Project 3: Resonance scan

Myroslav Kavatsyuk, ESRIG

October 3, 2022

1 Context

Quarks are the most elementary building elements of hadronic matter, such as protons and neutrons. The strong interaction between quarks is spectacular. At very short distance scales they behave as nearly free particles with small masses, whereas at larger distance scales, towards the size of a nucleon, the coupling increases drastically leading to effectively heavier objects. Hadrons which contain charm quarks are ideal objects to provide a better understanding of the mechanism behind the generation of the mass of hadrons and the confinement of quarks. The KVI-CART is involved in various international experiments which aim to perform precision measurements of the properties of "charmed" objects. Of particular interest are spectroscopy measurements of Charmonium states, pairs of charm and anti-charm quarks. For this, we work on plans for a future experiment at Darmstadt (Germany), PANDA (see figure 1), exploiting the annihilation of protons and antiprotons to study charmed objects [`http://panda.gsi.de`]. One of the unique features of the PANDA experiment is ability of precise measurement of a "width" of a particle – one of the measurable properties of a particle which is very sensitive to its internal structure. It is of particular interest to measure width of so-called Charmonium-like X-states – particles which have some properties of Charmonium states but a part of properties are completely unexpected. Understanding of a structure of such particles might reveal the mass-generation mechanism of hadrons.

In this project you will be given two spectra, generated by a Monte Carlo simulations (complete computer model of the PANDA detector with implemented particle generation, propagation and detection mechanisms). The spectra correspond to the width measurement for X(3772) state assuming two different width of the state. The aim of the project is to determine width of the X(3772) state from the given data. Some problems in this project are not directly related to the X(3772) and are focused more on statistics.

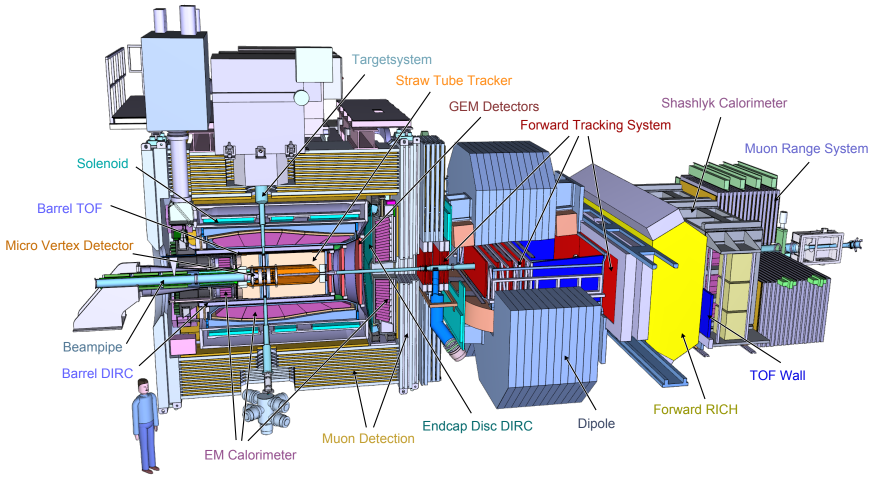

Figure 1: Schematic layout of the PANDA detector.

2 Life-time of particles

For this section let's assume that we have a radioactive source with rather short-lived radionuclide (life-time in order of minutes). If we would measure intensity of decays we would observe exponential behaviour of the decays as a function of time. In case we have a mixed source with **two** radionuclide with two different life-times, the measured intensity of decays as a function of time will have a shape of a sum of two exponents. Aim of this problem is to extract life-time of radioactive isotopes from the measured intensity of decays:

- generate two samples of the same size of a random data distributed according exponential distributions with parameters $\lambda_1 = 10$, $\lambda_2 = 50$, respectively;
- mix both data samples;
- using Method of Moments estimator determine both parameters λ from obtained data;
- create four histograms with the same range $[0, 1]$ and number of bins equal to 5, 10, 50 and 100;
- determine both parameters λ from the generated histograms using Least Square Estimator method (fitting):
  - for each non-linear fit use $(1, 1)$ or $(10, 50)$ as starting parameters;
  - perform fit which does not take into account statistical uncertainties;
  - perform fit which takes into account statistical uncertainties;

  - perform fit with a fitting function which integrates probability density function over each bin;

- apply method of Maximum likelihood to extract both parameters λ from histograms:
  - use integration to determine probabilities from PDF for each bin in case of broad bins;
  - plot likelihood function close to obtained maxima.

Plot all results and provide discussion of the outcomes.How two different methods compare? How do different methods behave? What is the influence of starting parameters?

3 Fitting & Interpretation

One of the advantages of the PANDA experiment is so-called "cooled" antiproton beam. This means that energy spread of individual antiprotons in the beam bundle has very low spread, in order of 10^{-5}. Therefore, it is possible to measure production cross-section (or just number of produced particles within fixed time) for well-defined energy of the beam. By changing the beam energy in small steps one can observe how the production cross-section behaves. Typically, one obtains a resonance structure. The probability density function (pdf) of the resonance is a convolution of a pdf for the beam-energy and the pdf of the resonance. For the pdf of a beam-energy one can take Gaussian distribution with a width of about 50 keV (for the PANDA experiment). PDF of the resonance is Lorentzian distribution. Width of this distribution corresponds to the "width" of the state. In figure 2 two simulated data-sets are shown. Simulations were performed assuming two different intrinsic widths of X(3772). On Nestor you will find files with these scans. Please determine width for both data-sets:

- fit data with a combination of a smooth background together with a signal in the form of a Voigtian (convolution of a Gaussian and Lorentzian);
- fit data with a combination of a smooth background together with a signal in the form of a Gaussian (convolution of two Gaussian corresponding to the resonance and beam-energy);
- fit data with a signal in the form of a Voigtian (convolution of a Gaussian and Lorentzian);
- conclude, based on a Pearson test, which fit is significant and report obtained width of the X(3772) state for both data sets.

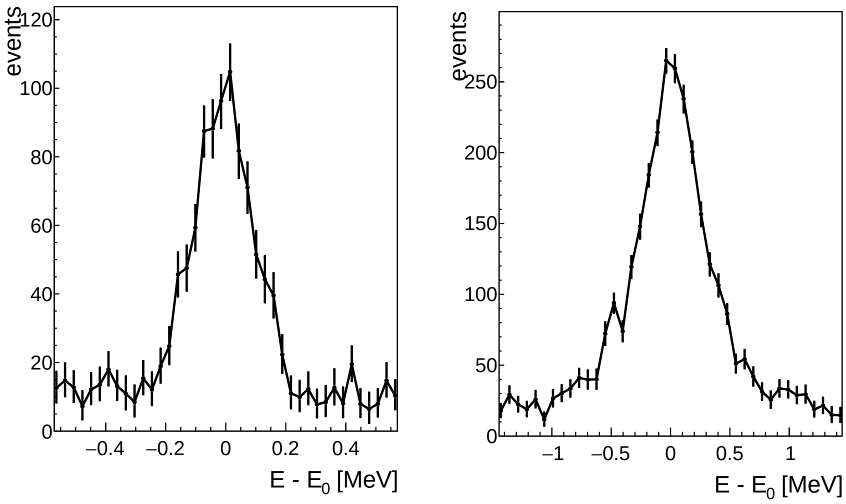

Figure 2: Simulated data for the energy scan of X(3772) state assuming different intrinsic width of the state, Γ_1 – left panel and Γ_2 – right panel.