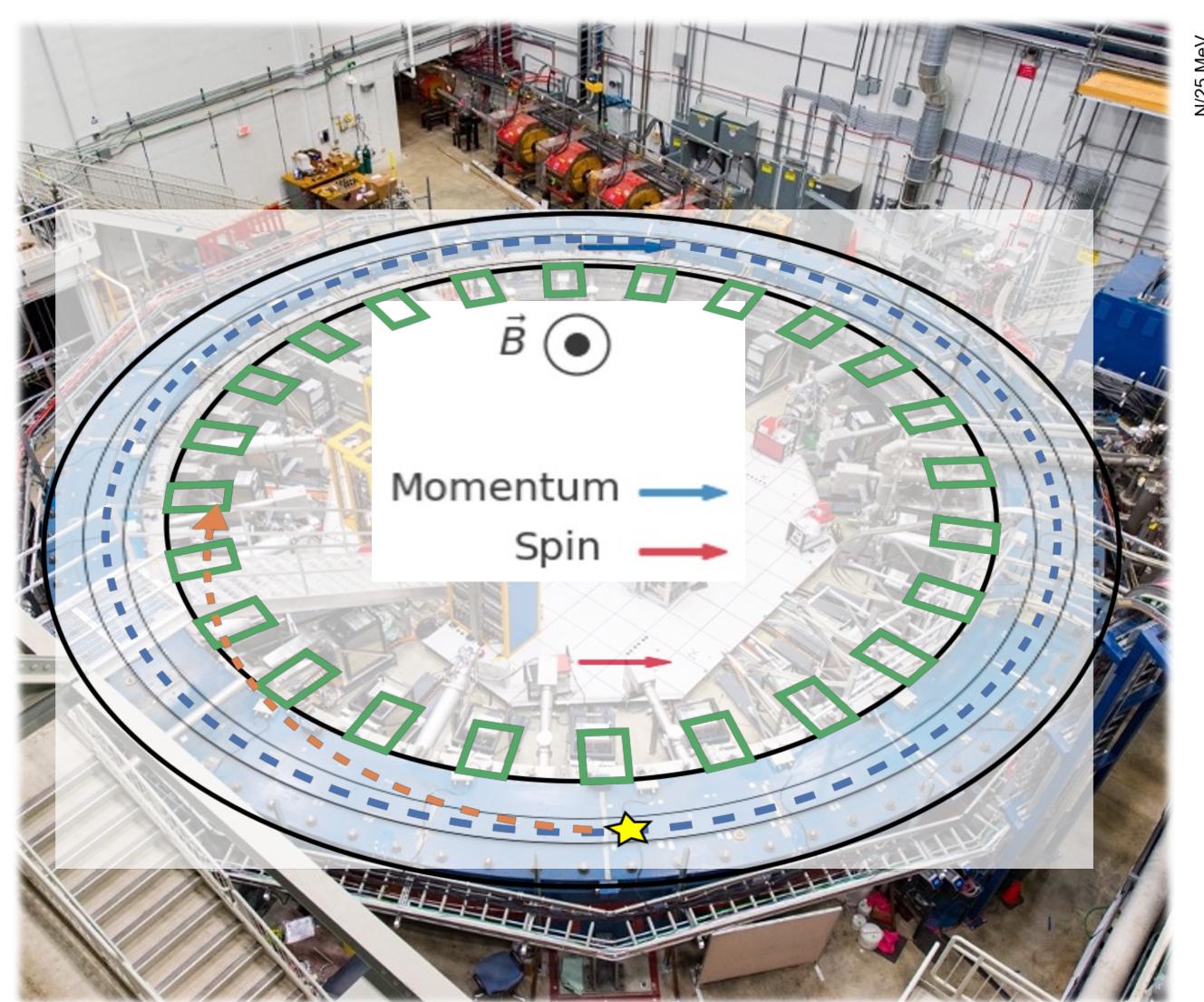
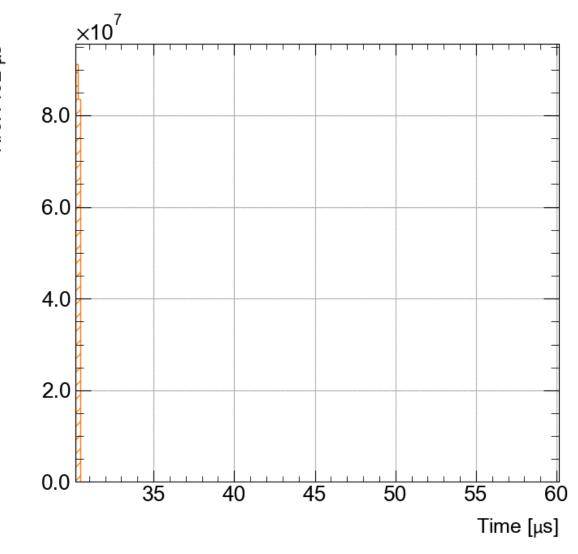**High energy $e^+$ tends to be emitted along the muon spin direction due to parity-violating weak decay**

E=26.4 MeV (a=0)

E=52.8 MeV (a=1)

17
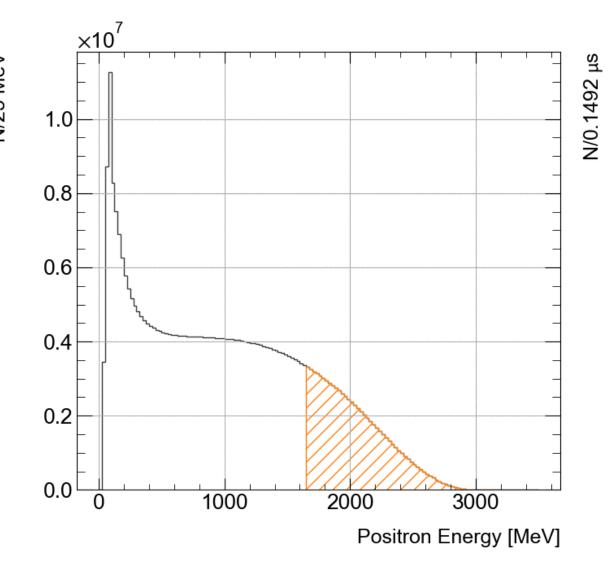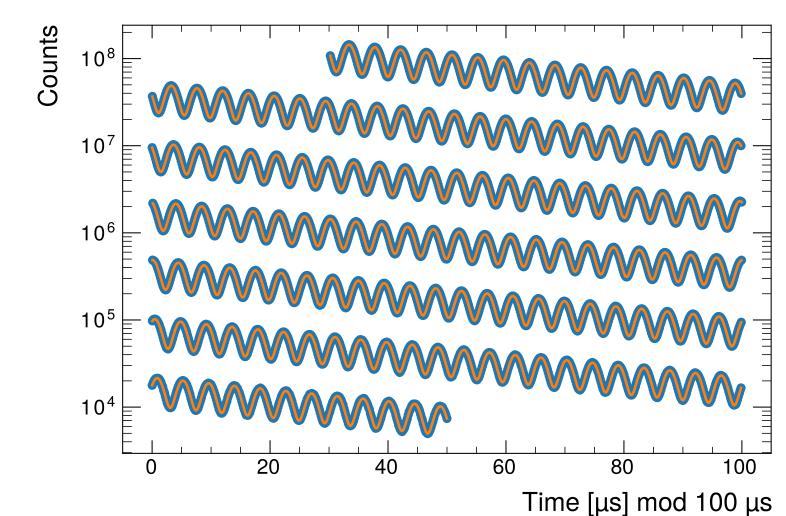
**The g-2 wiggle plot!**



$$N(t) = N_0 e^{-t/\tau}[1 + A_\mu \cos(\boldsymbol{\omega_a}t - \phi_0)]$$



18

李政道研究所
TSUNG-DAO LEE INSTITUTE

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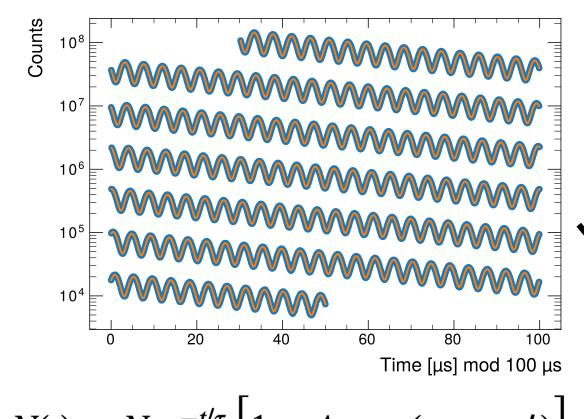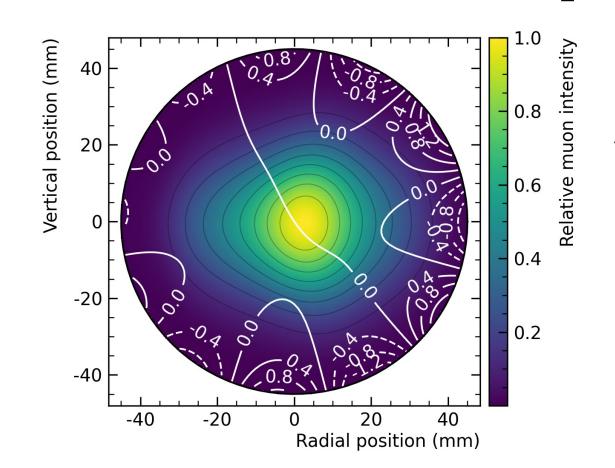
**Beam Dynamics Corrections**

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

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

$$a_\mu \sim \frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m} \frac{1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml}}{1 + B_k + B_q}$$
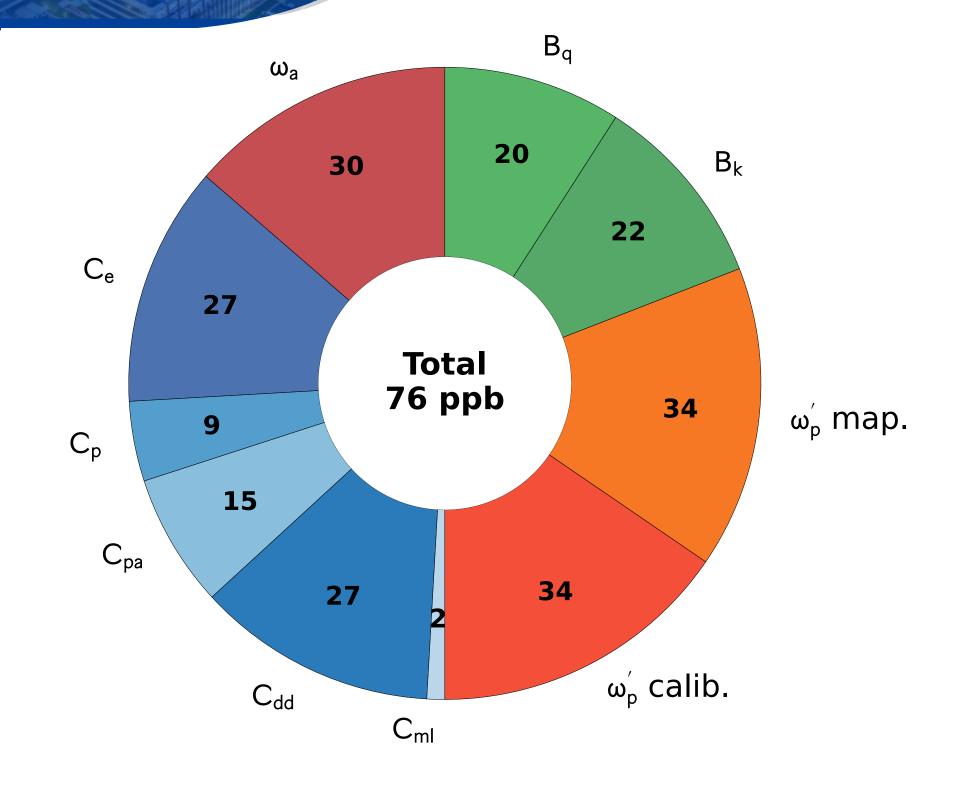
**Transient magnetic fields: Quad vibrations and kicker eddy current**

**Transient Field Corrections**

| Quantity | Correction (ppb) | Uncertainty (ppb) |
|---|---|---|
| $\omega_a^m$ (statistical) | ... | 114 |
| $\omega_a^m$ (systematic) | ... | 30 |
| $C_e$ | 347 | 27 |
| $C_p$ | 175 | 9 |
| $C_{pa}$ | -33 | 15 |
| $C_{dd}$ | 26 | 27 |
| $C_{ml}$ | 0 | 2 |
| $\langle \omega_p' \times M \rangle$ | ... | 48 |
| $B_k$ | -37 | 22 |
| $B_q$ | -21 | 20 |
| $\mu_p'/\mu_B$ | ... | 4 |
| $m_\mu/m_e$ | ... | 22 |
| Total systematic for $\mathcal{R}_\mu'$ | ... | 76 |
| Total for $a_\mu$ | 572 | 139 |



**TDR systematics goal : 100 ppb** ✓

- "Evenly" distributed
- No dominant source
- Further improving would require reducing in many categories

20

- Measuring $a_\mu$ reveals the particle and force content of the univer...

- Most prec... come (12...

- Benchma...

- More to c...

  - Experim...

  - Theory: ... process... e+e- da...



### Physical Review Letters

ACCEPTED PAPER

**Measurement of the positive muon anomalous magnetic moment to 127 ppb**

D. P. Aguillard et al.

Export Citation

**Abstract**

A new measurement of the magnetic anomaly a_ of the positive muon is presented based on data taken from 2020 to 2023 by the Muon g -2 Experiment at Fermi National Accelerator Laboratory (FNAL). This dataset contains over 2.5 times the total statistics of our previous results. From the ratio of the precession frequencies for muons and protons in our storage ring magnetic field, together with precisely known ratios of fundamental constants, we determine a = 116 592 0710(162) ^(-12) (139 ppb) for the new datasets, and a = 116 592 0705(148) ^(-12) (127 ppb) when combined with our previous results. The new experimental world average, dominated by the measurements at FNAL, is a(exp) = 116 592 0715(145) -12 (124 ppb). The measurements at FNAL have improved the precision on the world average by over a factor of four.

Theory
LO-HVP e⁺e⁻

...itiative ...025)

... the spread of ... interpreted as ...ted from WP 2025.

17    18    19    20    21

$a_\mu \cdot 10^9 - 1165900$
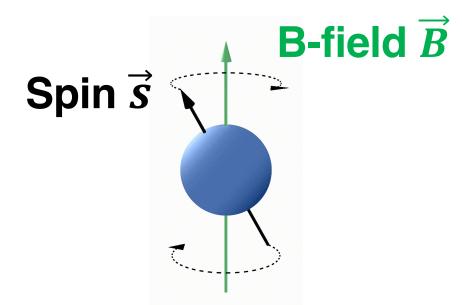
# Spin-Field Interactions
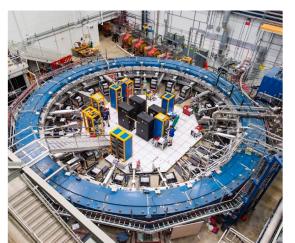
**Spin $\vec{s}$**
**(Quantum Effect)**

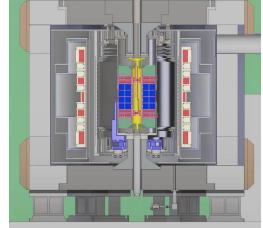**Testing SM prediction and searching for BSM with the muon spin!**

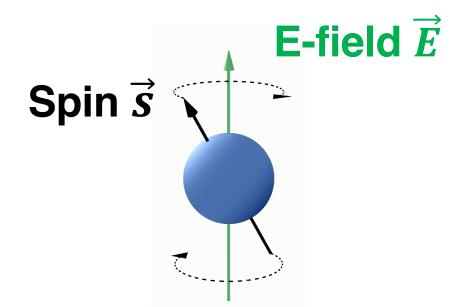### Magnetic Dipole Moment
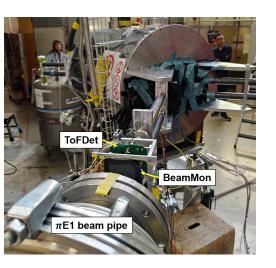$$\vec{\mu} = \mu\vec{s}$$

Spin $\vec{s}$

B-field $\vec{B}$

**Spin Precession**

Fermilab Muon g-2, J-PARC Muon g-2/EDM

### Electric Dipole Moment
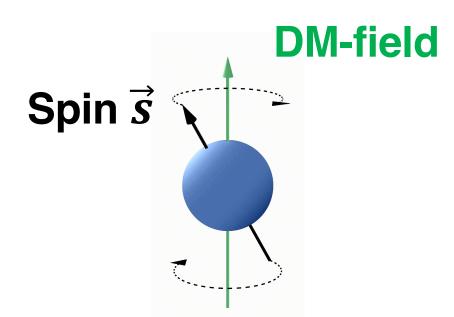$$\vec{d} = d\vec{s}$$

Spin $\vec{s}$
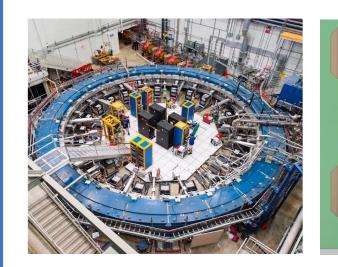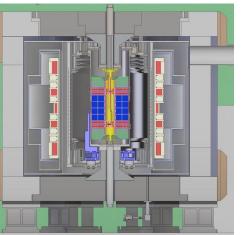
E-field $\vec{E}$

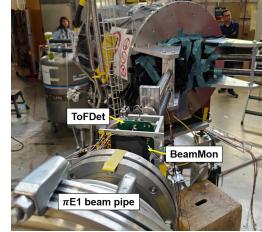**Spin Precession**

PSI muEDM

### Ultralight Bosonic DM
- Scalar DM with muon Yukawa coupling
- ALP DM with muon EDM coupling
- ALP DM with muon wind coupling
- Vector DM with muon gauge coupling

Spin $\vec{s}$

DM-field

**Spin Precession
(Amplitude + Frequency Modulation)**

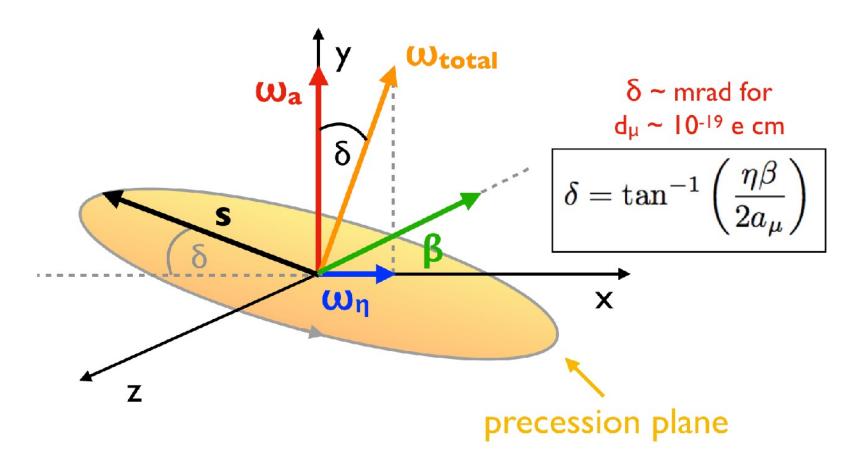## Muon Electric Dipole Moment (EDM)

- The spin precession plane is tilted in the presence of the EDM.

- Run-2/3 analysis to be announced soon!

- Current limit (BNL): $1.8 \times 10^{-19}$ e · cm
  → Projected limit: $\sim \mathcal{O}(10^{-20}$ e · cm$)$
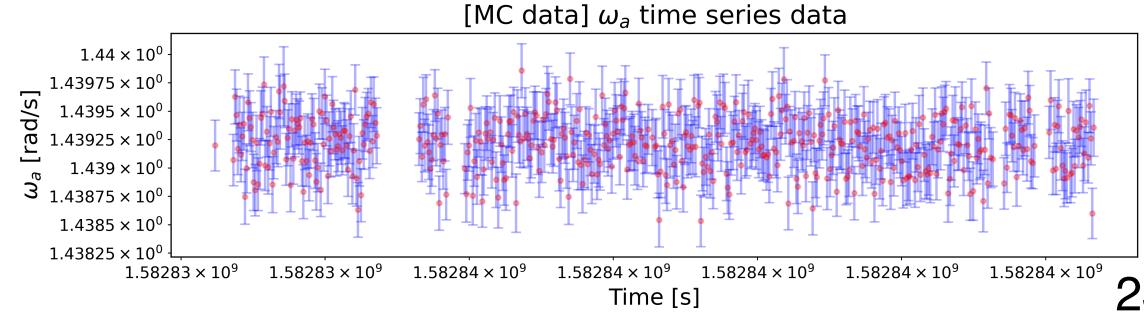
## CPT and Lorentz Invariance Violation

- $\omega_a$ modulated at the sidereal motion freq.
- Run-2/3 analysis in review.
- Current limit (BNL): $1.4 \times 10^{-24}$ GeV →
  Projected limit (FNAL Run-2/3): $\mathcal{O}(10^{-25})$ GeV

## Ultralight Muonic Dark Matter (scalar)

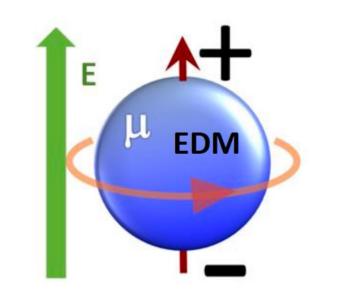- $\omega_a$ modulated at the DM Compton frequency.
- Run-2/3 analysis in progress.



$\delta \sim$ mrad for
$d_\mu \sim 10^{-19}$ e cm

$$\delta = \tan^{-1}\left(\frac{\eta\beta}{2a_\mu}\right)$$

precession plane



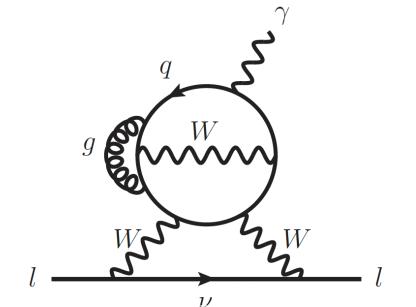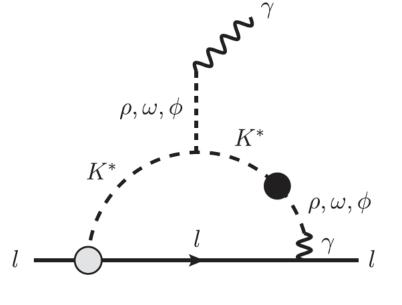[MC data] $\omega_a$ time series data

23

# Motivation for EDM searches

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

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

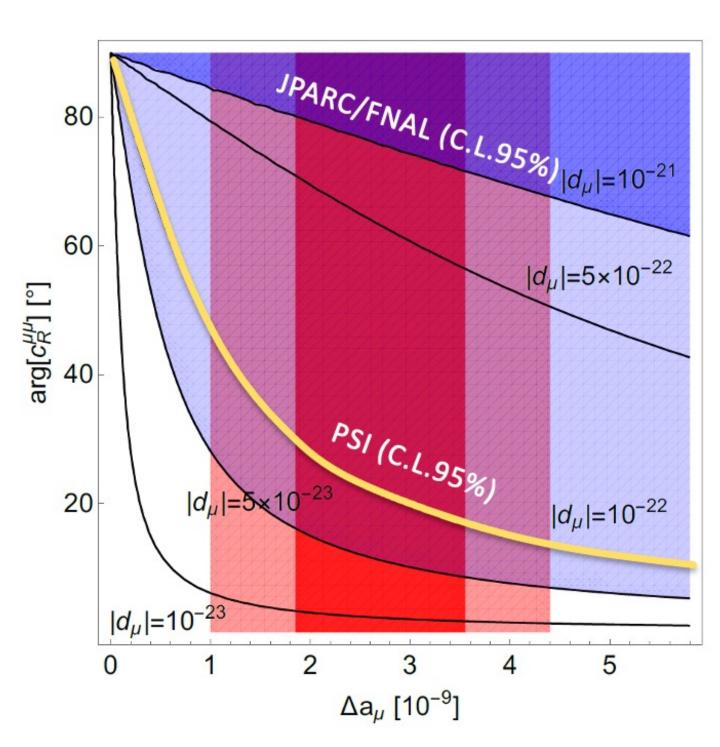- Standard Model predicts small EDMs for fundamental particles
  PRD 89 (2014) 056006
  PRL 125 (2020) 241802

  - CKM contribution: $d_\mu^{CKM} \sim 10^{-42}$ e · cm, hadronic long-range effect: $d_\mu^{HLR} \sim 10^{-38}$ e · cm

  - Current experimental limit $d_\mu^{\text{BNL}} < 1.8 \times 10^{-19}$ e · cm (95% C. L. )   PRD 80 (2009) 052008

  - 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)
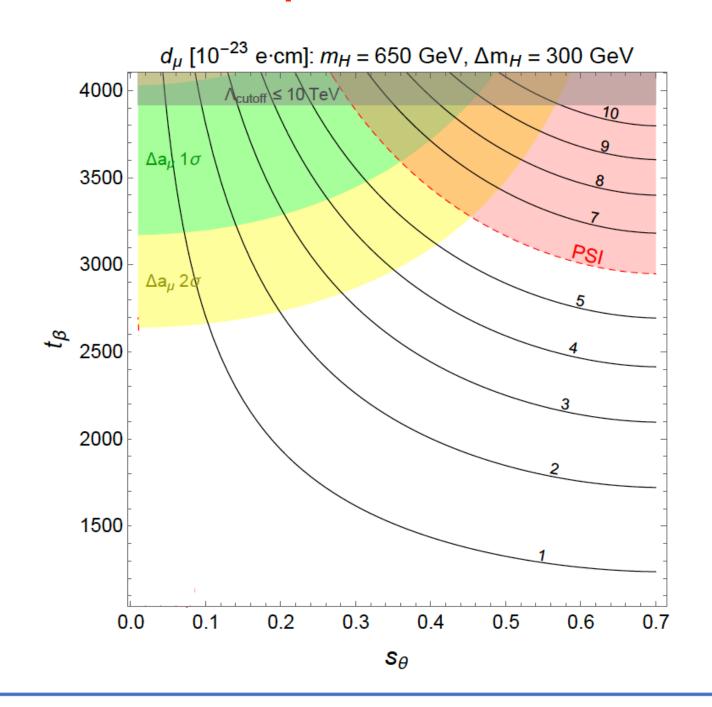
# BSM/EFT models with large EDMs

## EFT Analysis
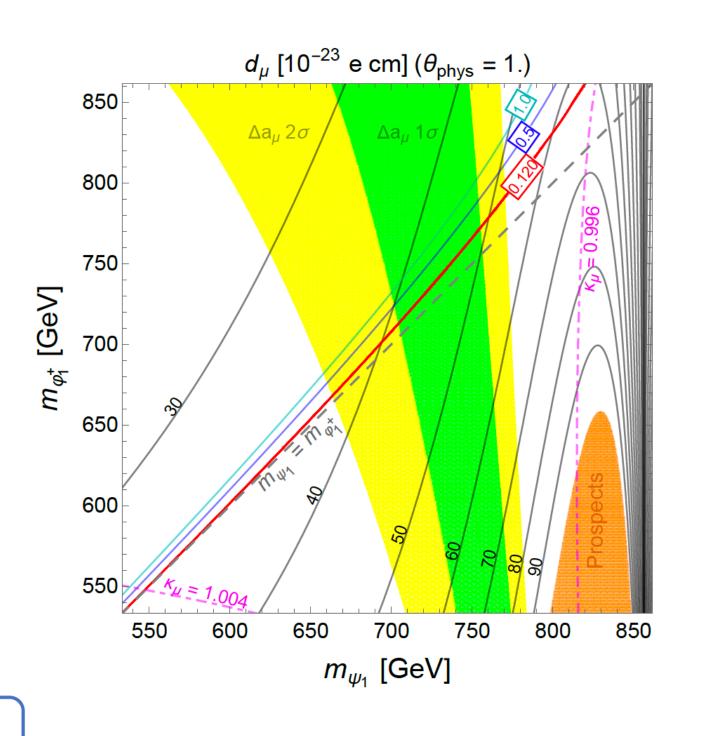


PRD 98 (2018) 113002

## Muon specific 2HDM



Interesting parameter space: $s_\theta \sim 0.35$, $\tan\beta \sim 3700$

PLB 831 (2022) 137194

## Radiative muon mass model



JHEP02 (2023) 234 (4)
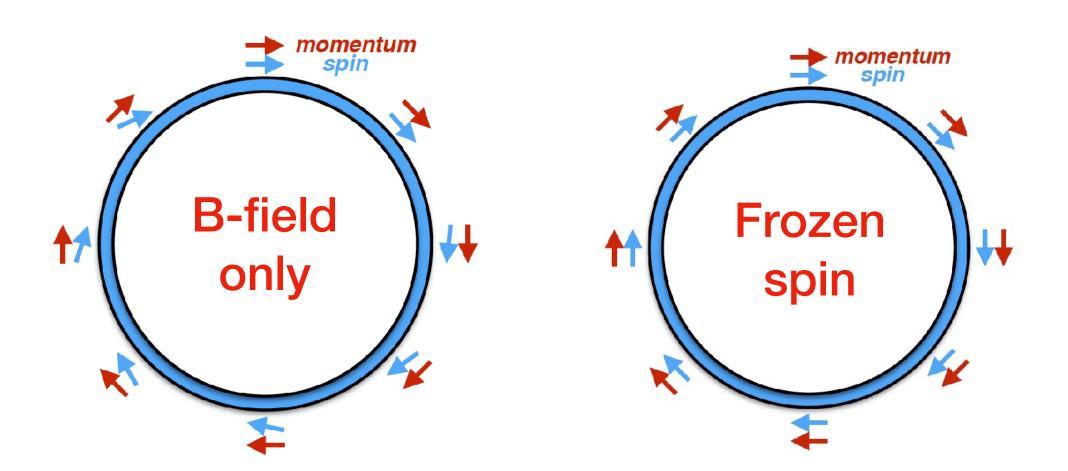
**Strong motivation to go beyond FNAL/J-PARC goal of $10^{-21}$ e cm!**
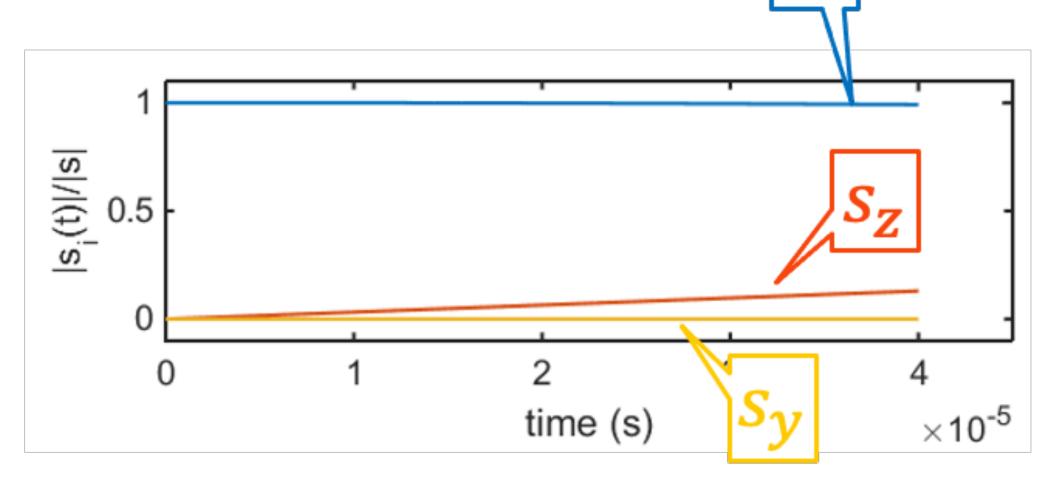
# The "frozen-spin" technique

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

$\omega_a$ : g-2 $\qquad\qquad\qquad$ $\omega_\eta$: EDM

- Developed in 2004 for the muon EDM search $\quad$ PRL 93 (2004) 052001

- Freeze g-2 component by applying a radial E-field of $\sim aBc\beta\gamma^2$
  - → no anomalous precession in the storage plane
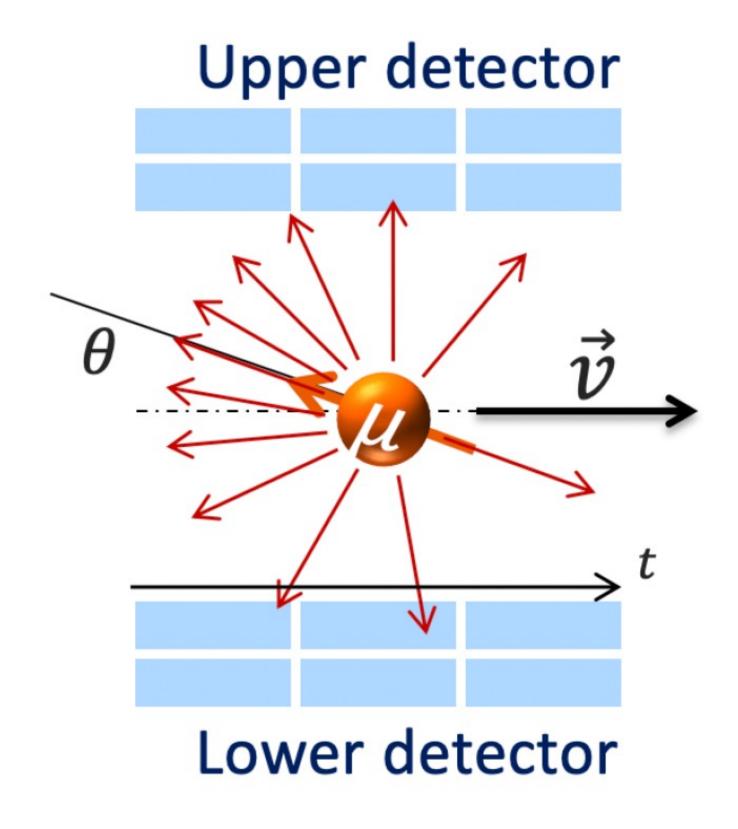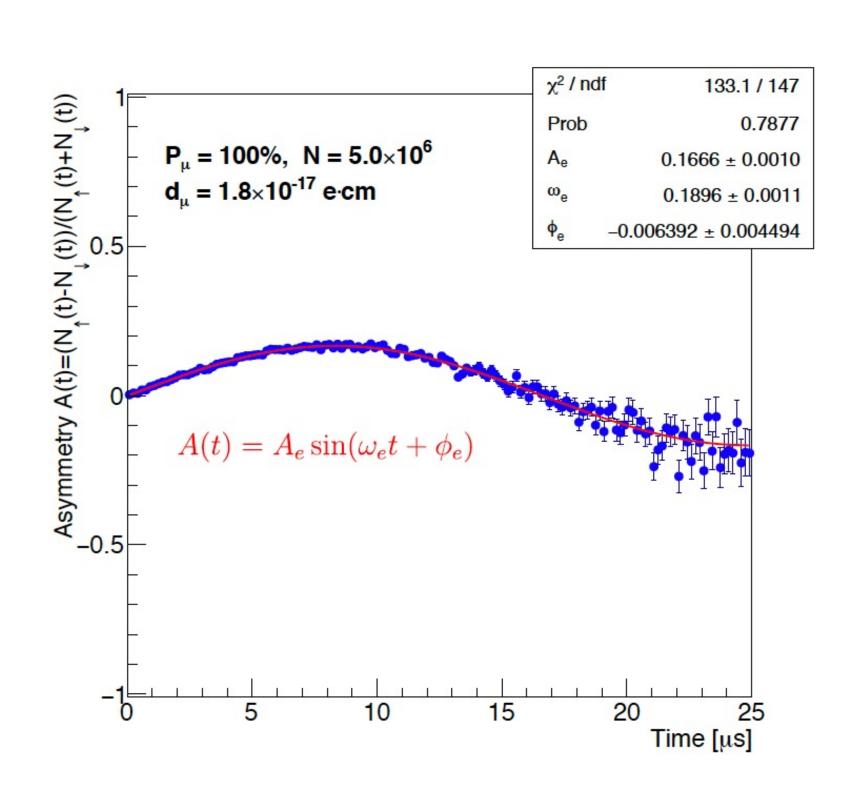  - → EDM causes an increasing vertical polarization

- Up-down asymmetry measured using upper and lower detectors



$P_\mu = 100\%, \quad N = 5.0 \times 10^6$

$d_\mu = 1.8 \times 10^{-17} \text{ e·cm}$

| $\chi^2$ / ndf | 133.1 / 147 |
|---|---|
| Prob | 0.7877 |
| $A_e$ | 0.1666 ± 0.0010 |
| $\omega_e$ | 0.1896 ± 0.0011 |
| $\phi_e$ | −0.006392 ± 0.004494 |

$A(t) = A_e \sin(\omega_e t + \phi_e)$

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

$P$ := initial polarization

$E_f$ := Electric field in lab

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

$\tau_\mu$ := lifetime of muon

$\alpha$ := mean decay asymmetry

# The PSI muEDM collaboration


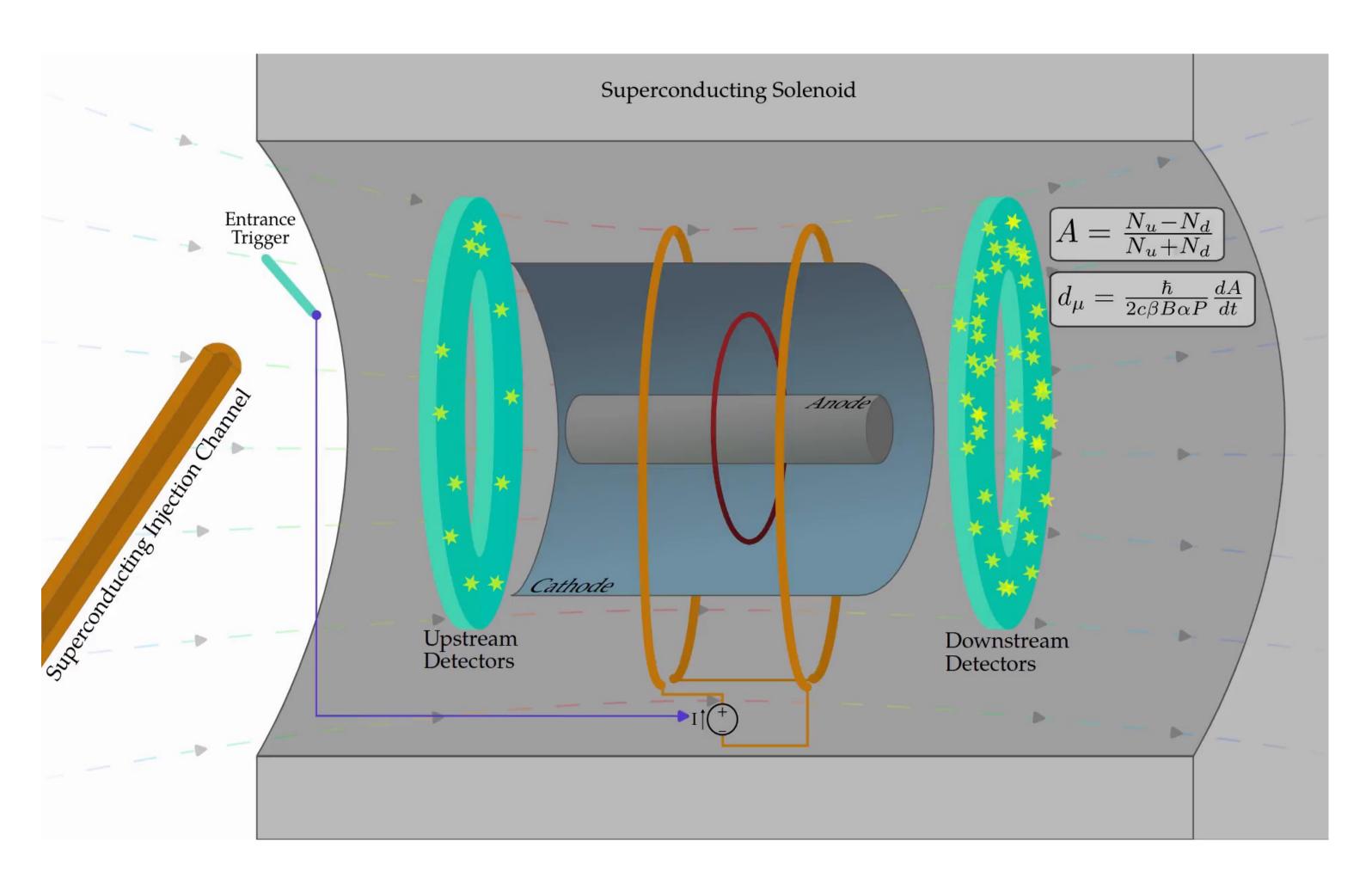
~ 30 active members from 6 countries

# Principle of the FS-EDM measurement

Superconducting Solenoid

Entrance Trigger

Superconducting Injection Channel

Anode

Cathode

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

$$d_\mu = \frac{\hbar}{2c\beta B\alpha P}\frac{dA}{dt}$$

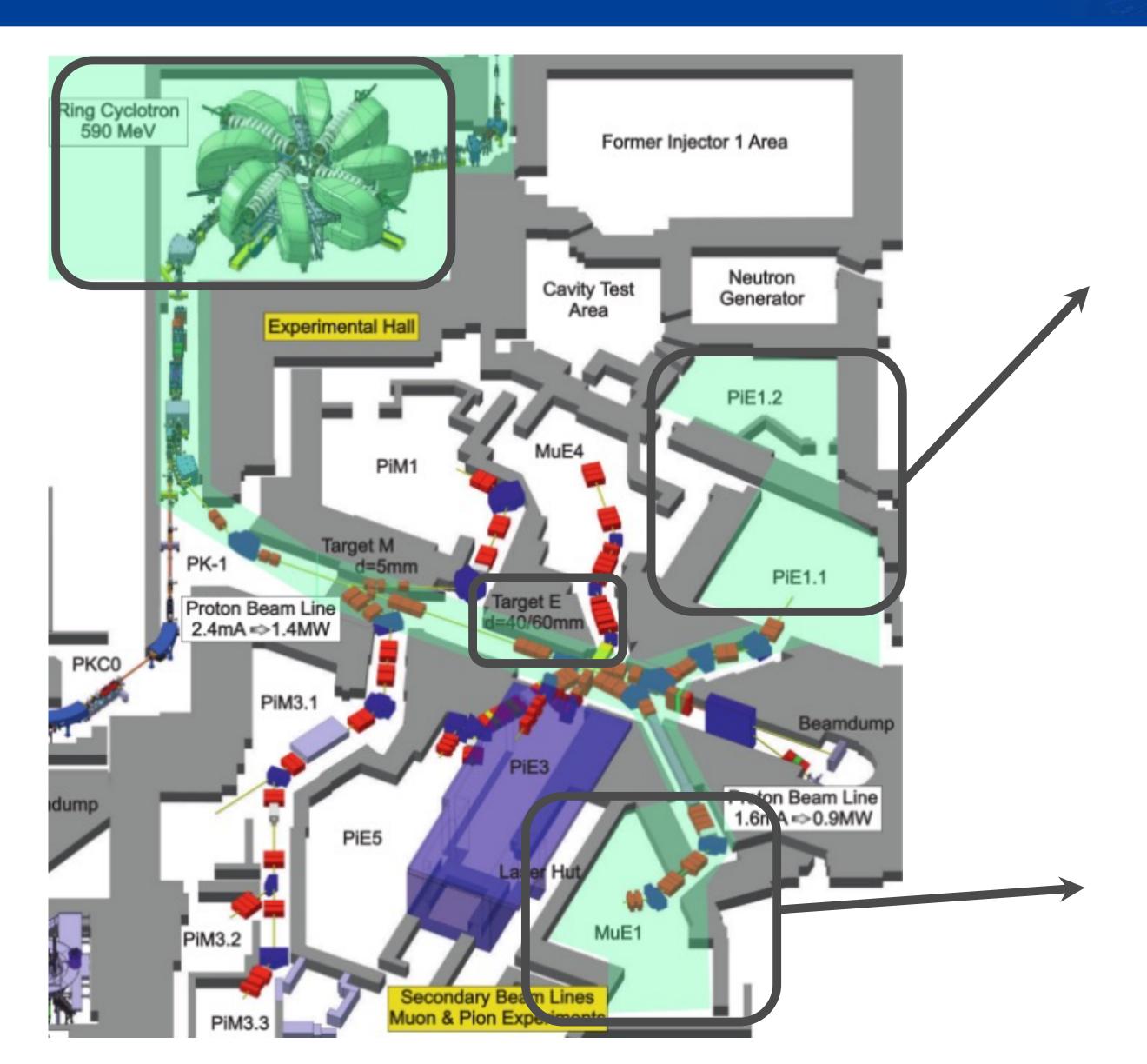Upstream Detectors

Downstream Detectors

- 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

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Phase 1:

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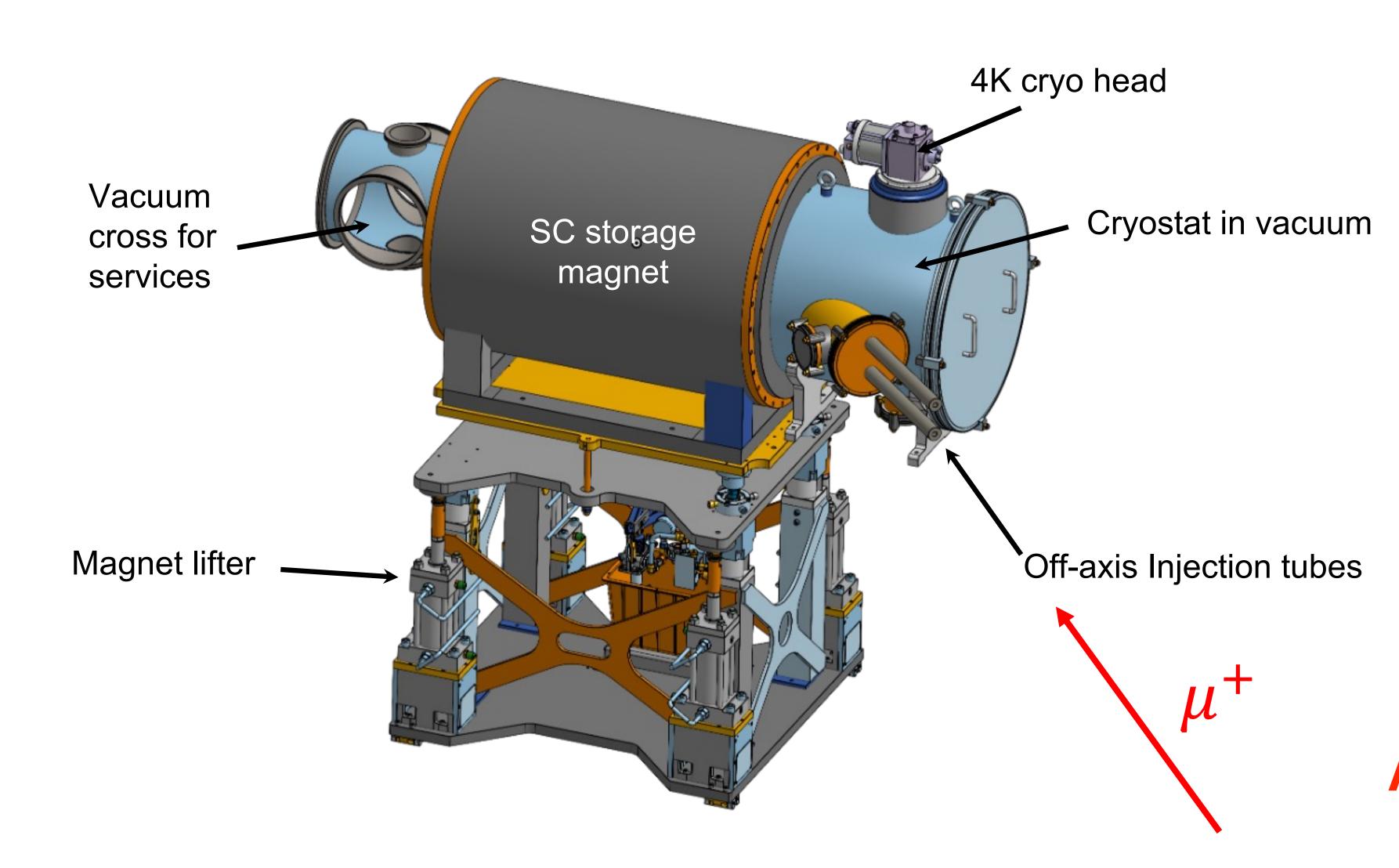- Sensitivity/year $< 3 \times 10^{-21}$ e·cm

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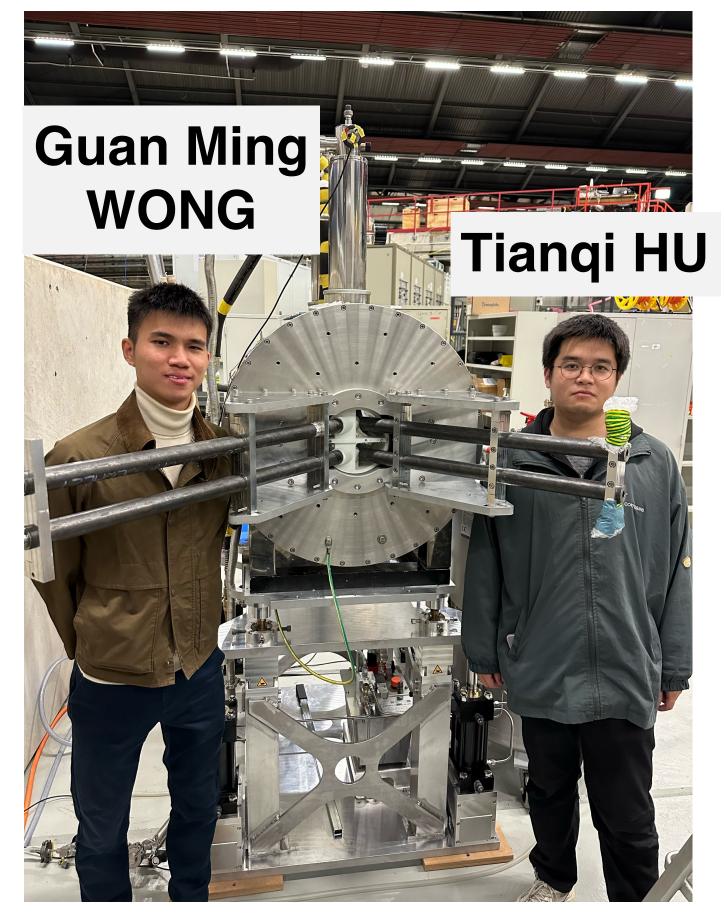
Phase 2:

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

4K cryo head

Vacuum cross for services

SC storage magnet

Cryostat in vacuum

Magnet lifter

Off-axis Injection tubes

$\mu^+$

Guan Ming WONG

Tianqi HU
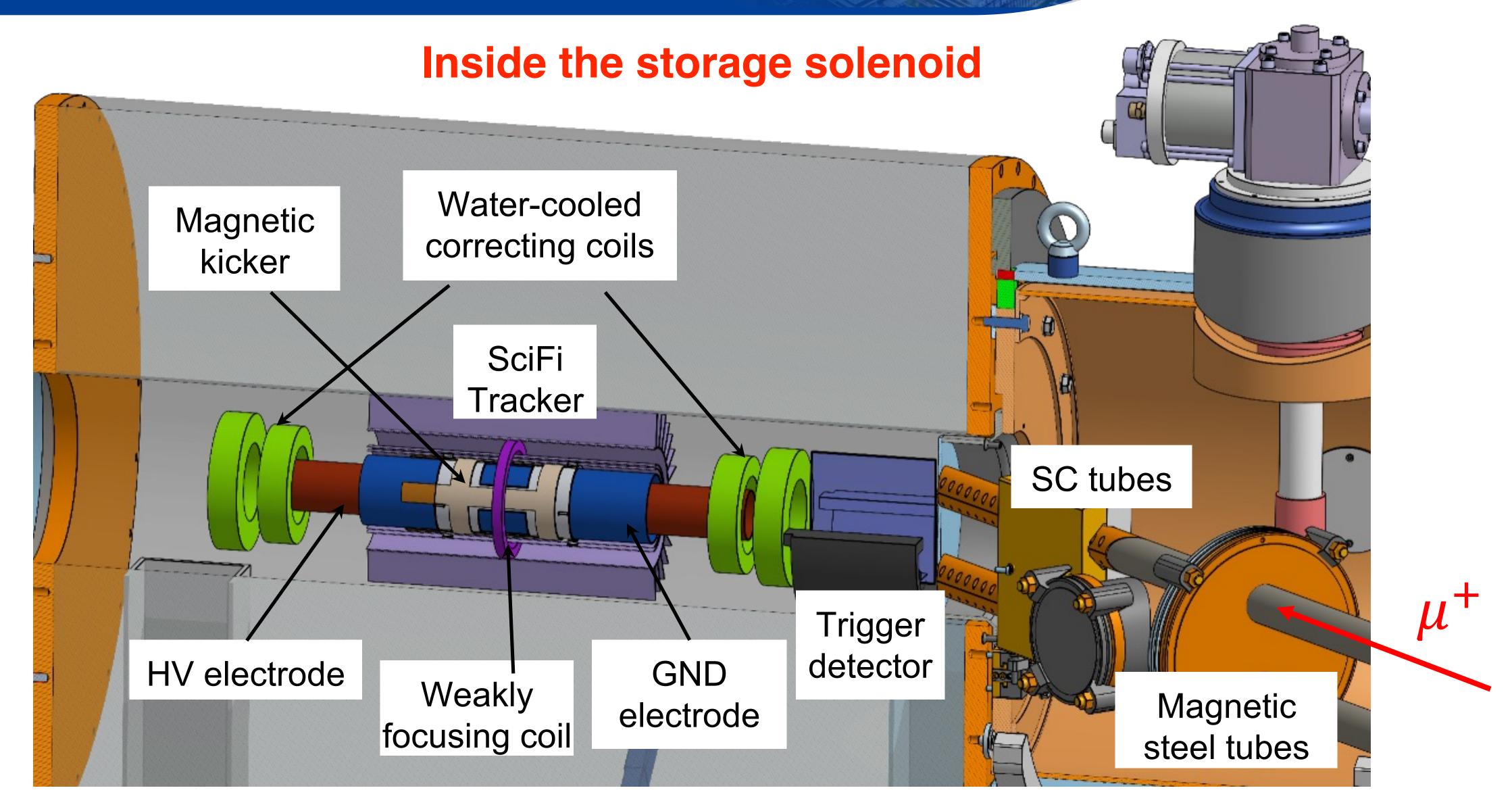
**A "tabletop" experiment**

**Inside the storage solenoid**
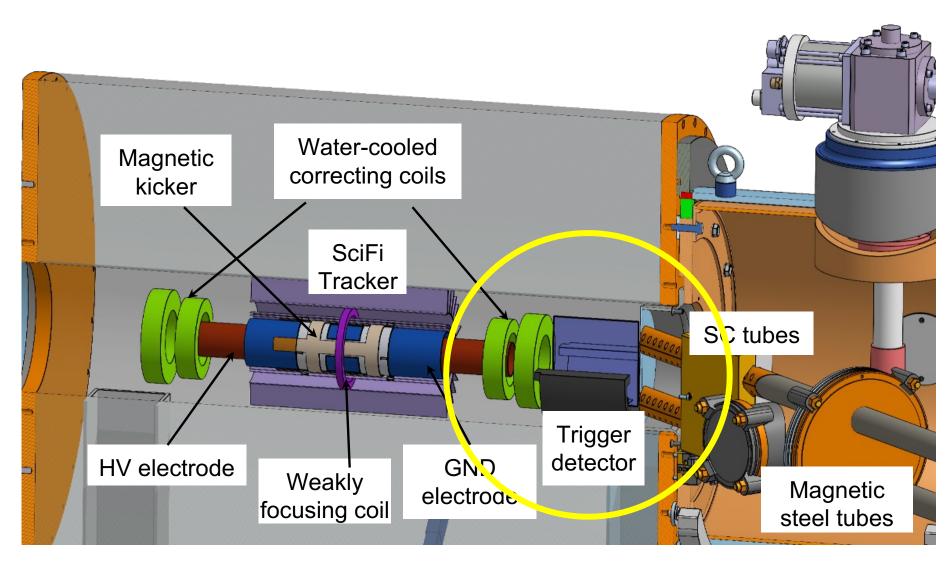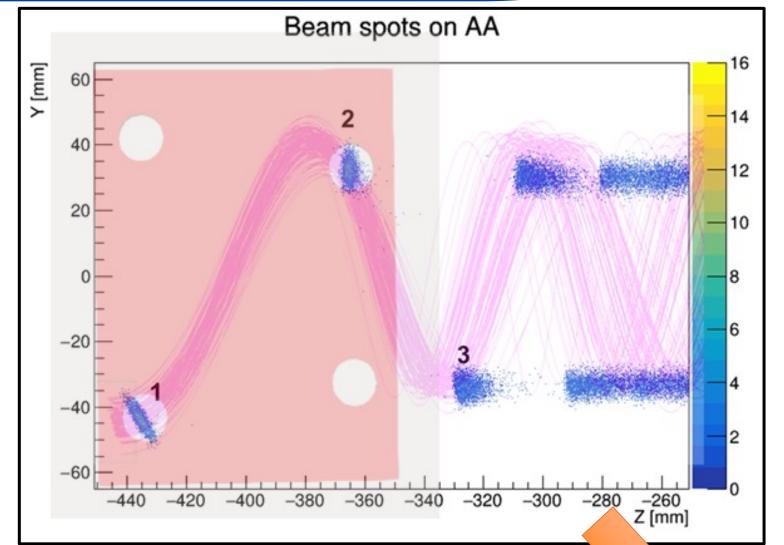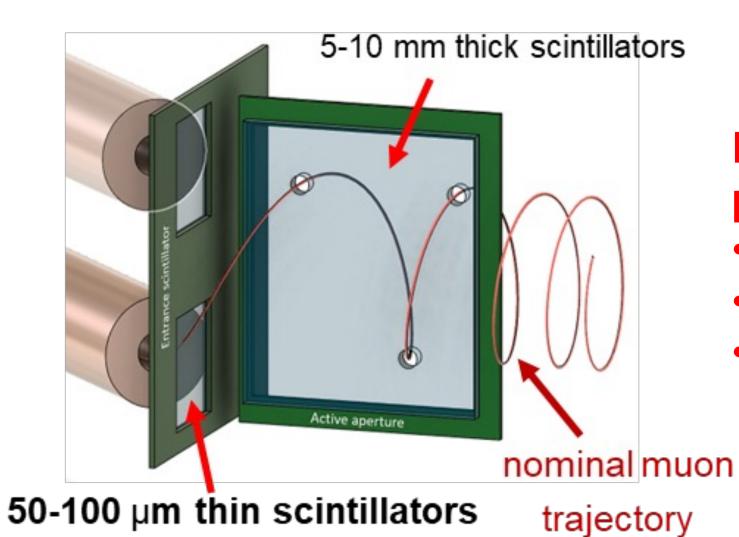
# Muon trigger detector
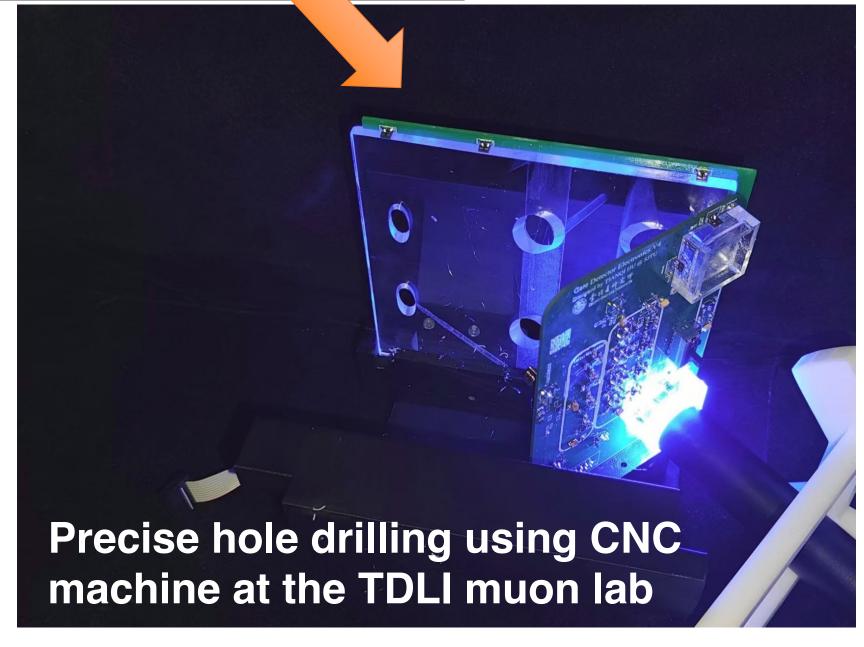




**Optimized detector geometry to maximize storage muons**



5-10 mm thick scintillators

Active aperture

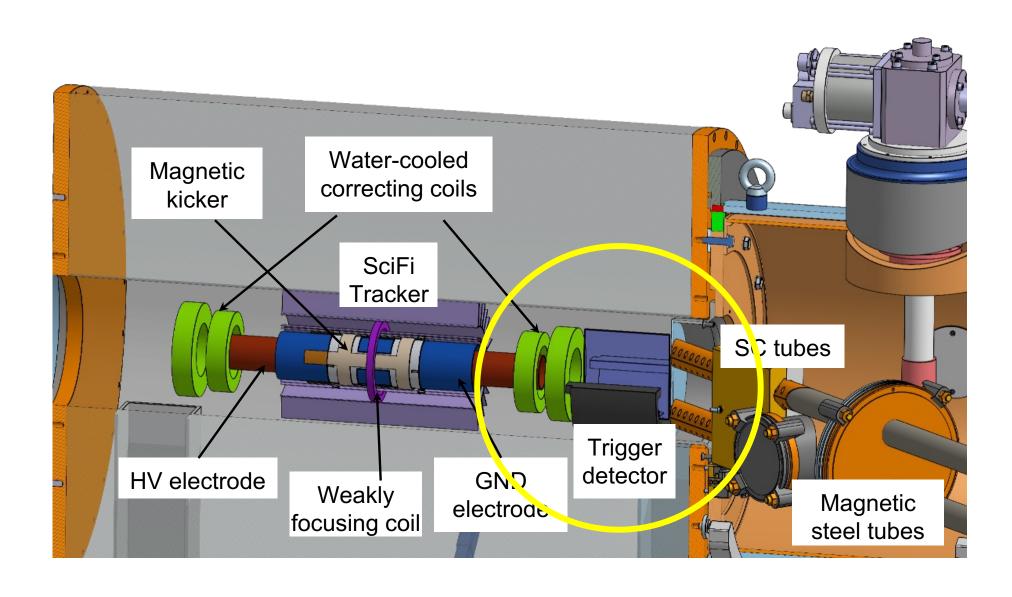nominal muon trajectory

50-100 μm thin scintillators

**Provides trigger signal of storage pulse kick**

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

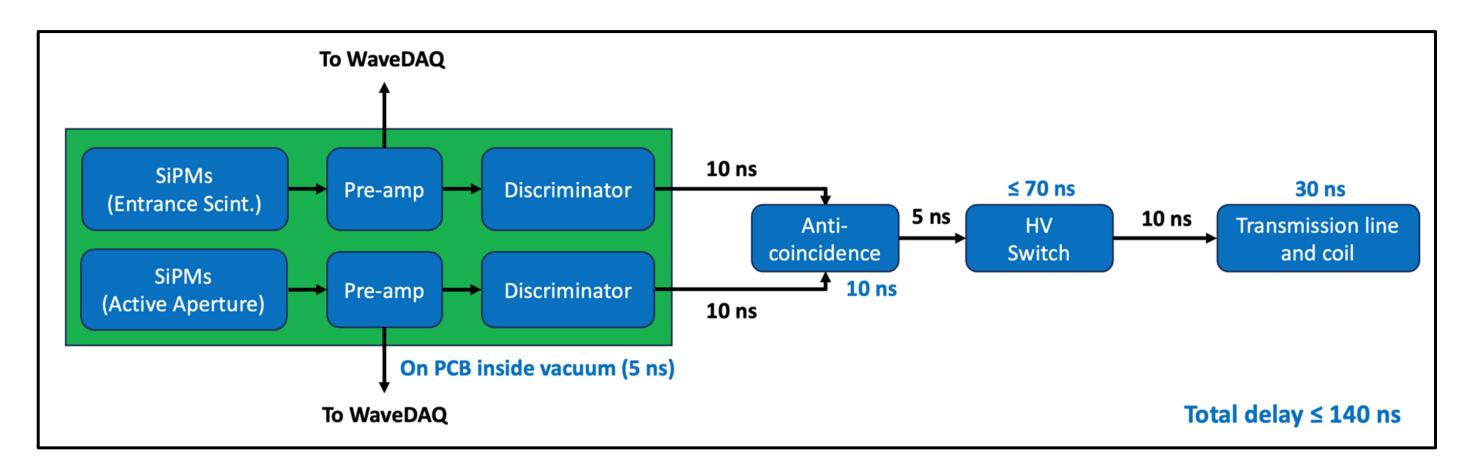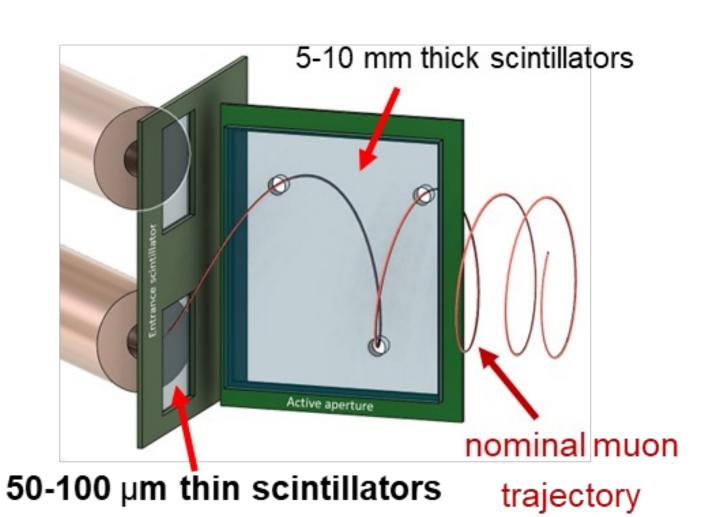**Precise hole drilling using CNC machine at the TDLI muon lab**
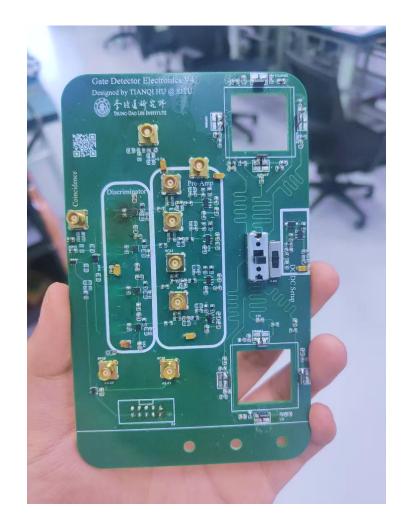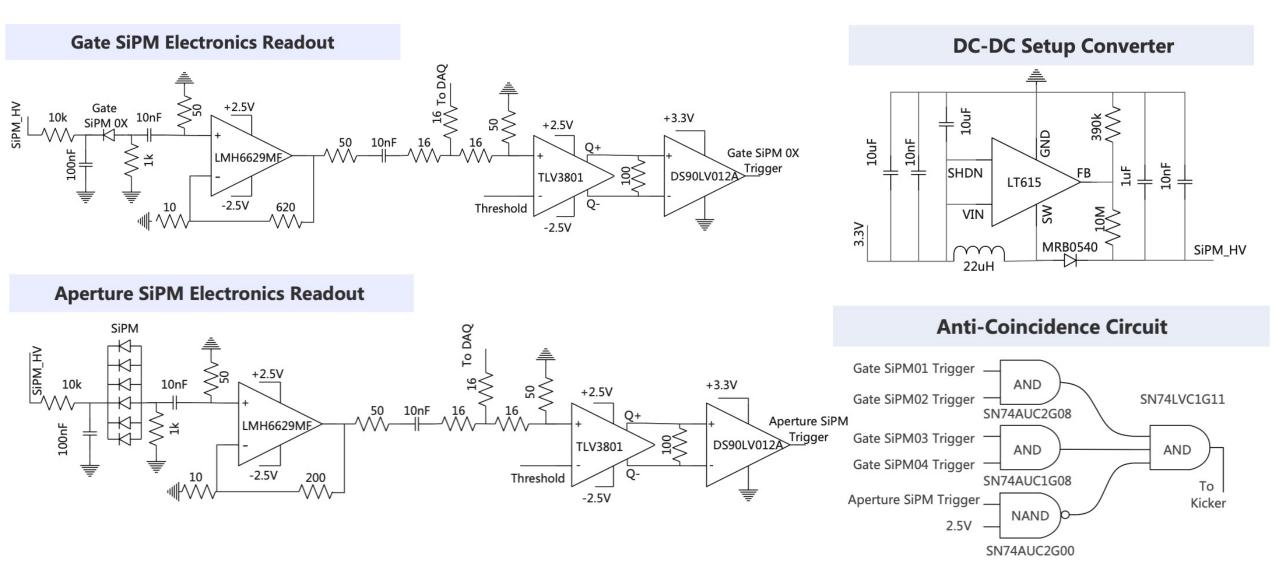
# Fast trigger for kicker coils



**Fast electronics design to satisfy stringent timing requirements**





5-10 mm thick scintillators

50-100 µm thin scintillators

nominal muon trajectory



**Gate SiPM Electronics Readout**
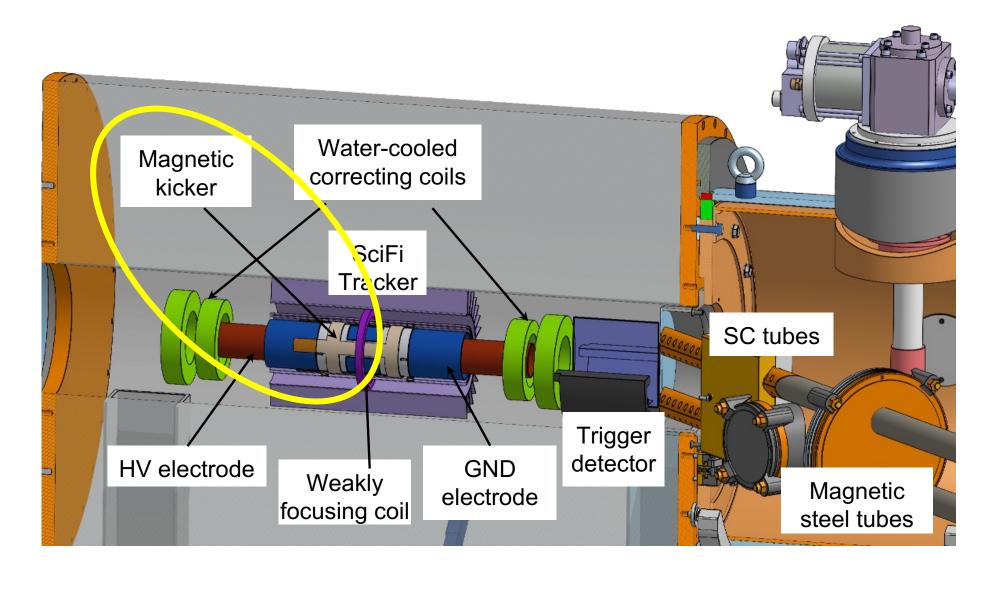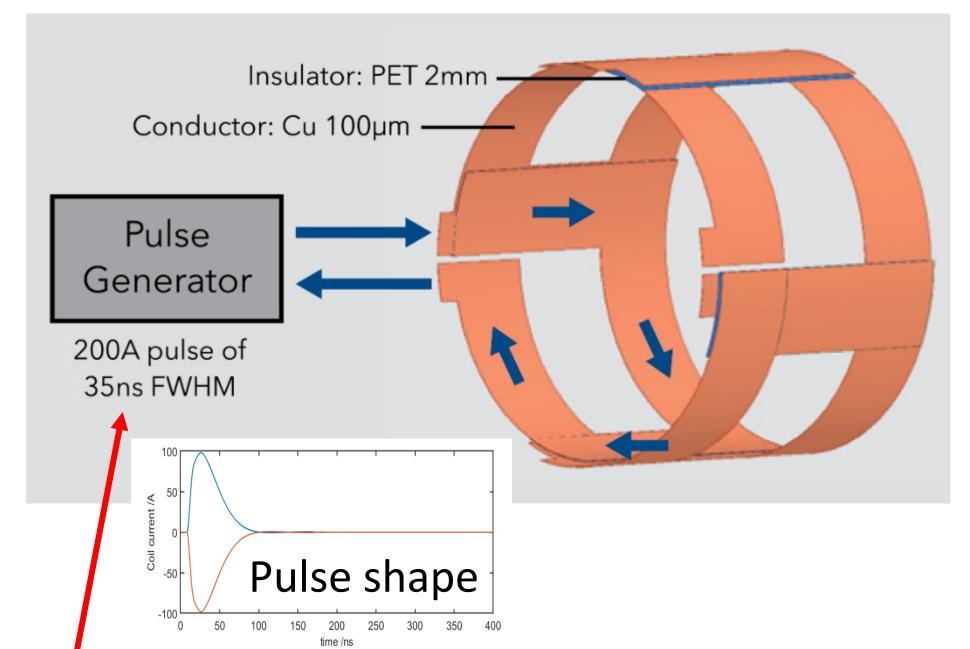
**Aperture SiPM Electronics Readout**

**DC-DC Setup Converter**

**Anti-Coincidence Circuit**
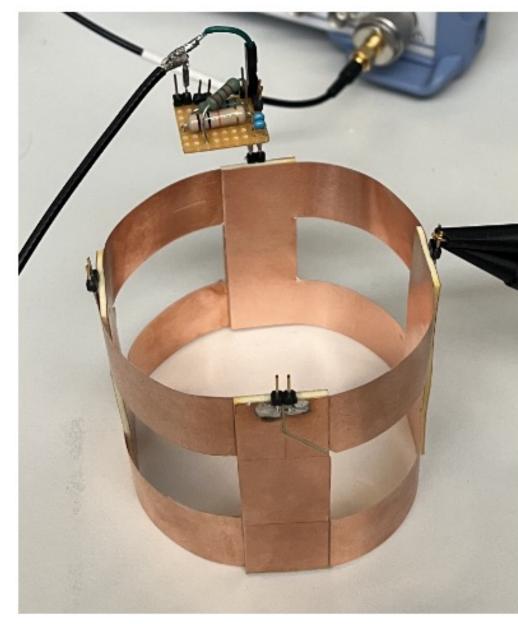
# Storage pulse kicker

**First prototype**



Magnetic kicker

Water-cooled correcting coils

SciFi Tracker

SC tubes

HV electrode

Weakly focusing coil

GND electrode

Trigger detector

Magnetic steel tubes

Insulator: PET 2mm

Conductor: Cu 100μm

Pulse Generator

200A pulse of 35ns FWHM

Pulse shape

To WaveDAQ

SiPMs (Entrance Scint.) — Pre-amp — Discriminator — 10 ns

SiPMs (Active Aperture) — Pre-amp — Discriminator — 10 ns

Anti-coincidence — 10 ns

5 ns

≤ 70 ns — HV Switch — 10 ns — 30 ns — Transmission line and coil

On PCB inside vacuum (5 ns)

To WaveDAQ

Total delay ≤ 140 ns
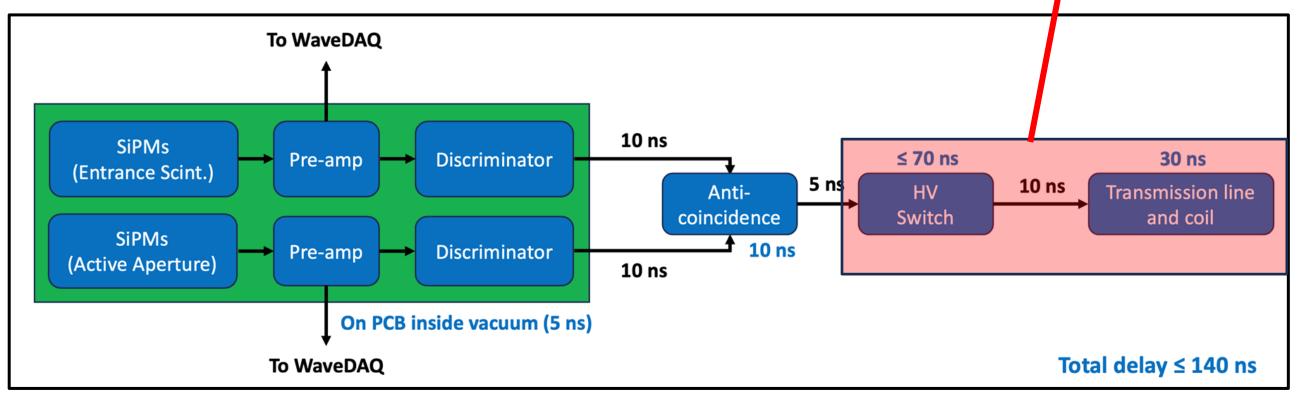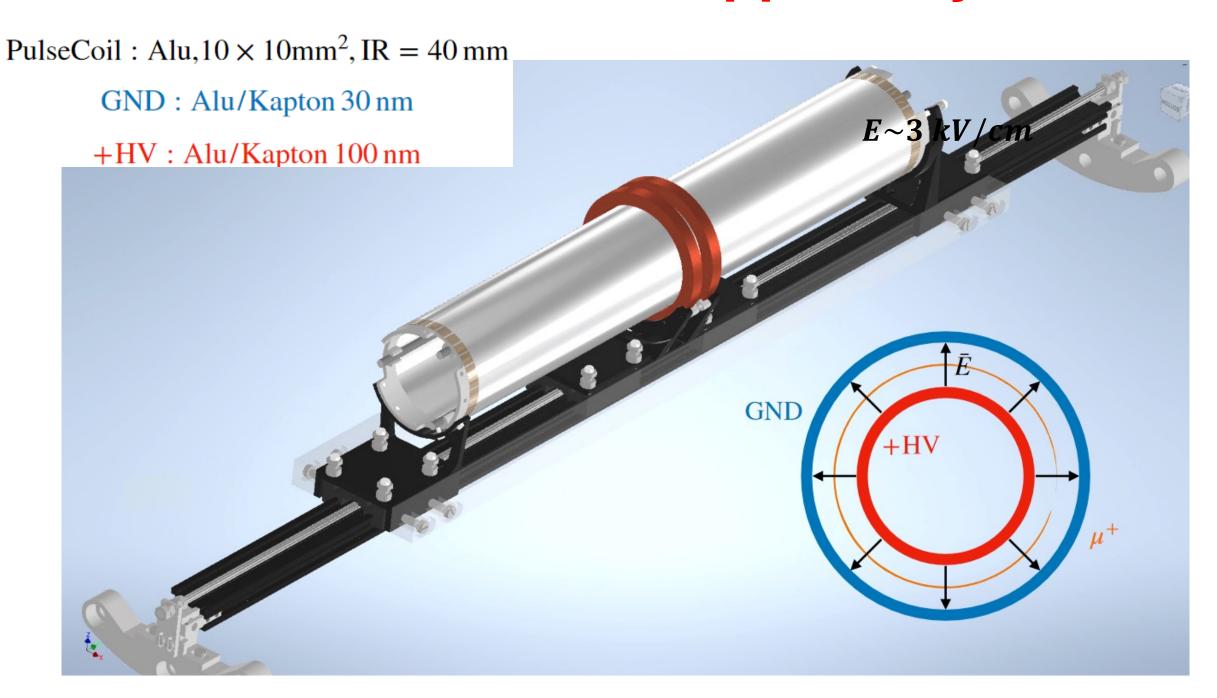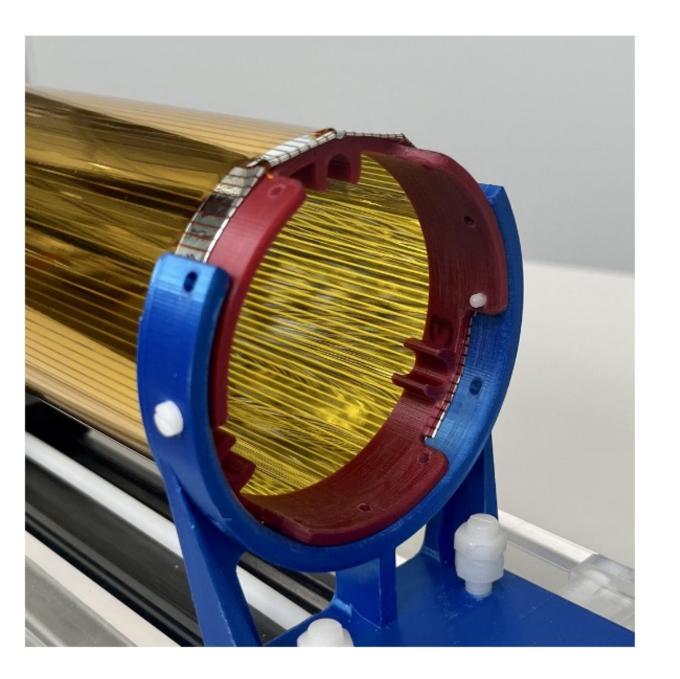
- Coil quadrants generating pulsed longitudinal kick to store muons

- Technical requirements:
  - large amplitude
  - rapid triggering of short-duration pulsed magnetic field, with strong tail suppression

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

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# Frozen-spin electrodes

## Radial electric field applied by two concentric electrodes enclosing muon orbit

PulseCoil : Alu, $10 \times 10 mm^2$, IR = 40 mm

GND : Alu/Kapton 30 nm

+HV : Alu/Kapton 100 nm

$E \sim 3\ kV/cm$

GND

$\vec{E}$

+HV

$\mu^+$

**Current solution:**

- 25 $\mu$m Kapton films
- Strip-segmented ~30 nm Al coating
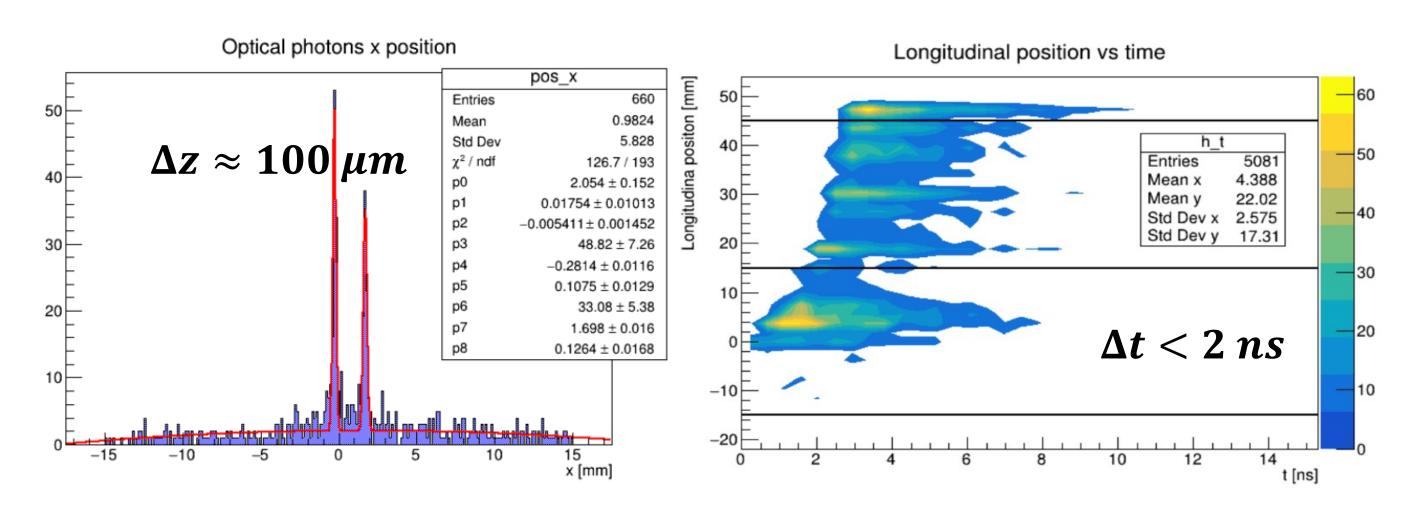- 2.2 mm pitch

**Technical requirements:**

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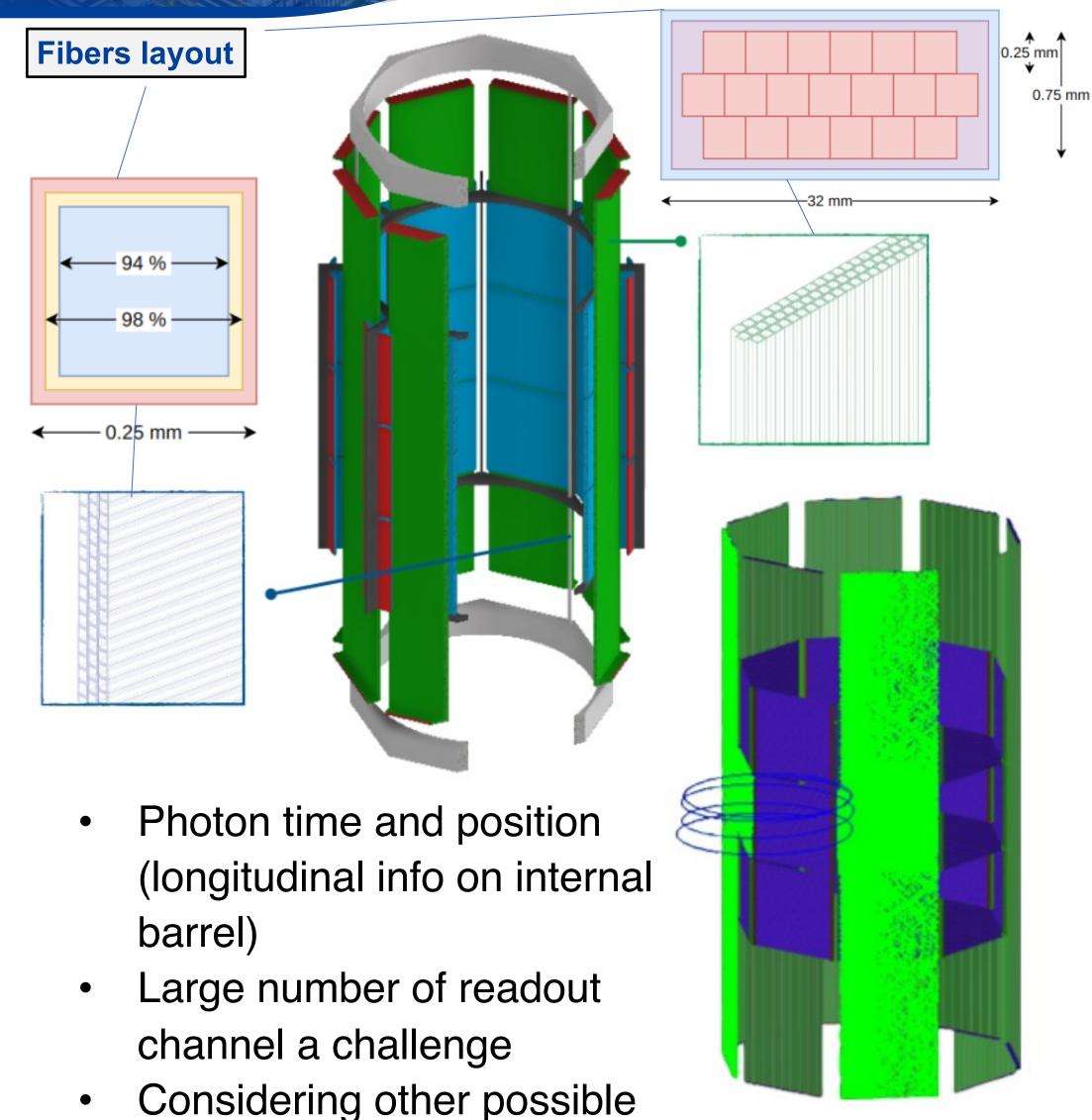- Minimal multiple scattering for positrons
- Suppress Eddy current

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
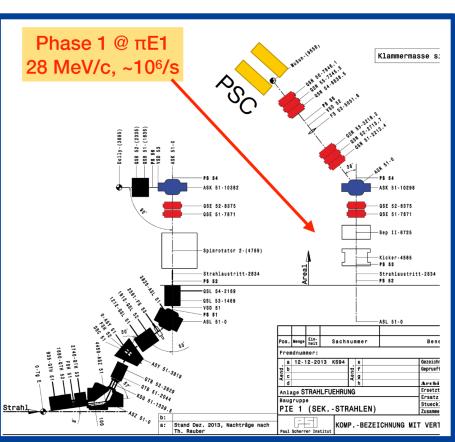


Fibers layout



$\Delta z \approx 100 \; \mu m$

$\Delta t < 2 \; ns$

- Photon time and position (longitudinal info on internal barrel)
- Large number of readout channel a challenge
- Considering other possible geometries
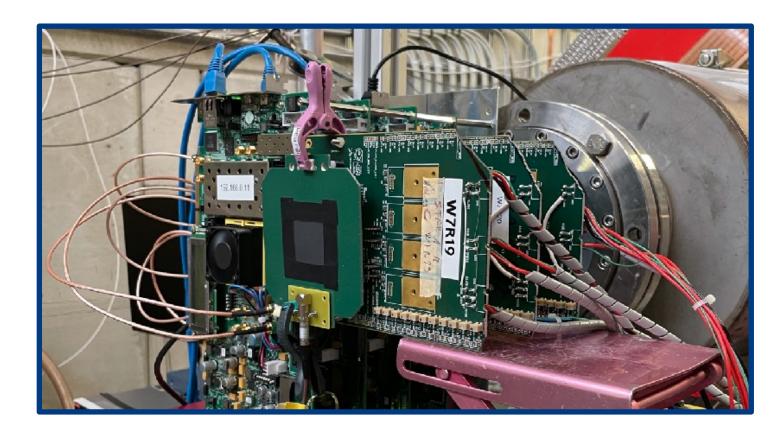
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# Annual beam tests at PSI

**2019**



**Characterisation of potential beam lines**

**2020**



**Study multiple scattering of e⁺ at low momenta**
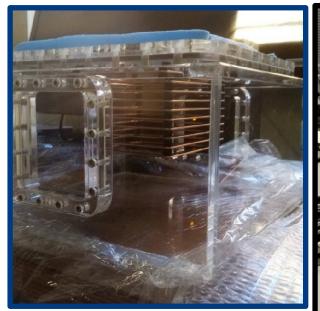
**2021**



**Characterization of potential electrode material with e⁺ and $\mu^+$**
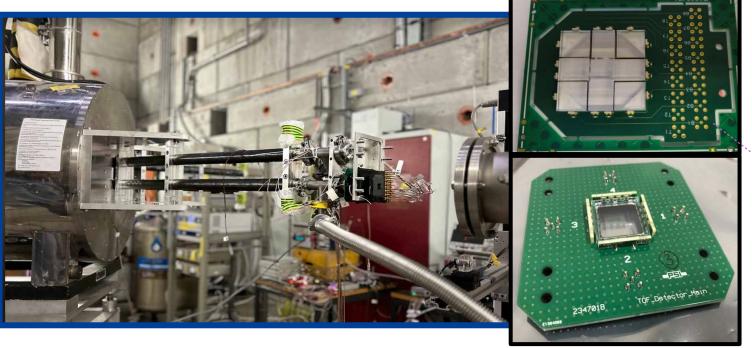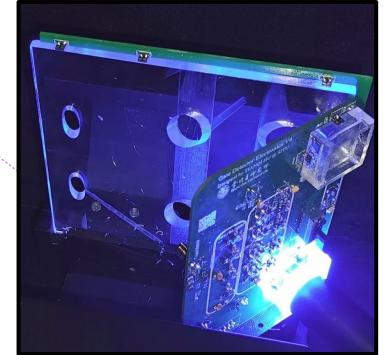
**2022**



**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**

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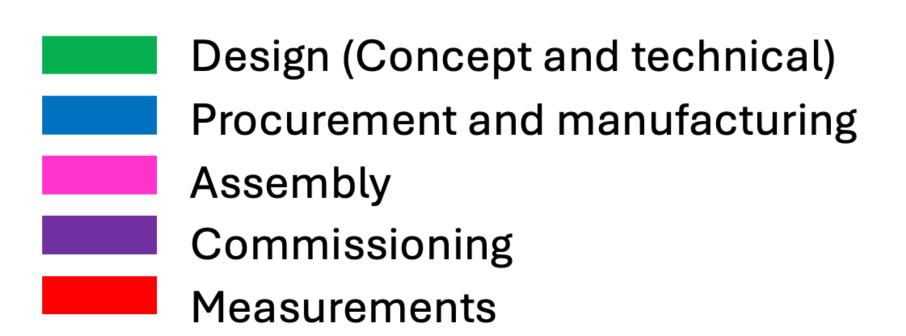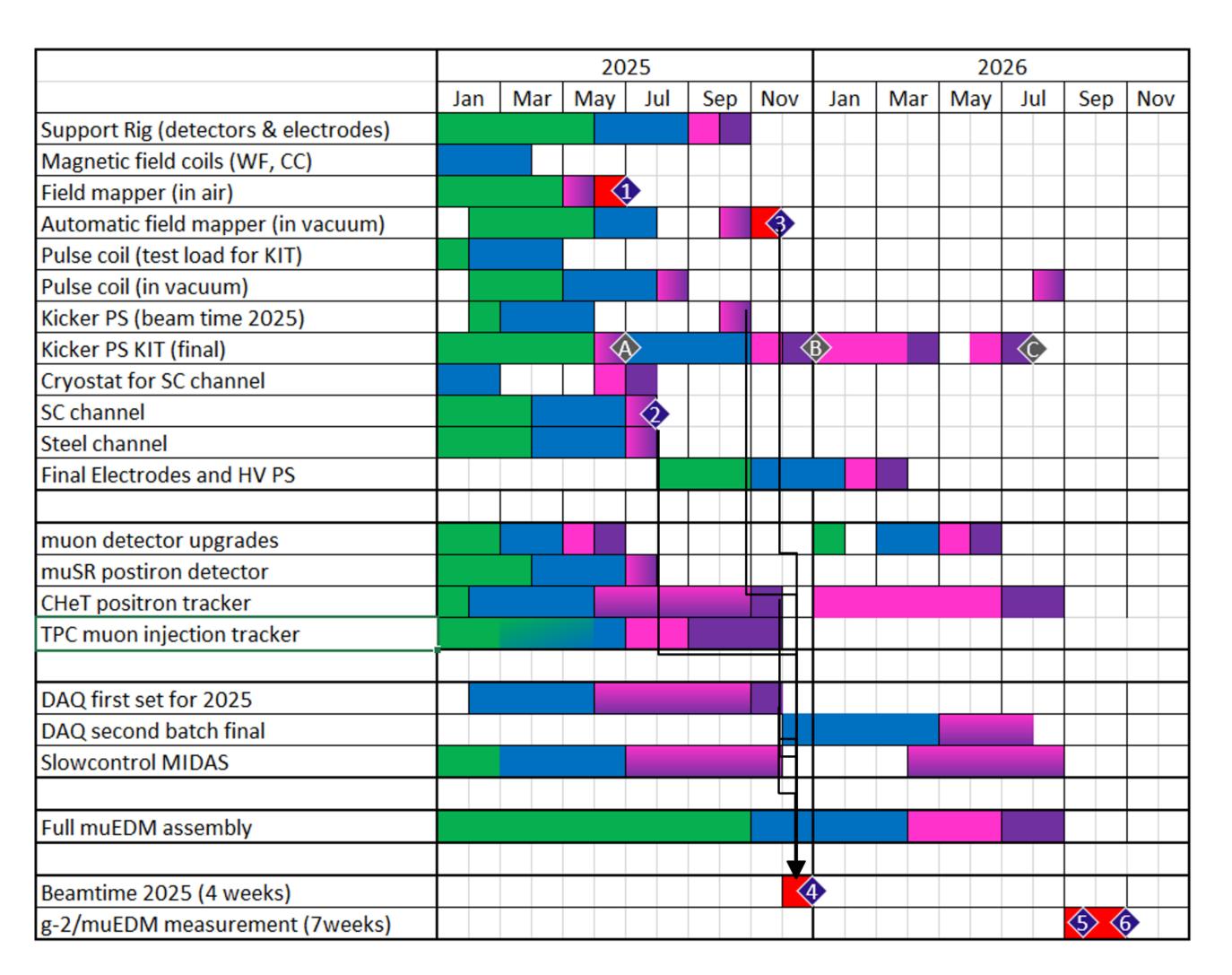
2025: Demonstration of

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 |

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# Summary and outlook

- **Muon g-2 at Fermilab**

  - Final results released, reached 127 ppb uncertainty!

  - In good agreement with TI WP 2025 (HVP based on LQCD)

  - However, more work is needed to understand the data-driven approach versus LQCD

  - BSM searches ongoing: EDM, CPT/LV, Dark Matter

- **Muon EDM at PSI**
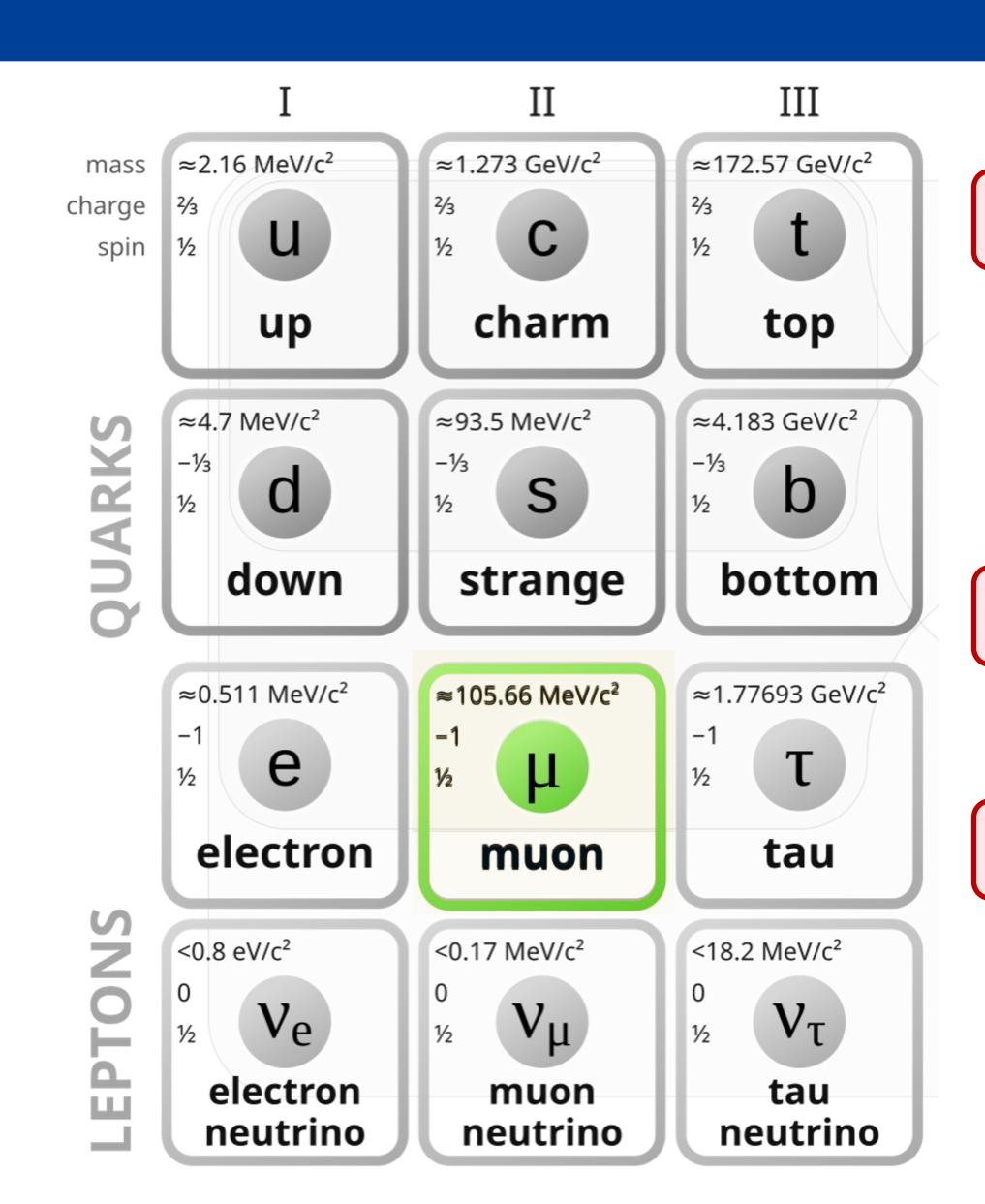
  - Aiming for sensitivity $10^{-23}$ e·cm using the frozen-spin technique.

  - Phase I progressing well: Beam tests since 2019, first measurement expected by 2026.

  - Sensitive to new CP-violation sources, complementary to Muon g-2

  - BSM searches to be performed: Muonphilic Dark Matter

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

Thank you for your attention!

# Why the muon?



**Muons ~ 200 times heavier than electrons**

- Electron g-2 is ~1,000 times more precise, but muon's sensitivity is ~40,000 times greater to quantum loop effects

**Relatively long lifetime of 2.2 µs**

- It can be produced copiously and stored

**Muon spin is self-analyzing**
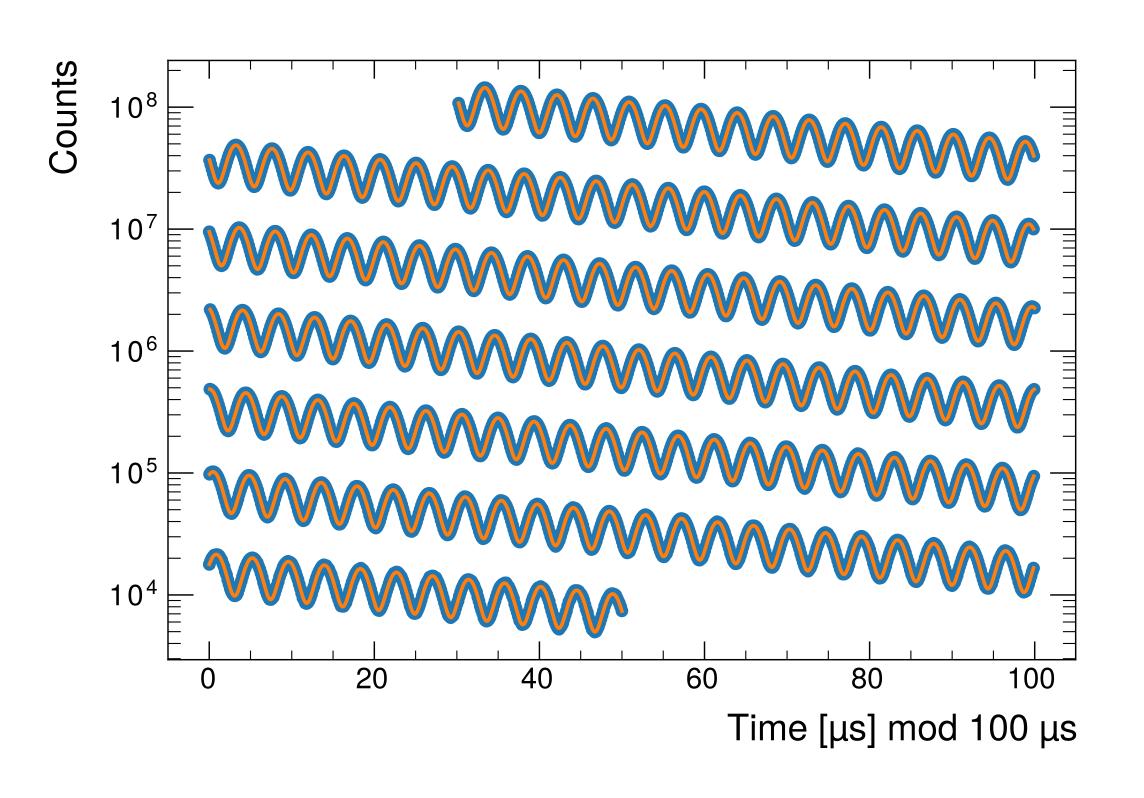
- Decay positrons are emitted primarily along the muon spin direction.
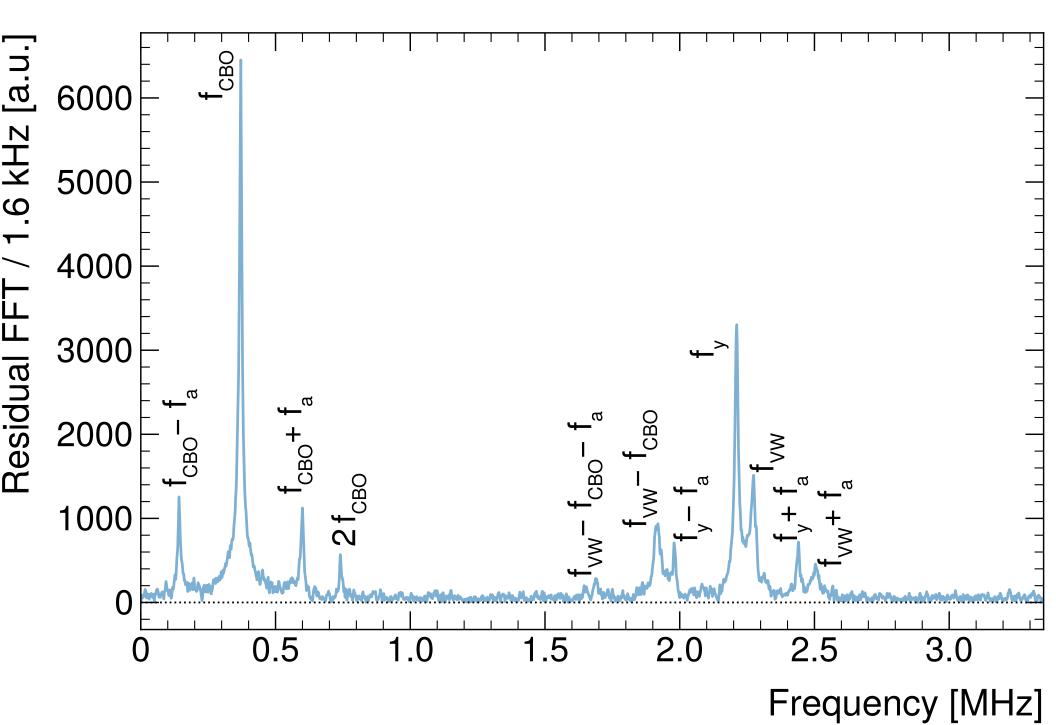
Simplest fit model captures **exponential decay** & **g-2 oscillation**

$$N(t) = N_0 \, e^{-t/\tau} \left[ 1 + A \cos(\textcolor{red}{\omega_a} t - \phi_0) \right]$$



**Larger statistics reveal even more prominent frequency components.**
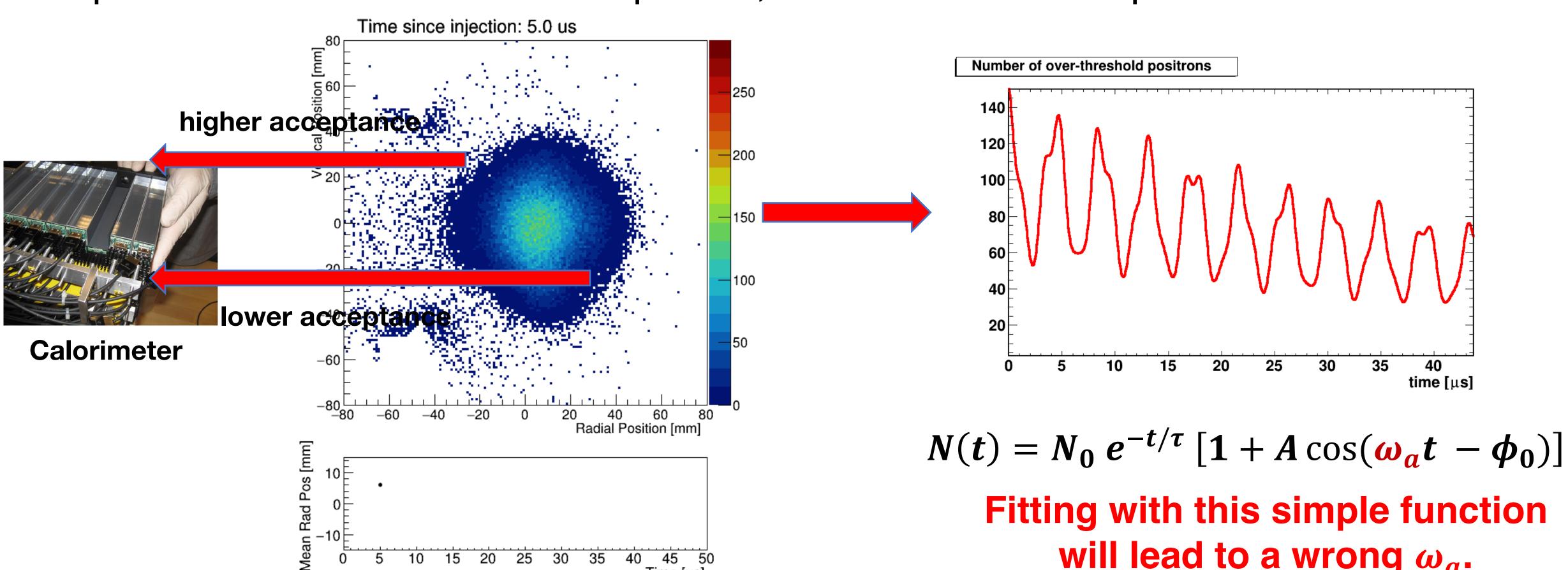
- Stored muon beam exhibits coherent betatron oscillation (CBO)
- Coupled with the calorimeter acceptance, it distorts the time spectrum



higher acceptance

lower acceptance

Calorimeter

$$N(t) = N_0\, e^{-t/\tau}\,[1 + A\cos(\omega_a t - \phi_0)]$$

**Fitting with this simple function will lead to a wrong $\omega_a$.**

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# Ultralight Bosonic DM

DM is manifest locally as a AC classical background field

$$\phi(t) = \phi_0 \cos(m_{\mathrm{dm}} t)$$

$10^{-21}$ eV = 1 year

$10^{-13}$ eV = fill rate

$10^{-11}$ eV = bunch duration

$10^{-9}$ eV = $\omega_a$

| DM mass: | $10^{-22}$ eV | $10^{-18}$ eV | $10^{-14}$ eV | $10^{-10}$ eV | $10^{-6}$ eV | $10^{-2}$ eV | $10^2$ eV |
| --- | --- | --- | --- | --- | --- | --- | --- |
| | $10^{-8}$ Hz | $10^{-4}$ Hz | 1 Hz | $10^4$ Hz | $10^8$ Hz | $10^{12}$ Hz | |

DM field is static over each bunch, but oscillates many times over the lifetime of the experiment.

## A Scalar DM Precession Signal

Scalar DM $\phi$ of mass $m_\phi$ with a muon Yukawa coupling:

$$\mathcal{L} \supset y\,\phi\,\bar{\mu}\mu$$

DM background field is:

$$\phi(t) = \sqrt{\frac{2\rho_{\mathrm{dm}}}{m_\phi}}\cos(m_\phi t)$$

DM field generates a time-varying muon mass and MDM:

$$m(t) = m_\mu + y\phi(t)$$

$$\vec{\mu} = \frac{e\,g_\mu}{2\,m(t)}\vec{S}$$

Ryan Janish[1,2] and Harikrishnan Ramani[1,3,4]
[1]Department of Physics, University of California, Berkeley, California 94720, USA
[2]Theoretical Physics Department, Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
[3]Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
[4]Stanford Institute for Theoretical Physics, Stanford University, Stanford, California 94305, USA

## A DM EDM Signal

Pseudoscalar DM of mass $m_a$ with an EDM interaction:

$$\mathcal{L} \supset -\frac{i}{2}g\,a\,\bar{\mu}\,\sigma_{\alpha\beta}\,\gamma_5\,\mu\,F^{\alpha\beta}$$

DM field generates an time-varying EDM for the muon. The precession frequency is:

$$\vec{\omega}_a = \omega_{sm}\hat{B} + \omega_{dm}\cos(m_a t)\left(\hat{p}\times\hat{B}\right)$$

$$\omega_{dm} = 2g\frac{\sqrt{2\rho_{dm}}}{m_a}v_\mu B$$

## ALP-Muon Wind

$$\mathcal{L} \supset g\,\partial_\nu a\,\bar{\mu}\,\gamma^\nu\gamma_5\,\mu$$

In the rest frame of the muon: $H \supset g\,\vec{\nabla}a\cdot\vec{S}$

Muon spin precesses about the relative velocity of DM, which is essentially the muon velocity.

$$\vec{\omega}_a = \omega_{sm}\hat{B} + \omega_{dm}\cos(m_a t)\,\hat{v}$$

$$\omega_{dm} = g\,\sqrt{2\rho_{dm}}$$

## Muonic Vector DM

Ultralight vector DM manifests as a local dark electric and magnetic field:

$$E_{\mathrm{dm}} = \sqrt{2\rho_{\mathrm{dm}}}\cos(m_{\mathrm{dm}} t)$$

$$B_{\mathrm{dm}} = v_{\mathrm{dm}} E_{\mathrm{dm}}$$

Four distinct contributions to precession – the dominant one is the component of $\vec{E}_{\mathrm{dm}}$ transverse to the orbital plane:

$$\vec{\omega}_{\mathrm{dm}} = \frac{g_{\mathrm{dm}}}{m_\mu \gamma^2}\,\vec{v}\times\vec{E}_{\mathrm{dm}}$$

# Ultralight Bosonic DM limits

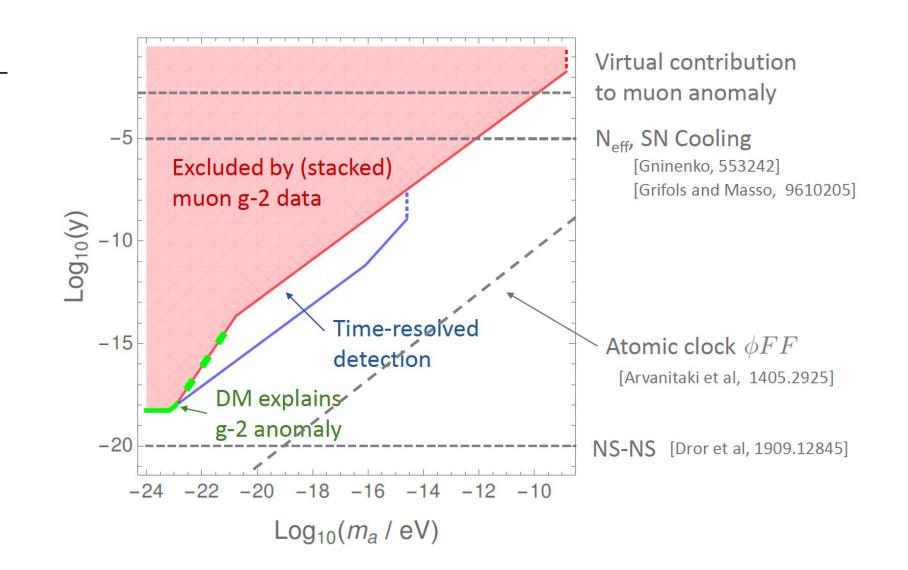**Muon g-2 and EDM experiments as muonic dark matter detectors**

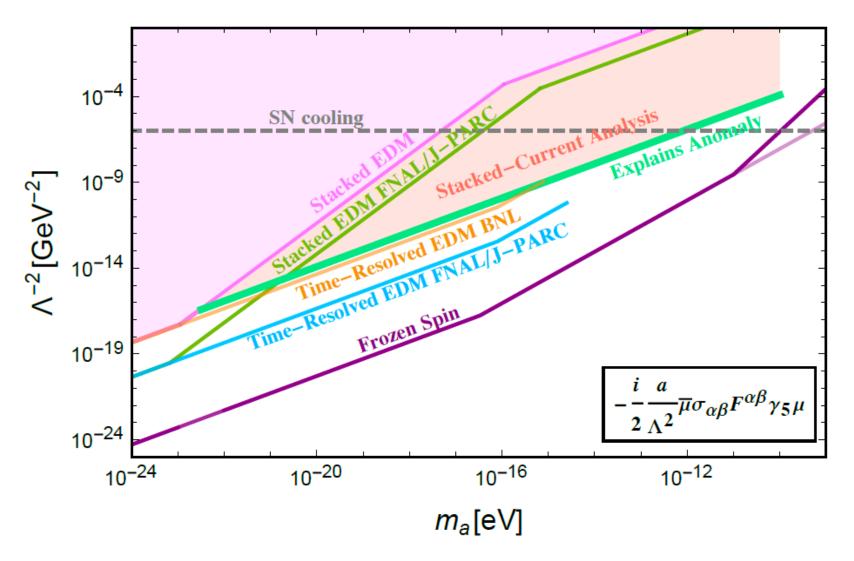Ryan Janish[1,2] and Harikrishnan Ramani[1,3,4]

[1]Department of Physics, University of California, Berkeley, California 94720, USA
[2]Theoretical Physics Department, Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
[3]Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
[4]Stanford Institute for Theoretical Physics, Stanford University, Stanford, California 94305, USA
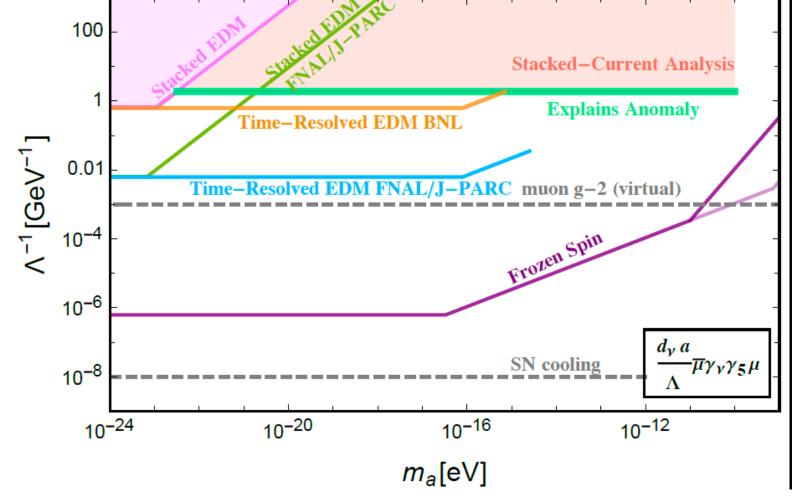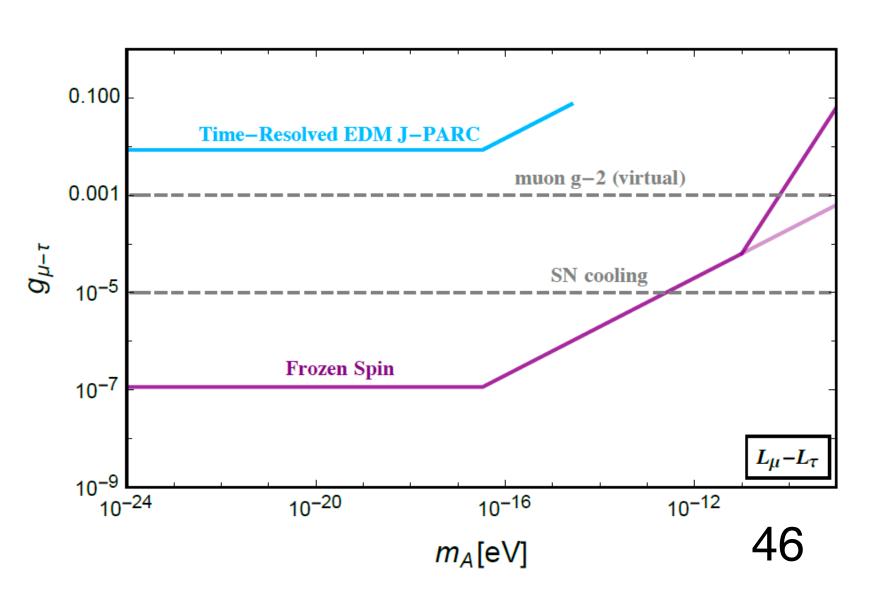
The detection of ultralight dark matter through interactions with nucleons, electrons, and photons has been explored in depth. In this work we propose to use precision muon experiments, specifically muon g-2 and electric dipole moment measurements, to detect ultralight dark matter (DM) that couples predominantly to muons. We set direct, terrestrial limits on DM-muon interactions using existing g-2 data, and show that a time-resolved reanalysis of ongoing and upcoming precession experiments will be sensitive to dark matter signals. Intriguingly, we also find that the current muon g-2 anomaly can be explained by a spin torque applied to muons from a pseudoscalar dark matter background that induces an oscillating electric dipole moment for the muon. This explanation may be verified by a time-resolved reanalysis.

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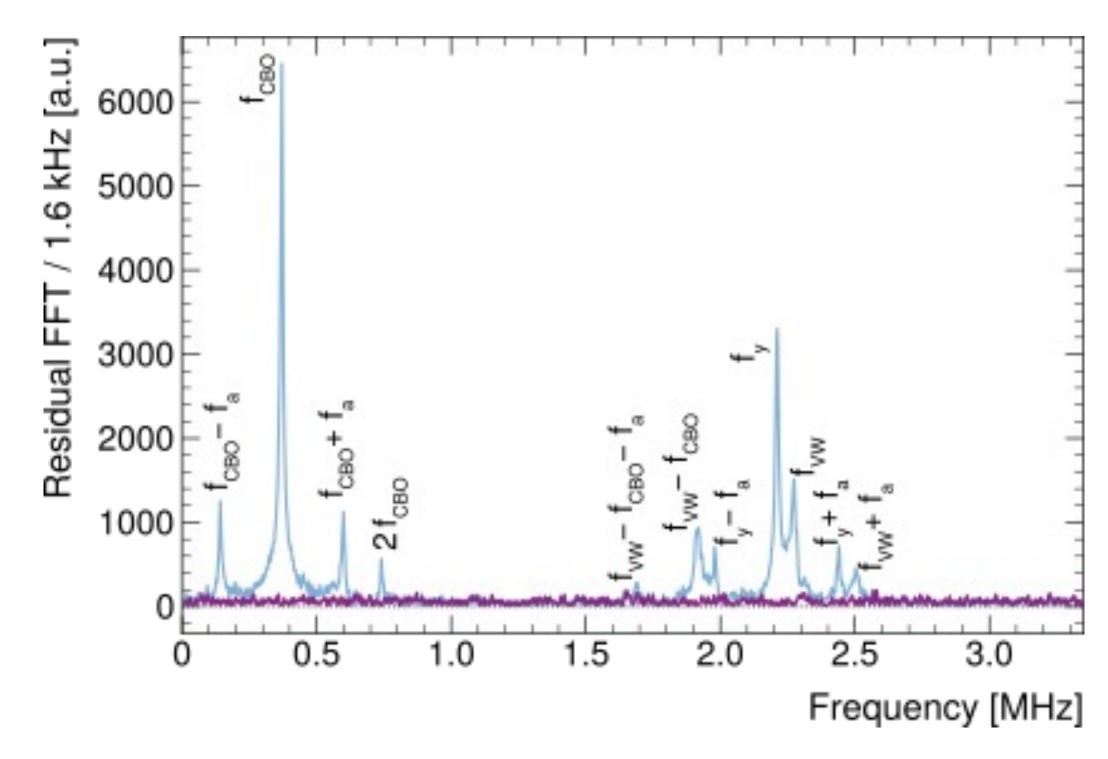Simplest fit model captures **exponential decay** & **g-2 oscillation**

$$N(t) = N_0\, e^{-t/\tau}\, [1 + A\cos(\omega_a t - \phi_0)]$$

Must account for **beam oscillations**, **muons losses**, and **detector effects**

**Example:**

Beam dynamics modeling, such as CBO

- If not accounted for: **~800 ppb** effect without the additional RF

- If not accounted for: **~80 ppb** effect with the additional RF



**Final fit functions include 40+ additional parameters to model these effects!**

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# Corrections: Time-Dependent Mean Phase

## Phase Acceptance $C_{pa}$

- Detector Acceptances x Beam Motion

## Differential Decay $C_{dd}$

- Momentum-dependent muon lifetime x phase-momentum correlations

## Muon Loss $C_{ml}$

- Muons scattered out from the storage ring
- Negligible in Run-4/5/6