Status of a_μ analysis

Marco Incagli – INFN Pisa

Pisa, 2 July 2019

The spin equation

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

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

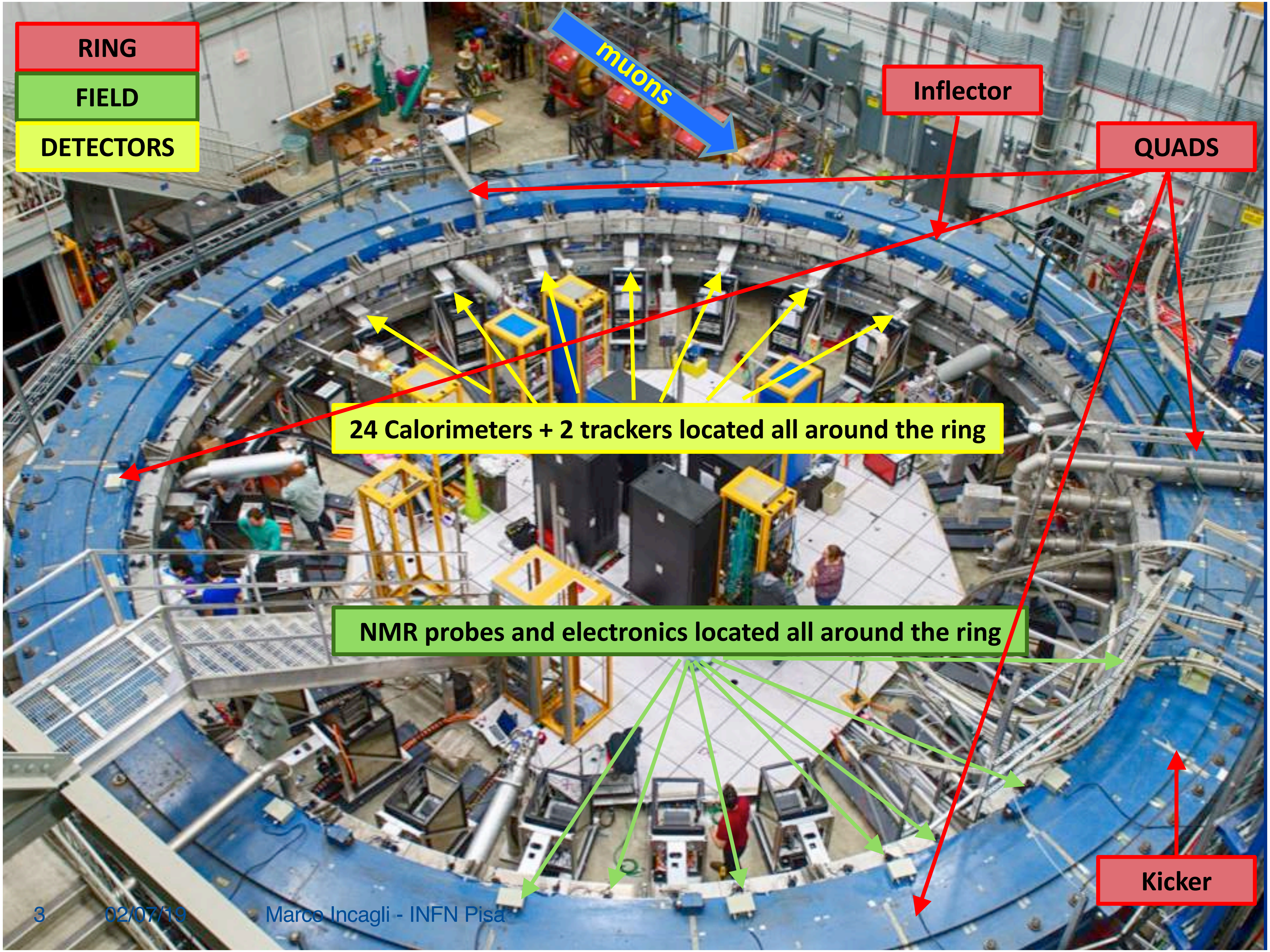
- neglecting beam size and oscillations, assuming that all muons momentum is p_{magic}=*3.01GeV/c* and is perpendicular to B, than the above expression greatly simplifies to:

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

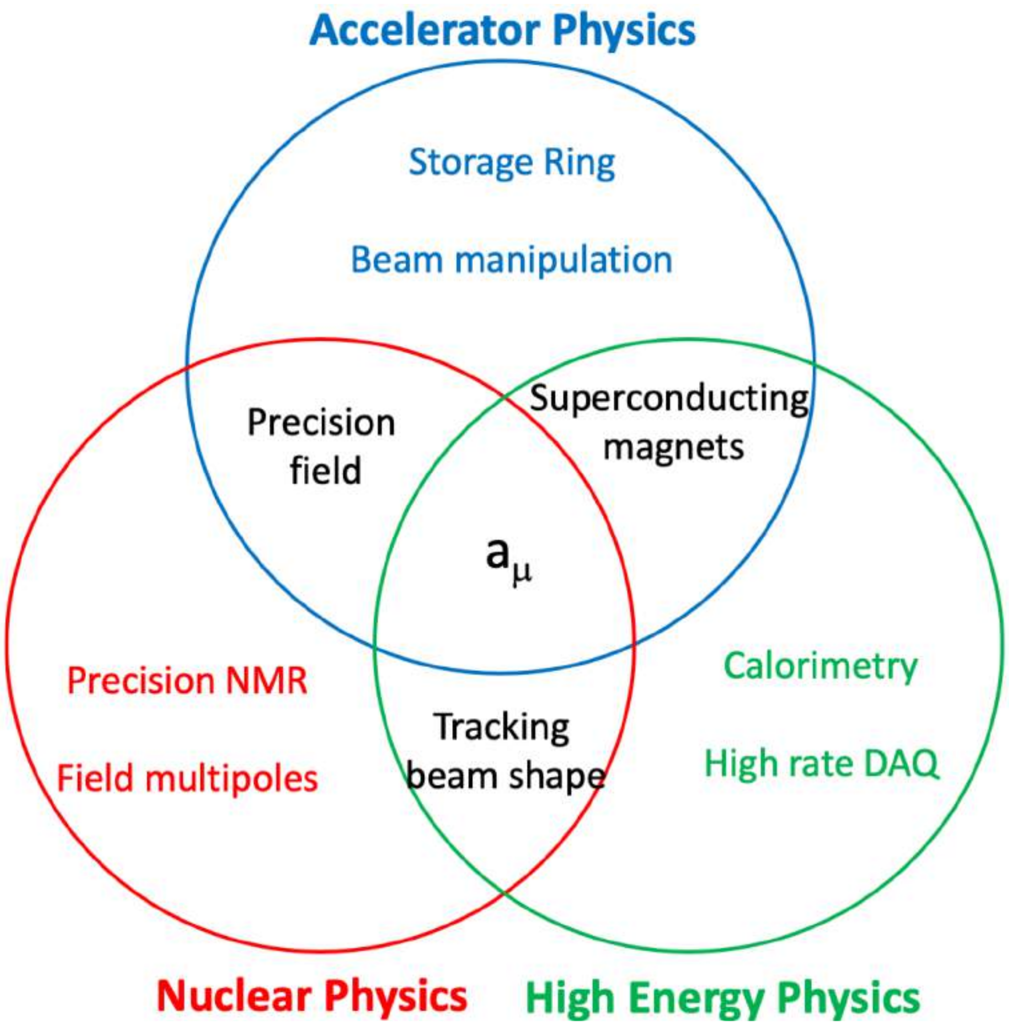
$\omega_{\mu,p}$ = precession
ω_c = cyclotron

- from which:

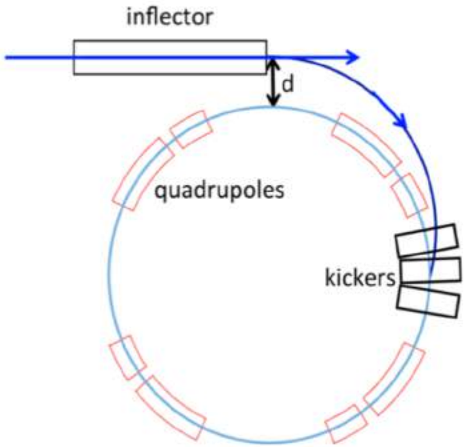
$$a_\mu = \frac{g_e}{2}\frac{m_\mu}{m_e}\frac{\mu_p}{\mu_e}\frac{\omega_a}{\omega_p} = \frac{R_\mu}{\lambda - R_\mu} \quad ; \quad R_\mu = \frac{\omega_a}{\omega_p}, \quad \lambda = \frac{\mu_\mu}{\mu_p}$$

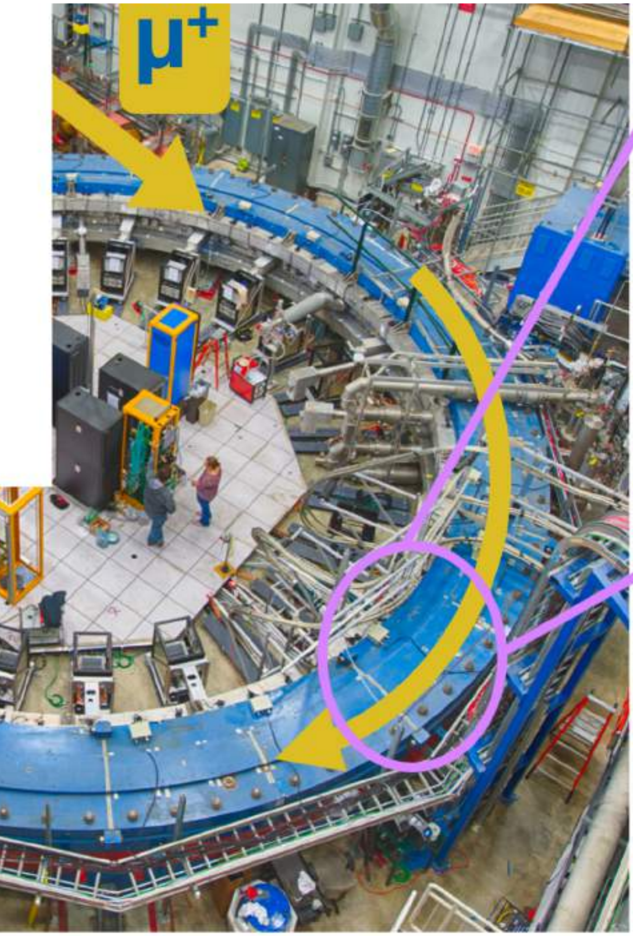

RING
FIELD
DETECTORS
muons
Inflector
QUADS
24 Calorimeters + 2 trackers located all around the ring
NMR probes and electronics located all around the ring
Kicker

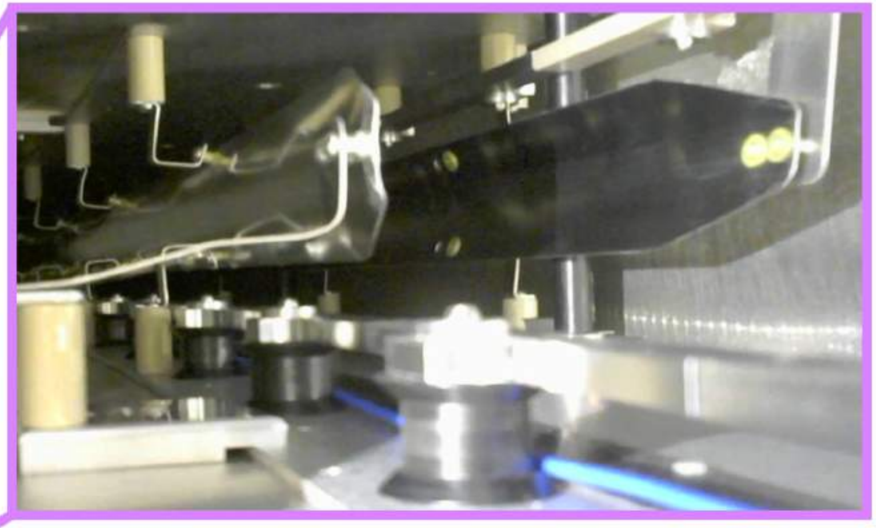
- Three different communities converging to measure a_μ



Muon beam storage and focusing







3 Kicker Magnets

- Incident beam center 77 mm off from center of storage region
- Provide 10.8 mrad “kick” to put muons onto the storage orbit

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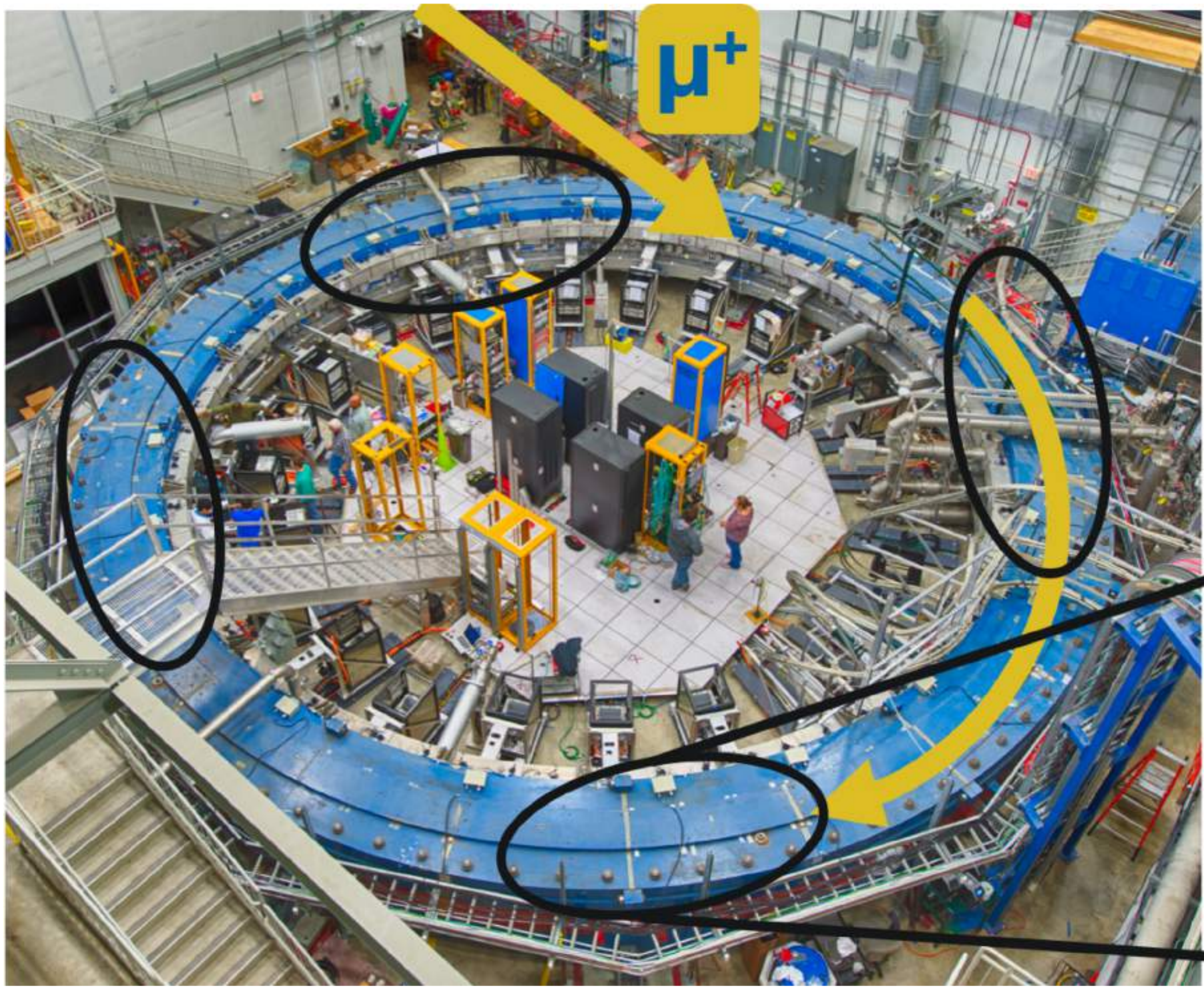
Muon beam storage and focusing



$$\vec{\omega}_a = -\frac{Qe}{m}\left[a\vec{B} - \left(a - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

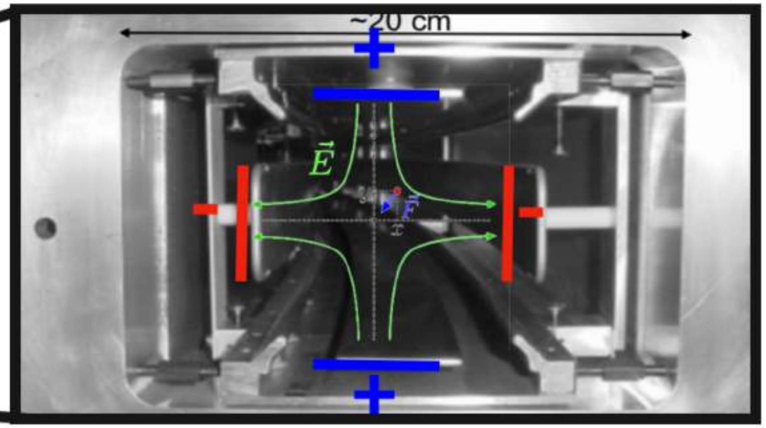
= 0

At p_{magic}= 3.094 GeV/c

for γ_{magic}= 29.3

Electrostatic Quadrupoles

- Focuses muon beam vertically



Effects of Beam Dynamics

$$\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_C = -\frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E} - a_\mu\left(\frac{\gamma}{\gamma+1}\right)\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta}\right]$$

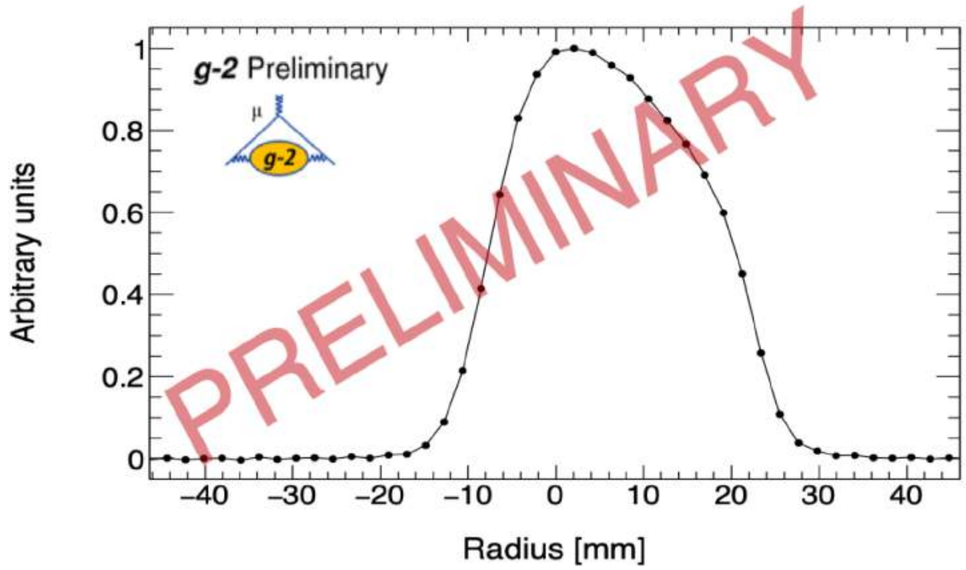
γ_{magic} = 29.3 (p_μ = 3.094 GeV/c)

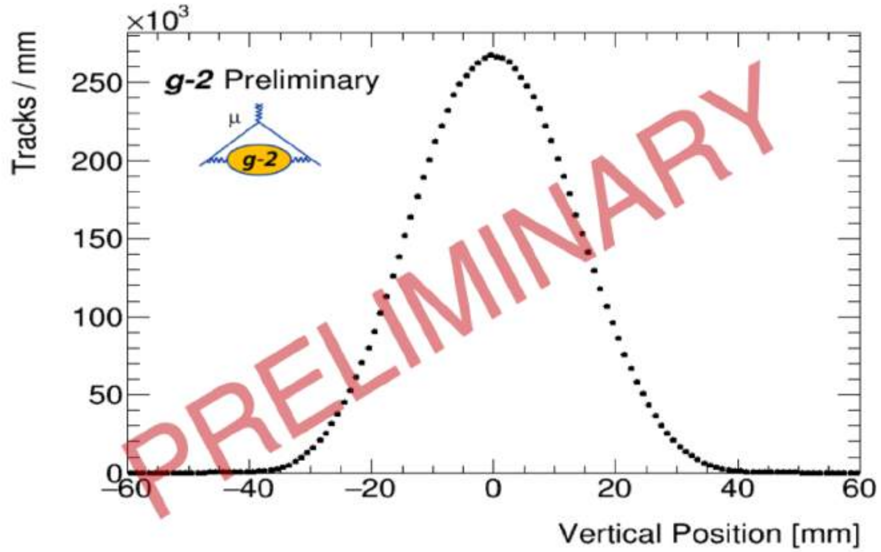
- **If all muons at P_{magic} = 3.09 GeV/c → $E = 0$**
- **Stored beam has a momentum spread → $E \neq 0$ → E-field correction**

$$C_E = -2n(1-n)\beta^2 \frac{\langle x_e^2 \rangle}{R_0^2}$$

Vertical motion of the beam, Field felt by the muons is reduced →Pitch Correction

$$C_P = \frac{\Delta\omega_a}{\omega_a} = -\frac{n}{2R_0^2}\langle y^2 \rangle$$





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Other Beam Dynamic Corrections

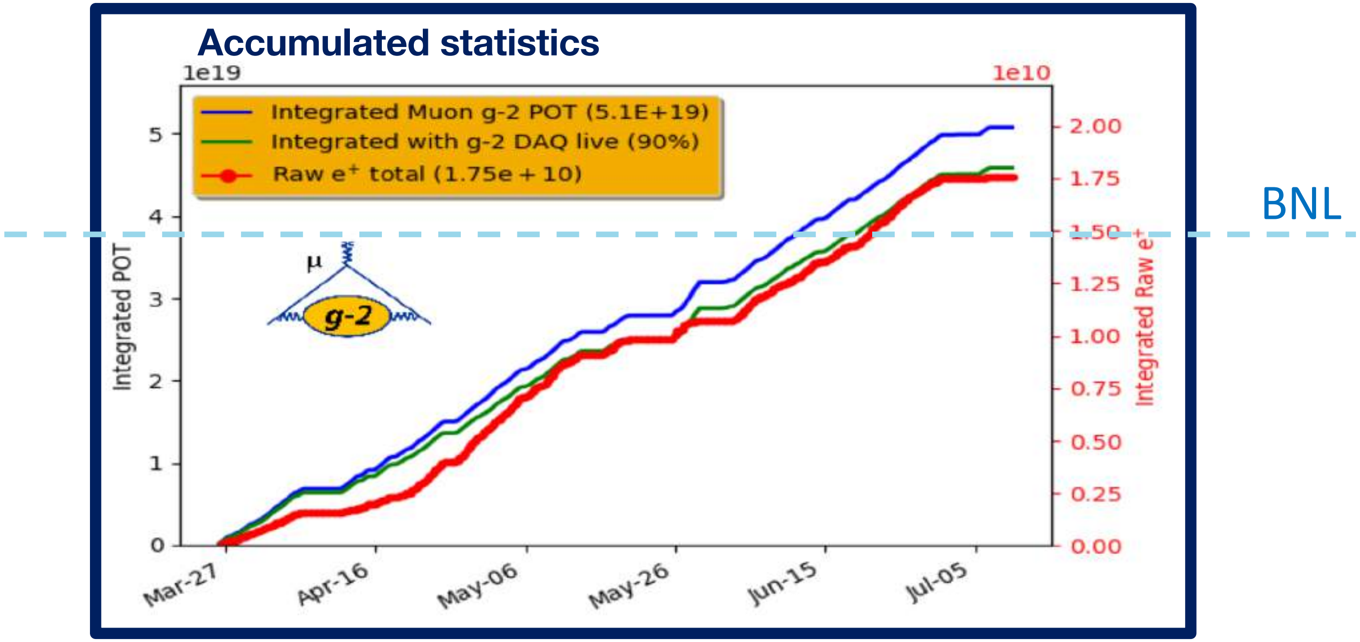
ω_a Goal: Factor of 3 Improvement		
Category	E821 (ppb)	E989 Goal (ppb)
Gain Changes	120	20
Lost Muons	90	20
Pileup	80	40
Horizontal CBO	70	< 30
E-field/pitch	110	30
Quadrature Sum	**214**	**70**

Current estimated C_E systematic $\leq$ 50 ppb
Current estimated C_p systematic ~15 ppb

} For 0.3X BNL statistics

Run 1 Overview

- Data taking period: April—July 2018
- Accumulated ~ 1.3 x BNL statistics (after data quality cuts) — **δωa(stat) ~ 350 ppb (BNL δωa(stat) ~ 460 ppb)**
- Field uniformity ~ 2x better than BNL



Run 1 Overview

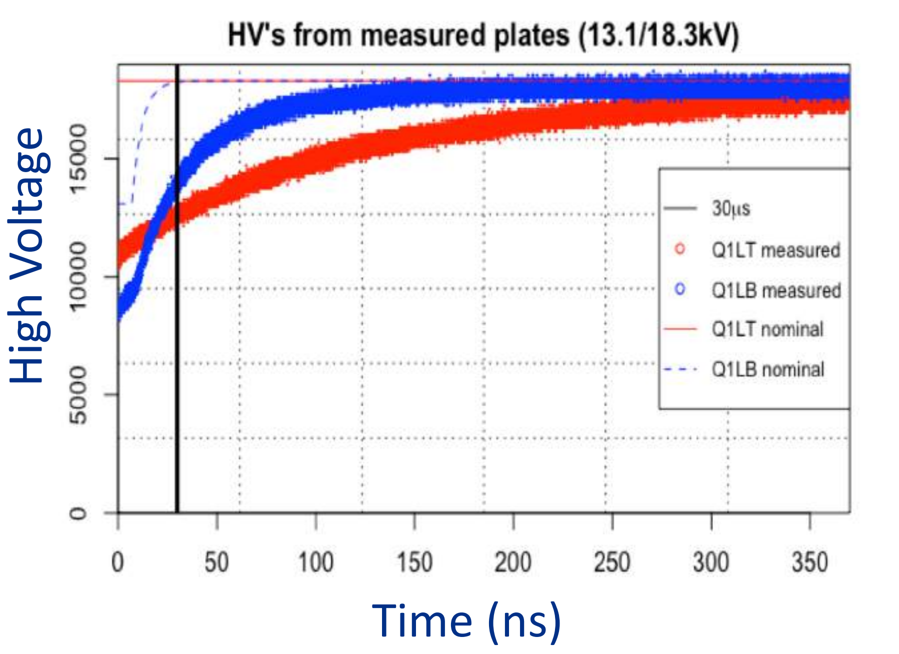
- In Run1, data have been taken in different Quad and Kicker conditions, while optimizing Storage Ring operations (Run2 data are much more uniform)
- Six datasets identified:

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

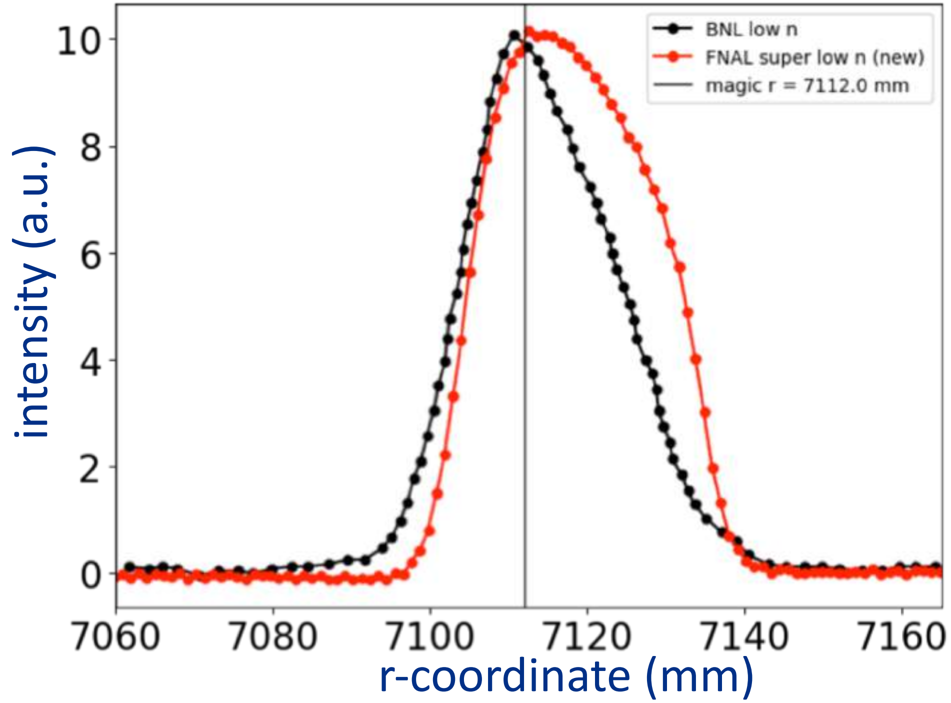
Relative unblinding

Problems related to Storage Ring in Run1

- Two main problems observed in storing muons:
  - bad resistor (QUAD)
  - low current (KICKER)

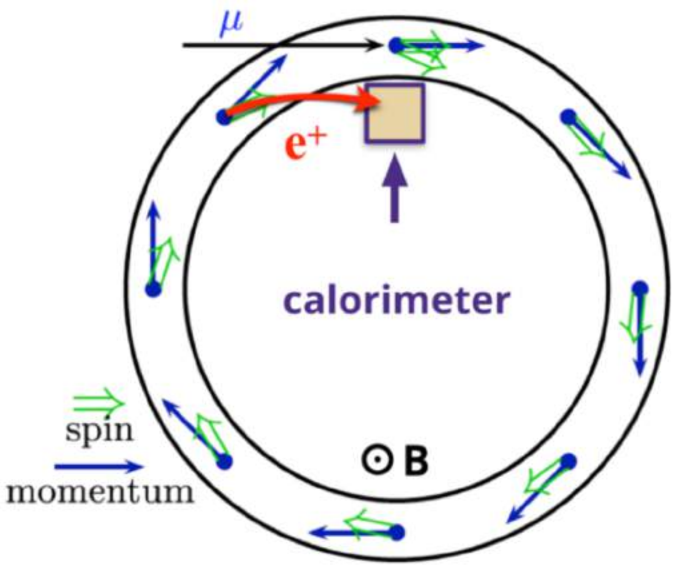


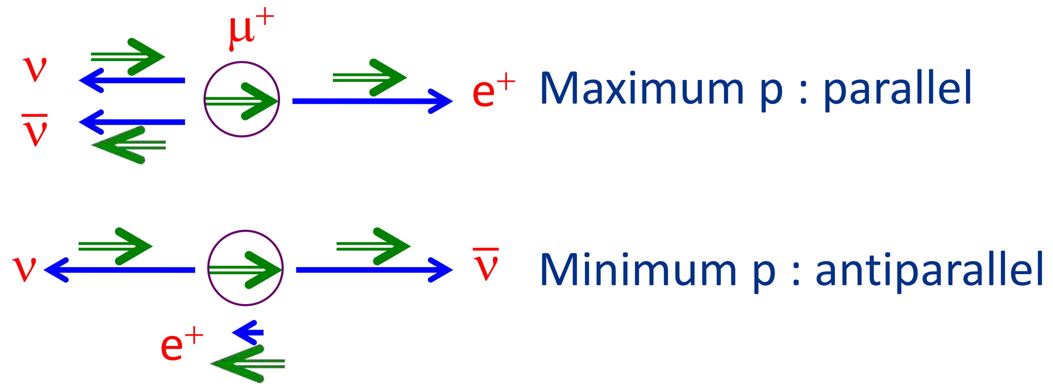
Two resistors providing HV to the vertical plates of QUAD1-L had a slow recovery time (fixed for Run2)
The beam slowly moved vertically during fill.



Radial profile corresponding to a ring acceptance Δp = ±0.5%
Asymmetry due to not perfect kick

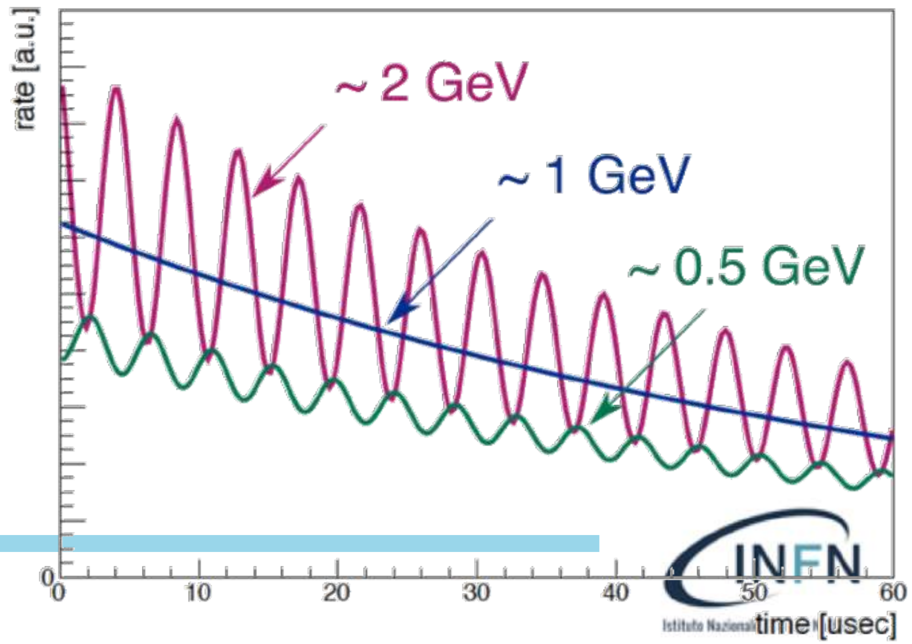
ω_a principle of measurement





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

- spin rotates faster than momentum in costant B
- positron direction correlated with muon spin direction
- correlation depends on *positron momentum* : the Asymmetry A(E) can be positive, null or negative



The wa analysis strategy

- 6 independent analysis groups using different *Reconstruction algorythms* and different *Fit methods*
- One method is completely different from all others (Q-method); it has a larger error → used as crosscheck
- 2 Independent Reconstruction algorythms developed (East, West); the Europa team contributes to both algos providing the SiPM gain functions

Team	Reconstruction	Analysis
CU (Cornell)	East	T,E
UW (Washington)	West	T,A
Europa (INFN+UK)	West/Europa	T,A
SJTU (Shangai)	West	T,E
BU (Boston)	West	T,R
Uky (Kentucky)	Q	Q

INFN contribution to SiPM gain corrections

Run 1 In-Fill Gain Correction

ω_a-europa analysis support document

E. Bottailco, P. Girotti, M. Incagli - INFN Pisa
A. Driutti - University of Udine

May 23, 2019

1 Introduction

Fluctuations in the gain of the calorimeter system in the Fermilab Muon g-2 Experiment, E989, is one of the major systematic errors. For the previous

- the gain corrections due to «muon splash» or to «close-by» positrons is an evident contribution of the INFN component to the g-2 analysis

The Short-Time Double-Pulse correction

ω_a-Europe analysis support document

Paolo Girotti, Elia Bottalico, Anna Driutti, Marco Incagli

June 13, 2019

Contents

Long Term Double Pulse Gain Study

E. Bottalico[1], F. Bedeschi[1], P. Girotti[2], G. Venanzoni[1]

[1] *University and INFN Sezione di Pisa, Pisa, Italy*
[2] *INFN Sezione di Pisa, Pisa, Italy*

Abstract
In this note we study the Sipm's gain drop in the ten-hundred μs range with the Long Term Double Pulse system. The results obtained show good agreement with the ones obtained by the In Fill Gain functions (IFG).

1 Double Pulse

The wa-europa ω_a analysis group

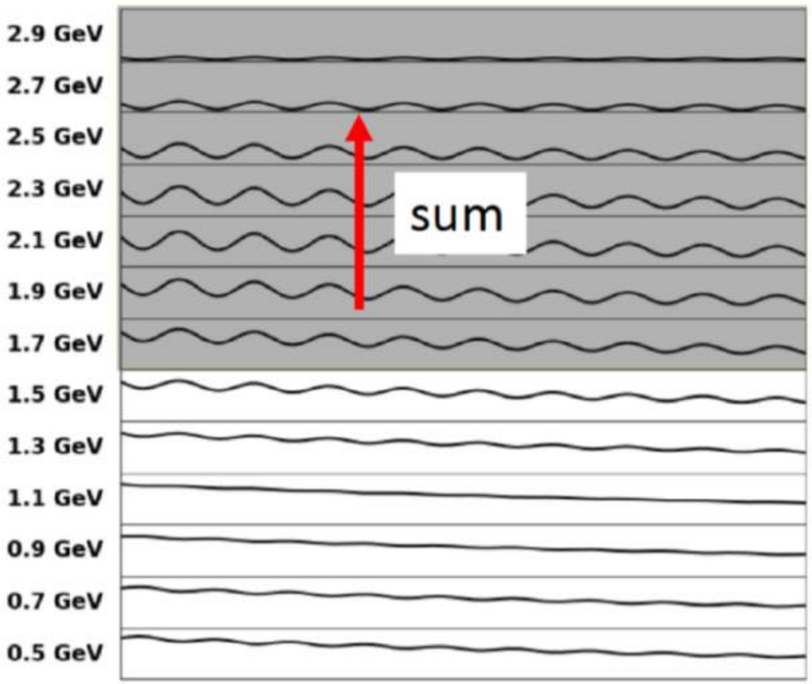
The *60h* dataset relative unblinding; fitting procedure for ω_a—Europa
Revision 1

E. Bottalico[1], S. Di Falco[1], A. Driutti[2], P. Girotti[1], A. Gioiosa[3], G. Hesketh[4], M. Incagli[1], J. Price[5], M. Smith[1], M. Sorbara[6]

[1]INFN Pisa
[2]INFN Trieste & University of Udine
[3]INFN Roma 2 & University of Molise
[4]University College London
[5]University of Liverpool
[6]INFN & University Rome2

April 25, 2019

The methods

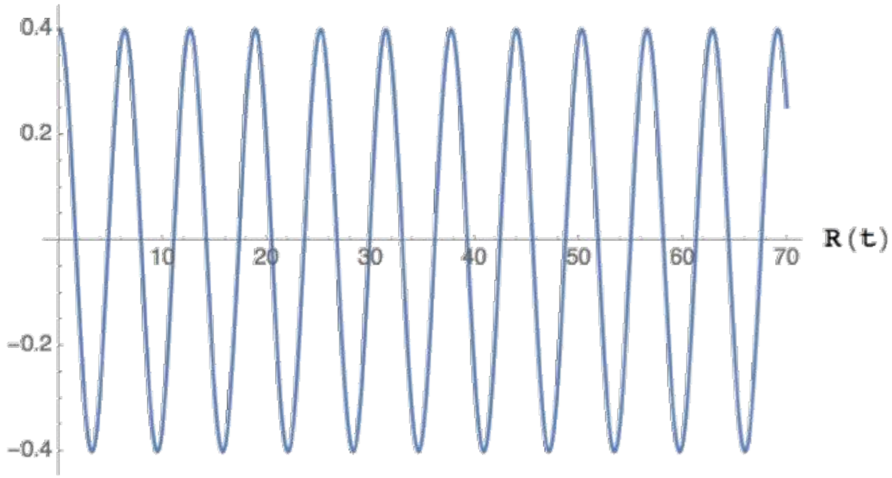


- **T-method**: count all positrons with E>1.7GeV and plot them vs time to get the *«Wiggle plot»* ; reference method
- **E-method** (Energy binned) : fit each energy slice, combine the resulting values for wa
- **A-method** (Asimmetry weighted) : weight each event with its own contribution to asimmetry A(E). From the statistical point of view, this method uses most of the information.

R-method (Ratio)

- 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

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



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

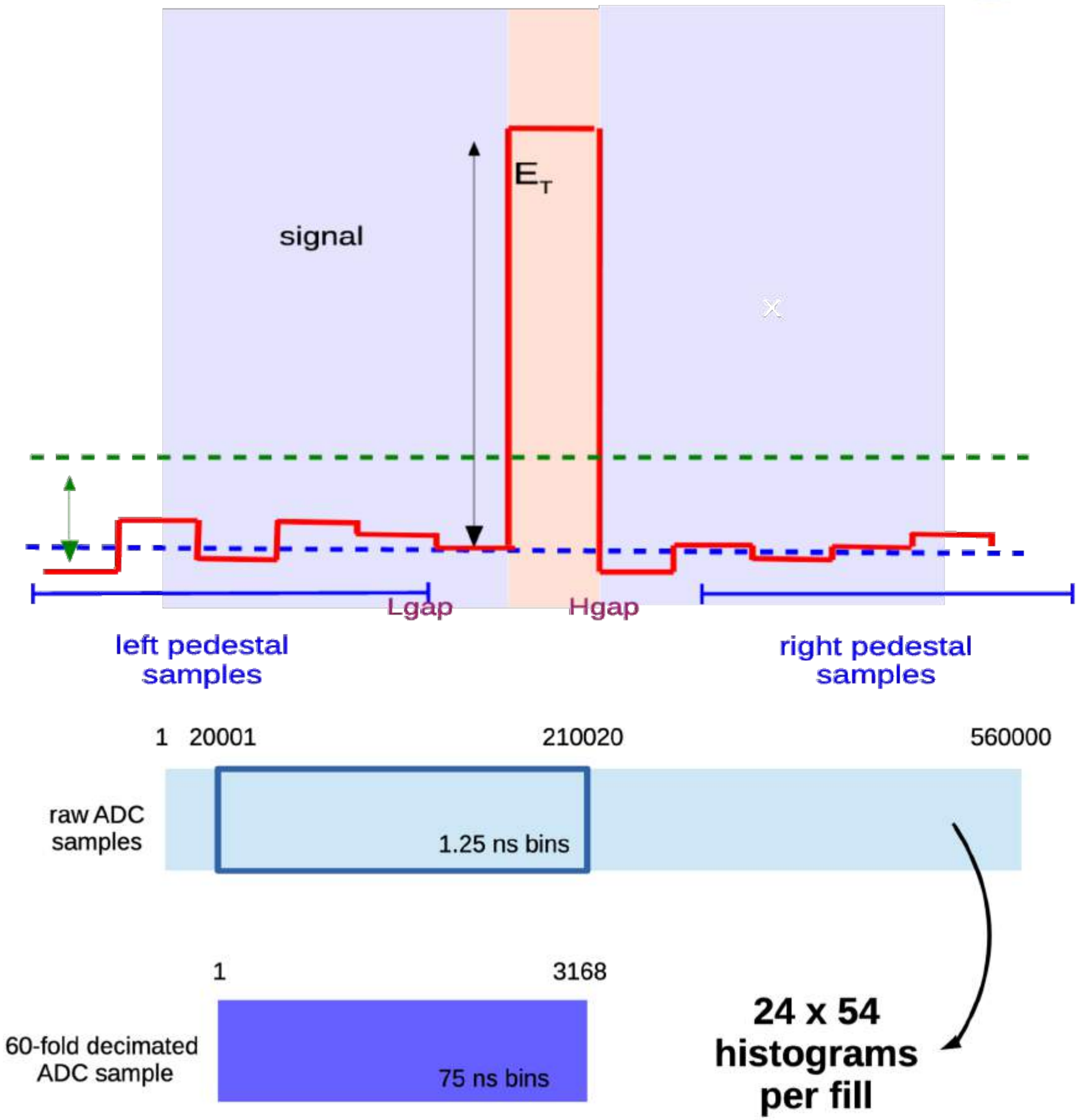
$$R(t) = \frac{N(t) - U(t)}{N(t) + U(t)}$$

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

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

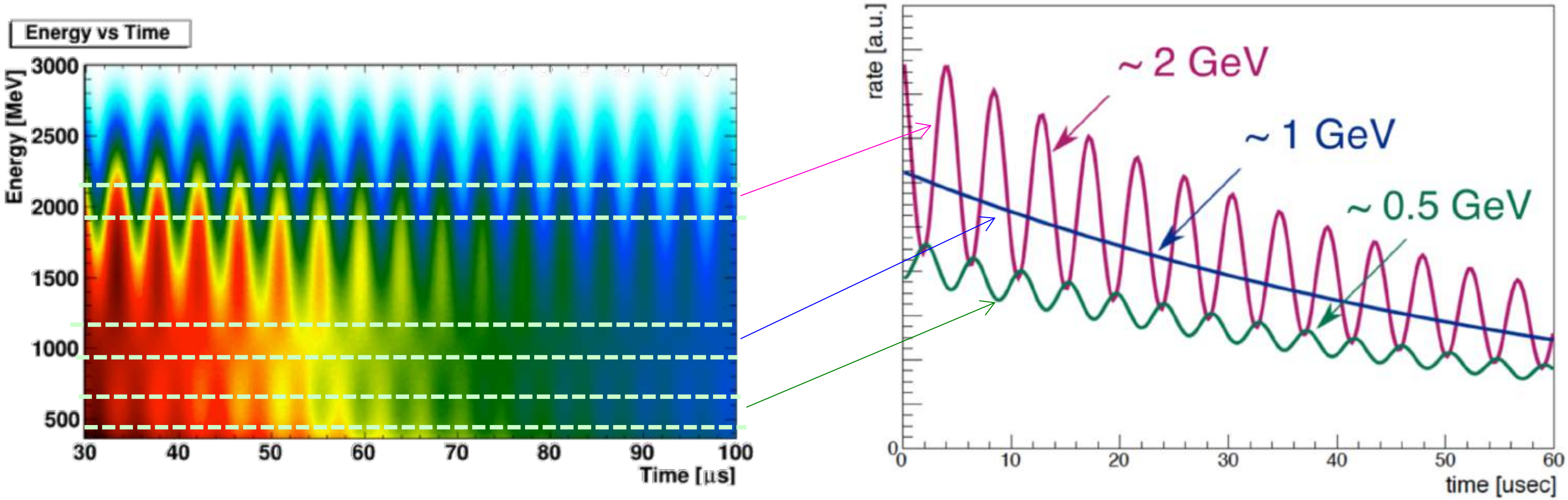
Q-method

- No clustering: just integrate energy above threshold (in theory no threshold should be applied) for each crystal
- To reduce the amount of data stored offline, time bins are summed up in groups of 60
- <u>The total energy per event fluctuates with ω_a frequency</u>



Building the histogram

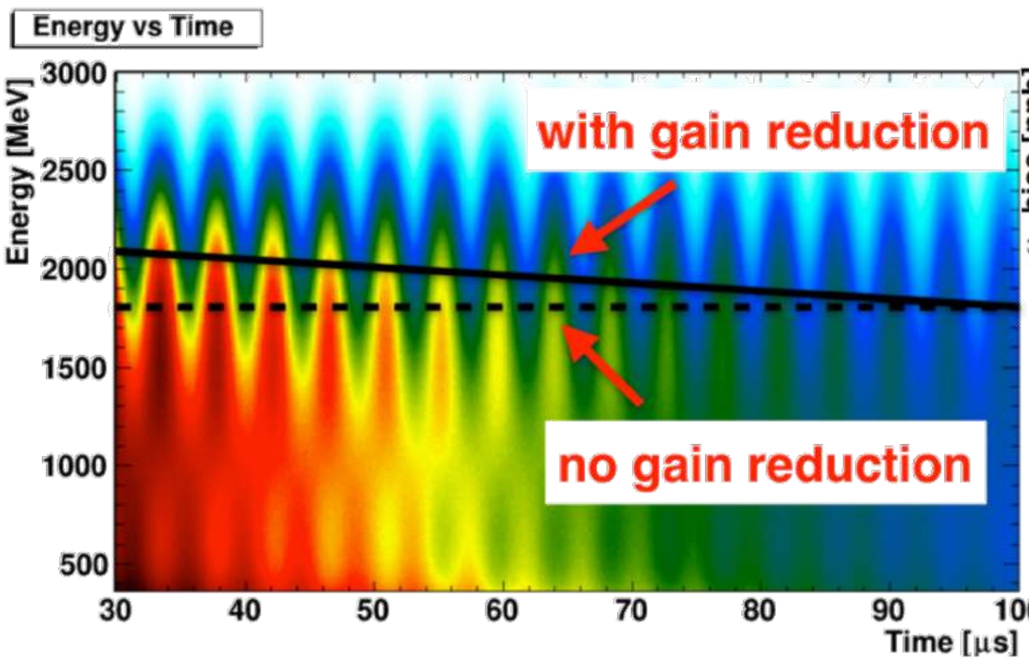
- The collected events are plot as a function of the **muon decay time** (clock) and of the **positron energy** (polarimeter)

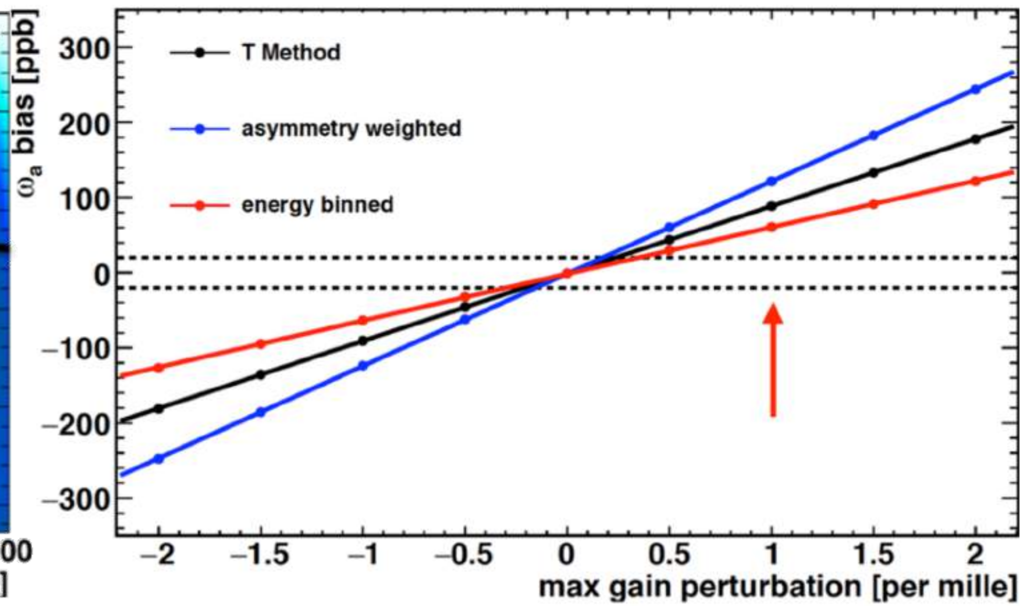


- Note that the *phase* depends on the positron energy
- If the energy threshold varies during the *muon fill* then wa is systematically shifted: $\omega_a t + \varphi(t) \sim (\omega_a + \varphi')t + \varphi_0$

Gain stability

- SiPM gain variations during fill, due to initial “splash” or to the overlap of close-in-time events, mixes different energies in the same plot → phase variation effect corresponding to bias on wa
- A 1 per mille uncorrected gain variation causes a 100 ppb shift of wa
- The laser system measures and corrects for this gain sag effect





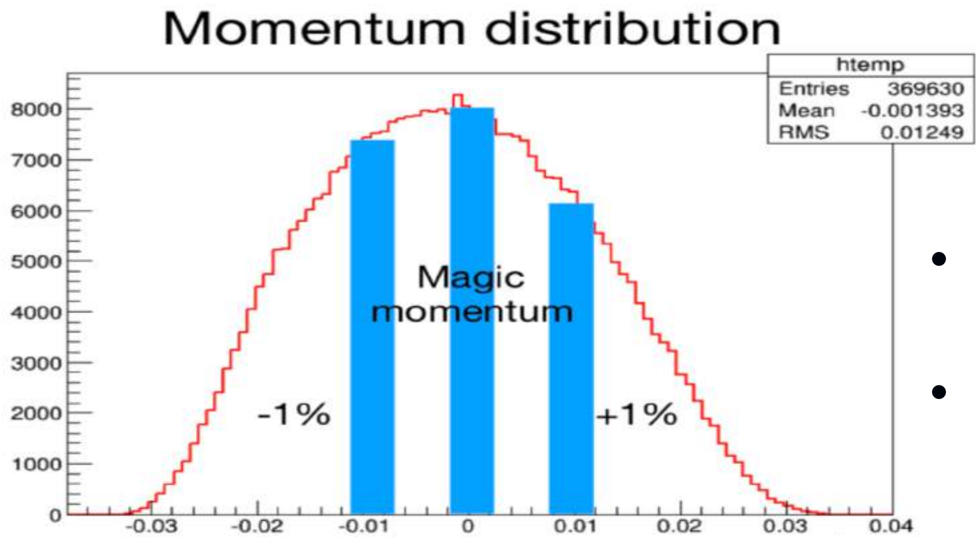
50-150 ppb bias is expected for uncorrected in-fill gain perturbation

Muon Phase-Momentum Coupling

- If the average muon phase varies during the fill, then wa is sistematically shifted: $\omega_a t + \varphi(t) \sim (\omega_a + \varphi')t + \varphi_0$
- This can happen in case of phase-momentum correlation

Bias in $\boldsymbol{\omega_a}$: $\Delta\boldsymbol{\omega_a} = \frac{\mathbf{d}<\boldsymbol{\phi}>}{\boldsymbol{dt}} = \frac{d\boldsymbol{\phi}}{d<p>} \cdot \frac{d<p>}{dt}$

Measured with dedicated systematic runs



phase shift (rad)

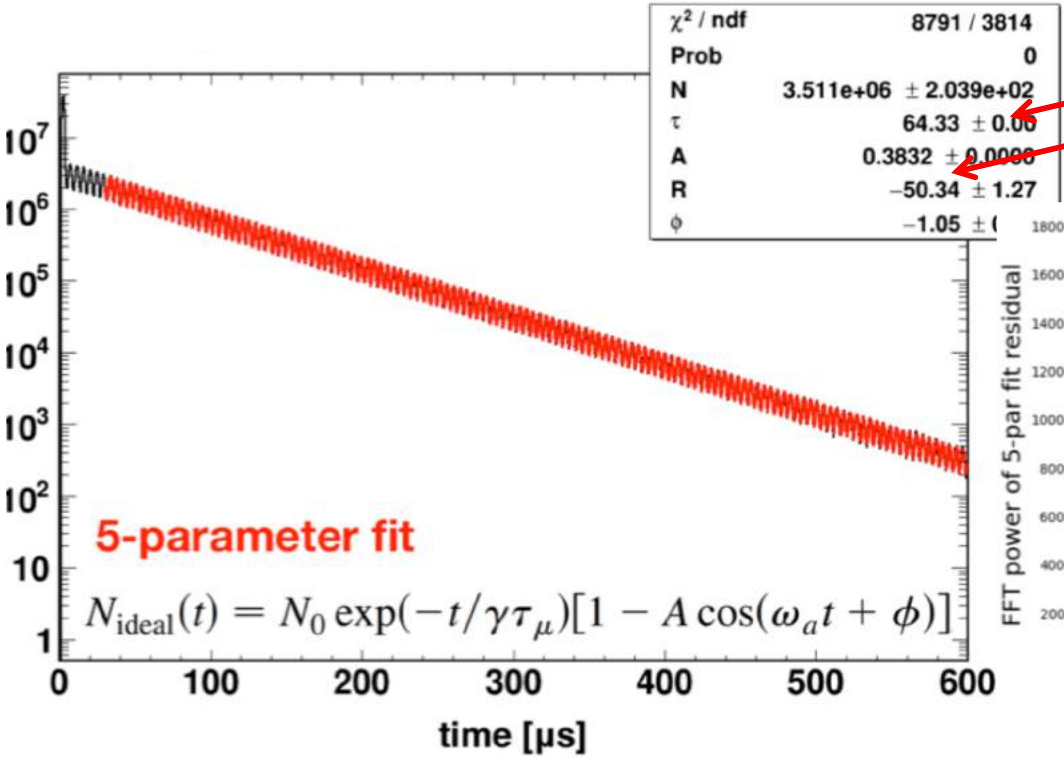
- Take data at higher than nominal momentum
- Compare higher momentum phase to nominal momentum phase

The 60h dataset: 5-par fit

- Simple (ideal) positron oscillation:

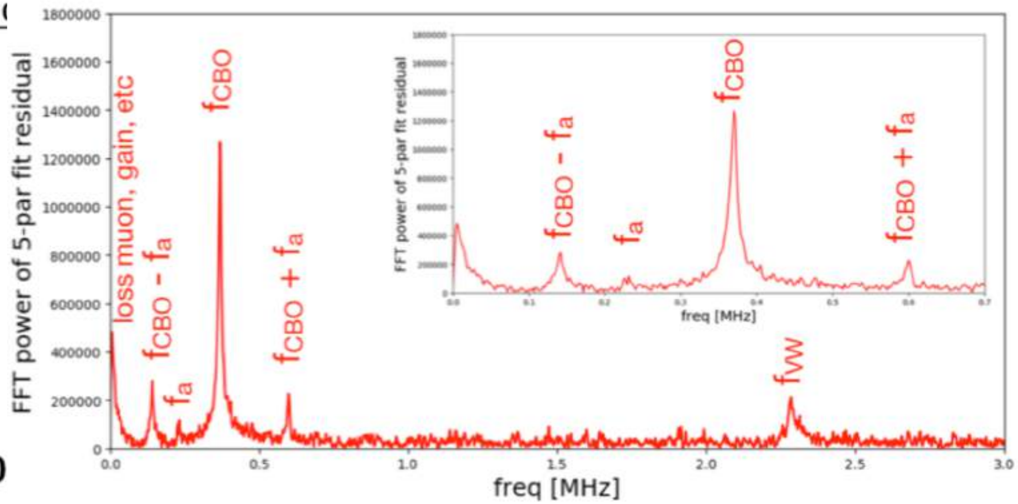
$$N_{\text{ideal}}(t) = N_0 \exp(-t/\gamma\tau_\mu)[1 - A\cos(\omega_a t + \phi)]$$

- This simple fit is clearly not sufficient and typical resonances are observed in the residuals



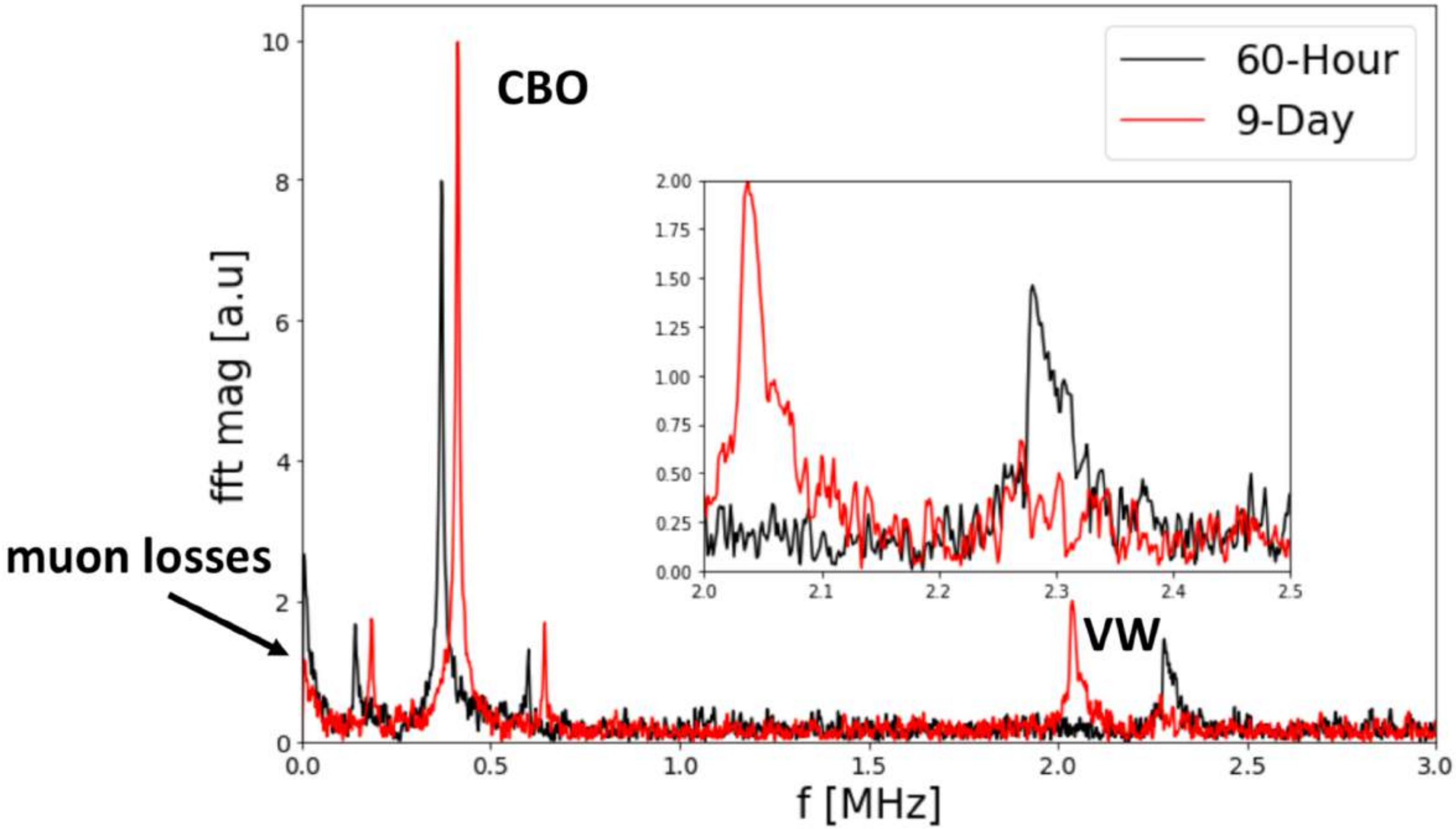
muon lifetime: γ=29.3

NOTE: blinding on ω_a!



Residuals for two datasets

- The betatron oscillations depend on the beam parameters → different for each Run1 dataset → datasets cannot be combined and must be fitted separately



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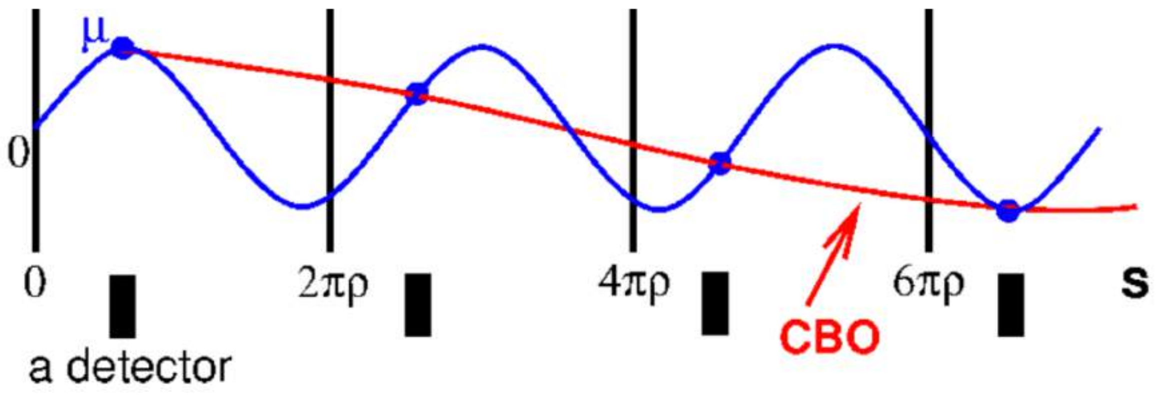
Structure in residual: Beam Oscillations

- Coherent Betatron Oscillations (CBO) sampled by each detector at one point around the ring

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



- 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

Typical 18 (or 22) parameters fit function

$$N(t) = N_0 \cdot \left(1 - K_{loss} \int_0^t e^{t'/\tau} L(t')\,\mathrm{d}t'\right) \cdot N_{CBO}(t) \cdot N_{VW}(t) \cdot e^{-t/\tau} \cdot [1 + A(t) \cos(\omega_a(R) - \phi(t))]$$

$$N_{CBO}(t) = 1 + A_{CBO,N} \cdot e^{-t/\tau_{CBO}} \cos(\omega_{CBO} \cdot t - \phi_{CBO,N})$$

$$N_{VW}(t) = 1 + A_{VW,N} \cdot e^{-t/\tau_{VW}} \cos(\omega_{VW} \cdot t - \phi_{VW,N})$$

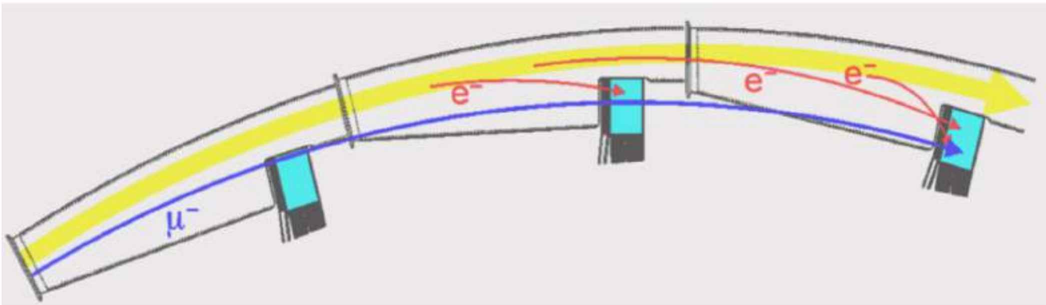
- ω_{CBO} and ω_{VW} are not constant due to QUAD HV faulty resistor:
  - $\omega_{CBO}(t) = \omega_{CBO}(0) * (1 + \delta_{CBO}(t))$
- (similar for ω_{VW}). The number of parameters depends on the parametrization of the correction δ_{CBO}
- The first term in parenthesis corresponds to the lost muons term → next slide

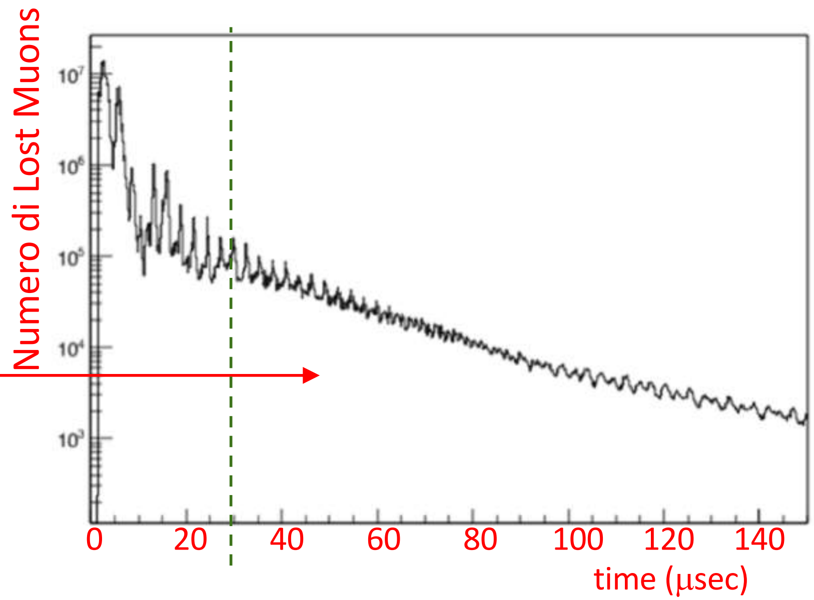
Distorting muon life time: lost muons

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

$$\left(1 - K_{loss} \int_0^t e^{t'/\tau} L(t')\, dt'\right)$$

- 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: Di Falco, Sorbara, Gioiosa*

Internal Note on Lost Muons Corrections

Lost Muons Correction

Supporting note for the ω_a-Europa analysis

S. Di Falco, A. Driutti, A, Gioiosa, M. Sorbara*

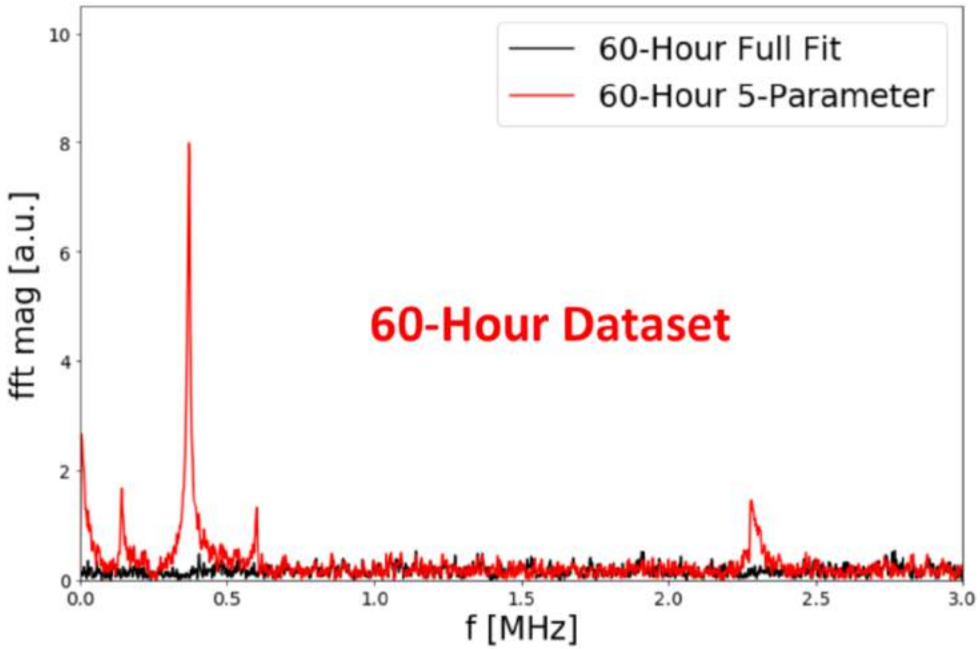
February 19, 2019

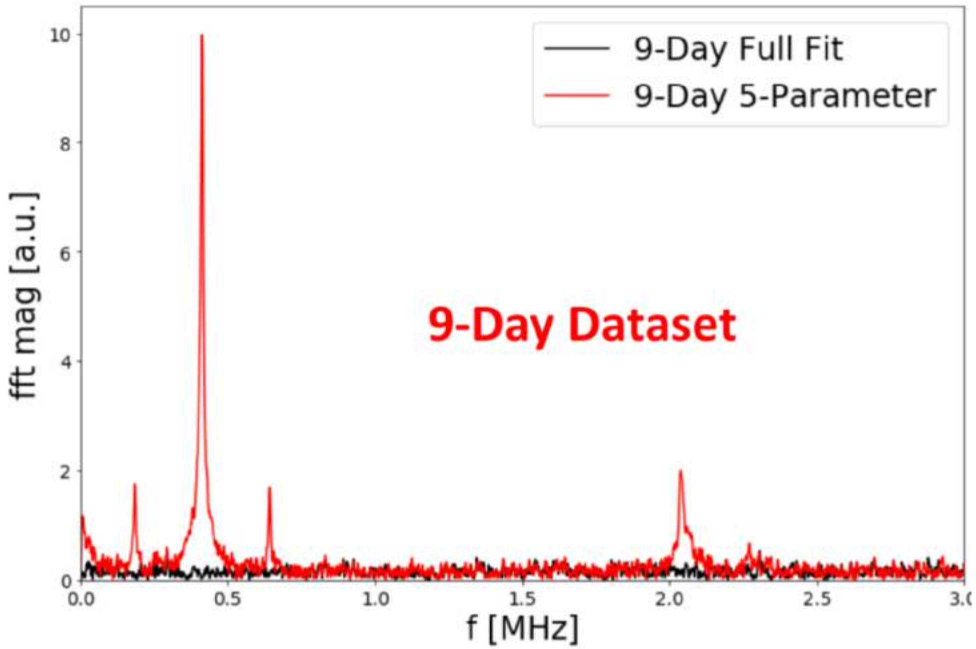
1 Introduction

During their path into the g-2 storage ring some of the muons are lost mainly because of their interaction with collimators. Lost muons can produce a systematic effect in the measurement of ω_a since they reduce the number of positrons measured by the calorimeters with typical lifetime that is different from the one of the muon. For this reason lost muons have to be measured and accounted for in the final ω_a fit.

Lost muons correction can be parametrized, in the Wiggle plot fit function, with the multiplicative factor $\Lambda(t)$, defined as :

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



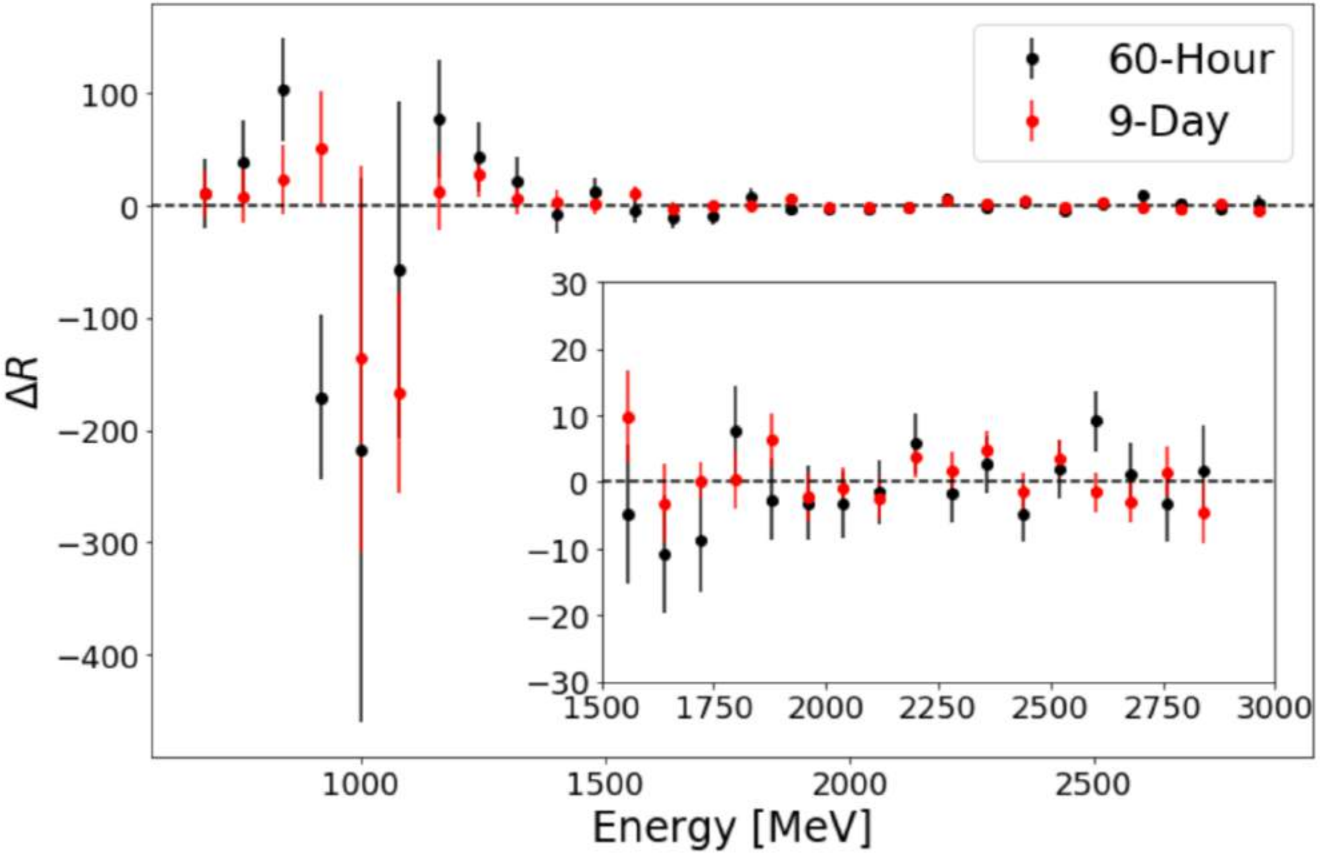


1×10^9 positrons
1.33 ppm precision
$$\frac{\chi^2}{ndf} = 4077/4137$$

2.3×10^9 positrons
0.88 ppm precision
$$\frac{\chi^2}{ndf} = 4161/4133$$

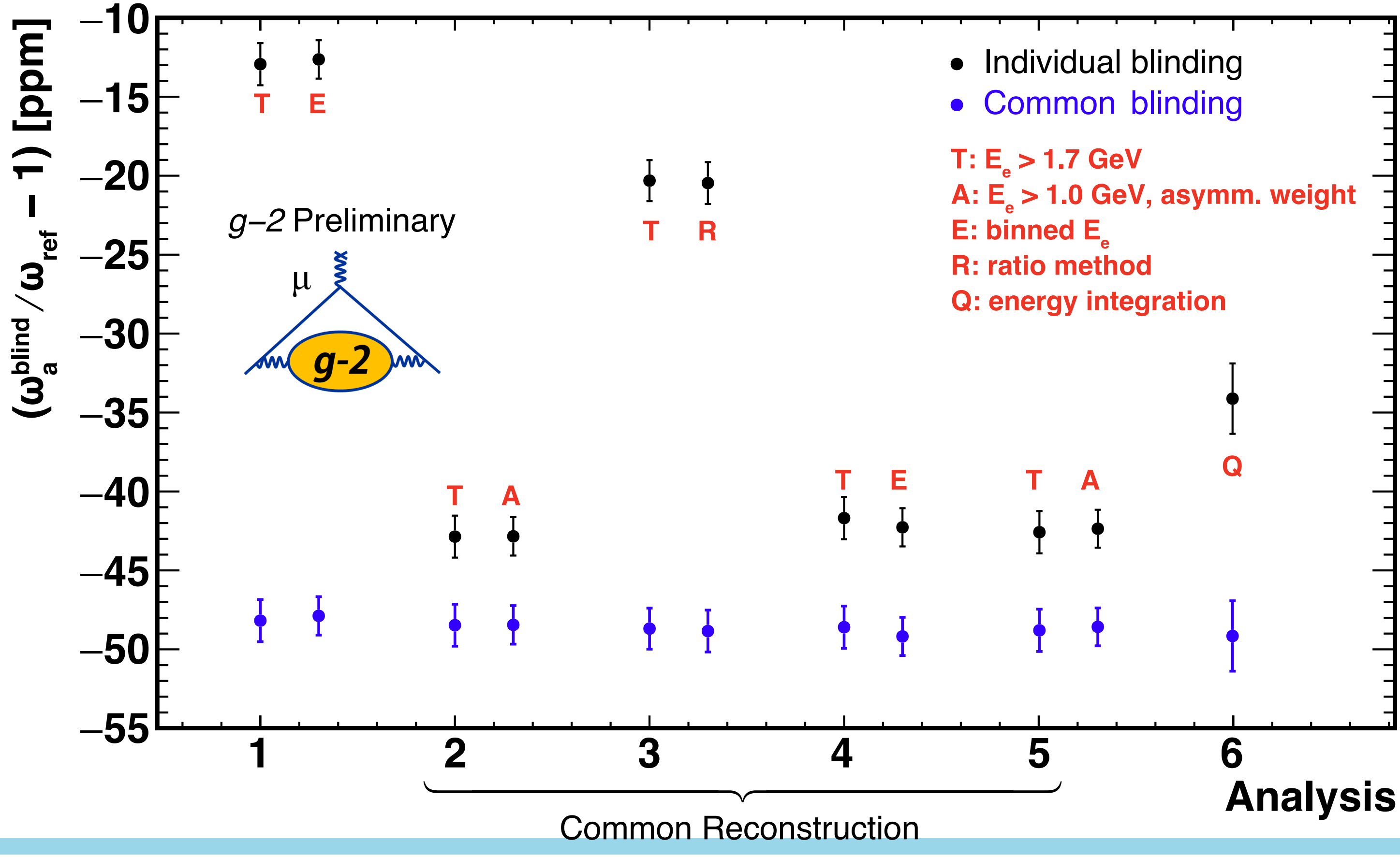
R vs positron energy

- Due to blinding, we do not measure directly wa, but a variable R which is a fractional offset (in ppm) from some unkown (blinded) value



First combination of results

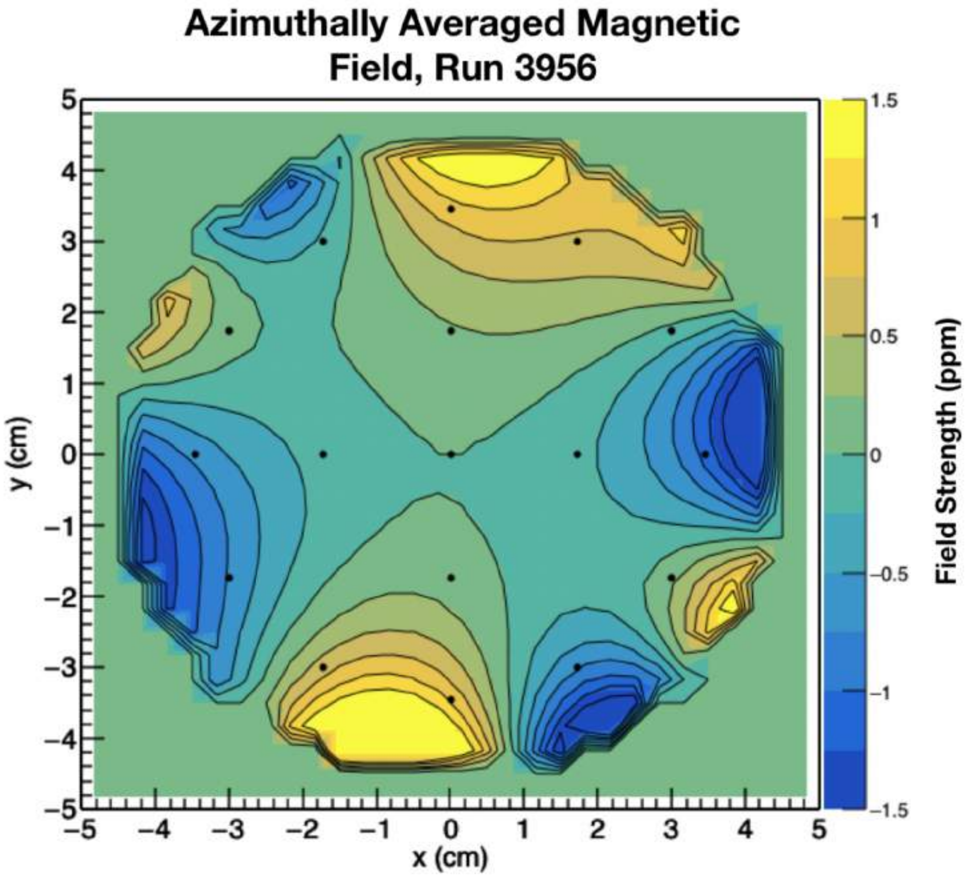
- In Elba Physics Week, results presented separately by the different analysis groups on wa and wp have been compared for the first dataset (the 60h dataset)
- The T-method is used as a reference

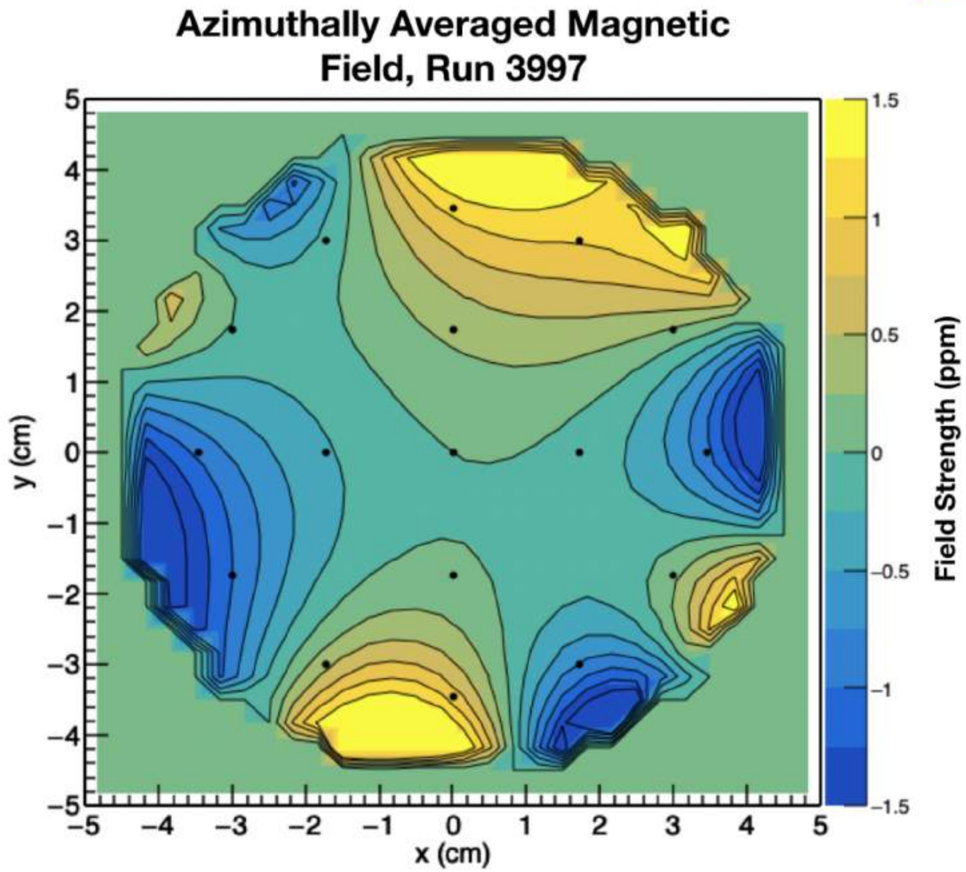


Combining ω_a

What about wp ?

- Two trolley runs, one before and one after the 60h dataset, fix the magnetic field:

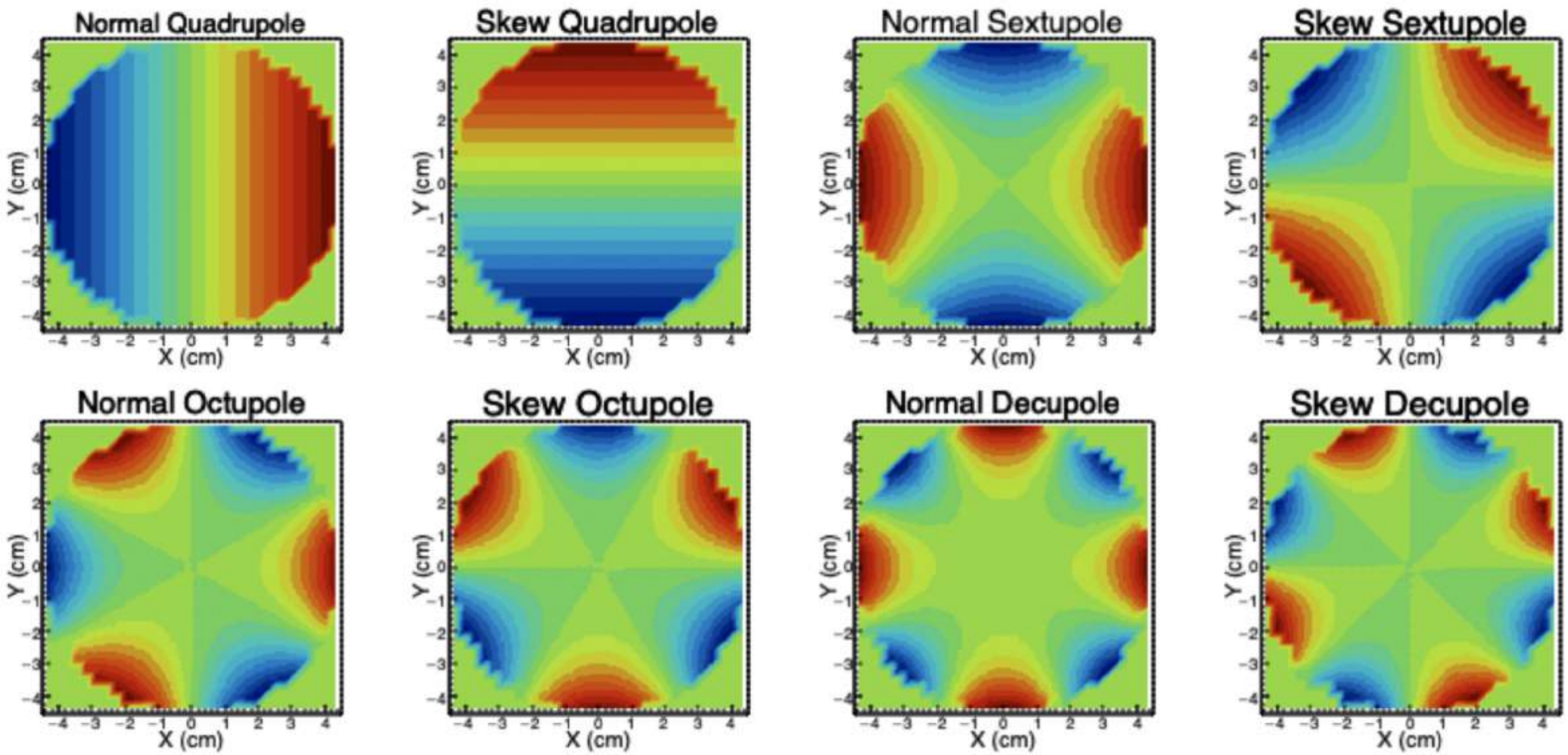




Multiple expansion

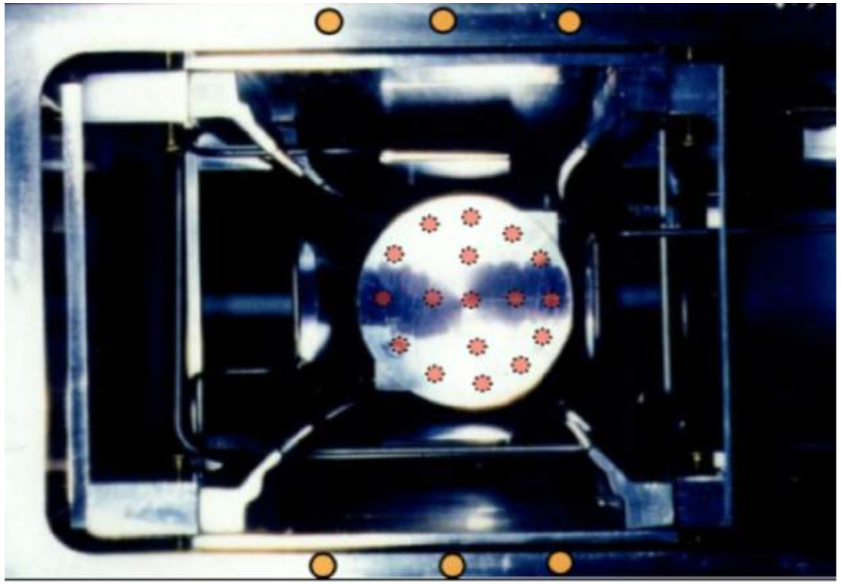
- Trolley data fit to 2D expansion of the form

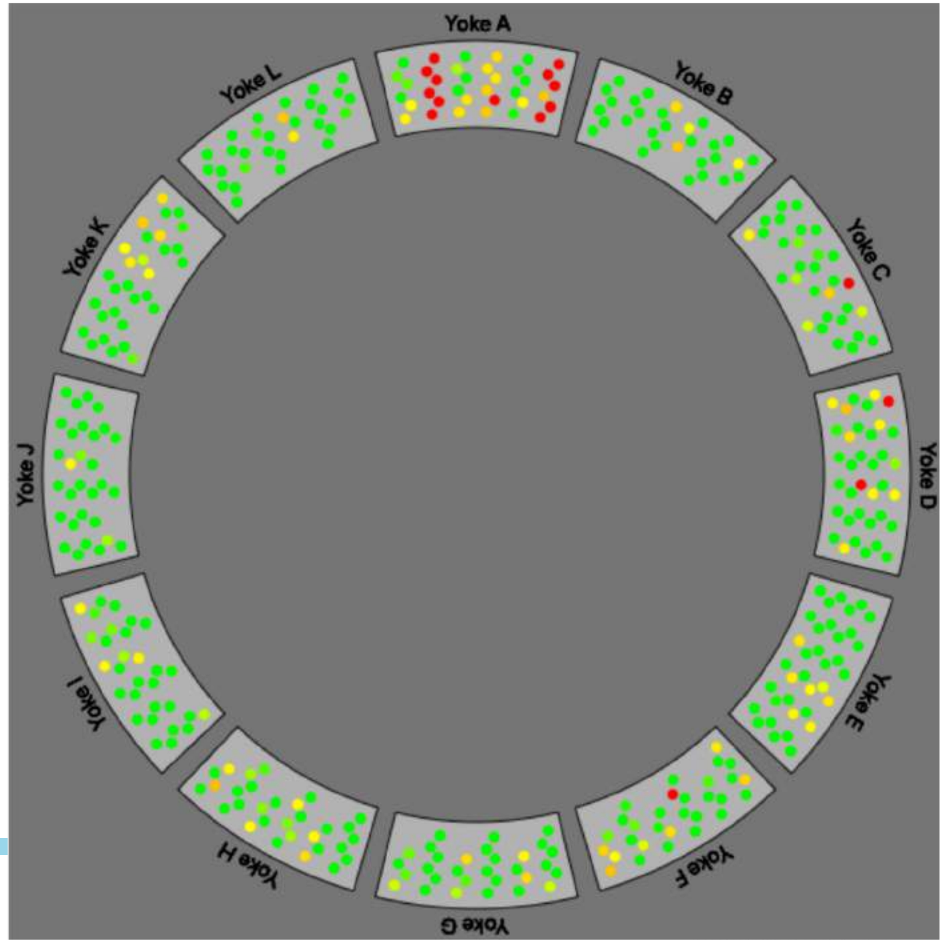
$$B(r,\theta) = B_0 + \sum_{n=0}^{n=6} \left(\frac{r}{r_0}\right)^n [a_n \cos(n\theta) + b_n sin(n\theta)]$$



How to extrapolate during 60h?

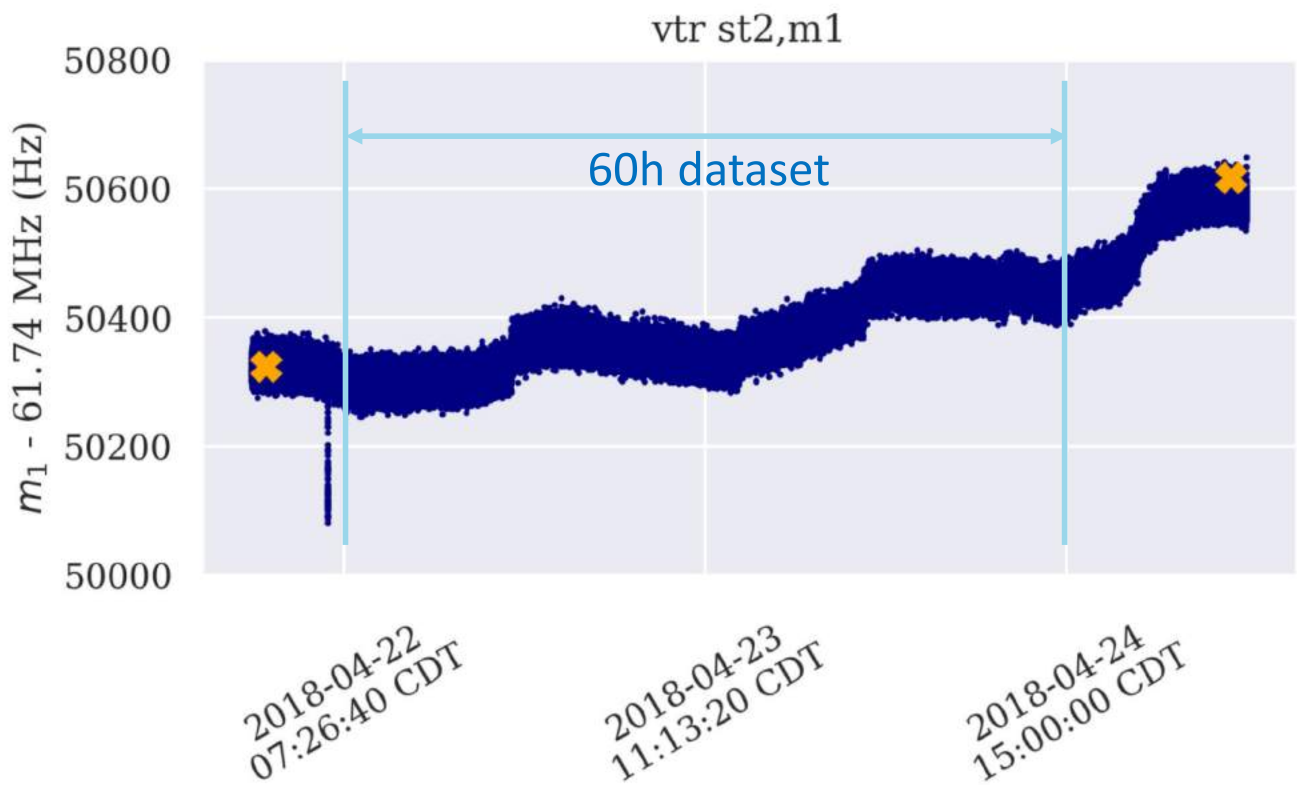
- Fixed probes are used to extrapolate, but
  - far from beam center
  - 4 or 6 probes per station: only first multiples tracked





Interpolation effect

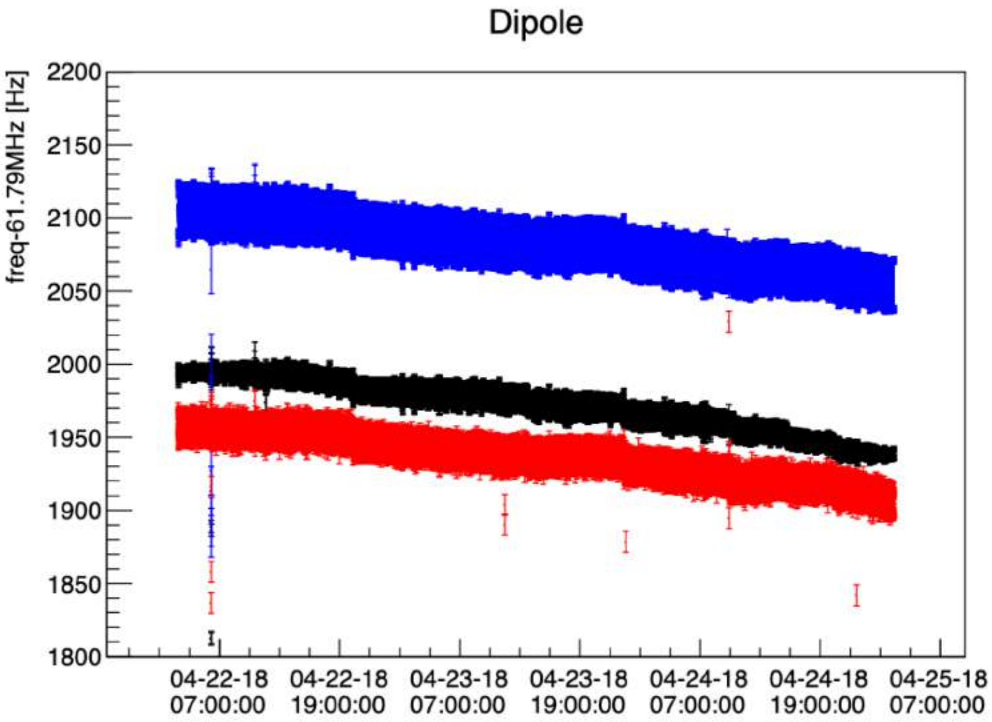
- Interpolating between two trolley runs using fixed probe stations is the largest source of incertitude in B measurement
- x yellow crosses = trolley probes; blue point = fixed probes

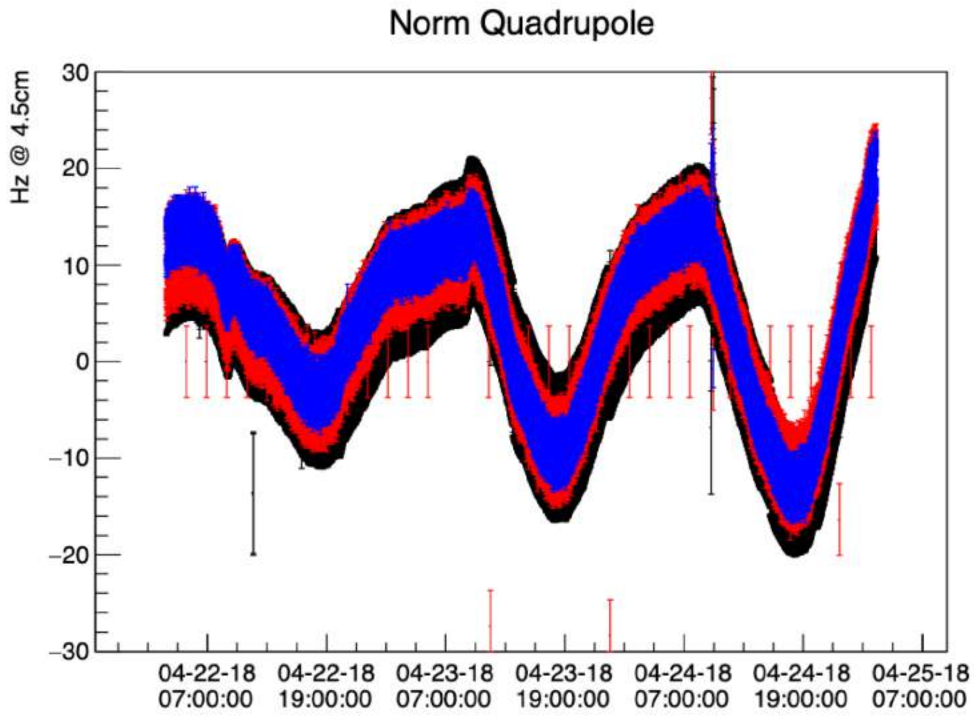


Blinded comparison

- Three independent analyses performed on wp
- Not authorized to show unblinding here ...

1Hz = 16 ppb
Bloch, Purcell , Ran





Each moment has independent blinds from the analyzers
→ (vertical offset)

Summary - 1

- Analysis of Run1 going on
- 6 datasets to be studied independently and combined
- 1 analysis completed (60h), 2 well advanced (9d + endgame), corresponding to ~70% of Run1
- High visibility of INFN contribution to the analysis
  - many analysis tools, mostly, but not only, related to gain functions
  - leading role in data production and reconstruction (Anna Driutti)
  - leading role in wa analysis (wa-europa)
  - reviewer of wp analysis (M.I.)
  - important role in Data Quality Control
  - slow control monitoring (Antonio Gioiosa)
  - ...

Summary - 2

- Publication expected by calendar year 2019 ... but ... should we wait for Run2?
  - more stable conditions
  - no competition
  - must be sure to do it right
- ... tough decision