Mesurement of the Negative Muon Anomalous Magnetic Moment to 0.7 ppm

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New physics search

- Energy Frontier (High energy experiment)
  - LHC, ILC → observe new heavy particle **by direct production**

Complementary

- Luminosity Frontier (Precise experiment)
  - Muon physics
  - B physics
  - K physics
  - EDM search

  } observe new heavy particle **via loop process**

Key to identify a correct theory for NP

The muon (g-2) measurement is one of the most sensitive test of the SM.

Magnetic Moment

Magnetic moment

- Magnetic moment is a strength of coupling between a magnetic field and a charged particle with a spin.

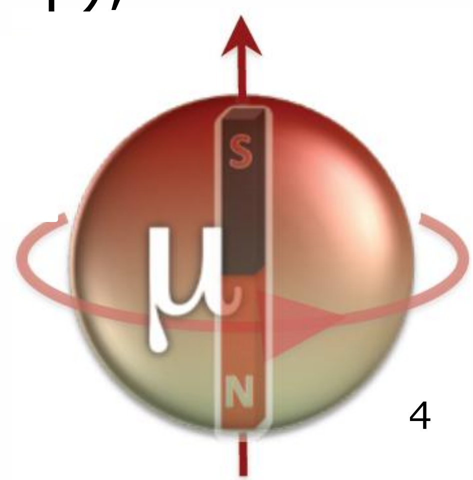
$$\vec{\mu} = g\frac{e}{2m}\vec{s}$$

Force from B $\vec{\tau} = \vec{\mu} \times \vec{B}$

Potential energy $U = -\vec{\mu} \cdot \vec{B}$

- In the case of μ and e(spin1/2, Dirac e.q.), we find

$$\vec{\mu} = g\frac{e}{2m}\vec{s} = g\frac{e}{2m}\frac{\vec{\sigma}}{2} \Rightarrow g = 2$$



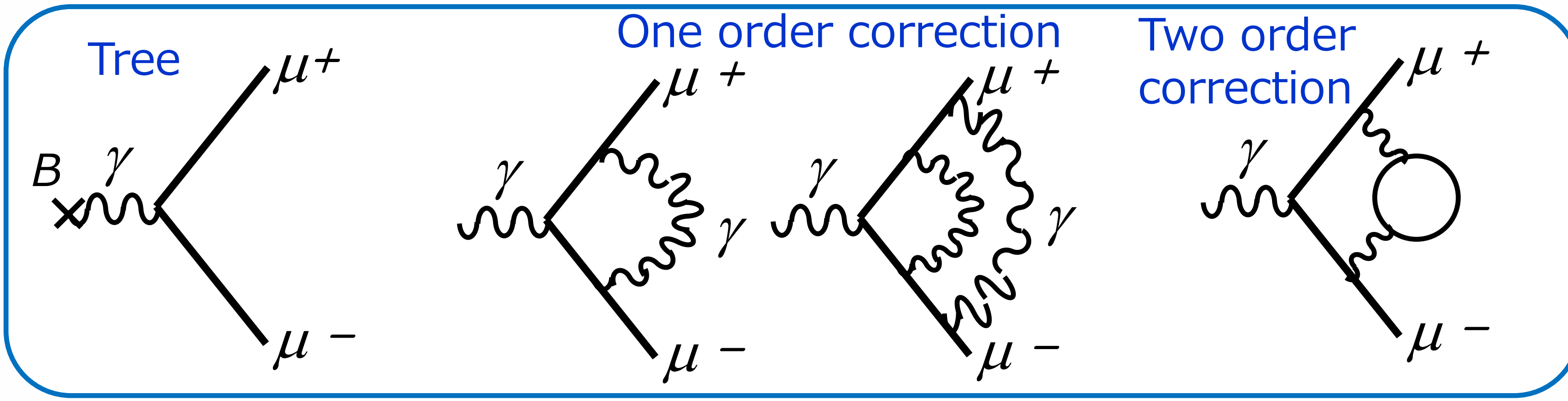
Anomalous magnetic moment

Gap between experiment result and "2"

g^{exp}= 2.0023318

Internal structure

→ Higher order correction



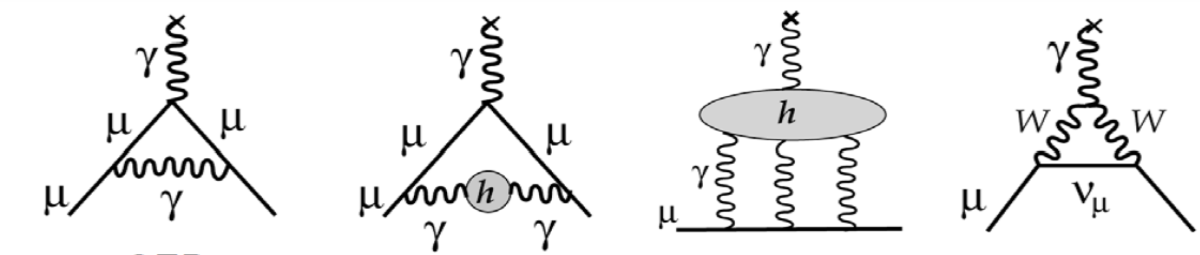
Anomalous magnetic moment

$$a = \frac{g-2}{2}$$

$$a^{QED} = C_1\left(\frac{\alpha}{\pi}\right) + C_2\left(\frac{\alpha}{\pi}\right)^2 + C_2\left(\frac{\alpha}{\pi}\right)^2 + \cdots \qquad \alpha = 1/137$$

Magnetic moment and New physics

- In the SM, there are corrections from QCD and EW as well as QED.



QED
Up to 5-loop leading
Kinoshita et al

Hadronic vacuum polarization (HVP)

Light-by-light scattering (LBL)

Electroweak at twe-loop level

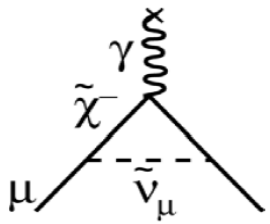
Precision of 0.6ppm =0.00006 % !!!!!!!!!!!!!!!!

- A measurement of a_μ provide one of the most sensitive test of the SM.

→ can be a breakthrough in reaching to beyond the SM.
(Because the mass is so much heavier than electron's there is larger contribution.)

Magnetic moment and New physics

- The a_μ is paticularly sensitive to SUSY(smuon-neutrarlino and sneutrino-chargino loops).



Beyond SM

- Large tanb
- Degenerate spectrum of superparticles with mass $\tilde{m}$

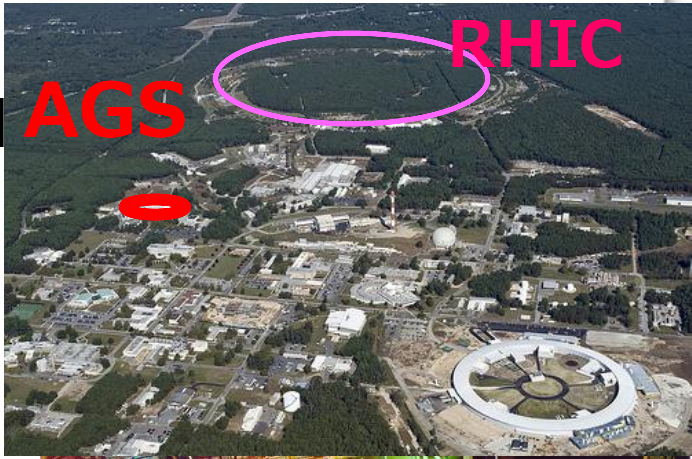
$$a_\mu(\text{SUSY}) \approx 140 \times 10^{-11} \left(\frac{100\ \text{GeV}}{\tilde{\text{m}}} \right)^2 \tan\beta$$

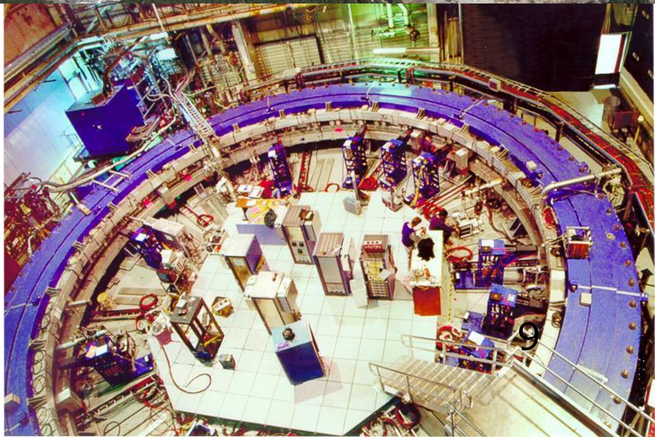
E-821

experiment

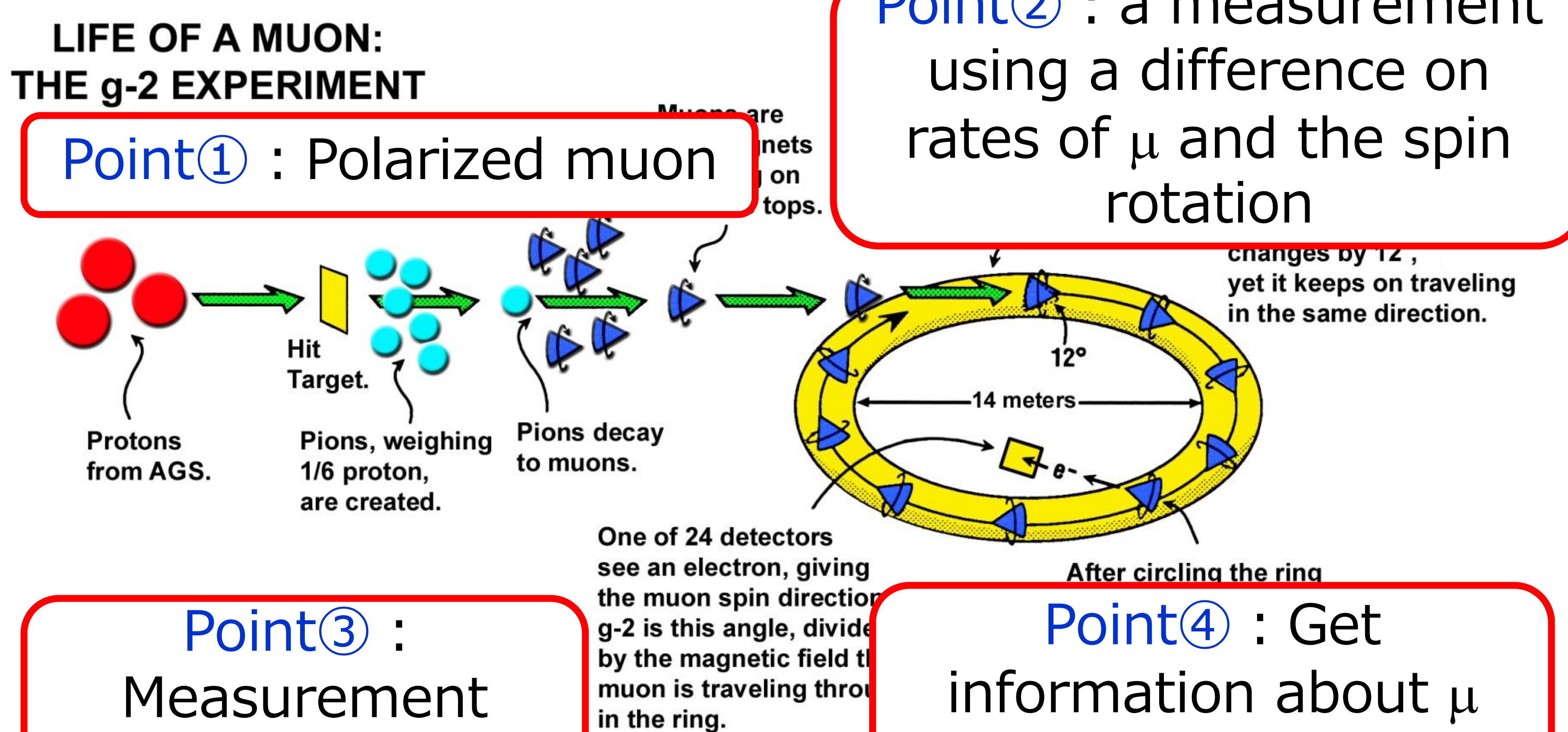
Brookhaven National Laboratory

- Located on Long Island, New York, Brookhaven
- RHIC(Relativistic Heavy Ion Collider)、2000-
  - First heavy ion accelerator
  - only spin-polarized proton collid
  - PHENIX experiment etc.
- AGS booster(Alternating Gradient Synchrotron)
  - Radius : 7.1m
  - B : 1.45 T





Experiment overview



Point① : Polarized muon

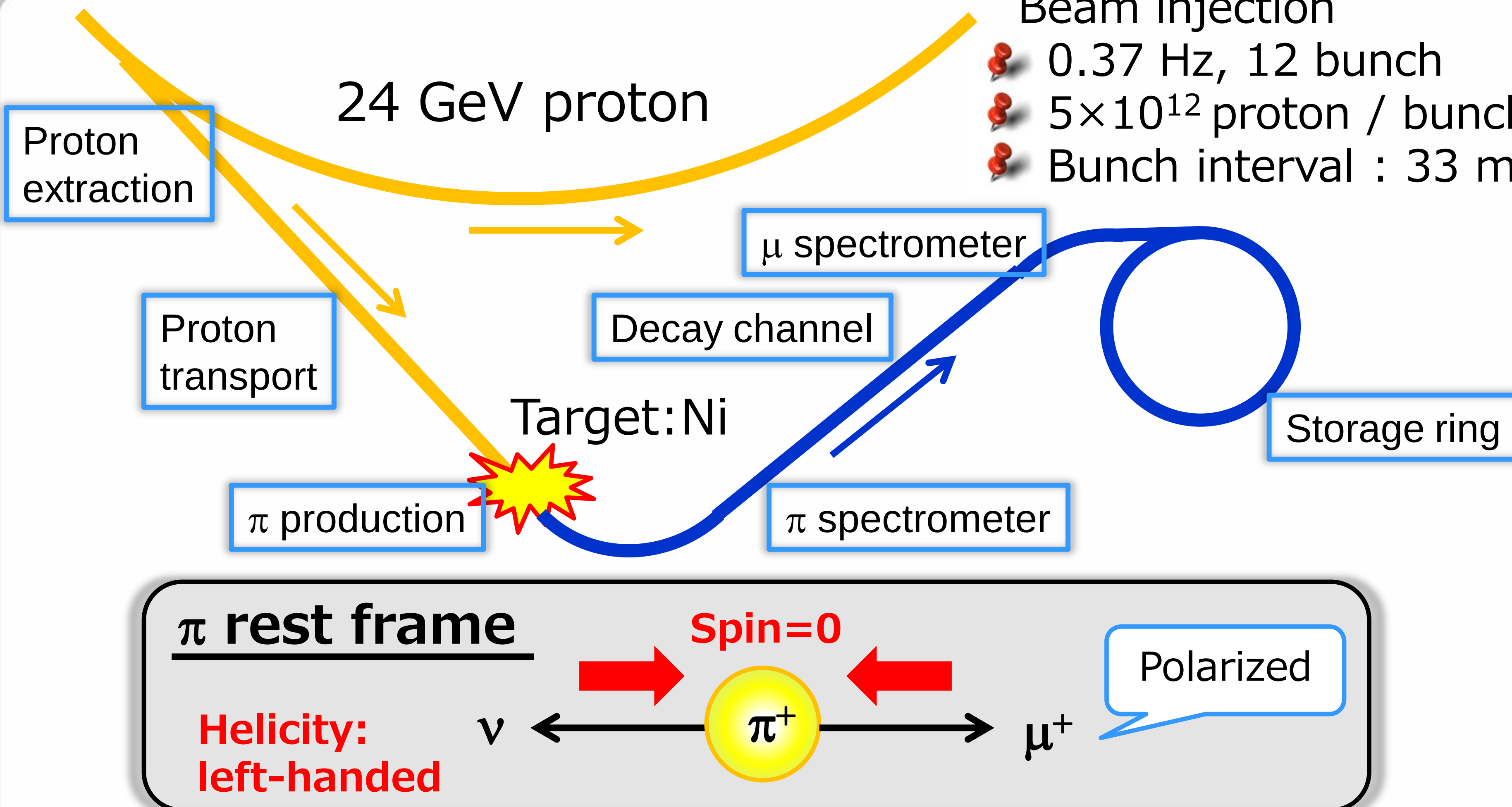
Point② : a measurement using a difference on rates of μ and the spin rotation

Point③ : Measurement magnetic field

Point④ : Get information about μ spin from decay e^+

Point① : Polarized muon

Beam injection
- 0.37 Hz, 12 bunch
- 5×10^{12} proton / bunch
- Bunch interval : 33 ms



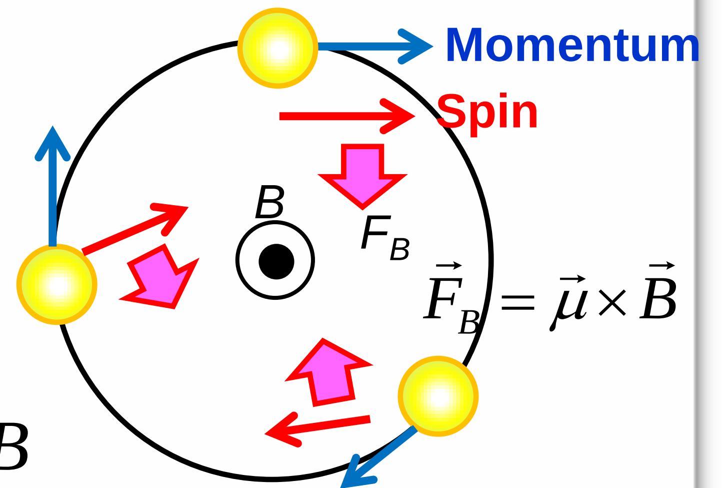
μ spin is initially lined up in the direction of the momentum.

Point② : Measurement principle

To measure a_μ,

- spin precession frequency(ω_s)
- cyclotron frequency(ω_c)
- angular frequency difference

($\omega_a = \omega_s - \omega_c$)



Larmor — Thomas

$$\vec{\omega}_s = g\frac{e}{2m}\vec{B} + (\gamma - 1)\frac{eB}{m\gamma}, \qquad \vec{\omega}_c = \frac{eB}{m\gamma}$$

$$\vec{\omega}_a = \gamma\left(\frac{g-2}{2}\right)\frac{e\vec{B}}{m\gamma} = a_\mu \frac{e\vec{B}}{m}$$

Considering the interaction with E to confine μ,

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

Point② : Measurement principle

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

- It is easier if the second term is disappeared.

$$a_\mu - \frac{1}{\gamma^2 - 1} = 0 \xrightarrow{a_\mu \approx 0.001166} \gamma = 29.3$$

$$\xrightarrow{\gamma = E/m} p_\mu = 3.094[GeV/c]$$

Magic momentum !

Accurate determination a_μ
= Accurate measurement of ***B* and ω_a**

Point② : Measurement principle

- Additional idea to get higher precision
  ⇒ use Larmor frequency of proton

$$\omega_a = a_\mu \frac{eB}{m_\mu} \qquad \omega_s = \frac{g_\mu}{2}\frac{eB}{m_\mu}$$ (Larmor precession)

$$a_\mu = \frac{\omega_a}{\omega_s - \omega_a} = \frac{\omega_a/\omega_p}{\omega_s/\omega_p - \omega_a/\omega_p} = \frac{R}{\lambda - R}$$

$$\lambda \equiv \frac{\omega_s}{\omega_p} = \frac{\mu_\mu}{\mu_p} = 3.18334539(10)$$

Utilize more sensitive result

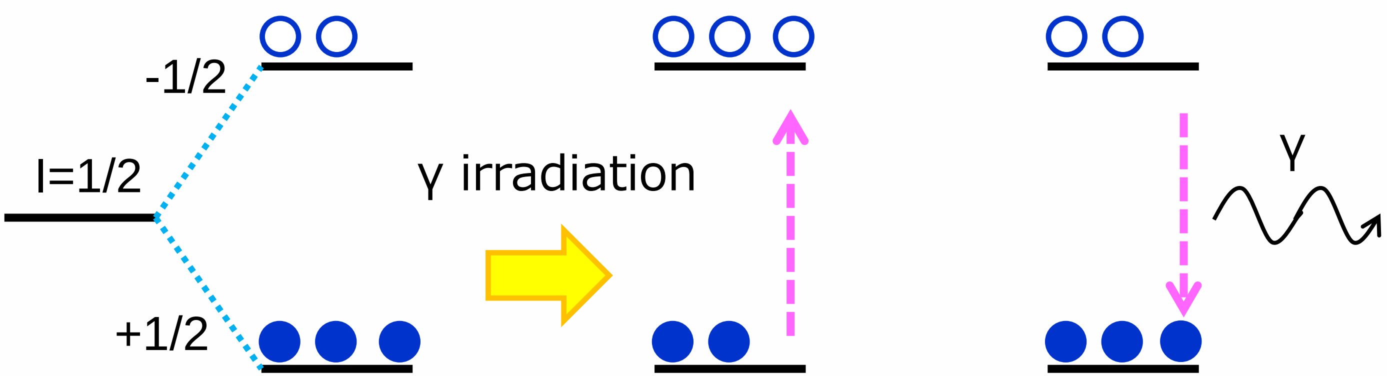
$$R \equiv \frac{\omega_a}{\omega_p}$$

These two are measured to obtain a_μ

Point③： Magnetic field measurement

NMR(Nuclear Magnetic Resonance)

- A proton sets up a magnetic field B and the energy level is split into two.



- This technique is used for MRI

$$\frac{\omega_p}{2\pi} = 61791400(11)Hz$$

Point④： Muon spin and detected e

- There is a correlation between μ spin direction and e emission direction due to the P violation.

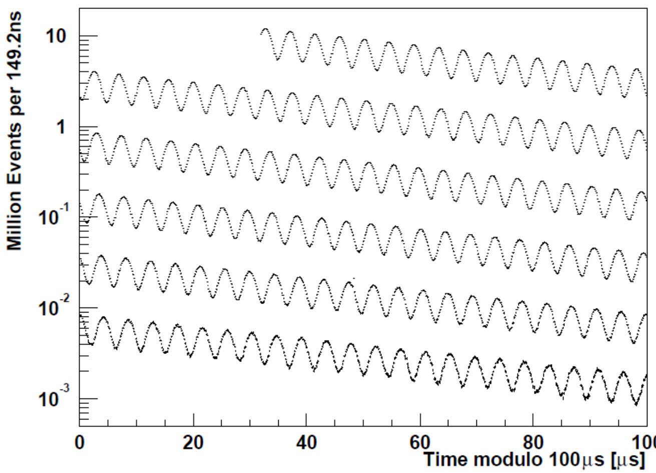
$$N = N_0 e^{(-t/\gamma\tau)}\{1 - A\cos(\omega_a + \phi)\} \qquad \gamma\tau = 64.4\mu s$$

[μ polarization(~95%)]×[asymmetry in μ-e decay]

e direction highly correlated to the muon spin direction

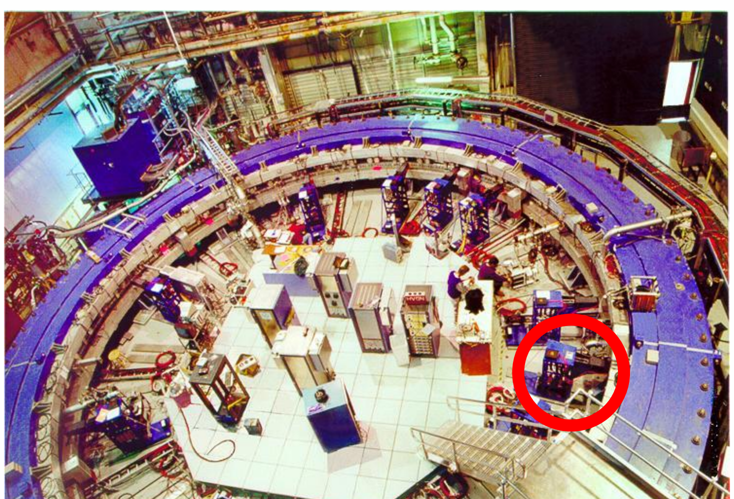
- Fitting to the time distribution of the detected electrons in a given energy bin.

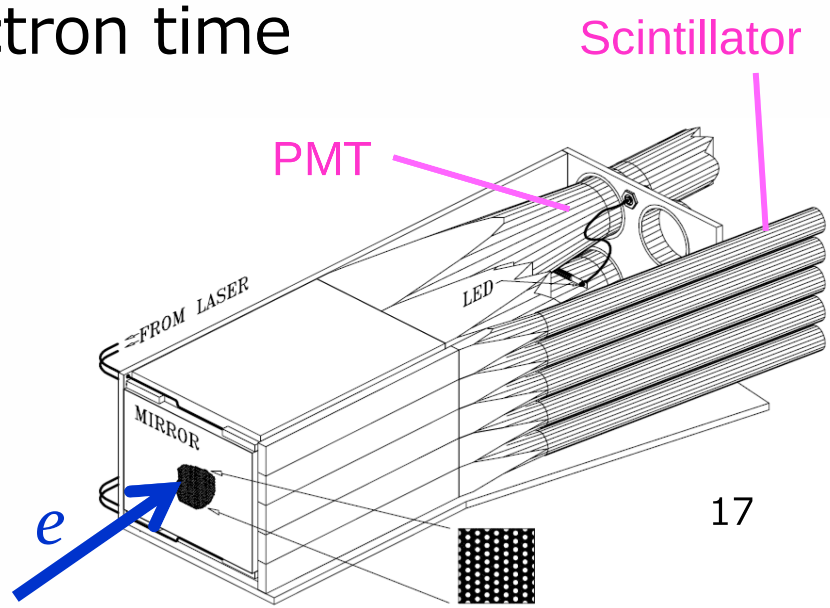
$$\frac{\omega_a}{2\pi} = 229073.59(15)(5)Hz$$



Point④： Detector

- Maximizes the acceptance of the high energy electron
- 24 detector stations(15 degree intervals)
  - Calorimeter → Electron energy
    - consists of scintillating fibers embedded in lead
    - depth:13X_0
  - 5 scintillator paddles → Electron time





Result

Result

Final result: $a_{\mu^-} = \dfrac{R}{\lambda - R} = 11659214(8)(3) \times 10^{-10} (0.7\, ppm)$

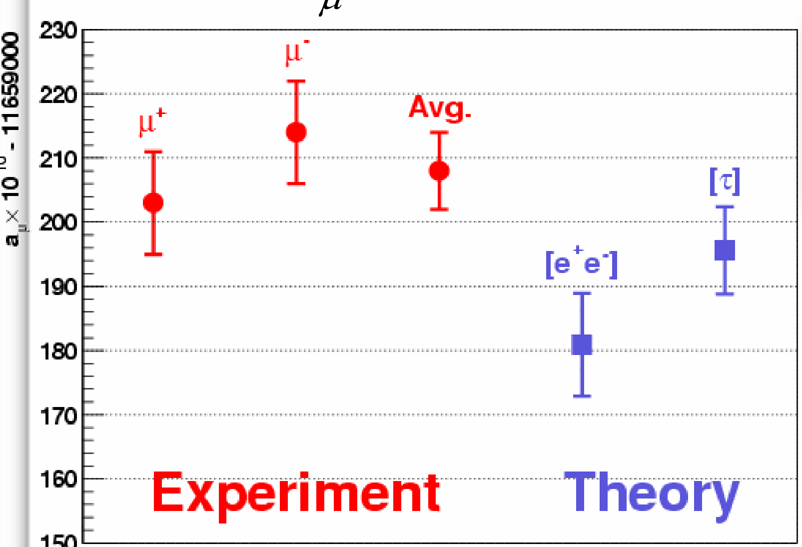
$$R_{\mu^-} = \frac{\omega_a}{\omega_p} = 0.0037072083(26)$$

Previous result

$$R_{\mu^+} = 0.0037072048(25)$$

Good agreement

CPT theorem



New average

$$a_\mu = 11659203(6) \times 10^{-10} (0.5\, ppm)$$

2.7σ deviation!!!

$$a_\mu(SM) = 11659181(8) \times 10^{-10} (0.7\, ppm)$$

Current situation

- SM prediction has been improved.

$$a_\mu^{SM} = 116591834(2)(41)(26)\times 10^{-11}$$

$$\Delta a_\mu = a_\mu^{\exp} - a_\mu^{SM} = 255(63)(49)\times 10^{-11}$$

3.2σ deviation!!!

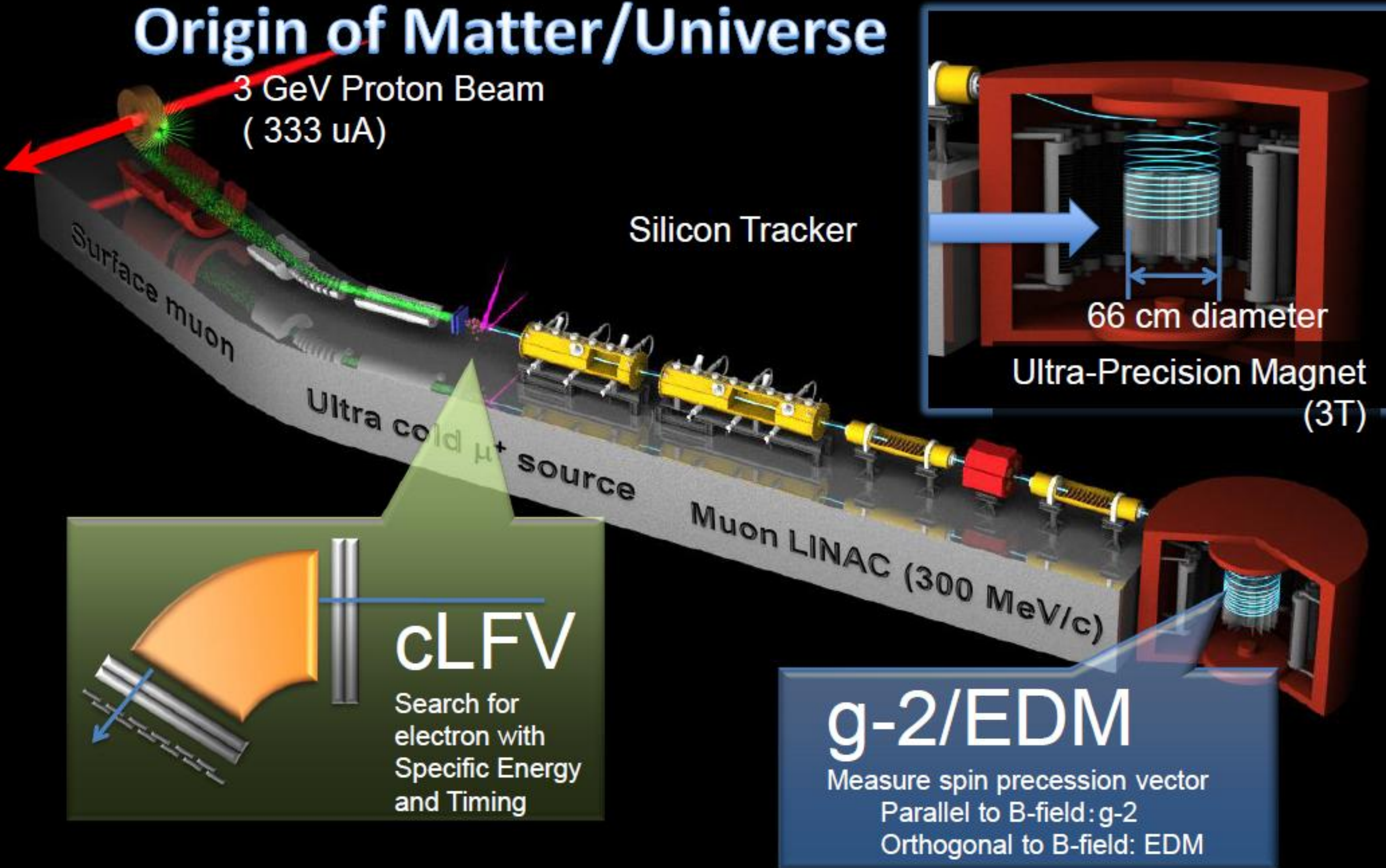
New experiment is needed to improve the experimental result.

Proposed experiment

	BNL-E821	Fermilab	J-PARC
Muon momentum	3.09 GeV/c		0.3 GeV/c
gamma	29.3		3
Storage field	B=1.45 T		3.0 T
Focusing field	Electric quad		None
# of detected μ+ decays	5.0E9	1.8E11	1.5E12
# of detected μ- decays	3.6E9	-	-
Precision (stat)	0.46 ppm	0.1 ppm	0.1 ppm

High Intensity Muon Beam for

Space-time Symmetry and Origin of Matter/Universe



g-2/EDM @J-PARK

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

- Measure the muon spin precession
- Off magic momentum with ultra-cold muon beam at 300 MeV/c
- Stored in ultra-precision B-field without E-field so that the β×E drops-> ω_aとω_dが直交になる→両方独立に測れる→Eをなくすのはchallenging
- Many technical challenges are undergoing

Summary

- The anomalous magnetic moment of the muon has played an important role in the search for BSM.

- This is the final analysis of the anomalous magnetic moment from E821.

$$a_{\mu} = 11659203(6) \times 10^{-10} (0.5\, ppm)$$

2.7σ deviation (current : 3.2σ)

- To improve the result some new experiments are proposed.