Pion lifetime measurement with g-2 storage ring?

Tim Gorringe, Univ. of Kentucky, 25 May 2021

Charged pion lifetime measurements

Status (PDG)

$\tau_{\pi+}$ = 26.033 ± 0.005 ns [192 ppm] (using stopped π+)

$(\tau_{\pi+} - \tau_{\pi-}) / \tau_{av}$ = (5.5 ± 7.1) x 10^{-4} (using inflight $\pi^{\pm}$)

$\tau_{\mu+}$ = 2.1969811 ± 0.0000022 μs [1.0 ppm] (using stopped μ+)

$(\tau_{\mu+} - \tau_{\mu-}) / \tau_{av}$ = (2 ± 8) × 10^{-5} (discuss inflight $\mu^{\pm}$)*

Interest?

charged pion lifetimes determine pion decay constant f_π, offer CPT test, and needed for R(π→eν / π→μν) universality test (precision measurement of π^o lifetime was recently made at JLab)

as lightest hardron and approximate Goldstone boson the pion's important roles in sub-atomic physics and basic properties (mass, lifetime) are enduring, textbook quantities.

* for stopped lifetime measurements are not feasible for π- but possible for μ- after correcting for μ- capture

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~10^{-2} level

COMPARISON OF PION AND ANTIPION LIFETIMES*

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Columbia University, New York, New York

(Received 23 March 1966)

muon counting

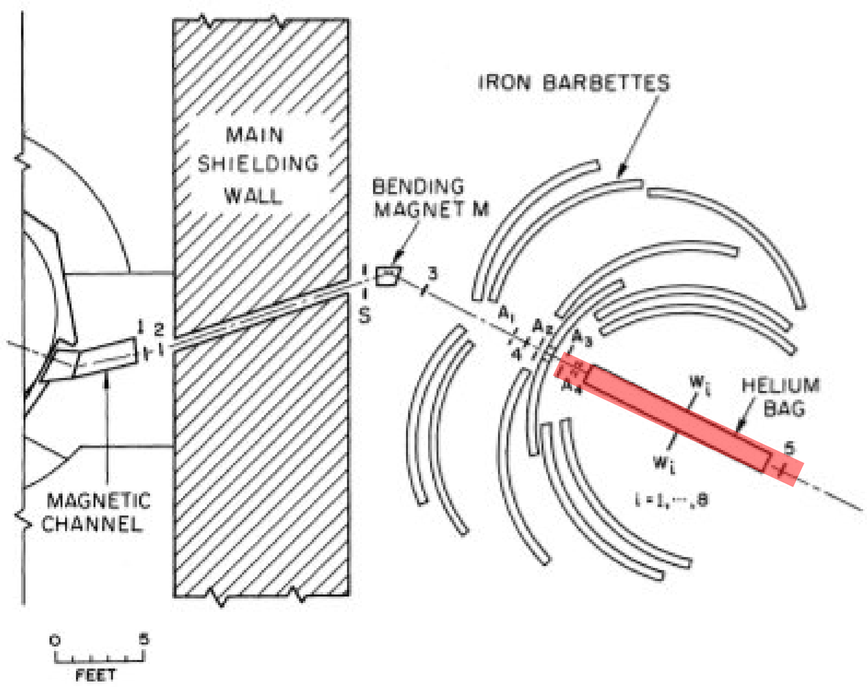

FIG. 1. Layout of the experimental apparatus.

measurement of $\pi \rightarrow \mu \nu$ in-flight decays from 120 MeV/c pion beam in he-filled, 2.0 m length decay region

time-of-flight counters define pion momentum and provide π, μ, e

aperture and veto counters define decay region

muons detected by annular array surrounding decay region

$$(\tau_{\pi+} - \tau_{\pi+}) / \tau_{av} = (4 \pm 7) \times 10^{-3}$$

THIRD SERIES, VOL. 3, NO. 5 1 MARCH 1971

~10^{-3} level

Measurements of the Lifetimes of Positive and Negative Pions*

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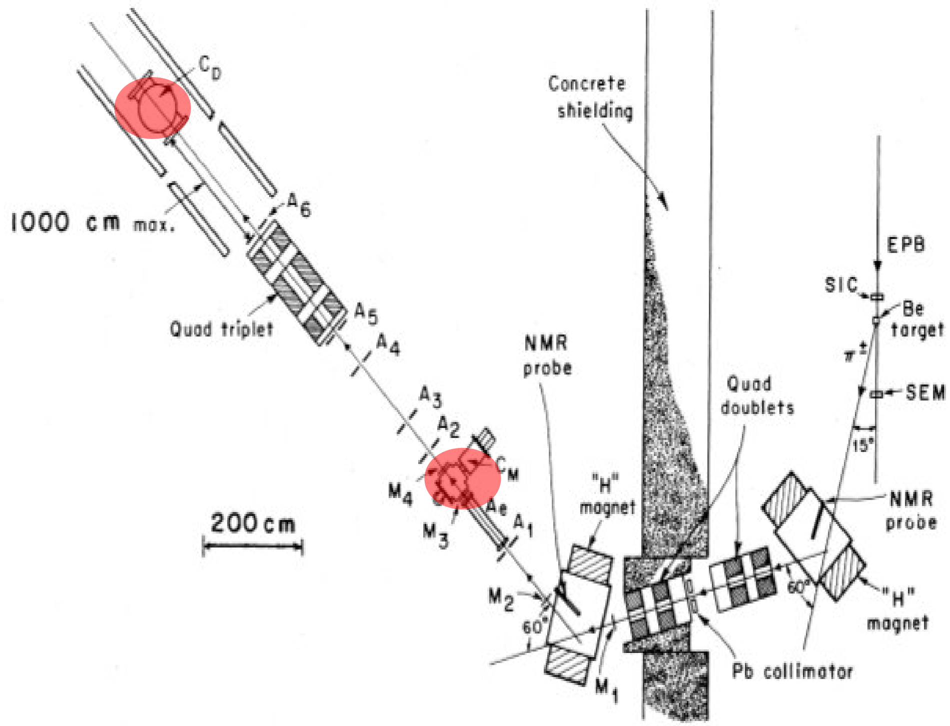


FIG. 1. Beam layout. EPB: 732-MeV external proton beam of the 184-in. cyclotron. SIC: split ion chamber. SEM: secondary-emission monitor. NMR probes: nuclear-magnetic-resonance probes. M_1–M_4: 0.18-cm-thick scintillation counters. A_1–A_6: scintillation anti-coincidence counters. A_e: electron veto counter. C_M and C_D: focusing Čerenkov counters.

pion counting

measuring the π survival fraction along 1000-cm (one-half lifetime) path

survival measured by one fixed & one movable differential Cerenkov counter that only see pions

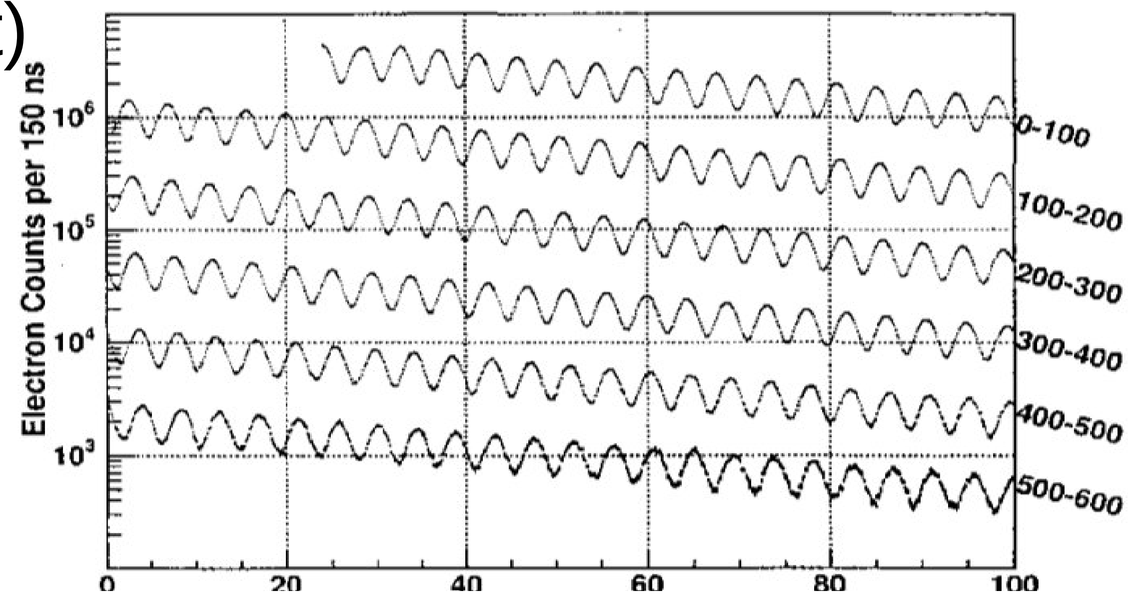
aperture and veto counters define decay region

$$(\tau_{\pi+} - \tau_{\pi-}) / \tau_{av} = (5.5 \pm 7.1) \times 10^{-4}$$

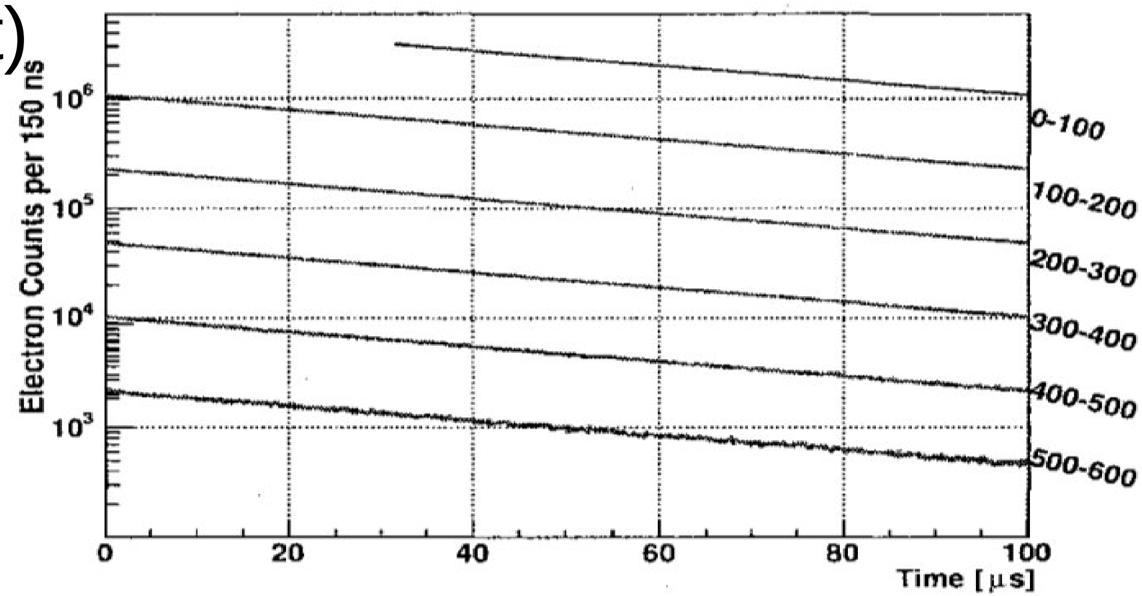
Muon lifetime measurement with g-2 storage ring

Tao Qian, Dissertation, Univ. of Minnesota, 2006

N(t)



n(t)



Disentangling ω_a, τ_μ

randomly divide data into 4 datasets $n^+(t)$, $n^-(t)$, $n^0(t)$, $n^0(t)$

two time-shifted $\pm\tau_a/2$, two not time-shifted

$n^+(t) = N(t+T_a/2)$

$n^-(t) = N(t+T_a/2)$

$n^0(t) = N(t)$

$n^0(t) = N(t)$

$n(t) = n^0 + n^0 + n^+ + n^-$, isolates τ_μ

$n'(t) = n^0 + n^0 - n^+ - n^-$, isolates ω_a

no wiggle in $\pi^\pm$ lifetime

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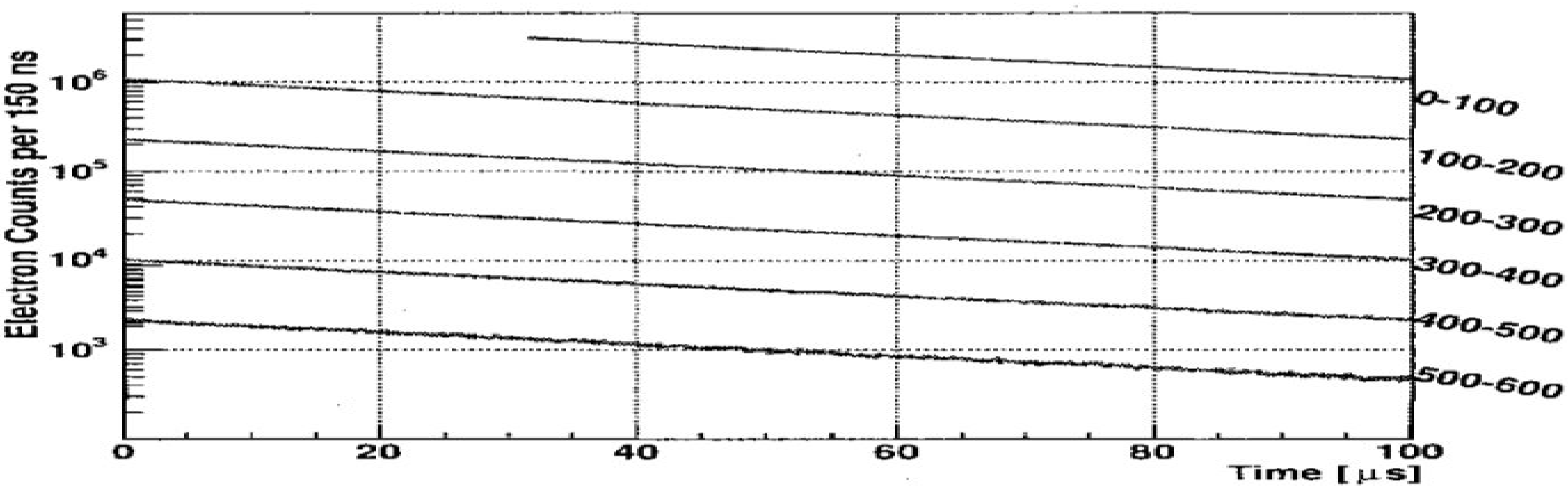
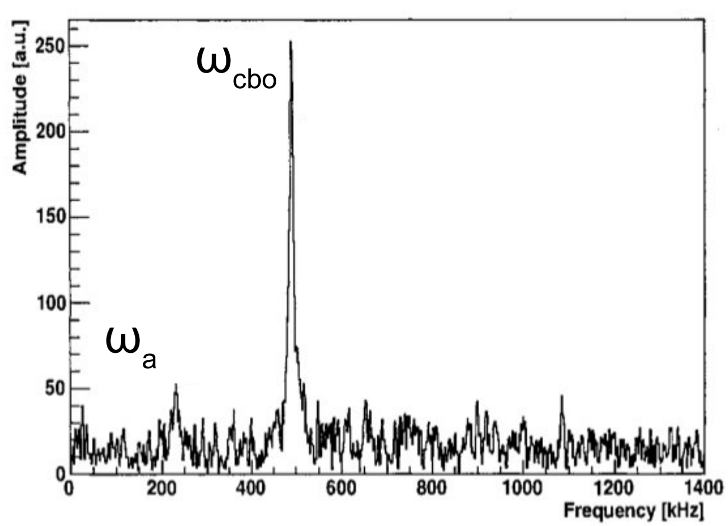
n(t)





Simple fit to $e^{-t/\tau}$ shows

fit residuals show beam oscillation A_{cbo}, τ_{cbo}, ω_{cbo}, φ_{cbo} with period T_{cbo} ~ 2.5 μs

more problematic for 0.6 μs pion time-dilated lifetime than 64 μs muon time-dilated lifetime

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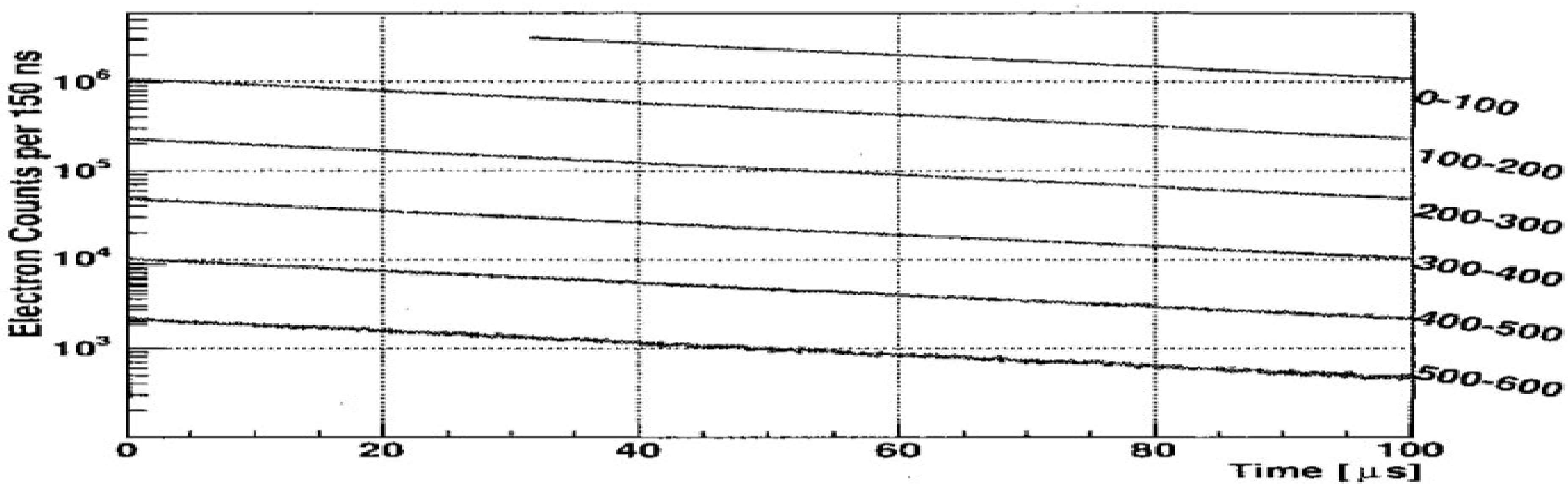
n(t)



full fit function

$$n(t)=N_o e^{-t/\gamma\tau}\left[1+\frac{1}{16}\left(\frac{T_a}{\gamma\tau}\right)^2\left(1+A\cos(\omega_a t+\phi)\right)+A_{cbo}e^{-t/\tau_{cbo}}\cos(\omega_{cbo}t+\phi_{cbo})+k_{loss}L(t)\right]$$

time-dilated lifetime

residual fixed-T_a contribution

beam dynamics A_{cbo}, τ_{cbo}, ω_{cbo}, φ_{cbo}

beam losses k_{loss}

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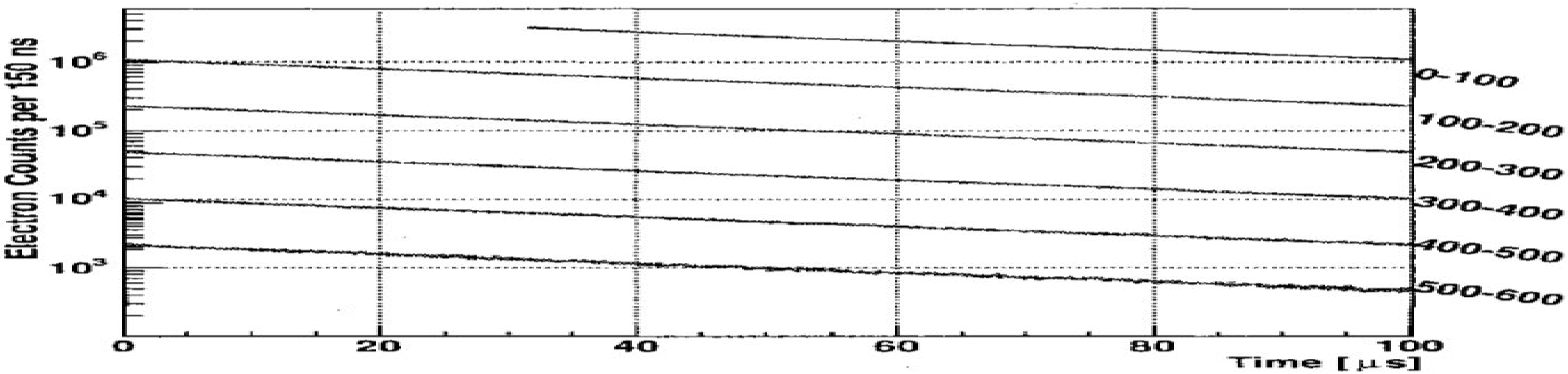
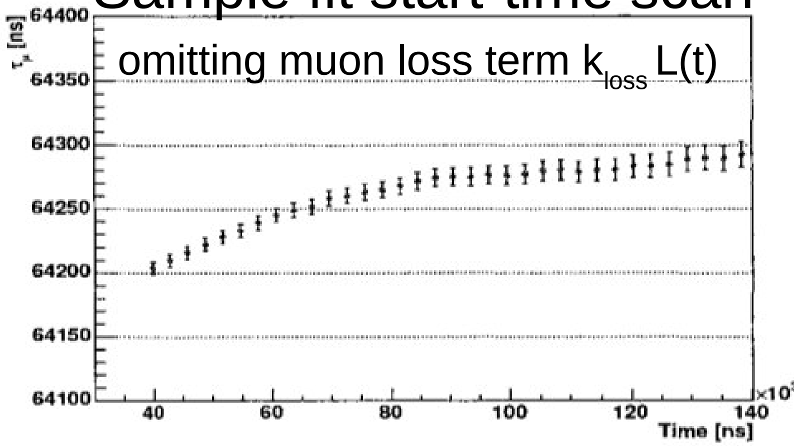
n(t)



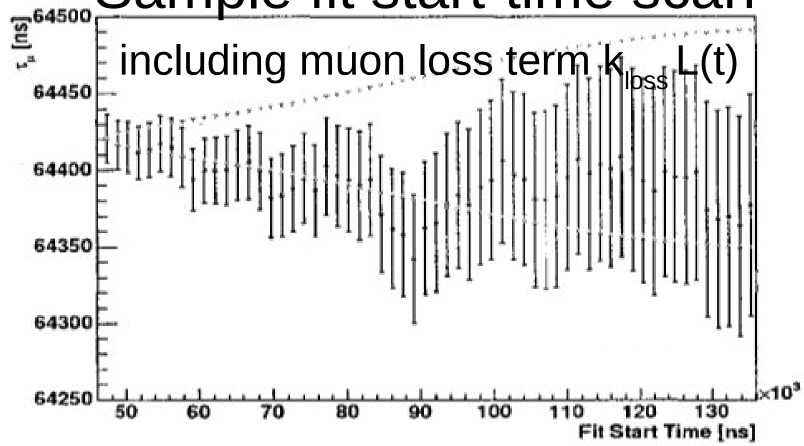
Sample fit start-time scan

omitting muon loss term $k_{loss} L(t)$



Sample fit start-time scan

including muon loss term $k_{loss} L(t)$



long-time constant beam loss term would couple less to 0.6 μs pion time-dilated lifetime than 64 μs muon time-dilated lifetime

pileup, gain changes would be larger for the 0.6 μs pion lifetime than 64 μs muon lifetime

Muon lifetime measurement with g-2 storage ring

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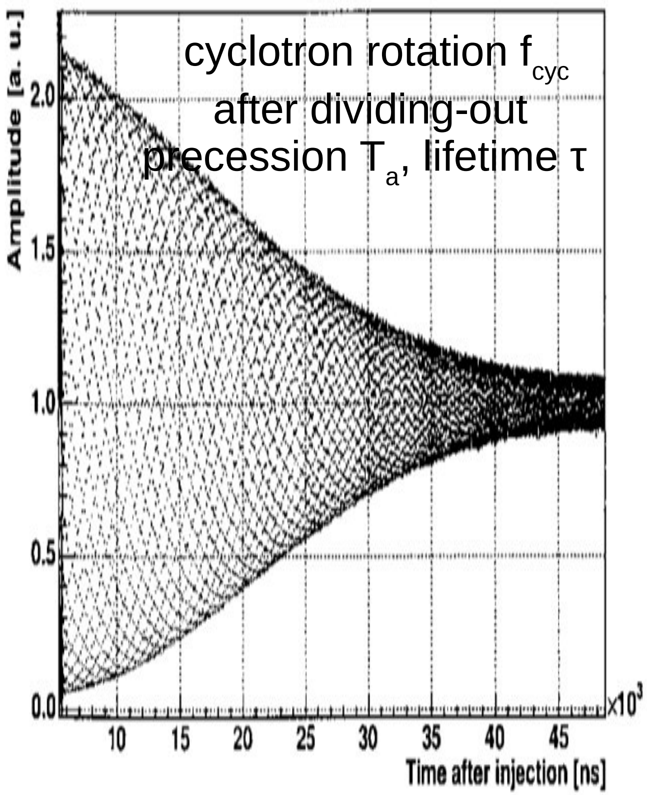
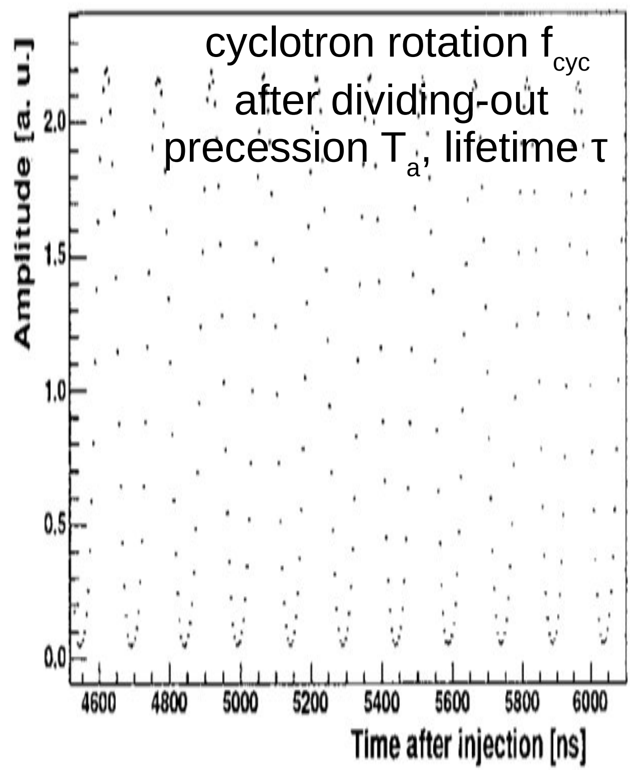
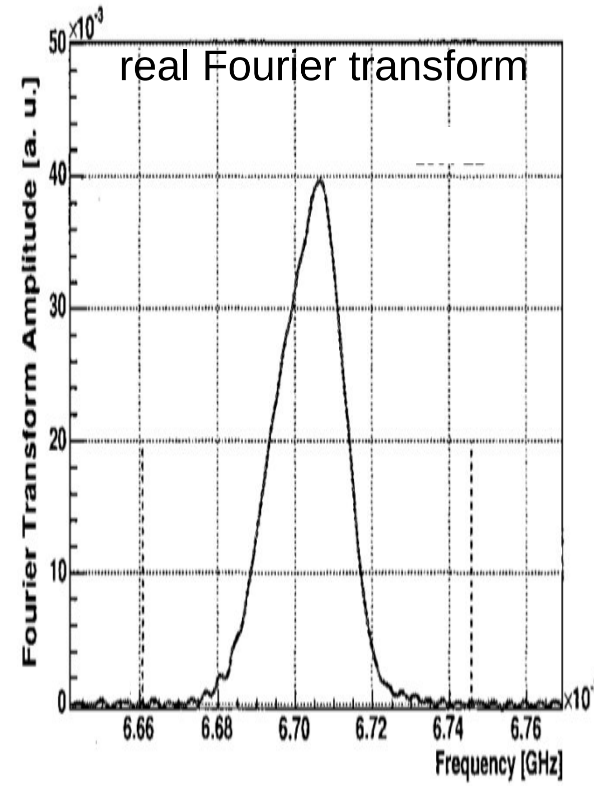
the mean Lorentz factor $\bar{\gamma}$ is obtained from cyclotron rotation analysis

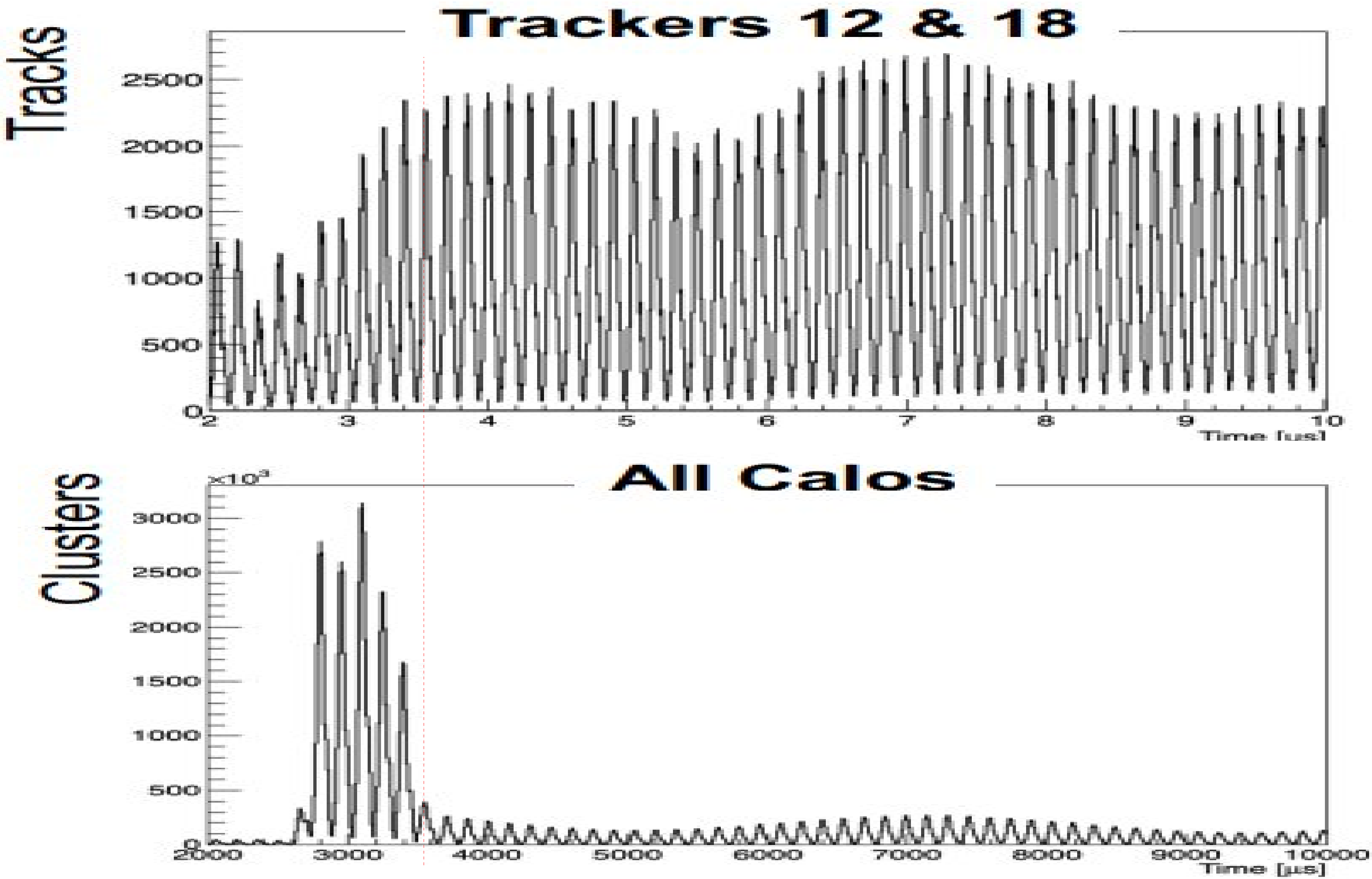






extraction of mean Lorentz factor $\bar{\gamma}$ more difficult for 0.6 μs pion lifetime than 64 μs muon lifetime

Problem of flash (FNAL data)



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$\tau_{\mu+}$ = 2.197.30 +/- 0.20 (89 ppm)

$\tau_{\mu-}$ = 2.197.66 +/- 0.15 (69 ppm)

$(\tau_{\mu+} - \tau_{\mu-}) / \tau_{av} = (16 \pm 12) \times 10^{-5}$

Year	Data	τ_μ [ns]	$\sigma_{stat}(\tau_\mu)$ [ppm]	$\bar{\gamma}$	τ_0 [ns]
2000 μ^+	P1	64 420.92	246	29.315 47	2 197.505
	P2	64 413.77	116	29.312 13	2 197.512
	P3	64 396.61	128	29.314 91	2 196.718
	P4	64 406.71	47	29.313 78	2 197.147
	P5	64 412.94	70	29.308 89	2 197.726
2001 μ^-	LB	64 415.32	70	29.312 91	2 197.507
	LA	64 420.20	125	29.313 44	2 197.633
	HB	64 426.47	66	29.313 92	2 197.811
	HA	64 421.08	209	29.312 77	2 197.713

Source of Uncertainty	2000 Data Set [ns]	2001 Data Set [ns]
Muon losses	4.25	3.16
Gain stability	2.87	0.89
Pileup subtraction	0.76	0.49
Coherent betatron oscillations	0.80	0.15
Total Uncertainty	5.2	3.3

Pion lifetime versus muon lifetime with ring?

pion lifetime 26.0 ns, time-dilated lifetime 0.577 μs (3.094 GeV/c, $\gamma = 22.2$)

x10 improvement in pion lifetime difference requires ~4×10^8 pion decays

$\pi \rightarrow \mu\nu$ signal is muon MIP in calorimeters, muon trajectories in trackers

systematics from flash, CBO, pileup, gain , pileup mean $\bar{\gamma}$ look challenging

Conclusion - further study worthwhile?

- practical? ease / difficulty of storing pions by 0, 1 recycler turns?
- stored pions / muons per fill? x23 (0 recycler turns), 0.64 (1 recycler turn)
- detected pions / muons? MIPS in calo’s? tracks in trackers?
- fit start-time cost $e^{-t_0/\tau}$? 1.0 μs → 0.2, 2.0 μs → 0.03, 3.0 μs → 0.006, ...
- systematics pros? ~~ω_a~~, losses
- systematics cons? flash ω_c, ω_{cbo}, pileup, gain