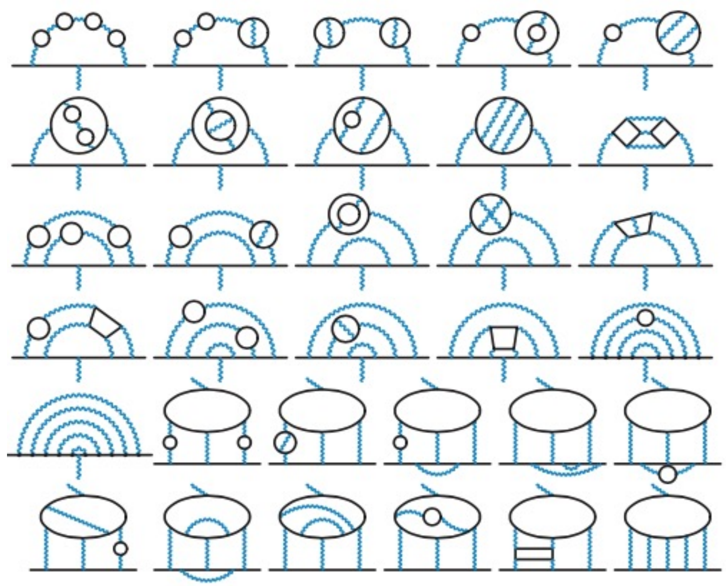
Precise measurements of muon g-2 and EDM

NEWS colloquium

March 25, 2021

Tsutomu Mibe (KEK IPNS)



https://g-2.kek.jp

Particle dipole moments

$$\mathcal{H} = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

P,C,T-even P,T-odd (CP-odd)

Magnetic Dipole Moment
$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s}$$

Electric Dipole Moment
$$\vec{d} = \eta\left(\frac{q}{2mc}\right)\vec{s}$$

	$\vec{E}$	$\vec{B}$	$\vec{\mu}$ or $\vec{d}$
P	-	+	+
C	-	-	-
T	+	-	-

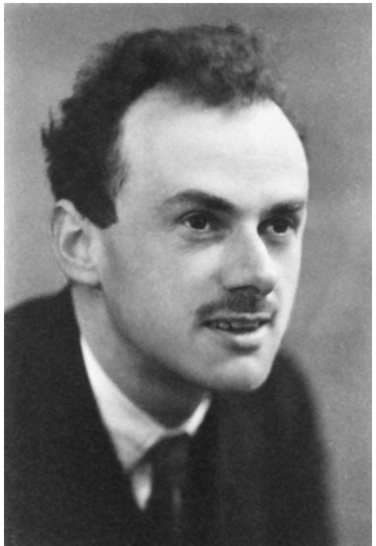
Quantum theory of the electron (1928)

Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 117 (778): 610.

- In a non-relativistic limit of the Dirac equation:

$$i\hbar\frac{\partial\psi}{\partial t} = \left[\frac{p^2}{2m} - \frac{e}{2m}(\vec{L} + 2\vec{S})\right]\psi$$

- From this, *g* = 2 for a point-like fermion.



Magnetic moment of electron

Phys. Rev. 74, 250 (1948)

The Magnetic Moment of the Electron†

P. Kusch and H. M. Foley
Department of Physics, Columbia University, New York, New York

(Received April 19, 1948)

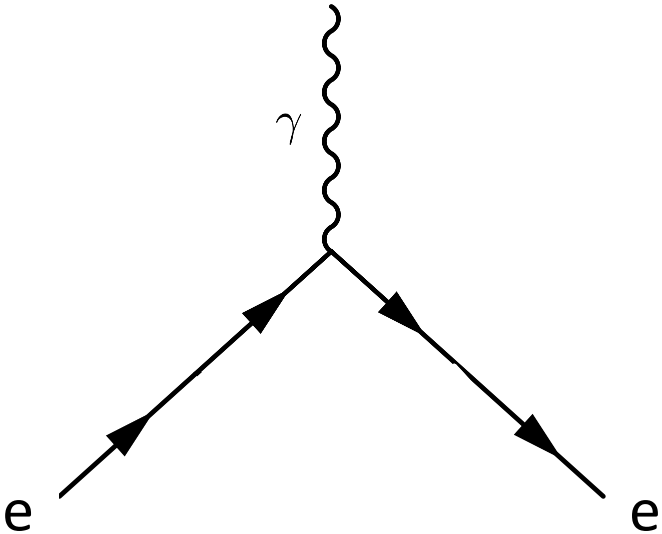
A comparison of the g_J values of Ga in the $^2P_{3/2}$ and $^2P_{\frac{1}{2}}$ states, In in the $^2P_{\frac{1}{2}}$ state, and Na in the $^2S_{\frac{1}{2}}$ state has been made by a measurement of the frequencies of lines in the *hfs* spectra in a constant magnetic field. The ratios of the g_J values depart from the values obtained on the basis of the assumption that the electron spin gyromagnetic ratio is 2 and that the orbital electron gyromagnetic ratio is 1. Except for small residual effects, the results can be described by the statement that $g_L = 1$ and $g_S = 2(1.00119 \pm 0.00005)$. The possibility that the observed effects may be explained by perturbations is precluded by the consistency of the result as obtained by various comparisons and also on the basis of theoretical considerations.

$$\mathcal{H} = g_L \mu_0 L_z H_z + g_S \mu_0 S_z H_z,$$

$g_S > 2$!

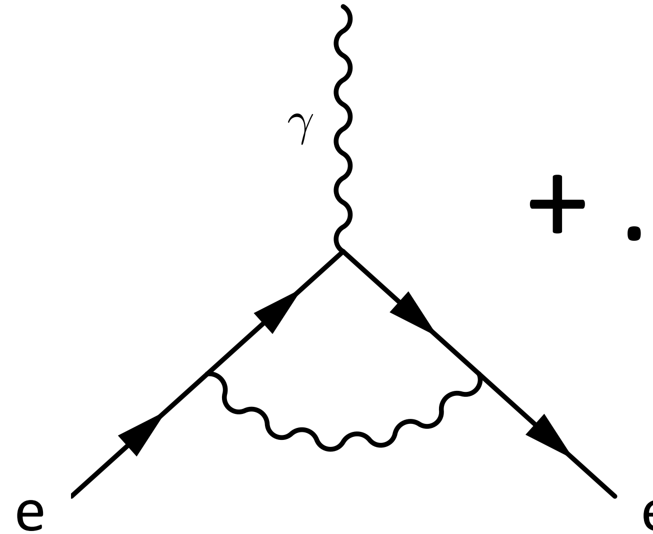
Quantum corrections

Dirac's theory



$g \quad = 2$

QED



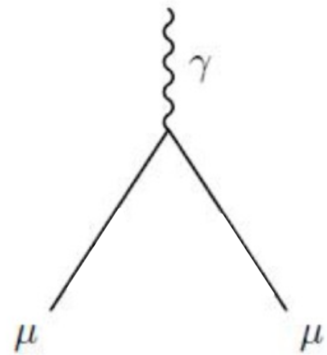
+ ...

$g \quad = 2\,(1 + \alpha/2\pi + \ldots)$

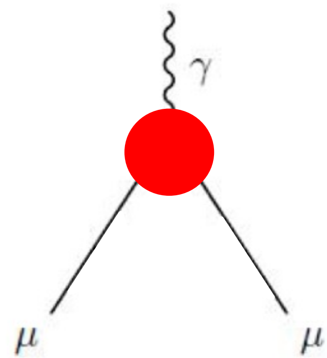
Schwinger

Anomalous magnetic moment (g-2) 6

- The Lande's g factor is 2 in tree level (Dirac equation)



- In quantum field theory, g factor gets corrections:



Anomalous magnetic moment a=(g-2)/2

$$g = 2\,(1 + a)$$

Breakdown of SM contributions

The "white paper", Phys. Rep. 887, 1 (2020)

Contribution	Value $\times 10^{11}$
QED	116 584 718.931(104)
Electroweak	153.6(1.0)
HVP (e^+e^-, LO + NLO + NNLO)	6845(40)
HLbL (phenomenology + lattice + NLO)	92(18)
Total SM Value	116 591 810(43)

Breakdown of hadronic SM contributions

The “white paper”, Phys. Rep. 887, 1 (2020)

	Contribution	Value $\times 10^{11}$
Hadronic contributions	HVP LO (e^+e^-)	6931(40)
	HVP NLO (e^+e^-)	$-98.3(7)$
	HVP NNLO (e^+e^-)	12.4(1)
	HVP LO (lattice , *udsc*)	7116(184)
	HLbL (phenomenology)	92(19)
	HLbL NLO (phenomenology)	2(1)
	HLbL (lattice, *uds*)	79(35)
	HLbL (phenomenology + lattice)	90(17)
	QED	116 584 718.931(104)
	Electroweak	153.6(1.0)
	HVP (e^+e^-, LO + NLO + NNLO)	6845(40)
	HLbL (phenomenology + lattice + NLO)	92(18)
	Total SM Value	116 591 810(43)

The muon g-2 anomaly

Relative uncertainty

$a_\mu^{Exp} = 11\ 659\ 209.1 \pm 6.3\ \times 10^{-10}$ (540ppb)

Phys. Rev. D73, 072003 (2006)

$a_\mu^{SM} = 11\ 659\ 181.0 \pm 4.3\ \times 10^{-10}$ (320ppb)

Phys. Rep. 887, 1 (2020)

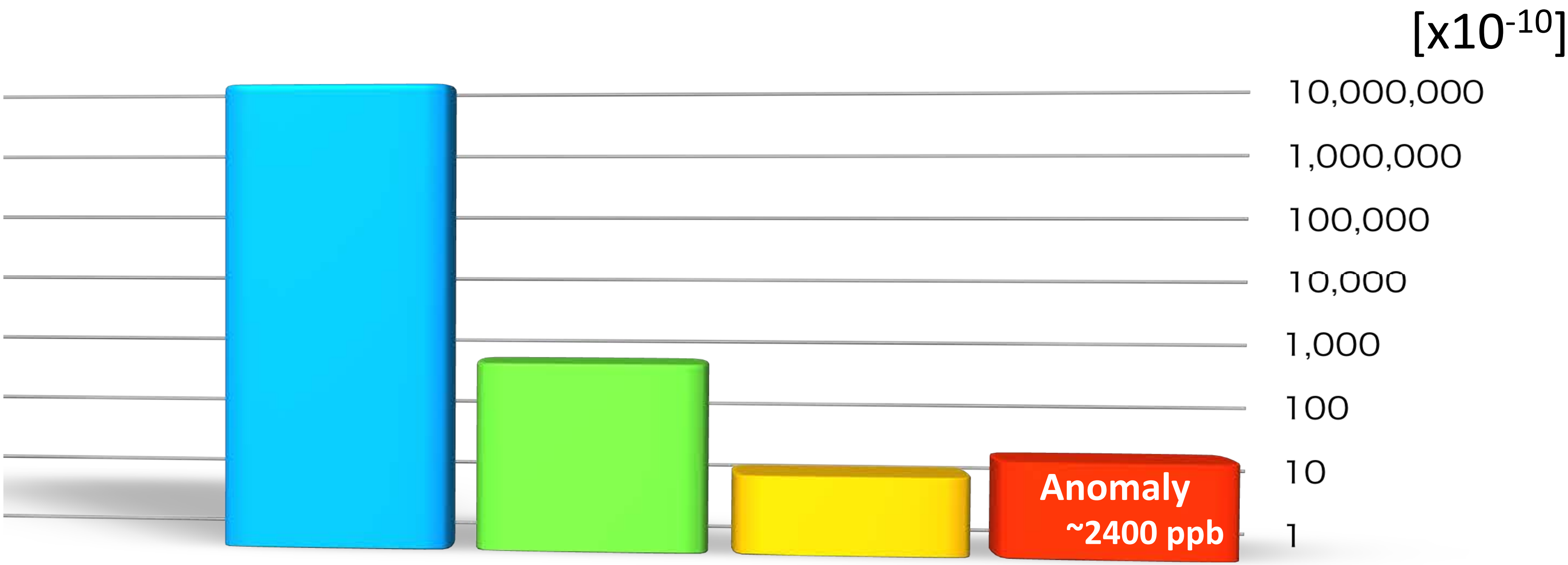
$\Delta a_\mu = a_\mu^{Exp} - a_\mu^{SM} = 27.9 \pm 7.6 \times 10^{-10}$ (650ppb)

(2400ppb)

[3.7σ]

ppb = parts per billion (10^{-9})

Breakdown of contributions



$$a_\mu = a_\mu(QED) + a_\mu(had) + a_\mu(weak) + a_\mu(BSM)$$

Anomaly as big as the weak contributions if BSM

Numbers from T. Aoyama, et al.,
arXiv:2006.04822 (2020)
(to be published in Phys. Rep.)

Breakdown of contributions

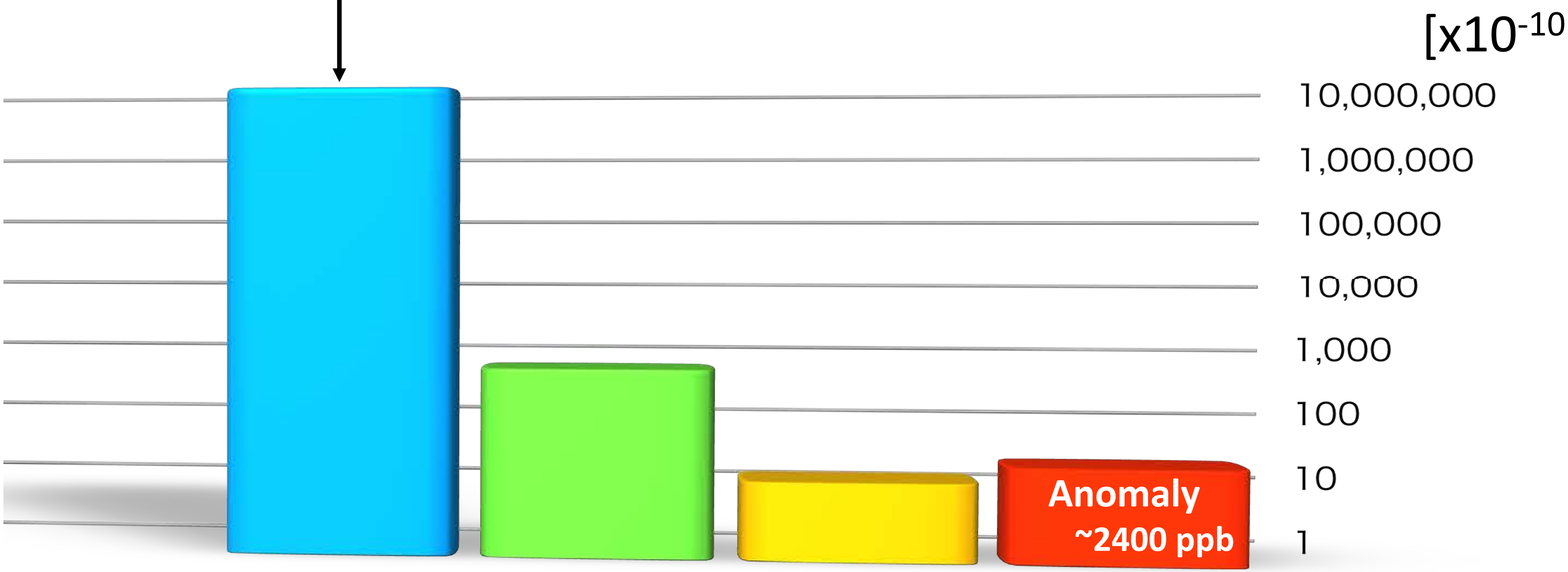
Super-precisely tested by electron g-2

The most precisely-calculated physical quantity to date

10^{th} order QED **(0.20 ppb)** [Aoyama, Kinoshita, Nio]

g-2 **(0.24 ppb) [**Gabrielse et al.]

Fine structure constant α **(0.08 ppb)** [L. Morel et al.]



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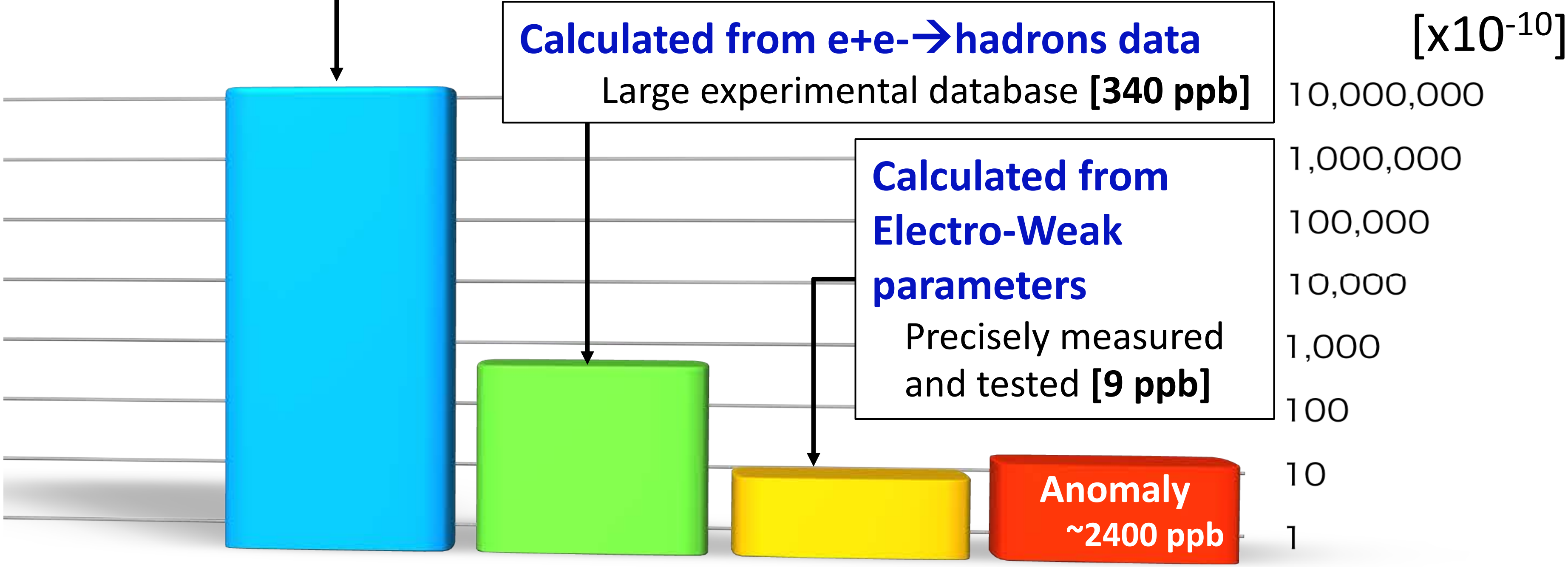
Calculated from e+e-→hadrons data

Large experimental database **[340 ppb]**

Calculated from Electro-Weak parameters

Precisely measured and tested **[9 ppb]**



$$a_\mu = a_\mu(QED) + a_\mu(had) + a_\mu(weak) + a_\mu(BSM)$$

Anomaly as big as the weak contributions if BSM

Numbers from T. Aoyama, et al.,
arXiv:2006.04822 (2020)
(to be published in Phys. Rep.)

The muon g-2 theory initiative

A group of 170 experts came to a consensus on **a single value** of muon g-2 in the standard model.

The white paper

Phys. Rep. 887 (2020) 1-166
(Submitted 15 June
Accepted 29 July
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Physics Reports 887 (2020) 1–166

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journal homepage: www.elsevier.com/locate/physrep

The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama [1,2,3], N. Asmussen [4], M. Benayoun [5], J. Bijnens [6], T. Blum [7,8], M. Bruno [9], I. Caprini [10], C.M. Carloni Calame [11], M. Cè [9,12,13], G. Colangelo [14,*], F. Curciarello [15,16], H. Czyż [17], I. Danilkin [12], M. Davier [18,*], C.T.H. Davies [19], M. Della Morte [20], S.I. Eidelman [21,22,*], A.X. El-Khadra [23,24,*], A. Gérardin [25], D. Giusti [26,27], M. Golterman [28], Steven Gottlieb [29], V. Gülpers [30], F. Hagelstein [14], M. Hayakawa [31,2], G. Herdoíza [32], D.W. Hertzog [33], A. Hoecker [34], M. Hoferichter [14,35,*], B.-L. Hoid [36], R.J. Hudspith [12,13], F. Ignatov [21], T. Izubuchi [37,8], F. Jegerlehner [38], L. Jin [7,8], A. Keshavarzi [39], T. Kinoshita [40,41], B. Kubis [36], A. Kupich [21], A. Kupść [42,43], L. Laub [14], C. Lehner [26,37,*], L. Lellouch [25], I. Logashenko [21], B. Malaescu [5], K. Maltman [44,45], M.K. Marinković [46,47], P. Masjuan [48,49], A.S. Meyer [37], H.B. Meyer [12,13], T. Mibe [1,*], K. Miura [12,13,3], S.E. Müller [50], M. Nio [2,51], D. Nomura [52,53], A. Nyffeler [12,*], V. Pascalutsa [12], M. Passera [54], E. Perez del Rio [55], S. Peris [48,49], A. Portelli [30], M. Procura [56], C.F. Redmer [12], B.L. Roberts [57,*], P. Sánchez-Puertas [49], S. Serednyakov [21], B. Shwartz [21], S. Simula [27], D. Stöckinger [58], H. Stöckinger-Kim [58], P. Stoffer [59], T. Teubner [60,*], R. Van de Water [24], M. Vanderhaeghen [12,13], G. Venanzoni [61], G. von Hippel [12], H. Wittig [12,13], Z. Zhang [18], M.N. Achasov [21], A. Bashir [62], N. Cardoso [47], B. Chakraborty [63], E.-H. Chao [12], J. Charles [25], A. Crivellin [64,65], O. Deineka [12], A. Denig [12,13], C. DeTar [66], C.A. Dominguez [67], A.E. Dorokhov [68], V.P. Druzhinin [21], G. Eichmann [69,47], M. Fael [70], C.S. Fischer [71], E. Gámiz [72], Z. Gelzer [23], J.R. Green [9], S. Guellati-Khelifa [73], D. Hatton [19], N. Hermansson-Truedsson [14], S. Holz [36], B. Hörz [74], M. Knecht [25], J. Koponen [1], A.S. Kronfeld [24], J. Laiho [75], S. Leupold [42], P.B. Mackenzie [24], W.J. Marciano [37], C. McNeile [76], D. Mohler [12,13], J. Monnard [14], E.T. Neil [77], A.V. Nesterenko [68], K. Ottnad [12], V. Pauk [12], A.E. Radzhabov [78], E. de Rafael [25], K. Raya [79], A. Risch [12], A. Rodríguez-Sánchez [6], P. Roig [80], T. San José [12,13], E.P. Solodov [21], R. Sugar [81], K. Yu. Todyshev [21], A. Vainshtein [82], A. Vaquero Avilés-Casco [66], E. Weil [71], J. Wilhelm [12], R. Williams [71], A.S. Zhevlakov [78]

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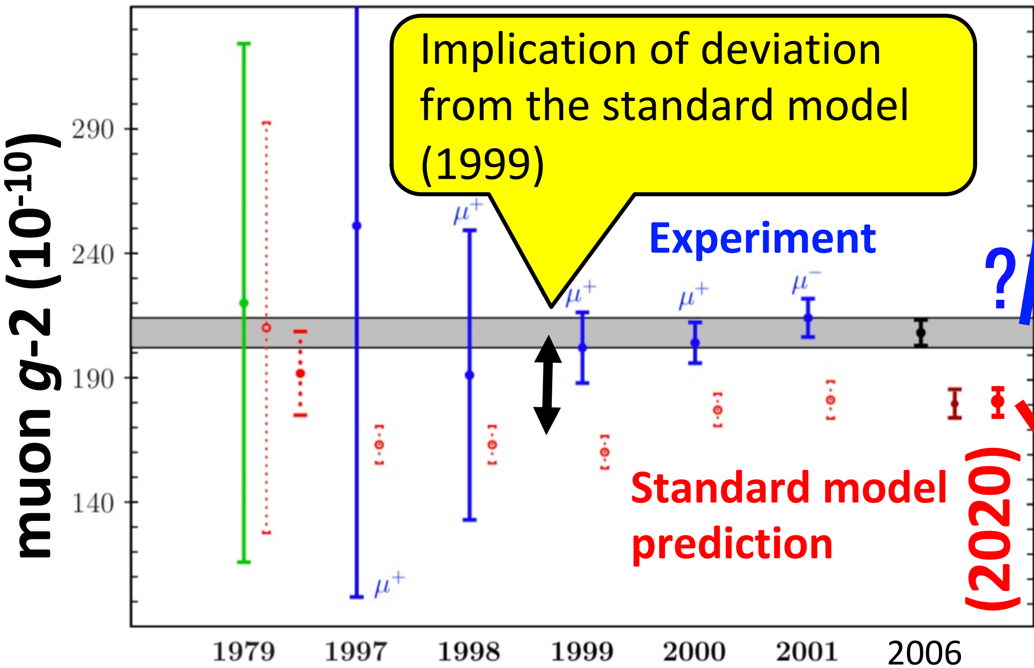
* Corresponding authors.
E-mail address: MUON-GM2-THEORY-SC@fnal.gov (G. Colangelo, M. Davier, S.I. Eidelman, A.X. El-Khadra, M. Hoferichter, C. Lehner, T. Mibe, A. Nyffeler, B.L. Roberts, T. Teubner).

https://doi.org/10.1016/j.physrep.2020.07.006

2017 workshop in Fermilab
2018 workshop in Mainz
2019 workshop in Seattle
~~2020~~→**2021 workshop in KEK**

Muon *g*-2 anomaly



1999 → **2020**

More than 20 years

Experimental value is larger than the theory prediction by more than 3σ.

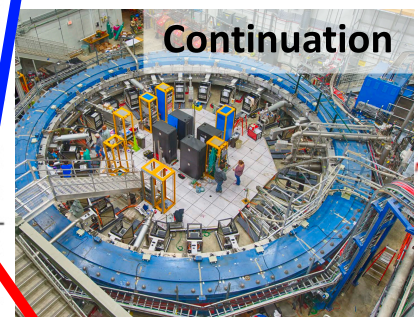
Experiment

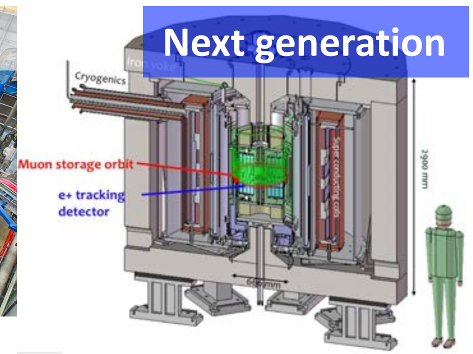
>4,000 citations

Previous: BNL (1997-2006)

Continuation: Fermilab (2018-)

Next generation: J-PARC (2025-)



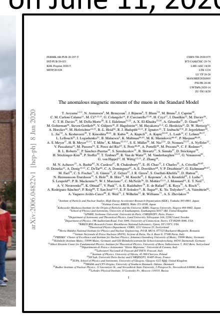


Theory

International collaboration formed since 2017

https://muon-gm2-theory.illinois.edu/

White paper arXiv:2006.04822 (released on June 11, 2020)

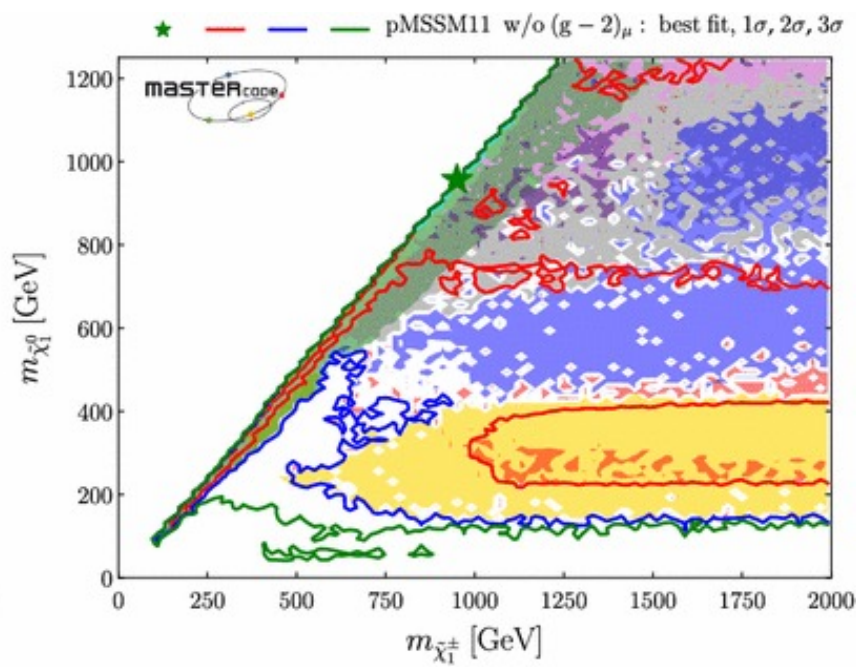


The previous values confirmed

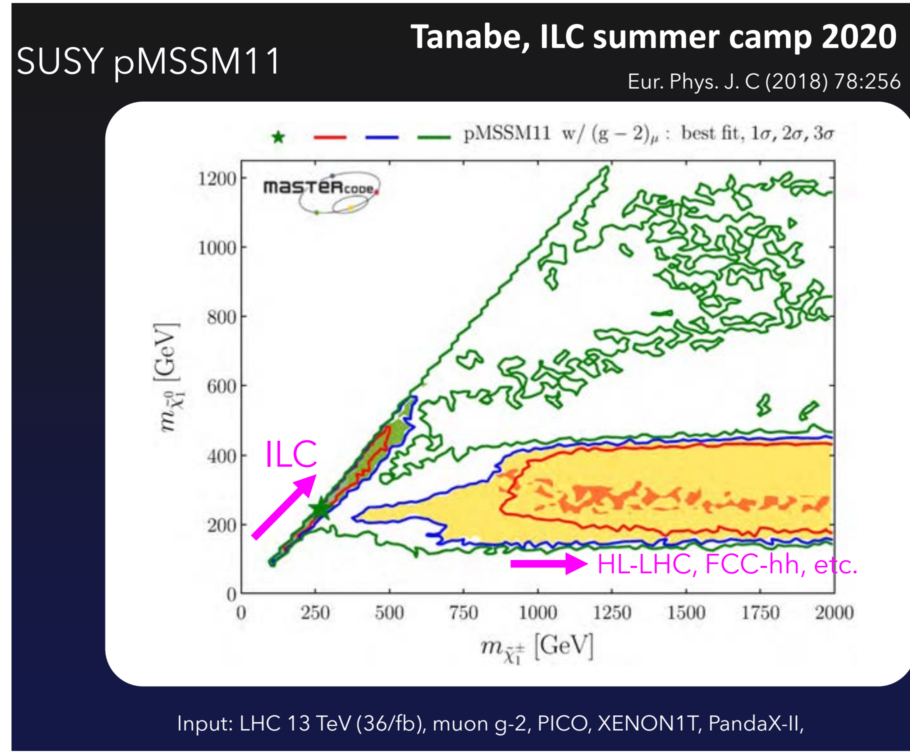
Power of g-2 constraints

Eur. Phys. J. C 78, 256 (2018)

Without g-2 anomaly



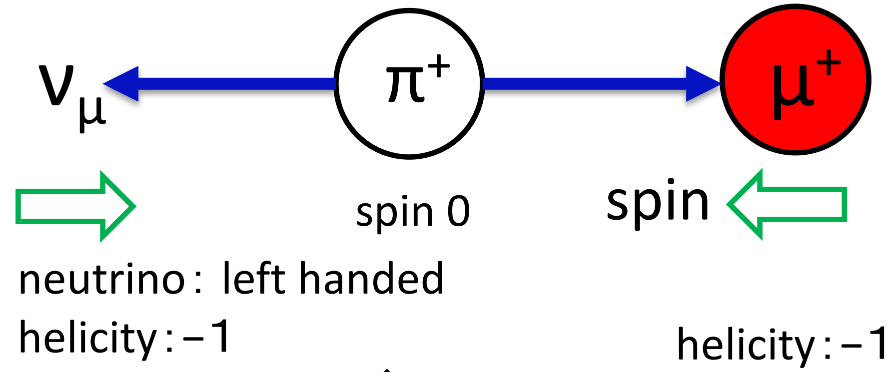
Including g-2 anomaly



DM mechanisms

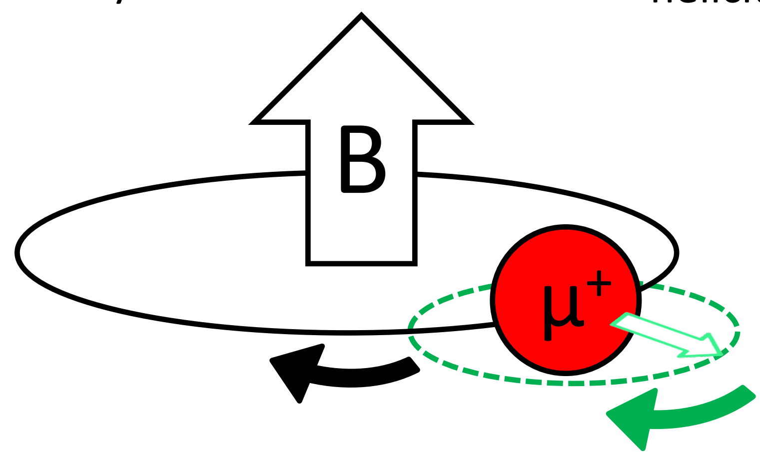
Three steps of g-2 measurement

1. Prepare a polarized muon beam.

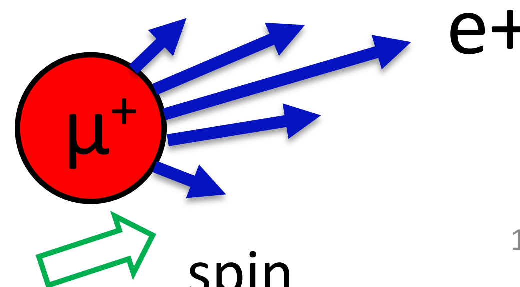


2. Store in a magnetic field (muon's spin precesses)

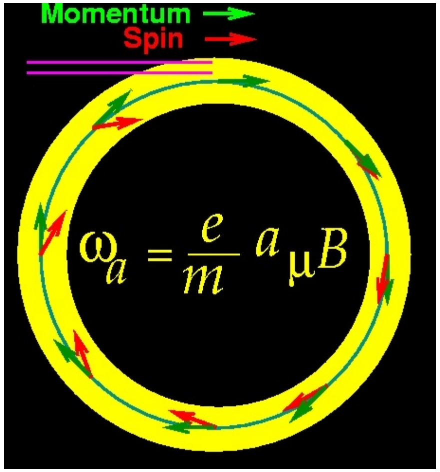
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$



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

general form of spin precession vector:

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

BNL E821 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

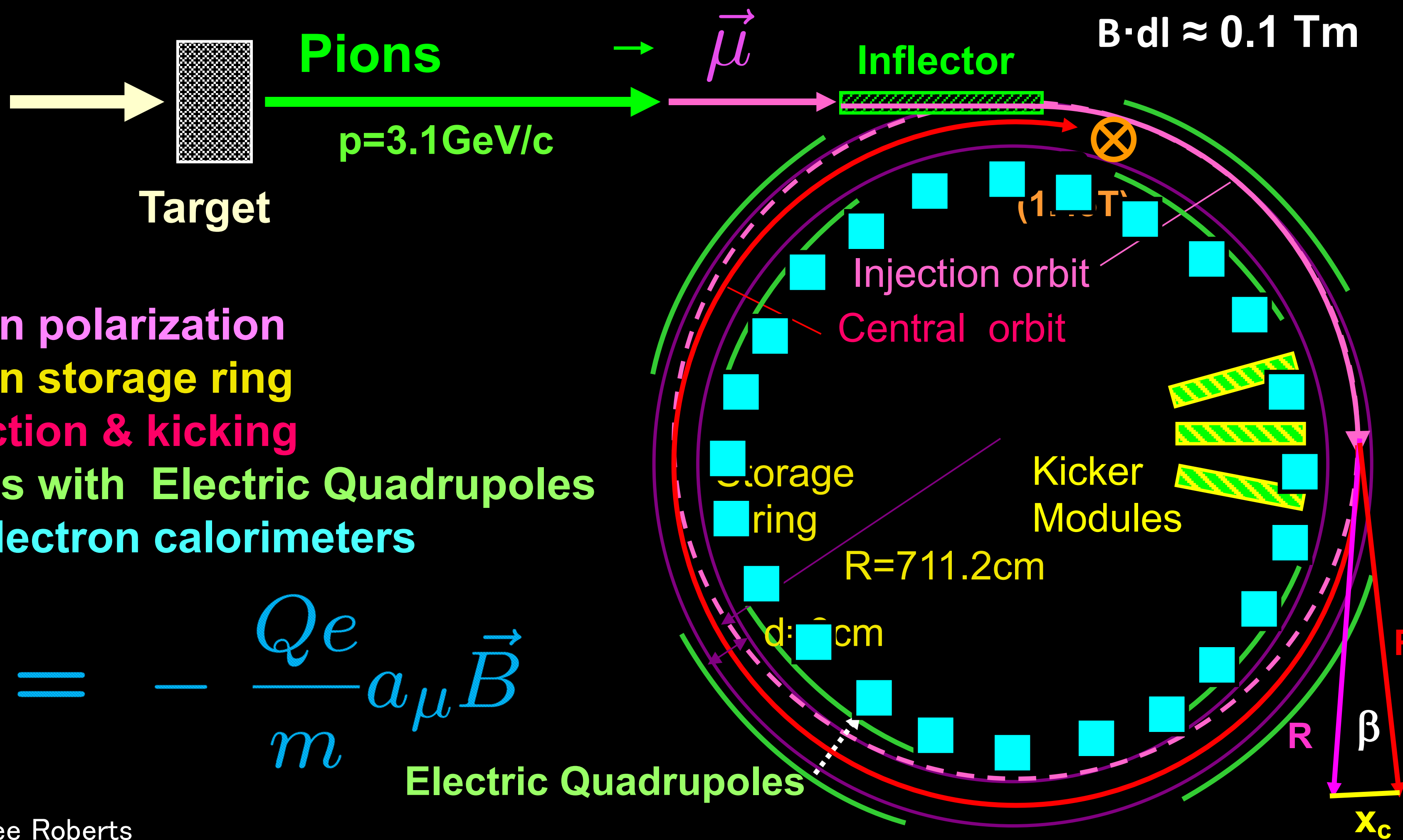
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

J-PARC E34

BNL & FNAL

Experimental Technique

narrow bunch of protons



$x_c \approx 77$ mm

$\beta \approx 10$ mrad

B·dl ≈ 0.1 Tm

- Muon polarization
- Muon storage ring
- injection & kicking
- focus with Electric Quadrupoles
- 24 electron calorimeters

$$\vec{\omega}_a = -\frac{Qe}{m} a_\mu \vec{B}$$

Slide by Lee Roberts

Previous experiment: BNL E824
Ongoing experiment: Fermilab E989

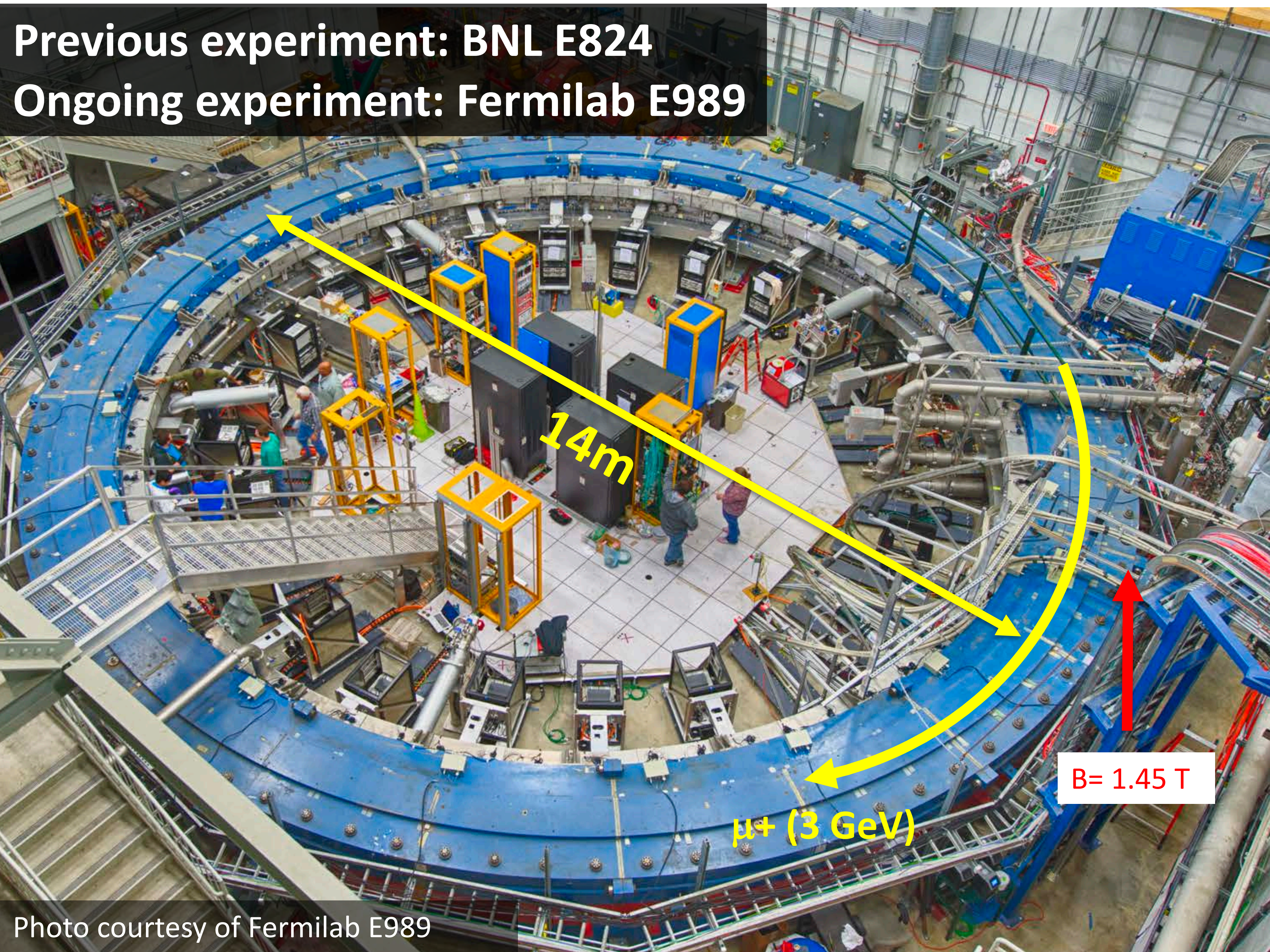


Photo courtesy of Fermilab E989

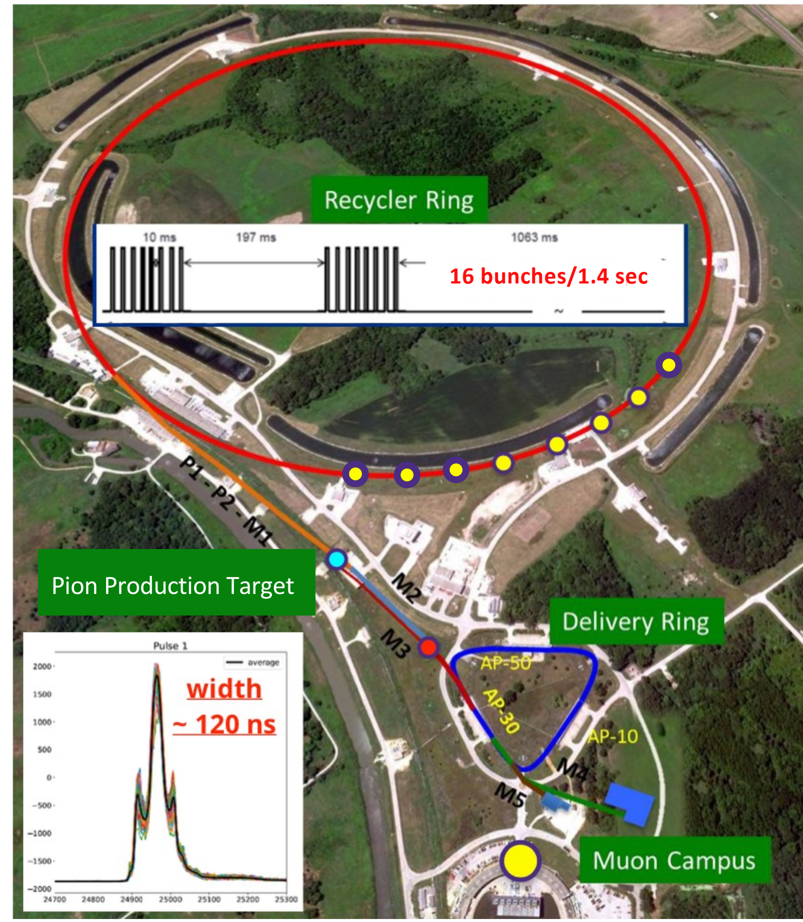
Why Fermilab?

J. Price, mu EDM WS at PSI, Feb 2020

- BNL limited by statistics (540 ppb on 9 x 10^9 detected e^+)
- E989 goal: Factor of 21 more statistics (2 x 10^{11} detected e^+)

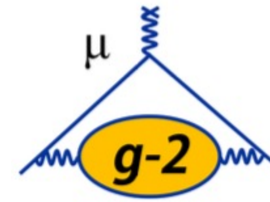
Fermilab advantages

- Long beam line to collect $\pi^+ \rightarrow \mu^+$
- Much reduced amount of p, π in ring
- 4x higher fill frequency than BNL

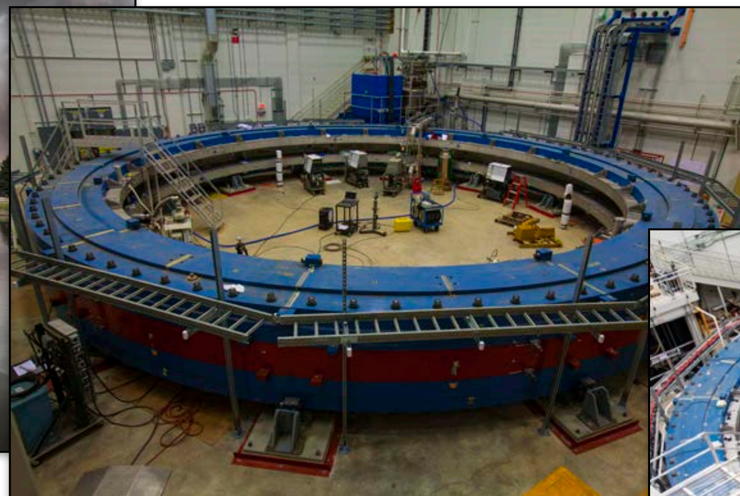


History of Fermilab muon g-2

Courtesy of Kim Siang Khaw

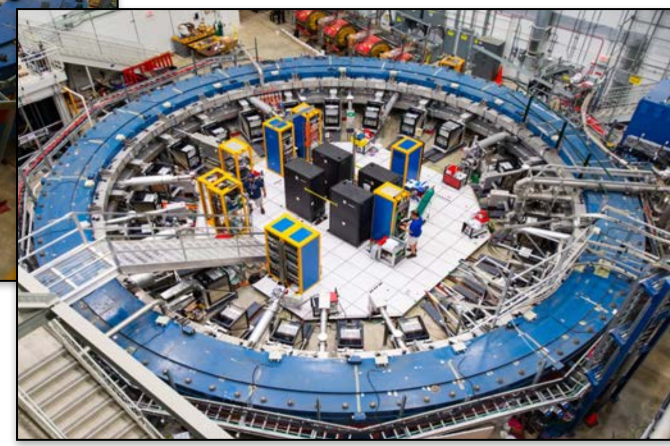


Transportation of magnet to FNAL (2013)

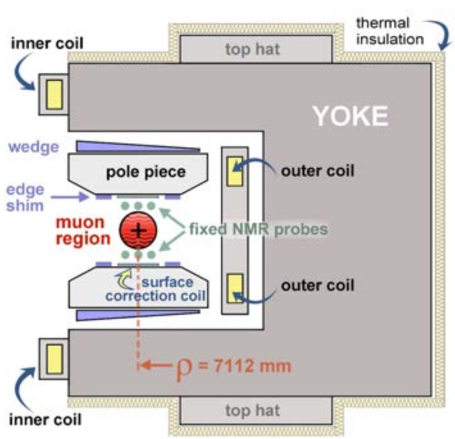


Assembly of the magnet (2014-2015)

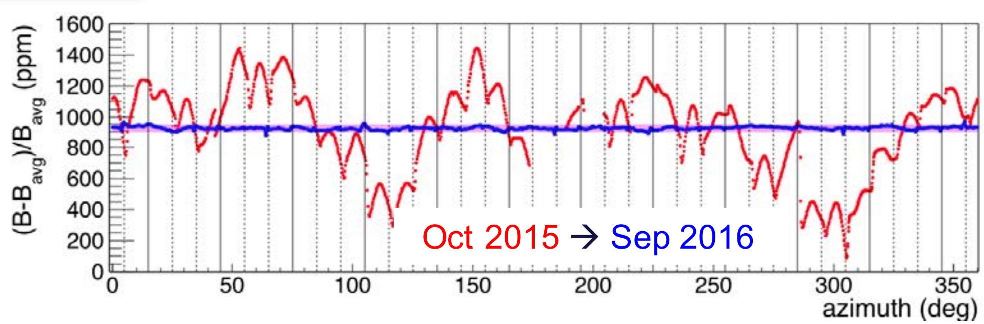
Passive shimming (2015-2016)



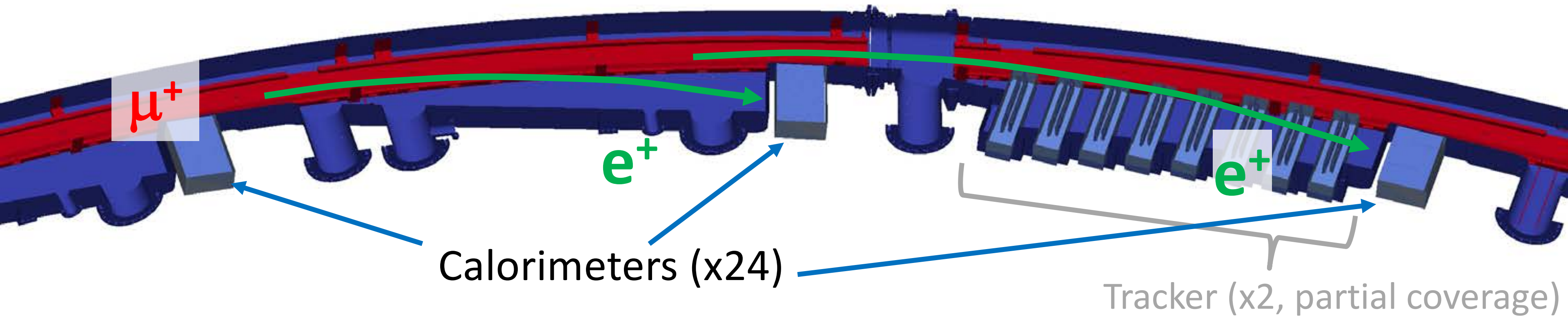
Full installation (2017)



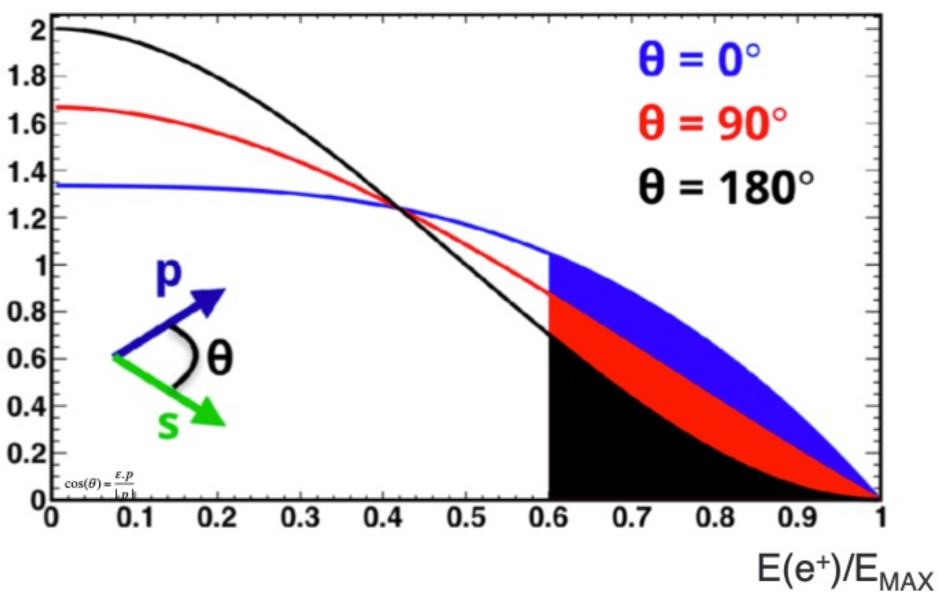
g-2 Magnet in Cross Section

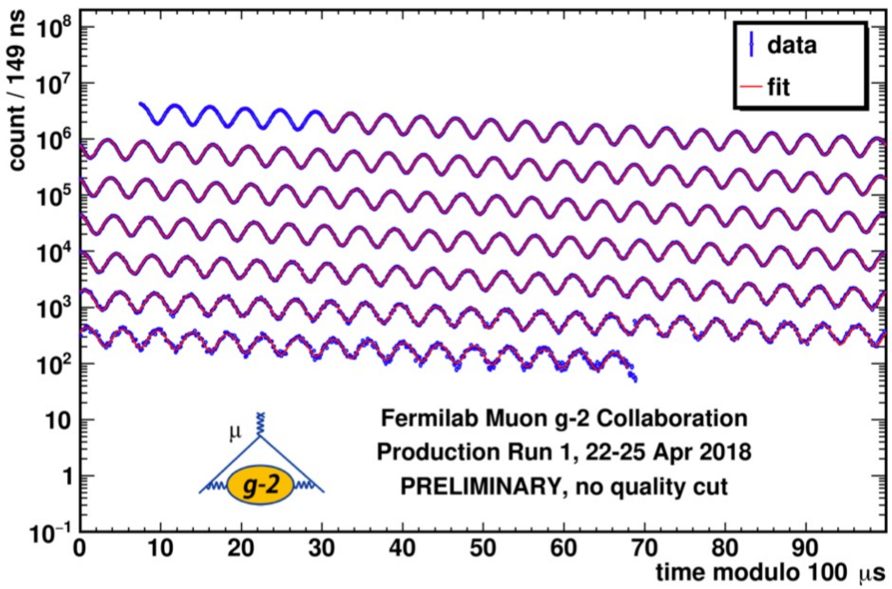


Time distribution of decay positrons



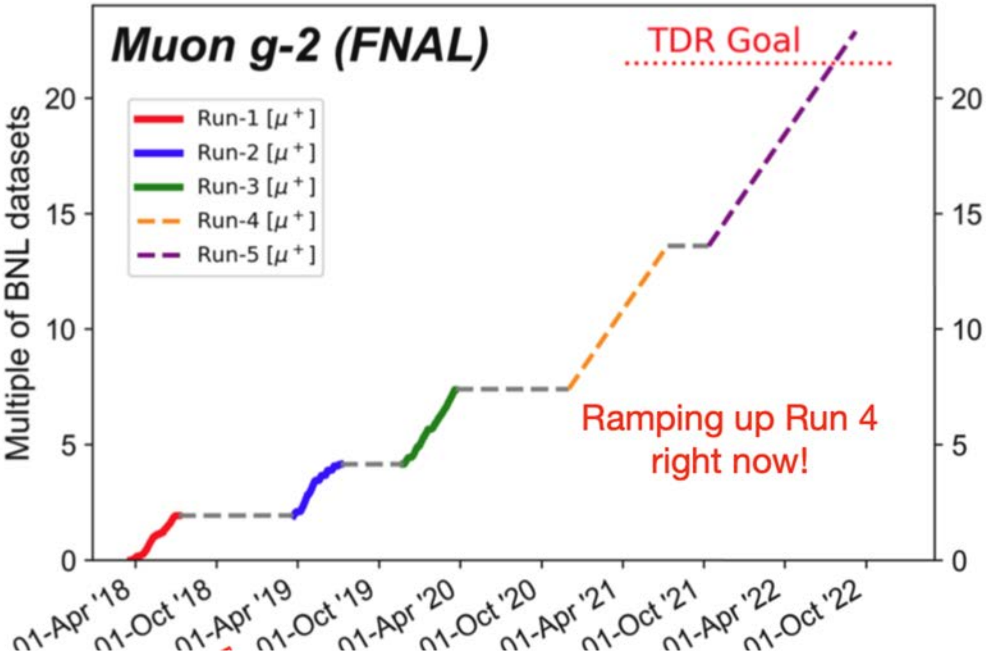
J. Price, Snowmass DM WS, Sep 2020.





Fermilab g-2 experiment (E989) has completed three data runs

Kim Siang Khaw on Dec 10, 2020

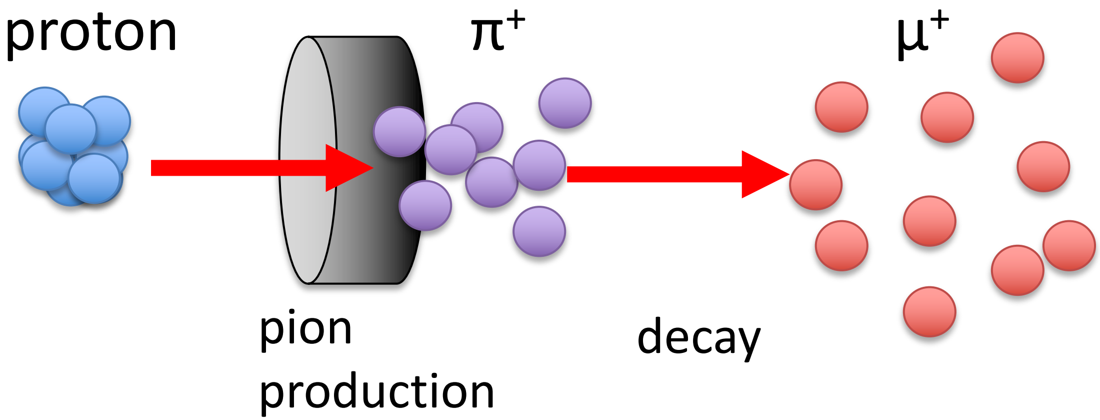


Take home messages:

- Collected > 7x BNL data over 3 years
- Systematics well below statistics (~450 ppb) for Run 1
- We are almost there (really)
  - We are leaving no stone uncovered in checking and double/triple/quadruple check blinded results
- As we go "beyond BNL", we are learning a lot with much better instruments and modeling
- Thank you for your patience and interest!

- **Announcement of the first results from Run 1 on April 8 midnight (Japan time).**
- **KEK online seminar by Prof. Lee Roberts on April 19 9:30.**

Conventional muon beam

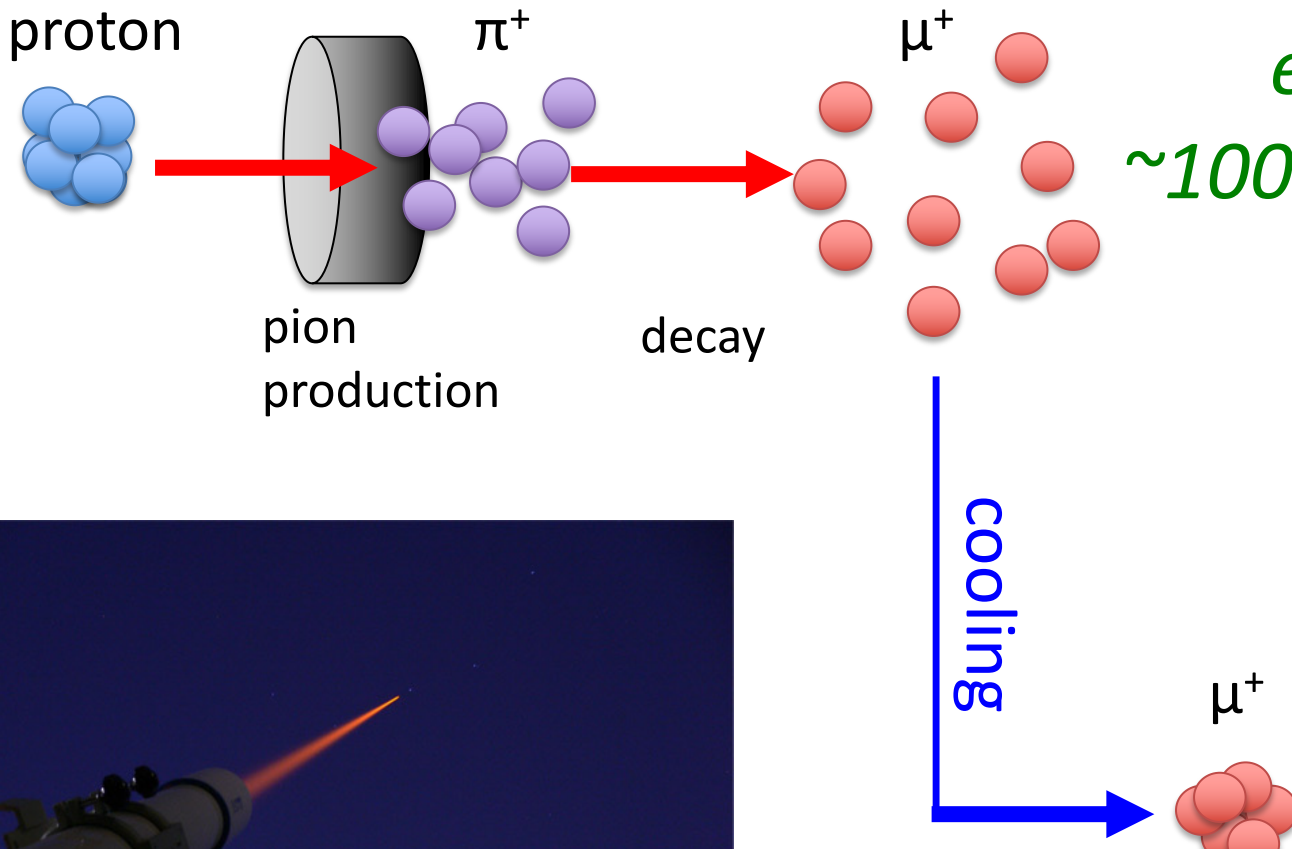


emittance

~1000π mm ·mrad

Strong focusing
Muon loss
BG π contamination

Muon beam at J-PARC



emittance

~1000π mm ·mrad

Strong focusing
Muon loss
BG π contamination

emittance

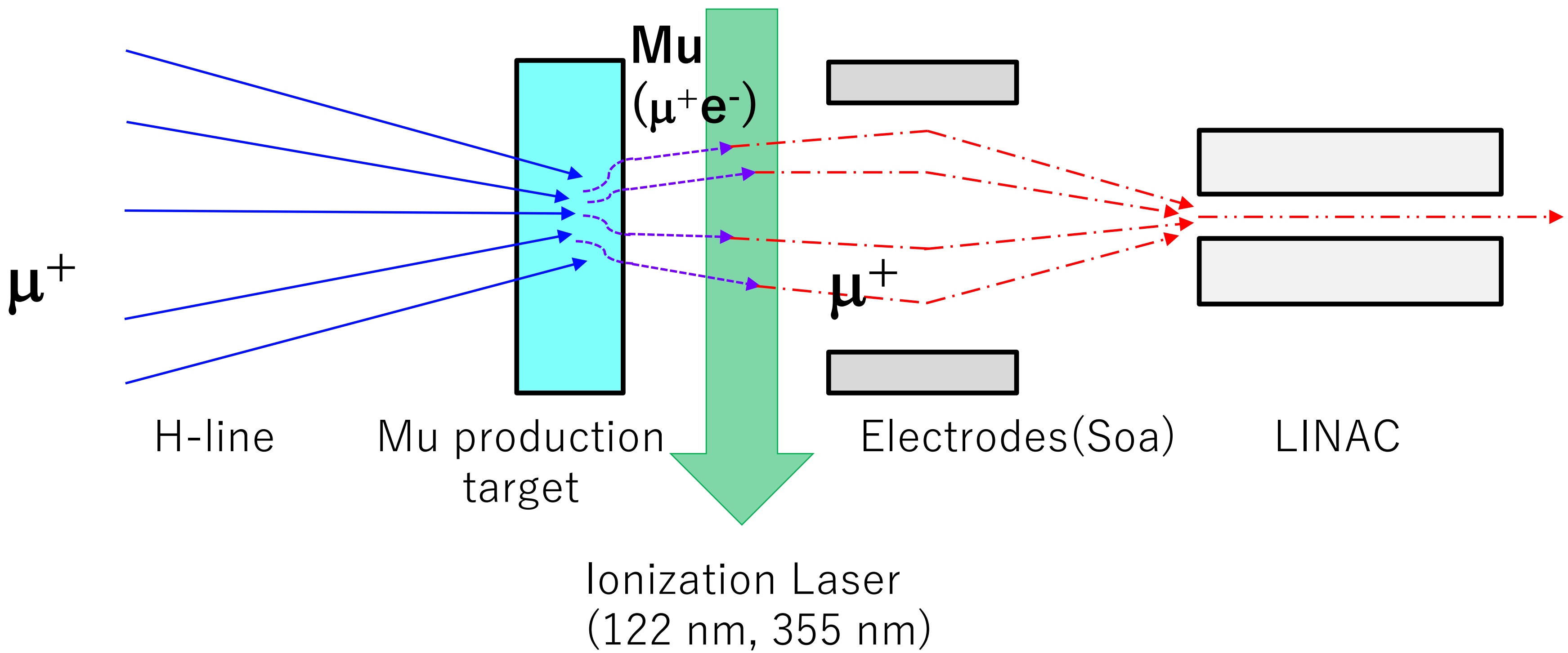
1π mm ·mrad

Reaccelerated thermal muon

Free from any of these

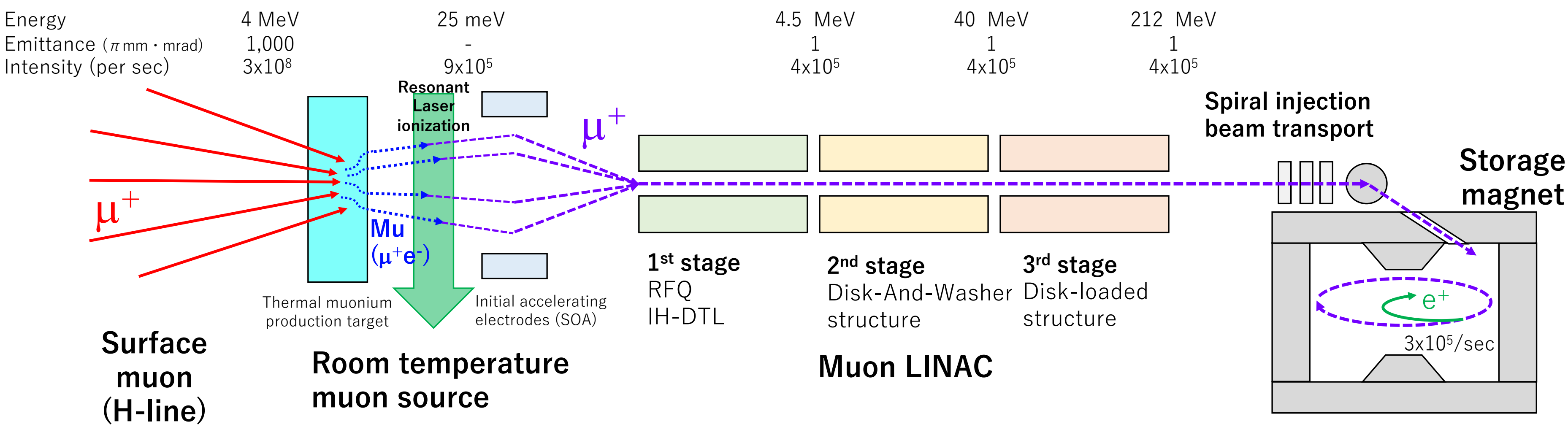
Re-accelerated thermal muon

	surface muon	thermal muon	accelerated muon
E	3.4 MeV	30 meV	212 MeV
p	27 MeV/c	2.3 keV/c	300 MeV/c
Δp/p	0.05	0.4	$4\text{x}10^{-4}$



Muon g-2/EDM experiment at J-PARC

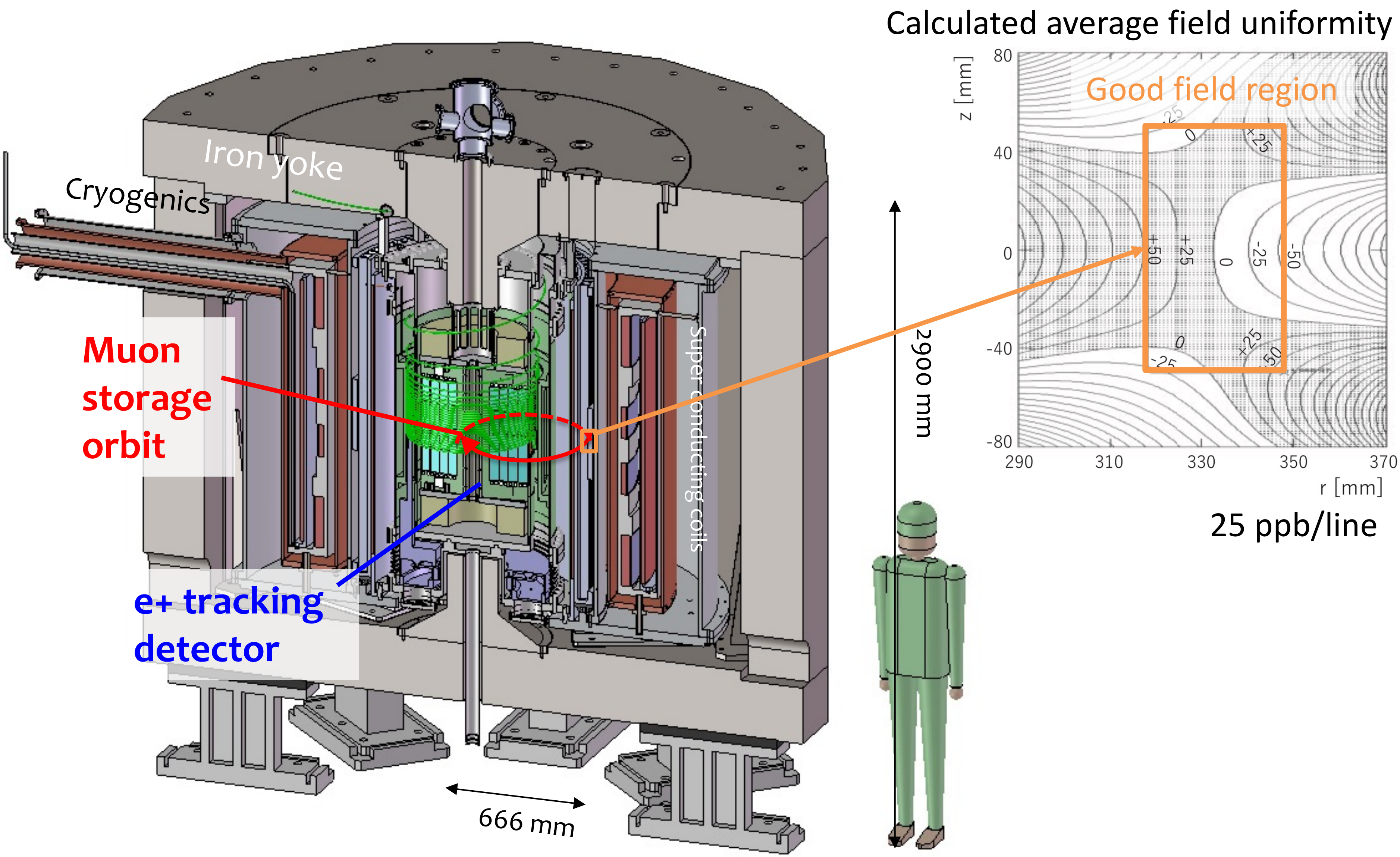
Prog. Theor. Exp. Phys. **2019**, 053C02



Features:

- Low emittance muon beam (1/1000)
- No strong focusing (1/1000) & good injection eff. (x10)
- Compact storage ring (1/20)
- Tracking detector with large acceptance
- Completely new method (different from BNL/FNAL)

Muon storage magnet and detector

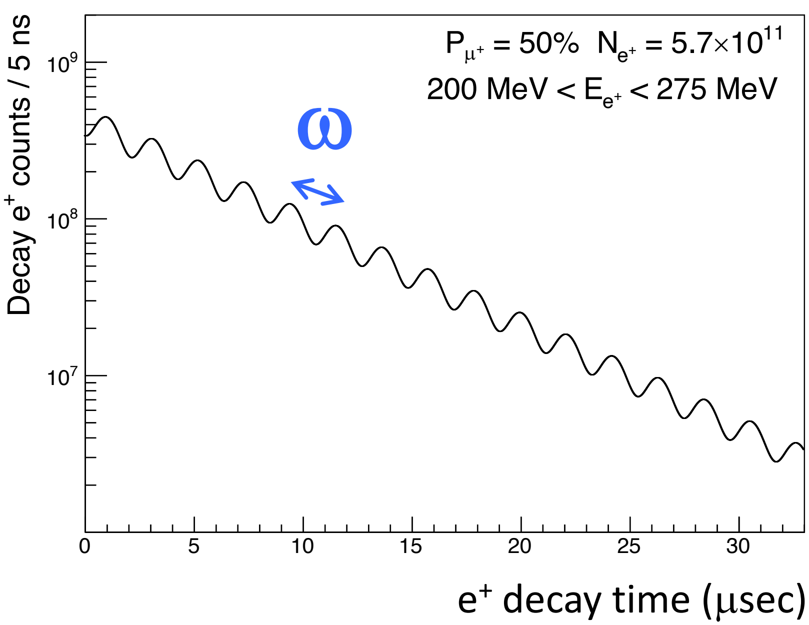


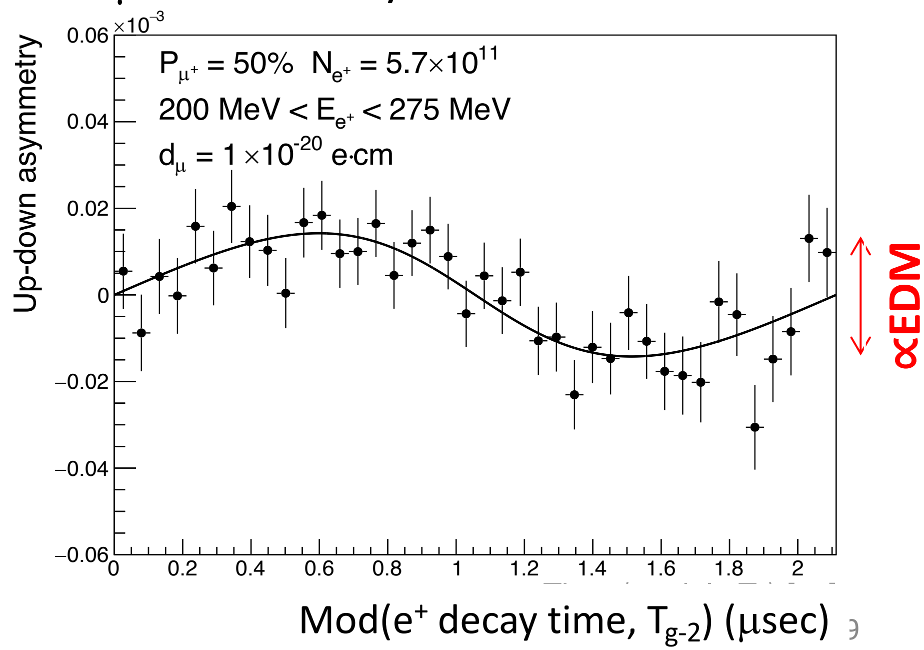
M. Abe et. al., Nuclear Inst. and Methods in Physics Research A 890, 51 (2018)

Expected results

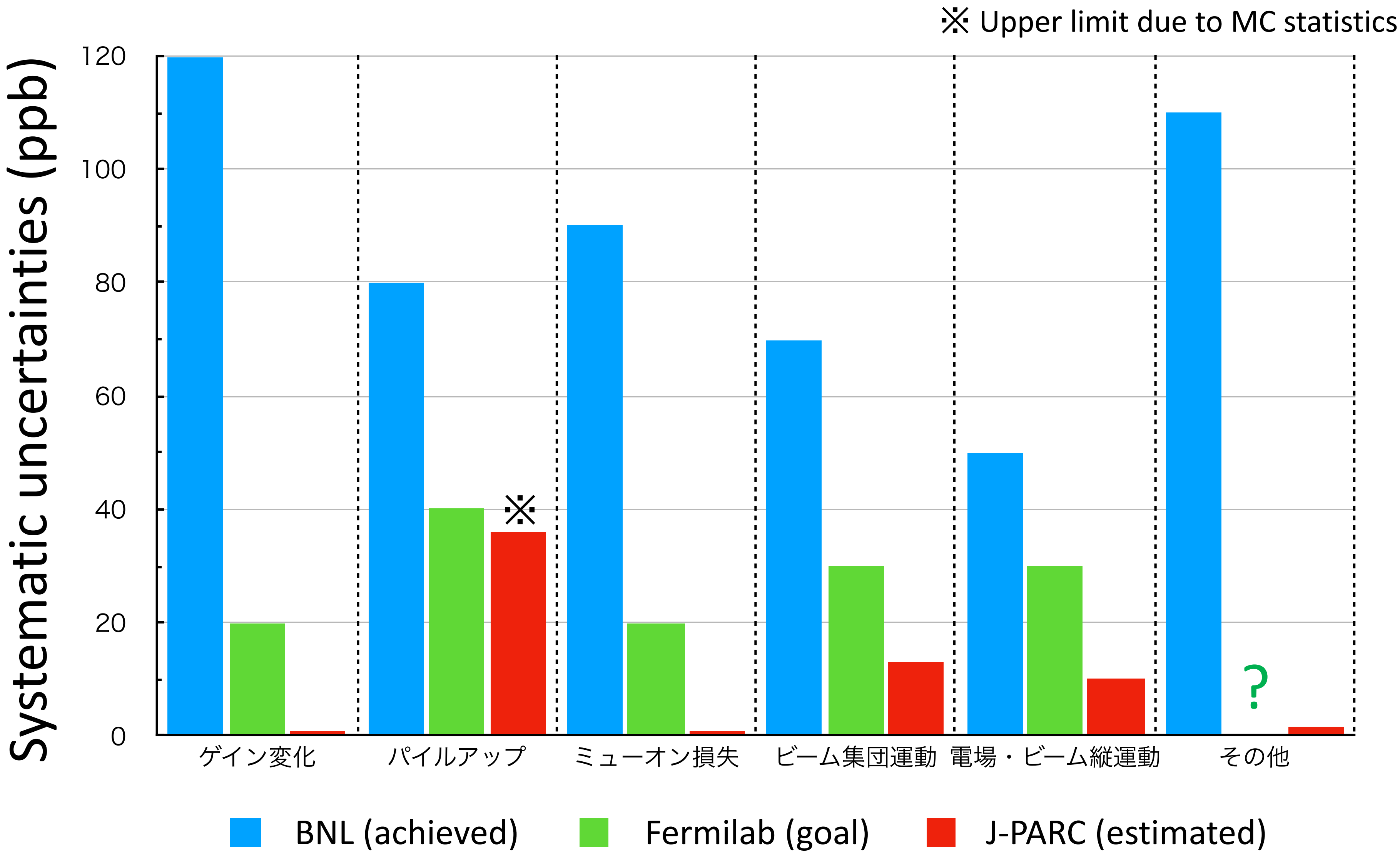
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

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





Systematic uncertainties



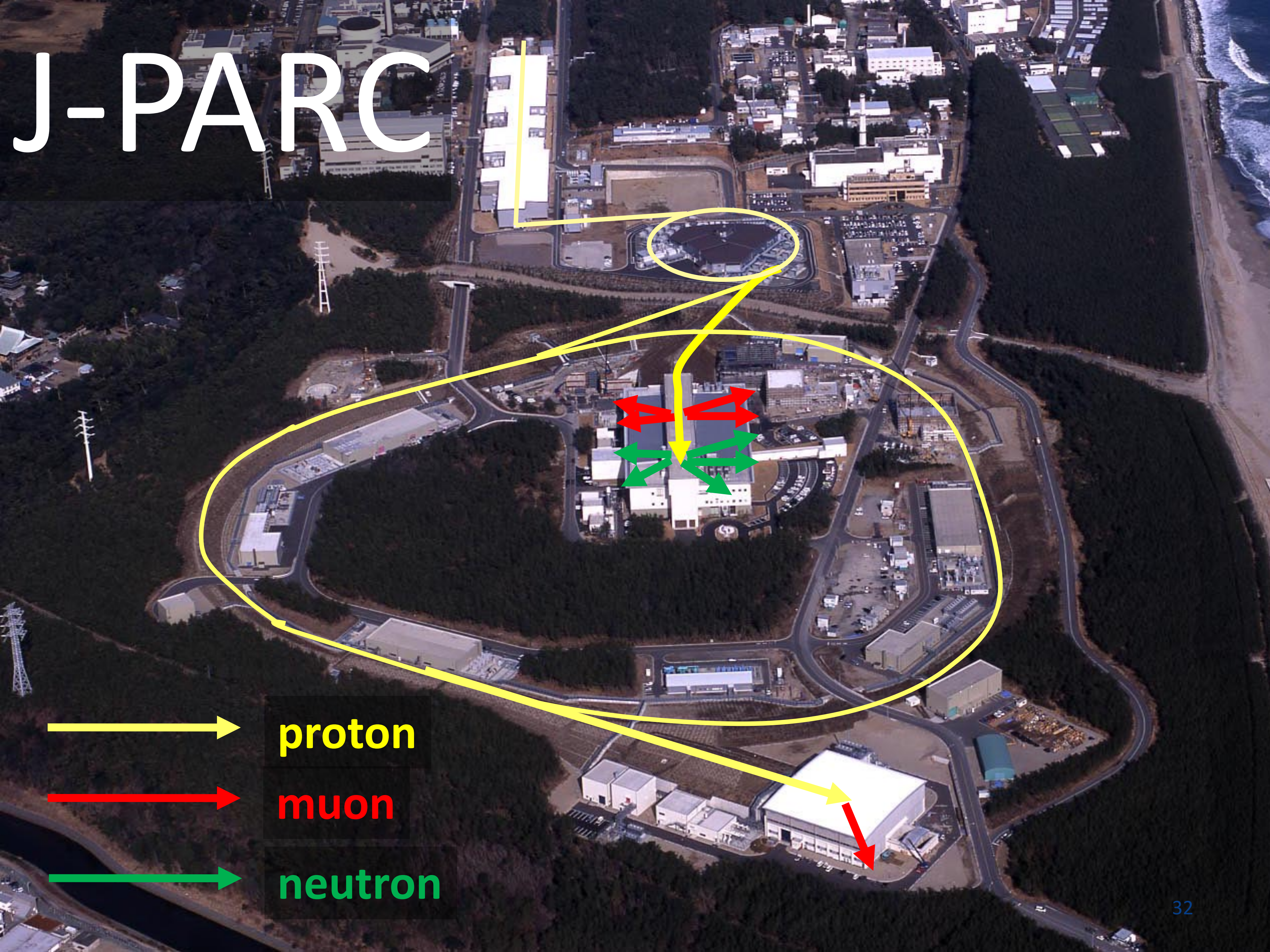
Significant improvements over the previous method

Comparison of g-2 experiments

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

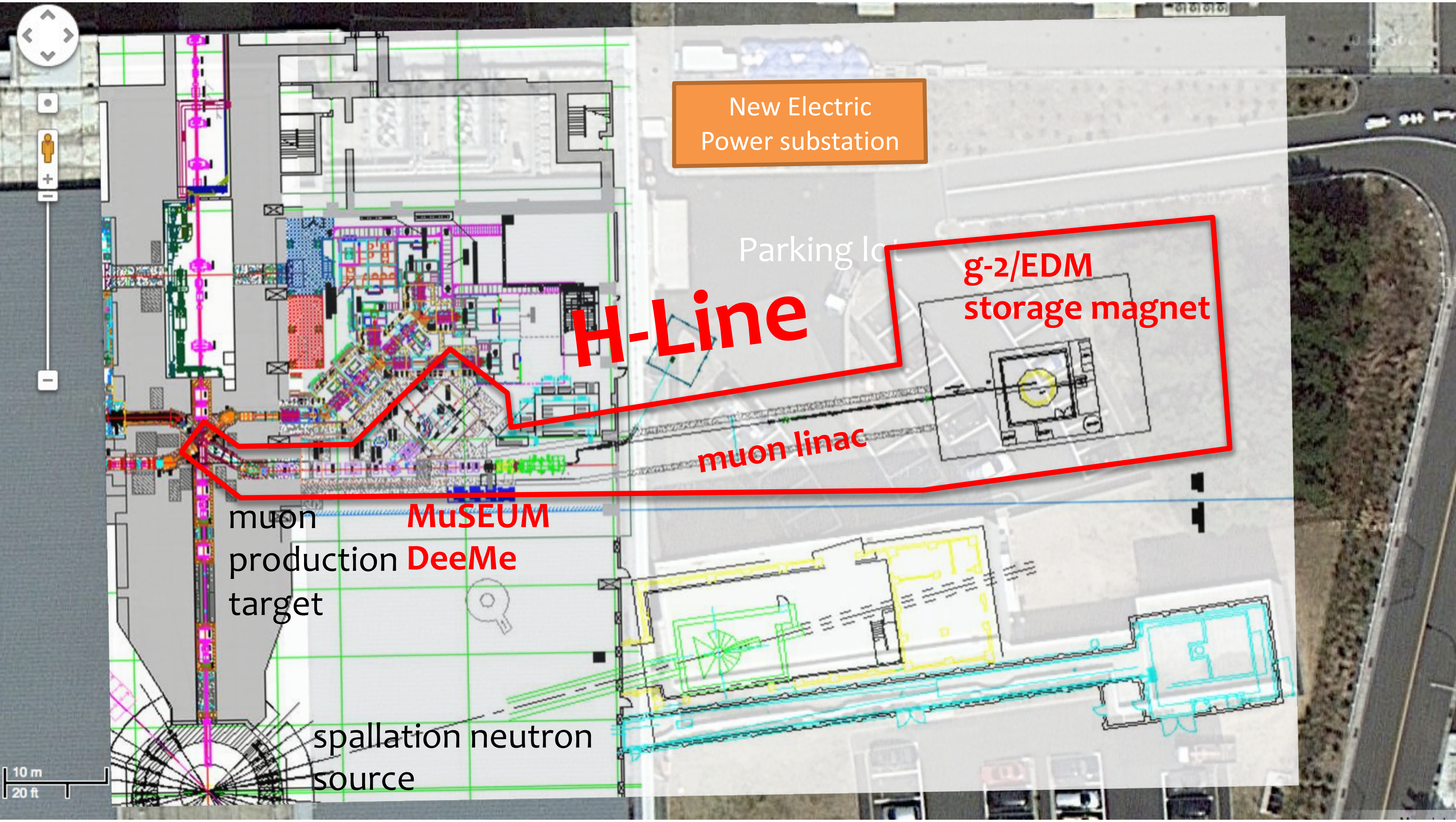
	BNL-E821	Fermilab-E989	Our experiment
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz γ	29.3		3
Polarization	100%		50%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric quadrupole		Very weak magnetic
Cyclotron period	149 ns		7.4 ns
Spin precession period	4.37 μs		2.11 μs
Number of detected 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


J-PARC
proton
muon
neutron

Proposed experimental site (H-line)

Material and Life science Facility in J-PARC

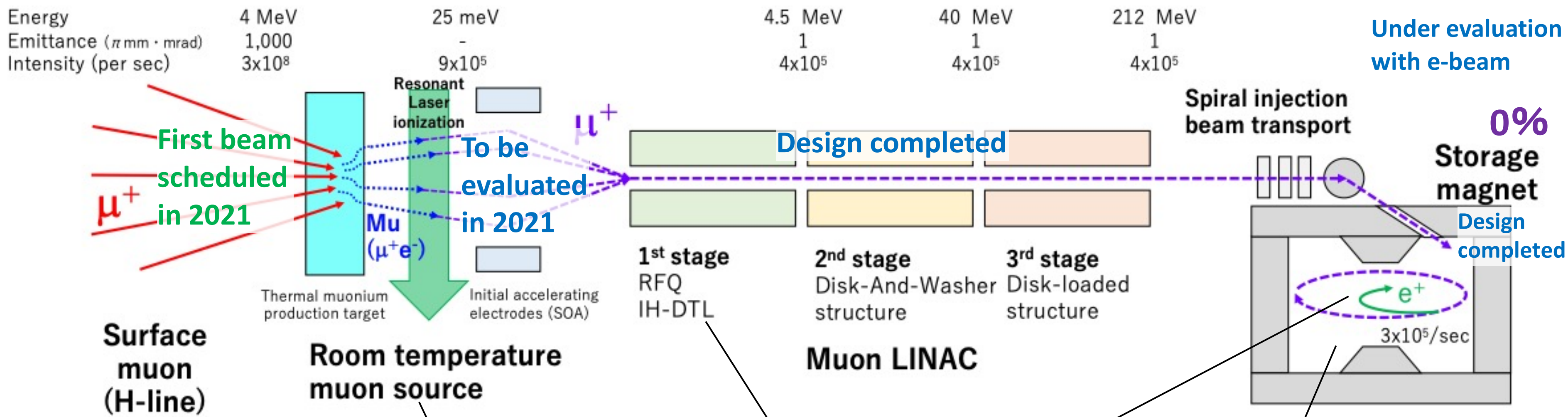


N. Kawamura et al., PTEP 2018, 113G01 (2018)

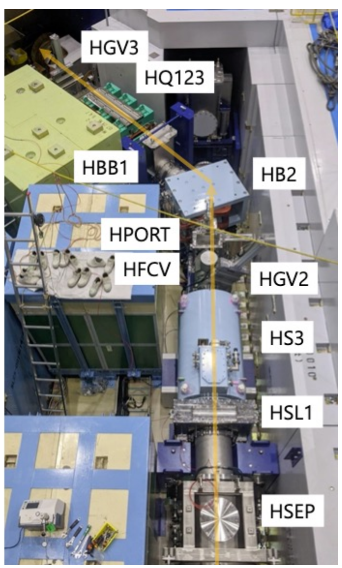
Achievements

Summary of technical design

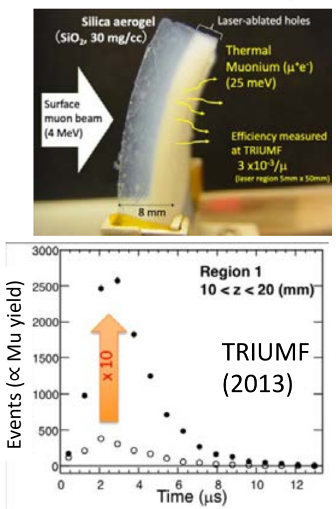
Prog. Theor. Exp. Phys. **2019**, 053C02



Beamline construction (2020)

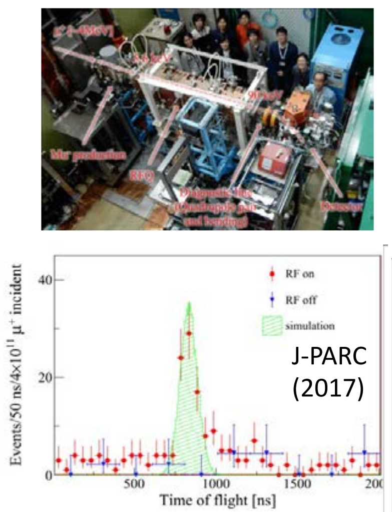


(a) Muonium production target



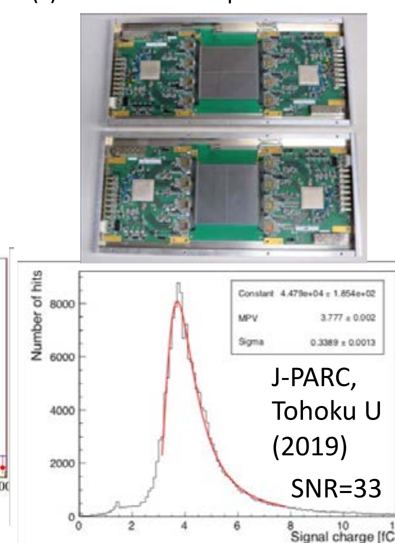
[PTEP 2013,103C01](#)
[PTEP 2014,091C01](#)
[PTEP 2020,123C01](#)

(b) Muon acceleration to 80 keV



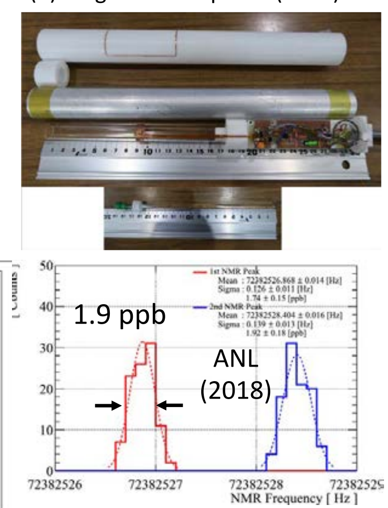
PRAB 19, 040101 (2016)
PRAB 21, 050101 (2018)
PRAB 23, 022804 (2020)
PRAB 24, 033403 (2021)

(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)

The collaboration received **a new Grant-in-Aids for 6 years (2020-2025)** for construction of detector system and other key components.

Construction of surface muon beamline

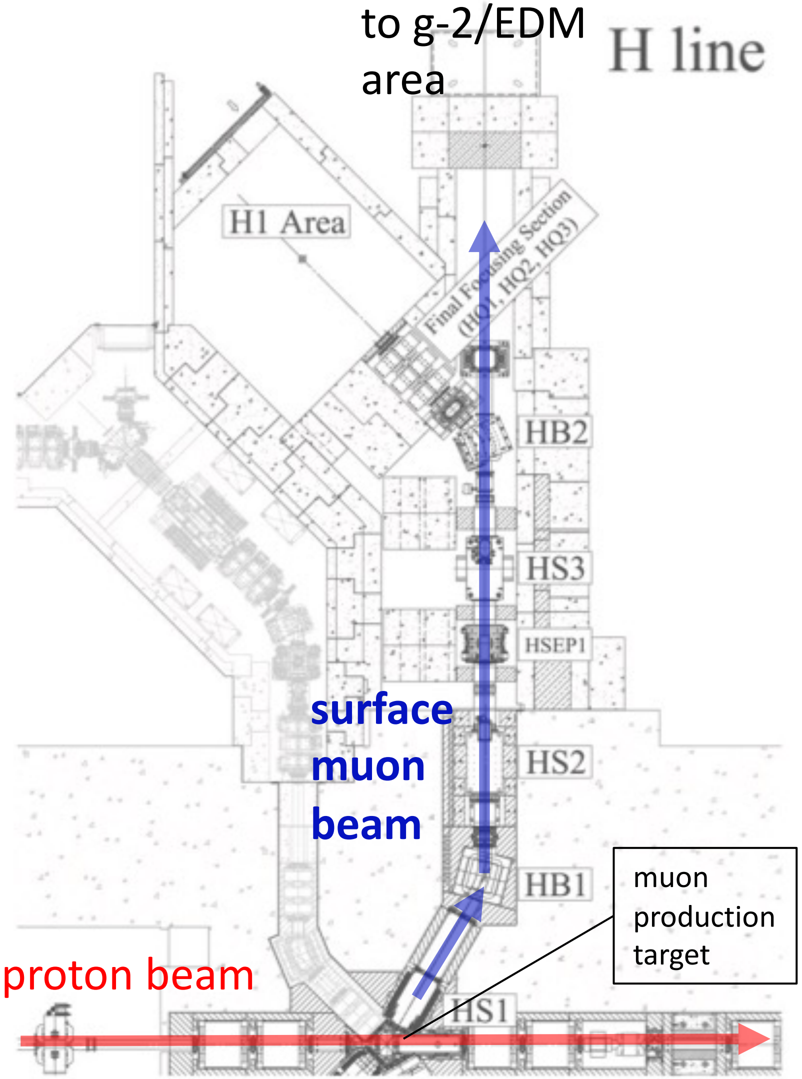
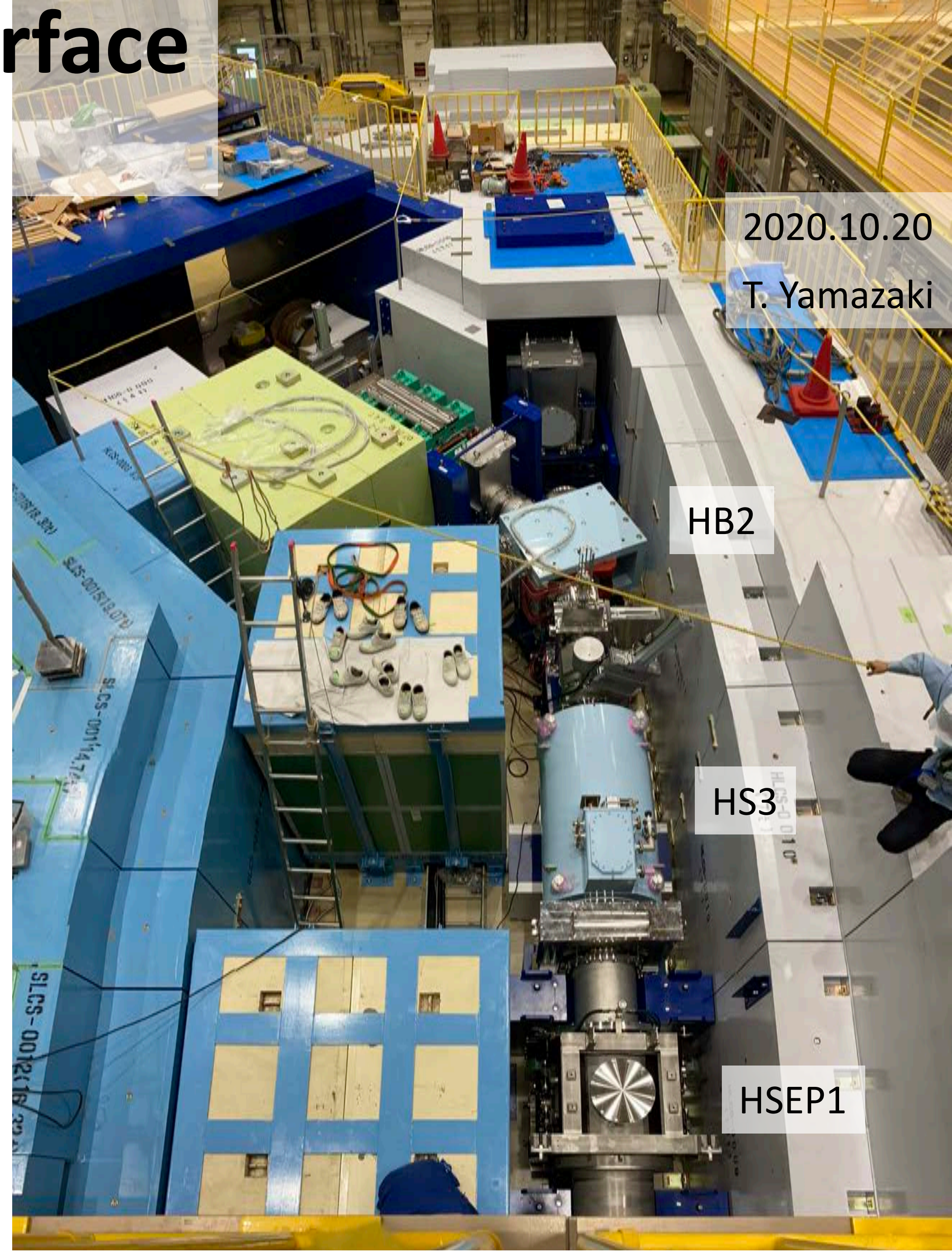


Fig. 2. The H-line layout.

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

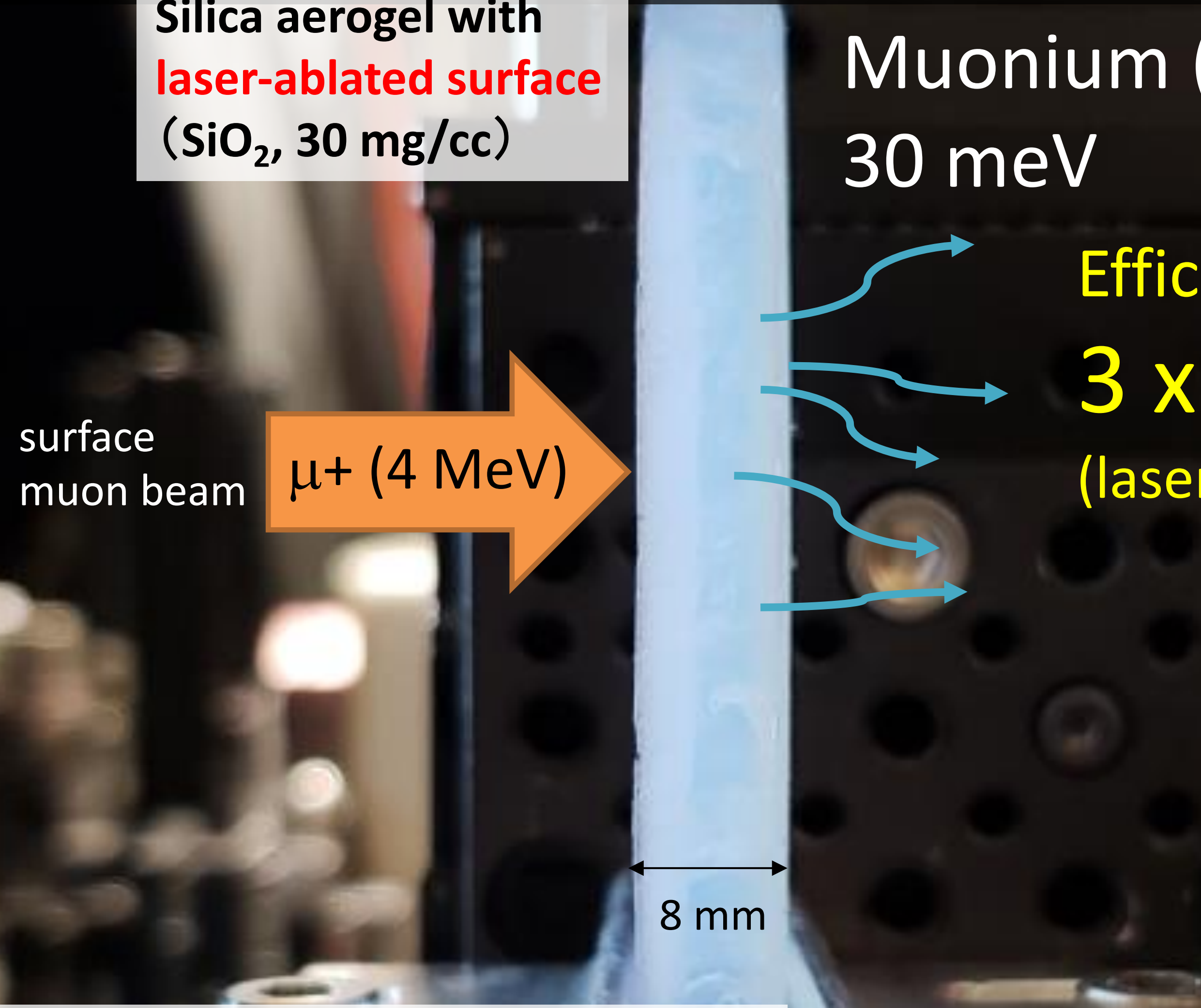


Production of thermal energy muon

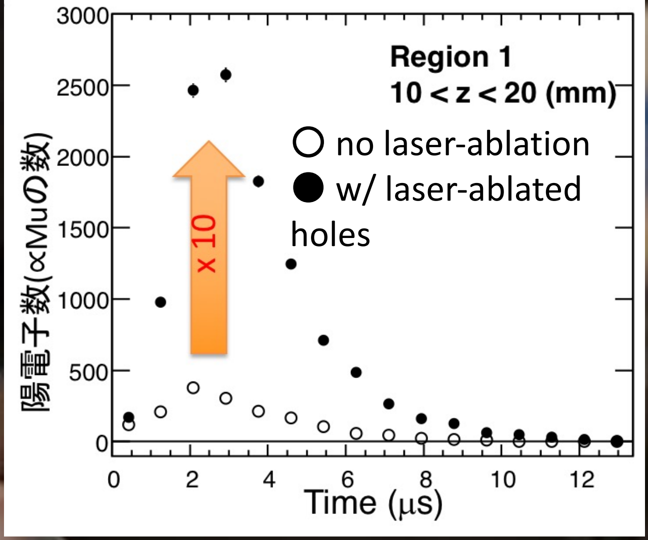
Silica aerogel with
laser-ablated surface
(SiO_2, 30 mg/cc)

Muonium (μ^+e^-)
30 meV

Efficiency
$3 \times 10^{-3}/\mu$
(laser region 5mm x 50mm)



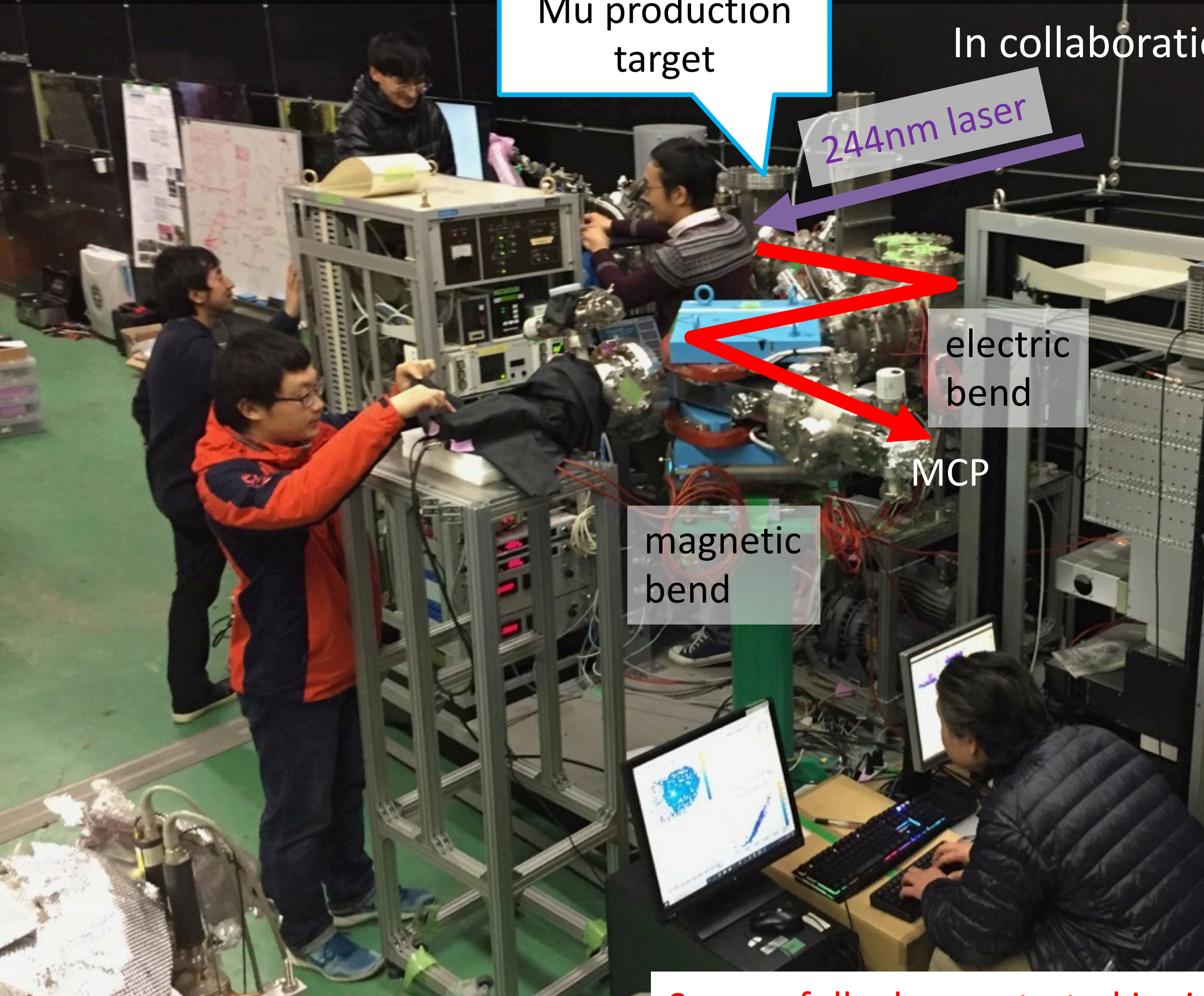
Data taken at TRIUMF

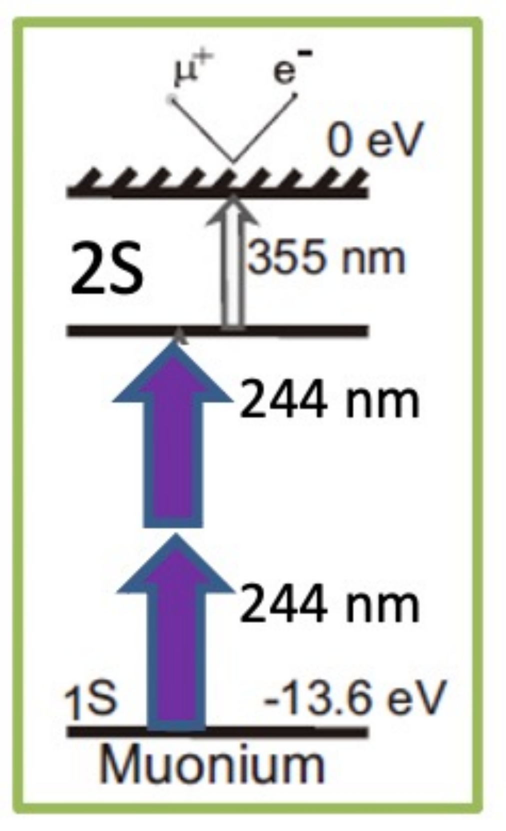


P. Bakule et al., PTEP 103C0 (2013)
G. Beer et al., PTEP 091C01 (2014)
J. Beare et al., PTEP 123C01 (2020)

Photo by S. Kamal

Setting up the Mu ionization experiment

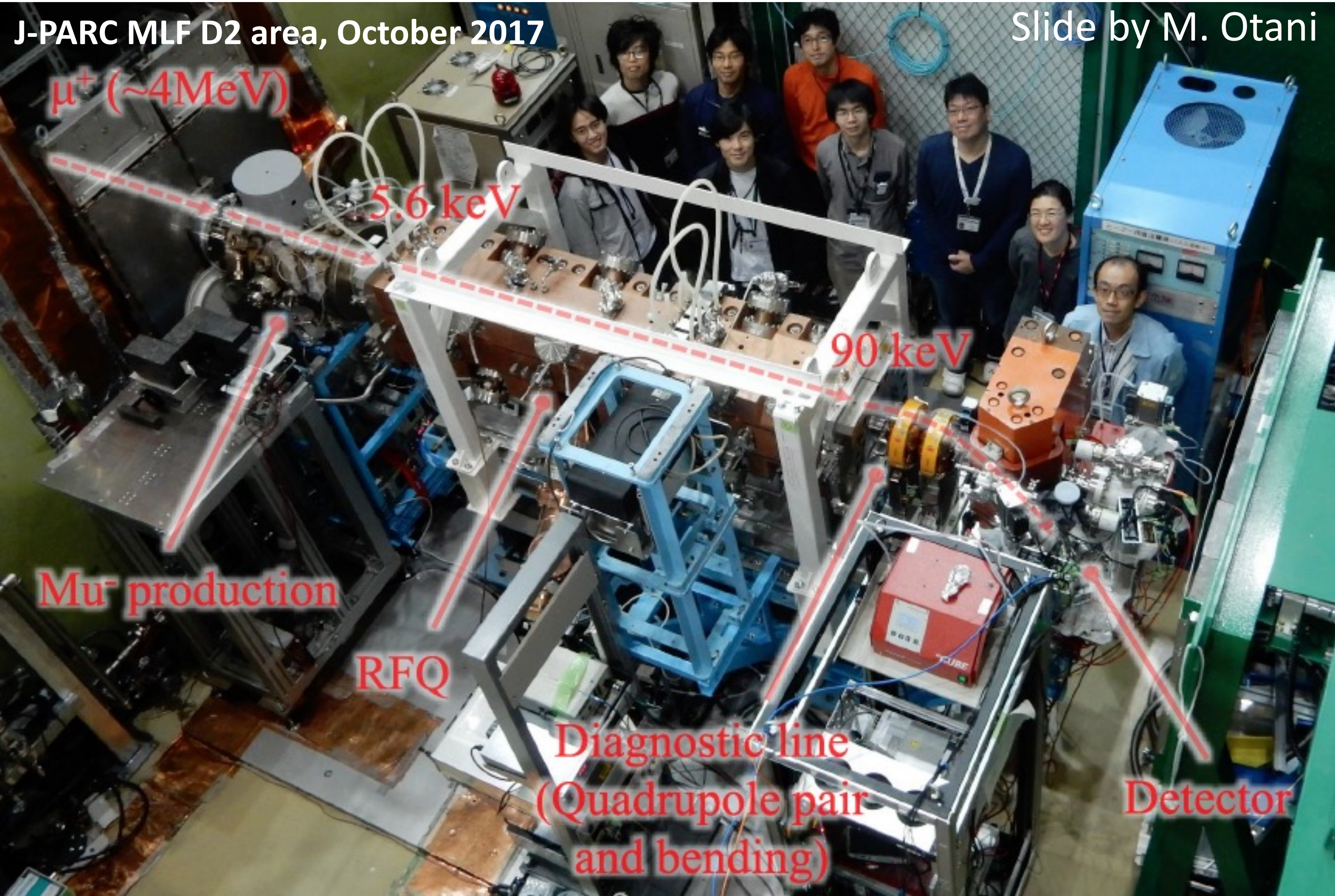




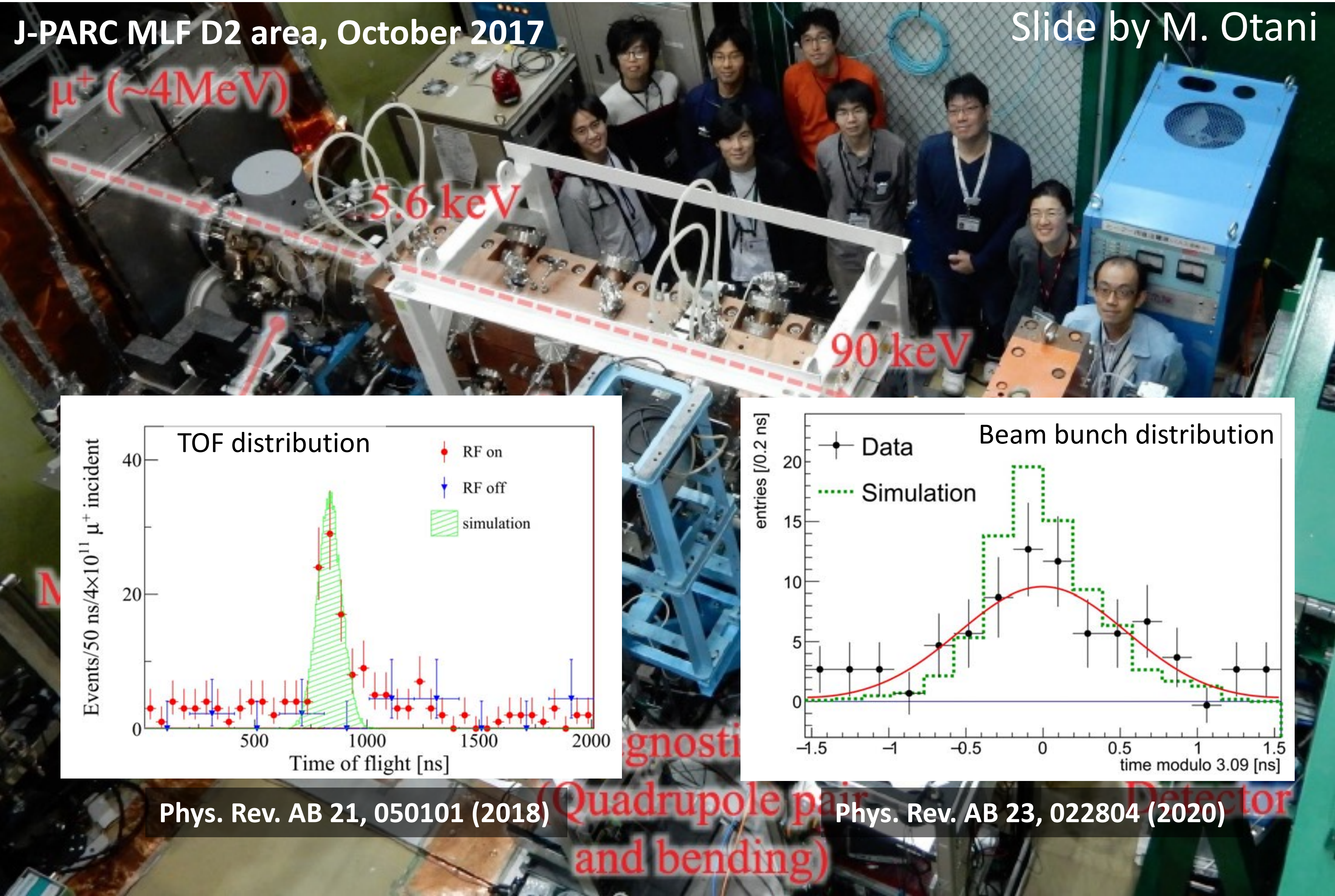
KEK, Tsukuba Campus

Successfully demonstrated ionization of hydrogen atoms
Transported to J-PARC MLF S-line in December 2020

Demonstration of muon RF acceleration



Demonstration of muon RF acceleration



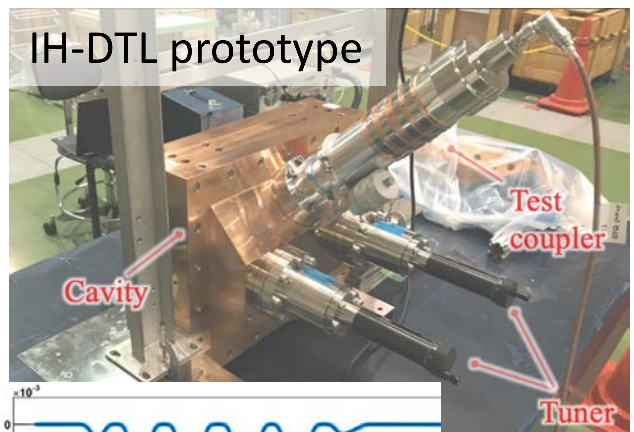
Muon LINAC

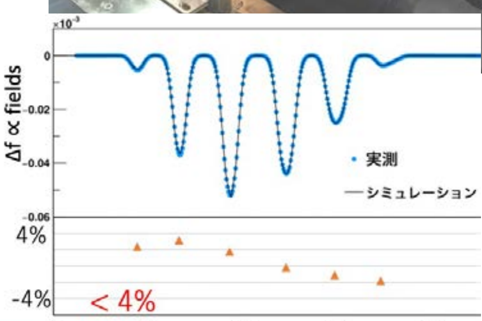
muon source → RFQ → IH-DTL → DAW → DLS → injection beamline

	RFQ	IH-DTL	DAW	DLS
length	3.2 m	1.4 m	16 m	10 m
RF	324 MHz	324 MHz	1296 MHz	1296 MHz

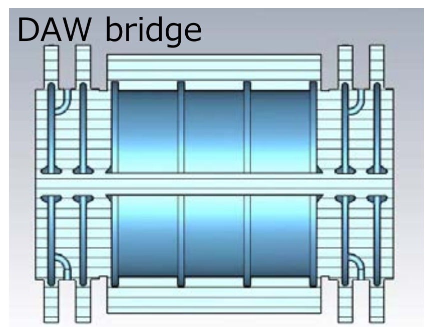
E	5.6 keV	0.34 MeV	4.5 MeV	40 MeV	212 MeV
β	0.01	0.08	0.3	0.7	0.94

IH-DTL prototype

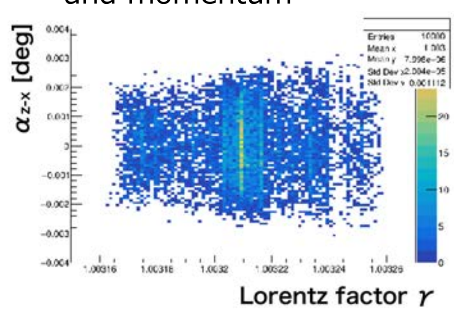




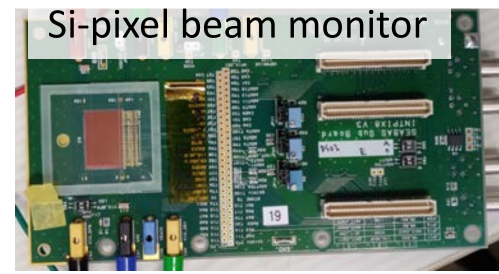
DAW bridge



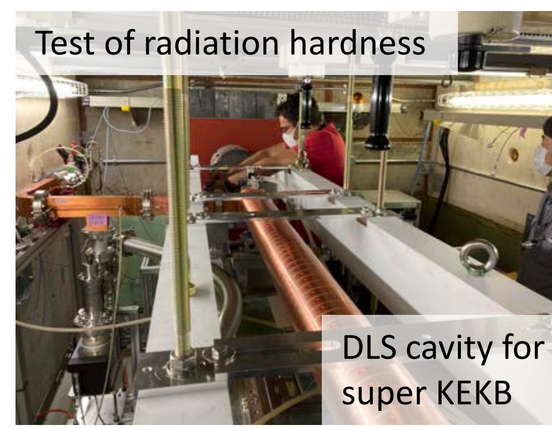
Simulated spin direction and momentum



Si-pixel beam monitor



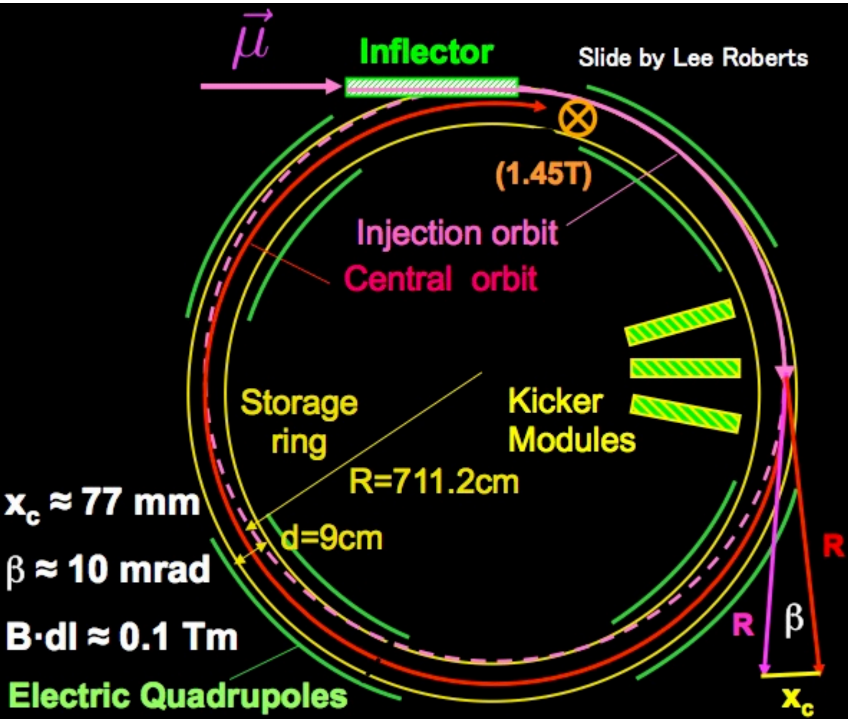
Test of radiation hardness



DLS cavity for super KEKB

Muon beam injection and storage

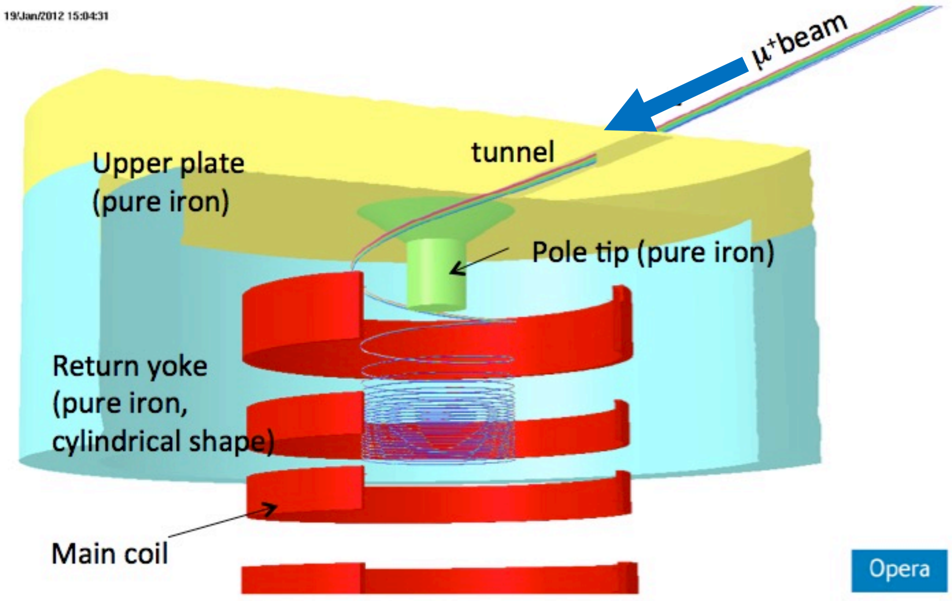
- Horizontal injection + kicker
- (BNL E821, FNAL E989)



Injection efficiency : 3-5%(*)

(*) PRD73,072003 (2006)

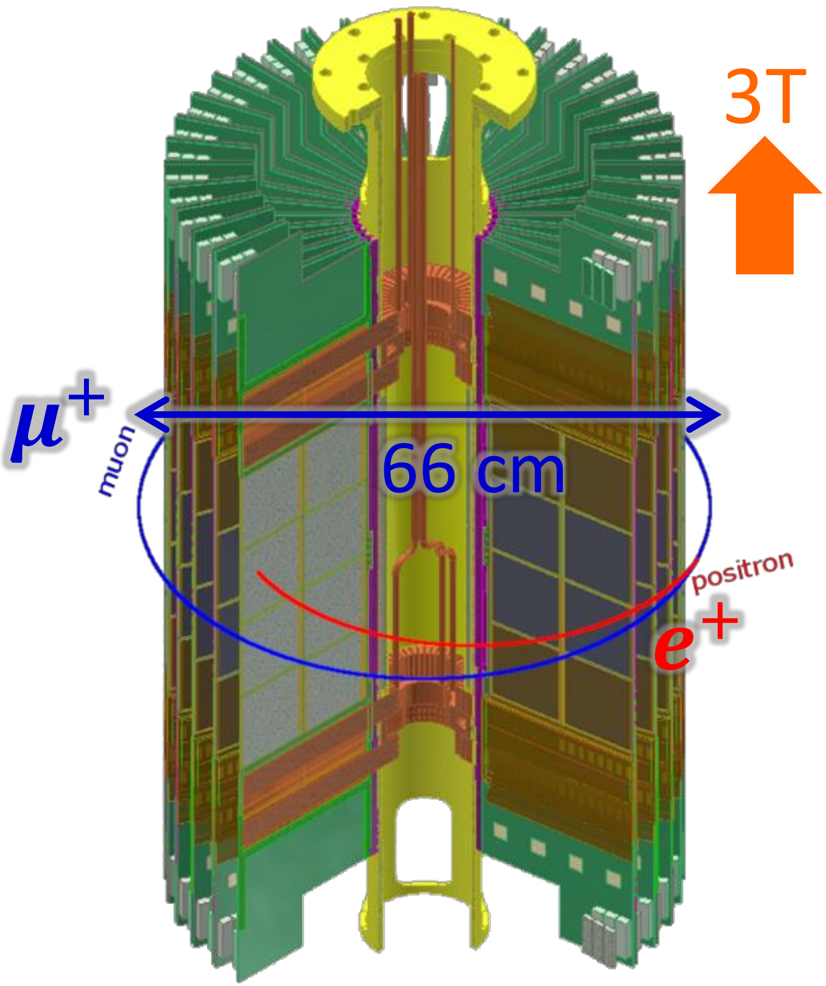
- 3D spiral injection + kicker
- (J-PARC E34)



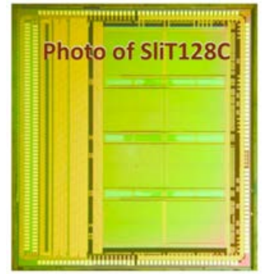
Injection efficiency : ~85%

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

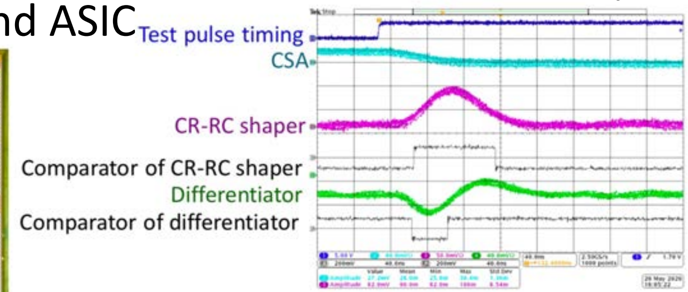
Positron tracking detector



New frontend ASIC

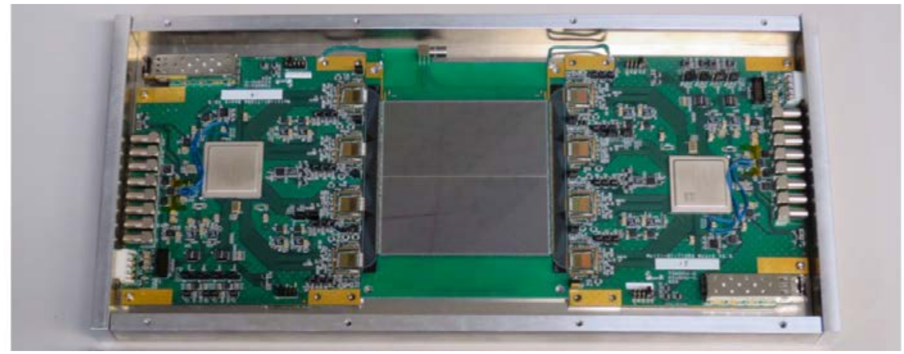


IEEE, TNS 67, 2089 (2020)

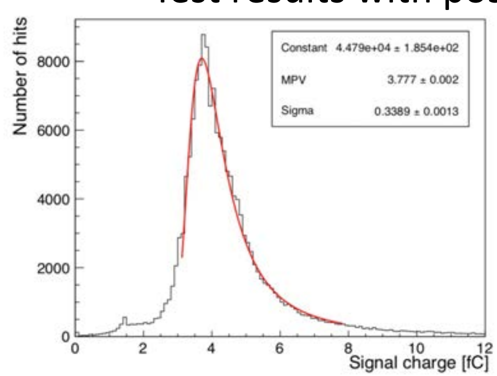


Test module

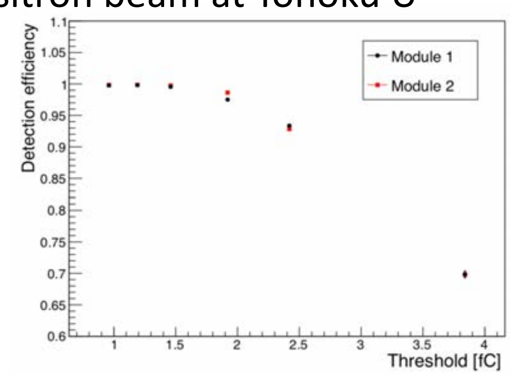
JINST 15 P04027 (2020)



Test results with positron beam at Tohoku U



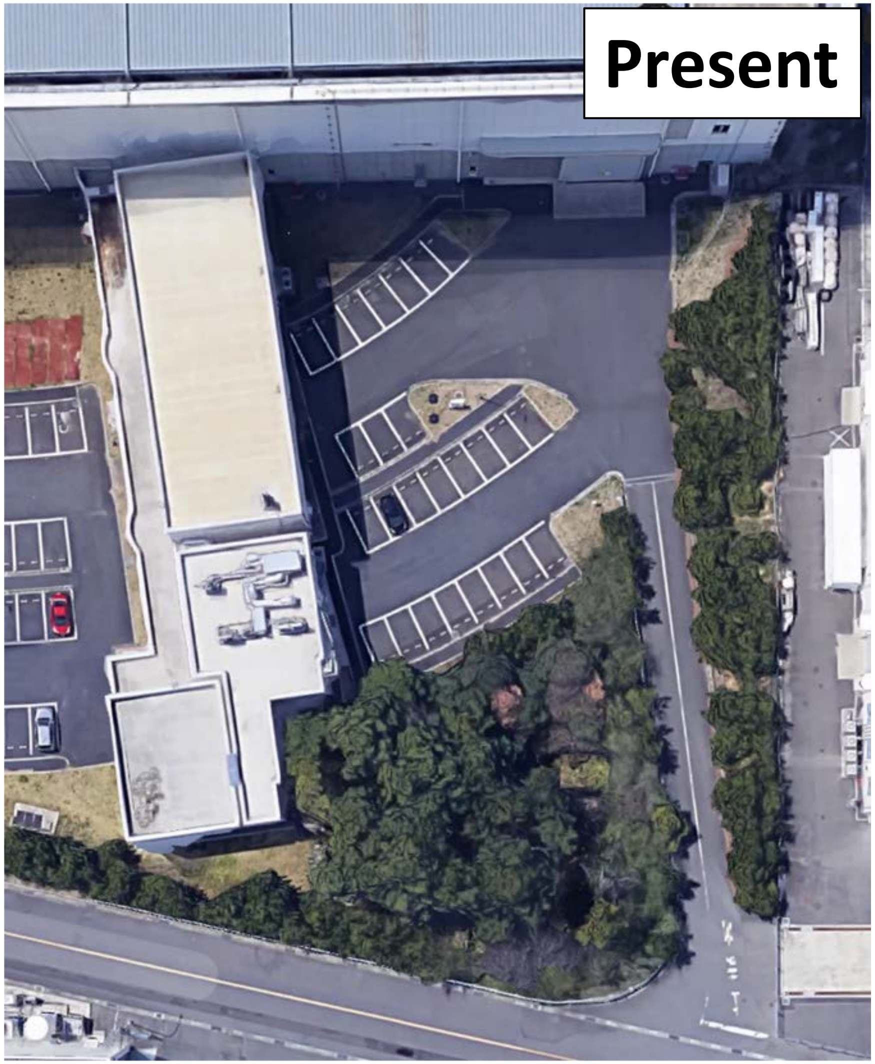
Charge distribution



Efficiency

Experimental site for g-2/EDM

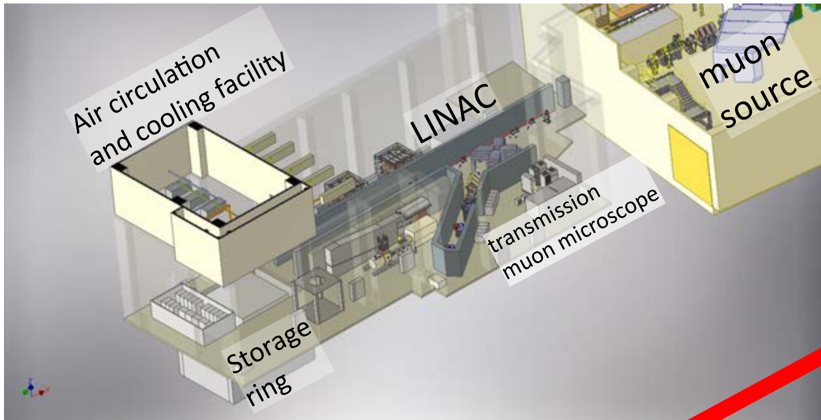
Materials and Life science Facility (MLF)



The J-PARC center taskforce endorsed the plan and construction procedure (Jan 2020).

Preparation for construction in 2020

Layout of utilities and experiment



☑ Partial removal of trees

☑ Survey of buried cultural properties (nothing found)

☑ Geotehcnical survey

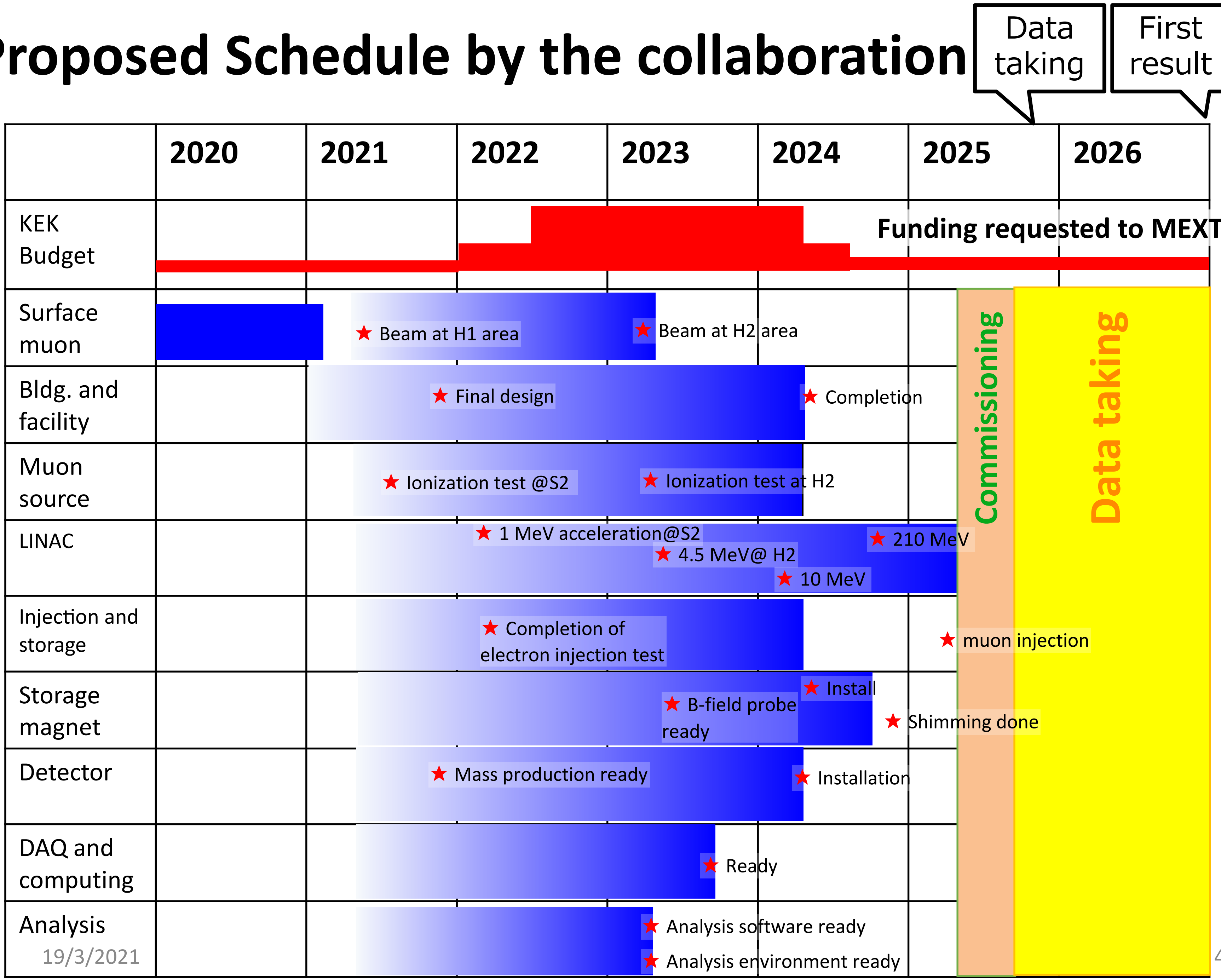
☑ Ground level survey

☑ Design of re-routing of the control cables

☑ Electric sub-station (2019)

The extension building is ready for the final design and construction.

Proposed Schedule by the collaboration

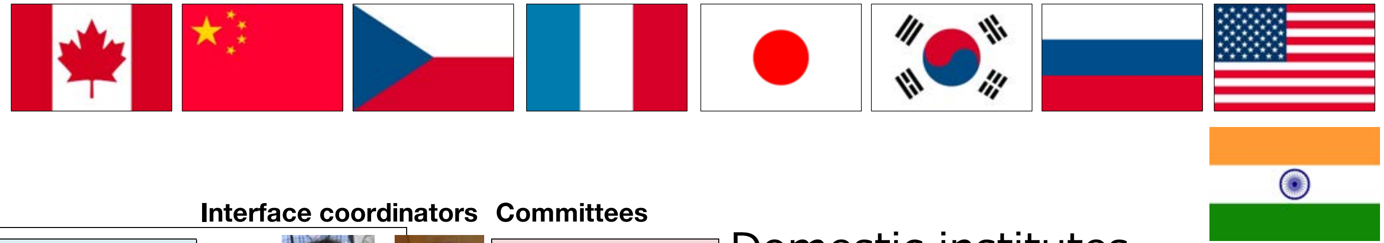


The collaboration

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

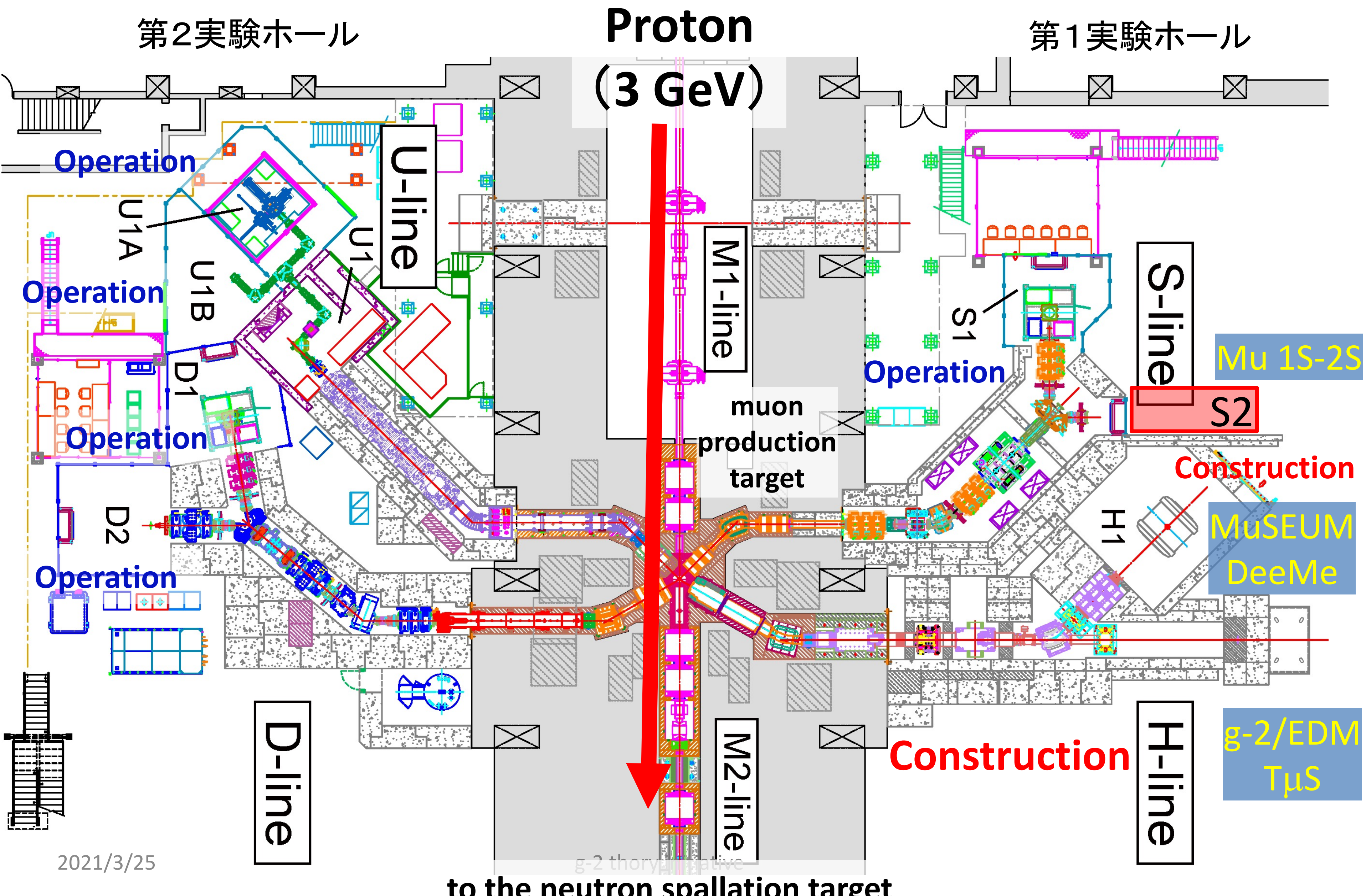
Speakers committee
chair: K.Ishida, E. Won

Publication committee
chair: S. Eidelman

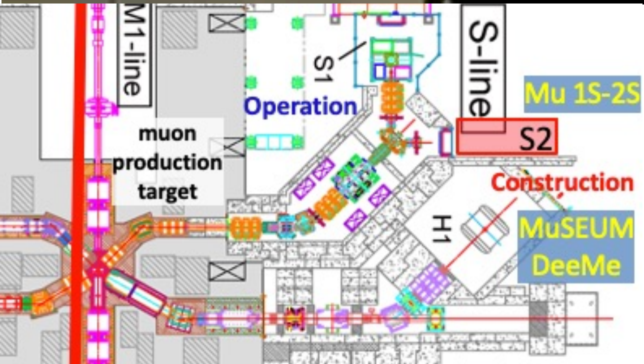
Domestic institutes：
Kyushu, Nagoya, Tohoku, Niigata, Tokyo, Ibaraki, RIKEN, JAEA, etc.

KEK: IPNS, IMSS, ACC, CRY, MEC, CRC

J-PARC Muon Science Facility (MUSE)




J-PARC


M1-line
S1
S-line
Mu 1S-2S
Operation
muon
production
target
S2
Construction
H1
MuSEUM
DeeMe

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-)**
  - **8 x BNL statistics collected**
  - **<u>First results to be announced on April 8 midnight (KEK online seminar on April 19 9:30)</u>**

- **J-PARC experiment (2025-)**
  - **New method (complementary to magic gamma experiments)**
  - **Aiming for data taking from 2025**