Past and future of the muon g–2 experiments

Anna Driutti

INFN Trieste g.c. Udine & University of Udine

on behalf of the Muon g–2 Collaboration

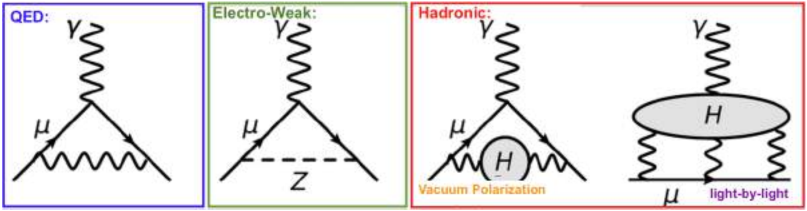
LFC17: Old and New Strong Interactions from LHC to Future Colliders

Trento, September 11 - 15, 2017

Interest in the muon anomaly

- a_μ could be used to test the Standard Model theory, which predicts:

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

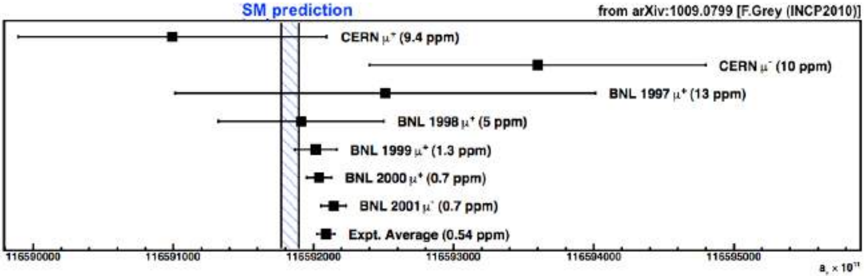


- A discrepancy with the SM value could be a hint of SUSY, dark photons, extra dimensions, or other new physics.

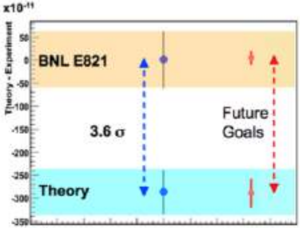
	Val.±Err. ($\times 10^{-11}$)
QED	116584718.951 ± 0.080
EW	153.6 ± 1
Had:	
HVP (lo)	6949 ± 43
HVP (ho)	−98.4 ± 0.7
HLbL	105 ± 26

SM Accuracy 420 ppb

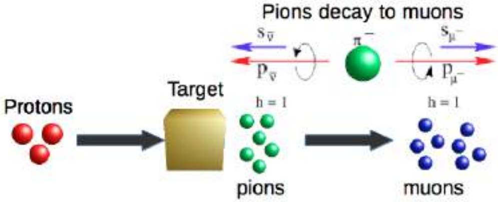
History of the experimental measurement



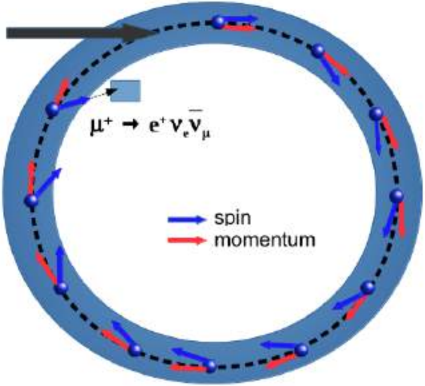
- current status: discrepancy $> 3\sigma$ between theoretical prediction (WA CODATA 2008) and experimental measurement (BNL E821 final report 2008)
- future:
  - **FNAL E989:** final goal of 140 ppb (commissioning run completed July, 2017)
  - **J-PARC E34:** initial goal of 340 ppb then 100 ppb (data-taking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



Measurement method



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

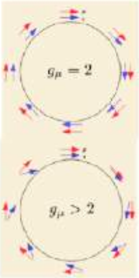


Precession Frequency is related to the muon anomaly:

$$\overbrace{\omega_a}^{\text{anomalous freq.}} = \overbrace{\omega_S}^{\text{Spin freq.}} - \overbrace{\omega_C}^{\text{Cyclotron freq.}}$$

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

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



Measurement method

Anomalous freq. depends on electric and magnetic fields:

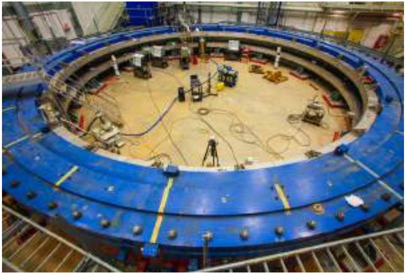
$$\vec{\omega}_a = -\frac{Qe}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

and two different approaches:

CERN III, BNL E821, FNAL E989:

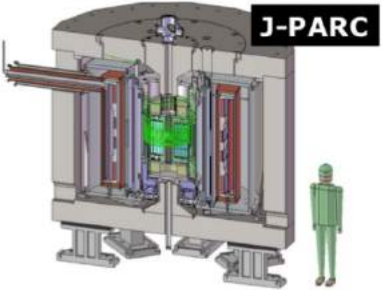
$p_\mu^{\text{magic}} = 3.094\text{GeV}/c \Rightarrow \gamma = 29.3$

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



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)

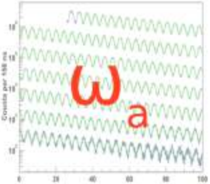
m_μ/m_e = 206.768 2826(46) (22 ppb)

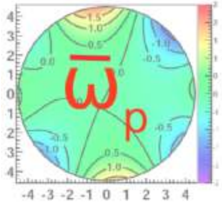
μ_e/μ_p = -658.210 6866(20) (3.0 ppb)

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

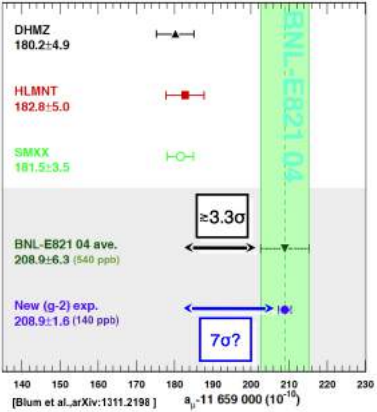
- ω_a anomalous spin precession frequency is extracted from decay positron time spectra
- $\overline{\omega}_p$ average magnetic field seen by the muons is measured by NMR
- δa_μ is determined by precision of ω_a and ω_p measurements:

δa_μ	BNL (ppb)	FNAL goal (ppb)
ω_a statistic	480	100
ω_a systematic	180	70
ω_p systematics	170	70
Total	540	140





Muon g-2 Experiment at Fermilab



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

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

If a_μ value is confirmed (using current theory uncertainty):

$$\mathbf{a}_\mu^{\mathbf{FNAL}} - \mathbf{a}_\mu^{\mathbf{SM}} > \mathbf{5}\sigma$$

FNAL improvements over BNL:

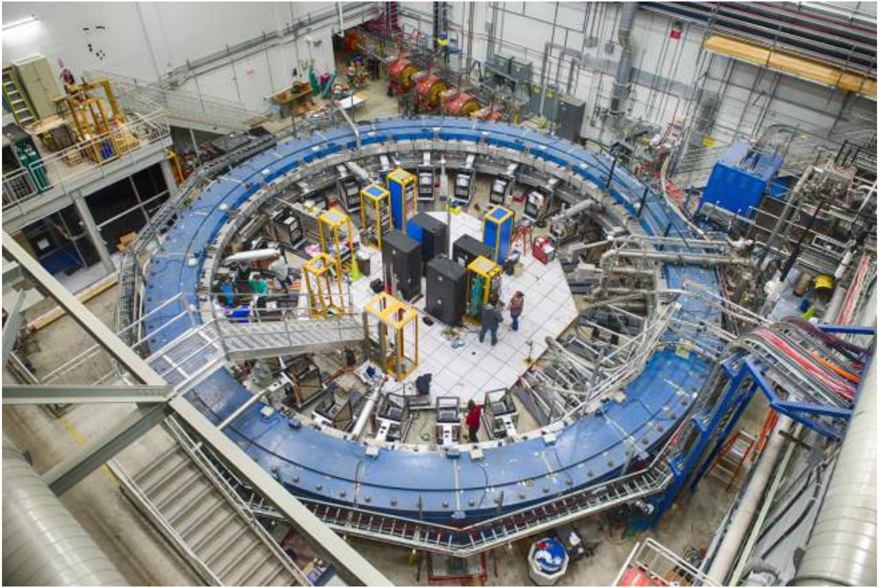
- muon beam: more statistics and fewer pions thanks to FNAL accelerator
- improved detectors, stored muon beam dynamics, field uniformity, field measurement and calibration procedures

Production of the muon beam

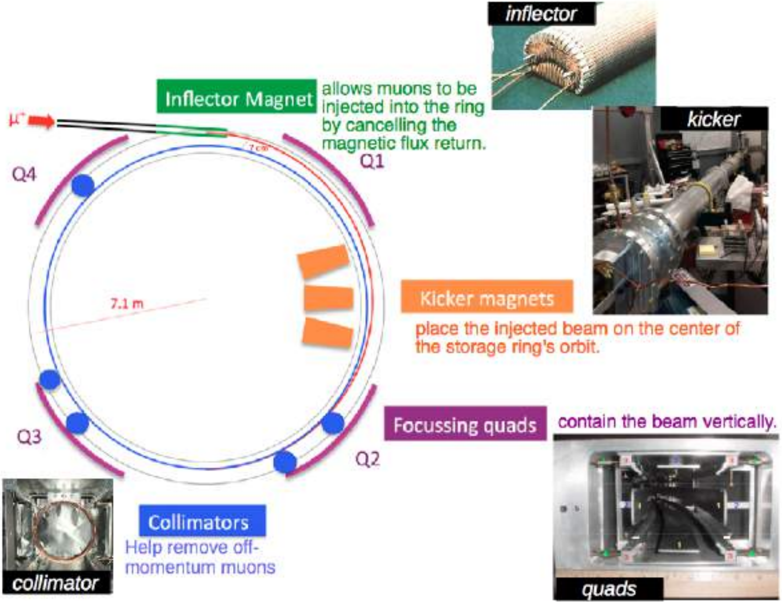
- **Recycler Ring:** 8 GeV protons from Booster are rebunched
- **Target Station:** protons are collided with the target e and π^+ with $p = 3.1$ GeV/c ($\pm 10\%$) are collected
- **Beam Transfer and Delivery Ring:** in the decay line muons from the pion decay are selected, while in the circular ring the muons are separated from protons and pions
- **Muon Campus:** a beam of μ^+ 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

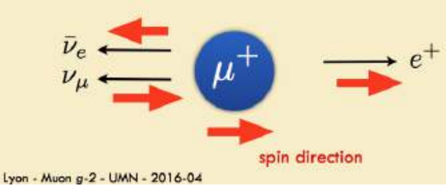


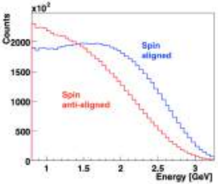
Beam Injection



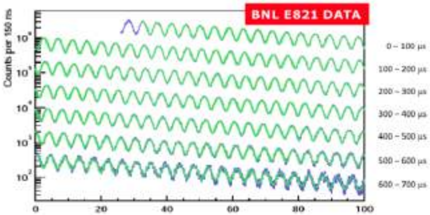
Measurement of ω_a

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



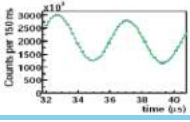


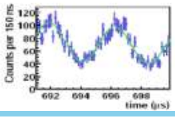
⇒ high energy e^+ are emitted with electron momentum direction strongly correlated with μ^+ spin.



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

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

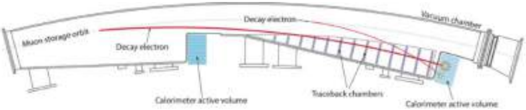




E_{e^+} and t need to be measured.

Detectors for ω_a measurement

e^+ from μ decays curve inside the ring and hit the detectors:



24 Calorimeters

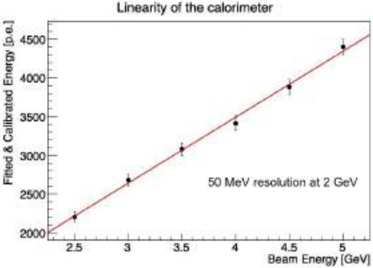
- composed of 6×9 PbF_2 crystals with SiPM readout
- custom 800 MHz waveform digitizers
- laser calibration system

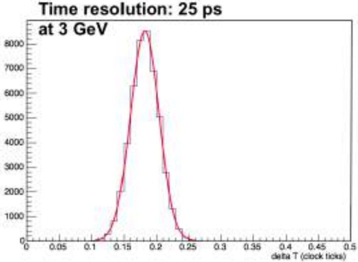
Tracker systems

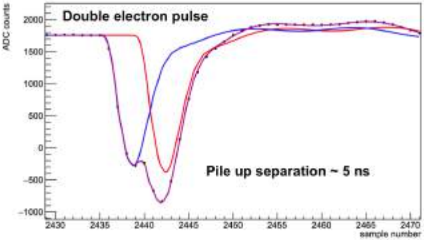
- planning to have 3 stations
- one station installed in front a of a calorimeter
- each station consist of 8 modules of $\sim$ 100 straws filled with $Ar:CO_2$

Calorimeters performance at the Test Beam

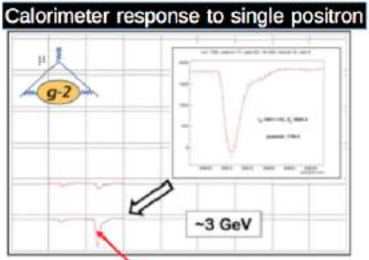
June 2106: test of a calorimeter with custom waveform digitizers, laser calibration system and DAQ at SLAC TB facility.



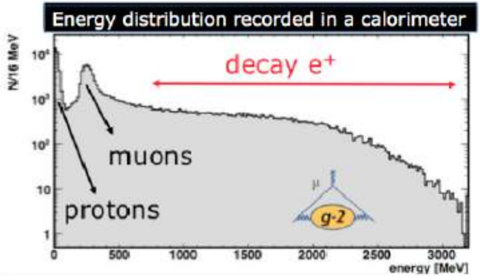




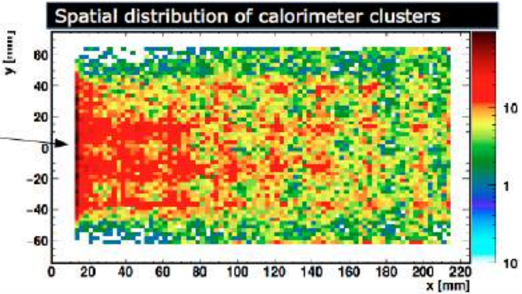
Calorimeters performance during the June 2017 run



3 GeV e+ in single crystal



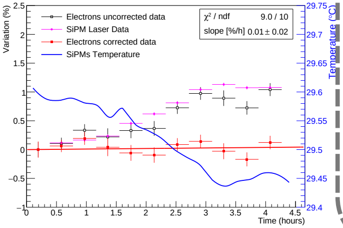
Majority of particle detected by the crystals near the storage ring

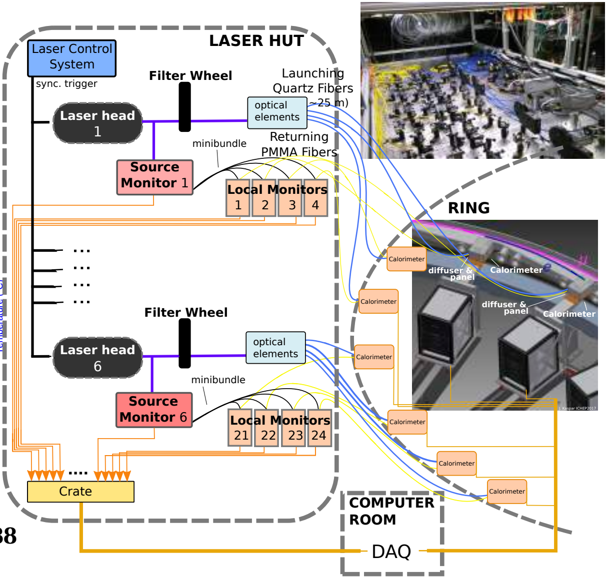


Laser calibration system

Purpose:

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

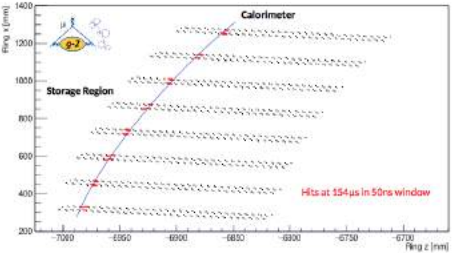




Nucl.Instrum.Meth. A788 (2015) 43-48

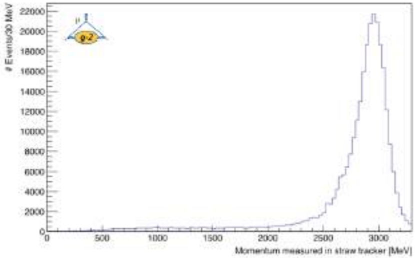
Tracker performance during the June 2017 run

Single charged particle trajectory

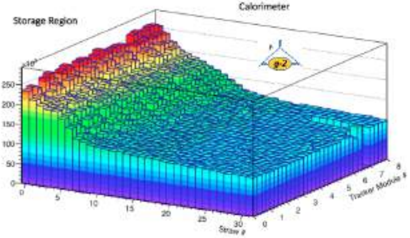


Trackers are useful to determine the spatial muon distribution and to study pileup in the calorimeters.

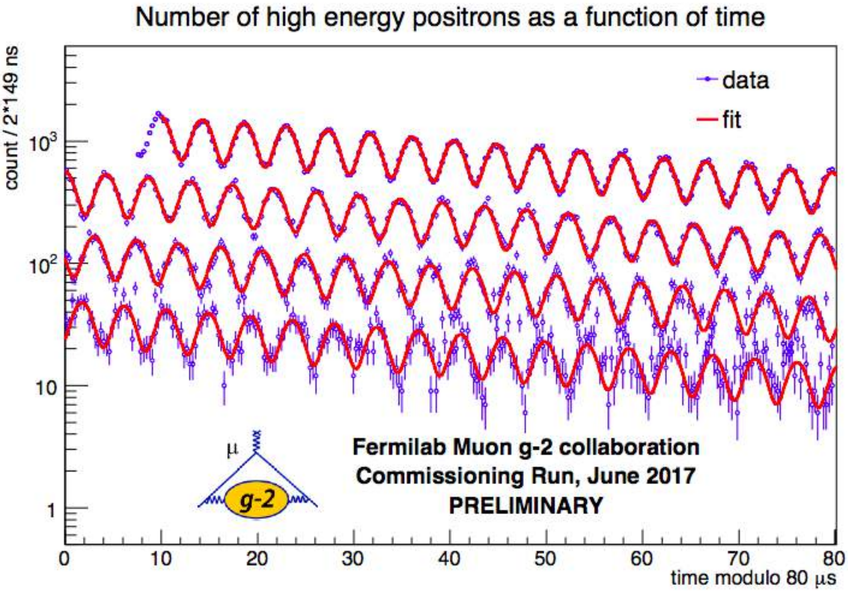
Momentum of tracks



Distribution of recorded hits

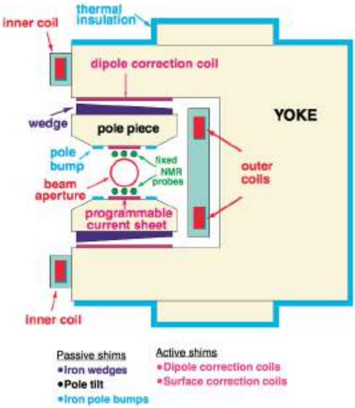


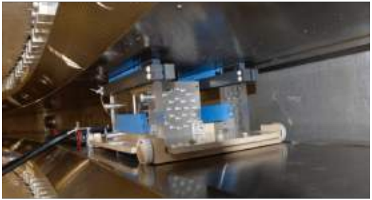
First E989 wiggle plot



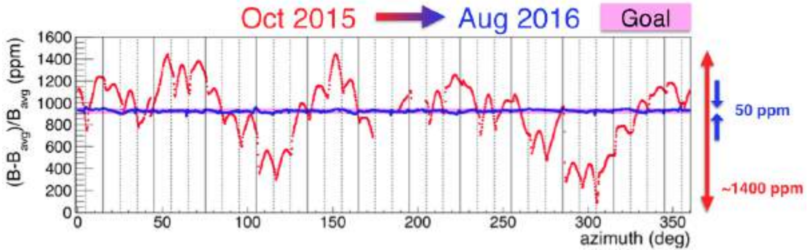
ω_P Measurement

- ω_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

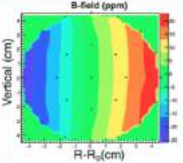




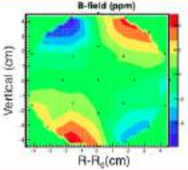
Field Measurements



Azimuthally-Averaged Map



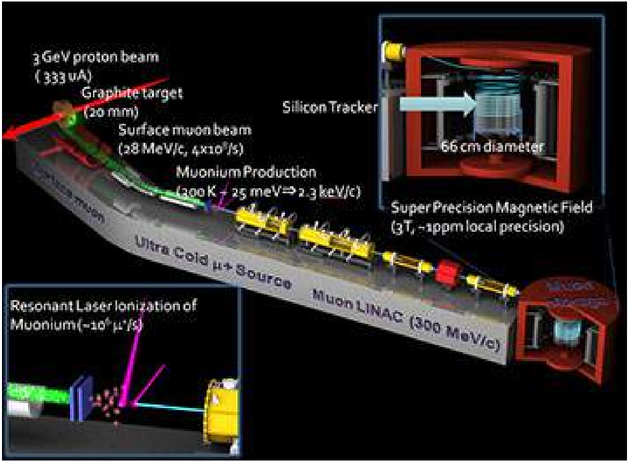
	Norm	Skew
Quad	25.13	-0.53
Sext	-1.99	-0.11
Octu	-1.16	-0.31
Decu	0.95	-0.07



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

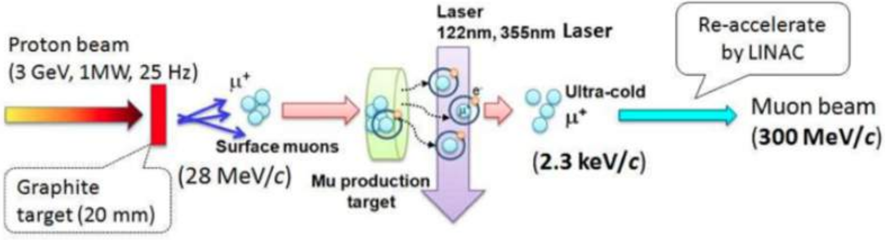
Muon g-2 at J- PARC

- Phase 1: a_μ 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

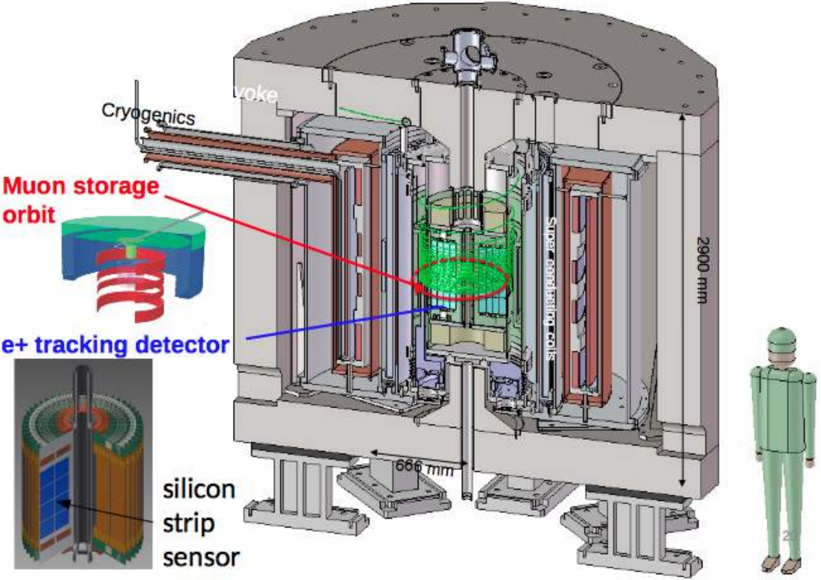
J- PARC Muon beam



- 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	9×10^9	5×10^{11}

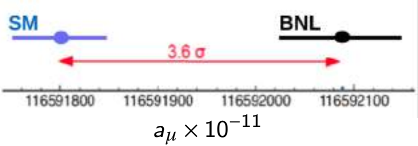
* in the energy region of interest

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_μ^{exp} and $a_\mu^{theo} > 3\sigma$



2013:

- begins the construction of FNAL E989
- the aim of the experiment is to measure a_μ 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