LEVERHULME TRUST

UNIVERSITY OF LIVERPOOL

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

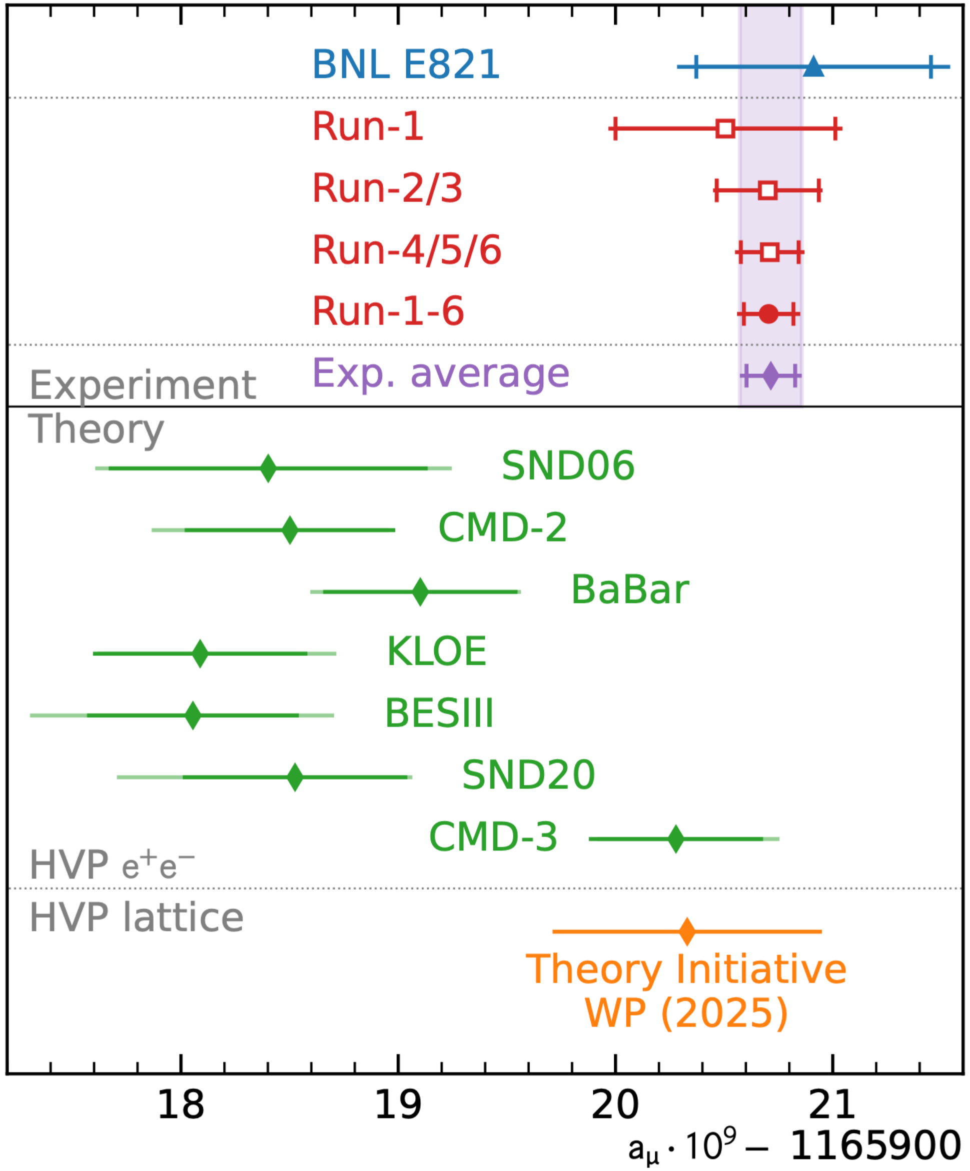
E. Bottalico on behalf of g-2 collaboration

MPPW 2025

11th November 2025

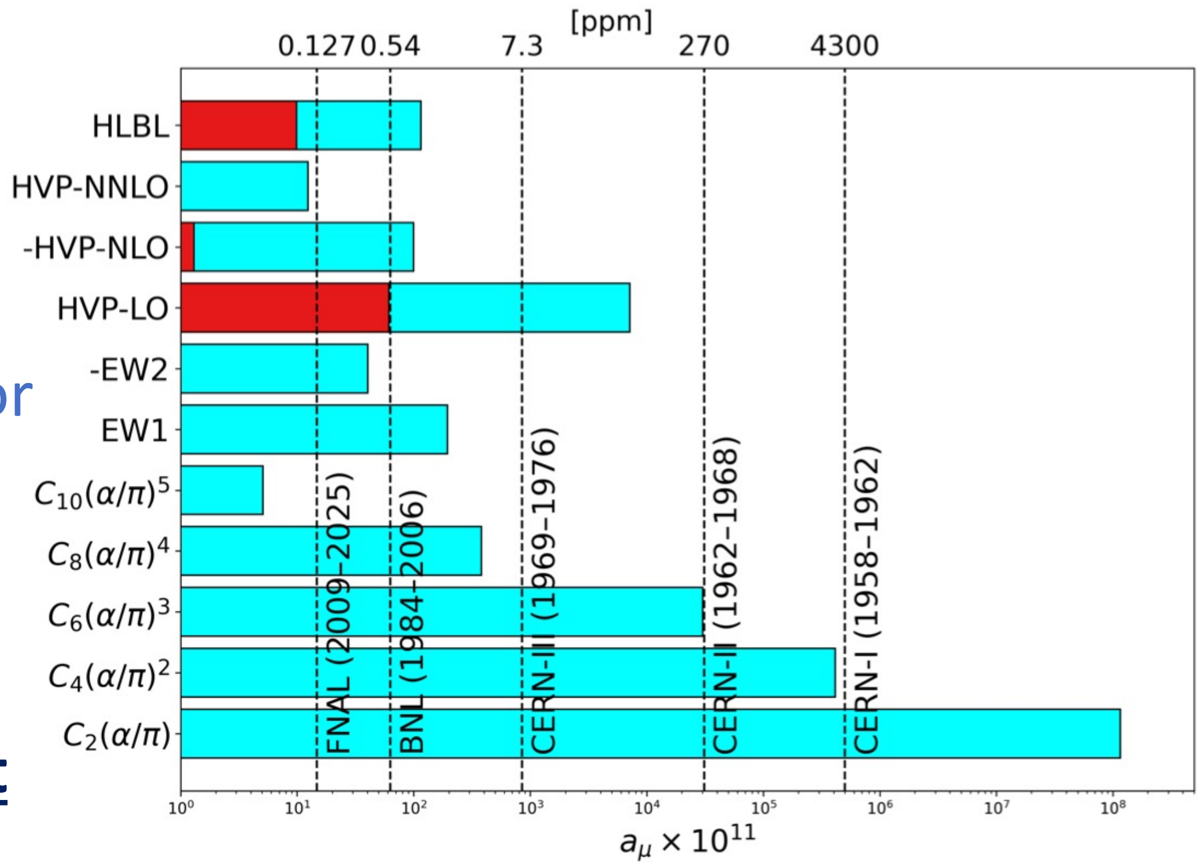
Current status

- 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



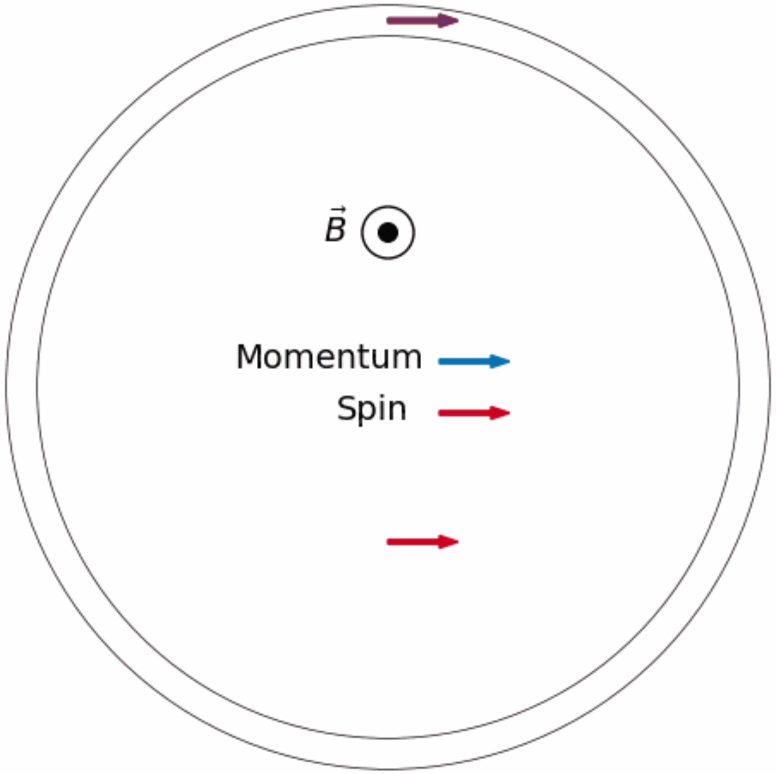
Current status

- The **HVP contribution** is still **leading** the total **uncertainty** on a_μ.
- 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.



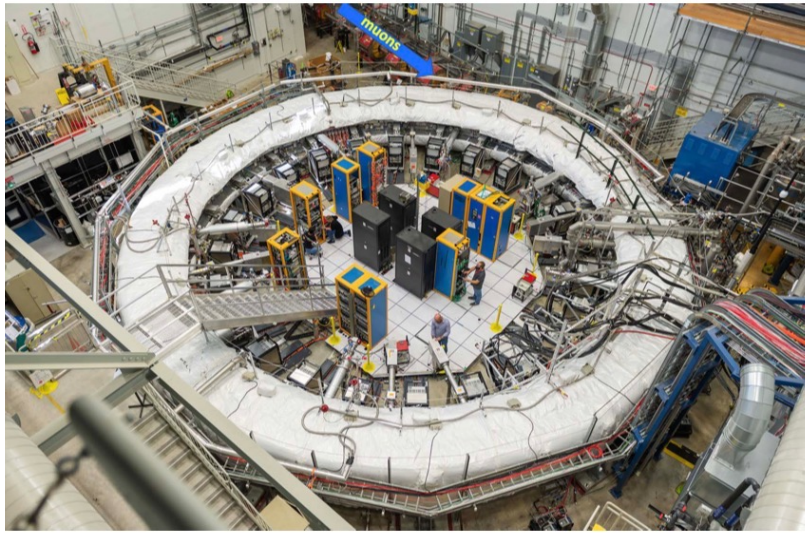
Measured Lepton Magnetic Moment – G. Gabrielse, G. Venanzoni

Measurement principle - Fermilab



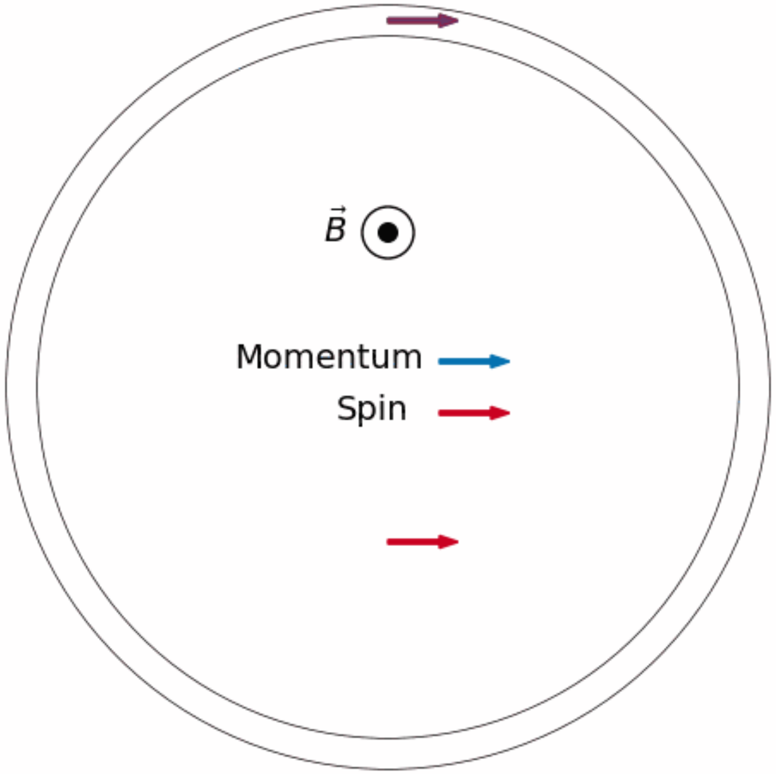
$$\vec{\omega}_a = \frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)(\vec{\beta}\times\vec{E})\right]$$

- 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

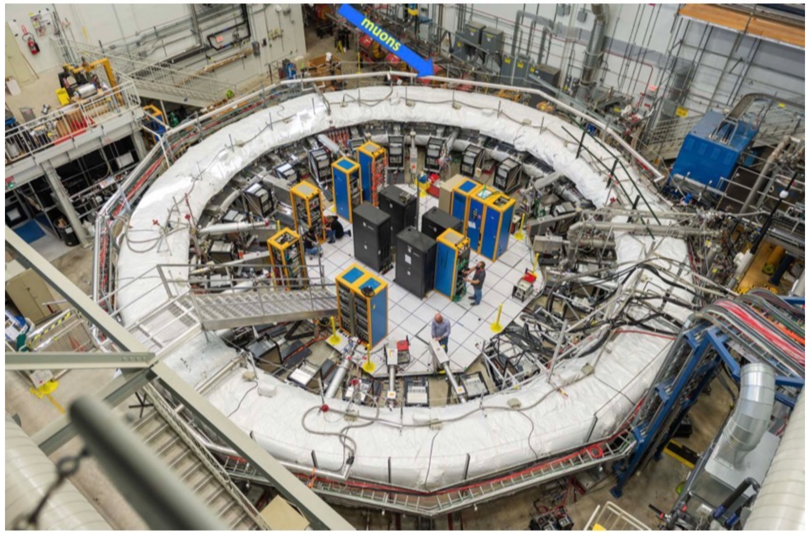


$$\vec{\omega}_a = \frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \cancel{\frac{1}{\gamma^2 - 1}}\right)(\vec{\beta}\times\vec{E})\right]$$

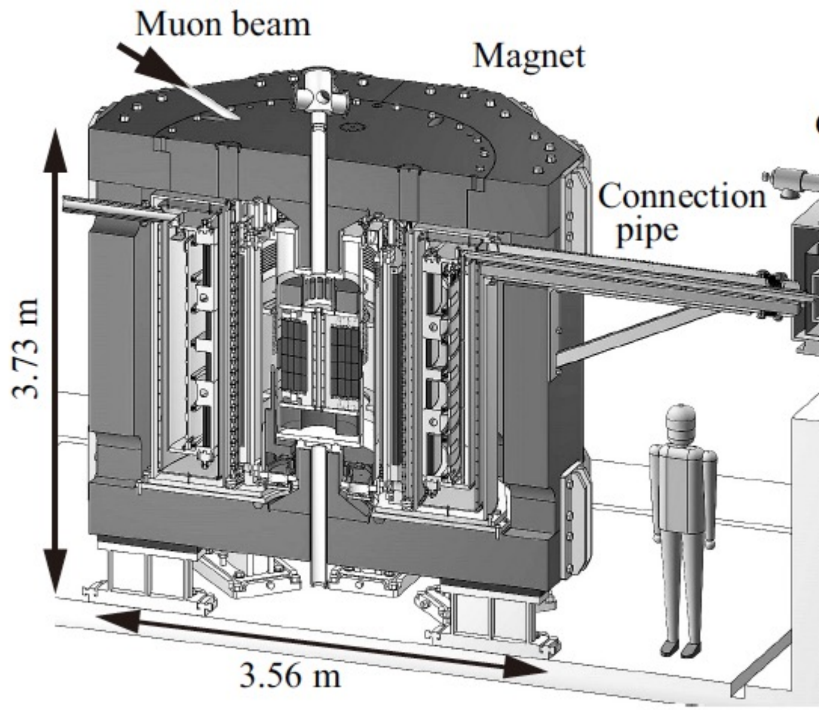
$$\boxed{\gamma = \sqrt{1 + \frac{1}{a_\mu}} \sim 29.3}$$

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

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



Measurement principle – J-PARC

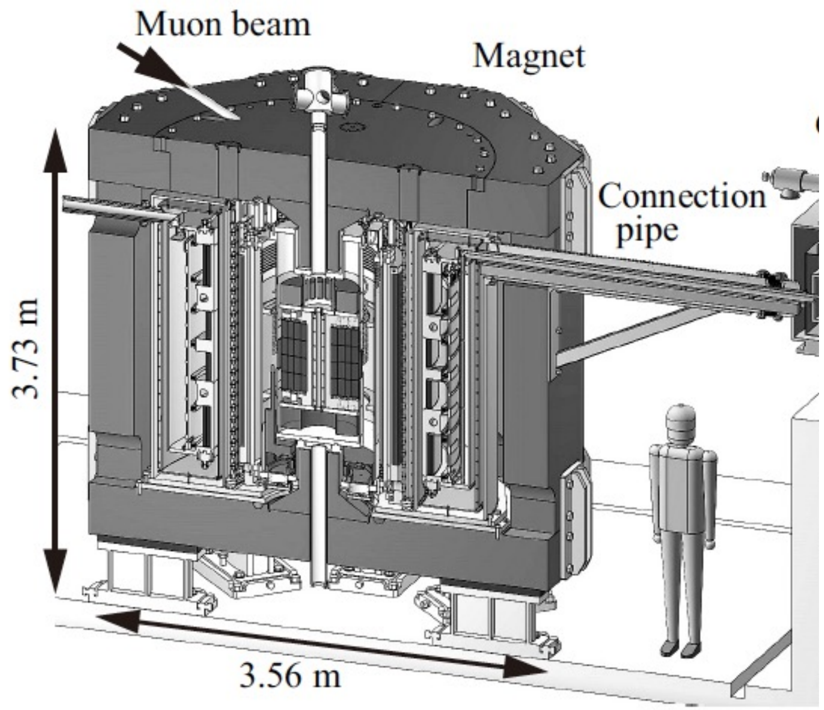


$$\vec{\omega}_a = \frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)(\vec{\beta} \times \vec{E})\right]$$

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

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

Measurement principle – J-PARC



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

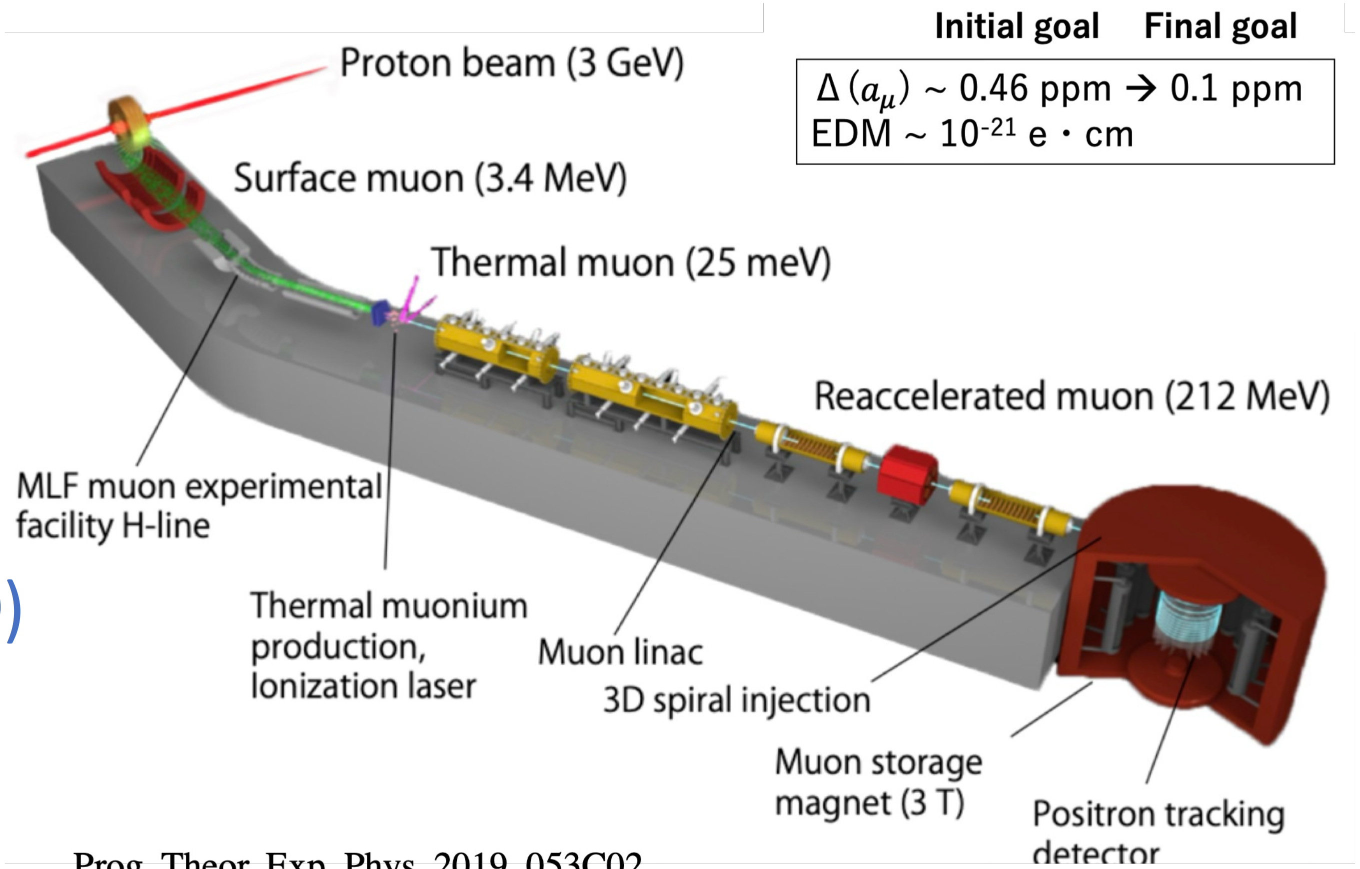
- 300 MeV/c momentum
- 0.66 m ring diameter (B = 3 T)
- No electric field (E=0)

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

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

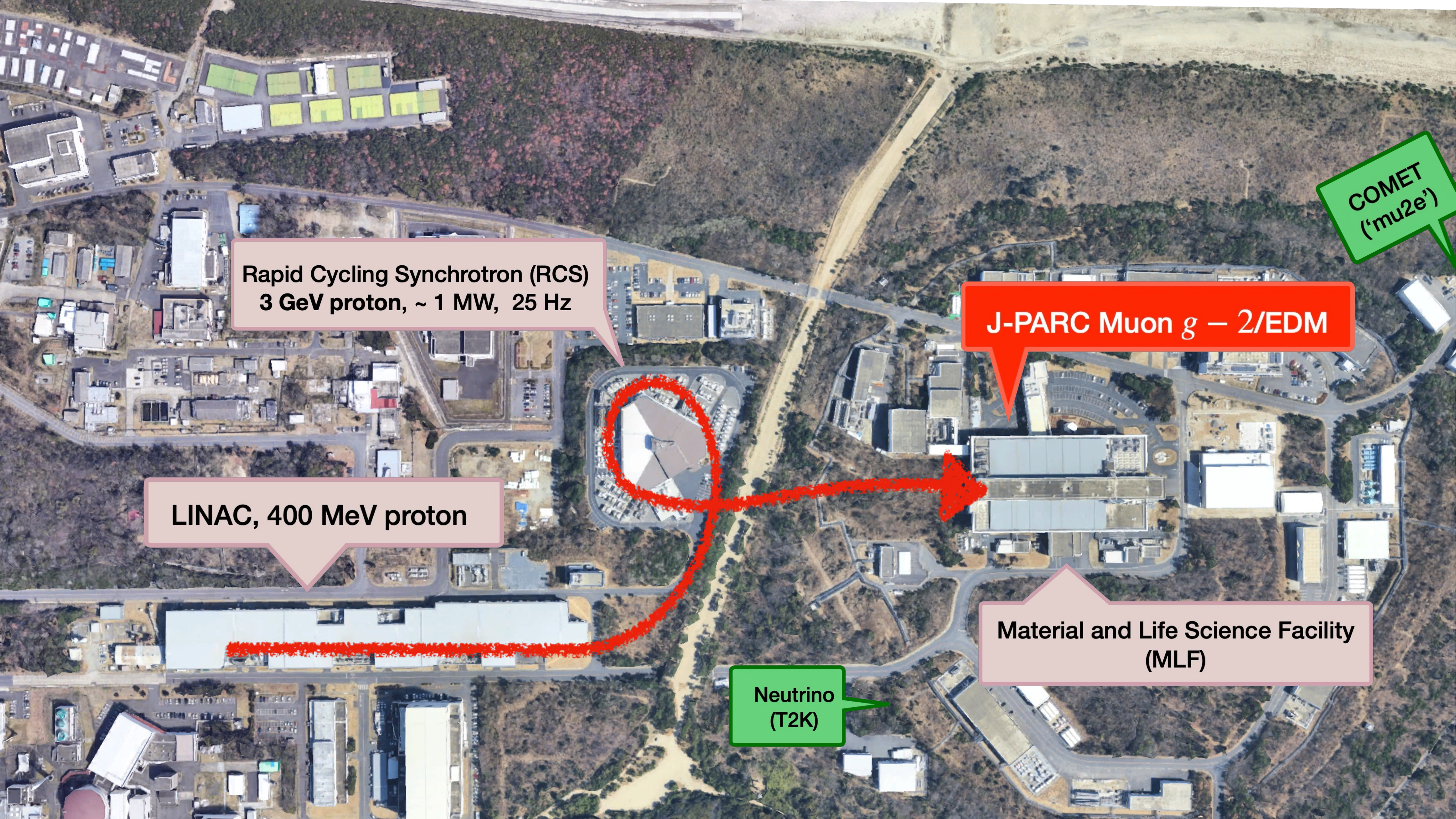
New features of E34

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



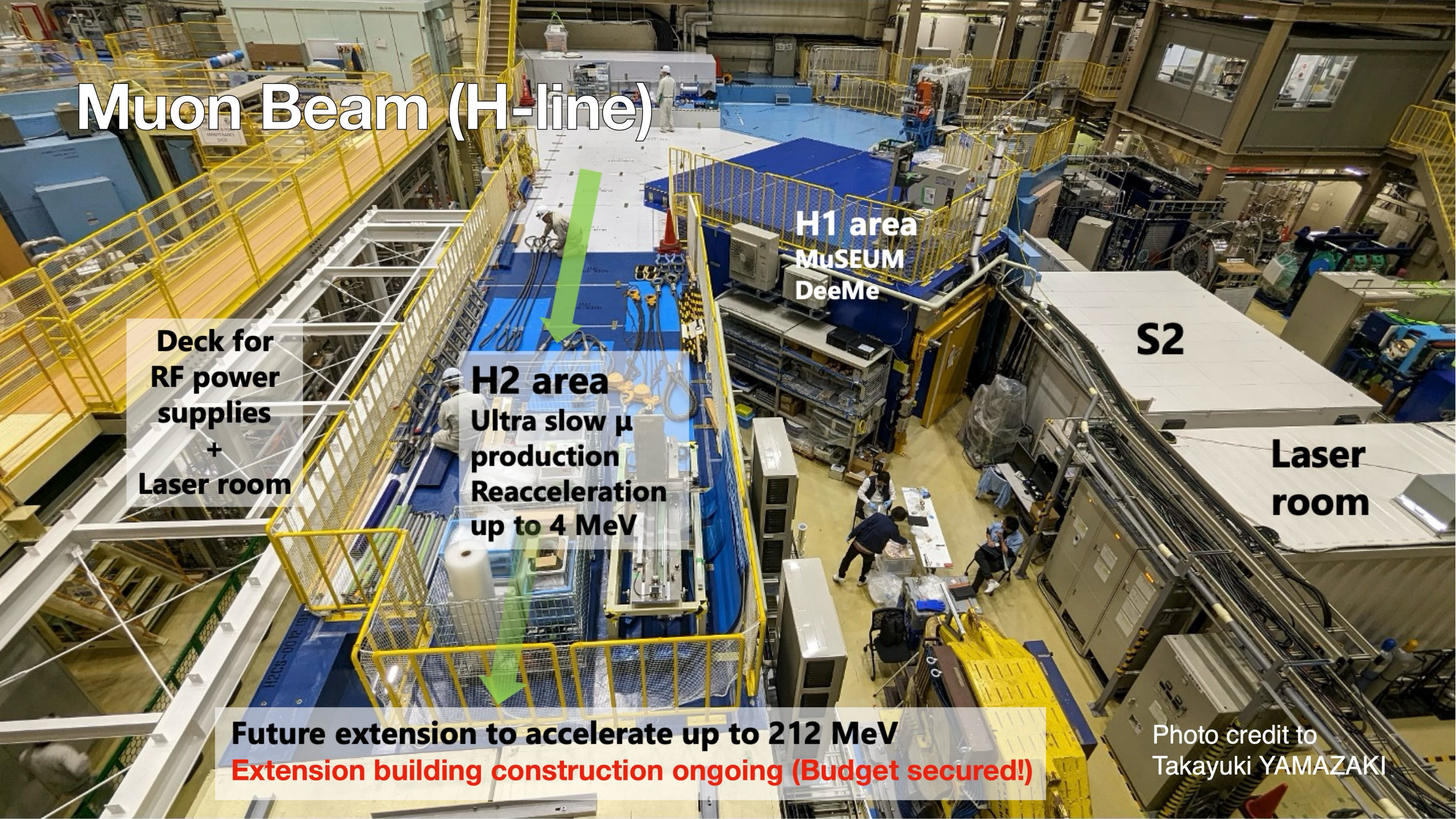
Prog. Theor. Exp. Phys. 2019, 053C02

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

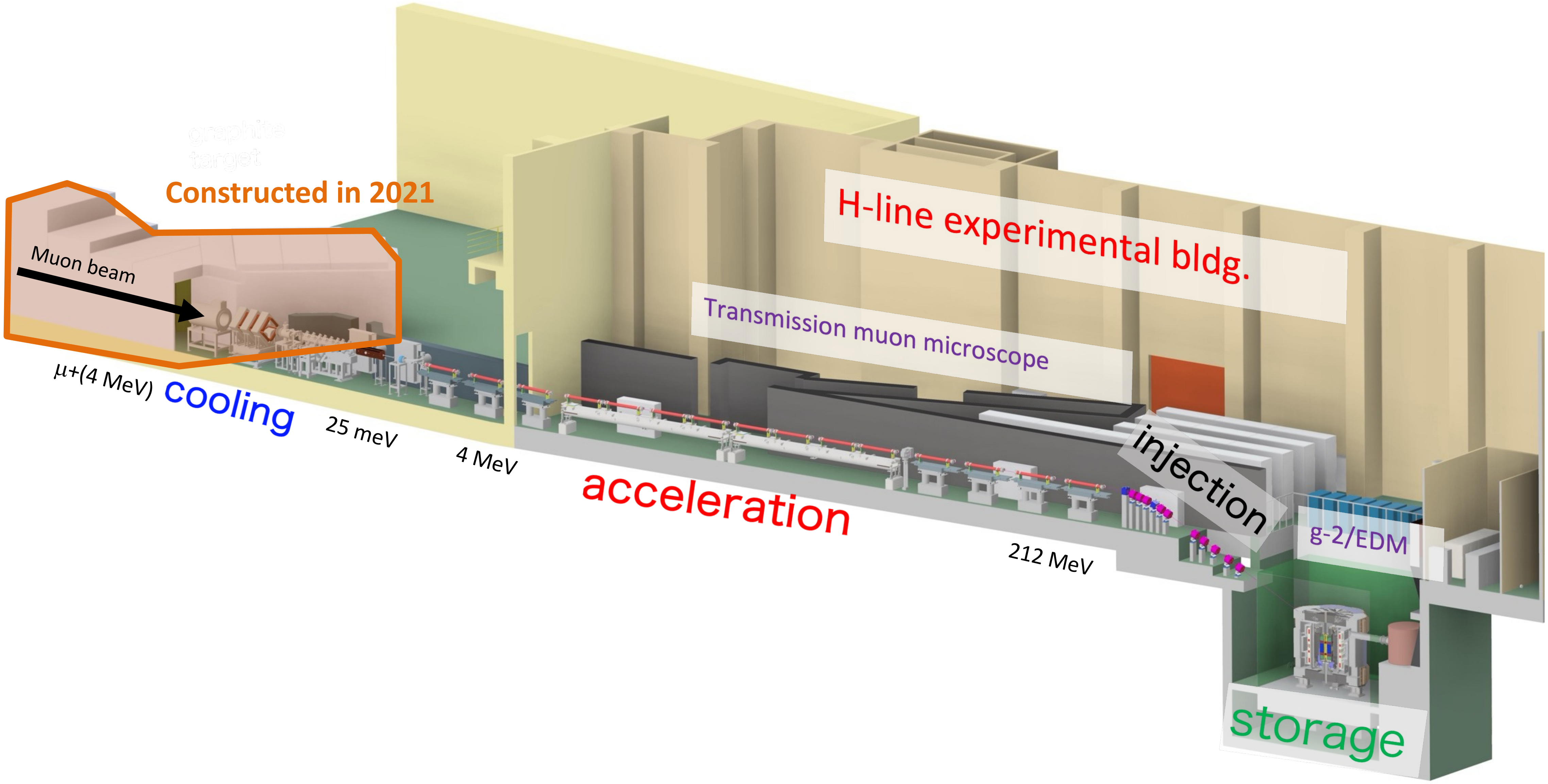


Rapid Cycling Synchrotron (RCS)
3 GeV proton, ~ 1 MW, 25 Hz
J-PARC Muon $g-2$/EDM
COMET
('mu2e')
LINAC, 400 MeV proton
Material and Life Science Facility
(MLF)
Neutrino
(T2K)

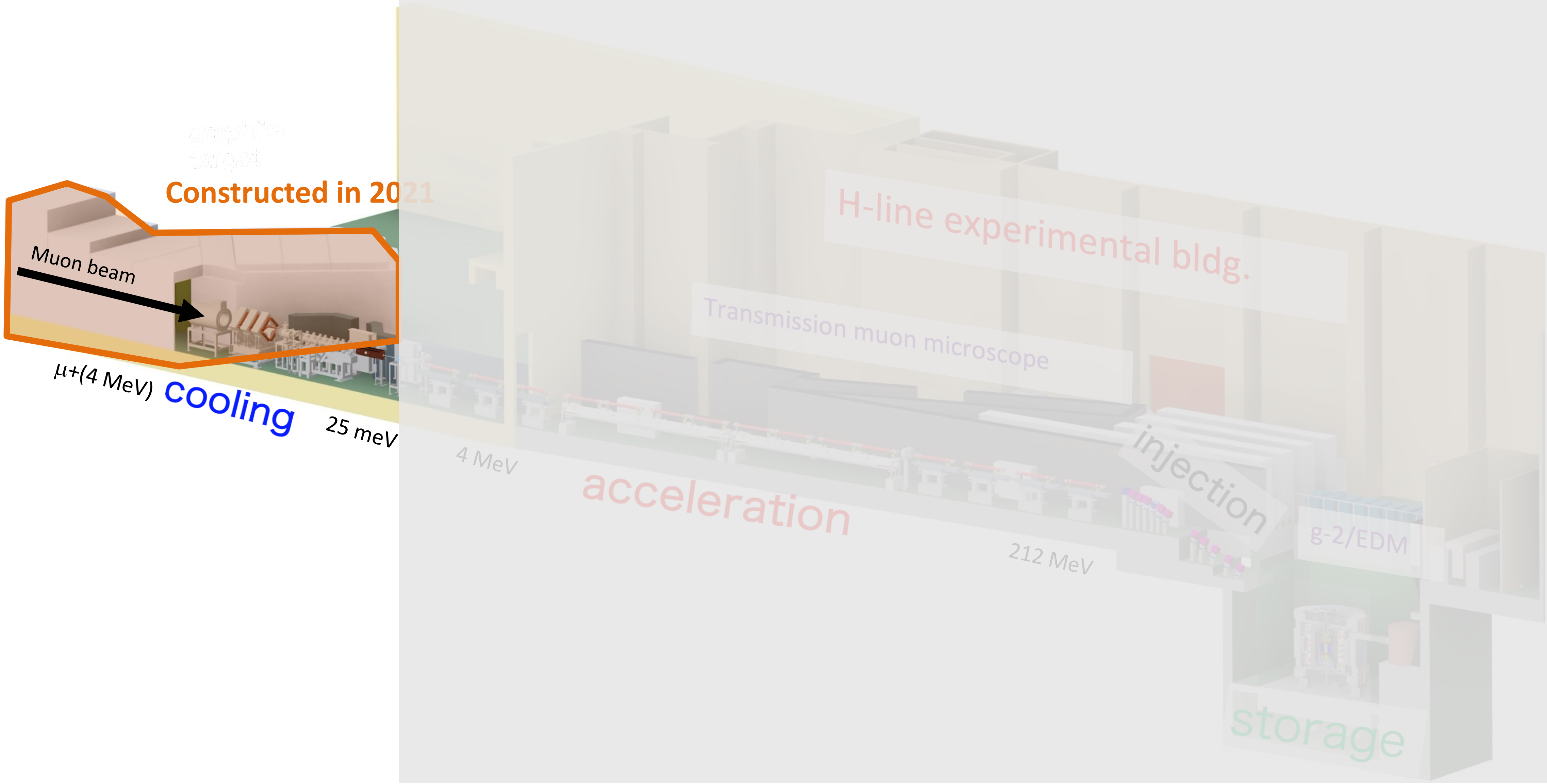
Muon Beam (H-line)



Muon g-2 at J-PARC (E34)

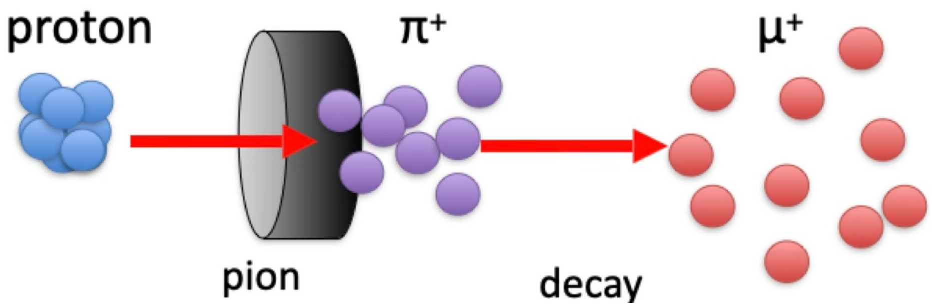


Muon cooling

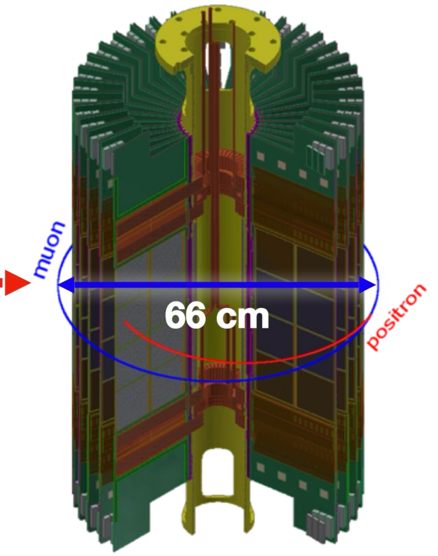


Shields, area control (2022)

Muon cooling

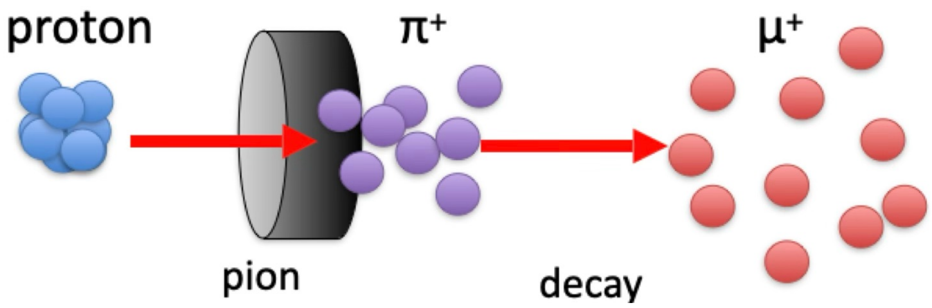


emittance
~1000π mm · mrad



- **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 $\sim$mm → never achieved before.

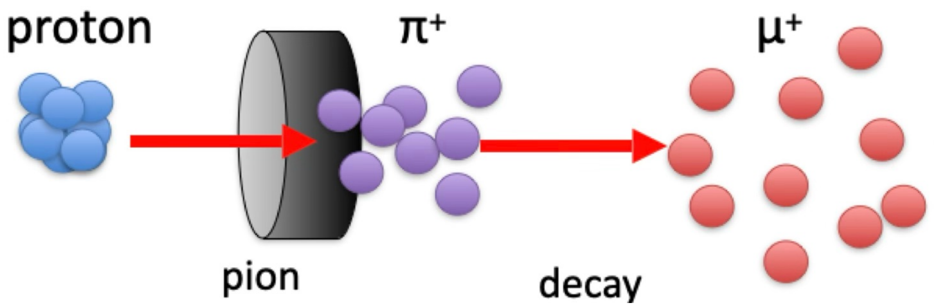
Muon cooling



emittance
~1000π mm · mrad

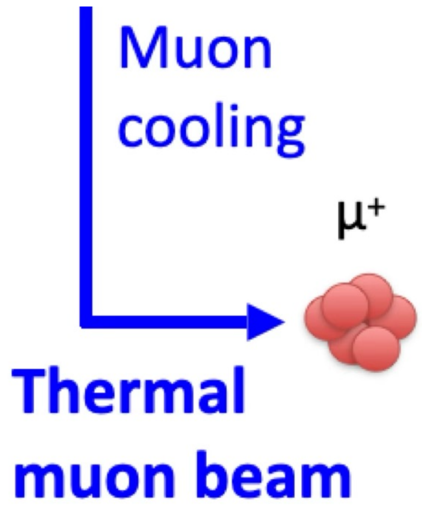
Flashlight

Muon cooling



emittance

~1000π mm・mrad

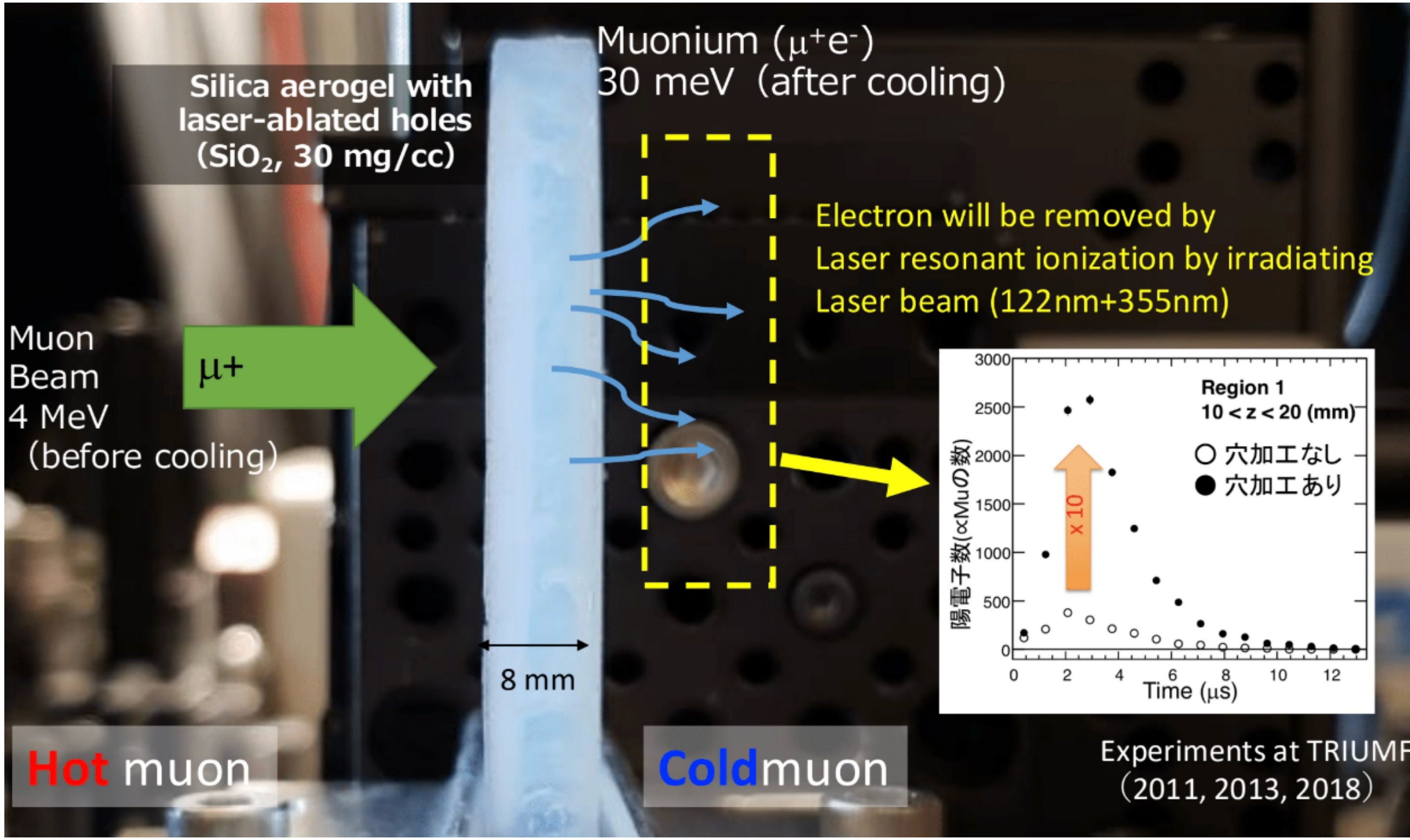


emittance

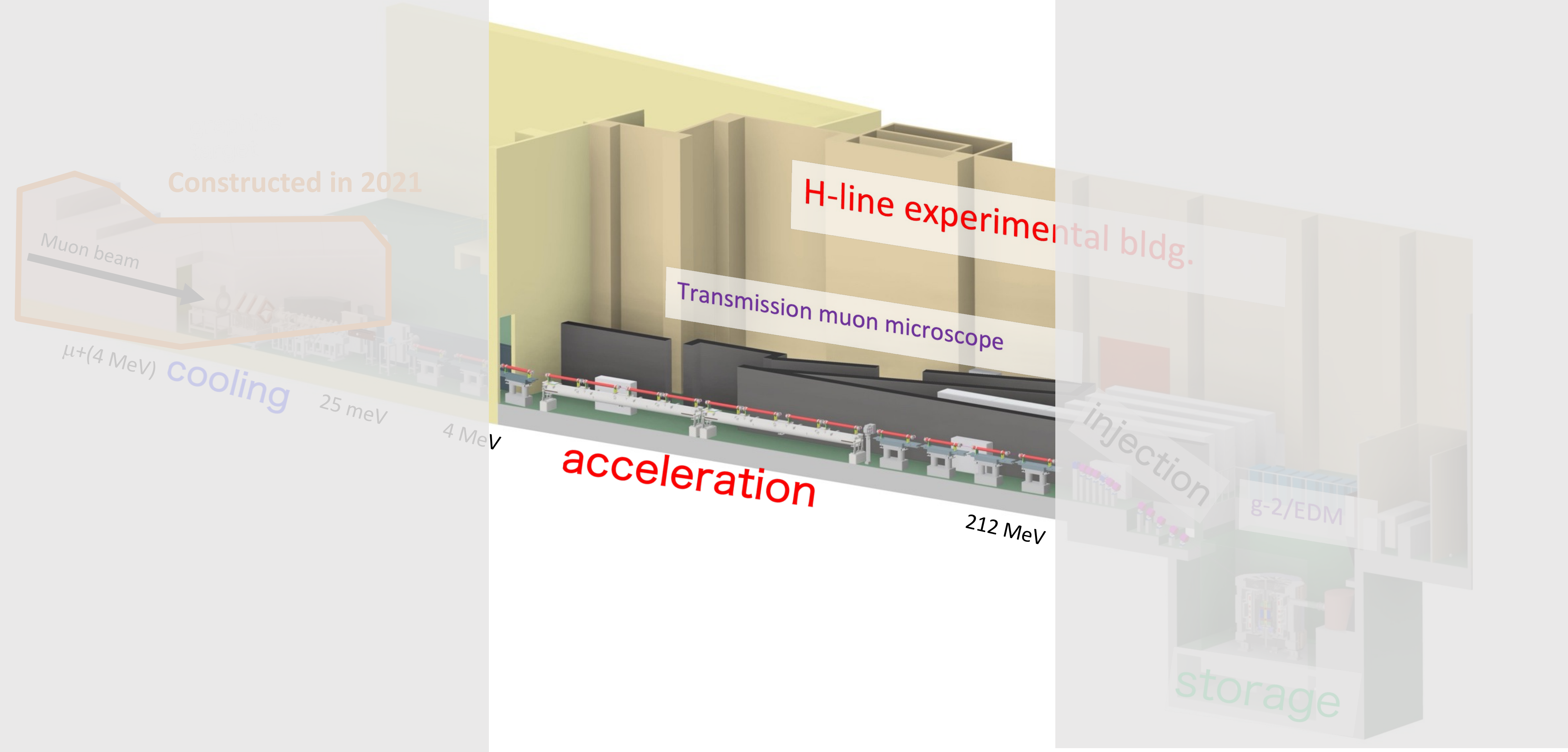
1π mm・mrad

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)



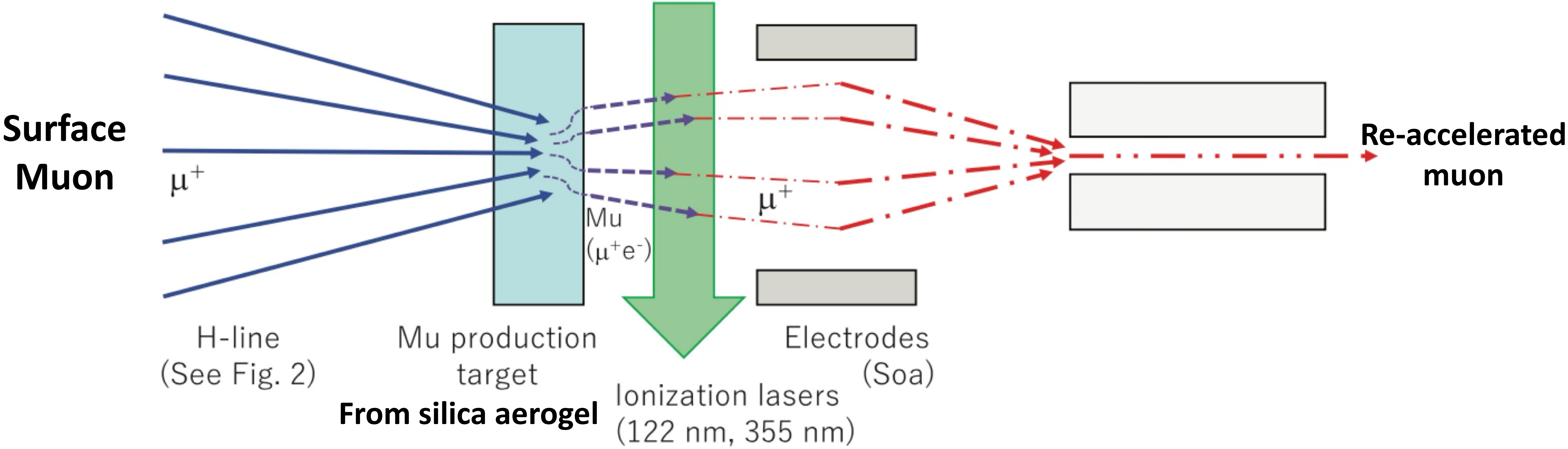
Re-accelerated thermal muon



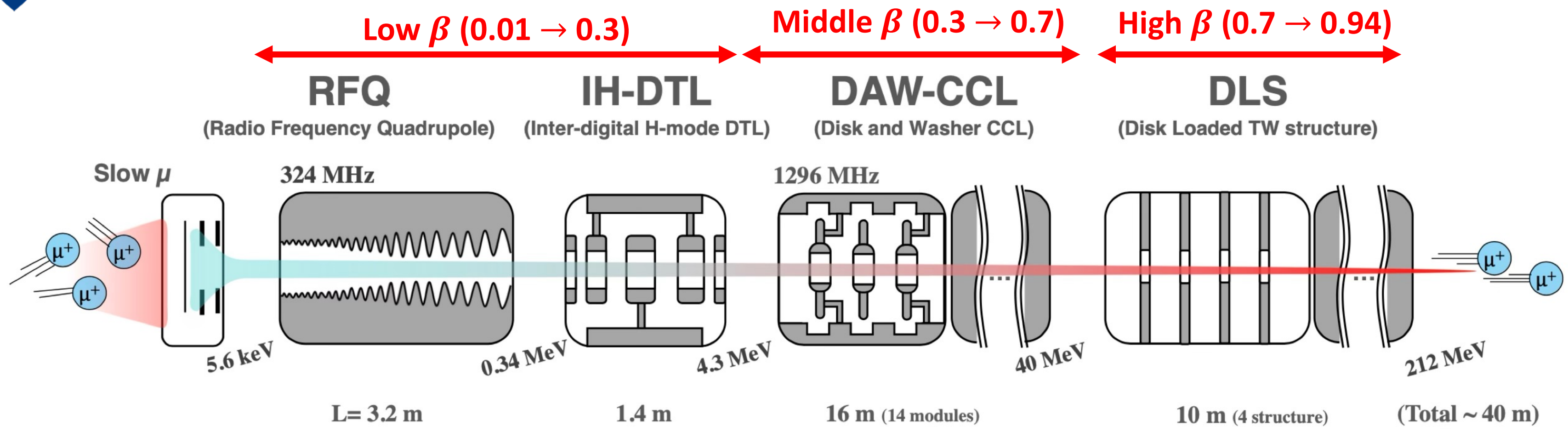
Shields, area control (2022)

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



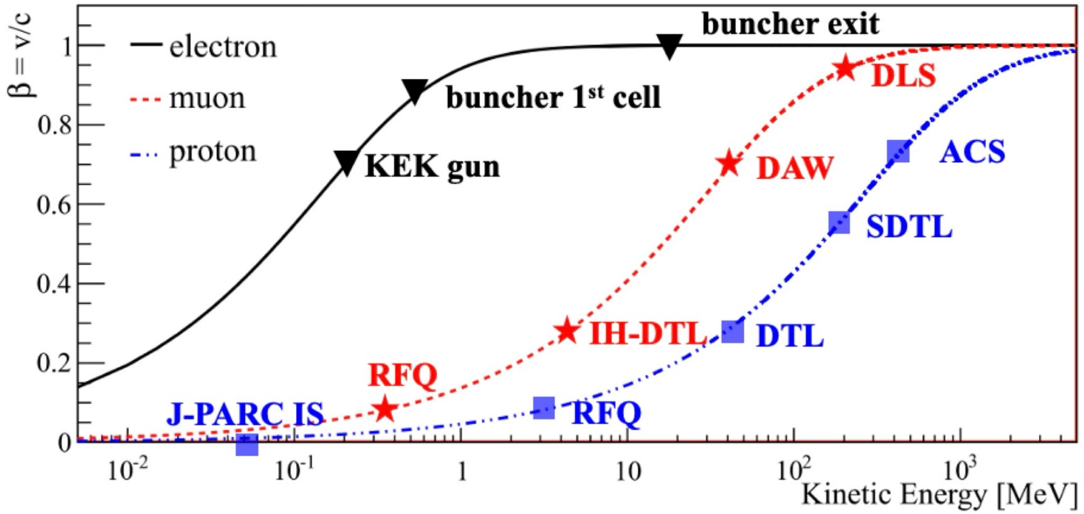
Re-accelerated thermal muon



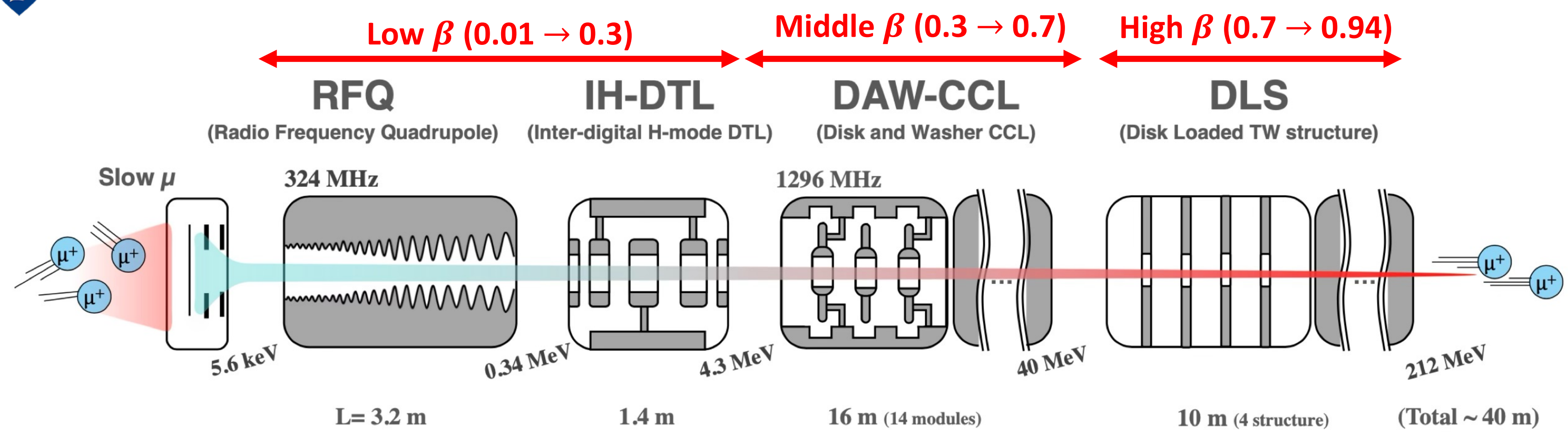
Muon LINAC parameters

Frequency (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 to 212 MeV**
- **4 steps acceleration depending on β -> total length 40 m**



Re-accelerated thermal muon



Acceleration test with thermal μ planned.

Fabrication completed. High power test on going

Prototype fabricated and tested

Prototype fabricated and tested

Muon LINAC parameters

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Intensity	1×10^6 /s
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Pulse width	10 ns
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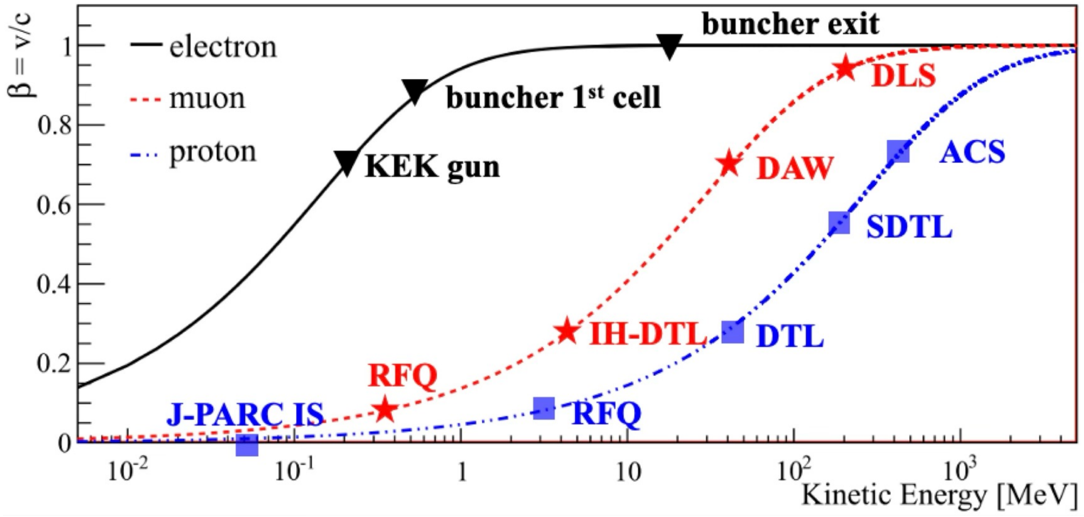

- **The first muon-dedicated linac in the world!**
- **Muon Acceleration to 212 MeV**
- **4 steps acceleration depending on β -> total length 40 m**

Re-accelerated thermal muon

[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]

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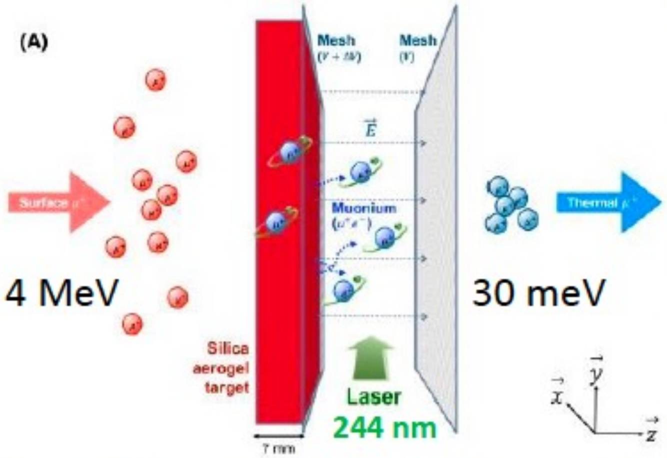
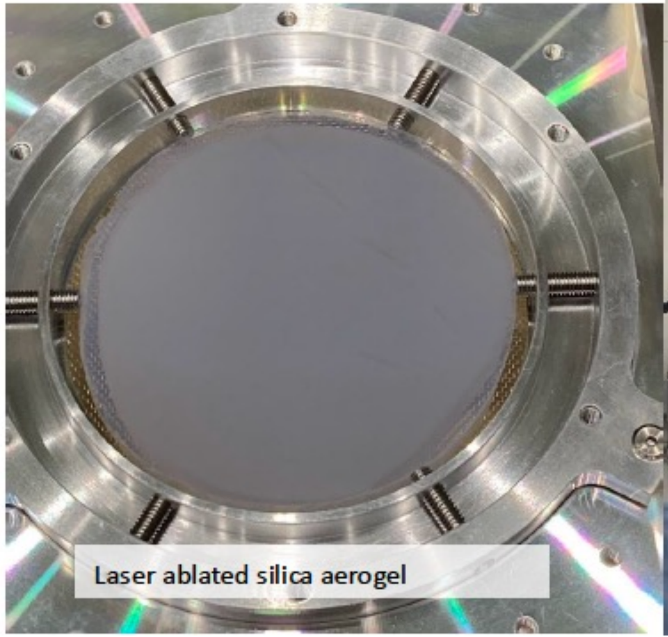
Acceleration of positive muons from thermal energy to 100 keV has been demonstrated. Thermal muons were generated by resonant multiphoton ionization of muonium atoms emitted from a sheet of laser-ablated aerogel. The thermal muons were first electrostatically accelerated to 5.7 keV, followed by further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

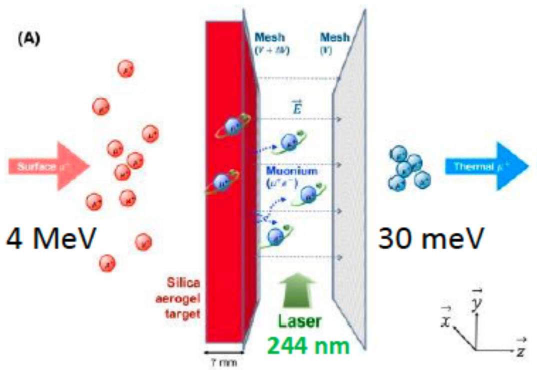




J-PARC S2 area

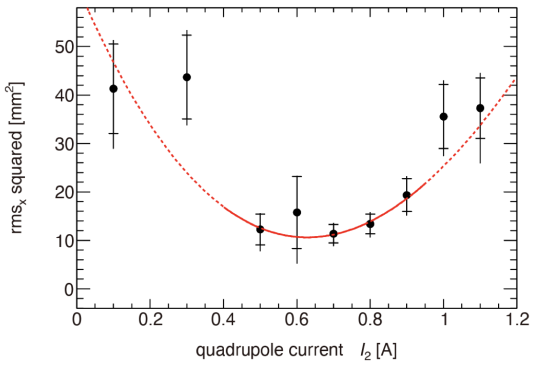
Re-accelerated thermal muon

- Muon Cooling demonstration:

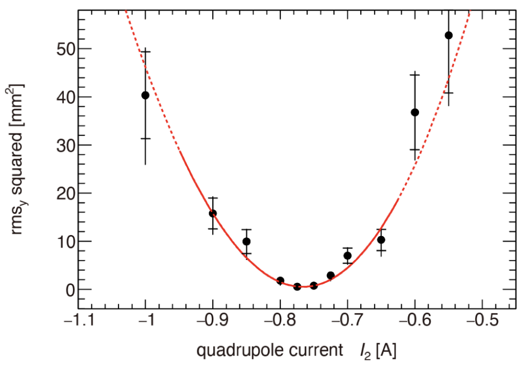


Electrostatic acceleration (10 kV) → Electric bend (energy filter) → Magnetic bend (momentum filter) → MCP

horizontal



vertical

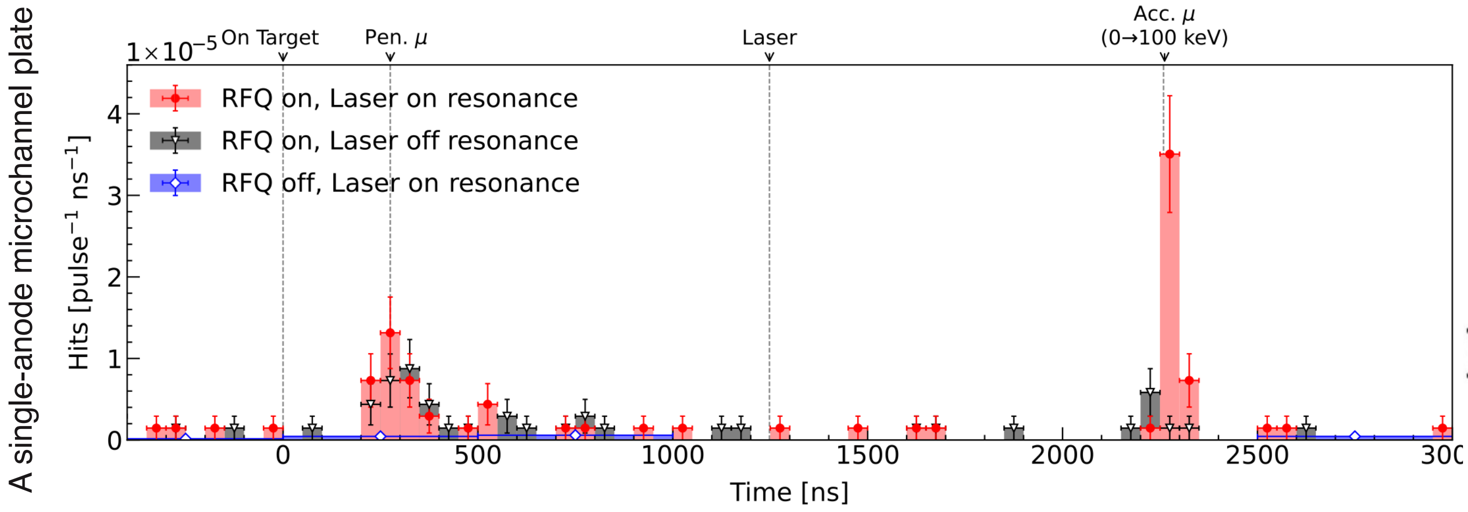


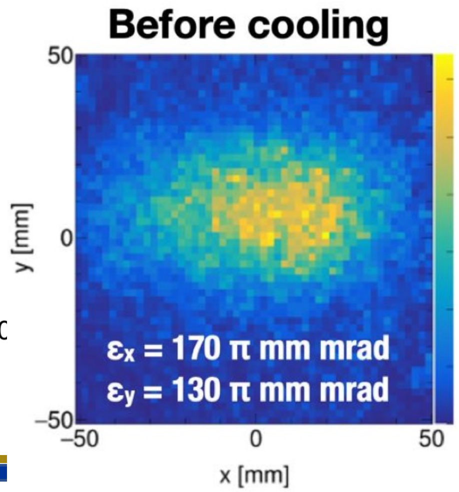
$\varepsilon_x = 0.85 \pm 0.25(\mathrm{stat})\ ^{+0.22}_{-0.13}(\mathrm{syst})$ [π mm mrad]

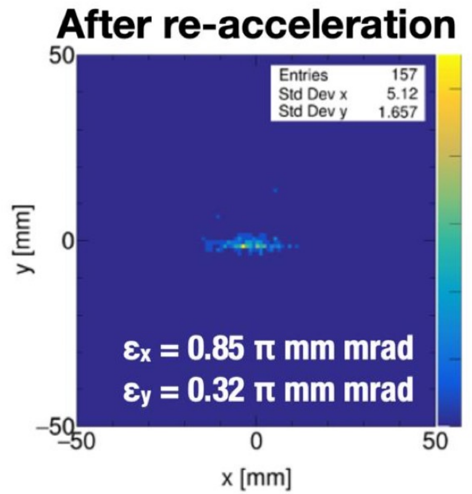
$\varepsilon_y = 0.32 \pm 0.03(\mathrm{stat})\ ^{+0.05}_{-0.02}(\mathrm{syst})$ [π mm mrad]

Emittance reduction by ~10^{-3}

The birth of low-emittance muon beam

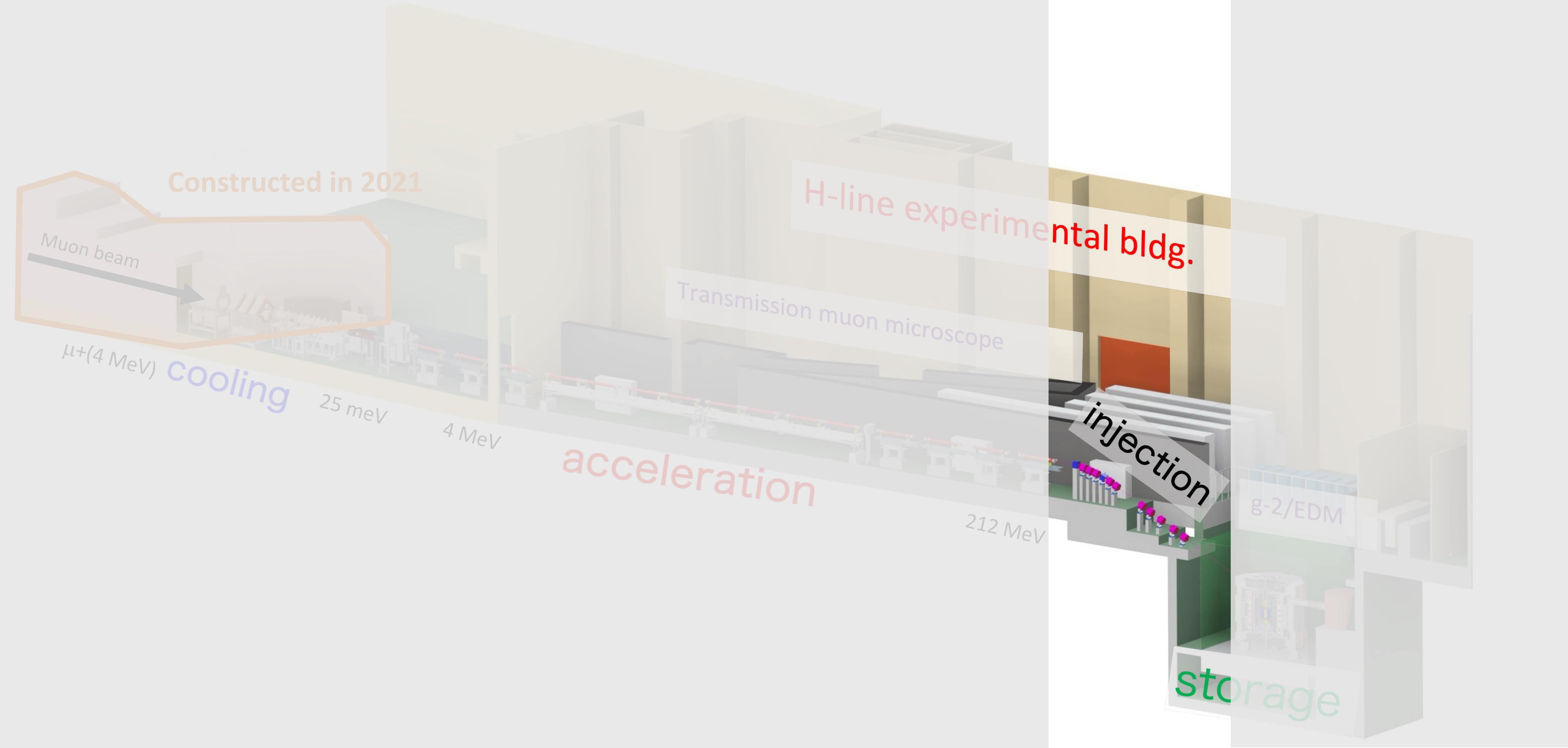






Phys. Rev. Lett. **134**, 245001

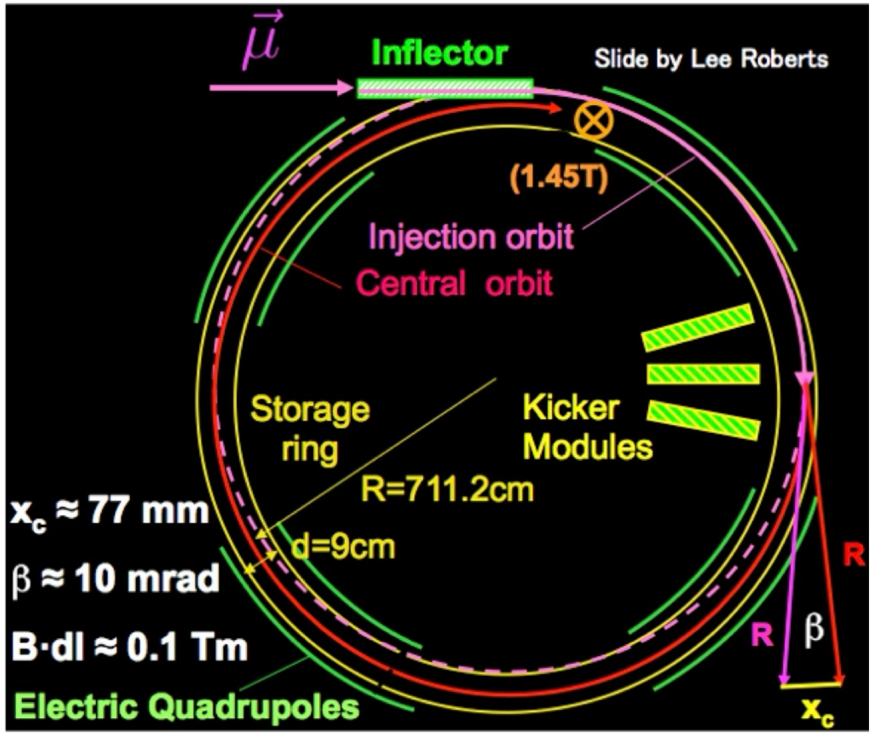
3D spiral injection



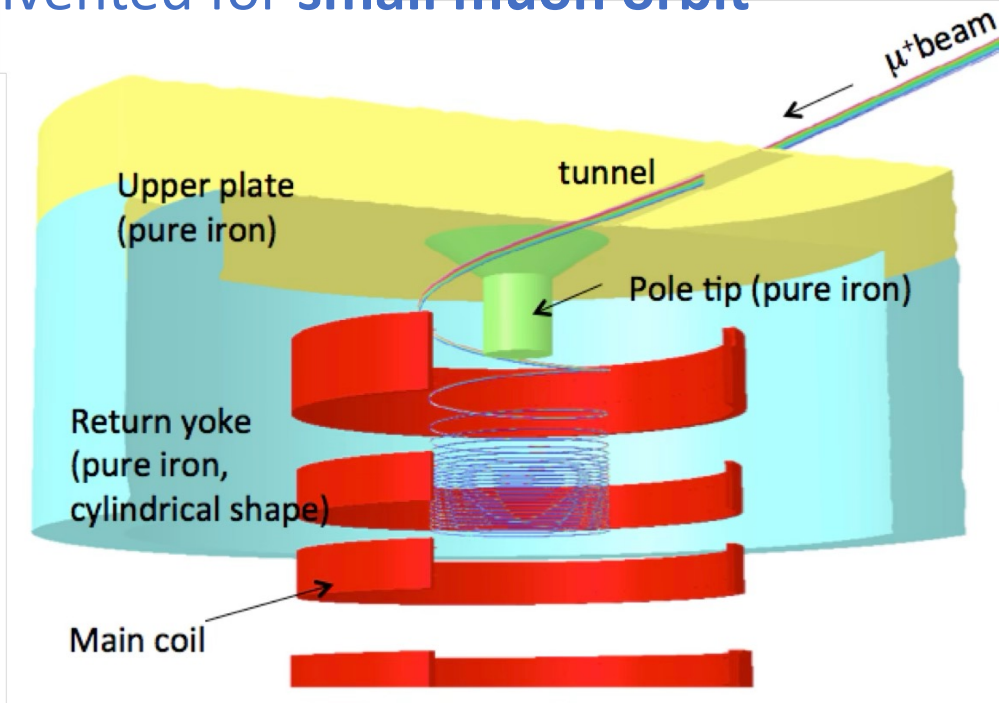
Shields, area control (2022)

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]

Conventional 2D injection @BNL and FNAL

•Inflector + horizontal kicker

•Efficiency ~3-5%

Novel injection @J-PARC

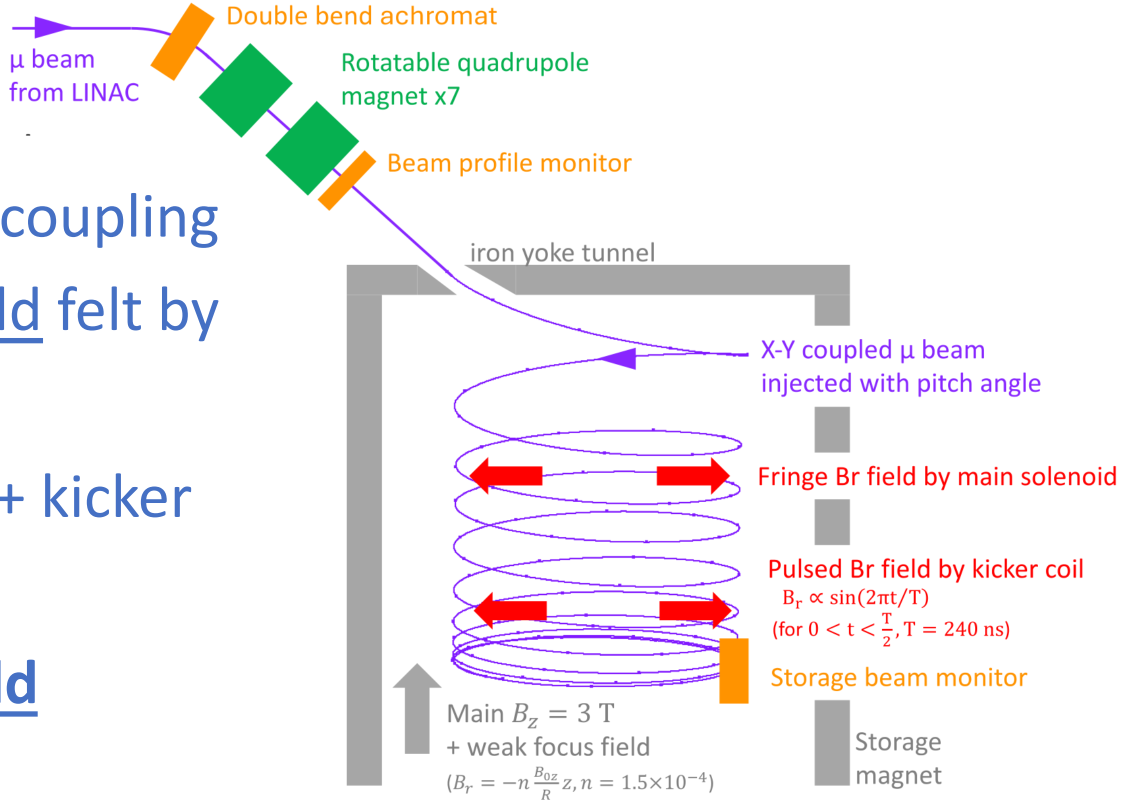
•3D spiral injection + vertical kicker

•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**.

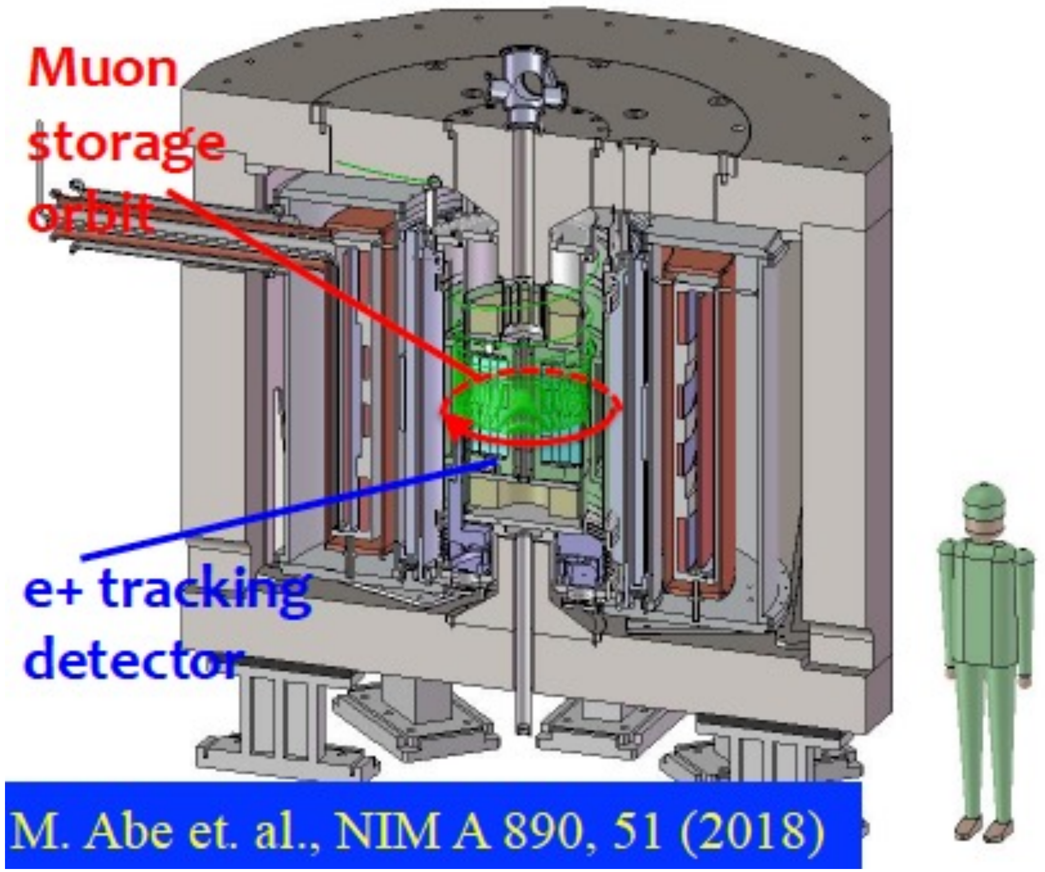
3. **Store muon** beam by **weak focusing**.

Storage Ring

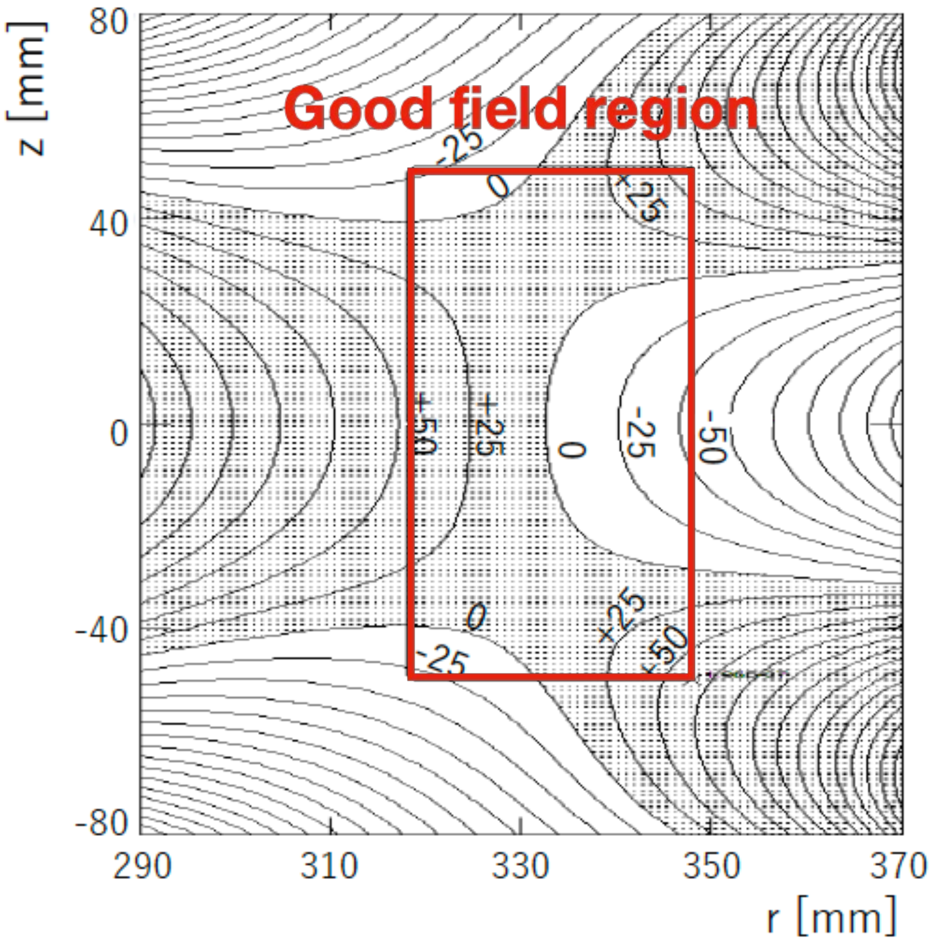
Shields, area control (2022)

Storage Magnet

3 Tesla MRI-type superconducting solenoid magnet is under design



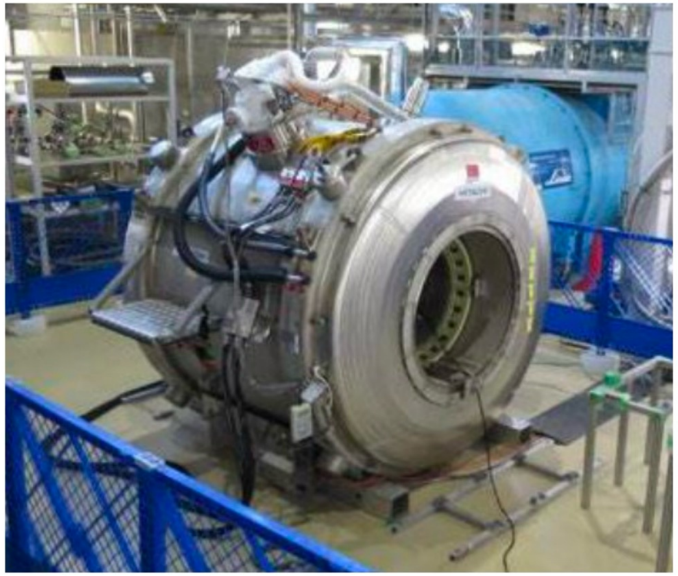
- Storage region :
  - radius : 33.3±1.5 cm
  - height : ±5 cm
  - Field strength : 3T
  - Uniformity : 0.1 ppm (Azimuthal integral)
- Injection region :
  - Smooth field for beam injection
- Weak focus field: -5e-4 T/m of Br at maximum



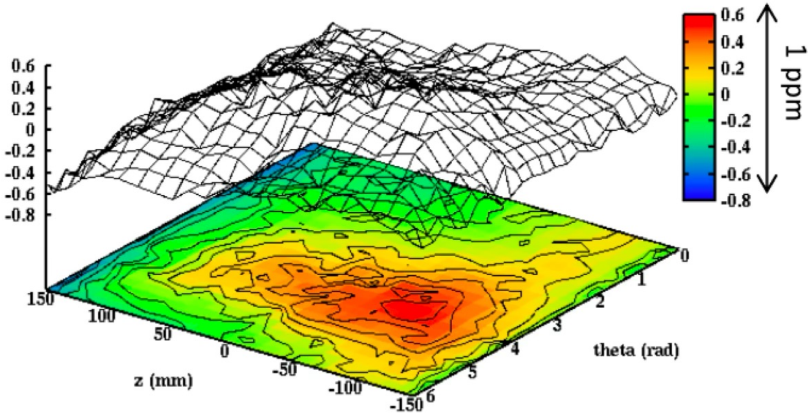
- Average magnetic field **uniformity** is better than **0.1 ppm**
- 25 ppb/line

Storage Magnet

- 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

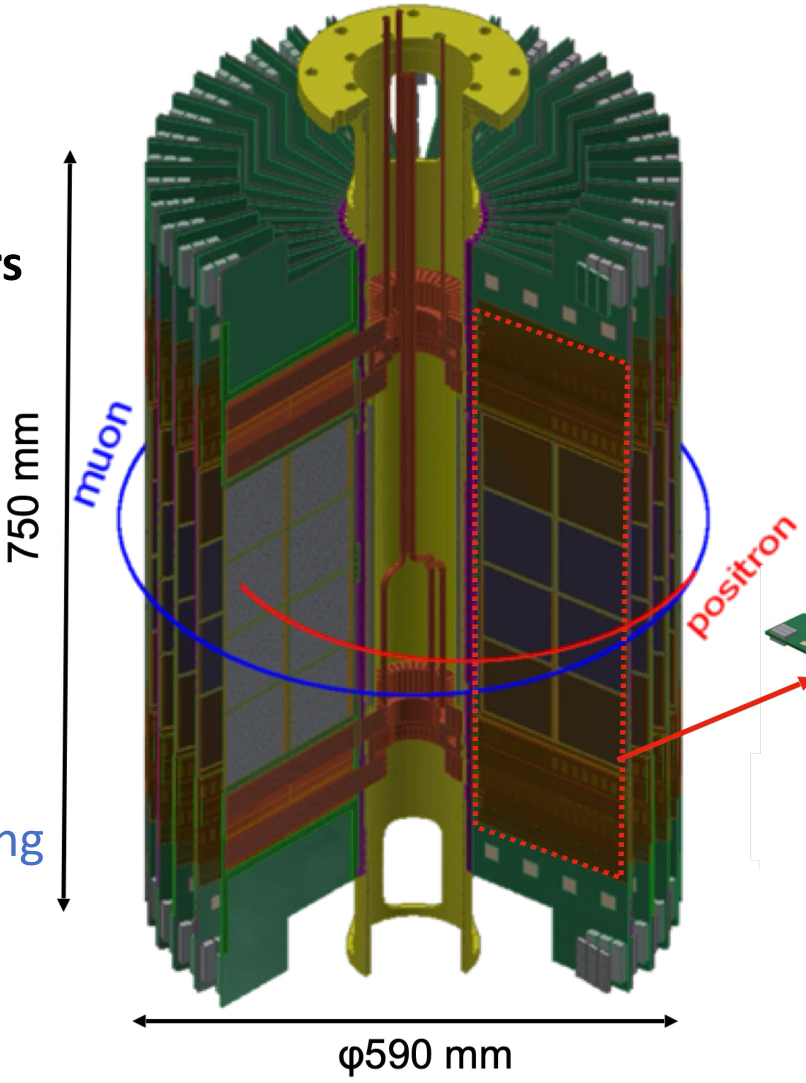


Magnetic field after shimming

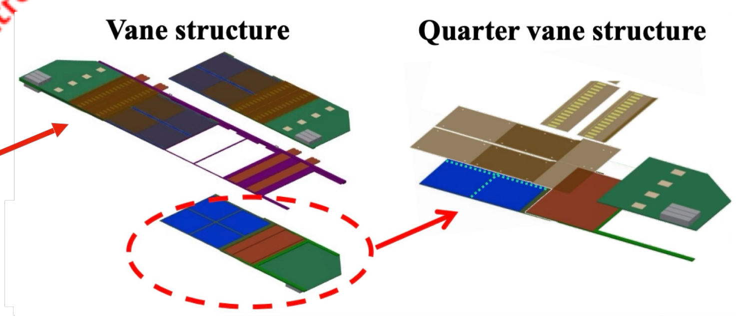
Cross calibration at ANL in January 2019

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 (**512 strips** with **190 µm pitch**)
- 32 Readout ASIC w/ 5nsec sampling rate.



“Prototype quarter-vane”



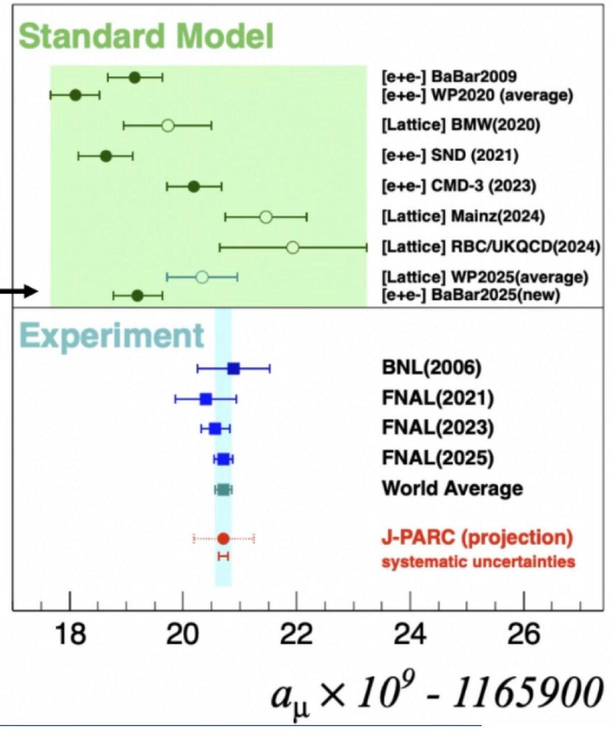
Expected sensitivity - Statistics

- 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 - Systematic

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

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

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

Expected sensitivity comparison with FNAL

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

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

J-PARC – TDR

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$\delta a_{\mu(syst)} \sim$ **78 ppb**

J-PARC – TDR

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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:

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

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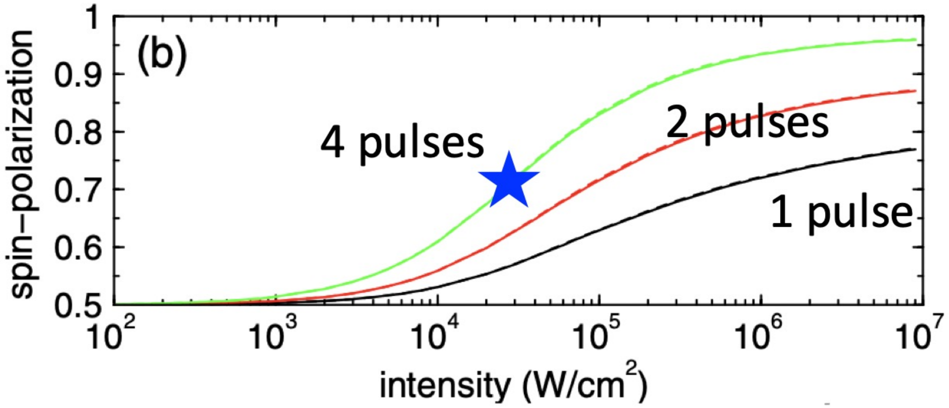
→ Doubling both momentum and field ⇒ **x4** improvement in ω_a precision.

Towards high sensitivity

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

- **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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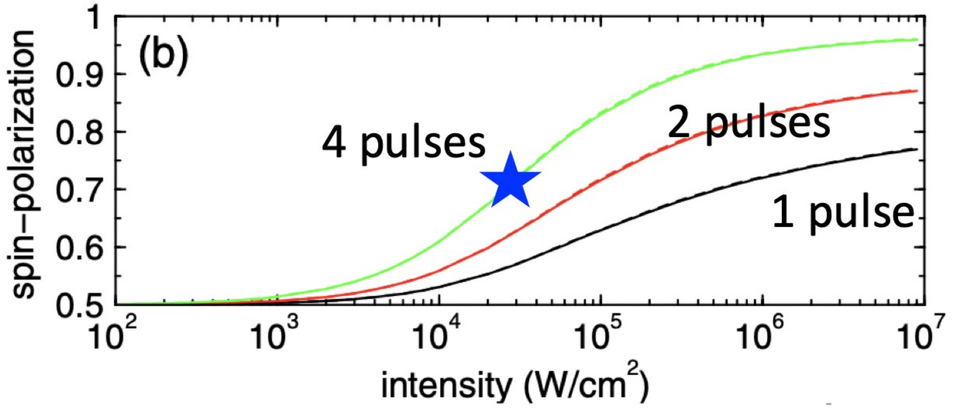
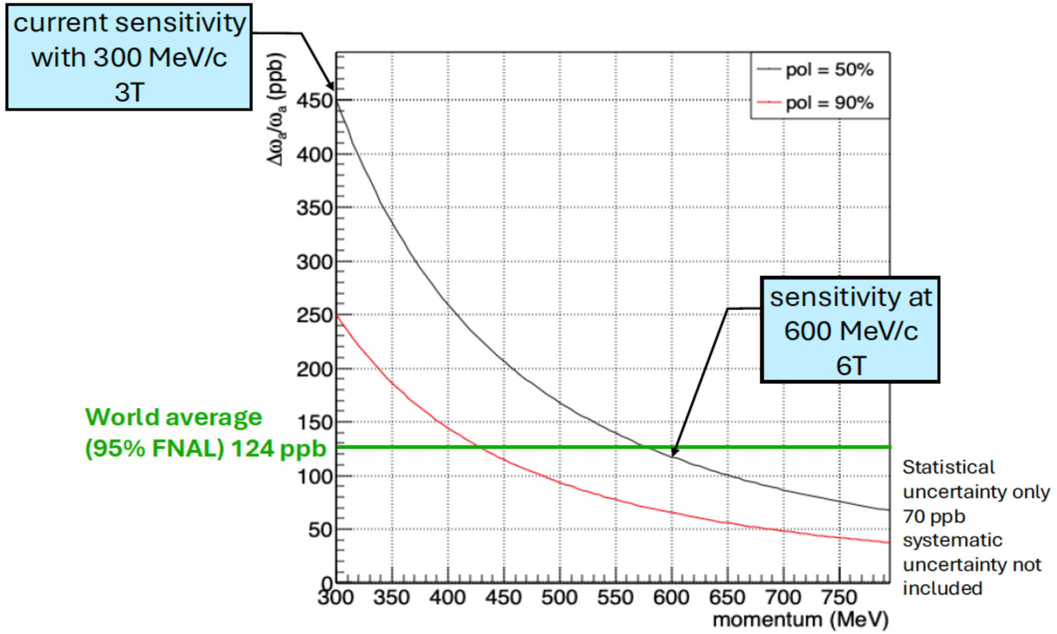


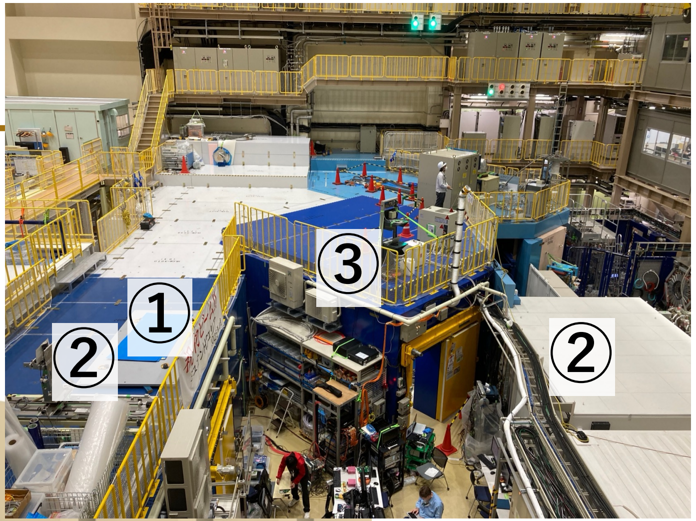
Optical pumping with train of laser pulse

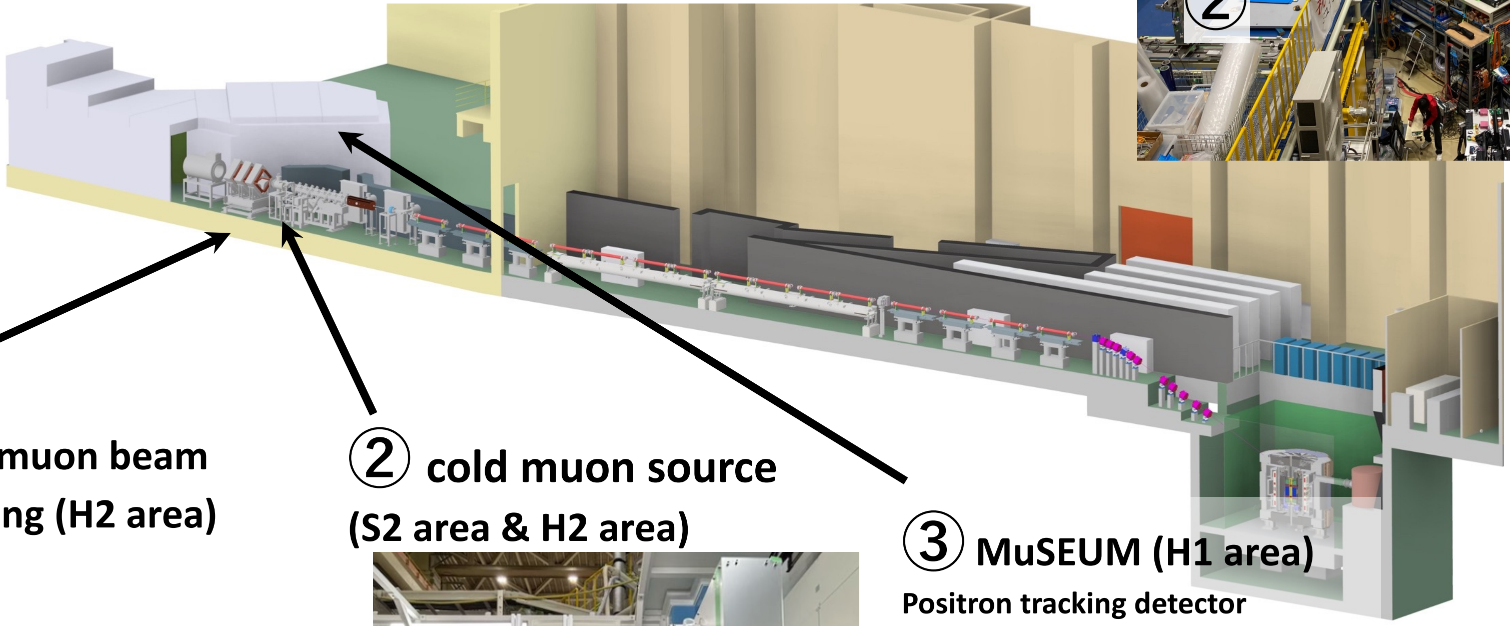
- Here is projected $\frac{\Delta\omega_a}{\omega_a}$ as function of the momentum.
- A task force has been built to check the feasibility:
  - Magnetic field;
  - Linac;
  - Polarization;
  - Other possible improvements.



Running test experiments

Three experiments are currently running at J-PARC MLF since October 29.



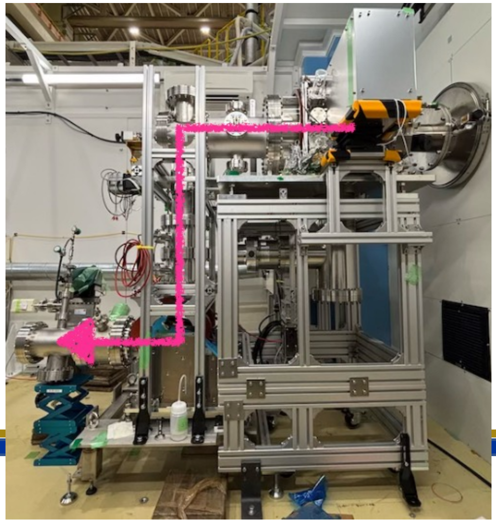


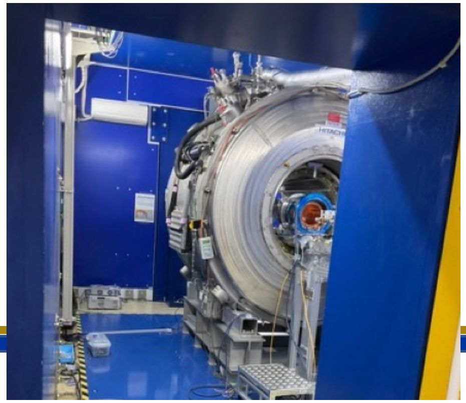
① Surface muon beam commissioning (H2 area)

② cold muon source (S2 area & H2 area)

③ MuSEUM (H1 area)

Positron tracking detector





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 to a turning point towards Fermilab precision.
- 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!

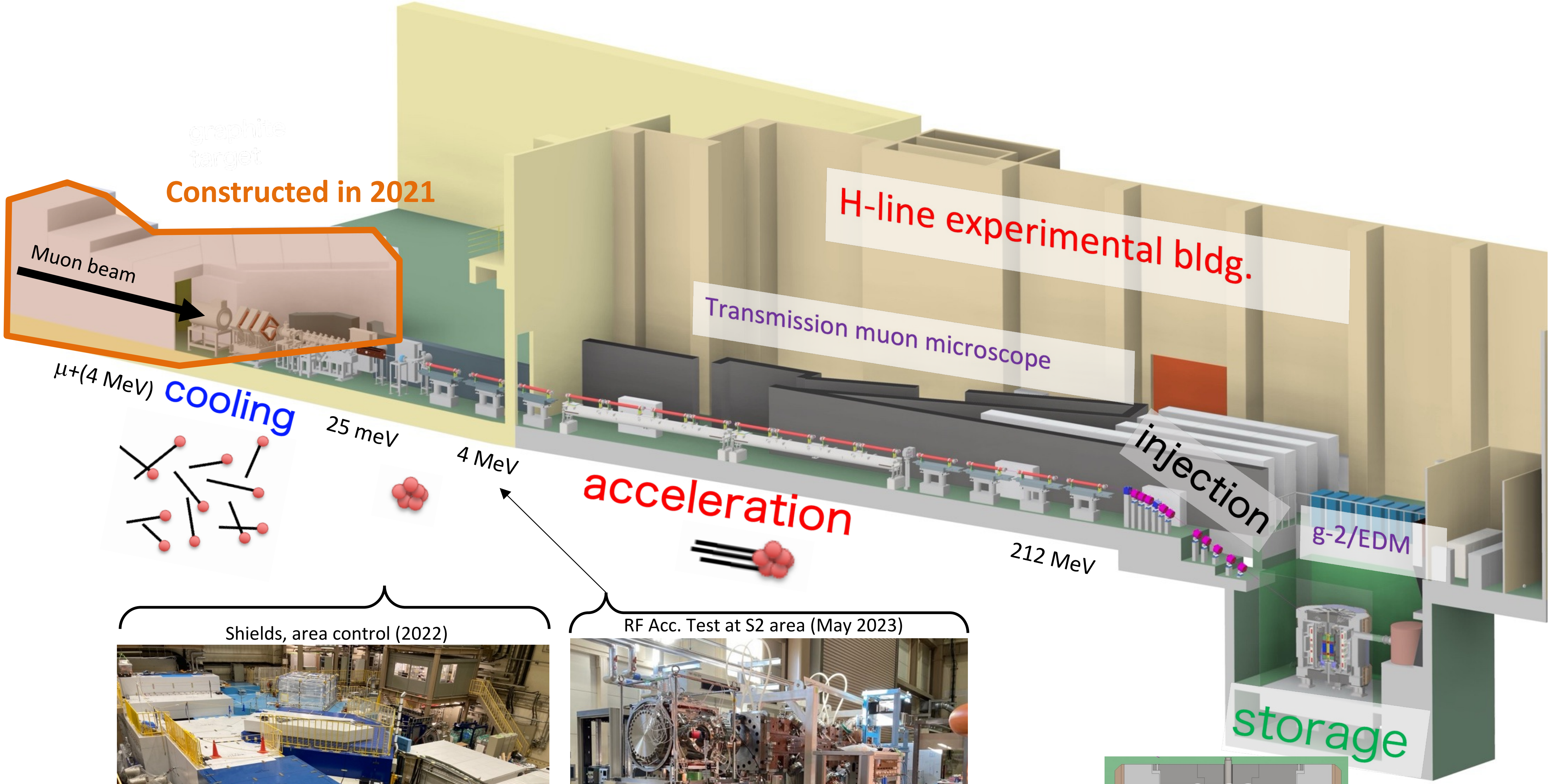
Ph. Stella Critelli

BACK-UP

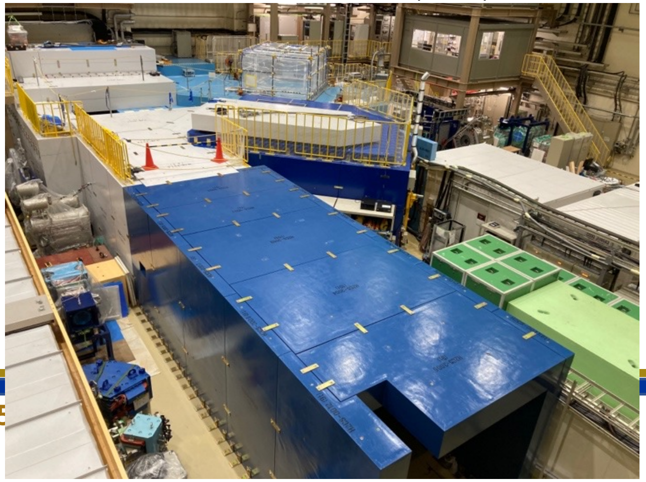
Comparison with Fermilab

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_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



Shields, area control (2022)



RF Acc. Test at S2 area (May 2023)