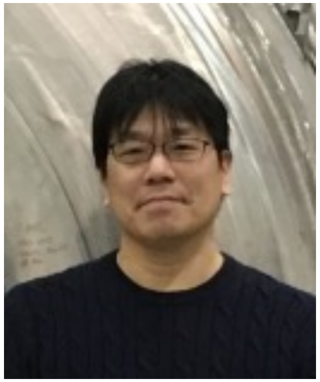
Measurement of muon g-2 and EDM



November 4, 2021

Brookhaven Forum 2021

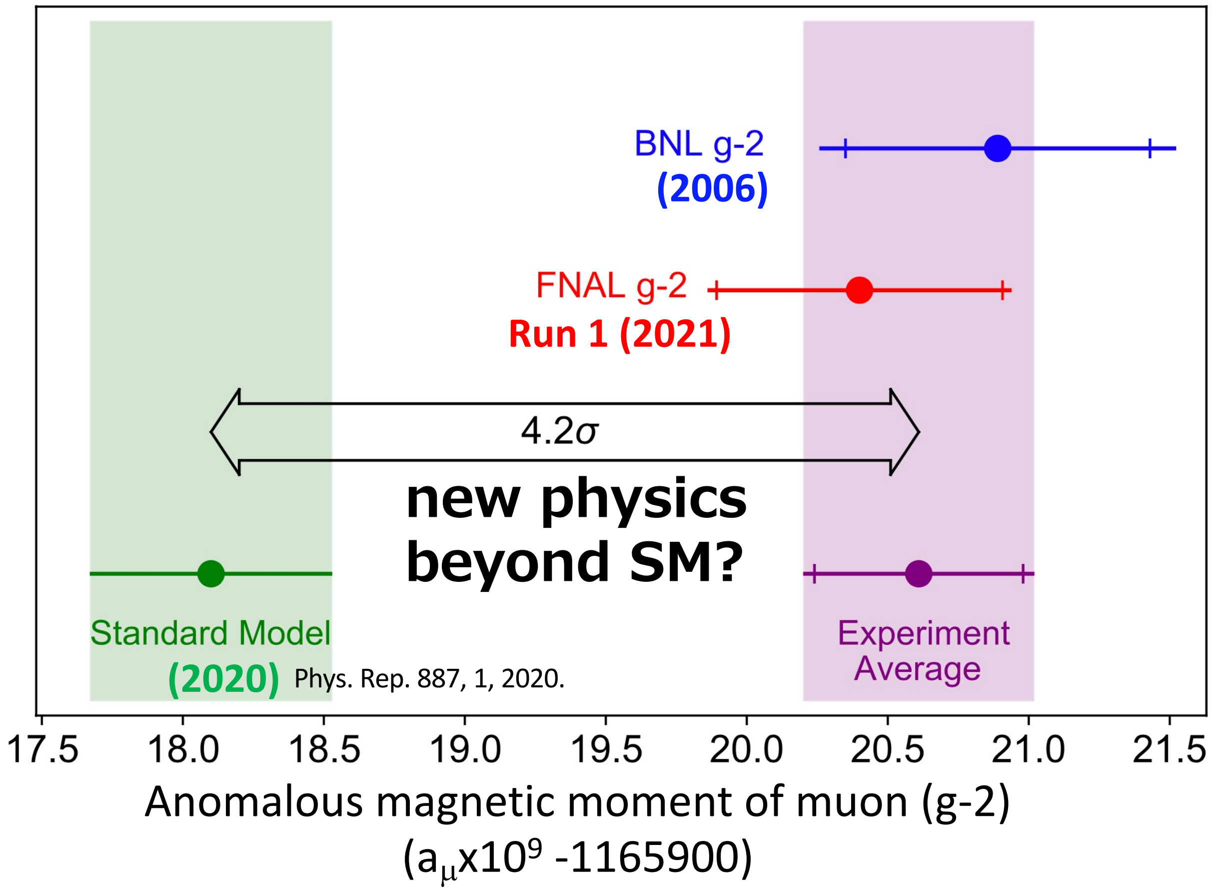
Tsutomu Mibe

Institute of Particle and Nuclear Studies, KEK

KEK50年

KEK 2021

Current status of muon g-2



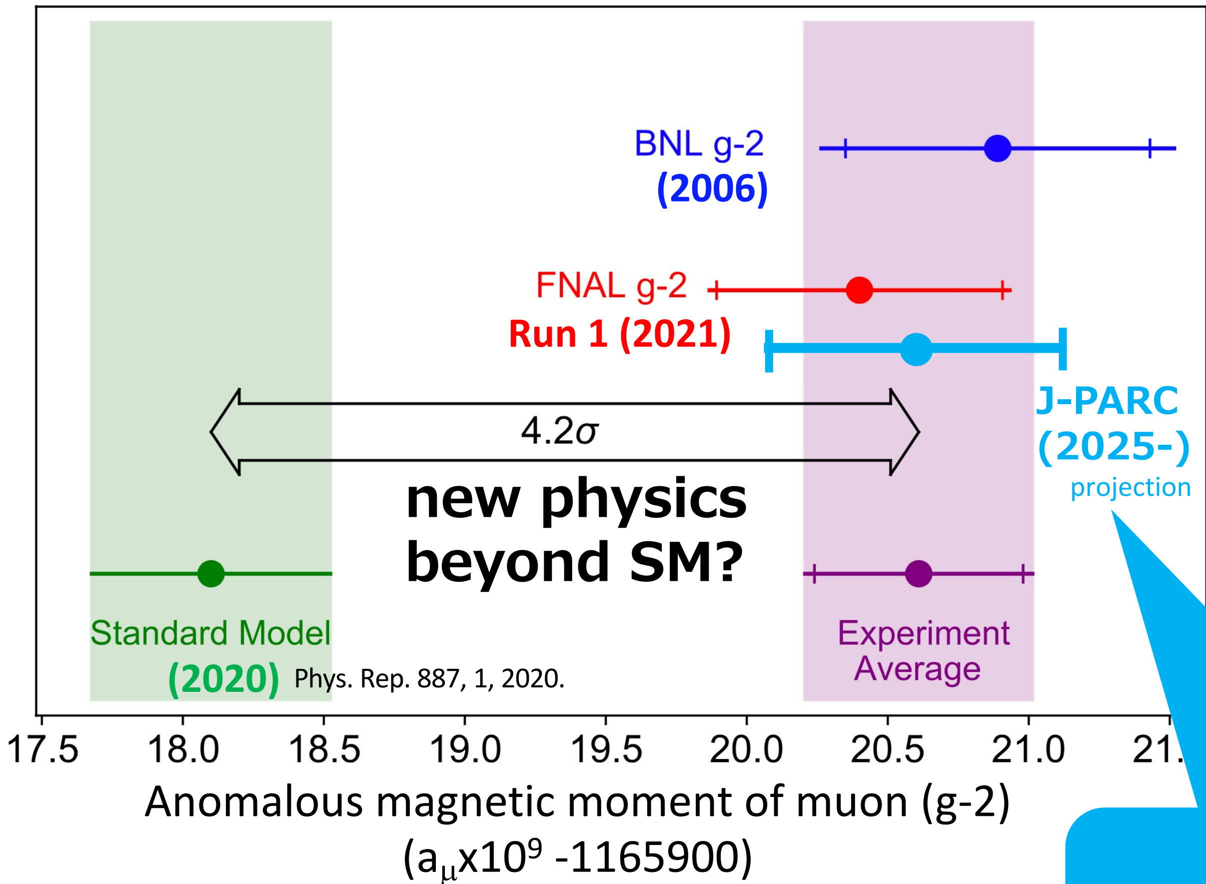
PRL 126, 141801 (2021)
Phys. Rev. D 103, 072002 (2021)
Phys. Rev. AB 24, 044002 (2021)
Phys. Rev. A 103, 042208 (2021)

New result from FNAL on April 7, 2021

(1) Confirmed previous BNL result
(2) Deviation from the SM became 4.2σ (was 3.7σ)

- **More than 70 BSM preprints appeared in arXiv in a few days.**
- **450 citations as of today**

Current status of muon g-2



PRL 126, 141801 (2021)
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- **450 citations as of today**

An independent measurement with entirely different systematics

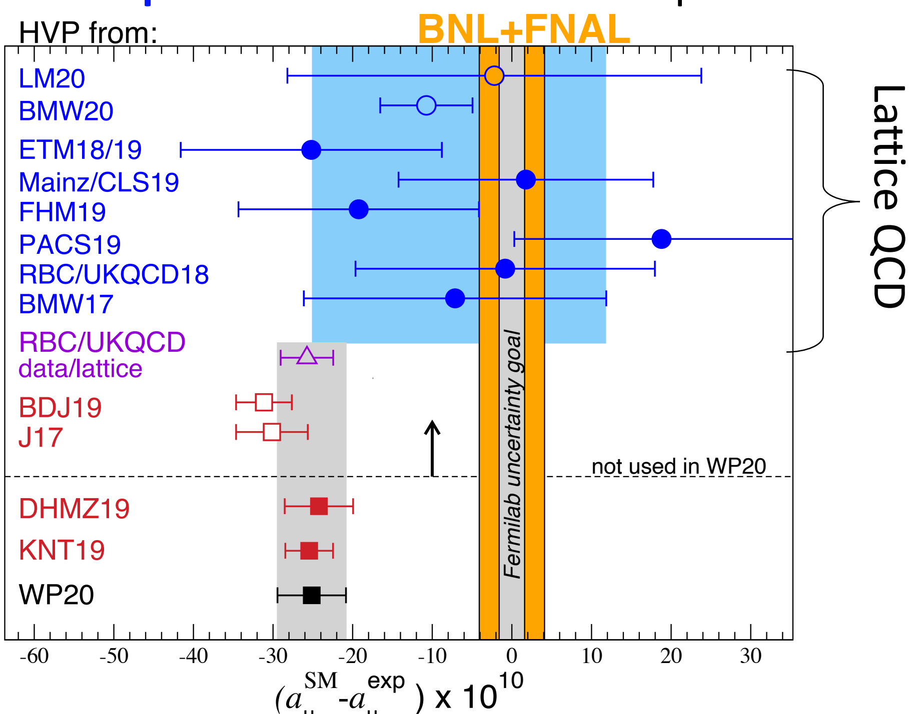
Muon g-2 theory initiative workshop

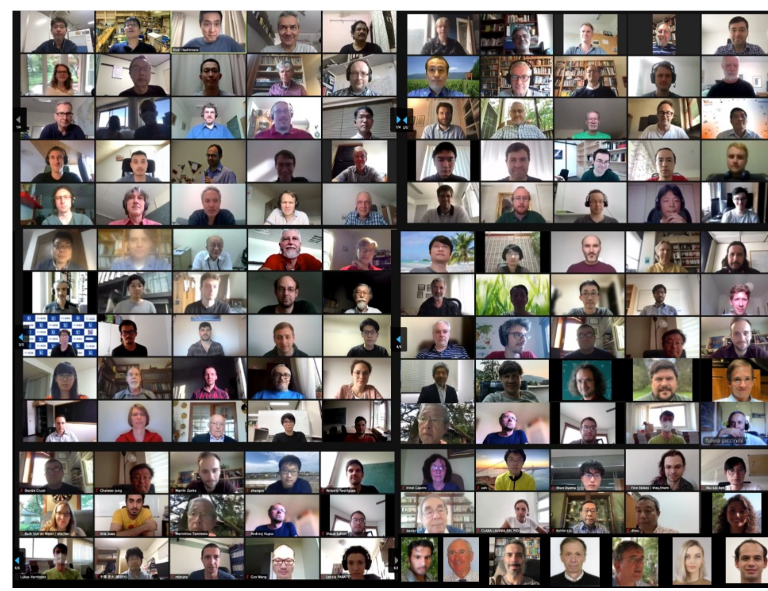
June 28 – July 2nd, 2021

https://www-conf.kek.jp/muong-2theory/

- Organized by the muon g-2 theory initiative (2017-)
- Hosted by KEK IPNS and Nagoya University
- 280 participants from 27 countries
- **The white paper** (Phys. Rep. 887,1 (2020)) describes the consensus value for the standard model prediction. A good plan **for the improvement of the SM prediction** has been developed in the workshop.

In memory of
Simon Eidelman
(1948-2021)





Next workshop : Sep. 5-9, 2022 at U. of Edinburgh

Muon EDM

EDM(d_μ) vs a_μ (model independent relation)

Current upper limit
$d_\mu < 10^{-19}$ e·cm (BNL E821)

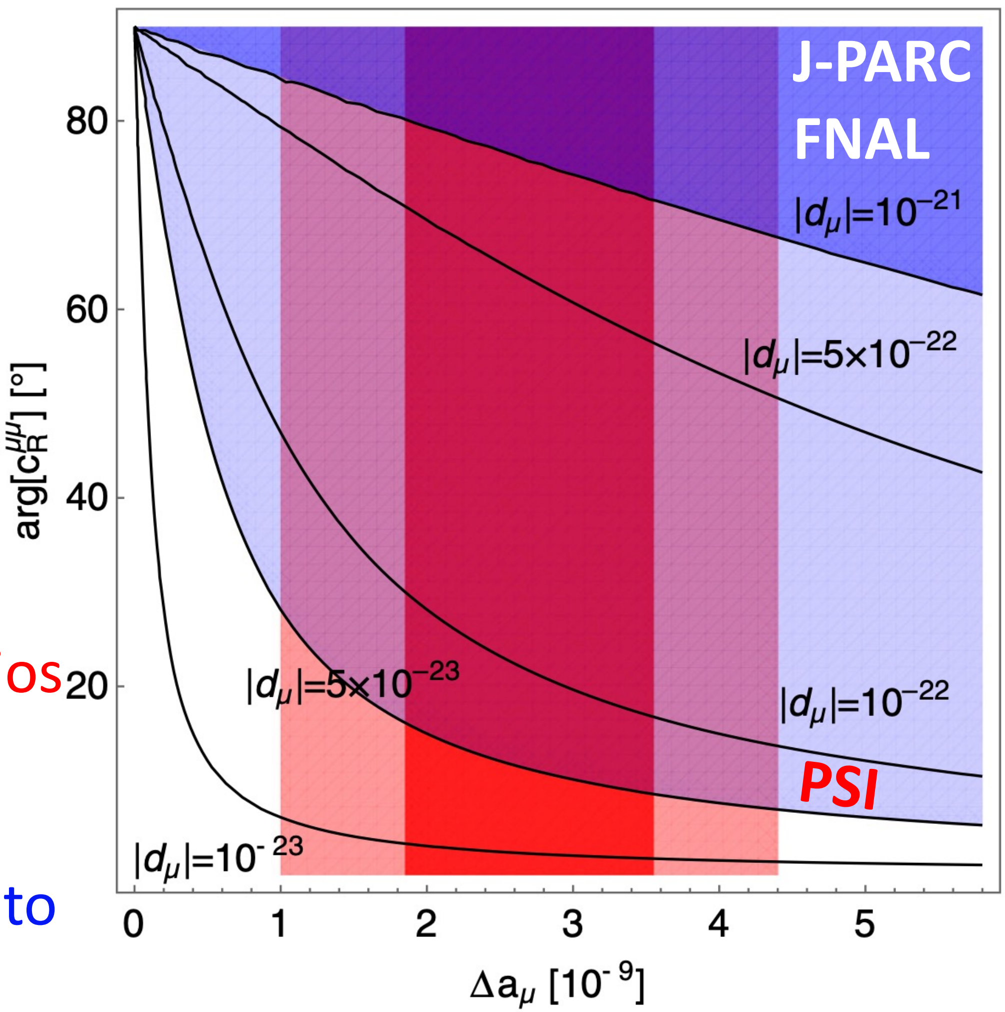
Complex representation of the dipole moment operator:

$$c_R^{\mu\mu} = -\frac{e}{4m_\mu} a_\mu - i\frac{1}{2} d_\mu$$

J-PARC and FNAL explore scenarios of the phase region (70-90 deg.)

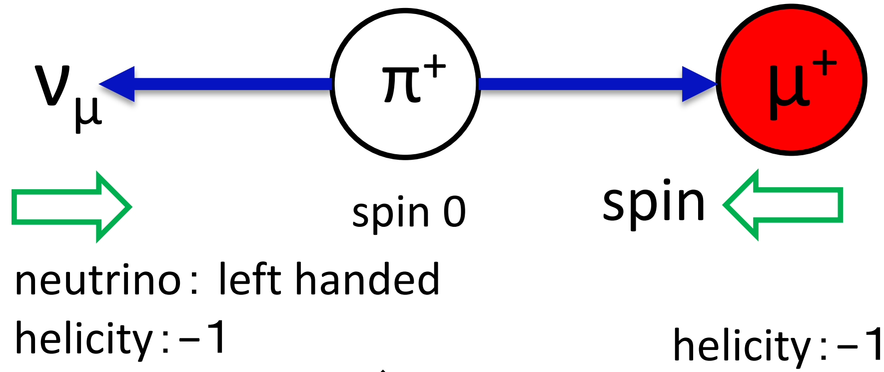
Future plan at PSI to push down to 10 deg.

A. Crivellin et al., PRD 98, 113002 (2018)

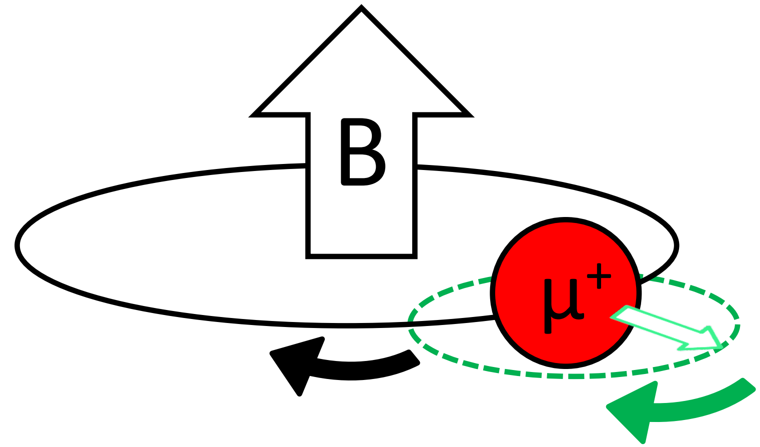


Three steps of g-2 & EDM measurement

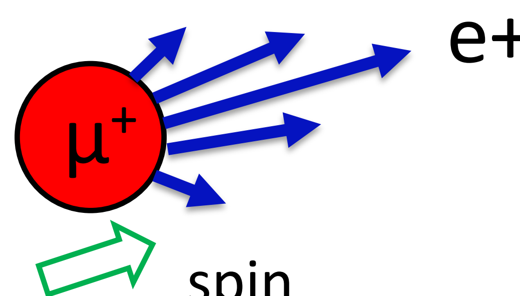
1. Prepare a polarized muon beam.



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

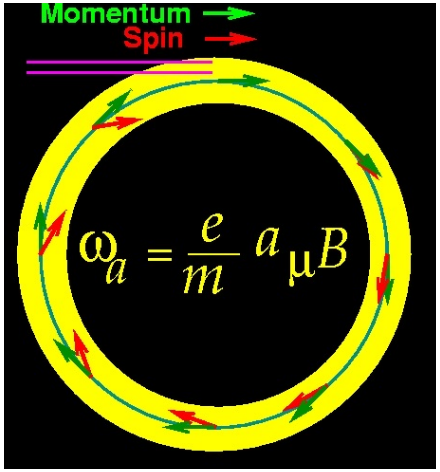


3. Measure decay positron



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)

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

BNL & FNAL E989

J-PARC approach
E = 0 at any γ

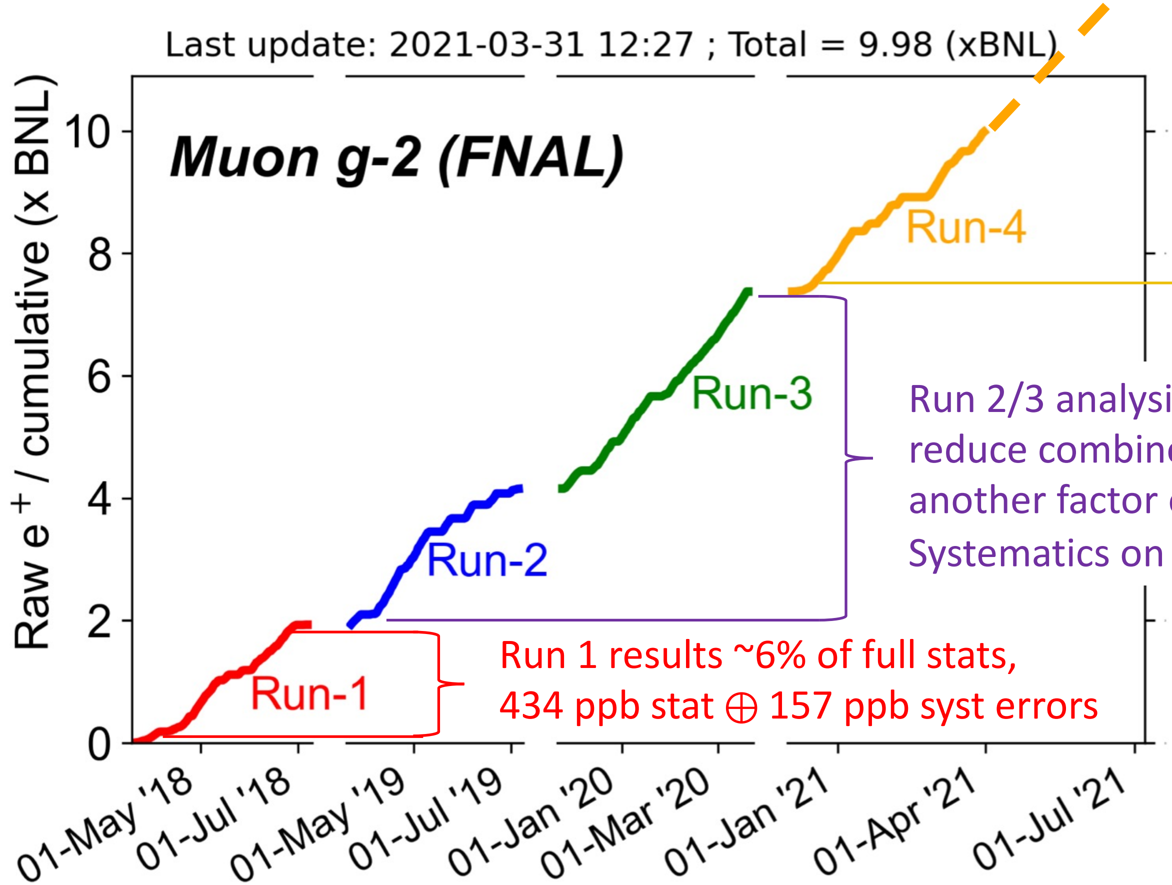
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

J-PARC E34

FNAL g-2 : outlook

L. Roberts (Apr. 2021)

Much more data to come!



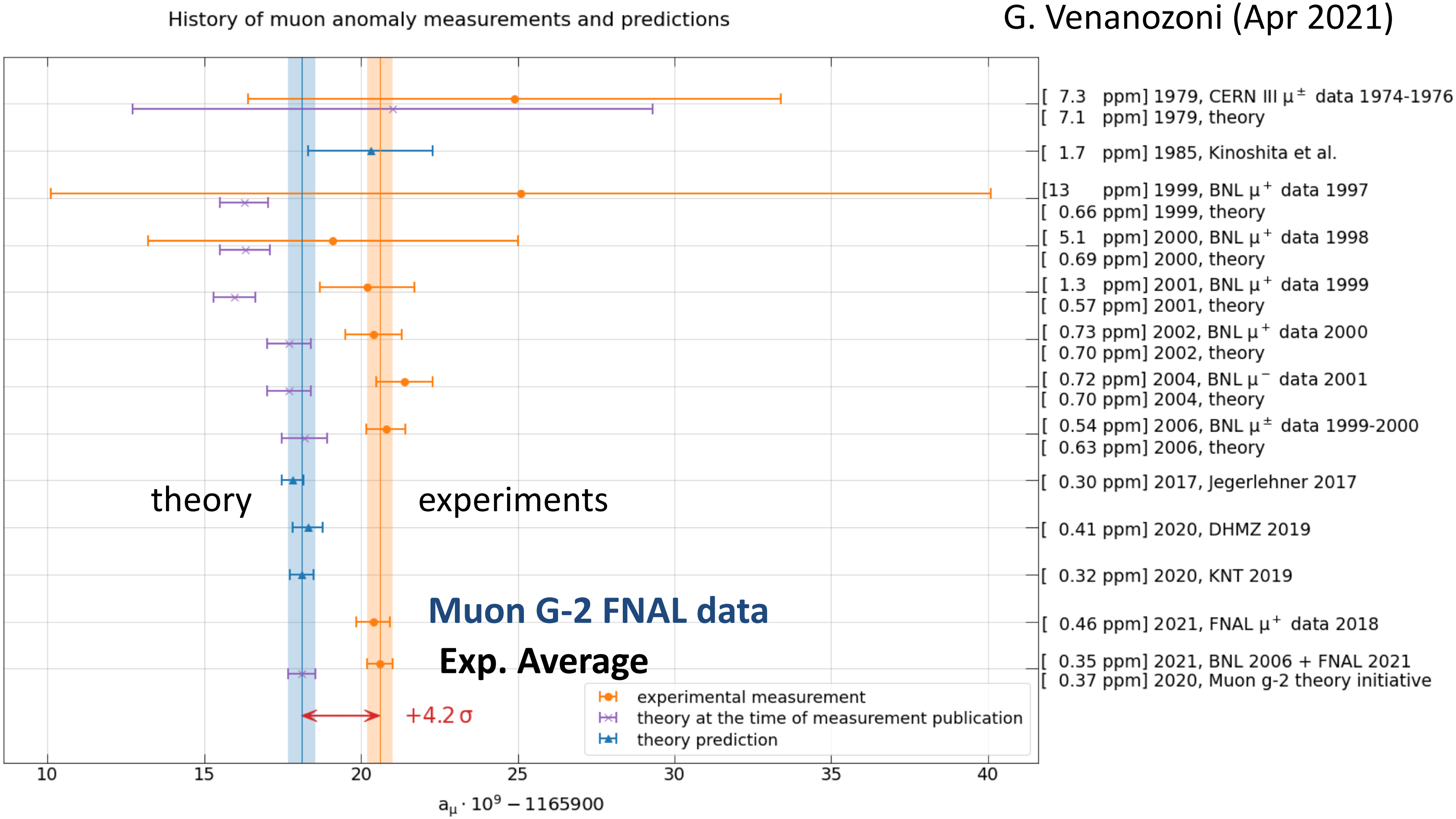
Run 4 (now) and beyond, aiming for 20xBNL and another factor of ~2 reduction in error

Run 2/3 analysis in progress, expecting to reduce combined experimental error by another factor of 2 by next summer. Systematics on track for < 100 ppb

Run 1 results ~6% of full stats, 434 ppb stat ⊕ 157 ppb syst errors

Improvements in experiment?

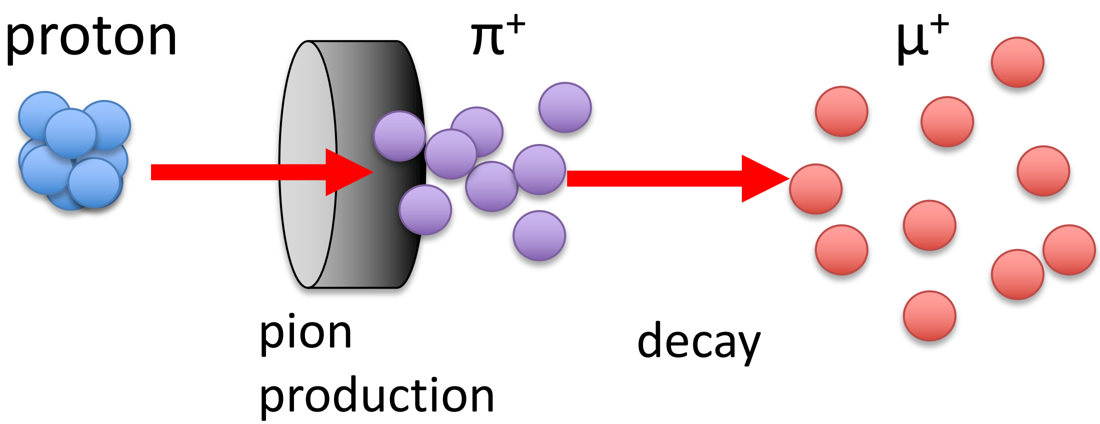
G. Venanozoni (Apr 2021)



The experimental average is dominated by the magic gamma experiments (BNL+FNAL).

→Independent measurements are important.

Conventional muon beam



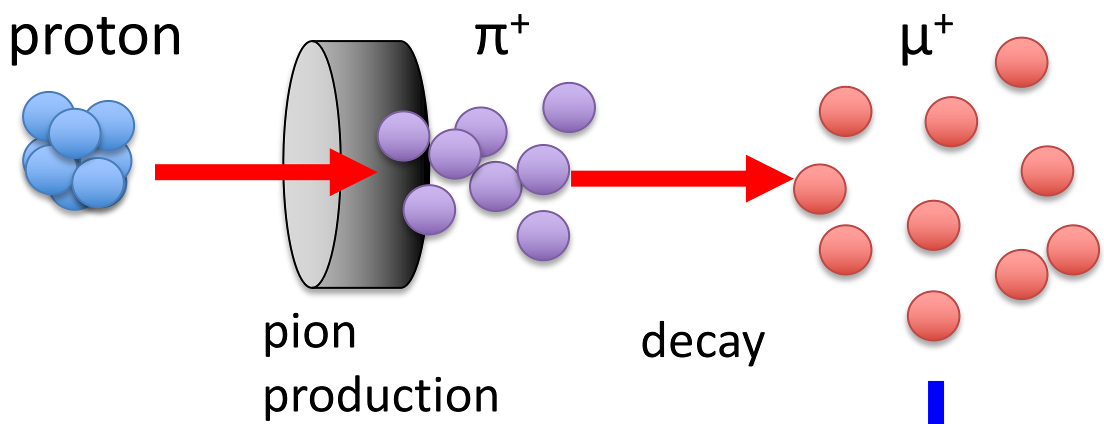
emittance

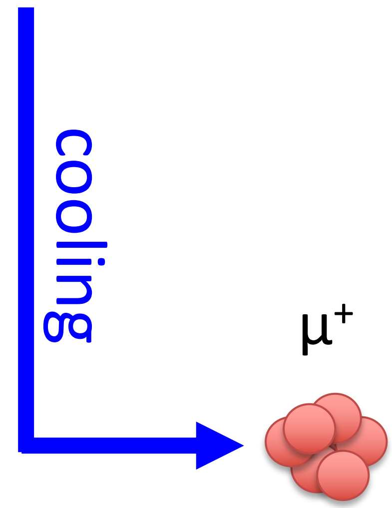
~1000π mm ·mrad

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

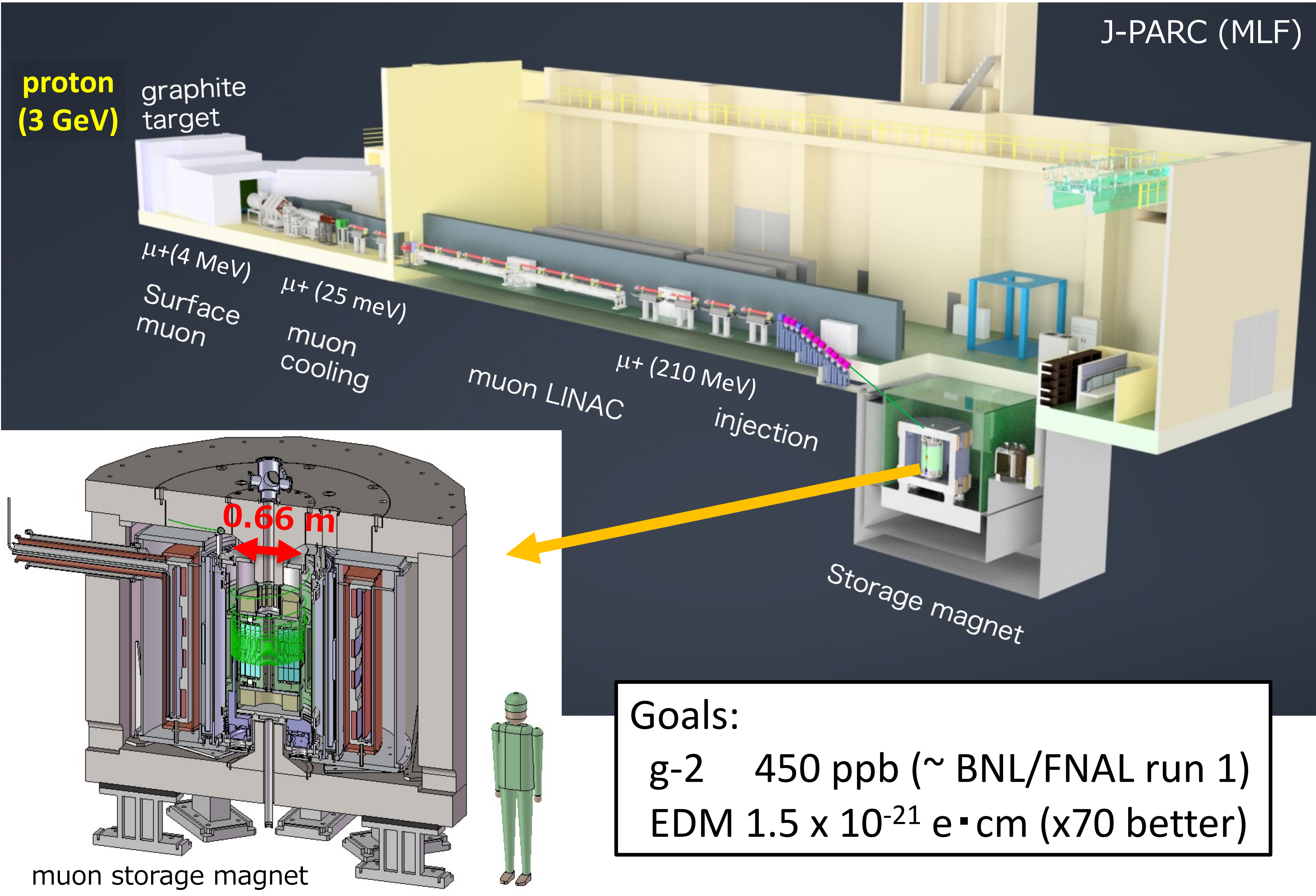
Source of systematic uncertainties

emittance
1π mm ･mrad

Free from any of these

Reaccelerated thermal muon

Muon g-2/EDM experiment at J-PARC

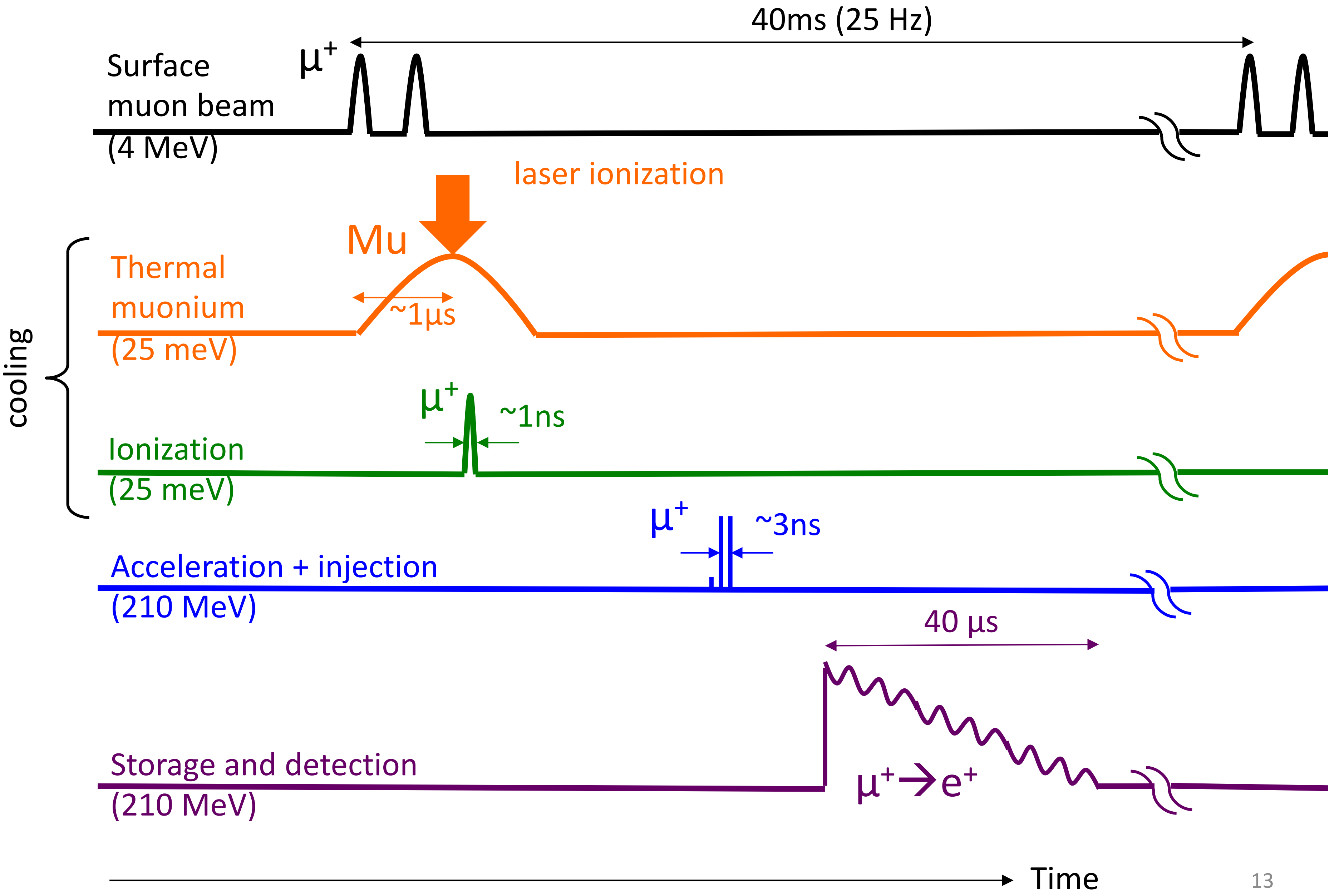


Goals:

g-2 450 ppb (~ BNL/FNAL run 1)

EDM 1.5 x 10^{-21} e･cm (x70 better)

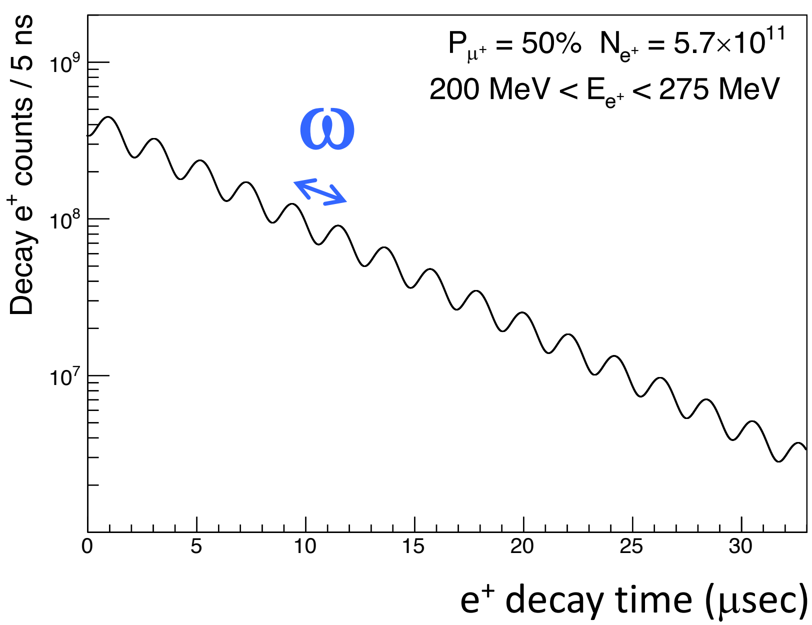
Experimental sequence

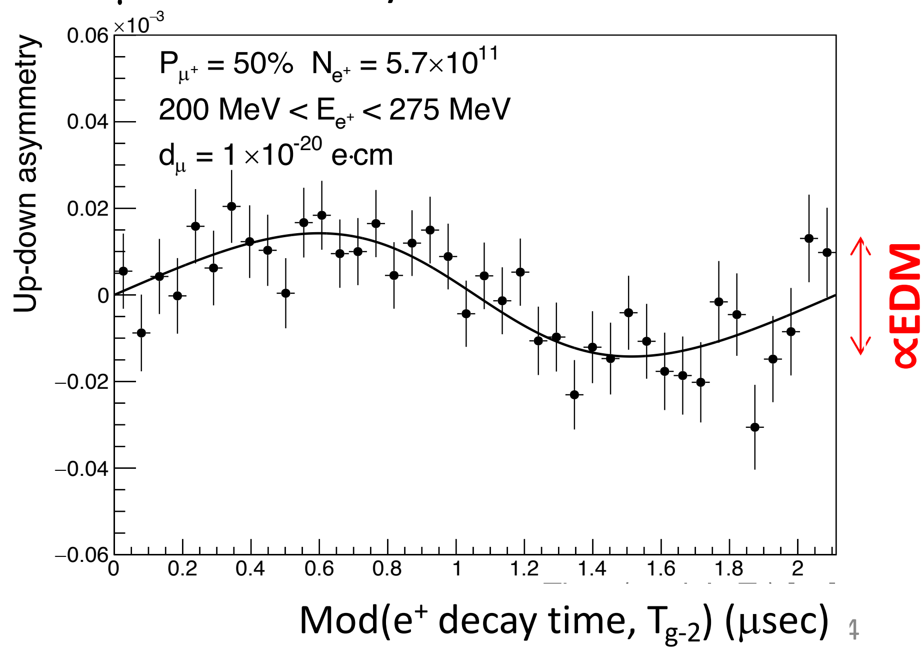


Expected results

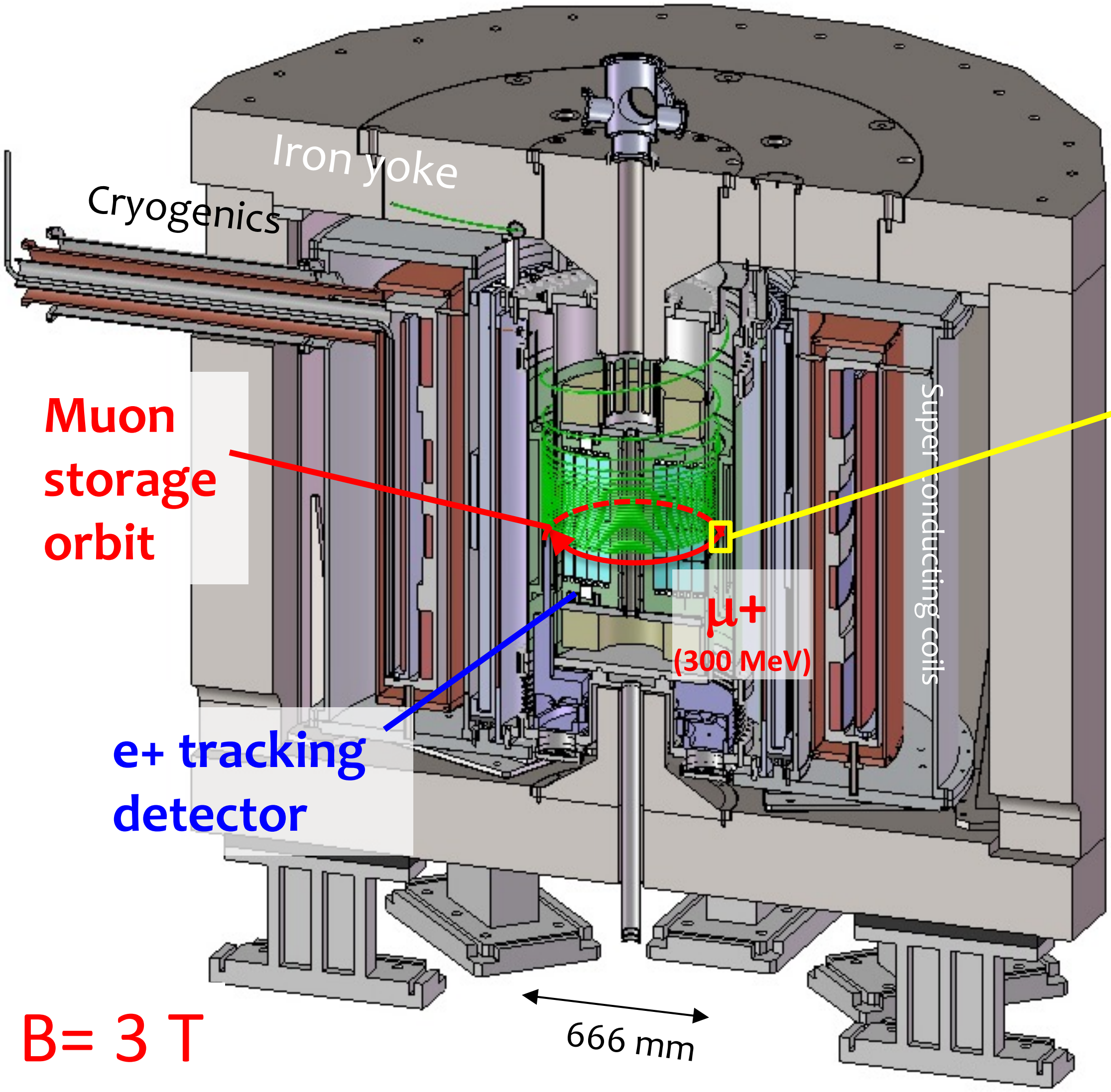
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

Expected time spectrum of e^+ in $\mu \rightarrow e^+\nu\nu$ decay

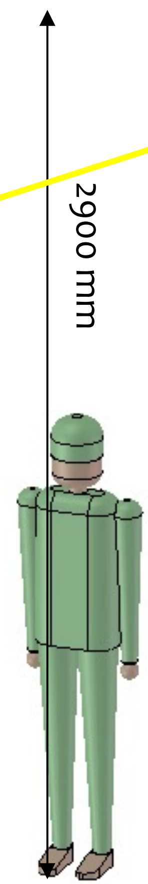




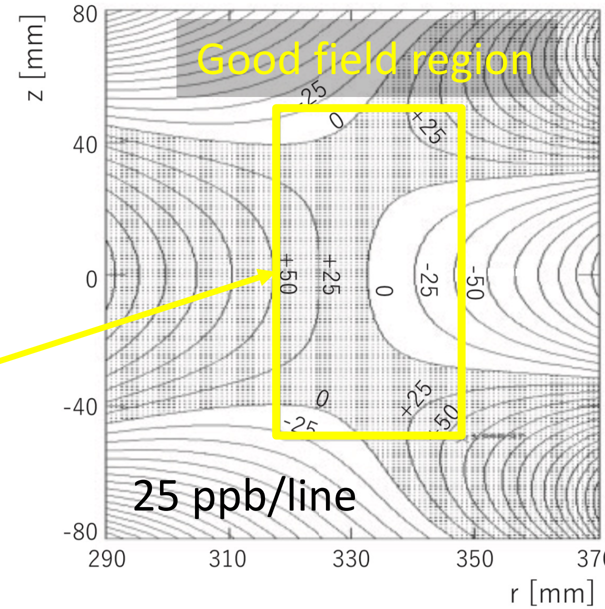
Muon storage magnet and detector



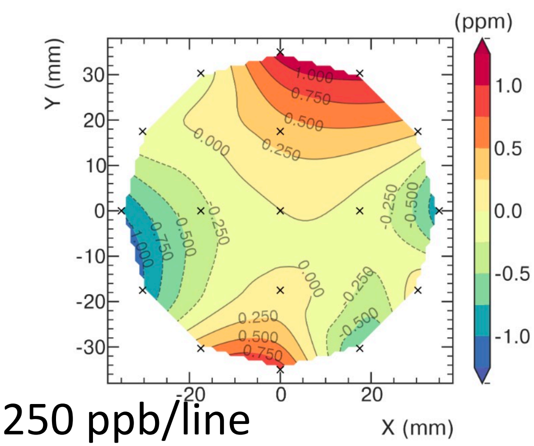
B= 3 T



Calculated average field uniformity



FNAL Run 1 PRA 103, 042208 (2021)



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

Very weak magnetic focusing

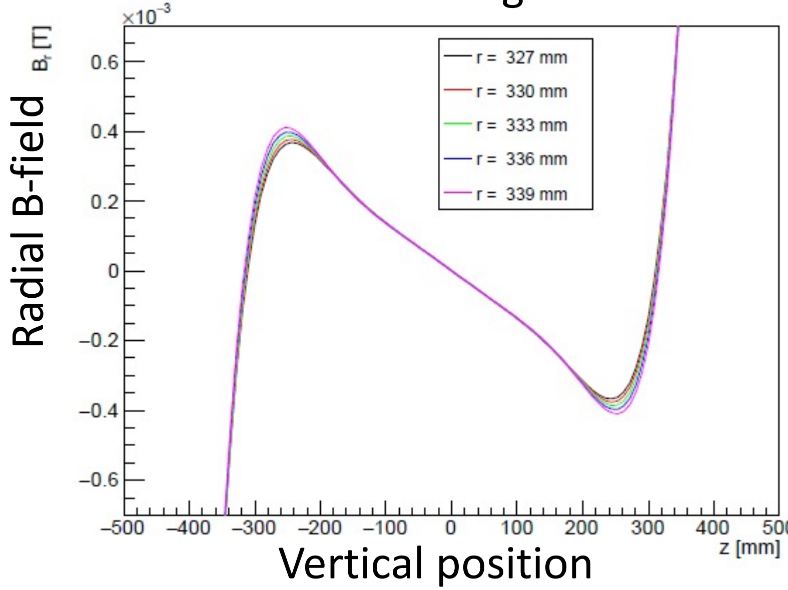
- **Radial magnetic field** can be a major source of systematics on EDM since the g-2 term mixes to the EDM term.

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

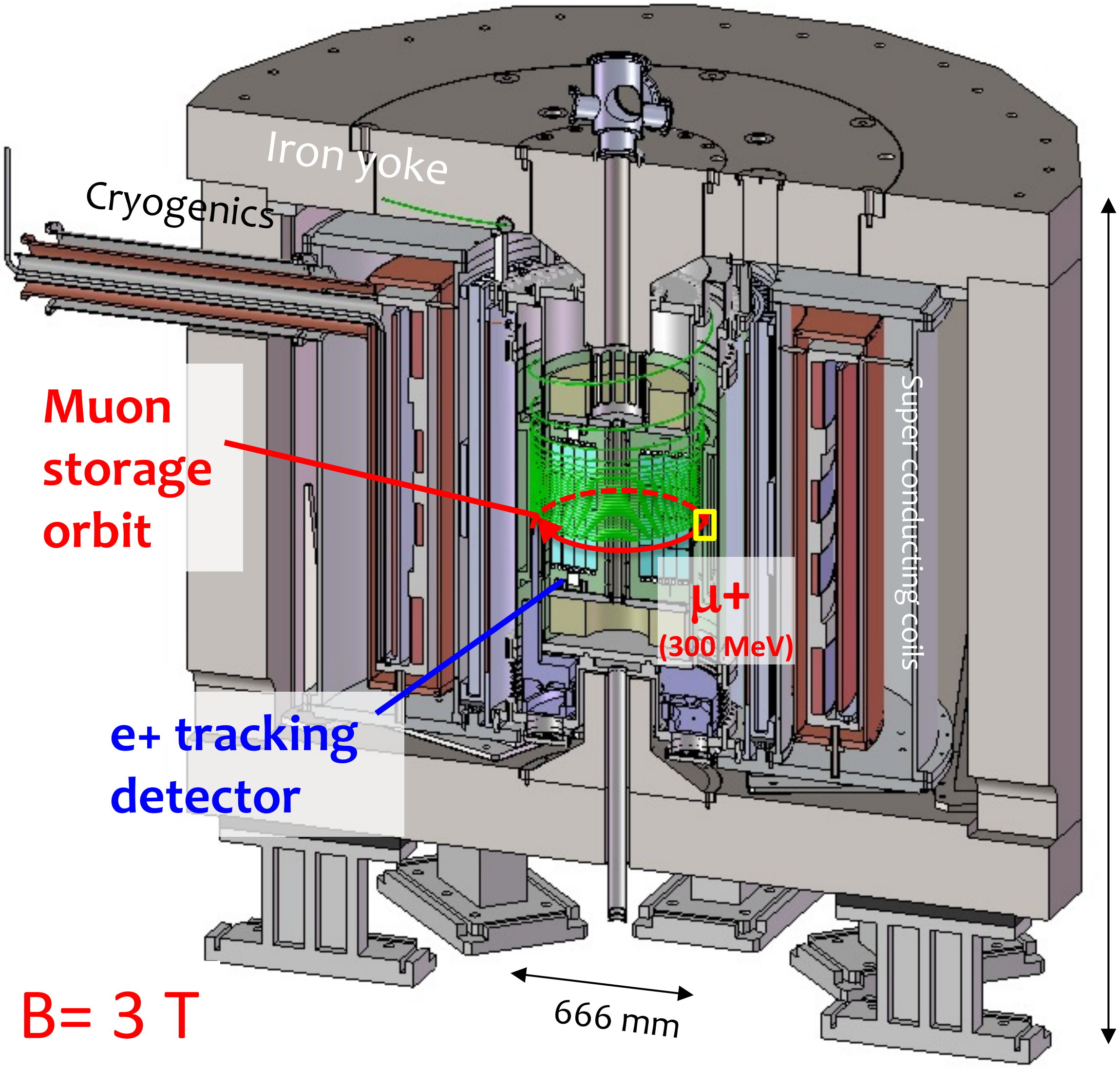
Radial direction

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

Weak focusing B-field



J-PARC muon g-2/EDM experiment

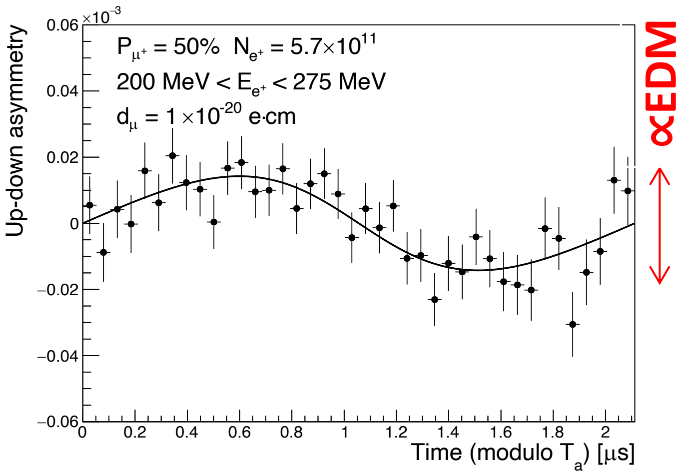


B= 3 T

- **No electric focusing**
- **Very weak magnetic focusing**

  n = 1.5 x 10^{-4} (1ppm/cm)

  Br = 0.1ppm → 0.2 mm shift in vertical position
- **Sensitivity: 1.5 x 10^{-21} ecm**



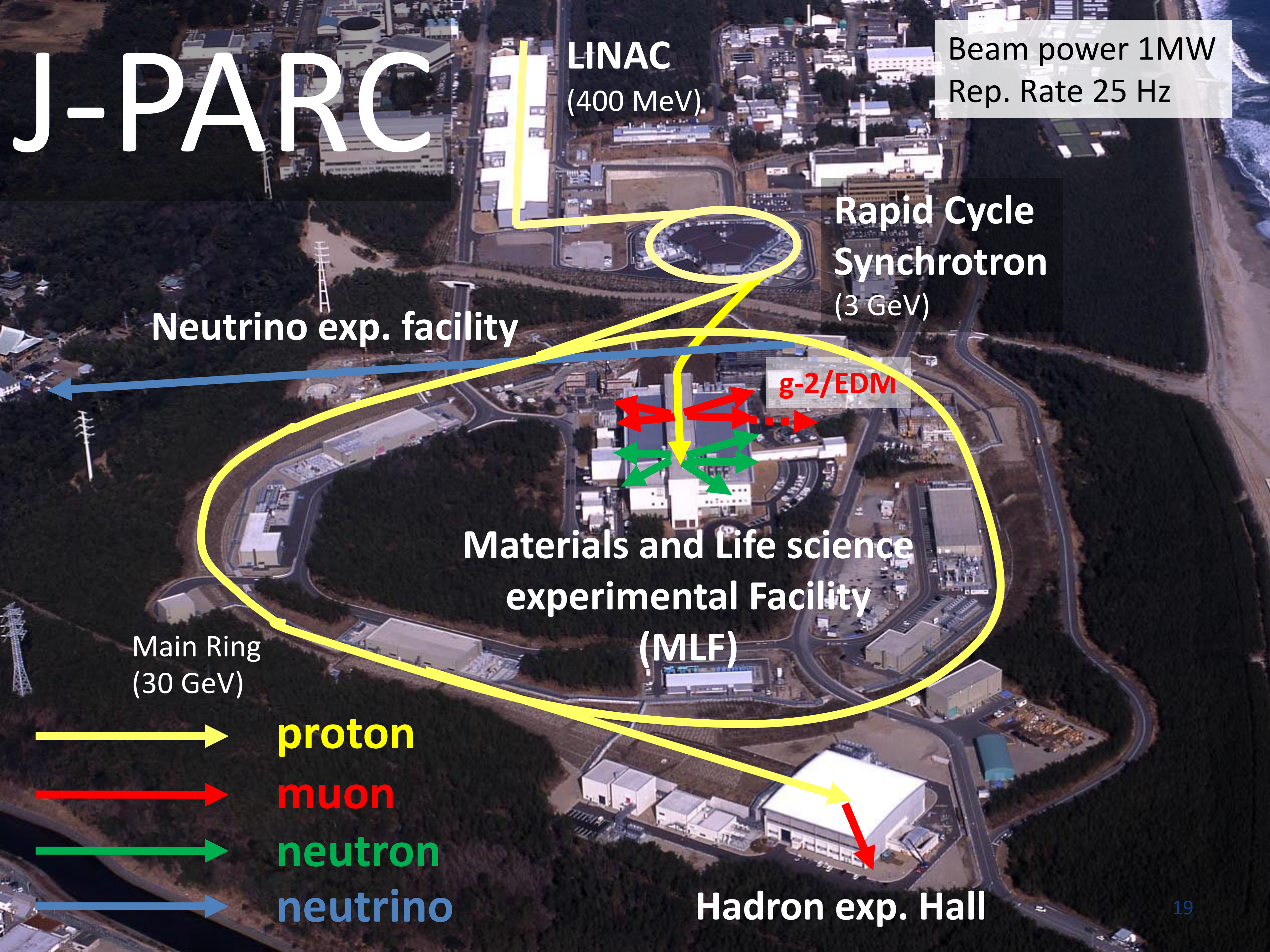
Mod(e^+ decay time, T_{g-2}) (μsec)

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

Expected uncertainties

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

	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} $e \cdot$cm]	1.5 (stat.)
	0.36 (syst.)


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

g-2 and muonium experiments 20

g-2

Fermilab E989

J-PARC E34 (this experiment)

$$a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\frac{\omega_a}{\omega_p} - \frac{\mu_\mu}{\mu_p}}$$

120 ppb

$$a_\mu = \frac{\omega_a}{\omega_p}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

8 ppb 120 ppb 0.3 ppt

μ_μ

m_μ

MuSEUM(J-PARC)

Mu HFS

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

Mu 1S-2S

m_μ

muonium

$$\Delta\nu_{\text{1S-HFS}} \simeq \frac{16}{3}\alpha^2 R_\infty \frac{\mu_\mu}{\mu_B}\left(1 + \frac{m_e}{m_\mu}\right)^{-3}$$

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

muonium

$$\Delta\nu_{\text{1S2S}} \simeq \frac{3\alpha^2}{8h} m_e c^2 \left(1 + \frac{m_e}{m_\mu}\right)^{-1}$$

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**

Mu HFS

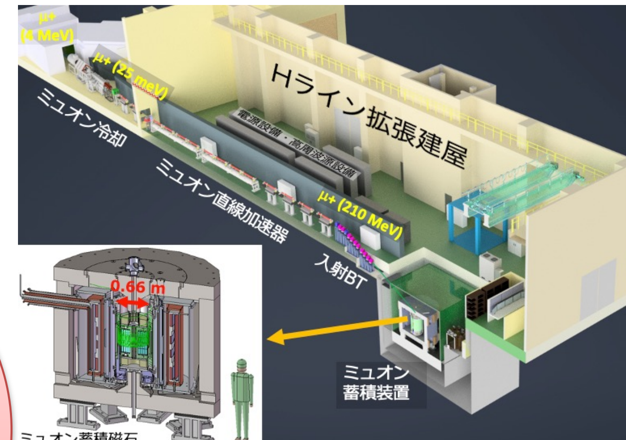
H. Torii's talk

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

g-2

Fermilab E989

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



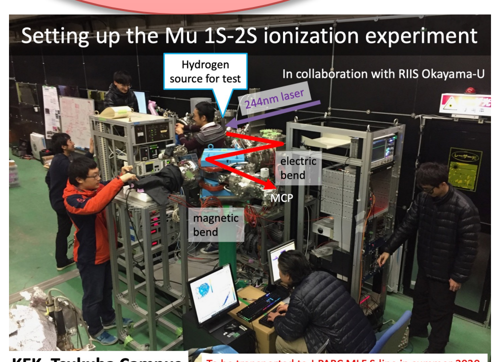
Positron detector
NMR probes

Muonium production
and ionization

Technical synergies

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

Mu 1S-2S

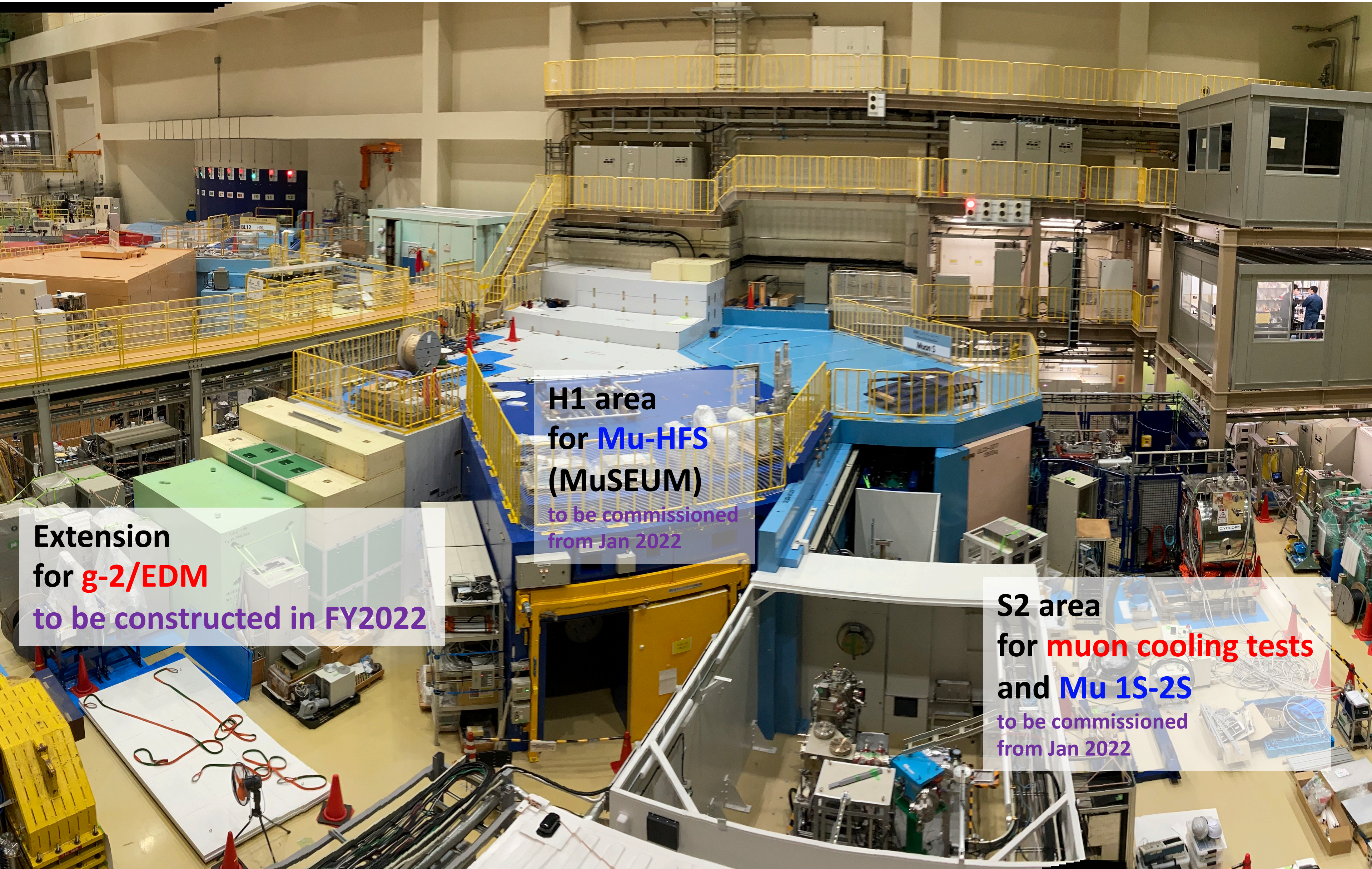


In preparation

Lead by S. Uetake (Okayama)


PC
30MR
KOMATSU

Experimental areas for experiments



Construction of surface muon beamline (H-line)

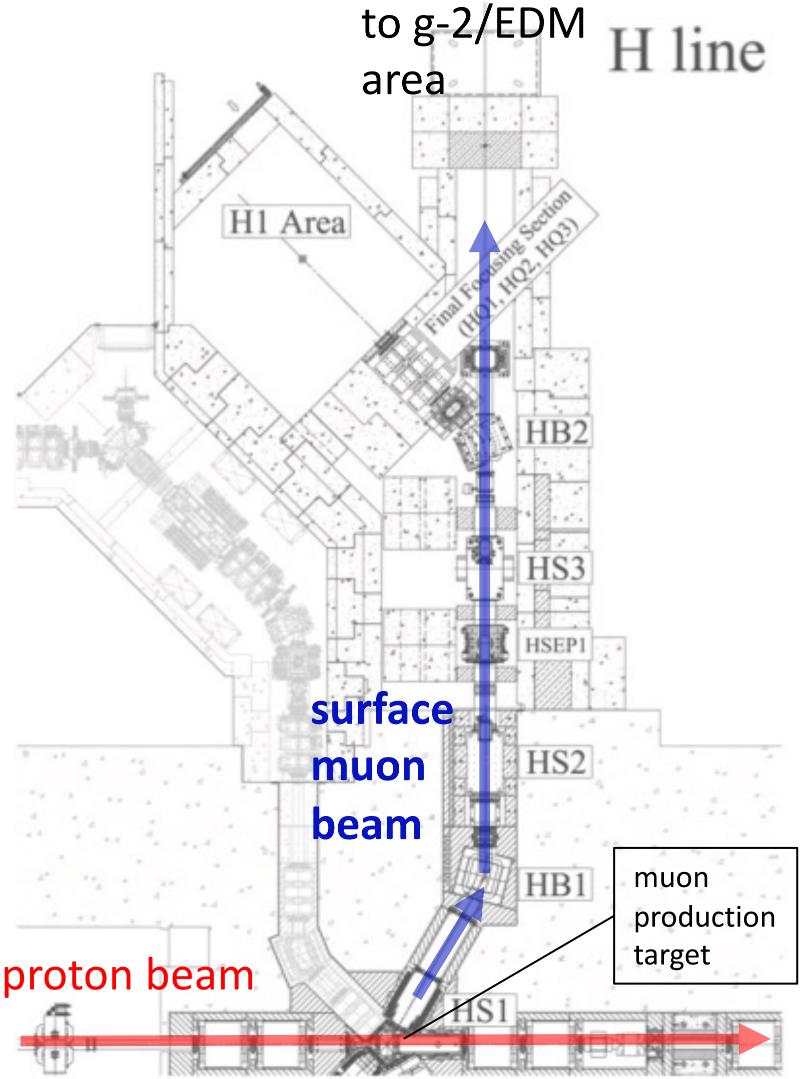
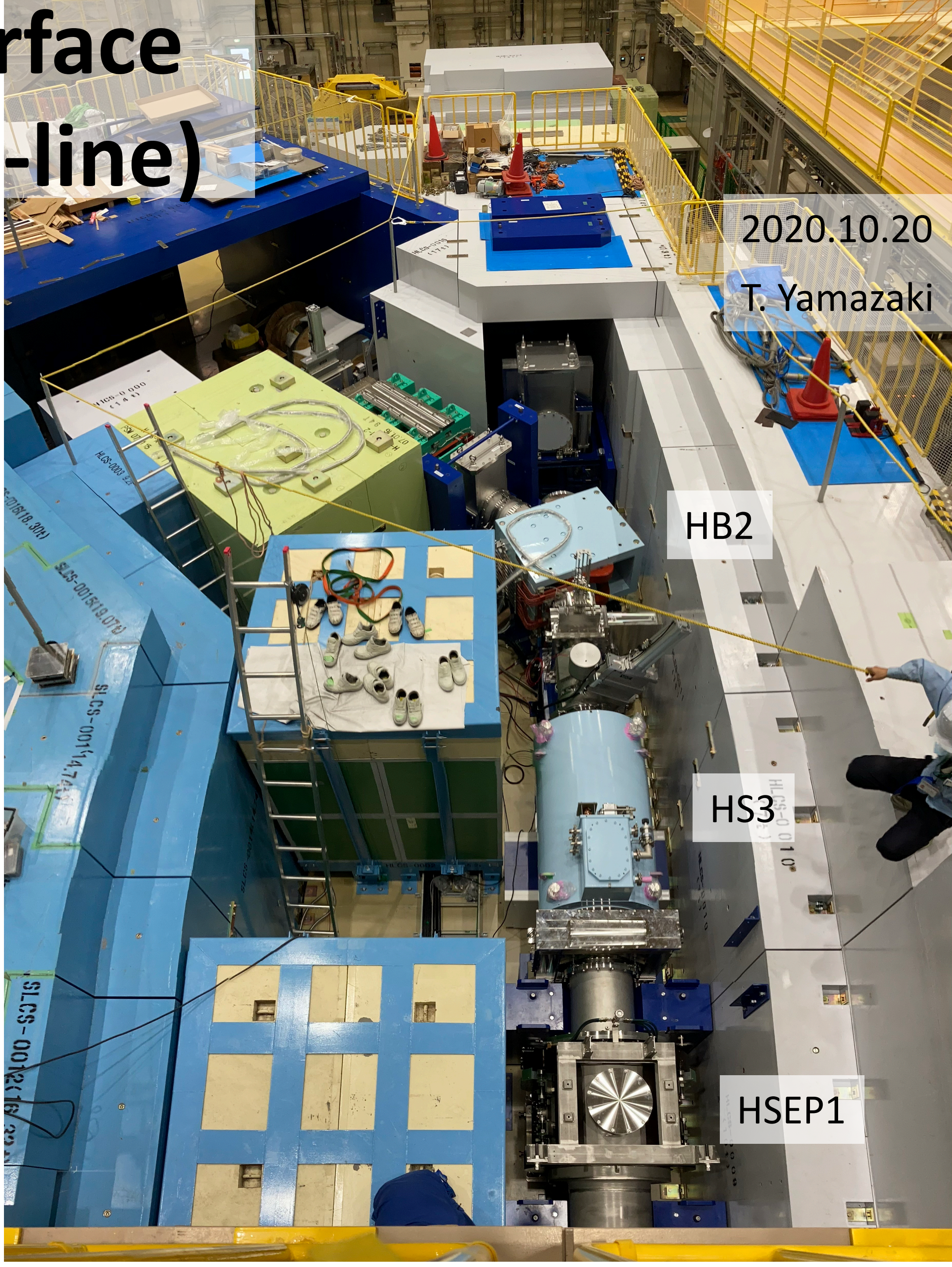


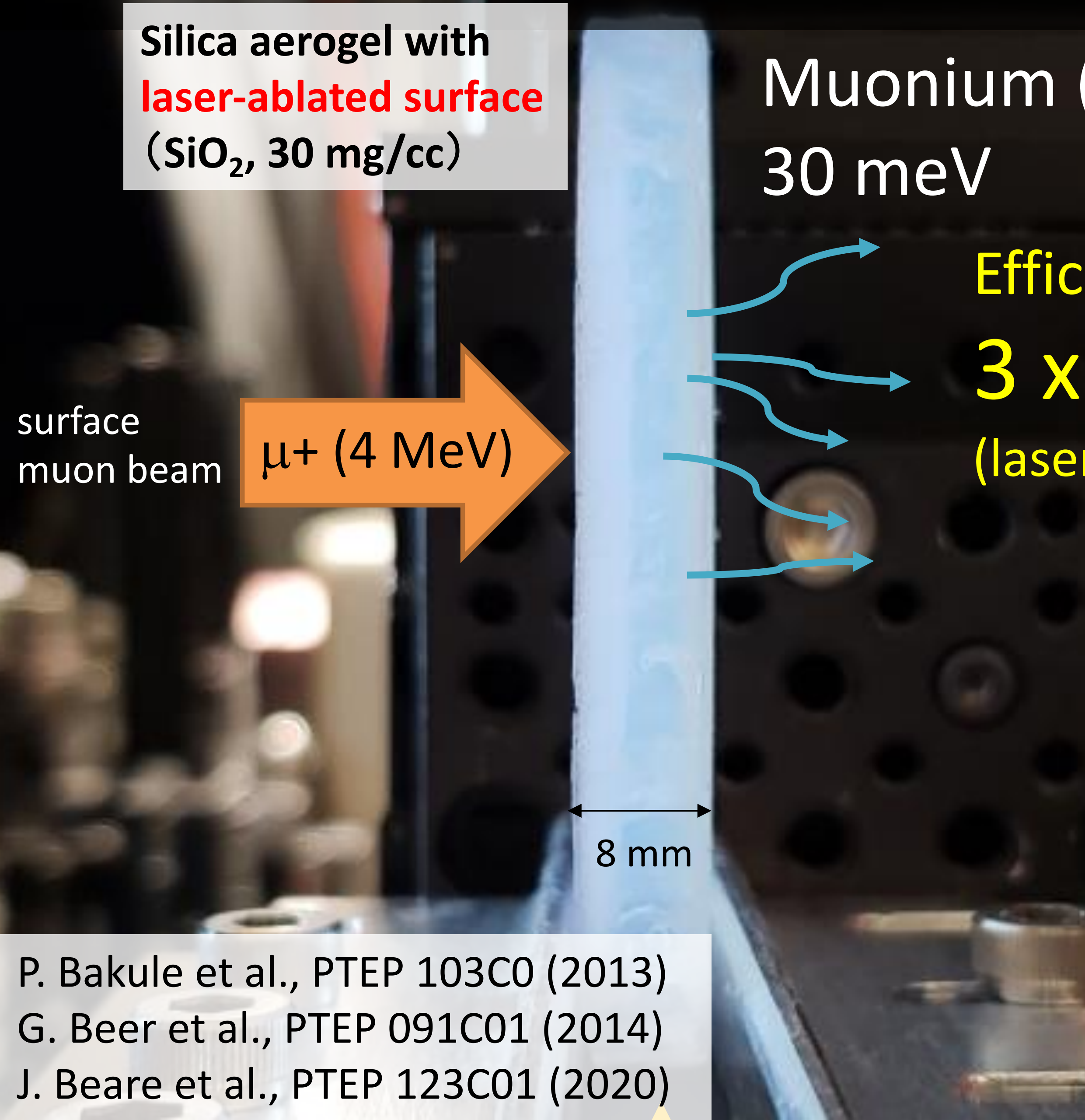
Fig. 2. The H-line layout.

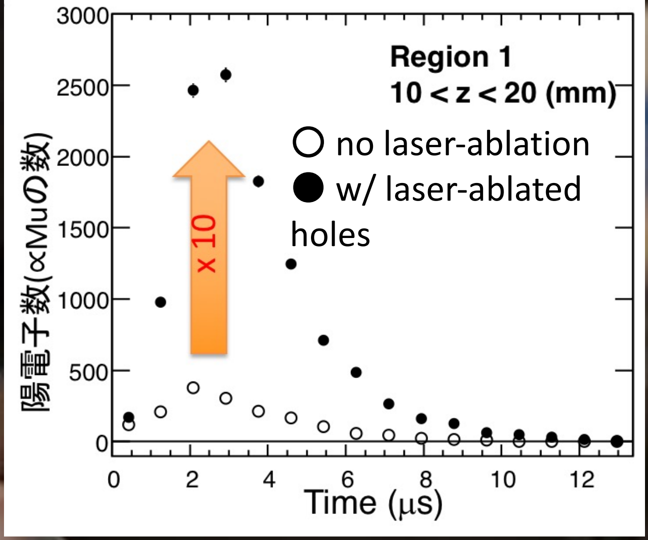
Prog. Theor. Exp. Phys. 2018, 113G01



Construction team of the S2 experimental area

Production of thermal energy muon

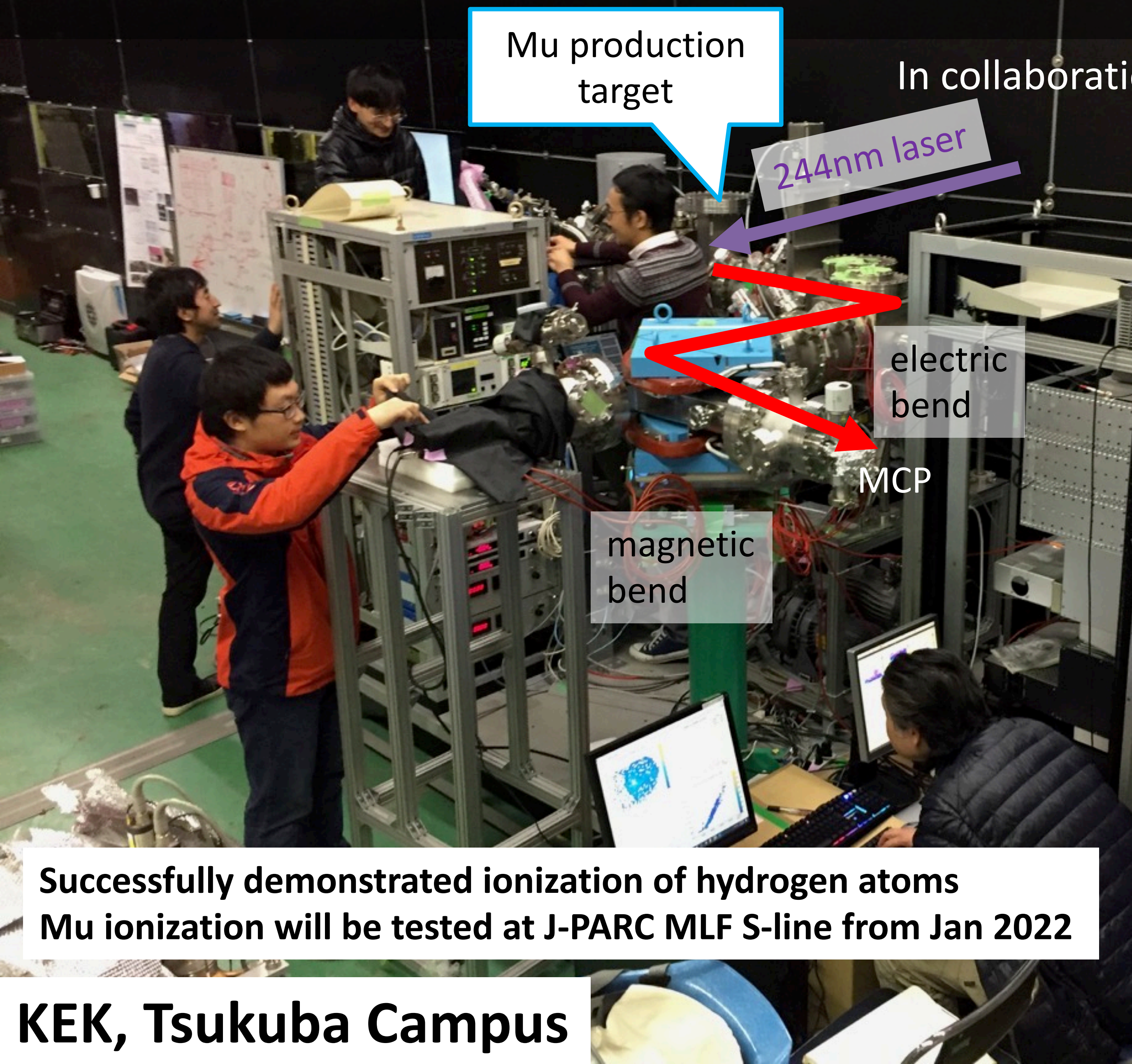


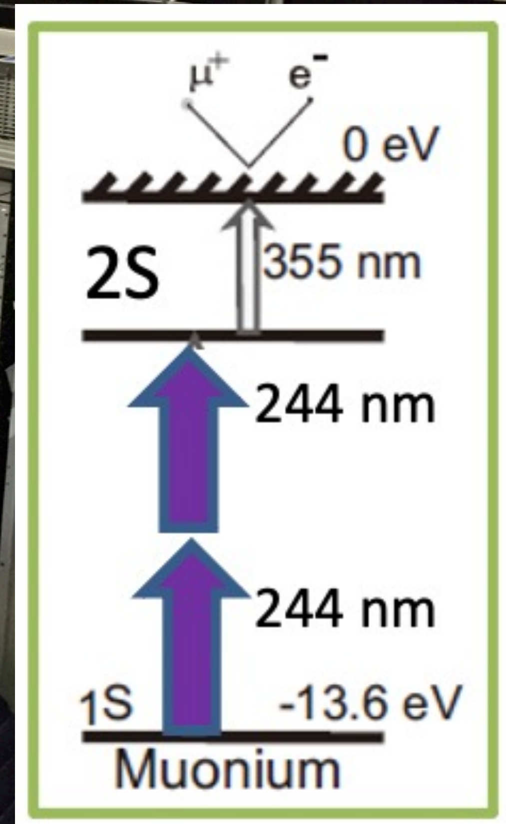


P. Bakule et al., PTEP 103C0 (2013)
G. Beer et al., PTEP 091C01 (2014)
J. Beare et al., PTEP 123C01 (2020)

Setting up the Mu ionization experiment

In collaboration with RIIS Okayama-U

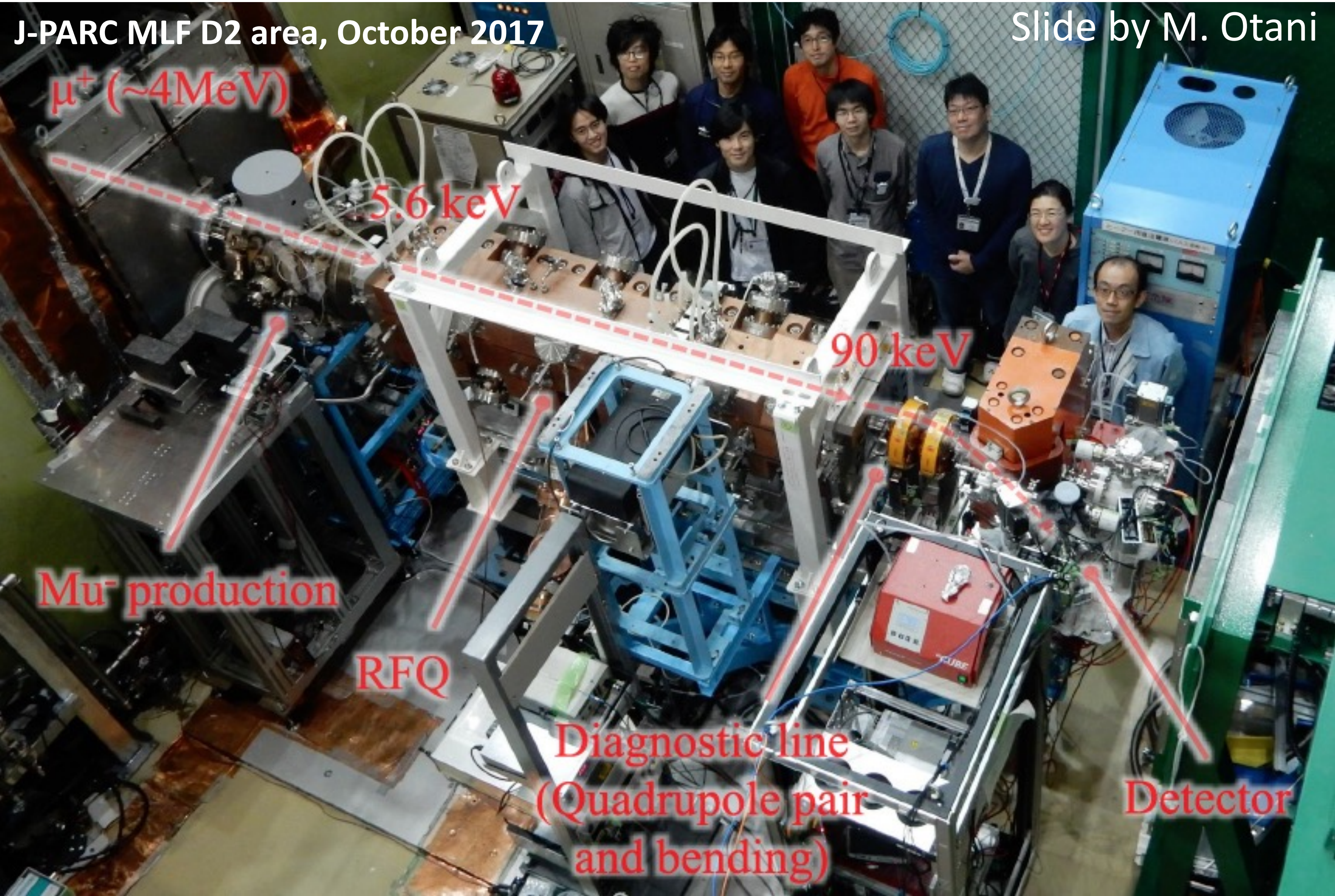




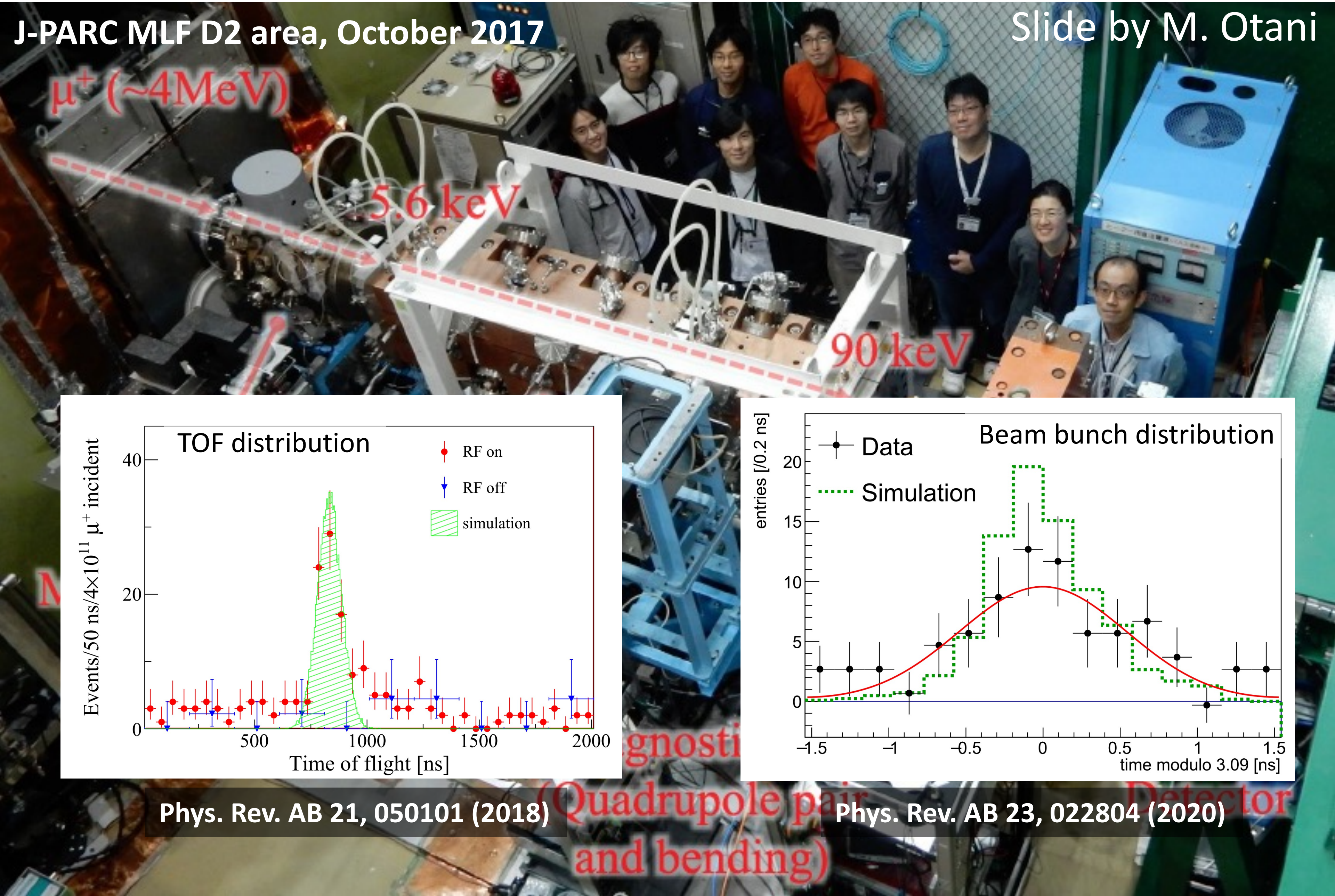
Successfully demonstrated ionization of hydrogen atoms
Mu ionization will be tested at J-PARC MLF S-line from Jan 2022

KEK, Tsukuba Campus

Demonstration of RF acceleration with Mu- ions



Demonstration of RF acceleration with Mu- ions

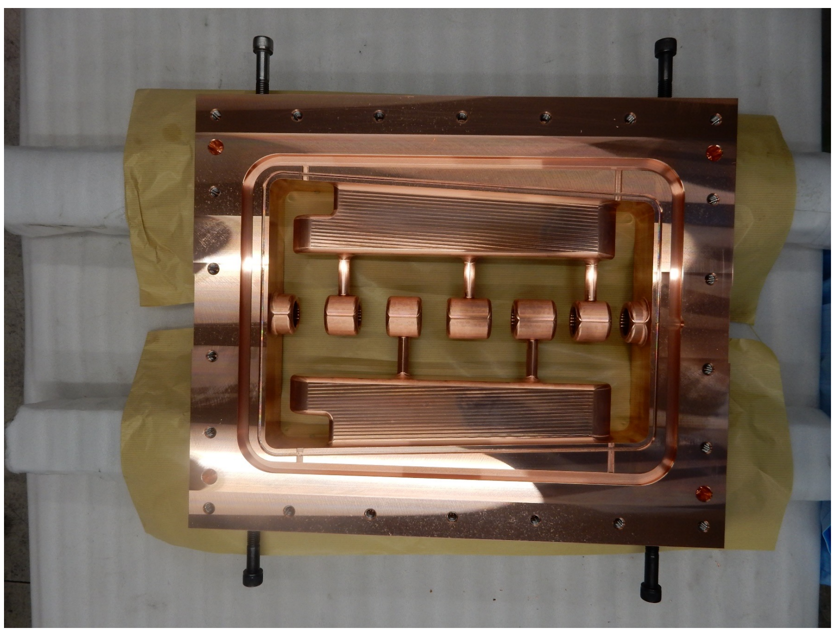


Muon LINAC developments

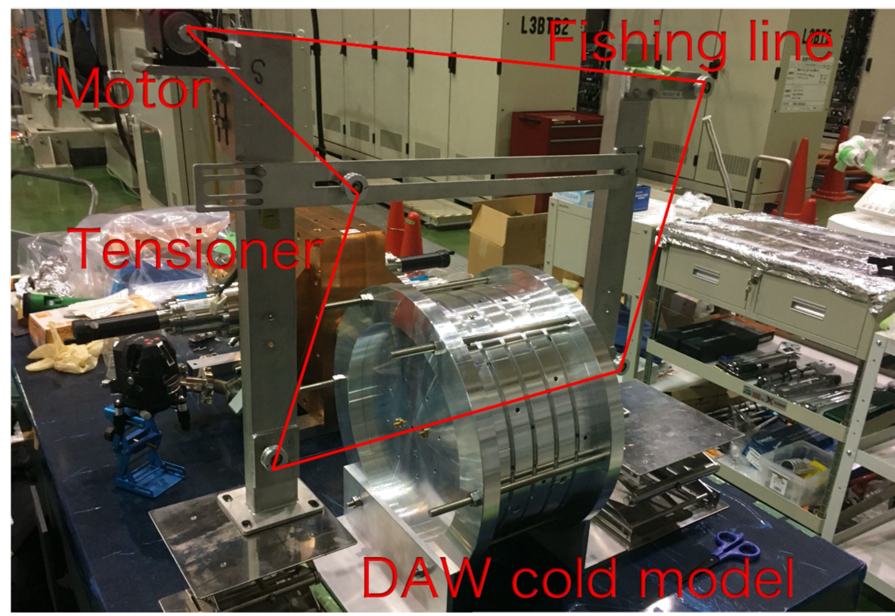
muon source → RFQ → IH-DTL → DAW → DLS → injection beamline

	muon source	RFQ	IH-DTL	DAW	DLS	injection beamline
length		3.2 m	1.4 m	16 m	10 m	
RF		← 324 MHz	→	← 1296 MHz	→	

E	5.6 keV	0.34 MeV	4.5 MeV	40 MeV	212 MeV
β	0.01	0.08	0.3	0.7	0.94



IH-DTL test cavity

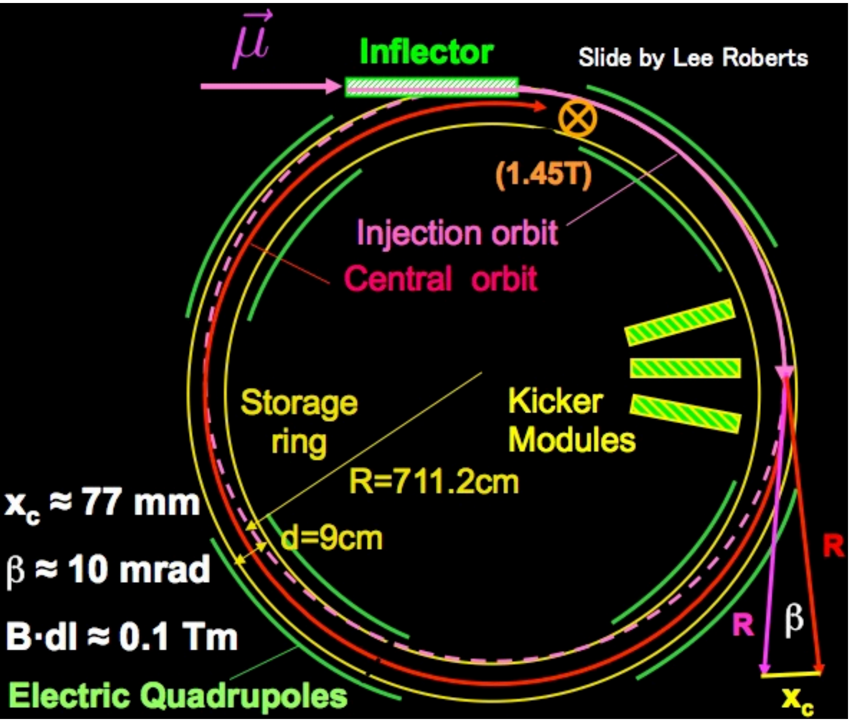


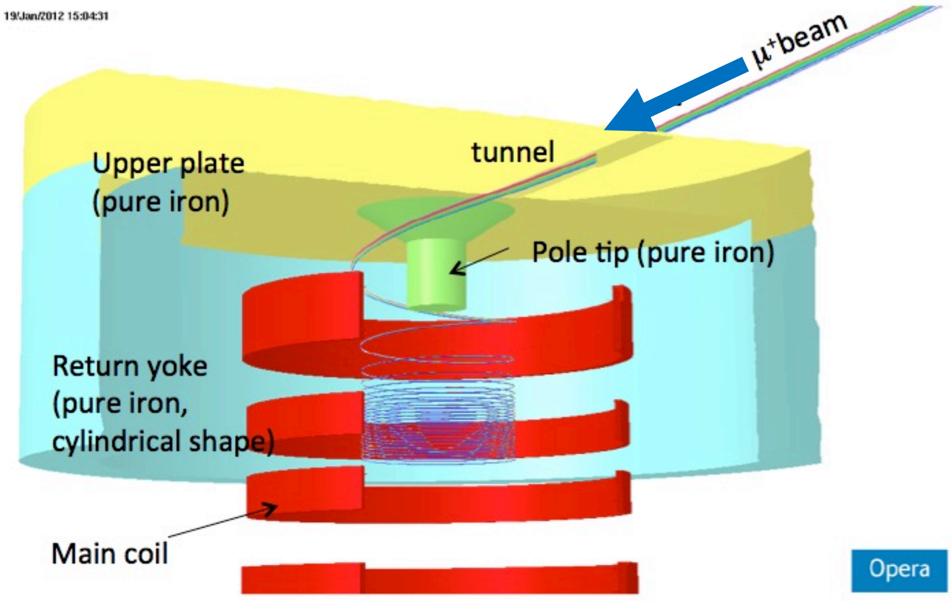
DAW cold model

Muon beam injection and storage

- Horizontal injection + kicker
- (BNL E821, FNAL E989)

- 3D spiral injection + kicker
- (J-PARC E34)





Injection efficiency : 3-5%(*)

Injection efficiency : ~85%

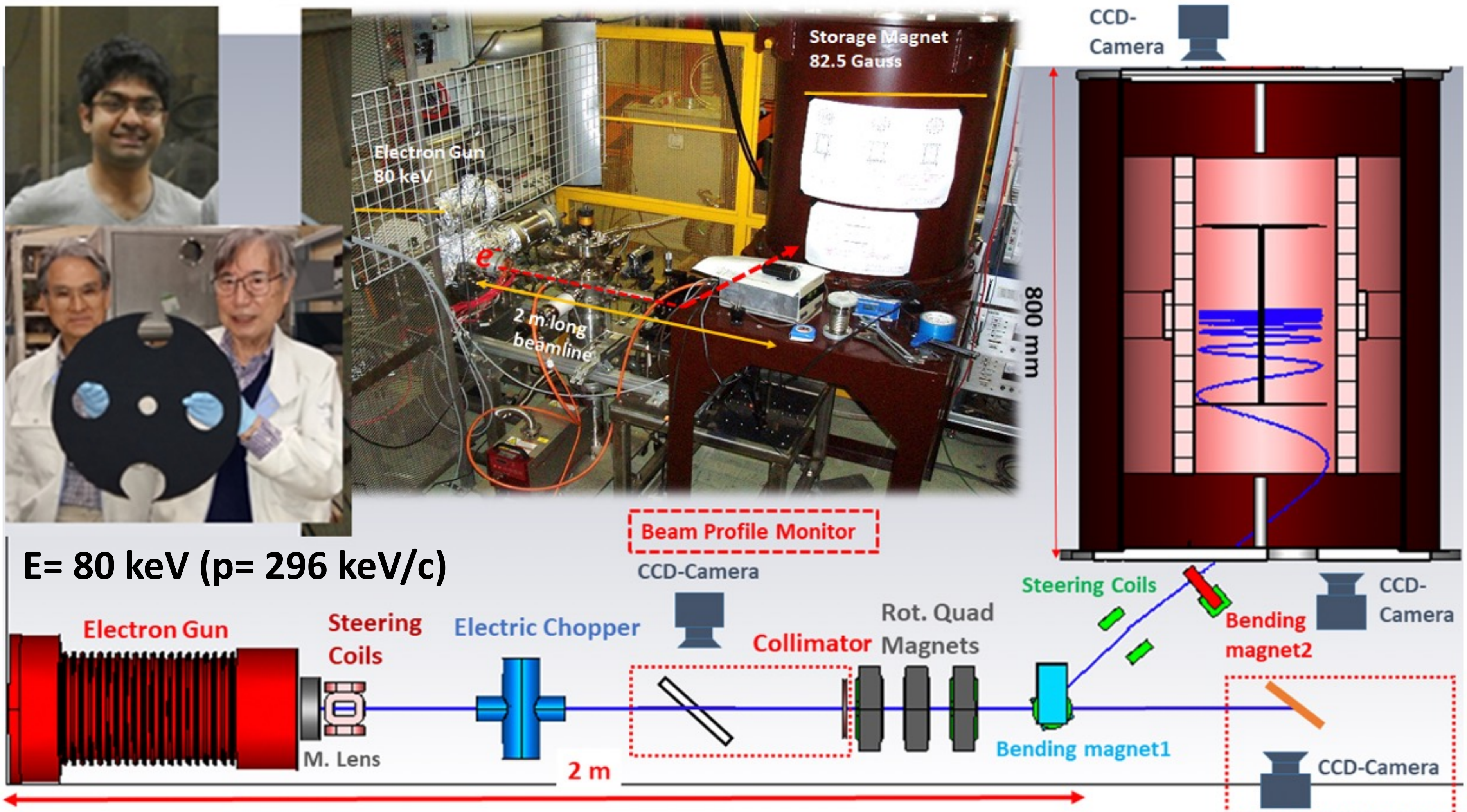
H. Iinuma et al., Nucl. Instr. And Methods. A 832, 51 (2016)

(*) PRD73,072003 (2006)

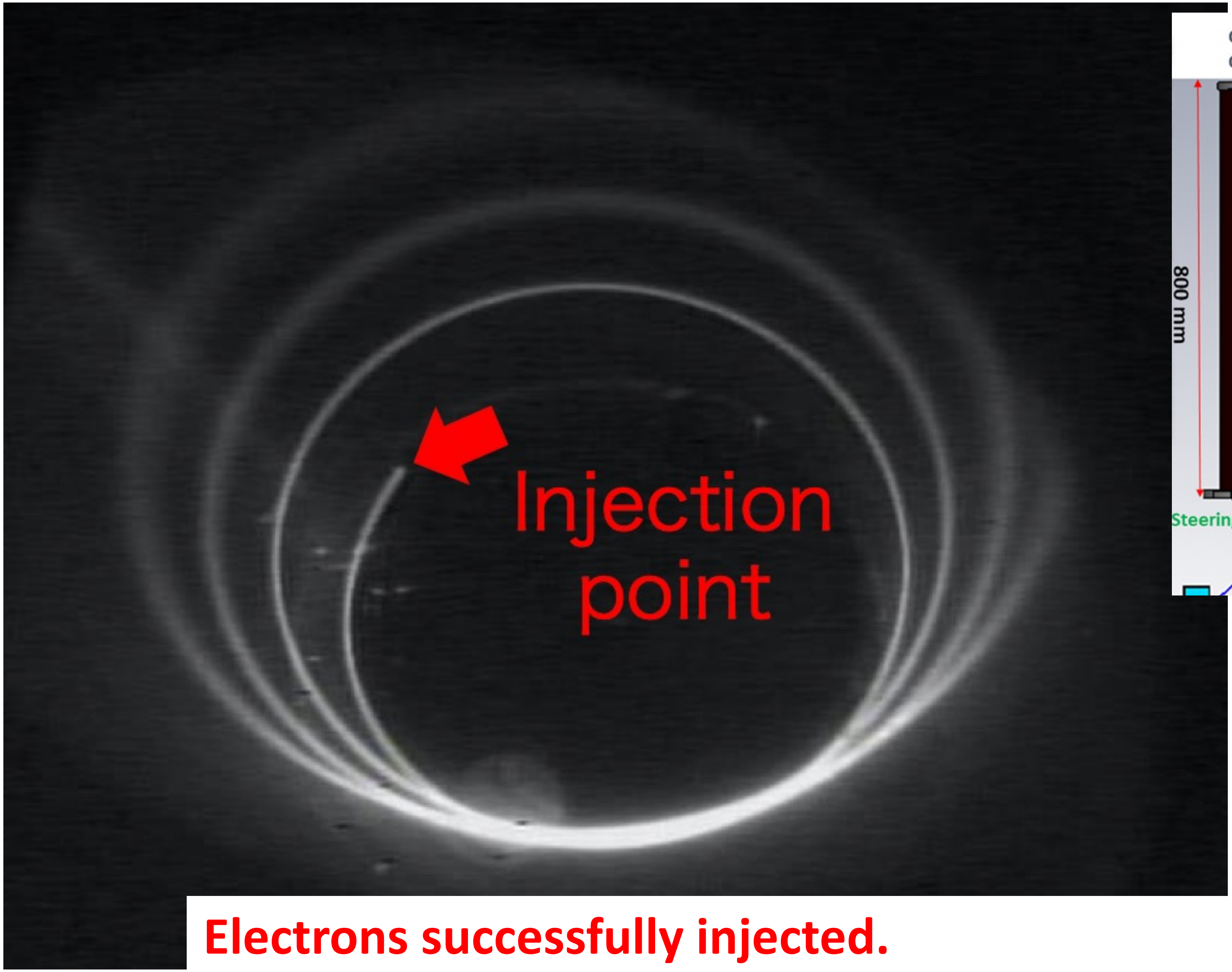
Sprial Injection Test Experiment with electron beam

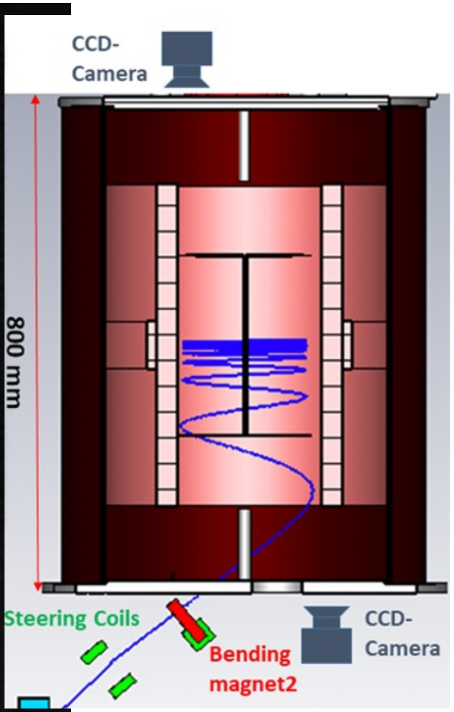
Ibaraki U, KEK, U. Tokyo

KEK Tsukuba campus



Spiral Injection Test Experiment with electron beam

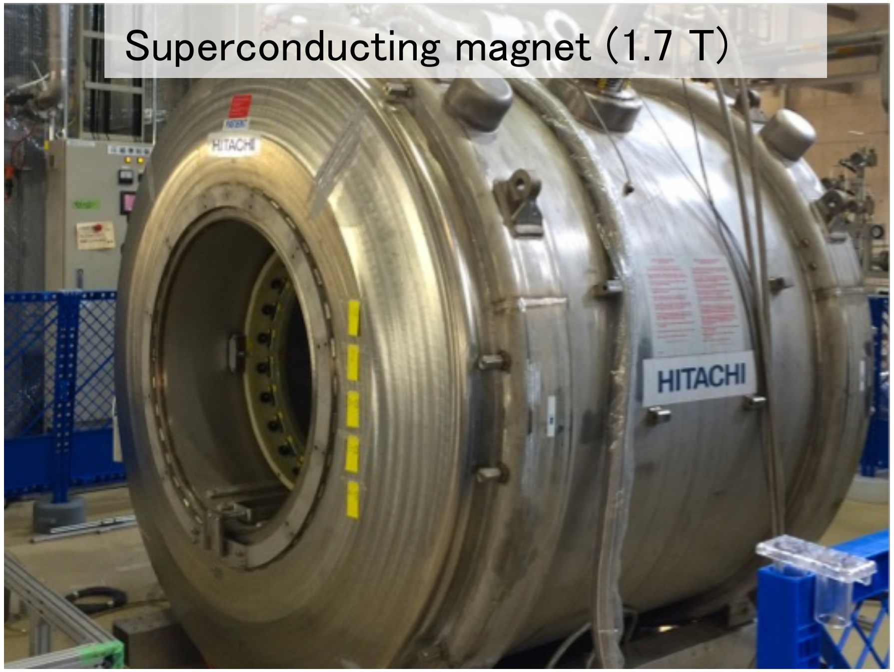




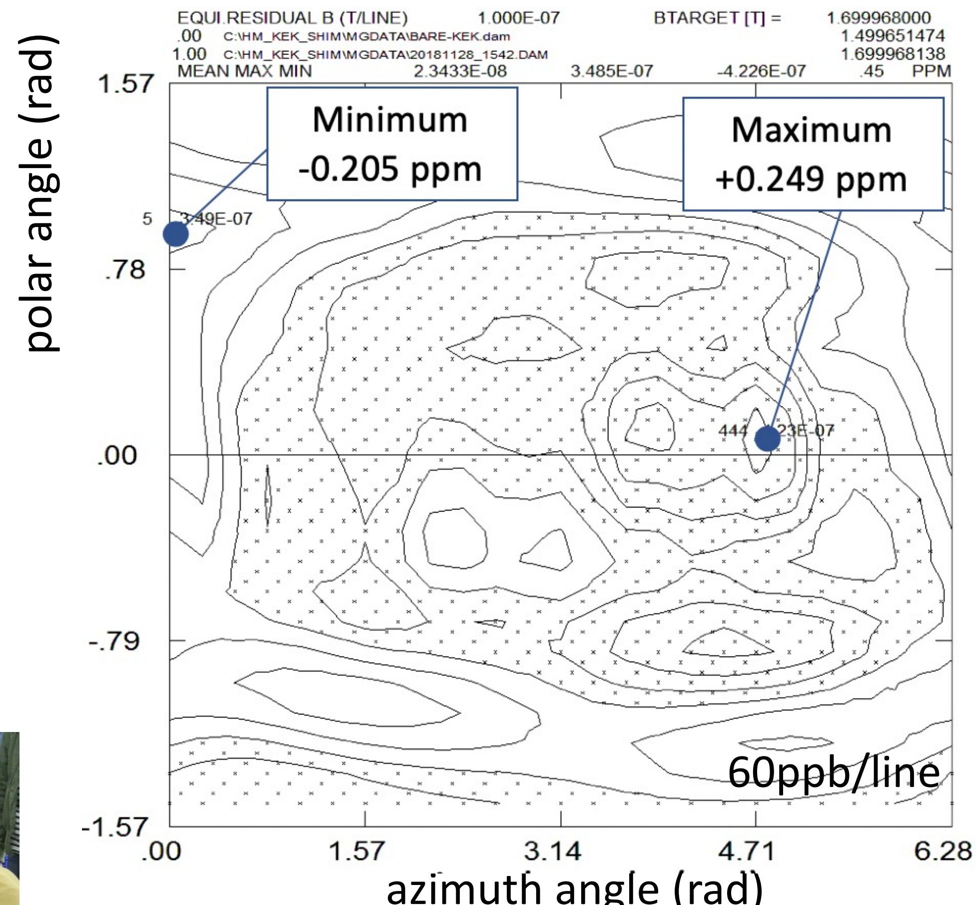
Electrons successfully injected.

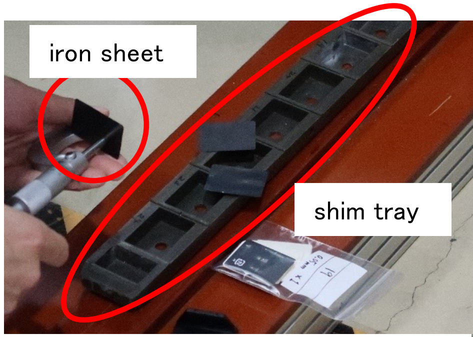
Next step: demonstration of storage by a pulsed kicker

Magnet shimming test



Residual field contour after shimming

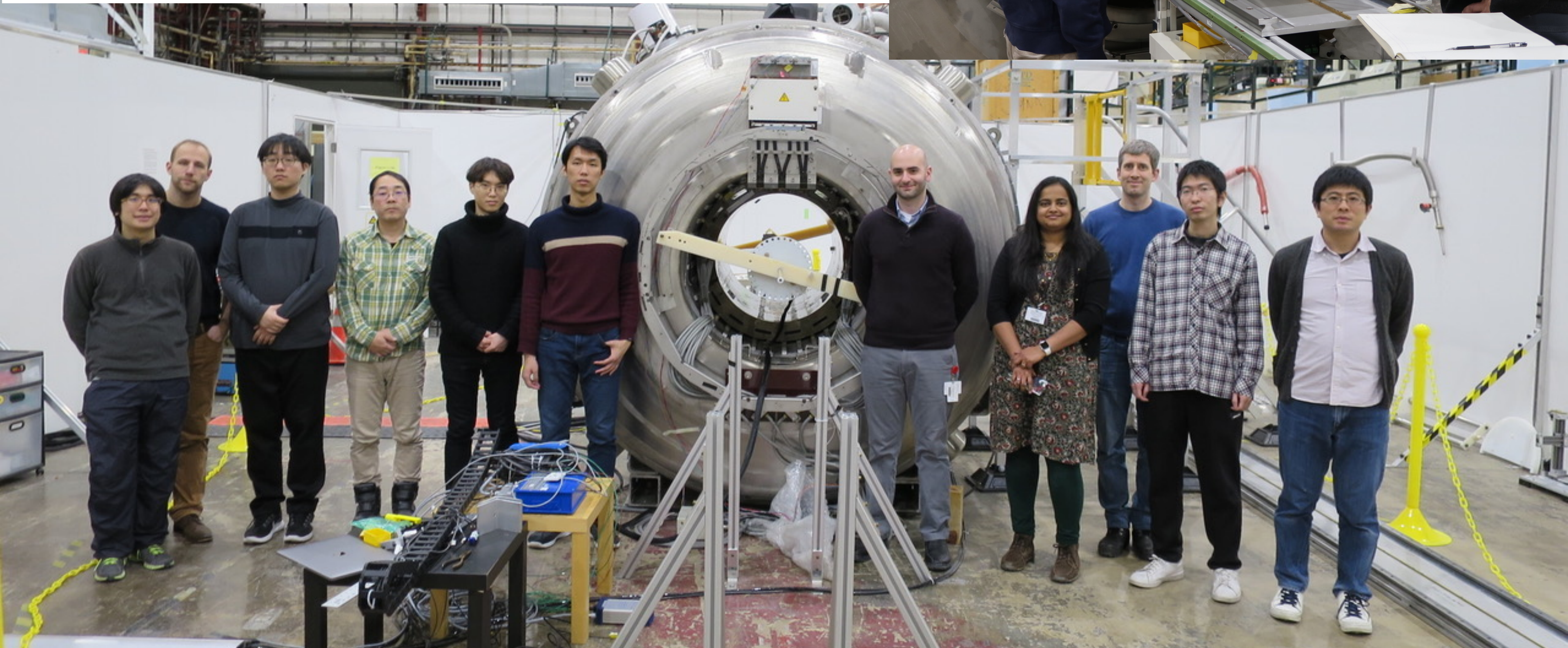




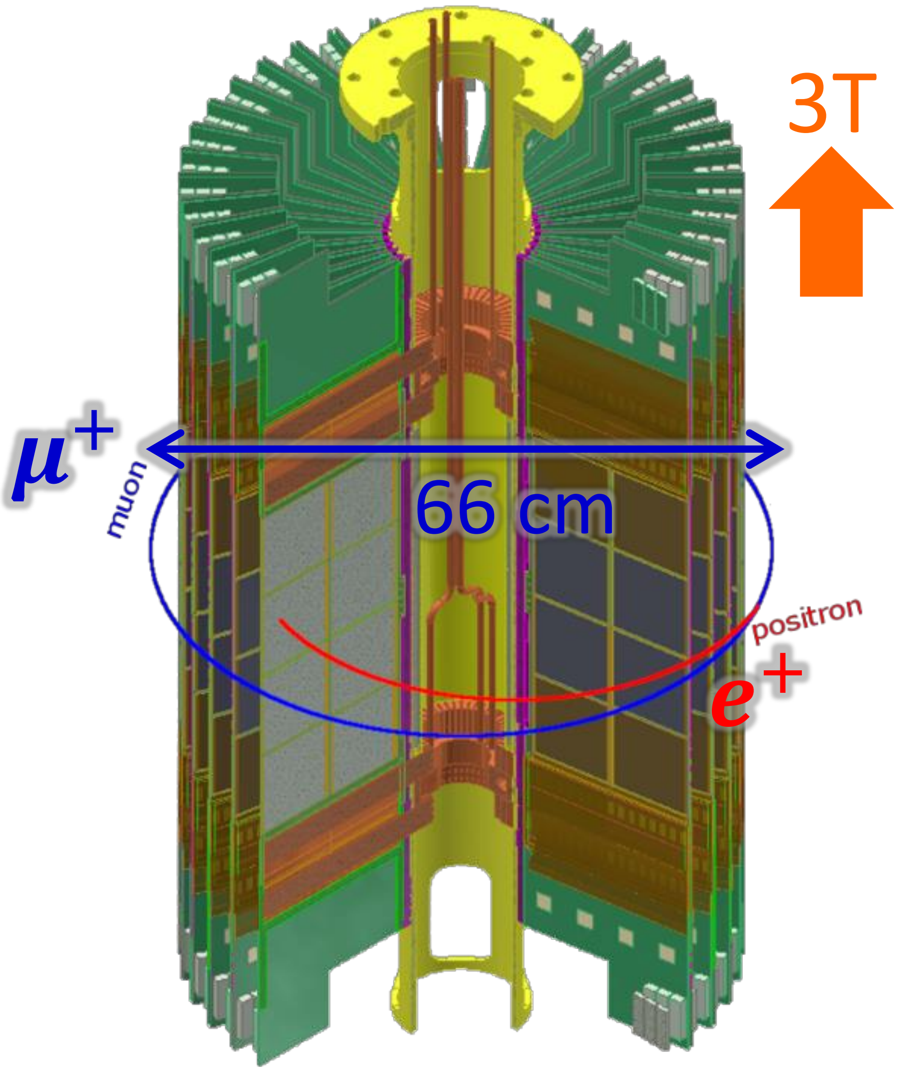
Field uniformity: **<u>0.454 ppm</u>** (peak-to-peak)
on the surface of sphere r=15 cm

Cross-calibration of absolute probe

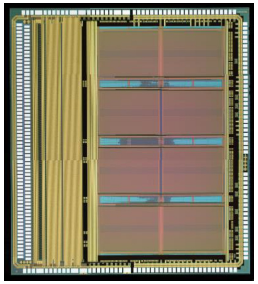
- Absolute probes from Fermilab g-2 and J-PARC are compared in the magnet at ANL for cross calibration.
- Data taking completed at B=1.45 T (Fermilab) and 1.7 T (MuSEUM). Planned another data taking at 3.0 T (J-PARC).
- Supported by the US-Japan cooperative program (2017-2020), P. Winter (US-PI), K. Sasaki (JP-PI)

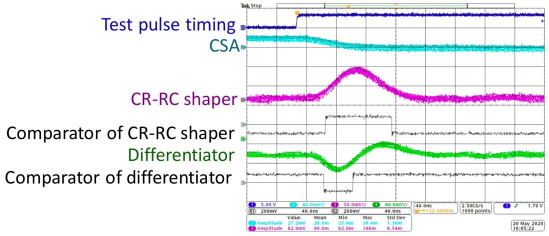


Positron tracking detector

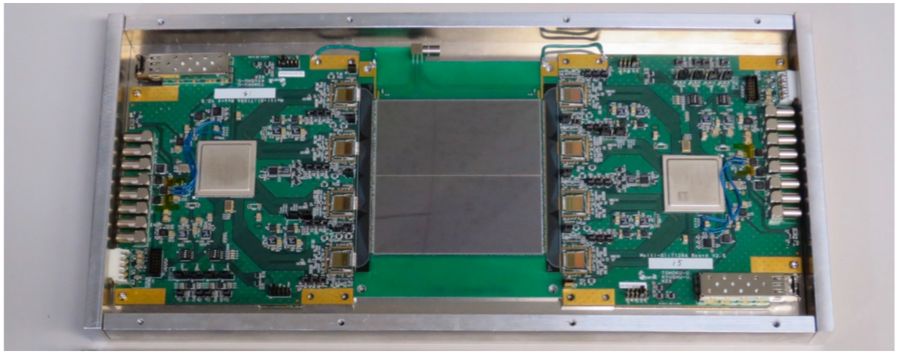


New frontend ASIC IEEE, TNS 67, 2089 (2020)

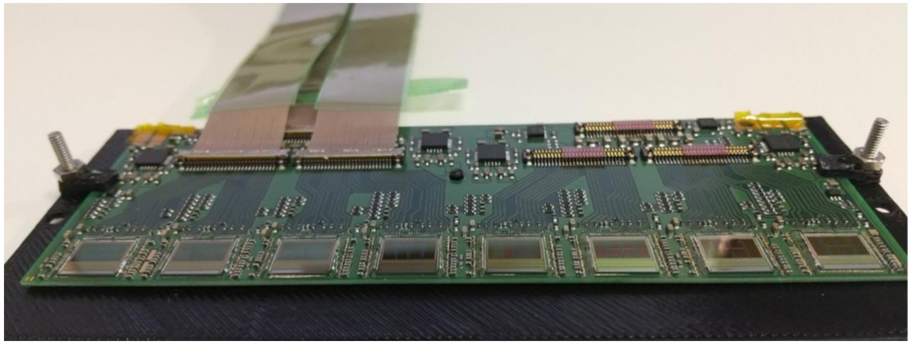




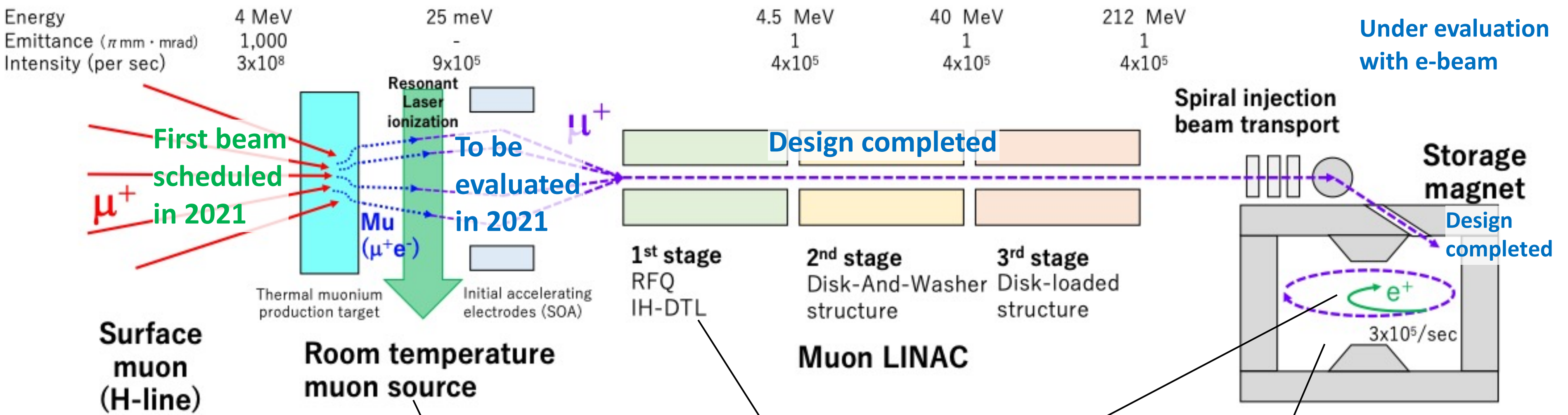
Basic performance test JINST 15 P04027 (2020)



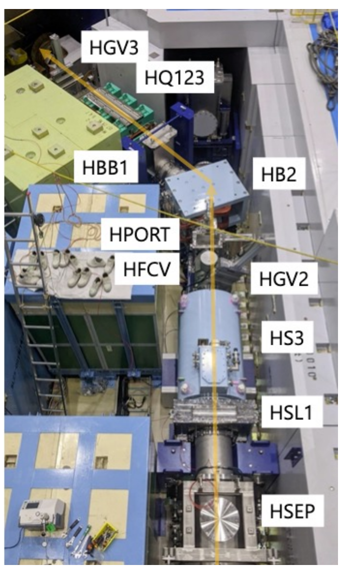
Full-scale prototype of the frontend board



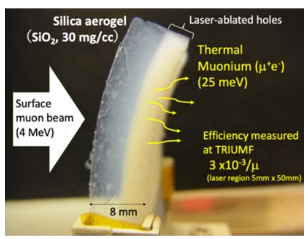
Achievements and plan

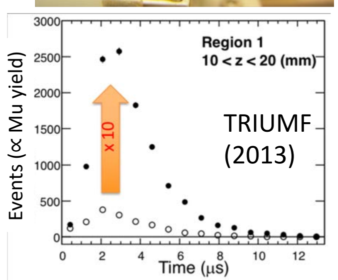


Beamline construction (2020)



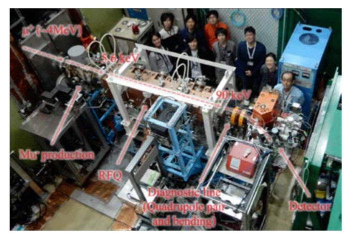
(a) Muonium production target

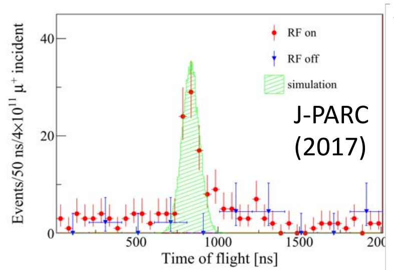




[PTEP 2013,103C01](#)
[PTEP 2014,091C01](#)
[PTEP 2020,123C01](#)

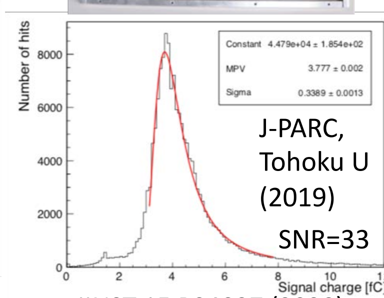
(b) Muon acceleration to 80 keV





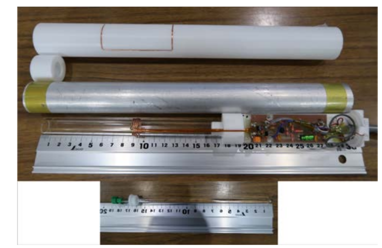
PRAB 19, 040101 (2016)
PRAB 21, 050101 (2018)
PRAB 23, 022804 (2020)
PRAB 24, 033403 (2021)

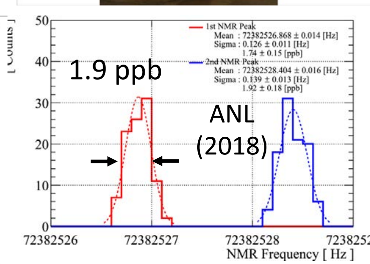
(c) Unit module of positron detector



JINST 15 P04027 (2020)
[IEEE TNS 67, 2089, 2020](#)

(d) Magnetic field probe (NMR)

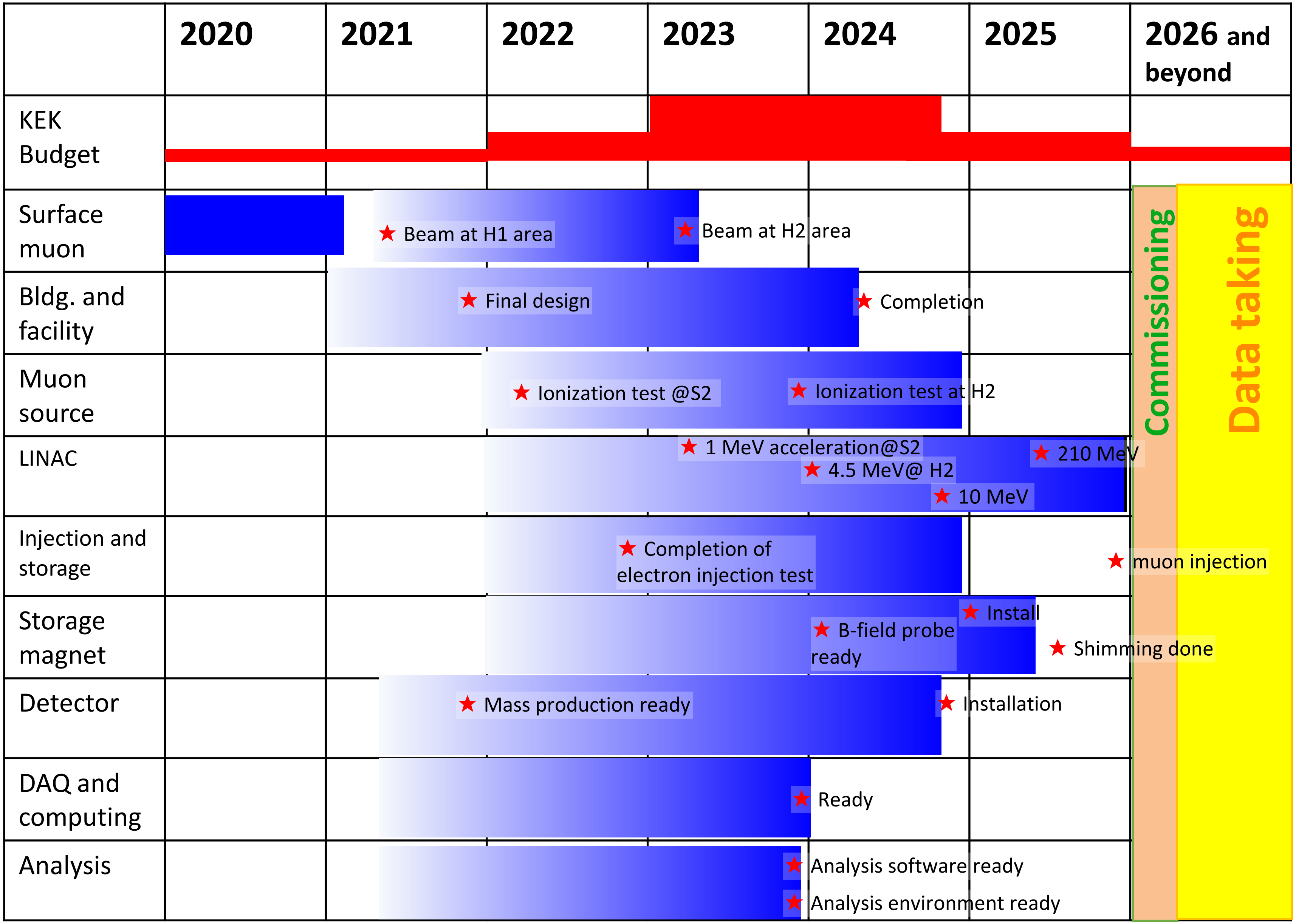




NIMA 890, 51 (2018)
IEEE TAS, 29, 9000904 (2019)

Intended schedule and milestone

Data taking

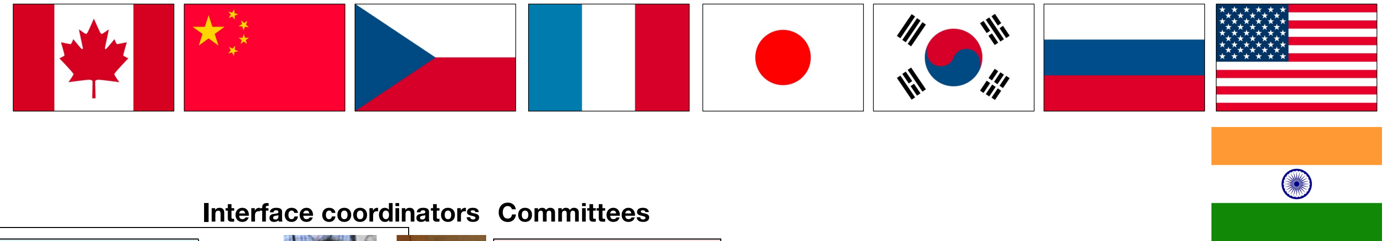


The collaboration

Collaboration board (CB)
Chair: Seonho Choi

Executive board (EB)
Spokesperson: T. Mibe

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



Subgroups

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

Ultra-slow muon
leader: K. Ishida, G. Marshall

LINAC
leader: Y. Kondo, M. Otani

Injection and storage
leader: H. Iinuma

Storage magnet, field measurements

Detector
leader: T. Yoshioka

DAQ and computing
leader: Y. Sato, S. Lee

Analysis
leader: T. Yamanaka (K. Hayasaka)

Interface coordinators

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

Committees

Speakers committee
chair: K.Ishida, E. Won

Domestic institutes:
Kyushu, Nagoya, Tohoku, Niigata, Tokyo, Ibaraki, RIKEN, JAEA, etc.

Summary

- **Muon g-2 (and also EDM) provides excellent sensitivities to new physics models via quantum loops.**

- **BNL experiment (1998-2004)**
  - **More than 3σ larger than the SM prediction**

- **Fermilab experiment (2018-)**
  - **Run 1 data confirmed the BNL results. More data to come.**

- **J-PARC experiment (2025-)**
  - **New method (complementary to magic gamma experiments)**
    - Compact storage ring
    - Very weak magnetic focusing
    - All-tracking detector

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.)	$0.2 \times 10^{-19}\ e \cdot \mathrm{cm}$	–	$1.5 \times 10^{-21}\ e \cdot \mathrm{cm}$
(syst.)	$0.9 \times 10^{-19}\ e \cdot \mathrm{cm}$	–	$0.36 \times 10^{-21}\ e \cdot \mathrm{cm}$
	Completed	**Running**	**In preparation**

Statistical and systematic uncertainties

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

Summary of statistical 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.)

Estimated systematic 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