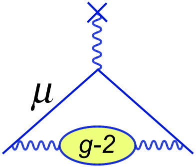


Laser calibration system and lost muons correction in the g-2 experiment

Maria Domenica Galati

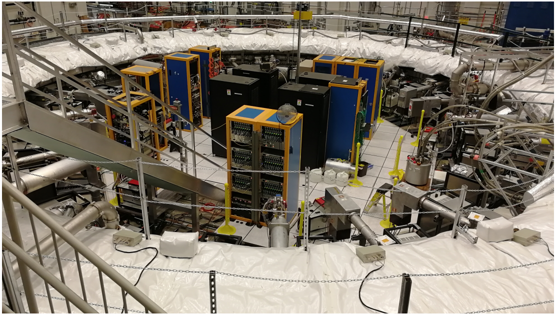
September 25th, 2019

Final Report

Supervisors: Anna Driutti, Marco Incagli

The Muon g-2 experiment

The Muon g-2 experiment examines the precession of muons that are subjected to a magnetic field.
The main goal is to measure the muon anomalous magnetic moment, $a_\mu = (g-2)/2$, to the unprecedented precision of 0.14 ppm.

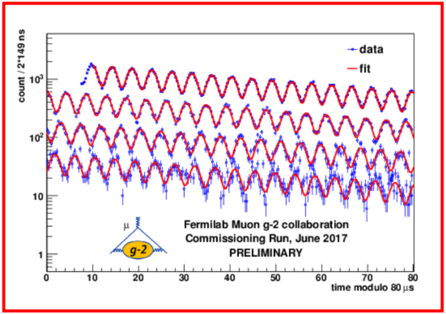


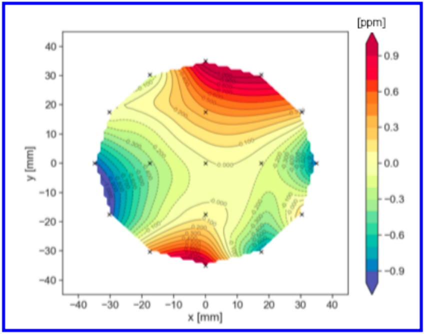
Experimental Technique

The experiment consists in filling a storage ring with polarized muons and measuring the anomalous precession via:

$$\omega_a = -\frac{e}{m_\mu} a_\mu B \tag{1}$$

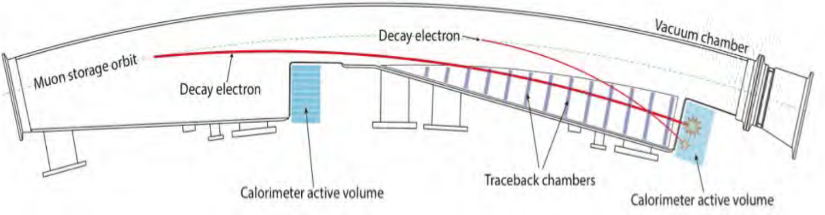
This is achieved by measuring the modulation of the rate of positrons produced by muon decays and the magnetic field inside the ring.





Calorimeters and laser calibration system

The positrons are detected by 24 calorimeter stations located along the storage ring.



Laser calibration system is used to:

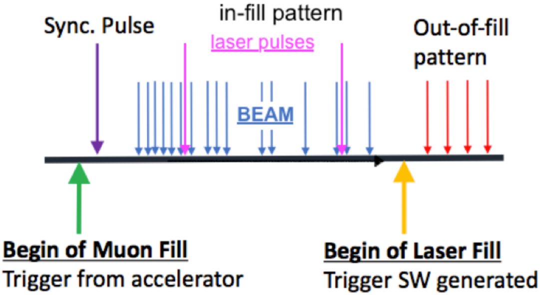
- monitor the gain fluctuations
- ensure performance stability of the detectors throughout long data taking periods
- synchronize different detectors
- emulate the time distribution of the signals coming from muon decays

Laser calibration pulses are generated by 6 identical lasers, each one serving 4 calorimeters.

Laser operation modes: Standard

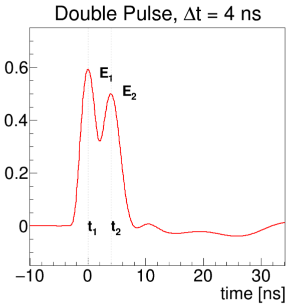
Laser calibration system can be used in:

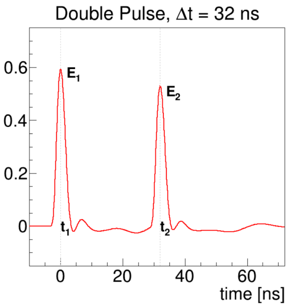
- ***Standard operation mode***: a regular pattern of laser pulses which are then used offline to calibrate the calorimeters.



Laser operation modes: Double-pulse

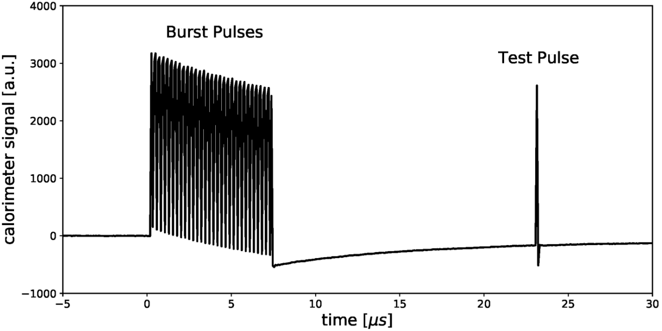
- **Double-pulse mode**: two consecutive laser pulses are sent to all crystals with a delay that can vary from 1 ns to several hundreds of μs.
  Goal: testing the calorimeter response to two or more consecutive particles and checking periodically the gain function for each of the 1296 crystals during data taking.
  → ***Short Term Double Pulse***: second pulse delayed by 0÷80 ns with respect to the first





Laser operation modes: Double-pulse

→ ***Long Time Double Pulse***: burst of pulses and test pulse with a delay in the 10÷20 μs range



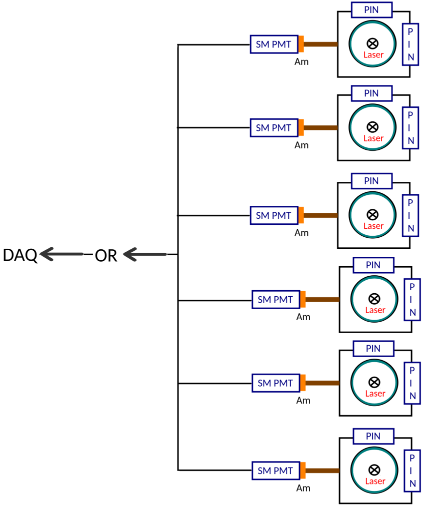
Asynchronous trigger

The Source Monitors purpose is to monitor the laser intensity event-by-event.

Each SM consists of:

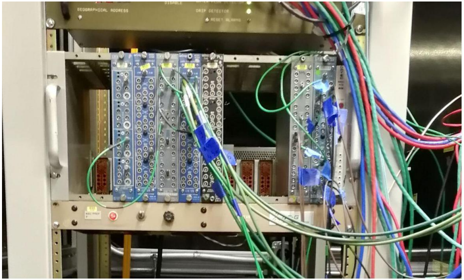
- two PIN diodes, used to monitor the intensity of laser pulses (fast monitoring);
- one PMT to monitor PINs. Since the PMT response is not constant with HV and temperature variations, an Americium source is used as an absolute monitor (slow absolute monitoring).

Since Americium signals are asynchronous with respect to the fill, a dedicated trigger is needed.

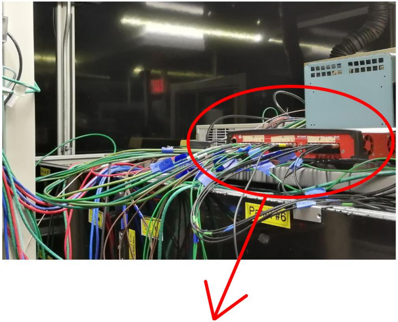


Reorganization of the trigger logic

Task: replacing the NIM logic of both the Americium and double pulse triggers with FPGA.



→



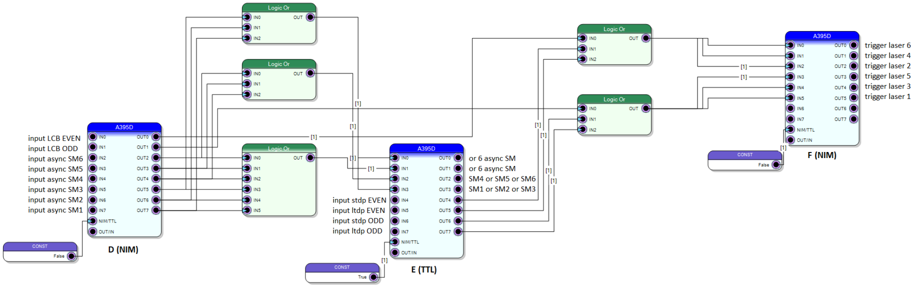
CAEN DT5495

Installation of softwares:

- Microsoft .NET Framework
- Sci-Compiler
- Quartus Prime: necessary to compile the .vhdl file generated with Sci-Compiler
- CAENUpgrader: necessary to upgrade the FPGA firmware with the .rpd file generated with Sci-Compiler

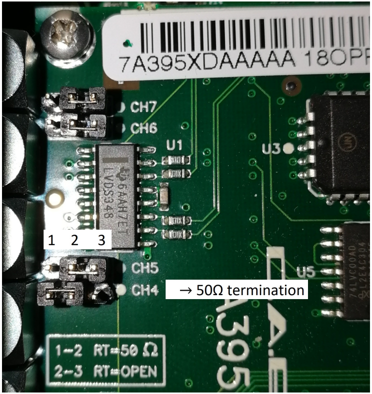
Sci-Compiler was used to program the DT5495.

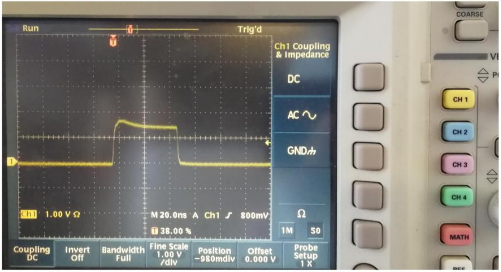
The input signals are from the PMTs of the SMs, the LCB and the DG.
The output signals are the triggers for the six lasers and a Logic OR to acquire the signals from SMs.



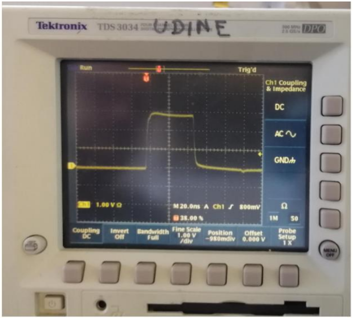
What was done next:

- Test of the output signals amplitude and check the triggers signals with the oscilloscope.
- A change in the position of the inside jumpers of the FPGA was made: there was no documentation about the fact that impedences were not terminated at 50Ω.





before ~1.8 V



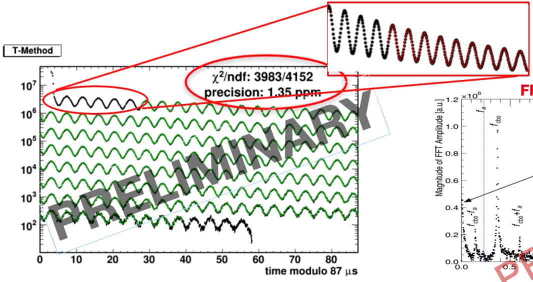
after ~3 V

Lost Muons

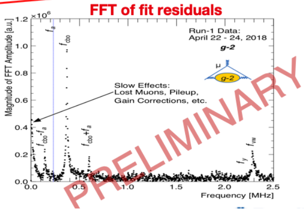
Some of the muons are lost mainly because they hit the collimators or other materials after injection, curving inward and eventually being lost from the ring.

Lost muons can produce a systematic effect in the measurement of ω_a.

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



~1.8 GeV energy cut on decay e⁺ events to see a wiggle plot



Lost muons have to be measured and taken into account in the final ω_a fit (3).
This correction can be parametrized with the multiplicative factor $\Lambda(t)$:

$$\Lambda(t) = 1 - K_{LM} \int_0^t L(t')\, e^{t'/\tau}\, dt' \tag{2}$$

$$N(t) = N_0 e^{-t/\tau}\left[1 - A\cos(\omega t + \varphi)\right] \longrightarrow N(t) = N_0 e^{-t/\tau}\Lambda(t)\left[1 - A\cos(\omega t + \varphi)\right] \tag{3}$$

The goal of lost muons analysis is the determination of the lost muon spectrum $L(t)$ and of its exponentially weighted integral:

$$J(t) = \int_0^t L(t')\, e^{t'/\tau}\, dt' \tag{4}$$

Lost muons have to be measured and taken into account in the final ω_a fit (3).
This correction can be parametrized with the multiplicative factor $\Lambda(t)$:

$$\Lambda(t) = 1 - K_{LM} \int_0^t L(t')\, e^{t'/\tau}\, dt' \tag{2}$$

$$N(t) = N_0 e^{-t/\tau} \left[1 - A\cos(\omega t + \varphi)\right] \longrightarrow N(t) = N_0 e^{-t/\tau} \Lambda(t) \left[1 - A\cos(\omega t + \varphi)\right] \tag{3}$$

The goal of lost muons analysis is the determination of the lost muon spectrum $L(t)$ and of its exponentially weighted integral:

$$J(t) = \int_0^t L(t')\, e^{t'/\tau}\, dt' \tag{4}$$

Lost muons have to be measured and taken into account in the final ω_a fit (3).
This correction can be parametrized with the multiplicative factor $\Lambda(t)$:

$$\Lambda(t) = 1 - K_{LM} \int_0^t L(t')\, e^{t'/\tau}\, dt' \tag{2}$$

$$N(t) = N_0 e^{-t/\tau}\,[1 - A\cos(\omega t + \varphi)] \longrightarrow N(t) = N_0 e^{-t/\tau} \Lambda(t)\,[1 - A\cos(\omega t + \varphi)] \tag{3}$$

The goal of lost muons analysis is the determination of the lost muon spectrum $L(t)$ and of its exponentially weighted integral:

$$J(t) = \int_0^t L(t')\, e^{t'/\tau}\, dt' \tag{4}$$

Lost muons preselection

Muons exiting the orbit curl inside the ring and can cross two or more calorimeters without stopping or losing a significant fraction of their energy: to identify lost muons, multiple coincidences between adjacent calorimeters can be used.

Data from the *60h Dataset* have been analyzed.

Name	Date acquired	Quad n	Kicker [kV]	Positrons
60 hour	22-25 / 4	0.108	128-132	1.0B
High Kick	26/4 - 2/5	0.120	136-138	1.2B
9 day	4-12 / 5	0.120	128-132	2.4B
Low Kick	17-19 / 5	0.120	123-127	1.2B
Superlow Kick	2-6 / 6	0.108	117-119	0.5B
End Game	6-29 / 6	0.108	122-127	4.0B

To start, this set of loose cuts has been applied:

- Number of cluster hits: $nHits = 1$ (Isolation cut)
- Cluster time difference: 4.2 ns $< \Delta t <$ 8.2 ns (Expected value: $\Delta t \simeq 6.2$ ns)
- Cluster energy: $E < 300$ MeV (Expected value: $E \simeq 170$ MeV)

An exclusive definition of coincidence has been used.

Lost muons preselection

Muons exiting the orbit curl inside the ring and can cross two or more calorimeters without stopping or losing a significant fraction of their energy: to identify lost muons, multiple coincidences between adjacent calorimeters can be used.

Data from the *60h Dataset* have been analyzed.

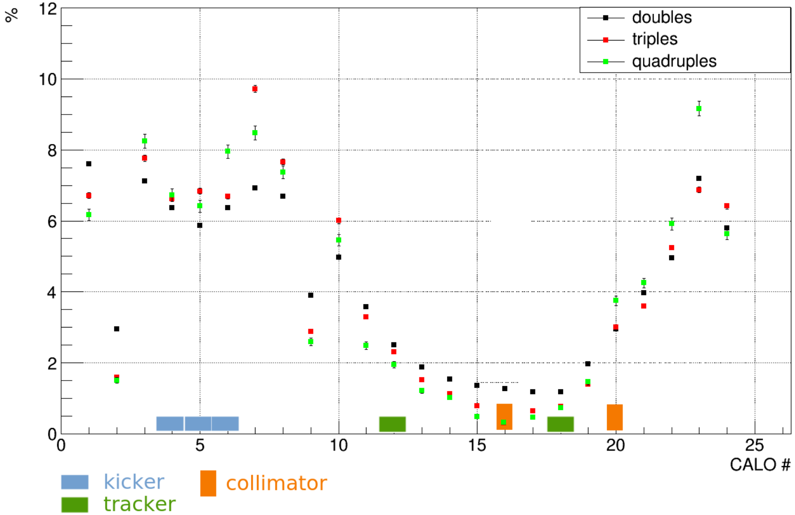
Name	Date acquired	Quad n	Kicker [kV]	Positrons
60 hour	22-25 / 4	0.108	128-132	1.0B
High Kick	26/4 - 2/5	0.120	136-138	1.2B
9 day	4-12 / 5	0.120	128-132	2.4B
Low Kick	17-19 / 5	0.120	123-127	1.2B
Superlow Kick	2-6 / 6	0.108	117-119	0.5B
End Game	6-29 / 6	0.108	122-127	4.0B

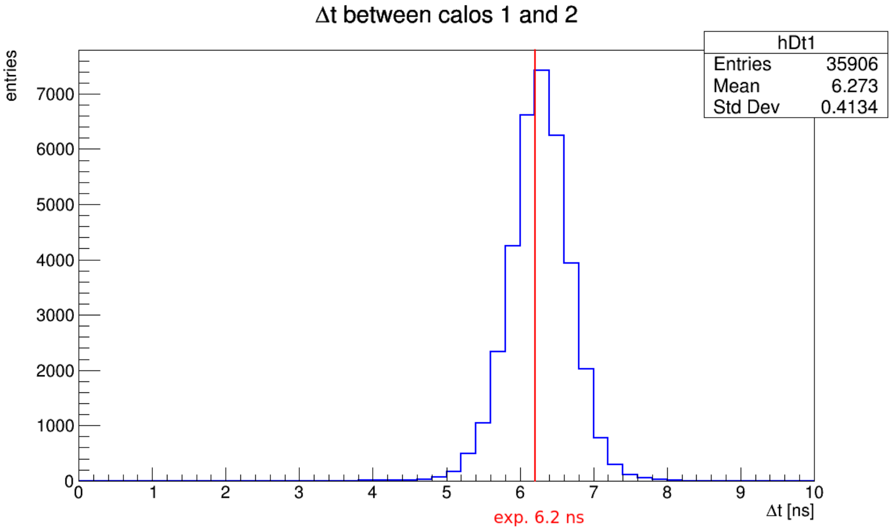
To start, this set of loose cuts has been applied:

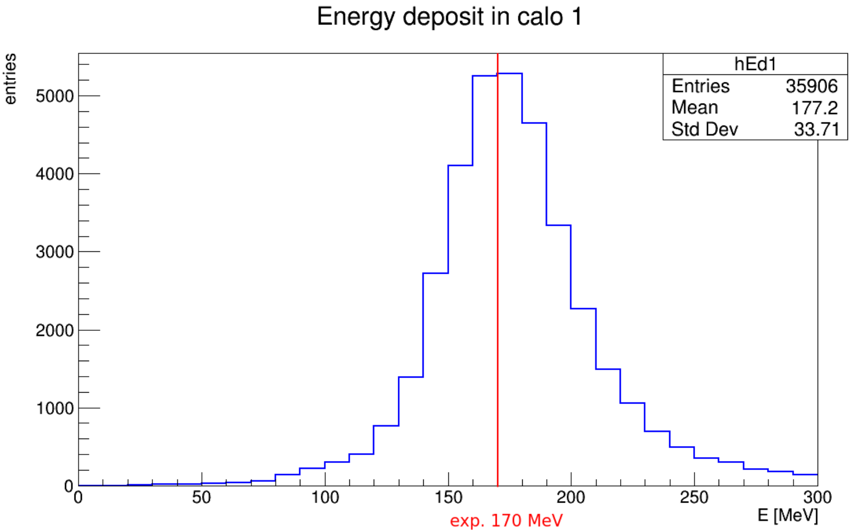
- Number of cluster hits: $nHits = 1$ (Isolation cut)
- Cluster time difference: 4.2 ns $< \Delta t < 8.2$ ns (Expected value: $\Delta t \simeq 6.2$ ns)
- Cluster energy: $E < 300$ MeV (Expected value: $E \simeq 170$ MeV)

An exclusive definition of coincidence has been used.

Distribution of coincidences along the ring



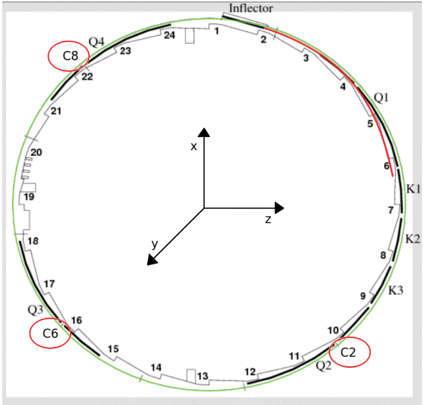

Δt between calos 1 and 2
hDt1
Entries 35906
Mean 6.273
Std Dev 0.4134
entries
7000
6000
5000
4000
3000
2000
1000
0
0 1 2 3 4 5 6 7 8 9 10
Δt [ns]
exp. 6.2 ns


Energy deposit in calo 1
entries
E [MeV]
exp. 170 MeV
hEd1
Entries 35906
Mean 177.2
Std Dev 33.71
0
1000
2000
3000
4000
5000
0
50
100
150
200
250
300

MonteCarlo simulations analyses

Aim

See the behaviour of a muon that hits a collimator and so it is lost from the storage region.



The muon is "lost" as soon as it exits from the storage region.

$$r_{Magic} = 7112 \text{ mm (corresponding to } p_{Magic} = 3.094 \text{ GeV}/c)$$

$$r_{storage} = 45 \text{ mm (radius of the storage region)}$$

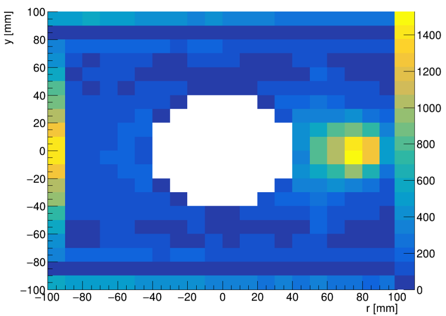
Defining

$$R = \sqrt{x^2 + z^2} - r_{Magic}$$

a muon is lost if:

$$\sqrt{R^2 + y^2} > r_{storage}$$

y vs r of lost muon birth



In particular we are interested in:

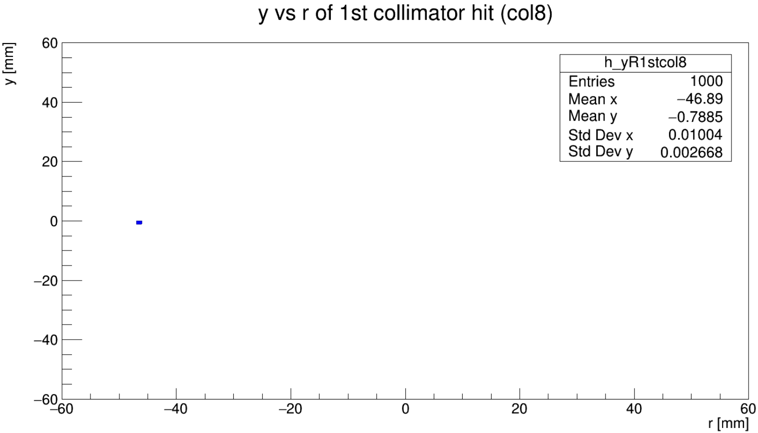
- the momentum of the muons that hit a collimator;
- where a collimator is hit;
- if the lost muon hits a calorimeter and how much energy it deposits in it.

and also:

- when we analyze real data, how can we improve the recognition of lost muons?

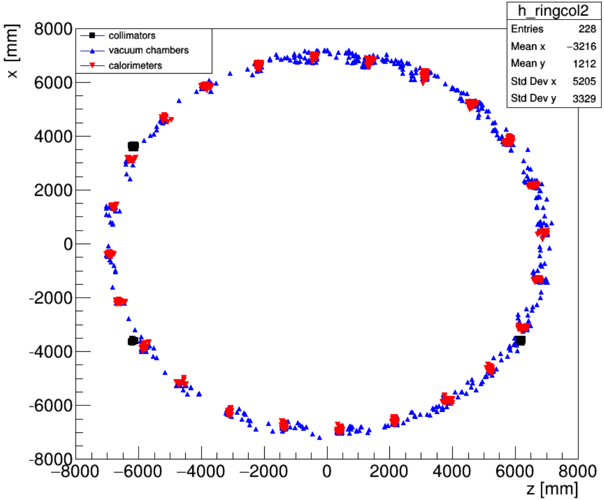
An *ad hoc* simulation was first used:
a single muon beam is simulated and sent on purpose on a collimator.

$\rightarrow$ generation of 1000 events

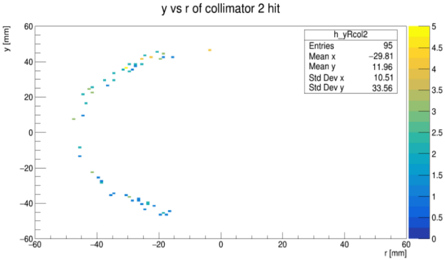


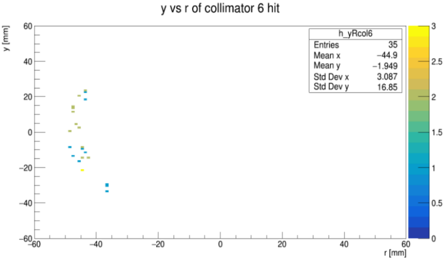
beam_gun_with_collimator MC

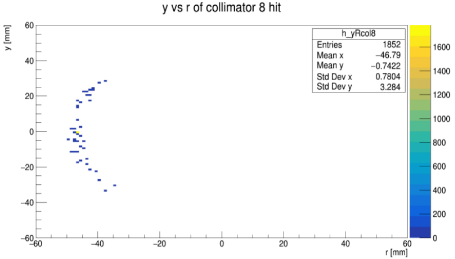
After the muon hits a collimator it can either decay or it can continue its path hitting other material.



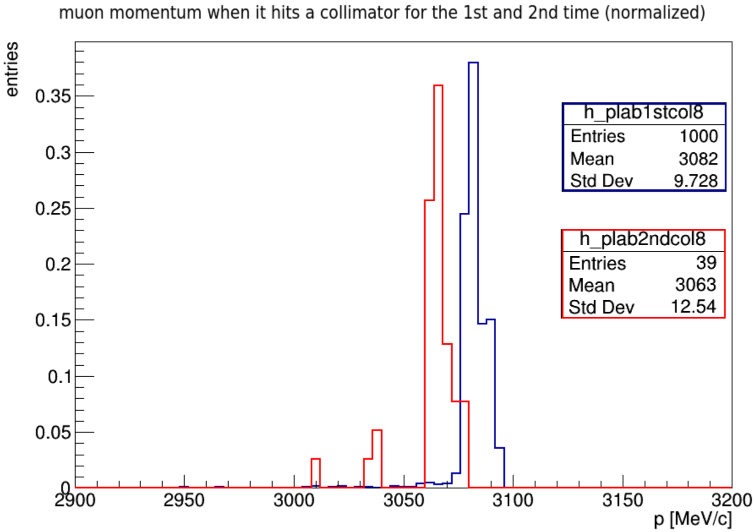
Collimators can be hit more than one time before the muon exits from the storage ring.





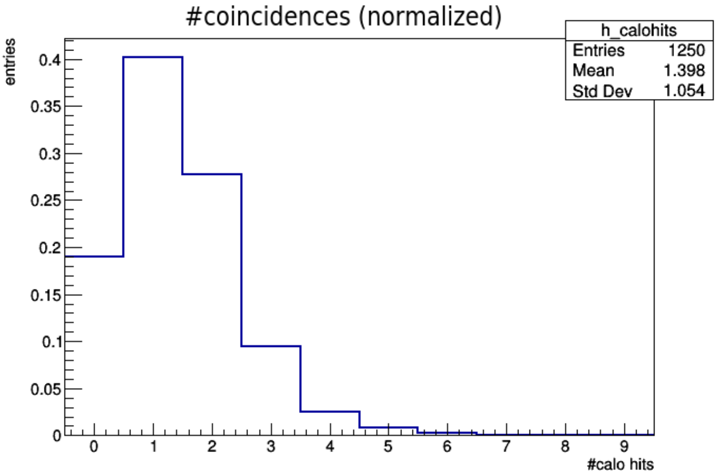


beam_gun_with_collimator MC



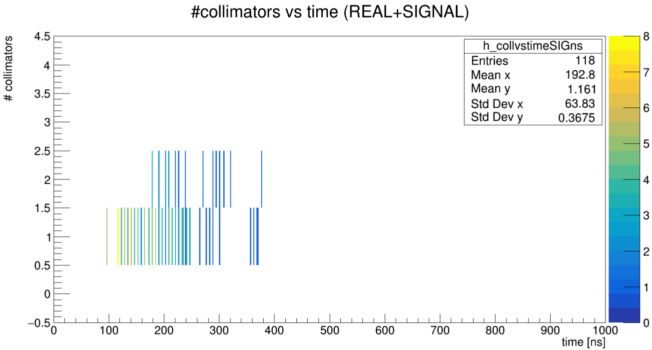
In both cases, the muon loses $\sim 1\%$ of its momentum.

After muons exit from the storage region they will act as MIPs and they can hit more than one calorimeter.



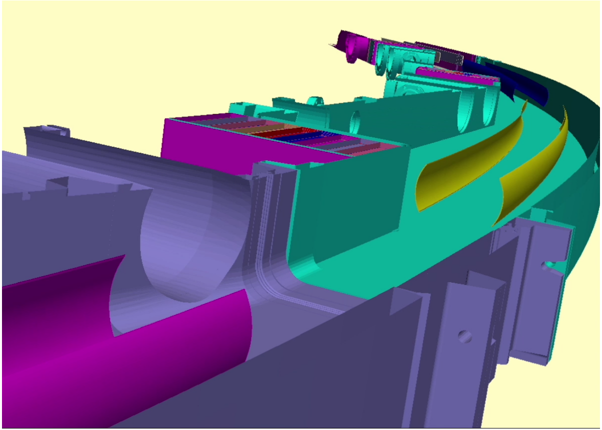
REAL+SIG data

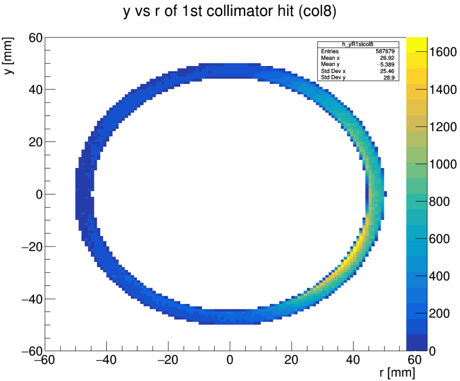
One way of selecting lost muons using real data was to looking at special triples coincidences:
we define REAL+SIG muons in MC simulations as those muons that hit three adjacent calorimeters in a row.
Just as a first example, we can see how many collimators the REAL+SIG muons hit before making a triple coincidence, and also many other informations with more statistics.

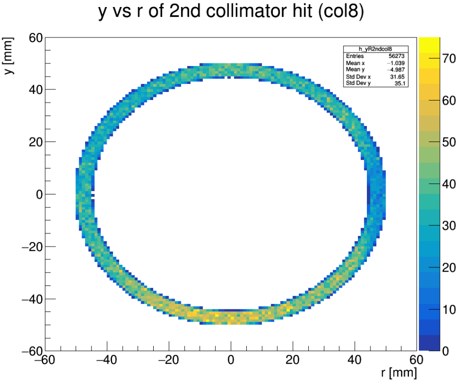


Run1 simulation

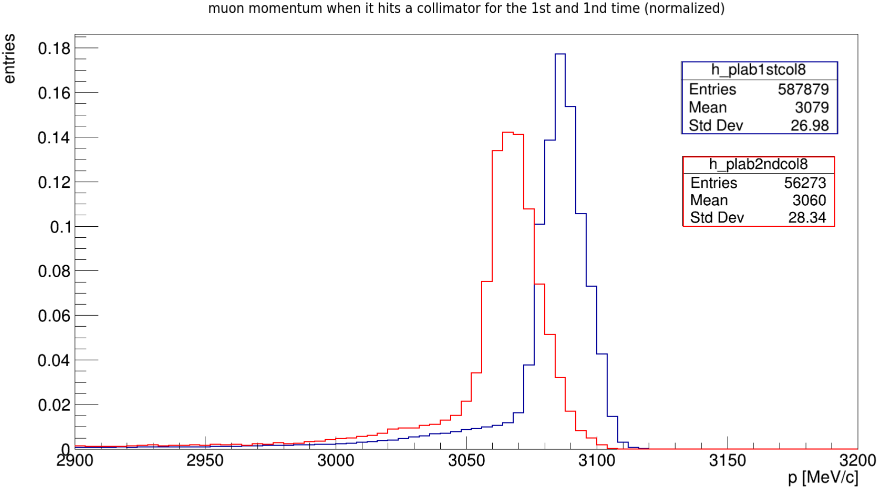
The same code used for the *beam_gun_with_collimator* is used with the MonteCarlo simulation of the *Run1* that simulates typical events we would see in real data.





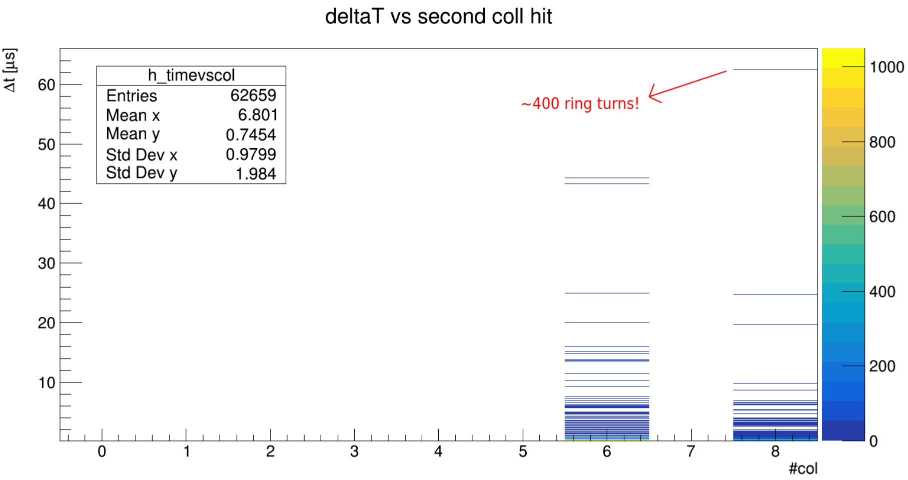


The second time a muon hits a collimator it does it more uniformly.

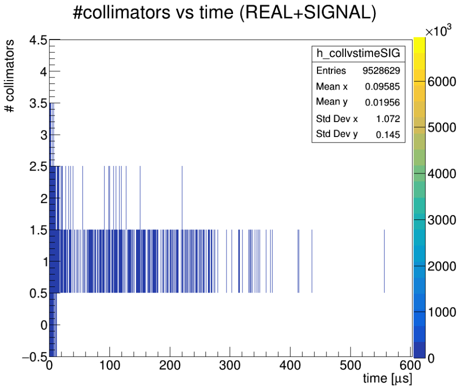


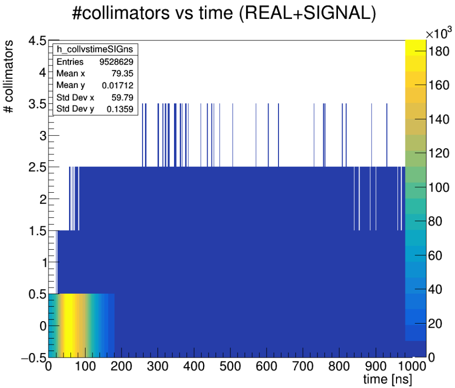
Low energy tail → future study!

When a muon hits two collimators, how much time passes between the two hits?



How many collimators a muon hits before it makes a triple coincidence?

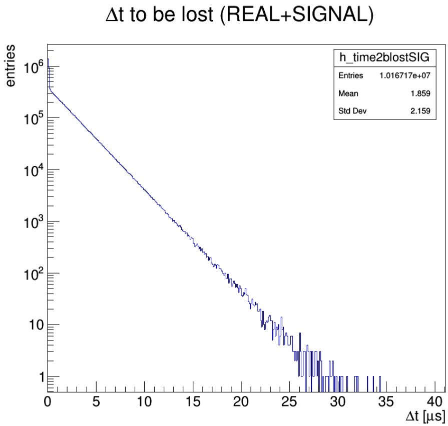


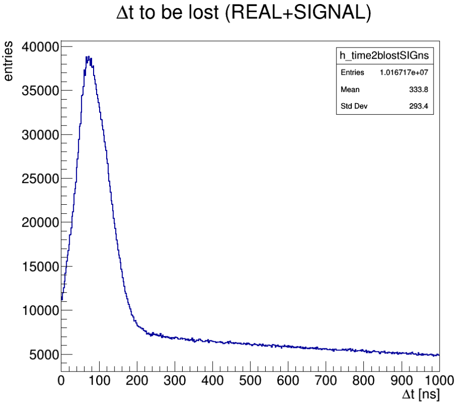


We need more statistics to study lost muons with time $\gtrsim \mu$s.

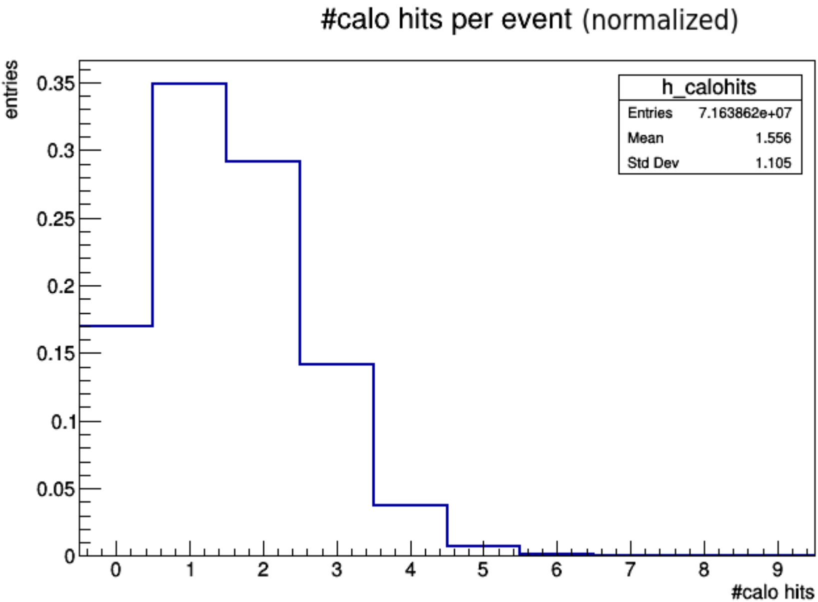
After how long a muon that hit a collimator makes a triple calorimeter coincidence?

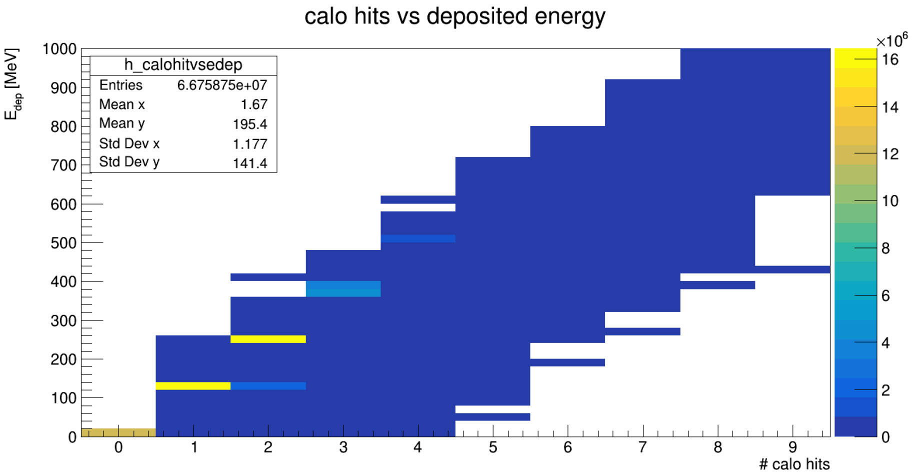
Δt = time a first calorimeter of a triple coincidence is hit - time the muon hits a collimator for the first time





Run1 MC


#calo hits per event (normalized)
h_calohits
Entries 7.163862e+07
Mean 1.556
Std Dev 1.105
entries
#calo hits
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0
1
2
3
4
5
6
7
8
9


calo hits vs deposited energy
h_calohitvsedep
Entries 6.675875e+07
Mean x 1.67
Mean y 195.4
Std Dev x 1.177
Std Dev y 141.4
E_dep [MeV]
calo hits
×10^6

Conclusions

- Hardware activity: programmation of an FPGA that is already in function.
- Data Analysis: implementation of a code that preselects lost muons (triples and quadruples coincidences) in real data, and energy and time analysis of the events.
- Studied with MC simulations: behaviour of a muon that hits a collimator and then spirals into a calorimeter (energy deposition in the collimators and calorimeters, time difference distribution between the collimator and the calorimeter, ...)
  - using a specific "collimator" MC simulation
  - using the official g-2 Run1 MC simulation
- Future: more accurate comparison between data and MC.

References:

- Anastasi et al., *The laser calibration system of the Muon g-2 experiment at Fermilab*
- Chris C. Polly, *A measurement of the anomalous magnetic moment of the negative muon to 0.7 ppm*
- S. Di Falco, A. Driutti, A. Gioiosa, M. Sorbara, *Lost Muons Correction*
- S. Ganguly, *Muon g-2: Measuring the Muon Magnetic Anomaly to High Precision*, 52nd Annual Fermilab Users Meeting

Backup: Experimental Technique

Inside the ring the muons are subject to both the spin precession frequency ω_s and the cyclotron frequency ω_c: the difference between them is called anomalous precession frequency ω_a.
These approximations are used:

- the muon velocity is perpendicular to the magnetic field $(\vec{\beta} \cdot \vec{B} = 0)$
- the magnetic field is perfectly uniform
- betatron oscillations of the beam are neglected

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\frac{e}{m_\mu}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right] \tag{5}$$

The muon beam enters the storage ring with a forward momentum of $\simeq 3.094$ GeV/c ($\gamma \simeq 29.4$), hence $a_\mu - 1/(\gamma^2 - 1) \simeq 0$ and Eq. 5 simplifies to:

$$\omega_a = -\frac{e}{m_\mu} a_\mu B \tag{6}$$

Backup: Incorporating muon losses into the fitting function (1/2)

$k_{LM}L(t)$: number of lost muons at a time t.
Adding the additional loss mechanism to the original differential equation of the exponential decay of muons:

$$\frac{dN_\mu}{dt} = -\left(\frac{N_\mu}{\tau} + k_{LM}L(t)\right) \tag{7}$$

We can recognize this equation as a simple first-order linear differential equation of the form:

$$\frac{dN_\mu}{dt} + P(t) \cdot N_\mu(t) = Q(t) \tag{8}$$

which has a solution:

$$N_\mu(t) = e^{-\int P(t')dt'} \cdot \int Q(t')e^{-\int P(t')dt'}dt' + ae^{-\int P(t')dt'} \tag{9}$$

where: $P(t) = 1/\tau$, $Q(t) = -k_{LM}L(t)$

Backup: Incorporating muon losses into the fitting function (2/2)

Making the substitutions, integrating from t_0 to t and applying the boundary condition that $N_{\mu 0}$ muons are stored at time t_0 (i.e. $a = N_{\mu 0}$):

$$N_\mu(t) = N_{\mu 0} e^{-(t'-t_0)/\tau}\left[1 - \frac{k_{LM}}{N_{\mu 0}}\int_{t_0}^{t} L(t')e^{(t'-t_0)/\tau}dt'\right] \quad (10)$$

The number of decay electrons becomes:

$$N(t) = A_e N_{\mu 0} e^{-(t'-t_0)/\tau}\left[1 - \frac{k_{LM}}{N_{\mu 0}}\int_{t_0}^{t} L(t')e^{(t'-t_0)/\tau}dt'\right][1 - A\cos(\omega t + \varphi)] \quad (11)$$

where A_e is the overall geometrical acceptance of the calorimeters.
We choose $t_0 = 0$. Defining $K_{LM} = k_{LM}/N_{\mu 0}$, and noticing that the number of decay electrons at the beginning is $N_0 = A_e N_{\mu 0}$ we have:

$$N(t) = N_0\,\Lambda(t)\,e^{-t/\tau}\,[1 - A\cos(\omega t + \varphi)] \quad (12)$$

where:

$$\Lambda(t) = 1 - K_{LM}\int_0^t L(t')\,e^{t'/\tau}dt' \quad (13)$$