A Study of Rare $\bar{D}$ Decays for the Tau-Charm Factory

Ian E. Stockdale

Physics Department
University of Cincinnati
Cincinnati, Ohio 45221

Abstract

We present a study of the sensitivity to rare D decays of a Tau-Charm Factory detector. We consider both flavour changing neutral currents and family number violating decays, and evaluate the impact of varying the solid angle coverage, lepton identification and neutral hadron identification of the detector. We find that stringent demands must be made on the detector design in order to effectively use the expected data sets to observe small signals (branching fractions $\sim 10^{-7}$ - 10^{-8}) at a five standard deviation level of statistical significance.

The study of the rare decays of charmed mesons is still in its infancy. Only with the relatively recent acquisition of data sets containing large numbers of observed D mesons have the initial searches for these final states been possible. A tau-charm factory would provide an extraordinary opportunity to pursue these studies, approaching sensitivities at which standard model effects are expected.

The rare decays fall into two classes. The first class consists of family number violating (FNV) decays, such as $D^0 \rightarrow \mu\, e$. These decays are forbidden to all orders in the standard model. It is difficult to make predictions based on extensions of the standard model, as these depend on both the couplings and masses of new heavy particles. These parameters are unspecified in most models; null searches thus produce correlated constraints on these new parameters. A positive result would be an indication of new physics. The second class of rare decays consists of the flavour changing neutral currents (FCNC), such as $D^0 \rightarrow e\, e$. These decays are allowed in the standard model, although the predicted branching ratios are small. Long distance effects, which are expected to dominate the rate, are expected to be smaller than 10^{-7}.[1]

The current experimental situation[2] is summarized in Table 1. The most powerful searches for FCNC are not yet sensitive to the branching ratios predicted by the standard model, and the FNV decays have not yet made their unexpected appearance. What capabilities are to be demanded from a tau-charm factory in order that it make a significant contribution to these studies? Three requirements may be specified in response to this question.

The first requirement is the production of a large number of events containing D and D_s mesons. The potential for observing new physics in the FCNC sector is greatest in the region where no standard model effects are expected. We thus should ask that a tau-charm factory be capable of exploring most of this unambiguous region in as many final states as possible. For the decays with charged leptons in the final state, this suggests that a tau-charm factory ought to produce 10^7 to 10^8 D mesons. Final states with neutrinos rather than charged leptons in the final state are not expected to have branching ratios larger than 10^{-11}. While this sensitivity is beyond the reach of the proposed tau-charm factory, it will still be possible to break new ground in these as yet unexplored final states. Sensitivities at the 10^{-7} to 10^{-8} level will also greatly benefit studies of the family number violating decays.

Table 1: Current Limits on Rare D Decays					
Decay Mode	Collaboration	90 % C.L. Limit on Branching Fraction ($\times 10^5$)	Decay Mode	Collaboration	90 % C.L. Limit on Branching Fraction ($\times 10^5$)
$D^0 \to \mu e$	Mark III	12	$D^0 \to K^0 ee$	MarkIII	170
	ARGUS	10	$D^0 \to \rho^0 ee$	CLEO	45
	CLEO	27	$D^0 \to \rho^0 \mu\mu$	CLEO	81
	TPL	8	$D^+ \to \pi^+ \mu e$	TPL	20
	ACCMOR	100		CLEO	380
	Mark II	210	$D^+ \to \pi^+ ee$	CLEO	260
$D^0 \to \mu\mu$	ARGUS	7	$D^+ \to \pi^+ \mu\mu$	CLEO	290
	CLEO	14	$D^0 \to ee$	Mark III	13
	TPL	10		ARGUS	17
	E615	1.1		CLEO	22
	EMC	34		TPL	8

A second requirement is the ability to measure a significant effect for very small branching ratios. When backgrounds are large it is easier to extract a useful limit in the absence of a signal than it is to establish the existence of a signal which is actually present. For example, a signal which produces ten observed events is much more statistically significant when 0.5 background events, rather than 5, are expected. A tau-charm detector should then be designed so as to allow only a hand-full of background events in most of the accessible channels.

It should be stressed that unlike experiments which are performed in hadron beams, or at e^+e^- B-factories, the physics backgrounds to these rare decays can be well-controlled. This is even more crucial in final states containing photons or missing particles (ν, K^0_L) than in the all-charged modes which will be discussed in the first part of this paper. At a tau-charm factory, the systematic uncertainty will be dominated by the understanding of the detector. When considering the ability to observe a significant *signal*, rather than to set a limit, controlling the systematics becomes an essential task.

The third requirement thus is the ability to understand systematic and instrumental effects at the same level as the sensitivity of the experiment. An observation of $D^0 \to \mu e$ will not be believed unless one is able to make a strong case for the reliability of the detector at the claimed sensitivity. This can only be done through cross-checks with large data sets. In addition to the large number of charmed mesons which a tau-charm factory would provide for this end, there would also be data sets containing 10^9 or more ψ and ψ' events which could be used to understand the detector and the data analysis procedures in rigourous detail.

In the absence of data, only the first two requirements may be quantitatively assessed. In this note, we attempt to evaluate the achievable sensitivities for a limited subset of the available modes. We first consider the simplest all-charged decays of the D^0. The features common to these decays are the lepton (e, μ) identification requirements. Performing these searches at the $\psi(3770)$ allows the rejection of all non-charm backgrounds and most charm backgrounds, through simple kinematic and and multiplicity cuts. The remaining backgrounds are the "kinematically similar" D^0 decays where hadrons are mis-identified as leptons. For instance, the decay $D^0 \to \pi\pi$ is the largest background to $D^0 \to \mu e$, $\mu\mu$, and $e e$ signals.

Table 2: Particle Identification requirements studied

	Solid Angle Coverage	e/π Rejection	μ/π Rejection
Loose criteria	95 %	2×10^{-3}	$4 \times 10^{-2}/p$ (GeV)
Stringent criteria	99.5 %	5×10^{-4}	$1 \times 10^{-2}/p$ (GeV)

Table 3: Sensitivities to Rare D^0 Decays with High Luminosity and Ultimate Detector. The B.R. Limit is the 90% C.L. limit attainable in the absence of a signal. The B.R. 5σ Signal is the minimum signal which may be observed at the 5σ level, given the expected number of background events.

Final State	Background	B.R. Limit (x 10^8)	B.R. 5σ Signal (x10^8)
μ *e*	0.55	4.6	8.8
ee	0.028	3.0	3.0
μ μ	1.1	3.9	12
ρ^0 e e	0.27	2.2	6.2
K^0 e e	0.26	13	3.6
ν ν	<0.22		800

Table 4: Comparison of improvements due to better particle id and to high luminosities. The Particle Identification Factor is the ratio of the minimum 5σ signal observable with 10^7 produced D^0's with strigent particle identification criteria *vs.* that with loose criteria (*cf.* Table 2). The Luminosity Factor is the ratio of the same quantity with loose particle identification criteria for 10^8 *vs.* 10^7 produced D^0's.

Final State	Particle Identification Factor (*cf.* Table 2)	Luminosity Factor (x10 improvement)
μ e	2.2	4.3
e e	1.8	5.3
μ μ	7.0	3.0
ρ^0 e e	2.8	5.6
K^0 e e	2.8	4.8

These backgrounds are rejected using particle identification. We have studied the effects of improving the particle identification from a minimal set of requirements to a more stringent set (*cf.* Table 2). The expected results for five all-charged final states are shown in Table 3 for the stringent particle identification criteria, and 10^8 produced D^0's. The difference between these two sets of detector requirements is evident in Table 4, which shows the ratio of the smallest observable 5σ effect in the two cases. Especially striking is the improvement in the detector's ability to see 5σ signals, which is a factor of 2 to 7 for most modes. This is entirely due to reducing the expected backgrounds from ≤ 10 events to < 1 event. Also shown are the improvement factors for 10^8 produced D^0's versus 10^7 produced D^0's using the loose particle identification criteria. The better detector is seen to be comparable to roughly a factor of five in luminosity.

The second study which we present here is the search for decays with neutrinos in the final state. The existence of these decays would indicate new physics, as they are not expected to have branching ratios larger than 10^{-11}. We choose the decay $D^0 \to \nu\nu$ as an example, and assume that 10^8 D^0's are produced. One good D^0 tag (e.g $D^0 \to K^-\pi^+$) is observed and the recoil system is required to have zero observed tracks (charged and neutral). In order to minimize backgrounds, we need good solid angle coverage near the beam-line, and at the cracks between the barrel and end cap. This elliminates most of the $D^0 \to K^-\pi^+$ backgrounds; it also drastically reduces the $D^0 \to K^0\pi^0$ and $K^0\eta$ backgrounds which result from undetected photons. The addition of a hadron calorimeter improves the ability to detect K^0_L which are associated with the latter two backgrounds. When the $k^-\pi^+$ tag is used, τ-pair production is also a background.

Table 5 Expected number of background events to $D^0 \to \nu\nu$ from the decay $D^0 \to K^0_L \pi^0$.

Detector:	Mark III	Minimal tau-charm detector	Ultimate tau-charm detector
No. of events:	930	510	0

As an example, the expected background feed-through from the decay $D^0 \to K^0_L \pi^0$ for the Mark III, a minimal tau-charm detector, and an extended solid angle tau-charm detector are shown in Table 5. While the minimal tau-charm detector is much better than the Mark III for this measurement, the ability to see a significant signal only emerges with the high solid angle detector. A branching ratio of 10^{-5} could then be seen (*cf.* Table 3). This is better than all but the very best limits which exist today for the all-charged modes. This is a *conservative* estimate of the sensitivity to this channel, as we have only considered $k^-\pi^+$ tags. Using other tags will improve the statistics by more than a factor of three[3] without increasing the τ-pair background (roughly 50 % of the total expected for $k^-\pi^+$ tags). Figure 1 shows the invariant mass of the $k^-\pi^+$ tag recoiling against the decay $D^0 \rightarrow \nu \nu$ where the branching ratio of the signal is 6 x 10^{-5}. The *total* expected background is shown in the shaded region.

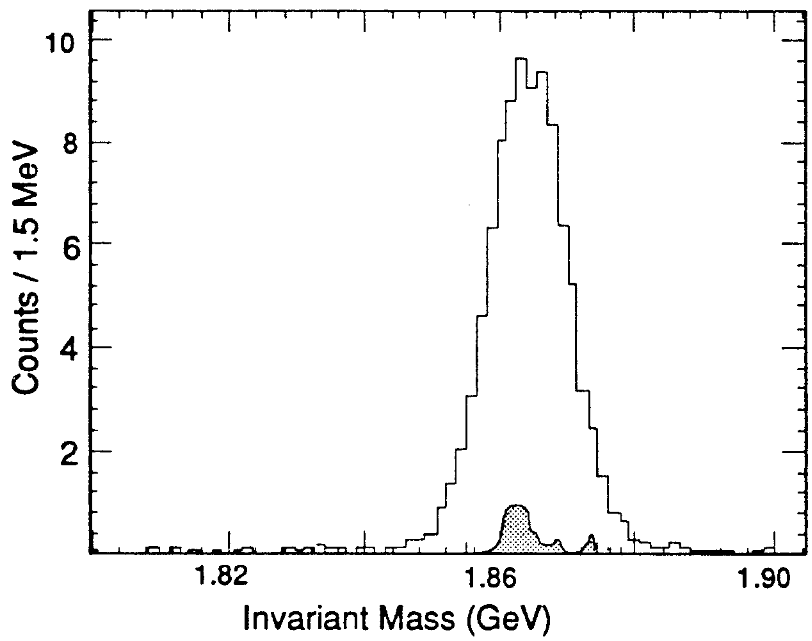

Figure 1: Invariant mass of $K^-\pi^+$ tags recoiling against $D^0 \rightarrow \nu \nu$ and background $D^0 \rightarrow K^0_L \pi^0$ Monte Carlo events. The branching ratio of the signal is 6 x 10^{-5}. The background events in the histogram are shaded. A data run of one year with an integrated luminosity of 10^{34} cm^{-2} is assumed.

In conclusion, we have studied the ability of various tau-charm detector configurations to measure a subset of rare *D* decays. In all cases, the design of the detector is seen to be just as critical as the expected luminosity when considering the ability to observe a significant (here, 5σ) effect. The achievable limits are not as sensitive to the detector design. One should not extend the numbers contained in this note to final states which are not explicitly mentioned (e.g. $D^0 \rightarrow \rho^0 \nu \nu$). The control of backgrounds for each particular mode is very important in these studies, and this varies surprisingly among apparently similar final states. The sensitivity of a tau-charm detector to rare D_s decays has not been studied due the the paucity of data on most possible backgrounds. A tau-charm factory, through detailed measurements of D_s decays, would provide the data needed to understand these presently unknowable backgrounds.

Acknowledgements

I would like to acknowledge the efforts of the organisers and staff of the Tau-Charm Factory workshop. They provided an enjoyable and productive environment in which to assess this interesting physics. This work was supported in part by the National Science Foundation (Grant No. PHY-8813018).

References

[1] R. Willey, Proceedings of this workshop.
[2] C. Grab, SLAC-PUB-4809, (Nov 1988).
[3] R. Schindler, Proceedings of this workshop.