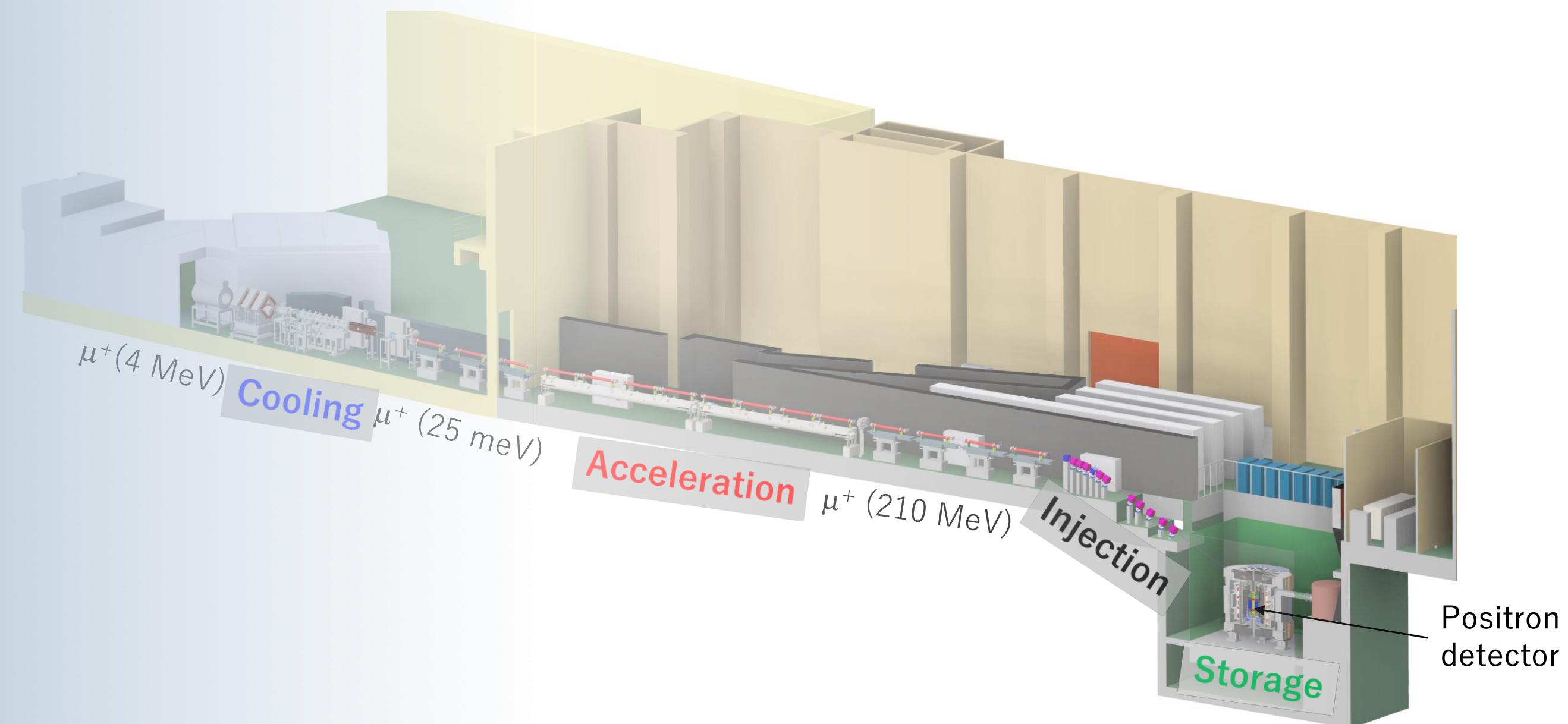


Status of the Muon $g - 2$ /EDM experiment at J-PARC

Ce ZHANG

School of Physics, Peking University

On behalf of the J-PARC E34 collaboration
NuFACT 2022



Status of the Muon $g - 2$ /EDM experiment at J-PARC

- **Introduction**
 - Muon $g - 2$ and EDM
 - J-PARC Muon $g - 2$ /EDM (E34) experiment
- **Status of the J-PARC E34 experiment**
 - Experimental components
 - Statistic and systematic uncertainties
 - Schedule
- **Summary**

Muon $g - 2$ and EDM

- The Hamiltonian for the spin 1/2 particle (charge e and mass m) in the external electromagnetic field is

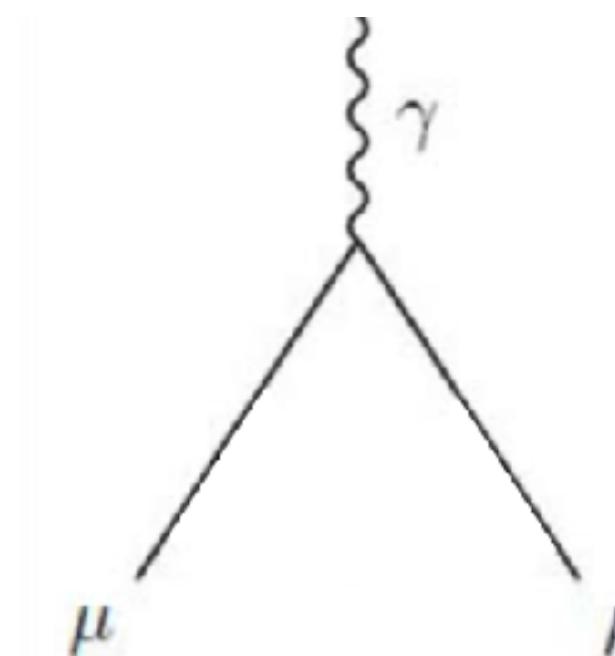
$$H = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

Magnetic dipole moment

Electric dipole moment

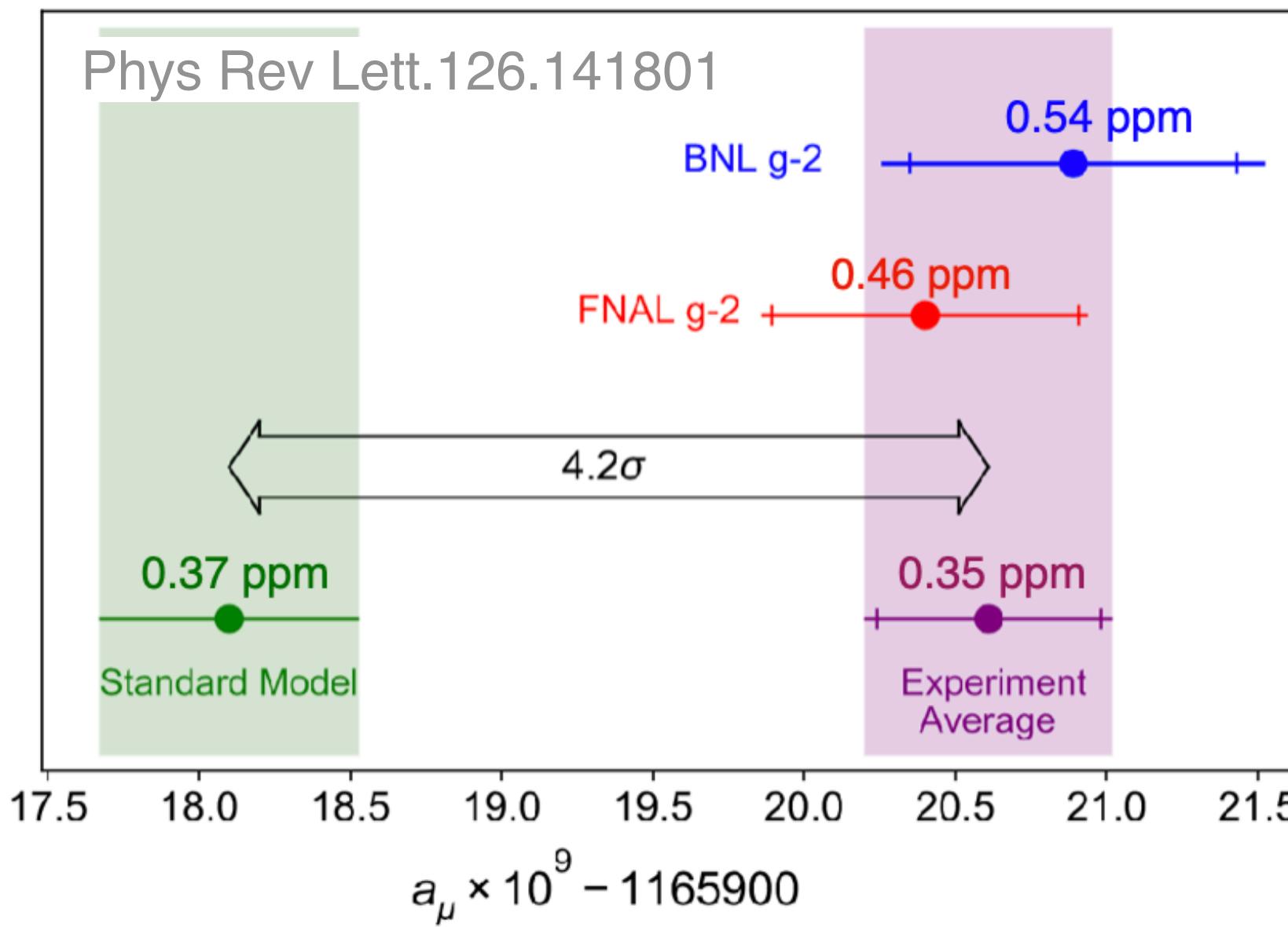
- $\vec{\mu}$ is proportional to the gyromagnetic ratio (g), which was predicted $g = 2$ by the Dirac equation.
 - But quantum fluctuations give **the anomaly of muon a_μ** :

$$a_\mu \equiv \frac{g_\mu - 2}{2}$$



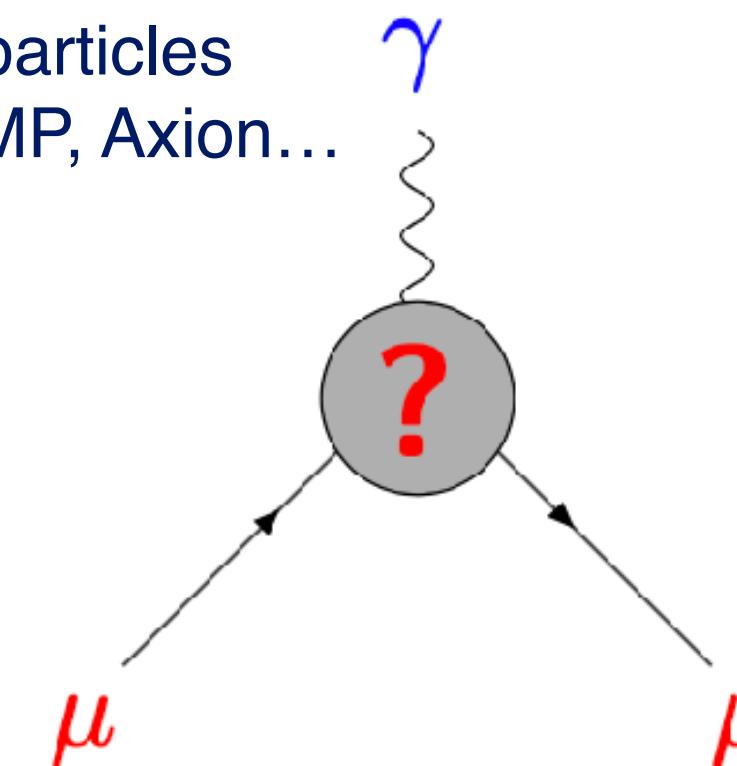
Muon Anomaly and New Physics BSM

- In April 2021, the Fermilab Muon $g - 2$ experiment released the latest measurement on a_μ . The new experimental average $a_\mu(\text{exp.})$ has a 4.2σ deviation from $a_\mu(\text{theory})$.



$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{Had}} + a_\mu^{\text{NP?}}$$

Unknown particles
SUSY, WIMP, Axion...



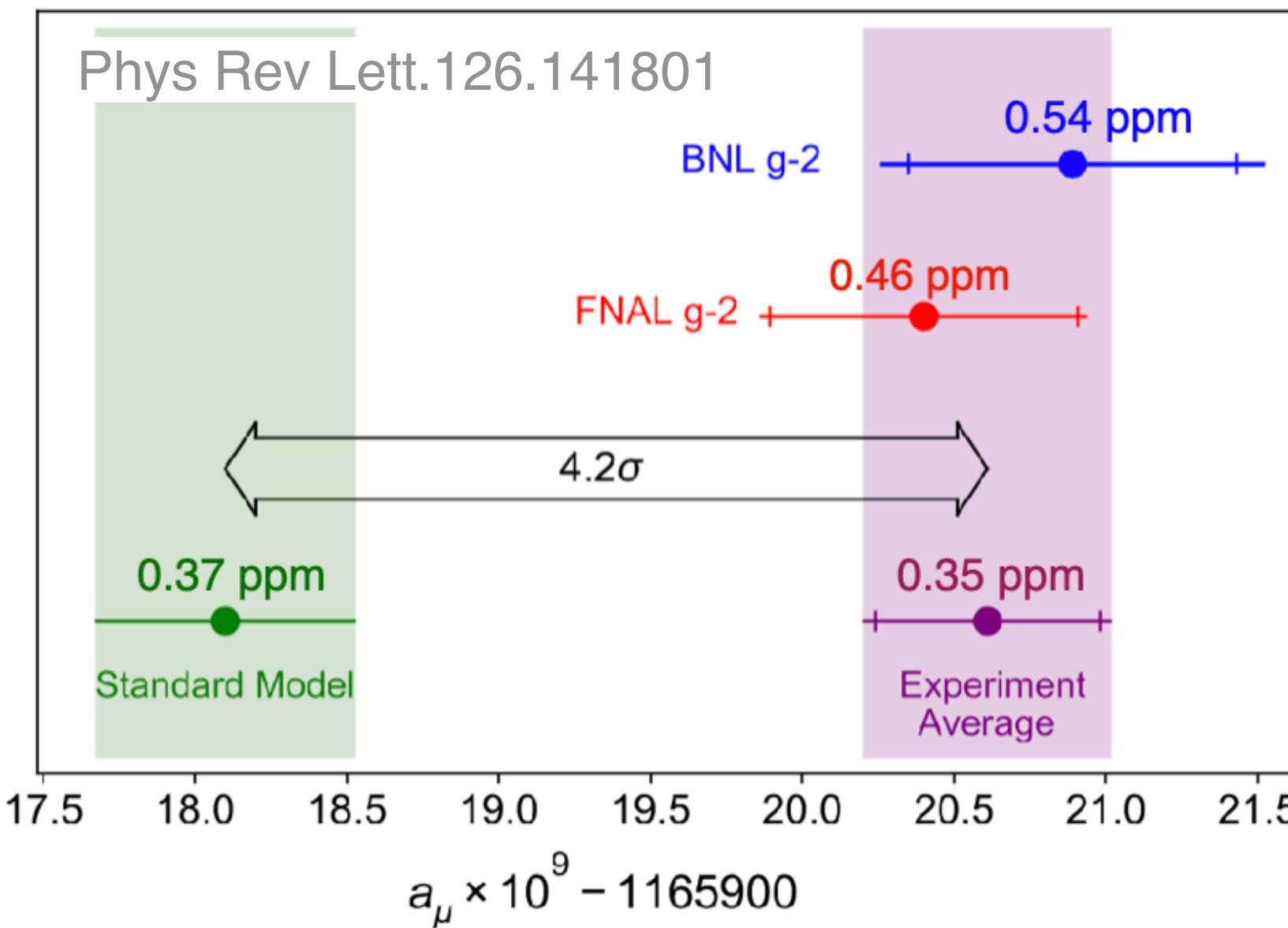
Why muon?

New physics effects enhanced by
 $\delta a_\ell \propto m_\ell^2/M_{\text{NP}}^2$

Muon is more sensitive by a factor
 $(m_\mu/m_e)^2 \approx 4.3 \cdot 10^4$

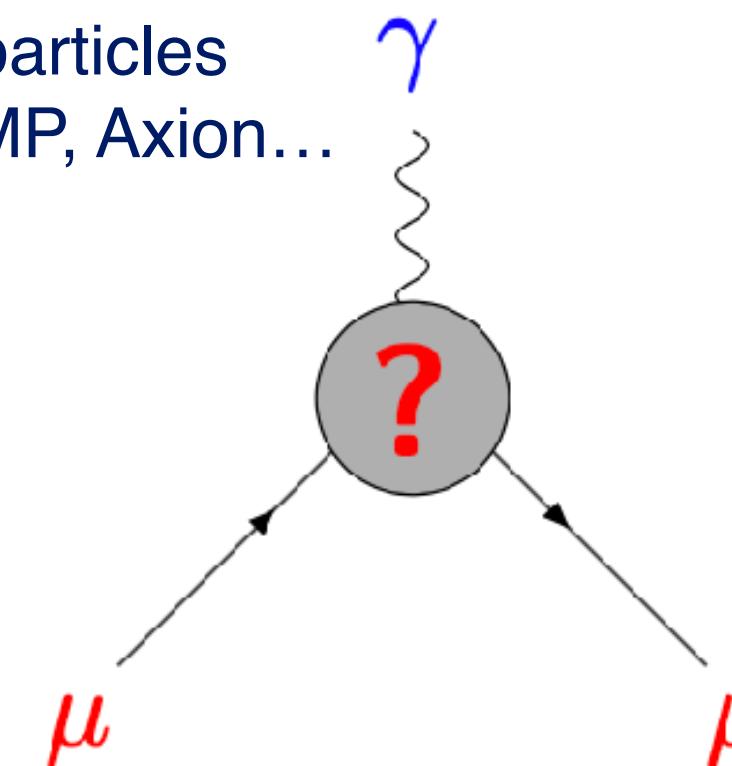
Muon Anomaly and New Physics BSM

- In April 2021, the Fermilab Muon $g - 2$ experiment released the latest measurement on a_μ . The new experimental average $a_\mu(\text{exp.})$ has a 4.2σ deviation from $a_\mu(\text{theory})$.



$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{Had}} + a_\mu^{\text{NP?}}$$

Unknown particles
SUSY, WIMP, Axion...



Why muon?

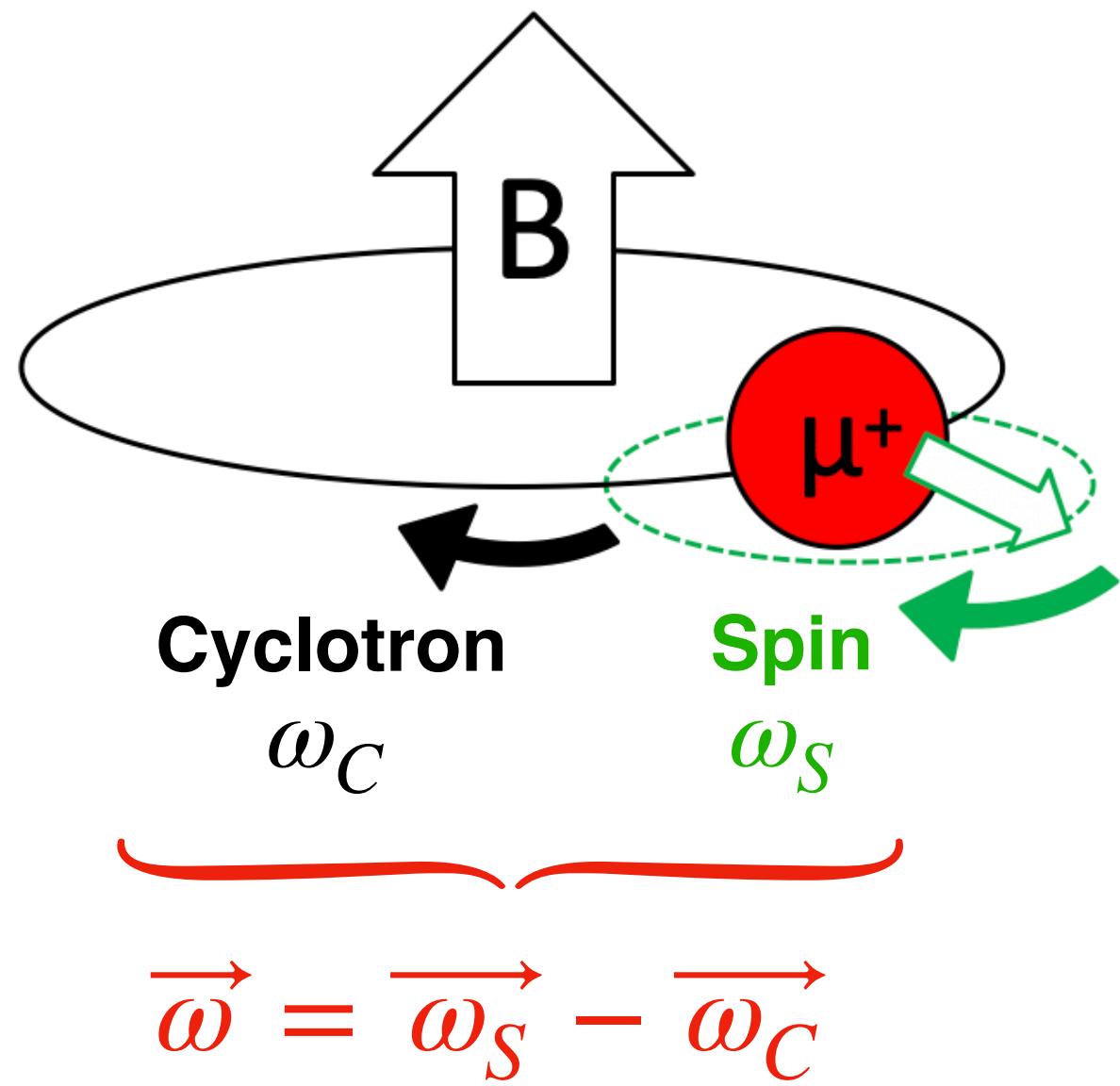
New physics effects enhanced by
 $\delta a_\ell \propto m_\ell^2/M_{\text{NP}}^2$

Muon is more sensitive by a factor
 $(m_\mu/m_e)^2 \approx 4.3 \cdot 10^4$

- Another independent experiment for muon $g - 2$ /EDM was proposed in Japan

Measurement Principle

Muon precession in the magnetic field



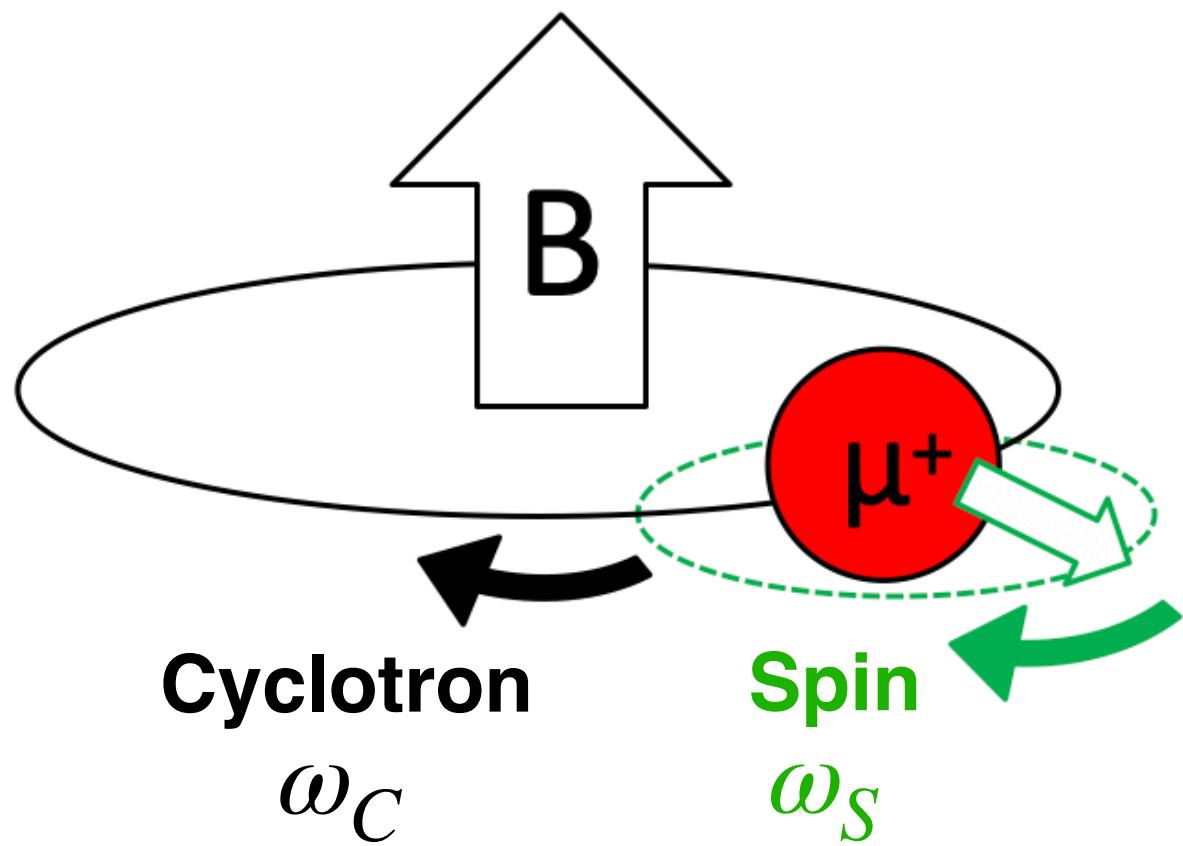
$$\vec{\omega} = -\frac{e}{m} \left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2} \left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right]$$

g - 2 terms EDM term

$$\vec{\omega} = \vec{\omega}_S - \vec{\omega}_C$$

Measurement Principle

Muon precession in the magnetic field



$$\vec{\omega} = -\frac{e}{m} \left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2} \left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right]$$

Magic “ γ ”: $\gamma^2 = \frac{1}{a_\mu} + 1$

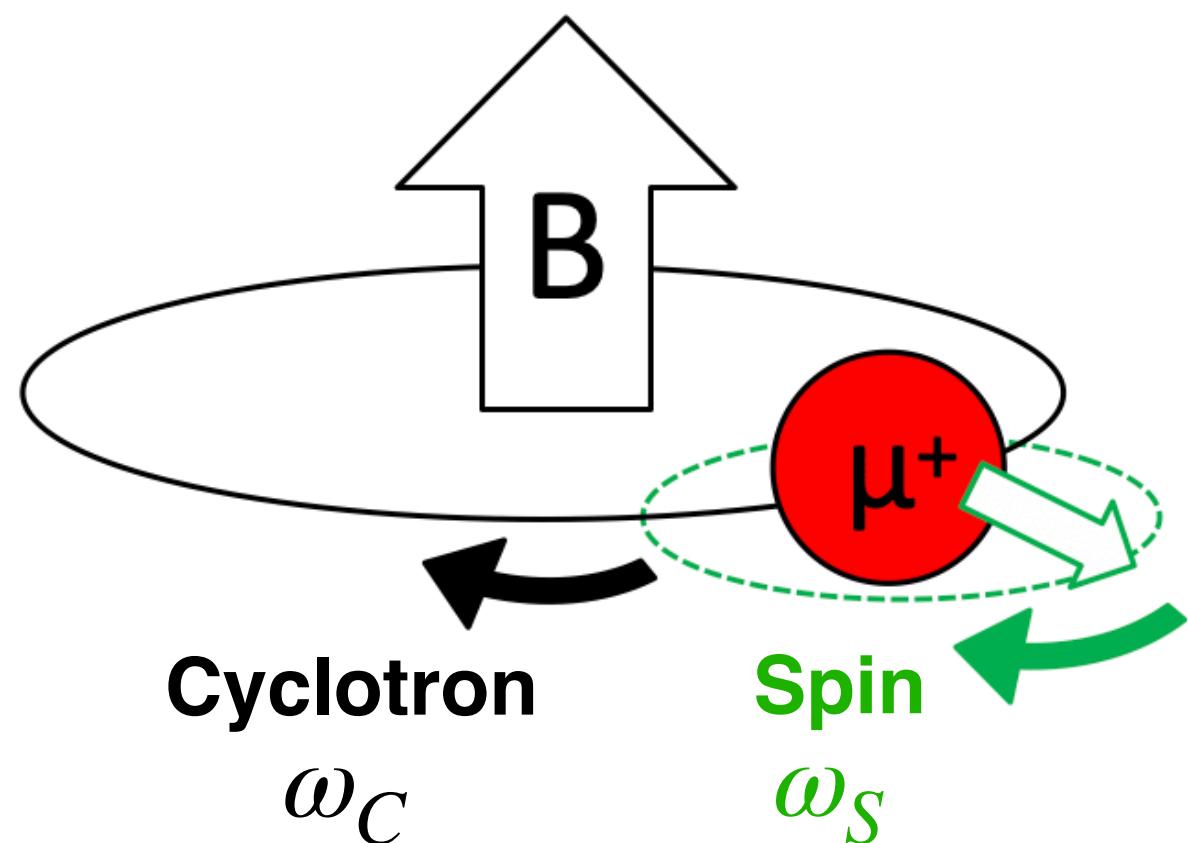
BNL E821 approach
 $\gamma=30$ ($P=3$ GeV/c)

$$\boxed{\vec{\omega} = -\frac{e}{m} \left[a_\mu \vec{B} + \frac{\eta}{2} \left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right]}$$

FNAL E989

Measurement Principle

Muon precession in the magnetic field



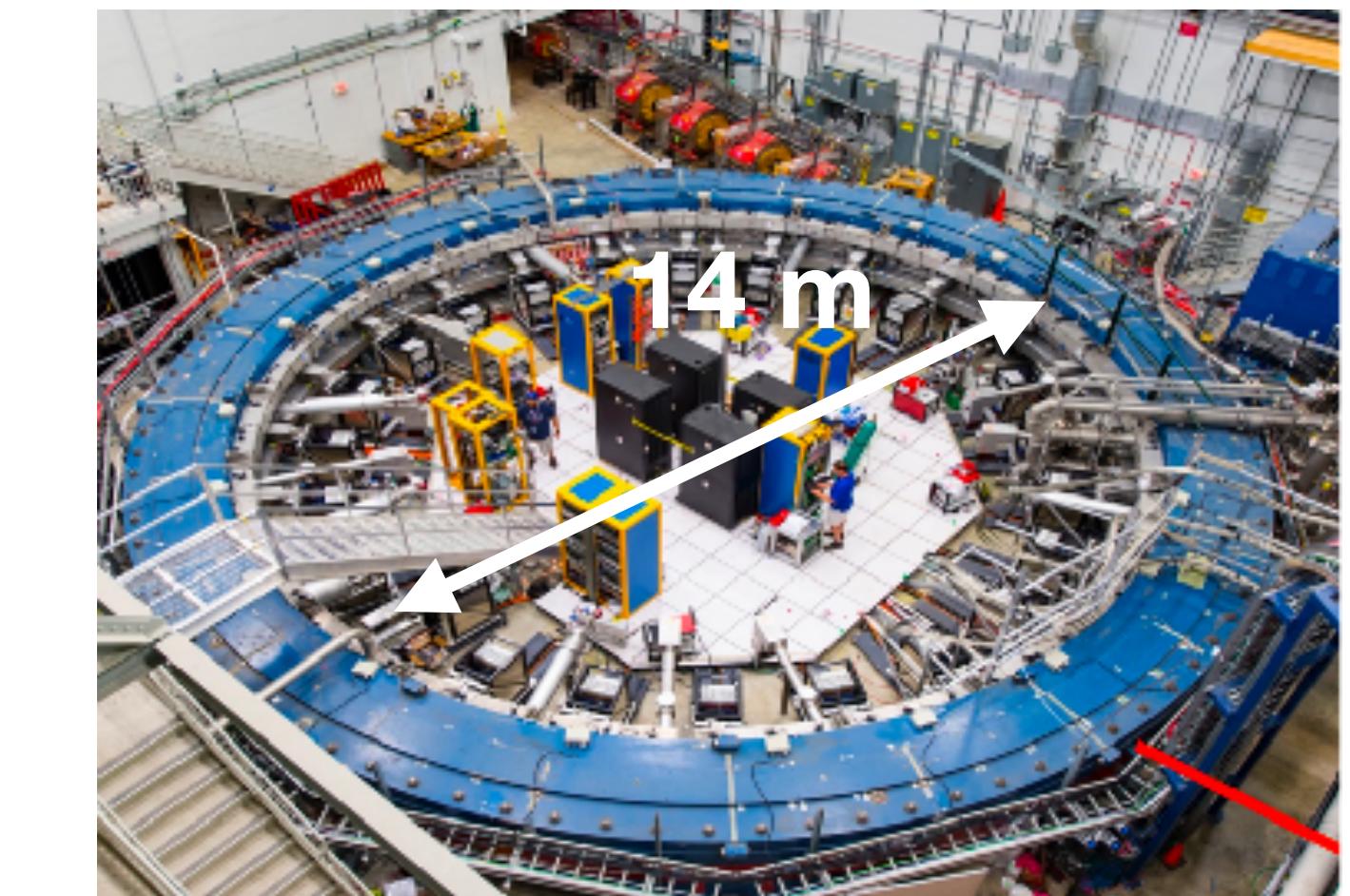
$$\vec{\omega} = -\frac{e}{m} \left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2} \left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right]$$

Magic “γ”: $\gamma^2 = \frac{1}{a_\mu} + 1$

BNL E821 approach
 $\gamma=30$ ($P=3$ GeV/c)

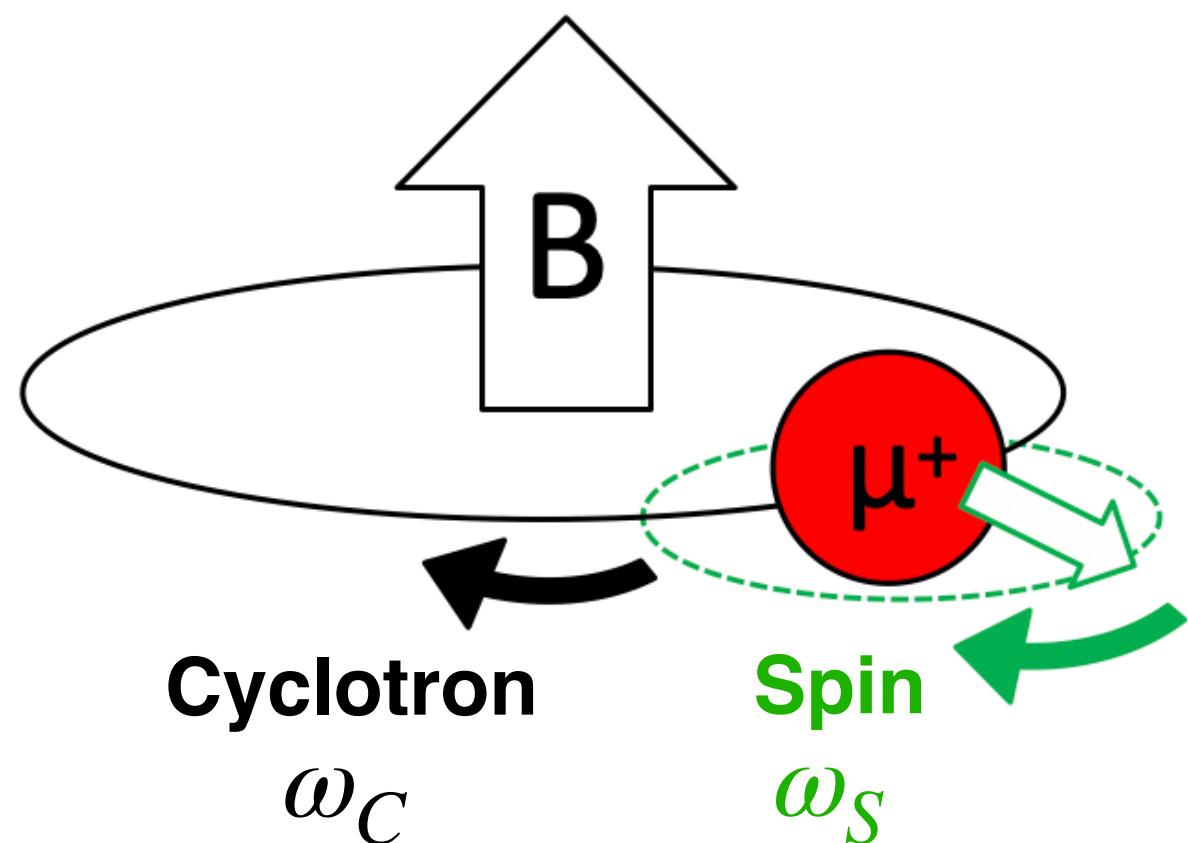
$$\boxed{\vec{\omega} = -\frac{e}{m} \left[a_\mu \vec{B} + \frac{\eta}{2} \left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right]}$$

FNAL E989



Measurement Principle

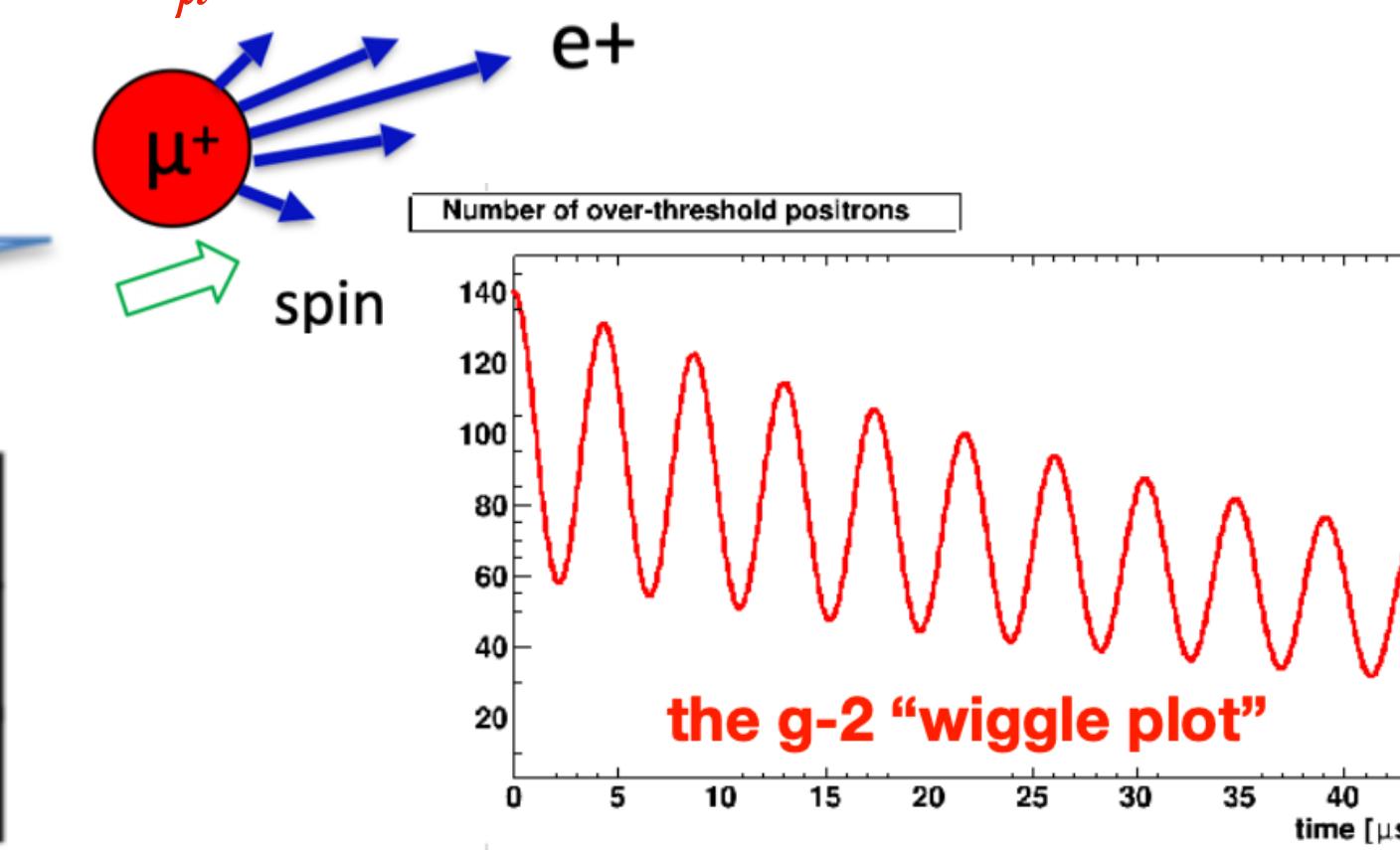
Muon precession in the magnetic field



$$\vec{\omega} = -\frac{e}{m} \left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2} \left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right]$$

Magic “ γ ”: $\gamma^2 = \frac{1}{a_\mu} + 1$

BNL E821 approach
 $\gamma=30$ ($P=3$ GeV/c)



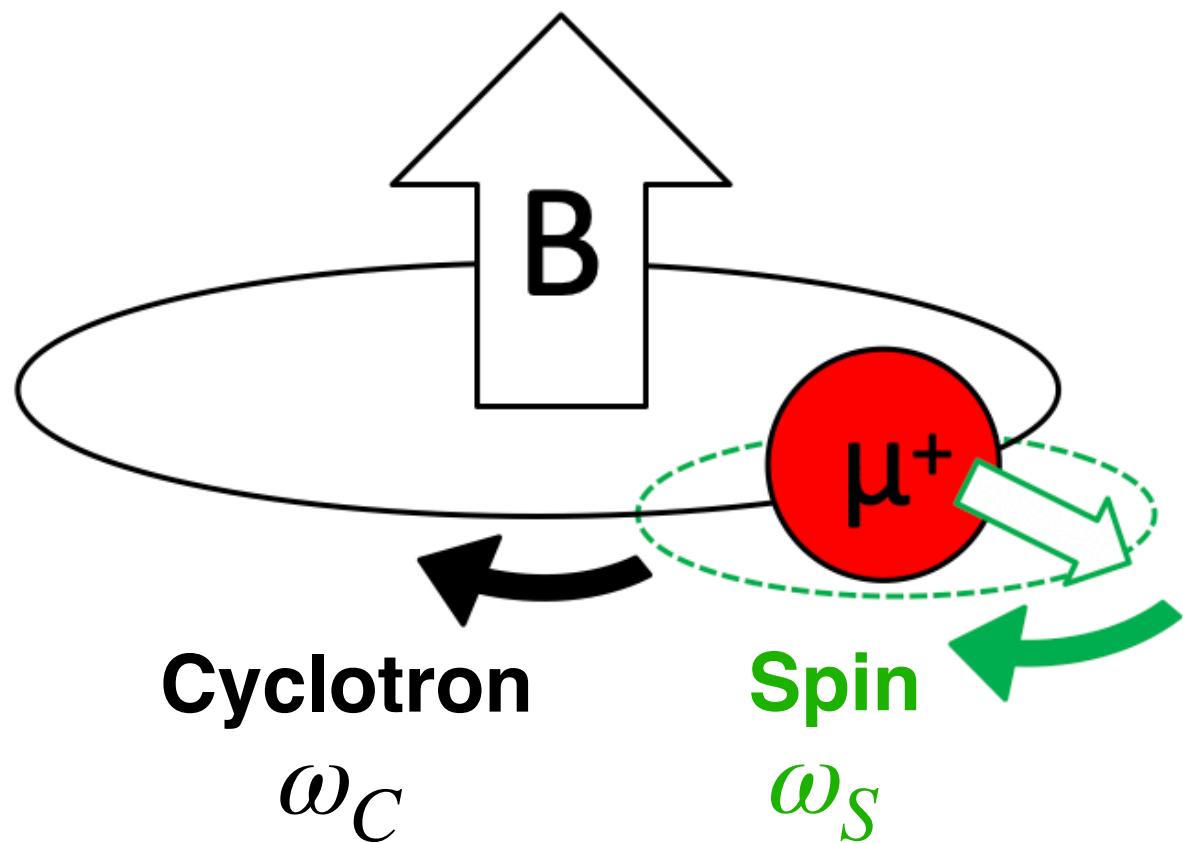
$$\vec{\omega} = -\frac{e}{m} \left[a_\mu \vec{B} + \frac{\eta}{2} \left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right]$$

FNAL E989

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

Measurement Principle

Muon precession in the magnetic field



$$\vec{\omega} = -\frac{e}{m} \left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2} \left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right]$$

Magic "γ": $\gamma^2 = \frac{1}{a_\mu} + 1$

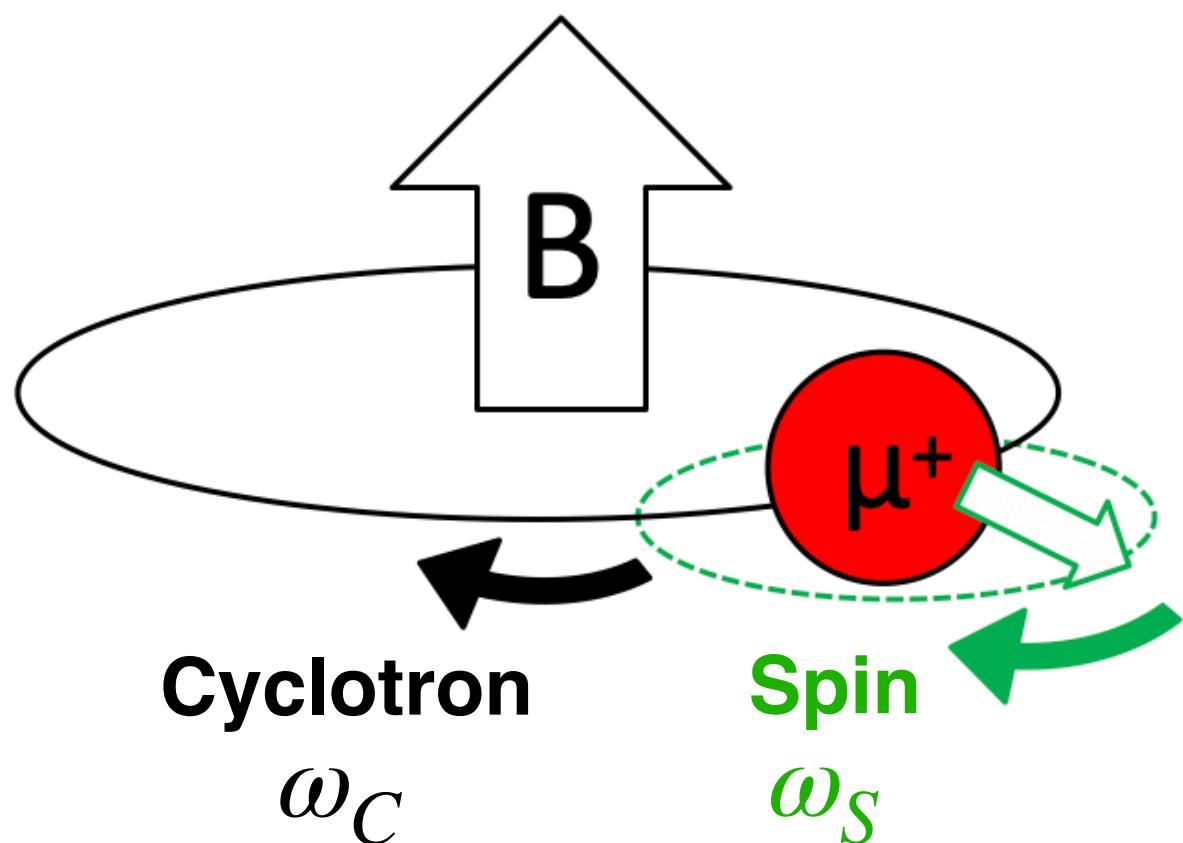
BNL E821 approach
 $\gamma=30$ (P=3 GeV/c)

$$\boxed{\vec{\omega} = -\frac{e}{m} \left[a_\mu \vec{B} + \frac{\eta}{2} \left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right]}$$

FNAL E989

Measurement Principle

Muon precession in the magnetic field



$$\vec{\omega} = -\frac{e}{m} \left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2} \left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right]$$

**Directly
remove E field**

BNL E821 approach
 $\gamma=30$ ($P=3$ GeV/c)

J-PARC approach
 $E = 0$ at any γ

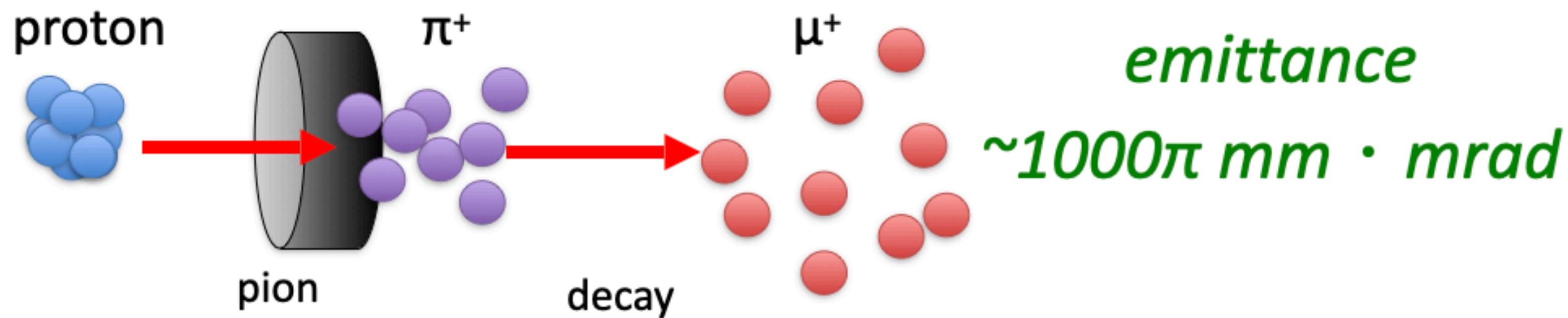
$$\boxed{\vec{\omega} = -\frac{e}{m} \left[a_\mu \vec{B} + \frac{\eta}{2} \left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right]}$$

FNAL E989

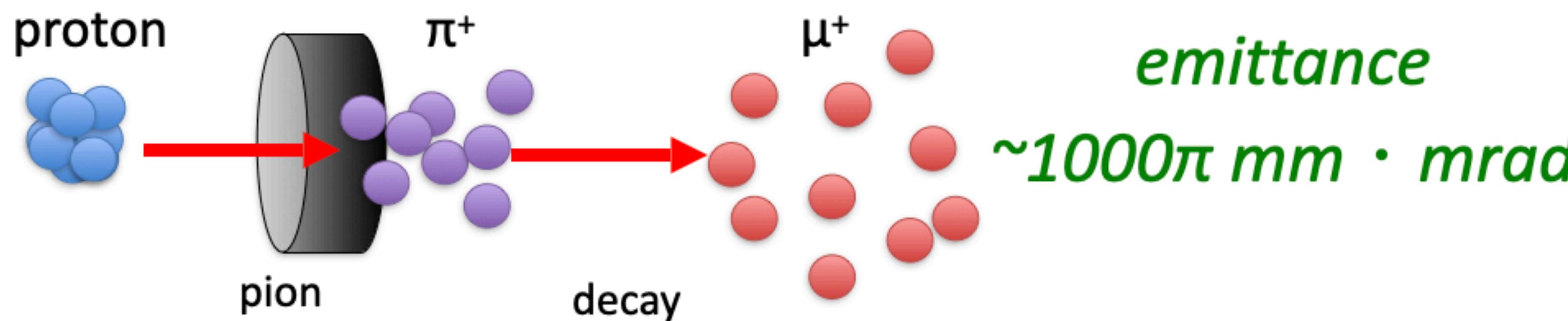
$$\boxed{\vec{\omega} = -\frac{e}{m} \left[a_\mu \vec{B} + \frac{\eta}{2} \left(\vec{\beta} \times \vec{B} \right) \right]}$$

J-PARC E34

Reaccelerated Thermal Muon Beam

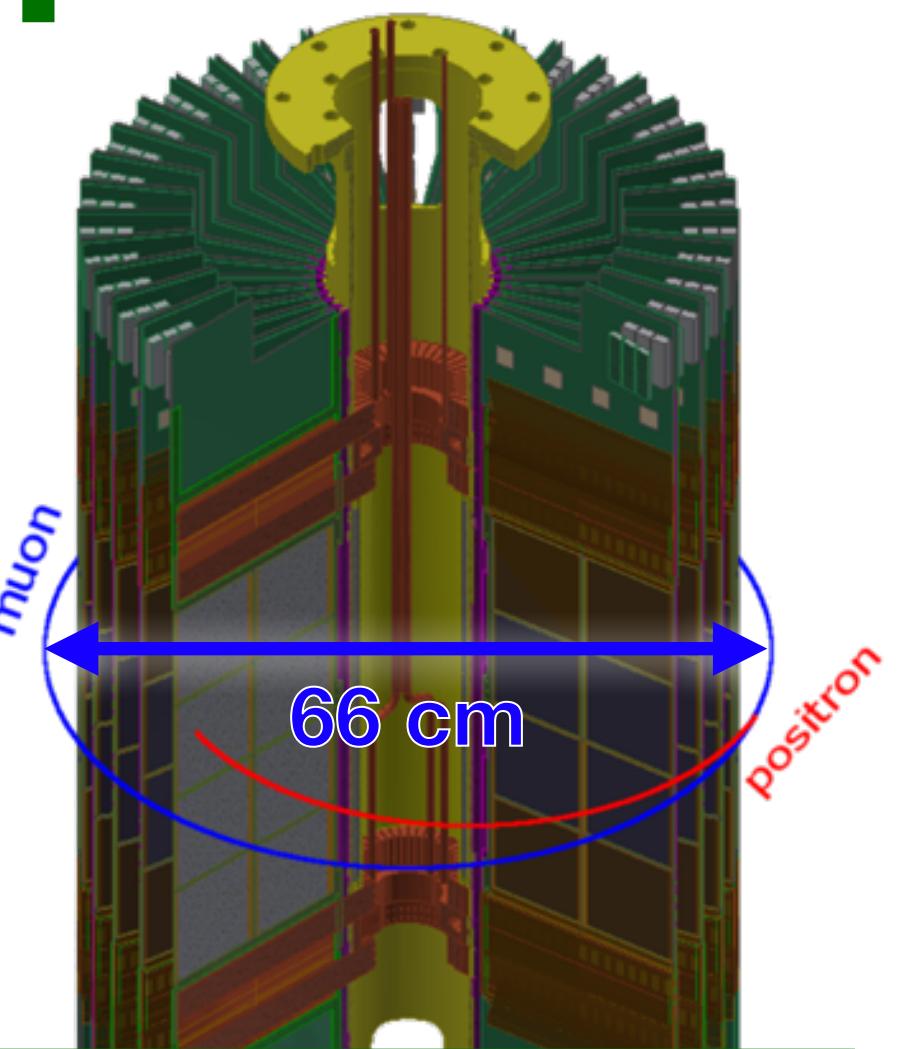
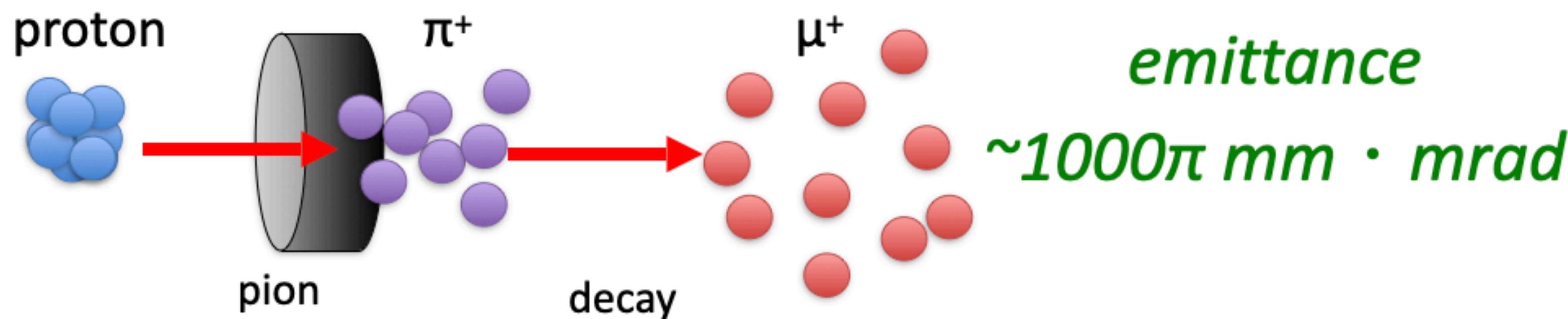


Reaccelerated Thermal Muon Beam



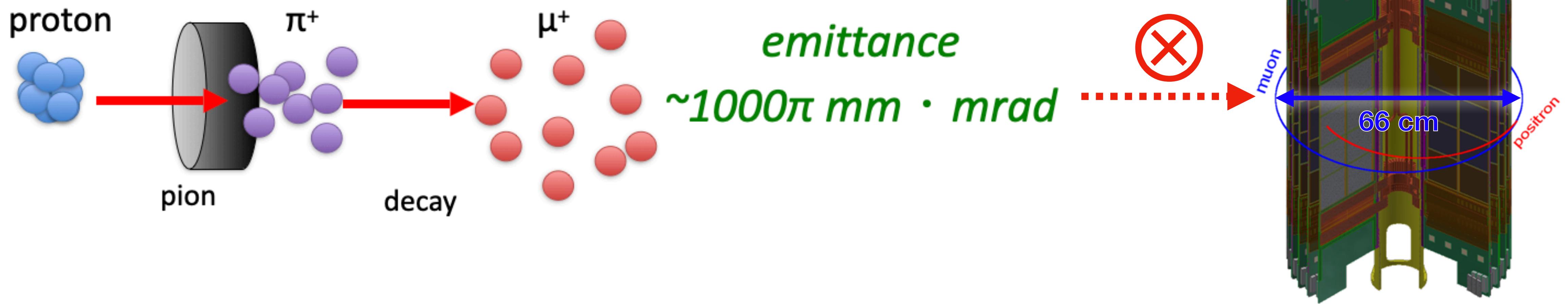
	Fermilab Muon g-2	J-PARC Muon g-2/EDM
Muon momentum	3.09 GeV/c	300 MeV/c
Storage Field	$B = 1.45 \text{ T}$	$B = 3 \text{ T}$ (Solenoidal)
Muon orbit diameter	14 m	66 cm
Cyclotron period	149 ns	7.4 ns
Focusing field	Electric quadrupole	$E = 0$, very weak magnetic

Reaccelerated Thermal Muon Beam



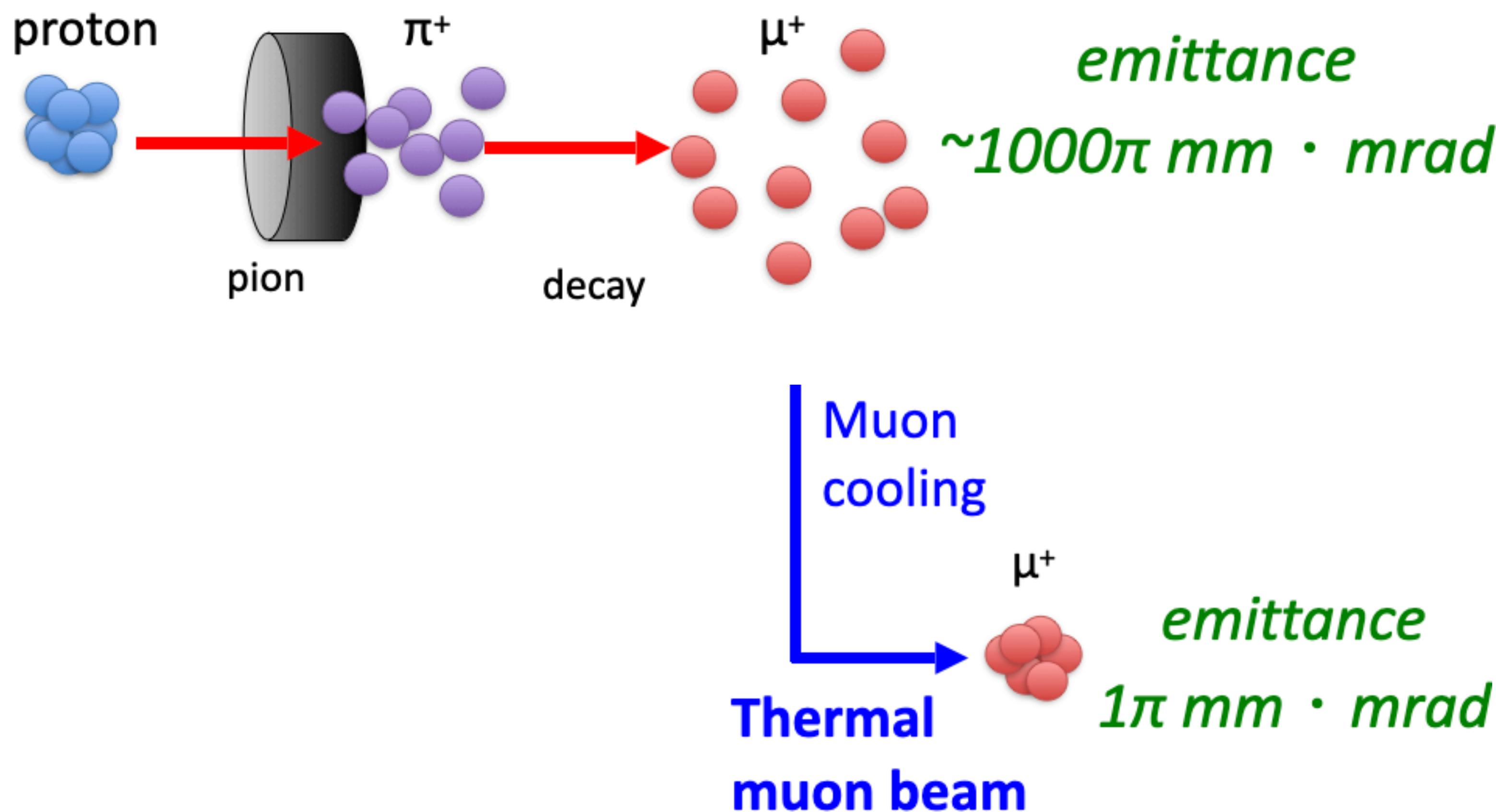
	Fermilab Muon g-2	J-PARC Muon g-2/EDM
Muon momentum	3.09 GeV/c	300 MeV/c
Storage Field	$B = 1.45 \text{ T}$	$B = 3 \text{ T}$ (Solenoidal)
Muon orbit diameter	14 m	66 cm
Cyclotron period	149 ns	7.4 ns
Focusing field	Electric quadrupole	$E = 0$, very weak magnetic

Reaccelerated Thermal Muon Beam

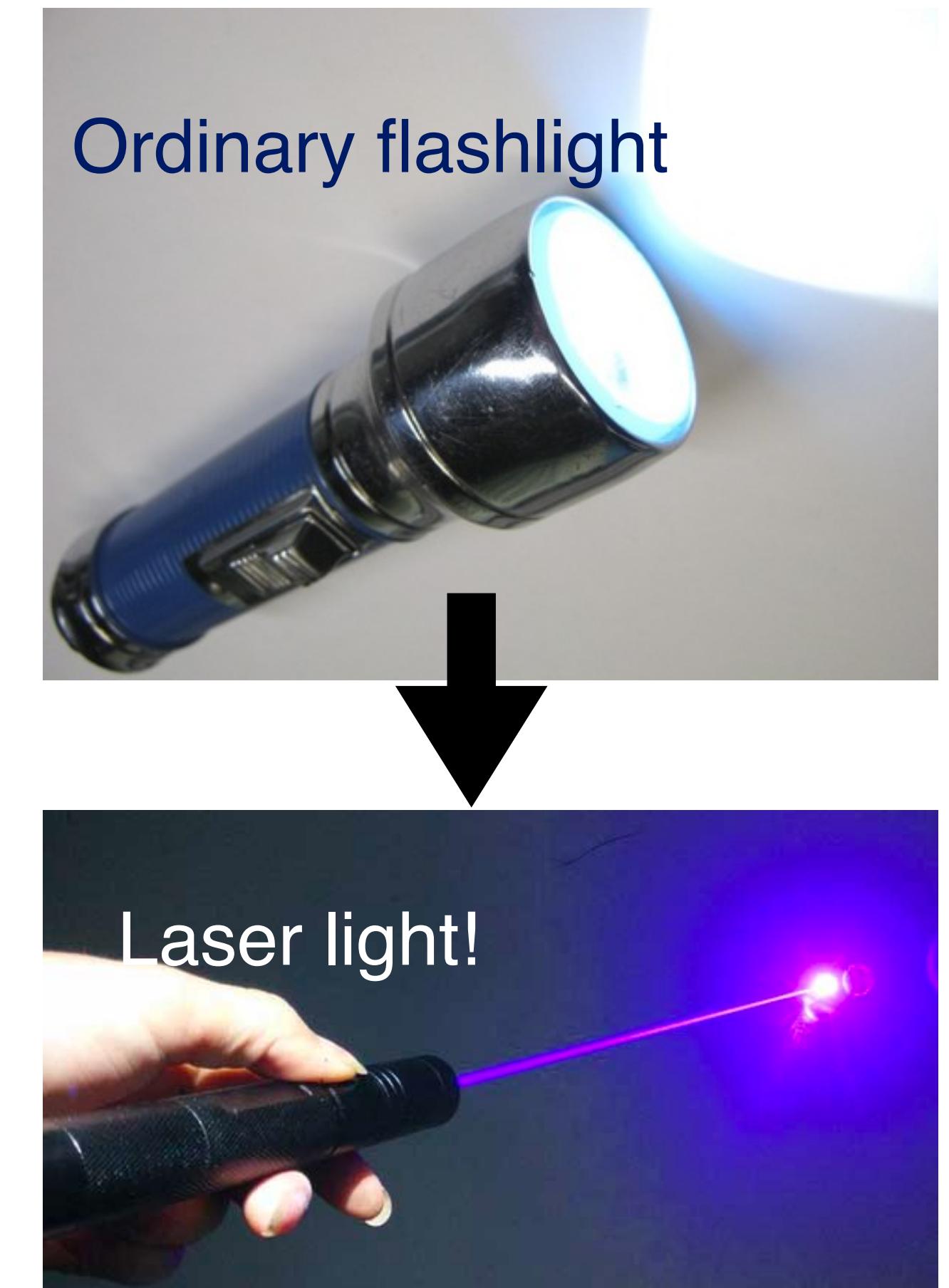
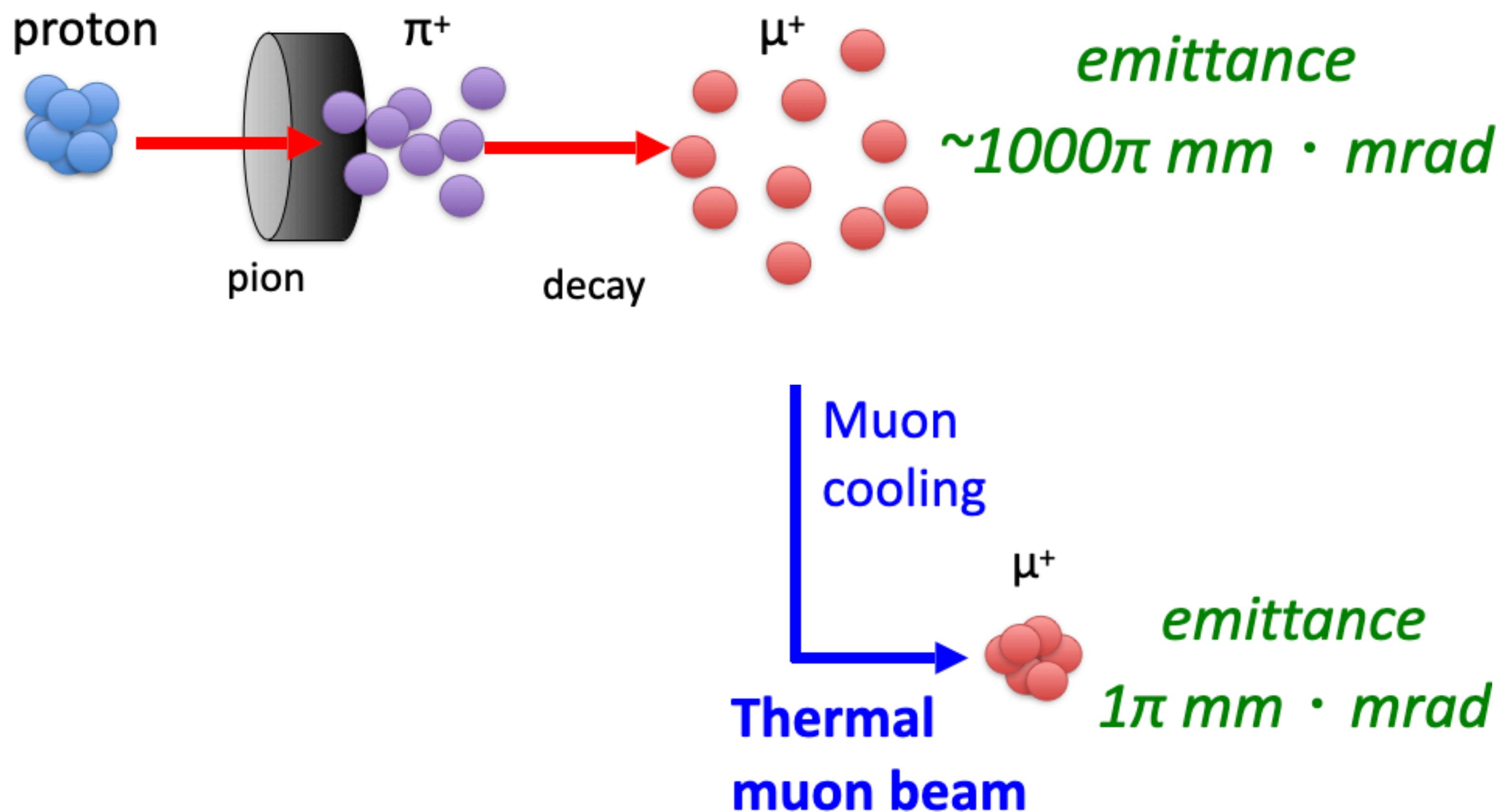


- The traditional surface muon beam is not applicable for J-PARC E34
- A novel thermal muon beam with low emittance was proposed

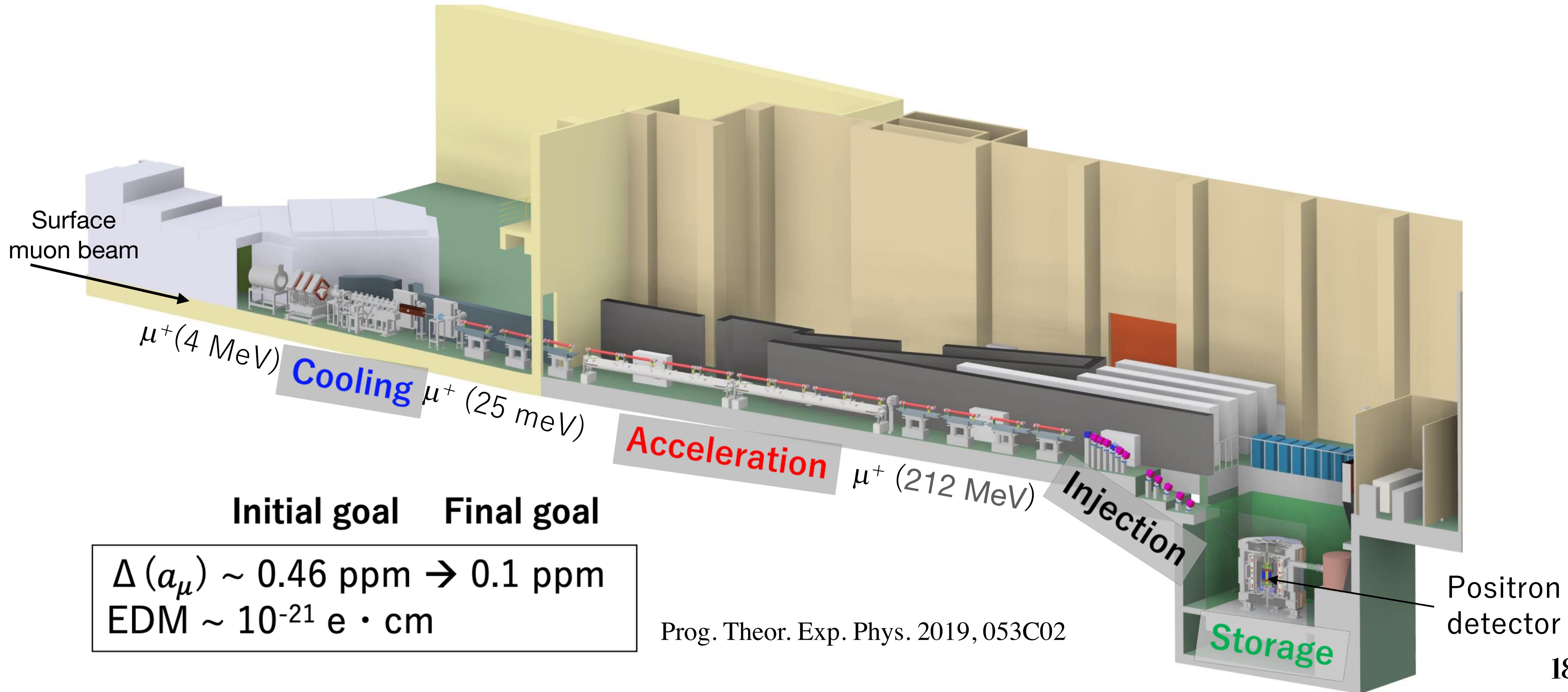
Reaccelerated Thermal Muon Beam



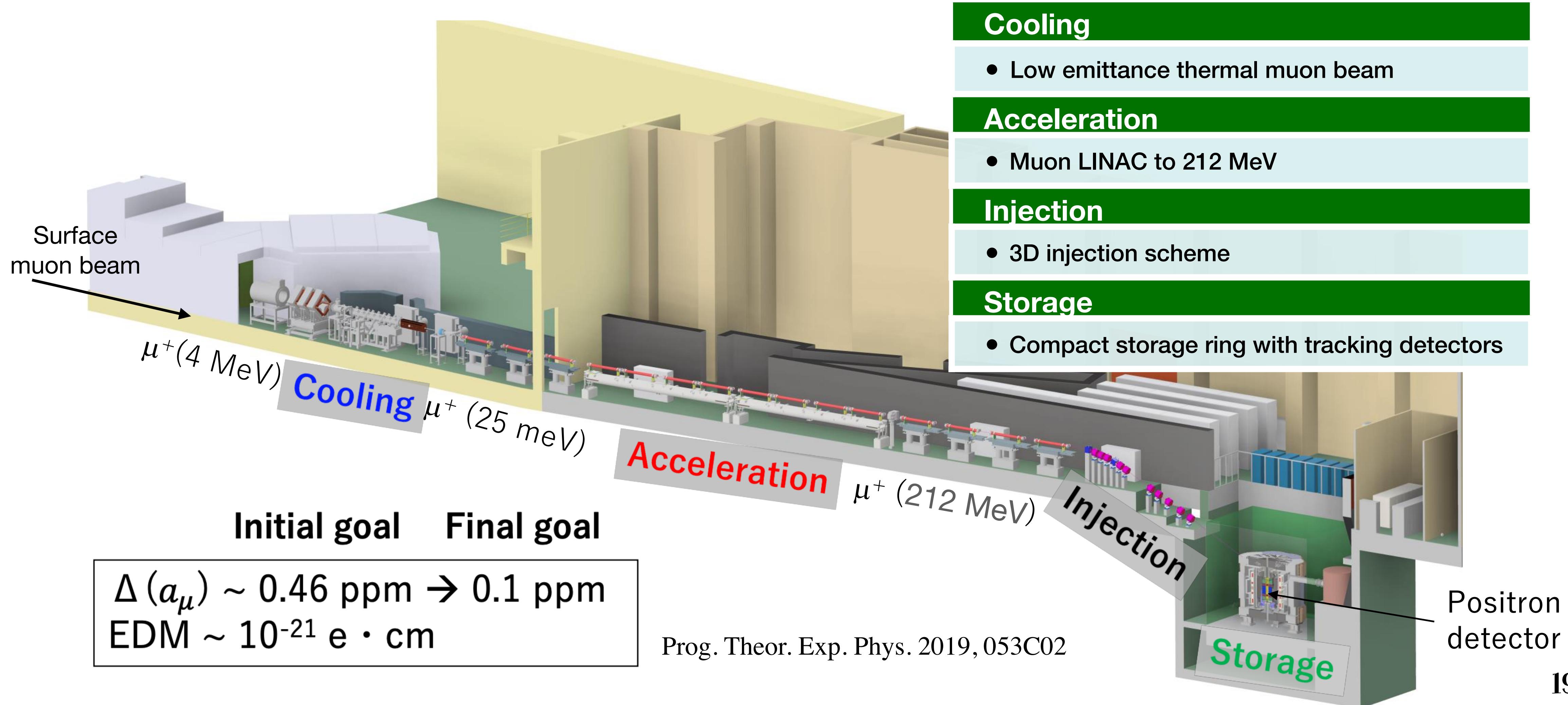
Reaccelerated Thermal Muon Beam



J-PARC Muon $g - 2$ /EDM experiment (E34)



J-PARC Muon $g - 2$ /EDM experiment (E34)



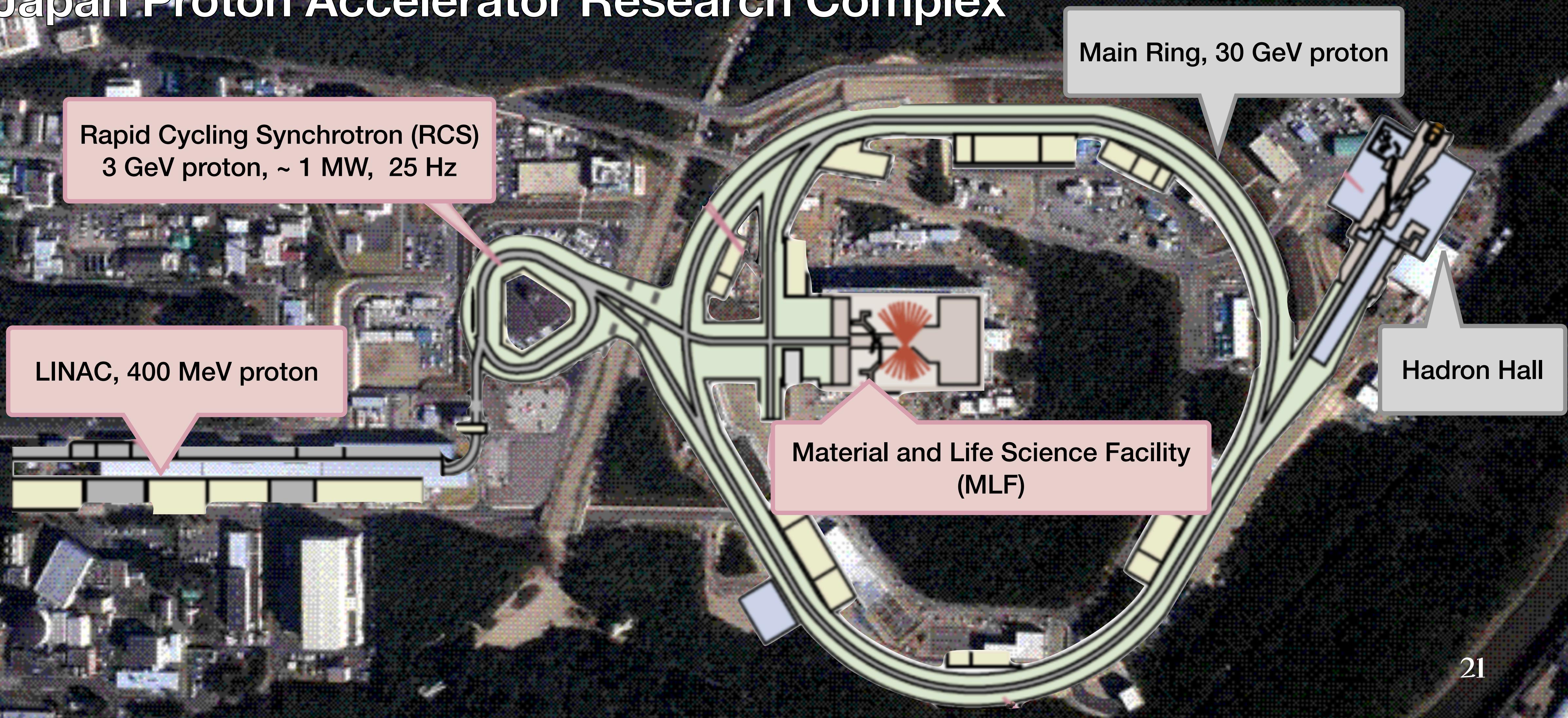
J-PARC

Japan Proton Accelerator Research Complex



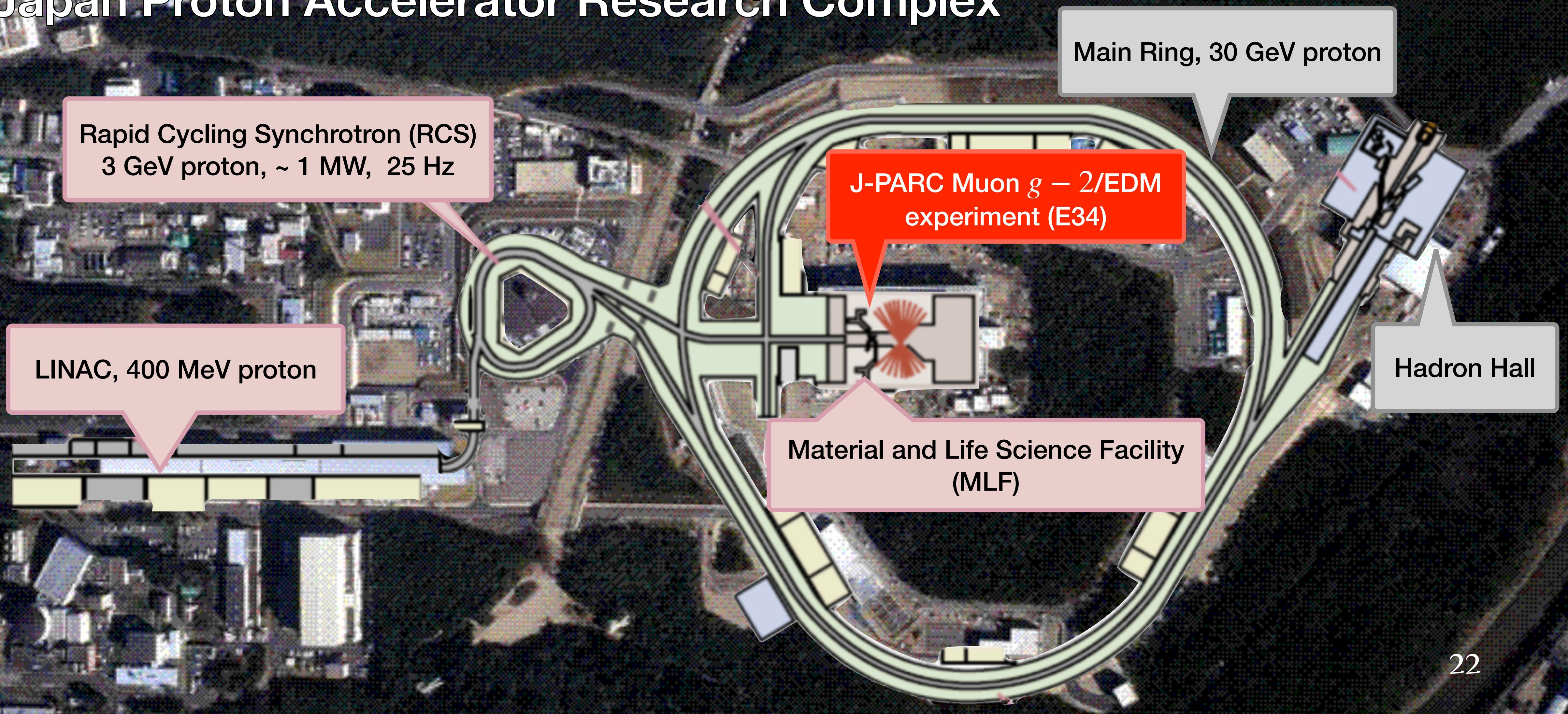
J-PARC

Japan Proton Accelerator Research Complex



J-PARC

Japan Proton Accelerator Research Complex



Muon Source at J-PARC MLF

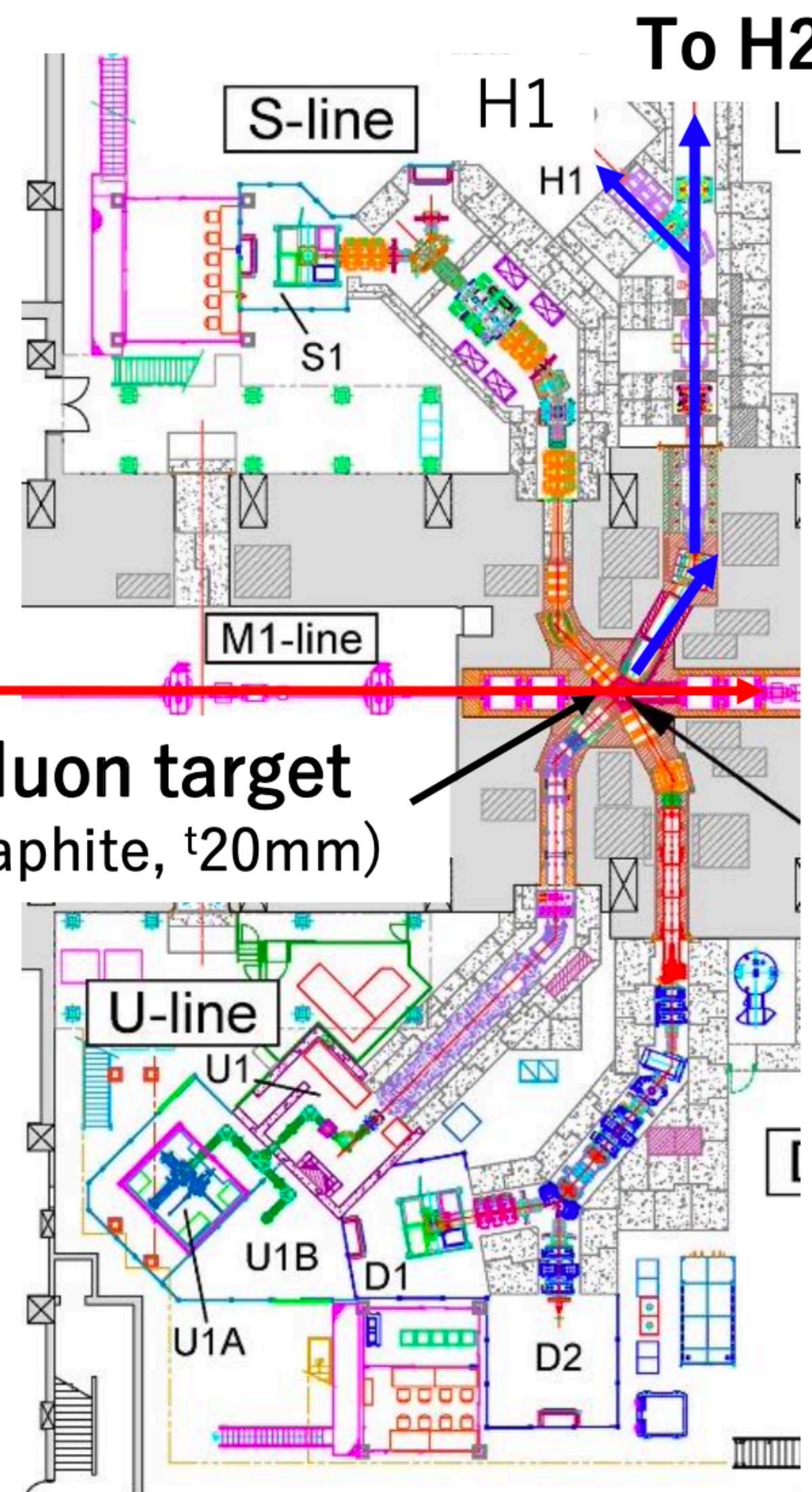
S-line

- surface μ^+
- dedicated to μ SR
- S1 area is available
- S2 is under construction
- S3/S4 are planned

3 GeV proton from RCS
 $2 \times 10^{15} /s @1\text{MW}$

U-line

- ultra slow μ^+
- U1A for nm- μ SR
- U1B for μ microscopy
- under commissioning



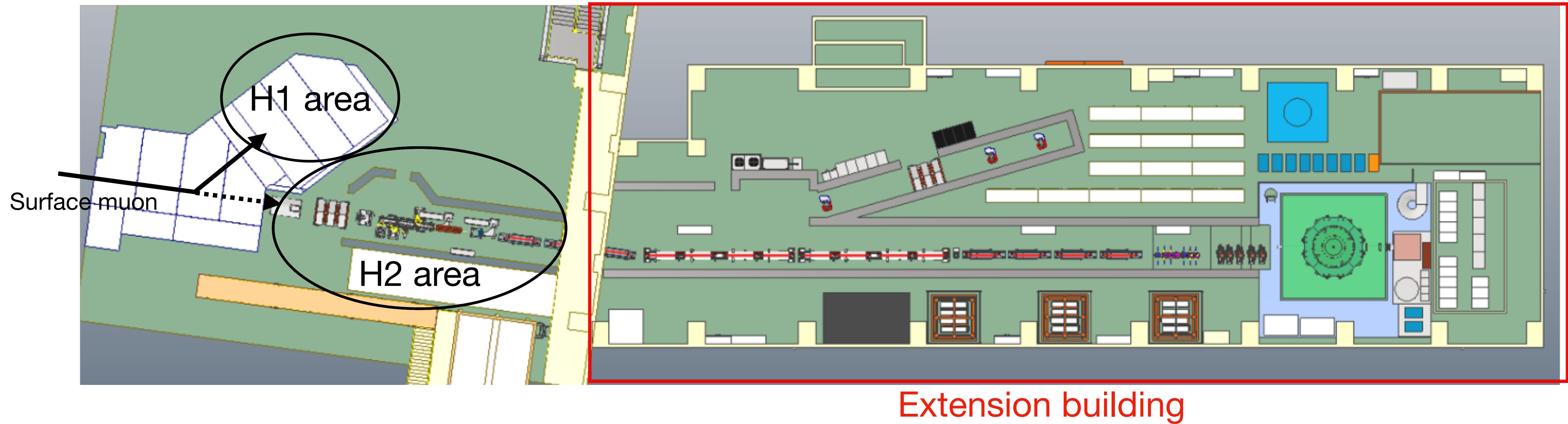
H-line

- surface $\mu^+ (>10^8 \mu^+/s)$, decay μ^+/μ^- , e^-
- for high intensity & long beamtime experiments
- H1 for DeeMe & MuSEUM
- H2 for **g-2/EDM** & transmission muon microscopy
- **under construction**

D-line

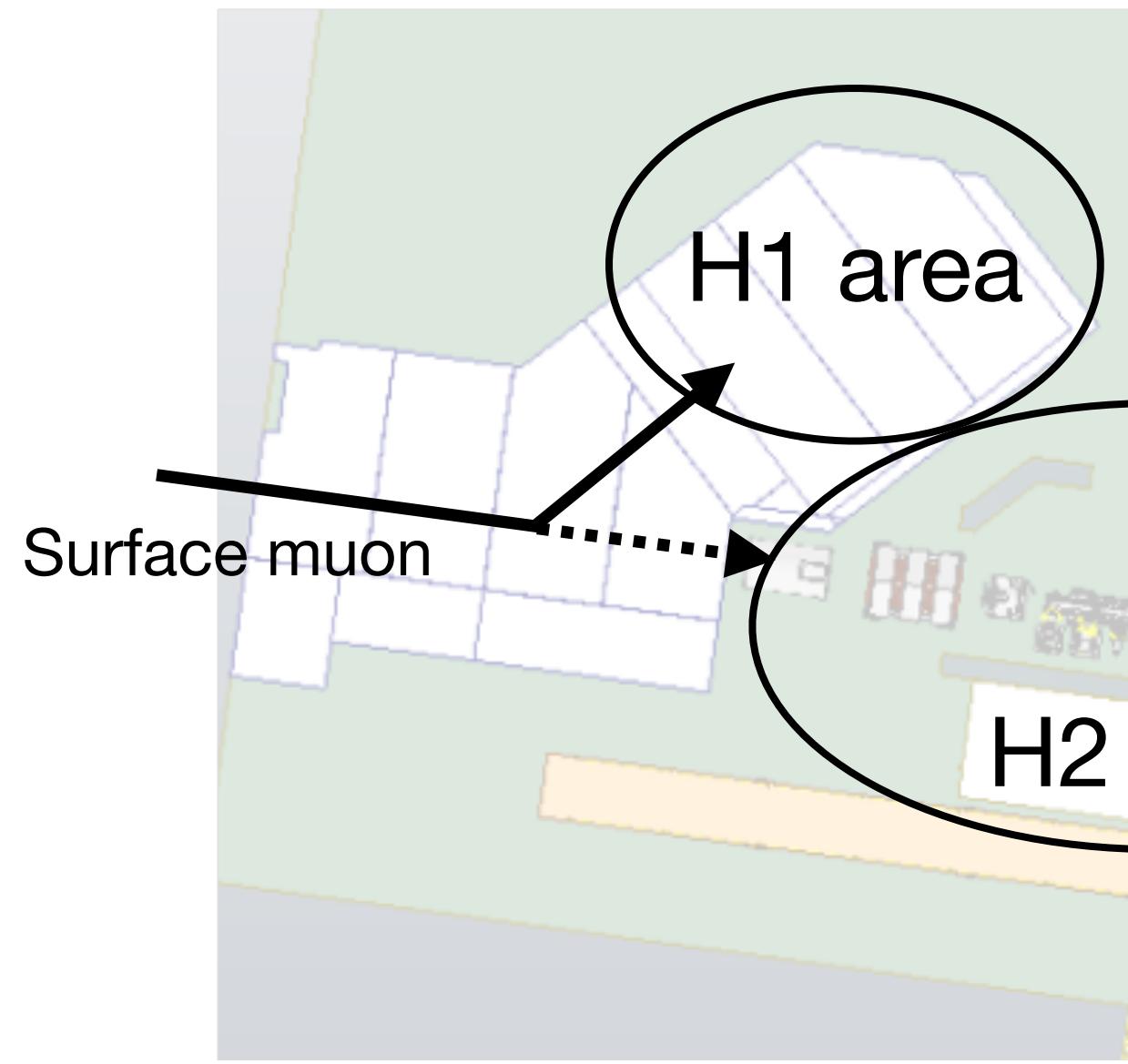
- decay μ^+/μ^- , surface μ^+
- D1 area for μ SR
- D2 for variety of science

Construction of Experimental Site

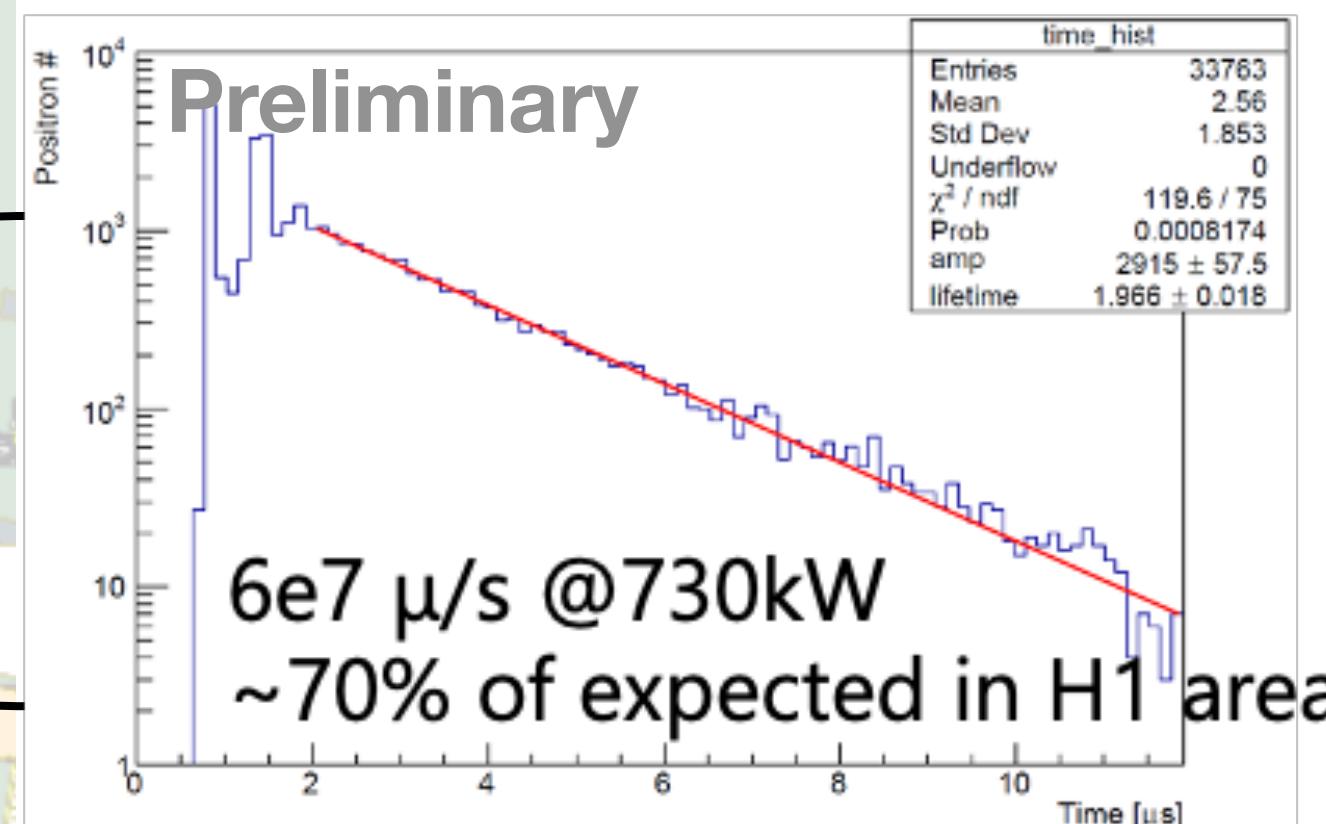


- Beam commissioning is ongoing at the **H1 area**.
- Construction of the **H2 area** is in progress.
- **The extension building** design is ready to start construction in 2023.

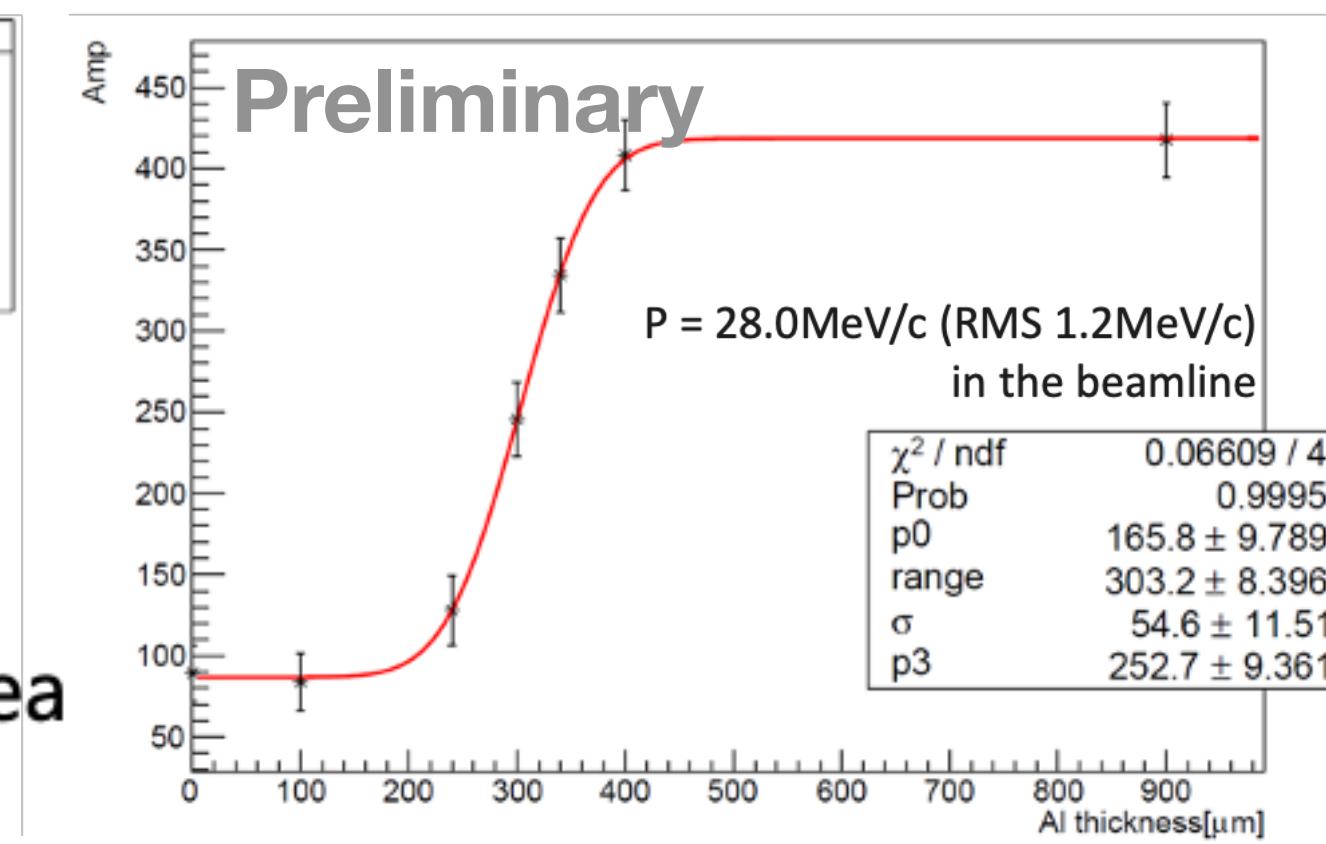
H-line Construction



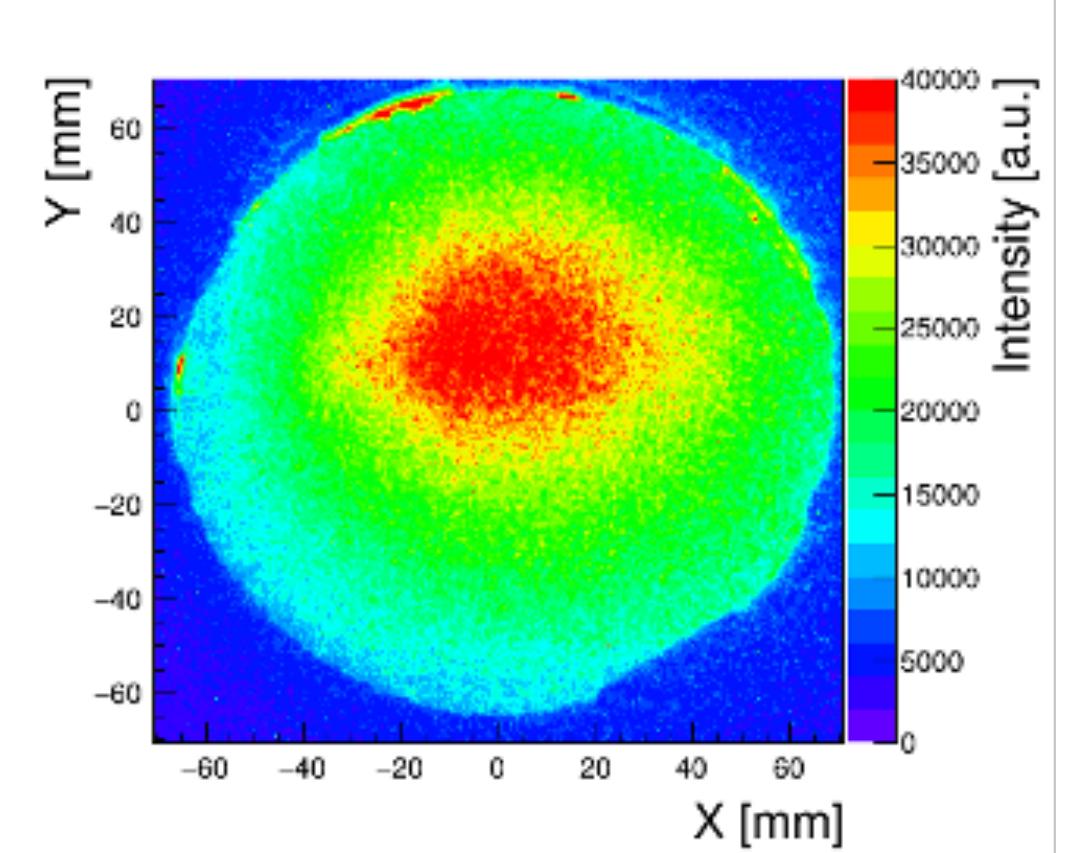
- The first beam was delivered to the **H1 area** on Jan. 15, 2022



① Beam intensity measurement



② Momentum estimation

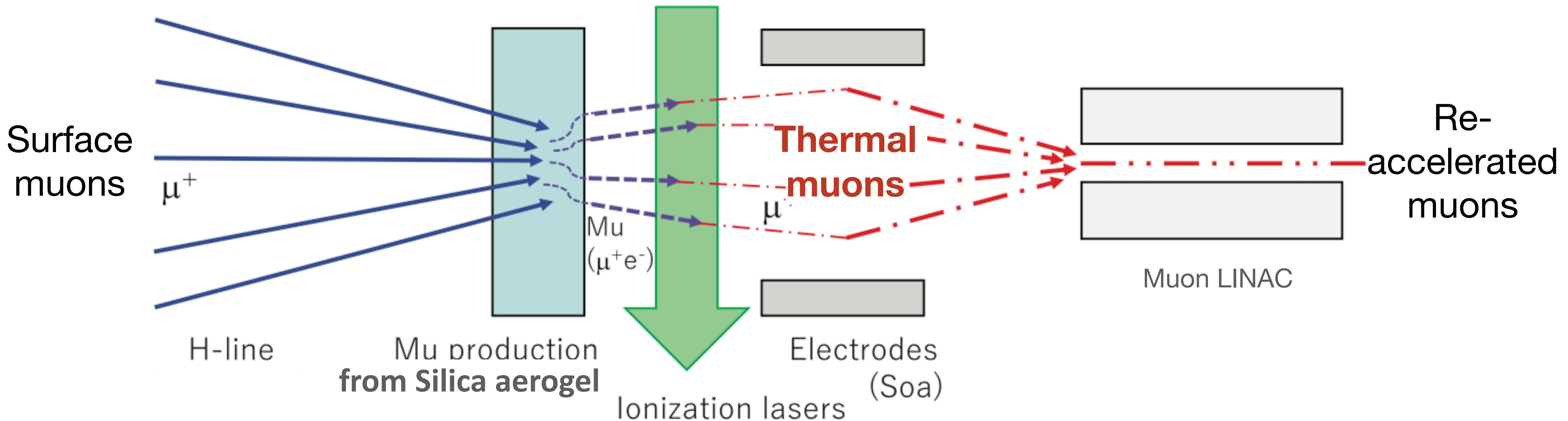


③ Beam profile measurement and optics tuning

- Beam commissioning is ongoing at the **H1 area**.
- Construction of the **H2 area** is in progress.
- The extension building** design is ready to start construction in 2023.

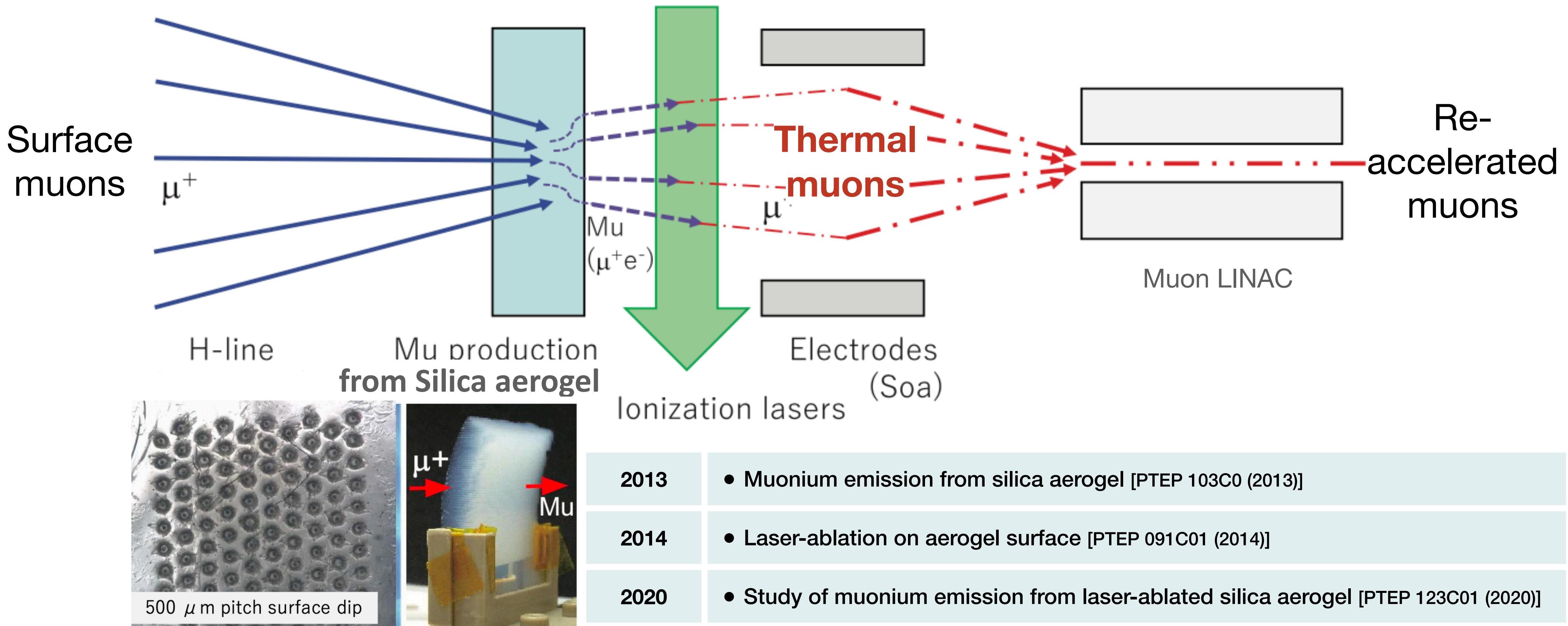
Thermal Muon Source

- Surface muon cooling by laser ionization of muonium (Mu) to thermal muon



Thermal Muon Source

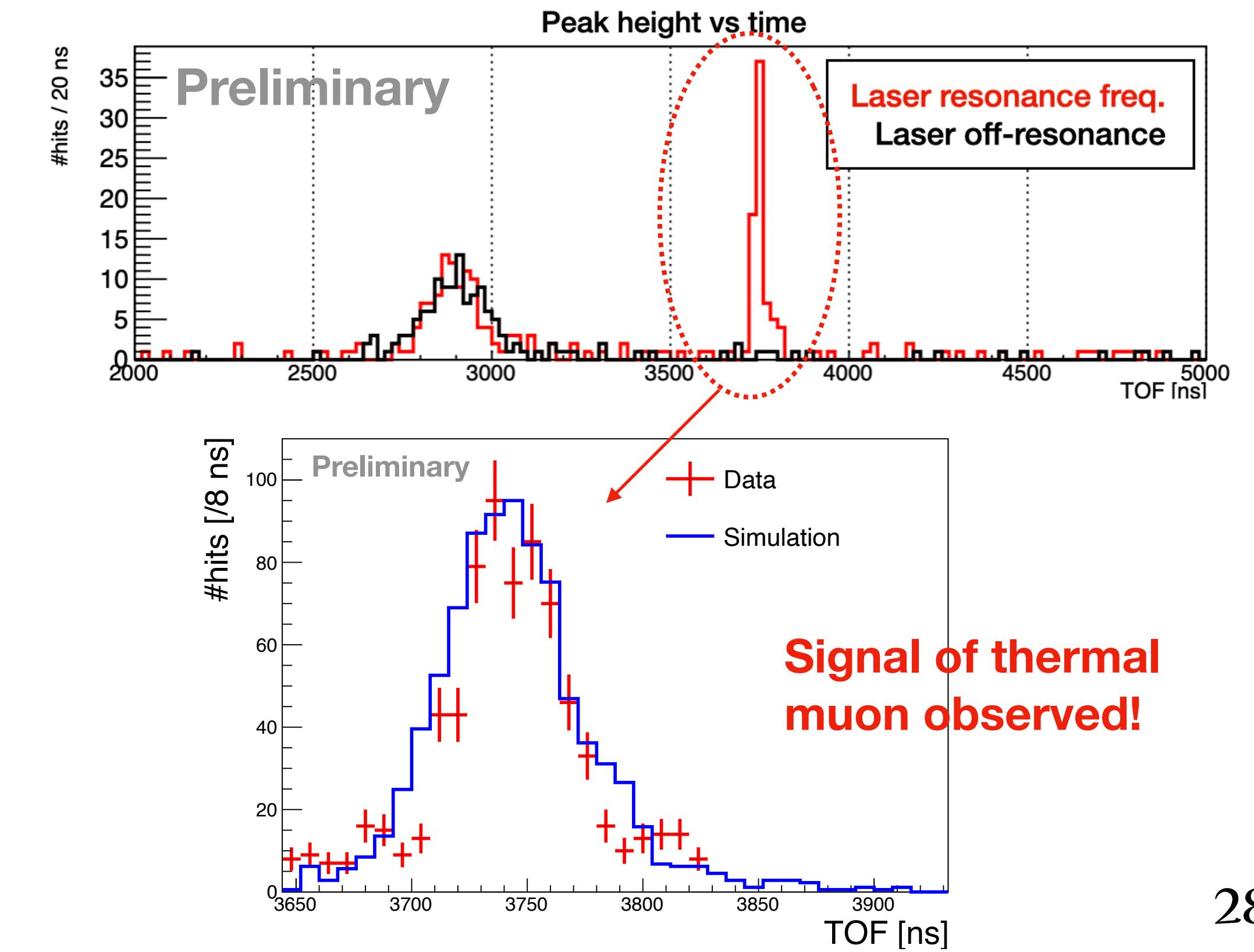
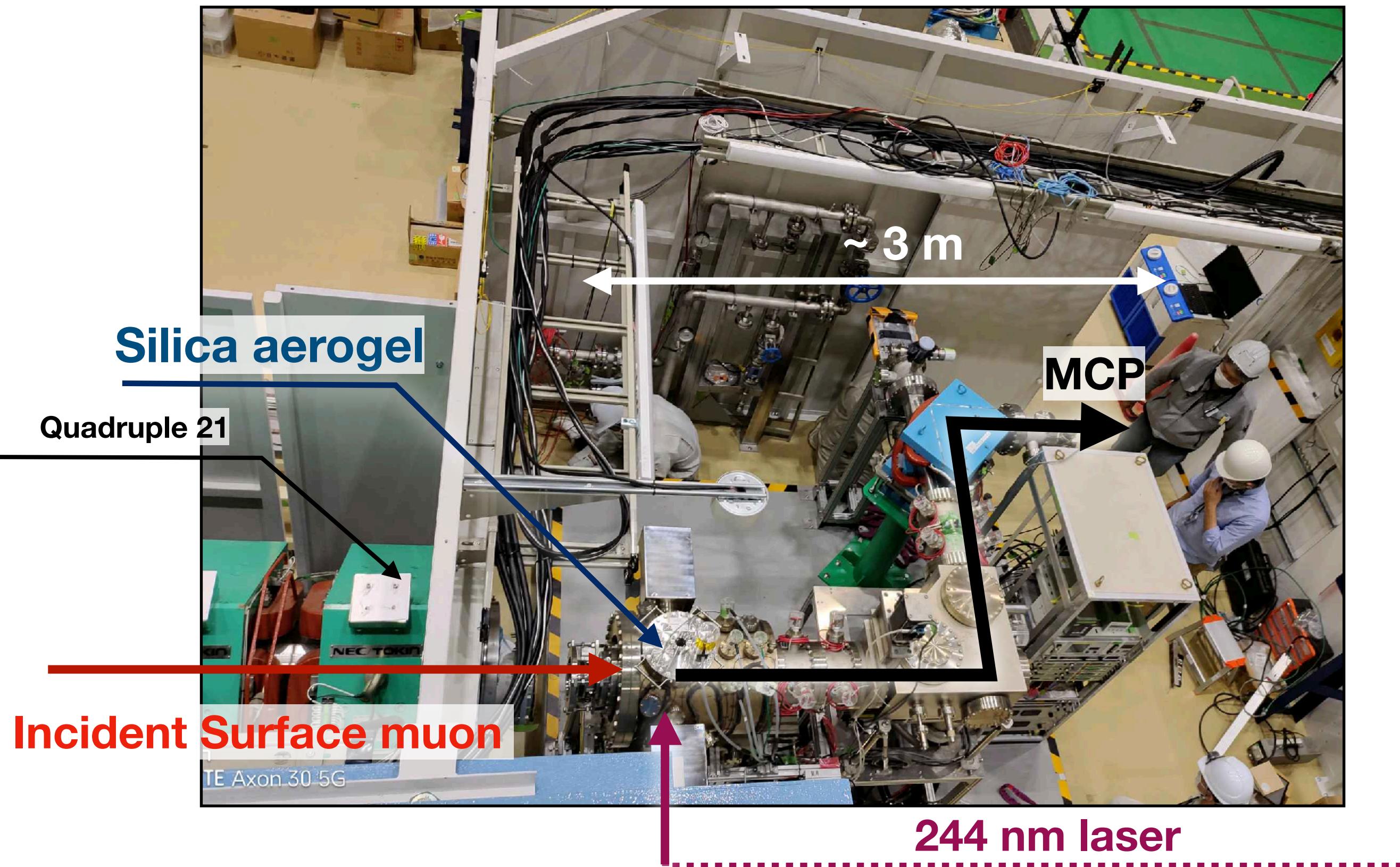
- Surface muon cooling by laser ionization of muonium (Mu) to thermal muon



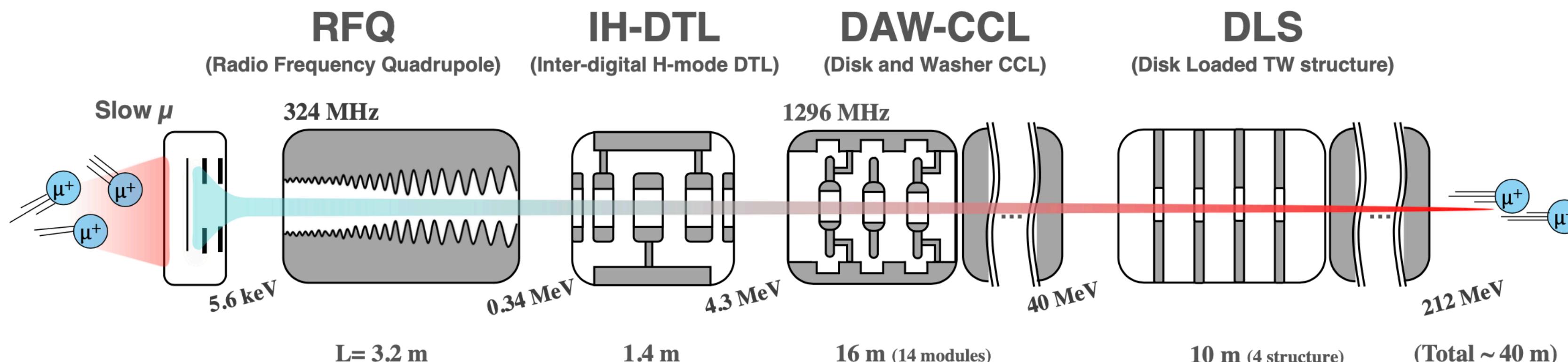
Thermal Muon Source

Mu laser ionization test

- The **demonstration** of thermal muon generation via laser ionization of muonium from silica aerogel at the J-PARC MLF S2 area

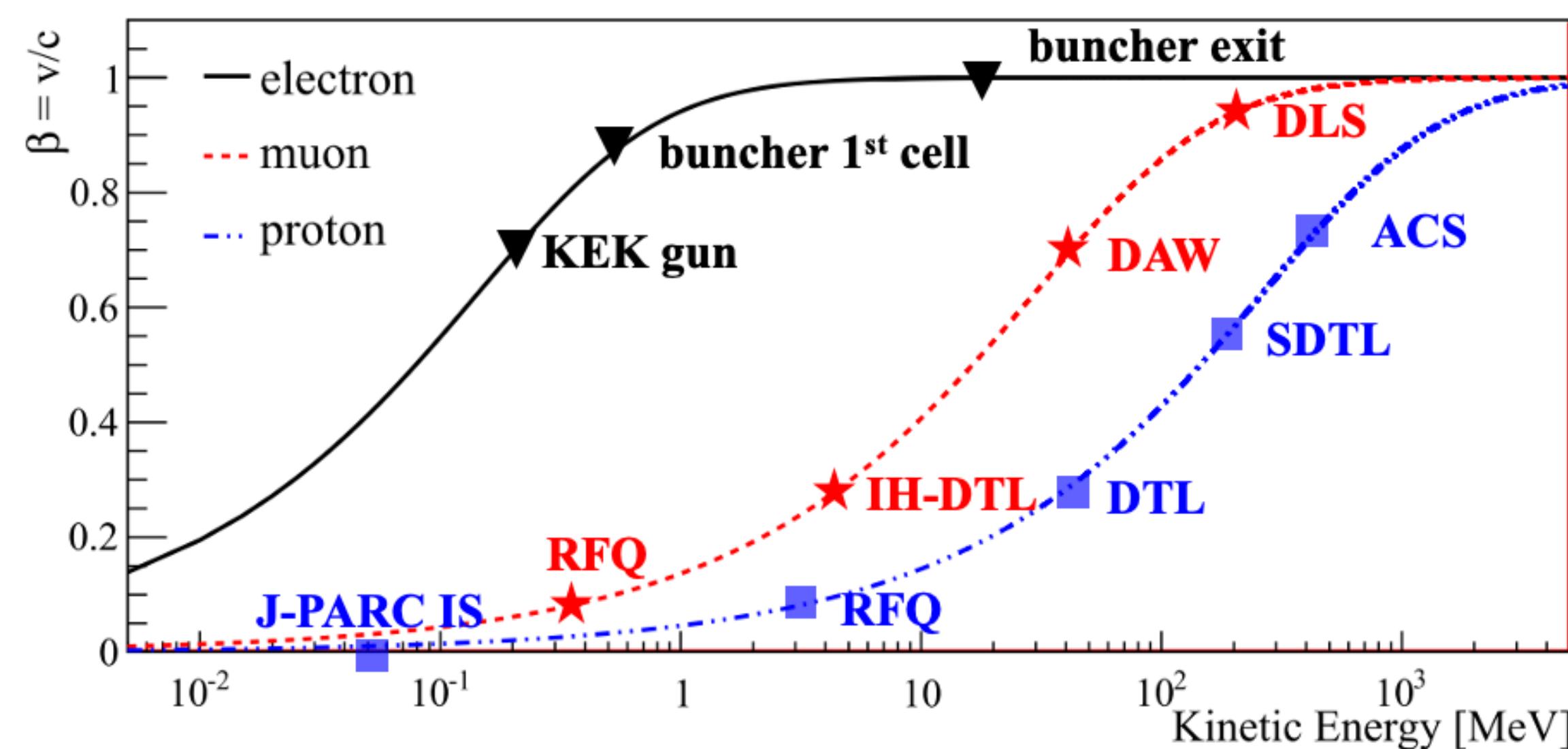


Muon Acceleration

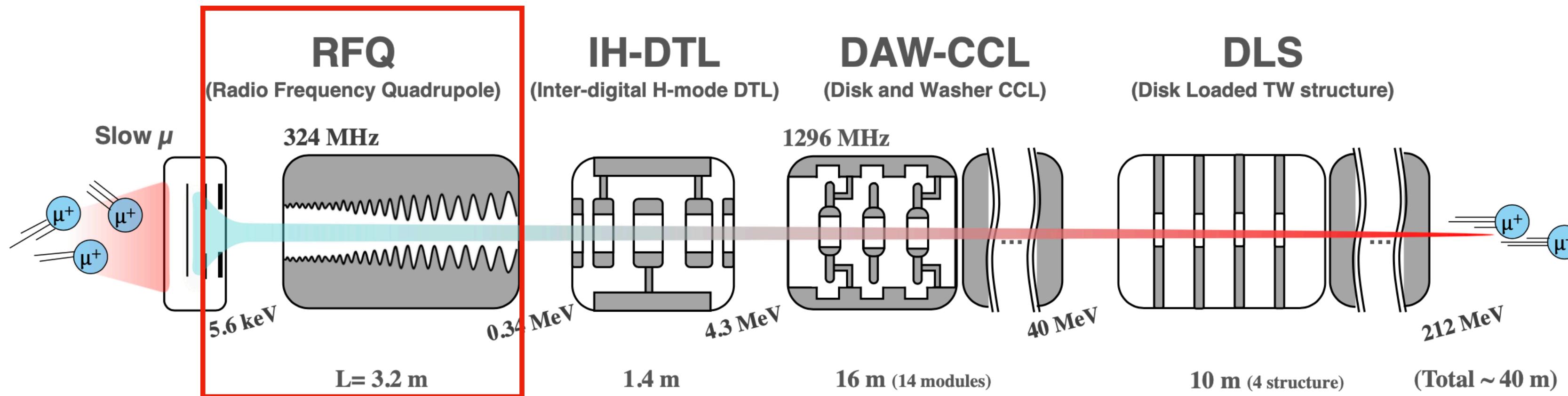


Muon LINAC parameters	
Frequency (2-stage)	324MHz, 1296MHz
Intensity	1×10^6 /s
Rep rate	25 Hz
Pulse width	10 ns
Norm. rms emittance	$1.5 \pi \text{ mm mrad}$
Momentum spread	0.1 %

- The first muon-dedicated linac in the world

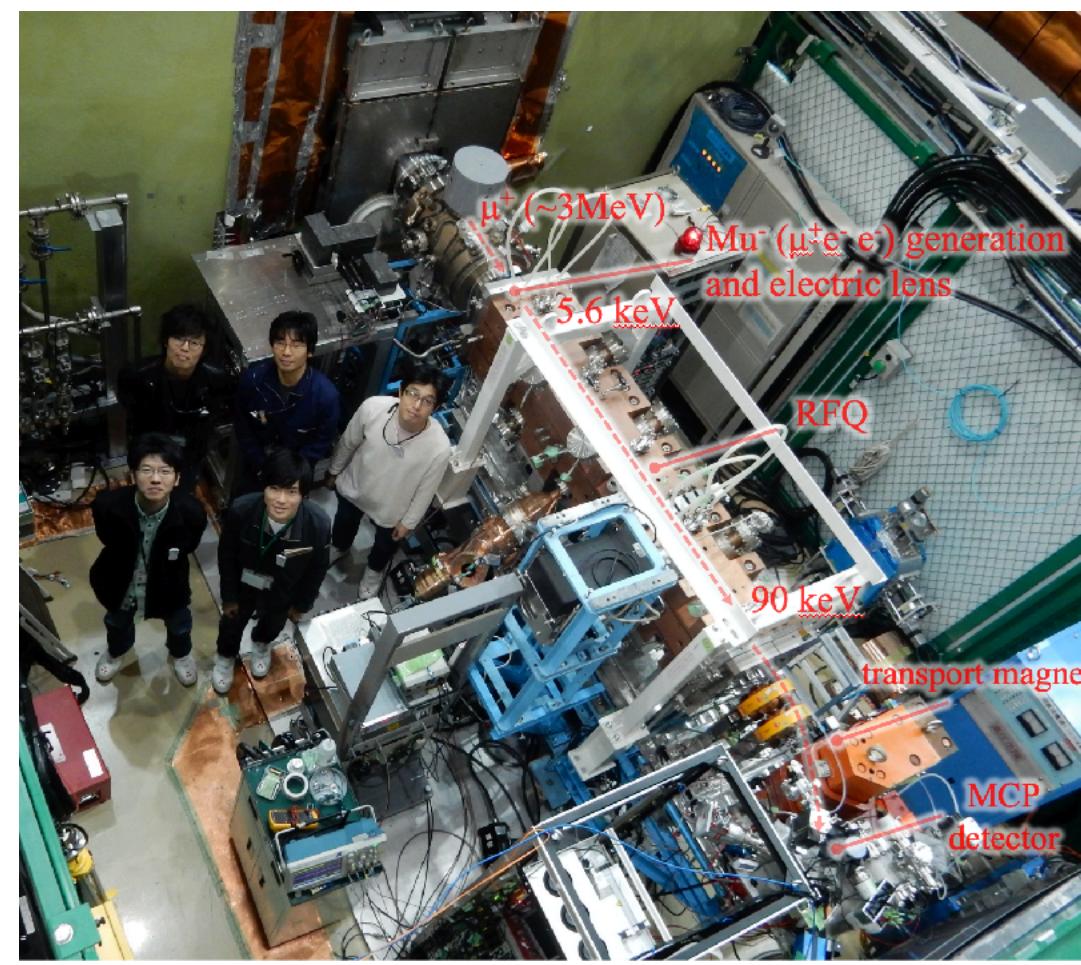
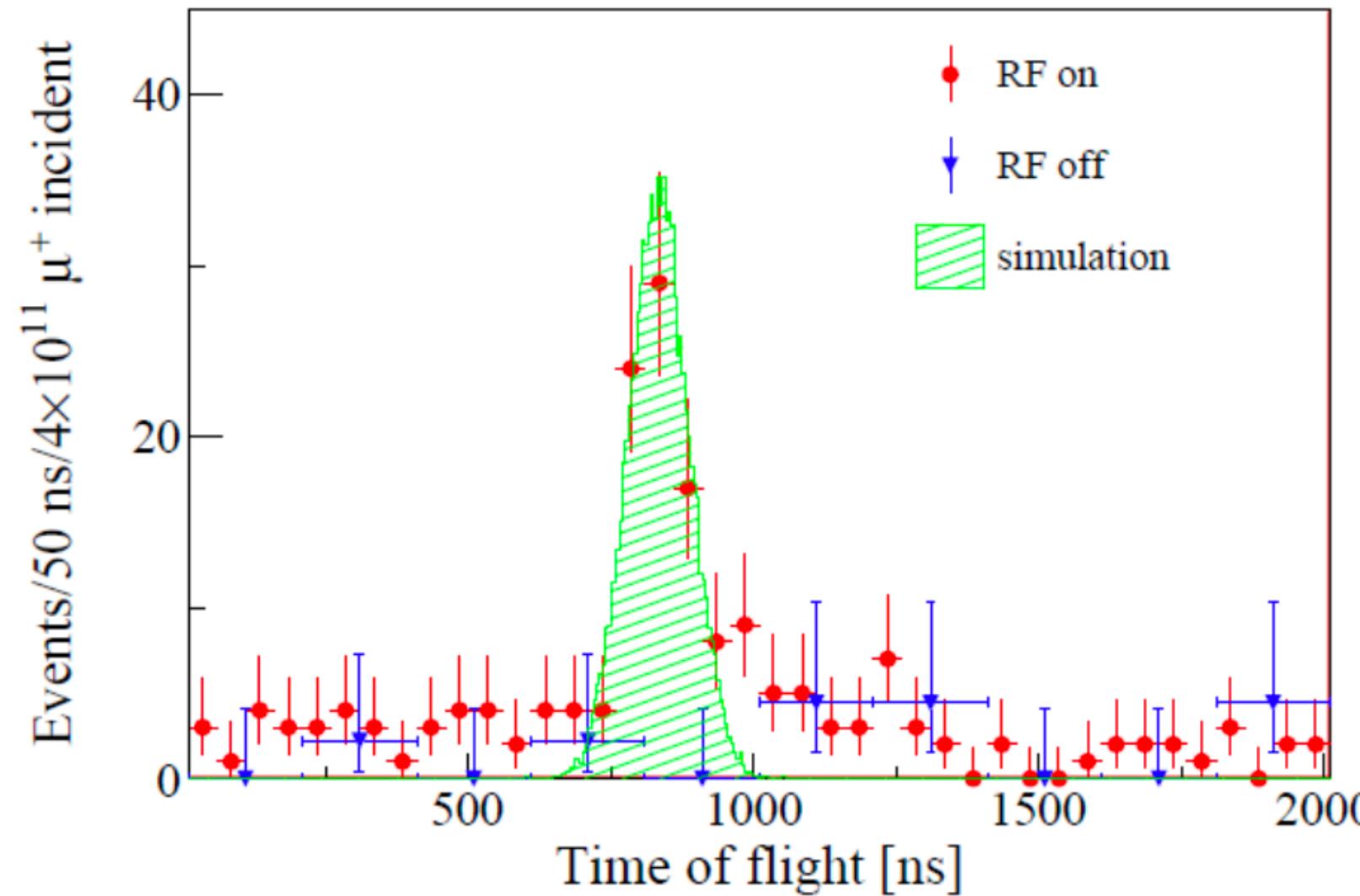


Muon Acceleration

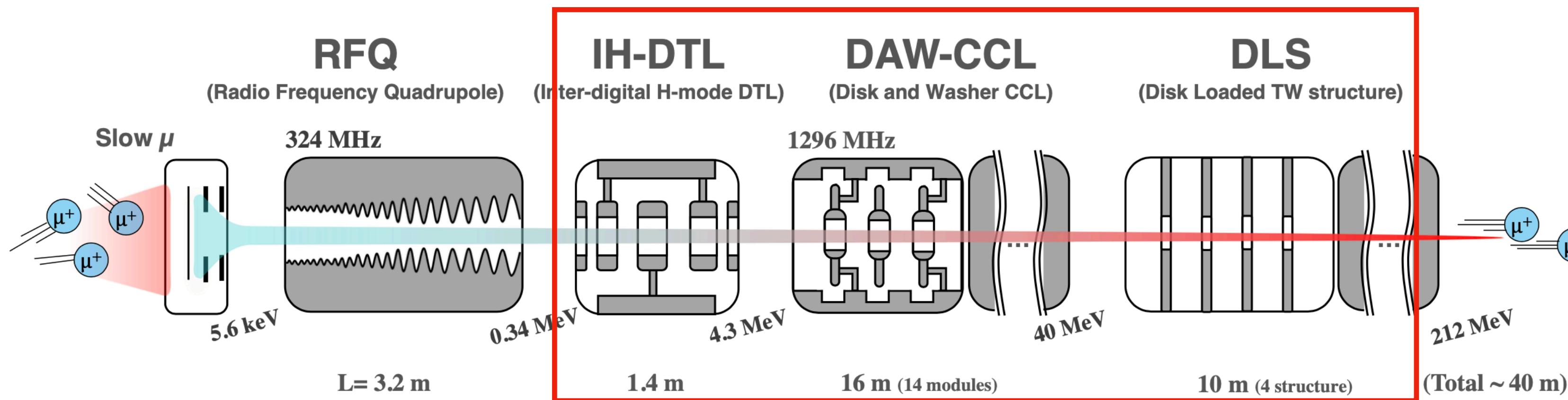


Muon LINAC parameters	
Frequency (2-stage)	324MHz, 1296MHz
Intensity	1×10^6 /s
Rep rate	25 Hz
Pulse width	10 ns
Norm. rms emittance	$1.5 \pi \text{ mm mrad}$
Momentum spread	0.1 %

- First muon acceleration using RF linac
(Phys. Rev. Accel. Beams 21, 050101 (2018))

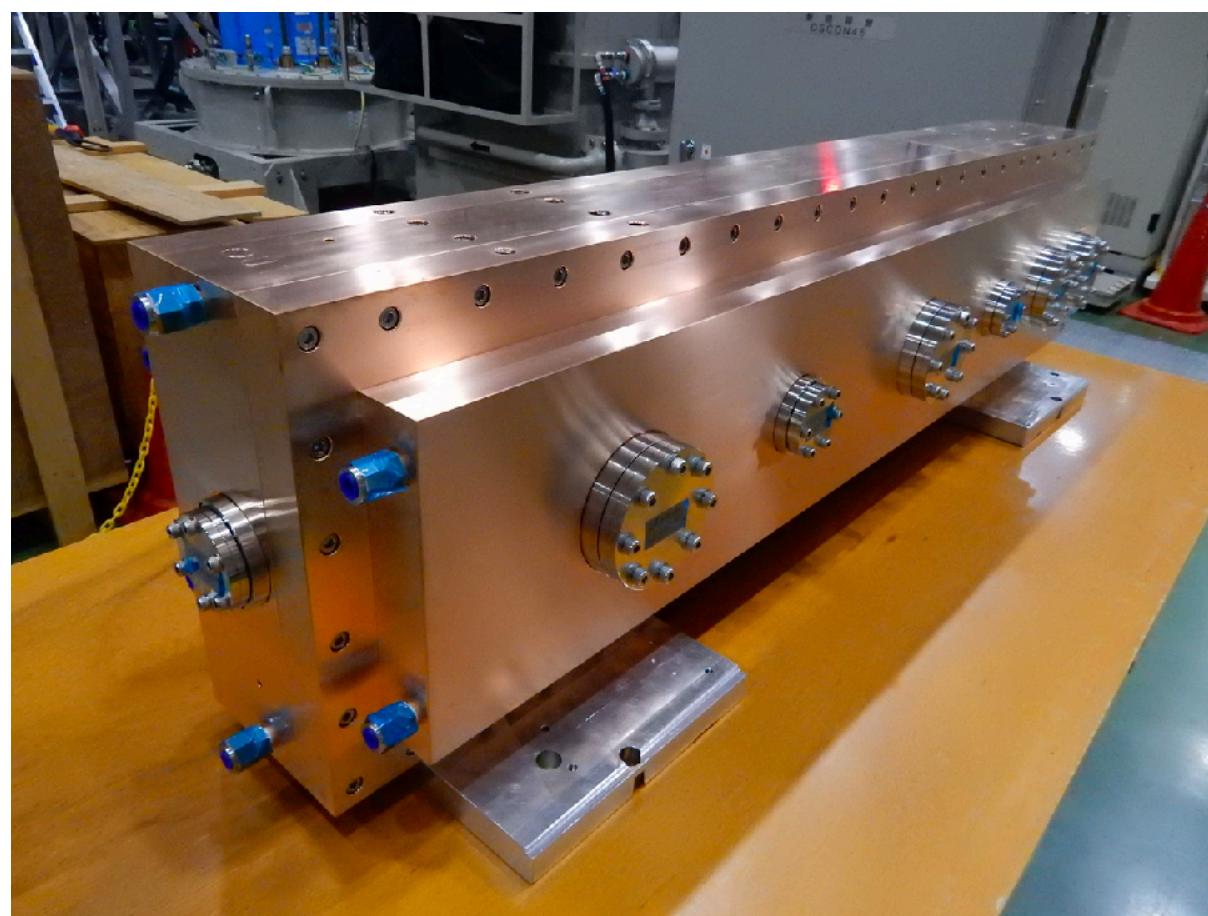


Muon Acceleration



Muon LINAC parameters	
Frequency (2-stage)	324MHz, 1296MHz
Intensity	$1 \times 10^6 / \text{s}$
Rep rate	25 Hz
Pulse width	10 ns
Norm. rms emittance	$1.5 \pi \text{ mm mrad}$
Momentum spread	0.1 %

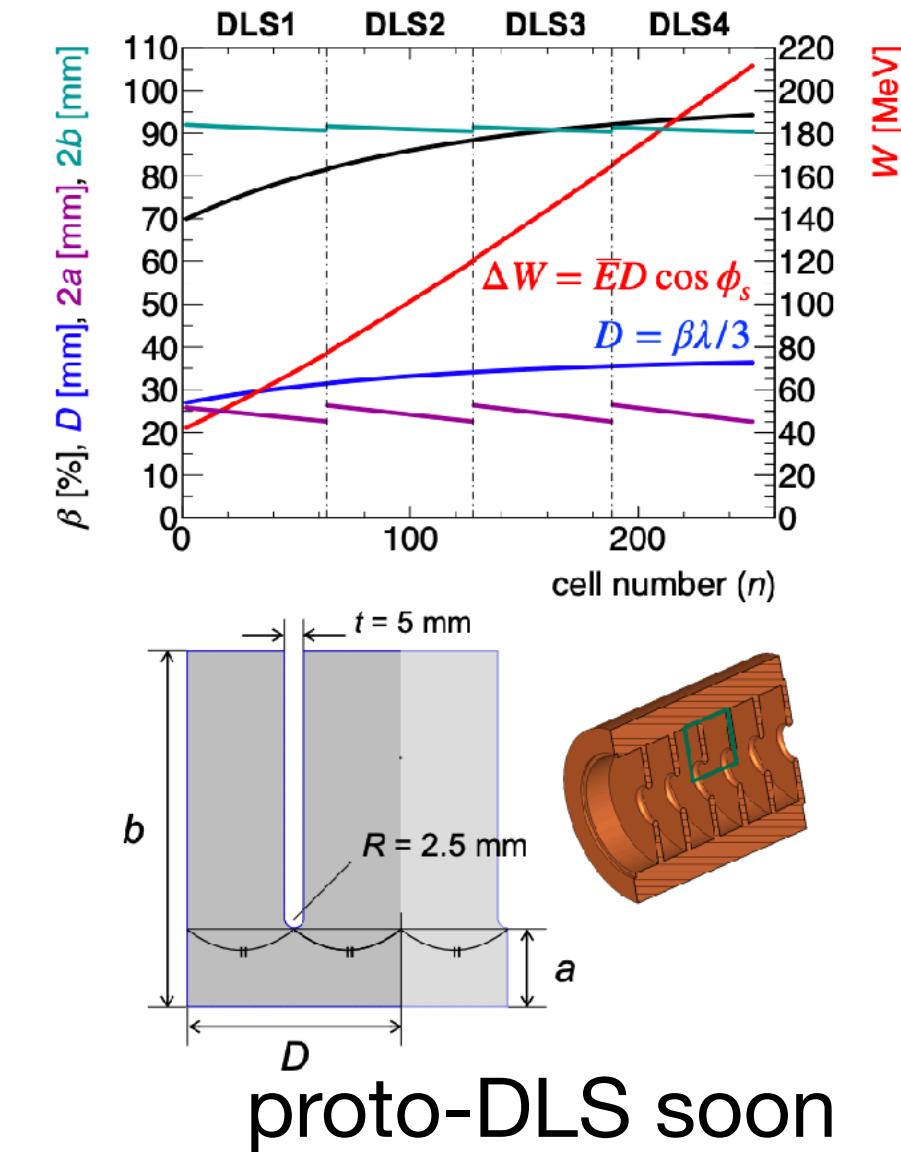
- Completed fabrication of the real IH-DTL
- Fabricating the 1st DAW tank & proto-DLS.



Real IH-DTL

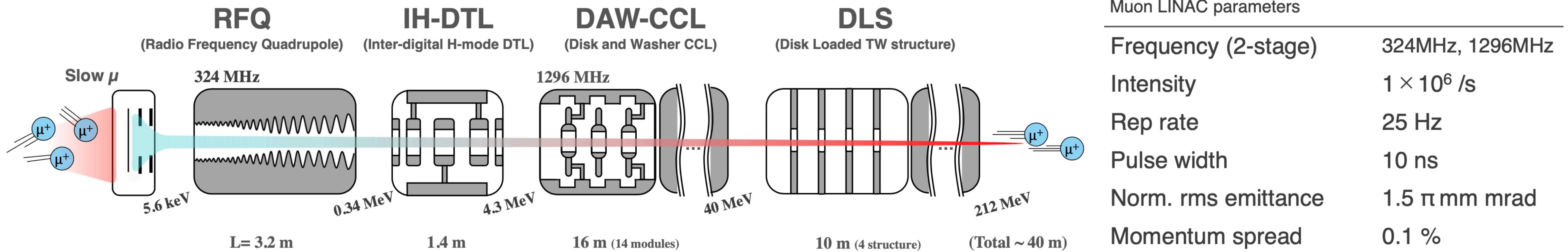


Real DAW in production



proto-DLS soon

Muon Acceleration



Muon acceleration for the muon g-2/EDM experiment at J-PARC

Aug 5, 2022, 11:15 AM | 25m | Magpie B

Talk | WG3: Accelerator P... | Joint Session

Speaker

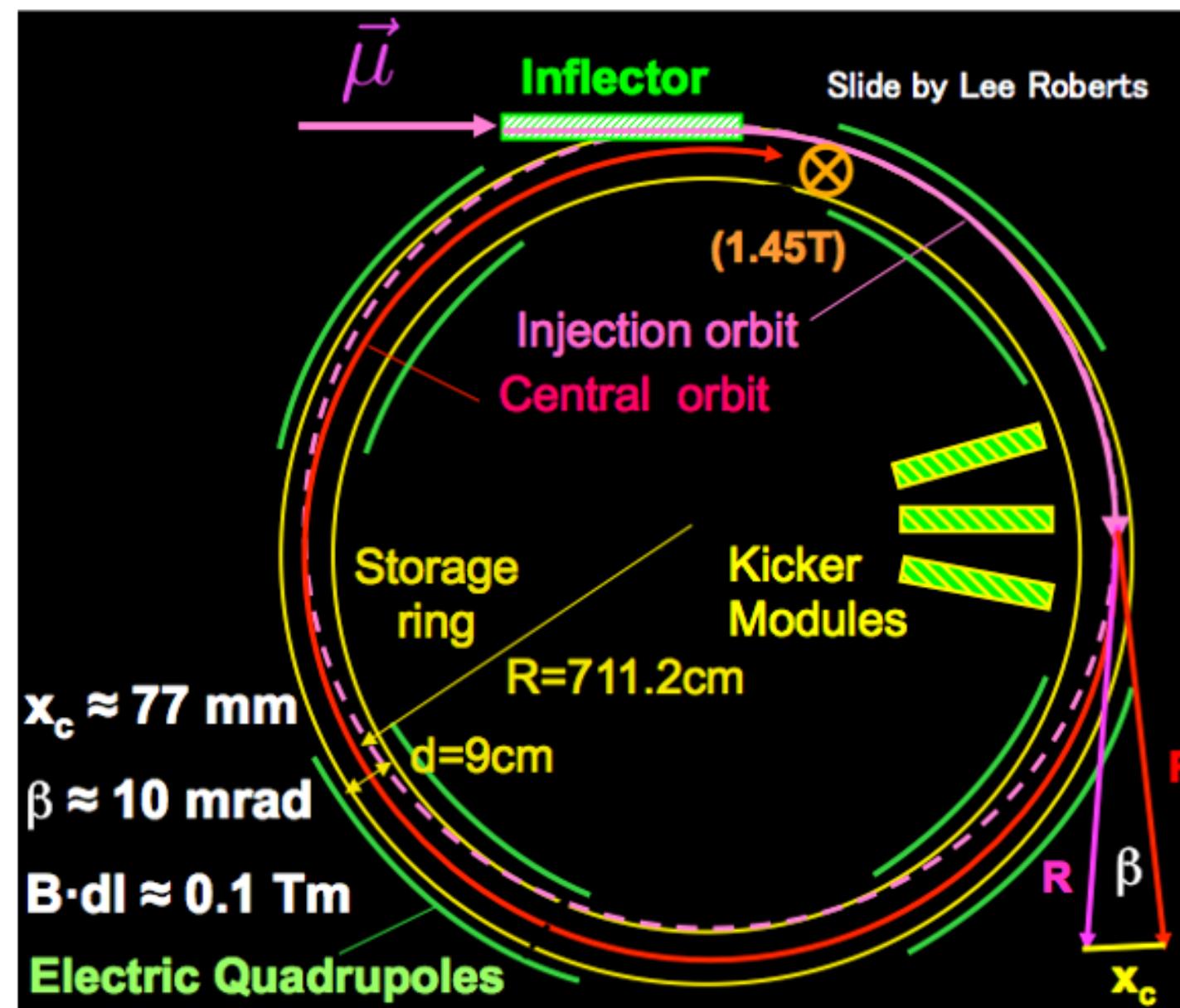
Yuga Nakazawa (Ibaraki University)

- Relevant talk on muon acceleration by Y. Nakazawa

3D Spiral Injection

Why inject beam 3D spirally?

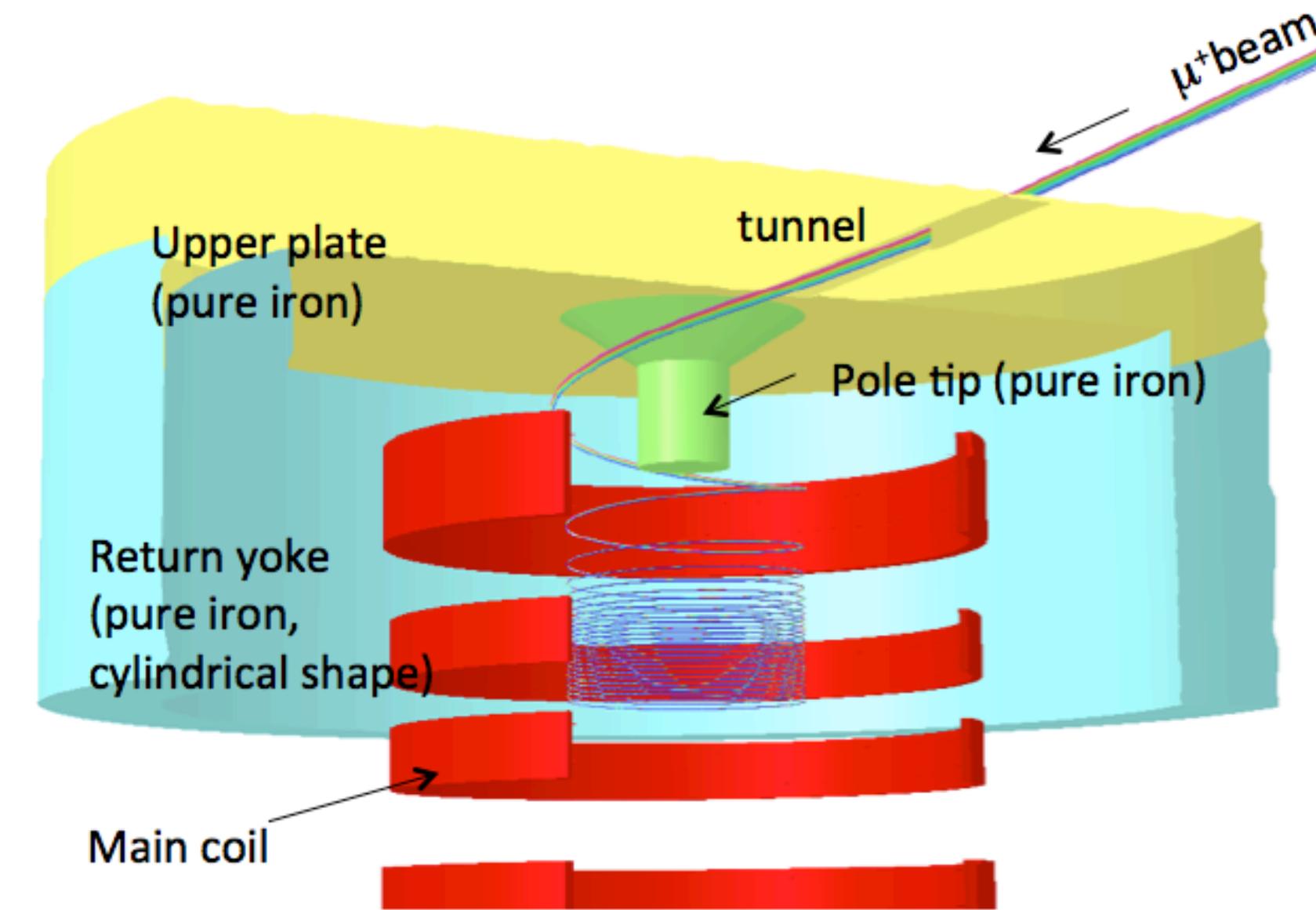
- The 3D spiral injection scheme has been invented for small muon orbit



Conventional 2D injection @BNL and FNAL

- Inflector + horizontal kicker
- Efficiency $\sim 3\text{-}5\%$

[PRD73, 072003, 2006]



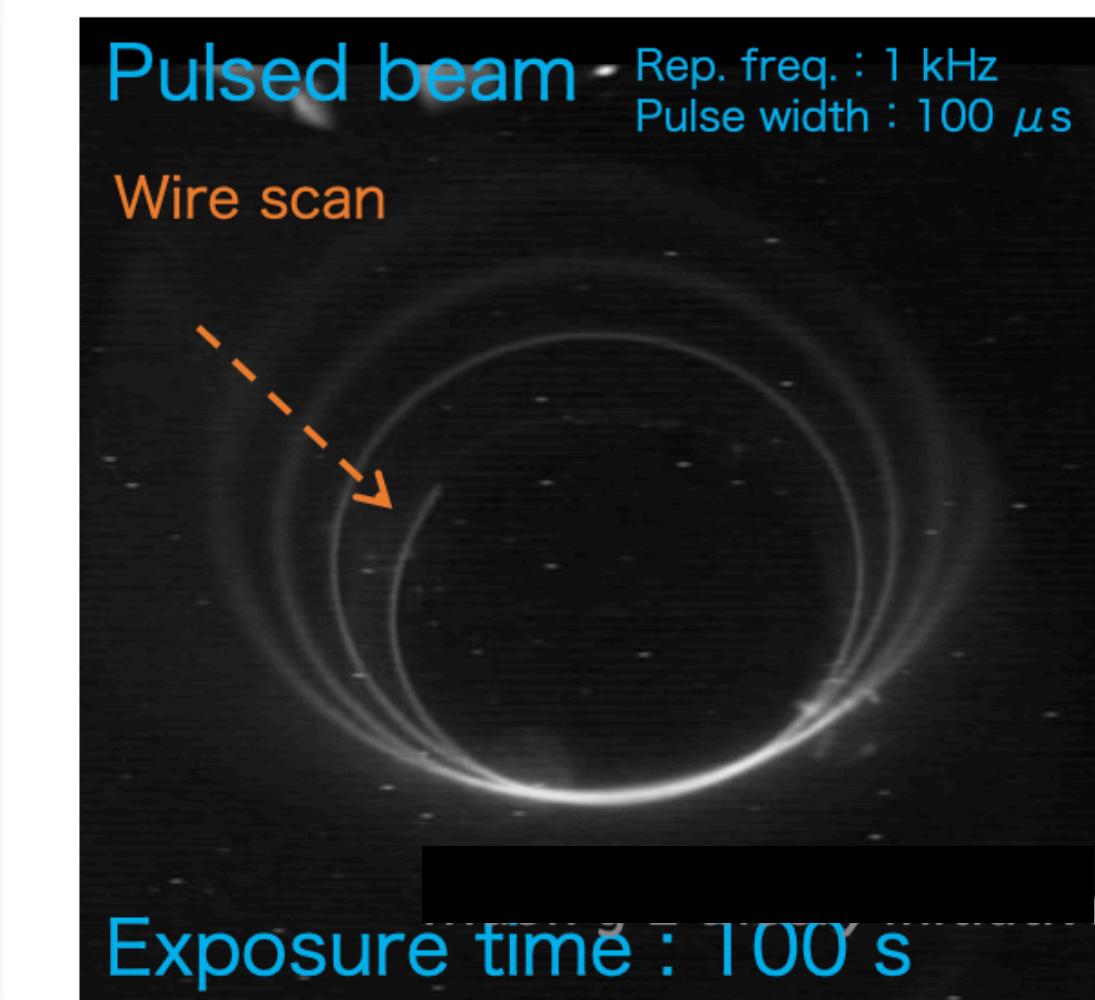
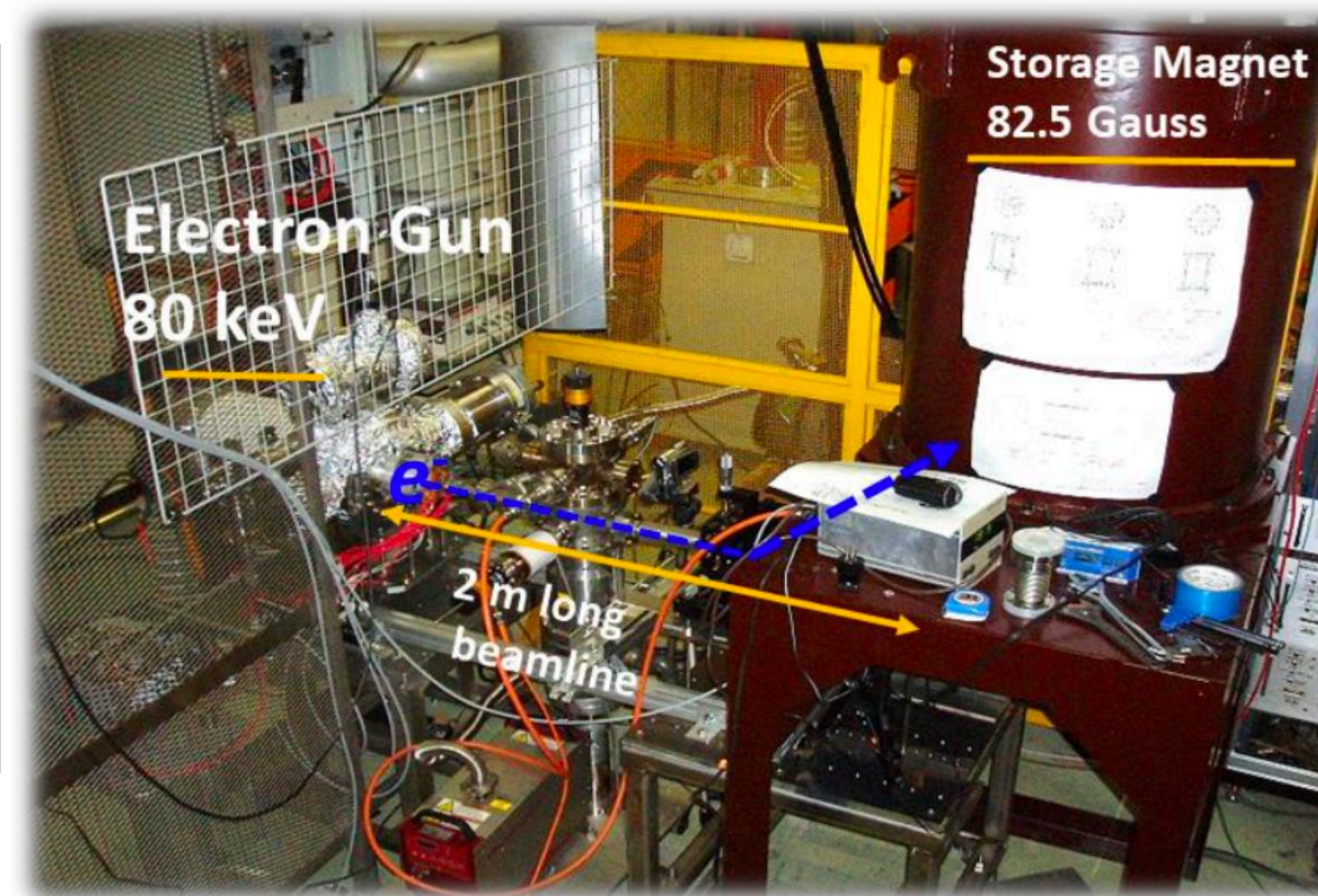
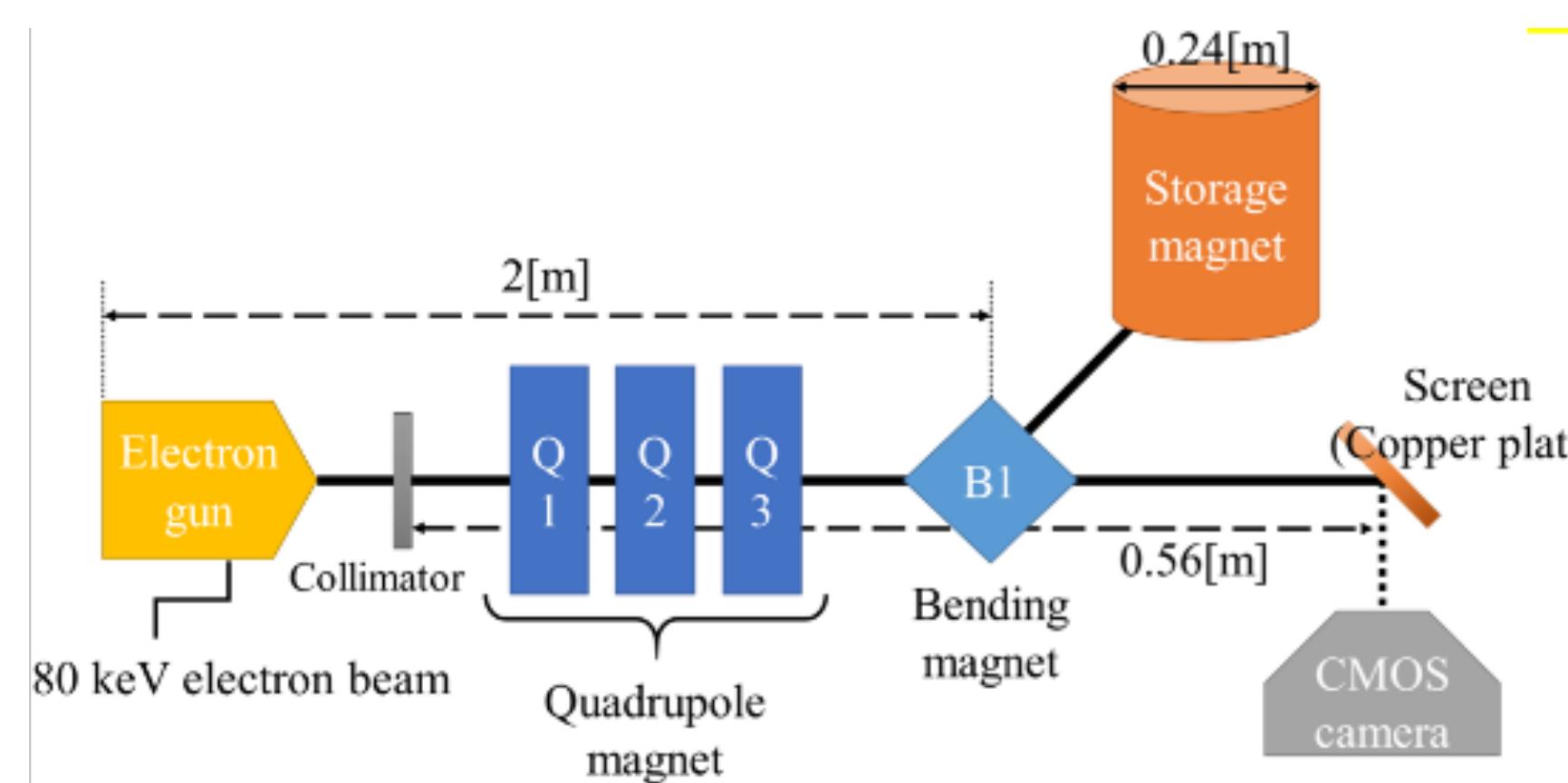
Novel injection @J-PARC

- 3D spiral injection + vertical kicker
- Efficiency $> 80\%$

[H. Iinuma et al., NIMA 832, 51, 2016]

3D Spiral Injection

- Prototypes of the kicker were fabricated, and the **3D injection scheme is validated** using a low momentum electron beam
- Injection and vertical kick for storage are being demonstrated using a pulsed electron beam
- Finalize kicker power supply specifications and purchase them in 2023

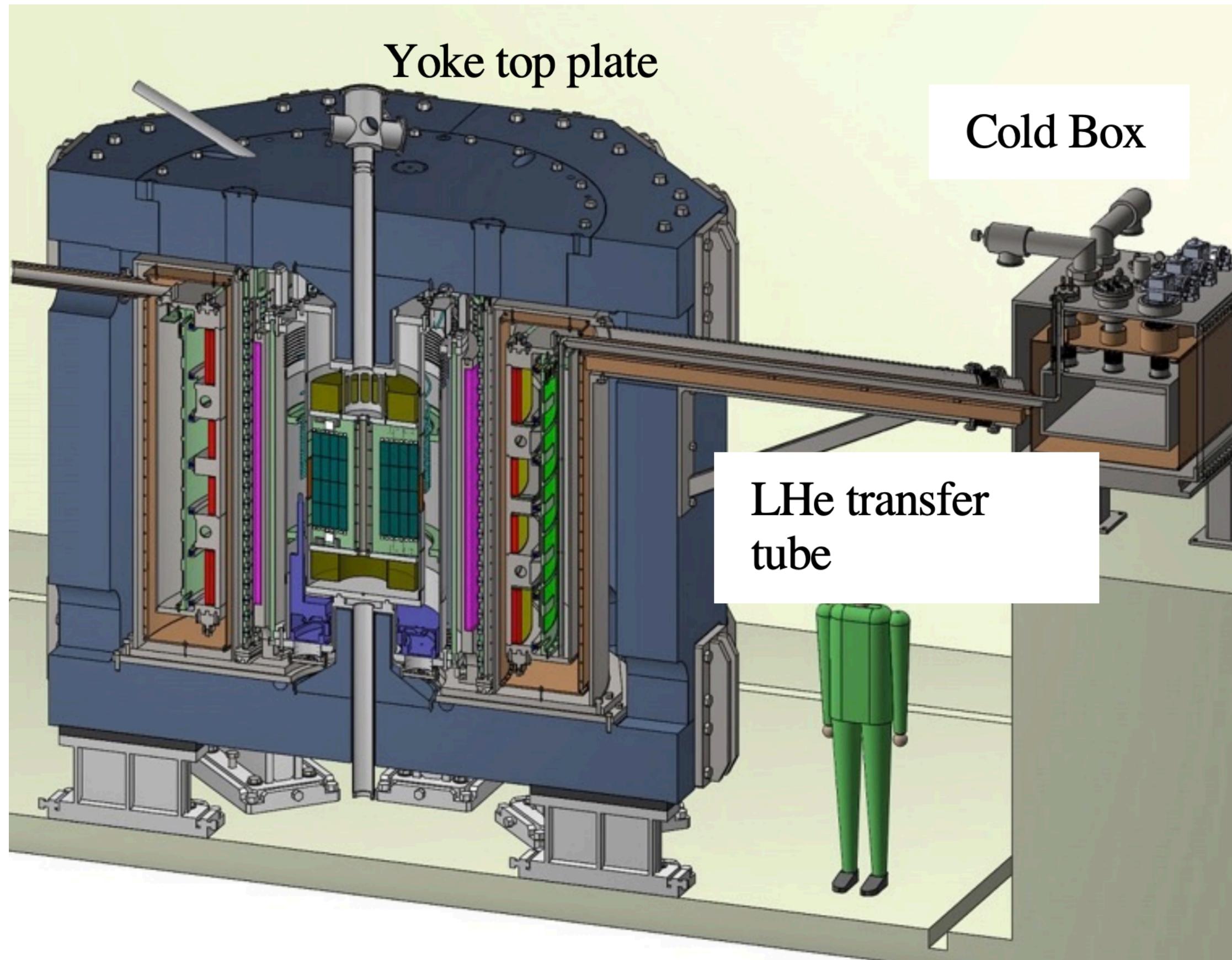


- Spiral injection test equipment using electron beam

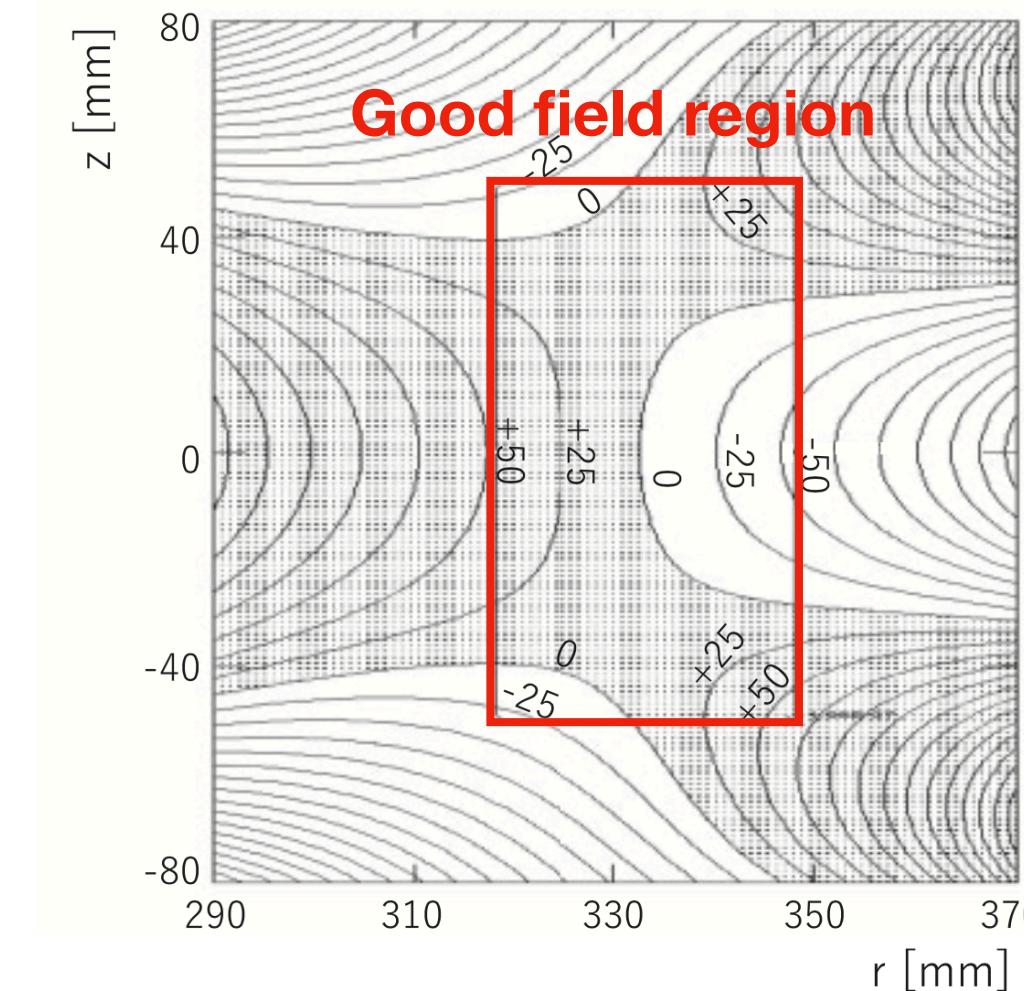
- visualization of 3D spiral geometry with a CCD camera

Storage Magnet

- 3T MRI-type superconducting solenoid magnet is under design



- ❖ Muon storage region:
 - radius : 33.3 ± 1.5 cm
 - height : ± 5 cm
 - Field strength : 3T
 - Uniformity : 0.1 ppm (Azimuthal integral)
- ❖ Injection region :
 - Smooth field for beam injection
- ❖ Weak focus field: $-5e-4$ T/m of Br at maximum



Average magnetic field uniformity is better than 100 ppb
25 ppb/line

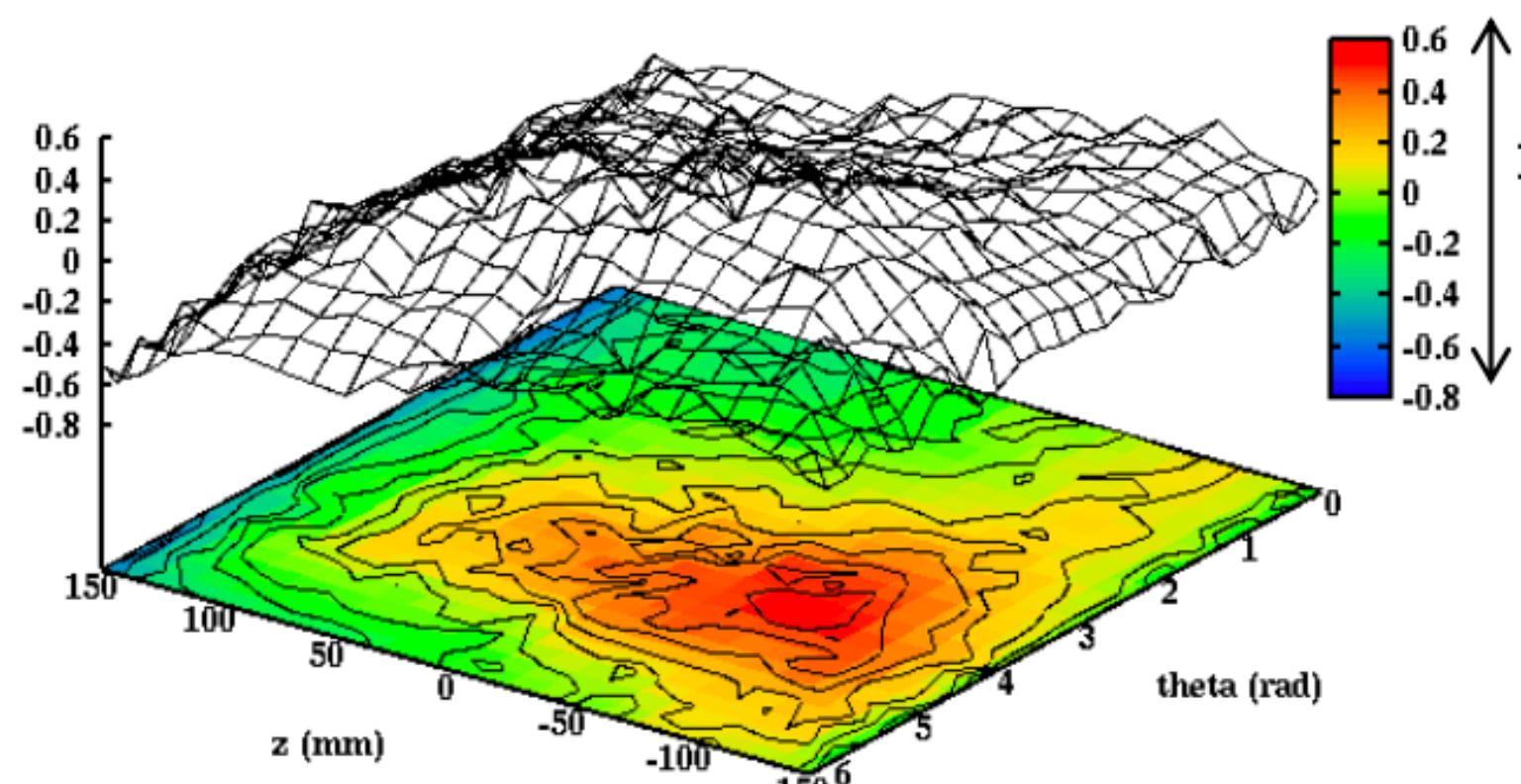
Storage Magnet

Magnetic field measurement

- Demonstration of sub-ppm field (<0.2 ppm) shimming at 1.2 T using magnet from MuSEUM (muonium hyperfine structure measurement), further tests will be carried out to 3T
- In the cross-calibration of FNAL and J-PARC field probes at ANL, ~7 ppb agreement was obtained with 15 ppb uncertainties.



MRI magnet for MuSEUM experiment

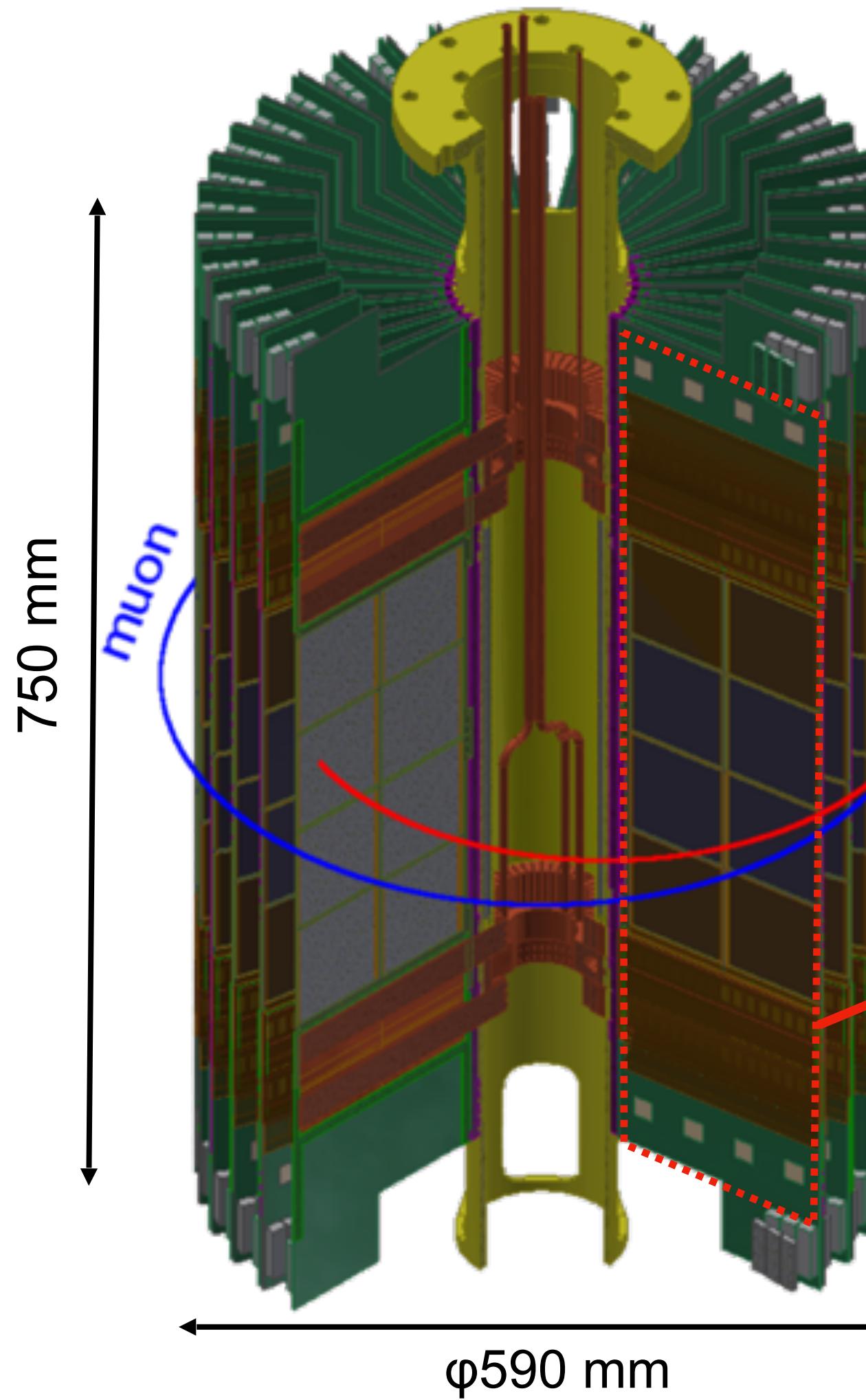


Magnetic field after shimming

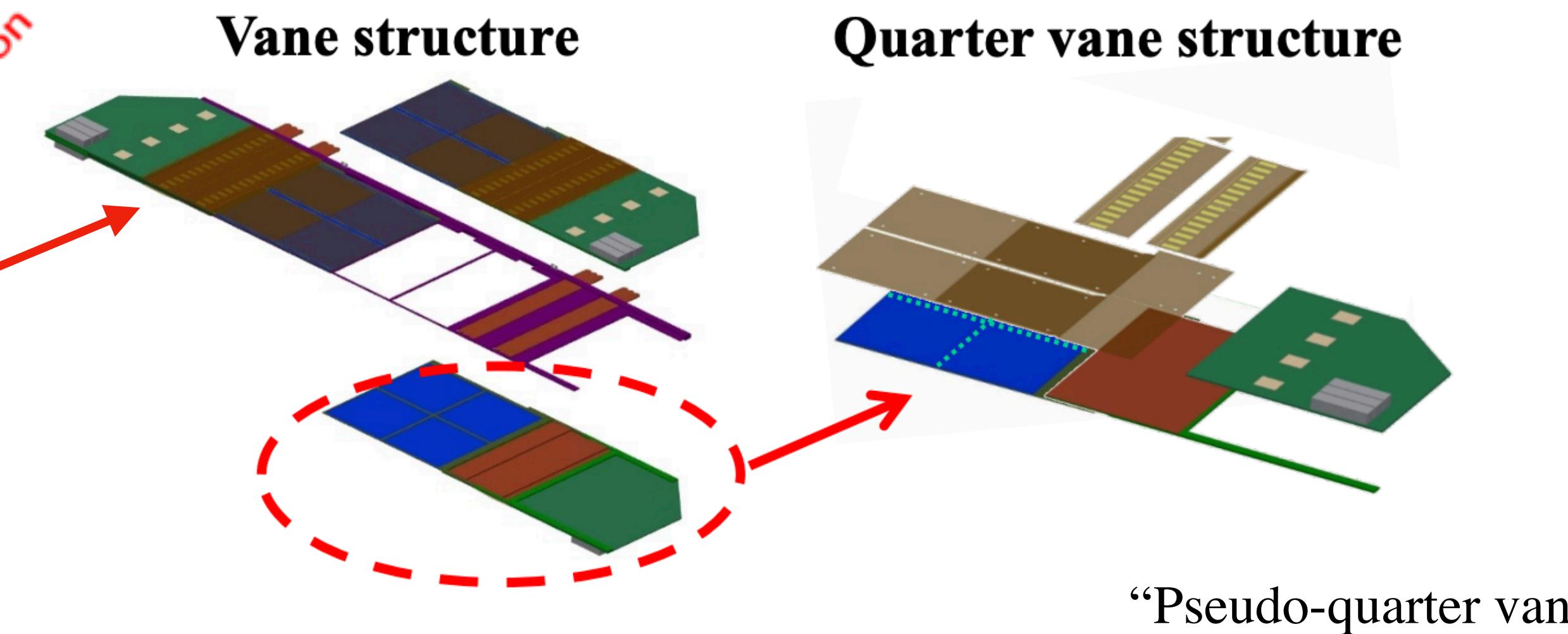


Cross calibration at ANL in January 2019

Positron Tracking Detector

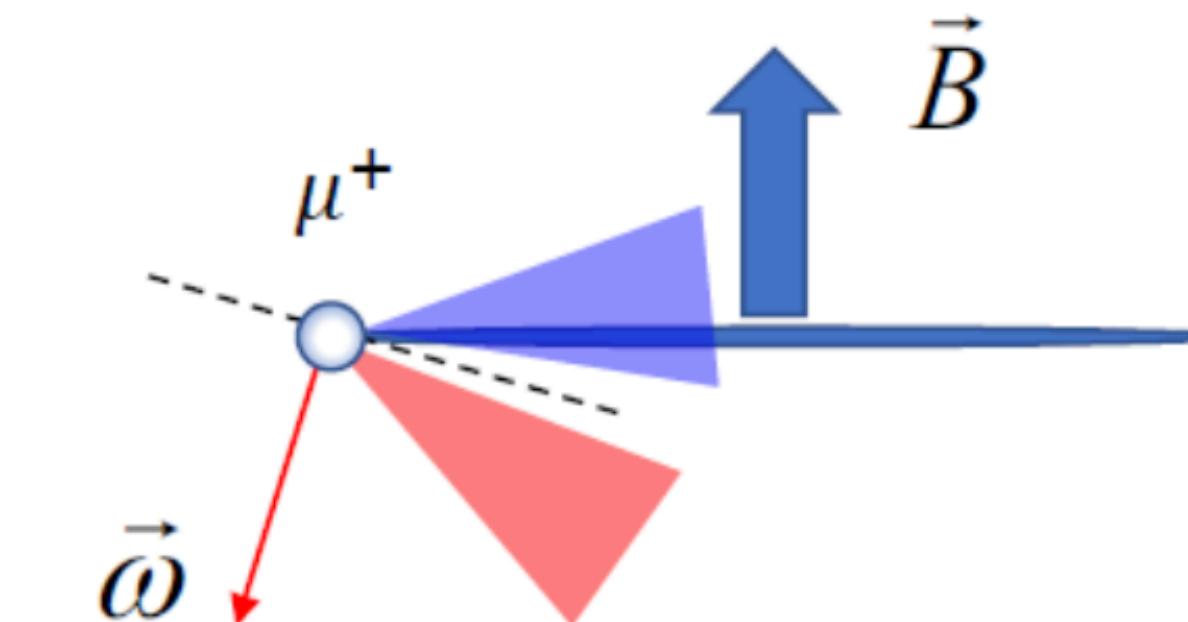
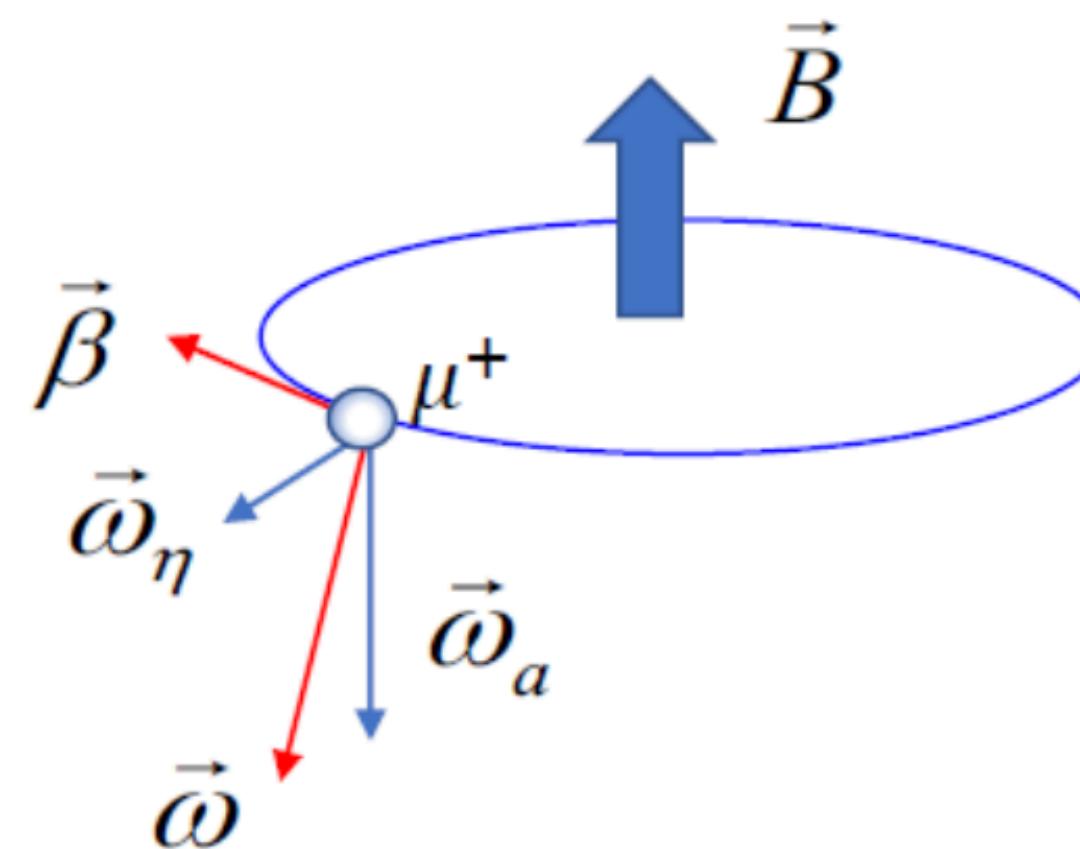


- Reconstruct positron track and precisely measure the decay time of muon.
- Consists of 40 radial rectangle modules (Vane). A quarter vane consists of 4 silicon sensors + 32 readouts ASICs.
- Two prototypes were fabricated & tested. Mass production of detector components is ongoing.



EDM Measurement

- EDM measurement relies on the tilt of muon precession to the mid plane.



- No E-field simplifies the measurement for J-PARC.

$$\vec{\omega} = -\frac{e}{m} \left[a_\mu \vec{B} + \boxed{\frac{\eta}{2} \left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right)} \right]$$

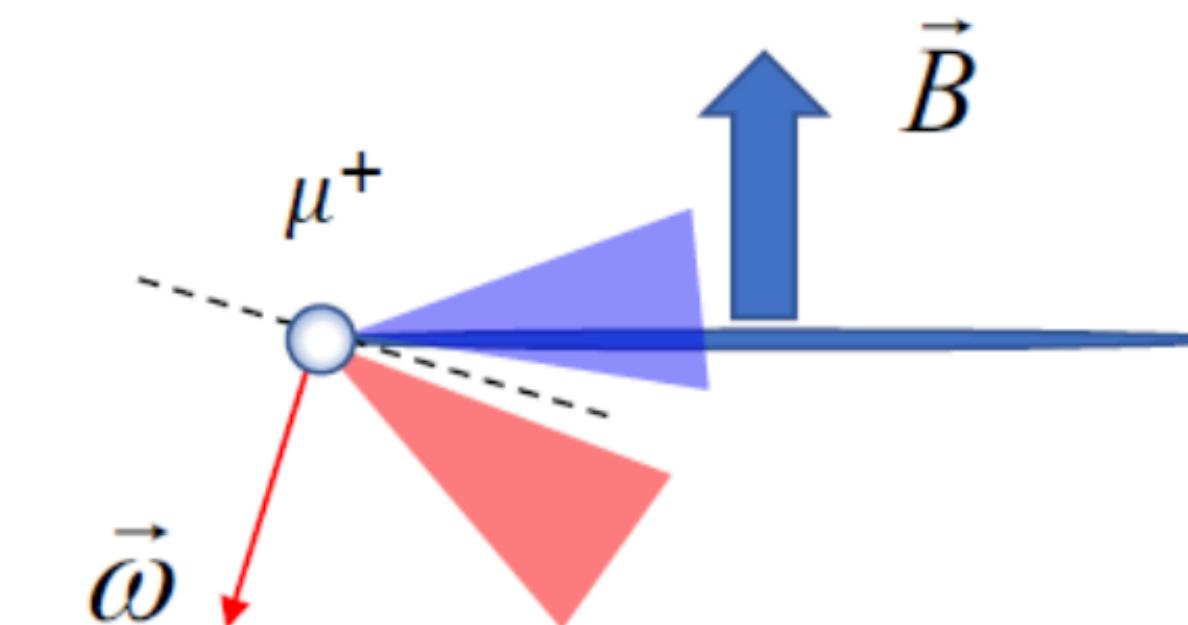
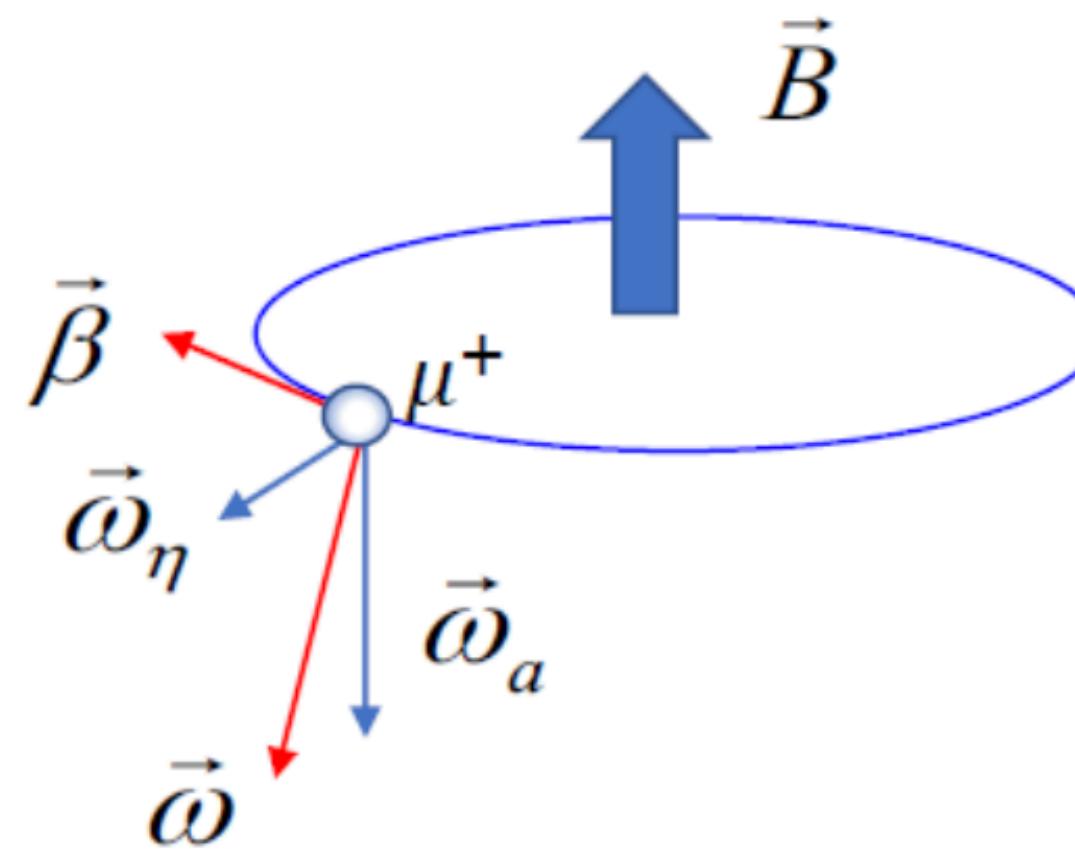
FNAL E989
(at magic γ)

$$\vec{\omega} = -\frac{e}{m} \left[a_\mu \vec{B} + \boxed{\frac{\eta}{2} (\vec{\beta} \times \vec{B})} \right]$$

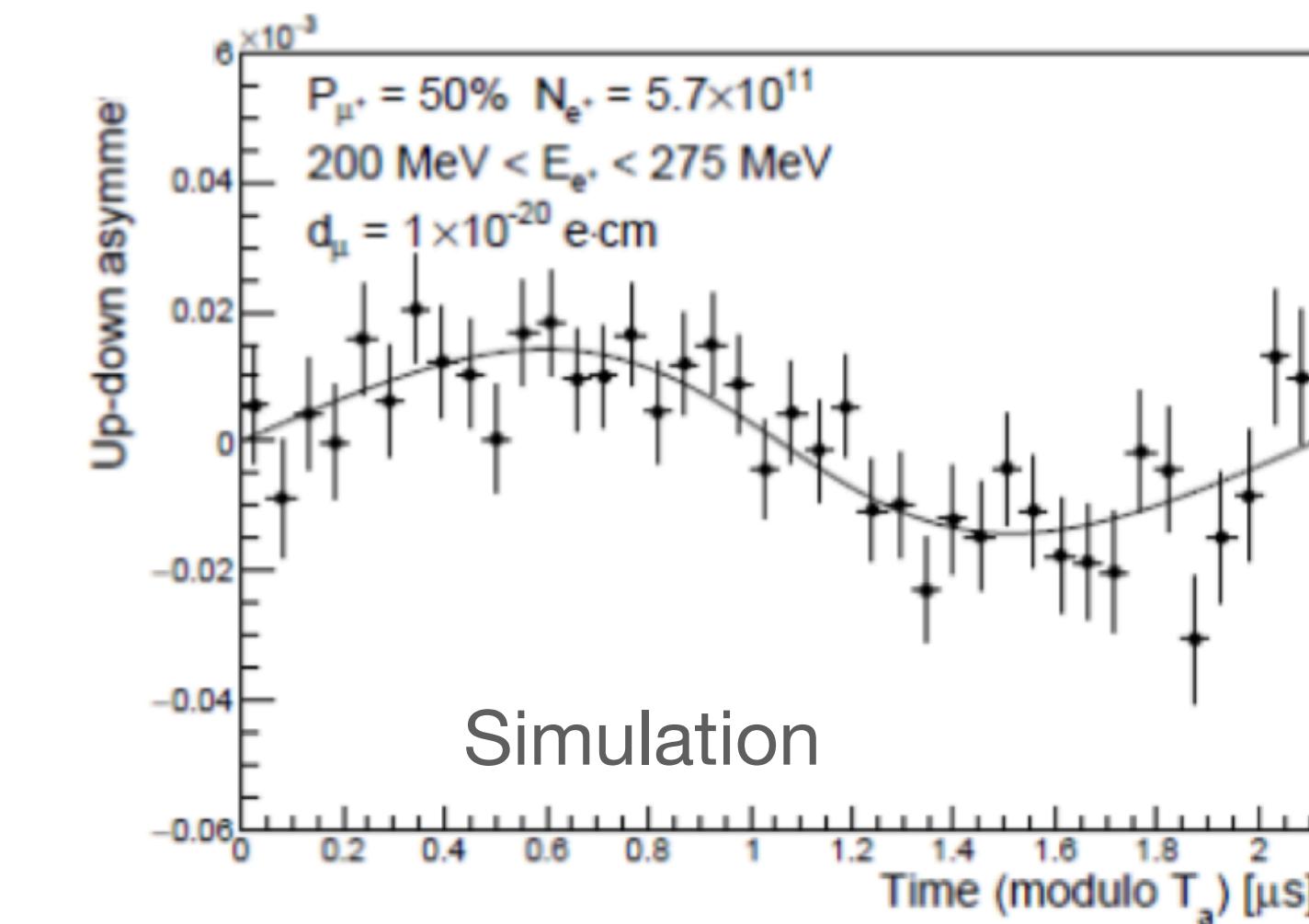
J-PARC E34
($E = 0$ at any γ)

EDM Measurement

- EDM measurement relies on the tilt of muon precession to the mid plane



- Observed in up-down asymmetry
- $\omega_\eta/\omega_a \sim (\eta\beta/2a_\mu)$
- Good detector alignment precision is essential
- aim at **10⁻²¹ e cm sensitivity (10⁻⁵ rad)**
- 1 μ m detector alignment measurement is developed



Statistics Estimation

- Initially, a **$3.2 \times 10^8 \mu/\text{sec}$** is expected at the entrance of the H2 area at 1 MW proton power.
- The expected intensity of stored muon is **$1.3 \times 10^5 \mu/\text{sec}$** . Cumulative efficiency from thermal muon generation to reconstructed positron is 8.1×10^{-5} .
- 2-year data (2×10^7 seconds, ~230 days) taking will give a total positron 5.7×10^{11} , achieving the BNL precision of **450 ppb** on a_μ .

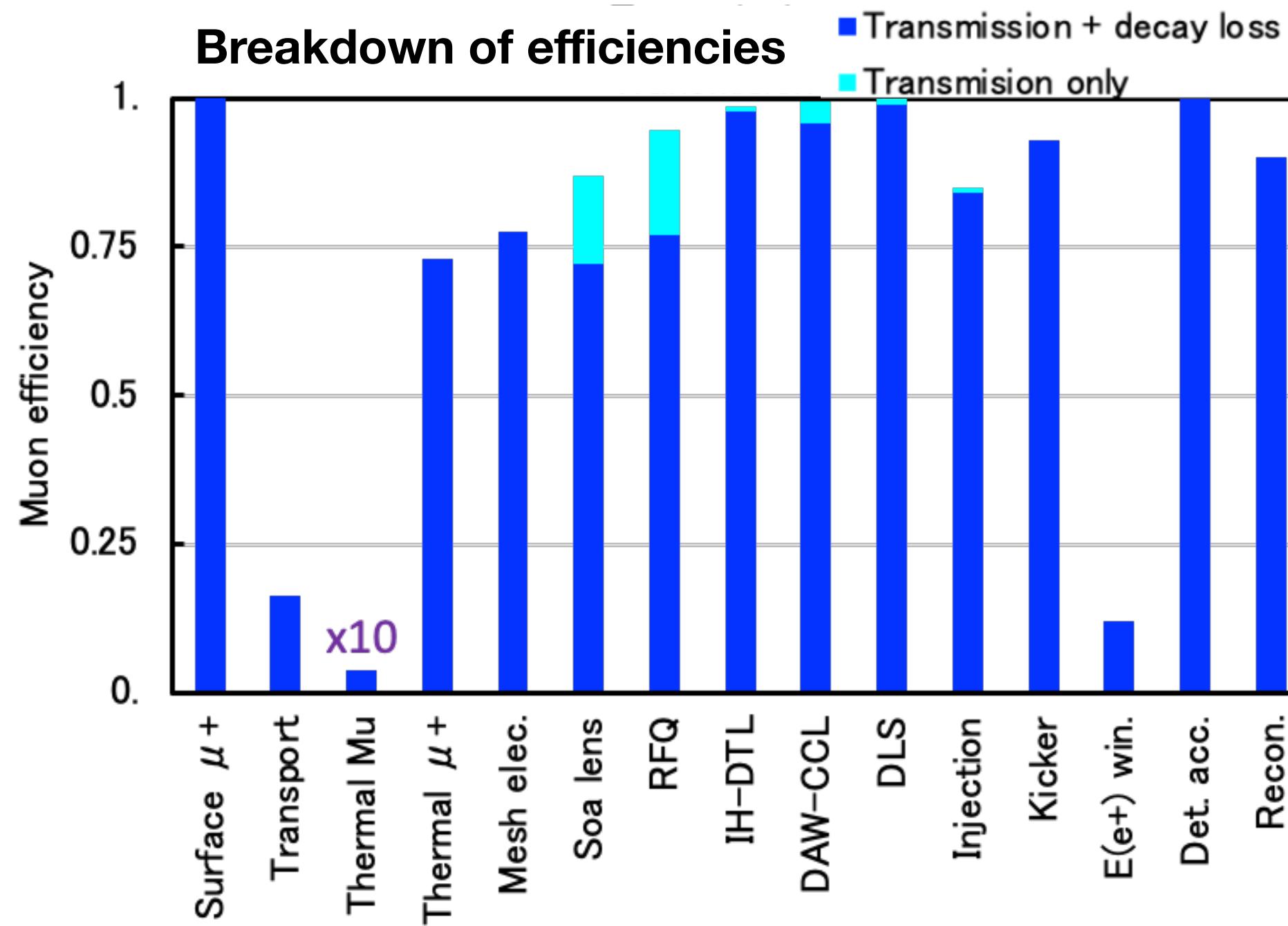


Table 5. Summary of statistics and uncertainties.

	Estimation
Total number of muons in the storage magnet	5.2×10^{12}
Total number of reconstructed e^+ in the energy window [200, 275 MeV]	5.7×10^{11}
Effective analyzing power	0.42
Statistical uncertainty on ω_a [ppb]	450
Uncertainties on a_μ [ppb]	450 (stat.)
< 70 (syst.)	
Uncertainties on EDM [$10^{-21} e\cdot\text{cm}$]	1.5 (stat.)
	0.36 (syst.)

Systematic Uncertainties of a_μ

- Systematic uncertainties will be much smaller than the statistical ones.

Table 6. Estimated systematic uncertainties on a_μ .

Anomalous spin precession (ω_a)		Magnetic field (ω_p)	
Source	Estimation (ppb)	Source	Estimation (ppb)
Timing shift	< 36	Absolute calibration	25
Pitch effect	13	Calibration of mapping probe	20
Electric field	10	Position of mapping probe	45
Delayed positrons	0.8	Field decay	< 10
Differential decay	1.5	Eddy current from kicker	0.1
Quadratic sum	< 40	Quadratic sum	56

$$\delta a_\mu \text{ (syst.)} < 70 \text{ ppb}$$

Precision Comparison

J-PARC E34

	BNL-E821	Fermilab-E989	Our Experiment
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz γ	29.3		3
Polarization	100%		50%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric quadrupole		Very weak magnetic
Cyclotron period	149 ns		7.4 ns
Spin precession period	4.37 μ s		2.11 μ s
Number of detected e^+	5.0×10^9	1.6×10^{11}	5.7×10^{11}
Number of detected e^-	3.6×10^9	—	—
a_μ precision (stat.)	460 ppb	100 ppb	450 ppb (Phase-1)
(syst.)	280 ppb	100 ppb	<70 ppb
EDM precision (stat.)	$0.2 \times 10^{-19} e \cdot \text{cm}$	—	$1.5 \times 10^{-21} e \cdot \text{cm}$
(syst.)	$0.9 \times 10^{-19} e \cdot \text{cm}$	—	$0.36 \times 10^{-21} e \cdot \text{cm}$

Schedule

- A part of the construction has been started.
- The R&D stage is OVER. Construction is ongoing aiming at data taking from 2027.

JFY	2021	2022	2023	2024	2025	2026	2027
H2 area			Shields Magnets				
H-line experimental building				Building construction			
Muon Source, LINAC, injection, storage magnet, detector					Installation		
Grant-in-Aids		Kakanhi “specially promoted research”				Commissioning	Data taking

Collaboration Status

- Now the collaboration consists of 110 members from 9 countries and still growing



Date	Events
Dec. 2017	Responses and revised TDR were submitted to review committee.
Mar. 2019	KEK-SAC endorsed the E34 for the near-term priority.
May 2019	Summary paper of TDR was published (PTEP 2019 (2019), 053C02)
July 2020	Funded by KAKENHI “Specially Promoted Research” by JSPS
Jun. 2021	KEK requested a funding to Japanese government (MEXT), then MEXT requested to MOF.



24th Collaboration Meeting in June 2022@Online/J-PARC

Summary

- J-PARC E34 experiment will measure muon $g - 2$ /EDM in a different approach than BNL and FNAL.
 - A thermal muon beam enables muon beam focusing without an electric field.
 - The muon beam is accelerated by muon LINAC and 3D injected into the compact storage region with a highly uniform magnetic field.
 - The tracking detector reduces pile-up and is able to measure the momentum direction of positrons.
- 0.4 ppm of a_μ measurement will be achieved with 2 years of data taking.
- We are moving from the development stage to the construction stage. Construction is ongoing aiming at the start of the data taking in 2027.

