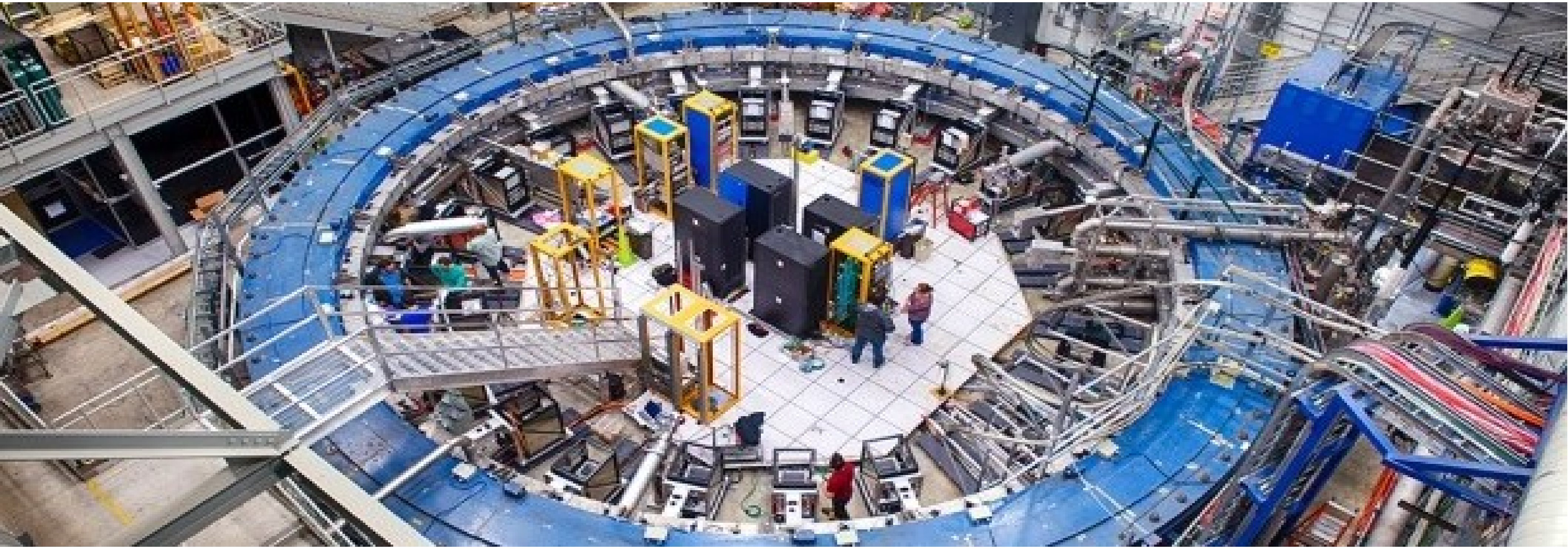


Measurement of ω_a with g-2 experiment

Stefano Di Falco, INFN Pisa
for the ω_a european analysis group

Muse collaboration meeting

October 22, 2018

The muon anomaly and ω_a

- Muon anomaly is defined as: $a_\mu = \frac{g}{2} - 1$ where $\boldsymbol{\mu} = g\frac{e}{2m}\boldsymbol{S},$
- If $a_\mu \neq 0$, the spin (s) of a muon travelling in a magnetic (B) and electric (E) field rotates with respect to its velocity (β). The spin projection on velocity vector varies according to:

$$\frac{d}{dt}(\hat{\beta} \cdot \vec{s}) = -\frac{e}{mc} \cdot \left[\left(\frac{g}{2} - 1\right) \hat{\beta} \times \vec{B} + \left(\frac{g\beta}{2} - \frac{1}{\beta}\right) \vec{E} \right]$$

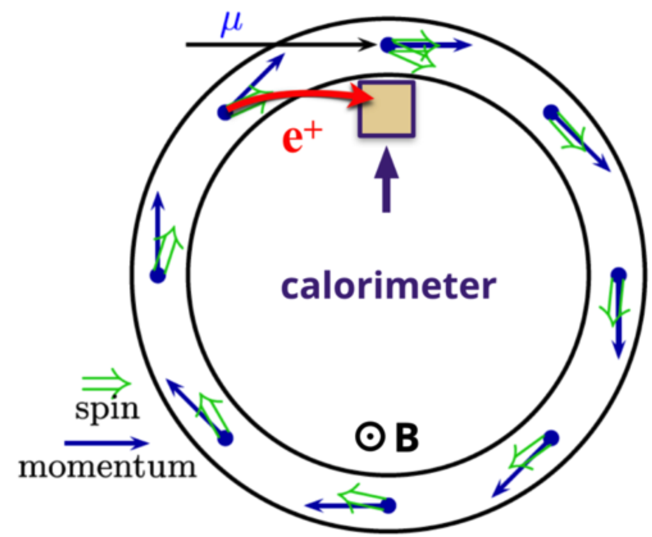
- neglecting beam size and oscillations, assuming that all muons have a “magic” momentum $p_{magic}=3.01 GeV/c$ perpendicular to B, the rotation frequency is given by:

$$\omega_a = \omega_\mu - \omega_c = a_\mu \frac{e}{m} B$$

- If the magnetic field is known ω_a measures the muon anomaly. In fact B is also obtained by measuring the rotation frequency of the momentum (ω_p) in the magnetic field.

The measurement of ω_a

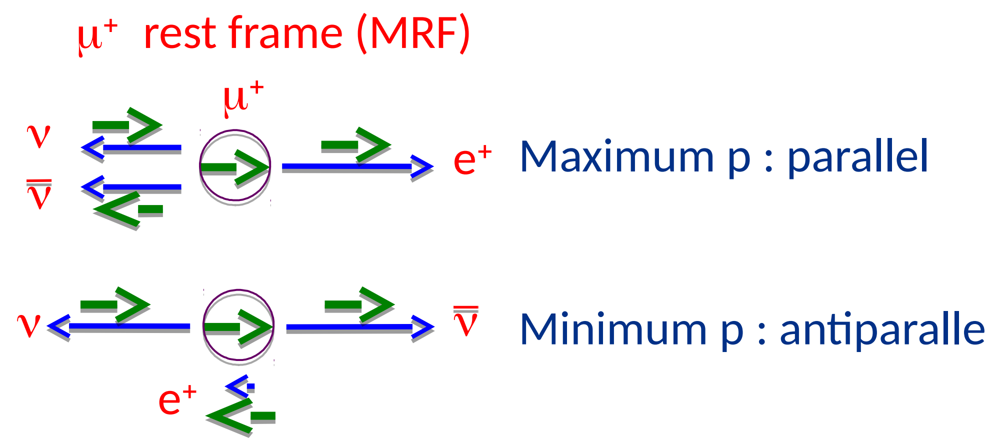
- Positive (or negative) **muons** are **stored** in a ring in presence of a magnetic field where they **decay to positrons** (or electrons), neutrinos and antineutrinos. Positrons, e^+ (or electrons, e^-) can be detected by a set of **calorimeters** and **trackers** located around the ring.

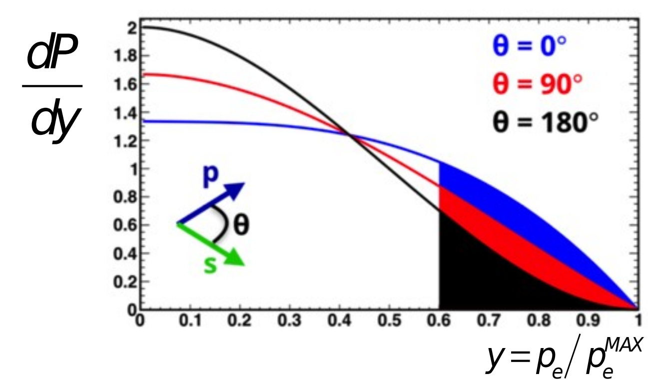


- When e^+ **spin** is **parallel** to μ^+ spin, ν's directions must be paralllel and e^+ **energy** in MRF is **maximum**.

  When e^+ spin is antiparallel to μ^+ spin, νs are emitted back-to-back and e^+ energy in MRF is lower.

- Since it's more probable to have e^+ with spin parallel to their velocity (**h=+1**) than the contrary, **higher e^+ energies** are **more probable** when the e^+ velocity is parallel to μ^+ spin (**θ=0**).
- The directions of the e^+ detected by a calorimeter are fixed, but μ^+ spin rotates: **e^+ spectrum changes with ω_a!**

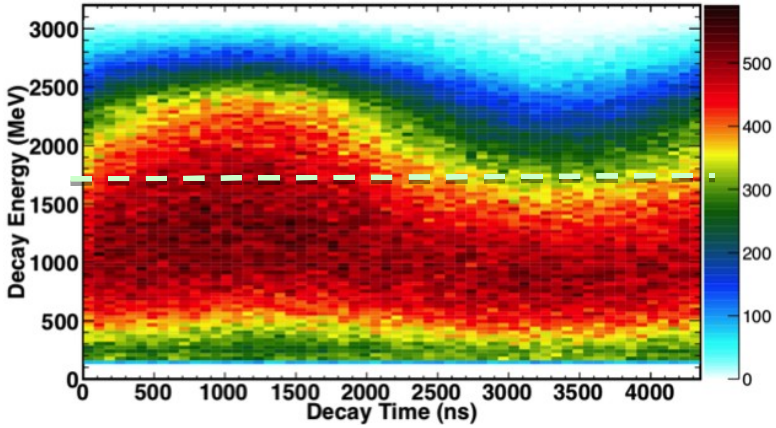




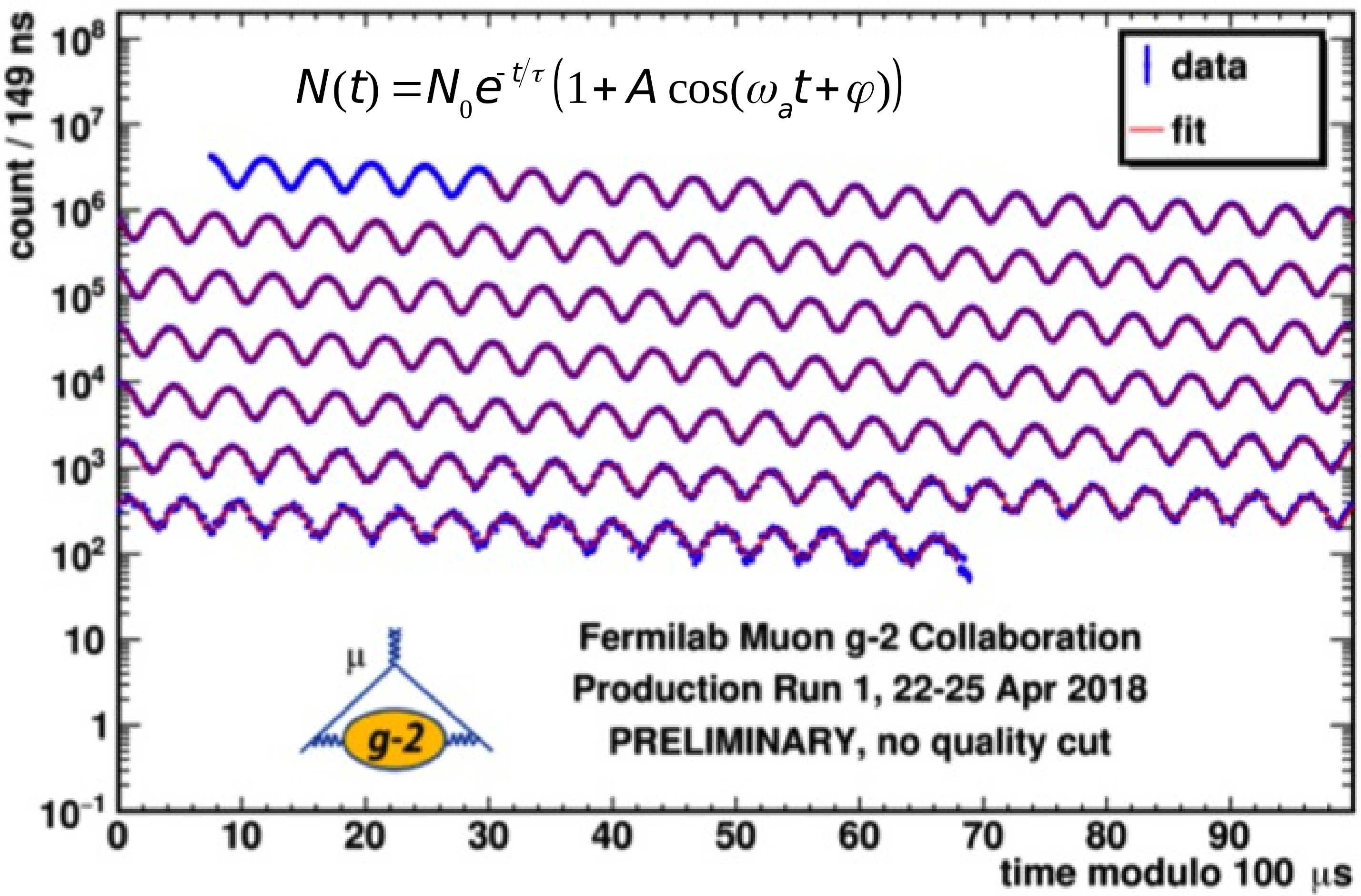
$$y = \frac{p_e}{p_e^{MAX}}$$

The wiggle plot

- The counting of e^+ above a given threshold is sensitive to ω_a!



One oscillation period ~4.4 μs



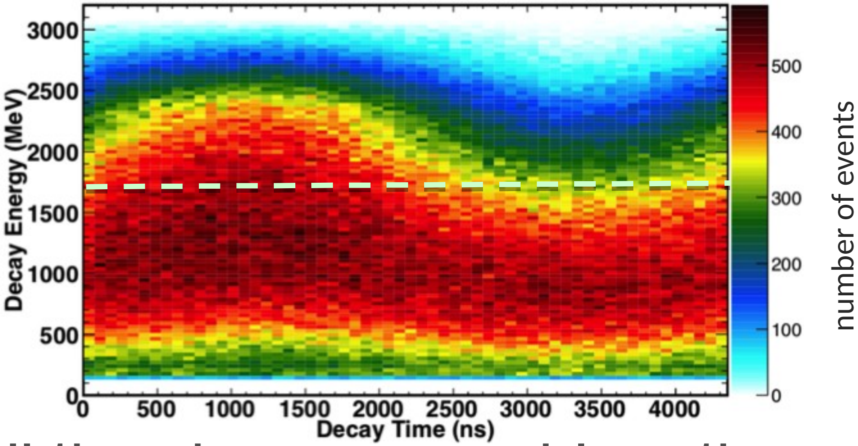
Muon lifetime: $\tau \sim 64.4$ μs

ω_a~240 kHz

Experiment goal: measure ω_a with a systematic error better than **70 ppb**!

Methods to obtain ω_a

- **T-method (time)**: look at number of positrons above threshold
  - Reconstruct single positron events
  - Can use different event weights to enhance statistical significance



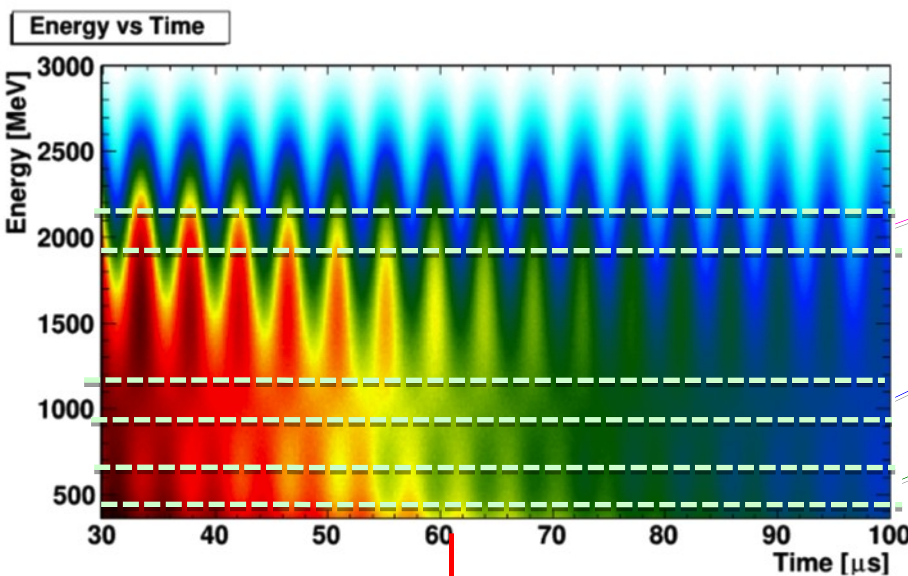
- **Q-method (charge)**: integrate all the charge, possibly with no (or minimal) threshold
  - No need to reconstruct single positron, avoid pileup and clustering
- **R-method (ratio)**: randomly split the dataset in 4 subsets. Shift the first by π/ω_a, the second by $-\pi/\omega_a$ and leave the other two unchanged. Call U(t) the sum of the first two and V(t) the some of the last two.

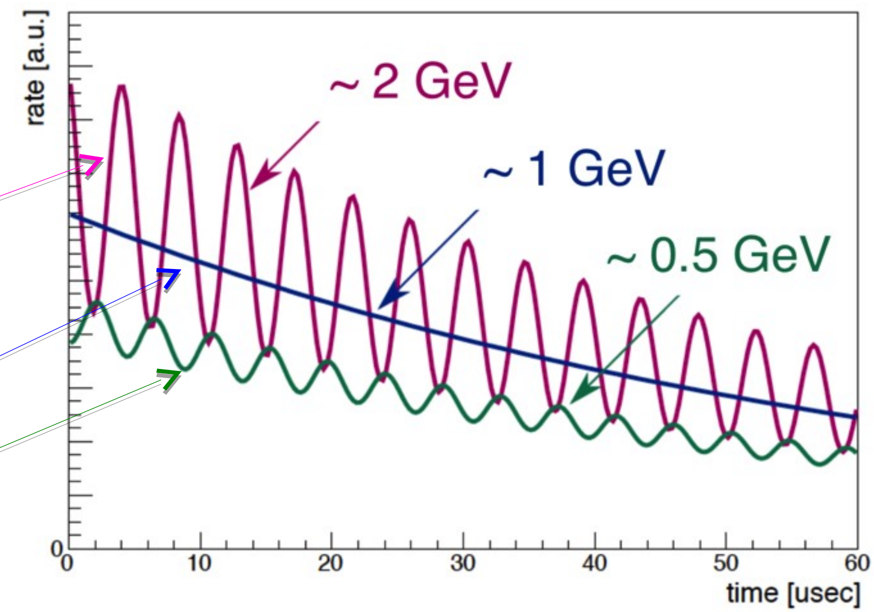
$$R(t)=\frac{V(t)-U(t)}{V(t)+U(t)}$$

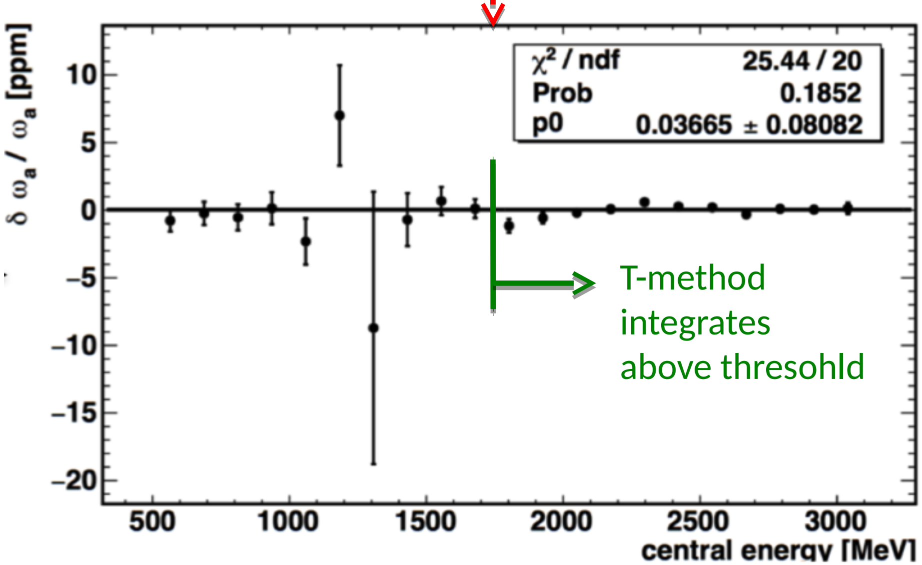
- Is a sinusoide with frequency ω_a
- Independent on τ_μ

T method energy weighted to obtain ω_a

- **T-method (time)**: look at number of positrons above threshold







- Each energy bin has its different phase, *Asymmetry* and *sensitivity to* ω_a
- Fitting each slice separately allows to use positrons down to 0.5 GeV

Systematics on ω_a

- The goal of the Fermilab experiment is to reduce the systematic error on ω_a from ***180*** to ***70 ppb***

Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to ring	< 30
E and pitch	50	Improved tracker	
		Precise storage ring simulations	30
Total	180	Quadrature sum	70

Key element:

Laser

Calo + Laser

Calo + Laser

Inflector + Beam

Tracker

- Systematics effects can be reduced by:
  - Correcting the positron energy before fitting (gain, pileup)
  - Introducing additional terms in the fit function

Analysis groups

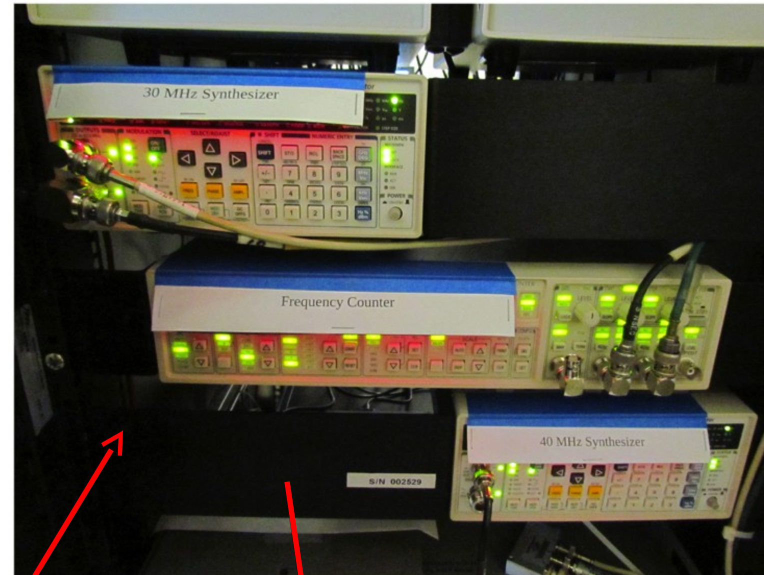
- 7 independent analysis groups using different *Reconstruction algorythms* and different *Fit methods*

Team	Reconstruction	Analysis
UKy	Q	Q
CU	East	T,E
Miss/UIUC	East	T
Europa	West/Europa	T,E
UW	West	T,E
SJTU	West	T
BU	West	R

- An european analysis, composed by italian and english researchers supported by Muse program, is exploiting its specific competences on *calorimeter laser calibration* (gain) and *tracker reconstruction* (muon beam profile) to reach the required control of systematic effects on ω_a.

Analysis is blind!

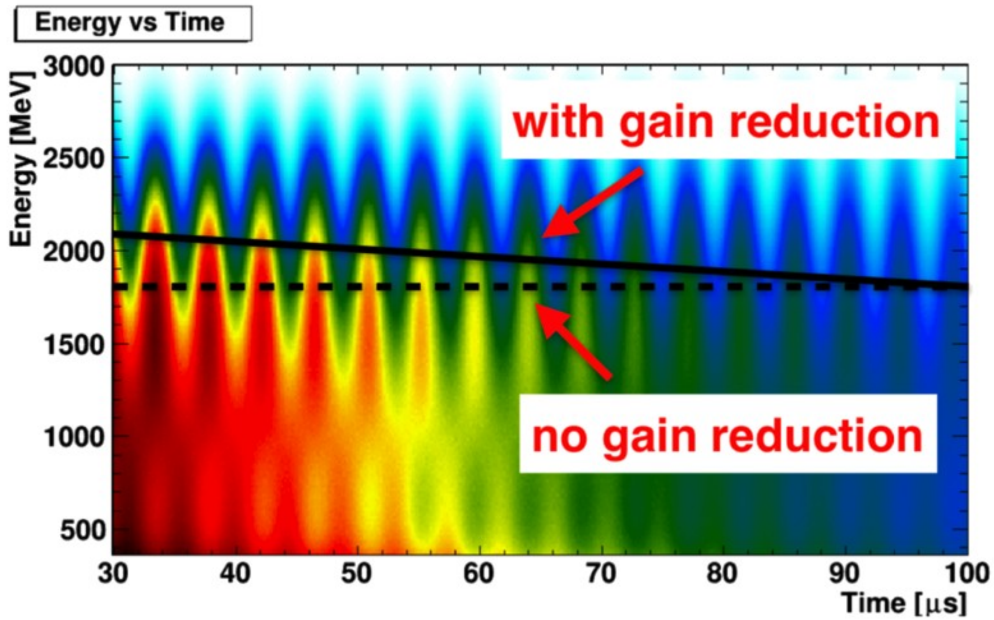
Two clocks blinded ($40+\varepsilon$, $30+\delta$) MHz
Bias values in closed envelopes
No one knows the correspondence between time ticks and ns
In addition, also the ω_a fit parameter is differently blinded for each analysis group!

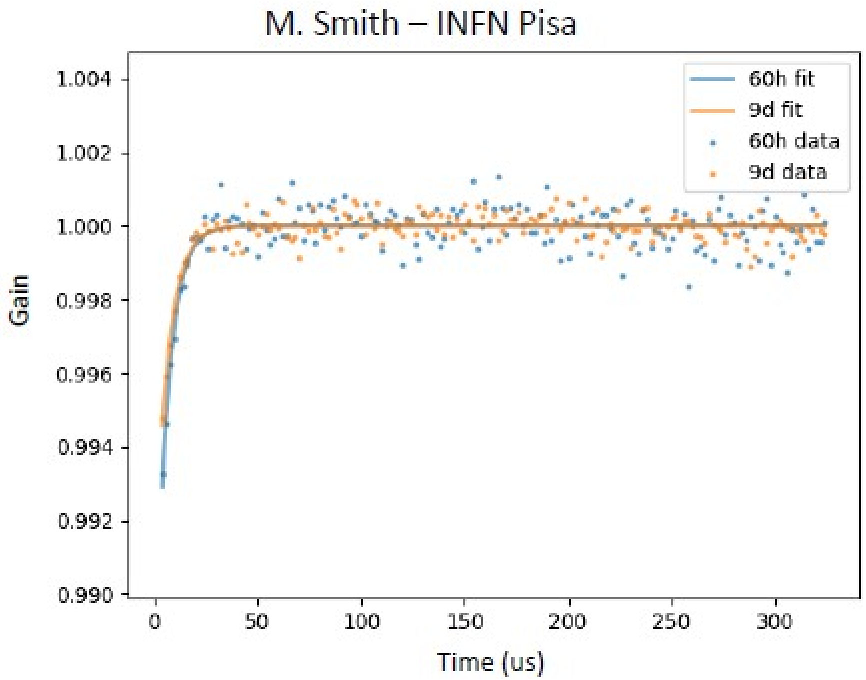


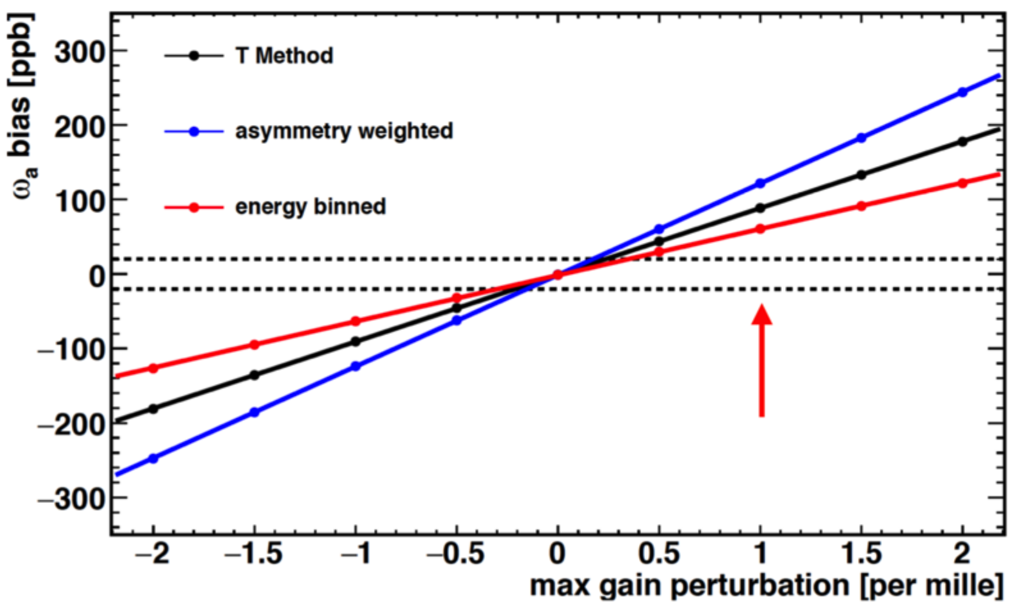
Locked Clock Panel

Gain stability correction

- SiPM gain shows a dependence from the time distance from the start of the spill, mainly due to saturation
- Analysis performed by laser group (all Muse members) has brought to the gain correction functions now inserted in official production





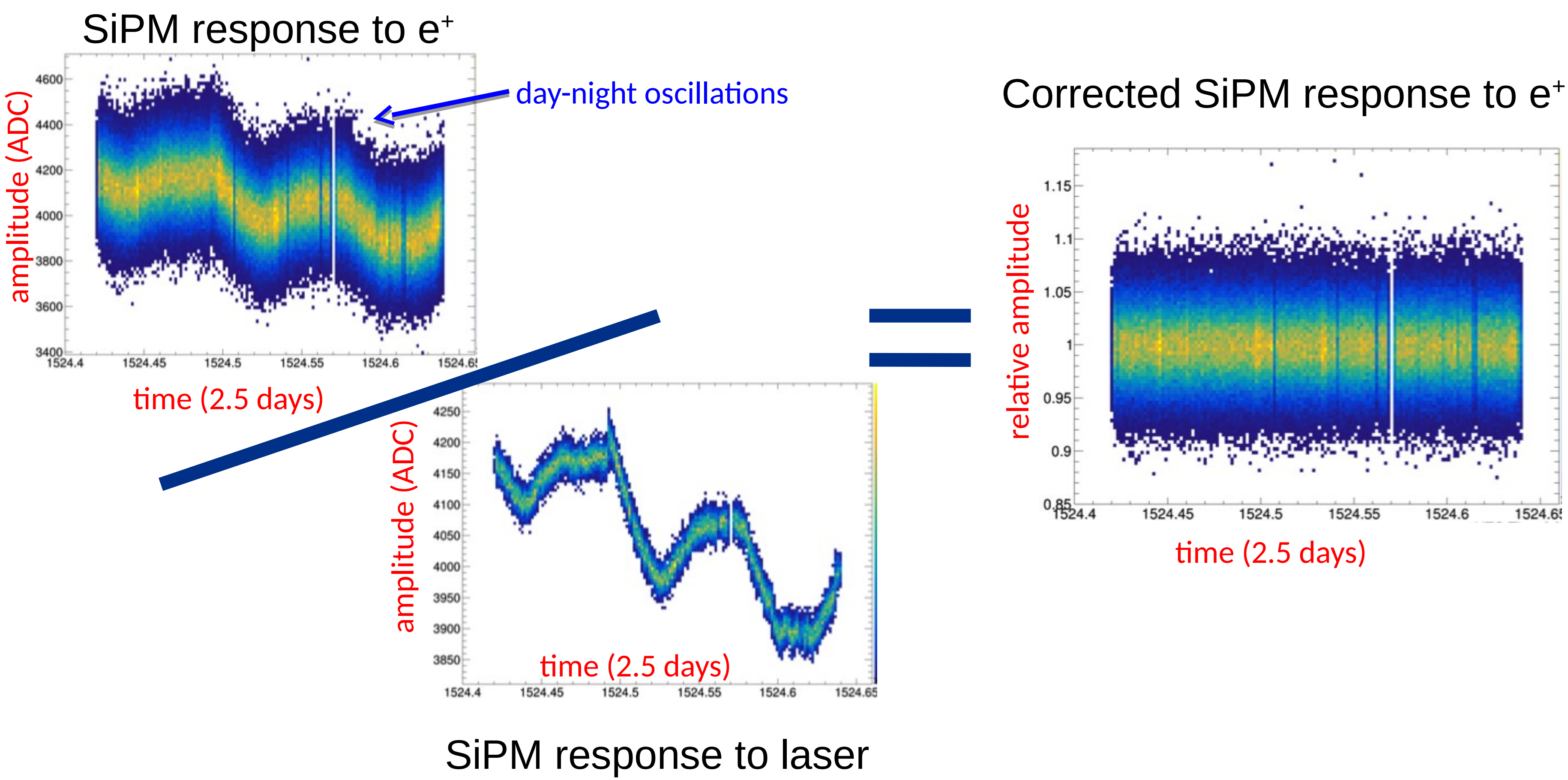


50-150 ppb bias is expected for uncorrected in-fill gain perturbation

- A 0.1% effect at 30 ms is small but not negligible!

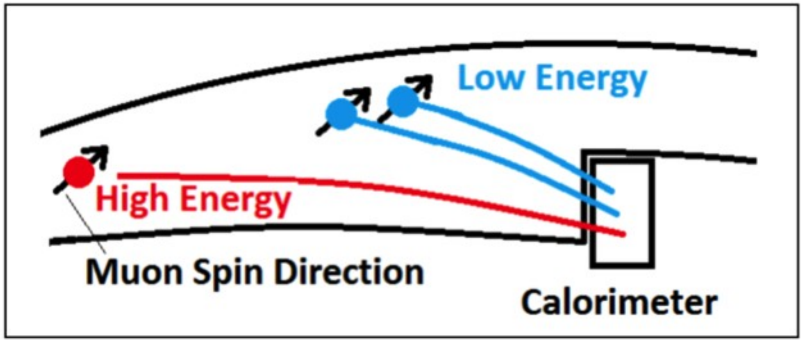
Long term gain stability correction

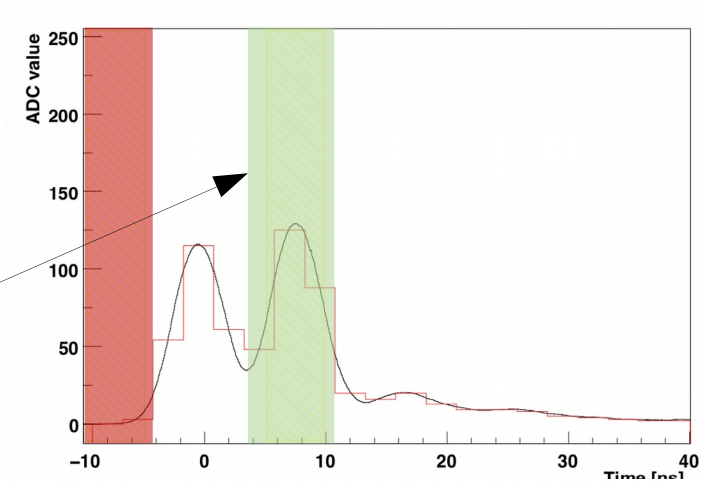
- Laser data are used to correct SiPM response for environmental instabilities: mostly temperature variations (but also pressure, humidity, ...)



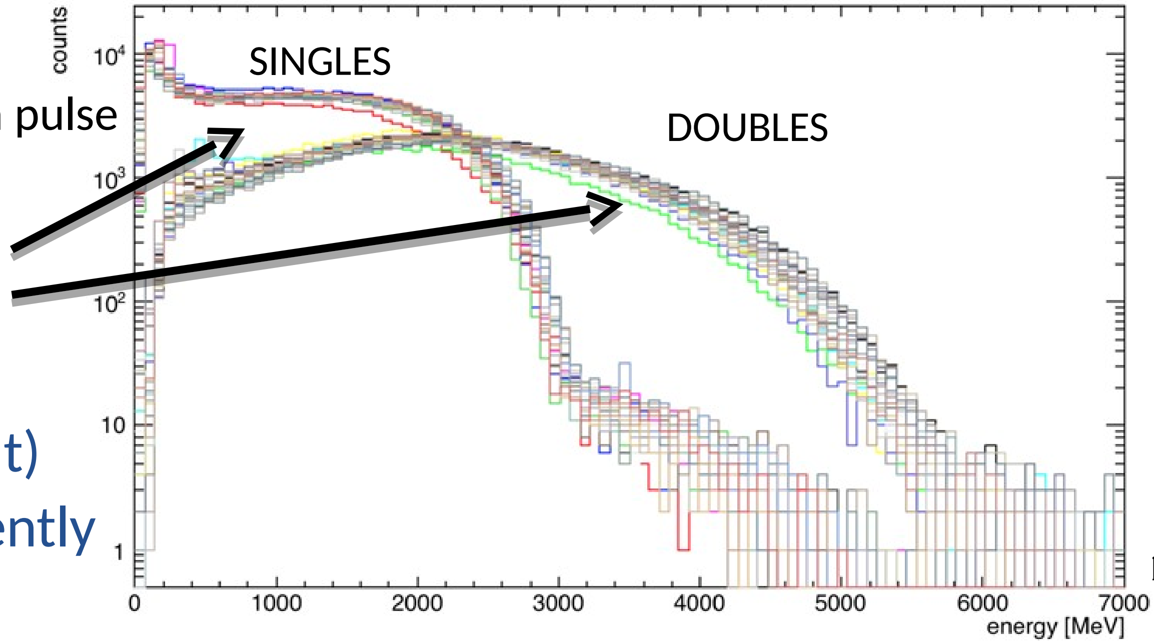
Pile up correction

- Two clusters within ~ 4 ns in the same calorimeter can be merged
- Unphysical tail above positron end point
- Pile up probability is higher in the first part of the fill, then muons decay out





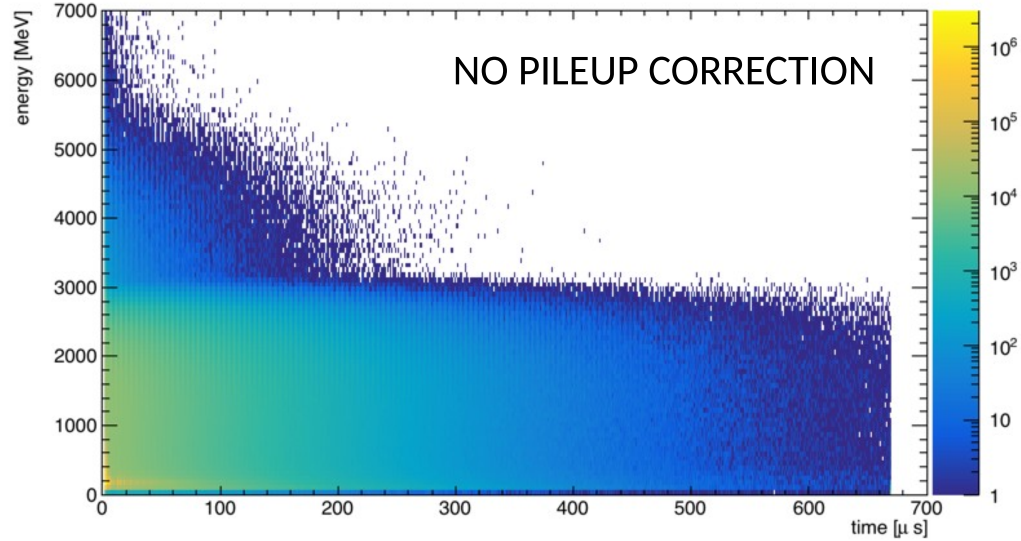
- Pileup Correction
  - Look at ~5ns window after each pulse
  - If another pulse is present,
    E1&E2 into singles histogram,
    E1+E2 into doubles histogram

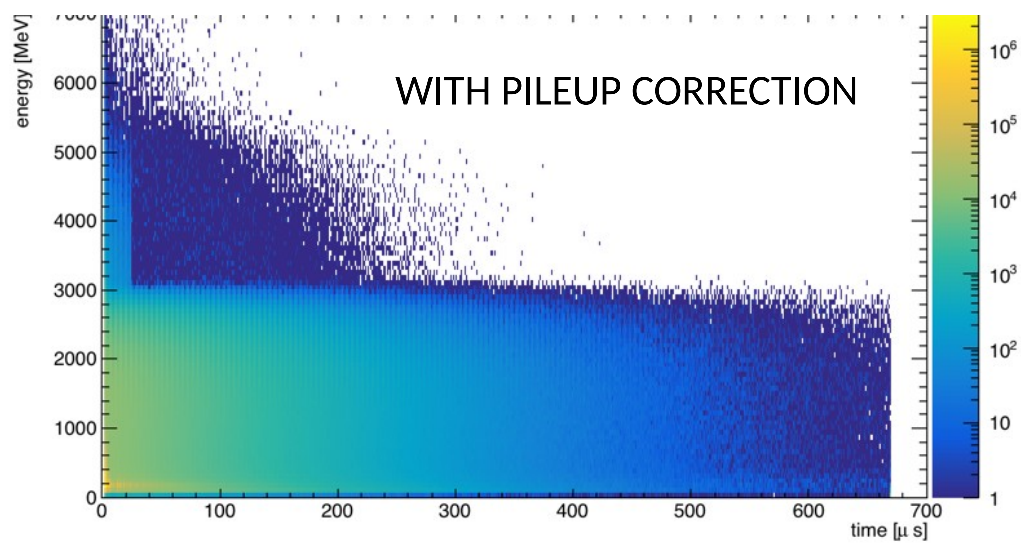


- $N'(E, t) = N(E, t) - D(E, t) + S(E, t)$
- Triples not accounted for currently

Effect of pile up correction

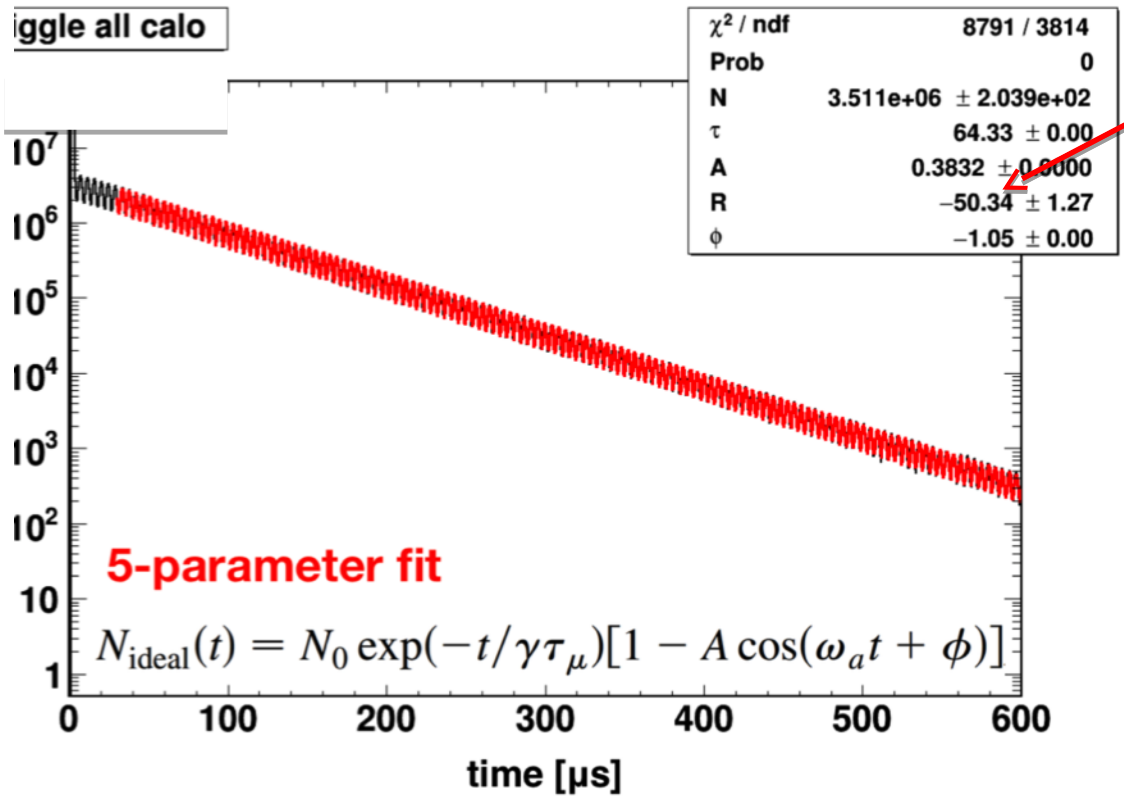
- The number of unphysical events with E > 3.1 GeV decreases when pileup is accounted for
- Still some work to be done to remove them completely, but 1st pass is in and working
- Correction only applied from 30μs onwards - determines our earliest start time





The 60h dataset: 5-parameter fit

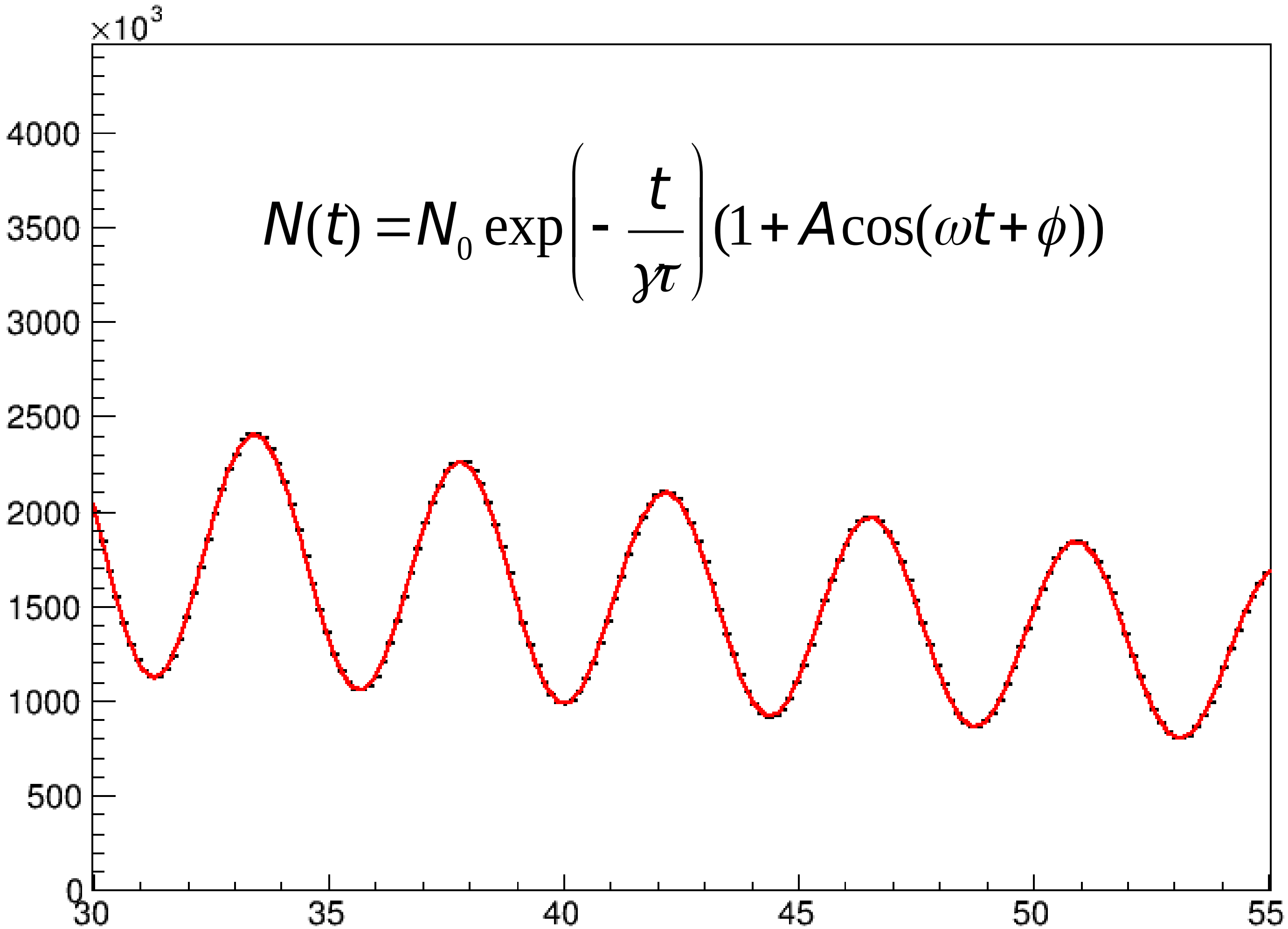
- First analysis "challenge": 2.5 days of data acquired in stable conditions between April 24 and 26 (*~10^9 positrons, ~10%* of *Run1)*



NOTE: blinding on ω_a!

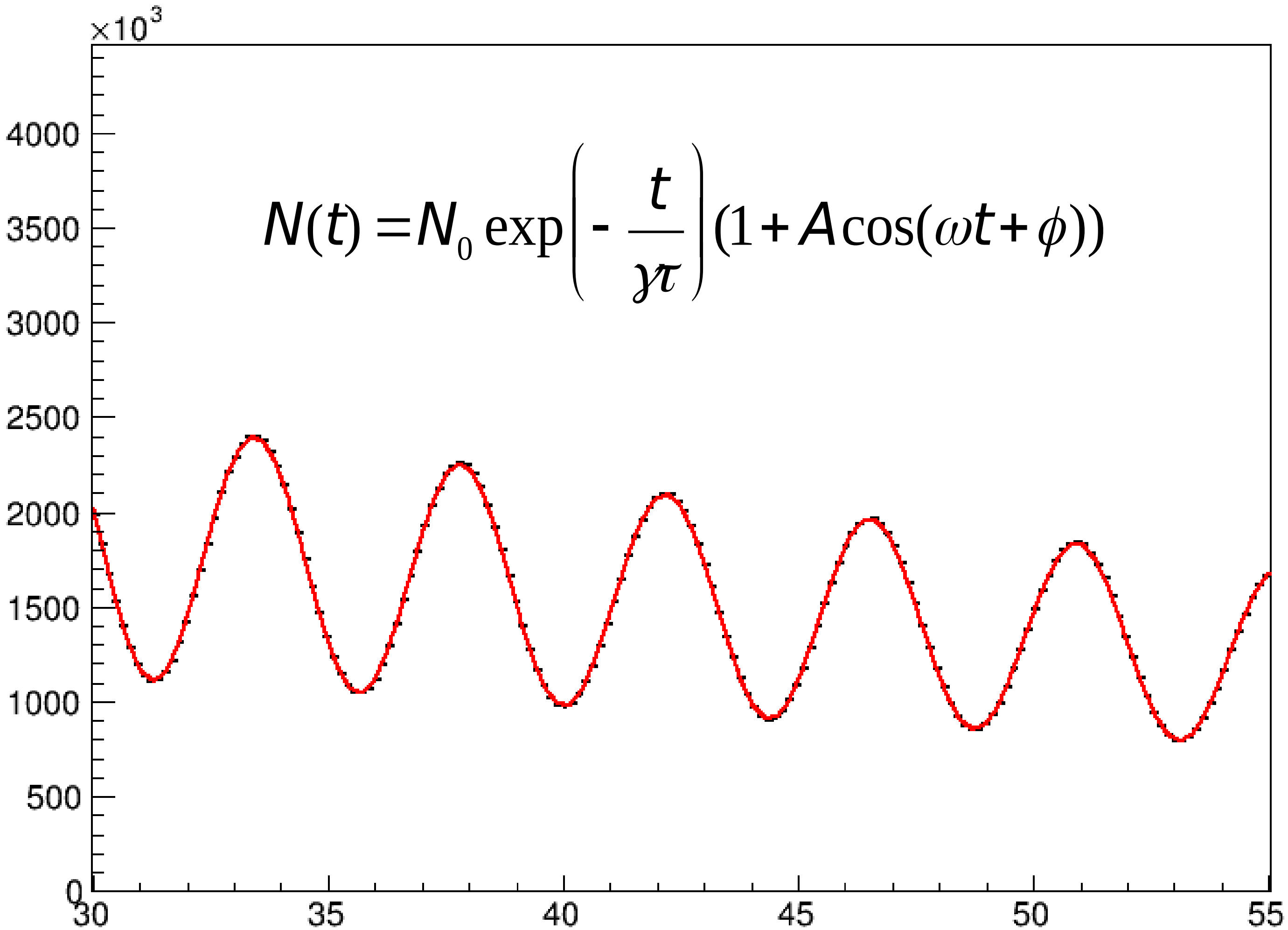
Fit starts at 30 μs

Wiggle plot WITHOUT pileup correction: 5 parameters fit



Gain corrections applied

Wiggle plot WITH pileup correction: 5 parameters fit

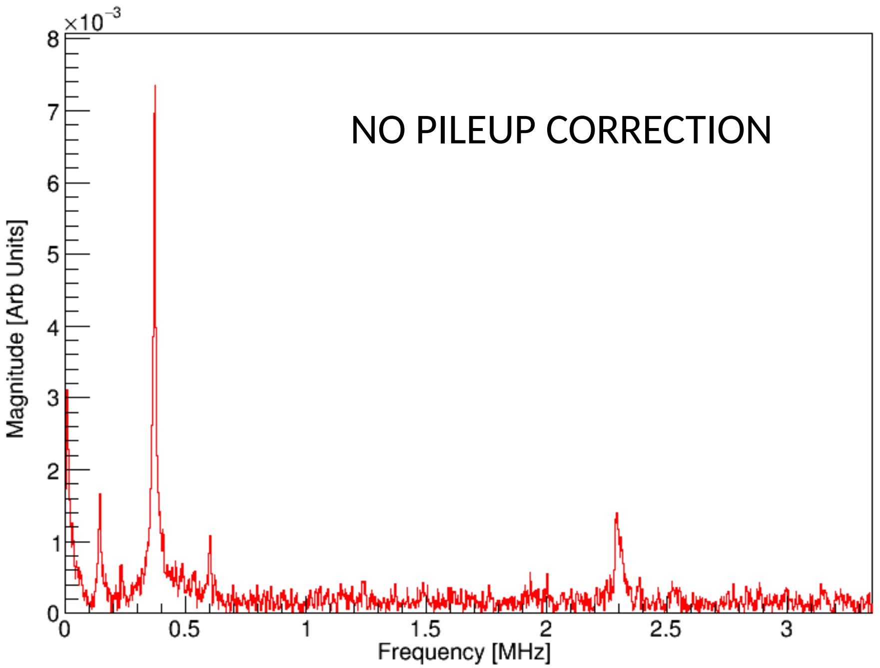


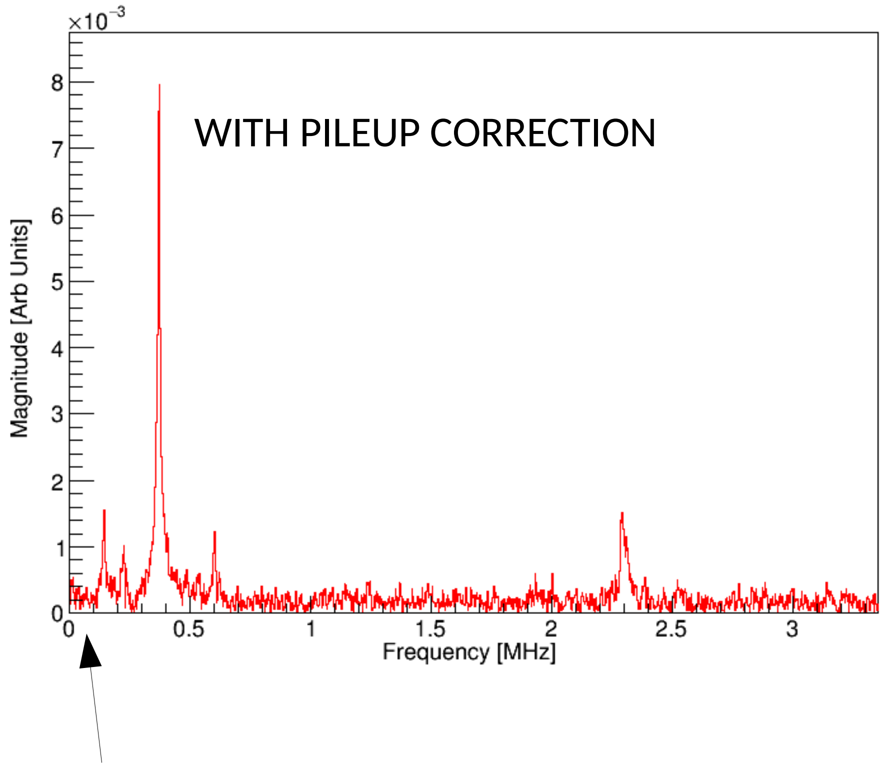
$$N(t) = N_0 \exp\left(-\frac{t}{\gamma\tau}\right)(1 + A\cos(\omega t + \phi))$$

Gain corrections applied

No difference can be seen by eye...

Wiggle plot 5 parameters fit residuals: FFT

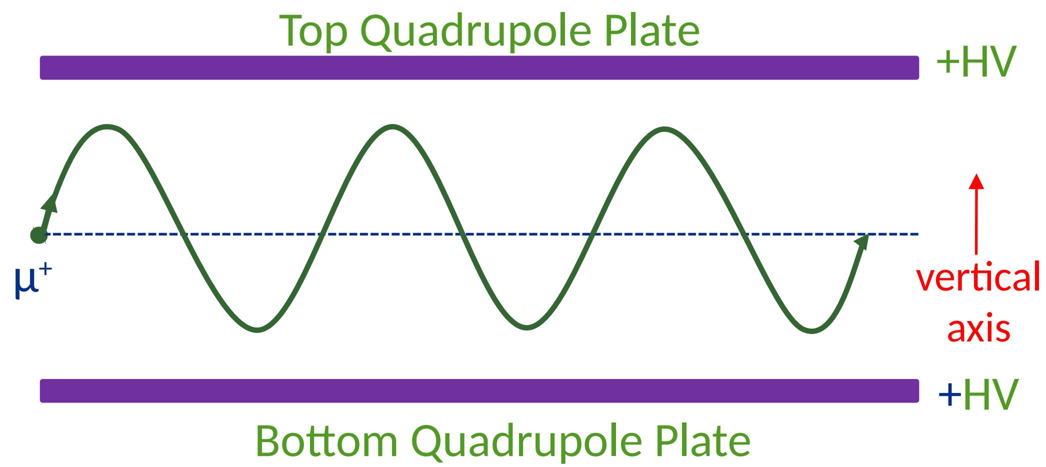


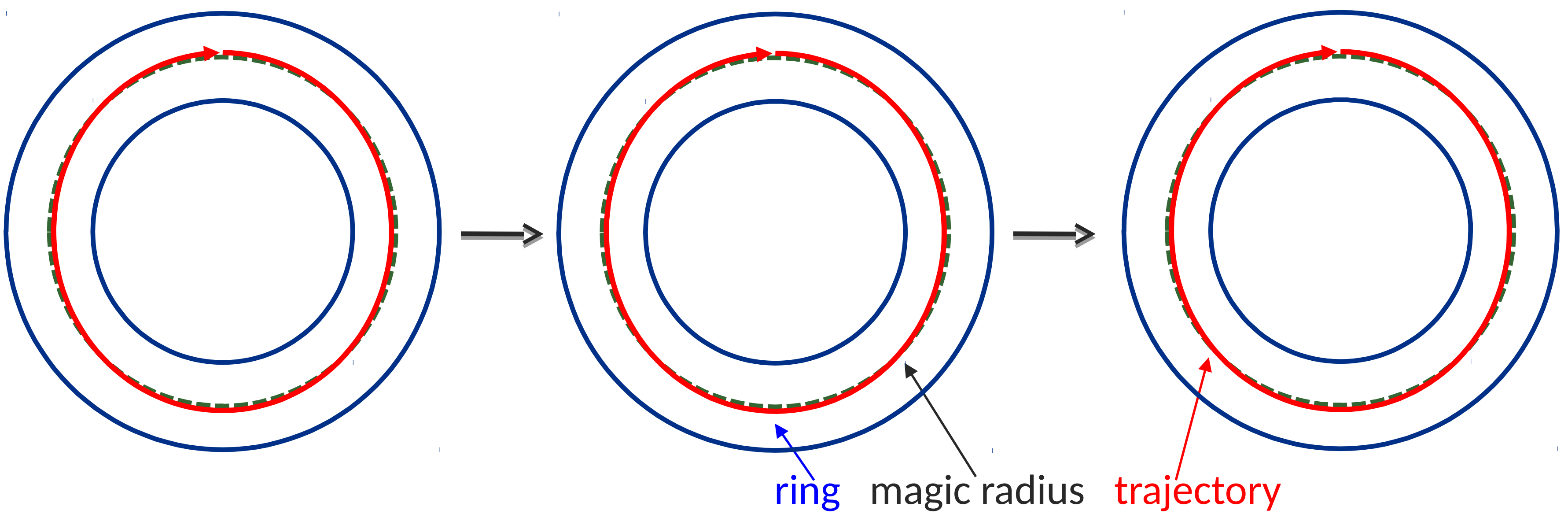


- You can see that the low frequency residual has been removed by the pileup correction
- Now let's remove the frequencies associated with the beam…

Beam oscillations

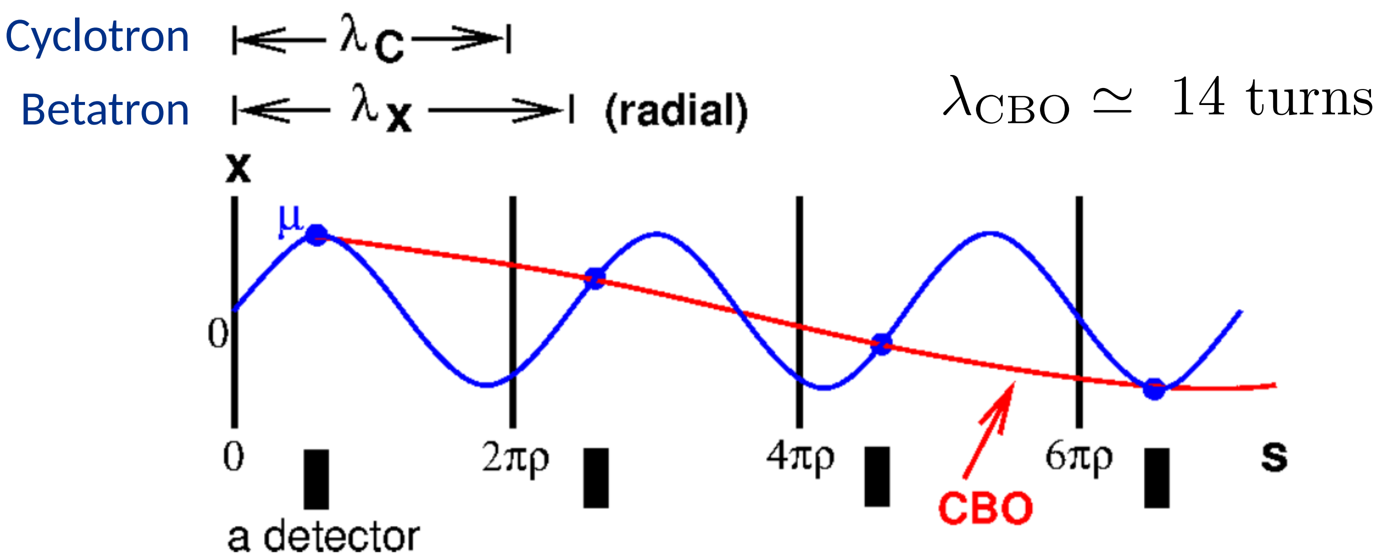
- The beam "oscillates" both radially and vertically, mostly due to the effect of the electrostatic quadrupoles





Coherent Betatron Oscillation (CBO)

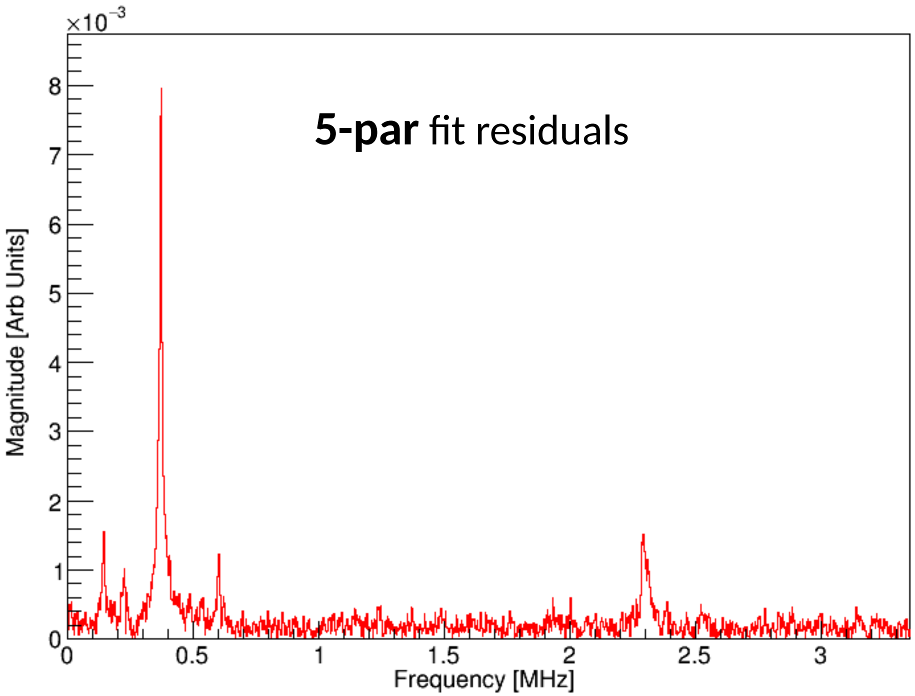
- Each detector is only at one point around the ring so we sample the radial CBO at the cyclotron frequency (f_C)

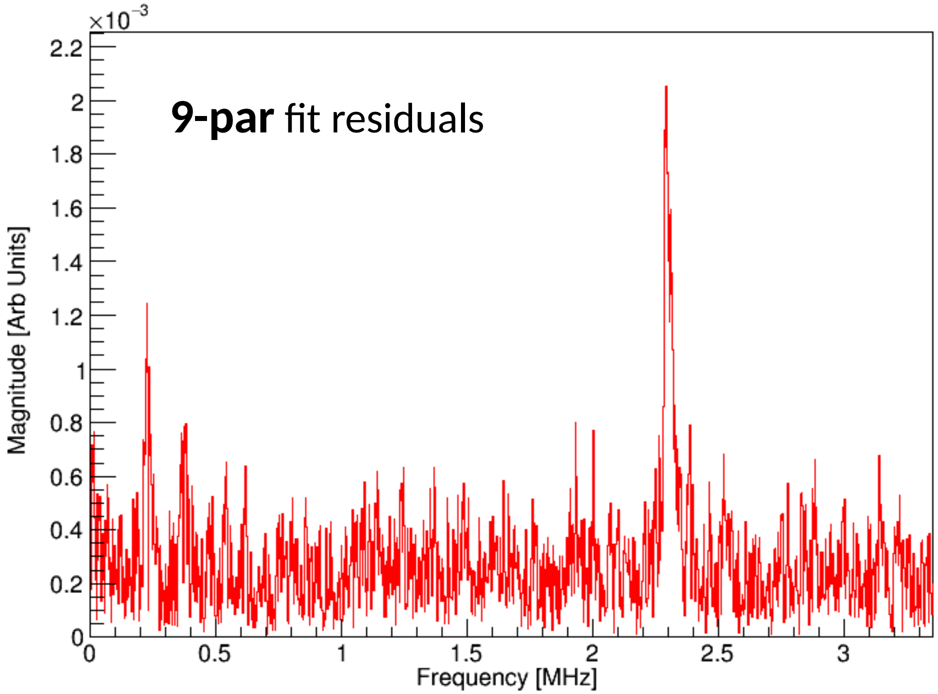


- Beating effect: the frequency measured by any one detector is $f_{CBO} = f_C - f_x$ (much smaller than both individual freqs)
- Similar effect in vertical direction

Wiggle plot 9 parameters fit residuals: FFT

$$N(t) = N(t)_{5\,par}[1 - (\exp\left(-\frac{t}{\tau_{CBO}}\right) A_{CBO}\cos(\omega_{CBO}t+\phi_{CBO}))]$$





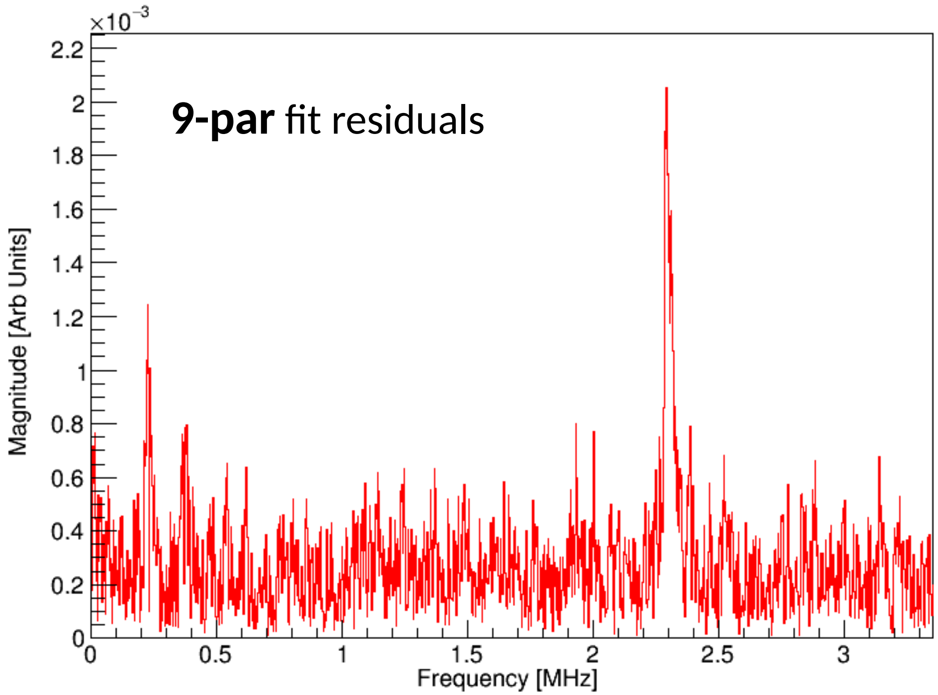
Use the results from 5 parameter fit as initial guesses for 9 par fit

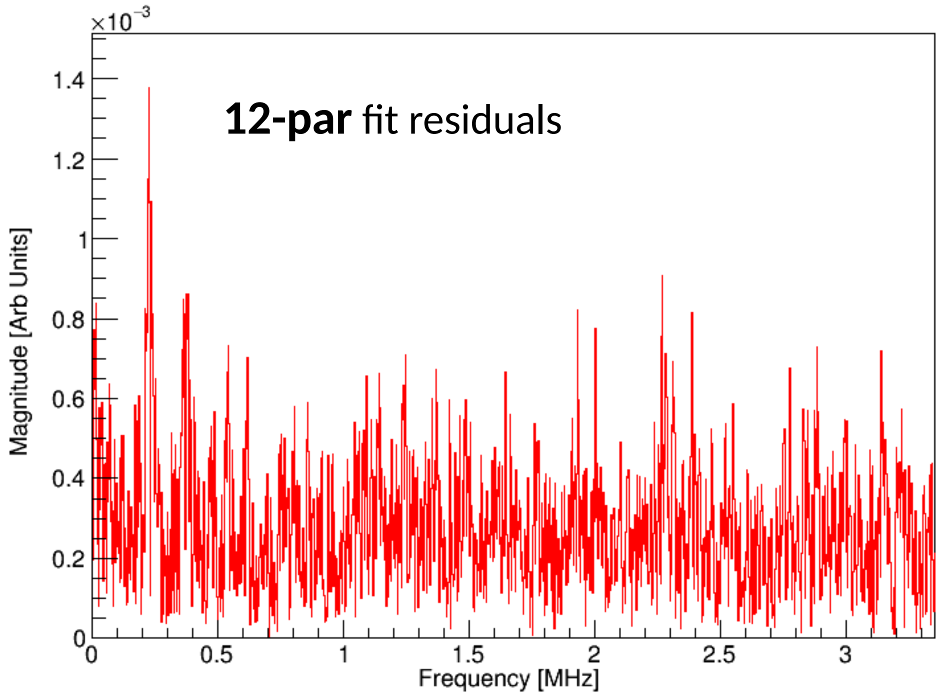
The peak at f_{CBO}~0.4 MHz has disappeared!

Wiggle plot 9 parameters+vCBO fit residuals: FFT

$$N(t) = N(t)_{9\,par}\left[1 - \left(\exp\left(-\frac{t}{\tau_{vCBO}}\right) A_{vCBO}\cos(\omega_{vCBO}t + \phi_{vCBO})\right)\right] \qquad \tau_{vCBO} = \tau_{CBO}\frac{\omega_{CBO}}{\omega_{vCBO}}$$

FIXED



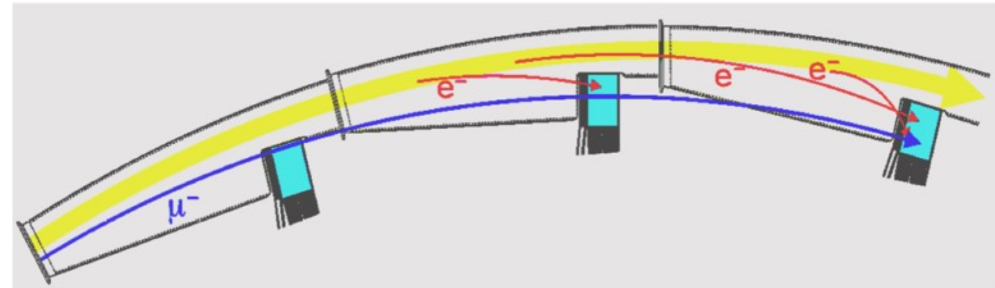


Lifetime of vertical oscillation is fixed so that ratio of lifetime with radial oscillation lifetime is equal to the inverse of frequency ratio

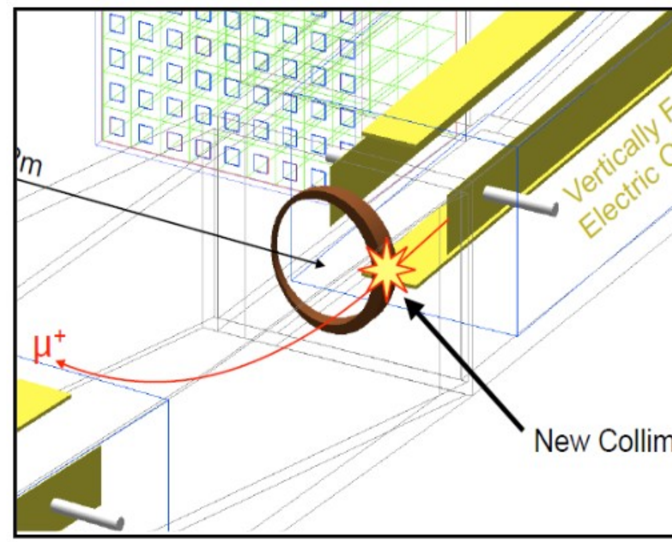
Also the peak at fV_{CBO}~2.3 MHz has disappeared!

Distorting muon life time: lost muons

- Decay is not the only mechanism by which muons are removed from the orbit



- Muons with *r > 45mm* wrt magic radius hit the collimators and bend (tipically) inward



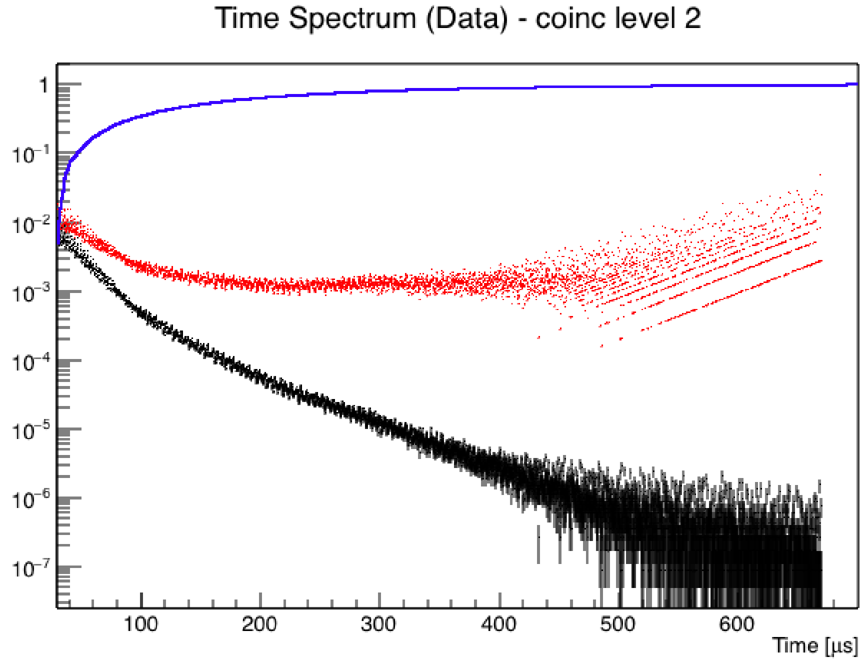
- A correction to "wiggle function", $\Lambda(t)$, is needed to take into account these additional muon losses:

$$N(t) = N_0 e^{-t/\tau} \cdot \boxed{\Lambda(t)} \cdot \left(1 + A\cos(\omega_a t + \varphi)\right)$$

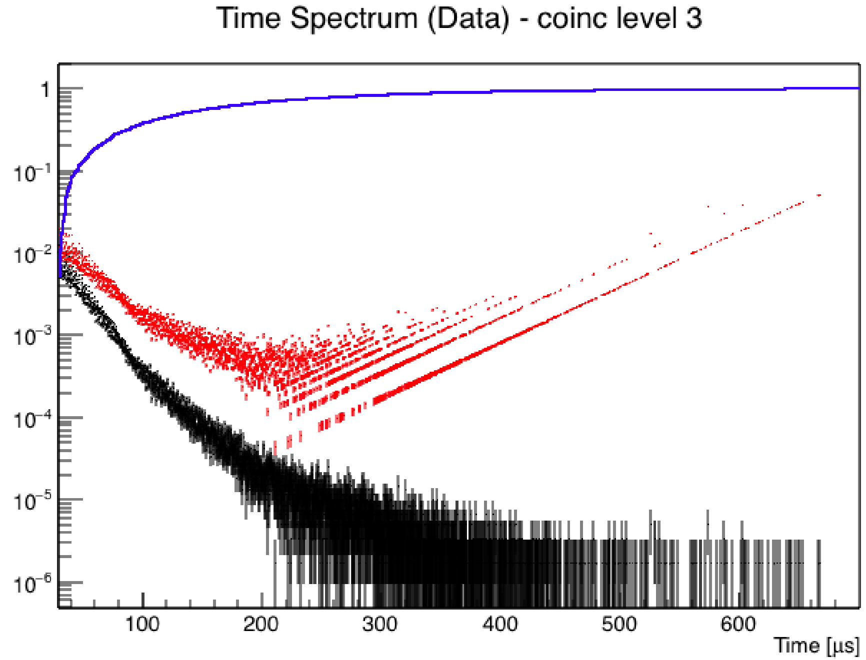
where: $$\Lambda(t) = 1 - \frac{C}{N_0} \int_{t_0}^{t} L(t')\, e^{\frac{t'-t_0}{\tau}} dt'$$ and L(t) is the number of lost muons

Lost muons probability

- Look for double and triple coincident calorimeter events:
  - Double: $5 < \Delta t_{2,1} < 7.5$ns & $\Delta E_{2,1} < 40$MeV & 1 xtal hit in 1st calo
  - Triple: Double + $10 < \Delta t_{3,1} < 15$ns + $\Delta E_{3,1} < 40$MeV + 1 xtal hit in 1st calo
- Below shows the L(t), L(t)exp(t/64.4) and the Integral
- The muon losss probability for double ($L_2(t)$) and triple ($L_3(t)$) coincidences have a different shape



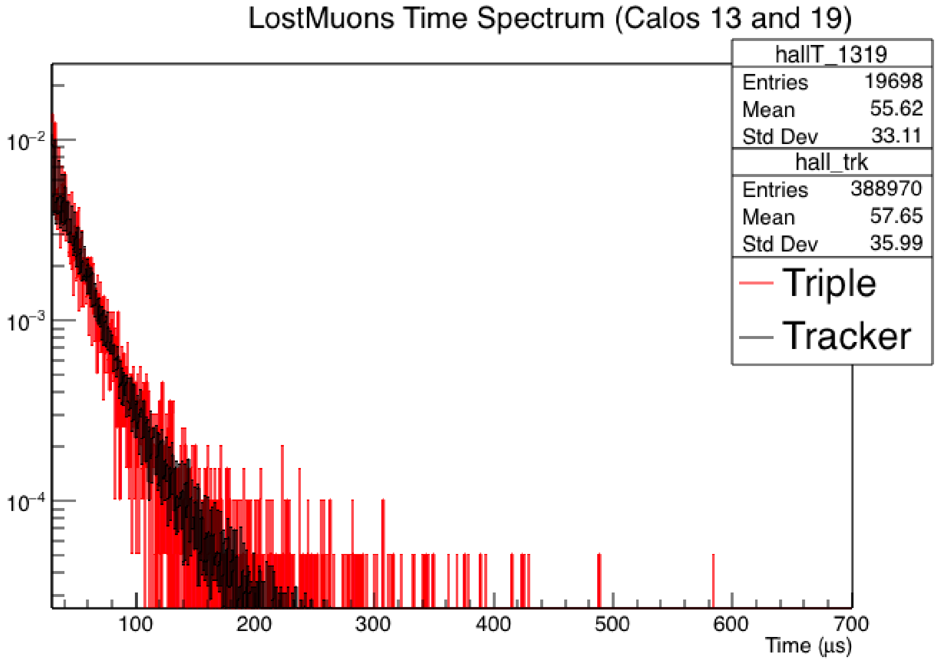
Double coincidences

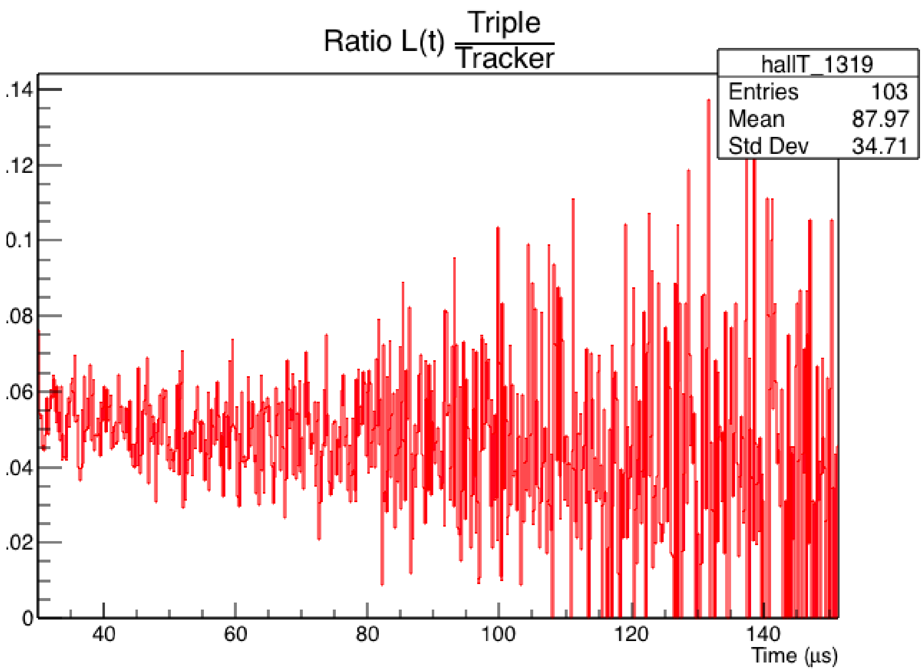


Triple coincidences

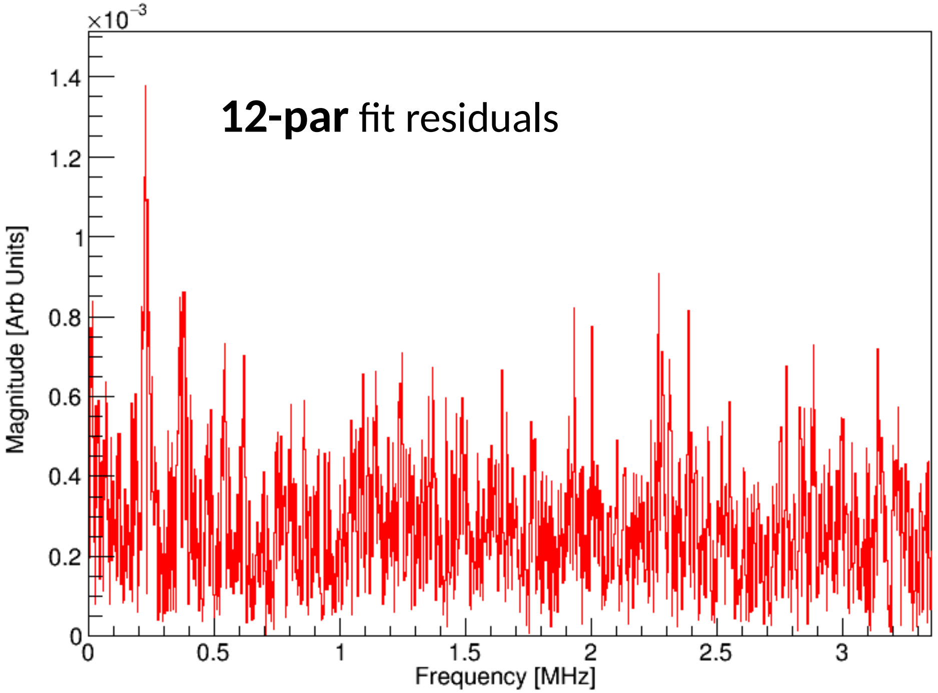
Lost muons (LM) probability using tracker

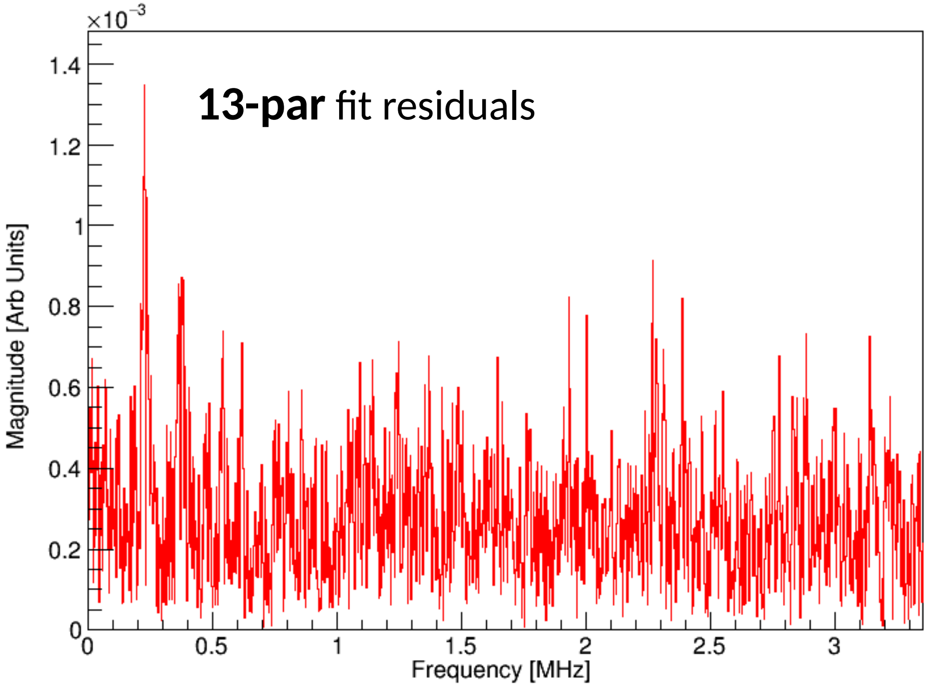
- An independent way extracting L(t) is to use energy-momentum matching between trackers and calos as a function of time in fill
  - Tracker: $2.3 < p_{TRACKER} < 3.0$ GeV + $130 < E_{CALO} < 220$ MeV
- Good agreement between shape of tracker and triples





Wiggle plot 12 parameters+LM fit residuals: FFT

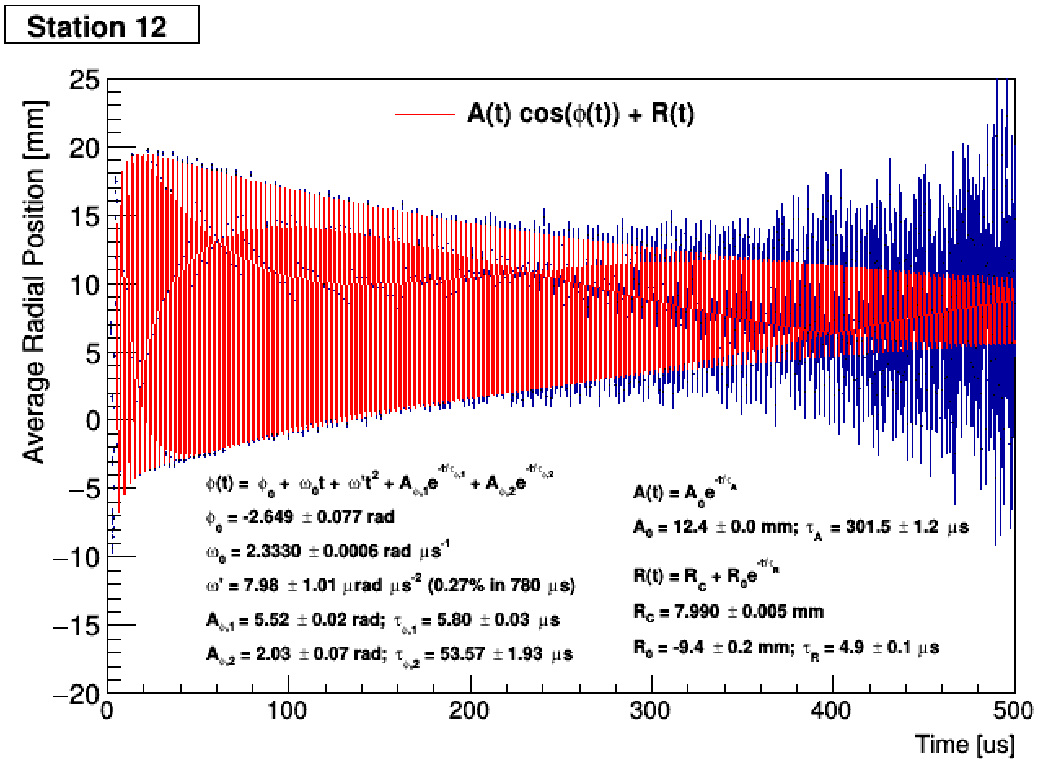


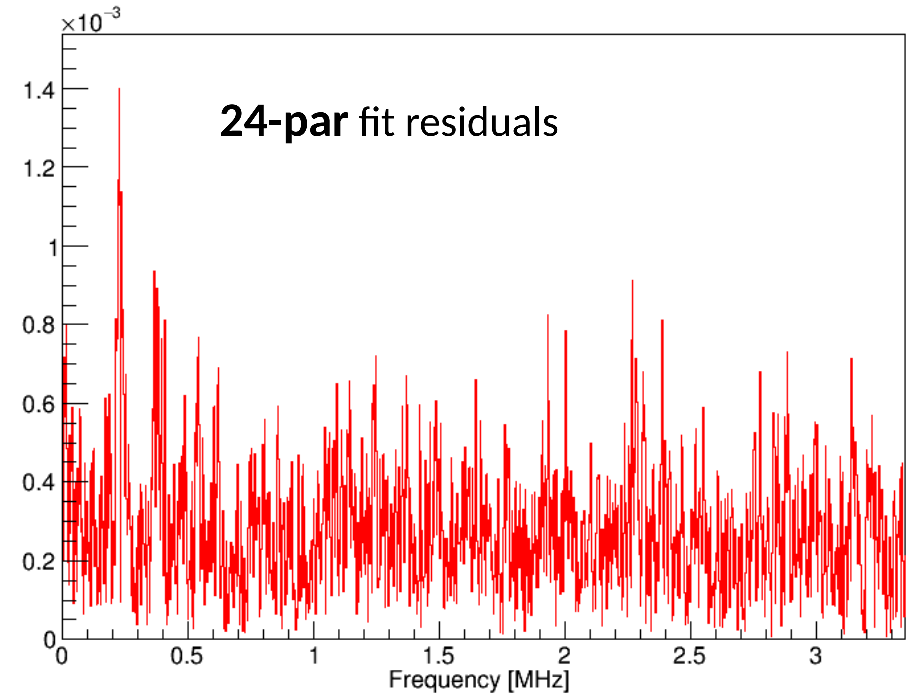


Low frequency component reduced, χ^2 also improves

Varying CBO

The average radial position measured by the tracker changes with time: can be parametrized with 11 additional parameters





No additional improvement observed up to now

Results Summary

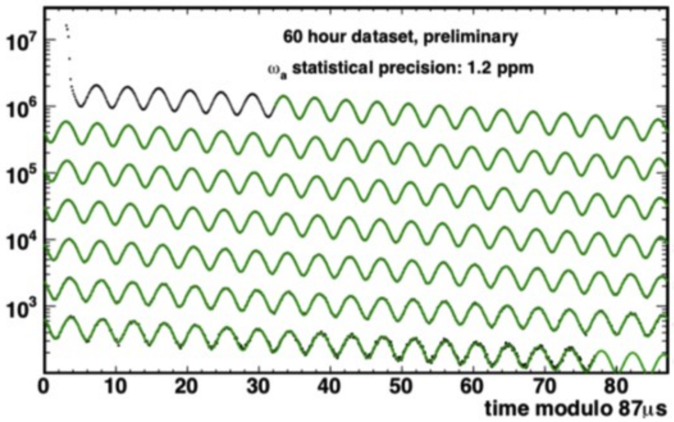
blinded ω_a blinded ω_a

Fitting function	no pileup correction			with pileup correction		
	χ^2/NDF	prob	R(ppm)	χ^2/NDF	prob	R(ppm)
5 par	2.24	~0	-43.5 +/- 1.41	1.97	~0	-44.4 +/- 1.40
9 par	1.33	~0	-42.3 +/- 1.43	1.04	0.04	-43.1 +/- 1.41
9 par + vertical CBO	1.27	~0	-42.3 +/- 1.41	0.99	0.69	-43.2 +/- 1.40
9 par + vCBO + LM	1.13	~0	-42.5 +/- 1.41	0.99	0.70	-43.3 +/- 1.40
varying CBO	1.13	~0	-43.1 +/- 1.41	0.98	0.78	-43.1 +/- 1.40

Work still in progress, statistical error is encouraging and is expected to improve when the energy weighted T analysis will be performed

BACKUP

Systematics on ω_a: phase shift



$$N(t) = N_0 e^{-t/\tau}[1 + A_\mu \cos(\omega t + \phi)]$$

If the phase is time dependent ("early-to-late" effect)

$$\omega t + \phi = \omega t + \phi(t) = (\omega + \phi')t + \phi_0$$

Frequency shifted!

- since *phase* and *amplitude* are energy dependent, any effect that *combines together different energies within the same fill* can cause a "phase shift"