

Muon g-2, present and future



May 14, 2022

Physics in LHC and beyond

Tsutomu Mibe (KEK)

A reminder

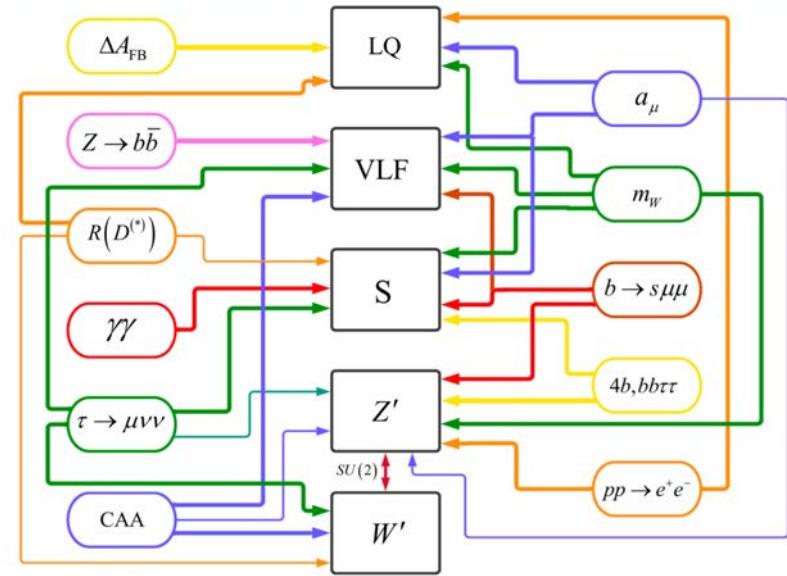
IV'. Pheno Consequences: one-loop muon g-2

- $gg \rightarrow H, A \rightarrow \mu\tau$: stringent bound on $\rho_{tt} \rho_{\mu\tau}$, so could appear soon!
 $\rho_{tt} > 0.1$ can still drive EWBG.
- $gg \rightarrow H, A \rightarrow t\bar{c}$: ρ_{tc} can dilute the above
→ $cg \rightarrow bH^+ \rightarrow \mu tbW^+, tcbW^+$ fancy LHC signatures.
WSH, Jain, Kao, Kumar, Modak, 2105.11315 (PRD'21)
- Revival of muon-related physics:
 - MEG II discovery plausible (with $\rho_{te} \sim \lambda_e$)
 - follow-up by $\mu N \rightarrow eN$, can even probe $\rho_{qq}!$
 - $\tau \rightarrow \mu\gamma$: probe $\rho_{\tau\tau} \sim \lambda_\tau!$ / $\tau \rightarrow 3\mu$: probe $\rho_{\mu\mu} \sim \lambda_\mu!$
 WSH, Kumar, 2107.14114 (EPJC'21)
- μ EDM: Same one-loop diagram, complex $\rho_{\tau\mu} \rho_{\mu\tau}$
CPV → Possibly discoverable at PSI with planned sensitivity!
WSH, Kumar, 2109.08936 (JHEP'22)
 $6 \times 10^{-23} \text{ e cm}$

N.B. This one-loop muon g-2 would make Nature appear "whimsical".

CPV-BAUD_e George W.S. Hou (NTU) Beyond-LHC 220513 22

Explanations



Page 15

Leptoquark catalogue

[cf. Angelescu, Bećirević, Faroughy, Jaffredo, Sumensari, 2103.12504;
Athron, Balazs, Jacob, Kotlarski, Stockinger, Stockinger-Kim, 2104.03691]

- Leptoquarks that do not lead to proton decay and can contribute precision measurements

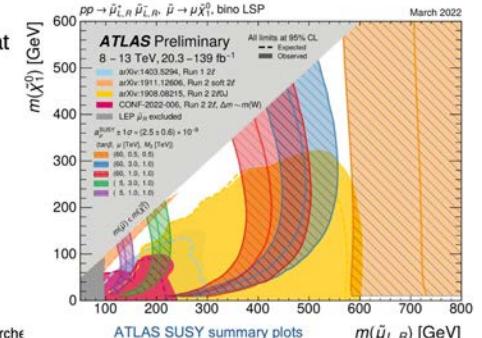
Label	Spin	Charge	R(D ^(*))	R(K ^(*))	muon g-2	M _w
S ₁ LQ	0	(̄3, 1, 1/3)	✓	Loop	✓	With S ₃
U ₁ LQ	1	(3, 1, 2/3)	✓	✓	✗	✗
R ₂ LQ	0	(3, 2, 7/6 [1/6])	✓	Loop	✓	Small
V ₂ LQ	1	(̄3, 2, 5/6)	Small	Electron	Small	✓
S ₃ LQ	0	(̄3, 3, 1/3)	✗	✓	✗	With S ₁
U ₃ LQ	1	(3, 3, 2/3)	✗	✓	✗	?

B anomaly hunting at the LHC: tau + b + missing search for leptoquarks

Teppi Kitahara (Nagoya Univ.), Physics in LHC and Beyond, May 13, 2022, Matsue

Search for slepton and chargino production

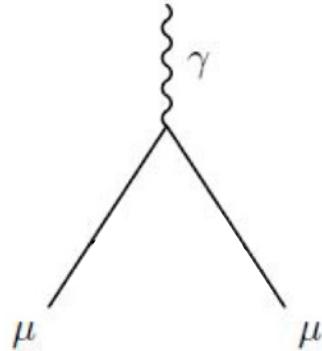
- ATLAS has searched for the production of sleptons and charginos that decay into leptons
- The analysis is optimised for mass differences around m_w
- In general the observed event yields agree well with the prediction
- This allows to fill wholes from the previous analyses
- Together with the previous analyses this puts strong constraints on the regions that could explain the g-2 anomaly



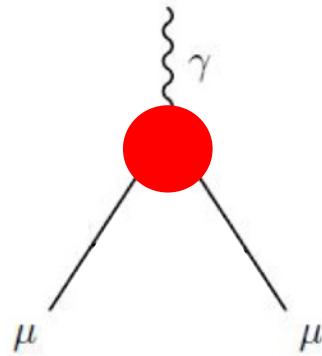
Anomalous magnetic moment (g -2)

3

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



- In quantum field theory, g factor gets corrections:

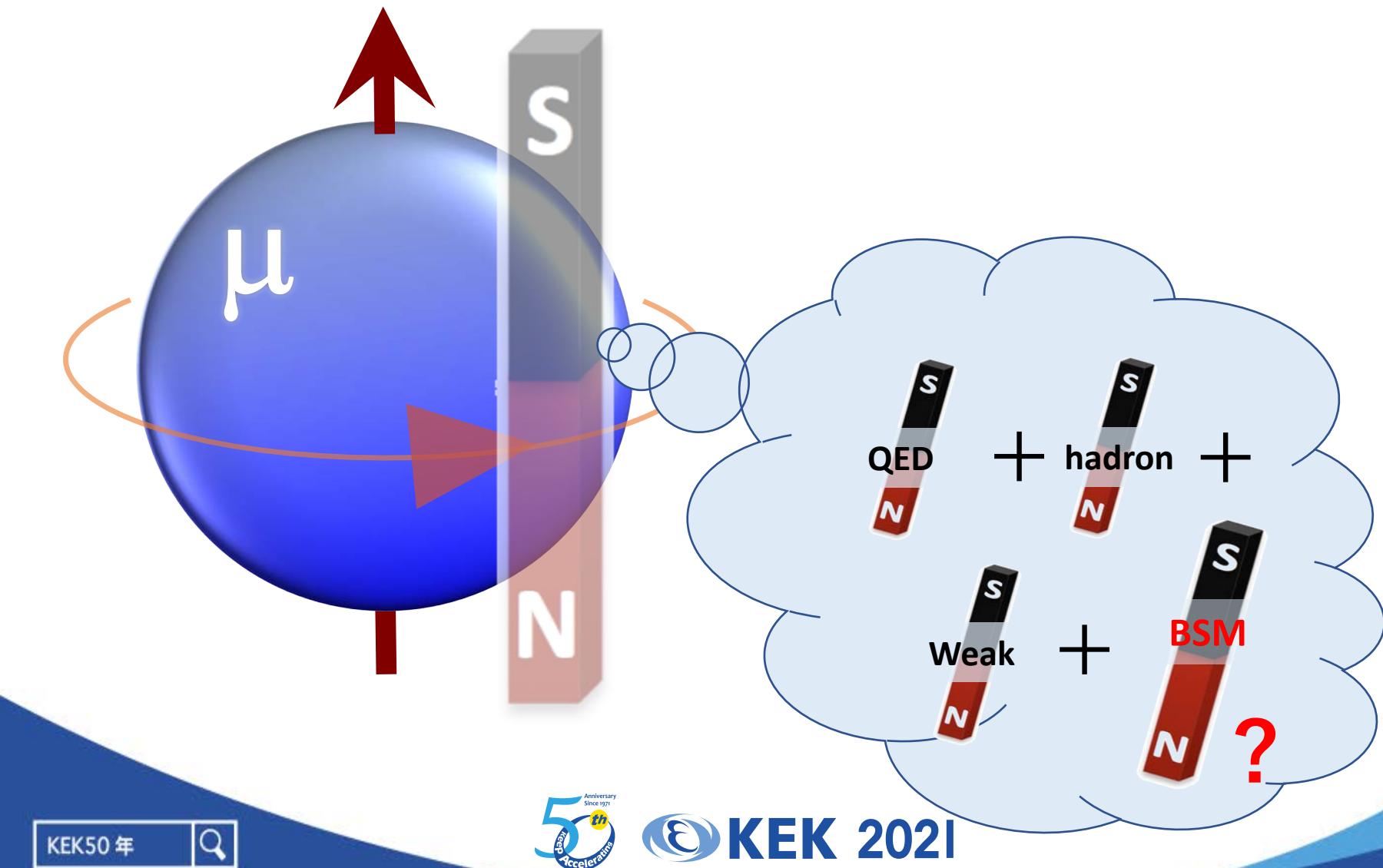


Anomalous magnetic
moment $a = (g-2)/2$

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

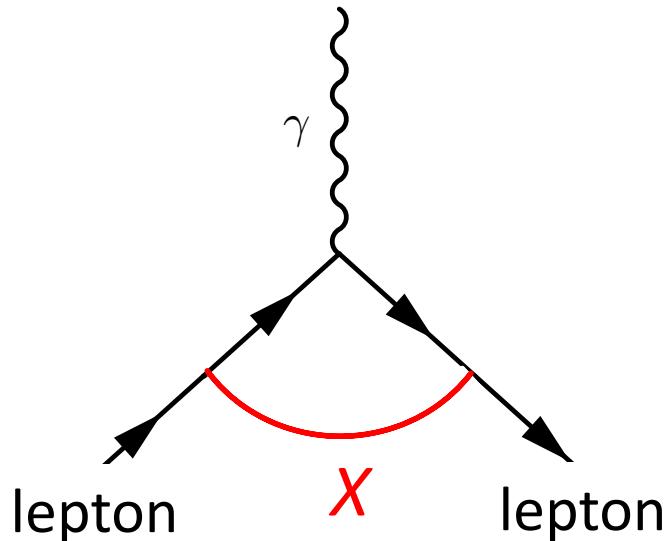
Anomalous magnetic moment ($g-2$)

4



Lepton g-2

- Contributions to lepton g-2 can be written as



$$a_l(X) \sim C_X \left(\frac{m_l}{\Lambda_X} \right)^2$$

C_x : Coupling strength
 Λ : Mass Scale

$$\left(\frac{m_\mu}{m_e} \right)^2 \sim 43,000$$

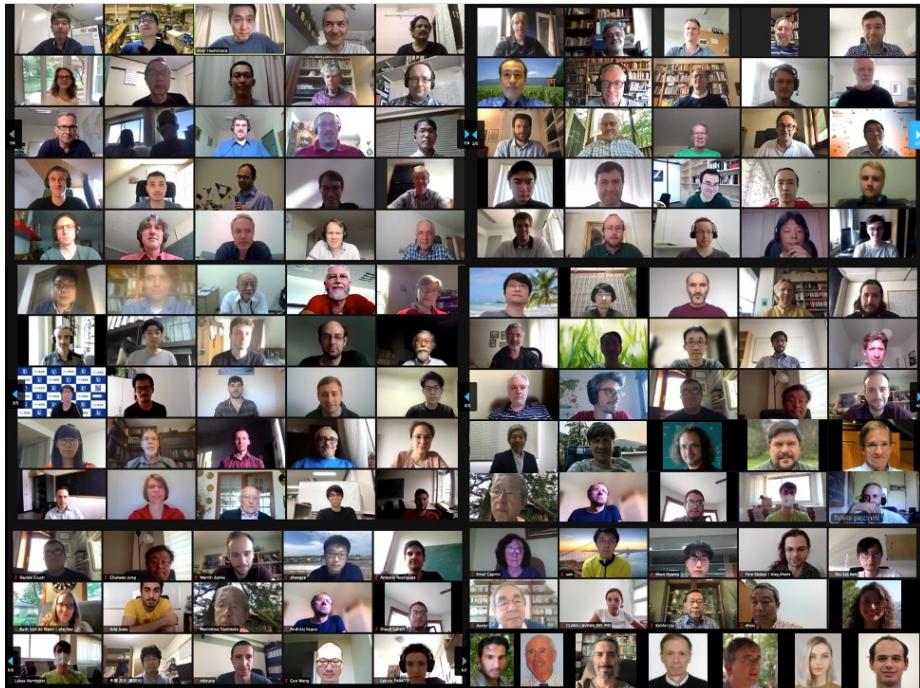
Much larger contributions to muon than electron.

$$\left(\frac{m_\tau}{m_\mu} \right)^2 \sim 170$$

Muon g-2 theory initiative (since 2017)

A group of world experts come together aiming for a precise determination of muon g-2 in the standard model.

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



The white paper
 Phys. Rep. 887 (2020) 1-166
 (Submitted 15 June
 Accepted 29 July
 Published 14 Aug)



Muon g-2 theory initiative workshop (hosted by KEK)
 June 28 – July 2nd, 2021 <https://www-conf.kek.jp/muong-2theory/>



KEK 2021



The anomalous magnetic moment of the muon in the Standard Model

O. Aoyama^{1,2,3}, N. Aasmussen⁴, M. Benayoun⁵, J. Bijnens⁶, T. Blum^{7,8}, M. Bruno⁹, L. Caprini¹⁰, C.M. Carlson Calame¹¹, M. Czakoc^{12,13}, G. Colangelo^{14*}, F. Cudell¹⁵, H. Czyz¹⁶, J. Darmont¹⁷, N. Davier¹⁸, C.T.H. Davies¹⁹, M. Della Morte²⁰, S. Descotes-Genon²¹, A.S. Descotes-Genon²², D. Di Giusti²³, M. Golterman²⁴, Steven Gottlieb²⁵, V. Gómez²⁶, G. Gómezsteiner²⁷, D. Guetta²⁸, M. Hirschstein²⁹, G. Herdoiza³⁰, D.W. Hertzog³¹, A. Hoecker³², M. Hayakawa³³, G. Hiller³⁴, D. Hoyle³⁵, R.J. Hughes³⁶, I. Ignatov³⁷, T. Inanaga³⁸, E. Jenkins³⁹, J. Jia⁴⁰, H. Keshavarzi⁴¹, T. Kinoshita⁴², B. Kubis⁴³, A. Kupiela⁴⁴, A. Kuspe⁴⁵, L. Laub⁴⁶, C. Lehner^{47,48}, L. Lellouch⁴⁹, I. Logashenko⁵⁰, B. Malaezu⁵¹, K. Maltman⁵², M.K. Marinovich⁵³, P. Meier⁵⁴, A.S. Mereghetti⁵⁵, H.B. Meyer⁵⁶, T. Mibe⁵⁷, M. Miura⁵⁸, S.E. Müller⁵⁹, M. Nauenberg⁶⁰, D. Neufeld⁶¹, A. Nyffeler⁶², V. Palencia⁶³, M. Passera⁶⁴, E. Pérez del Rio⁶⁵, S. Peris^{66,67}, A. Portelli⁶⁸, M. Procura⁶⁹, C.F. Redmer⁷⁰, B.L. Roberts⁷¹, P. Sánchez-Puertas⁶⁴, S. Serednyakov⁷², B. Shwartz⁷³, S. Simula⁷⁴, D. Stocino⁷⁵, J. Stricker⁷⁶, G. von Gersdorff⁷⁷, P. Stoffer⁷⁸, T. Tiefenbacher⁷⁹, V. Veltman⁸⁰, M. Veltman⁸¹, G. von Hippel⁸², H. Wittig^{83,84}, Z. Zhang⁸⁵, M.N. Achasov⁸⁶, A. Bashir⁸⁷, G. Cardoso⁸⁸, B. Chakraborty⁸⁹, E.-H. Choi⁹⁰, J. Charles⁹¹, A. Crivellin⁹⁴, N. Dernicka⁹², A. Désilets⁹³, C. Delaunay⁹⁴, C.A. Dominguez⁹⁵, A.E. Dorokhov⁹⁶, V.P. Dovbush⁹⁷, G. Eichmann⁹⁸, M. Ewerz⁹⁹, C.S. Fischer¹⁰⁰, E. Gámiz¹⁰¹, Z. Gelzer¹⁰², J.R. Green¹⁰³, S. Guellati-Khelifa¹⁰⁴, D. Hattori¹⁰⁵, N. Hermannson-Truedsson¹⁰⁵, S. Holt¹⁰⁶, B. Hörl¹⁰⁷, M. Knecht¹⁰⁸, J. Koponen¹⁰⁹, A.S. Kronfeld¹¹⁰, J. Laiho¹¹¹, J. Laiho¹¹², P.B. Mamedov¹¹³, W.J. Marciano¹¹⁴, C. Mertens¹¹⁵, D. Mihaila¹¹⁶, J. Miquel¹¹⁷, J. Nefkens¹¹⁸, A.S. Pivovarov¹¹⁹, K. Ottrott¹²⁰, V. Pauk¹²¹, E. Radzbabov¹²², E. de Rafael¹²³, K. Ray¹²⁴, A. Rischi¹²⁵, A. Rodriguez-Sánchez¹²⁶, P. Roig¹²⁷, T. San José^{128,129}, E.P. Solodov¹²², R. Sugar⁸¹, K. Yu. Totsuka¹³⁰, A. Vainshtein¹³¹, A. Valencia Avilés-Casco¹³², A. Zhitnikov¹³³.

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Breakdown of SM contributions

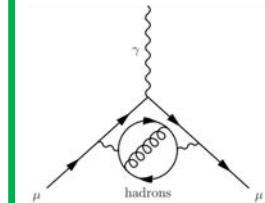
The “white paper”, Phys. Rep. 887, 1 (2020)

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)

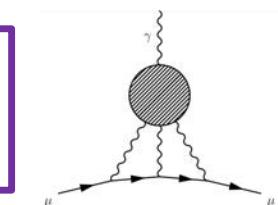
[370 ppb]

Contribution	Value $\times 10^{11}$
HVP LO ($e^+ e^-$)	6931(40)
HVP NLO ($e^+ e^-$)	-98.3(7)
HVP NNLO ($e^+ e^-$)	12.4(1)
HVP LO (lattice, uds)	7116(184)

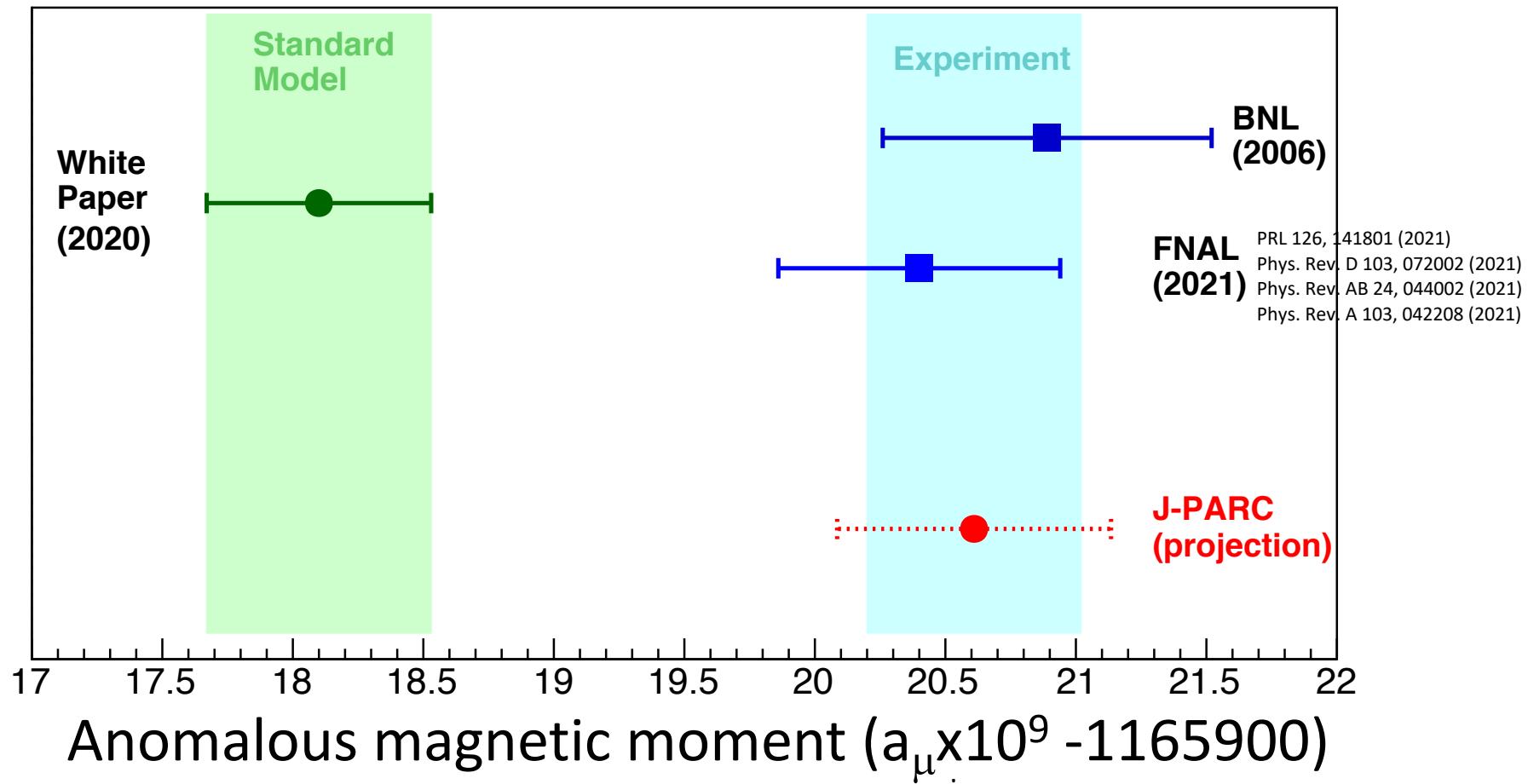
parts per billion = 10^{-9}



HLbL (phenomenology)	92(19)
HLbL NLO (phenomenology)	2(1)
HLbL (lattice, uds)	79(35)
HLbL (phenomenology + lattice)	90(17)



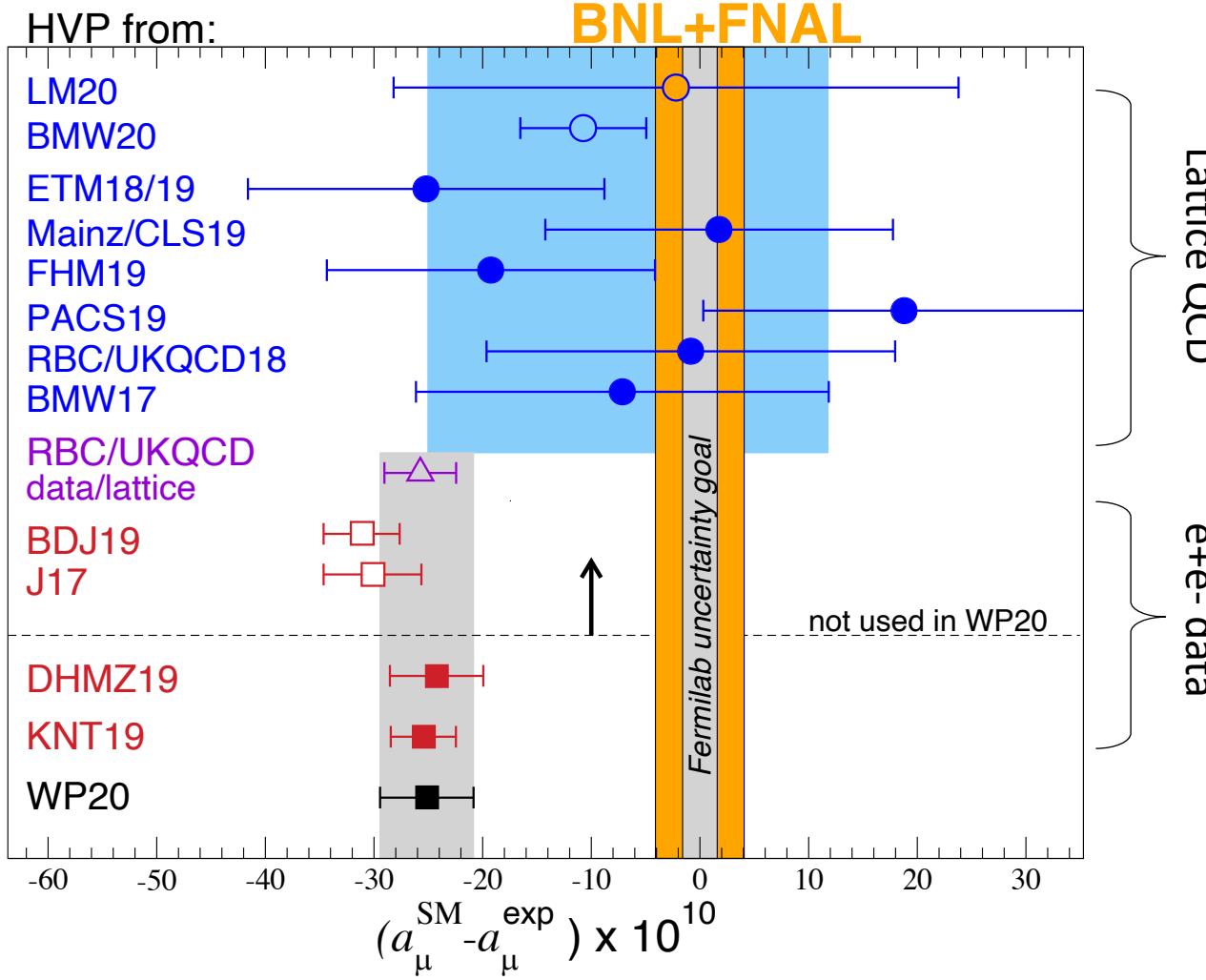
Current status of muon g-2



The FNAL run 1 result

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

Hadronic vacuum polarization

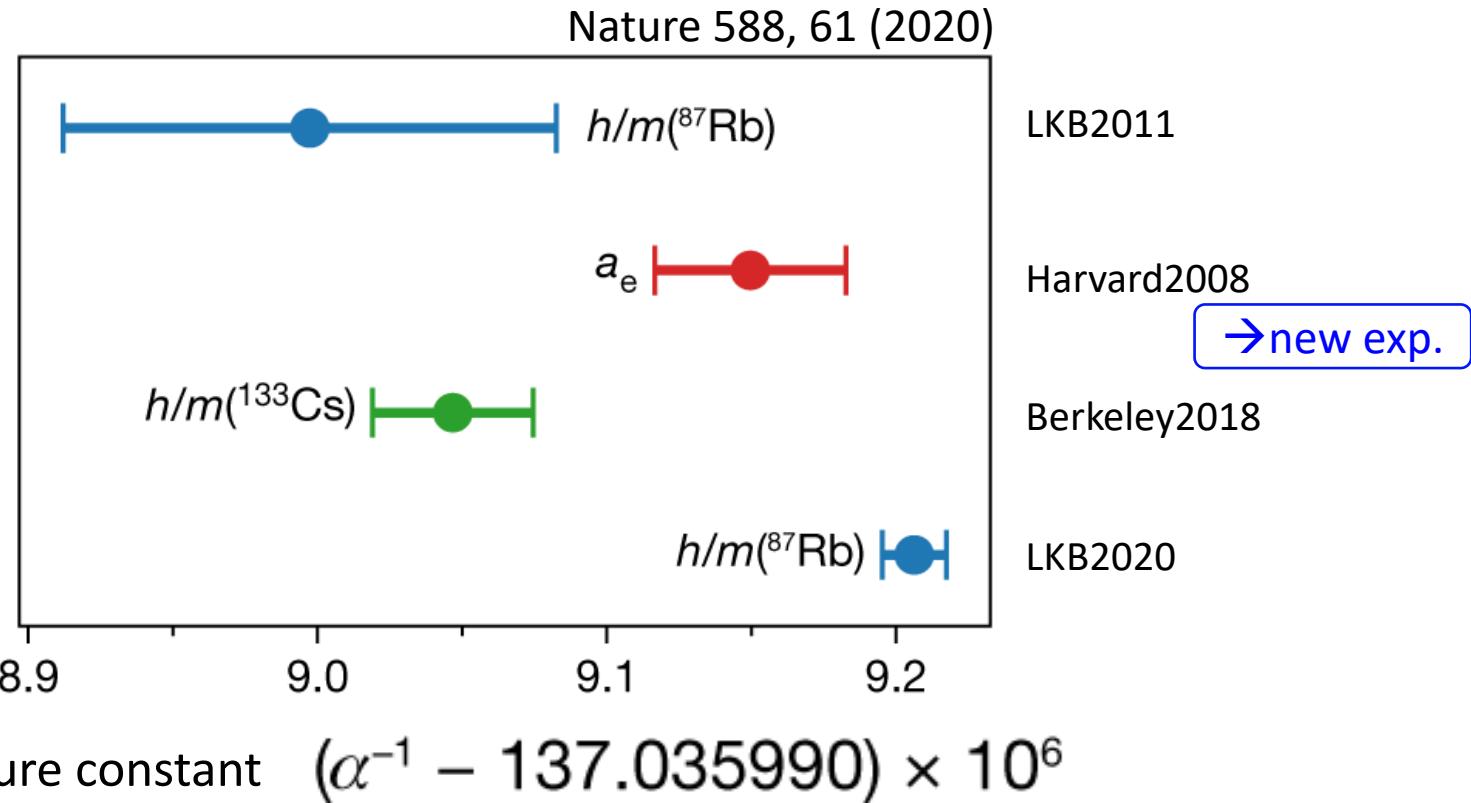


Crosscheck of the results from lattice groups is in progress.

Future inputs from Belle II (e^+e^-) MUonE ($\mu^+\mu^-$) ...



Electron g-2 (a_e) and fine structure constant 10



Translation of tension in α into a_e

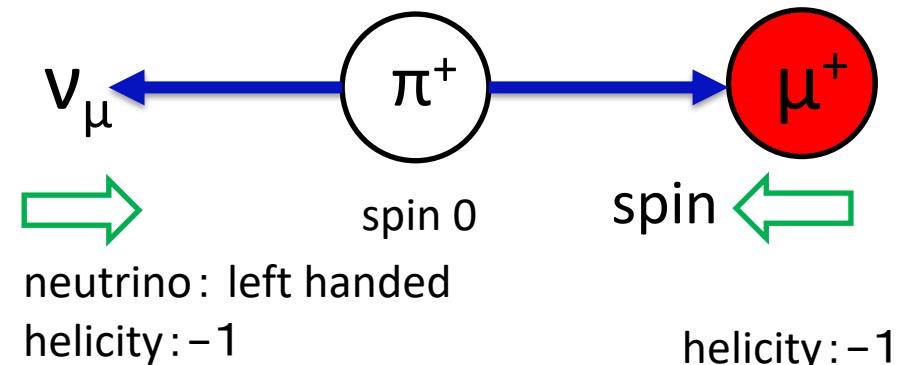
$$\Delta a_e = a_e(\text{exp}) - a_e(\text{Berkeley2018}) = -8.8 \pm 3.6 \times 10^{-13} (-2.5\sigma)$$

$$\Delta a_e = a_e(\text{exp}) - a_e(\text{LKB2020}) = 4.6 \pm 3.0 \times 10^{-13} (+1.6\sigma)$$

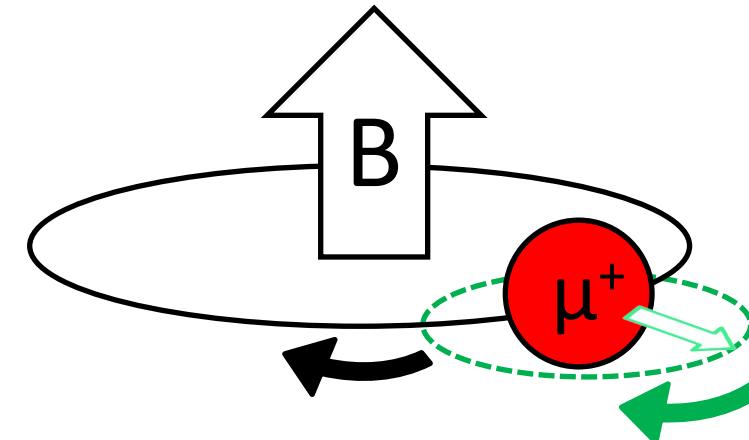
$$\Delta a_e(\text{scaled from } \Delta a_\mu) = \Delta a_\mu(\text{exp-SM}) \times (m_e/m_\mu)^2 = 0.6$$

Three steps of g-2 & EDM measurement 11

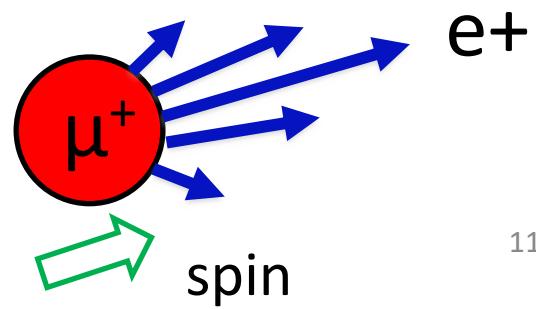
1. Prepare a polarized muon beam.



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



3. Measure decay positron



Spin precession of muon

12

In uniform magnetic field, muon spin rotates ahead of momentum due to $g-2 \neq 0$

Spin precession vector w.r.t momentum :

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

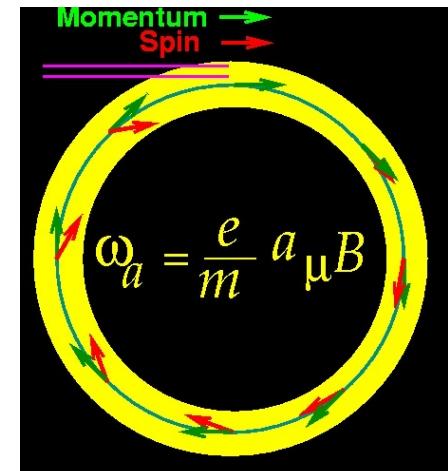
g-2 precession
in B-field

g-2 precession in
motional B-field

EDM precession

BNL/FNAL approach
 $\gamma=30$ ($P=3$ GeV/c)

J-PARC approach
 $E = 0$ at any γ



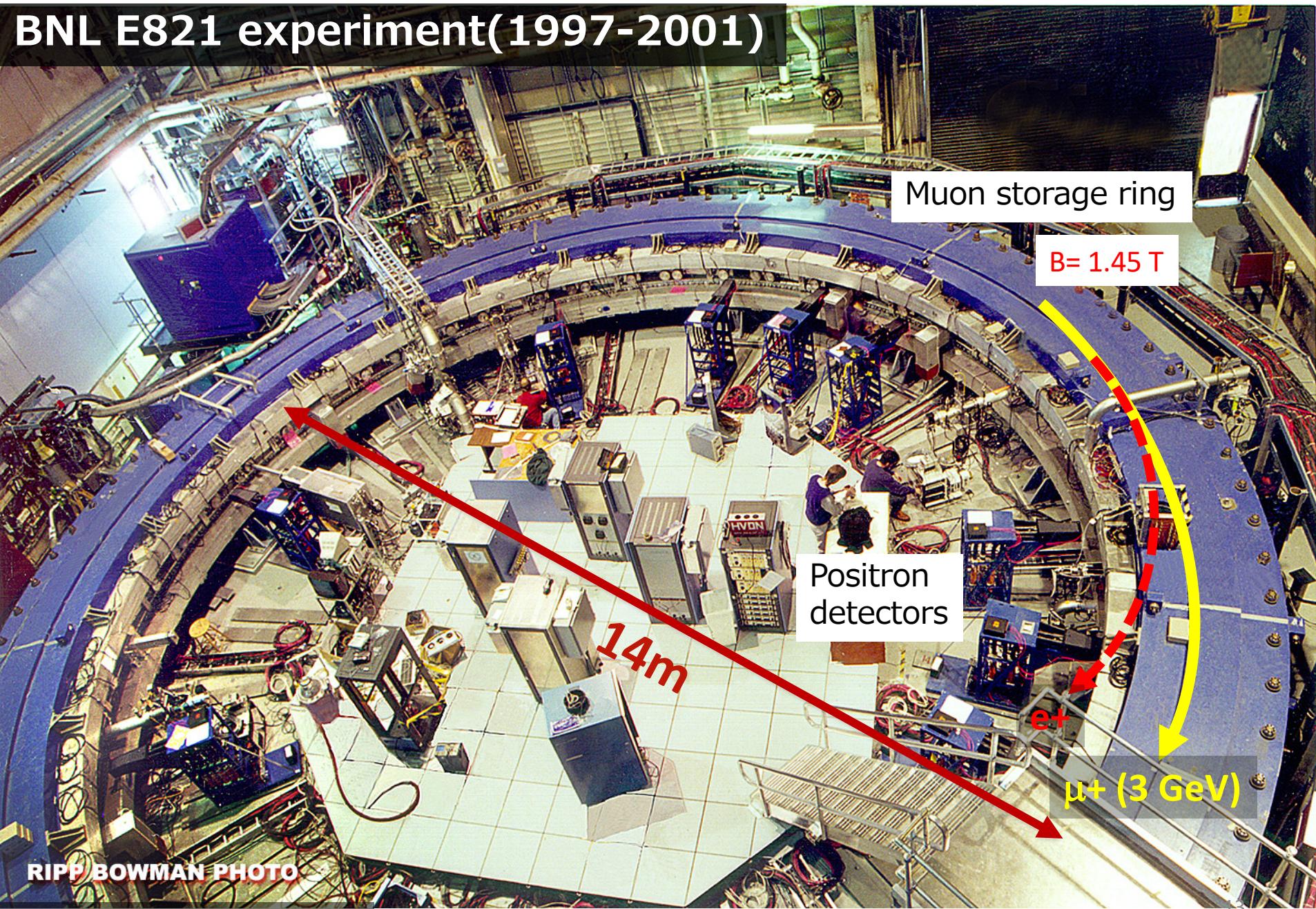
$$\vec{\omega} = -\frac{e}{m} \left[a_\mu \vec{B} + \frac{\eta}{2} \left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right]$$

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

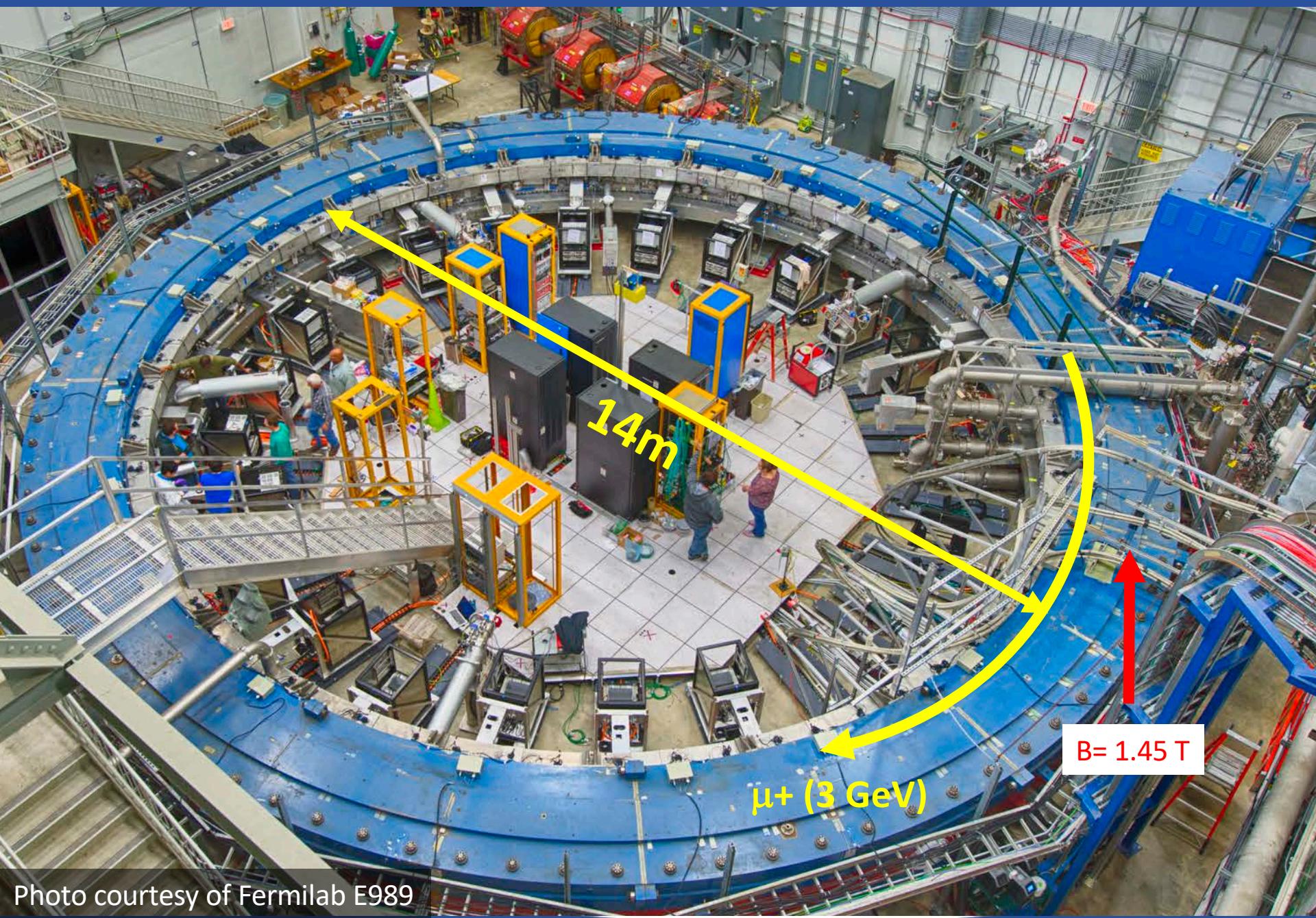
BNL E821 experiment(1997-2001)



RIPP BOWMAN PHOTO

Photo courtesy of BNL E821

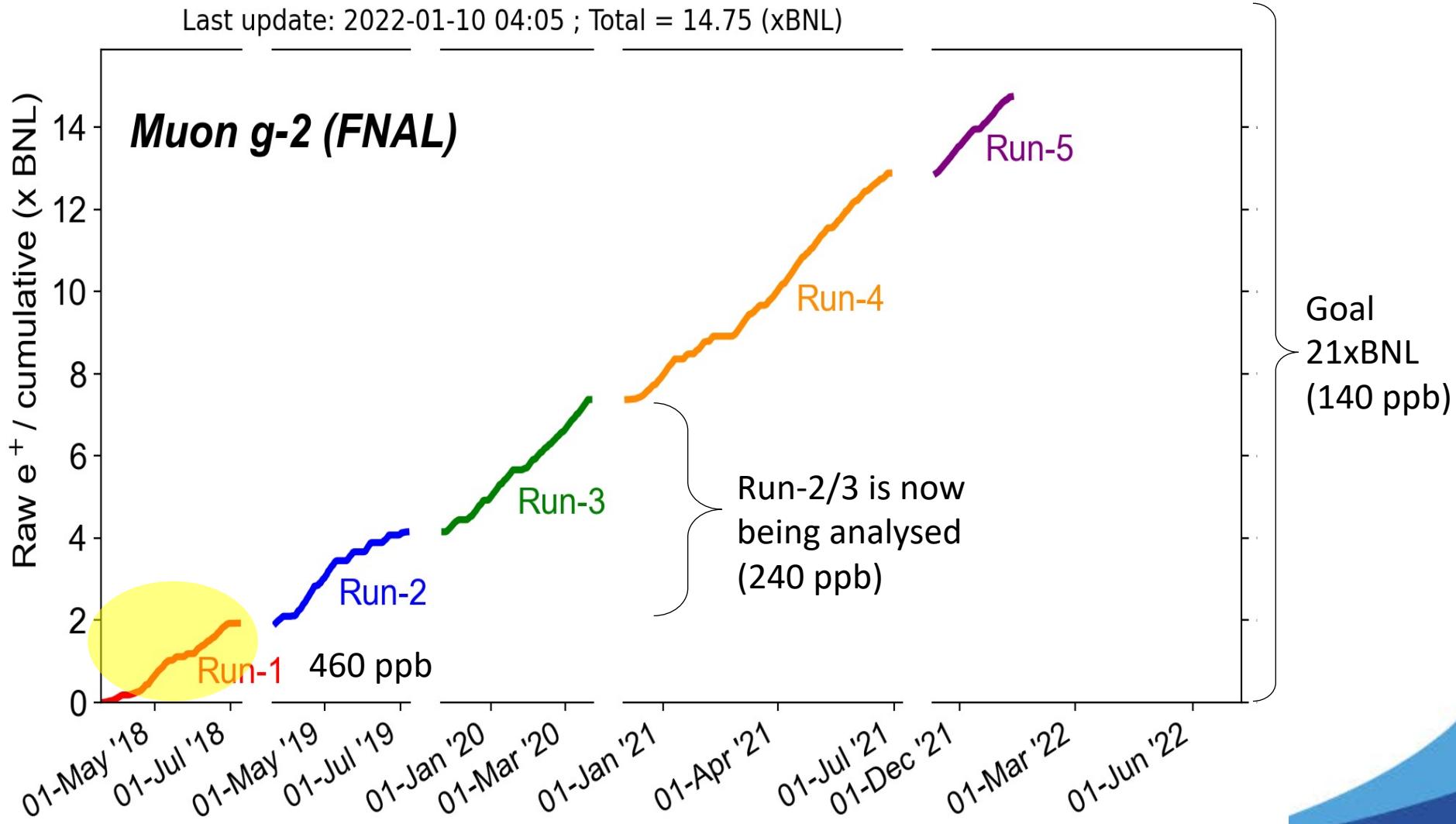
Fermilab muon g-2 experiment (2018-)



FNAL g-2 : outlook

15

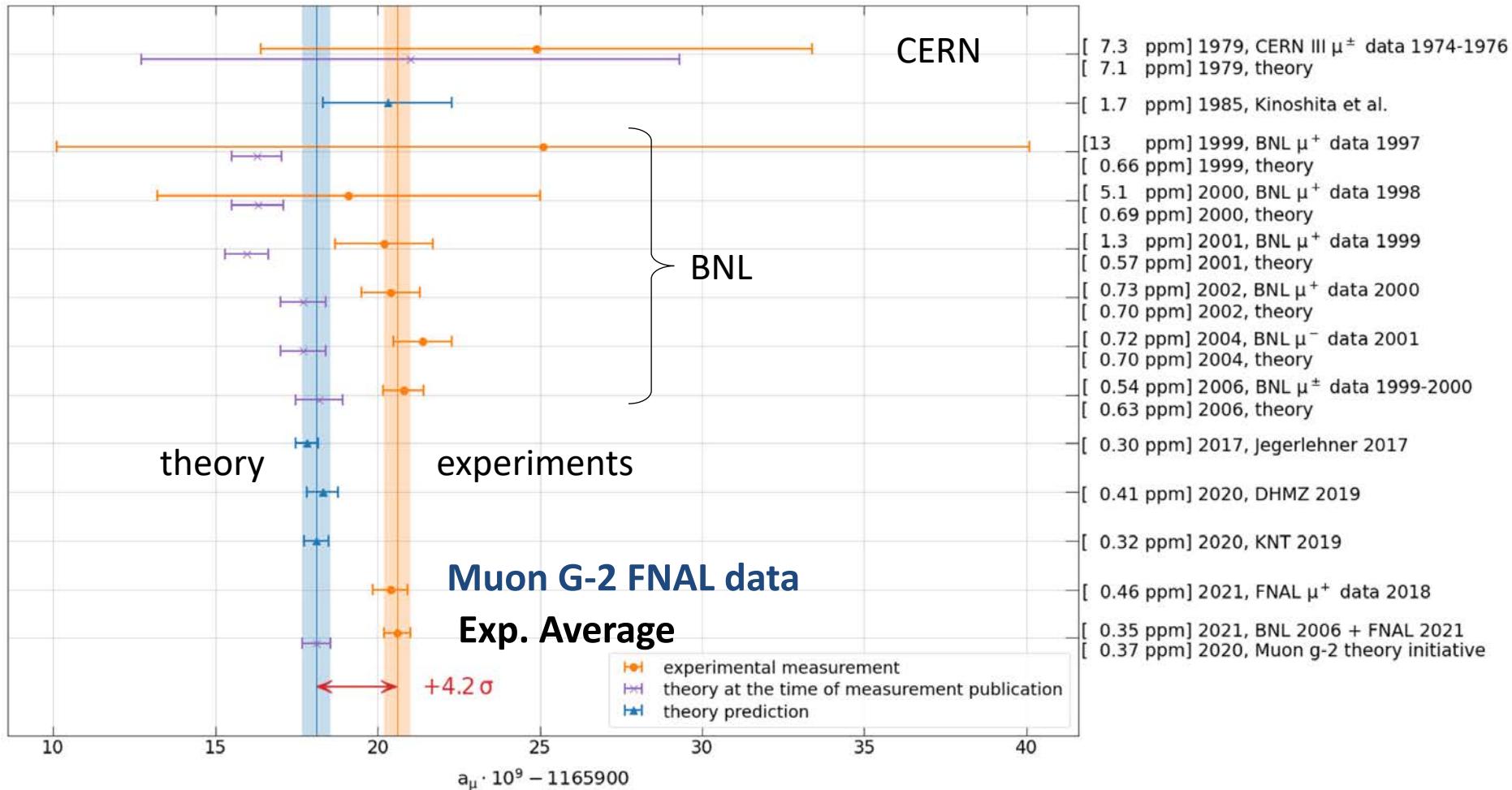
Based on Mark Lancaster's slide
(LP2021)



Why new experiment?

History of muon anomaly measurements and predictions

G. Venanzoni (Apr 2021)

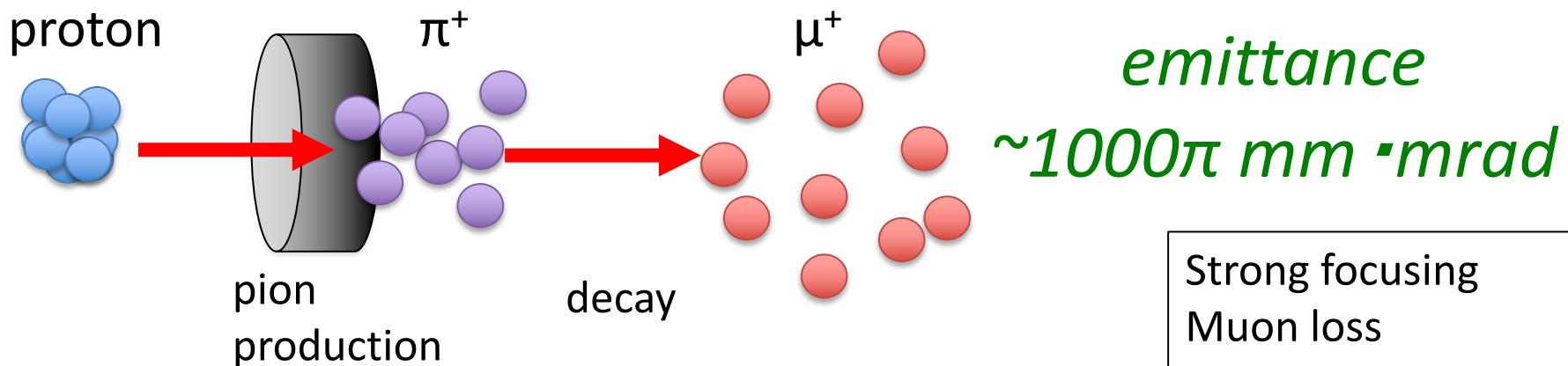


Dominated by the magic gamma experiments (BNL+FNAL).

→Independent measurements are important.

Conventional muon beam

17



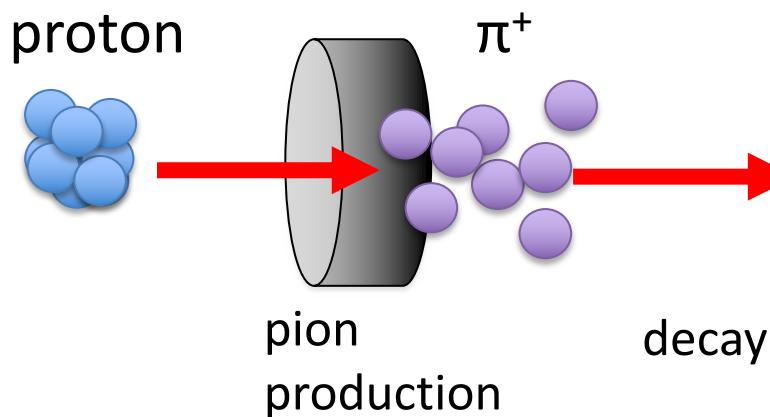
Strong focusing
Muon loss
BG π contamination

Source of systematic
uncertainties



Muon beam at J-PARC

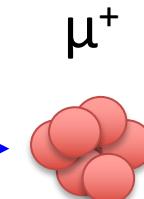
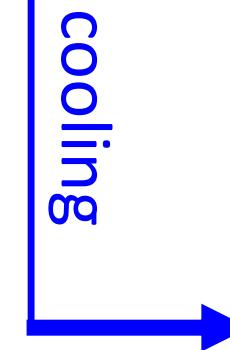
18



emittance
 $\sim 1000\pi \text{ mm} \cdot \text{mrad}$

Strong focusing
Muon loss
BG π contamination

Source of systematic
uncertainties



emittance
 $1\pi \text{ mm} \cdot \text{mrad}$

Reaccelerated
thermal muon

Free from any of these



Muon g-2/EDM experiment at J-PARC

J-PARC (MLF)

proton
(3 GeV)



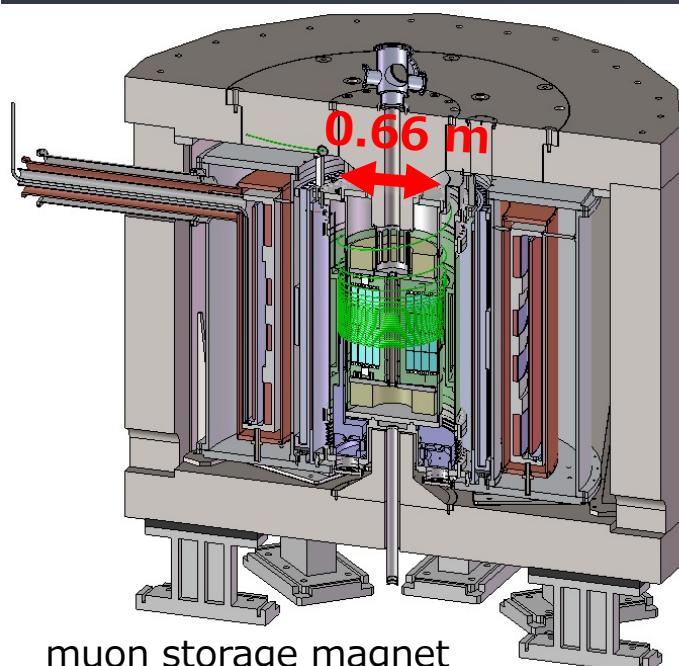
μ^+ (4 MeV)
Surface muon
 μ^+ (25 meV)
muon cooling

muon LINAC

μ^+ (210 MeV)
injection

Storage magnet

0.66 m

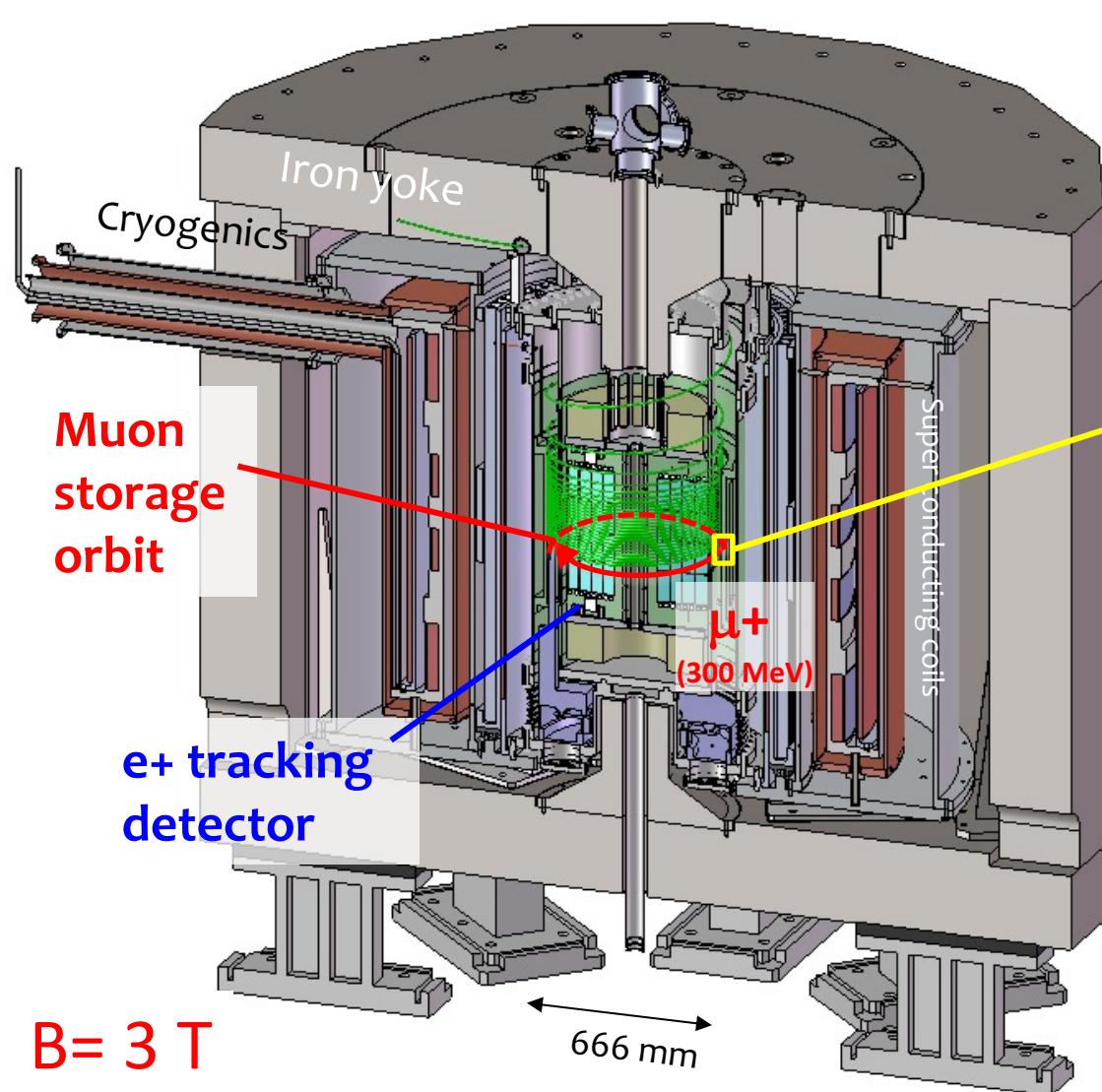


Goals:

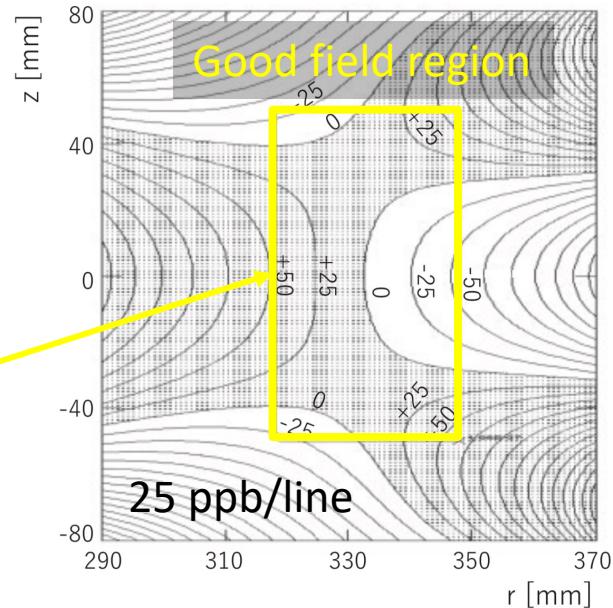
g-2 450 ppb (\sim BNL/FNAL run 1)
EDM $1.5 \times 10^{-21} \text{ e}\cdot\text{cm}$ (x70 better)

Muon storage magnet and detector

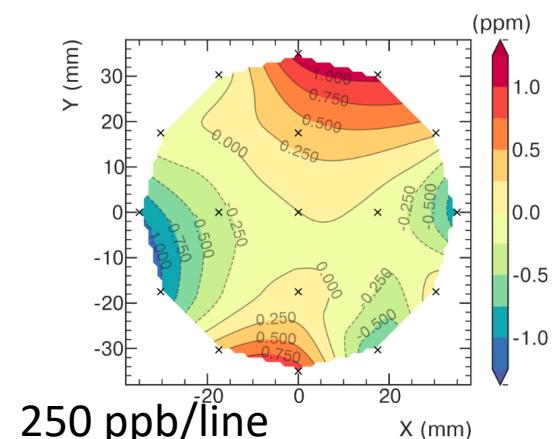
20



Calculated average field uniformity

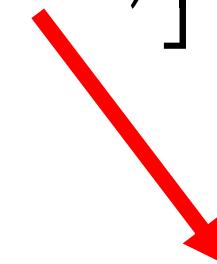
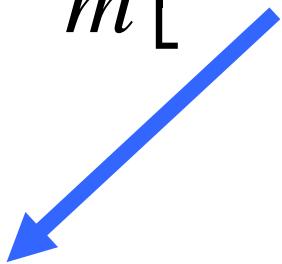


FNAL Run 1 PRA 103, 042208 (2021)

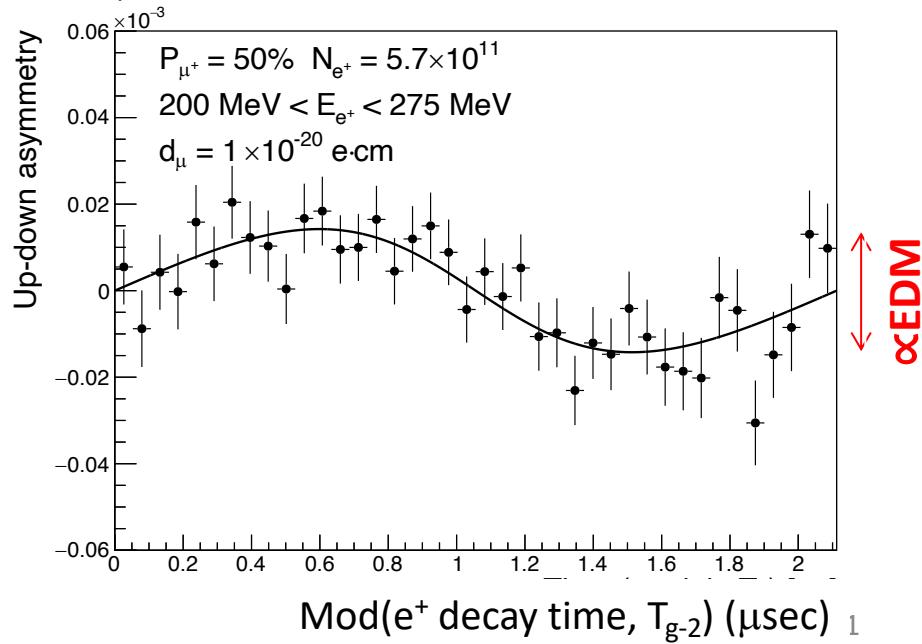
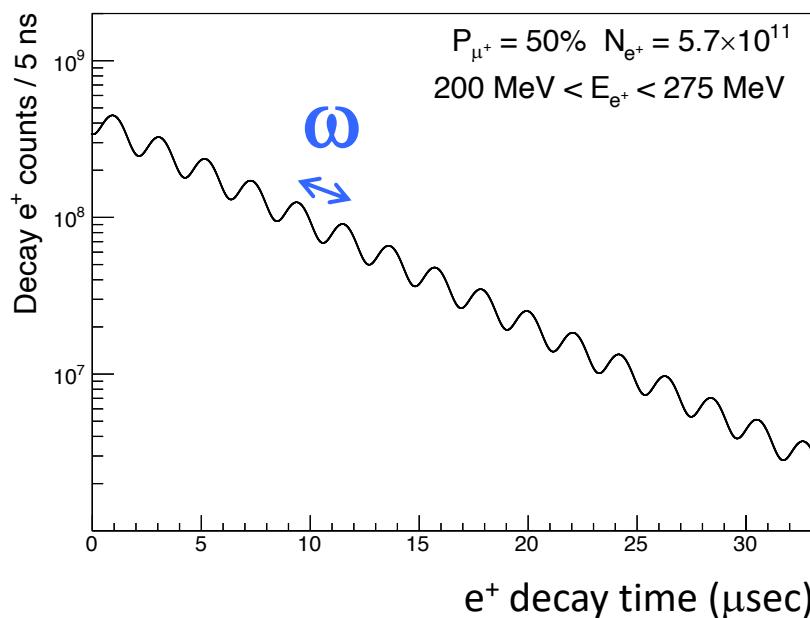


Simultaneous measurements: g-2, EDM

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



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



Comparison of g-2 experiments

22

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

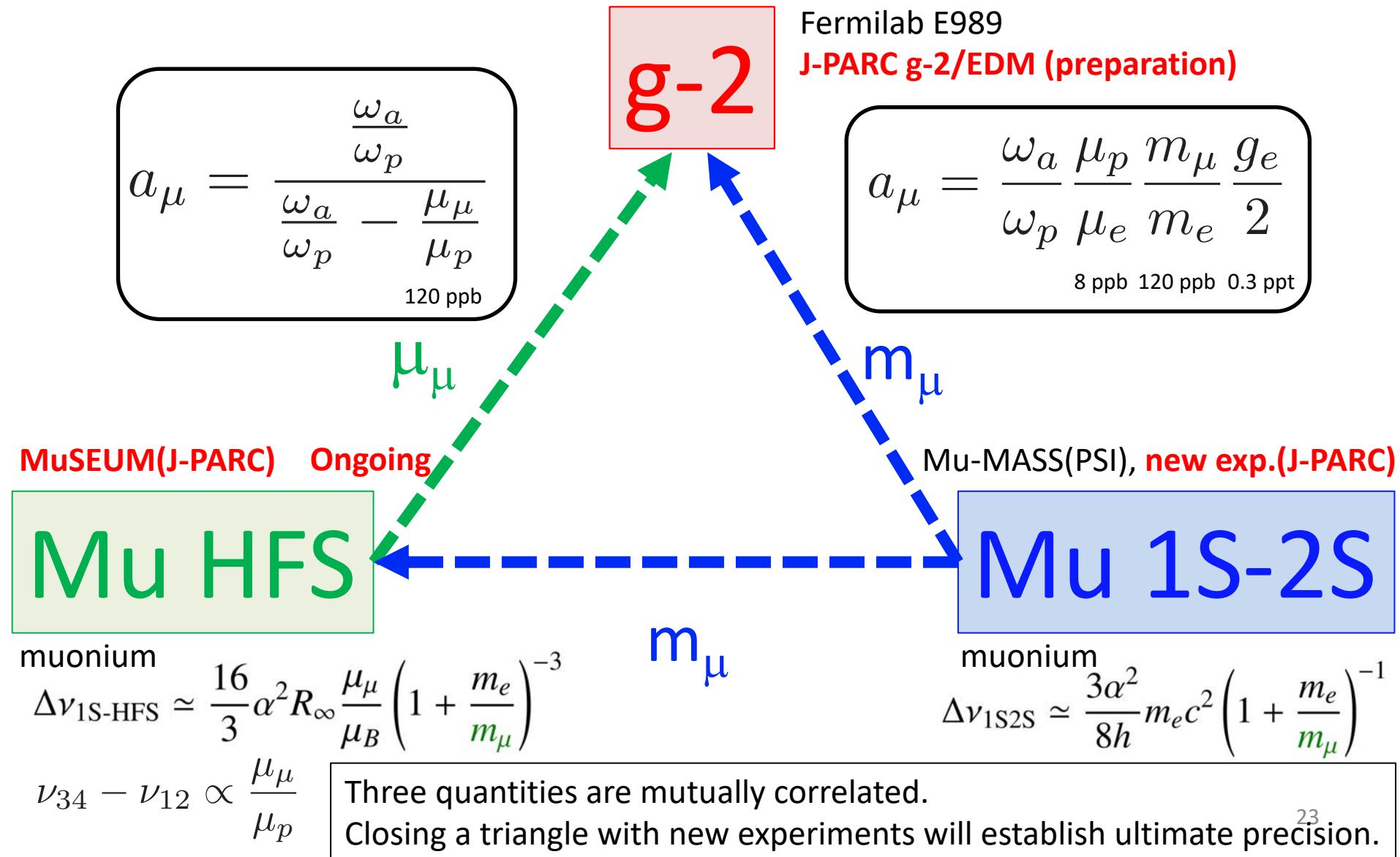
	BNL-E821	Fermilab-E989	Our experiment
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz γ	29.3		3
Polarization	100%		50%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric quadrupole		Very weak magnetic
Cyclotron period	149 ns		7.4 ns
Spin precession period	4.37 μ s		2.11 μ s
Number of detected 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.)	$0.2 \times 10^{-19} e \cdot \text{cm}$	—	$1.5 \times 10^{-21} e \cdot \text{cm}$
(syst.)	$0.9 \times 10^{-19} e \cdot \text{cm}$	—	$0.36 \times 10^{-21} e \cdot \text{cm}$

Completed

Running

In preparation

g-2 and muonium experiments 23



g-2 and muonium experiments 24 at J-PARC

Lead by K. Shimomura (IMSS/KEK)

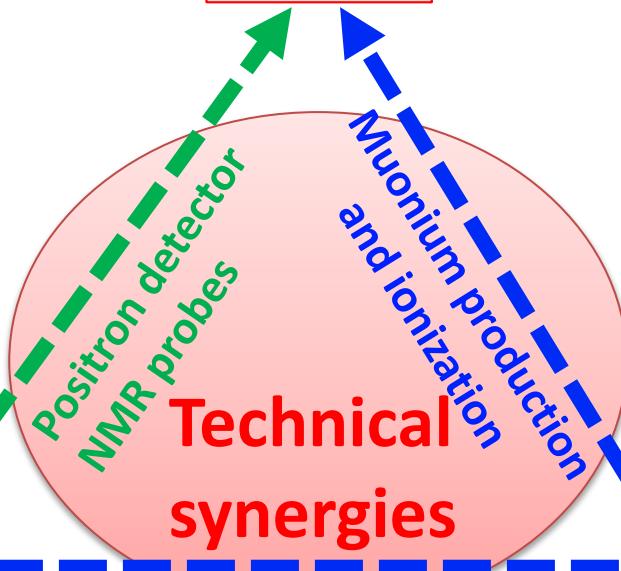
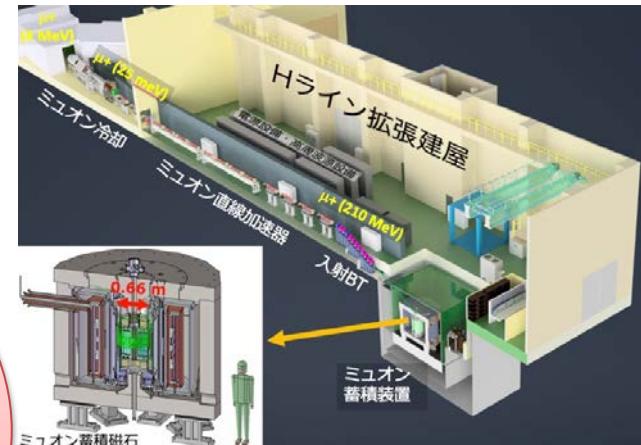


Mu HFS

g-2

Fermilab E989

J-PARC g-2/EDM (preparation)



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

Mu 1S-2S

In preparation

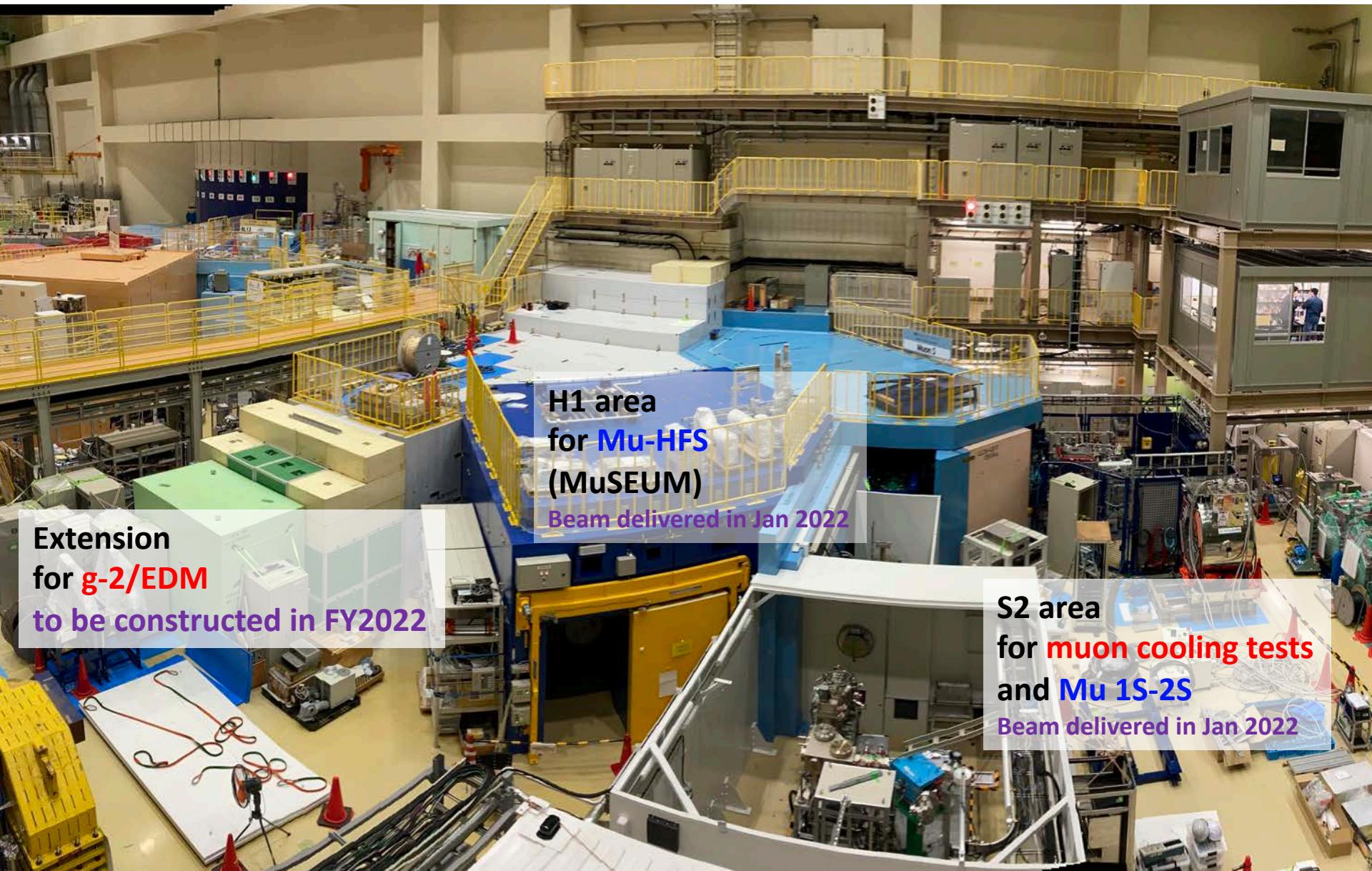
Lead by S. Uetake (Okayama)



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

Experimental areas for experiments

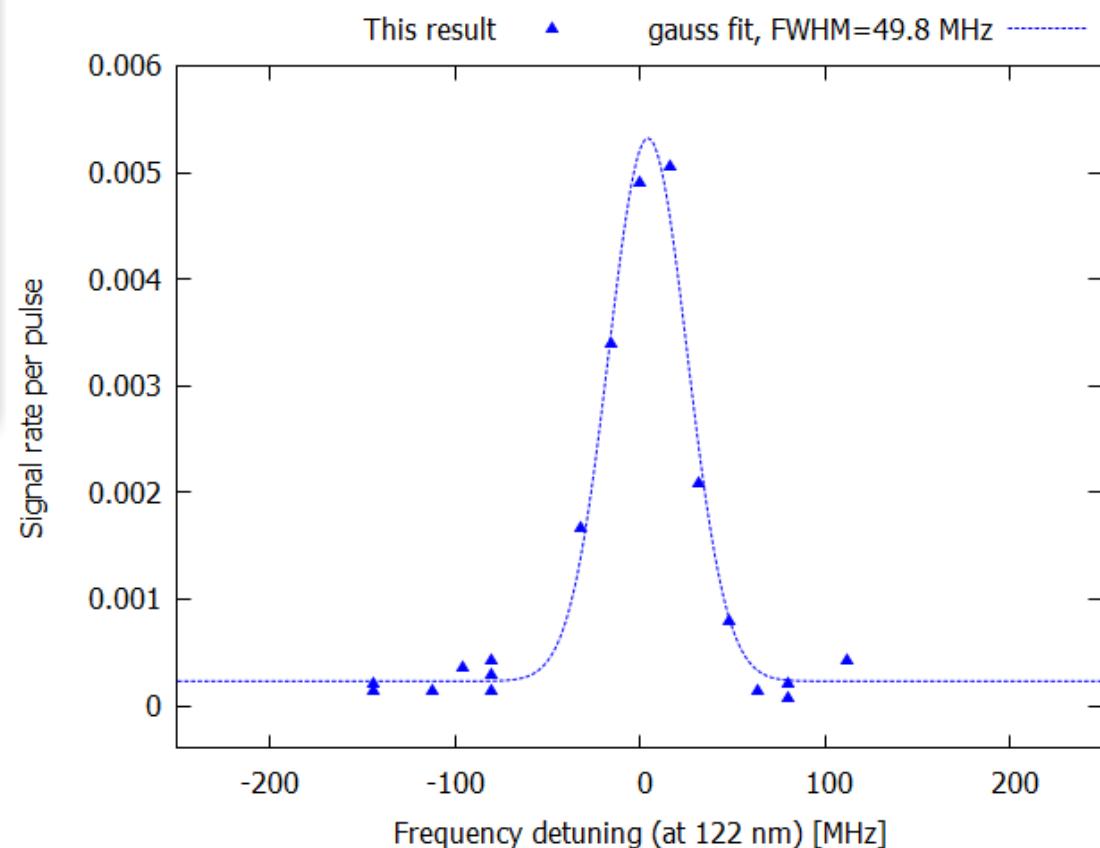
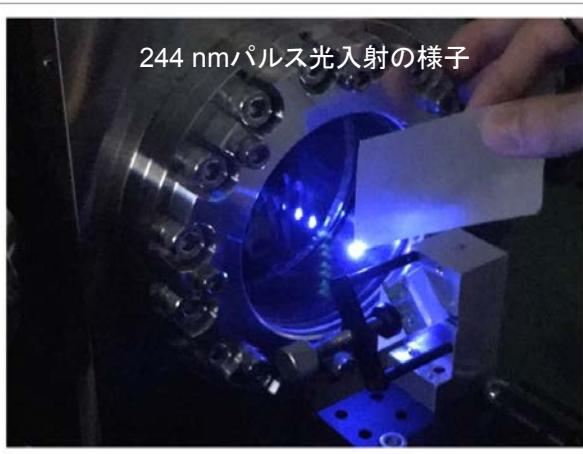
25



Mu ionization via 1S-2S: a demonstrator of muon source

Slide by Yamamoto, JPS 2022

2022/3/3 共鳴初観測成功



Intended schedule and milestone

27

	2021	2022	2023	2024	2025	2026	2027 and beyond
KEK Budget							
Surface muon		★ Beam at H1 area		★ Beam at H2 area			
Bldg. and facility			★ Final design			★ Completion	
Muon source	★ Ionization test @S2			★ Ionization test at H2			
LINAC		★ 80keV acceleration@S2		★ 4.3 MeV@ H2		★ fabrication complete	★ 210 MeV
Injection and storage			★ Completion of electron injection test				★ muon injection
Storage magnet				★ B-field probe ready		★ Install	★ Shimming done
Detector		★ Quoter vane prototype	★ Mass production ready			★ Installation	
DAQ and computing		★ grid service open	★ small DAQ system				
Analysis		★ common computing resource usage start	operation test		★ Ready		
			★ Tracking software ready			★ Analysis software ready	

Commissioning

Data taking

Busy with preparations ...

28



Summary

29

- 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 (2027-)**
 - New method (complementary to magic gamma experiments)
 - Starting related experiments with muonium

The collaboration

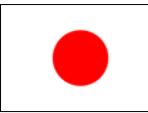
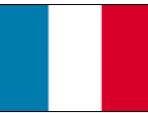
30



Collaboration board (CB)

Chair: Seonho Choi

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



Executive board (EB)

Spokesperson: T. Mibe

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, (K. Hayasaka)



Analysis

leader: T. Yamanaka



Interface coordinators

Committees

Speakers committee

chair: K. Ishida

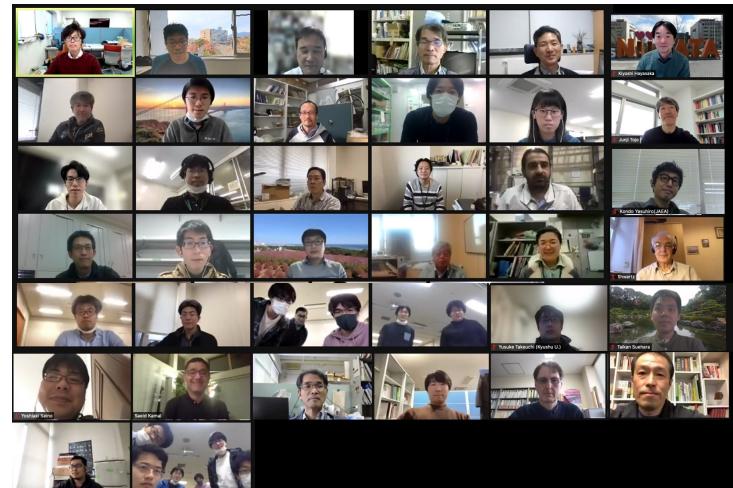
Publication committee

chair: B. Schwartz

Domestic institutes:

Kyushu, Nagoya, Tohoku, Niigata, Tokyo, Ibaraki, RIKEN, JAEA, etc.

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

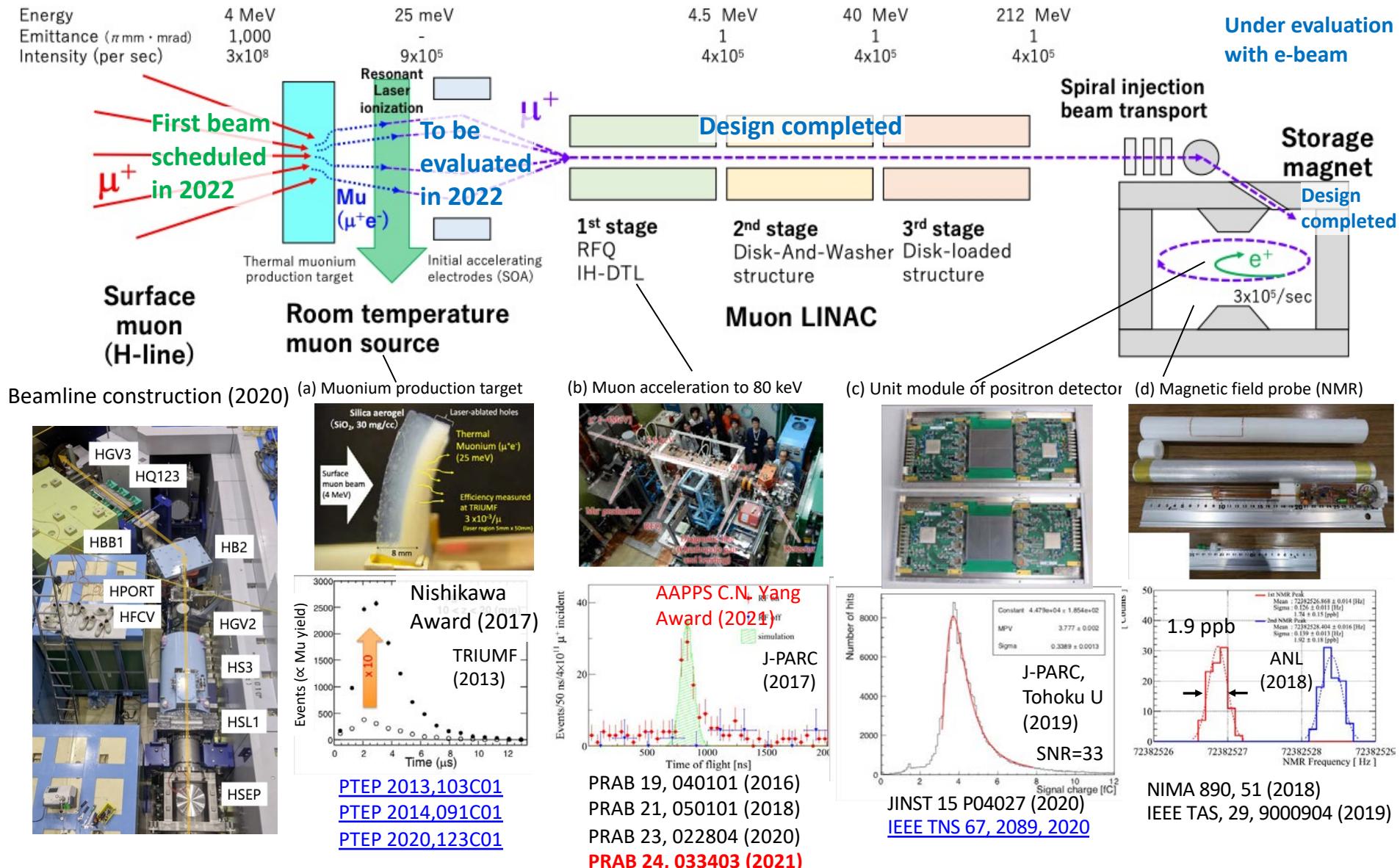


We welcome new members from
IIT, Hyderabad (India)
Central University of Karnataka (India)

Achievements in the past

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

31



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

J-PARC

LINAC
(400 MeV)

Beam power 1MW
Rep. Rate 25 Hz

Neutrino exp. facility

Rapid Cycle
Synchrotron
(3 GeV)

g-2/EDM

Materials and Life science
experimental Facility
(MLF)

Main Ring
(30 GeV)

proton

muon

neutron

neutrino

Hadron exp. Hall

The collaboration

33



Collaboration board (CB)

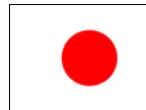
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Surface muon beam

leader: T. Yamazaki, N. Kawamura



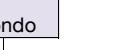
Ultra-slow muon

leader: K. Ishida, G. Marshall



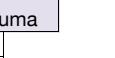
LINAC

leader: Y. Kondo, M. Otani



Injection and storage

leader: H. Iinuma



Storage magnet, field measurements

leader: T. Kume



Detector

leader: T. Yoshioka



DAQ and computing

leader: Y. Sato, S. Lee



Analysis

leader: T. Yamanaka (K. Hayasaka)

Domestic institutes:

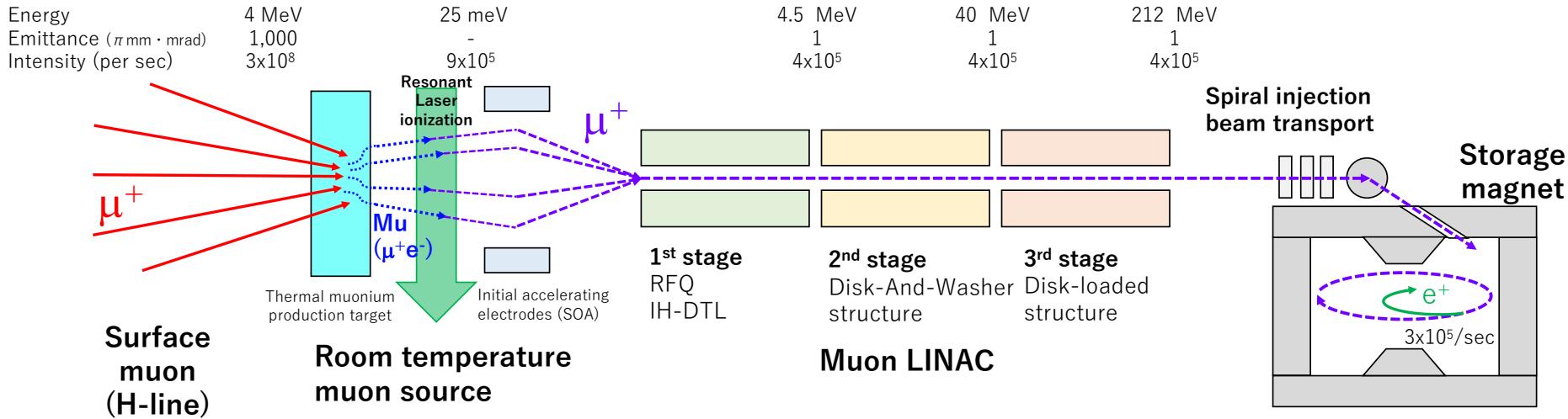
Kyushu, Nagoya, Tohoku, Niigata, Tokyo, Ibaraki, RIKEN, JAEA, etc.



Muon g-2/EDM experiment at J-PARC

34

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)

Re-accelerated thermal muon

surface muon

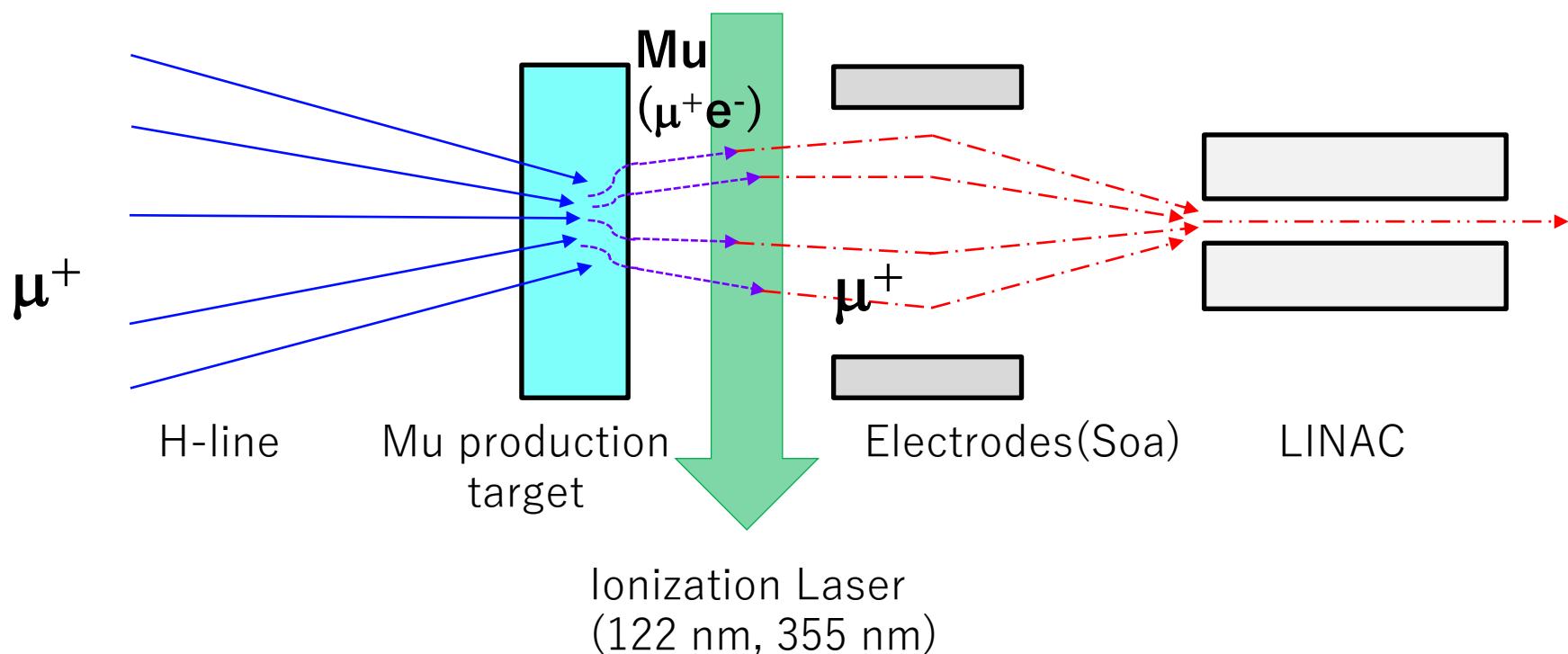
E	3.4 MeV
p	27 MeV/c
$\Delta p/p$	0.05

thermal muon

30 meV
2.3 keV/c
0.4

accelerated muon

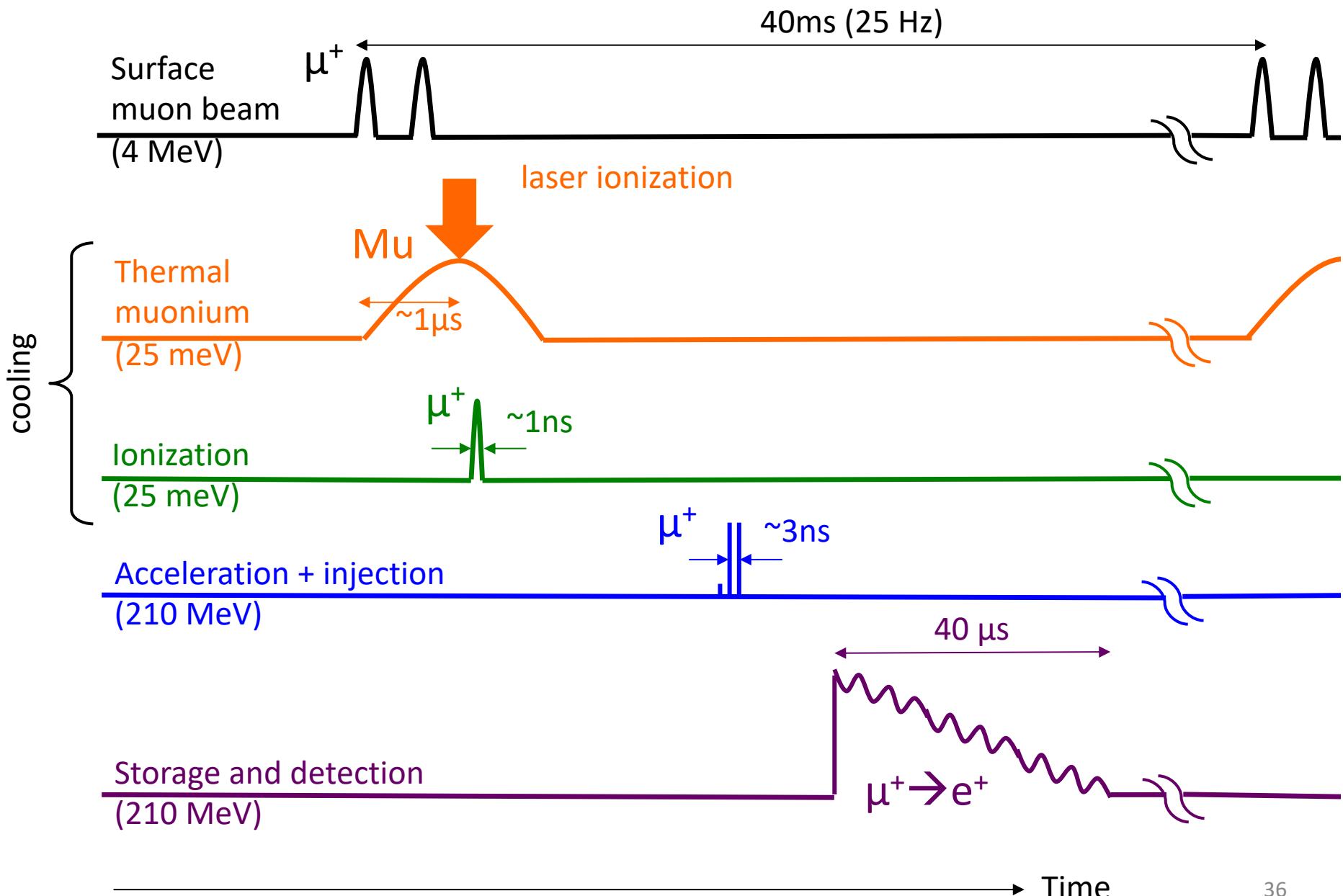
212 MeV
300 MeV/c
4×10^{-4}



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

Cooling+LINAC → The world-first muon accelerator

Experimental sequence



Construction of surface muon beamline (H-line)

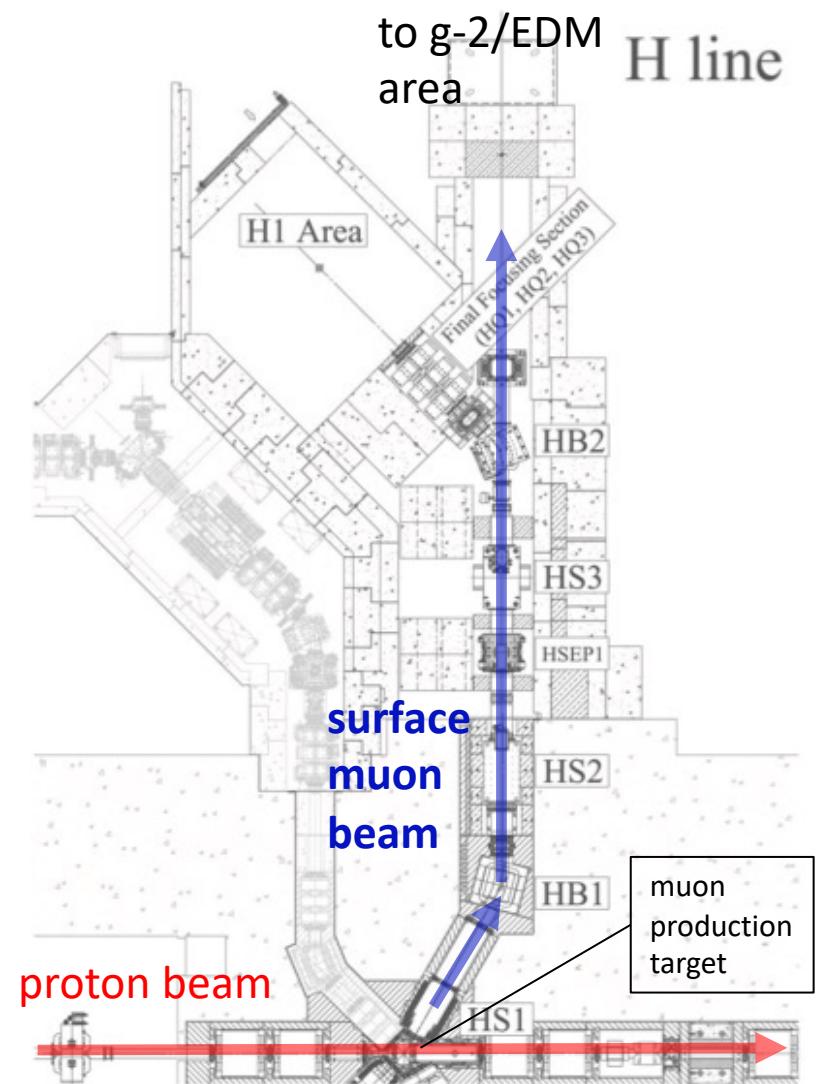
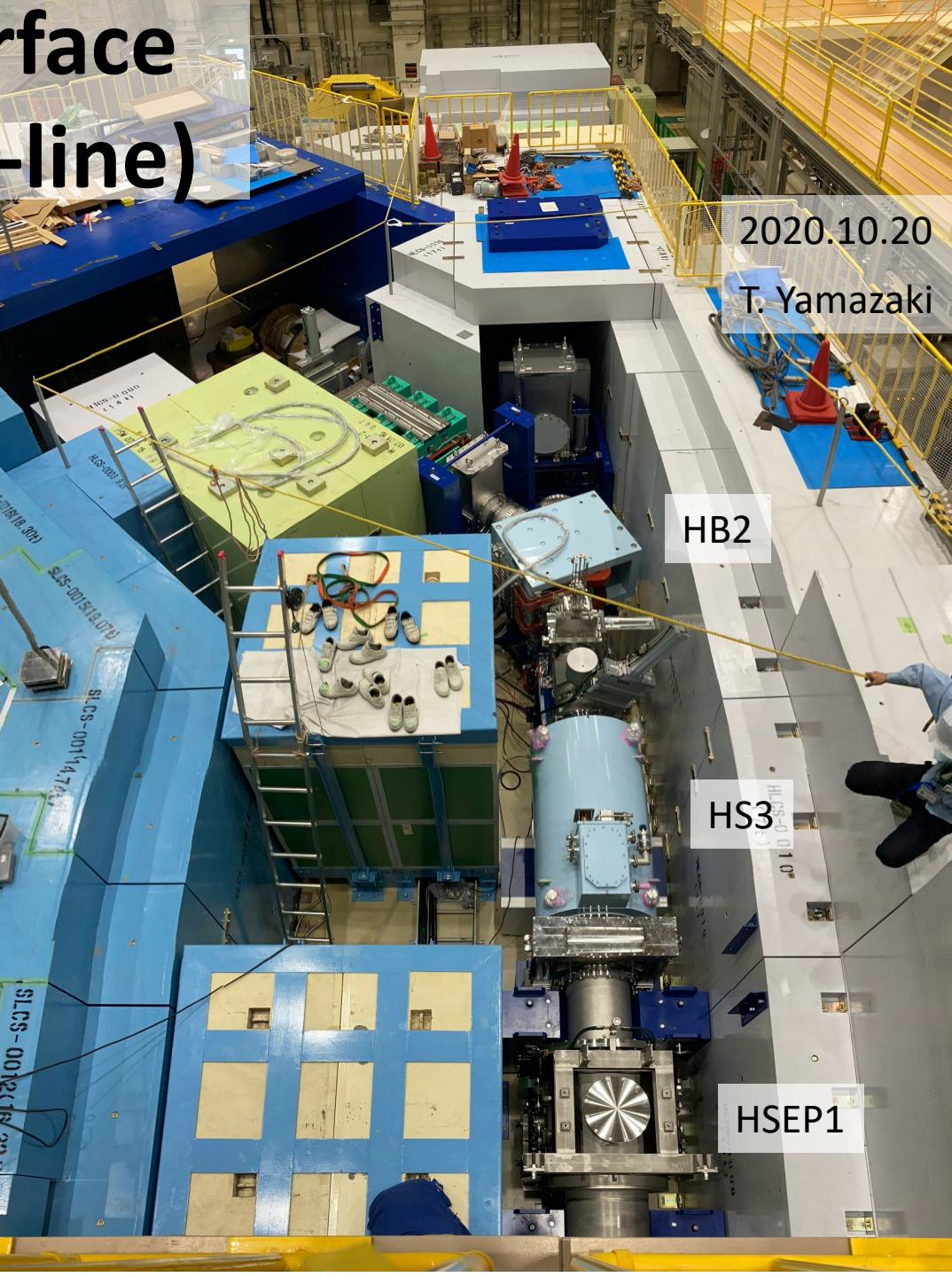


Fig. 2. The H-line layout.

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



Production of thermal energy muon

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

surface
muon beam

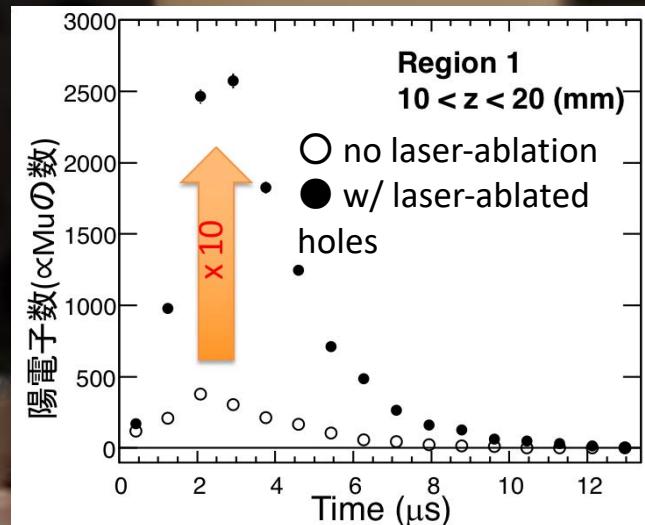
μ^+ (4 MeV)

8 mm

Muonium (μ^+e^-)
30 meV

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

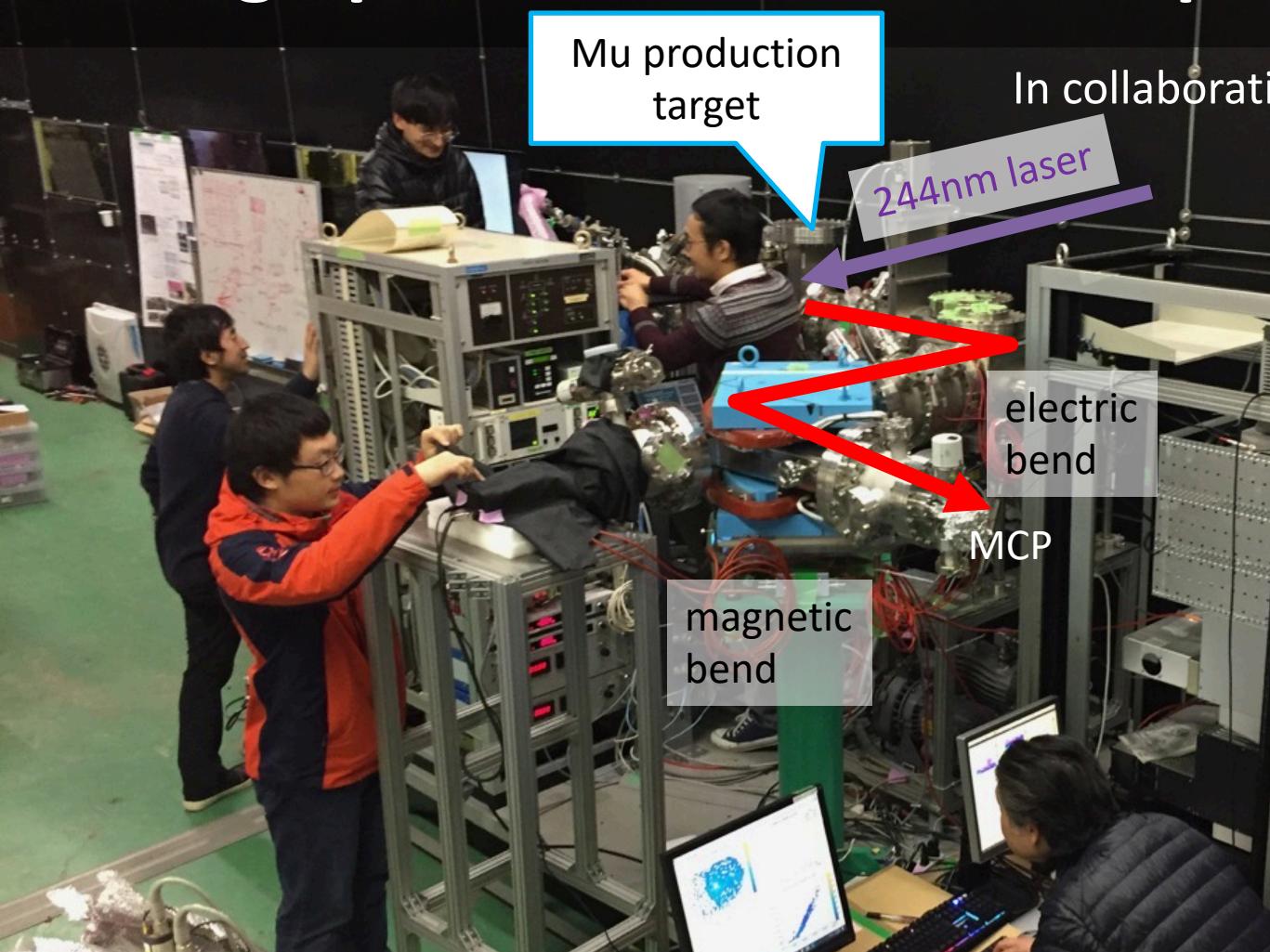
Data taken at TRIUMF



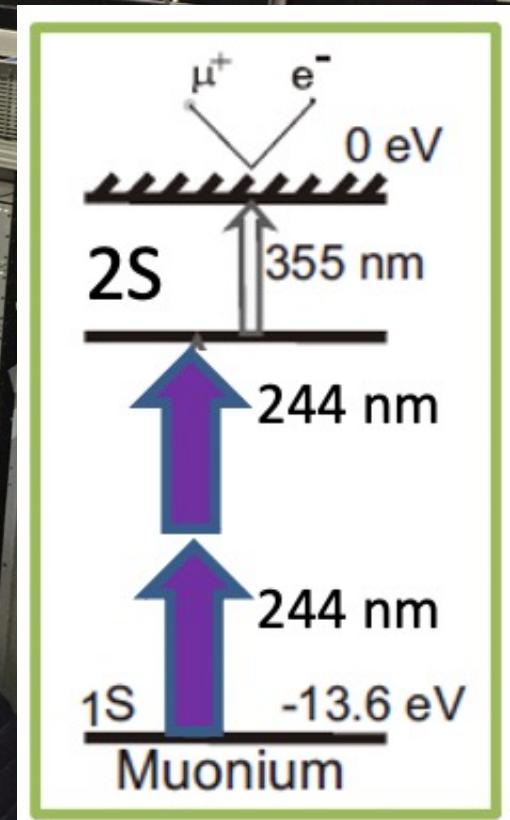
- P. Bakule et al., PTEP 103C0 (2013)
G. Beer et al., PTEP 091C01 (2014)
J. Beare et al., PTEP 123C01 (2020)

Photo by S. Kamal

Setting up the Mu ionization experiment

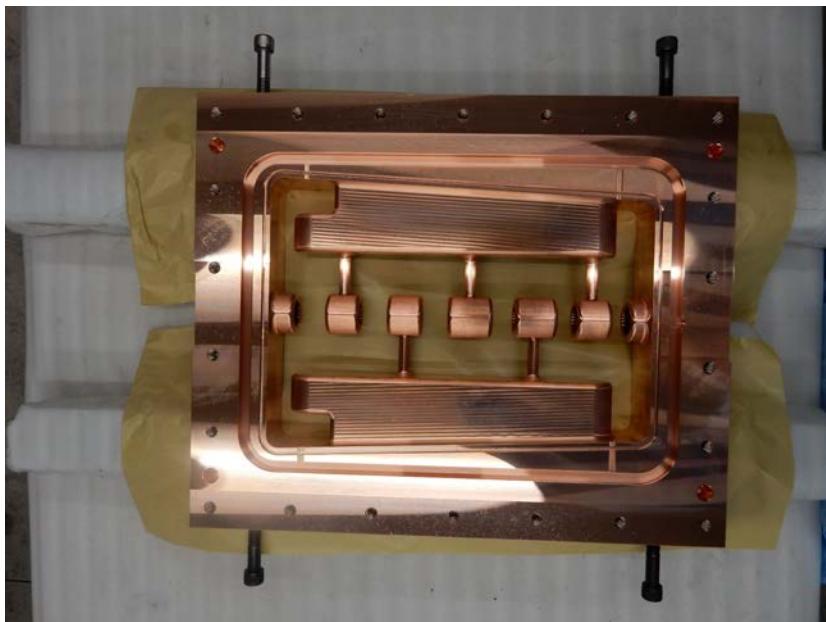
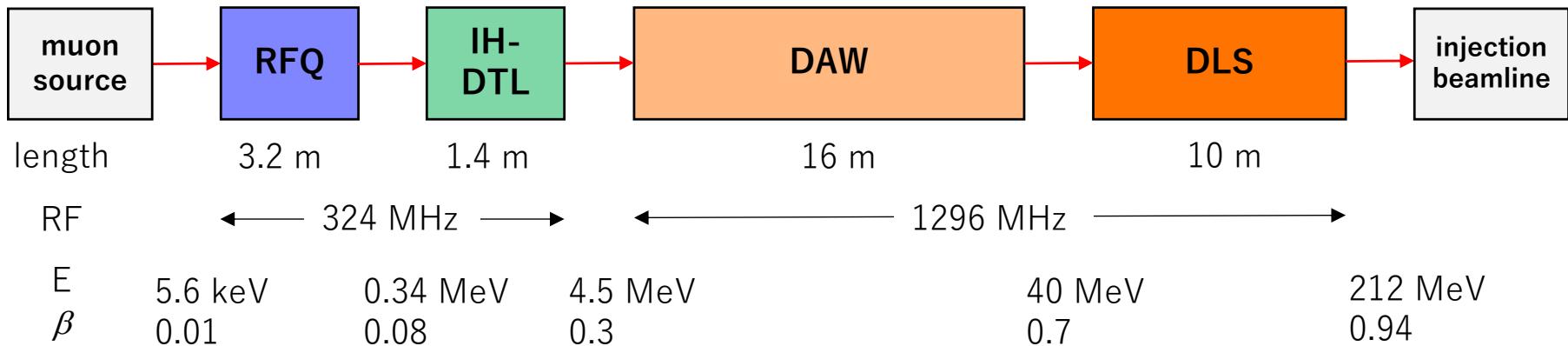


In collaboration with RIIS Okayama-U

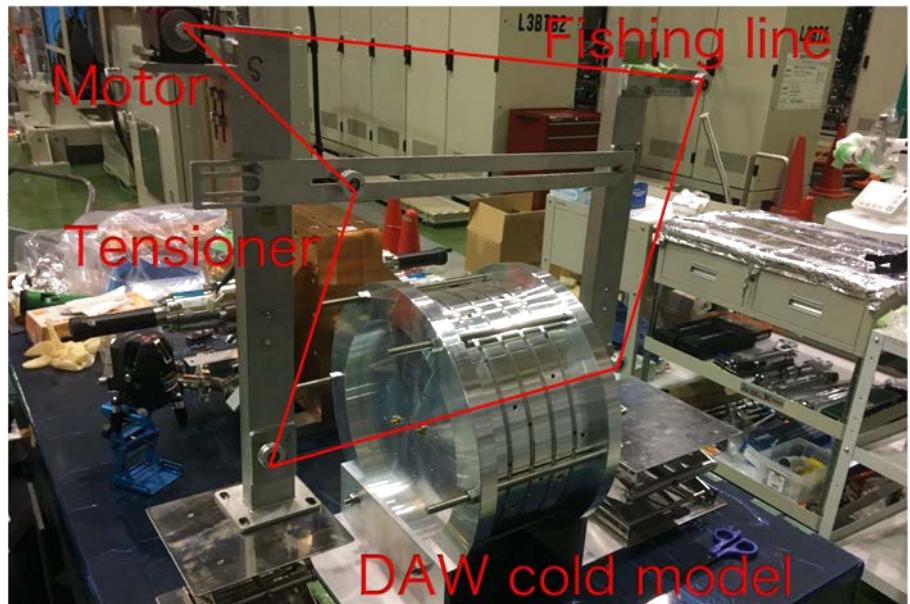


Successfully demonstrated ionization of hydrogen atoms
Mu ionization will be tested at J-PARC MLF S-line from Jan 2022

Muon LINAC developments



IH-DTL test cavity



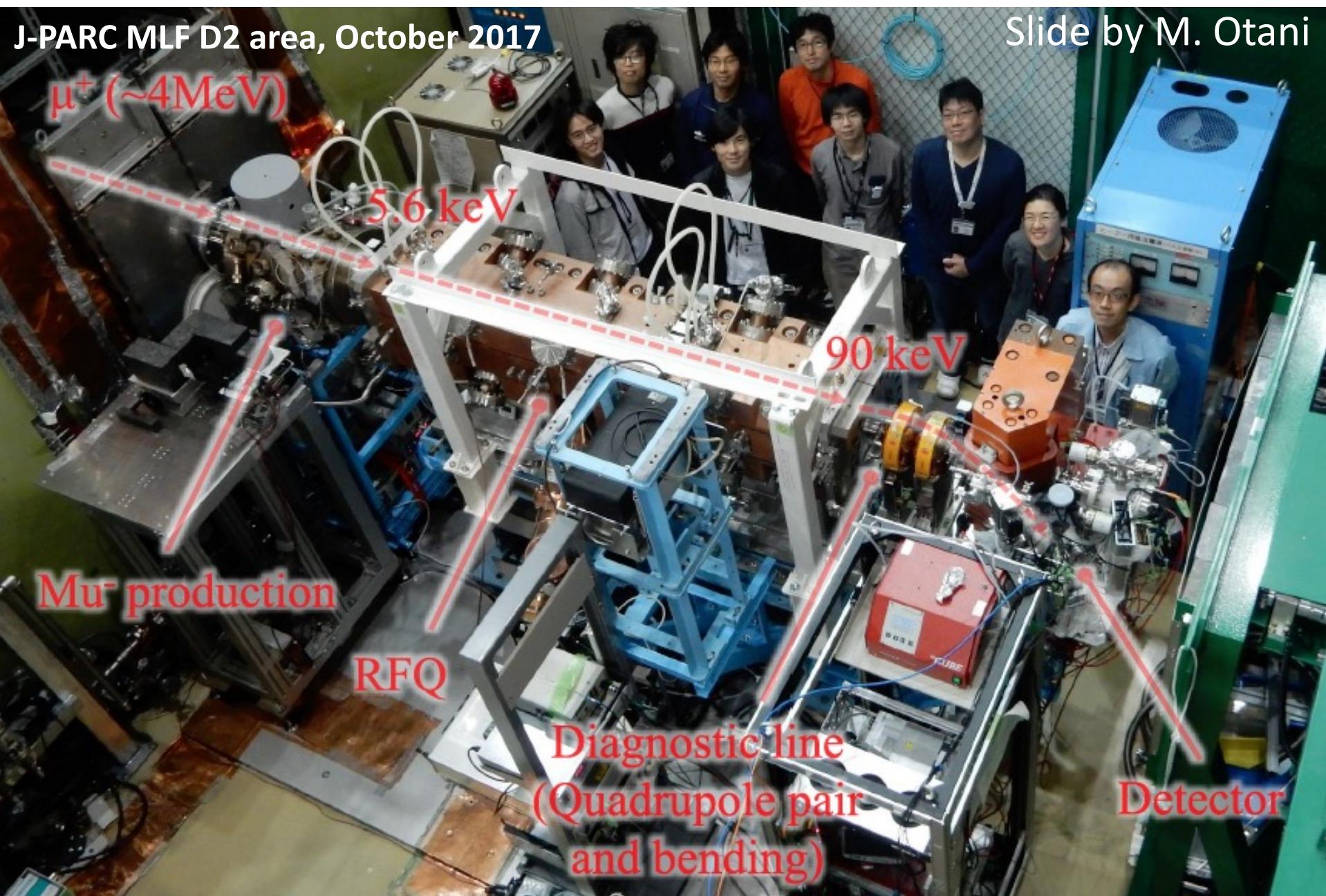
DAW cold model

Demonstration of RF acceleration with Mu- ions

41

J-PARC MLF D2 area, October 2017

Slide by M. Otani

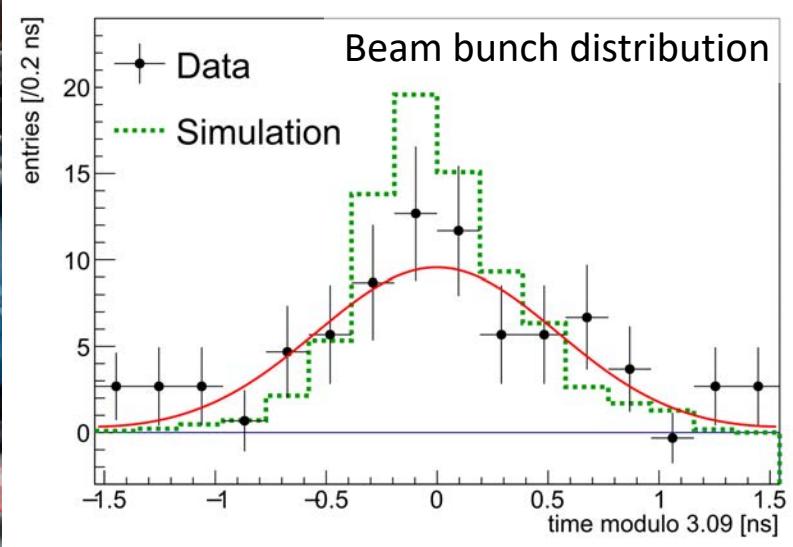
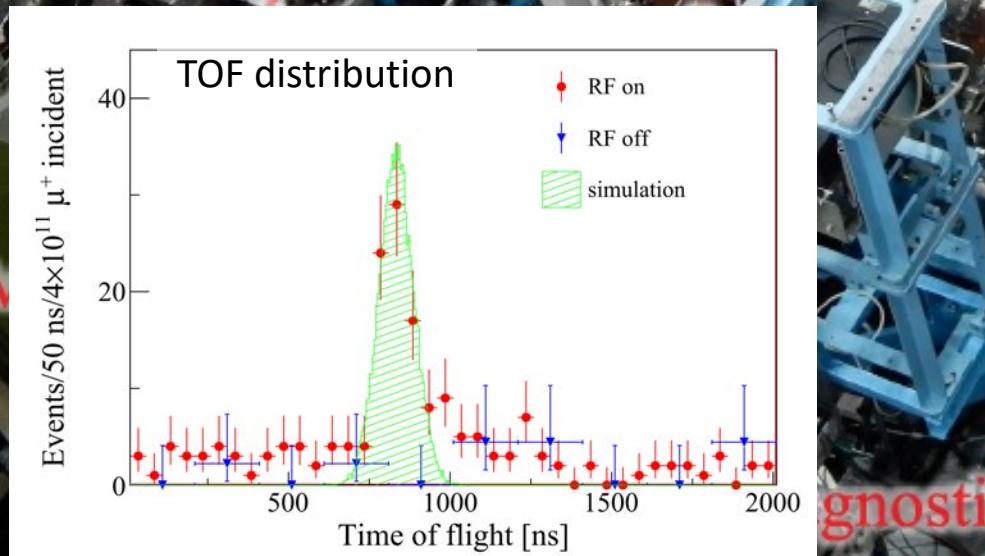


Demonstration of RF acceleration with Mu- ions

42

J-PARC MLF D2 area, October 2017

Slide by M. Otani



Phys. Rev. AB 21, 050101 (2018)

(Quadrupole pair
and bending)

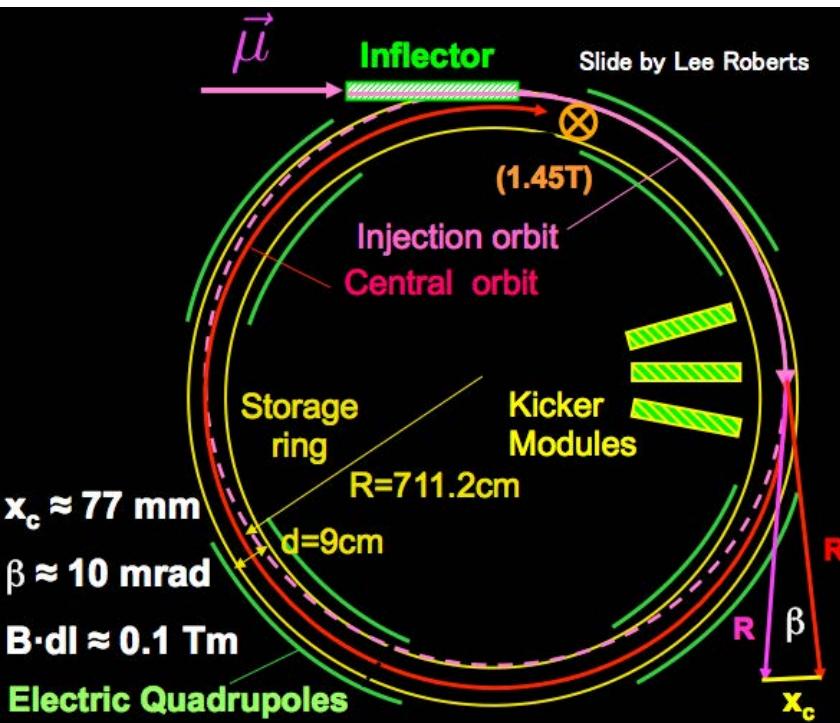
Phys. Rev. AB 23, 022804 (2020)

Detector

Muon beam injection and storage

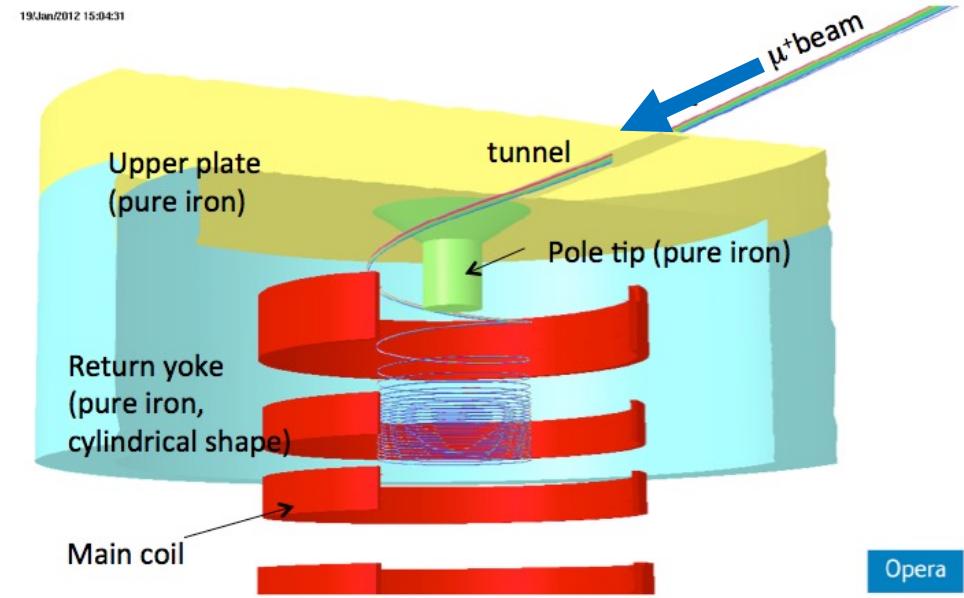
43

- Horizontal injection + kicker
- (BNL E821, FNAL E989)
- 3D spiral injection + kicker
- (J-PARC E34)



Injection efficiency : 3-5%^(*)

(*) PRD73,072003 (2006)



Injection efficiency : ~85%

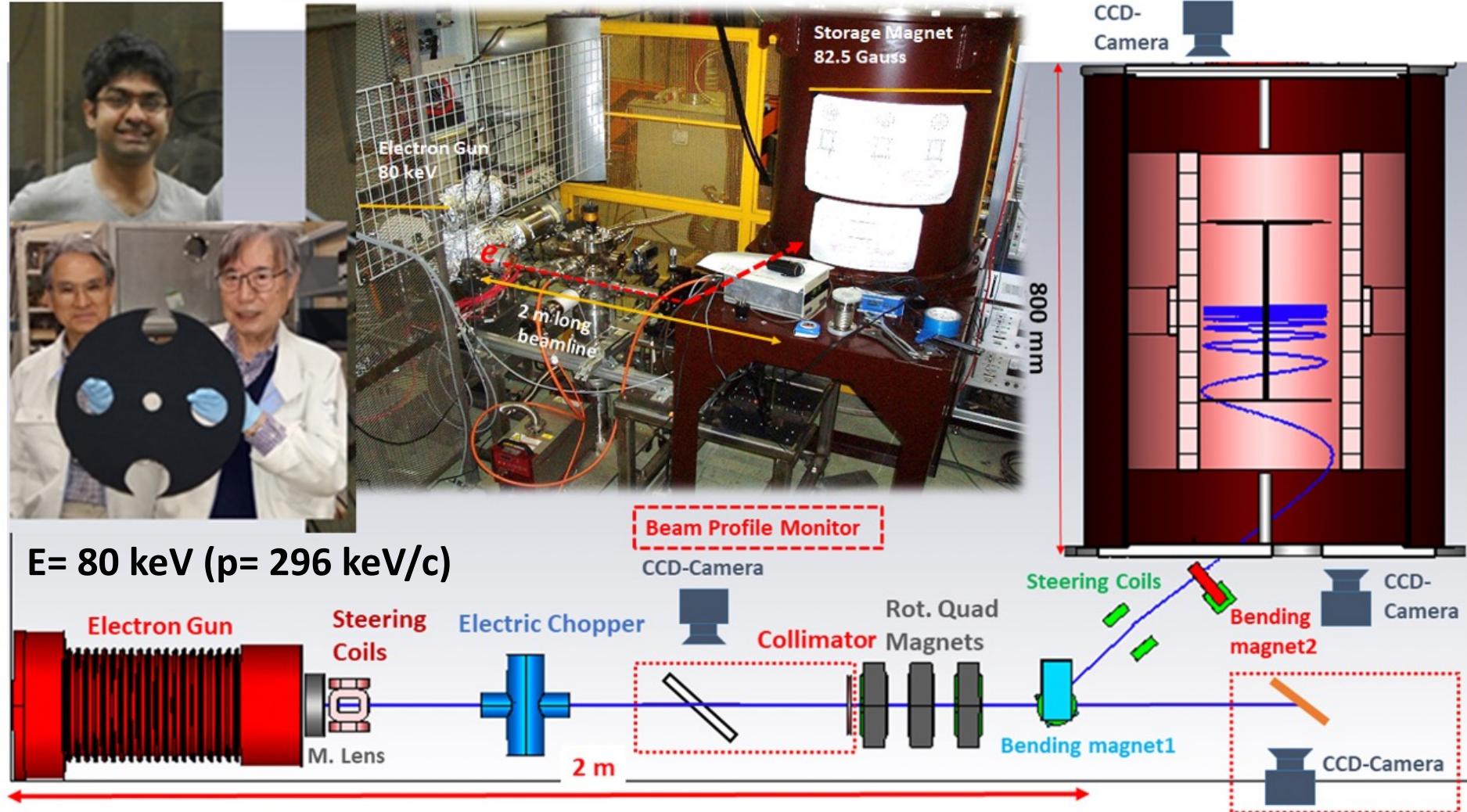
H. Iinuma et al., Nucl. Instr. And Methods. A 832, 51 (2016)

Spiral Injection Test Experiment with electron beam

44

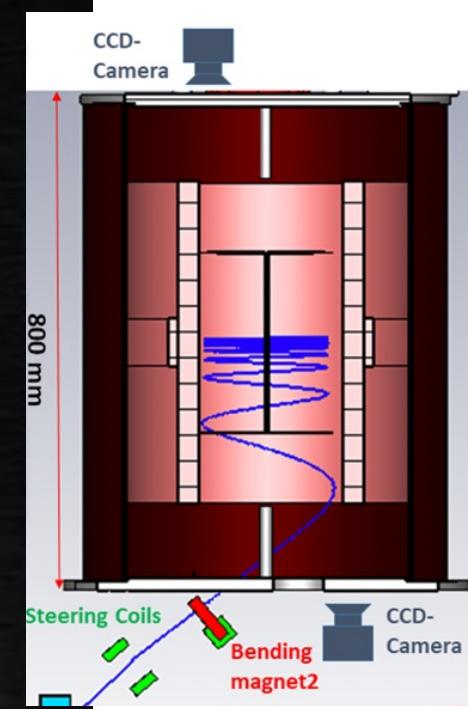
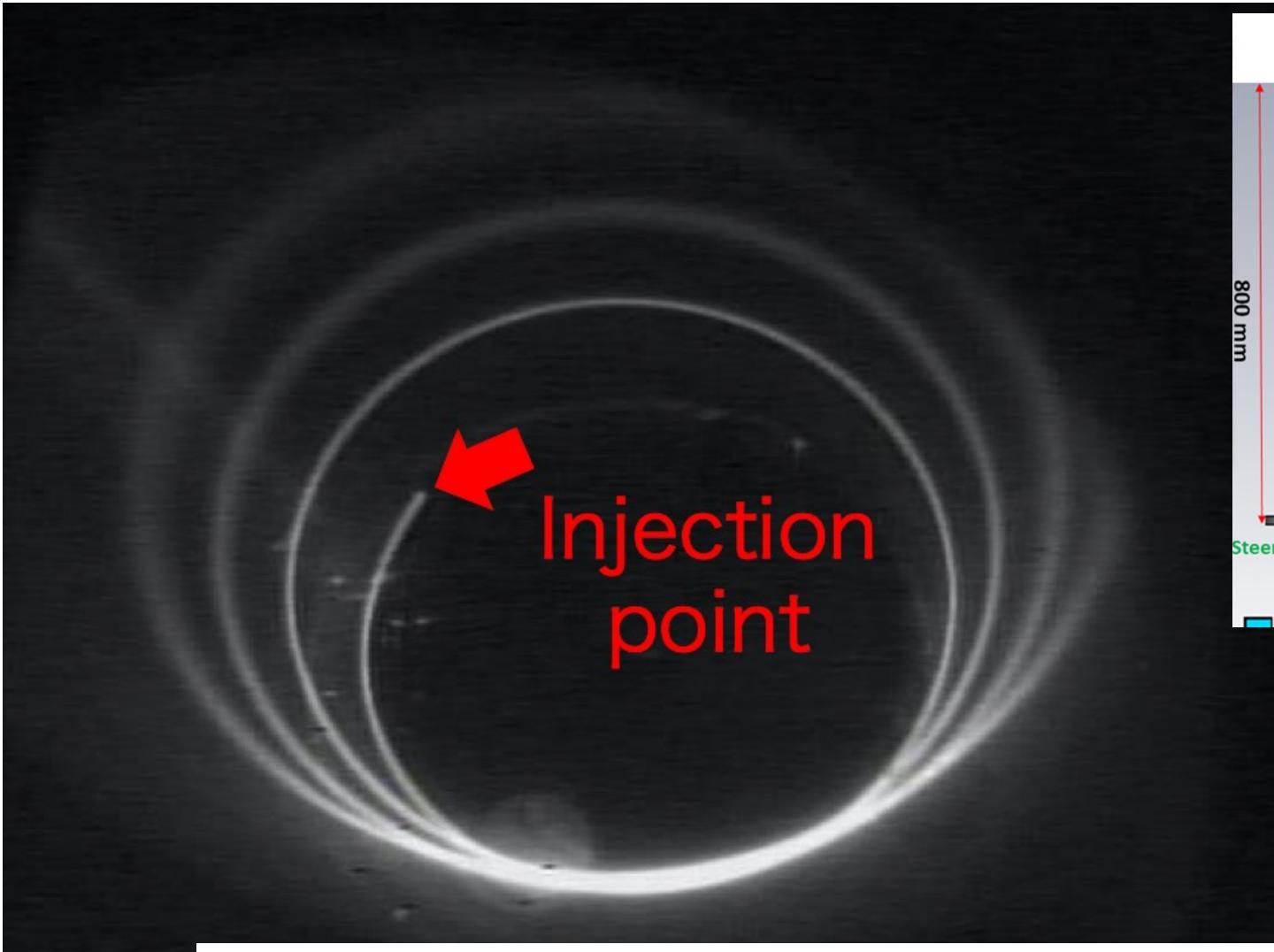
Ibaraki U, KEK, U. Tokyo

KEK Tsukuba campus



Spiral Injection Test Experiment with electron beam

45

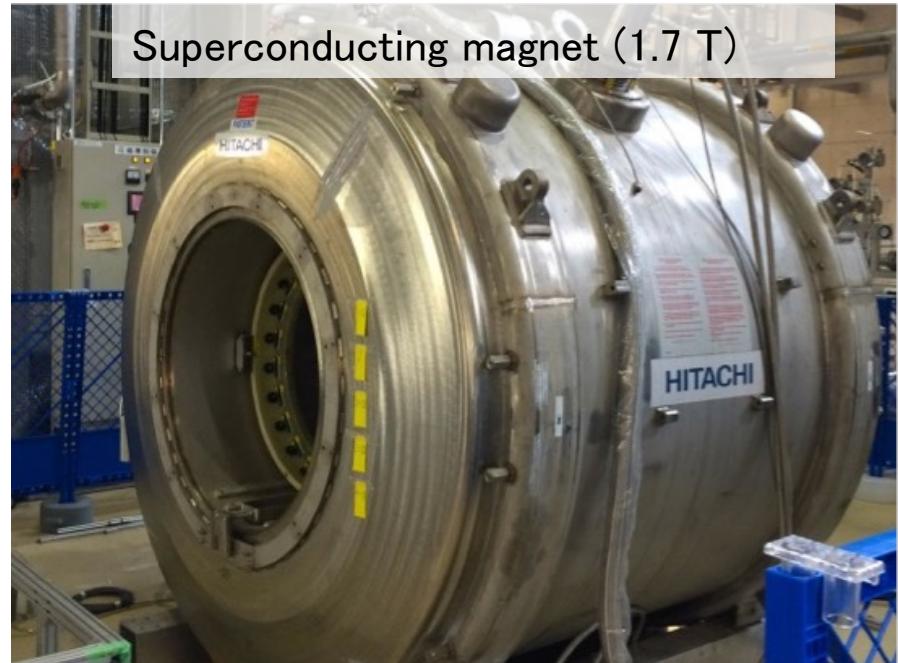


Electrons successfully injected.

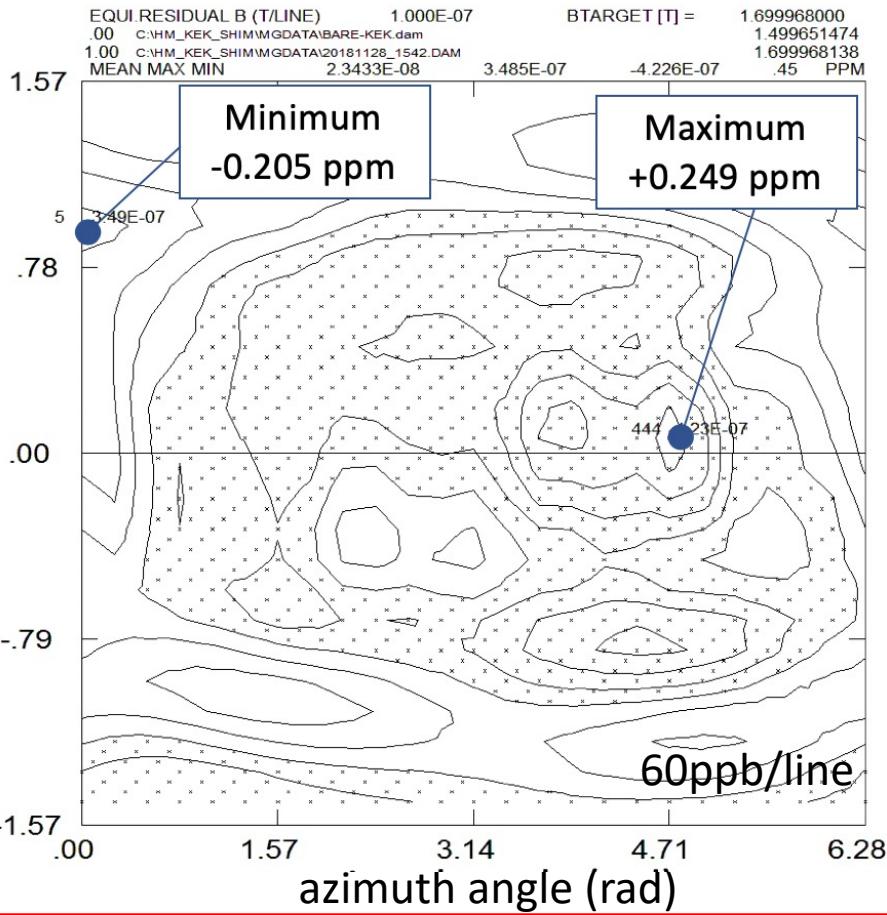
Next step: demonstration of storage by a pulsed kicker

Magnet shimming test

Superconducting magnet (1.7 T)



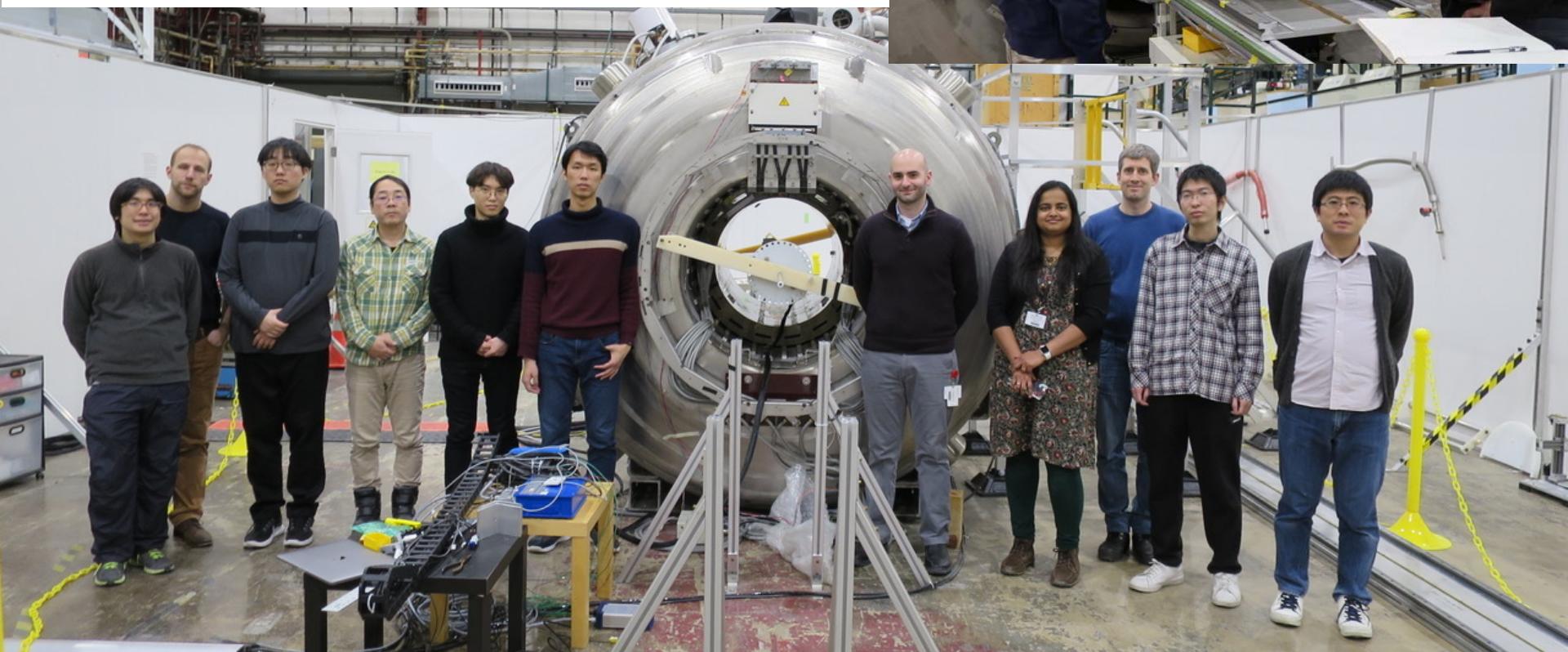
Residual field contour after shimming



Field uniformity: 0.454 ppm (peak-to-peak)
on the surface of sphere $r=15$ cm

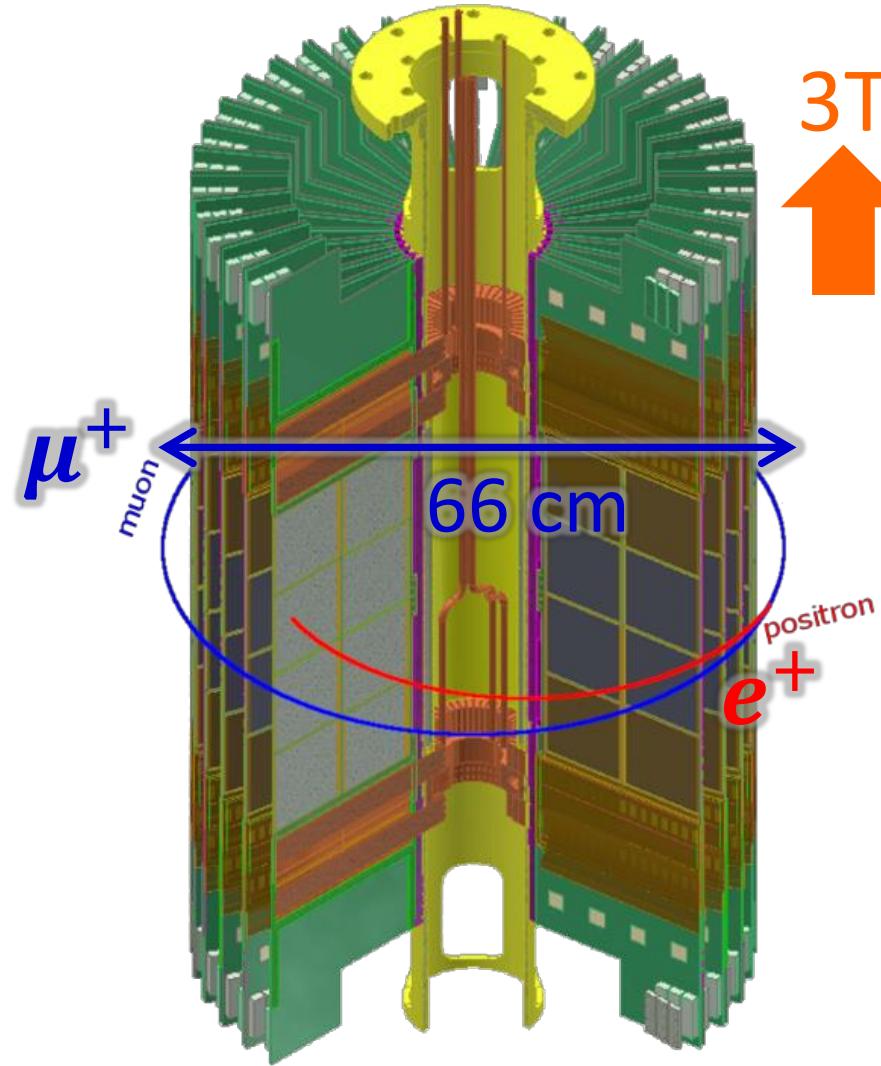
Cross-calibration of absolute probe

- 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)

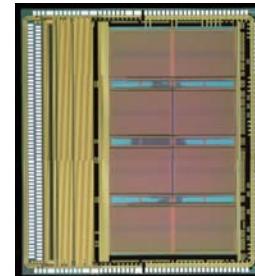


Positron tracking detector

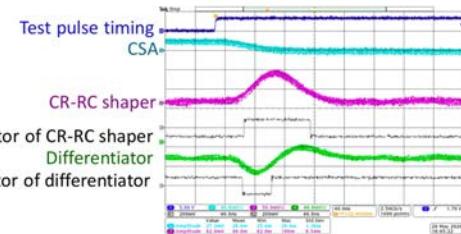
48



New frontend ASIC

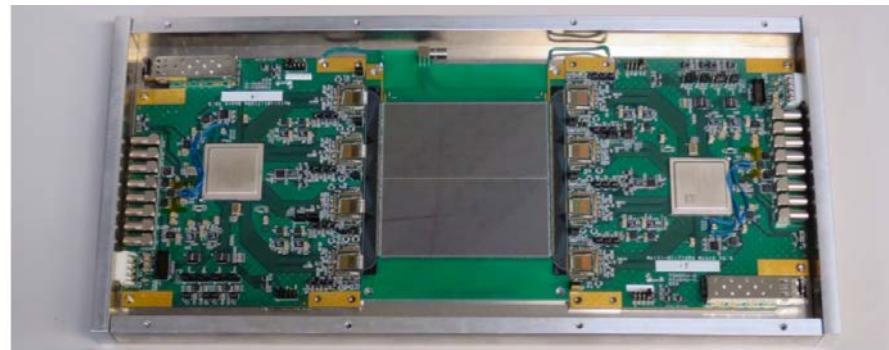


IEEE, TNS 67, 2089 (2020)



Basic performance test

JINST 15 P04027 (2020)



Full-scale prototype of the frontend board



Statistical and systematic uncertainties

49

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 [$10^{-21} e\cdot\text{cm}$]	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
Differential decay	1.5	Eddy current from kicker	0.1
Quadratic sum	< 40	Quadratic sum	56

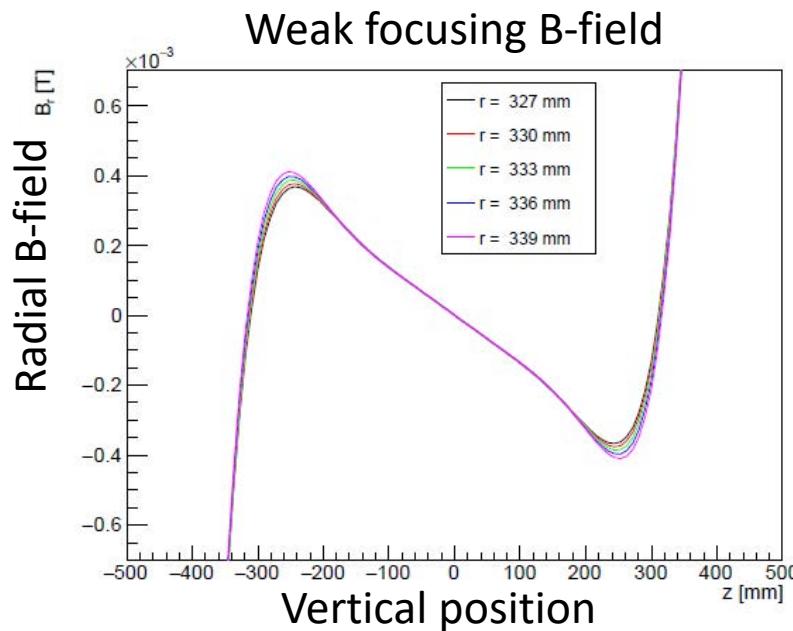
Very weak magnetic focusing

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

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

Radial direction

- **Very weak magnetic focusing**
 - Bill Morse, Yannis Semertzidis (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).



Particle dipole moment

51

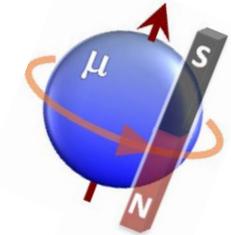
$$\mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

P,C,T-even

P,T-odd (CP-odd)

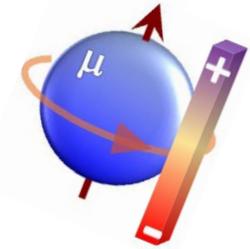
Magnetic Dipole Moment

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



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	+	-	-



Muon EDM

EDM(d_μ) vs a_μ (model independent relation)

Current upper limit

$$d_\mu < 10^{-19} \text{ e}\cdot\text{cm} \text{ (BNL E821)}$$

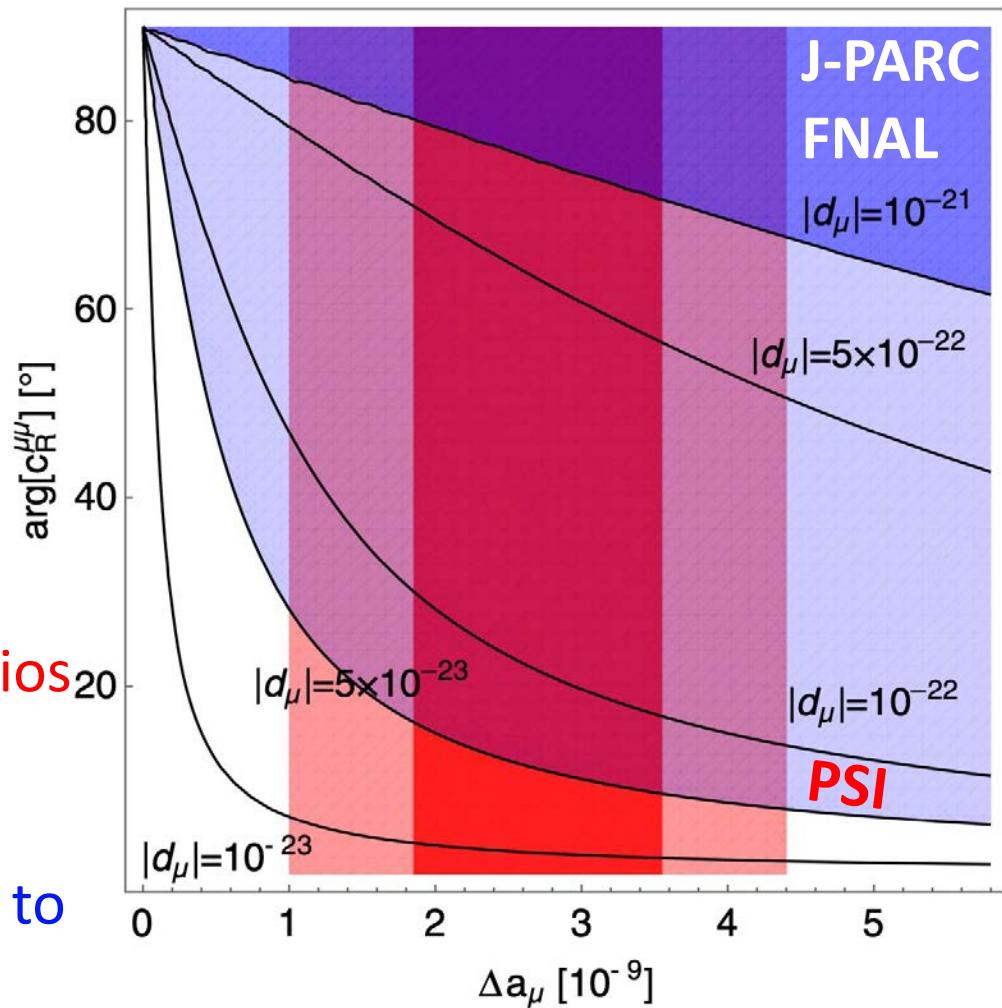
Complex representation of the dipole moment operator:

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

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)



EDM and radial magnetic field

53

$$\vec{\omega} = \vec{\omega}_{g-2} + \vec{\omega}_\eta$$

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

$$\vec{B}' = \vec{B}_\perp + \vec{B}_r$$

$$\vec{\omega}' \simeq -\frac{e}{m} \left[a \vec{B}_\perp + a \vec{B}_r + \frac{\eta}{2} (\vec{\beta} \times \vec{B}_\perp) \right]$$

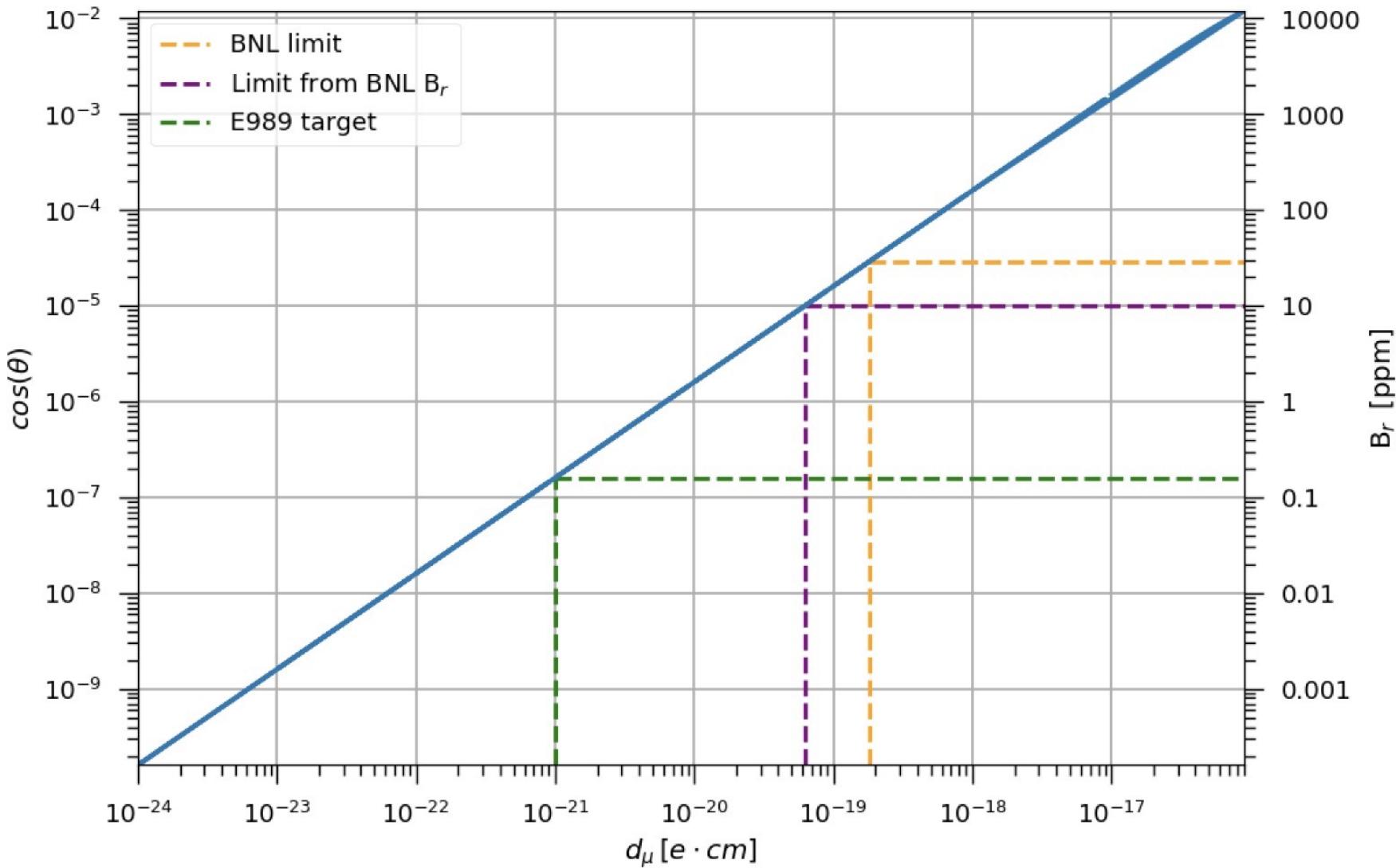
 
radial

Indistinguishable

EDM and radial magnetic field

54

Slide from Joe Price (muEDM workshop at PSI)



Muon storage with magnetic focusing

55

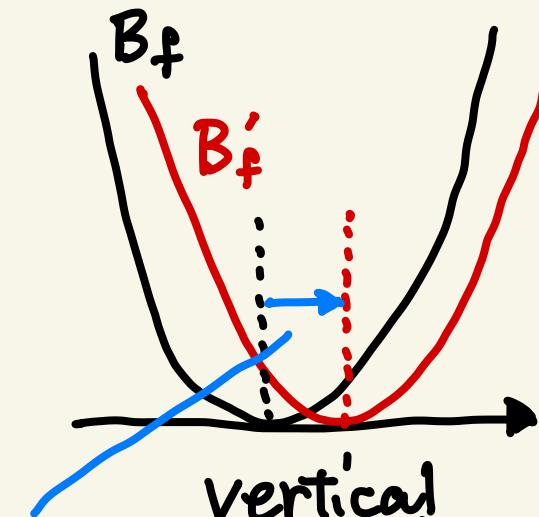
A. Silenko, arXiv:1705.10859

$$\vec{\omega}' \simeq -\frac{e}{m} \left[\alpha \vec{B}_z + \alpha \vec{B}_r + \frac{\eta}{2} (\vec{p} \times \vec{B}_\perp) \right]$$

↑ ↓
radial Indistinguishable

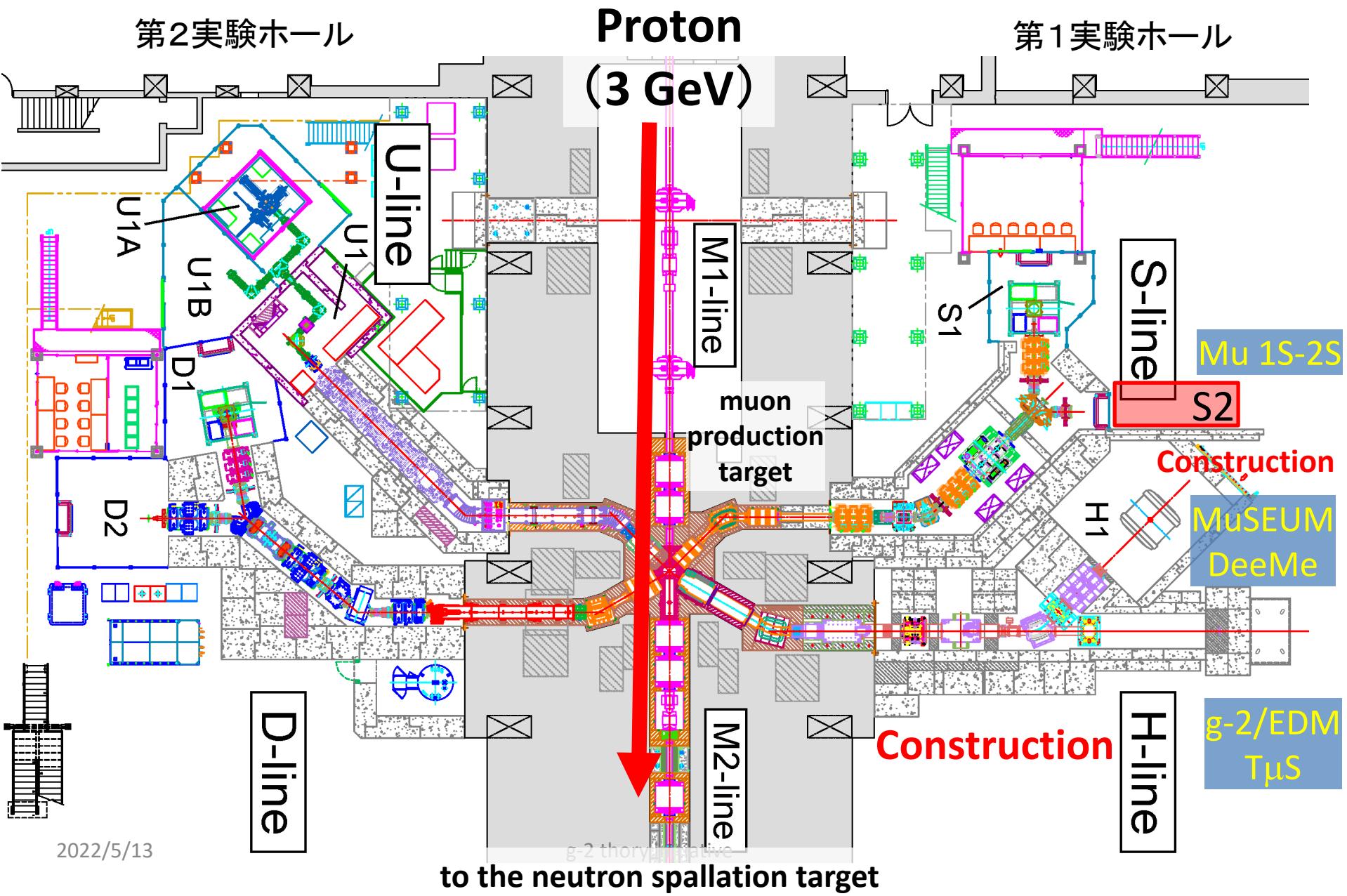
Magnetic focusing

$$\begin{aligned}\vec{B} &= \vec{B}_0 + \vec{B}_f \\ &= \vec{B}_{0z} + \vec{B}_{0r} + \vec{B}_f \\ &= \vec{B}_{0z} + \vec{B}'_f\end{aligned}$$



Beam will
find itself at $\vec{B}_r = 0$ position

J-PARC Muon Science Facility (MUSE)



Experimenter's view of charged leptons

57

	electron	muon	tau
Yield / cross sections	Avogadro number N_A $\sim 10^{23}$	$10^8/\text{sec} \rightarrow$ $10^{11}/\text{sec}$ (future) Pion production $O(10 \text{ mb})$	5×10^{10} tau pairs for 50 ab^{-1} (Belle II goal) Tau production $\sim 1\text{nb}$ @Belle II
Lifetime, $c\tau$ (dominant decay)	infinity	$2.2 \mu\text{s}$, 660 m (leptonic 100%)	0.3 ps , $87 \mu\text{m}$ (hadronic 65% leptonic 35%)
Natural polarization	none	100% (at birth)	none
Self analyzing?	none	yes	yes only for leptonic decays

Precision of physical quantities

58

with mass scaling

	electron	muon	tau
Mass	0.510 998 946 1 (31) MeV 6 ppb	105.658 374 5 (24) MeV 23 ppb	1776.86 (12) MeV 68 ppm
Anomalous magnetic moment (g-2) quadratic	$115\ 965\ 218.091\ (26)$ $\times 10^{-10}$ 0.2 ppb 1/43000	$116\ 592\ 061(41)$ $\times 10^{-10}$ 350 ppb 1	>0.052 and < 0.013 (95% CL) 10(?) 280
Electric dipole moment (EDM) linear	$< 1.1 \times 10^{-29}$ ecm (90% CL) 1/207	$< 1.8 \times 10^{-19}$ ecm (95% CL) 1	$< 0.45 \times 10^{-16}$ ecm (95% CL) 17
cLFV BR limits	---	$O(10^{-13})$	$O(10^{-8})$