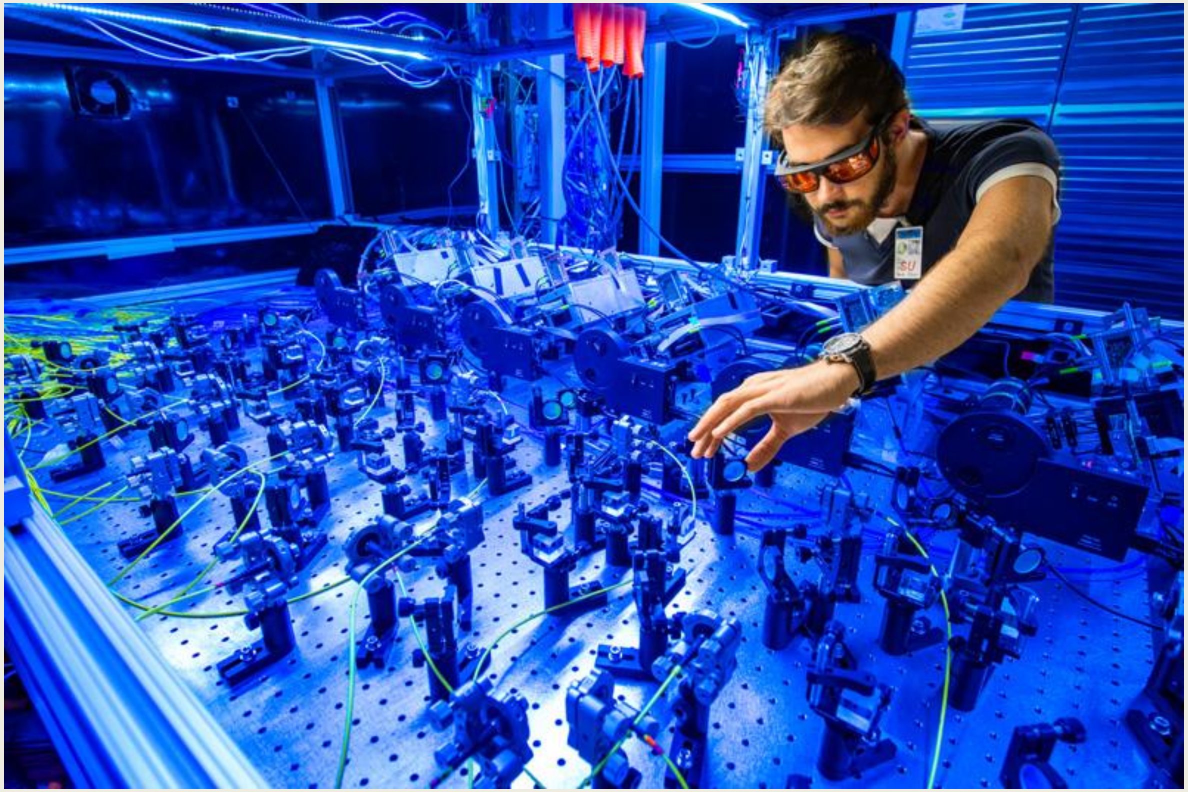

Muon g-2 laser overview

Andrea Fioretti, CNR-INO and INFN, Pisa, Italy

on behalf of the g-2 italian collaboration

MUSE General Meeting, Frascati 23-25 October 2019

Istituto Nazionale di Fisica Nucleare

CNR-INO ISTITUTO NAZIONALE DI OTTICA CONSIGLIO NAZIONALE DELLE RICERCHE

Outline

- Introduction
- Laser *distribution* system
- Laser *monitoring* system
- Control Electronics and data readout
- *Operation modes and gain calibration*
- Conclusions

The laser calibration system

Idea:

- Send trains of laser pulses on known intensity synchronously on all calorimeters' channels (24X54=1296 SiPMs)

Goals:

- Calibration of the of the SiPMs gain: short term (in fill – 700 μs, gain sag) at 10^{-4} level; long term (bias and temperature variations) gain function at 10^{-3} level
- Synchronization signals of the 1296 traces: sync pulse before muon
- Debugging of Calorimeters and Data Acquisition System (flight simulator mode)
- Gain equalization of the SiPMs response (photoelectrons/photons response)

Outline

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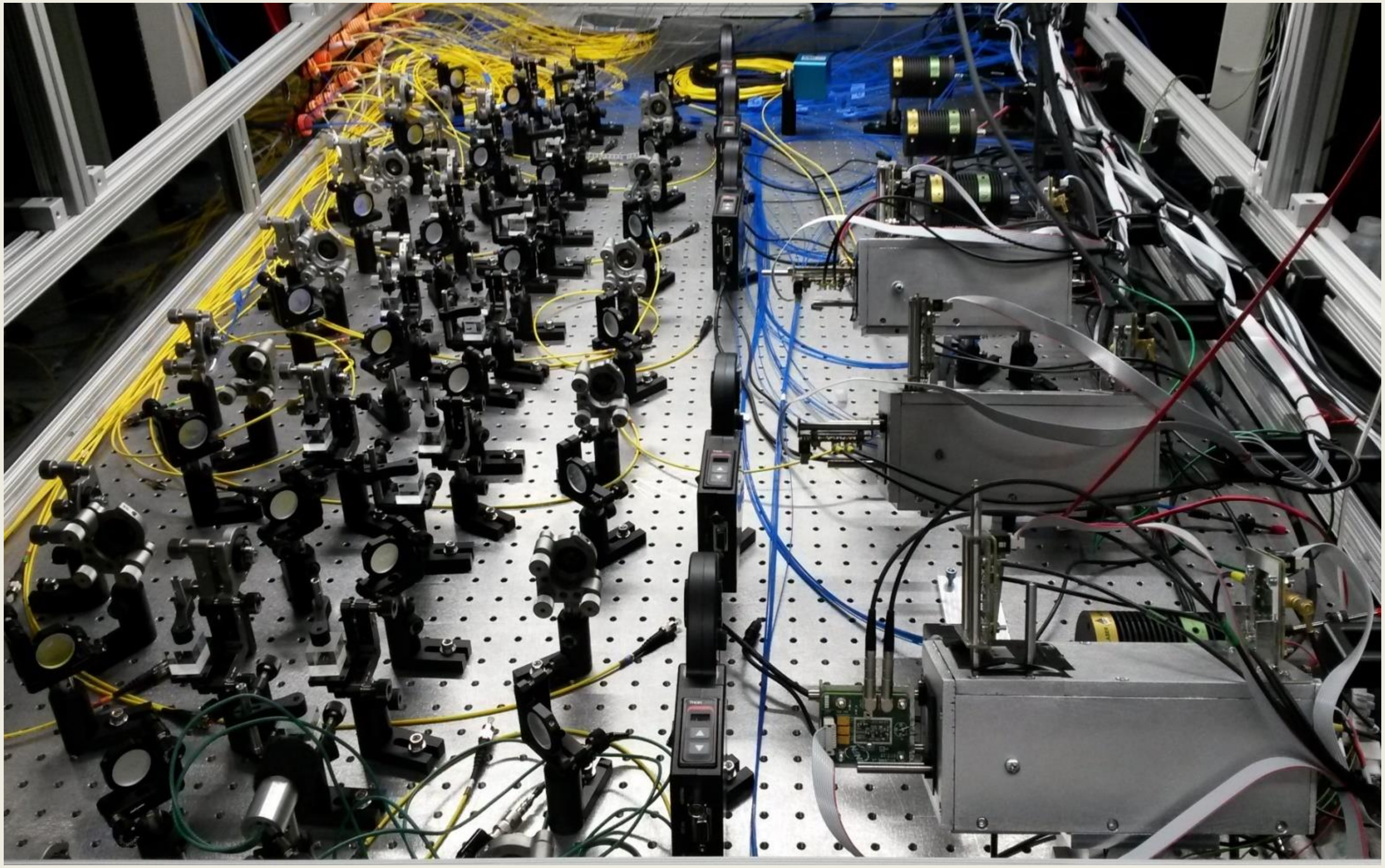
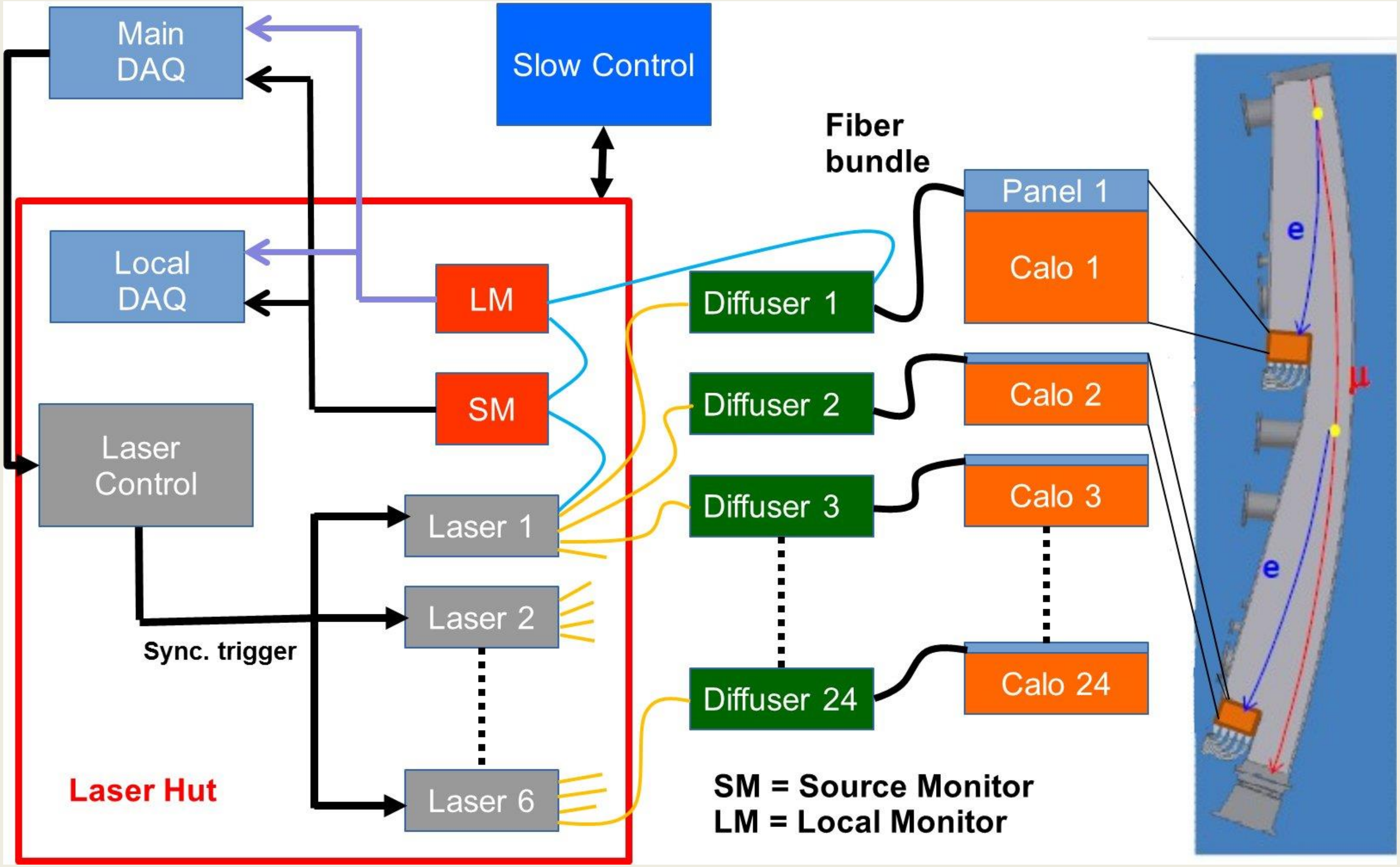
The laser system

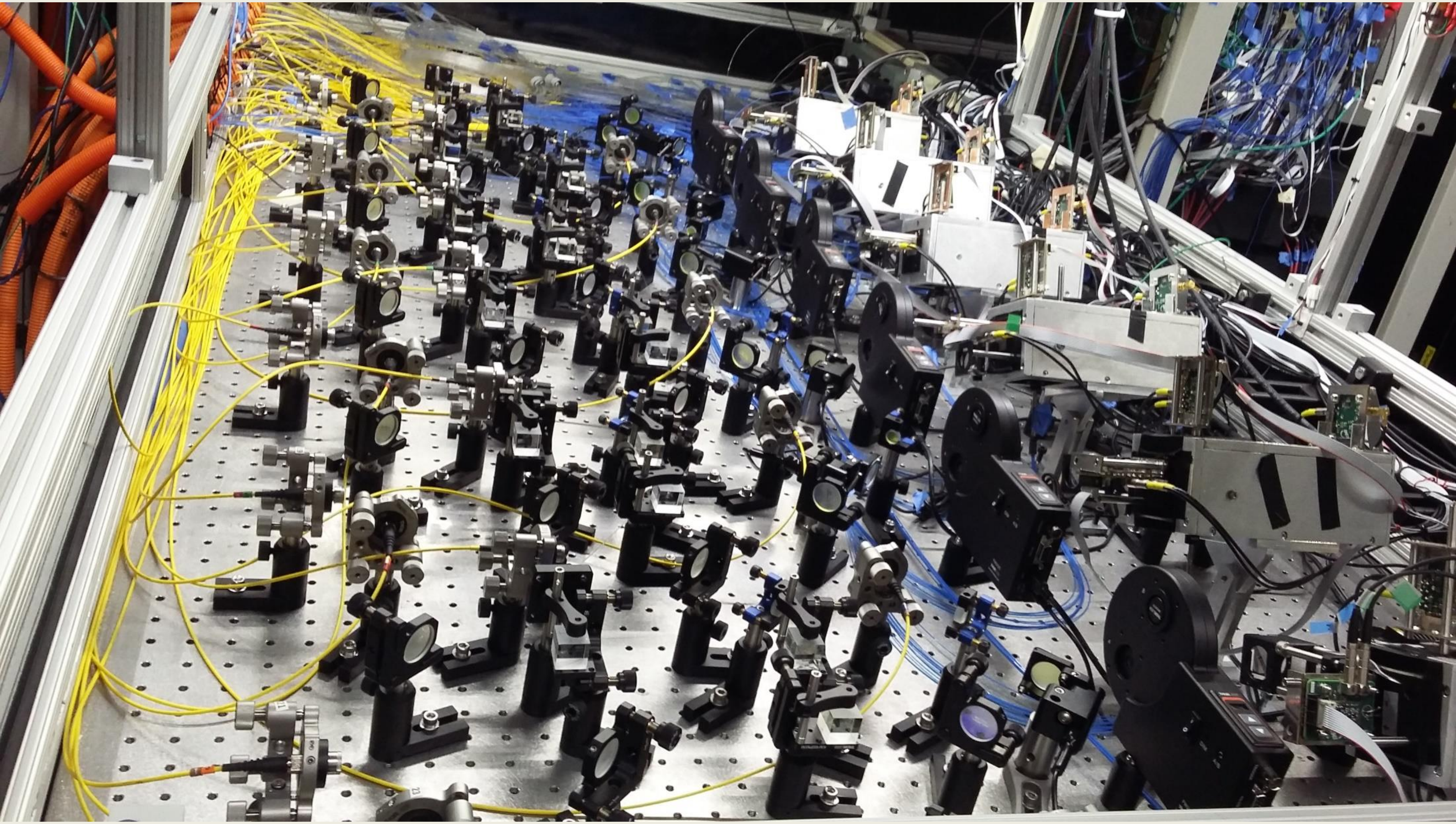


6 Picoquant Laser diodes @405nm, 600ps, 1nJ/pulse, 0-40 MHz rep. rate

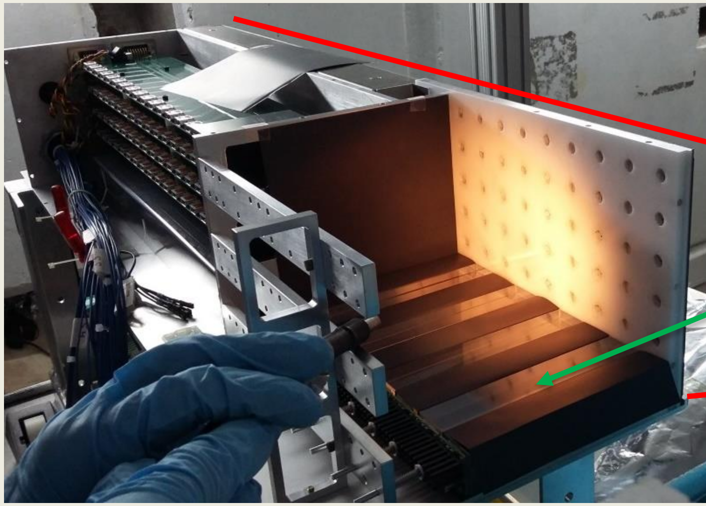
The laser distribution system



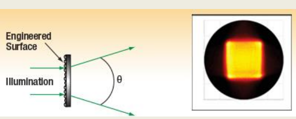
The laser system

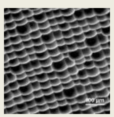


The diffusing system for each calorimeter



Crystal

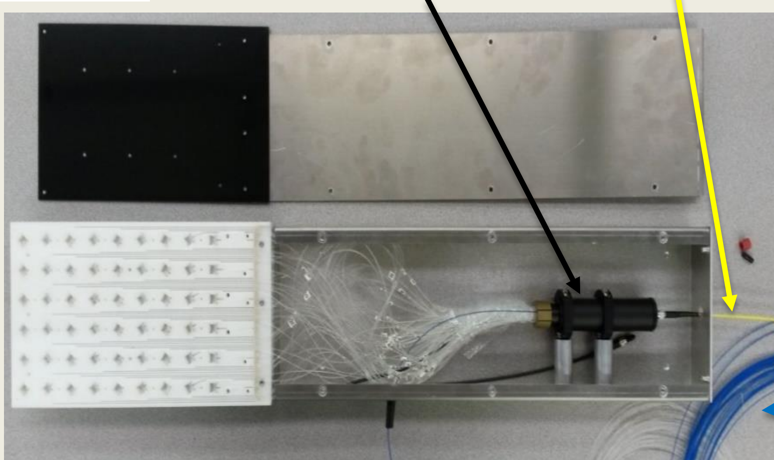




Engineered diffuser

Launching fiber

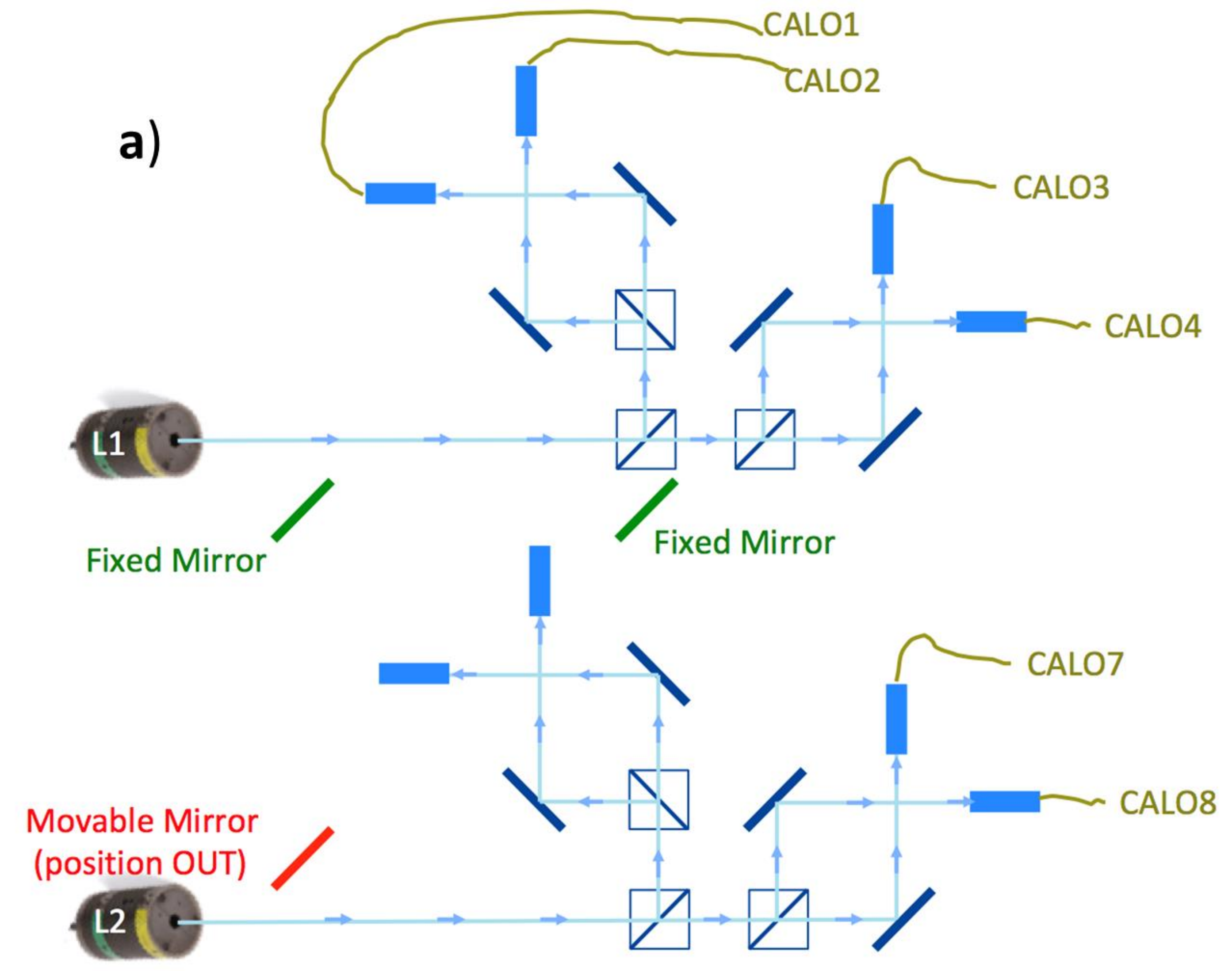
Delrin panel



Monitor fiber

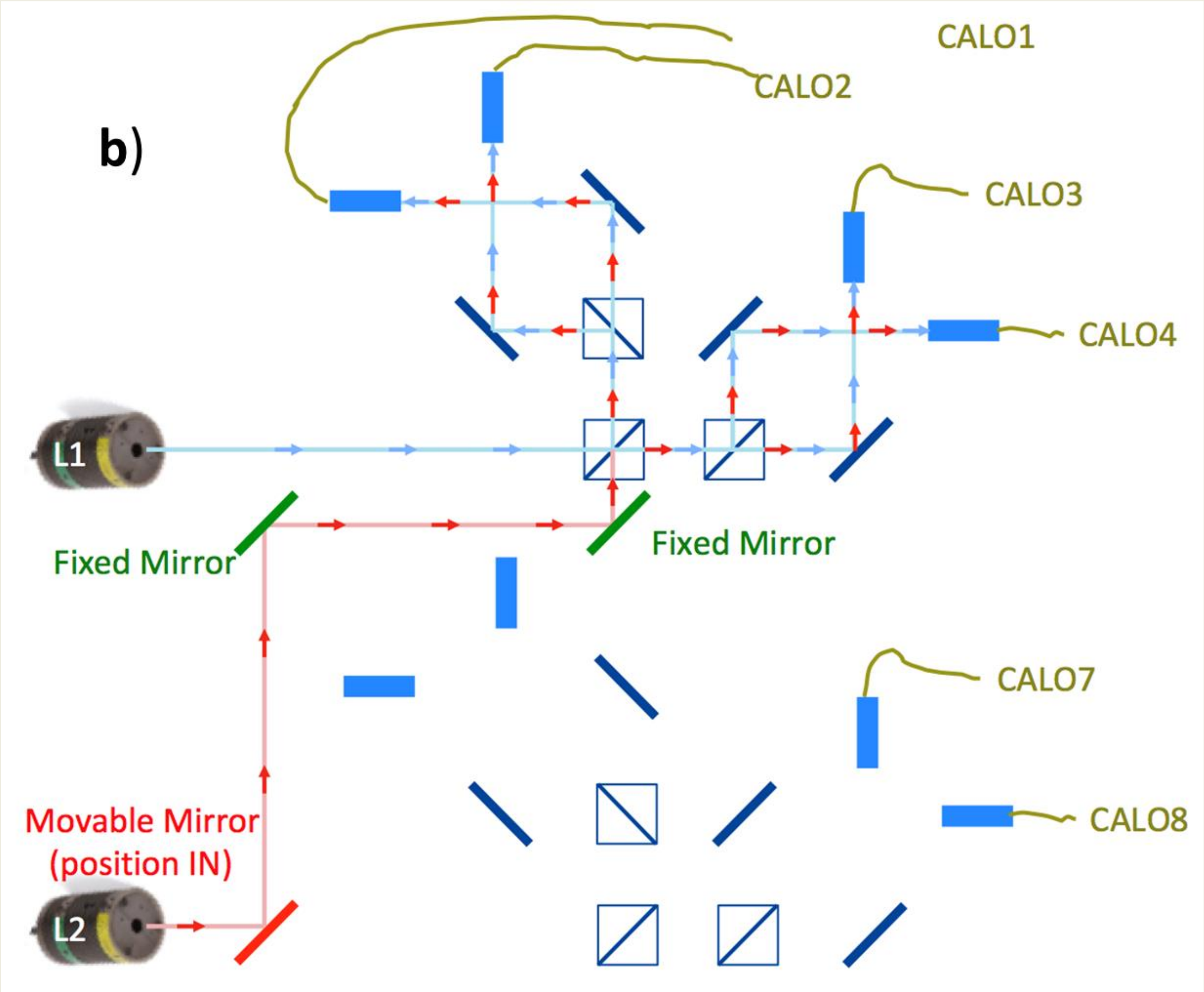
Panel holding 54 reflecting prisms, one in front of each crystal

A special system: the Double-Pulse setup



Double Pulse OFF

A special system: the Double-Pulse setup

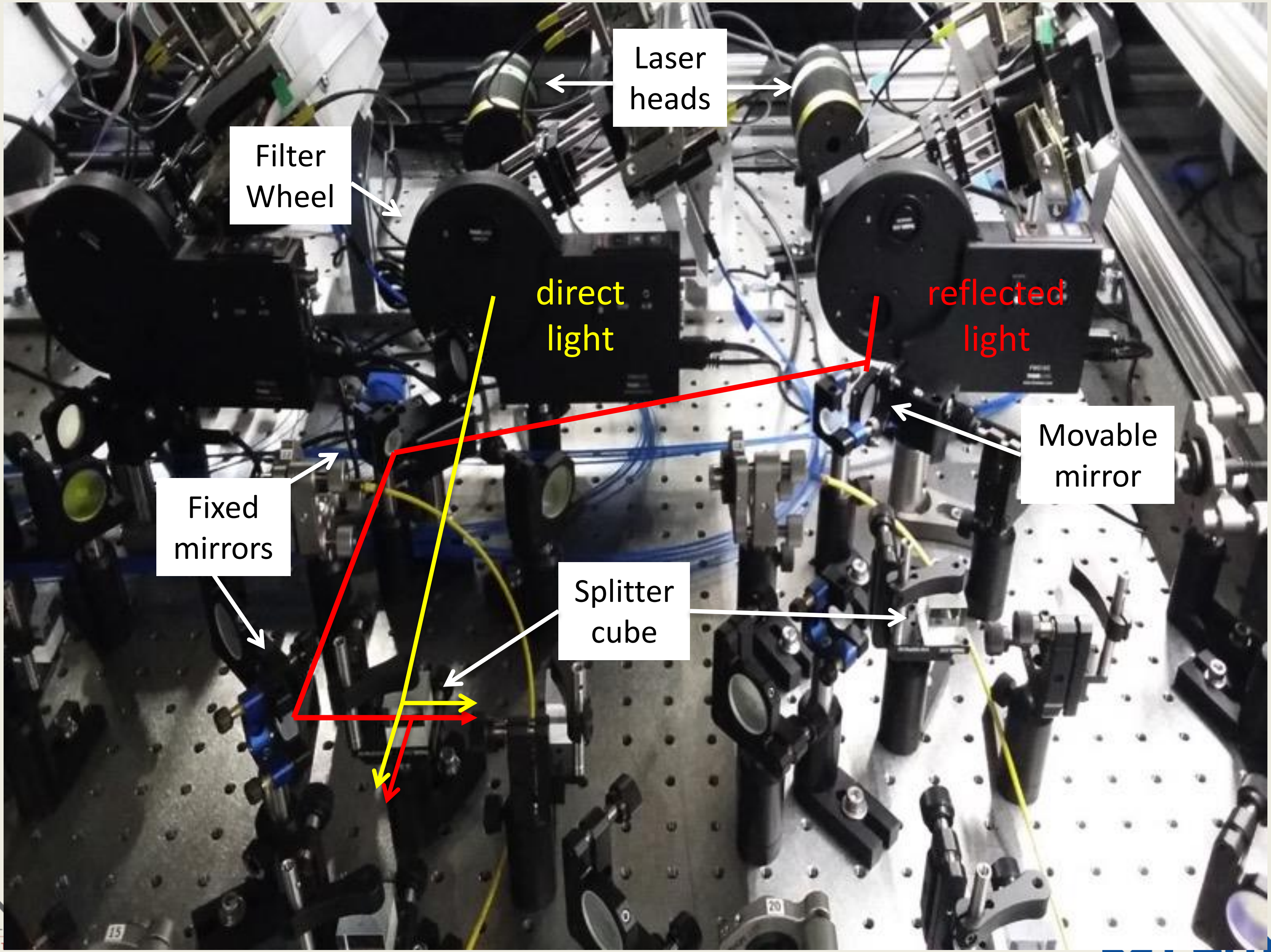


Double Pulse ON

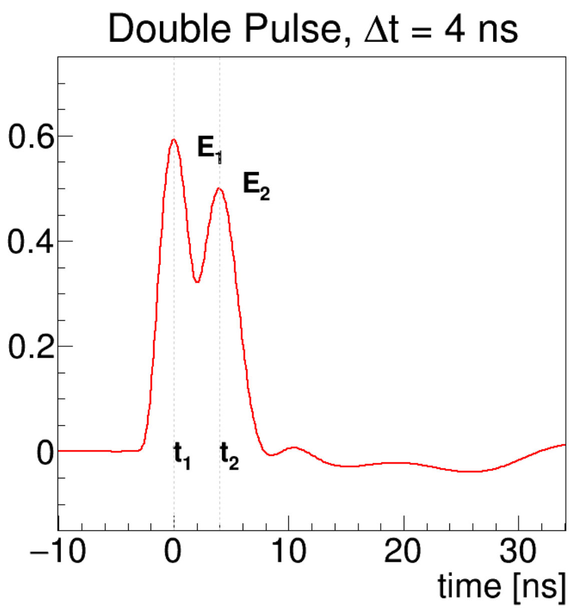
It is used to study the Gain Sag of SIPMs (pileup and splash)

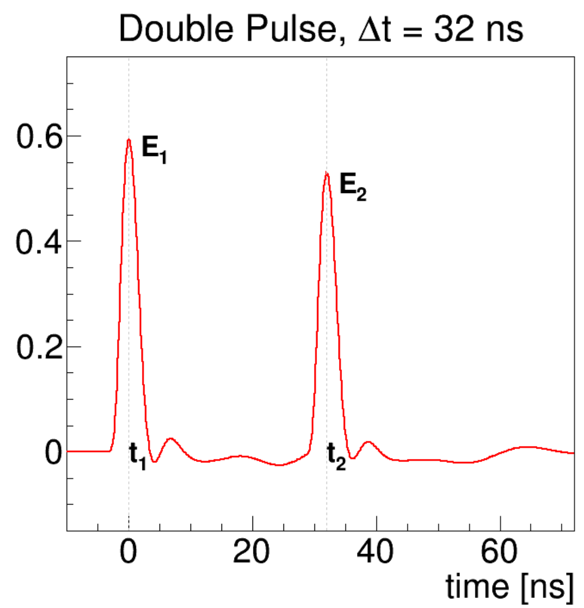
Delay generator: (SRS DG645) from ps to ms

Double-pulse mode ON

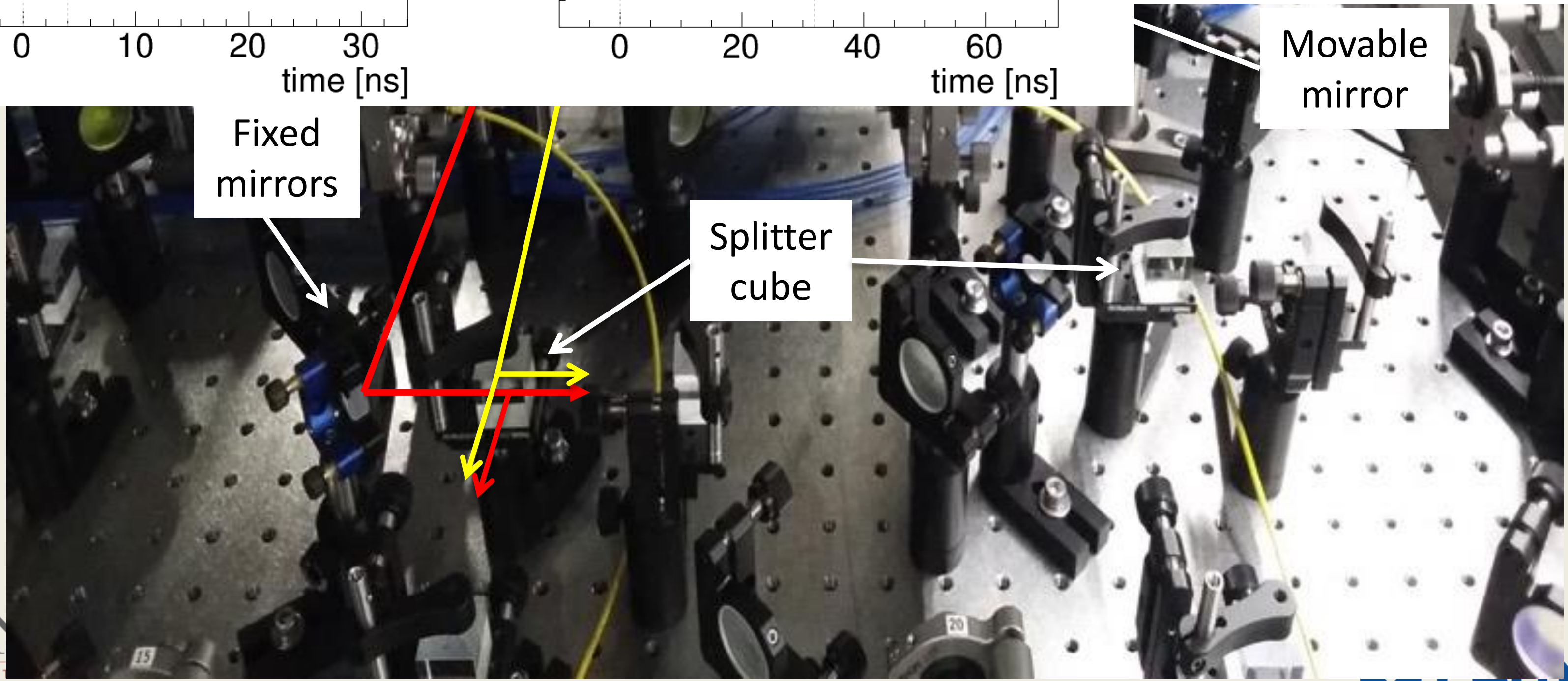


Double-pulse mode ON

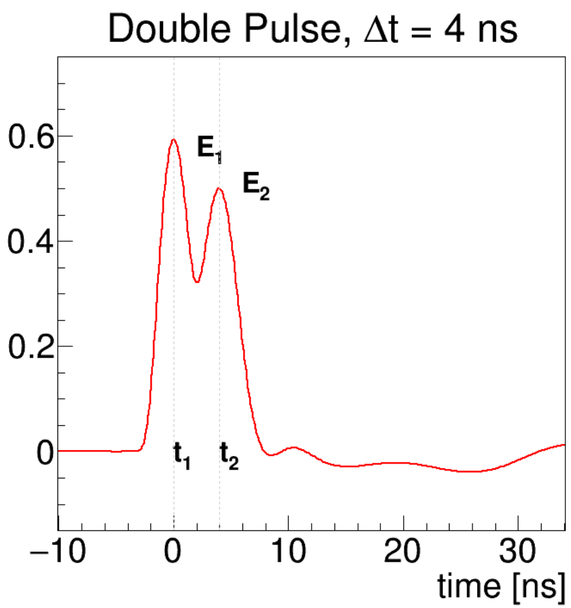


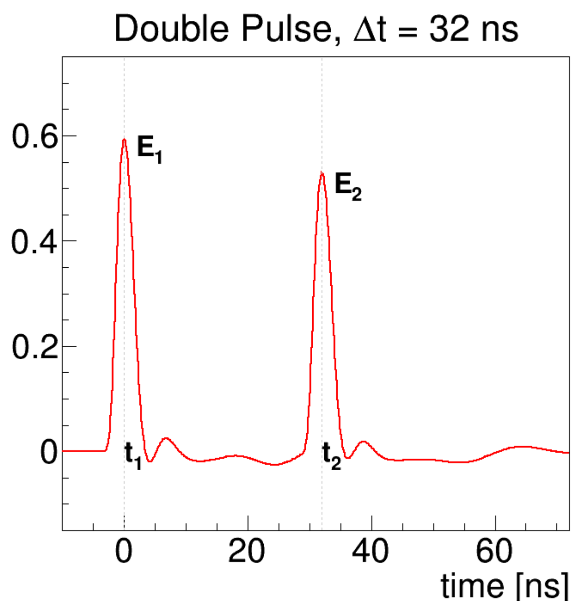


Short-Term Double Pulse (see Paolo GIROTTI's talk)



Double-pulse mode ON





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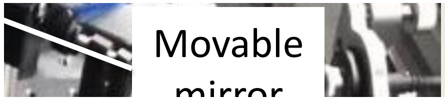
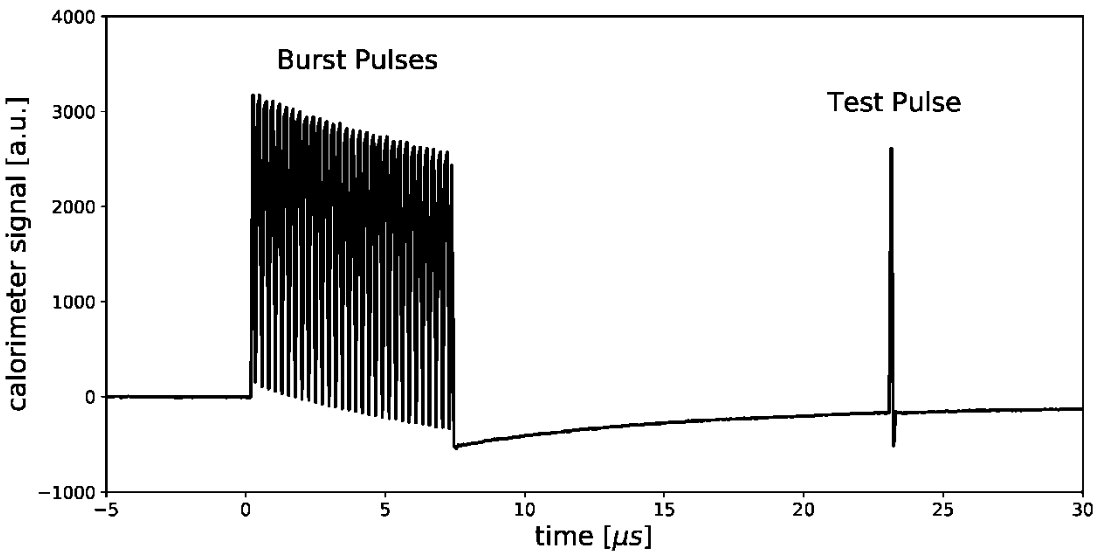
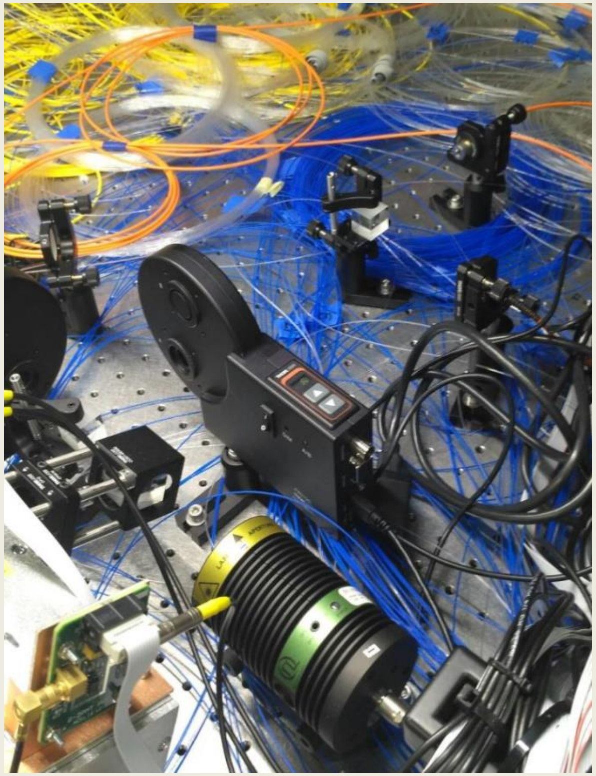


Long-Term Double Pulse (see Elia BOTTALICO's talk)

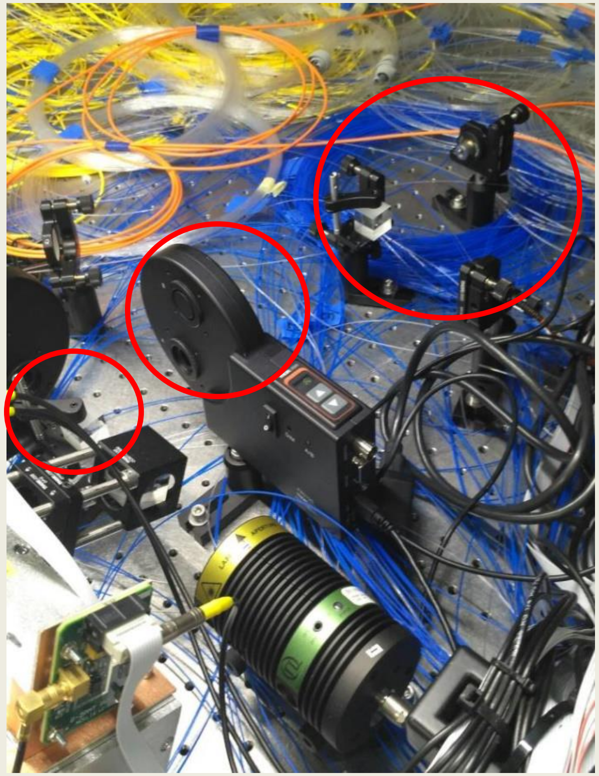


Synchronization of *T0* and *Fiber Harps*



Installation of the optics and 2 new optical fibers to send laser signals to Fiber Harps

Synchronization of *T0* and *Fiber Harps*



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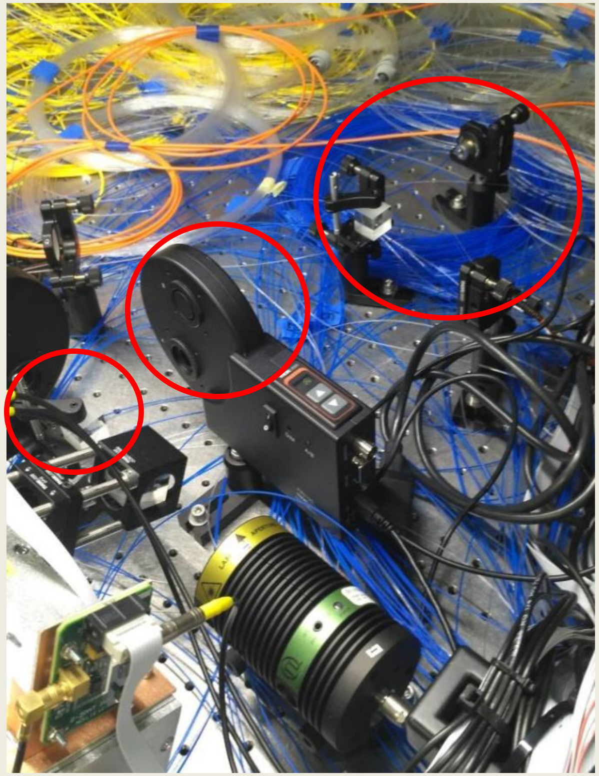
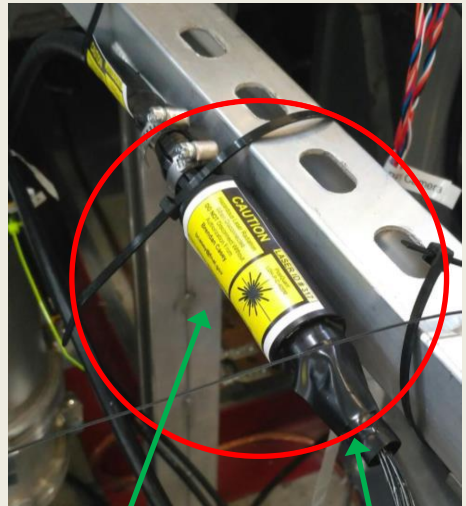


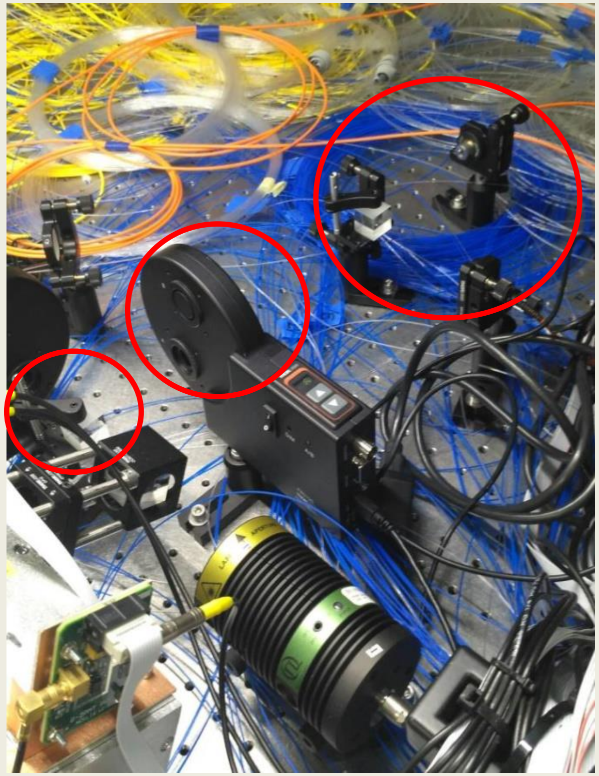


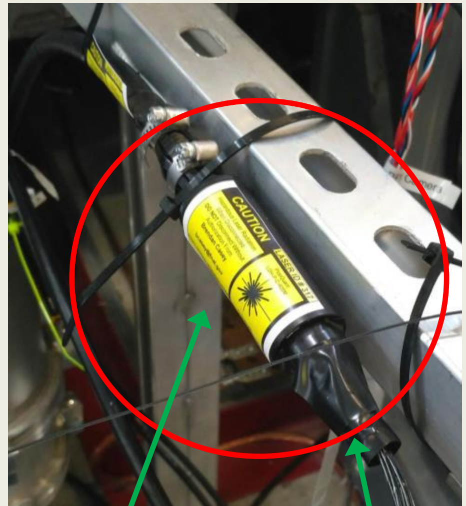
Engineered diffuser

Fiber bundle

Installation of the optics and 2 new optical fibers to send laser signals to Fiber Harps

Synchronization of *T0* and *Fiber Harps*





Installation of the optics and 2 new optical fibers to send laser signals to Fiber Harps

T0 detectors have been connected to spare fibers from the diffusers of 2 calorimeters

Laser energy in the distribution system

Position in distribution/monitoring chain	Energy per laser pulse	notes
Laser head	700 pJ	
After Source Monitor	490 pJ	
Onto Source Monitor	210 pJ	
Towards Fiber Harps detectors	70 pJ	Only from one laser head
After filter wheel	170 pJ	From now on values are with filter n. 6 (standard working mode)
Before each launching fiber	40 pJ	
Onto each diffuser	30 pJ	
Onto each front panel's fiber	30 fJ	Diffuser-bundle at 40 mm working distance
Onto each PbF_2 crystal	18 fJ	
Onto each SiPM	4 fJ	
Onto LM from diffuser	4 – 6 fJ	
Onto T0 detector	4 – 6 fJ	
Onto Fiber Harps	5 – 10 fJ	

Table 1: Laser energy per single pulse at various points of the laser distribution and monitoring systems. These values are only indicative and may vary by 5-10% at each step going from one distribution line to another.

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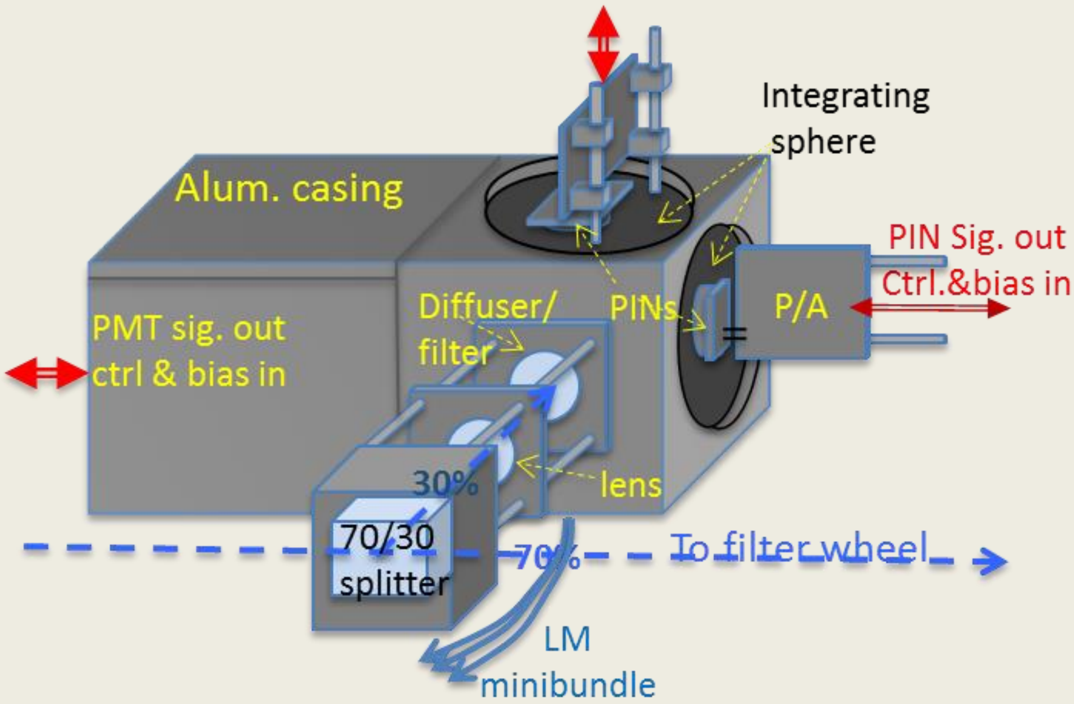
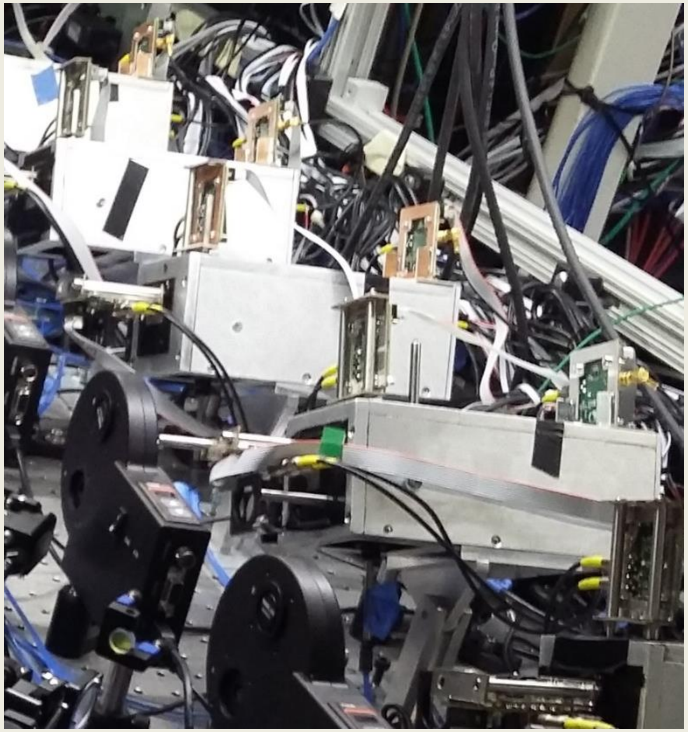
The source monitor

- It takes 30% of the laser beam
- It is based on an integrating sphere illuminating 2 PIN photodiodes, 1 PMT+ reference pulser (Am/NaI source), one fiber minibundle for LM
- It provides an early reference signals for the PMTs of the local monitor.





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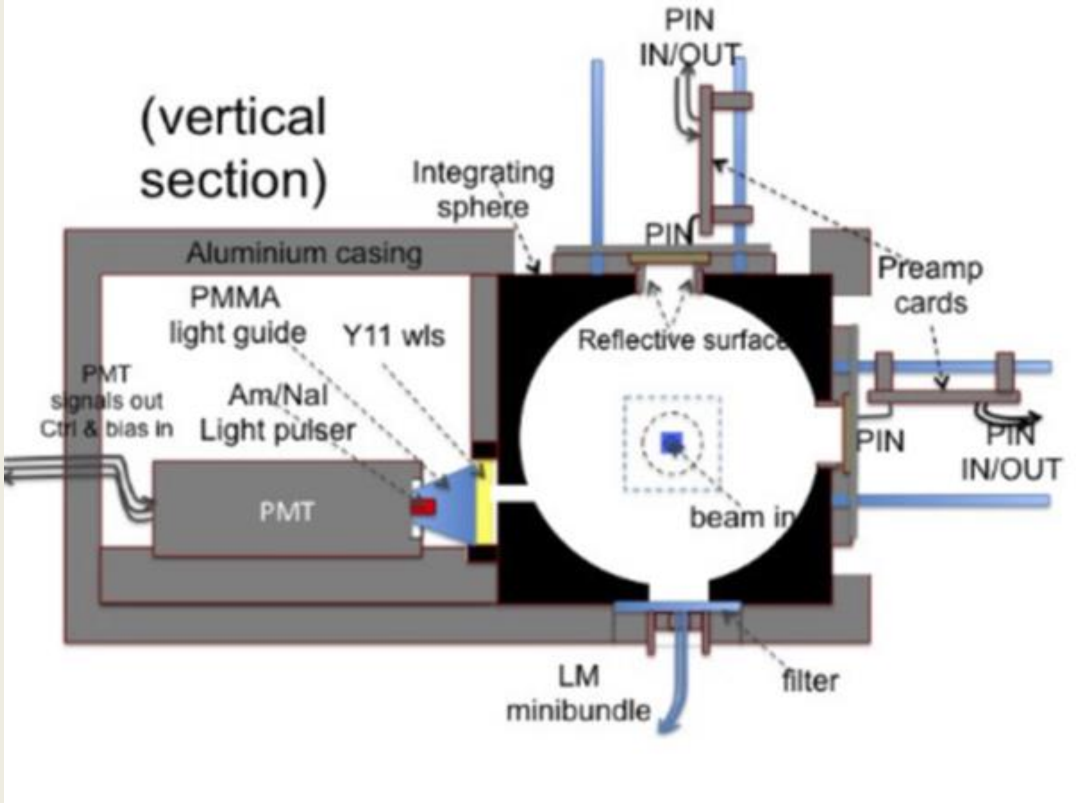

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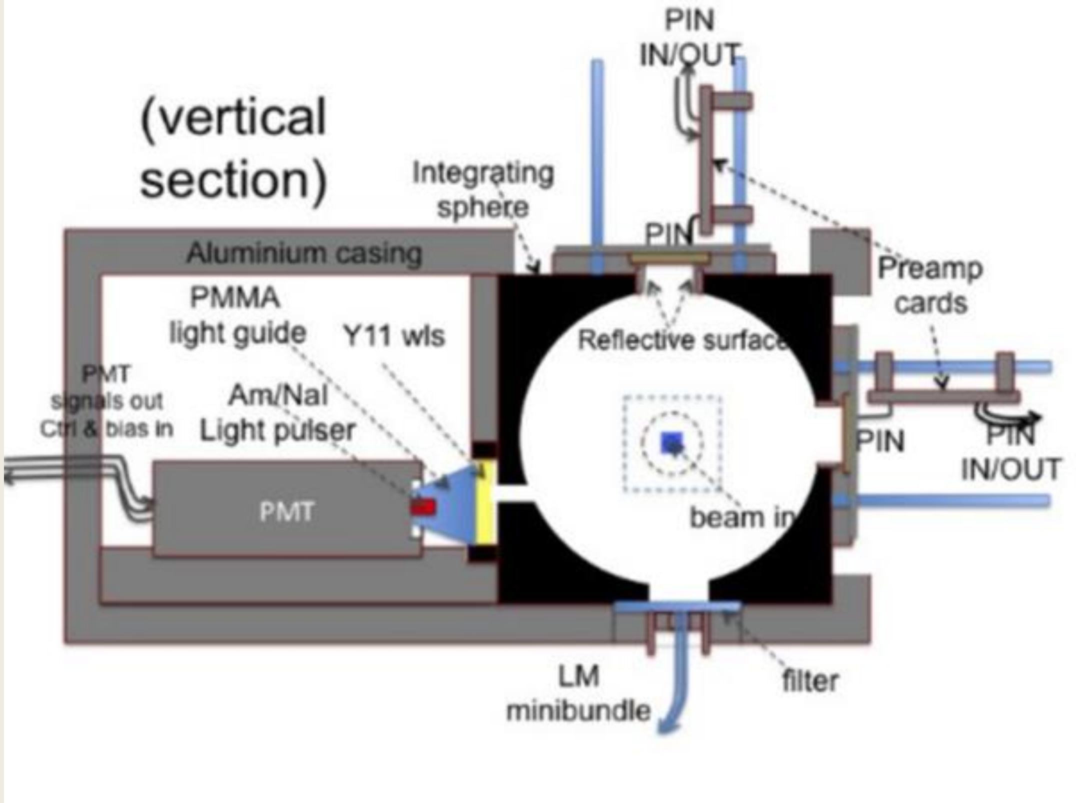
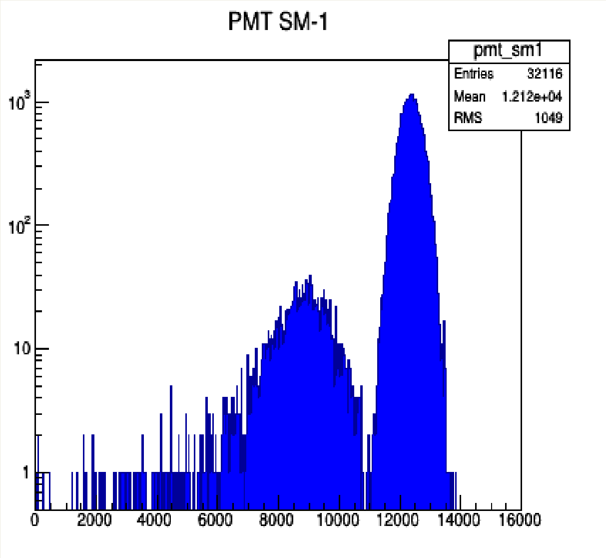
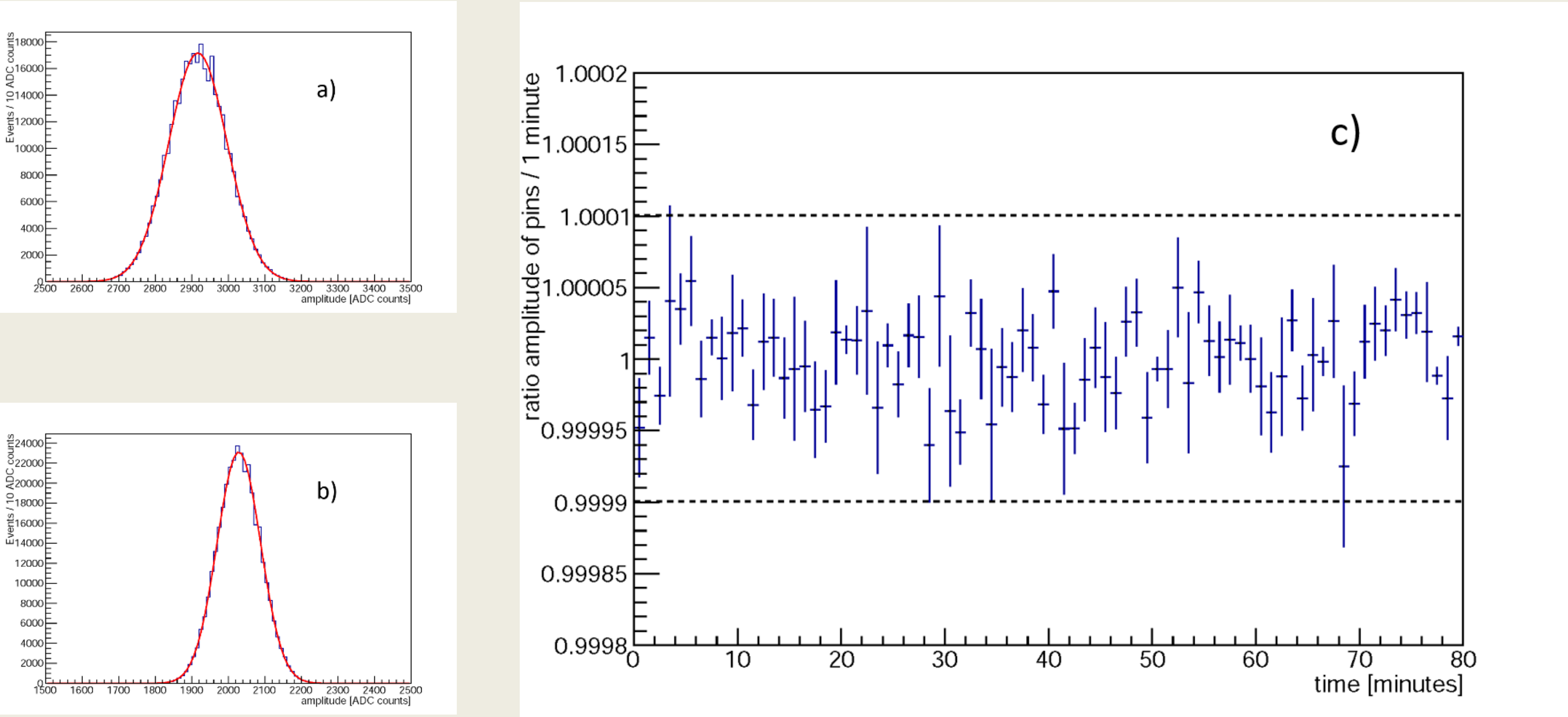




Laser and Am/NaI source on PMT
DAQ in Asynchronous Mode

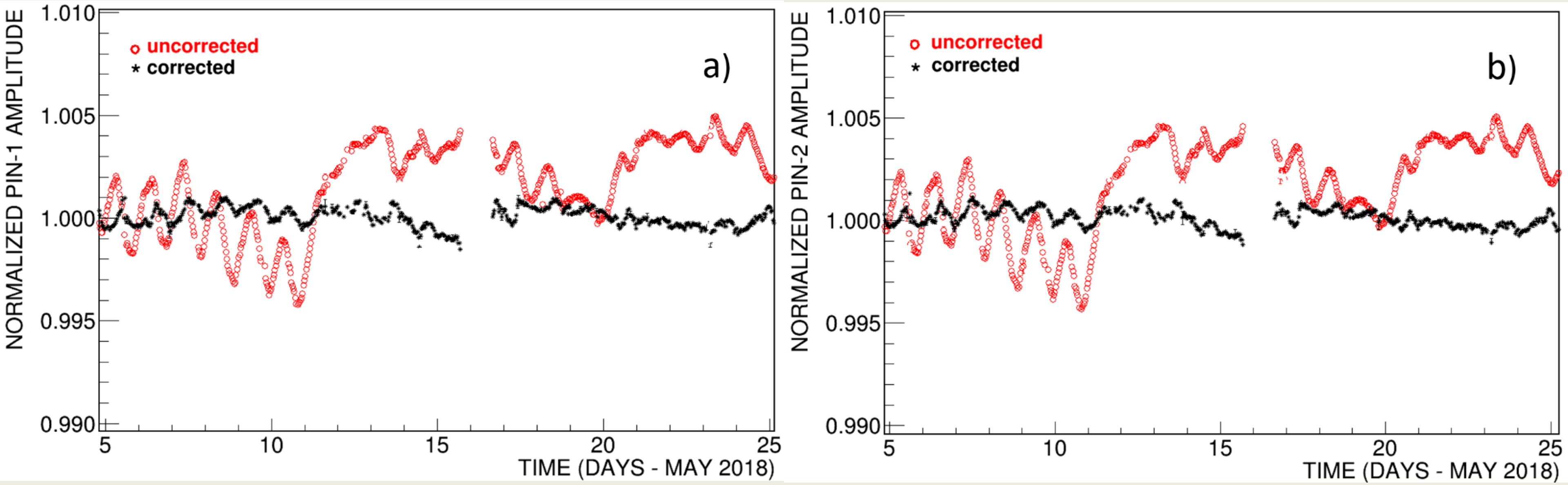
Performance of the Source Monitor



Statistical distributions of laser signals from (a) the PMT and (b) one of the PIN diodes, as measured at the input to the DAQ

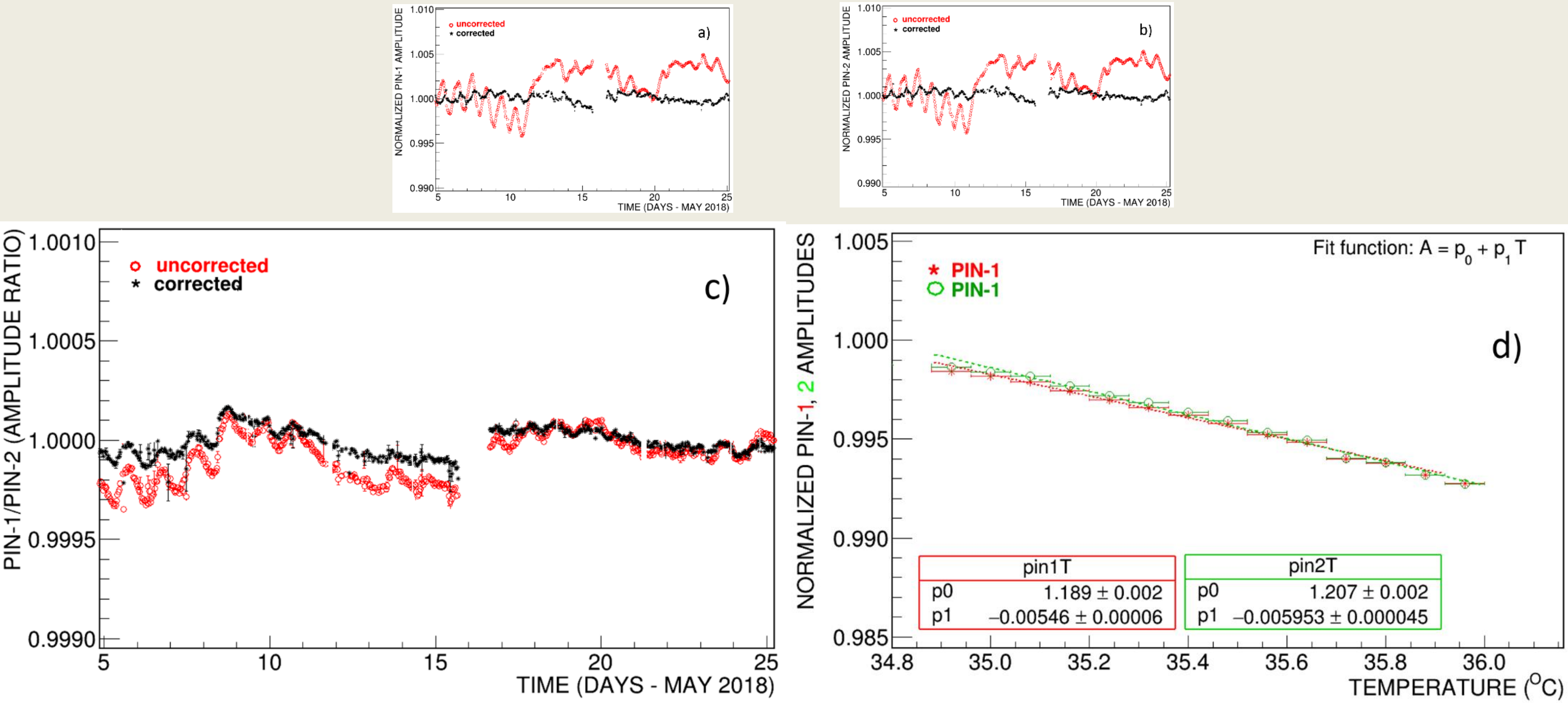
(c) The variation of the ratio between the two PIN diode signals for SM1. Each point is an average of 3000 ratios and the two dashed lines indicate the 10 stability limit over the 80-minutes acquisition period.

Stability of SM versus Temperature



Stability of SM versus temperature changes in a two-week period.
A linear correction is applied to the data to compensate for the temperature effect.
The final stability is better than 0.2% for the single PIN

Stability of SM versus Temperature



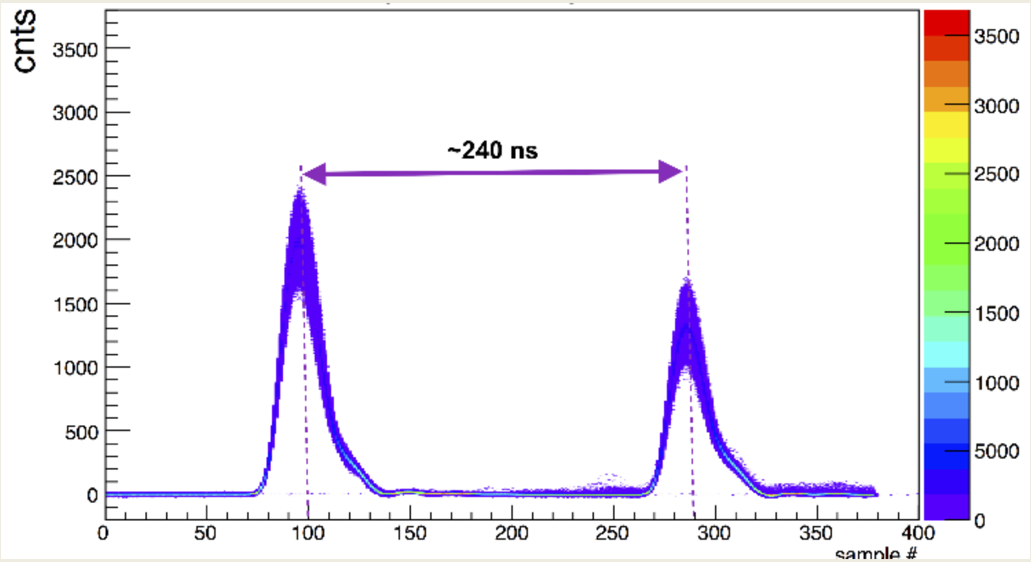
Stability of SM versus temperature changes in a two-week period.

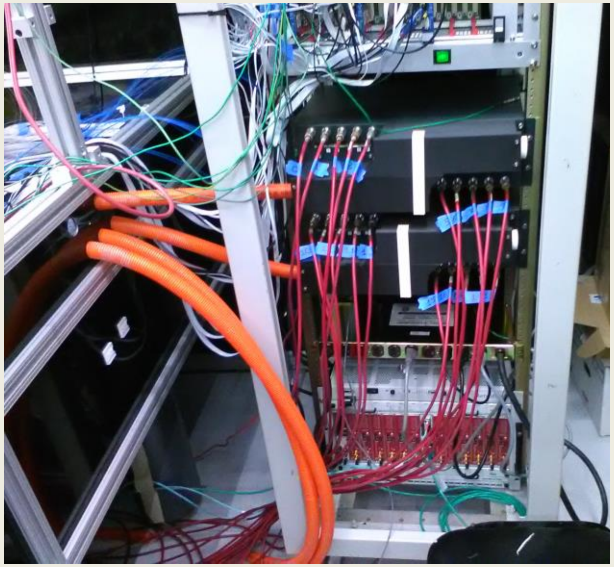
A linear correction is applied to the data to compensate for the temperature effect.

The final stability is better than 0.2% for the single PIN and 10^{-4} for the ratio.

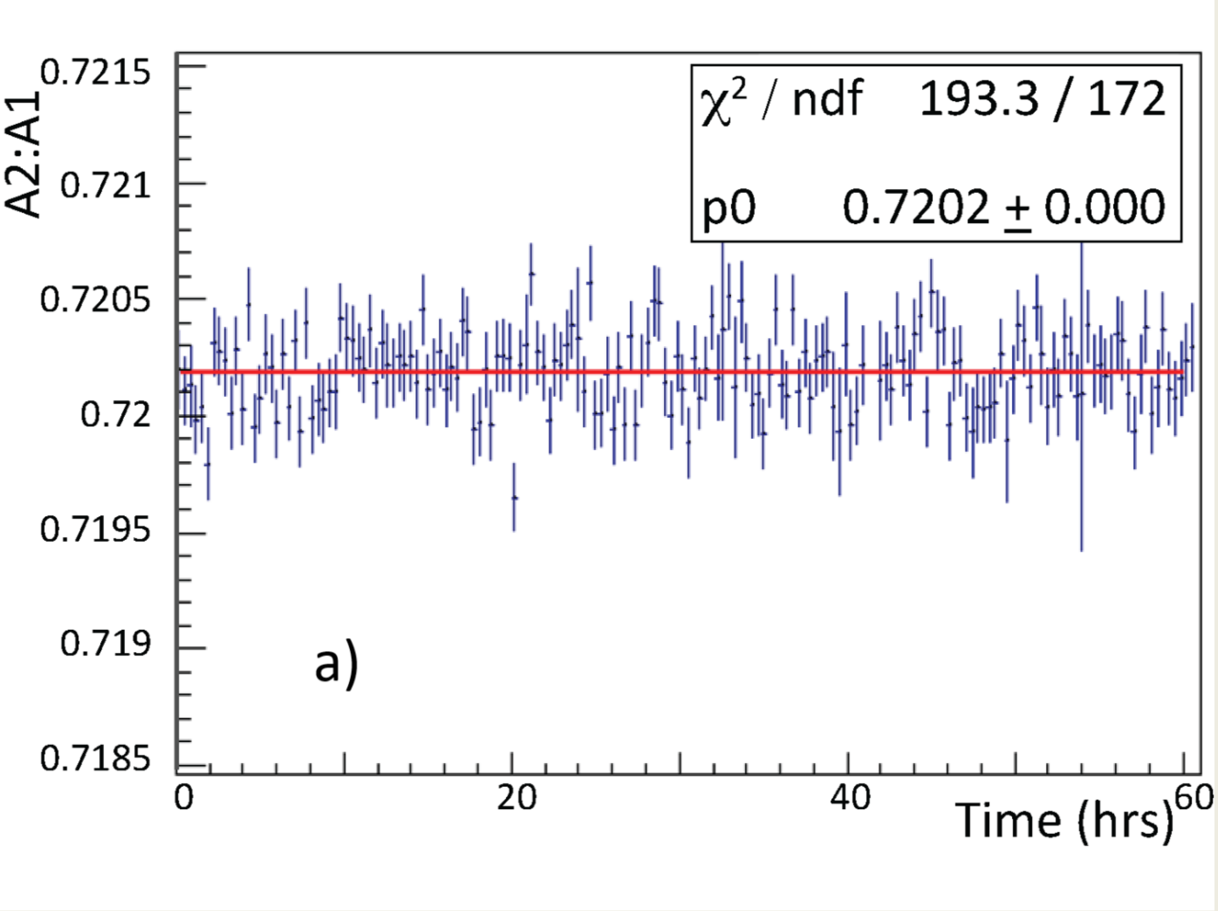
The local monitor

- 24 + 24 PMTs (TWO fore ach calorimeter)
- Each PMT receives an early pulse from the SM integrating sphere
- Each PMT receives a pulse from a calorimeter (through an optical fiber)
- **The ratio of the two pulse amplitudes monitors the optical transmission from the SM to each calorimeter**





Performance of the Local Monitor



Ratio of amplitudes of the delayed LM peak to the respective SM peak for one particular LM channel. It is below the per mille level.

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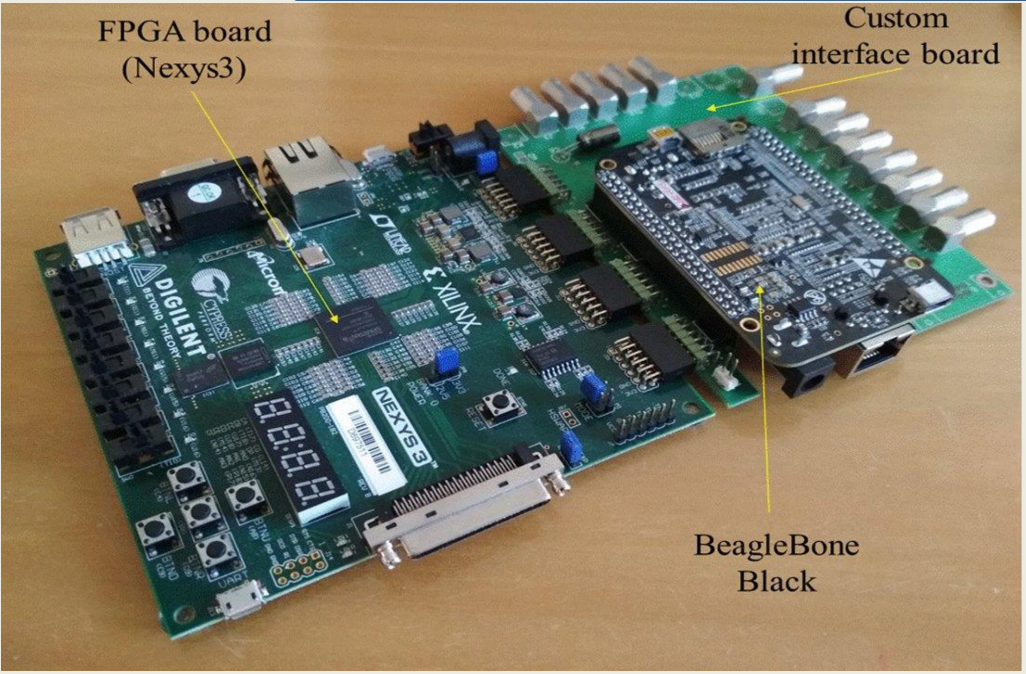
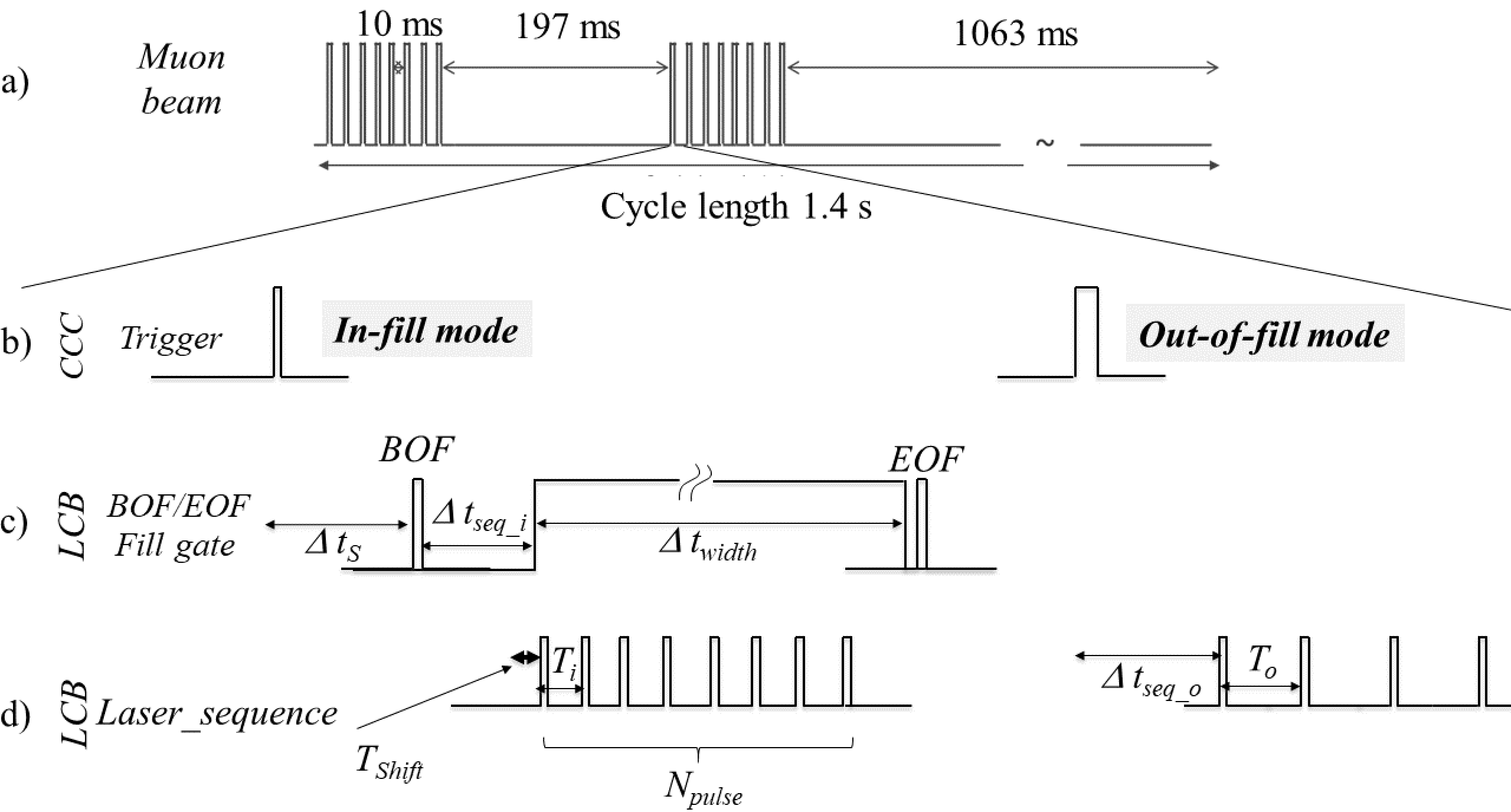
The control electronics and data readout

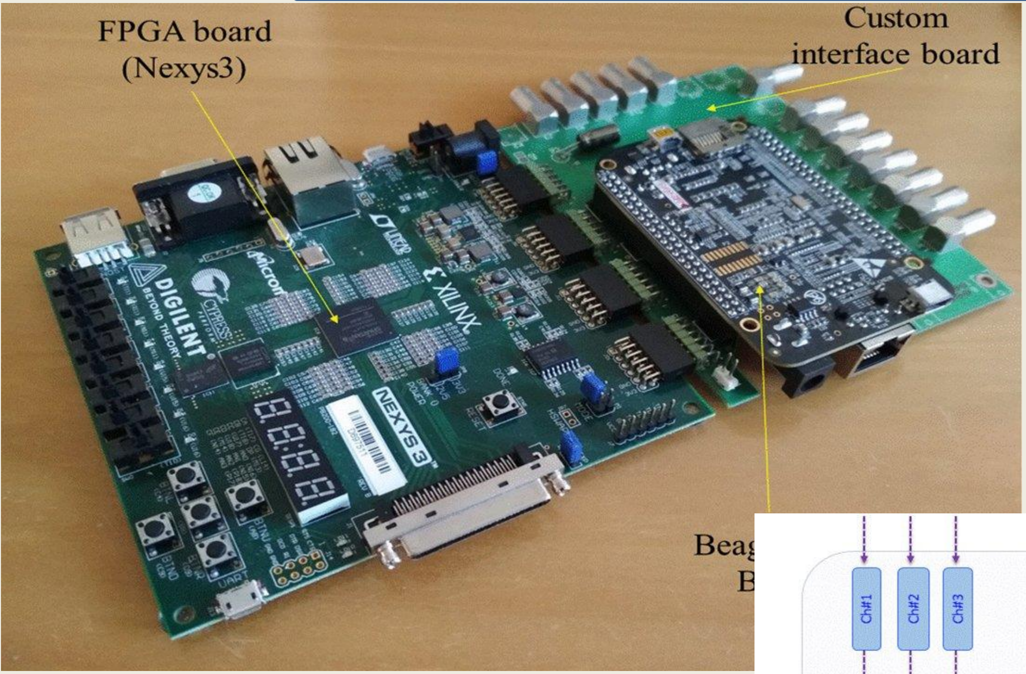


Picture of the Laser Control Board, which is implemented by a hybrid platform hosting a Spartan6 FPGA board and an embedded CPU

The control electronics and data readout

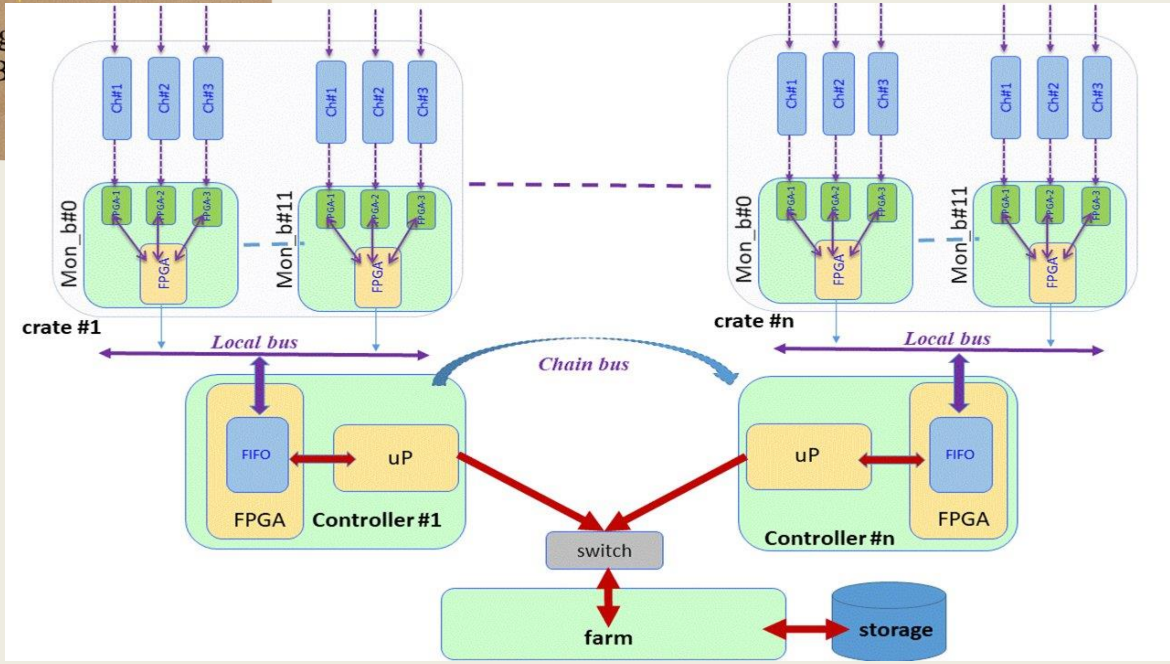


The control electronics and data readout



Picture of the Laser Control Board, which is implemented by a hybrid platform hosting a Spartan6 FPGA board and an embedded CPU

Schematics of the locally implemented data acquisition system, based on multiple crates.



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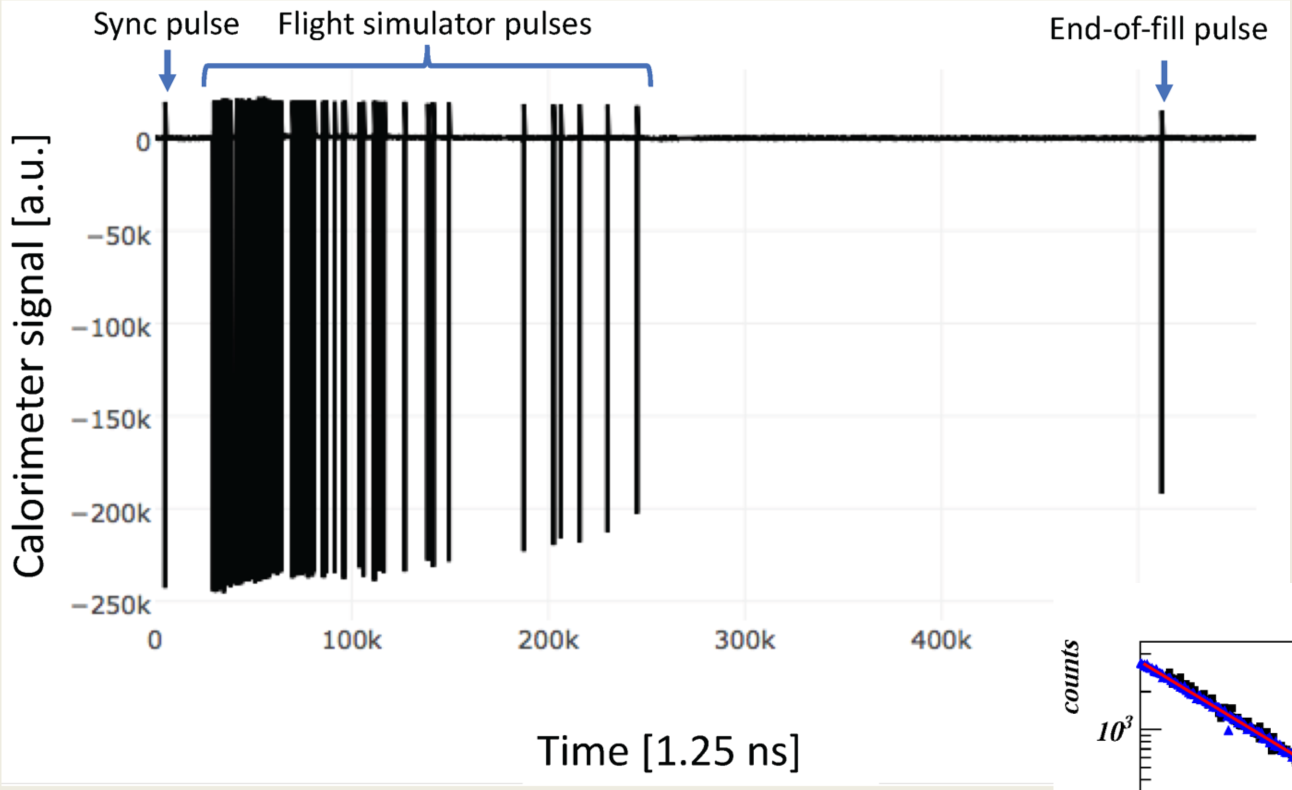
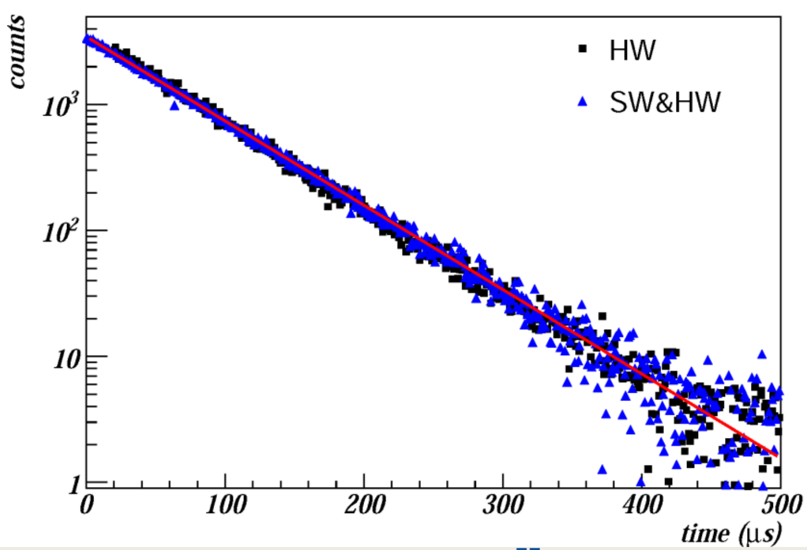
Flight simulator mode

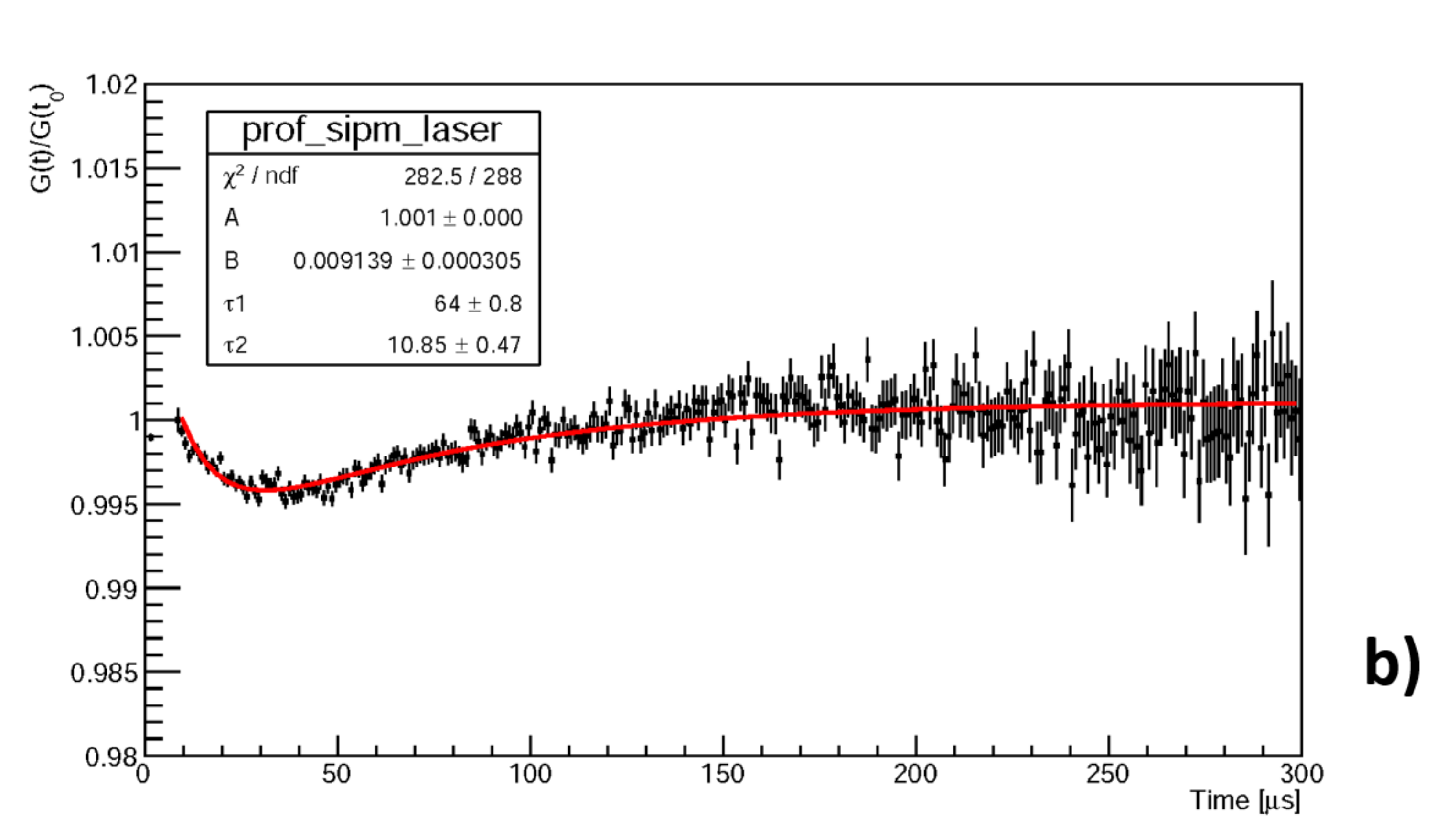


Laser pulses are generated according to an exponential function



This function was heavily used during the commissioning phase for Calorimeters and DAQ debugging

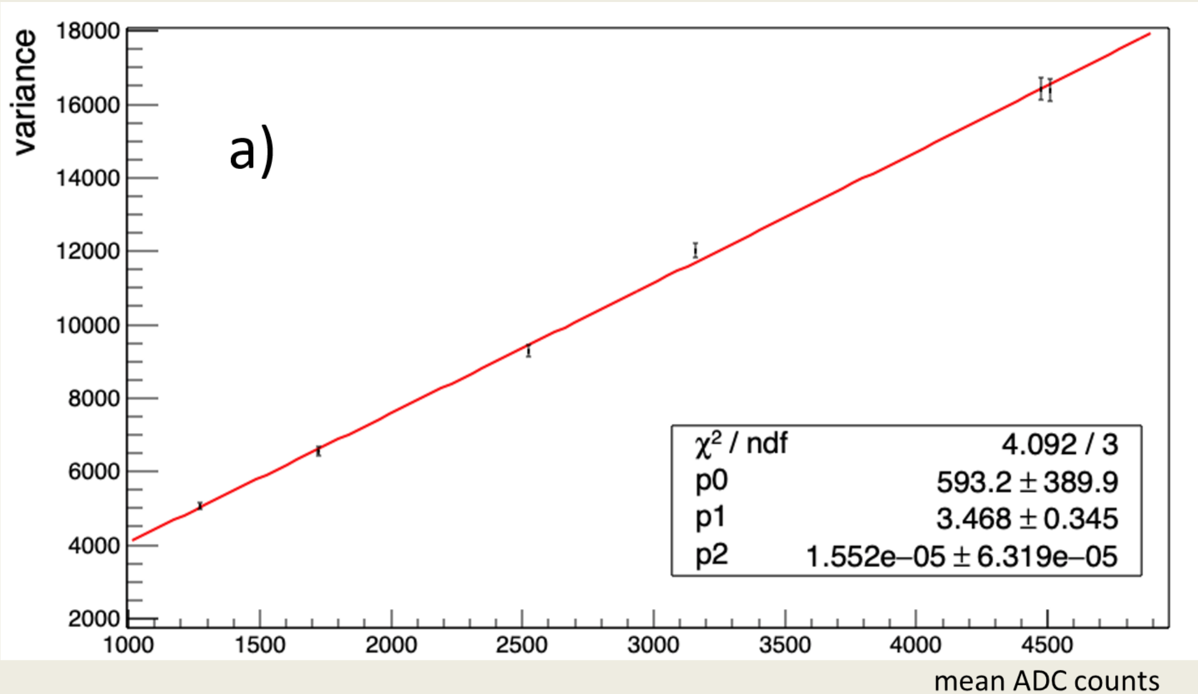
Flight simulator mode



A gain sag was evident already in Flight Simulator Mode

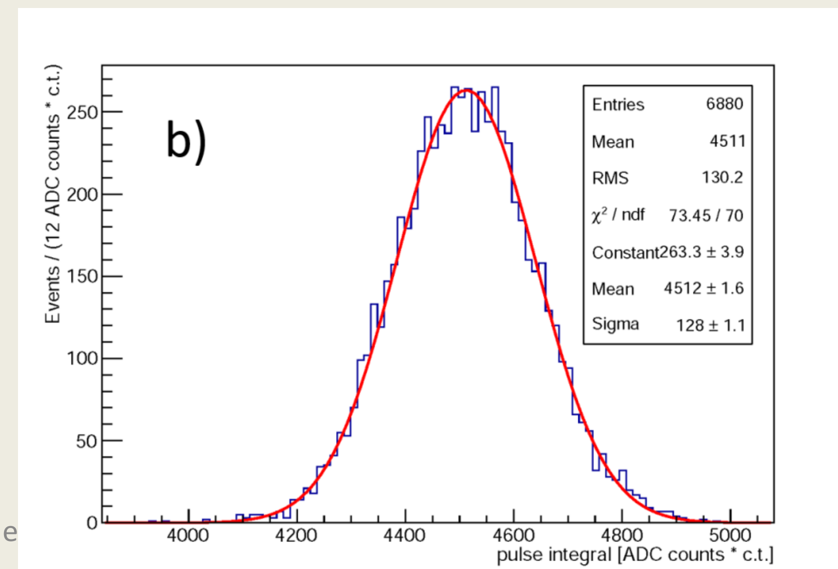
FSM is NOT used to compute gain corrections

SiPMs gain equalization



Plot of the variance σ^2 versus mean pulse-integral, M, of a distribution of fitted laser pulses on a SiPM. The different discrete mean values are obtained using a multi-step filter wheel to attenuate the light intensity

A typical distribution of pulse energies for a given laser intensity



Double-Pulse operating mode

It is used to study the response of the Calorimeters to a large number of particle

Short-Term, Double-Pulse (0-100 ns, 1 ns step) analysis

⇩

SIPM response ⇨ see Paolo's talk

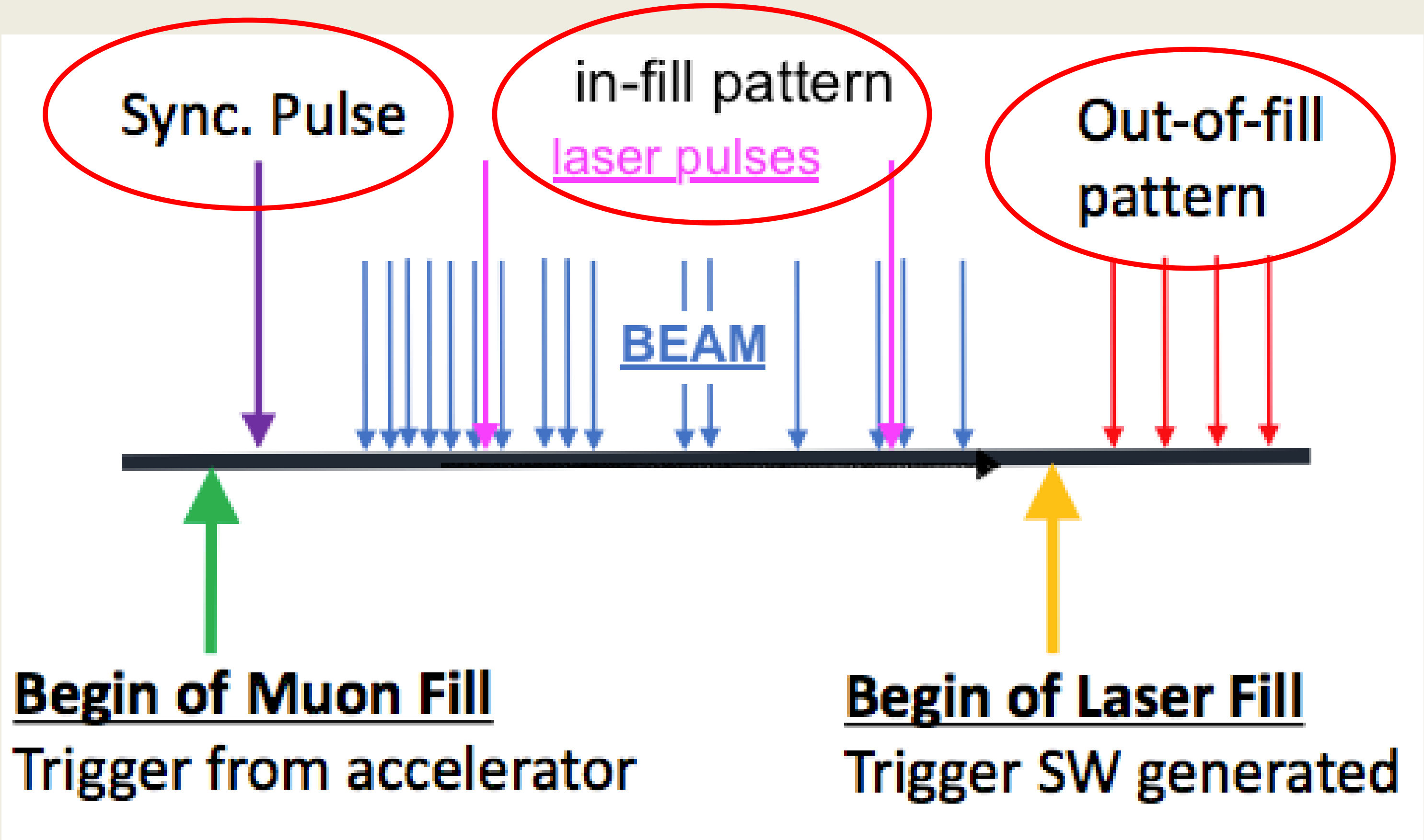
Long-Term, Double-Pulse (0-200 μs, 1 μs step) analysis

⇩

Power supply response ⇨ see Elia's talk

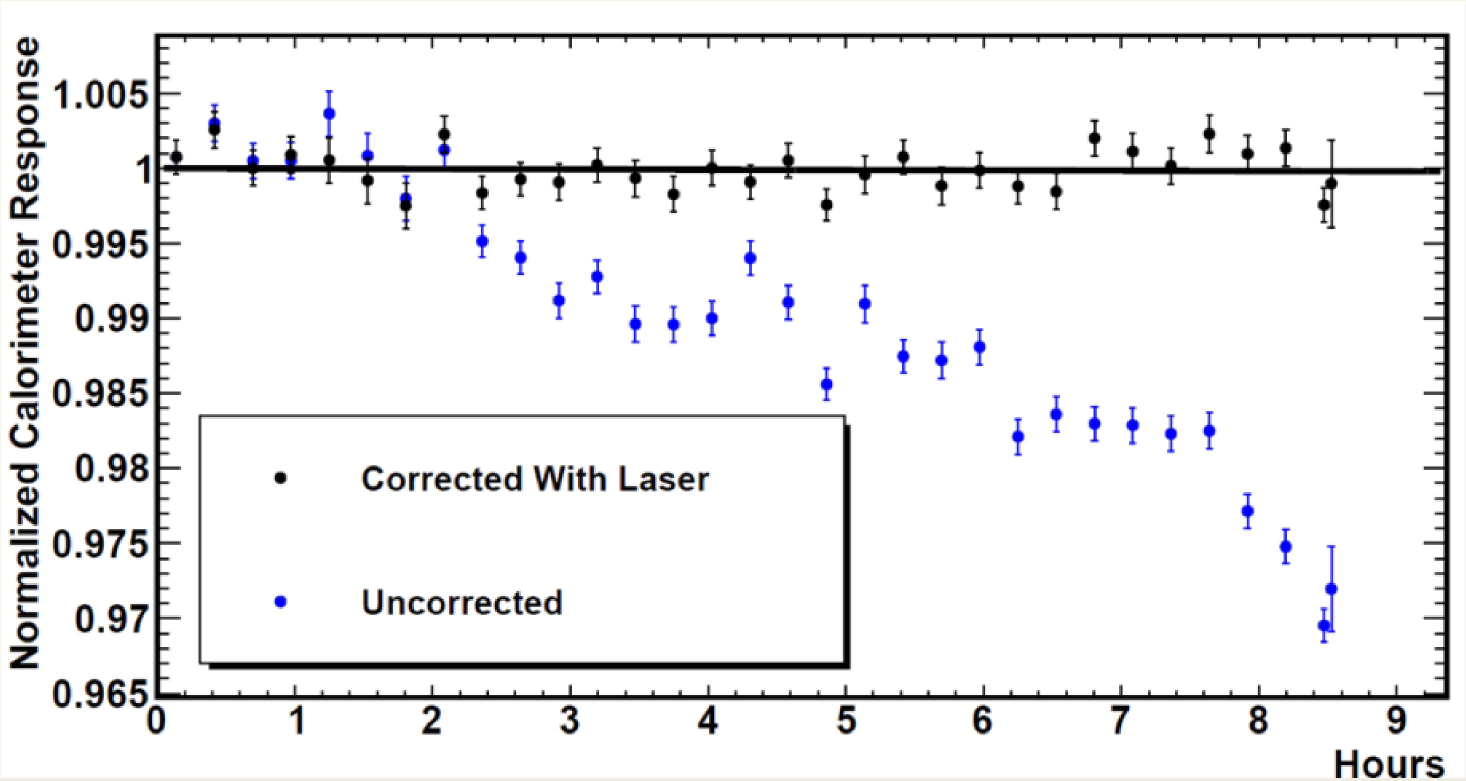
Double-Pulse studies should be performed regularly (each 3 days) to compute gain corrections

Standard operation for data taking



In-Fill pulses are **prescaled** and **time-shifted** in time from fill to fill

(old) Results for the gain correction

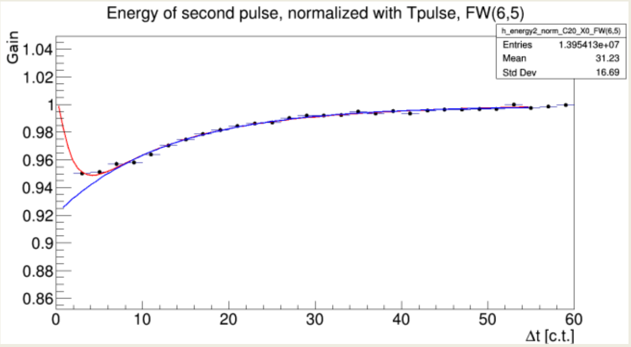


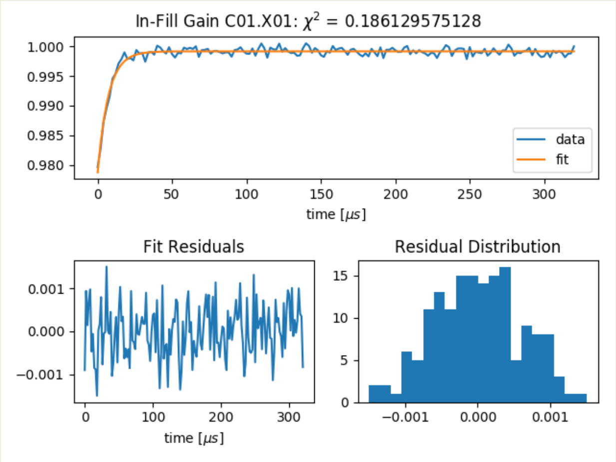
10^{-4} / h stability demonstrated
with mono-energetic test beam at SLAC

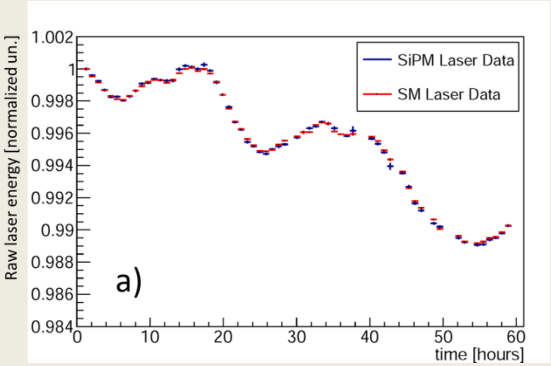
(new) Results for the gain correction

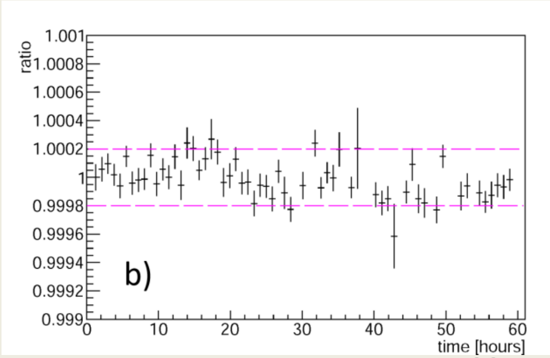
- Out-of-Fill gain corrections
- In-Fill gain corrections
- Short- and Long-Term Double-Pulse studies

ALL THESE TOGETHER ARE USED TO COMPUTE THE GAIN CORRECTION TABLES









See Anna DRIUTTI's talk

DQM laser monitor page

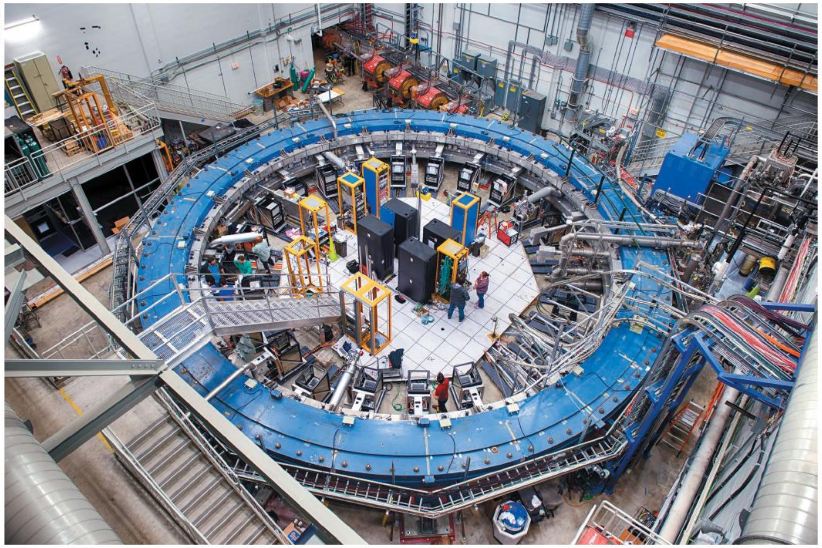
Local monitor

Source monitor

relative timing
of the 6 laser

Conclusions

- The main purpose of the laser calibration system is to provide calibration and time alignment to the 1296 SiPMs and to guarantee gain stability to achieve the challenging precision of 20 ppb on the ω_a measurement
- The adopted solution is based on a triggerable diode laser system with multiple laser heads with fluctuations below the percent level, an optical distribution system ensuring adequate intensity and homogeneity, and a system for monitoring the laser system itself with a stability at the 0.01% level.



The Muon g−2 experiment will look for deviations from the standard model by measuring how muons wobble in a magnetic field.

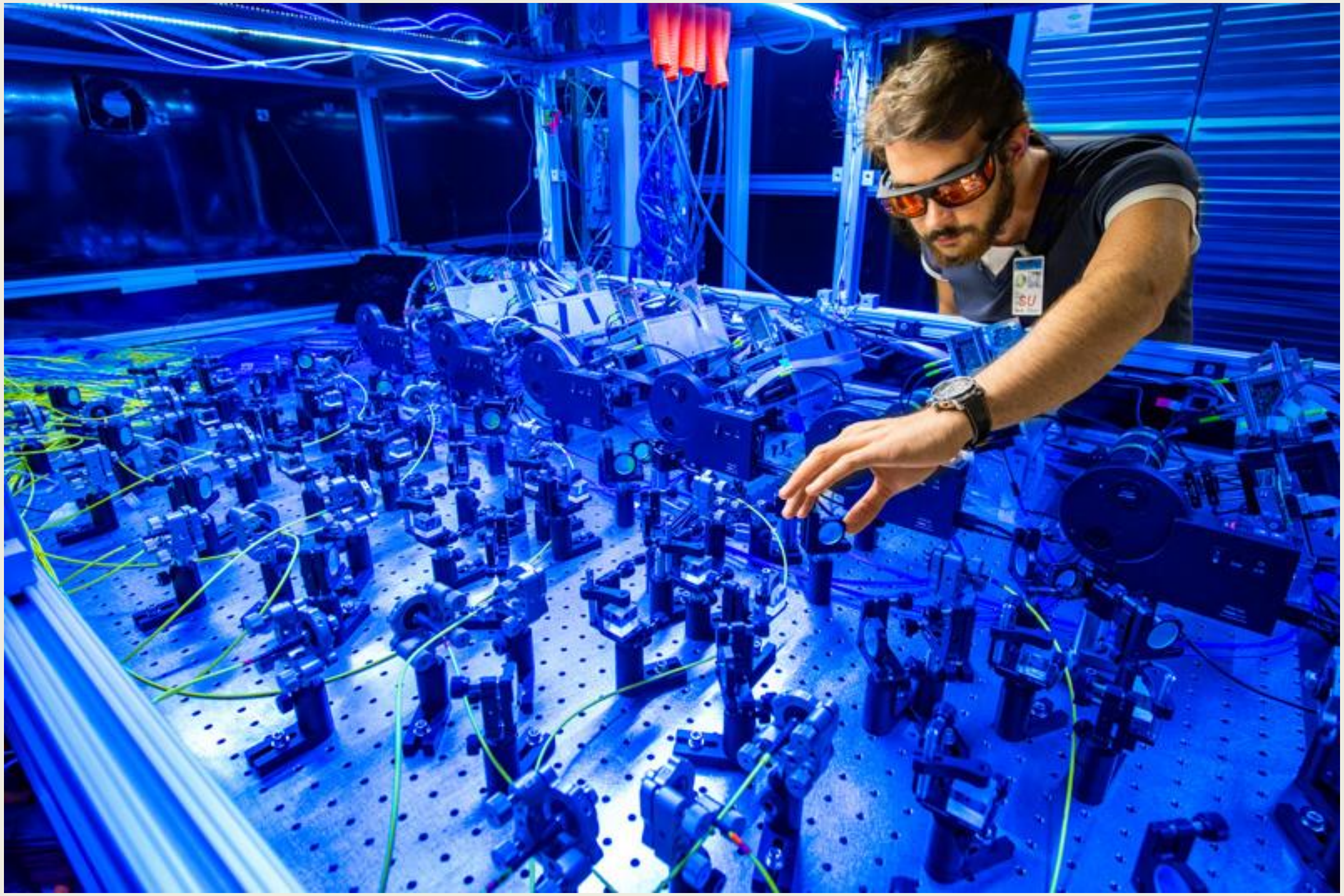
PARTICLE PHYSICS

Muons' big moment

Nature, April 11th 2017

- The laser system has been running with no main problems for the last three years, providing debugging DAQ and Calorimeters. Now it provides gain correction tables

The end - *Thank you for your attention*



Backup slides

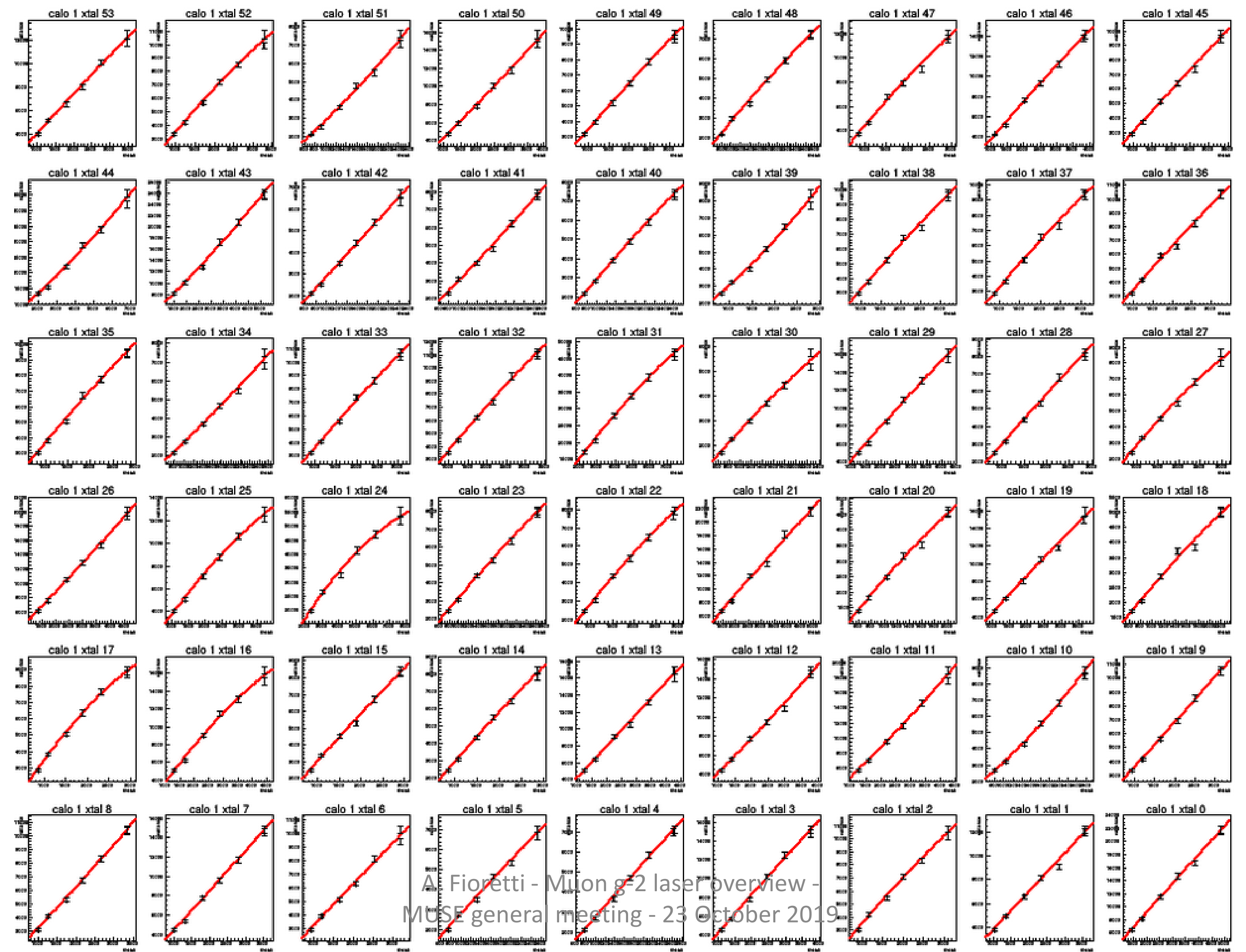
Backup

Filter wheel calibration

High rate laser pulses (10 kHz) to each SiPM (crystal), fit with gaussian distribution.

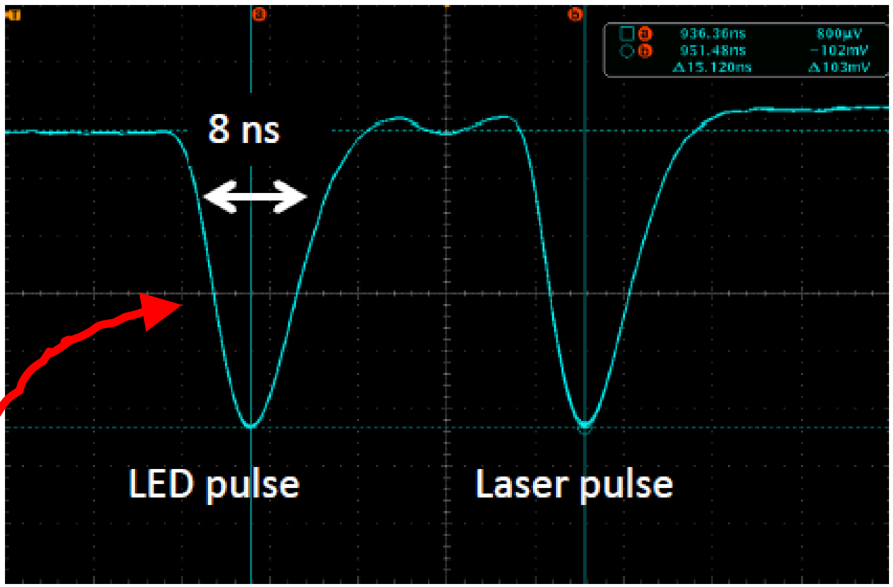
Filter wheel calibration

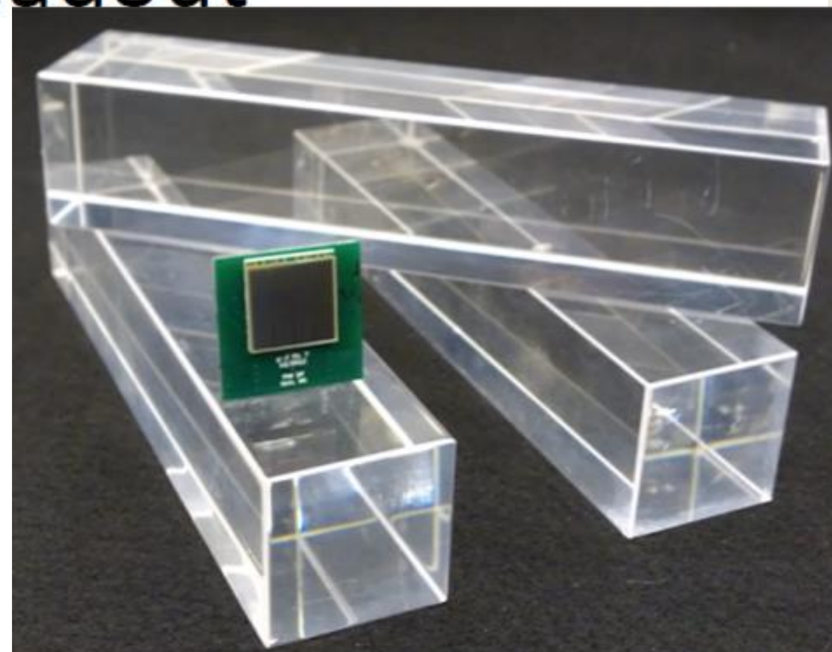
Plot of variance σ^2 versus pulse-integral mean μ of the distribution using a multi-step filter wheel to attenuate the light.

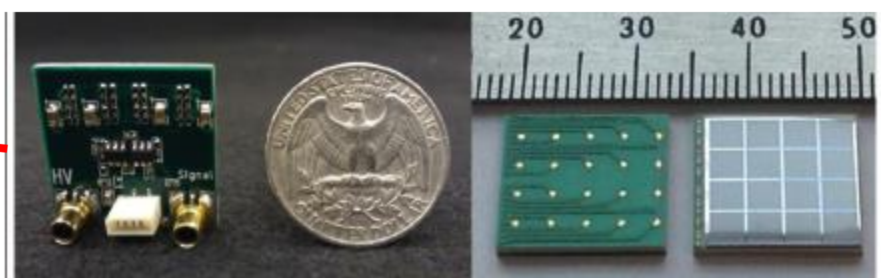


Segmented PbF_2 Calorimeter with SiPM Readout

SiPM boards optimized to produce PMT-like pulses to exploit short pulse duration of Cherenkov crystals (relevant: pileup)



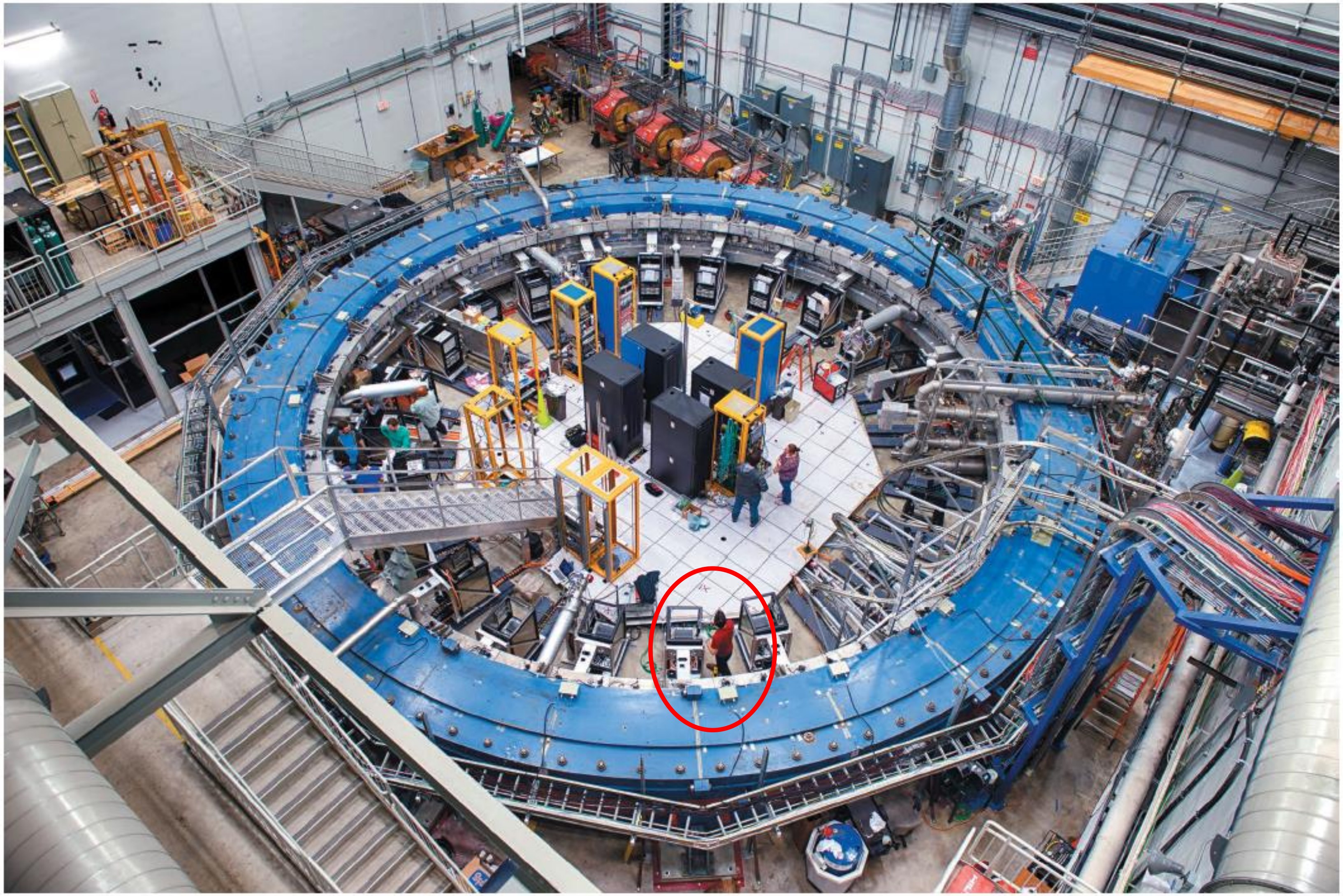




28-channel prototype calorimeter tested at SLAC

Nature, April 11th 2017

FERMILAB



The Muon g−2 experiment will look for deviations from the standard model by measuring how muons wobble in a magnetic field.

http://www.nature.com/news/muons-big-moment-could-fuel-new-physics-1.21811

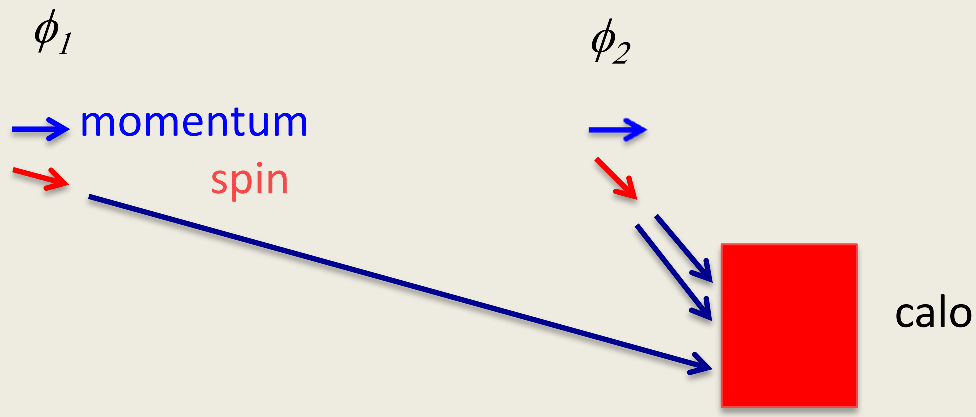
PARTICLE PHYSICS

Muons' big moment

Systematics

Pileup: two low energy positrons fake a high energy positron
(happens early, not late)

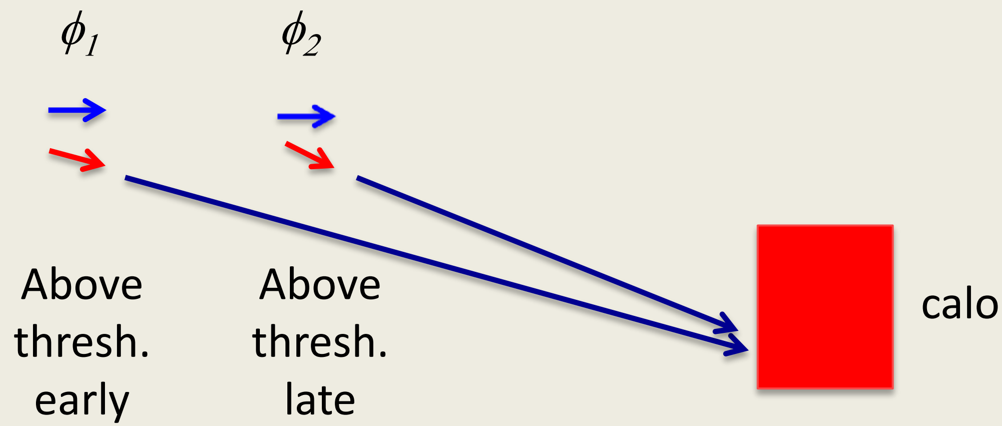
$\phi_{early} \sim \phi_1 + \phi_2$
$\phi_{late} \sim \phi_1$



Gain change:
example: saturation (happens early, not late)

$\phi_{early} \sim \phi_1$
$\phi_{late} \sim \phi_2$

$\Delta\omega \sim \Delta\phi$



Design not driven by absolute performance, but relative stability early to late

Know how well we did on these for BNL experiment. Need to do better by a factor of 4. Detector package designed to contain the tools to enable this.

from B. Casey, FNAL

Muon $g-2$ SM test uncertainties summary

Quantity	Uncertainty $\times 10^{-11}$	$\delta a_\mu / a_\mu$ (ppb)
ω_a statistical	53	458
ω_a systematic	24	210
$\tilde{\omega}_p$ systematic	20	170
CODATA m_μ / m_e	2.6	22
CODATA μ_p / μ_e	0.35	3
Electron g factor, g_e	0.000035	0.0003
QED	0.08	0.7
EW	1	8.6
hadLBL	26	223
hadLO	33	280
hadNLO	0.9	7.6
hadNNLO	0.1	0.86

from A. Lusiani, INFN (Italy)

Uncertainty of E821 ω_a measurement

Statistical uncertainty

- fit $N_e(E_e > E_{thr}) = N_0(E_{thr}) e^{-t/\gamma\tau} [1 + A(E_{thr}) \cos(\omega_a t + \phi(E_{thr}))]$
- $\frac{\delta\omega_a}{\omega_a} = \frac{1}{\omega_a \gamma \tau_\mu} \sqrt{\frac{2}{NA^2P^2}}$ N = number of muons, P = muon polarization, A = asymmetry
  - improves with B field since $\omega_a \propto B$
  - improves with number of muons, asymmetry, polarization
  - improves with muon momentum (γ)

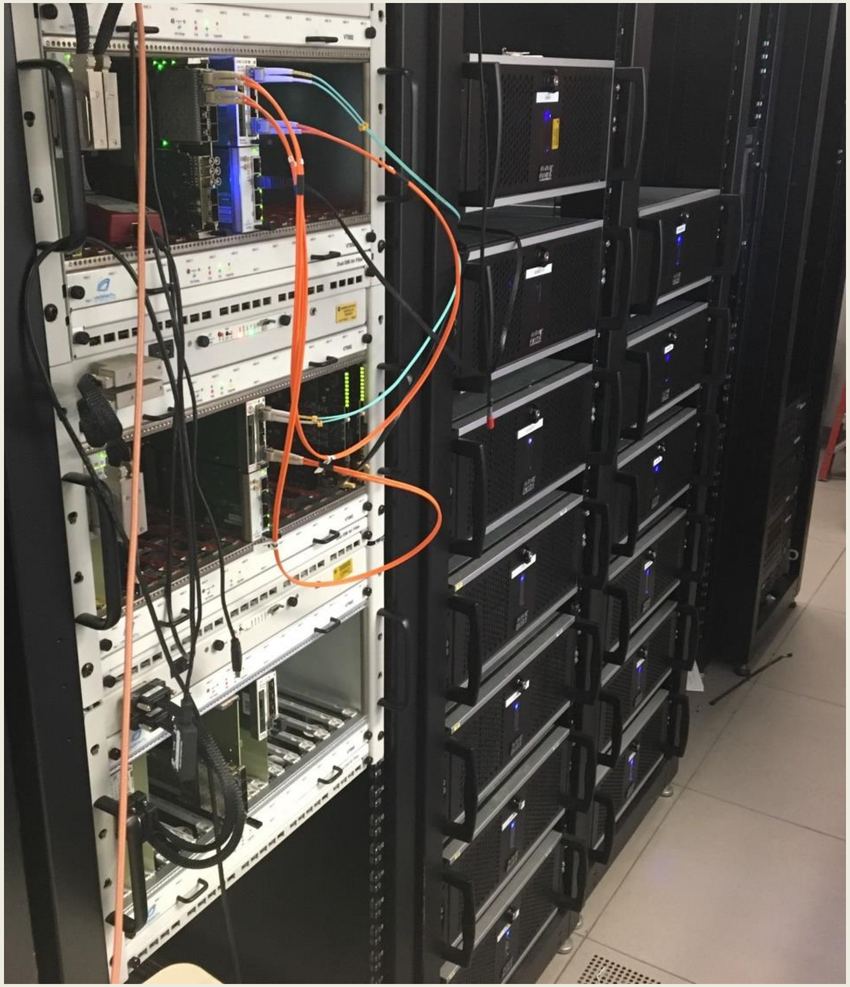
Systematic uncertainty

	E821 [ppb]
detector gain variation	120
event pileup	80
lost muons	90
coherent betatron oscillations	70
electric-field and pitch corrections	50

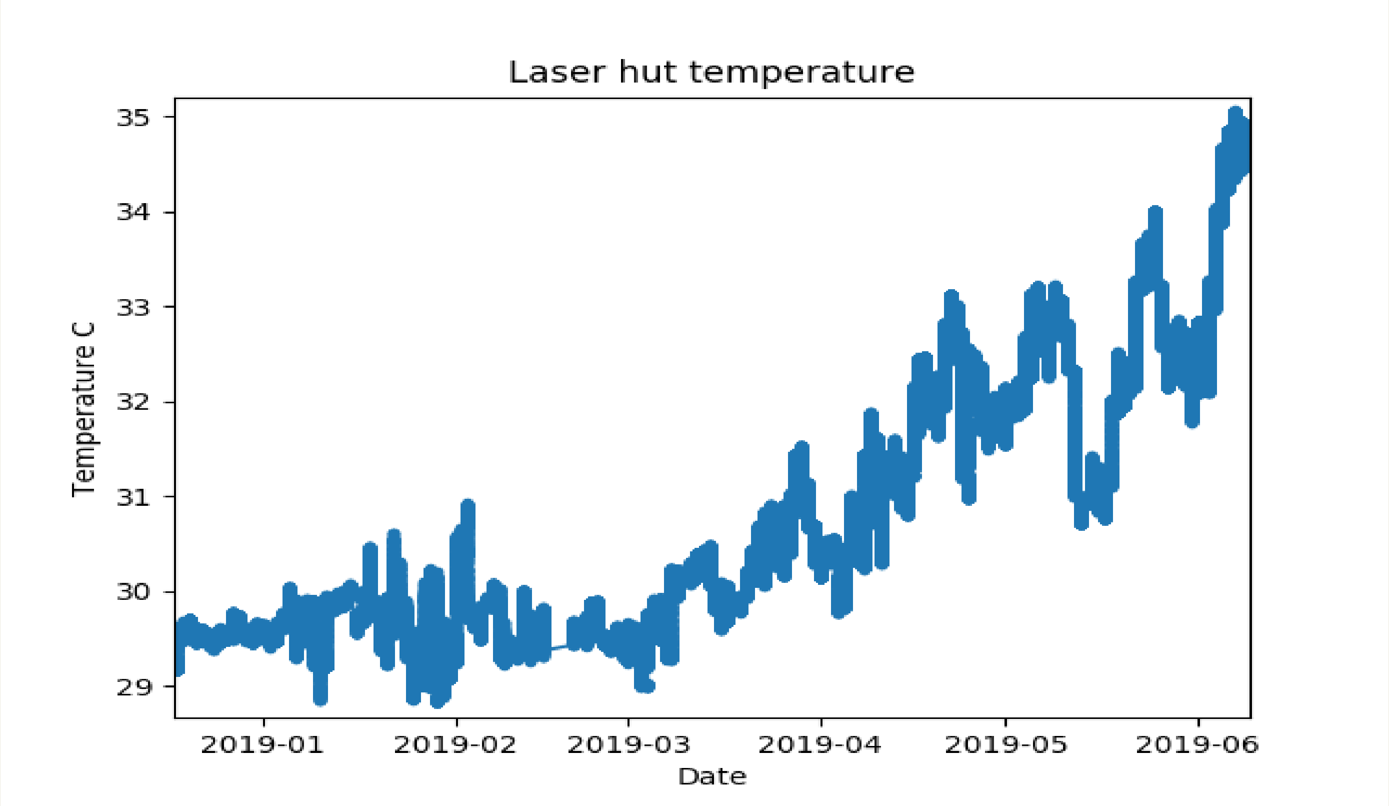
from A. Lusiani, INFN (Italy)

Data Acquisition System

- Calorimeters, trackers and the laser monitoring system are read out by custom 800 MSPS waveform digitizers.
- The DAQ produces a deadtime-free record of each 700 μs muon fill. We get 12 fills per second, providing a total data rate of 20 GB/s.
- Data from each calorimeter is processed by an NVidia Tesla K40 GPU, which processes 33M threads per event.
- Data is sorted by T-method (chopped islands) and Q-method (current integrated) data, from which timing info can be extracted.
- The DAQ software is MIDAS based



A Temperature problem



One laser head failed due to high room temperature
Independent conditioning needed