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Search for $D^0 \to K^+\pi^-\pi^0$

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Abstract

Using the CLEO II data sample with an integrated luminosity of 2.5 fb^{-1} at and near the Υ(4S) resonance, we conduct a search for the 'wrong sign' decay $D^0 \to K^+\pi^-\pi^0$ (which includes $K^+\rho^-$, $K^{*+}\pi^-$, $K^{*0}\pi^0$ as well as non-resonant $K^+\pi^-\pi^0$). No signal events have been found, leading to an upper limit on inclusive $D^0 \to K^+\pi^-\pi^0$ as R $\equiv \mathcal{B}(D^0 \to K^+\pi^-\pi^0)$ / $\mathcal{B}(D^0 \to K^-\pi^+\pi^0) < 0.68\%$. This upper limit includes the possible effects of the interference between Doubly Cabibbo Suppressed Decay and $D^0\bar{D}^0$ mixing for each submode as well as the interference between submodes.

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The reaction $D^0 \to K^+\pi^-\pi^0$ (where the submodes are $K^+\rho^-$, $K^{*+}\pi^-$, $K^{*0}\pi^0$ and non-resonant $K^+\pi^-\pi^0$) [1] can occur either through the Doubly Cabibbo Suppressed Decay (DCSD) $D^0 \to K^+\pi^-\pi^0$ or through $D^0\bar{D}^0$ mixing followed by Cabibbo favored decay $D^0 \to \bar{D}^0 \to K^+\pi^-\pi^0$. Both DCSD and $D^0\bar{D}^0$ mixing are substantially suppressed in the Standard Model. The rate for inclusive $D^0 \to K^+\pi^-\pi^0$ relative to inclusive $D^0 \to K^-\pi^+\pi^0$ is defined as $\mathrm{R} \equiv \mathcal{B}(D^0 \to K^+\pi^-\pi^0)$ / $\mathcal{B}(D^0 \to K^-\pi^+\pi^0)$, where the symbol $\mathcal{B}(D^0 \to K\pi\pi^0)$ refers to the rate integrated over all times of a pure D^0 state decaying to a final state $K\pi\pi^0$. The rate for exclusive two-body modes, such as $D^0 \to K^+\rho^-$ relative to $D^0 \to K^-\rho^+$, is defined similarly: $\mathrm{R_{K\rho}} \equiv \mathcal{B}(D^0 \to K^+\rho^-)$ / $\mathcal{B}(D^0 \to K^-\rho^+)$. The inclusive rate R is sensitive to the possible effects of the interference between DCSD and $D^0\bar{D}^0$ mixing for each submode as well as the interference between submodes. While R for mixing is expected to be very small in the Standard Model (estimates range from 10^{-10} to 10^{-4}) [2], R for DCSD is expected to be of the order of $\tan^4\theta_C(\sim 0.3\%)$, where θ_C is the Cabibbo angle. Theoretical predictions for R in DCSD have only been made for some exclusive modes. One estimate gives R for $D^0 \to K^+\rho^-$ and $D^0 \to K^{*+}\pi^-$ to be $0.5\tan^4\theta_C$ and $3\tan^4\theta_C$ respectively [3]. The Cabibbo favored decay $D^0 \to K^-\pi^+\pi^0$ has been studied in detail experimentally [4,5]. To date, however, there is no published result on $D^0 \to K^+\pi^-\pi^0$. The Mark III experiment previously reported [6] preliminary results for wrong sign D^0 decays which could be interpreted as evidence for either DCSD in the mode $D^0 \to K^+\pi^-\pi^0$ or $D^0\bar{D}^0$ mixing. Experiment E691 [7] has set an upper limit on R for mixing to be 0.004-0.007, where the range reflects the possible effects of interference between DCSD and mixing. CLEO [8] has recently reported a signal for $D^0 \to K^+\pi^-$ which could be due to either $D^0\bar{D}^0$ mixing or DCSD, and has found $\mathrm{R} \equiv \mathcal{B}(D^0 \to K^+\pi^-)$ / $\mathcal{B}(D^0 \to K^-\pi^+) = 0.0077 \pm 0.0025\,(\mathrm{stat.}) \pm 0.0025\,(\mathrm{sys.})$. Below we will describe a search for $D^0 \to K^+\pi^-\pi^0$ using CLEO II data.

We consider the decay chain $D^{*+} \to D^0\pi_s^+ \to (K\pi\pi^0)\pi_s^+$, where the π_s^+ has a soft momentum spectrum and is thus referred to as the slow pion. The technique employed is similar to the technique used for the $D^0 \to K^+\pi^-$ mode [8]. We search for wrong sign $D^{*+} \to D^0\pi_s^+ \to (K^+\pi^-\pi^0)\pi_s^+$ decays in which the slow pion has the same charge as the kaon. The right sign signal $D^{*+} \to D^0\pi_s^+ \to (K^-\pi^+\pi^0)\pi_s^+$ is used for normalization. The main complication faced by this analysis is that the resonant substructure is not necessarily the same for DCSD and for Cabibbo favored decays, therefore the variation of the detection efficiency across the Dalitz plot has to be taken into account when we measure R. The measurement of R in $D^0 \to K^+\pi^-$ does not depend on the detection efficiency. Two complementary analyses can be performed: a) an inclusive search for D^0 decays to the final state $K^+\pi^-\pi^0$; b) a search for each resonant component, including non-resonant decay mode. In this paper, we will only describe the inclusive search.

In this analysis, we use a set of relatively loose cuts for right sign events which result in a flat detection efficiency across the Dalitz plot, and we call these cuts "the right sign cuts". For the wrong sign events, we apply additional cuts in order to reduce backgrounds even though they result in a detection efficiency which is not uniform over the Dalitz plot, these cuts will be called "the wrong sign cuts". Both the right sign and wrong sign cuts are discussed in detail later. To set a conservative upper limit, we can assume the detection efficiency for the wrong sign cuts is flat across the Dalitz plot at ϵ_w^{min} for a worst case scenario, where ϵ_w^{min} is the minimum efficiency over the entire Dalitz plot for the wrong sign cuts. Thus we have $\mathrm{R} < \frac{M_w}{M_r} * \frac{1}{\xi_w^{min}}$, where M_w is the total number of measured wrong sign events with the wrong sign cuts, M_r is the total number of measured right sign events with the right sign cuts, and $\xi_w^{min} = \frac{\epsilon_w^{min}}{\epsilon_r^0}$ is the lowest relative detection efficiency for the wrong sign cuts relative to the right sign cuts. We will show later that ξ_w^{min} can be calculated from right sign data and therefore avoid the use of Monte Carlo simulation. This is the formula we will use to obtain our final result.

The data sample used in this study consists of 2.5 fb^{-1} of integrated luminosity near the $\Upsilon(4S)$ resonance, collected with the CLEO II detector operating at the Cornell Electron Storage Ring (CESR). The CLEO II detector has been described in detail elsewhere [9]. Isolated photons, detected by the barrel CsI calorimeter, with a minimum energy of 30 MeV/c, are paired to form π^0 candidates. Combinations within 2σ (standard deviation) of the nominal π^0 mass are selected as π^0 candidates. All D^{*+} candidates are required to have $x_{D^{*+}} > 0.60$, where $x_{D^{*+}} = \mathrm{p}/\mathrm{p}_{\mathrm{max}}$ and $\mathrm{p}_{\mathrm{max}} = \sqrt{\mathrm{E}^2_{\mathrm{beam}} - \mathrm{M}^2_{\mathrm{D}^{*+}}}$. This cut significantly reduces combinatorial background and keeps about 35% of the continuum D^{*+}s. These are the cuts we apply to the right sign events and are designed to keep the reconstruction efficiency as flat as possible across the Dalitz plot. We have used a large statistics Monte Carlo sample ($D^{*+} \to D^0\pi^+$ followed by $D^0 \to K^-\pi^+\pi^0$ non-resonant decay) and used the distribution of the accepted Monte Carlo events to study the detection efficiency across the Dalitz plot. Since the events were generated according to three-body phase space (flat across the Dalitz plot), any deviation from flatness is a direct indication of efficiency variation. With the right sign cuts, the detection efficiency is quite flat over the Dalitz plot, as can be seen in Fig 1(a). The overall detection efficiency for $D^0 \to K^-\pi^+\pi^0$ from $D^{*+} \to D^0\pi^+$ with $x_{D^{*+}} > 0.60$ is about 60%. The right sign cuts make no use of particle identification.

For the wrong sign, there are three sets of additional cuts: i.e. the π^0 momentum cut, the particle identification cuts and a cut on a kinematic quality called M_{flip}. These cuts were designed to reject background as much as possible and to avoid regions where the Monte Carlo-determined efficiency may not be reliable. The π^0 momentum cut is designed to remove background from random π^0 candidates which peaks in the low momentum region and can be effectively removed by a cut $\mathrm{p}(\pi^0) > 400$MeV/c. The particle identification cuts combine information from time-of-flight scintillation counters and dE/dx in drift chamber and calculate χ^2 probabilities for a given track to be a pion, kaon or proton. For each track, a particle likelihood ratio for particle type i ($\mathcal{L}_i$) is defined as the ratio of the probability of type i to the sum of the probabilities for all three types. We require $\mathcal{L}_K > 0.1$ and $\mathcal{L}_\pi < 0.30$ for kaon candidates, $\mathcal{L}_\pi > 0.1$ and $\mathcal{L}_K < 0.7$ for pion candidates. The requirements on kaon candidates are more stringent than those for pion candidates because there are more pions in the background which mimic kaons than kaons which mimic pions. These cuts are chosen to maximize the $S/\sqrt{B}$ in data, where S is the right sign signal yield, B is the number of wrong sign background events in the mass difference ($\Delta M \equiv M(K\pi\pi^0\pi) - M(K\pi\pi^0) - M(\pi)$) sideband. The M_{flip} cut is designed to remove the background from the doubly misidentified $D^0 \to K^-\pi^+\pi^0$ where the particle type assignments of K^- and π^+ are interchanged, and the D^0 is from $D^{*+} \to D^0\pi_s^+$ decay. This background peaks in the mass difference plot, and will show up in the D^0 mass plot as a broad enhancement around the D^0 peak. Note that the shape of the broad enhancement is different for different submode. When the kaon and the pion momenta are nearly equal, the doubly misidentified kaon-pion combination may still give a good D^0 mass. To remove this background, we invert the kaon and pion assignments and recalculate the D^0 mass, denoted M_{flip}. If M_{flip} is within 4 σ (standard deviation) of the nominal D^0 mass, the combination is discarded.

With the wrong sign cuts, the detection efficiency across the Dalitz plot is no longer flat, as can be seen in fig 1(b). The lower right corner has the lowest efficiency. This can also be seen by comparing the distribution of the right sign signal events in the Dalitz plot before and after the wrong sign cuts in fig 1(c)(d). The π^0 momentum cut p(π^0) > 400MeV/c is the principal cause of the detection efficiency variation, because the low momentum π^0s from $D^0 \to K\pi\pi^0$ accumulate around the lower right corner (high $K^-\pi^+$ mass region where π^0 is soft in D^0 rest frame) of the Dalitz plot. To estimate the lowest relative detection efficiency for the wrong sign cuts relative to the right sign cuts (ξ_w^{min}), we can measure the reduction in the number of right sign events from data in this region after applying the three additional cuts (fortunately the right sign data has large statistics in this very region). In this way we can avoid the uncertainties in Monte Carlo predictions. It is worth pointing out here that the Monte Carlo is used only to find the region of the lowest relative efficiency over the Dalitz plot, which can be also understood by kinematics. We define the region in the lower right corner to be $cos\theta_\rho < -0.4$ and $cos\theta_{K^{*-}} < -0.3$, where θ_X is the helicity angle of the resonance X. The lowest relative efficiency we obtained this way is $\xi_w^{min} = (31.0 \pm 1.0)\%$. For comparison, the highest relative efficiency is $\xi_w^{max} = 48\%$, using the right sign data in the upper left corner of the Dalitz plot: $cos\theta_\rho > 0.4$ and $cos\theta_{K^{*0}} < -0.3$.

To determine the right sign yield with the right sign cuts we fit the mass difference plot (after the D^0 mass sideband subtraction). The $K\pi\pi^0$ mass is required to be within 39 MeV/c^2 (about 2σ) of the D^0 nominal mass. The D^0 mass sideband is chosen as 1.743 GeV $< M_{K\pi\pi^0} <$ 1.823 GeV. The mass difference plot after D^0 mass sideband subtraction is fitted to a sum of two Gaussians (with the same mean but different σ). There are $M_r = 13424 \pm 180$ signal events in the mass difference plot. As a consistency check, we also fit the D^0 mass plot (after the mass difference sideband subtraction) to a Gaussian and a linear background. There are 13774 ± 195 signal events in the D^0 mass fitting, which is consistent with the result from the mass difference fitting. Note that it is conservative to use the yield from the mass difference fitting (which is smaller) to set the upper limit. Figure 2 shows the mass difference plots for the right sign and wrong sign after the wrong sign cuts are applied. The right sign mass difference plot has the D^0 mass sideband subtraction, while the wrong sign plot does not. The right sign yield is 5149.3 ± 84.6, which means the overall signal loss for the right sign is 38% due to the wrong sign cuts (this can be compared to the lowest relative efficiency 31% and the highest relative efficiency 48% on the Dalitz plot). To determine the wrong sign yield with the wrong sign cuts, we also fit the mass difference plot, but without the D^0 mass sideband subtraction. The reason we do not use the D^0 mass sideband subtraction is that the singly misidentified $D^0 \to K^+K^-\pi^0$ and $D^0 \to \pi^+\pi^-\pi^0$ will appear below and above the D^0 mass peak, respectively. Although Monte Carlo studies show that the amount of this background is small, it peaks at the mass difference signal location. The wrong sign mass difference plot is fitted the same way as the right sign mass difference plot except for an additional phase space background function (the same function used in reference 8). We fix the mean and widths for the fit to the wrong sign plot from the fit to the corresponding right sign plot. The total yield for the wrong sign is $M_w = 14.2 \pm 11.1$ from the mass difference fit. Using the total yield of the right sign events with the right sign cuts $M_r = 13424 \pm 180$ and the lowest relative efficiency $\xi_w^{min} = (31.0 \pm 1.0)\%$, we find R $< \frac{M_w}{M_r} * \frac{1}{\xi_w^{min}} = (0.34 \pm 0.27\,(\mathrm{stat})\,)\%$, leading to an 90% C.L. upper limit R < 0.68%.

One might question our method of using ξ_w^{min} instead of integrating the efficiency over the Dalitz plot, as the latter may give us a better upper limit. The answer is that our method gives a Monte Carlo-independent result (the value of ξ_w^{min} is obtained from data, not from the Monte Carlo simulation), while it degrades the upper limit by no more than 20%. If we apply the wrong sign cuts to both the right sign and wrong sign events and ignore the detection efficiency variation across the Dalitz plot, then we find R $= \frac{M_w}{M_r} = \frac{14.2\pm 11.1}{5149.3\pm 84.6} = (0.28 \pm 0.21\,(\mathrm{stat}))\%$ leading to an 90% C.L. upper limit R $< 0.56\%$. This is the lowest upper limit we can possibly get if we choose any other method.

The inclusive rate of $D^0 \to K^+\pi^-\pi^0$ contains much less information than the exclusive rate for each submode. Although the upper limit we obtained is close to $\tan^4\theta_C = 0.264\%$, we do not learn very much from this, as the upper limit is for the inclusive rate. We are attempting to obtain separate limits on the individual submodes, but due to the fact that the resonance substructure for the wrong sign is not necessarily the same as that for the right sign events, measuring the exclusive rate for each submode is rather complicated.

In conclusion, we have set an upper limit on the inclusive decay $D^0 \to K^+\pi^-\pi^0$. We find R $\equiv \Gamma(D^0 \to K^+\pi^-\pi^0, D^0 \to \overline{D}^0 \to K^+\pi^-\pi^0) \;/\; \Gamma(D^0 \to K^-\pi^+\pi^0) < 0.68\%$ or R $< 2.6\ \tan^4\theta_C$ (where $\tan^4\theta_C = 0.264\%$). This upper limit includes the possible effects of the interference between Doubly Cabibbo Suppressed Decay and $D^0\bar{D}^0$ mixing for each submode as well as the interference between submodes.

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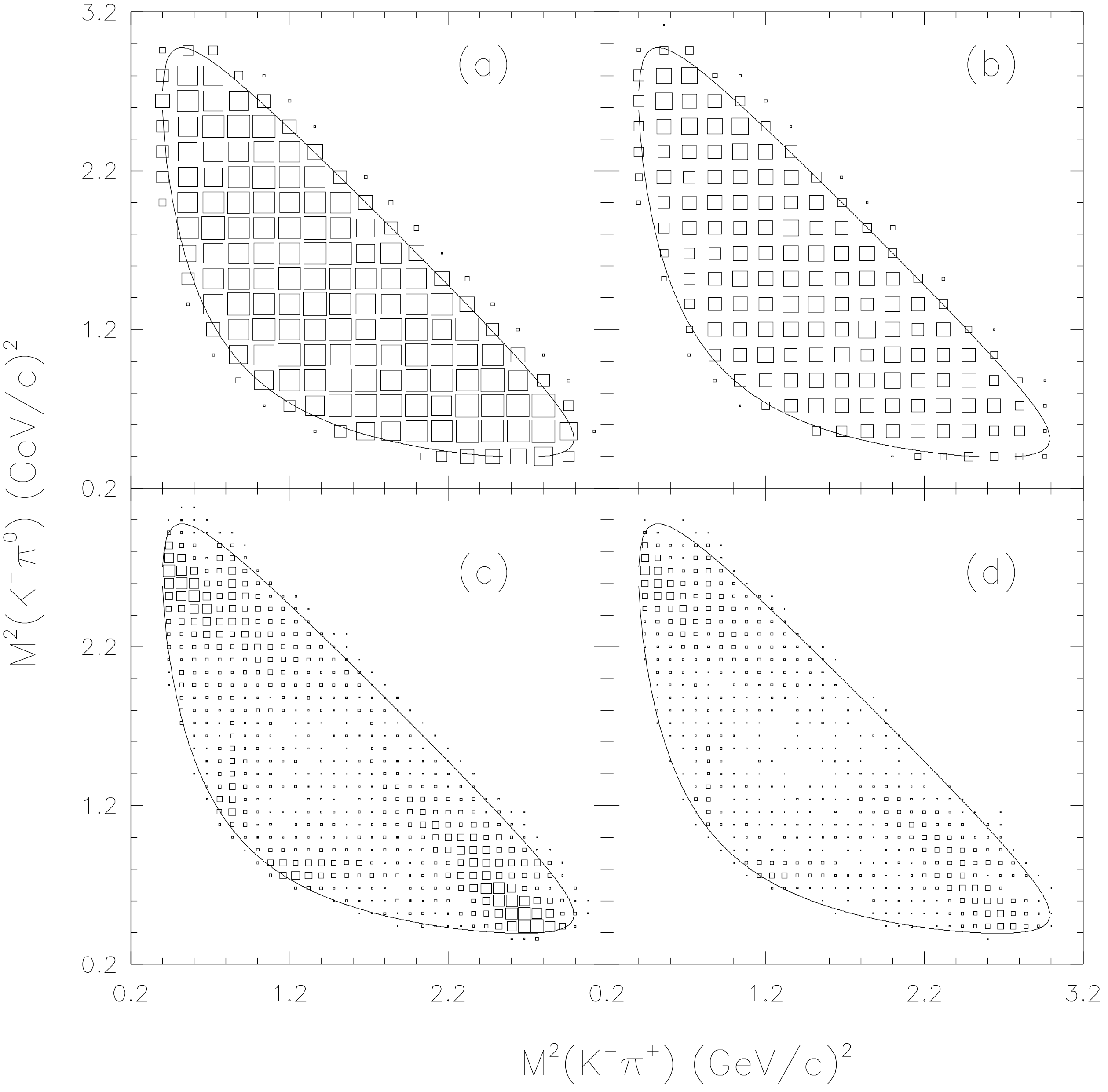

FIG. 1. (a) Detection efficiency across the Dalitz plot with the right sign cuts; (b) Detection efficiency across the Dalitz plot with the wrong sign cuts; (c) The right sign signal events with the right sign cuts; (d) The right sign signal events with the wrong sign cuts.

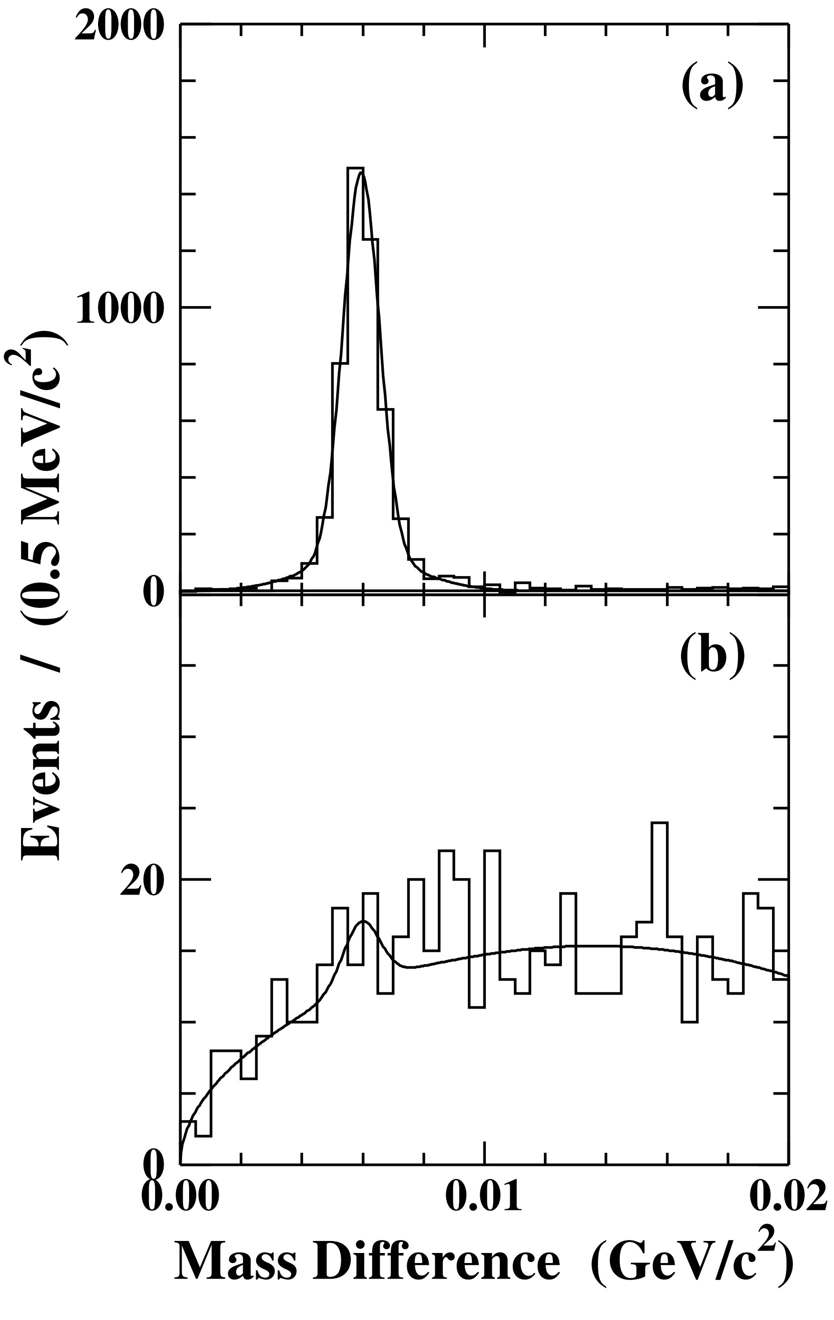

FIG. 2. The mass difference plots for the right sign and wrong sign after all the cuts are applied.