Muon g-2 and EDM

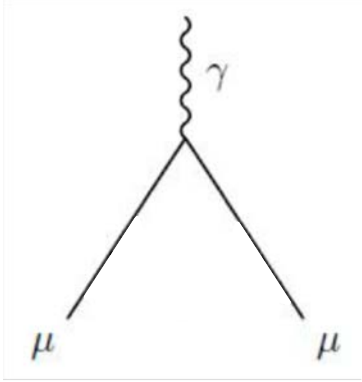
FFK

June 11, 2019

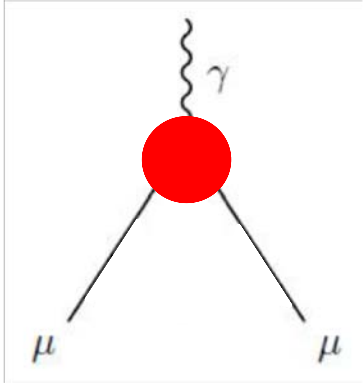
Tsutomu Mibe (IPNS, KEK)

Anomalous magnetic moment

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



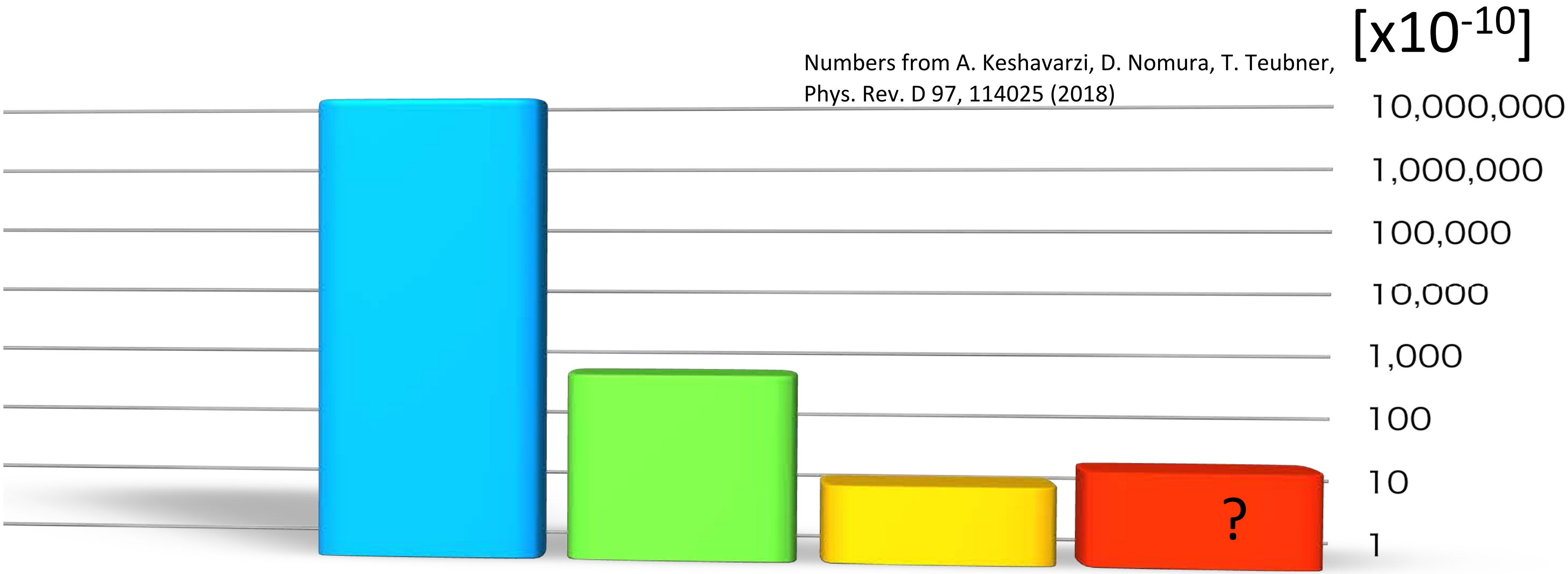
- In quantum field theory, *g* factor gets corrections:



Anomalous magnetic moment

$$g = 2\,(1 + a_\mu)$$

Anomalous magnetic moment



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

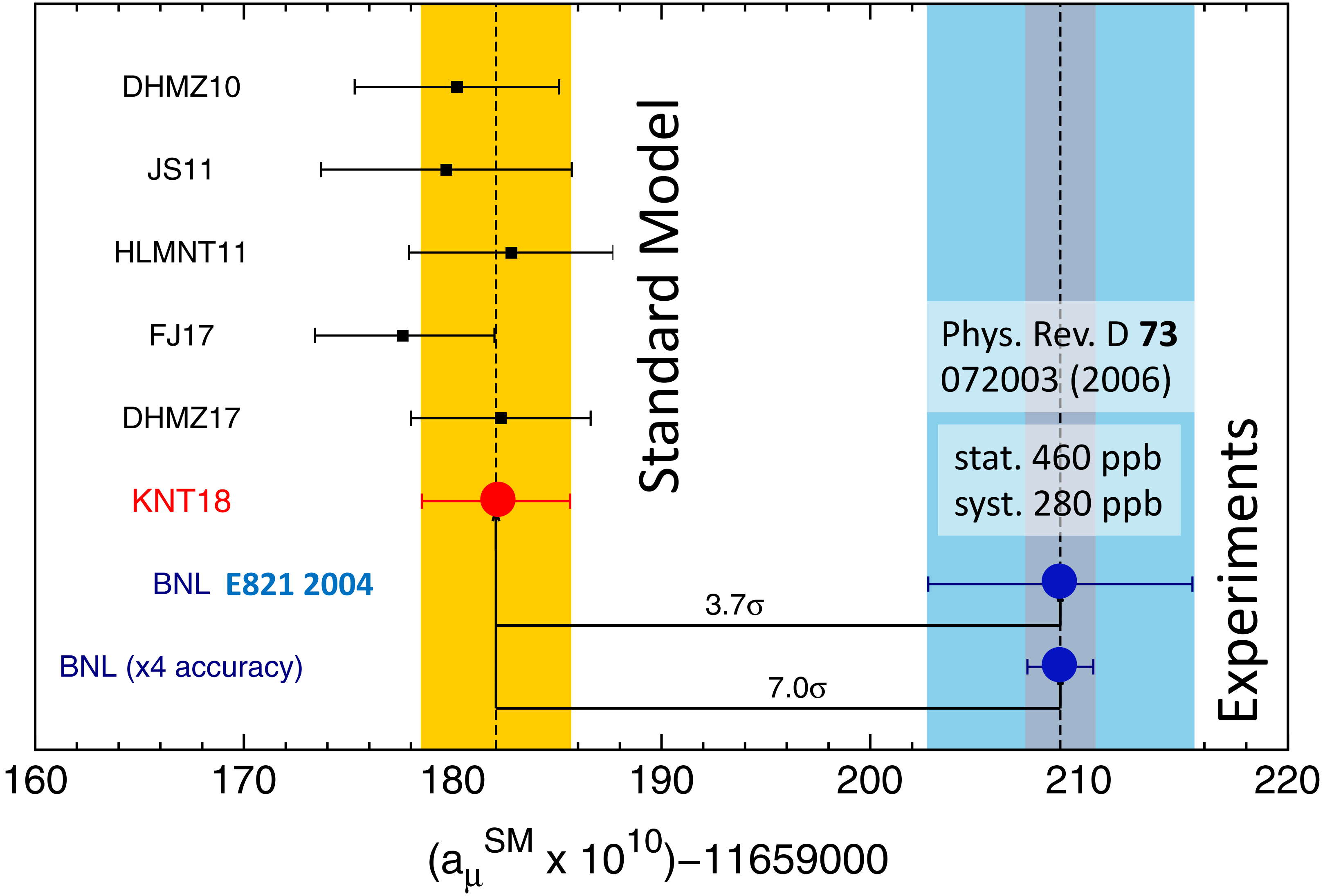
All interactions, *including those ones we don't know*, appear in quantum loops, and add up to contribute to a_μ

Theory collaboration
"Muon g-2 theory initiative"
meets at Mainz, June 18-22, 2018

Next meeting : INT, University of Washington, Seattle) 9-13 September 2019.

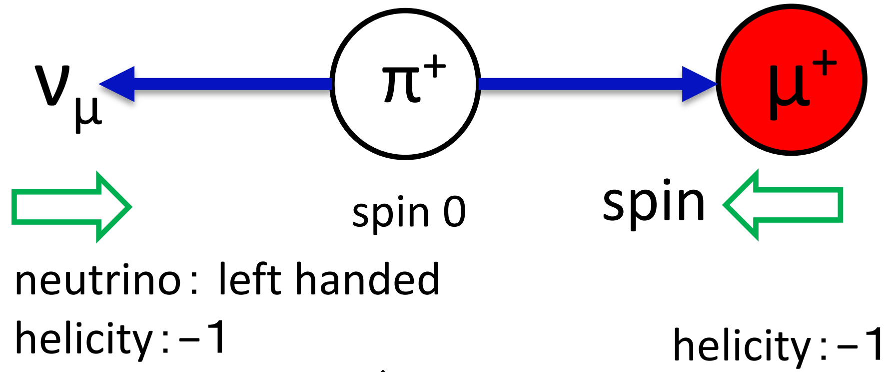
Comparison between SM and a_μ

A. Keshavarzi, D. Nomura, T. Teubner, Phys. Rev. D 97, 114025 (2018)



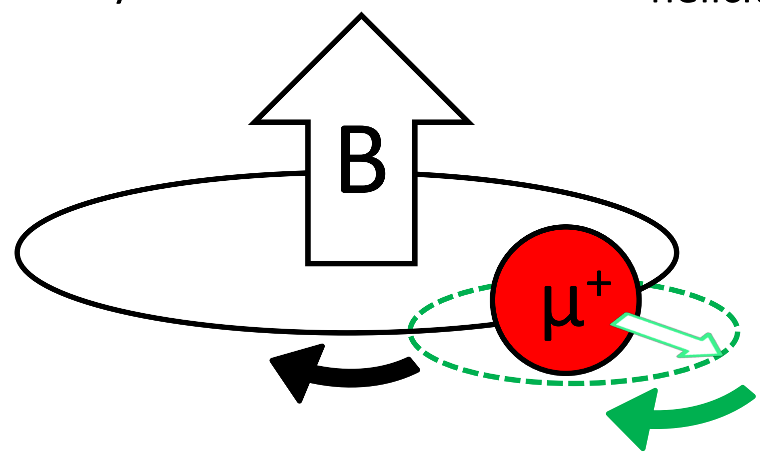
Three steps of g-2 measurement

1. Prepare a polarized muon beam.

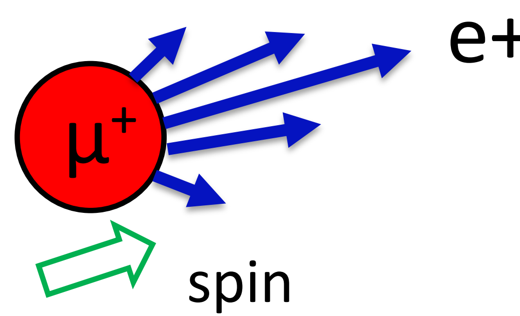


2. Store in a magnetic field (muon's spin precesses)

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



3. Measure decay positron



Extraction of a_μ

- **muon spin precession** $$\omega_a = \frac{e}{m_\mu} a_\mu B$$
- **proton spin precession**
  (proton NMR) $$\omega_p = \mu_p B$$
- muon magnetic moment $$\mu_\mu = g\frac{e}{2m_\mu} = (1 + a_\mu)\frac{e}{m_\mu}$$

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

540 ppb (BNL)
140 ppb
(Fermilab/J-PARC)

Magnetic moment ratio

LAMPF(1999)

$$\Delta\left(\frac{\mu_\mu}{\mu_p}\right) = 120\ ppb\ (30\ ppb)$$

direct

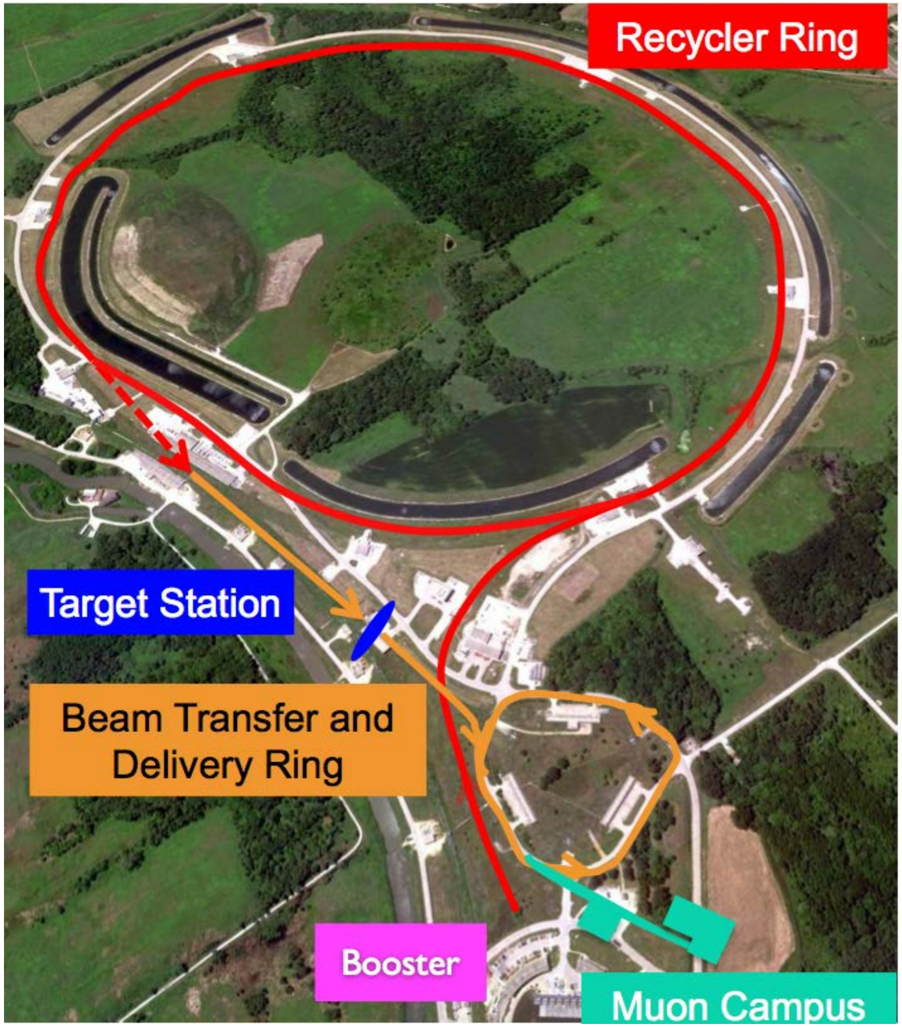
using Δν
+ theory

g-2 experiment at Fermilab

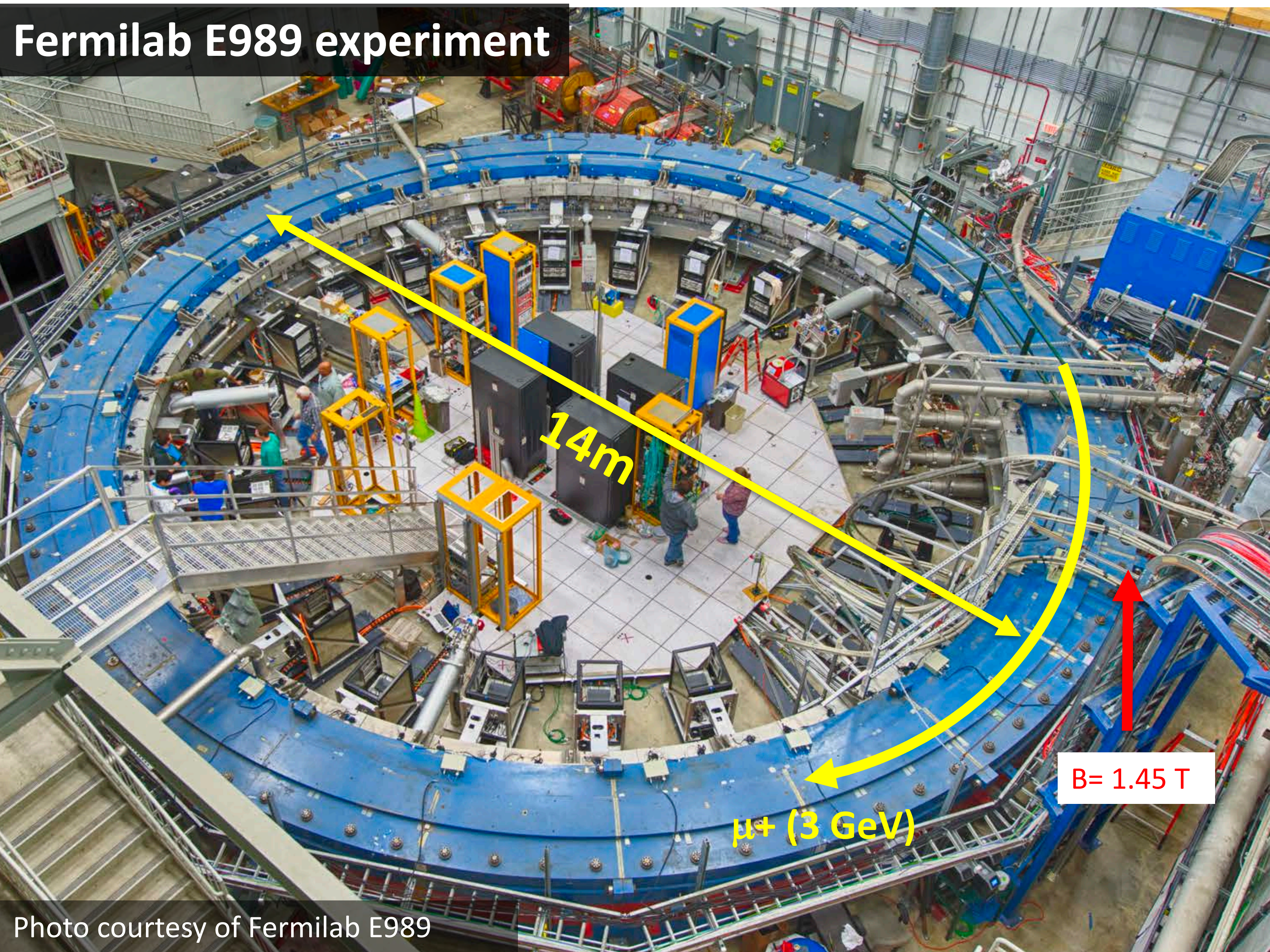
arXiv:1501.06858

Courtesy of D. Kawall

- BNL result statistic limited.
  - 540 ppb (stat)
  - 330 ppb (syst)
- Fermilab goal
  - A factor of **21 more statistics**
    - 2×10^{11} e^+ detected
- Advantages
  - Long π decay channel
    - Reduced π in the ring
  - 4 times higher fill frequency
    - **keeping muons per fill about the same**



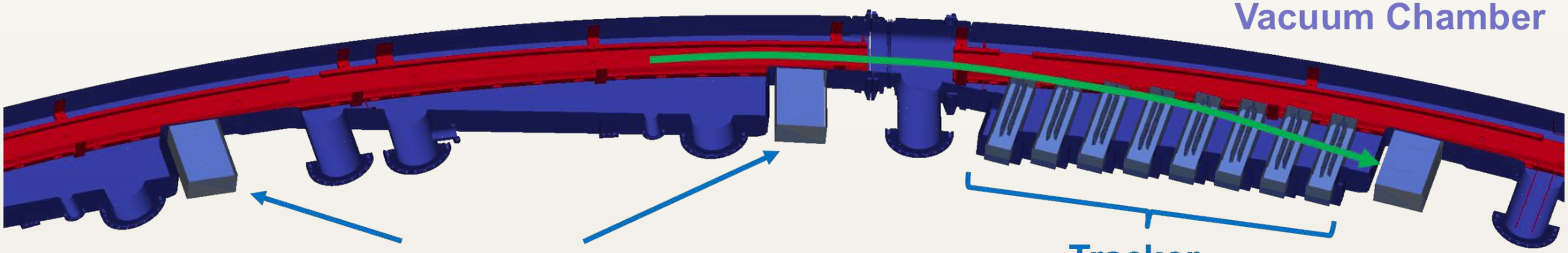
21 times more detected e^+

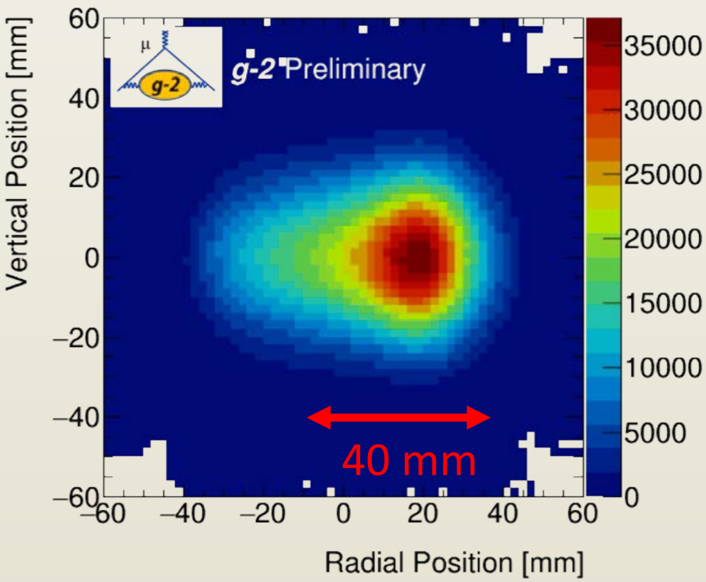


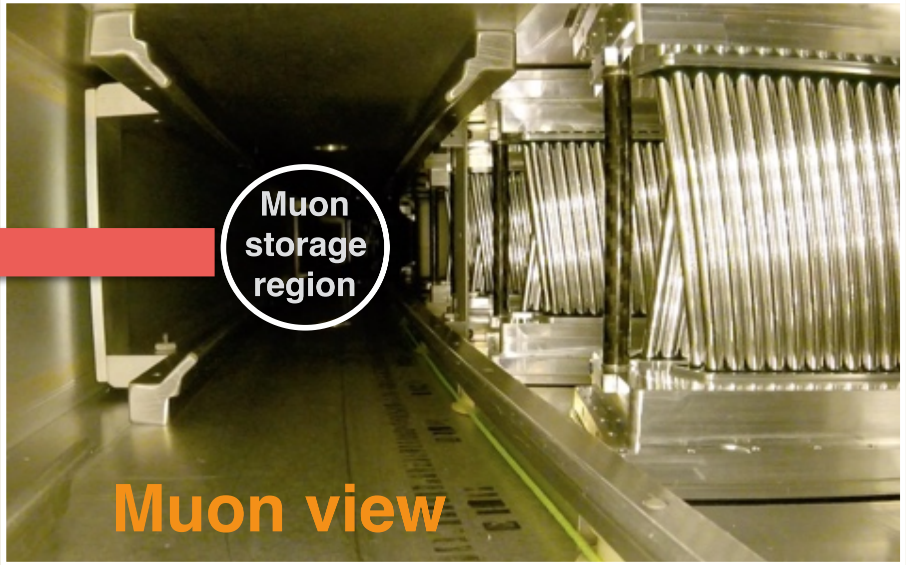
Fermilab E989 experiment
14m
μ+ (3 GeV)
B= 1.45 T
Photo courtesy of Fermilab E989

Stored muon beam

Slide by Nam Tran, FPCP 2019

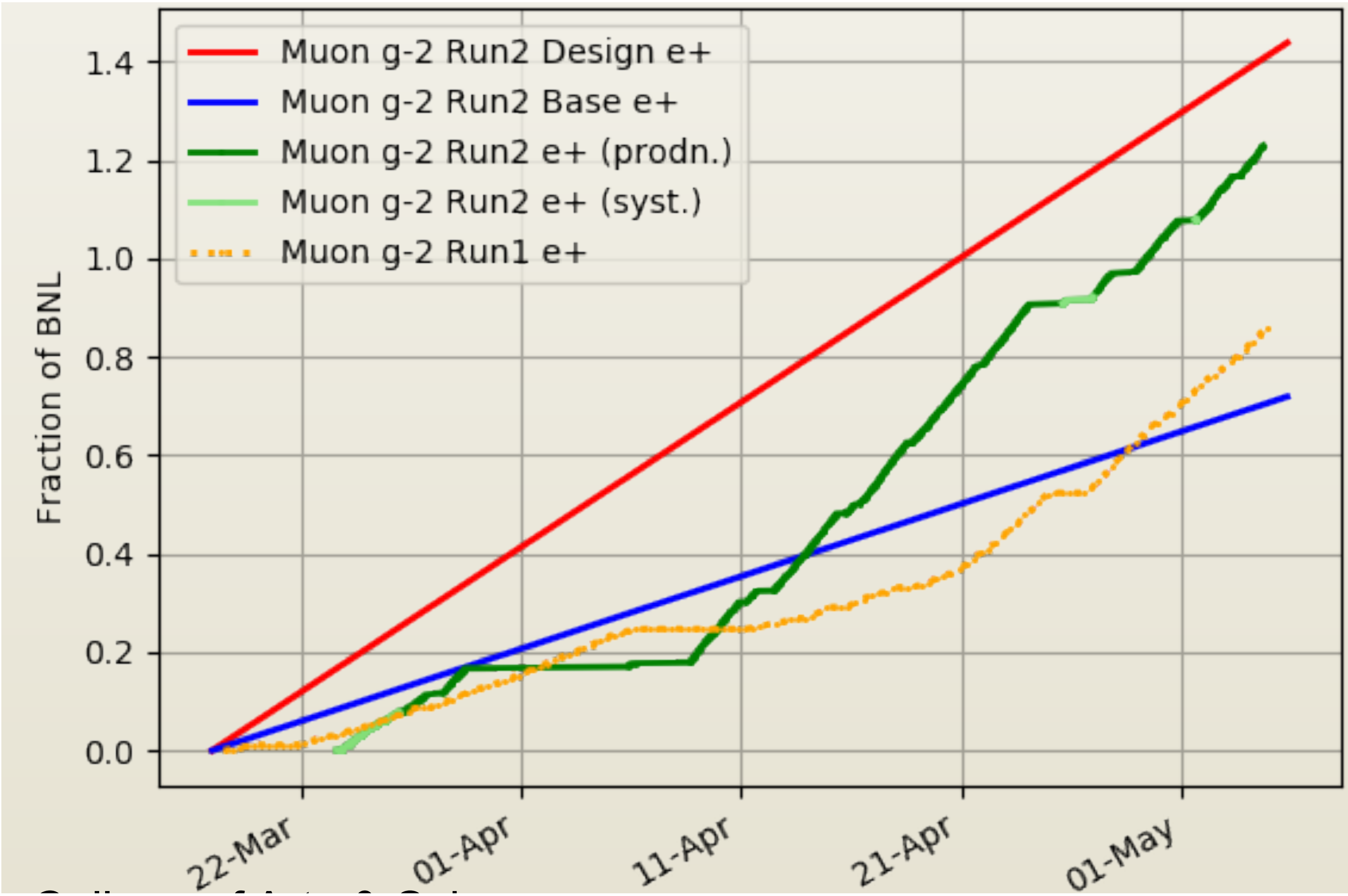






BOSTON UNIVERSITY

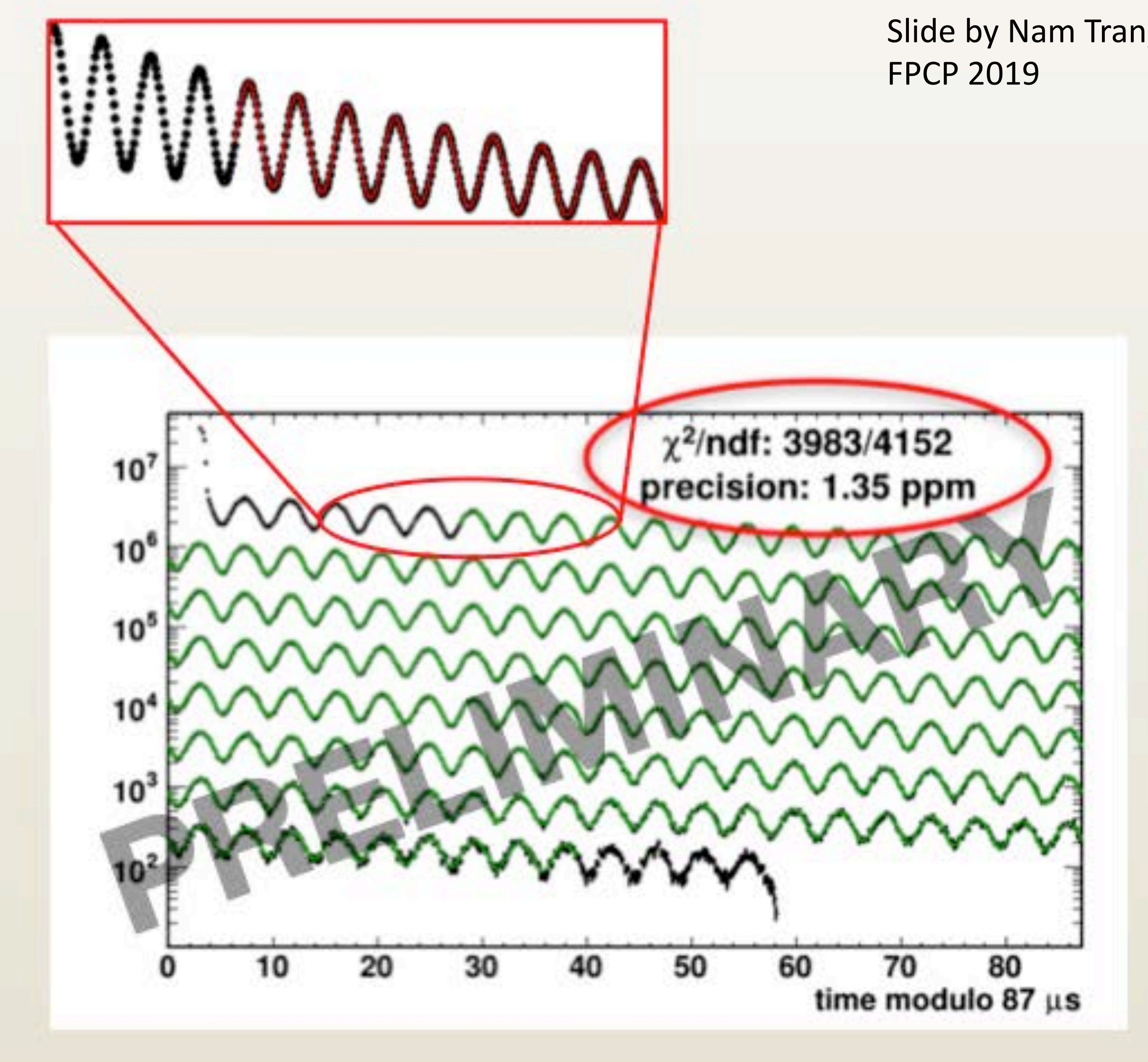
Data taking progress



Slide by Nam Tran, FPCP 2019

- Finished first physics run, **Run 1**, in July 2018. Analysis in progress
  - 2x BNL stats collected (2x10^{10} e+), **1.4x BNL stats after cuts ($\Delta\omega_a/\omega_a$ =350 ppb)**
  - Field uniformity 2x better than BNL ($\Delta B/B$~210 ppb RMS)
- Half way through the **Run 2** with improvements

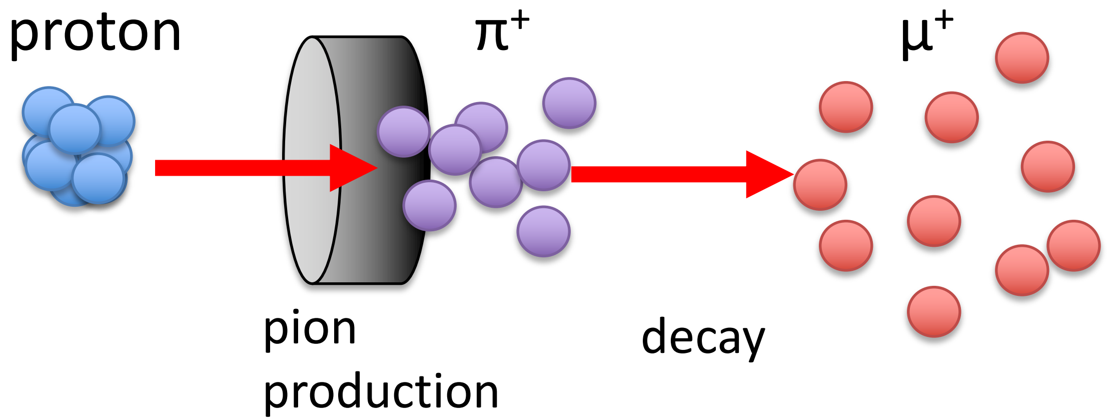
Spin precession data in Run 1



Slide by Nam Tran, FPCP 2019

- Two-fold blindings
  - Clock offset
  - Random offset
- Relative unblinding test successful
- First result from Run 1 will be released soon.

Conventional muon beam

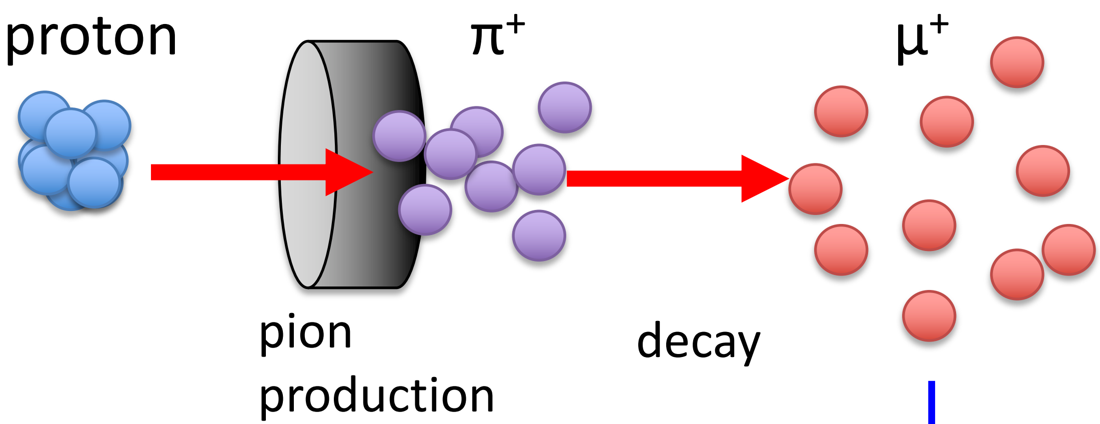


emittance

~1000π mm ·mrad

Strong collimation
Strong focusing
Muon loss
BG π contamination

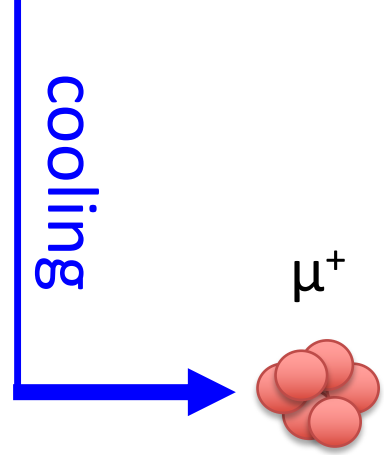
Muon beam at J-PARC



emittance

~1000π mm ･mrad

Strong collimation
Strong focusing
Muon loss
BG π contamination



emittance

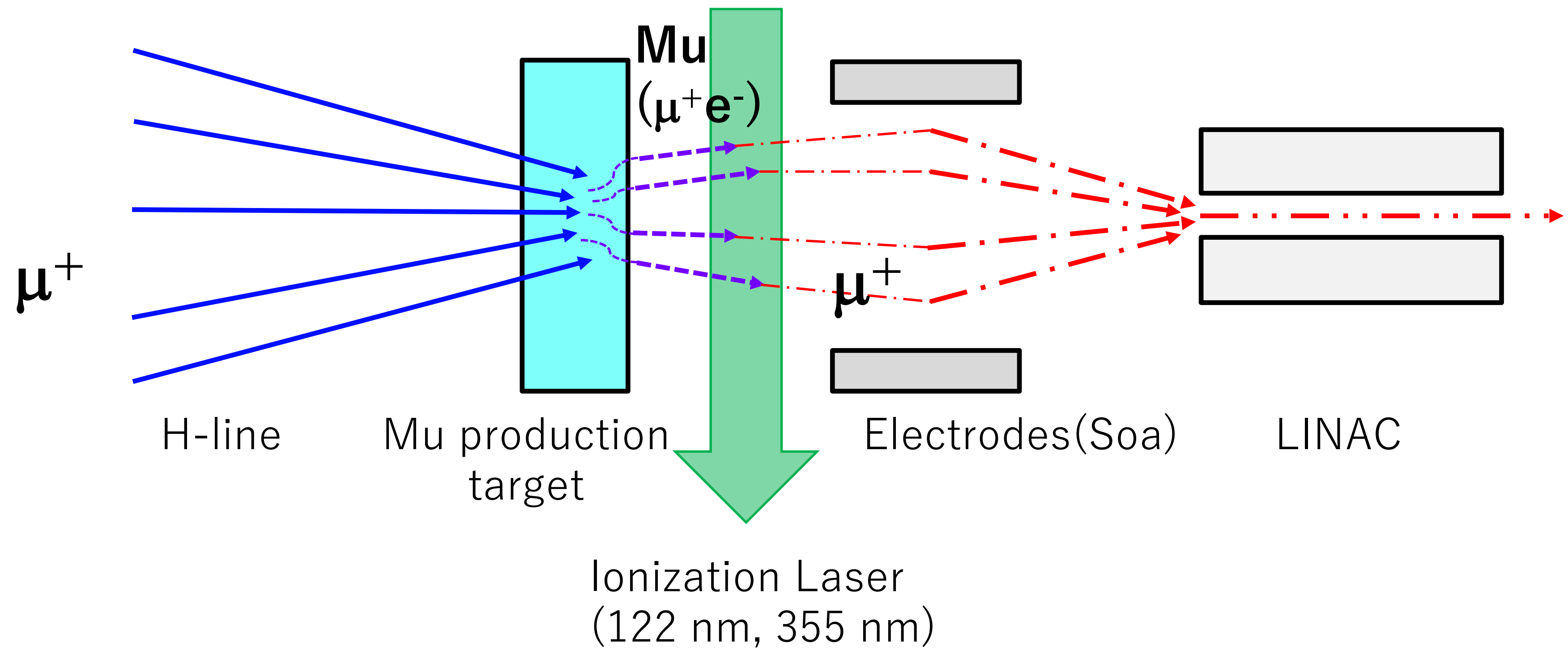
1π mm ･mrad

Free from any of these

Reaccelerated thermal muon

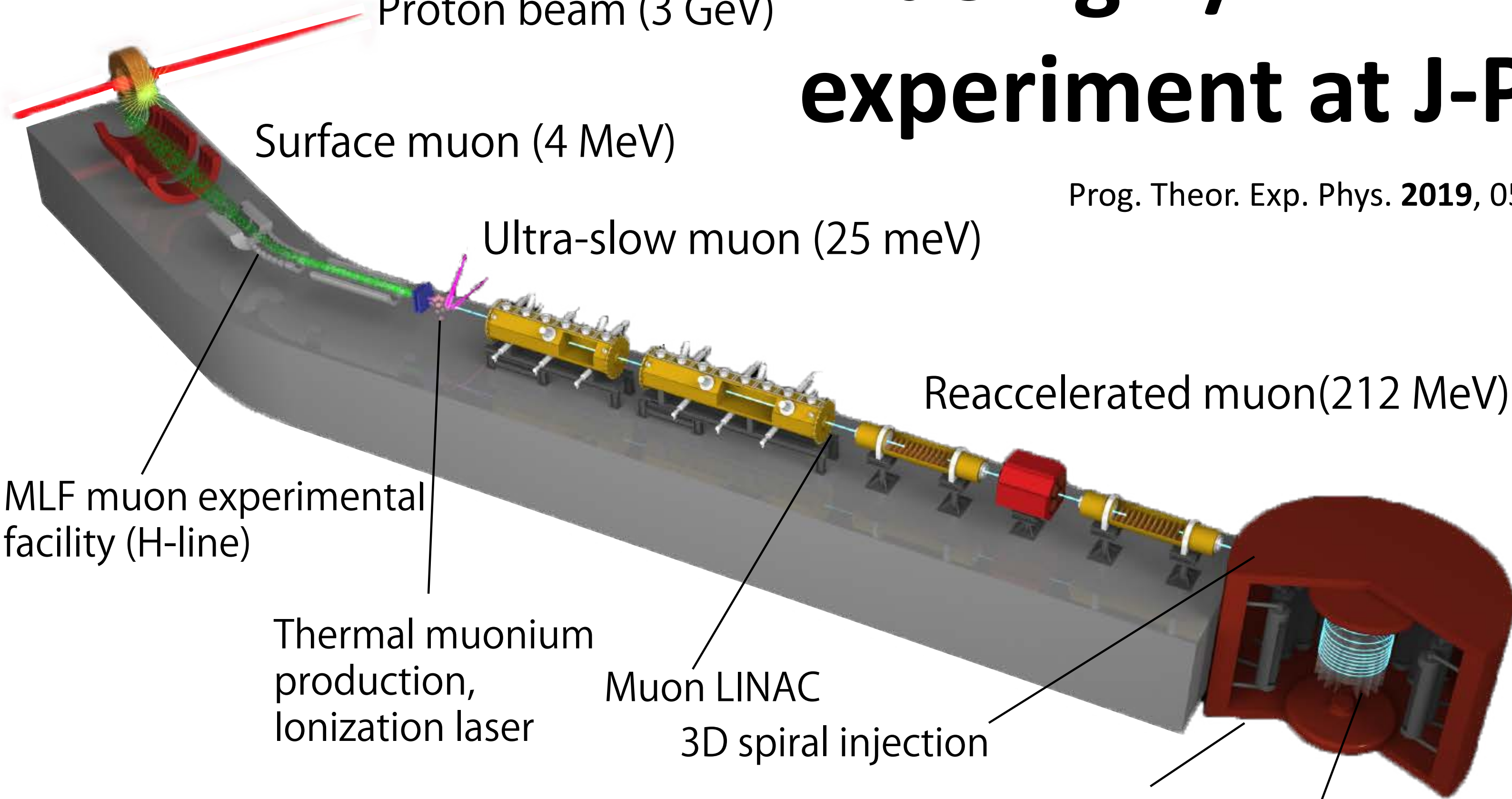
Re-accelerated thermal muon

	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	4×10^{-4}



Muon g-2/EDM experiment at J-PARC

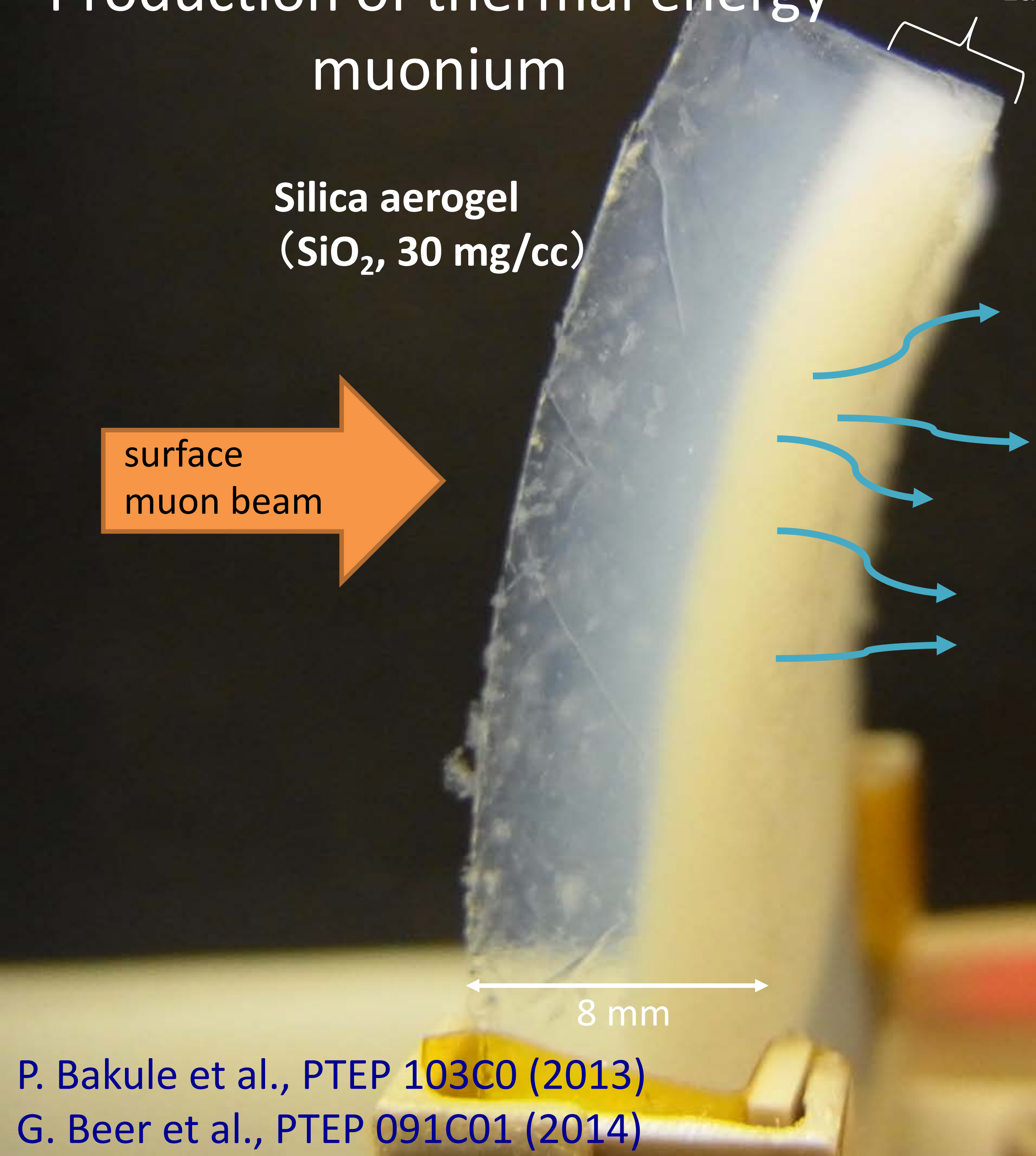
Prog. Theor. Exp. Phys. **2019**, 053C02 (2019)



Features:

- **Low emittance muon beam (1/100 of BNL)**
- **No strong focusing (1/1000) & good injection eff. (x10)**
- **Compact storage ring (1/20)**
- **Tracking detector with large acceptance**
- **Completely different from BNL/FNAL method**

Production of thermal energy muonium



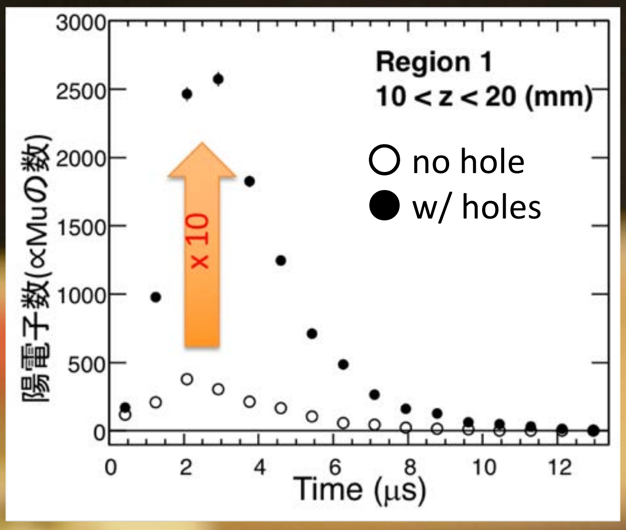
Muonium
(μ^+e^-)

Efficiency (measured)

3 x10^{-3}/μ

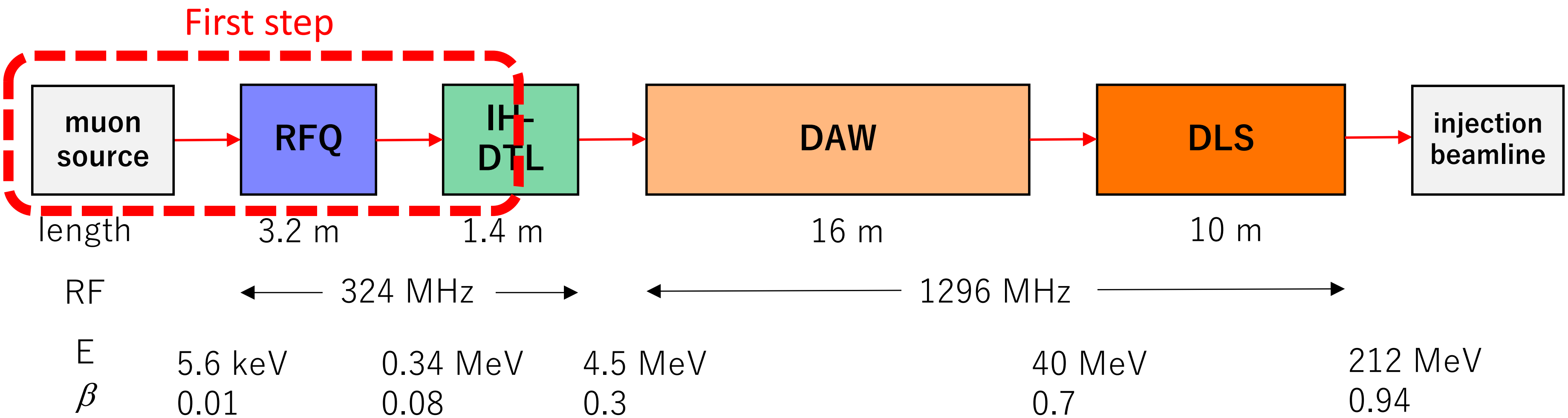
(laser region 5mm x 50mm)

Data taken at TRIUMF

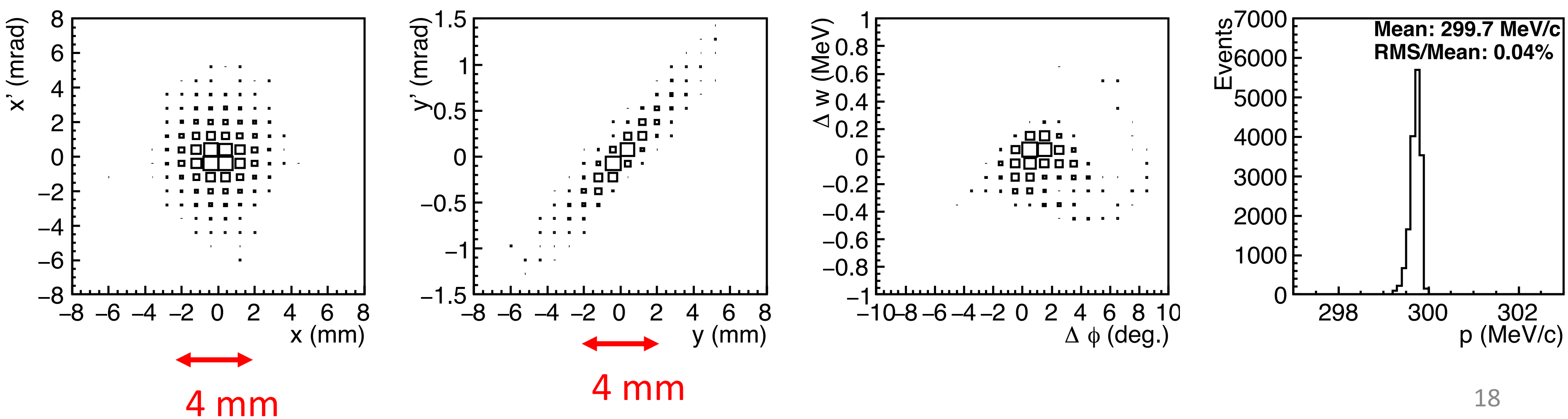


P. Bakule et al., PTEP 103C0 (2013)
G. Beer et al., PTEP 091C01 (2014)

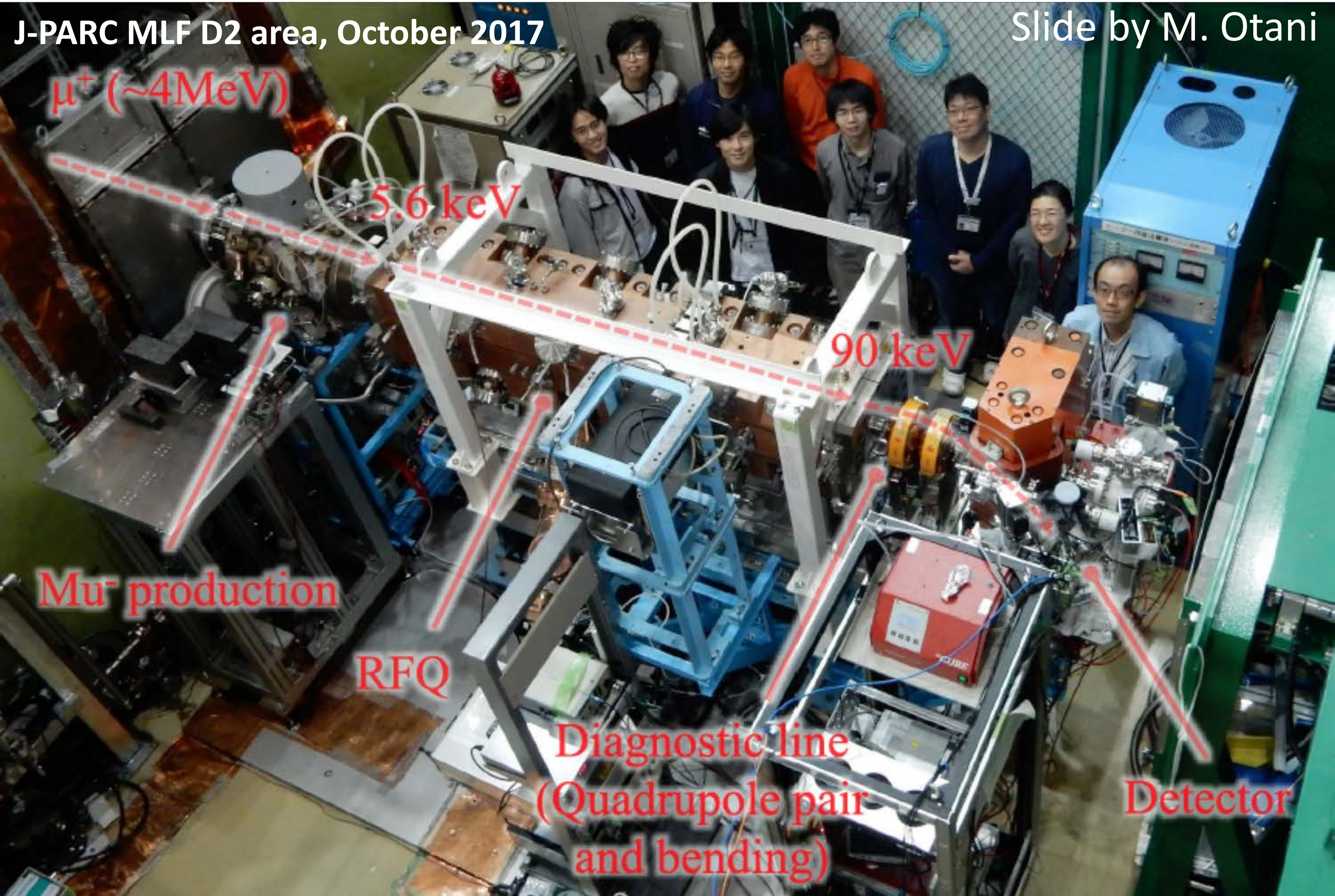
Muon LINAC



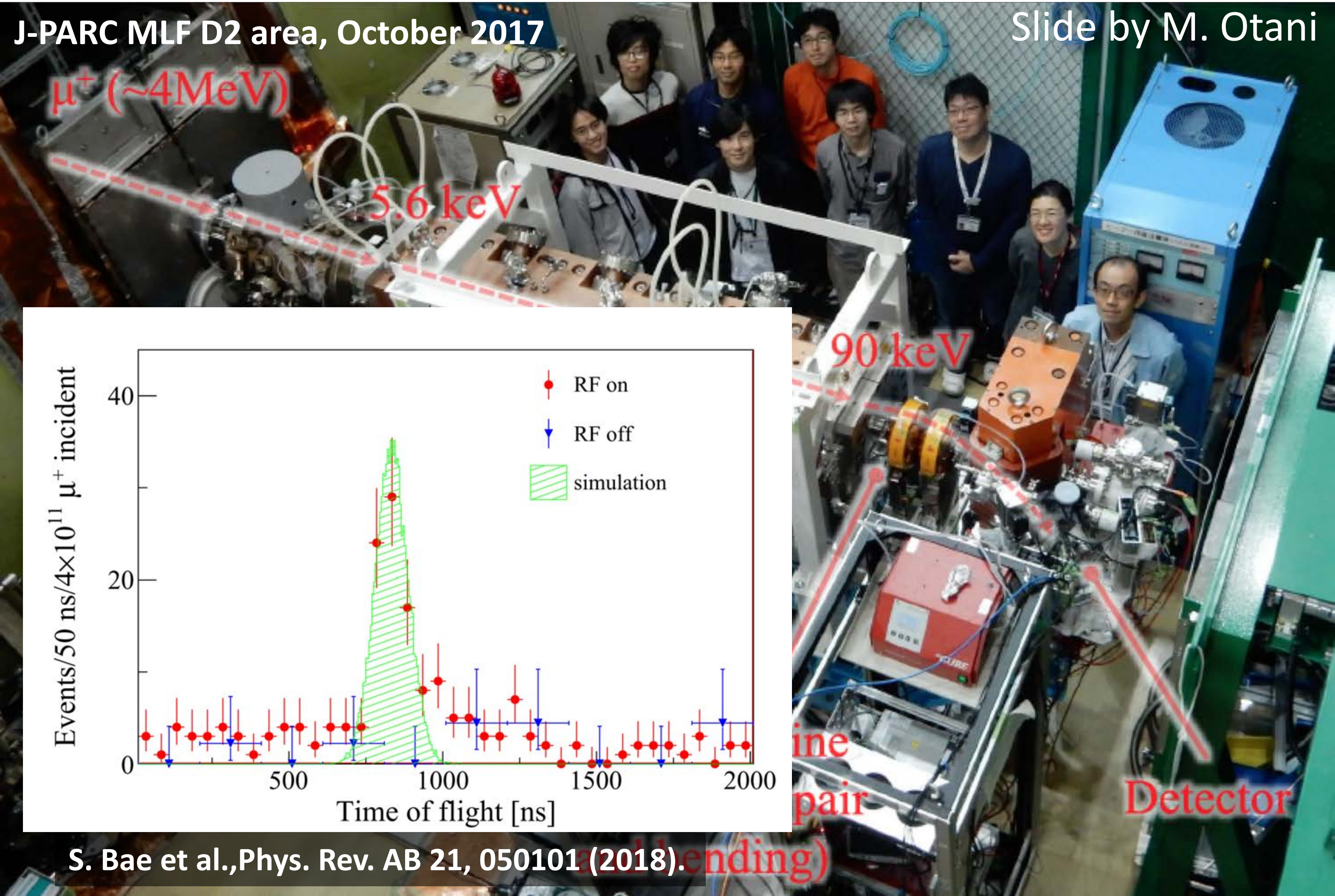
Phase space distributions after muon LINAC (simulation)



RF acceleration of Mu^- for the first time!

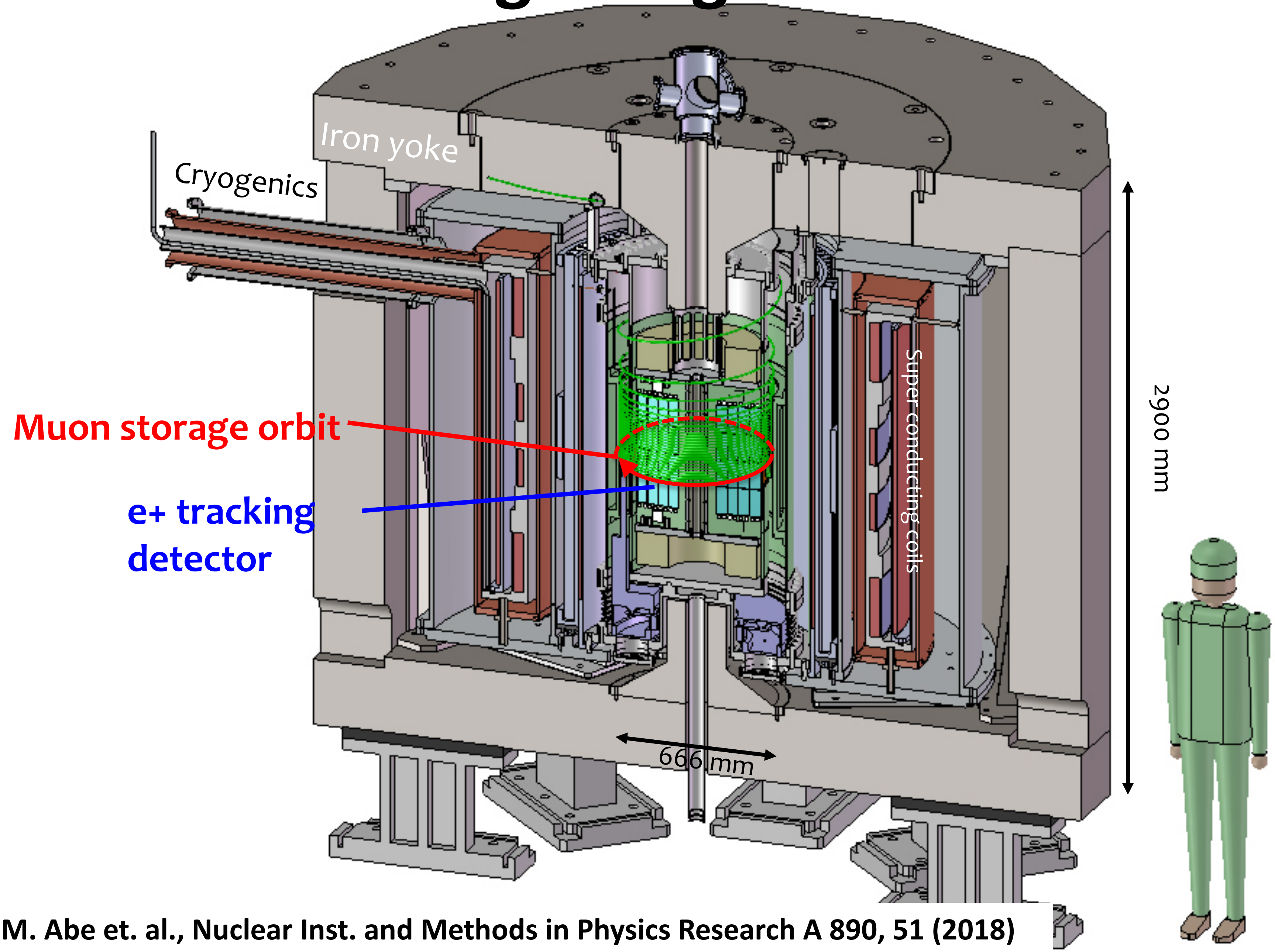


RF acceleration of Mu^- for the first time!



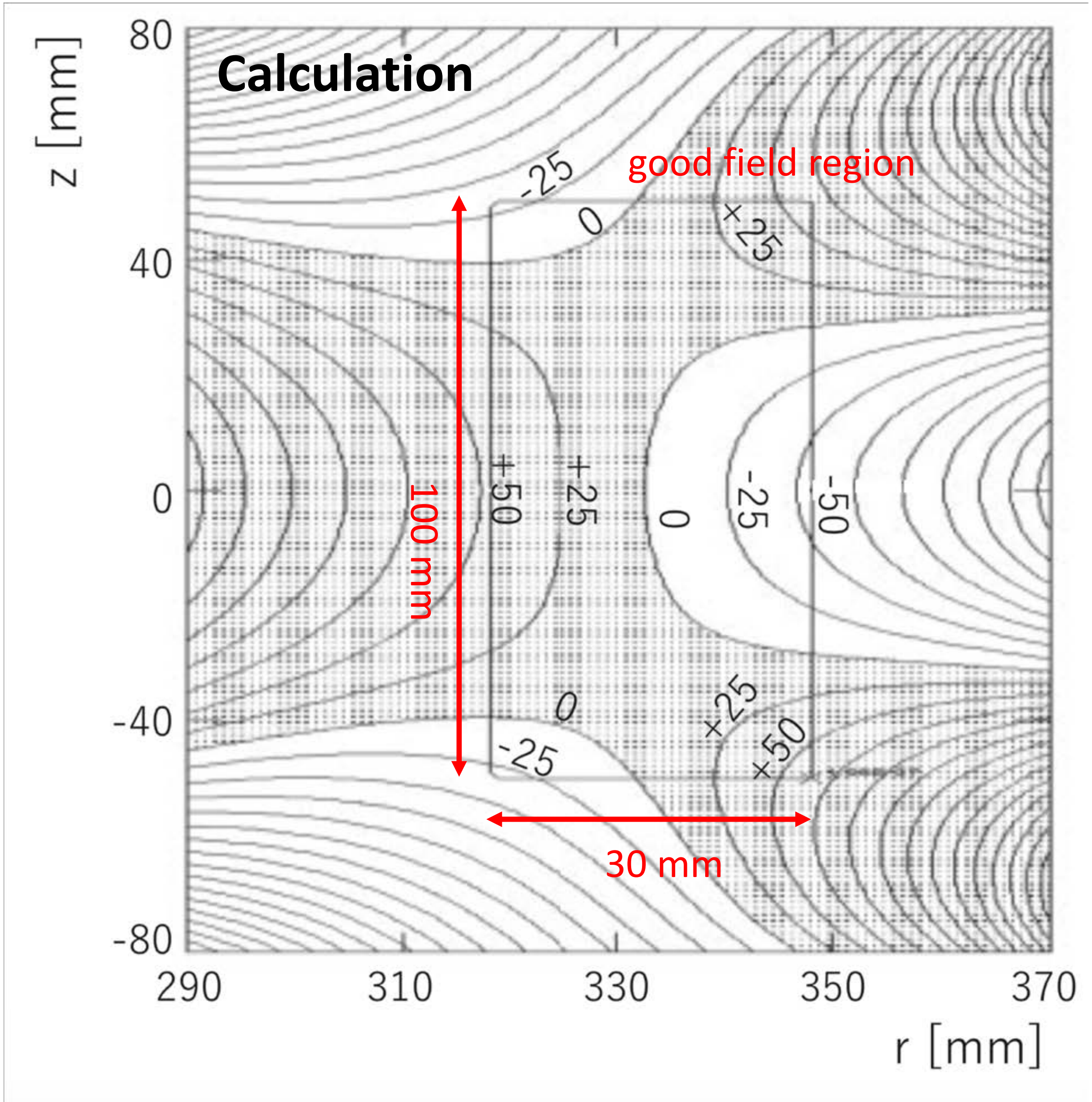
S. Bae et al.,Phys. Rev. AB 21, 050101 (2018).

Muon storage magnet and detector



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

Average magnetic field



25 ppb/line

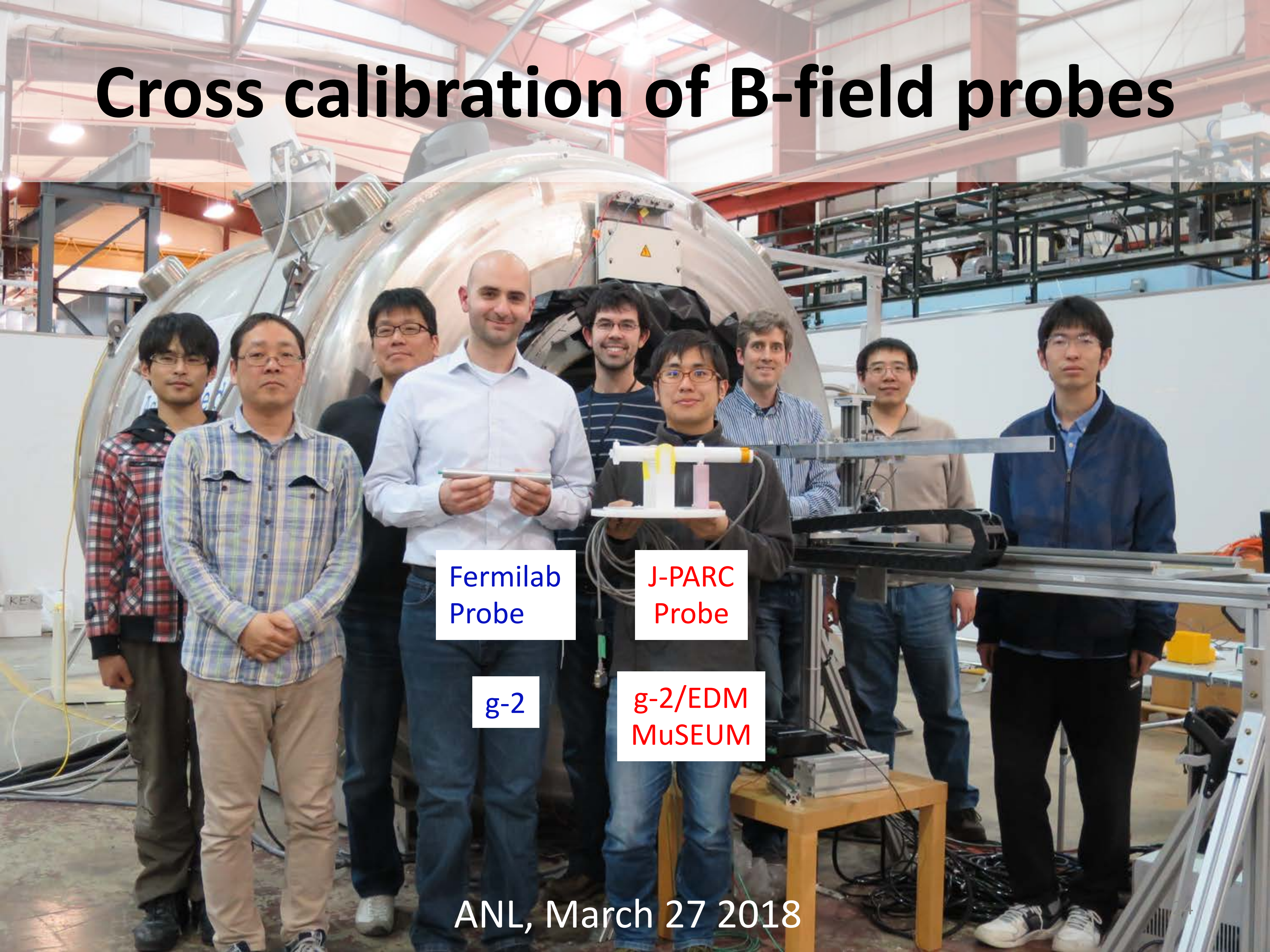
Comparison of experiments

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

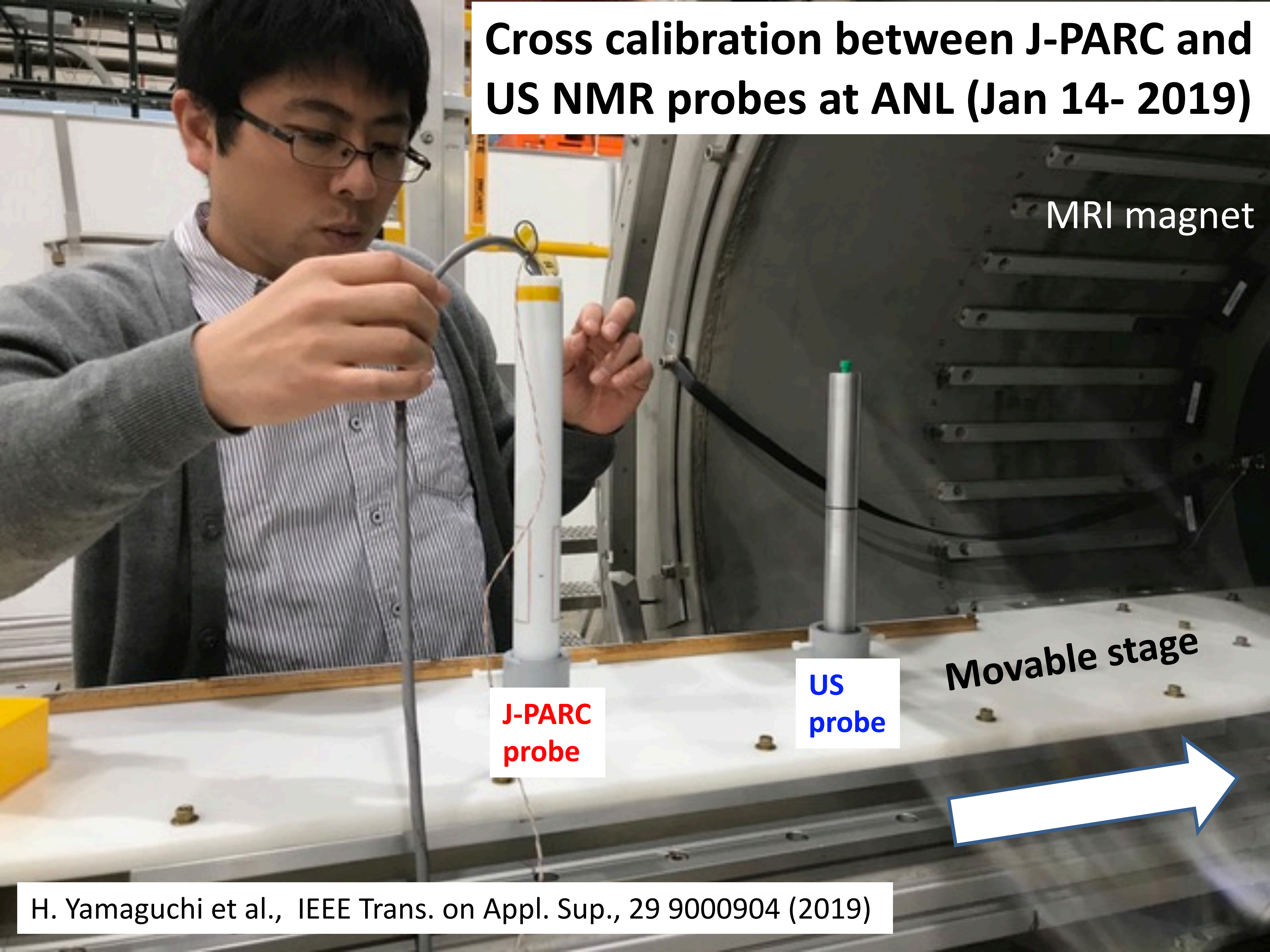
	BNL-E821	Fermilab-E989	Our experiment
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz γ	29.3		3
Polarization	100%		50%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric quadrupole		Very weak magnetic
Cyclotron period	149 ns		7.4 ns
Spin precession period	4.37 μs		2.11 μs
Number of detected 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.)	$0.2\times10^{-19}\ e\cdot$cm	–	$1.5\times10^{-21}\ e\cdot$cm
(syst.)	$0.9\times10^{-19}\ e\cdot$cm	–	$0.36\times10^{-21}\ e\cdot$cm
	Completed	**Running**	**In preparation**

Full approval by the lab (March, 2019)

Cross calibration of B-field probes

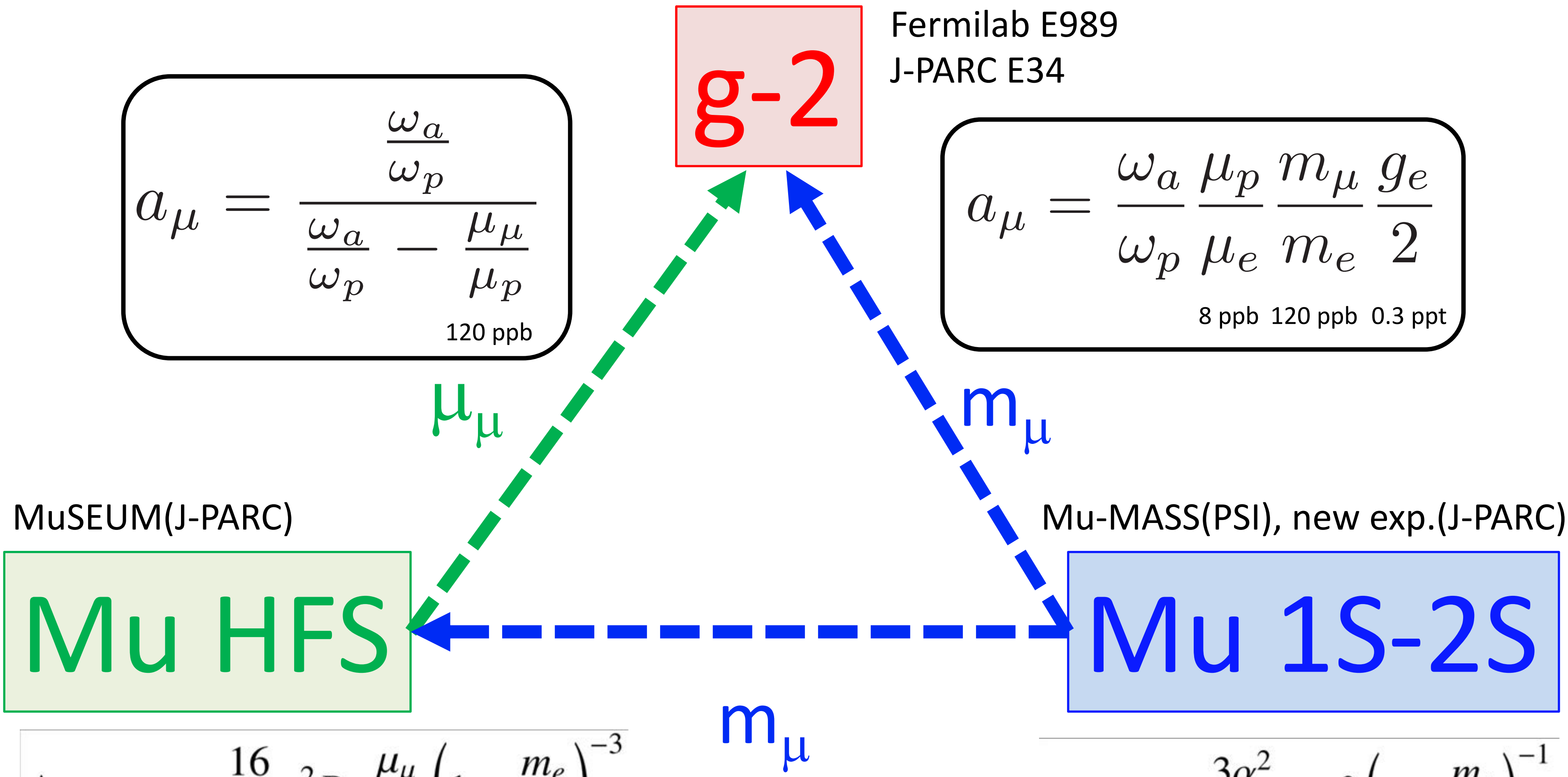


Cross calibration between J-PARC and US NMR probes at ANL (Jan 14- 2019)



H. Yamaguchi et al., IEEE Trans. on Appl. Sup., 29 9000904 (2019)

Muon g-2 and muonium spectroscopy



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

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

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

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

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

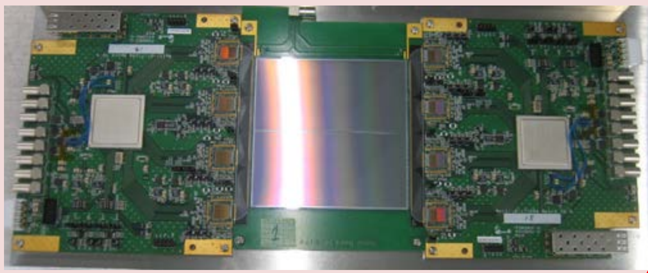
inspired by K. Jungmann's slide

Muon g-2 and muonium spectroscopy

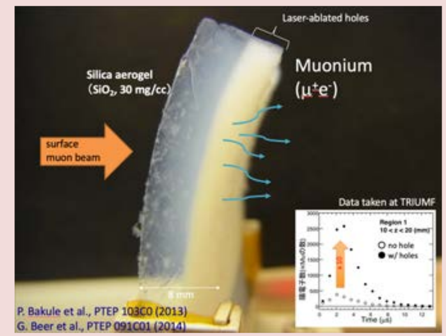
g-2

J-PARC E34

Silicon strip detector for e+ detection



Efficient muonium production target



MuSEUM(J-PARC)

Mu HFS

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

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

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

Mu 1S-2S

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

International School on muon g-2 and hadronic effects

August 23 - 28, 2020

Erbracher hof, Mainz, Germany

Previous school: Sep 17-21, 2018 @BINP

https://indico.inp.nsk.su/event/14/

Summary

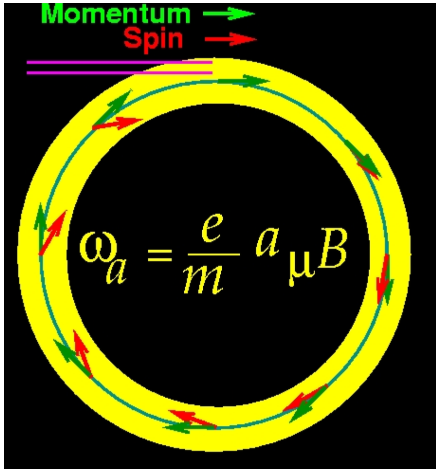
- Muon g-2/EDM offers rich physics cases to study beyond the standard model in **quantum loops**.

- **BNL muon g-2 results**
  - More than 3σ deviation from the SM.

- **Fermilab muon g-2 experiment** is taking physics run.
- **J-PARC muon g-2/EDM experiment** is in preparation with completely different method.

- **Many new results will come in next 5 years.**

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)

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

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

BNL/Fermilab systematic uncertainties ω_a

Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to ring	< 30
E and pitch	50	Improved tracker	
		Precise storage ring simulations	30
Total	180	Quadrature sum	70

BNL/Fermilab systematic uncertainties ω_p

Source of uncertainty	1999	2000	2001		E989
Systematics of calibration probes	50	50	50	→	35
Calibration of trolley probes	200	150	90	→	30
Trolley measurements of B_0	100	100	50	→	30
Interpolation with fixed probes	150	100	70	→	30
Uncertainty from muon distribution	120	30	30	→	10
Inflector fringe field uncertainty	200	–	–		–
Time dependent external B fields	–	–	–	→	5
Others †	150	100	100	→	30
Total systematic error on ω_p	400	240	170	→	70
Muon-averaged field [Hz]: $\omega_p/2\pi$	61 791 256	61 791 595	61 791 400		–

J-PARC g-2/EDM : expected uncertainties

Table 5. Summary of statistics and 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.)

Table 6. Estimated systmatic 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

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J-PARC g-2/EDM
Breakdown of efficiencies

Subsystem	Efficiency	Subsystem	Efficiency
H-line acceptance and transmission	0.16	DAW decay	0.96
Mu emission	0.0034	DLS transmission	1.00
Laser ionization	0.73	DLS decay	0.99
Metal mesh	0.78	Injection transmission	0.85
Initial acceleration transmission and decay	0.72	Injection decay	0.99
RFQ transmission	0.95	Kicker decay	0.93
RFQ decay	0.81	e^+ energy window	0.12
IH transmission	0.99	Detector acceptance of e^+	1.00
IH decay	0.99	Reconstruction efficiency	0.90
DAW transmission	1.00		

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