LEVERHULME TRUST

UNIVERSITY OF LIVERPOOL

Status of J-PARC muon g-2/EDM experiment

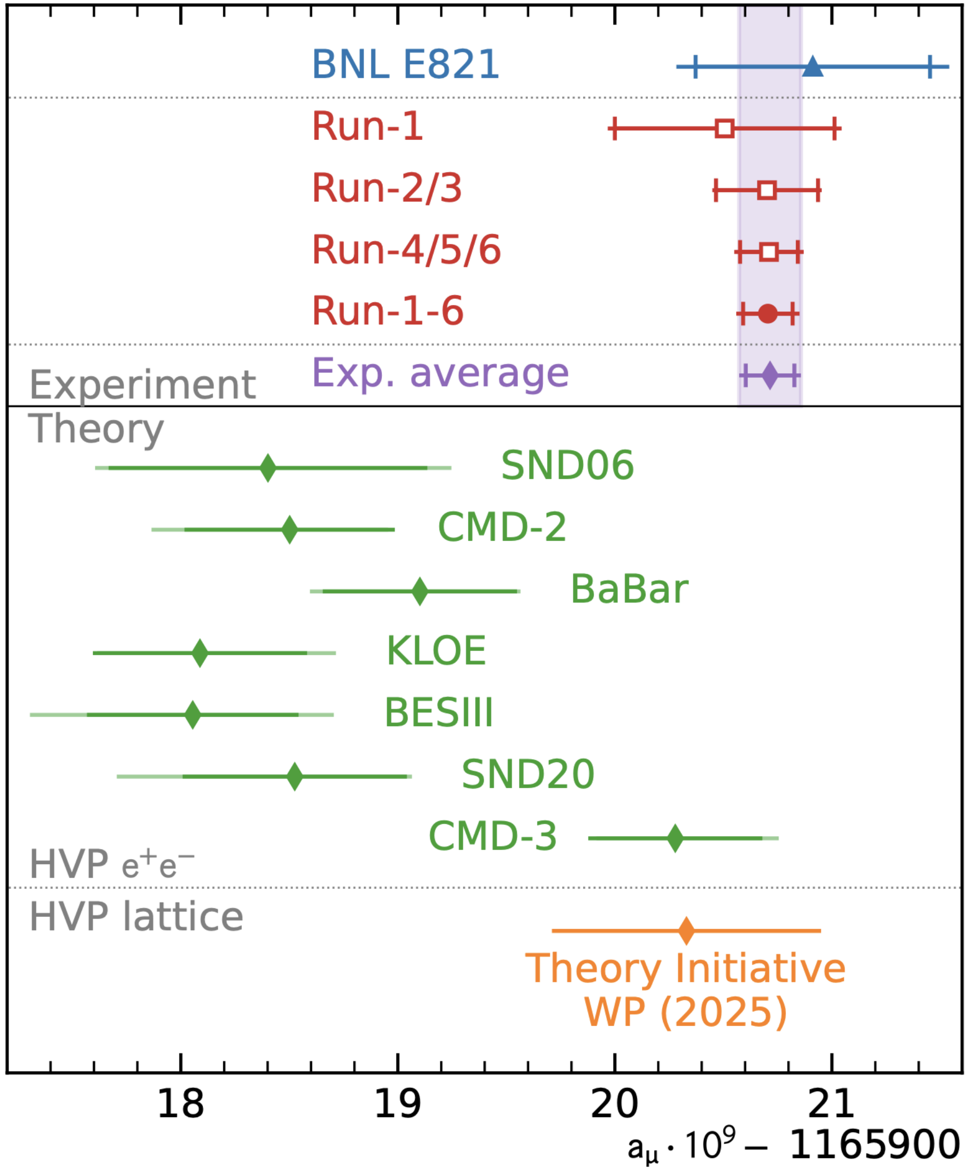
E. Bottalico on behalf of g-2 collaboration

PhiPsi 2026

11th June 2026

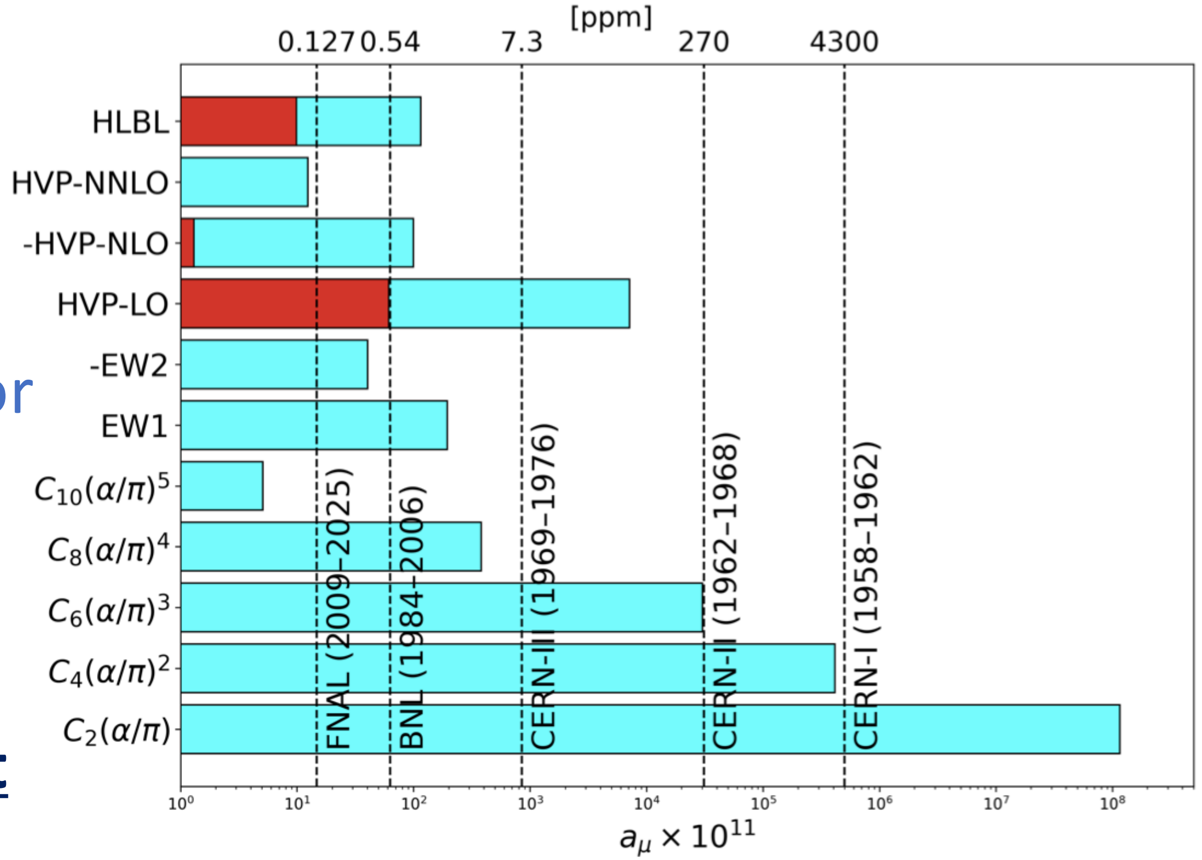
Muon g-2: current status

- The theory situation still puzzling!
- The Muon $g-2$ Theory Initiative latest compilation White Paper 2025: Phys.Rept. 1143 (2025) 1-158
- WP25 (based on lattice QCD) agrees with the experiment
- HVP e^+e^- (data-driven approach) was not included for the WP25
  - tensions still to be understood
  - New result from BaBar experiment confirming previous result! - TI Workshop 2025
- CMD3 result with data-driven approach agrees with WP25 and disagrees with other HVP



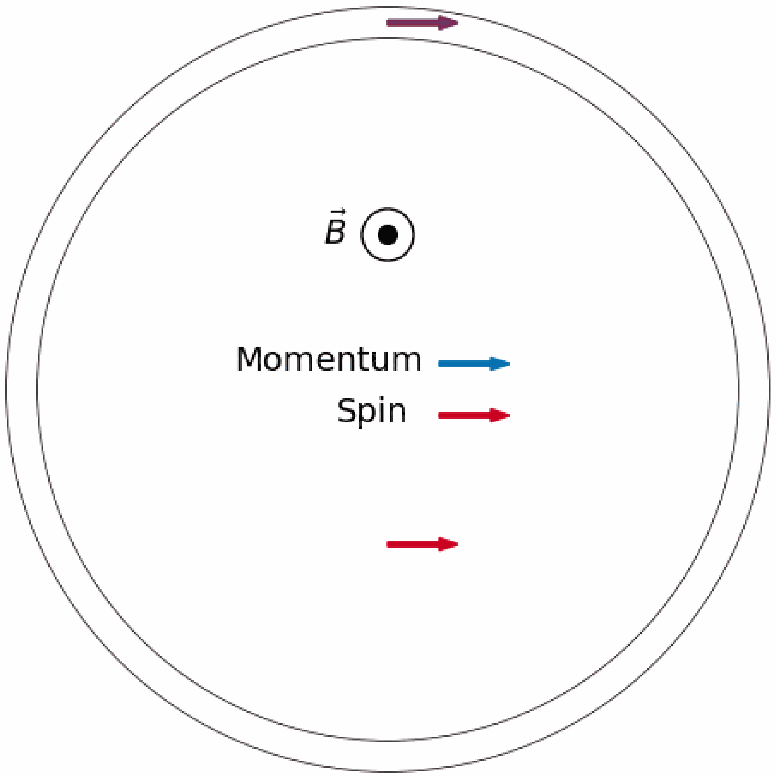
Muon g-2: current status

- The **HVP contribution** is still **leading** the total **uncertainty** on $\boldsymbol{a_\mu}$.
- The Fermilab precision is beyond the HVP contribution, but on a near future this error can be further reduced.
- In a new scenario where the theory puzzle is resolved, an **independent measurement** of a_μ would be important.



Measured Lepton Magnetic Moment – G. Gabrielse, G. Venanzoni

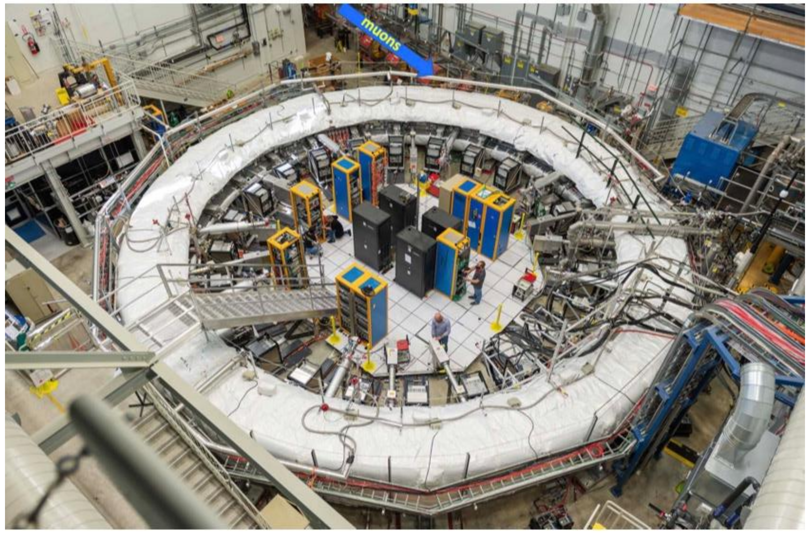
Measurement principle - Fermilab



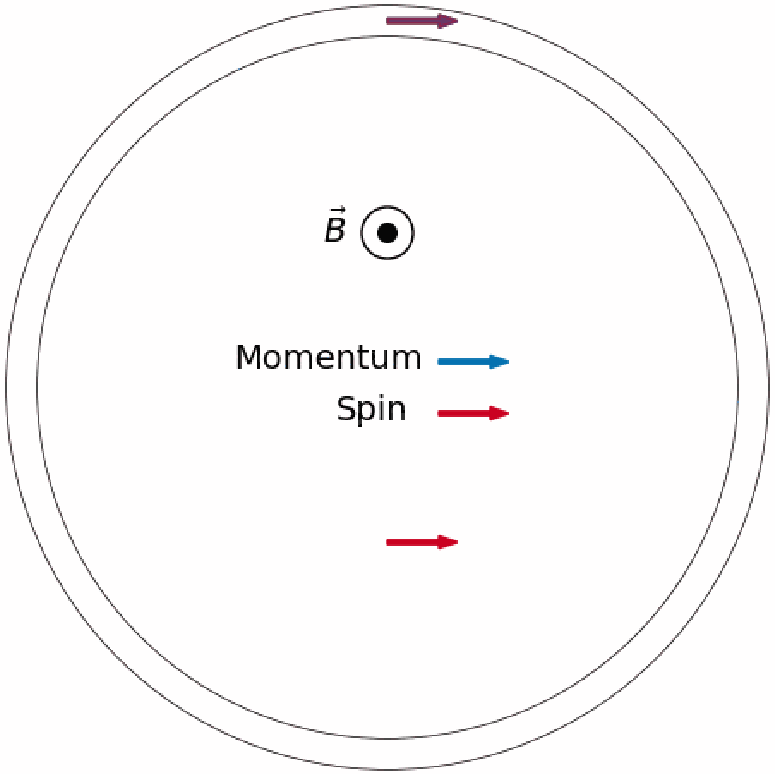
$$\vec{\omega}_a = \frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)(\vec{\beta} \times \vec{E})\right]$$

- Electric focusing (vertical confinement)
- 14 m ring diameter (B= 1. 45T)

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = a_\mu \frac{e\vec{B}}{m}$$



Measurement principle - Fermilab

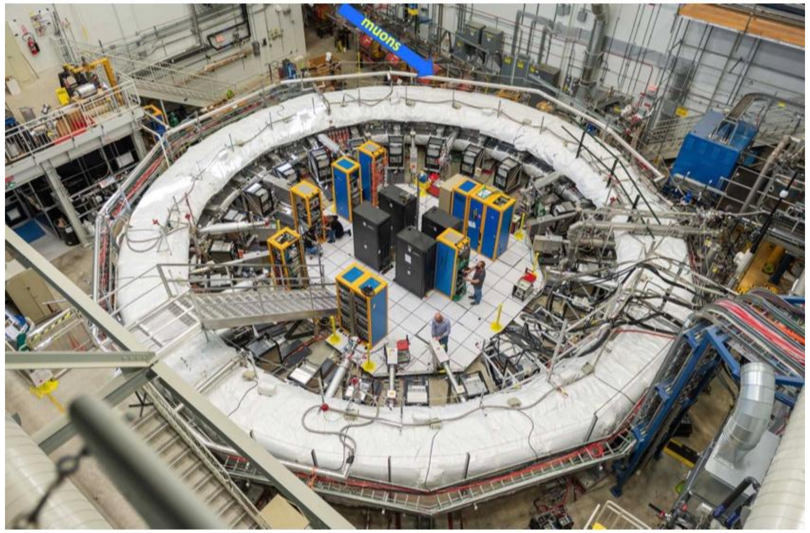


$$\vec{\omega}_a = \frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\left(\vec{\beta} \times \vec{E}\right)\right]$$

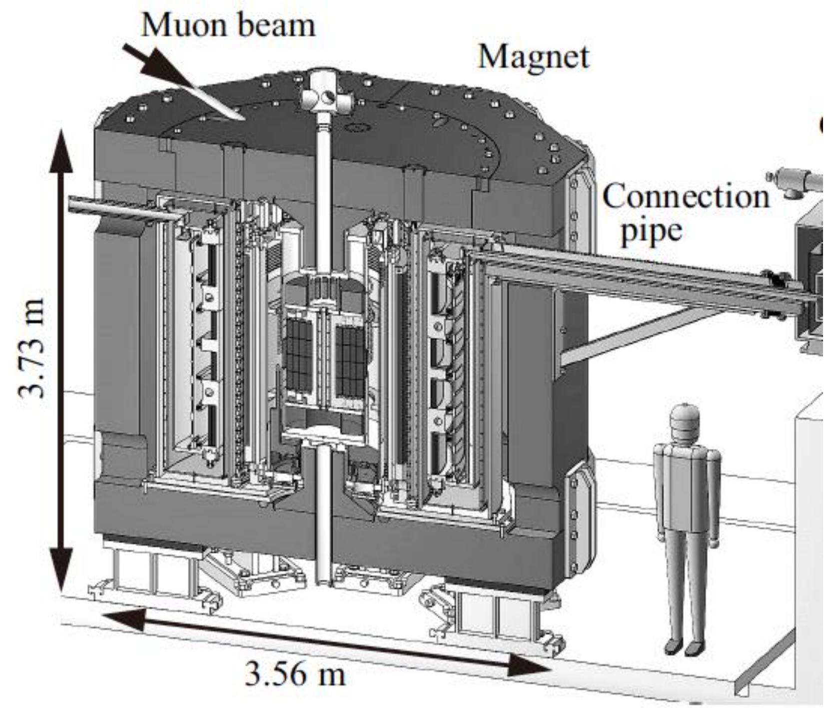
$$\gamma = \sqrt{1 + \frac{1}{a_\mu}} \sim 29.3$$

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

$$\overrightarrow{\omega_a} = \overrightarrow{\omega_s} - \overrightarrow{\omega_c} = a_\mu \frac{e\vec{B}}{m}$$



Measurement principle – J-PARC

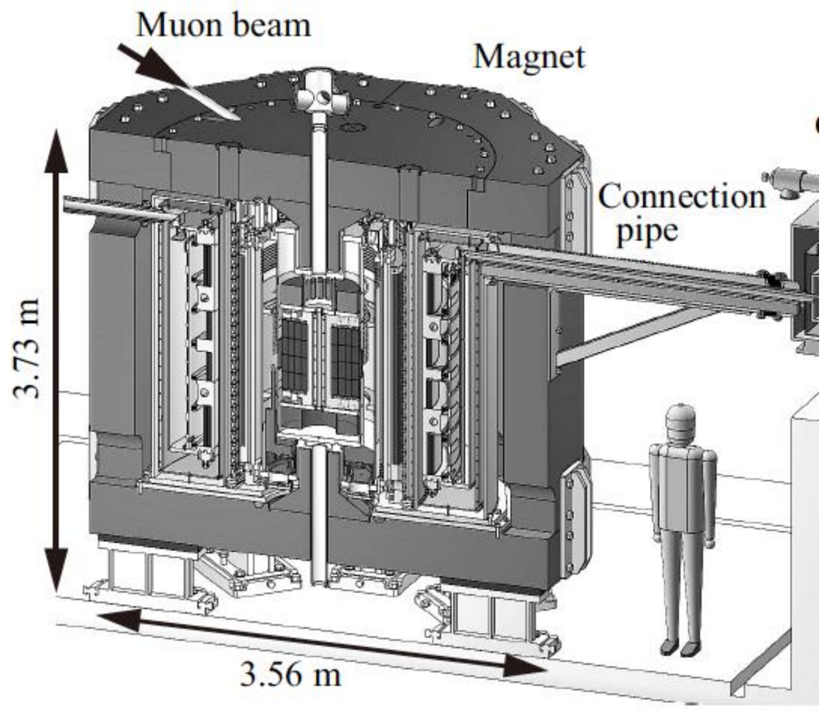


$$\vec{\omega}_a = \frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)(\vec{\beta} \times \vec{E})\right]$$

- 300 MeV/c momentum
- 0.66 m ring diameter (B = 3 T)

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = a_\mu \frac{e\vec{B}}{m}$$

Measurement principle – J-PARC



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

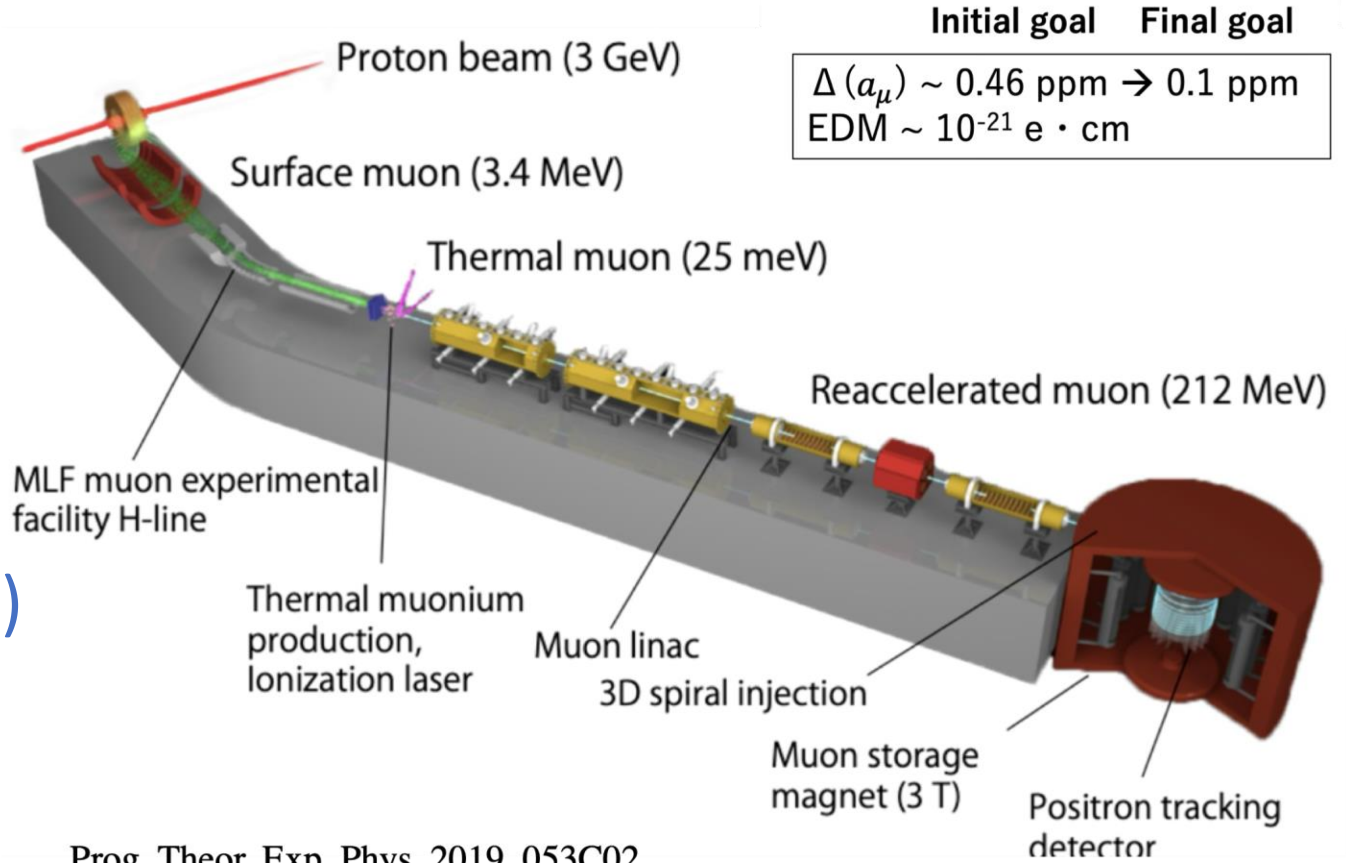
- 300 MeV/c momentum
- 0.66 m ring diameter (B = 3 T)
- No electric field (E=0)

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = a_\mu \frac{e\vec{B}}{m}$$

Both the experiment can extract a_μ very precisely measuring $\vec{B}$ and $\vec{\omega}_a$

New features of E34

- Low emittance muon beam (**1/1000**)
- Muon acceleration -> **212 MeV**
- **No strong** focusing
- 3D spiral injection:
  - Large kick
  - Good injection efficiency (**x10**)
- Compact storage ring (**1/20**)
- Tracking detector

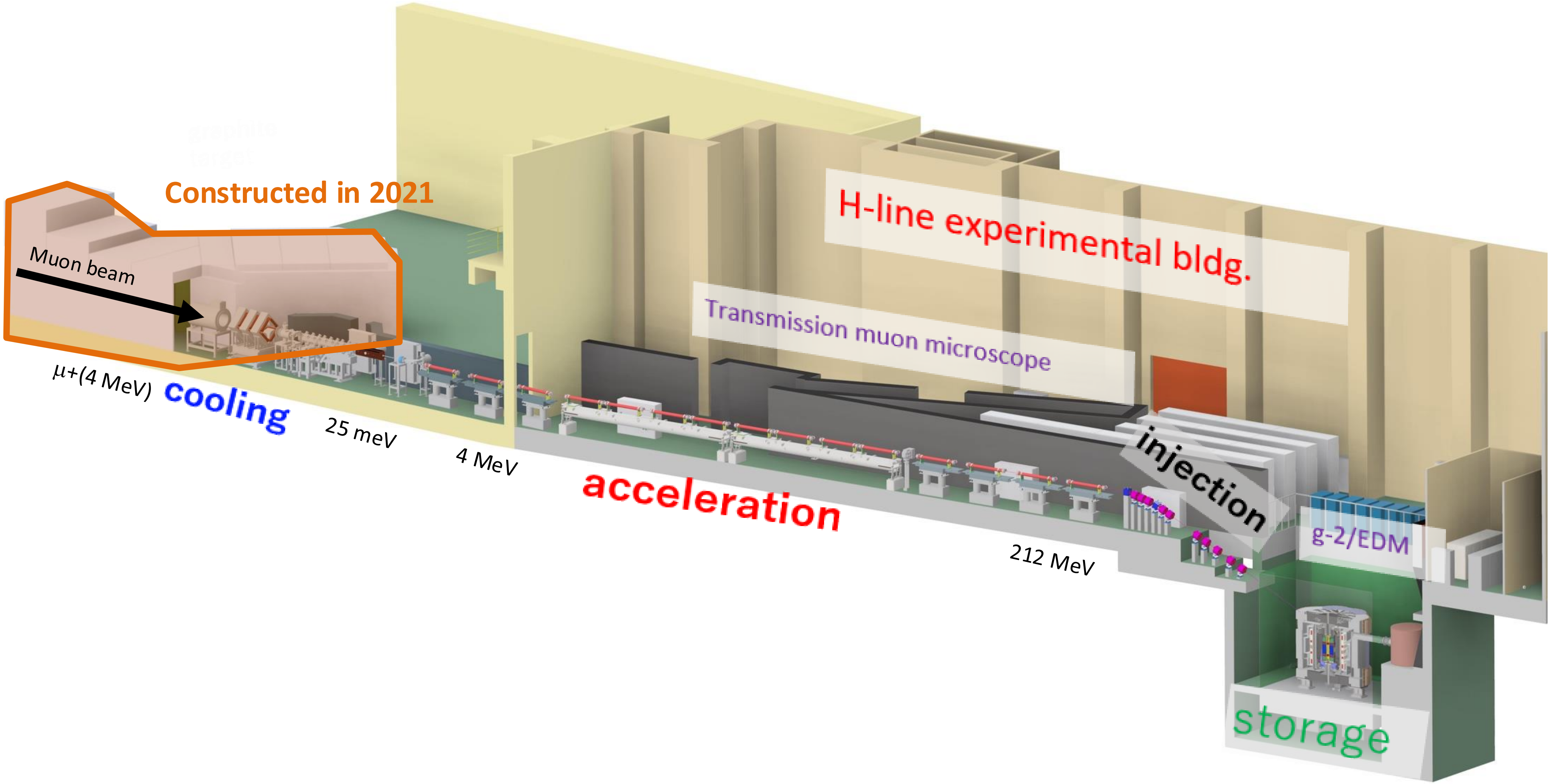


Prog. Theor. Exp. Phys. 2019, 053C02

- Excellent sensitivity to **muon EDM** about **100 times** better than the previous limit

COMET ('mu2e')
Rapid Cycling Synchrotron (RCS)
3 GeV proton, ~ 1 MW, 25 Hz
J-PARC Muon $g-2$/EDM
LINAC, 400 MeV proton
Material and Life Science Facility (MLF)
Neutrino (T2K)

Muon g-2 at J-PARC (E34)

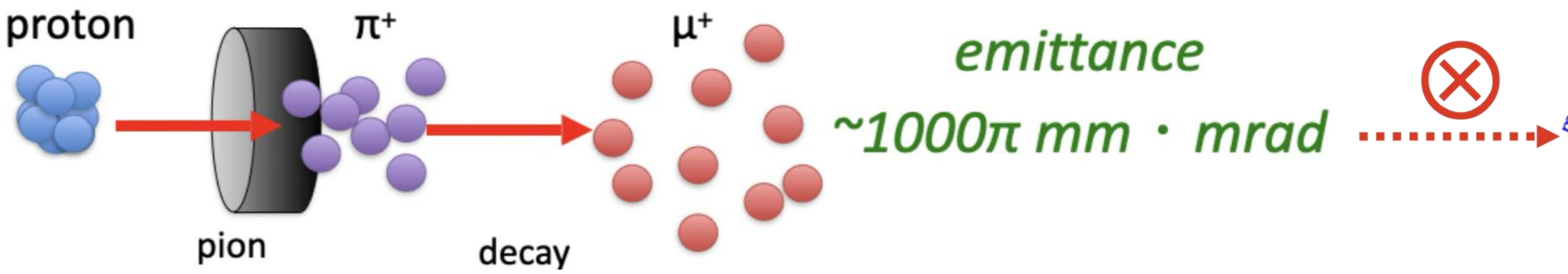


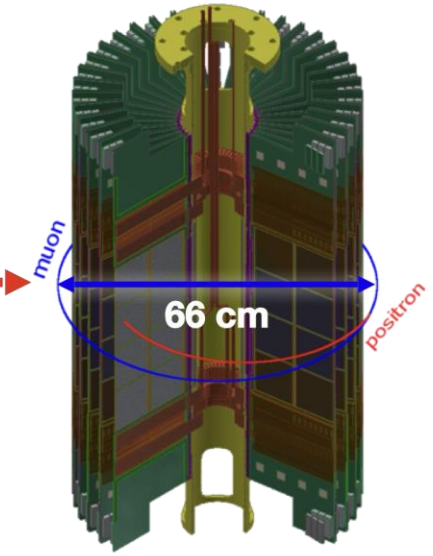
Shields, area control (2022)

Muon cooling

Shields, area control (2022)

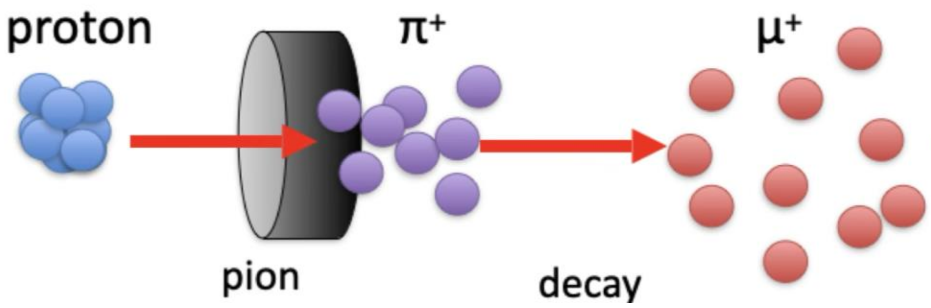
Muon cooling





- **A conventional muon beam:**
  - can not be injected without a strong focusing → electric field;
  - This leads to muon losses and background contamination from π.
- **Desired beam:**
  - The muon must be compact and non-divergent;
  - Typically with a RMS of ~mm → never achieved before.

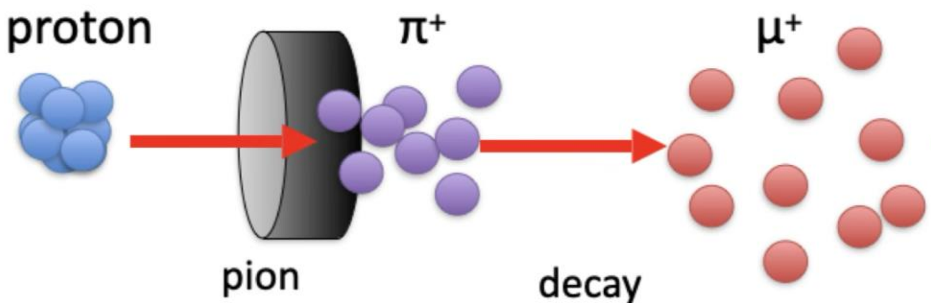
Muon cooling



emittance

~1000π mm · mrad

Muon cooling



emittance

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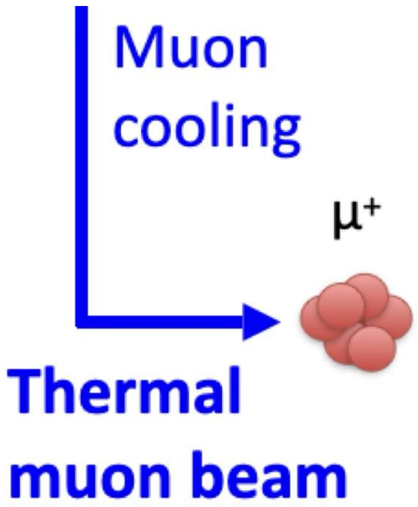
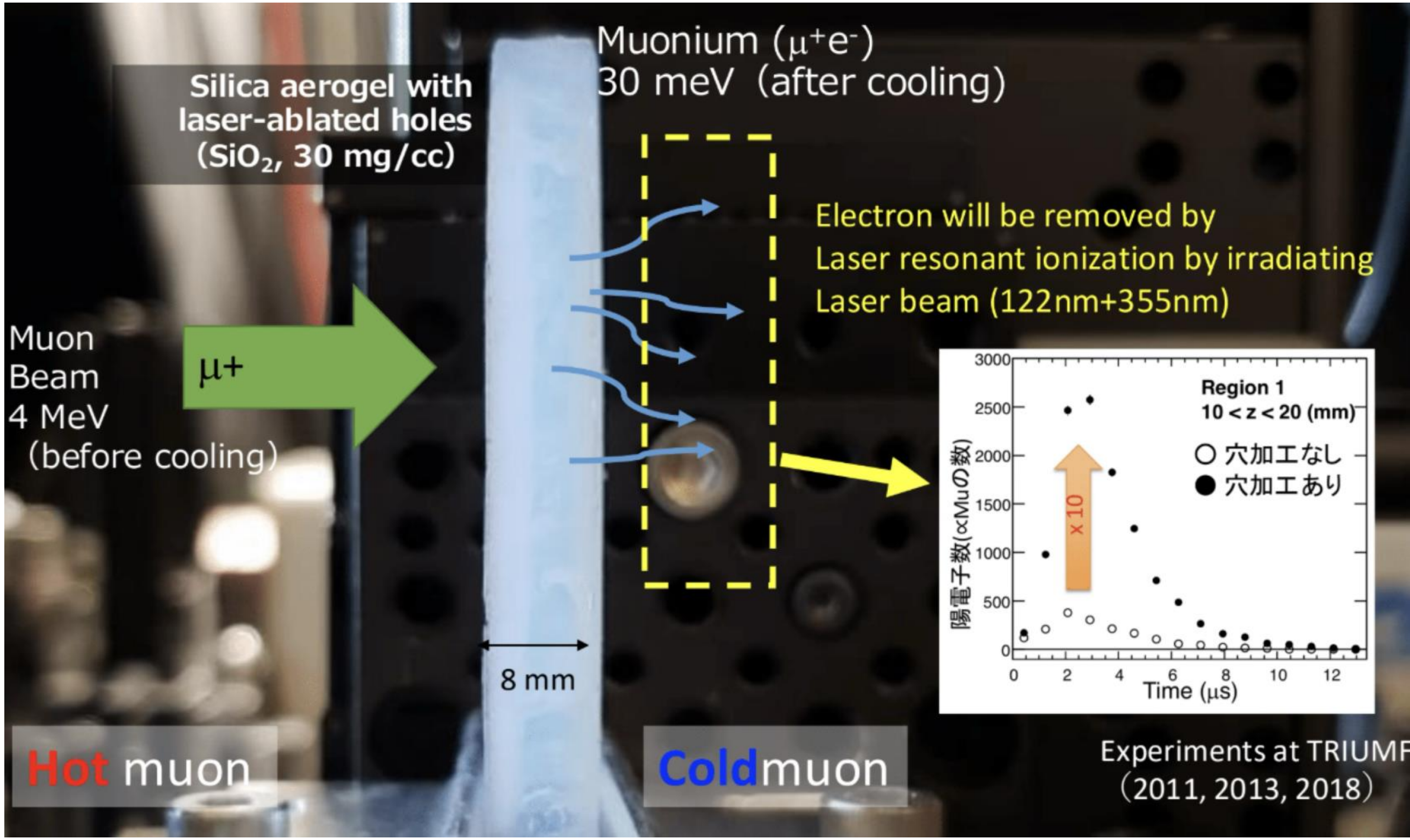


emittance

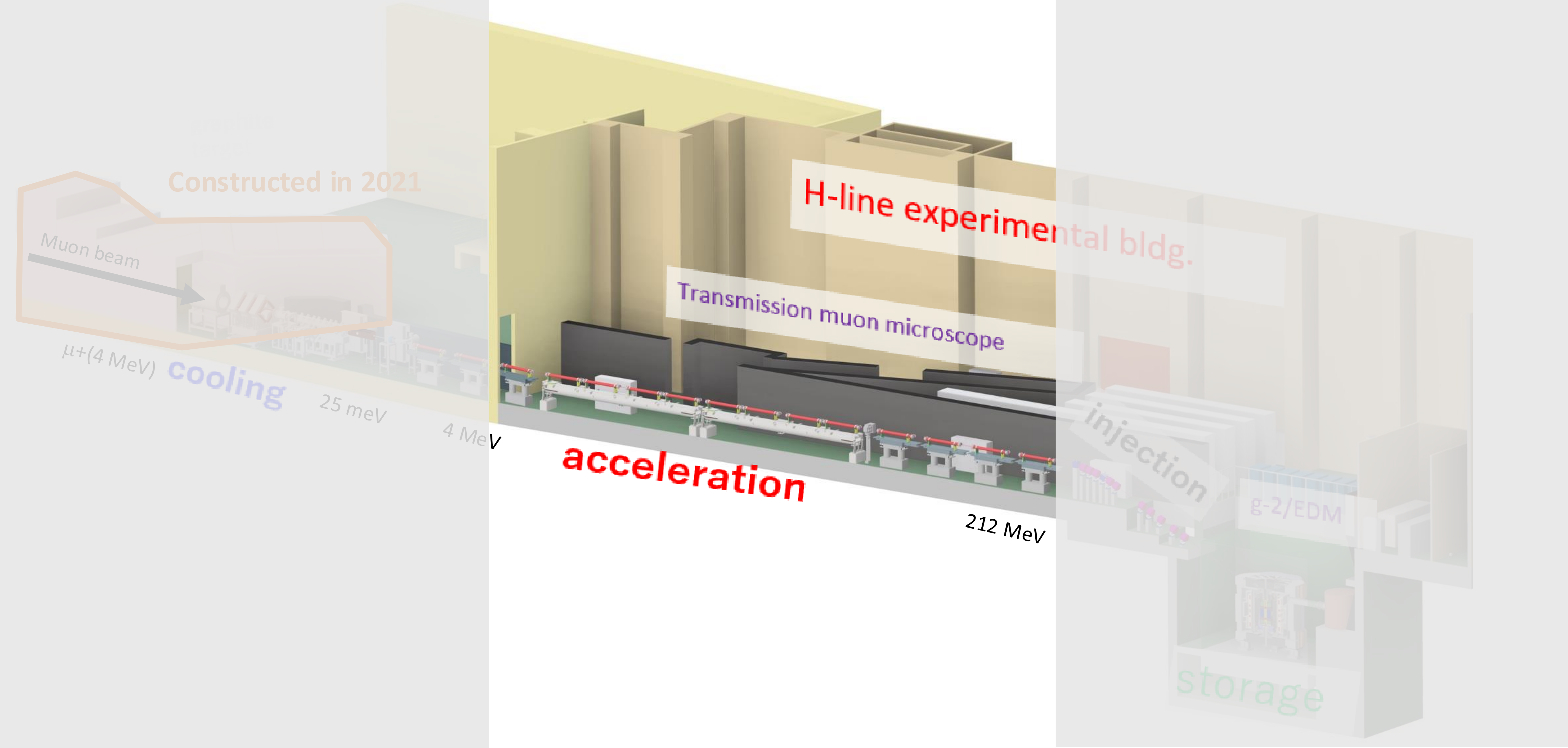
1π mm · mrad

Ultra-cold muons

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



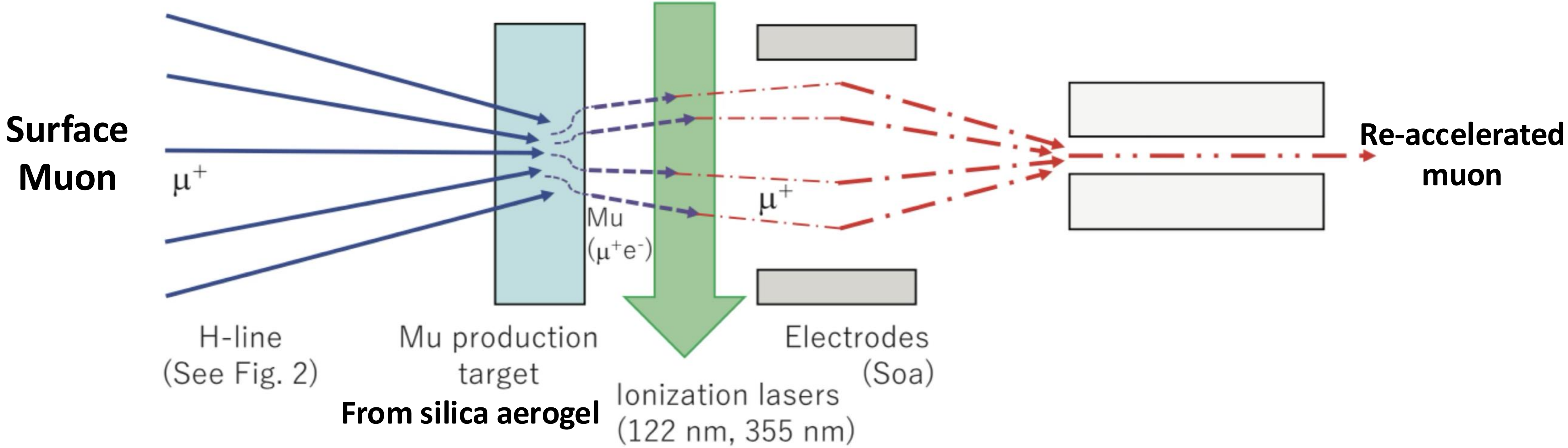
Re-accelerated thermal muon



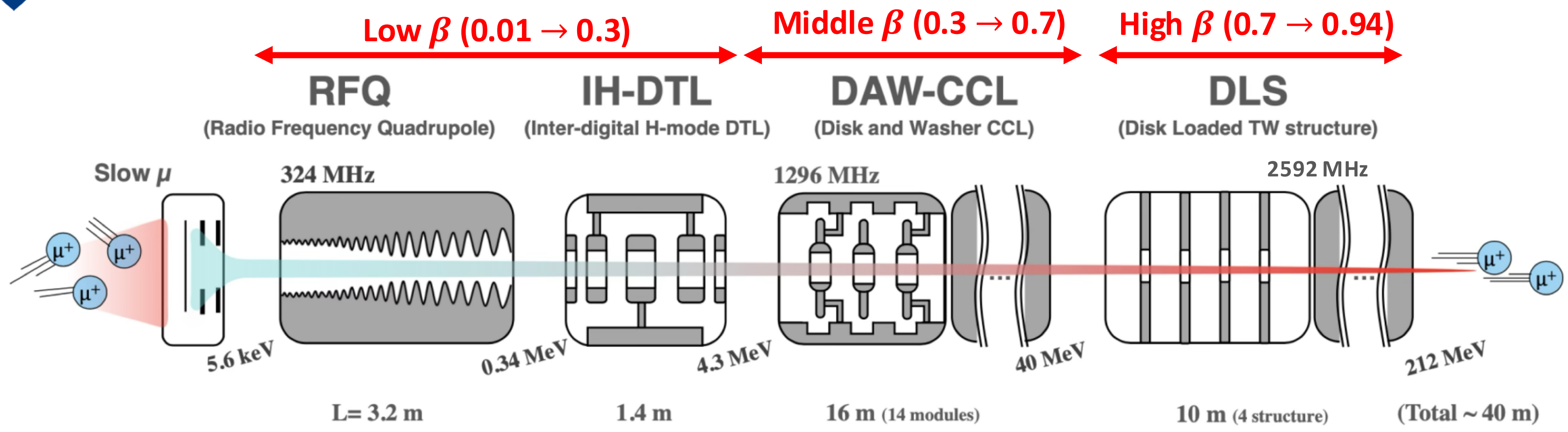
Shields, area control (2022)

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
Δp/p	0.05	0.4	$4\text{x}10^{-4}$

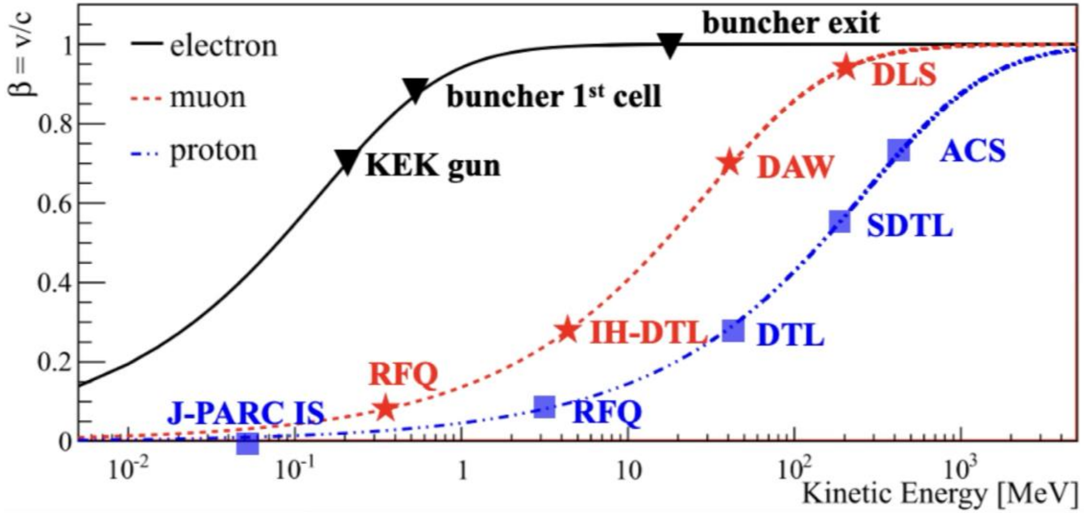


Re-accelerated thermal muon

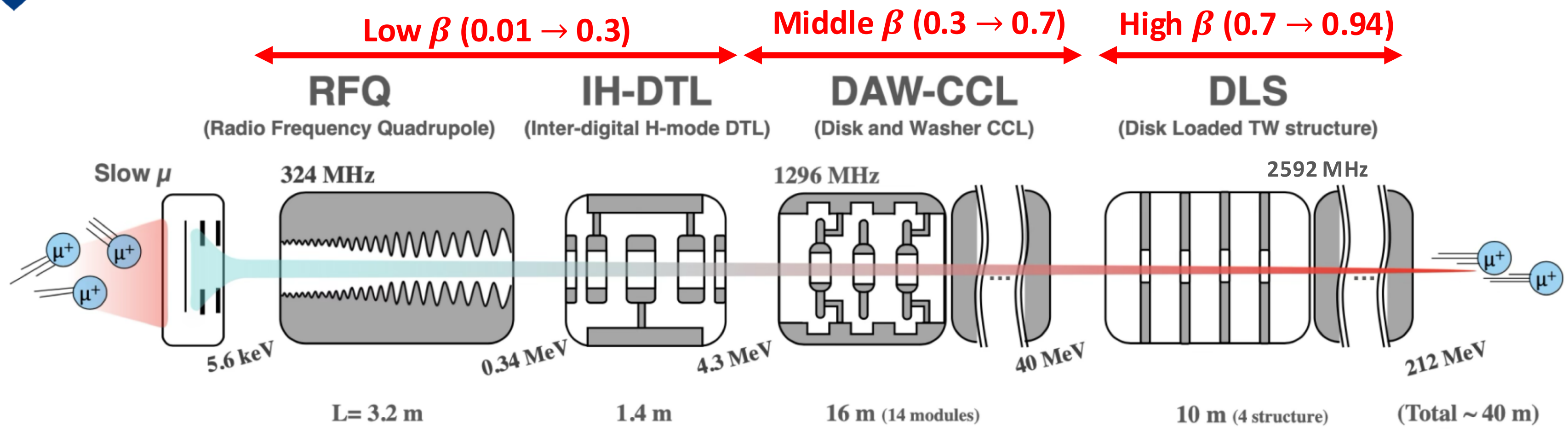


Muon Linac Parameters	
Frequency	324MHz, 1296MHz, 2592MHz
Intensity	1×10^6/s
Rep rate	25 Hz
Pulse width	10 ns
Norm RMS emittance	1.5 π ·mm·rad
Momentum spread	0.1%

- **The first muon-dedicated linac in the world!**
- **Muon Acceleration to 212 MeV**
- **4 steps acceleration depending on β -> total length 40 m**



Re-accelerated thermal muon



Acceleration test with thermal μ planned.

Fabrication and high-power testing completed.

Prototype fabricated and tested.

Prototype fabricated and tested.

Muon Linac Parameters	
Frequency	324MHz, 1296MHz, 2592MHz
Intensity	1×10^6/s
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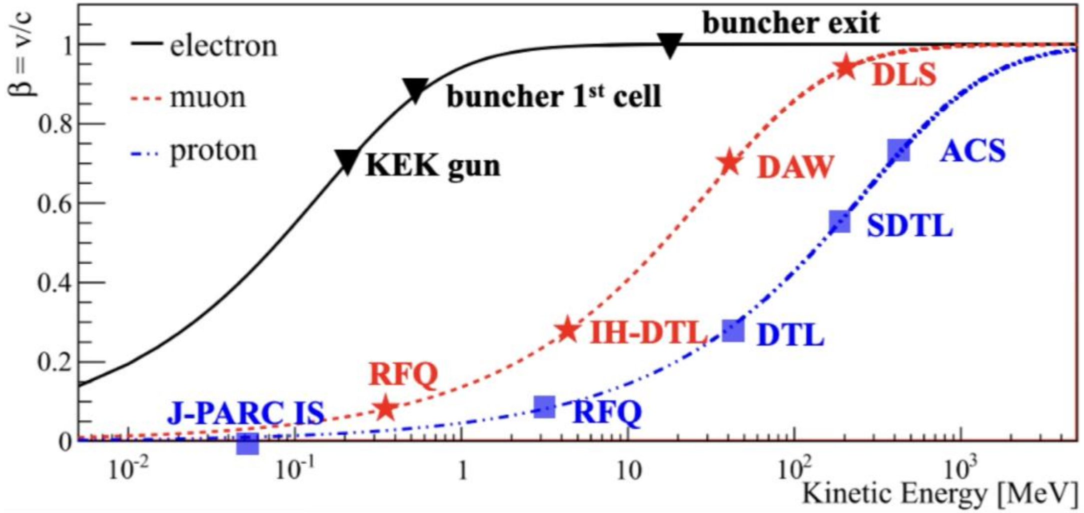


Re-accelerated thermal muon

[Phys. Rev. Lett. **134**, 245001]

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

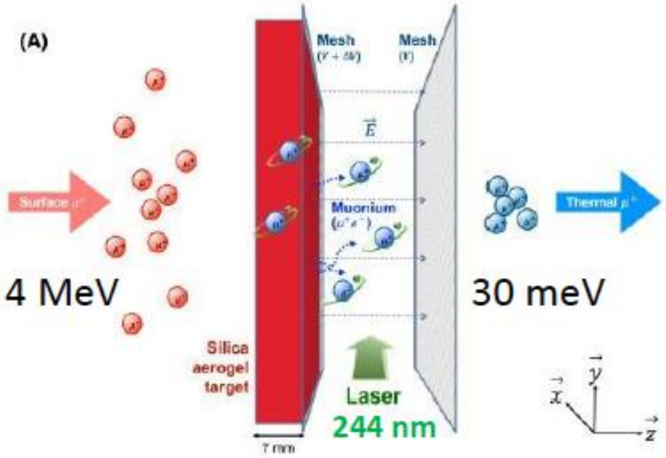
S. Aritome,[1] K. Futatsukawa,[2] H. Hara,[3] K. Hayasaka,[4] Y. Ibaraki,[5] T. Ichikawa,[5] T. Iijima,[5,6] H. Iinuma,[7] Y. Ikedo,[2] Y. Imai,[3] K. Inami,[5,6] K. Ishida,[2] S. Kamal,[8] S. Kamioka,[2,*] N. Kawamura,[2] M. Kimura,[2] A. Koda,[2] S. Koji,[5] K. Kojima,[6,‡] A. Kondo,[5] Y. Kondo,[9] M. Kuzuba,[7] R. Matsushita,[1] T. Mibe,[2] Y. Miyamoto,[3] J. G. Nakamura,[2] Y. Nakazawa,[7,‡] S. Ogawa,[10,‡] Y. Okazaki,[2] A. Olin,[11,12] M. Otani,[2] S. Oyama,[1] N. Saito,[2] H. Sato,[7] T. Sato,[1] Y. Sato,[4] K. Shimomura,[2] Z. Shioya,[13] P. Strasser,[2] S. Sugiyama,[5] K. Sumi,[5,†] K. Suzuki,[6] Y. Takeuchi,[13,§] M. Tanida,[13] J. Tojo,[13,10] K. Ueda,[5] S. Uetake,[3] X. H. Xie,[14,15] M. Yamada,[13] S. Yamamoto,[3] T. Yamazaki,[2] K. Yamura,[4] M. Yoshida,[2] T. Yoshioka,[10,13] and M. Yotsuzuka[5]

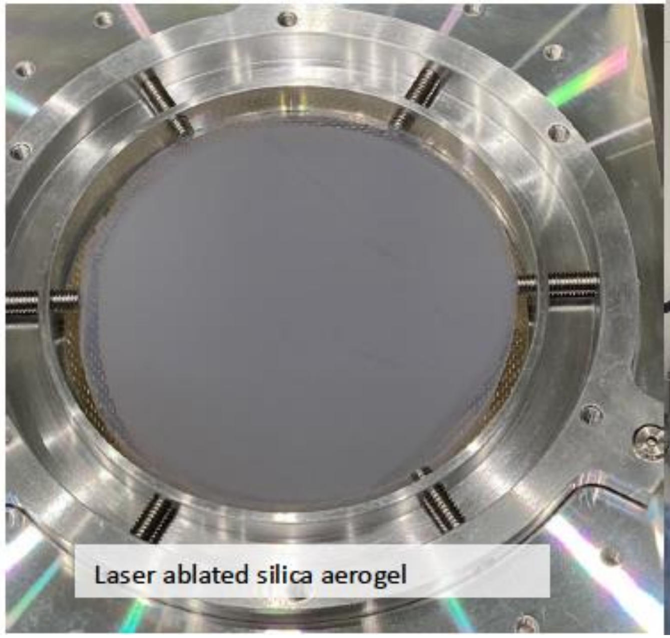
[1]Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
[2]High Energy Accelerator Research Organization, Ibaraki 319-1106, Japan
[3]Research Institute for Interdisciplinary Science, Okayama University, Okayama 700-8530, Japan
[4]Institute of Science and Technology, Niigata University, Niigata 950-2181, Japan
[5]Graduate School of Science, Nagoya University, Nagoya, Aichi 464-8602, Japan
[6]Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Nagoya, Aichi 464-8602, Japan
[7]Graduate School of Science and Engineering, Ibaraki University, Mito, Ibaraki 310-8512, Japan
[8]Department of Chemistry, Laboratory for Advanced Spectroscopy and Imaging Research (LASIR), University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada
[9]Japan Atomic Energy Agency (JAEA), Tokai, Naka, Ibaraki 319-1195, Japan
[10]Research Center of Advanced Particle Physics, Kyushu University, Fukuoka, Fukuoka 819-0395, Japan
[11]Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia V8P 5C2, Canada
[12]TRIUMF, Vancouver, British Columbia V6T 2A3, Canada
[13]Faculty of Science, Kyushu University, Fukuoka, Fukuoka 819-0395, Japan
[14]School of Physics, Peking University, Beijing 100871, China
[15]State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China

(Received 16 October 2024; accepted 21 April 2025; published 16 June 2025)

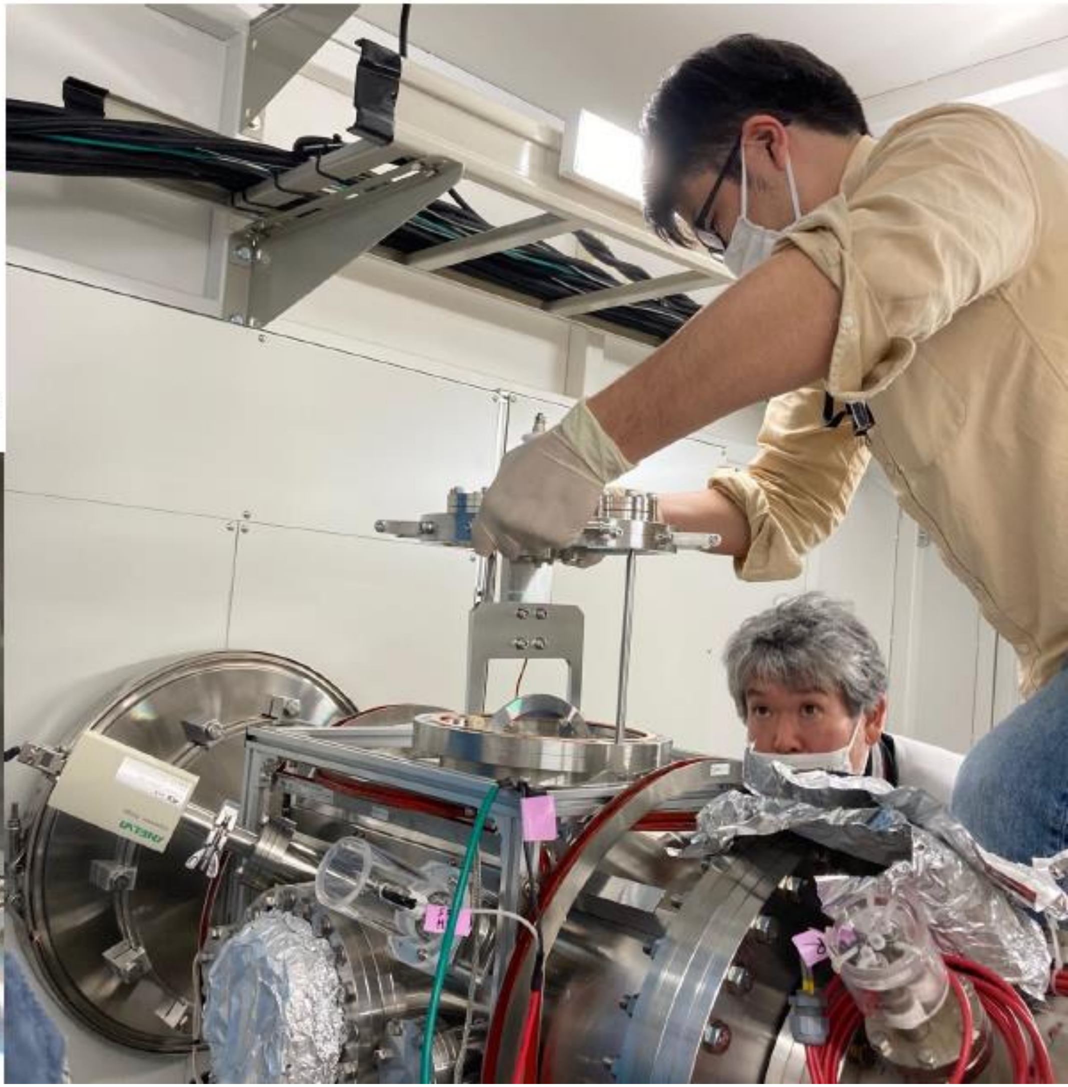
Acceleration of positive muons from thermal energy to 100 keV has been demonstrated. Thermal muons were generated by resonant multiphoton ionization of muonium atoms emitted from a sheet of laser-ablated aerogel. The thermal muons were first electrostatically accelerated to 5.7 keV, followed by further 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 $0.85 \pm 0.25(\mathrm{stat})^{+0.22}_{-0.13}(\mathrm{syst})$ π mm mrad and $0.32 \pm 0.03(\mathrm{stat})^{+0.05}_{-0.02}(\mathrm{syst})$ 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



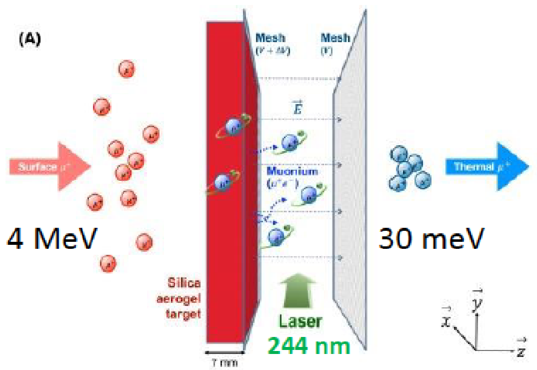

Laser ablated silica aerogel

J-PARC S2 area



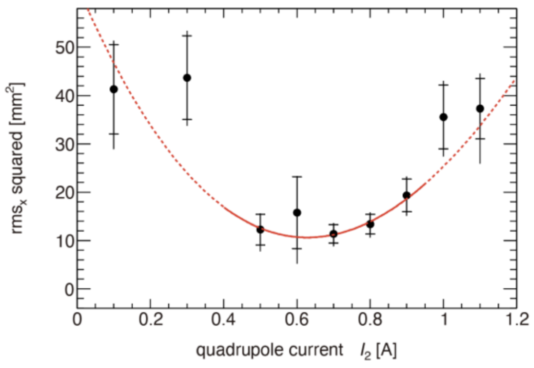
Re-accelerated thermal muon

- Muon Cooling demonstration:

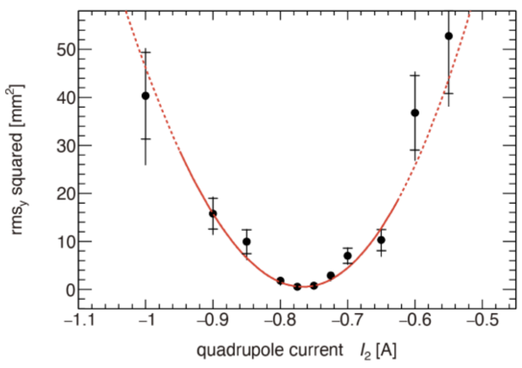


Electrostatic acceleration (10 kV) → Electric bend (energy filter) → Magnetic bend (momentum filter) → MCP

horizontal



vertical

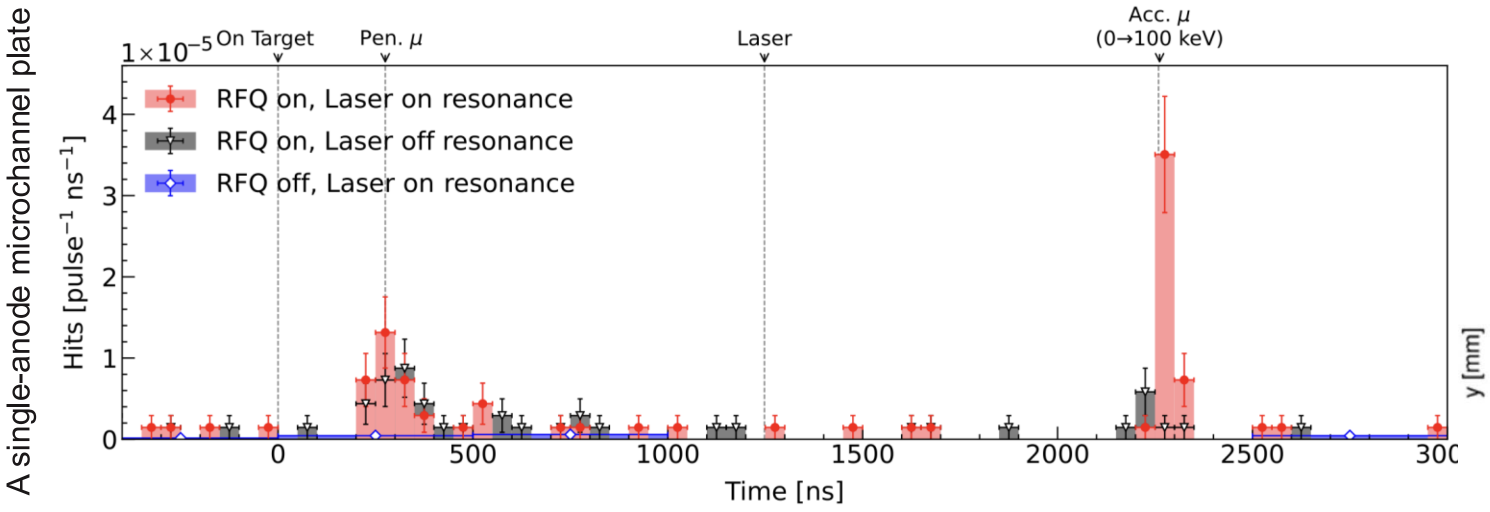


ε_x = 0.85 ±0.25(stat) $^{+0.22}_{-0.13}$(syst) [π mm mrad]

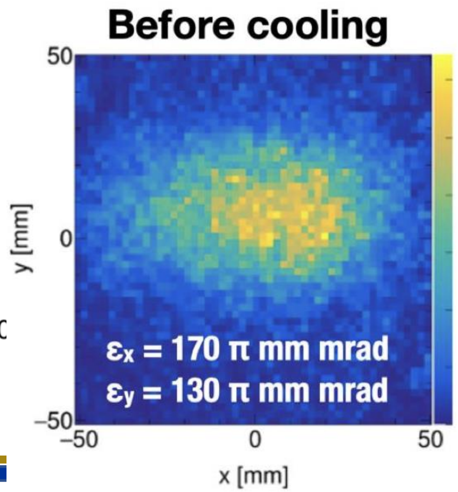
ε_y = 0.32 ±0.03(stat) $^{+0.05}_{-0.02}$ (syst) [π mm mrad]

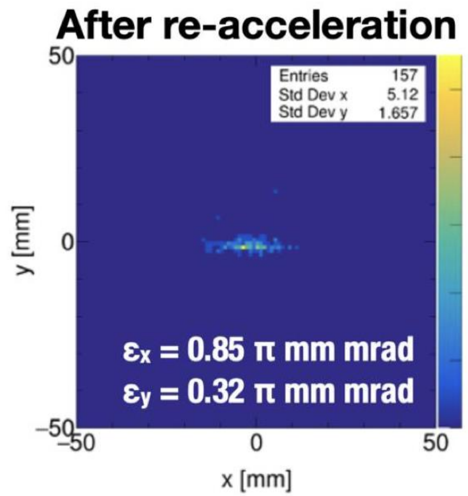
Emittance reduction by ~10^{-3}

The birth of low-emittance muon beam

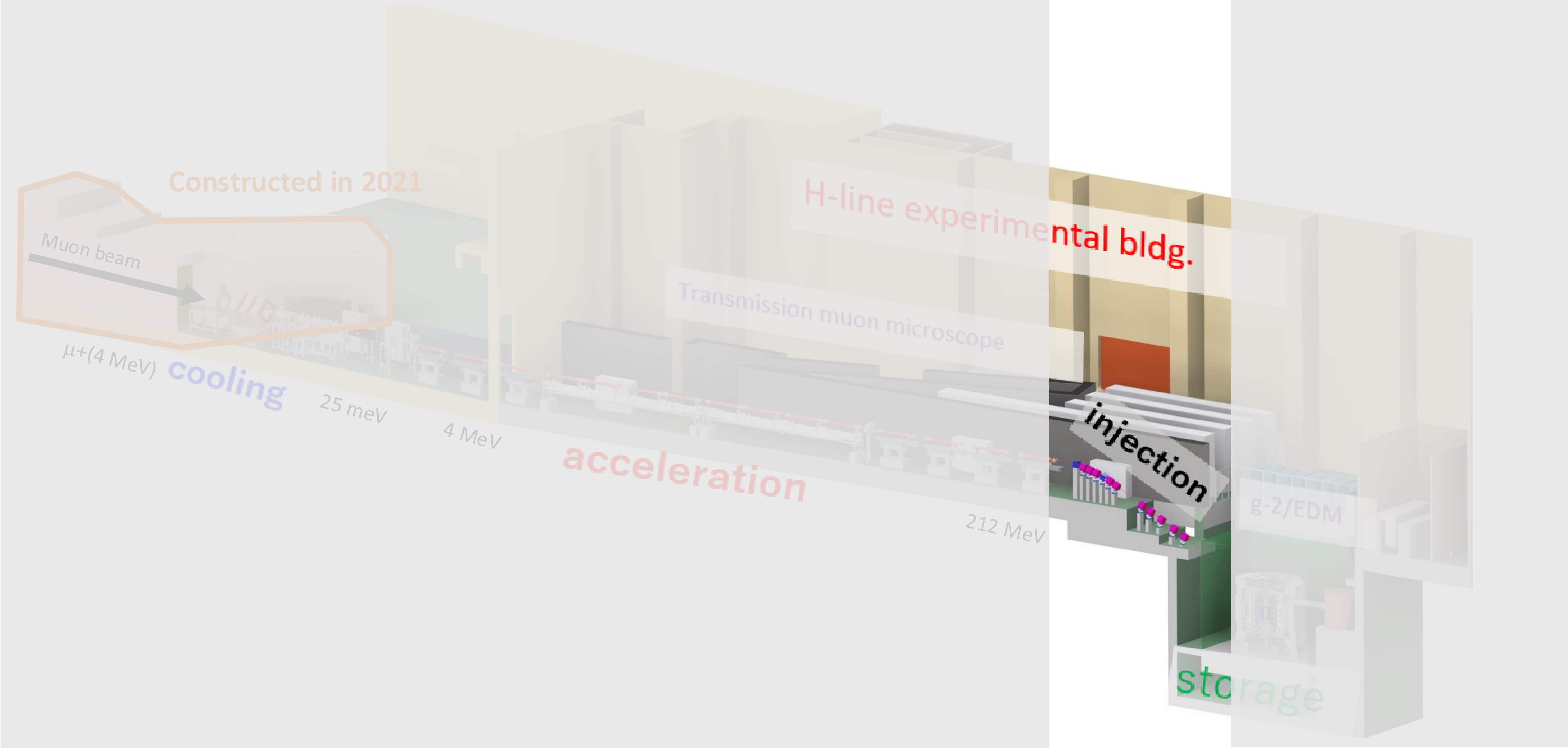


Phys. Rev. Lett. **134**, 245001





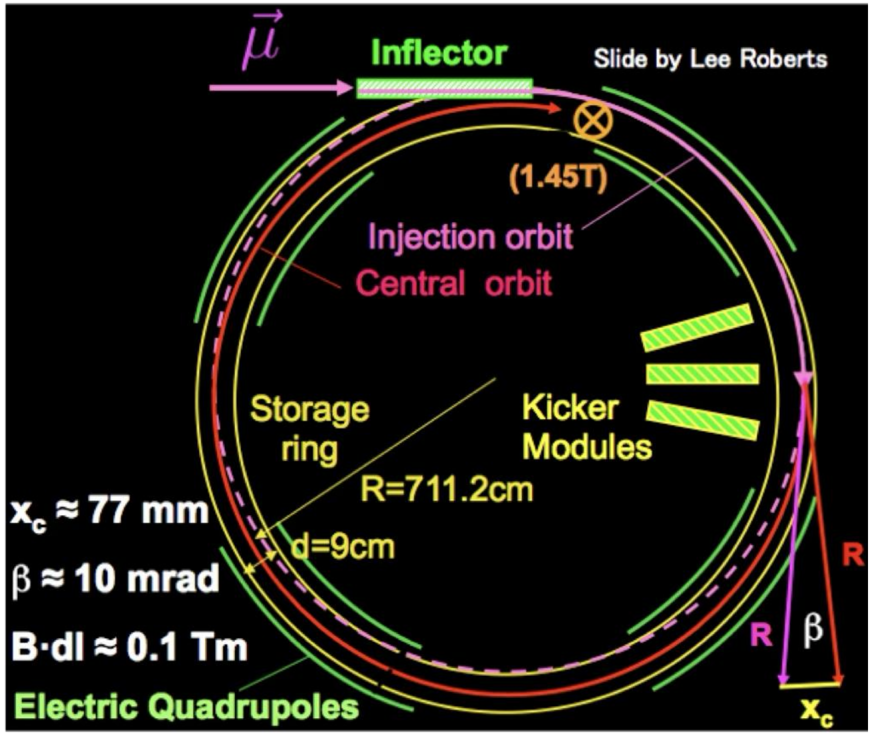
3D spiral injection



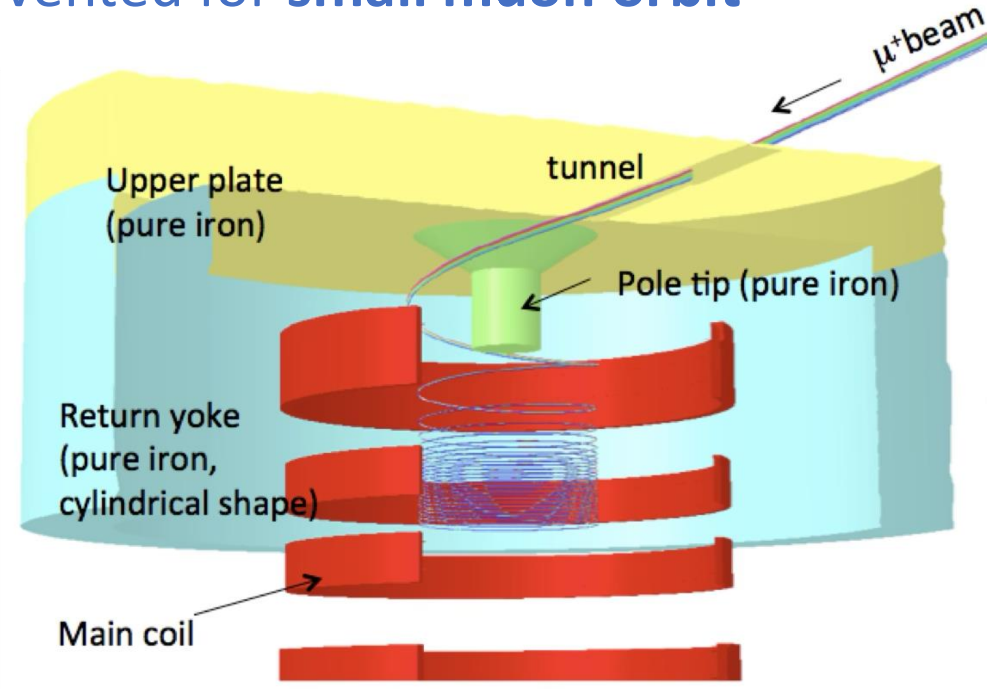
Shields, area control (2022)

3D spiral injection

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



[PRD73, 072003, 2006]



[H. Iinuma et al., NIMA 832, 51, 2016]
[https://journals.aps.org/prl/accepted/10.1103/8nxx-srgz]

Conventional 2D injection @BNL and FNAL

- Inflector + horizontal kicker
- Efficiency ~3-5%

Novel injection @J-PARC

- 3D spiral injection + vertical kicker
- Efficiency > 80%
- to be adopted for the EDM @ PSI too

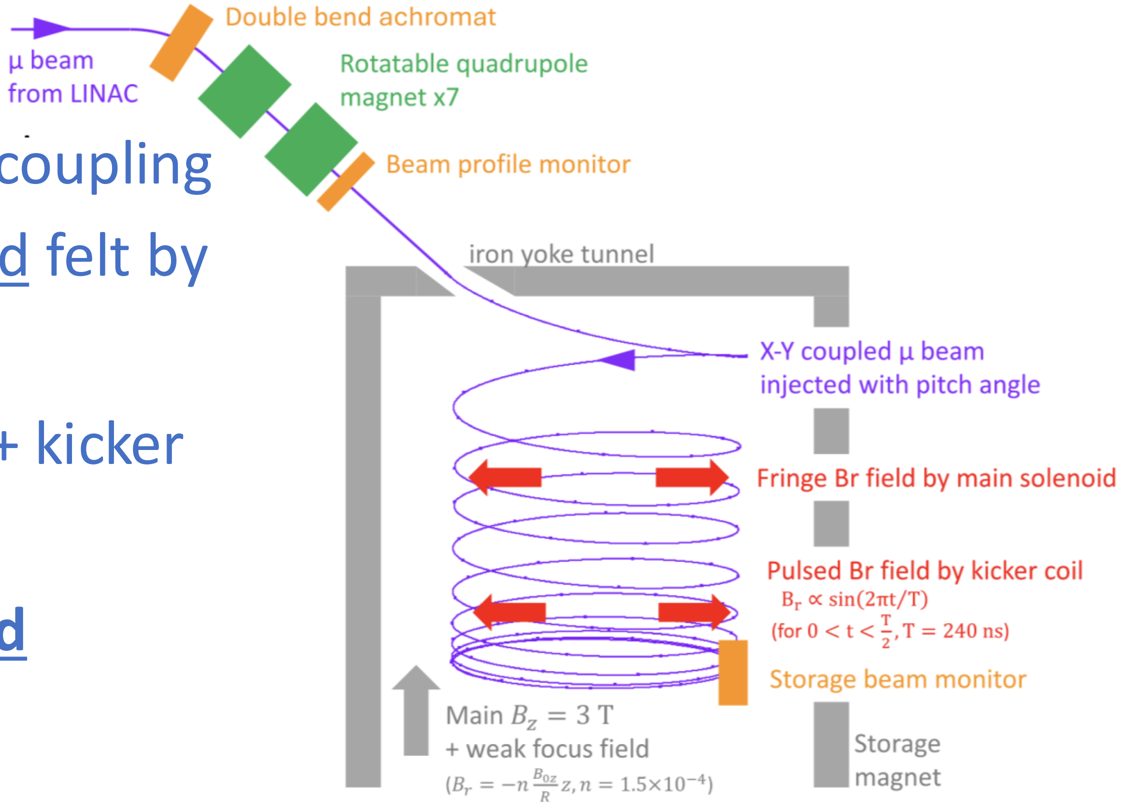
3D spiral injection

- **Low emittance muon beam** (300MeV, 0.3π mm-mrad) will be injected into the storage orbit and stored without electric focusing with good injection efficiency.

Key points

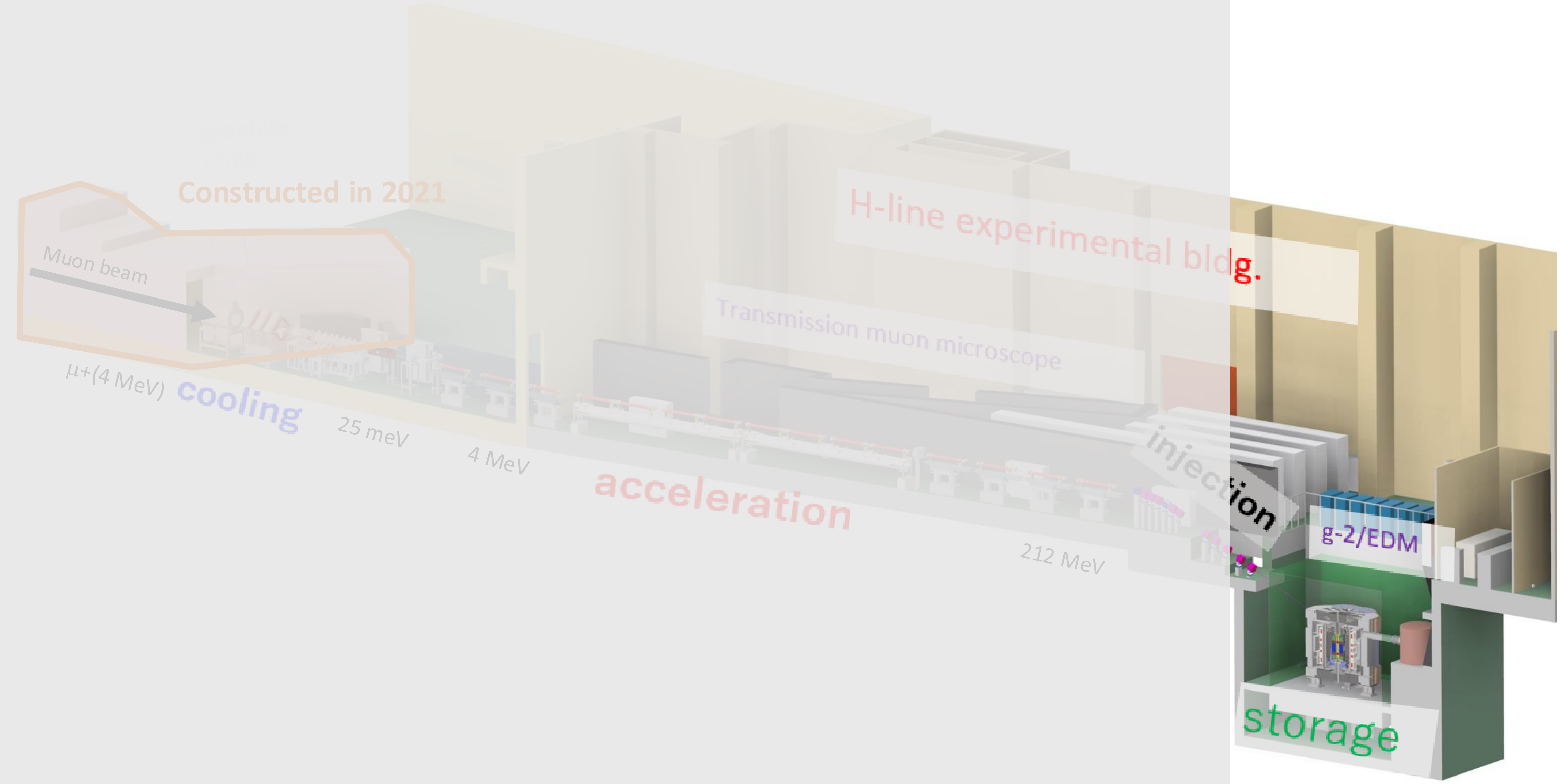
1. Inject low emittance beam with appropriate X-Y coupling into solenoid magnet – to compensate fringe field felt by each muon
2. Apply appropriate radial Br-field (Fringe Br-field + kicker coil Br-field).
   - to guide muons to the **uniform magnetic field region**.

3. **Store muon** beam by **weak focusing**.



3D spiral injection **demonstrated** with an electron-beam -> Published on PRL!!!

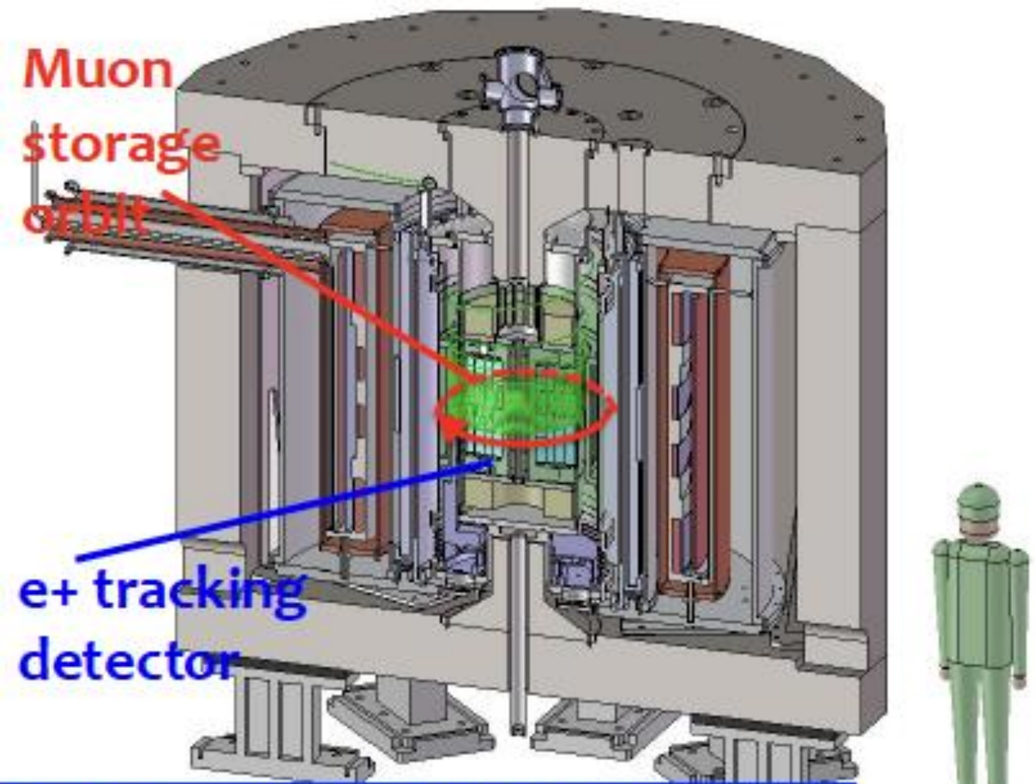
Storage Ring



Shields, area control (2022)

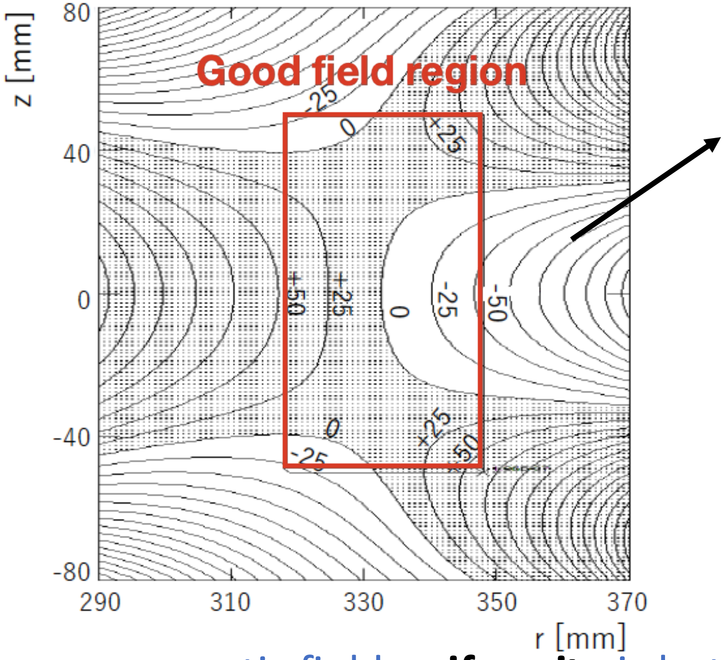
Storage Magnet

3 Tesla MRI-type superconducting solenoid magnet is under design



M. Abe et. al., NIM A 890, 51 (2018)

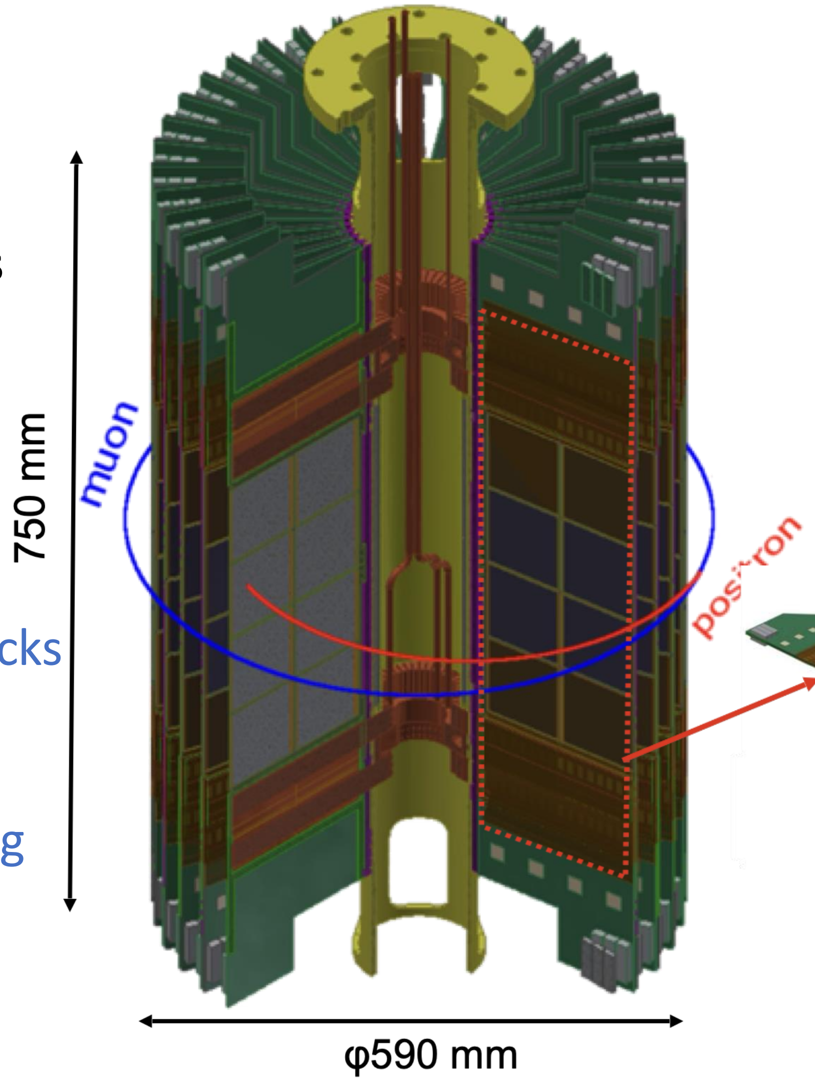
- Storage region :
  - radius : 33.3±1.5 cm
  - height : ±5 cm
  - Field strength : 3T
  - Uniformity : 0.1 ppm (Azimuthal integral)
- Injection region :
  - Smooth field for beam injection
- Weak focus field: -5e-4 T/m of Br at maximum

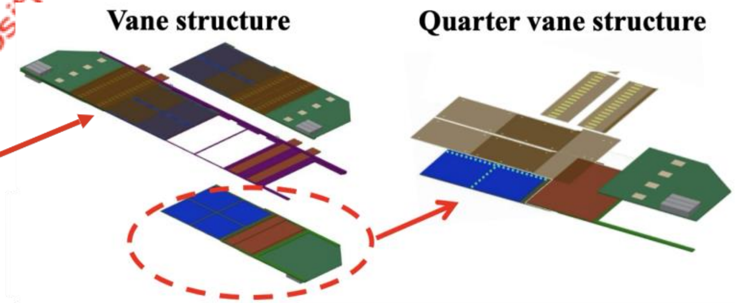


- Average magnetic field **uniformity** is better than **0.1 ppm**
- Local uniformity of **1 ppm** was demonstrated by the MUSEUM experiment magnet at **1.2 T**;
  - Further tests will be carried out at **3 T**.
- In the cross-calibration of FNAL and J-PARC field probes at ANL, **~7 ppb** agreement was obtained with **15 ppb** uncertainties.

Positron Tracking Detector

- **40 modules** (vanes) each 200mm (radial) x 400mm (axial)
- Each vane consists of **16 Si sensors** (10x10 cm^2, 320 μm thickness).
- Two-dimensional hit position is reconstructed from orthogonally arranged silicon strip sensor (2 blocks of **512 strips** with **190 µm pitch**)
- 32 Readout ASIC w/ 5nsec sampling rate per quarter vane.





“Prototype quarter-vane”

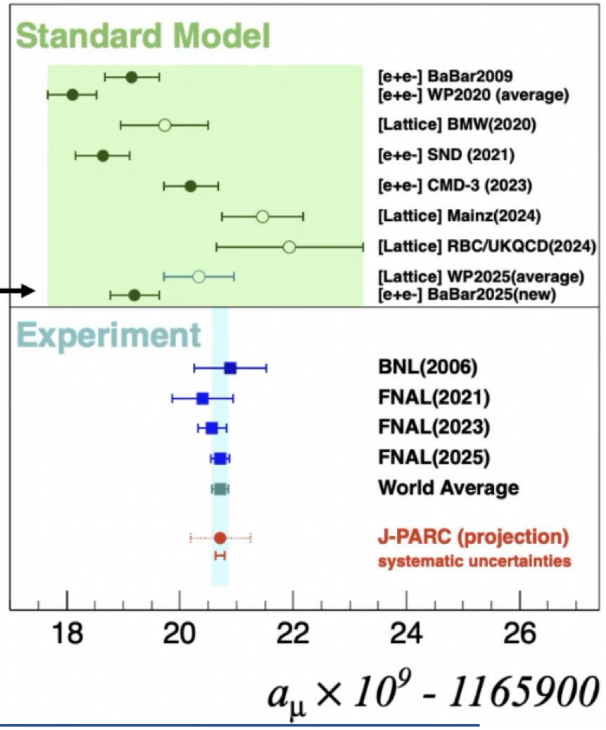
Expected sensitivity - Statistics

- A TDR muon rate **3.2×10^{8}μ/sec** at the entrance at 1 MW proton power.
- The expected intensity of stored muon is **1.3×10^{5} μ/sec.** Cumulative efficiency from thermal muon generation to reconstructed positron is 4.0×10^{-4}
- **2-years data taking** (2×10^{7} seconds, ~230 days) 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·cm]	1.5 (stat.)
	0.36 (syst.)

The NEW BaBar measurement confirmed their 2009 result.



Expected sensitivity comparison with FNAL

- Here is the comparison between the Run-456 FNAL result and the project error for J-PARC experiment:

J-PARC – TDR

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Anomalous spin precession (ω_a)		Magnetic field (ω_p)	
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$\boldsymbol{\delta a_{\mu(syst)} \sim 70}$ **ppb**

FNAL – Run456

Quantity	Correction (ppb)	Uncertainty (ppb)
ω_a^m (statistical)		114
ω_a^m (systematic)		30
C_e	347	27
C_p	175	9
C_{pa}	−33	15
C_{dd}	26	27
C_{ml}	0	2
$\langle \omega'_p \times M \rangle$ (mapping, tracking)		34
$\langle \omega'_p \times M \rangle$ (calibration)		34
B_k	−37	22
B_q	−21	20

$\delta\omega_{a\,syst} \sim 52$ ppb $\delta\omega_{p\,syst} \sim 57$ ppb

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Towards high sensitivity

- Given the strong **limitation** on **statistics** we can tweak the current set-up to increase the statistics.
- The statistical precision on the anomalous precession frequency ω_a is:

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→ Doubling both momentum and field ⇒ **x4** improvement in ω_a precision.

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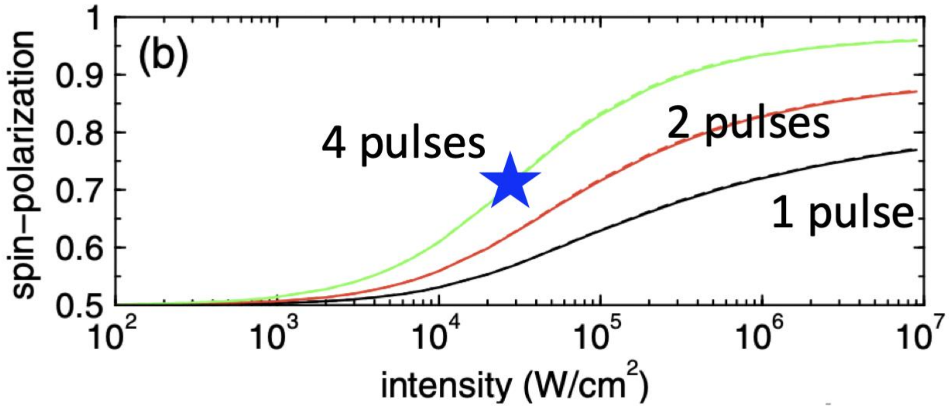
- **Polarization Contribution (*P*):**
  - Current polarization: 50% Possible improvement: → **75%** (realistically) → Adds an additional **x1.5** gain in total precision.

Higher momentum beam (needs higher B-field)



Optical pumping with train of laser pulse

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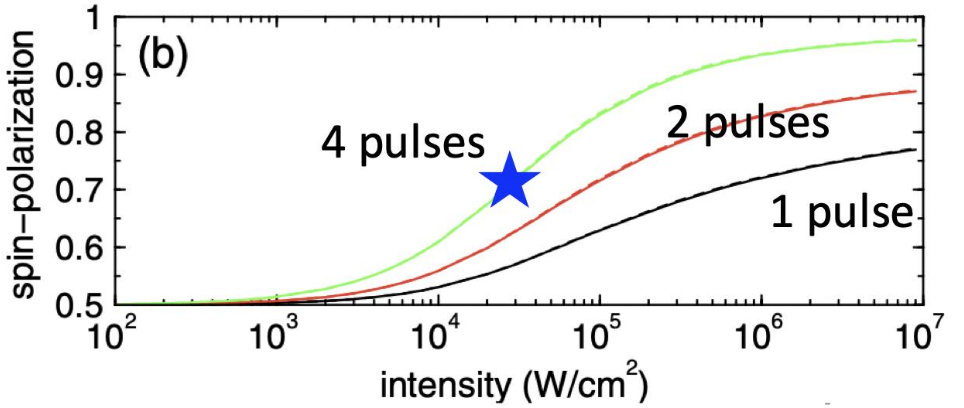
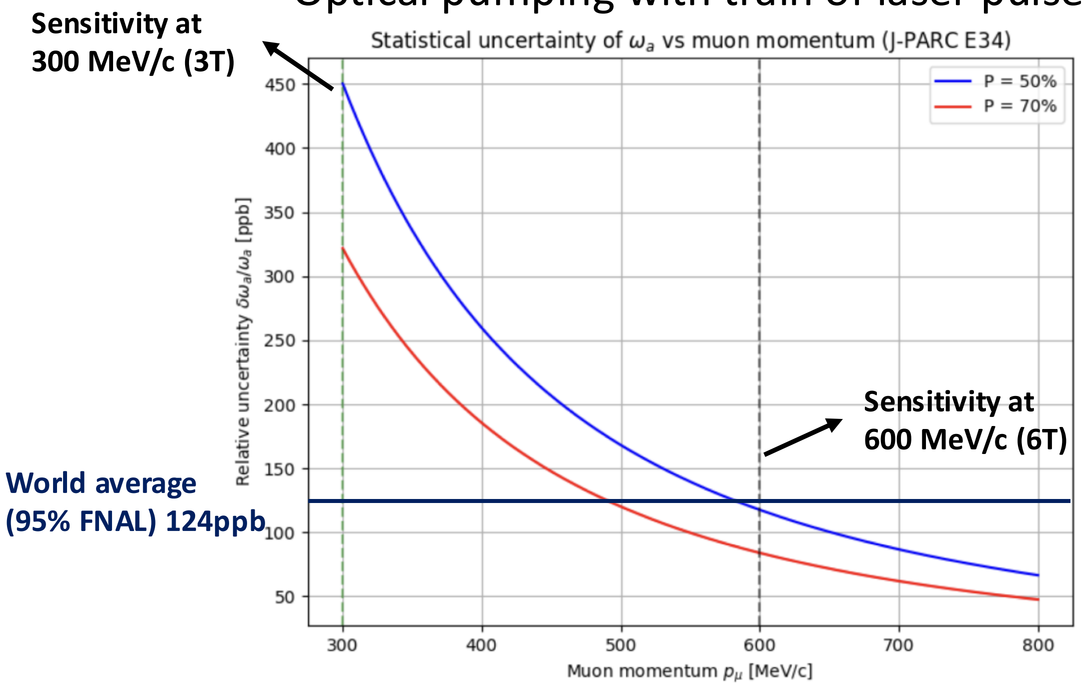


Optical pumping with train of laser pulse

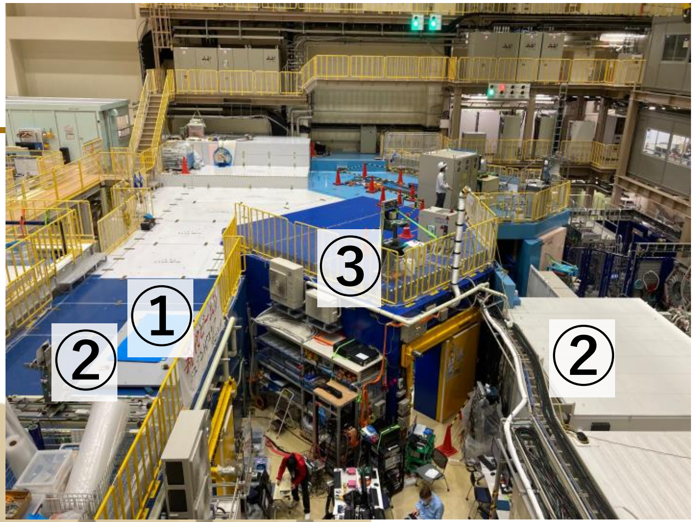
- Here is projected $\frac{\Delta\omega_a}{\omega_a}$ as function of the momentum.
- A task force has been built to check the feasibility:
  - Magnetic field;
  - Linac;
  - Polarization;
  - Other possible improvements.

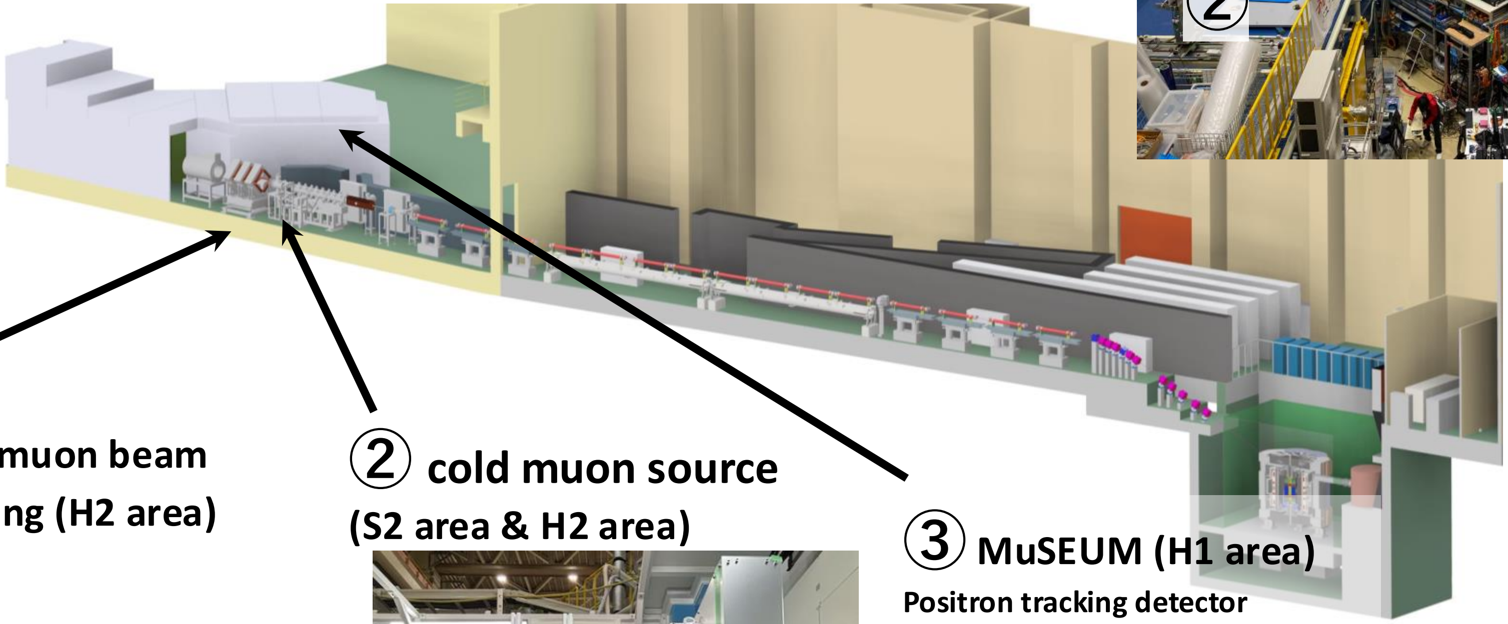


https://arxiv.org/pdf/2512.20335

Running test experiments

At the end of last year/beginning of this year, three experiments were conducted at J-PARC MLF.



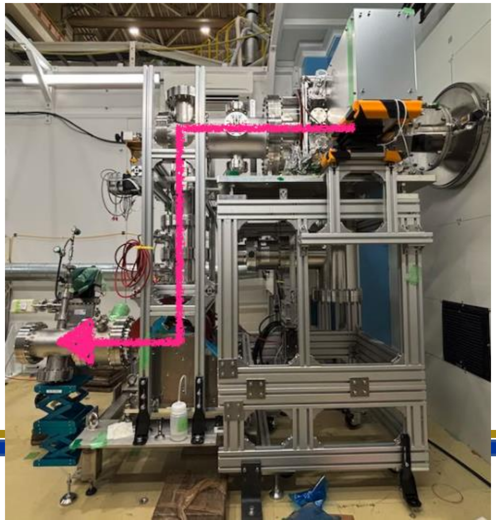


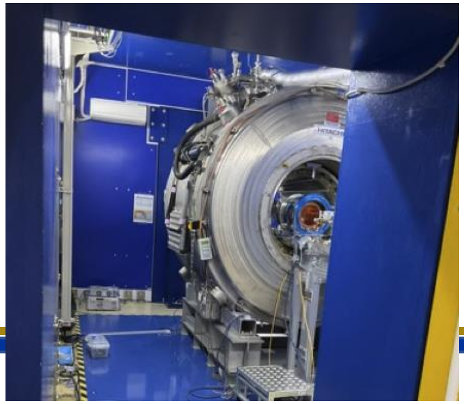
① Surface muon beam commissioning (H2 area)

② cold muon source (S2 area & H2 area)

③ MuSEUM (H1 area)

Positron tracking detector





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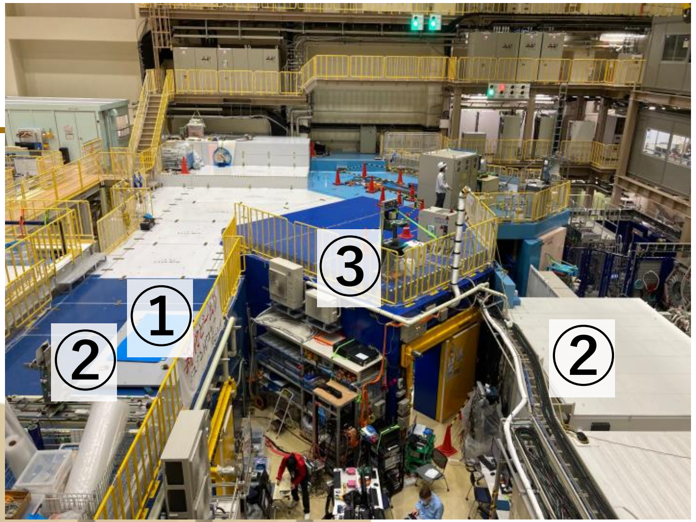

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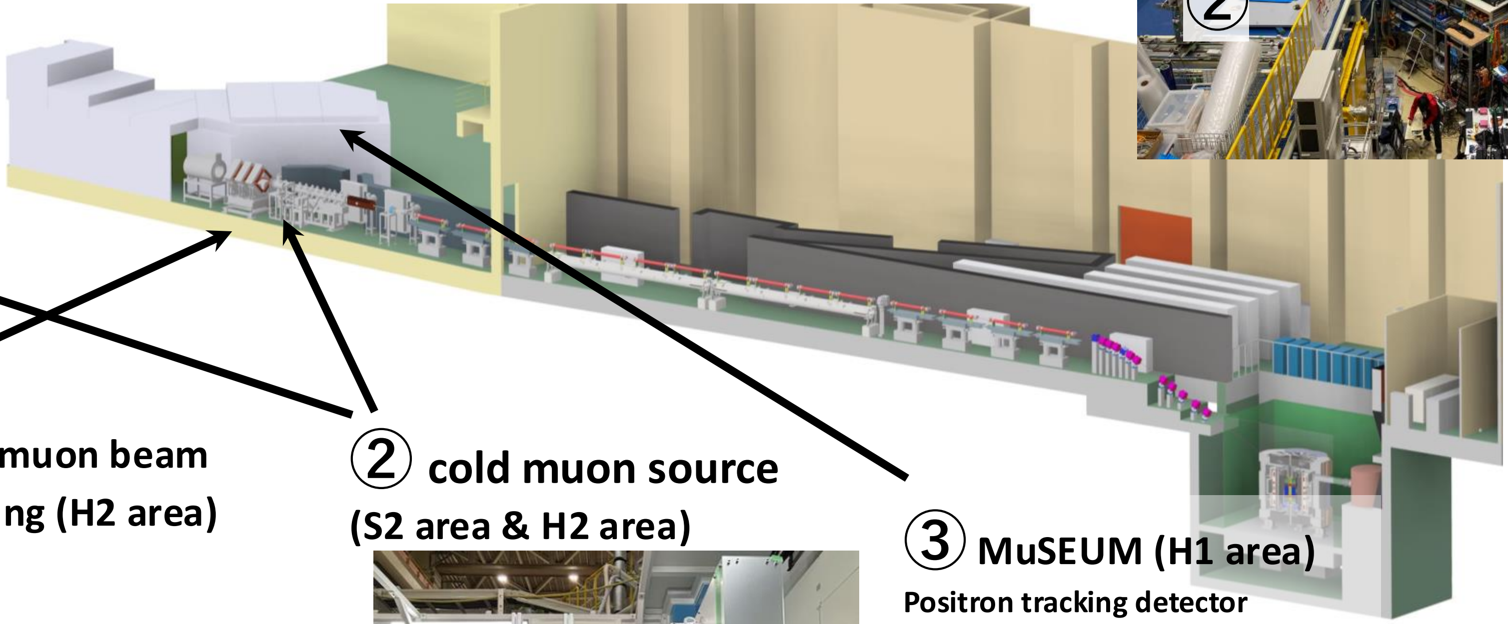
New test beam for slow muon acceleration is planned between 10-23 June!



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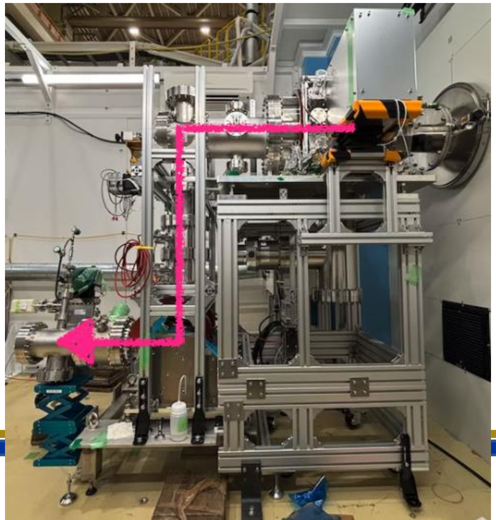
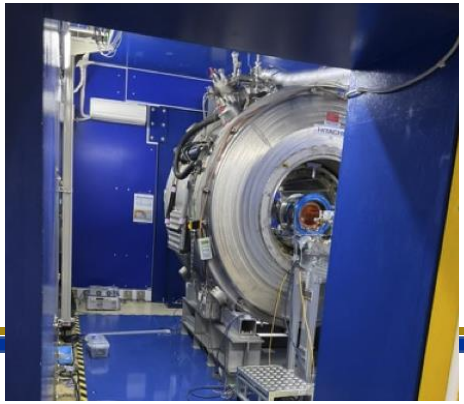




Conclusion

- J-PARC's **independent approach** can provide an **excellent cross check** of Fermilab's measurement;
- J-PARC has achieved **great progress recently -> First cold muon beam acceleration was an historical achievement.**
- It aims for 0.45 ppm precision (~BNL level with data expected 2030+)
  - The high sensitivity study could bring the precision to O(100ppb).
- This will be another fundamental step towards our final goal: Measuring muon g-2 with ever-increasing precision – testing the SM and probing new physics.

“The closer you look the more there is to see”

F. Jegerlehner

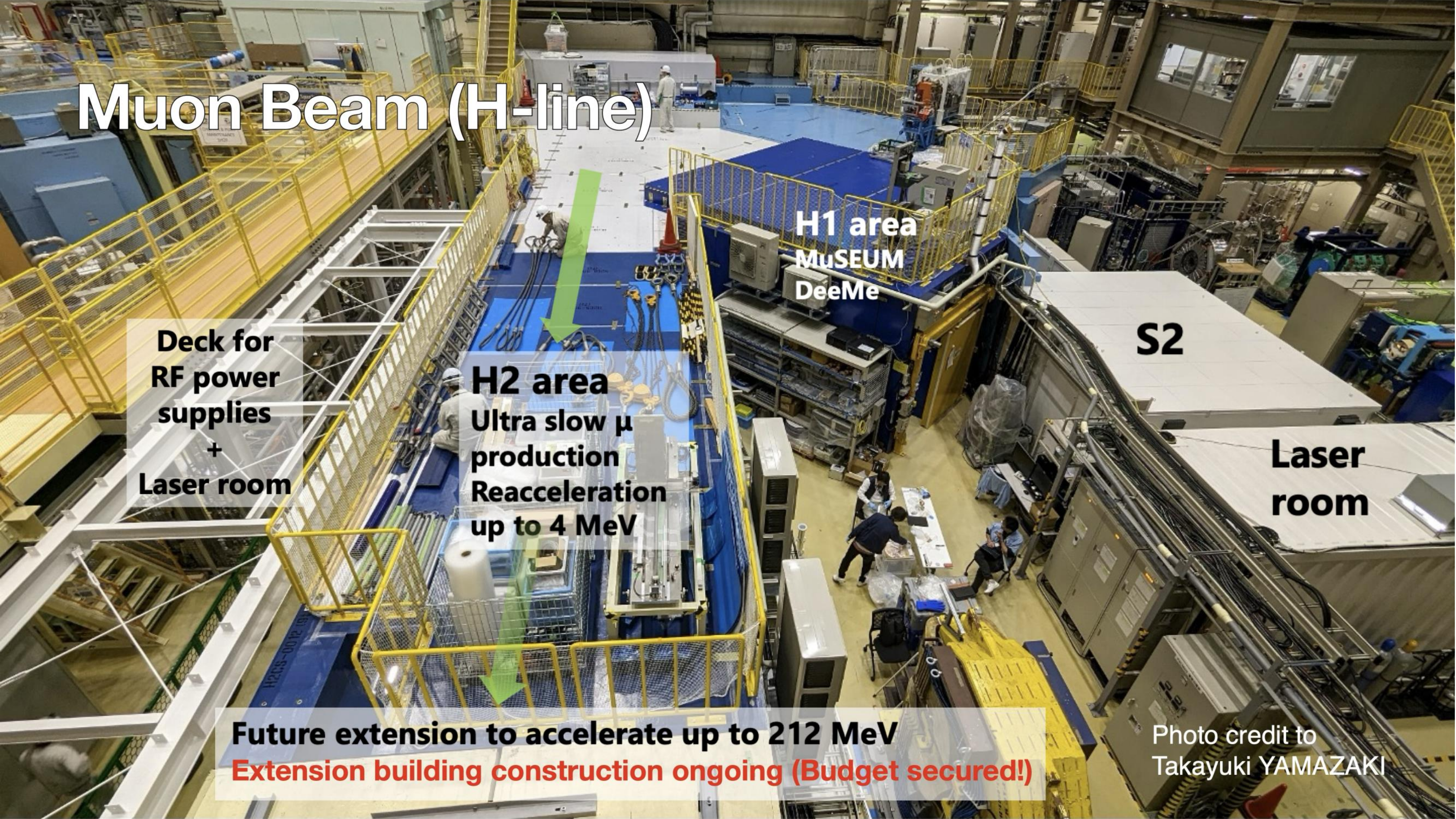
THANK YOU!

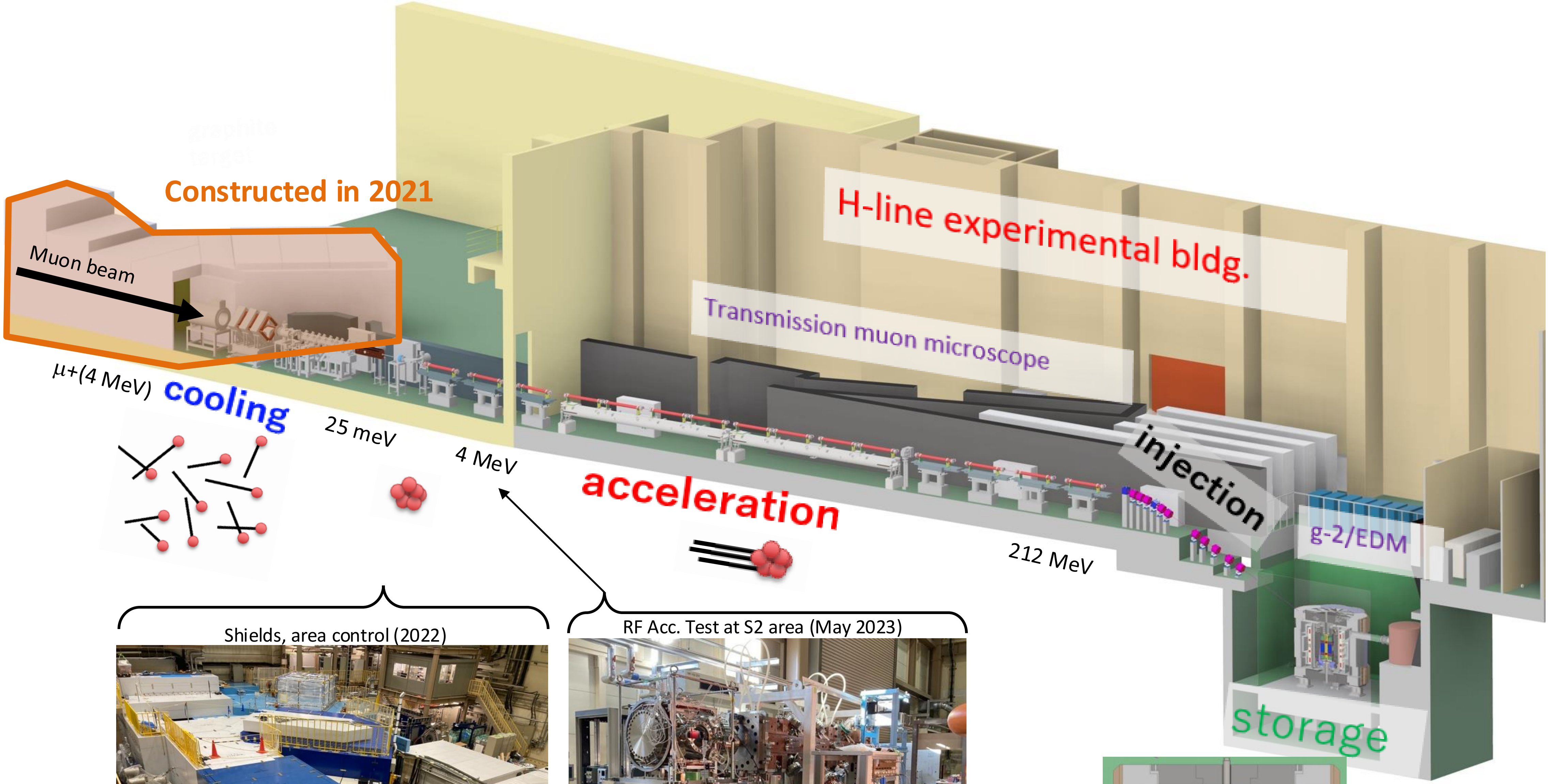
BACK-UP

Comparison with Fermilab

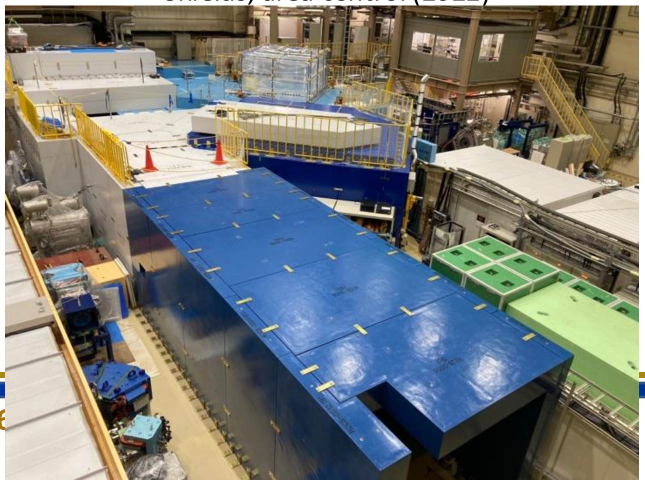
Prog. Theor. Exp. Phys. **2019**, 053C02 (2019)

	BNL-E821	Fermilab-E989	Our experiment
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz γ	29.3	$t_\mu \sim$ 64.4 us	3 $t_\mu =$ 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.)	$0.2 \times 10^{-19}\ e\cdot$cm	–	$1.5 \times 10^{-21}\ e\cdot$cm
(syst.)	$0.9 \times 10^{-19}\ e\cdot$cm	–	$0.36 \times 10^{-21}\ e\cdot$cm
	Completed	Completed	In preparation

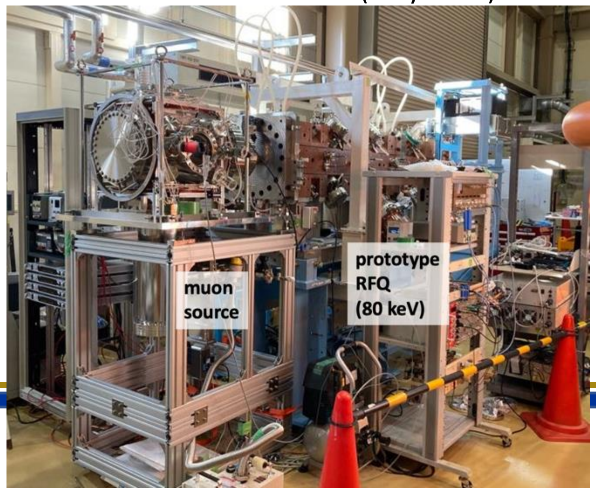

Muon Beam (H-line)
H1 area
MuSEUM
DeeMe
S2
Deck for
RF power
supplies
+
Laser room
H2 area
Ultra slow μ
production
Reacceleration
up to 4 MeV
Laser
room
Future extension to accelerate up to 212 MeV
Extension building construction ongoing (Budget secured!)
Photo credit to
Takayuki YAMAZAKI

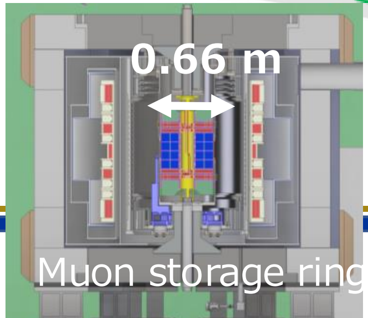


Shields, area control (2022)



RF Acc. Test at S2 area (May 2023)





Expected sensitivity - Systematic

- The systematic uncertainties are estimated to be less than 70 ppb – smaller than the statistical one:

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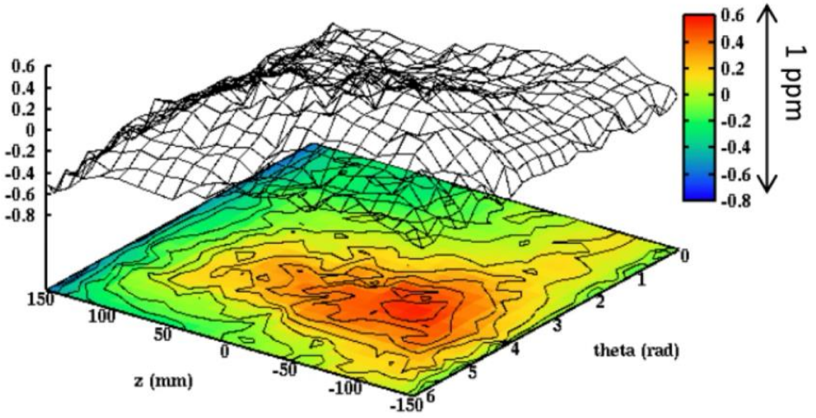
$\boldsymbol{\delta a_{\mu(syst)}} \sim$ **70 ppb** → this experiment is expected to be strongly **statistically limited**.

Storage Magnet

- Local uniformity of **1 ppm** was demonstrated by the MUSEUM experiment magnet at **1.2 T**;
    - Further tests will be carried out at **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