Measurement of the anomalous spin precession frequency ω_a in the Muon $g-2$ experiment at Fermilab

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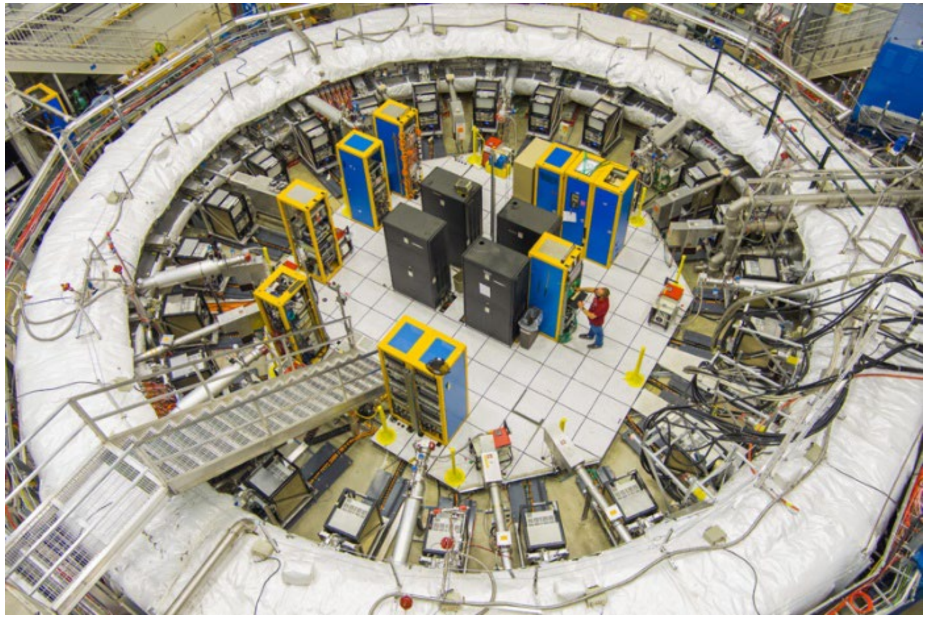
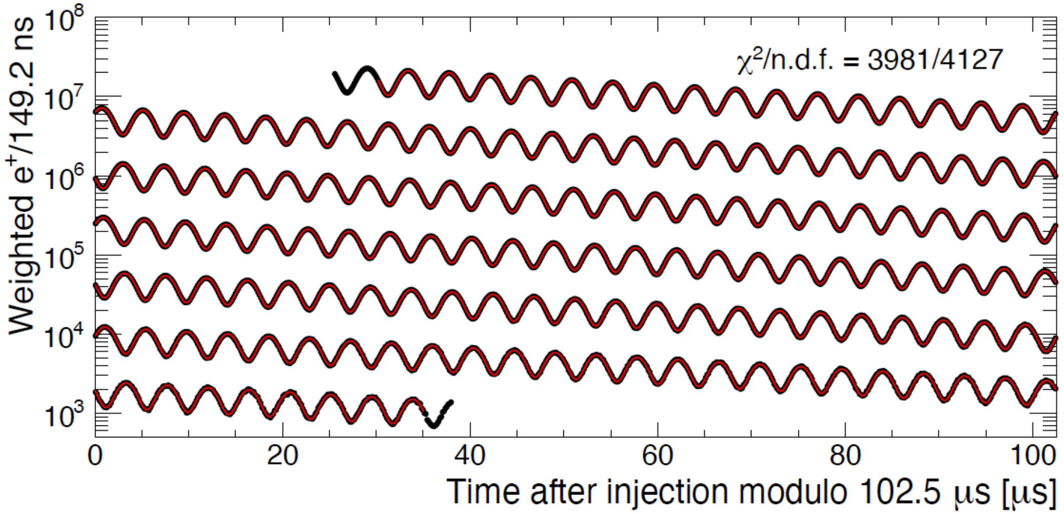
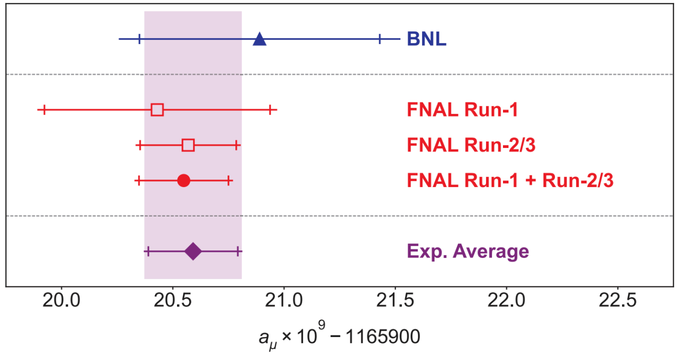
Outline

- The Muon $g - 2$ Experiment at Fermilab
- Anomalous precession frequency ω_a
- Run-2/3 result (2023):
  - Improved running conditions
  - Improved analysis and new methods
  - Systematic sources of uncertainty
- Status of Run-4/5/6 (projections)







Experiment at Fermilab Muon Campus


Ph: Ryan Postel


Ph: Reidar Hahn

Presented in the previous talk by **C. Zhang**

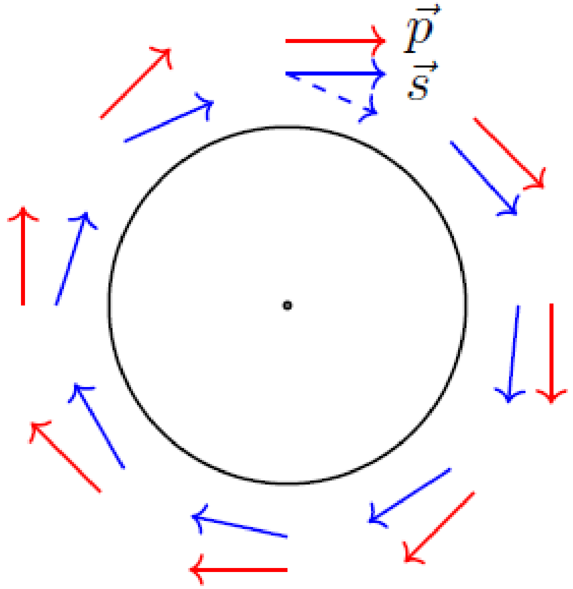
Anomalous spin precession in B-field

$$\left.\begin{array}{l} g-2\neq 0 \\ a_\mu \neq 0 \end{array}\right\} \rightarrow \text{spin precesses with anomalous frequency } \vec{\omega}_a = \vec{\omega}_{\text{spin}} - \vec{\omega}_{\text{c}}$$

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

$\gamma = 29.3 \rightarrow p = 3.094\ \text{GeV/c}$
"magic momentum"

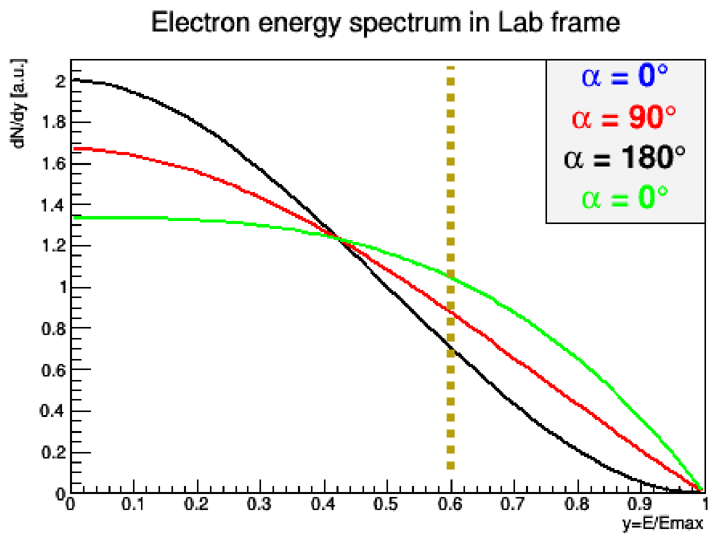
$\vec{\beta}\cdot\vec{B} = 0$

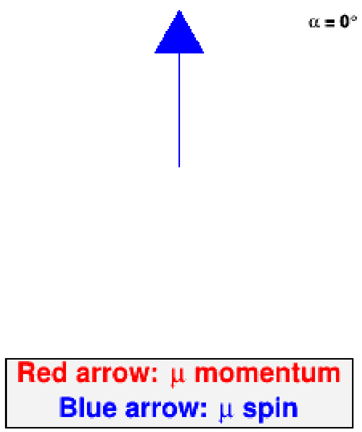


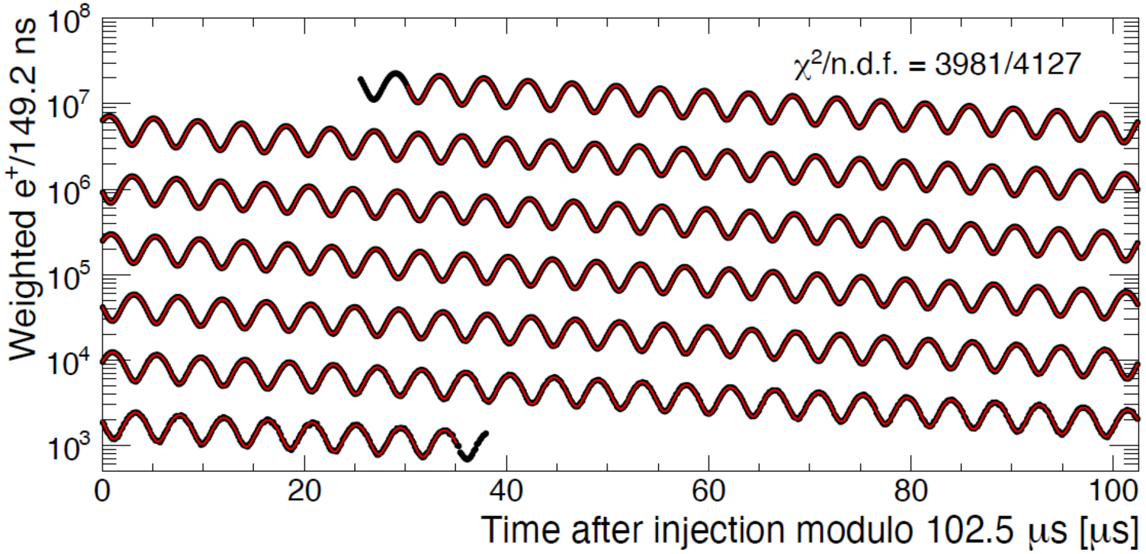
$\omega_c \sim 42.1$ rad/μs

$\omega_a \sim 1.439$ rad/μs ~
~ 12.4° per turn

Principle of ω_a measurement

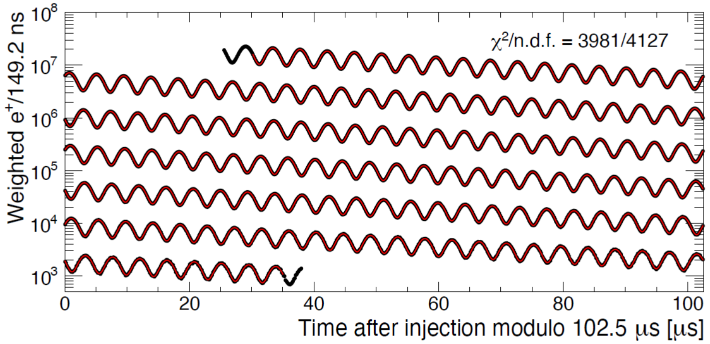

Electron energy spectrum in Lab frame

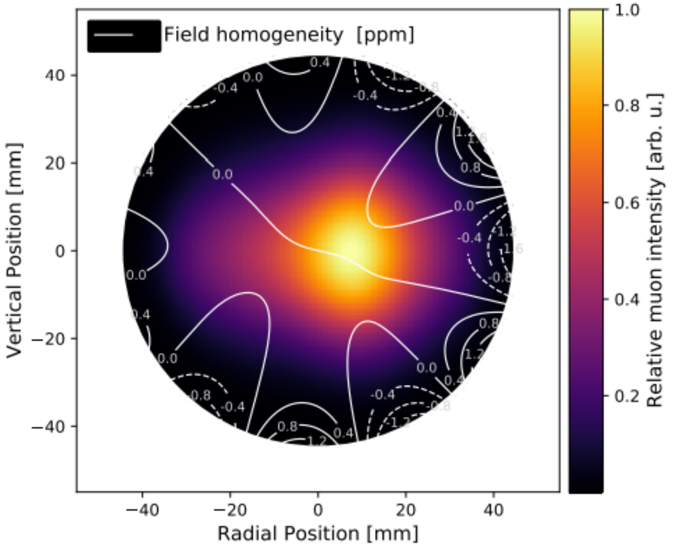




1. Weak decays violate parity:
   - polarized muon beam
   - preferred high-energy e^+ direction
2. Correlation in the lab frame between e^+ energy spectrum and ω_a phase
3. «Wiggle plot»: count high-energy e^+ over time, for about 700 μs (muon lifetime is $\sim$ 64 μs in the lab)

Master formula for a_μ





$$a_\mu = \frac{\omega_a}{\omega_p} \times \boxed{\frac{\mu_p'(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}}$$

External factors, known to 25 ppb

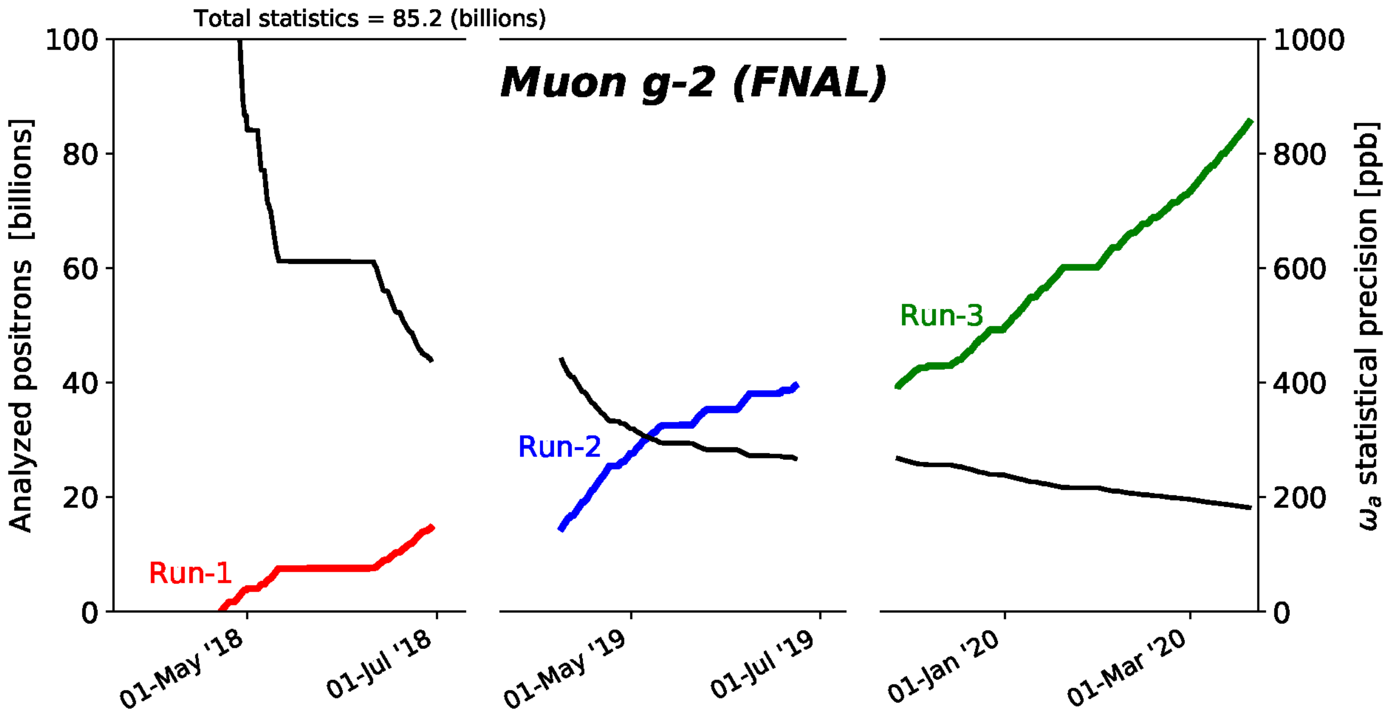
$$\frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m} \times$$

corrections for effects that…

- Make spin precess slower (E-field, vertical motion)
- Make phase change within 700 µs
- Induce transient magnetic fields

m=Measured values

Run-2/3 (2019-2020 campaign)



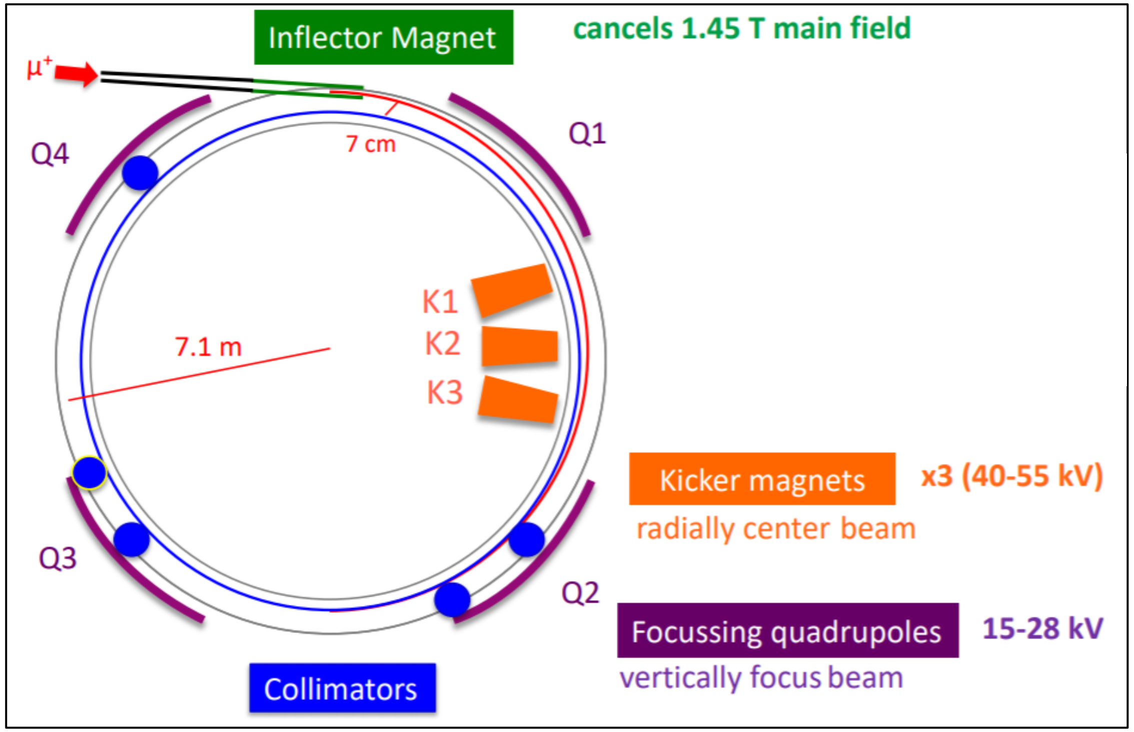
Run-2/3: ~ 5 more muon decays than Run-1

Systematic limitations in Run-1 were fixed

Dataset	Stat. unc. [ppb]
Run-1	434
Run-2/3	201
Combined Run-1+Run-2/3	185
FNAL design goal	100

Injection and muon storage

1. **Inflector** cancels main dipole field and injects at ~8 cm radially away from nominal orbit
2. **3 fast magnetic kickers** provide 10 mrad kick and place muons in orbit
3. **8 Electrostatic Quadrupoles** (ESQ) focus in the vertical direction



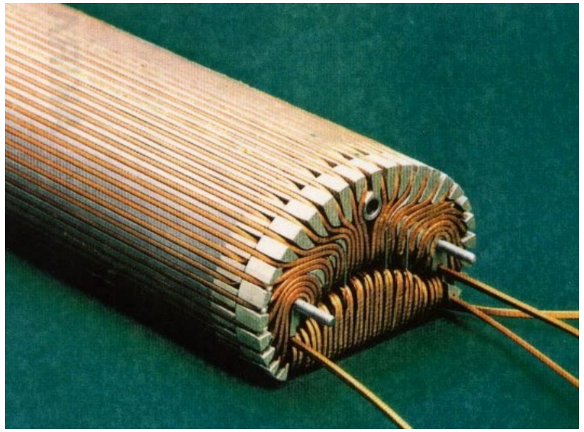
Inflector Magnet — cancels 1.45 T main field

Kicker magnets x3 (40-55 kV) — radially center beam

Focussing quadrupoles 15-28 kV — vertically focus beam

Collimators

1.



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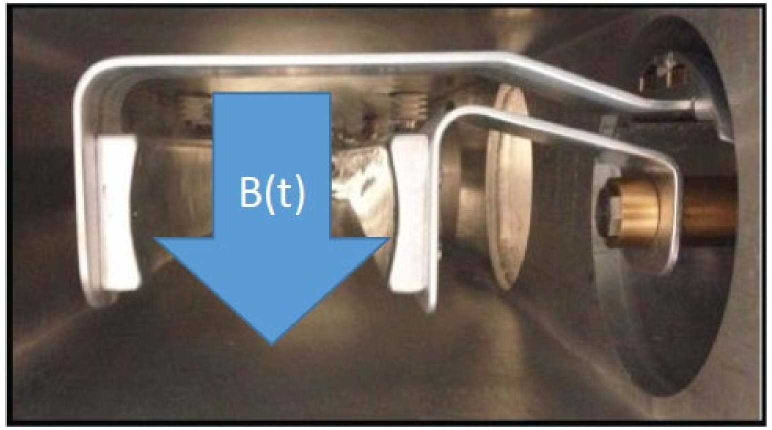

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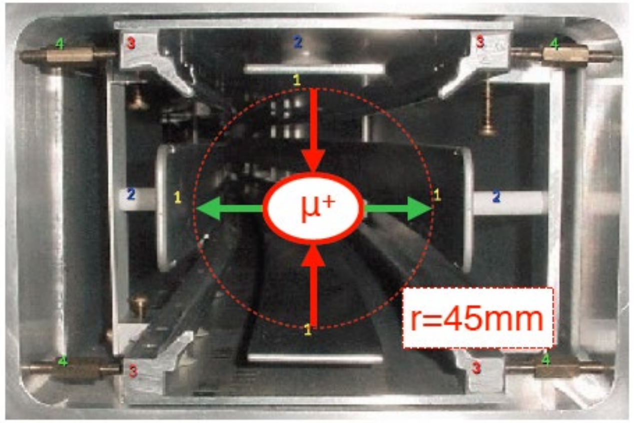
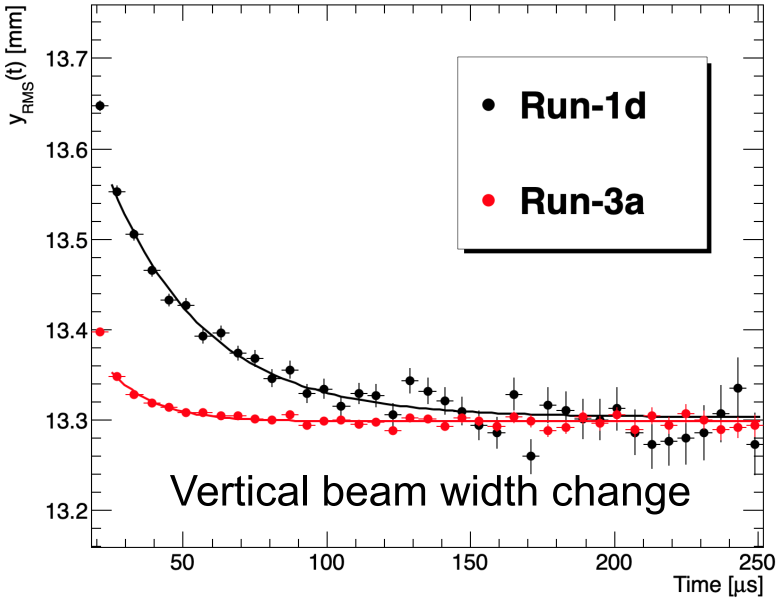
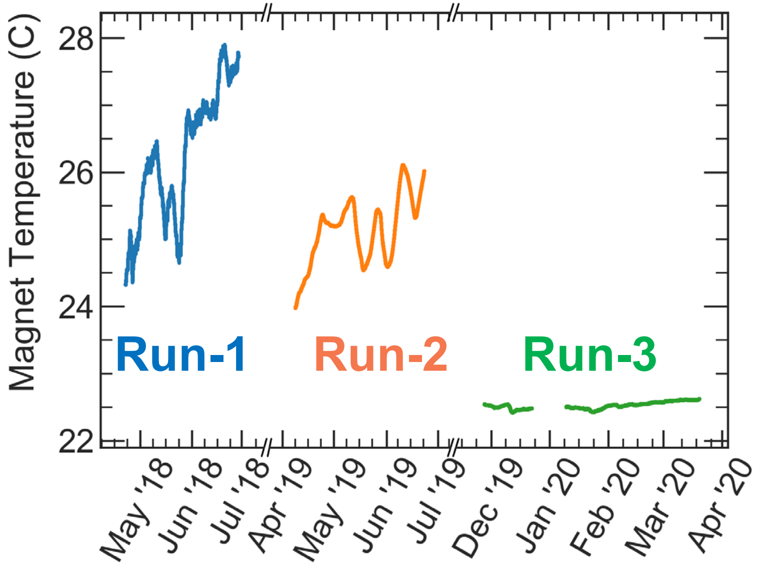
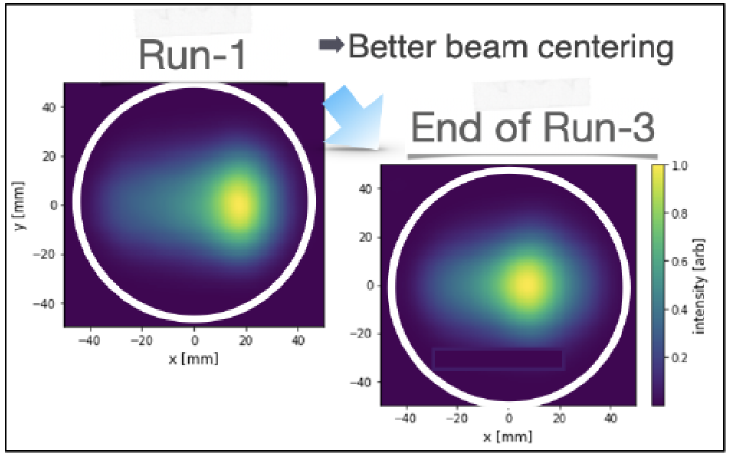


Run-2/3 improved running conditions

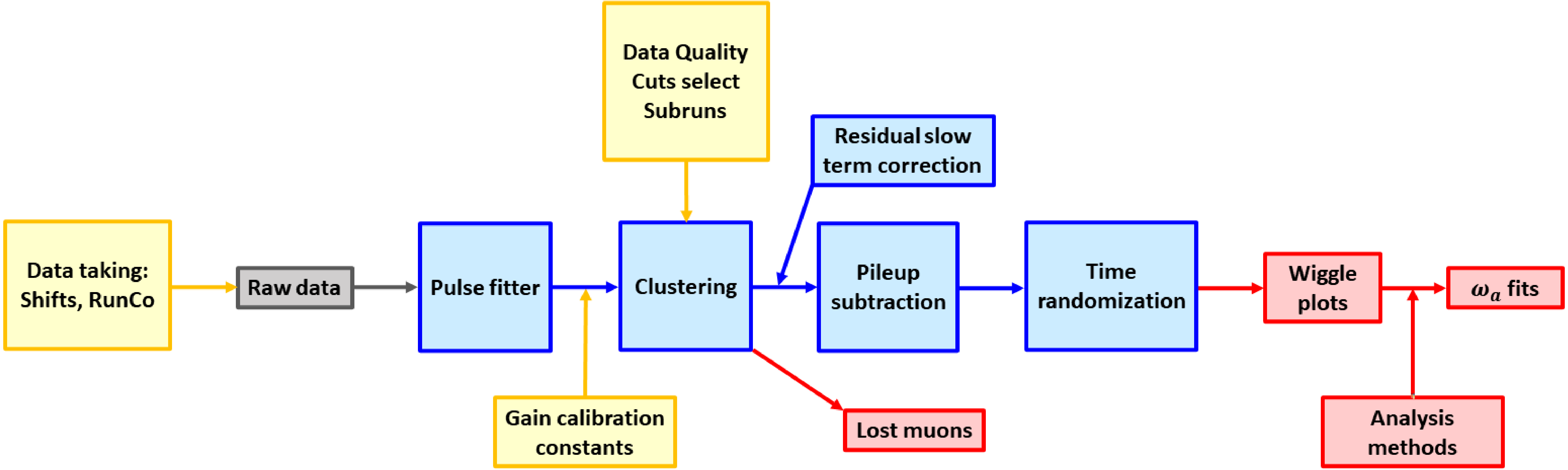
- Before Run-2: **fixed faulty resistors** in 2/32 quadrupole plates → better storage, more stable beam oscillations and reduced systematics
- After Run-2: added thermal insulation to ring → less variable magnetic field
- Mid Run-3: **upgraded kicker** cables for optimal kick → more centered beam







ω_a analysis flowchart



Data taking: Shifts, RunCo

Raw data

Pulse fitter

Gain calibration constants

Data Quality Cuts select Subruns

Clustering

Lost muons

Residual slow term correction

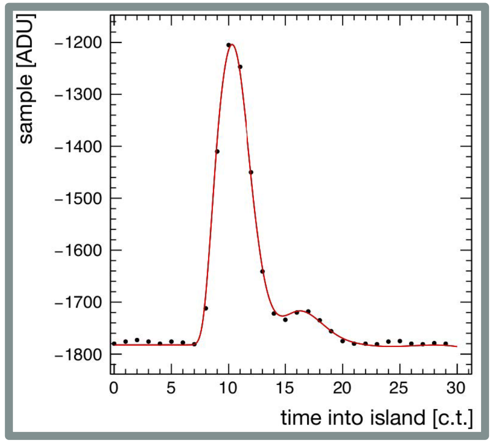
Pileup subtraction

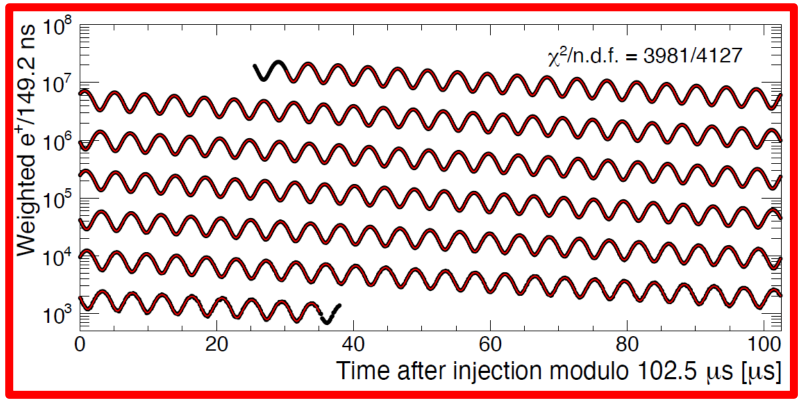
Time randomization

Wiggle plots

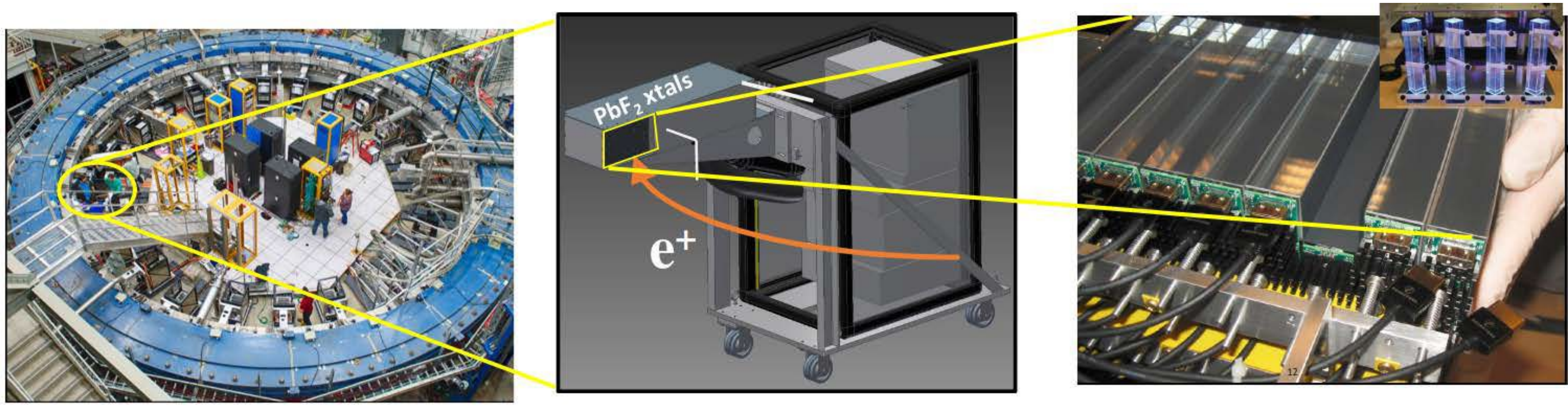
Analysis methods

ω_a fits





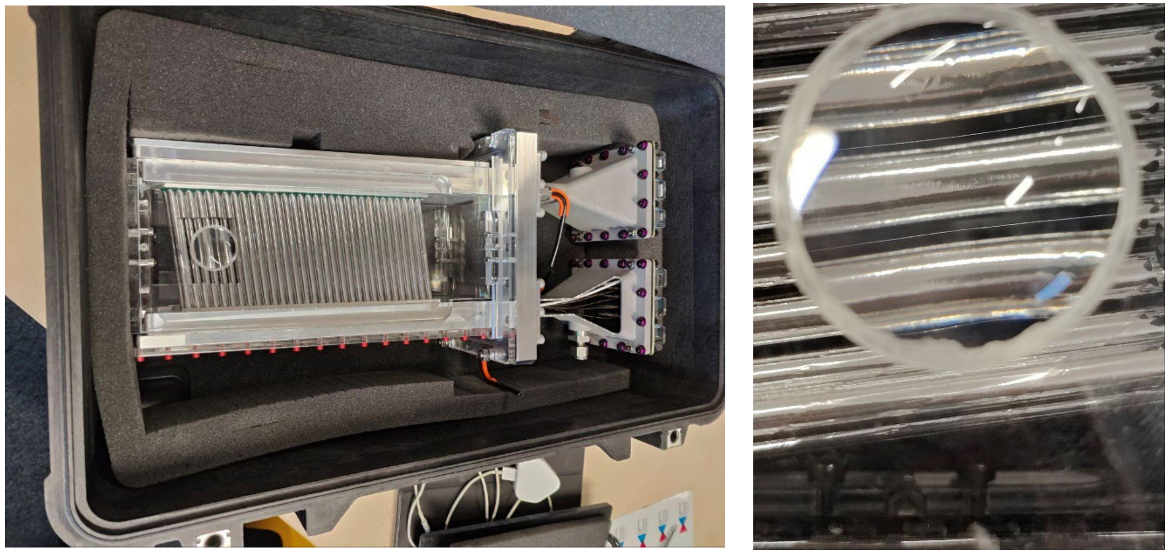
Detectors



24 e.m. calorimeters

- Measure (E,t) of e^+
- Each made of 6×9 PbF_2 crystals, $15X_0$, read out by large-area SiPMs
- e^+ generate electromagnetic shower, SiPMs detect Cherenkov light ($n = 1.8$)

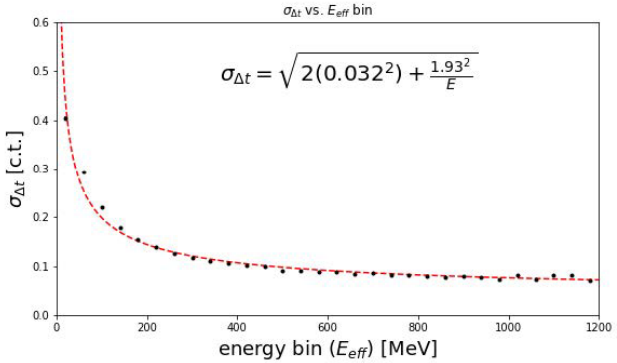
2 straw tube trackers

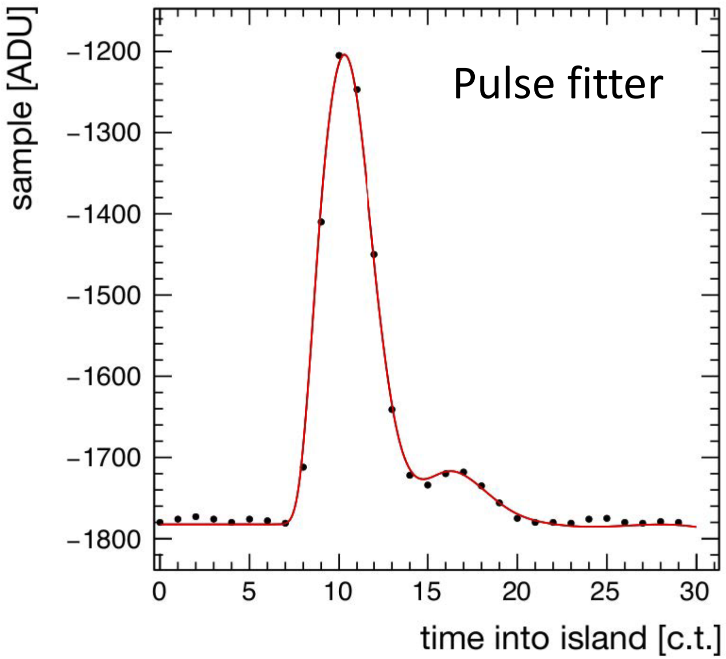


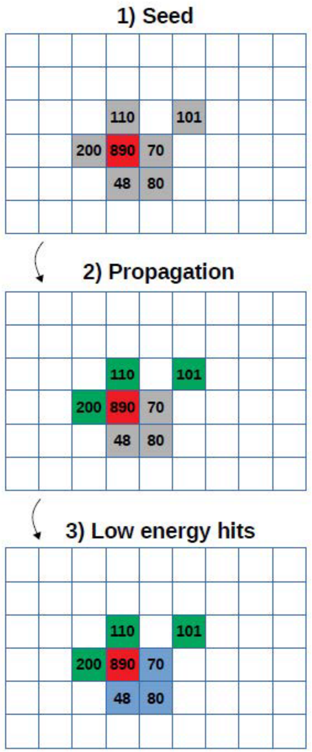
- Each has 8 modules and 32 planes
- 50:50 Argon:Ethane at 1 atm pressure
- Extrapolate decay vertex location to measure beam distribution

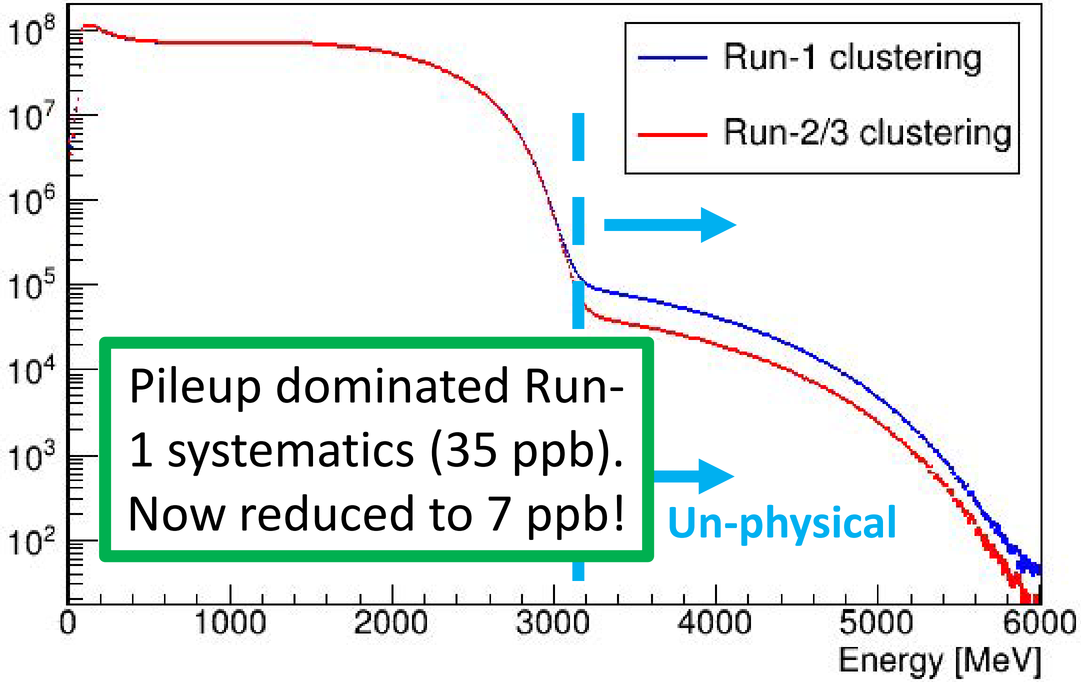
Reconstruct e^+ events

- Pulse fitter identifies traces on crystals
- Seed-and-propagation algorithm, with functions that take into account detector time and energy resolutions
- Reduced pileup in un-physical region (after 3.1 GeV)



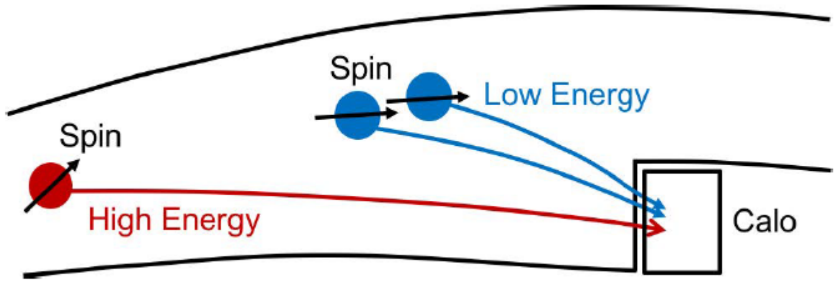


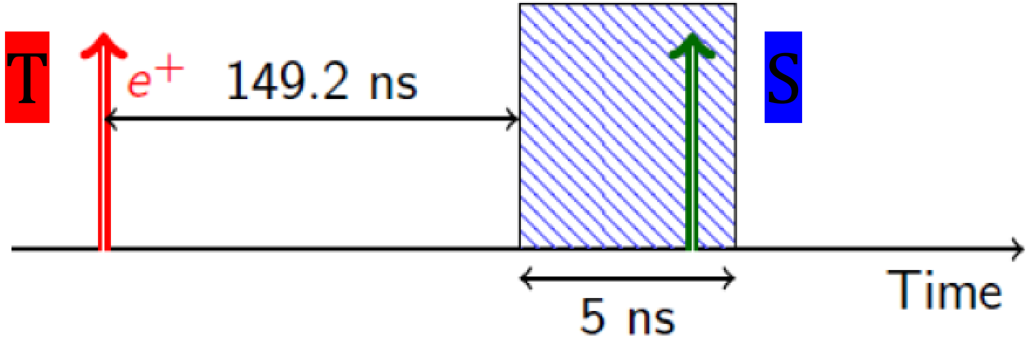




Pileup dominated Run-1 systematics (35 ppb). Now reduced to 7 ppb!

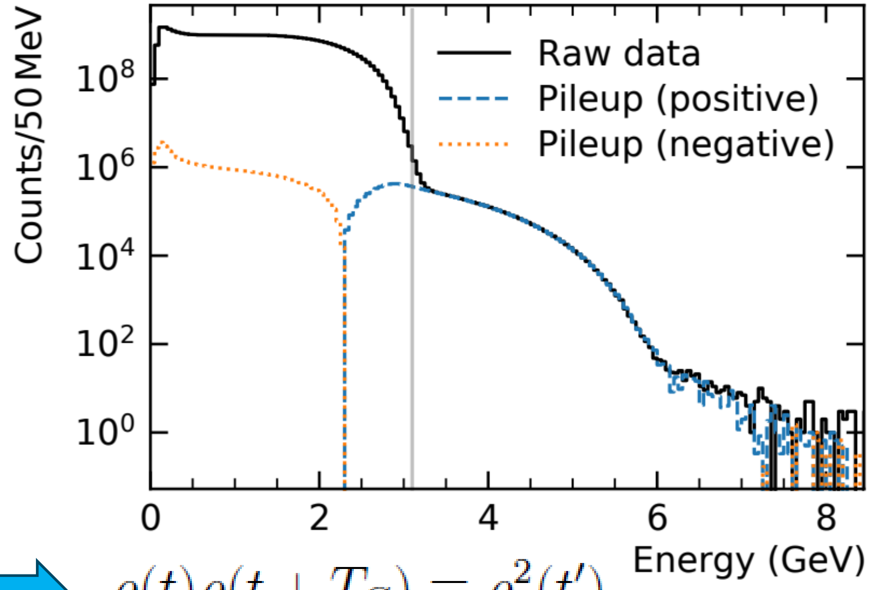
Example of new method to subtract pileup





For each T (Trigger) cluster that we find:

- Search for coincidence e^+ in S (Shadow) window, after 149.2 ns
- Superimpose the two clusters and pass to reconstruction algorithm
  →If not resolved: merge them and build pileup



$$E_2 = (E_T + E_{S_1}) \qquad t_2 = \frac{(t_T + T_G/2)E_T + (t_{S_1} - T_G/2)E_{S_1}}{E_T + E_{S_1}}$$

$$\rho(t)\rho(t + T_G) \equiv \rho^2(t')$$

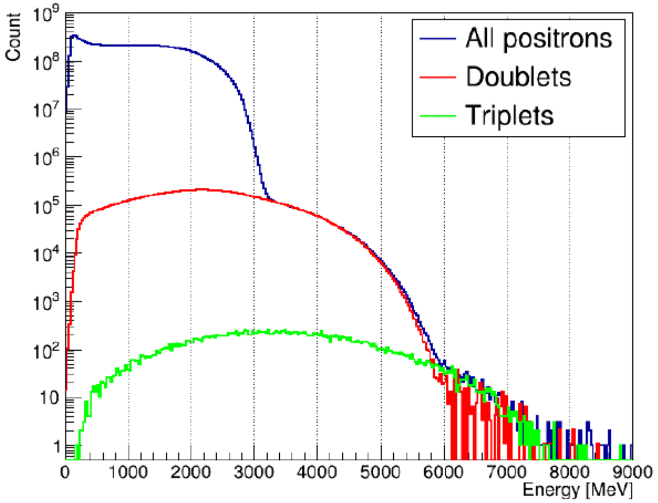
Finally: subtract merged event and add single events

Improved pileup correction since Run-1

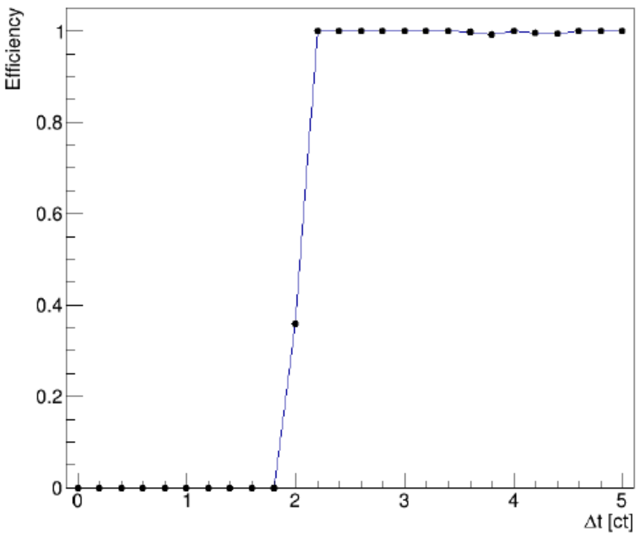
1. In Run-2/3 we also searched for triplets (treated as systematics in Run-1): 1 trigger, 2 subsequent shadows

2. We took into account pulse fitter behaviour:

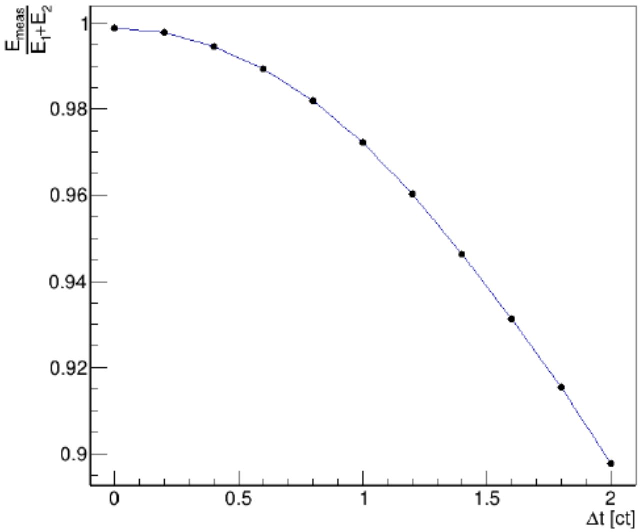
Splits two hits in the same SiPM OR Merges them with reduced energy



Separation efficiency



$$E' = f_{corr}(E_1 + E_2)$$



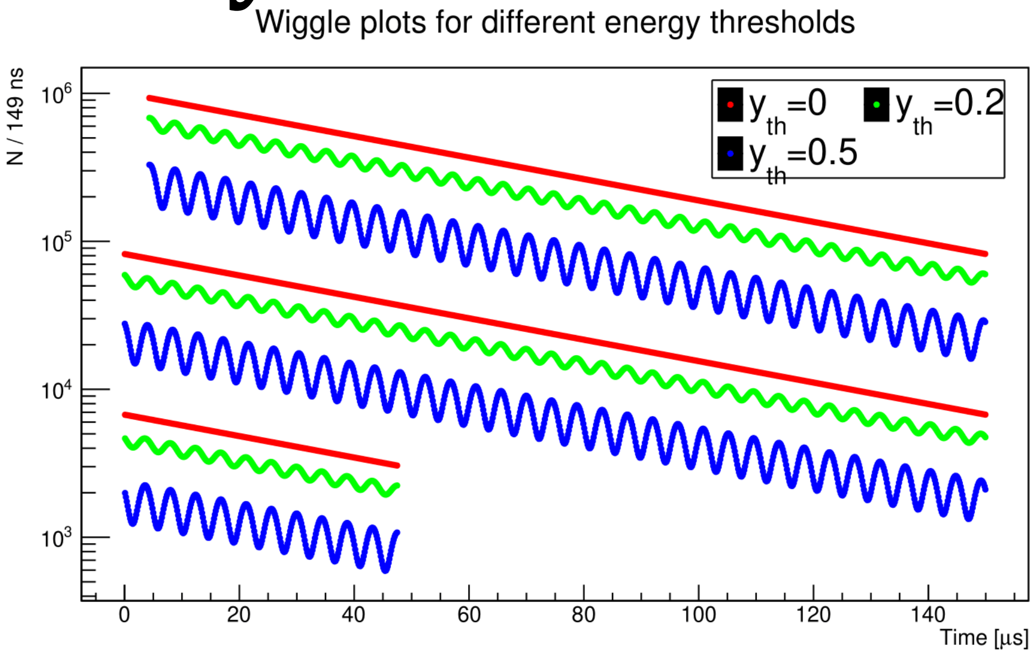
Methods for ω_a analysis

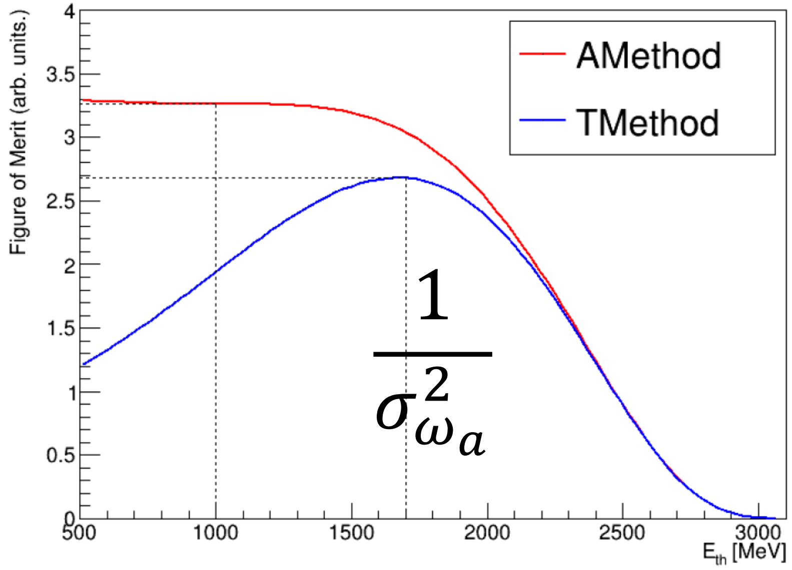
T-Method:

- Greater threshold: wider ω_a oscillations
- Lower threshold: more positrons
- Compromise: 1.7 GeV

A-Method:

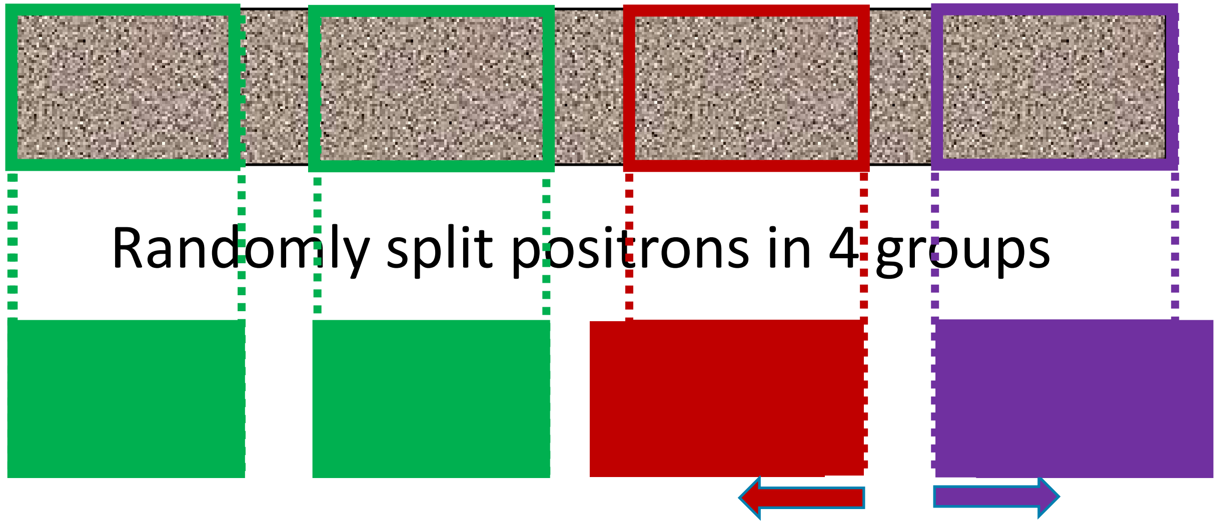
- Extract asymmetry (oscillation amplitude) as function of positron energy → $A(E)$
- Weight each positron event with $A(E)$
- σ_{ω_a}(A-Method)~ 90% σ_{ω_a}(T-Method)





$$\frac{1}{\sigma_{\omega_a}^2}$$

Ratio method wiggle plots



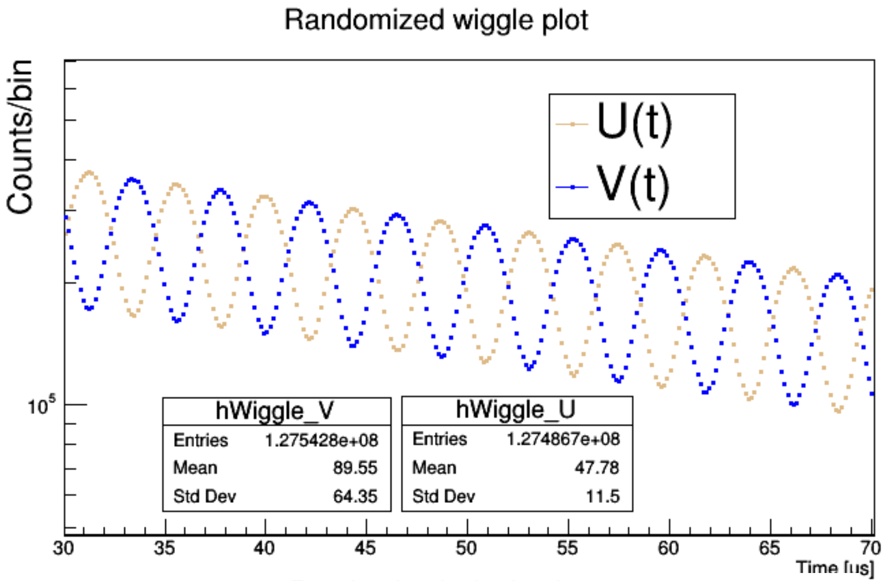
Randomly split positrons in 4 groups

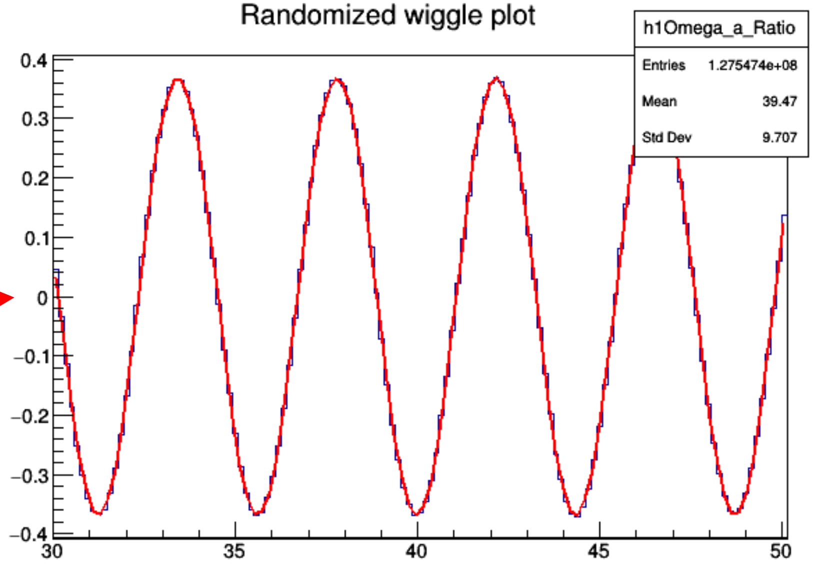
Shift two groups in time by ± half precession period $T_a/2$. Recombine:

$\boldsymbol{V(t)}$	$\boldsymbol{U(t)}$

$$R(t) = [V(t) - U(t)]/[V(t) + U(t)]$$

It gets rid of muon lifetime and normalization N_0 in fit function. Any «slow» effect is highly reduced!





NEW! “Ratio” A-Method NEW!

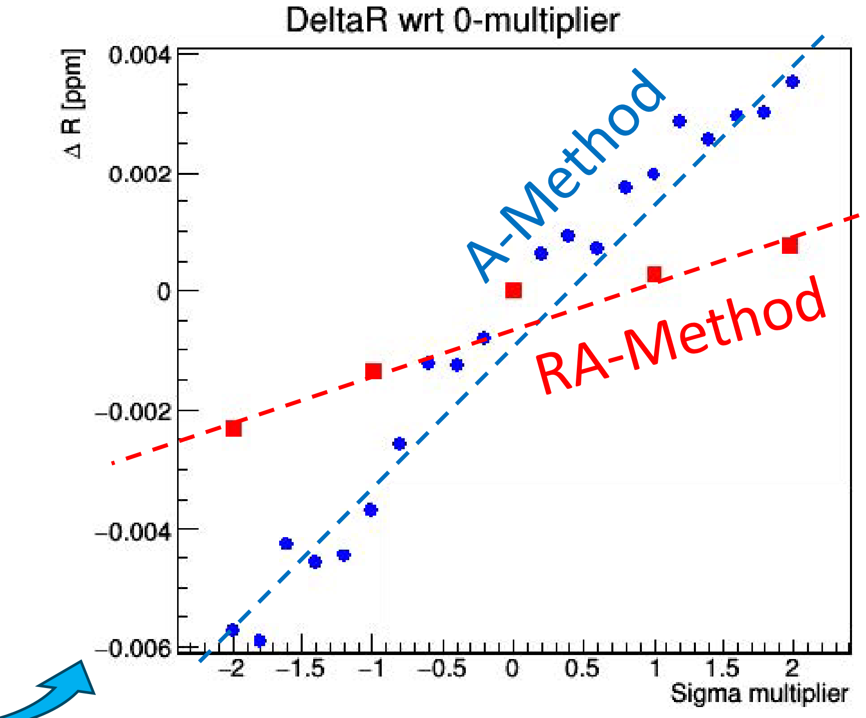
- Developed in Run-2/3: weight each positron with asymmetry function (like A-Method) → RA-Method

$$\textbf{R}: \{v_i(t);\ u_i(t)\} \rightarrow \textbf{RA}: \{\bar{v}_i(t) = \textstyle\sum_E A(E)\, v_i(E,t);\ \bar{u}_i(t) = \textstyle\sum_E A(E) u_i(E,t)\}$$

- Errors assigned:

$$\sigma_R(t) = \left[\frac{2U(t)V(t)}{\left(U(t)+V(t)\right)^2}\right]\sqrt{\left(\frac{\delta U(t)}{U(t)}\right)^2 + \left(\frac{\delta V(t)}{V(t)}\right)^2}$$

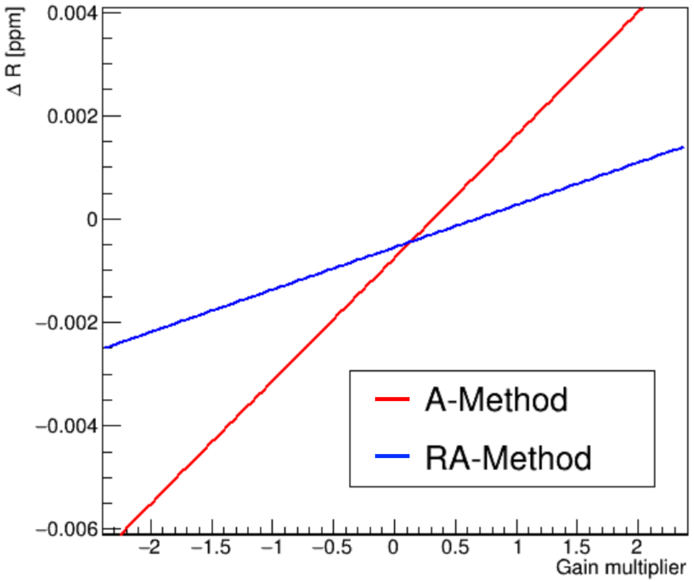
- Immediately visible advantage: reduce «slow effects», such as **gain systematics**!



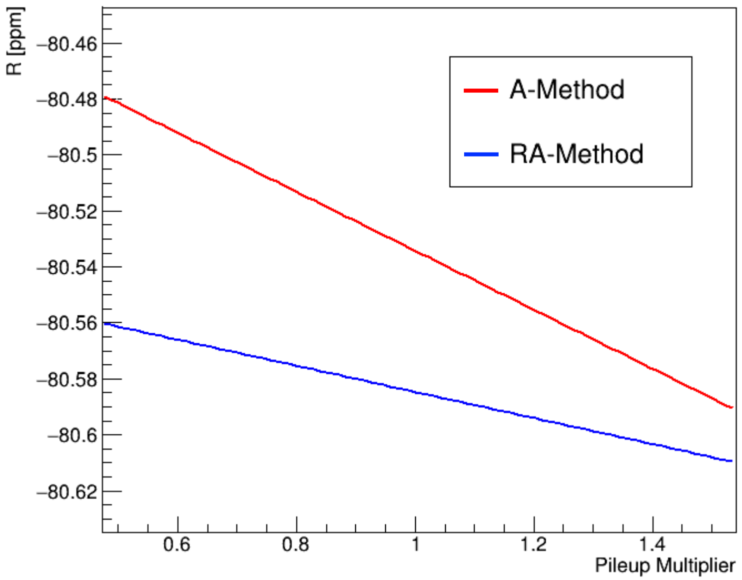
«Slow» effects: ratio vs non-ratio

$$\frac{d\langle p\rangle}{dt} \neq 0 \rightarrow \frac{\Delta\omega_a}{\omega_a} = \frac{1}{\omega_a}\cdot\frac{d\langle\varphi\rangle}{dt} = \frac{1}{\omega_a}\cdot\frac{d\langle\varphi\rangle}{d\langle p\rangle}\cdot\frac{d\langle p\rangle}{dt} \neq 0$$

$$\varphi(t) = \varphi(0) + \dot{\varphi}t + \cdots \rightarrow \boldsymbol{\omega_a}t + \varphi(t) = (\boldsymbol{\omega_a} + \dot{\boldsymbol{\varphi}})t + \cdots$$

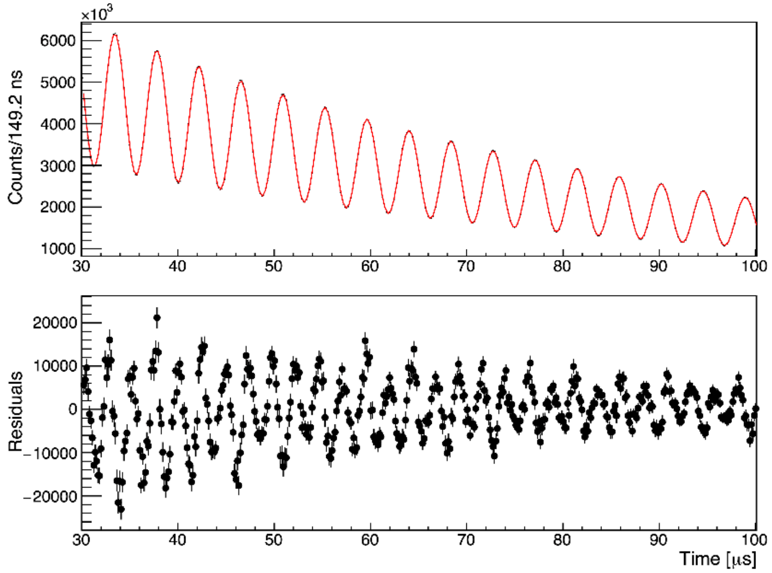


Gain calibration



Pileup

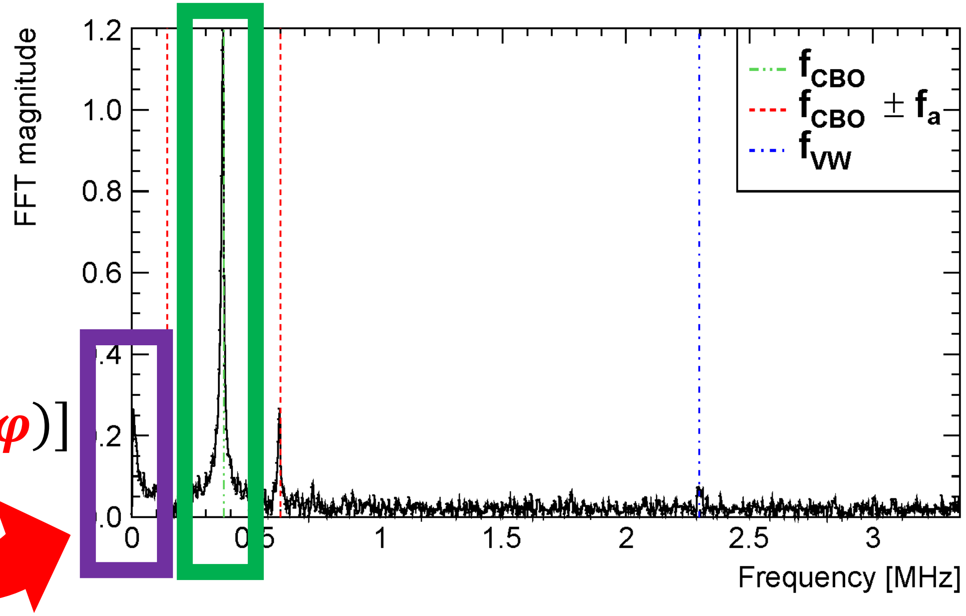
ω_a fit

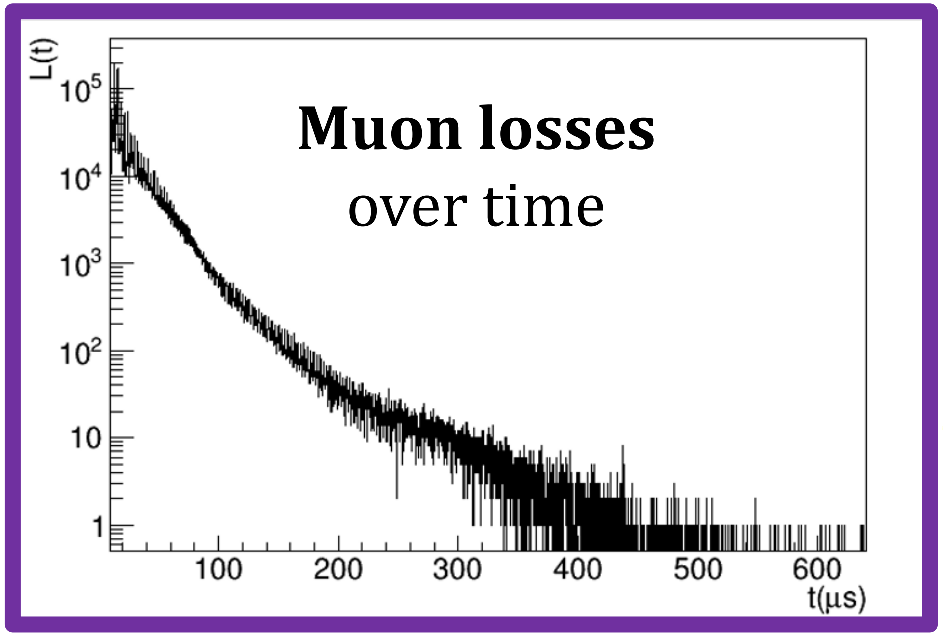


5-parameter fit

$$N(t) = N_0 e^{-\frac{t}{\gamma\tau_\mu}}[1 + A\cos(\omega_a t + \varphi)]$$

FFT of residuals

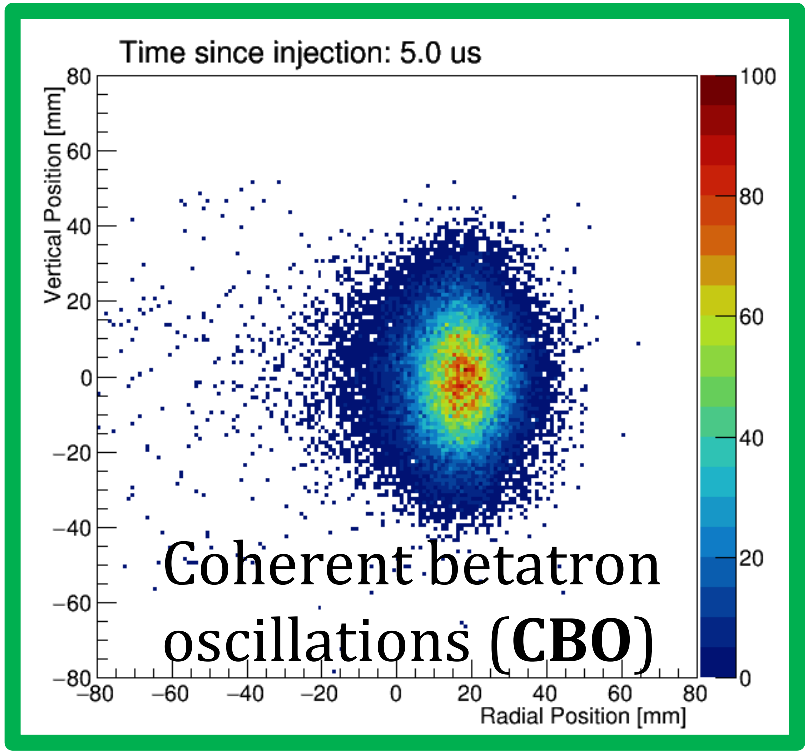




Muon losses
over time

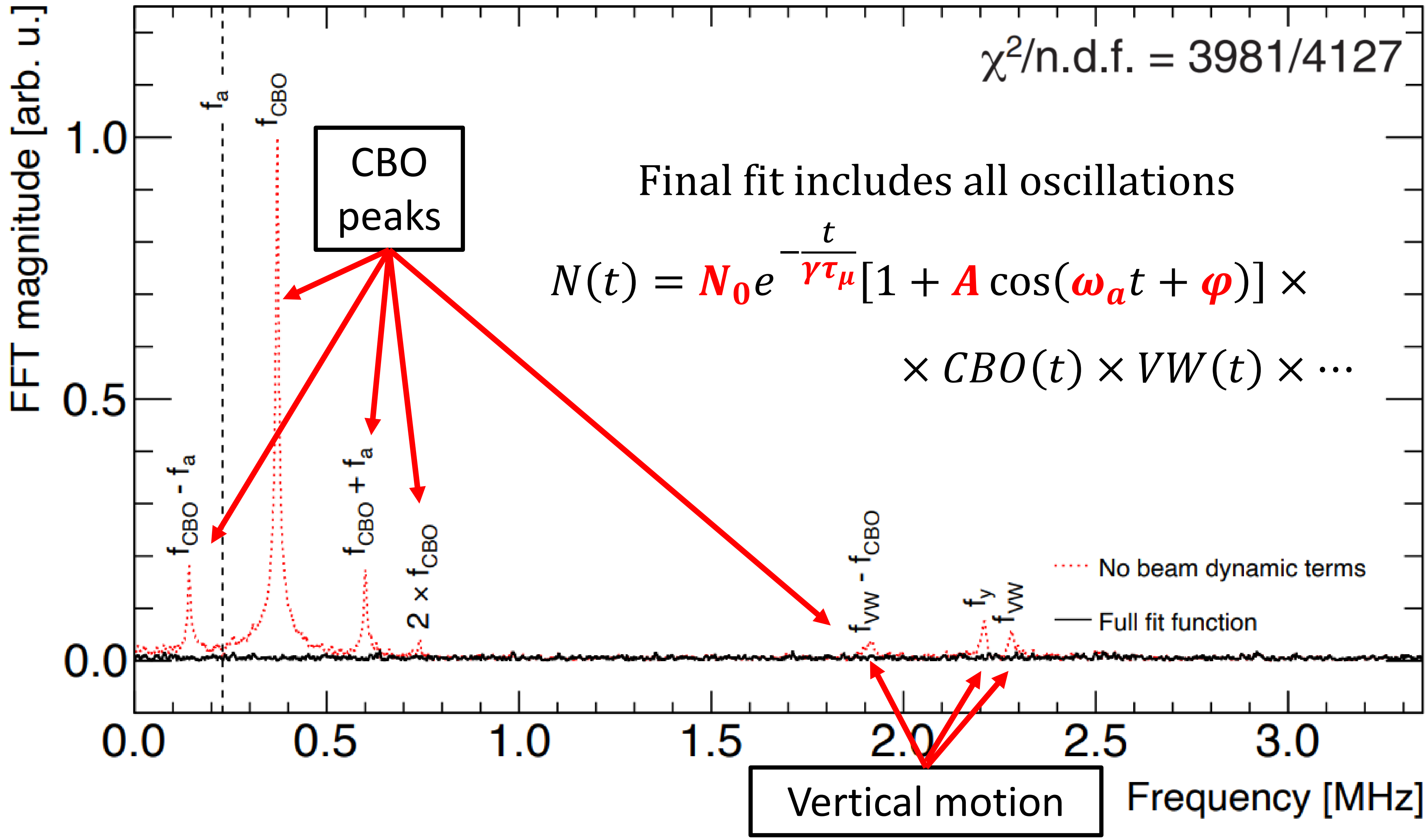
$$\Lambda(t) = 1 - k_{LM} \cdot J(t)$$

$$J(t) = \frac{\int_{t_0}^{t} L(t')e^{t'/\gamma\tau}dt'}{\int_{t_0}^{t_{end}} L(t)e^{t/\gamma\tau}dt}$$



Coherent betatron oscillations (**CBO**)

Run-2/3: ω_a fit and FFT of residuals



CBO peaks

Final fit includes all oscillations

$$N(t) = \boldsymbol{N_0} e^{-\frac{t}{\boldsymbol{\gamma\tau_\mu}}}[1 + \boldsymbol{A}\cos(\boldsymbol{\omega_a} t + \boldsymbol{\varphi})] \times$$

$$\times CBO(t) \times VW(t) \times \cdots$$

Vertical motion

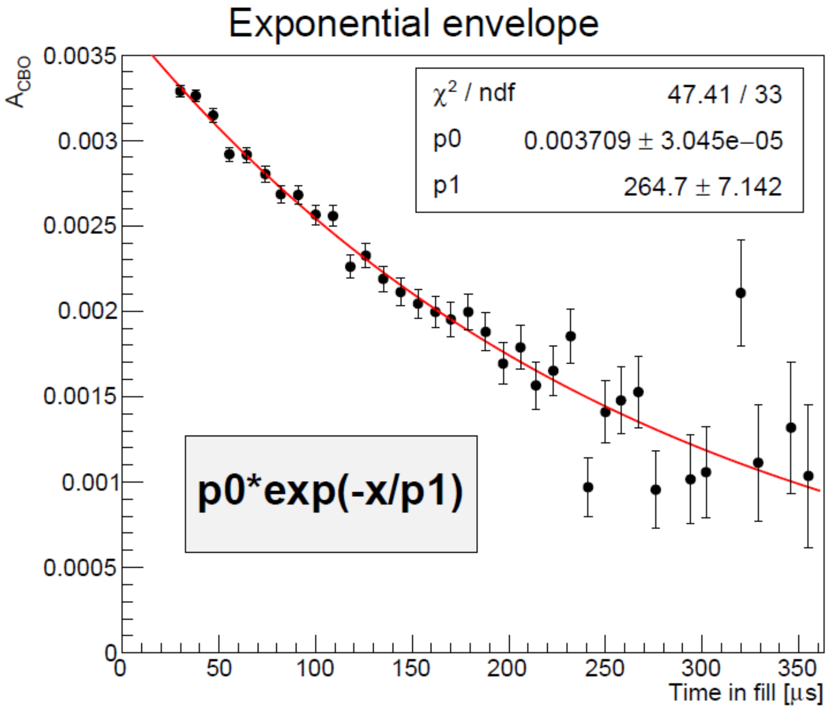
CBO model: amplitude vs time

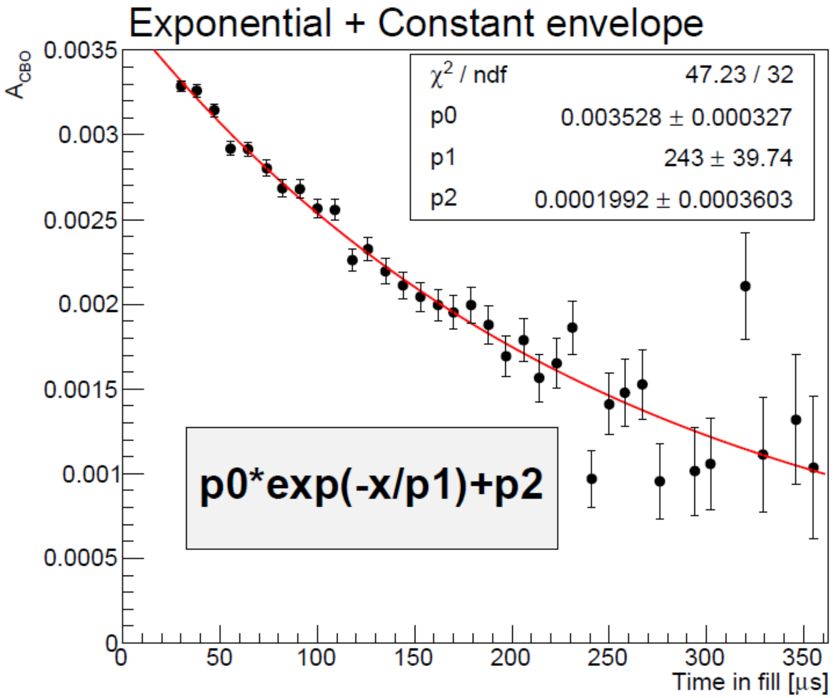
CBO dominated Run-1 systematics (38 ppb). Now reduced to 21 ppb!

$$CBO(t) = 1 + A_{CBO}\cos(\omega_{CBO}t + \varphi_{CBO}) \times \boxed{e^{-t/\tau}}$$

Decoherence

- Muons are an ensemble: betatron oscillations decohere over time
- Sliding window fits to determine good or bad envelopes: more statistics→more studies than Run-1; also input from tracker data





… and many other models tested

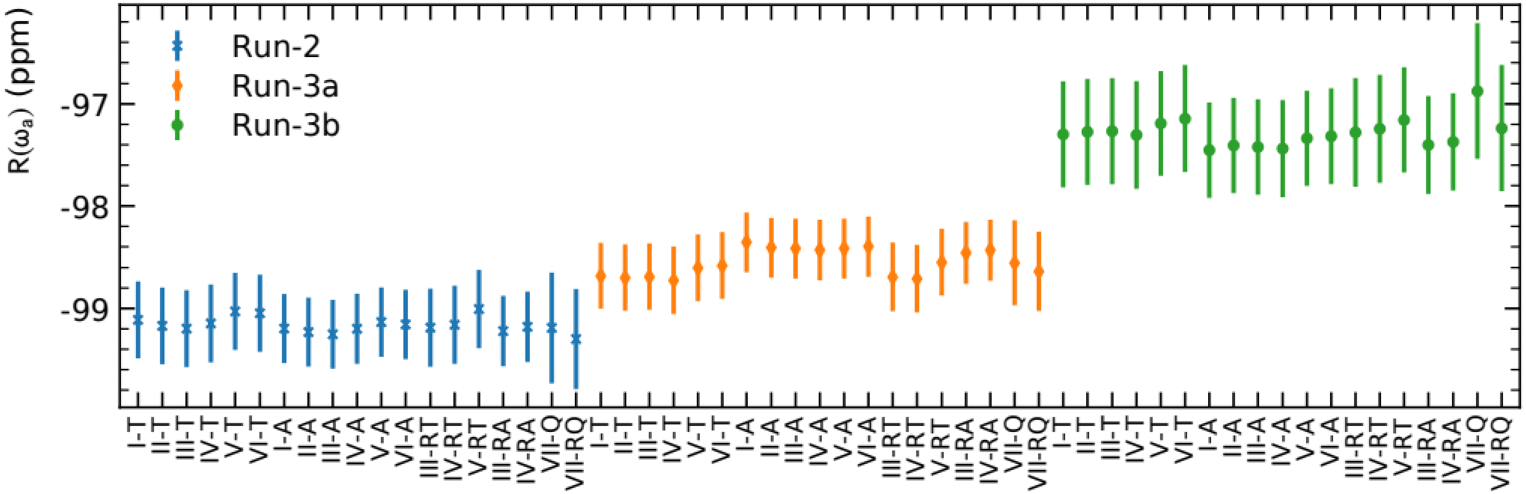
Run-2/3 ω_a analyses

	BU	CU	ω_aEuropa	IRMA	UKy	SJTU	UW
Pulse fitting and clustering	Local $\Delta t'$	Global	ReconITA	Global	Q	Local	Local $\Delta t'$
Pileup subtraction	Empirical	Empirical	Semi-empirical	Empirical	-	Shadow	Empirical
Analysis methods	T, A, R, RA	T, A	T, A, R, RA	T, A, R	Q, RQ	T, A	T, A

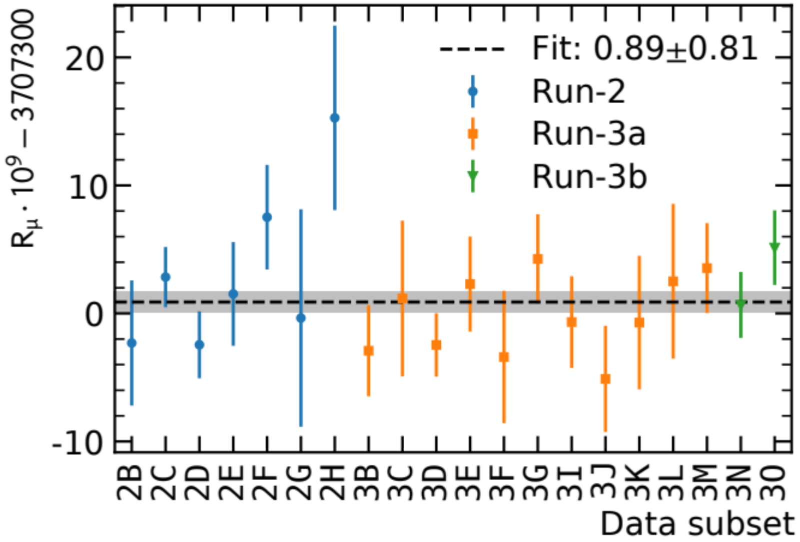
- Two more analysis groups since Run-1: each applies secret offset («software blinding») to their result
- Many analysis improvements and different methods tested
- Many consistency checks before publishing

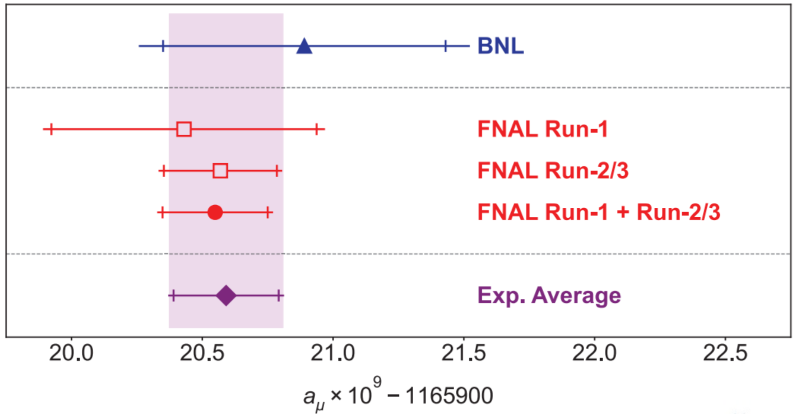
Run-2/3 unblinding

- **Software unblinding:**



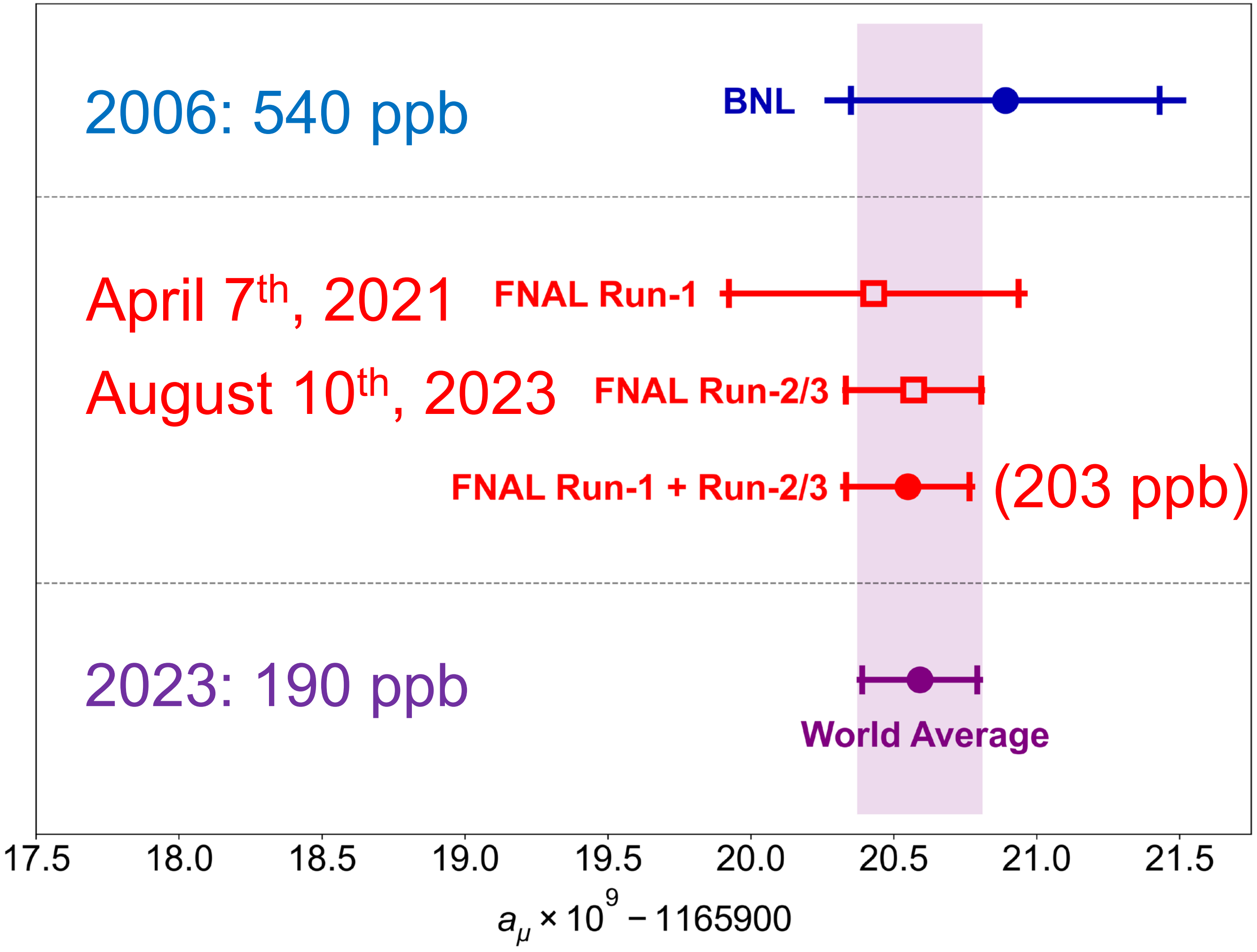
- **Hardware unblinding:**

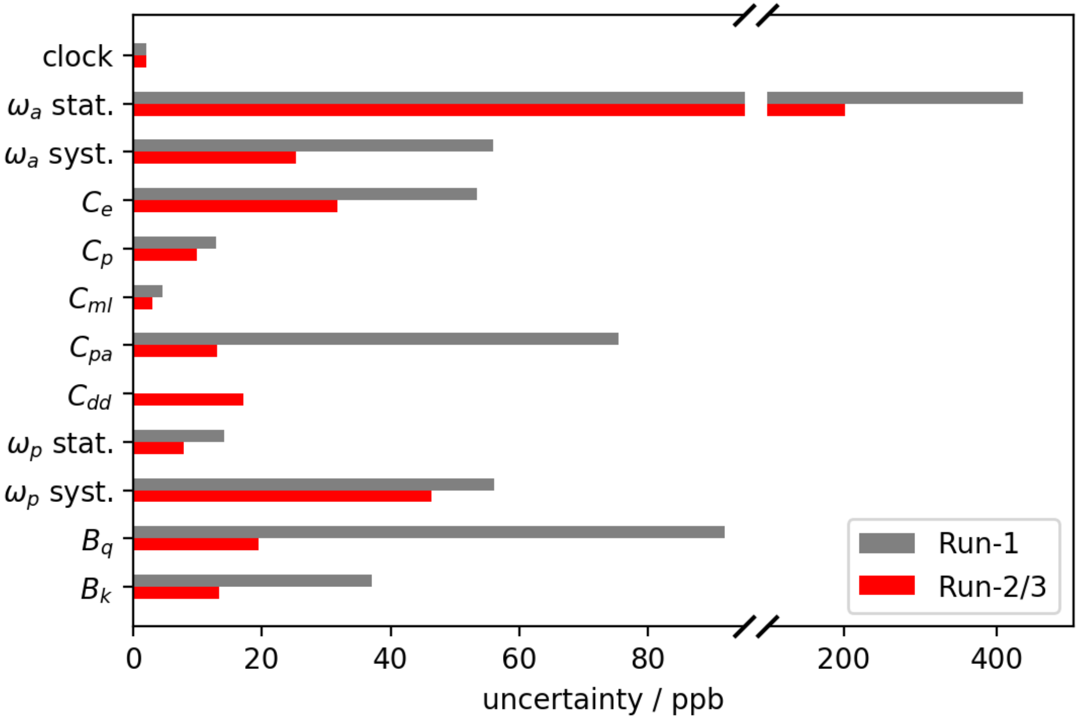




Run-2/3 Result: FNAL + BNL Combination

D. P. Aguillard et al, Phys. Rev. Lett. 131.161802 (2023)
D. P. Aguillard et al, arxiv:2402.15410 (2024)

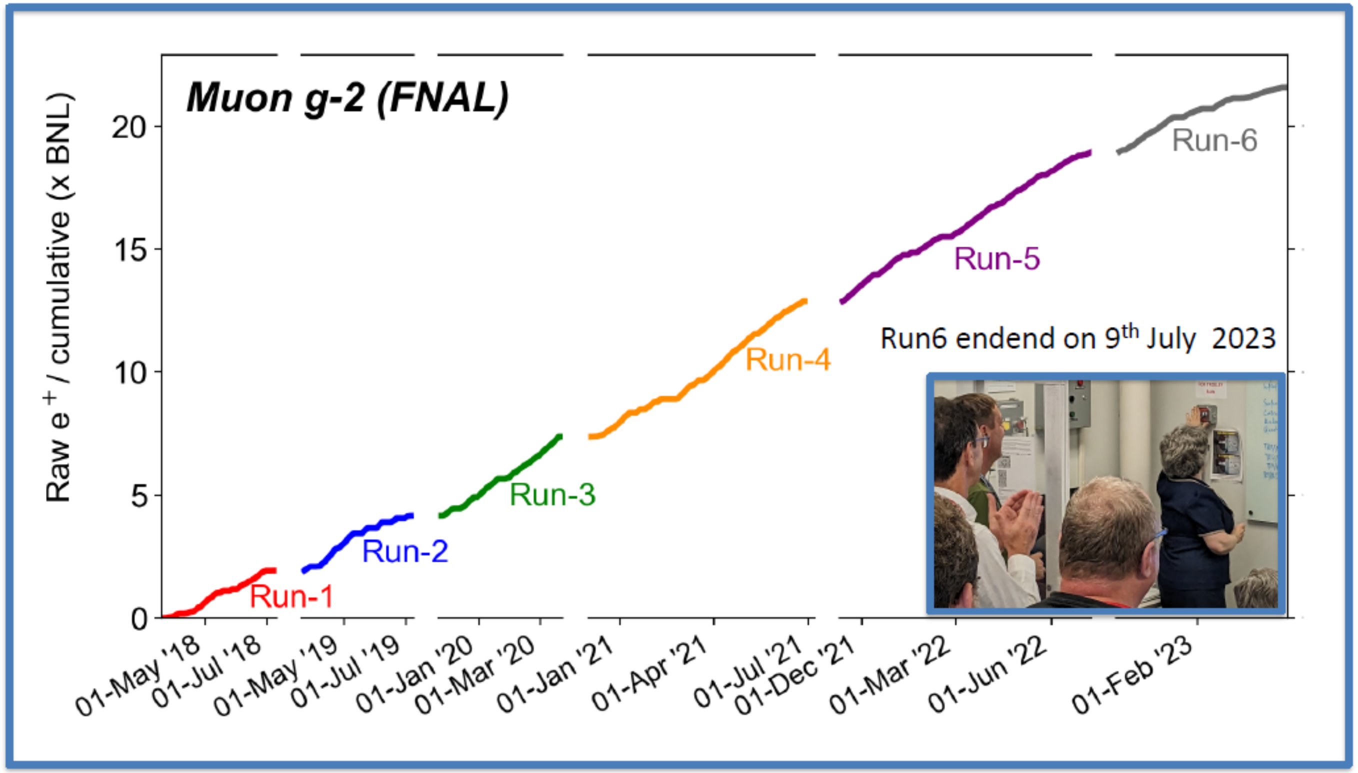




- Running improvements
- ~ 5x statistics
- Analysis improvements (CBO, pileup, reconstruction, …)
- 70 ppb syst. → exceeded goal!

Prospects for Run-4/5/6

On 27 February 2023: proposal Goal of x21 BNL datasets!



Run6 endend on 9th July 2023

Dataset	Stat. unc. [ppb]
Run-1	434
Run-2/3	201
Combined Run-1+Run-2/3	185
Expected total from Run-1 to Run-6	≤100

We expect to complete the analysis by 2025

- Quadrupole Radio-Frequency switched on during Run-5 → reduced radial and vertical motion of muons, more stable beam and less muon losses
- Ongoing studies reduce largest Run-2/3 systematics

Summary and conclusions

- New muon a_μ experimental average has **unprecedented precision of 190 ppb**:
  - Many running improvements and more statistics in Run-2/3
  - Upgraded reconstruction and pileup subtraction
  - Systematic errors: 25 ppb on ω_a, 70 ppb on a_μ → exceeded expected value of 100 ppb on a_μ at proposal
- Future analysis is expected to meet desing goals:
  - Much more statistics, 21+ times w.r.t. previous BNL experiment
  - RA-Method reduces sensitivity to many slow systematics
  - RF system ON: improved beam dynamics, task forces in place to study it

THANK YOU FOR YOUR ATTENTION!

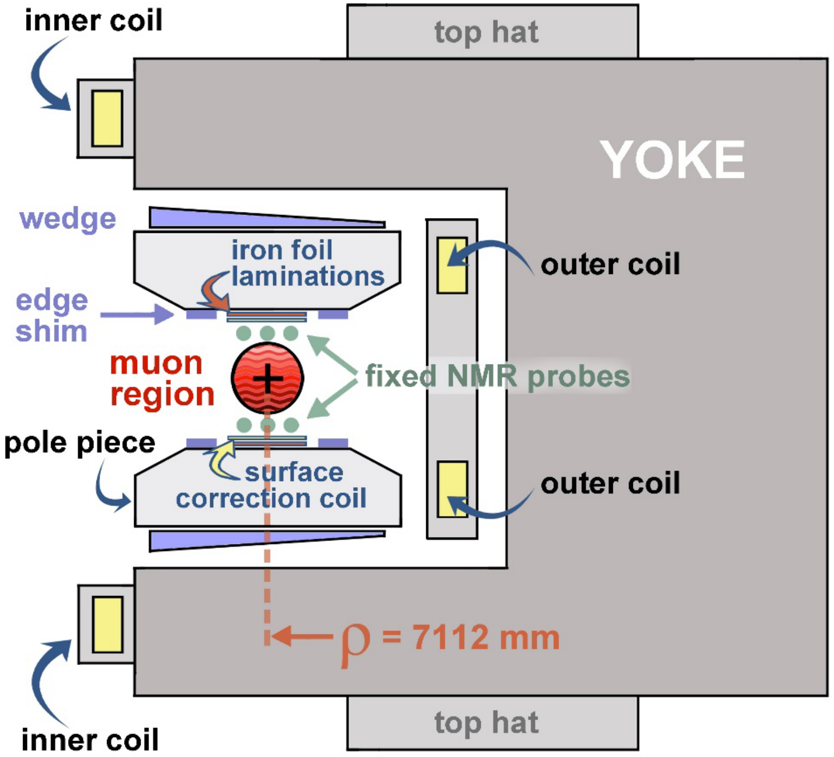
lorenzo.cotrozzi@liverpool.ac.uk

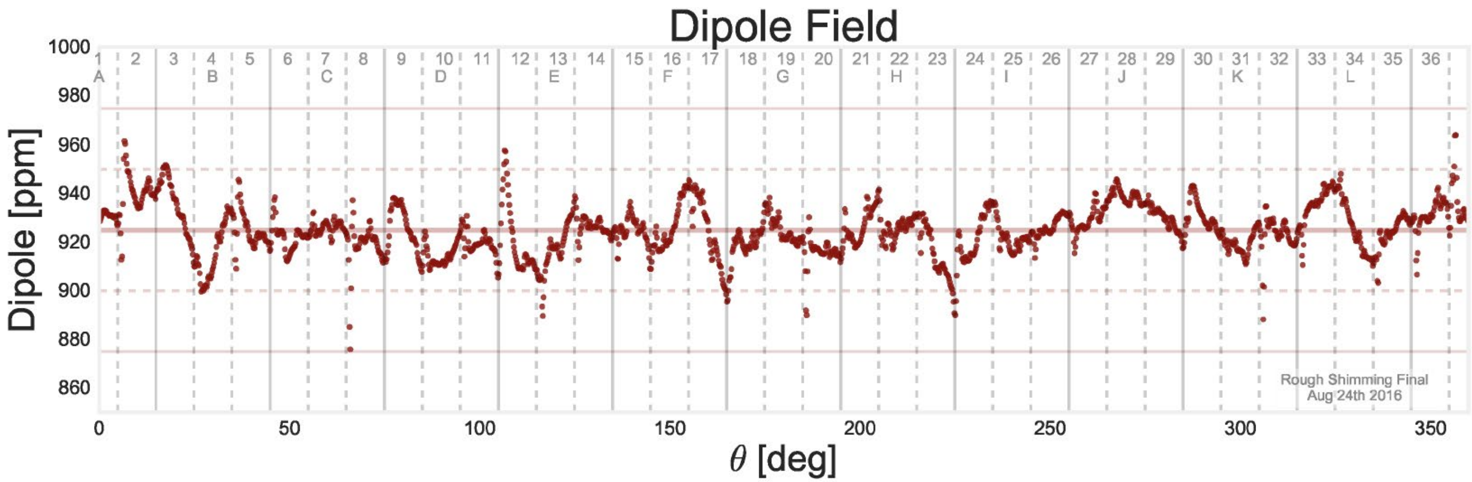
July 2023 collaboration meeting @ Liverpool, UK

Extra: magnetic field

Magnetic field

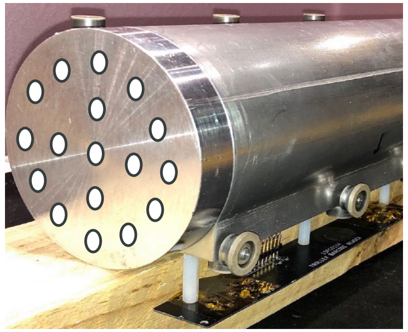
- 3.1-GeV muons are stored for 700 μs in the superconductive storage ring, kept at ~ 5K
- Highly uniform vertical magnetic field: 1.45 T
- Shimmed passively by wedges, iron top hats and surface iron foils
- Actively stabilized by surface current coils



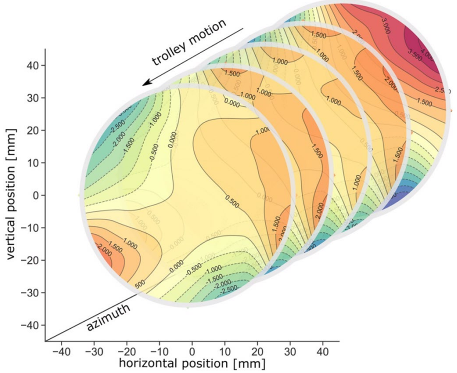


14 ppm RMS across azimuth

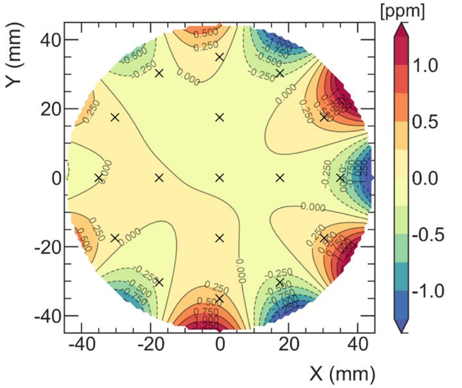
Magnetic field: ω_p analysis in a nutshell



17 petroleum jelly NMR probes

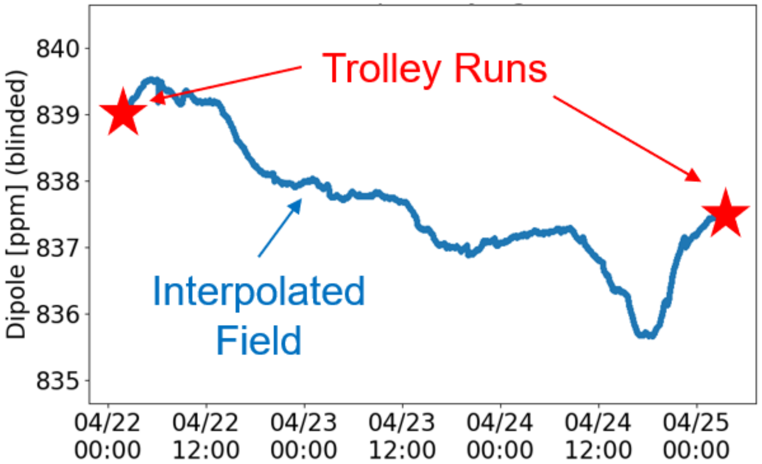


2D field maps (~8000 points)



Azimuthally-Averaged
Variation < 1 ppm

17 NMR (Nuclear Magnetic Resonance) probes: placed on trolley for special runs, every 2 or 3 days between muon fills, to provide 3-D map



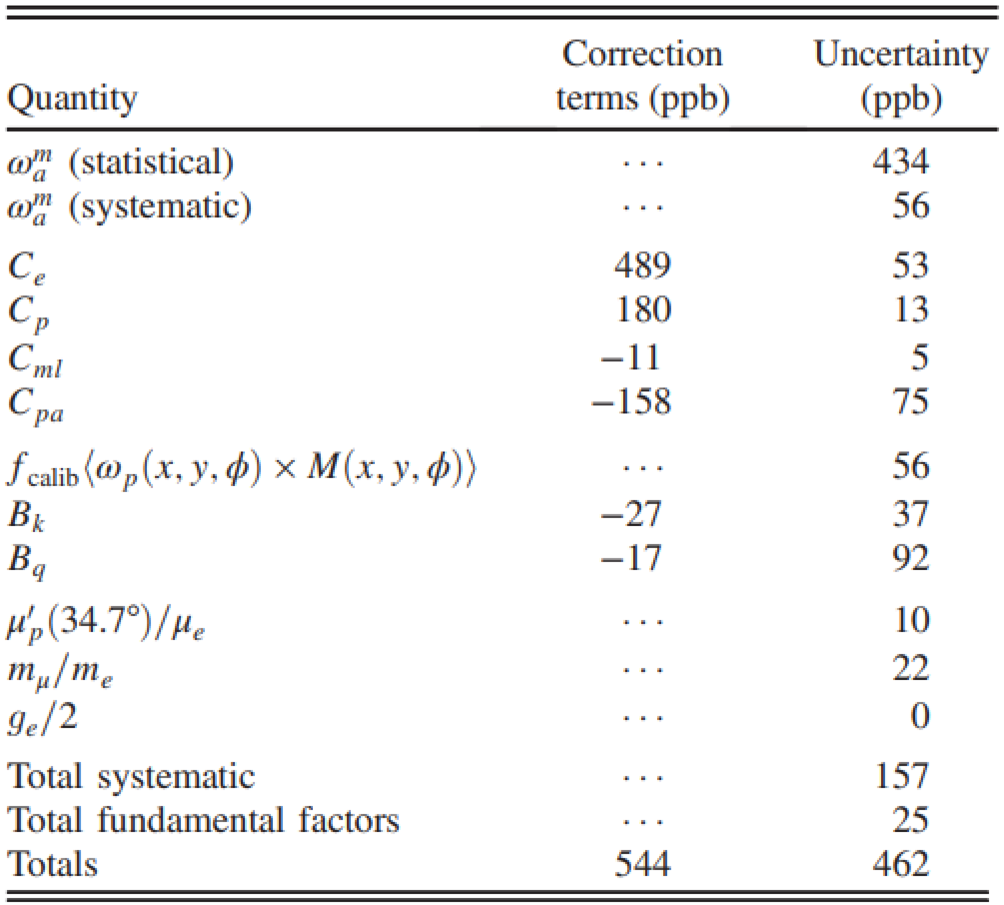
378 fixed NMR probes continuously monitor field during muon storage at 72 azimuthal locations

Absolute calibration with water probes

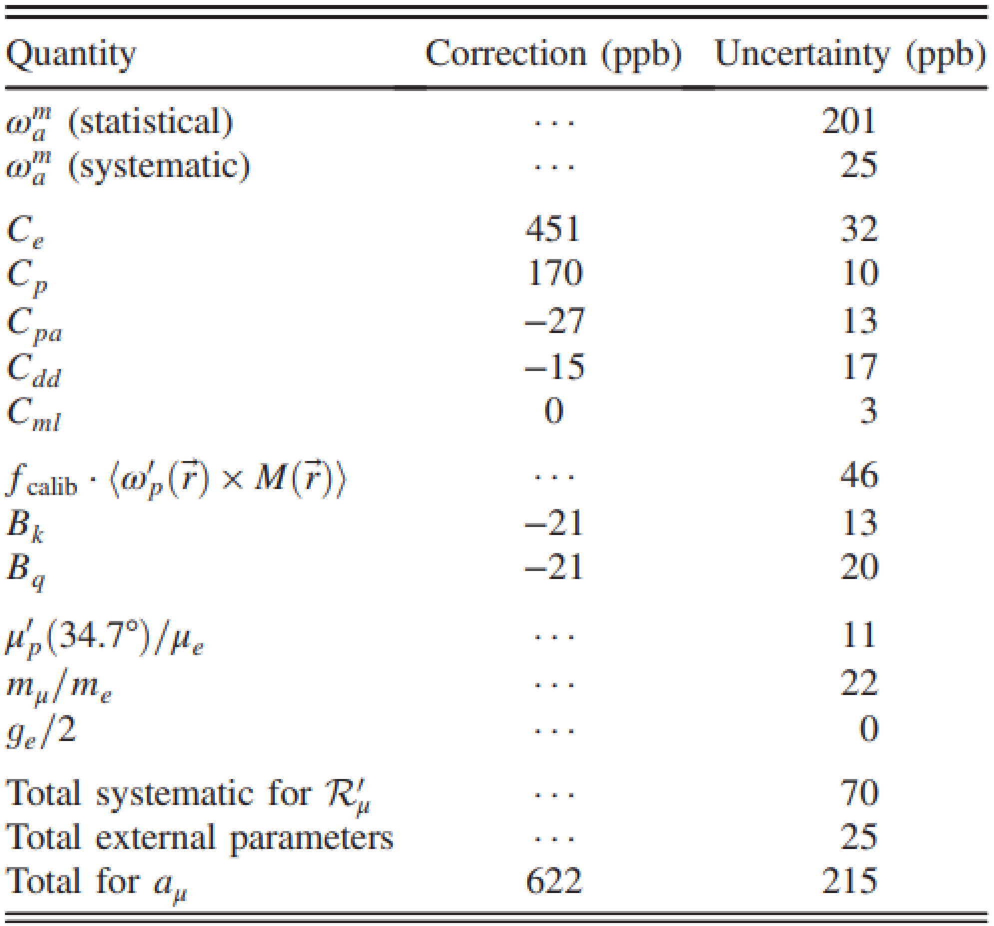
Field is weighted with muon distribution, measured by trackers

Extra: ω_a backup

Run-1 vs Run-2/3 systematics



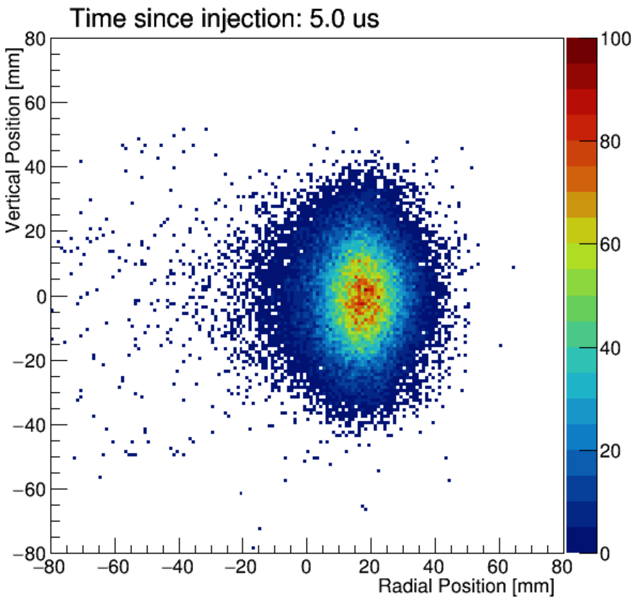
Quantity	Correction terms (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	$\cdots$	434
ω_a^m (systematic)	$\cdots$	56
C_e	489	53
C_p	180	13
C_{ml}	–11	5
C_{pa}	–158	75
$f_{\text{calib}}\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle$	$\cdots$	56
B_k	–27	37
B_q	–17	92
$\mu'_p(34.7°)/\mu_e$	$\cdots$	10
m_μ/m_e	$\cdots$	22
$g_e/2$	$\cdots$	0
Total systematic	$\cdots$	157
Total fundamental factors	$\cdots$	25
Totals	544	462

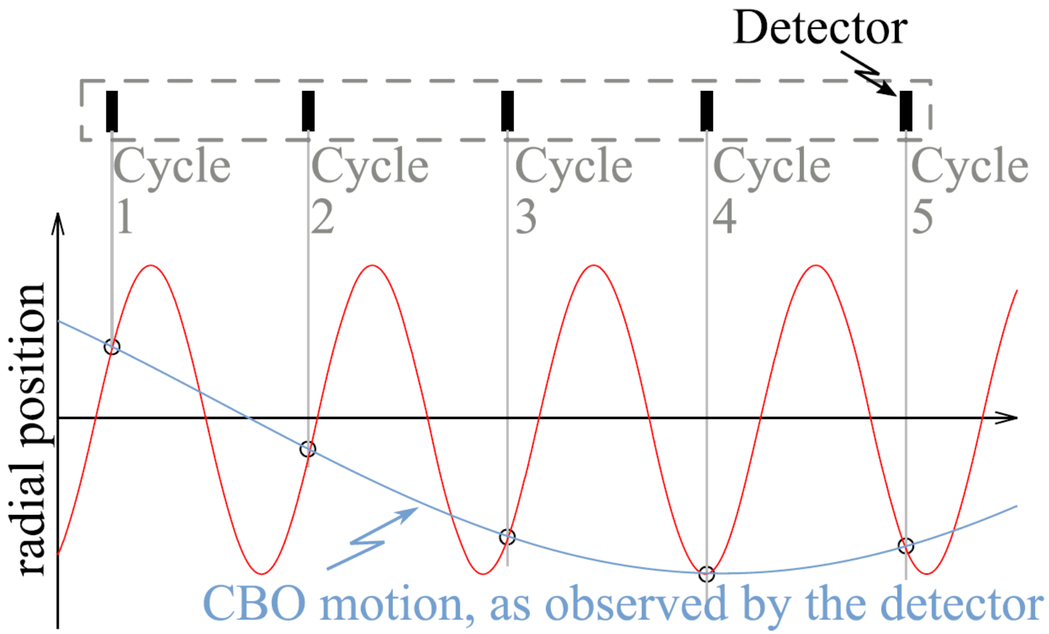


Quantity	Correction (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	$\cdots$	201
ω_a^m (systematic)	$\cdots$	25
C_e	451	32
C_p	170	10
C_{pa}	–27	13
C_{dd}	–15	17
C_{ml}	0	3
$f_{\text{calib}}\cdot\langle\omega'_p(\vec{r})\times M(\vec{r})\rangle$	$\cdots$	46
B_k	–21	13
B_q	–21	20
$\mu'_p(34.7°)/\mu_e$	$\cdots$	11
m_μ/m_e	$\cdots$	22
$g_e/2$	$\cdots$	0
Total systematic for $\mathcal{R}'_\mu$	$\cdots$	70
Total external parameters	$\cdots$	25
Total for a_μ	622	215

Radial and vertical motion of the beam

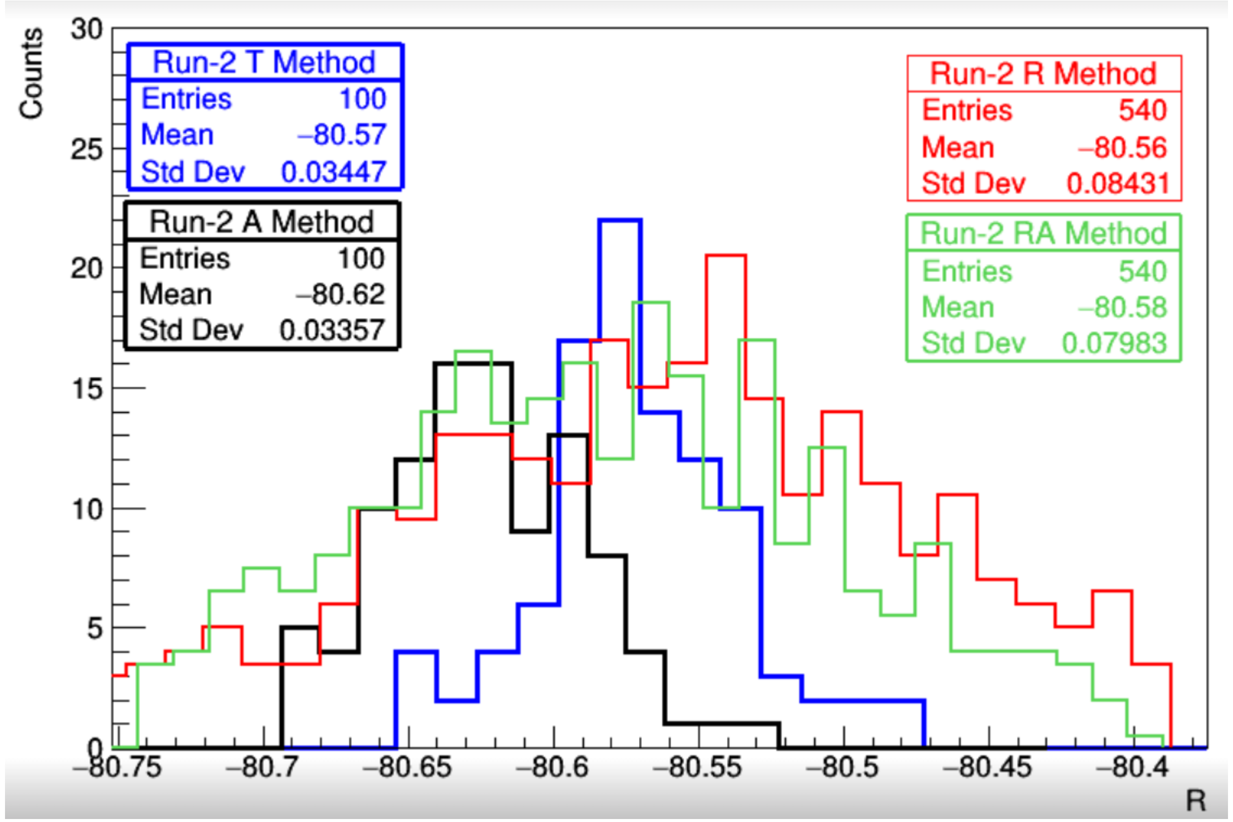
- Field index: n (quad voltages)
- Radial motion of the beam: $\omega_x = \omega_c\sqrt{1-n}$
- CBO is the aliased frequency $\omega_{CBO} = \omega_c - \omega_x$
- CBO period of about 2.7 µs

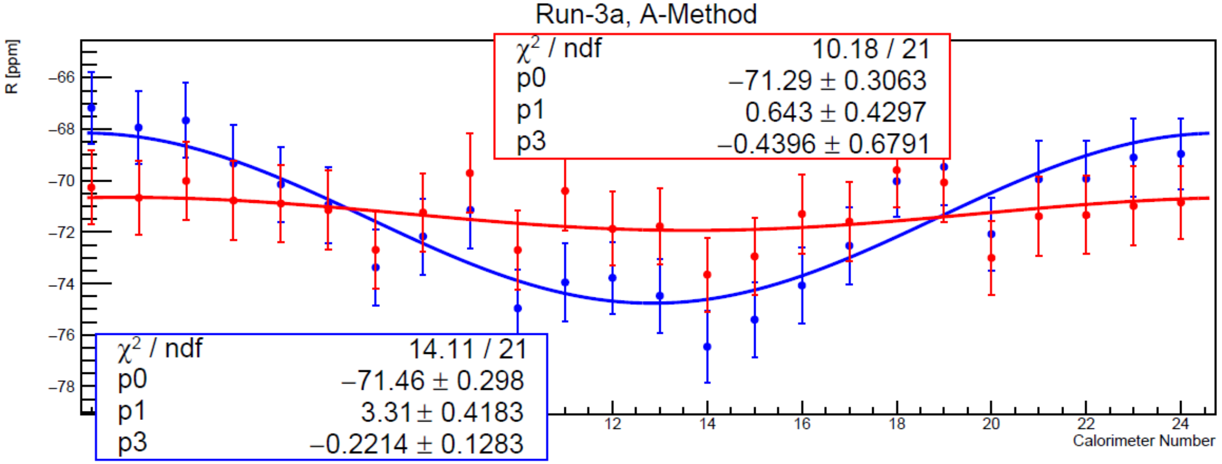




Quantity	Expression	Frequency [MHz]	Frequency [rad/µs]	Period [ns]
ω_a	$ea_\mu B/m$	0.23	1.439	4365
ω_C	v/R_0	6.7	42.0	149.2
ω_x	$\omega_C\sqrt{1-n}$	6.3	39.7	158.0
ω_y	$\omega_C\sqrt{n}$	2.2	13.8	454.2
ω_{CBO}	$\omega_C - \omega_x$	0.37	2.33	2686
ω_{VW}	$\omega_C - 2\omega_y$	2.3	14.4	435.3

Randomization



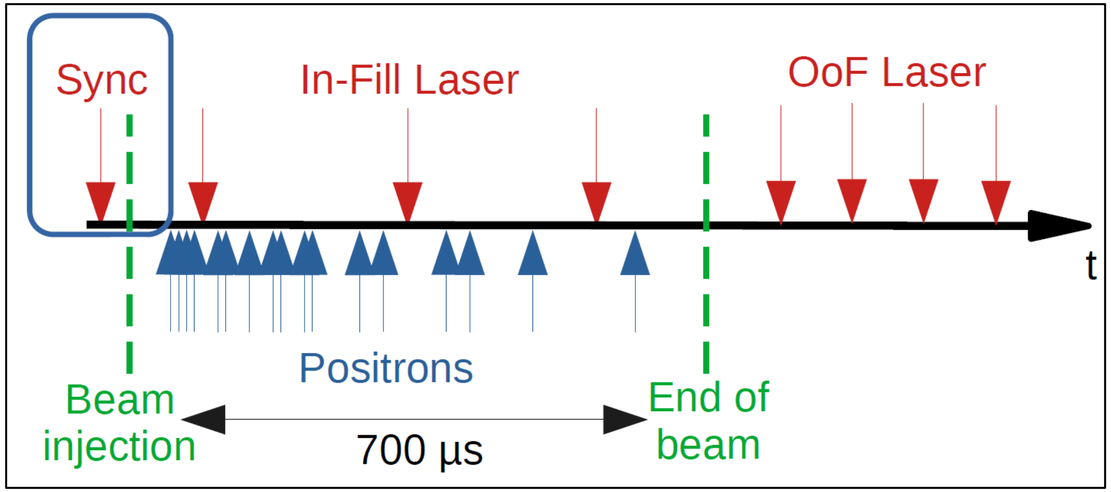


Laser-based gain monitoring system

Built by INFN/CNR-INO: time synchronization and calibration of 1296 SiPMs on timescales from ns to days/weeks. Gain changes dominated ω_a systematics at BNL: exceeded goal of 20 ppb at FNAL.

Standard operating mode:

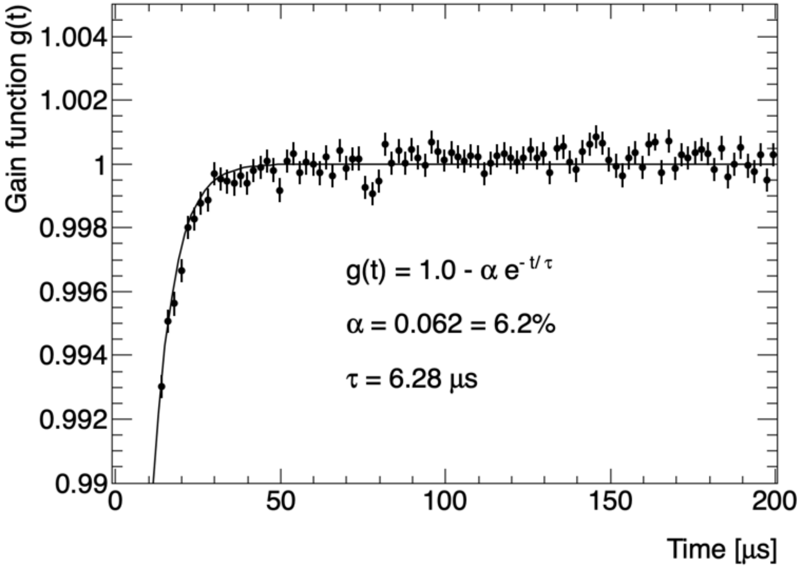
- **Sync pulse**: time synchronization at ~ 50 ps
- **In-Fill pulses**: monitor rate-dependent gain changes at 10^{-4} during 700 µs of μ^+ beam
- **Out-of-Fill pulses**: monitor stability over days



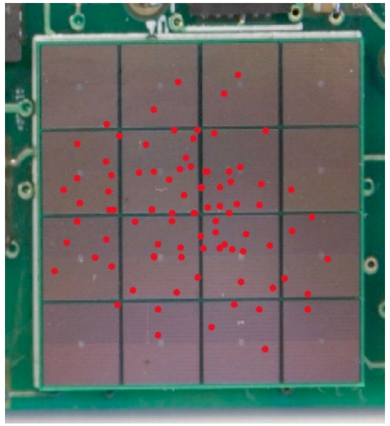
SiPM gain calibration

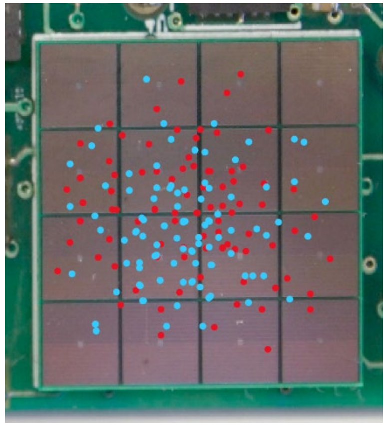
In-Fill: sag in power supply due to initial injection splash.

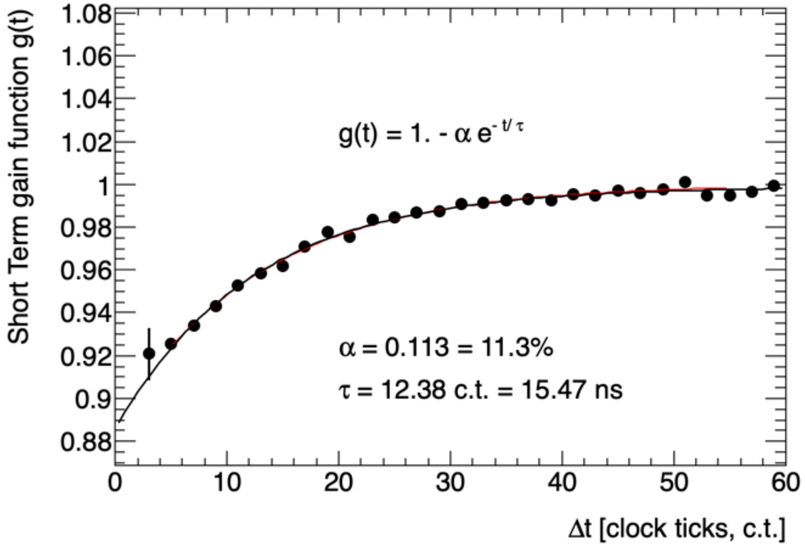
Recovery timescale of front-end electronics: $\mathcal{O}(10\ \mu s)$.



Short-term: consecutive positron hits within $\mathcal{O}(100\ ns)$. After the first hit, the recovery time of pixels reduce the gain experienced by the second hit.



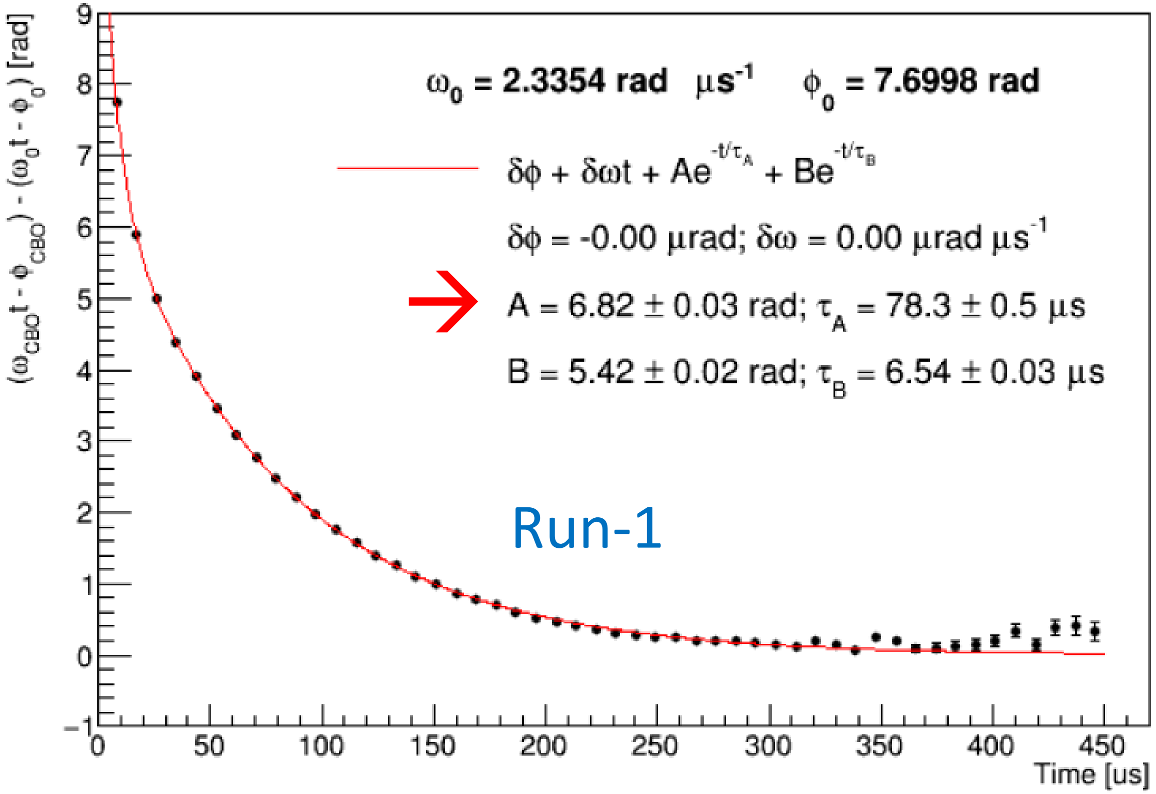


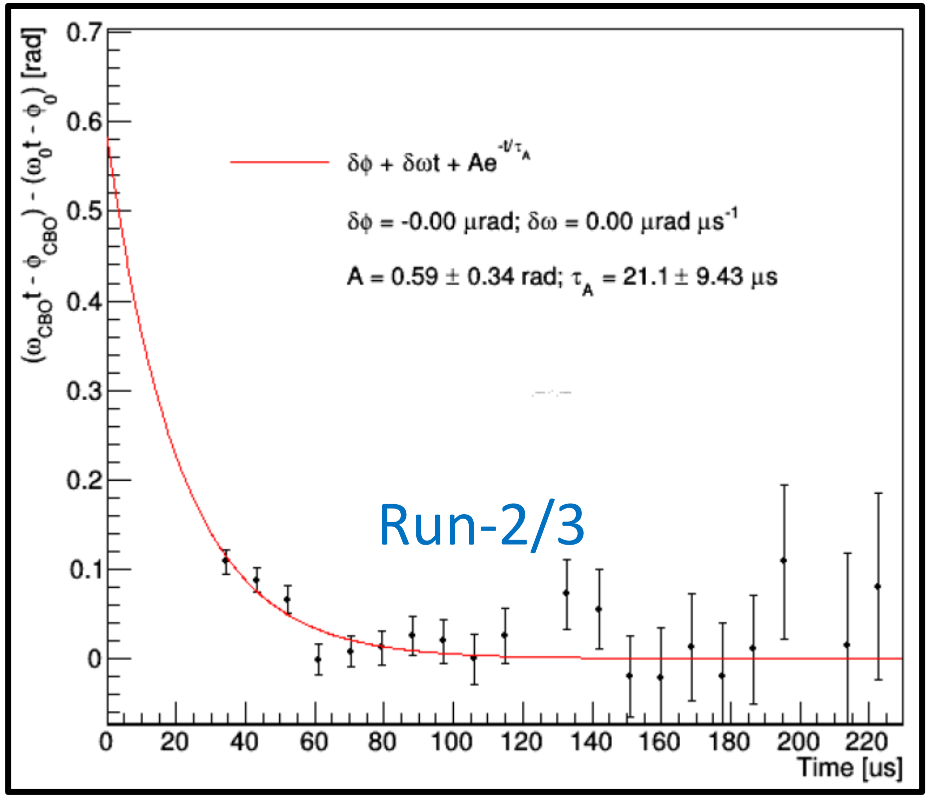


CBO model: frequency vs time

CBO dominated Run-1 systematics (38 ppb). Now reduced to 21 ppb!

- Exponential relaxation of CBO frequency
- Run-1: faulty ESQ resistors enhanced this effect 10 times!
- Sliding window fits to determine lifetime and constrain it in ω_a fits





Blinded analysis

- **Hardware**: main clock is tuned at $(40 - \varepsilon)$ MHz
  Offset only known to two scientists external to the collaboration

- **Software**: each ω_a analyzer applies their own, secret offset to their results

Run-4/5/6: current status and puzzles

- With much more statistics, we can investigate the residual slow term
  → energy leakage in calorimeters?
  → reconstruction effect?
- Further improved reconstruction with new pulse fitting technique
- Task forces in place to address dominating Run-2/3 systematics
- Quadrupole Radio-Frequency switched on during Run-5, to highly reduce radial and vertical motion of muons → more stable beam dynamics and much fewer lost muons!