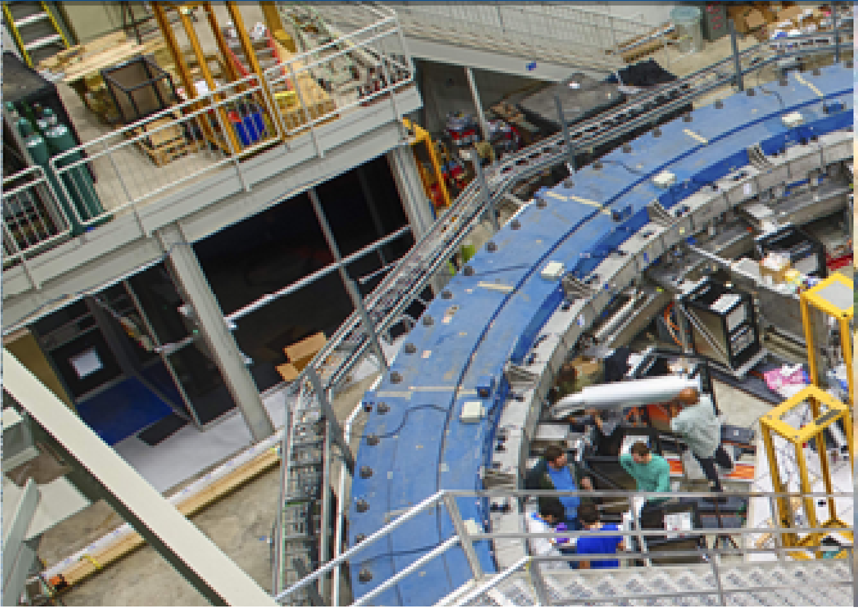

The Calibration System of the muon g-2 experiment at Fermilab

Antonio Gioiosa *on behalf of g-2 collaboration*

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INFN Sezione di Tor Vergata(RM)

Società Italiana di Fisica

104° Congress - September 21 2018

Outline

- E989 g-2 Experiment overview
- The E989 Calibration System
    - Physics motivation
    - Configuration
    - Performance
- Conclusions

The E989 g-2 Experiment

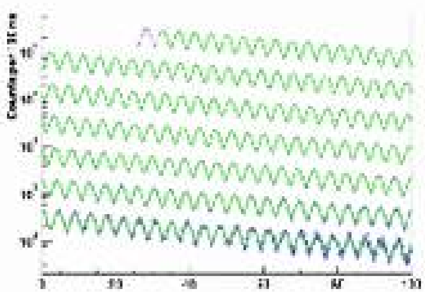
Store longitudinally polarized muons in a ring and observe their decay product (positrons). If $g \neq 2$ then the spin $\vec{S}$ rotates faster than momentum $\vec{p}$.

- measure the uniform magnetic field $\vec{B}$
- measure the "anomalous" precession $\omega_a = \omega_S - \omega_C$

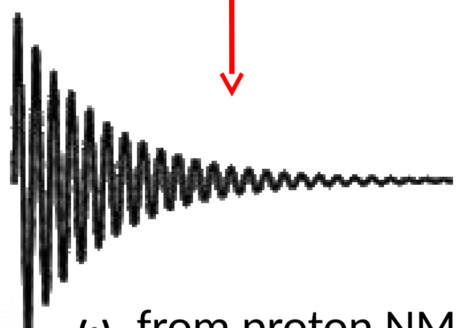
$\Big\}$ get a_μ

$$\omega_S = g_\mu \frac{eB}{2m} + (1-\gamma)\frac{eB}{\gamma m} \qquad \omega_C = \frac{eB}{m\gamma}$$

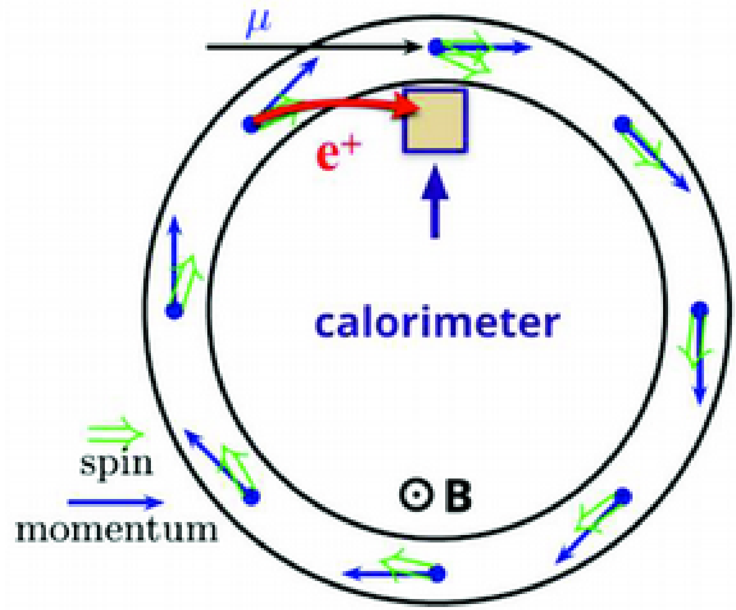
$$\frac{g_\mu - 2}{2} = a_\mu = \omega_a \frac{m}{eB}$$



N posit. with $E > E_{th}$ vs time



ω_p from proton NMR



Need to measure ω_a and ω_p with an accuracy of 70 ppb !

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The E989 Laser Calibration System

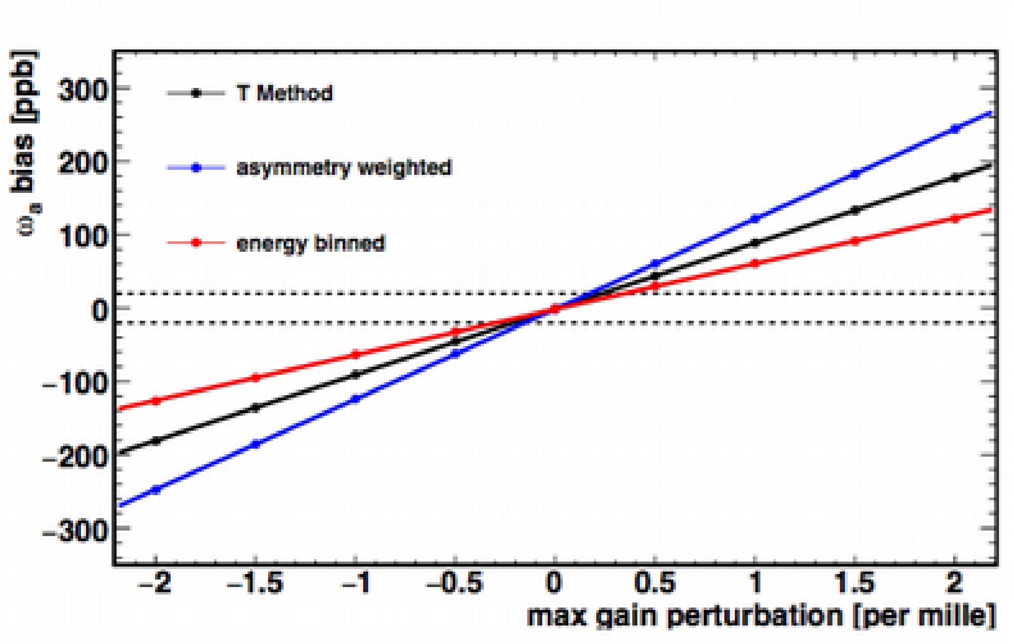
The goal of the Fermilab experiment is to reduce the systematic error on ω_a from 180 to 70 ppb

The main goal of the Calibration System is to reduce the systematic error on ω_a from 120 to 20 ppb

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

The Laser Calibration System

A central component to reach this fourfold improvement in accuracy is the high-precision laser calibration system, which is designed to monitor the gain fluctuations of the calorimeter photodetectors at 0.04% accuracy during the time when muons are kept inside the storage ring (700 μsec)



Gain variation during fill "mixes" different energies

The E989 Calorimeters

The E989 (g-2) experiment at Fermilab uses

24 electromagnetic calorimeter stations

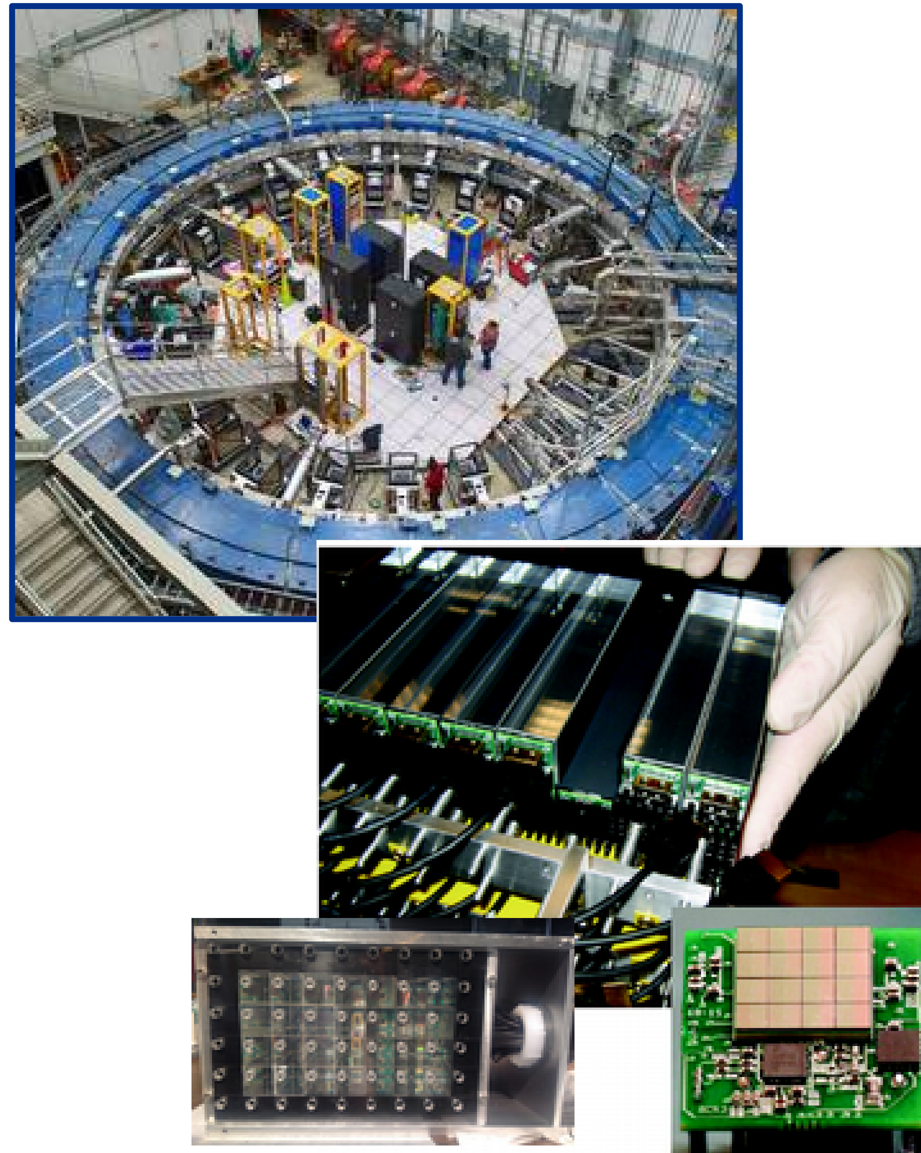
placed on the inside radius of the magnetic storage ring

Each calorimeter consist of

arrays of 54 PbF_2 Čerenkov crystals

read out by large-area silicon photo-multiplier (SiPM) sensors

(1296 overall)



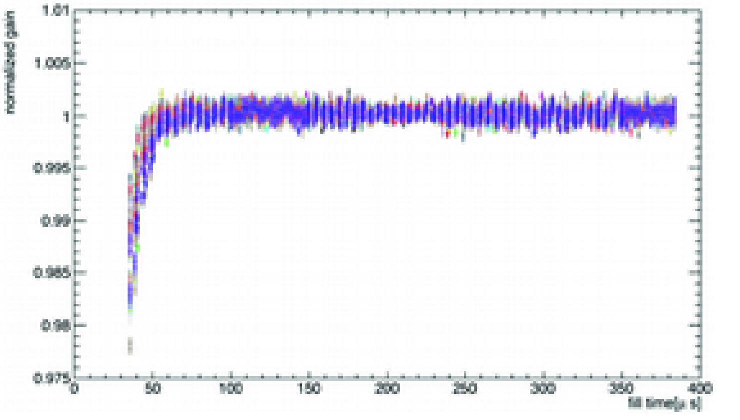
The E989 Laser Calibration System

The gain of the calorimeters is subject to variations during the muon fill. **SiPM Gain is mainly affected by:**

The splash after the beam injection

(first 30µS)

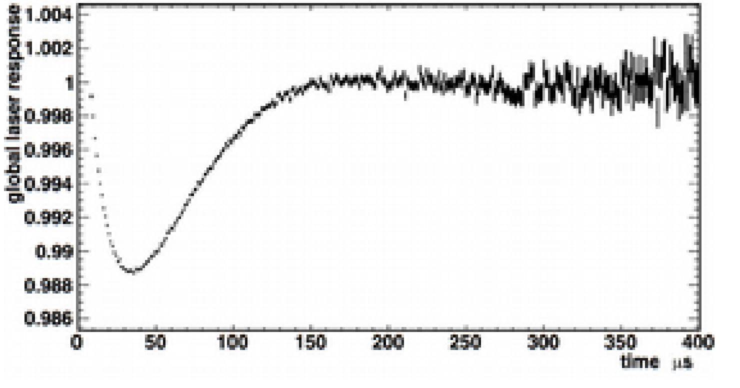
Characterized with Laser system



The recovery time of the power supply from the rate of muon decay

(recovery time ~20µS order)

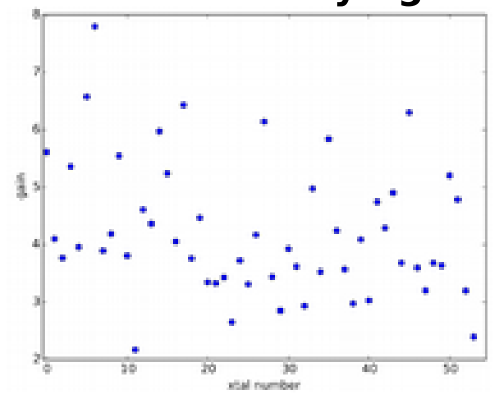
Characterized with Laser system

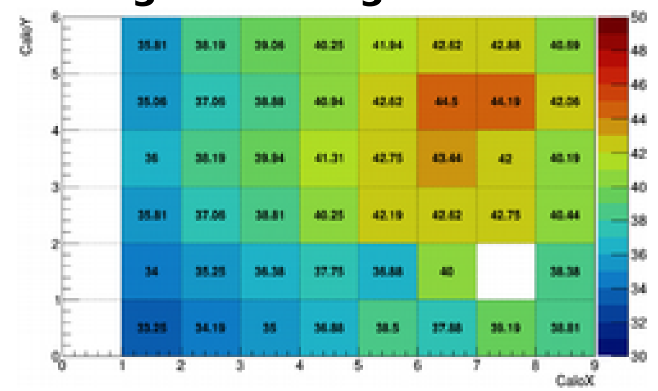


SiPM Gain is mainly affected by:

Large nonuniformity in SiPM temperature

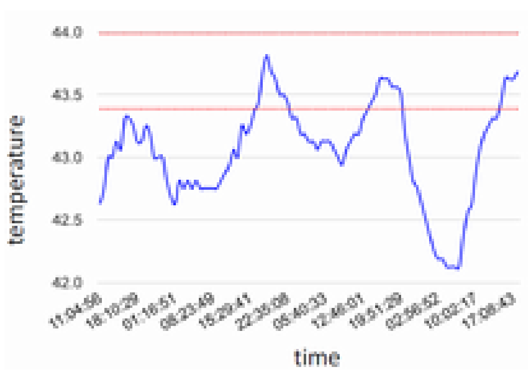
Optimized with a gain equalization, varying bias and gain settings

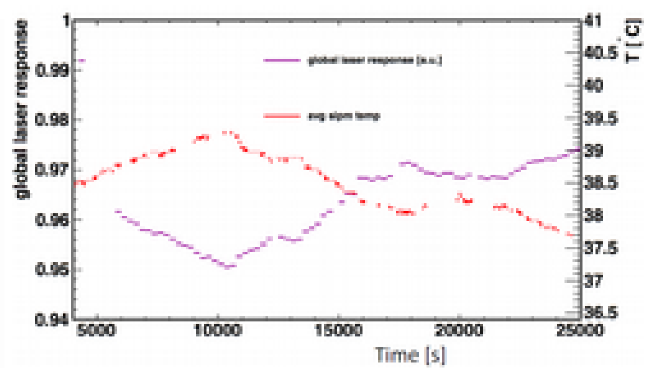




SiPM temperature drifts over time

Corrected with laser response





The Laser Calibration System

Idea:

- **Send trains of laser pulses on known intensity synchronously on all calorimeters' channels**

Main goals:

- **Absolute calibration of the SiPMs response (photoelectrons/photons response)**
- **Provide short term (in fill, gain saturation) and long term (bias and temperature variations) calibration of the SiPM gain function**
- **Debugging of Calorimeters and Data Acquisition System (DAQ debugging) by providing physical signals**
- **Provide additional synchronization signals**

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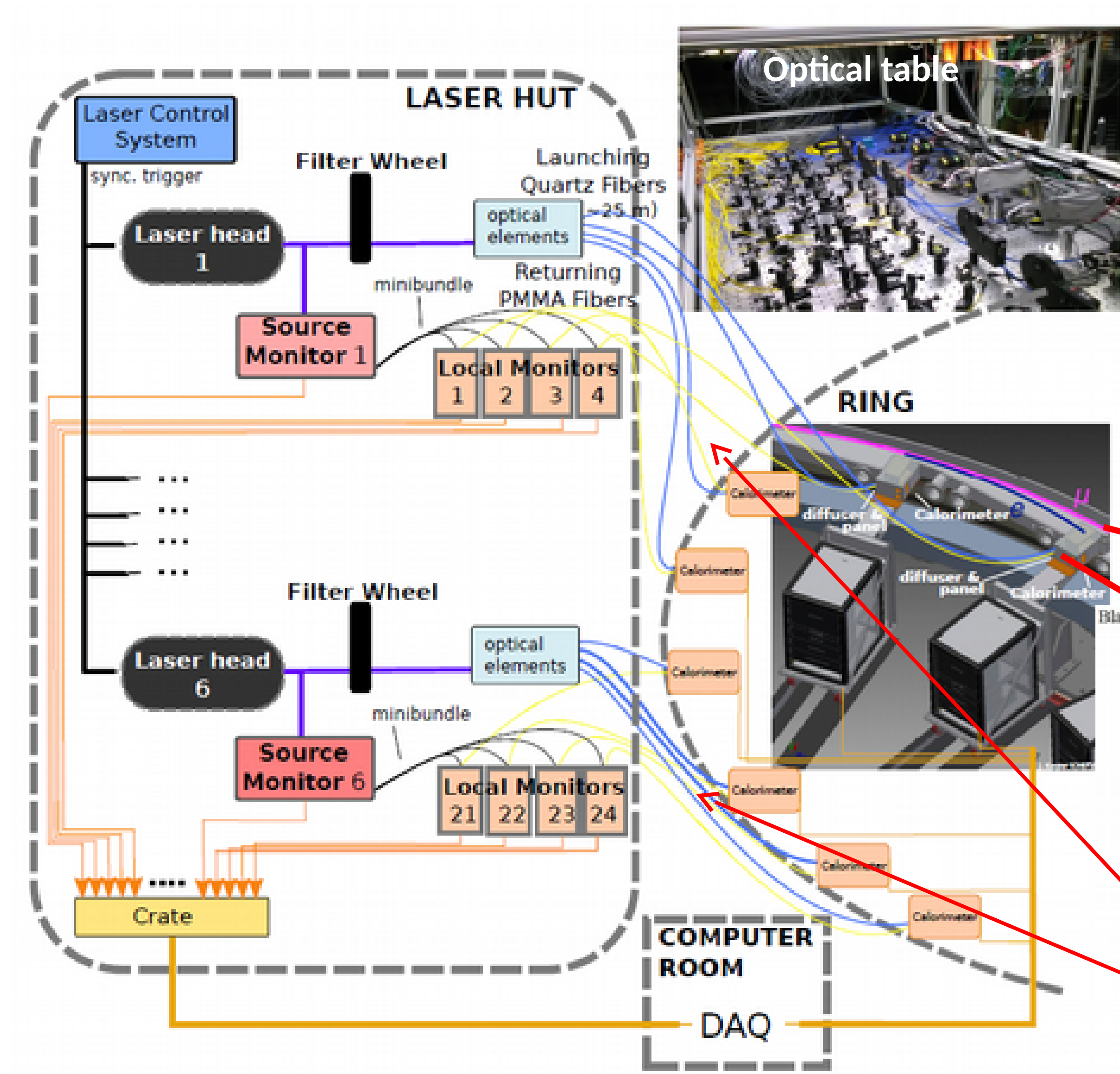
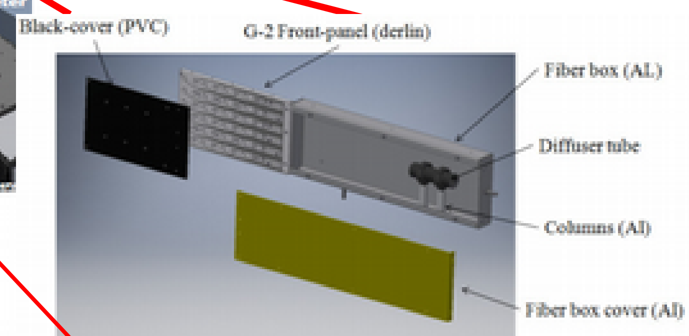
The Laser Calibration System



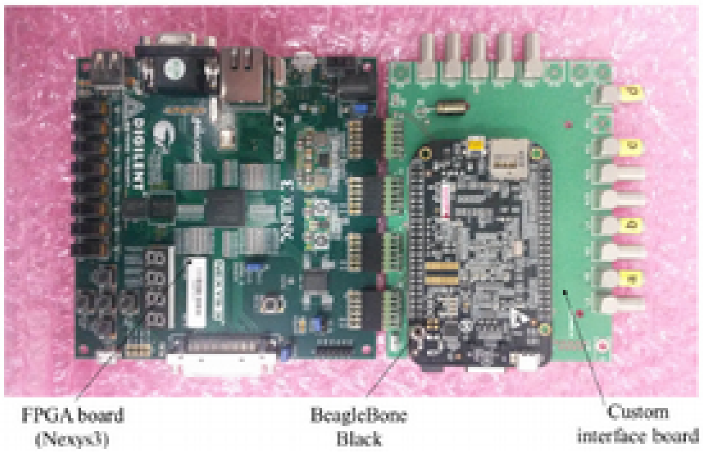
- 6 laser heads
- The control board interfaced with a laser driver
- 6 Source Monitors (SM), one for each laser
- Optical distribution system from laser head to calorimeters
- 24 Local Monitors (LMs)

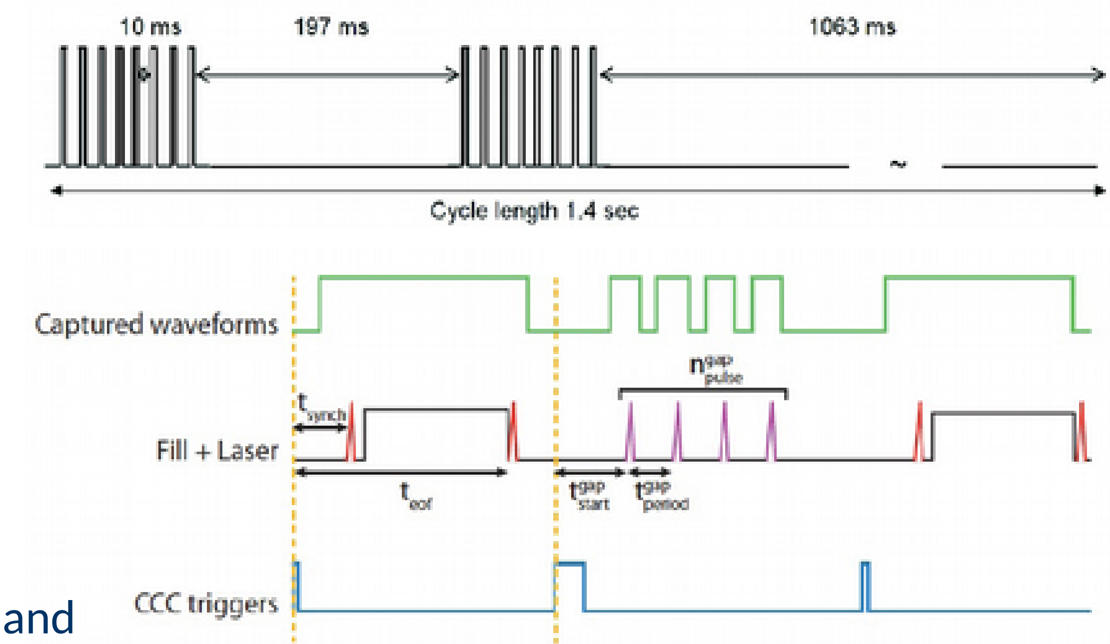


25m silica fibers

The Laser Calibration System

Laser Control System



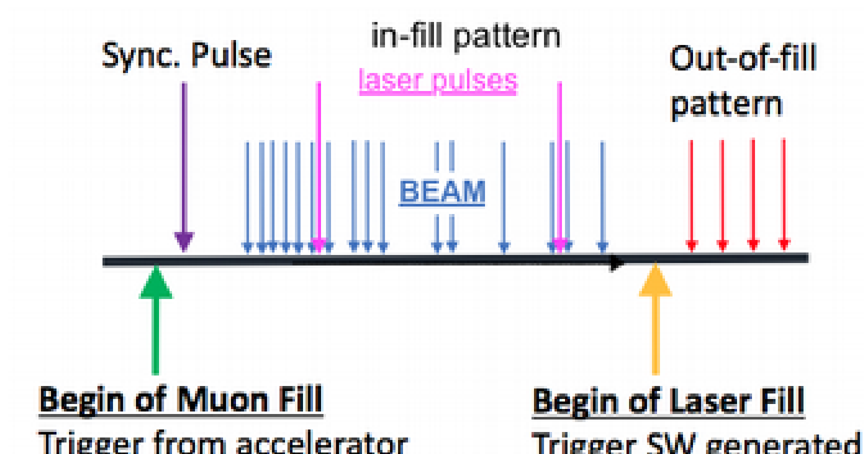


Synchronized with the Clock, Control and Command system (CCC)

Prescaling programmation

Generation of the laser pulse trains at programmable frequencies both in-fill (Muon Fill) and out-of-fill (Laser Fill)

physics event simulation (“flight simulator”)

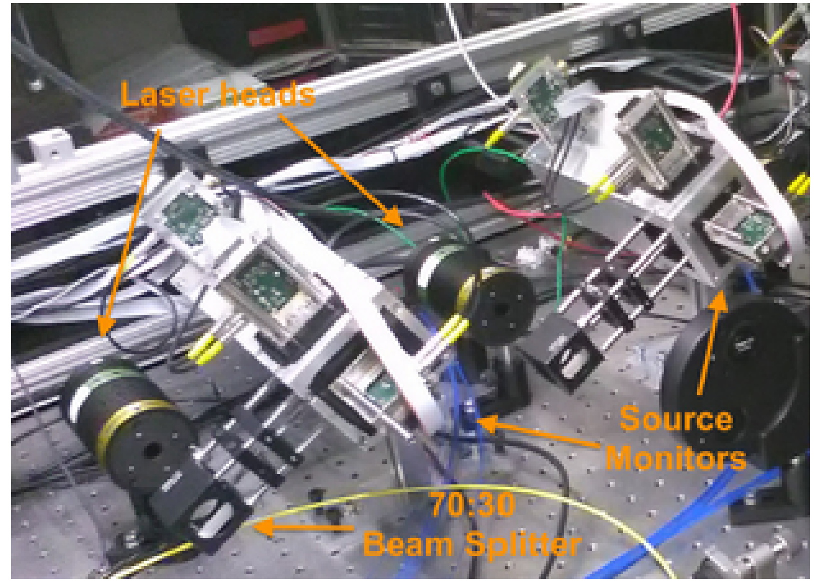


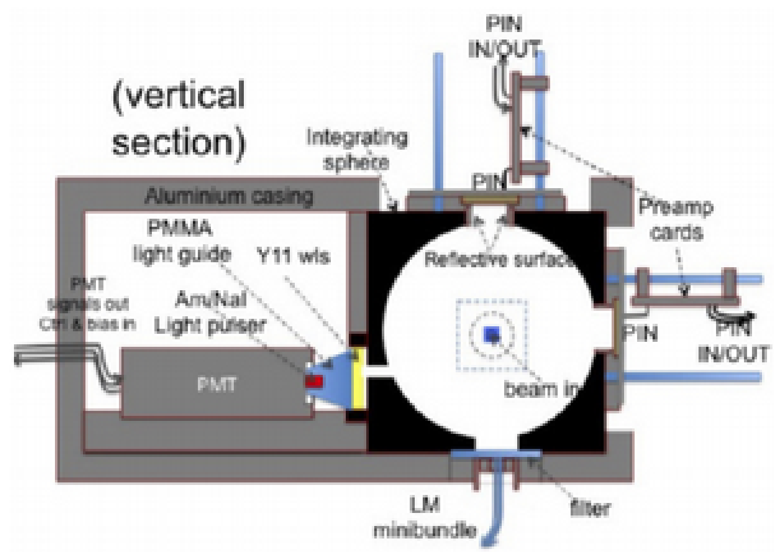
The Laser Calibration System

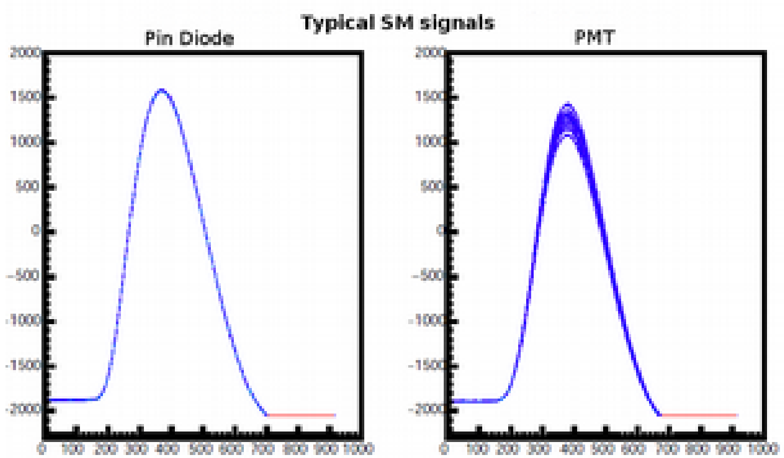
6 Source Monitors

30% of the laser light distributed to 3 Photo-detectors:

- 2 fast PIN diodes and 1 PMT
- pin diodes monitor stability at sub-0.1% level
- PMT also views an Am/NaI light pulse for long term absolute stability





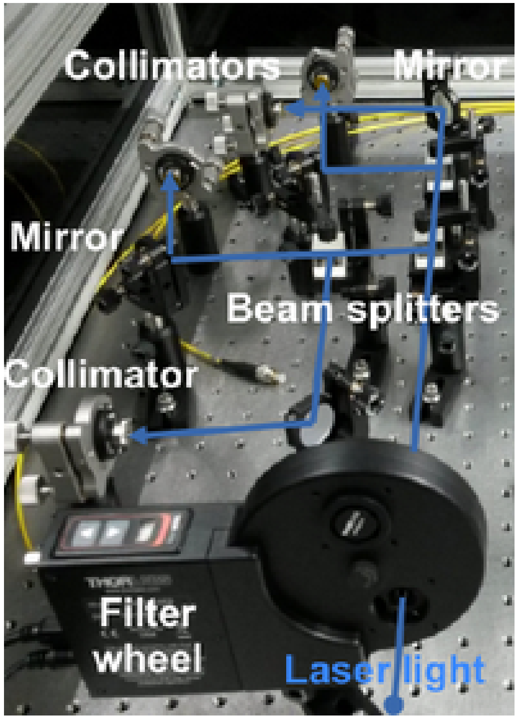


The E989 Laser Calibration System

Light Distribution System

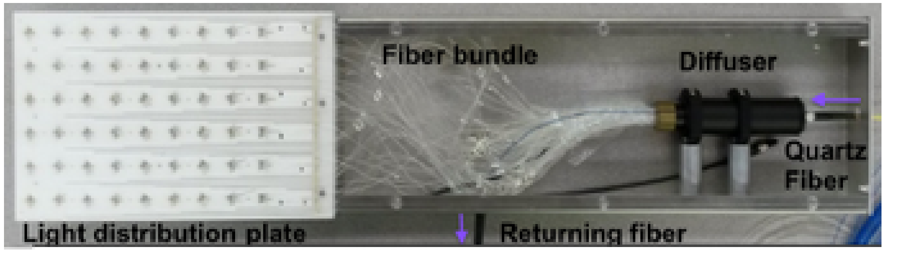
Light from each laser is equally distributed between 4 calorimeters by means of optical elements

Remotely controlled filter wheels varies light intensity during calibration



Laser diodes @405nm, 600ps, 1nJ/pulse, 0-40 MHz rep. rate

Light transported to each calorimeter by single quartz fiber and distributed by diffuser and PMMA fiber bundle to crystals via coupling prisms

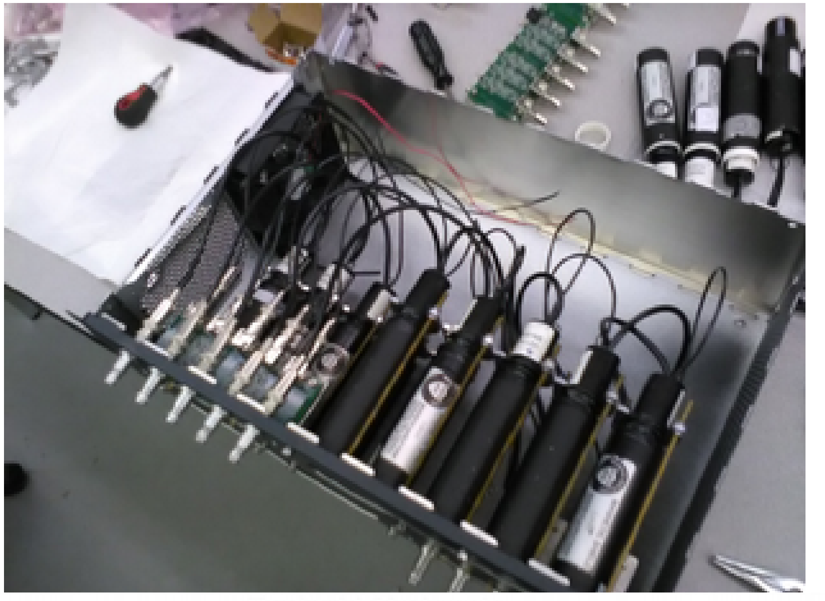


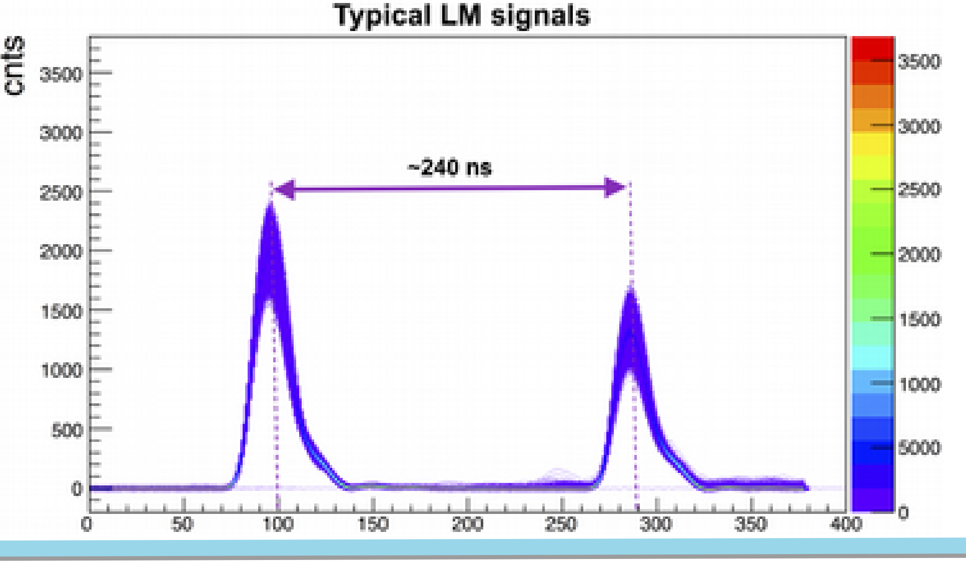
The E989 Laser Calibration System

24 Local Monitors

Each LM consists of a Photonics XP2982 PMT which views light pulses from the
SM (LP1, before distribution) and from the diffuser (LP2, after distribution)

stability of the light distribution to each calorimeter is monitored by the ratio LP2/LP1





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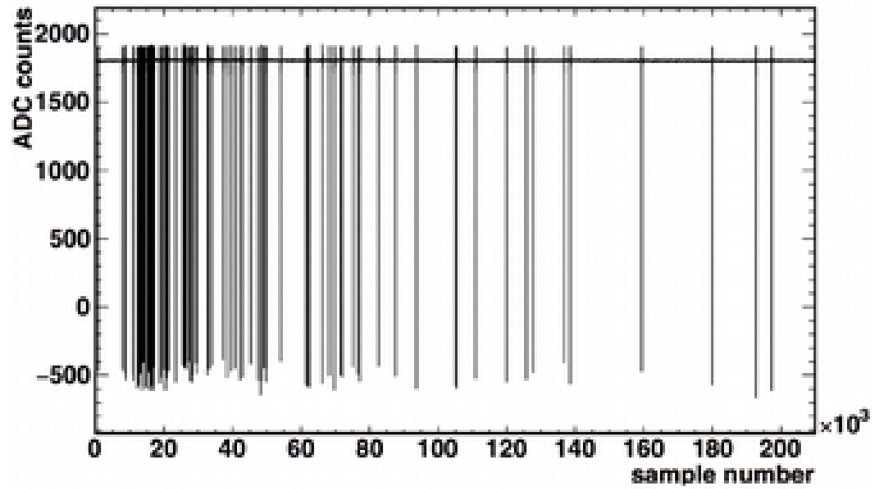
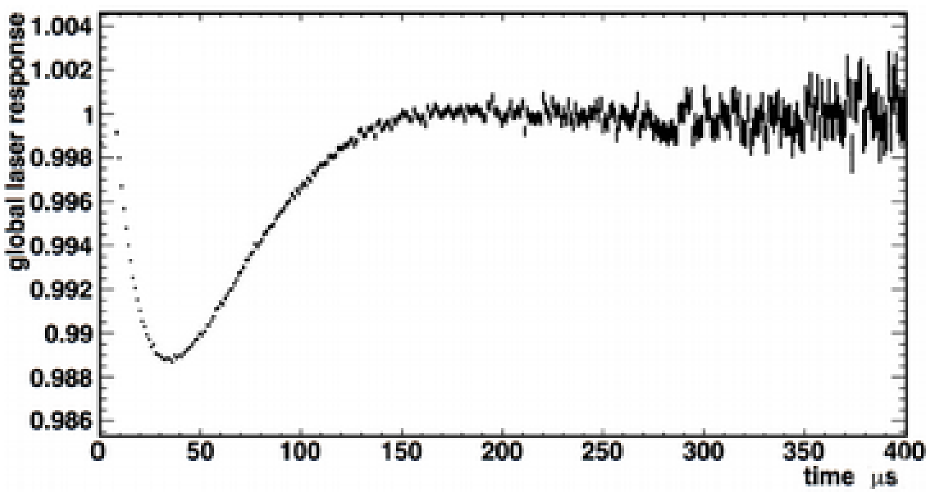
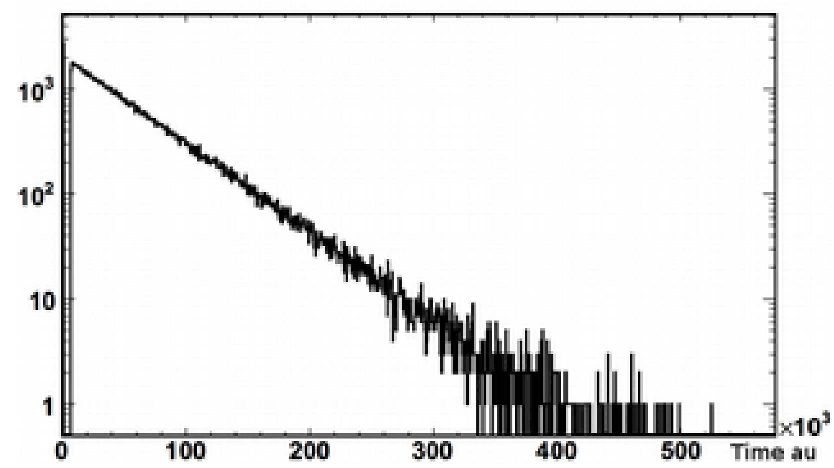
The E989 Laser Calibration System

Flight simulator

- laser control board used to simulate (g-2) fill (with no wiggles)
- lets us exercise analysis tools and daq
- enables all sorts of interesting tests







Typical calibration procedures

Absolute Calibration with the filter wheels

Convert the pulse integral into npe

Out-of-fill

To correct the long-term gain variation (mostly temperature and vbias dependence of the SiPMs)

Firing the laser between fills

In-fill

To correct systematic gain shifts while positrons are present

Firing the laser within fills

Example:

- *Prescale of 10*
- *2 pulses per fill shifting 5 us each step*
- *Carves out gain function for first 300 us after injection*

Short-time Double Pulse

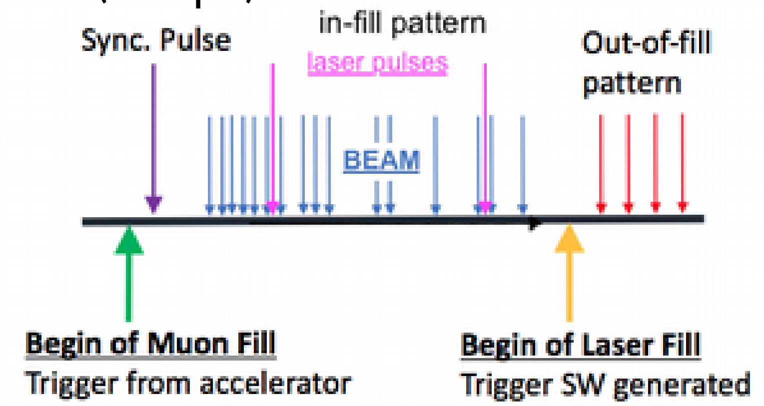
The SiPM gain drops after one pulse, so next could have lower energy

Firing 2 laser pulses within fills systematically vary E1, E2, dt(~nS)

long-time double pulse

To caratterize the splash after the beam injection

Firing burst of load pulses followed by a test pulse (~20 μS)



The E989 Laser Calibration System

Convert the pulse integral into npe

Vary laser intensity with filter wheel

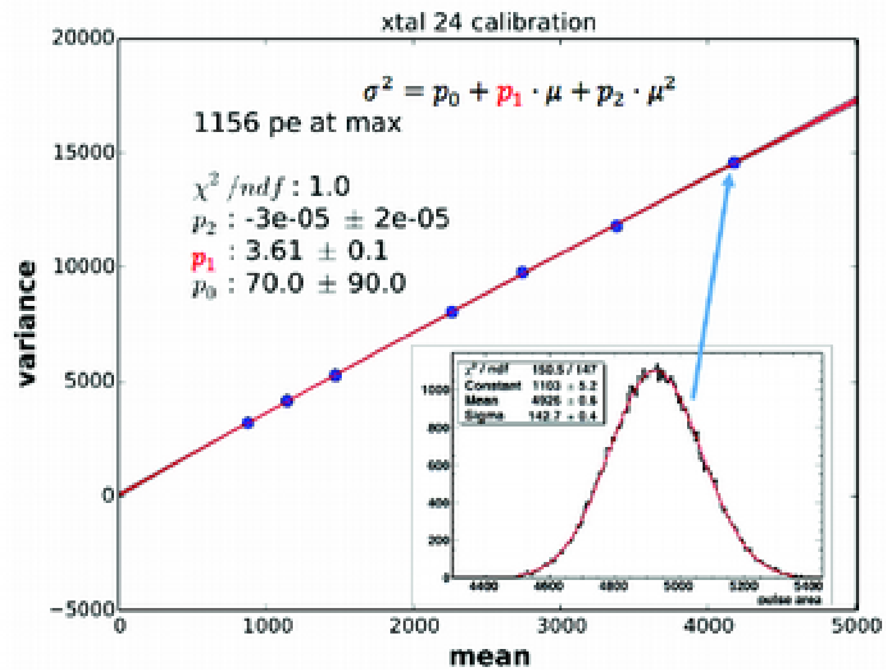
Measure pulse area variance vs mean p1

Identify p1 as pulse area/pe (gain)

Measure beam energy in pe

This technique does not require that each segment receive same light

Example of npe calibration

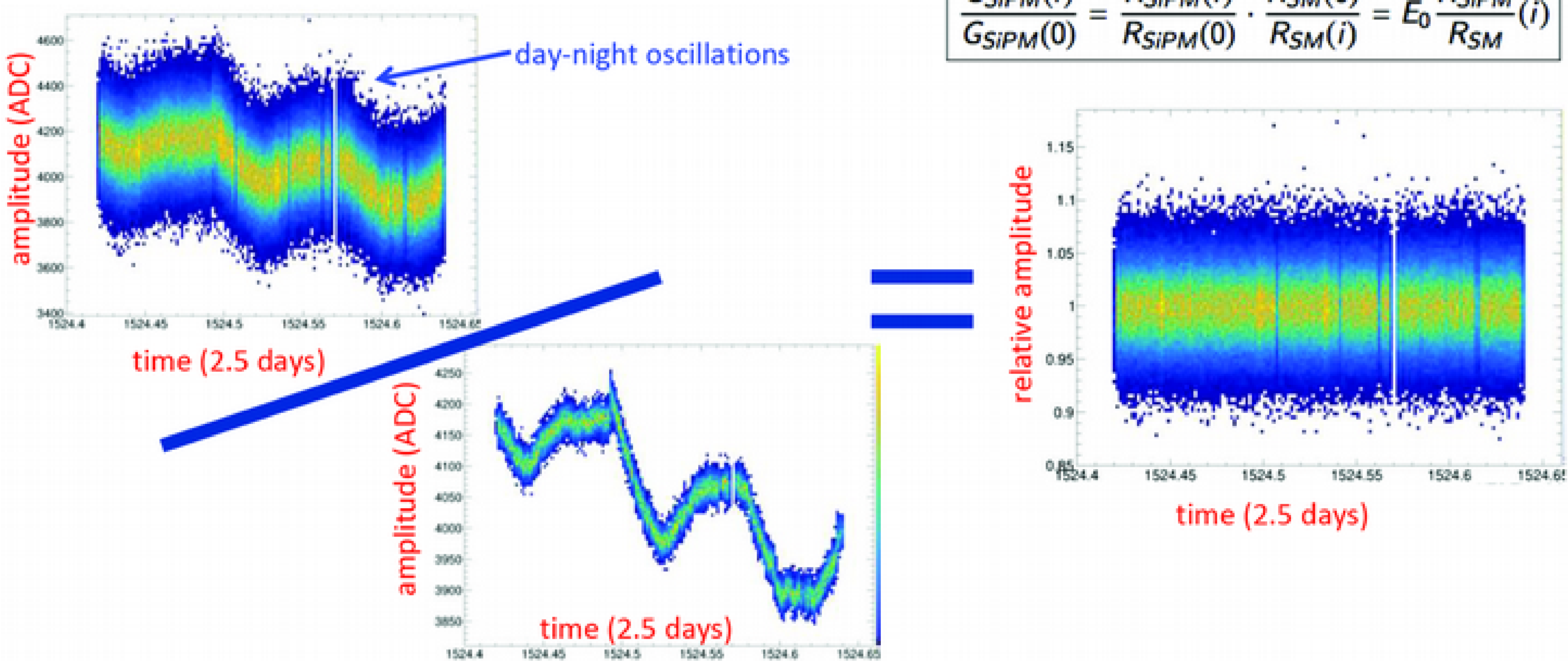


The E989 Laser Calibration System

Out-of-fill systematic correction

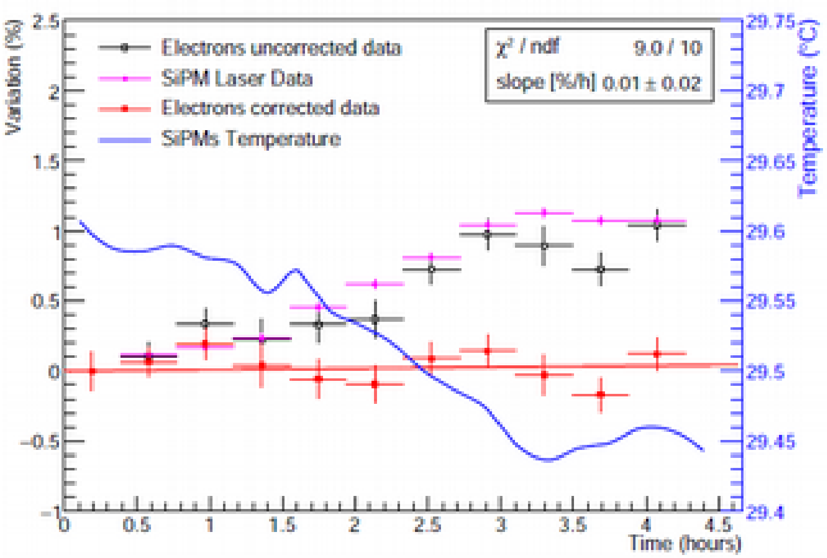
A correction factor for each SiPM is measured by considering the response of SiPMs to the laser light (R_{SiPM}) and by monitoring this response using the SM (R_{SM})

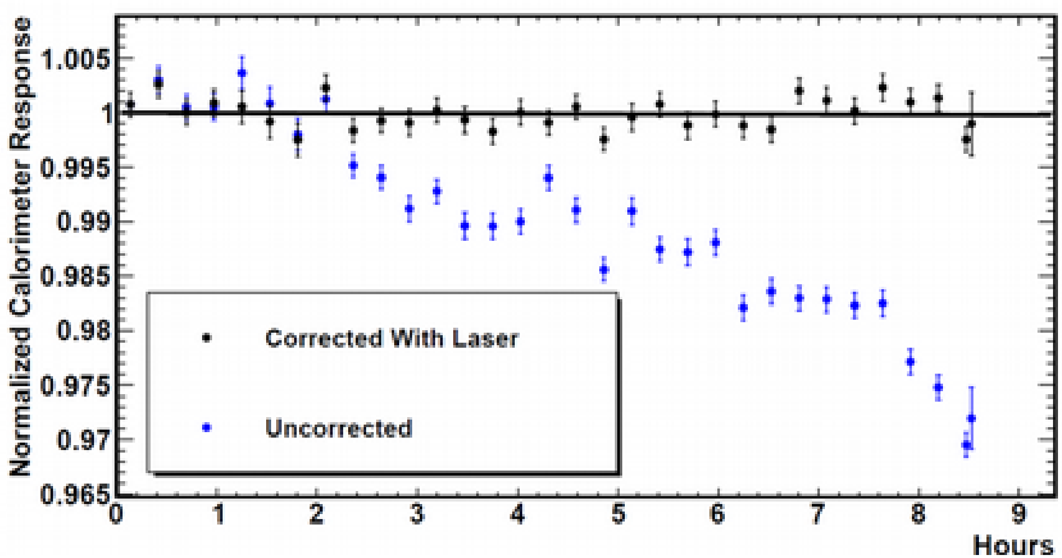
$$\frac{G_{SiPM}(i)}{G_{SiPM}(0)} = \frac{R_{SiPM}(i)}{R_{SiPM}(0)} \cdot \frac{R_{SM}(0)}{R_{SM}(i)} = E_0 \frac{R_{SiPM}}{R_{SM}}(i)$$



The E989 Laser Calibration System

10^{-4} / h stability demonstrated "Long-Term" Gain Correction
with mono-energetic electron beams
at the Frascati and SLAC test beam facilities in 2016



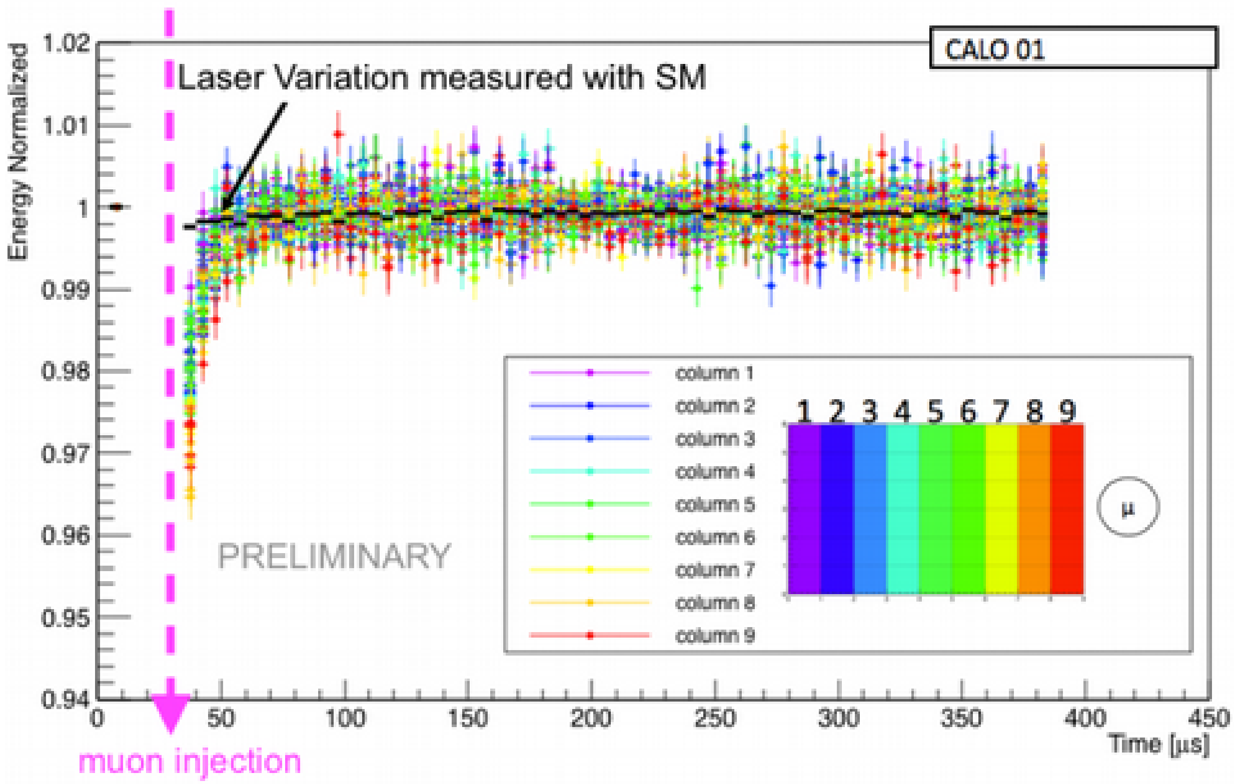


Ref:
"Electron beam test of key elements of the laser-based calibration system for the muon g-2 experiment," Nucl. Instrum. Meth. A 842, 86 (2017)
"Studies of an array of PbF2 Cherenkov crystals with large-area SiPM readout," Nucl. Instrum.Meth. A 783 (2015)

The E989 Laser Calibration System

In-fill “Short-Term” (order of μs) Gain Correction

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

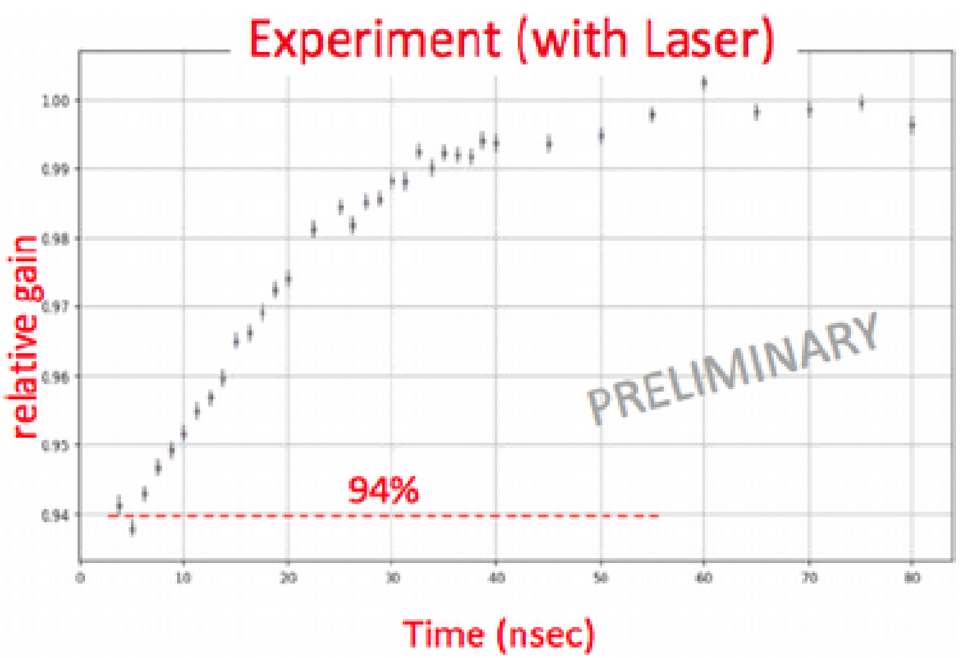


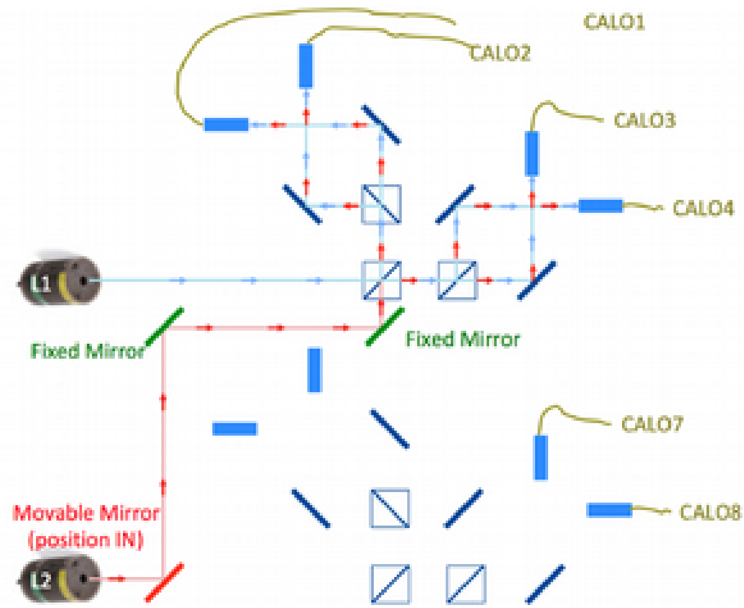
The E989 Laser Calibration System

Short-time Double Pulse

A “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

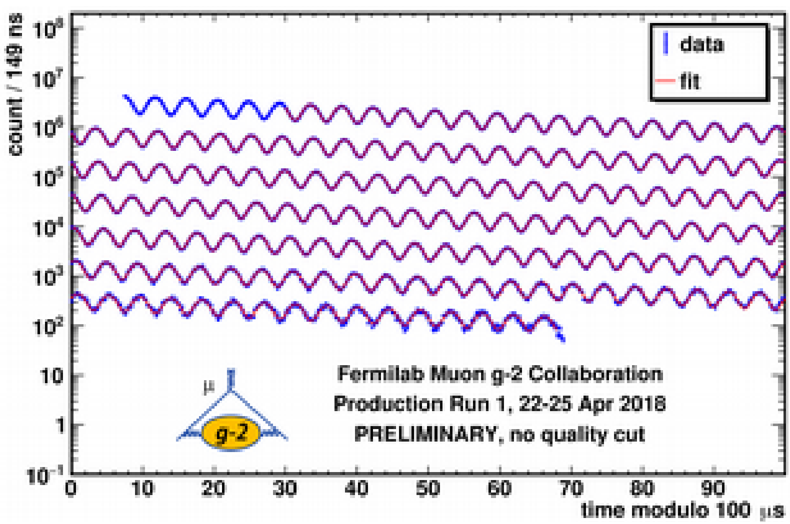
Example: measurement of pile up effect

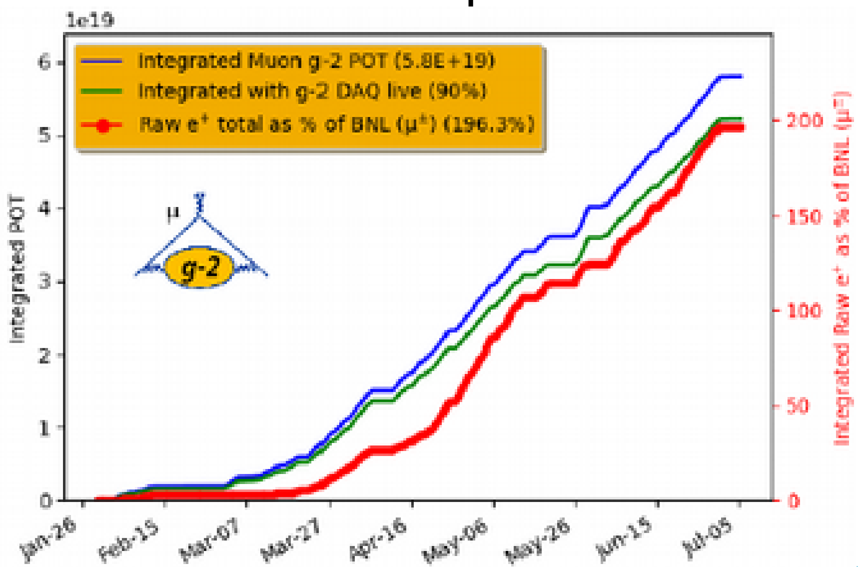




Conclusions

- The E989 g-2 experiment at Fermilab after commissioning is now ready for next data taking
- The Laser Calibraion System at Fermilab is capable to provide time alignement and to measure the gain function of each of the 1296 calorimeter channels to ensure a systematic error under 20 ppb (The stability of Calibration System is less than 0.4 per mille level)
- The double of brookhaven experiment statistic is collected up to last summer

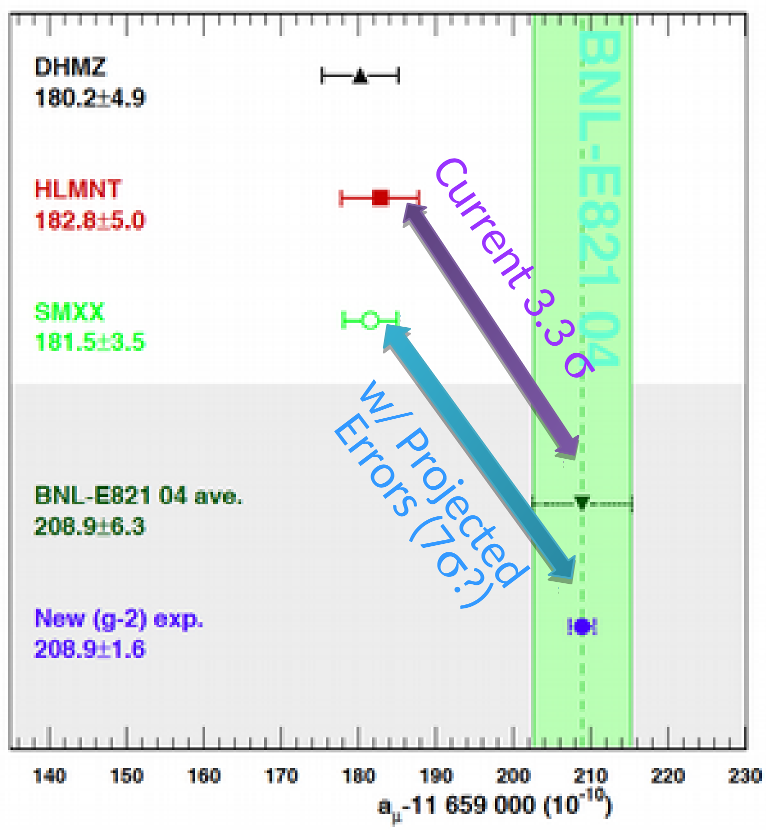




Backups

The E989 g-2 Experiment

The muon anomaly has been measured to 0.54 parts per million by the E821 experiment at the Brookhaven National Laboratory. This result shows a 3 to 4 standard-deviation difference with respect to the SM prediction (540ppb → 140ppb)



- Reduce the experimental error by a factor 4
- Resolve the long-standing E821 *g*-2 discrepancy
  - With new e+e- hadron data samples and improvements on LbL contribution theory error should come down by about 30% in the next 5 years
  - Lattice community provides avenues to independent calculations
  - If current discrepancy persists, significance will be pushed beyond 5σ discovery threshold
  - Anticipated theoretical improvement could lead to >7σ discrepancy

The E989 g-2 Experiment: 4 key elements

(1) **Polarized muons**

~ 97% polarized for forward decays

(2) **Precession proportional to (*g*-2)**

(3) **P_μ magic momentum = 3.094 GeV/c**

No *E* effect on precession when $\gamma = 29.3$

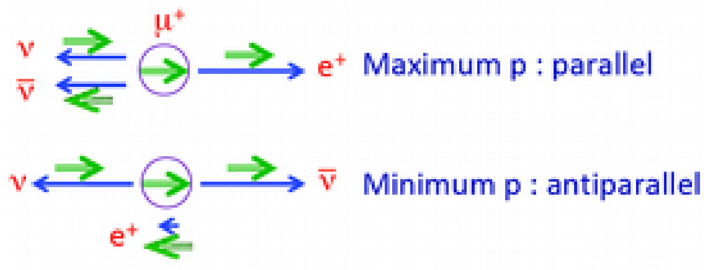
An Electric field is necessary for vertical focusing of the beam so:

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

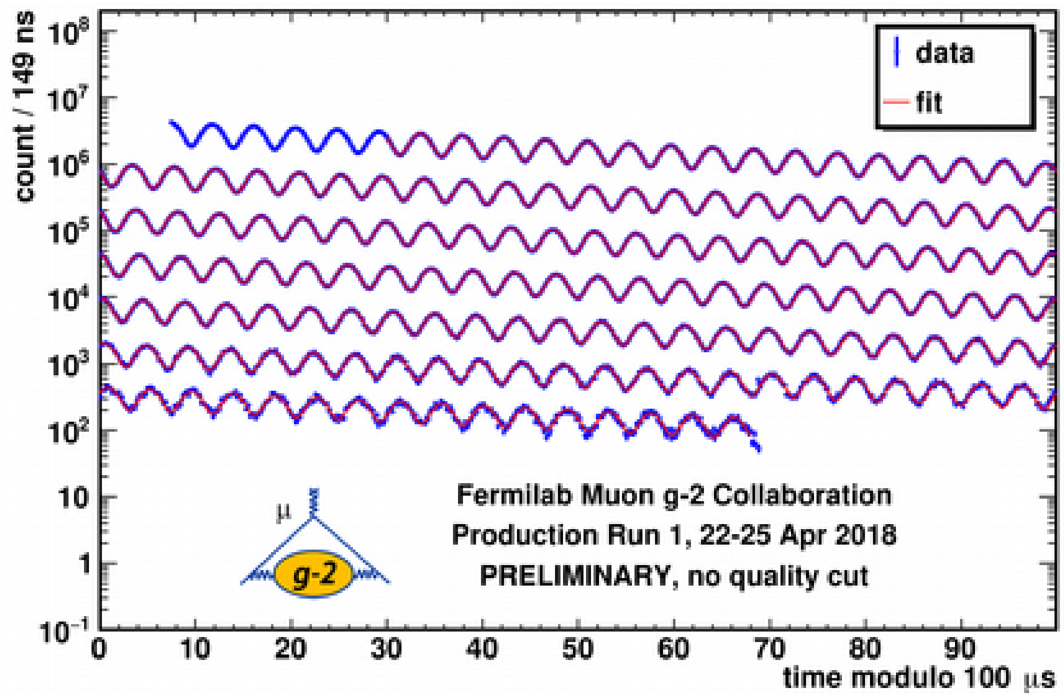
The extra term is zero for $\gamma = 29{,}3$ ($P_\mu = 3.09$ GeV/c)

The E989 g-2 Experiment: 4 key elements

(4) **Parity violation in the decay gives average spin direction.** The number of higher energy positrons is modulated at ω_a



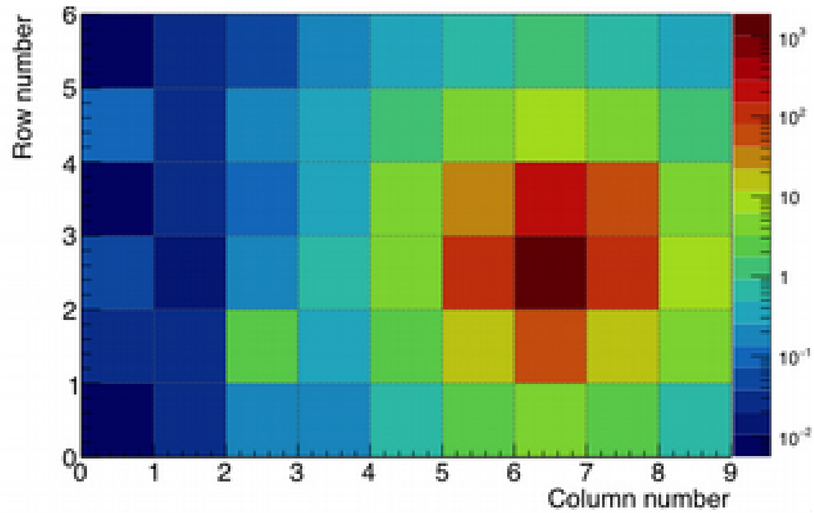
$$N(t) = N_0 e^{-t/\tau}\left(1 + A\cos(\omega_a t + \varphi)\right)$$

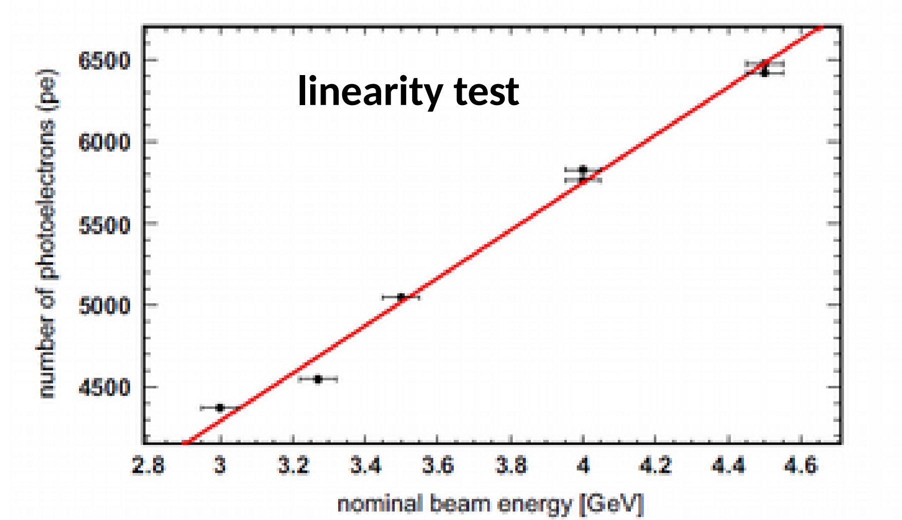


$$\omega_a \sim 240\ kHz$$

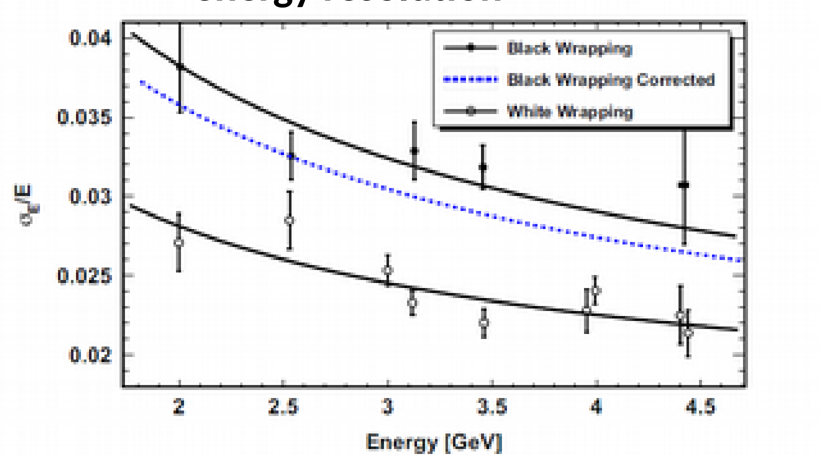
$$\tau_a \sim 4.4\ \mu s$$

The E989 Calorimeters

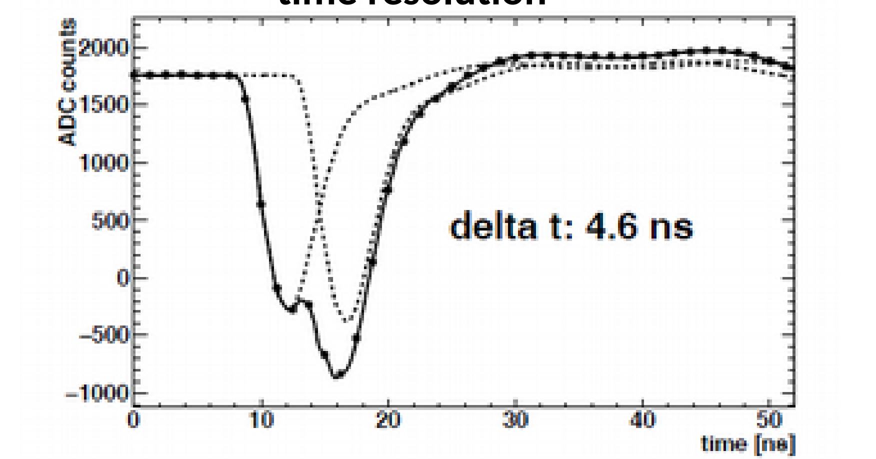




energy resolution



time resolution



A. Fienberg, NIM A 783, 12 (2015); J. Kaspar, Jinst (2017)