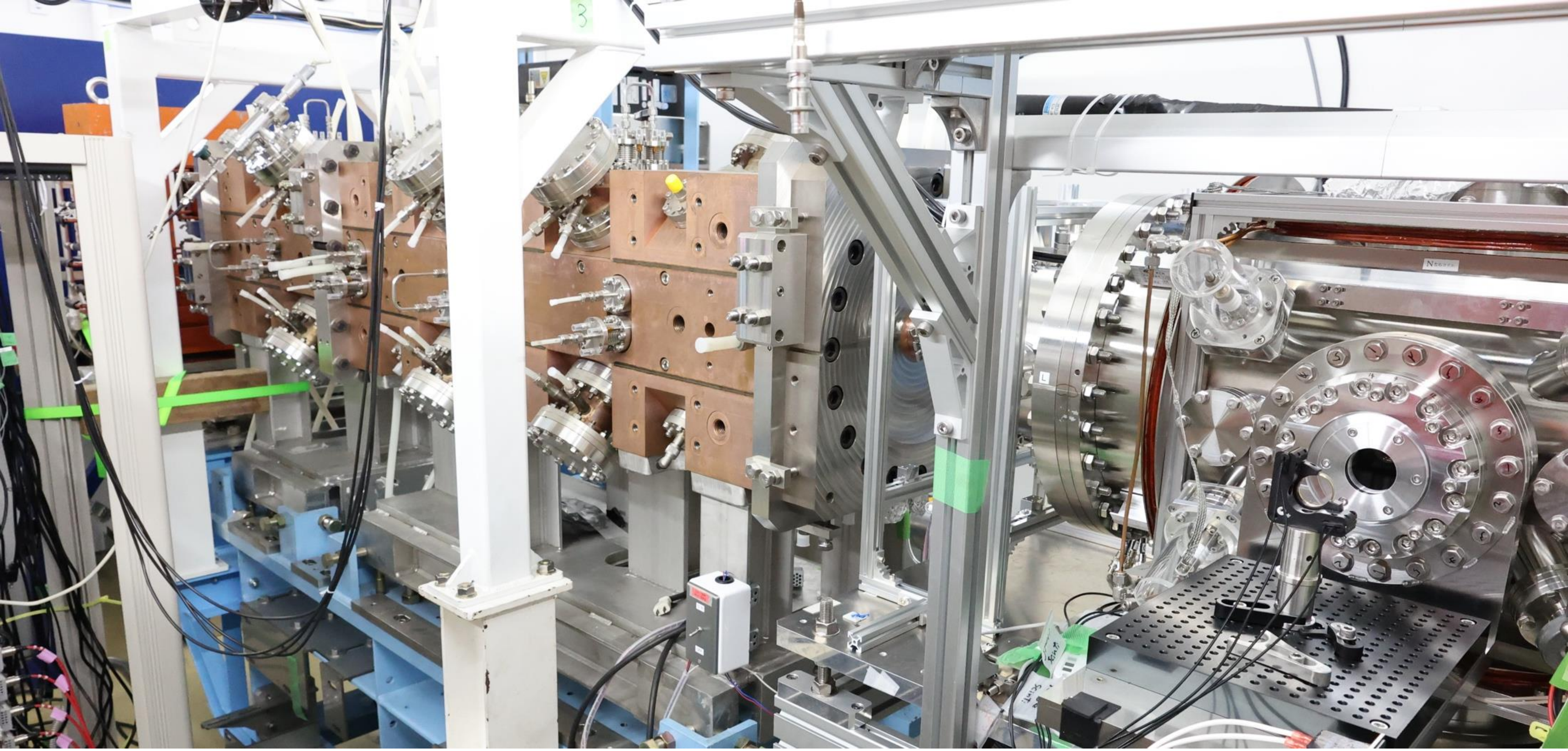
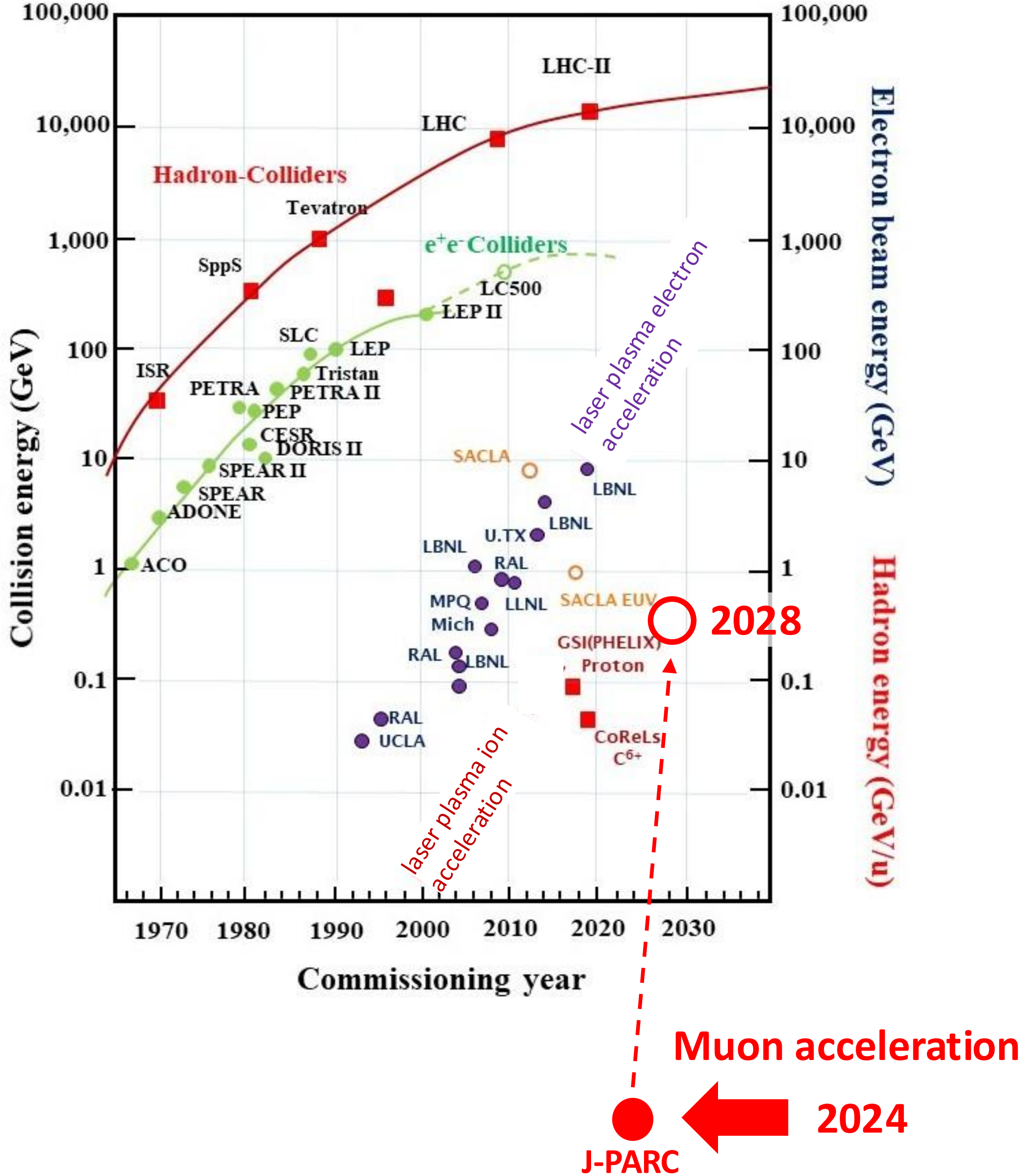


Acceleration of Positive Muon and Precision Measurement of Muon Dipole Moments at J-PARC

October 2, 2024

Tsutomu Mibe (KEK)

History of accelerator technology



Experimental particle physics with muon

THE IBARAKI SHIMBUN　2024年(令和6年)6月16日　日曜日　©茨城新聞社2024　(日刊)

茨城新聞　6月16日　日曜日

ミューオン加速器開発

世界初 実証に成功

高エネ研・茨城大など

高エネルギー加速器研究機構（KEK）や茨城大などの研究グループが、物質を通り抜けるミュー粒子（ミューオン）を停止、加速させる技術の実証に世界で初めて成功した。技術開発を進め、2026年にもミューオン加速器が実現する。素粒子理論の検証や人体の細部が観察できる顕微鏡、コンテナ貨物の検査など、さまざまな形での応用に期待がかかる。

ミューオンは、宇宙から地球に降り注ぐ「宇宙線」の一種。高い透過性を持つことから建物の内部を透視する際などに使われ、東京電力福島第1原発の炉内調査やピラミッド探索などに用いられた。加速器を使って人工的に作ることはできるが、向きや速さのばらつきが大きく、実験の多くで効率よく活用できていなかった。

ミューオンにはプラスとマイナスの電荷があり、プラスの電荷を持つ正ミューオンは、ほぼ止まるまで減速して向きや速さをそろえる（冷却する）ことができる。その上で加速すれば、向きや速さがそろった指向性の高いミューオンビームが実現する。

研究グループは23年3月〜24年4月、J-PARC物質・生命科学実験施設（東海村）で試験を実施。ミューオンをガラスと同じ素材に打ち込み、レーザーを照射することでほぼ停止状態とした正ミューオンを生成。高周波電場をかけ、光速の4%まで加速させることに成功した。実証は世界初という。

今後はミューオンを4段階で加速させる加速器（全長約50㍍）を同施設に設置。26年度に光速30%で運用を開始し、28年度に光速94%

ミューオンの停止や加速の技術について説明する三部勉教授＝東海村白方

水面を色鮮やかに彩るスイレン＝15日、常陸太田市大中町

茨城新聞社
〒310-8686
水戸市笠原町978-25
電話(029)239-3001㈹
http://ibarakinews.jp
編集局
電話(029)239-3020
FAX(029)301-0362
購読申し込みは
0120-029-218
(平日午前9時〜午後5時)

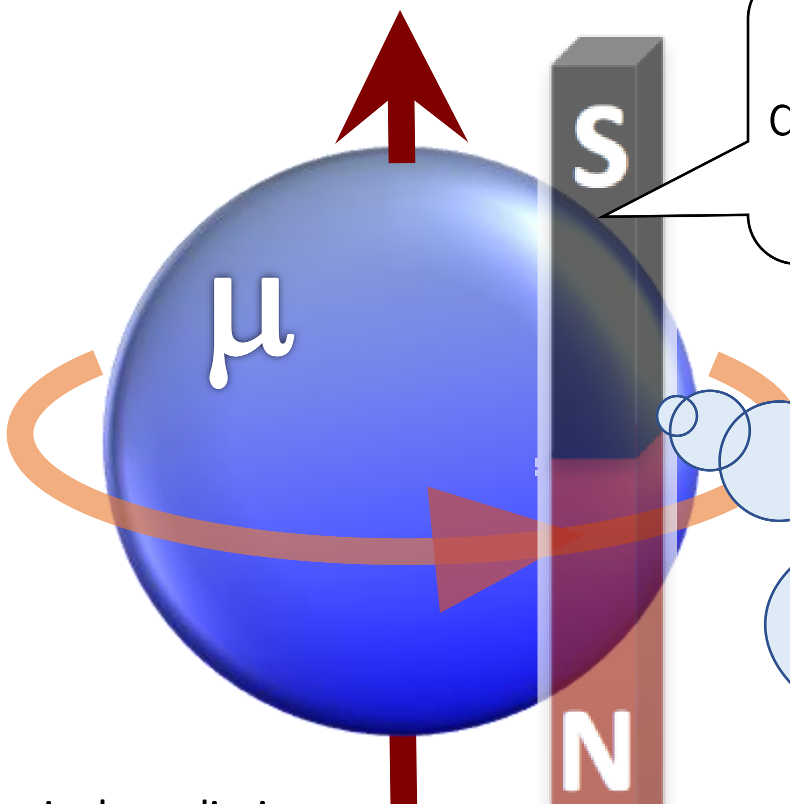
Muons first accelerated in 2024

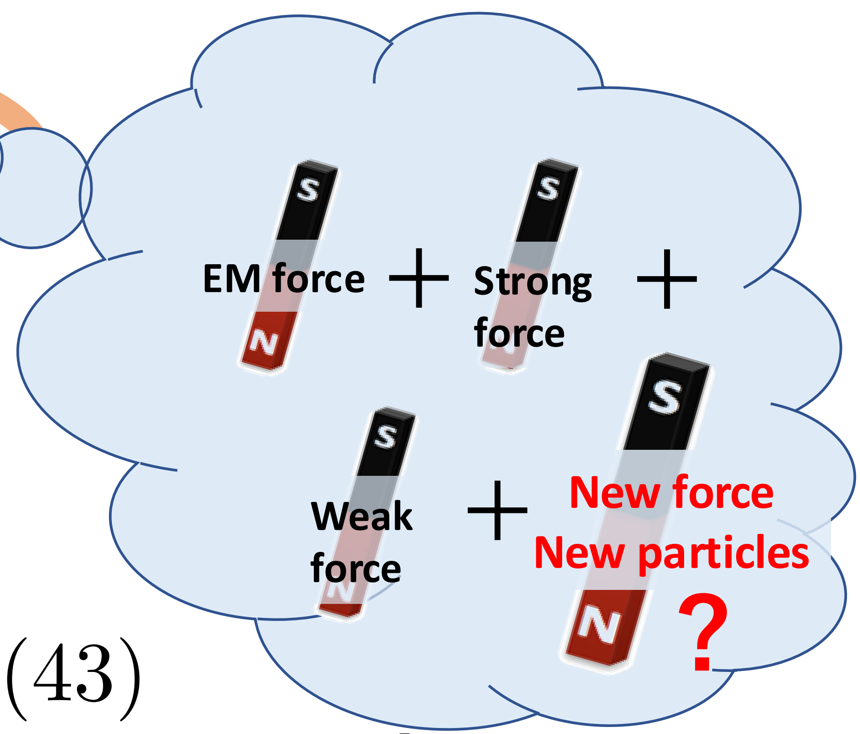
祝「μ加速元年」

Anomalous magnetic moment : g-2

The most precisely calculated physical quantity to date

Strength of the magnet **(g-2)** is determined by **ALL** particles and interactions





Theoretical prediction

$$\frac{g-2}{2} = 0.00116591810(43)$$

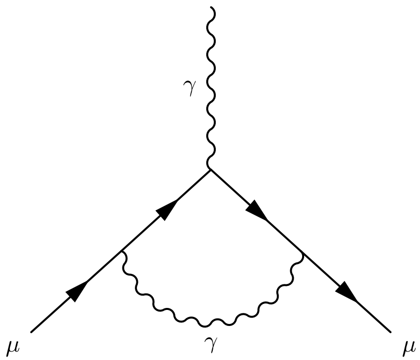
(digits numbered 1 2 3 4 5 6 7 8 9)

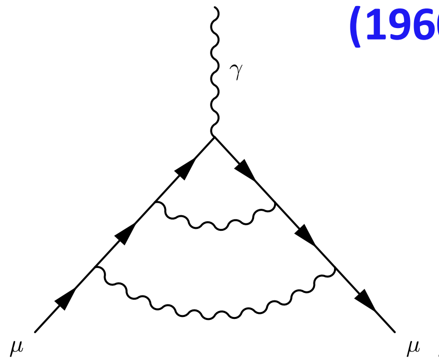
uncertainty 4 parts in 10^7

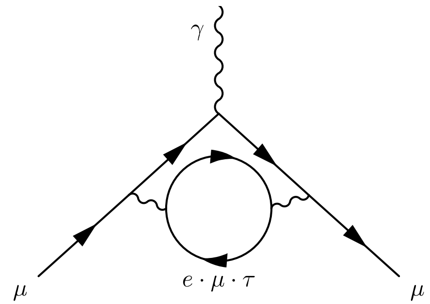
Breakdown of *g-2* contributions

Quantum electro dynamics (QED)

electron g-2, atomic spectroscopy (1960's~)







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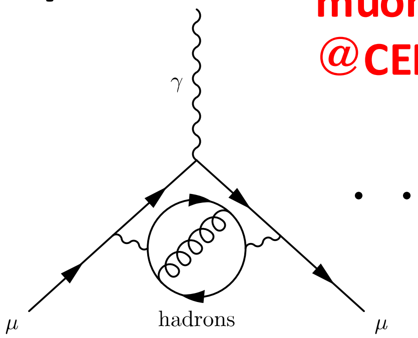
Quantum Chromo Dynamics (QCD)

muon g-2 @CERN(1970's~)



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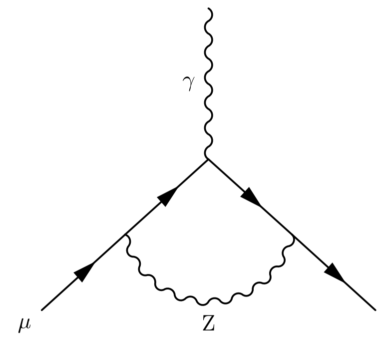
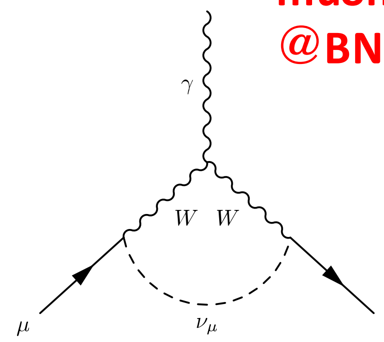
Weak interaction (EW)

muon g-2 @BNL (1990's~)





. . .

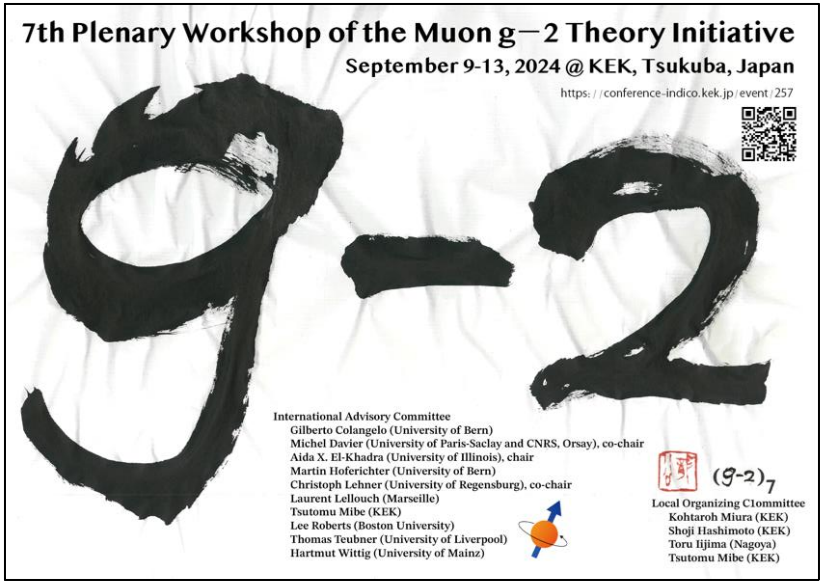
Muon g-2 theory initiative

An initiative formed in 2017 by a group of experts on muon g-2 theory towards the precision prediction of muon g-2

Seventh workshop at KEK (Sep 9-13, 2024)

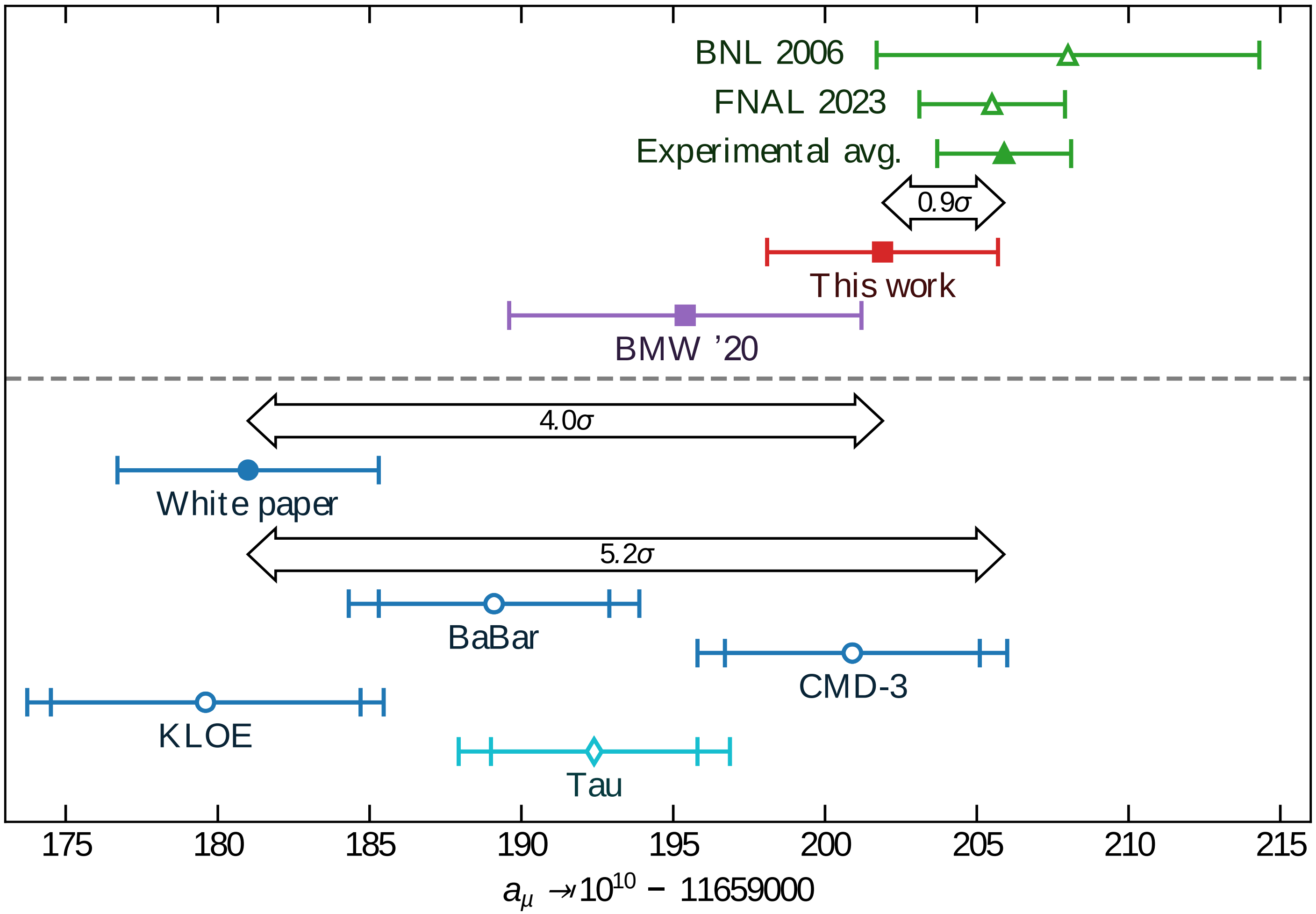
https://conference-indico.kek.jp/event/257/

Thank you very much for many participants from Liverpool!



Standard model theory prediction is work in progress

BMWc + DHMZ, arXiv:2407.10913



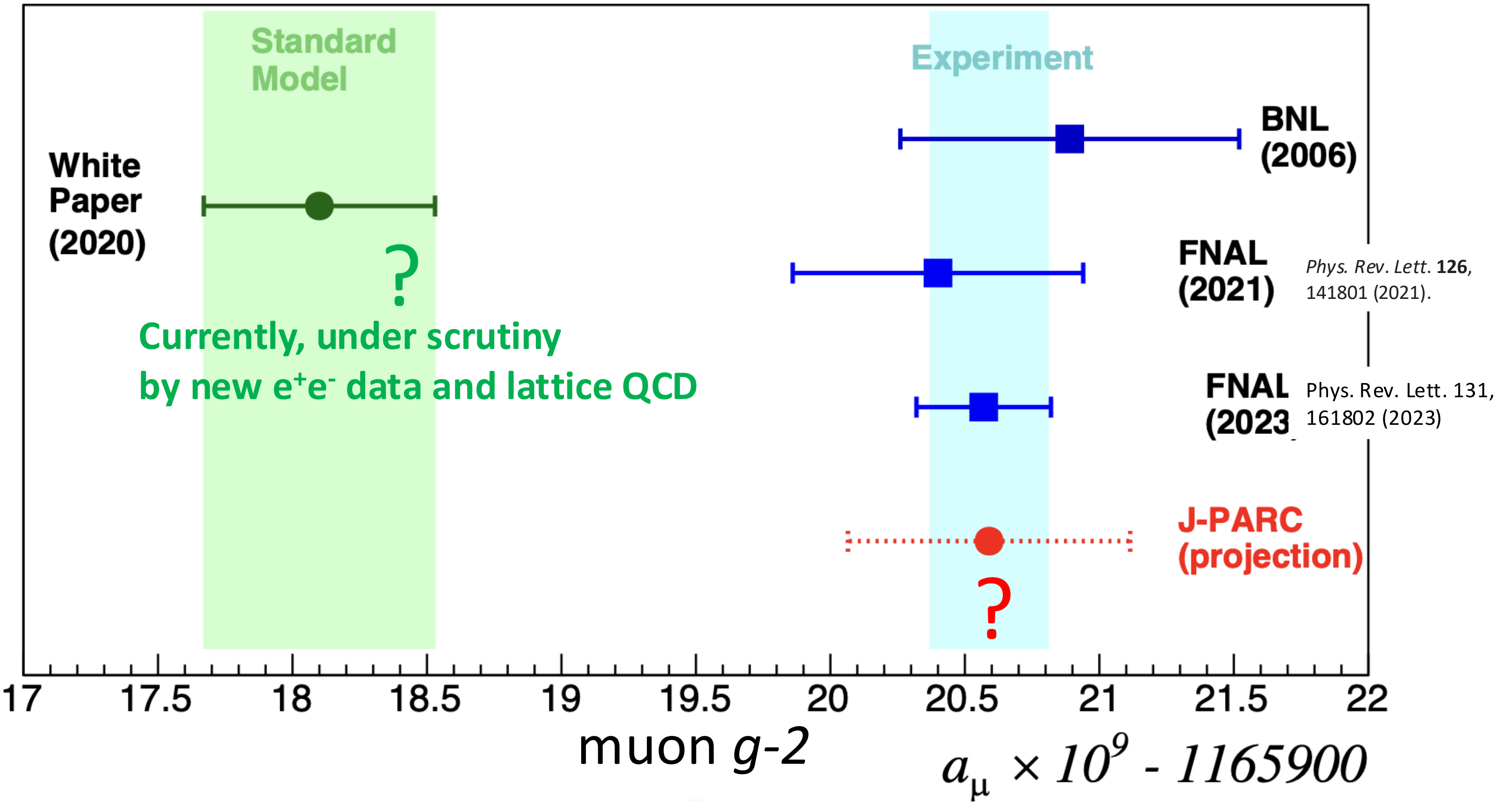
See review slides by Martin Hoferichter in Exploring BSM physics with muons (Sep. 30, 2024)

Status of muon *g-2*

There will be lots of inputs to come on SM predictions.

Check out slides : https://conference-indico.kek.jp/event/257/

White paper will be updated before the FNAL final result (early 2025)



J-PARC will independently test BNL+FNAL results.

School on muon dipole moments

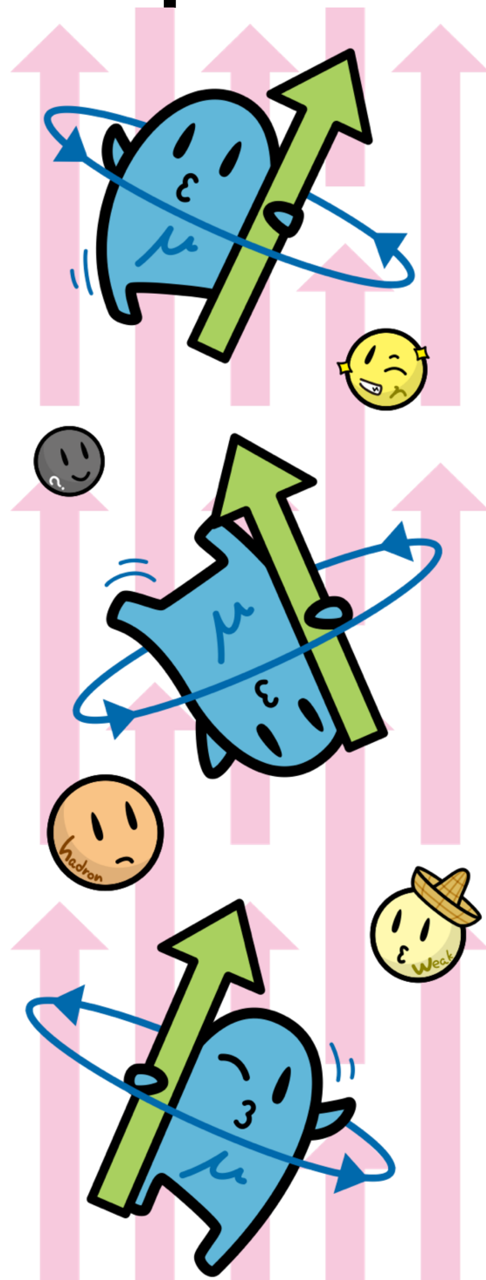
Simon Eidelman School on

Muon Dipole Moments and Hadronic Effects

supported by Wilhelm and Else Heraeus Foundation

Sep 2nd-6th 2024
KMI, Nagoya University, Japan

Web ■ https://indico.kmi.nagoya-u.ac.jp/event/8/
contact ■ muonschool24_contact@hepl.phys.nagoya-u.ac.jp



Topics & Lecturer

Muon magnetic moment: Experiment
Anna Driutti (Pisa)

Muon magnetic moment: Theory
Martin Hoferichter (Bern)

Data input to hadronic vacuum polarization
Zhiqing Zhang (IJCLab)

Lattice QCD: Hadronic vacuum polarization
Aida El-Khadra (UIUC)

Lattice QCD: Light-by-light
Harvey Meyer (Mainz)

Hadronic light-by-light: Phenomenology
Franziska Hagelstein (Mainz)

Hadronic light-by-light: Data input
Andrzej Kupsc (NCBJ/Uppsala)

New physics contributions
Kei Yamamoto (Hiroshima Tech)

Detector technology
Paula Collins (CERN)

Accelerator technology
Mika Masuzawa (KEK)

Precision measurements
Fan Xin (Northwestern)

Monte Carlo generators
Yannick Ulrich (Durham)

Scientific organizers

Achim Denig (Maintz), Boris Shwartz (BINP), Gilberto Colangelo (Bern), Jim Libby (Indian Inst. Tech. Madras), Kenji Inami (Nagoya), Toru Iijima (Nagoya, Chair), Tsutomu Mibe (KEK)

Local organizers

Kazuhito Suzuki (Nagoya), Kazumichi Sumi (Nagoya), Kenji Inami (Nagoya), Masato Kimura (KEK), Seiso Fukumura (Niigata), Toru Iijima (Nagoya), Tsutomu Mibe (KEK), Yuki Sue (Nagoya)

Kobayashi-Maskawa Institute for the Origin of Particles and the Universe

FlaP Flavor Physics International Research Center

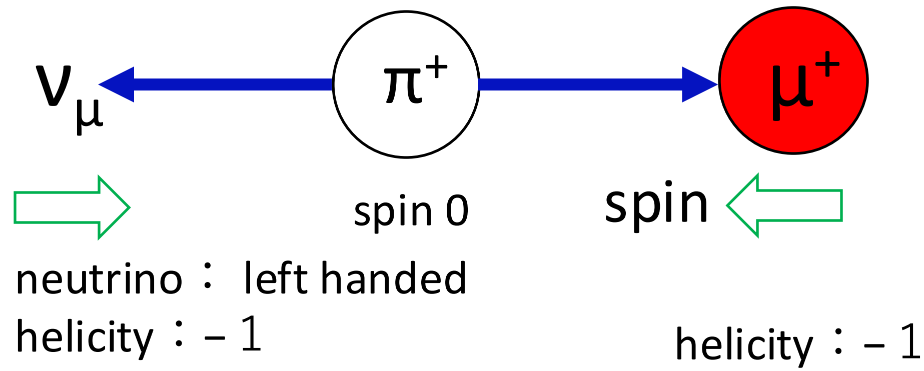
科研費 KAKENHI
22K21347, 22K21347, 22K21350

WILHELM UND ELSE HERAEUS-STIFTUNG

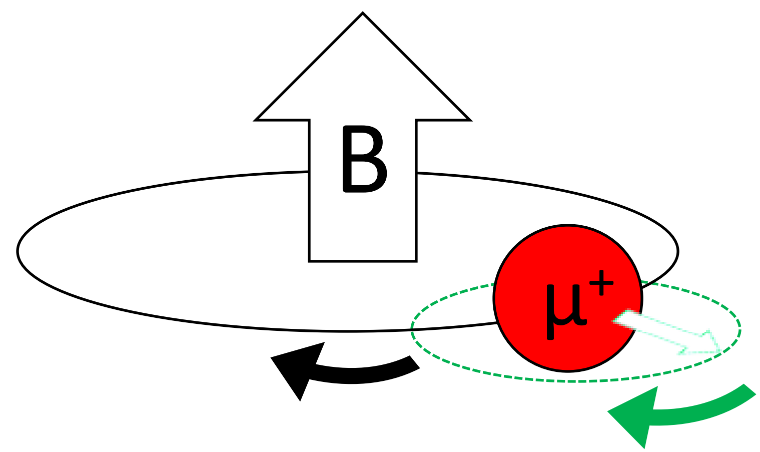
School on muon dipole moments

Experimental steps

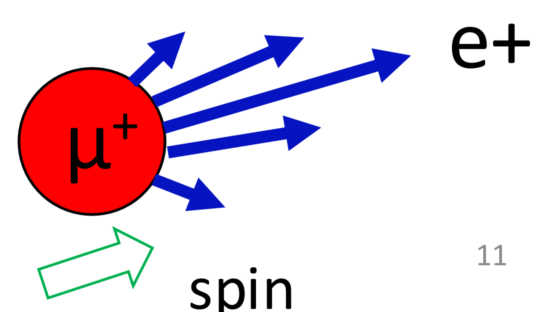
1. Prepare a polarized muon beam.



2. Store in a magnetic field (muon’s spin precesses)

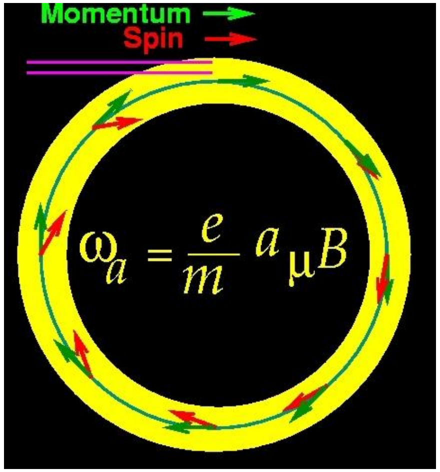


3. Measure decay positron



muon *g*-2 and EDM measurements

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

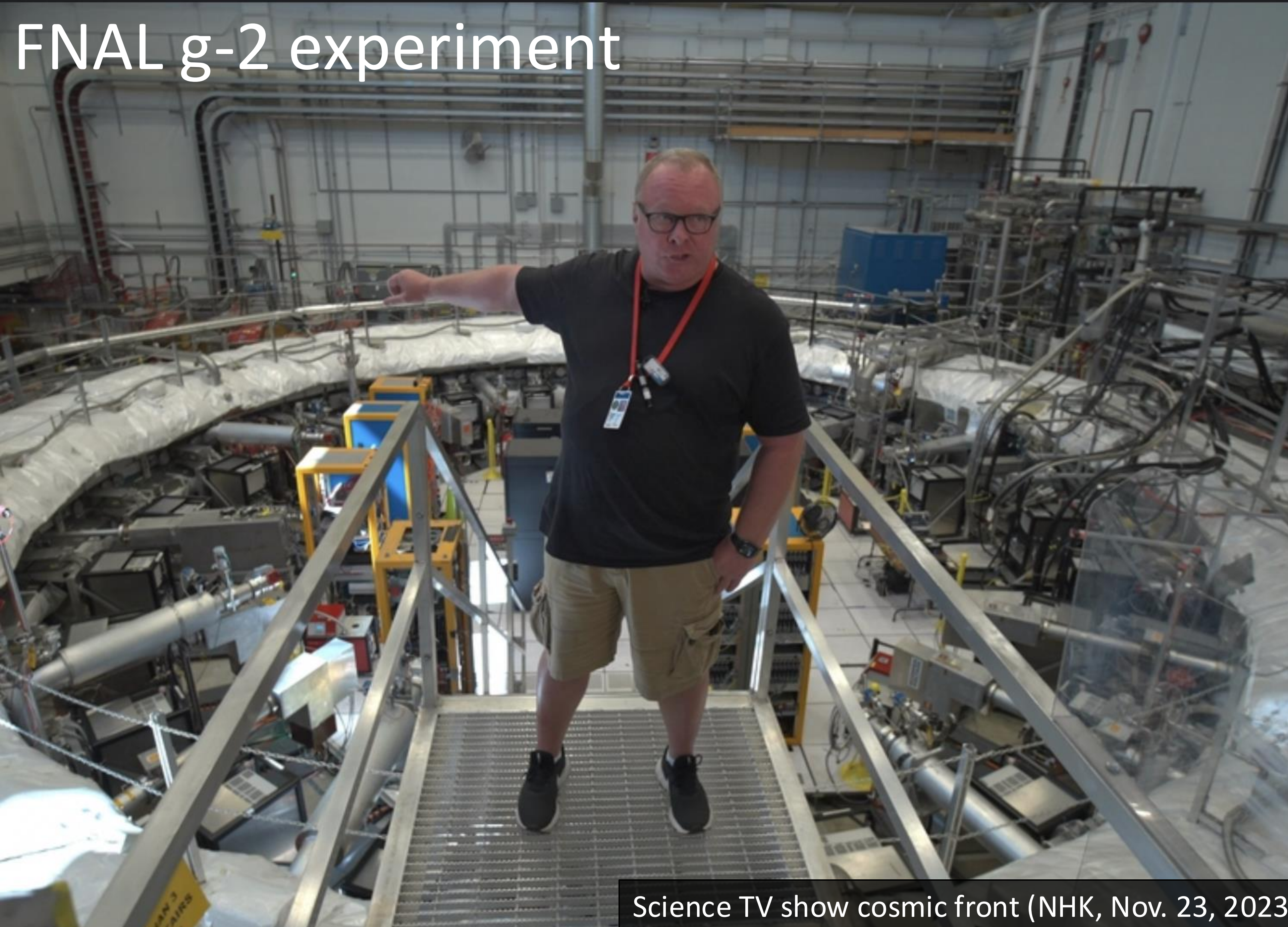
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

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

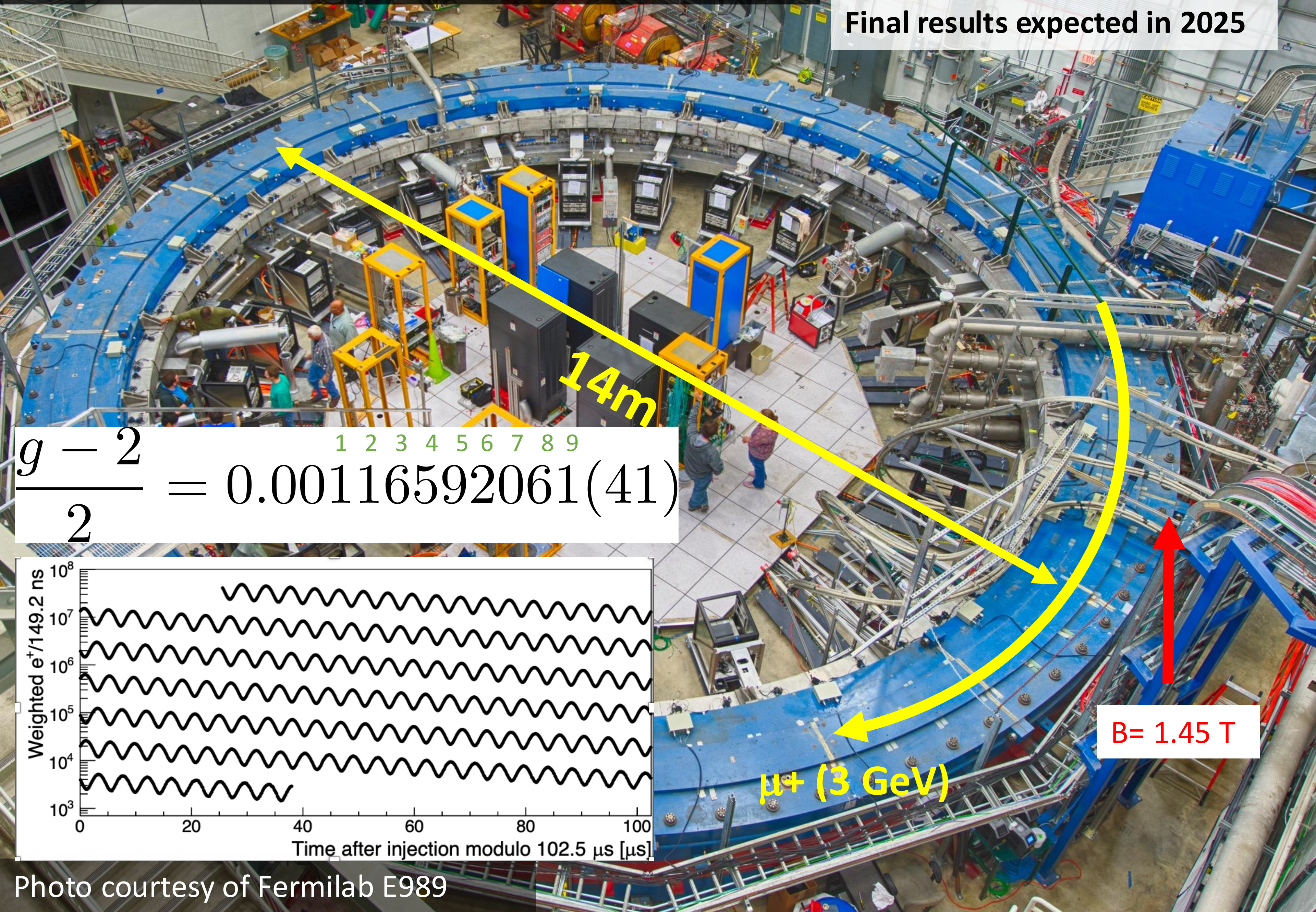
FNAL g-2 experiment



Science TV show cosmic front (NHK, Nov. 23, 2023

FNAL E989 experiment (2018- 2023)

Completed data taking in 2023
Final results expected in 2025

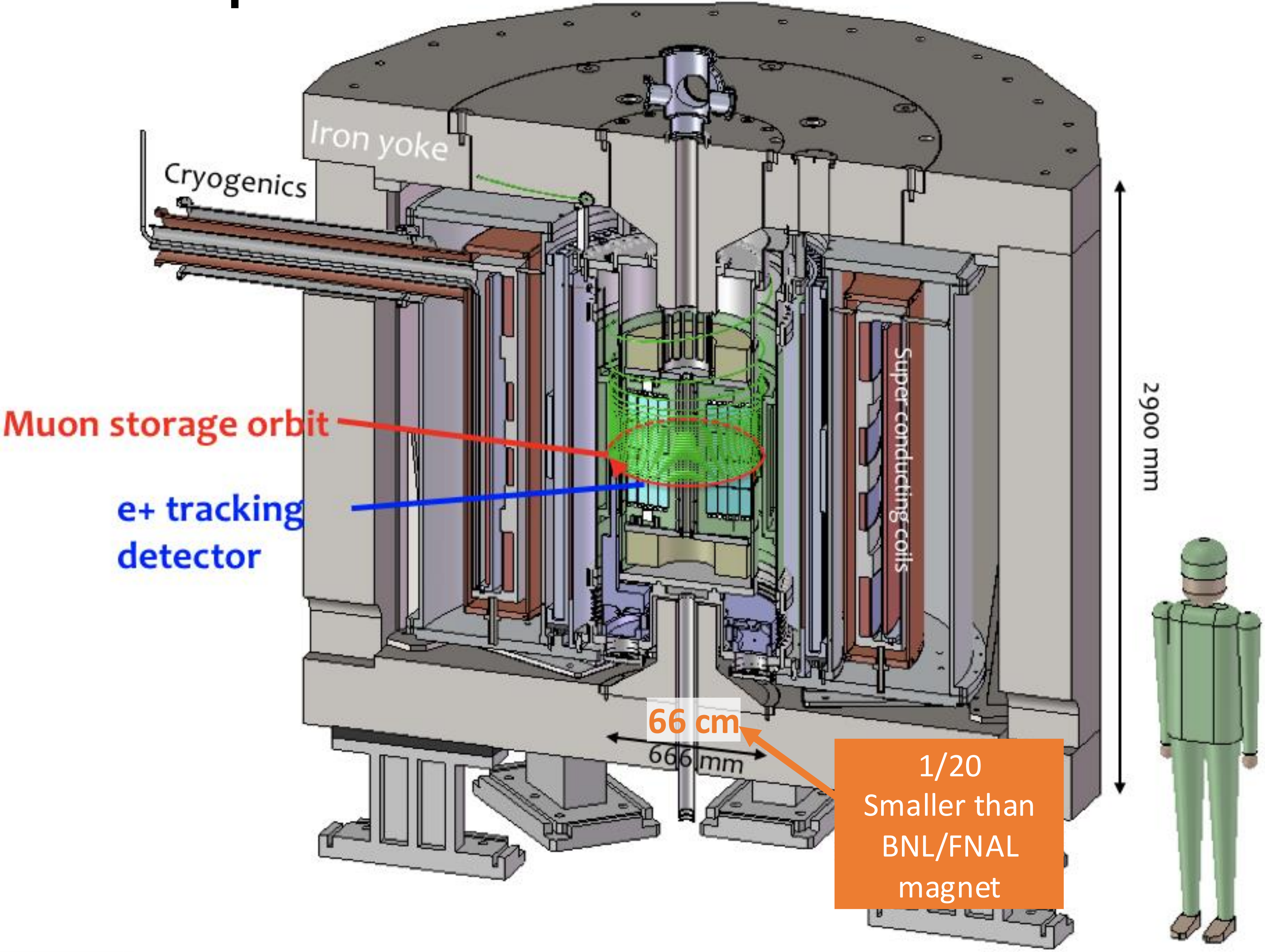


1 2 3 4 5 6 7 8 9

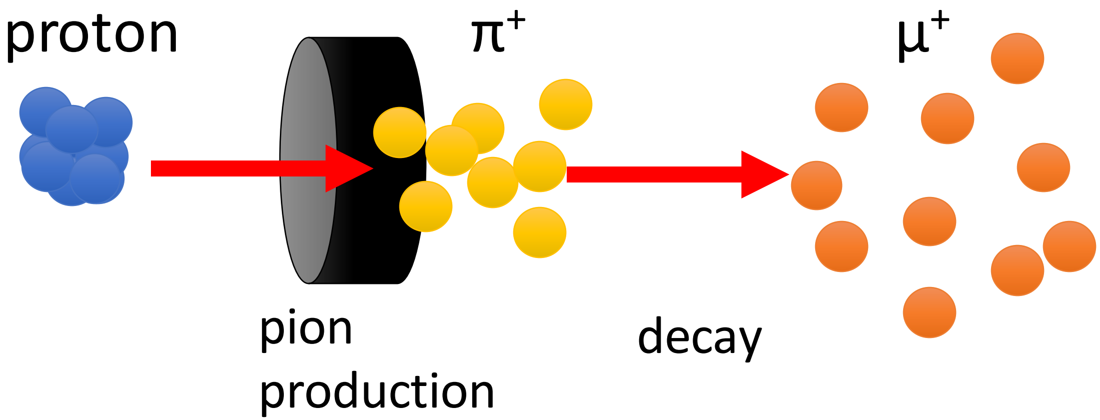
$$\frac{g-2}{2} = 0.00116592061(41)$$

Photo courtesy of Fermilab E989

Independent test of muon g-2 : New experiment at J-PARC



Conventional muon beam



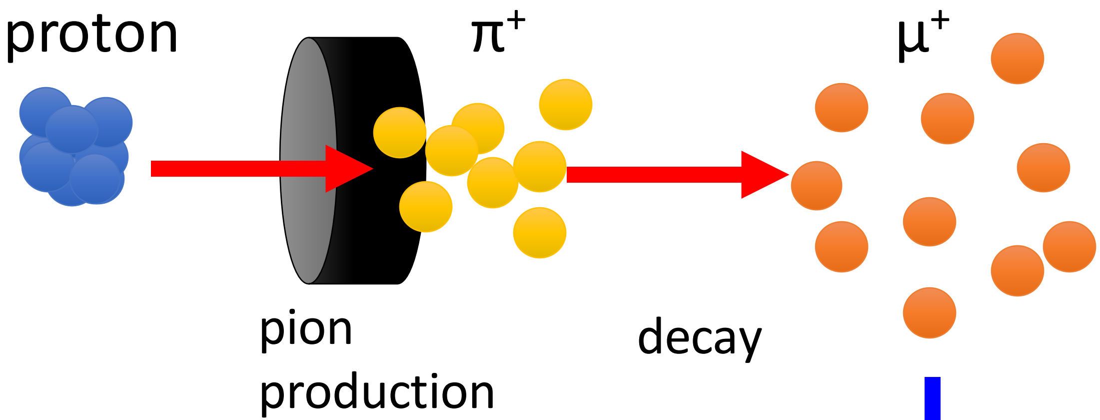
emittance

~1000π mm・mrad

Strong focusing
Muon loss
BG π contamination

Source of systematic uncertainties

Muon beam at J-PARC

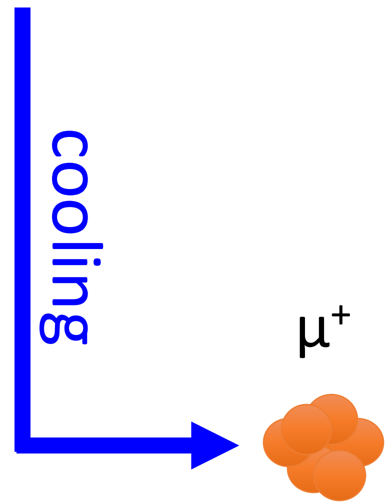


emittance

~1000π mm ･mrad

Strong focusing
Muon loss
BG π contamination

Source of systematic uncertainties



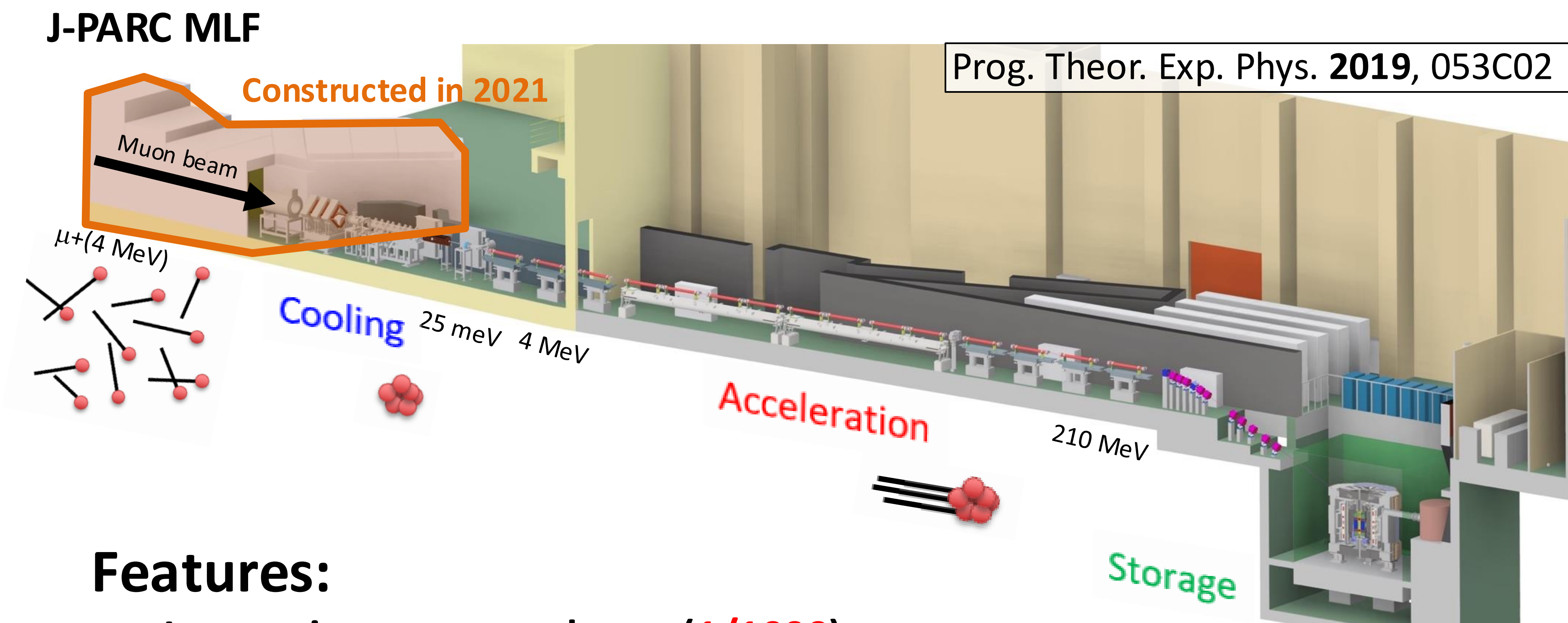
emittance

1π mm ･mrad

Reaccelerated thermal muon

Free from any of these

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



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)

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 $B_r = 0$**

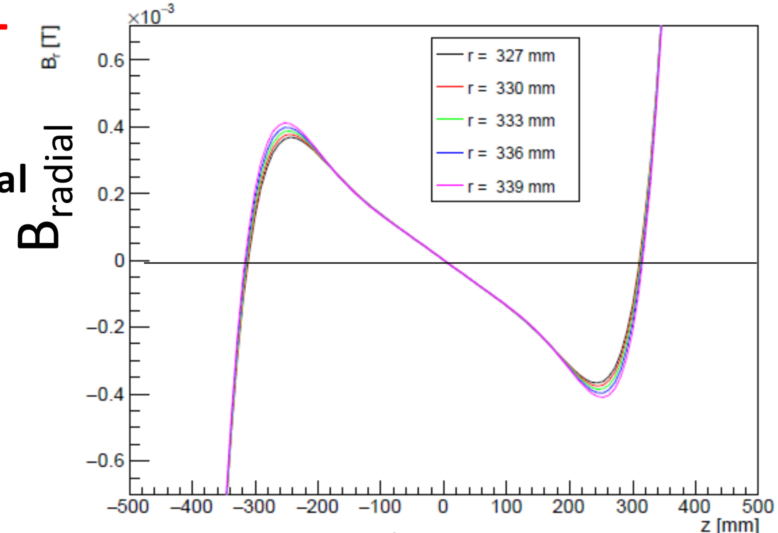
  → no systematics associated with B_{radial}

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

Weak focusing B-field

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

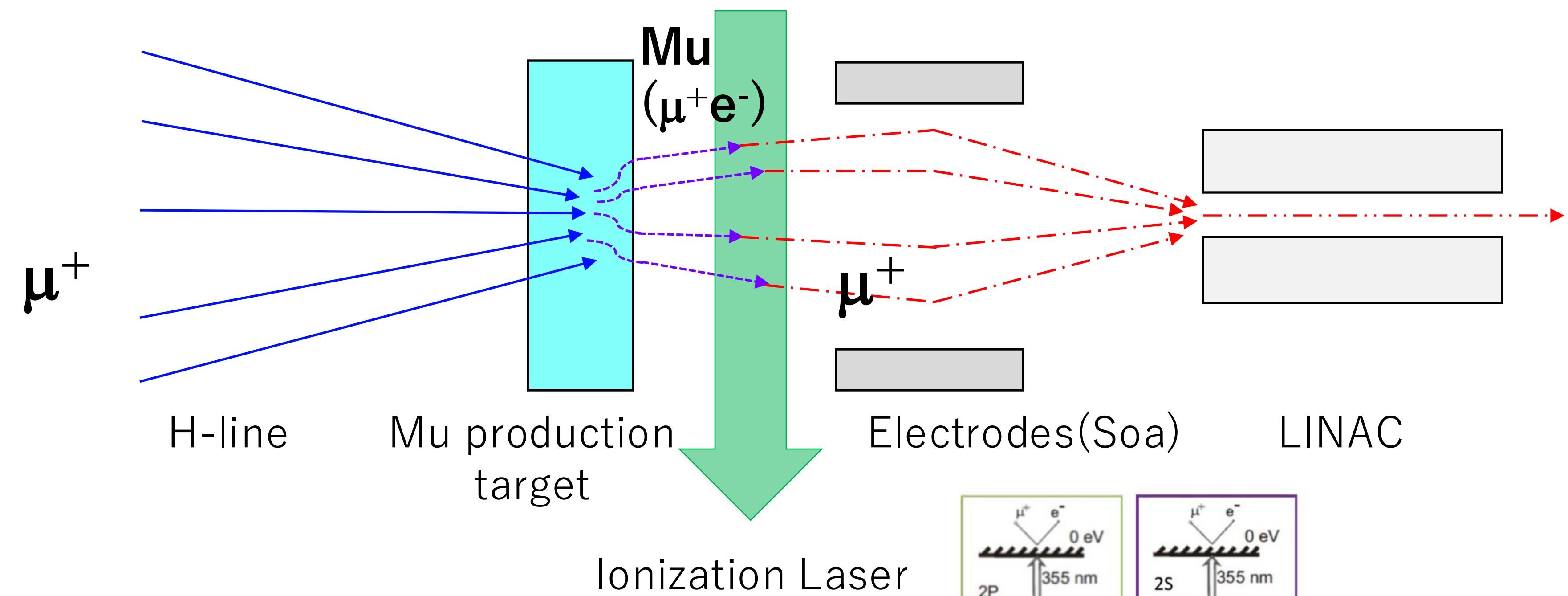
$$B_z = B_{0z} - n\frac{B_{0z}}{R}(r-R) + n\frac{B_{0z}}{2R^2}z^2$$

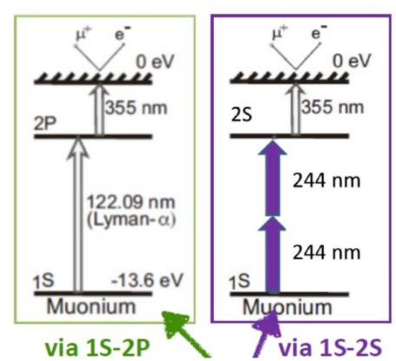


Vertical position

Acceleration of thermal muons

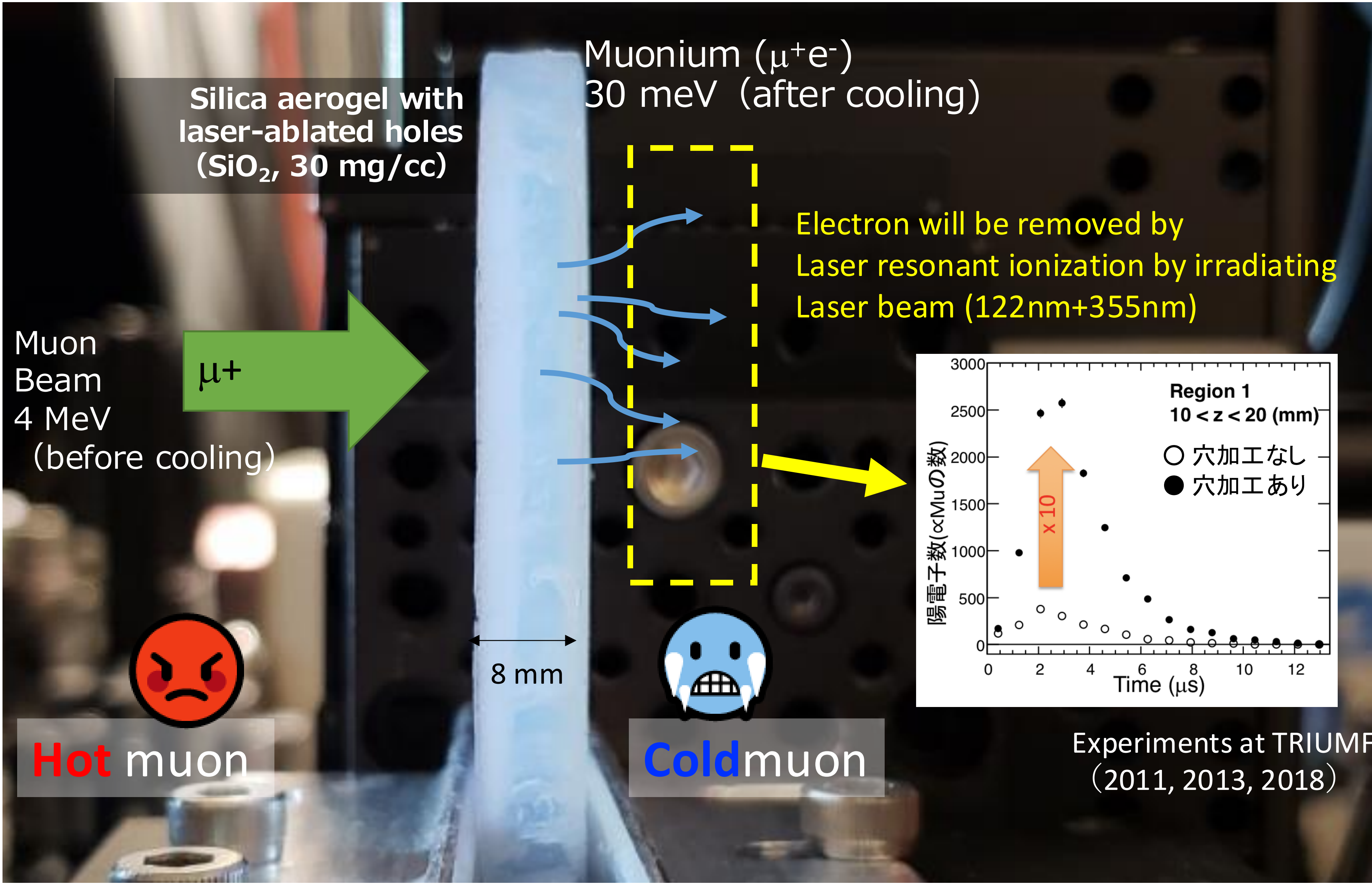
	surface muon	thermal muon	accelerated muon
E	4 MeV	30 meV	212 MeV
p	30 MeV/c	2.3 keV/c	300 MeV/c
Δ p/p	0.05	0.4	4×10^{-4}





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

Muon cooling

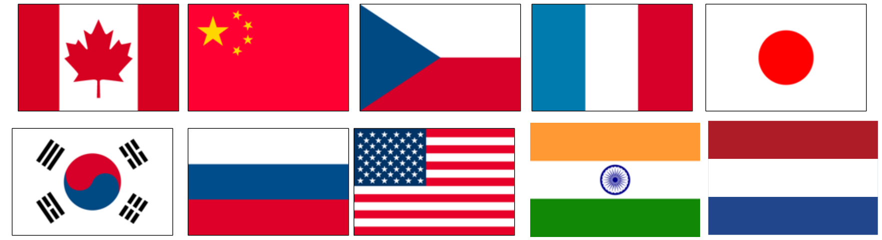


Experiments at TRIUMF (2011, 2013, 2018)

The collaboration

Tamaki Yoshioka (Kyushu)

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



Collaboration board (CB)
Chair: Seonho Choi

2024.3 Shanghai Jiao Tong University
2024.6 Iwate University

Executive board (EB)
Spokesperson: T. Mibe

Subgroups

- **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

Interface coordinators

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

Committees

Speakers committee
chair: K.Ishida, **Y. Sato**

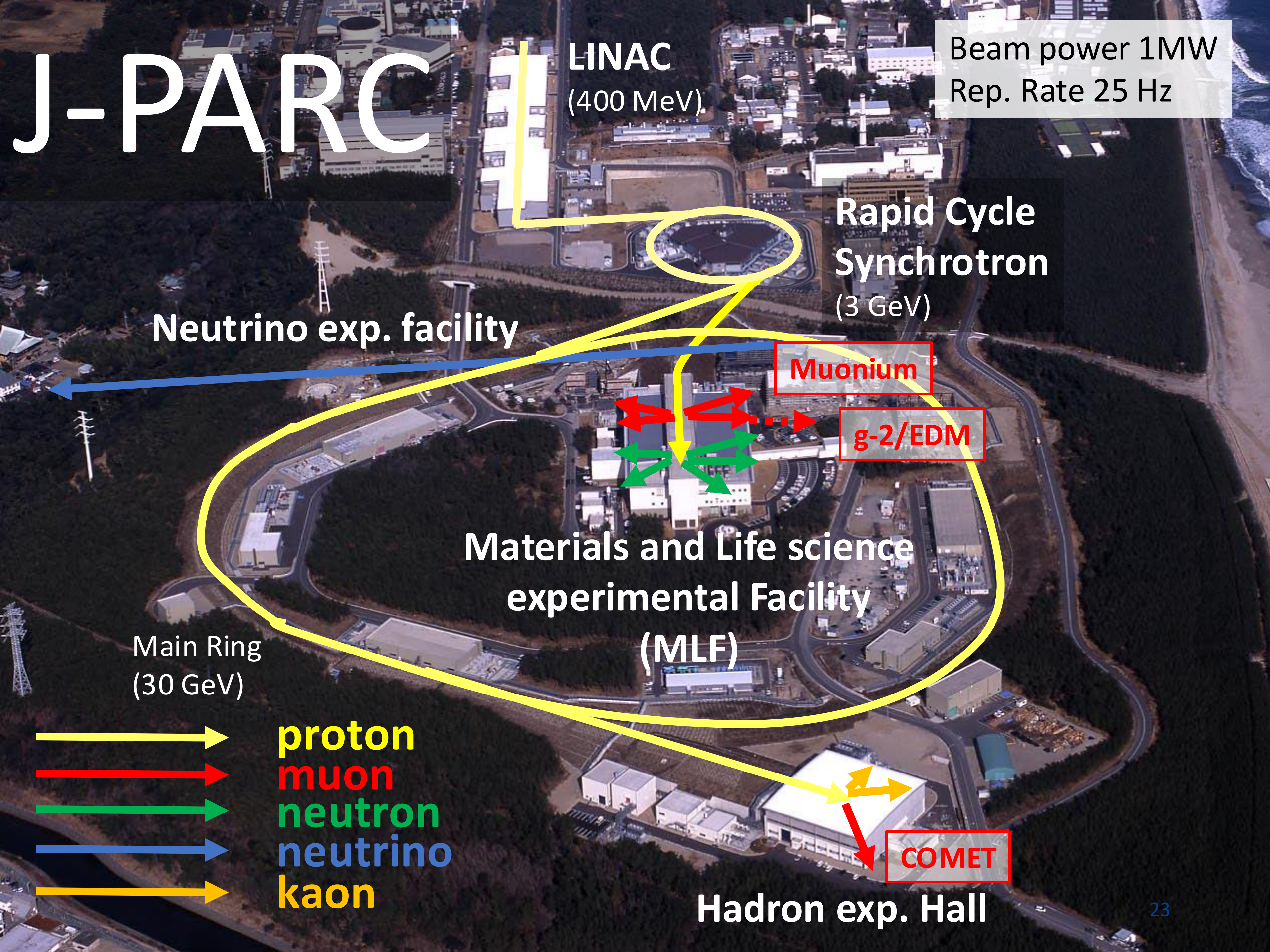
Publication committee
chair: B. Shwartz

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

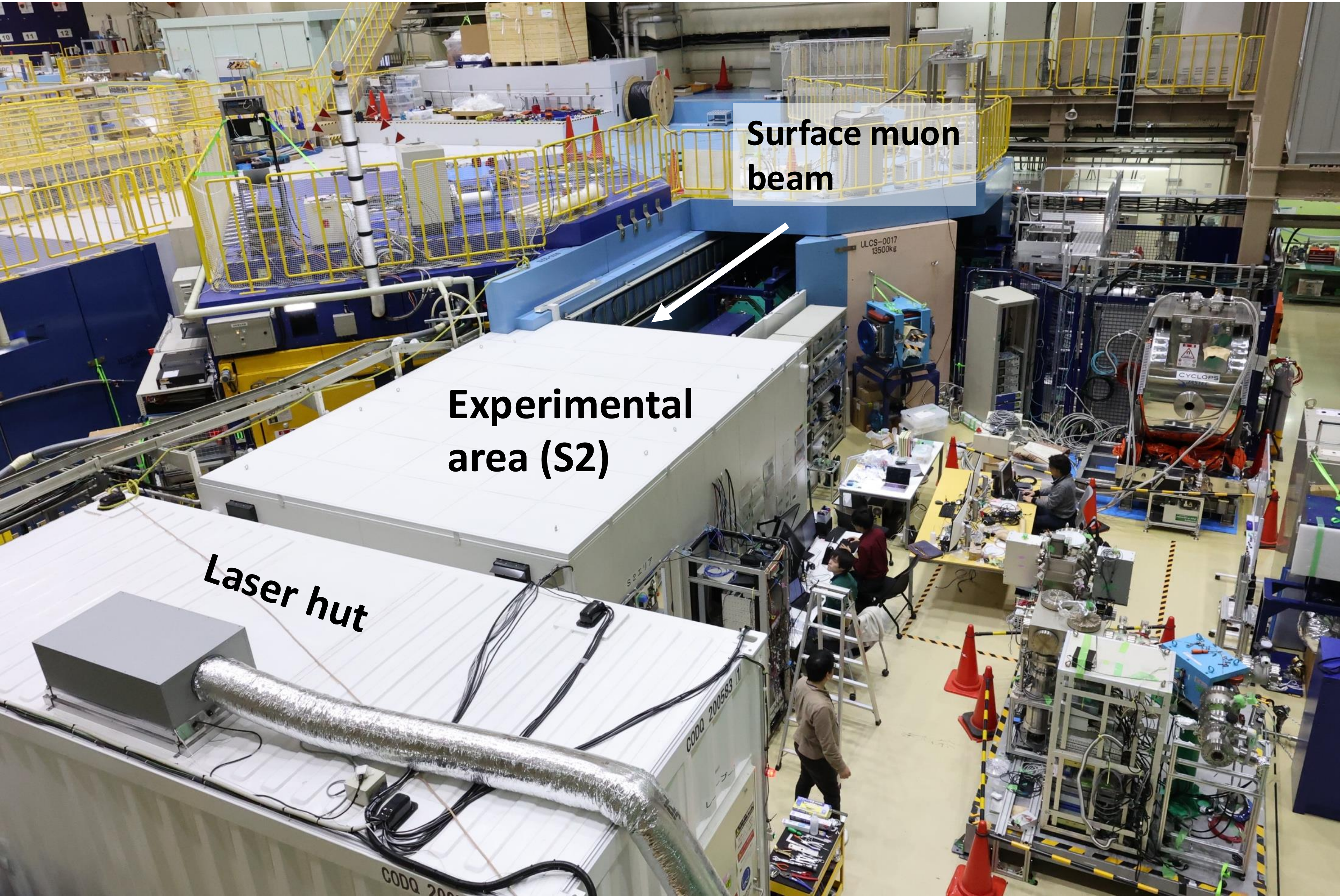
Working groups

physics analysis
T. Yamanaka, S. Ogawa

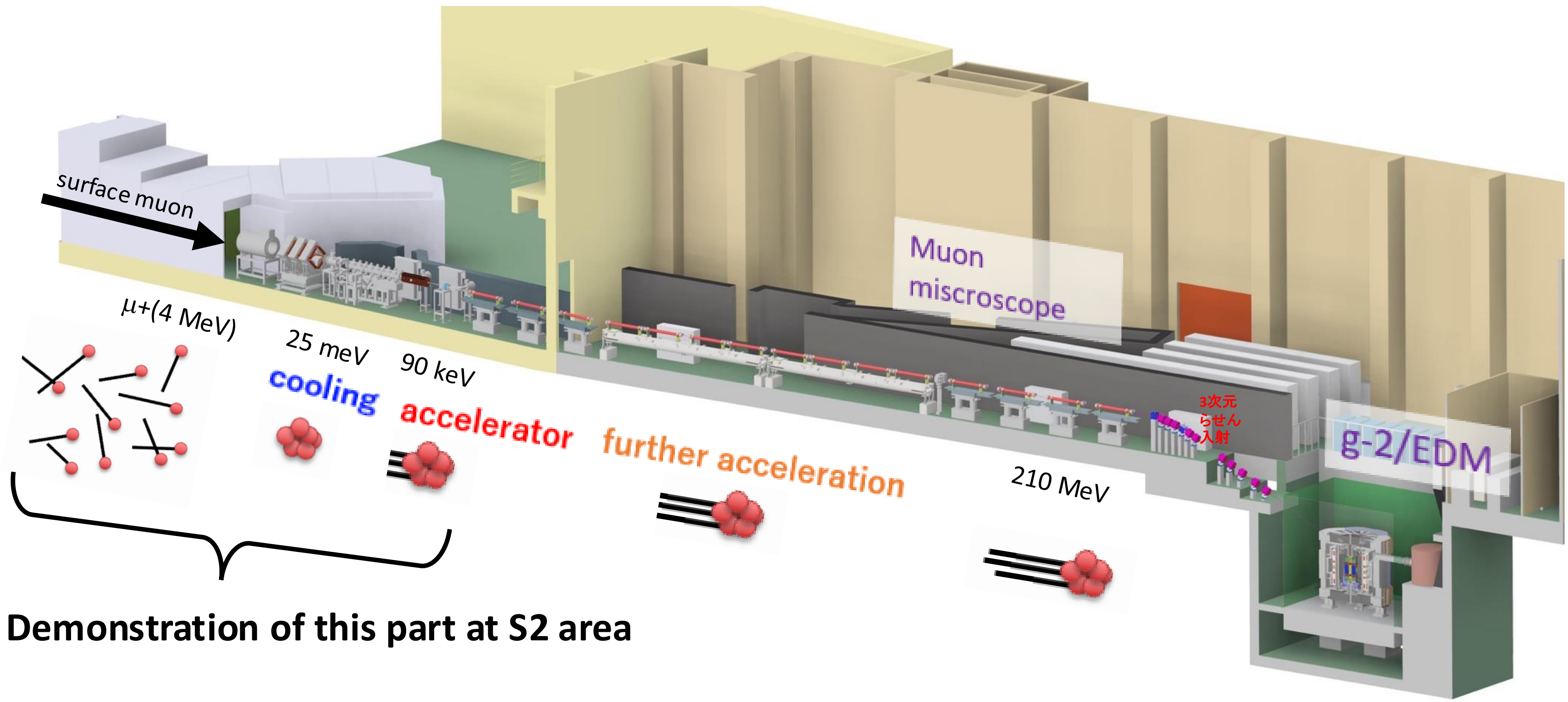
The 28th collaboration meeting at J-PARC, June 26-28, 2024


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

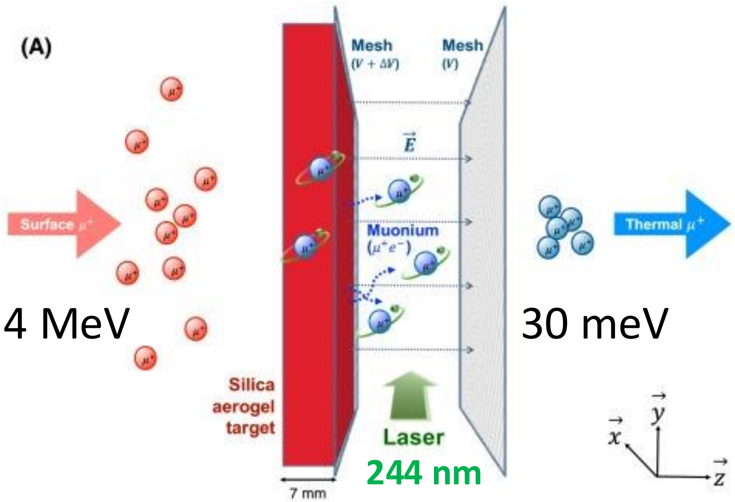
Demonstration of muon cooling and acceleration

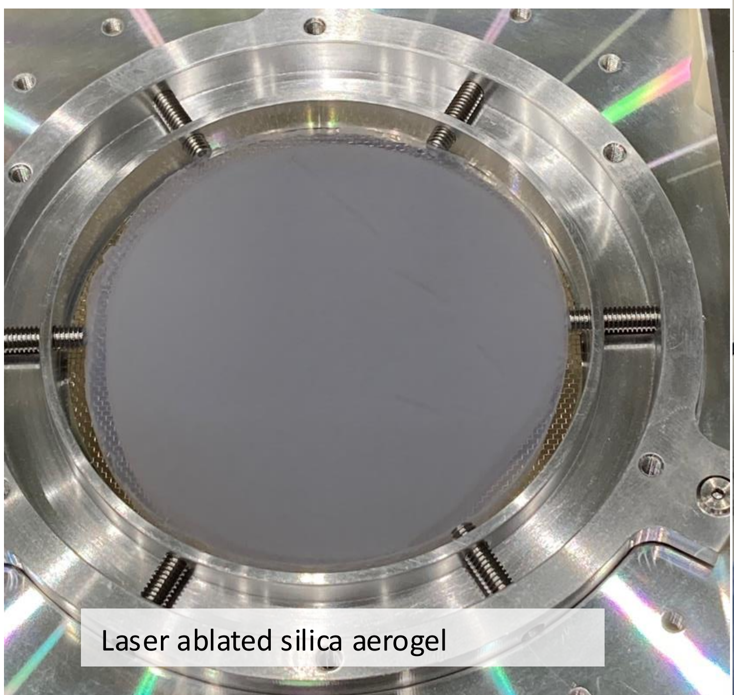


Demonstration of cooling and acceleration



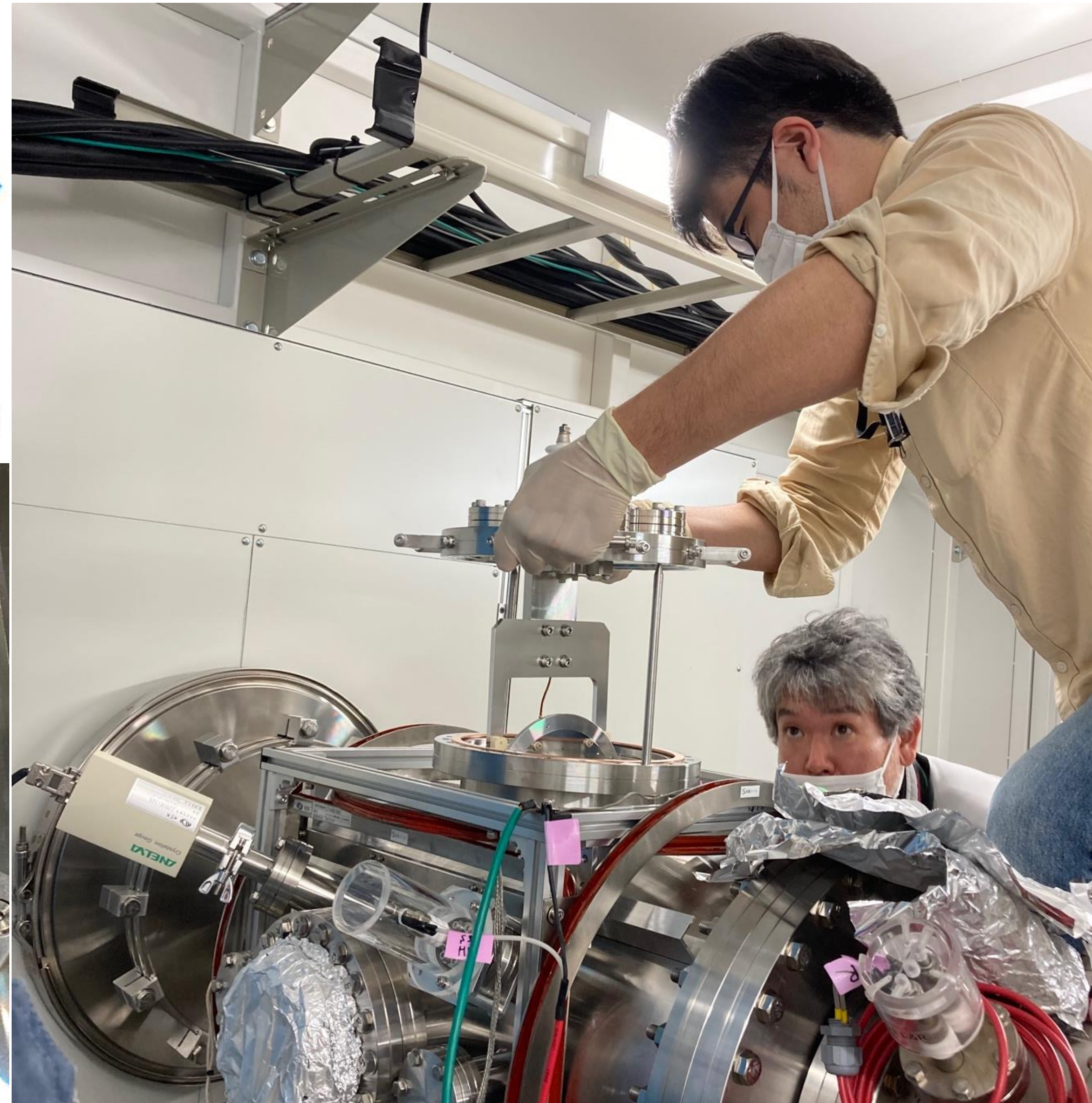
Muon cooling demonstration



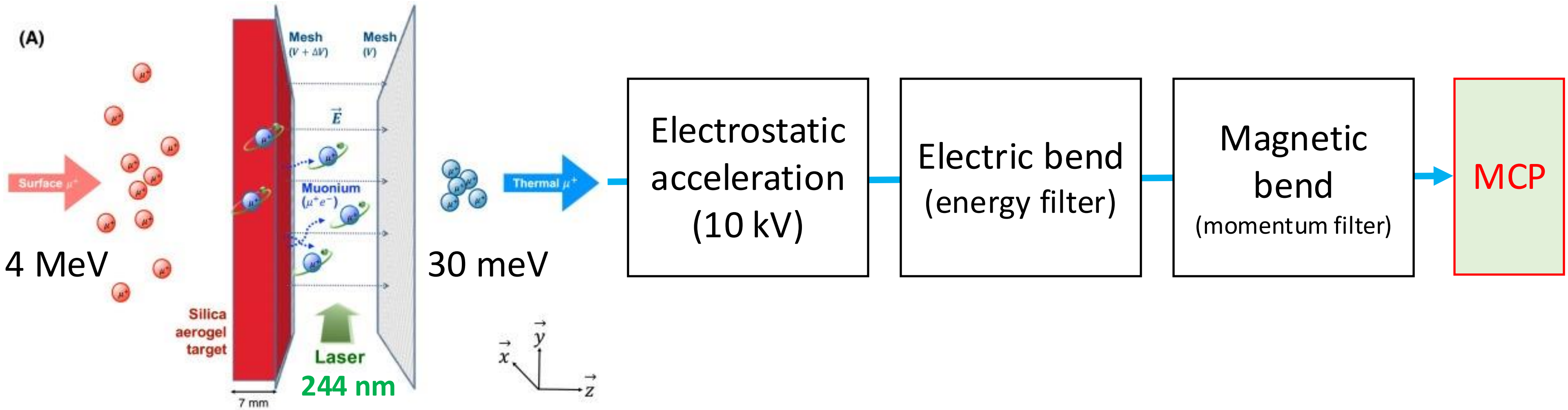


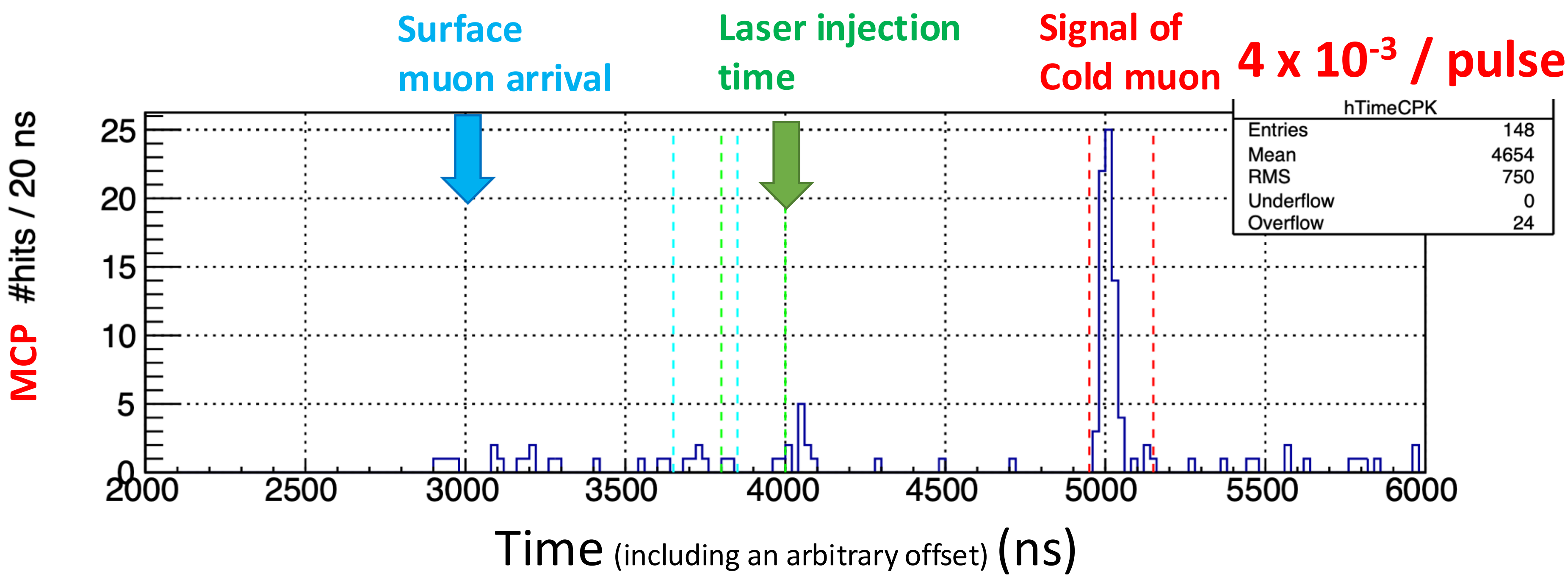
Laser ablated silica aerogel

J-PARC S2 area



Muon cooling demonstration



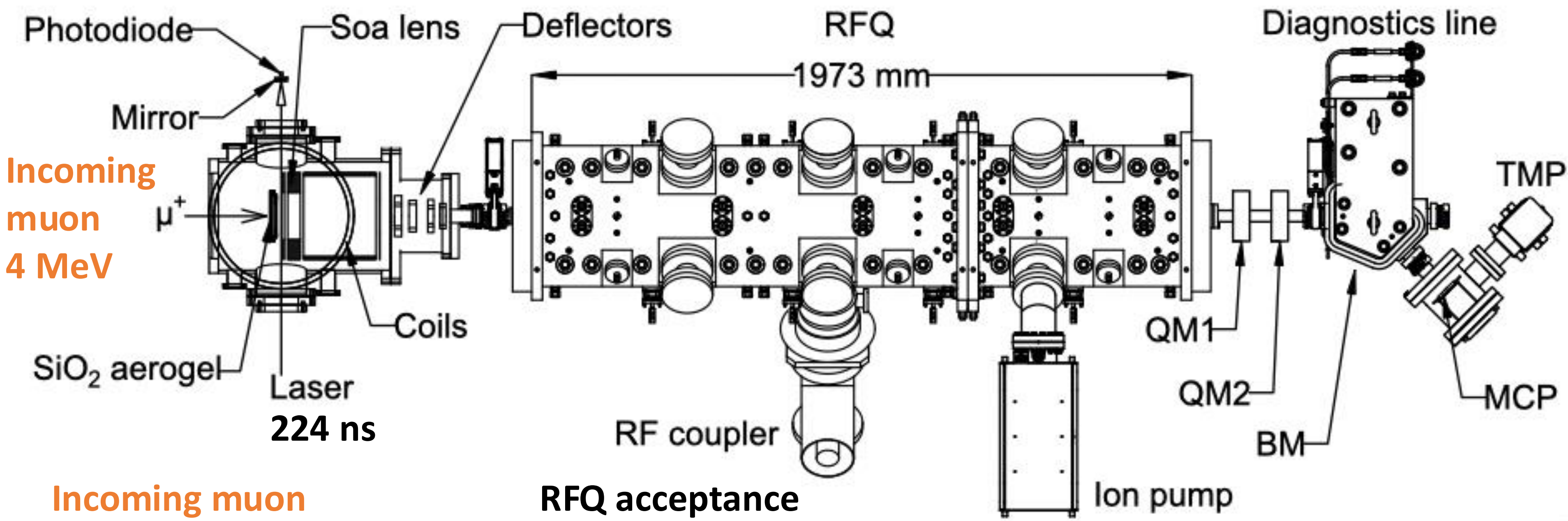


Experimental setup

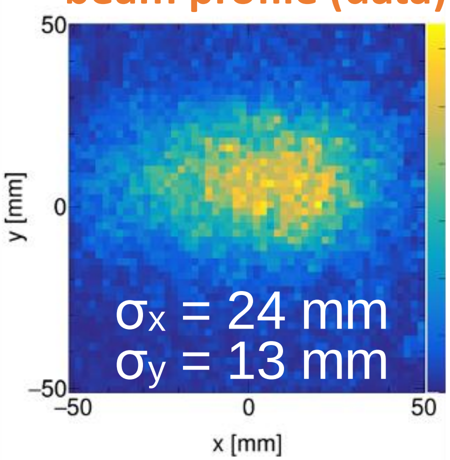
Cooling
30 meV

Acceleration
100 keV

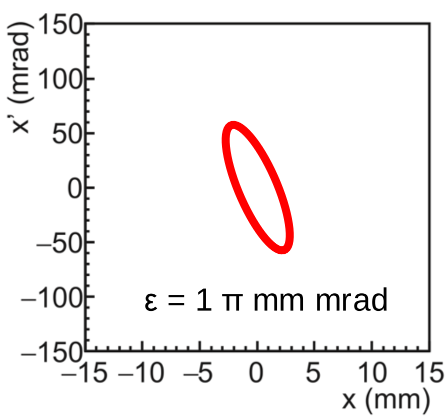
Diagnosis



Incoming muon beam profile (data)



RFQ acceptance (simulation)

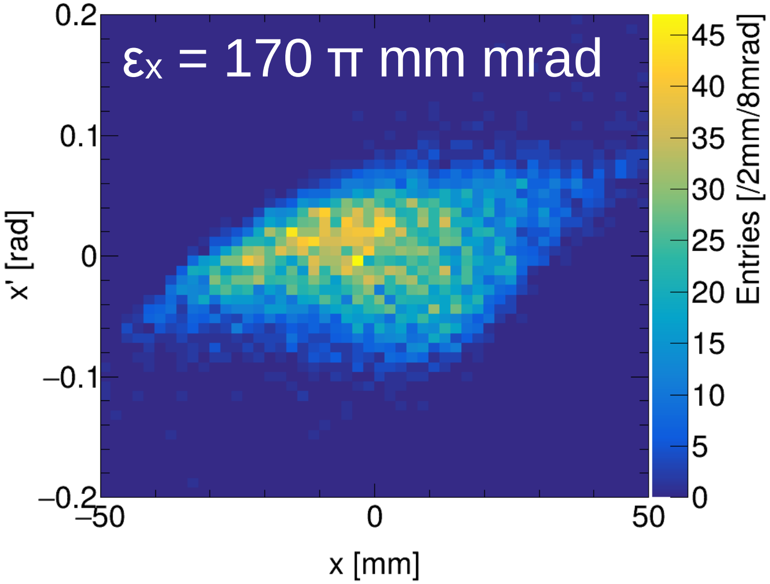


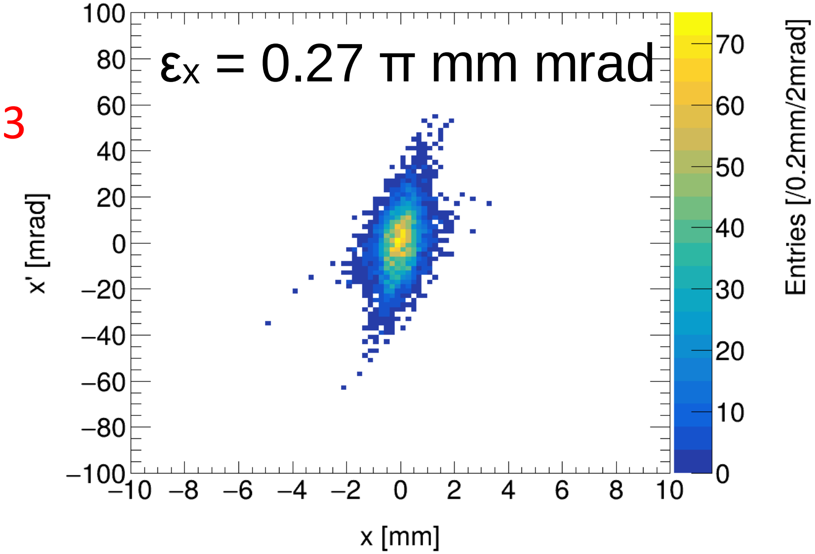
RF frequency: 324 MHz
RF power: 2.6 kW
RF pulse width: 40 μs
Acceleration energy: 100 keV

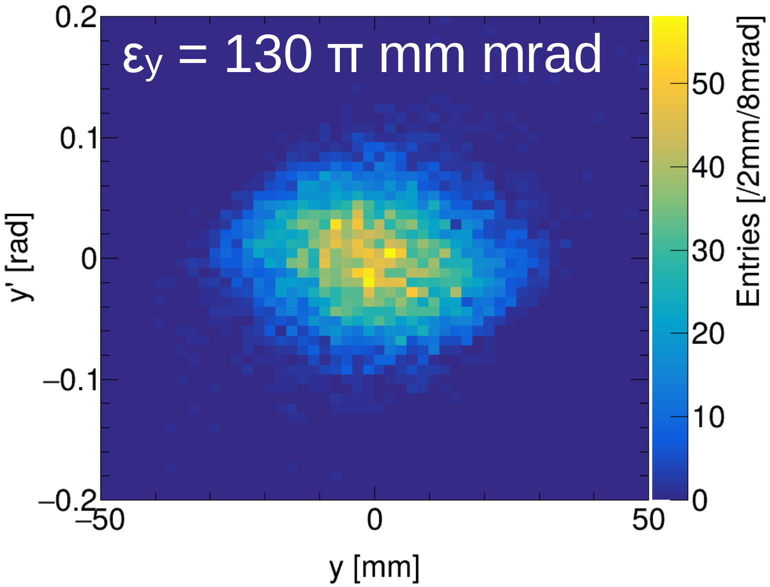
Simulation

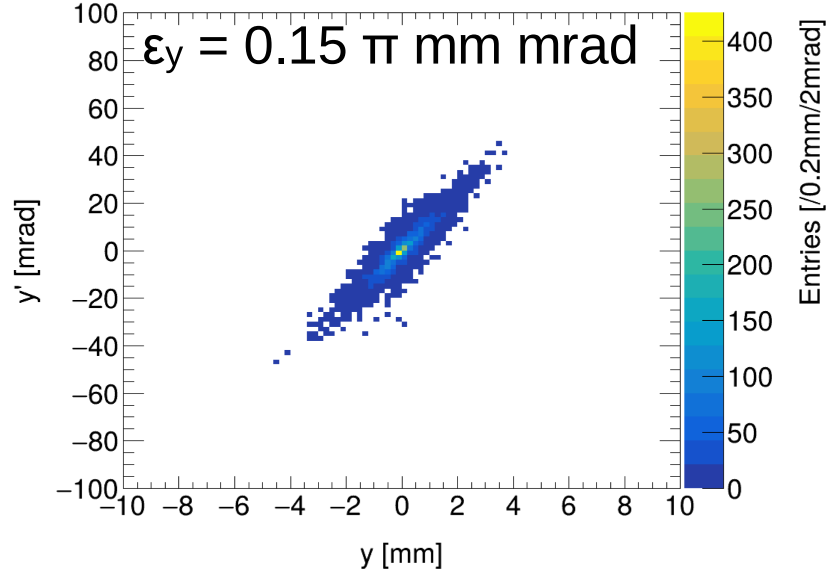
Incoming surface muon → After acceleration

cooling by ~10^{-3}



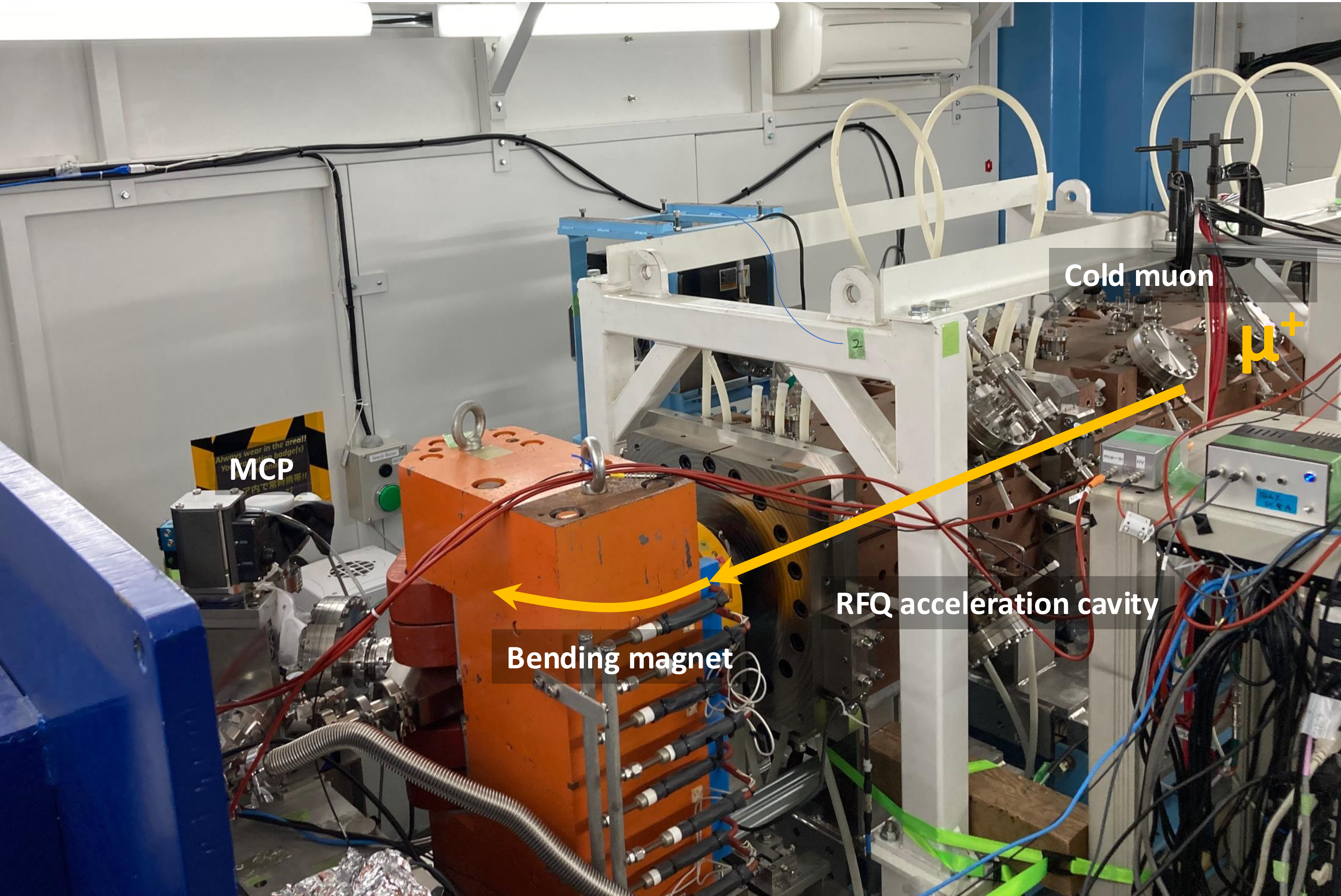




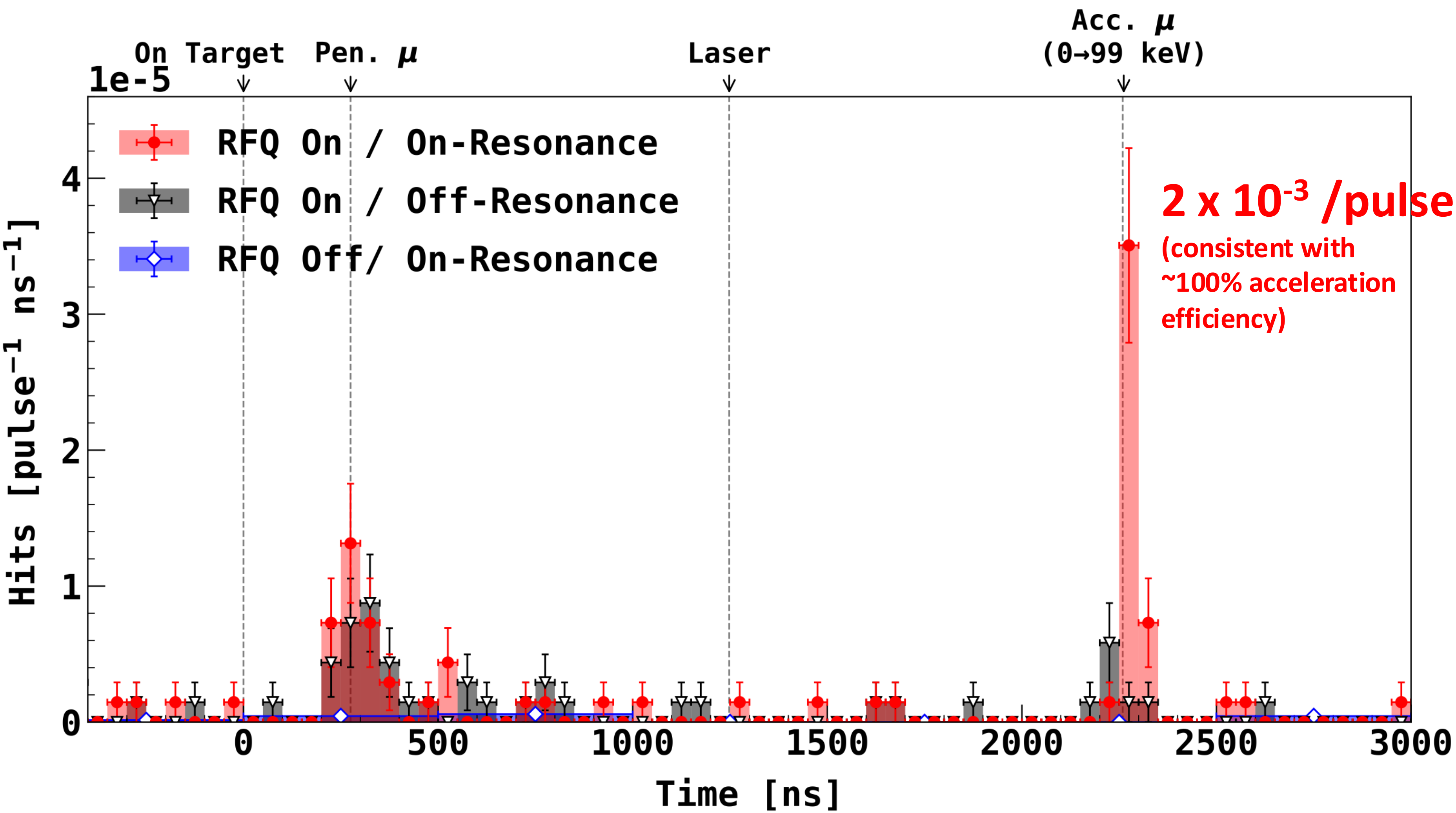


Experimental setup: Source & RFQ

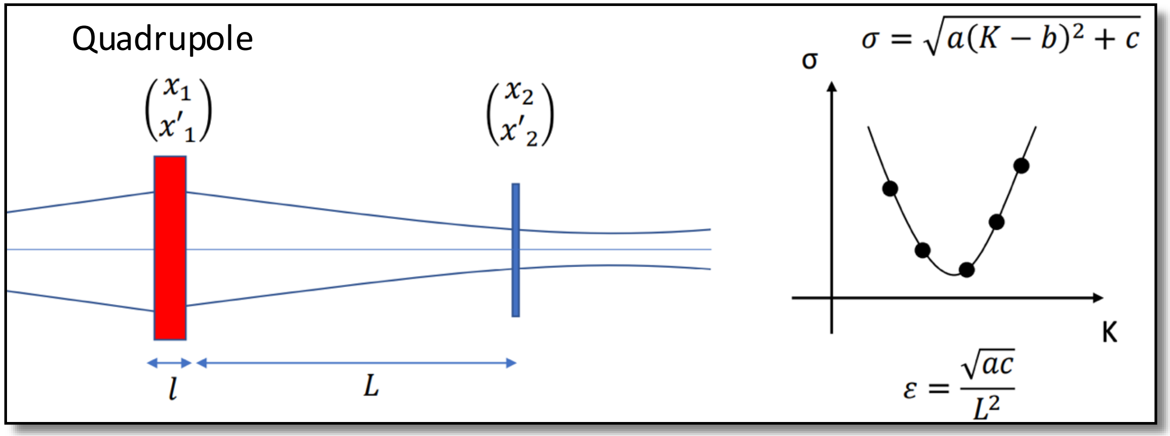
Experimental setup: Diagnosis



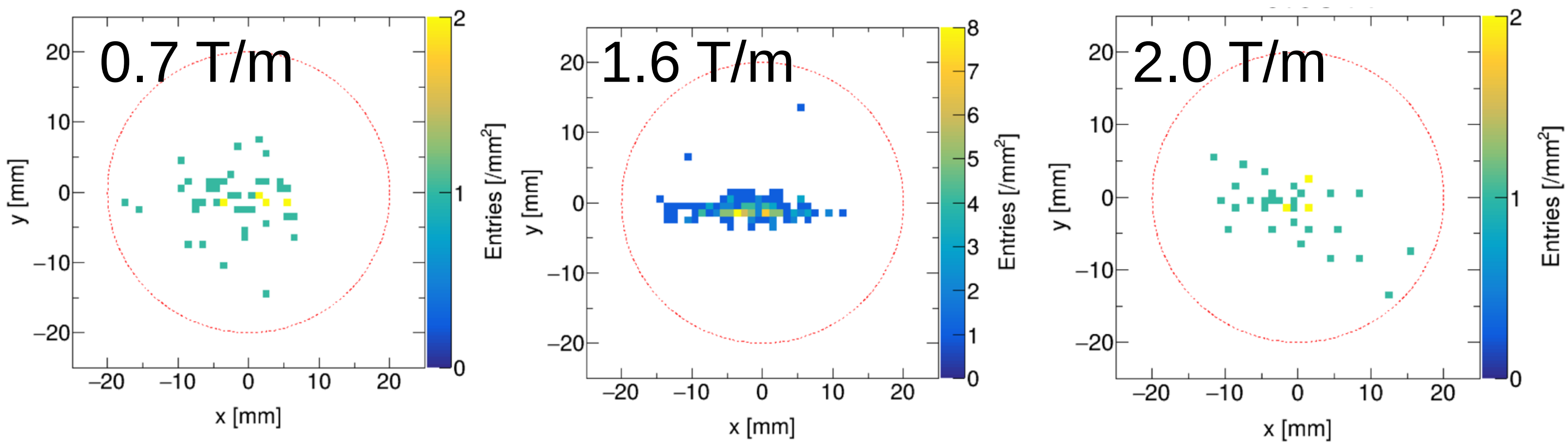
Results: time of flight



Results: beam emittance: Q-scan

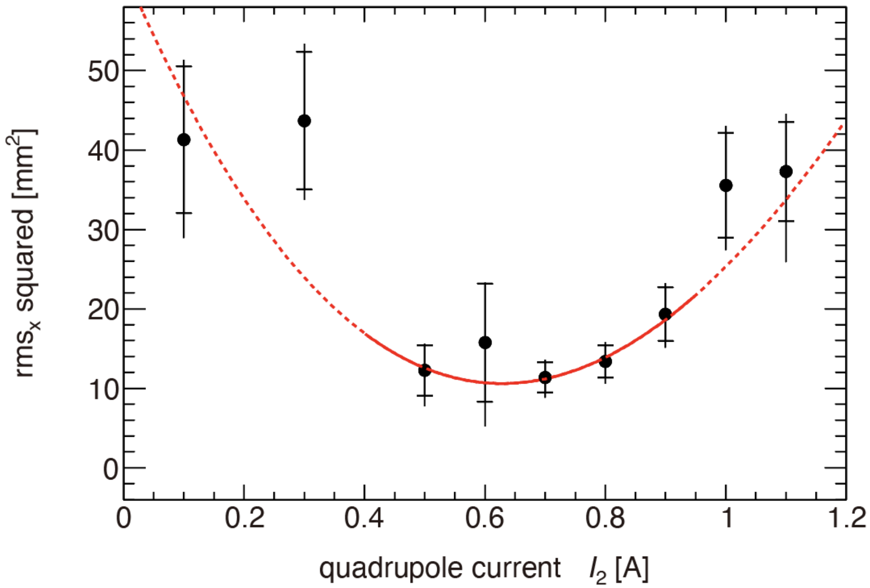


Stronger Focusing (vertical)

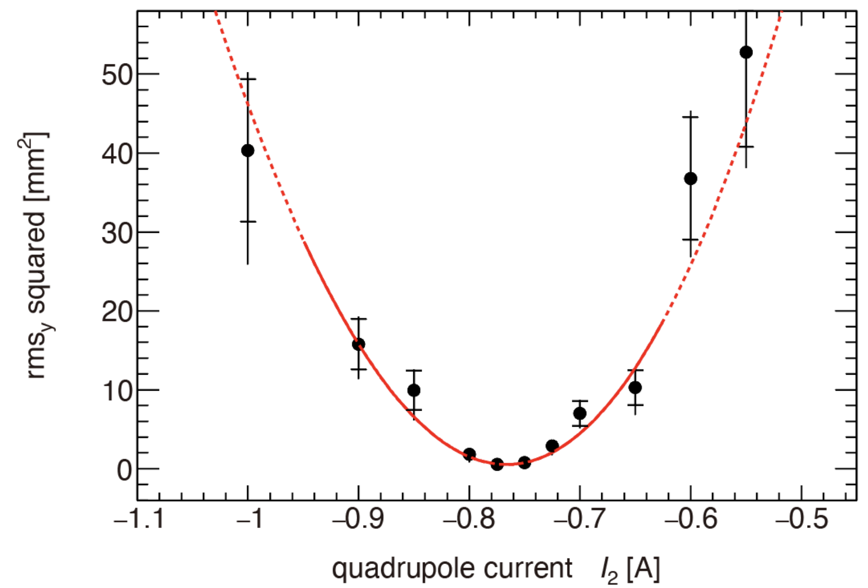


Results: beam emittance: Q-scan

horizontal



vertical



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

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

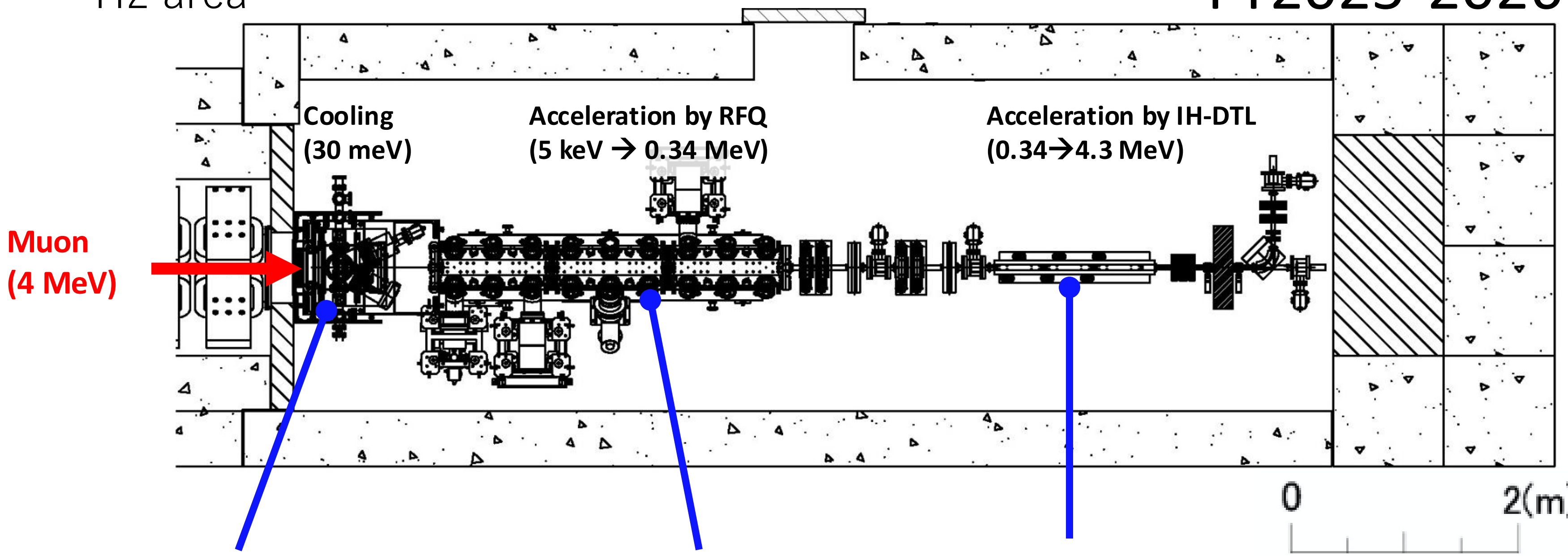
Emittance reduction by ~10^{-3}

The birth of low-emittance muon beam

Next step: Acceleration to 4 MeV

FY2025-2026

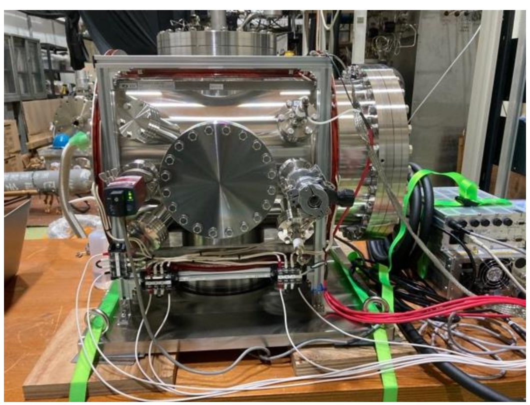
H2 area



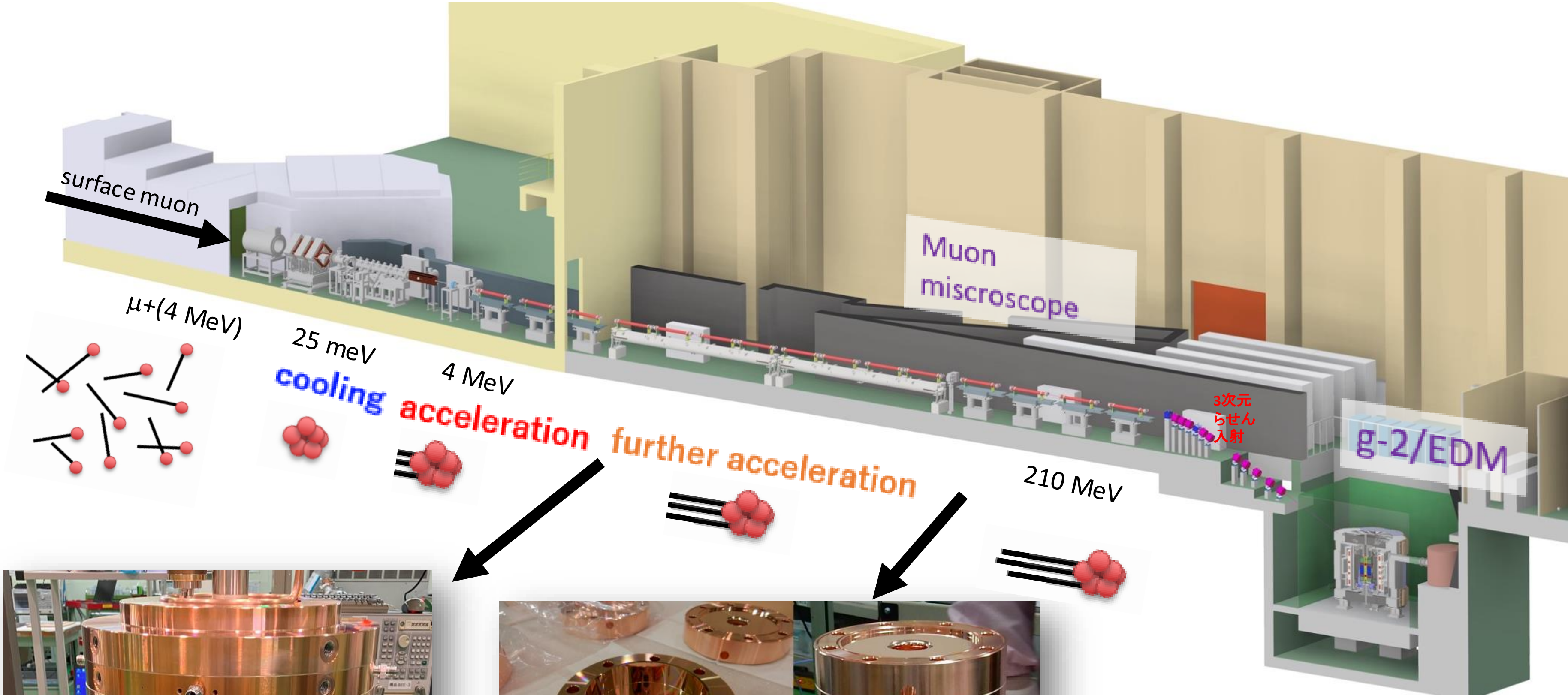
Mu production chamber
(available)

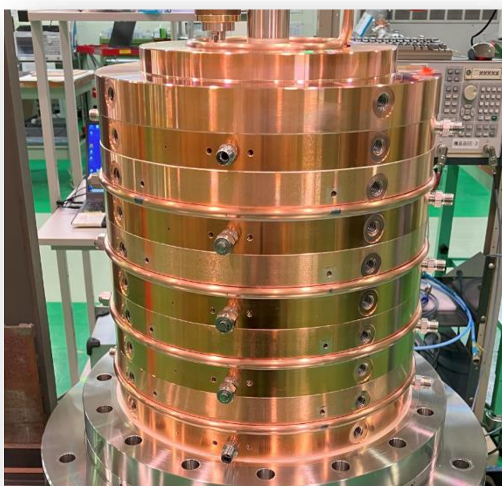
J-PARC LINAC
RFQ (available)

IH-DTL
(fabricated and evaluated in FY2022)

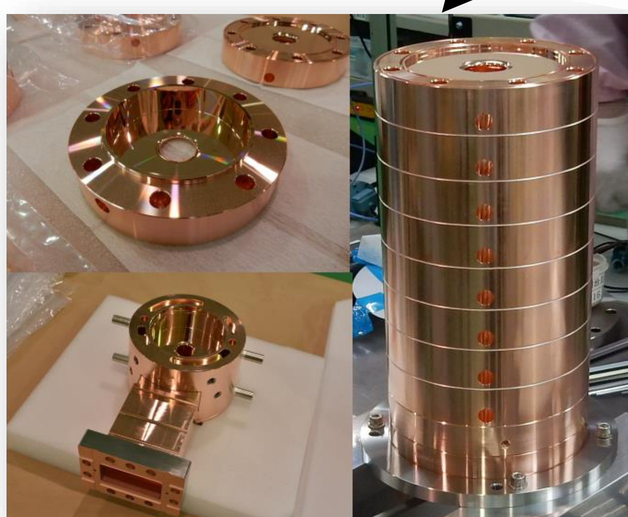


Further acceleration to 210 MeV





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

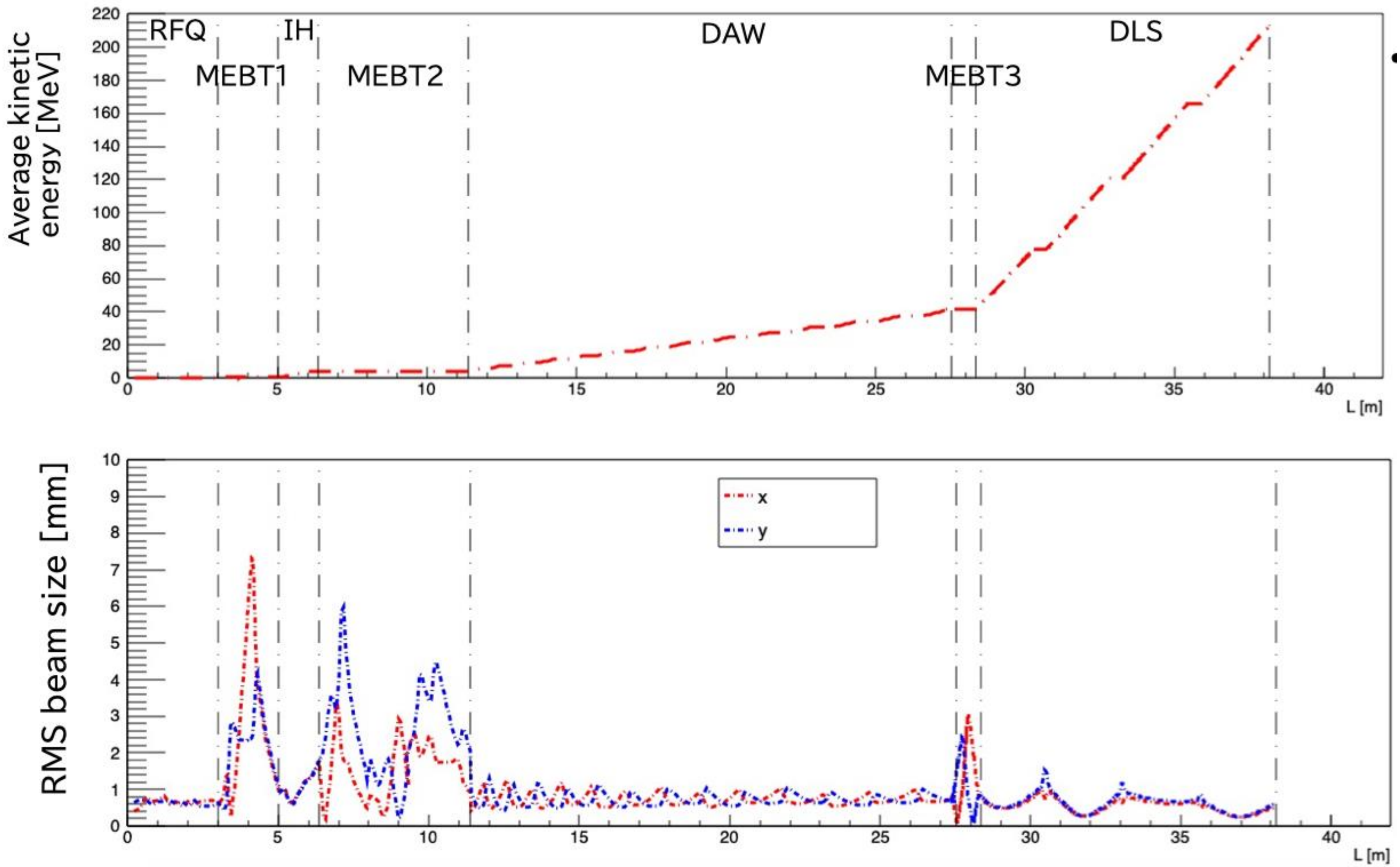


Disk Load Structure (DLS) (from 40 MeV to 210 MeV)

Start-to-end simulation

Simulated beam in the muon LINAC

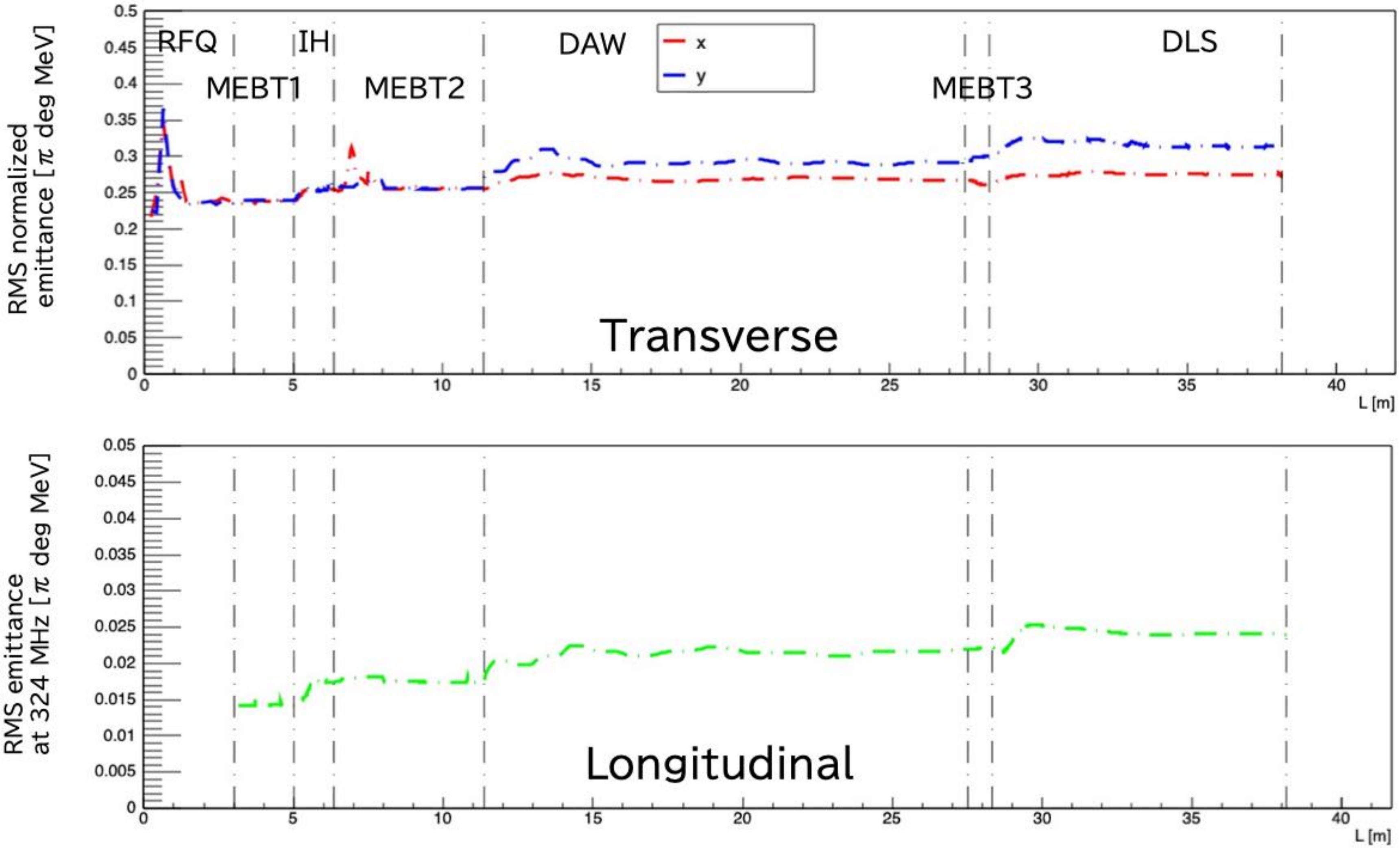
Y. Takeuchi



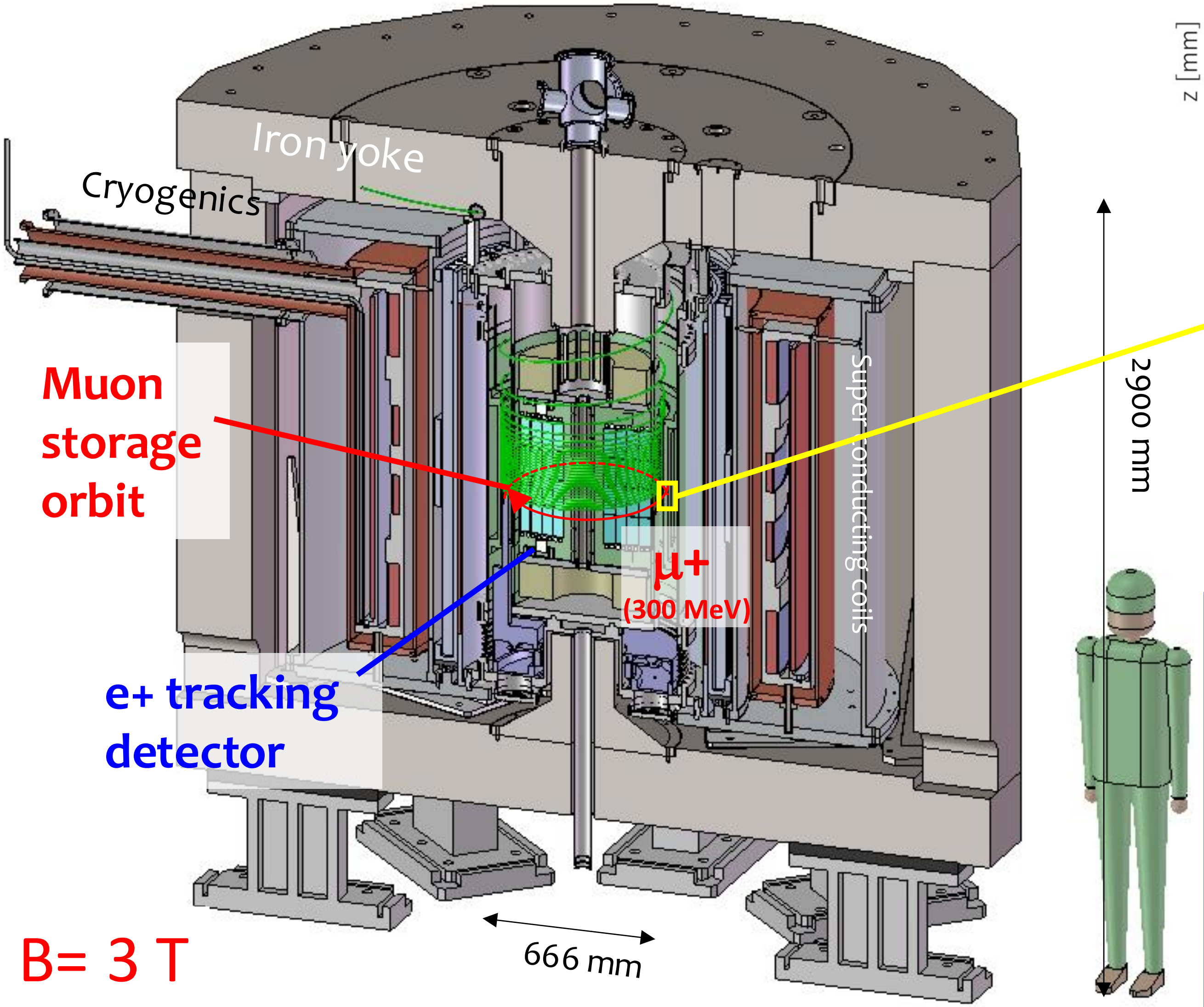
Start-to-end simulation

Simulated beam in the muon LINAC

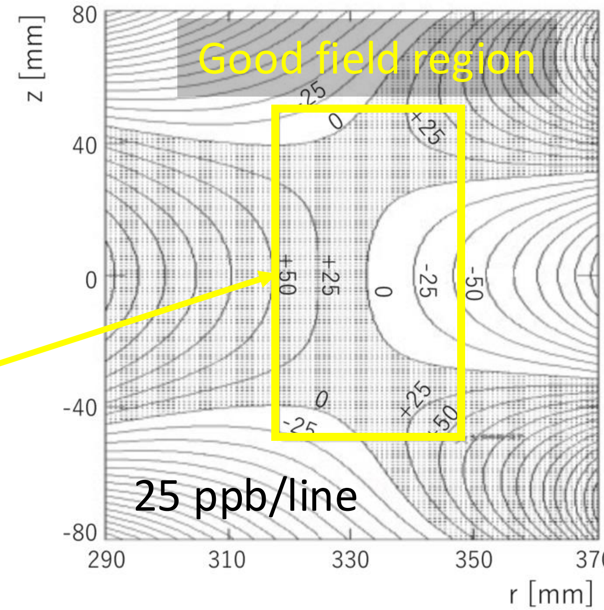
Y. Takeuchi

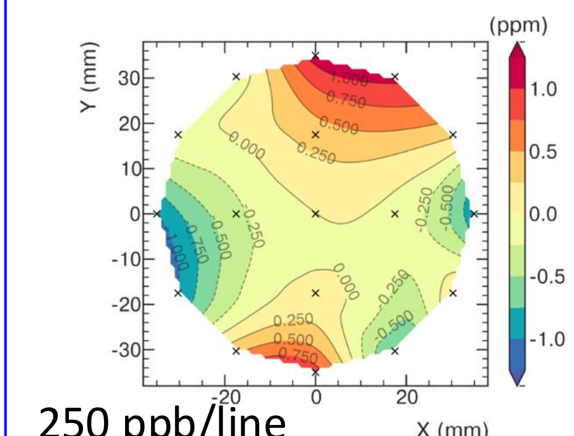


Muon storage magnet and detector



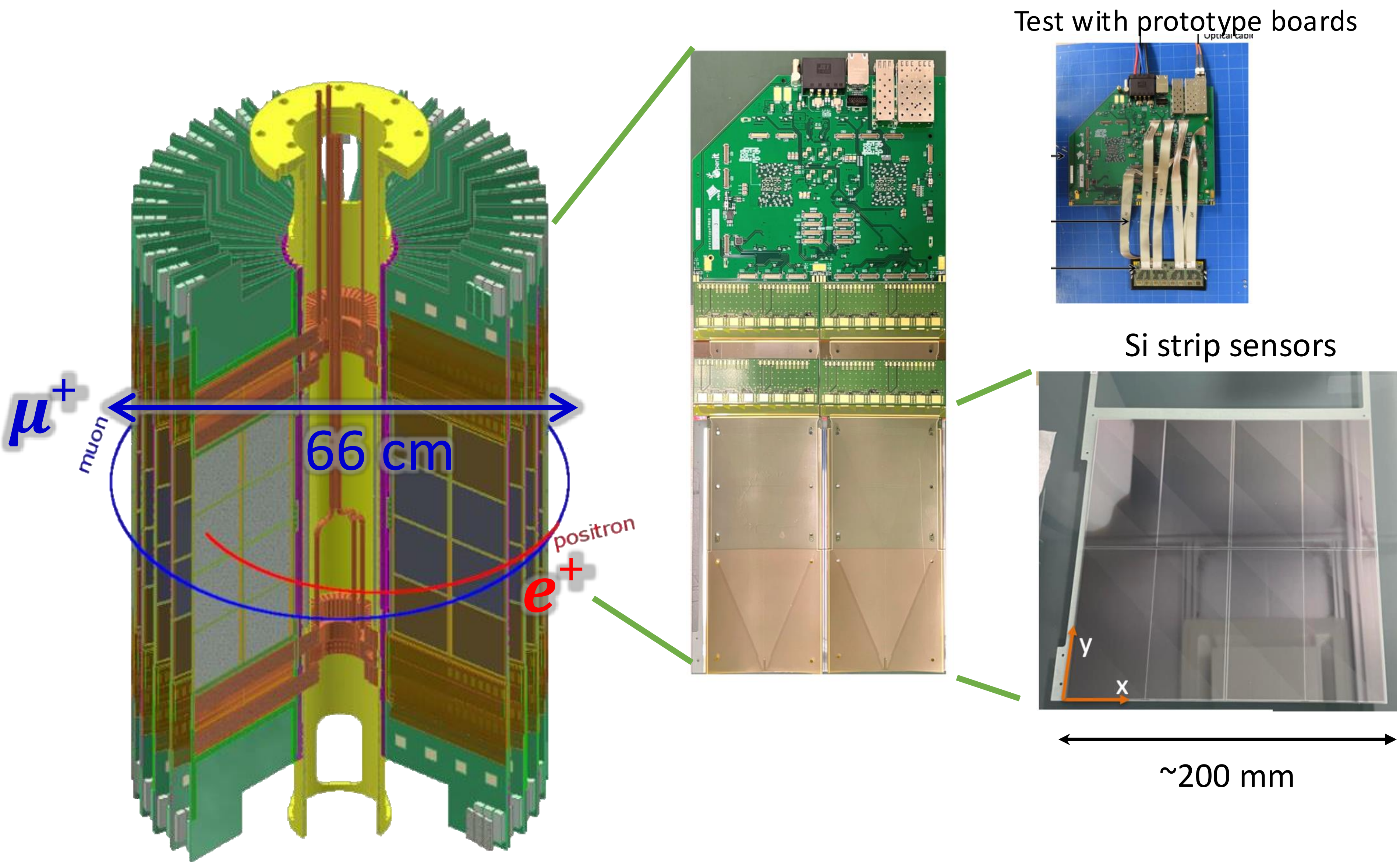
Calculated average field uniformity





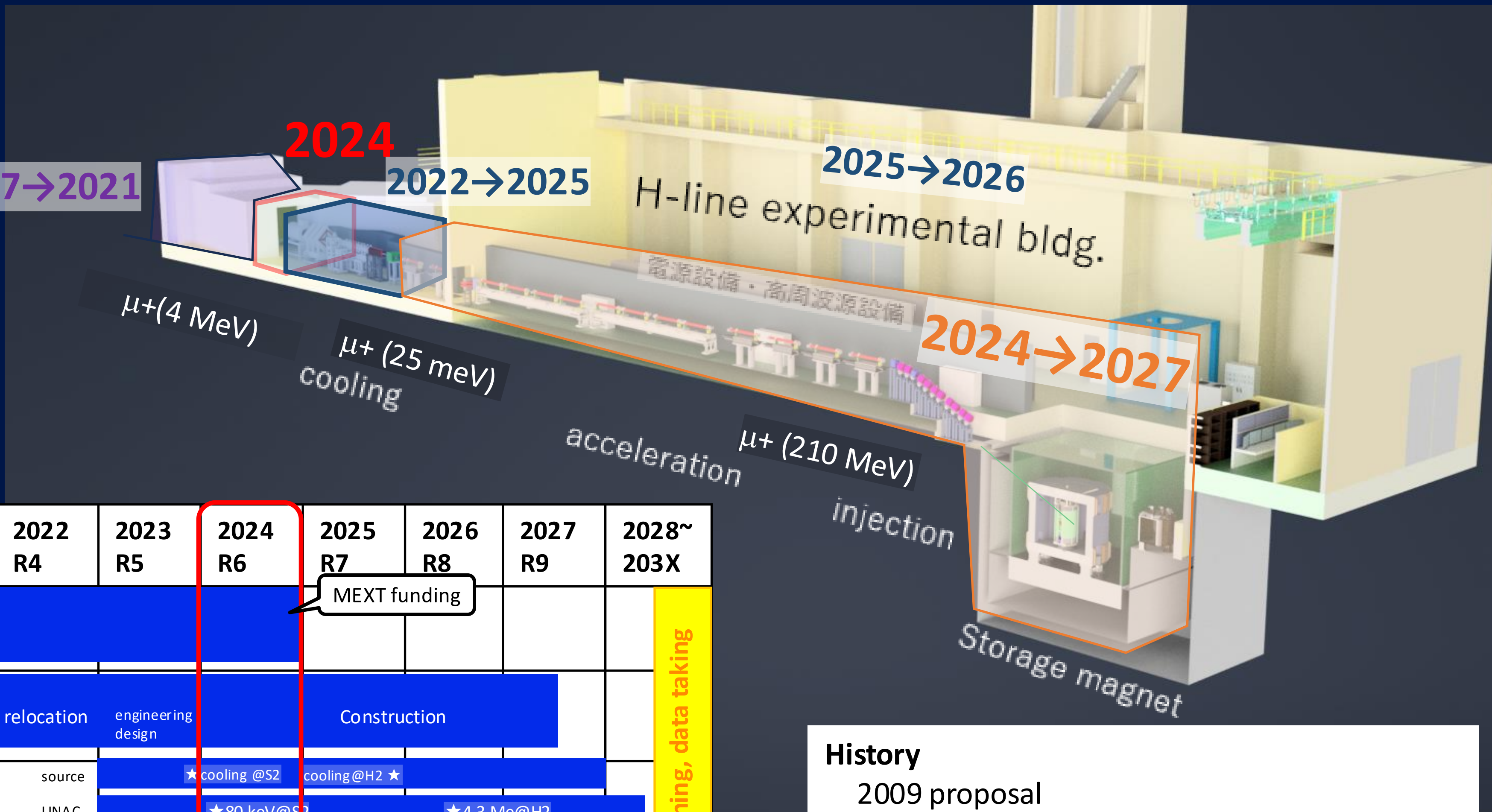
M. Abe et. al., NIM A 890, 51 (2018)

Positron tracking detector



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

Intended schedule



	2022 R4	2023 R5	2024 R6	2025 R7	2026 R8	2027 R9	2028~ 203X
Beamline				MEXT funding			Commissioning, data taking
Bldg. & facility	relocation	engineering design		Construction			
Source, LINAC, storage — source			★cooling @S2	cooling@H2 ★			
LINAC			★80 keV@S2		★4.3 Me@H2		
Storage			procurement			Installation ★	
Detector	positron tracker magnetic field monitors						

History

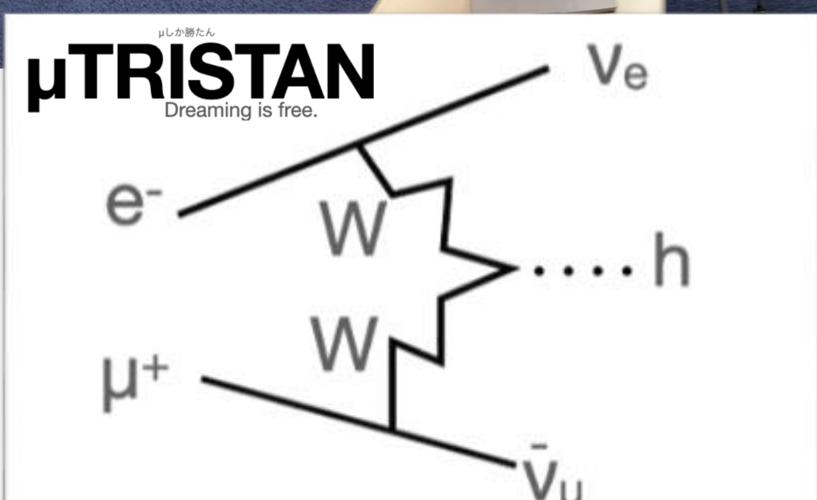
- 2009 proposal
- 2015 TDR
- 2016 IPNS focused review
- 2016 SAC (priority #3)
- 2019 KEK-IPNS stage-2, KEK-IMSS stage-2
- 2024 MEXT funding (construction)

Muon acceleration and future colliders

KEK IPNS workshop, Nov. 2, 2023

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

$\mu^+ \mu^-$ or $\mu^+ e^-$?



[Prog Theor Exp Phys (2022)]

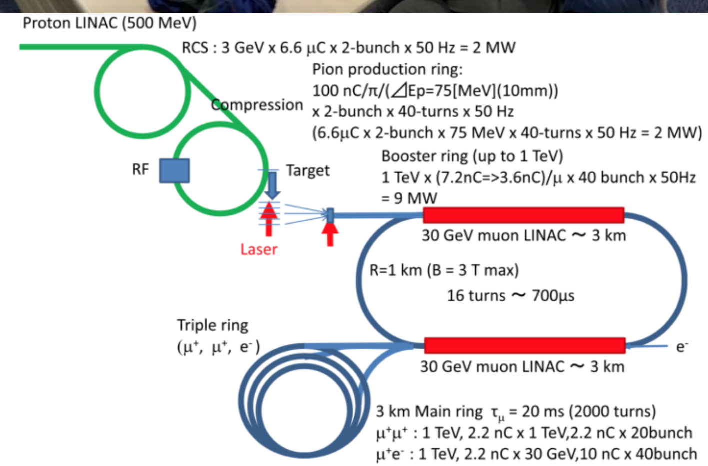


Fig. 1. Conceptual design of the $\mu^+e^-/\mu^+\mu^+$ collider.

Comparison of muon beam phase space

Normal muon beam

1

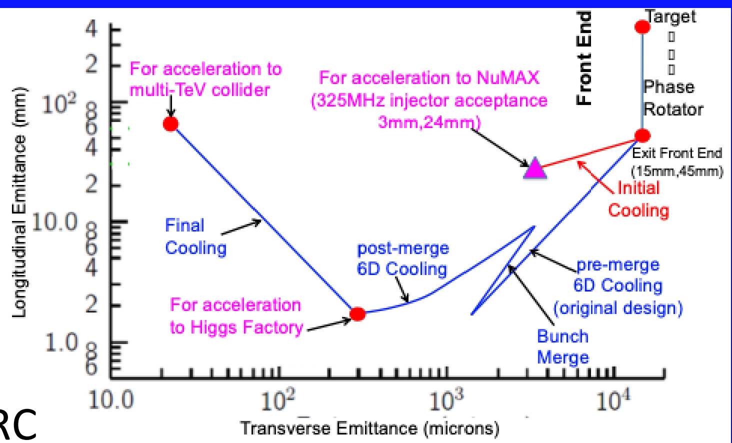
Ionization cooling
(proposed for Muon Collider)

10^{-2}

Cooling at J-PARC

10^{-4}

Caveat: only for μ^+
(not applicable for μ^-)

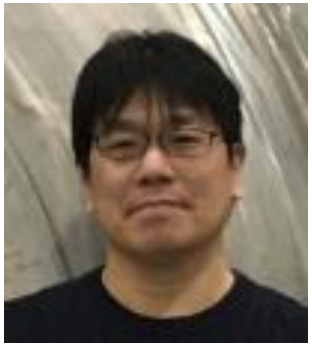


J-PARC cooling

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

Quotes

More in the cern courier article (July 5, 2024)



We are open to any possible applications of this technology in the future

This will profit the development of muon-beam technology and use.

International Muon Collider study leader
Daniel Schulte (CERN)

Ryuichiro Kitano (KEK)

a μ^+e^- or $\mu^+\mu^+$ collider!

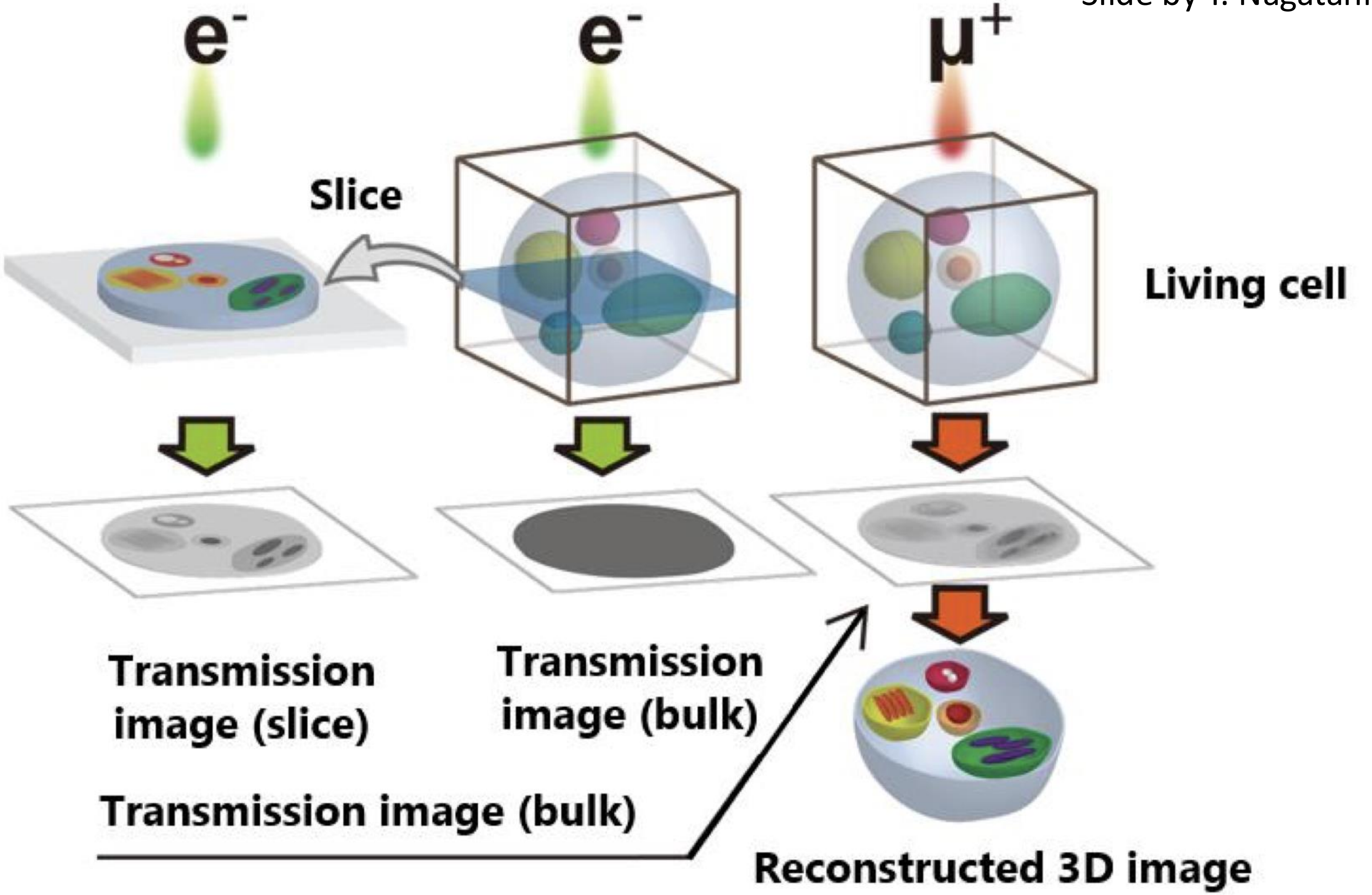
The annihilations of the initial particles into a photon and/or a Z boson, or a Higgs boson are absent for a μ^+e^- or $\mu^+\mu^+$ collider.

John Ellis (CERN/KCL)

what do you say?

Transmission muon microscope

Slide by Y. Nagatani

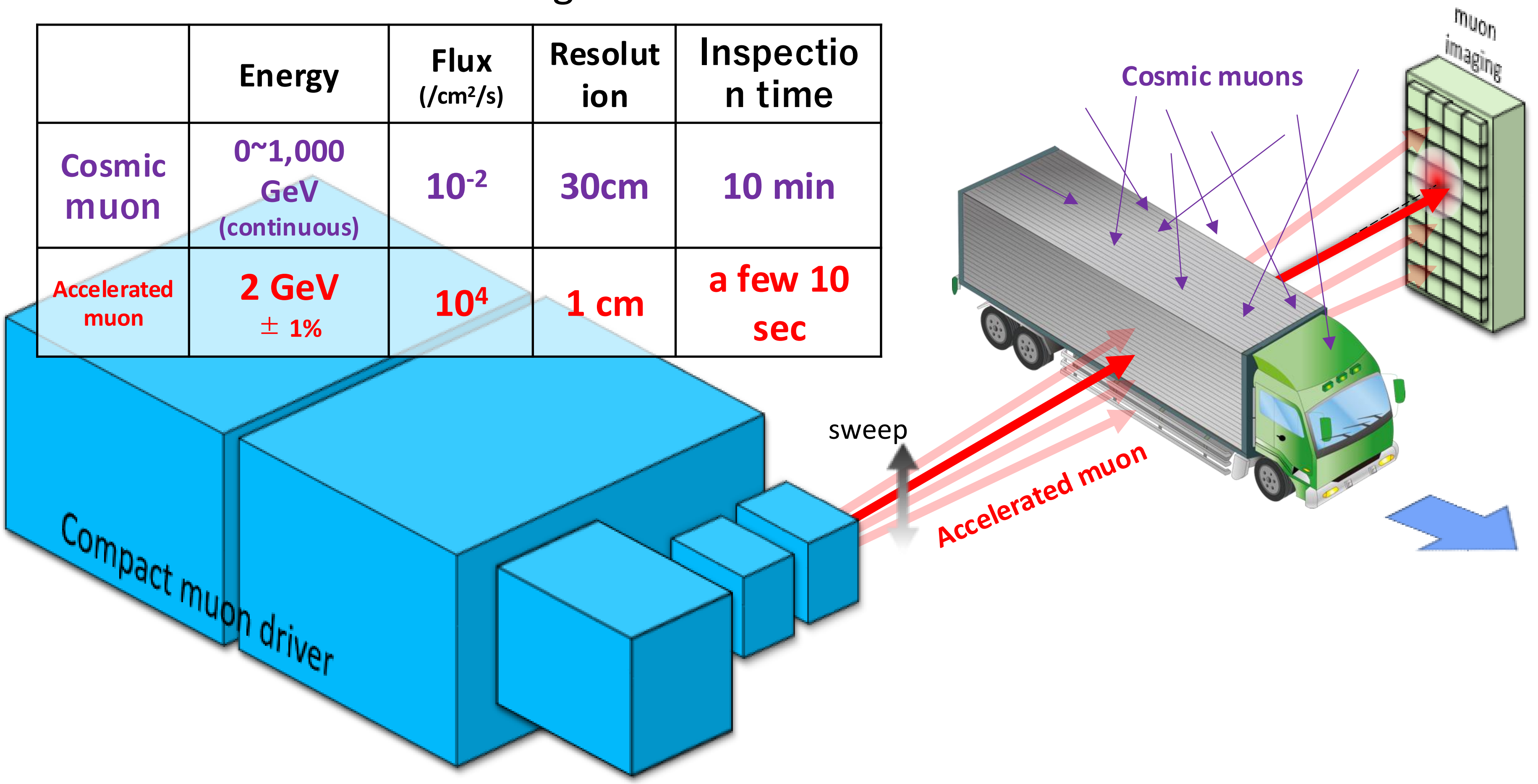


Drive-thru cargo scanning

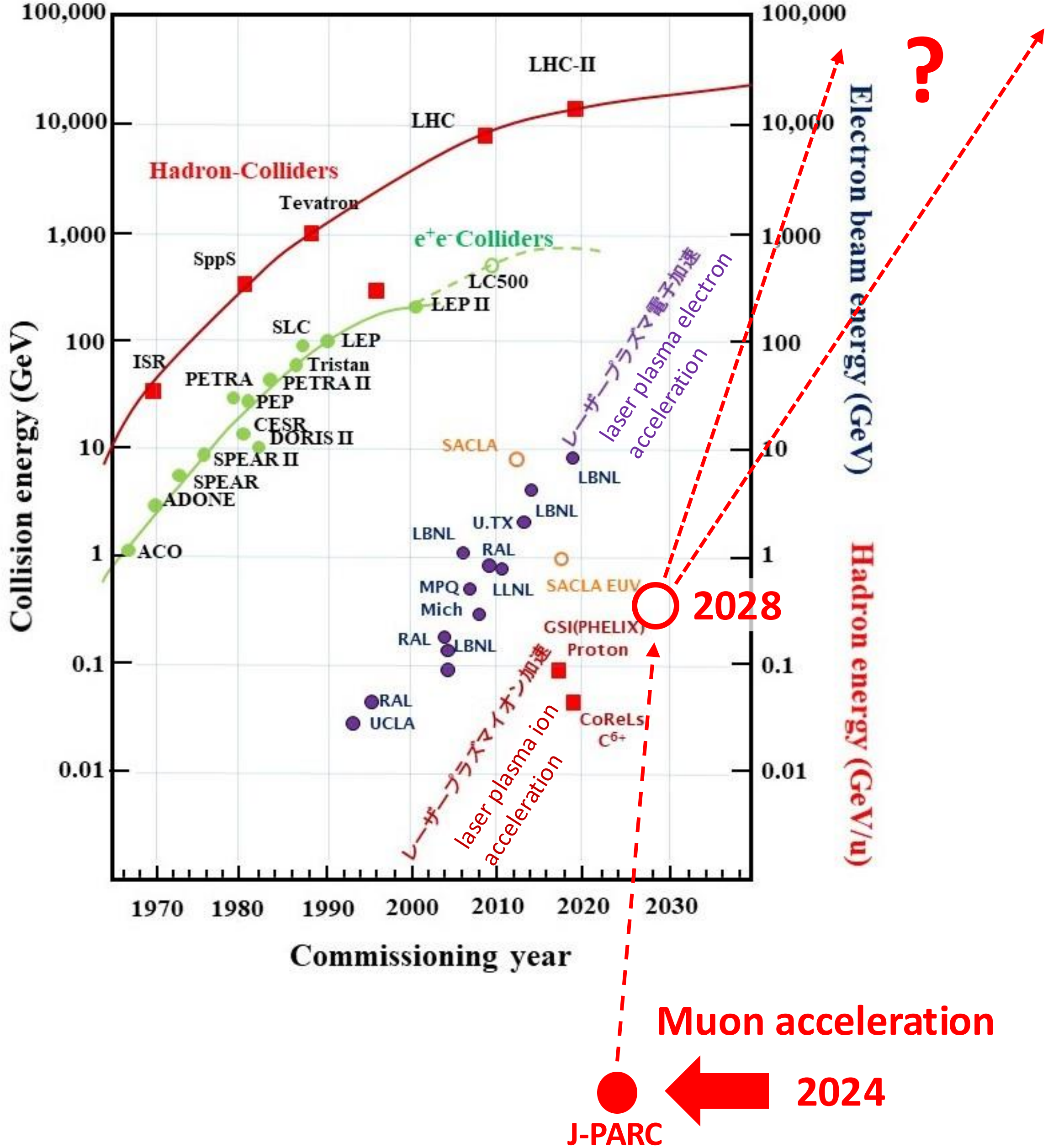
Proposal approved in JST K-program (2024-2029)

Detection of heavy materials (nuclear fuel, weapon, etc)
with muon transmission image

	Energy	Flux (/cm²/s)	Resolution	Inspection time
Cosmic muon	0~1,000 GeV (continuous)	10^{-2}	30cm	10 min
Accelerated muon	2 GeV ± 1%	10^{4}	1 cm	a few 10 sec



History of accelerator technology



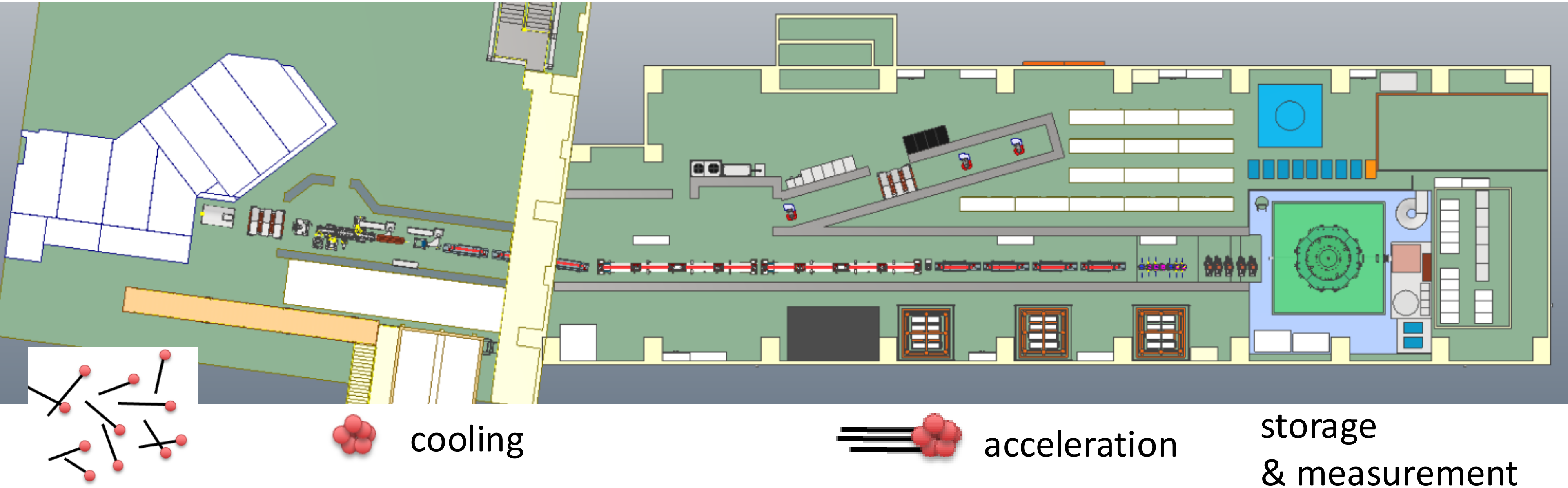
Summary

- A new experiment to measure muon g-2 and EDM is under preparation.
  - **Cooling & acceleration of positive muon**
  - **Compact storage ring**

- April 2024, we succeeded in the first ever demonstration of muon acceleration.

- Construction of the experiment is in progress. Expected year of data taking from 2028.

- Wide range of applications are anticipated.



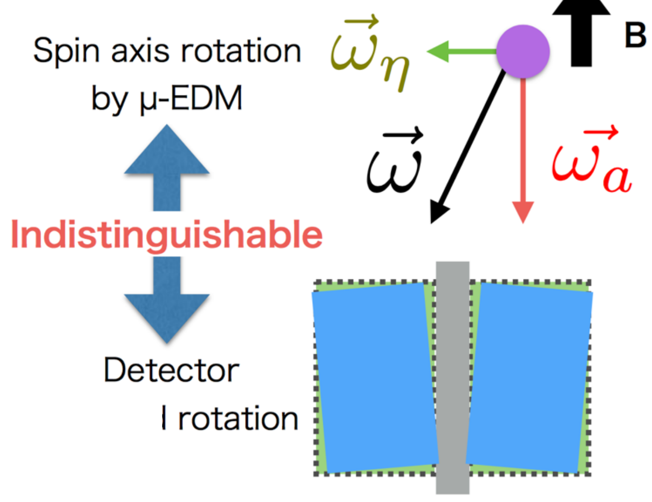
Systematic uncertainties on EDM

T. Yoshioka, T. Yamanaka

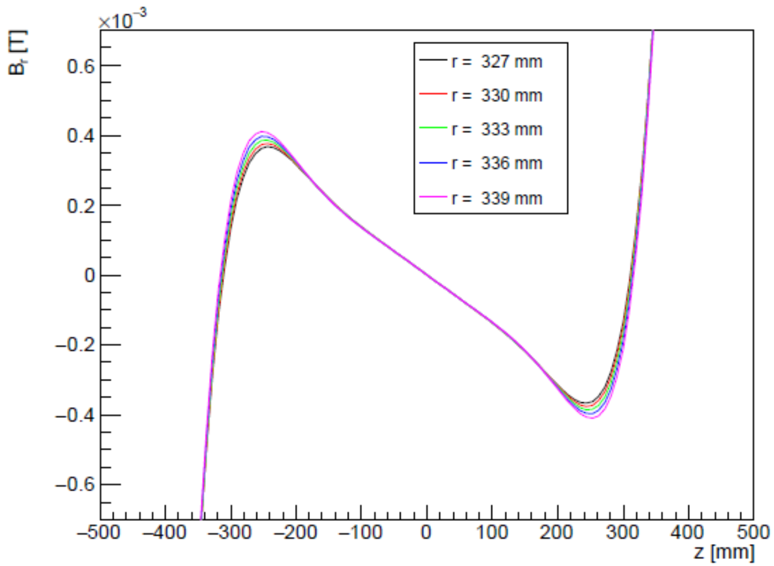
Table 7: Summary of systematic uncertainties on the EDM measurement

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	

Detector misalignment



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} $e\cdot$cm]	1.4 (stat.)
	0.36 (syst.)

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

EDM and radial magnetic field

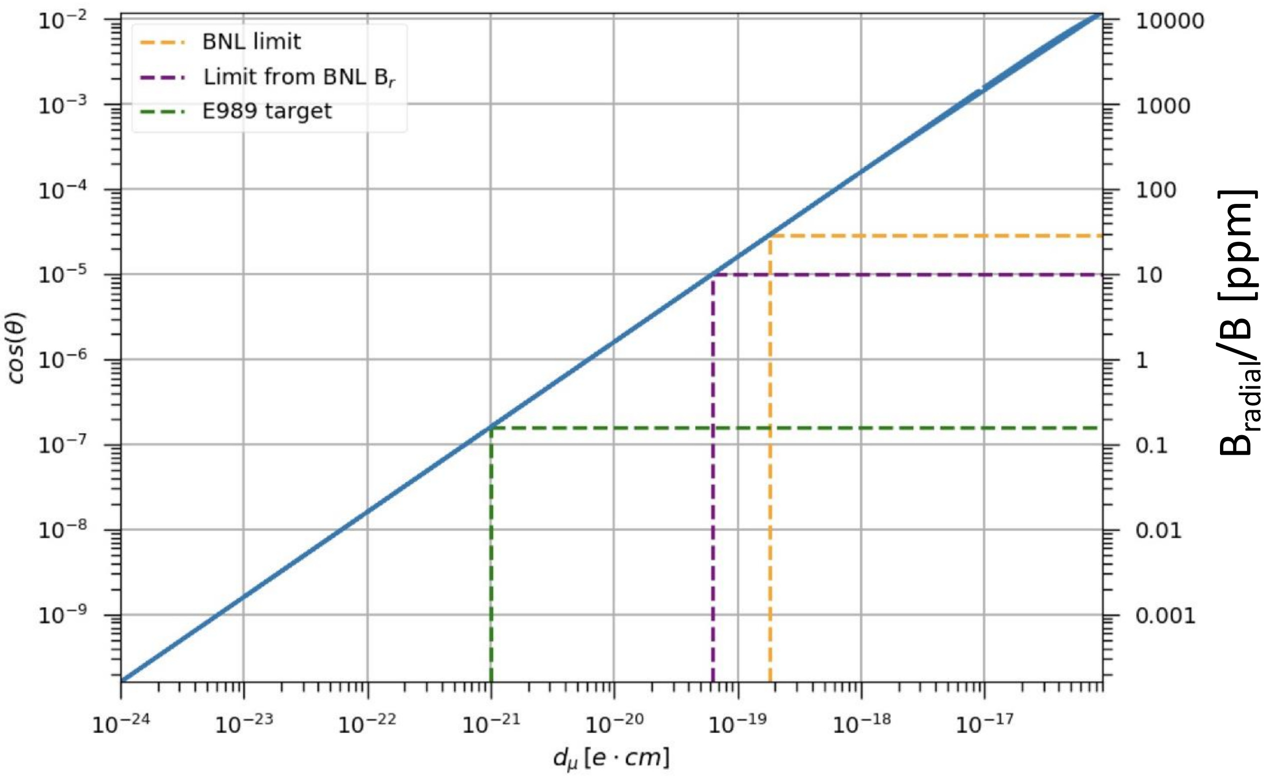
- **Radial magnetic field** can be a major source of systematics on EDM since the *g*-2 term mixes to the EDM term.

g-2 precession >> EDM precession

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

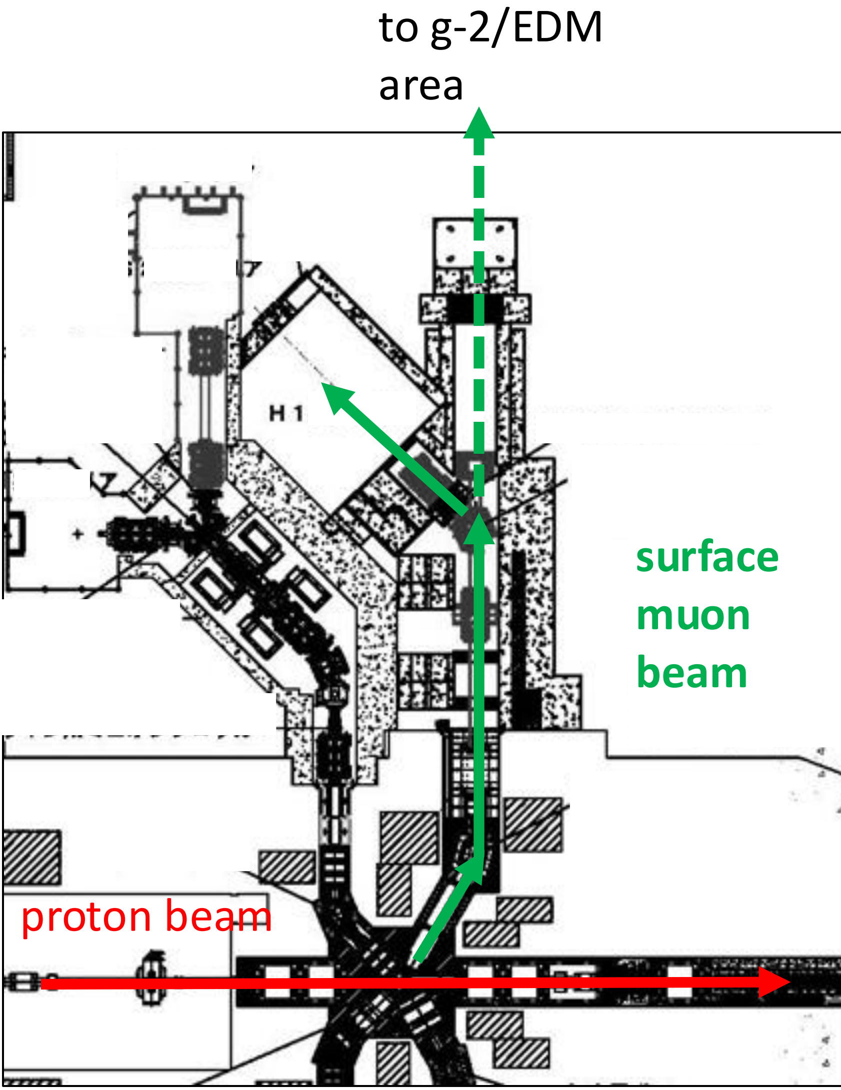
$$\vec{B} = \vec{B}_{axial} + \vec{B}_{radial}$$

plot from Joe Price (muEDM workshop at PSI)

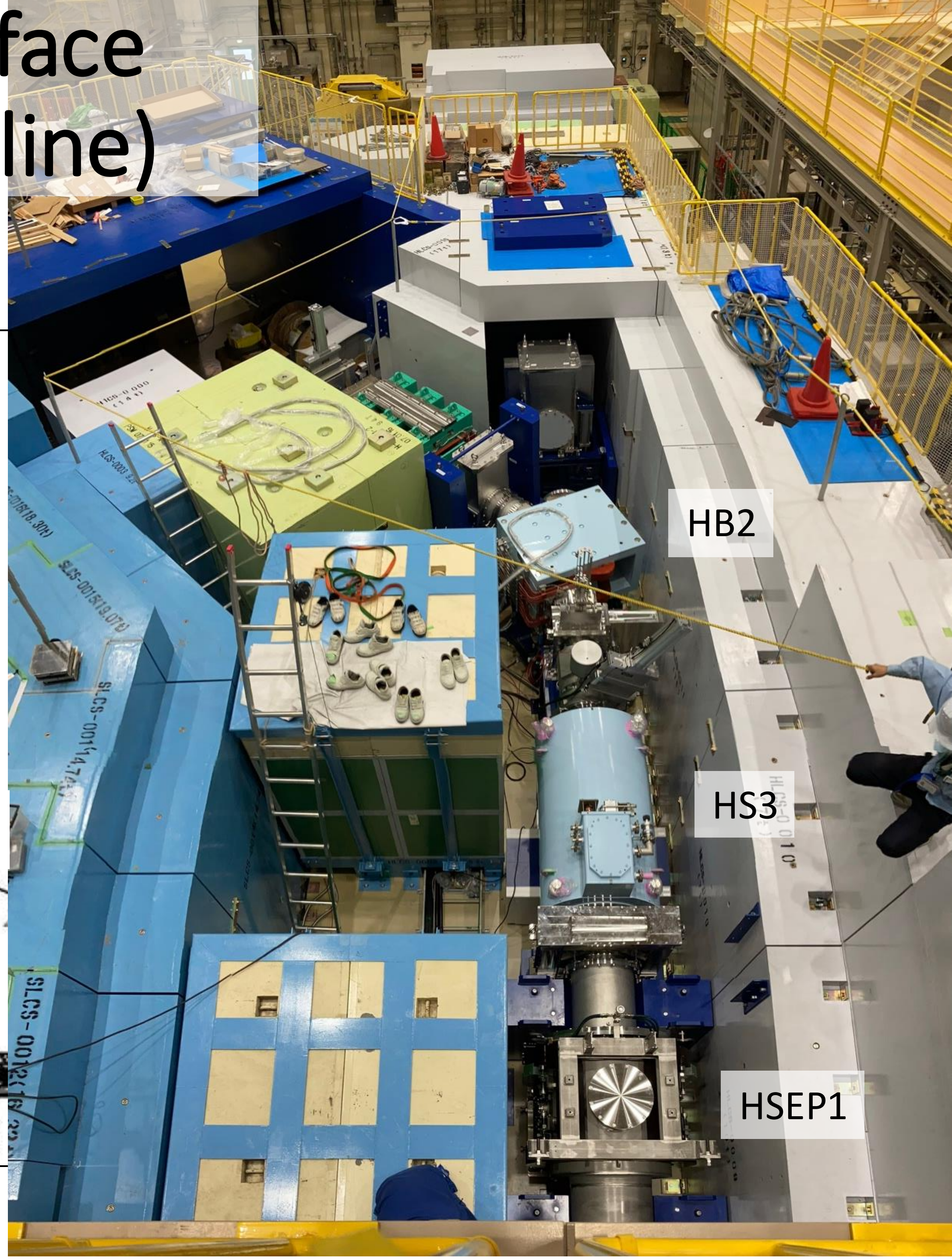


EDM

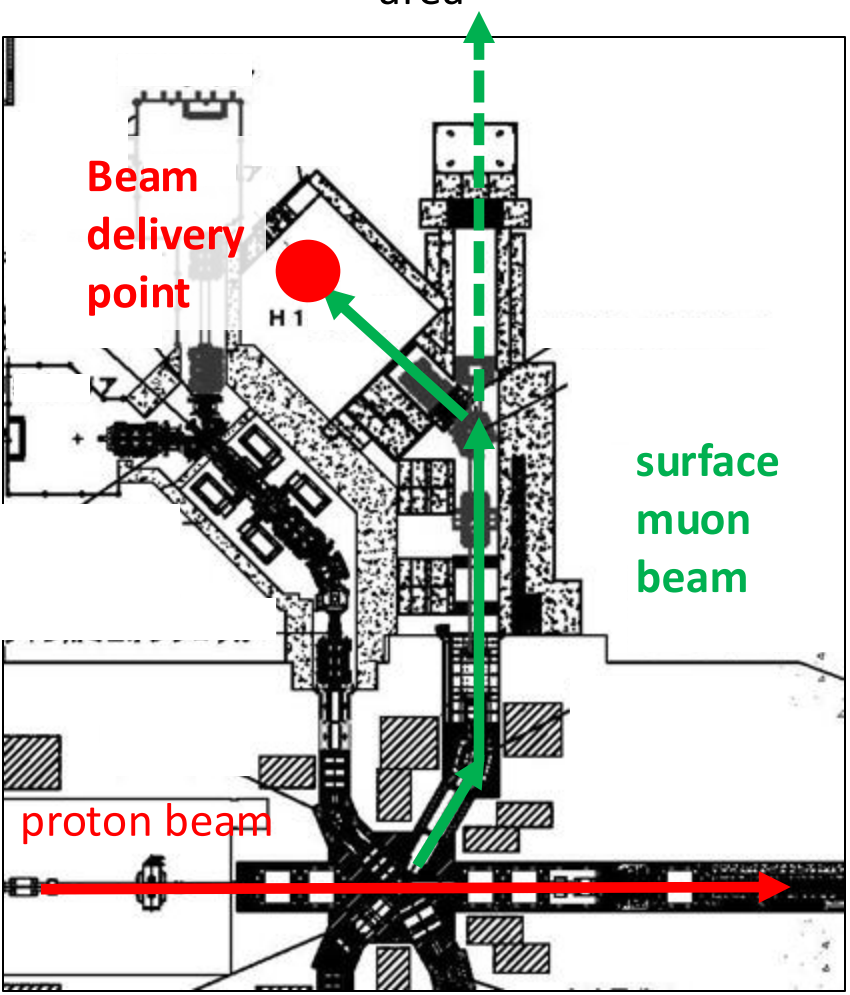
Construction of surface muon beamline (H-line)



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

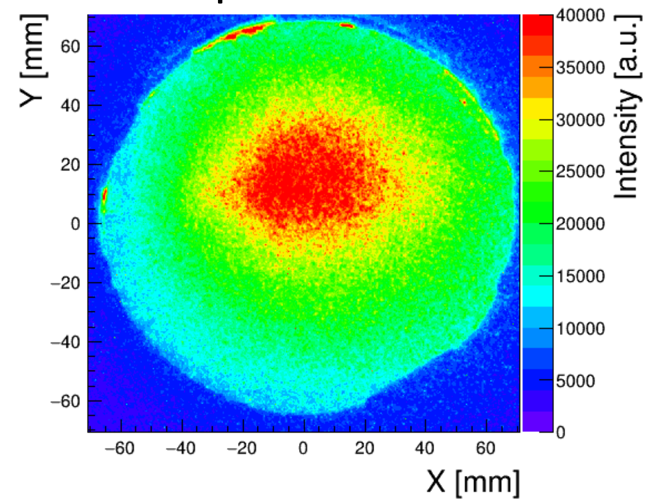


First beam to H1 area (Jan 15, 2022)

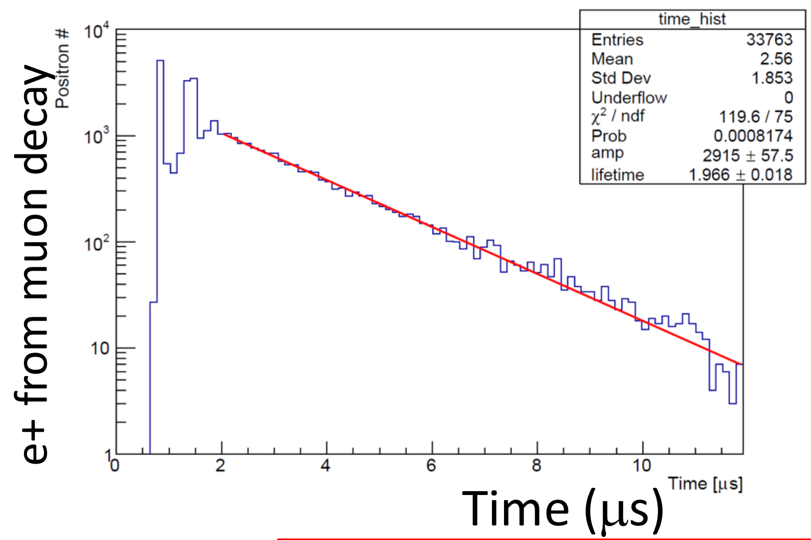


Prog. Theor. Exp. Phys. 2018, 113G01

Beam profile



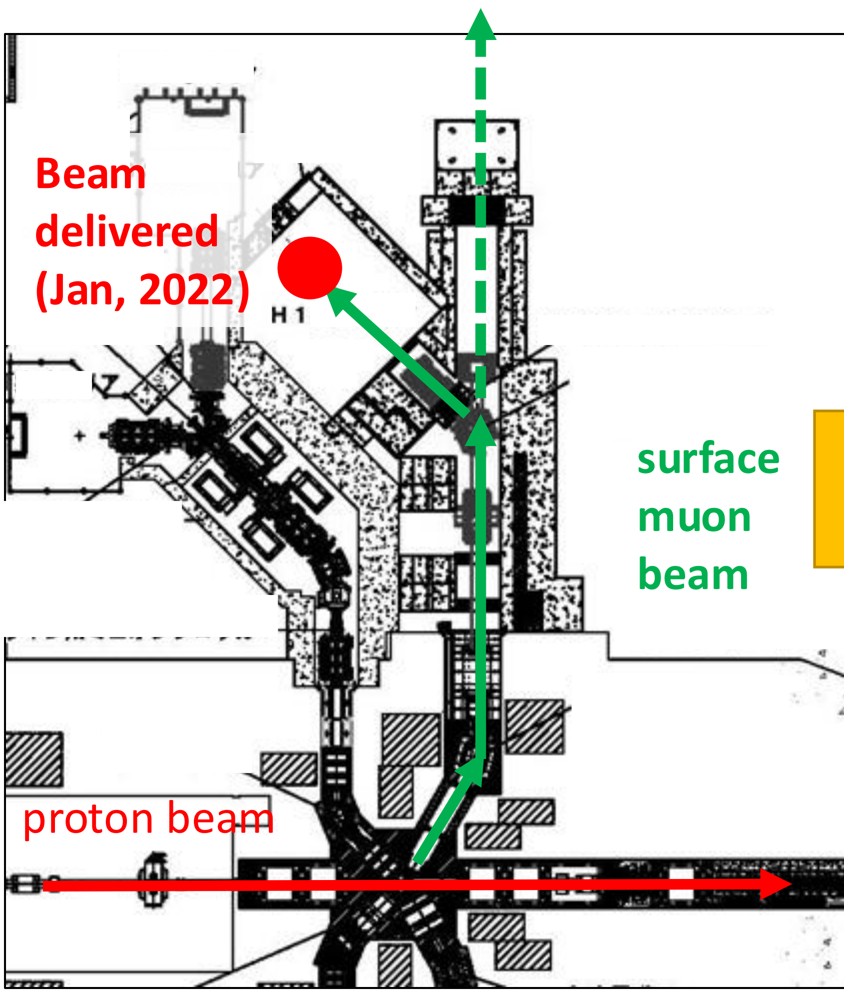
σ_x = 44 mm
σ_y = 24 mm



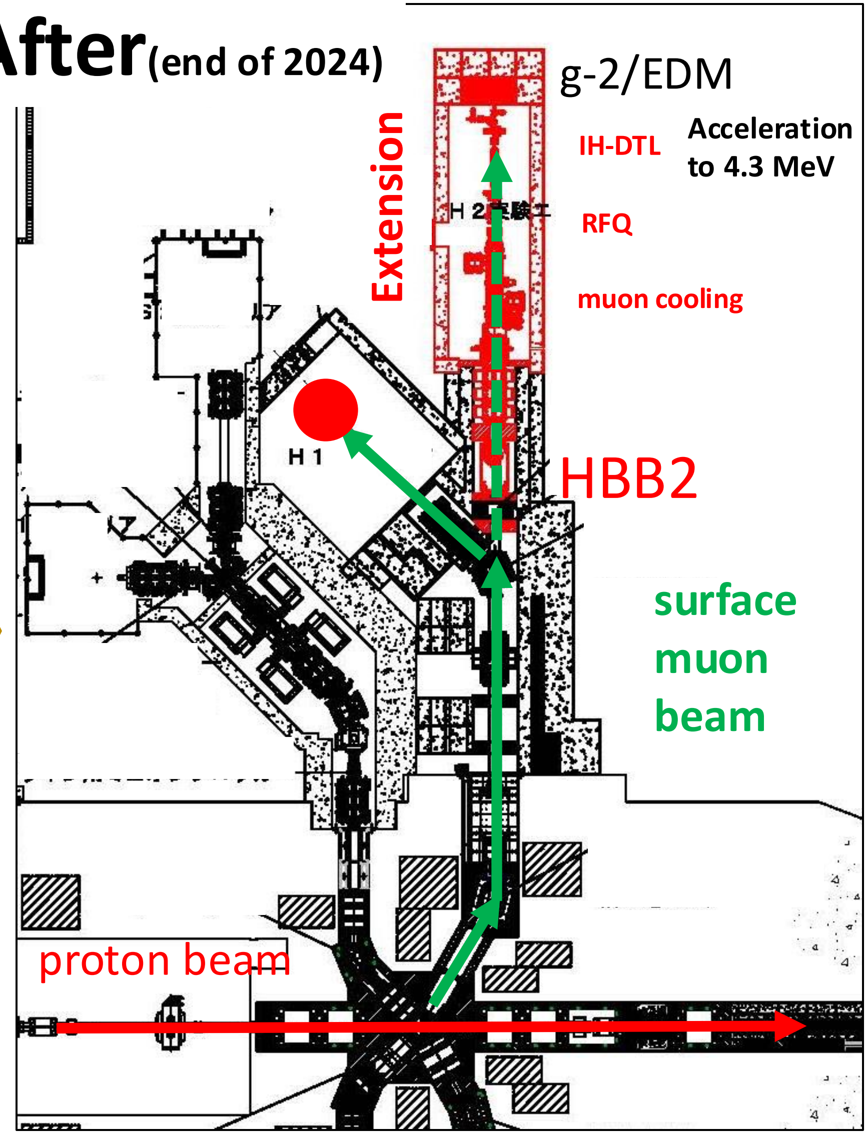
7 x 10^7/sec@p=28 MeV/c, 730kW
→ consistent with expectation

H-line extension

Before

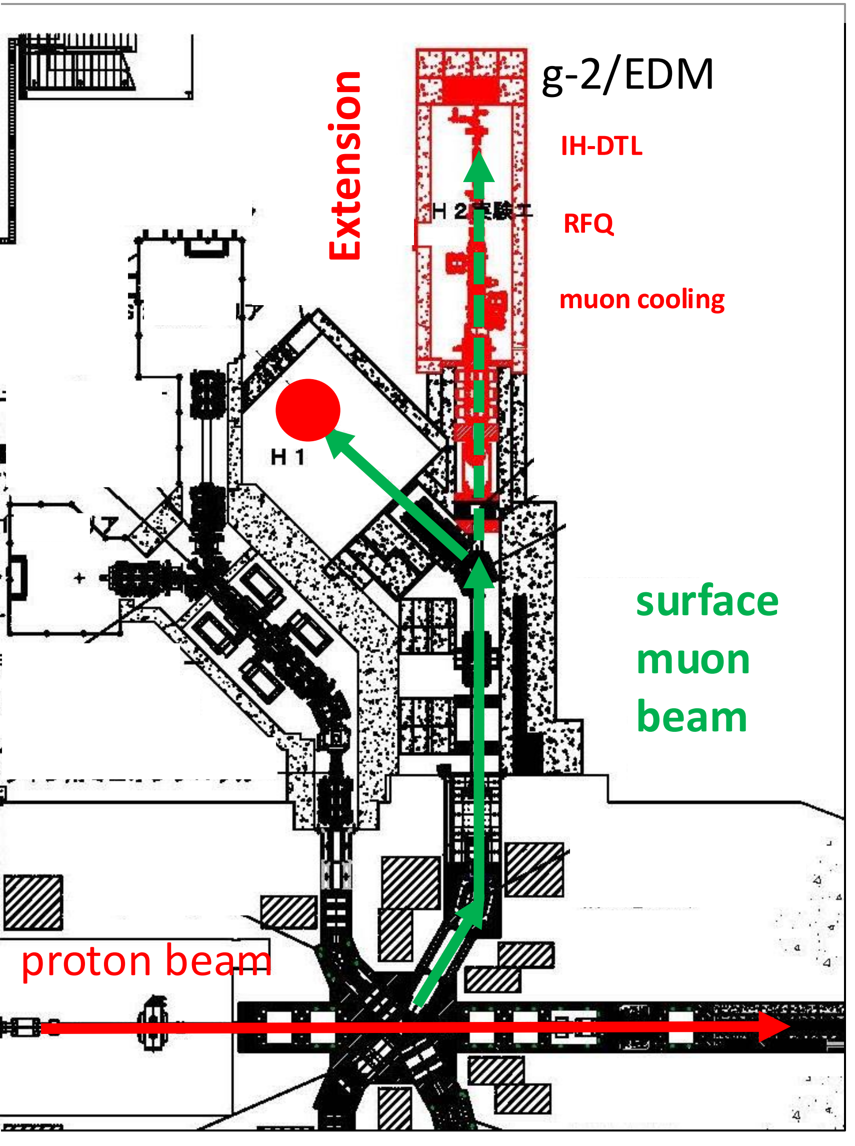


After(end of 2024)



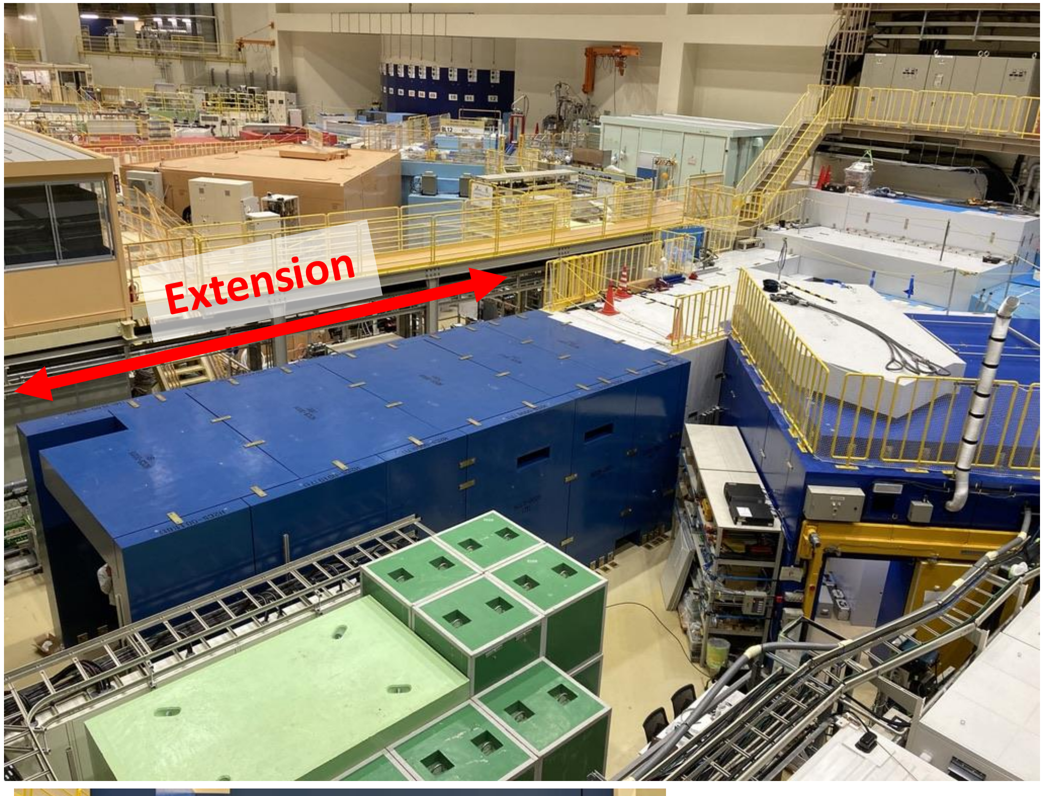
Prog. Theor. Exp. Phys. 2018, 113G01

Extension of H-line



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

Assembled radiation shields for extension (Oct 15, 2022)



Muon cooling