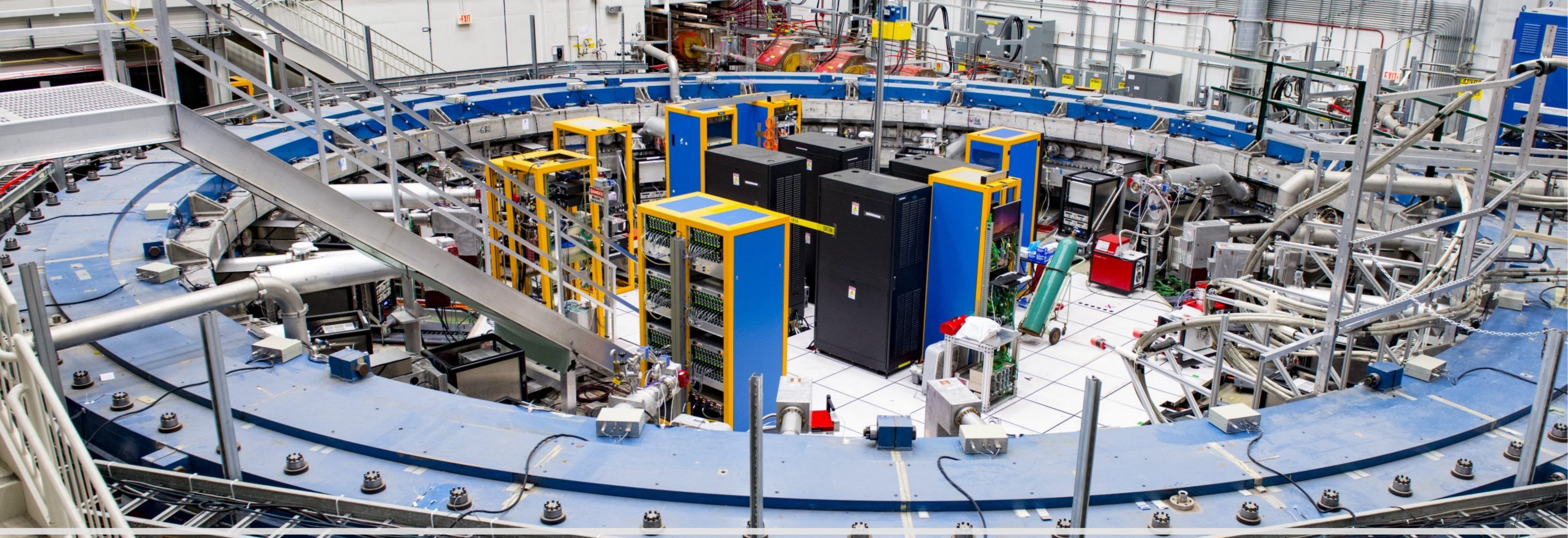


High precision requires perfect calibration: The g-2 laser calibration system

E. Bottalico

Fermilab 2021 Summer Student School – 04 August 2021

Spot the differences

Can you spot the difference between those images?

Spot the differences

And now?

Spot the differences

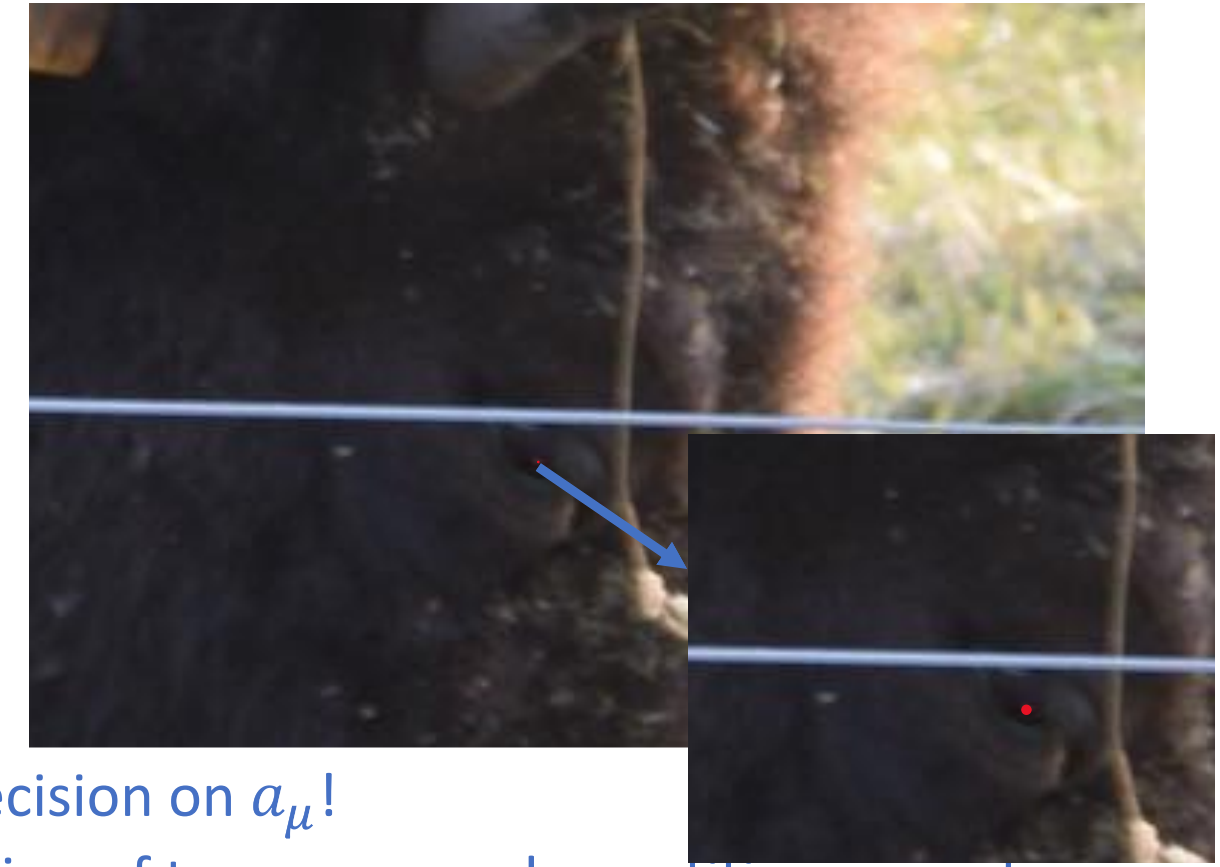
Maybe now!?

One pixel over 7 MILION, this is the final precision on a_μ!

Since this value is obtained by the combination of two measured quantities ω_a and ω_p any systematic should be known even better!

Spot the differences

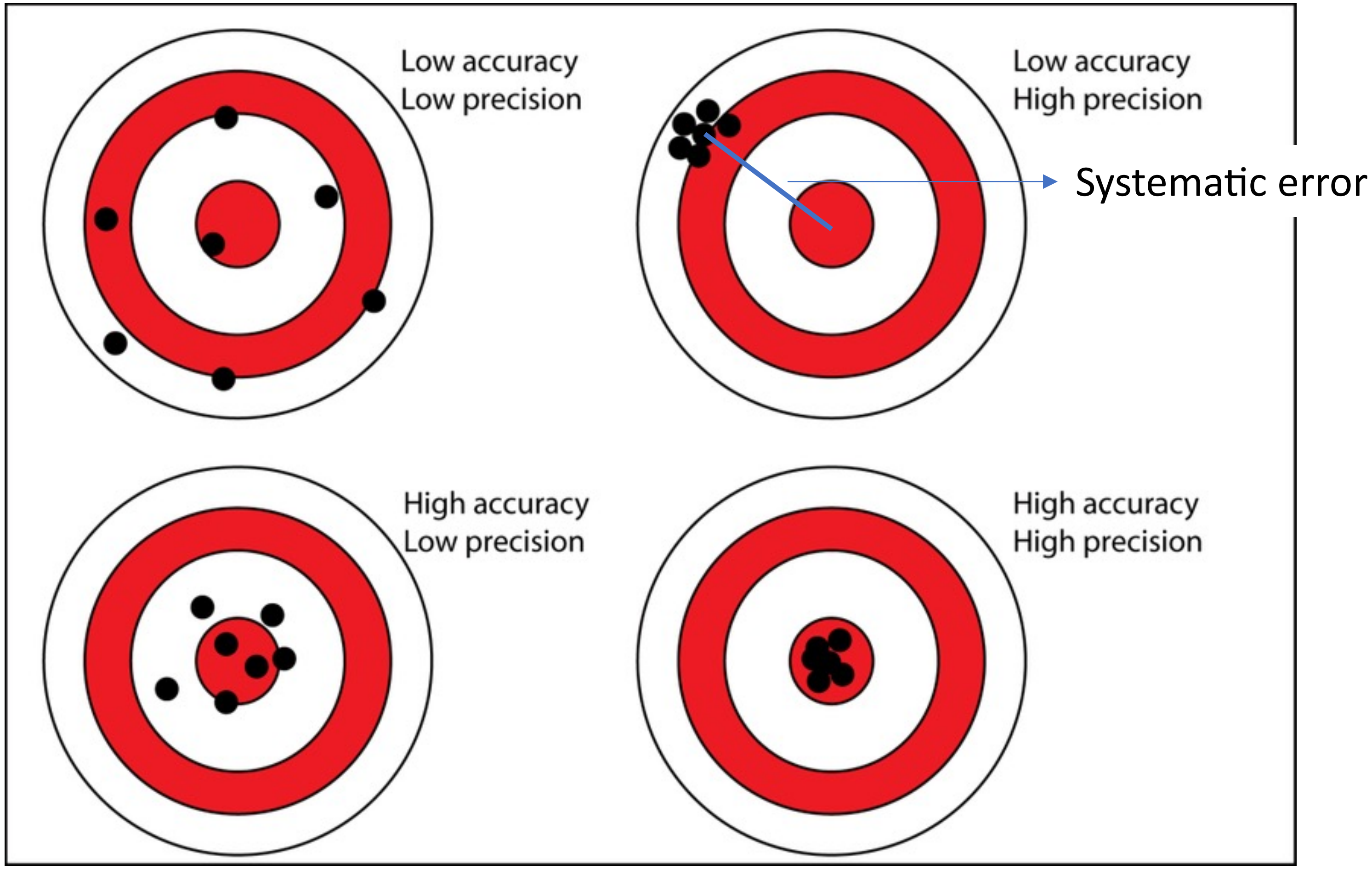
Maybe now!?



One pixel over 7 MILION, this is the final precision on a_μ!
Since this value is obtained by the combination of two measured quantities ω_a and ω_p any systematic should be known even better!

Systematics on ω_a

What is a systematic error?



Systematics on ω_a - Gain Corrections

- Total budget for systematic error on ω_a is **70 ppb**, while only **20 ppb** are permitted for **gain correction**!

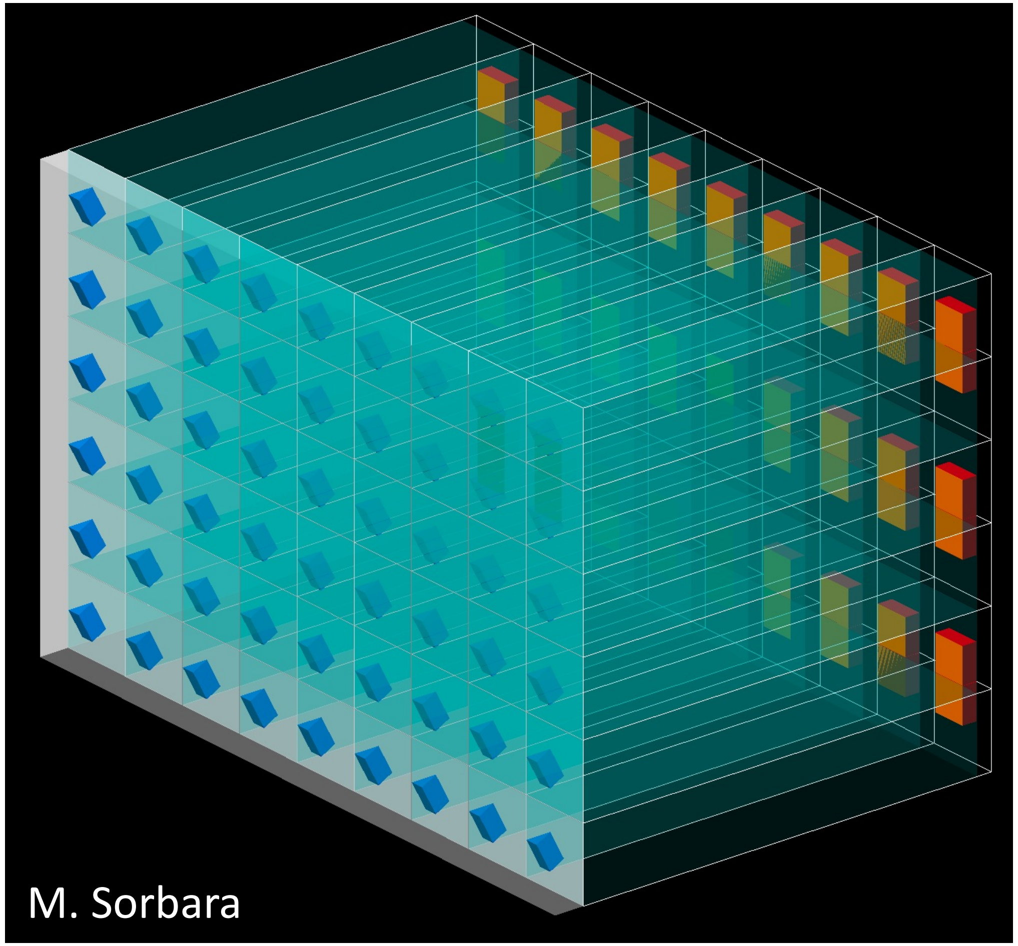
Source	E821 [ppb]	E989 goal [ppb]
Gain Correction	120	20
Lost Muons	90	20
Pile-Up	80	40
CBO	70	40
E-field and Pitch	50	30
Total	180	70

VADEMUCUM

- Remember in g-2:
  - Everything which changes during the *fill* (700μs) ☹️
  - Everything which changes within hours/days/months 😕
  - Everything which never change 😃

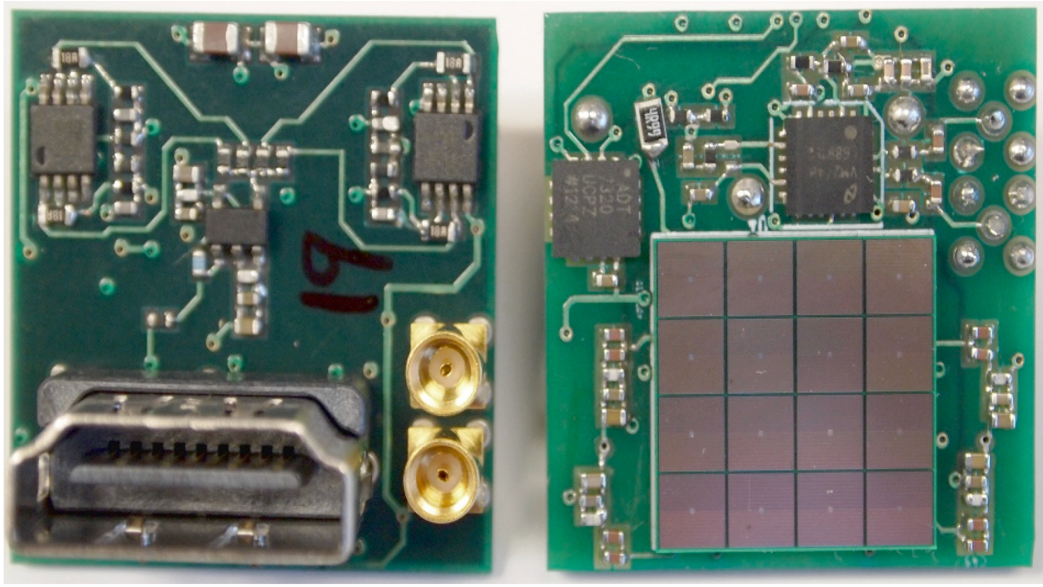
Gain fluctuations – A long story

- The 24 electromagnetic calorimeters in Muon g-2 are made of:
  - 54 crystals of PbF2 (9 columns x 6 rows) read by 54 SIPMs (240x240pixel).
  - Crystal's length is 14 cm, 15 X_0.
  - The Cherenkov light is used, it is faster than particles shower, allowing fast reading (signal width $\sim$nanoseconds).



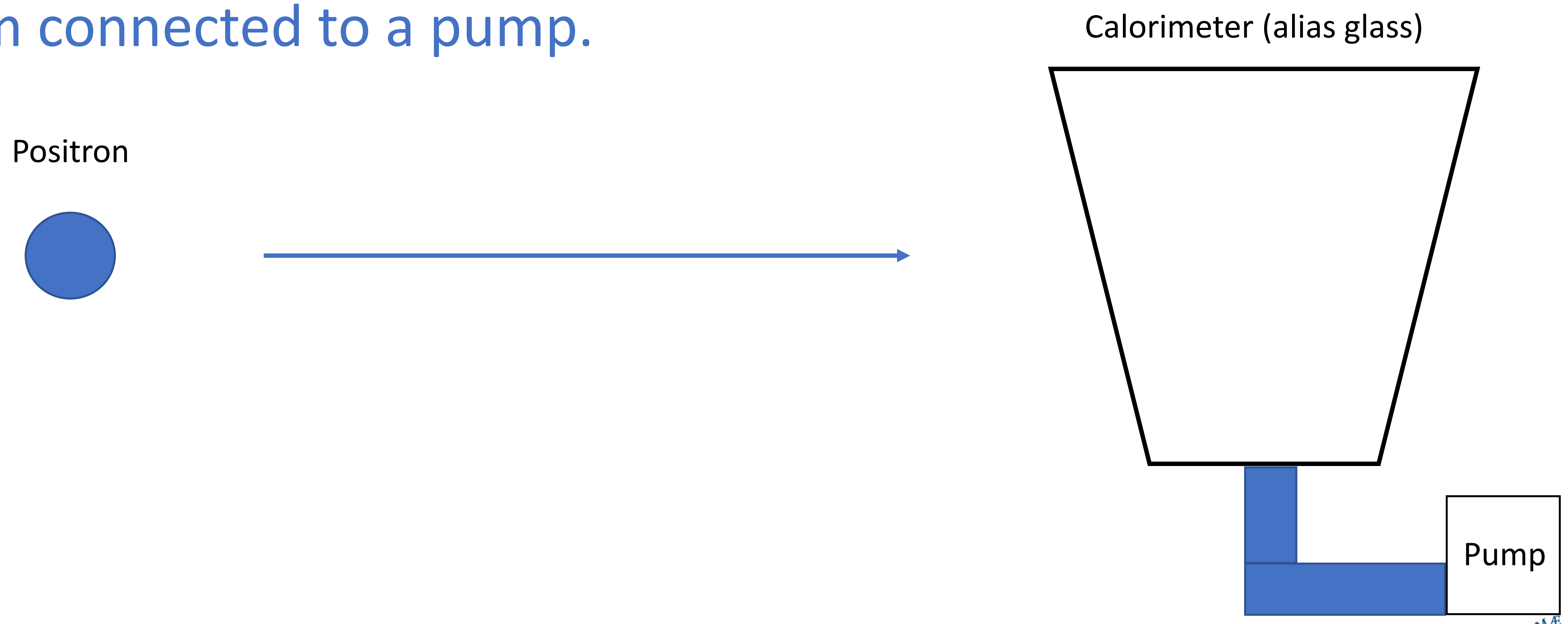
Gain fluctuations – A long story

- The 1296 SIPMs which constitute the electromagnetic calorimeters experience a gain fluctuation in three different time scales:
  - Days: Long term variation due to environmental conditions as temperature;
  - During the muon *fill* (700μs): due to the huge flux of particles which hit the calorimeters near to the injection time *(splash).*
  - Tens of nanosecond: due to double positron hits in the same crystal within 80ns.



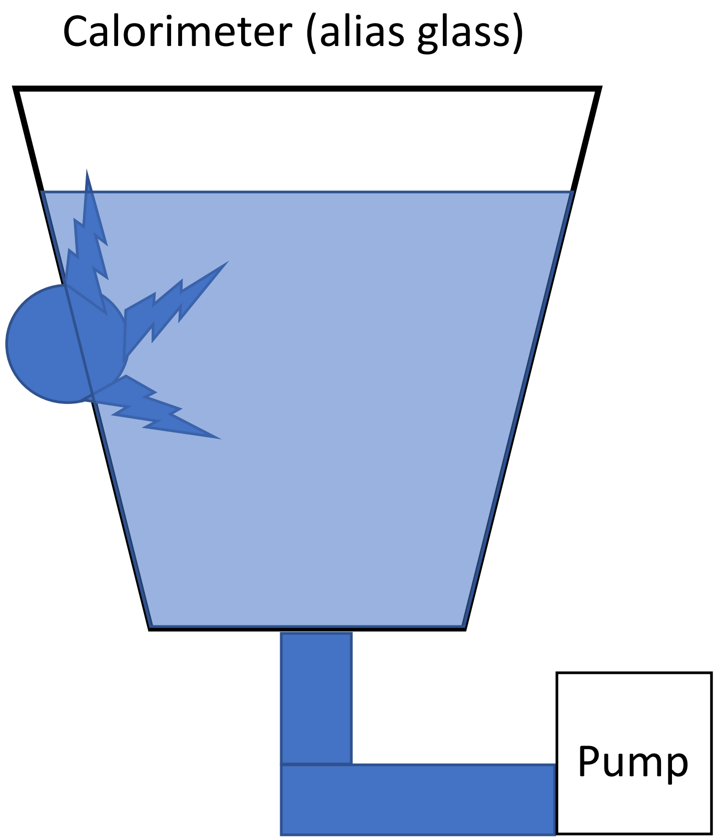
Gain fluctuations – In Fill correction

- We can image the calorimeter as a glass of water, with a hole at the bottom connected to a pump.



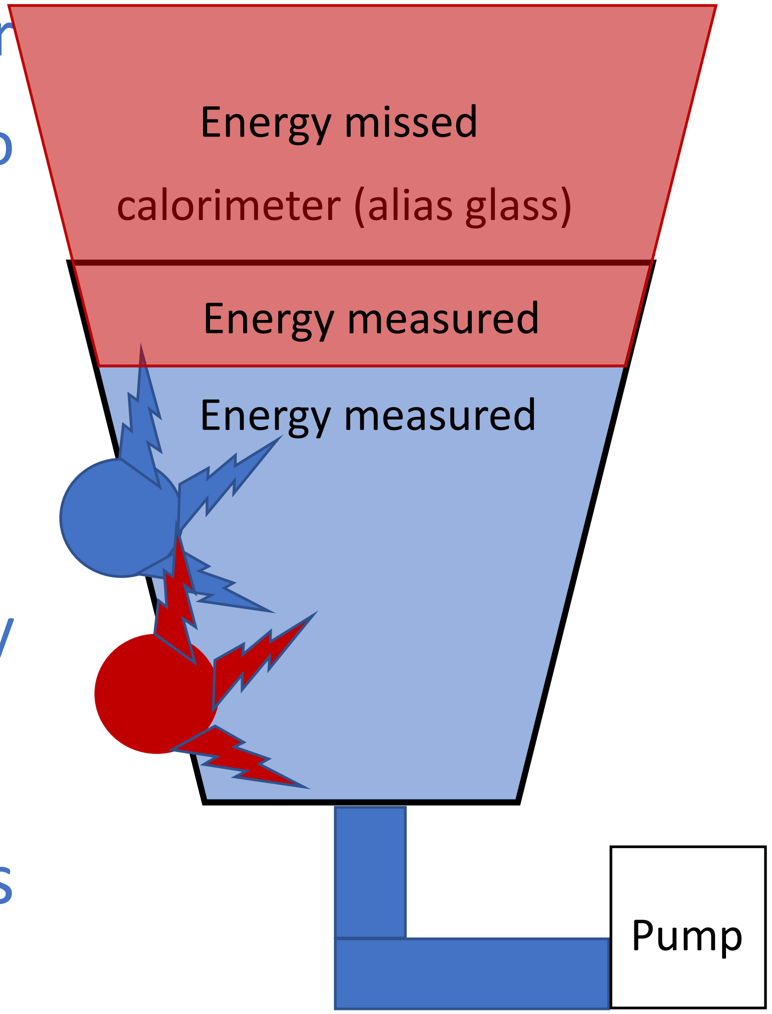
Gain fluctuations – In Fill correction

- When the positron hits the calorimeter (glass), it realeses energy (water) inside of it.
- An istant after the interaction, the glass contains water, proportionally to positron energy.



Gain fluctuations – In Fill corrections

- Next the first collision another positron hits the detector (within tens of microseconds), the latter is not able to measure correctly the energy of the second particle.
- This happens for two main reasons:
  - The capacity of the glass is not infinite;
  - The pump cannot drain all the water instantaneously (there is an *RC* which discharge the system)
- We need a system able to correct the for this effect.

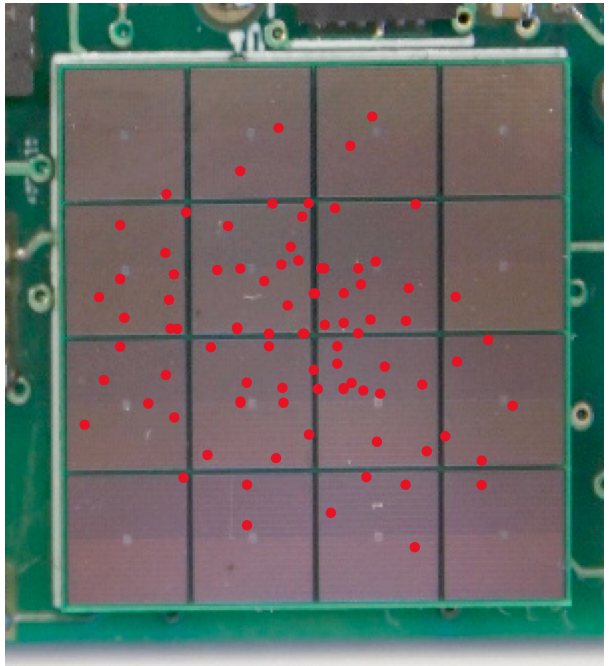


Gain fluctuations – Short Term corrections

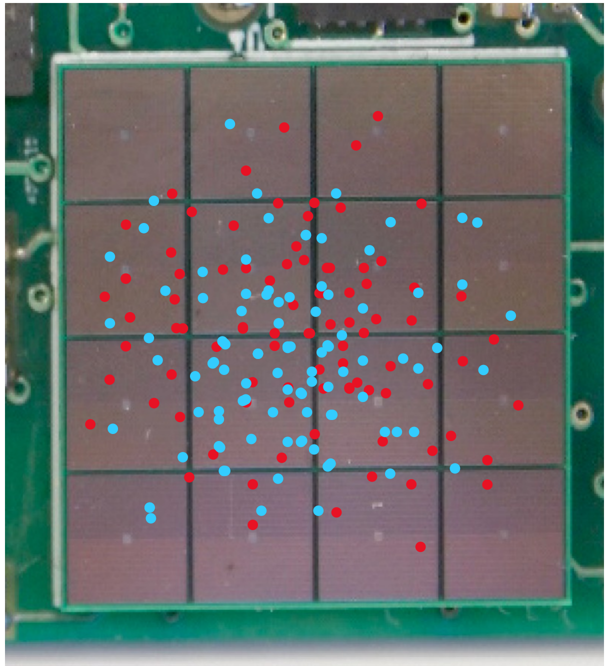
- The short term gain fluctuations happen when 2 positrons hits the same crystal → SIPM within 80 ns.

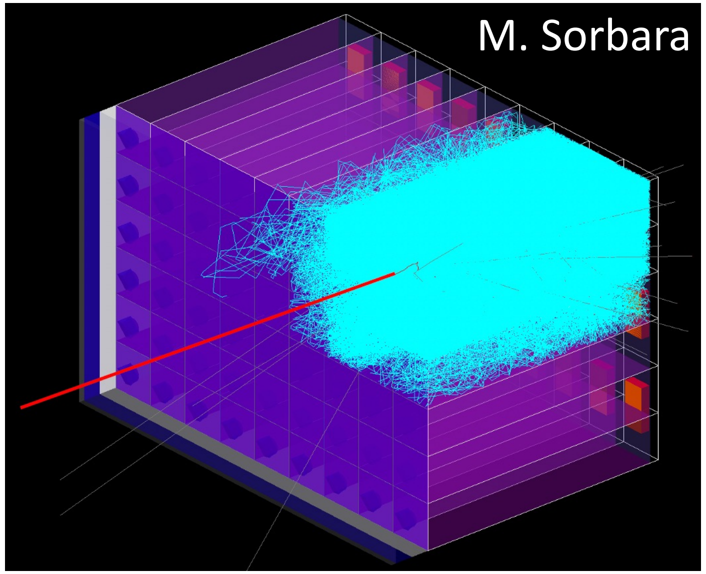
SIPM surface -> 16 channels -> 54k pixel

- First Positron



- Second Positron



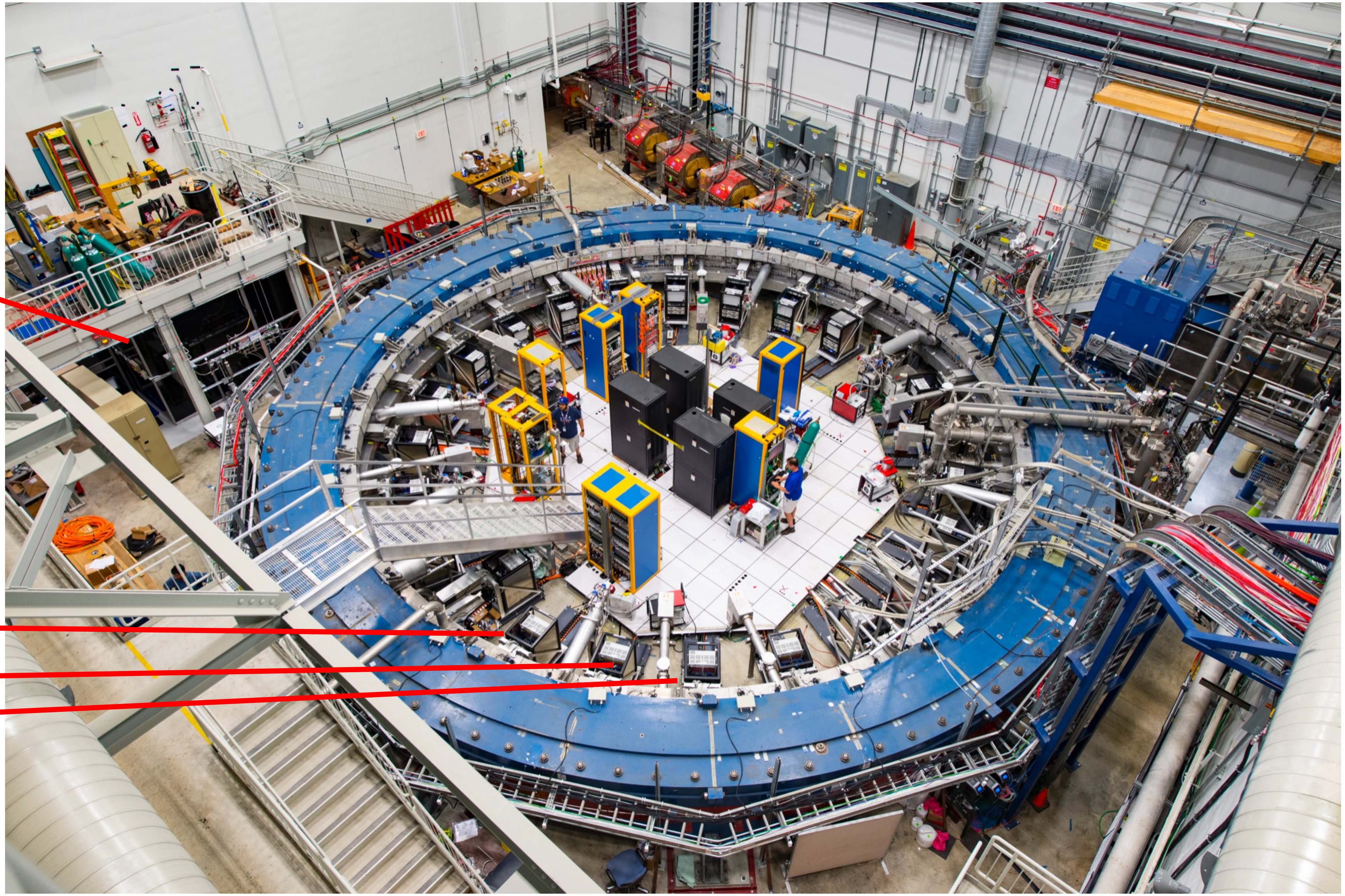


Each SIPM behaves like a infinitesimal Geiger counter, it remains blinded by the previous hit with a characteristic time of about 15ns.

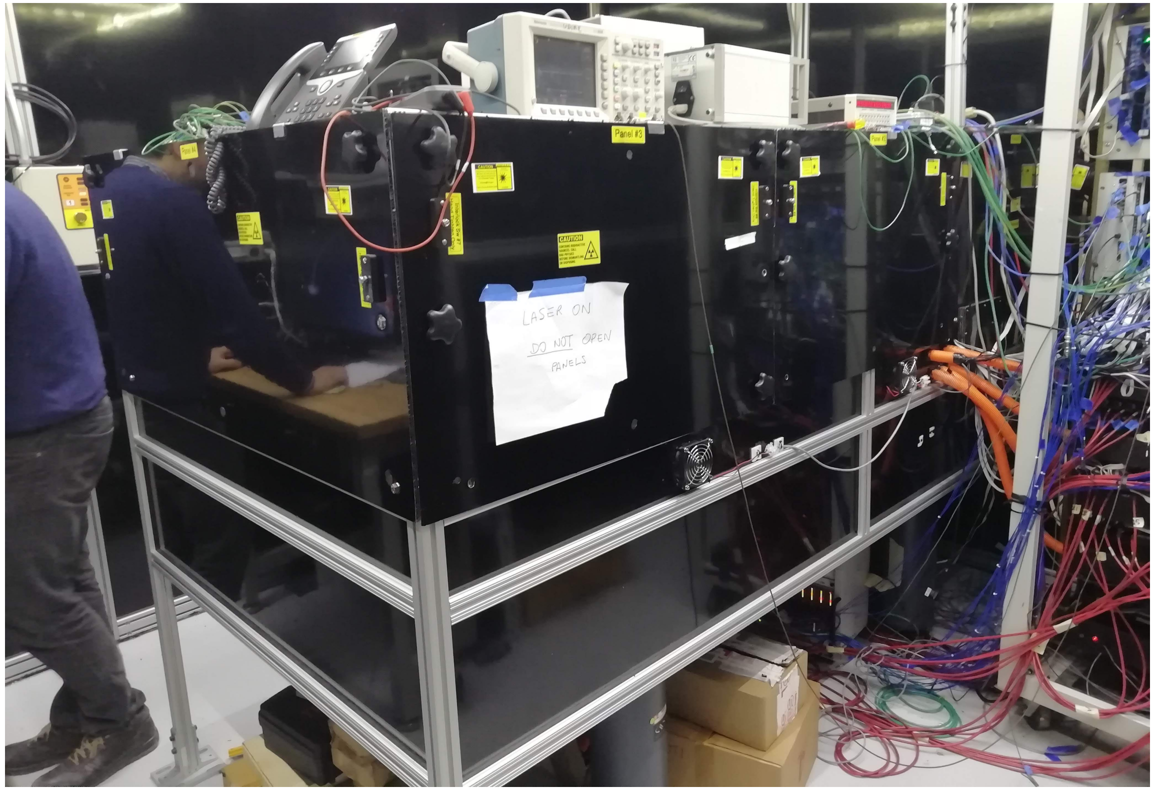
Laser system

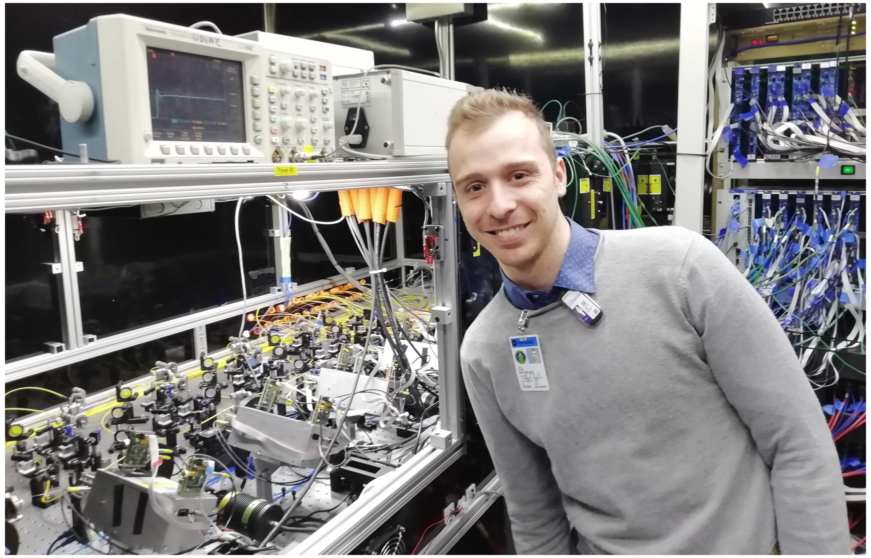
LASER HUT

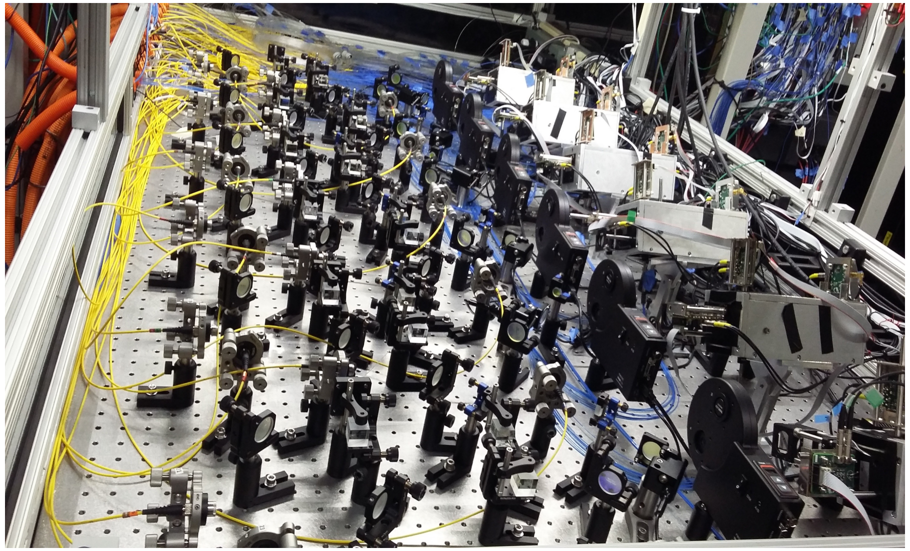
CALORIMETERS



Laser Hut

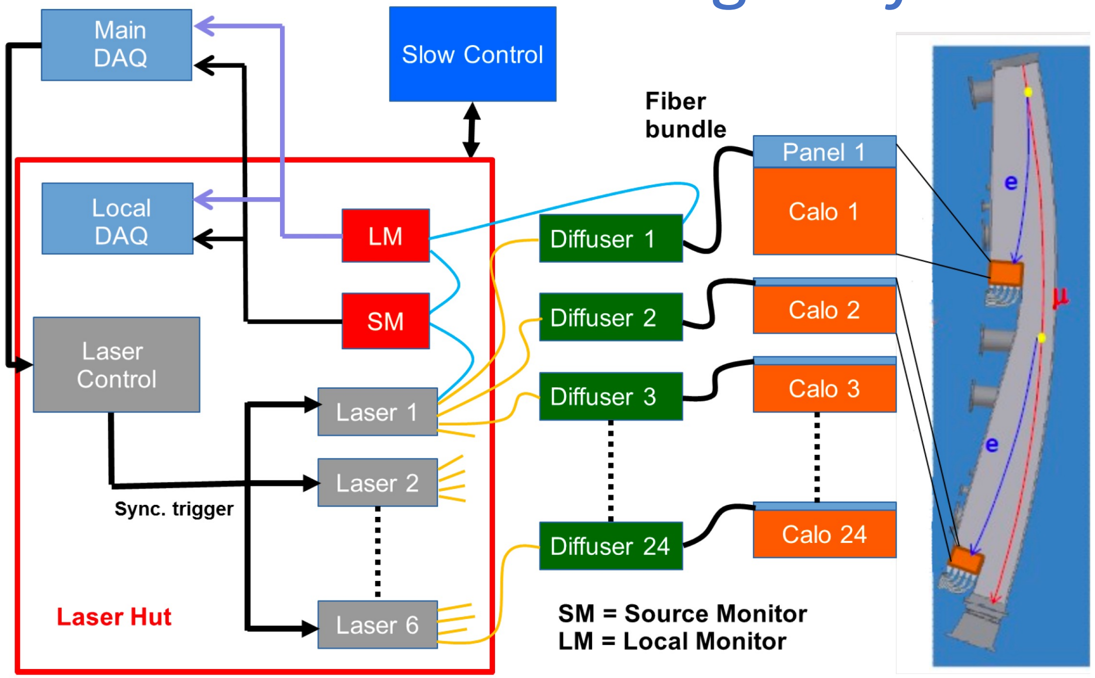


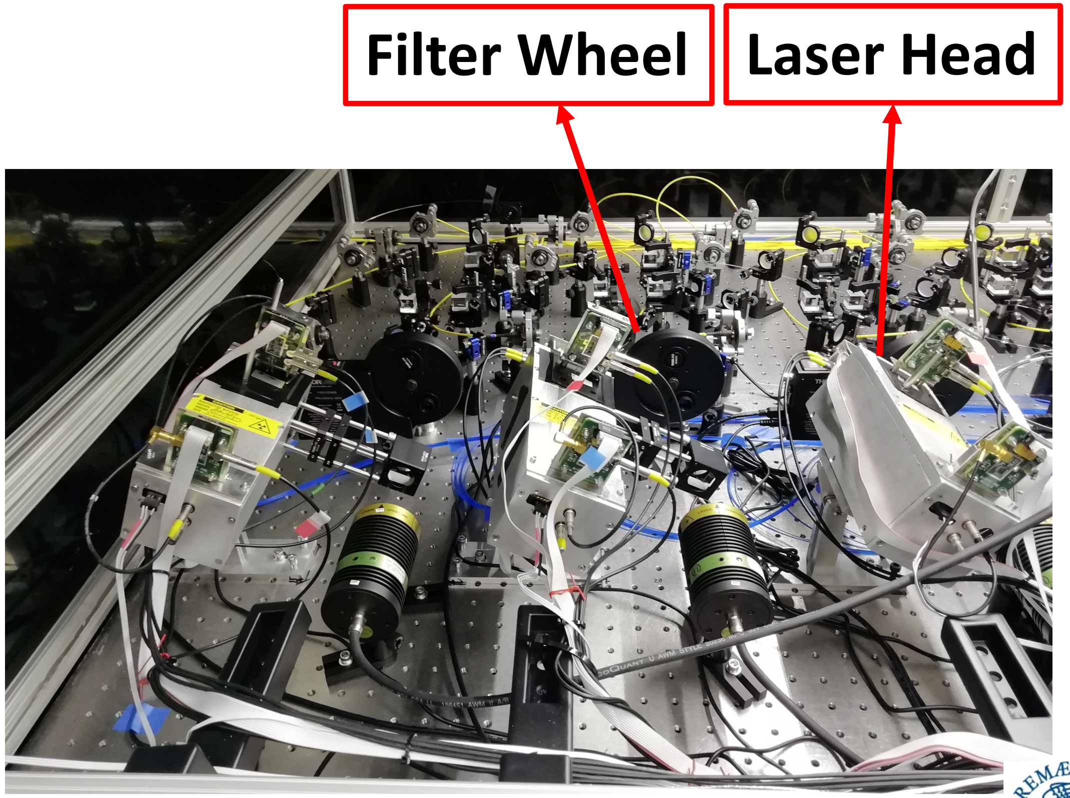




Laser system

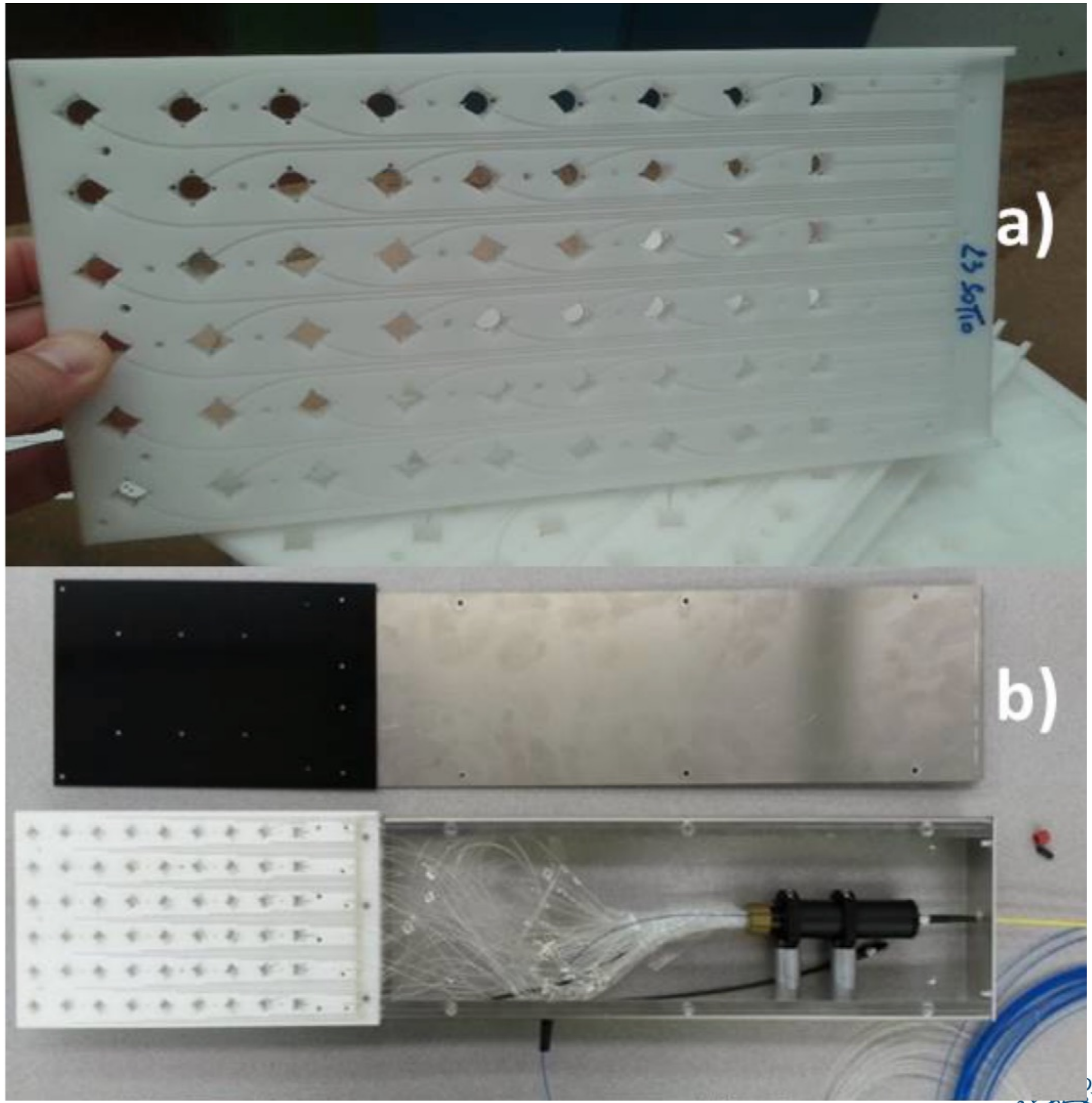
- An high precision laser system were built by INFN in collaboration with INO.
- The system is able to correct the SIPM's response due to gain fluctuations.
- To reach the 20ppb systematic uncertainty a continuous calibration is needed at 0.04% during the *fill* time.



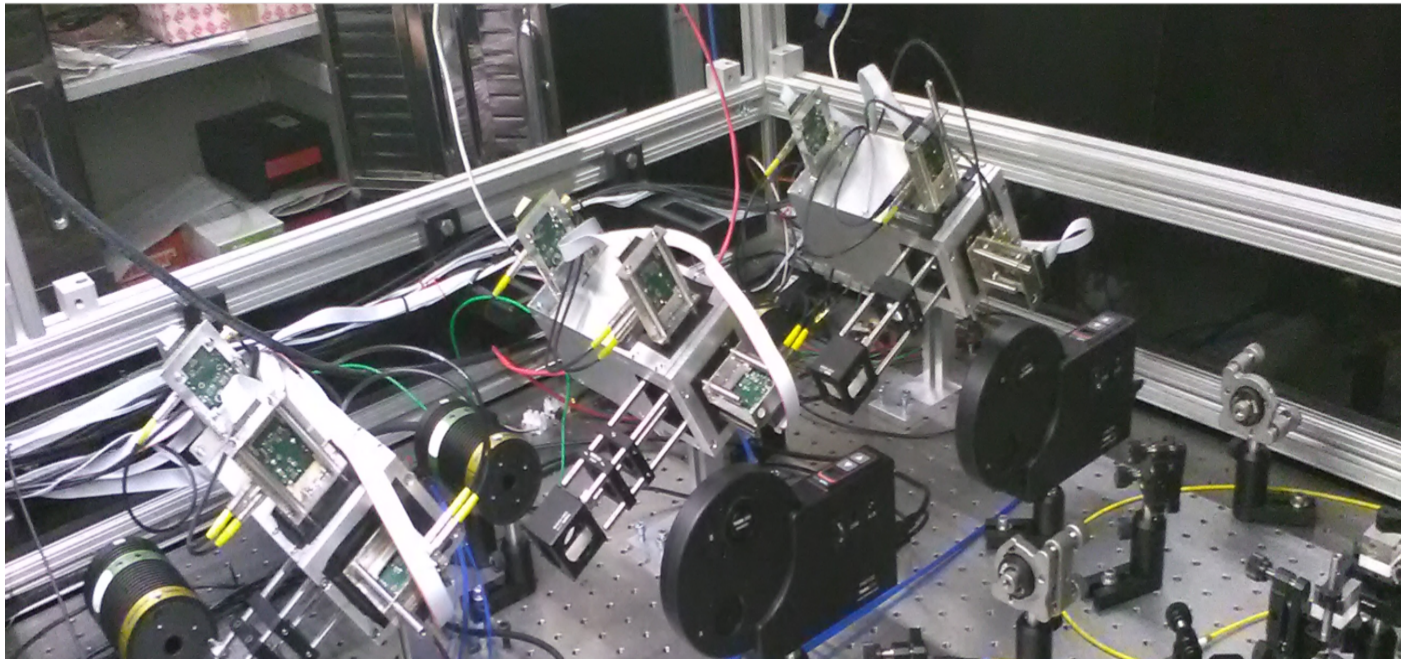


Laser system

- Via optical fibers the laser light is brought to calorimeters.
- The light is sent to a bundle with 54 fibers.
- A Delrin panel with optical prisms allows to illuminate each crystal of each calorimeter.

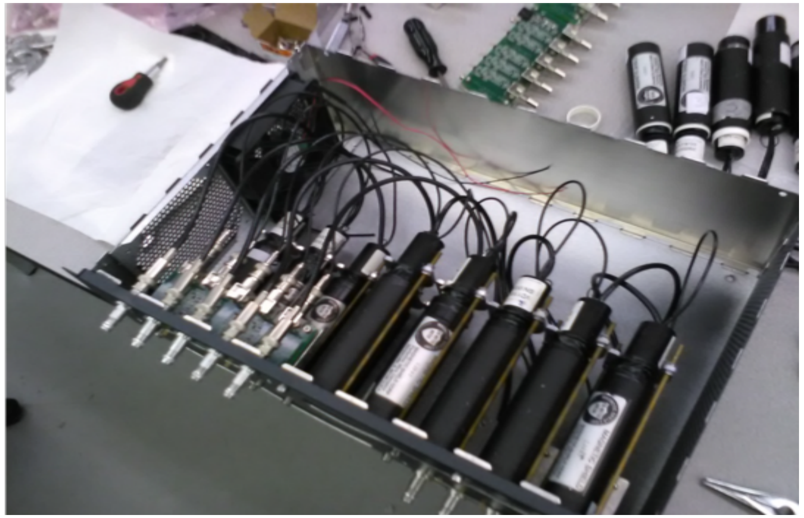


Monitoring System



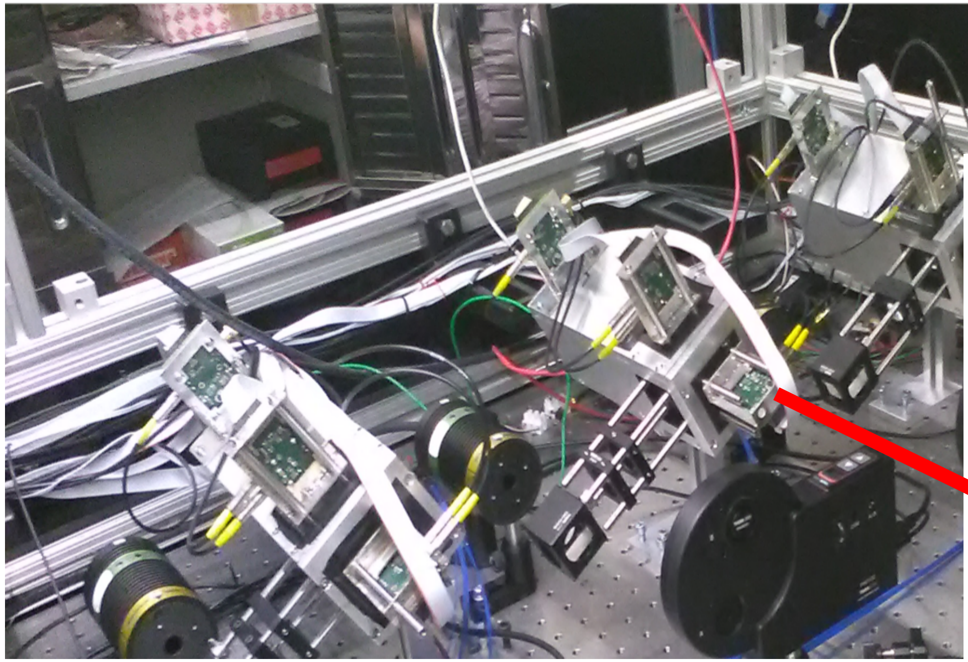
The monitoring system is composed by:

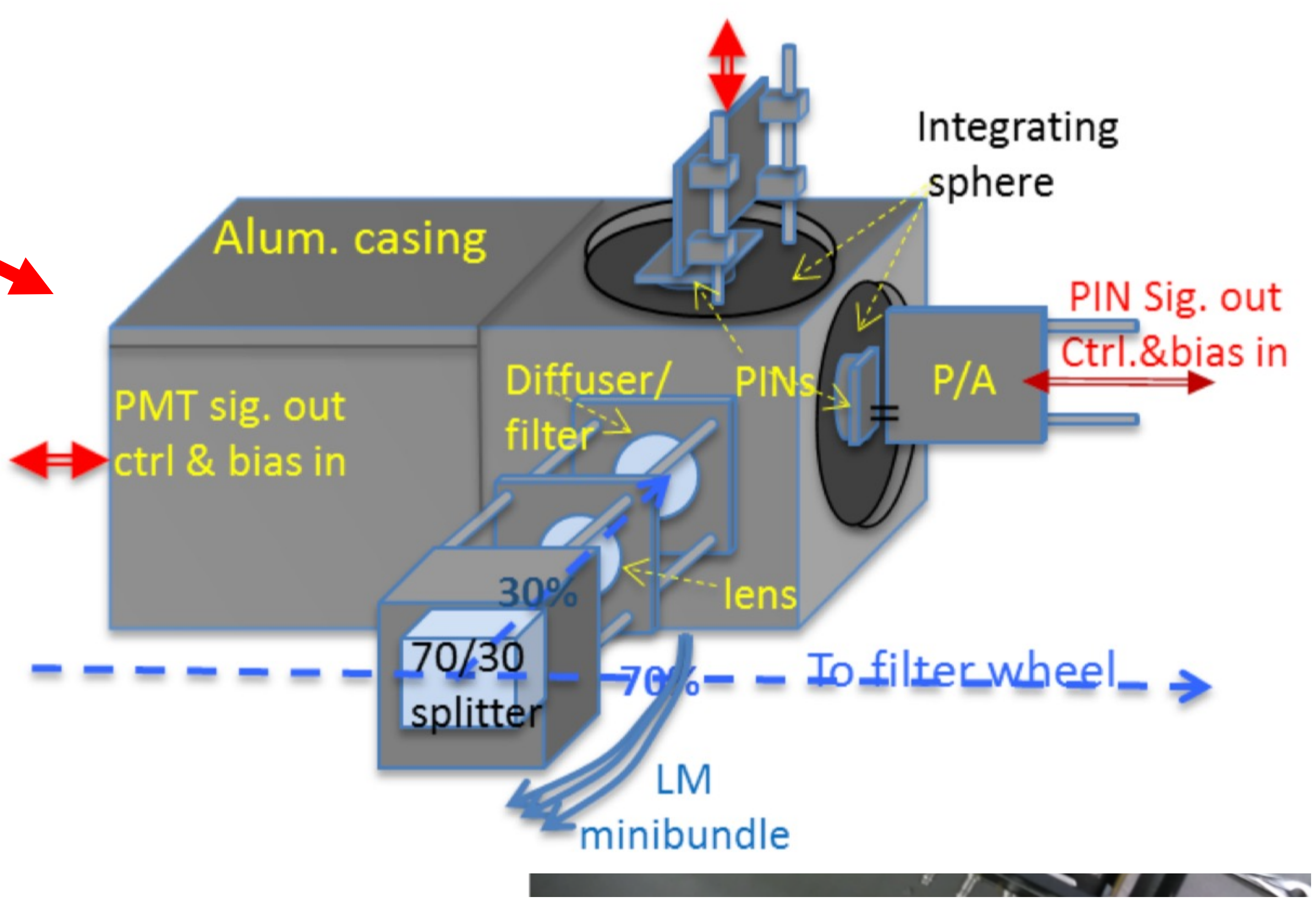
- Source Monitor (SM): 2 pin diode at the heads of laser heads, with a resolution of 0.3%;



- Local Monitor (LM): Consists of a pair of PMT which read the signal sent to calorimeters

Monitoring System





The monitoring system is composed by:

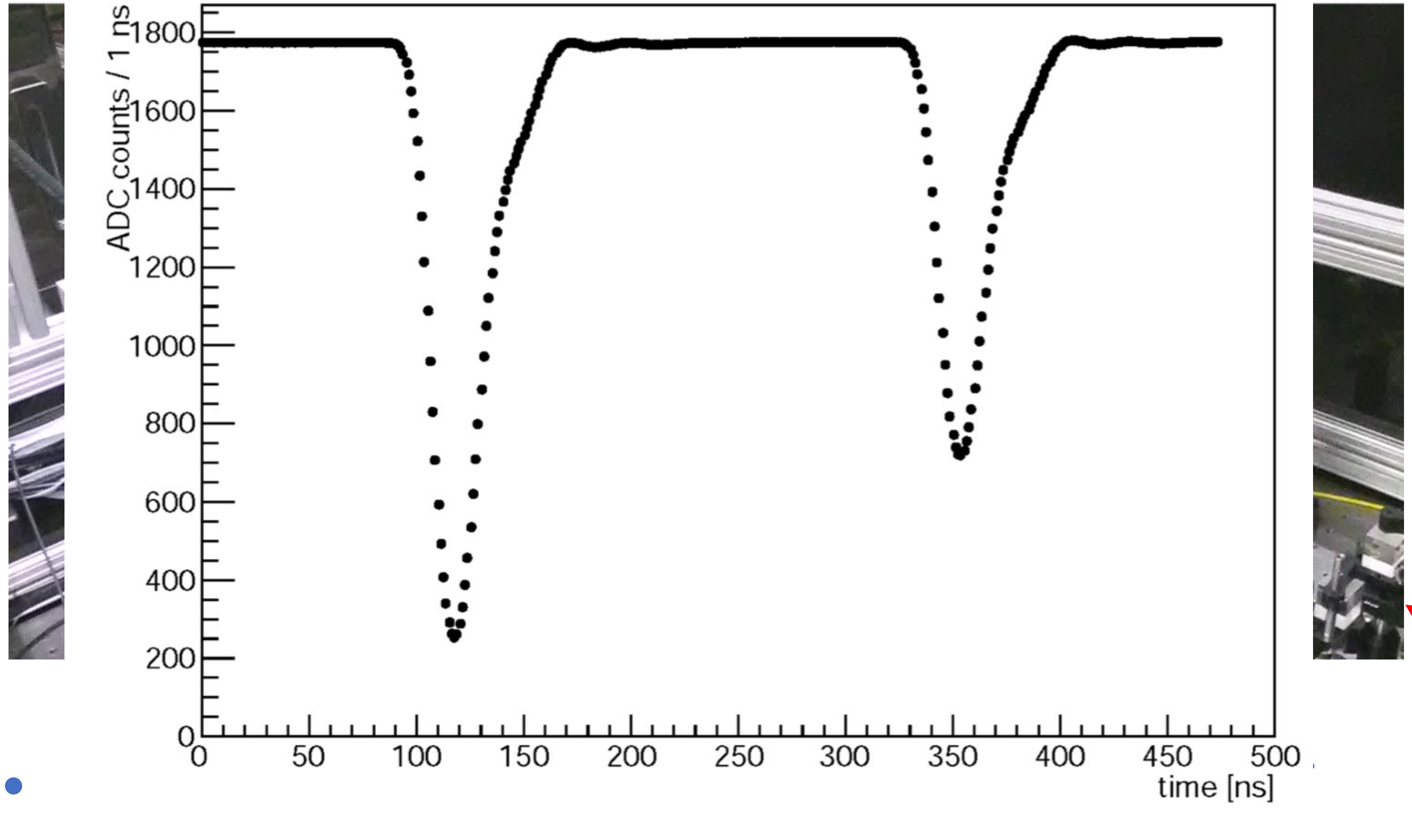
pin

ser

of

- Local Monitor (LM): Consists PMT which read the sign calorimeters

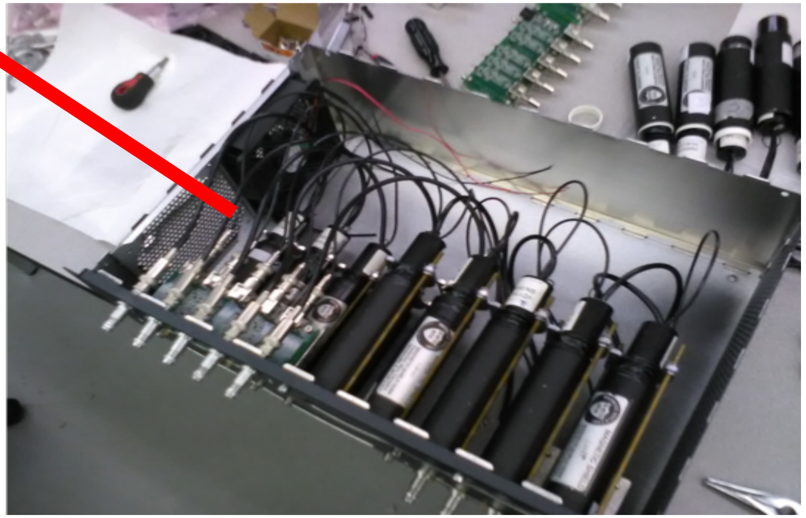
Monitoring System



The monitoring system is composed by:

- Source Monitor (SM): 2 pin diode at the heads of laser heads, with a resolution of 0.3%;

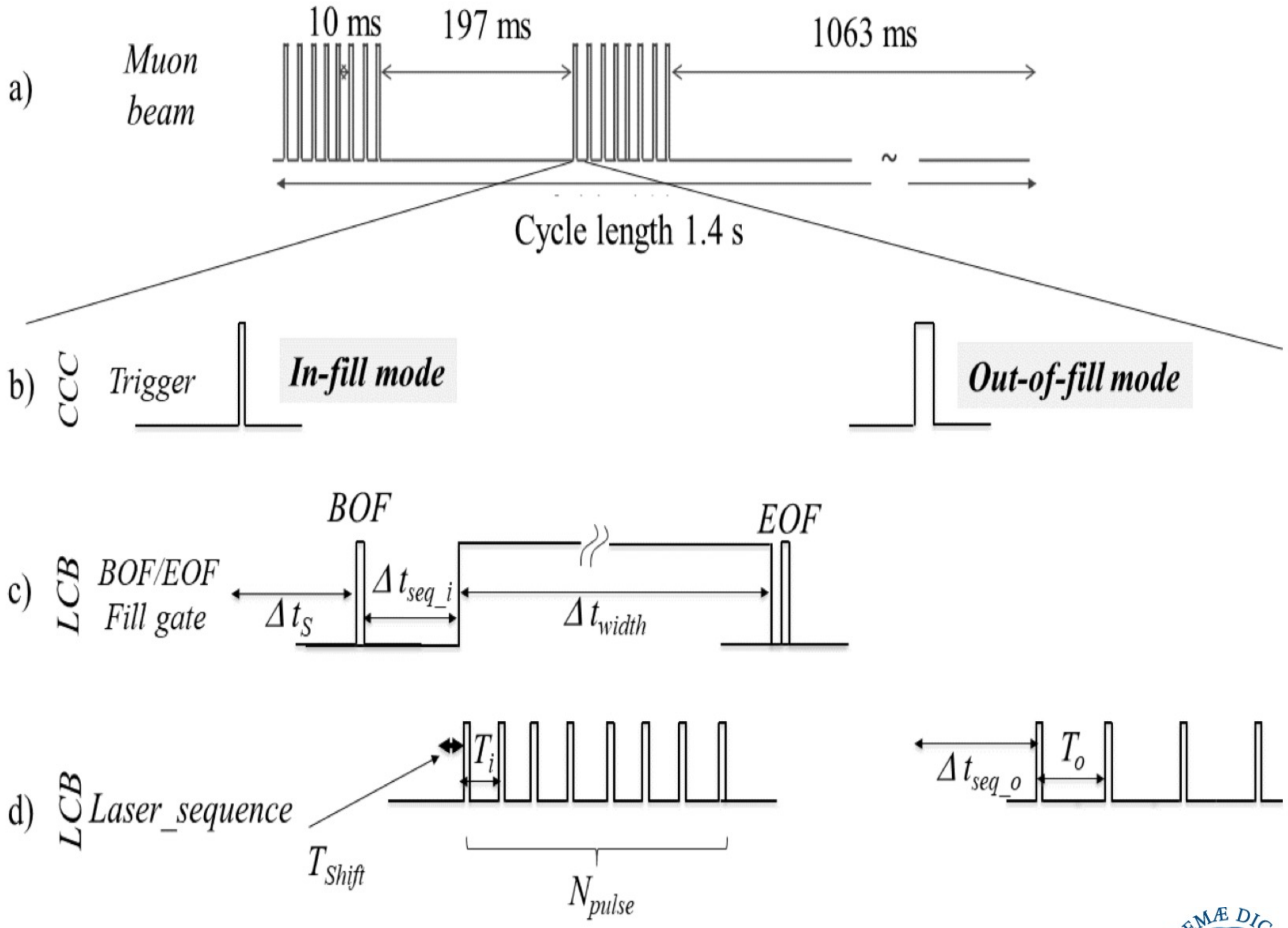
- PMT which read the signal sent to calorimeters



Standard operation mode

The standard mode is divided into 3 different kind of pulses sent to the detector.

- SYNC: The *Sync Pulse* sent to the 1296 crystal in order to time synchronize the crystals
- IN-FILL: A series of pulses during the *fill* time, with a set delay of 2.5μs
- OUT OF FILL: Each muon *fill* is ~ 10 ms apart, allowing to send 4 laser pulses to study the stability over days time scale and provides also the normalization for the IN-FILL pulses.



Gain Curve In-Fill Gain

The *In-Fill* corrections are applied to the data during the *fill*.

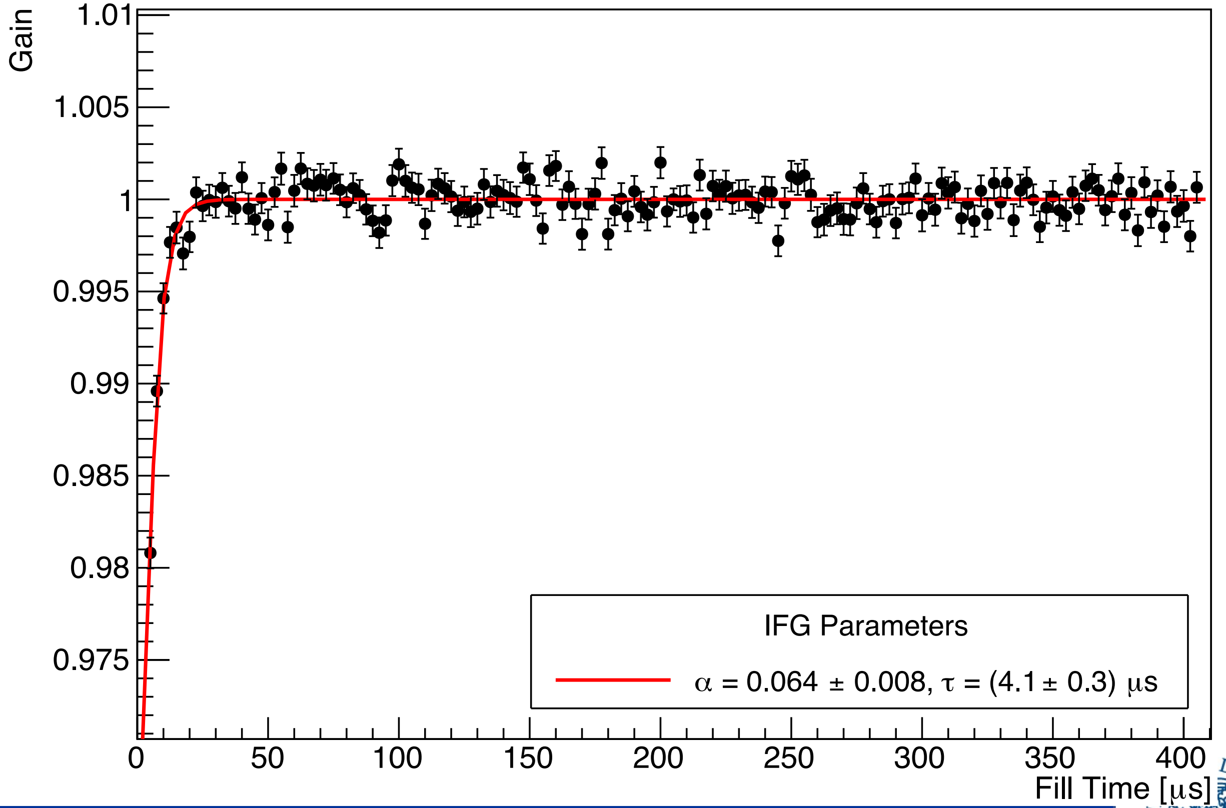
The so-called gain functions are obtained by sending a series of laser pulses (3 per each *fill*) with 200 μs of delay.

The gain as function of time is computed:

$$G(t_i) = \left\langle \frac{SiPM_{if}}{SM_{if}} \right\rangle_{t_i} \left\langle \frac{SM_{oof}}{SiPM_{oof}} \right\rangle_{subrun}$$

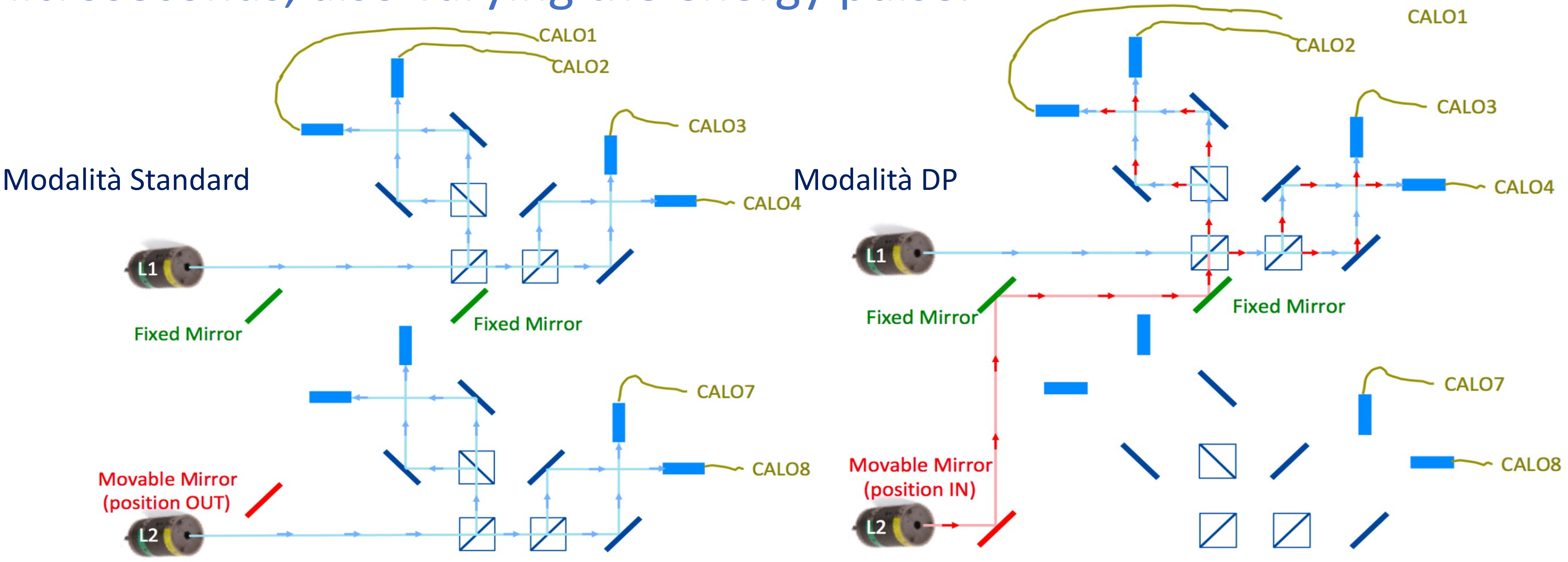
The function are fitted with a simple exponential:

$$G_{IFG}(t) = 1 - \alpha_{IFG} \cdot e^{-\frac{t}{\tau_{IFG}}}$$



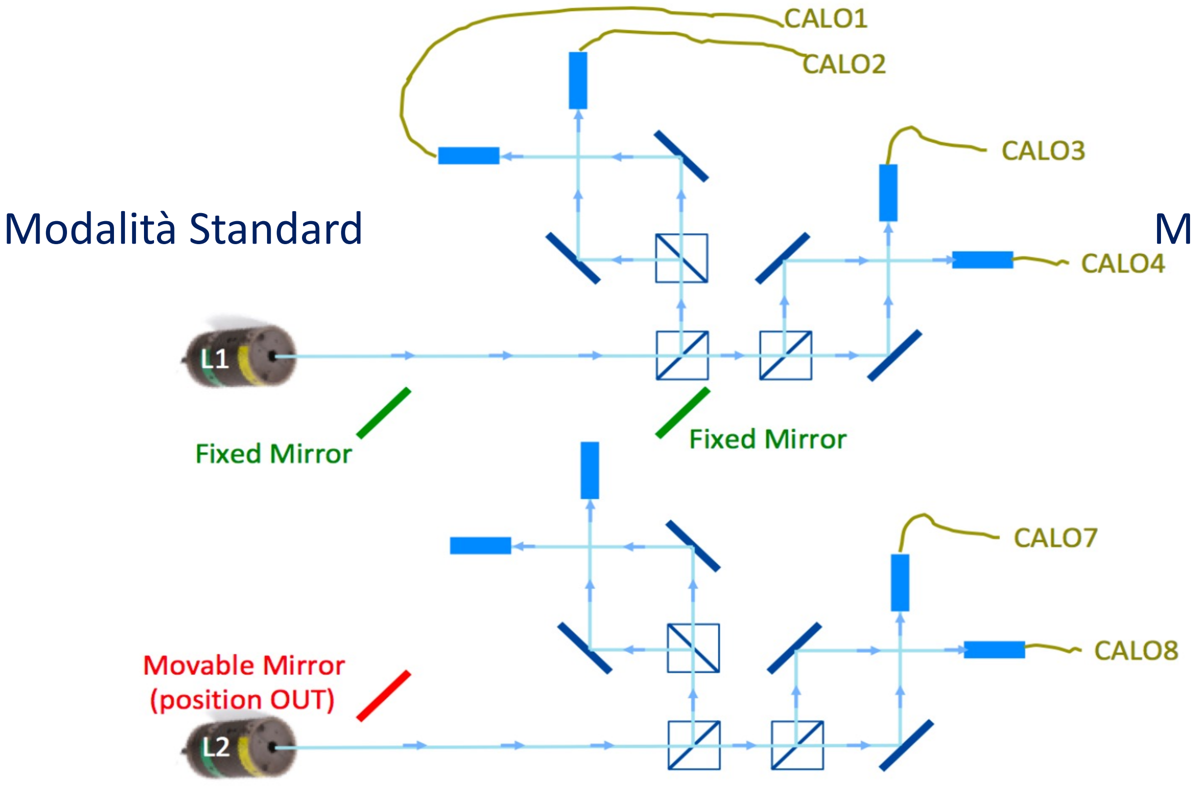
Double Pulse Mode

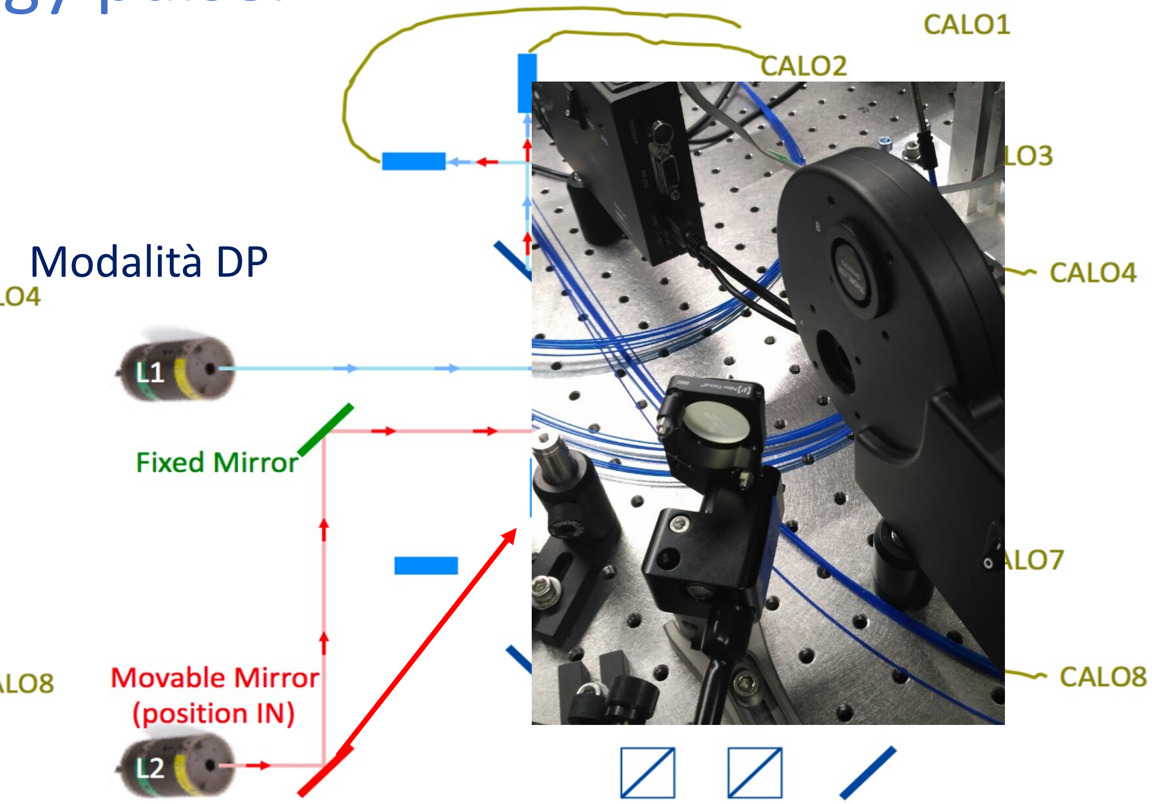
Via movable mirrors (commanded remotely) it's possible to switch in Double pulse mode allowing to send at the same crystal the light of 2 laser heads with a variable delay settable from 1ns up to hundreds microseconds, also varying the energy pulse.



Double Pulse Mode

Via movable mirrors (commanded remotely) it’s possible to switch in Double pulse mode allowing to send at the same crystal the light of 2 laser heads with a variable delay settable from 1ns up to hundreds microseconds, also varying the energy pulse.





Short Term Double Pulse

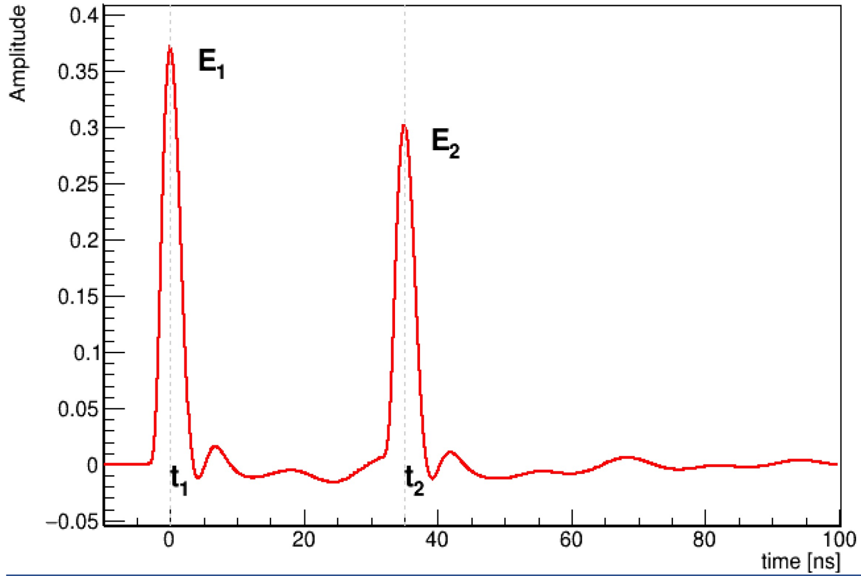
The *Short Term Double Pulse* (STDP) are built using dedicated laser campaign, without beam, using the scheme:

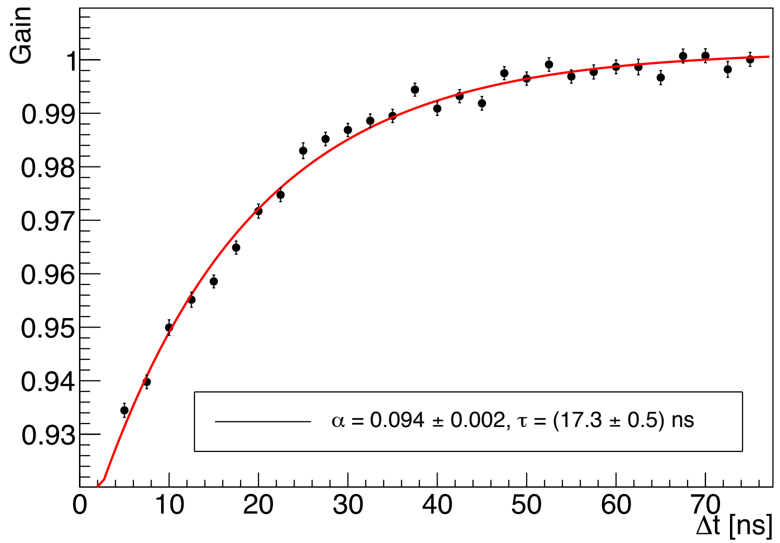
$$P_1 + P_2 : P_{Norm} : P_1 + P_2 : P_{Norm} \dots$$

The gain curves are computed as:

$$G(t_i) = \frac{\langle E_2 \rangle_{t_i}}{\langle E_{Norm} \rangle_{t_i}}$$

The shapes are fitted as $G(t) = 1 - \alpha \cdot e^{-\frac{t}{\tau}}$, characterized by α e τ.



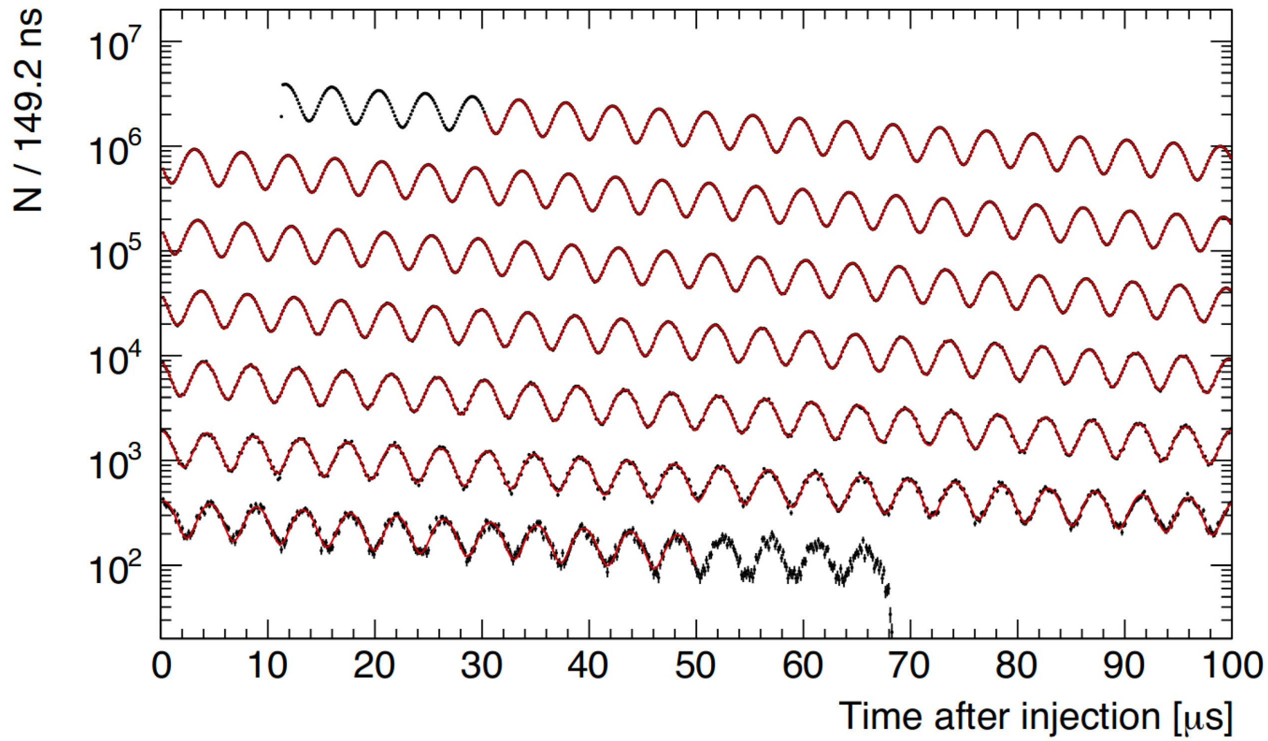


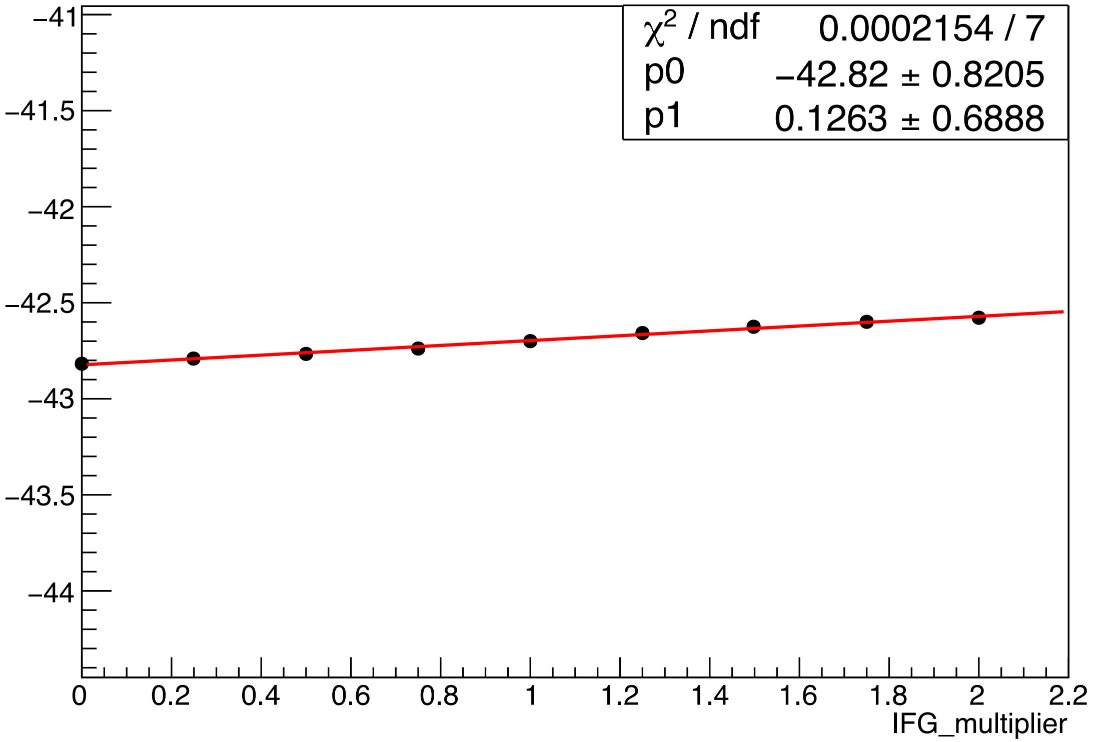
Gain corrections – Systematic study

Once all the corrections are applied, a 22 parameters fit is done to extrapolate ω_a.

The systematic effect on *IFG* is computed applying a multiplier *A* on positron energy:

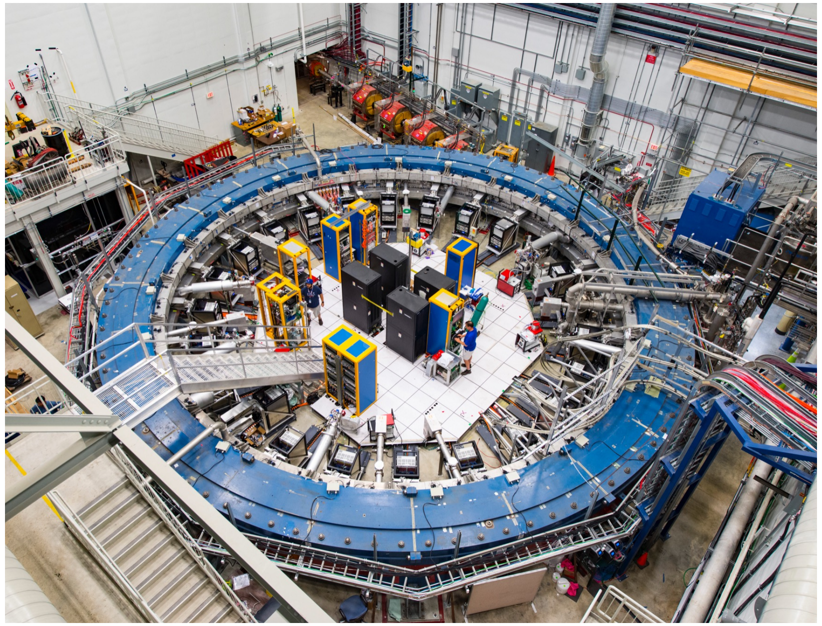
$$E'_p = \frac{E_p}{1 - \alpha_{IFG} \cdot A \cdot e^{-\frac{t}{\tau_{IFG}}}}$$

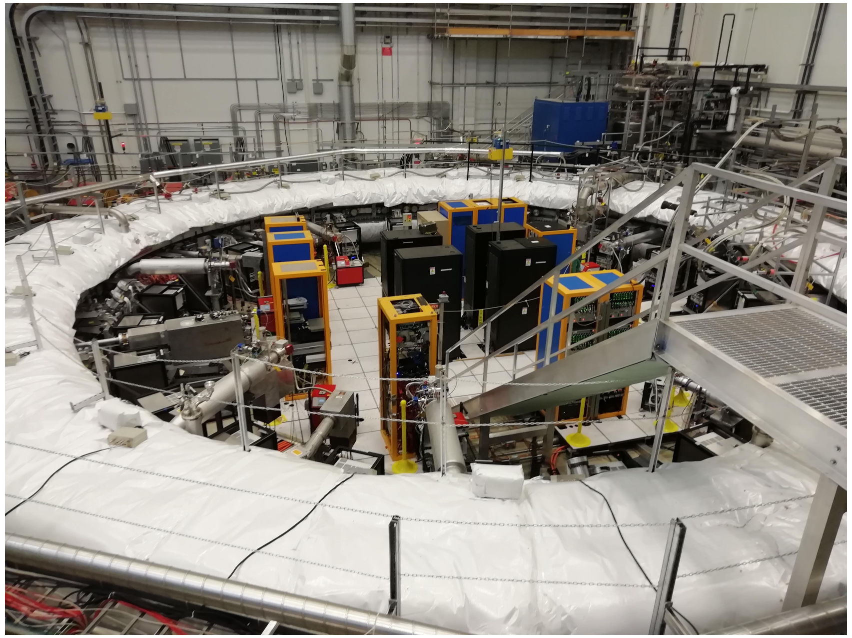




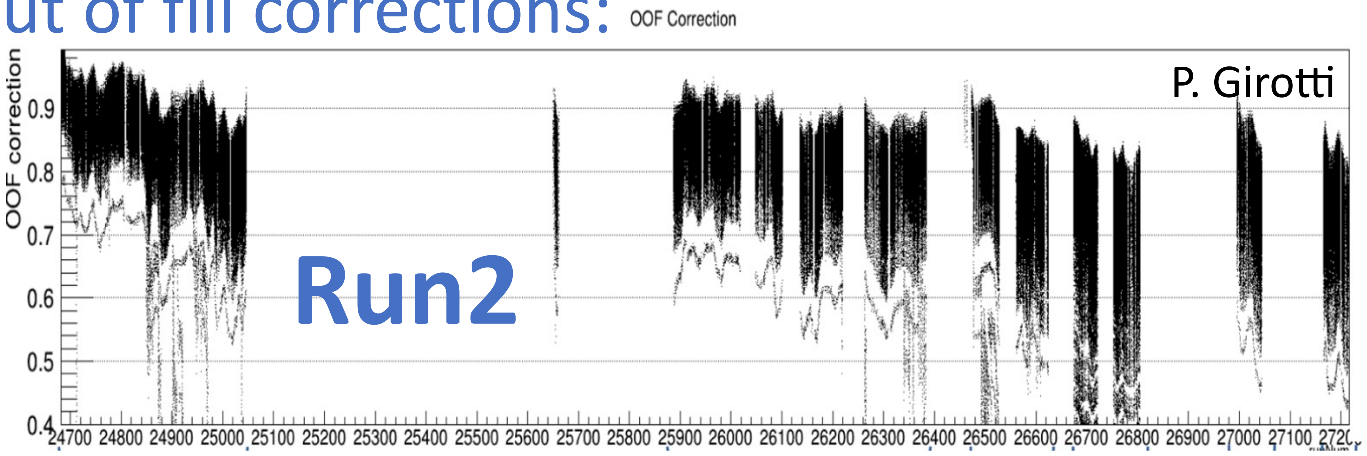
System Upgrades

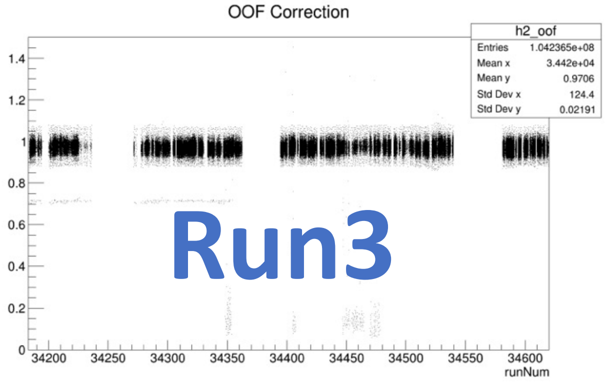
Ring's thermal coat:





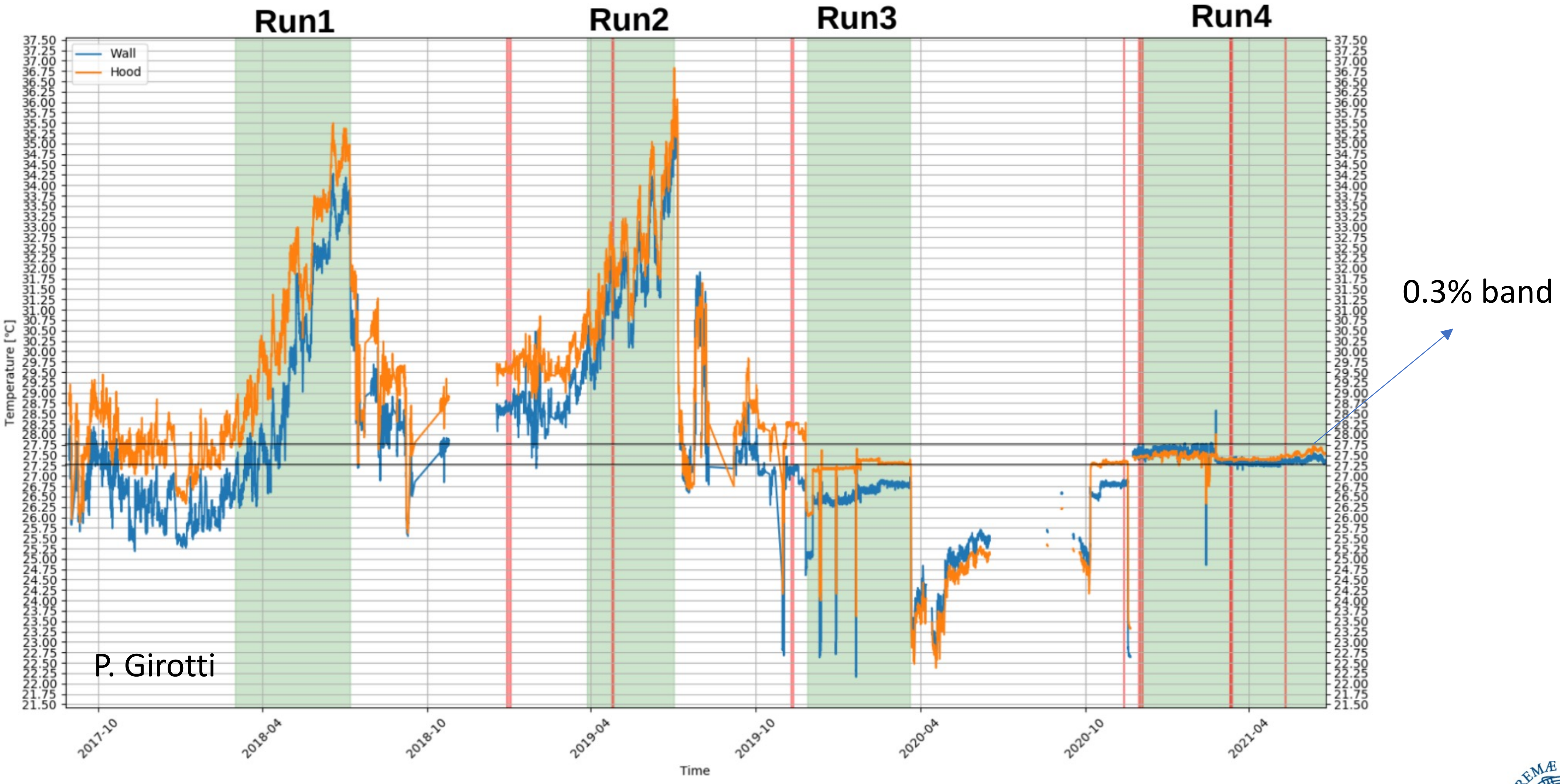
Out of fill corrections:





Laser System Upgrades

Run4 Thermal cooling in Laser Hut:



Conclusion

- Thanks to the laser calibration system, we can correct for calorimeter gain fluctuations the g-2 data.
- This is a novel method to energy calibration and time synchronization.
- From Run1 analysis we reach a systematic error on gain correction of about 20ppb.

“The closer you look the more there is to see”

F. Jegherlehner

Thank you!!!

- For any question or just to have a chat – elia.bottalico@phd.unipi.it