Muon $g-2$/EDM Experiment at J-PARC

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on behalf of the J-PARC E34 Collaboration

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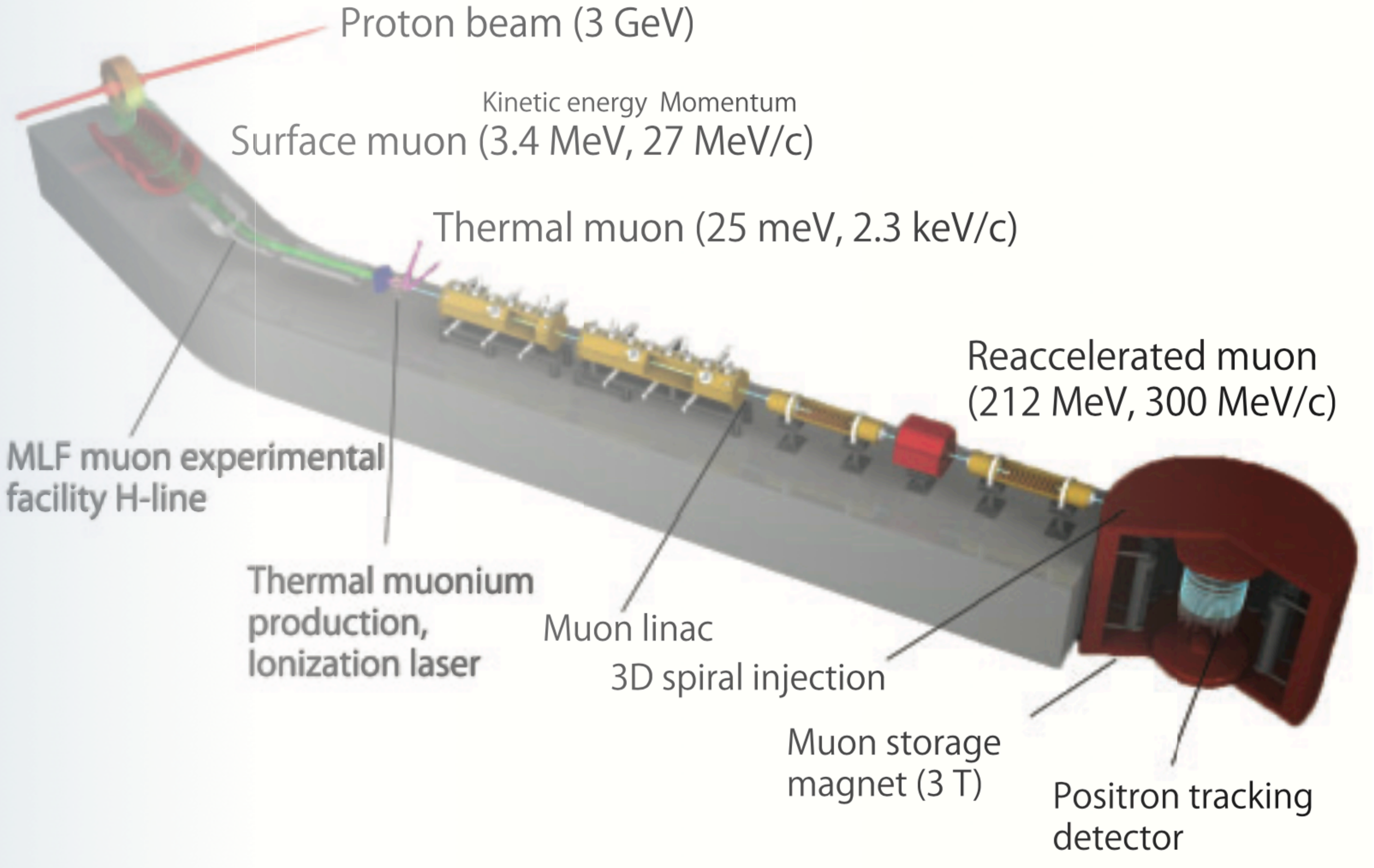
PHIPSI 2022



Muon $g-2$/EDM Experiment at J-PARC

- **Introduction**
  - Muon $g-2$ and EDM
  - Measurements and SM prediction
- **Muon $g-2$/EDM (E34) Experiment at J-PARC**
  - Experimental Components
  - Statistical 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

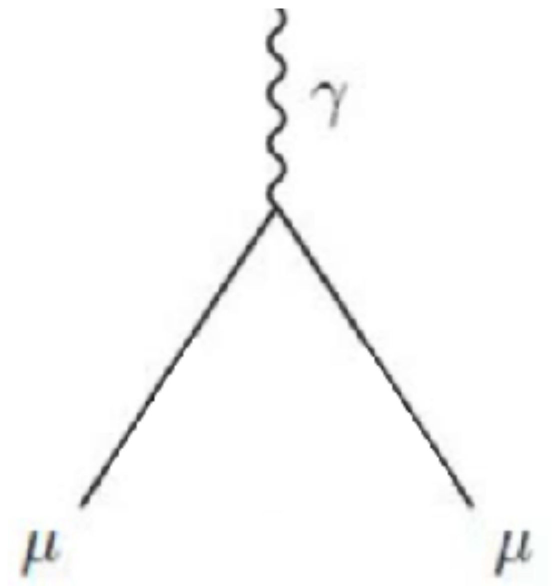
$$\vec{\mu} = g\frac{e\hbar}{2m}\vec{S}$$

Electric dipole moment

$$\vec{d} = \eta\frac{e\hbar}{2m}\vec{S}$$

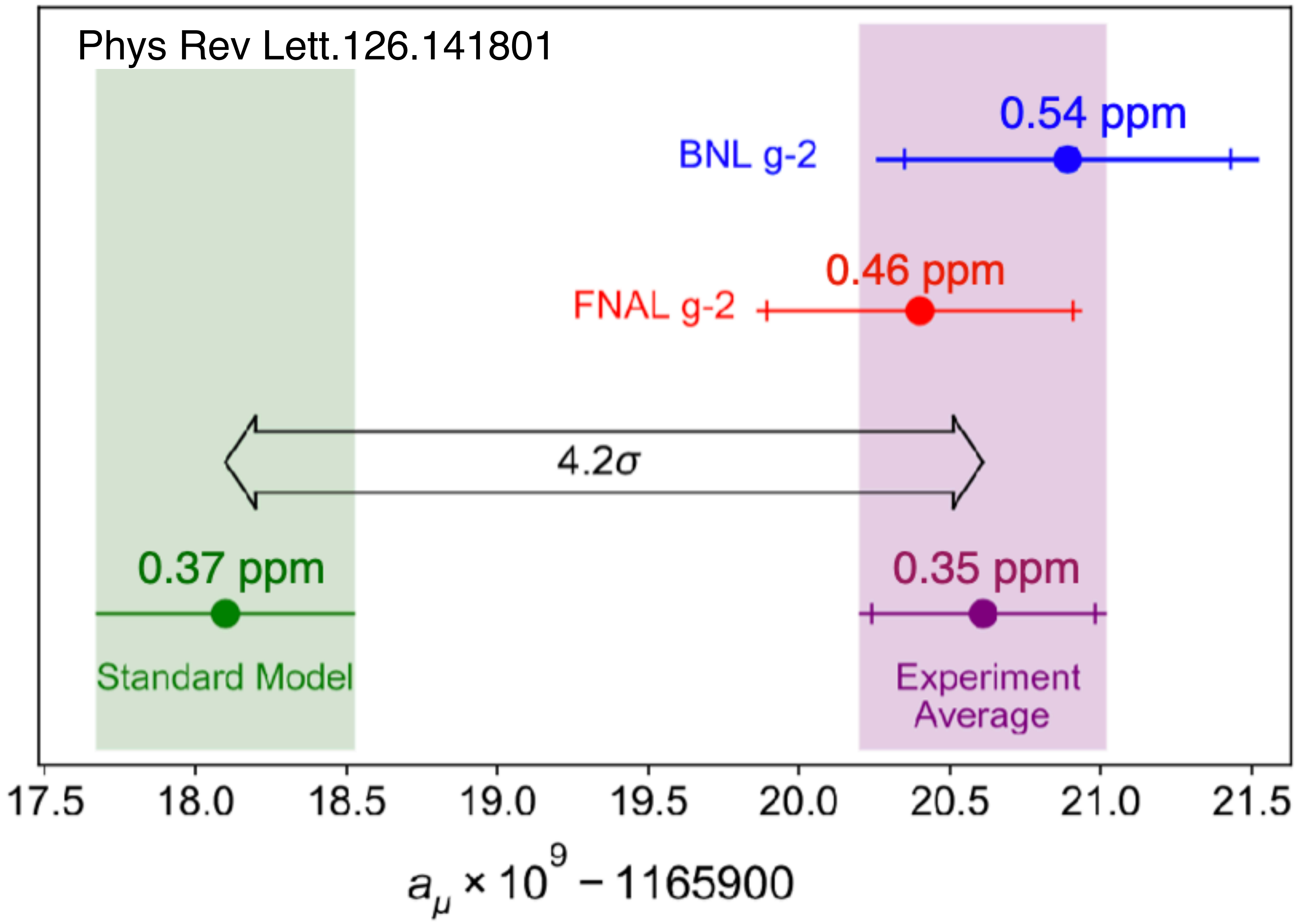
- $\vec{\mu}$ is proportional to the gyromagnetic ratio (g), which was predicted $g = 2$ by the Dirac equation.
- But quantum fluctuations give **the anomaly of muon** a_μ:

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



Measurements and SM prediction

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



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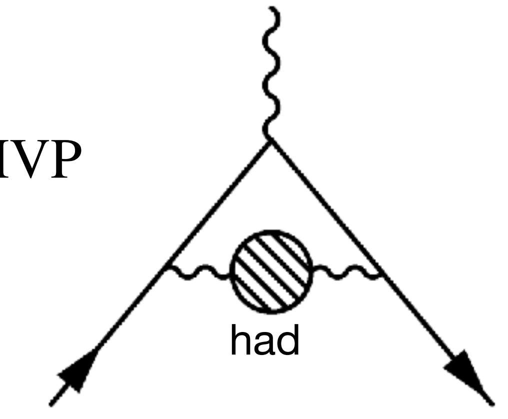
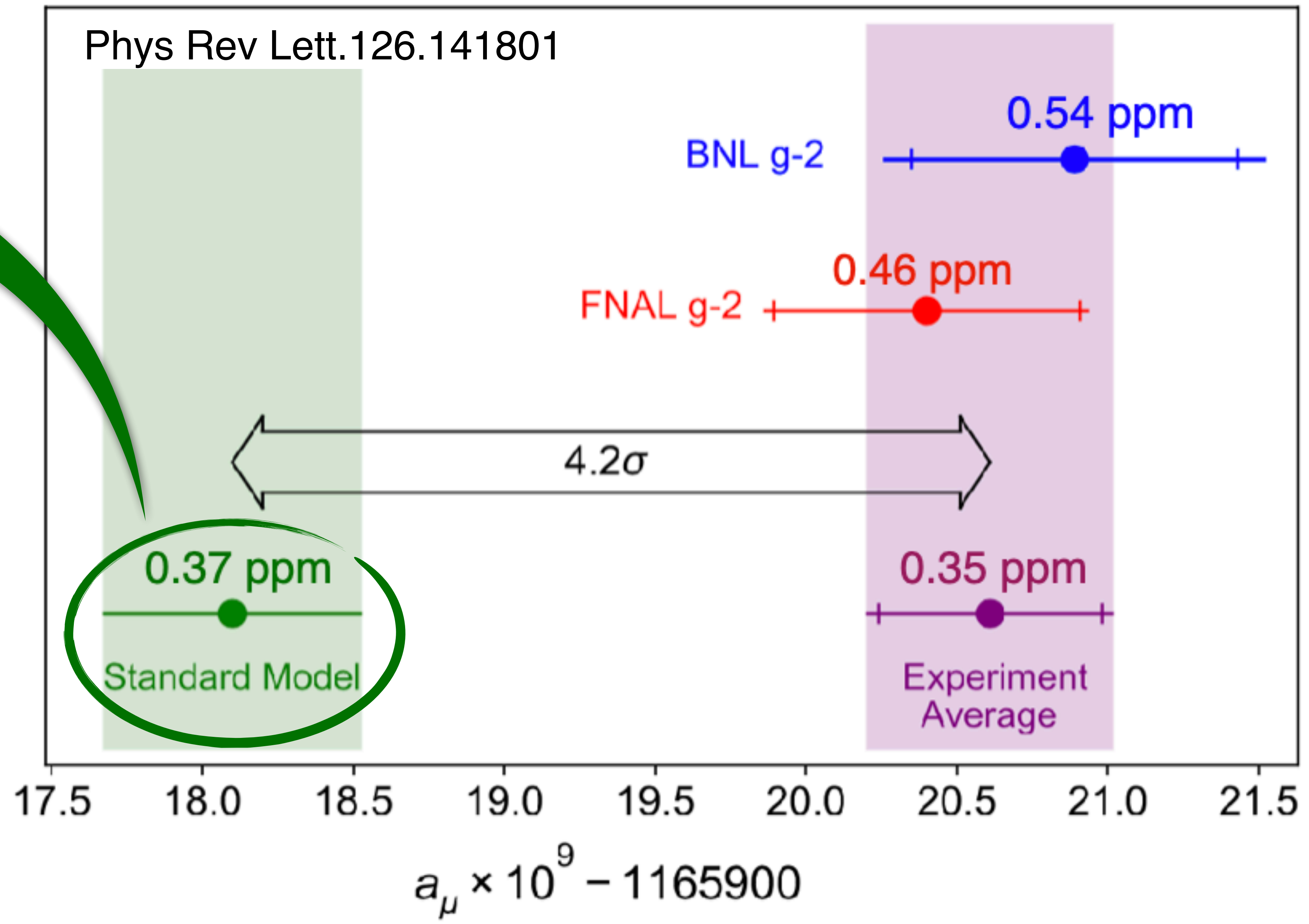
$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + \underline{a_\mu^{\text{Had}}} + a_\mu^{\text{EW}}$$

a_μ^{HVP}





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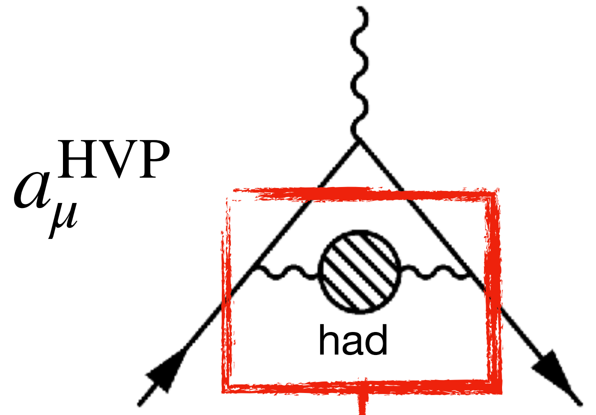
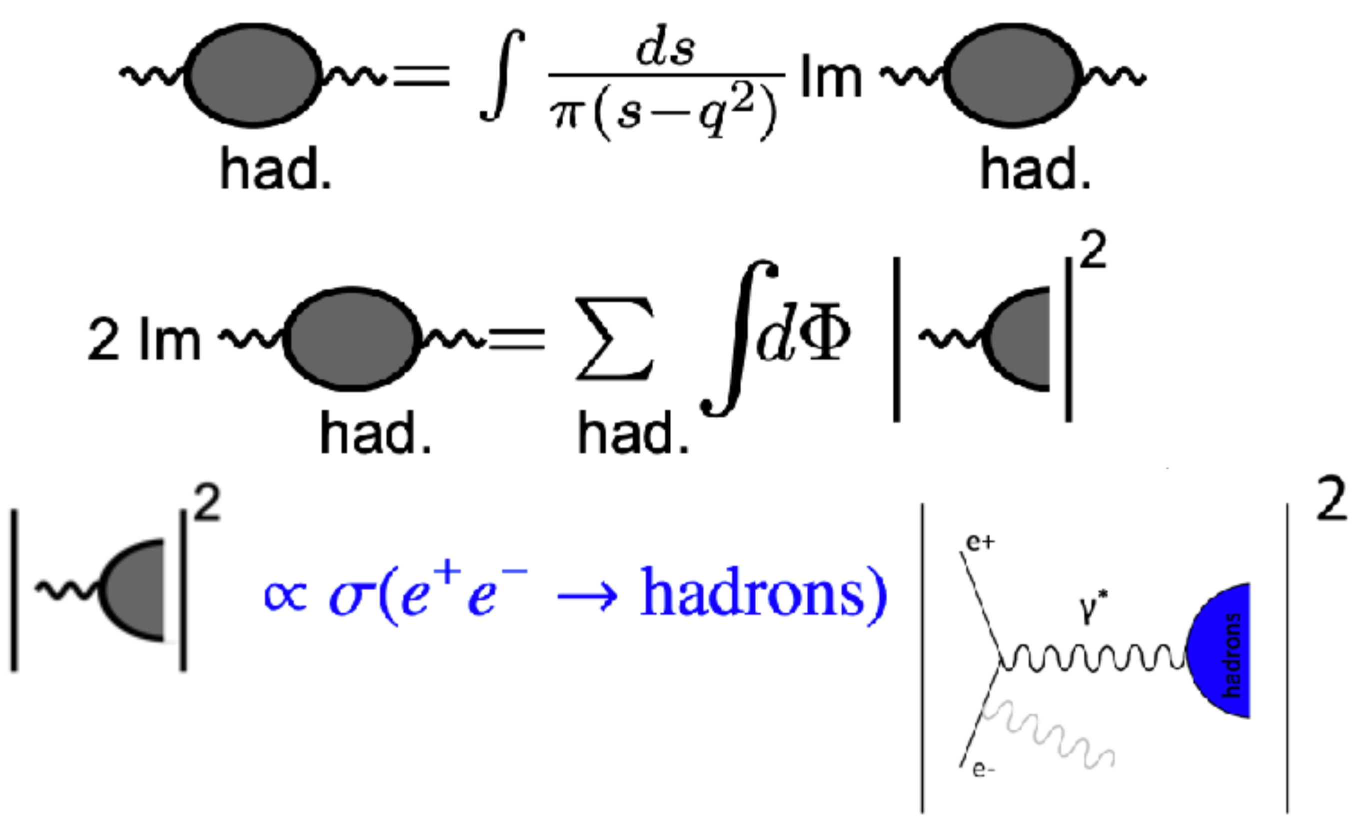
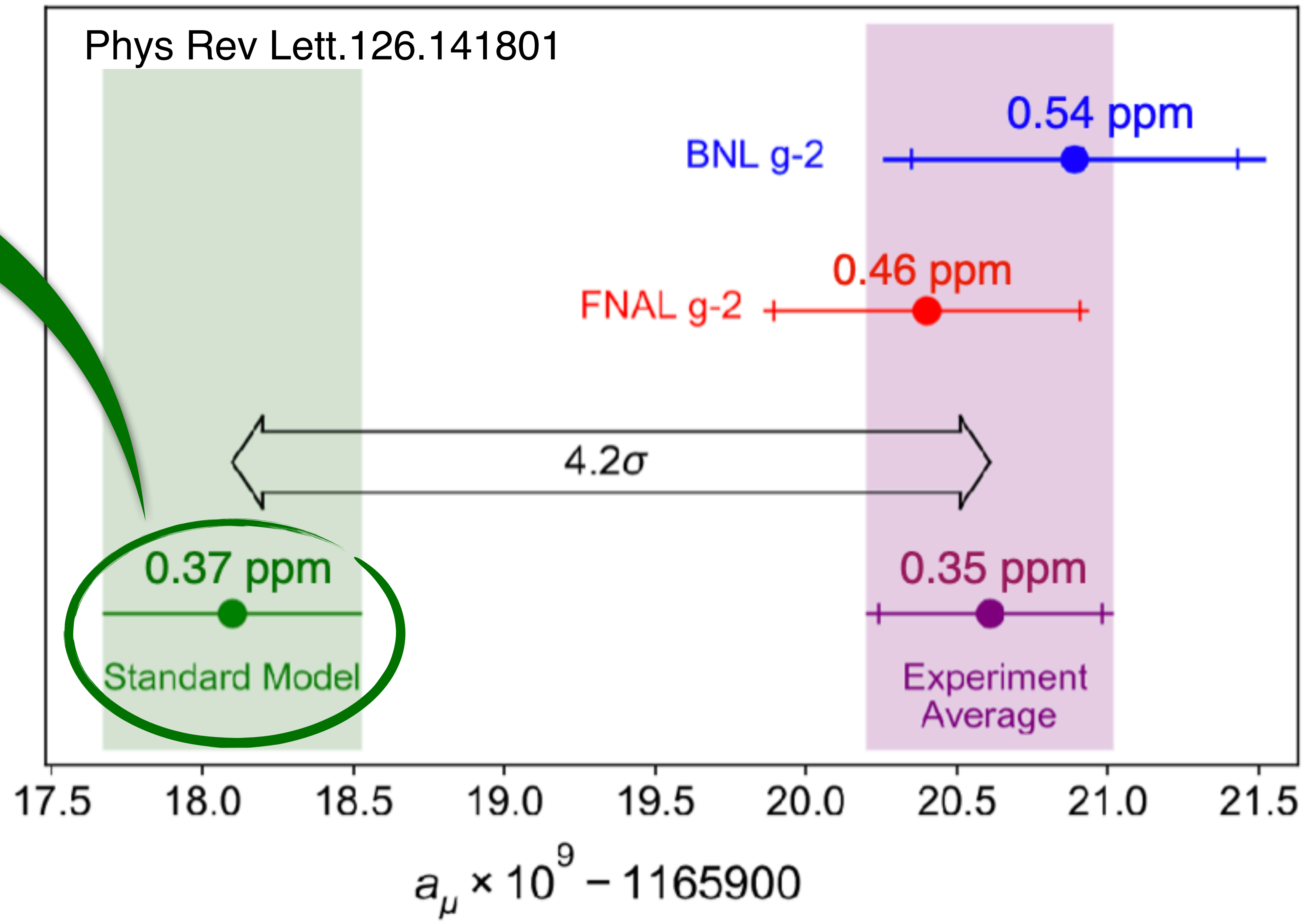


Dispersion relation and optical theorem





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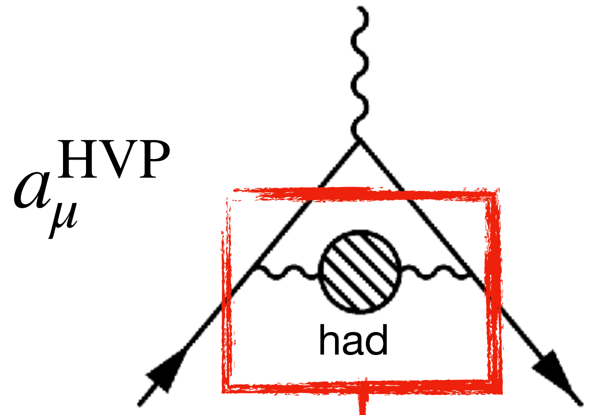

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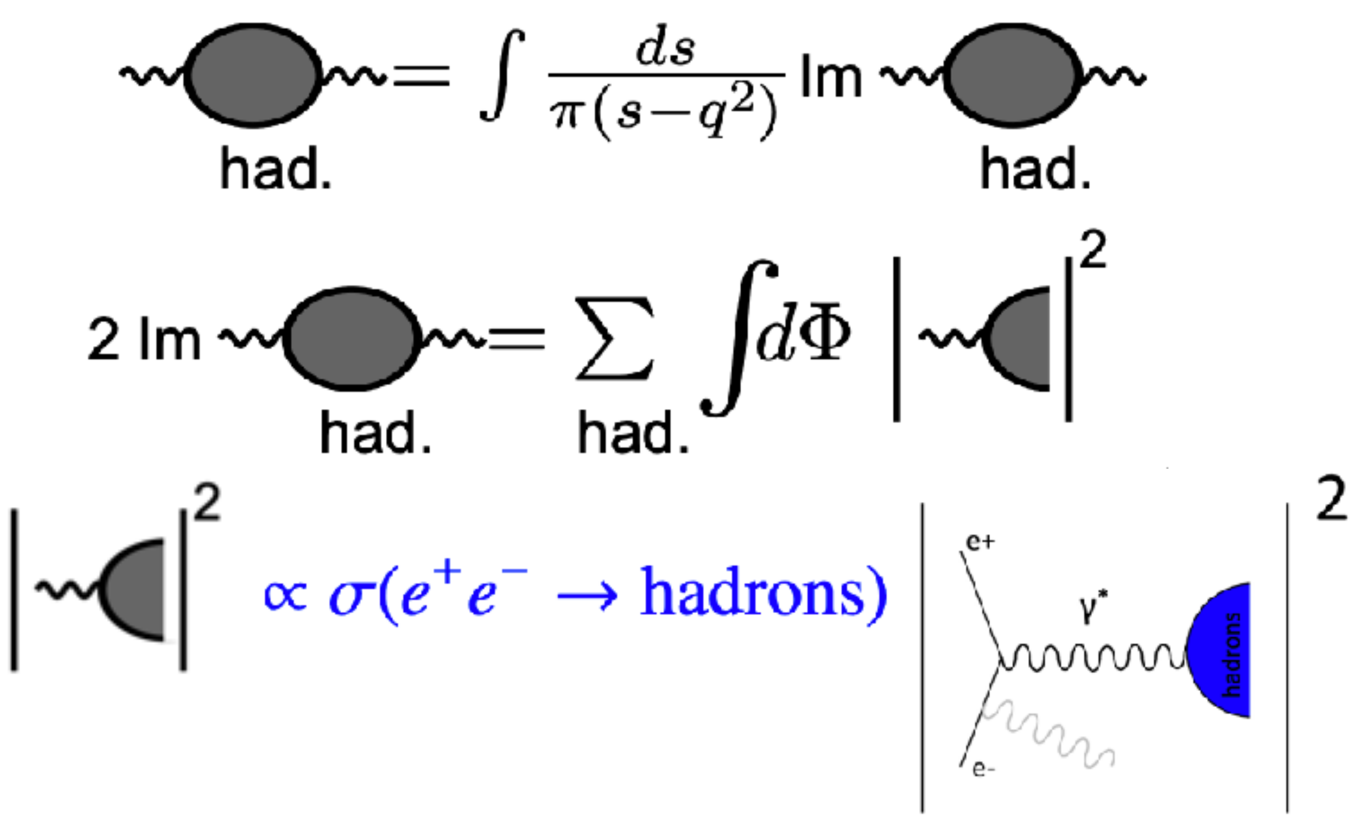

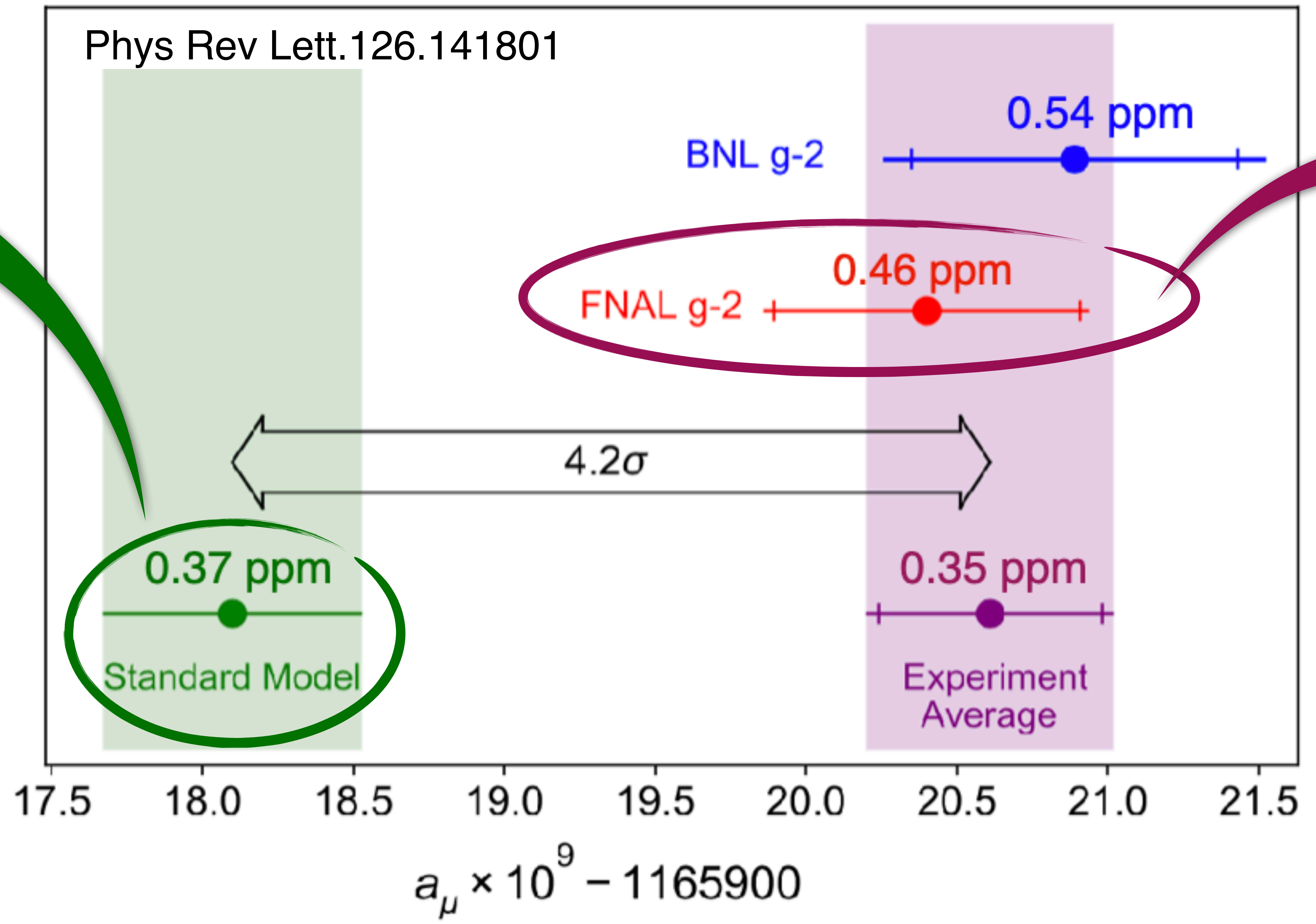

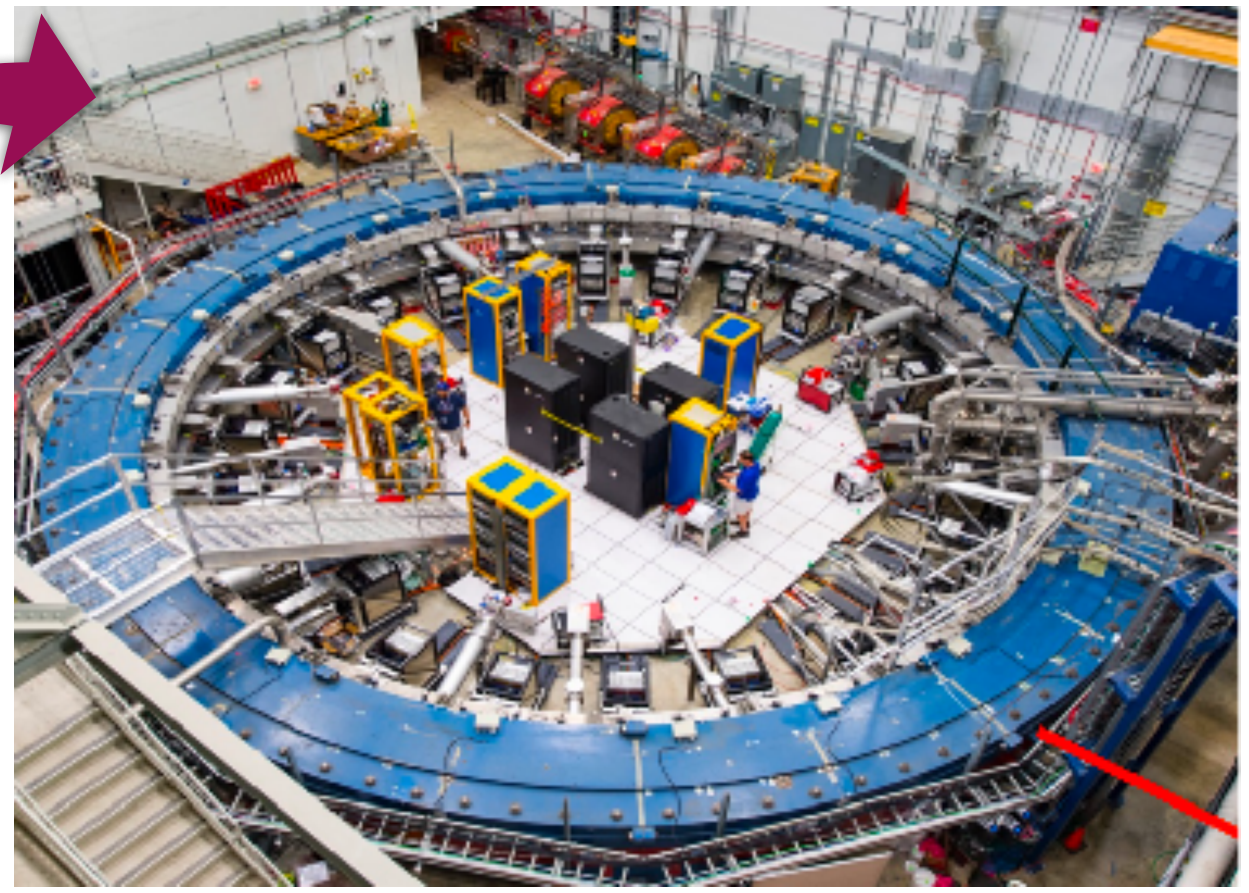

Muon storage ring used for BNL & FNAL Muon $g-2$ measurement

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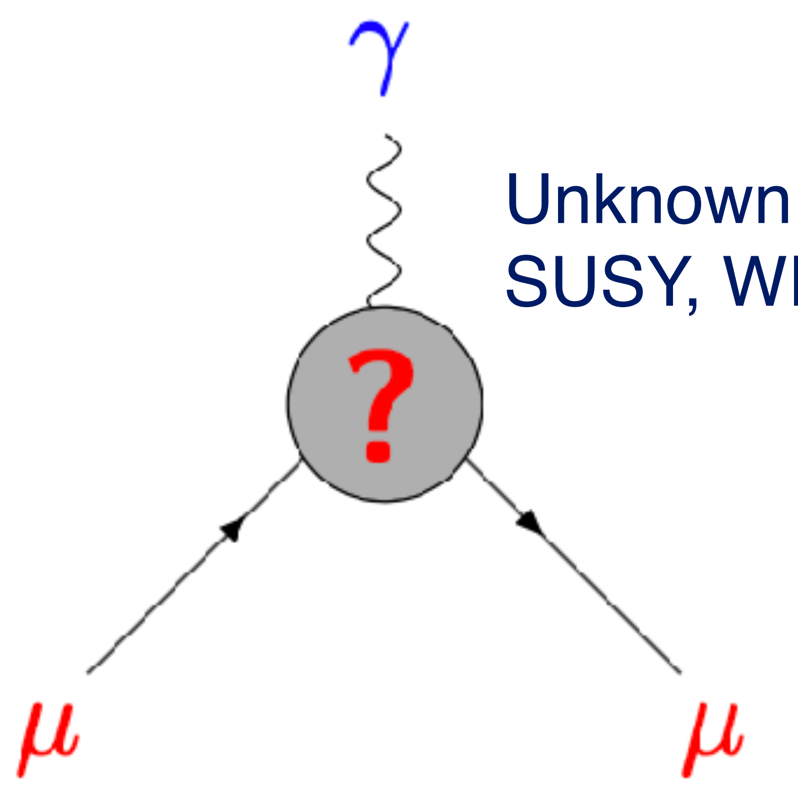
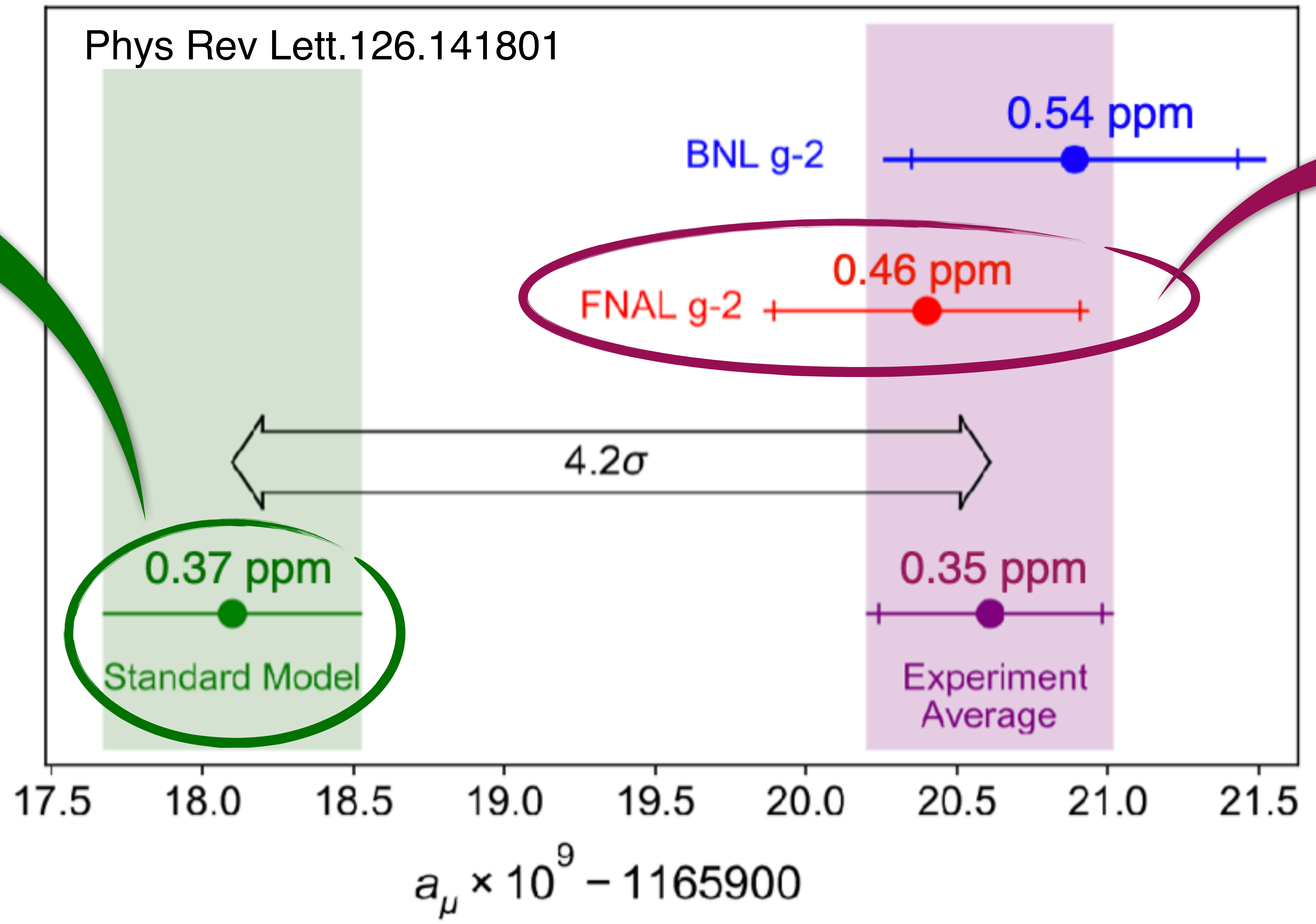
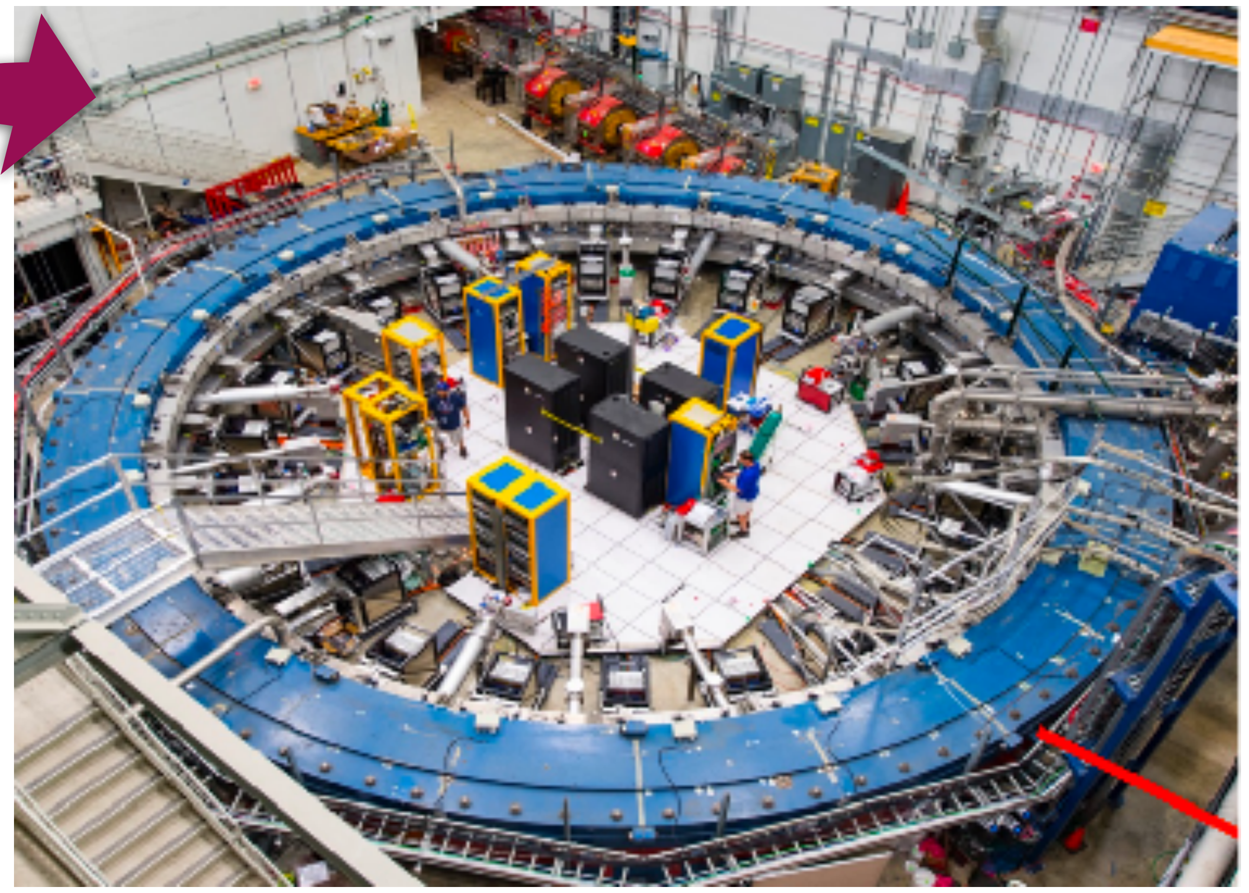
$$+ \, a_\mu^{\mathrm{NP}}?$$



Unknown particles
SUSY, WIMP, Axion…





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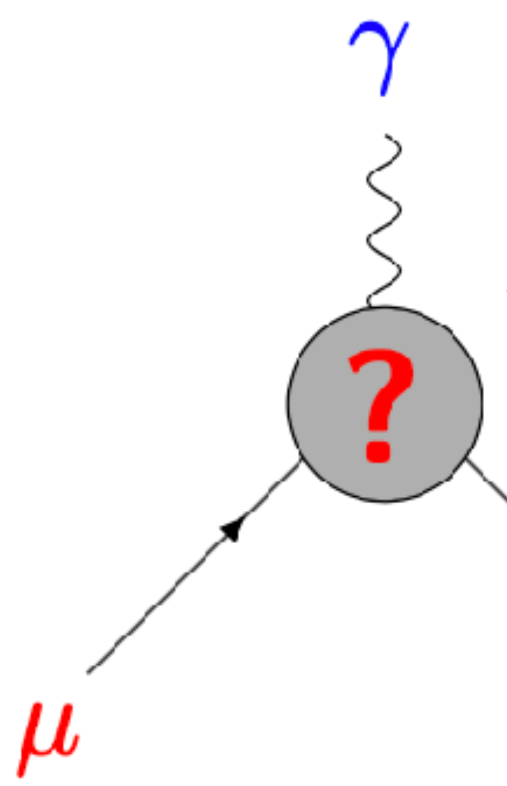

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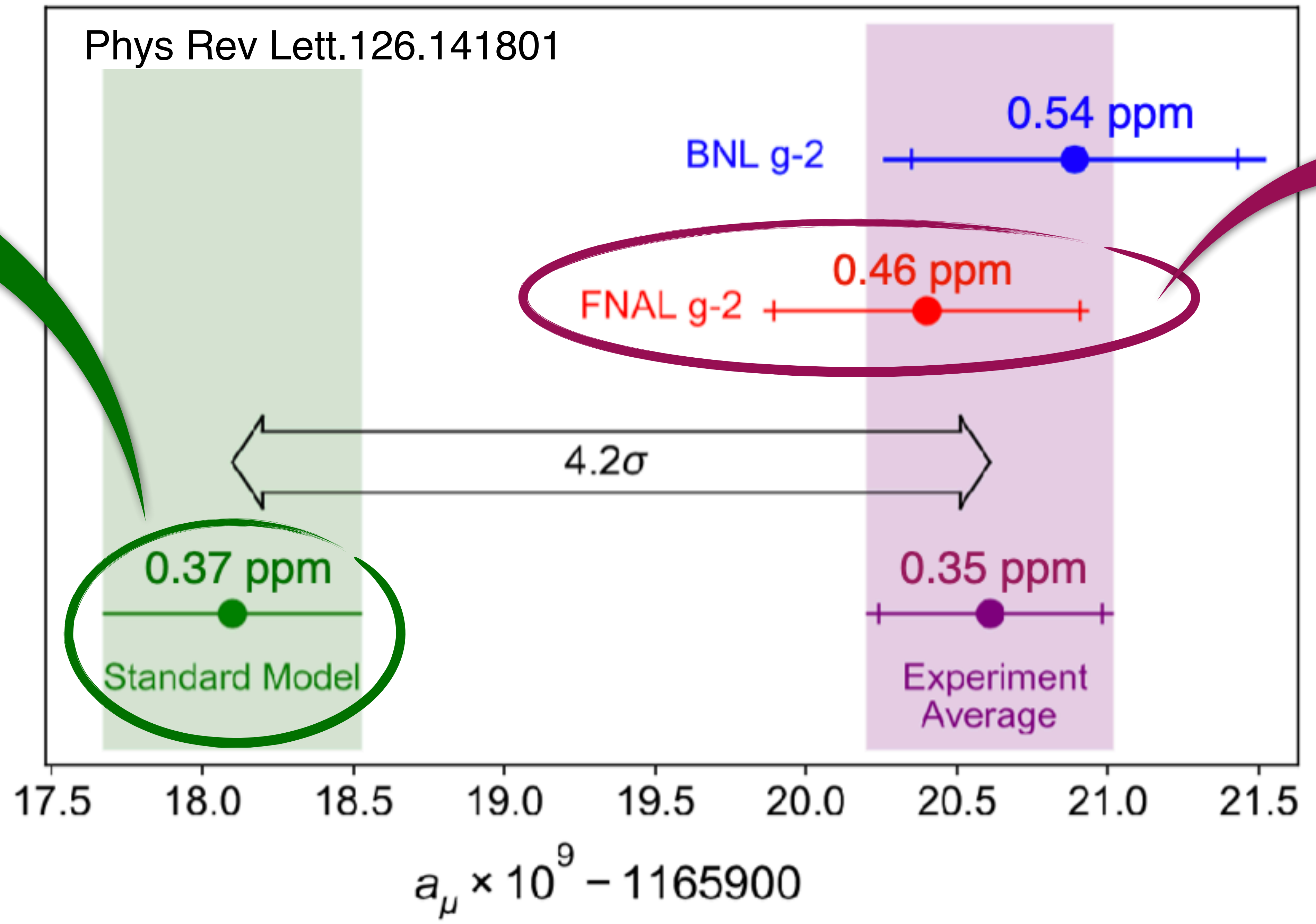
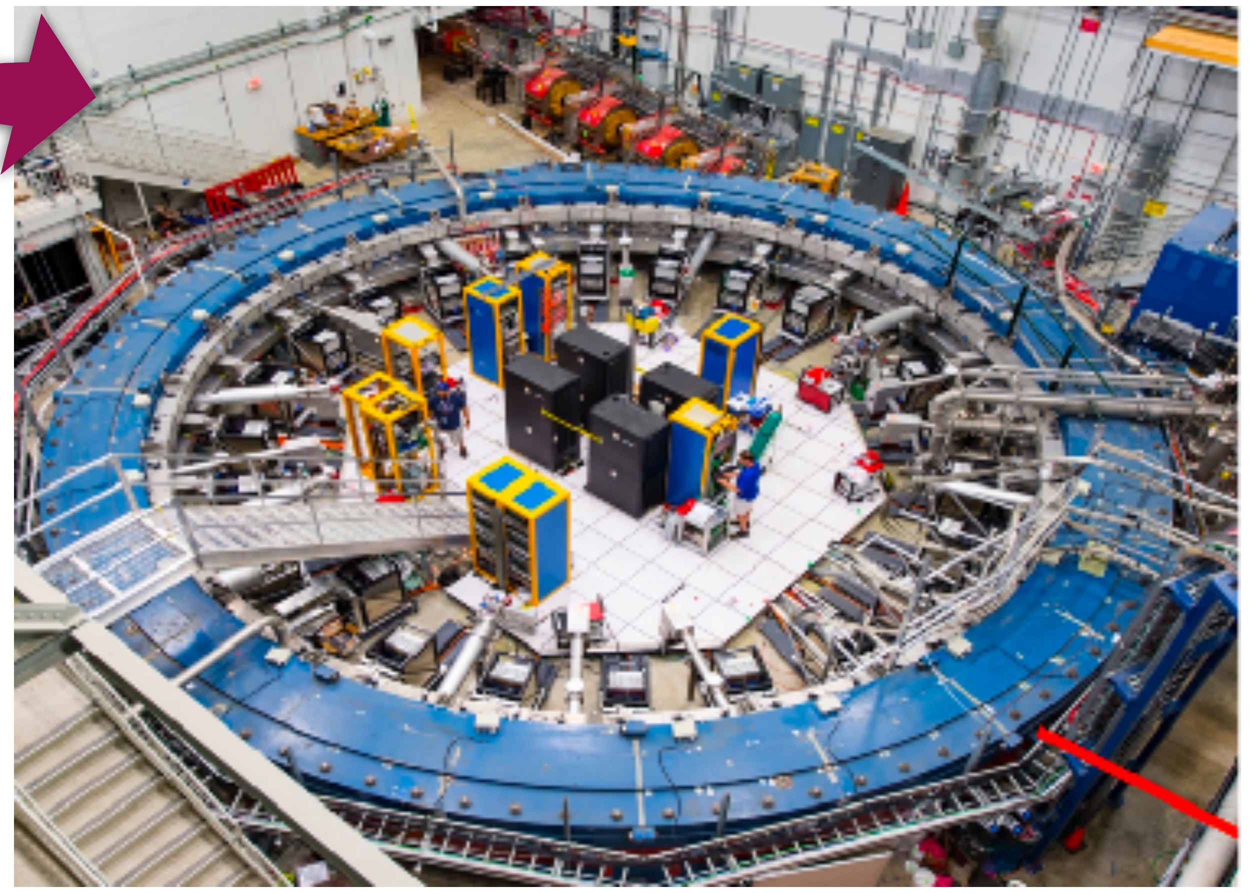


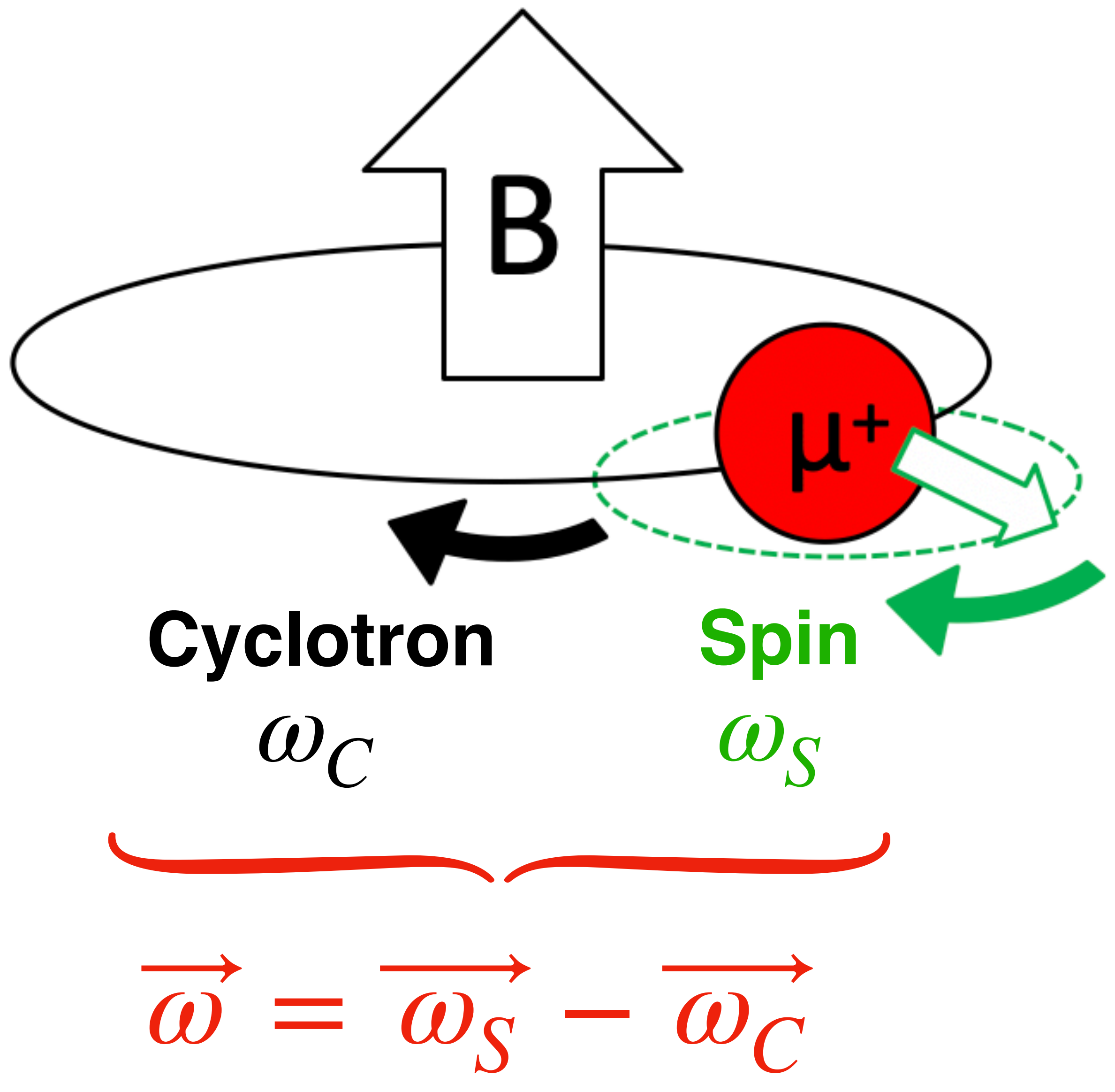


Muon storage ring used for BNL & FNAL Muon $g-2$ measurement

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

Measurement Principle

Muon Precession in the Magnetic Field



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

Measurement Principle

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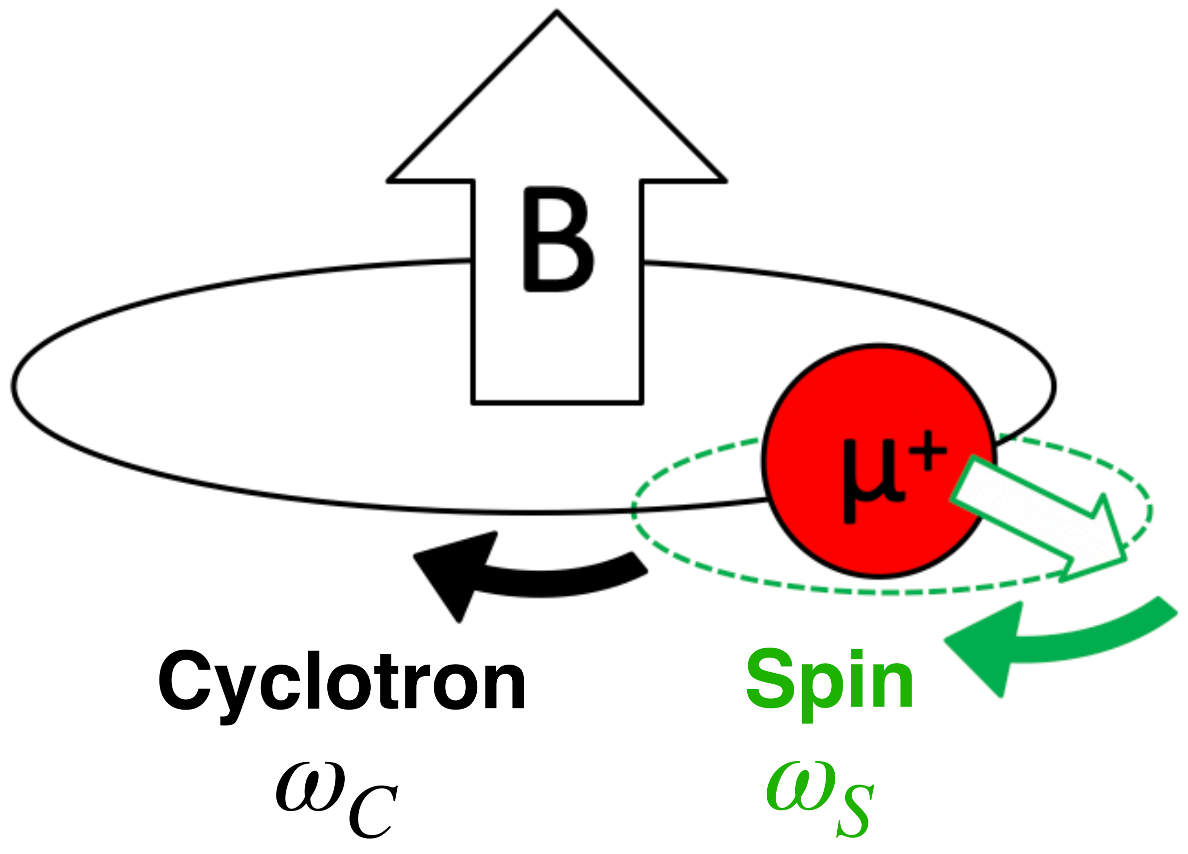

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Magic "γ": $a_\mu = \dfrac{1}{\gamma^2 - 1}$

BNL E821 approach

γ=30 (P=3 GeV/c)

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FNAL E989

Measurement Principle

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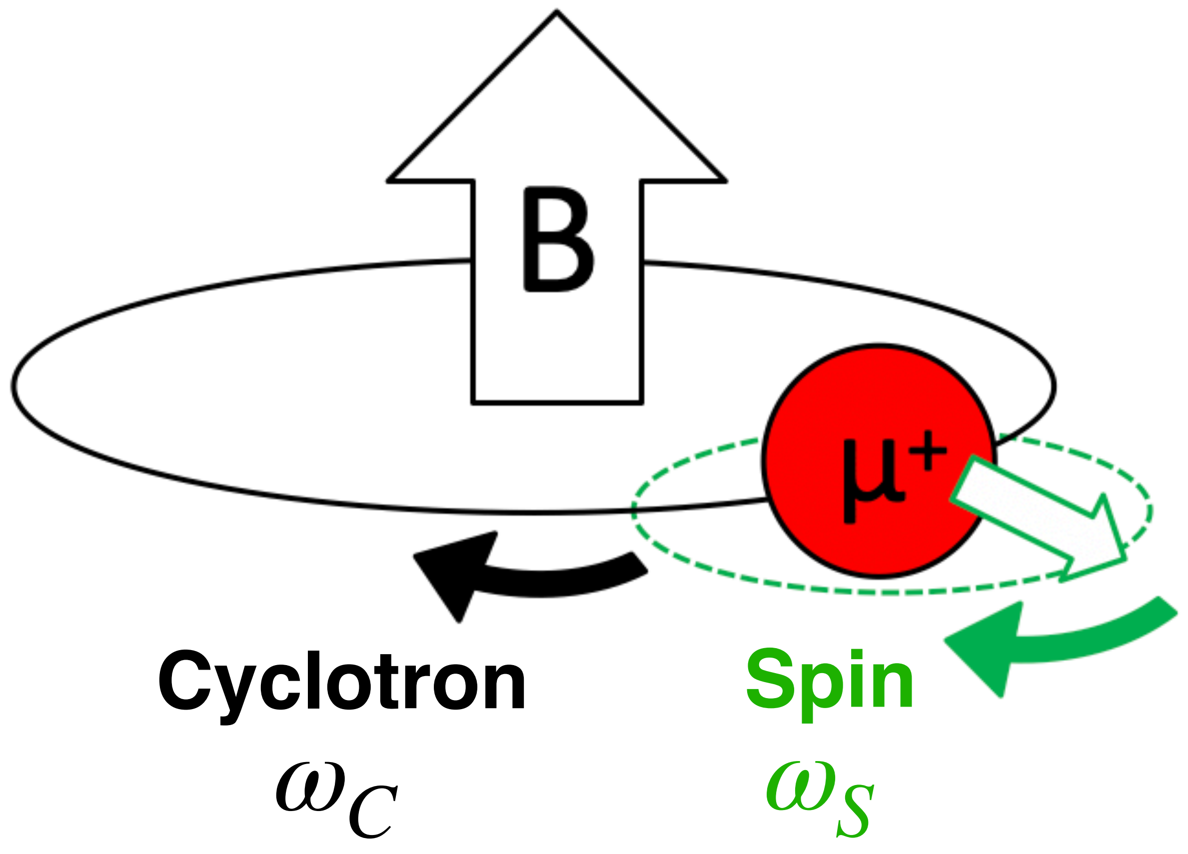

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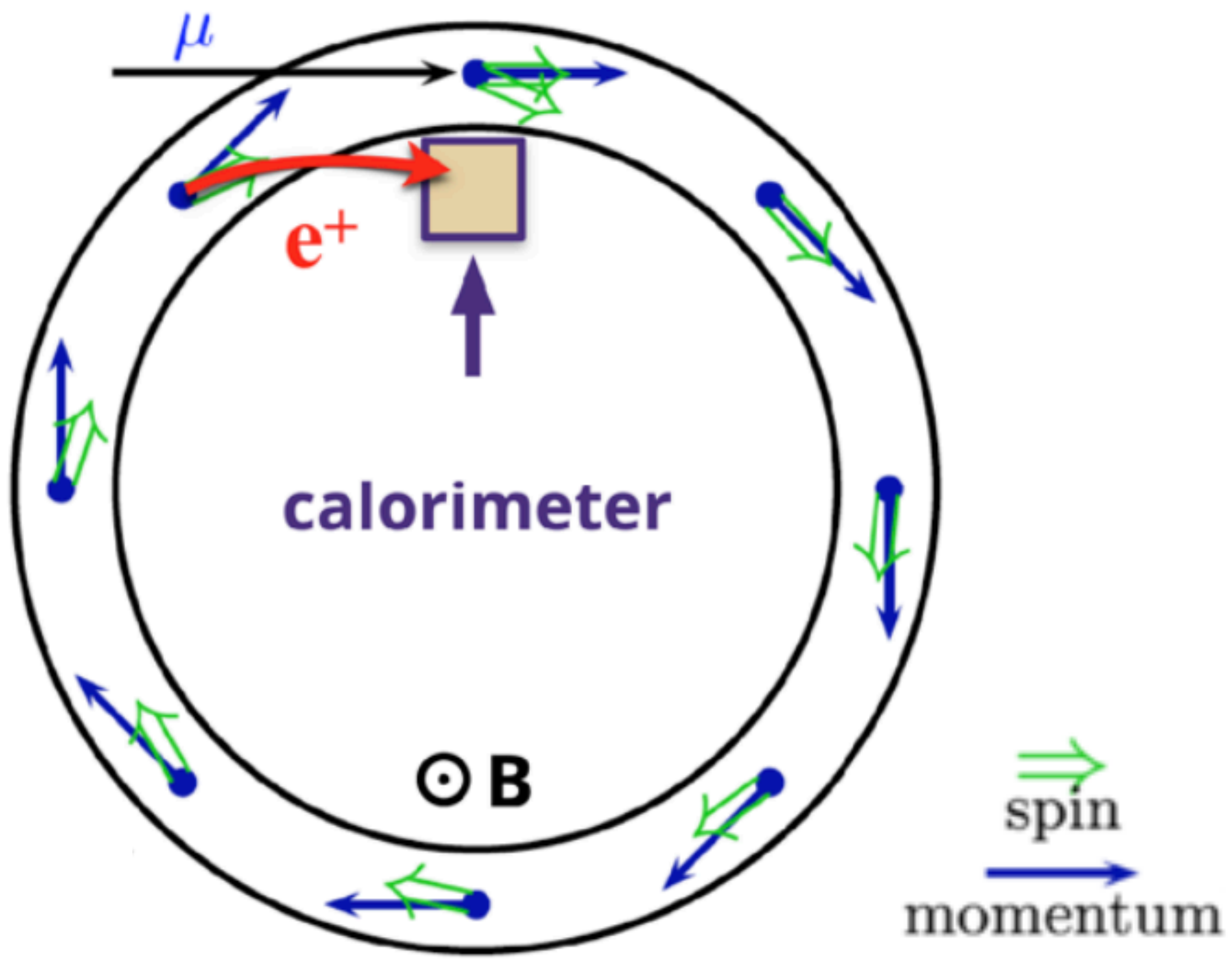

Measurement Principle

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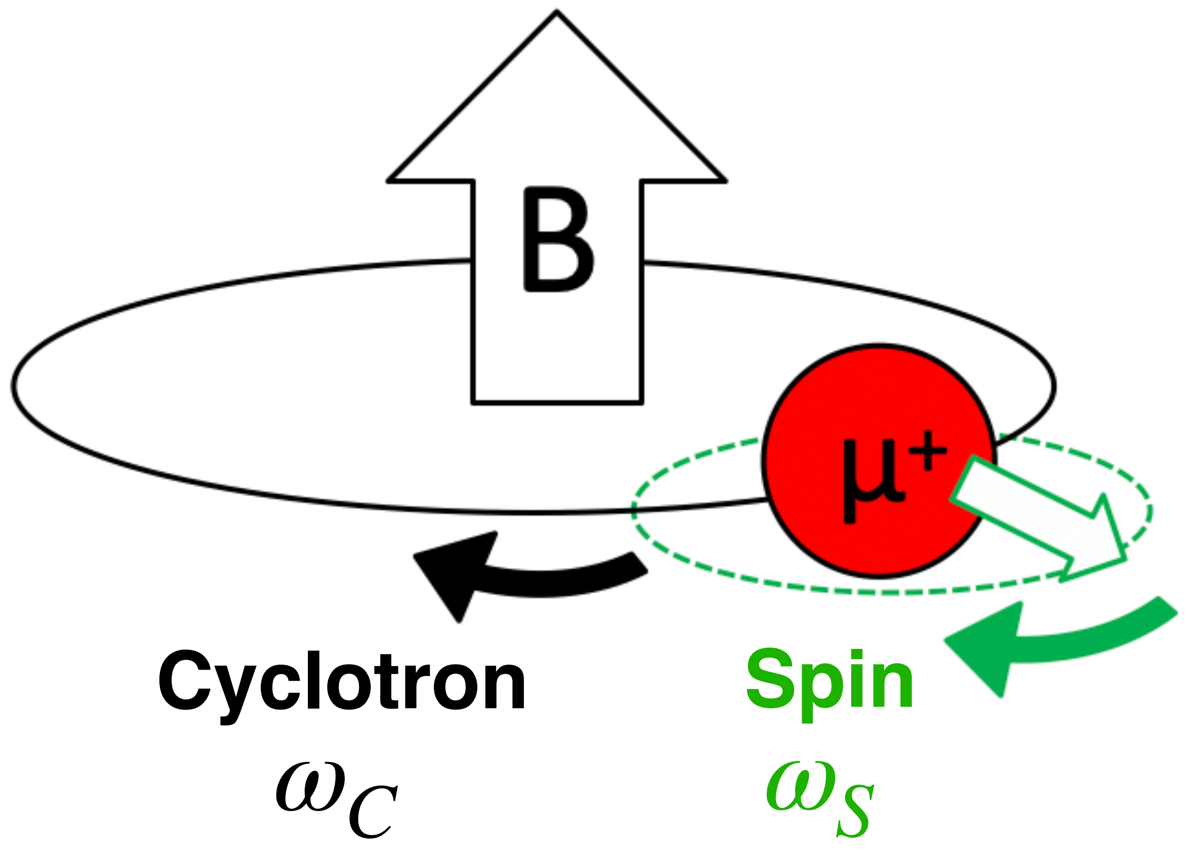

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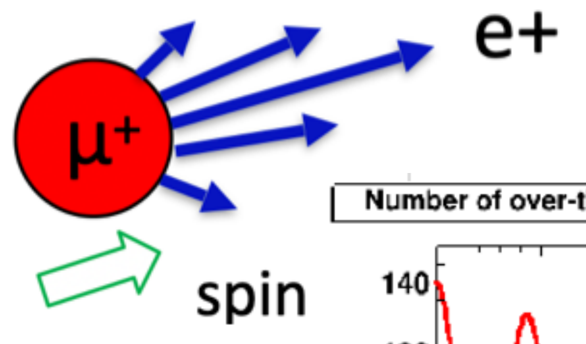
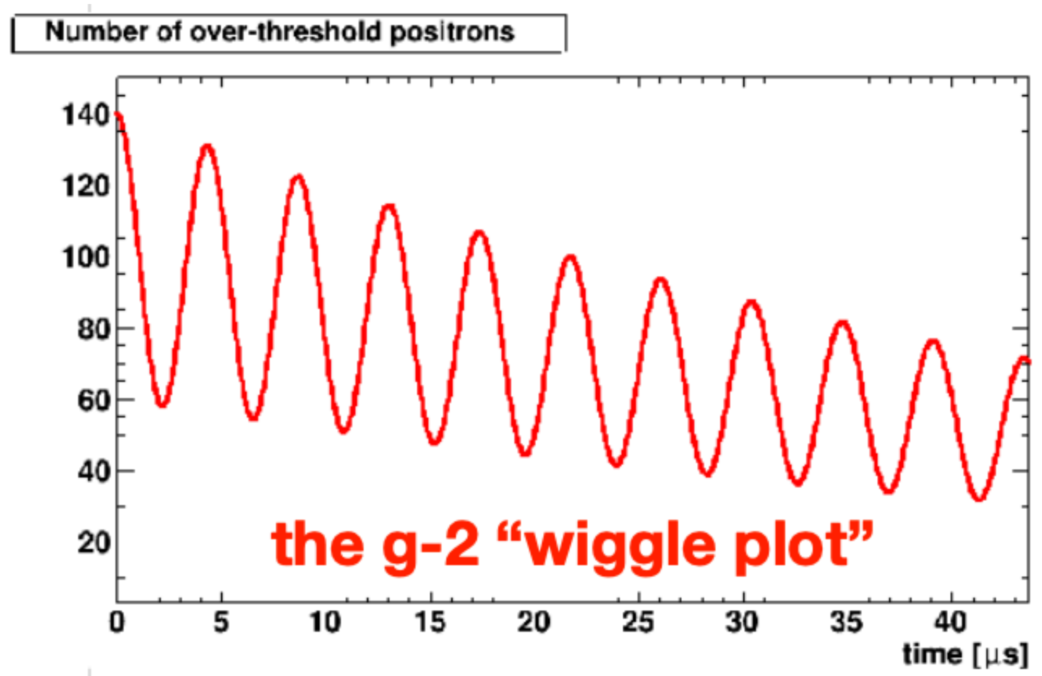
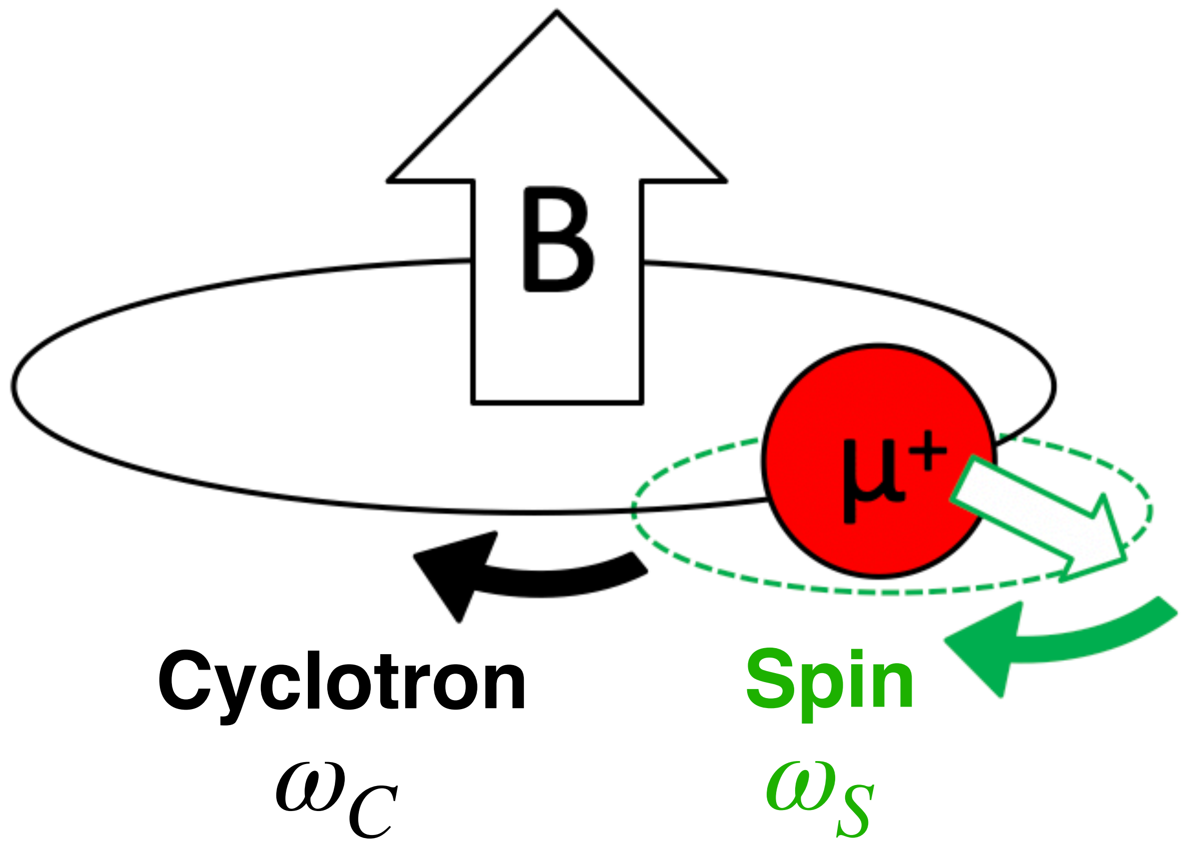




$$N(t) = N_0 e^{-t/\tau}\left[1 + A_\mu \cos(\omega_a t + \phi)\right]$$

Measurement Principle

Muon Precession in the Magnetic Field



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FNAL E989

Measurement Principle

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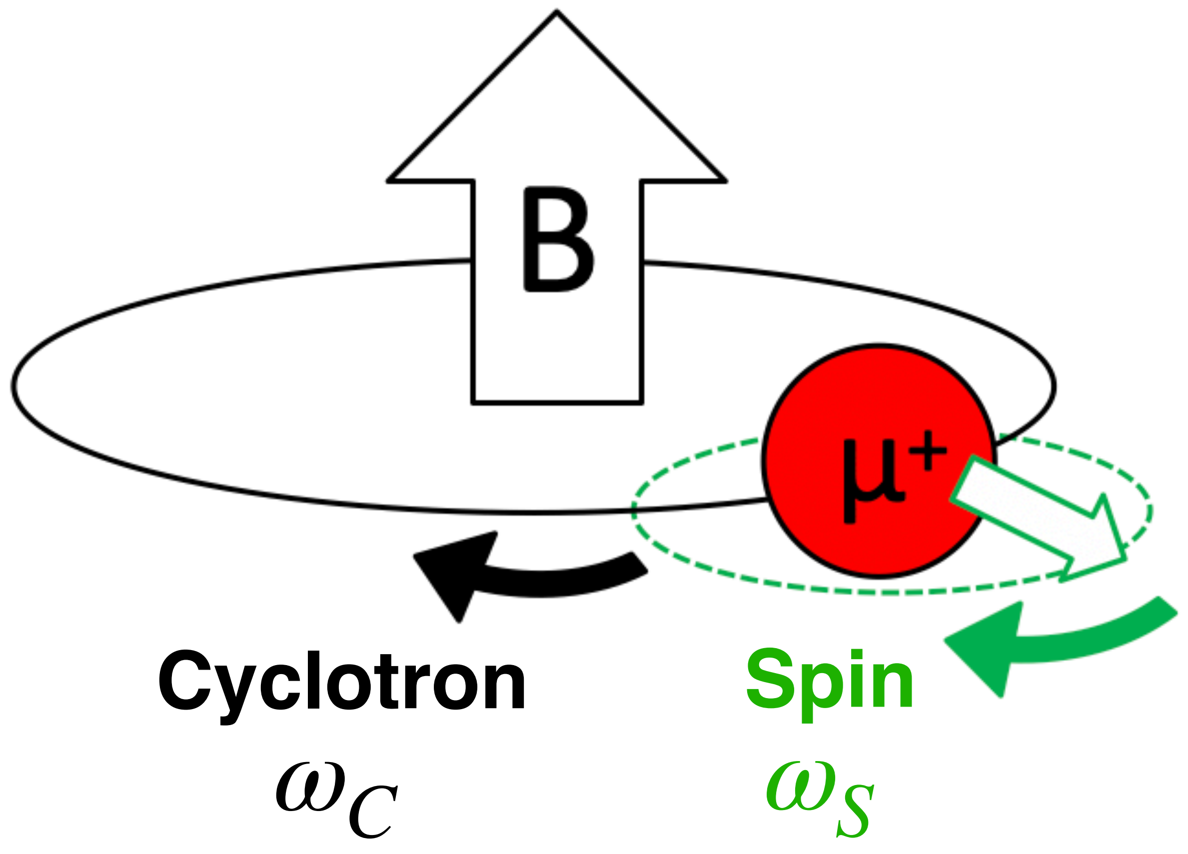

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Directly
remove E field

BNL E821 approach
γ=30 (P=3 GeV/c)

J-PARC approach
E = 0 at any γ

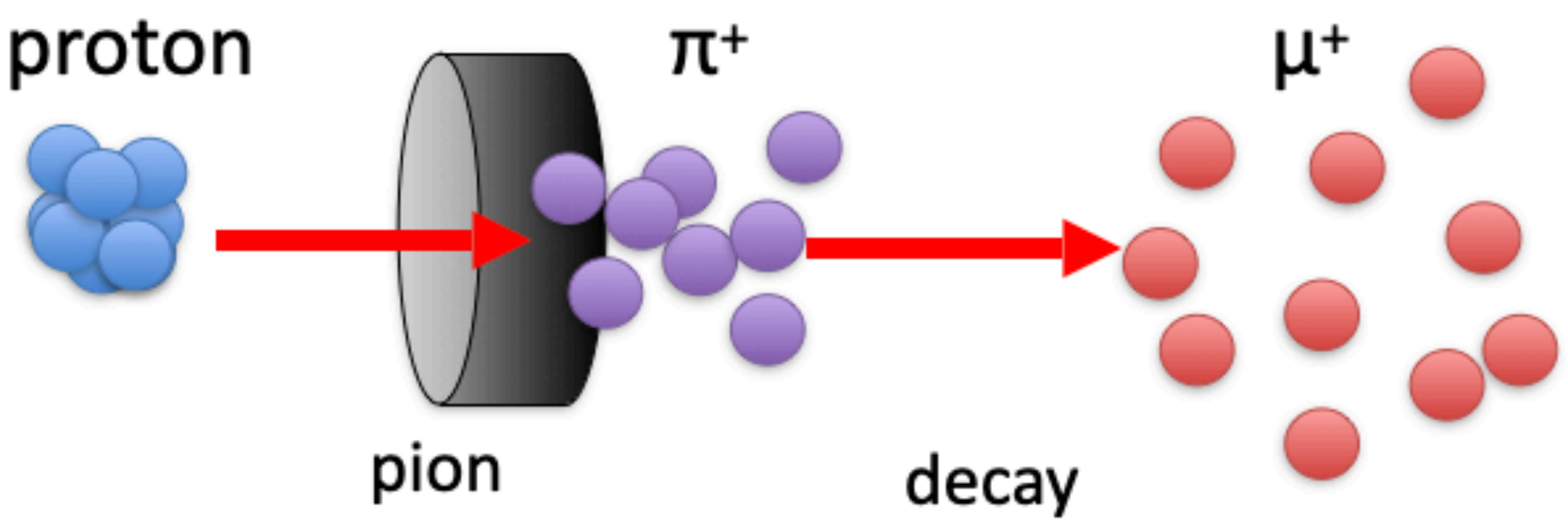
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

FNAL E989

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

J-PARC E34

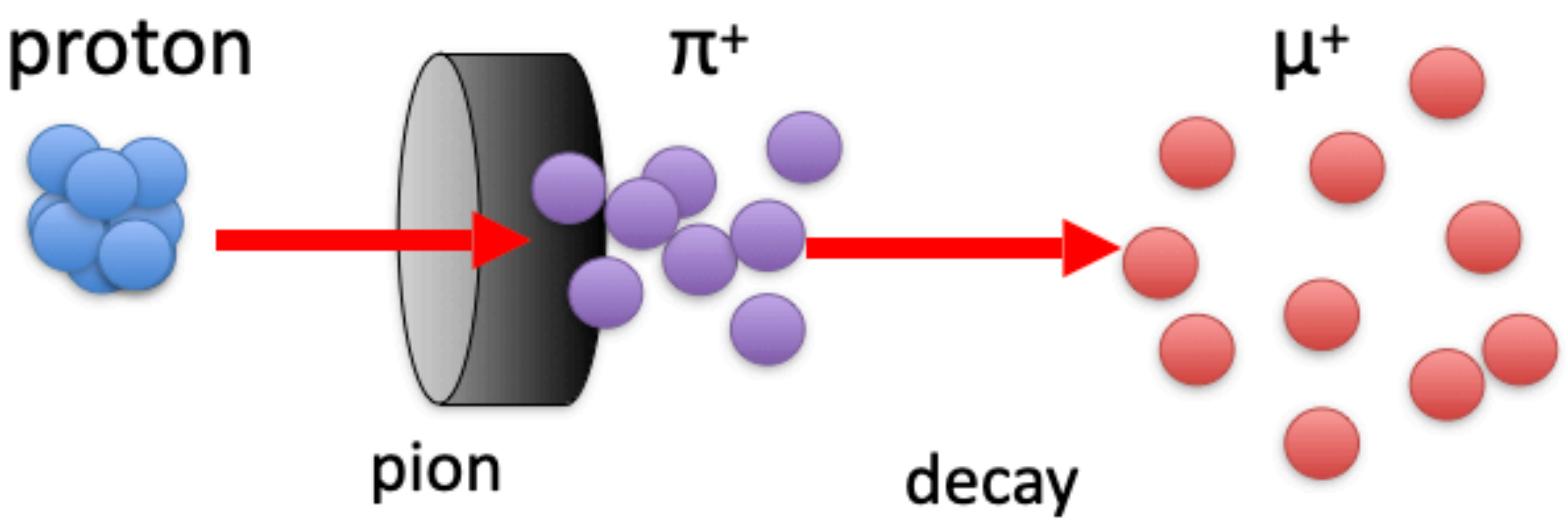
Low-emittance Thermal Muon Beam



emittance

~1000π mm・mrad

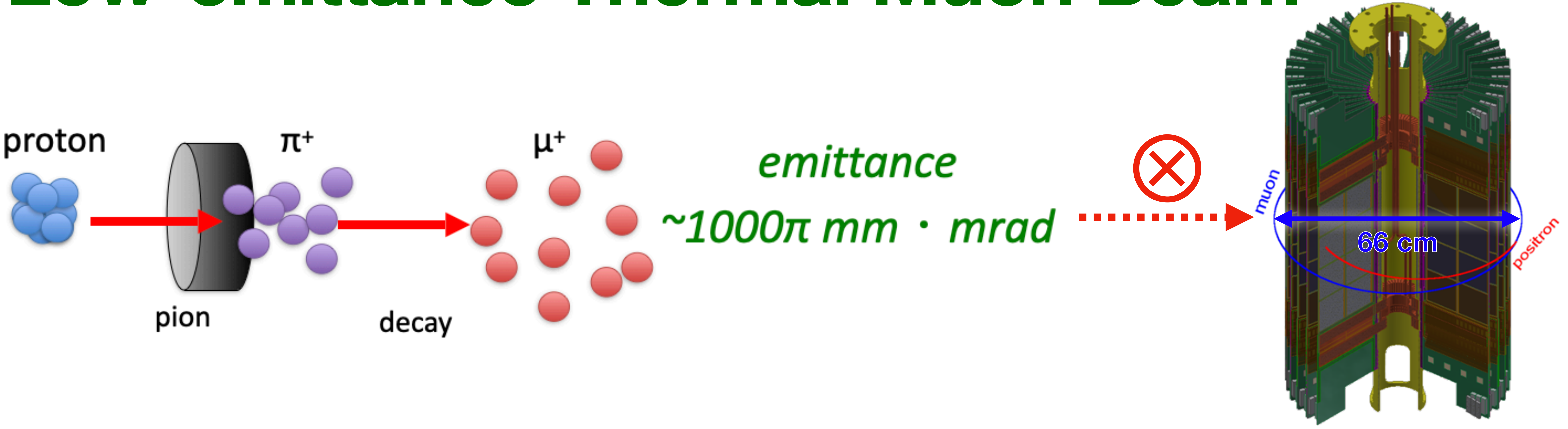
Low-emittance Thermal Muon Beam



emittance
~1000π mm・mrad

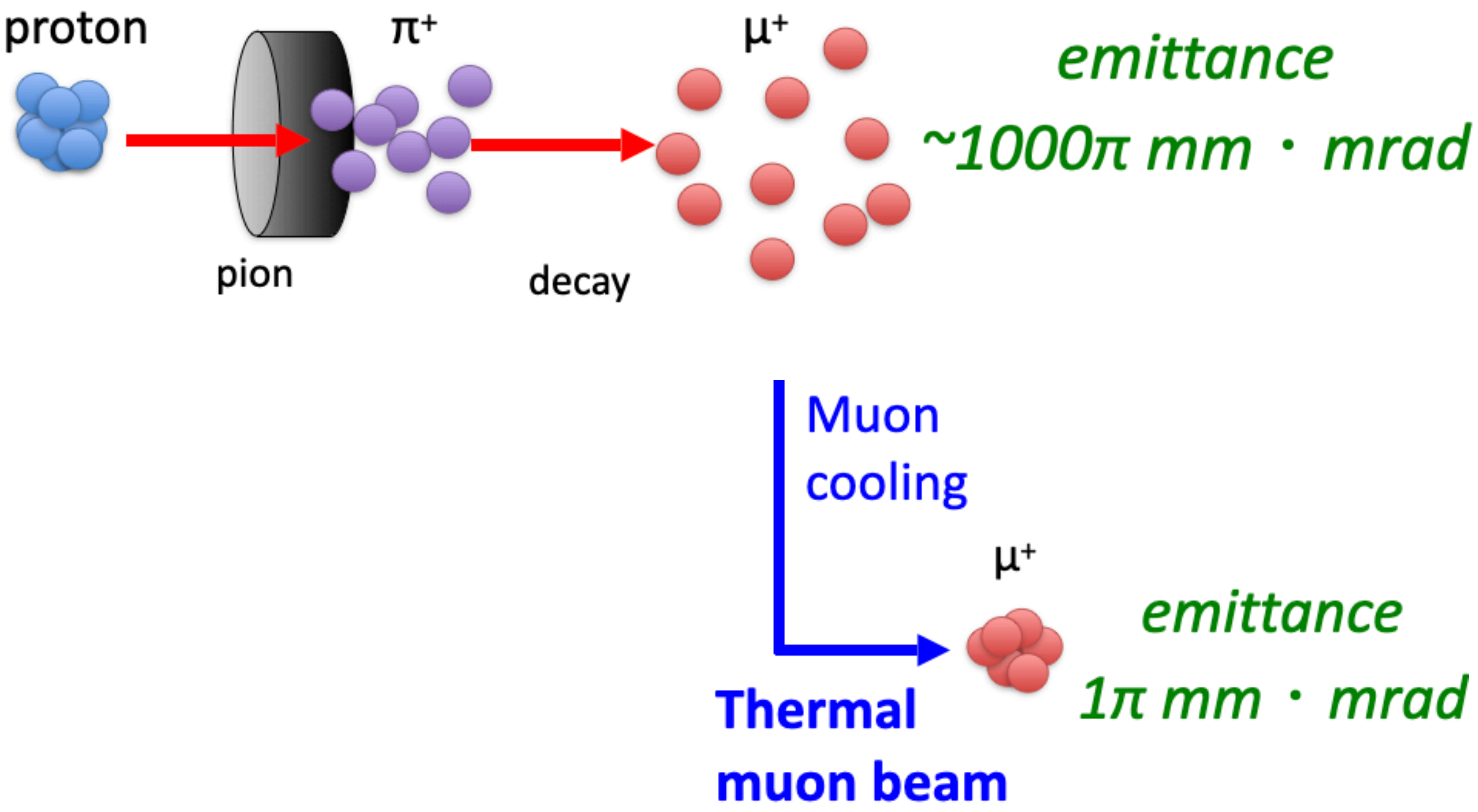
	Fermilab Muon g-2	J-PARC Muon g-2/EDM
Muon momentum	3.09 GeV/c	300 MeV/c
Storage Field	B = 1.45 T	B = 3 T (Solenoidal)
Cyclotron period	149 ns	7.4 ns
Muon orbit diameter	14 m	66 cm
Focusing field	Electric quadrupole	E = 0, very weak magnetic

Low-emittance Thermal Muon Beam



- The traditional surface muon beam without E focusing is not applicable for J-PARC E34
- A novel low-emittance thermal muon beam was proposed

Low-emittance Thermal Muon Beam



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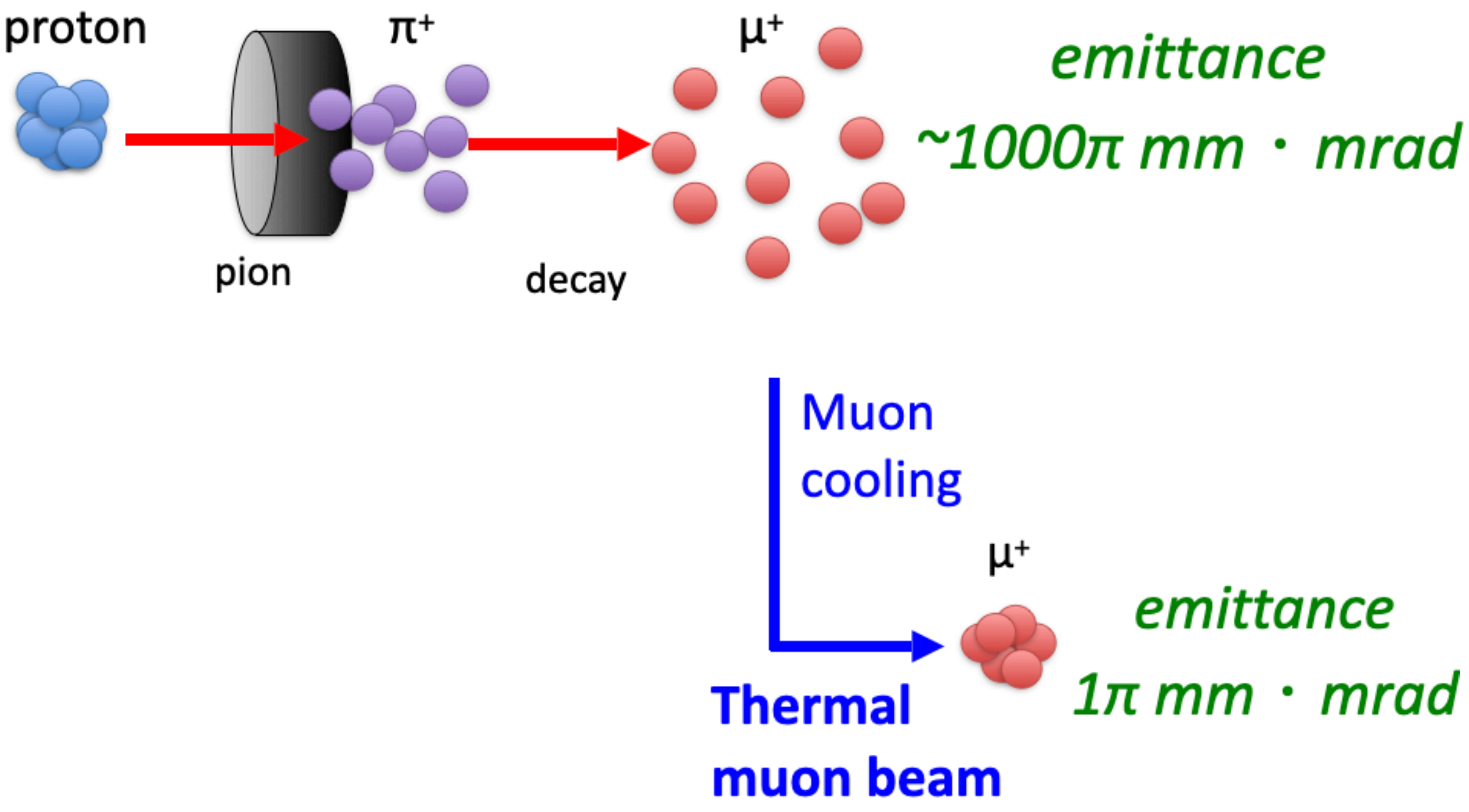
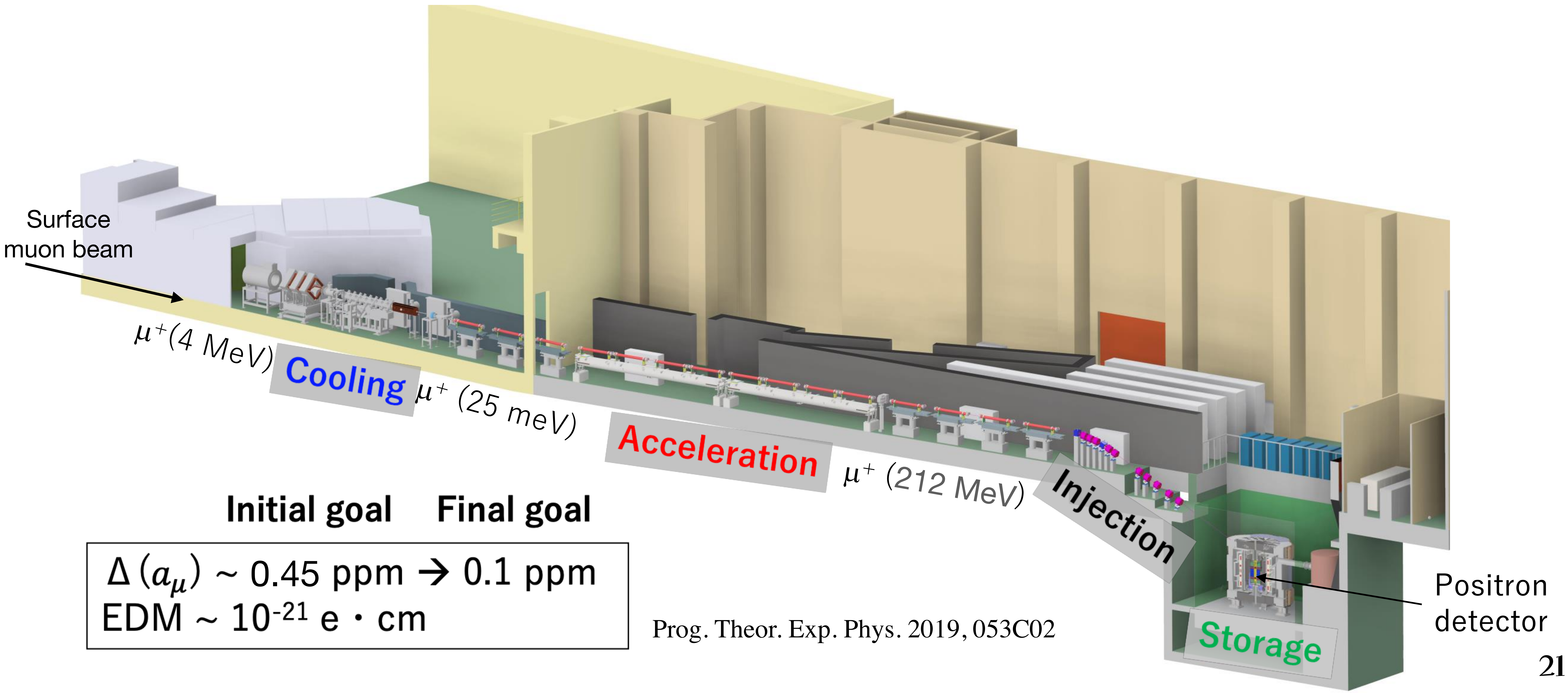


J-PARC Muon $g-2$/EDM experiment (E34)

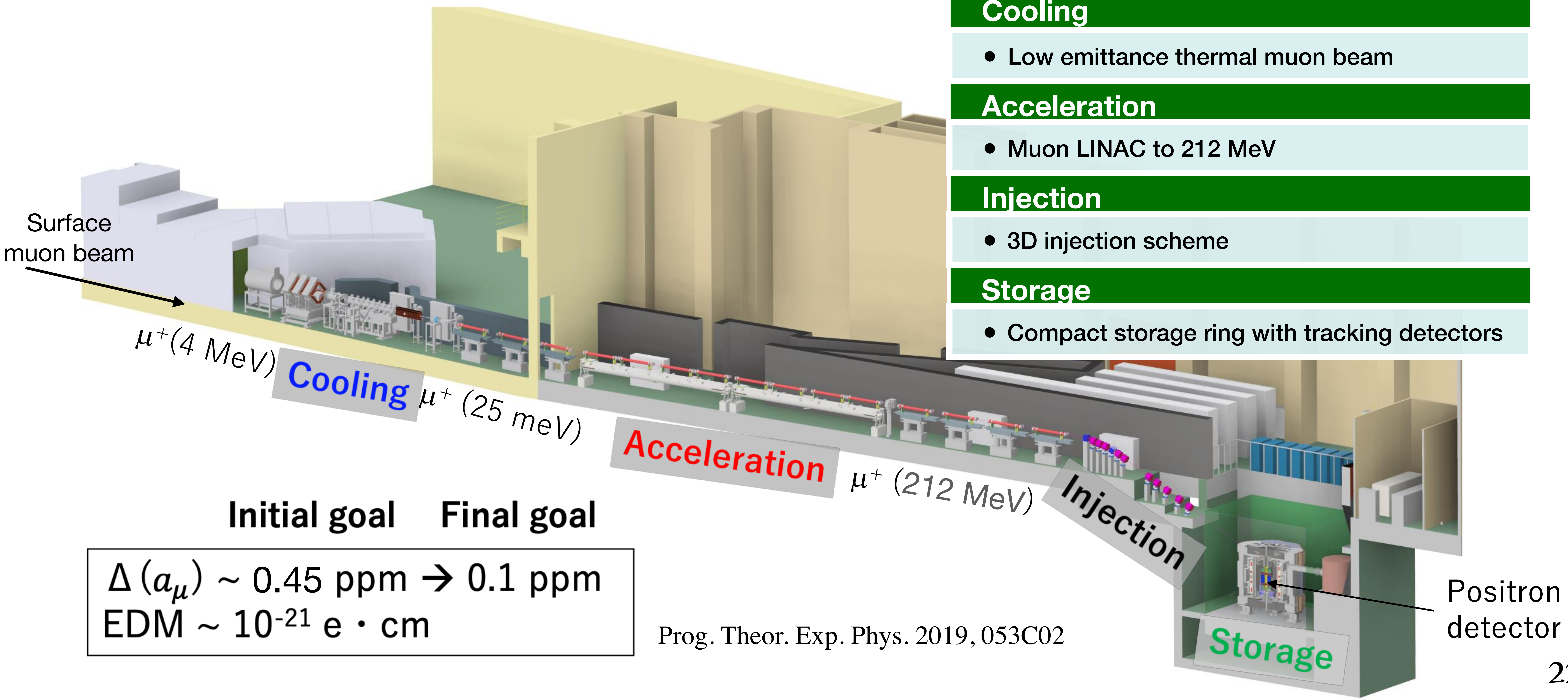


Initial goal **Final goal**

$\Delta(a_\mu) \sim 0.45$ ppm → 0.1 ppm
EDM ~ 10^{-21} e · cm

Prog. Theor. Exp. Phys. 2019, 053C02

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



Cooling
• Low emittance thermal muon beam
Acceleration
• Muon LINAC to 212 MeV
Injection
• 3D injection scheme
Storage
• Compact storage ring with tracking detectors

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$\Delta(a_\mu)$ ~ 0.45 ppm → 0.1 ppm
EDM ~ 10^{-21} e · cm

Prog. Theor. Exp. Phys. 2019, 053C02

J-PARC
Japan Proton Accelerator Research Complex

J-PARC
Japan Proton Accelerator Research Complex

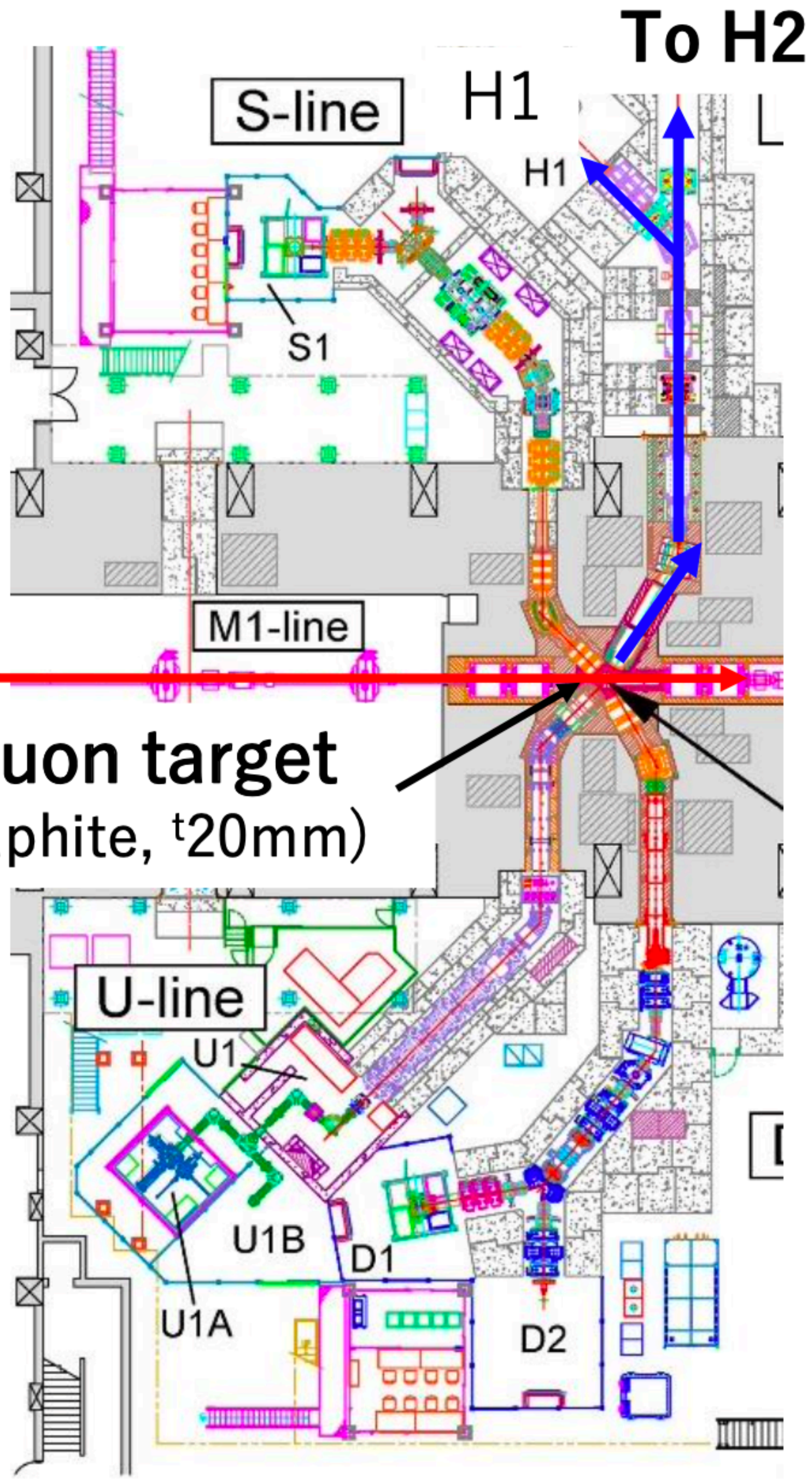
Muon Source at J-PARC MLF

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

3 GeV proton from RCS

2×10^{15} /s @1MW

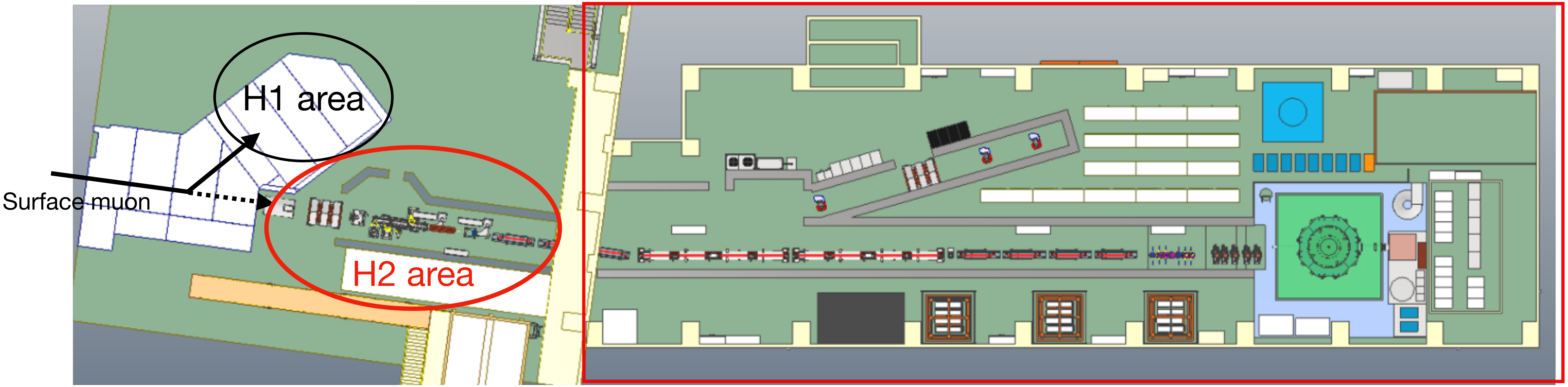
U-line
- ultra slow μ^+
- U1A for nm-μSR
- U1B for μ microscopy
- under commissioning



H-line
- **surface μ^+ (>10^8 μ^+/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 μSR
- D2 for variety of science

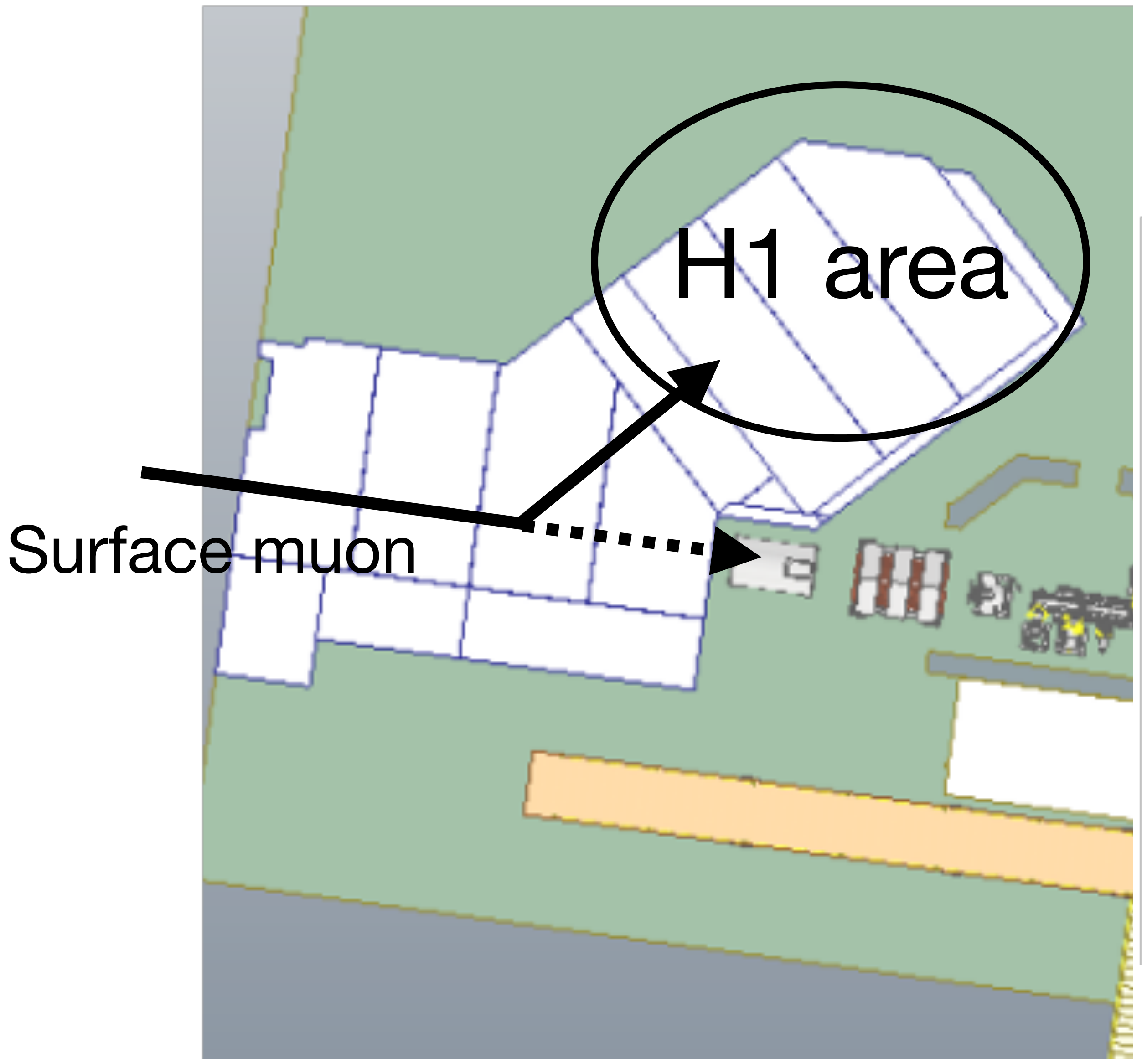
H-line Construction



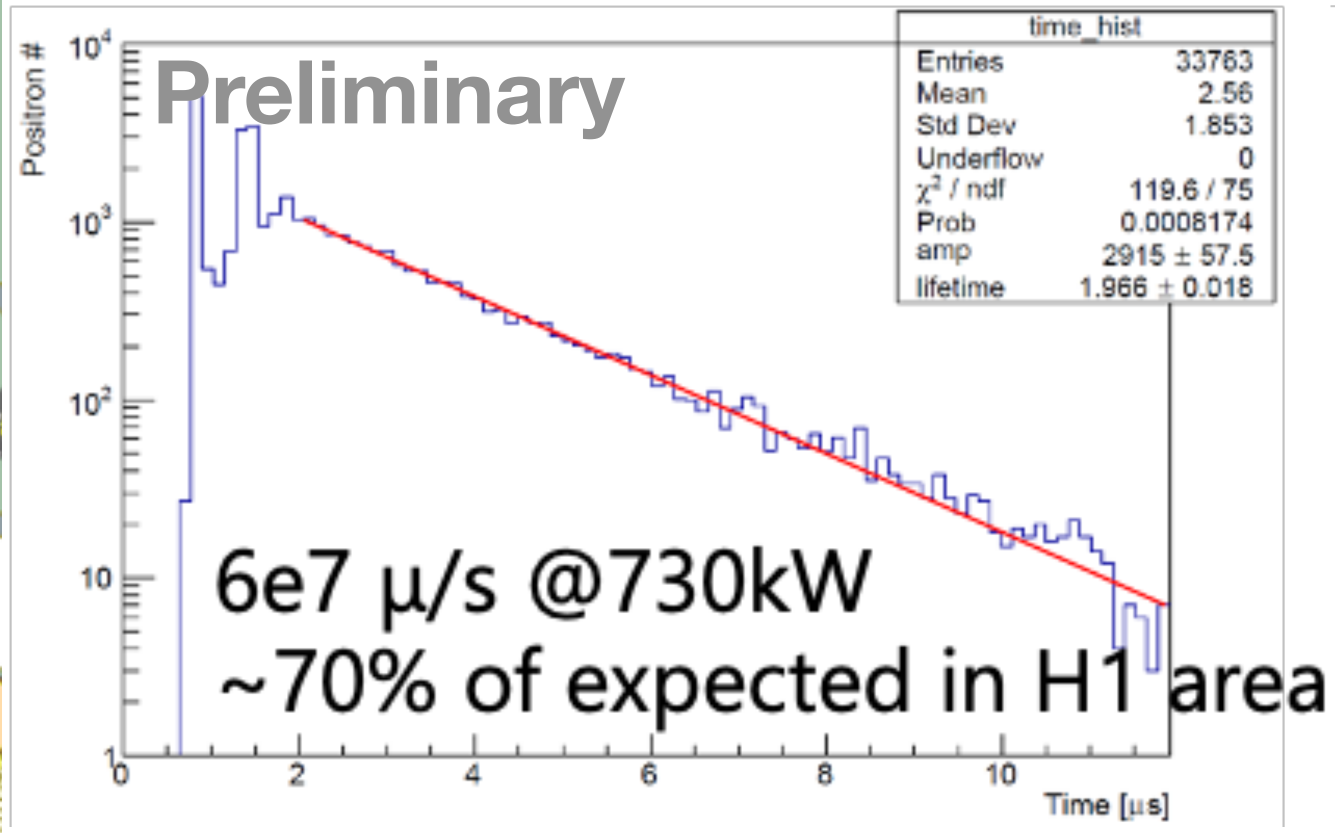
Extension building for muon LINAC, kicker and storage ring

- 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.

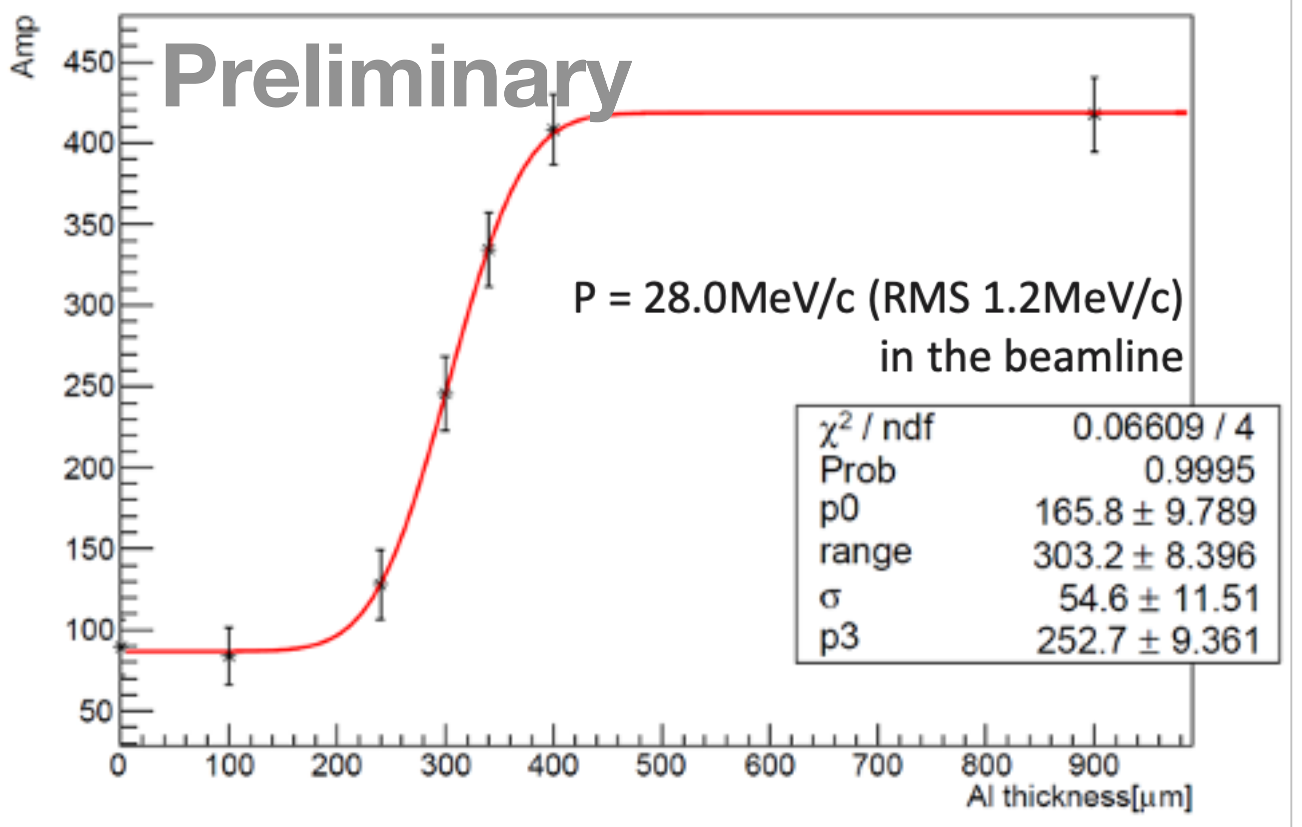
H-line Construction



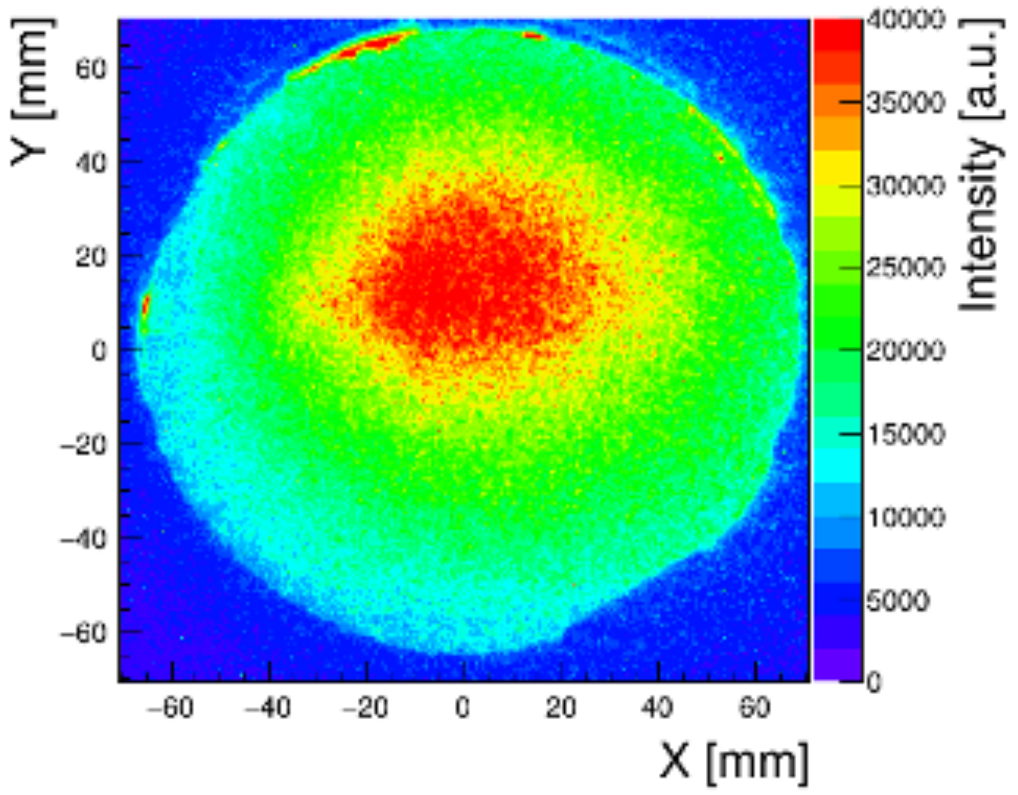
- The first beam was delivered to the **H1 area** on Jan. 15th, 2022



① Beam intensity measurement



② Momentum estimation



③ Beam profile measurement

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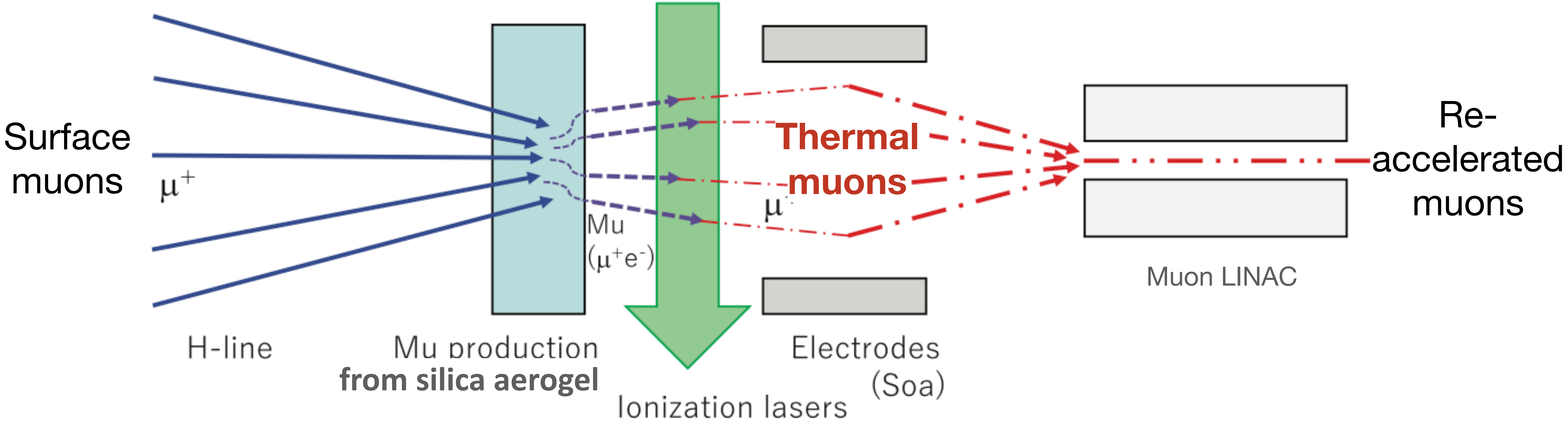
Thermal Muon Source

- Surface muon cooling by <u>laser ionization of muonium (Mu)</u> to thermal muon



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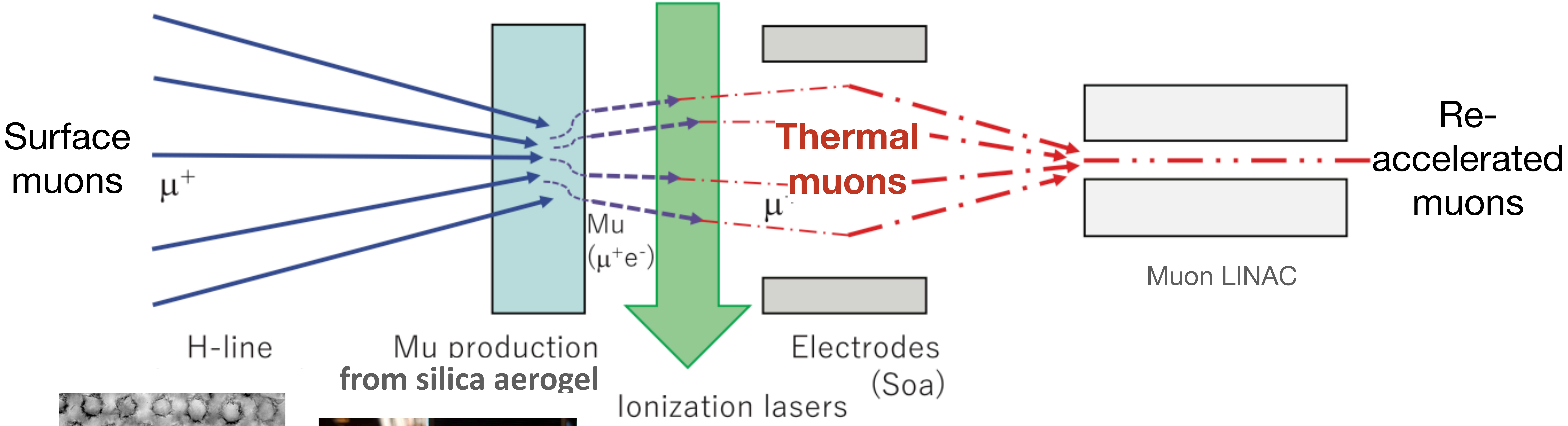
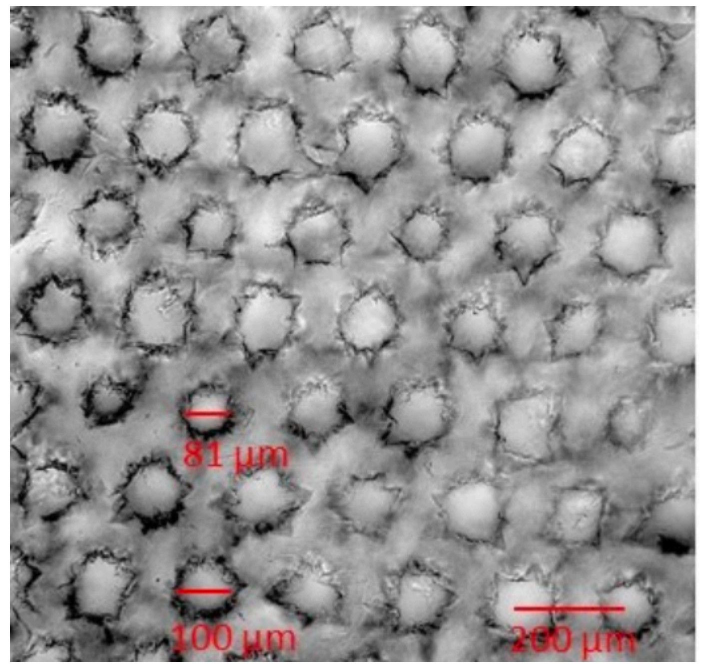
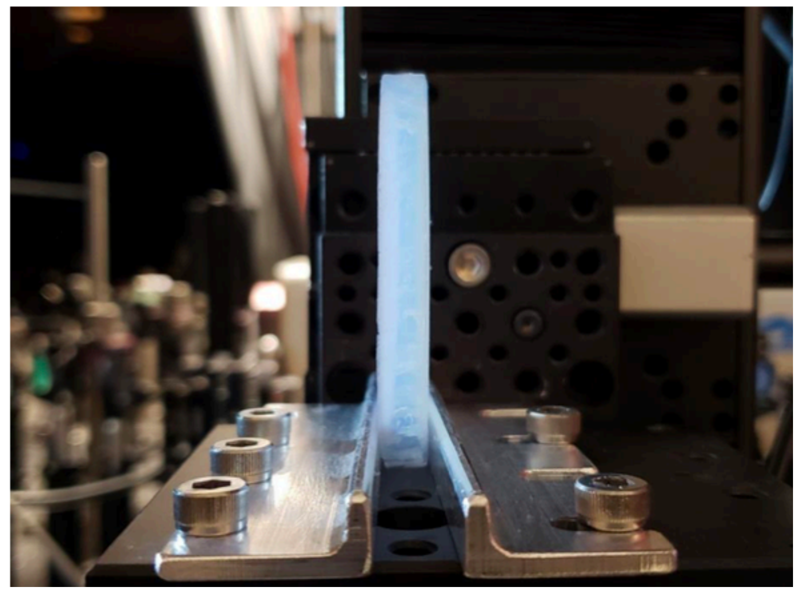




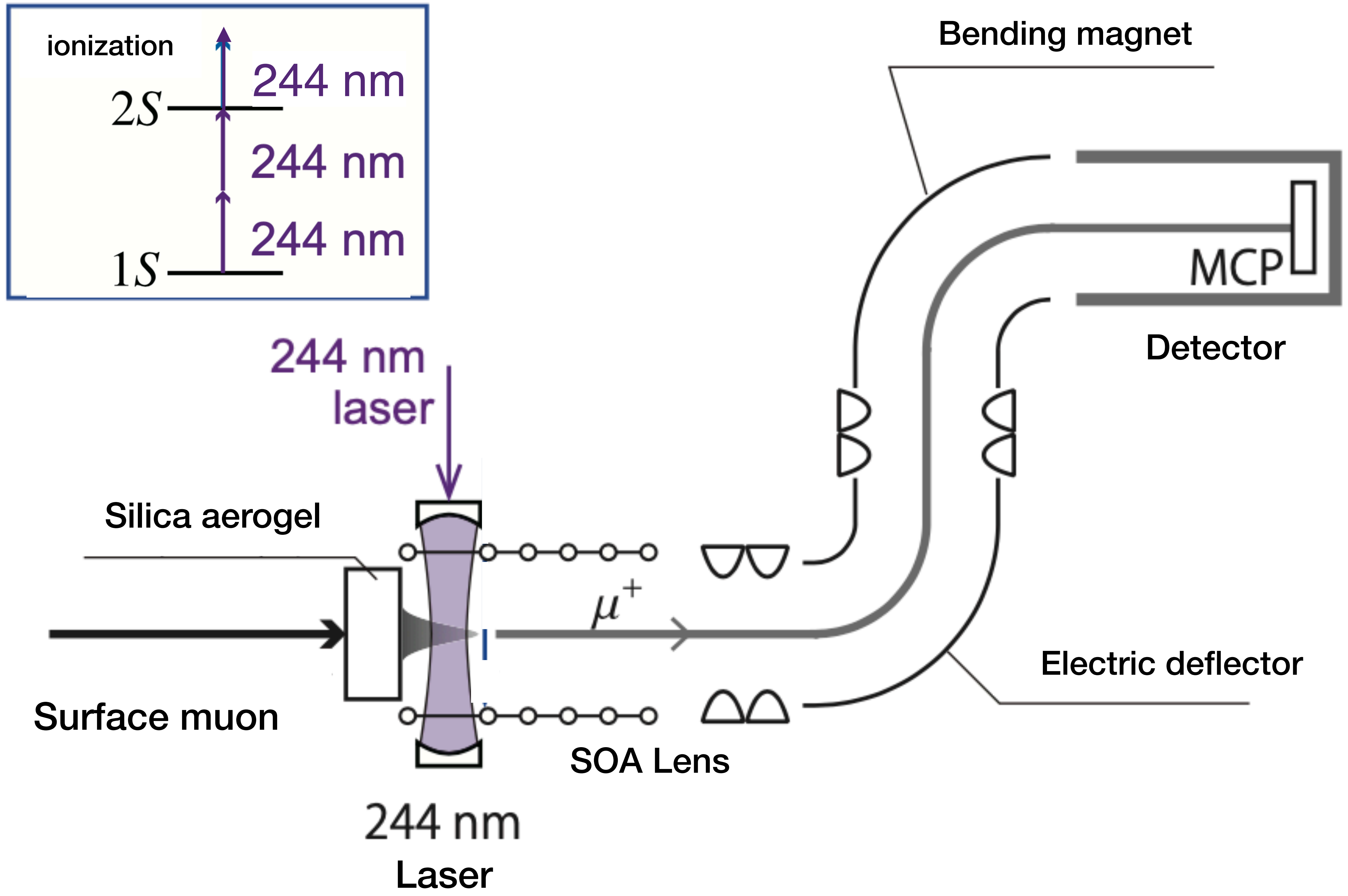


2013	• Muonium emission from silica aerogel [PTEP 103C0 (2013)]
2014	• Laser-ablation on aerogel surface [PTEP 091C01 (2014)]
2020	• Study of muonium emission from laser-ablated silica aerogel [PTEP 123C01 (2020)]

Thermal Muon Source

Muonium (Mu) Laser Ionization Test

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



Thermal Muon Source

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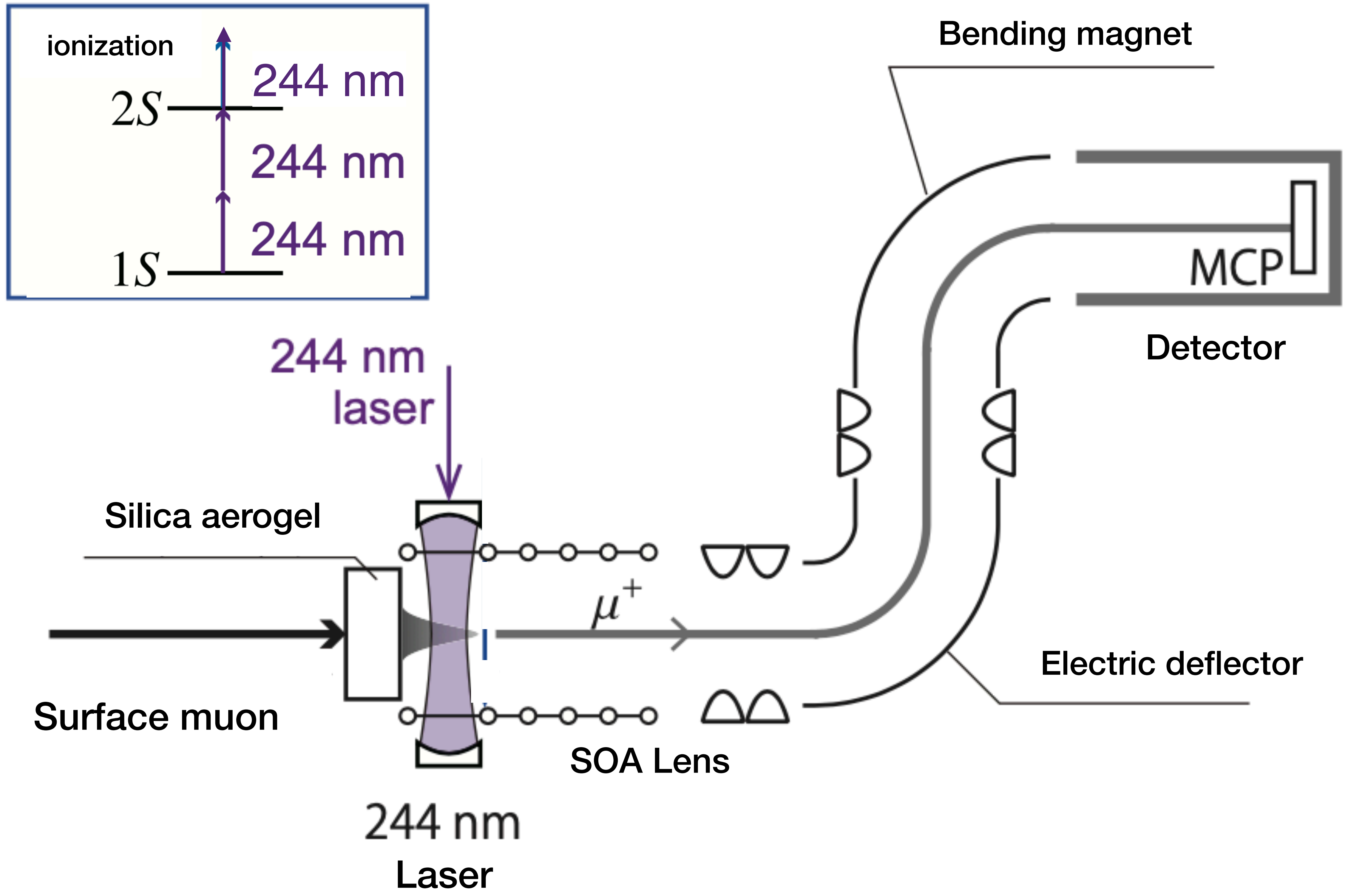


$$\Delta\nu_{1S2S} \simeq \frac{3\alpha^2}{8h} m_e c^2 \left(1 + \frac{m_e}{m_\mu}\right)^{-1}$$

- With the 244 nm laser, It is also a direct measurement of Mu 1S-2S interval → **determination of muon mass**

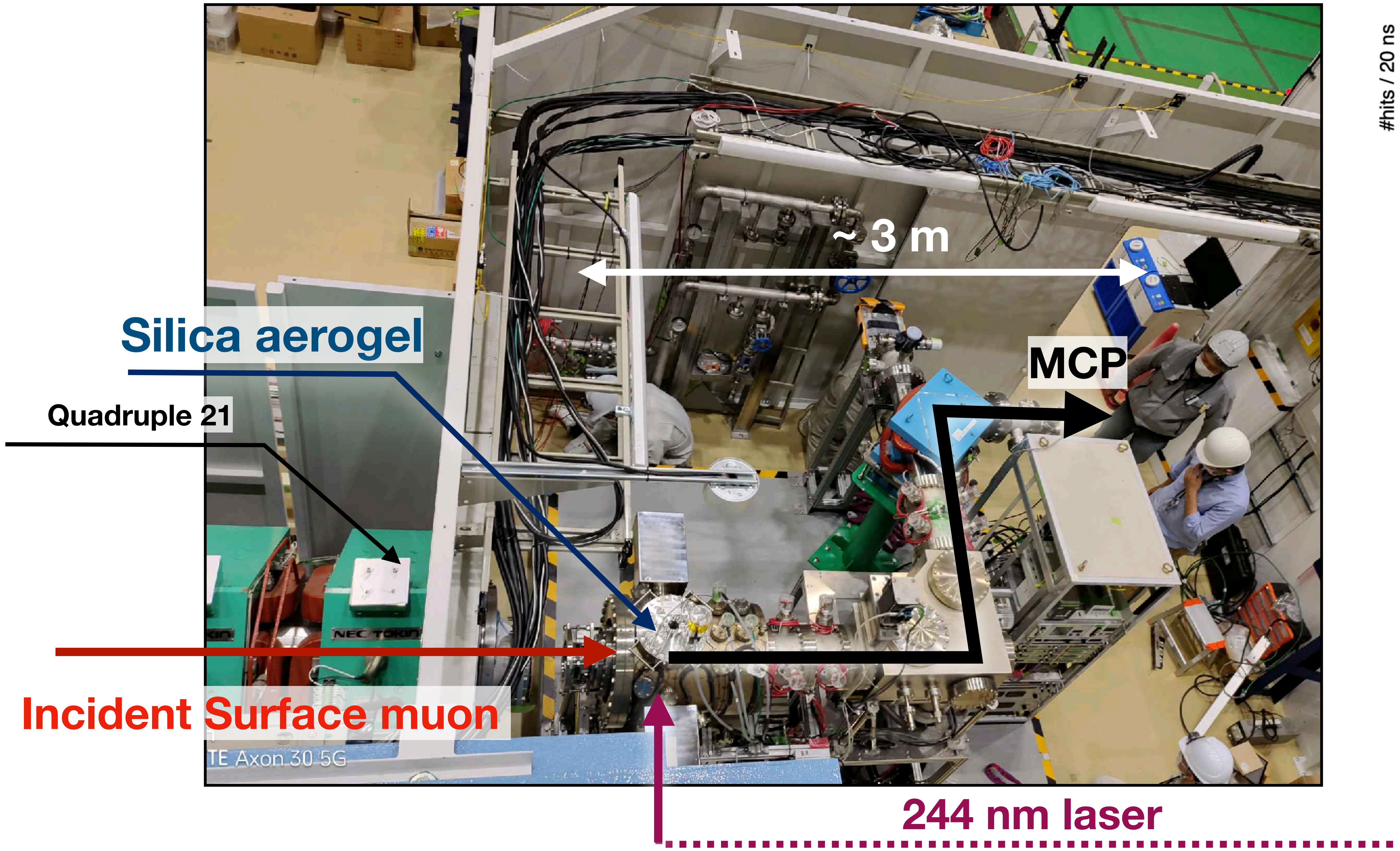
  (Similar to Mu-MASS at PSI)

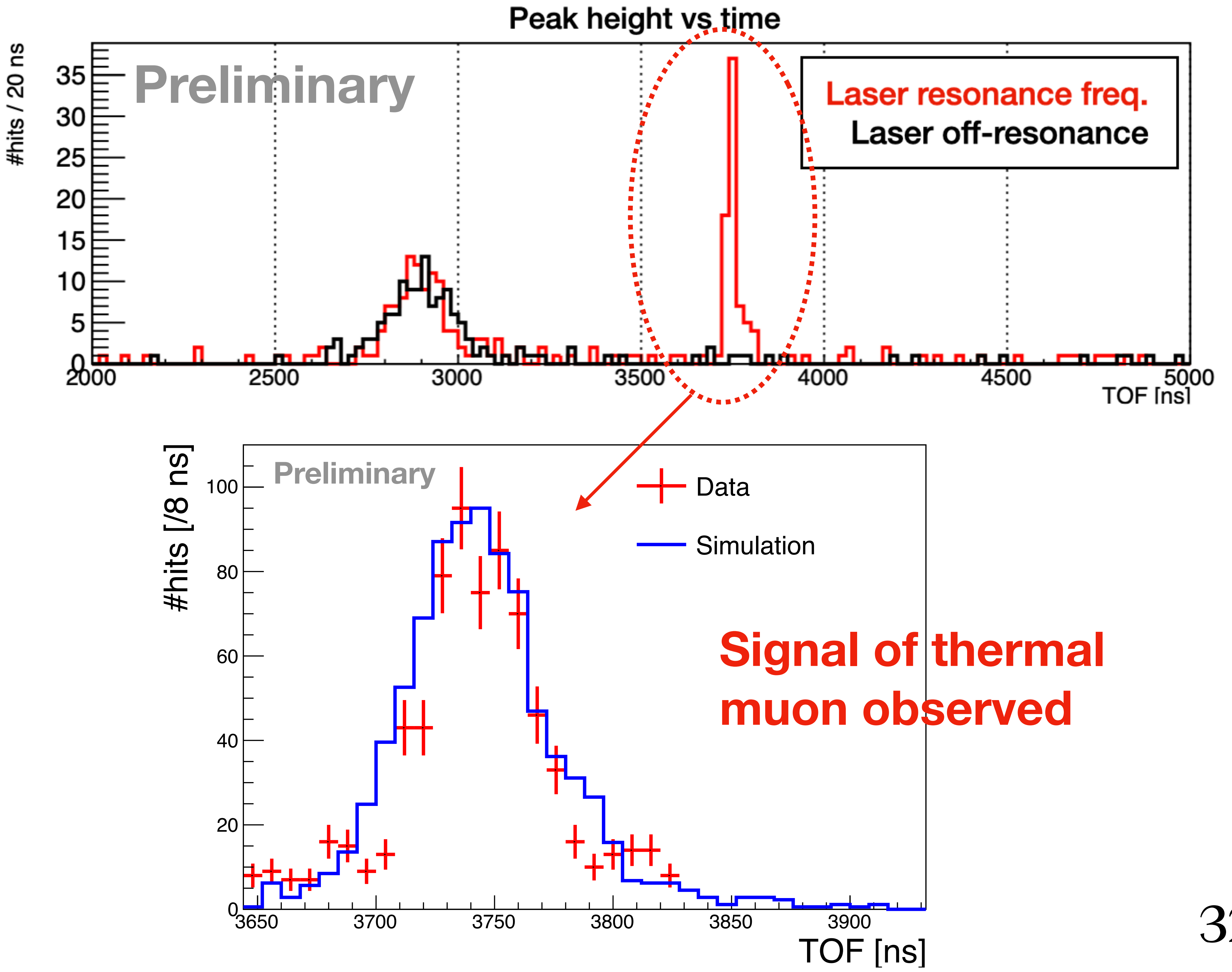
- **Final goal:**
  - Muon mass: 1 ppb
  - (1S-2S: 10 kHz, 4 ppt)

Thermal Muon Source

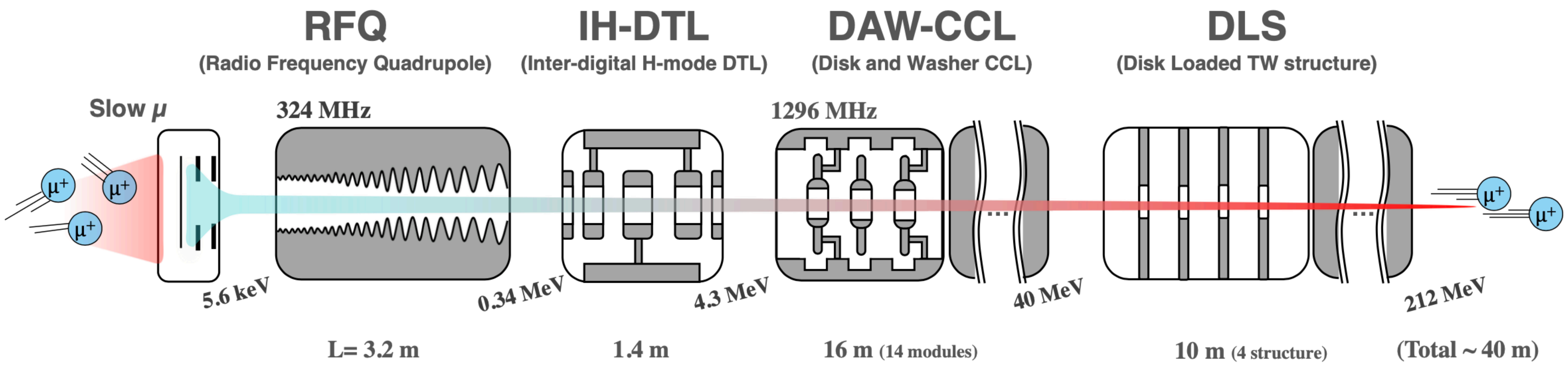
Muonium (Mu) Laser Ionization Test

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





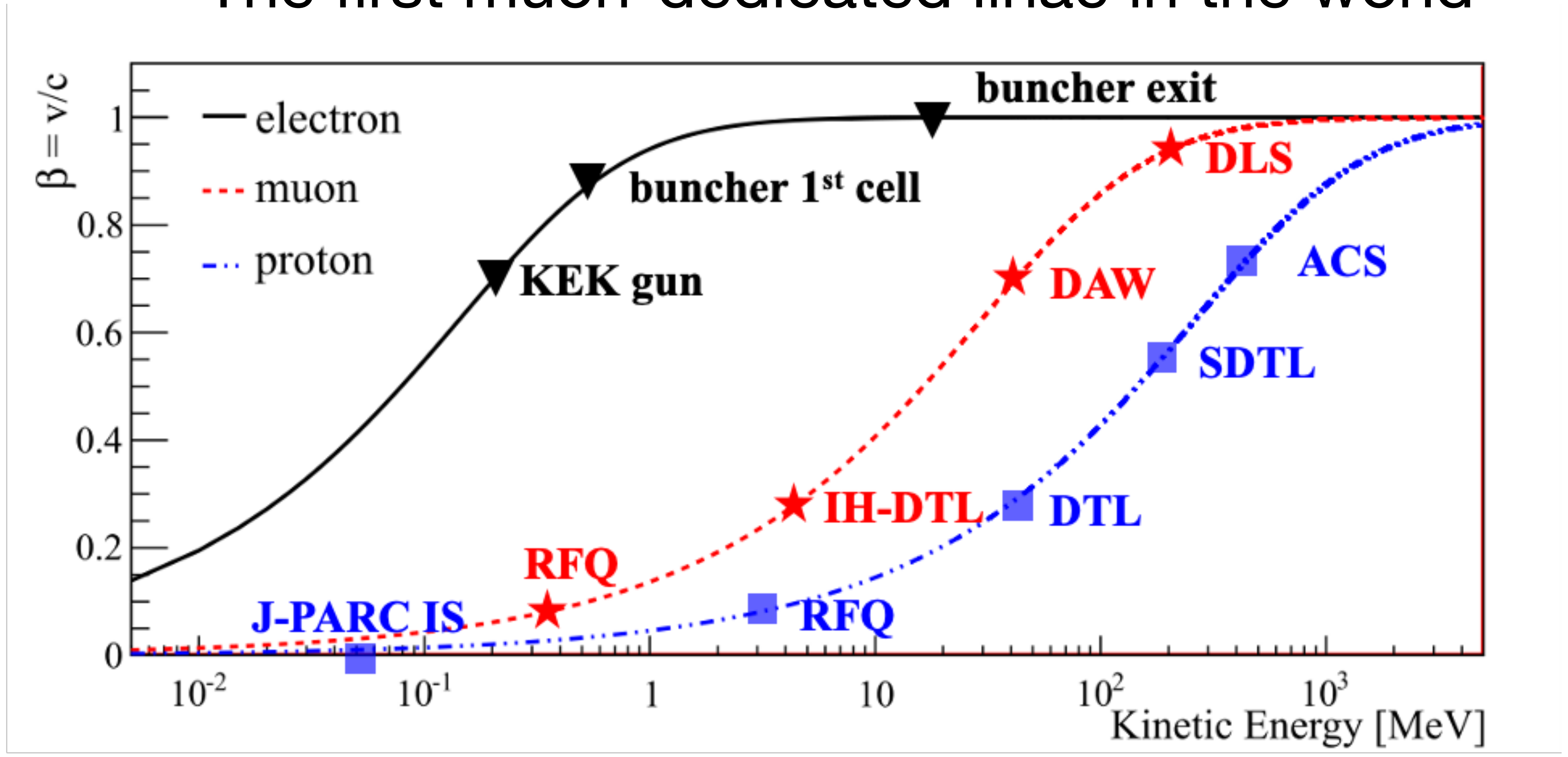
Muon Acceleration



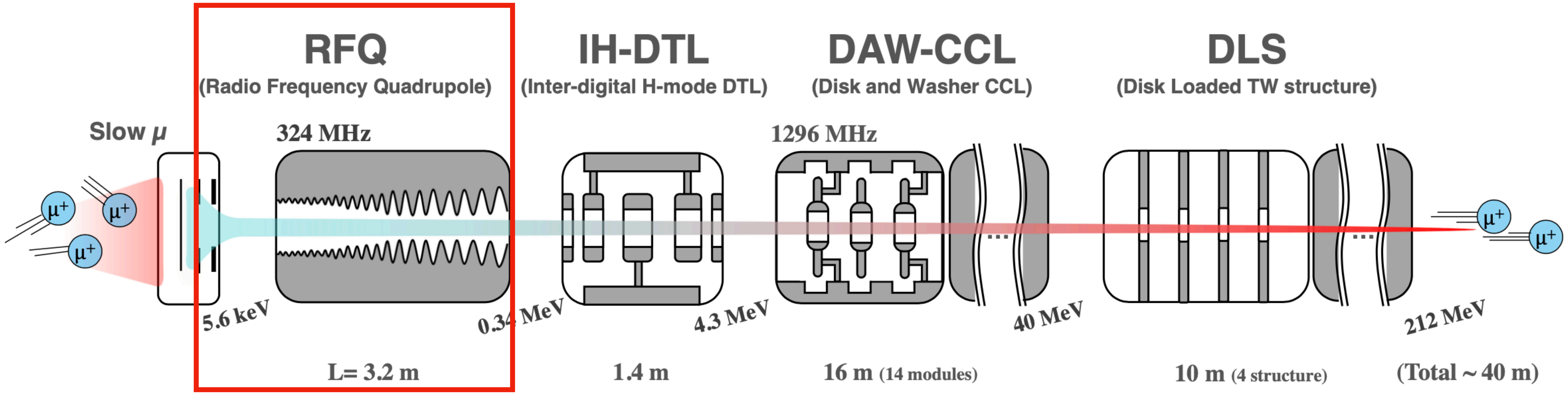
Muon LINAC parameters

Frequency (2-stage)	324MHz, 1296MHz
Intensity	1×10^6 /s
Rep rate	25 Hz
Pulse width	10 ns
Norm. rms emittance	1.5 π mm mrad
Momentum spread	0.1 %

- The first muon-dedicated linac in the world



Muon Acceleration



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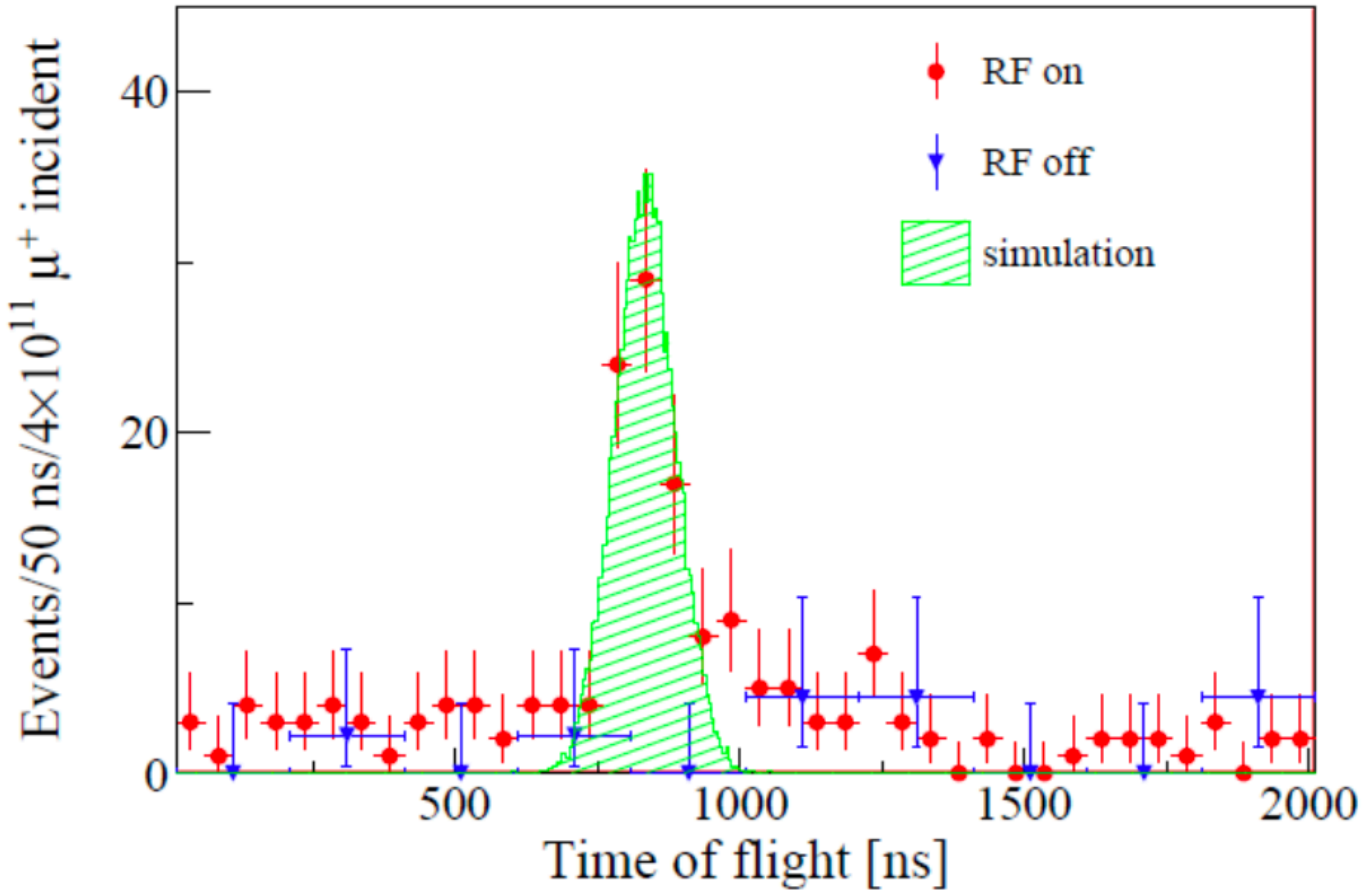
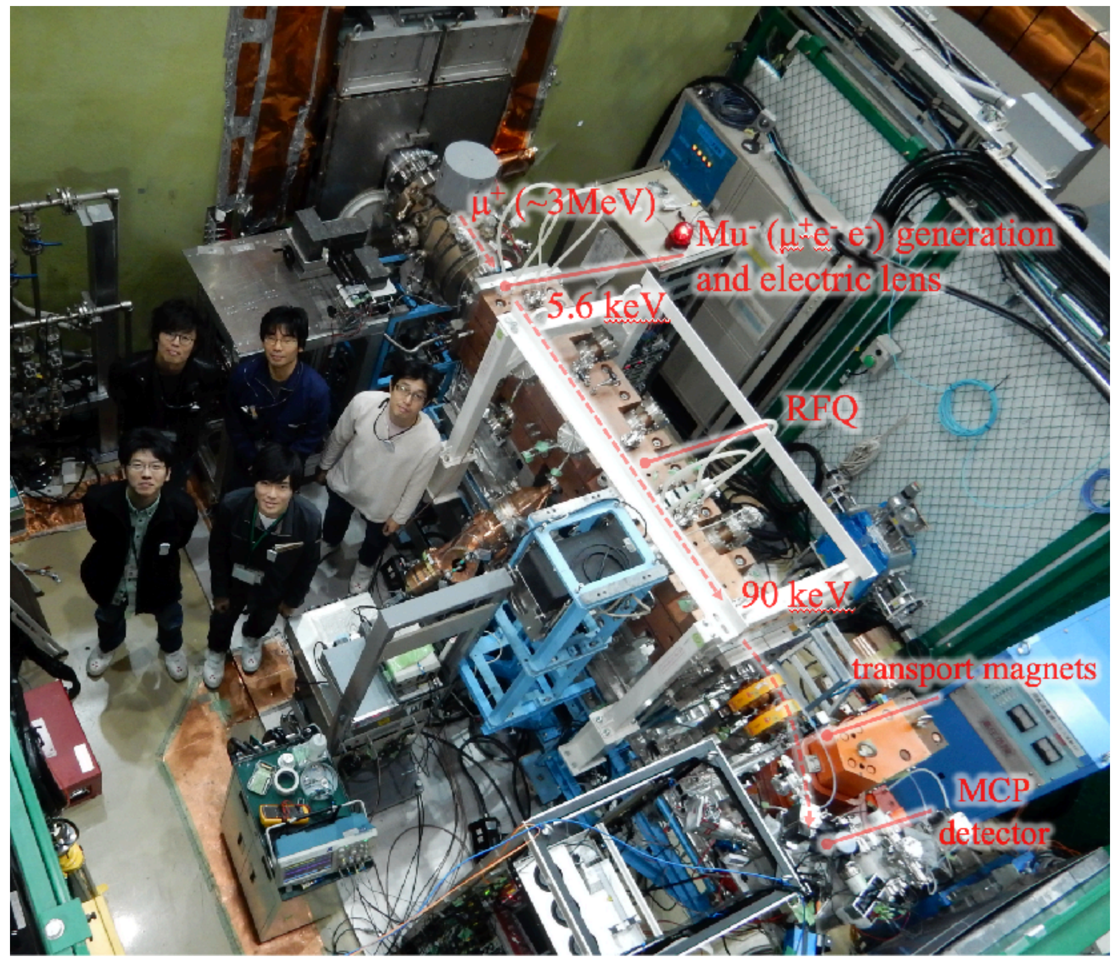
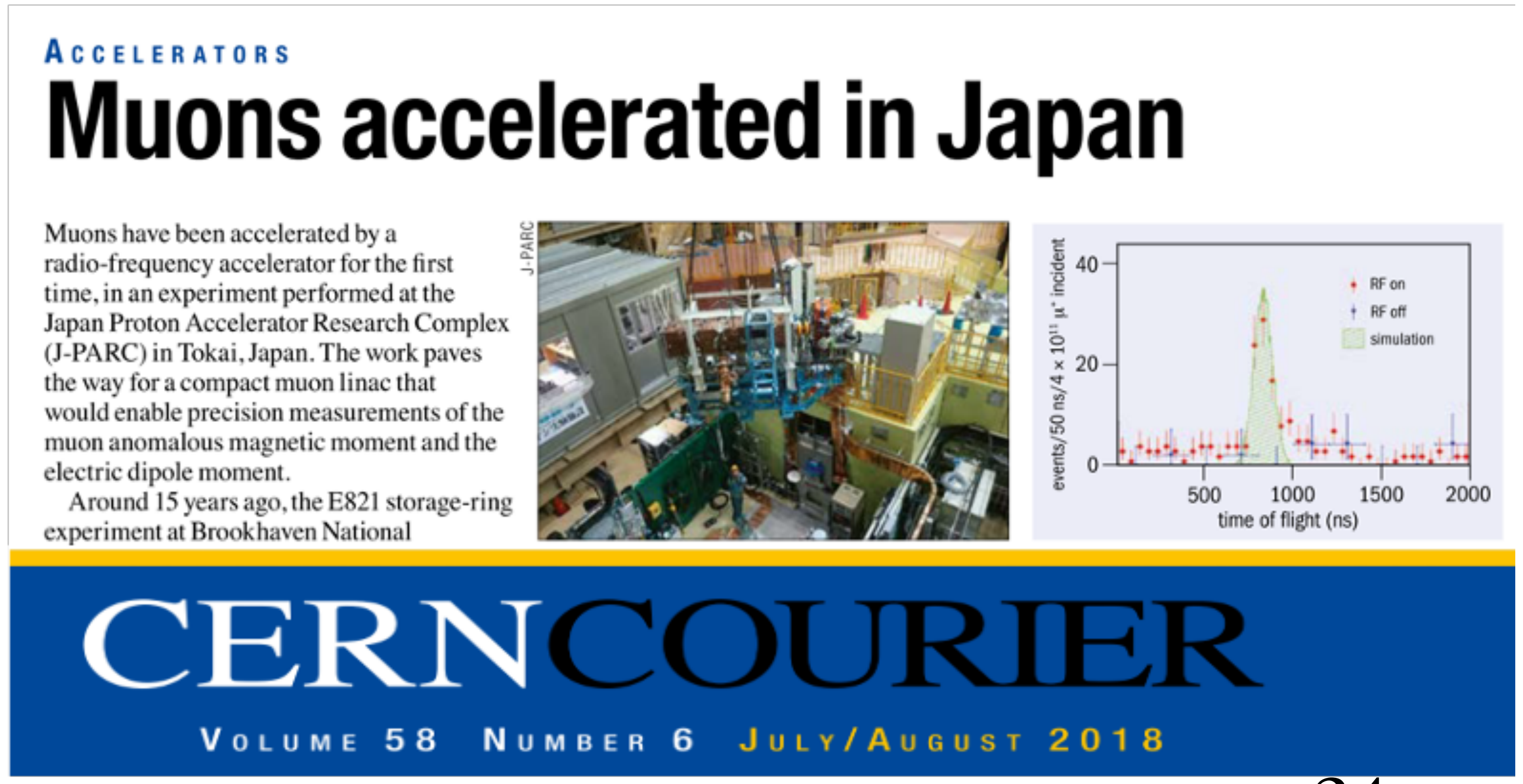
Rep rate	25 Hz
Pulse width	10 ns
Norm. rms emittance	1.5 π mm mrad
Momentum spread	0.1 %

- **First muon acceleration using RF linac!**

Phys. Rev. Accel. Beams 21, 050101 (2018)







ACCELERATORS

Muons accelerated in Japan

Muons have been accelerated by a radio-frequency accelerator for the first time, in an experiment performed at the Japan Proton Accelerator Research Complex (J-PARC) in Tokai, Japan. The work paves the way for a compact muon linac that would enable precision measurements of the muon anomalous magnetic moment and the electric dipole moment.

Around 15 years ago, the E821 storage-ring experiment at Brookhaven National

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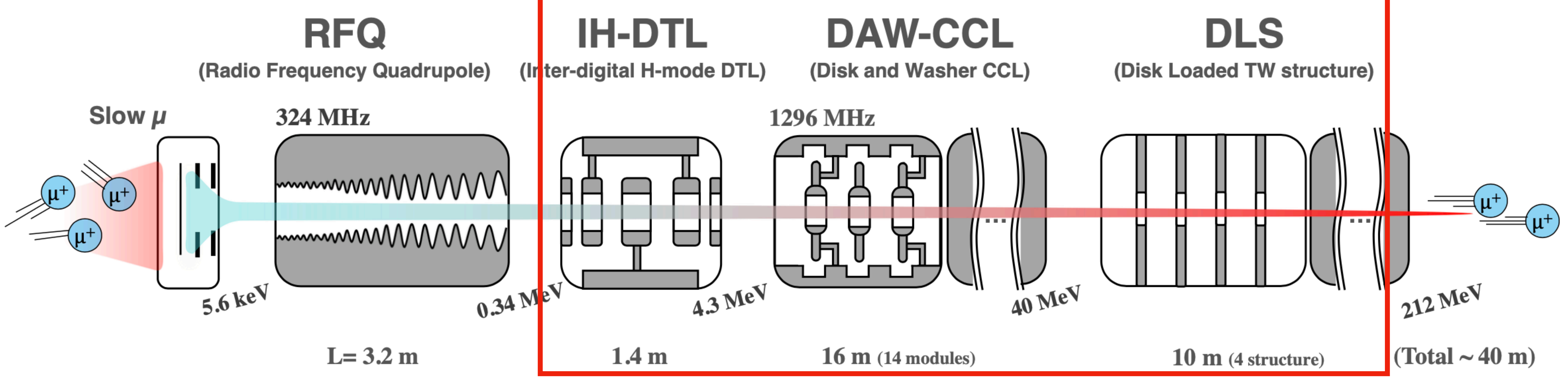
VOLUME 58 NUMBER 6 JULY/AUGUST 2018

Muon Acceleration



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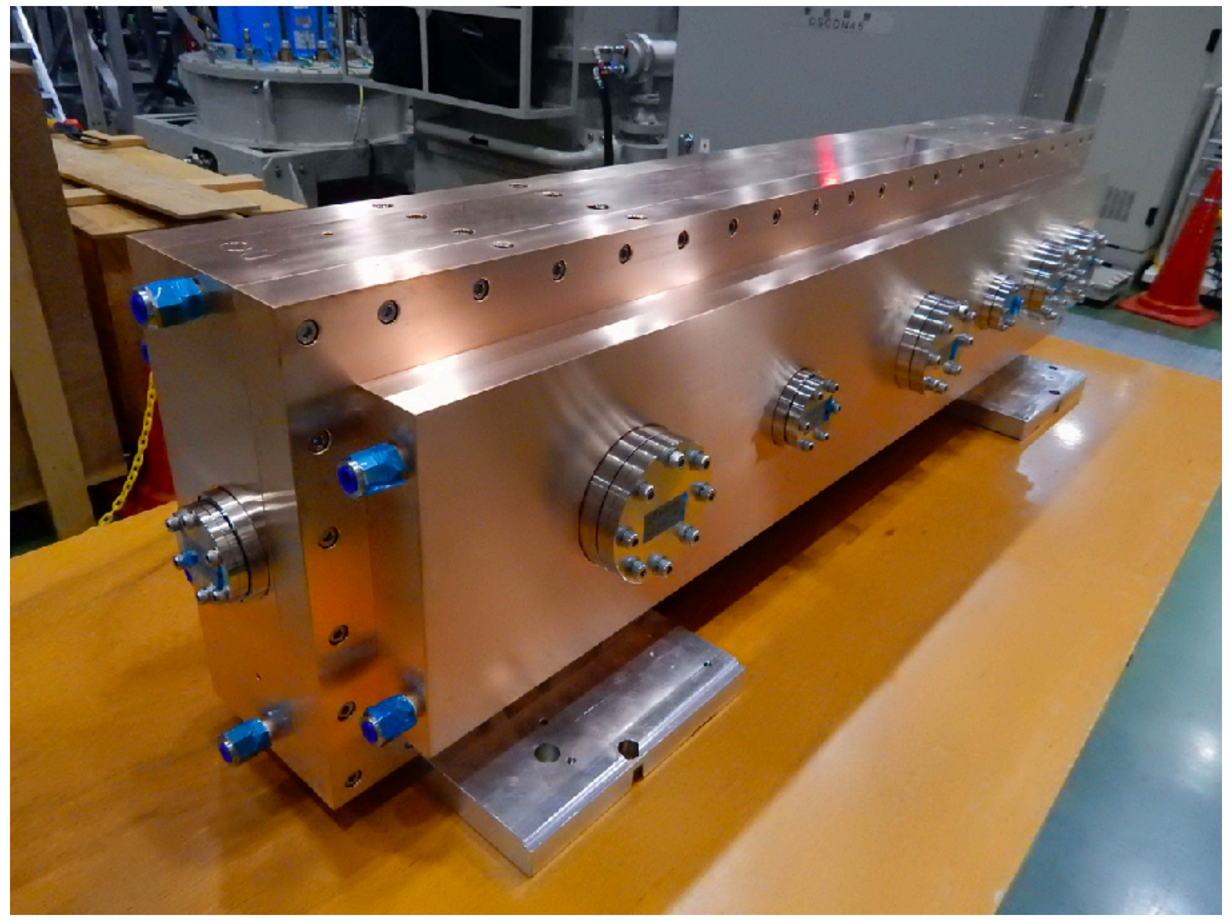
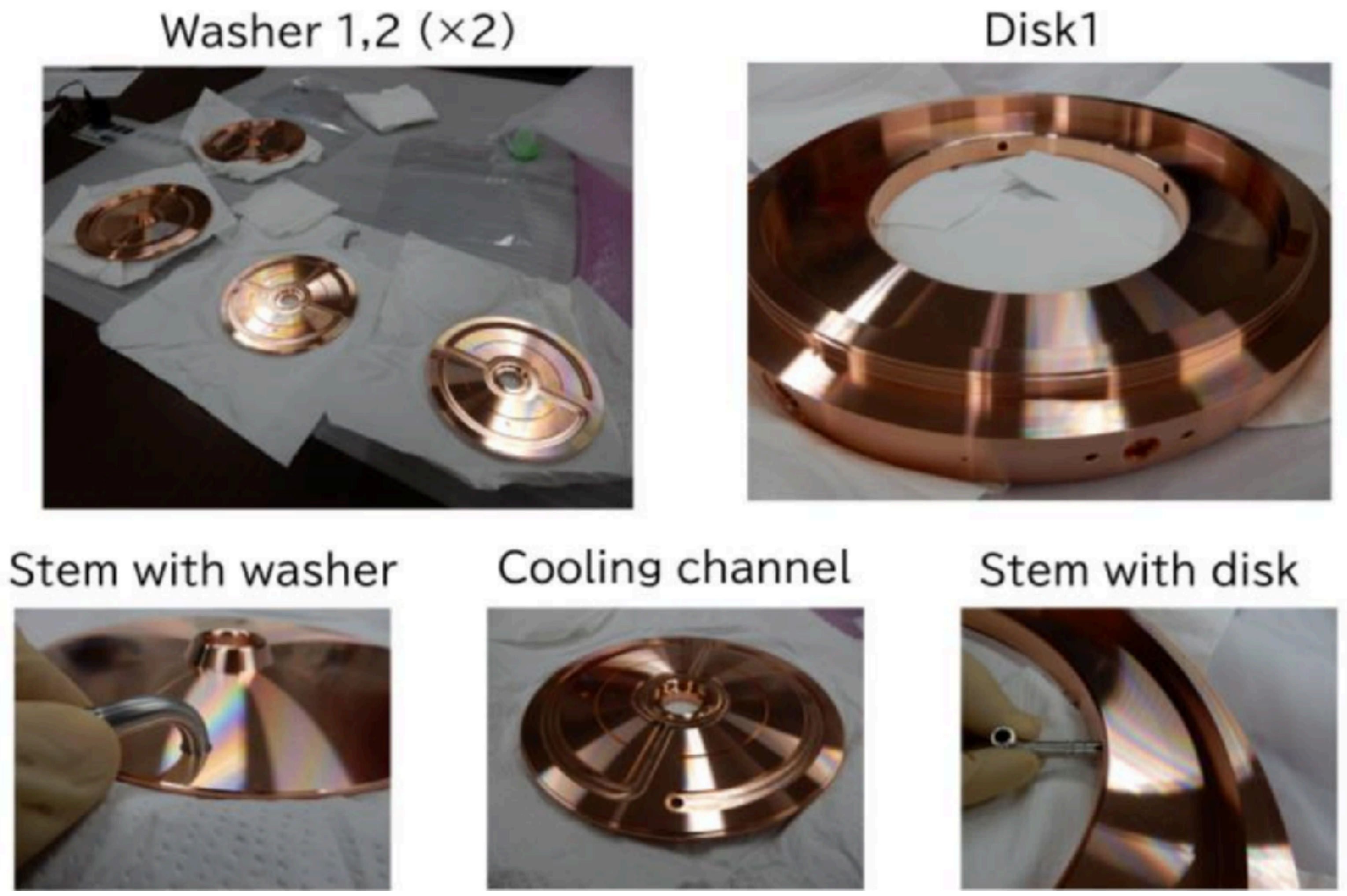
Momentum spread	0.1 %

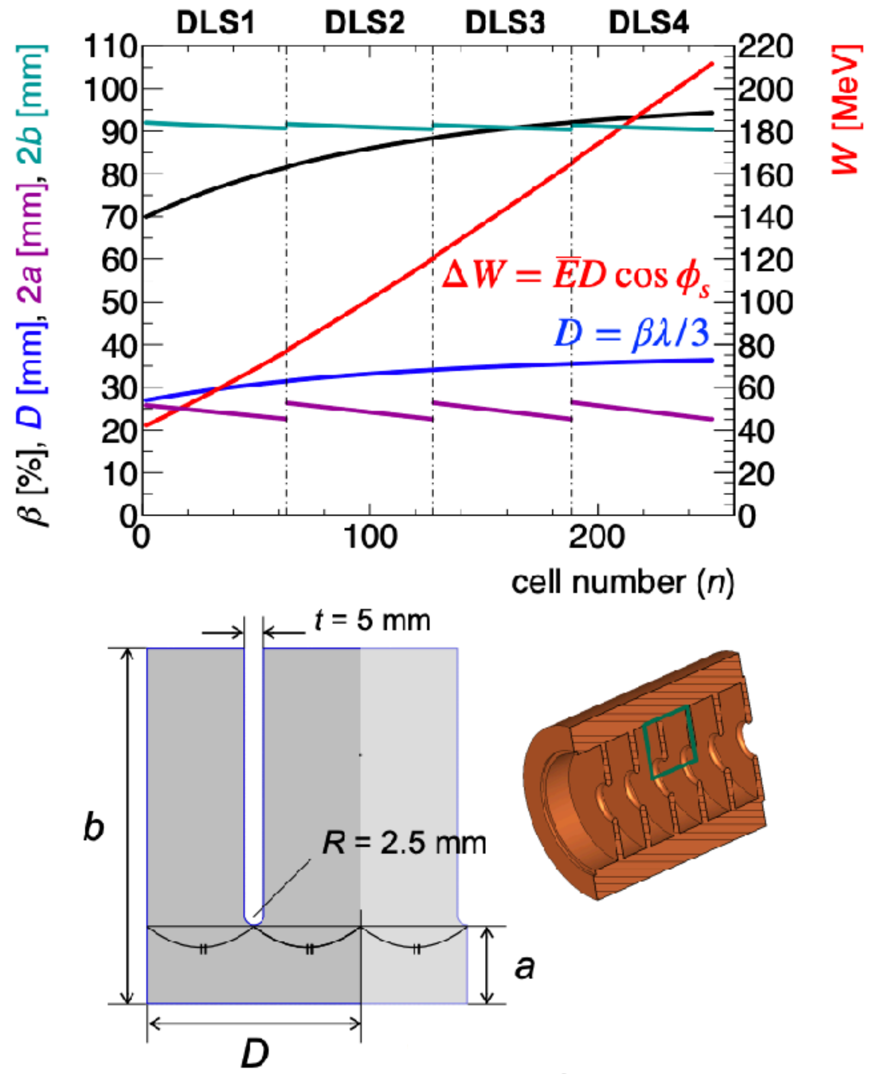
- Completed fabrication of the real IH-DTL
- Fabricating the 1st DAW tank & proto-DLS.



Real IH-DTL



Real DAW in production

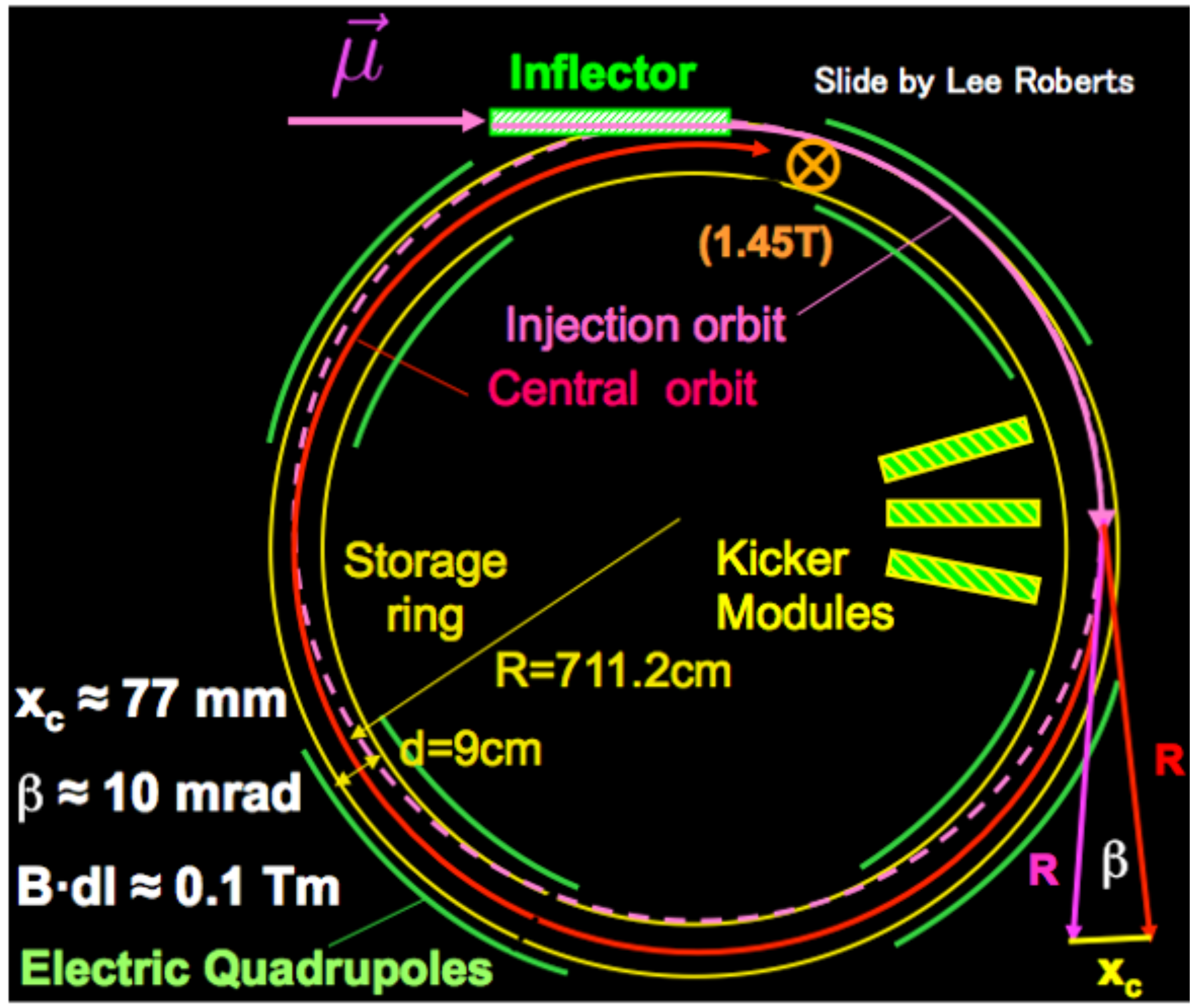


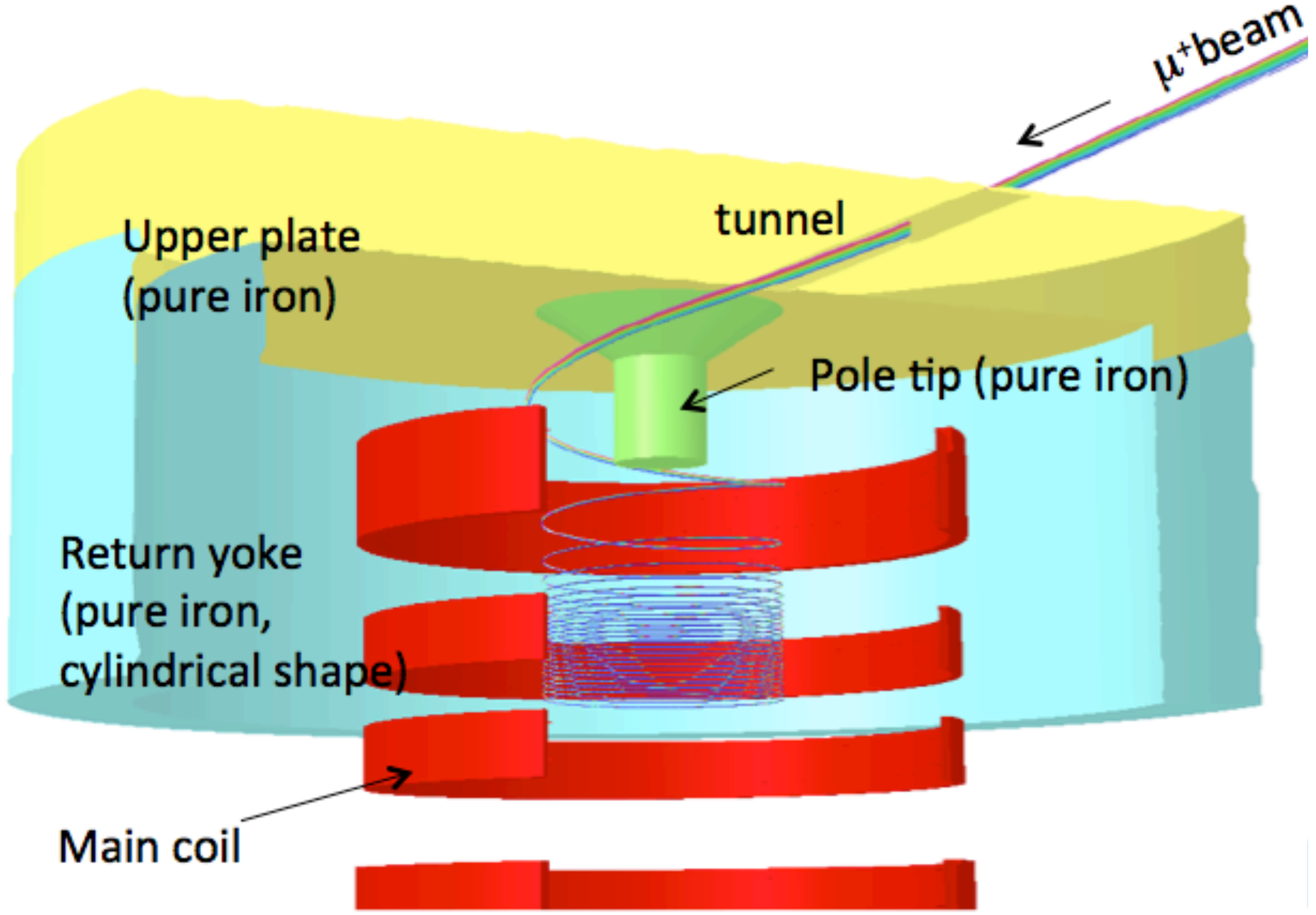
proto-DLS soon

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 ~3-5%

[PRD73, 072003, 2006]

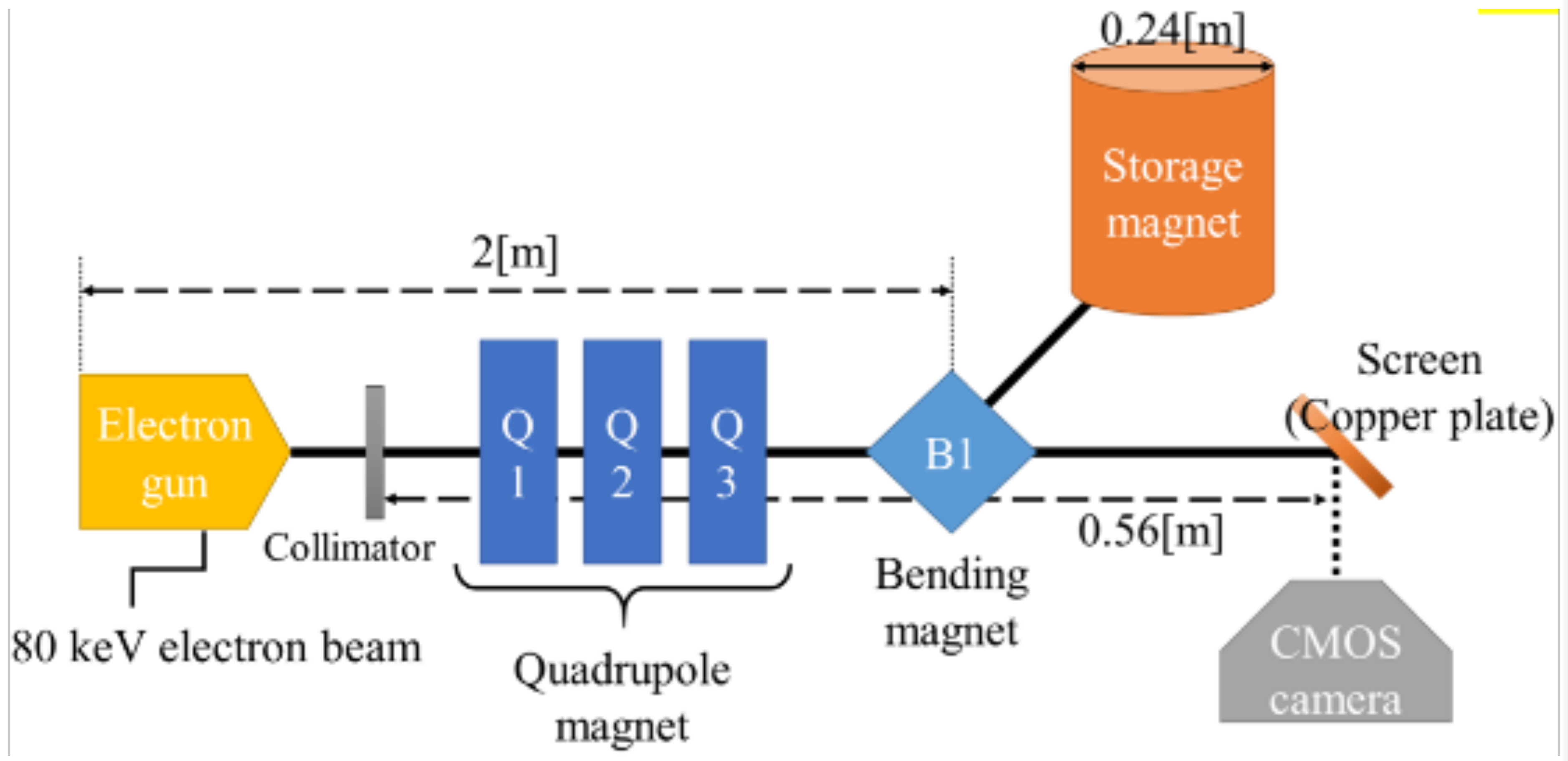
Novel injection @J-PARC

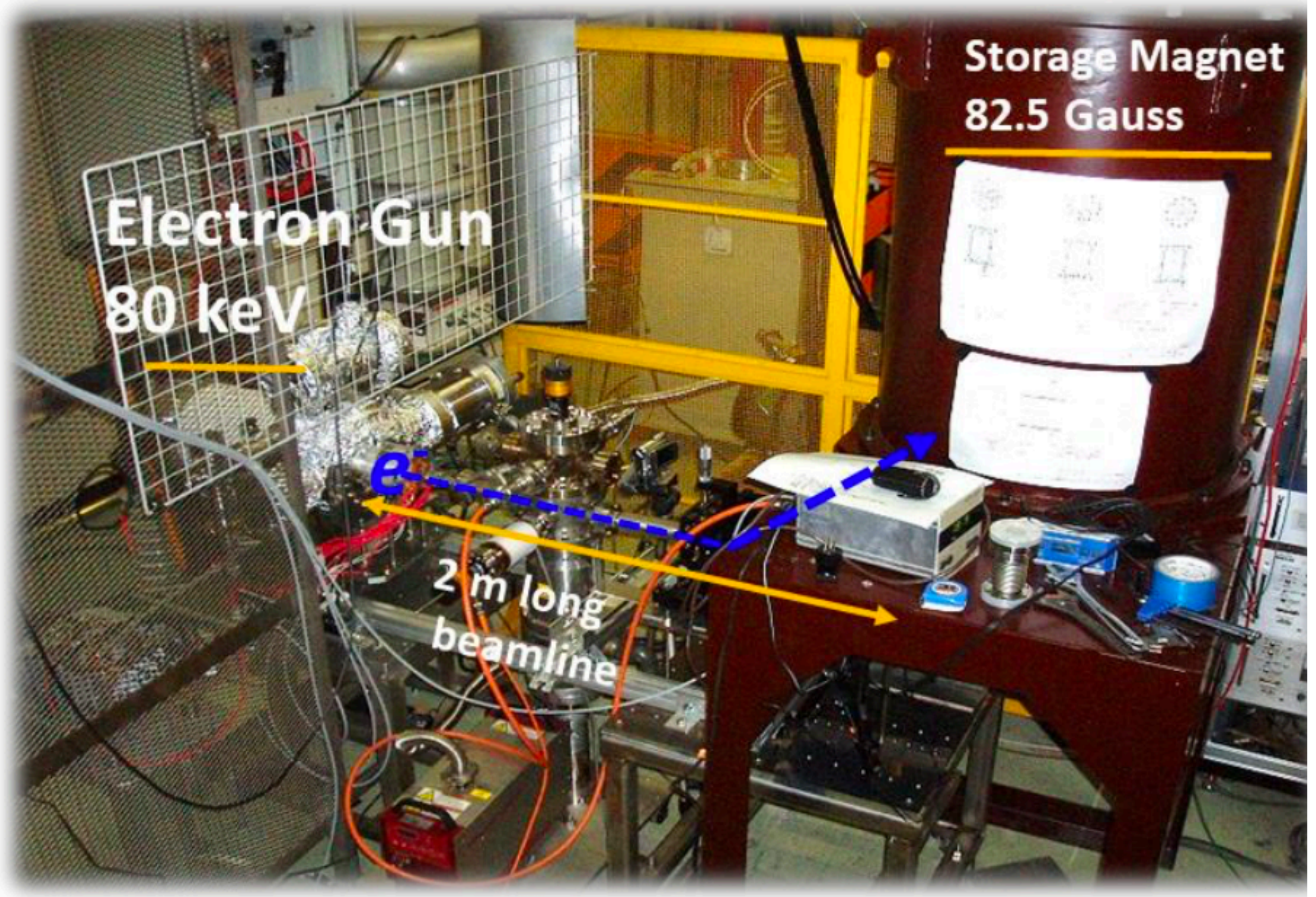
- 3D spiral injection + vertical kicker
- Efficiency > 80%

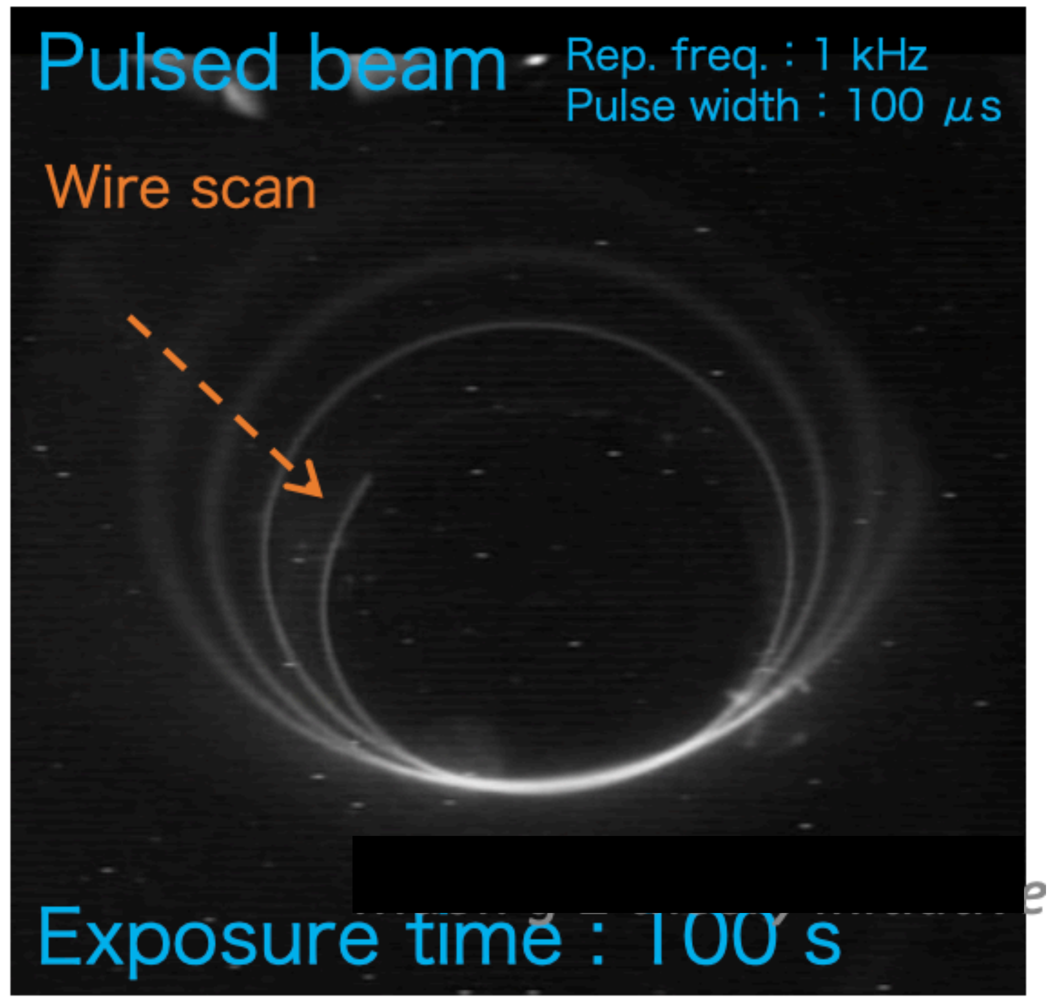
[H. Iinuma et al., NIMA 832, 51, 2016]

3D Spiral Injection

- Prototypes of the kicker were fabricated, and the 3D injection scheme is validated using a low momentum pulsed electron beam at KEK
- Finalize kicker power supply specifications and purchase them in 2023



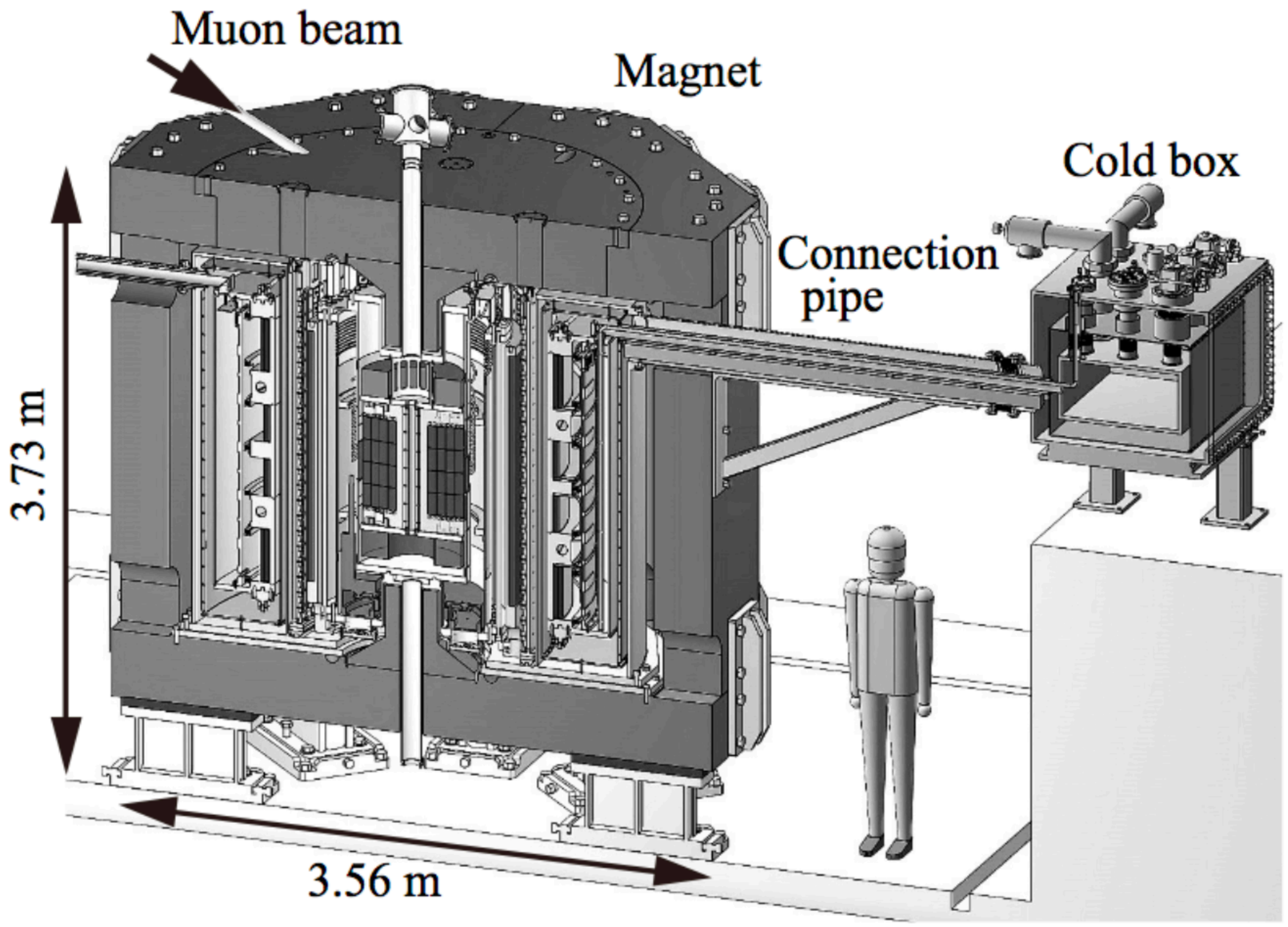




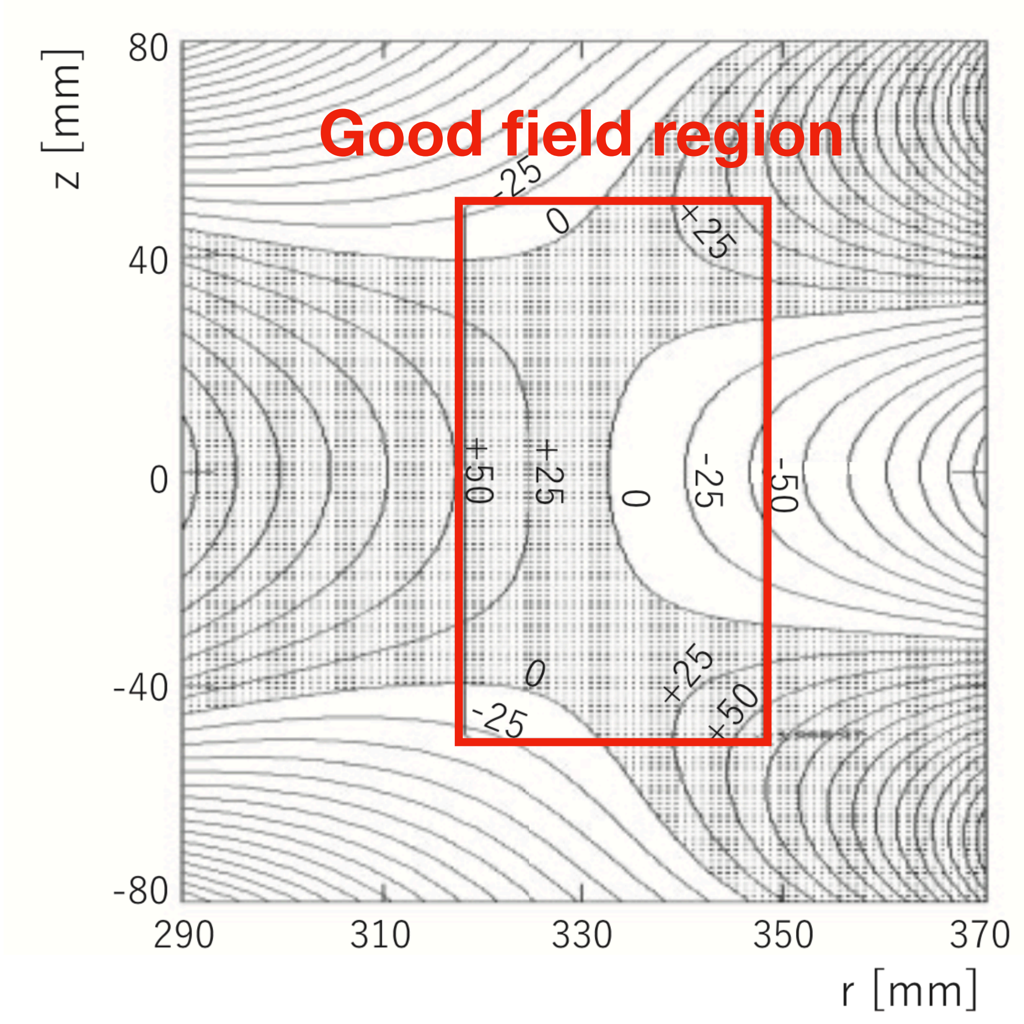
- Spiral injection test equipment using electron beam
- visualization of 3D spiral geometry with a CCD camera

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



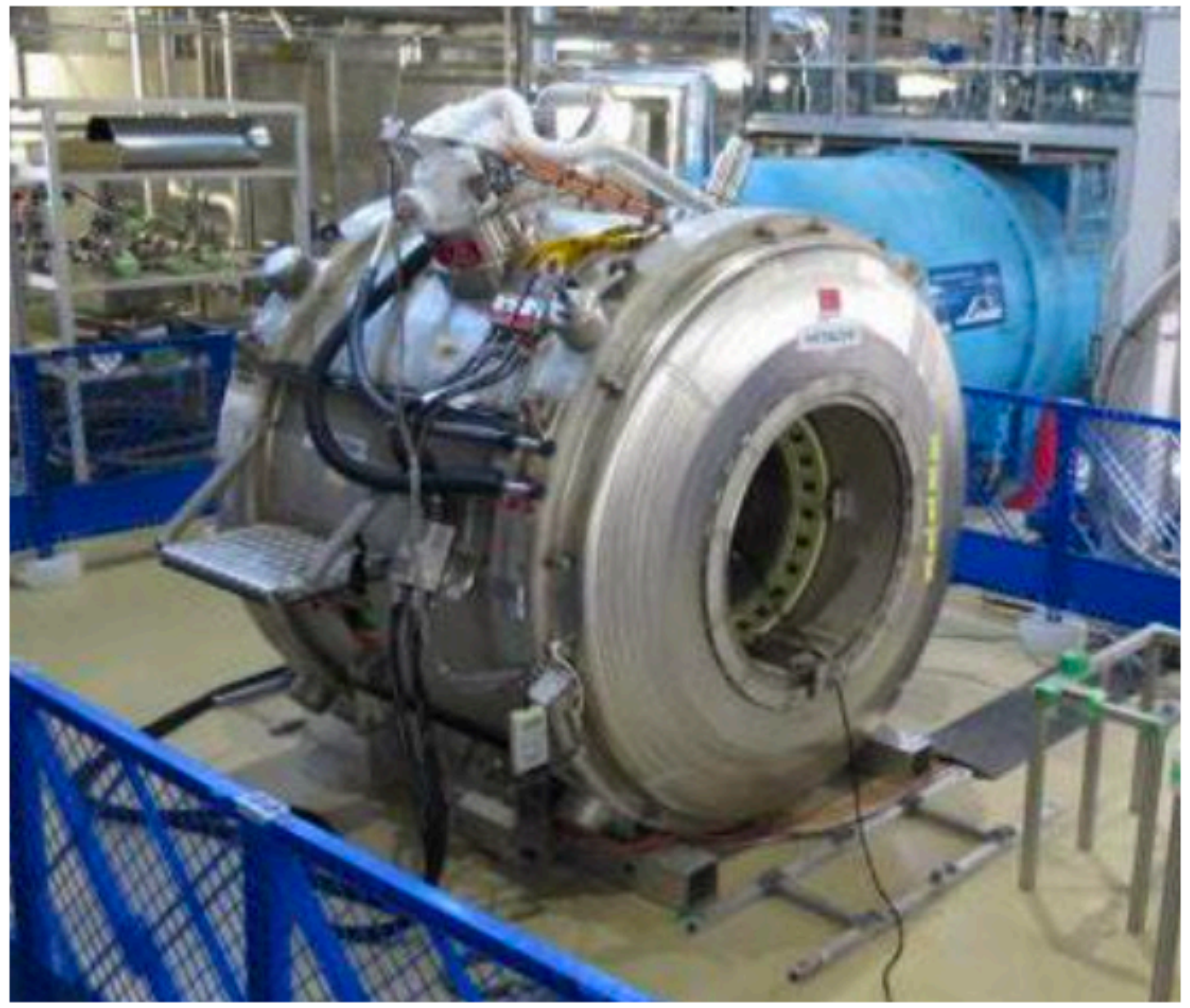
Average magnetic field uniformity is better than 0.1 ppm

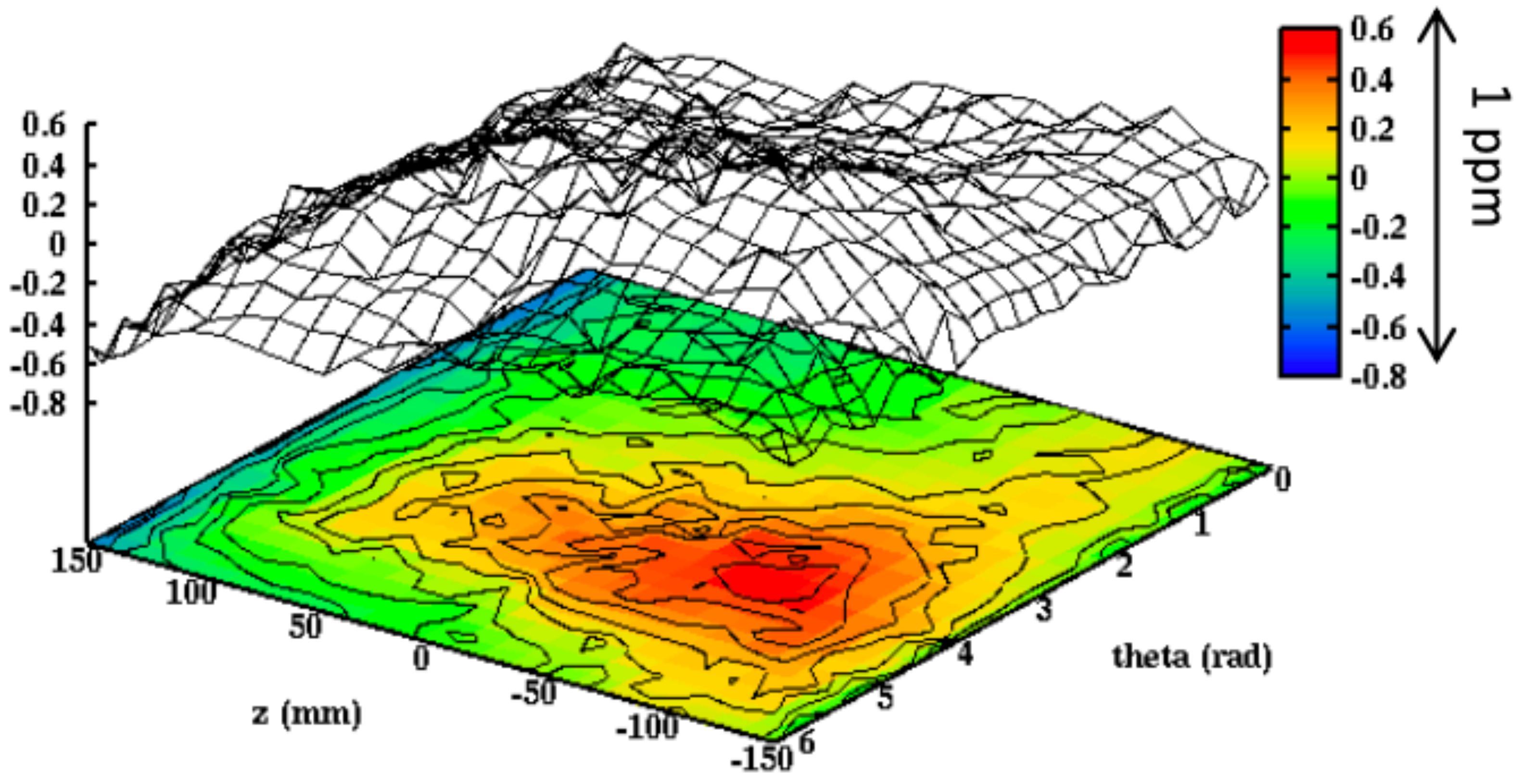
25 ppb/line

Storage Magnet

Magnetic Field Measurement

- Demonstration of sub-ppm field (<0.2 ppm) shimming at **1.2 T** using magnet from MUSEUM; further tests will be carried out to **3 T.**
- 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

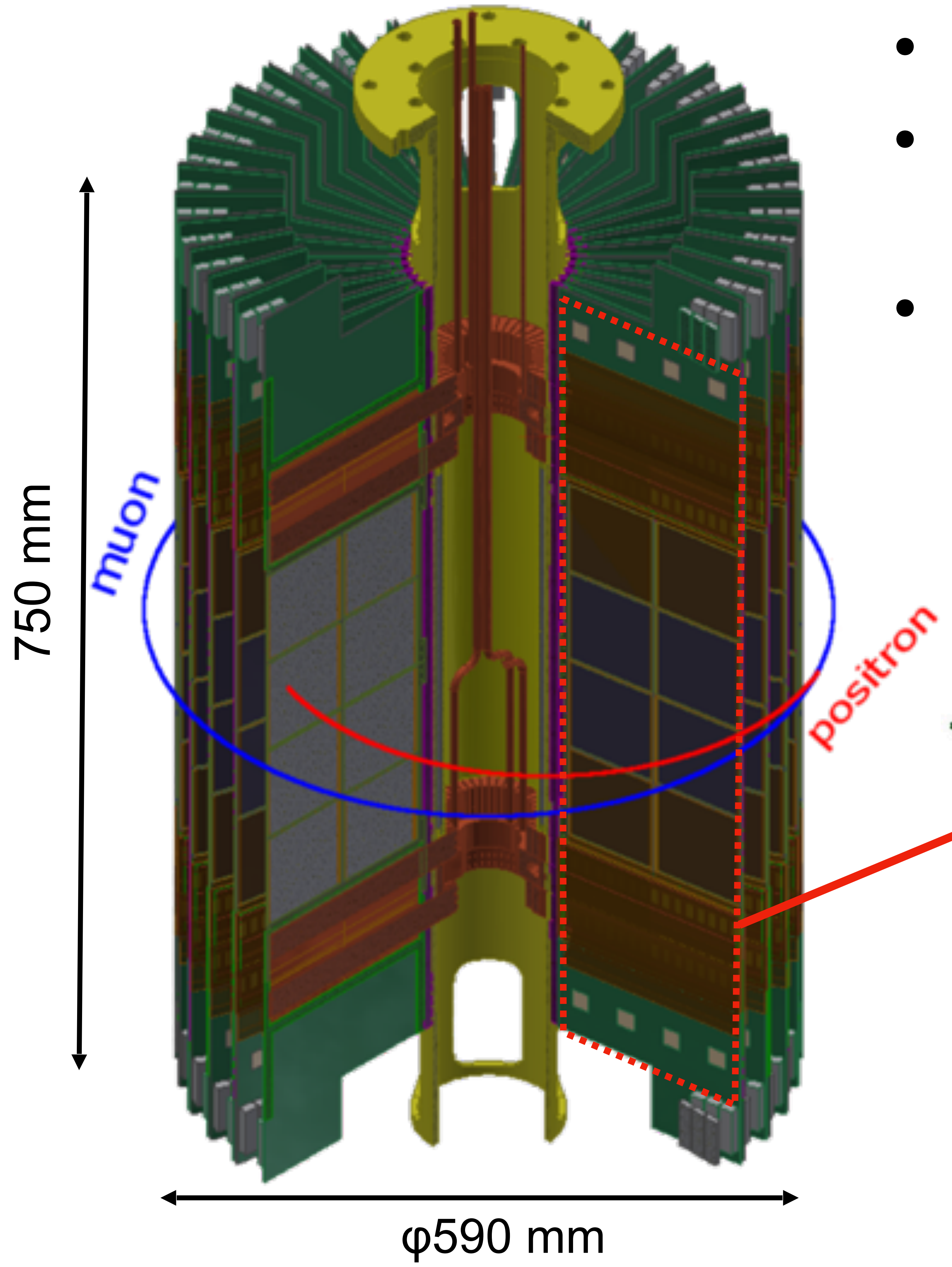


Magnetic field after shimming

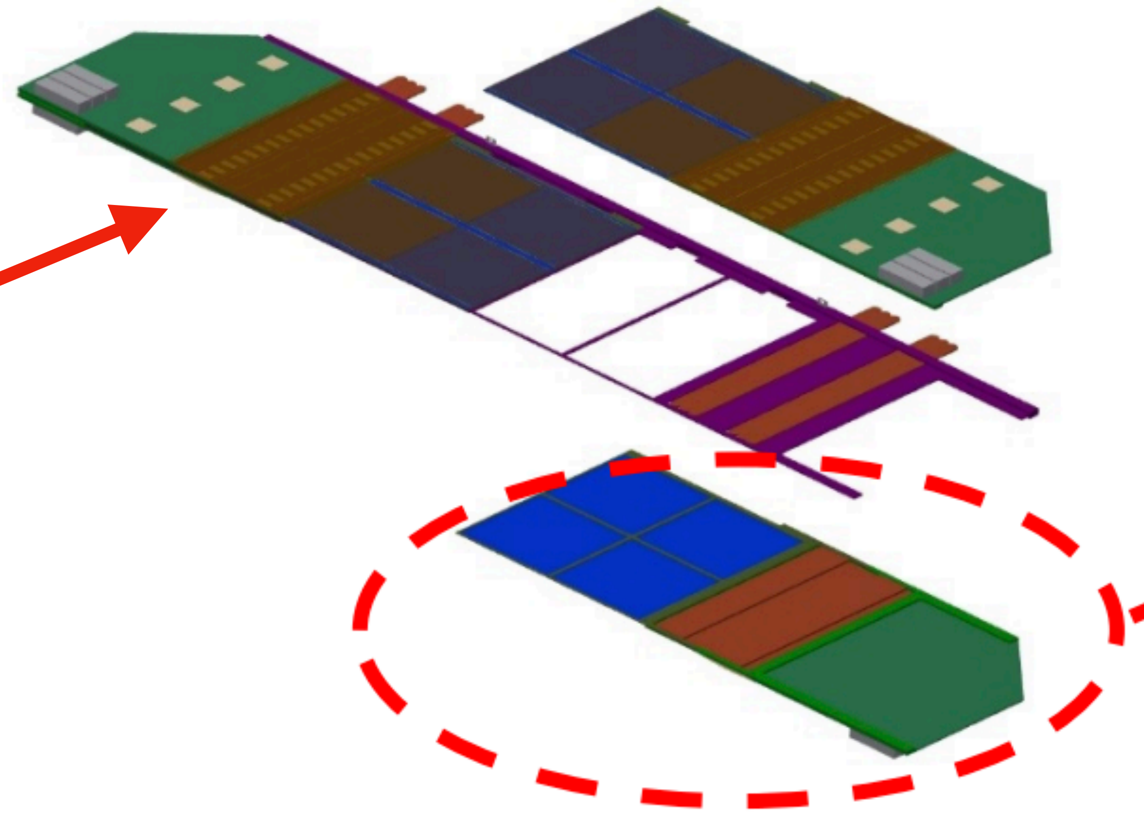

Cross calibration at ANL in January 2019

Positron Tracking Detector

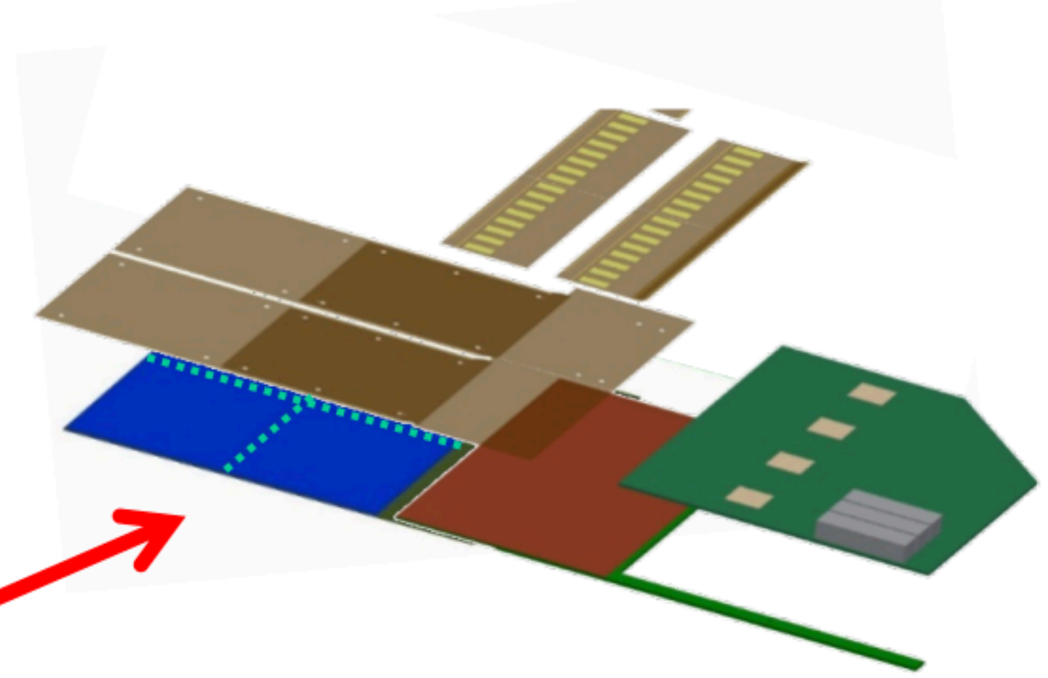
- Reconstruct positron track and precisely measure muon decay time.
- Consists of 40 radial rectangle modules (Vane). A quarter vane consists of 4 silicon sensors + 32 readouts ASICs.
- Two prototypes were fabricated & tested. Mass production of detector components is ongoing.

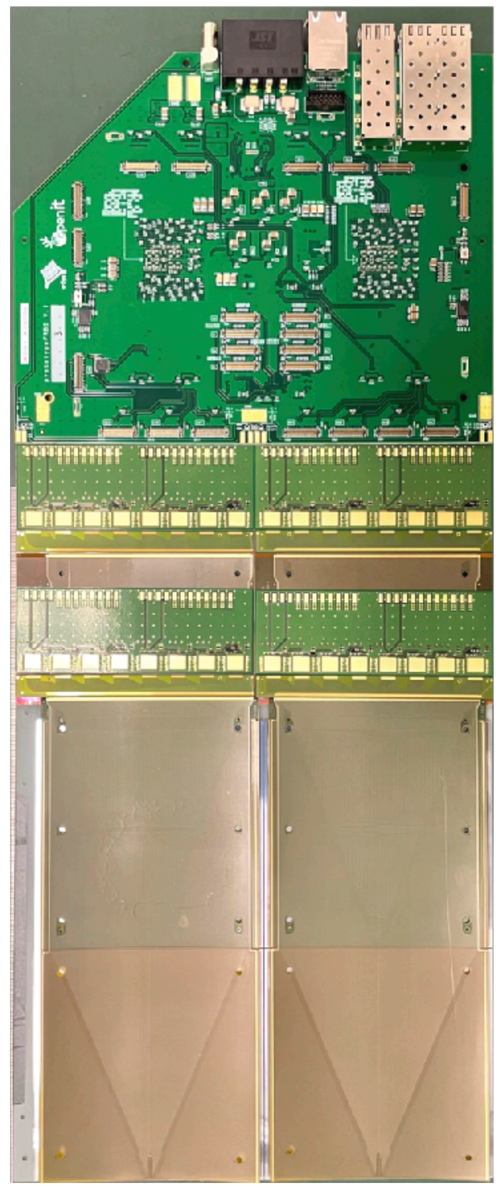


Vane structure



Quarter vane structure

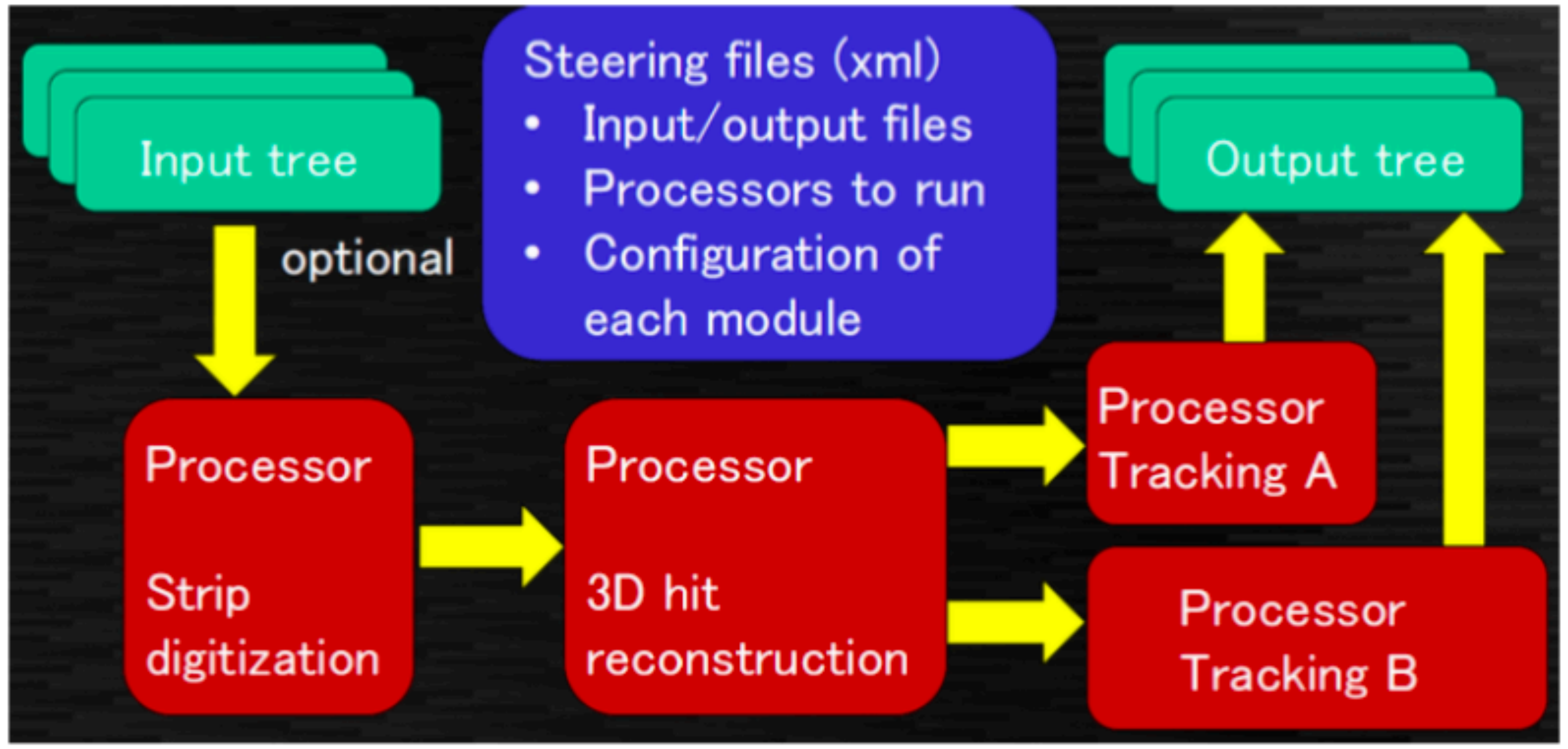




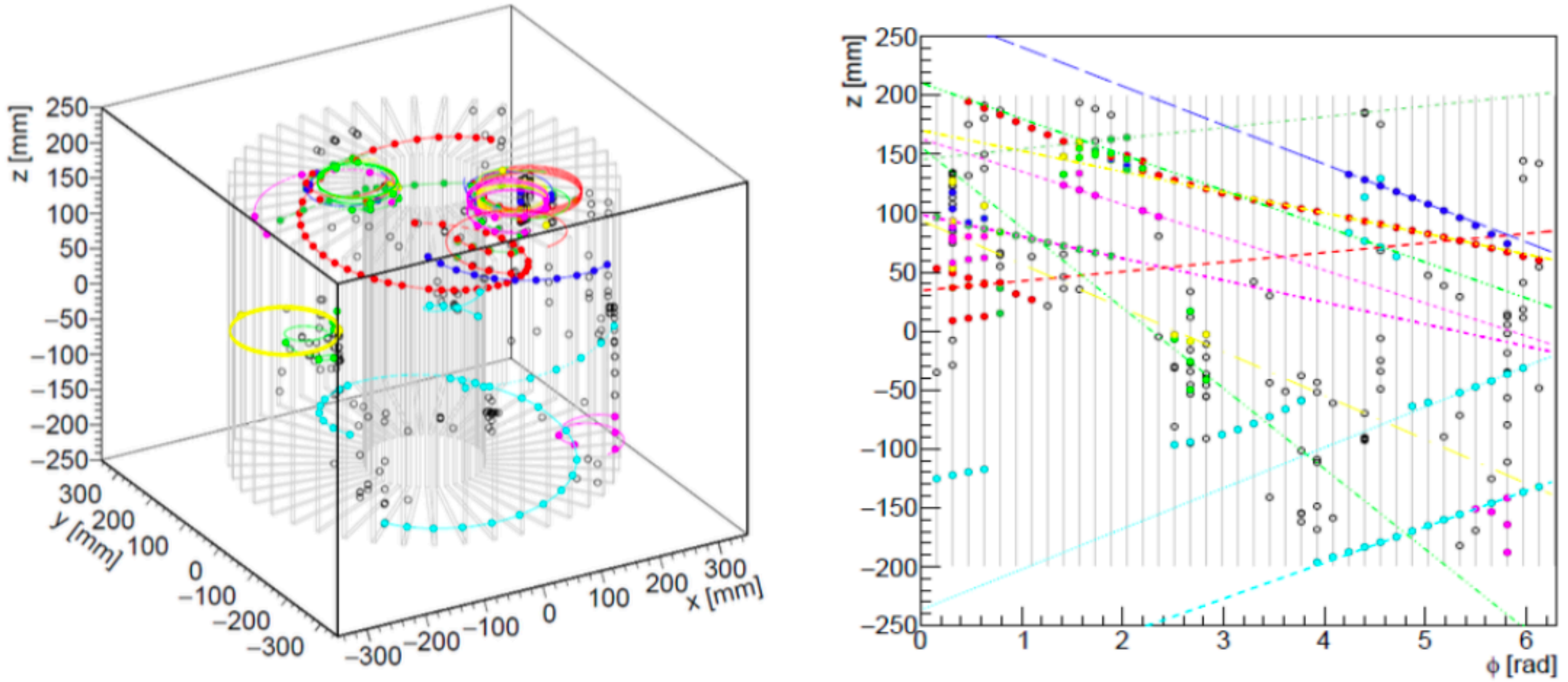
“Pseudo-quarter vane”

Software Development

- To manage detector simulation and track reconstruction, a new software framework was developed (named “g2esoft”).
- Track reconstruction algorithm operating in high track density is being implemented in this software framework.



Concept of g2esoft



Simulated positron hits and reconstructed tracks with 25 positrons

Statistics Estimation

- Initially, a **$3.2\times10^8 \mu$/sec** is expected at the entrance of the H2 area at 1 MW proton power.
- The expected intensity of stored muon is **$1.3\times10^5 \mu$/sec.** Cumulative efficiency from thermal muon generation to reconstructed positron is 4.0×10^{-4}.
- 2-year data (2×10^7 seconds, ~230 days) taking will give a total positron 5.7×10^{11}, achieving the BNL precision of **0.45 ppm** on a_μ.

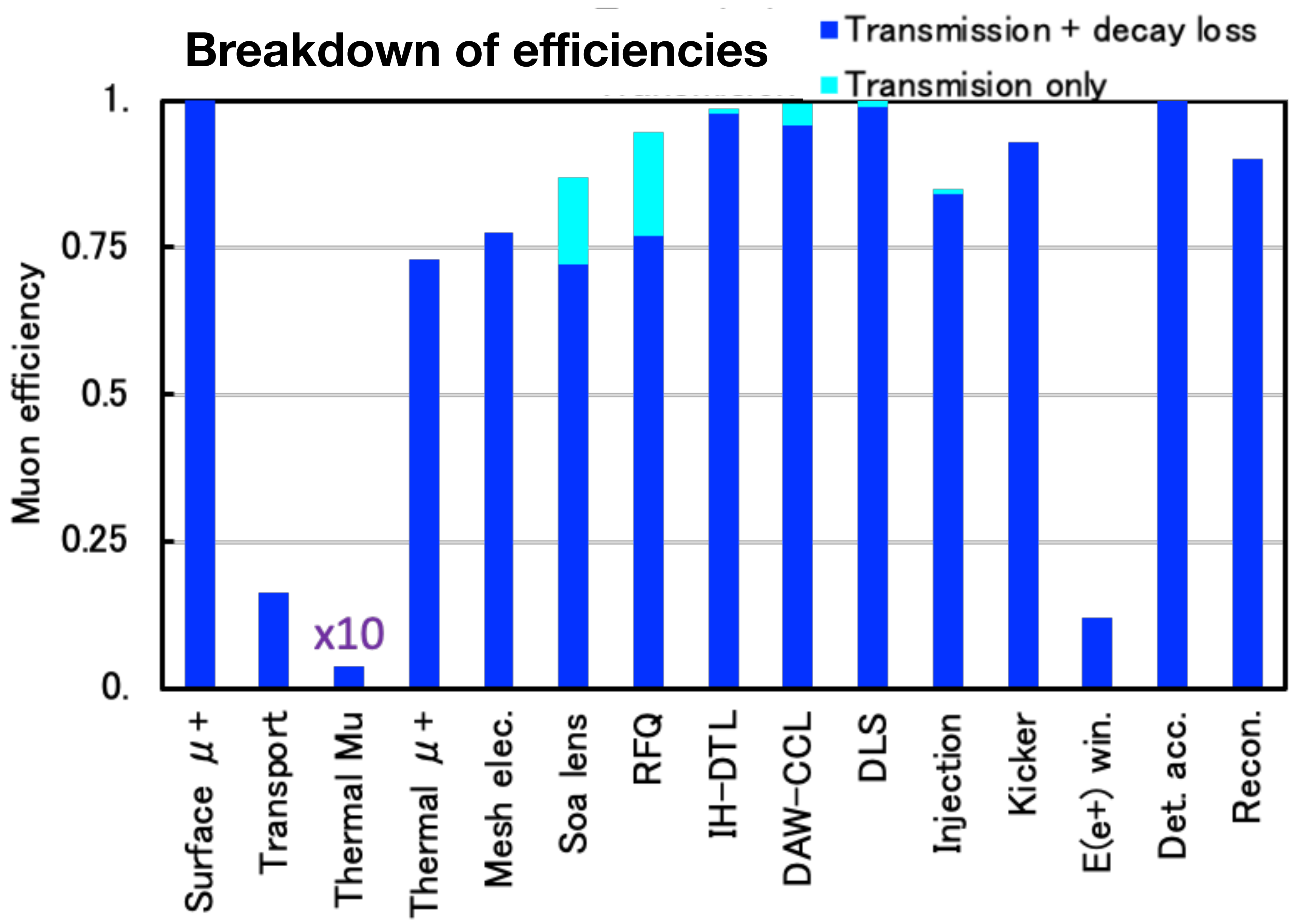


Table 5. Summary of statistics and uncertainties.

	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} $e\cdot$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 systmatic 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
Diffential decay	1.5	Eddy current from kicker	0.1
Quadratic sum	< 40	Quadratic sum	56

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

→ our experiment is still statistical limited

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				Commissioning Data taking
H-line experimental building				Building construction			
Muon Source, LINAC, injection, storage magnet, detector						Installation	
Grant-in-Aids		Kakanhi "specially promoted research"					

Towards the Ultimate Muon Anomaly Test

Slides by T. Mibe, inspired by K. Jungmann's slide

Muon $g - 2$

Fermilab Muon g-2 (E989)

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

$$a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\frac{\omega_a}{\omega_p} - \frac{\mu_\mu}{\mu_p}}$$

120 ppb

$$a_\mu = \frac{\omega_a}{\omega_p}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

8 ppb 120 ppb 0.3 ppt

μ_μ

m_μ

MuSEUM(J-PARC)

Mu HFS

$$\nu_{34} - \nu_{12} \propto \frac{\mu_\mu}{\mu_p}$$

$$\Delta\nu_{\text{1S-HFS}} \simeq \frac{16}{3}\alpha^2 R_\infty \frac{\mu_\mu}{\mu_B}\left(1 + \frac{m_e}{m_\mu}\right)^{-3}$$

m_μ

Mu-MASS(PSI), J-PARC Mu1S-2S exp.

Mu 1S-2S

$$\Delta\nu_{1S2S} \simeq \frac{3\alpha^2}{8h} m_e c^2 (1 + \frac{m_e}{m_\mu})^{-1}$$

Collaboration Status

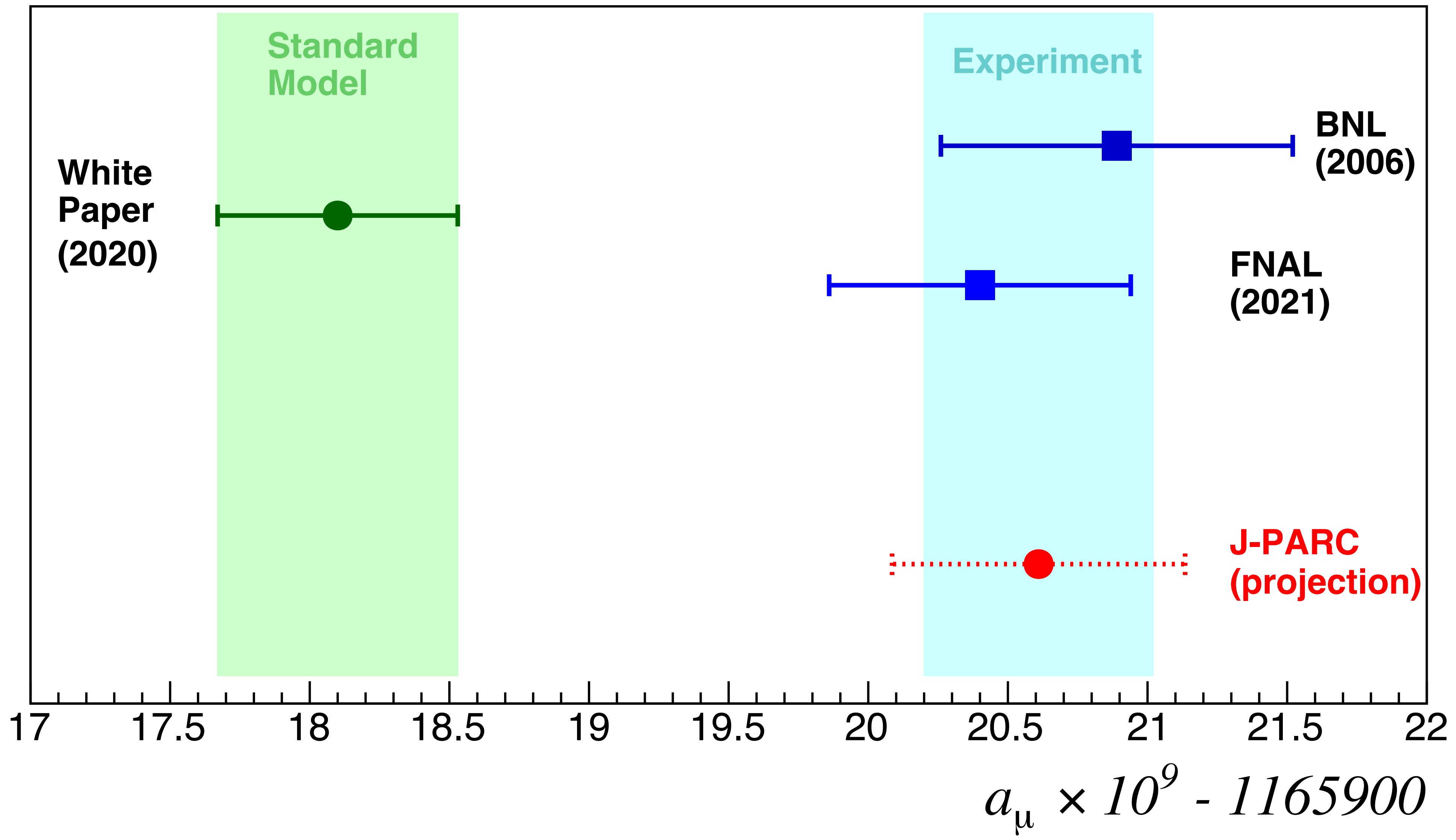
- Now the collaboration consists of 110 members from 9 countries and still growing

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

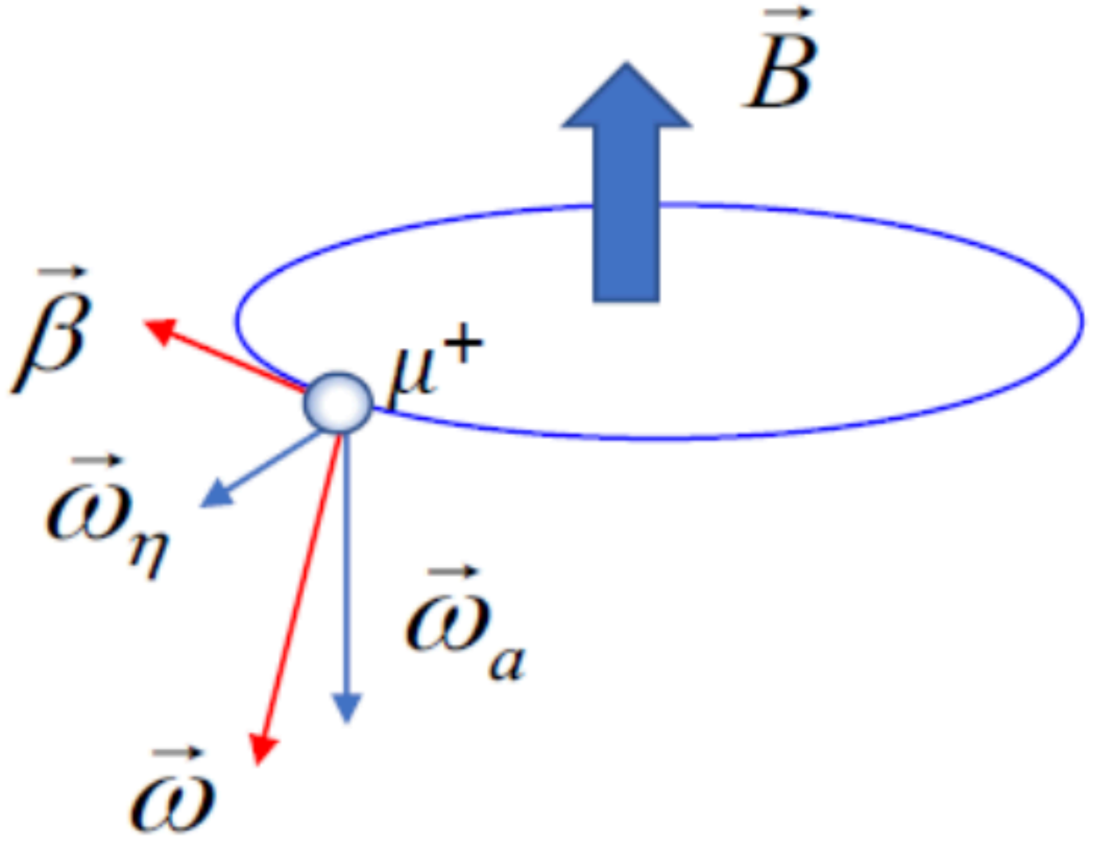
- J-PARC E34 experiment will measure muon $g-2$/EDM in a different approach than BNL and FNAL.
  - A thermal muon beam enables a high-quality muon beam.
  - Muon LINAC re-accelerates muon beam, which is 3D injected into the compact storage region.
  - The tracking detector reduces pile-up and measures the momentum direction of positrons in a highly uniform B-field.
- 0.45 ppm of a_μ measurement is expected with 2 years of data taking.
- The development stage is over; the construction stage has started aiming at the first run in 2027.

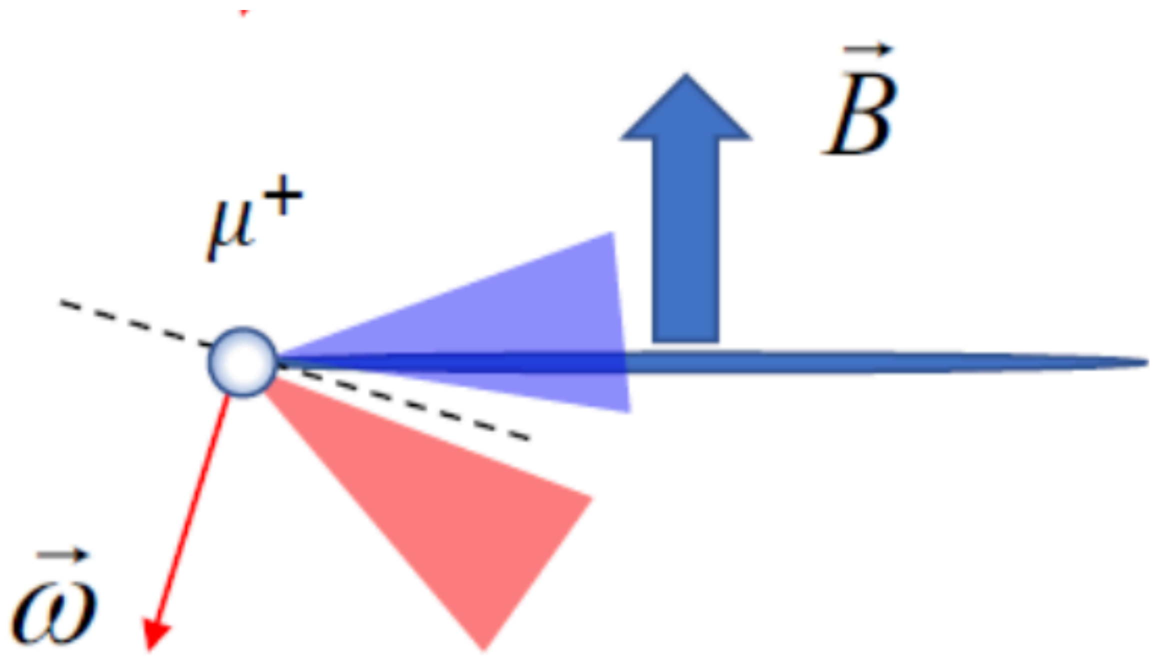


Backup

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)

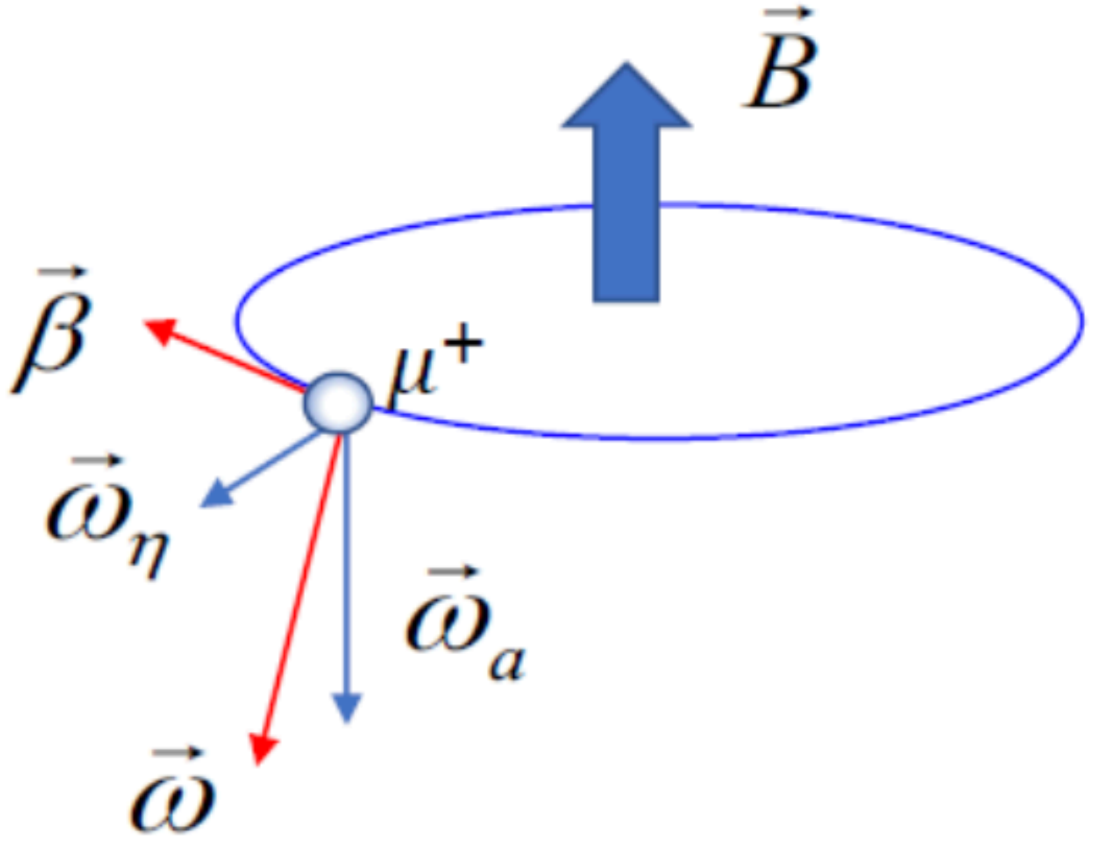
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \boxed{\frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)}\right]$$

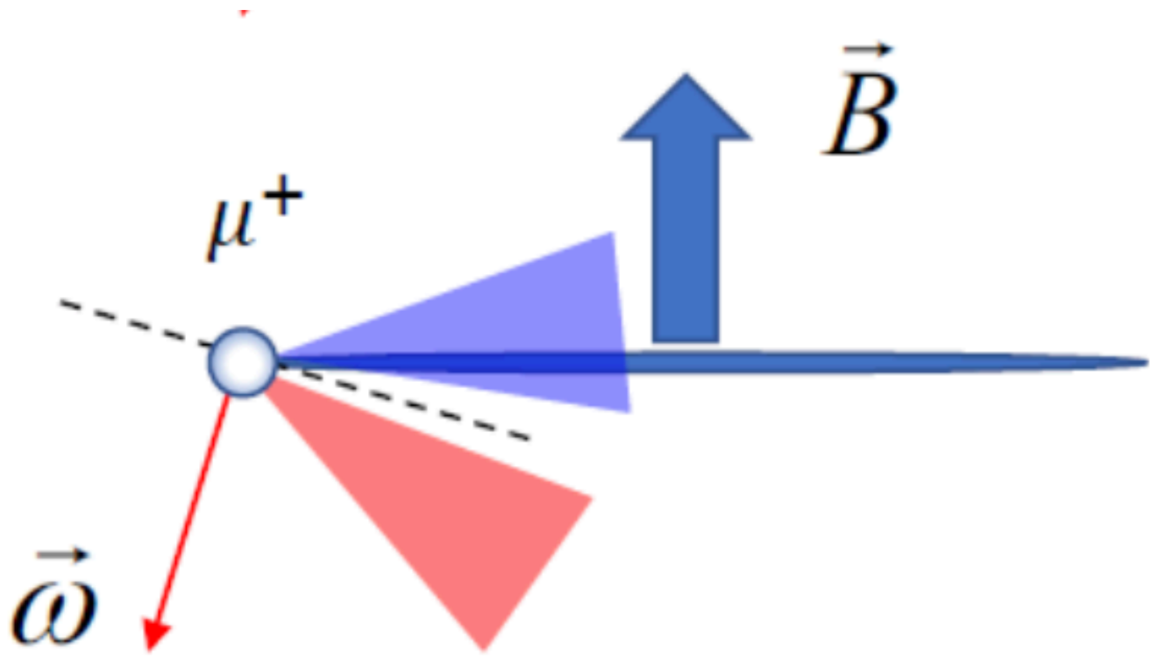
J-PARC E34

(E = 0 at any γ)

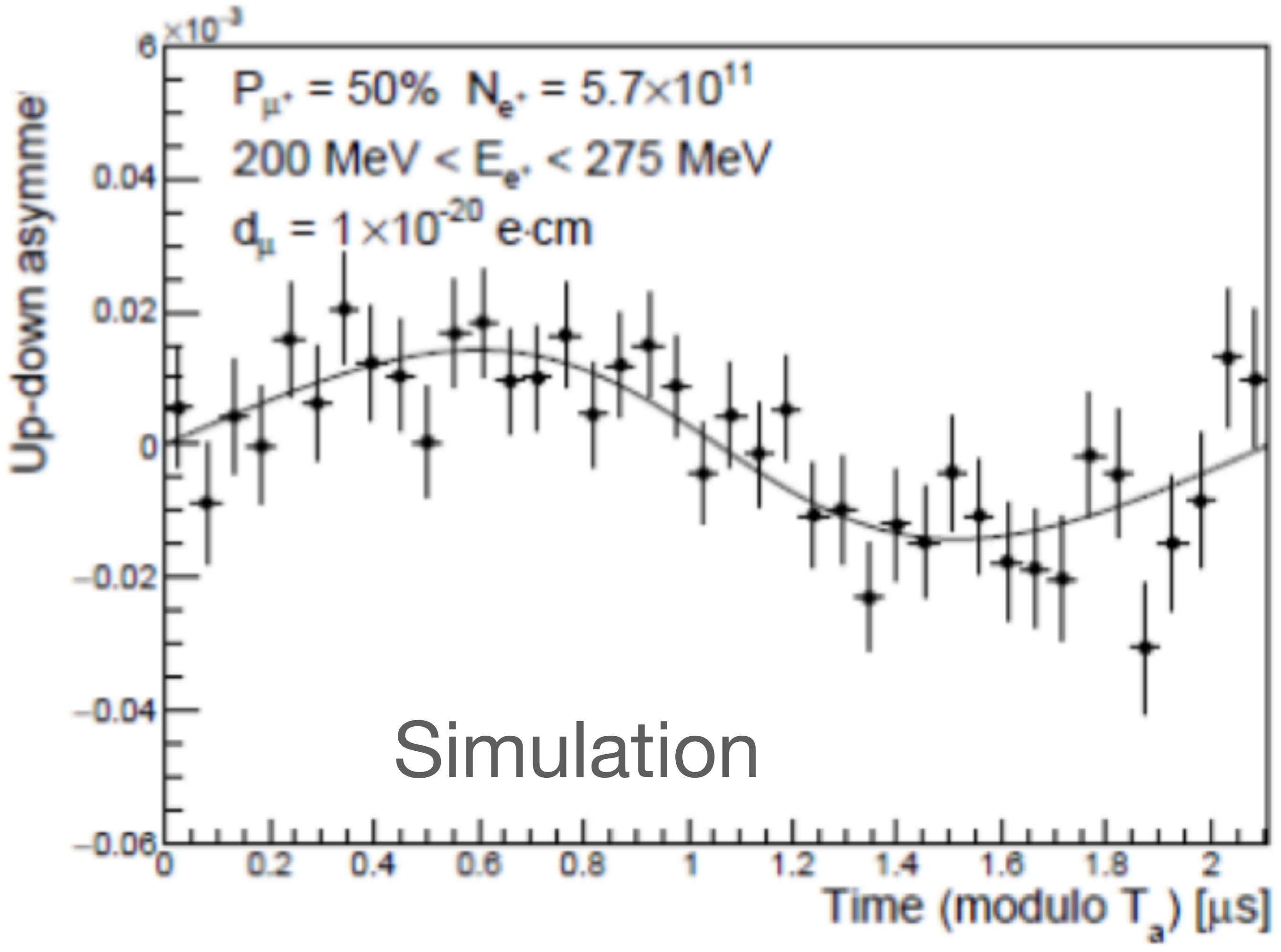
EDM Measurement

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



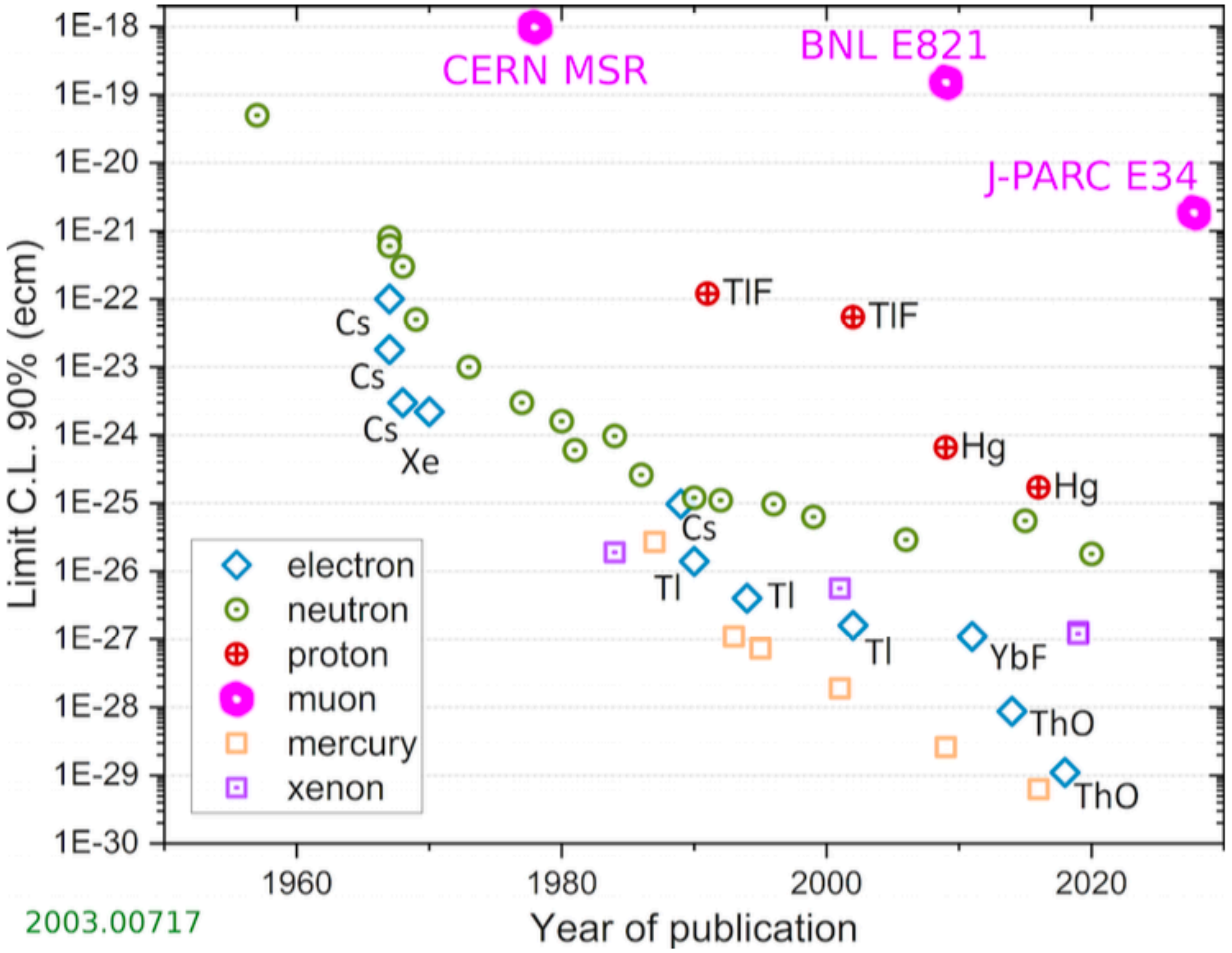


- Observed in up-down asymmetry
- $\omega_\eta/\omega_a \sim (\eta\beta/2a_\mu)$
- Good detector alignment precision is essential
- aim at 10^{-21} e cm sensitivity (10^{-5} rad)
- 1 μm detector alignment measurement is developed



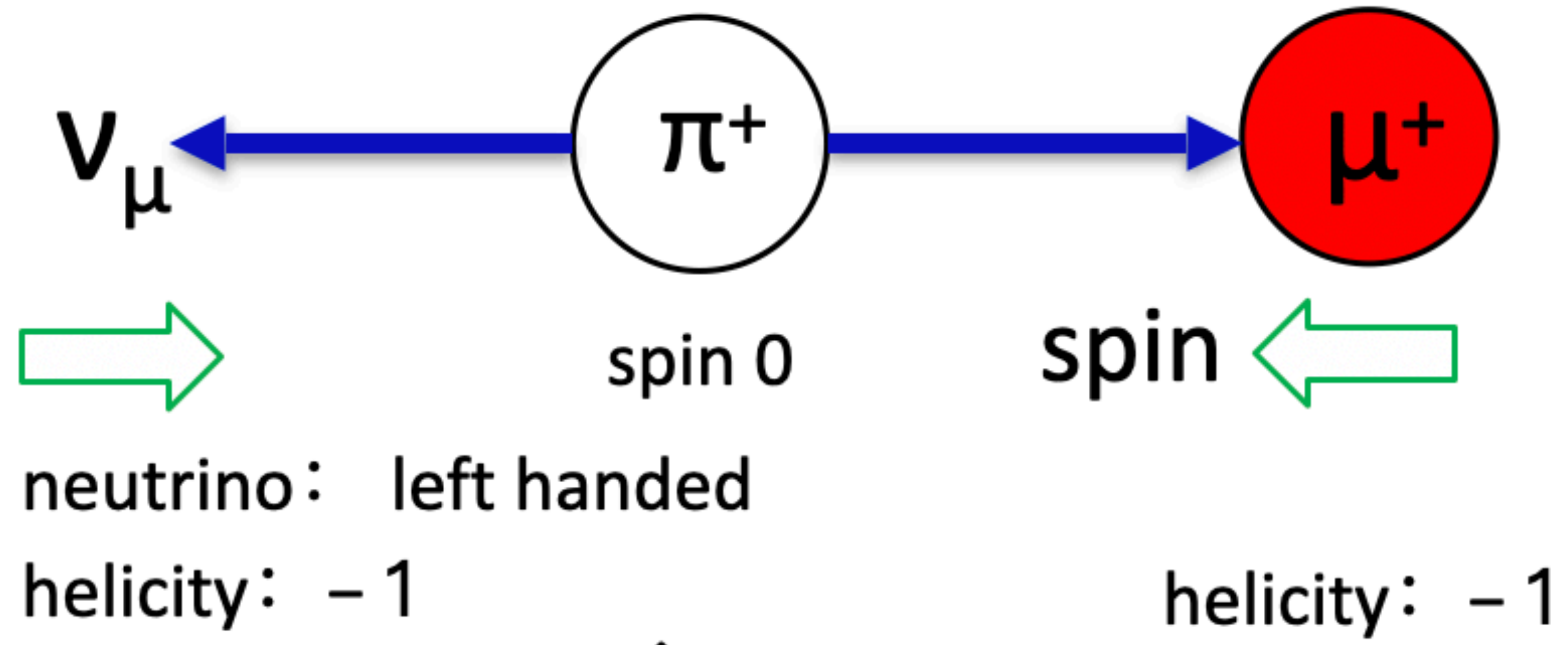
EDM Measurement

- The muon EDM SM expectation is ~ 2×10^{-38} e cm
- The current experimental limit is 1.8×10^{-19} e cm by the BNL E821.



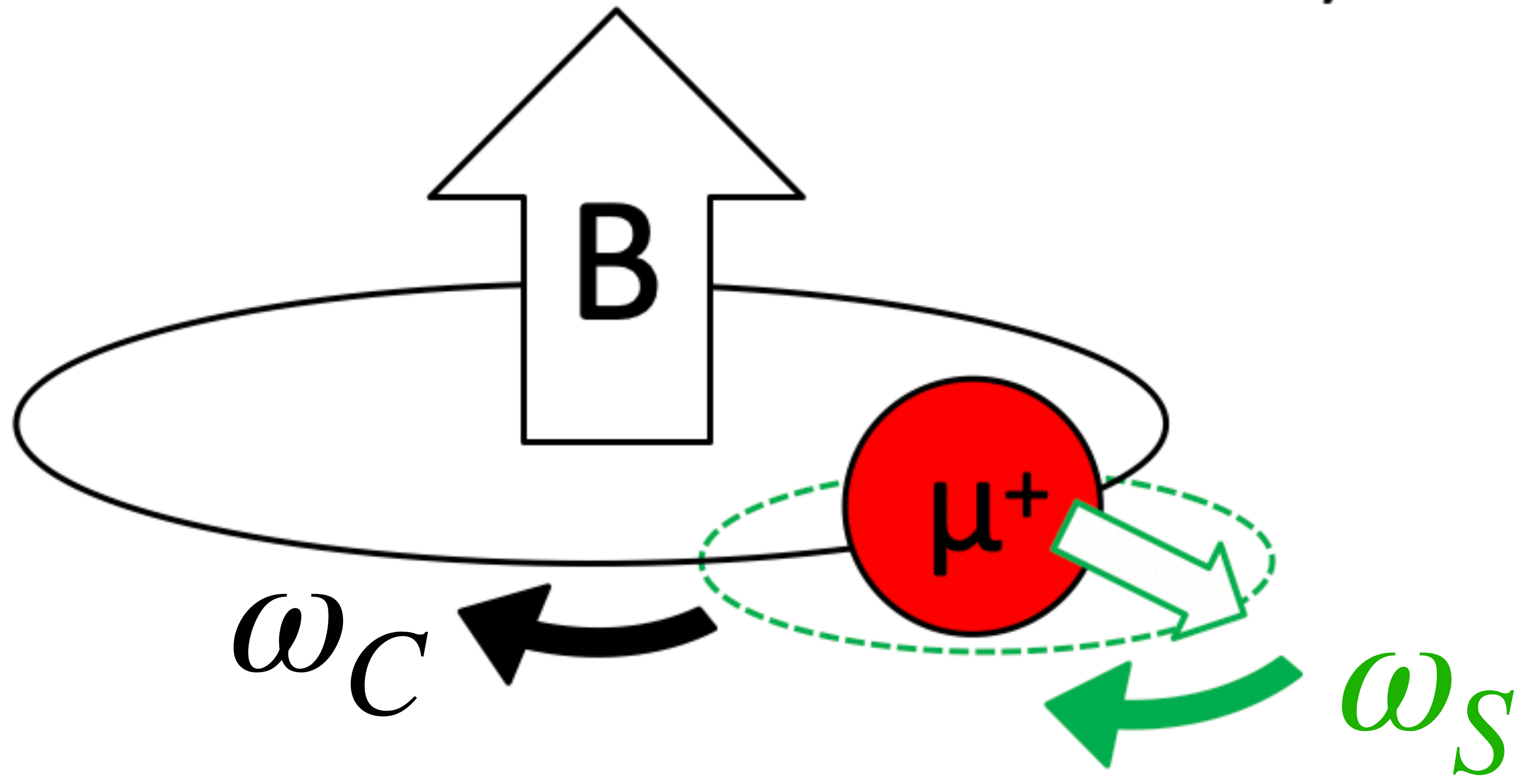
Experimental Determination of a_μ

1. Prepare a polarized muon beam



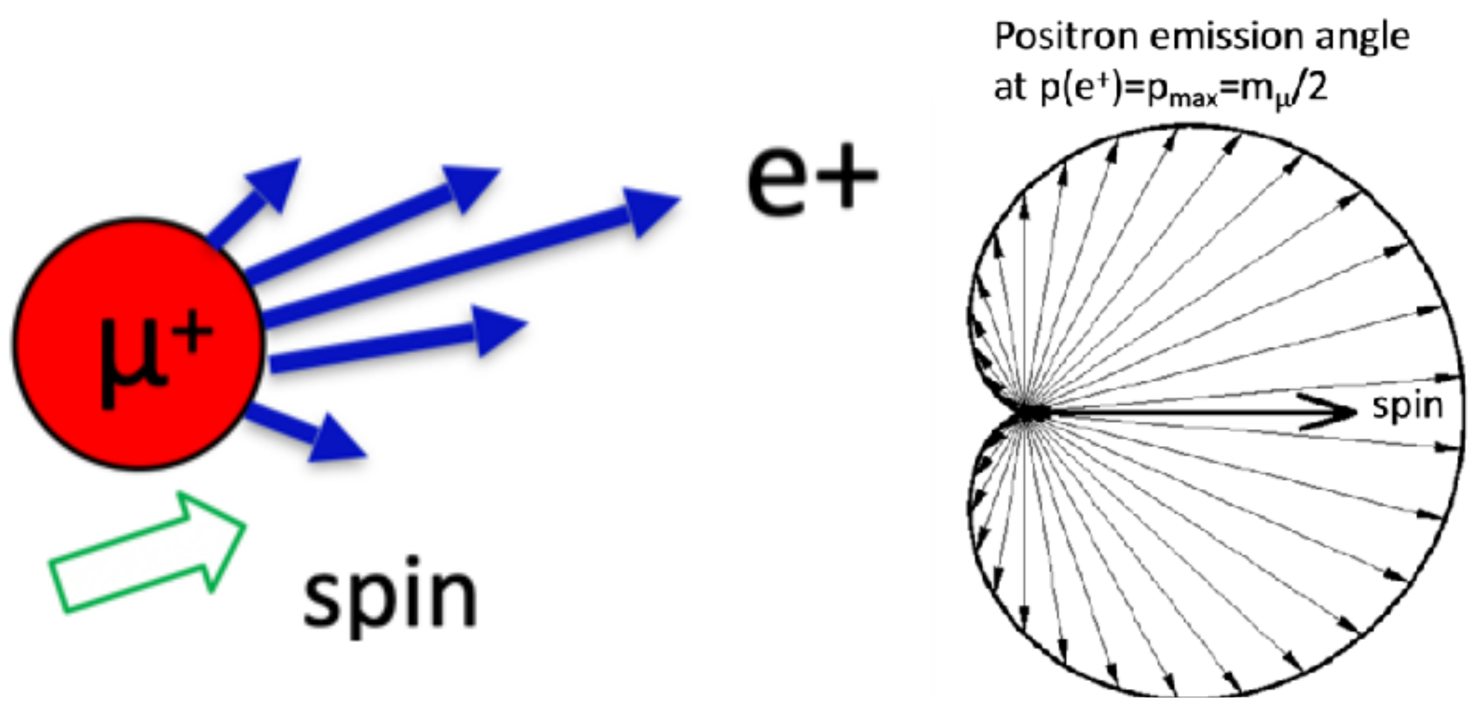
2. Store in a magnetic field (muon's spin precesses)

$$\omega_a = \omega_S - \omega_C = -\underbrace{\tfrac{1}{2}(g-2)}_{a_\mu}\,\frac{eB}{m}$$

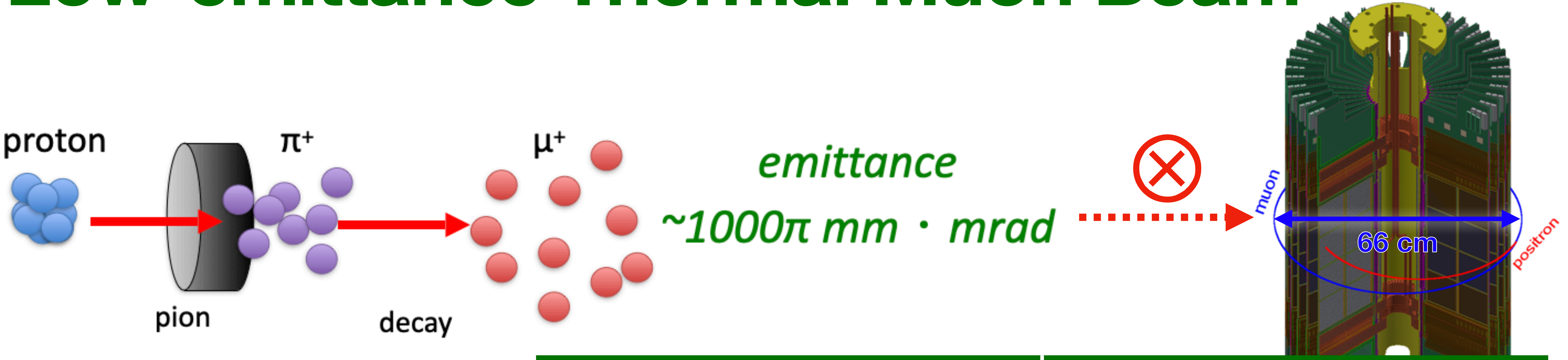


3. Detect a decay positron

(Higher energy positron tends to emit along muon's spin direction).



Low-emittance Thermal Muon Beam



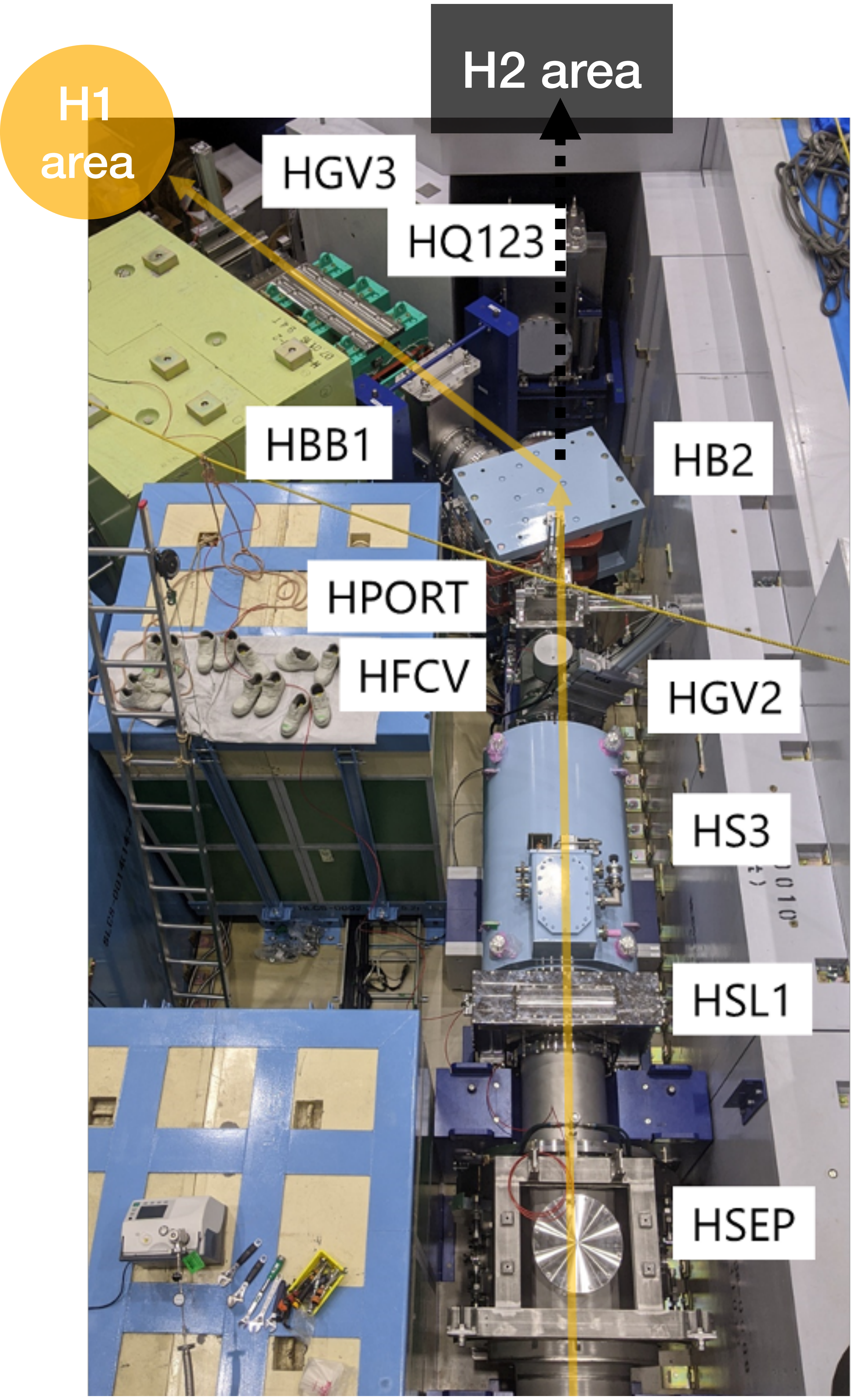
	Fermilab Muon g-2	J-PARC Muon g-2/EDM
Muon momentum	3.09 GeV/c	300 MeV/c
Storage Field	B = 1.45 T	B = 3 T (Solenoidal)
Muon orbit diameter	14 m	66 cm
Cyclotron period	149 ns	7.4 ns
Focusing field	Electric quadrupole	E = 0, very weak magnetic

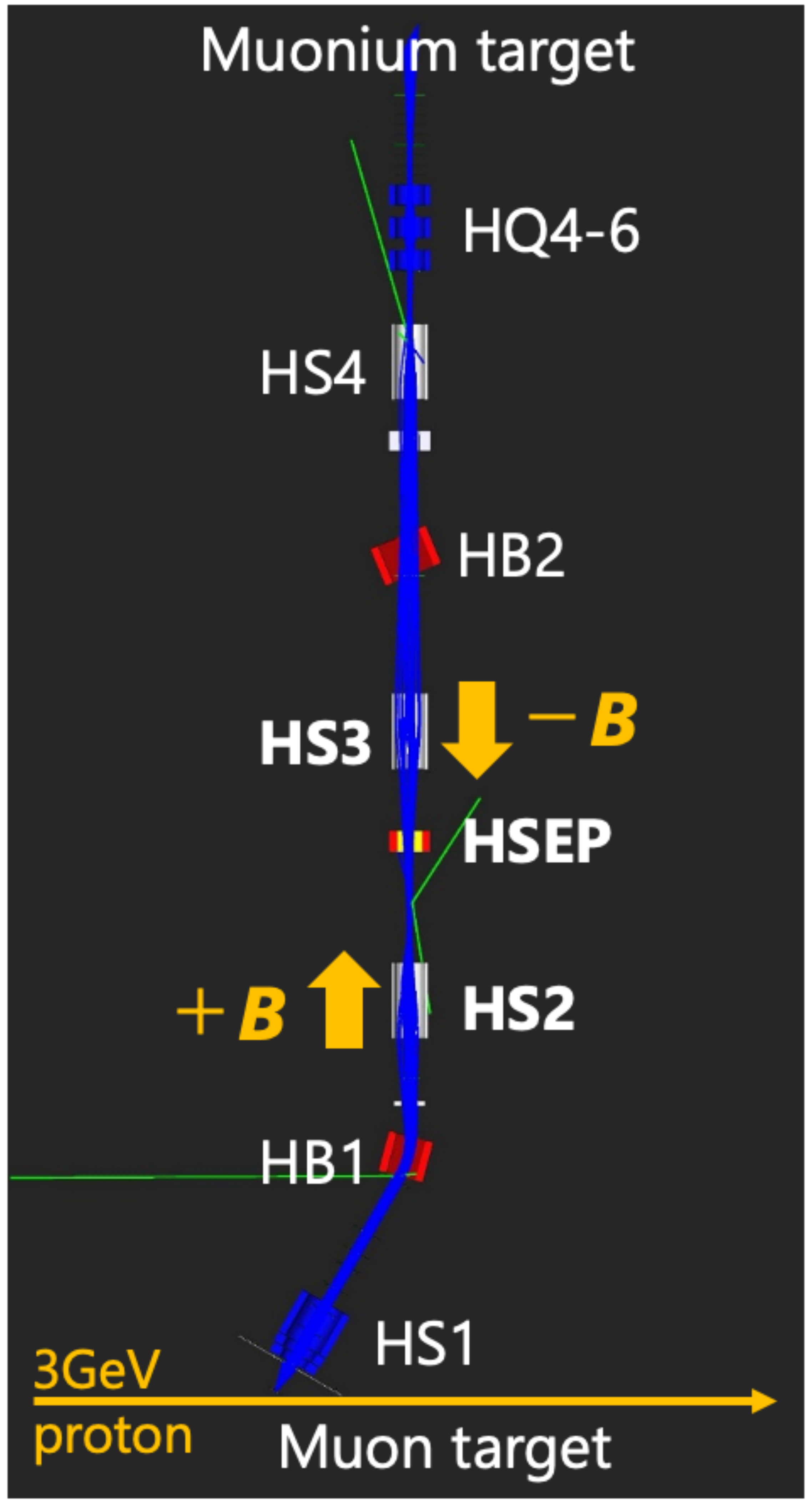
Precision Comparison

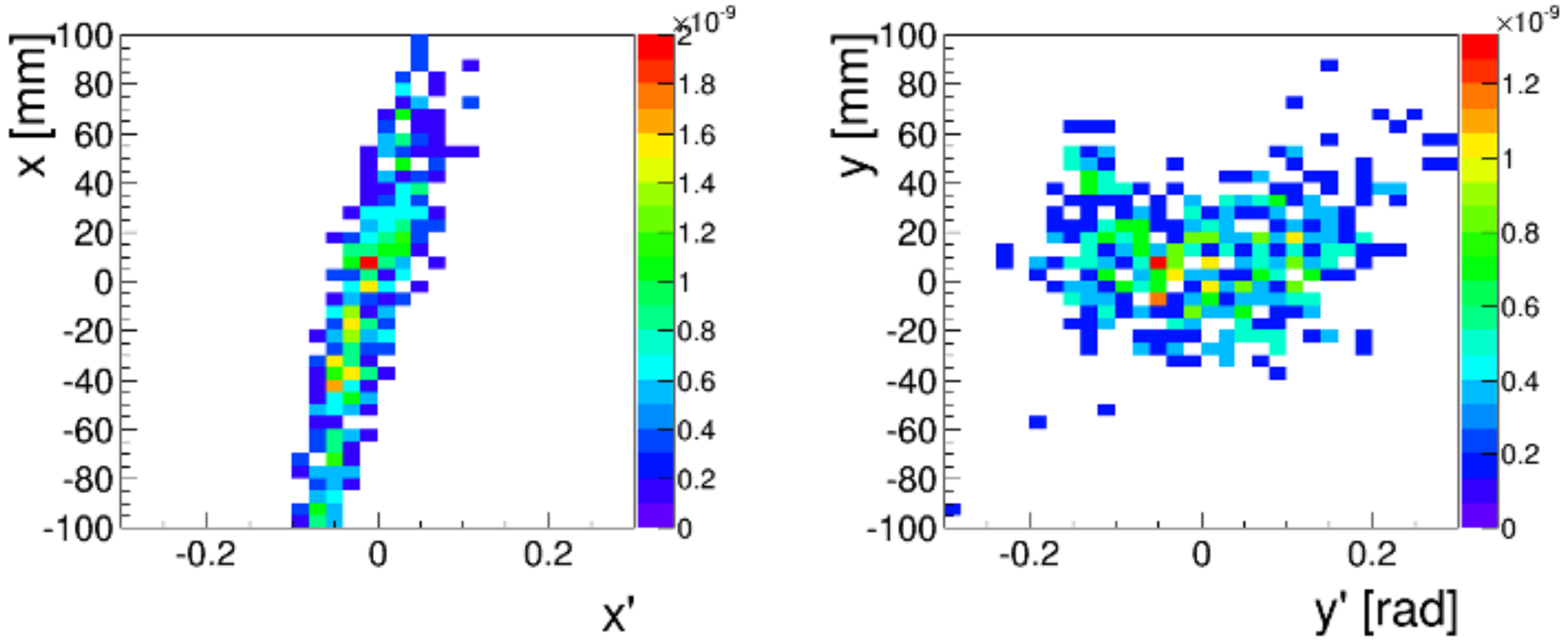
J-PARC E34

	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 μs		2.11 μs
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.)	0.2×10^{-19} $e \cdot$ cm	—	1.5×10^{-21} $e \cdot$ cm
(syst.)	0.9×10^{-19} $e \cdot$ cm	—	0.36×10^{-21} $e \cdot$ cm

H-line Surface Muon Optics







Simulated beam profile at H2 area entrance

- The beam-line consist of solenoids ("HS"), bending magnets ("HB"), DC separator ("HSEP"), quadruples ("HQ"), etc.
- Beam-line optics was tuned to deliver 1.6×10^8 surface μ/s at the muonium production target under a 1MW proton beam power.