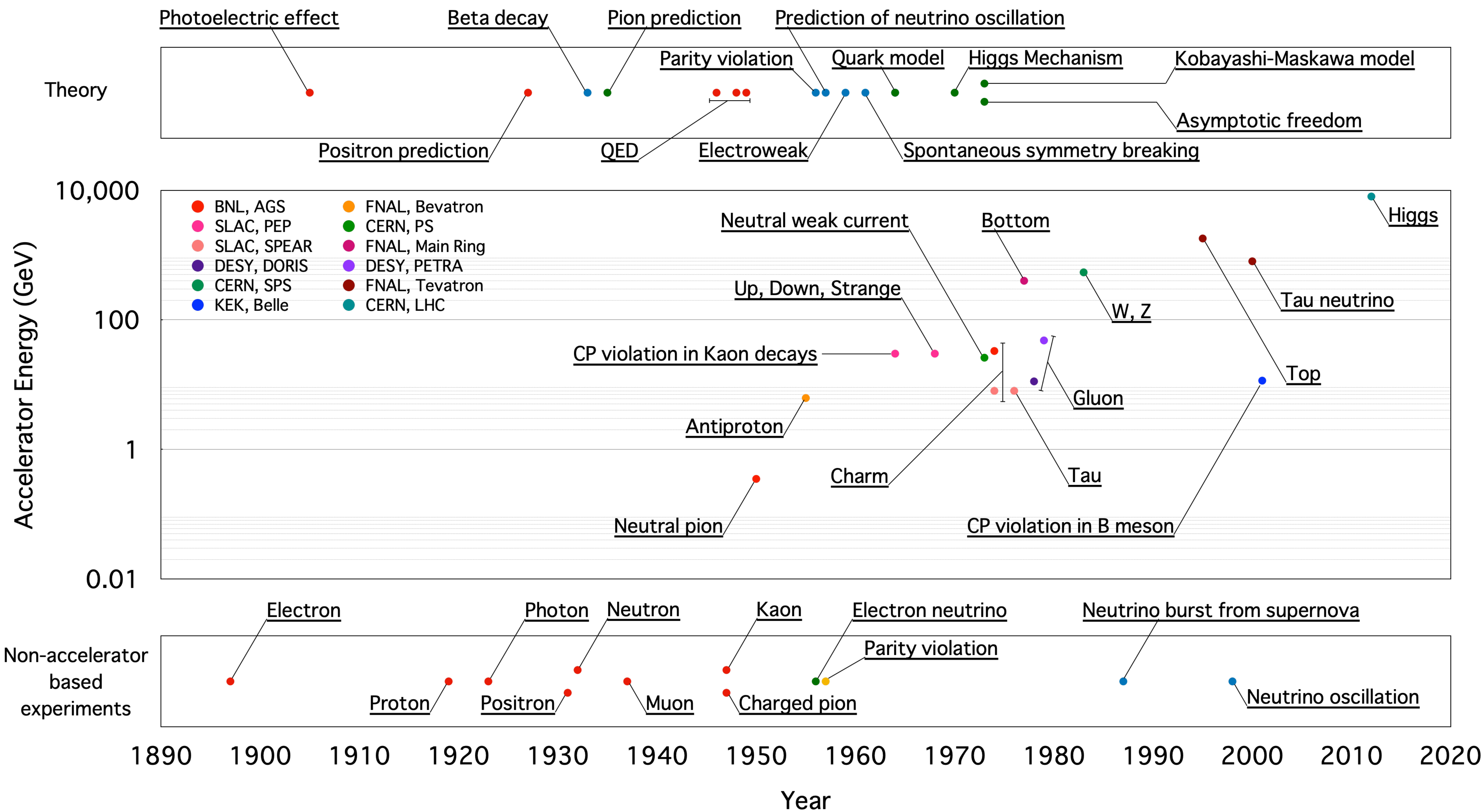
Present and Future of Muon Experiments

Sohtaro Kanda (神田 聡太郎) / KEK IMSS MSL / kanda@post.kek.jp

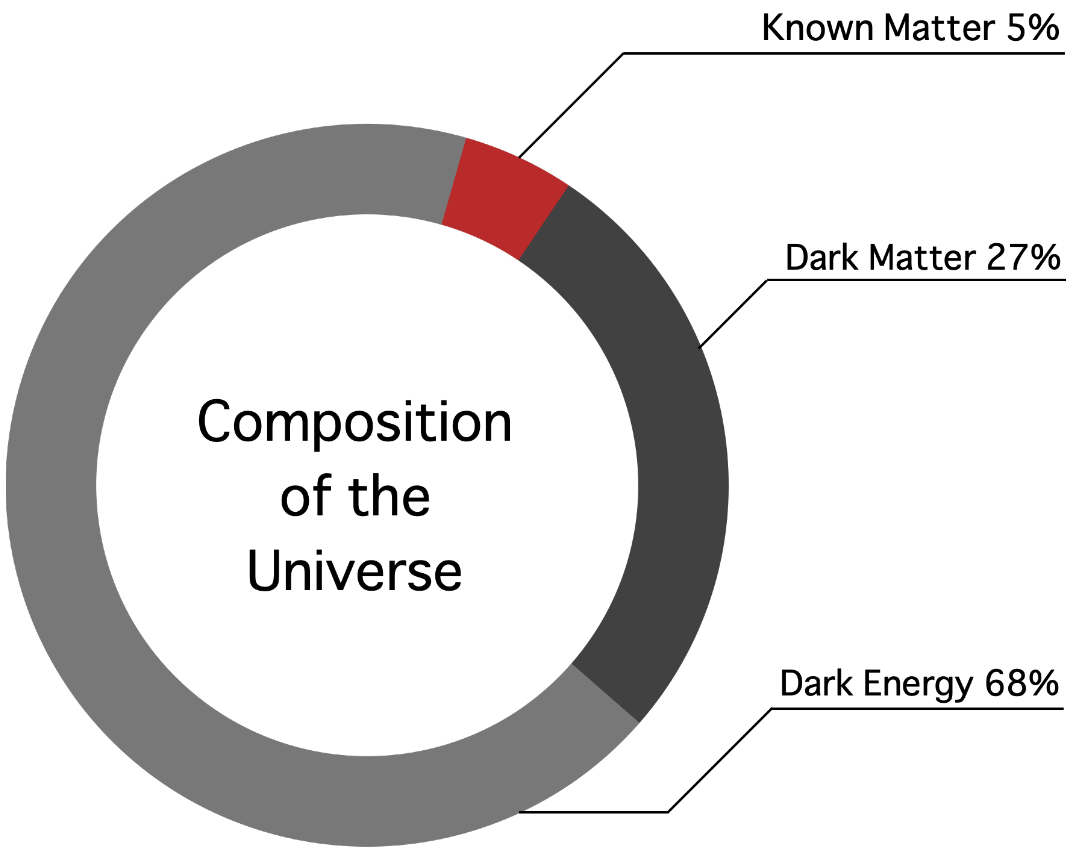
History of the Standard Model

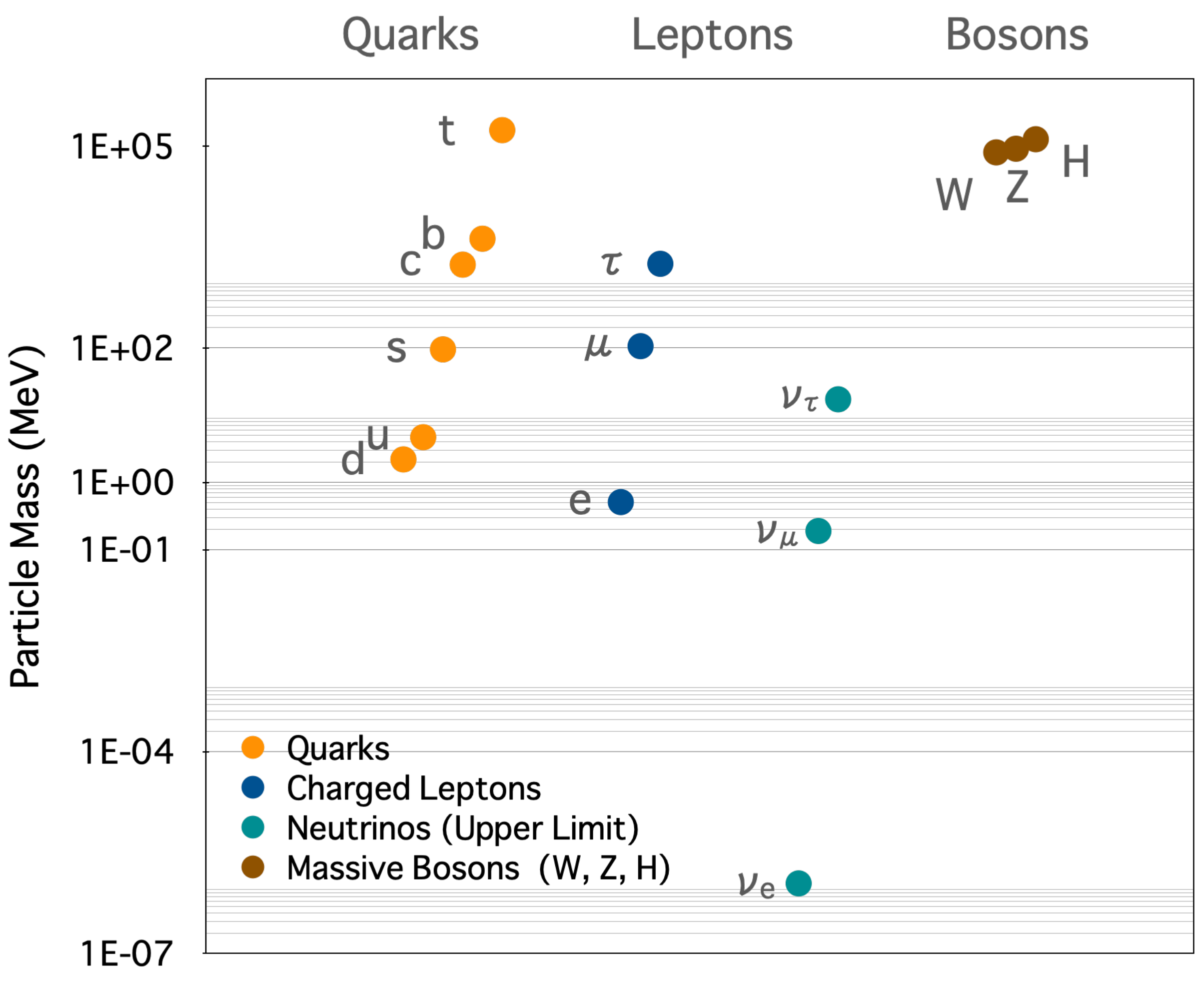
a timeline of discoveries



Unsolved Problems

of fundamental physics



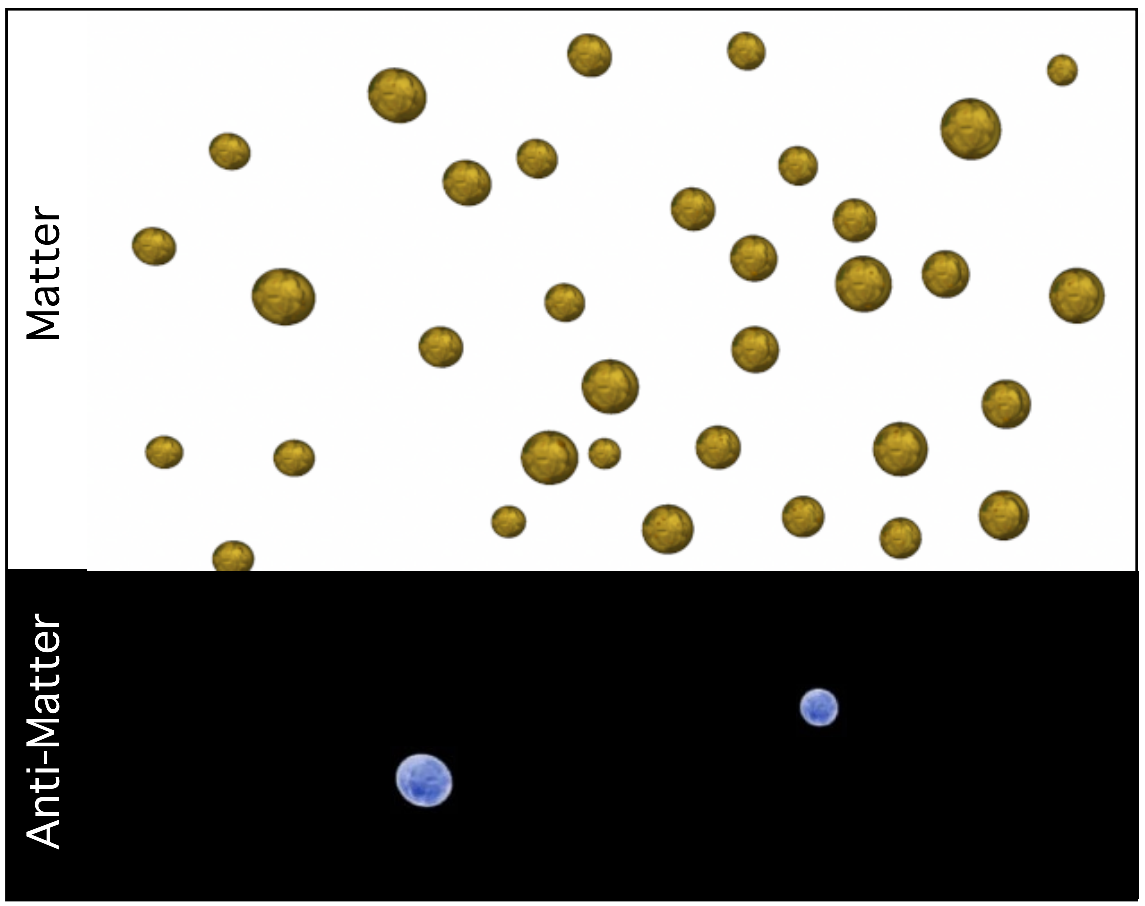


Dark sector

Generations of matter

Unsolved Problems

of fundamental physics



$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} = 6.1 \times 10^{-10}$$

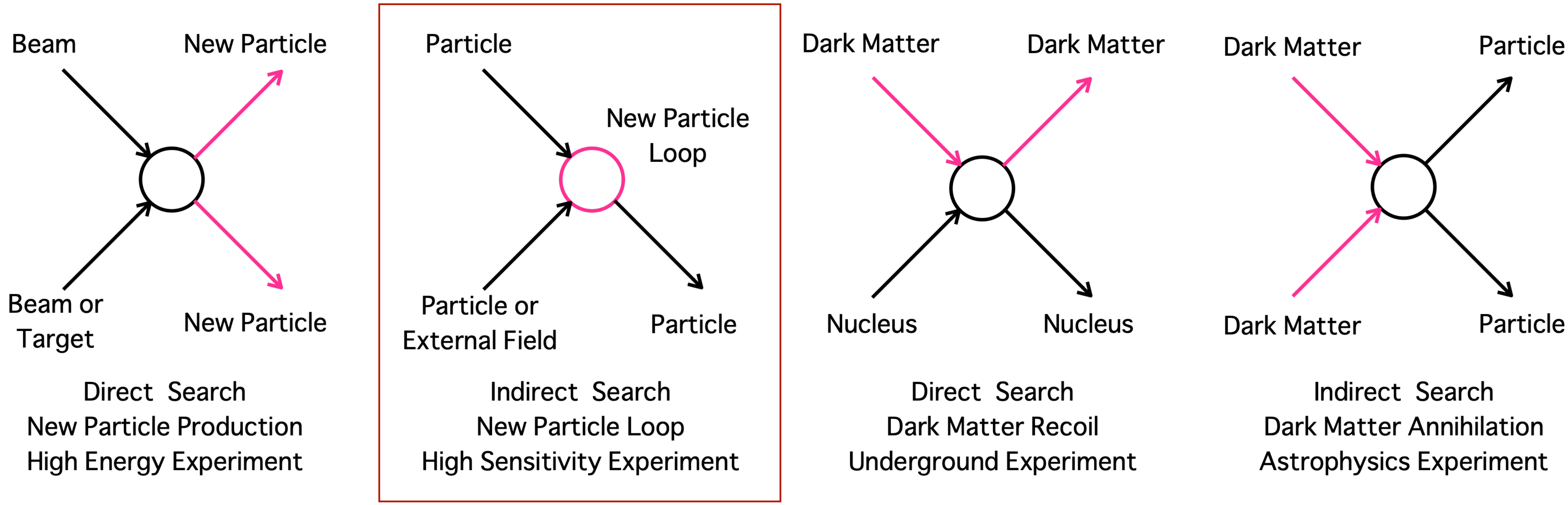
Baryon asymmetry

$$\mathrm{SU(3)} \times \mathrm{SU(2)_L} \times \mathrm{U(1)}$$

Grand unification

Approaches to the Problems

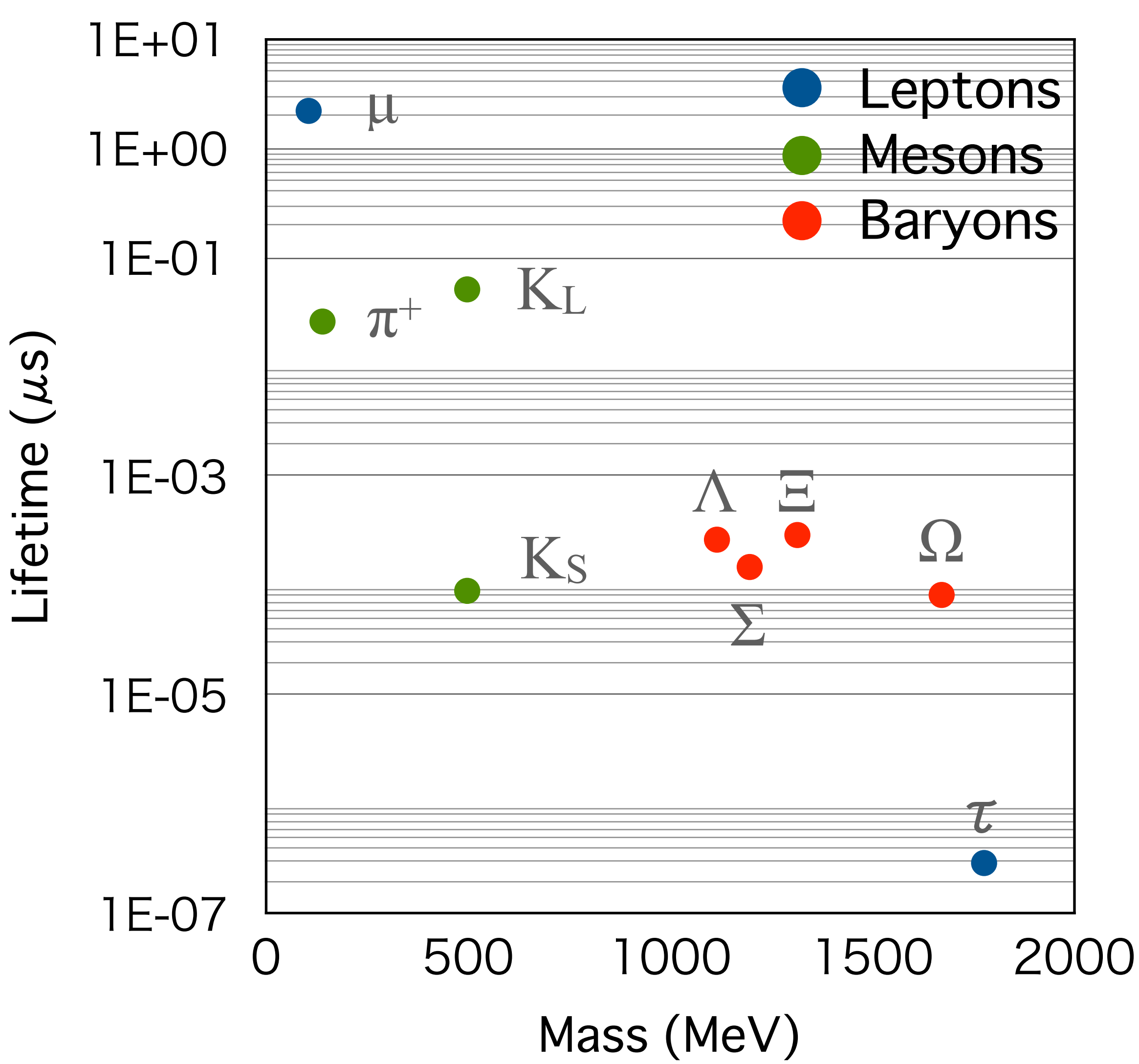
for a case of dark matter searches



- We have various ways to seek an unknown particle.
- Complementary approaches help us to understand new physics.
- Muons play a key role in high-sensitivity experiments.

Muon Properties

as an elementary particle



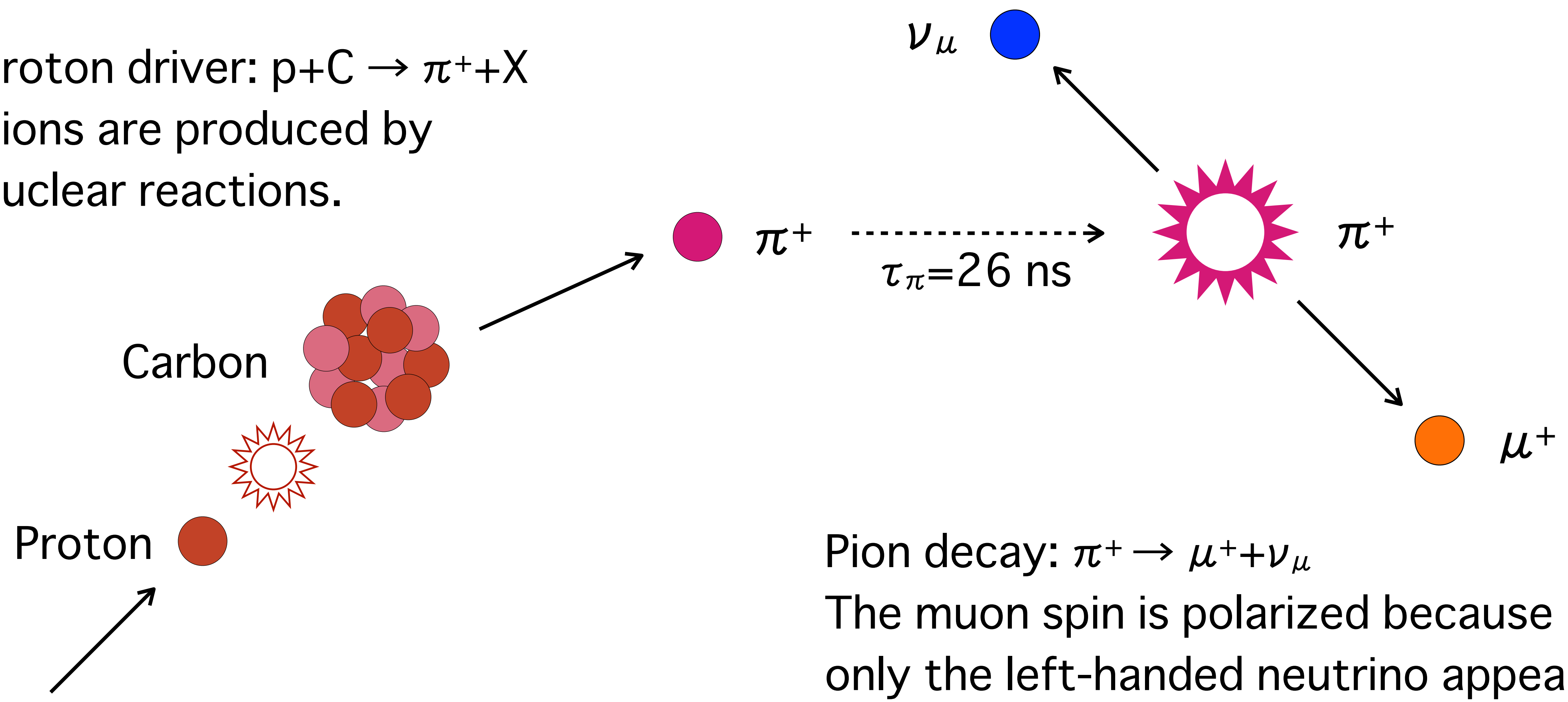
- The 2nd generation charged lepton
  - Charge e-
  - Spin 1/2
- Mass 105.7 MeV/c^2
- Lifetime 2197 ns
- Weak decay
- Heavy electron (207m_e)
- Light proton (1/9 m_p)

We don't know "who ordered that?", but it is useful.

Muon Production

proton driver and pion decay

Proton driver: p+C $\rightarrow \pi^+$+X
Pions are produced by
nuclear reactions.



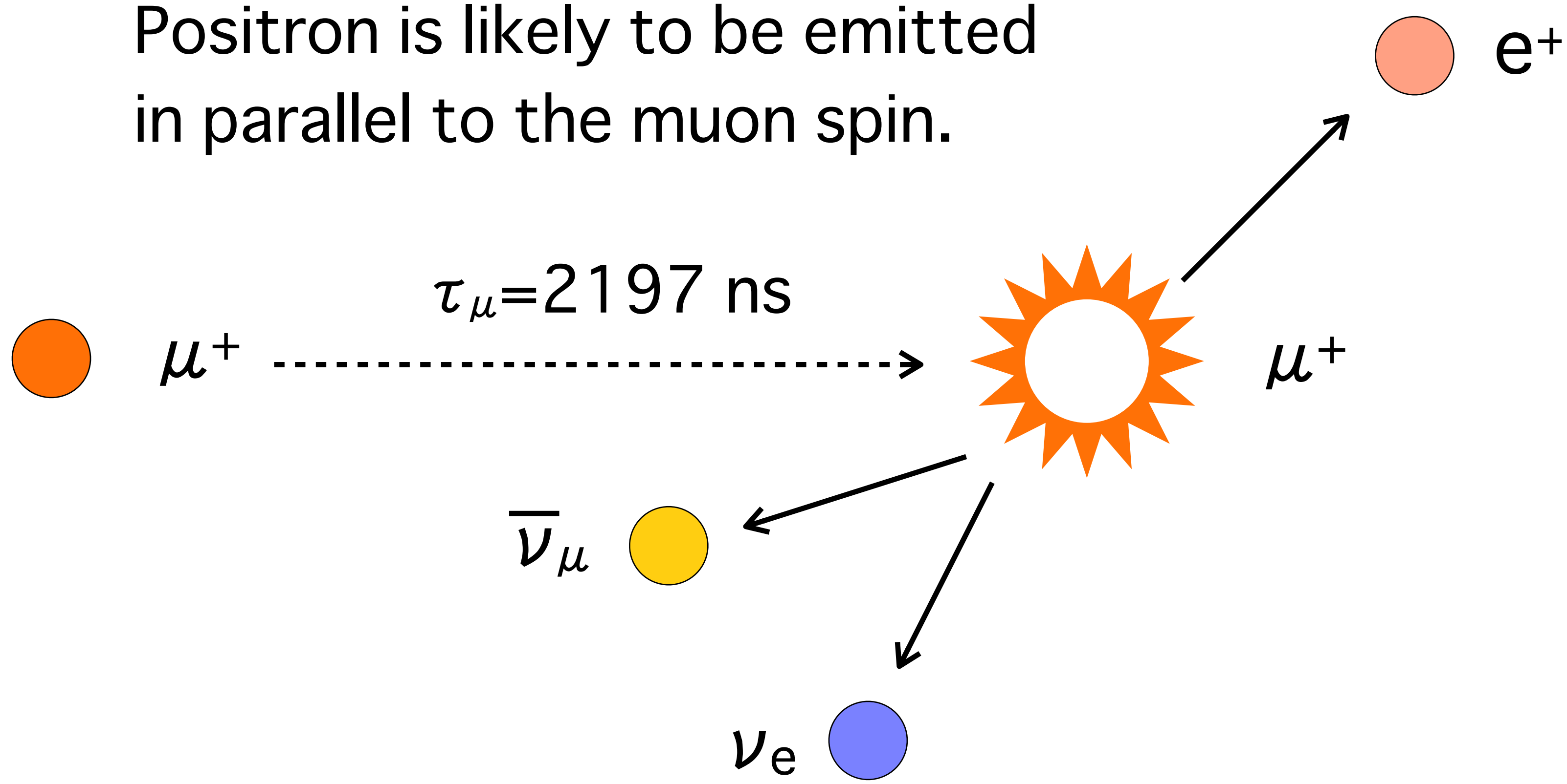
Pion decay: $\pi^+ \rightarrow \mu^+ + \nu_\mu$
The muon spin is polarized because
only the left-handed neutrino appears.

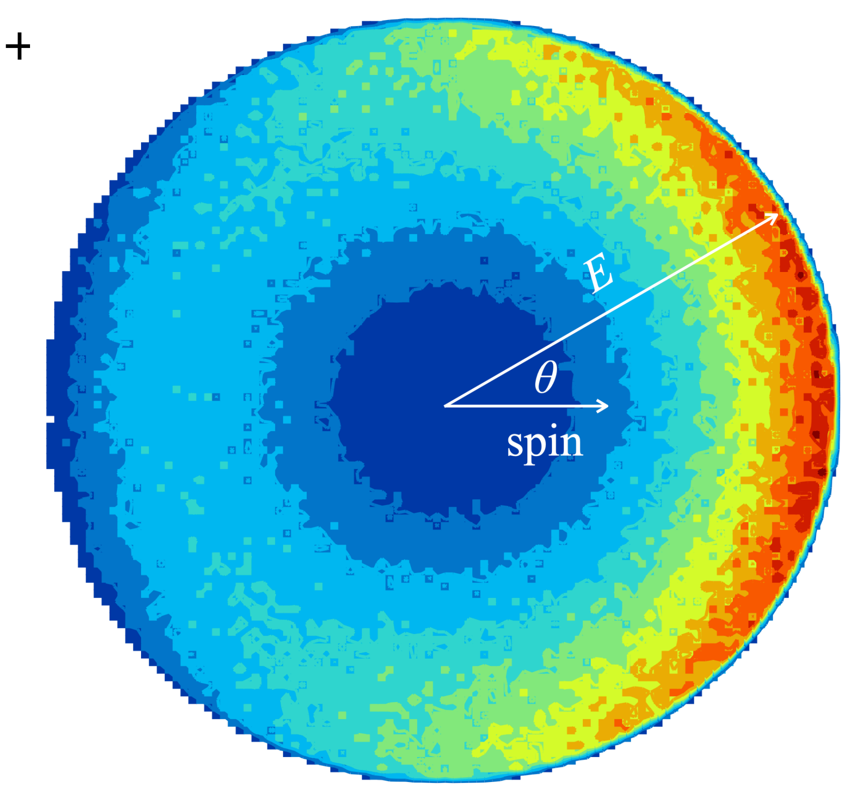
High intensity proton beams are essential for muon production.

Muon Decay

parity-violating three-body decay

Muon decay: $\mu^+ \rightarrow e^+ + \overline{\nu}_\mu + \nu_e$
Positron is likely to be emitted
in parallel to the muon spin.



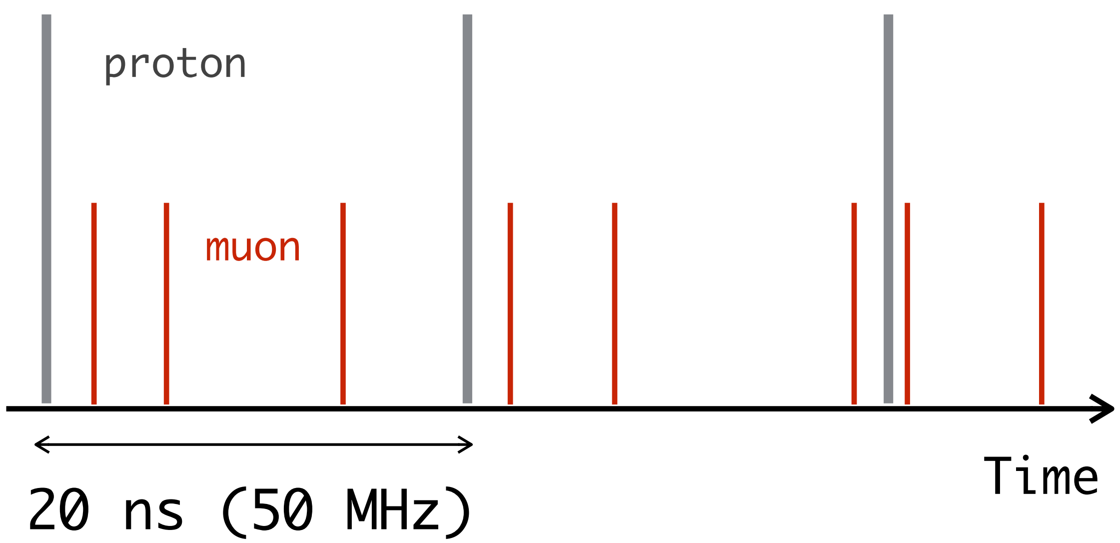


Muon decay emits anisotropic electron/positron.

Muon Beams

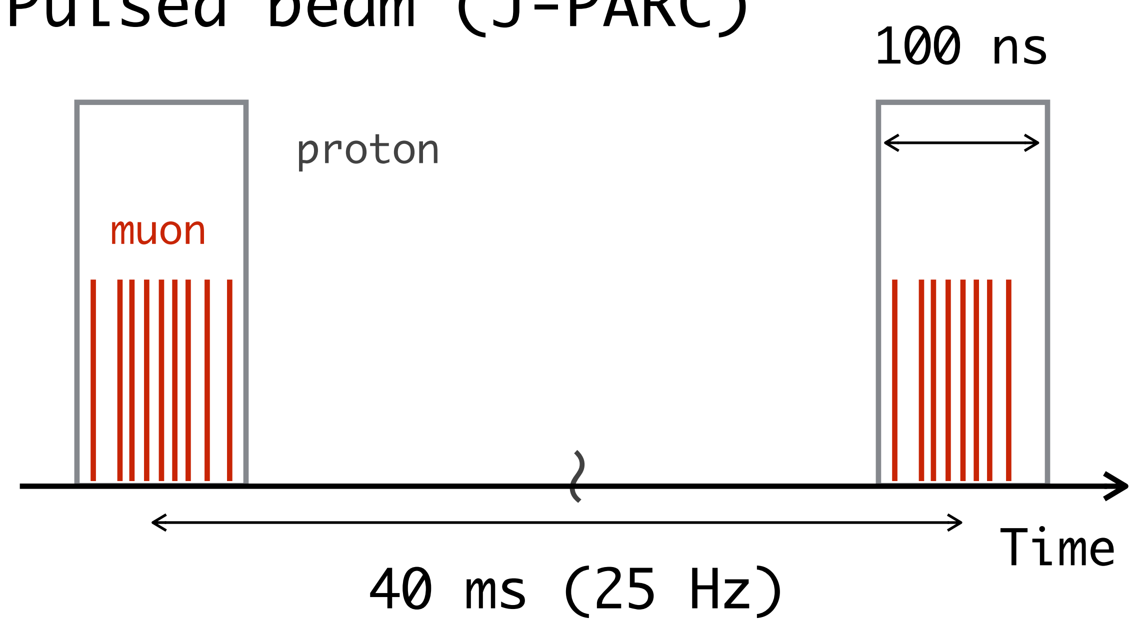
two types of timing structure

Continuous beam (PSI)



- Muons at random timing
- Event-by-event analysis
- High timing resolution
- Necessity of trigger detector
- Beam oriented background

Pulsed beam (J-PARC)

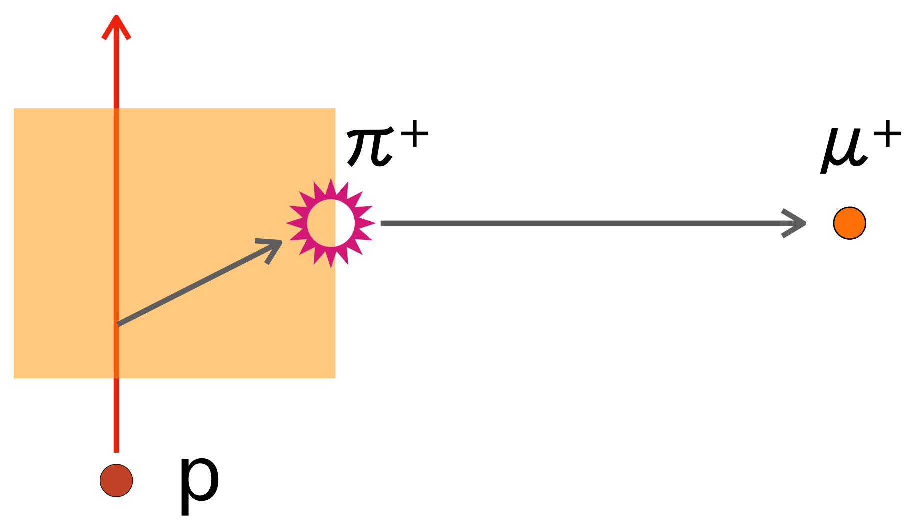


- A periodic bunch of muons
- Ensemble average
- High statistics and S/N
- Pulse synchronized trigger
- Severe requirements for detectors

Muon Beams

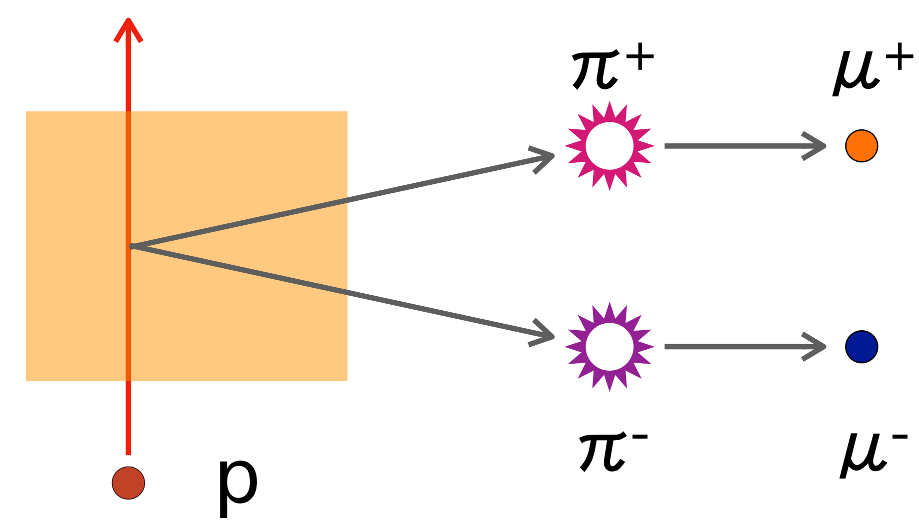
two types of production scheme

Surface muon beam



- Muons from pions stopped at the production target surface
- 4 MeV monochromatic
- 100% polarization
- Only available for μ^+

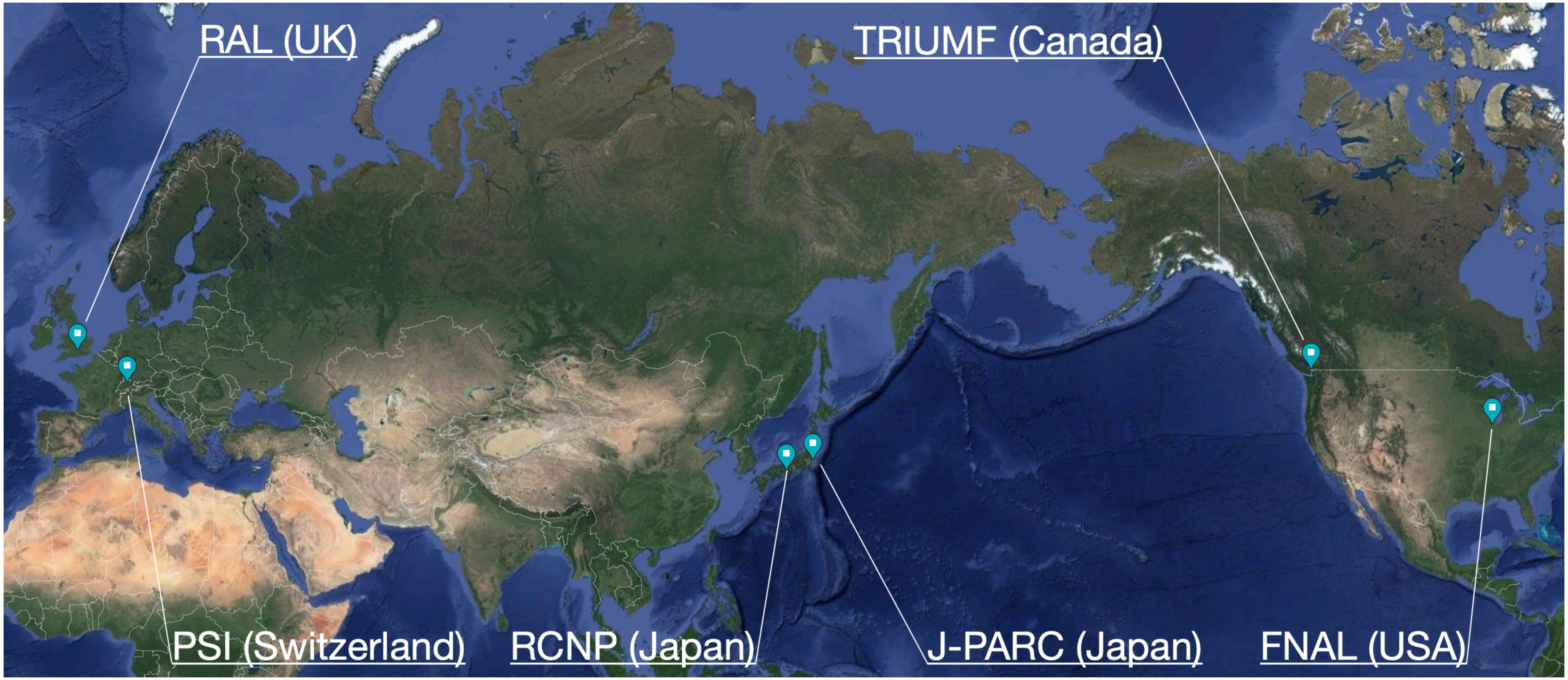
Decay muon beam

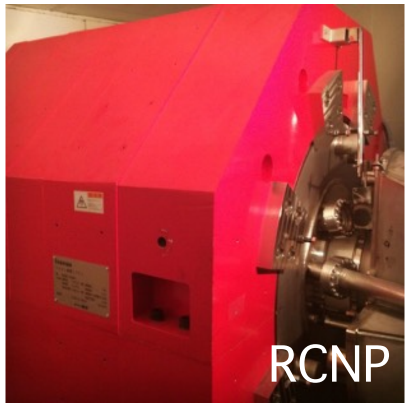


- Muons from pion decays in-flight
- Energy tunable
- Polarization depends on kinematics
- Both μ^+ and μ^- are available.

Muon Facilities

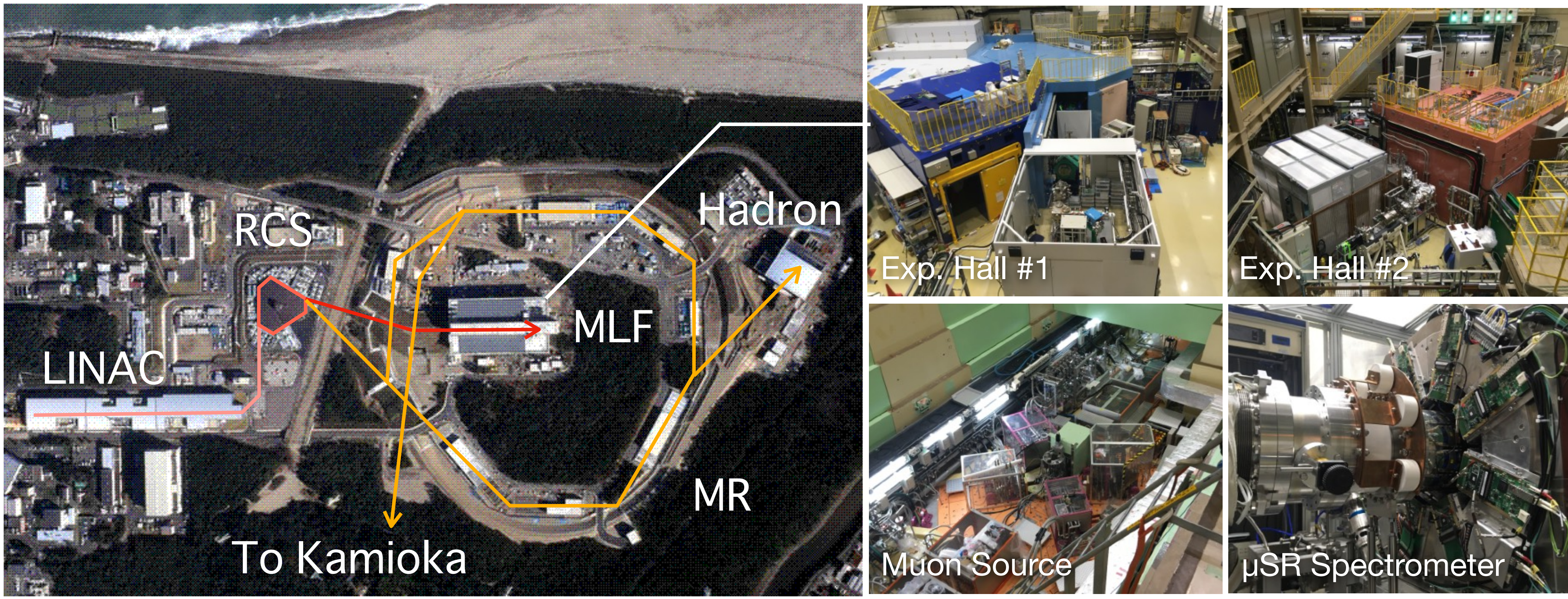
around the world





J-PARC

Japan Proton Accelerator Research Complex



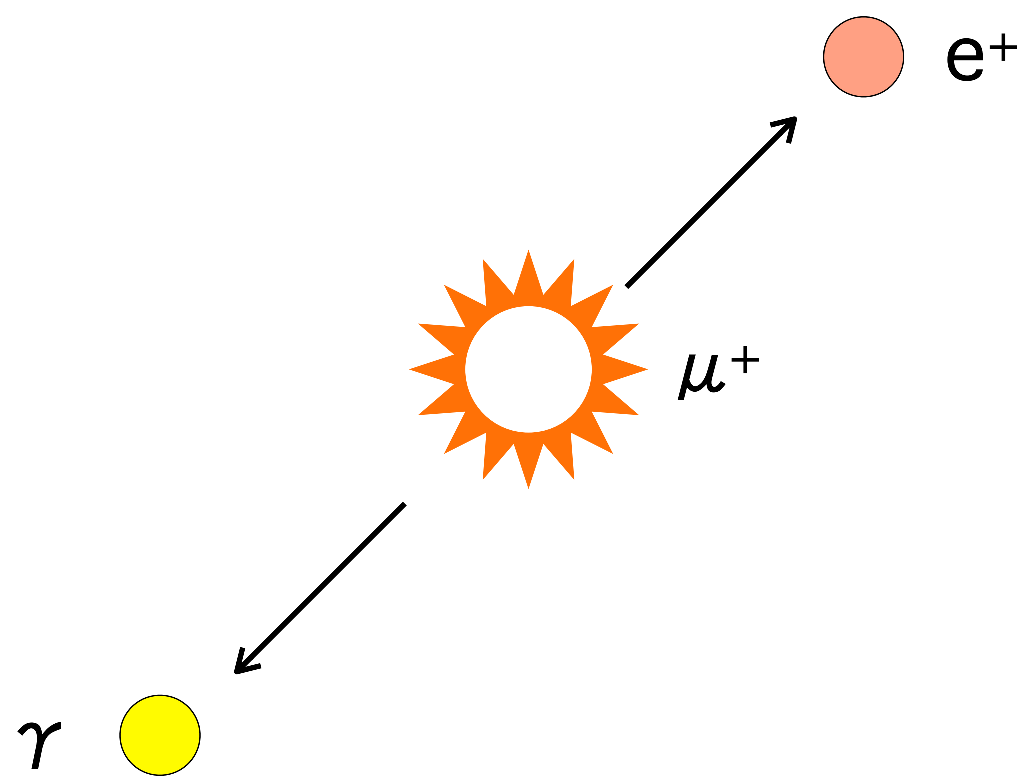
- World most intense pulsed proton driver.
- RCS provides 3 GeV protons for muon production at MLF.
- MR delivers 8 GeV protons for the COMET experiment.

Present and Future of Muon Experiments: A Review of rare event searches and precise measurements using muons

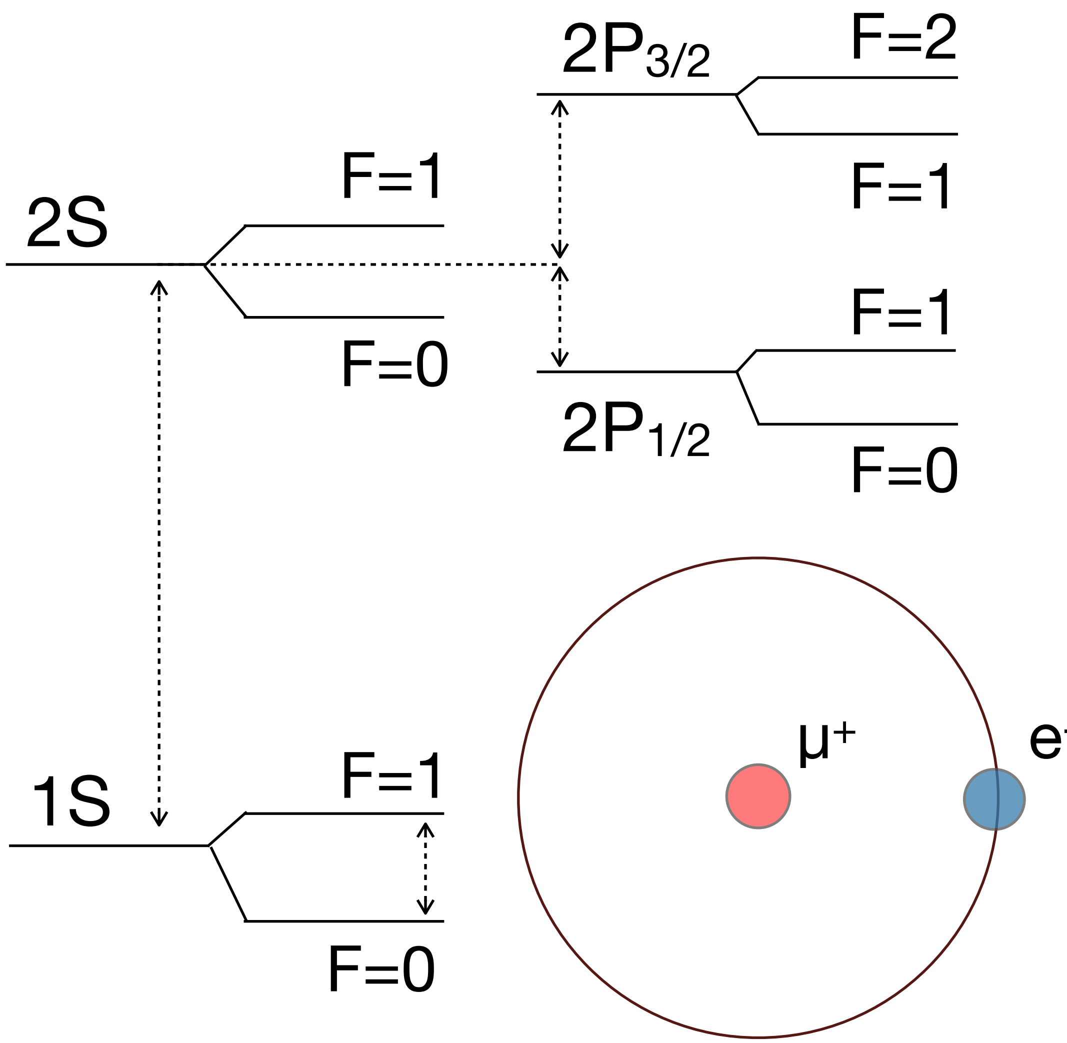
Sohtaro Kanda (神田 聡太郎) / KEK IMSS MSL / kanda@post.kek.jp

Muon Experiments

two types of approaches



Rare event searches

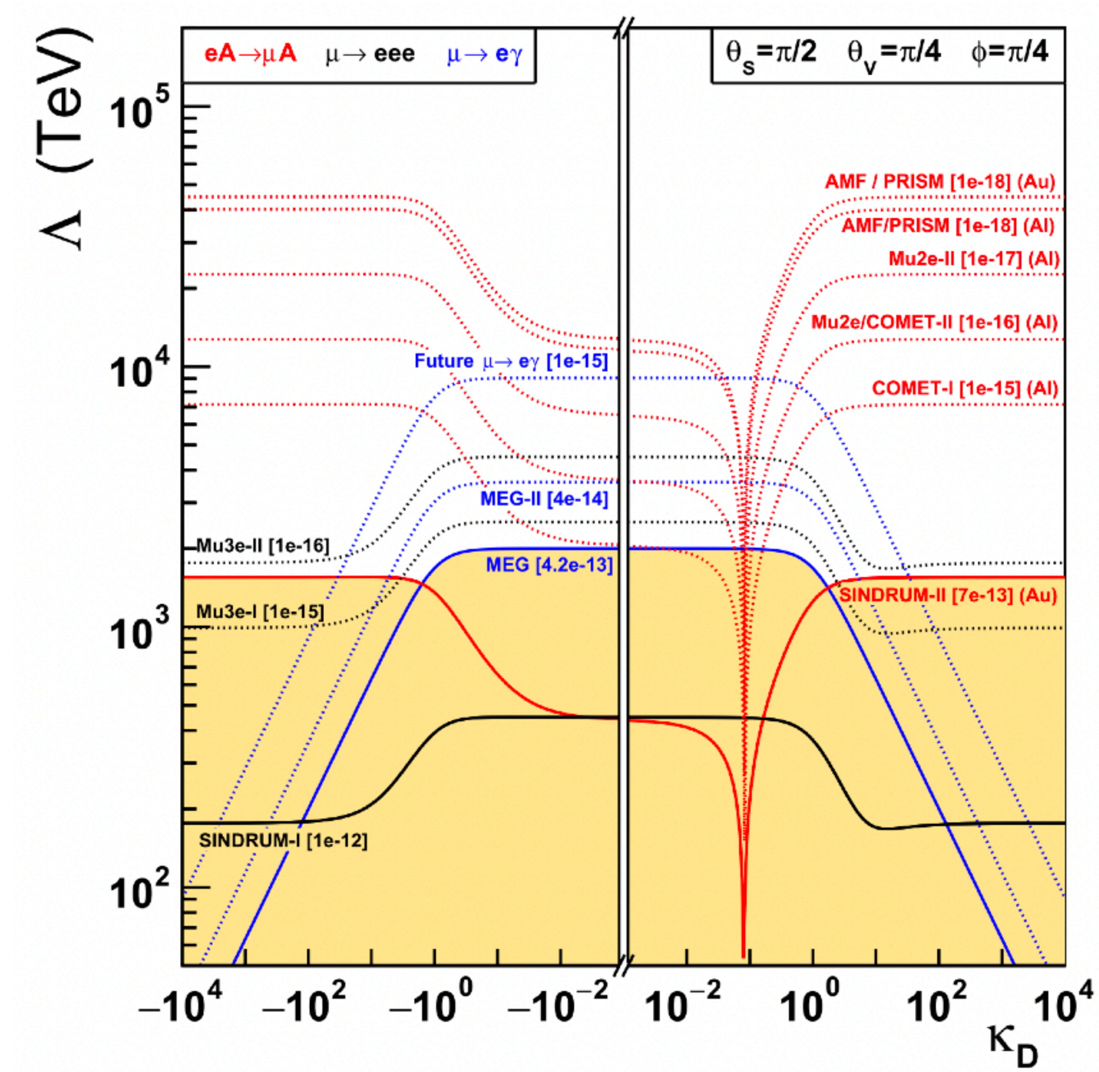


Precise measurements

Rare-Event Searches

processes violating the lepton flavor conservation

- Basic approach: trying to observe a rare event which is suppressed in the Standard Model.
- Typical setup: a spectrometer for detecting muon decay products
- $\mu^+ \to e^+ \gamma$
- $\mu^+ \to e^+ e^- e^+$
- $\mu^- \to e^-$ conversion
- $\mu^+ e^- \to \mu^- e^+$ conversion
- Different modes have different sensitivity to new physics.



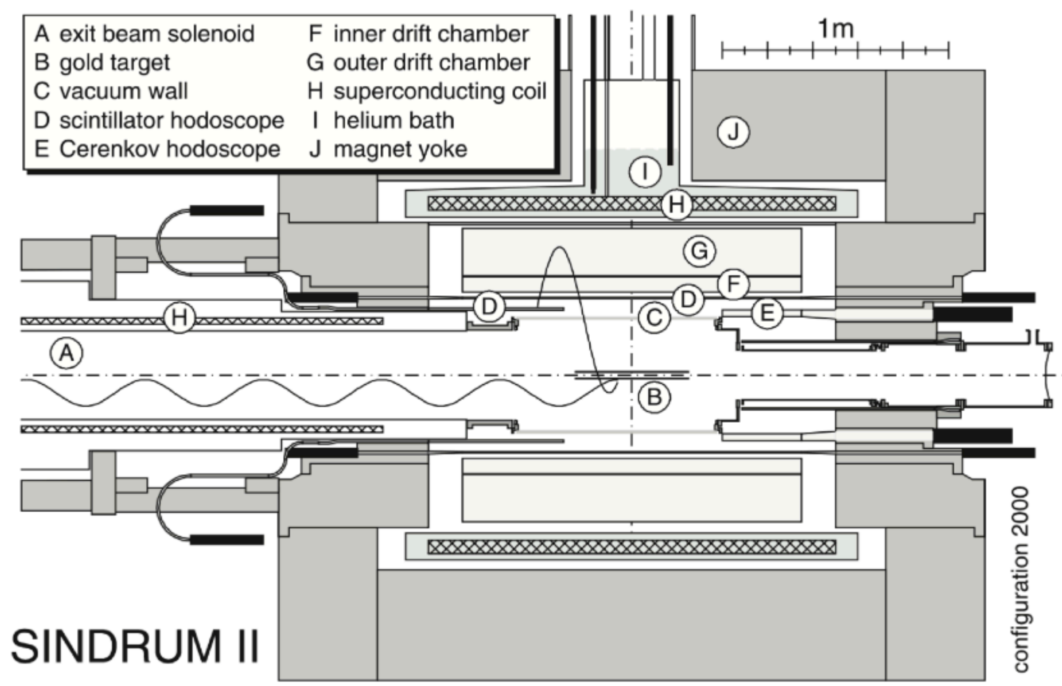
photonic ←→ non-photonic

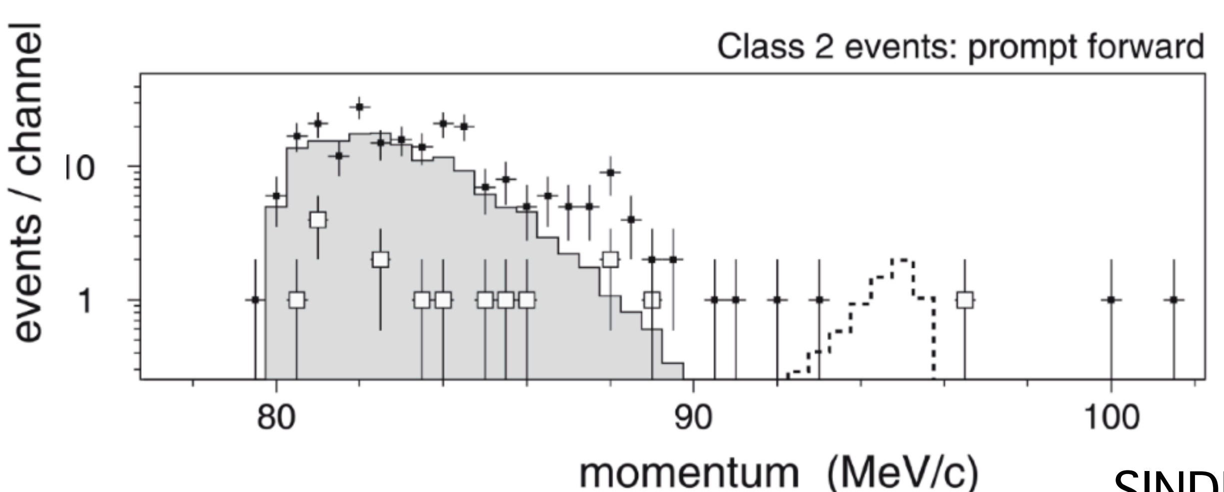
(dipole operator dominant) (4-fermion operator dominant)

S. Davidson, B. Echenard et al., "Charged Lepton Flavor Violation Experiments", arXiv:2209.00142 [hep-ex.

Muon-to-Electron Conversion

SINDRUM-II Experiment at SIN



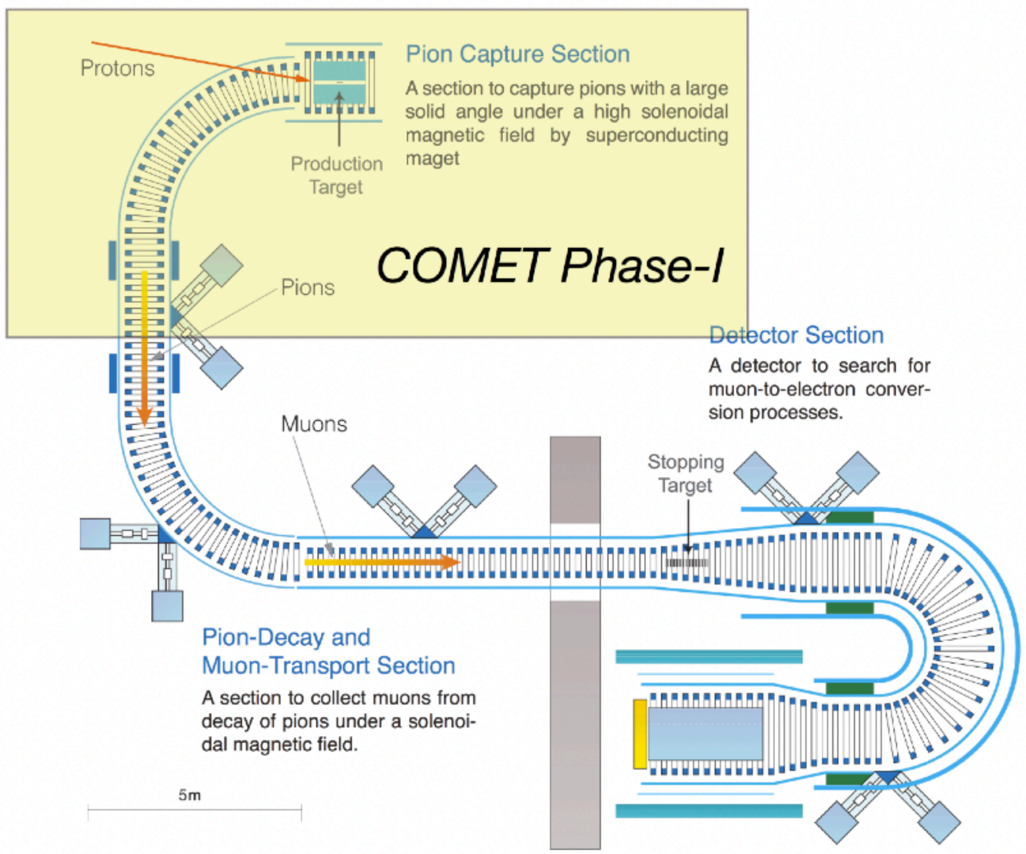


- A search for μe conversion.
- Electron tracking using radial drift chambers.
- Scintillator and Cherenkov hodoscopes for timing.
- Final result was published in 2000, the upper limit was 7×10^{-13}.
- The sensitivity was limited by background events (decay in oibit, DIO).

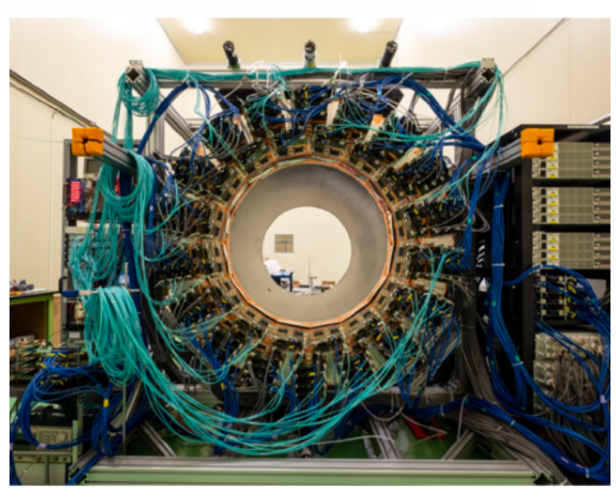
SINDRUM-II Collaboration, "A Search for muon to electron conversion in muonic gold" Eur. Phys. J. C 47 (2006) 337.

Muon-to-Electron Conversion

COMET Experiment at J-PARC



Transport solenoid



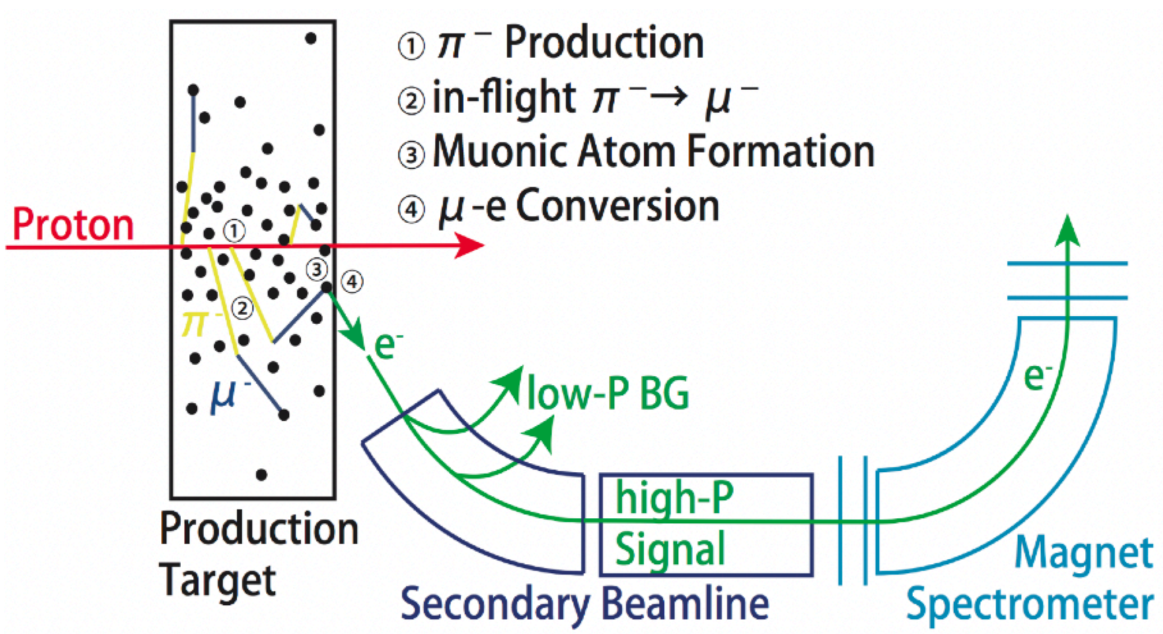
Cylindrical drift chamber

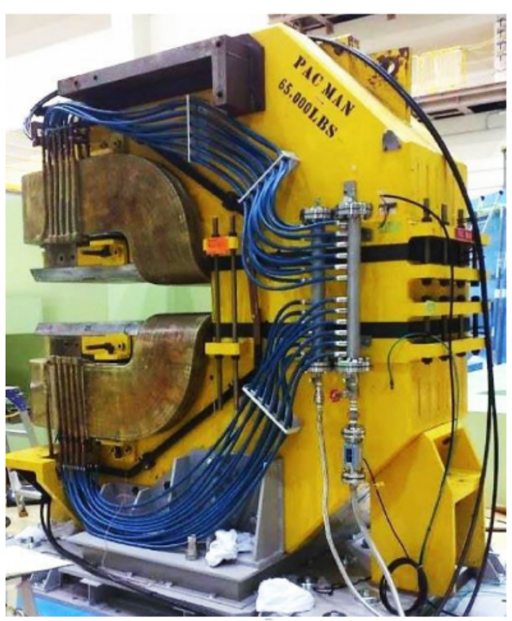
- A search for μe conversion.
- Pulsed proton beam from J-PARC Main Ring.
- Superconducting solenoids for pion capture and transport.
- Low-mass straw-tube tracker and calorimeters.
- Engineering run (Phase-α) will start 2023.

M. J. Lee, S. Middleton, and Y. Seiya, A Contributed Paper for Snowmass 2021, arXiv:2203.07089 [hep-ex].
M. Moritsu, Universe 8 (2022) 196.

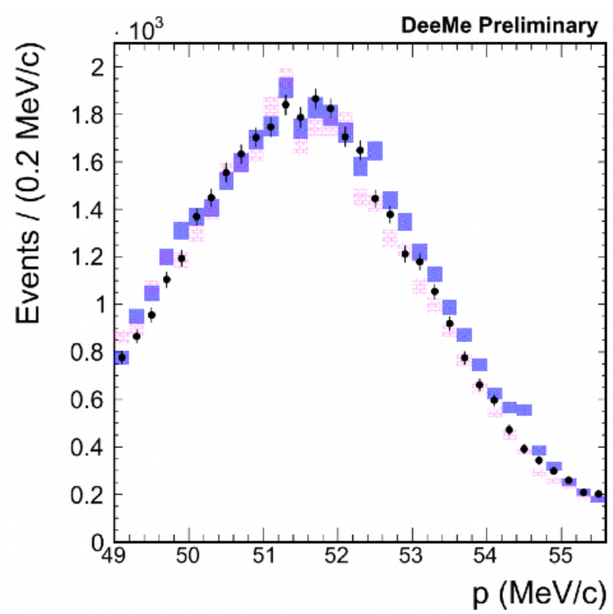
Muon-to-Electron Conversion

DeeMe Experiment at J-PARC





PACMAN magnet



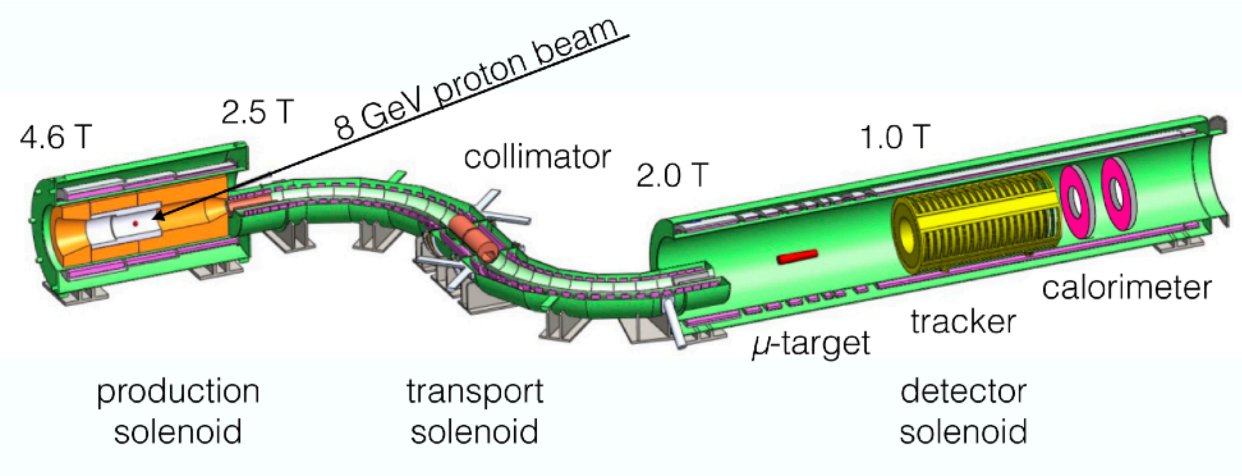
DIO momentum spectrum

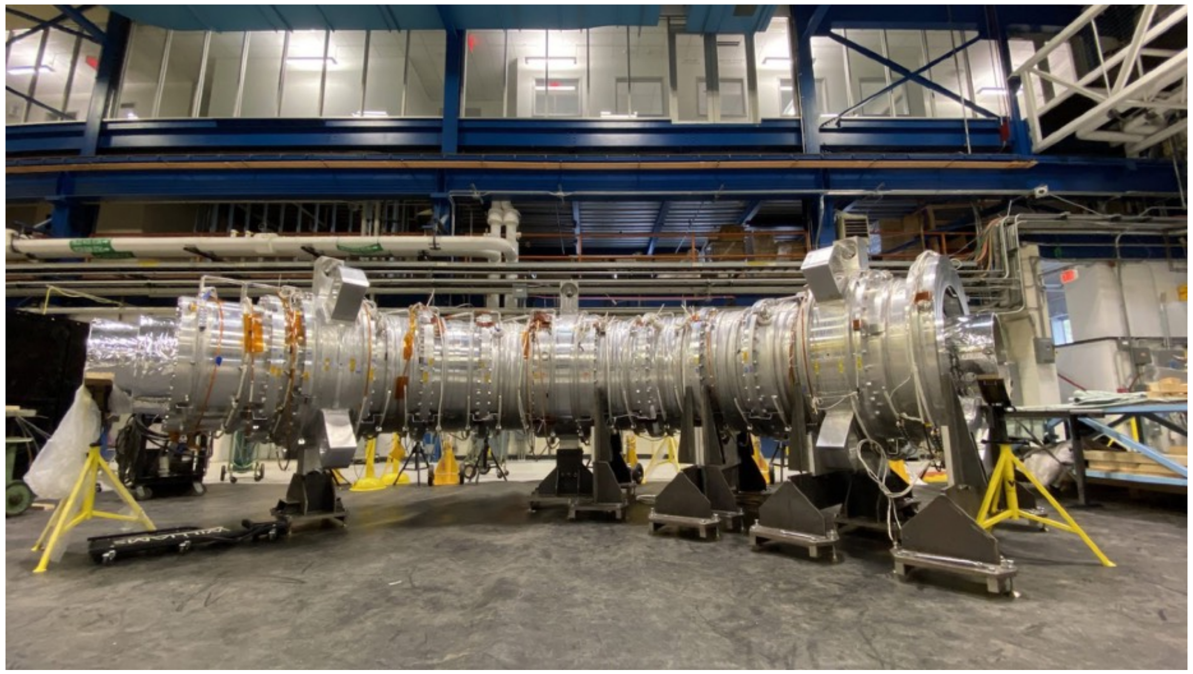
- A search for μe conversion.
- The sensitivity goal is $O(10^{-13})$.
- Pulsed beam from J-PARC RCS.
- Muonic atoms formation at the muon production target.
- A magnetic spectrometer using MWPCs with fast bias-switching.
- Physics run started from 2023, but the beamline is not operated as originally expected.

Y. Seiya, presentations at NuFACT2022.
S. Middleton, M. Lee, Y. Seiya, arXiv:2203.07089 [hep-ex].

Muon-to-Electron Conversion

Mu2e Experiment at FNAL





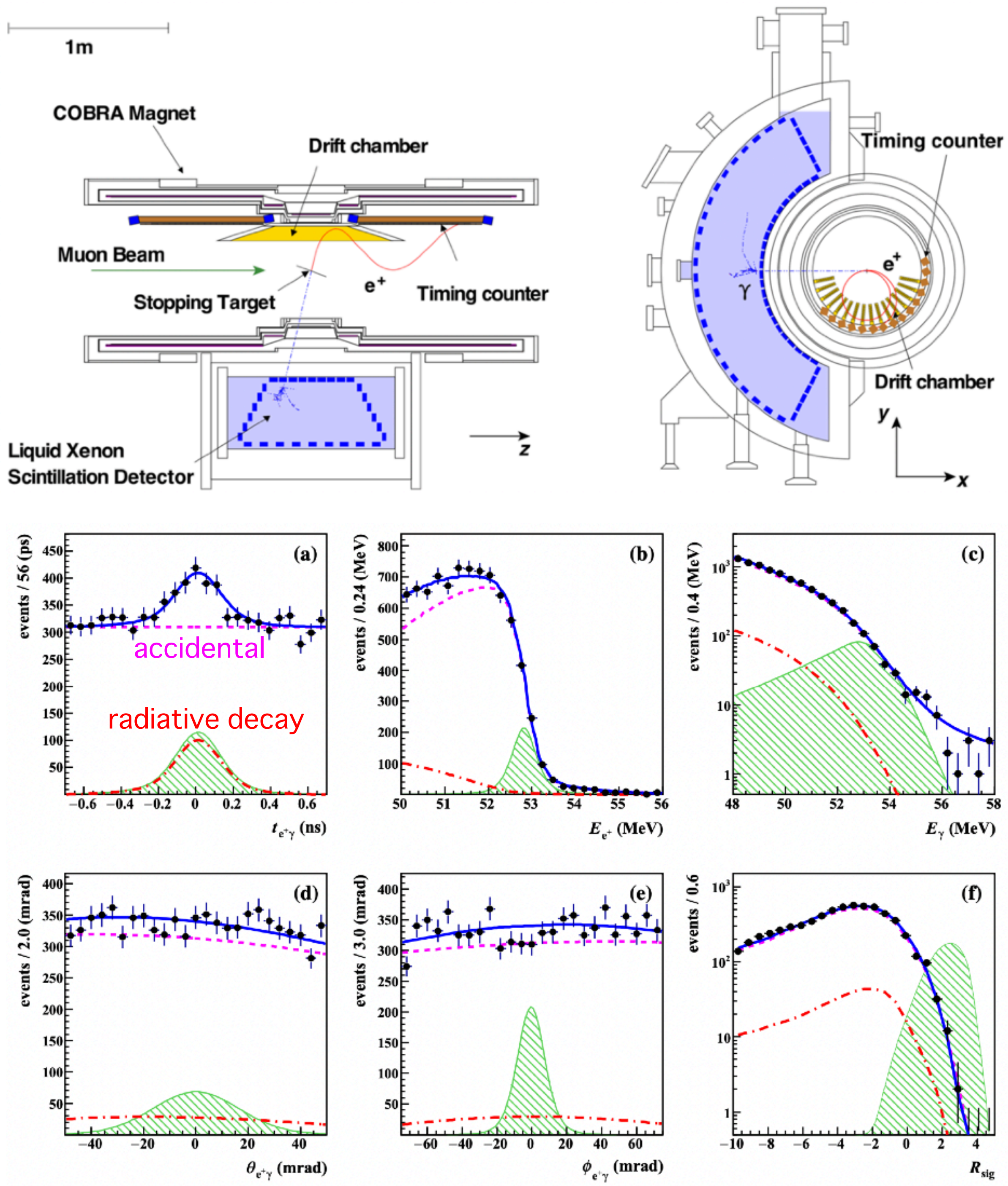
Transport solenoid

- A search for μe conversion.
- Pulsed beam from FNAL.
- Superconducting solenoids for pion capture and transport.
- Construction of the experiment has begun and first beam commissioning is expected to start in early 2025.

https://mu2e.fnal.gov/
https://news.fnal.gov/2020/11/one-step-closer-mu2e-reaches-milestone-in-construction-of-novel-experiment/

Muon-to Electron and Gamma

MEG Experiment at PSI

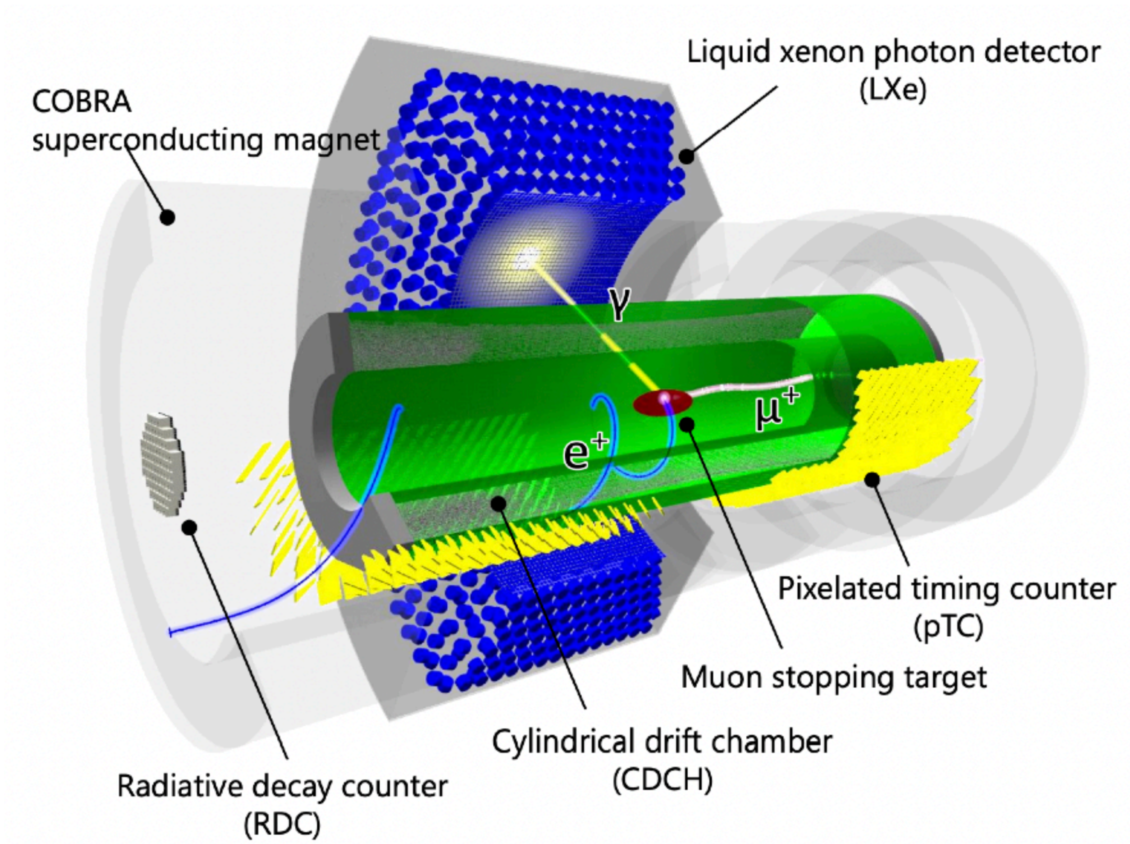


- A search for $\mu^+ \rightarrow e^+ \gamma$.
- Liquid Xe calorimeter for photon calorimetry.
- Drift chamber for positron tracking, scintillation counter for positron timing.
- Final result was published in 2016, Br<4.2x10^{-13}.
- The sensitivity was limited by background events.

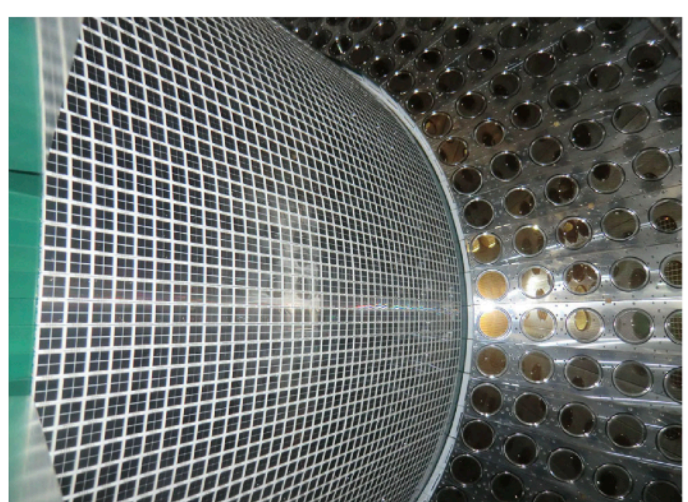
A. M. Baldini et al. (MEG Collaboration), "Search for the lepton flavour violating decay $\mu^+ \rightarrow e^+\gamma$ with the full dataset of the MEG experiment", Eur. Phys. J. C 76 434 (2016).

Muon-to Electron and Gamma

MEG-II Experiment at PSI



Drift chamber



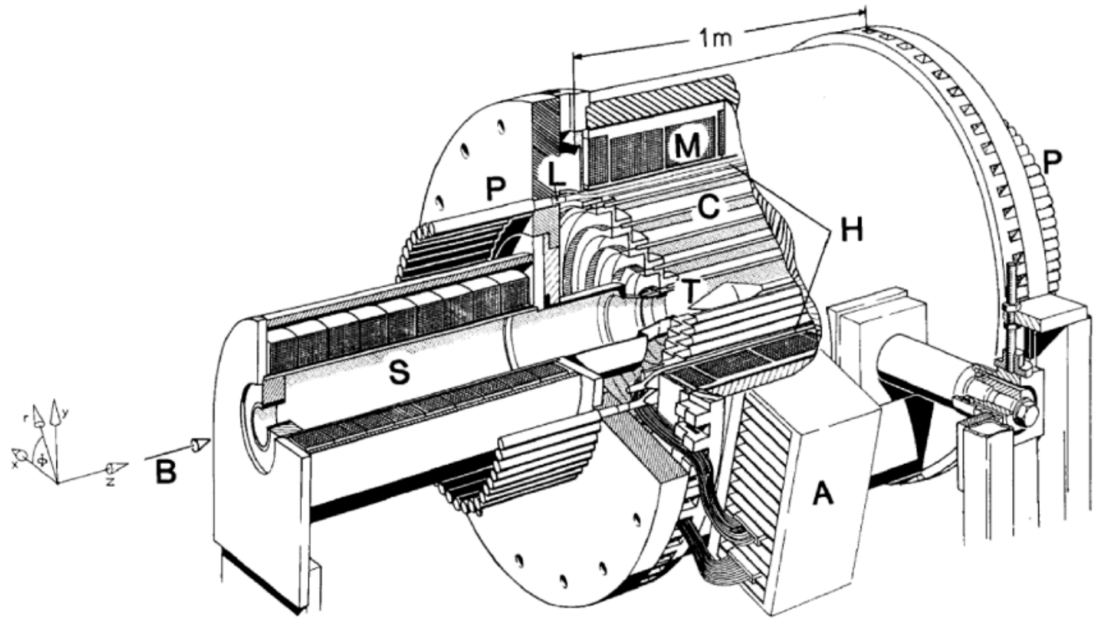
SiPMs for the calorimeter

- Upgrade of the MEG.
- Sensitivity goal is $6\text{x}10^{-14}$.
- Resolution improvements for background rejection.
- SiPM readout for the liquid xenon calorimeter.
- Pixelated timing counter and radiative decay counter.
- New low-mass drift chamber.
- Physics run started in 2021.

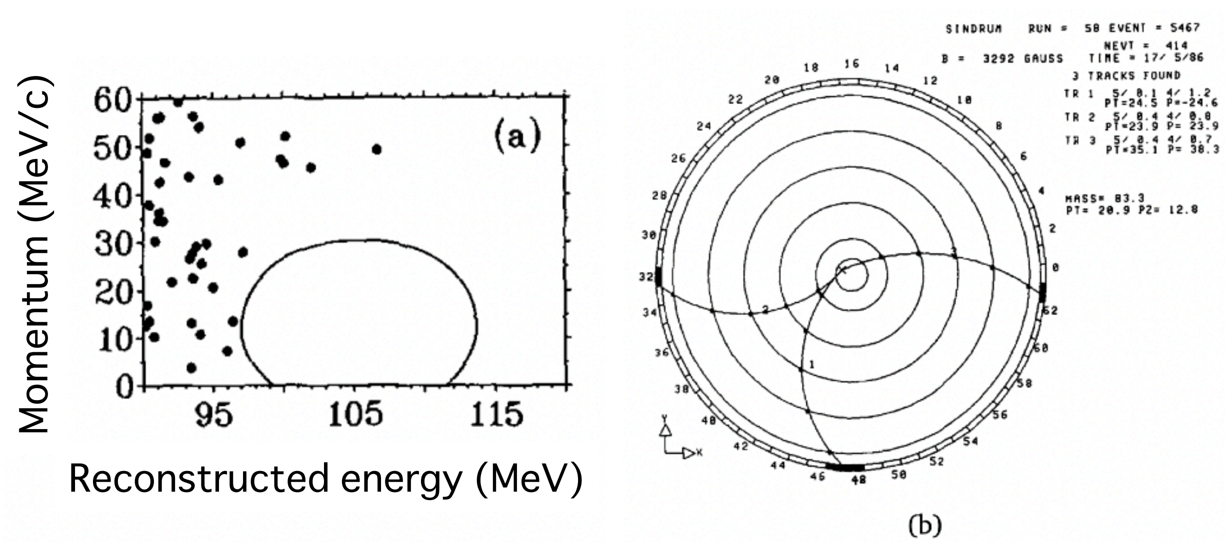
The MEG-II Collaboration, "The design of the MEG II experiment", Eur. Phys. J. C 78 (380) (2018).

Muon-to Three Electrons

SINDRUM Experiment at SIN



S: Solenoid, T: Target, C: MWPC, H: Hodoscope



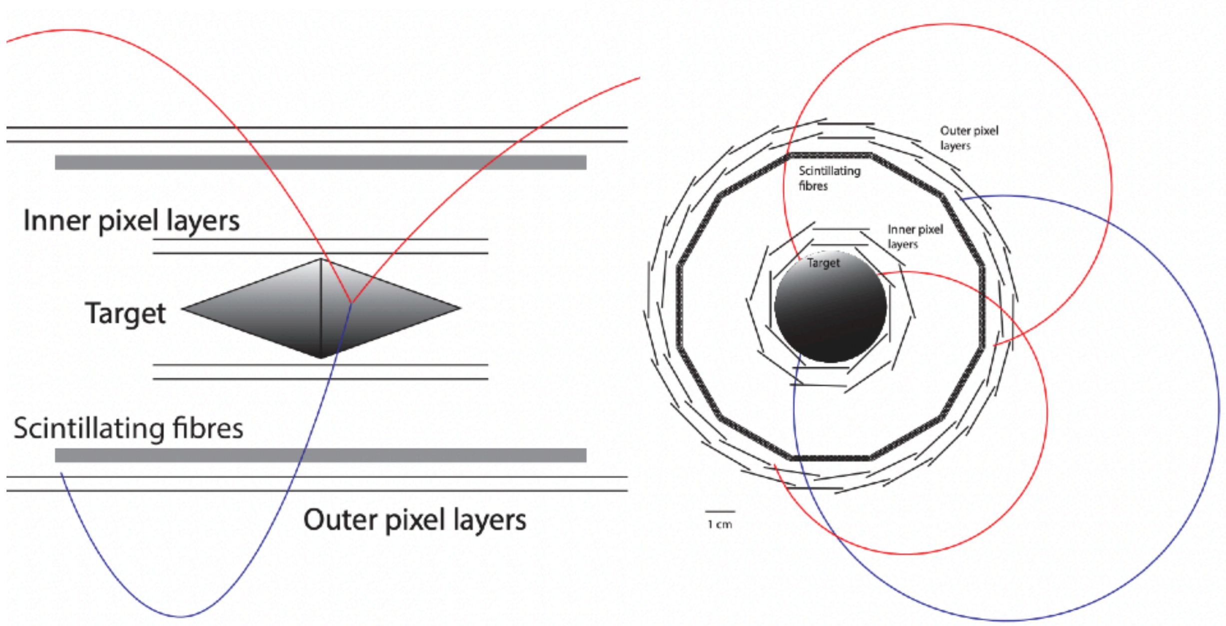
Reconstructed energy spectrum and tracks

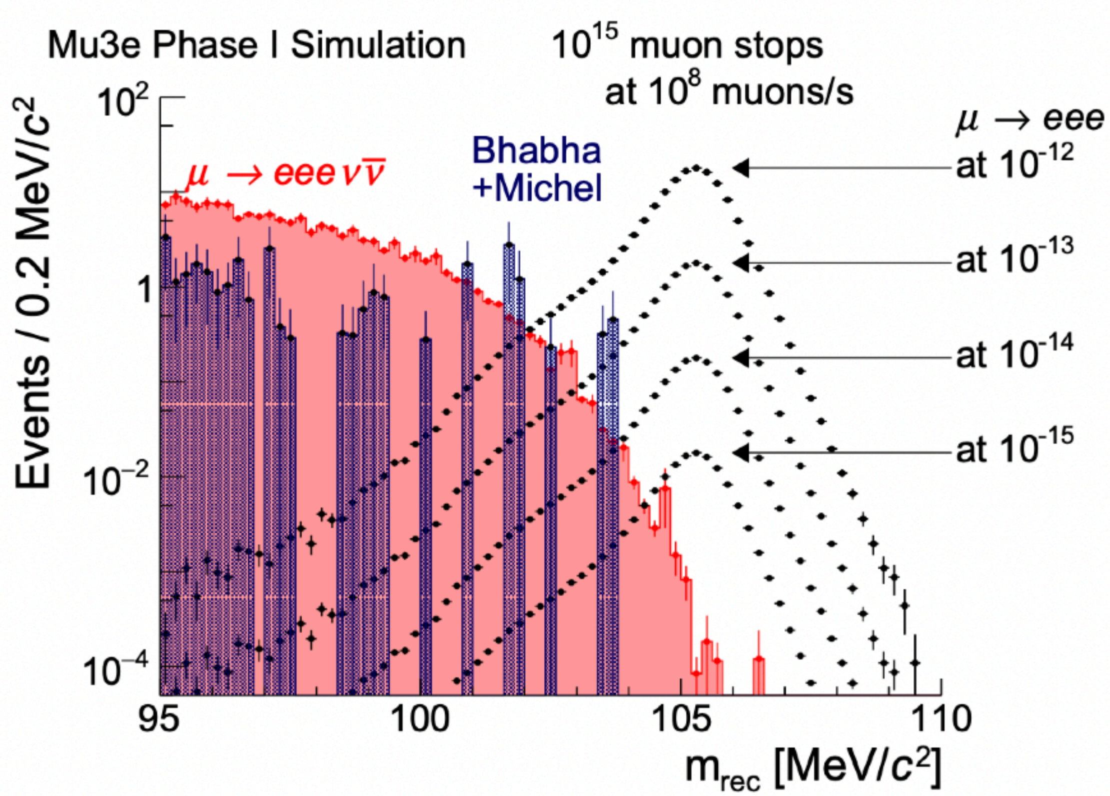
- A search for $\mu^+ \rightarrow e^+ e^- e^+$.
- A spectrometer with a cylindrical magnet and five concentric multiwire proportional chambers
- A cylindrical scintillator hodoscope for timing.
- Final result was published in 1988, $Br<1.0 \times 10^{-12}$.
- The sensitivity was limited by statistics.

SINDRUM Collaboration, "Search for the decay $\mu^+ \rightarrow e^+e^-e^+$", Nucl. Phys. B 299 (1988).

Muon-to Three Electrons

Mu3e Experiment at PSI



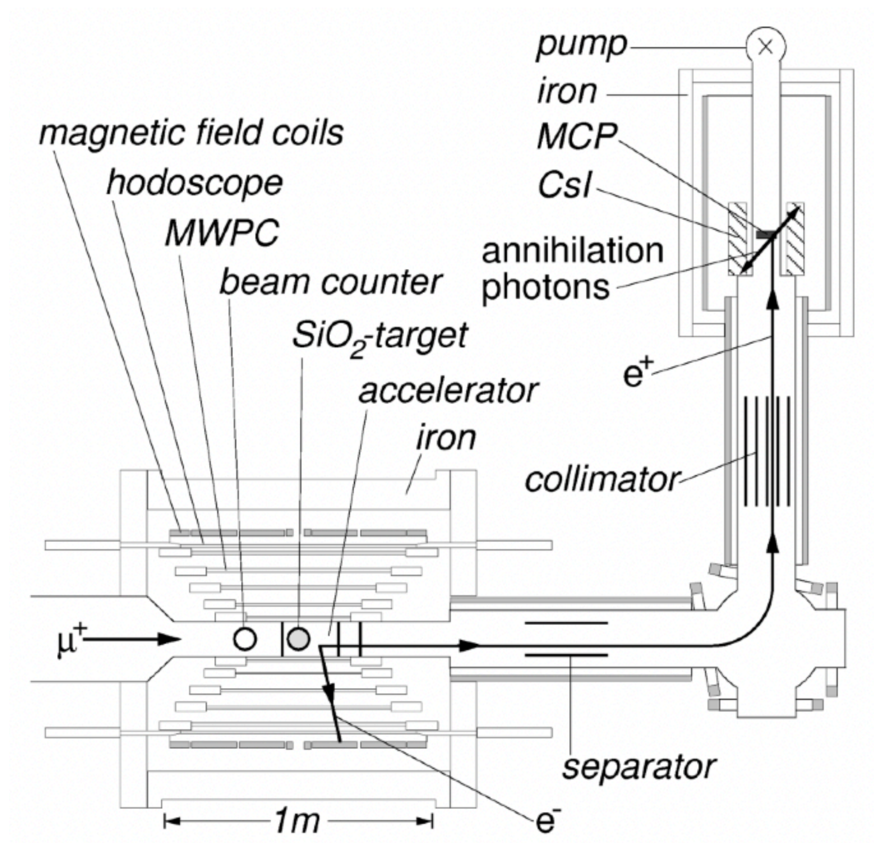


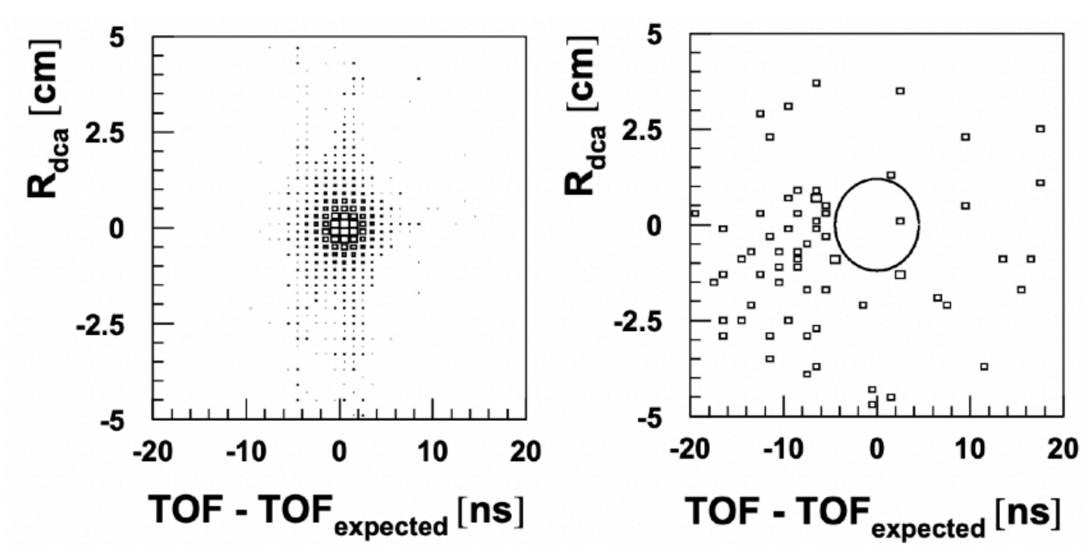
- A search for $\mu^+ \rightarrow e^+ e^- e^+$.
- The sensitivity goals are Br<1x10^{-16} for phase II and Br<1x10^{-15} for phase I.
- Silicon pixel detectors for tracking.
- Scintillating fibre and tile detectors for timing.
- First integration run of phase I was performed in 2021, commissioning is ongoing.

Mu3e collaboration, K. Arndt et al., Technical design of the phase I Mu3e experiment, NIM A 1014 (2021) 165679.

Muonium anti-Muonium Conversion

MACS Experiment at PSI



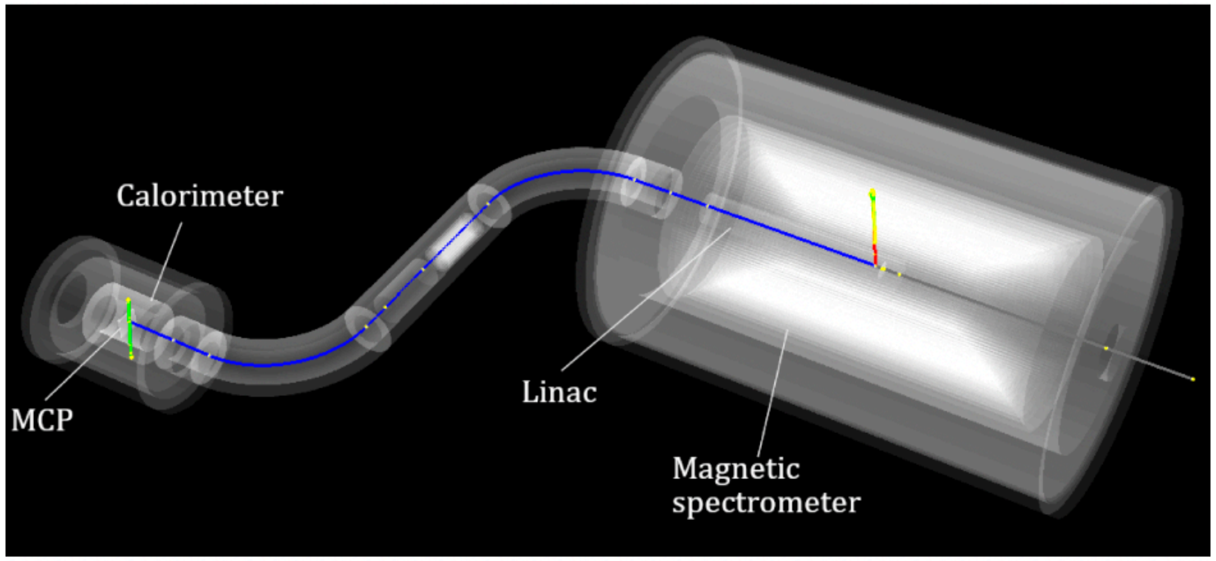


- A search for $\mu^+ e^- \rightarrow \mu^- e^+$.
- The final result was published in 1999 and the upper limit was 8.2×10^{-11}.
- Muonium production using a silica target.
- Time-of-flight and annihilation gamma of decay positron.
- The sensitivity was limited by background.

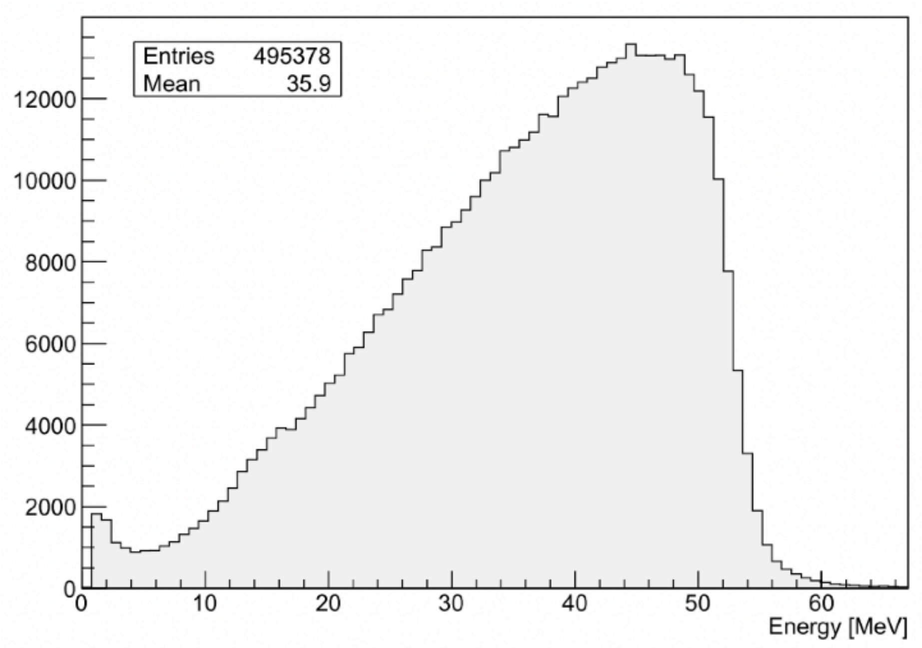
L. William at al., "New bounds from searching for muonium to anti-muonium conversion", Phys. Rev. Lett. 82 (1999).

Muonium anti-Muonium Conversion

MACE Experiment at CSNS



Experimental setup



Simulated electron energy reconstruction

- A search for $\mu^+ e^- \to \mu^- e^+ e^-$.
- The sensitivity goal is $O(10^{-13})$.
- Triple coincidence of Michel electron, slow positron, and annihilation gammas.
- A drift chamber for electron tracking.
- Accelerator and spectrometer for positron and gammas.

A. Y. Bai et al., "Muonium to antimuonium conversion", contributed paper for Snowmass 21.

Precision Measurements

to search for physics beyond the Standard Model

- Basic approach: measuring muon properties precisely and comparing with theoretical predictions.
- Typical setup:
  - Detecting muon decay products
  - Laser/microwave spectroscopy of muonic bound systems
- Lifetime
- Dipole moments (a_μ, EDM)
- Decay parameters (Michel parameters, polarization)
- Mass (muon-to-electron mass ratio)
- Magnetic moment (muon-to-proton magnetic moment ratio)

Muon Lifetime

determination of the Fermi constant

- Three pillars of EW Standard Model tests: [1,2,3]
  - Fine structure constant α
  - Fermi coupling constant G_F
  - Weak boson masses M_W and M_Z

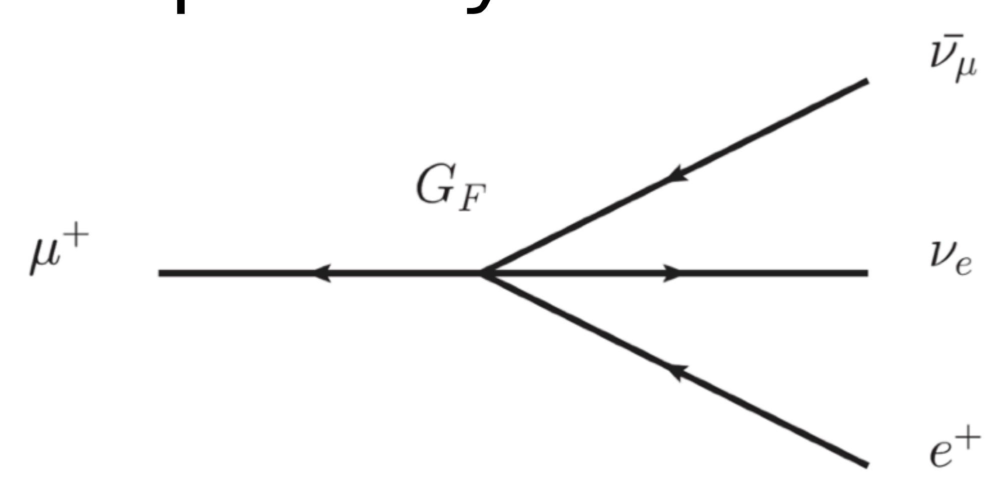
$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}\left(1+\sum_i r_i\right)$$

higher order

- The muon lifetime determines G_F most precisely

$$\frac{1}{\tau_\mu}=\frac{G_F^2 m_\mu^5}{192\pi^3}\left(1+\sum_i \Delta q^{(i)}\right)$$

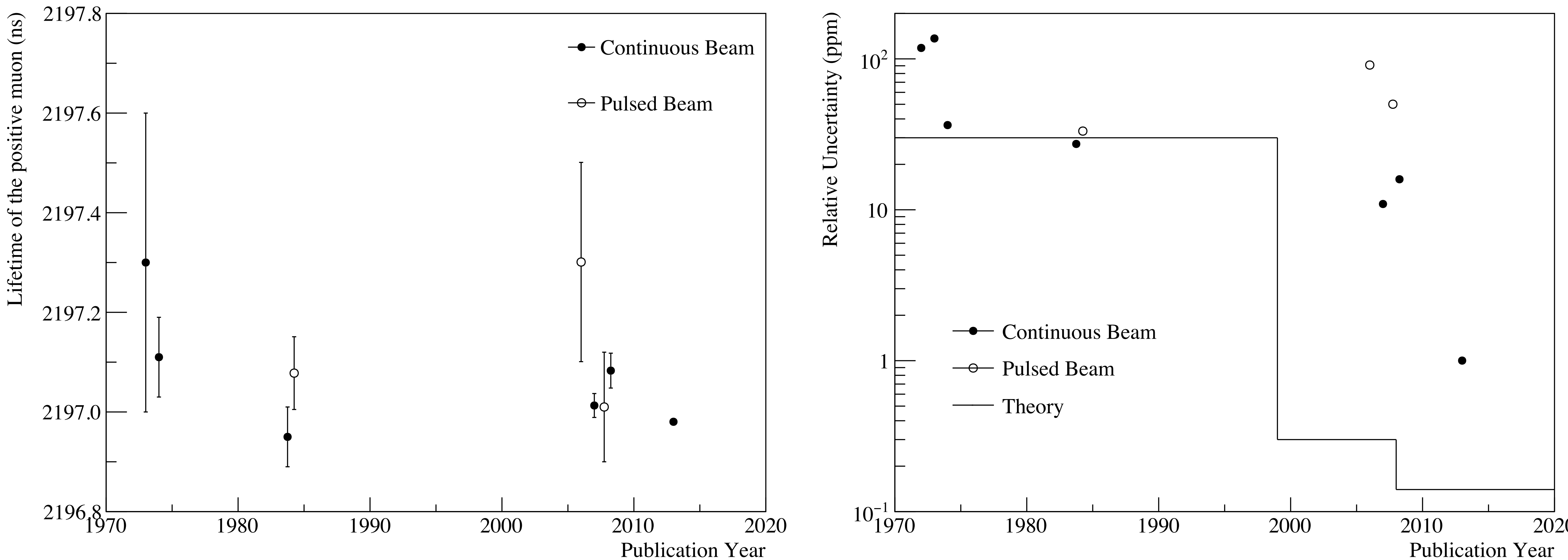
$$G_F = 1.1663787(6)\times 10^{-5}\ \mathrm{GeV}^{-2}$$ [4]



[1] W. Marciano, PRD 60, 093006 (1999). [2] M.E. Peskin and T. Takeuchi, PRD 46, 381 (1992).
[3] M. Awramik et al., PRD 69, 053006 (2004). [4] P.A. Zyla et al. (Particle Data Group), PTEP 083C01 (2020).

Muon Lifetime

history of the theory and experiments

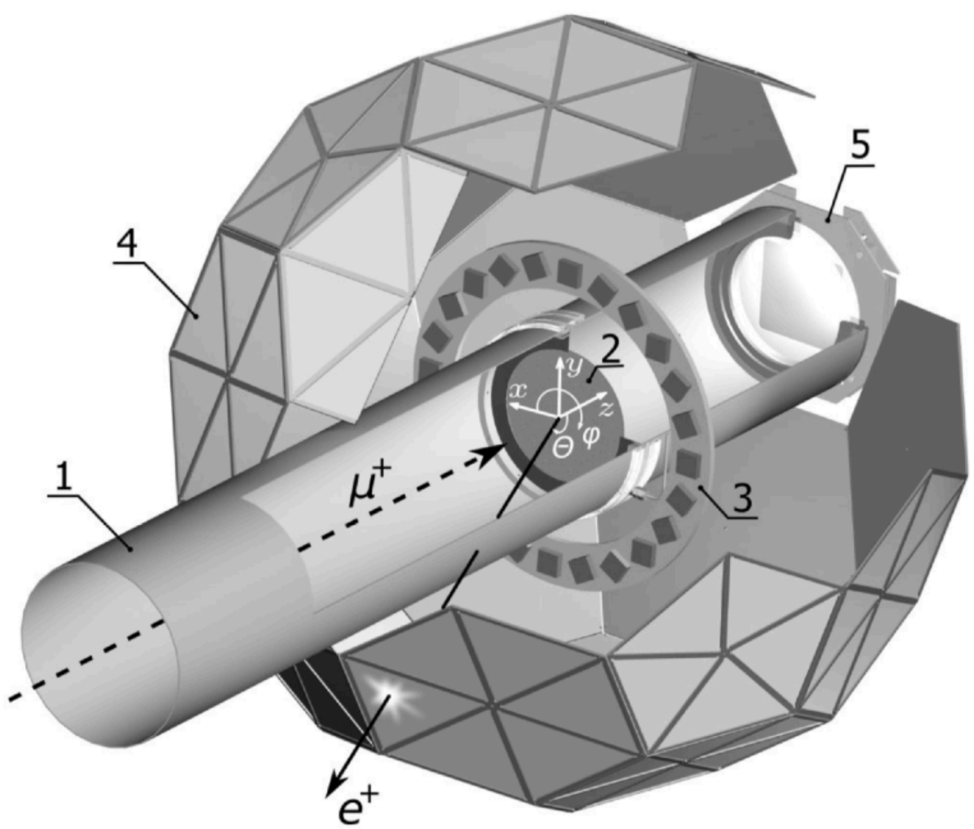


Experiments:
[1] J. Duclos et al., Phys. Lett. 47B, 491 (1973). [2] M. Balandin et al., Zh. Eksp. Theor. Fiz. 67, 1631 (1974).
[3] G. Bardin et al., Phys. Lett. 137B, 135 (1984). [4] K. Giovanetti et al., Phys. Rev. D 29, 343 (1984).
[5] T. Qian, Ph.D. Thesis, Univ. of Minnesota (2006). [6] D. Chitwood et al., Phys. Rev. Lett. 99, 032001 (2007).
[7] D. Tomono et al., Presentation at the NP08 conference (2008). [8] A. Barczyk et al., Phys. Lett. B 663, 172 (2008).
[9] V. Tishchenko et al., Phys. Rev. D 87, 052003 (2013).
Theory:
[10] T. Kinoshita and A. Sirlin, Phys. Rev. 113, 1652 (1959). [11] T. van Ritbergen and R.G. Stuart, Phys. Rev. Lett. 82, 488 (1999), Nucl. Phys. B 564, 343 (2000). [12] A. Pak and A. Czarnecki, Phys. Rev. Lett. 100, 241807 (2003).

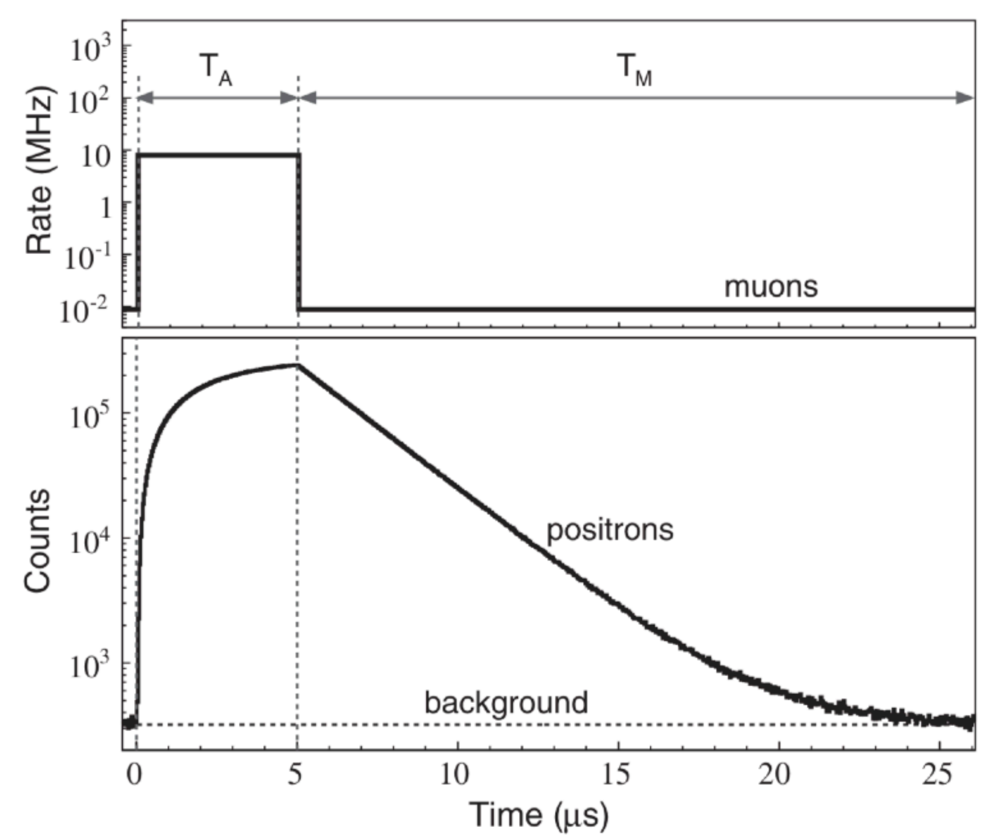
Muon Lifetime

MuLan Experiment at PSI

- Two types of target configuration (1.6×10^{12} e^+ in total):
  - Ferromagnet in a field of 0.4 T (μ^+)
  - Quartz in a field of 0.013 T (Muonium=μ^+e^-)
  - → Combined result: τ_μ=2.1969803(21)$_{stat}$(7)$_{syst}$ μs (1 ppm)



MuLAN setup

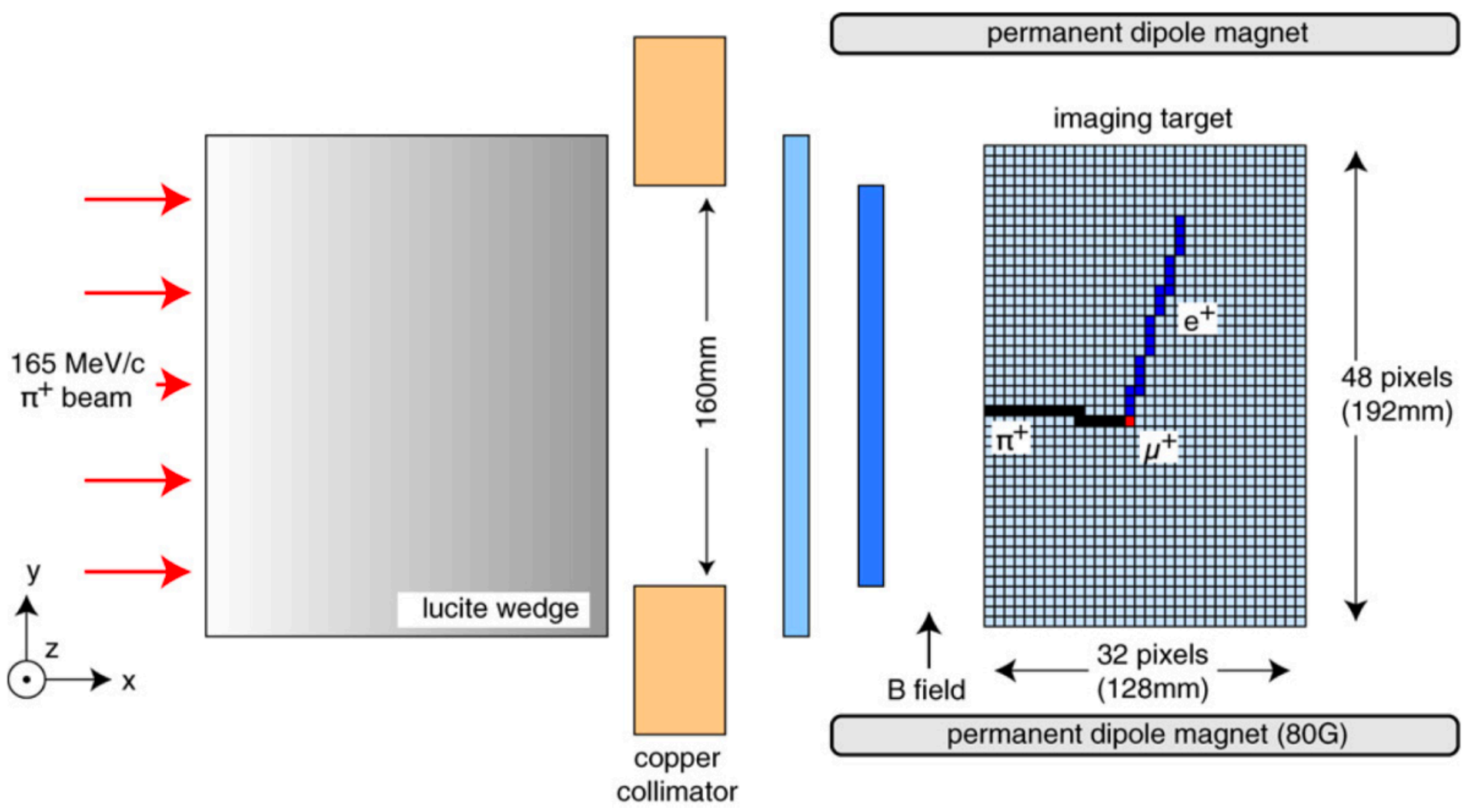


Timing structure of the beam

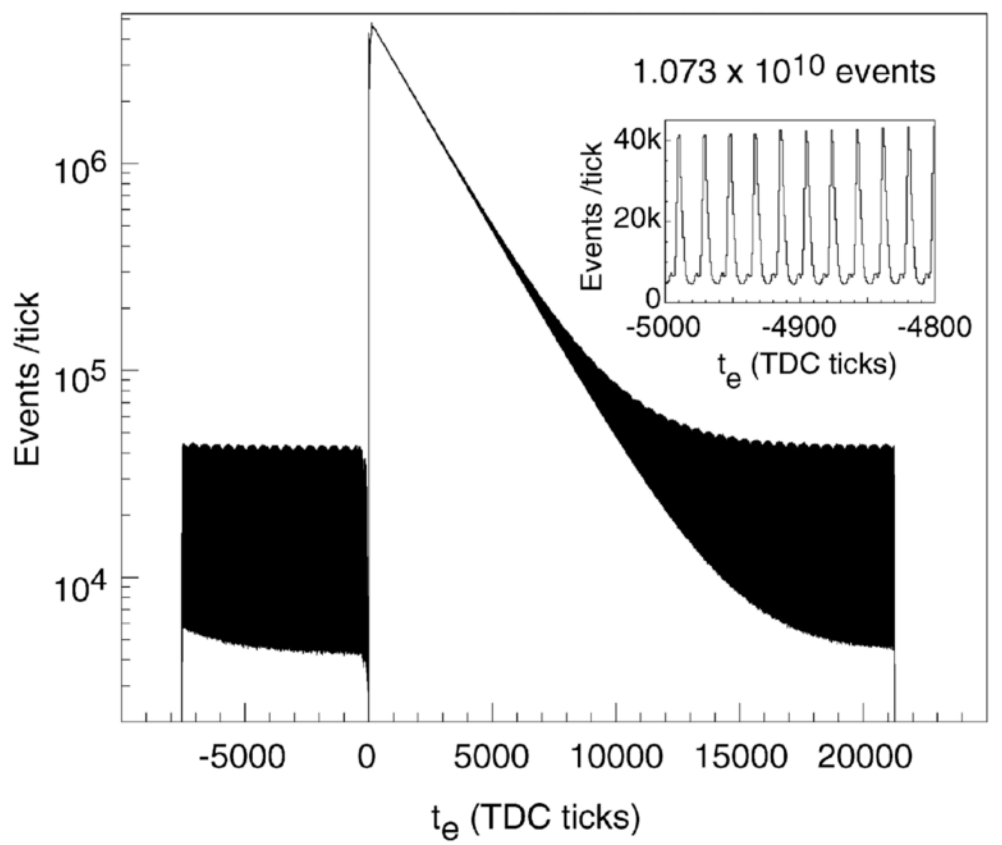
Muon Lifetime

FAST experiment at PSI

- Measurement of decay chain $\pi^+ \to \mu^+ \to e^+$ using stacked scintillation fibers (1.073×10^{10} e^+)
  - → Result: $\tau_\mu = 2.197083(32)_{stat}(15)_{syst}$ μs (8 ppm)



FAST setup (top view).

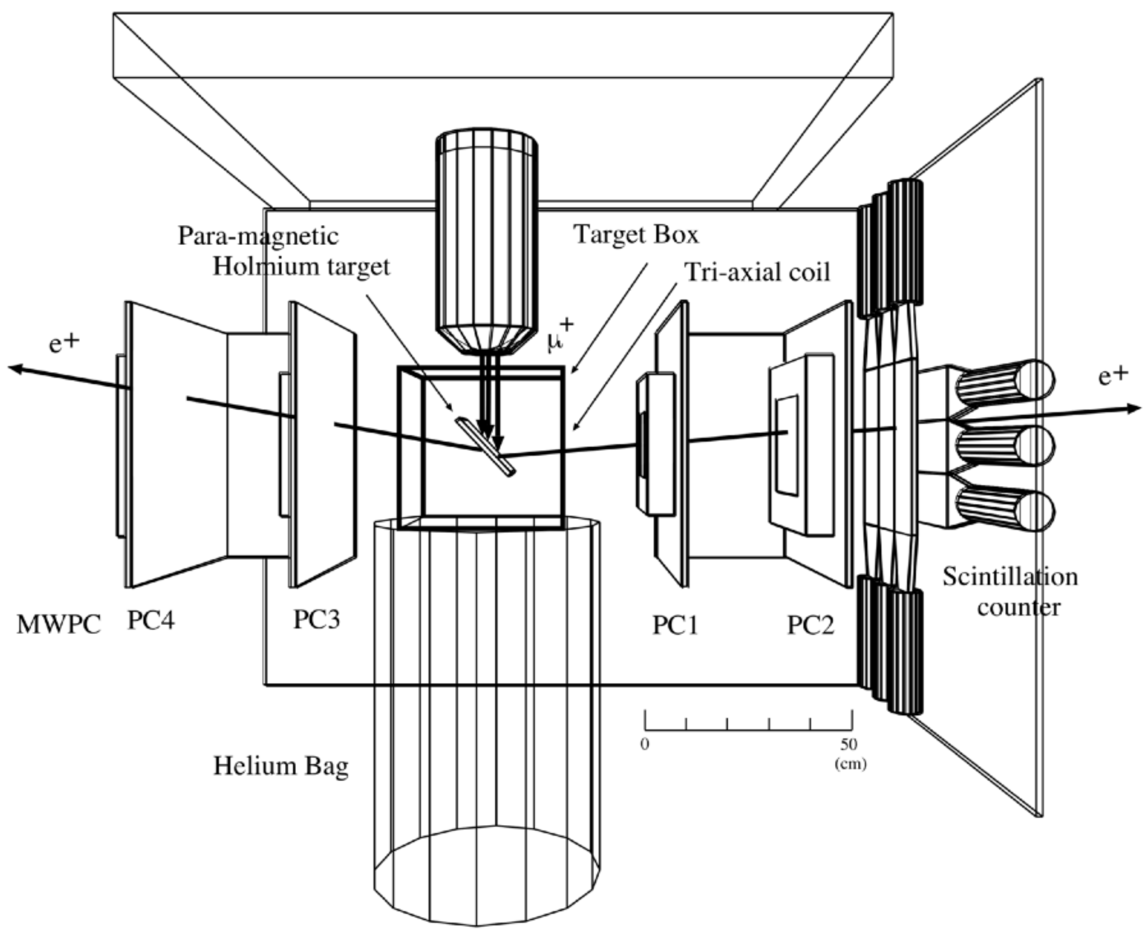


Decay positron time spectrum.

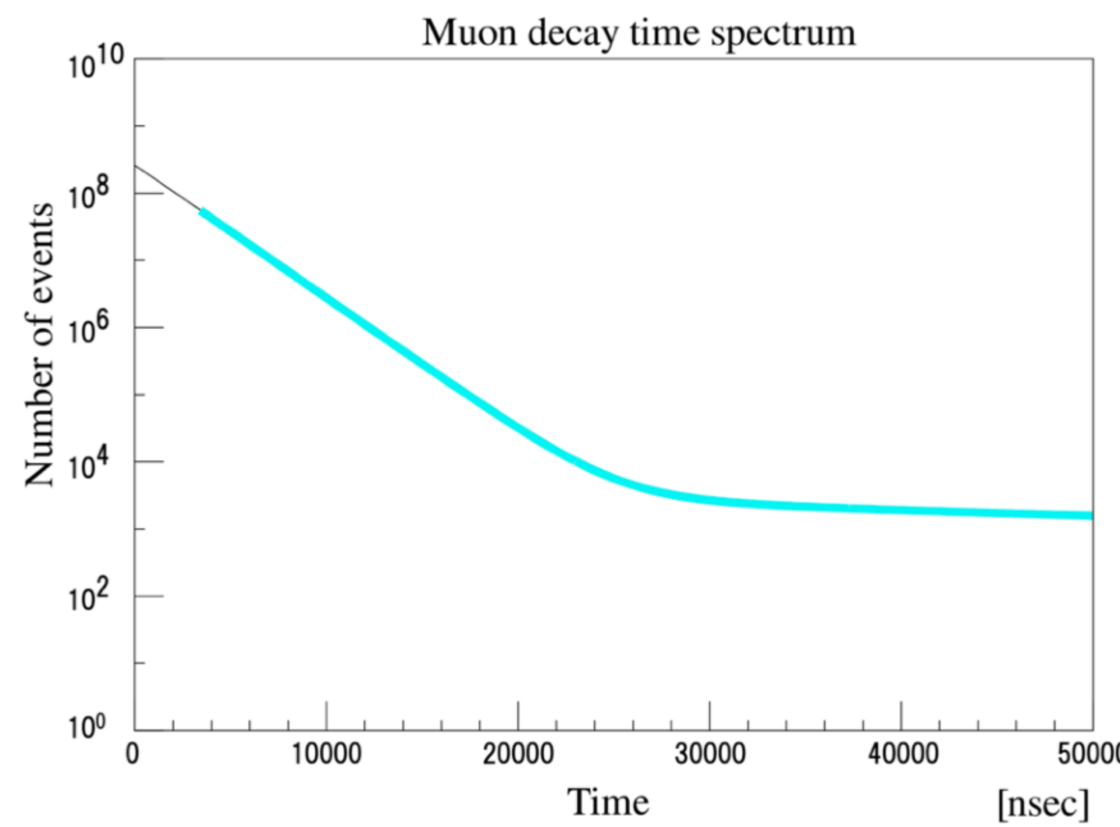
Muon Lifetime

R77 experiment at RIKEN-RAL

- Decay positron tracking using MWPCs ($1.15\text{x}10^{10}$ e^+)
  - → Result: $\tau_\mu = 2197.01 \pm 0.11^{+0.006}_{-0.034}$ ns (51 ppm)



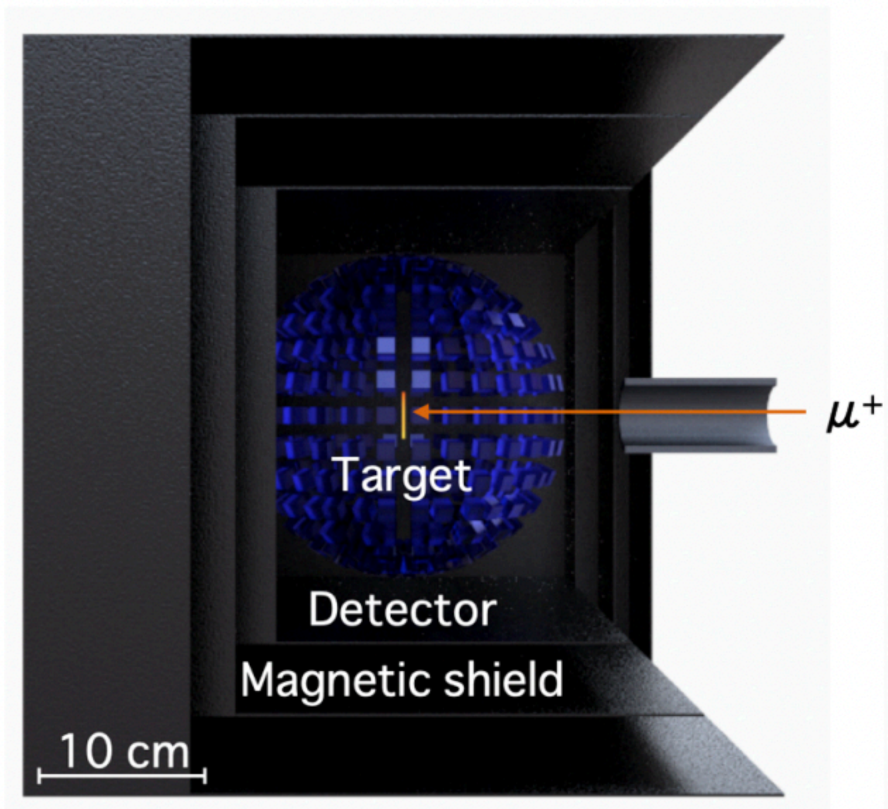
R77 setup (top view). A para-magnetic holmium target was employed for muon stopping with fast spin relaxation.

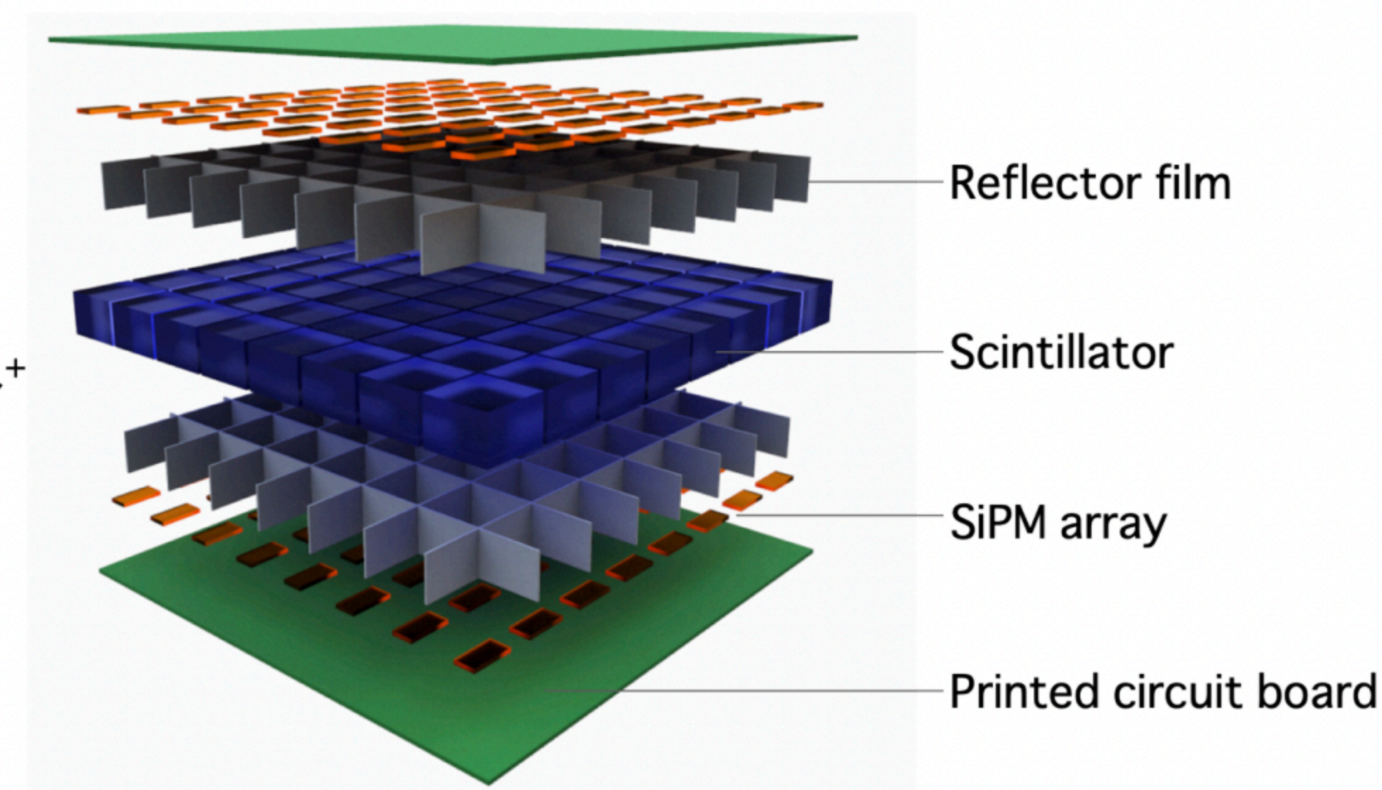


Decay positron time spectrum. A pulsed muon beam enables a low-background measurement.

Muon Lifetime

New Proposal at J-PARC



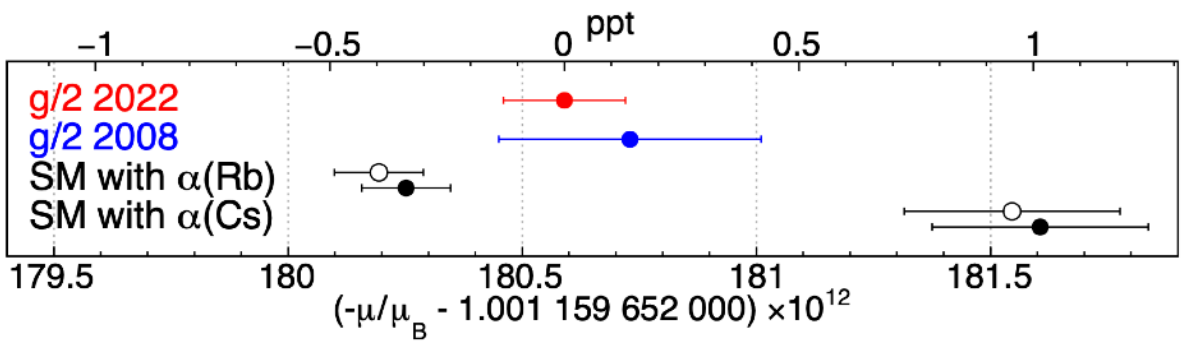


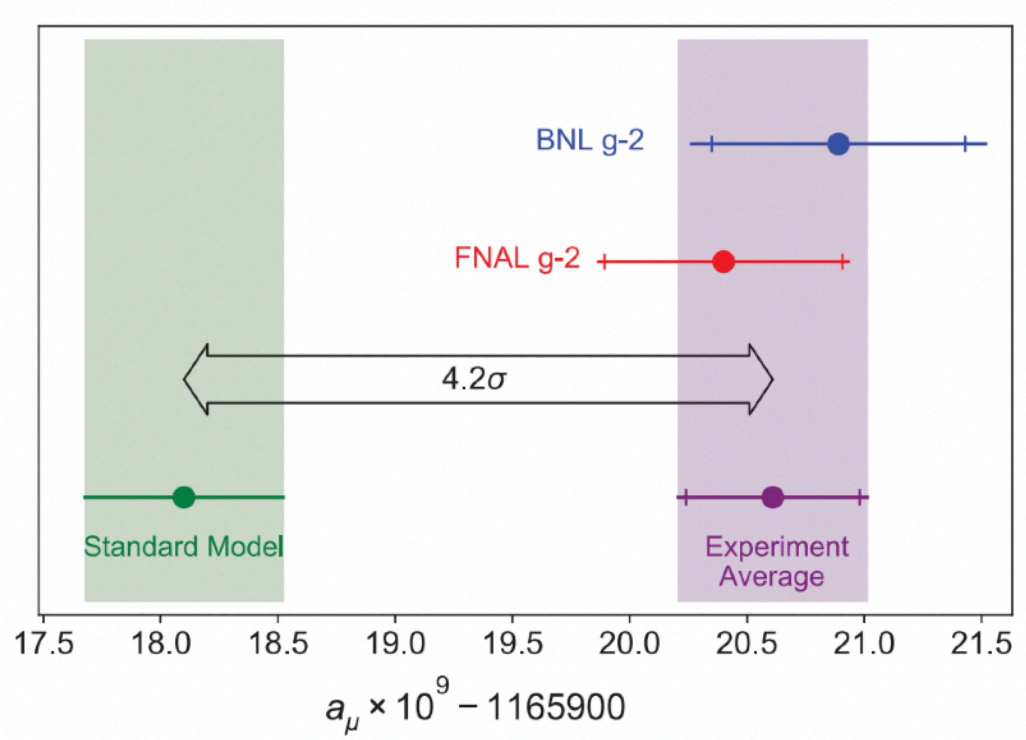
- Scintillation counters with SiPM readout are placed on a spherical surface (r=10 cm)
- 23 days of measurement will give x100 stat. of MuLan.
- The apparatus is enclosed in a magnetic shield to suppress the effect of μSR.
- Detector R&D is in progress.

S. Kanda “Toward a high-precision measurement of the muon lifetime with an intense pulsed muon beam at J-PARC”, PoS NuFact2021 (2022) 215.

Lepton Magnetic Moment

Anomalous magnetic moment of electron and muon



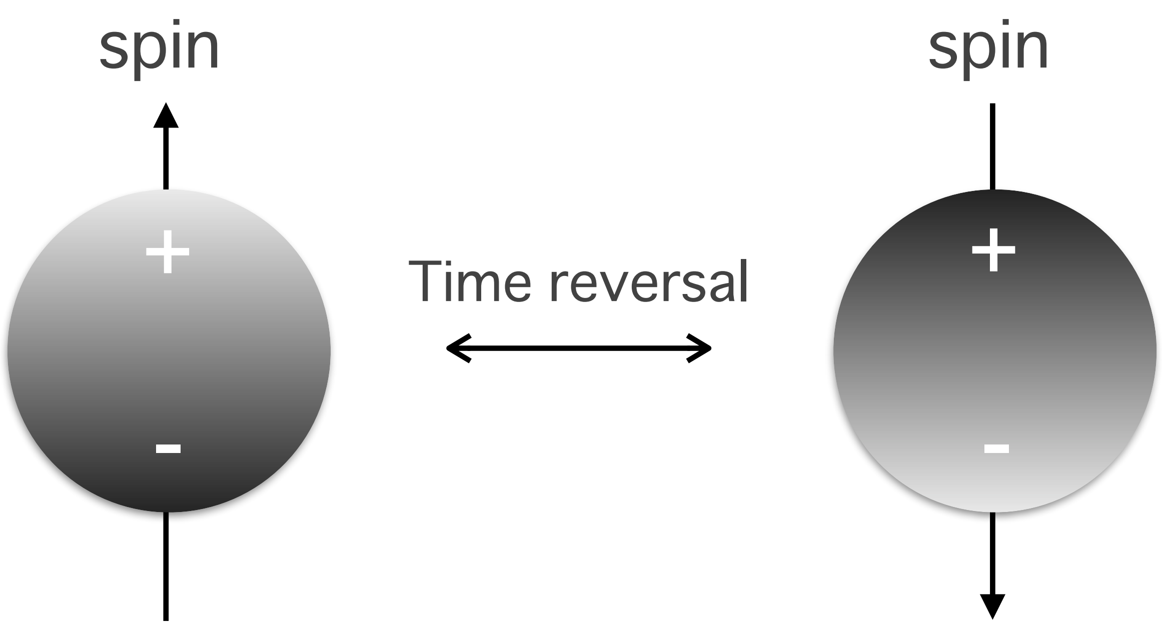


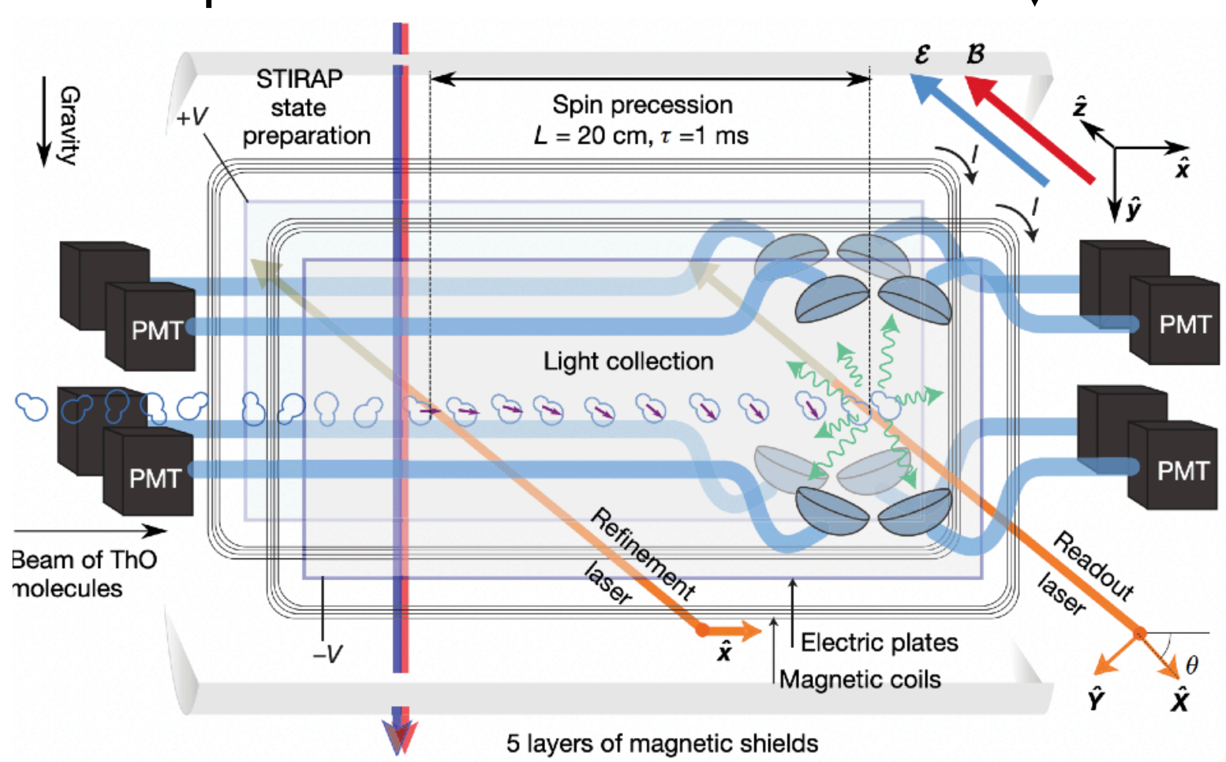
- Electron g-2
  - New result was published in 2023. The precision was 0.13 ppt.
  - A tension between atom interferometer measurements.
- Muon g-2
  - The FNAL experiment confirmed the BNL result.
  - 4.2 σ discrepancy between the Standard Model prediction.

X. Fan et al., “Measurement of the Electron Magnetic Moment”, Phys. Rev. Lett., 130 071801 (2023).
Muon g-2 Collaboration, “Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm”, Phys. Rev. Lett., 126, 121801 (2021).

Lepton Electric Dipole Moment

Time-reversal symmetry-breaking observable



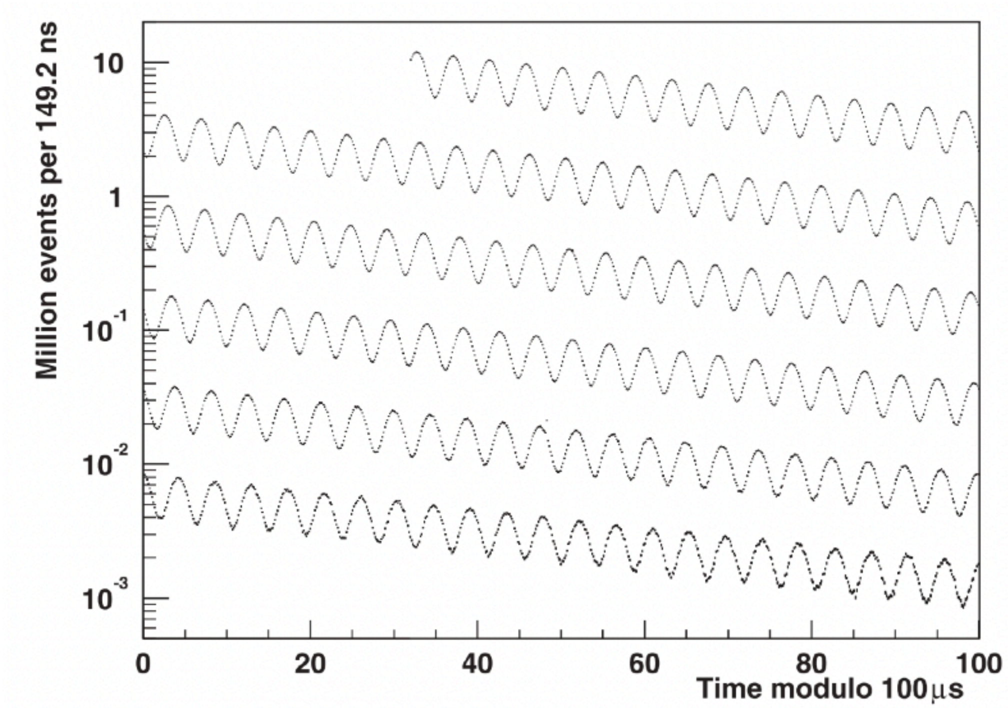


- Electric dipole moment of elementary particle breaks time-reversal symmetry.
- The tightest limit of the electron EDM was obtained by ThO molecule experiment as $|d_e|<1.1\text{x}10^{-29}$ e cm
- The limit of the muon EDM is obtained by analyzing the spin precession in a storage ring.

The ACME Collaboration, "Order of Magnitude Smaller Limit on the Electric Dipole Moment of the Electron", Nature 562 (2018) 355.

Muon Magnetic Moment

E821 Experiment at BNL



σ_{syst} ω_a	R99 (ppm)	R00 (ppm)	R01 (ppm)
Pileup	0.13	0.13	0.08
AGS background	0.10	0.01	[a]
Lost muons	0.10	0.10	0.09
Timing shifts	0.10	0.02	[a]
E-field and pitch	0.08	0.03	[a]
Fitting/binning	0.07	0.06	[a]
CBO	0.05	0.21	0.07
Gain changes	0.02	0.13	0.12
Total for ω_a	0.3	0.31	0.21

[a]In R01, the AGS background, timing shifts, E field and vertical oscillations, beam debunching/randomization, binning and fitting procedure together equaled 0.11 ppm.

- Muon spin precession measurement using a storage ring.
- The final result was published in 2006, the precision was 0.54 ppm, statistically limited.
- The upper limit of muon EDM was $|d_\mu|<1.8\text{x}19^{-19}$ e cm.

G. W. Bennet at al., “Final report of the E821 muon anomalous magnetic moment measurement at BNL”, Phys. Rev. D 73, 072003 (2006).
G. W. Bennet at al., “Improved limit on the muon electric dipole moment”, Phys. Rev. D 80, 052008 (2009).

Muon Magnetic Moment

E989 Experiment at FNAL

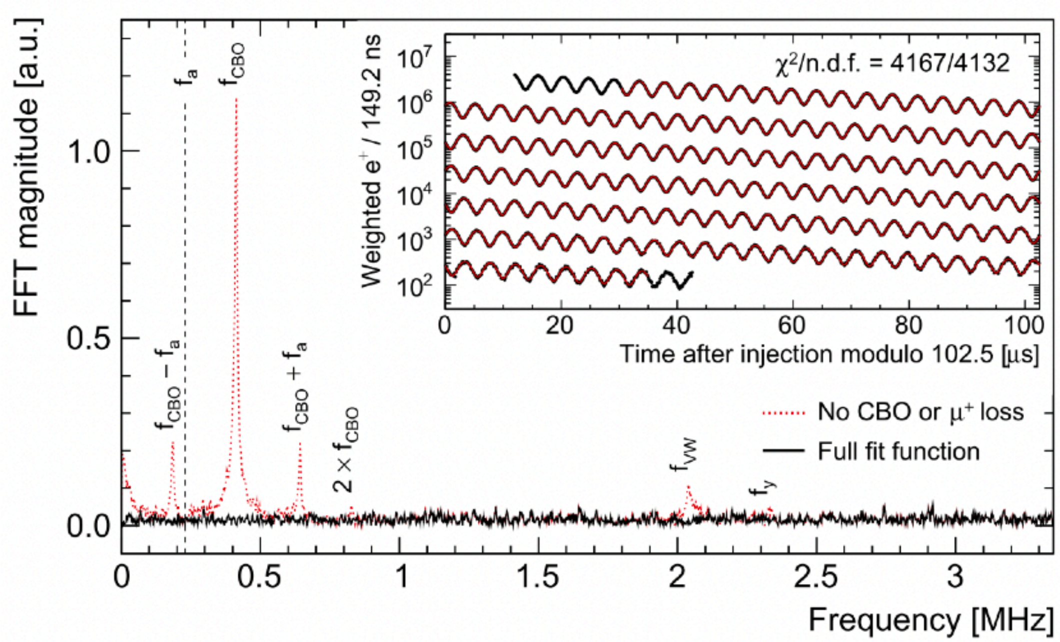


TABLE VII. The combination result for each dataset when using a staged approach.

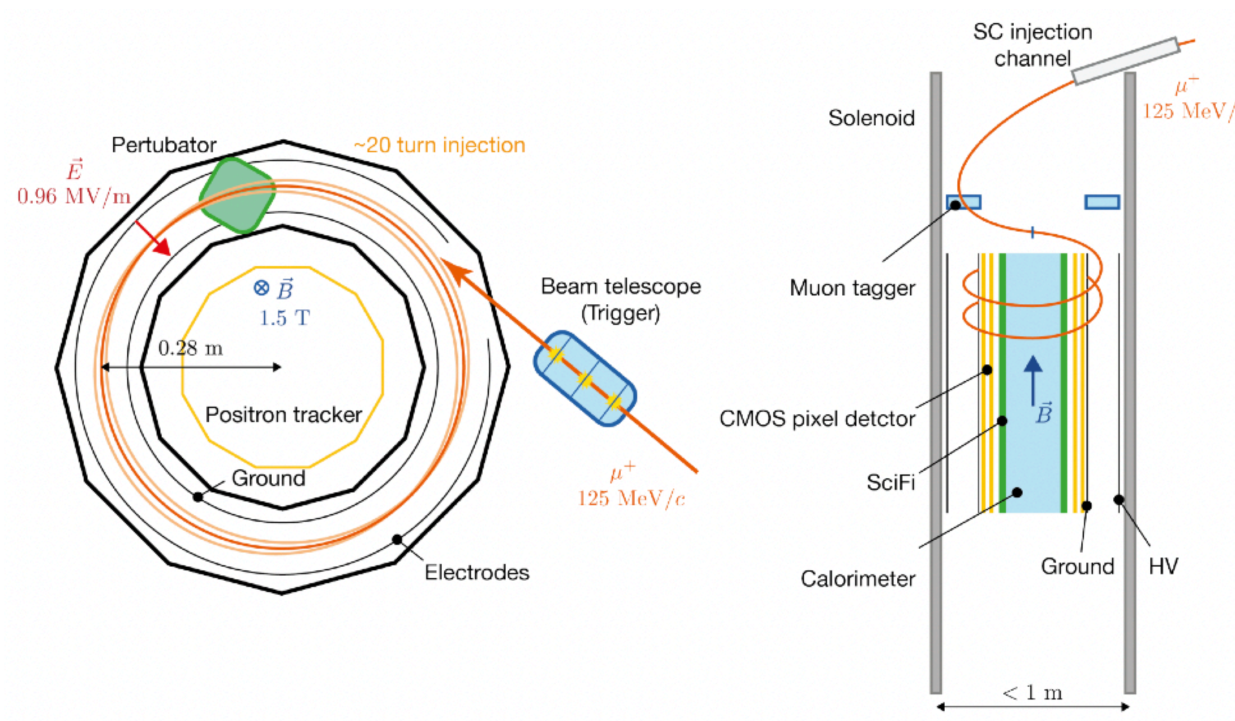
Run-1 dataset	1a	1b	1c	1d
$\omega_a^m/2\pi$ (s^{-1})	229 080.957	229 081.274	229 081.134	229 081.123
Δ ($\omega_a^m/2\pi$) (s^{-1})	0.277	0.235	0.189	0.155
Statistical uncertainty (ppb)	1207	1022	823	675
Gain changes (ppb)	12	9	9	5
Pileup (ppb)	39	42	35	31
CBO (ppb)	42	49	32	35
Time randomization (ppb)	15	12	9	7
Early-to-late effect (ppb)	21	21	22	10
Total systematic uncertainty (ppb)	64	70	54	49
Total uncertainty (ppb)	1209	1025	825	676

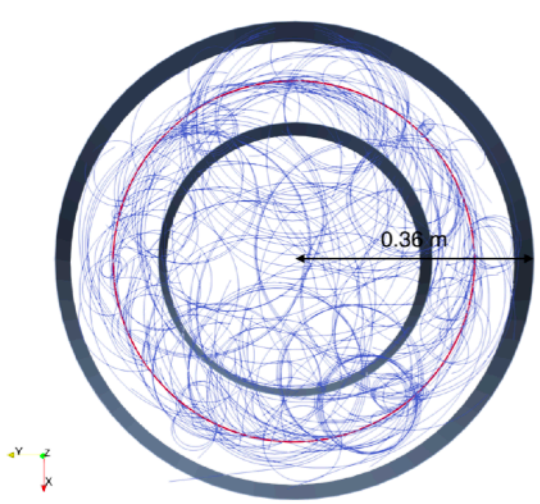
- The storage ring was moved from BNL to FNAL.
- Improvements in muon flux and purity, field uniformity, beam dynamics, and segmented calorimeter.
- The uncertainty of a_μ was 0.46 ppm (Run-1), statistically limited.
- The discrepancy was confirmed.

Muon g-2 Collaboration, "Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm", Phys. Rev. Lett., 126, 121801 (2021).
Muon g-2 Collaboration, "Measurement of the anomalous precession frequency of the muon in the Fermilab Muon g-2 Experiment", Phys. Rev. D, 103, 072002 (2021).

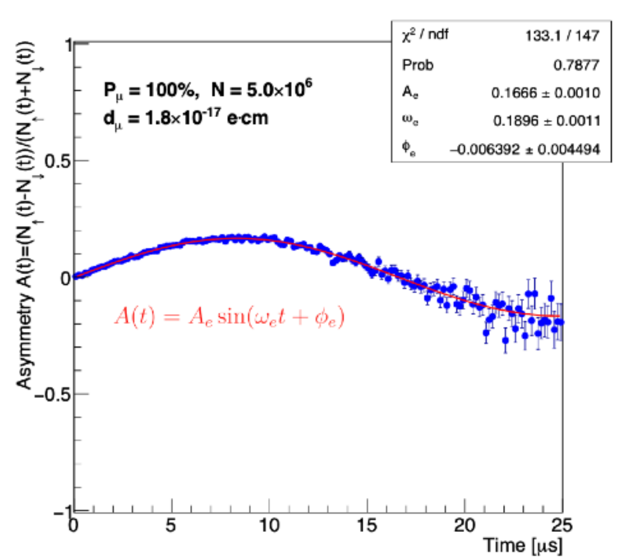
Muon Electric Dipole Moment

Experiment at PSI





Simulated muon tracks



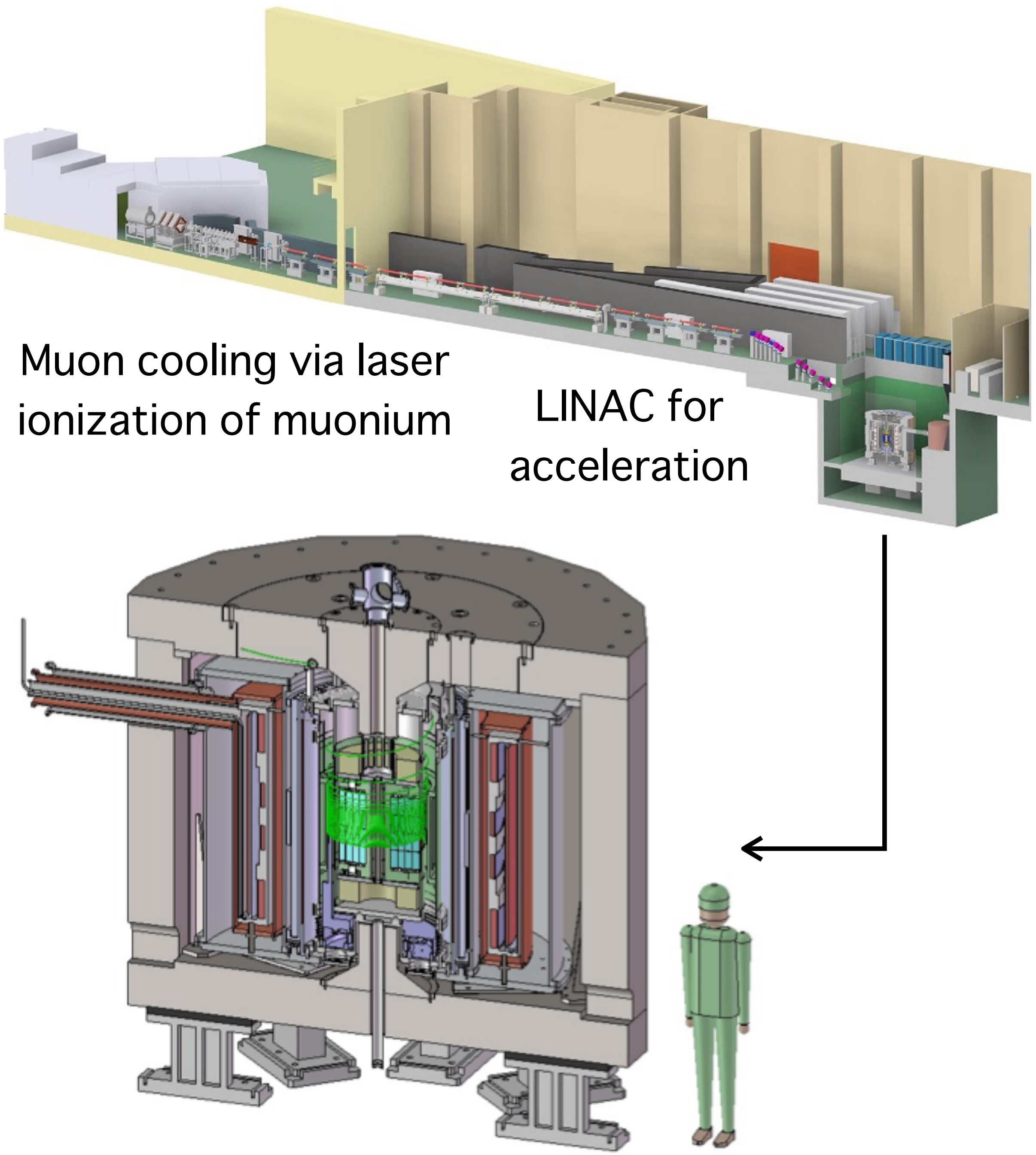
Up/down asymmetry

- A storage ring experiment dedicated to muon EDM search.
- A careful selection of electric field to cancel the effect of anomalous magnetic moment (spin frozen).
- Cold muon source and spiral injection.
- The sensitivity goal is 6×10^{-23} e cm.
- A letter of intent was submitted to PSI.

, .. Adelmann et al., "Search for a muon EDM using the frozen-spin technique", arXiv:2102.08838 [hep-ex].

Muon Magnetic Moment

E34 Experiment at J-PARC

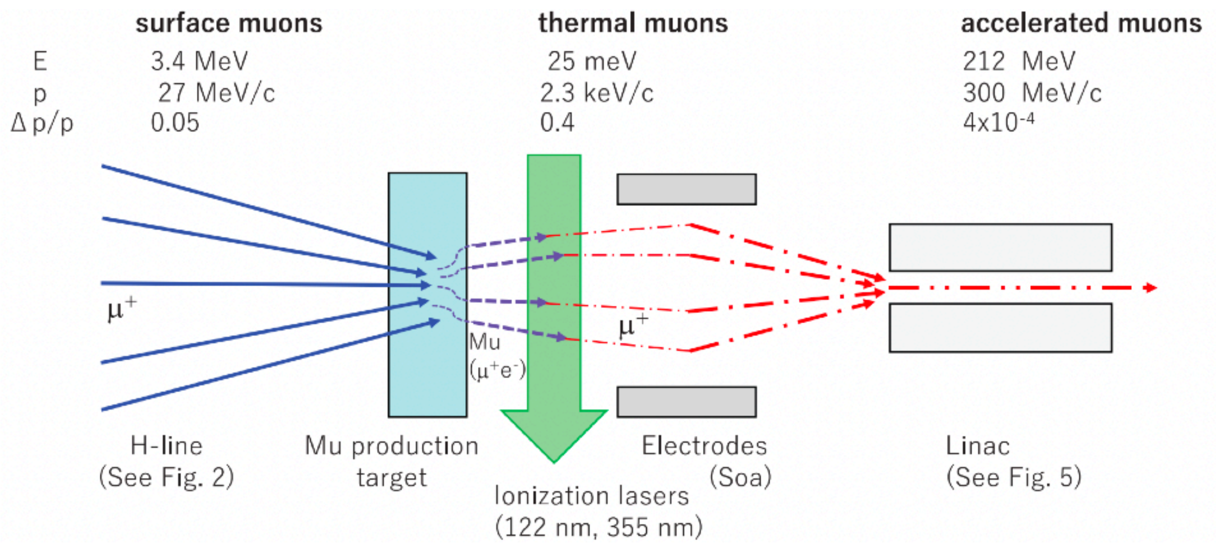


- A new approach using low-emittance muon beam.
- Low energy muons are obtained via laser ionization of muonium at room temperature.
- Slow muons are accelerated by LINAC.
- A compact storage ring and silicon strip positron tracker.
- Independent systematics from BNL and FNAL measurements.
- The facility is under construction.

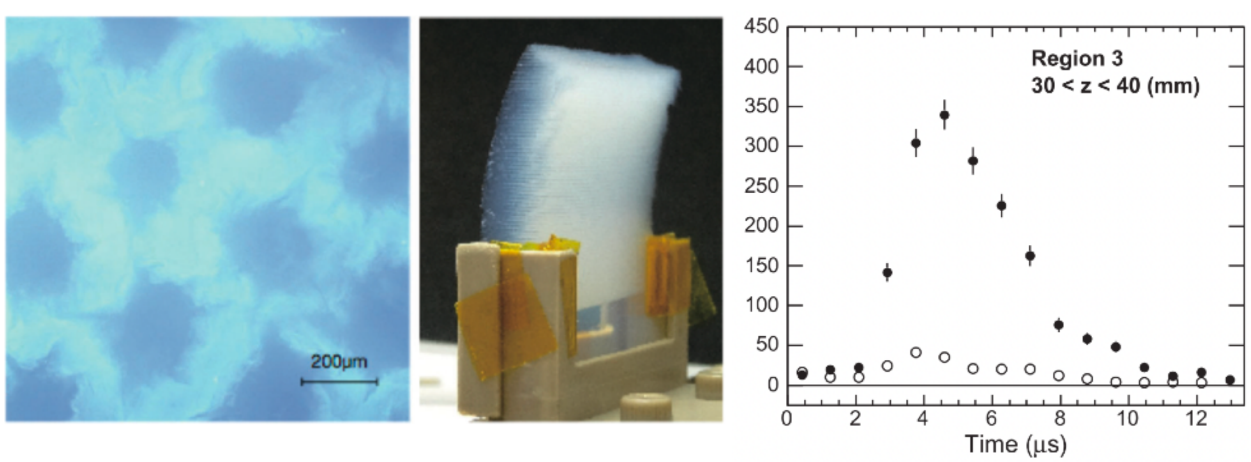
https://g-2.kek.jp/overview/

Muon Magnetic Moment

E34 Experiment at J-PARC



Scheme for re-accelerated thermal muon beam



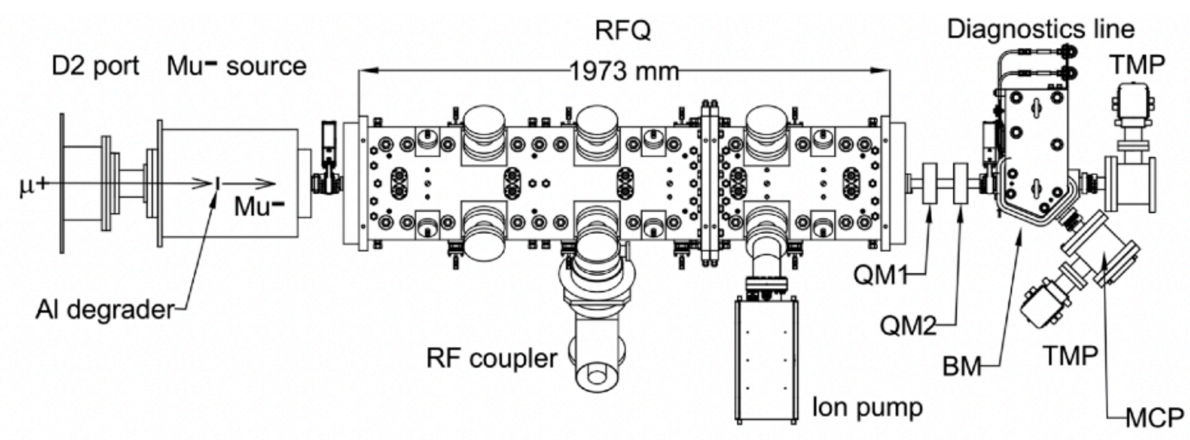
Laser-ablated silica aerogel and muonium emission enhancement

- A surface muon beam irradiates a muonium production target.
- Muonium atoms in vacuum are excited and ionized by two laser beams.
- Thermal muons are collected and accelerated for a low-emittance beam.
- Laser-ablation enhances the muonium emission efficiency.

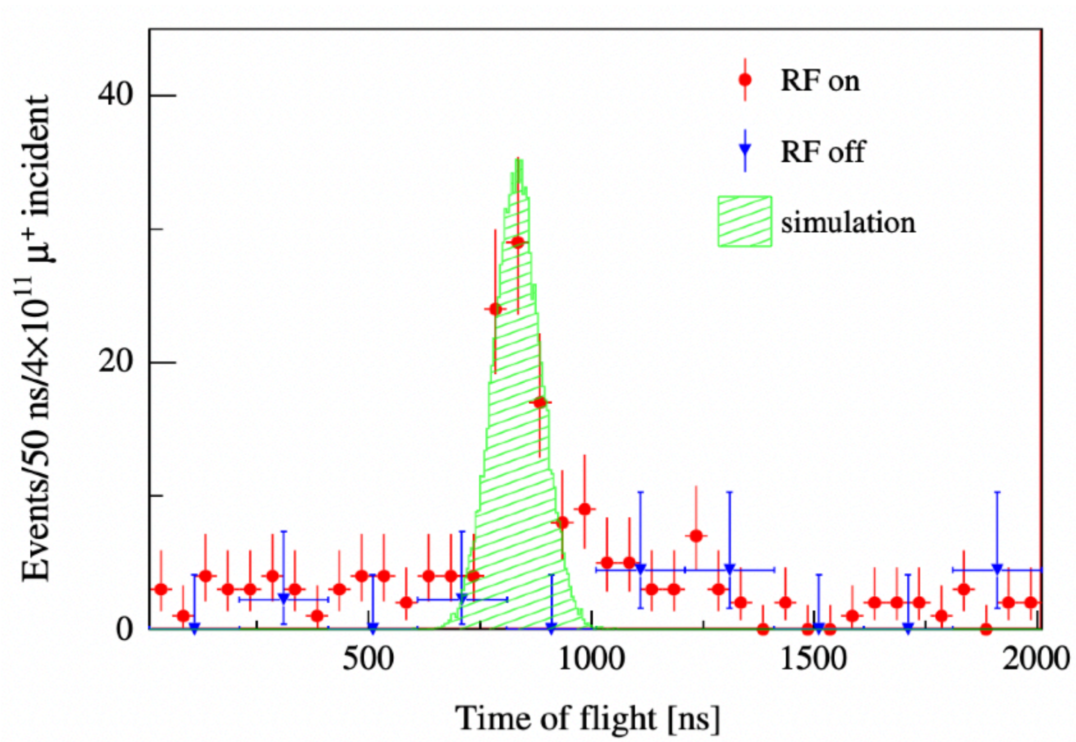
M. Abe et al., Prog. Theor. Exp. Phys. 2019, 053C02
G. Beer et al., Prog. Theor. Exp. Phys. 2014, 091C01

Muon Magnetic Moment

E34 Experiment at J-PARC



RFQ for muon acceleration



TOF spectrum of accelerated Mu$^-$

- Acceleration of slow muons by RFQ was demonstrated using negative muonium ions (Mu$^-$).
- World-first RFQ acceleration of muon.
- Extraction scheme and transport optics were tested with Mu$^-$ and μ^+.
- Preparations for an acceleration test using laser ionized slow muon is in progress.

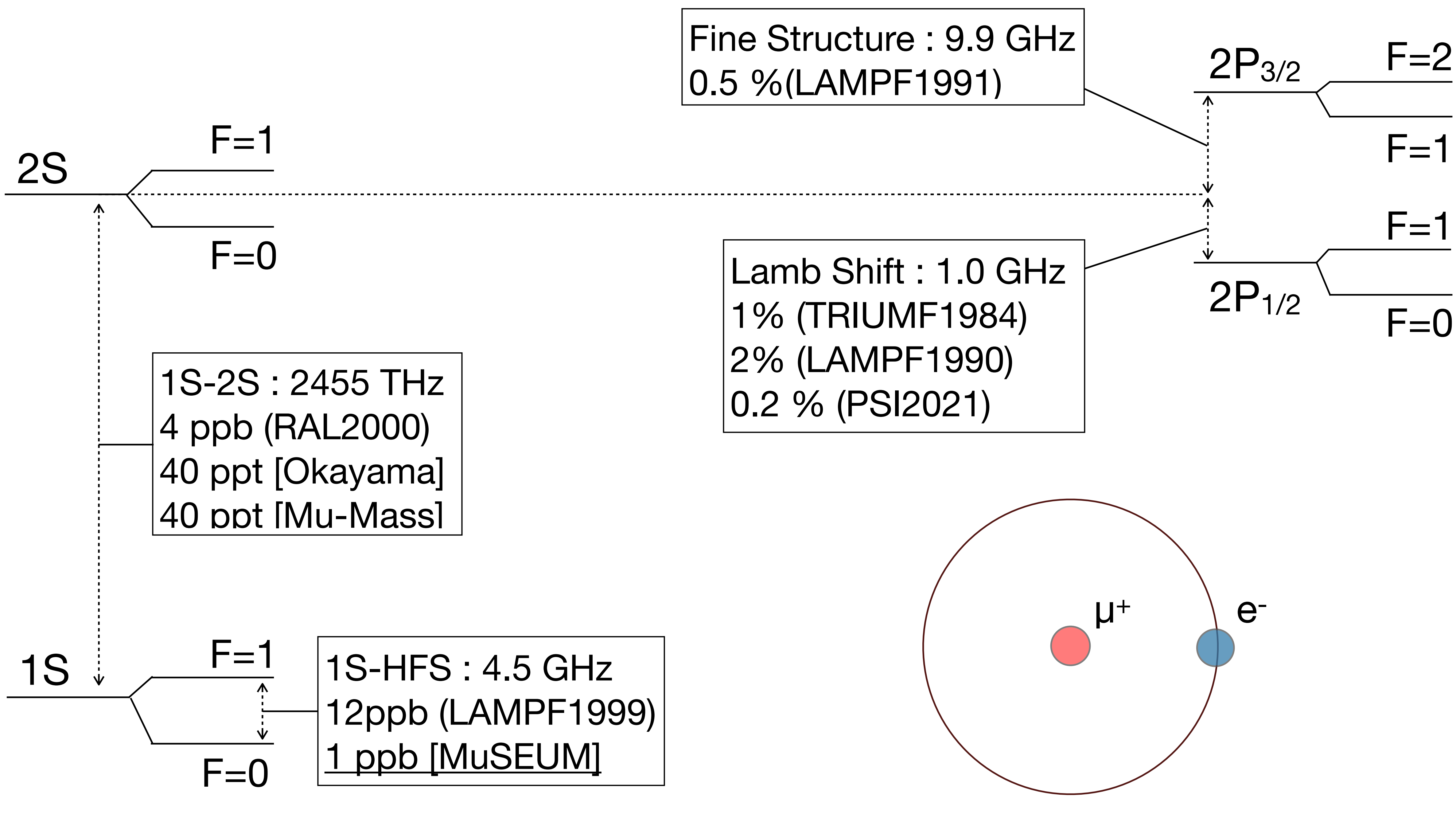
S. Bae et al., Phys. Rev. AB 21, 050101 (2018).
R. Kitamura et al., Phys. Rev. AB 24, 033403 (2021).

Present and Future of Muon Experiments: Precise Spectroscopy of Atoms involving Muons

Sohtaro Kanda (神田 聡太郎) / KEK IMSS MSL / kanda@post.kek.jp

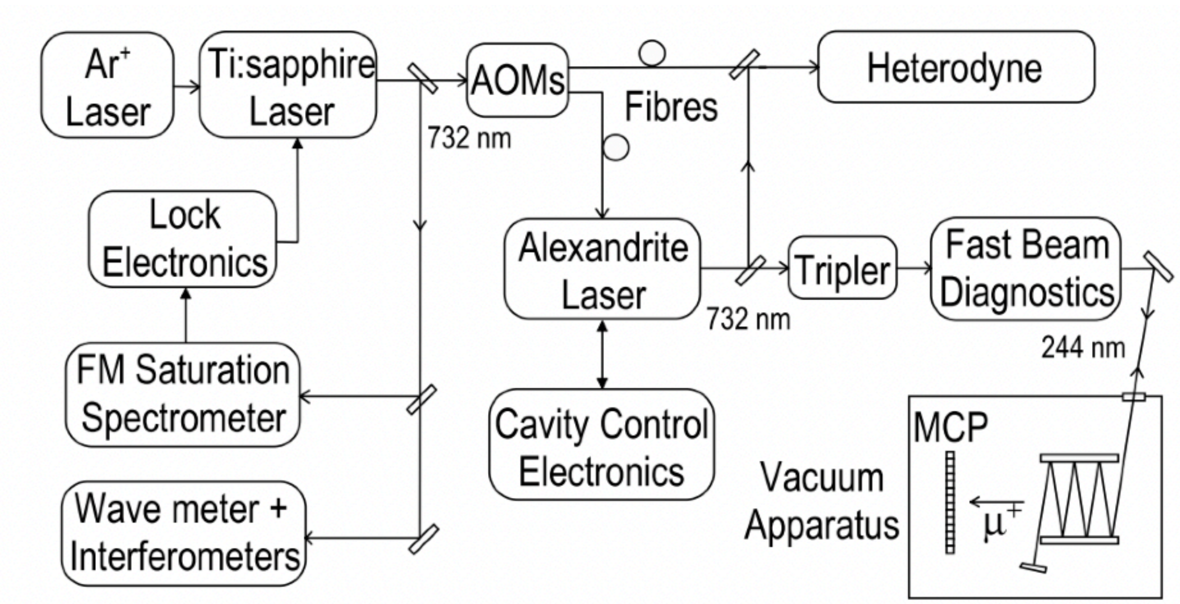
Muonium Spectroscopy

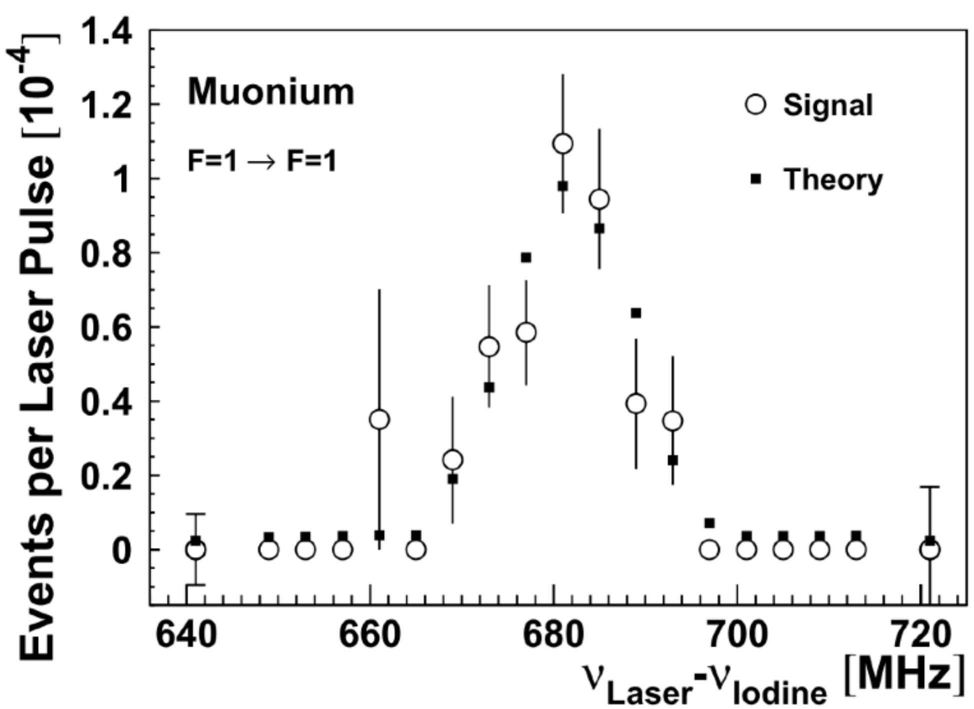
Leptonic two-body system



Muonium 1S-2S

Experiment at RAL





- Spectroscopy using counter-propagating 244-nm laser light.
- The result was f=2455 528 941.0 (9.8) MHz, 4 ppb.
- The mass ratio was determined to be m_{μ}/m_e = 206.76838(17), 0.8 ppm.
- Statistically limited (9.1 MHz).
- The major systematics was residual linear Doppler (3.4 MHz.)

V. Meyer et al., "Measurement of the 1s-2s Energy Interval in Muonium", Phys. Rev. Lett. 84, 1136 (2000).

Muonium 1S-2S

MuMass Experiment at PSI

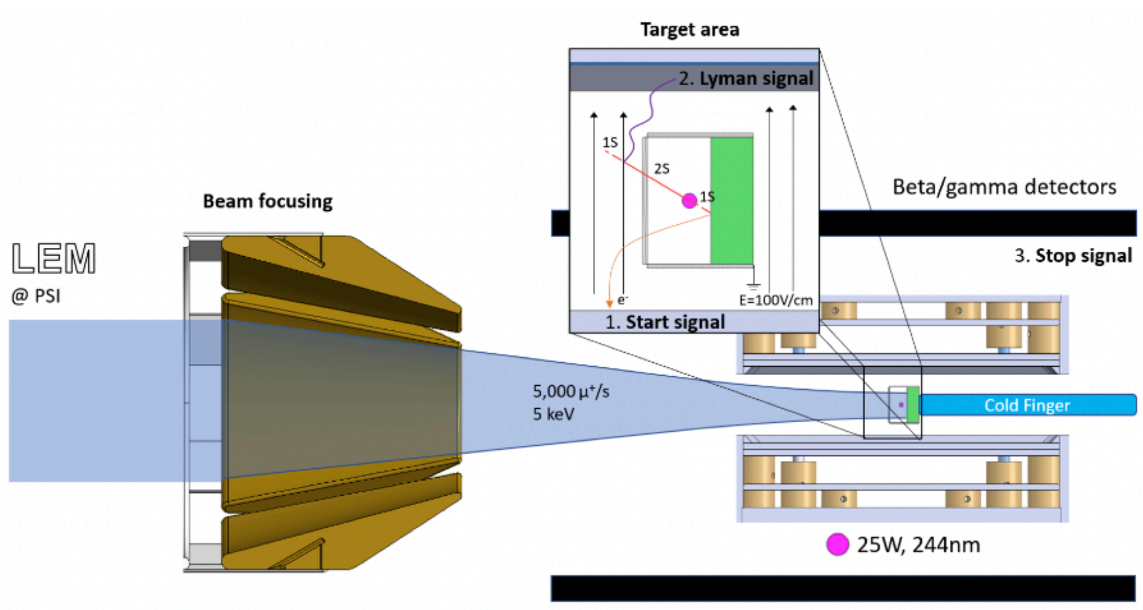


Table 1 Comparison between the RAL experiment (1999) and Mu-MASS. NE = Experimental linewidth

	RAL (1999)	Mu-MASS Phase1	Mu-MASS Phase2
μ^+ beam intensity	3500 × 50 Hz	5000 s^{-1}	> 9000 s^{-1}
μ^+ beam energy	4 MeV	5 keV	5 keV
M atoms temperature	300 K	100 K	100 K
Spectroscopy	Pulsed laser	CW	CW
Exp. linewidth	20 MHz	750 kHz	300 kHz
Laser chirping	10 MHz	0 kHz	0 kHz
Residual doppler	3.4 MHz	0 kHz	0 kHz
2nd-order doppler	44 kHz	15 kHz	1 kHz (corrected)
Frequency calibration	0.8 MHz	< 1 kHz	< 1 kHz
Background	2.8 events/day	1.6 events/day	1.6 events/day
Total of 2S events	99	1900 (10 d)	> 7000 (40 d)
Statistical uncertainty	9.1 MHz	<100 kHz	10 kHz
Total uncertainty	9.8 MHz	<100 kHz (NE/10)	10 kHz (NE/30)

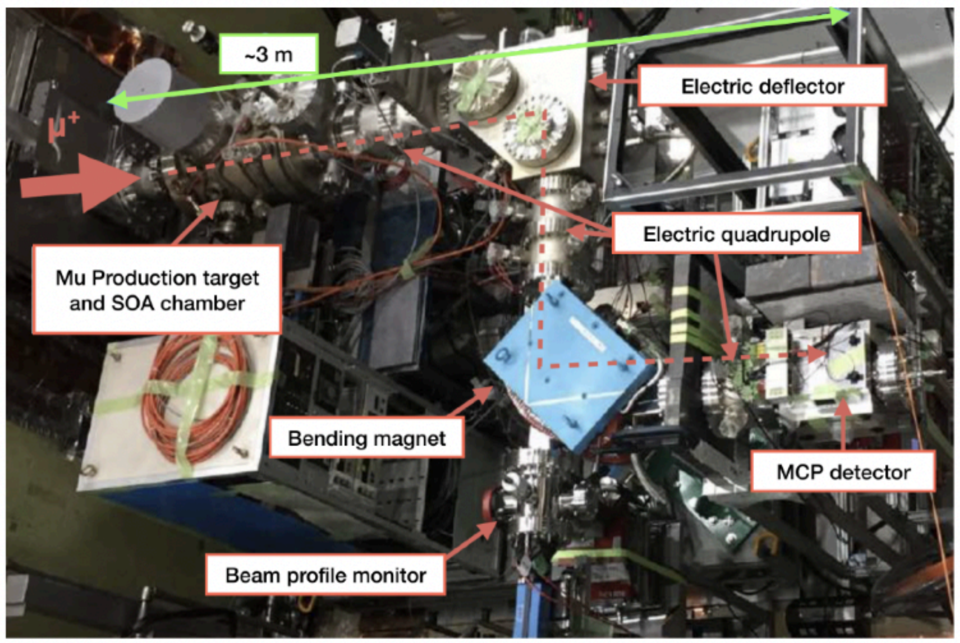
- Muonium 1S-2S spectroscopy using low-energy muons.
- A cold muonium converter to reduce the Doppler broadening.
- The target precision is 100 kHz for Phase1, 10 kHz for Phase2.
- Data-taking will start soon.

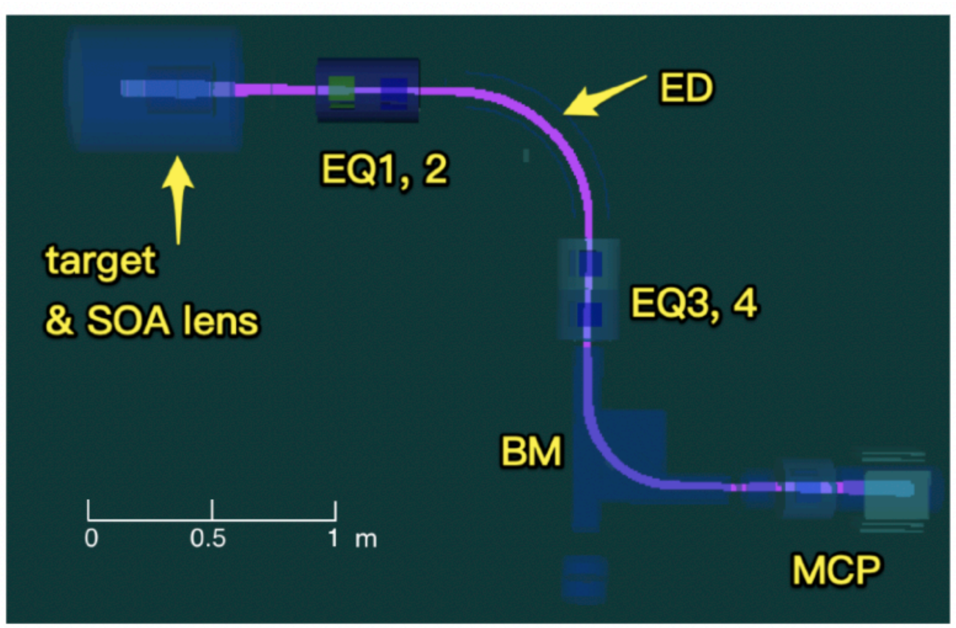
P. Crivelli, "The Mu-MASS (muonium laser spectroscopy) experiment", Hyperfine Interact (2018) 239: 49.

B. Ohayon, Z. Burkley, P. Crivelli, "Current status and prospects of muonium spectroscopy at PSI", SciPost Phys. Proc. 5, 029 (2021).

Muonium 1S-2S

Experiment at J-PARC





- Muonium 1S-2S spectroscopy using laser-ablated silica aerogel as a muonium emitter.
- The target precision is 1 MHz for Phase1, 10 kHz for Phase2.
- Data-taking and analysis are ongoing.

S. Uetake, "New frontier with Laser spectroscopy of Muonium", Presentation at J-PARC Symposium 2019.
C. Zhang et al., "Simulation Study of Laser Ionization of Muoniumby 1S-2S Excitation for the Muong2/EDMExperiment at J-PARC", JPS Conf. Proc. , 011125 (2021).

Muonium Lamb Shift

Lamb shift and fine structure measurements at PSI

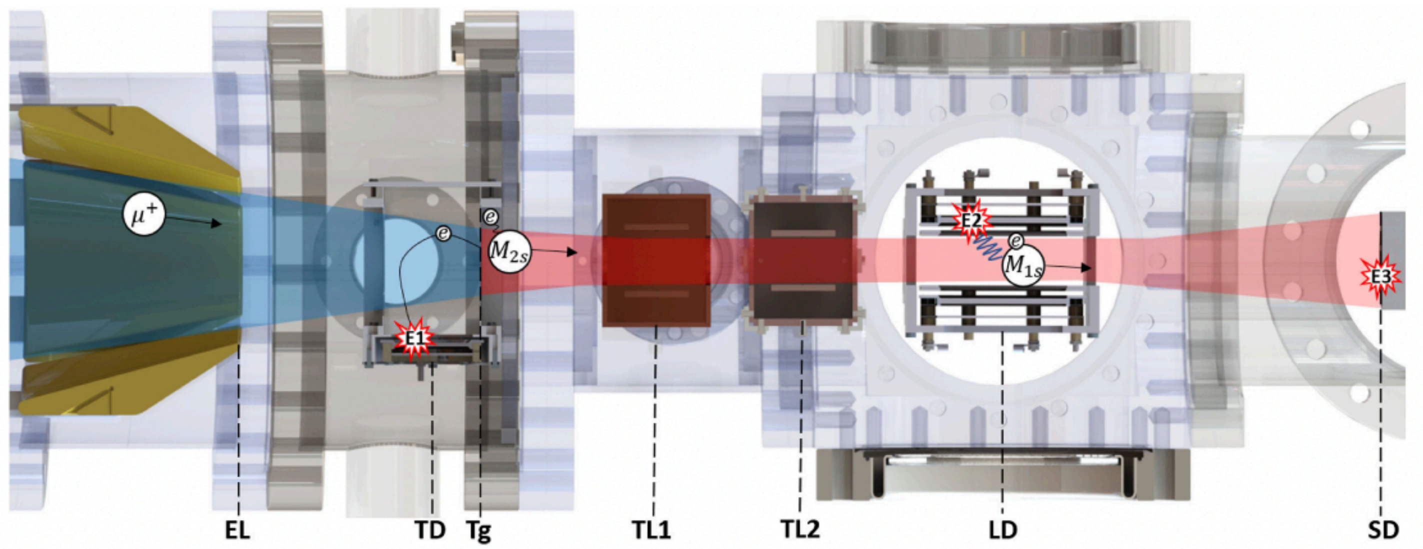
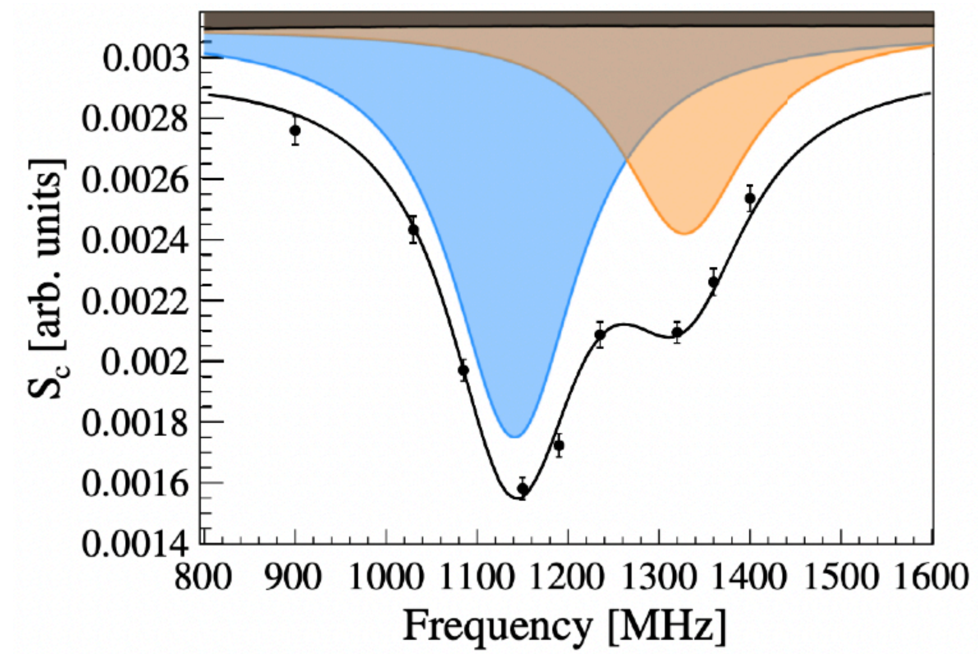


FIG. 1. Main elements of the experimental system. Conical electrostatic lens (EL), tagging detector (TD), carbon foil target (Tg), transmission line (TL), Lyman-alpha detector (LD), stop detector (SD). The normalization signal is given by the coincidence between an event in TD (E1) and SD (E3) within the expected time of flight, while a valid event includes also a reading in LD (E2).

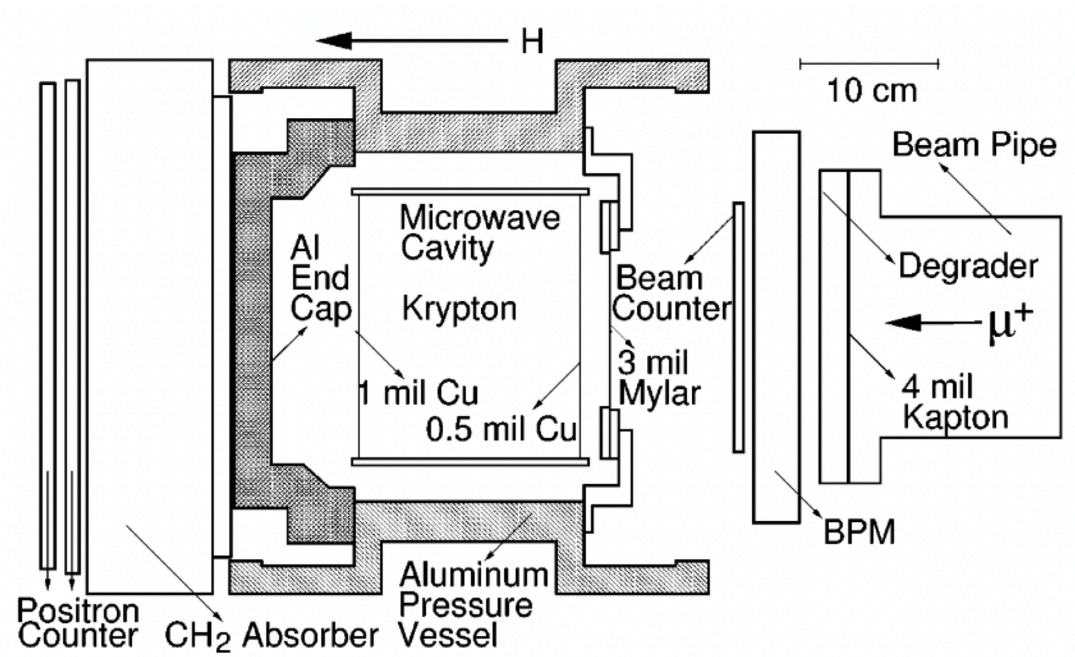


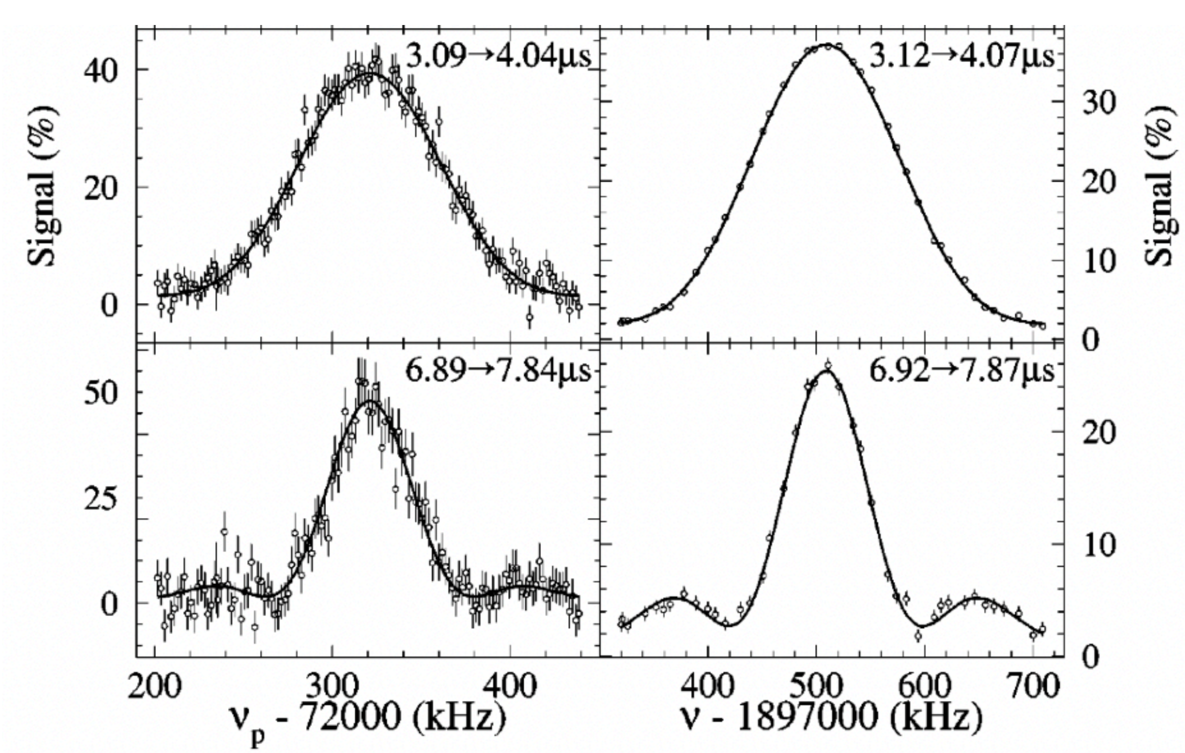
- A 2S-Mu beam was obtained at LEM for in-flight microwave spectroscopy.
- Transmission lines select the muonium state.
- An electric-field quencher and a UV-sensitive MCP detect 2S-Mu.

B. Ohayon et al., PRL 128, 011802 (2022).

Muonium Hyperfine Splitting

Experiment at LAMPF





- Muonium 1S-HFS microwave spectroscopy under a high magnetic field.
- The final result was published in 1999.
- The precision was 12 ppb, statistically limited.
- The muon-to-proton magnetic moment ratio was determined with 120 ppb precision.
- The largest systematics was field uniformity.

W. Liu et al., "High Precision Measurements of the Ground State Hyperfine Structure Interval of Muonium and of the Muon Magnetic Moment", Phys. Rev. Lett., 82 711 (1999).

Muonium Hyperfine Splitting

Theoretical prediction and experimental result

- Theoretical prediction: $\Delta_{\text{HFS}} = 4.463\,302\,872(515)$ GHz

$$\Delta_{\text{HFS}} = \frac{16}{3} Z^4 \alpha^2 \frac{m_e}{m_\mu} \left(1 + \frac{m_e}{m_\mu}\right)^{-3} c R_\infty + \Delta_{\text{QED}} + \Delta_{\text{QCD}} + \Delta_{\text{EW}}$$

237 Hz (QCD) 65 Hz (EW)

- Experimental result: $\Delta_{\text{HFS}} = 4.463\,302\,776(51)$ GHz (11 ppb)

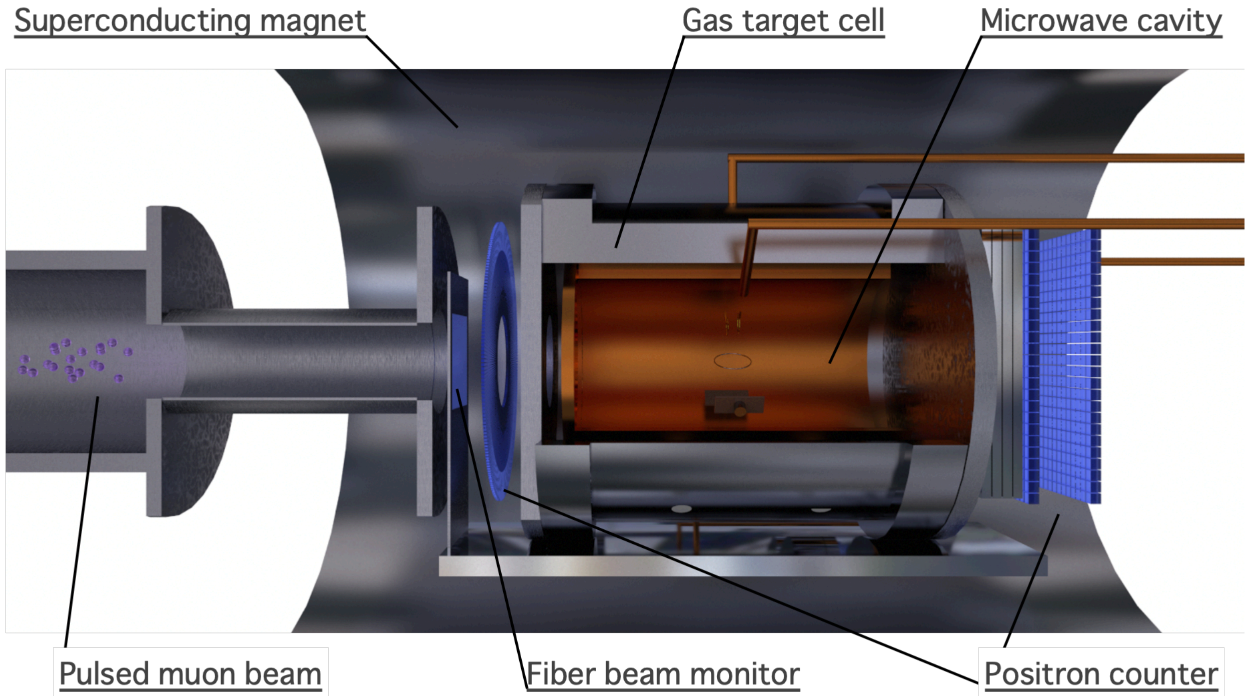
$$m_\mu / m_e = 206.768277(24) \quad \text{(116 ppb)}$$

Theory : M. I. Eides, Phys. Lett. B 795, 113(2019).
S. G. Karshenboim and E. Y. Korzinin, Phys. Rev. A 103, 022805 (2021).
Experiment : W. Liu et al., Phys. Rev. Lett., 82 711 (1999).

- The precision of the experimental result is limited by statistics.
  - A high-intensity pulsed muon beam is beneficial.
- The theoretical uncertainty is limited by the measurement result of muon mass.
  - The mass can be independently obtained with the muonium 1S-2S spectroscopy.

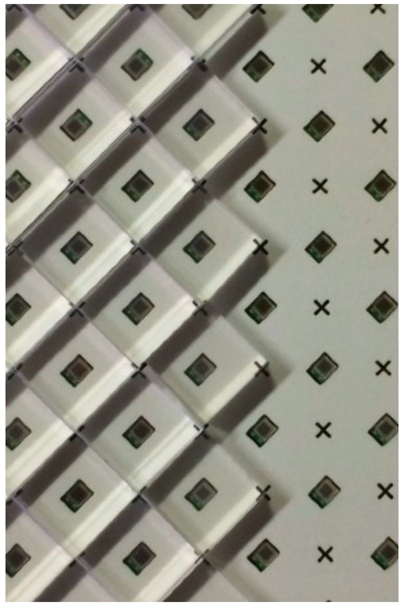
Muonium Hyperfine Splitting

MuSEUM Experiment at J-PARC



Magnet

NMR probe



Positron detector

- Muonium 1S-HFS microwave spectroscopy using a high-intensity pulsed beam at J-PARC.
- A segmented positron detector for precise signal counting.
- Improved field uniformity and precise mapping of the field.
- The target precision is 1 ppb for HFS, 12 ppb for μ_μ/μ_p.
- Phase-1 measurements under a zero-field have been completed.
- Preparing for Phase-2.

Project Timeline of MuSEUM

Since the experiment was proposed

2011 — 2013 — 2015 — 2017 — 2019 — 2021

Proposal submitted
K. Shimomura, AIP Conf. Proc. 1382, 245 (2011).

Cavity R&D
K.S. Tanaka et al. PTEP 2021, 053C01(2021).

Detector R&D
S. Kanda, PoS(PhotoDet2015)039 (2016).

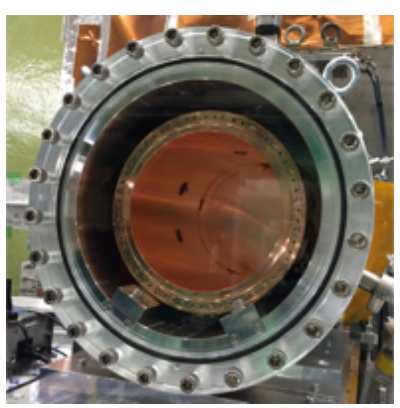
First ZF Result
S. Kanda, PoS(INPC2016)170 (2017).

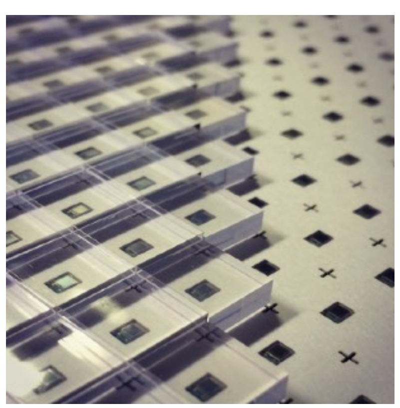
Second ZF Result
S. Kanda et al., Phys. Lett. B 815, 136154 (2021).

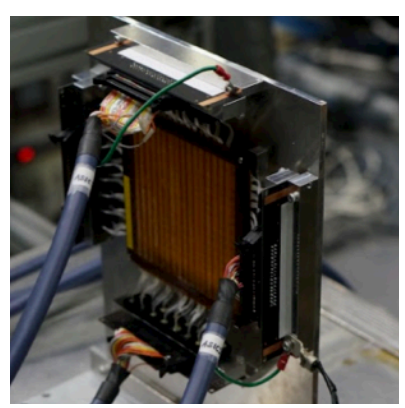
Rabi-oscillation Spectroscopy
S. Nishimura et al., Phys. Rev. A 104, L020801 (2021).

NMR Probe R&D
H. Yamaguchi et al., IEEE Trans. Appl. Supercond. 29, 9000904 (2019).

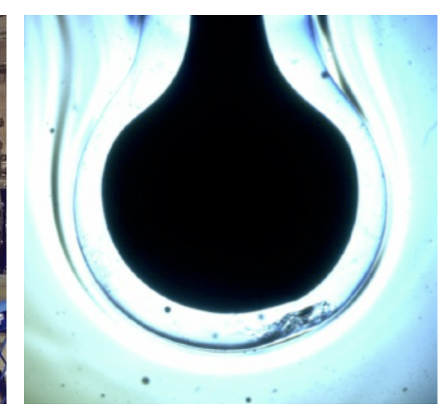
Shimming R&D
M. Sugita et al., Proc. Ann. Mtg Part. Accel. Soc. Jpn, 13 (2020).

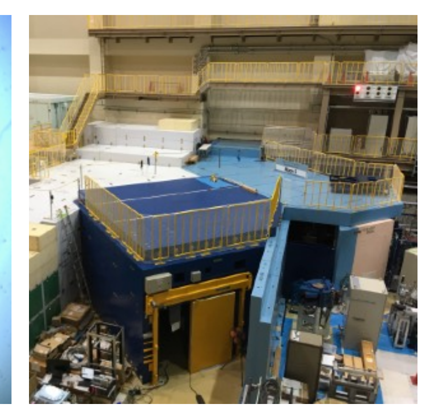

Microwave Cavity


Positron Detector


Beam Monitor

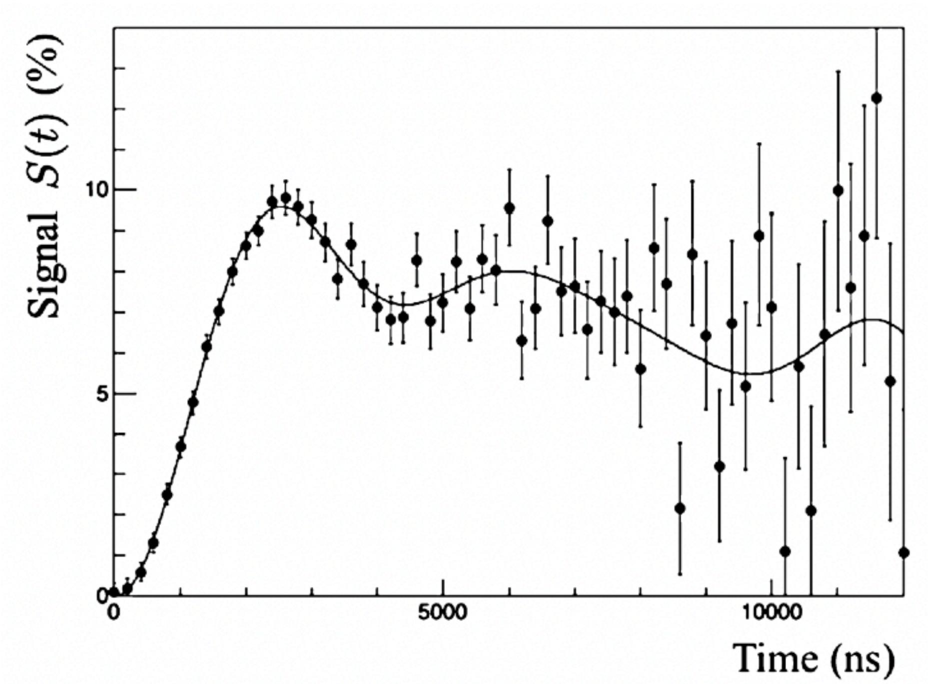
Magnet


NMR Probe

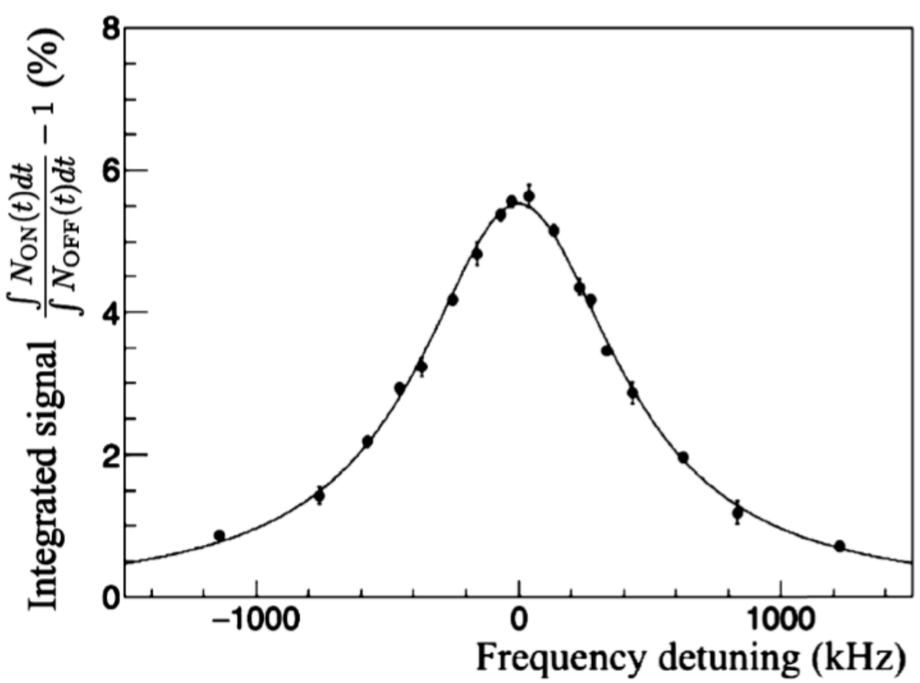

Muon Beamline

Zero-Field Results

First Letter has been published in 2021



Rabi-oscillation of muonium

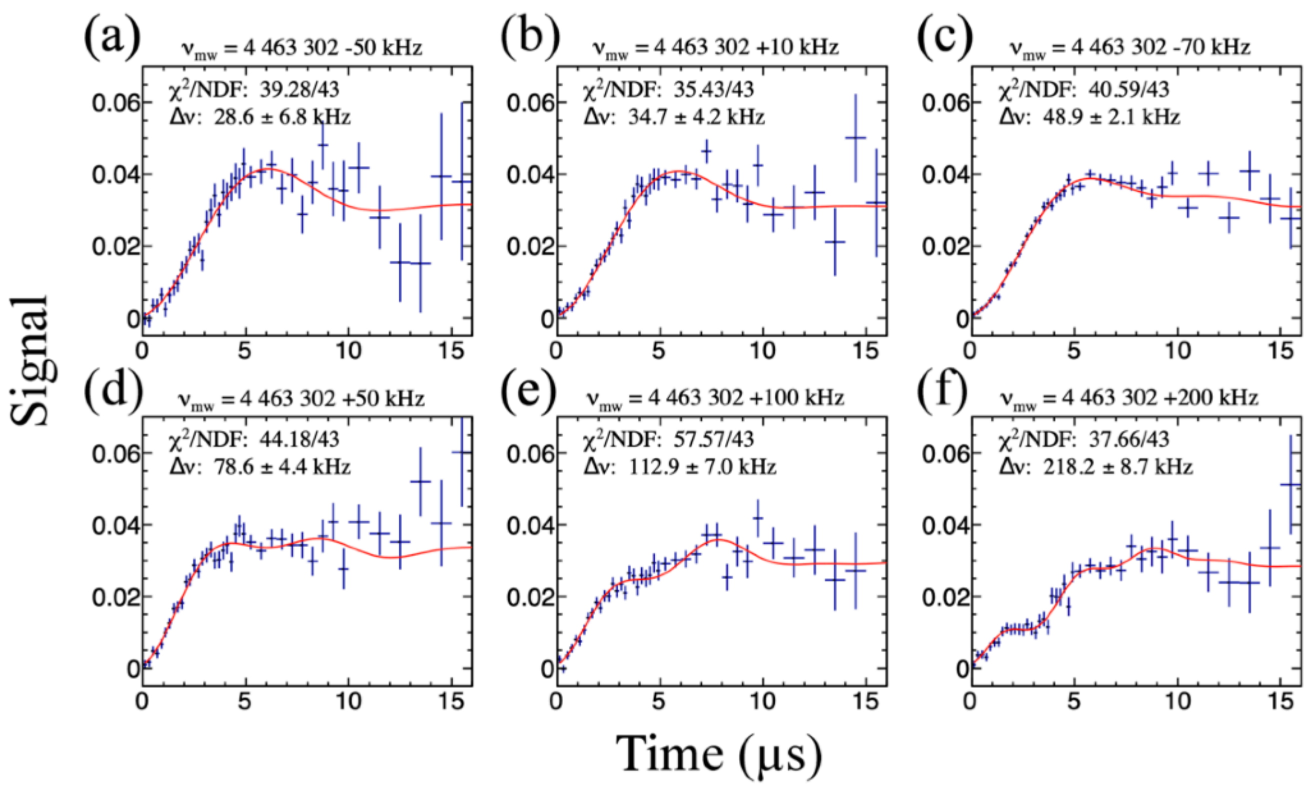


- Phase-1 experiment under zero-magnetic field.
- Direct observation of the hyperfine transition with a microwave at 4.463 GHz.
- The first precise spectroscopy of muonium HFS using a pulsed beam (900 ppb).

S. Kanda et al., "New precise spectroscopy of the hyperfine structure in muonium with a high-intensity pulsed muon beam", Phys. Lett. B 815 (2021) 136154.

Zero-Field Results

A new analysis technique to improve precision



Fitting results for different microwave frequencies

Rabi-oscillation formula

$$f(t;\ A,\ |b|,\ \Delta\omega) = A \sum N_i \left(\frac{G_i^+}{\Gamma_i} \cos G_i^- t + \frac{G_i^-}{\Gamma_i} \cos G_i^+ t - 1 \right)$$

$$G^{\pm} = \frac{\Gamma \pm \Delta\omega}{2},$$

$$\Gamma = \sqrt{(\Delta\omega)^2 + 8|b|^2},$$

$\Delta\omega$: freq. detuning
b: microwave power

- A new method to directly analyze the Rabi oscillation was developed.
- Tolerant to time-varying systematic errors such as microwave power drift.
- The highest precision among zero-field measurements was achieved (159 ppb).

S. Nishimura et al., "Rabi-oscillation spectroscopy of the hyperfine structure of muonium atoms",Phys. Rev. A 104, L020801 (2021).

Superconducting Magnet

A key element for the high-field experiment

- K. Sasaki, M. Abe (KEK).

- A superconducting solenoid for a precise controlled magnetic field of 1.7 T.
  - A second-hand MRI magnet with an axial length of 2 m and a bore diameter of 925 mm.
- Requirements for the field are

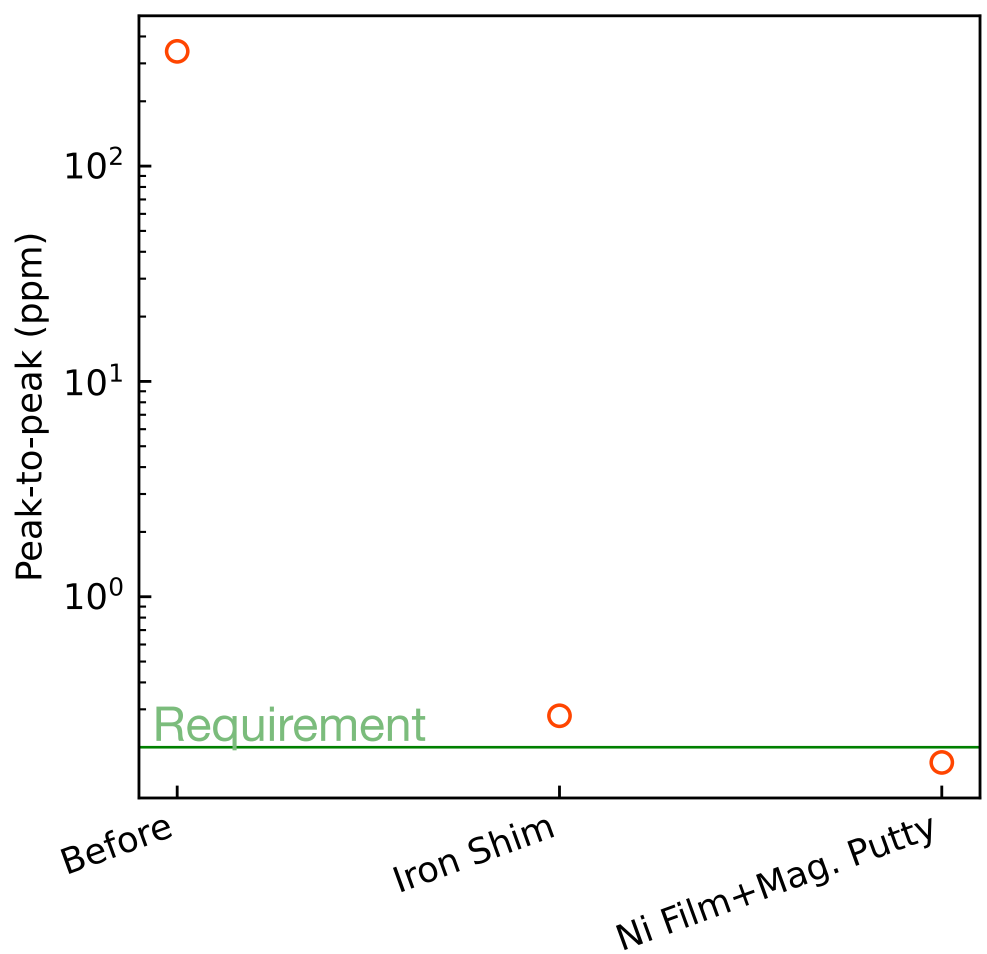
→0.2 ppm (peak-to-peak) uniformity in a spheroidal volume with z=30 cm, r=10 cm.

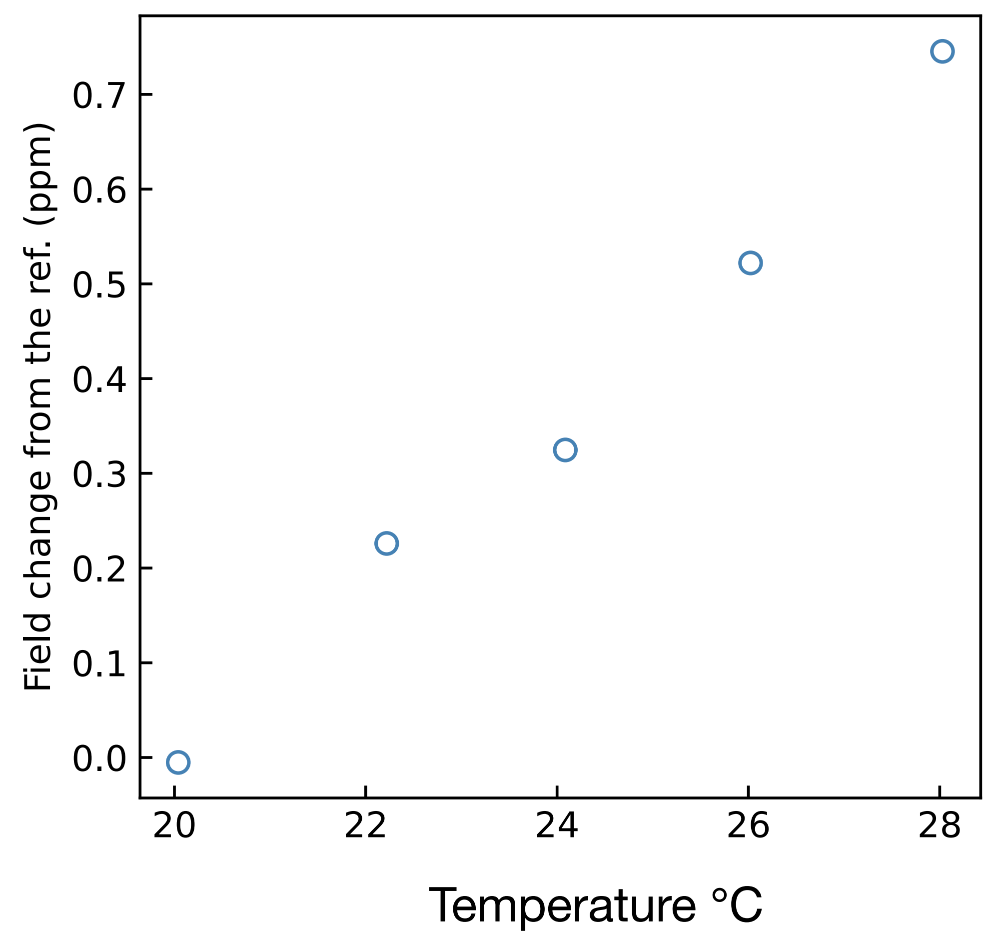
→±0.1 ppm stability during measurement.

K. Sasaki, M. Abe (KEK)

Passive Shimming

For highly uniform magnetic field





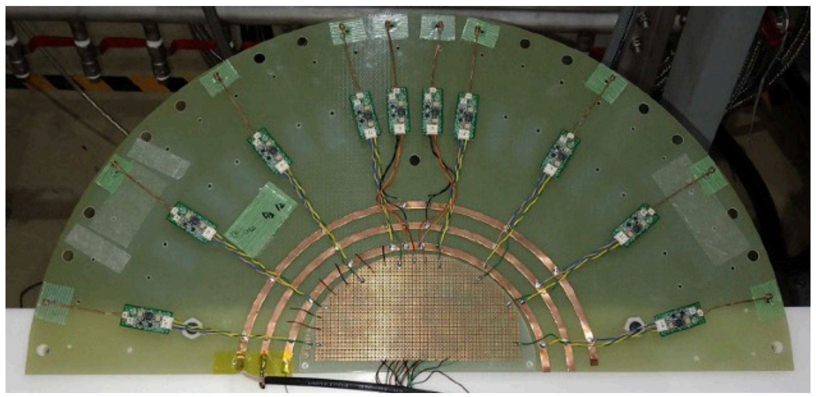
- The requirement for the uniformity was achieved.
- The temperature needs to be controlled with an accuracy of ±1 degree.
- A precise air conditioner was prepared and to be tested.

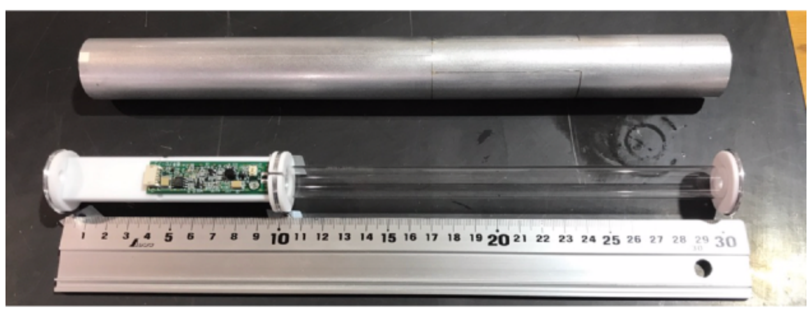
M. Sugita et al., Proc. Ann. Mtg Part. Accel. Soc. Jpn, 13 (2020).

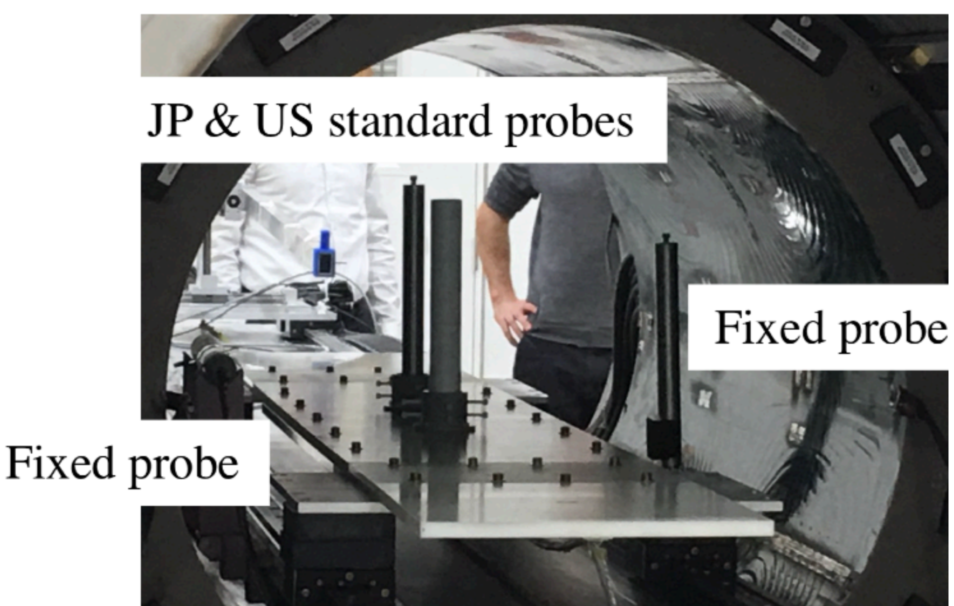
M. Sugita (JAEA),
C. Oogane, H. Iinuma (Ibaraki U.),
M. Abe, K. Sasaki (KEK)

NMR Probes

Three types of magnetometer







- Field camera
  - A 24-channel rotating NMR probe that maps magnetic fields in three dimensions.
  - Studies are underway for simultaneous multi-channel readouts.
- Fixed probe
  - A compact probe to monitor magnetic field stability during experiment.
- Standard probe
  - A high-precision NMR probe to calibrate others.
  - An accuracy of 15 ppb has been achieved.
  - Cross-calibration is underway in a joint research project between Japan and the US.

K. Sasaki (KEK), H. Tada (Nagoya U.), S. Oyama, T. Tanaka (U. Tokyo),
H. Yamaguchi(JASRI), P. Winter (ANL), D. Kawall (U. Mass.), D. Flay (JLab)

Present and Future of Muon Experiments

Sohtaro Kanda (神田 聡太郎) / KEK IMSS MSL / kanda@post.kek.jp

Present of Muon Experiments

Summary of a review

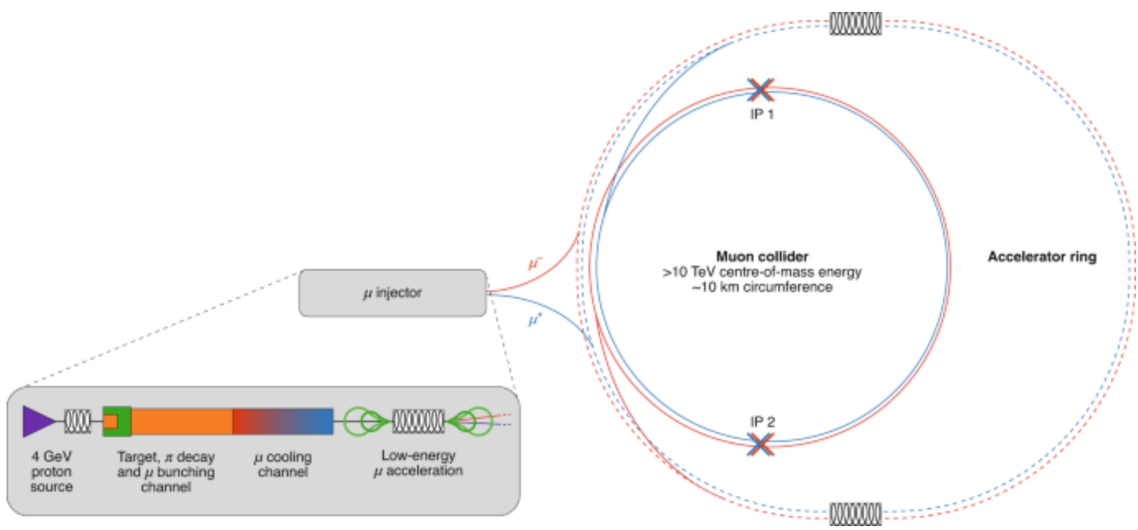
- High-sensitivity searches for new physics and precision measurements using muons were briefly reviewed.
- Many projects are underway to break past records using modern accelerators, new detector technologies, advanced lasers, etc.
- Due to time constraints, I was unable to present various important projects.
  - Please see a more comprehensive review:

    T. P. Gorringe, D. W. Hertzog, "Precision muon physics", Progress in Particle and Nuclear Physics 84 (2015) 73-123.

What are the possible future directions?

Future Directions

Quo Vadis

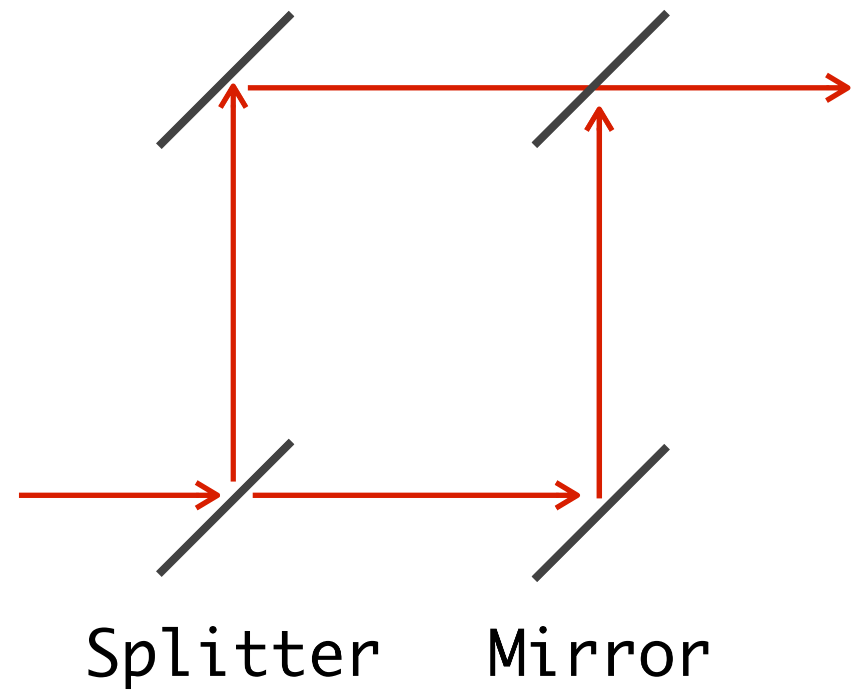


https://muoncollider.web.cern.ch/

Large-scale facility

Advanced Muon Facility

Muon collider



Quantum control

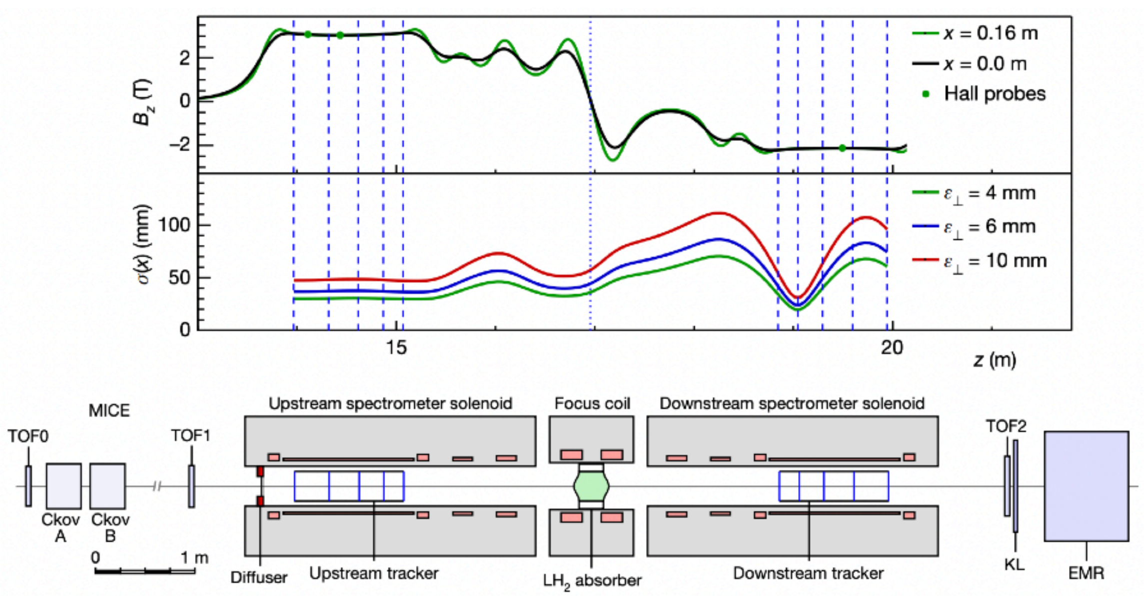
precise state control

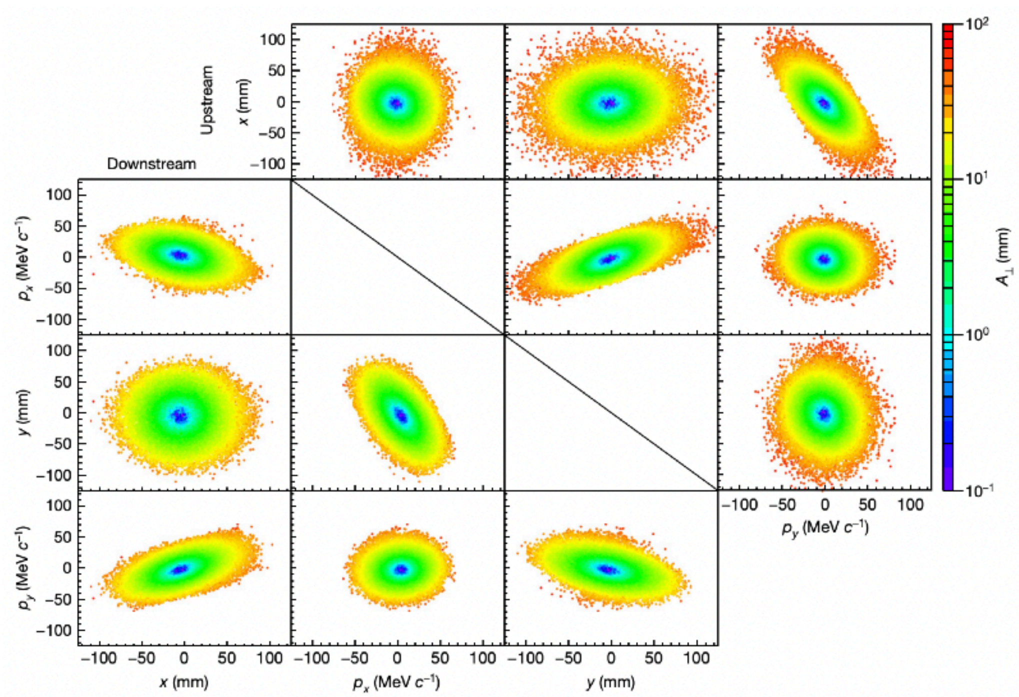
and interferometry

Muon cooling is important for both directions.

Muon Cooling

MICE Experiment at RAL





Measured phase-space distributions

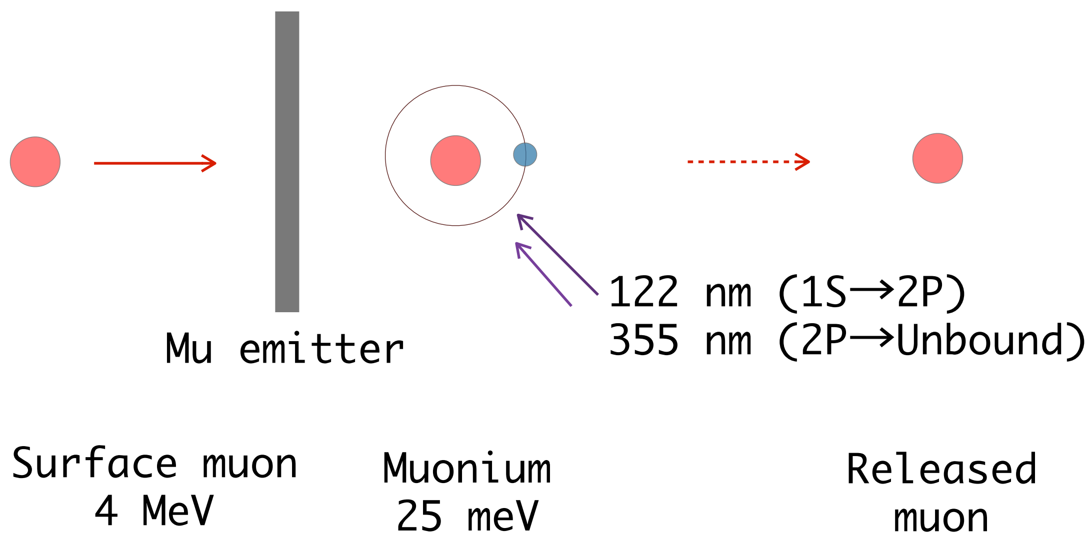
- Ionization cooling of muons.
- Cooling by repeated deceleration in RF cavities and acceleration in moderators.
- Phase-space compression of muons in liquid hydrogen.
- Precise measurement of muon emittance.

MICE Collaboration, "Demonstration of cooling by the Muon Ionization Cooling Experiment", Nature 578, 53-39 (2020).

Low Energy Muons

for low-emittance muon beams

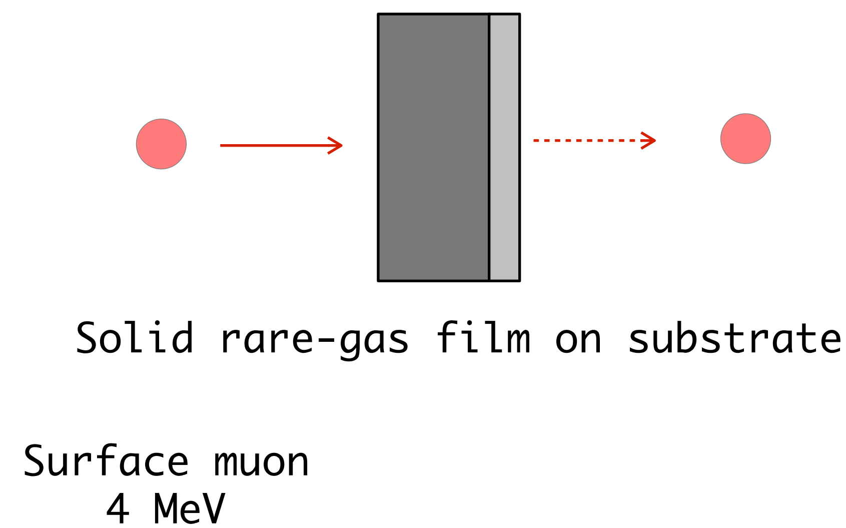
Laser ionization of muonium



Ultra-Slow Muon (USM) at J-PARC

K. Nagamine et al., PRL 74, 4811 (1995).

Cold rare-gas moderator



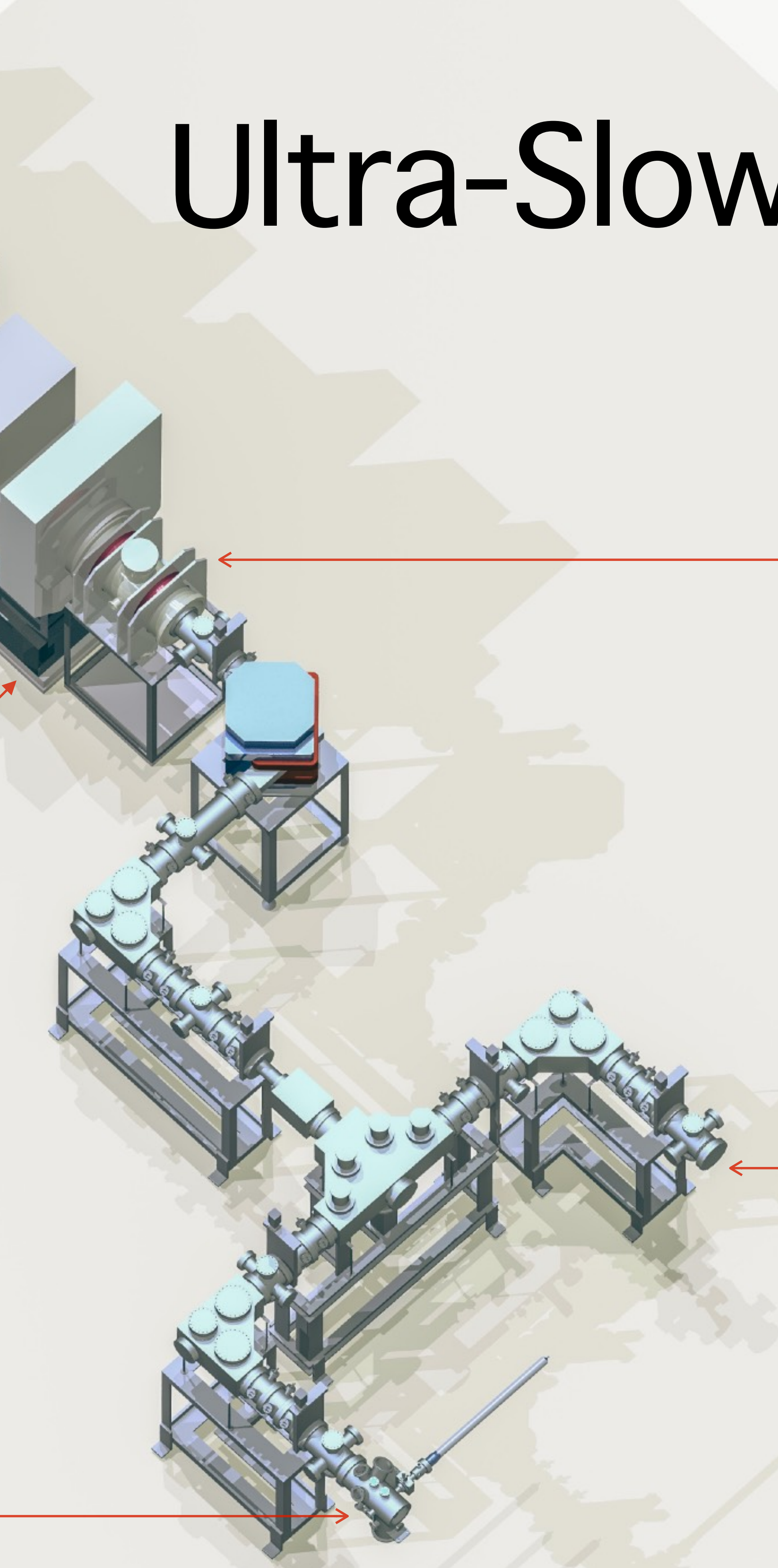
Low-Energy Muon (LEM) at PSI

E. Morenzoni et al., PRL 72, 2793 (1994).

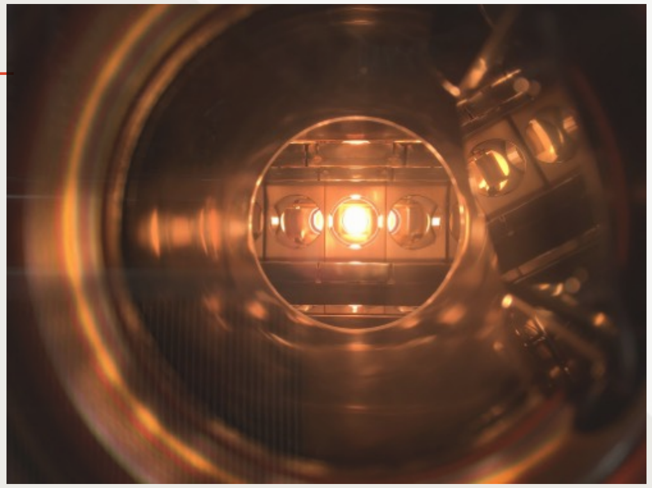
- Due to the short lifetime of muons, the slowing down and cooling methods for stable atoms are not applicable.
- USM and LEM are promising methods to obtain slow muons.

Ultra-Slow Muon Facility

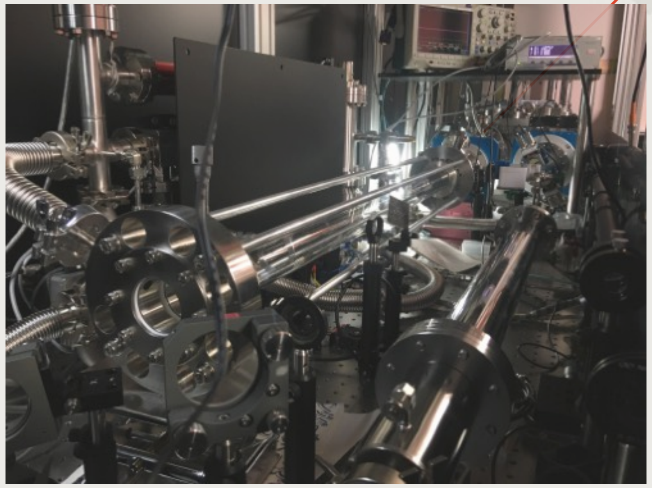
at J-PARC MLF MUSE



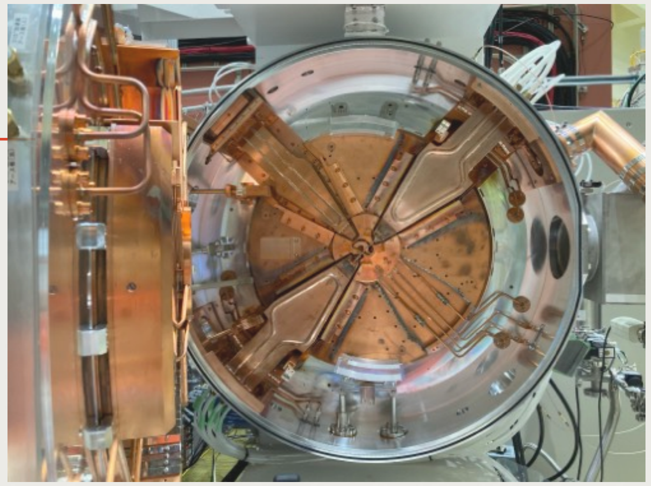
The Super-Omega
surface muon beamline



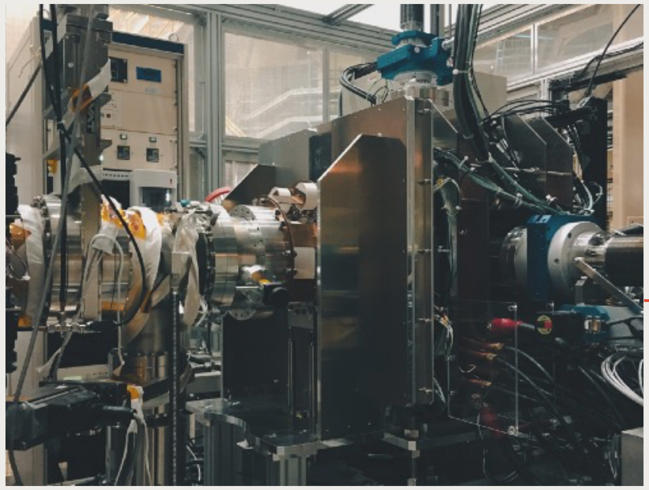
Muonium emitter



Ionization laser



Cyclotron at U1B



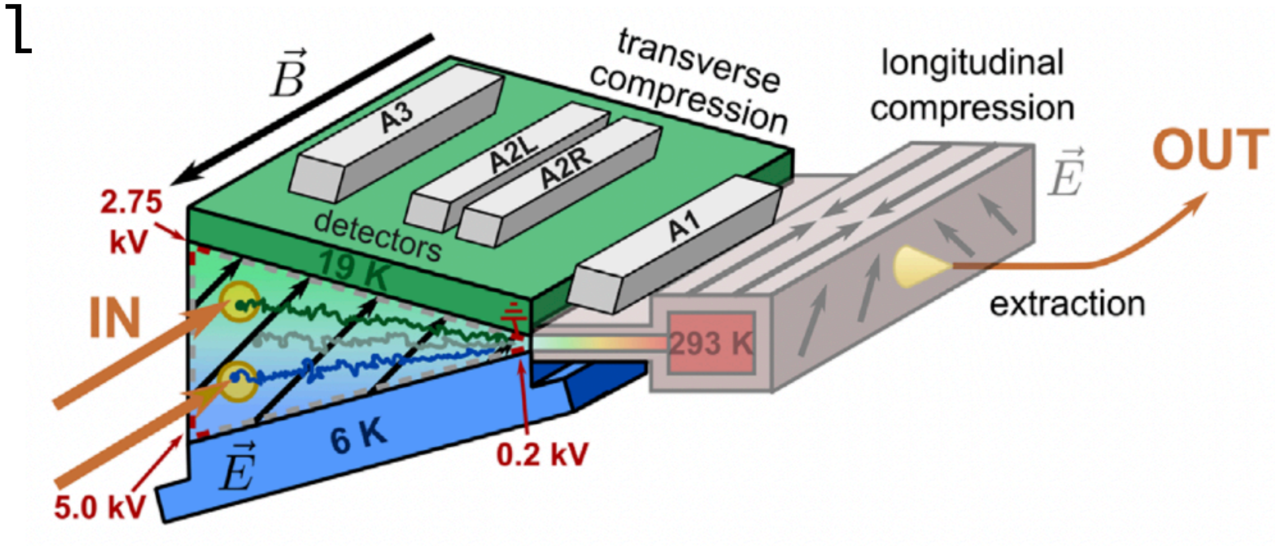
Spectrometer at U1A

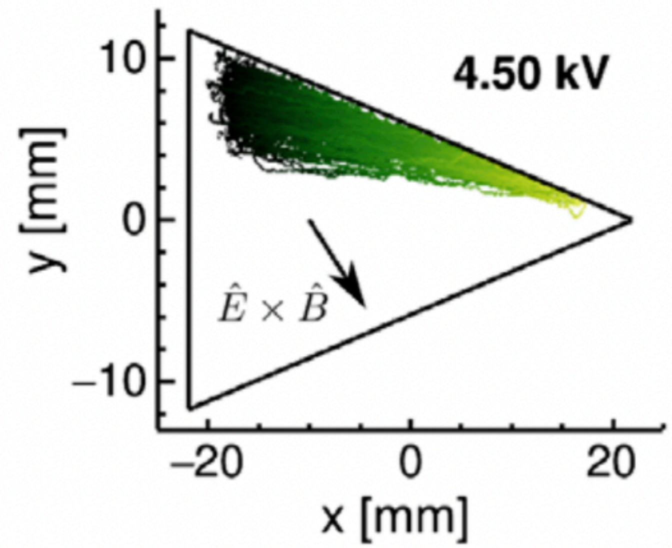
Commissioning is in progress.
First condensed matter
experiment will start 2023.

Novel Techniques

for muon cooling and slow muonium atoms

- MuCool

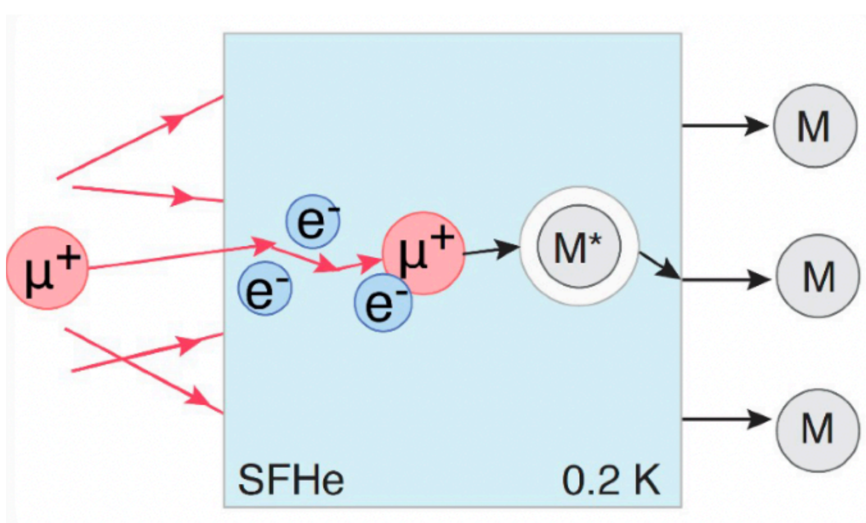


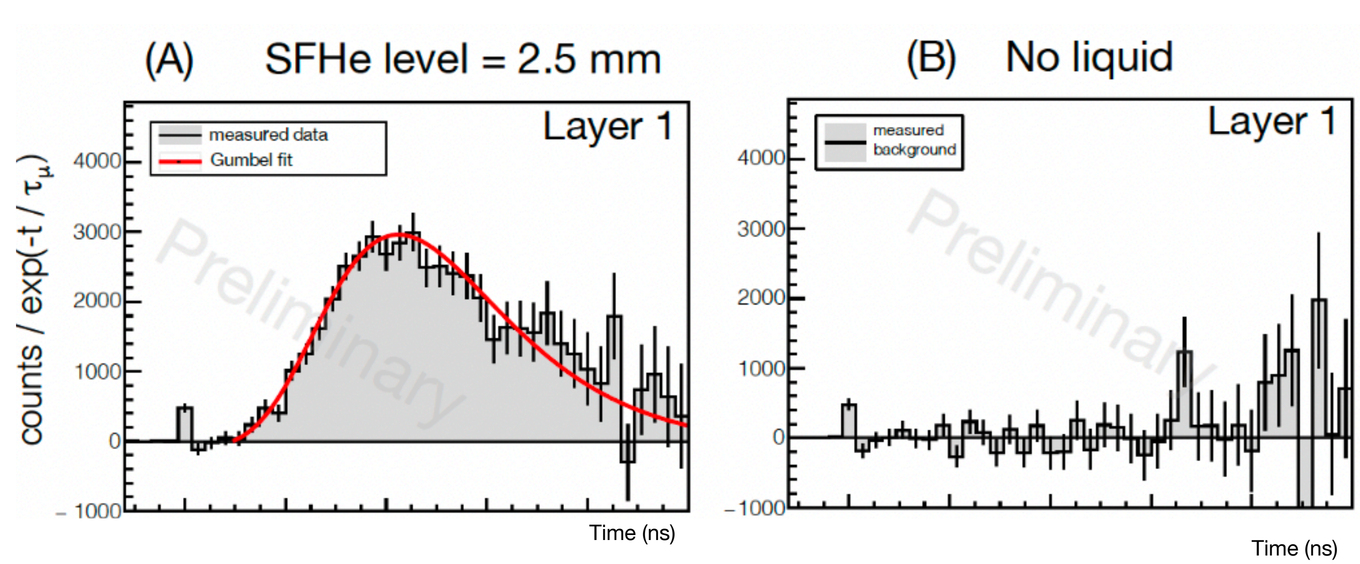


Beam compression demonstrated

A. Antognini et al., Phys. Rev. Lett. 125, 164802 (2020).

- Super-Fluid Helium Muonium Source



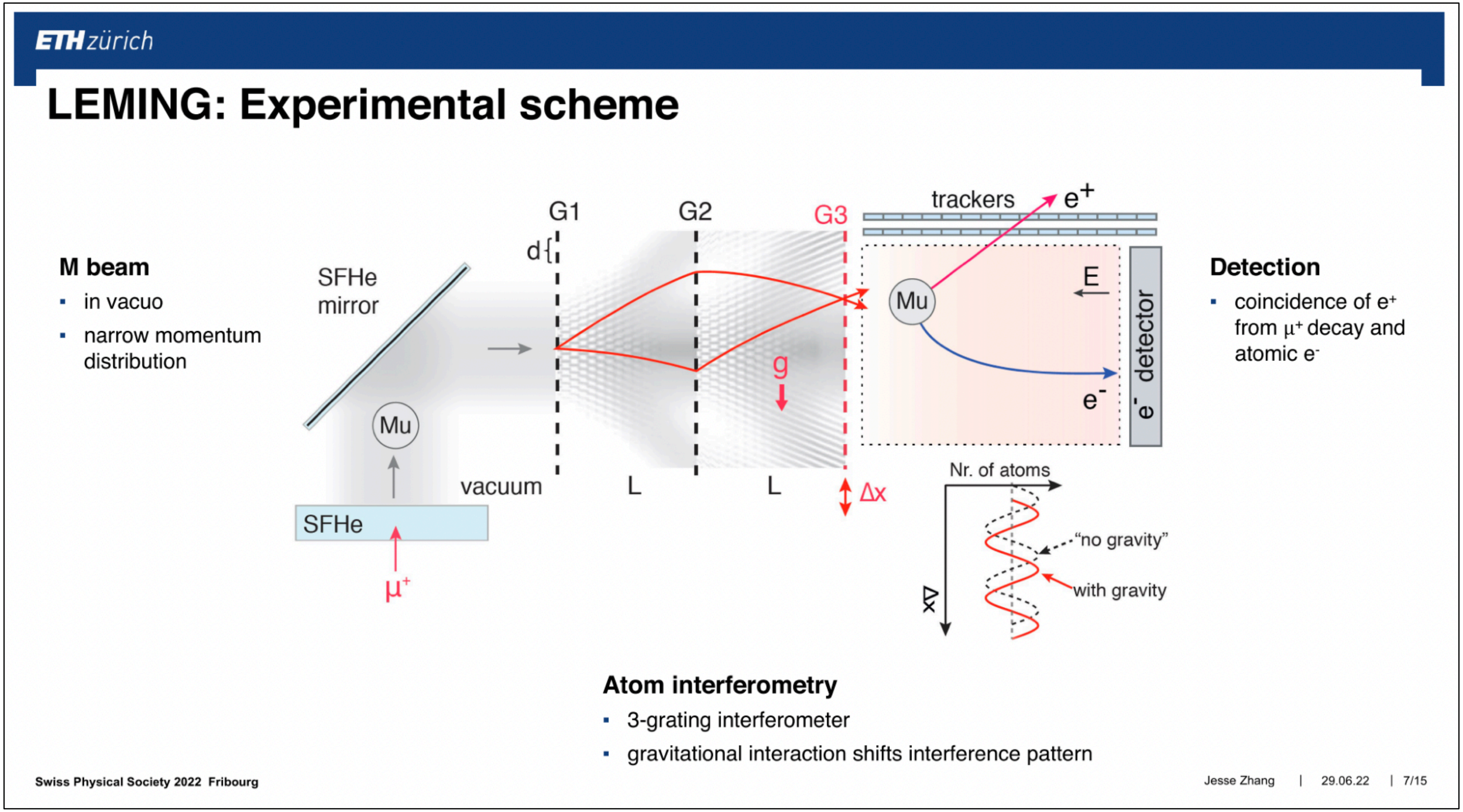


Mu from SFHe observed

J. Zhang, Presentation at Swiss Physical Society Meeting (2022).

Muonium Gravity

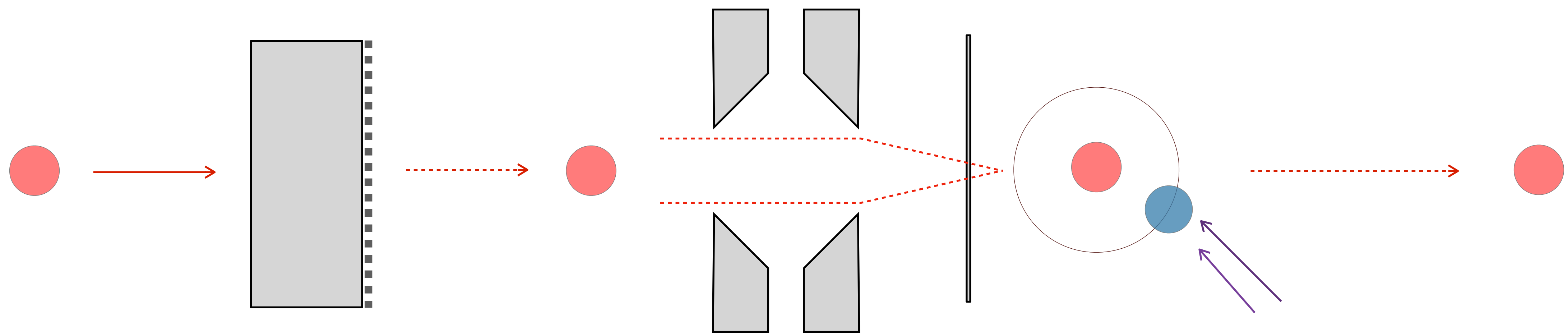
An application of muonium interferometry



J. Zhang, presentation at Swiss Physical Society Meeting (2022).

Multistage Muon Cooling

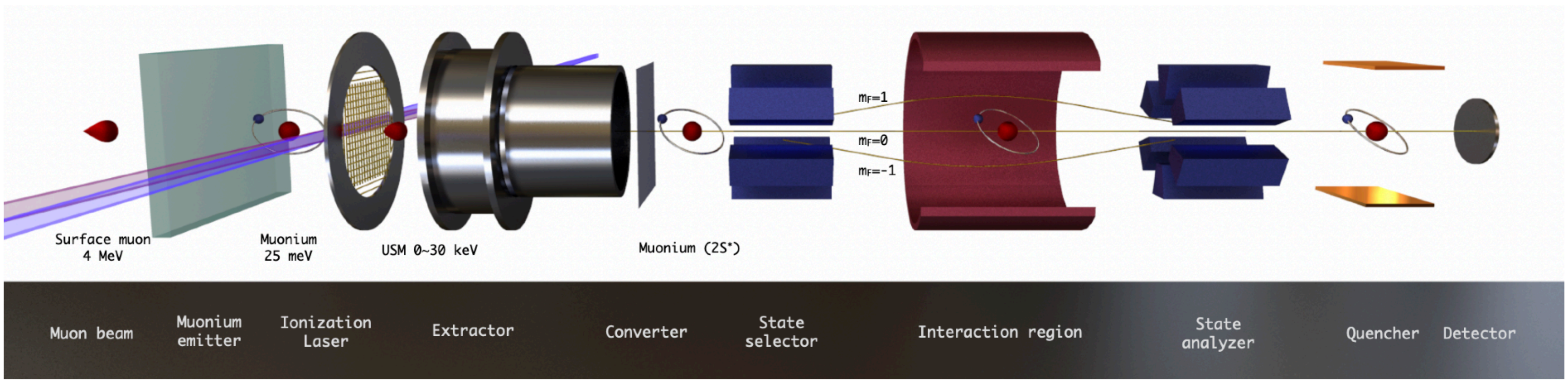
A proposal to combine LEM and USM



- A solid gas moderator is used to obtain epithermal muons, which are focused by an electrostatic lens before being converted to muonium through a graphene foil.
- The spatial overlap between laser beams and muonium improves dramatically.

Muonium Interferometry

A longitudinal Stern-Gerlach experiment

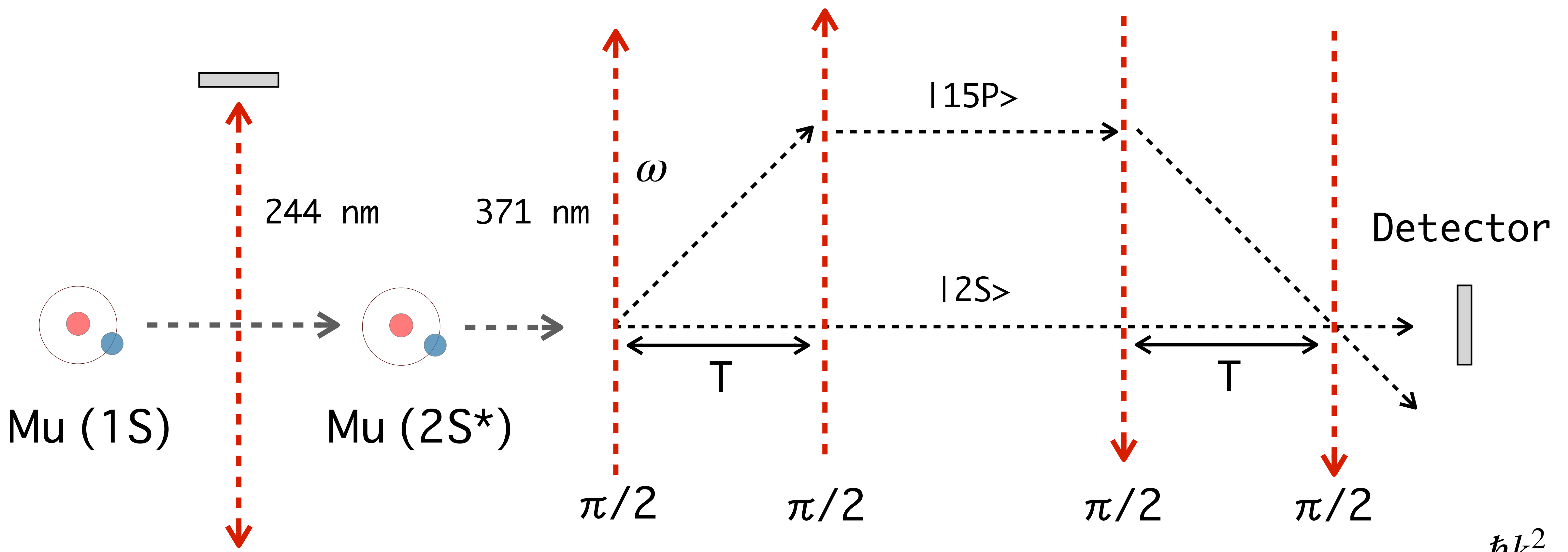


- The magnetic quantum number of muonium is selected by a sextupole magnet.
- Using the spiral magnetic field, the Berry phase can be obtained.
- Simulation studies for feasibility check in ongoing.

S. Kanda, "In-flight muon spin resonance and muonium interferometry ", to be published in J. Phys. Conf. Ser.

Ramsey-Bordé Interferometry

for a precise muon mass measurement



The phase difference between the two paths: $\delta\phi = 2(\omega - \omega_0)T - \frac{\hbar k^2}{2m}T$

- The ratio h/m can be determined from observation of the Ramsey fringe due to the recoil frequency shift.
- No experiment has been performed for muonium. A hydrogen atom interferometer using a photon echo scheme has been reported.

T. Heupel et al., Europhys. Lett. 57, 158 (2002).

Summary

and prospects

- Present of muon experiments is a frontier of fundamental science where various projects are underway.
- Future of muon experiments is bright with both large-scale projects and small but creative innovators.
- Muon cooling and application of quantum techniques will bring a breakthrough.