ω_a analysis and INFN contribution

Marco Incagli – INFN Pisa

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The spin equation

- spin vector projection on momentum angle in presence of static **B** and **E** fields changes with time according to:

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

- neglecting beam size and oscillations, assuming that all muons momentum is $p_{magic}=3.01 GeV/c$ and is perpendicular to B, than the above expression greatly simplifies to:

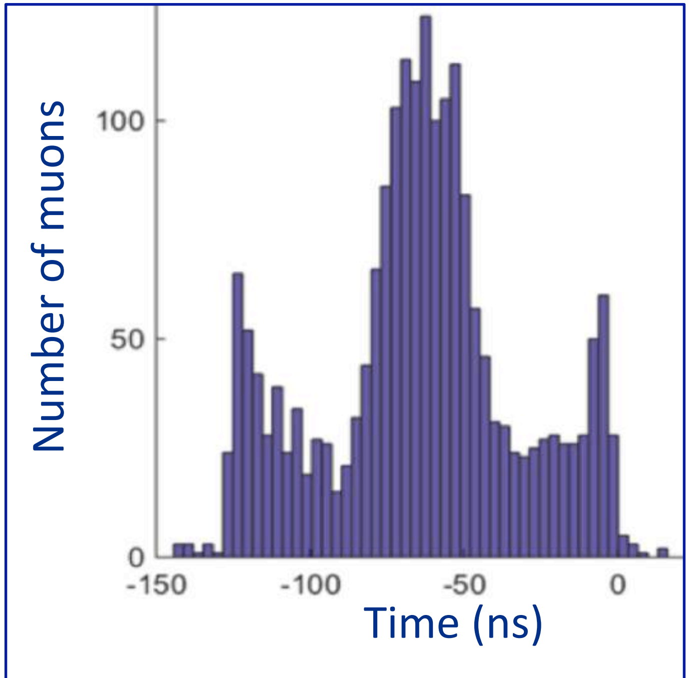
$$\omega_a = \omega_\mu - \omega_c = a_\mu \frac{e}{m} B$$

$\omega_{\mu,p}$ = precession
ω_c = cyclotron

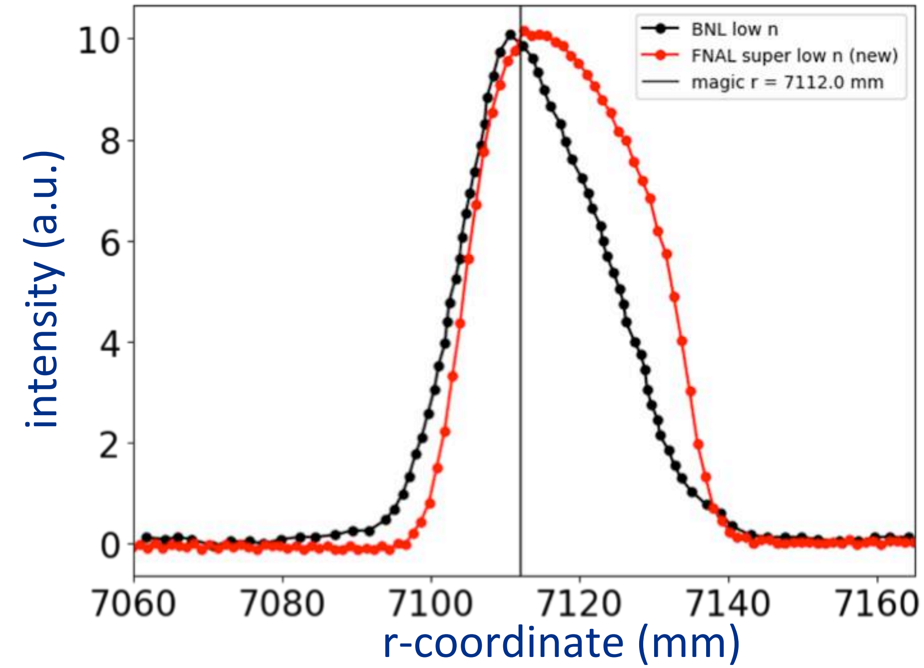
- from which:

$$a_\mu = \frac{g_e}{2}\frac{m_\mu}{m_e}\frac{\mu_p}{\mu_e}\frac{\omega_a}{\omega_p} = \frac{R_\mu}{\lambda - R_\mu} \quad ; \quad R_\mu = \frac{\omega_a}{\omega_p} \quad , \quad \lambda = \frac{\mu_\mu}{\mu_p}$$

- the simple expression of previous slide has to be corrected by many effects, like beam dimensions, momentum dispersion, betatron oscillations (radial and vertical), ...



Intensity profile is 120 ns wide with "W" shape (orbit time = 149 ns)



Radial profile corresponding to a ring acceptance $\Delta p = \pm 0.5\%$; asymmetry due to not perfect kick

g-2: two "different" experiments

- need to measure ω_a and ω_p with an accuracy of 70 ppb !

- Source of uncertainty on ω_p:

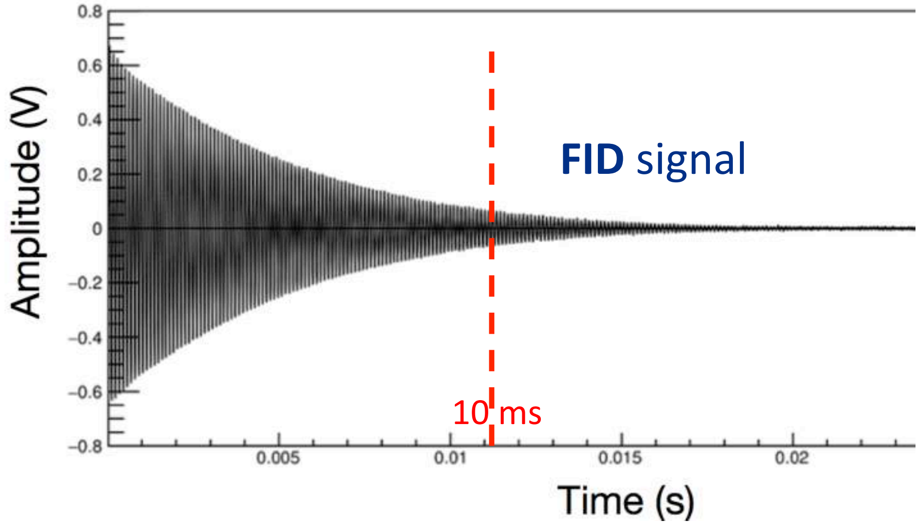
E821 @ Brookhaven

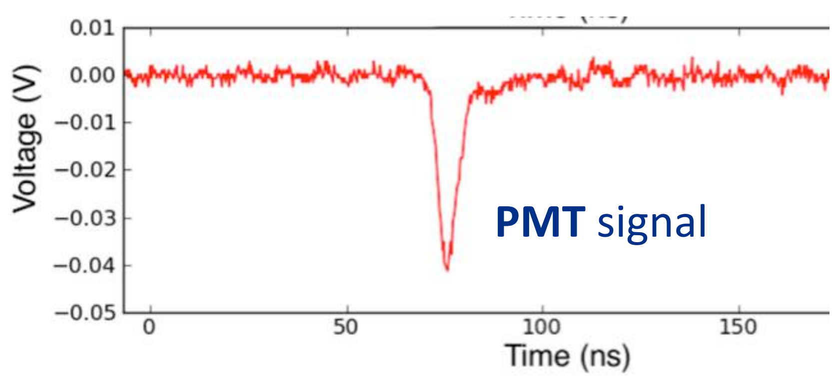
E989 @ Fermilab

Source of uncertainty	R01 [ppb]	E989 [ppb]
Absolute calibration of standard probe	50	35
Calibration of trolley probes	90	30
Trolley measurements of B_0	50	30
Interpolation with fixed probes	70	30
Uncertainty from muon distribution	30	10
Inflector fringe field uncertainty	–	–
Time dependent external B fields	–	5
Others †	100	30
Total systematic error on ω_p	170	70

how do we measure ω_p - 1

- *Pulsed Nuclear Magnetic Resonance on "free" protons:*
  - Protons are aligned in magnetic field
  - Apply a $\pi/2$ shift by an external pulse
  - With the same coil, pick up the *Free Induction Decay (FID)* signal

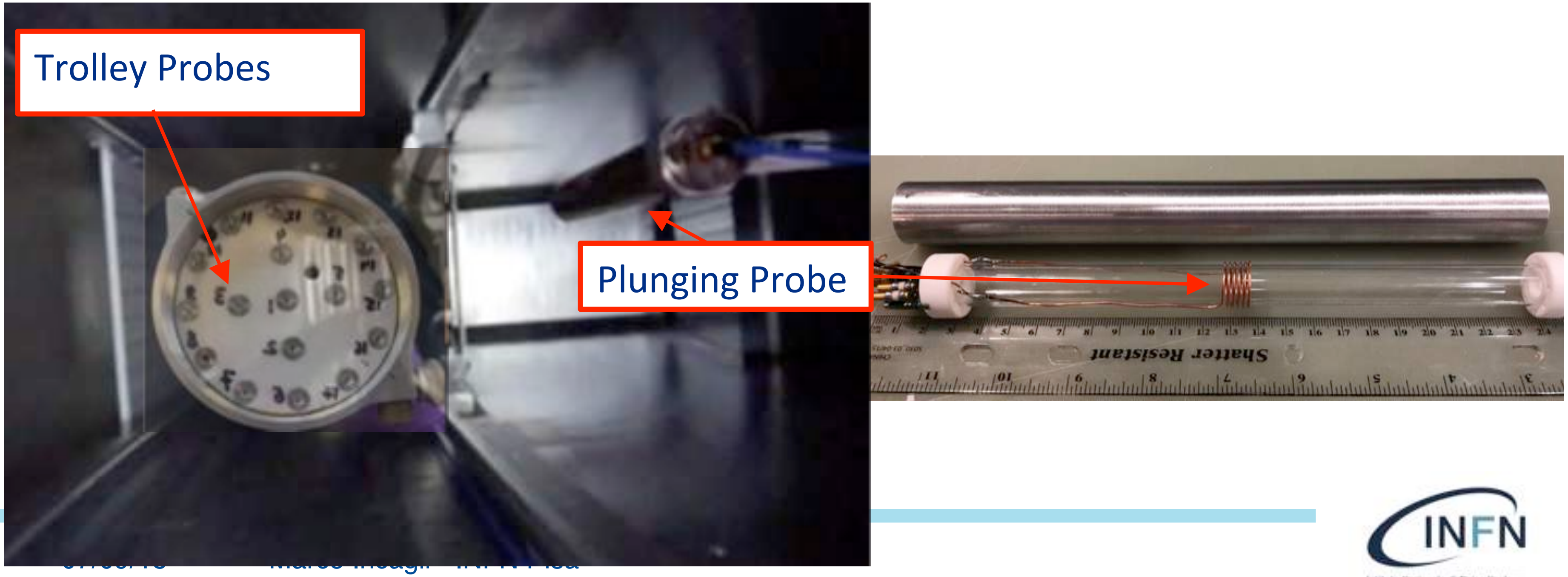




- The FID signal is the basis of the magnetic field measurement as a PMT pulse for the energy measurement

how do we measure ω_p - 2

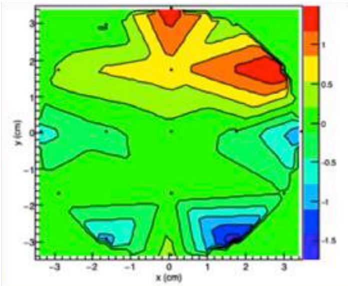
- local measurement with a set of 17 probes mounted on a trolley ~1 run every 3 days (1 run takes 2-3 hours)
- time interpolation: a set of 378 fixed probes measure the field
- the fixed probes are not at the same location as the trolley probes → space interpolation
- absolute calibration: a *plunging probe* is inserted periodically in the trolley garage to measure the field in the same location (with ~mm precision)



How do we measure ω_p - 3

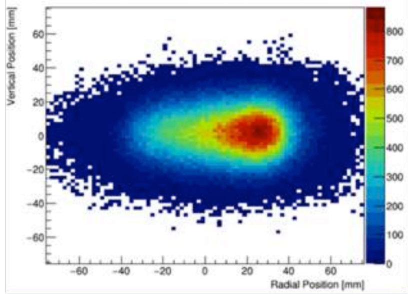
$$a_\mu = \frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}\frac{\omega_a}{\tilde{\omega}_p}$$

NMR map of field



X

Muon distribution



X

Field

$$B(r,\theta) = \sum_{n=1}^{\infty} r^n (c_n \cos n\theta + s_n \sin n\theta)$$

Beam

$$I_0 = \int_0^{r_0}\int_0^{2\pi} M(r,\theta) r dr d\theta$$

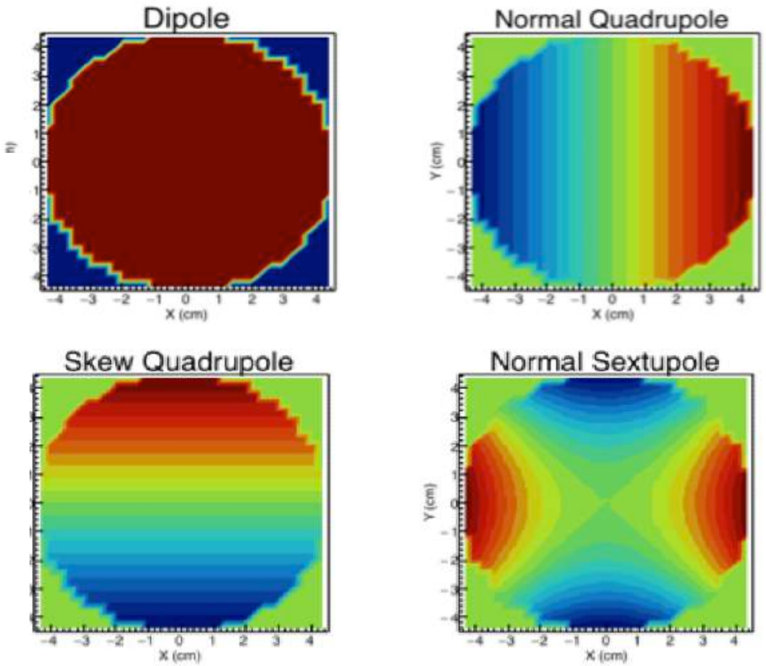
$$I_n = \int_0^{r_0}\int_0^{2\pi} r^n M(r,\theta) \cos n\theta r dr d\theta$$

$$J_n = \int_0^{r_0}\int_0^{2\pi} r^n M(r,\theta) \sin n\theta r dr d\theta.$$

The average field seen by the muons is then given by

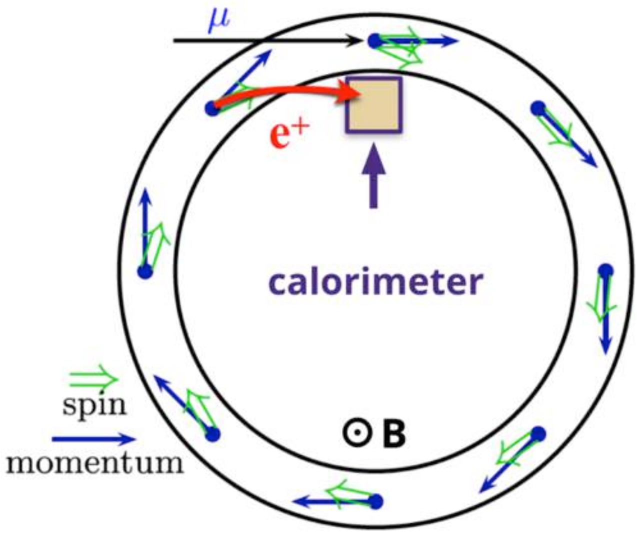
Convolution

$$\bar{B} = c_0 + \frac{1}{I_0}\sum_{n=1}^{\infty}(c_n I_n + s_n J_n).$$

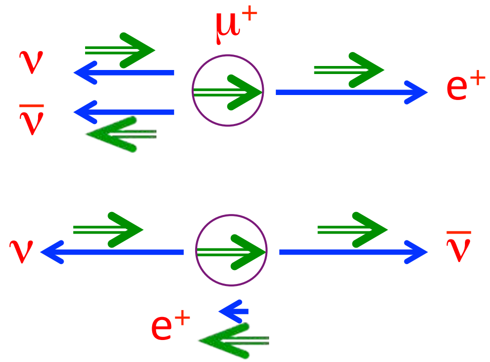


wa principle of measurement

- spin rotates faster than momentum in costant B
- positron direction correlated with spin direction
- correlation depends on *positron momentum fraction*: $y = \frac{p_e}{p_e^{MAX}}$

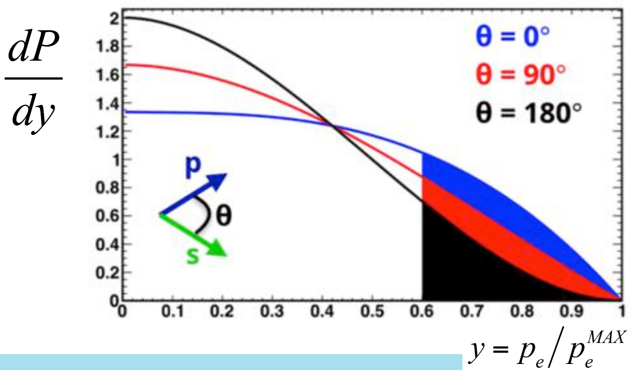


μ+ Center of Mass

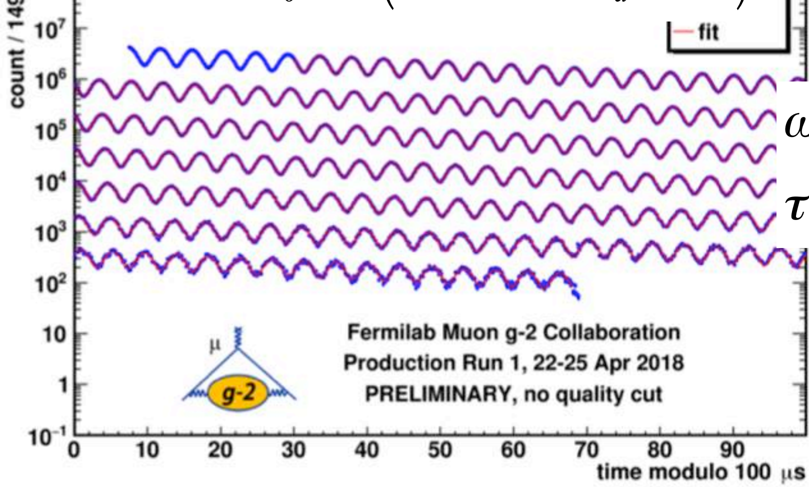


Maximum p : parallel

Minimum p : antiparallel



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

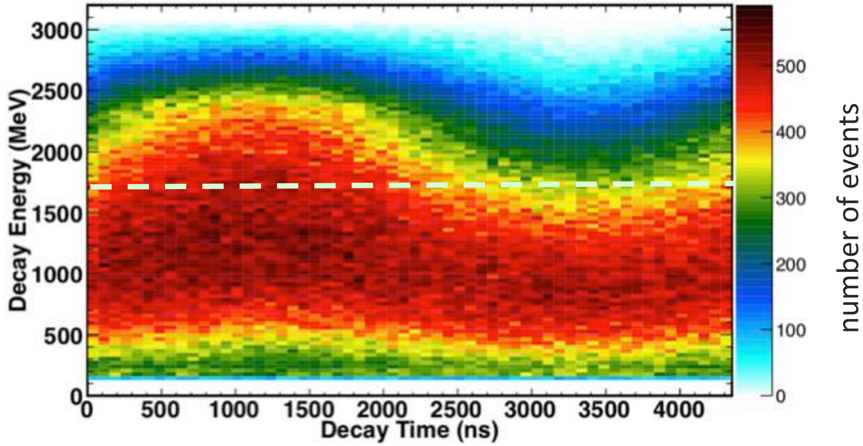


$\omega_a \sim 240\ \mathrm{k}Hz$

$\tau_a \sim 4.4\ \mu s$

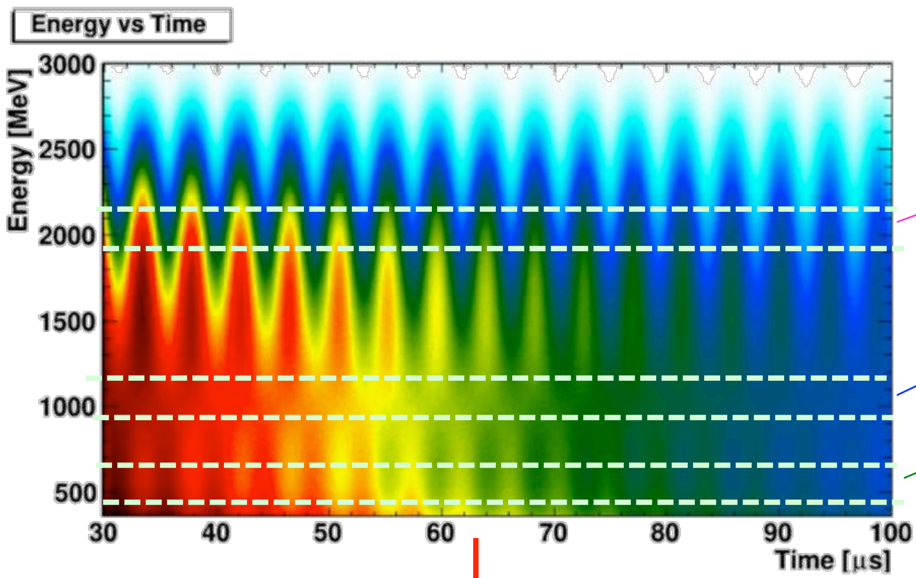
Three methods to obtain ω_a

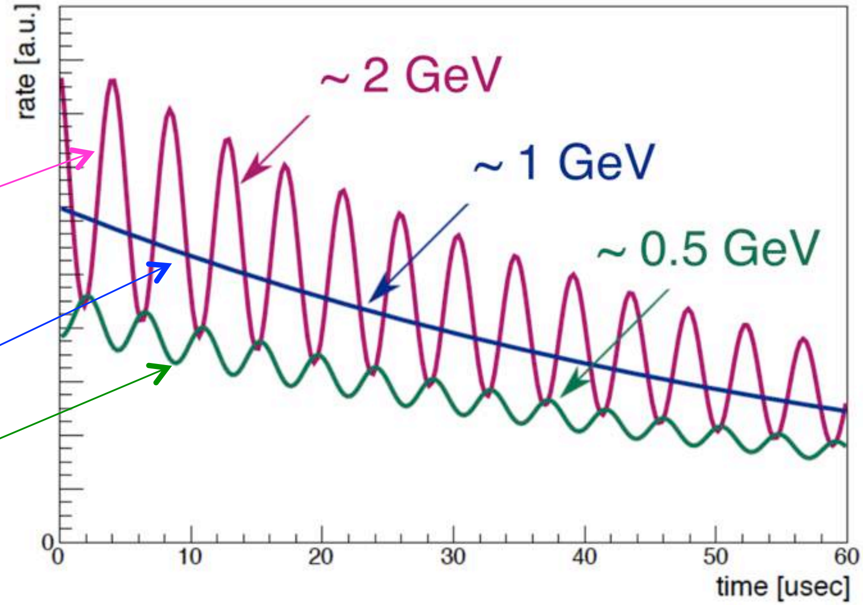
- **T-method (time)**: count number of positrons above threshold
  - Reconstruct single positron events
  - Number of events per (E,t) bin

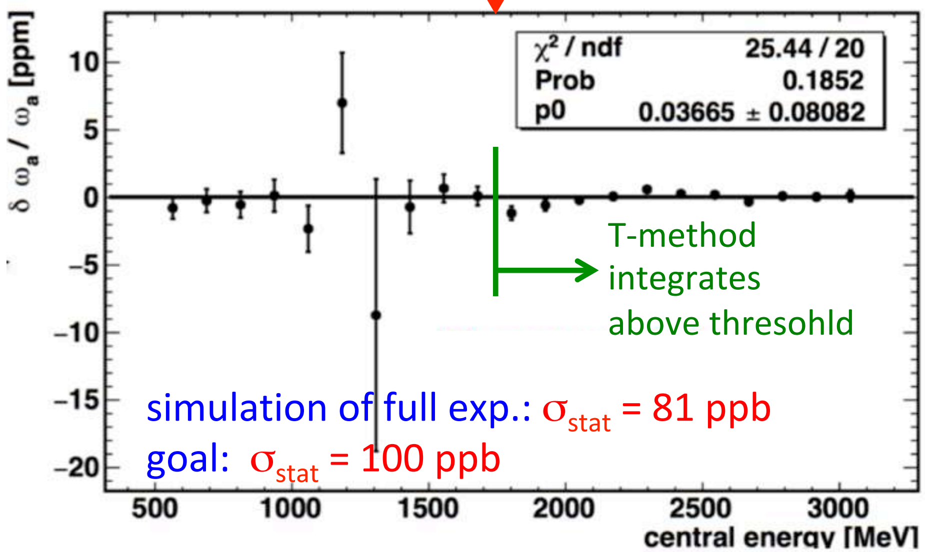


- **Q-method (charge)**: integrate all the charge, possibly with no (or minimal) threshold
  – no need to reconstruct single positrons, avoid clustering
- **R-method (ratio)**: randomly split half the dataset in 2 subsets shifted by ±half a g-2 period
  – build combinations which eliminate the exponential behaviour and leave just a sinusoidal term

T, E-weighted sub-method







- Each energy bin has a different *Asymmetry* and *Phase* value
- Fitting each slice separately allows to use positrons down to 500 MeV

The analysis strategy

- 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

The analysis strategy

- 7 independent analysis groups using different *Reconstruction algorythms* and different *Fit methods*
- 3 Independent Reconstruction algorythms developed (Q, East, West); a 4th one under construction by the Europa team

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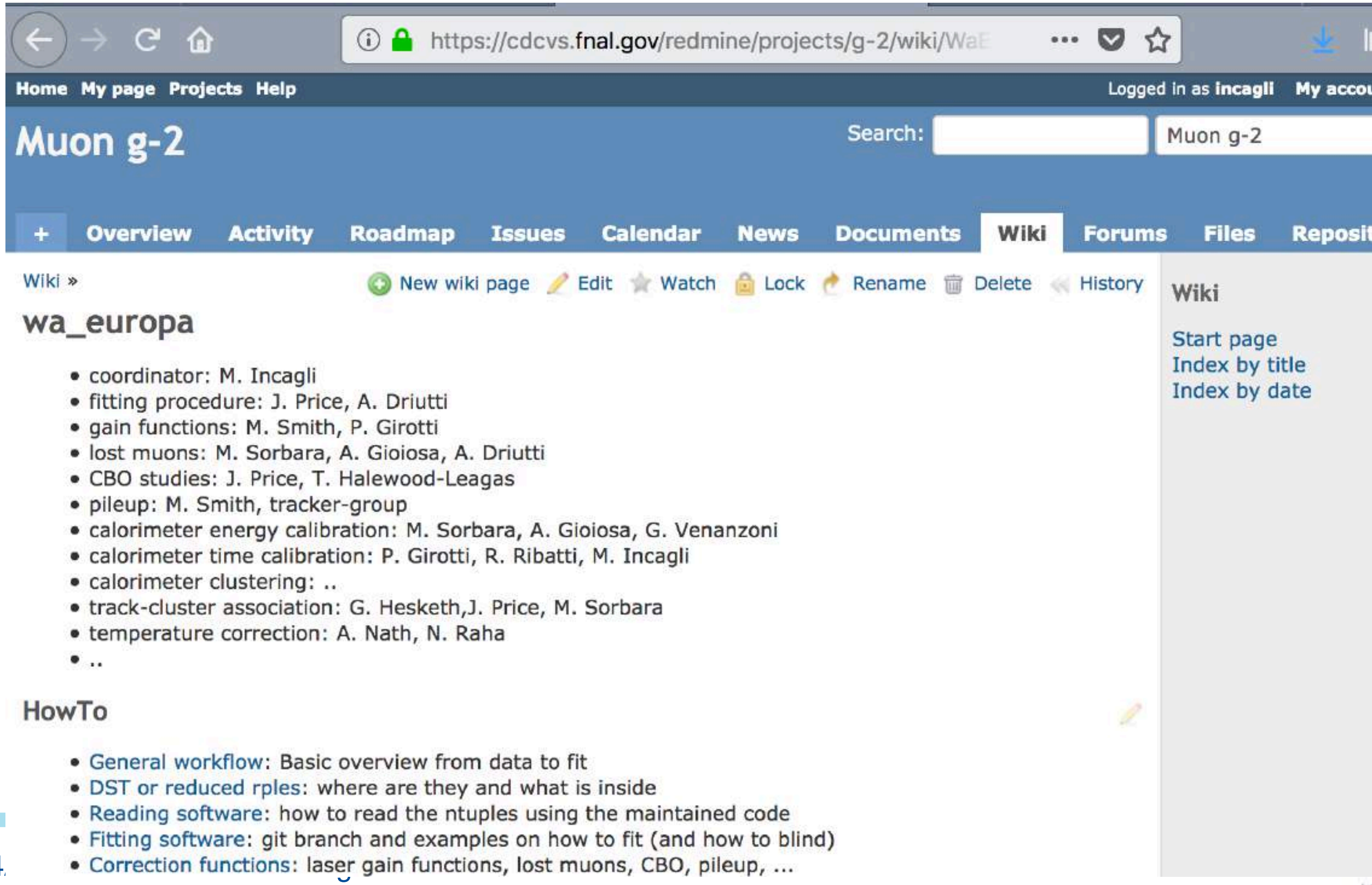
The Europa group

- An analysis group has been formed by italian and english institutions, with specific competences on *laser calibration* (gain) and *tracker reconstruction* (muon beam profile)



Systematics on ω_a

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

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

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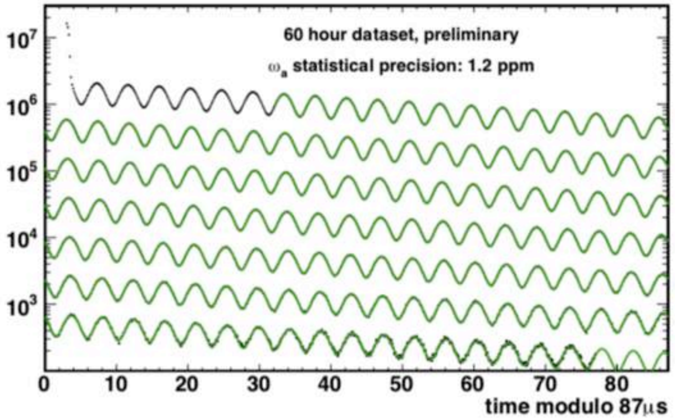
Systematics on ω_a: phase shift



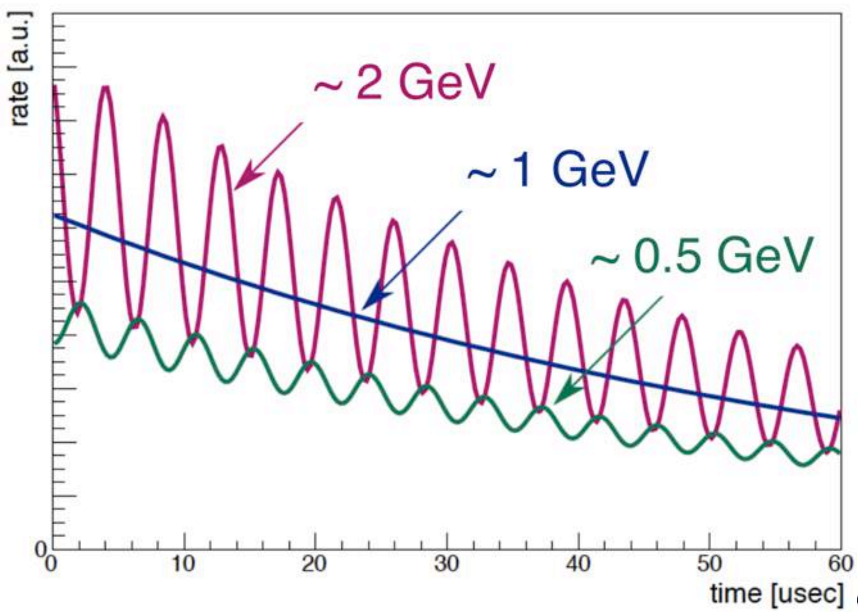
$$N(t) = N_0 e^{-t/\tau}[1 + A_\mu \cos(\omega t + \phi)]$$

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

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

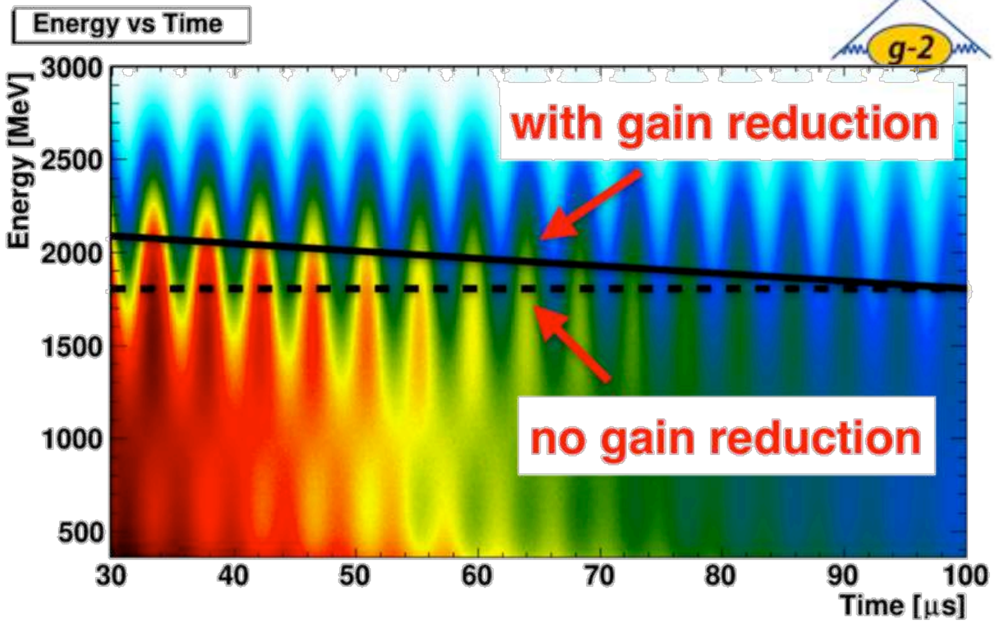
Frequency shifted!

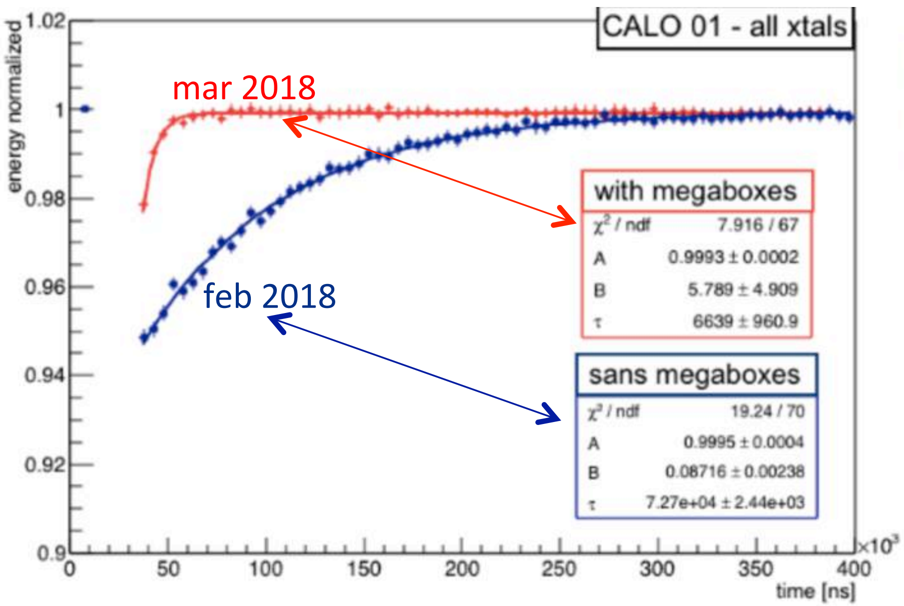
- since *phase* and *amplitude* are energy dependent, any effect that *combines together different energies within the same fill* can cause a "phase shift"



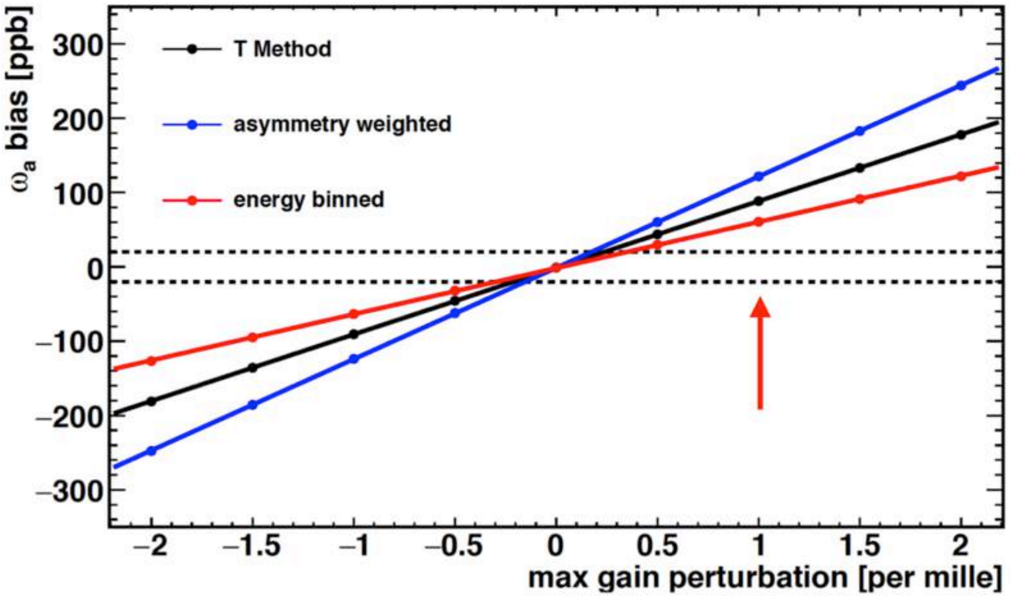
Gain stability

- Gain variation during fill "mixes" different energies
- Laser system: fundamental tool
- Analysis totally performed by INFN, correction functions in official production





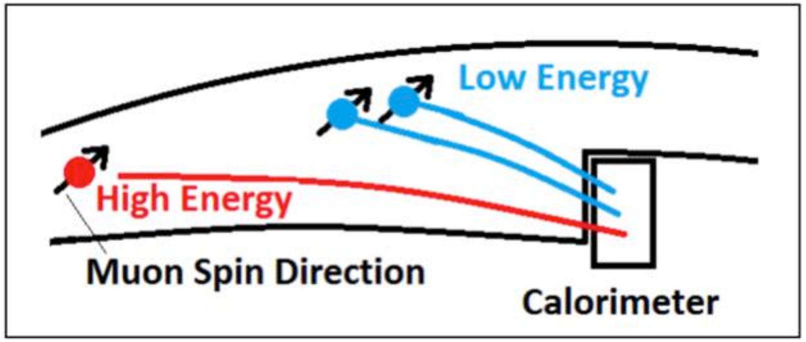
laser gain monitoring system measured 0.1% perturbation at 30 us

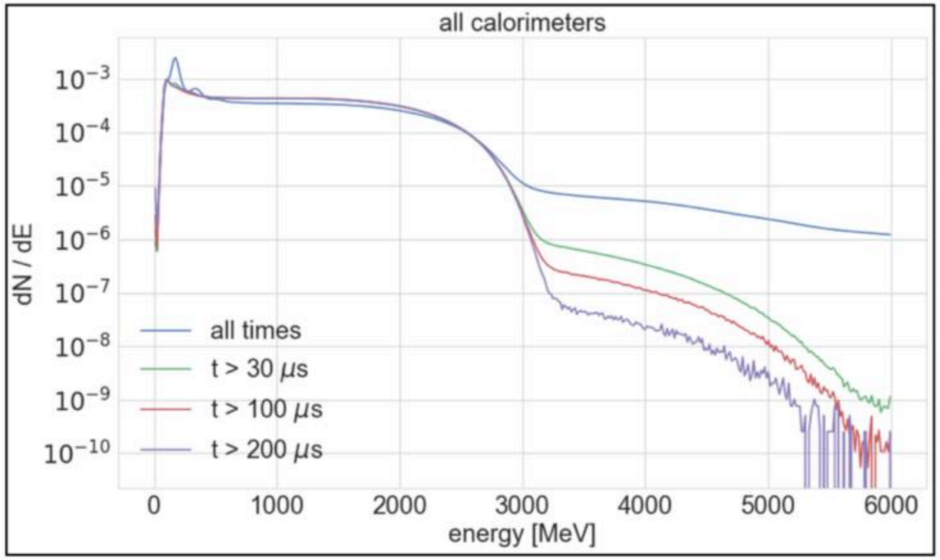


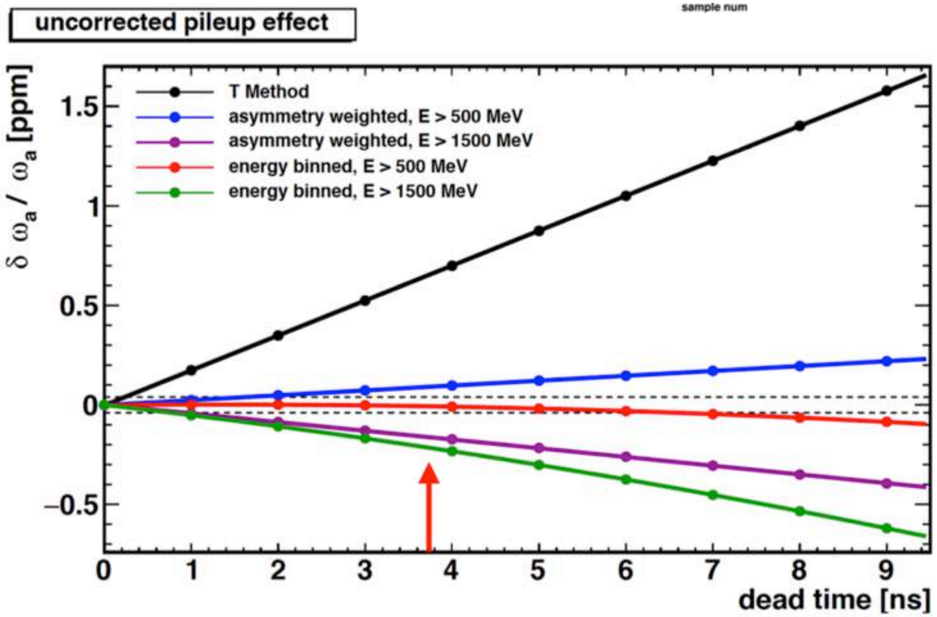
50-150 ppb bias is expected for uncorrected in-fill gain perturbation

Pile up

- 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
- *wa-europa group just started working on this* (calo+tracker)



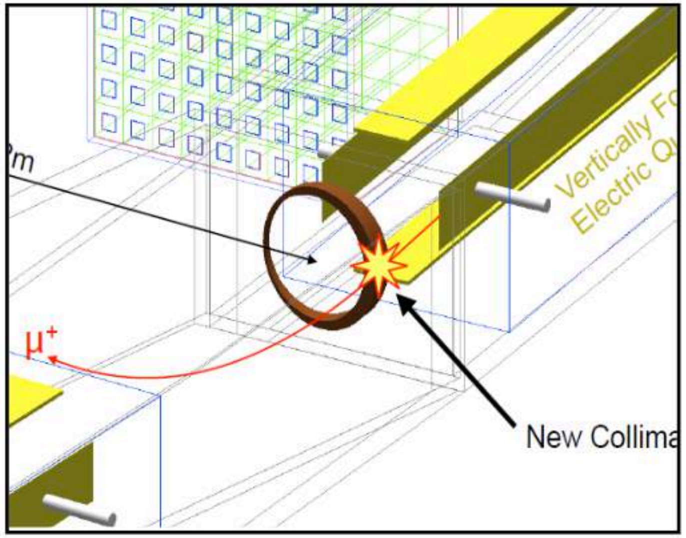




Distorting muon life time: lost muons

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

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



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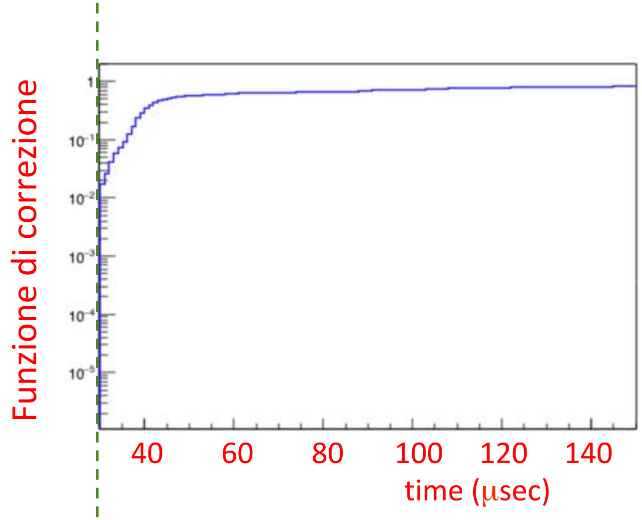
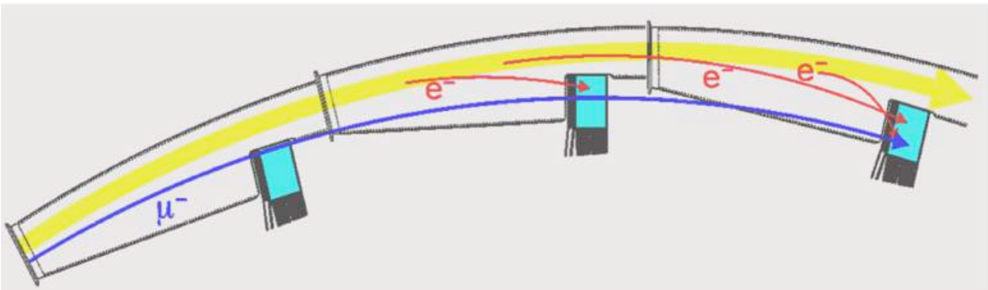
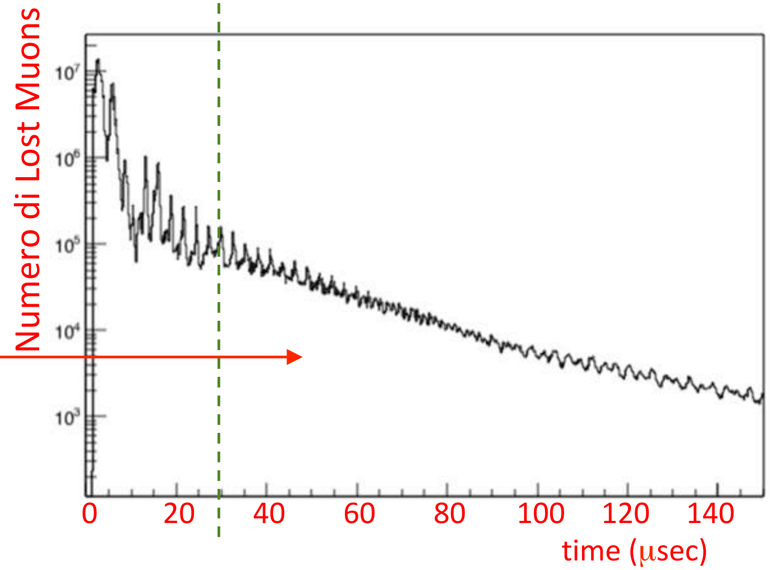
$$N(t) = N_0 e^{-t/\tau} \cdot \left(1 - A_{LM} I(t)\right) \cdot \left(1 + A\cos(\omega_a t + \varphi)\right)$$



- Lost muons selected as MIP particles which hit 2 (or 3) calos with Δt=6.2 ns

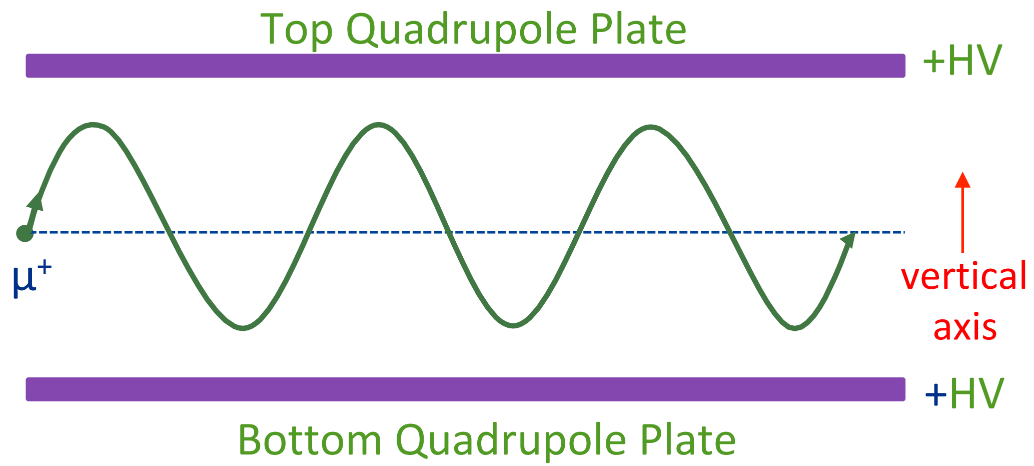


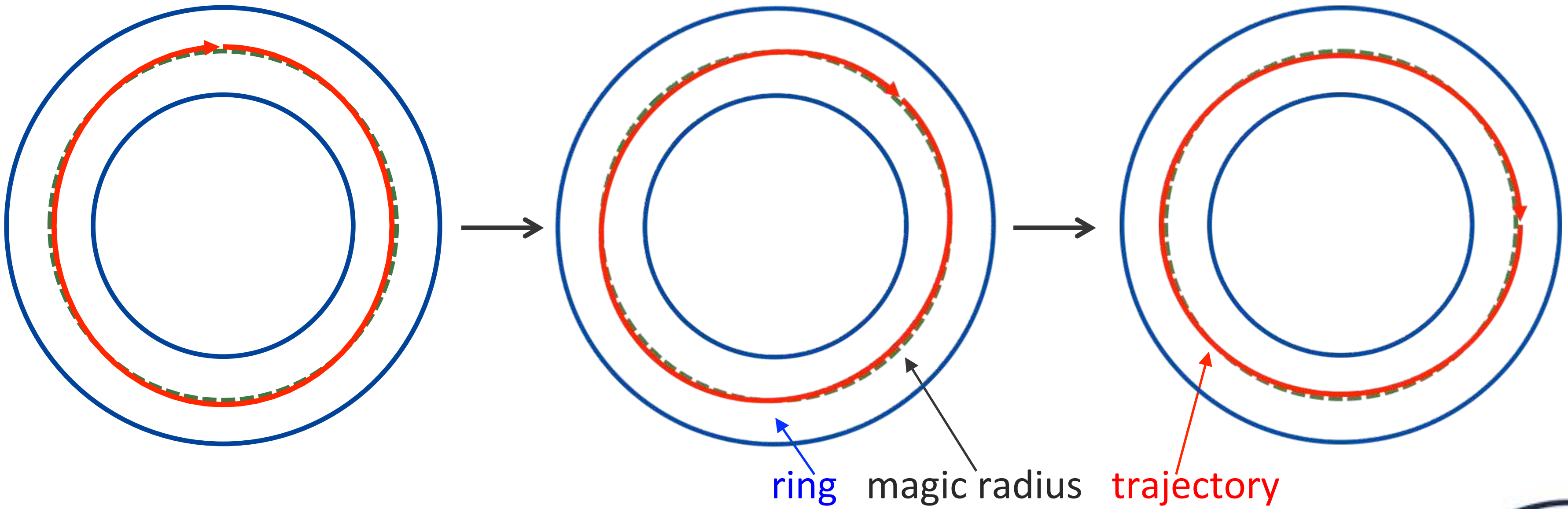


- Fraction of lost muons for t>30μs is $<10^{-4}$
- *wa-europa: Sorbara, Gioiosa, Driutti*

Beam oscillations

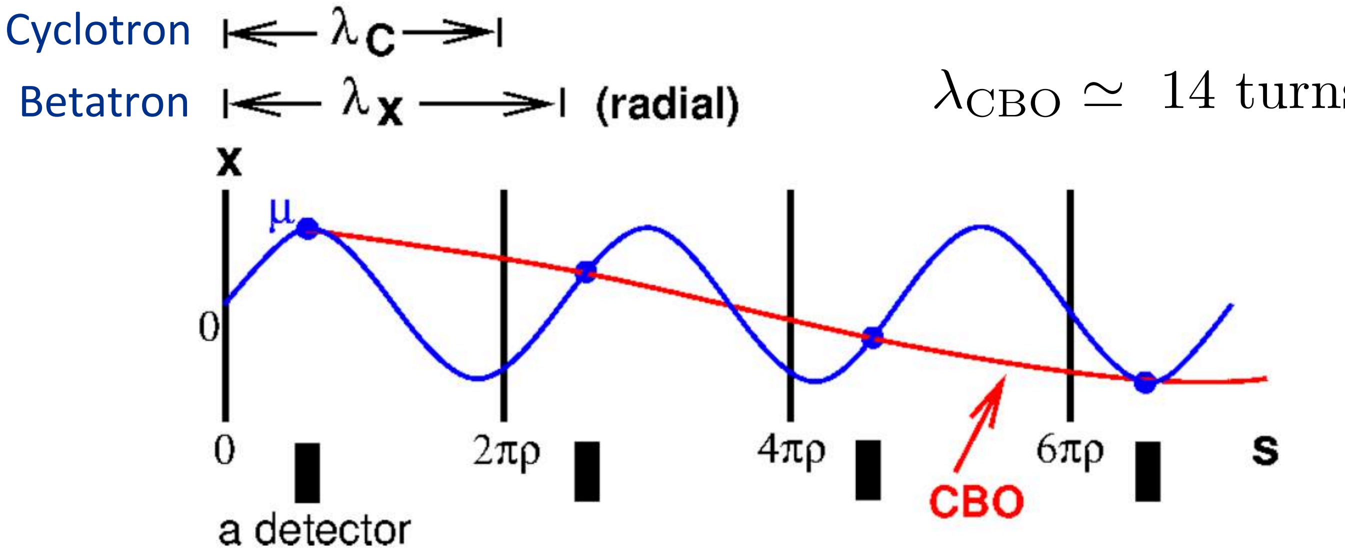
- The beam "oscillates" both radially and vertically, mostly due to the effect of the electrostatic quadrupoles





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)



$\lambda_{\mathrm{CBO}} \simeq 14$ turns

- 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

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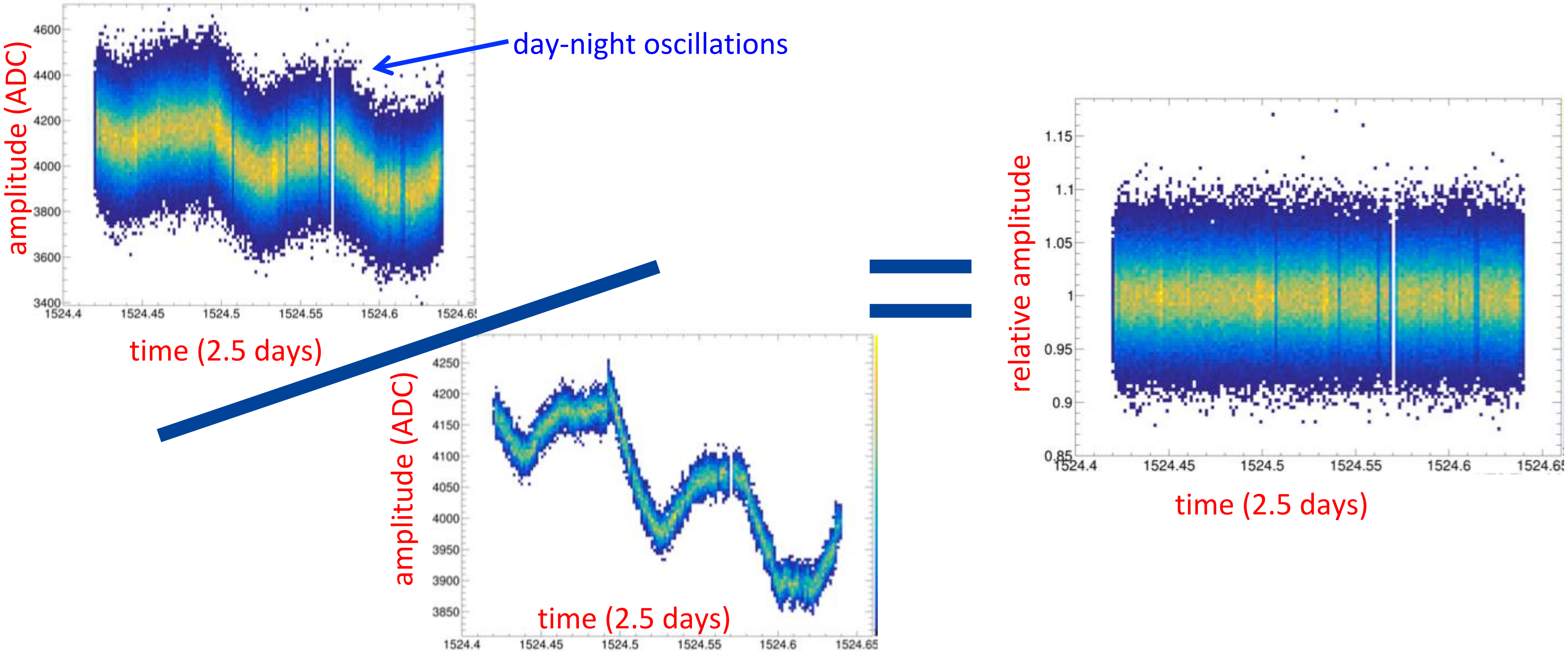
Additional systematic: temperature stability

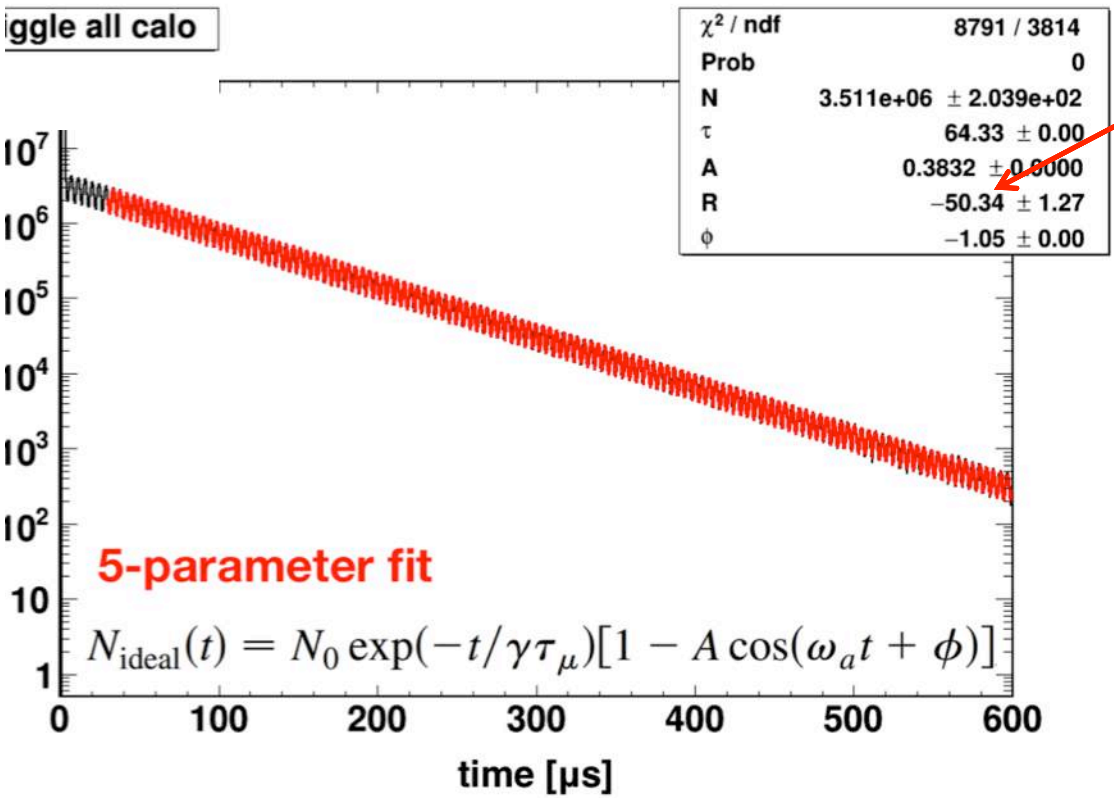
- Laser data are used to correct SiPM response for environmental instabilities: mostly temperature variations (but also pressure, humidity, ...)



- Software: the laser temperature stability is monitored using Local (Atanu) and Source (Nandita + Anna) Monitors
- Hardware: hall temperature control is being improved to reduce Δt

The 60h dataset: 5-par fit

- First "challenge": analysis 24-26 april data, 2.5 days between 2 trolley runs, *~10^9 positrons* *(Run1 ~1.2×10^{10} ; TDR ~1.6×10^{11})*



NOTE: blinding on ω_a!

Digression: blinding

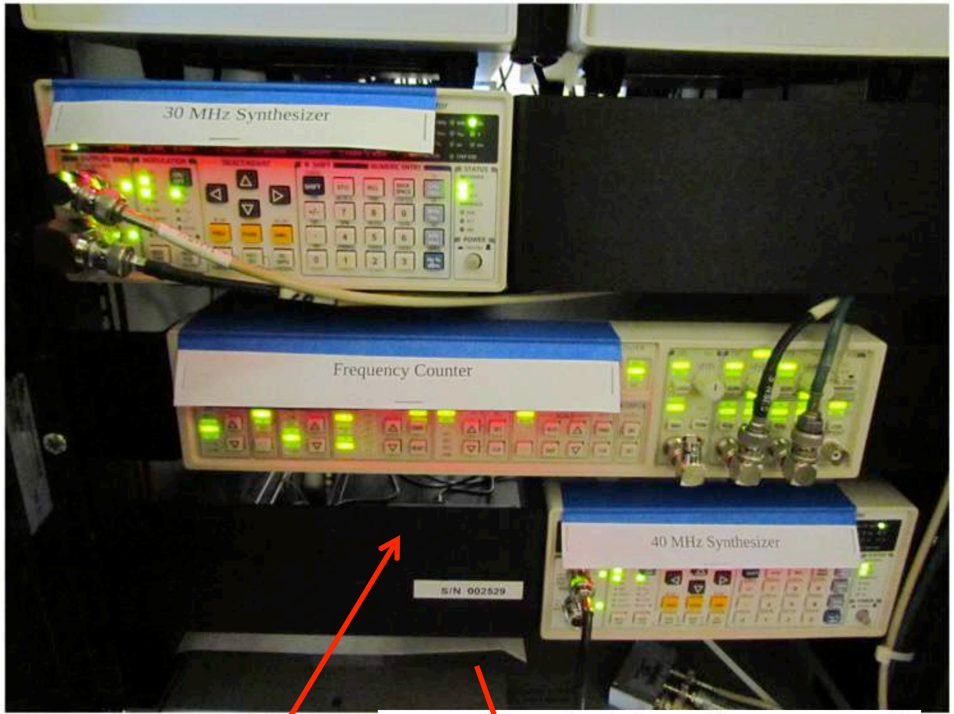
HARDWARE BLINDING ω_a

THE GREG AND JOE MANUAL

1. Setting **ε** and **δ**
    - General considerations
        - 25 ppm within nominal central value: “40 MHz” ⟹ ±1 kHz
            - range will be adjusts as expected precision of datasets increases
        - Dave H: 40.000011 vs 39.999989 too easy to distinguish
        - Central value for reconstruction = range midpoint 39.998 MHz
    - Procedure
        1. Get trained on setting / reading clock synthesizer
        2. Choose “40+**ε**” in range 39.997 to 39.999 MHz (draw from flat distribution)
        3. Choose “30+**δ**” in range 29.997 to 29.999 MHz
        4. Greg and Joe individually record both values: compare notes
            1. Each stores a record for use in monitoring
            2. Copies in sealed, signed envelopes sent to UW, UCL admin

Digression: blinding

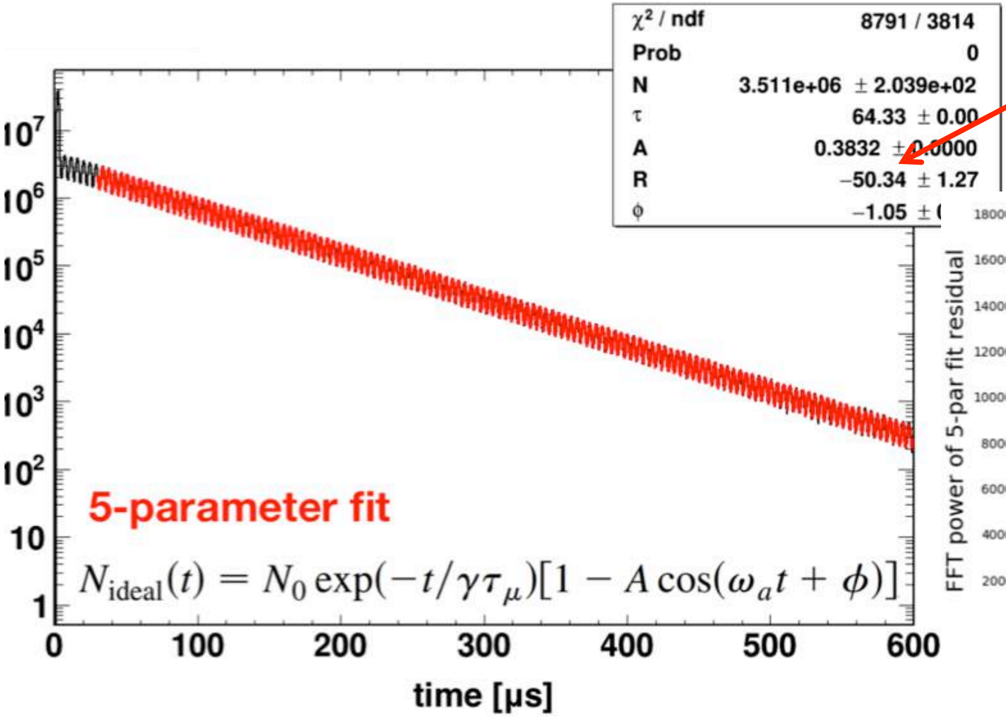
- Greg and Joe enthusiastically blinding the clock



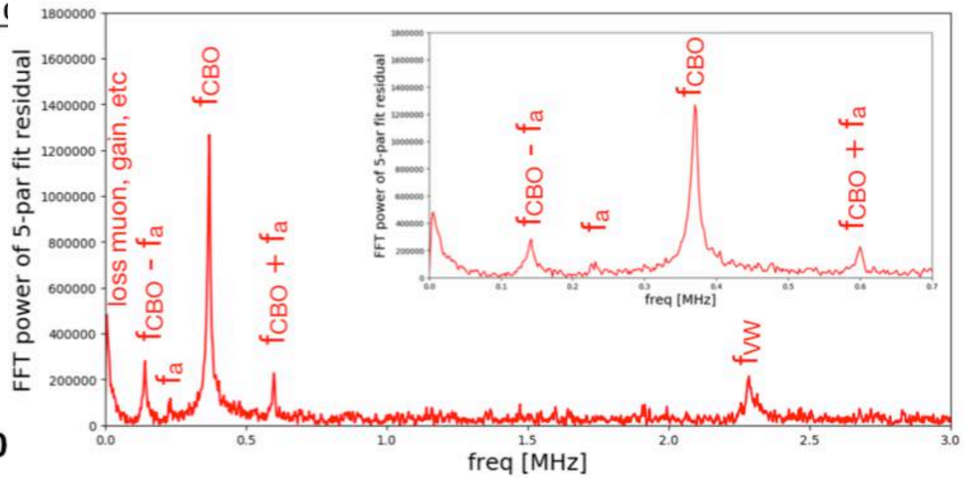
Locked Clock Panel

The 60h dataset: 5-par fit

- Back to the analysis: the residuals *data-fit* show structures
- In particulare typical resonances are observed in the FFT



NOTE: blinding on ω_a!



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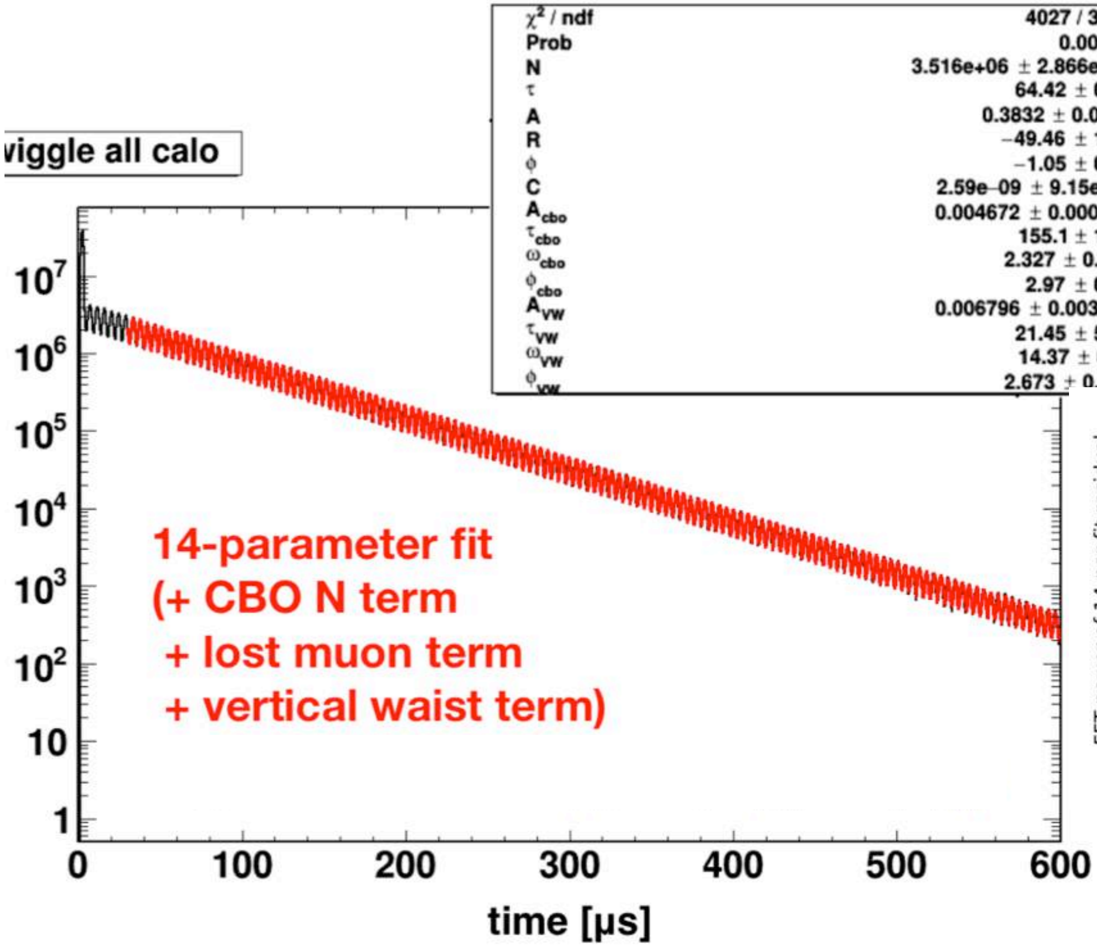
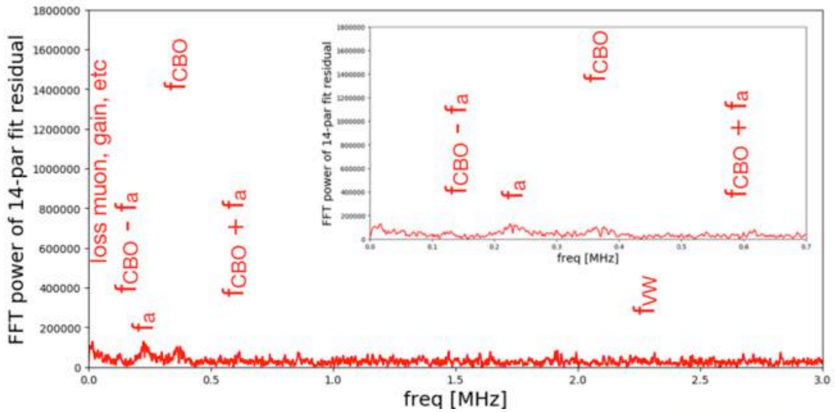
14-par fit

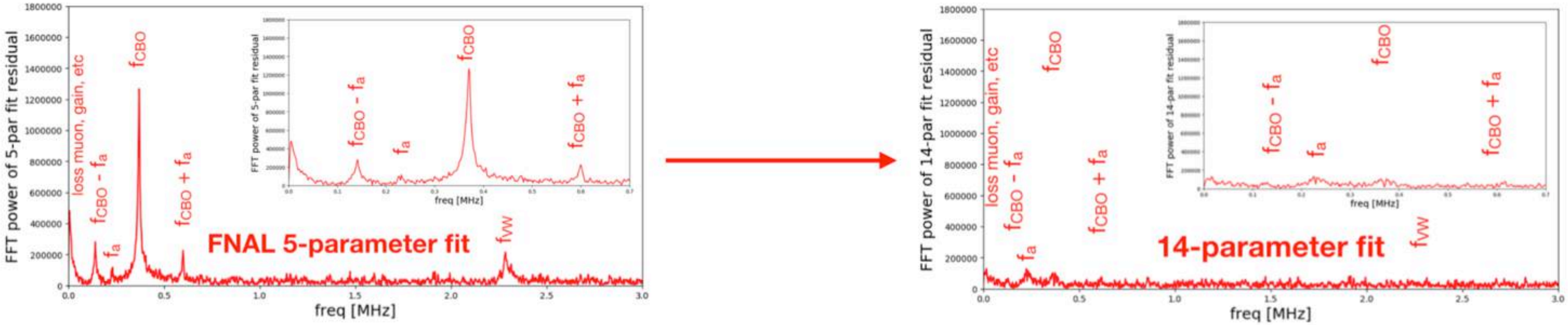
- By including in the fit also the corrections discussed above (lost muons, beam oscillations, pileup, gain corrections) the residuals show (almost) no structure





First summary of 60h dataset

- With 2.5 days of Run1, the value of wa is determined with a statistical error of 1.27 ppm
- Still work to be done on systematics!



Fit type	5-par	9-par	10-par	14-par
Physics	ω_a	CBO (N)	lost muon	vertical waist
Chi2/NDF	8791/3814 ~ 2.30	5010/3810 ~ 1.31	4212/3809 ~ 1.11	4027/3805 ~ 1.06
lifetime (μs)	64.335(2)	64.334(2)	64.424(4)	64.424(4)
Blinded R (ppm)	-50.34(1.27)	-49.07(1.27)	-49.44(1.27)	-49.46(1.27)
CBO lifetime (μs)	-	160(12)	155(11)	155(11)
VW lifetime (μs)	-	-	-	21(5)

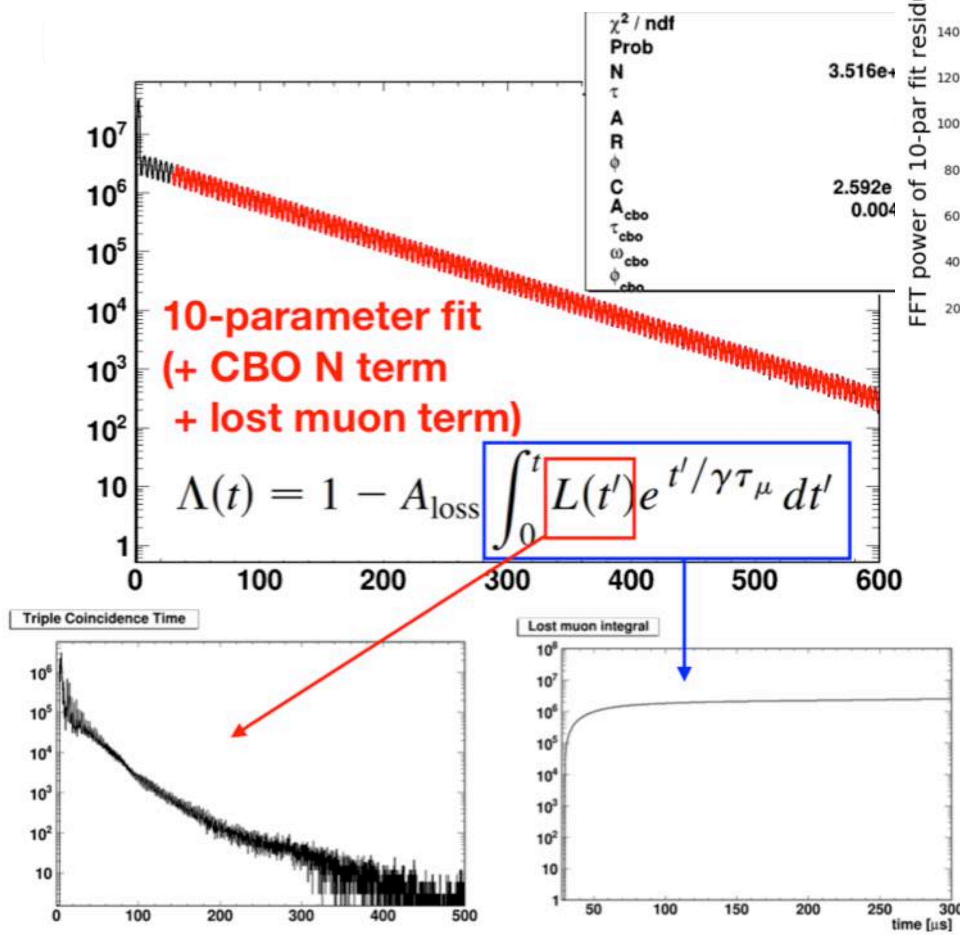
Conclusions

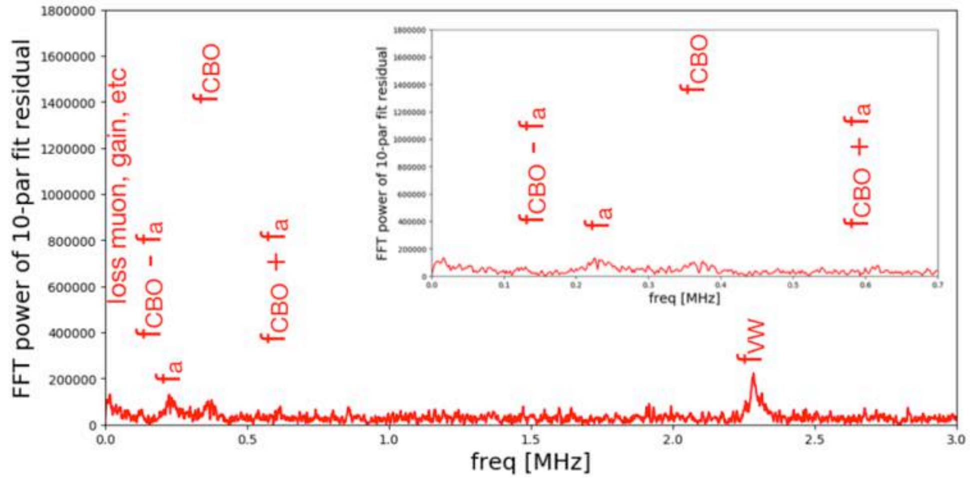
- Analysis structure well defined, both for ω_p and for ω_a
- Goal is to publish in 2019 (~summer) on data collected in 2018 with error similar to BNL → important check of central value!
- INFN team well inserted into the analysis and reconstruction flow with leadership and many key-roles in one group (wa-europa) and with other istitutional positions

BACKUP

10-par fit: adding lost muons

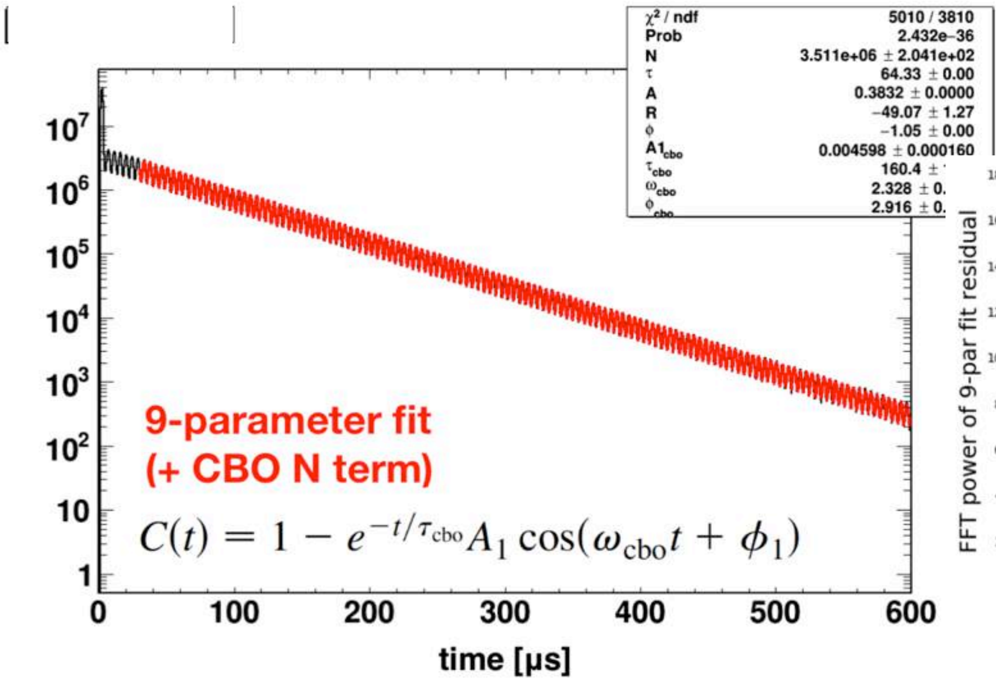
- The lost muon correction improves the fit at short times
- This correction has no particular time structure, so it appears as a peak at *f=0* in the FFT plot

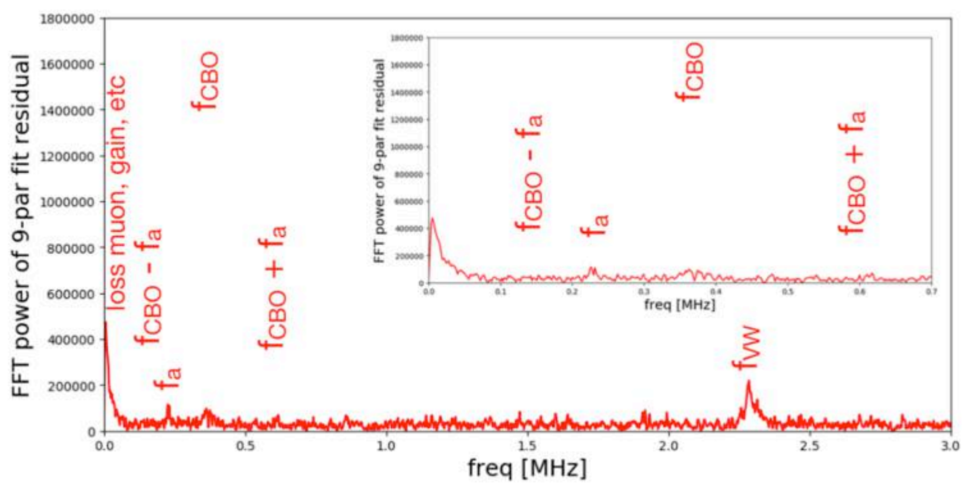




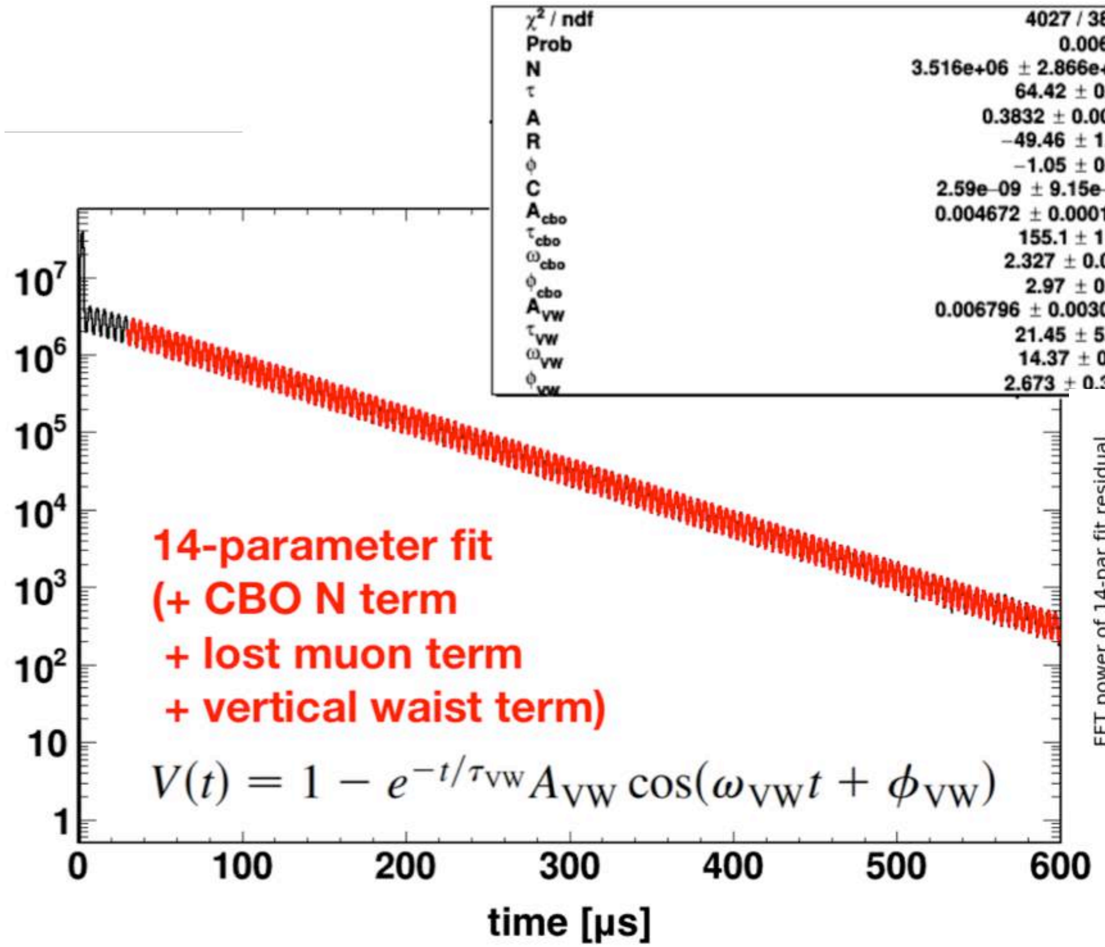
9-par fit

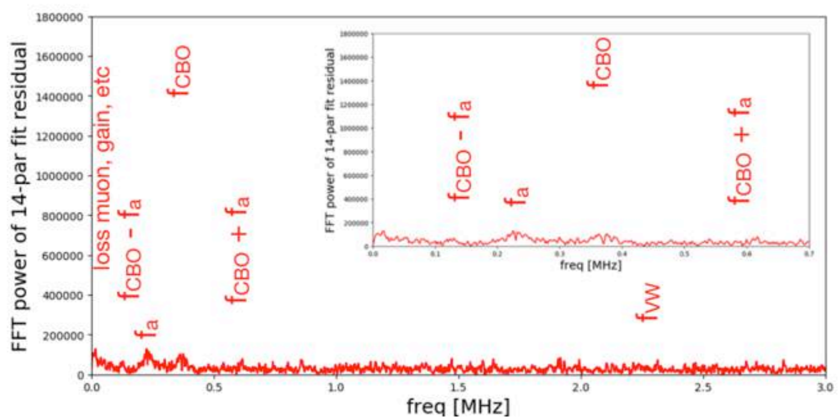
- The effect of Coherent Betatron Oscillation is parametrized as a factor with similar structure as the muon modulated decay
- In fact the CBO shows a frequency which depends on time → more exact correction to be applied





14-par fit: adding vertical oscillation

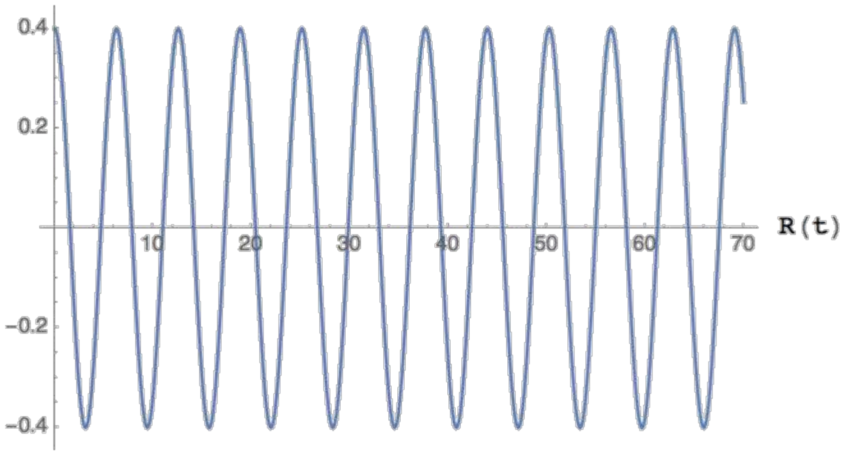




R-method

- Ratio method: randomly split dataset in 2 subsets shifted by ±half a g-2 period
- Build combinations of the 2 subsets which eliminates the exponential behaviour and leaves just a sinusoidal term

$$u^{\pm}(t) = N(t \pm \mathrm{T}/2) = N_0 e^{-t/\tau \mp T/2\tau}\left(1 + A\cos(\omega_a t \pm \omega_a \frac{T}{2} + \varphi)\right)$$



$$U(t) = u^{+}(t) + u^{-}(t)$$

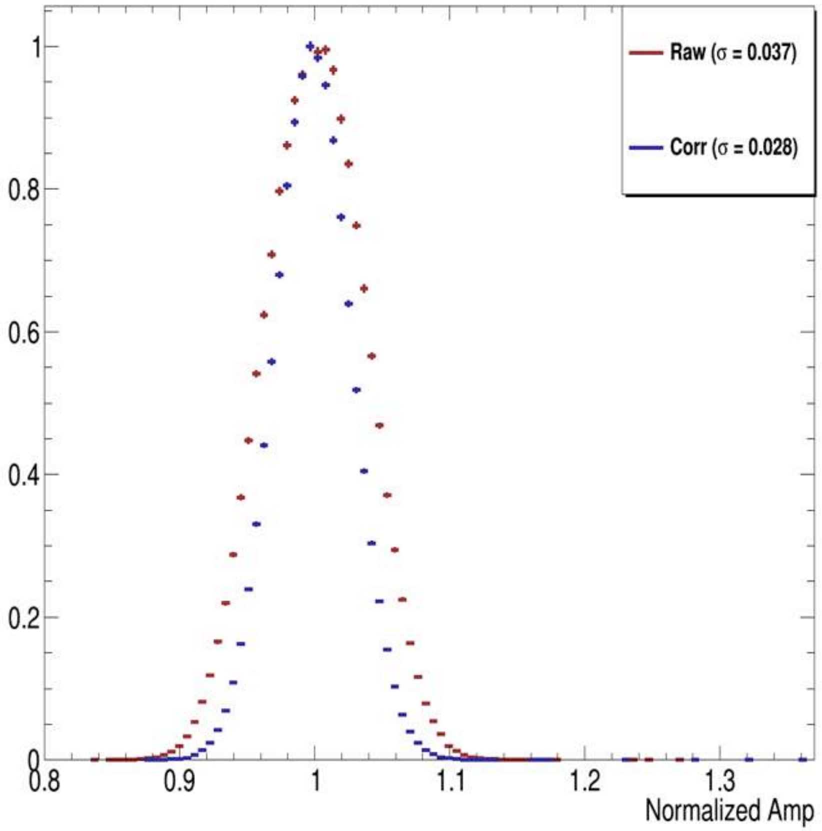
$$R(t) = \frac{N(t) - U(t)}{N(t) + U(t)}$$

$$R(t) = A\cos(\omega_a t + \phi) - \frac{1}{16}(\frac{T}{\gamma\tau})^2 + (h.o.)$$

3 parameters fit: less sensitive to slow effects which divide out

Energy Spread After Out-of-fill Correction

In-fill Laser SiPM Pulse Energy Distribution



- Around this energy expect ~3.1% resolution from SiPM
- Find 2.8% including laser fluctuations

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