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The g-2/EDM experiment @J-PARC

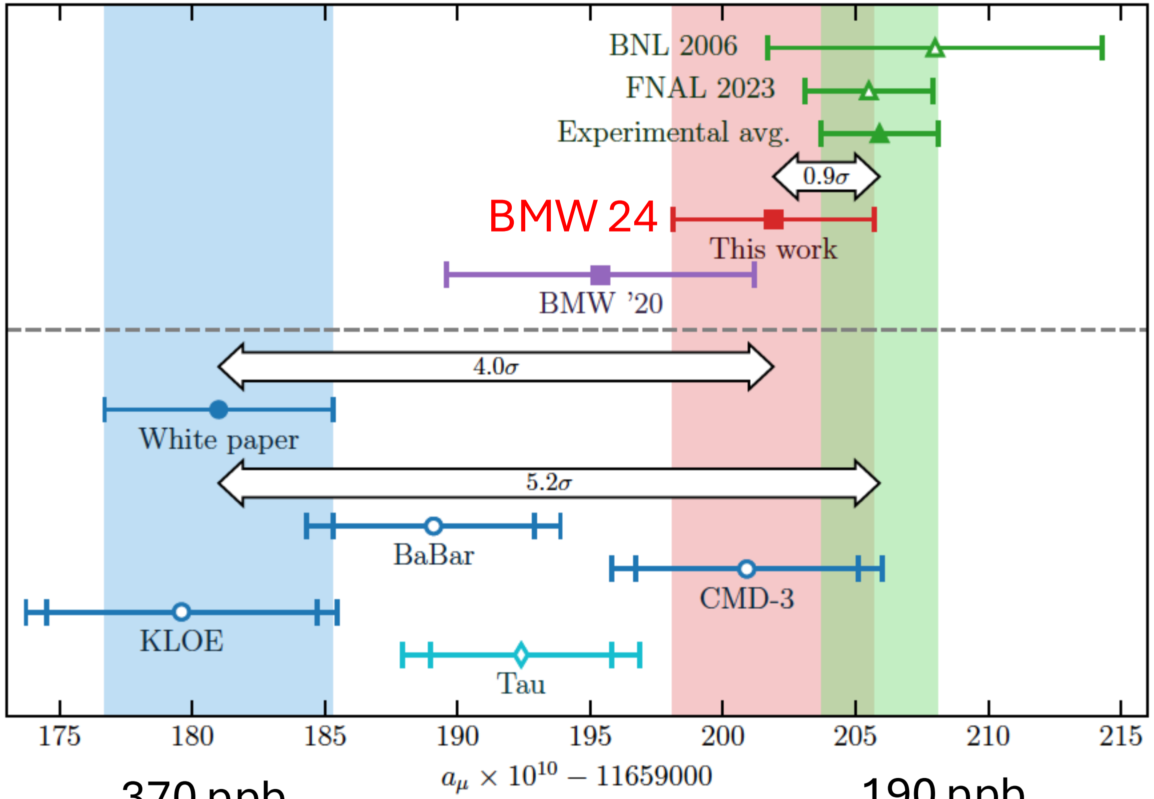
Graziano Venanzoni

Liverpool, HEP Annual Meeting, 23/5/2025

LEVERHULME TRUST

Status of the Muon g-2

WP20 SM predicton Experiment



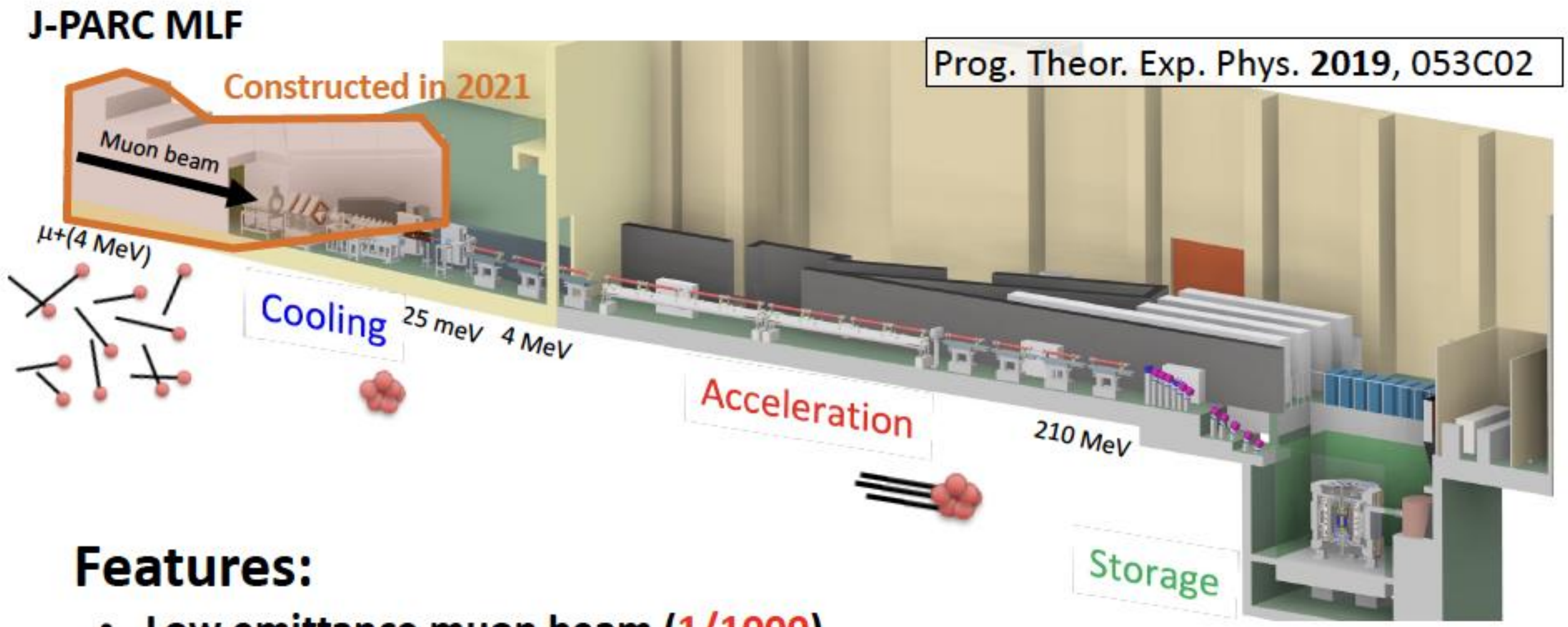
370 ppb 190 ppb

Waiting for the new Muon g-2 result

Quite confused situation:

- WP20 SM prediction (blue band, HVP based on e^+e^- data) in significant tension (> 5σ) with Fermilab (FNAL) muon g-2 experimental result;
- New (precise) lattice prediction for HVP (BMW20-24) in significant tension with wp20 and much closer to FNAL experimental result
- New result from CMD3 (e+e-) in significant tension with old e+e- data (used for WP20), and in agreement with BMW20-24
- Test of HVP in progress from e+e- data, lattice, tau and more in future from MUonE
- In parallel to this clarifications...cross check of the experimental result with a new method?

g-2/EDM experiment at JPARC

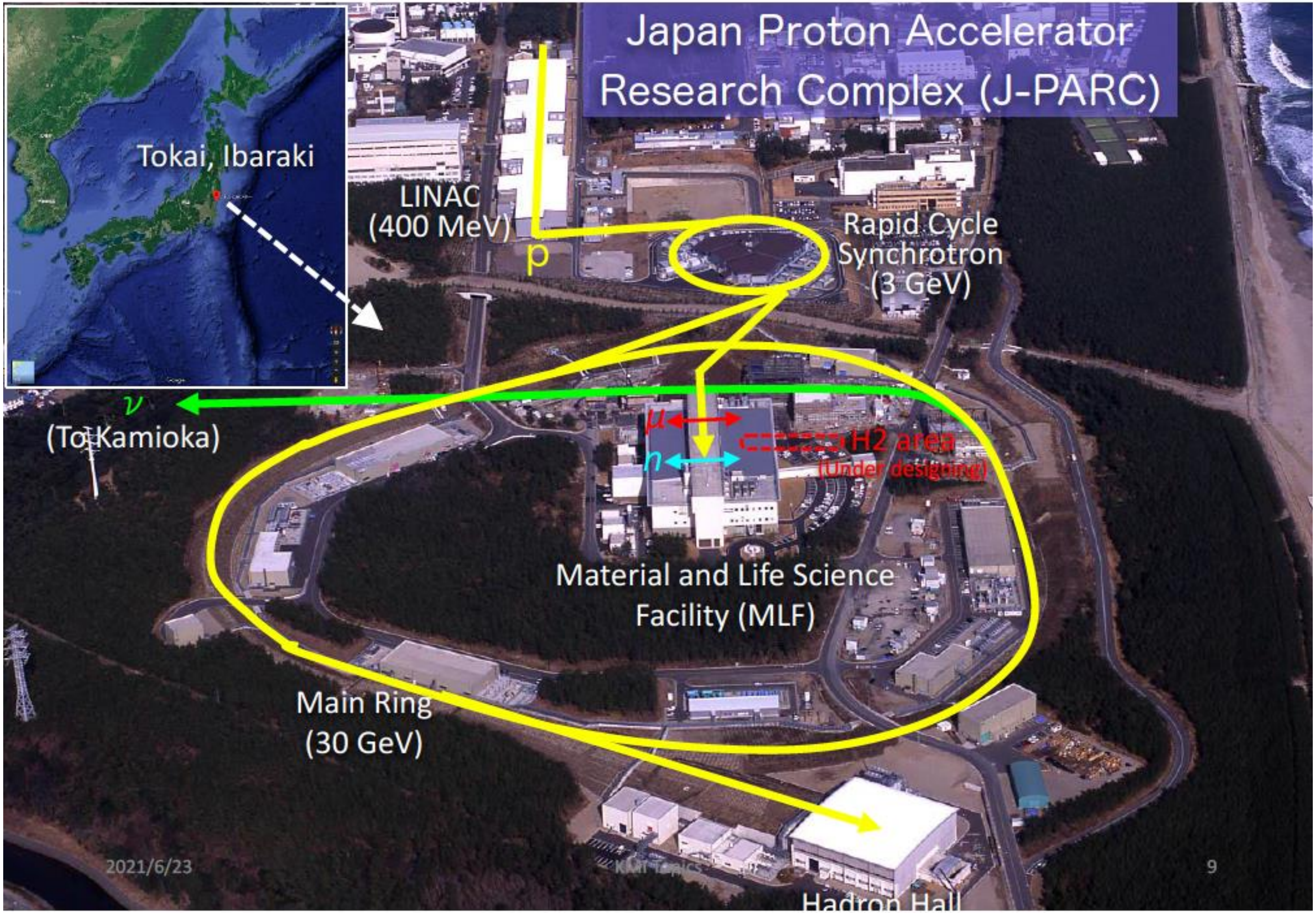


Features:

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

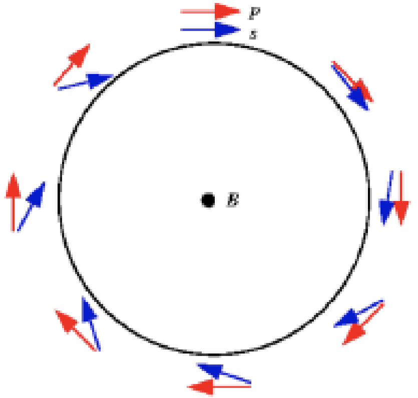
- Tracking detector with large acceptance
- Completely different from BNL/FNAL method

Japan Proton Accelerator Research Complex (J-PARC)

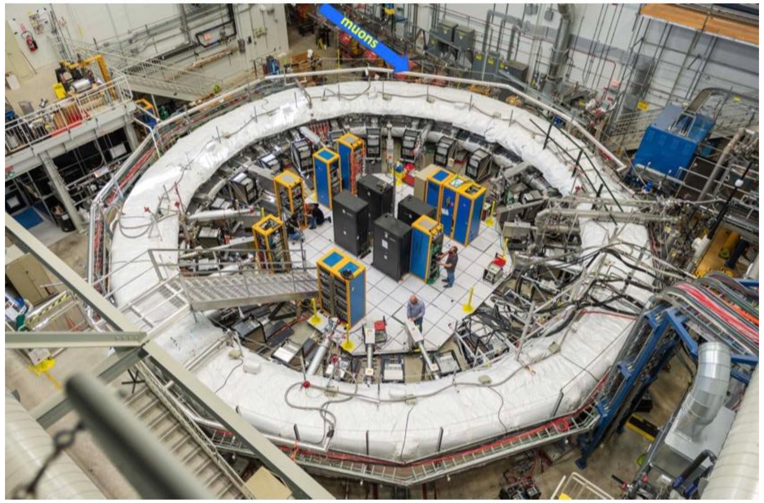


What makes them different?

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



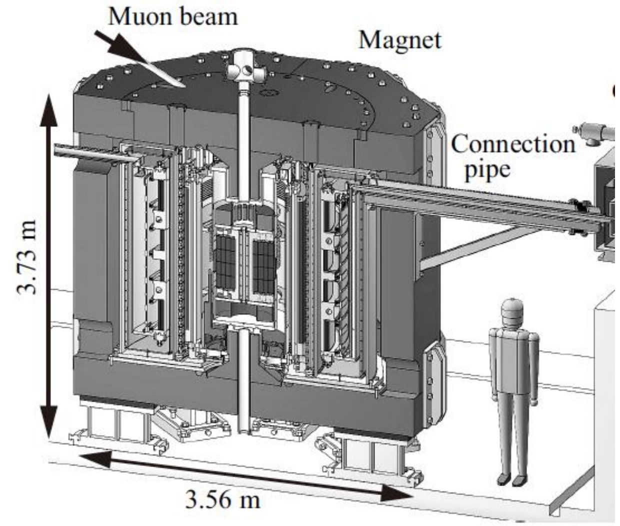
Fermilab (BNL) muon g-2 experiment(s)



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

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

JPARC muon g-2/EDM experiment



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

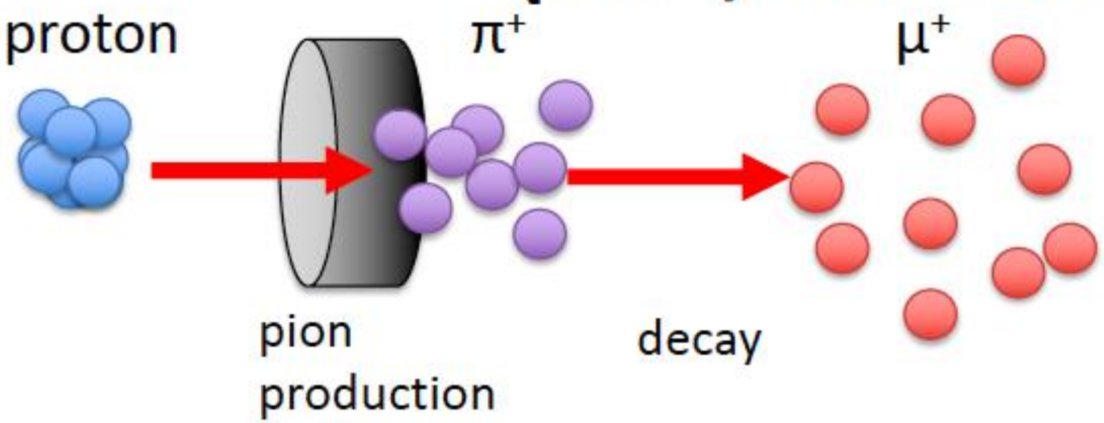
- **No electric field** (E=0)
- 300 MeV/c momentum
- 0.66 m ring diameter (B = 3 T)

-Different systematics

-Simultaneous measurement of g-2/EDM

a_μ can be extracted by precisely measuring B and ω.

Conventional muon beam (BNL, Fermilab)

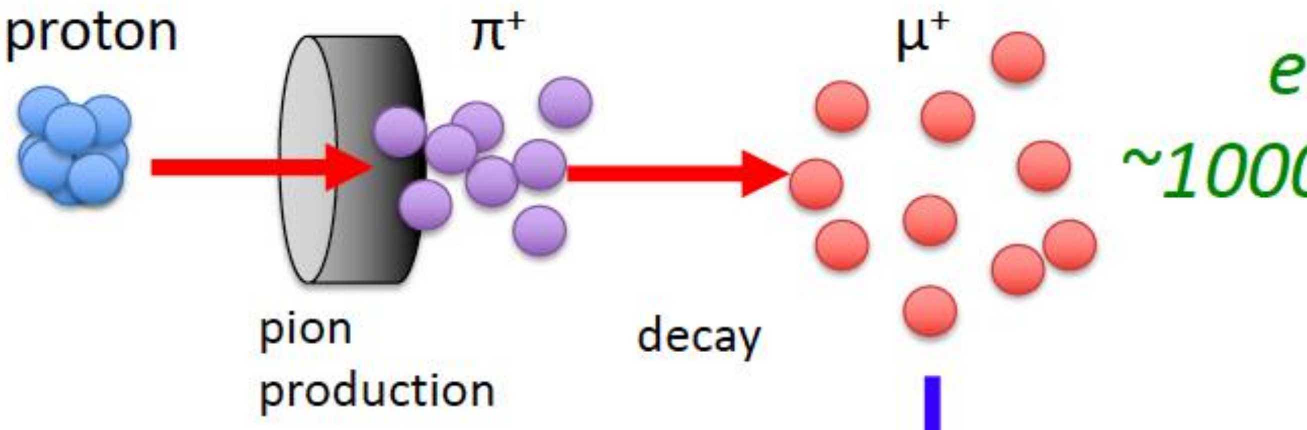


emittance ~1000π mm ·mrad

Strong focusing
Muon loss
BG π contamination

$\sigma_p/p \sim 0.2\%$
($\sim 1\%$ before entering the ring)

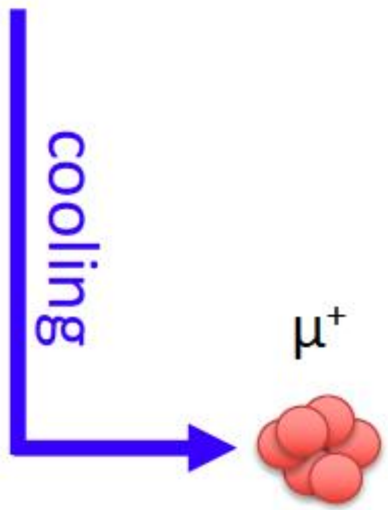
Muon beam at J-PARC



emittance

~1000π mm ·mrad

Strong focusing
Muon loss
BG π contamination



emittance

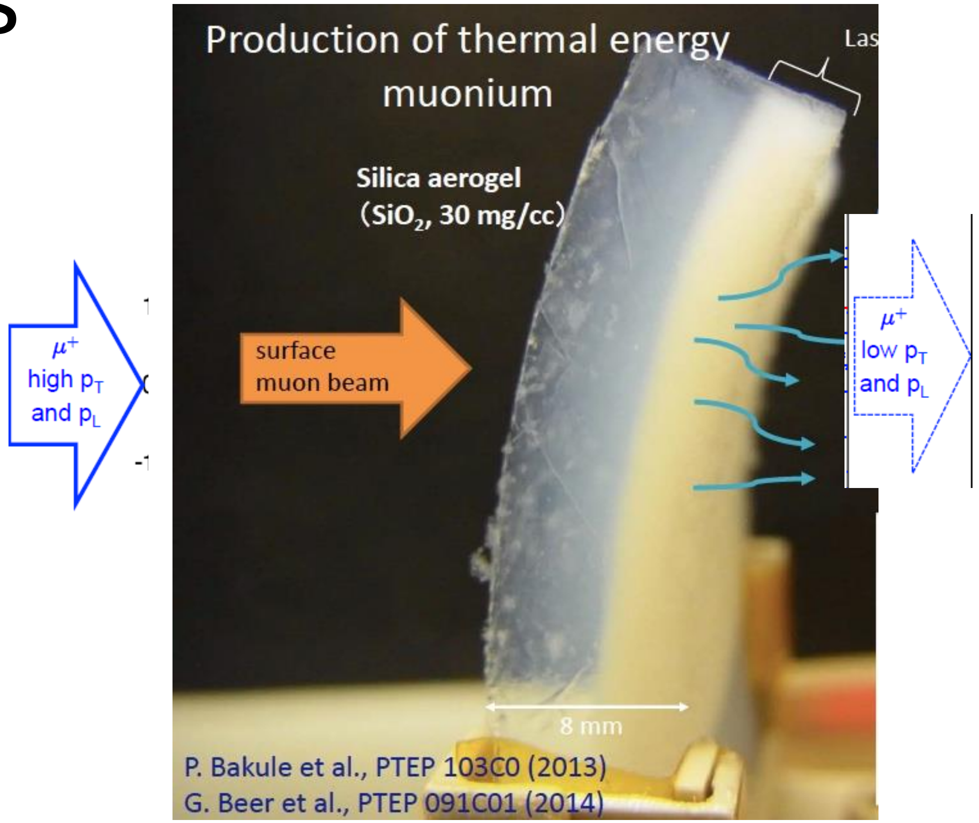
1π mm ·mrad

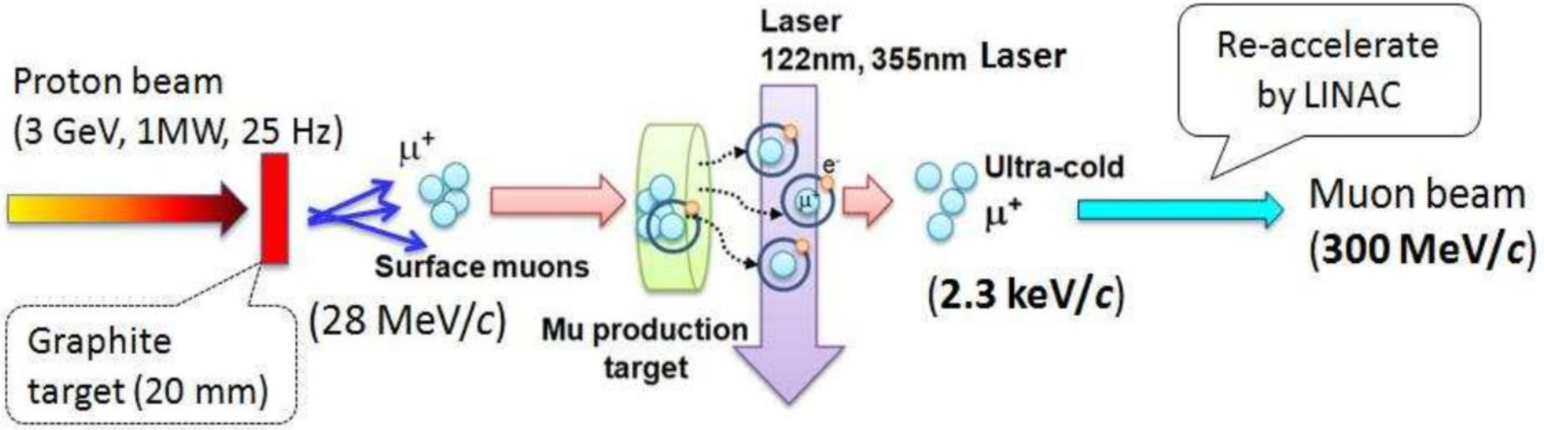
Reaccelerated thermal muon

Free from any of these

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
  - p= 210 MeV/c

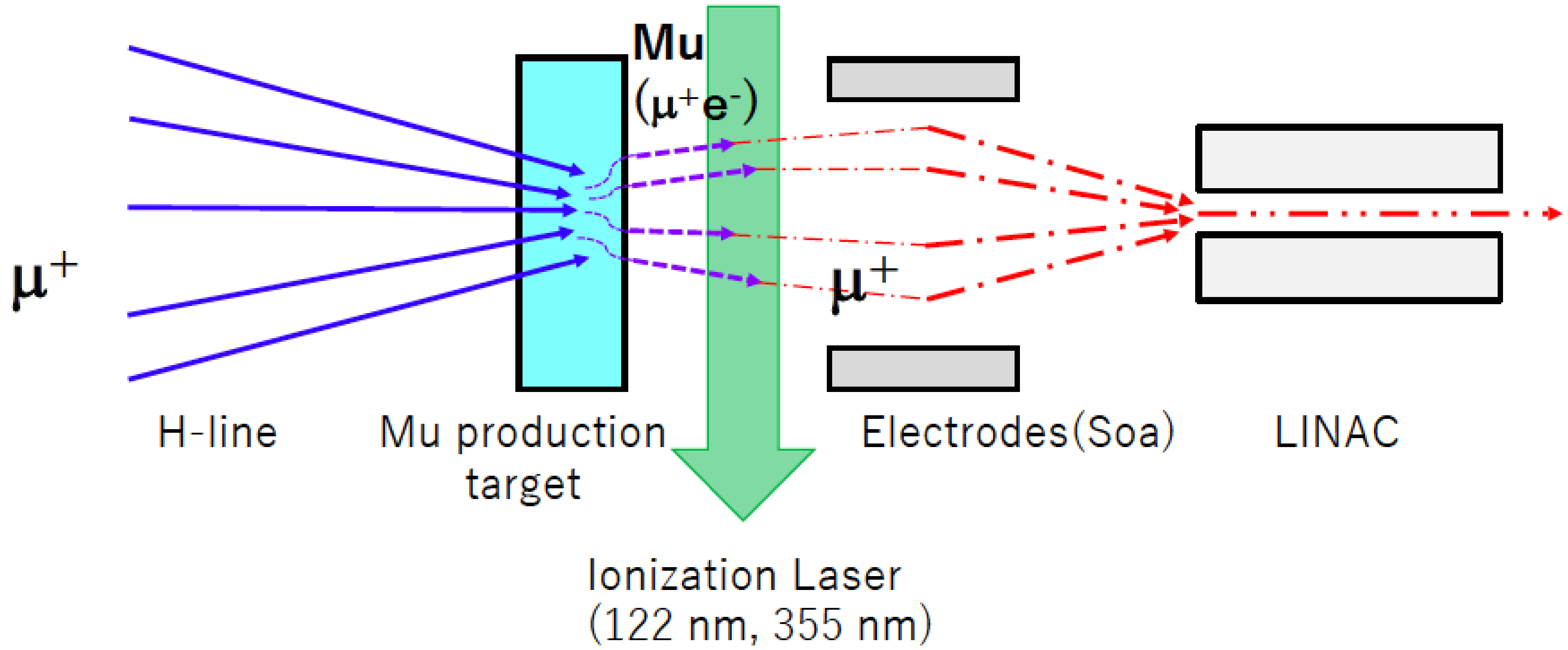




Ultra-cold Muons

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	$4\mathrm{x}10^{-4}$



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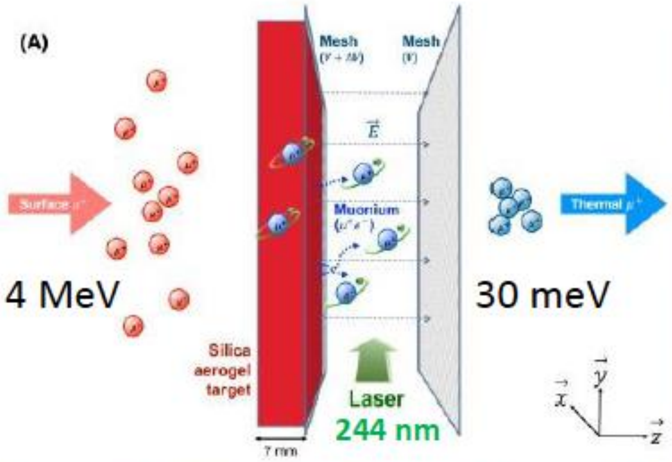
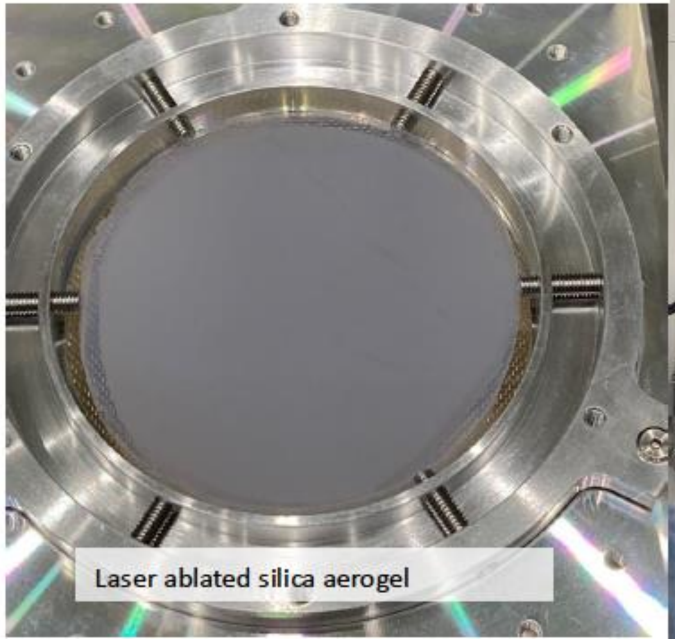
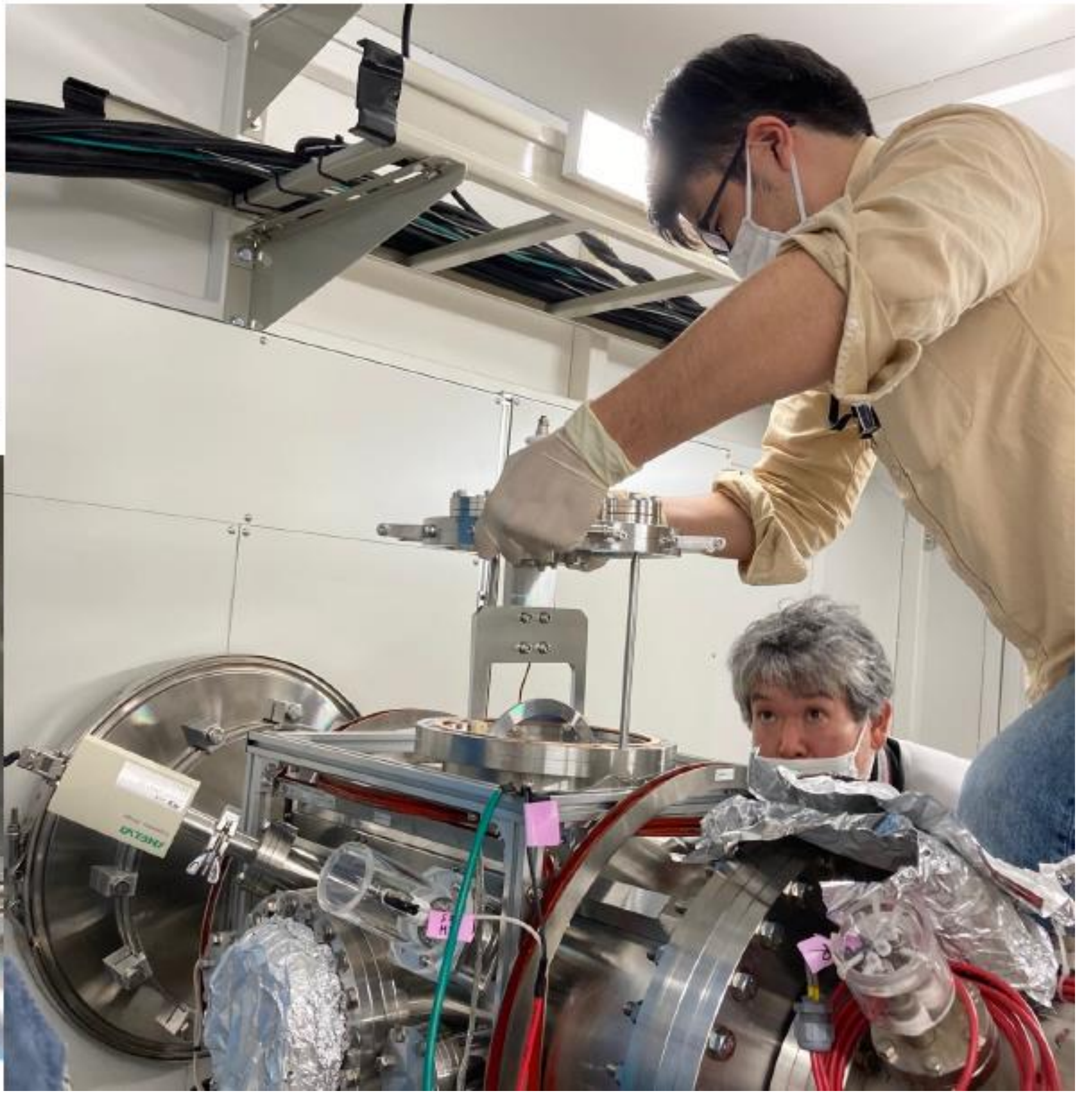
Muon cooling demonstration (2024)

Acceleration from termal energy to 100 keV by RF system



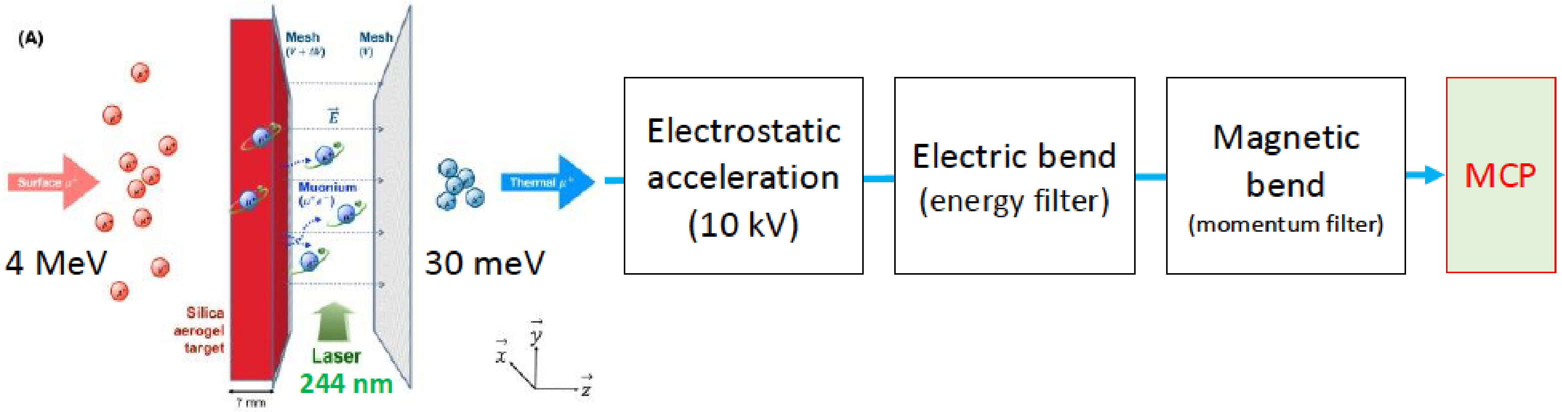


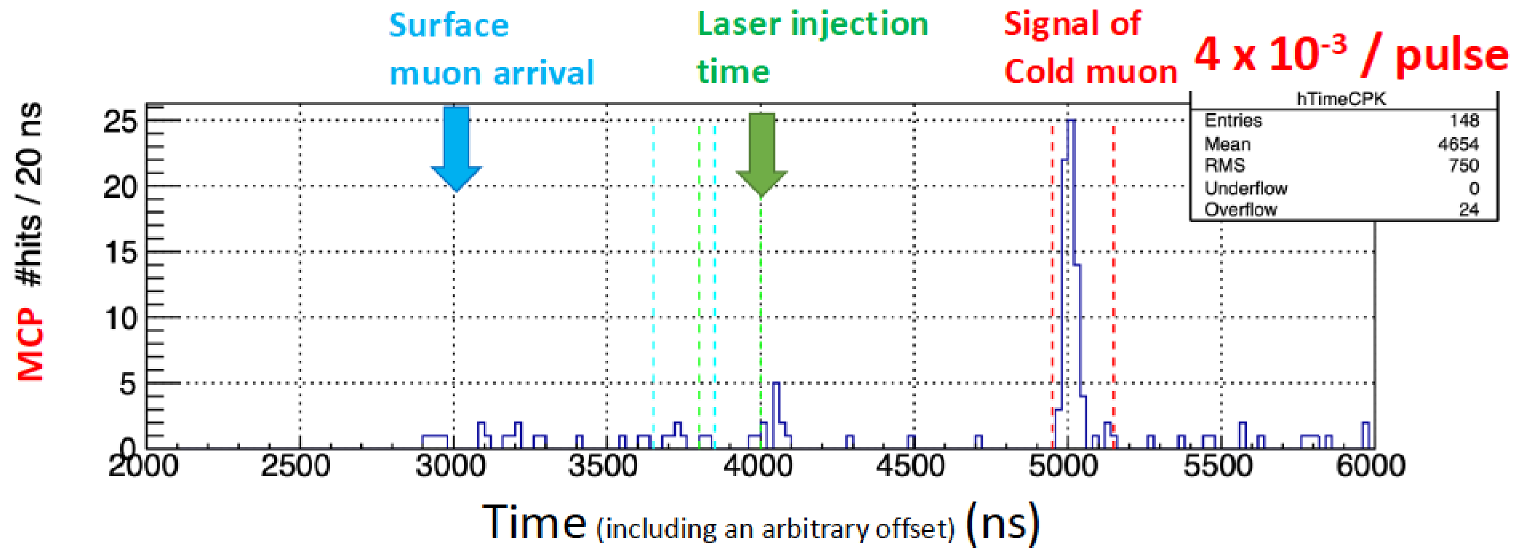
J-PARC S2 area



http://arxiv.org/abs/2410.11367v1

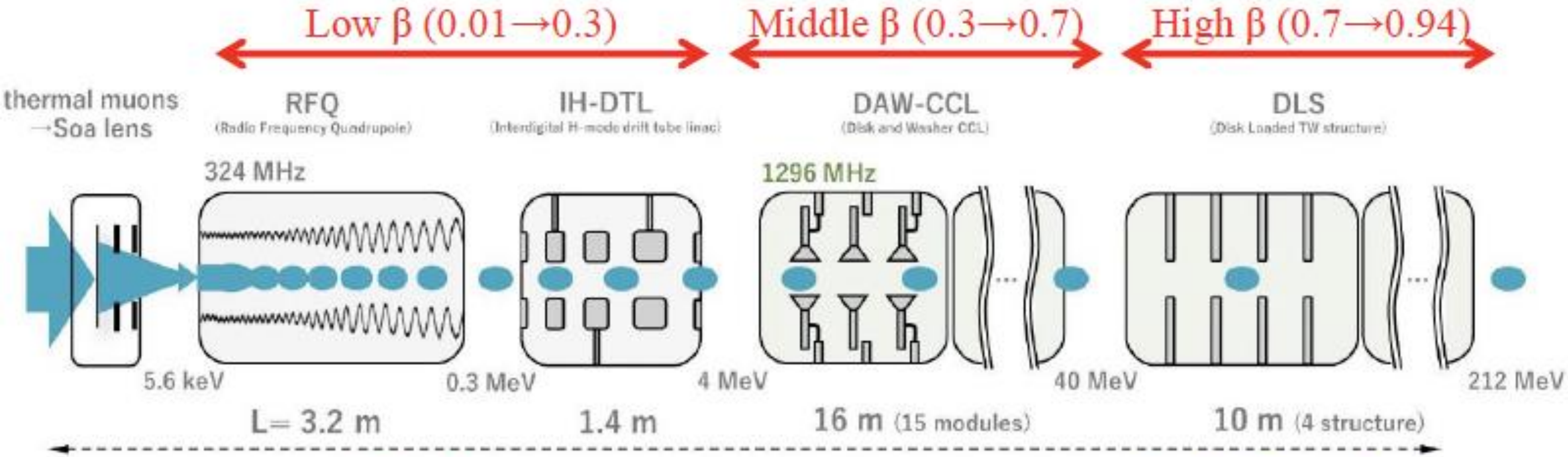
Muon cooling demonstration





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.



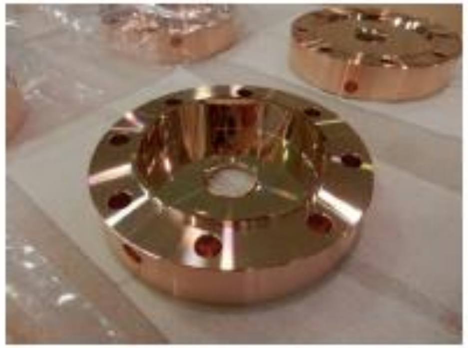
Ready

Ready: Acceleration test in 2026/2027

Ready for production except for bridge coupler

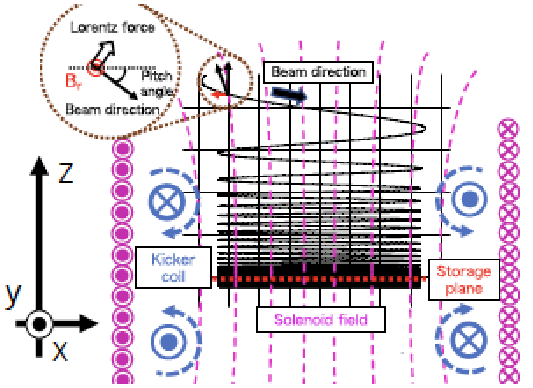
Ready for production except for pulse compressor

Washer 1,2 (×2)

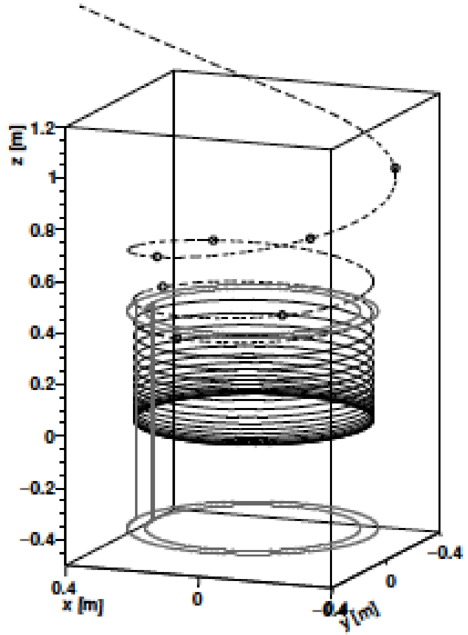


Muon storage magnet

- 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 T= 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
(|z| < 40cm)

storage region
(|z| < 5cm; r =33.3+-0.15 cm)

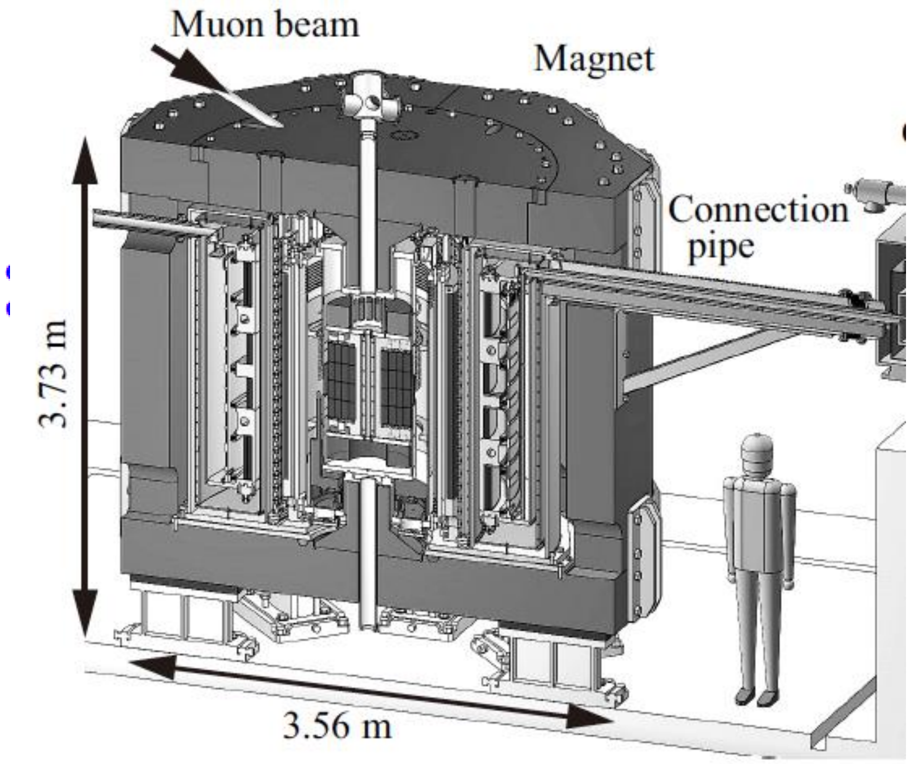
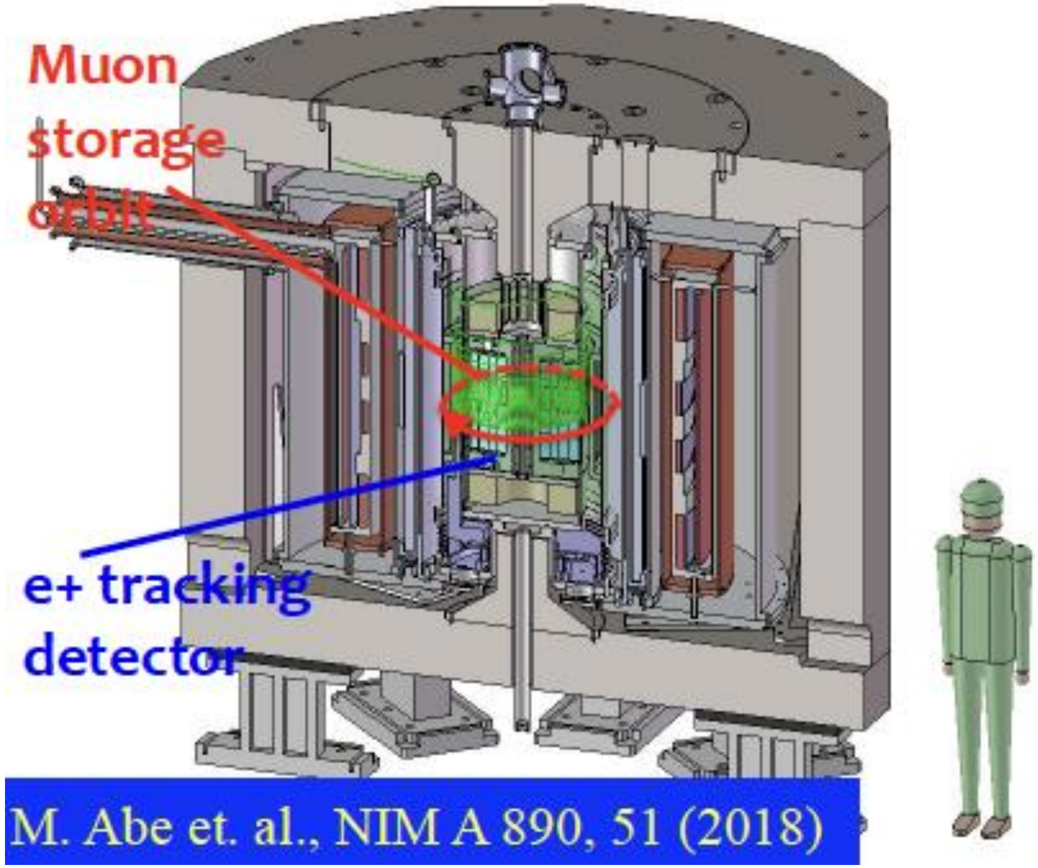
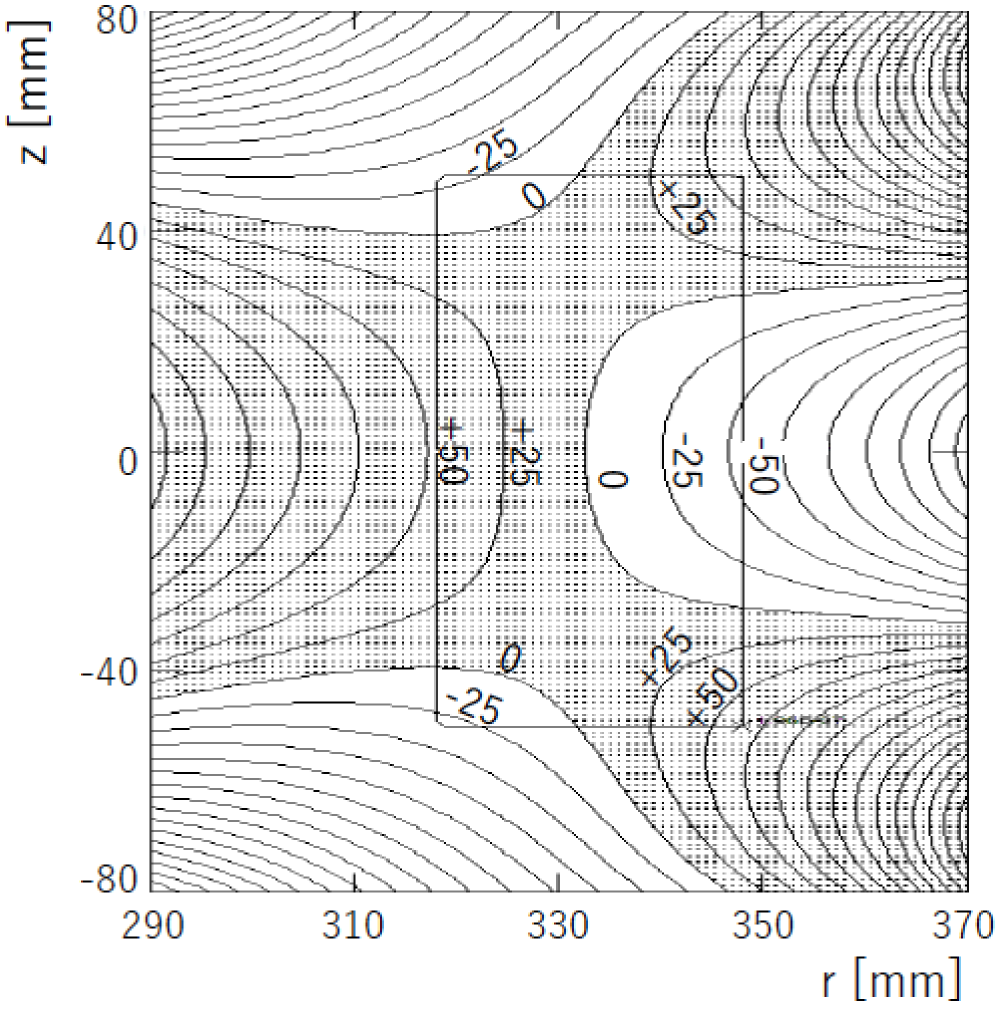


Fig. 8 Overview of the muon storage magnet

MRI magnet B=3T, d=66 cm



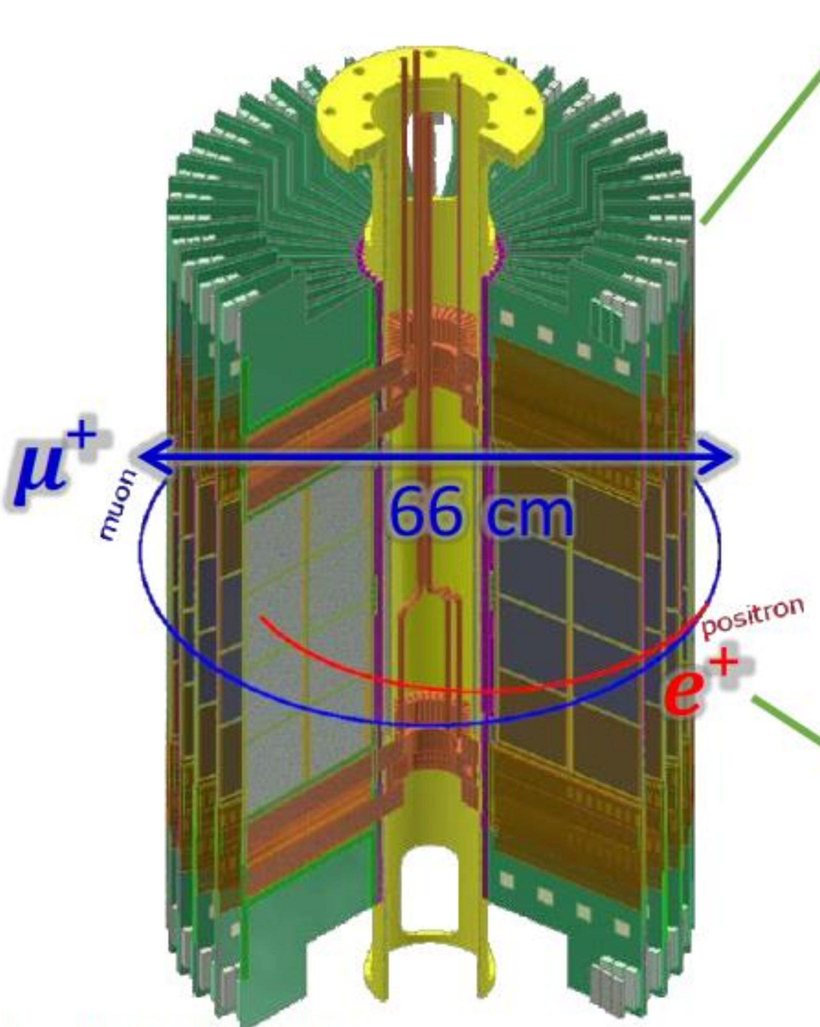


Storing region confinded in |z| < 5 cm; 32 <r < 35 cm

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

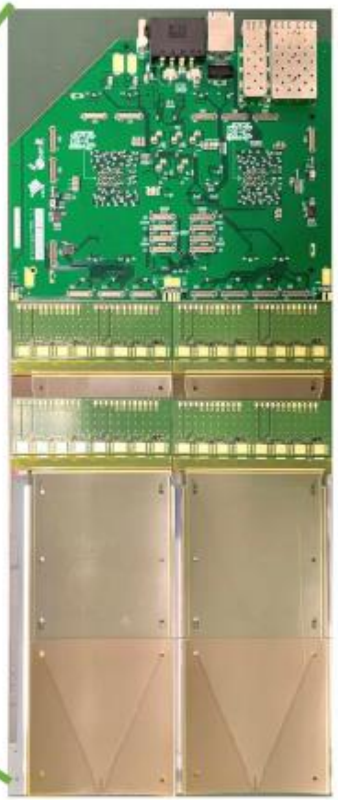
Positron tracking detector

- 40 modules (vanes) each 200mm (90-290 mm, radial) x 400mm (axial)
- Each vane consists of 16 Si sensors (10x 10 cm^2, 320 um 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.



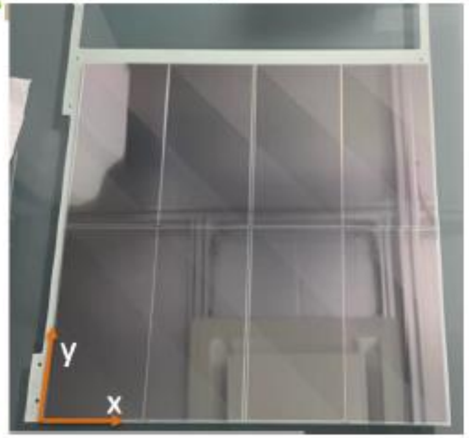
IEEE, TNS 67, 2089 (2020)
JINST 15 P04027 (2020)

$200<p_e<275$ MeV/c

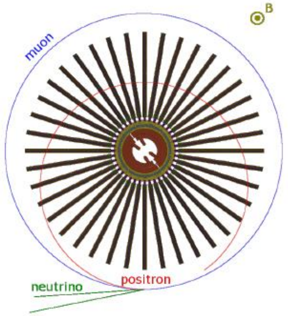


Test with prototype boards

Si strip sensors



~200 mm



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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	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	Running	In preparation

Expected uncertainties

	Estimation
Total number of muons in the storage magnet	5.2×10^{12}
Total number of positrons	0.57×10^{12}
Effective analyzing power	0.42
Statistical uncertainty on ω_a [ppb]	450
Statistical uncertainty on ω_p [ppb]	100
Uuncertainties on a_μ [ppb]	460 (stat.) $<$ 70 (syst.)
Uncertainties on EDM [10^{-21} e·cm]	1.4 (stat.) 0.36 (syst.)

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

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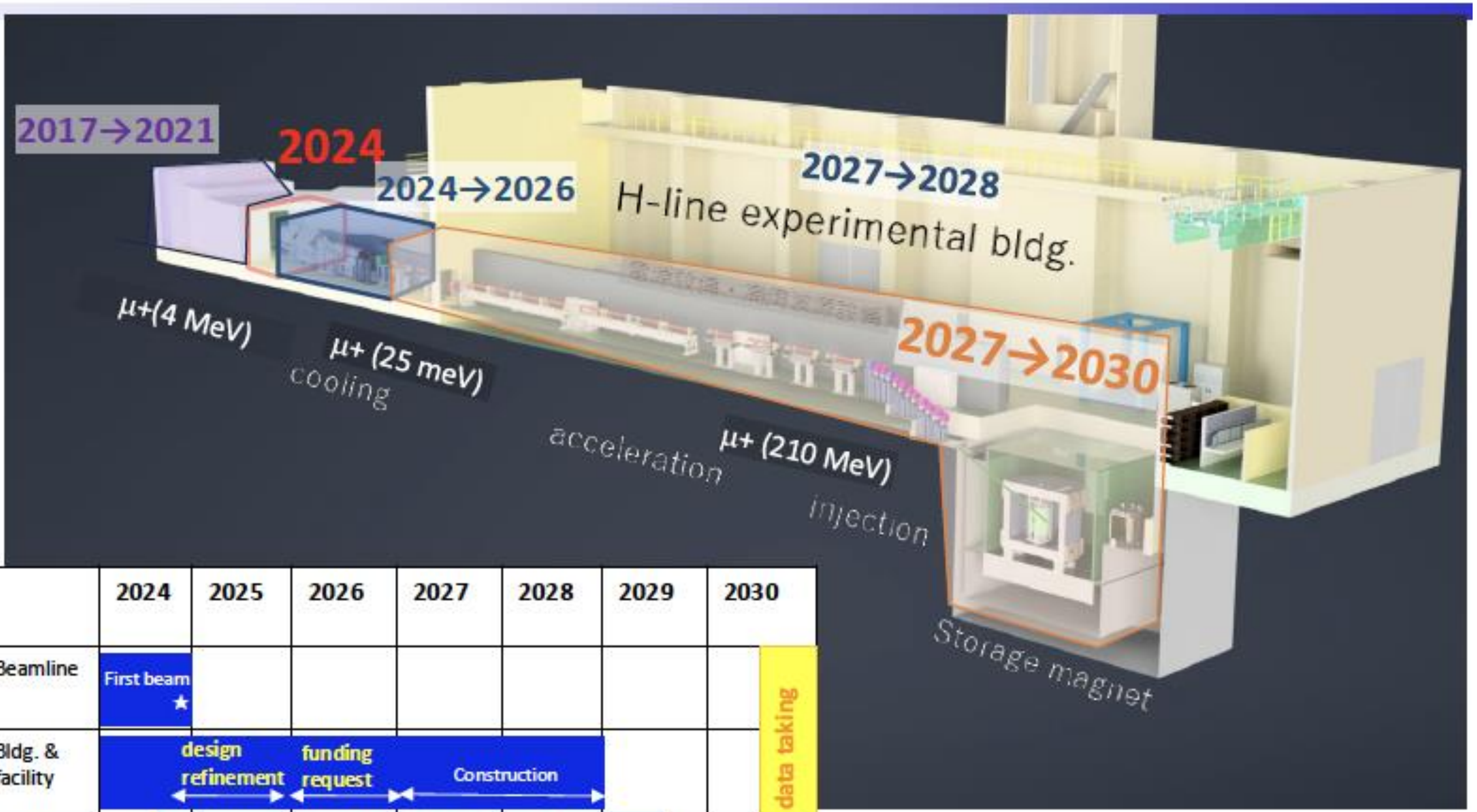
Schedule and Milestones



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

Possibility to go beyond 450 ppb for a_μ uncertainty

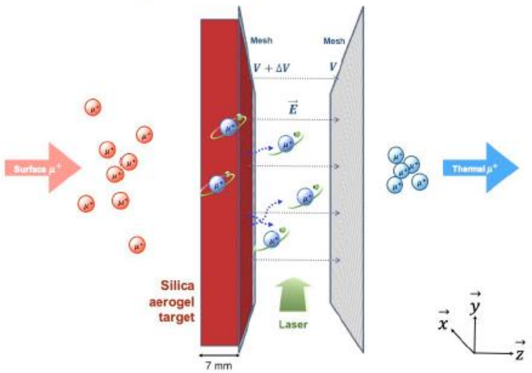
1. Increase in muon polarization using a laser beam (50% → ?) see J. Tensley presentation
2. More efficient muonium production target (3.4×10^{-3} → ?)
3. Increase the momentum (→ 600 MeV/c?) and magnetic field (→ 6T?)

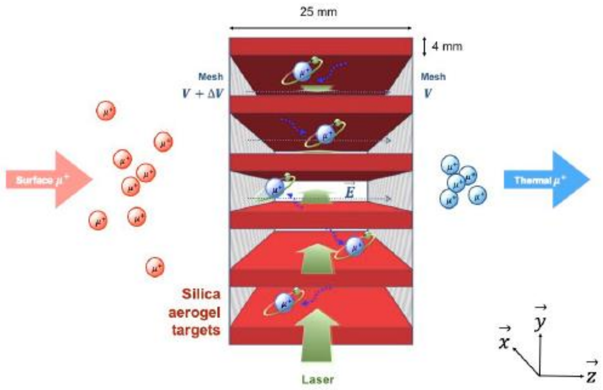
$$\frac{\delta\omega_a}{\omega_a} = \frac{1}{\omega_a \gamma \tau P}\sqrt{\frac{2}{NA^2}}$$

These are preliminary investigations

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)

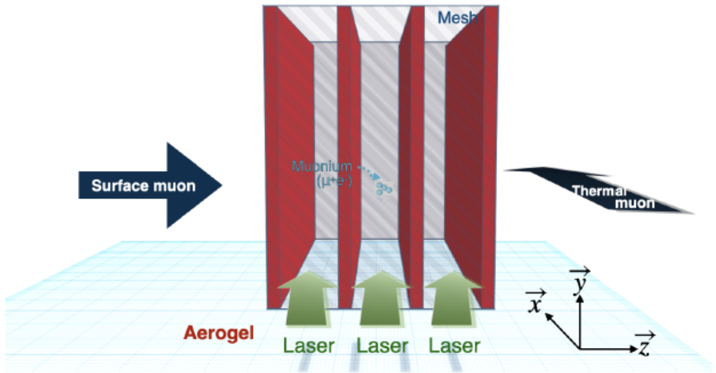
Novel multi-layer target design

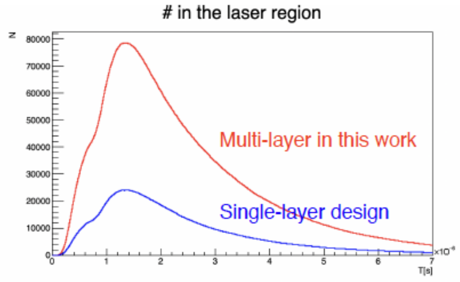
- Multi-layer targets stop incident muon
- Mu emits from upper and lower surfaces

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)

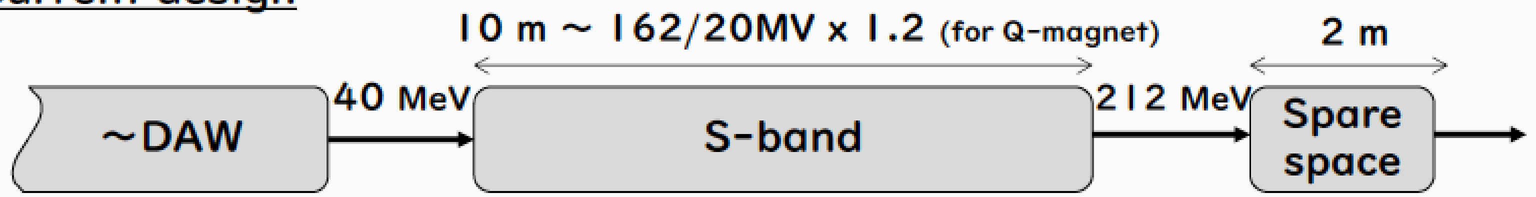
Courtesy of C. Zhang

Increasing the muon momentum to 600 Mev/c

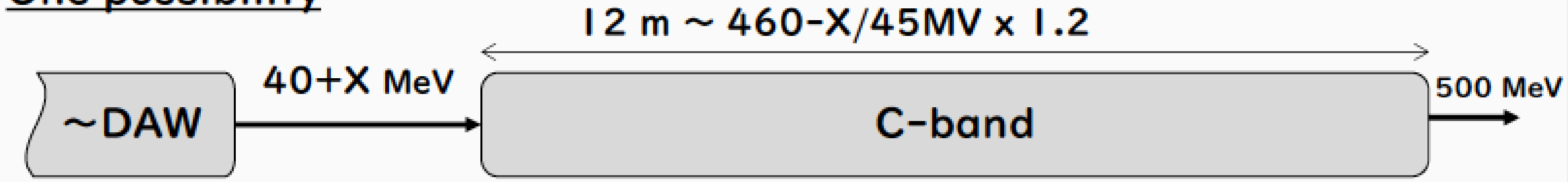
- Adding a C-band accelerator (~45 MV/m, compared to 20 MV/m in S-band) is a natural choice for this option.

  1. Design muon-dedicated C-band accelerator.
  2. Update the upstream design to accommodate the smaller acceptance of the C-band accelerator. One possible approach is to use a compact system with higher energy (40 + X MeV).

Current design



One possibility



9/9

Ongoing discussion with Carsten Welsh on RF cavities

Interest in the Muon g-2/EDM experiment at J-PARC

- Important (independent) crosscheck of the Fermilab result (especially at similar accuracy)
- Possible contribution(s):
  - Laser for muon polarization (see J. Tinsley presentation)
  - Beam dynamics simulation
  - Detector
  - Magnetic field measurement
  - Higher precision/energy (600 MeV/c) option
- Synergy with muon activities in Liverpool (MUonE, muEDM, etc...)
- Common grants (*e.g.* UKRI – JST Funding application)

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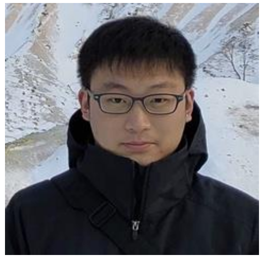
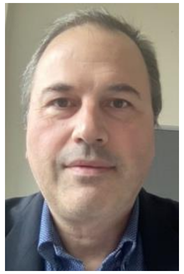
Liverpool group interested to g-2/EDM@J-PARC

- Themis Bowcock (staff)
- Thomas Teuber (staff)
- Joost Vossebeld (staff)
- Graziano Venanzoni (staff)
- Jonathan Tinsley (staff)
- Saskia Charity (staff)
- Fedor Ignatov (staff)
- Elia Bottalico (PDRA)
- Riccardo Pilato (PDRA)
- Estifa’a Zaid (PDRA)
- Cedric Zhang (PDRA)
- Lorenzo Cotrozzi (PDRA)





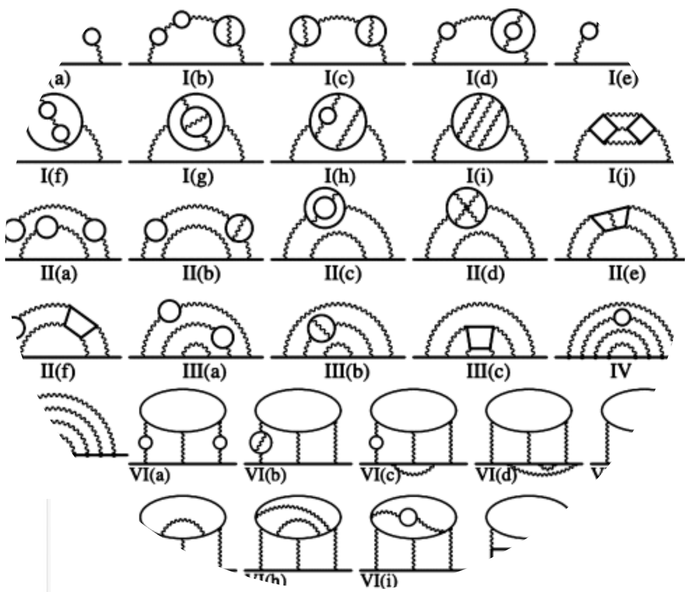

THANKS!

Interest in the Muon g-2/EDM experiment @JPARC

- The Liverpool group has significantly contributed to the Muon g-2 experiment in Fermilab:
  - **One of the largest group in the g-2 collaboration**
  - Built **straw tracking detectors** to measure the muon beam → crucial to reach uncertainty goal
  - Leadership in several areas including: **magnetic field**, **beam dynamics**, **EDM**; **spin precession**. Spokesperson, analysis coordinators, run coordinators, committee membership
  - Deeply involved in g-2 analysis and first EDM result
- The group is also involved in clarifying/improving the muon g-2 theoretical prediction through MUonE experiment at CERN and analysis of KLOE data. Strong connection with (Liverpool) theory group
- Involvement also on μEDM experiment at PSI

Collaboration with Theory

- A > 20 years **common** activity on the evaluation of the Muon g-2
- Development of theoretical tools (MC, RC) for interpretation of data
- Participation to common Working Groups



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Physics Reports

Volume 887, 3 December 2020, Pages 1-166

The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama [1,2,3], N. Asmussen [4], M. Benayoun [5], J. Bijnens [6], T. Blum [7,8], M. Bruno [9], I. Caprini [10], C.M. Carloni Calame [11], M. Cè [9,12,13], G. Colangelo [14], F. Curciarello [15,16], H. Czyż [17], I. Danilkin [12], M. Davier [18], C.T.H. Davies [19], M. Della Morte [20], S.I. Eidelman [21,22], A.X. El-Khadra [23,24] ... A.S. Zhevlakov [78]

Show more

Dec 2024

Radiative corrections and Monte Carlo tools for low-energy hadronic cross sections in e^+e^- collisions

RadioMonteCarLow 2 Working Group: Riccardo Aliberti [1], Paolo Beltrame [2], Ettore Budassi [3,4], Carlo M. Carloni Calame [4], Gilberto Colangelo [5], Lorenzo Cotrozzi [2], Achim Denig [1], Anna Driutti [6,7], Tim Engel [8], Lois Flower [2,9], Andrea Gurgone [3,6,7], Martin Hoferichter [5], Fedor Ignatov [2], Sophie Kollatzsch [10,11], Bastian Kubis [12], Andrzej Kupść [13,14,*], Fabian Lange [11,10], Alberto Lusiani [15,7], Stefan E. Müller [16], Jérémy Paltrinieri [2], Pau Petit Rosàs [2], Fulvio Piccinini [4], Alan Price [17], Lorenzo Punzi [7,15], Marco Rocco [10,18], Olga Shekhovtsova [19,20], Andrzej Siódmok [17], Adrian Signer [10,11,*], Giovanni Stagnitto [21], Peter Stoffer [10,11], Thomas Teubner [2], William J. Torres Bobadilla [2], Francesco P. Ucci [3,4], Yannick Ulrich [2,5,*], and Graziano Venanzoni [2,7,*]

https://arxiv.org/pdf/2410.22882

Submitted to SciPost

The RadioMonteCarlow 2 Effort

Riccardo Aliberti [1] Paolo Beltrame [2] Ettore Budassi [3,4]
Carlo M. Carloni Calame [4] Gilberto Colangelo [5] Lorenzo Cotrozzi [2]
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Andrea Gurgone [3,4,6] Martin Hoferichter [5] Fedor Ignatov [2]
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Alberto Lusiani [15,7] Stefan E. Müller [16] Jérémy Paltrinieri [2] Pau Petit Rosàs [2]
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https://radiomontecarlow2.gitlab.io

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Quest for precision in hadronic cross sections at low energy: Monte Carlo tools vs. experimental data

Working Group on Radiative Corrections and Monte Carlo Generators for Low Energies, S. Actis, A. Arbuzov, G. Balossini, P. Beltrame, C. Bignamini, R. Bonciani, C. M. Carloni Calame, V. Cherepanov, M. Czakon, H. Czyż, A. Denig, S. Eidelman, G. V. Fedotovich, A. Ferroglia, J. Gluza, A. Grzelińska, M. Gunia, A. Hafner, F. Ignatov, S. Jadach, F. Jegerlehner, A. Kalinowski, W. Kluge, ... C. Z. Yuan

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Letter

An alternative evaluation of the leading-order hadronic contribution to the muon g − 2 with MUonE

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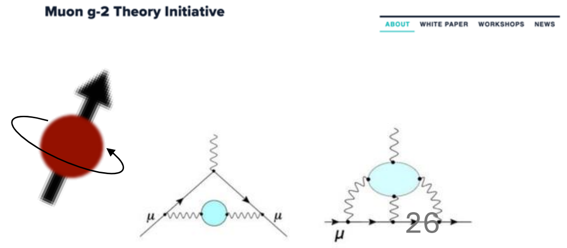

What makes them different?

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

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

- Eliminate electric focusing removes ***β*** x ***E*** term

Do need ~zero P_T to store muons

- → Not constrained to run at the “magic momentum”
- Create “ultra-cold” muon source; accelerate, and inject into compact storage ring.
- Consequences are quite interesting …
  - Smaller magnet; intrinsically more uniform
- Aim for BNL level precision as an important check