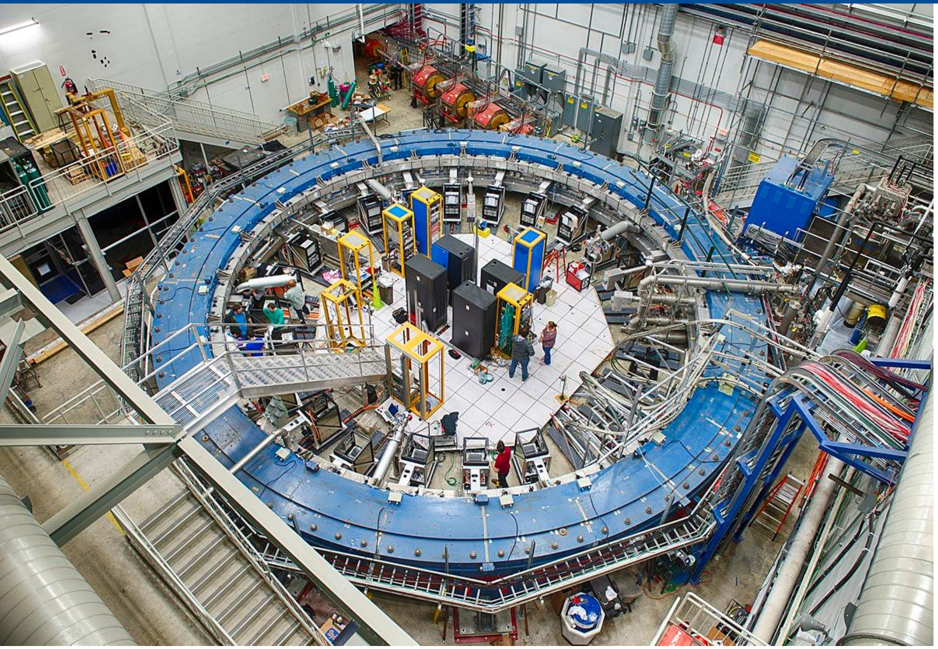

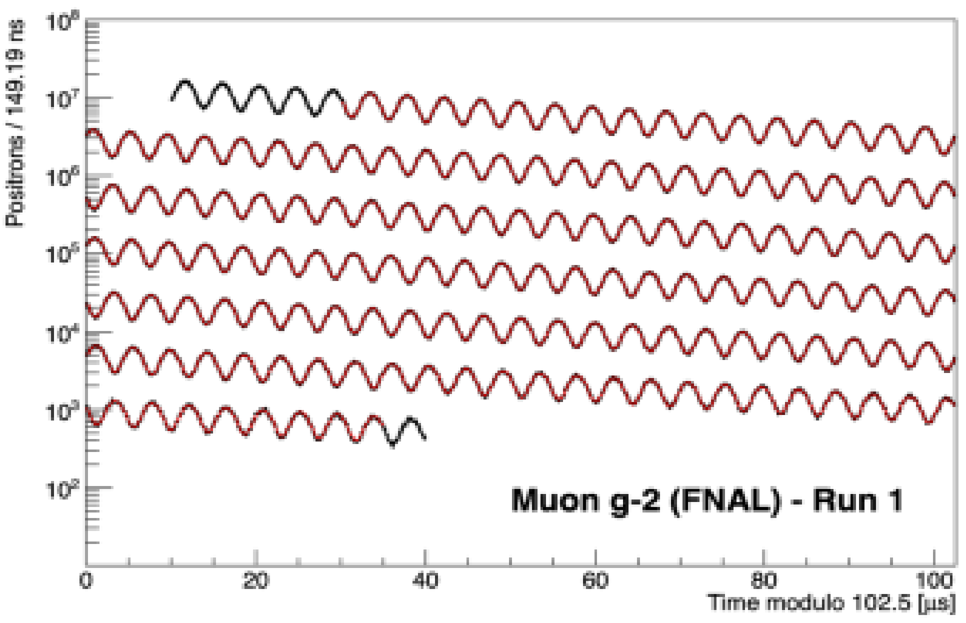

Analysis of the muon’s spin anomalous precession frequency

Midterm Report

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29/08/2022

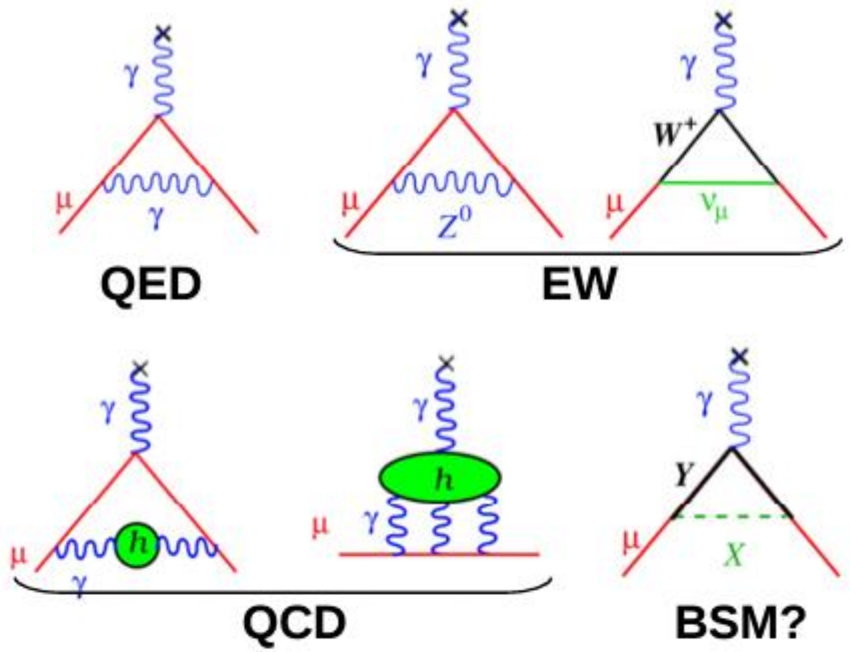
The muon magnetic moment

The muon's magnetic moment is given by $\vec{\mu} = g\frac{q}{2m}\vec{S}$

The g-factor of an elementary particle is predicted to be 2 at the first order. Higher order corrections shift this value by $\sim 10^{-3}$.

We define the muon anomaly as:

$$a_\mu = \frac{g-2}{2}$$



All particles interacting with the muon (high order loops) contribute to a_μ, even the ones we haven't discovered yet! This makes any discrepancy between the theoretical and experimental value of a_μ hint of new physics.

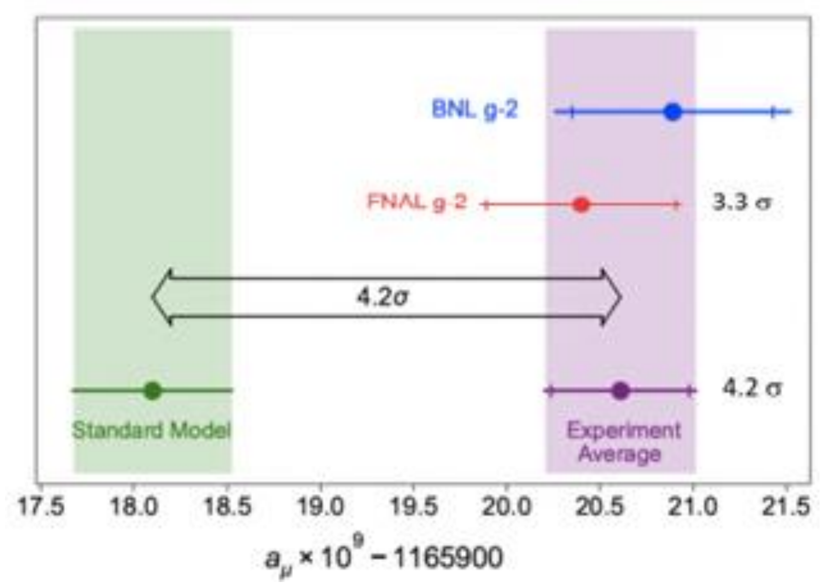
Muon precession

A magnetic field induces a precession motion of the particle's spin.

The precession frequency is given by:

$$\vec{\omega}_a = a_\mu \frac{e\vec{B}}{m}$$

The Muon g-2 collaboration aims to measure a_μ with a 140 ppb uncertainty, by measuring with high precision both the spin precession frequency and the magnetic filed.



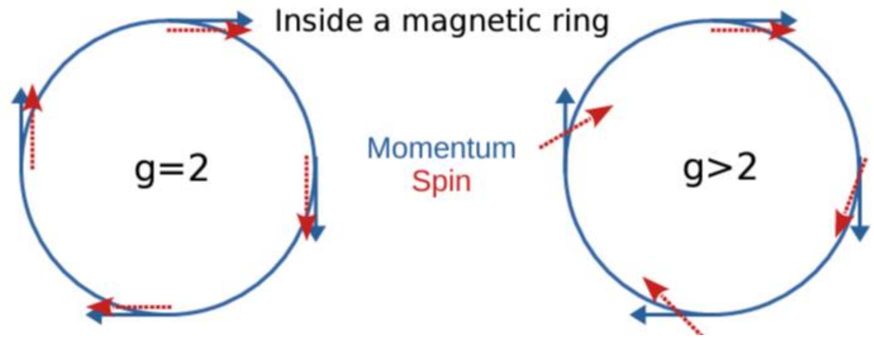
Note: the experiment uses electric fields to focus the muon beam, this makes the relation between $\vec{\omega}_a$ and a_μ more complicated. For muons with momentum ~3.1 GeV, this effect is cancelled!

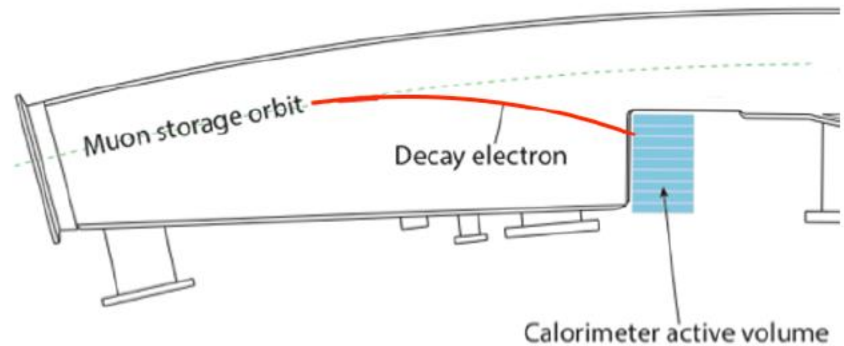
Measuring precession frequency

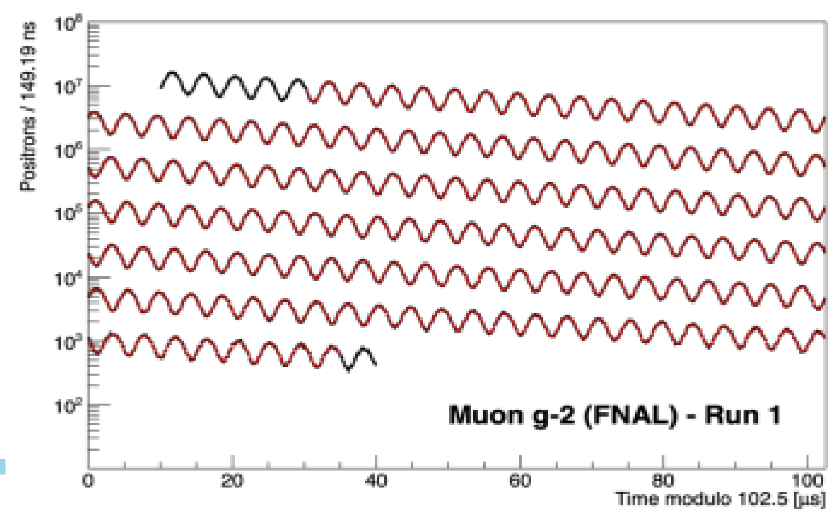
To measure the spin precession a beam of polarized muons is injected into a superconducting storage ring, where muons circulate for roughly 750 μs.

The spin rotates around the magnetic field direction.

Muons decay into positrons. High energy positrons have higher probability to be emitted in the muon spin direction: we detect more positrons when the spin faces towards the calorimeters and less when it faces away. The frequency of this oscillation is the signal we want to measure: $\vec{\omega}_a$



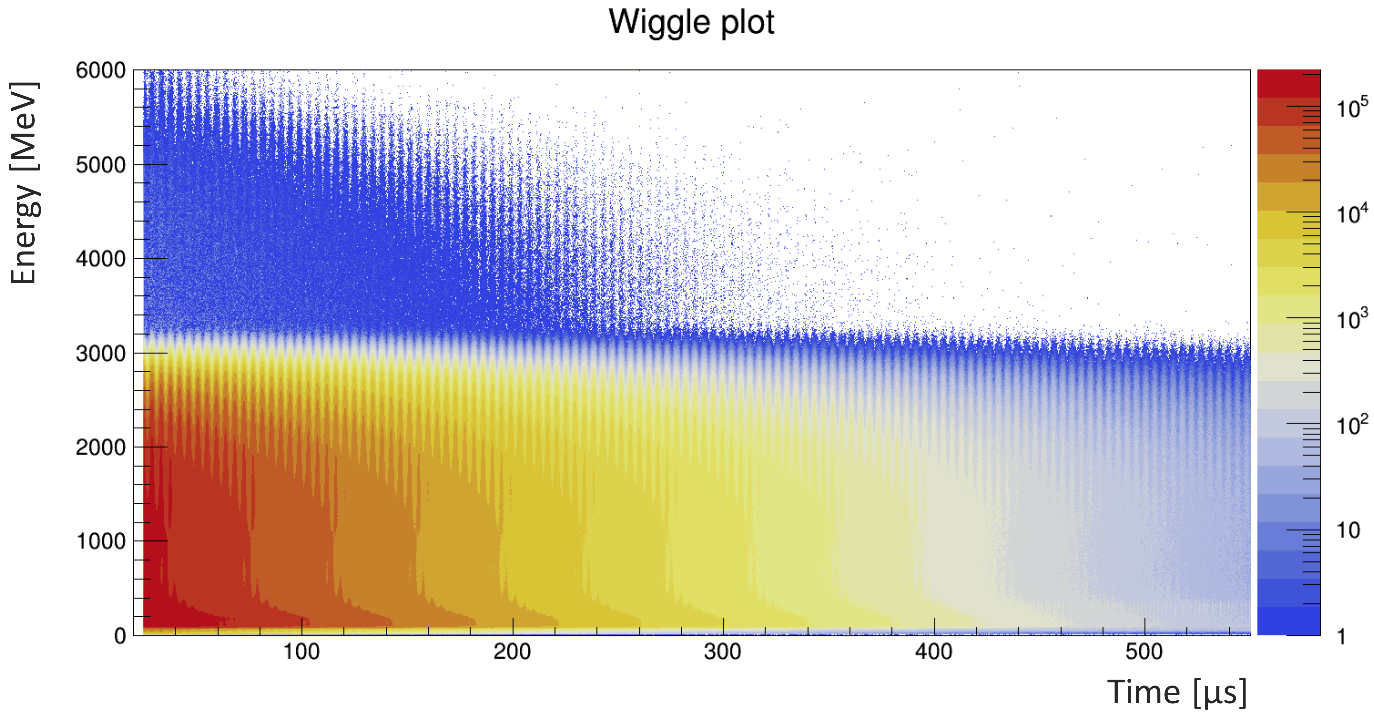




Positrons distribution

In the past weeks I have analyzed data from Run-2 acquisition period (2019). This plot shows the positron time of arrival (X axis) and its energy (Y axis) as measured by the calorimeters.

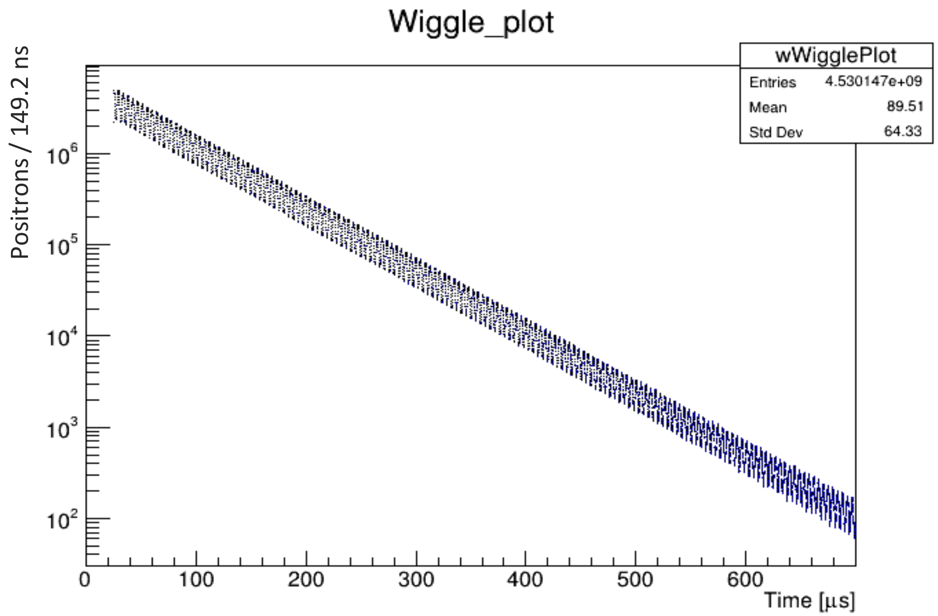
Events above 3100 MeV are due to pile-up.



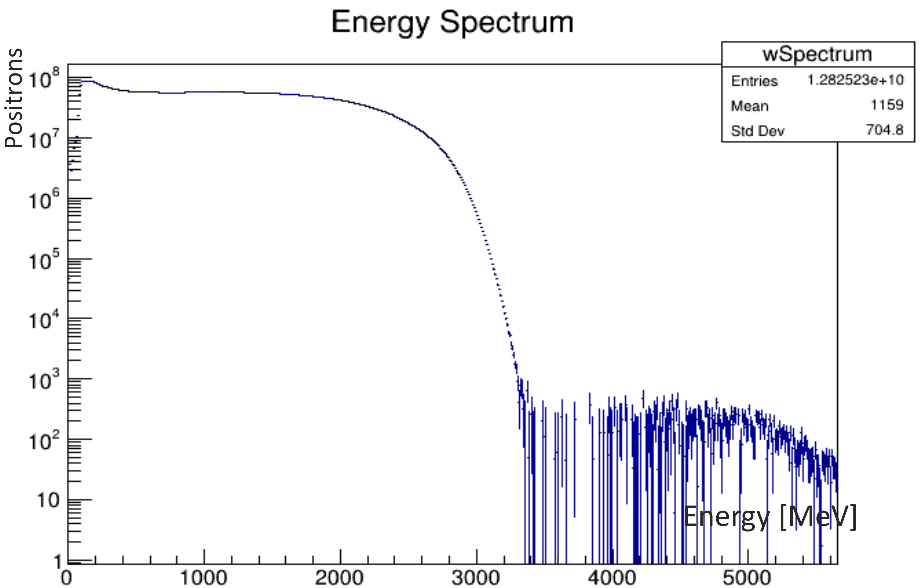
Fermilab

Wiggle Plot and Energy Spectrum

Projecting on the Y axis we get the 1-D Wiggle Plot (this figure is obtained integrating events from 1700 MeV)



Projecting on the X axis (i.e. integrating from 30 μs to 650 μs) we get the energy spectrum.



5 parameters fit function

The simplest equation that describes the number of positrons detected by the calorimeters is the following:

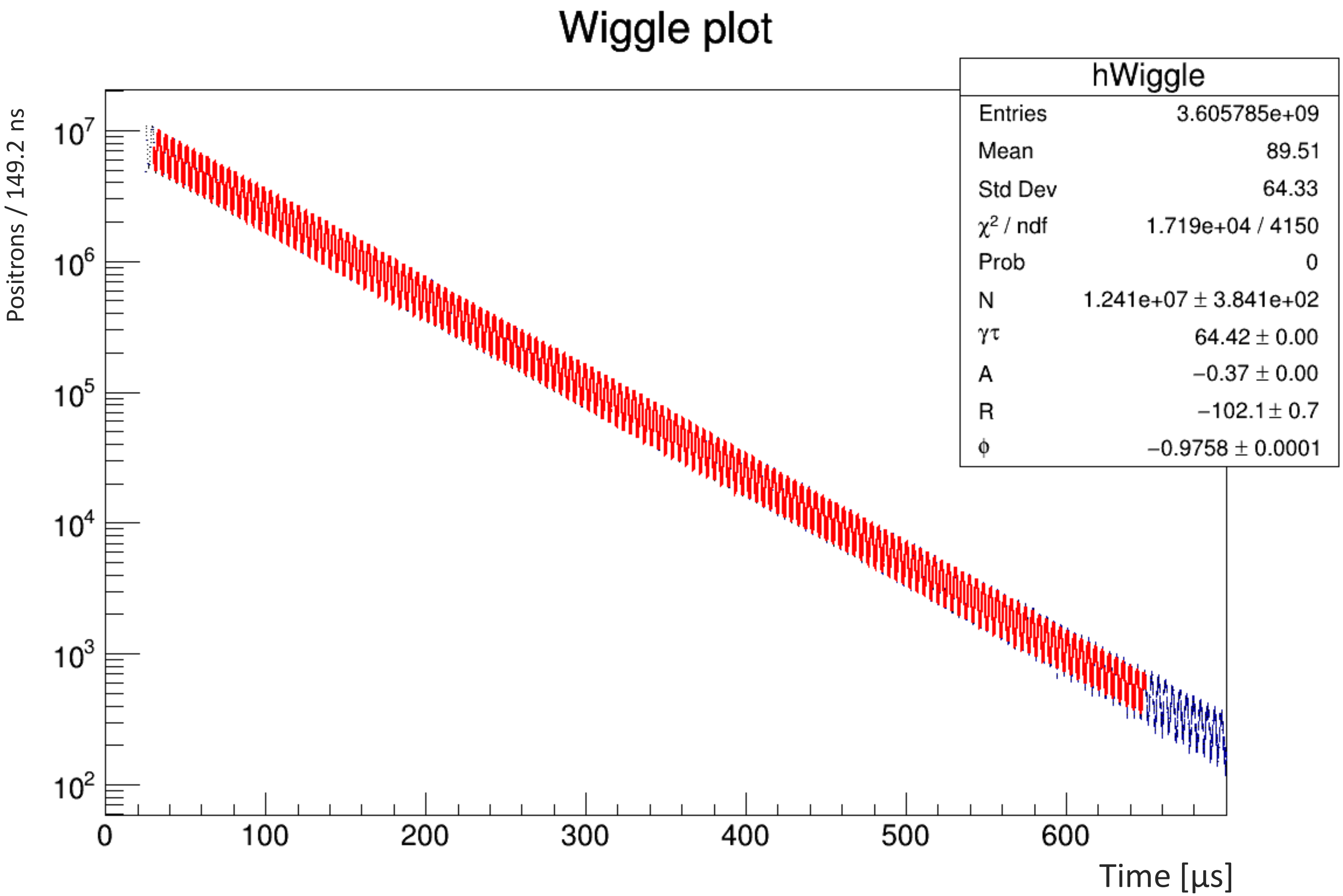
$$\mathrm{N(t)} = \mathrm{N}_0 e^{-\frac{t}{\gamma\tau}} (1 + A\cos(\omega_a t + \phi))$$

Where:

- N_0 is the number of muons at t=0
- $\gamma\tau$ is the muon lifetime in the lab frame of reference
- A is the asymmetry, related to the probability that a positron is emitted in the same direction of the spin
- ω_a is the precession frequency we want to measure
- φ is the phase at t=0

To avoid cognitive bias, ω_a is blinded by a dimensionless parameter R, defined as the unknown offset in ppm from a reference value.

5 parameter fit results



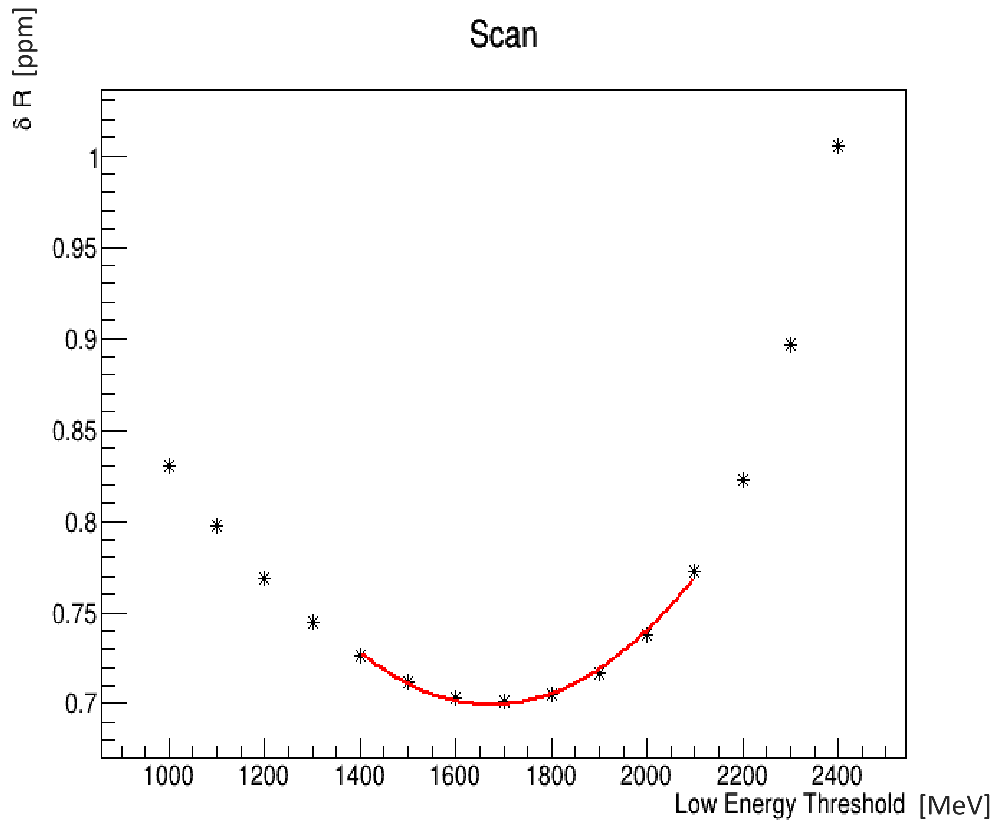
T-Method

The T-Method consist in building the wiggle plot summing all positrons above an energy threshold:

- At high energy positrons have higher asymmetry, which is better for the fit, but there’s low statistics
- At low energy positrons have lower asymmetry, but there is more statistics
- It’s necessary to find a compromise between the two cases: we have to determine the ideal energy threshold that minimizes the error on R
- We build different wiggle plots by changing the lower energy threshold
- We fit every one of them and the figure of merit will be the smallest uncertainty on R

T-Method

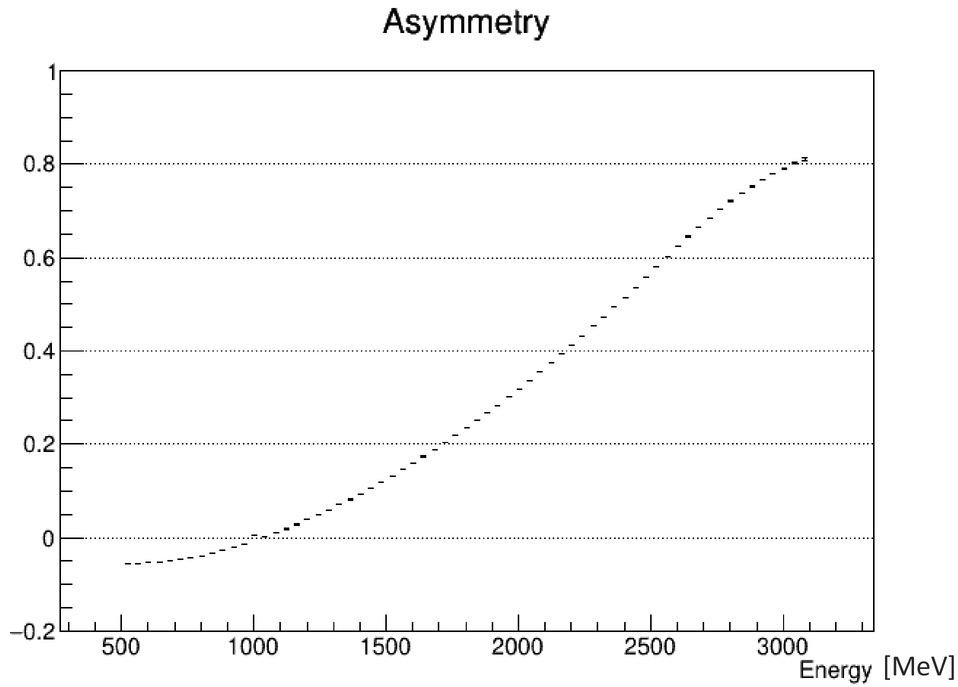
- The plot shows the fit uncertainty on the R parameter as a function of the energy threshold
- The distribution is fitted with a quadratic function and shows a minimum at the optimal point
- The minimum found for this dataset is at 1673 MeV



A-Method

The wiggle plot can be also built by weighting the positrons with their asymmetry (function of the energy). High energy positrons weight more, increasing the sensitivity to the precession frequency signal. This also allows to lower the energy threshold, hence the statistics increases.

- To obtain the asymmetry the region from 500 MeV to 3100 MeV is sliced into bins of 40 MeV
- From each slice a wiggle plot is produced
- Each wiggle plot is fitted to extract the asymmetry
- The fit is less precise near 1000 MeV because A is zero in that region.

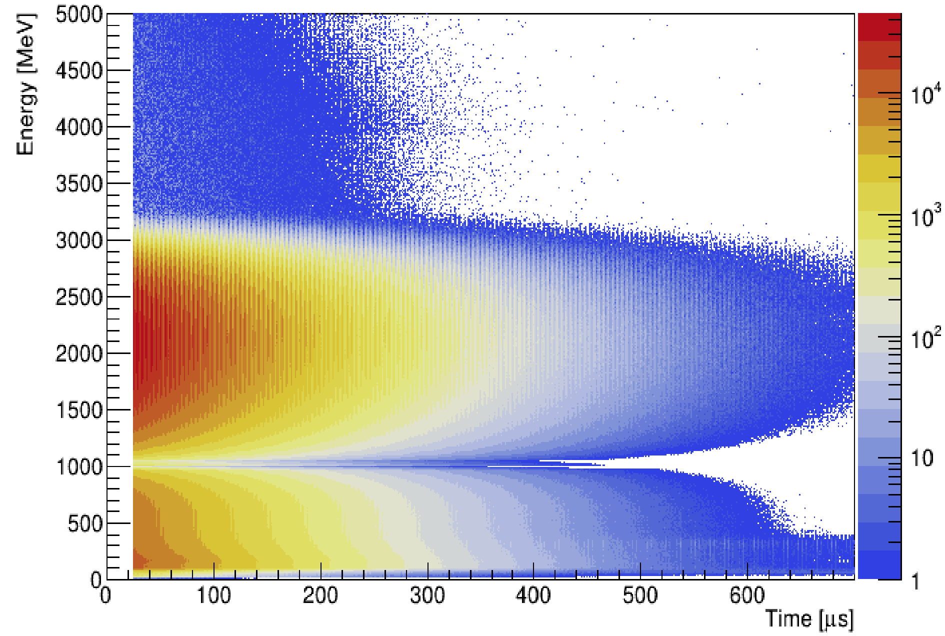


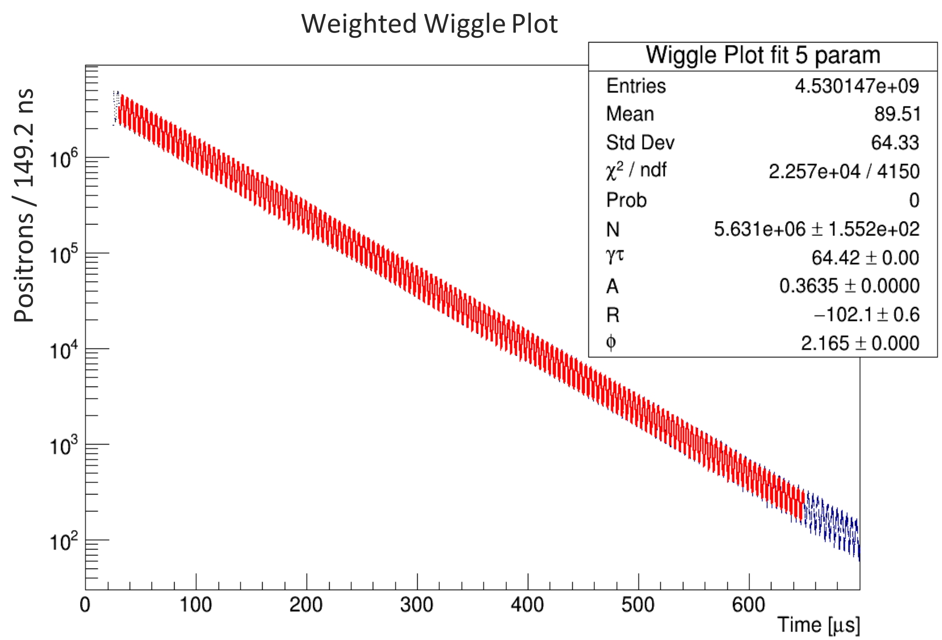
Weighted Wiggle Plot

Positron distribution where each entry has been multiplied by its asymmetry.

Note: the asymmetry below 1000 MeV is negative, here the absolute value is plotted for better visualization.

The wiggle plot is built integrating from 1100 MeV to 3000 MeV. The number of entries increased from 3.6×10^9 to 4.5×10^9





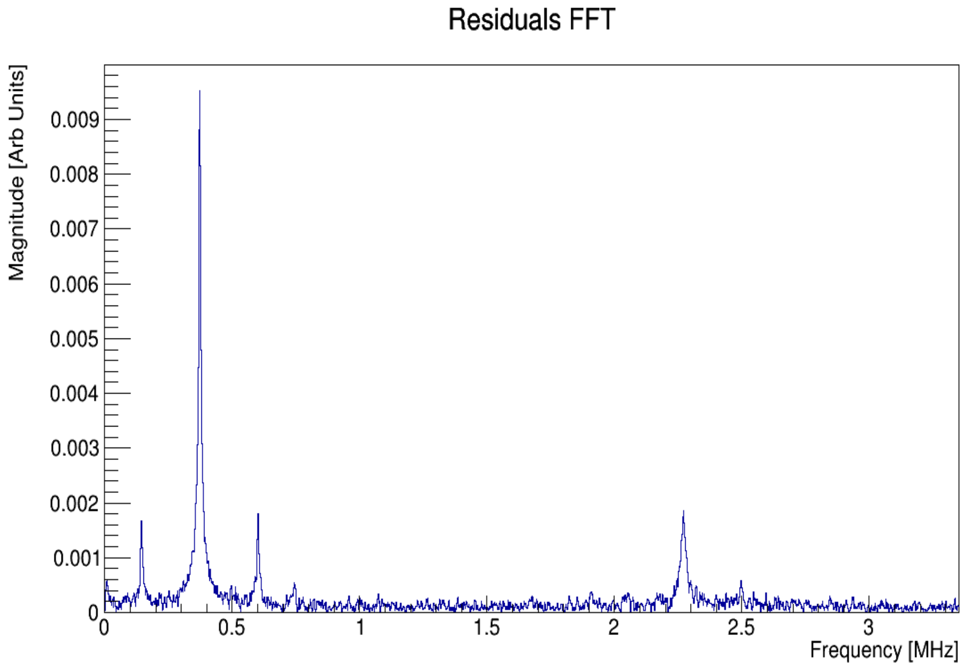
Beam motion effects

In this experiment, effects of beam dynamics have direct impact on the result. The most important one is the effect of coherent betatron oscillations (CBO): the oscillation of the beam along the horizontal plane.

The fit is also sensitive to oscillations in the width of the beam in the vertical plane (vertical waist) and of its mean.

The Fourier transform of the residuals of the fit highlights the frequencies of the beam dynamics oscillations:

- $f_{CBO} \sim 0.37\ MHz$
- $f_{CBO} \pm f_a$
- $f_{VW} \sim 2.3\ MHz$
- $f_y \sim 2.5\ MHz$
- Low frequency peak due to lost muons



9 parameters fit function

Since the FFT residuals show peaks at beam dynamics frequencies, the fitting function must be modified to include their contribution. This will also improve the fit χ^2.

The first step is to include the CBO term:

$$\mathrm{N}_{CBO}(t) = 1 + (A_{CBO}\cos(\omega_{CBO}t + \phi_{CBO}))e^{-\frac{t}{\tau_{CBO}}}$$

Where:

- A_{CBO} is the amplitude of the CBO
- ω_{CBO} is the frequency
- φ_{CBO} is the phase
- τ_{CBO} is the decoherence lifetime

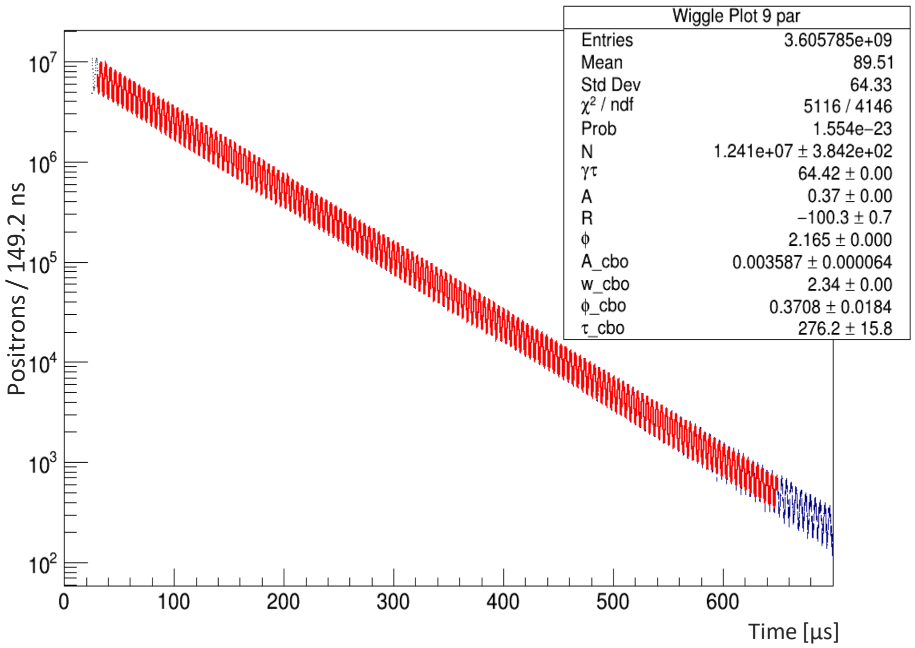
9 parameters fit function

The fit procedure we're using is the following:

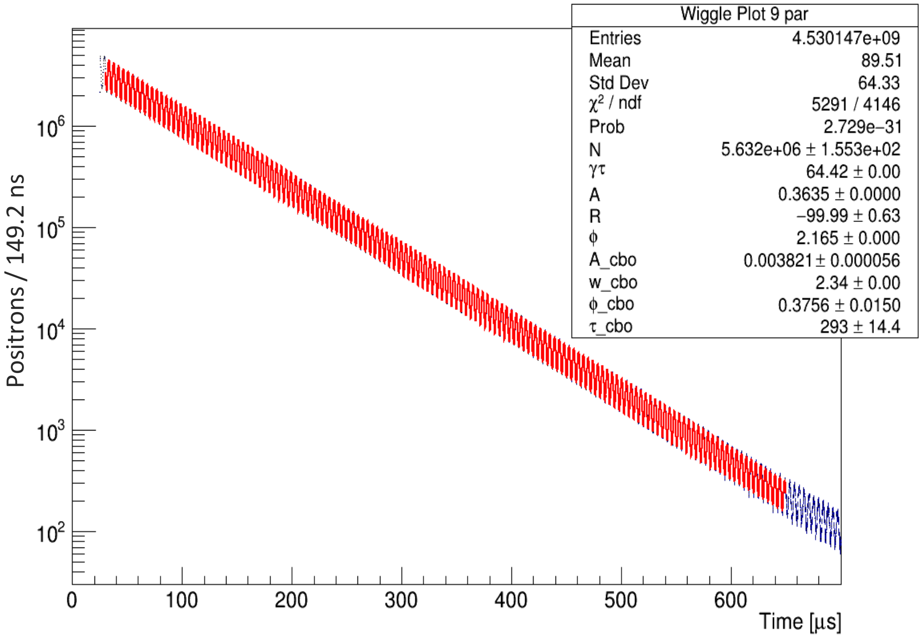
1. Fit with the 5 free parameters ($N_0, \gamma\tau, A, \omega_a, \varphi$) function (see slide 7)
2. Fit with $N_0, \gamma\tau, A, \omega_a, \varphi$ fixed to the values from point 1 and leave the 4 CBO parameters ($A_{CBO}, \omega_{CBO}, \varphi_{CBO}, \tau_{CBO}$) free
3. Release all parameters and initialize the CBO parameters with the values found in step 2
4. Perform the complete fit with all parameters floating

9 parameter fit results

T-Method wiggle plot



A-Method wiggle plot



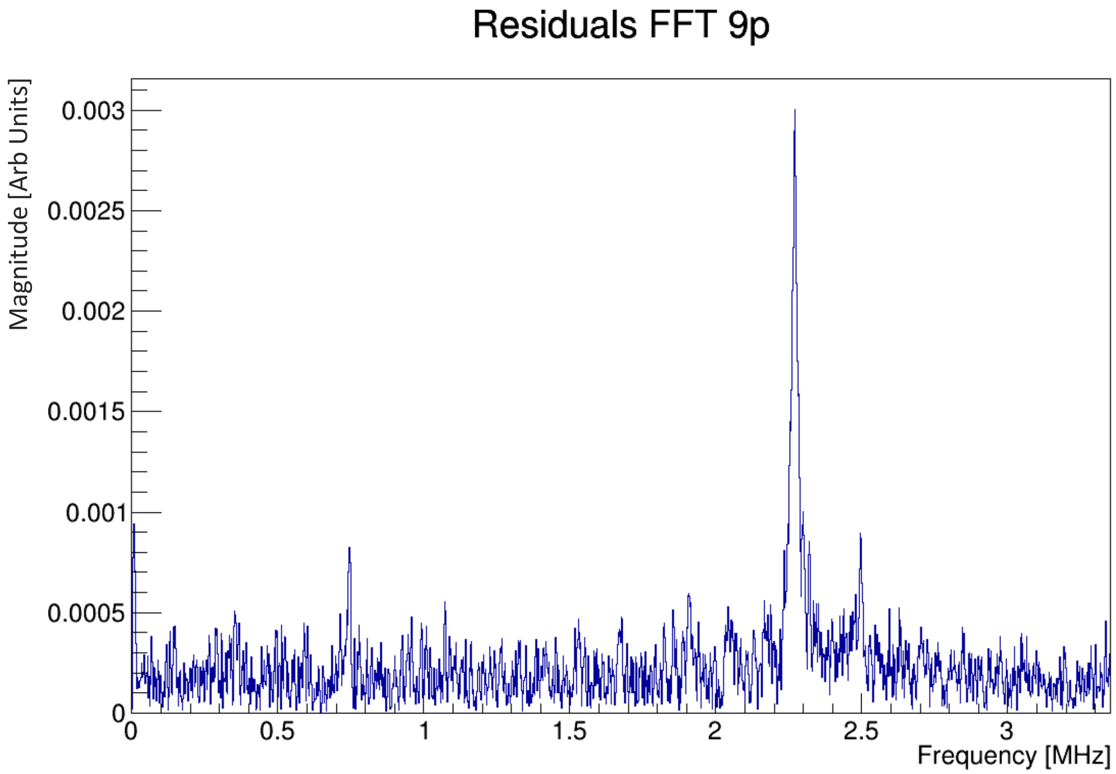
The 9 parameters fit improves the χ^2/ndf

	5 parameters	9 parameters
T-Method	4,1421	1,2339
A-Method	5,4385	1,2759

Fermilab

Fourier Transform

The analysis of the residuals of the 9 parameters fit shows that CBO is now correctly described by the function. The peak at 2.3 MHz is due to vertical waist and the peak at low frequencies is due to lost muons.



The complete fit is done with a 22 parameters function that takes into account every beam oscillation. The functional form of this oscillations will be the object of my future studies.

T and A methods comparison

The two methods give us these results:

	R (ppm)	δR (ppm)	X^2/ndf	X^2/ndf
T-method	-100.257	0.701	5116/4146	1,2339
A-method	-99.989	0.630	5290/4146	1,2759

Agreement between the two methods is checked calculating the difference

$$|R_T - R_A| = 0.268$$

Which should be lower than the allowed statistical deviation (the 1σ difference due to different amount of statistic used by the two methods)

$$\sqrt{\delta R_T^2 - \delta R_A^2} = 0.307$$

Coming soon

In the anomalous precession frequency fit, the description of the beam dynamics is crucial to obtain a precise result.

Next step: I will perform a fit including the full beam dynamics effects, i.e. with the 22 parameters function.

Moreover, the study of beam dynamics shows that CBO oscillations are dumped over time. In the fit function this trend is assumed to be exponential. I will study other functional forms to understand the systematic effect of this assumption on the fit.

THANKS FOR YOUR ATTENTION