The calorimeter of the muon g-2 experiment

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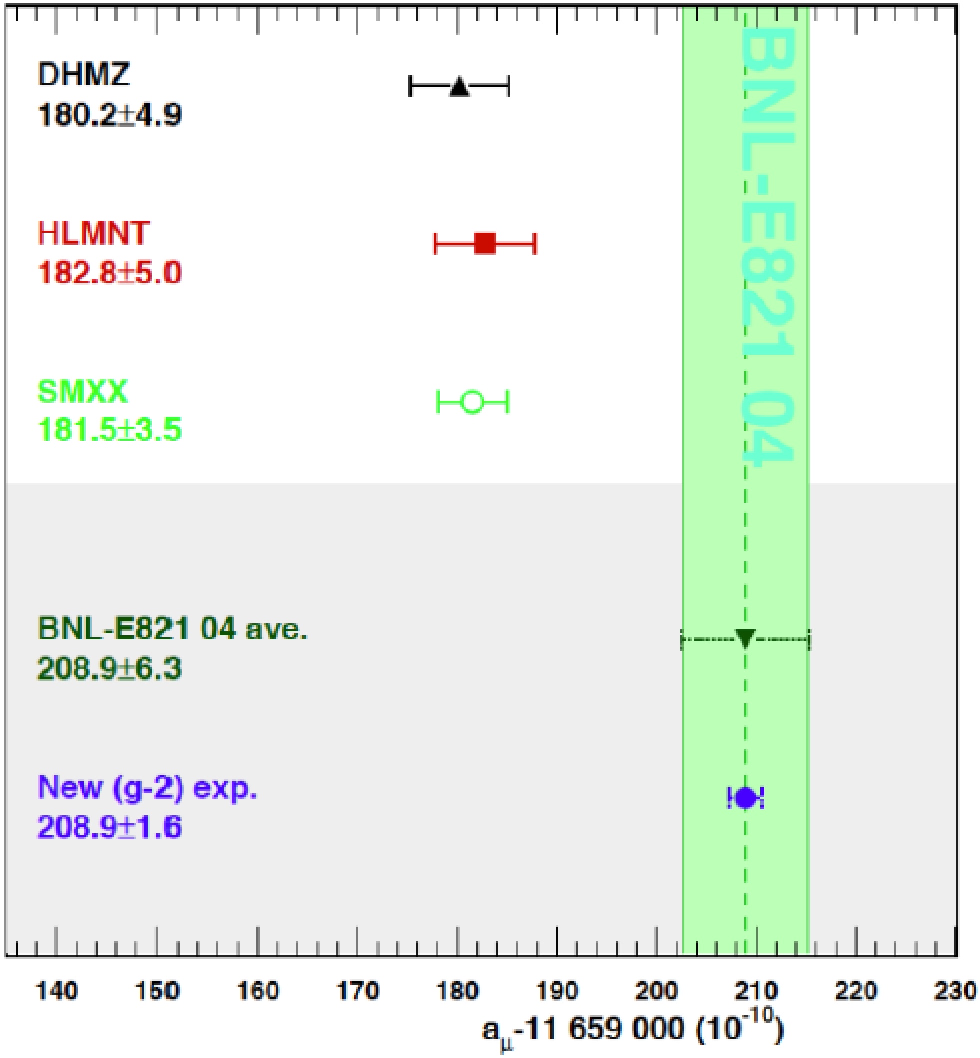
Principle of the Muon g-2 experiment

BNL E821 measured g-2 to have a 3.3σ discrepancy from the standard model (2006).

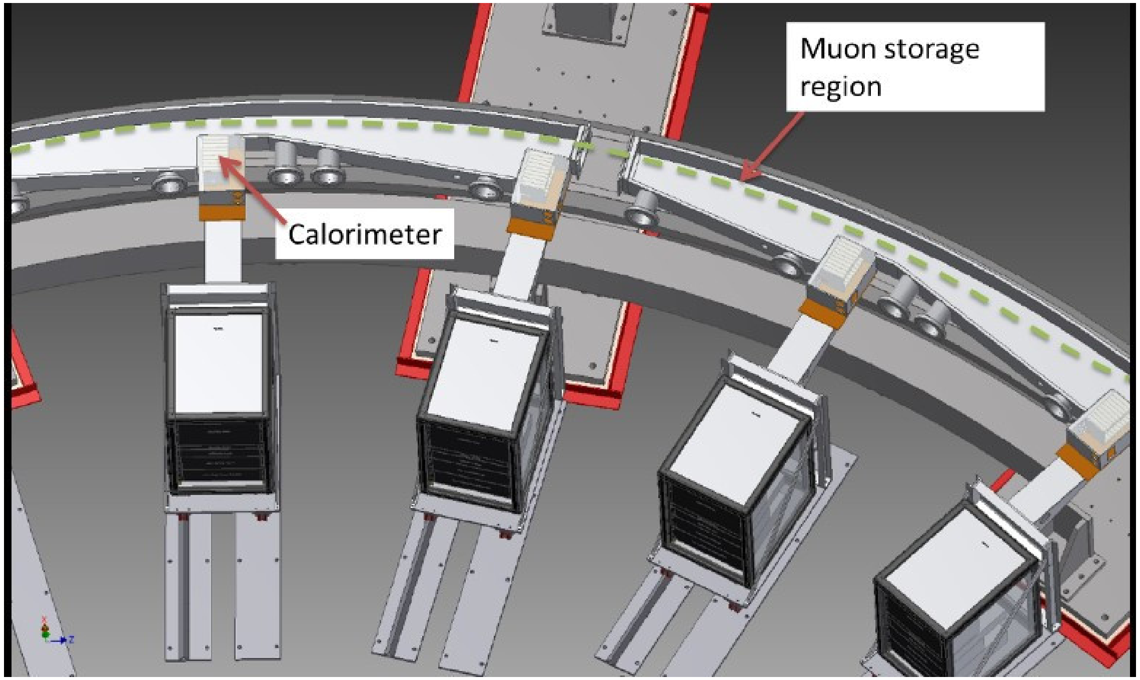
Fermilab E989 will measure 20 times the number of muons, reducing the uncertainty on this measurement by a factor of 4.

Without theory improvements, discrepancy could reach > 5σ.



Calorimeter Layout

The new muon (g-2) experiment at Fermilab will require 24 electromagnetic calorimeter stations placed on the inside radius of a magnetic storage ring.



The calorimeter of the muon g-2 experiment

The calorimeter system includes the following subsystems:

- **Absorber**
- **Photodetector**
- **HV bias control**
- **Laser calibration**
- **Mechanical**

Main Requirements for Calorimeter

1. **Energy resolution 5%.**
2. **Timing resolution better than 100 ps for e^+ > 100 MeV.**
3. **100% efficiency to resolve two showers for time separation ≥ 5 ns. 66% for time < 5 ns.**
4. **Gain stability $\delta G/G < 0.1\%$ within 200 μs.**
5. **More relaxed long term Gain stability $\delta G/G < 1\%$.**
6. **Laser calibration must provide Gain monitoring with a precision ~0.04%.**

The electromagnetic calorimeter of the muon g-2 experiment

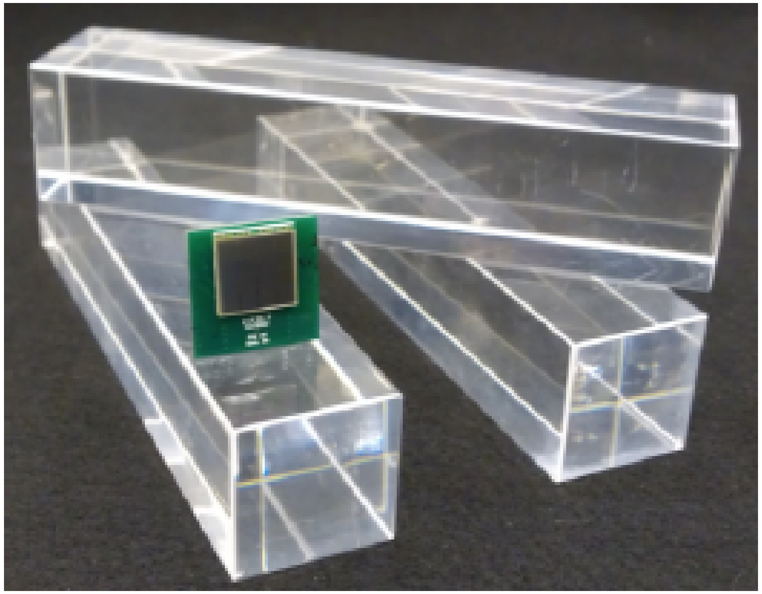
The electromagnetic calorimeter for the new muon (g-2) experiment at Fermilab will consist of arrays of 54 PbF_2 Čerenkov crystals read out by large-area silicon photo-multiplier (SiPM) sensors.

high density (7.77 g/cm^3)

Radiation length 9.3-mm

Molière radius (for energy deposition)

R^E_M = 22mm



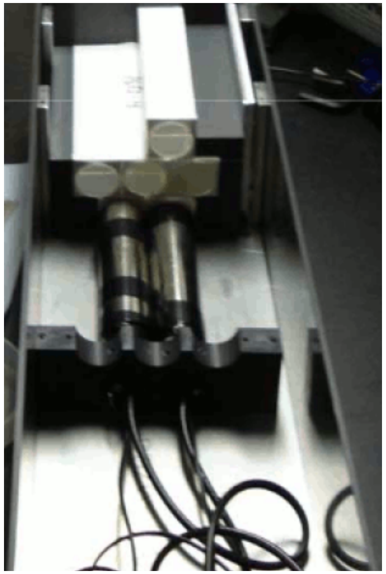
The electromagnetic calorimeter of the muon g-2 experiment

Two alternative calorimeter material options were tested (2012):

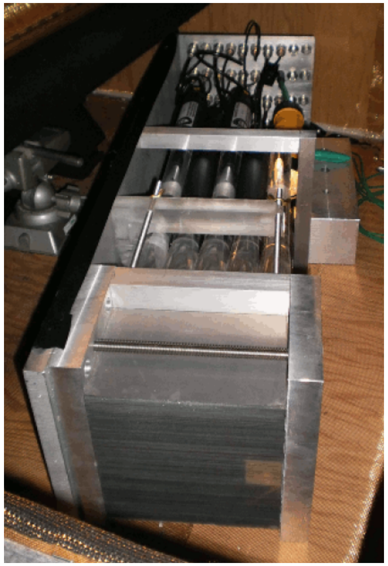
- **Home-built tungsten-scintillating fiber sampling calorimeter W/SciFi that has a fast-scintillator signal response but, unfortunately, it did not exhibit acceptable resolution.**
- **Custom undoped lead tungstate ($PbWO_4$) crystal with too slow scintillator light component for our application.**

PbF_2 Čerenkov crystals are combination of good energy resolution, very low magnetic susceptibility and a very fast Čerenkov signal response outperformed the other absorber options that we considered.

PbF_2



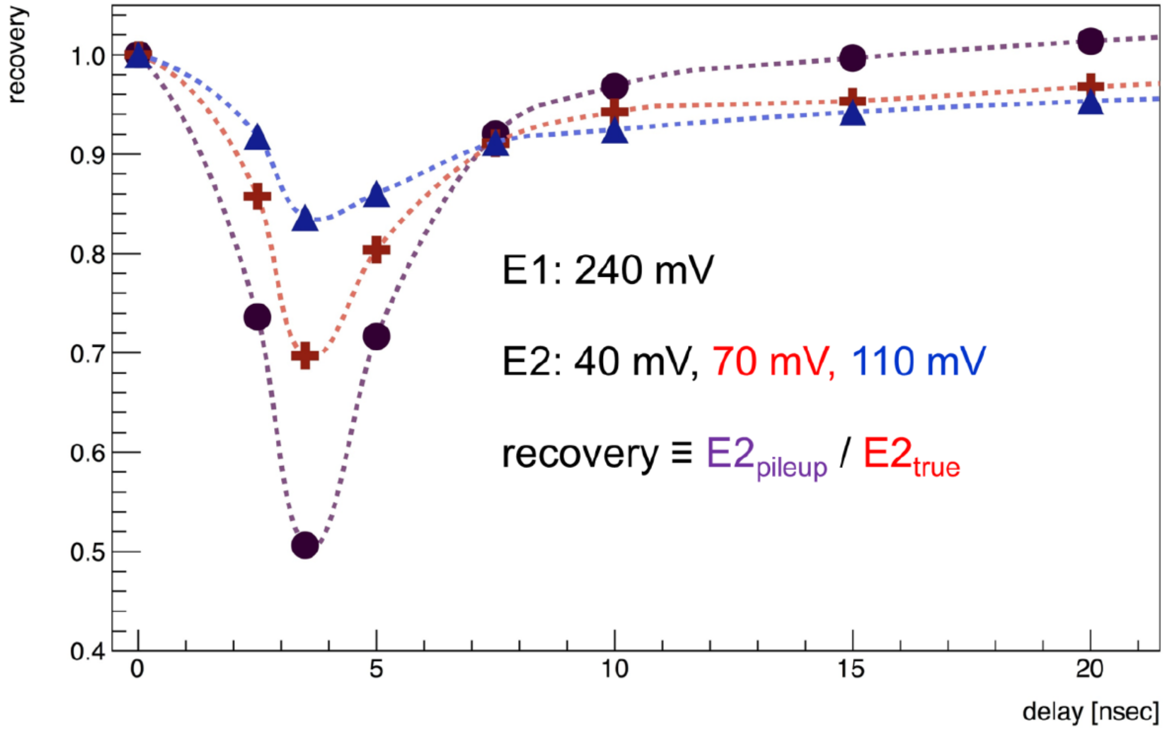
W/SciFi



The electromagnetic calorimeter of the muon g-2 experiment

Our simulations demonstrate that an array of PbF_2 crystals, having 54 independent segments and a smaller Moliere radius compared to the Pb/SciFi used in E821 experiment, will provide an effective three-fold reduction in the intrinsic pileup based on the implementation of a very simple and robust shower separation routine and a 9-element cluster algorithm.

Relative SiPM gain drop experienced by a second event closely following a larger primary one.
The gain loss is dependent on the time delay between events and on the number of photons in the second event.



The electromagnetic calorimeter of the muon g-2 experiment

We also evaluated fast photo-multiplier tubes as alternatives to SiPMs.

The major issues were:

- **The need to place these PMTs at least 1.5m from the calorimeter arrays (far from magnetic field) -** ***light-guide constraint***
- **The high cost of the PMTs (about 5 times higher than the SiPMs)**

A PMT-based solution would increase costs significantly and introduce delays compared to the SiPMs that can be located onboard the crystals.

The calorimeter test beams at SLAC 2014

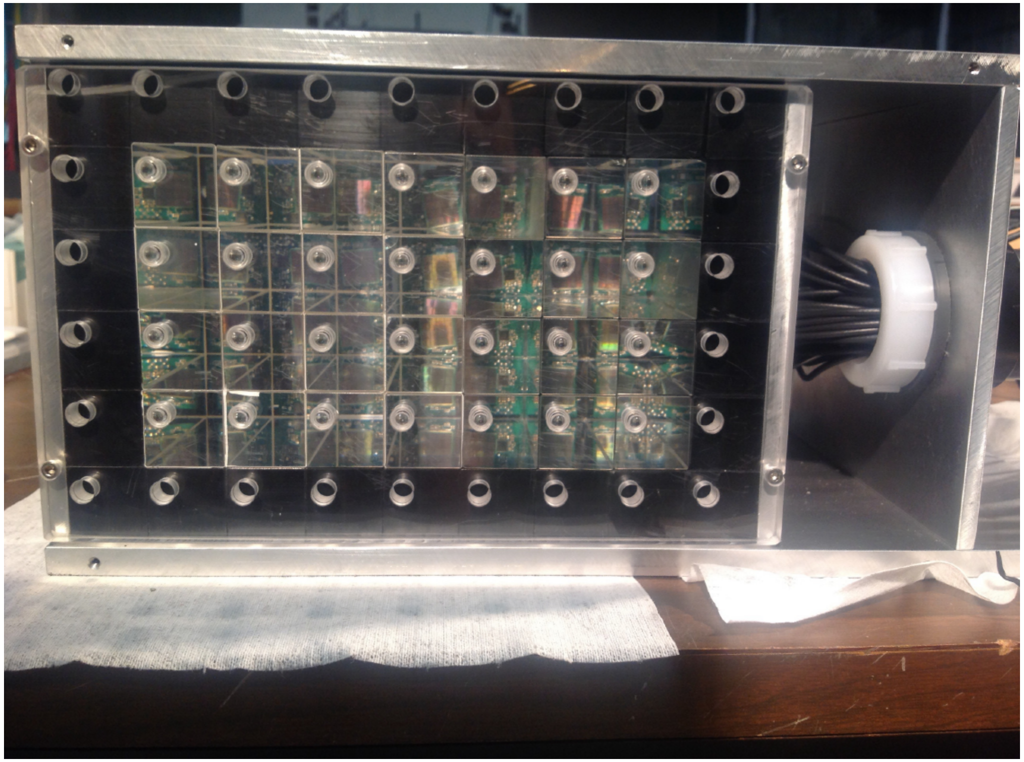
We report here the results obtained from a test beam using 2.0 - 4.5 GeV electrons with a 28-element prototype array at SLAC in summer 2014.

[*A. Fienberg et al, "Studies of an array of PbF2 Cherenkov crystals with large-area SiPM readout" - Nucl.Instrum.Meth. A783 (2015) 12-21*]

The calorimeter test beams at SLAC 2014: electromagnetic calorimeter

Calorimeter prototype used at SLAC 4x7 (28) crystal array. The final calorimeter is composed by a 6x9 (54) crystals array. Segmentation is used to improve spatial resolution.

4x7 array of 2.5x2.5x14 cm^3 ($15X_0$) high-quality PbF_2 crystals



The calorimeter test beams at SLAC 2014: electromagnetic calorimeter

Calorimeter prototype used at SLAC 4x7 (28) crystal array. The final calorimeter is composed by a 6x9 (54) crystals array. Segmentation is used to improve spatial resolution.

Front view of the array of 28 PbF_2 crystals.

Elements 1 - 16 are wrapped in white Millipore paper.

while elements 17 - 28 are wrapped in black Tedlar.

1	2	3	4	17	18	19
5	6	7	8	20	21	22
9	10	11	12	23	24	25
13	14	15	16	26	27	28

The calorimeter test beams at SLAC 2014: Linear responce correction

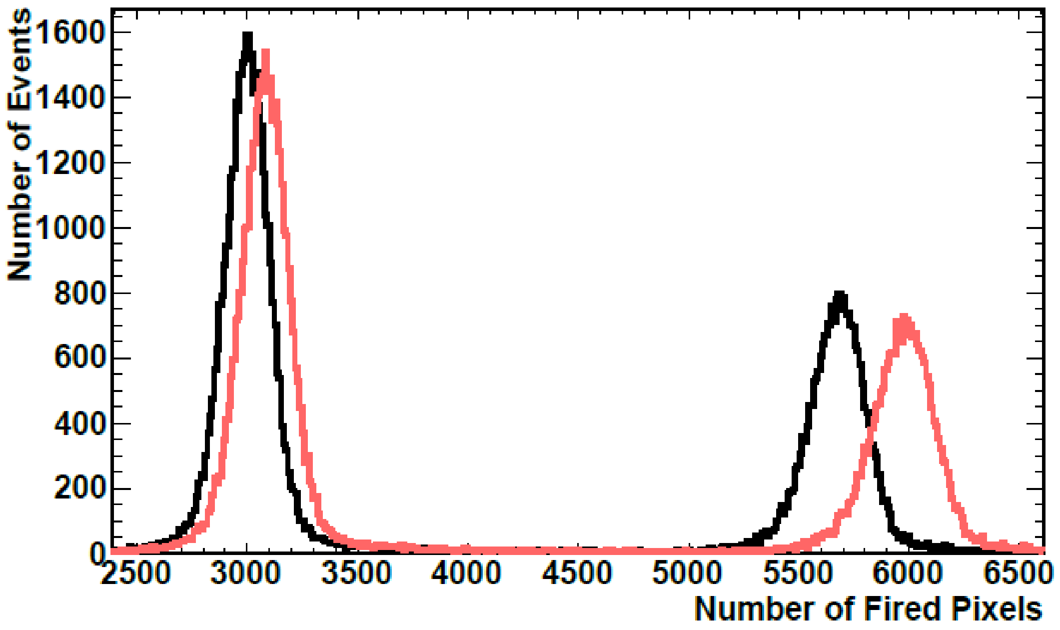
For good near-linear operation, the concept is to have a pixel count that greatly exceeds the highest photon count that would strike the device. A deviation from linearity at high light levels is caused by pixel saturation.

Correction:
$N_{fired} = N_{tot} [1 - \exp(-N_{primary}/N_{tot})]$

Here the response of a single crystal to one or two 3-GeV electrons within a beam bunch.

The raw trace (black) is corrected (light red) to account for pixel saturation.

The correction improves the energy linearity between the first and second peak.



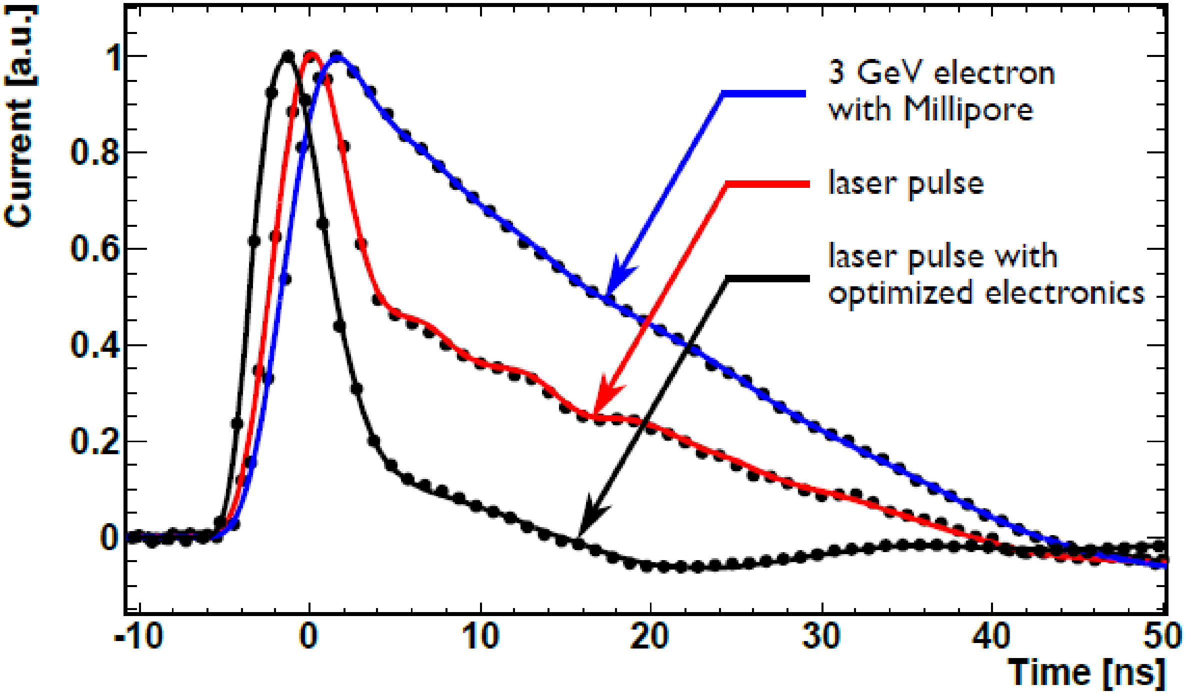
The calorimeter test beams at SLAC 2014: Pulse shape

The digitized pulse shape allows reliable reconstruction of hit energy, time and position because the shapes of an energy shower and the digitized pulse are directly related.

Sample traces from the digitizer:

SiPM traces from a 3-GeV electron in a Millipore-wrapped crystal and a laser pulse were recorded by a 1 GSa/s digitizer.

Also shown is a trace from a laser pulse read out by newest generation of electronics boards.



The calorimeter test beams at SLAC 2014: Results

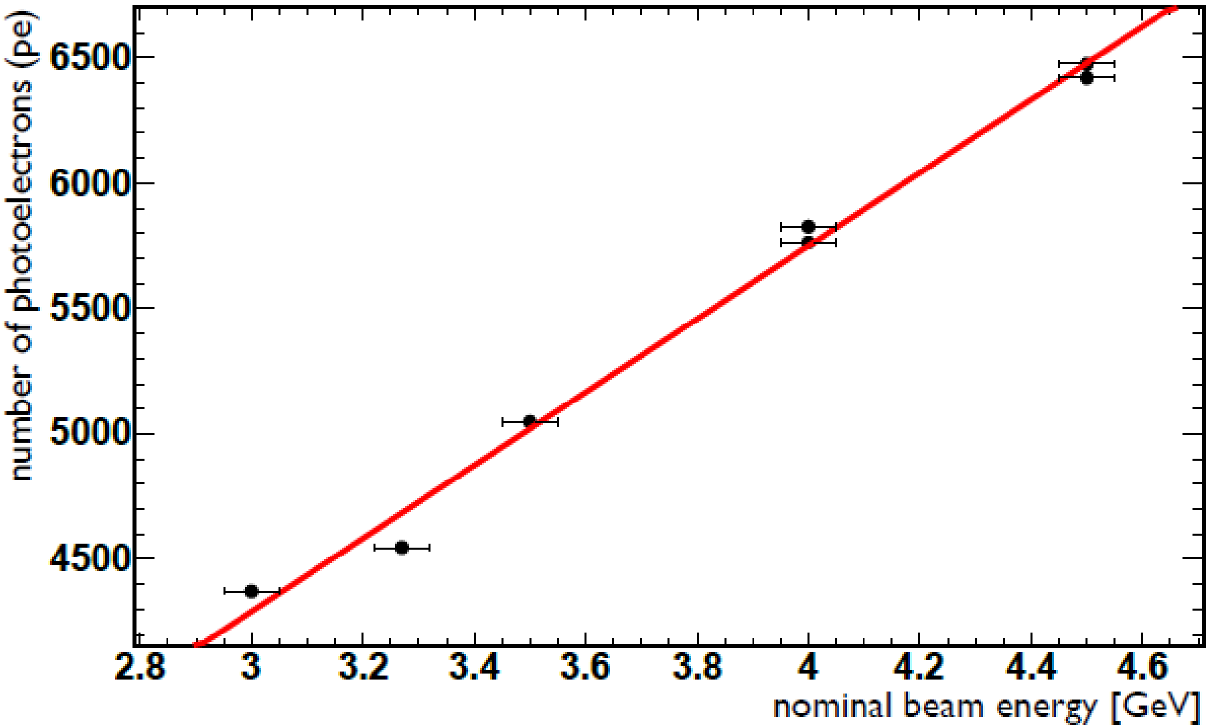
After laser calibration, the energy response, light yield, and resolution of the detectors were studied for 3x3 clusters of white- and black-wrapped crystals using a beam with energies ranging from 2 to 4.5 GeV.

For every beam event, the pulses in each of the nine crystals within a cluster were converted into pe and summed together.

The result is a linear relationship between pe extracted from the fit and the beam energy in the range from 3 to 4.5 GeV.

We obtained:
a slope of (1.45 ± 0.05) pe/MeV with an offest of (-80 ± 200) pe for the white array and

a slope of (0.76 ± 0.04) pe/MeV with an offest of (-150 ± 160) pe for the black array.



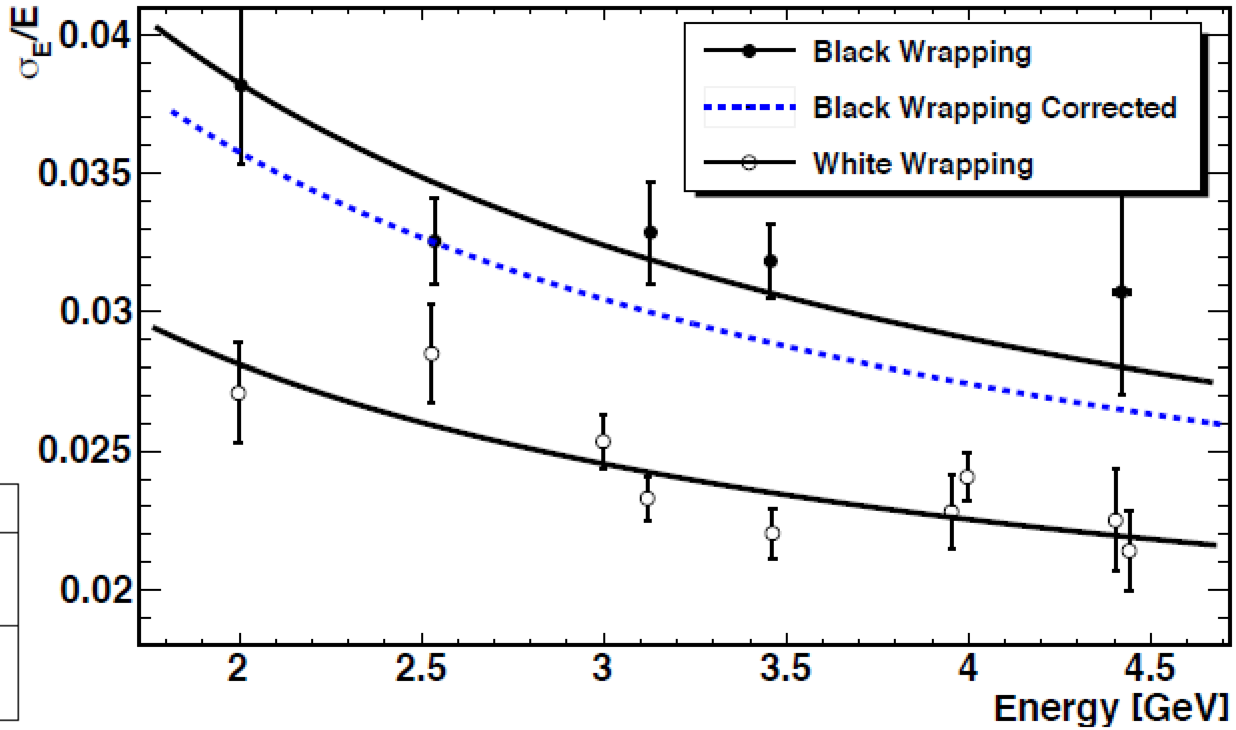
The calorimeter test beams at SLAC 2014: Results

We obtained Energy resolutions of 3x3 arrays of PbF_2 crystals with black and white wrappings as a function of energy. Fit functions are of the form $\sigma^2_E/E^2 = (1.5\ \%)^2 + a^2/(E/GeV)$.

Despite the SiPMs' small area coverage, the energy resolutions obtained here are better than those measured in previous studies of PbF_2 using phototubes.

	Millipore	Tedlar
Light yield [pe/MeV]	1.45 ± 0.05	0.76 ± 0.04
Energy resolution $[\%/\sqrt{E/\mathrm{GeV}}]$	3.4 ± 0.1	4.6 ± 0.3

a parameter



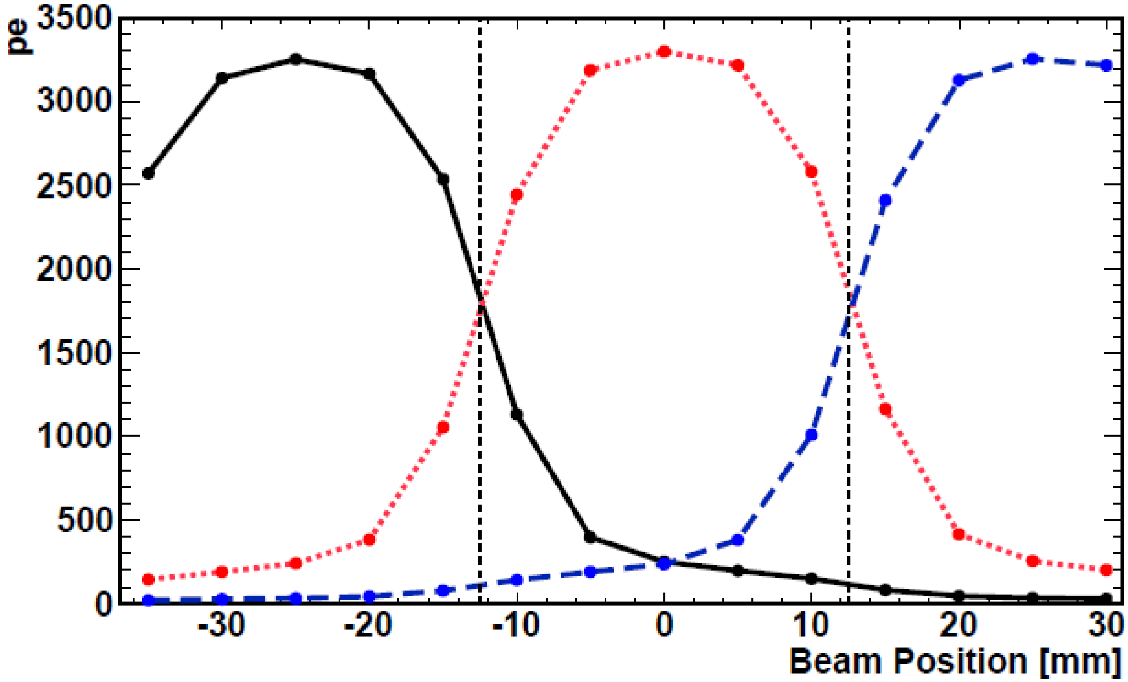
The calorimeter test beams at SLAC 2014: Results

Impact Position

A 3.1-GeV electron beam was scanned horizontally across the centers of three adjacent crystals in steps of 5 mm.

Behavior of the number of detected pe

The maximum numbers of pe observed in each crystal differ by under 2%.



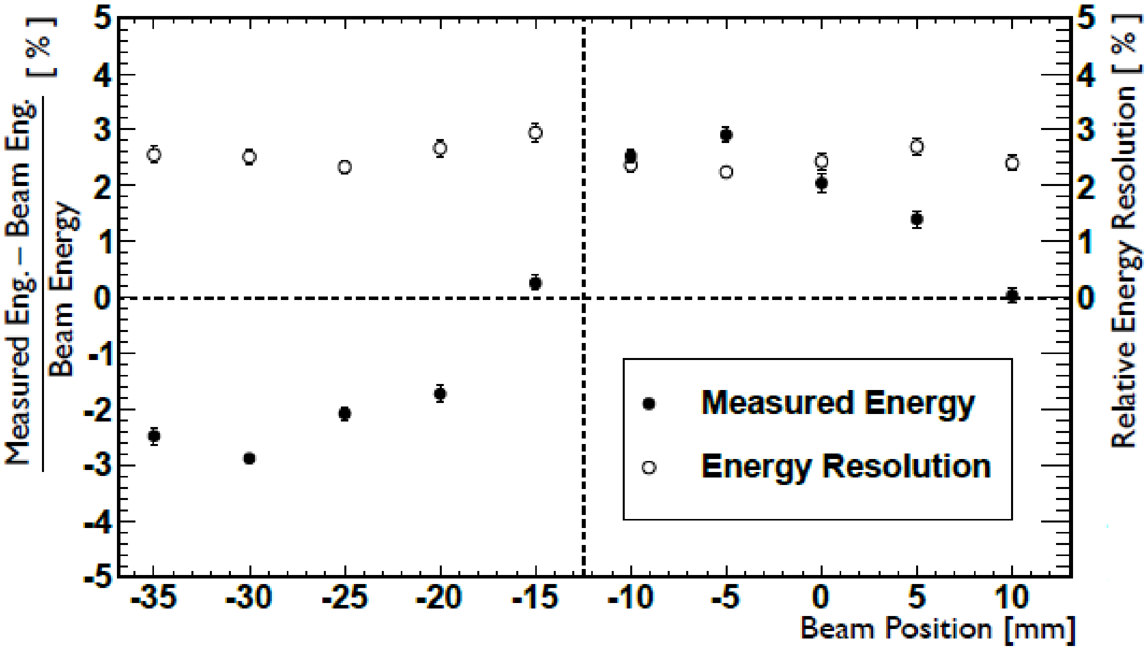
The calorimeter test beams at SLAC 2014: Results

Impact Position

A 3.1-GeV electron beam was scanned horizontally across the centers of three adjacent crystals in steps of 5 mm.

Total pe sum across the scan

The total sum over 12 crystals remains constant within 4% over the 45mm scan.



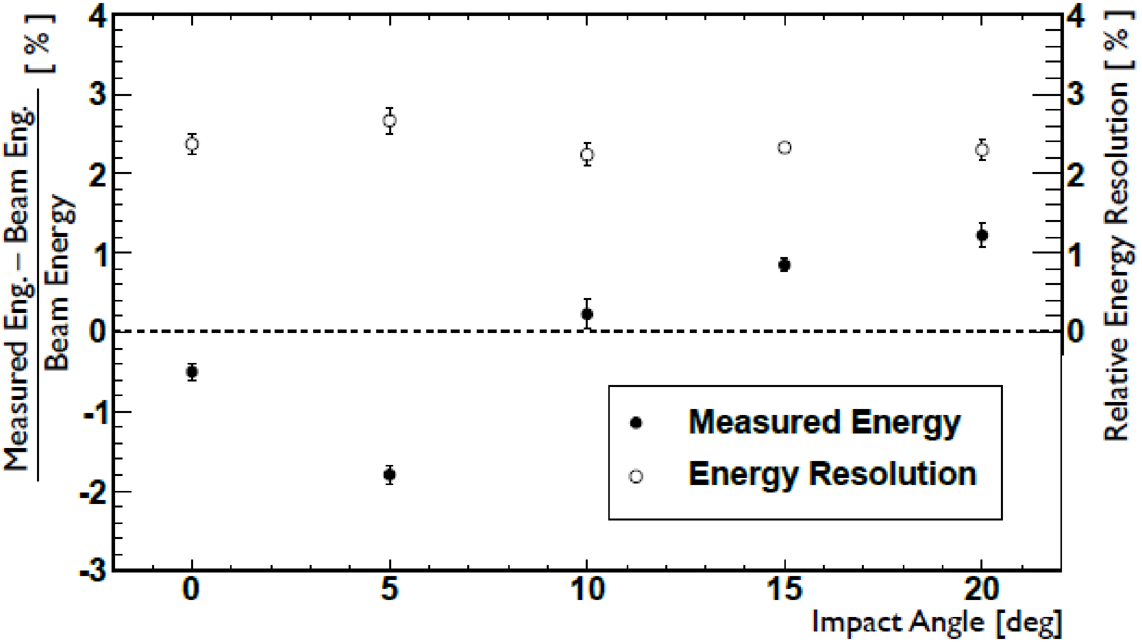
The calorimeter test beams at SLAC 2014: Results

Impact Angle

In the (g-2) experiment, decay positrons of interest curl inward from the storage ring and strike the calorimeter front face at energy-correlated angles in the range from 0 to 30 degrees.

Tested with a 3GeV beam

the reconstructed energy is constant within 3% and the energy resolution does not appear to be significantly affected by the electron angle.



The calorimeter test beams at SLAC 2014: Results

Long-term Gain stability

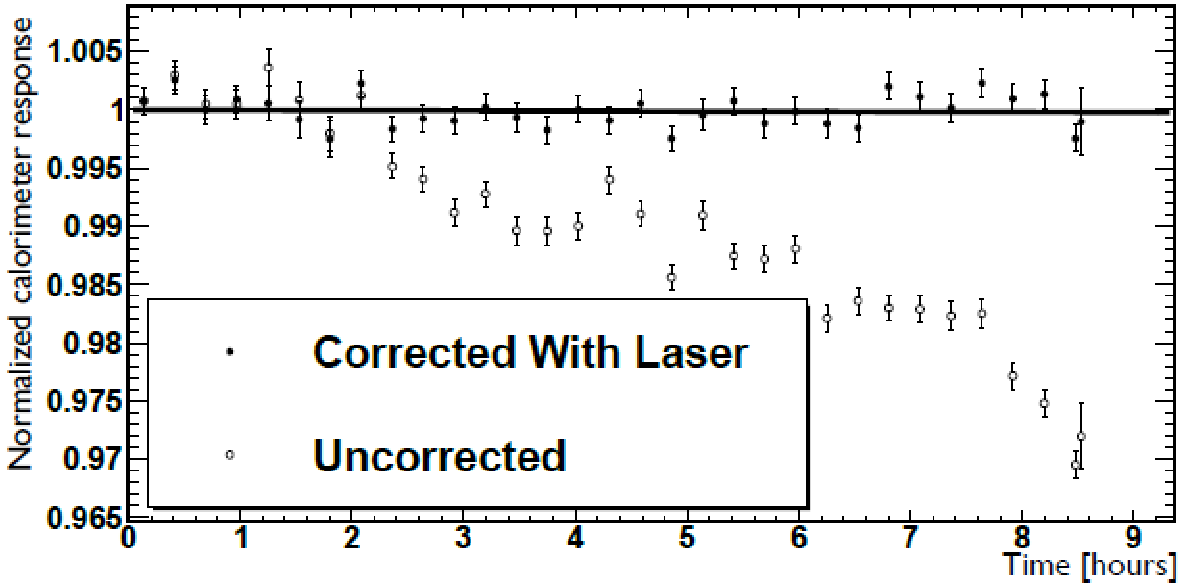
SiPMs sensitivity changes in temperature.

Over the course of the run, the drifts in gain were tracked using the laser calibration system, which ran in parallel to normal data taking using a separate trigger at roughly 20 Hz.

Each 15-minute period Average response (using the sum of the 12 individual normalized crystal responses) is corrected by the average laser response over this same period.

With the correction, δE/E is stable at the level of $(2\pm9)\times10^{-5}$ per hour.

(Tested with a 3GeV beam)



The calorimeter test beams at SLAC 2014: Results

the pulse shape varies with impact position for the white-wrapped crystals, but not for the black-wrapped crystals, as confirmed by the measurements.

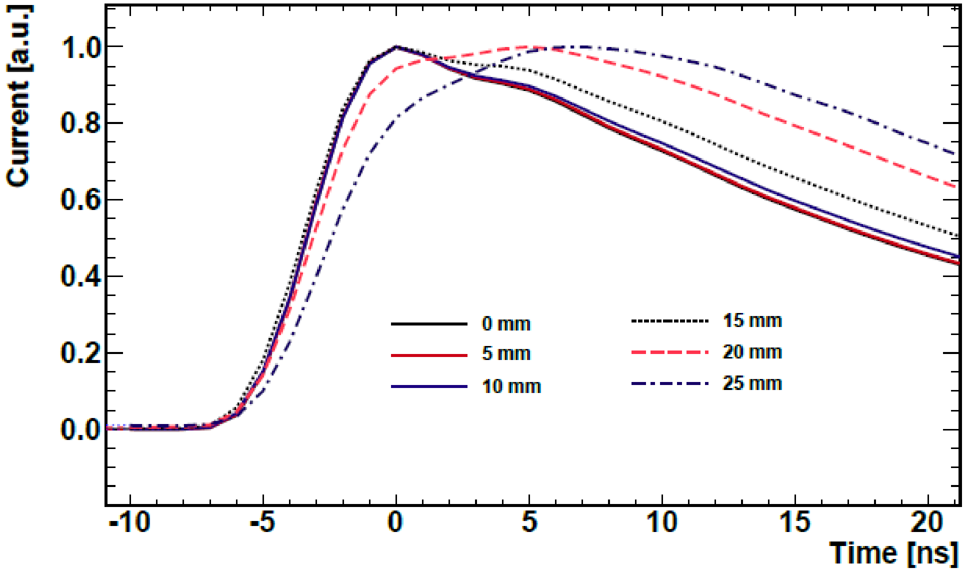
Distance from Beam [mm]	Relative FWHM	
	Millipore	Tedlar
0	1	1
5	$1.01 \pm .01$	$1.01 \pm .02$
10	$1.05 \pm .02$	$1.02 \pm .02$
15	$1.17 \pm .01$	$1.02 \pm .03$
20	$1.40 \pm .01$	
25	$1.52 \pm .02$	$0.96 \pm .05$

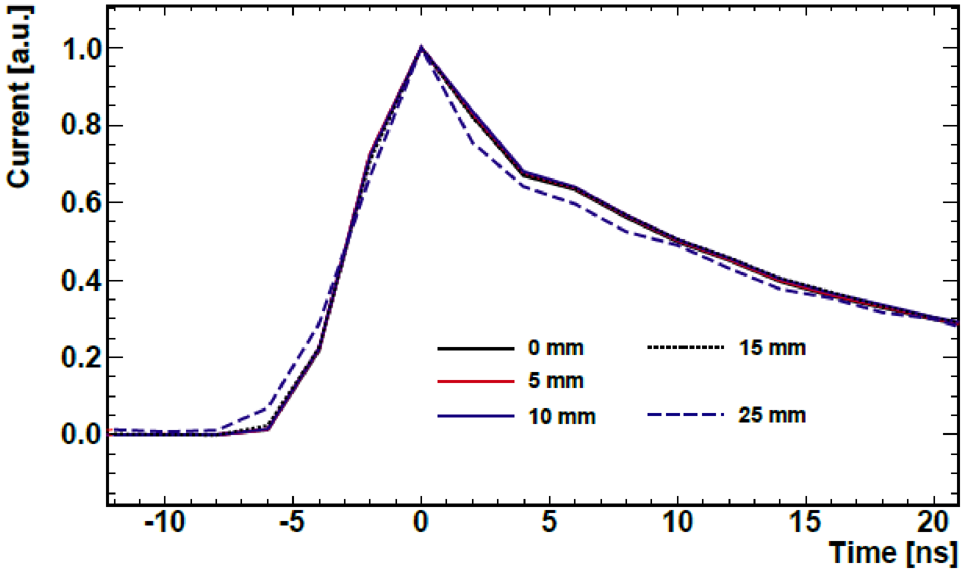
Pulse full width at half maximum evolution during position scan.

In a black-wrapped crystal the propagation of light is governed only by total internal reflection. White-wrapped crystals, in contrast, introduce an additional light propagation path, which allows photons generated with high polar angles to successfully reach a SiPM.

These photons have, on average, longer flight times prior to arriving at the photodetector and thus both widen and increase the pulse compared to a black-wrapped crystal.

In addition, as the impact position is displaced from the center, the average captured angular distributions change significantly and thus evolve the pulse width.





The calorimeter test beams at SLAC 2014: Conclusions

- This electromagnetic calorimeter used represents a half-sized prototype for one of the 24 calorimeter units that are required for the new muon (g-2) experiment at Fermilab.

- The energy resolution, light yield, and linearity characteristics of a PbF_2 calorimeter coupled with SiPM readout is found to either exceed or meet performance of previous PMT-coupled arrays.

- The absolute energy scale in units of photoelectron per pulse-integral can be obtained using only the laser system, independent of beam, and the calibration system can monitor the gain to a relative precision of better than 10^{-4} per hour.

- White-wrapped crystals exhibited an energy resolution σ/E of $(3.4\pm0.1)\%/\sqrt{(E/GeV)}$, with nearly twice the light yield compared to black-wrapped crystals, that had a resolution of $(4.6\pm0.3)\%/\sqrt{(E/GeV)}$.

- The crystal wrapping affects also the pulse-shape as a function of impact position, in particular with a white diffusive wrapping.