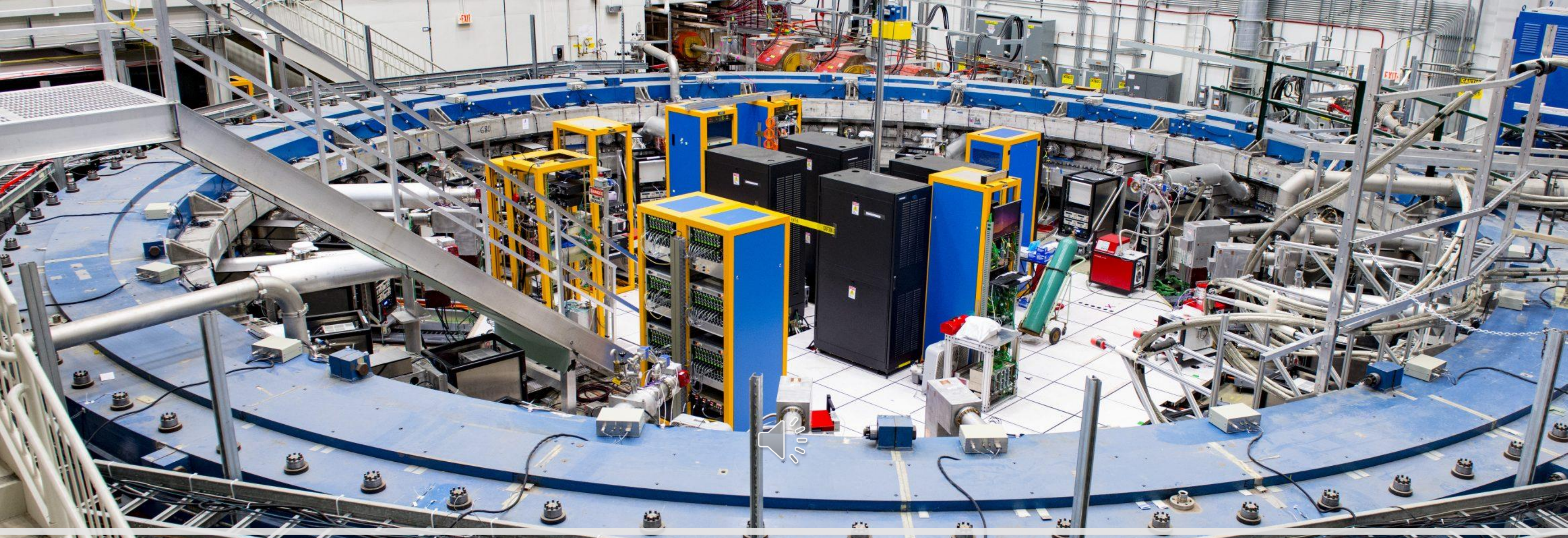

Muon g-2 at Fermilab: how we detect the positrons and measure ω_a from them

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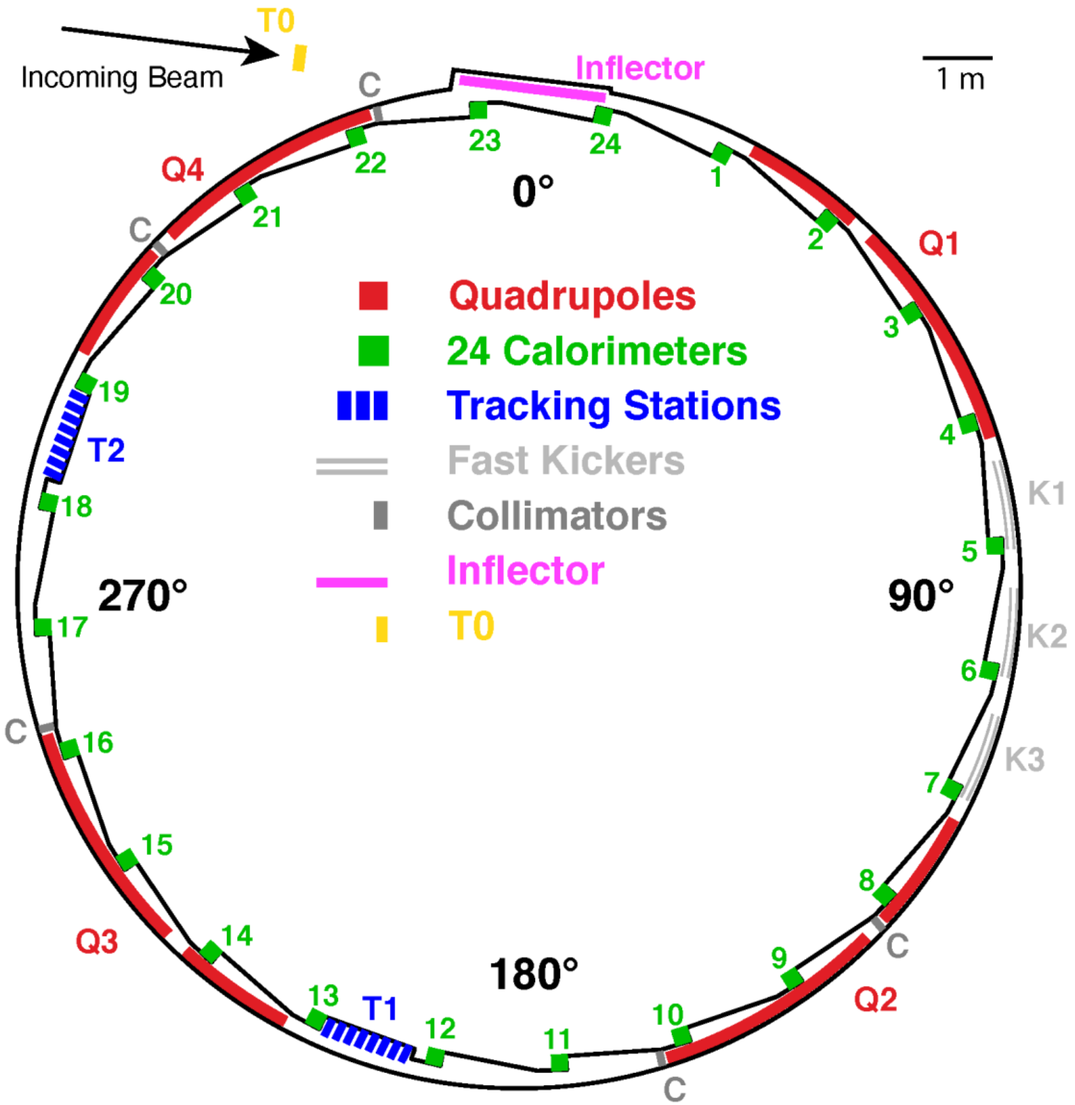
Outline

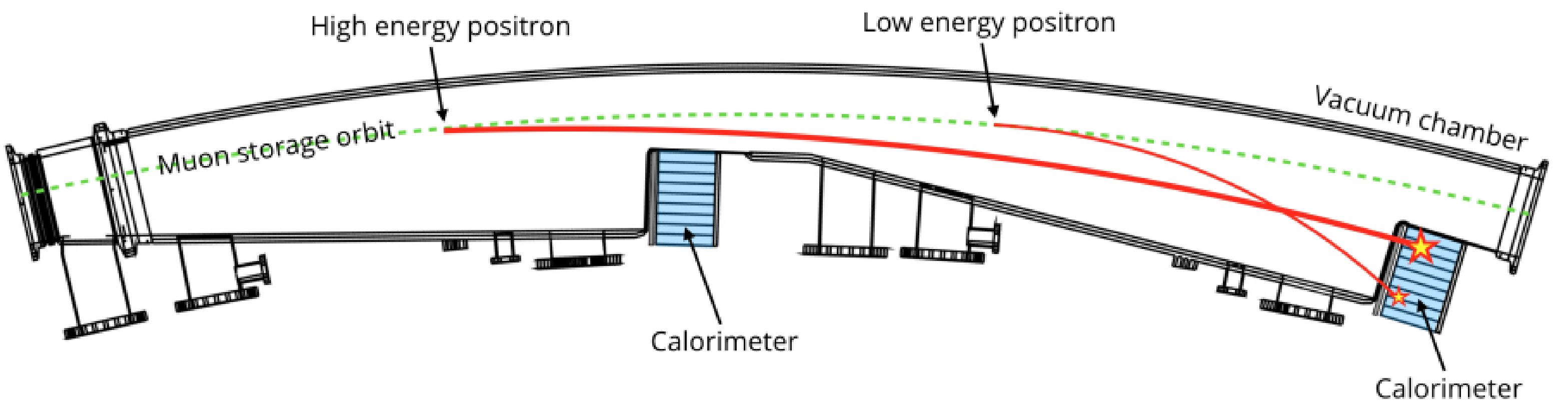
- Description of the apparatus: calorimeters
- Calibration and reconstruction of events
- Measurement principle of ω_a (anomalous precession frequency)
- ω_a analysis: Run1 fits and results

g-2 storage ring

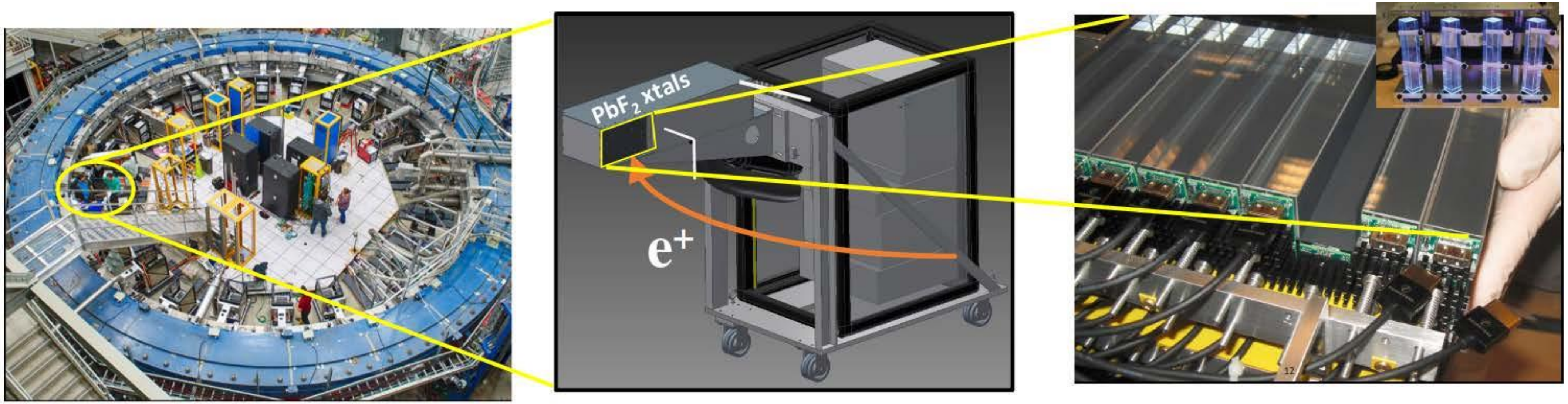


- About 10^4 muons at a time, injected with a rate of 13 Hz
- 1.45 T magnetic field, 7-meter radius: muons precede every 149.2 ns
- Each fill lasts for ~ 700 μs = 11 muon lifetimes
- Decay positrons are detected by 24 calorimeters placed along the inner circumference

Electromagnetic calorimeters

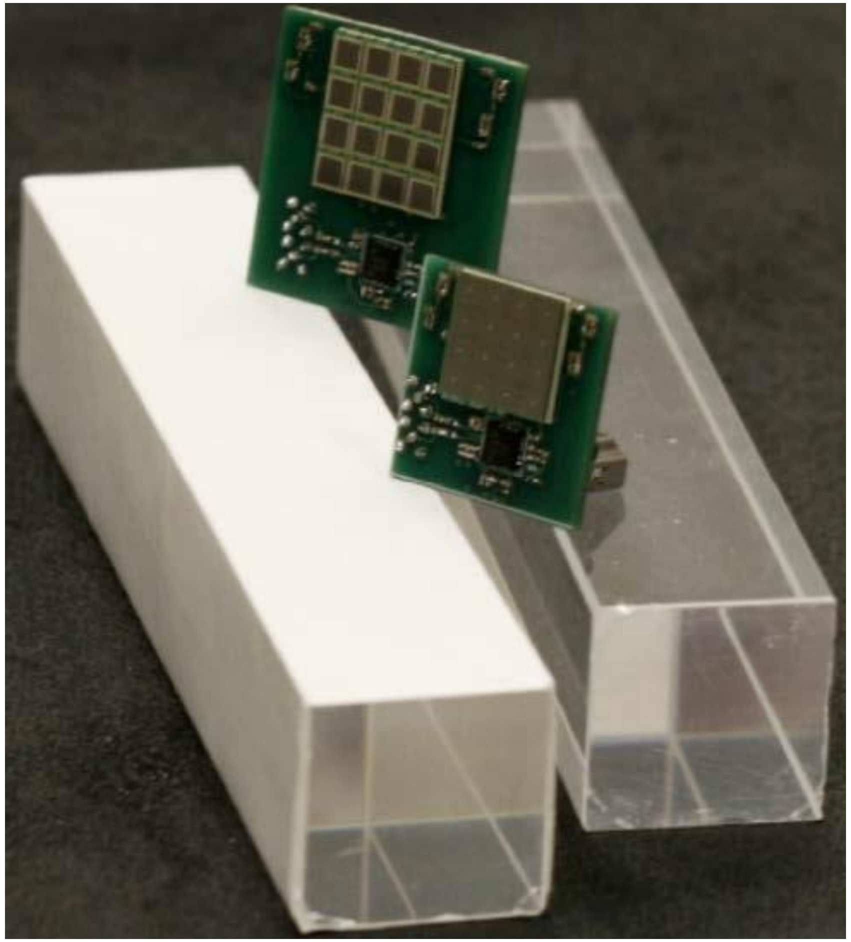


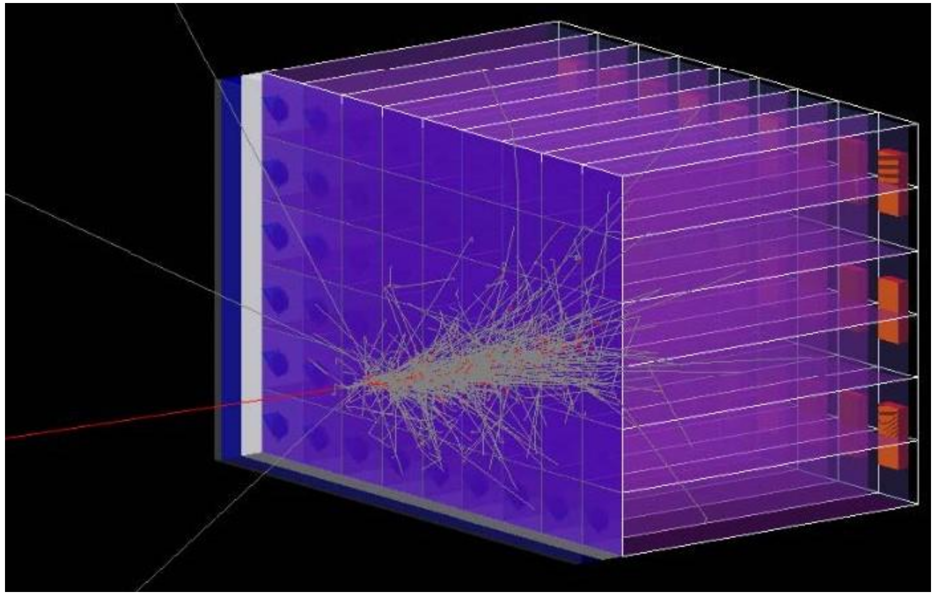
- Positrons drift away from storage orbit and hit calorimeters
- 24 stations, 54 crystals in each station (9x6 array)



Cherenkov crystals and SiPMs

- Homogeneous EM calorimeters: 6x9 PbF_2 crystals, refractive index n=1.8
- Each crystal is coupled with a SiPM working in Geiger mode: Cherenkov light is detected from EM shower





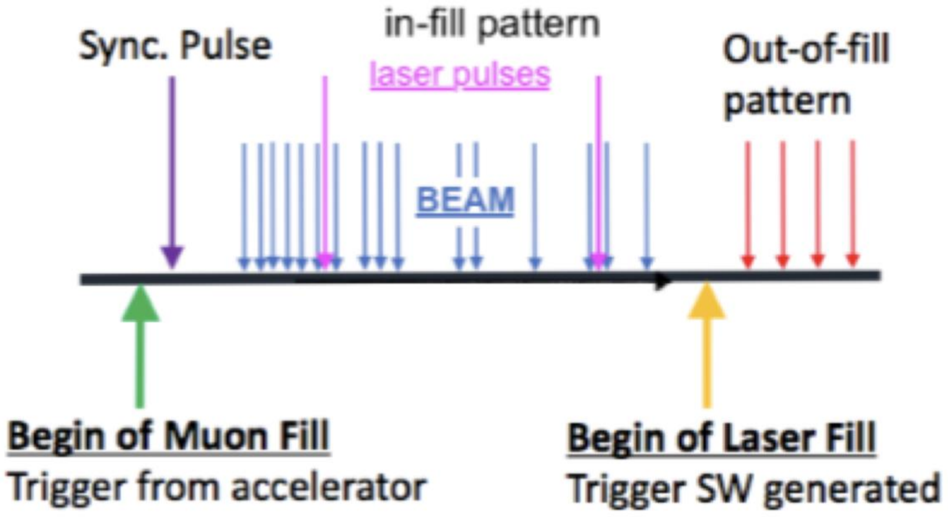
Incoming positron
@ 2.4 GeV (simulation)

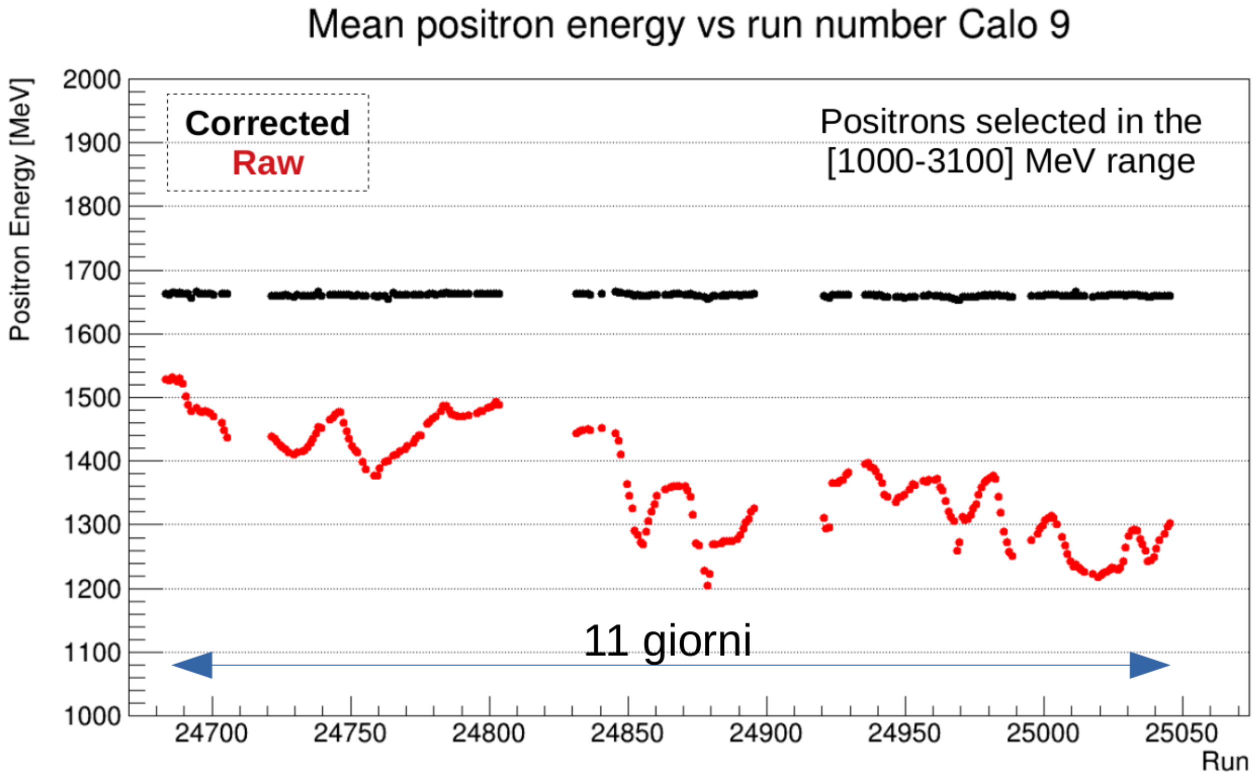
Laser calibration

- A high-precision laser system was built by INFN-INO to synchronize 1296 crystals at 0.1 ns level, and control gain fluctuations at 1e-4 level → 20 ppb systematic
- Crystal gains change at different time scales:
  - **Short term.** When a positron hits a crystal the SiPM is «blind» for O(10 ns); a second positron might hit before recovery
  - **In-fill (700 μs).** At the beginning there is a huge «splash» of particles
  - **Long term (days).** Gain changes due to external factors, mainly hall temperature

Laser calibration

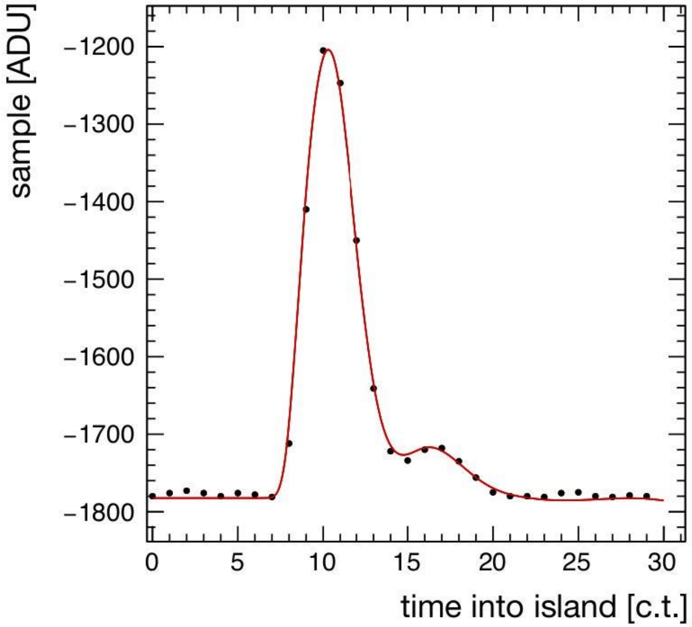
- Out-Of-Fill corrections: 4 laser pulses between two muon fills are used to study the stability over time
- Plot: positron mean energy before and after applying OOF correction

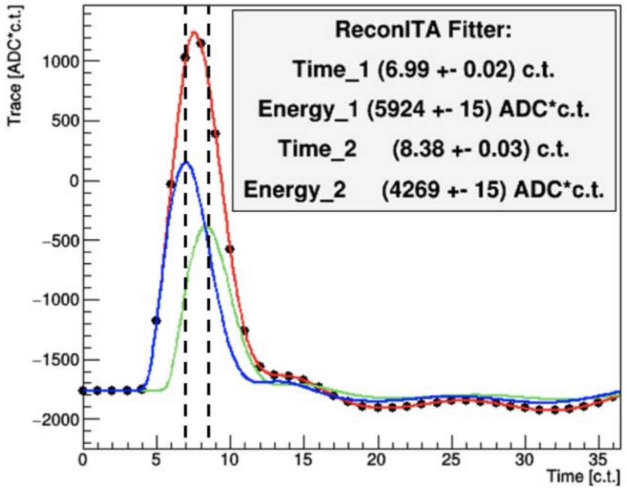


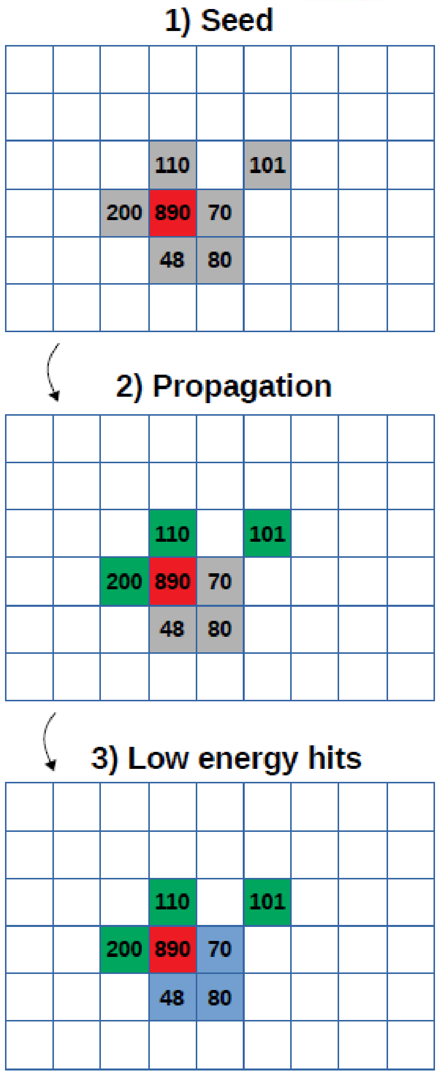


Reconstruction chain

- Fit to identify pulses on crystal hits
- Clustering algorithm to reconstruct time and energy of incoming e^+
- Run1: 4 different teams, each with its own reconstruction chain
- Following runs: more analysis teams, including new Italian reconstruction; many efforts to understand and reduce Run1 systematics

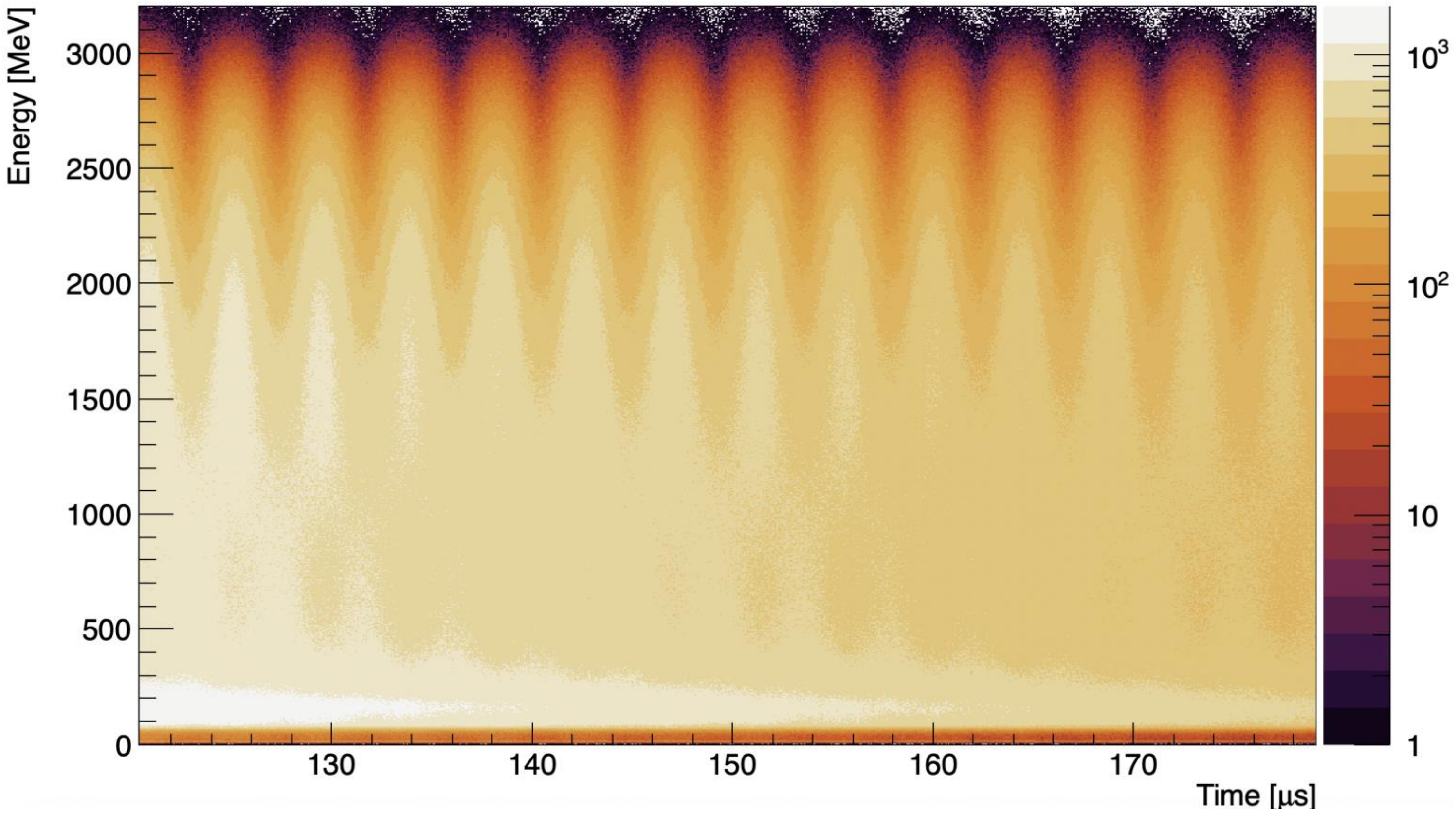




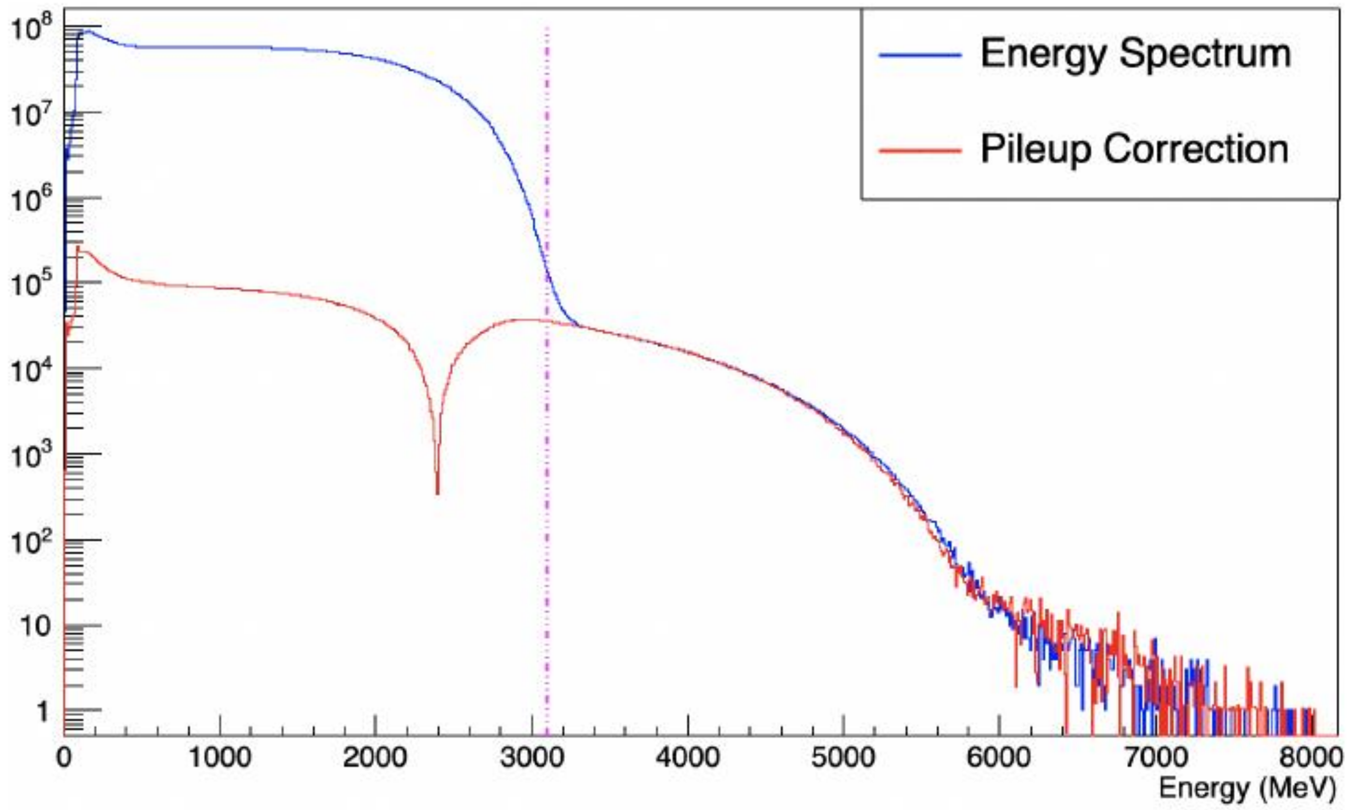


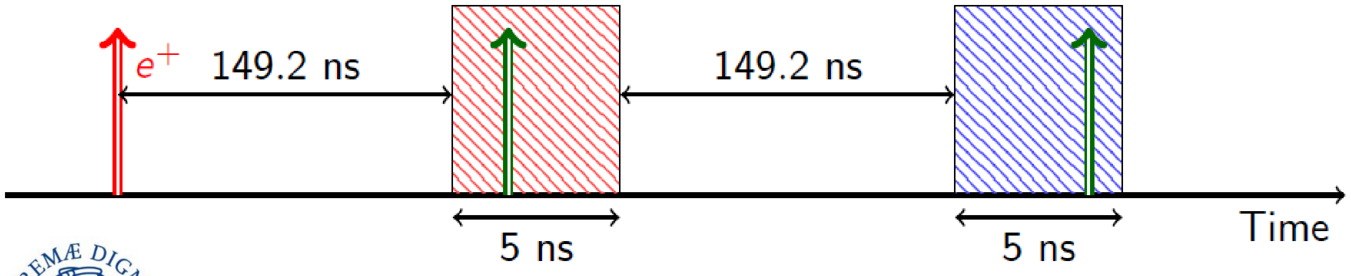
2D Maps: Energy vs Time

- Data collected in a single dataset, order of 100 hours of acquisition
- Periodic time modulation: anomalous precession frequency, $\sim 4.365\ \mu s$
- Project on Y axis: energy spectrum of detected positrons (see next slide)



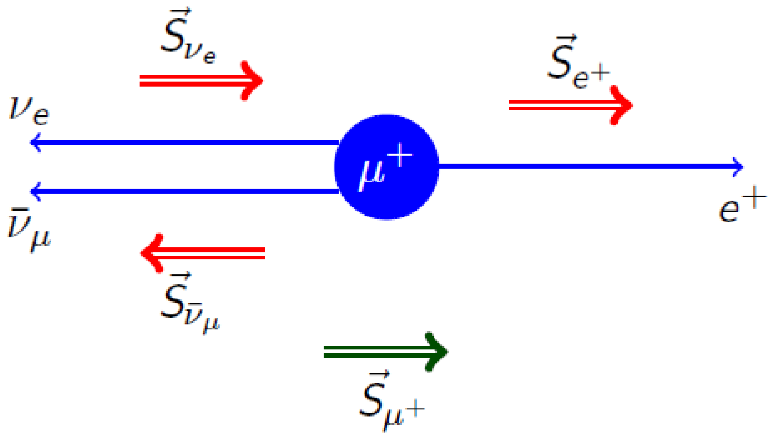
Pileup subtraction



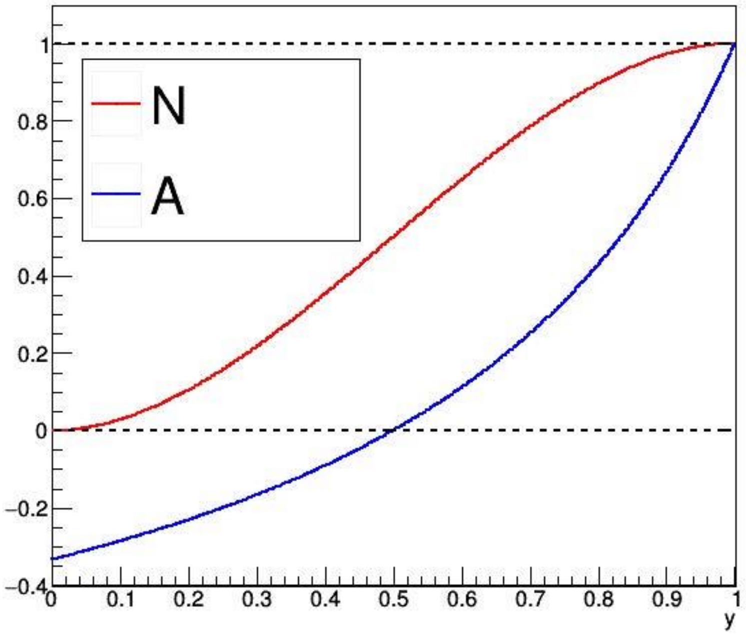


- Positrons decay from ~ 3 GeV muons, so max energy should be ~ 3 GeV (dashed line)
- But: pileup! Double and triple overlapping positrons, which we can subtract
- Red line: correction that is applied to data (absolute value, from positive to negative)

Energy spectrum in muon rest frame

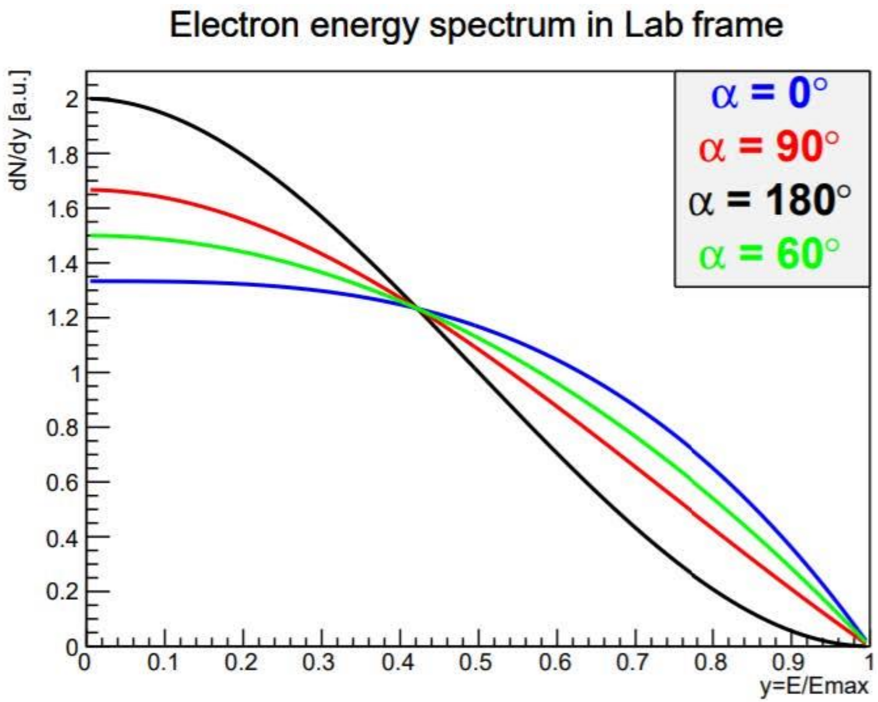


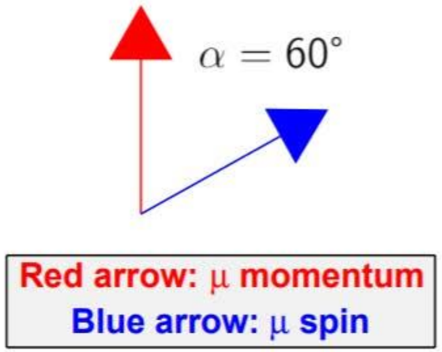
- Parity violation in muon decay:
  $$\Gamma(E,\theta) = N(E)[1 + A(E)\cos(\theta)]$$
- Correlation between high-energy decay positrons and θ, angle between positron and muon spin: highest rate for $\theta = 0$
- Positron energy spectra in the lab frame depends on muon spin direction
- Rest frame: e^+ max energy is $\sim m_\mu/2$

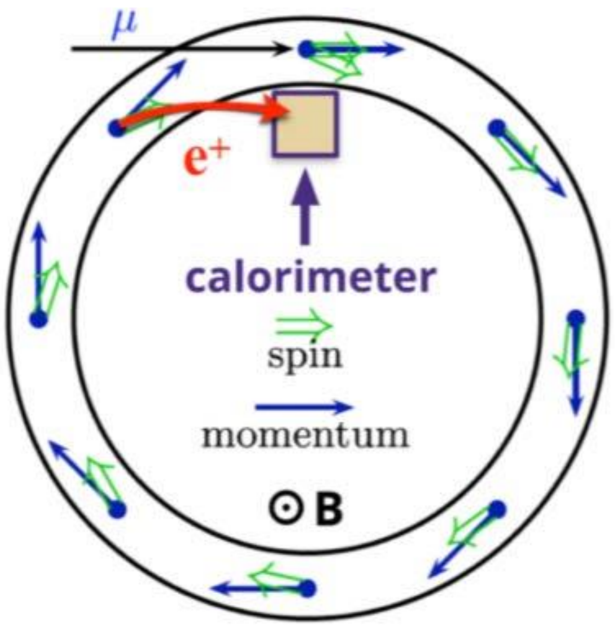


y = Positron energy normalized by ~52.8 MeV

Spectrum in lab frame



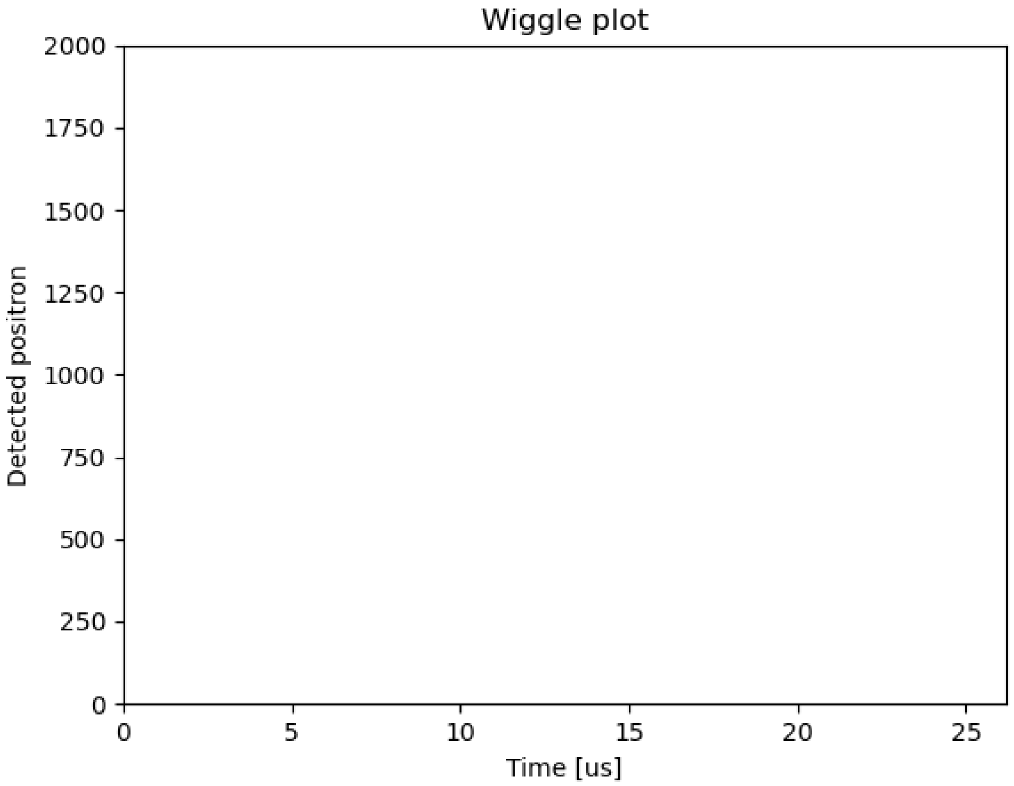


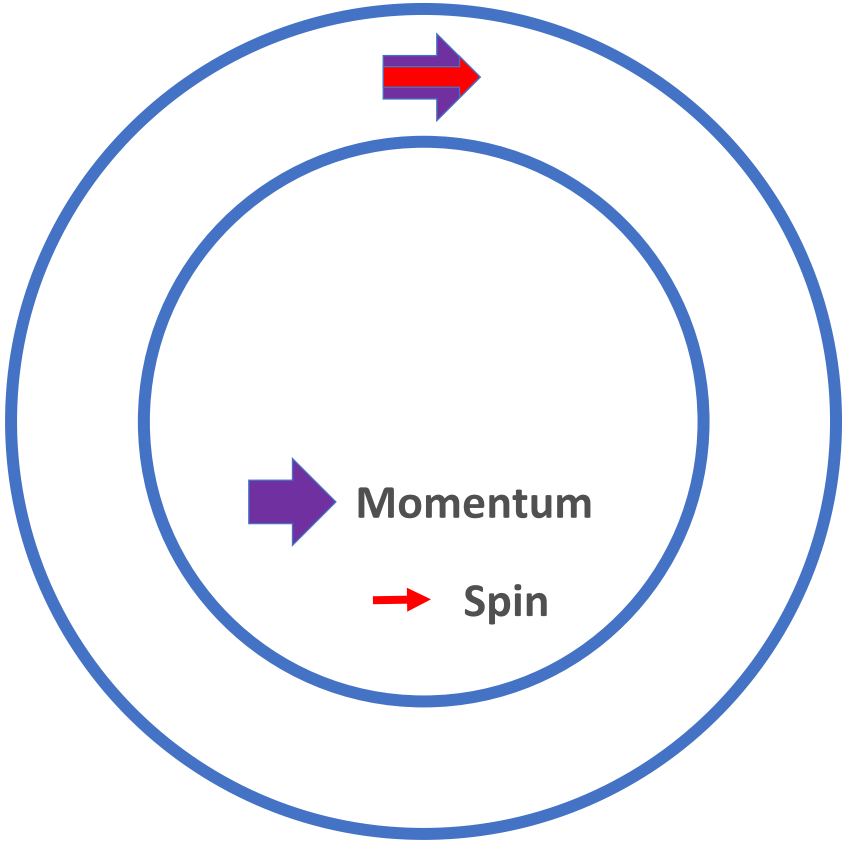


Positron spectrum changes with the angle between muon momentum and spin →time modulation ω_a, with period of $\sim 4.365\ \mu s$

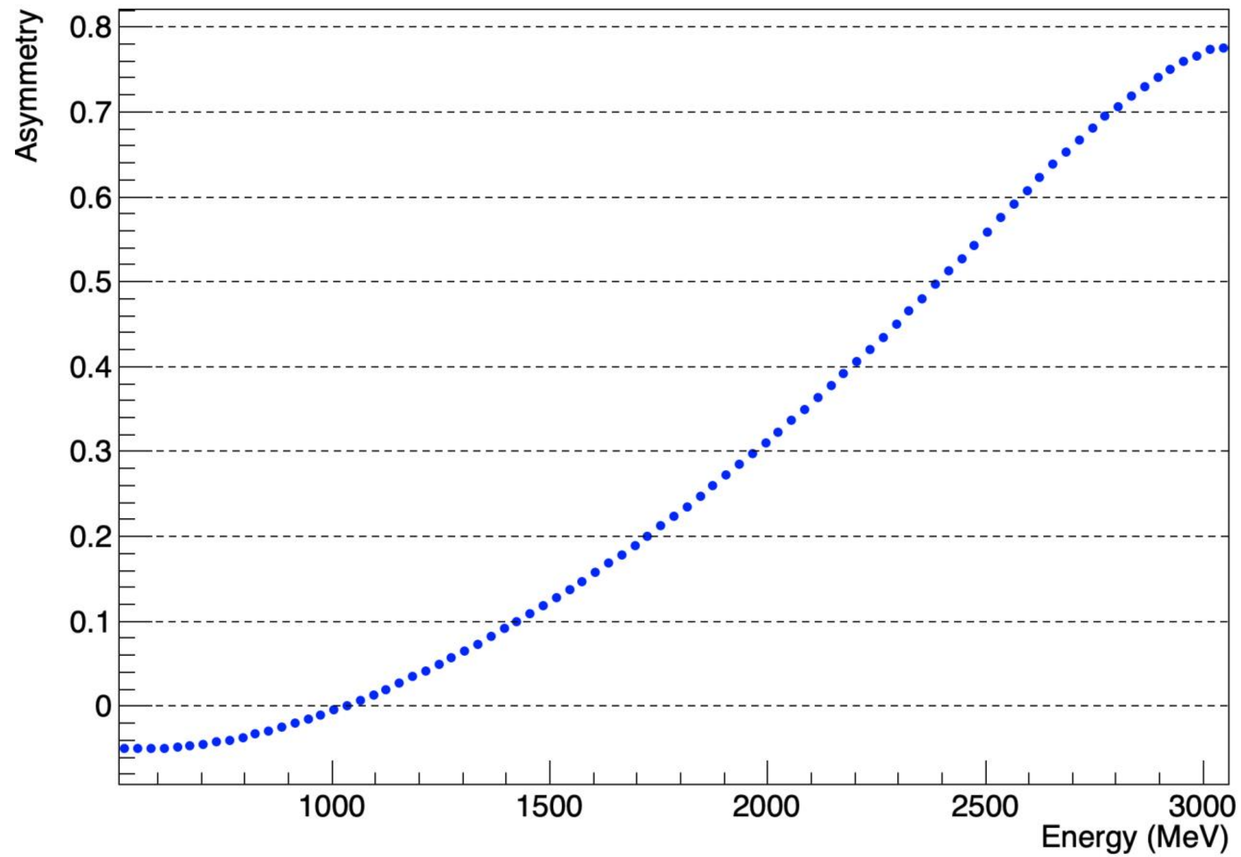
Wiggle plot

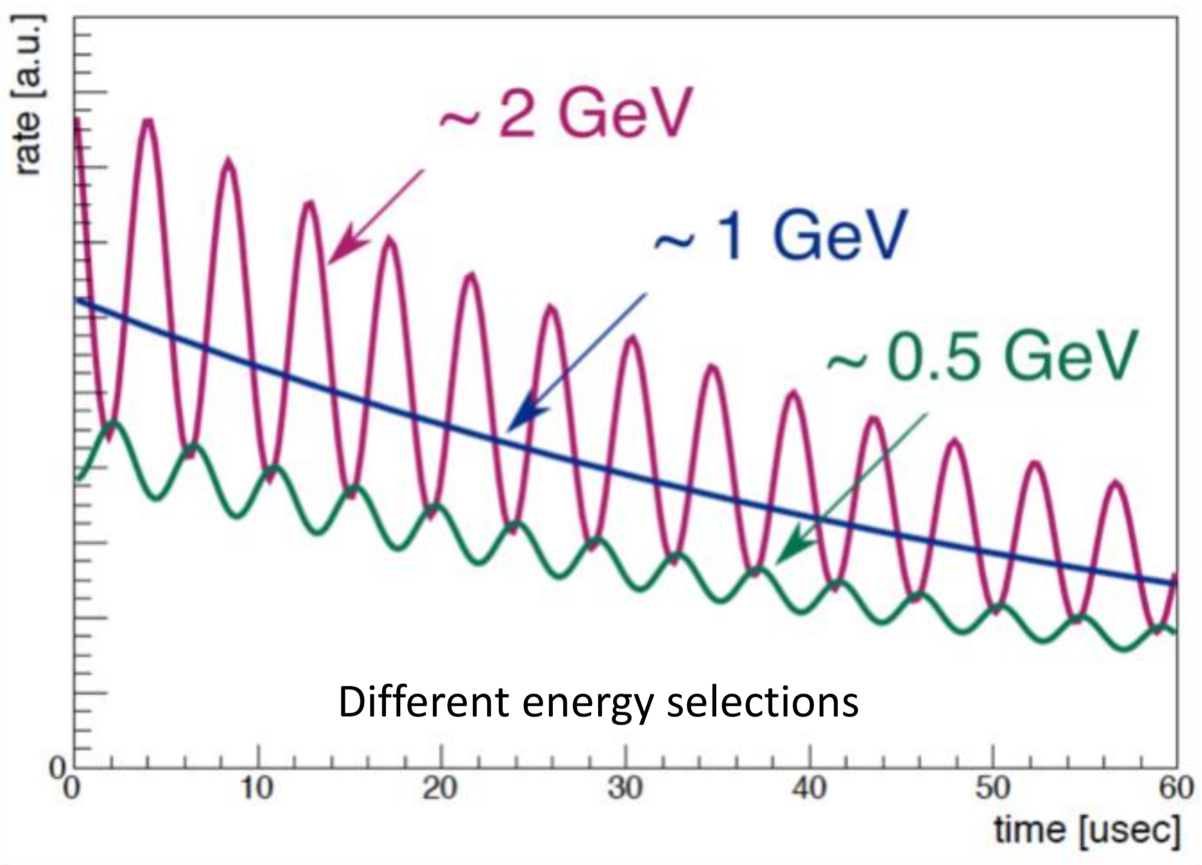
If we fix an energy threshold (e.g. 1700 MeV) and count all detected positrons above threshold, over time:





Asymmetry

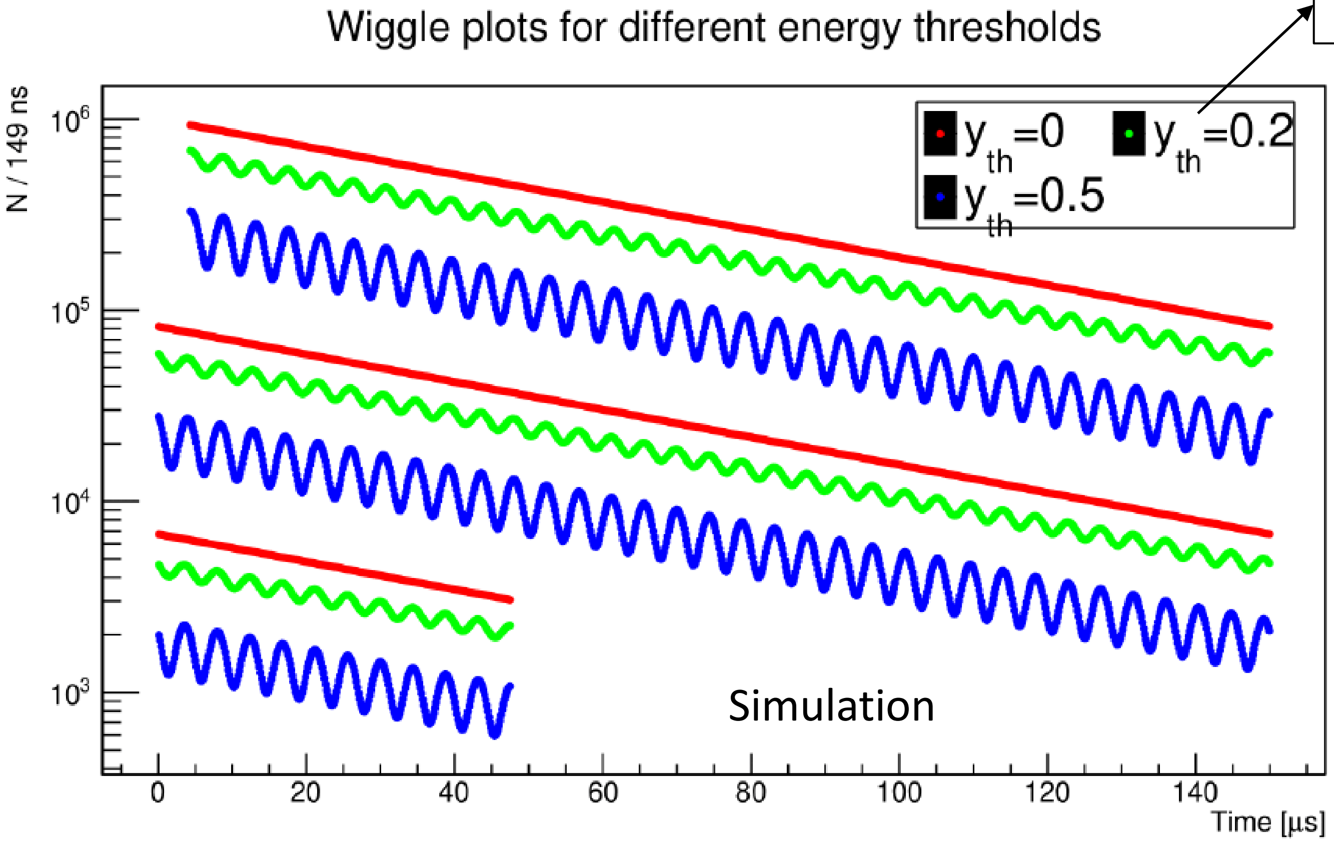


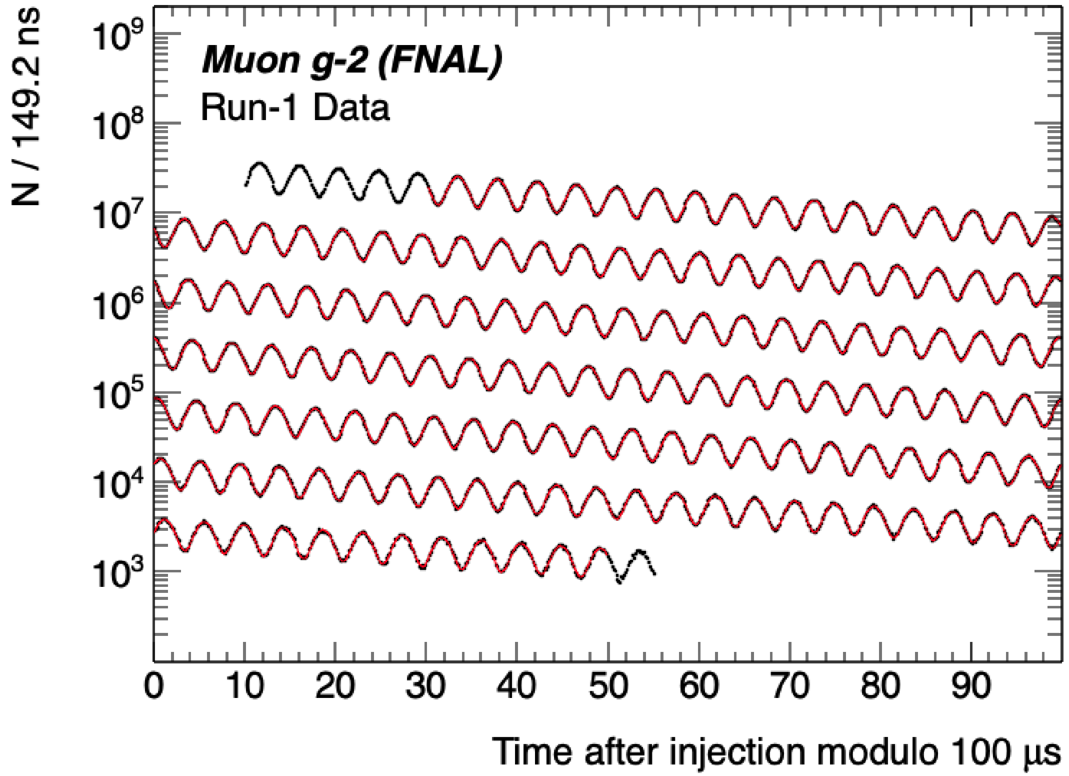


- Asymmetry is a function of energy: from negative to positive, crosses zero at ~ 1000 MeV

Wiggle plot

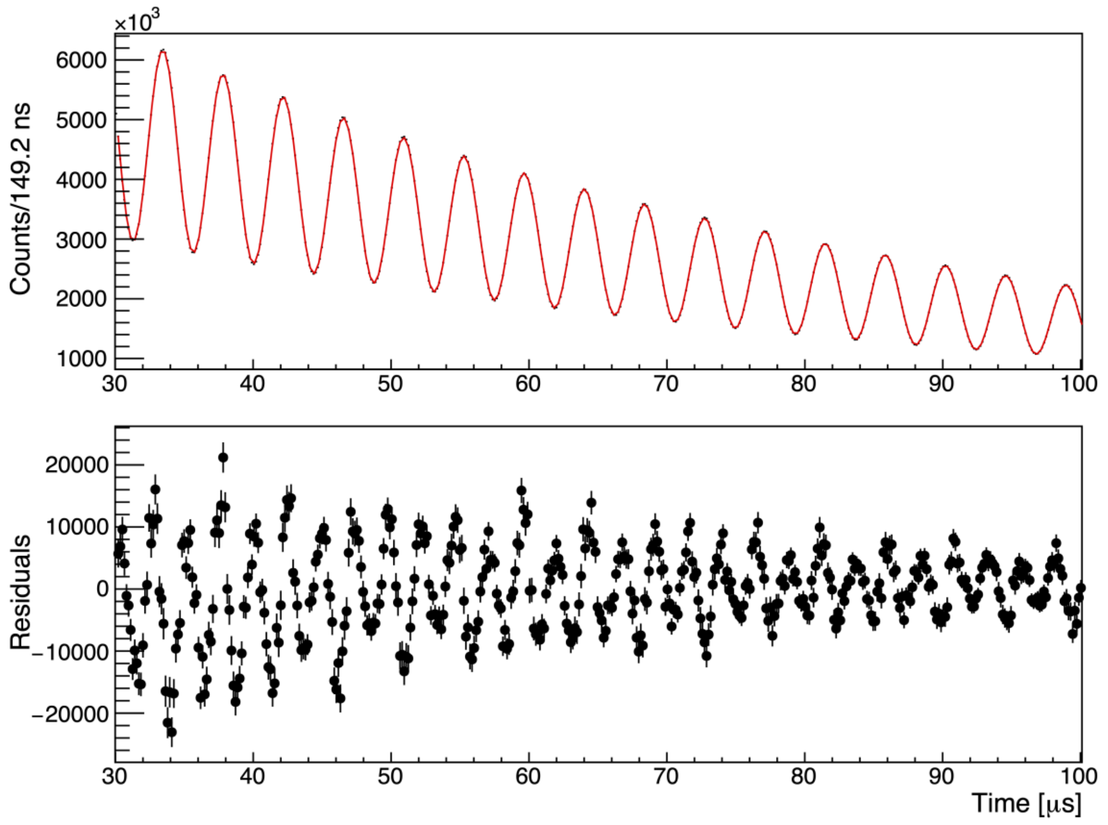
y = Positron energy normalized by max Energy ~ 3 GeV

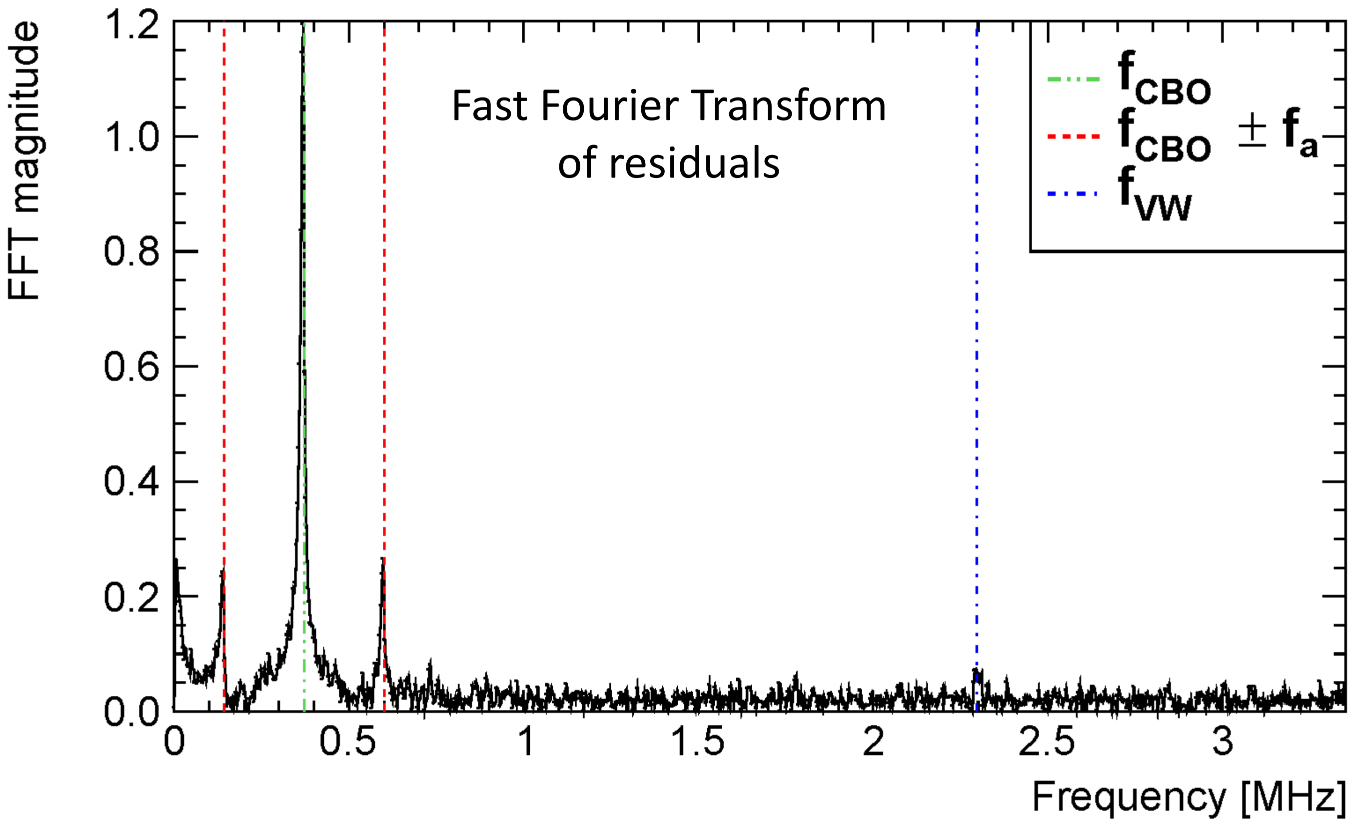




Integrating over 1700 MeV minimizes statistical uncertainty on ω_a

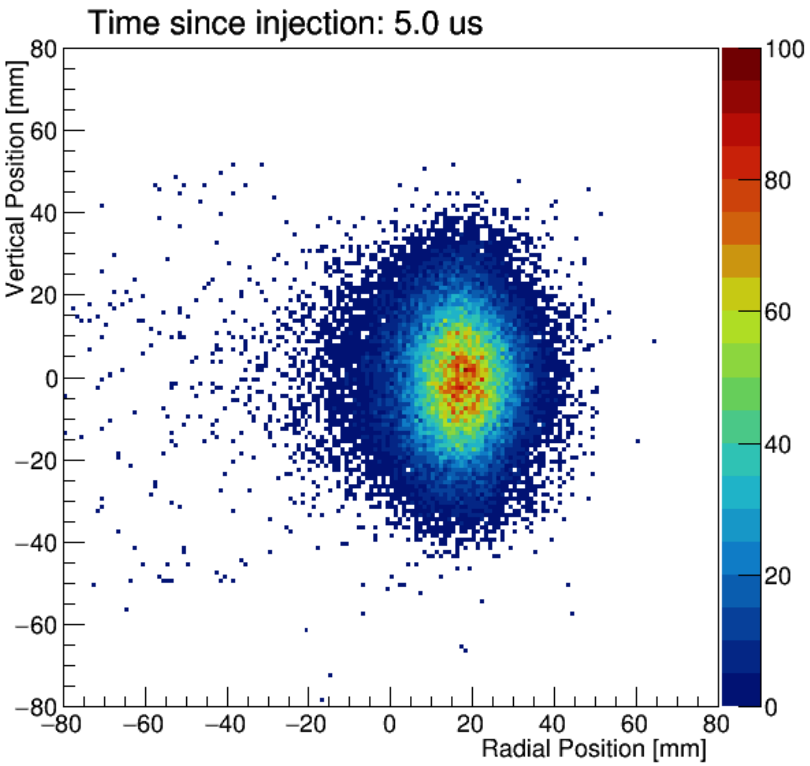
5-Parameter fit

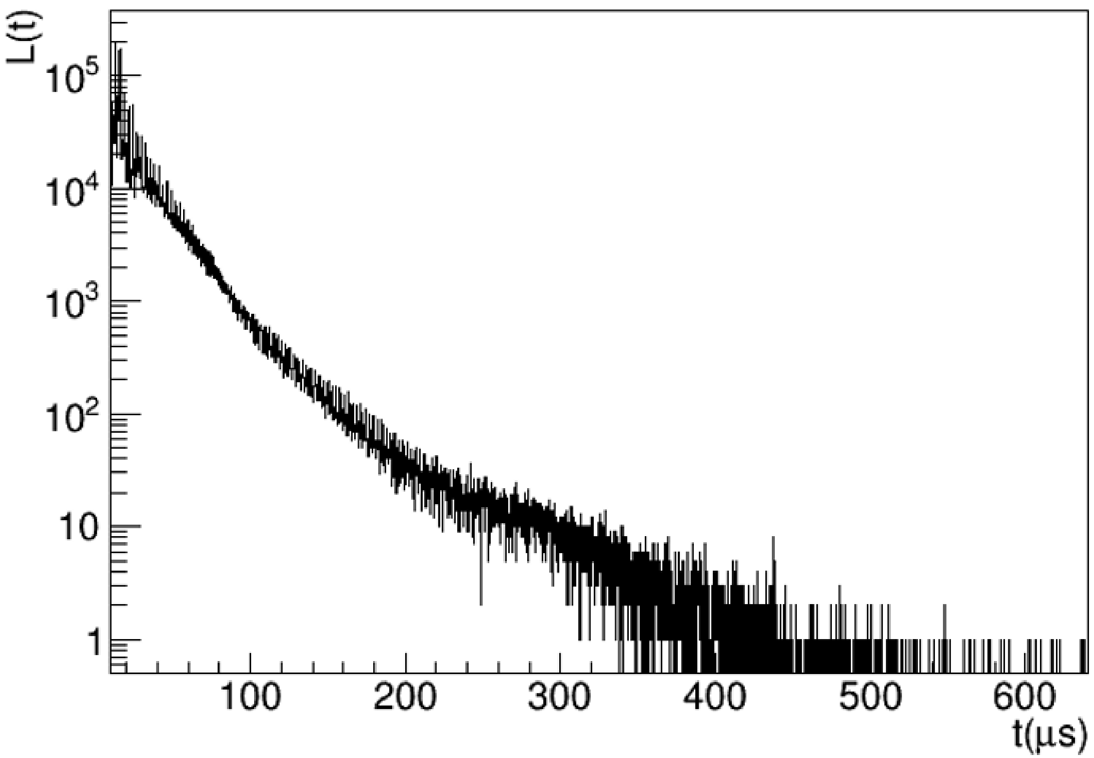




$$N(t) = N_0 e^{-\frac{t}{\tau_\mu}}[1 + A\cos(\omega_a t + \phi)]$$

Beam dynamics effects

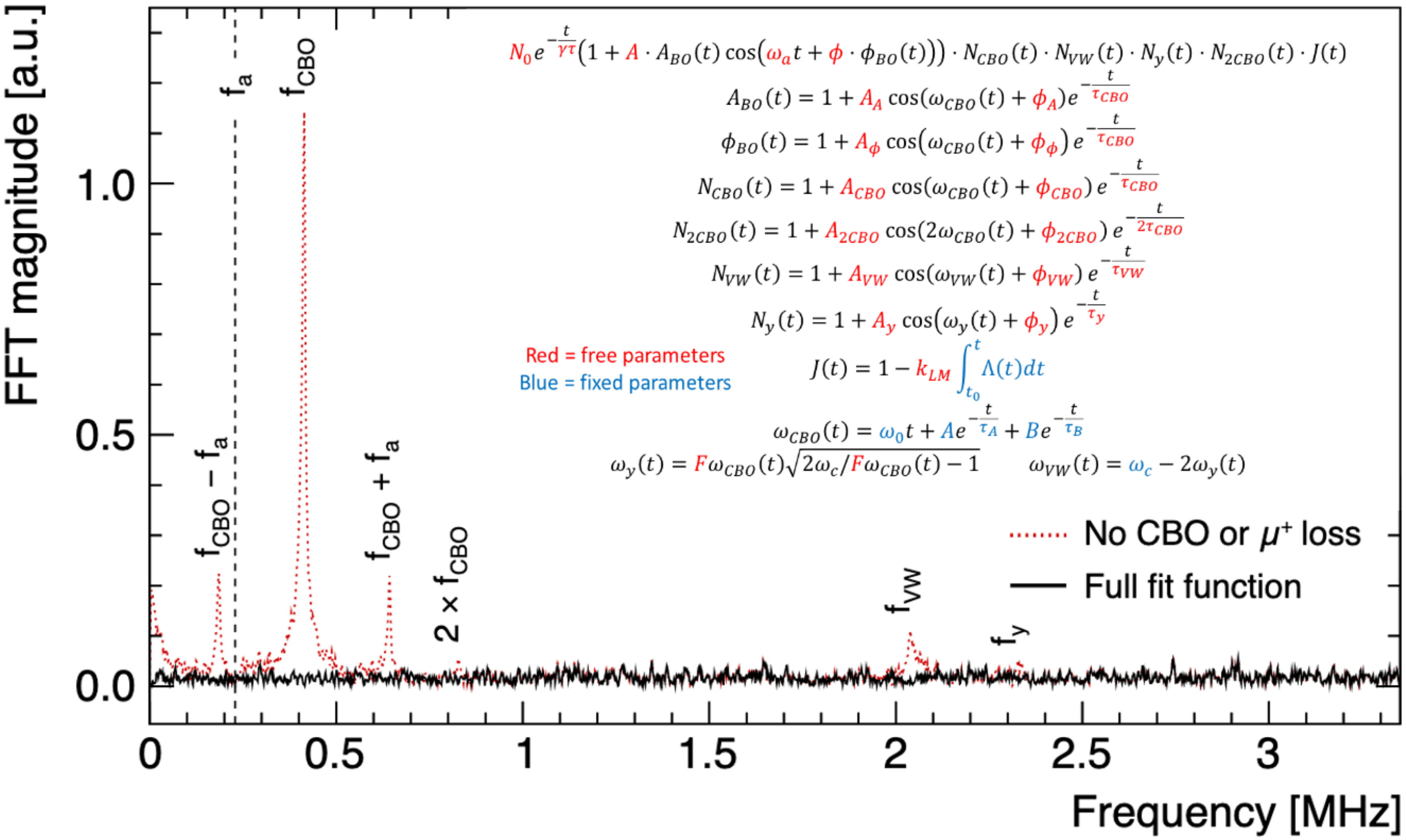




CBO: Coherent beam oscillations with $T \approx 2.7\mu s$

Lost muons: drift out of storage ring and hit consecutive calos

Full fit (22-par) and FFT



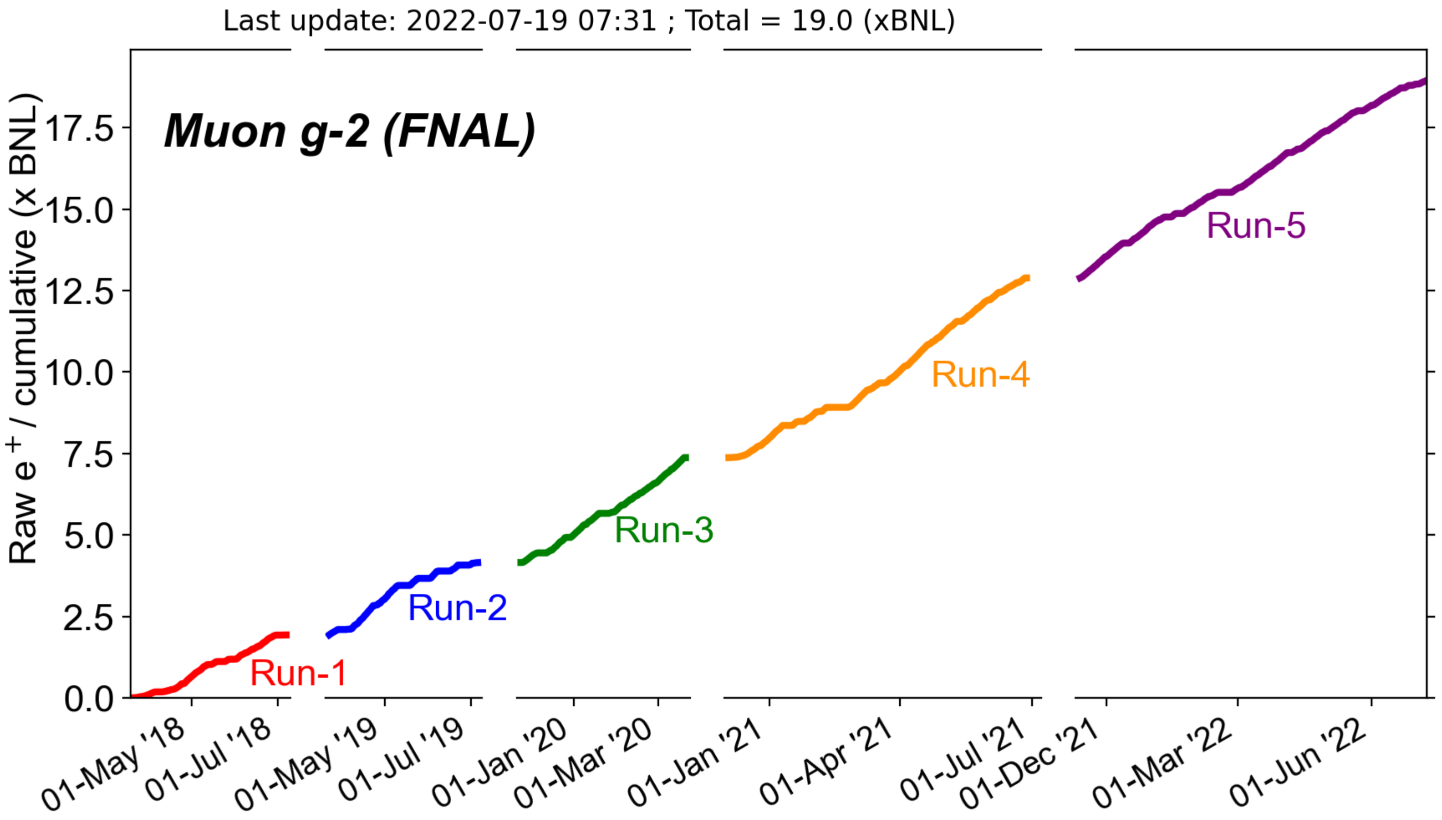
Different methods: T and A

- **T Method**: we count positrons over energy threshold, set to 1700 MeV to minimize statistical uncertainty on ω_a
- **A Method**: weight positrons with asymmetry function:
  - Allows to lower energy threshold to 1100 MeV
  - Reduces statistical uncertainty on ω_a by $\sim$10%
  - Run-1 result was the combination of 4 A-Weighted analyses

Main systematics and improvements

Run-1 main ω_a systematics

	Value [ppb]
Uncertainty (stat.)	434
Uncertainty (syst.)	56
Detailed Systematics	
Time Randomization	9
Time Correction	1
Gain	8
Pileup	35
Pileup Artificial Dead Time	3
Muon Loss	3
CBO (beam oscillations)	38
Residual Slow Term	17



After Run1 (published in April 2021) we collected more statistics and worked on hardware and analysis improvements to reduce largest systematics (in red boxes)

Ratio method histograms

Gets rid of «slow effects» such as muon decay lifetime: different sensitivity to ω_a systematics

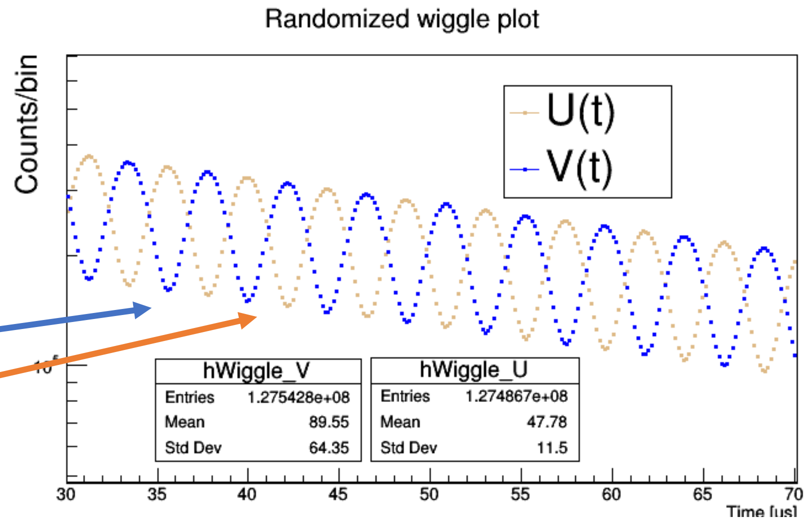
Positrons splitted in two histos:

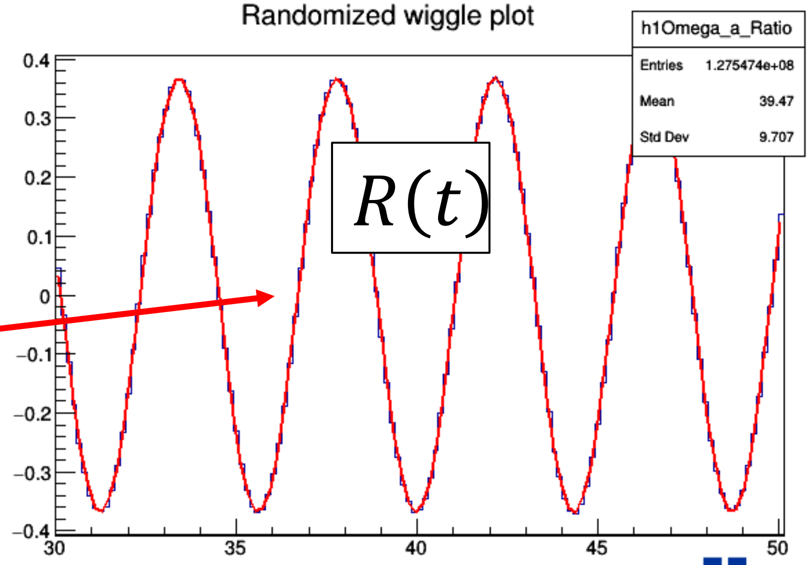
- $V(t) \equiv v_1(t) + v_2(t)$
- $U(t) \equiv u_+(t) + u_-(t)$

Where v_1, v_2, u_+, u_- get 25% of positrons each

$u_\pm$ shift positron times by $\pm\frac{T_a}{2}$ (half of ω_a period)

Ratio: $R(t) \equiv \frac{V(t)-U(t)}{V(t)+U(t)}$





Summary and conclusion

- The anomalous precession frequency ω_a is one of the two ingredients to obtain the muon magnetic anomaly a_μ (see Paolo's presentation):

$$a_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

- Parity violation in muon decay allows us to extract ω_a from fits to «wiggle plots» i.e. counting positrons vs time
- Run1 results (April 2021) will be improved with higher statistics, hardware upgrades and combined effort in data analysis
- More details on beam dynamics and magnetic field in next presentations by Elia and Anna ☺