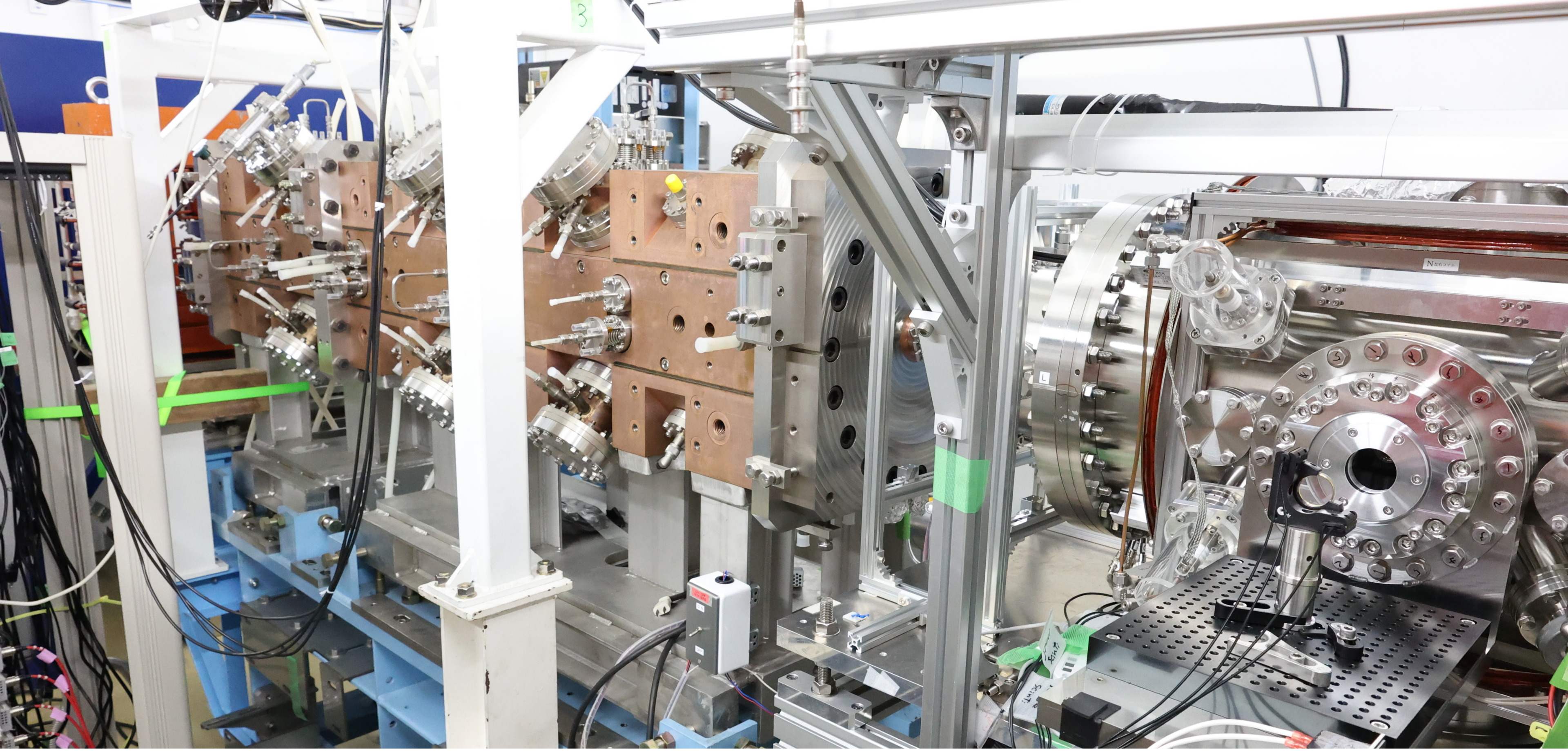
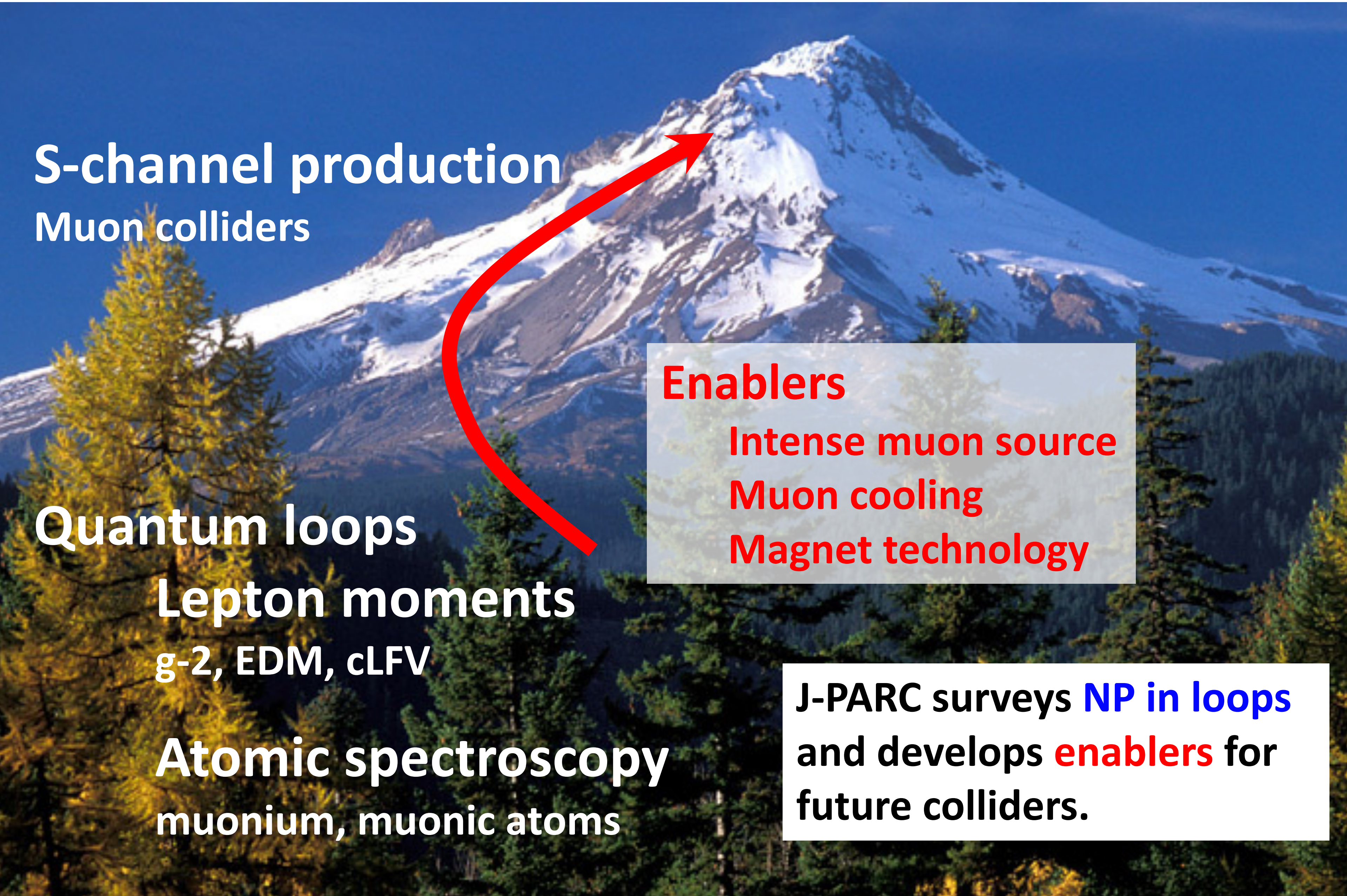


J-PARC muon experiments now and future

June 16, 2026

Tsutomu Mibe (IPNS / KEK)

Landscape



S-channel production

Muon colliders

Enablers

- **Intense muon source**
- **Muon cooling**
- **Magnet technology**

Quantum loops

Lepton moments

g-2, EDM, cLFV

Atomic spectroscopy

muonium, muonic atoms

J-PARC surveys NP in loops and develops enablers for future colliders.

Workshop on future colliders with muons 3

November 2, 2023 https://kds.kek.jp/event/48168/

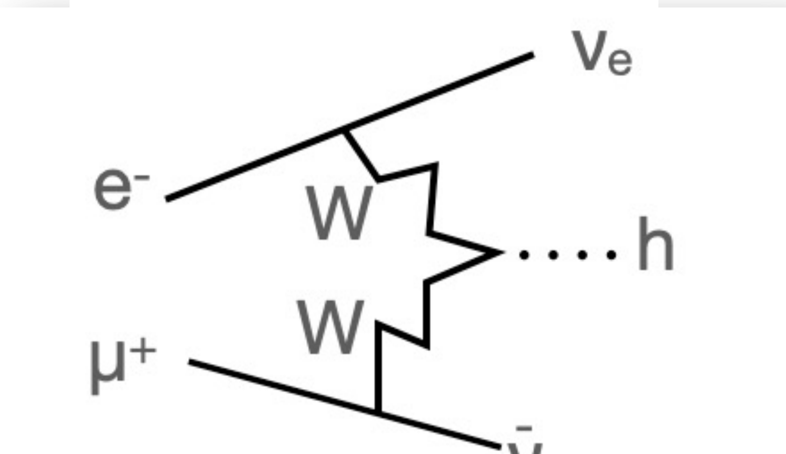
μしか勝たん

μTRISTAN

Dreaming is free.

Yu Hamada[1], Ryuichiro Kitano[1,3], Ryutaro Matsudo[1], Hiromasa Takaura[1] and Mitsuhiro Yoshida[2,3]

[1] *KEK Theory Center, Tsukuba 305-0801, Japan*
[2] *KEK Accelerator department, Tsukuba 305-0801, Japan*
[3] *Graduate University for Advanced Studies (Sokendai), Tsukuba 305-0801, Japan*



PTEP 2022, 053B02

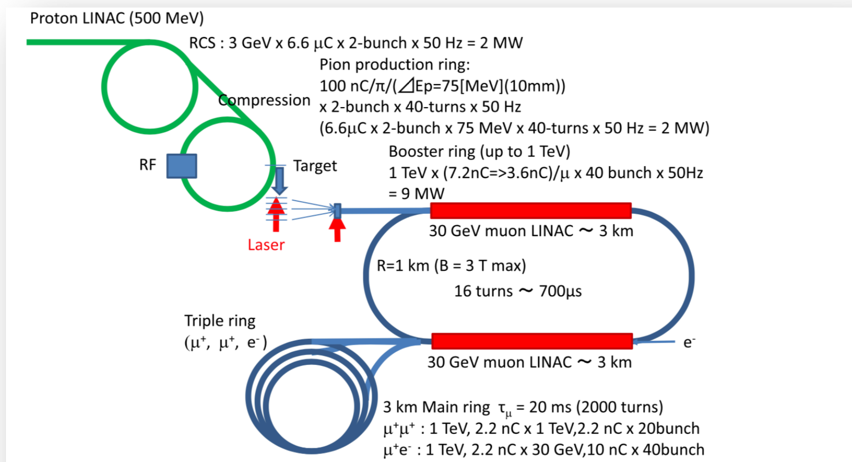


Fig. 1. Conceptual design of the $\mu^+e^-/\mu^+\mu^+$ collider.

Comparison of colliders **Slide by Mitsuhiro Yoshida**

FCC Circumference 100km

10km

Existing collider

3km TRISTAN - e^+e^- (0.03 TeV)
SuperKEKB - e^+e^-
(0.007x 0.004 TeV)

Cir: 27km
(Dia: 9km)

LEP-II - e^+e^- (0.2 TeV)
LHC - pp (1.5 TeV / parton)

Planned

20km ILC - e^+e^- (0.25 TeV, 300 fb)

50km

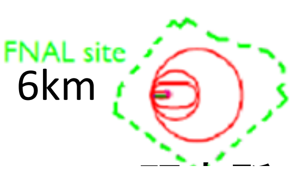
CLIC - e^+e^- (3 TeV = 0.08 GV/m x 40 km)

Muon collider : 1TeV in 3km ring same as SuperKEKB

Main issue is muon cooling method and small booster ring
No synchrotron radiation, so bunch length is not extended,
=> Ultra-high convergence and high luminosity are possible
using high quality muon production → <u>Ultra cooled μ+ is advanced at J-PARC</u>

Negative muon is not proved

Dramatic increase in ultra-low-cooling μ+
due to the development of composite targets



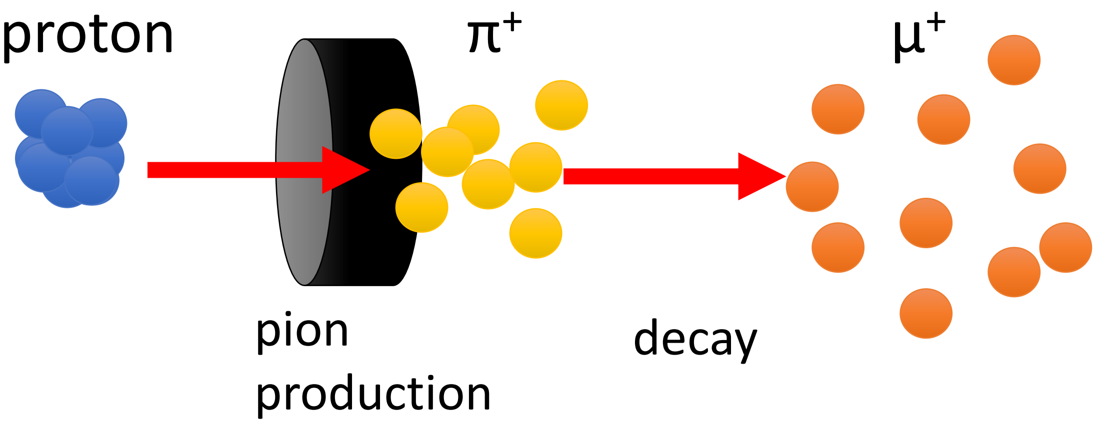
MuC@FNAL (6 TeV)

3km
μTRISTAN
(2 TeV, 100 fb)

400m↓ this point

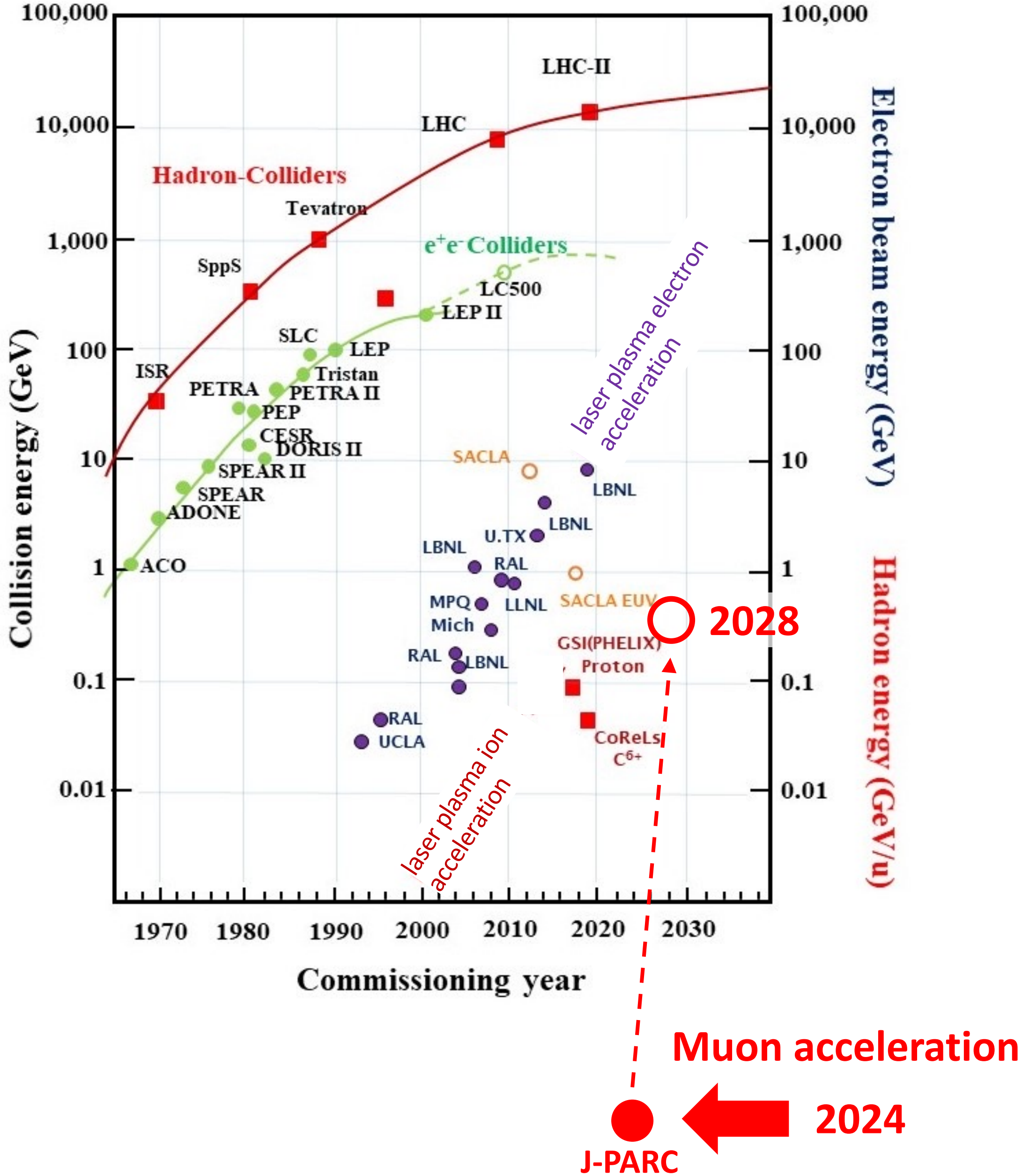
Higgs factory - $\mu^+\mu^-$
(0.126 TeV, 30,000 fb)

Experimental challenges

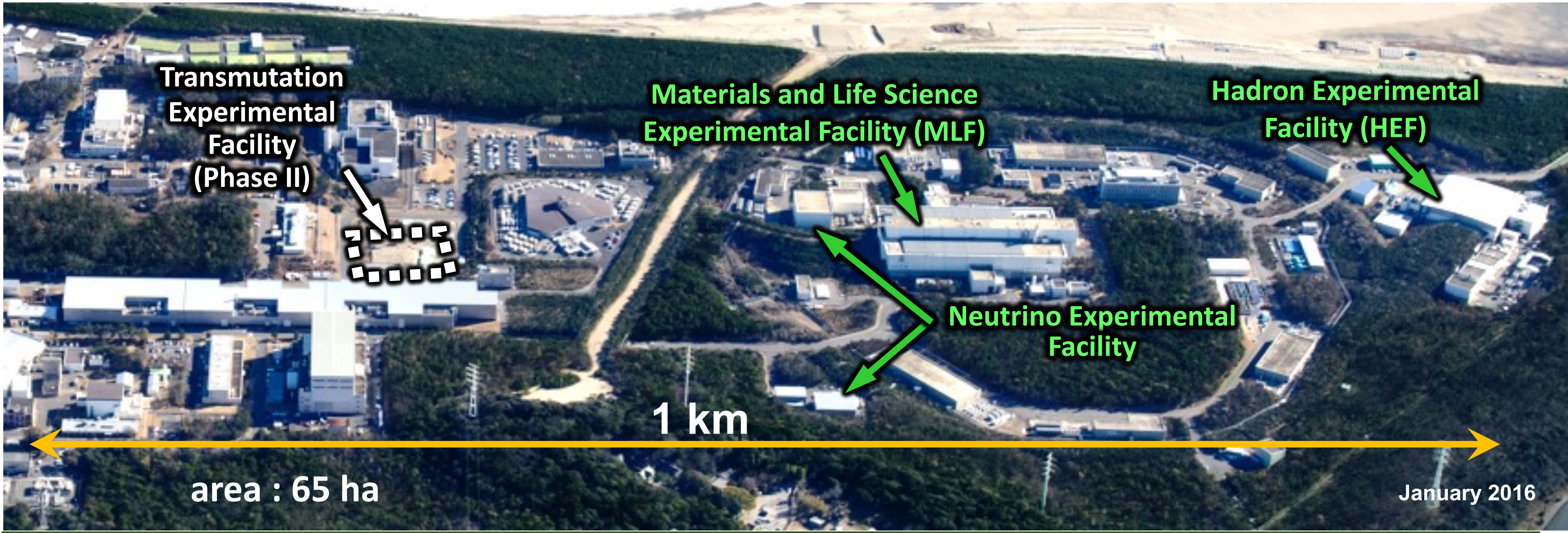


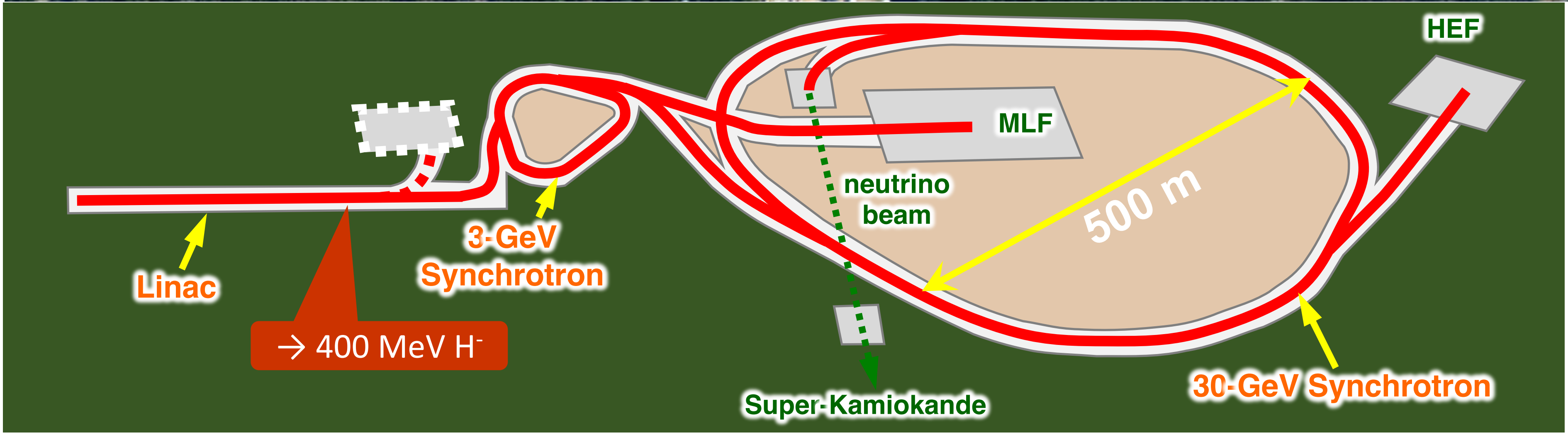
- **Intense muon source**
  - Efficient pion / muon capture
  - 10^7 μ/sec (conventional)
  - 10^{13} μ/sec for 0.1 ab^{-1}/year
- **Muon cooling**
  - Large phase space due to tertiary beam
  - Normalized emittance = 1,000 π mm mrad (conventional)
    1π mm mrad (muTRISTAN $\mu\mu$)
- **Magnet technology**
  - $B = E_{CM}/(2\text{x}0.3\rho) = 7$ T for E_{CM}=2 TeV in a 2km ring

History of accelerator technology



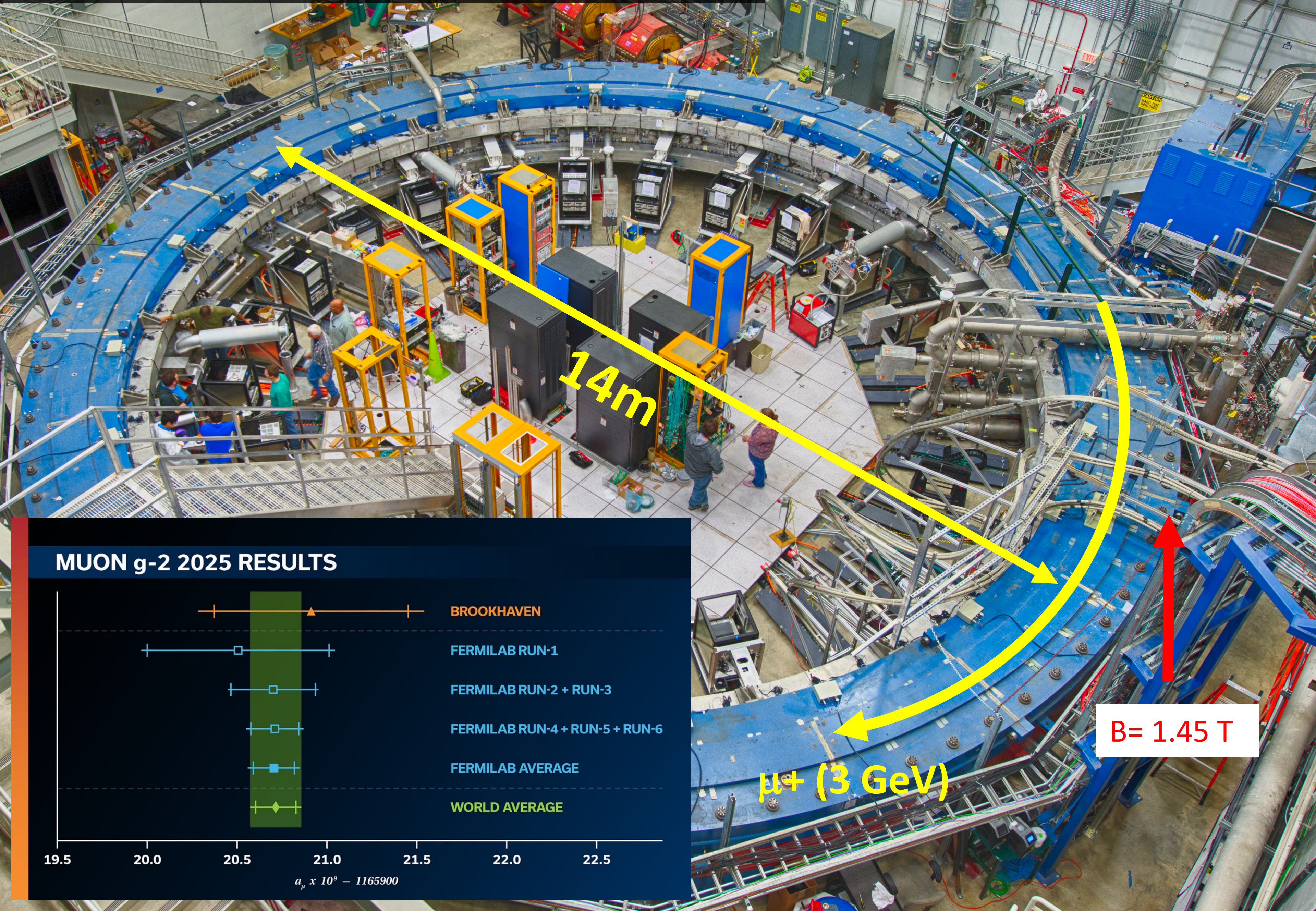
J-PARC : Japan Proton Accelerator Research Complex





3 proton accelerators and 3 experimental facilities

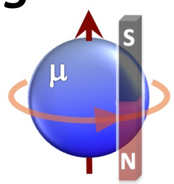
FNAL g-2 experiment (completed!)



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

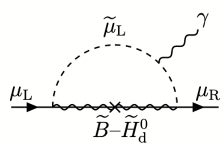
Studies on physics beyond the standard model in quantum loops

***g*-2**

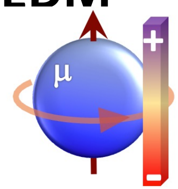


C, P, T conserved

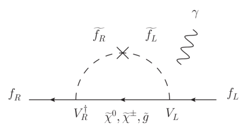
Examples: Super Symmetric particles



EDM

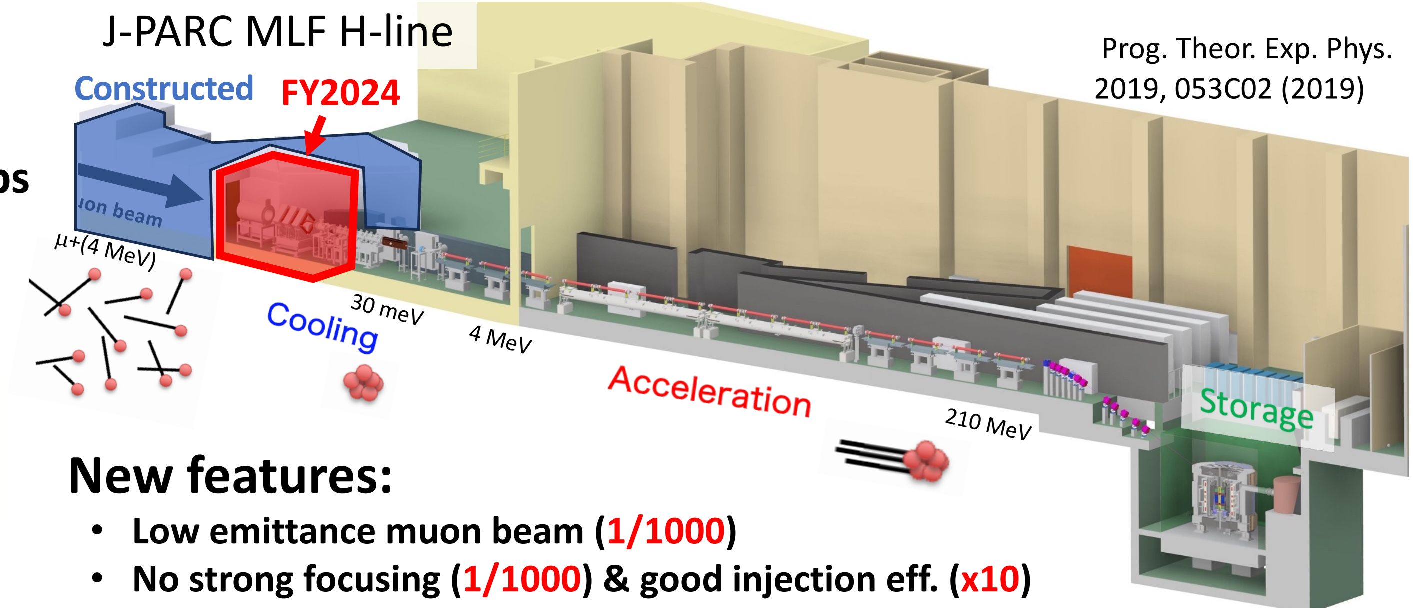


P & T-violating



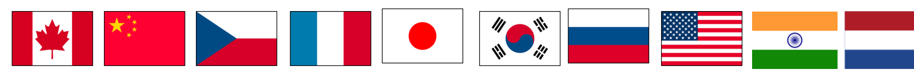
J-PARC MLF H-line

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



New features:

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

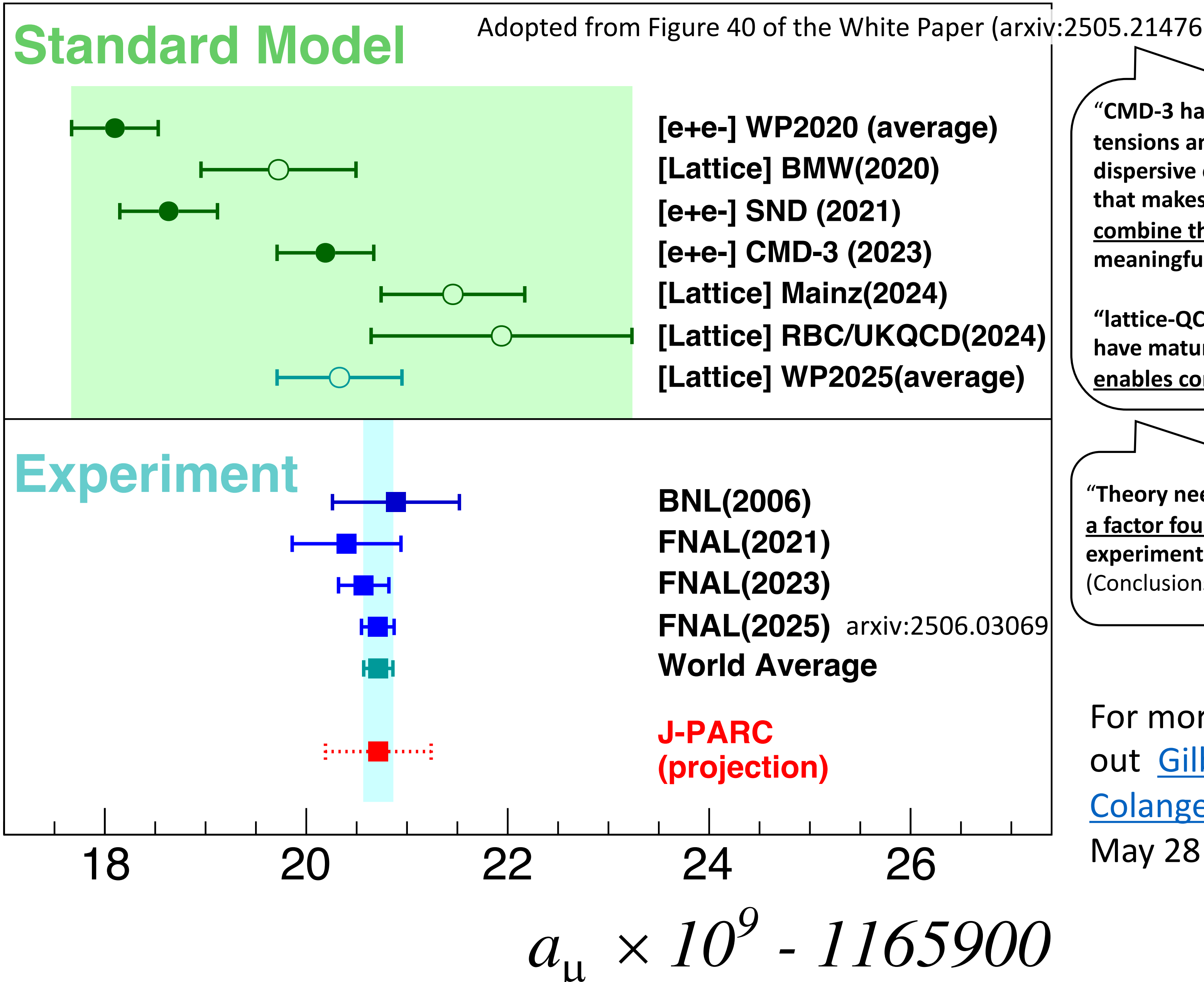


The only experiment to test FNAL/BNL *g*-2 results.

***g*-2 : 450 ppb**

EDM : 1.5 E-19 ecm

Status of muon g-2 (June 9, 2025)



"CMD-3 has increased the tensions among data-driven dispersive evaluations to a level that makes it impossible to combine the results in a meaningful way. "

"lattice-QCD calculations of HVP have matured considerably. … enables consolidate averages."

"Theory needs to be improved by a factor four to match the experimental precision. " (Conclusions and outlook)

For more detail, check out Gilberto Colangelo's talk on May 28

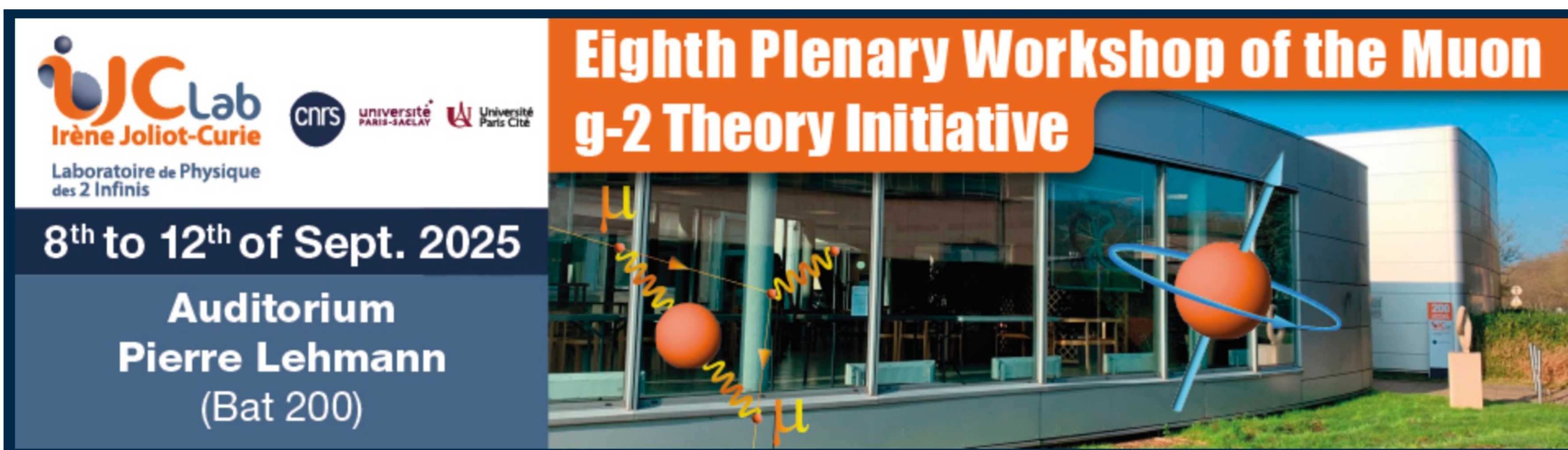
International workshop on muon *g*-2 theory at KEK

The seventh plenary workshop at KEK (Sep 9-13, 2024) https://conference-indico.kek.jp/event/257/

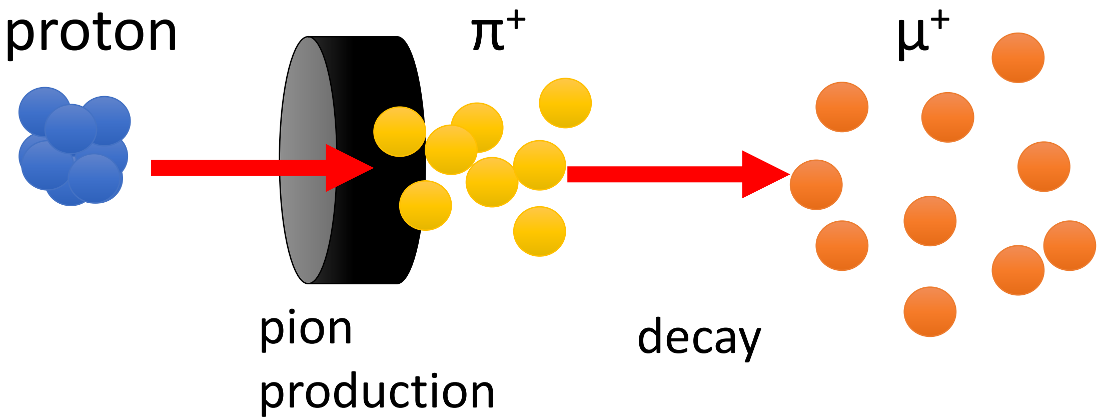
Special presentation on memories of T. Kinoshita

Next workshop at JLC lab, Orsay on Sep, 8-12, 2025

https://indico.ijclab.in2p3.fr/event/11652



Conventional muon beam



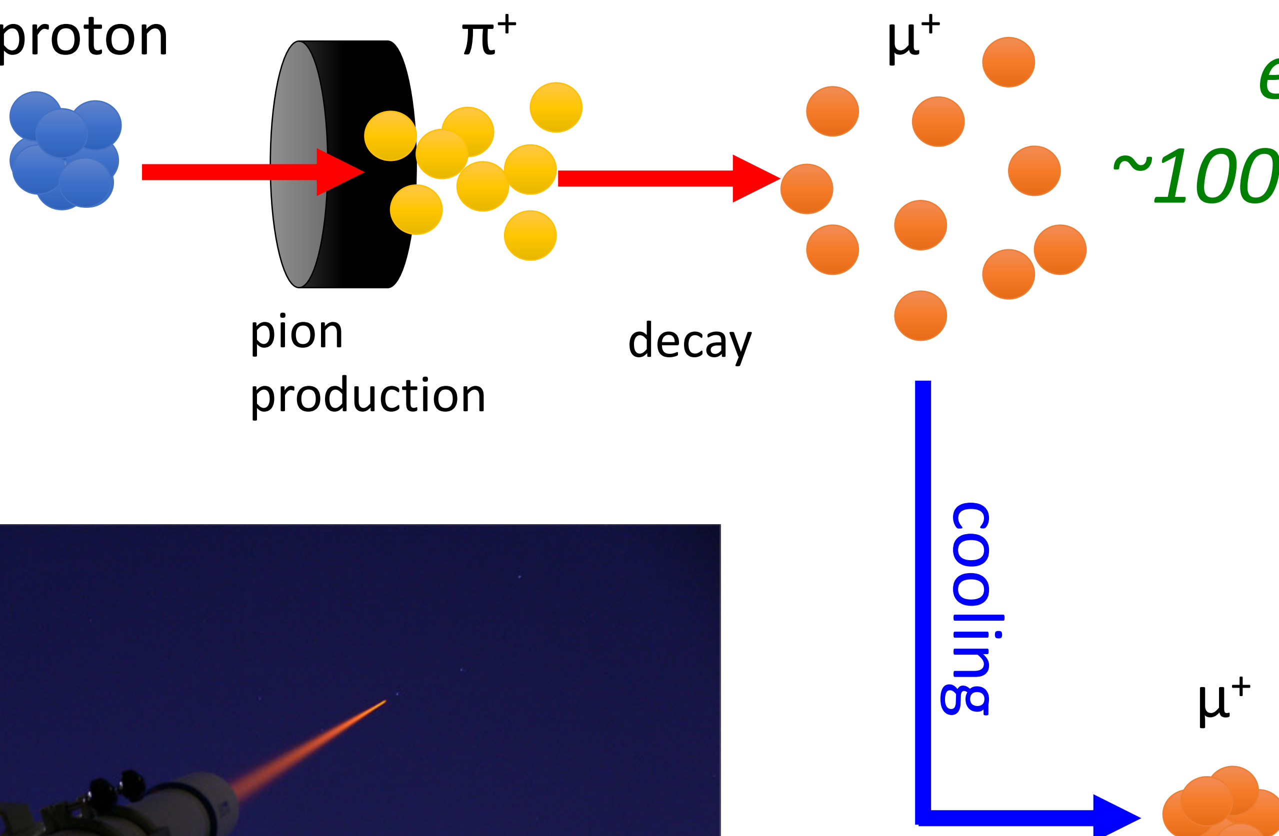
emittance

~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

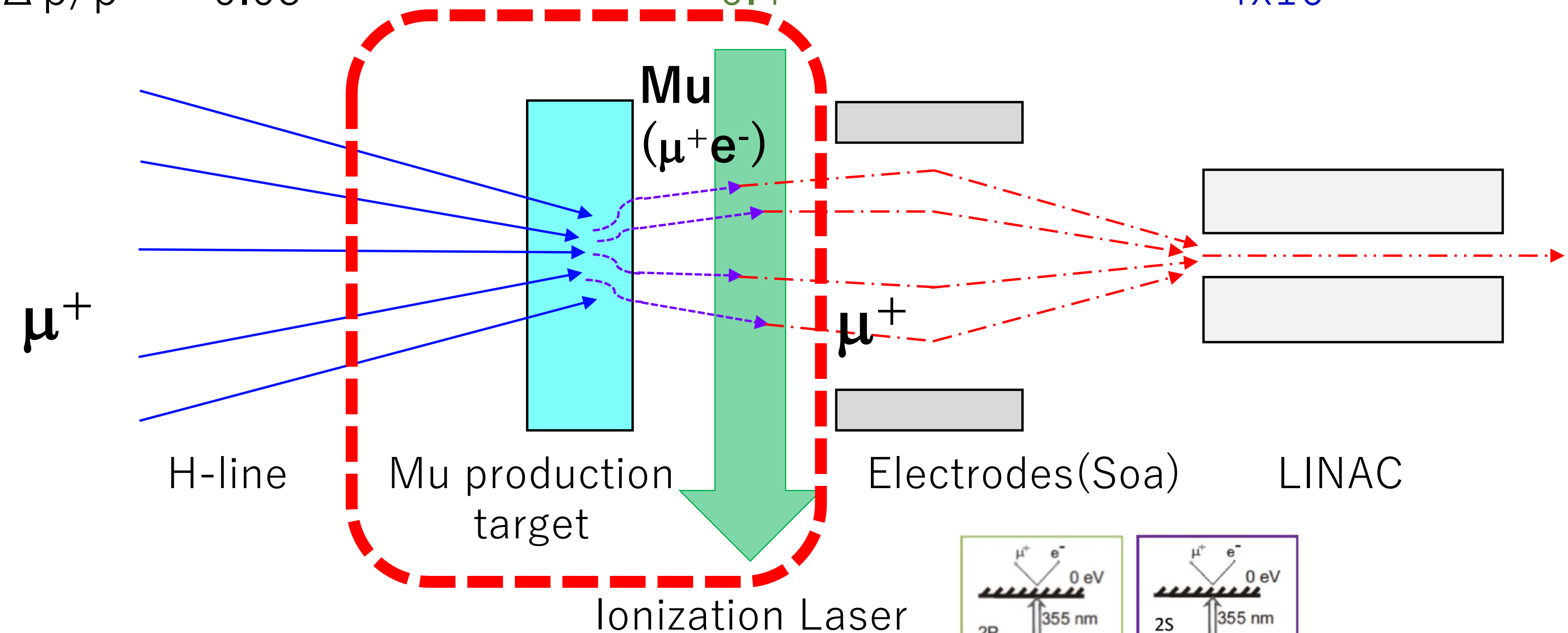
emittance
1π mm ·mrad

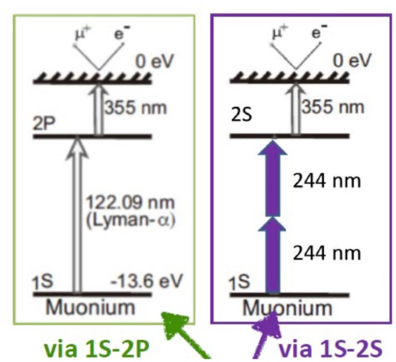
Reaccelerated thermal muon

Free from any of these

Acceleration of thermal muons

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





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

Efficient Muonium production demonstrated in TRIUMF

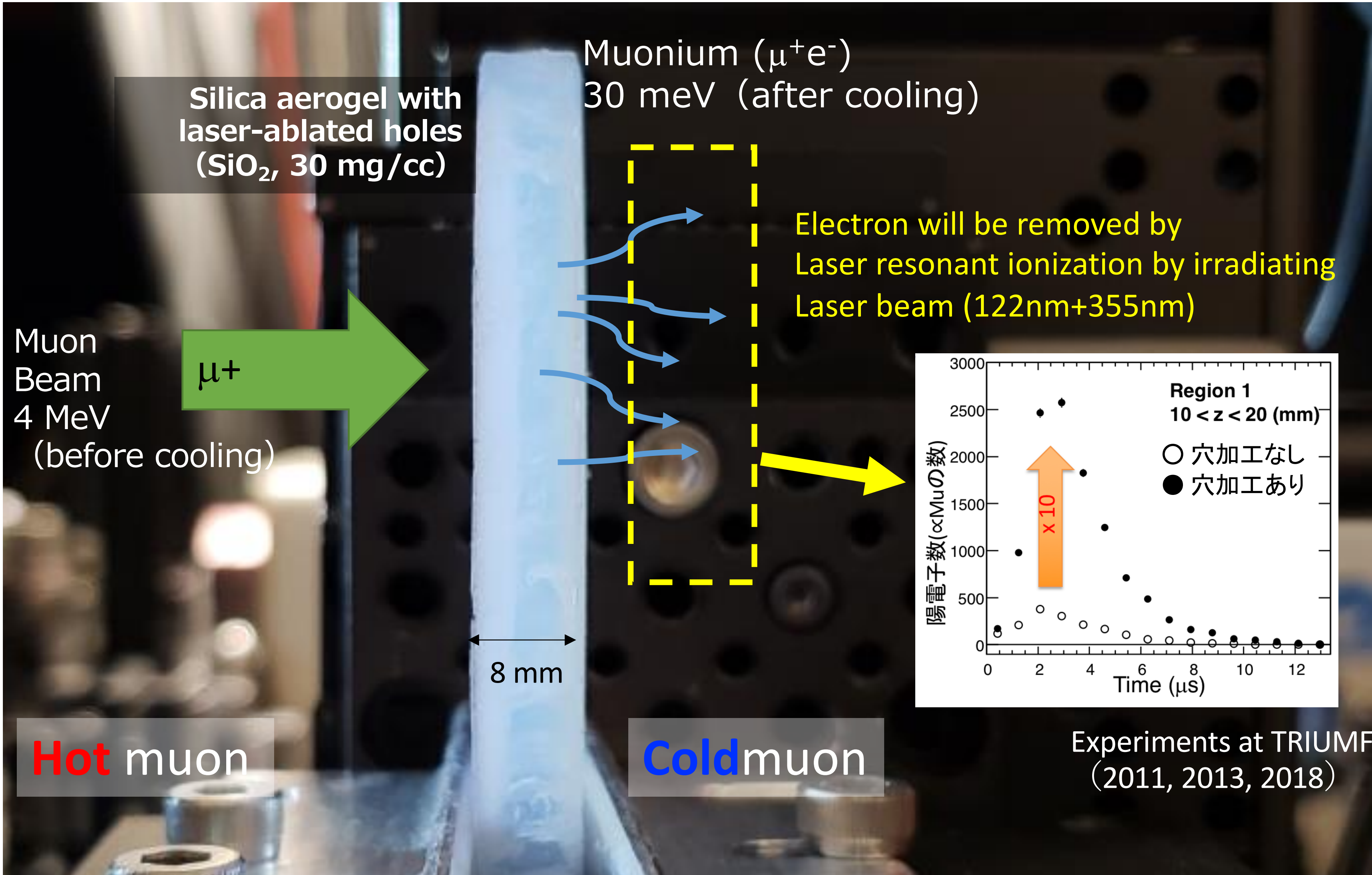
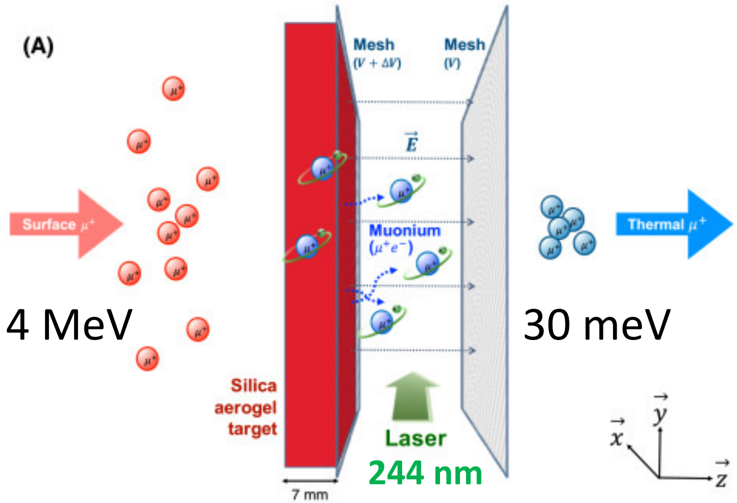


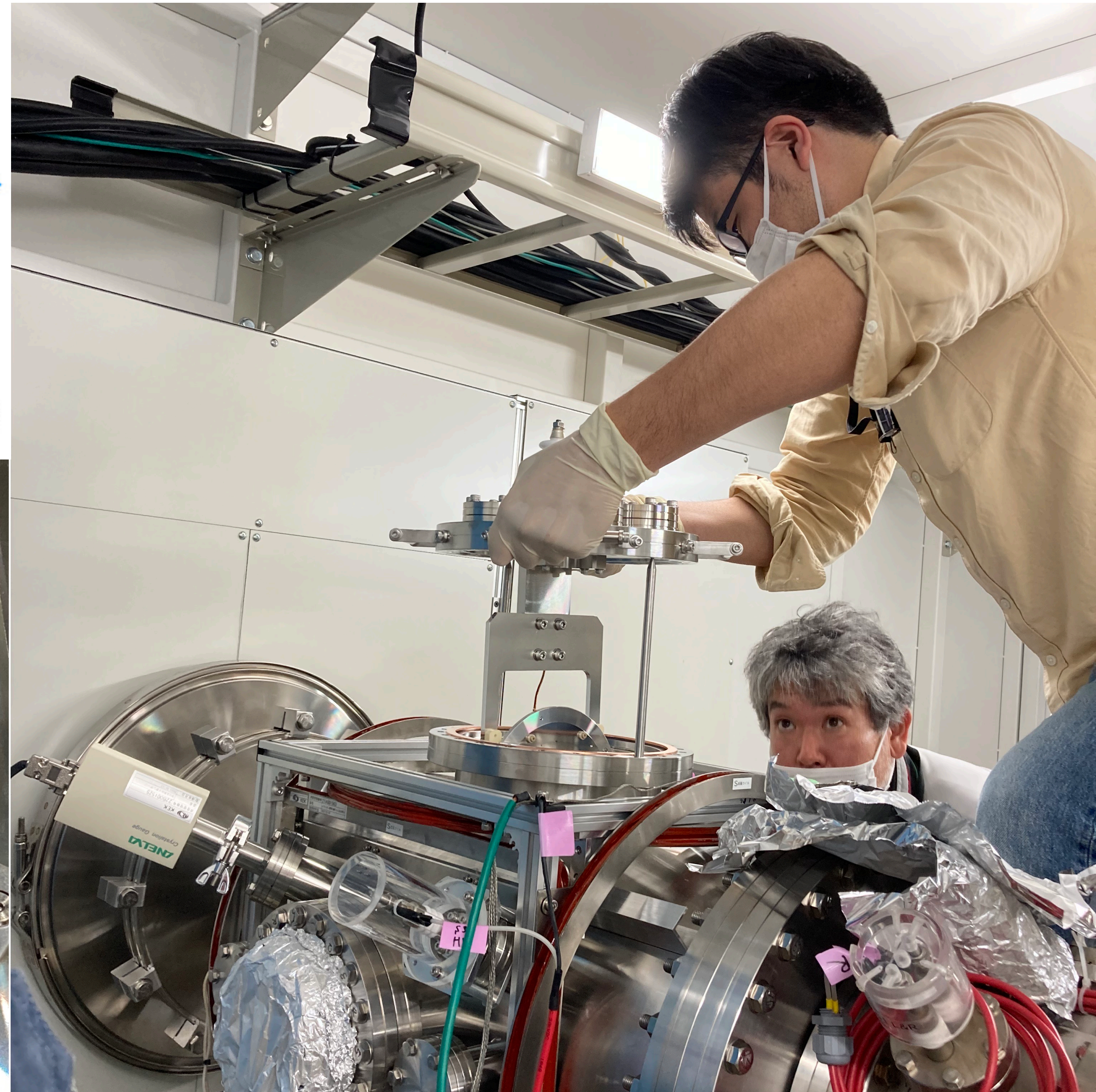
Photo by Saeid Camal (UBC)

Implementation at J-PARC (2023)




Laser ablated silica aerogel produced at UBC

J-PARC S2 area

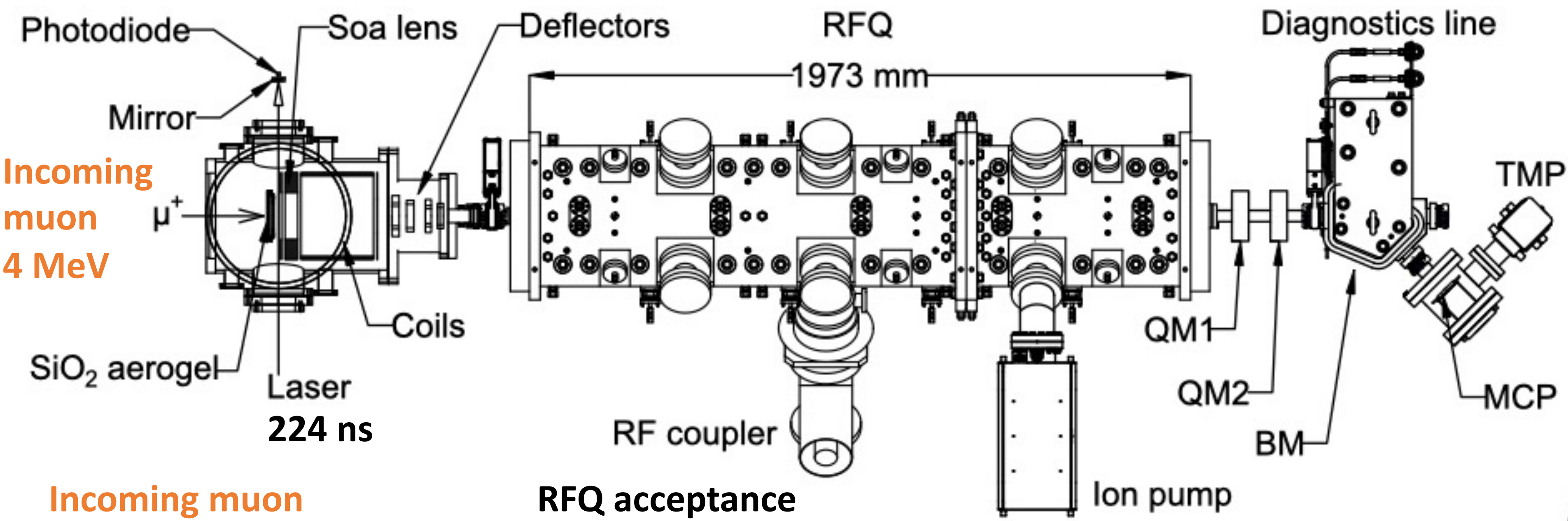


Demonstration of acceleration to 100 keV (2024)

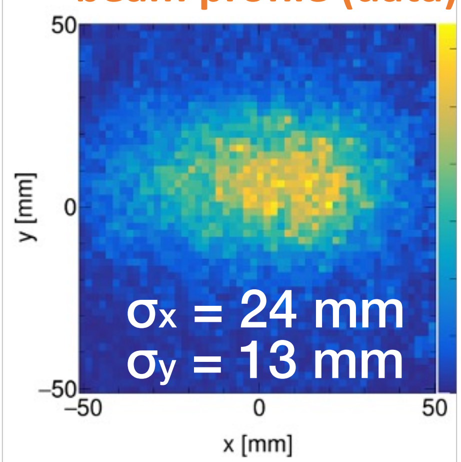
Cooling
30 meV

Acceleration
100 keV

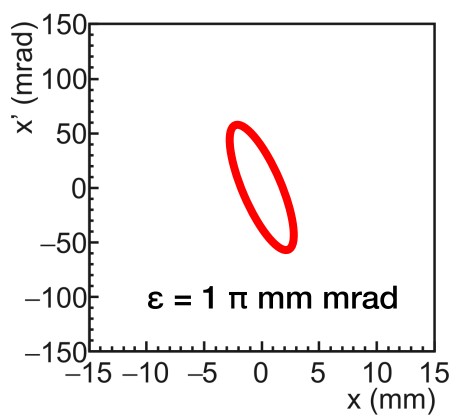
Diagnosis



Incoming muon beam profile (data)

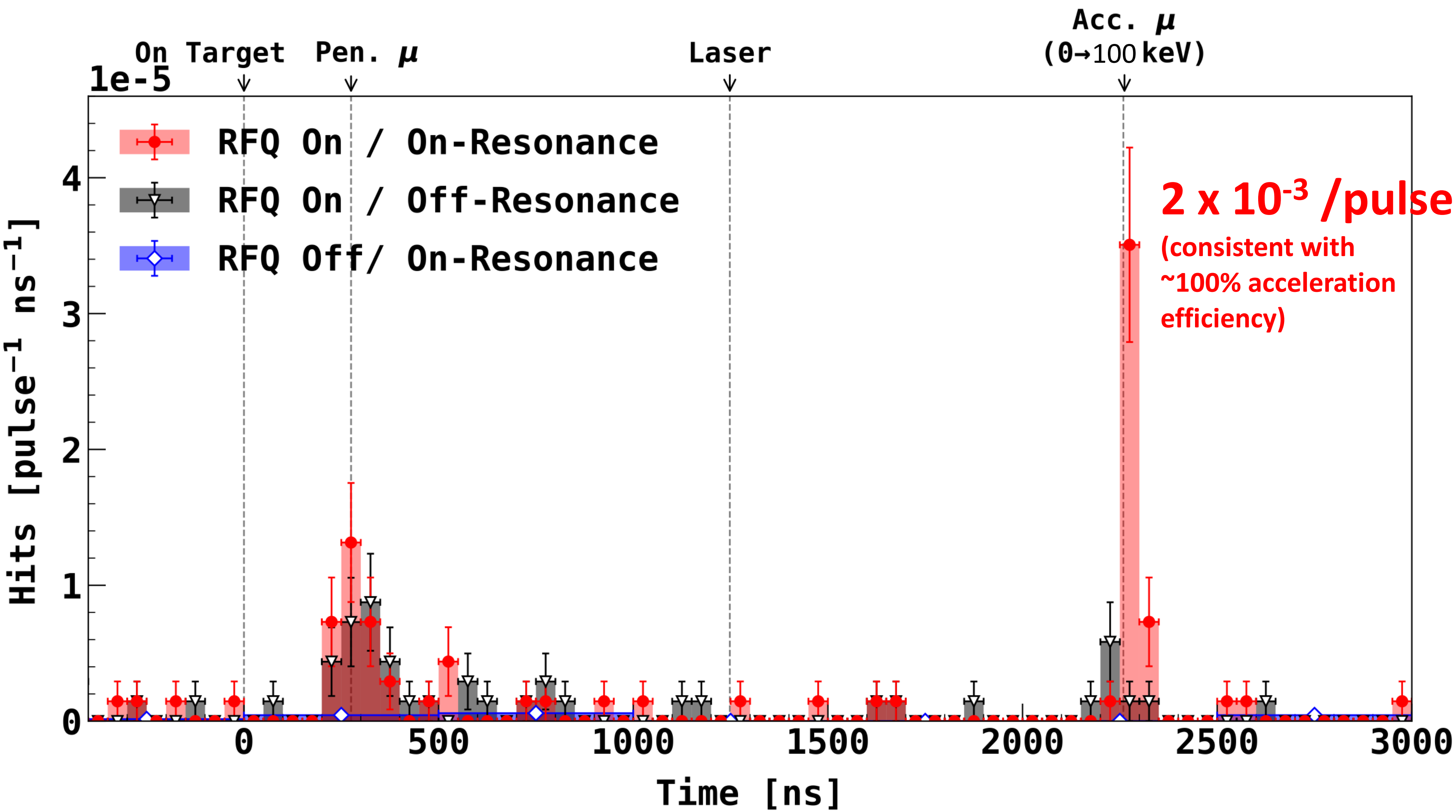


RFQ acceptance (simulation)



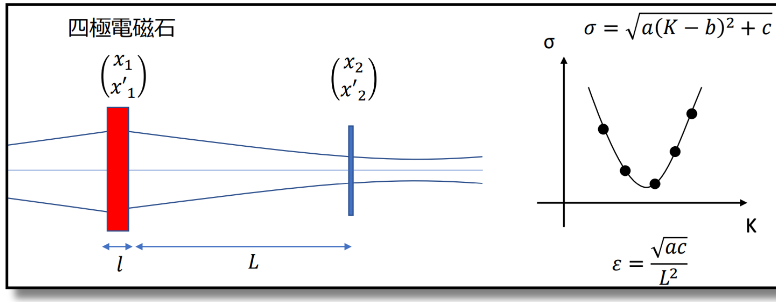
RF frequency: 324 MHz
RF power: 2.6 kW
RF pulse width: 40 μs
Acceleration energy: 100 keV

Results: time of flight

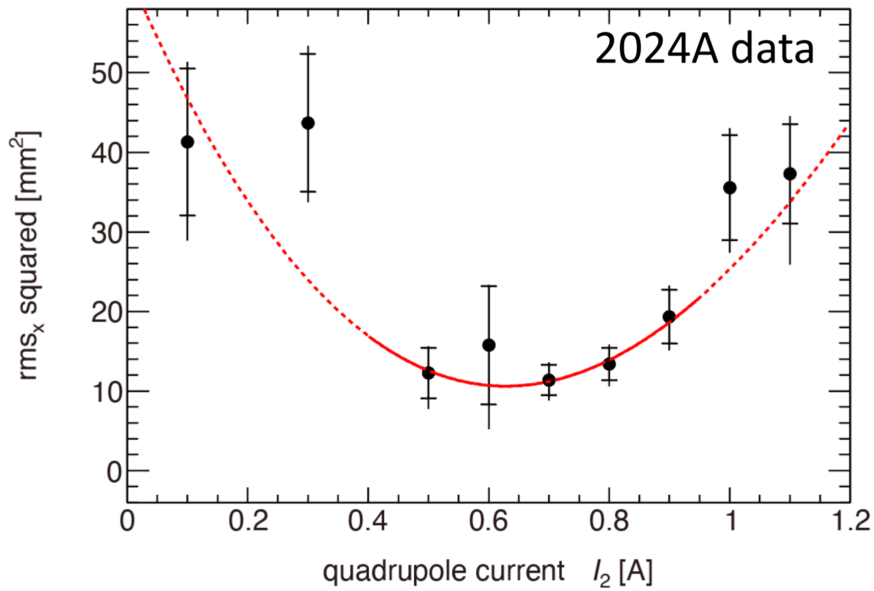


Results: transverse emittance at 100 keV

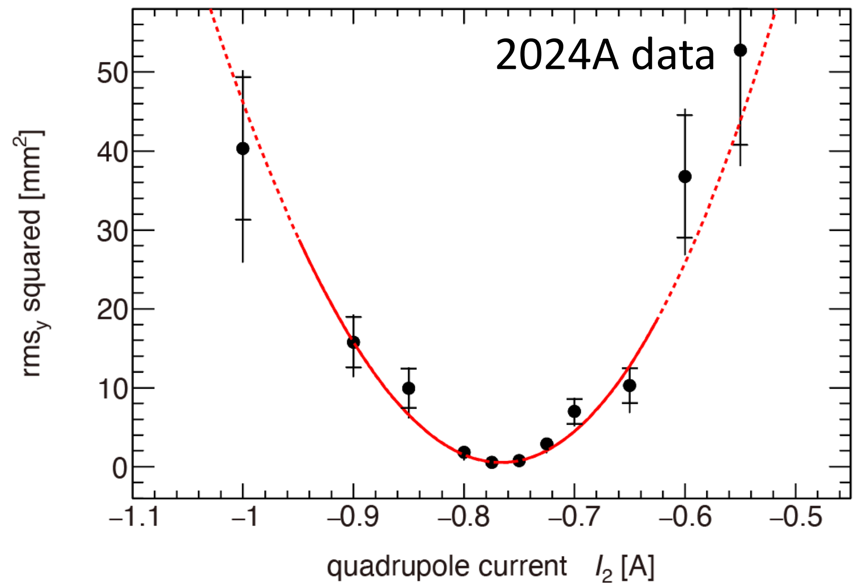
arXiv:2410.11367



horizontal



vertical



before cooling

ε_x = 170 π mm mrad

x 1/200

after cooling + acceleration

$\varepsilon_x = 0.85 \pm 0.25^{+0.22}_{-0.13}$ π mm mrad

before cooling

ε_y = 130 π mm mrad

x 1/400

after cooling + acceleration

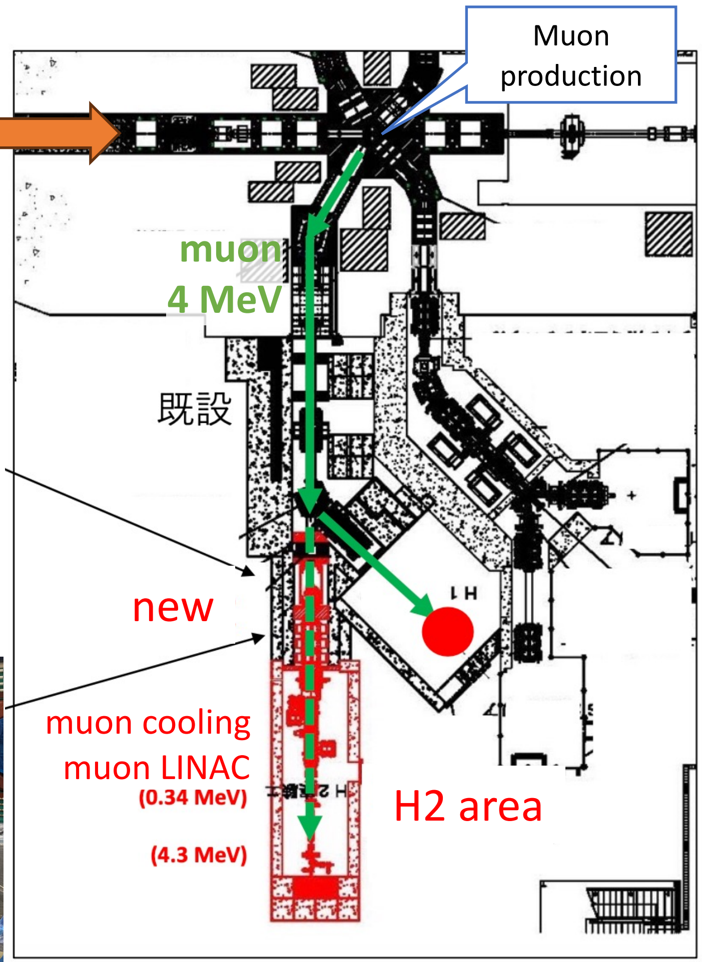
$\varepsilon_y = 0.23 \pm 0.03^{+0.05}_{-0.02}$ π mm mrad

The birth of low-emittance muon beam

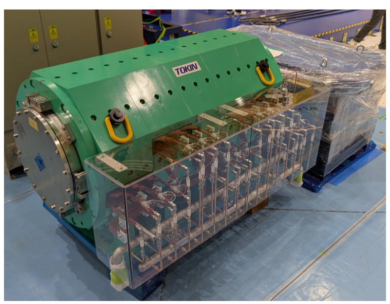
New beamline : MLF H2 area

Dedicated beamline for the muon cooling and acceleration

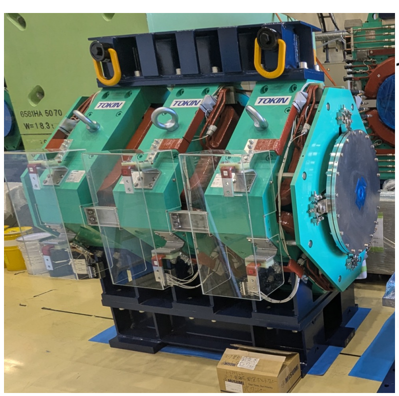
Surface muon rate : 1 x 10^8/sec

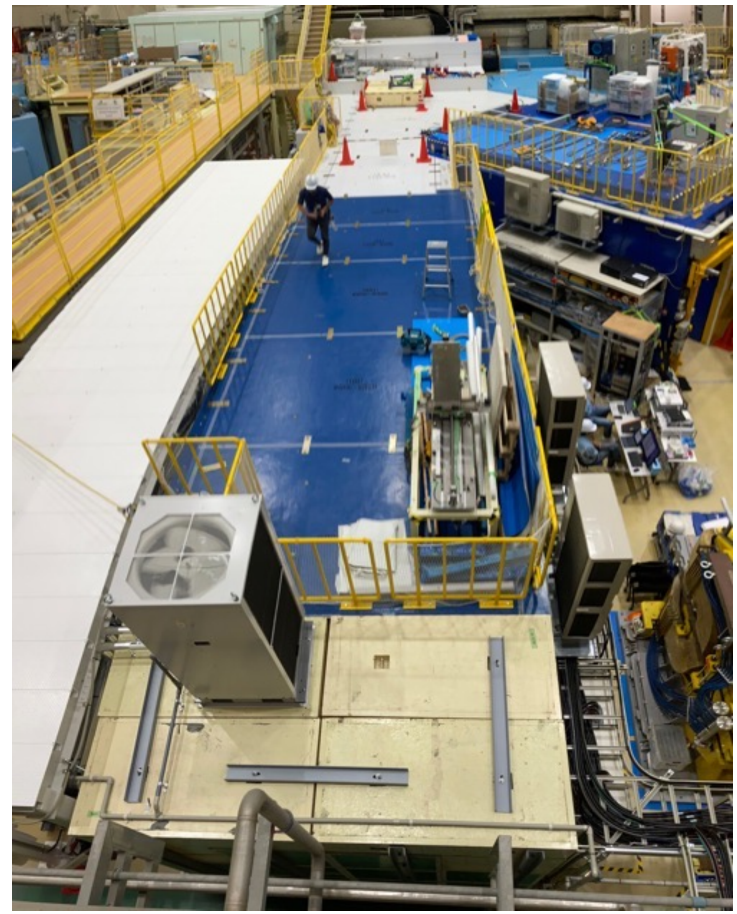


solenoid



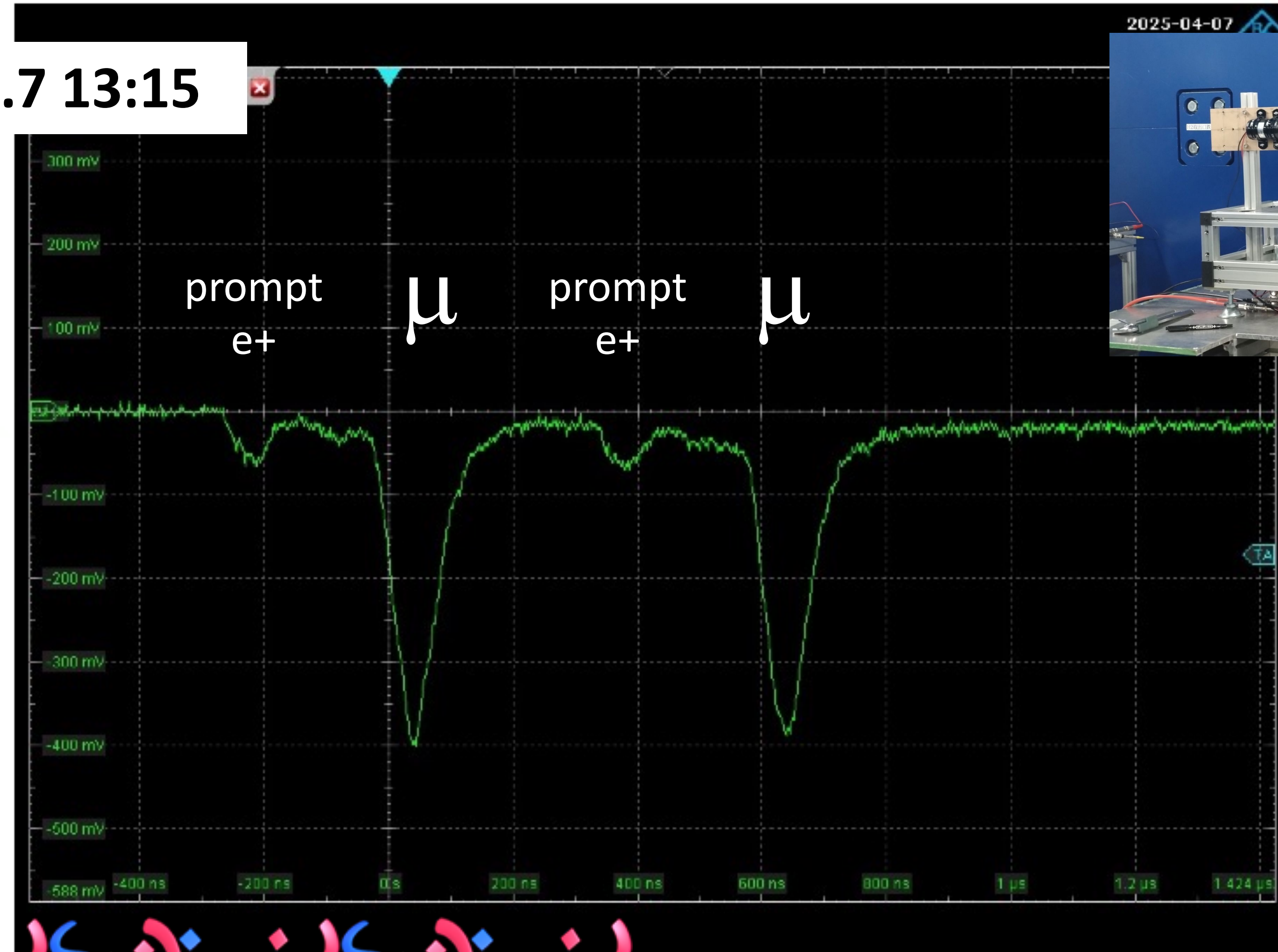
quadrupole magnets

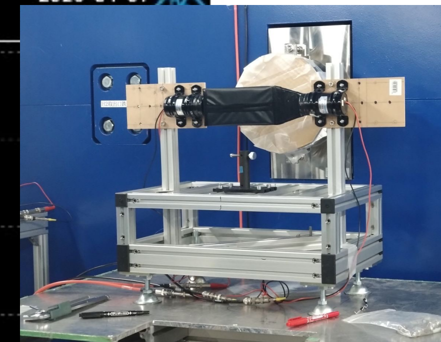




New beamline : MLF H2 area

2025.4.7 13:15

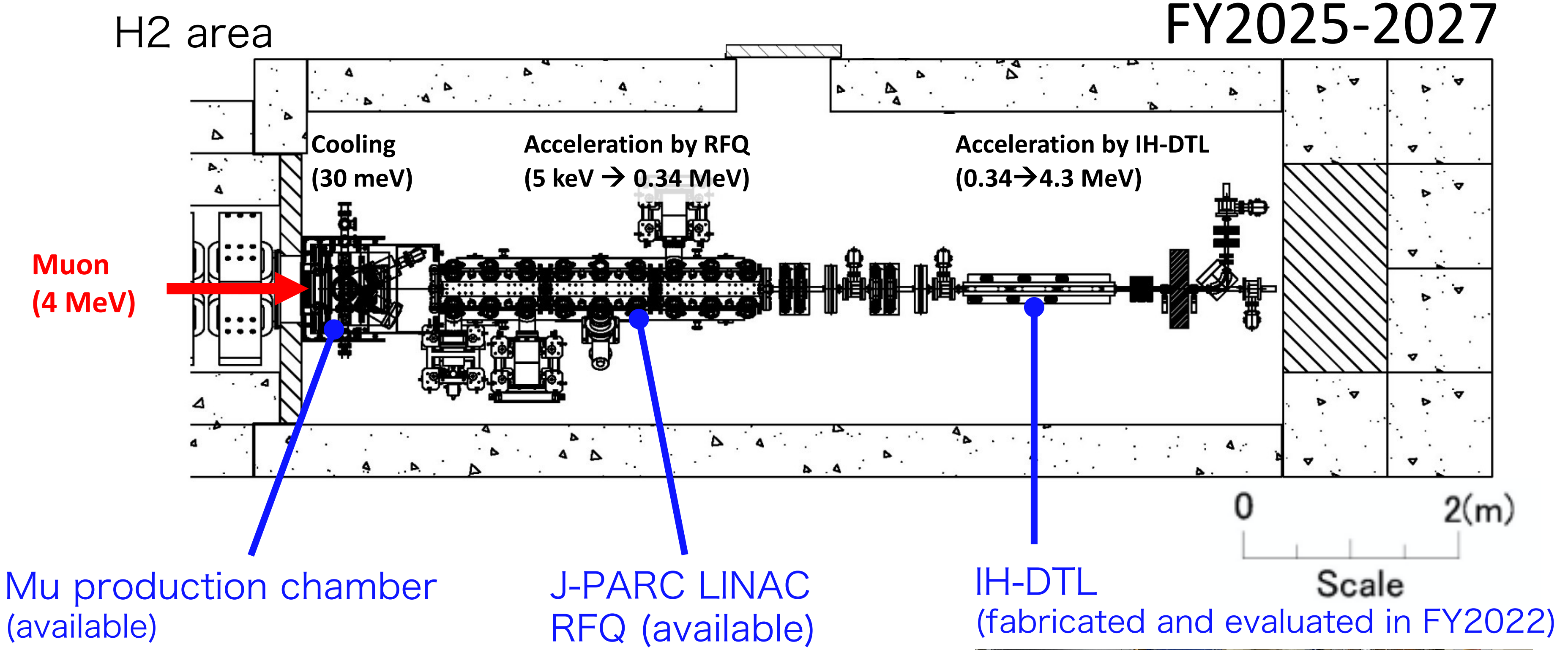


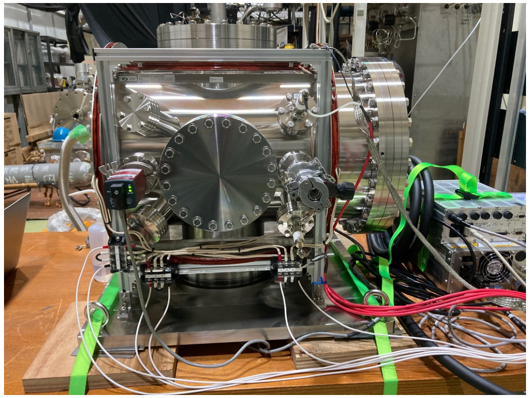


Successful delivery of the beam on April 7, 2025

Next step: Acceleration to 4 MeV

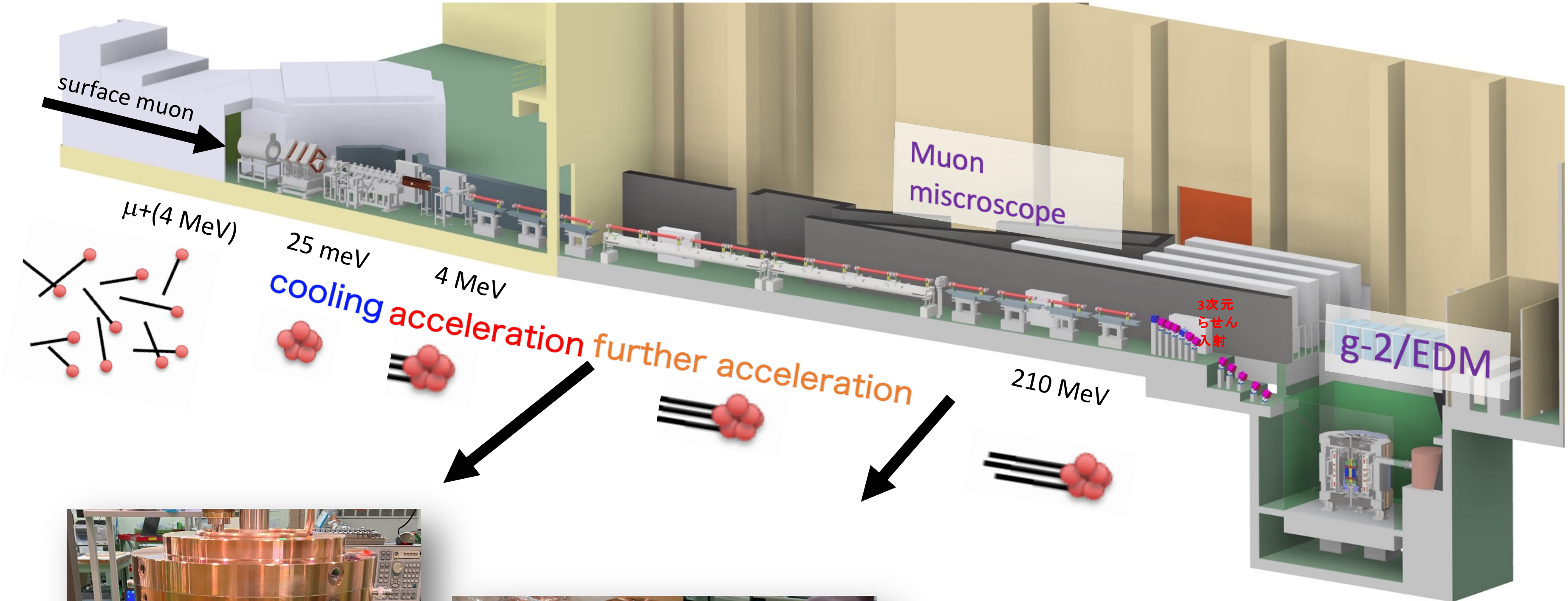
FY2025-2027

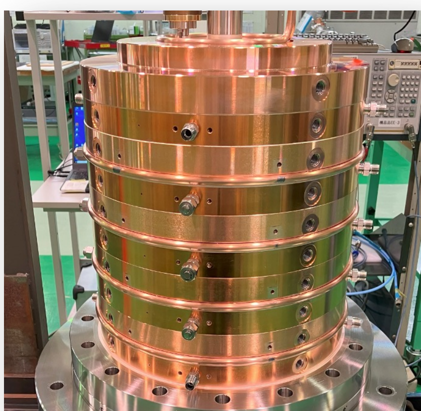




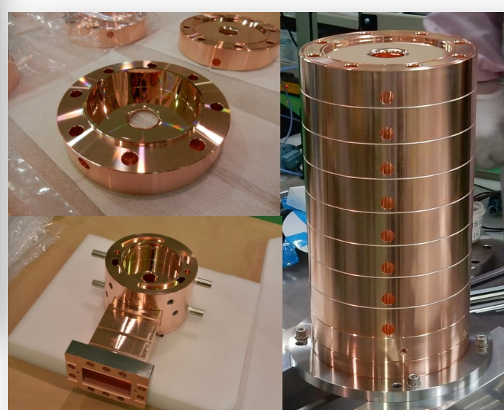
Currently, the cavity is located at J-PARC LINAC.

Future: acceleration to 210 MeV



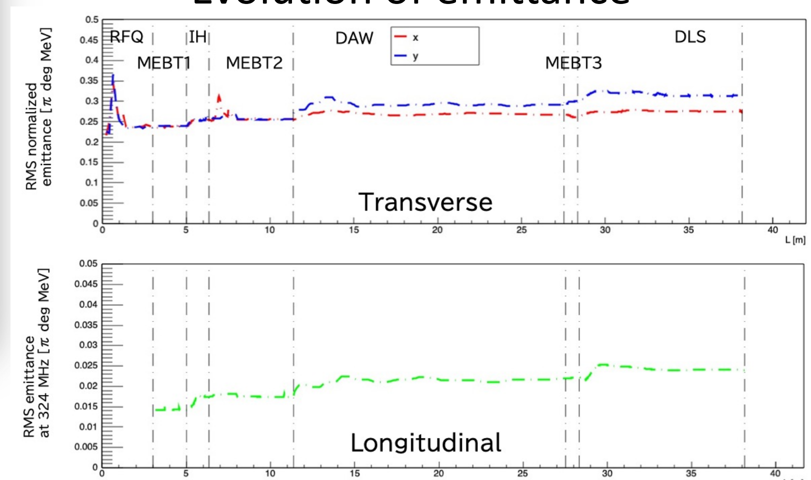


Disk And Washer (DAW)
(from 4 MeV to 40 MeV)

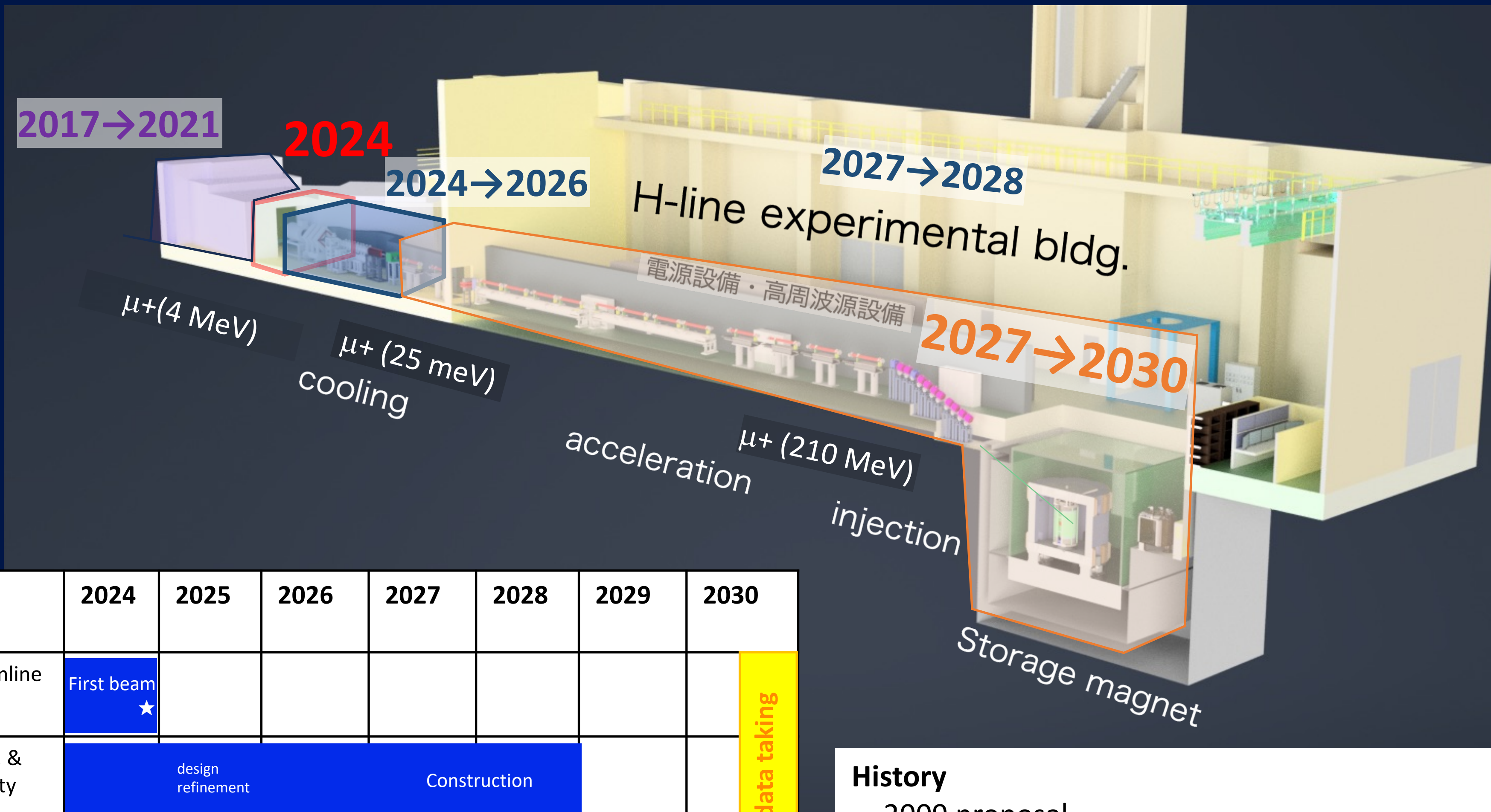


Disk Load Structure (DLS)
(from 40 MeV to 210 MeV)

Evolution of emittance



Muon g-2/EDM : intended schedule

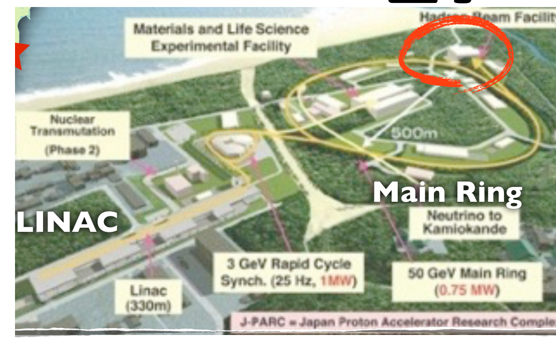


		2024	2025	2026	2027	2028	2029	2030
Beamline		First beam ★						Commissioning, data taking
Bldg. & facility			design refinement		Construction			Commissioning, data taking
Source, LINAC, storage	source		★ Ionization test with 1S-2P-unbound					Commissioning, data taking
	LINAC				★4.3 Me@H2		210 MeV ★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

History

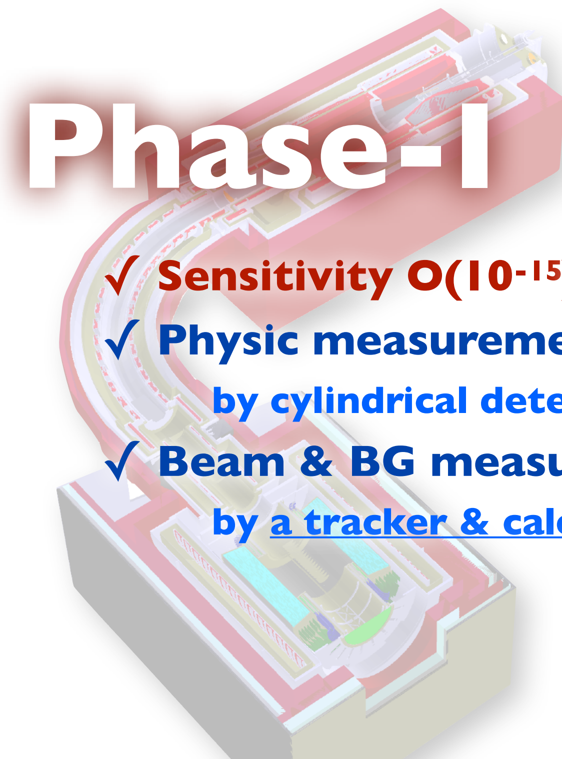
- 2009 proposal
- 2015 TDR
- 2016 IPNS focused review
- 2016 SAC (priority #3)
- 2019 KEK-IPNS stage-2, KEK-IMSS stage-2
- 2024 MEXT funding (construction)

COMET



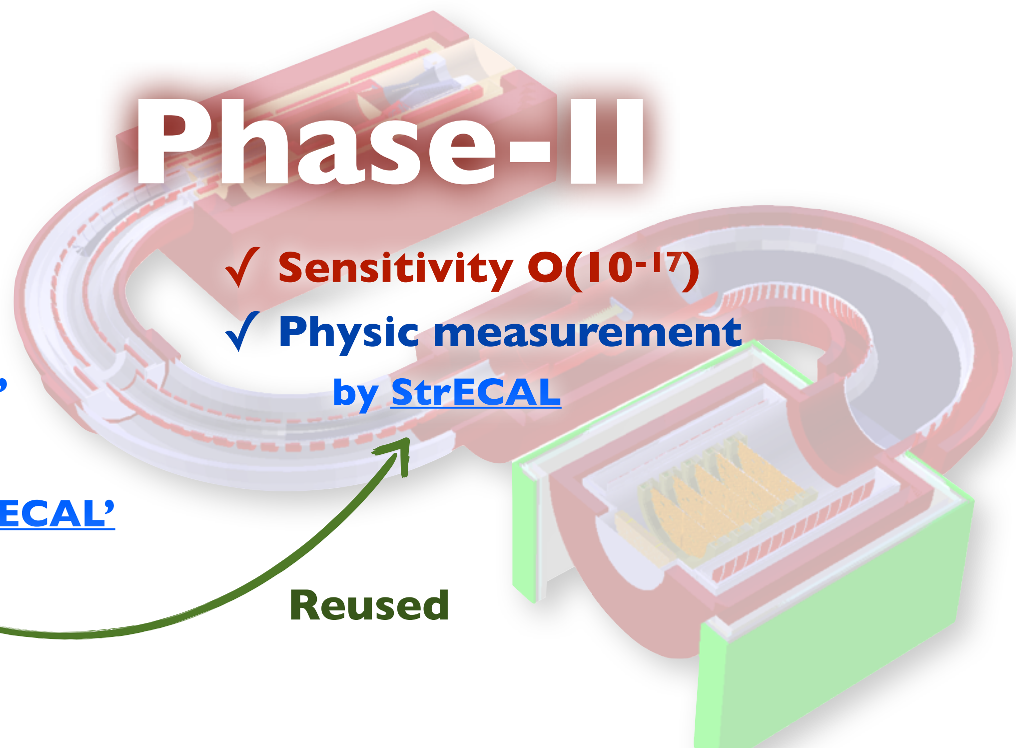
Searching for μ-e conversion at J-PARC

- The final goal: **$O(10^{-17})$** sensitivity.
  - $10,000\times$ improvement over the current limit.
- Dedicated facility and muon transport line being constructed.
- Two-staged plan: Phase-I and Phase-II



Phase-I

- ✓ **Sensitivity $O(10^{-15})$**
- ✓ **Physic measurement**
  by cylindrical detectors ‘CyDet’
- ✓ **Beam & BG measurement**
  by a tracker & calorimeter ‘StrECAL’



Phase-II

- ✓ **Sensitivity $O(10^{-17})$**
- ✓ **Physic measurement**
  by StrECAL

Reused

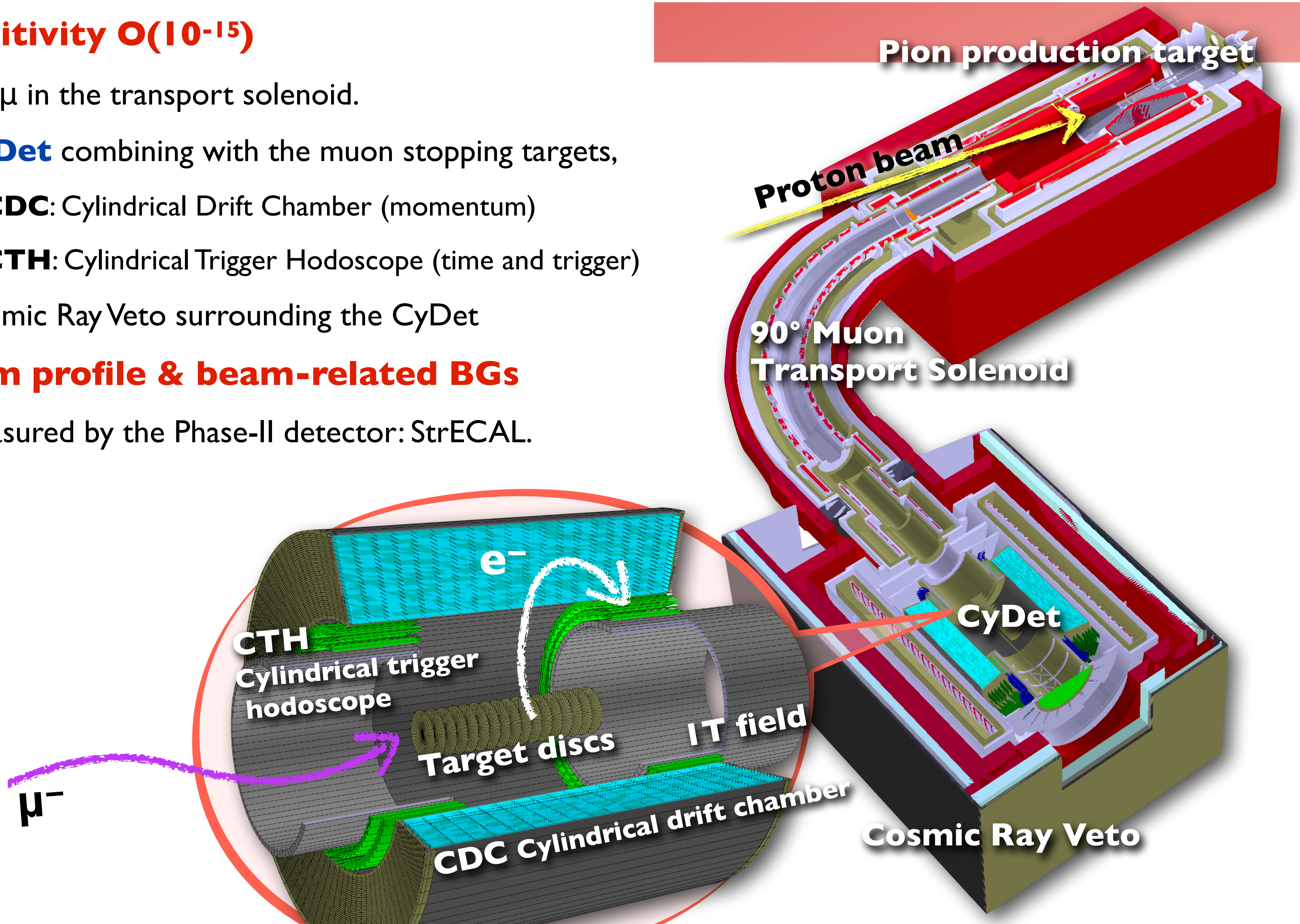
COMET Phase-I

Sensitivity O(10^{-15})

- $\pi \to \mu$ in the transport solenoid.
- **CyDet** combining with the muon stopping targets,
  - **CDC**: Cylindrical Drift Chamber (momentum)
  - **CTH**: Cylindrical Trigger Hodoscope (time and trigger)
- Cosmic Ray Veto surrounding the CyDet

Beam profile & beam-related BGs

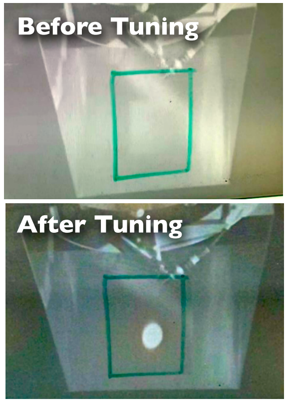
- Measured by the Phase-II detector: StrECAL.



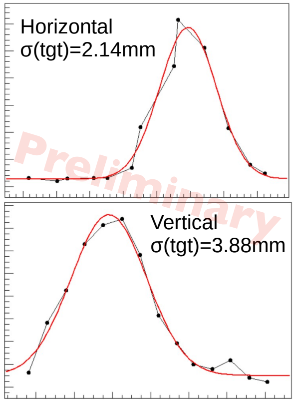
COMET Phase-α
(commissioning w/o capture solenoid)

The 1st Commissioning of the COMET facility in 2023

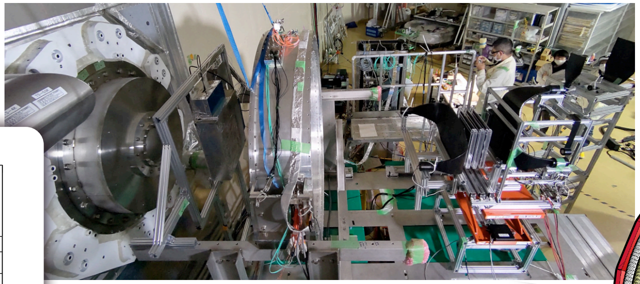
- ✦ Proton Beam
  - ★ Slow-extracted pulsed 8 GeV proton beam at 260 W (~1/10 of Phase-I)
  - ★ Beam tuning and profile measurement were well performed.
- ✦ The muon beam was successfully transported by the TS.
  - ★ Muon momentum spectrum was measured for the first time!



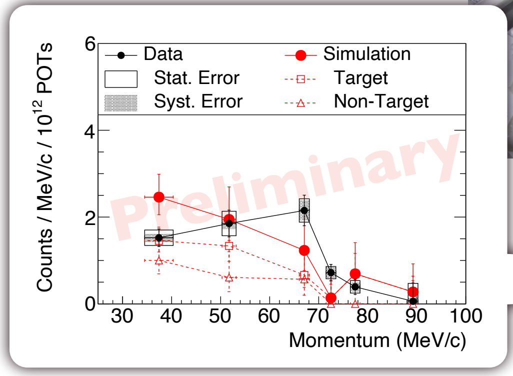
Phosphor plate response before and after beam tuning

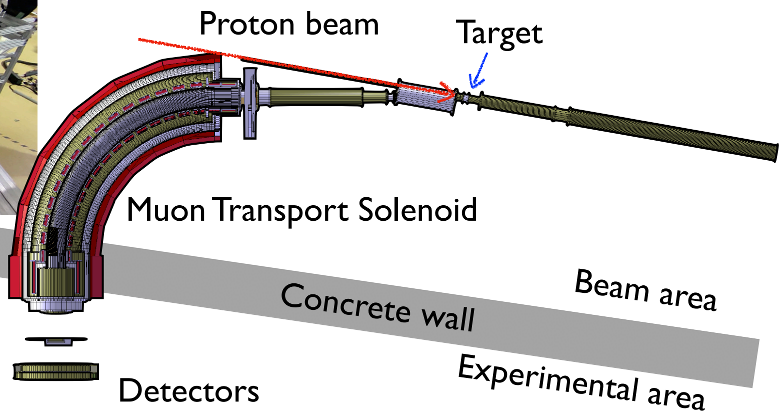


Measured beam size



Phase-α Detectors





Installation of capture solenoid

slide by K. Oishi

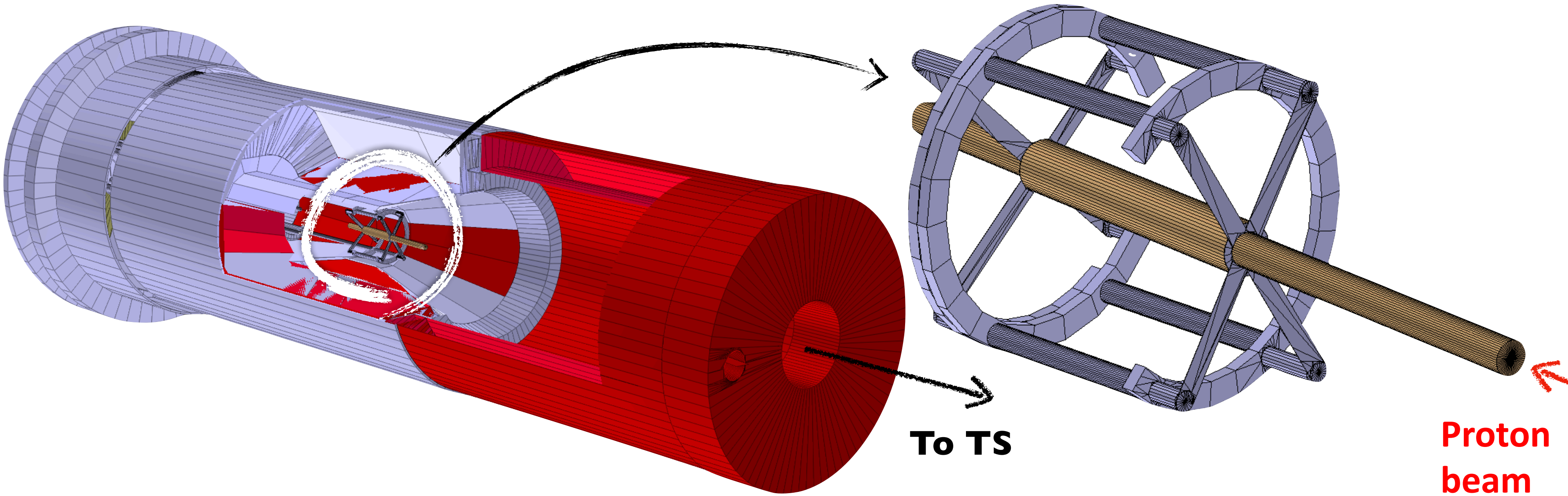
Pion capture solenoid

Proton Target

- Graphite (Tungsten) for Phase-I (II).

Pion capture solenoid

- 4.4 T superconducting magnet
- Pions extracted in the backward direction.
    - Better exclusive collection of low-momentum pions
- Delivered and installed in 2024!



COMET : schedule

Single Event Sensitivity (SES) Phase-I

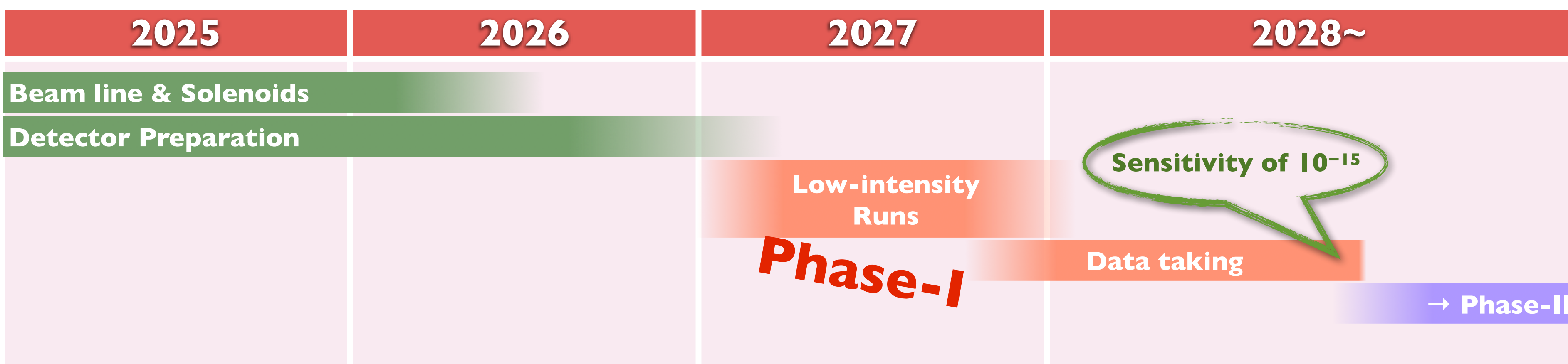
✦ Estimated **3×10^{-15}** for 150 days operation.

$$B(\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}) = \frac{1}{N_\mu \cdot f_{\mathrm{cap}} \cdot f_{\mathrm{gnd}} \cdot A_{\mu\text{-}e}} = 3 \times 10^{-15}$$

- ★ **N_μ = 1.5×10^{16}** : the number of muons stopped in the target
- ★ **f_{cap} = 0.61** : the fraction of captured muons to total muons on target
- ★ **f_{gnd} = 0.9** : the fraction of μ-e conversion to the ground state in the final state
- ★ **$A_{\mu\text{-}e}$ = 0.041** : the net acceptance for the μ-e conversion signal (see below)

10^{10} muon/sec
10^{9} muon stop/sec

Phase-II
~10^{11} muon/sec
~10^{10} muon stop/sec



Summary

- **J-PARC will start to survey NP in dipole moments and cLFV in coming years.**

- **J-PARC will deliver enablers for future facilities.**
- **Intense muon source**
  - 10^7 μ/sec (conventional)
  - **10^{10} μ/sec (COMET Phase-I, 2028)**
  - 10^{13} μ/sec for 0.1 ab^{-1}/year
- **Muon cooling**
  - Large phase space due to tertiary beam
  - Normalized emittance = 1,000 π mm mrad (conventional)

    1π mm mrad (200 MeV, g-2/EDM, 2030)

    but, only positive μ …

    1π mm mrad (muTRISTAN $\mu\mu$, 1 TeV)