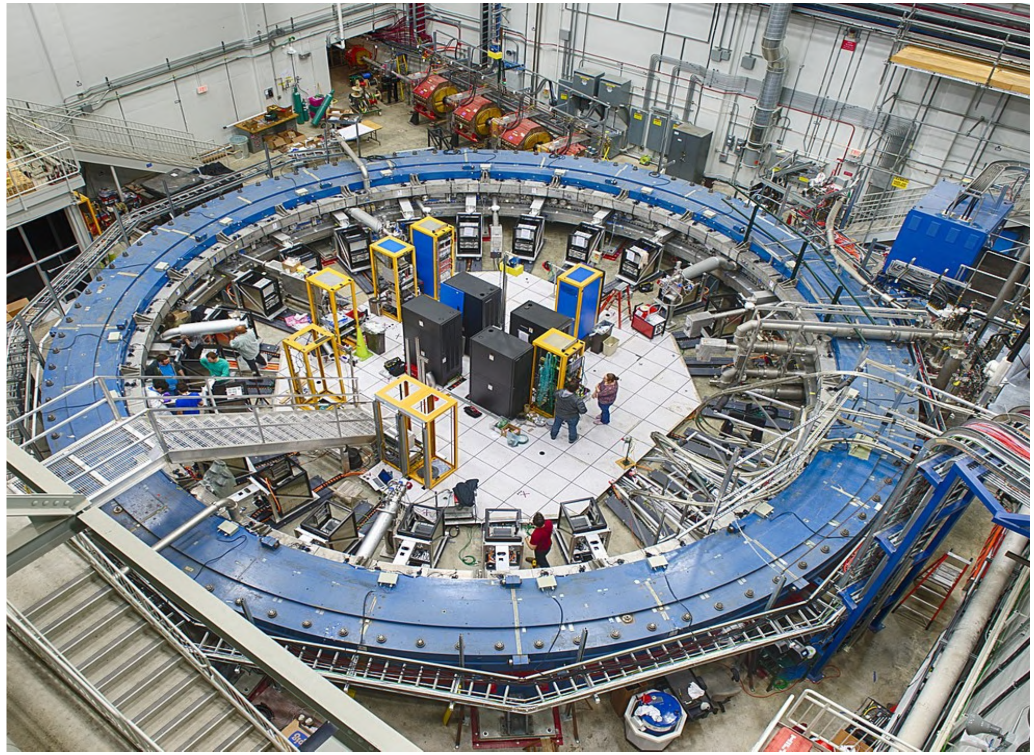


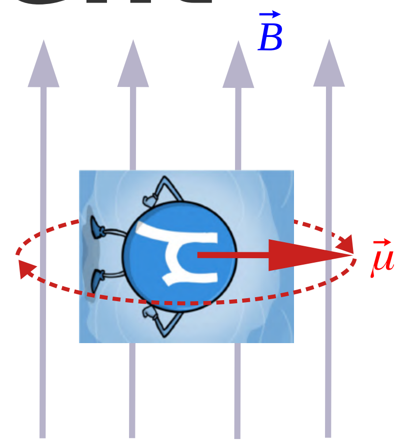
The positron reconstruction at the Muon g-2 Experiment

New Frontiers in Lepton Flavor

Pisa | 16 May 2023

Paolo Girotti (INFN Pisa)

The g-2 measurement

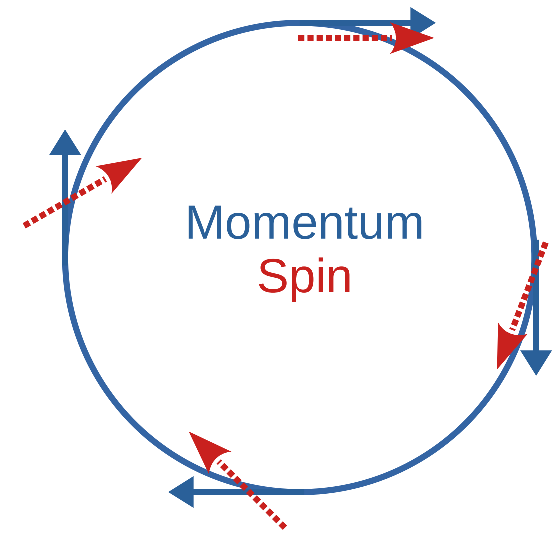


$$\vec{\mu} = g\frac{q}{2m}\vec{S}$$

$$a_\mu \equiv \frac{g-2}{2}$$

$$\vec{\omega}_s = -\frac{ge\vec{B}}{2m} - (1-\gamma)\frac{e\vec{B}}{m\gamma} \qquad \vec{\omega}_c = -\frac{e\vec{B}}{m\gamma}$$

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\left(\frac{g-2}{2}\right)\frac{e\vec{B}}{m} \equiv -a_\mu\frac{e\vec{B}}{m}$$

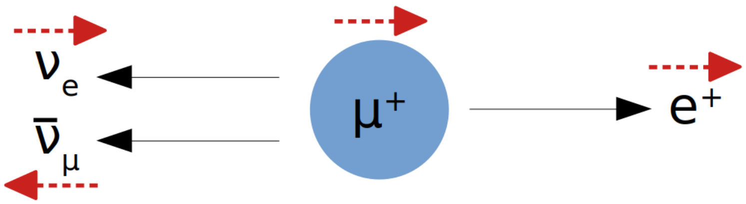


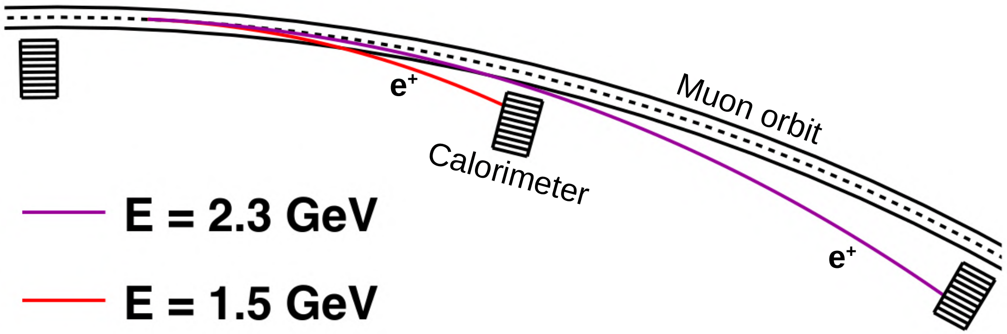
- The anomalous precession frequency of a muon in a known magnetic field is a measure of $\mathbf{a_\mu}$
- Magnetic field measured in terms of the Larmor precession of protons with NMR probes
- Experiment goal: **140 ppb** (100 stat, 100 syst)

$$\vec{\omega}_a = a_\mu\frac{e\vec{B}}{m} \longrightarrow a_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)}\frac{\mu'_p(T_r)}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

Constants known from other experiments with high precision (25 ppb)

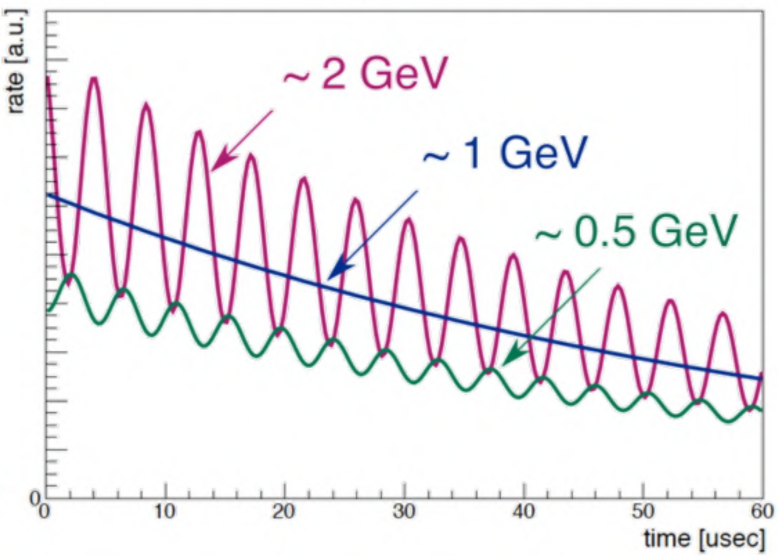
Precession measurement



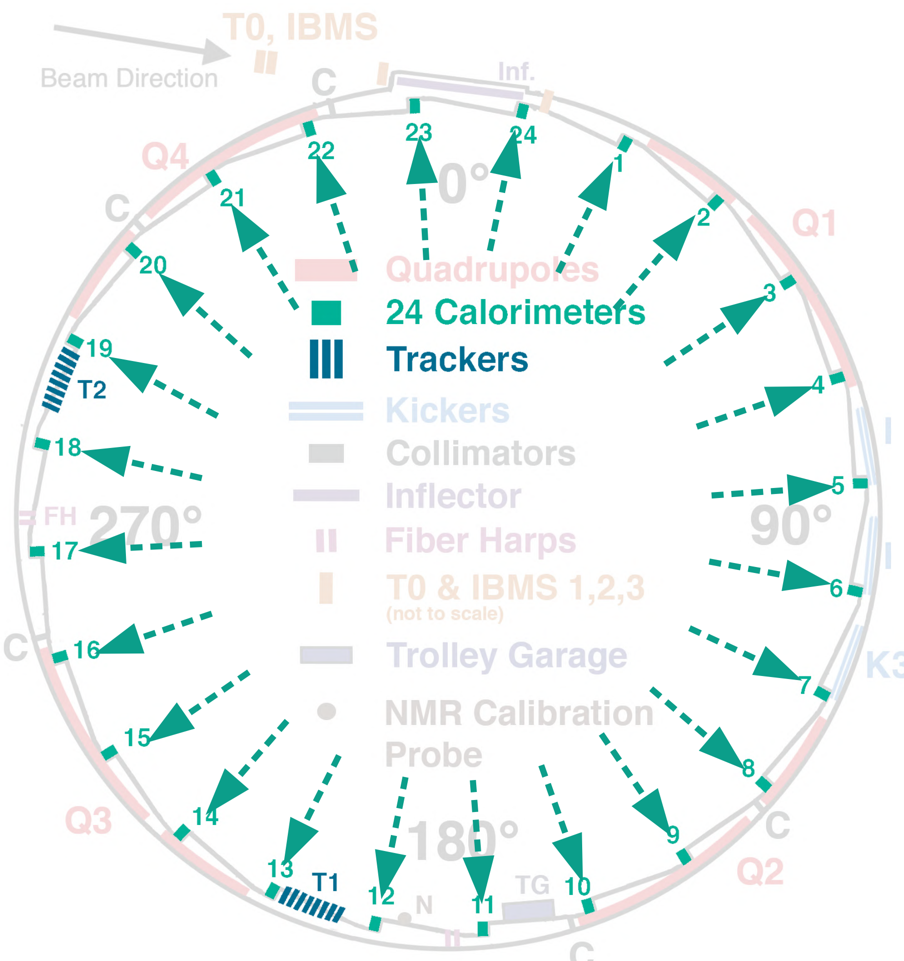


- 3.1 GeV/c polarized muon beam
- Parity violation in weak decay → high energy positrons in the c.m. frame are emitted preferably in the direction of muon spin
- Positrons (p≤3.1 GeV/c) curl inward and hit a calorimeter
- Decay **asymmetry** observed in the lab frame as an oscillation of the positron count over time

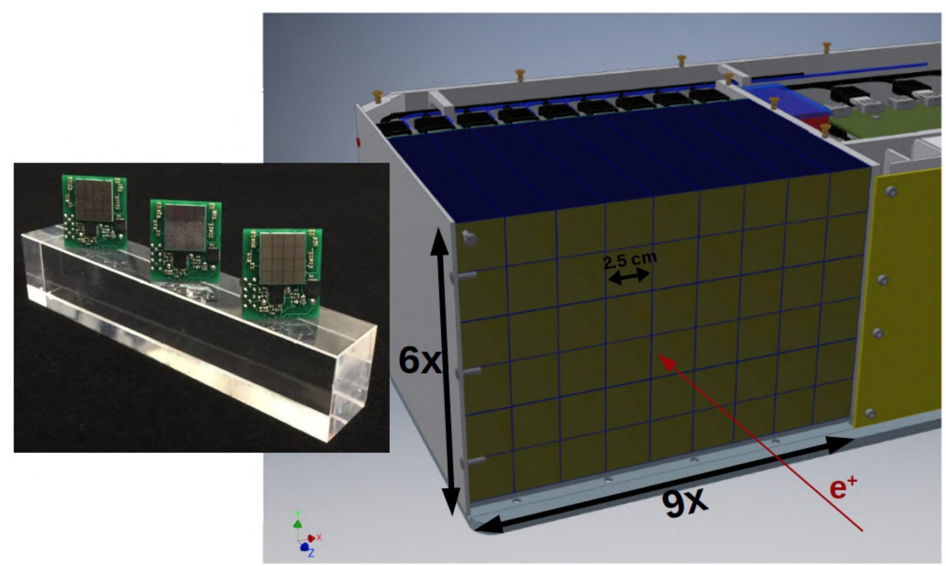
$$N(t) = N_0 e^{-t/\tau}\left(1 + A\cos(\omega_a t + \varphi)\right)$$



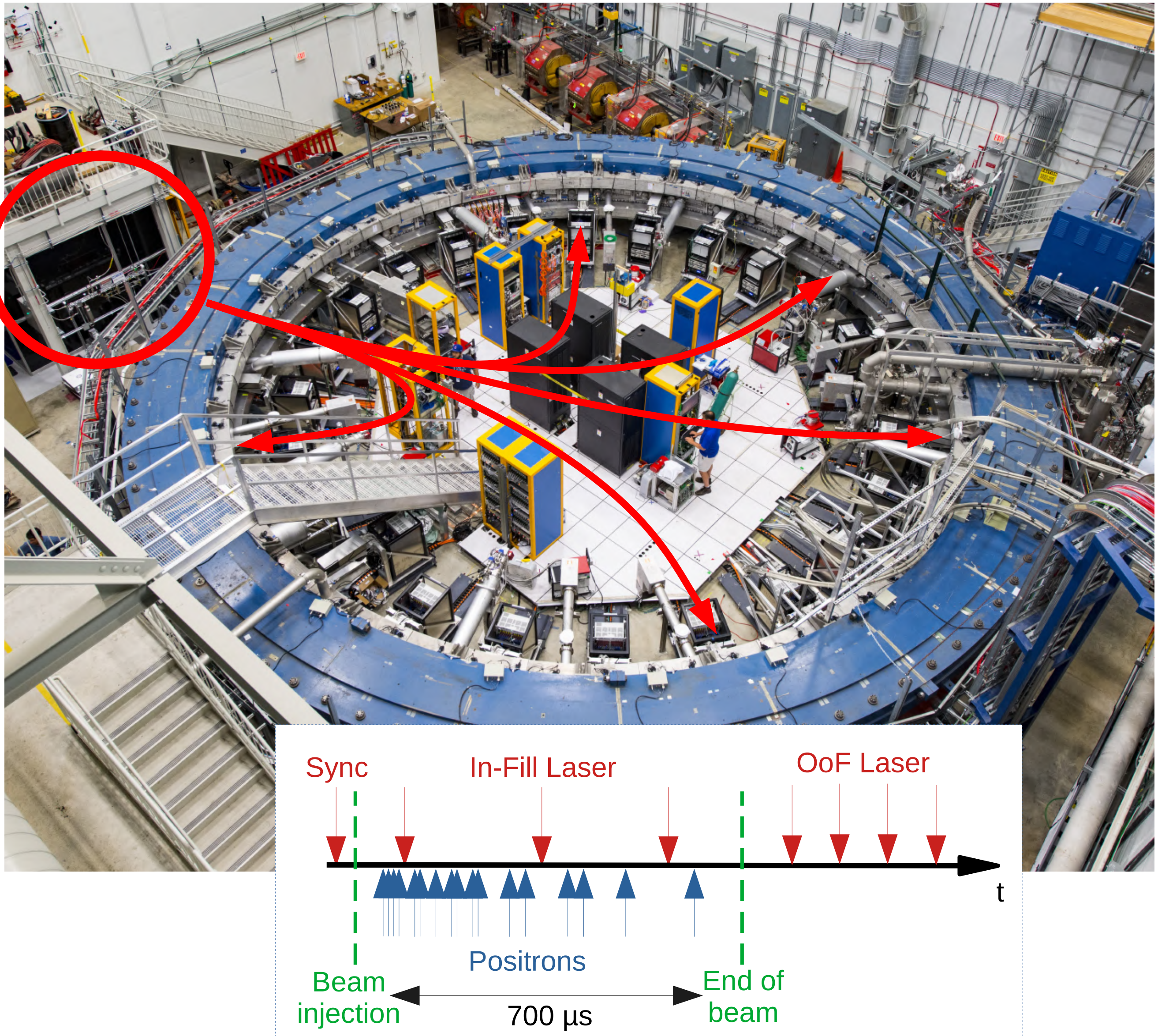
Calorimeters



- 24 electromagnetic **calorimeters** for positron energy and time measurement
- 9x6 PbF_2 crystals ($15X_0$ length) coupled with Hamamatsu SiPMs of 144 mm^2 active size (57344 pixels each)
- SiPMs collect Čerenkov light from the positrons EM shower
- Waveforms sampled at 800 MSps, with online GPU-based trigger

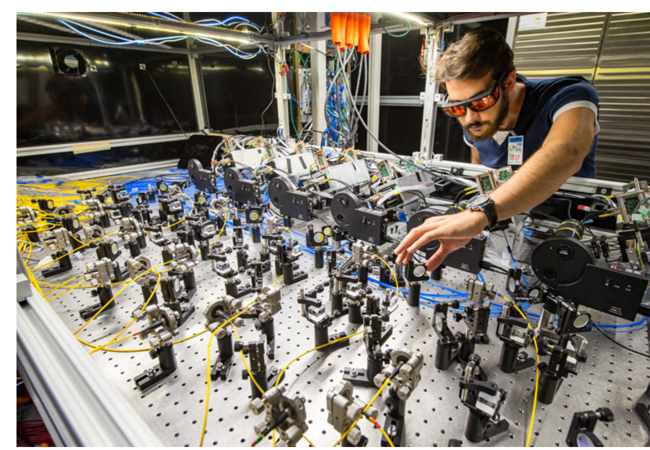


Laser Calibration System

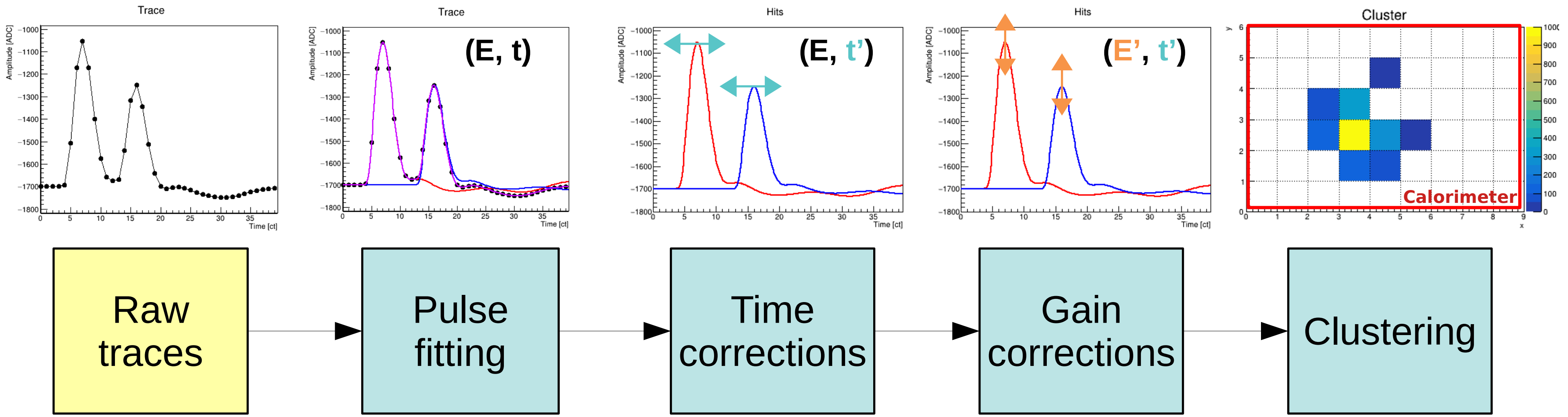


- Built by **INFN-INO**
- Laser sent to all 1296 crystals to mimick Čerenkov radiation
- Time synchronization at the ~50 ps level
- Gain calibration of the SiPMs at the 10-4 level at all timescales

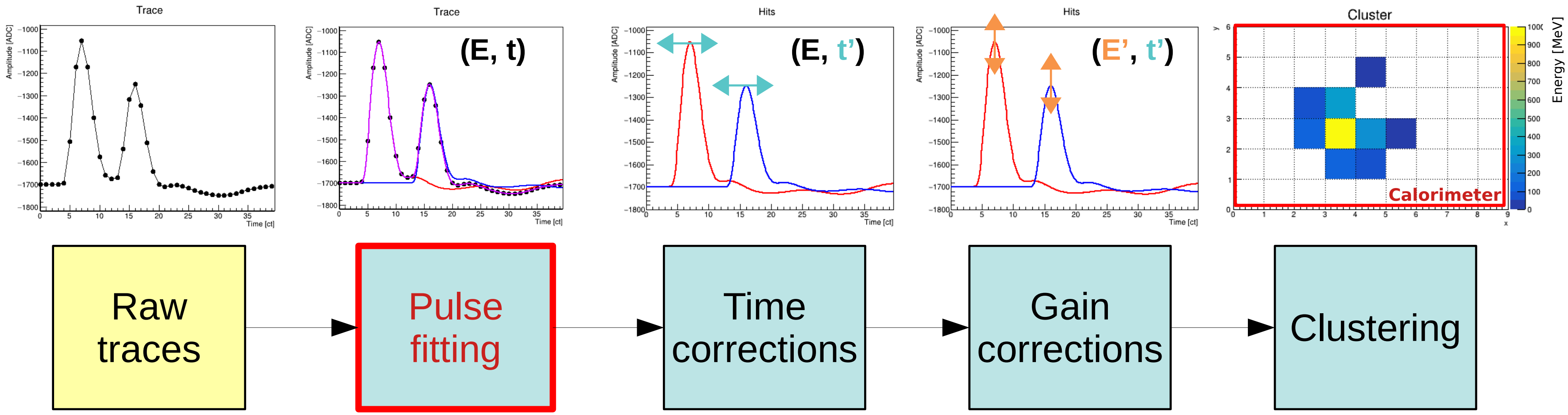
https://doi.org/10.1088/1748-0221/14/11/P11025



Positron reconstruction



Positron reconstruction

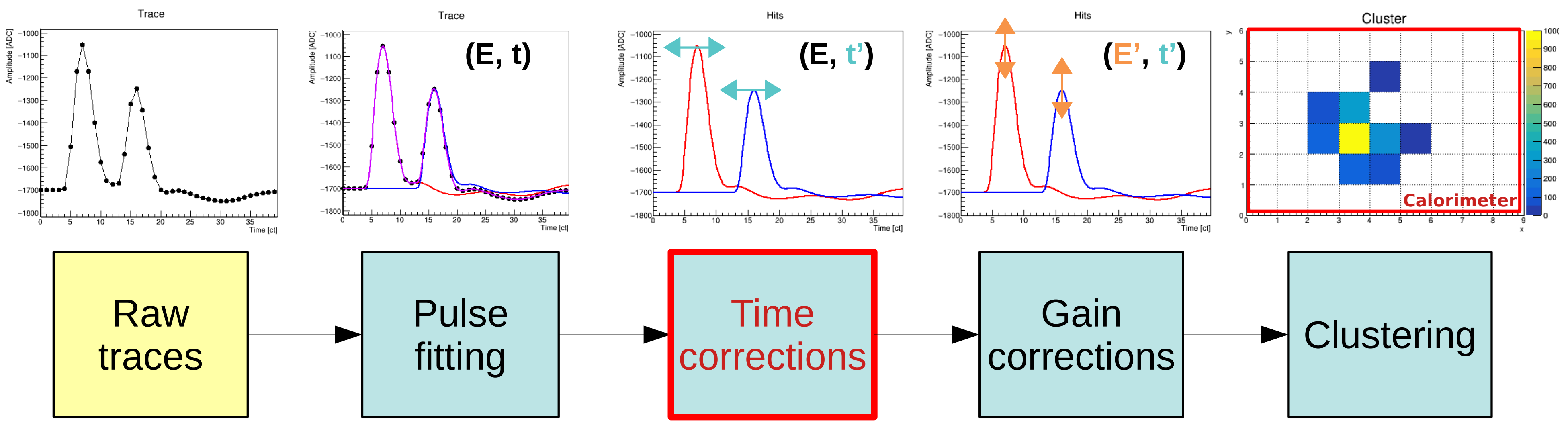


Raw traces are fitted with pulse templates. Each positron generates a pulse in one or more SiPMs.

Three approaches for fitting traces:

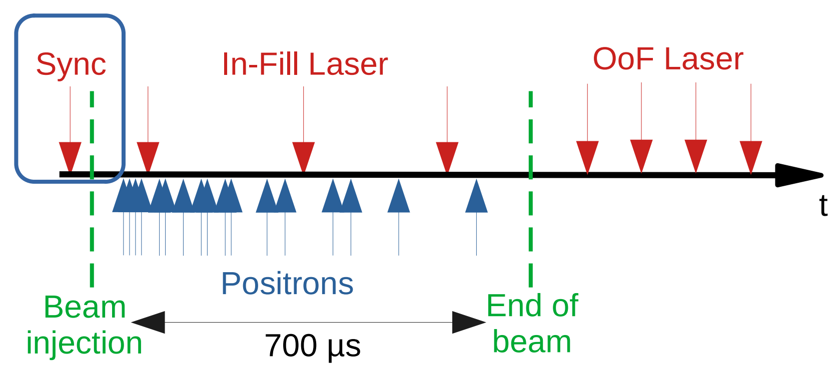
- **local**: each SiPM is treated separately
- **global**: fit all the calorimeter traces simultaneously with a single fixed time
- **hybrid**: after the first round of reconstruction, traces are re-fitted using the positron detection time to improve pulse separation

Positron reconstruction

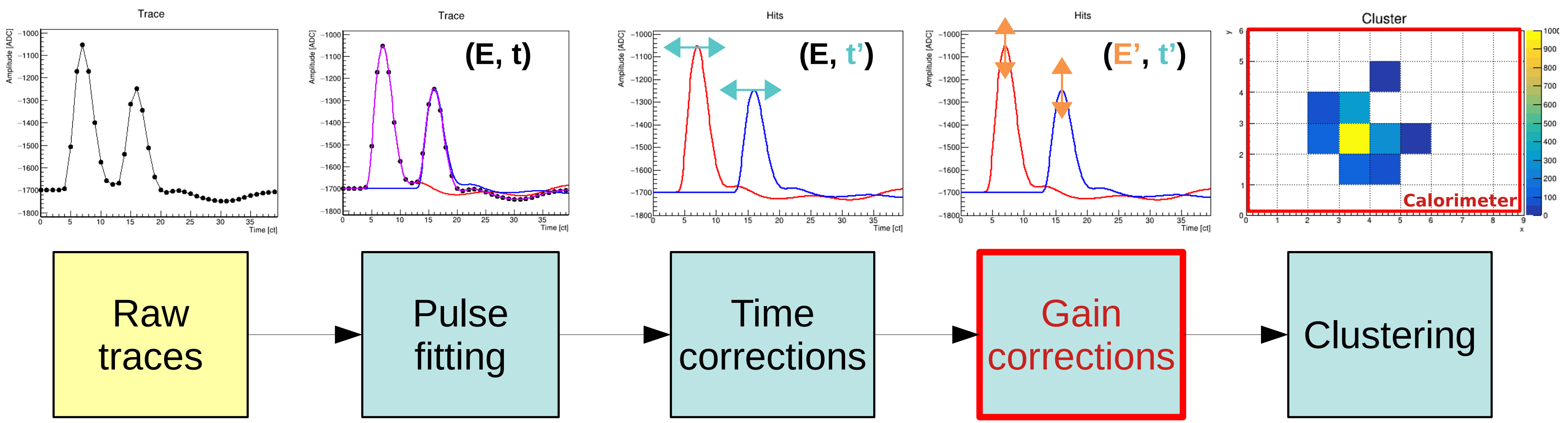


Laser Calibration System provides a synchronization laser pulse to all 1296 crystals ~100 µs before beam injection

- SiPM digitizers synchronized with ~50 ps accuracy
- T=0 set at beam injection

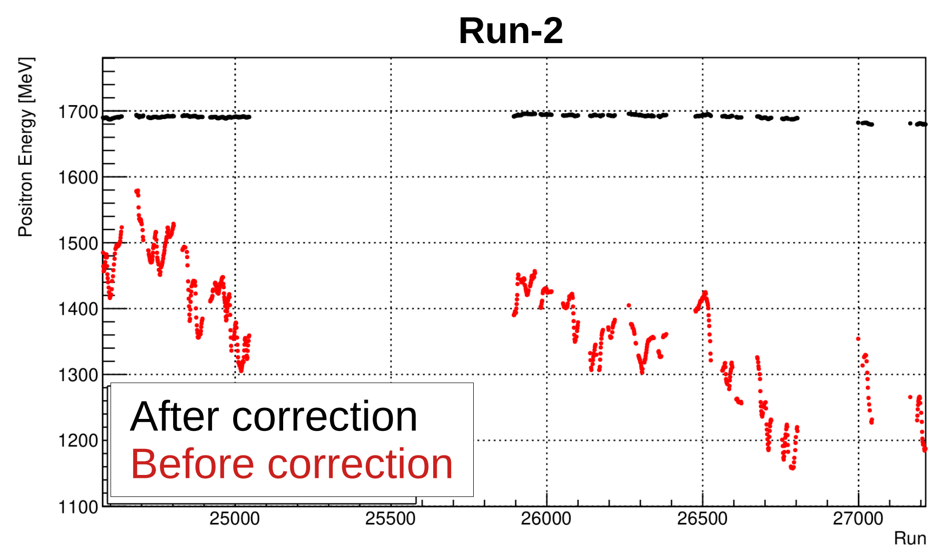


Positron reconstruction

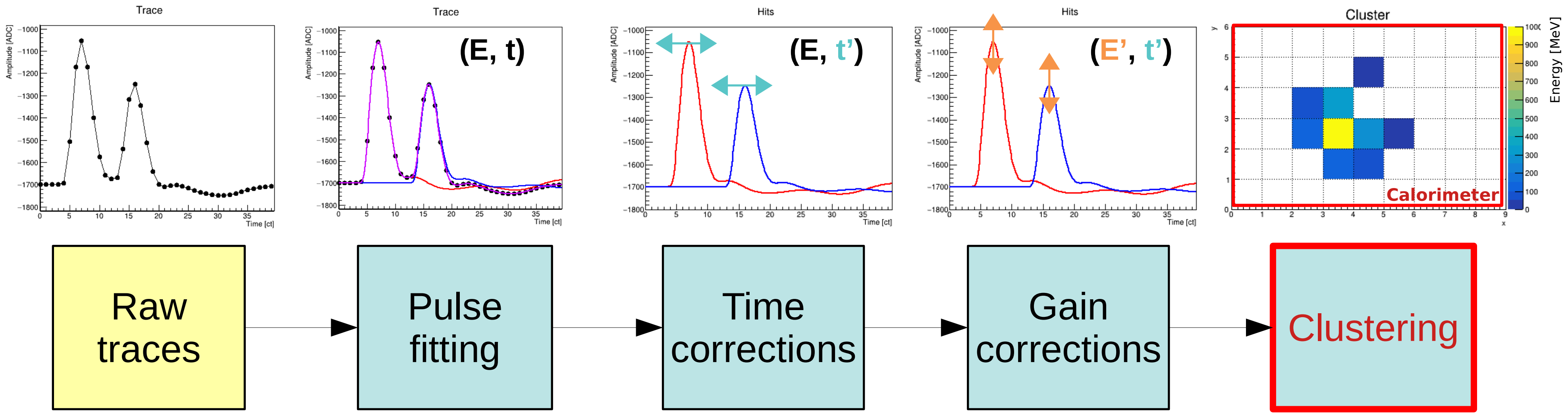


Laser Calibration System used to measure SiPM gain fluctuations and extract correction functions

- Dedicated Short-Term Double-Pulse studies to measure ns-scale SiPM dead time
- In-Fill laser pulses to measure any rate-dependent gain sag
- Out-of-Fill pulses to measure long term gain drifts

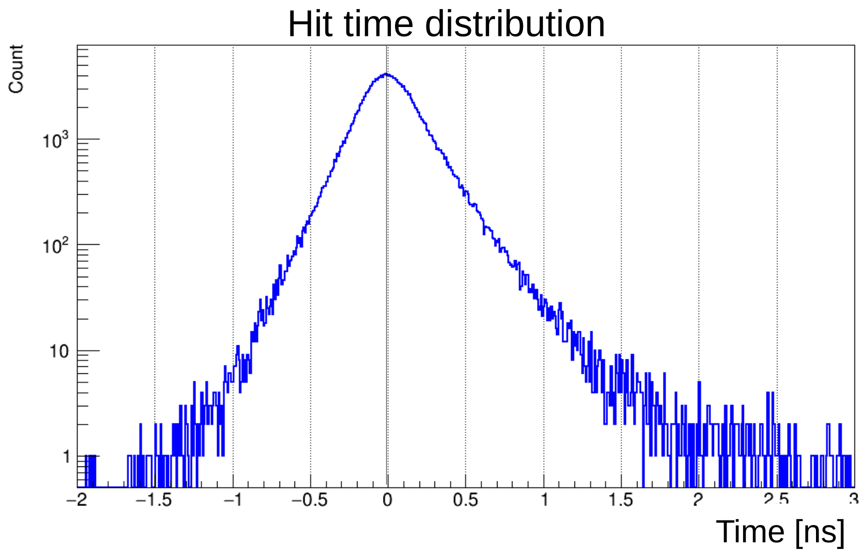


Positron reconstruction



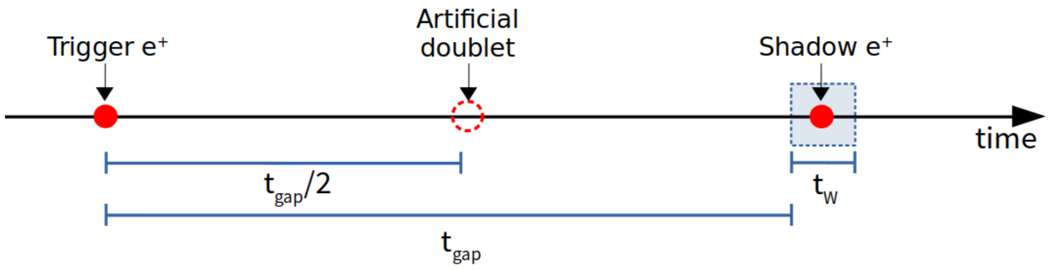
Clustering of SiPM pulses into individual positron candidates

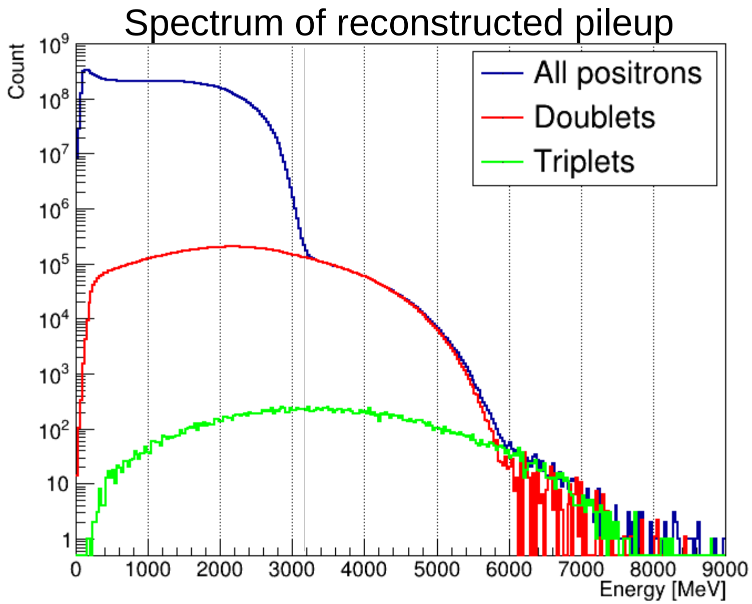
- Goal: maximize separation of pileup events
- Multiple approaches based on the time and energy distributions of the hits
- 0.1 ns spread between adjacent crystals

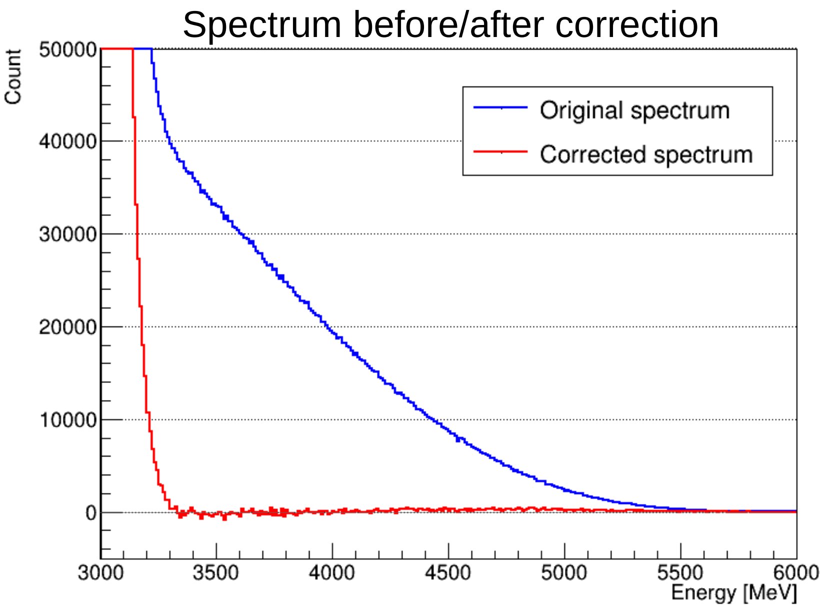


Pileup subtraction

- Pileup = two or more positrons are reconstructed as one
- Contamination subtracted statistically with a "shadow window" technique
- Run-1: 300 ppb effect if not corrected → 40 ppb systematics after correction
- Run-2/3 pileup contamination reduced by factor ~3

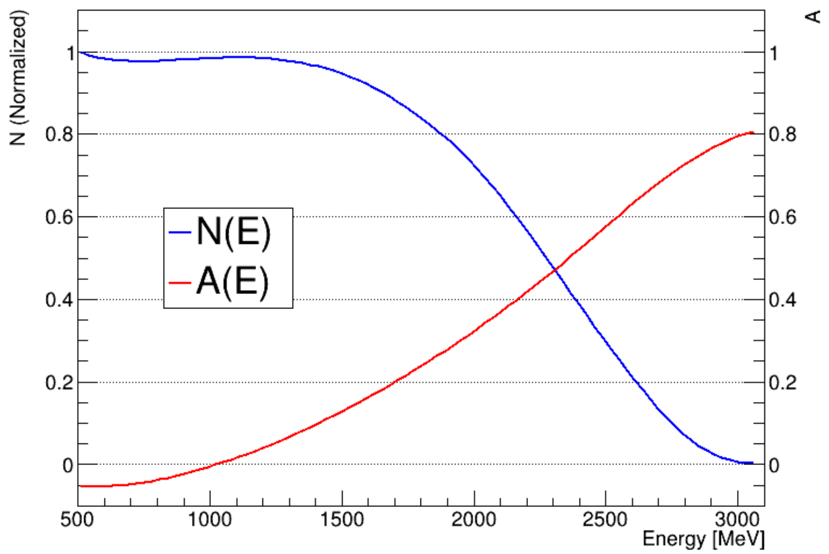


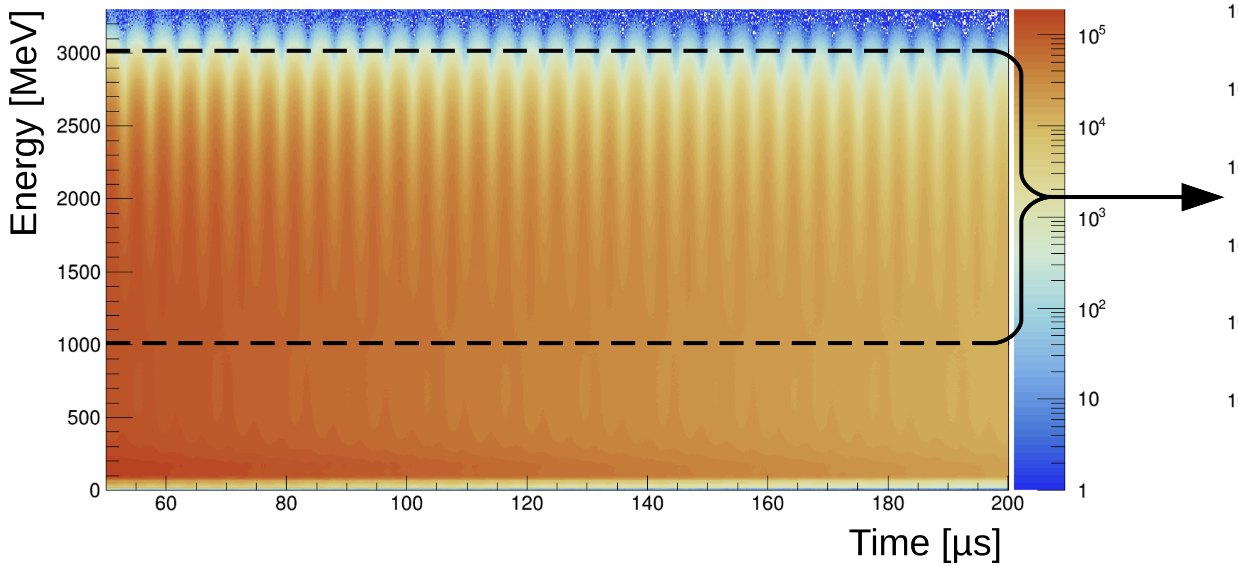




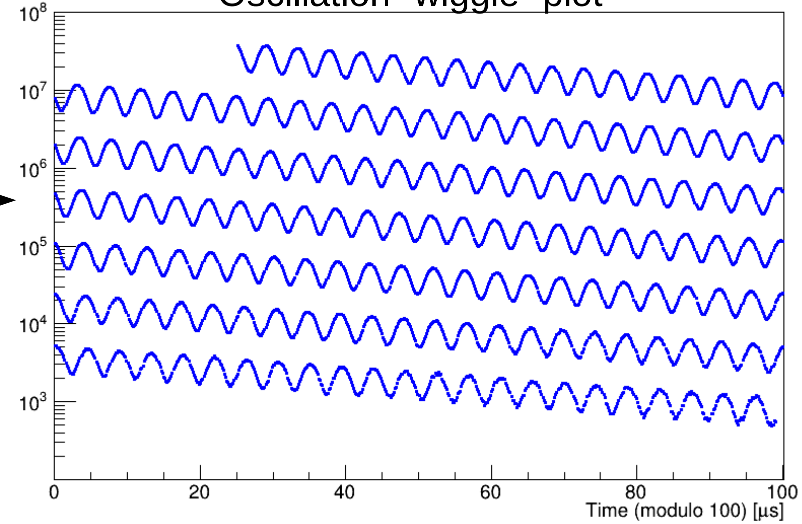
Positron weighting

- High energy positrons carry the largest asymmetry → Counting positrons above an energy threshold to produce “wiggle” plot
- Maximum statistical power achieved by weighting the positrons according to their asymmetry A(E) and then integrating over the [1000,3000] MeV range

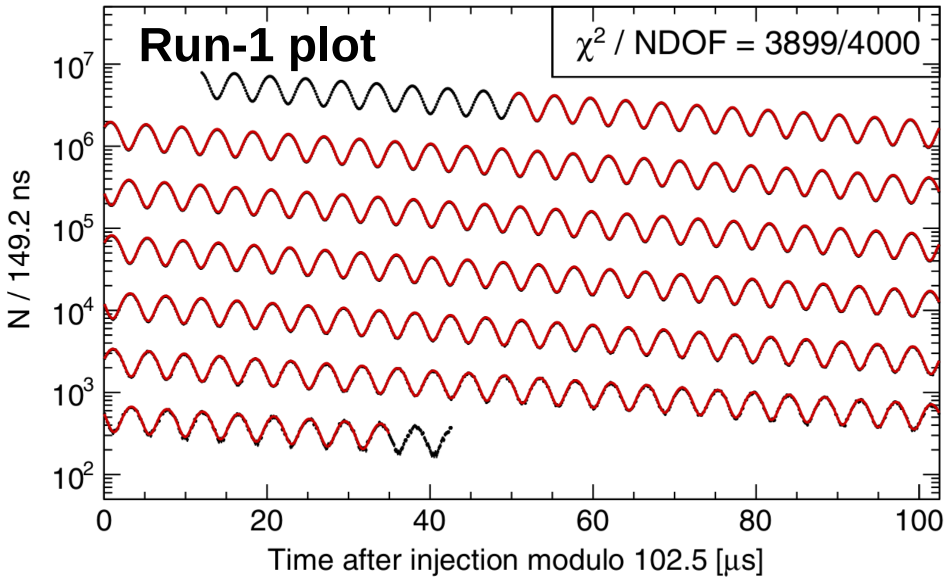


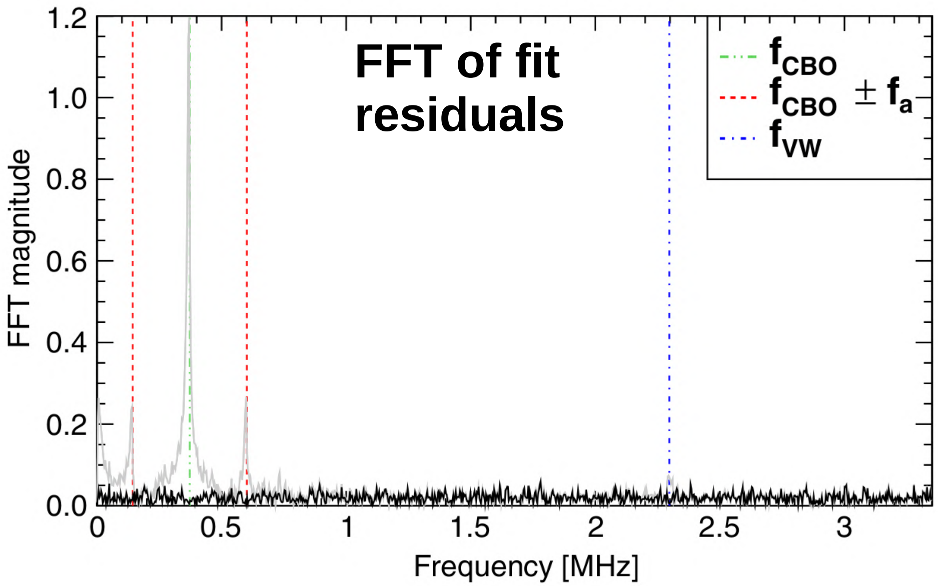


Oscillation “wiggle” plot



Measuring ω_a





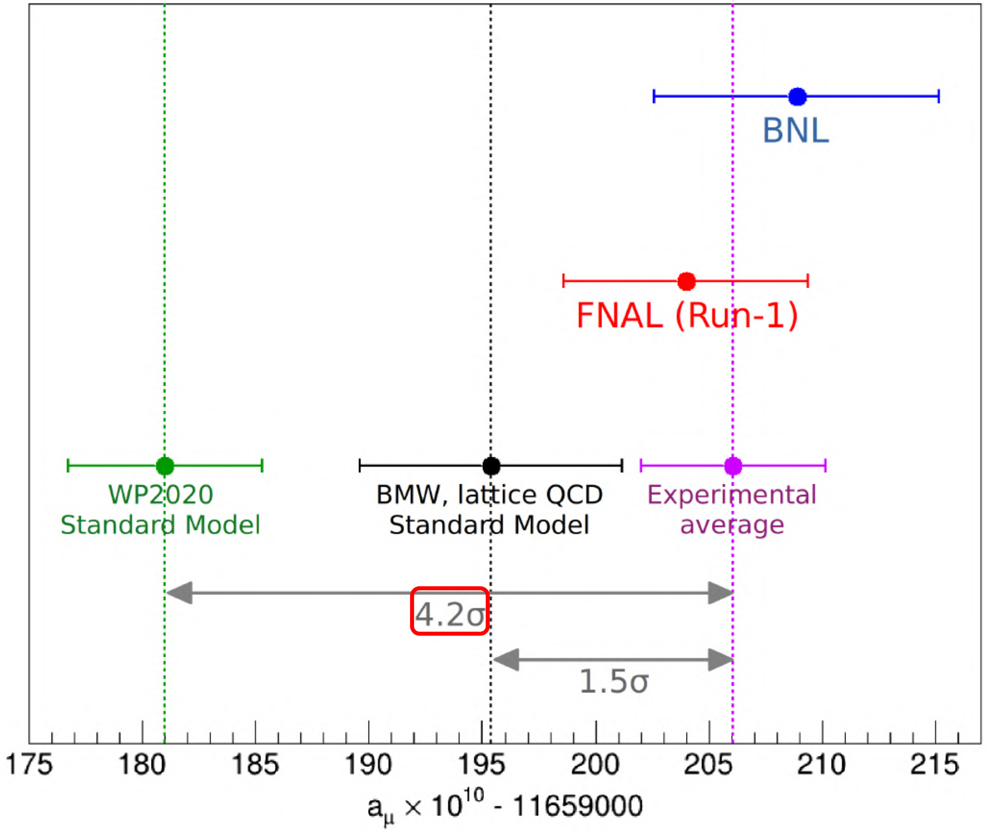
- Histogram fitted with 22-parameters function
- Muon precession, beam oscillations, lost muons
- 4 independent analyses averaged to extract the muon anomalous precession frequency ω_a

$$
\begin{aligned}
N(t) = N e^{-t/\tau_\mu} & [1 + A \cdot \cos(\omega_a t - \phi + \phi_{BO}(t))] \cdot \\
& \cdot \left(1 + A_{CBO} \cos(\omega_{CBO} t - \phi_{CBO}) e^{-\frac{t}{\tau_{CBO}}}\right) \cdot \\
& \cdot \left(1 + A_{VW} \cos(\omega_{VW} t - \phi_{VW}) e^{-\frac{t}{\tau_{VW}}}\right) \cdot \\
& \cdot \left(1 + A_{2CBO} \cos(\omega_{2CBO} t - \phi_{2CBO}) e^{-\frac{t}{\tau_{2CBO}}}\right) \cdot \\
& \cdot \left(1 + A_y \cos(\omega_y t - \phi_y) e^{-\frac{t}{\tau_y}}\right) \cdot \\
& \cdot \left(1 - k_{LM} \int_0^t L(t') e^{t'/\tau_\mu} dt'\right) \cdot
\end{aligned}
$$

https://doi.org/10.1103/PhysRevD.103.072002

Run-1 result

- Run-1 a_μ value computed with the field measurement and other correction terms → 462 ppb (434 ppb stat, 157 ppb syst)



a_μ (FNAL) = 116 592 040(54) × 10^{-11} (0.46 ppm)

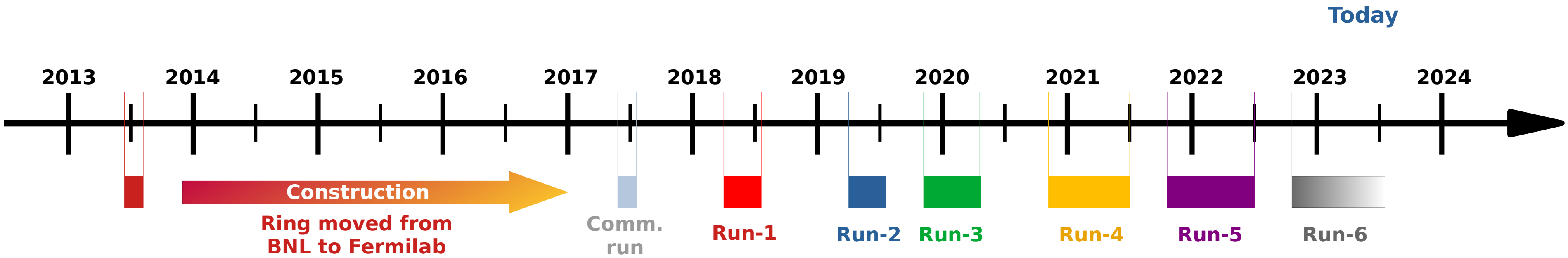
a_μ (World avg) = 116 592 061(41) × 10^{-11} (0.35 ppm)

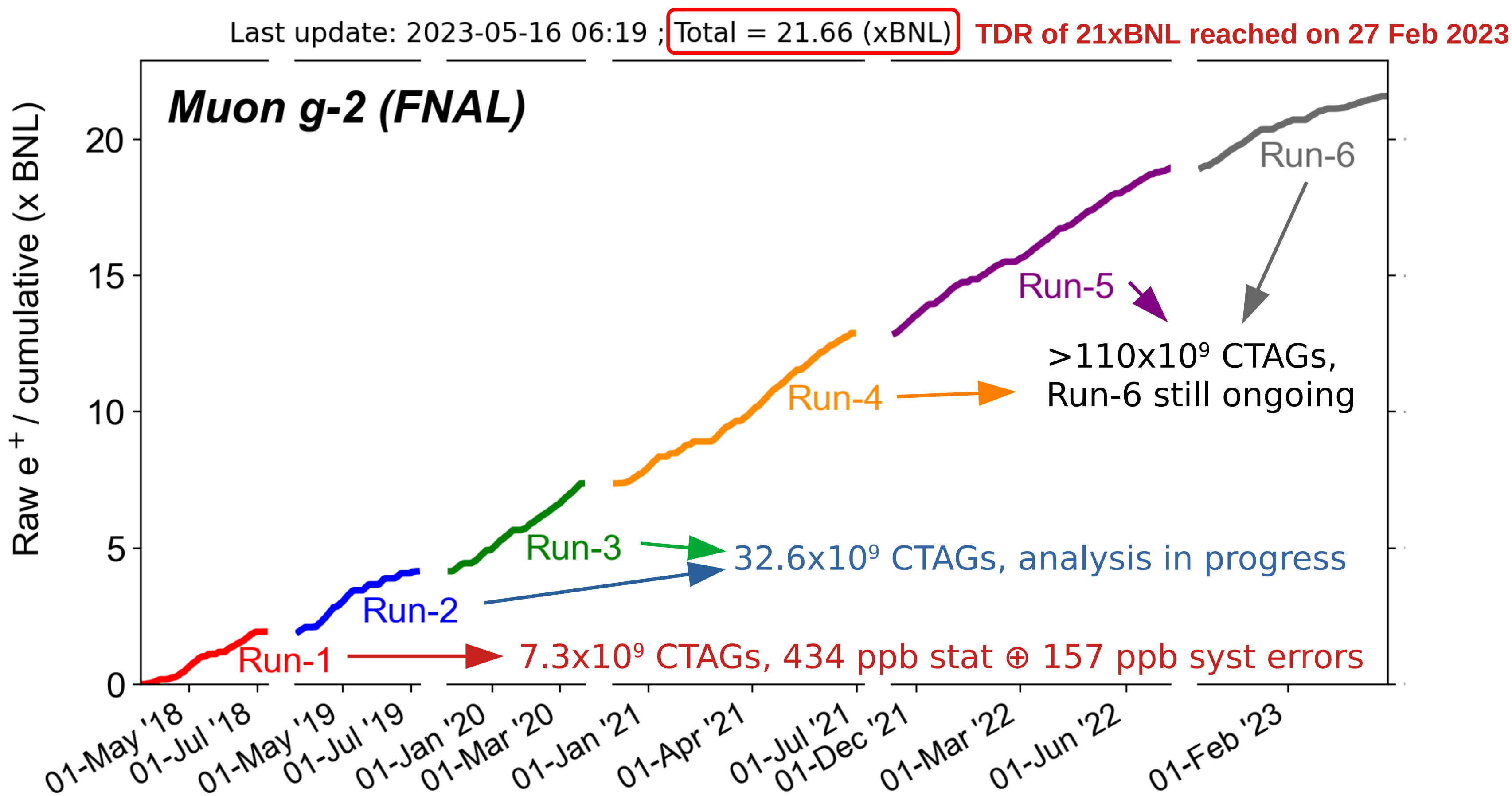
$$a_\mu \propto \frac{f_{clock}\,\omega_a^m\,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib}\,\langle \omega'_p(x,y,\phi) \times M(x,y,\phi)\rangle\,(1 + B_k + B_q)}$$

Quantity	Correction [ppb]	Uncertainty [ppb]
ω_a (statistical)	-	434
ω_a (systematic)	-	56
C_e	489	53
C_p	180	13
C_{ml}	-11	5
C_{pa}	-158	75
$f_{calib}\langle\omega'_p(x,y,\phi)\cdot M(x,y,\phi)\rangle$	-	56
B_q	-17	92
B_k	-27	37
μ'_p/μ_e	-	10
m_μ/m_e	-	22
g_e	-	0
Total systematic	-	157
Total external factors	-	25
Total	544	462

https://doi.org/10.1103/PhysRevLett.126.141801

Current status





Conclusions

- A precise reconstruction of the positrons is necessary to achieve <70 ppb systematics on the muon precession measurement
- Analysis of Run-2/3 is now at the final stages and a new publication with 2x precision wrt Run-1 (~230 ppb) is expected this summer
- Reconstruction of Run-4/5 is complete and analysis is starting. Run-6 (final run) is currently ongoing and reconstruction is proceeding in parallel.
- Run-4/5/6 will have 4x the statistics of Run-2/3. Final publication expected in 2025, on track to achieve or exceed the final goal of 140 ppb!

Thank you for listening!