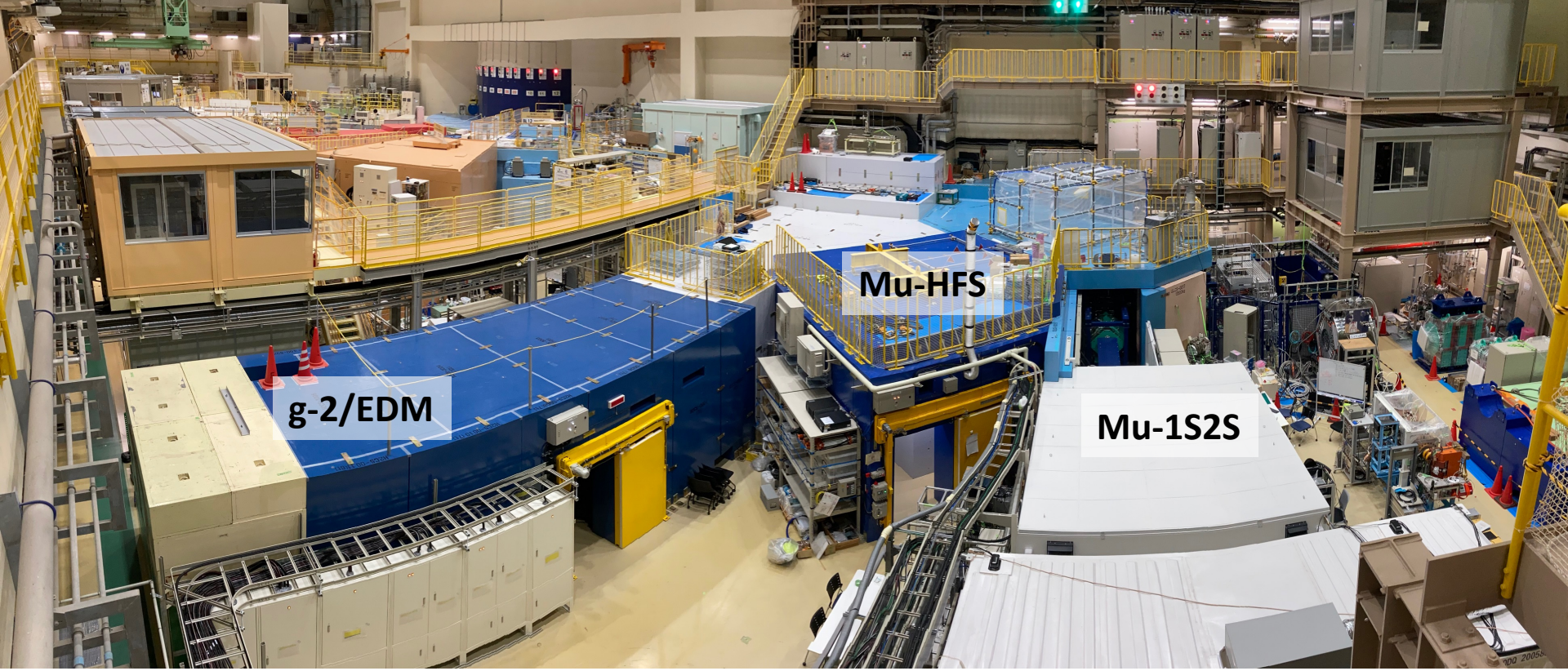
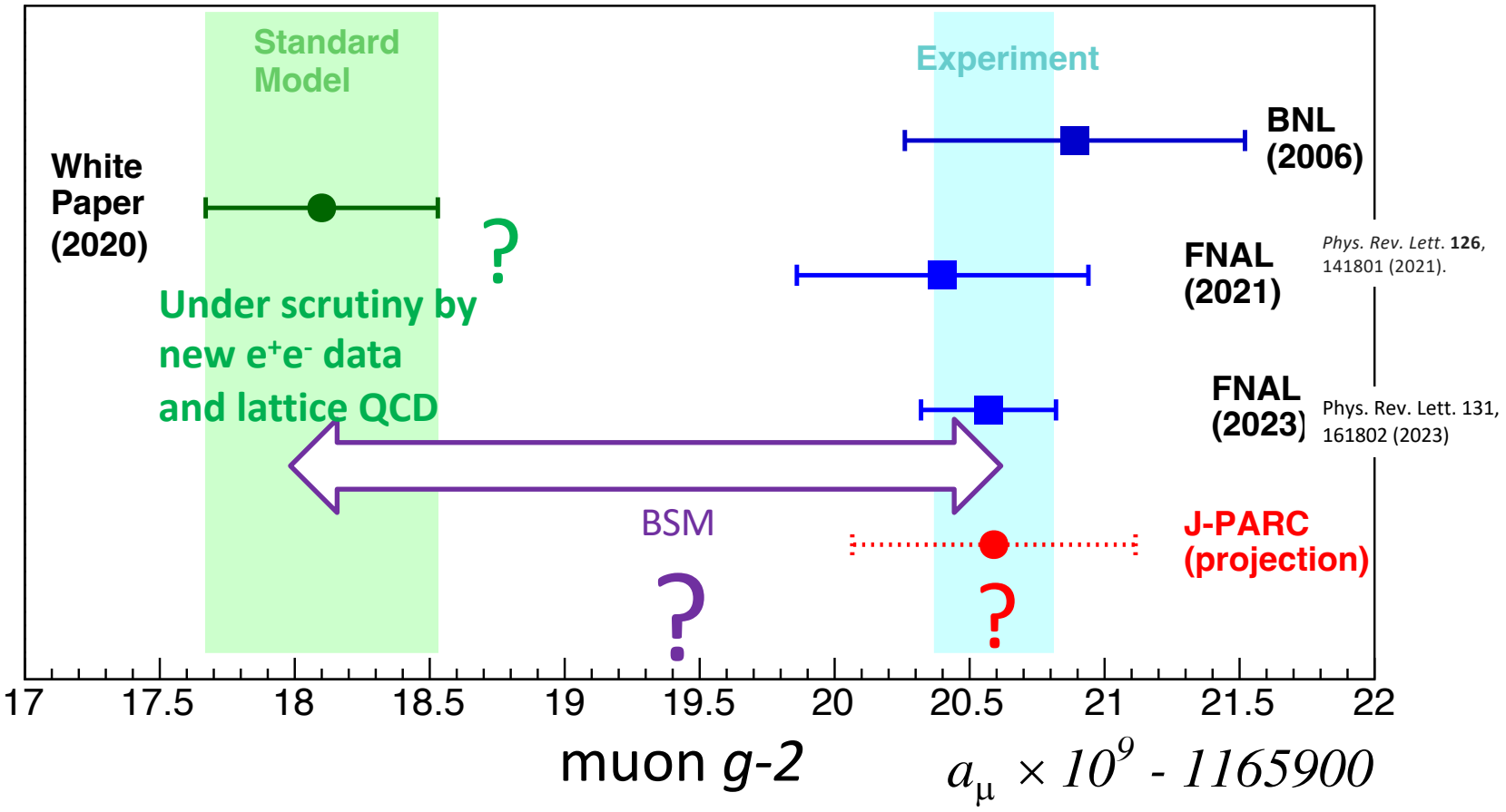


Muon acceleration and muon g-2, EDM at J-PARC

Muons in Minneapolis, December 6, 2023

Tsutomu Mibe (KEK IPNS)
on behalf of the J-PARC muon g-2/EDM collaboration

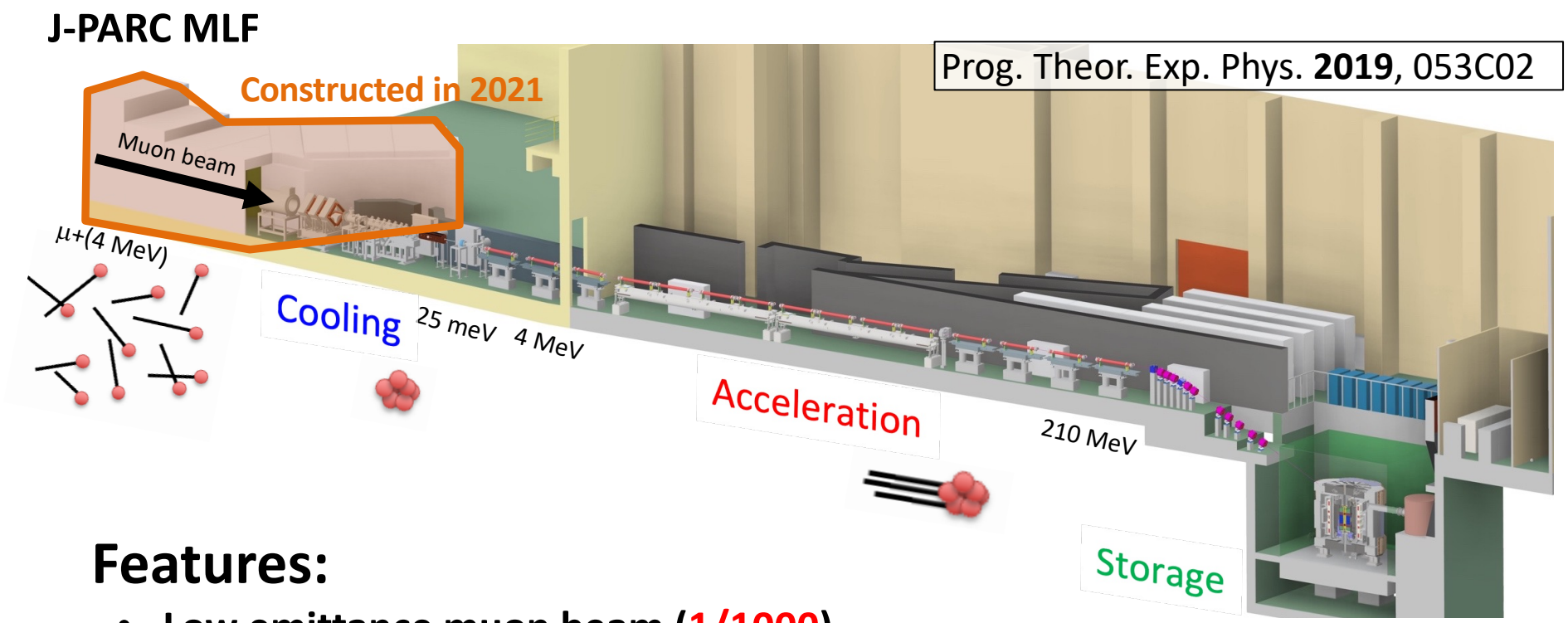
Muon anomalous magnetic moment g_μ-2 4



If the muon *g*-2 anomaly persists, next step is to understand **the origin of the anomaly**.

Muon EDM offers a way to study **time reversal symmetry of BSM**.

J-PARC muon *g*-2/EDM experiment 5



Features:

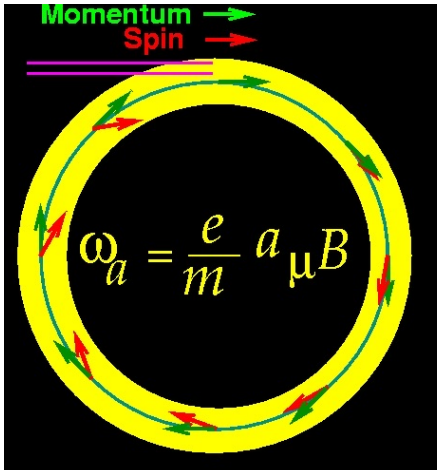
- **Low emittance muon beam (1/1000)**
- **No strong focusing (1/1000) & good injection eff. (x10)**
- **Compact storage ring (1/20)**

The only experiment to check FNAL/BNL *g*-2 results

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

muon *g*-2 and EDM measurements 6

In uniform magnetic field, muon spin rotates ahead of momentum due to *g*-2 = 0



Spin precession vector w.r.t momentum :

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

g-2 precession in B-field

g-2 precession in motional B-field

EDM precession

BNL/FNAL approach
γ=30 (P=3 GeV/c)

J-PARC approach
***E* = 0 at any γ**

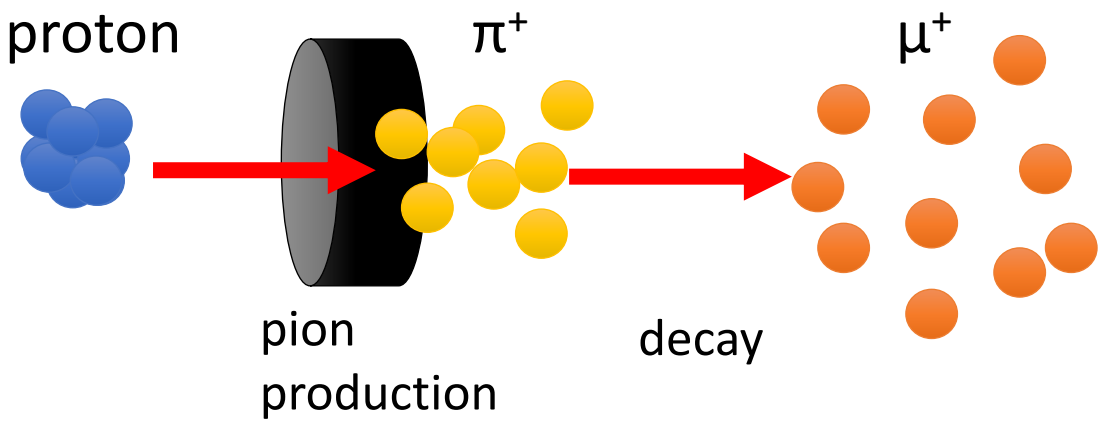
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

BNL & FNAL E989

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

J-PARC E34

Conventional muon beam



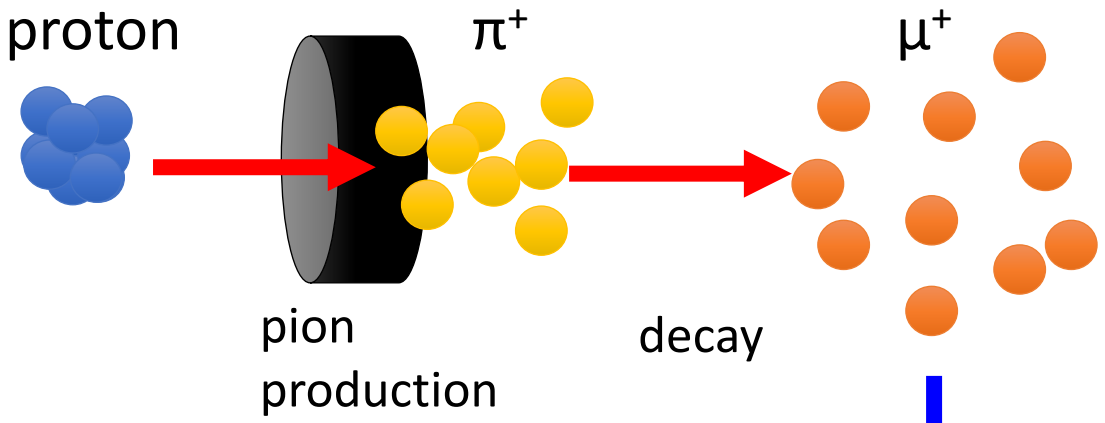
emittance

~1000π mm ·mrad

Strong focusing
Muon loss
BG π contamination

Source of systematic uncertainties

Muon beam at J-PARC



emittance
~1000π mm･mrad

Strong focusing
Muon loss
BG π contamination

Source of systematic uncertainties

cooling

μ+

emittance
1π mm･mrad

Reaccelerated thermal muon

Free from any of these

EDM and radial magnetic field

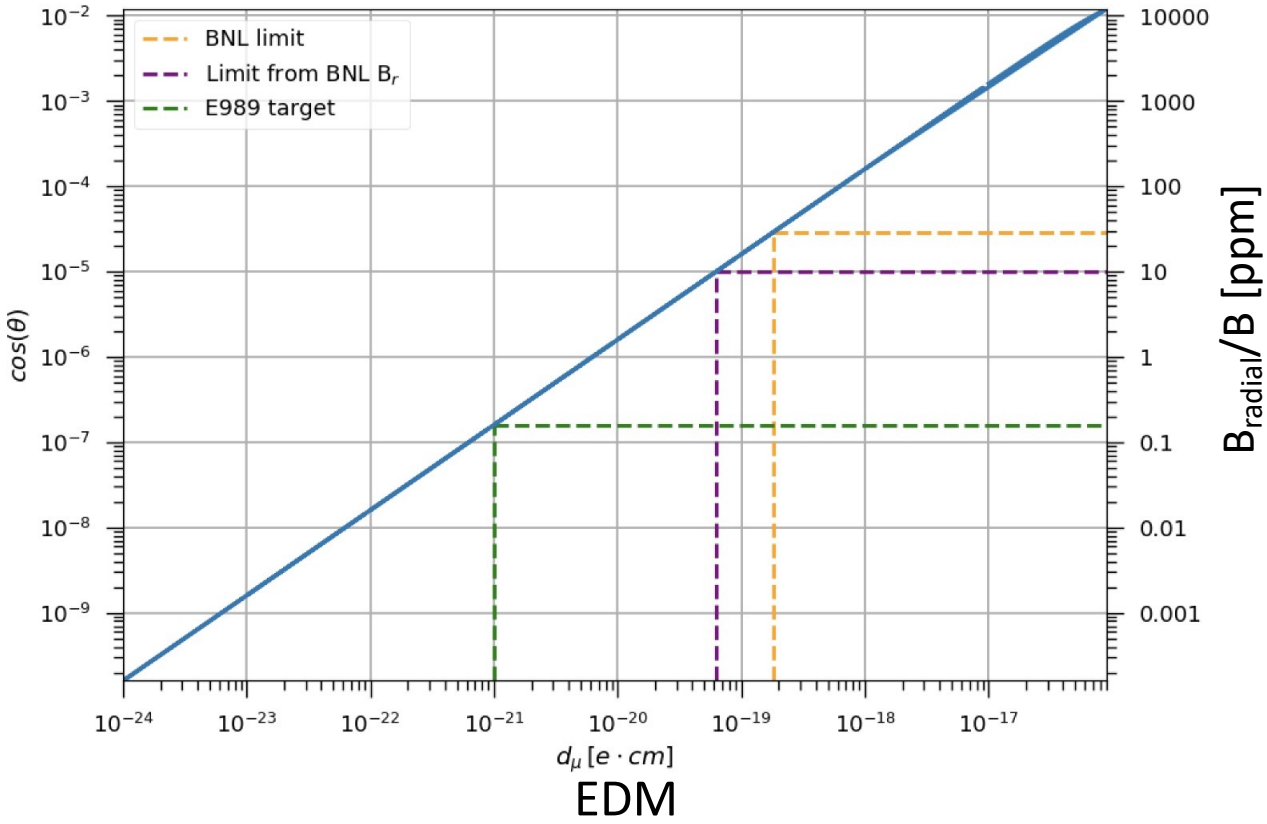
- **Radial magnetic field** can be a major source of systematics on EDM since the *g*-2 term mixes to the EDM term.

g-2 precession >> EDM precession

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

$$\vec{B} = \vec{B}_{axial} + \vec{B}_{radial}$$

plot from Joe Price (muEDM workshop at PSI)



B_{radial} supposed to be one of the dominant systematic uncertainties for FNAL E989

Very weak magnetic focusing

- FNAL/BNL g-2 exps use electric weak focusing (n ~0.1)

- We adopt **Very weak magnetic focusing**
  - Bill Morse, Yannis Semertizdis (2010)
  - Field index n = 1E-4 (1ppm/cm)

  - **Vertical position of muon beam will be self-adjusted to find $B_r = 0$**

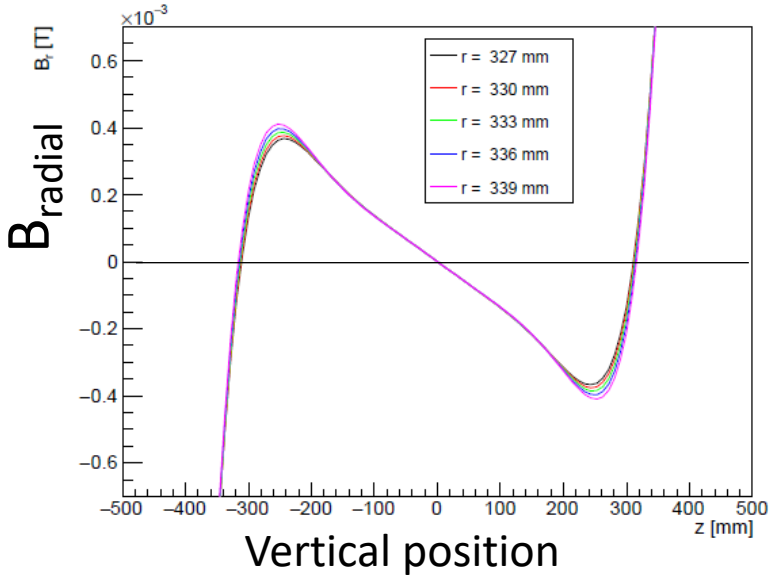
  → no systematics associated with B_{radial}

  - Also very powerful to **suppress the "pitch effect" on g-2** (~10 ppb).

Weak focusing B-field

$$B_r = -n\frac{B_{0z}}{R}z,$$

$$B_z = B_{0z} - n\frac{B_{0z}}{R}(r-R) + n\frac{B_{0z}}{2R^2}z^2$$



The collaboration

114 members from Canada, China, Czech, France, India, Japan, Korea, Netherlands, Russia, USA

Collaboration board (CB)
Chair: Seonho Choi

Executive board (EB)
Spokesperson: T. Mibe

Subgroups | **Interface coordinators** | **Committees**


Surface muon beam
leader: T. Yamazaki, N. Kawamura

Ultra-slow muon
leader: K. Ishida

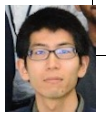
LINAC
leader: M. Otani

Injection and storage
leader: H. Iinuma

Storage magnet, field measurements
leader: K. Sasaki

Detector
leader: T. Yoshioka

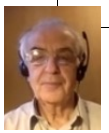
DAQ and computing
leader: Y. Sato



Analysis
leader: T. Yamanaka

K. Ishida
M. Otani
Y. Kondo
H. Iinuma
T. Kume
Y. Sato
T. Suehara
T. Yamanaka

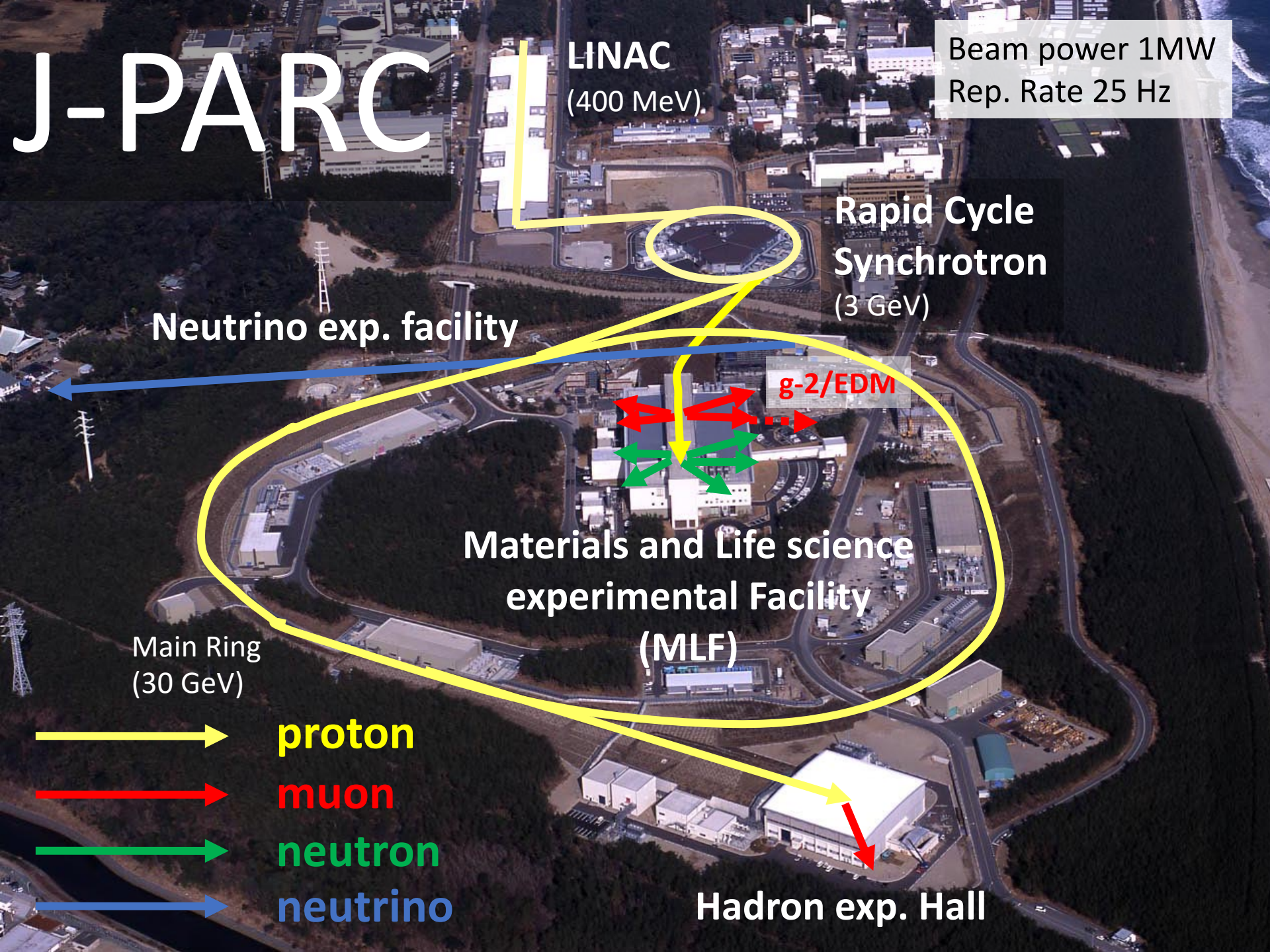
Speakers committee
chair: K.Ishida



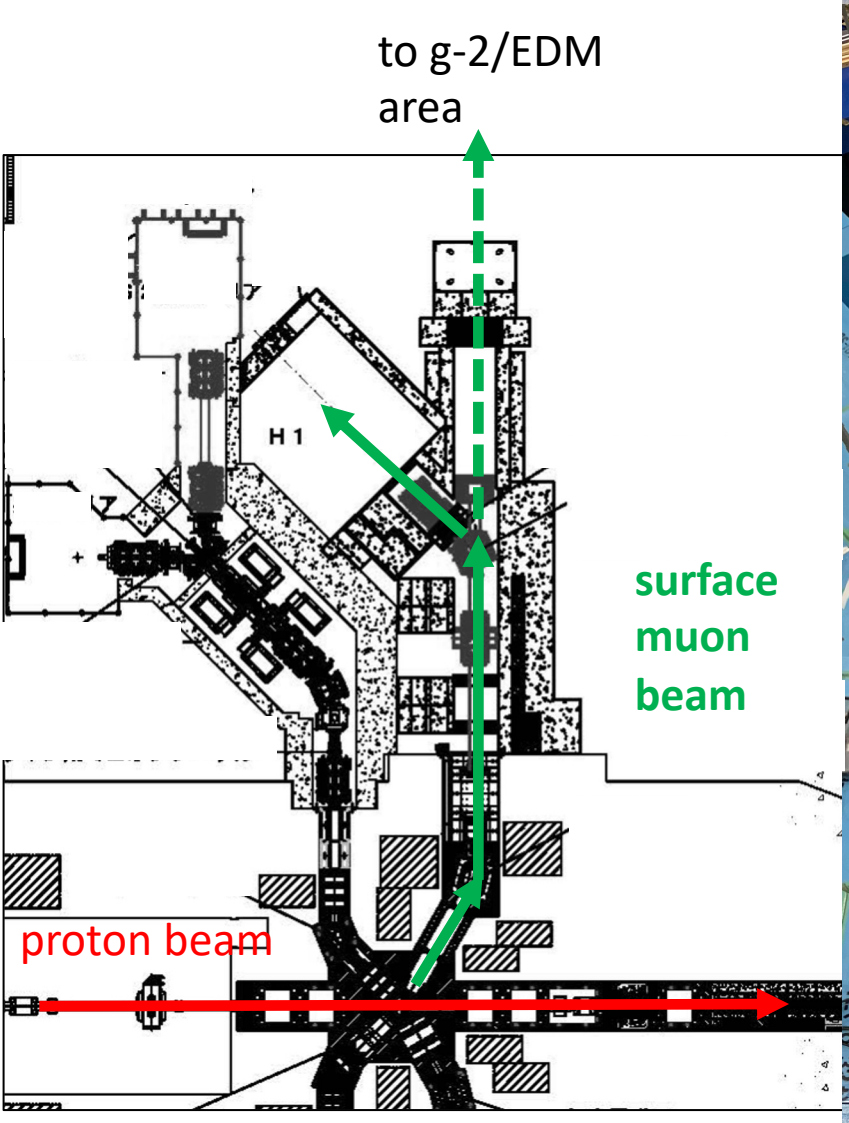
Publication committee
chair: B. Shwartz

Domestic institutes：
Kyushu, Nagoya, Tohoku, Niigata, Toyama C, Tokyo, Ibaraki, RIKEN, JAEA, etc.
KEK: IPNS, IMSS, ACC, CRY, MEC, CRC

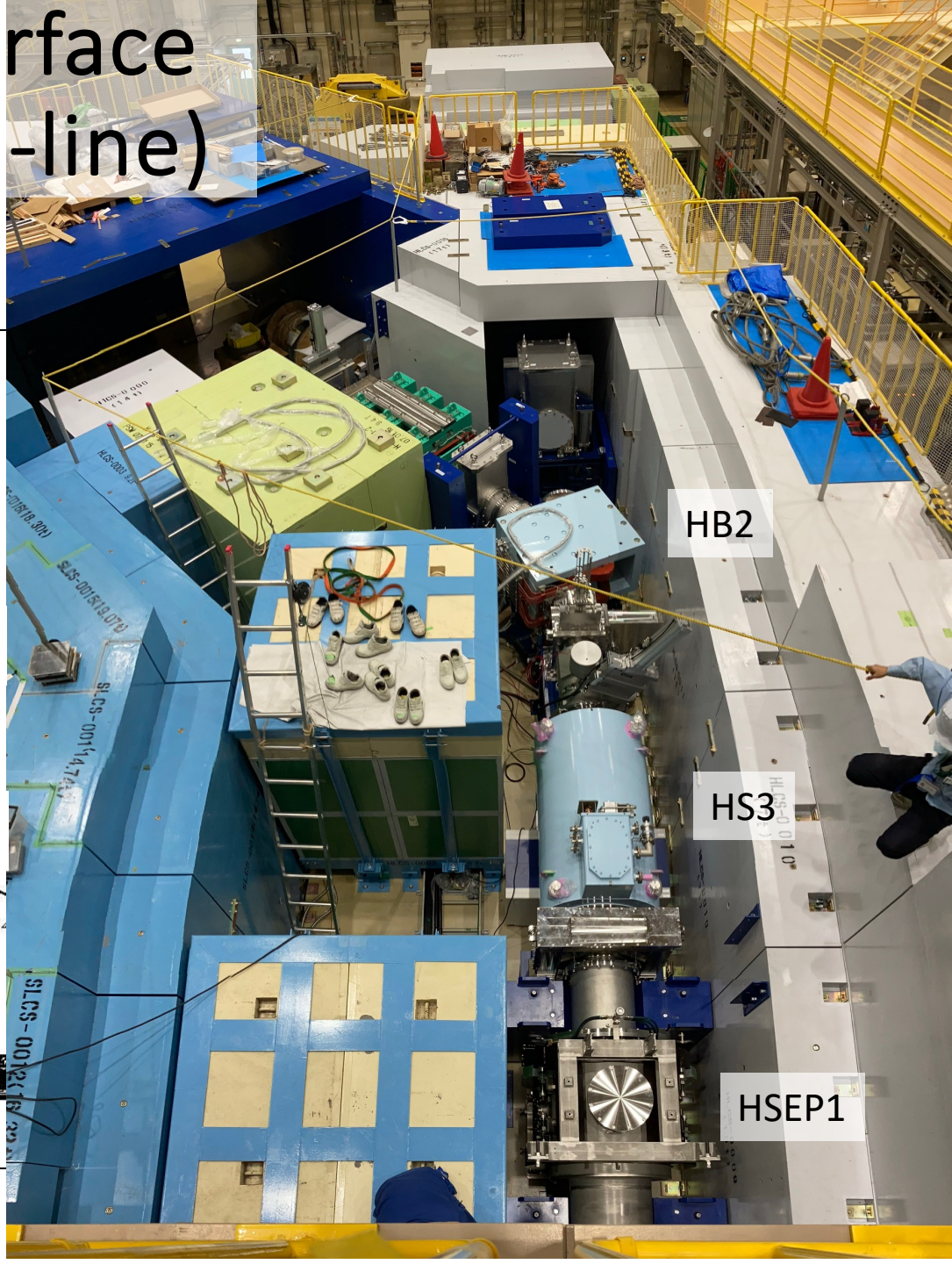
Mini-school for newcomers hosted by Niigata university in June 8-9, 2022


J-PARC
LINAC
(400 MeV)
Beam power 1MW
Rep. Rate 25 Hz
Rapid Cycle
Synchrotron
(3 GeV)
Neutrino exp. facility
g-2/EDM
Materials and Life science
experimental Facility
(MLF)
Main Ring
(30 GeV)
proton
muon
neutron
neutrino
Hadron exp. Hall

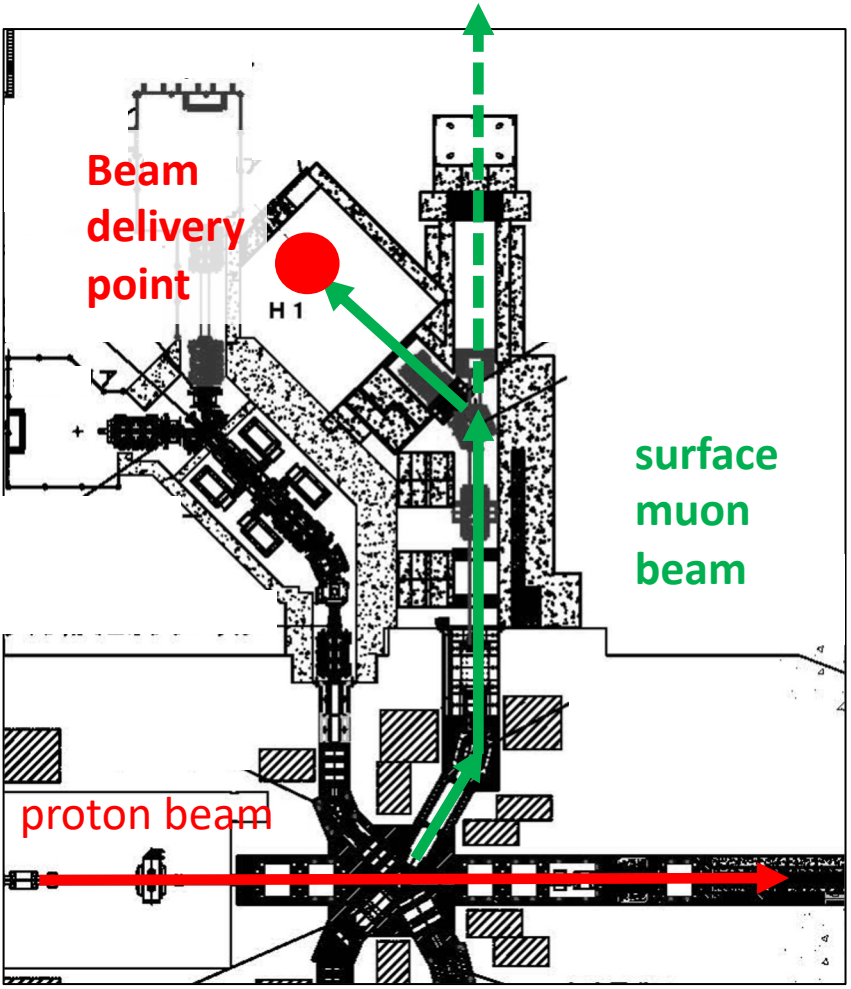
Construction of surface muon beamline (H-line)



Prog. Theor. Exp. Phys. 2018, 113G01

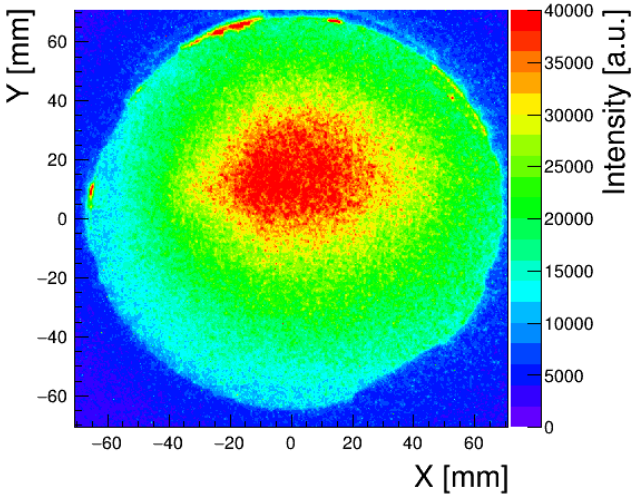


First beam to H1 area (Jan 15, 2022)



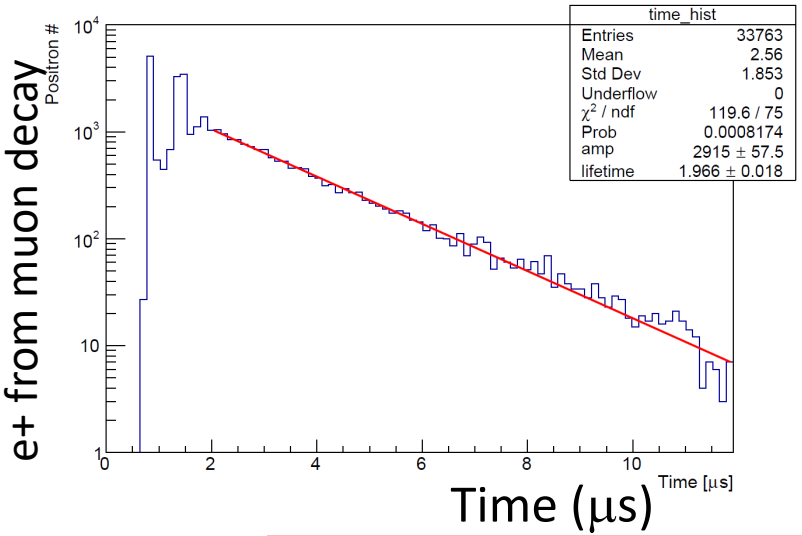
Prog. Theor. Exp. Phys. 2018, 113G01

Beam profile



σ_x = 44 mm

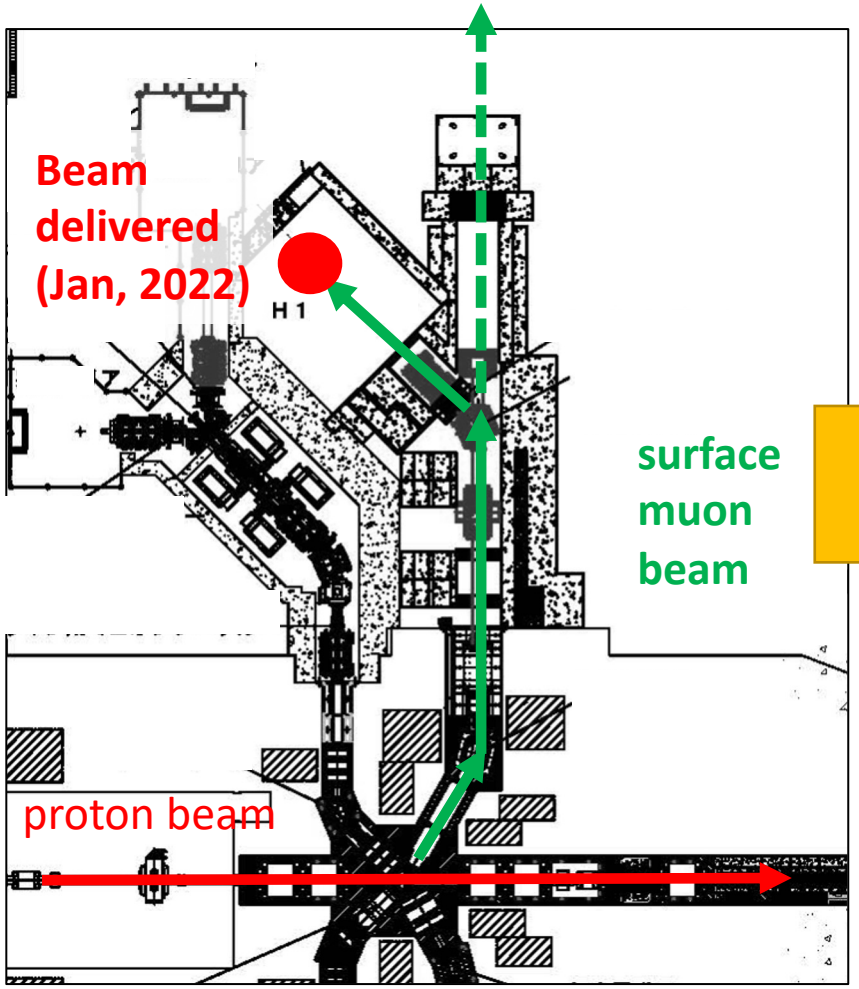
σ_y = 24 mm



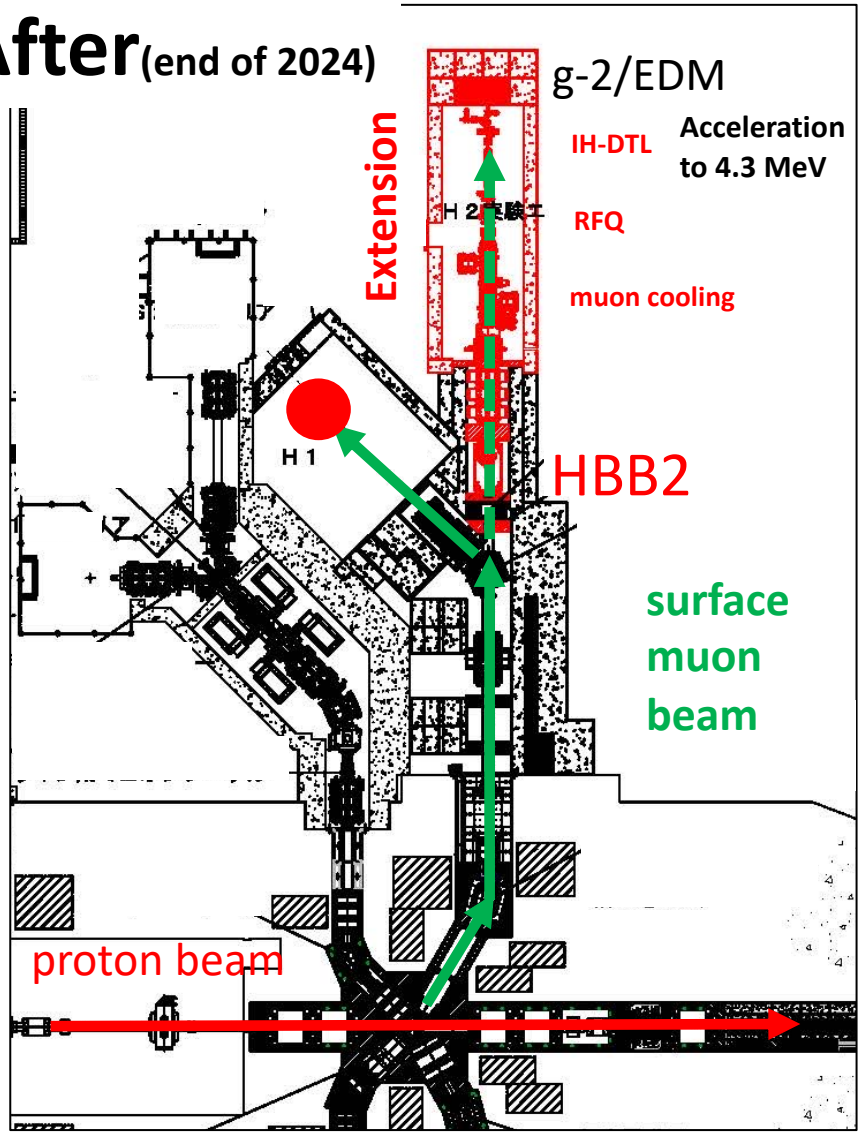
7 x 10^7/sec@p=28 MeV/c, 730kW
→ consistent with expectation

H-line extension

Before

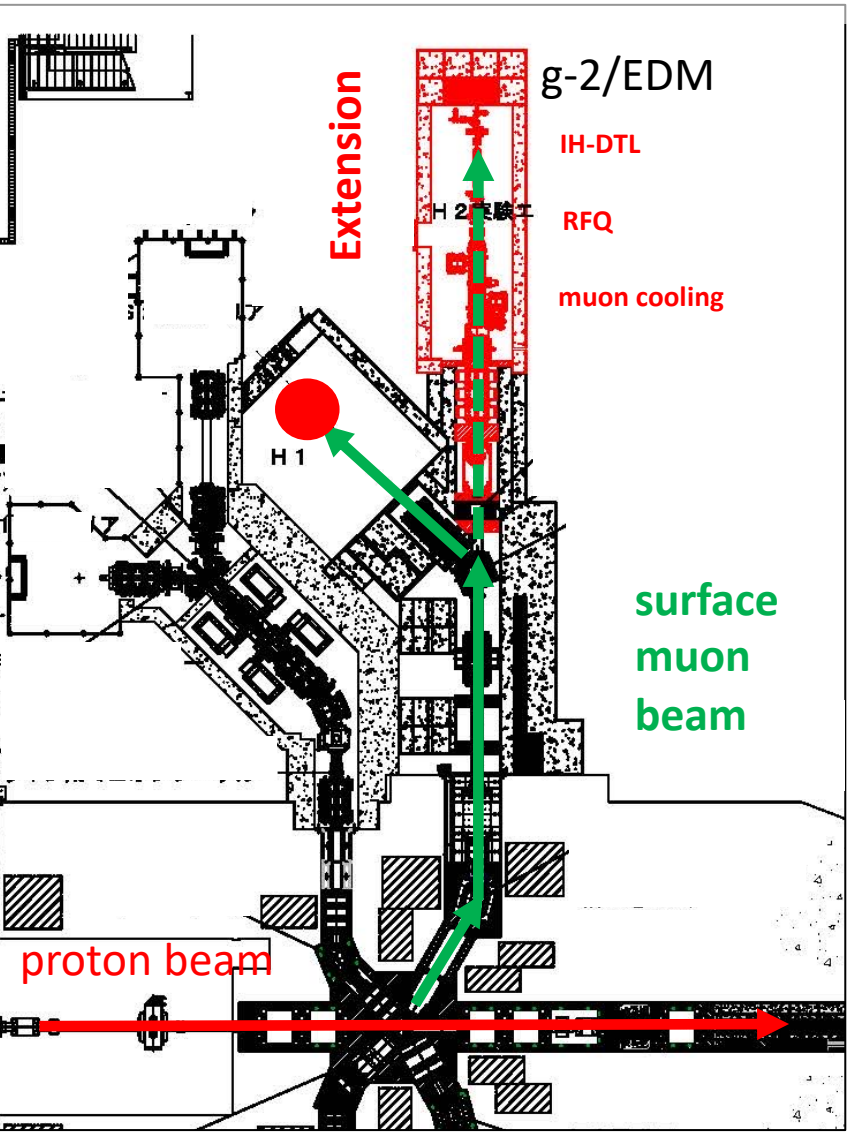


After (end of 2024)



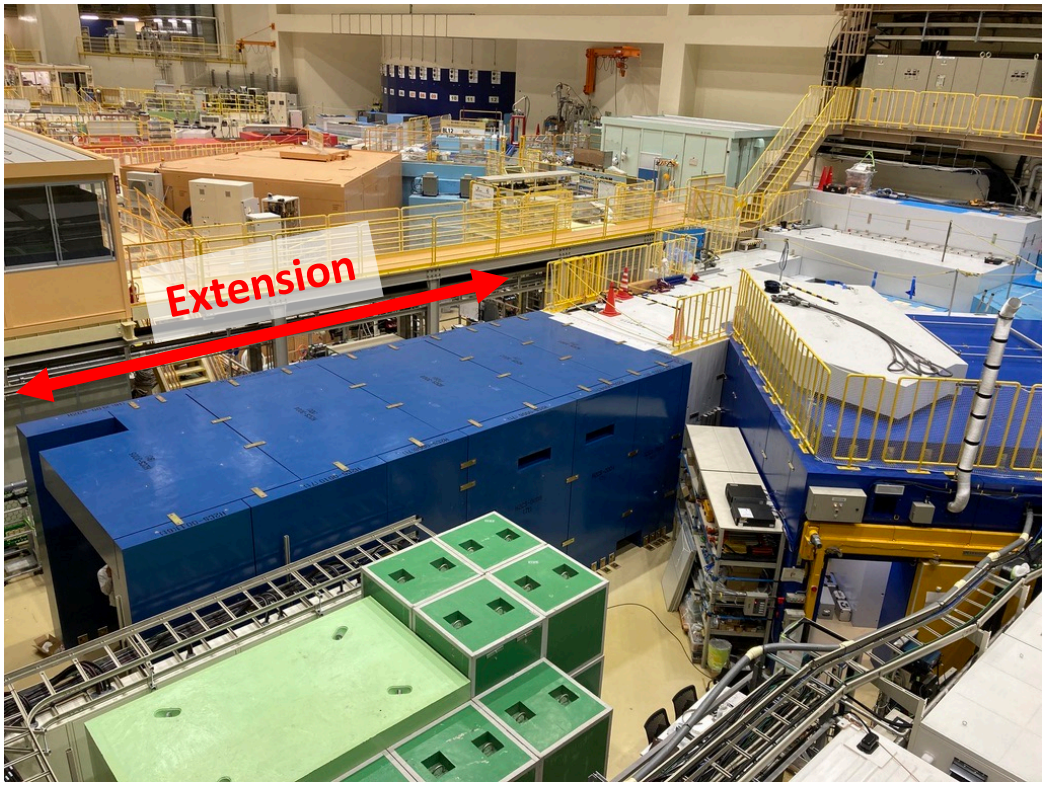
Prog. Theor. Exp. Phys. 2018, 113G01

Extension of H-line



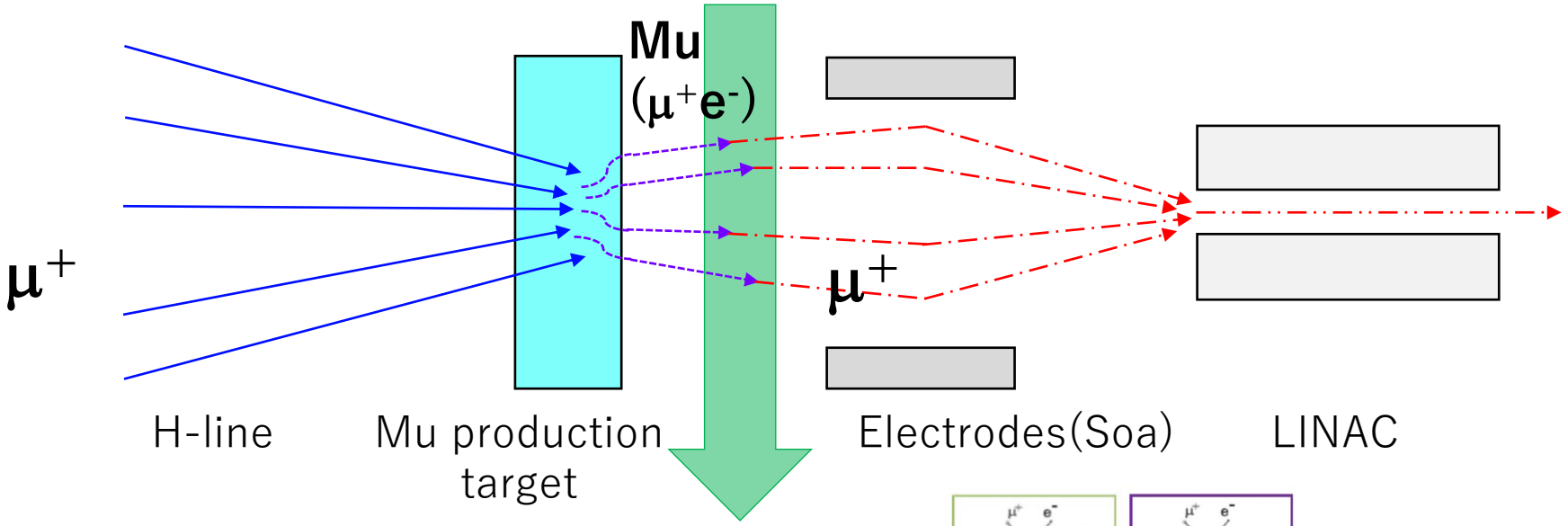
Prog. Theor. Exp. Phys. 2018, 113G01

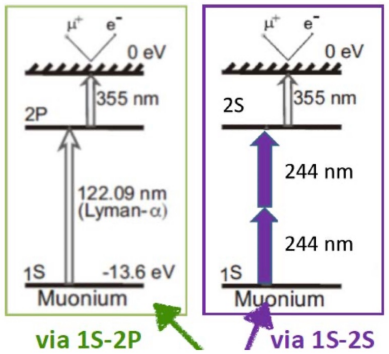
Assembled radiation shields for extension (Oct 15, 2022)



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
Δ p/p	0.05	0.4	4×10^{-4}





Muonium : a bound state of μ^+ and e^-

Muon cooling

Silica aerogel with laser-ablated holes (SiO_2, 30 mg/cc)

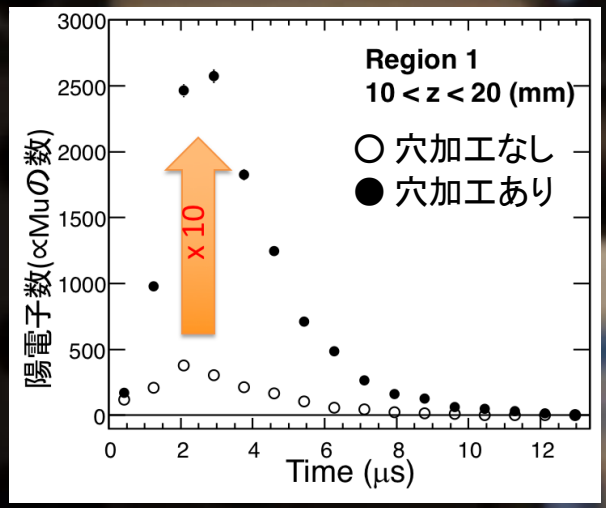
Muonium (μ^+e^-)
30 meV（after cooling）

Electron will be removed by
Laser resonant ionization by irradiating
Laser beam (122nm+355nm)

Muon Beam
4 MeV
（before cooling）

μ+

8 mm



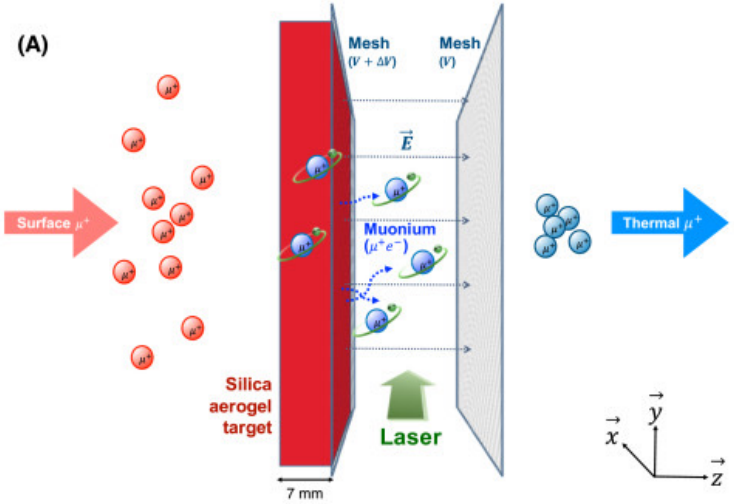
Hot muon

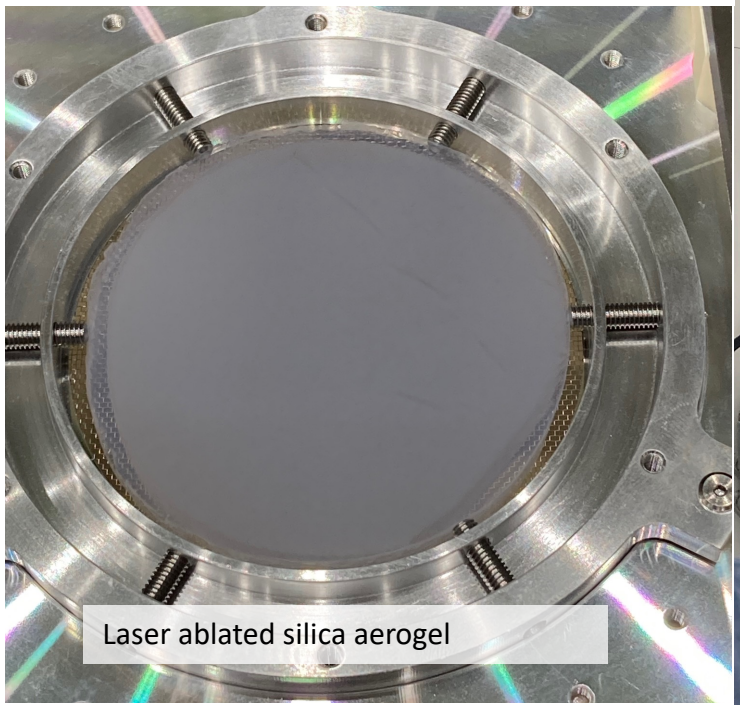
Coldmuon

Experiments at TRIUMF
（2011, 2013, 2018）

Muon cooling test (since Feb 2023)

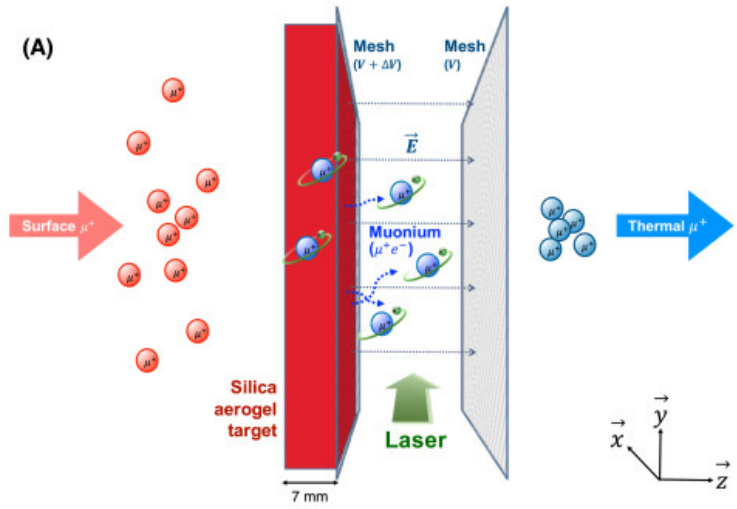
J-PARC S2 area



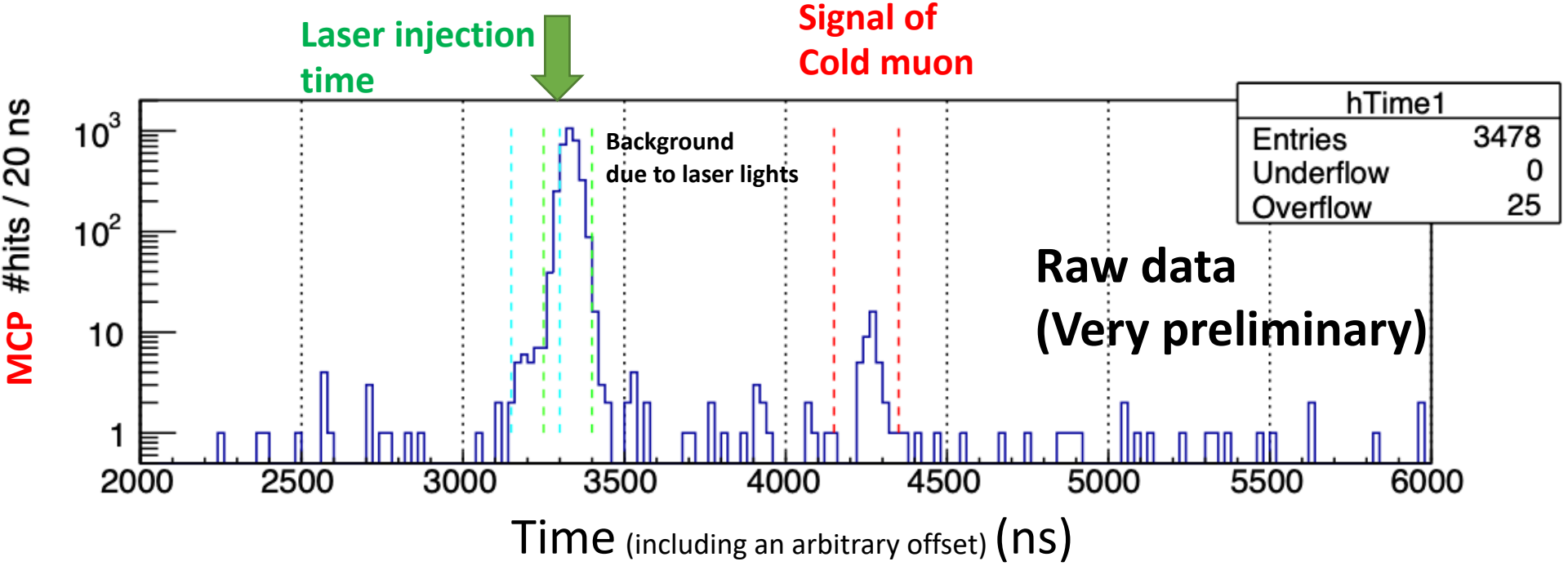


Laser ablated silica aerogel

Muon cooling test (since Feb 2023)



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



Assembly test completed (Dec. 2022)

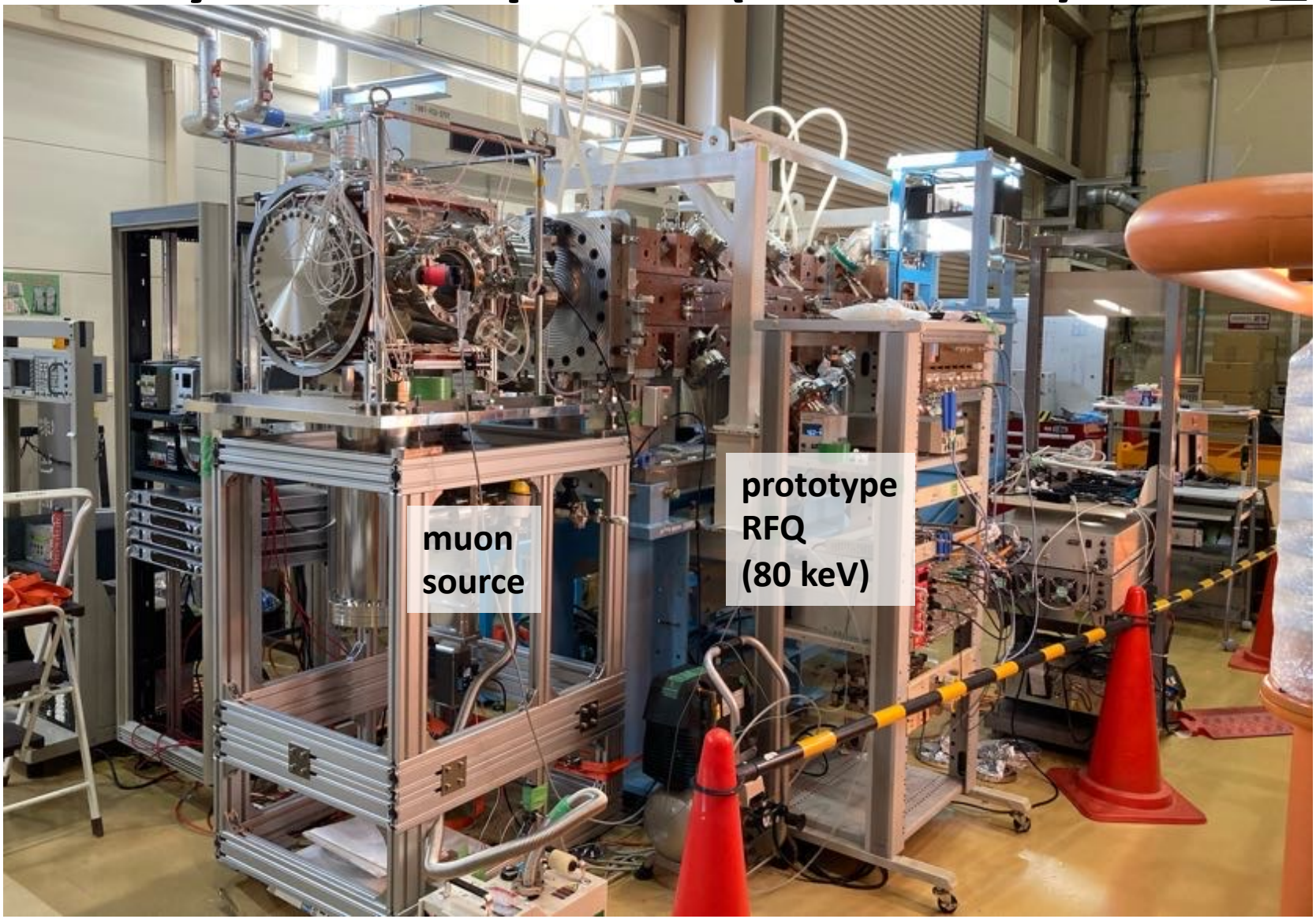


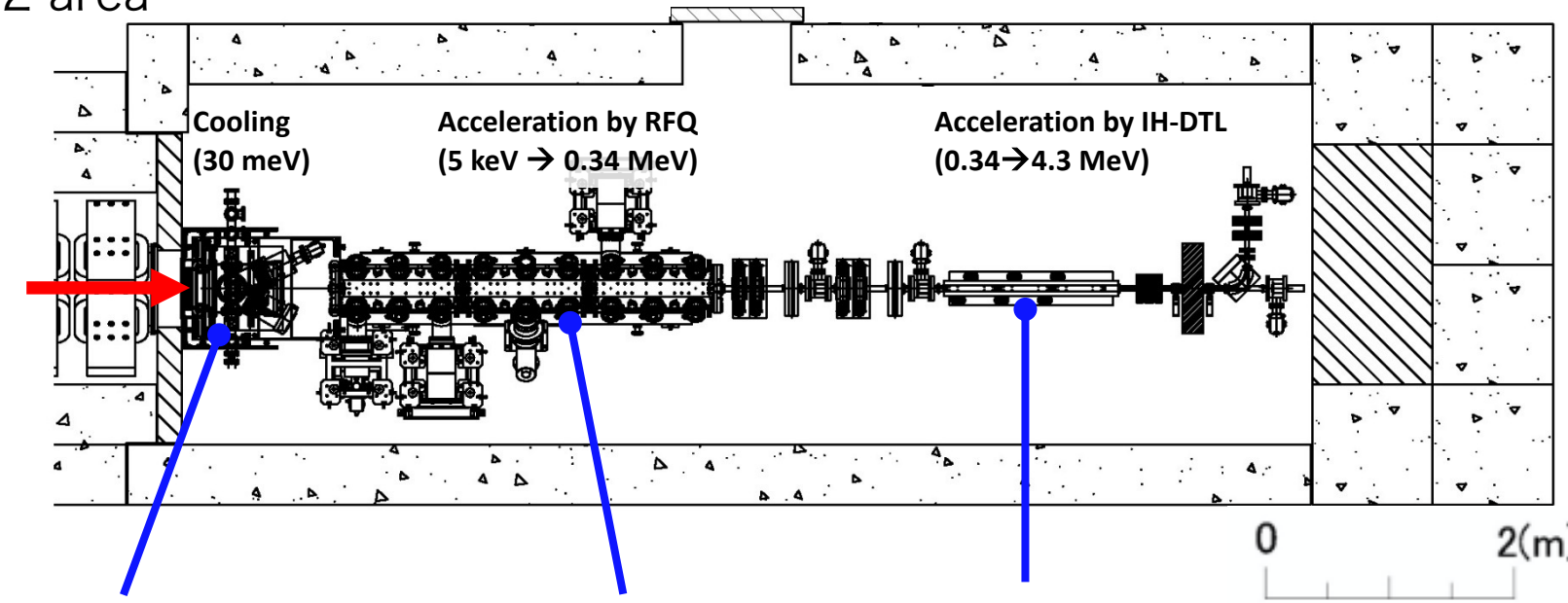
Photo by M. Yotsuzuka

To be installed to S2 area for the beam time in 2023

Muon cooling and acceleration @H2

FY2025

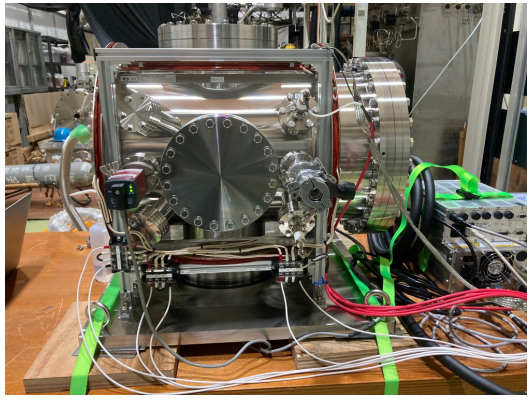
H2 area



Mu production chamber
(available)

J-PARC LINAC
RFQ (available)

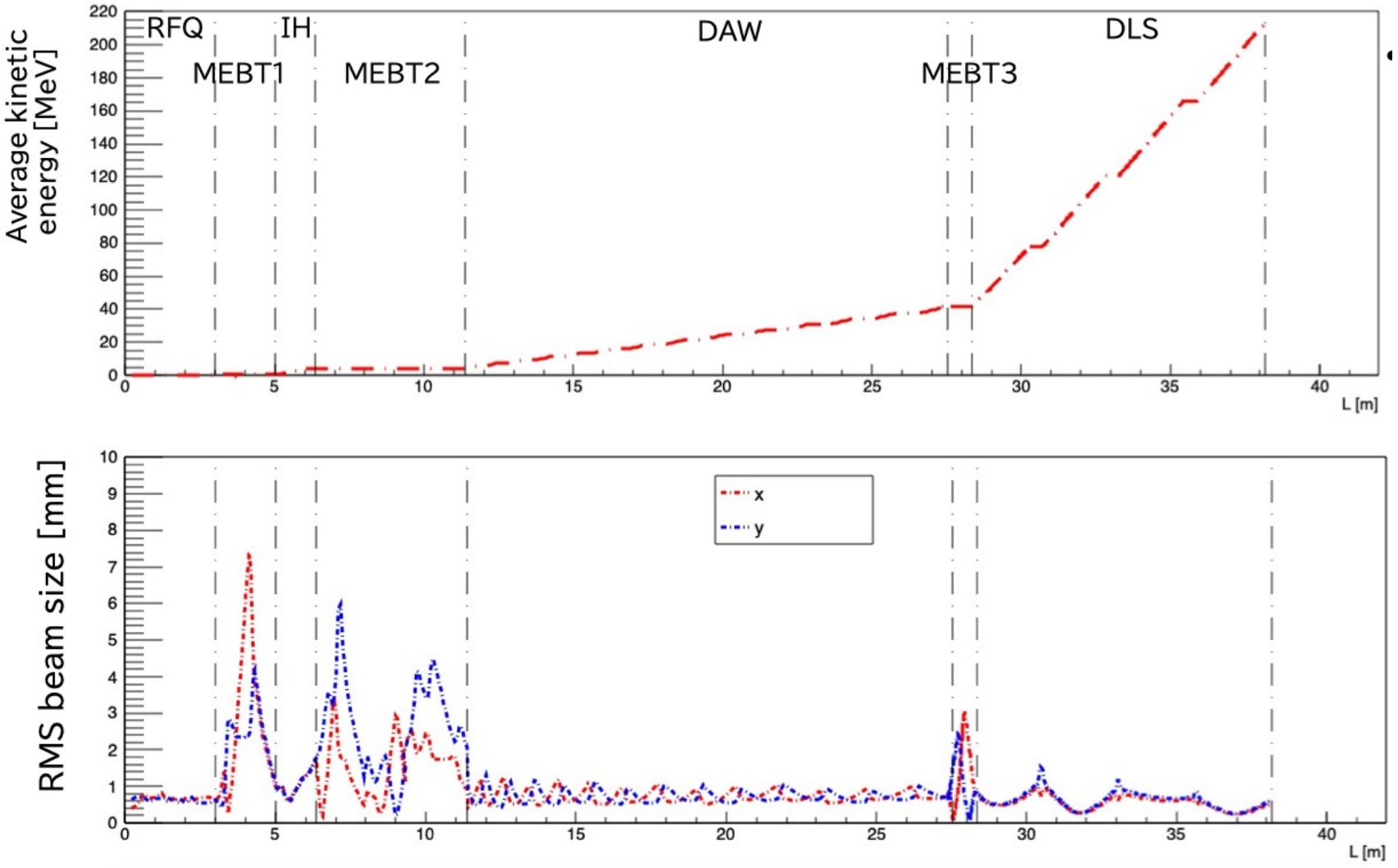
IH-DTL
(fabricated and evaluated in FY2022)



Start-to-end simulation

Simulated beam in the muon LINAC

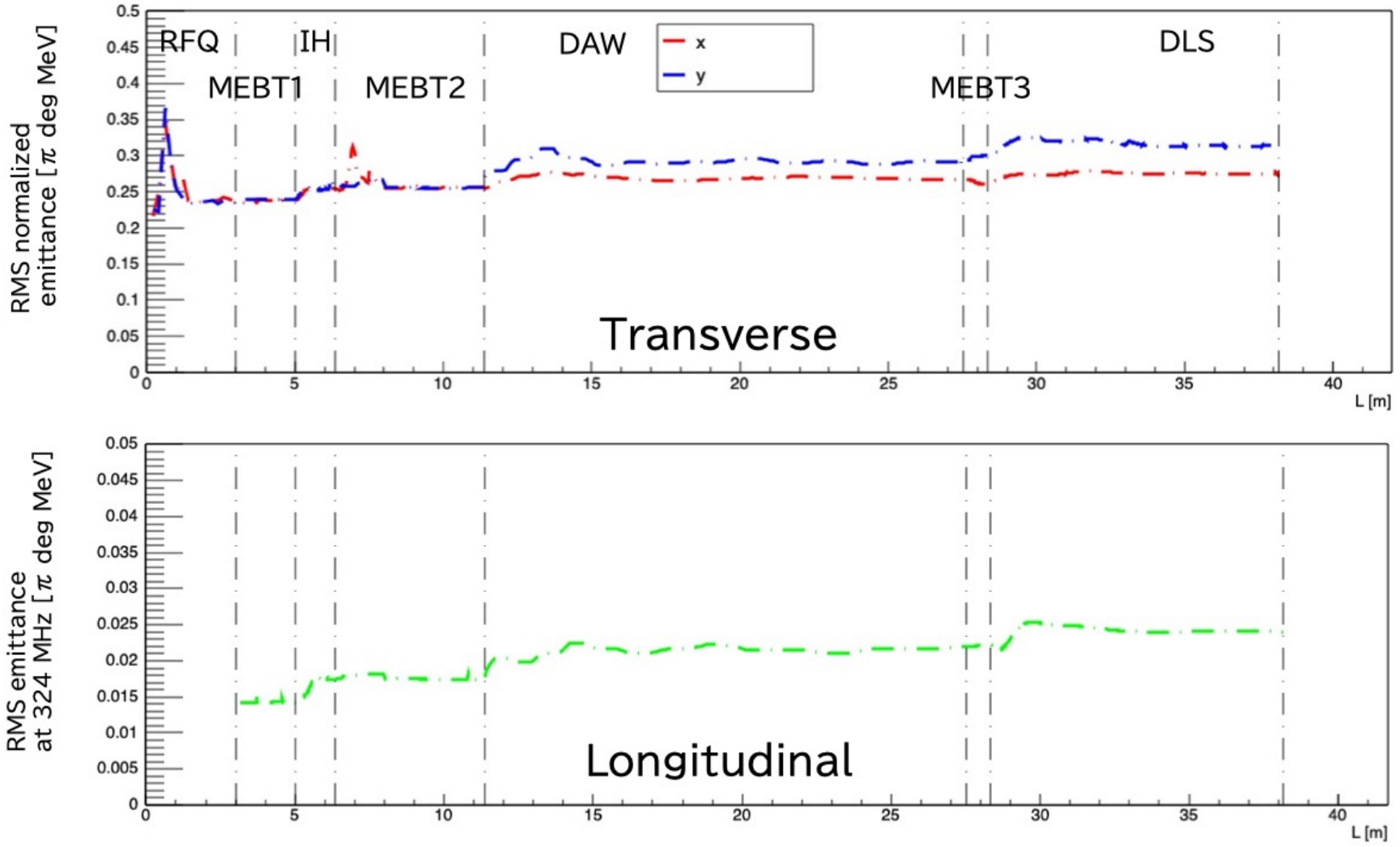
Y. Takeuchi



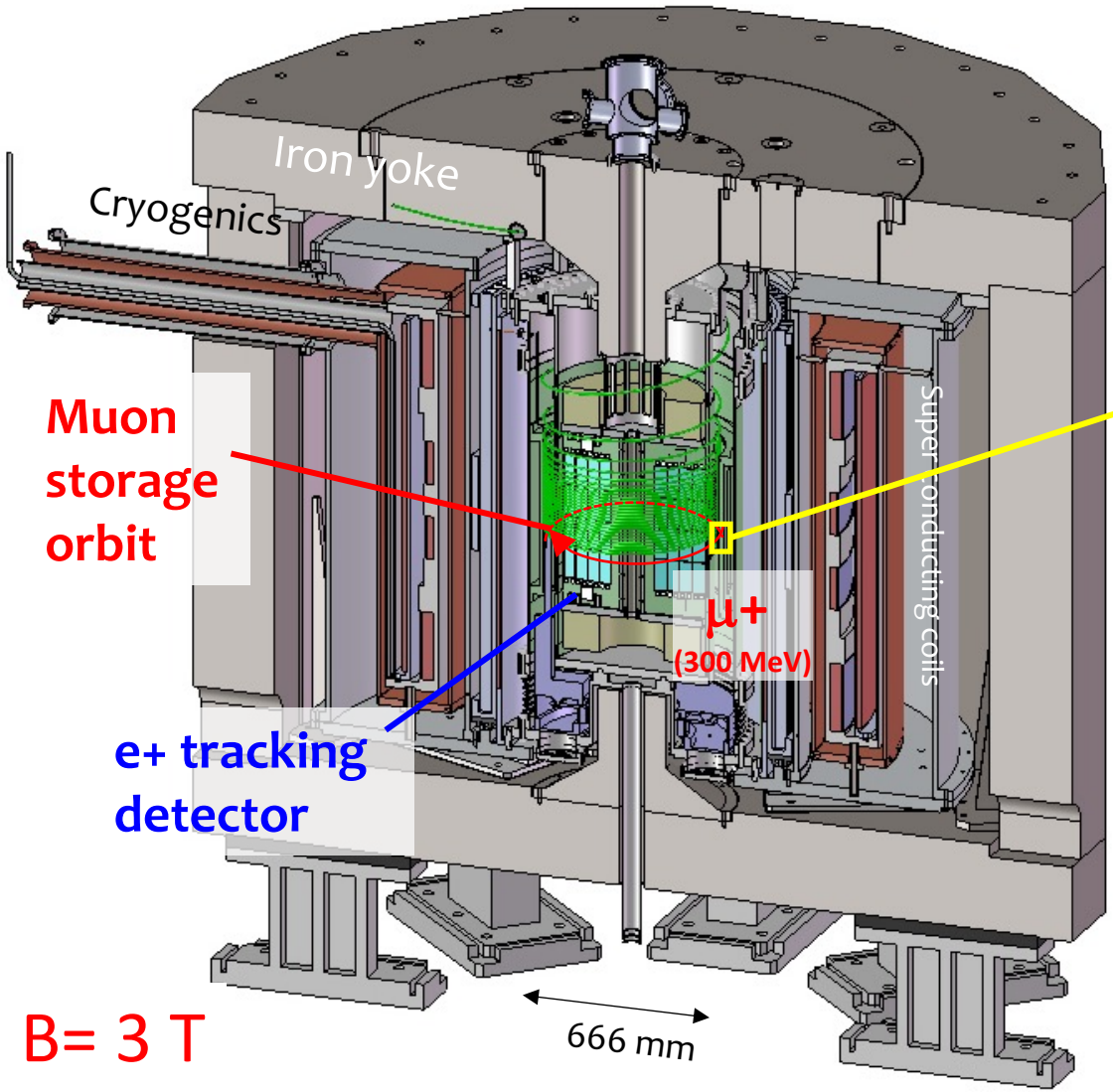
Start-to-end simulation

Simulated beam in the muon LINAC

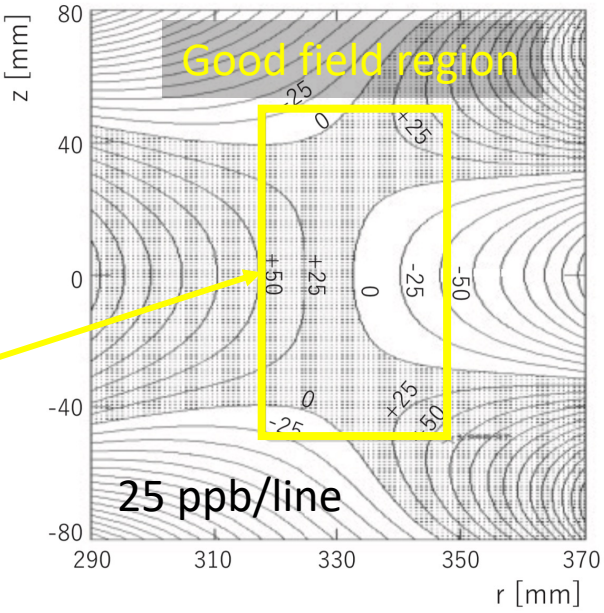
Y. Takeuchi

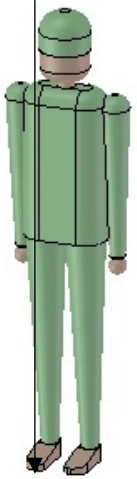


Muon storage magnet and detector

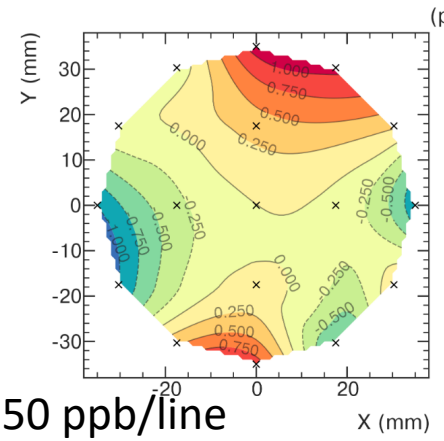


Calculated average field uniformity



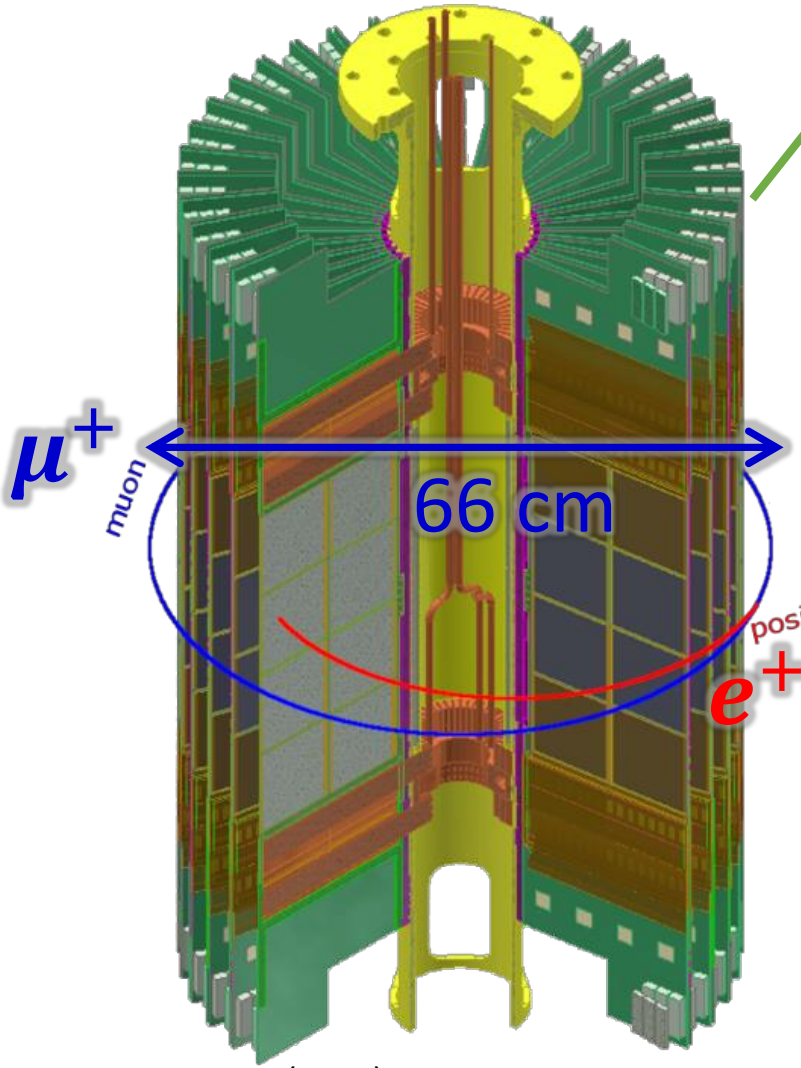


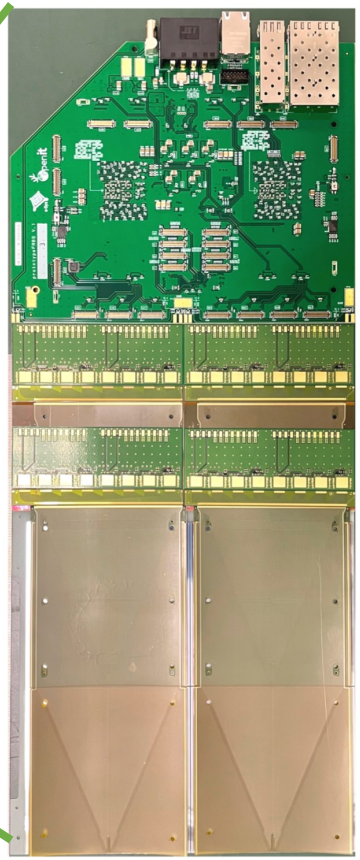
FNAL Run 1 PRA 103, 042208 (2021)



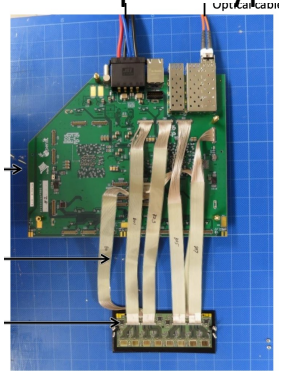
M. Abe et. al., NIM A 890, 51 (2018)

Positron tracking detector

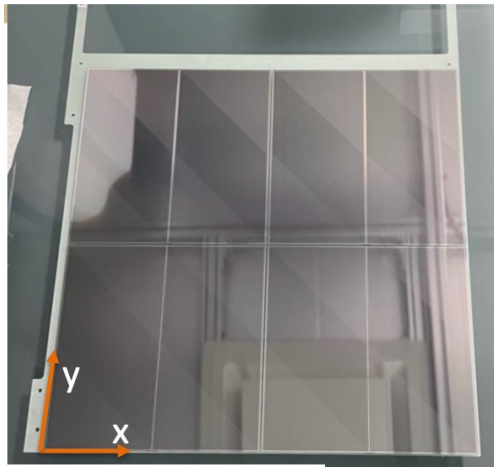




Test with prototype boards



Si strip sensors

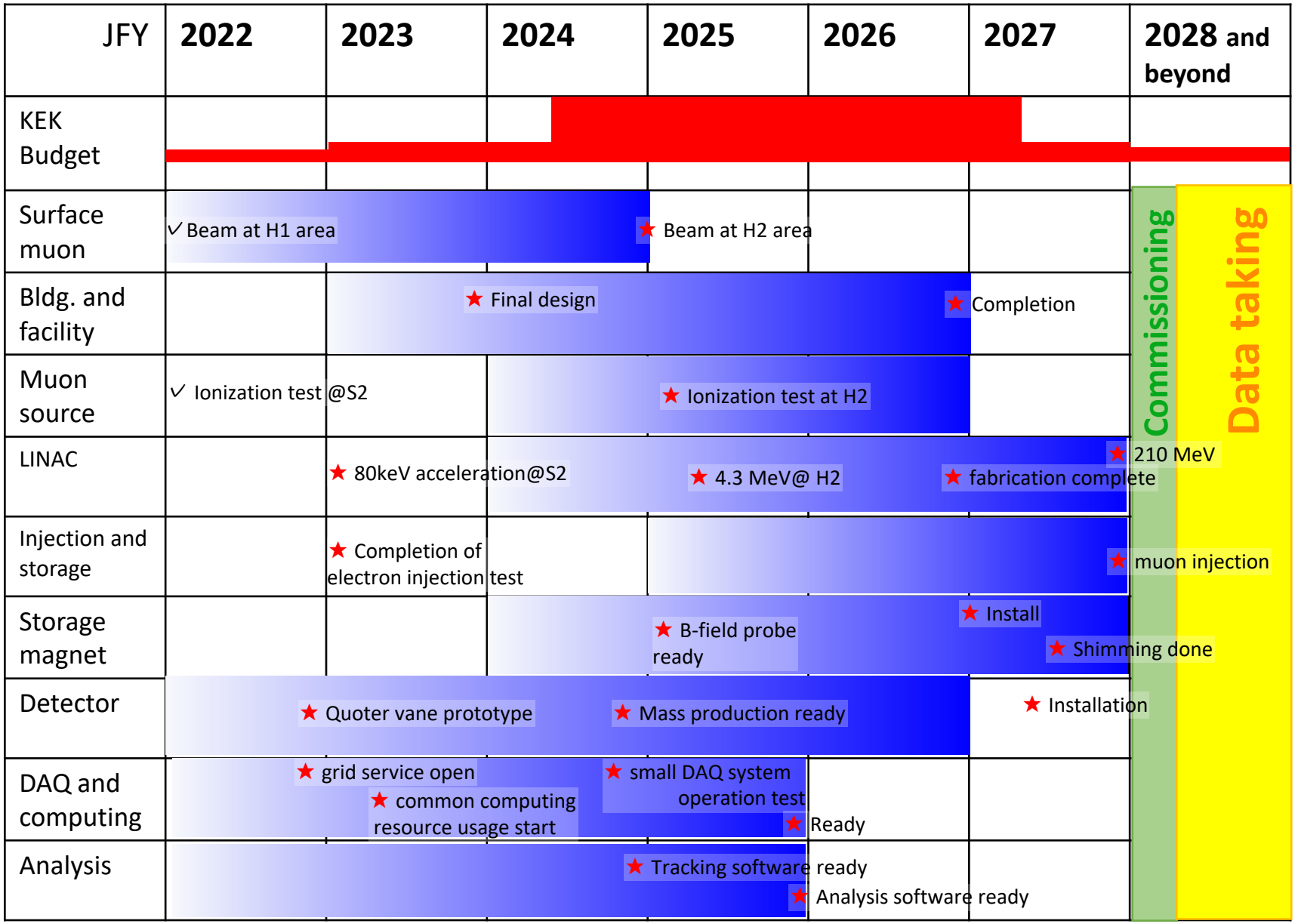


~200 mm

Development of the detector system is in progress.
Mechanical & electrical prototypes in production.

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

Schedule and milestone



Muon acceleration and future colliders

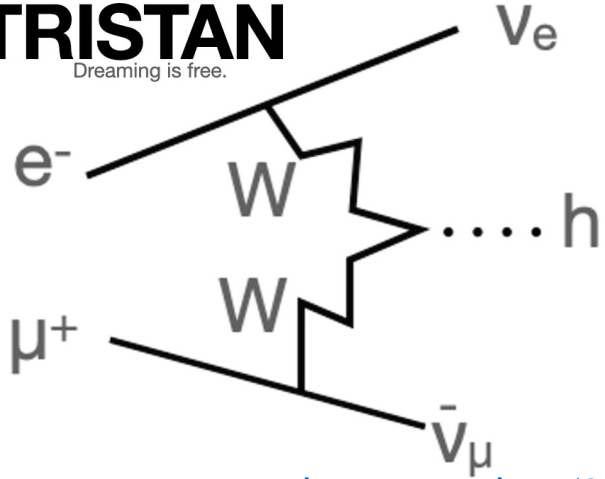
KEK IPNS workshop, Nov. 2, 2023

https://kds.kek.jp/event/48168/

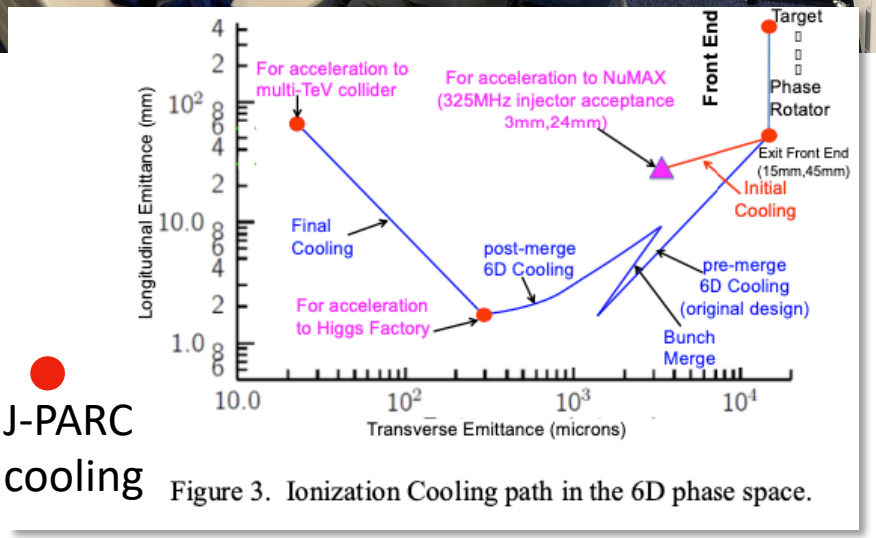
$\mu^+\mu^-$ or μ^+e^- ?

μTRISTAN

Dreaming is free.



Prog Theor Exp Phys (2022)

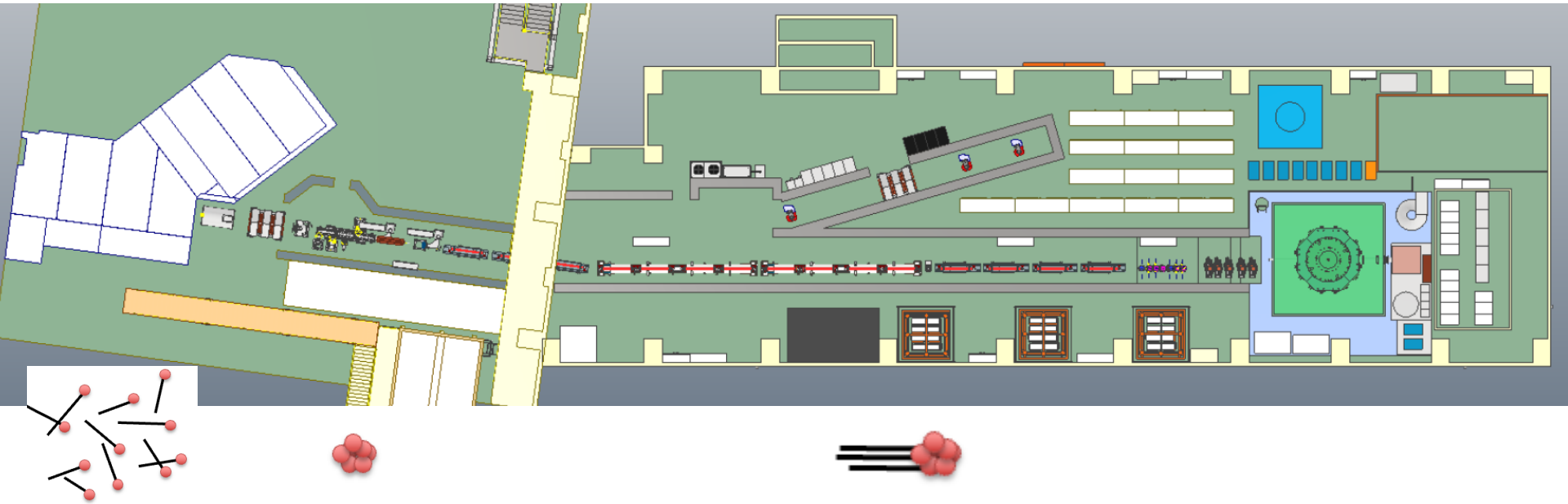


J-PARC cooling

Figure 3. Ionization Cooling path in the 6D phase space.

Summary

- We plan to measure muon g-2 and search for muon EDM with sensitivity 1.5E-21 ecm
- Experiment adopts new method
  - Low emittance muon beam (Cooling + acceleration)
  - Compact storage ring
  - Very weak magnetic focusing
- Experiment is under construction.
- Expected date of data taking from 2028.

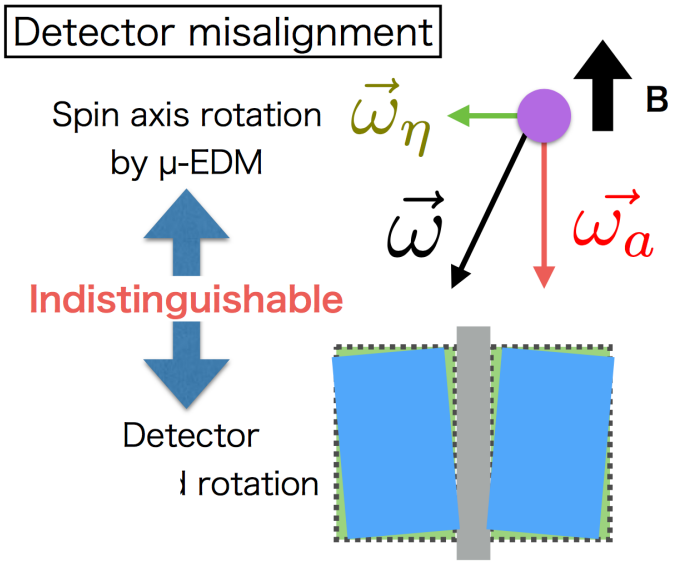


Systematic uncertainties on EDM

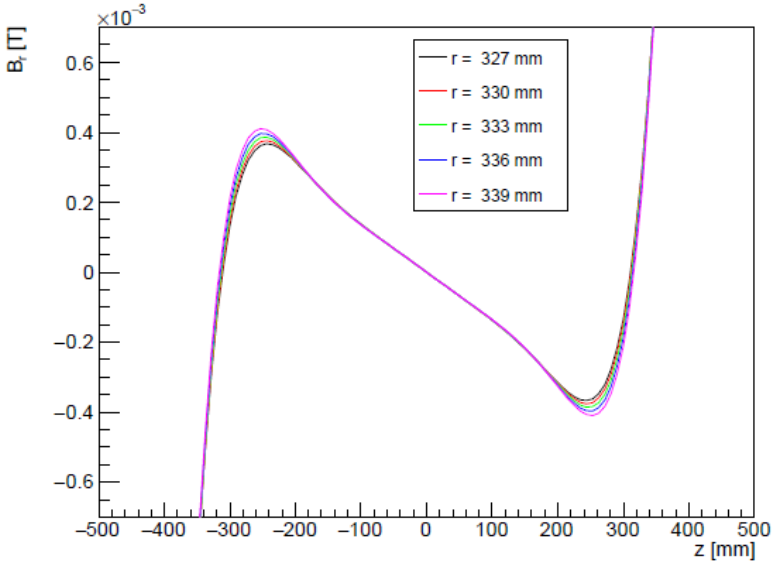
T. Yoshioka, T. Yamanaka

Table 7: Summary of systematic uncertainties on the EDM measurement

Uncertainty source	EDM 10^{-21} [e·cm]	Remarks on this experiment
Detector misalignment	0.36	Estimate based on laser alignment monitor system. Corresponds to ϕ-axis rotation of 3.6 μrad.
Axial E field	0.001	$E_z = 1$ mV/cm is assumed.
Radial B field	0.00001	$E_z = 1$ mV/cm causes a shift of z position and it becomes $B_r \sim 3.5 \times 10^{-10}$ T.
Total	0.36	



Weak focusing B-field



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		3
Polarization	100%		50%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric quadrupole		Very weak magnetic
Cyclotron period	149 ns		7.4 ns
Spin precession period	4.37 μs		2.11 μs
Number of detected e^+	5.0×10^9	1.6×10^{11}	5.7×10^{11}
Number of detected e^-	3.6×10^9	–	–
a_μ precision (stat.)	460 ppb	100 ppb	450 ppb
(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.)

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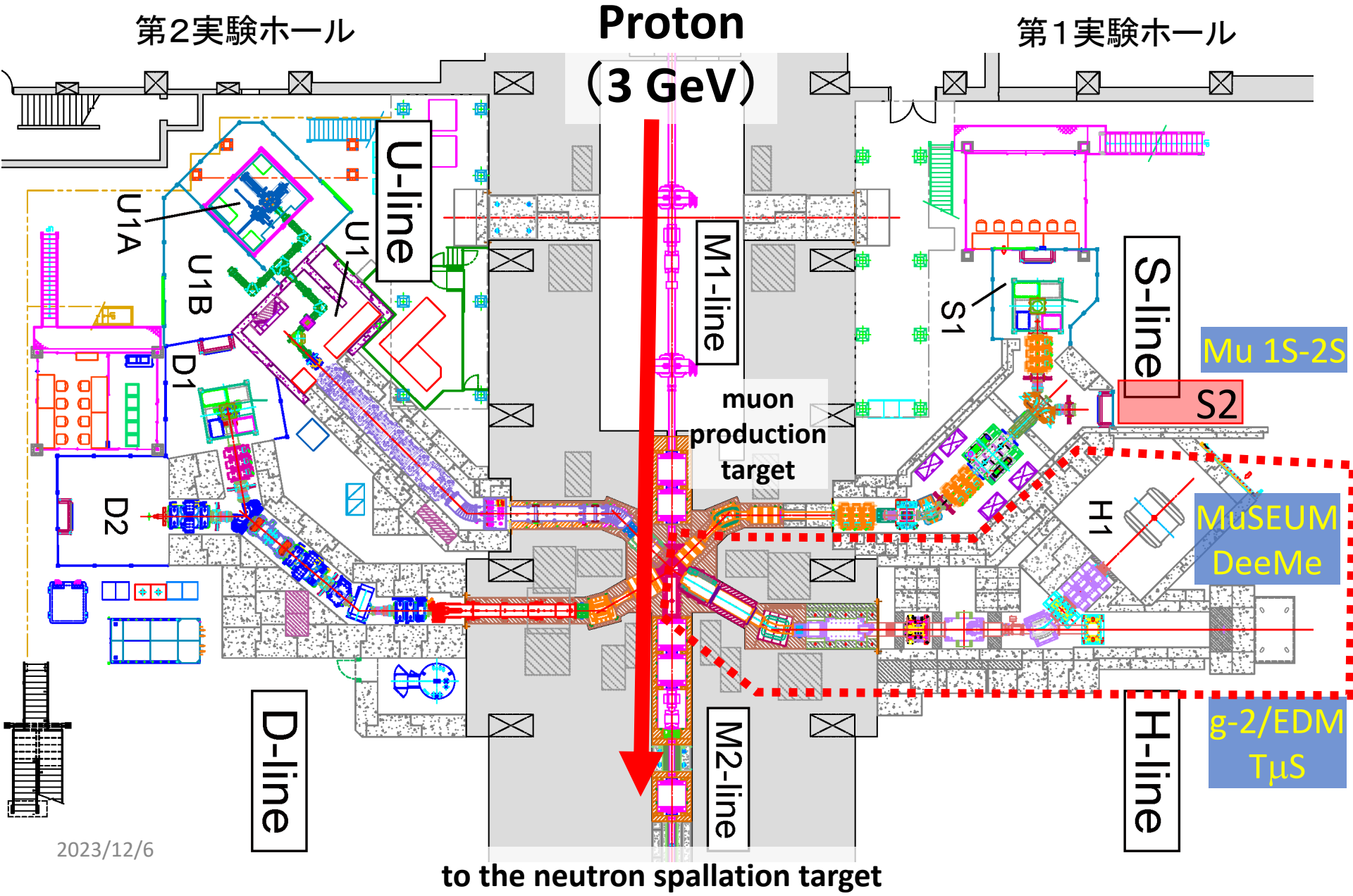
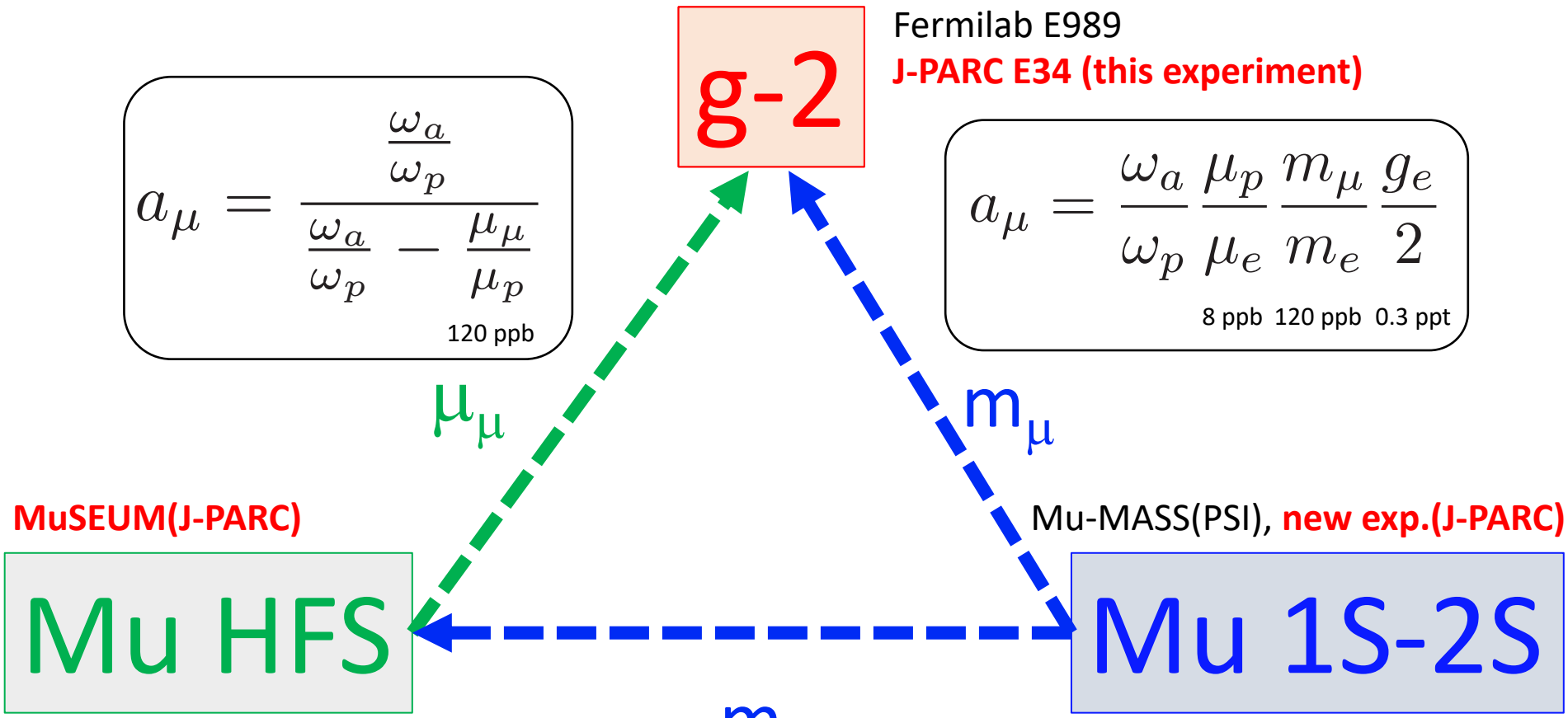
J-PARC Muon Science Facility (MUSE)



g-2 and muonium experiments



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

Three quantities are mutually correlated.
Closing a triangle with new experiments will establish ultimate precision.

g-2 and muonium experiments at J-PARC

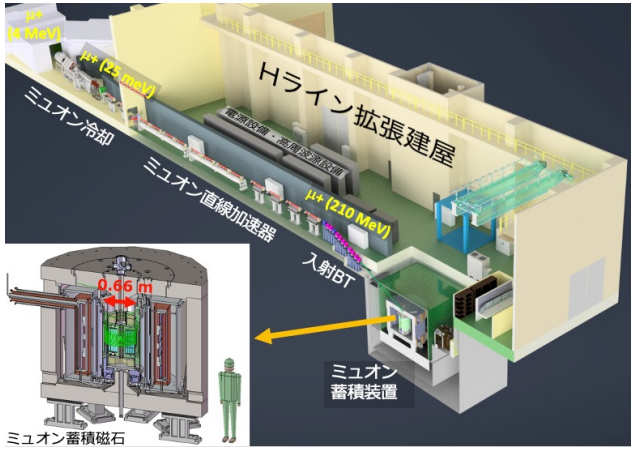
Lead by K. Shimomura (IMSS/KEK)

MuSEUM(J-PARC) **Ongoing**

g-2

Fermilab E989

J-PARC g-2/EDM (2025~)



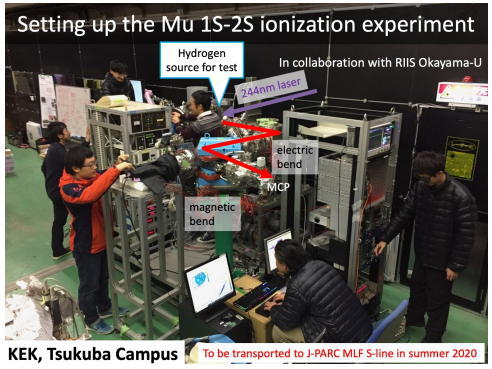
Mu-MASS(PSI), **new exp.(J-PARC)**

Positron detector

Muonium production target

Mu HFS

Mu 1S-2S



Ongoing

Lead by S. Uetake (Okayama)

Three independent experiments have launched at J-PARC for improved measurements.