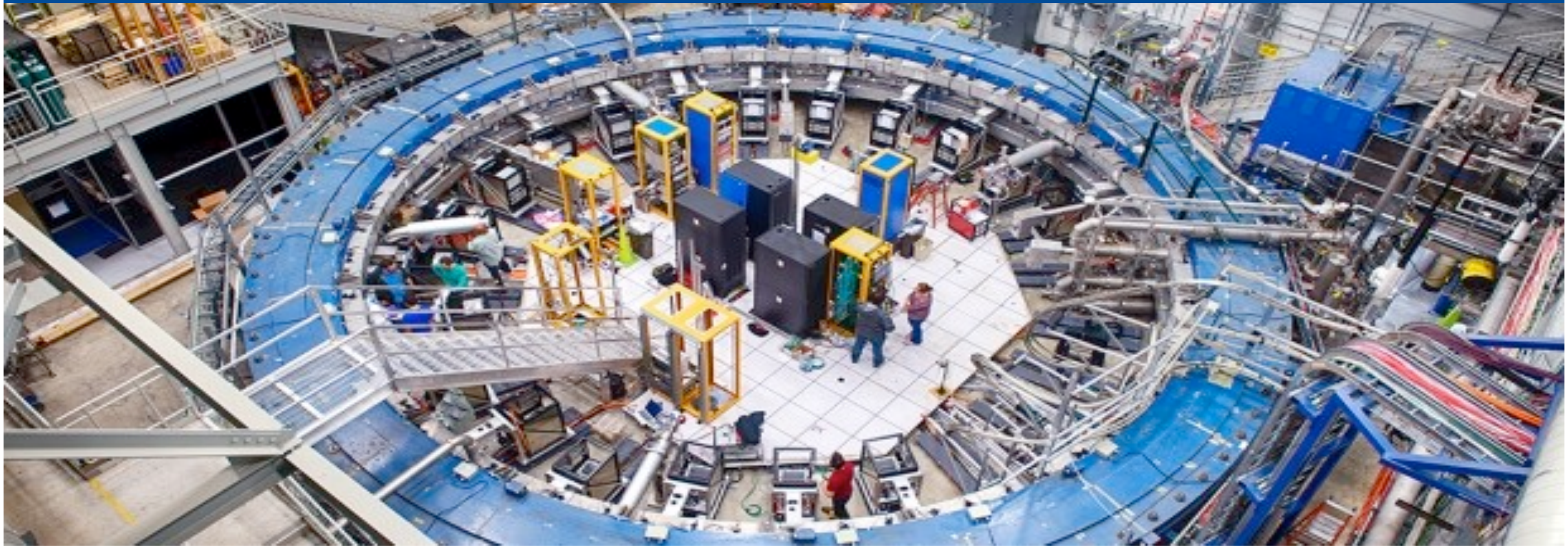


Status of ω_a analysis

Marco Incagli – INFN Pisa

NEWS General Meeting – November 4-5, 2019

The spin equation

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

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

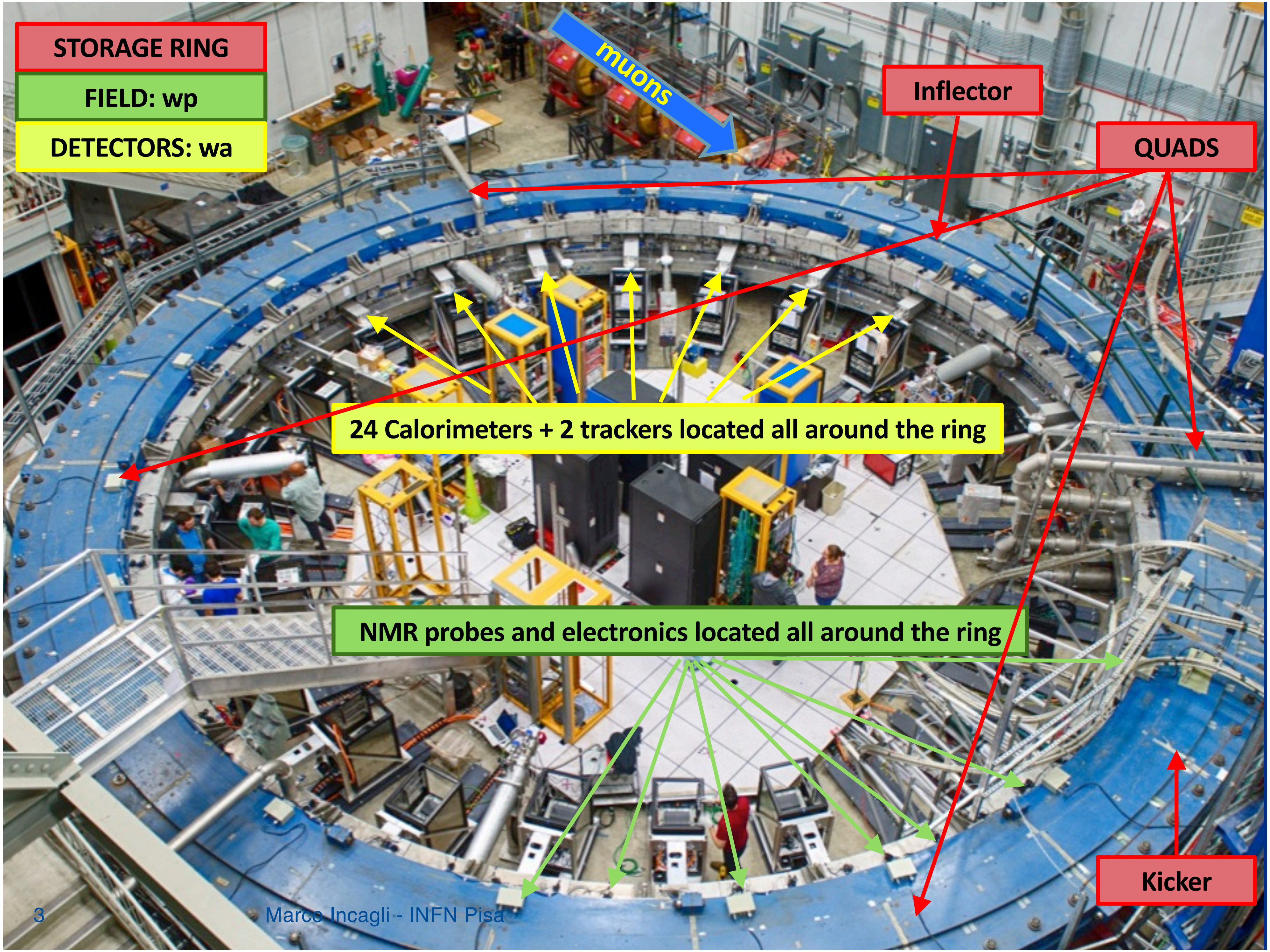
- neglecting beam size and oscillations, assuming that all muons momentum is $p_{magic}=3.01GeV/c$ and is perpendicular to B, than the above expression greatly simplifies to:

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

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

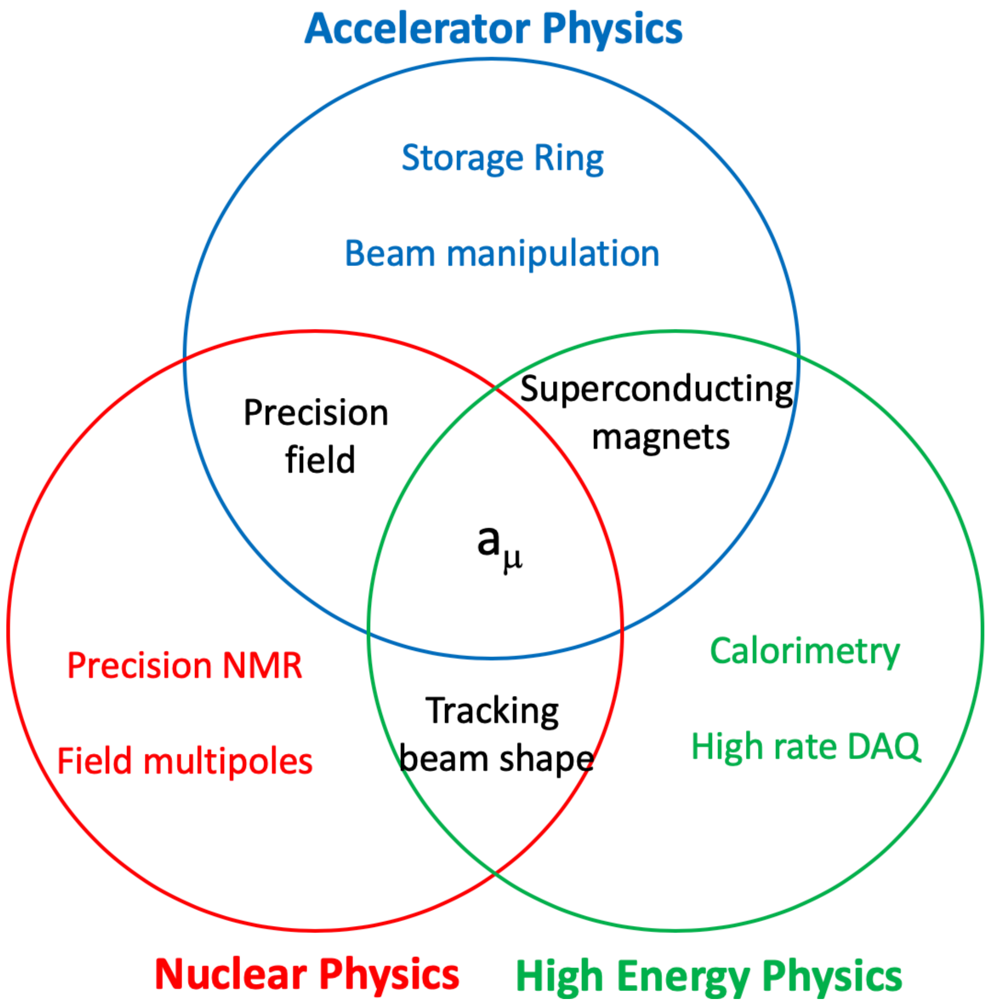
- from which:

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

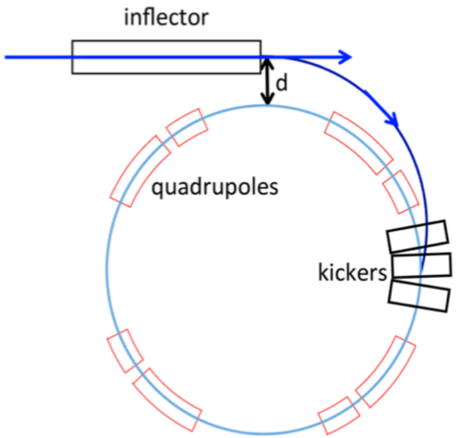


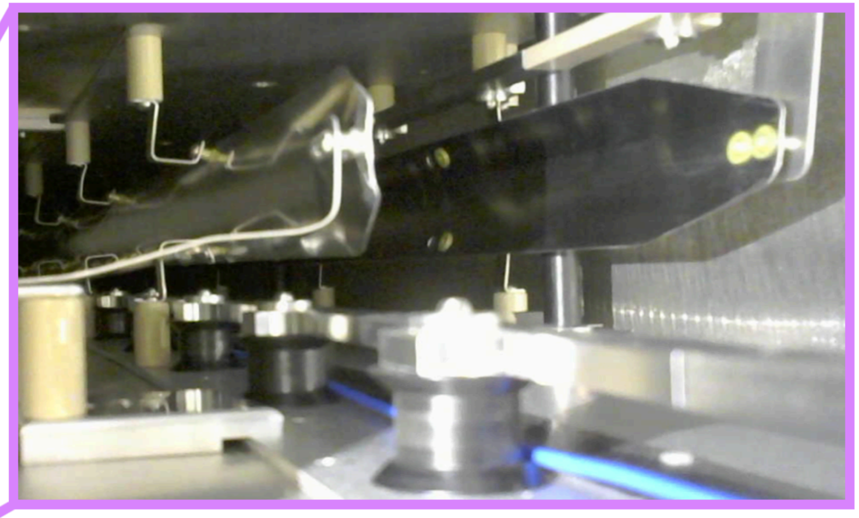
STORAGE RING
FIELD: wp
DETECTORS: wa
muons
Inflector
QUADS
24 Calorimeters + 2 trackers located all around the ring
NMR probes and electronics located all around the ring
Kicker

- Three different communities converging to measure a_μ



Muon beam storage and focusing

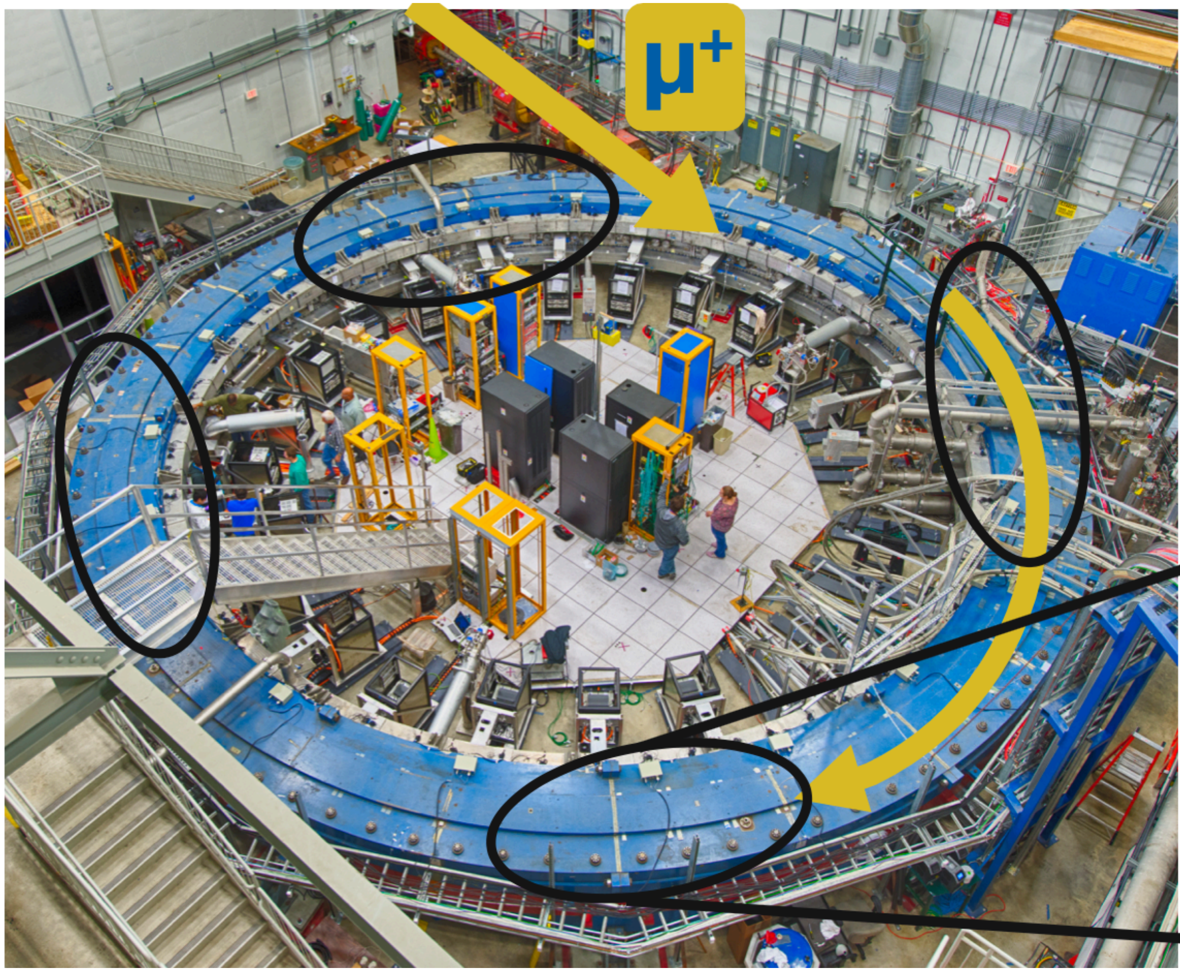




3 Kicker Magnets

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

Muon beam storage and focusing



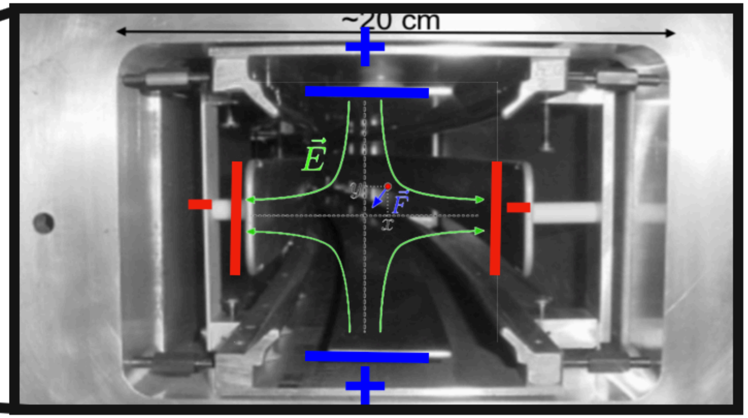
$$\vec{\omega}_a = -\frac{Qe}{m}\left[a\vec{B} - \left(a - \underbrace{\cancel{\frac{1}{\gamma^2-1}}}_{=0}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

At p_{magic}= 3.094 GeV/c

for γ_{magic}= 29.3

Electrostatic Quadrupoles

- Focuses muon beam vertically



Effects of Beam Dynamics

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

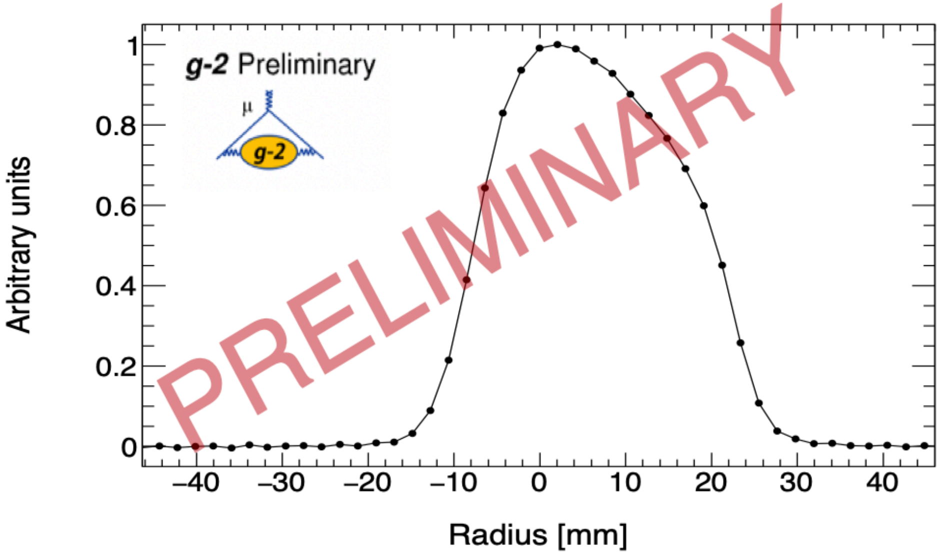
γ_{magic} = 29.3 (p_μ = 3.094 GeV/c)

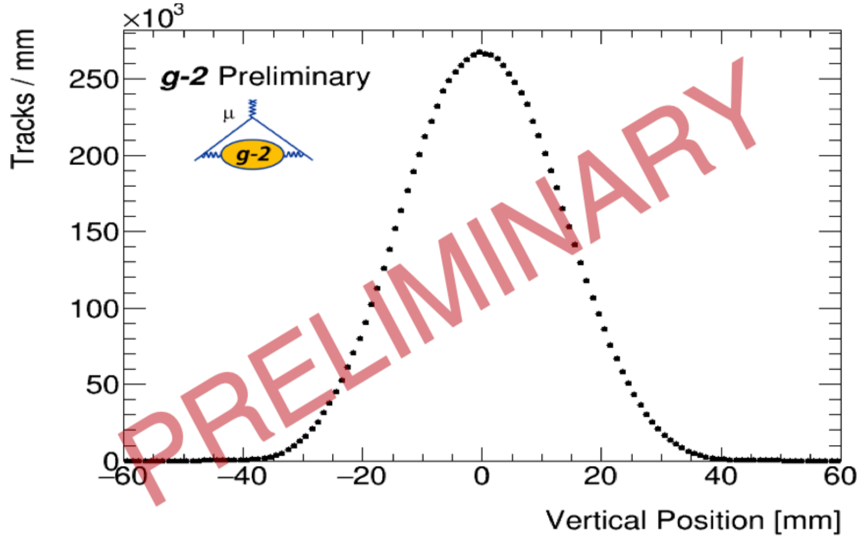
- **If all muons at P_{magic} = 3.09 GeV/c → $E = 0$**
- **Stored beam has a momentum spread → $E \neq 0$ → E-field correction**

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

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

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





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**

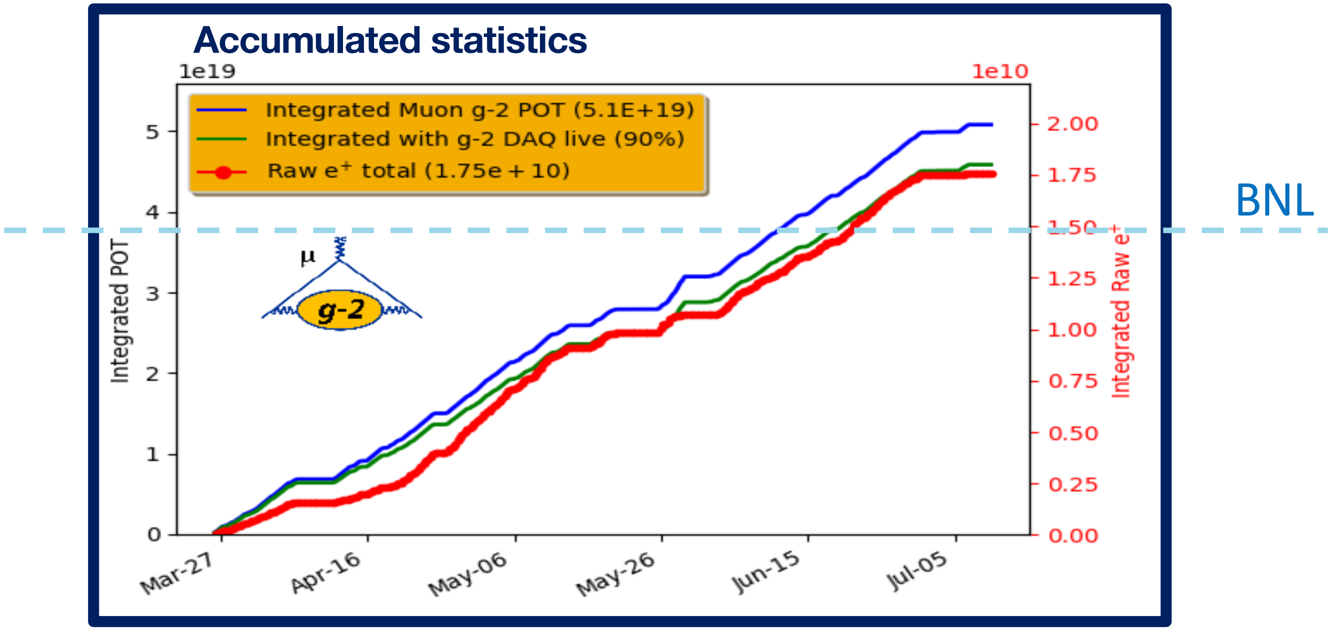
Current estimated C_E systematic $\leq$ 50 ppb

Current estimated C_p systematic $\sim$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) — **$\delta\omega_a$(stat) ~ 350 ppb (BNL $\delta\omega_a$(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

The wa-europa ω_a analysis group

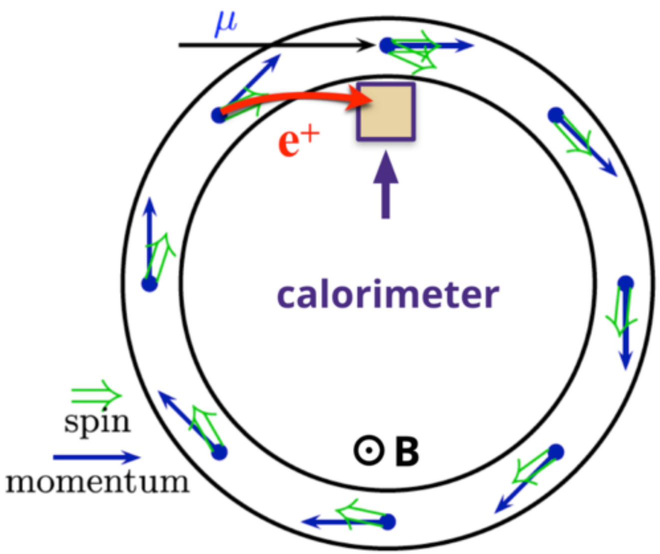
The *60h* dataset relative unblinding;
fitting procedure for ω_a−Europa
Revision 1

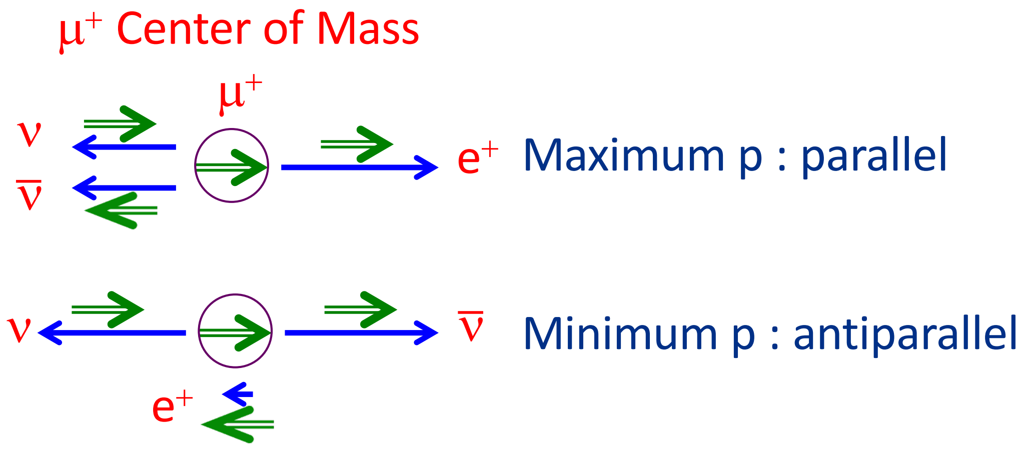
E. Bottalico[1], S. Di Falco[1], A. Driutti[2], P. Girotti[1], A. Gioiosa[3], G. Hesketh[4], M. Incagli[1], J. Price[5], M. Smith[1], M. Sorbara[6]

[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

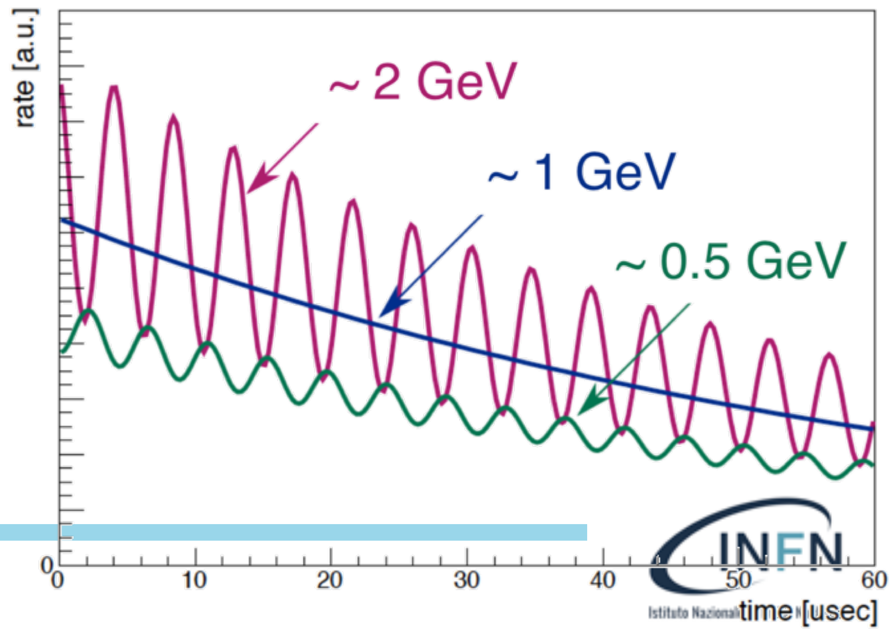
ω_a principle of measurement





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

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

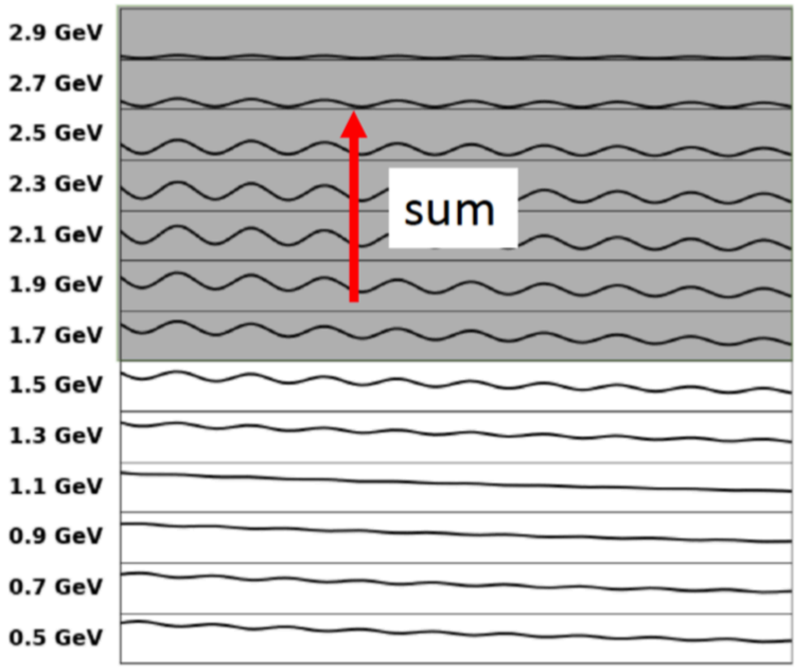


The wa analysis strategy

- 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

The methods

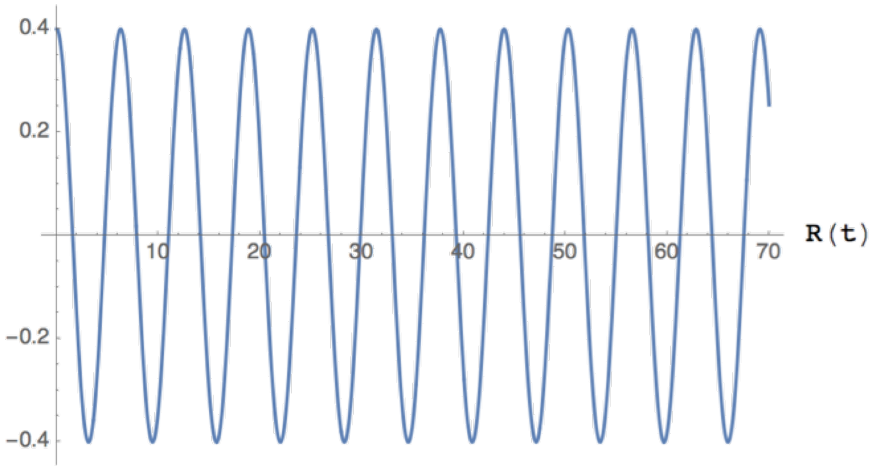


- **T-method**: count all positrons with E>1.7GeV and plot them vs time to get the *«Wiggle plot»* ; reference method
- **E-method** (Energy binned) : fit each energy slice, combine the resulting values for wa
- **A-method** (Asimmetry weighted) : weight each event with its own contribution to asimmetry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

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



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

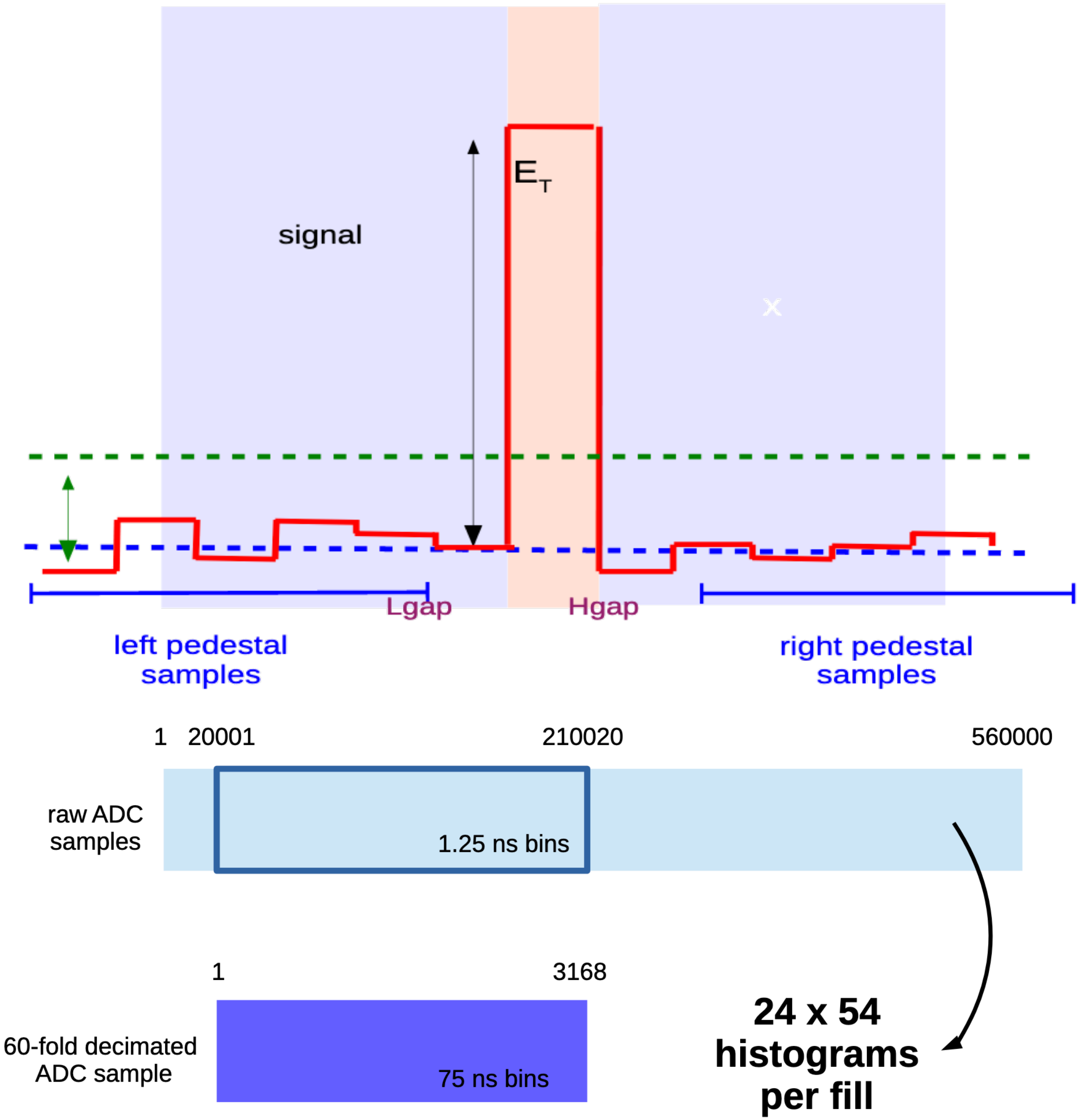
$$R(t) = \frac{N(t) - U(t)}{N(t) + U(t)}$$

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

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

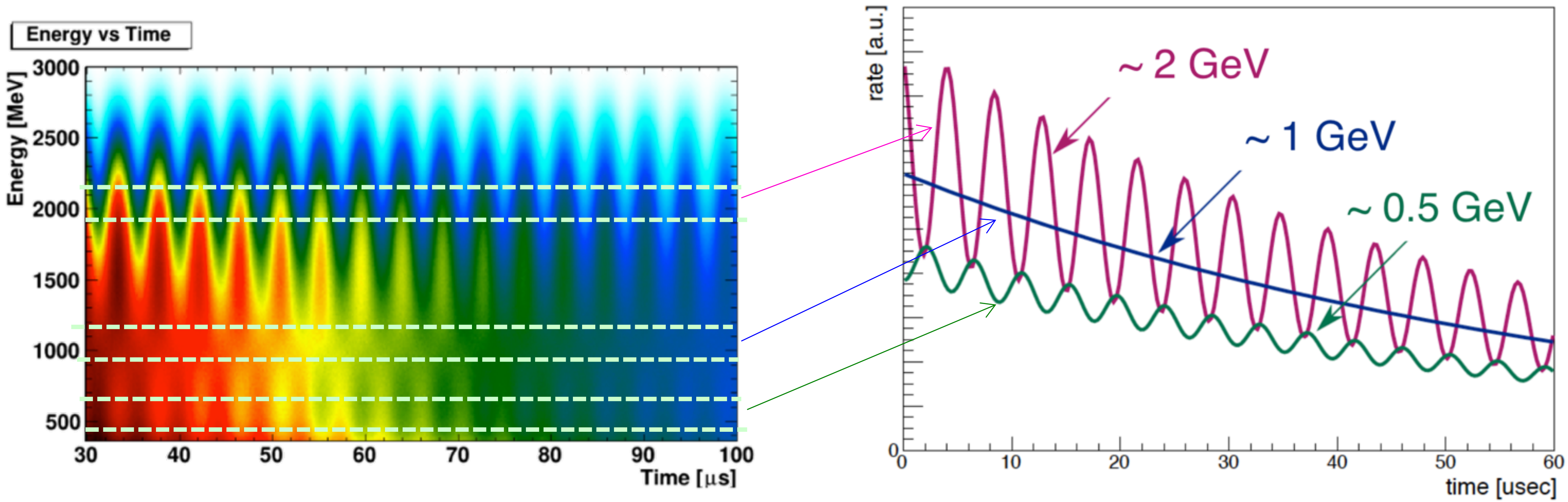
Q-method

- 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

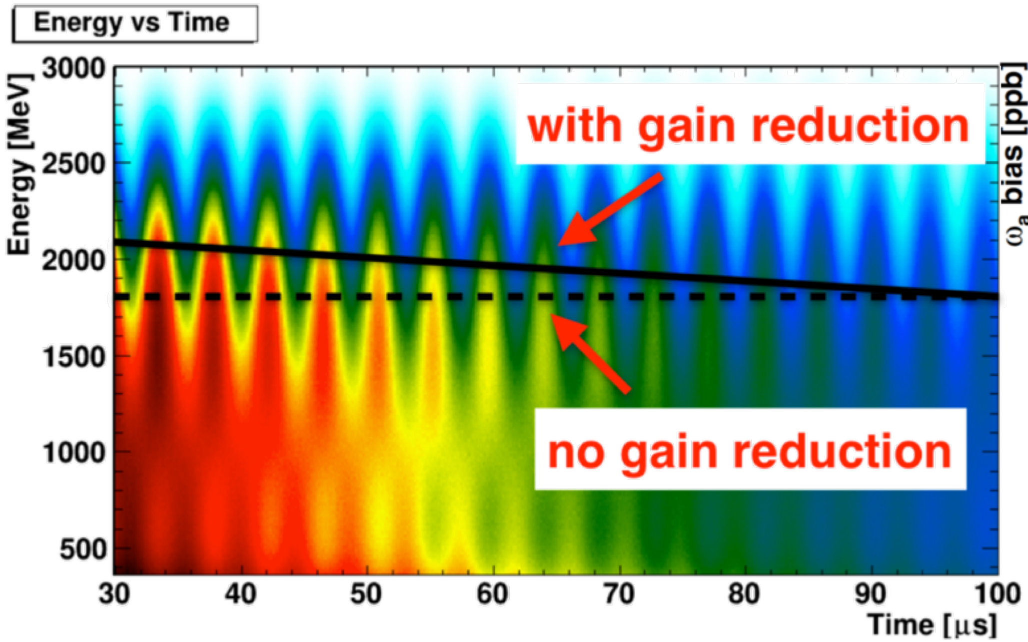
- The collected events are plot as a function of the **muon decay time** (clock) and of the **positron energy** (polarimeter)

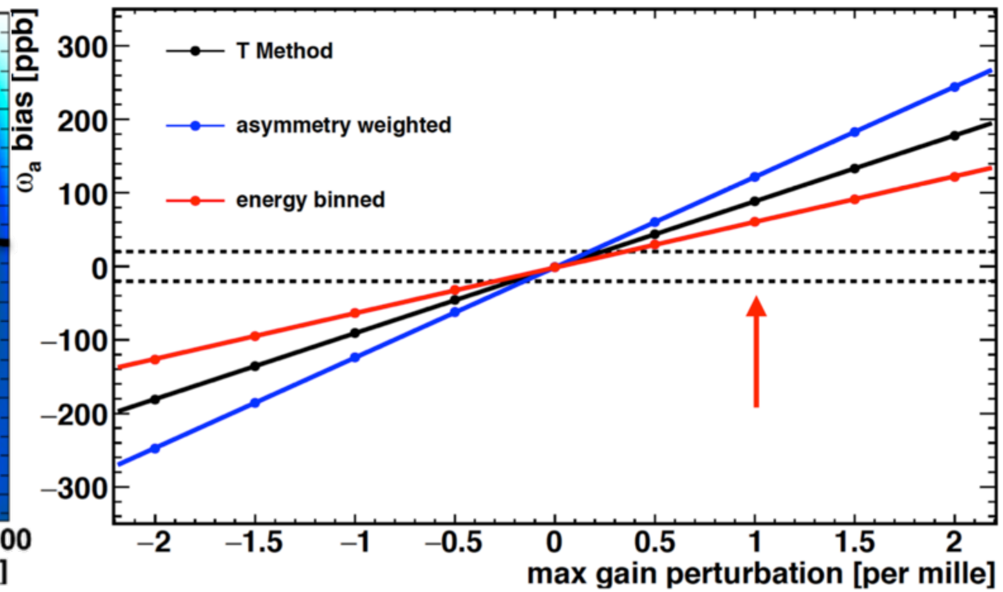


- Note that the *phase* depends on the positron energy
- If the energy threshold varies during the *muon fill* then wa is systematically shifted: $\omega_a t + \varphi(t) \sim (\omega_a + \varphi')t + \varphi_0$

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





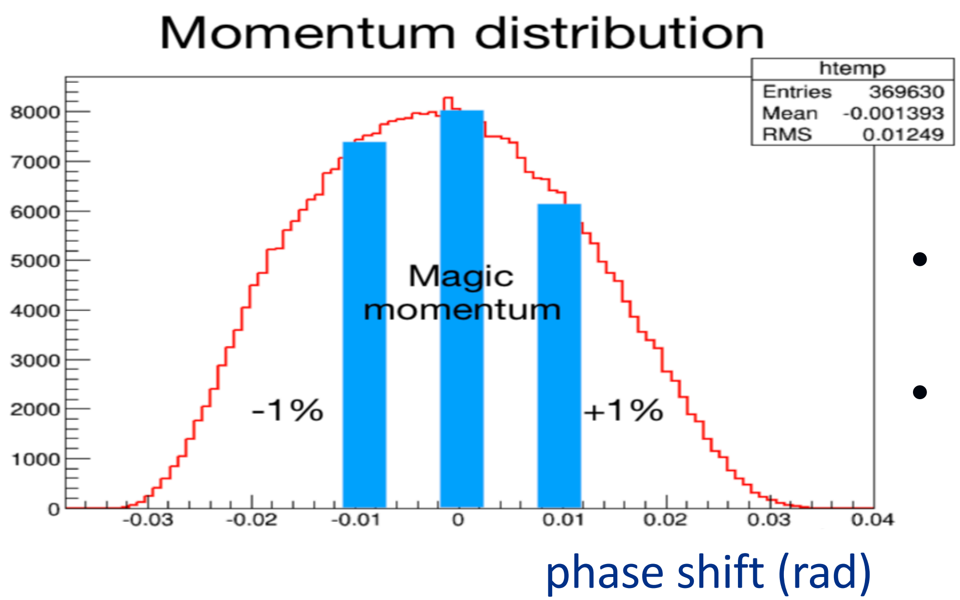
50-150 ppb bias is expected for uncorrected in-fill gain perturbation

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

$$\text{Bias in } \boldsymbol{\omega_a} : \Delta\boldsymbol{\omega_a} = \frac{d\langle\phi\rangle}{dt} = \frac{d\phi}{d\langle p\rangle} \cdot \frac{d\langle p\rangle}{dt}$$

Measured with dedicated systematic runs



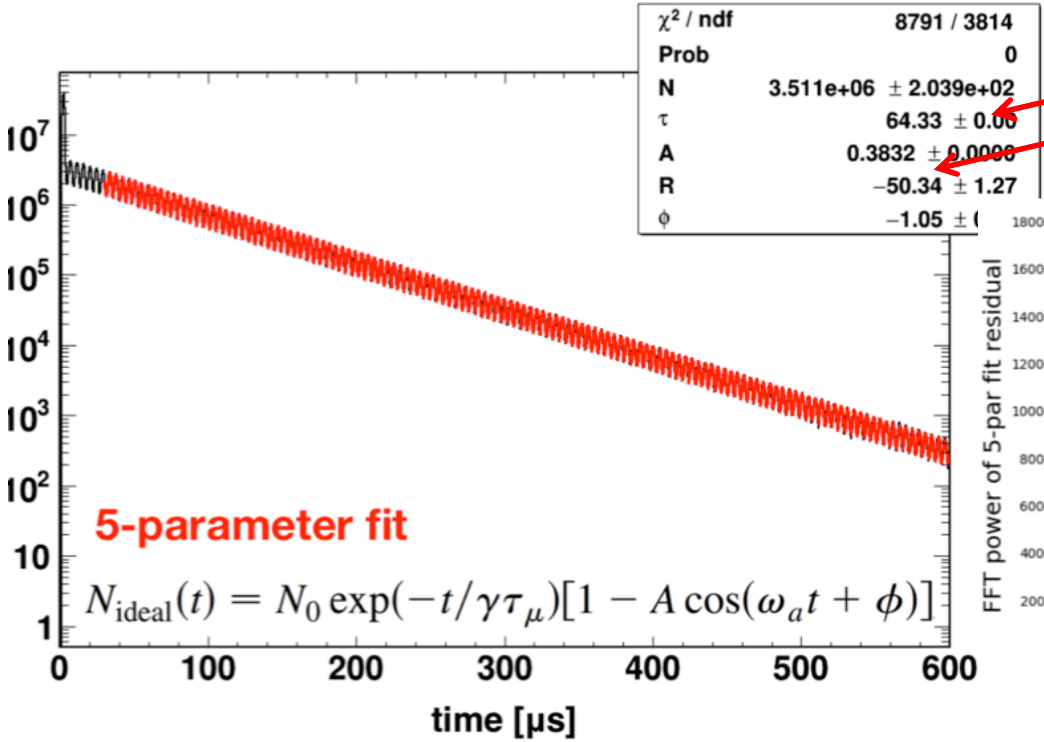
- Take data at higher than nominal momentum
- Compare higher momentum phase to nominal momentum phase

The 60h dataset: 5-par fit

- Simple (ideal) positron oscillation:

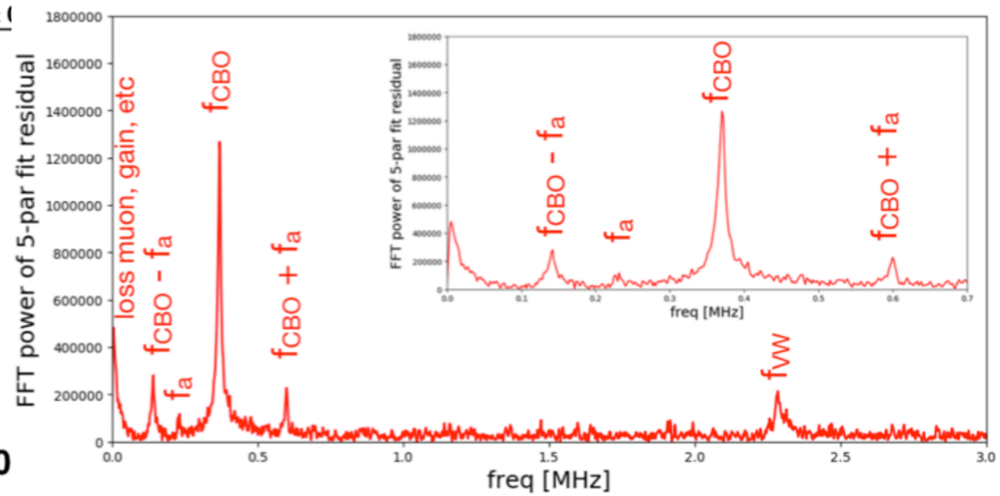
$$N_{\text{ideal}}(t) = N_0 \exp(-t/\gamma\tau_\mu)[1 - A\cos(\omega_a t + \phi)]$$

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



muon lifetime: γ=29.3

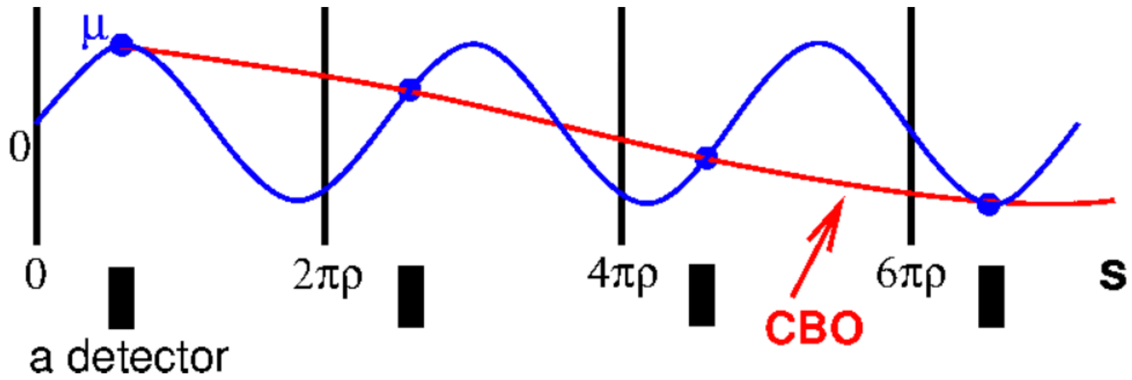
NOTE: blinding on ω_a!



Structure in residual: Beam Oscillations

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

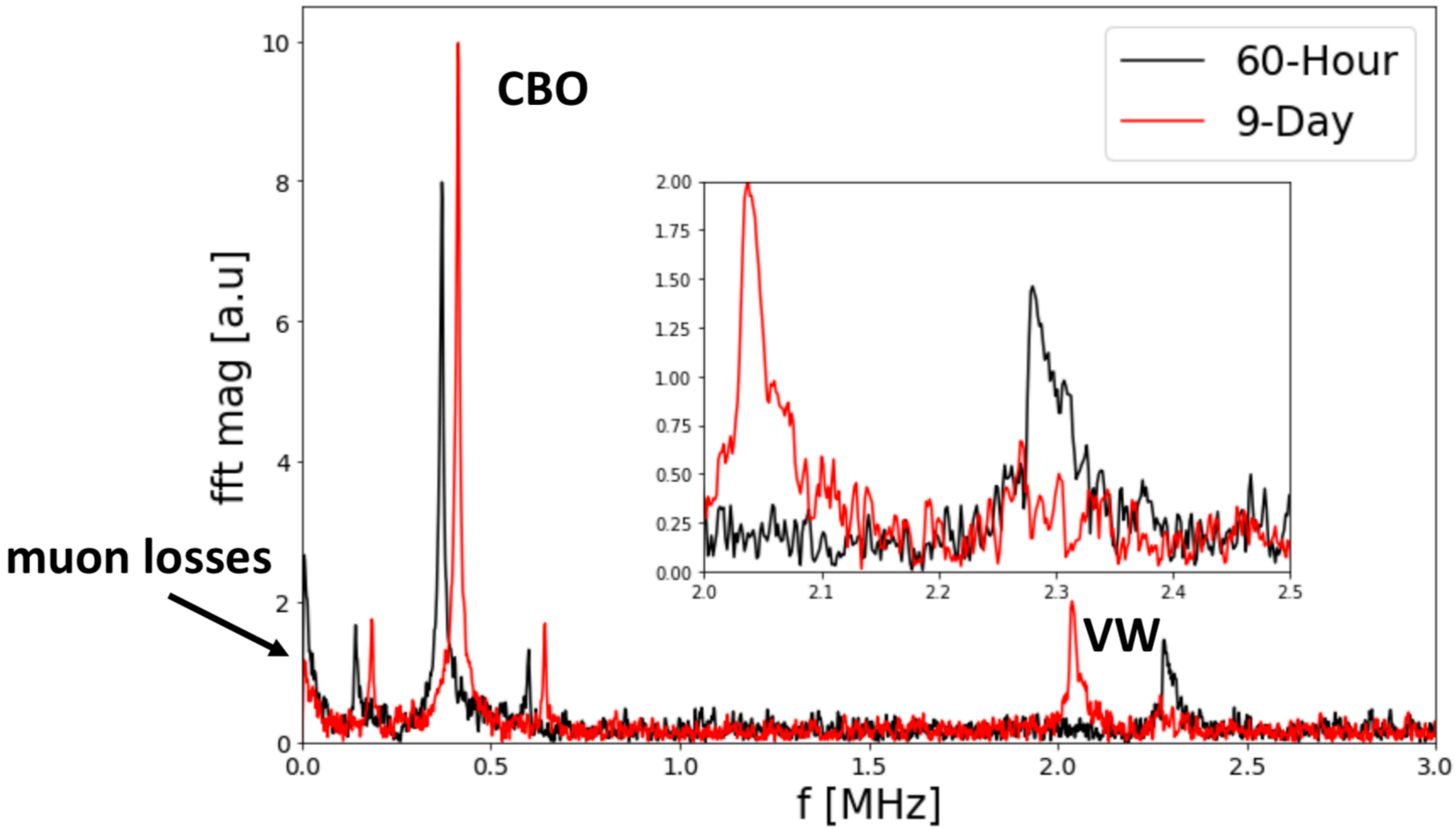
$$\lambda_{\mathrm{CBO}} \simeq \ 14 \text{ turns}$$



- 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 (*VW=Vertical Waist*)

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



Typical 18 (or 22) parameters fit function

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

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

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

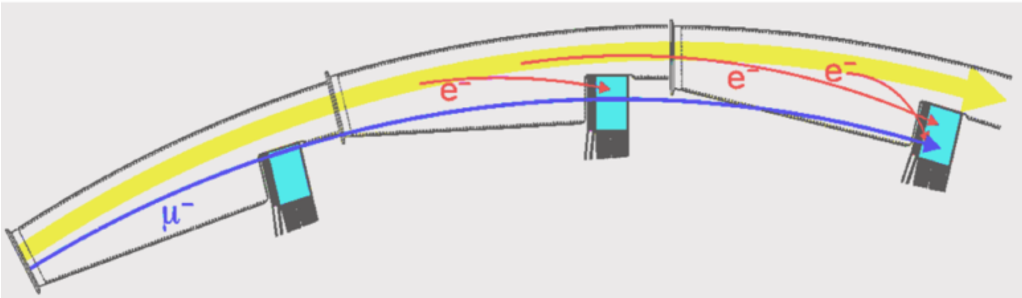
- ω_{CBO} and ω_{VW} are not constant due to QUAD HV faulty resistor:
  - $\omega_{CBO}(t) = \omega_{CBO}(0) * (1 + \delta_{CBO}(t))$
- (similar for ω_{VW}). The number of parameters depends on the parametrization of the correction δ_{CBO}
- The first term in parenthesis corresponds to the lost muons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

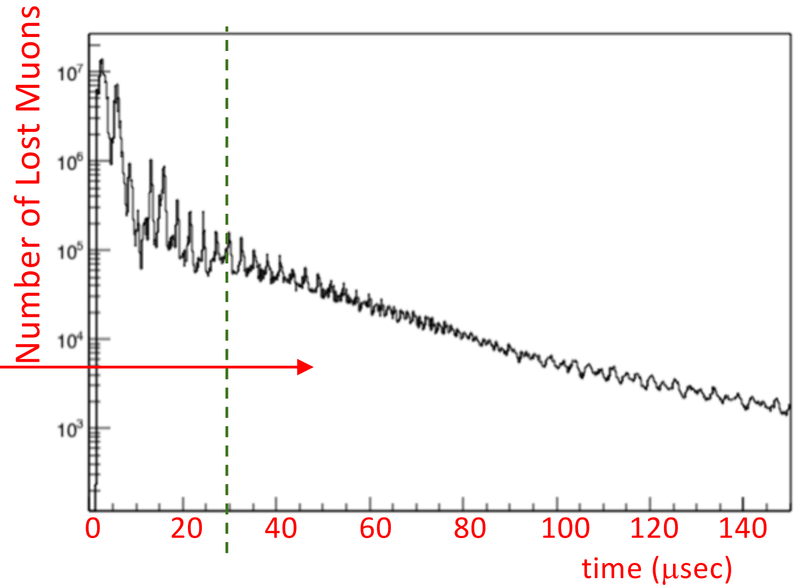
Distorting muon life time: lost muons

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

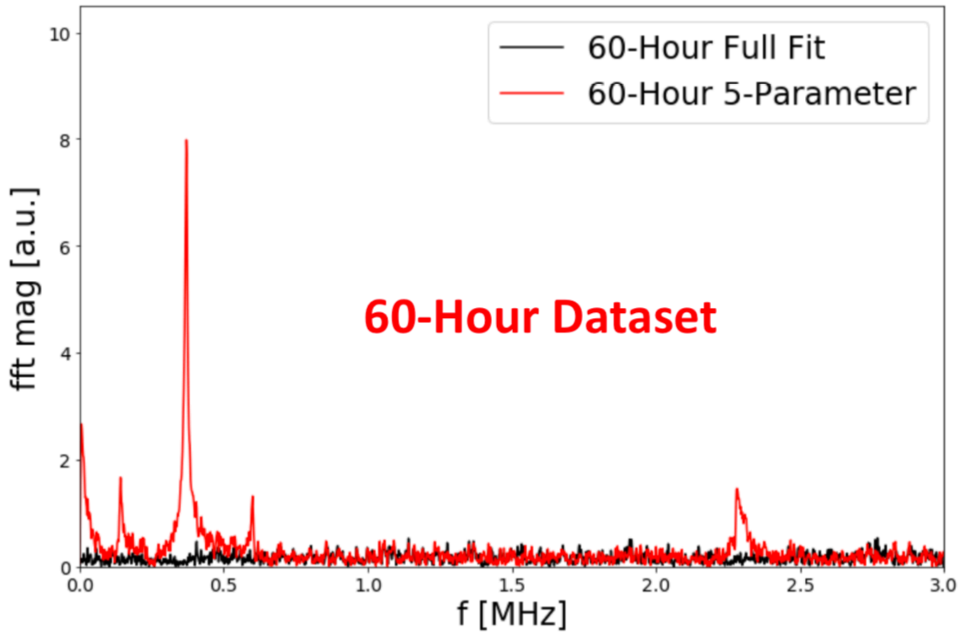
$$\left(1 - K_{loss}\int_0^t e^{t'/\tau} L(t')\,dt'\right)$$

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





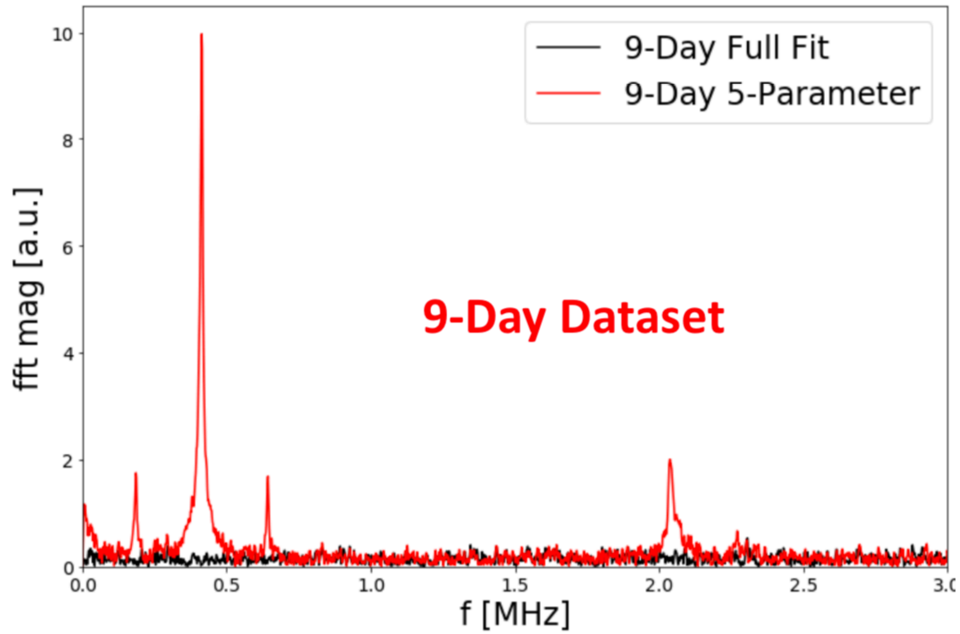
- Fraction of lost muons for t>30μs is $\boxed{<10^{-4}}$



1×10^9 **positrons**

1.33 ppm precision

$$\frac{\chi^2}{ndf} = 4077/4137$$



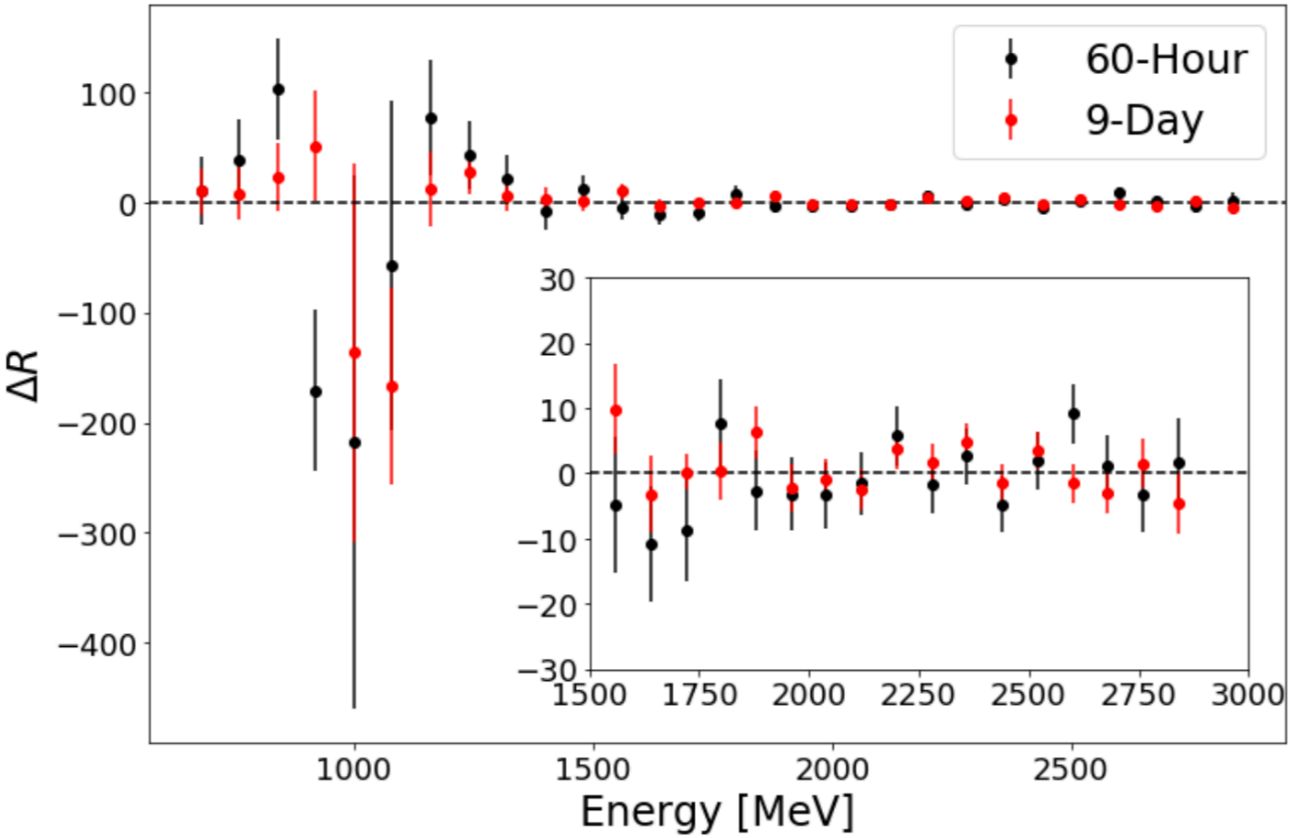
2.3×10^9 **positrons**

0.88 ppm precision

$$\frac{\chi^2}{ndf} = 4161/4133$$

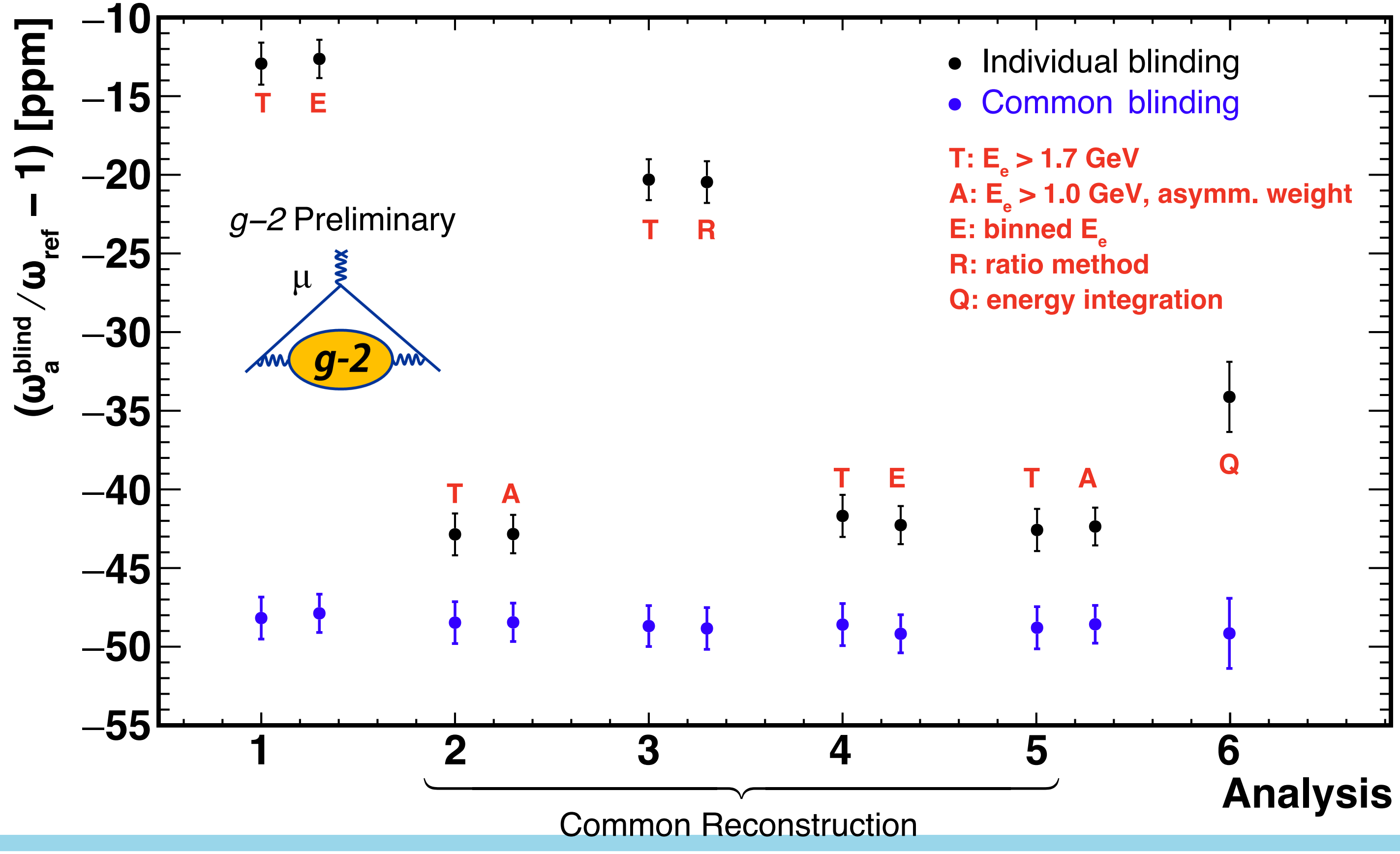
R vs positron energy

- 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 «relative unblinding»

- In April 2019, the ω_a value has been relatively unblinded – i.e. a common unknown shift still exists – for the «60h dataset»
- The T-method is used as a reference for all groups
- The (highly correlated) values agree within expected errors



Summary

- 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
- Publication expected soon based on Run1 data ... but ... should we wait for Run2?
  - more stable conditions
  - no competition
  - must be sure to do it right
- ... tough decision → Collaboration Meeting 20-22 Nov 2019