The Muon g-2/EDM experiment @J-PARC

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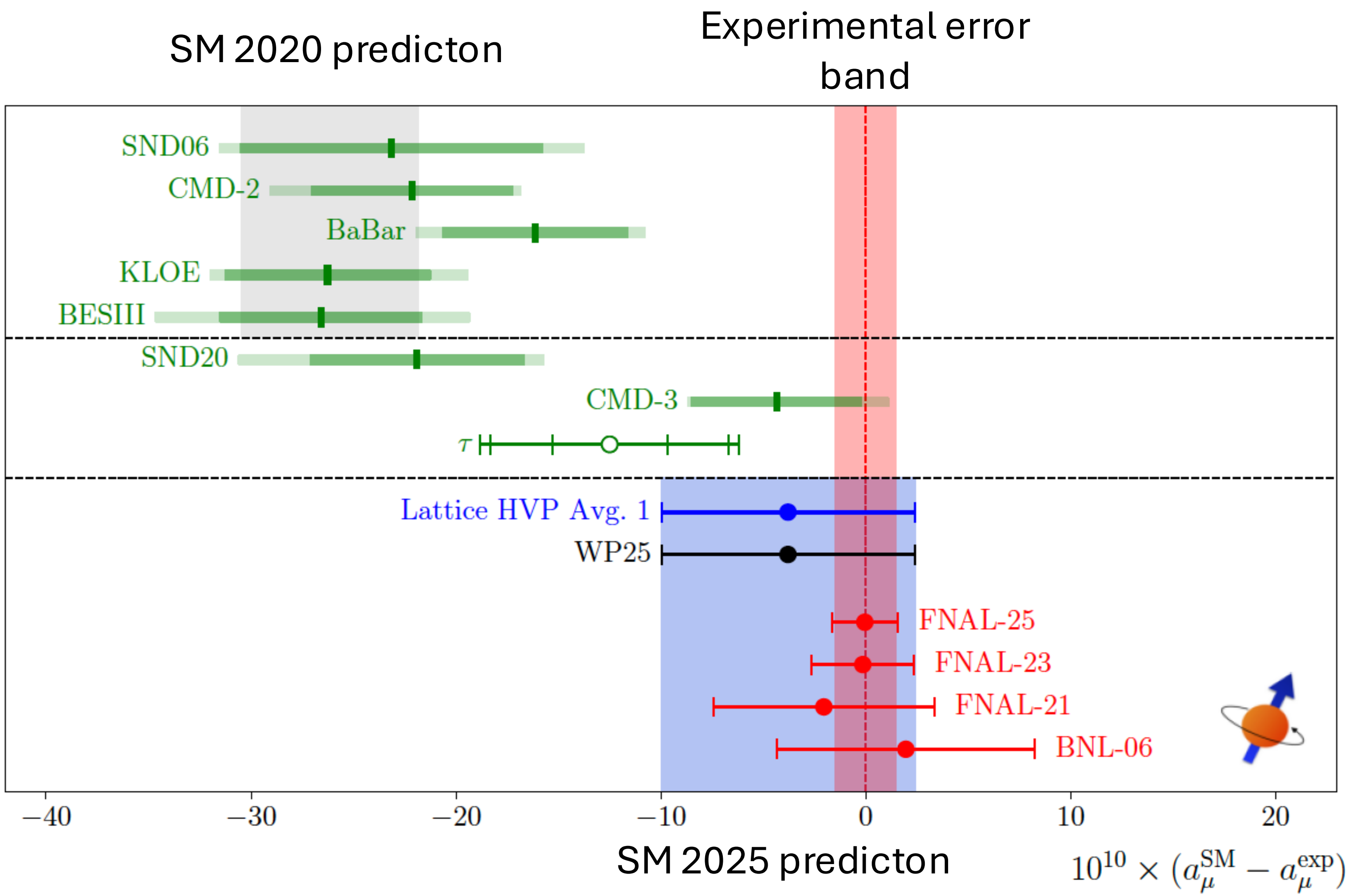
On behalf of the J-PARC g-2/EDM Collaboration

EPS-HEP CONFERENCE
07-11 JULY, 2025
PALAIS DU PHARO
MARSEILLE, FRANCE

Status of the Muon g-2

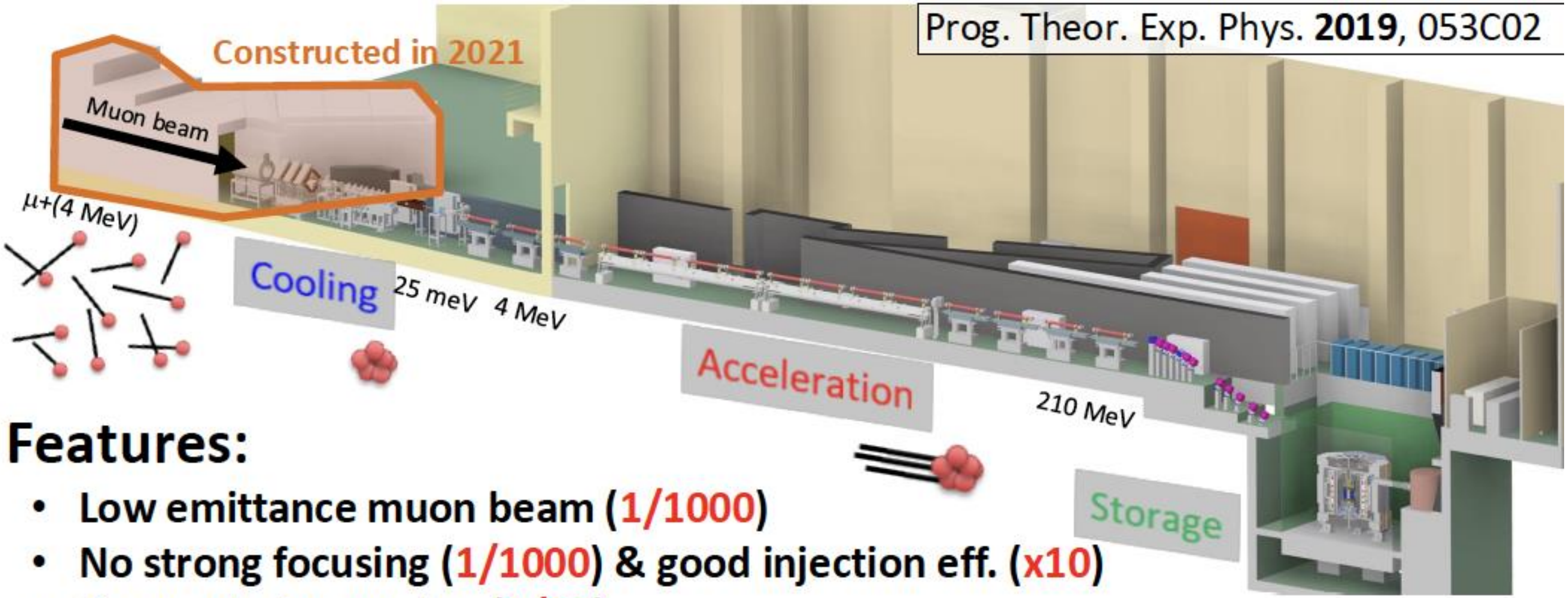


Confusing situation:

- SM 2020 prediction (pink band, HVP based on e^+e^- data) in significant tension (> 5σ) with BNL and FNAL
- SM 2025 (blue band, HVP from lattice QCD) shifted much closer to experimental value
- Test of HVP in progress from e+e- data, lattice, tau and in future from MUonE
- In preparation a measurement of the muon g-2 with a different technique at JPARC:
  - Systematic uncertainty at the same level of FNAL Muon g-2
  - Important cross check of the "storage ring method" BNL/FNAL

Muon g-2/EDM experiment at JPARC

J-PARC MLF



Features:

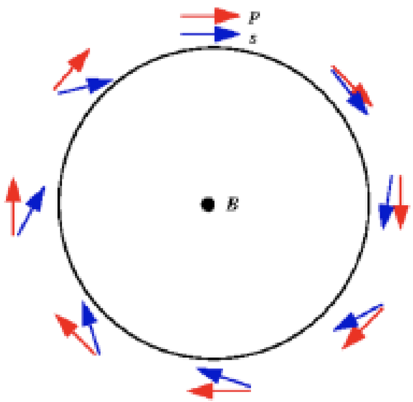
- Low emittance muon beam (1/1000)
- No strong focusing (1/1000) & good injection eff. (x10)
- Compact storage ring (1/20)

Excellent sensitivity to **muon EDM** about **100 times** better than the previous limit (sensitivity : **1.5 E-21 ecm**)

Injection of an ultra-cold, low-energy, muon beam into a small, highly uniform magnet

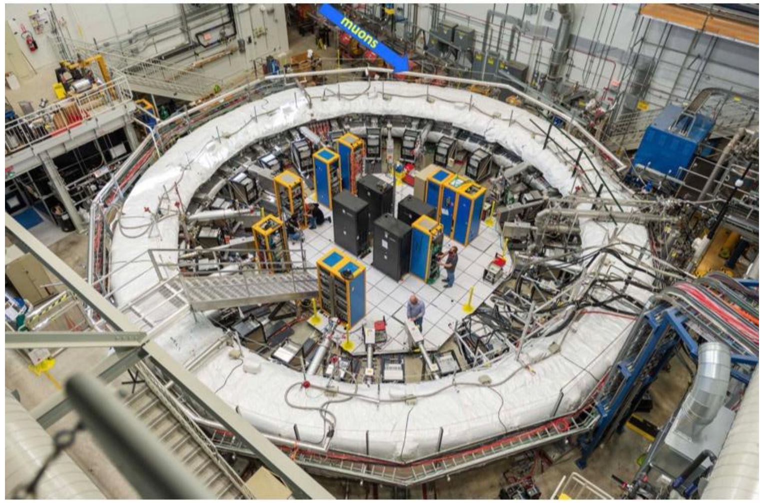
What makes them different?

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E}\right]$$



spin (ω_s)
momentum (ω_c)

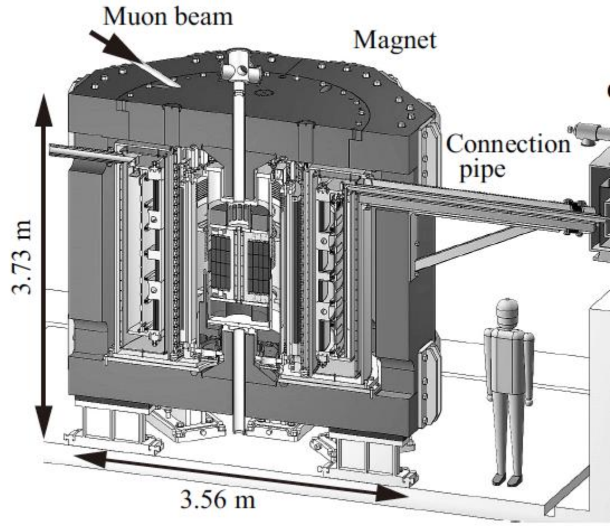
Fermilab (BNL) muon g-2 experiment(s)



$$\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \cancel{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)}\vec{\beta} \times \vec{E}\right]$$

- Electric focusing (vertical confinement)
- **Magic momentum** γ= 29.3 (p = 3.1 GeV/c)
- 14 m ring diameter (B= 1. 45T)

J-PARC muon g-2/EDM experiment



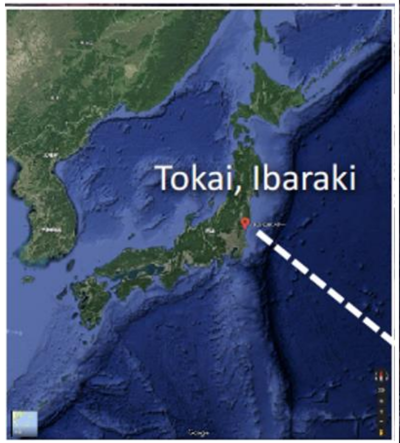
$$\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \cancel{\vec{E}}\right]$$

- **No electric field** (E=0)
- 300 MeV/c momentum
- 0.66 m ring diameter (B = 3 T)

-Different systematics

-Simultaneous measurement of g-2/EDM

a_μ can be extracted by precisely measuring B and ω.


Tokai, Ibaraki


J-PARC Facility
(KEK/JAEA)
LINAC
3 GeV
Synchrotron
Neutrino Beam
To Kamioka
Material and Life Science
Facility (MLF)
Main Ring
(30 GeV)
Hadron Hall
Bird's eye photo in Feb. 2008
2025/Mar/24
1st Europe-China-Japan Workshop on
Muon Physics
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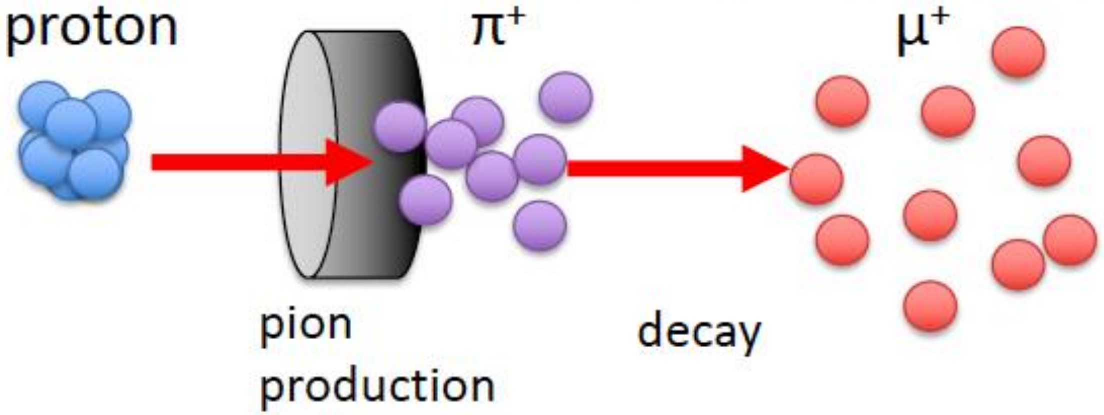
Conventional muon beam (BNL, Fermilab)



emittance ~1000π mm ·mrad

Strong focusing
Muon loss
BG π contamination

At Fermilab $\sigma_p/p{\sim}0.2\%$
($\sim$1% before entering the ring)

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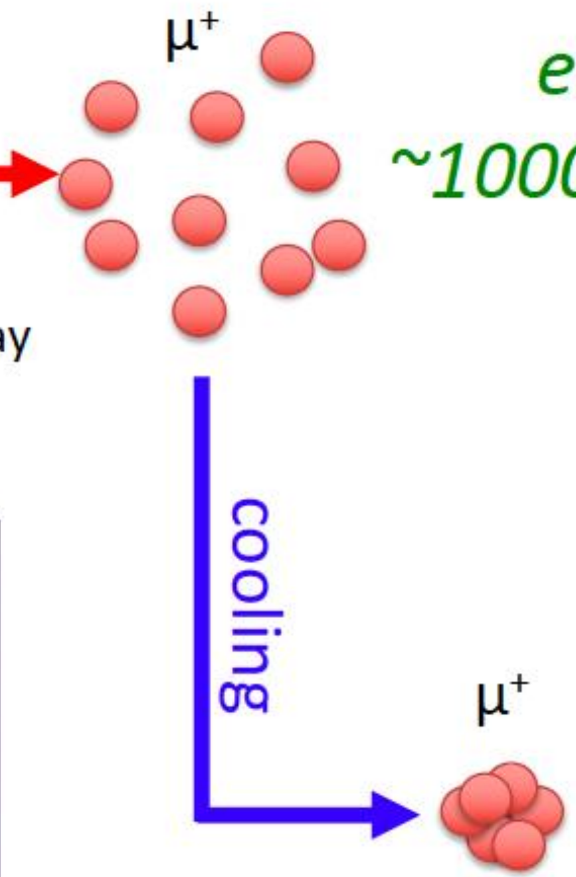
Muon beam at J-PARC



emittance

~1000π mm ·mrad

Strong focusing
Muon loss
BG π contamination

emittance

1π mm ·mrad

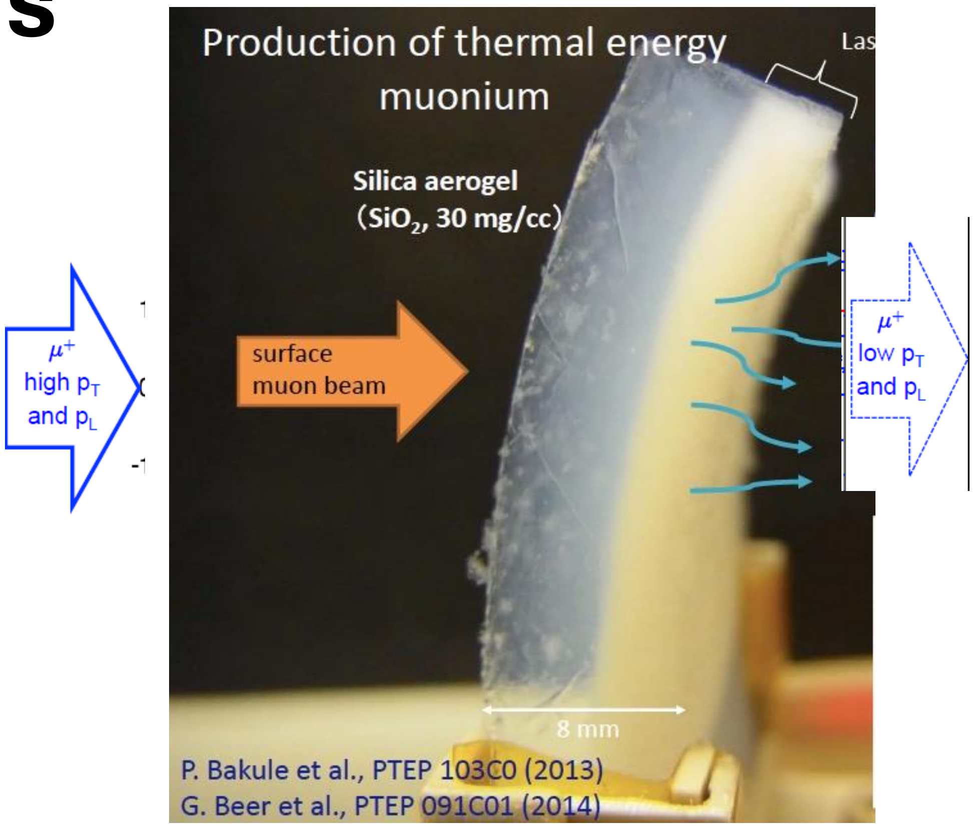
Reaccelerated thermal muon

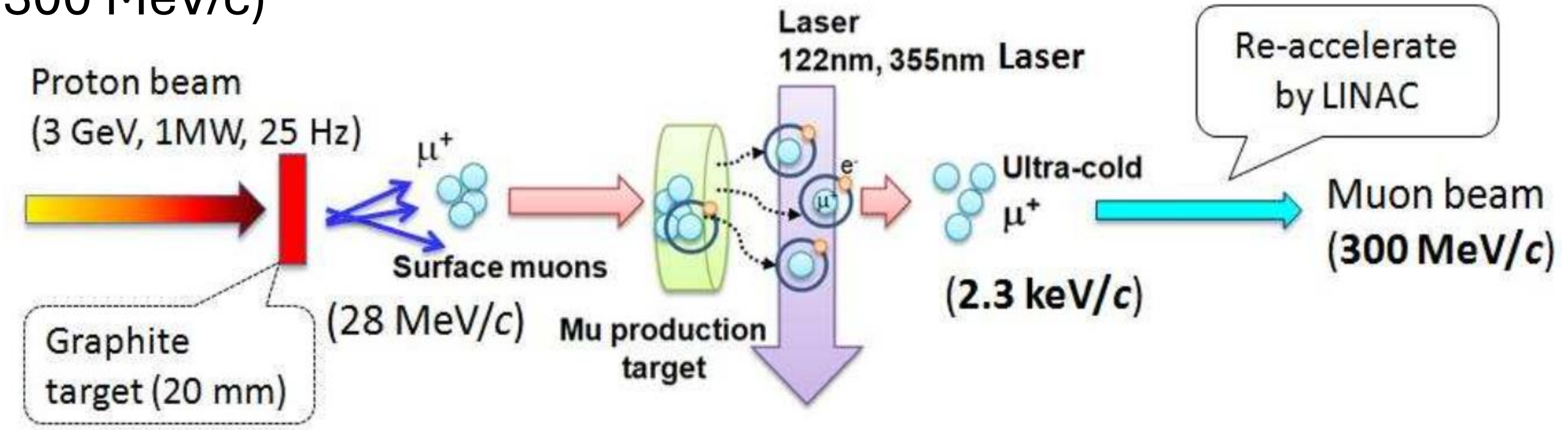
Free from any of these

7

Ultra-cold Muons

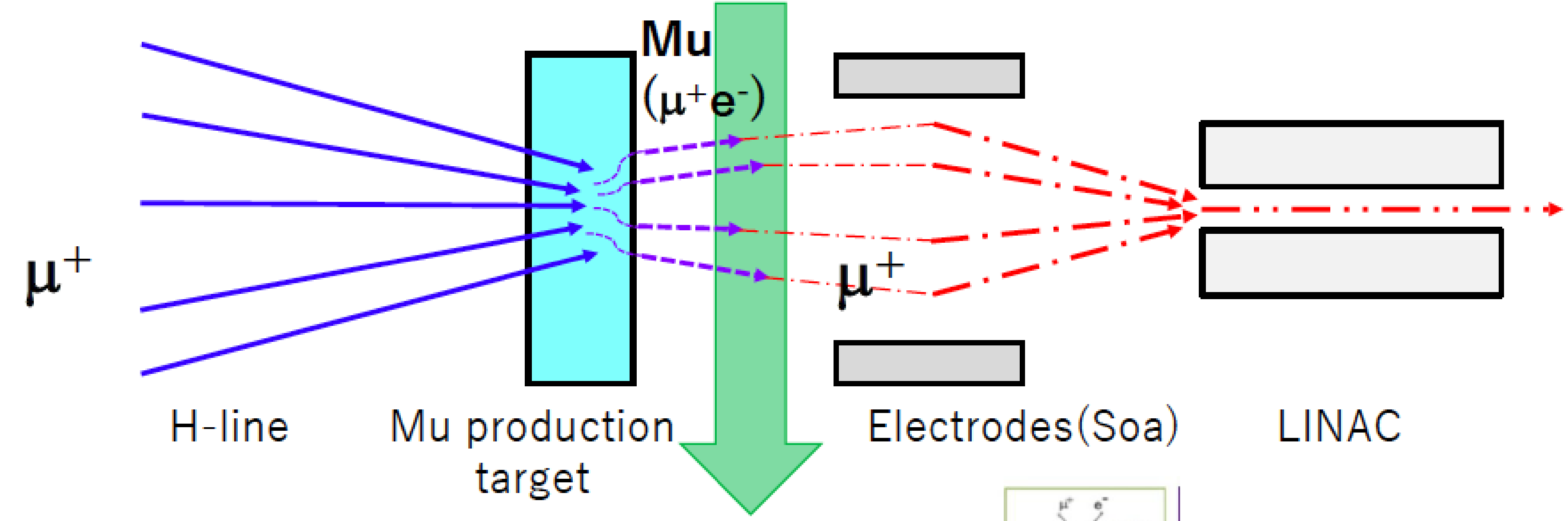
- Surface μ^+
- Stop in (laser ablated surface) Aerogel
- Diffuse Muonium (μ^+e^-) atoms into vacuum
- Ionize
  - 1S → 2P→unbound
  - **Max Polarization 50%**
- Accelerate
  - E field, RFQ, linear structures
  - E= 212 MeV (p= 300 MeV/c)

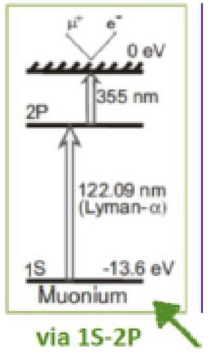




Re-accelerated thermal muon

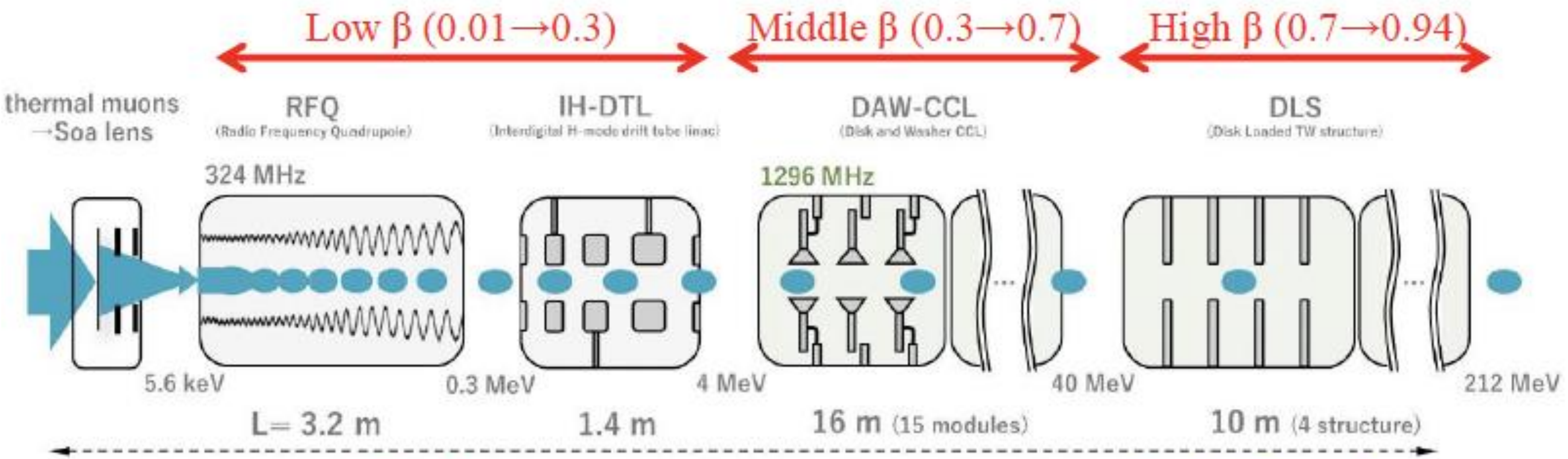
	surface muon	thermal muon	accelerated muon
E	3.4 MeV	30 meV	212 MeV
p	27 MeV/c	2.3 keV/c	300 MeV/c
$\Delta p/p$	0.05	0.4	4×10^{-4}





Muon linac (E_k =5.6 keV → 212 MeV)

- Muon acceleration to 212 MeV by dedicated muon LINAC.
- 4 steps acceleration depending on β. L = 40 m in total.



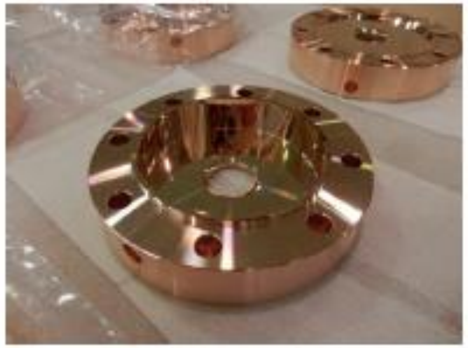
Ready

Ready: Acceleration test in 2026/2027

Ready for production except for bridge coupler

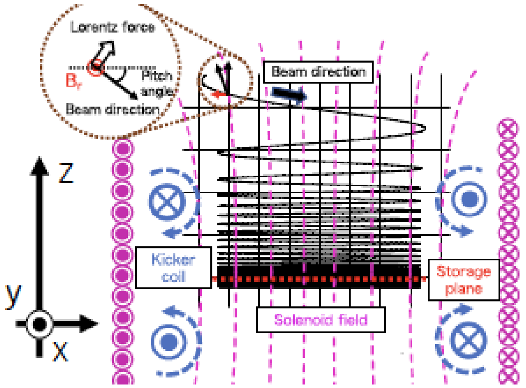
Ready for production except for pulse compressor

Washer 1,2 (×2)

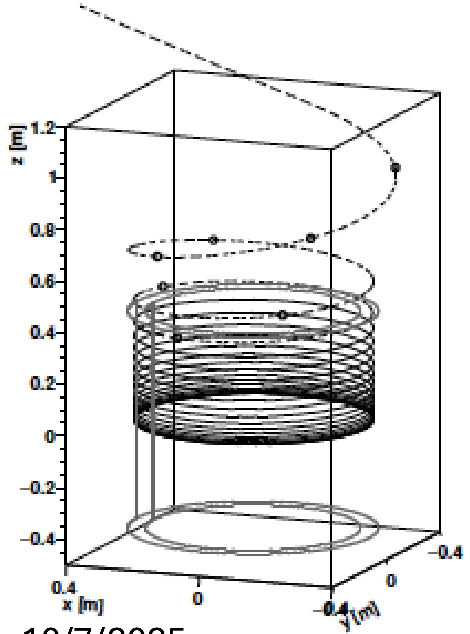


Muon storage magnet

- 3D spiral injection scheme is adopted for muon injection into the storage magnet.
- Injection radial magnetic field decreases pitch angle from 440 mrad (injection) to 40 mrad (after the first three turns)
- A kicker radial pulse (kicker coils inside the solenoid) reduces the pitch angle to ~0
- Main (Axial) field in the storage region B= 3 T



- Superconducting solenoid
  - cylindrical iron poles and yoke
  - vertical B = 3 Tesla, <1ppm locally
  - storage region r = 33.3±1.5 cm, h = ±5 cm
  - tracking detector vanes inside storage region
  - storage maintained by static weak focusing
    - n = 1.5 × 10^{-4}, $rB_r(z) = -n\, zB_z(r)$ in storage region



Injection region
(0.4< z < 1.1 m)

Kicker field
(5< |z| < 40cm)

storage region
(|z| < 5cm; 31.8 cm <r <34.8 cm)

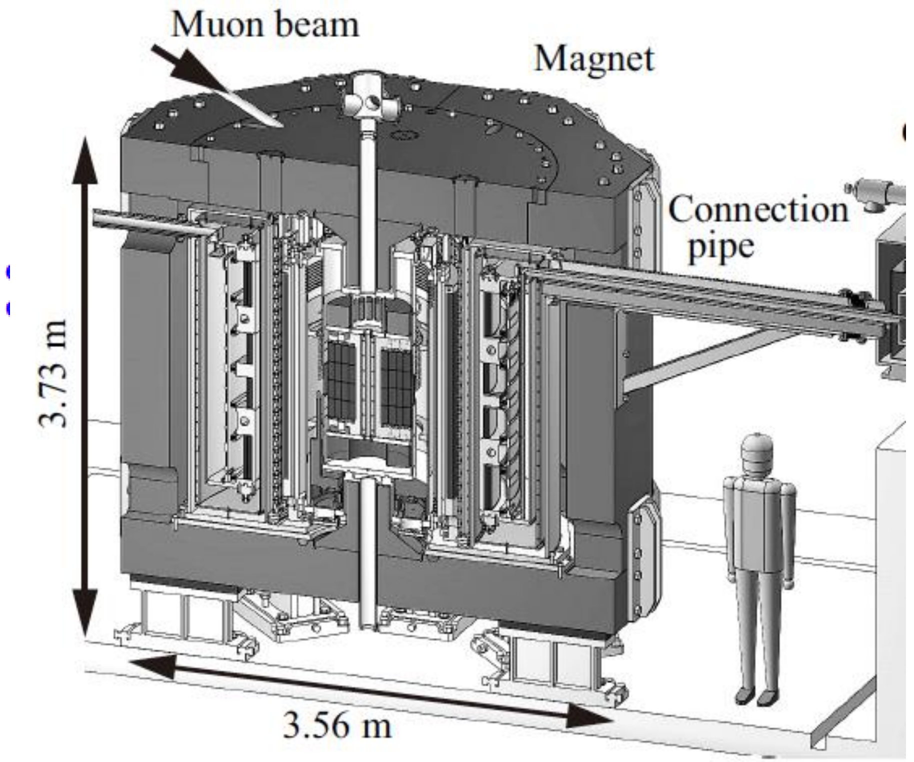
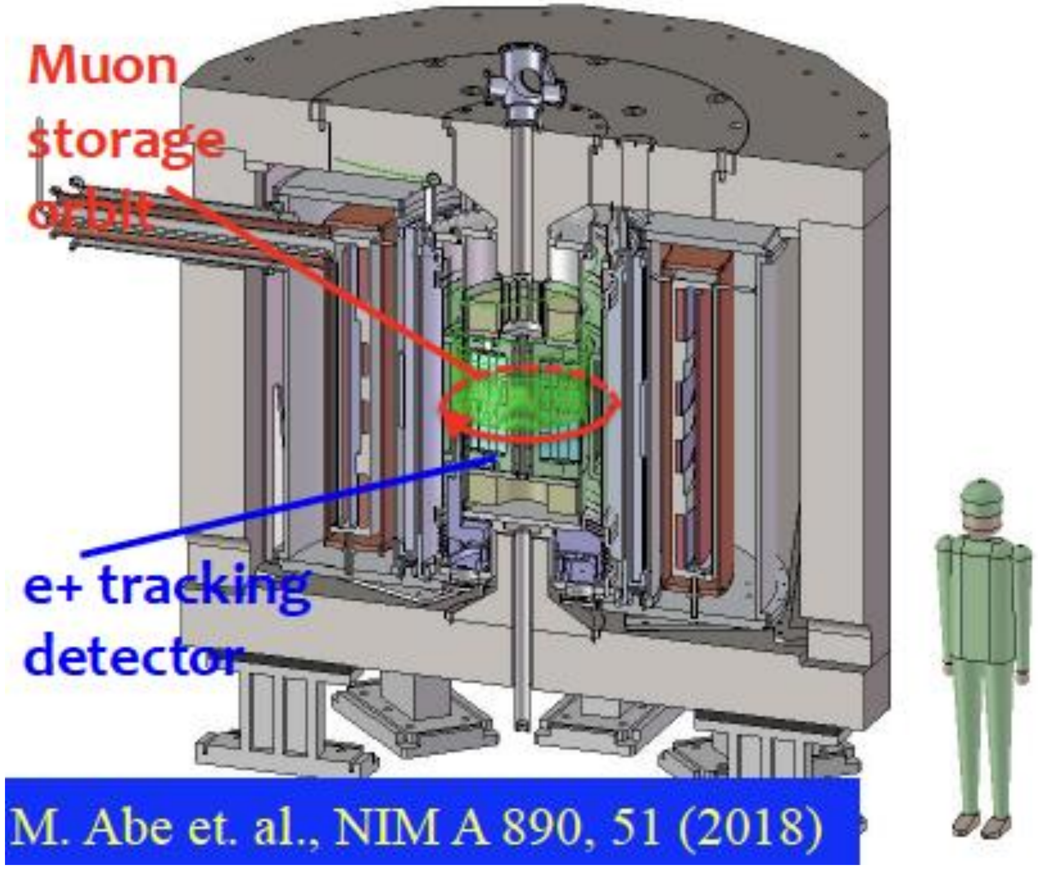
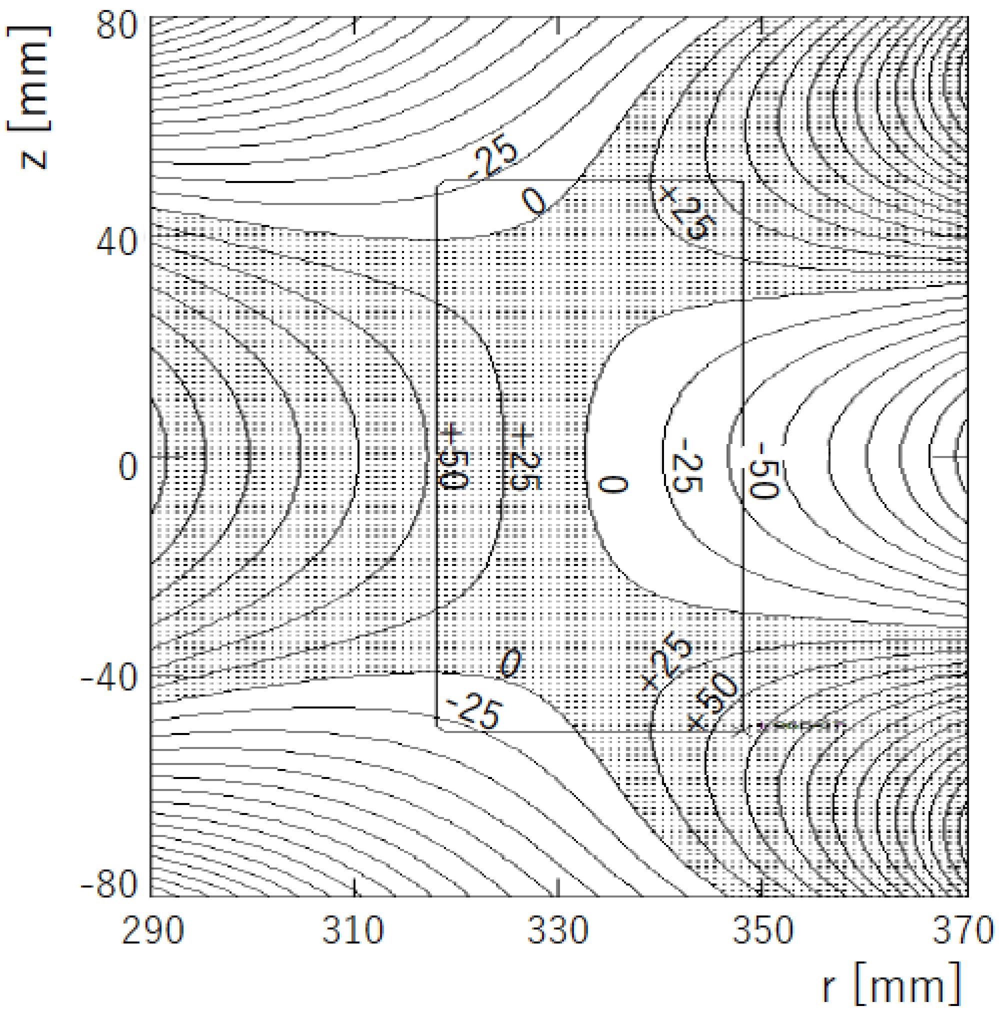


Fig. 8 Overview of the muon storage magnet

MRI-type magnet B=3T, d=66 cm



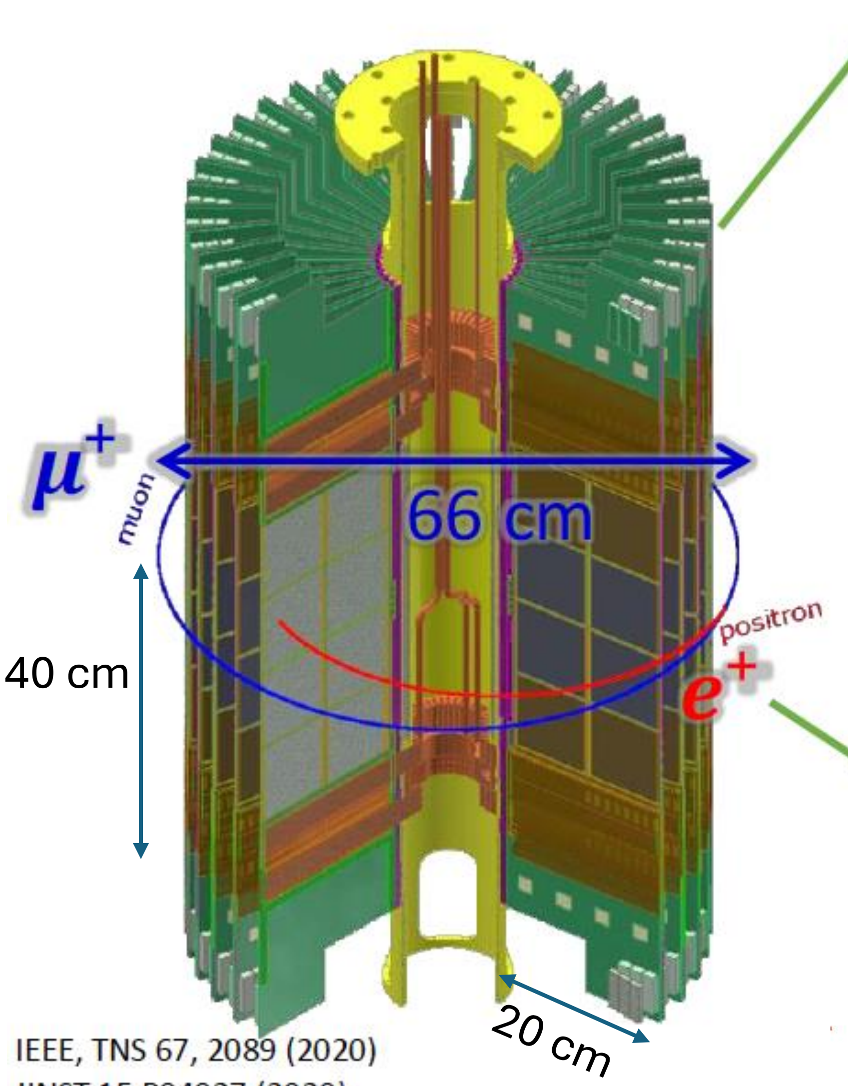
Storing region confinded in |z| < 5 cm; 32 <r < 35 cm



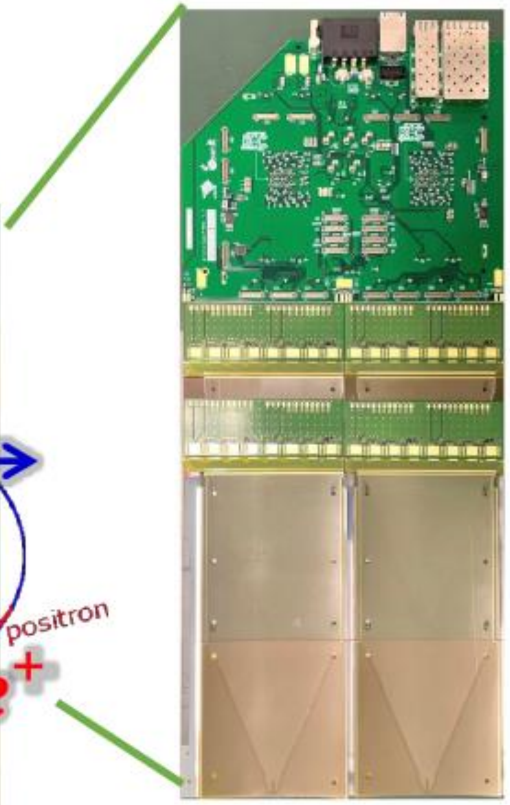
Average uniformity <=+- 50 ppb
(local uniformity <1ppm)

Postron tracking detector

- 40 modules (vanes) each 200mm (90-290 mm, radial) x 400mm (axial)
- Each vane consists of 16 Si sensors (10x 10 cm^2, 320 μm thickness).
- Two-dimensional hit position is reconstructed from orthogonally arranged silicon strip sensor (512 strips with 190 μm pitch)
- Readout ASIC w/ 5nsec sampling rate.

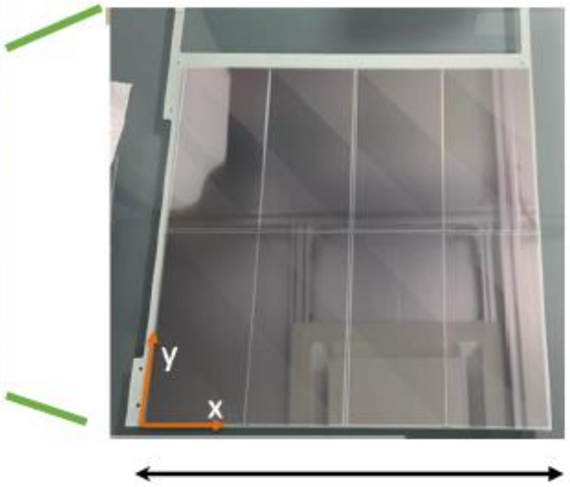


IEEE, TNS 67, 2089 (2020)
JINST 15 P04027 (2020)

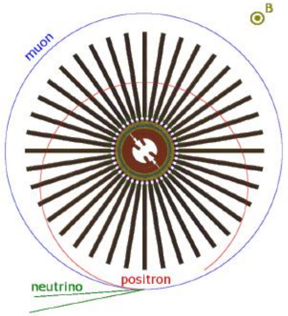


Test with prototype boards

Si strip sensors



~200 mm



200<p_e<275 MeV/c

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Comparison of g-2 experiments

Prog. Theor. Exp. Phys. **2019**, 053C02 (2019)

	BNL-E821	Fermilab-E989	Our experiment
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz γ	29.3	t_μ~ 64.4 us	3 t_μ= 6.6 us
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
(syst.)	280 ppb	80 ~~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
	Completed	Completed	In preparation

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.)

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Muon cooling demonstration (2024)

Acceleration from termal energy to 100 keV by RF system

PHYSICAL REVIEW LETTERS 134, 245001 (2025)

Editors' Suggestion | Featured in Physics

Acceleration of Positive Muons by a Radio-Frequency Cavity

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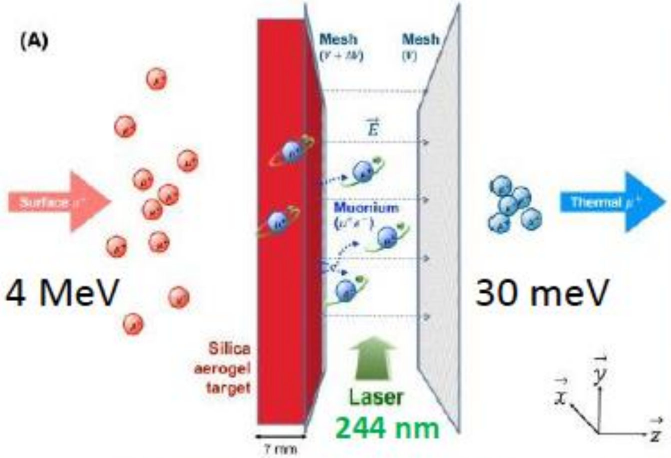
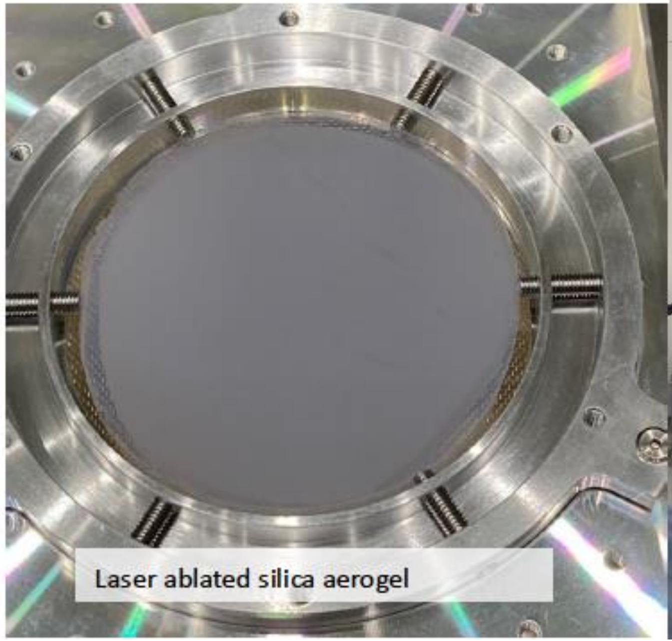
Acceleration of positive muons from thermal energy to 100 keV has been demonstrated. Thermal muons were generated by resonant multiphoton ionization of muonium atoms emitted from a sheet of laser-ablated aerogel. The thermal muons were first electrostatically accelerated to 5.7 keV, followed by further acceleration to 100 keV using a radio-frequency quadrupole with an intensity of 2×10^{-3} μ^+/pulse. The transverse normalized rms emittance of the accelerated muons in the horizontal and vertical planes were $0.85 \pm 0.25(\text{stat})^{+0.22}_{-0.13}(\text{syst})$ π mm mrad and $0.32 \pm 0.03(\text{stat})^{+0.05}_{-0.02}(\text{syst})$ π mm mrad, respectively. The measured emittance values demonstrated phase-space reduction by a factor of 2.0×10^2 (horizontal) and 4.1×10^2 (vertical) allowing good acceleration efficiency. These results pave the way to realize the first-ever muon accelerator for a variety of applications in particle physics, material science, and other fields.

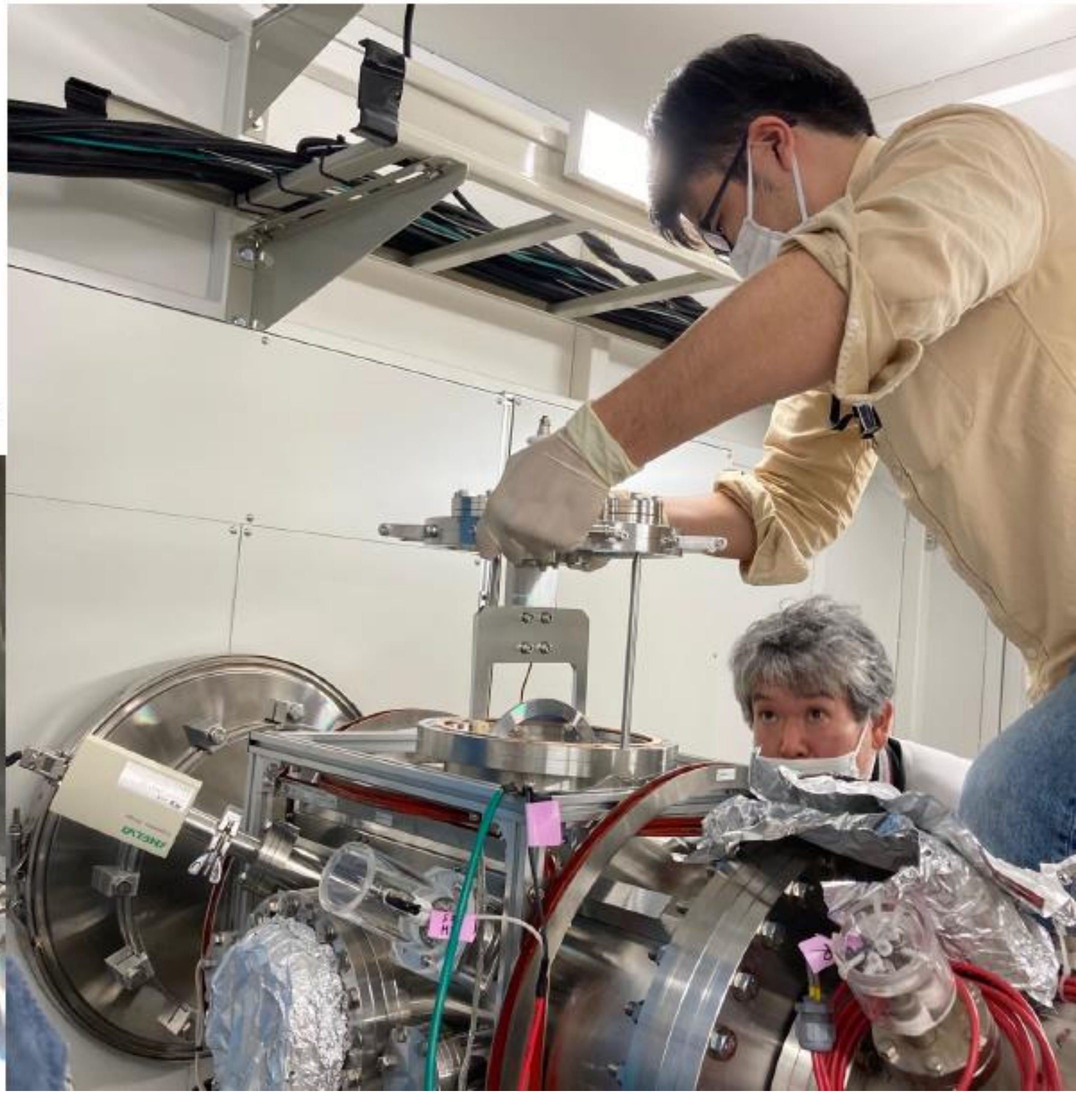
DOI: 10.1103/PhysRevLett.134.245001





Laser ablated silica aerogel

J-PARC S2 area



Phys. Rev. Lett. **134**, 245001 http://arxiv.org/abs/2410.11367v1

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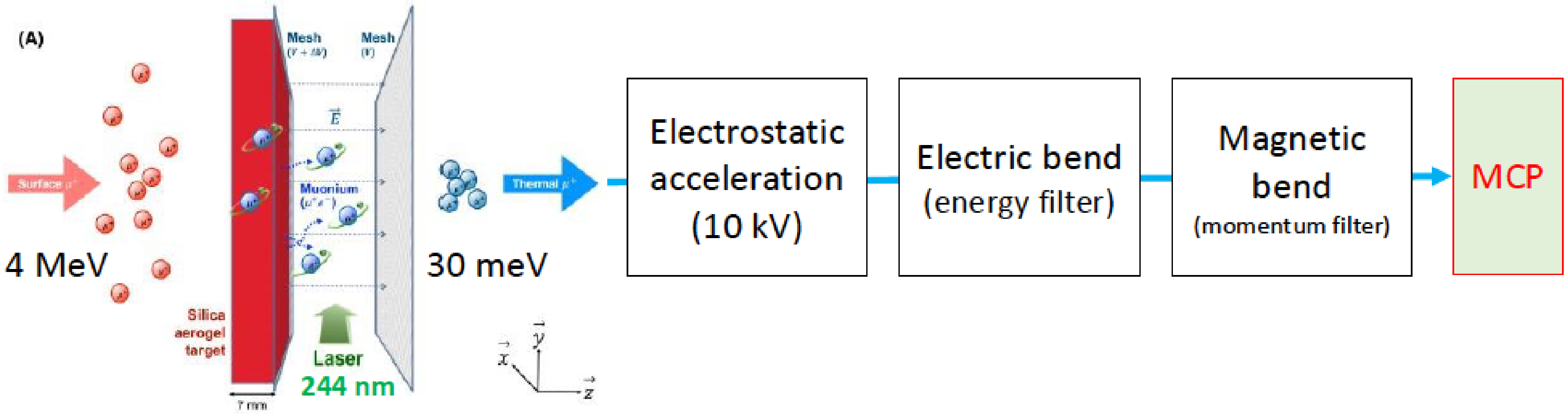
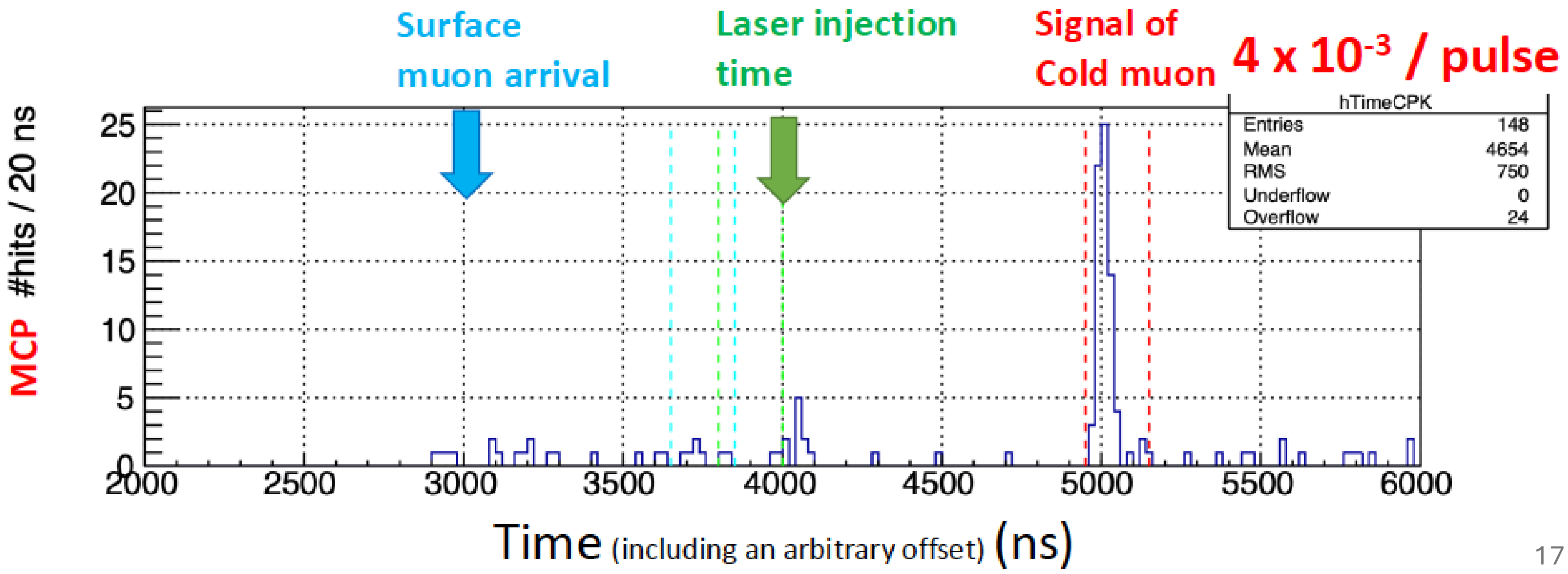
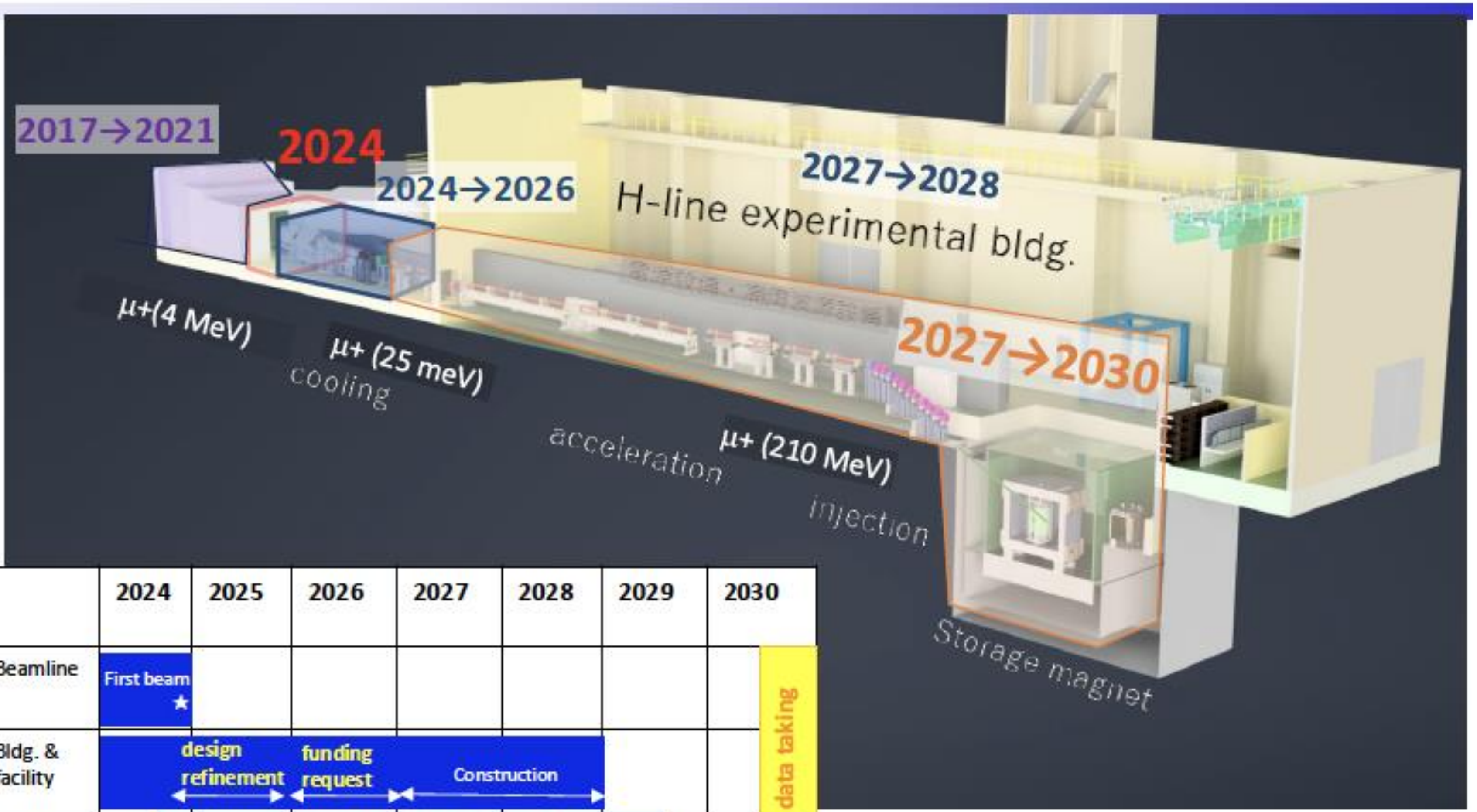
Muon cooling demonstration (2024)





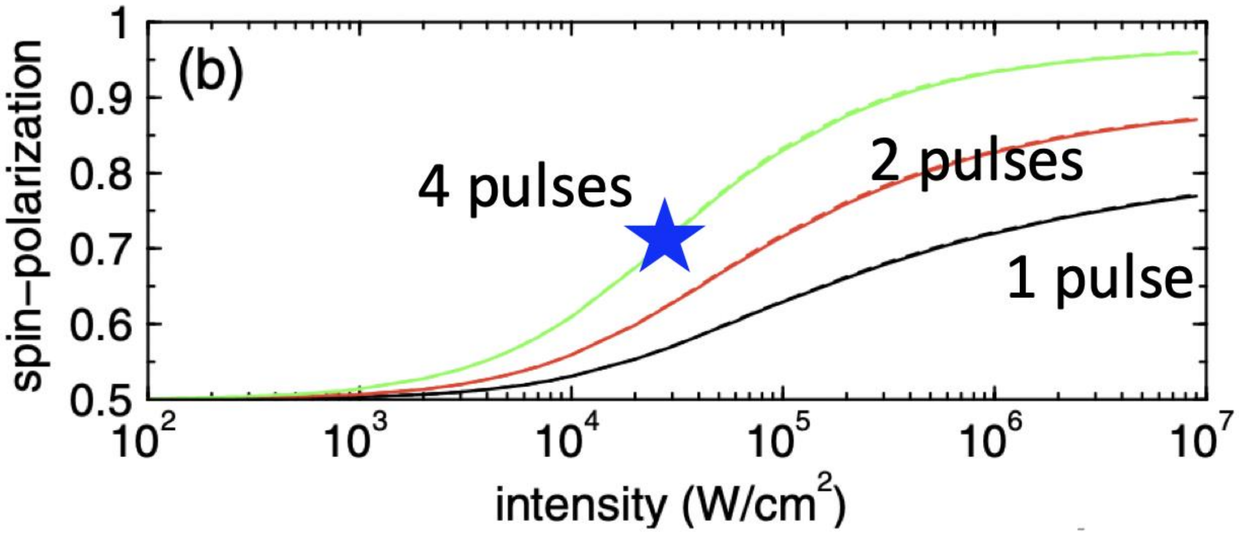
Schedule and Milestones



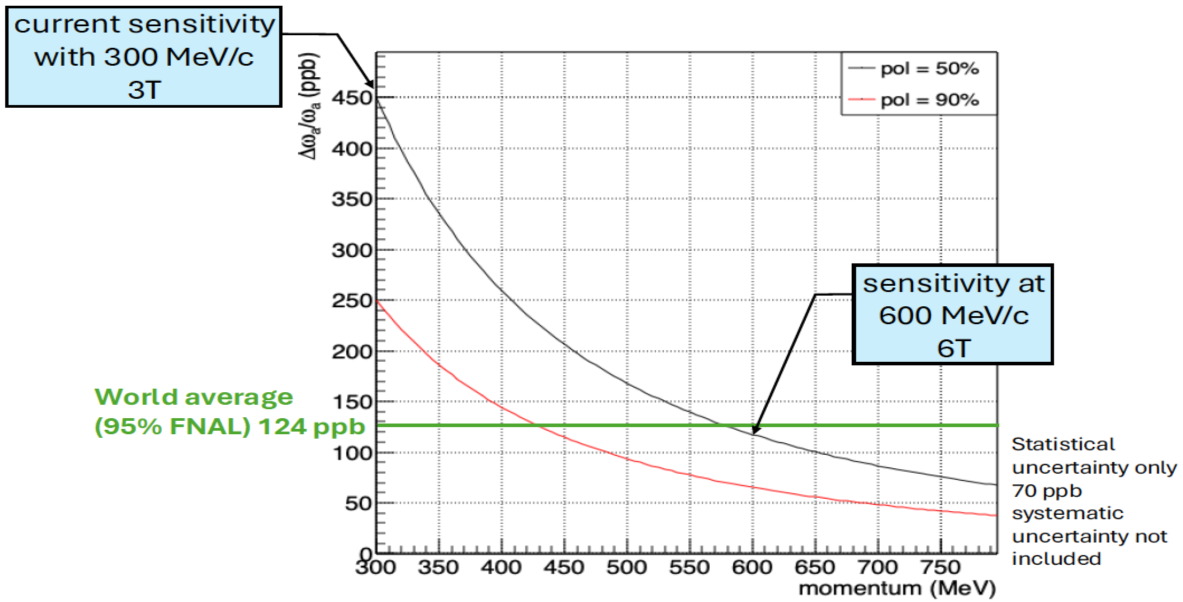
	2024	2025	2026	2027	2028	2029	2030
Beamline	First beam ★						Commissioning, data taking
Bldg. & facility	design refinement	design refinement	funding request	Construction	Construction		Commissioning, data taking
Source, LINAC, storage	source: ★ Ionization test with 1S-2P-unbound	★ Ionization test with 1S-2P-unbound	★ Ionization test with 1S-2P-unbound	★ Ionization test with 1S-2P-unbound	★ Ionization test with 1S-2P-unbound	★ Ionization test with 1S-2P-unbound	Commissioning, data taking
	LINAC: ★4.3 Me@H2					210MeV ★	Commissioning, data taking
	Storage			procurement		Installation ★	Commissioning, data taking
Detector	positron tracker, magnetic field monitors					Installation ★	Commissioning, data taking

Beyond 450 ppb statistical error?

1. Increase in muon polarization (currently 50%)
2. More efficient muonium production target (currently 3.4×10^{-3})
3. Increase the muon momentum (currently 300 MeV/c)



Optical pumping with train of laser pulse



Higher momentum beam (needs higher B-field)

Studies are in progress....

Conclusions

- New muon g-2 result from Fermilab reached impressive 127 ppb accuracy
  - Confirms consistency with previous results (inc. BNL)
  - Excellent agreement with new SM 2025 calculation
- Theory in progress however tensions in the hadronic sector
- Importance to check Fermilab/BNL result ("storage ring") with an alternative method
- Muon g-2/EDM experiments at J-PARC aims to measure muon g-2/EDM by utilizing low emittance muon beam stored in a compact region with a highly uniform B-field.
  - Same systematic error as Fermilab; statistical error 450 ppb (with room for improvement)
  - Muon EDM sensitivity at 1.5×10-21e・cm (stat.)
- Commissioning of the experiment around 2030
- Demonstrated muon cooling/acceleration for the first time in the world

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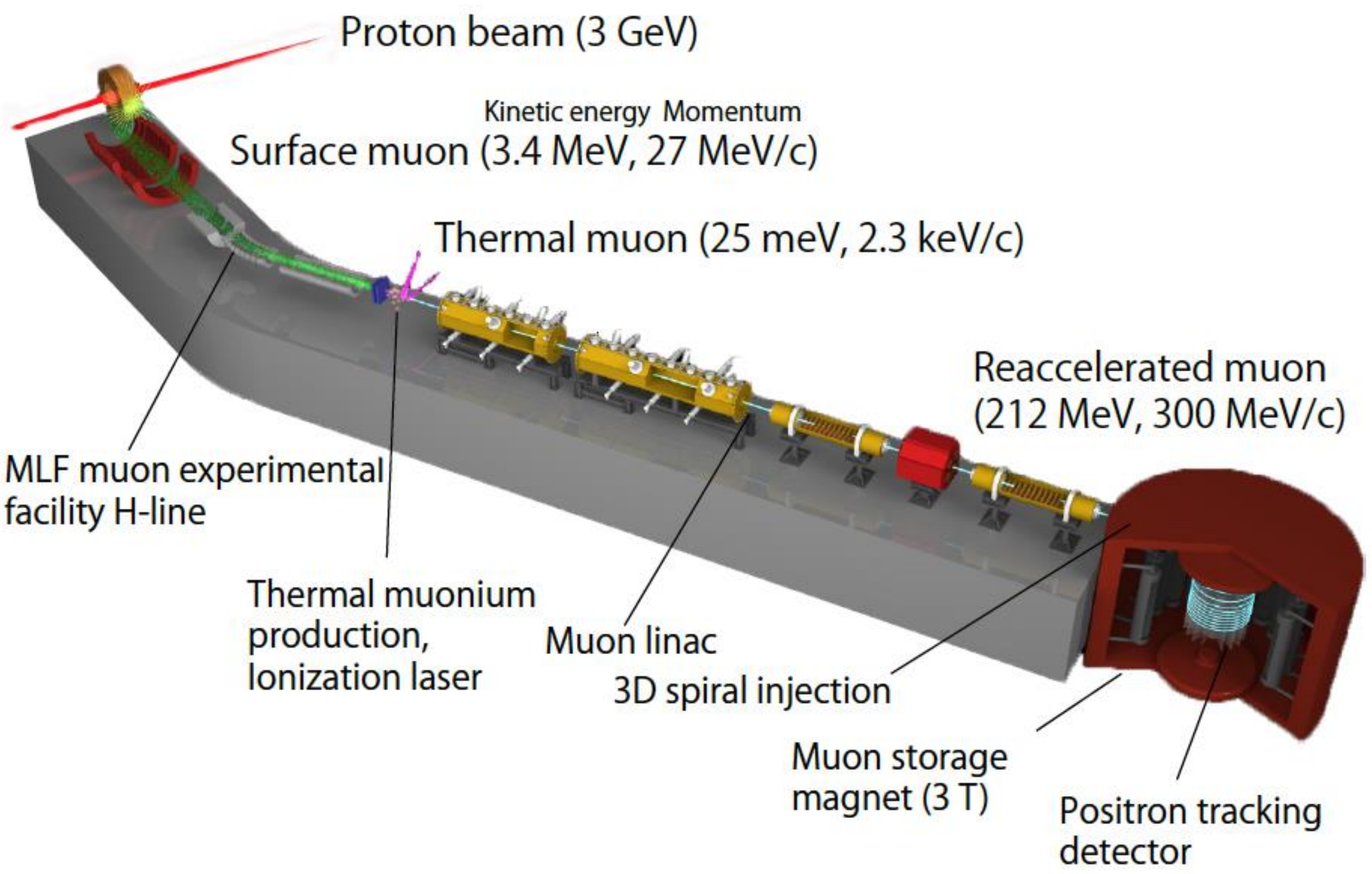
THANKS!

BACKUP



Proton beam (3 GeV)
Kinetic energy Momentum
Surface muon (3.4 MeV, 27 MeV/c)
Thermal muon (25 meV, 2.3 keV/c)
Reaccelerated muon (212 MeV, 300 MeV/c)
MLF muon experimental facility H-line
Thermal muonium production, Ionization laser
Muon linac
3D spiral injection
Muon storage magnet (3 T)
Positron tracking detector

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

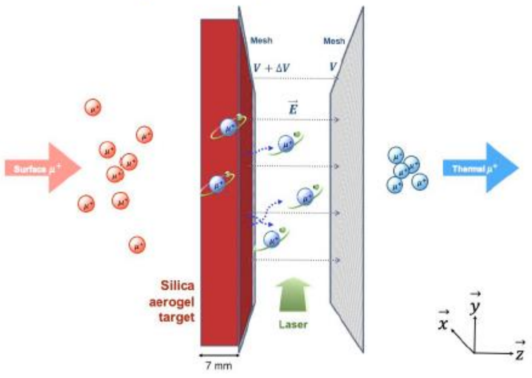
Table 4 Breakdown of estimated efficiency

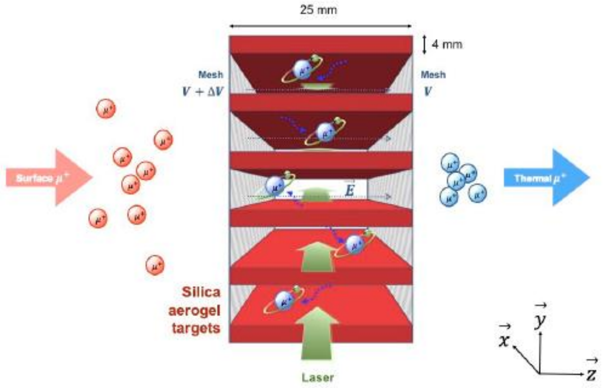
Subsystem	Efficiency	Subsystem	Efficiency
H-line acceptance and transmission	0.16	DAW decay	0.96
Mu emission	0.0034	DLS transmission	1.00
Laser ionization	0.73	DLS decay	0.99
Metal mesh	0.78	Injection transmission	0.85
Initial acceleration transmission and decay	0.72	Injection decay	0.99
RFQ transmission	0.95	Kicker decay	0.93
RFQ decay	0.81	e^+ energy window	0.12
IH transmission	0.99	Detector acceptance of e^+	1.00
IH decay	0.99	Reconstruction efficiency	0.90
DAW transmission	1.00		

$\text{Eff}_{\text{Tot}} = 1.3 \times 10^{-5}$ per produced muon

New ideas

Multi-layer target for Muonium production





Current design (single-layer)

- **Low Mu emission efficiency (0.0034):**
  - Muon stopping (0.418)
  - Vacuum emission (0.060)
  - Laser spatial constraint (0.269)

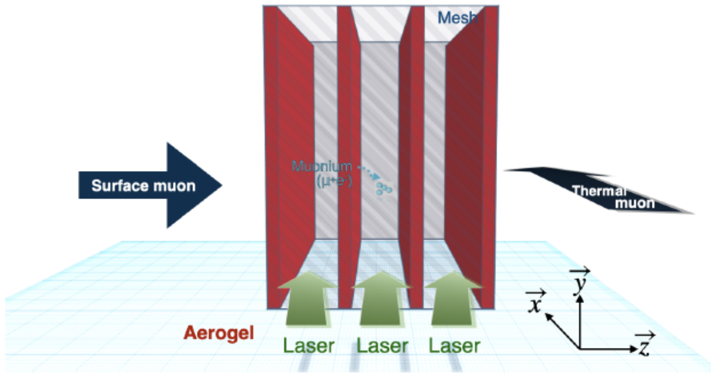
Novel multi-layer target design

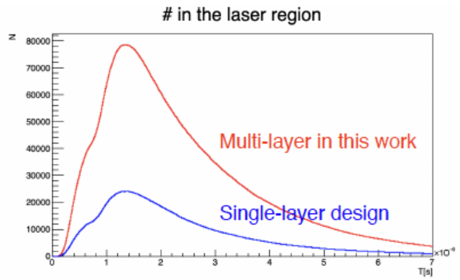
- Multi-layer targets stop incident muon
- Mu emits from upper and lower surfaces

New ideas

Multi-layer target for Muonium production

- Another version uses multi-layers facing the incident beam, resulting in a higher yield;
- The extraction is turned 90 degrees, making construction more challenging.





Simulation predicted even higher yields (4 times if 4 layers → 8 times at max)

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More detail on spin polarization

Assumption

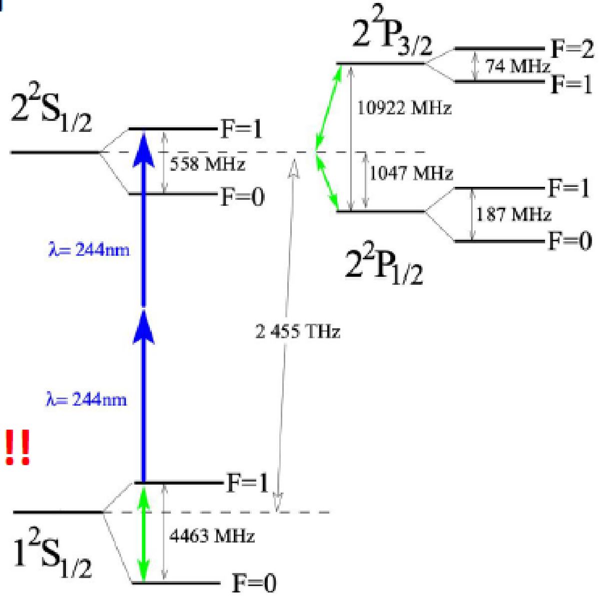
✓ Initial μ^+ has 100% spin pol.

✓ e^- has no spin pol. (↑ and ↓ equally)

Then, when muonium is formed…

➢ Half of Mu: $|S_\mu\rangle|S_e\rangle = |\uparrow\rangle|\uparrow\rangle$. **This is OK!!**

➢ **The other half:** $|S_\mu\rangle|S_e\rangle = |\uparrow\rangle|\downarrow\rangle$



$|S_\mu\rangle|S_e\rangle = |\uparrow\rangle|\downarrow\rangle$ *is not the eigen state !!*

$|S_\mu\rangle|S_e\rangle$ is a super position of $|F, m\rangle = |1, 0\rangle$ and $|F, m\rangle = |0, 0\rangle$.

→ $|\uparrow\rangle|\downarrow\rangle = \frac{1}{\sqrt{2}}|1, 0\rangle + \frac{1}{\sqrt{2}}|0, 0\rangle e^{i\omega t}$, where $\omega = 2\pi \times 4.4$ GHz

→ $\langle S_\mu^z\rangle \propto \cos(\omega t)$ → **0 (when t>> 1/(4GHz))**

Comparison of the statistical sensitivity: back of the envelope calculation

Parameter	Fermilab E989	J-PARC E24
Statistical goal	100 ppb	450 ppb
Magnetic field	1.45 T	3.0 T
Radius	711 cm	33.3 cm
Cyclotron period	149.1 ns	7.4 ns
Precession frequency, ω_a	1.43 MHz	2.96 MHz
Lifetime, $\gamma\tau_\mu$	64.4 μs	6.6 μs
Typical asymmetry, A	0.4	0.4
Beam polarization	0.97	0.50
Events in final fit	1.5×10^{11}	5.7×10^{11}
	T_{g-2} = 4.4 us	T_{g-2} = 2.2 us

$$\frac{\delta\omega_a}{\omega_a} = \frac{1}{\omega_a \gamma \tau P}\sqrt{\frac{2}{NA^2}}$$

FNAL

$$\frac{0.0381}{\sqrt{N}} = \frac{0.0381}{\sqrt{1.5*10\hat{}11}} = 100\text{ppb}$$

J-PARC

$$\frac{0.362}{\sqrt{N}} = \frac{0.362}{\sqrt{5.7*10\hat{}11}} = 480\text{ppb}$$

Expected Sensitivity

- Total efficiency of muon: 1.3×10^{-5}.
- Muon g-2
  - Statistical uncertainty: 450 ppb (2 year of data taking)
    - ✓ Comparable to BNL.
  - Systematic uncertainty: less than 70 ppb.
- Muon EDM
  - Statistical uncertainty: 1.5×10^{-21} e・cm.
  - Systematic uncertainty: 0.4×10^{-21} e・cm.
    - ✓ Mainly from detector mis-alignment

Subsystem	Efficiency	Subsystem	Efficiency
H-line acceptance and transmission	0.16	DAW decay	0.96
Mu emission	0.0034	DLS transmission	1.00
Laser ionization	0.73	DLS decay	0.99
Metal mesh	0.78	Injection transmission	0.85
Initial acceleration transmission and decay	0.72	Injection decay	0.99
RFQ transmission	0.95	Kicker decay	0.93
RFQ decay	0.81	e^+ energy window	0.12
IH transmission	0.99	Detector acceptance of e^+	1.00
IH decay	0.99	Reconstruction efficiency	0.90
DAW transmission	1.00		

Anomalous spin presession (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