Search for Mixing and CP Violation in Charm Decays

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Standard model mixing and CP violation are expected to be small in the charm sector. Some argue that only in the presence of new physics do we currently expect to observe these effects. Fermilab experiment E791 has the largest sample of reconstructed charm decays recorded to date. We have made an exhaustive search for $D^0\bar{D}^0$ mixing and CP violation in this data. We present the charm mixing limits on the mixing parameter $r_{mix}$ using hadronic and semileptonic decays, and also present preliminary limits on the CP asymmetry parameter, $A_{CP}$, for Cabibbo suppressed decays.

1. E791

E791 is a high statistics charm hadroproduction experiment completed at Fermilab in 1992. We recorded 20 billion triggers in 500 GeV $\pi^-N$ interactions at the Tagged Photon Spectrometer. Over 200K charm particles were reconstructed in the presence of new physics do we currently expect to observe these effects. Fermilab experiment E791 has the largest sample of reconstructed charm decays recorded to date. We have made an exhaustive search for $D^0\bar{D}^0$ mixing and CP violation in this data. We present the charm mixing limits on the mixing parameter $r_{mix}$ using hadronic and semileptonic decays, and also present preliminary limits on the CP asymmetry parameter, $A_{CP}$, for Cabibbo suppressed decays.

2. $D^0\bar{D}^0$ MIXING

$D^0\bar{D}^0$ mixing is expected to be small within the standard model (SM) [3]. The time-integrated fraction of mixed decays relative to Cabibbo favored (CF) decays is experimentally defined as the parameter $r_{mix} = \frac{N(D^0\rightarrow\pi^+\pi^-f)}{N(D^0\rightarrow f)}$, where $f$ is the final state. SM estimates for the mixing parameter $r_{mix}$ are in the range $10^{-7} - 10^{-10}$. Any sign of mixing above these SM predictions, could be seen as a sign of new physics, although long range effects cannot be easily ruled out [3].

We look for $D^0\bar{D}^0$ mixing by searching for wrong-sign (ws) final states $f$, in a sample of initially tagged $D^0$'s, decaying to right sign (rs) final state $f$. In the limit of small mixing (LSM) this is expressed as $r_{mix} \approx \tfrac{1}{2}(\Delta m^2 + \Delta \gamma^2)$, $\Delta m << 1$ and $\Delta \gamma << 1$. $\Delta m$ and $\Delta \gamma$ are the mass and decay rate differences between CP eigenstates, and $\gamma$ is the average decay rate.

Doubly Cabibbo suppressed (DCS) decays can mimic the process. The total $D^0$ wrong sign decay (ws) rate, is given (LSM) by

$$\Gamma_{ws}(D^0(t) \rightarrow f) \approx |\Delta m^2 + (\Delta \gamma)^2| t^2 + 4 |\rho|^2 + 2 Re(\rho)\Delta t + 4 Im(\rho)\Delta m | e^{-\gamma t} \quad (1)$$

The true mixing ($r_{mix}$), DCS interference $Re(\rho)$ and $Im(\rho)$, and pure DCS ($|\rho|^2$) components can be separated by their different time evolutions. Here mixing peaks at $2\tau_{D^0}$ and is sensitive to the tails of the DCS decay time distribution. In semileptonic final states DCS decays are not allowed and the mixing rate follows a pure $t^2 \times e^{-\gamma t}$ dependence.
2.1. Hadronic Decay Channels

We search for mixing in hadronic channels by using the charm decays $D^{*+} \rightarrow D^0 \pi_b^+$, then $D^0 \rightarrow K^\mp \pi^+$, $K^\mp \pi^+ \pi^- \pi^0$. The initial charm state is tagged by the sign of $\pi_b$, the bachelor pion originating in the primary vertex, to form a right sign (rs) and wrong sign (ws) sample. A neural network optimization of signal-over-root-background, $S/\sqrt{B}$, in the rs samples is used to search for mixing with maximum sensitivity in the ws samples. The Q-value, $Q = M(K\pi\pi\pi\pi) - M(K\pi\pi) - M(\pi_b)$, and associated proper decay time spectrum of right sign and wrong sign decays are extracted for each decay.

A maximum likelihood fit (MLF) is performed which accounts for the true signal, and background sources: misidentified $D \rightarrow \pi\pi, KK$, random pions with real $D^0$'s, and random pions with fake $D^0$'s. The $K\pi$ and $K3\pi\pi$ rs and ws data is fit simultaneously for $r_{mix}$ and $\rho$ parameters. We assume the residual background under the rs and ws signals is the same in shape, and fit it to a form determined from combining $D^0$'s and $\pi_b$'s from different events. We do not assume CP invariance when fitting any of the ws rates (mixing, DCS, interference), thus particle and antiparticle mixing rates are differentiated. Since it is most likely that CP will be violated in the DCS interference term, a special fit is performed under this condition. We also examine the cases of fits with no interference term and no CP violation, and no mixing term, to compare with previous experiments. A summary of fit results for the hadronic channels is given in Table 1.

2.1. Semileptonic Decay Channels

Charm decays through semileptonic channels offer a unique opportunity to search for mixing without DCS interference effects ( $\rho = 0$ in eq. 1). E791 has reported the first measurement of $D^0\bar{D}^0$ mixing with semileptonic decays, through the decay chain, $D^{*+} \rightarrow D^0 \pi_b^+$, then $D^0 \rightarrow K^-\ell^+\bar{\nu}_\ell$. Even though there is a missing neutrino in the decay, due to the small phase space available, an approximate, but narrow, $Q = M(K\ell\pi_b) - M(K\ell) - M(\pi_b)$ distribution results, see Figure 2. The momentum of the $D$ can only be determined up to a two-fold ambiguity, based on balancing the the momentum of the $D$ meson decay products about its line-of-flight, as determined from the vertexing information. The shape of the background for the ws signal fits is determined from combining $D^0$'s and $\pi_b$'s from different events as in the hadronic case. A MLF to the $Q$ and decay time distributions is performed. The results for $r_{mix}$ are summarized in Table 2.
3. CP Violation

CP violating effects are also predicted to be small in the standard model. In order for CP violation to occur there must exist two transition amplitudes to a final state $f$ which interfere with nonzero relative phase. The situation is reached in $D^0$ decays through mixing (indirect CP violation, $\Delta C = 2$), when interference of CKM couplings in the relevant amplitudes ($\Psi$) of the box diagrams occurs, $\Psi(D^0 \rightarrow f) \neq \Psi(D^0 \rightarrow D^0 \rightarrow f)$. This CP violating asymmetry is suppressed by an already low mixing rate, and is not expected to be seen, $O(10^{-10})$. Direct CP violating effects will manifest themselves in decay rate asymmetries of both neutral and charged $D$ mesons, $A_{CP}^f = \frac{\Gamma(D\rightarrow f) - \Gamma(D\rightarrow \bar{f})}{\Gamma(D\rightarrow f) + \Gamma(D\rightarrow \bar{f})}$. A particle and antiparticle asymmetry may be produced by final state interactions and penguin terms in Cabibbo suppressed modes. These CP violating rate asymmetries in singly Cabibbo suppressed (SCS) $D^0$ and $D^+$ decays may be as high as a few times $10^{-3}$. Current experiments have not tested $A_{CP}$ beyond the $\approx 10^{-1}$ range.

3.1. Singly Cabibbo Suppressed Searches

E791 has searched for CP violating effects in the SCS decay channels $D^0 \rightarrow K^+ K^- , \pi^+ \pi^- \pi^0$ decays, and $D^+ \rightarrow K^+ K^- \pi^+$ decays. Previous searches in these channels have yielded null results. We have also searched for decay rate asymmetries in $D^+ \rightarrow \pi^+ \pi^- \pi^+$ decays, for the first time. To remove $D\bar{D}$ production and reconstruction asymmetries, we normalize each SCS mode to its CF counterpart ($K^-\pi^+, K^+\pi^+\pi^+$) and reformulate a working definition of the CP asymmetry as

$$A_{CP} = \frac{\eta(D) - \eta(D)}{\eta(D) + \eta(D)}.$$  \hspace{1cm} (2)$$

where $\eta(D) = \frac{N(D\rightarrow f_{SCS})}{N(D\rightarrow f_{CF})}$, is the ratio of the number of SCS to CF decays.
In the decay $D^+ \rightarrow K^+K^−\pi^+$, we have inspected each subresonance $φ\pi^+$, $K^*K$, as well as the nonresonant $KK\pi$ for individual $CP$ violating asymmetries. We have investigated $D^+ \rightarrow π^+π^−π^+$ decays, inclusively, shown in Figure 3. In each case the selection criteria for the SCS mode is arrived at by optimizing $S/\sqrt{S+B}$ where $S$ is the scaled-to-SCS-level CF decay and $B$ is the background for that SCS decay. The normalizing CF mode is subject to the same optimizing cuts as its SCS counterpart to minimize systematic uncertainties. Backgrounds from CF mass reflections and particle misidentification are also removed. A simultaneous MLF fit for the particle/antiparticle yields is performed to arrive at the preliminary $CP$ asymmetries listed in Table 3.

In the two-body $D^0 \rightarrow π^+π^−, K^+K^+$ decays, Figure 4, a similar approach is taken. Here we show the joint $D^0 \rightarrow K \pi, KK$, and $ππ$ decay modes used in the $CP$ asymmetry analysis. We use SCS $D^0$ decays which are tagged by the $D^+ \rightarrow D^0π_0^+$ and then $D^0 \rightarrow K^+K^−, π^+π^−$ decays. We normalize each SCS yield to the tagged CF counterpart, $D^0 \rightarrow K^−π^+$. Again, we remove backgrounds from the CF mass reflections and particle misidentification. As a consistency check of a null result we also determine $A_{CP}$ for the CF mode $D^0 \rightarrow K^−π^+π^+π^−$. A MLF fit is performed to determine the particle/antiparticle yields. We list preliminary results for these $CP$ asymmetry measurements, also in Table 3.

Figure 3. $D^+ \rightarrow π^±π^±π^±$ events used in the $CP$ asymmetry calculation. The $K\pi\pi$ reflection below 1.83 GeV was excluded from the fit.

Figure 4. $D^0 \rightarrow π^±π^−, K^+K^−$ events used in the $CP$ asymmetry calculation

4. Conclusion

E791 has made an exhaustive search for $D^0\overline{D}^0$ mixing in Cabibbo favored hadronic and semileptonic decays. We have also searched for $CP$ violating asymmetries in singly Cabibbo suppressed modes including $D^+ \rightarrow π^+π^−$ decays for the first time. All measurements of mixing and $CP$ violation are consistent with zero. With both hadronic and semileptonic mixing studies we have achieved sensitivities on the order of $5 \times 10^{-3}$ based on general assumptions, possibly testing standard model extensions. We have improved $CP$ asymmetry measurements of SCS decays, in some cases to the (2-5)% range, but are not yet approaching a sensitivity of $O(10^{-3})$ where $CP$ violating asymmetries are predicted in SCS decays in the standard model.
Table 3
Preliminary CP asymmetry limits set by E791 and other experiments for CS $D^+$ and $D^0$ decays

| Mode   | $A_{CP}$  | 90%CL Limit (%) | Other          |
|--------|-----------|------------------|----------------|
| $K\pi\pi$ | -0.014 ± 0.029 | $-6.2 < A_{CP} < +3.4$ | -0.031 ± 0.068 [11] |
| $KK\pi$  | -0.028 ± 0.036  | $-8.7 < A_{CP} < +3.1$ | 0.066 ± 0.086 [11] |
| $\phi\pi$ | -0.010 ± 0.050  | $-9.2 < A_{CP} < +7.2$ | -0.012 ± 0.013 [11] |
| $\pi\pi\pi$ | -0.017 ± 0.042  | $-9.3 < A_{CP} < +6.7$ | 0.080 ± 0.061 [12] |
| $\pi\pi$  | -0.049 ± 0.078  | $-17.8 < A_{CP} < +8.0$ |                |
| $K\pi\pi\pi$ | -0.003 ± 0.021  | $-3.6 < A_{CP} < +3.1$ |                |

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