
# Past and future of the muon g–2 experiments

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**on behalf of the Muon g–2 Collaboration**

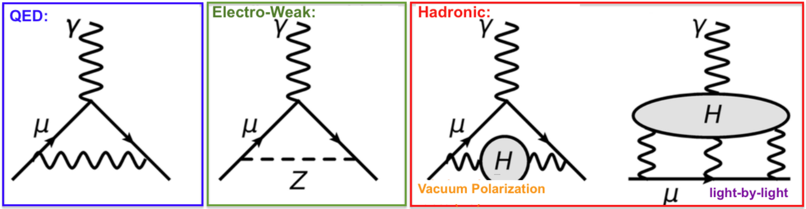
**LFC17: Old and New Strong Interactions from LHC to Future Colliders**
Trento, September 11 - 15, 2017

INFN Istituto Nazionale di Fisica Nucleare
$\mu$ g-2
Fermilab

# Interest in the muon anomaly

- $a_\mu$ could be used to test the Standard Model theory, which predicts:

$$\mathbf{a}_\mu^{\mathbf{SM}} = \frac{\mathbf{g}_\mu - 2}{2} = \mathbf{a}_\mu(\mathbf{QED}) + \mathbf{a}_\mu(\mathbf{EW}) + \mathbf{a}_\mu(\mathbf{Had}) = (\mathbf{116591802} \pm \mathbf{49}) \times \mathbf{10}^{-11}$$

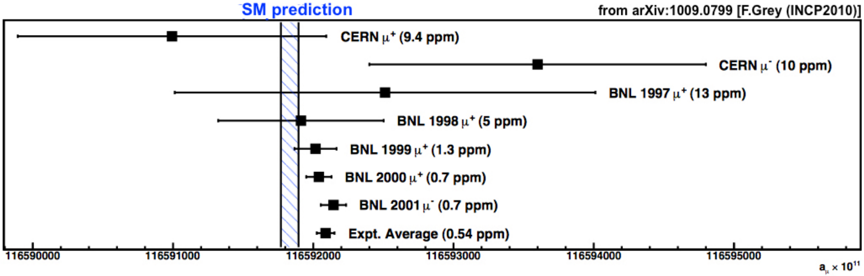



- A discrepancy with the SM value could be a hint of SUSY, dark photons, extra dimensions, or other new physics.

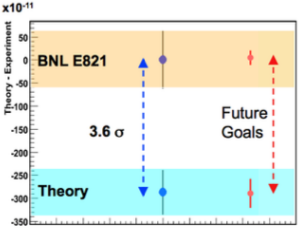
| | Val.±Err. ($\times 10^{-11}$) |
|---|---|
| QED | 116584718.951 ± 0.080 |
| EW | 153.6 ± 1 |
| Had: | |
| HVP (lo) | 6949 ± 43 |
| HVP (ho) | −98.4 ± 0.7 |
| HLbL | 105 ± 26 |

**SM Accuracy 420 ppb**

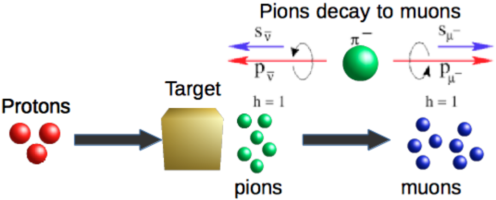
# History of the experimental measurement



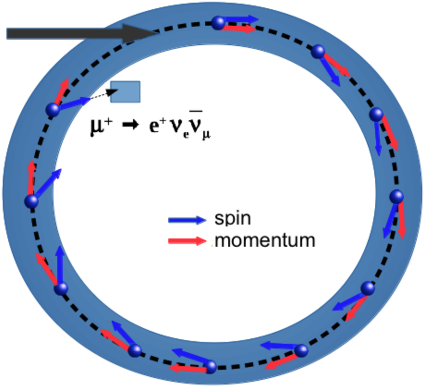

- current status: discrepancy $> 3\sigma$ between theoretical prediction (WA CODATA 2008) and experimental measurement (BNL E821 final report 2008)
- future:
  - **FNAL E989:** final goal of 140 ppb (commissioning run completed July, 2017)
  - **J-PARC E34:** initial goal of 340 ppb then 100 ppb (data-taking expected to begin in 2021)



# Measurement method




Polarized muons are injected into a magnetic storage ring and will precess in the magnetic field.

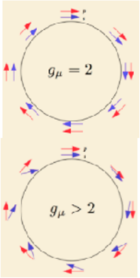



Precession Frequency is related to the muon anomaly:

$$\underbrace{\omega_a}_{\text{anomalous freq.}} = \underbrace{\omega_S}_{\text{Spin freq.}} - \underbrace{\omega_C}_{\text{Cyclotron freq.}}$$

$$= \frac{g_\mu eB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc} - \frac{eB}{mc\gamma}$$

$$= \left(\frac{g_\mu - 2}{2}\right)\frac{eB}{mc} = a_\mu \frac{eB}{mc}$$



# Measurement method

Anomalous freq. depends on electric and magnetic fields:

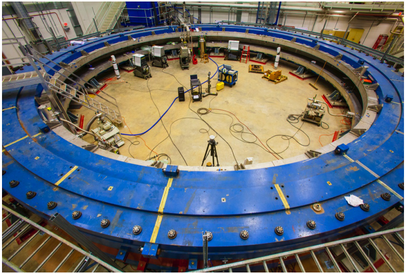
$$\vec{\omega}_a = -\frac{Qe}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

and two different approaches:

**CERN III, BNL E821, FNAL E989:**

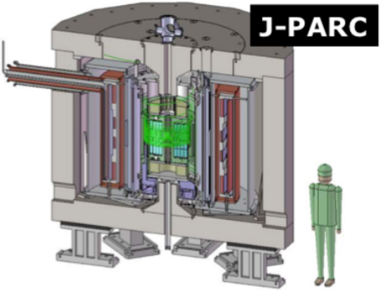
$p_\mu^{\text{magic}} = 3.094\text{GeV}/c \Rightarrow \gamma = 29.3$

$$\Rightarrow \boxed{\left(a_\mu - \frac{1}{\gamma^2-1}\right) \sim 0}$$



**J-PARC:**

$$E = 0 \Rightarrow \boxed{\vec{\beta}\times\vec{E} = 0}$$



# Final formula

In the final analysis the anomaly is extracted with:

$$a_\mu = \frac{\frac{g_e}{2}\frac{m_\mu}{m_e}\frac{\omega_a}{\overline{\omega}_p}}{\frac{\mu_e}{\mu_p}}$$

**Get from CODATA[3]:**

**$g_e$ = -2.002 319 304 361 82(52) (0.00026 ppb)**

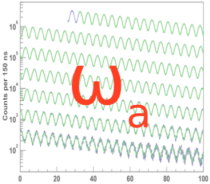
**$m_\mu/m_e$ = 206.768 2826(46) (22 ppb)**

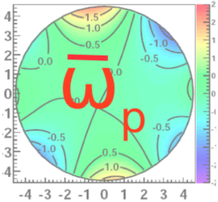
**$\mu_e/\mu_p$ = -658.210 6866(20) (3.0 ppb)**

[3] Rev. Mod. Phys. 88, no. 3, 035009 (2016) [arXiv:1507.07956]

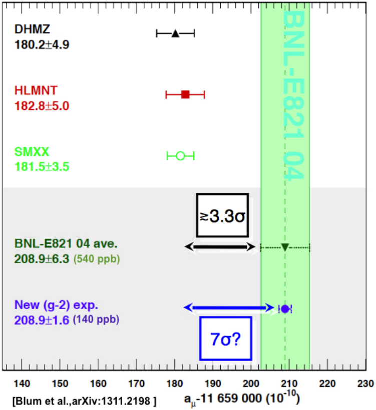
- $\omega_a$ anomalous spin precession frequency is extracted from decay positron time spectra
- $\overline{\omega}_p$ average magnetic field seen by the muons is measured by NMR
- $\delta a_\mu$ is determined by precision of $\omega_a$ and $\omega_p$ measurements:

| $\delta a_\mu$ | BNL (ppb) | FNAL goal (ppb) |
|---|---|---|
| $\omega_a$ statistic | 480 | 100 |
| $\omega_a$ systematic | 180 | 70 |
| $\omega_p$ systematics | 170 | 70 |
| Total | 540 | 140 |



# Muon g-2 Experiment at Fermilab




<u>Aim:</u> reduction of the experimental uncertainty by a <u>factor of 4</u> with respect to BNL result:

$$\delta(a_\mu)^{\text{exp.}} : 540 \text{ ppb} \rightarrow 140 \text{ ppb}$$

If $a_\mu$ value is confirmed (using current theory uncertainty):

$$a_\mu^{\text{FNAL}} - a_\mu^{\text{SM}} > 5\sigma$$

<u>FNAL improvements over BNL:</u>

- muon beam: more statistics and fewer pions thanks to FNAL accelerator
- improved detectors, stored muon beam dynamics, field uniformity, field measurement and calibration procedures

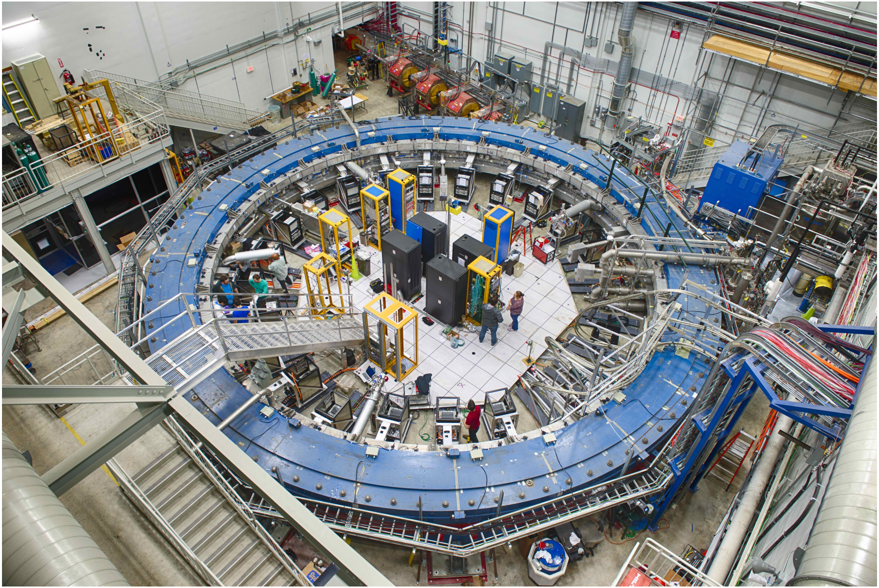
# Production of the muon beam

- **Recycler Ring:** 8 GeV protons from Booster are rebunched
- **Target Station:** protons are collided with the target e and $\pi^+$ with $p = 3.1$ GeV/$c$ ($\pm 10\%$) are collected
- **Beam Transfer and Delivery Ring:** in the decay line muons from the pion decay are selected, while in the circular ring the muons are separated from protons and pions
- **Muon Campus:** a beam of $\mu^+$ polarize is ready to be injected into the storage ring. We expect 21 times BNL statistics

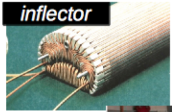
# Journey of the storage ring: from BNL to FNAL



# FNAL Muon g-2 Experimental Hall

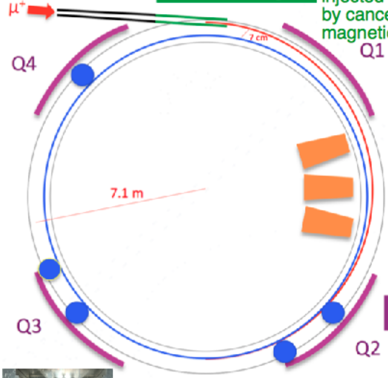


# Beam Injection




Inflector Magnet

allows muons to be injected into the ring by cancelling the magnetic flux return.

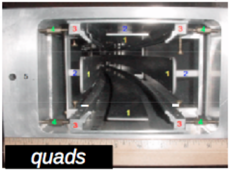




Kicker magnets

place the injected beam on the center of the storage ring's orbit.

Focussing quads

contain the beam vertically.



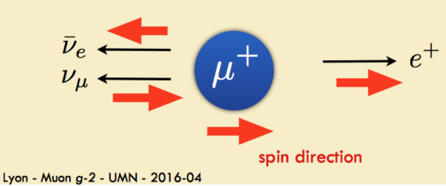


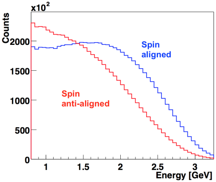
Collimators

Help remove off-momentum muons

# Measurement of $\omega_a$

Injected polarized muons decay: $\mu^+ \to e^+ + \nu_e + \nu_\mu$:



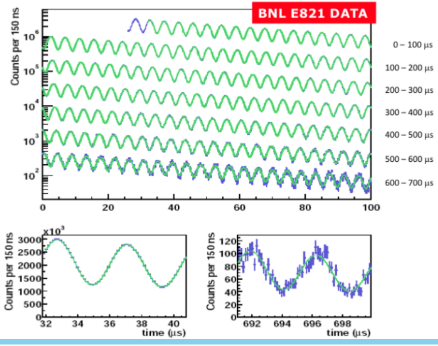




$\Rightarrow$ high energy $e^+$ are emitted with electron momentum direction strongly correlated with $\mu^+$ spin.

Counting the number of $e^+$ with $E_{e^+} > E_{\text{threshold}}$ as a function of time (wiggle plot) leads to $\underline{\omega_a}$:

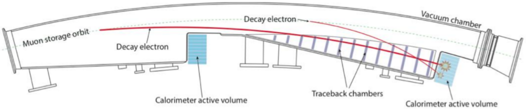
$$N(t) = N_0 e^{-t/\tau}[1 + A\cos(\omega_a t + \phi)]$$

$E_{e^+}$ and $t$ need to be measured.



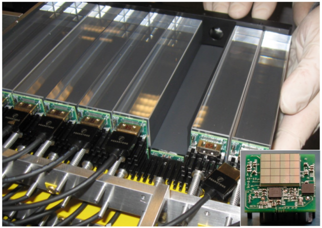
# Detectors for $\omega_a$ measurement

$e^+$ from $\mu$ decays curve inside the ring and hit the detectors:



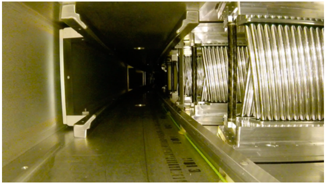

## 24 Calorimeters

- composed of 6×9 $PbF_2$ crystals with SiPM readout
- custom 800 MHz waveform digitizers
- laser calibration system



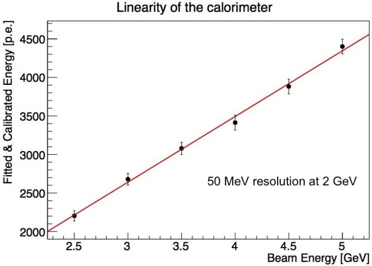
## Tracker systems

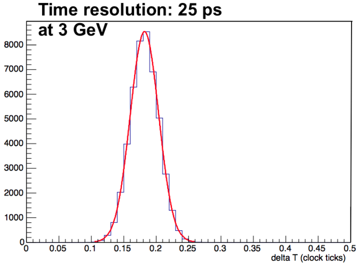
- planning to have 3 stations
- one station installed in front a of a calorimeter
- each station consist of 8 modules of $\sim$ 100 straws filled with $Ar{:}CO_2$

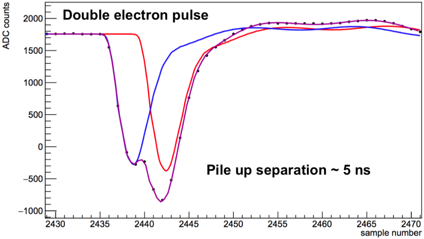


# Calorimeters performance at the Test Beam

June 2106: test of a calorimeter with custom waveform digitizers, laser calibration system and DAQ at SLAC TB facility.

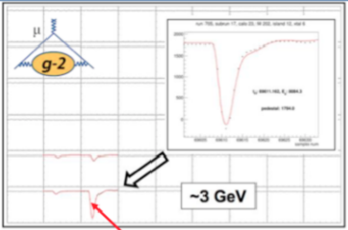


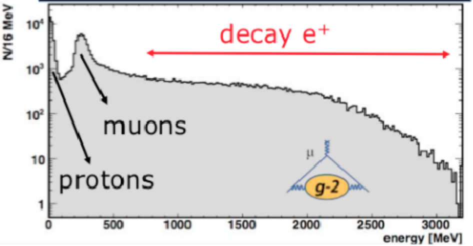

# Calorimeters performance during the June 2017 run

Calorimeter response to single positron



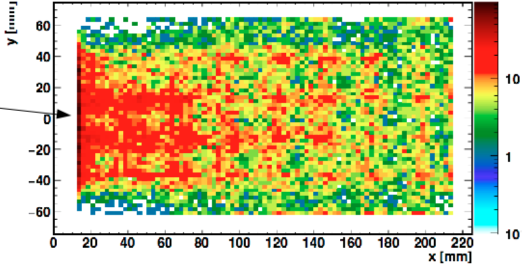

3 GeV $e^+$ in single crystal

Energy distribution recorded in a calorimeter




Spatial distribution of calorimeter clusters

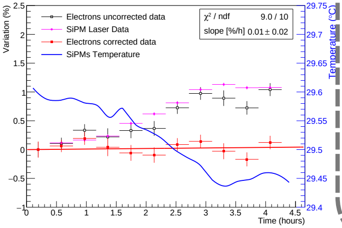
Majority of particle detected by the crystals near the storage ring



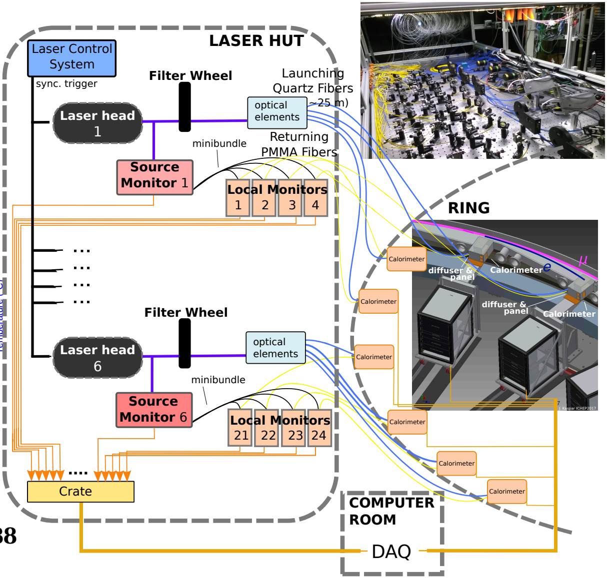
# Laser calibration system

**Purpose:**

- calorimeter gain stability monitoring
- calibration of the calorimeters at the sub-‰ level
- timing

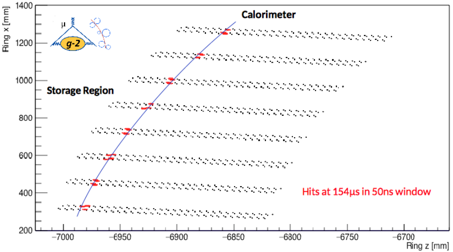



**Nucl.Instrum.Meth. A788 (2015) 43-48**



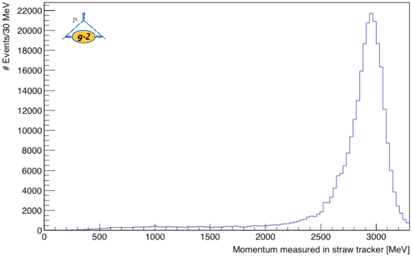
# Tracker performance during the June 2017 run

## Single charged particle trajectory

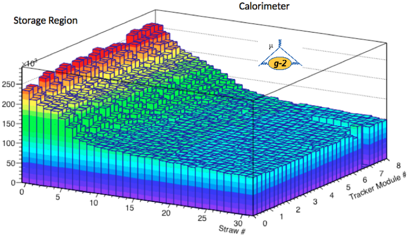



Trackers are useful to determine the spatial muon distribution and to study pileup in the calorimeters.

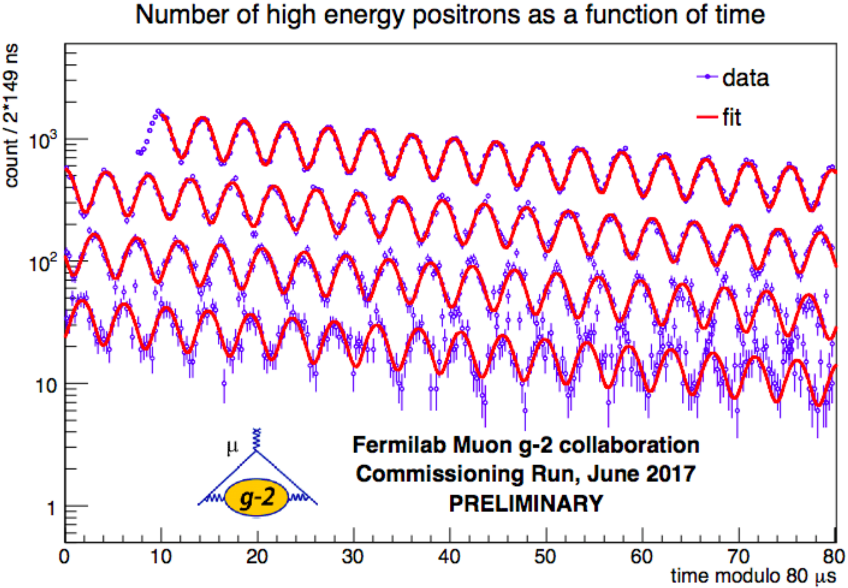
## Momentum of tracks




## Distribution of recorded hits

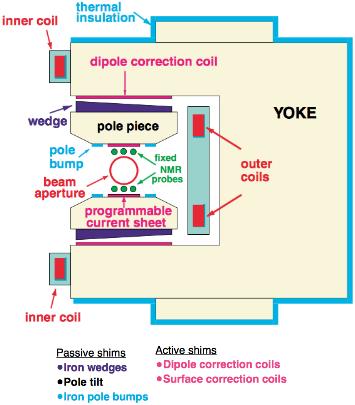


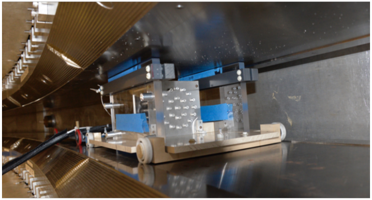
# First E989 wiggle plot



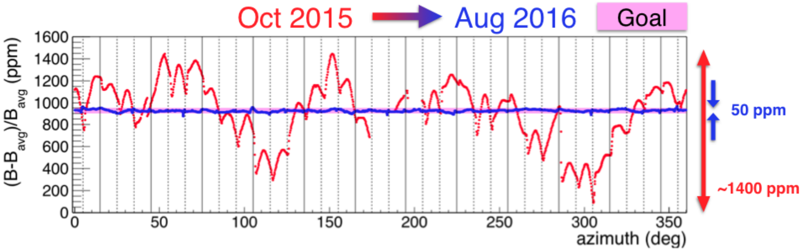
# $\omega_P$ Measurement

- $\omega_P$ is proportional to the magnetic field;
- magnetic field is created as uniform as possible (shimming procedure) and kept mechanically and thermally stable
- during data-taking the field is monitored by fixed NMR probes
- field is periodically mapped by a trolley that runs around the inside of the ring and calibrates the stationary probes

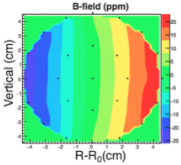


# Field Measurements

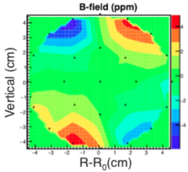



## Azimuthally-Averaged Map




| | Norm | Skew |
|---|---|---|
| Quad | 25.13 | -0.53 |
| Sext | -1.99 | -0.11 |
| Octu | -1.16 | -0.31 |
| Decu | 0.95 | -0.07 |

Oct 2015

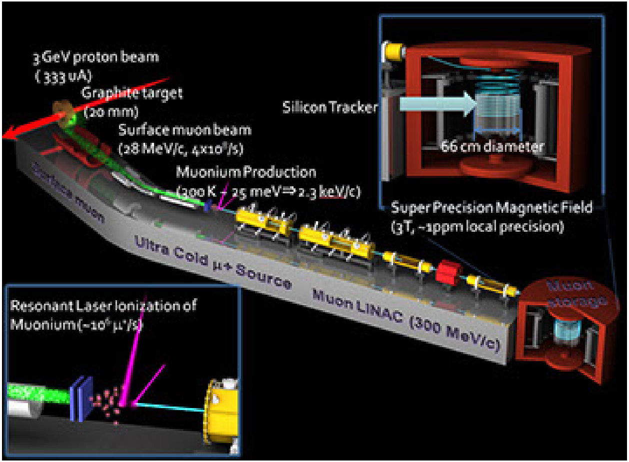



| | Norm | Skew |
|---|---|---|
| Quad | -0.02 | -0.57 |
| Sext | -0.70 | 3.84 |
| Octu | -0.76 | 0.56 |
| Decu | 0.44 | -1.61 |

Aug 2016

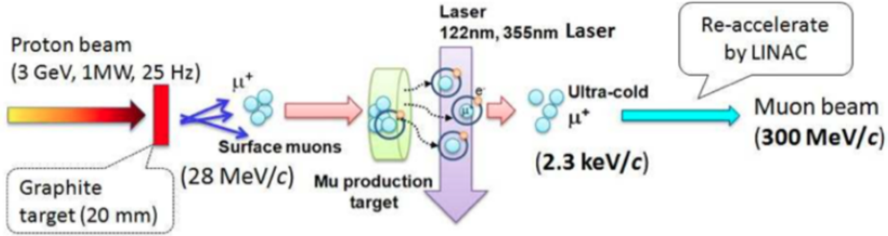
# Muon g-2 at J- PARC

- Phase 1: $a_\mu$ result with an uncertainty of 350 ppb
- new method with completely different systematic wrt FNAL measurement
- data taking in about four years




http://g-2.kek.jp/portal/index.html

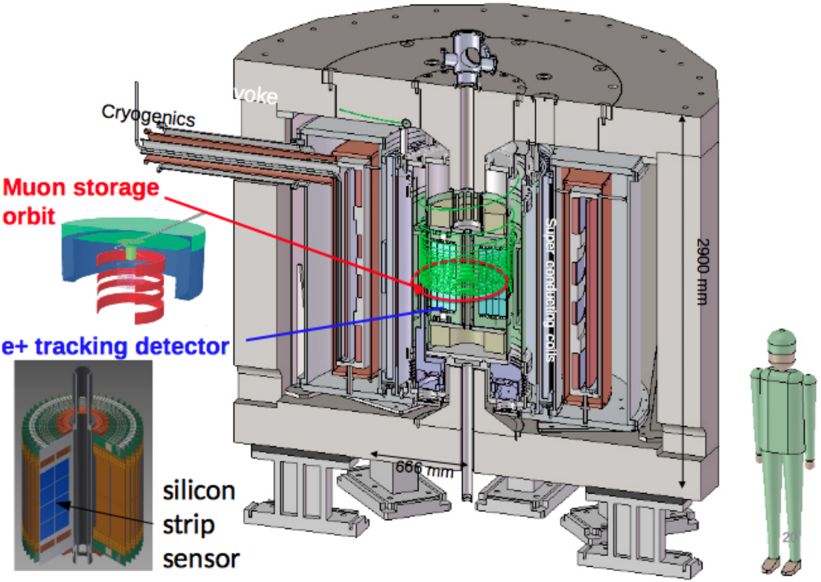
# J- PARC Muon beam




- ultra cold muons beam with 50% polarization
- $\Delta p_T/p_T < 10^{-5}$
- the 300 MeV muons are then injected into 3.0T, 33cm-radius solenoidal magnet

Picture from Journal of Physics: Conference Series 295 (2011) 012032

# J- PARC Storage Ring and Detector




Pictures from talk presented by Tsutomu Mibe at Muon g-2 Theory Initiative workshop, June 2017.

# Comparison between Muon g-2 BNL and J- PARC

| | BNL E821 | J-PARC E34 |
|---|---|---|
| muon momentum | 3.09 GeV/c | 0.3 GeV/c |
| storage ring radius | 7 m | 0.33 m |
| storage field | 1.5 T | 3.0 T |
| focusing field (n-index) | 0.14 (electric) | 1.5 E-4 (magnetic) |
| average field uniformity | ≈1 ppm | << 1ppm |
| (local uniformity) | ≈50 ppm | ≈1ppm |
| Injection | inflector + kick | spiral + kick |
| Injection efficiency | 3-5% | 80% |
| muon spin reversal | -- | pulse-to-pulse |
| positron measurement | calorimeters | tracking |
| positron acceptance* | 65% | ≈100% |
| muon polarization | ≈100% | ≈50% |
| events to 0.46 ppm | $9 \times 10^9$ | $5 \times 10^{11}$ |

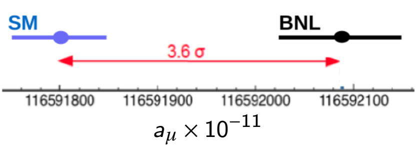
* in the energy region of interest

Table from talk presented by Tsutomu Mibe at Muon g-2 Theory Initiative workshop, June 2017.

# Summary and Conclusions

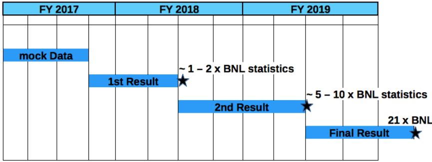
**2004:**

- BNL E821 final report announces a discrepancy $a_\mu^{exp}$ and $a_\mu^{theo} > 3\sigma$



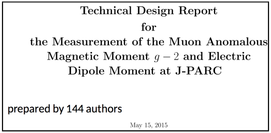

**2013:**

- begins the construction of FNAL E989
- the aim of the experiment is to measure $a_\mu$ with one-fourth of the BLN uncertainty
- finished the commissioning run in July, 2017 and plan on starting to collect more data this coming Fall/Winter
- a BNL level result is expected by late 2018




**2020:**

- J-PARC Muon g-2 experiment expect to begin data-taking
- new experimental method, complementary systematics


Technical Design Report
for
the Measurement of the Muon Anomalous Magnetic Moment $g-2$ and Electric Dipole Moment at J-PARC

prepared by 144 authors

May 15, 2015