University of Zurich[UZH]

Pion and muon lifetimes

Data analysis 2025 – Group project IV

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1 Motivation

In this project you perform a simplified simulation of an experiment for measuring the lifetimes of charged pions and muons. The experiment is one that you will actually carry out yourselves at a PSI beam line if you sign up for the lecture "Particle Physics II" (KT2).

Negatively charged pions (π^-) are composite particles that consist of a down quark and an up antiquark. They are unstable and decay predominantly to a muon (μ^-) and a muon-antineutrino ($\overline{\nu}_\mu$). The muon, a heavier partner of the electron, is also unstable and decays into an electron (e^-), a muon-neutrino (ν_μ) and an electron antineutrino ($\overline{\nu}_e$). Neglecting any experimental effects, the time distribution of the e^- produced in the decay chain is given by

$$N(t) \; = \; \frac{N_0}{\tau_\mu - \tau_\pi} \cdot \left[\exp\left(-\frac{t}{\tau_\mu}\right) - \exp\left(-\frac{t}{\tau_\pi}\right) \right] \tag{1}$$

where τ_π and τ_μ are the mean lifetimes of the π^- and the μ^-, respectively. A measurement of this time distribution allows to extract estimates for τ_π and τ_μ.

An important cross check in simulation studies is the so-called "pull", defined as

$$\text{pull} = \frac{\text{reconstructed quantity} - \text{generated quantity}}{\text{uncertainty on reconstructed quantity}} \, ,$$

where the "uncertainty on reconstructed quantity" is for example that returned from your fit to the data. If the reconstruction is unbiased and the uncertainties on the reconstructed quantities is estimated correctly, the distribution of the pulls over many simulated experiments should follow a Gaussian distribution with $\mu = 0$ and $\sigma = 1$. If μ deviates significantly from zero, the measurement is biased. If σ deviates significantly from one, the uncertainties are not estimated correctly.

2 Setup

The basic elements of the experiment are illustrated in Fig. 1: we stop π^- in a first scintillator (Scintillator 3 in the sketch) and detect the emitted e^- in a second scintillator (Scintillator 5). The signal measured in the first scintillator starts a clock and the signal measured in the second

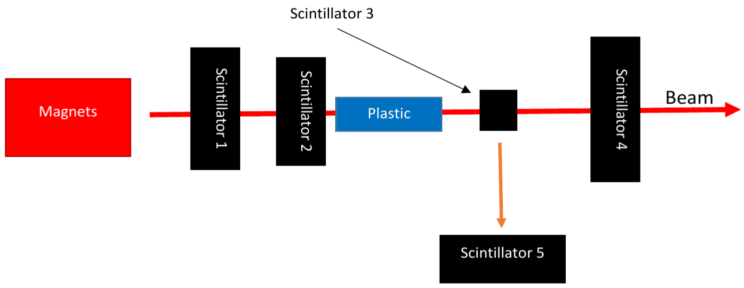

Figure 1: Simplified sketch of the setup of the experiment at PSI (stolen from the lab report prepared by your colleagues who did the lab in summer 2017). A beam containing π^- passes through Scintillators 1 and 2 and a piece of plastic to slow them down such that they stop in Scintillator 3. Scintillator 4 is a veto counter to reject events in which the beam particle was not stopped in Scintillator 3. Electrons created in the decay chain are detected in Scintillator 5. The signal from Scintillator 3 starts a clock, the signal from Scintillator 5 stops it.

scintillator stops it, i.e. we measure the time difference between the time at which the π^- is stopped and the time at which the e^- is emitted. We accumulate a time spectrum from many such events and determine estimates for τ_π and τ_μ from a fit to this spectrum.

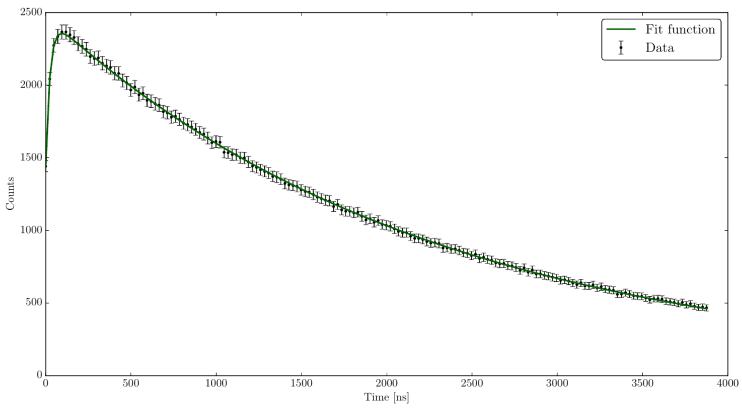

Figure 2: Decay-time spectrum measured during the KT2 lab at PSI in summer 2016.

For illustration, Fig. 2 shows a decay-time spectrum measured by your colleagues in summer 2016.

3 Simple simulation

Generate a decay-time spectrum according to Eqn. 1 and using the known values of τ_π and τ_μ, which you can find in the web page of the Particle Data Group (`pdg.lbl.gov`). Neglect any possible experimental effects in your simulation.

(a) Generate 10'000 simulated decay times and produce a histogram of these (choose an appropriate range and binning for your histogram).

(b) Perform a binned maximum likelihood fit to the histogram to extract estimates $\hat{\tau}_\pi$ and $\hat{\tau}_\mu$ for the two mean lifetimes, as well as uncertainties on your two estimates. Compare the results with the values that you put into the simulation.

Now simulate many measurements to check that the uncertainties returned by your fit make sense:

(c) Repeat the simulation 100 times and produce histograms with the 100 values of $\hat{\tau}_\pi$ and $\hat{\tau}_\mu$ that you obtain. Determine the standard deviations of the two distributions.

(d) Produce histograms of the pull distributions for $\hat{\tau}_\pi$ and $\hat{\tau}_\mu$. Determine the means and standard deviations of the two pull distributions.

4 Make the simulation a bit more realistic

Include the finite time resolution of the apparatus in the simulation and observe how this affects the results of your fit.

(a) Generate one set of 10'000 simulated decay times according to Eqn. 1. "Smear" each decay time with a random offset drawn from a Gaussian distribution with mean $\mu = 0$ and standard deviation σ_t. Do this for $\sigma_t = 1/100, 1/10, 1 \times \tau_\pi$.

(b) Fit your three "smeared" time spectra with the original function from Sec. 3. Judge the quality of the fit and the results you obtain for the fit parameters.

(c) Voluntary: modify your fit function to include a Gaussian term for the finite time resolution and repeat the fits.