Searching for $D^0 \to K^- \pi^+ \eta^0$ in Belle Data

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Abstract

We describe the reconstruction of the CP- decay mode $D^0 \to K^- \pi^+ \eta^0$in the Belle I data set. Using a set of simulated signal and a generic simulated sample equal in size to the Belle I data set, we reconstructed 826 events from an initial sample of 18,900 simulated events for an efficiency of 4.4%. We studied backgrounds in the generic simulated sample, and checked in the real data. We found, in agreement with the simulations, no obvious signal in the Belle I data indicating that further work has to go into supressing the background.

Contents

1 Introduction

The Standard Model (SM) is a theory that explains the laws of the sub-atomic world of particle physics. The SM encompasses the theory of the electromagnetic, the weak, and the strong nuclear interactions. Unfortunately, SM does not predict a series of observed decays in particle physics; along with gravity, neutrino oscillation, and matter and anti-matter asymmetry. The SM nature of quark-mixing and CP violation is represented by Cabibbo-Kobayashi-Maskawa, otherwise known as CKM matrix. The CKM matrix is a 3×3 unitary matrix, which can be parameterized by three mixing angles and a CP violating phase [1], [2]. As seen below, the matrix operates on the mass eigenstate in order to get the weak eigenstate form

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}. \tag{1}$$

Each of these values can ideally be determined from the weak decays of the quarks in question, and at times even from inelastic neutrino scattering [3]. There are several parameterizations that can be used for V, on which the values would vary by a small amount. An example of a commonly used matrix is showed below using the angles $\theta_{12}, \theta_{23}, \theta_{13}$

$$M = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{bmatrix}. \tag{2}$$

with $c_{ij} = \cos(\theta_{ij})$ and $c_{ij} = \sin(\theta_{ij})$ where $i, j = 1, 2, 3$.

Charm decays are governed by the upper left corner of the CKM matrix where the CP-violating phase is highly suppressed. Thus we expect small CP-violating effects in charm decays. Mixing has been established in charm decays by comparing the lifetime of D0's decaying to CP+ and CP neutral modes. We are studying a CP- D0 decay to cross-check the observed mixing signal and to search for CP-violating effects by comparing the CP-, CP-neutral, and CP+ decay lifetimes. The level of CP-violation in charm decays is sensitive to physics beyond the SM.

2 Reconstruction

2.1 Monte Carlo and Data Samples

The measurements performed in this paper are mainly based on Monte Carlo (MC) simulations. MC was a great tool to use since it was an effective way to analyze how the decay would appear before getting to the Belle I data. In generic MC, we can study the background events and can come up with cuts to reduce backgrounds from our desired signal. The four types used were: charged, mixed, charm, and uds. In order to represent the results similar to the real data, the stream used had a luminosity corresponding to 913 fb^{-1}. Additionally, the signal MC ran from a total of 10^6 events in order to reconstruct a signal peak for the decay being studied. Lastly, we performed a quick measurement of the real data to see if any significant peaks appeared in the signal region of D^0.

2.2 Charge Conjugation

The decay that is being selected from the $c\bar{c}$ continuum of D^0 candidates comes from $D^{*\pm} \to D^0\pi^\pm$ which would then decay to $D^0 \to K^-\pi^+\eta^0$. The purpose for this specific form of decay chain is to show that charge conjugation works. But for simplicity we relied on just using $K^-\pi^+\eta^0$ and not the conjugated form ($K^+\pi^-\eta^0$).

2.3 Simplifying the work

For this project, we determined the most efficient way to build our D^0 from Belle I data set was to work backwards. We first reconstructed a neutral η particle, with two charge tracks and a π^0. We then looked for two other charged tracks in order to combine with η^0 and build our exclusive D^0. By colliding $e^+e^- \to c\bar{c}$, we were able to manufacture events that contained solely D^0 meson. The following event shows how the process works

$$e^+e^- \to c\bar{c} \to D^{*\pm}X_{frag},\ D^{*\pm} \to D^0\pi^\pm. \tag{3}$$

This equation would not occur in nature as it stands since there are others particles, such as the ones involved in fragmentation energies, X_{frag}, and D_{tag} modes that one has to consider in order to simulate a real collision. With these events, the charm quark produced from the electron and positron collision would decay to the $D^{*\pm}$, while the other (the anticharm) quark would produce other charm hadrons, which one would designate as D_{tag} modes (tagging modes) [4]. On the other hand, X_{frag} particles would come from the excess energies Belle creates. This is because the data collected is well above the energy level where $D^0 \to K\pi\eta$ decay would form, thus the X_{frag} particles can consist of particles such as kaons, pions, and photons which together make up such excess energies.

2.4 Inclusive Reconstruction

Before the reconstruction of the signal decay of interest, ideally one would have to obtain a fully inclusive sample of D^0. These inclusive D^0 would then be used for normalization procedures and calculations of the branching fractions for the signal D^0 [4]. The inclusively reconstructed D^0 mesons are done by finding the missing mass, M_{D^0}, distribution recoiling against everything else that would come from the decay of $c\bar{c}$ of interest. An example of a recoil mass can be seen below for an equation that looks like this $e^+e^- \to c\bar{c} \to D_{tag}KX_{frag}D_s^*, D_s^* \to D_s\gamma$, is:

$$M_{miss}(D_{tag}KX_{frag}) = \sqrt{p_{miss}(D_{tag}KX_{frag})^2} \tag{4}$$

where p is the missing three momentum.

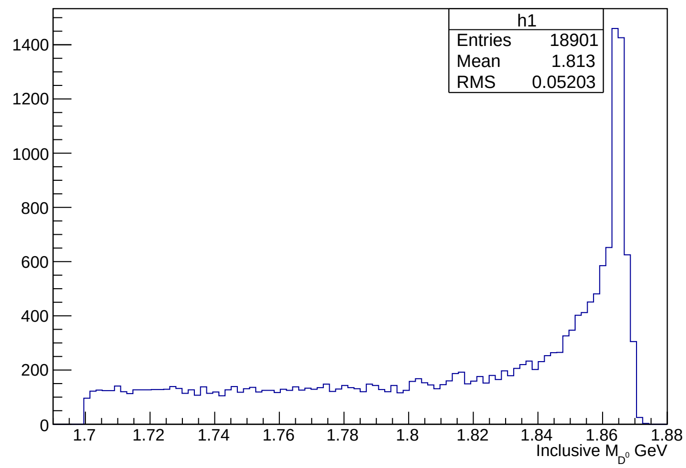

Figure 1: Inclusively reconstructed D^0 from 10^6 total events

By having the correct equation decay from $e^+e^- \rightarrow c\bar{c}$ and the correct momenta, a correctly reconstructed D^0 decaying from $D^{*+} \rightarrow D^0\pi^+$ can be seen in Figure 1 peaking at the correct mass. Enforcing specific requirements, such as having a narrow range for the mass distribution and a center of mass momentum cut, one can eliminate some of the extra backgrounds as well as eliminate the charmed hadrons that can also be produced by the decay of the B neutral meson. Ideally, a more in depth study of our event, $D^{*\pm} \rightarrow D^0\pi^\pm$, would require a large variety of D_{tag} modes of charmed hadrons in order to increase the efficiency of the exclusive D^0 decay [4].

3 Reconstruction of exclusive decay $D^0 \rightarrow K^- + \pi^+ + \eta^0$

3.1 Basic selections

3.2 $\eta^0 \rightarrow \pi^+ + \pi^- + \pi^0$

Since we want to work backwards, the first step was to build a good $\pi^0 \rightarrow \gamma + \gamma$. The π^0 was built by having the criteria shown below:

- The γ having an energy greater than 50 MeV if detected in barrel region of ECL
- The γ having an energy greater than 100 MeV if detected in forward region of ECL
- The γ having an energy greater than 150 MeV if detected in backward region of ECL
- The daughter photons are not used anywhere else in the reconstruction from the decay of $c\bar{c}$
- The invariant mass for π^0 has to be between 117.8 and 150.2 MeV

After having a π^0, two charge tracks were combined with the π^0 to build the invariant mass of η^0 in Signal MC. The tracks had a PID cut, $L_{K/\pi} < 0.9$, in order to make sure they were pions. In the code, we also specified these two charge tracks could not be used for any other purposes. Lastly, we gave the η^0 a range of 10^6 eV and a nominal mass of 547.51 MeV (see Figure 2, 3, 4, and 5).

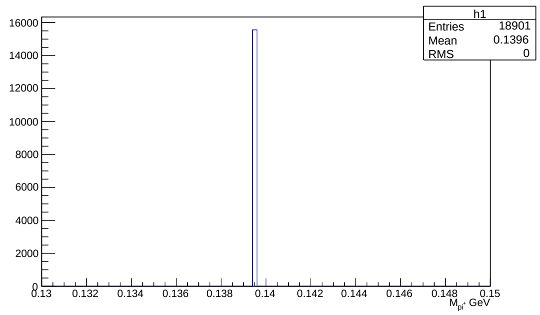

Figure 2: π^+ charge track

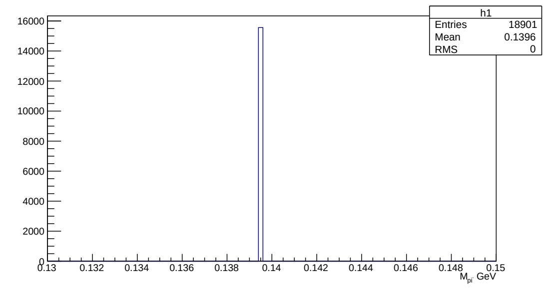

Figure 3: π^- charge track

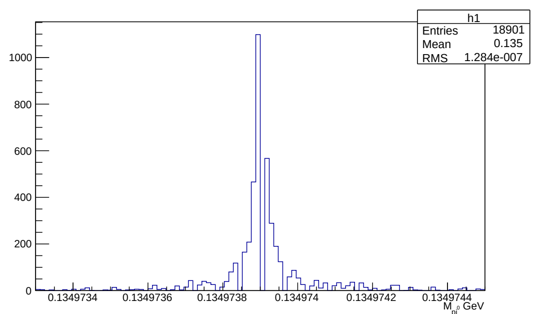

Figure 4: A distribution of π^0 decaying to $\gamma\gamma$ in signal MC

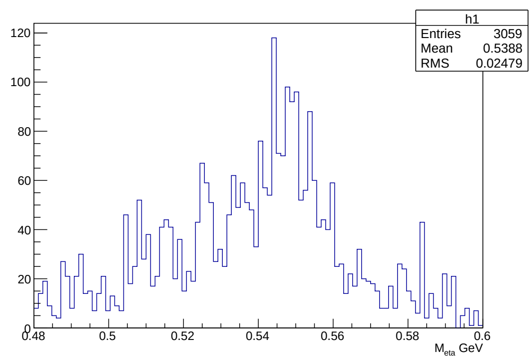

Figure 5: A distribution of η^0 decaying to $\pi\pi\pi^0$ in signal MC

3.3 $D^0 \to K^- + \pi^+ + \eta^0$

For the reconstruction of D^0 meson, all kaons and pions were combined into pairs. If such a pair was found, then we combined them with a neutral eta gave to give a total charge equal to that of the neutral D meson candidate, therefore conserving total charge. The kaon candidates in the D^0 decay were selected by applying a PID likelihood cut of $L_{K/\pi} > 0.6$ (see Figure 6), while the pion candidates were selected with a PID cut of $L_{K/\pi} < 0.9$ (see Figure 7). Both of these selections, "hard cut", are making sure the pions and kaons are correctly reconstructed [5]. Below, one can also see a complete reconstruction of $D^0 \to K\pi\eta$ with the histogram peaking at the correct nominal mass (Figure 8).

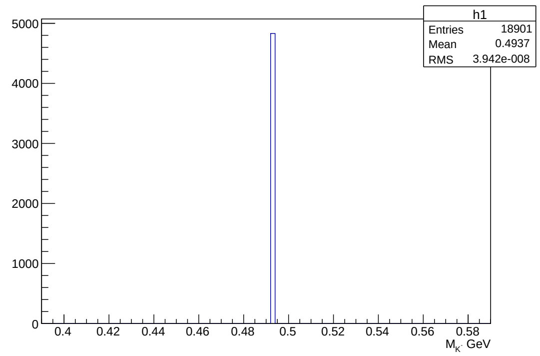

Figure 6: Charge track K^- in signal MC

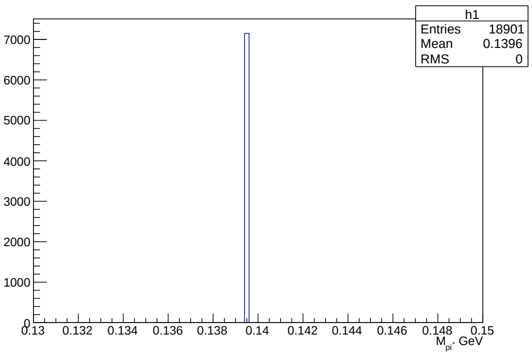

Figure 7: Charge track π^+ in signal MC

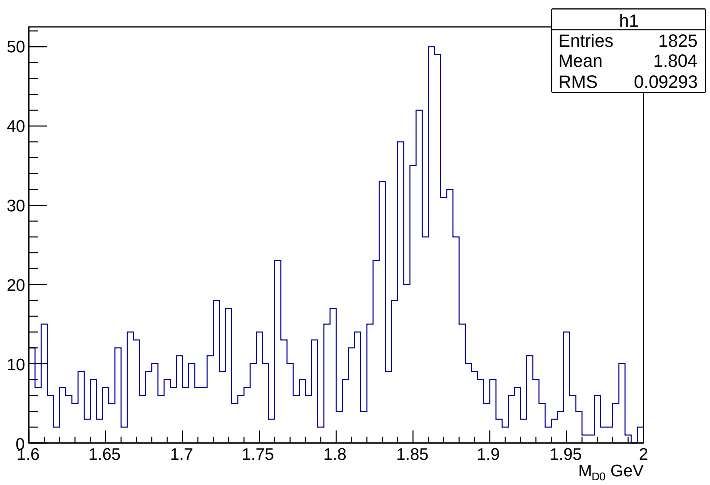

Figure 8: D^0 decaying to $K^-\pi^+\eta^0$ in signal MC

4 Results

The yield for the exclusively built D^0 in MC is determined by fitting the invariant mass distribution M_{D^0}. The fit has both a polynomial and a gaussian (see Figure 9) to describe the invariant mass plot for D^0. Below one can see the total probability density function (PDF) for M_{D^0} $(M(K\pi\eta))$ in signal MC:

$$f_S(M(K\pi\eta)) = f_1 * G(M(K\pi\eta; \mu_1, \sigma_1)) + f_2 * Poly(M(K\pi\eta)), \tag{5}$$

$$Poly(M(K\pi\eta)) = \sum_i a_i(M(K\pi\eta)) \qquad \text{i} = 0, 1, 2$$

$$\mu_1 : width \qquad \sigma_1 : mean$$

Here, in Eq. (5), we have a combination of the PDF from signal MC (f_1) and a PDF reconstructed with 1 stream of generic MC (see Figure 9):

$$f_C(M(K\pi\eta)) = f_1 * G(M(K\pi\eta;\mu_1,\sigma_1)) + f_3 * PolyB(M(K\pi\eta)), \tag{6}$$

$$PolyB(M(K\pi\eta)) = \sum_i b_i(M(K\pi\eta)) \qquad \text{i}= 0,1,2$$

$$\mu_1 : width \qquad \sigma_1 : mean$$

The G stands for the gaussian component of the peak of the invariant mass, with parameters μ and σ on which they describe the shape of the peak. The polynomial function (Poly) is used to describe the rest of the signal that is not part of the actual peak. In this case a 2nd degree polynomial was sufficient to give a good fit of the invariant mass of D^0. Using this fit of the signal MC, we were then able to apply to the results of the Belle I data set (see Eq. (6)). With the data fit (see Figure 10), we used the same gaussian fit ($f_1(G(M(K\pi\eta;\mu_1,\sigma_1))$, with a fixed width and mean found from the signal MC fit, along with a background function on which we parameterized using a 2nd order polynomial (f_3). The PDFs describe well enough the invariant mass distribution for the signal and the generic MC, with a normalized χ^2 value of about 3.67 and 4.90, respectively. The total number of reconstructed signal decays is:

$$N_s(D^0 \to K\pi\eta) \approx 826$$

With this result, we are able to calculate an efficiency of about 4.4% for the signal region of the invariant mass (M_{D^0}). Figure 10 shows a plot distribution of the real data fitted with Eq. (6). As expected, no distinct signal peak is visible, which coincides well with our expectation based on the MC simulations.

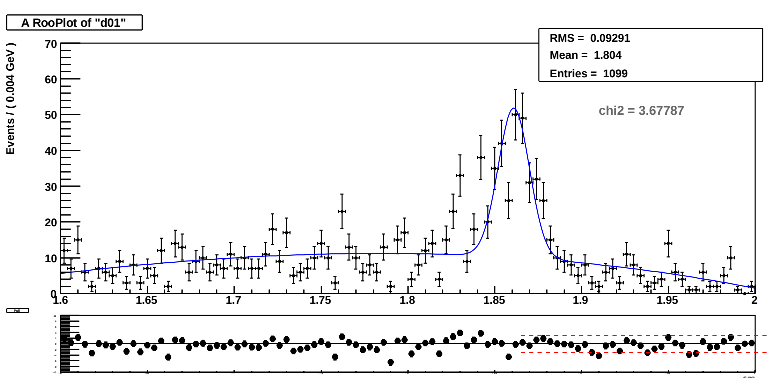

Figure 9: A fitted results from the distribution of D^0 peaking at the correct nominal mass in signal MC.

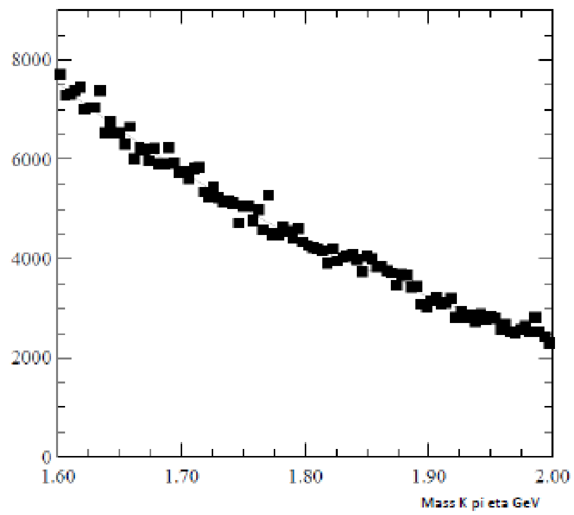

Figure 10: The invariant mass of D^0 with Belle I data, and fitted with a 2nd degree polynomial and gaussian function

5 Conclusion

The work done in this project gave us a better understanding of which path to take with this decay. The results from the signal MC invariant mass of D^0 compared to the background results from 1 stream of generic MC showed that the signal is too weak for anything to be seen with this decay at the moment. To further prove this point, the sample from the Belle I data set was also plotted, but no definitive peak was seen peaking at the nominal mass of D^0.

We now have a better understanding on how this decay looks and if any real calculations, such as the lifetime and branching fraction of D^0, could be calculated. Further work will have to be done in order to explore other areas of this decay and also help us to be more certain whether this decay is worth studying in greater detail. For instance, the branching fraction of η^0 decaying to $\pi\pi\pi^0$ is about 22% while an η^0 decaying to $\gamma\gamma$ is about 39% [6]. Having a higher branching fraction will help reconstruct a better signal for eta, thus helping increase the efficiency of the D neutral meson signal. Also, a more extensive study of the background will have to be done in order to suppress the current background since the signal is essentially too weak to be detected.

References

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