The calibration system for the g–2 calorimeters

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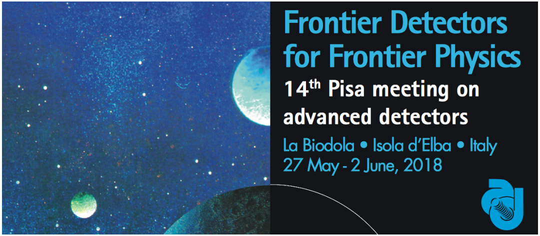
μ g-2

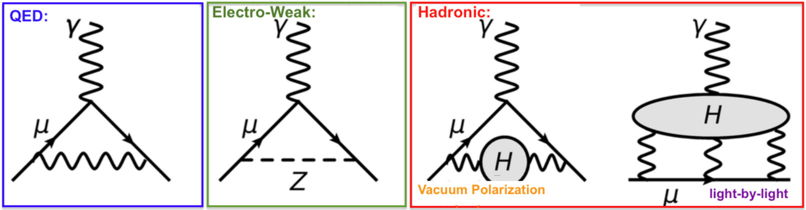
Fermilab



Anomalous Magnetic Dipole Moment

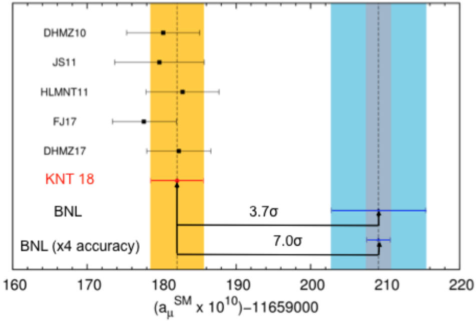
- Magnetic moment: $\vec{\mu}_\mu = g_\mu \frac{Qe}{2m} \vec{S}$
- From the Dirac equation: $g_\mu = 2$
- Adding quantum corrections: $g_\mu > 2$
- Anomalous magnetic moment:

$$a_\mu^{SM} = \frac{g_\mu - 2}{2} = a_\mu(QED) + a_\mu(EW) + a_\mu(Had) = (116591802 \pm 49) \times 10^{-11}$$



- Measurement of a_μ allows for a precise test of the Standard Model and to look for new physics.

Muon g-2 Experiment at Fermilab



arXiv:1802.02995v1 [hep-ph]

BNL $g-2$ experiment (E821) found a discrepancy $> 3\sigma$ w.r.t. theoretical prediction.

Fermilab $g-2$ experiment (E989) aims for a reduction of the experimental uncertainty by a factor of 4 with respect to BNL result:

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

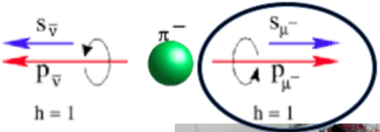
If a_μ value is confirmed (using current a_μ^{SM}):

$$\mathbf{a_\mu^{FNAL} - a_\mu^{SM}} \sim \mathbf{7\sigma}$$

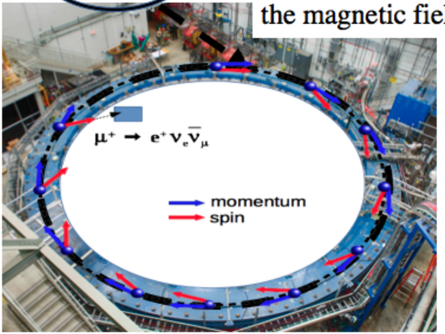
Same experimental technique but improved:

- Muon beam (more statistics and fewer pions thanks to FNAL accelerator)
- Magnetic field uniformity and measurement, detectors and calibration procedures

Experimental Technique



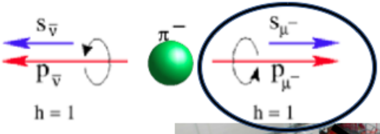
Polarized muons from pion decay are injected into a magnetic storage ring and will precess in the magnetic field



For a muon moving in a magnetic field a_μ is proportional to the difference between spin precession and cyclotron motion :

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = g\frac{e}{2m}\vec{B} - \frac{e}{m}\vec{B} = a_\mu \frac{e}{m}\vec{B}$$

Experimental Technique



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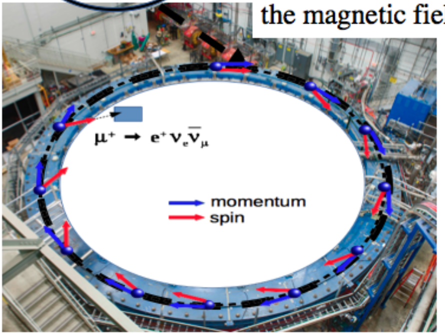


For a muon moving in a magnetic field a_μ is proportional to the difference betwee… and cyclotron motion :

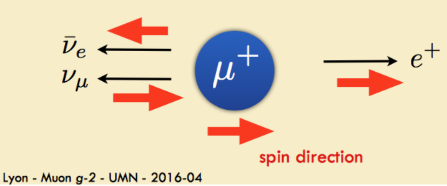
Measure these

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = g\frac{e}{2m}\vec{B} - \frac{e}{m}\vec{B} = a_\mu \frac{e}{m}\vec{B}$$

Get a_μ

Measurement of ω_a

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

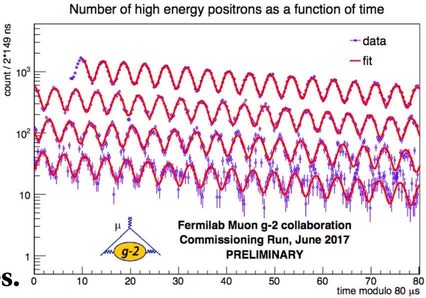


$\Rightarrow$ high energy e^+ are emitted preferentially with electron momentum direction strongly correlated with μ^+ spin (parity violation of the weak decay)

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

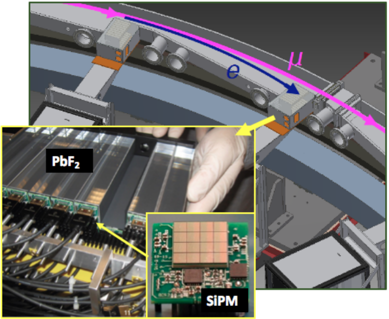
$$N(t) = N_0 e^{-t/\tau}[1 + A\cos(\omega_a t + \phi)]$$

E_{e^+} and t are the measured observables.



Detectors for ω_a Measurement

- The energy and hit time of the e^+ from the μ decay are measured by the 24 calorimeters positioned inside the ring.
- Each calorimeter is composed of 6×9 PbF_2 crystals read out individually by large-area SiPMs
- Calibration, time alignment and gain stability for each of 1296 channels is provided by the laser calibration system



Systematic budget for ω_a:

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

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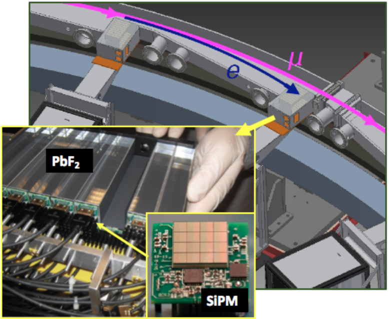

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Total	180	Quadrature sum	70

Key element:

Laser } Largest improvement

Calo + Laser

Calo + Laser

Inflector + Kicker

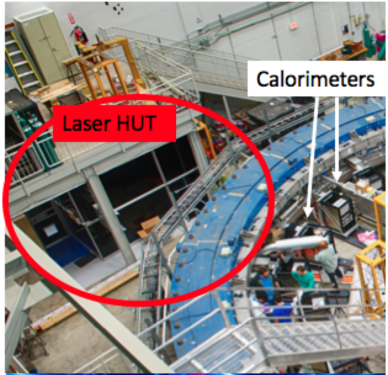
Tracker

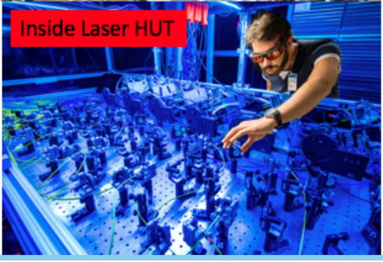
Requirements of the Calibration System

- Absolute calibration of the SiPMs response
- Provide gain stability at sub-per-mil in the short term (during the 700 μs after injections) and at the sub-percent-level in the long term (days)
- Time synchronization of the 1296 calorimeters' channels.

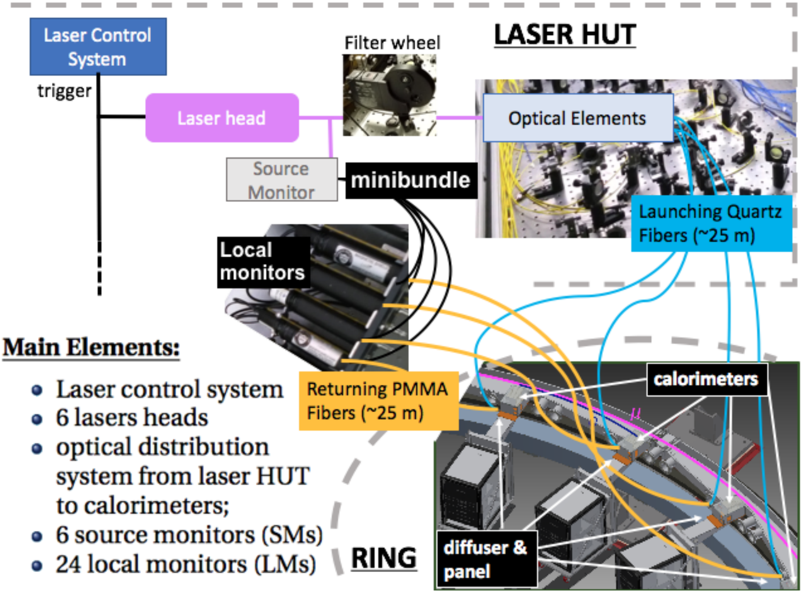
$\Downarrow$

Laser based Calibration System with light intensity monitored at 10^{-4} and time resolution at the ps level





Laser Based Calibration System

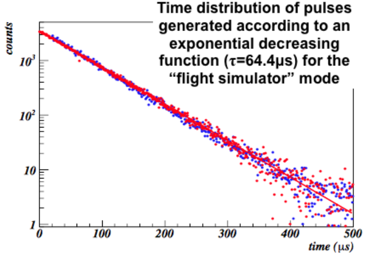


Main Elements:

- Laser control system
- 6 lasers heads
- optical distribution system from laser HUT to calorimeters;
- 6 source monitors (SMs)
- 24 local monitors (LMs)

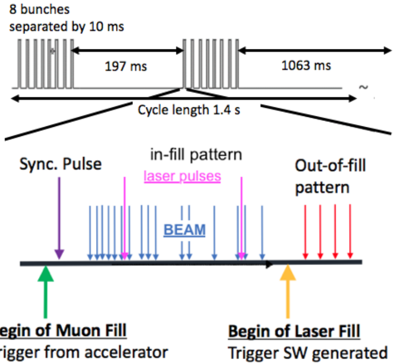
Laser Control System

- Synchronized with the clock, control and command system (CCC) of the experiment
- Provides the laser pulse trains at programmable frequencies
- Generates physics event simulation (“flight simulator”)



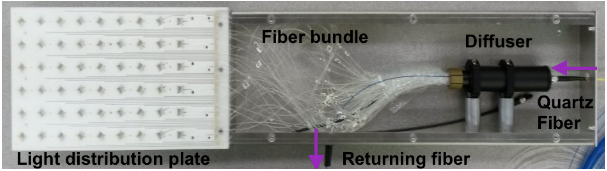
typical calibration mode:

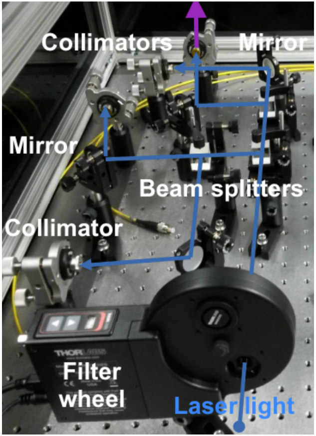
- Sync pulse: before beam injection provides time synchronization for the 1296 calorimeters’ channels
- In-Fill pulses: for calorimeter gain function
- Out-of-Fill pulses: for long-term gain variations (temperature , bias voltage)



Light Distribution System

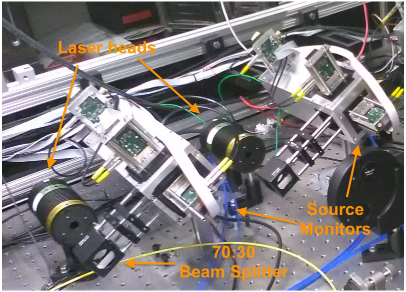
- 70% of the light from each laser is equally distributed
  between 4 calorimeters by means of optical elements;
- Remotely controlled filter wheels vary the light intensity during calibration;
- Light transported to each calorimeter by single quartz fiber and distributed by diffuser
  and PMMA fiber bundle to crystals via coupling prisms.

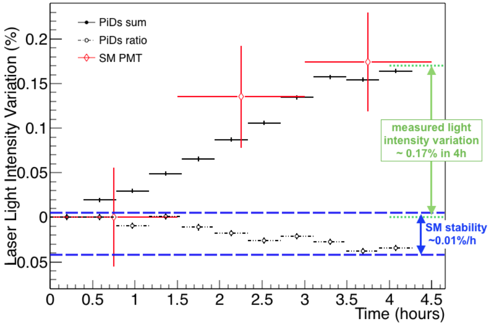


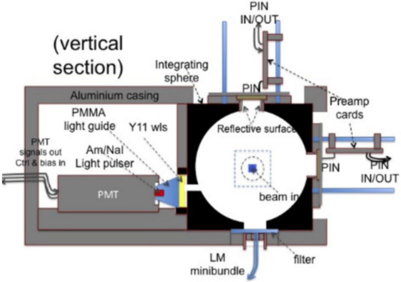


6 Source Monitors (SMs)

- Designed to monitor pulse by pulse the laser light intensity
- 30% of the laser light distributed to 3 photo-detectors: 2 fast PIN diodes and 1 PMT
- PMT also views an Am/NaI light pulser for long term absolute stability.







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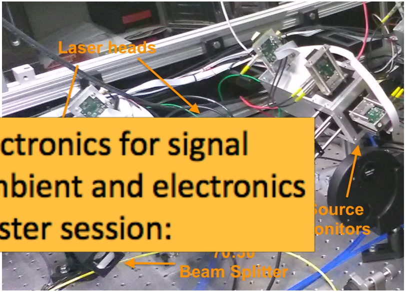
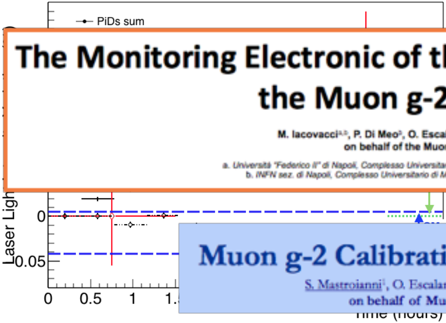
- PM... fo...



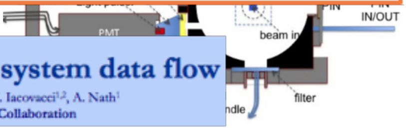
Details about the custom electronics for signal digitization and monitoring of ambient and electronics temperatures in the poster session:



The Monitoring Electronic of the Laser Calibration system in the Muon g-2 experiment

M. Iacovacci[a,b], P. Di Meo[b], O. Escalante[a,b], S. Mastroianni[b], A. Nath[b]
on behalf of the Muon g-2 Collaboration

a. Università "Federico II" di Napoli, Complesso Universitario di Monte Sant'Angelo, ViaCinthia, 80126 Napoli, Italy
b. INFN sez. di Napoli, Complesso Universitario di Monte Sant'Angelo, Via Cinthia, 80126 Napoli, Italy

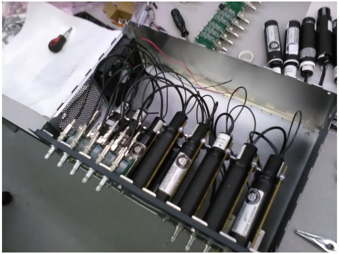


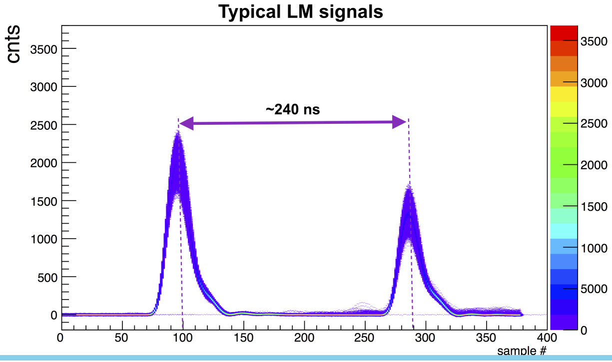
Muon g-2 Calibration system data flow

S. Mastroianni[1], O. Escalante[1,2], M. Iacovacci[1,2], A. Nath[1]
on behalf of Muon g-2 Collaboration

24 Local Monitors (LMs)

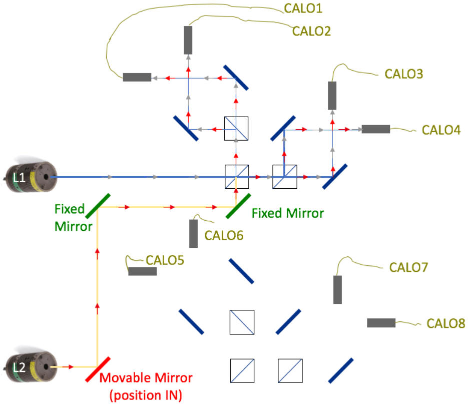
- Each LM consists of a PMT which views light pulses from the SM (P_1, before distribution) and from the diffuser (P_2, after distribution).
- Stability of the light distribution to each calorimeter is monitored by the ratio P_2/P_1.

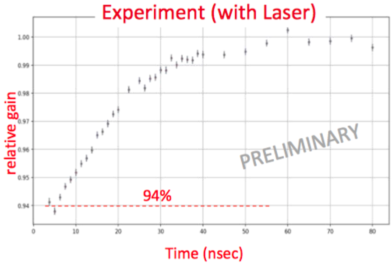


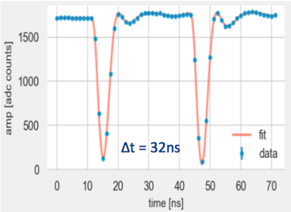


Example of "Very Short-Term" (order of ns) Gain Correction

- By using movable mirrors the light of two lasers can be sent to the same 4 calorimeters
- This configuration permits tests of the SiPMs' gain variation;
- Example: measurement of pile up effect:

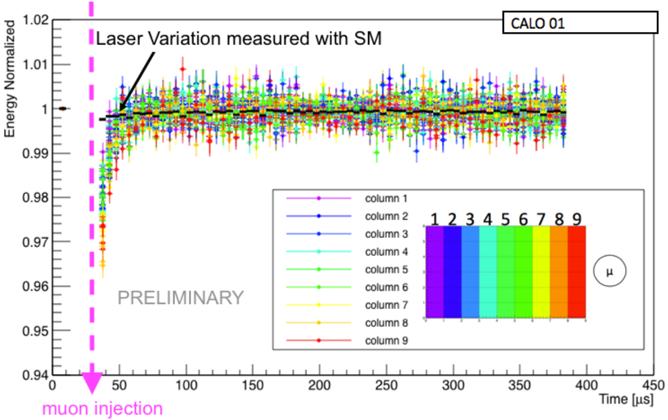






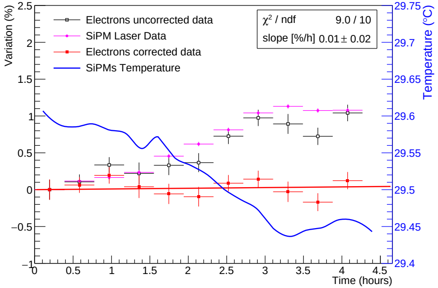
Example of "Short-Term" (order of μs) Gain Correction

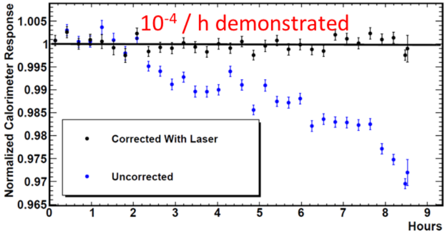
- For each SiPM the gain function is determined by pulsing the laser during muon fills;
- The gain variation is caused by the positron rate (higher at early-time and in the calorimeter's side near the ring) and by the power supply recovery time



Example of "Long-Term" (order of hours) Gain Correction

Laser gain correction of SIPMs demonstrated using mono-energetic electron beams at the Frascati and SLAC test beam facilities:





1. *"Electron beam test of key elements of the laser-based calibration system for the muon g − 2 experiment," Nucl. Instrum. Meth. A* **842**, *86 (2017)*

2. *"Studies of an array of PbF_2 Cherenkov crystals with large-area SiPM readout," Nucl. Instrum. Meth. A* **783** *(2015)*

Summary and Conclusions

- The $g-2$ experiment at Fermilab has the goal to measure a_μ with a systematic uncertainty of 140 ppb
- The main purpose of **the laser calibration system** is to provide calibration and time alignement to all the 1296 calorimeters' channels and to guarantee their gain stability with the challenging precision of 20 ppb!
- The experiment is taking data: 1×BNL statistics (raw data) has already been collected!