Heavy Quark Hadronic Weak Decays from CLEO-II

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ABSTRACT

We present results from the CLEO-II collaboration on a variety of hadronic final states of mesons containing heavy quarks. In particular, the pattern of 2-body B decays is now decisively different that that of D decays, and we have observed 'wrong-sign' $D^0 \to K^+\pi^-$ decays.

Introduction

We present preliminary results on the decays of mesons containing b and c quarks to a variety of hadronic final states. The data sample for these analyses is typically $1 - 1.8\mathrm{fb}^{-1}$ accumulated by the CLEO-II detector, 2/3 of which is on the $\Upsilon(4S)$, and 1/3 of which is in the continuum just below that resonance.

Of primary importance are the high statistics measurements of the decays of B-mesons to two body final states. The evidence is now that the description of decays to two body final states for D and K mesons *does not pertain for* B's.

We present results on inclusive measurements of D and J/ψ mesons in B decays. Also, results on Cabibbo-suppressed decays of D mesons, the observation of the wrong-sign decay $D^0 \to K^+\pi^-$, and precision measurement of absolute branching ratios for the D^0 and D^+ are presented.

Two Body Decays of B's

Consider the generic Cabibbo-favored decay of a flavored pseudoscalar meson with one light quark, M, to two pseudoscalars. The neutral pseudoscalar, M^0, can decay either to a charged final state $(-+)$ or a neutral final state (00); the charged pseudoscalar, M^+, decays to a mixed charge final state, $(0+)$; consider $\Gamma(M^0 \to -+)/\Gamma(M^+ \to 0+)$. In the kaon system, due to the $\Delta I = 1/2$ rule:

$$\Gamma(\overline{K}^0 \to \pi^+\pi^-)/\Gamma(K^- \to \pi^-\pi^0) \approx 225 \qquad (1)$$

In the D system, where the relative enhancement of the amplitude that produces the smallest change in isospin is not as prominent,

$$\Gamma(D^0 \to K^-\pi^+)/\Gamma(D^+ \to \overline{K}^0\pi^+) \approx 3.6 \qquad (2)$$

However, the results we present here indicate that:

$$\Gamma(\overline{B^0} \to D^+\pi^-)/\Gamma(B^- \to D^0\pi^-) \approx 0.6 \pm 0.1 \qquad (3)$$

decisively *less* than unity. Because the ratio $\Gamma(-+)/\Gamma(0+)$ is near to unity, the spectator quark processes shown in Fig. 1, rather than final state effects, presumably dominate the two-body decay amplitudes for the B system. Because $\Gamma(-+)/\Gamma(0+) < 1$, the two amplitudes for B^- decay that lead to identical final states add *constructively.*

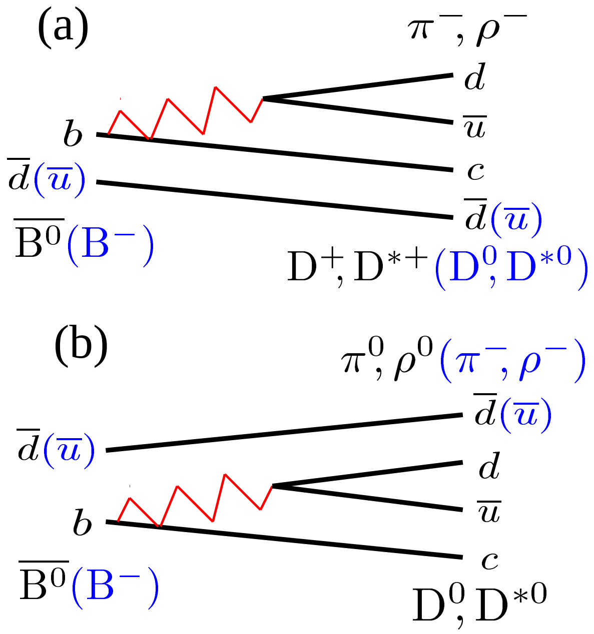

Figure 1: Spectator Diagrams for Two-Body B Decay: (a) External, which under the assumption of factorization can be related to an exclusive semileptonic amplitude, and (b) Internal, which can suffer color suppression. For the B^-, the two amplitudes add *constructively*, according the results presented here.

The reconstructed D decay modes are shown in Table 1. Two variables, the beam constrained mass, $M_B^2 = E_{\mathrm{beam}}^2 - (\sum_i \vec{p}_i)^2$, and the energy difference with the beam, $\Delta E = E_{\mathrm{beam}} - (\sum_i E_i)$ where the sums run over the particles assigned to the $D(\overline{u}d)$ system, are important in the B reconstruction. Typically $\sigma_{M_B} \approx 2.6\,\mathrm{MeV}$, and is insensitive to the final state mode, while $\sigma_{\Delta E} \approx 15 - 40\,\mathrm{MeV}$ and is sensitive to the final state mode.

Mode	$\mathcal{B}$ Assumed	Source
$D^0 \to K^-\pi^+$	$(3.91 \pm 0.10)\%$	CLEO-II
$D^0 \to K^-\pi^+\pi^0$	$(12.1 \pm 1.1)\%$	PDG
$D^0 \to K^-\pi^+\pi^+\pi^-$	$(8.0 \pm 0.5)\%$	PDG
$D^+ \to K^-\pi^+\pi^+$	$(10.0 \pm 1.4)\%$	CLEO-II
$D^{*+} \to D^0\pi^+$	$(67.9 \pm 2.3)\%$	CLEO-II
$D^{*0} \to D^0\pi^0$	$(62.5 \pm 4.2)\%$	CLEO-II

Table 1: Charm Decay Modes and Branching Ratios used in the B reconstructions.

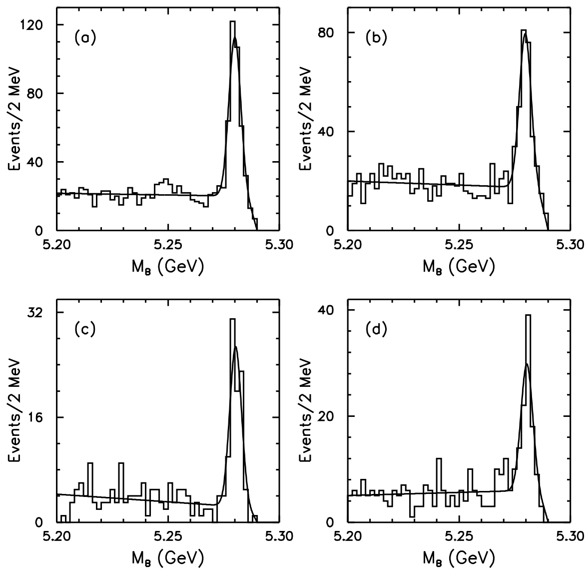

Figure 2: Beam constrained mass ($M_{\rm B}$) distributions for (a) $B^- \to D^0\pi^-$ decays; (b) $B^- \to D^0\rho^-$ decays; (c) $\overline{B^0} \to D^+\pi^-$ decays; and (d) $\overline{B^0} \to D^+\rho^-$ decays.

Typical signals in the $B \to D(\pi \mathrm{or} \rho)$ modes are shown in Fig. 2. The background function is determined in several ways, including studies of the sidebands and Monte Carlo simulations: the background function shape is linear far from the B mass, and parabolic just under the B mass. Branching ratio results for $(+-)$ and $(0-)$ modes are given in Tables 2 and 3, in which the assumption that the $\Upsilon(4S)$ decays equally to B^+B^- and $B^0\overline{B^0}$ ($f_{+-} = f_{00}$) is made.

One can see in all cases that $\Gamma(B^- \to 0-) > \Gamma(\overline{B^0} \to +-)$. A simple physical explanation is that the diagrams of Fig. 1(a) and Fig. 1(b) add constructively for the B^-.

No evidence exists in our data sample for the mode

$\overline{B^0} \to$	#	$\mathcal{B}(\%)$
$D^+\pi^-$	76±10	$0.22^{\pm 0.03}_{\pm 0.02 \pm 0.03}$
$D^{*+}\pi^-$	73±10	$0.27^{\pm 0.04}_{\pm 0.04 \pm 0.013}$
$D^+\rho^-$	86±11	$0.62^{\pm 0.08}_{\pm 0.08 \pm 0.09}$
$D^{*+}\rho^-$	52±8	$0.74^{\pm 0.11}_{\pm 0.13 \pm 0.03}$

Table 2: Two body decay modes of the $\overline{B^0}$. The top error is statistical, on the inner bottom is intrinsic systematic error, and on the outer bottom is the extrinsic systematic error from, for example, errors in D branching ratios.

$B^- \to$	#	$\mathcal{B}(\%)$
$D^0\pi^-$	302±22	$0.47^{\pm 0.03}_{\pm 0.05 \pm 0.02}$
$D^{*0}\pi^-$	93±12	$0.50^{\pm 0.06}_{\pm 0.07 \pm 0.04}$
$D^0\rho^-$	248±22	$1.07^{\pm 0.10}_{\pm 0.16 \pm 0.04}$
$D^{*0}\rho^-$	92±12	$1.41^{\pm 0.19}_{\pm 0.13 \pm 0.11}$

Table 3: Two body decay modes of the B^-. The error notation is the same as the previous table.

$\overline{B^0} \to 00$. The plots for $M_{\rm B}$ for the various modes are shown in Fig. 3. Based upon the absence of signal in these plots, one arrives at the limits in Table 4. Note that the ratio $\Gamma(00)/\Gamma(+-)$ is at least less than 1/16 for the $\overline{B^0}$, in marked contrast to the situation for the $D^0$and the $\overline{K}^0$, where this ratio is typically 1/2.

$\overline{B^0} \to$	$\mathcal{B}\%$ (90% C.L.)	$\frac{\Gamma(00)}{\Gamma(+-)}$ %	BSW (%)
$D^0\pi^0$	< 0.03	< 14	$76\lvert\frac{a_2}{a_1}\rvert^2$
$D^{*0}\pi^0$	< 0.06	< 22	$84\lvert\frac{a_2}{a_1}\rvert^2$
$D^0\rho^0$	< 0.08	< 13	$22\lvert\frac{a_2}{a_1}\rvert^2$
$D^{*0}\rho^0$	< 0.17	< 23	$32\lvert\frac{a_2}{a_1}\rvert^2$

Table 4: Limits on decays of the type $B^0 \to 00$, which can proceed via the internal spectator amplitude of Fig. 1(b). In addition to $f_{+-} = f_{00}$, $\tau_- = \tau_0$ is assumed for all extractions of the BSW parameters a_1 and a_2.

The two body decay data can be described by the phenomenology of Bauer, Stech, and Wirbel (BSW)[1], where the external spectator in Fig. 1(a) is associated with the coefficient a_1, and the internal spectator in Fig. 1(b) is associated with the coefficient a_2. From

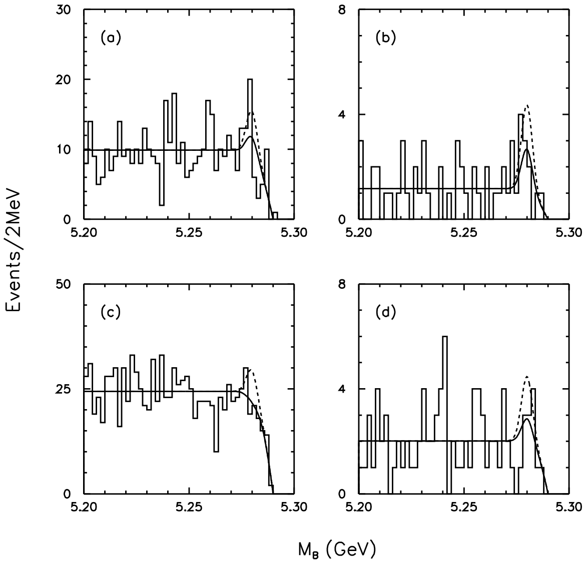

Figure 3: Beam constrained mass ($M_{\rm B}$) distributions for (a) $\overline{\rm B^0} \to {\rm D}^0\pi^0$ decays; (b) $\overline{\rm B^0} \to {\rm D}^{*0}\pi^0$ decays; (c) $\overline{\rm B^0} \to {\rm D}^0\rho^0$ decays; and (d) $\overline{\rm B^0} \to {\rm D}^{*0}\rho^0$ decays. The solid curves show just the background shape, the dotted curves the 90% CL upper limit.

the decays $\overline{\rm B^0} \to +-$, which are purely external spectator, one can infer $|a_1| = 0.98 \pm 0.03 \pm 0.04 \pm 0.09$, as detailed in Table 5. One can also test the correctness of the association of $\overline{\rm B^0} \to +-$ with the external spectator by relating its branching ratio to ${\rm B} \to {\rm D}\ell\nu$, an association known also as factorization. Factorization predicts $\mathcal{B}(\overline{\rm B^0} \to {\rm D}^{*+}\pi^-) = 6\pi^2 c_1^2 f_\pi^2 |V_{ud}|^2 \times \frac{d\mathcal{B}}{dQ^2}(B \to D^*\ell\,\nu)|_{Q^2=m_\pi^2} = (0.26\pm0.04\%)$, and $\mathcal{B}(\overline{\rm B^0} \to {\rm D}^{*+}\rho^-) = 6\pi^2 c_1^2 f_\rho^2 |V_{ud}|^2 \times \frac{d\mathcal{B}}{dQ^2}(B \to D^*\ell\,\nu)|_{Q^2=m_\rho^2} = (0.75\pm0.10\%)$, in good agreement with the measurements.

$\overline{\rm B^0}\to$	$\mathcal{B}(\%)$	BSW
${\rm D}^+\pi^-$	0.22±0.05	$0.264\|a_1\|^2$
${\rm D}^{*+}\pi^-$	0.27±0.05	$0.254\|a_1\|^2$
${\rm D}^+\rho^-$	0.62±0.14	$0.621\|a_1\|^2$
${\rm D}^{*+}\rho^-$	0.74±0.17	$0.702\|a_1\|^2$

Table 5: Comparison of measured $\overline{\rm B^0} \to +-$ branching ratios with the BSW parameterization

We see, from Table 4, that the absence of $\overline{\rm B^0} \to 00$ modes imply that $|a_2| < 0.5$ or so. There are two ways in which we obtain increased sensitivity to a_2: first, for the ${\rm B}^-$ decays, in the BSW phenomenology, the external and internal amplitudes coherently interfere, so the rates for ${\rm B}^- \to 0-$ are crudely $\propto |a_1 + a_2|^2$, yielding a linear sensitivity to a_1 in the interference term; second, we can measure the modes produced by the internal spectator diagram where the W hadronizes as a $\overline{c}s$ rather than $\overline{u}d$, such as $\overline{\rm B^0} \to J/\psi{\rm K}_S^0$. For the first method, define:

$$R_1 = \frac{\mathcal{B}(\overline{\rm B^0}\to{\rm D}^+\pi^-)}{\mathcal{B}({\rm B}^-\to{\rm D}^0\pi^-)} = \frac{1}{(1+1.23a_2/a_1)^2} \quad (4)$$

$$R_2 = \frac{\mathcal{B}(\overline{\rm B^0}\to{\rm D}^{*-}\pi^-)}{\mathcal{B}({\rm B}^-\to{\rm D}^{*0}\pi^-)} = \frac{1}{(1+1.292a_2/a_1)^2} \quad (5)$$

$$R_3 = \frac{\mathcal{B}(\overline{\rm B^0}\to{\rm D}^+\rho^-)}{\mathcal{B}({\rm B}^-\to{\rm D}^0\rho^-)} = \frac{1}{(1+0.662a_2/a_1)^2} \quad (6)$$

$$R_4 = \frac{\mathcal{B}(\overline{\rm B^0}\to{\rm D}^{*-}\rho^-)}{\mathcal{B}({\rm B}^-\to{\rm D}^{*0}\rho^-)} \approx \frac{1}{(1+1.5a_2/a_1)^2} \quad (7)$$

With these definitions, we find the results given in Table 6, which indicate $a_2/a_1 \approx 0.24$. Note the relative sign is *positive*, in contradiction to the destructive interference obtained in the BSW analysis of the analogous charm decays.

Ratio	$a_2/a_1 = -0.24$	$a_2/a_1 = 0.24$	**CLEO-II**
R_1	2.0	0.59	$0.56 \pm 0.09 \pm 0.11$
R_2	2.1	0.58	$0.64 \pm 0.06 \pm 0.05$
R_3	1.4	0.74	$0.69 \pm 0.11 \pm 0.12$
R_4	1.3	0.54	$0.63 \pm 0.07 \pm 0.05$

Table 6: Estimation of a_2 by interference in ${\rm B}^- \to 0-$ decays.

When the W hadronizes as $\overline{c}s$, the internal spectator can produce the decays ${\rm B} \to J/\psi{\rm K}$. The decays of the $\overline{\rm B^0}$ of this type produce CP eigenstates, and are expected to be useful in the measurement of CP violation in the ${\rm B}^0 - \overline{\rm B^0}$ system, in particular to extract $\sin 2\beta$. The CLEO-II signals in these modes, where the $J/\psi \to \ell^+\ell^-$, are shown in Fig. 4. The numbers for extraction of a_2 are shown in Table 7, and yield $|a_2| = 0.25 \pm 0.013 \pm 0.006 \pm 0.02$, in agreement with the determination from interference.

$\overline{\rm B^0}\to$	$\mathcal{B}(\%)$	BSW (%)	$\mathcal{B}(\%)$	${\rm B}^-\to$
$J/\psi\overline{\rm K}^0$	$0.08^{\pm0.03}_{\pm0.01}$	$1.82\|a_2\|^2$	$0.11^{\pm0.02}_{\pm0.01}$	$J/\psi{\rm K}^-$
$J/\psi\overline{\rm K}^{*0}$	$0.19^{\pm0.04}_{\pm0.02}$	$2.93\|a_2\|^2$	$0.21^{\pm0.06}_{\pm0.03}$	$J/\psi{\rm K}^{*-}$

Table 7: Measurement of $|a_2|$ by rate of ${\rm B} \to J/\psi{\rm K}$ decays.

To conclude this discussion of the two body decays of the B: given that a number of partial widths for the ${\rm B}^-$ are greater than those for the $\overline{\rm B^0}$, one can truly wonder whether the oft-quoted prediction that $\tau_- > \tau_0$ really has a solid foundation. It is easy to see that

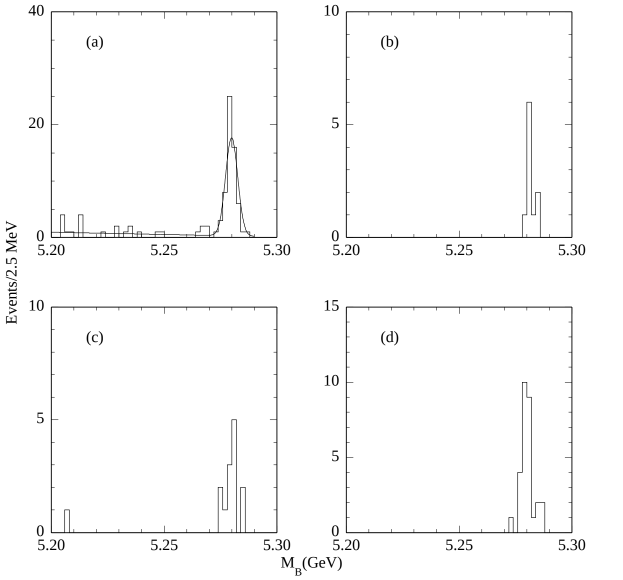

Figure 4: Beam constrained mass (M_{B}) distributions for (a) $\mathrm{B}^- \to J/\psi \mathrm{K}^-$ decays; (b) $\overline{\mathrm{B}^0} \to J/\psi \mathrm{K}^0_S$ decays; (c) $\mathrm{B}^- \to J/\psi \mathrm{K}^{*-}$ decays; and (d) $\overline{\mathrm{B}^0} \to J/\psi \mathrm{K}^{*0}$ decays.

the large differences between exclusive $\mathrm{B}^- \to 0-$ and $\overline{\mathrm{B}^0} \to +-$ rates, where the W hadronizes as $\overline{u}d$, will wash out in the inclusive decay rate: partial widths when the W hadronizes as $\overline{c}s$ or couples to leptons are surely the same between B^- and $\overline{\mathrm{B}^0}$. What is harder to see is how the remaining decay rates, predominantly high multiplicity decays where the W hadronizes $\overline{u}d$, could push the $\overline{\mathrm{B}^0}$ decay rate higher than the B^-.

Inclusive measurements of D's and J/ψ's

We have recently made new measurements of the inclusive branching ratios of B mesons to various openly charmed and hidden charmed mesons. The statistics involved in these measurements is much better than earlier results: for example, about 1500 events are used to measure $\mathrm{B} \to J/\psi X$. These measurements are summarized in Table 8. Whether the excess of D^{*0} relative to D^{*+} is due to isospin breaking in the decay sequence of excited D's, $f_{+-} \neq f_{00}$, or $\tau_- < \tau_0$ remains to be seen.

$D \to \pi\pi$

The CsI calorimeter of CLEO-II as allowed the observation of the decay modes $\mathrm{D}^+ \to \pi^+\pi^0$ and $\mathrm{D}^0 \to 2\pi^0$. The $\mathrm{D}^+ \to \pi^+\pi^0$ signal is shown in Fig. 5. CLEO-II results on all three $\pi\pi$ decay modes are given in Table 9.

One can see from Table 9 and the D lifetimes that $\Gamma(-+)/\Gamma(0+) = 1.19 \pm 0.26$, which is rather low for the D system. Before concluding that this process is spectator driven, however, note $\Gamma(00)/\Gamma(-+) = 0.63 \pm 0.12$, which is similar to the K system, so an isospin

$\mathrm{B} \to$	$\mathcal{B}$ (%)
$\mathrm{D}^0 X$	$59.1 \pm 2.3 \pm 2.1 \pm 1.6$
$\mathrm{D}^+ X$	$20.2 \pm 1.3 \pm 0.9 \pm 2.8$
$\mathrm{D}^{*0} X$	$25.1 \pm 1.9 \pm 1.2 \pm 1.7$
$\mathrm{D}^{*+} X$	$20.6 \pm 1.5 \pm 0.9 \pm 0.7$
$\mathrm{D}^0{}_{\mathrm{direct}} X$	$19.9 \pm 3.1 \pm 1.0$
$\mathrm{D}^+{}_{\mathrm{direct}} X$	$14.3 \pm 1.6 \pm 2.3$
$J/\psi X$	$1.10 \pm 0.05 \pm 0.08$
$\psi' X$	$0.28 \pm 0.05 \pm 0.05$

Table 8: Results on inclusive branching ratios. The second systematic error, when given, reflects the extrinsic systematic from propagation of errors on branching ratios used in reconstruction.

analysis is appropriate. The result of such an analysis is that the ratio of $\Delta I = 2$ to $\Delta I = 0$ amplitudes, $|A_2/A_0| = 0.72 \pm 0.13 \pm 0.11$, which is far greater than the K system, while $\delta_2 - \delta_0 = 82° \pm 8° \pm 5°$, a large phase shift.

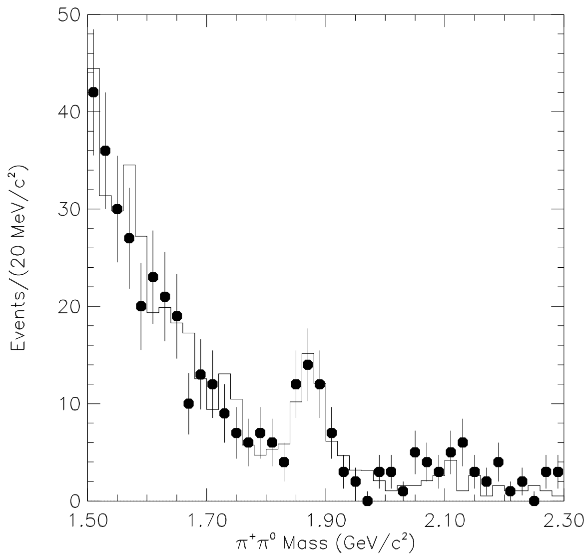

Figure 5: $\pi^0\pi^-$mass; the peak at the D^+ mass is evident. The background is from $\mathrm{K}\rho$ and $\mathrm{K}^*\pi$.

Wrong Sign Decays of the D^0

We have observed a signal from tagged D^0's decaying to $\mathrm{K}^+\pi^-$. We tag the D^0 with the charge of the soft pion from $\mathrm{D}^{*+}(\mathrm{D}^{*-}) \to \mathrm{D}^0\pi^+(\overline{\mathrm{D}}^0\pi^-)$. The $\mathrm{K}^+\pi^-$ could either result from the doubly Cabibbo-suppressed decay of the D^0, or from $\mathrm{D}^0 \to \overline{\mathrm{D}}^0$ mixing, followed by Cabibbo-allowed decay of the $\overline{\mathrm{D}}^0$.

$D\rightarrow$	$\mathcal{B}$ (%)
$\pi^-\pi^+$	$0.136 \pm 0.012 \pm 0.012$
$\pi^0\pi^0$	$0.086 \pm 0.016 \pm 0.015$
$\pi^0\pi^+$	$0.24 \pm 0.05 \pm 0.05$

Table 9: Results on $D\rightarrow\pi\pi$ branching ratios

The basic quantities of the analysis are the mass of the putative $K^+\pi^-$ system, $m_{K^+\pi^-}$, and the mass difference computed by addition of the soft pion to this system, δm. Backgrounds from K/π misidentification will tend to peak in δm, but $m_{K^+\pi^-}$ will not peak at m_{D^0}; in fact, any $m_{K^+\pi^-}$ that reconstructs near m_{D^0} under the hypothesis that a misidentification occurred is cut. Backgrounds from random slow pions will tend not to peak in δm.

The distribution of δm for $D^0\rightarrow K^+\pi^-$ candidates is shown in Fig. 6(a). For this figure, hard K/π separation cuts have been made. A signal region is defined in δm, and the projection of this signal region on the $m_{K^+\pi^-}$ axis is shown in Fig. 6(c). Sidebands in δm are projected onto the $m_{K^+\pi^-}$ axis and shown in Fig. 6(d); little peaking is evident. The difference between (c) and (d) is the signal, shown if Fig. 6(b), and is 14.9 events on an expected background of 0.9, a rather significant result.

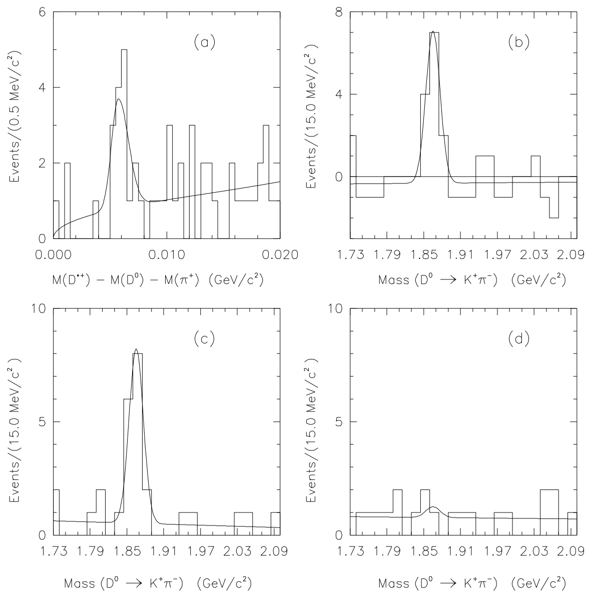

Figure 6: $D^0\rightarrow K^+\pi^-$ candidates, (a) projected on the δm axis; (c) after a cut around the expected δm, and projected on the $m_{K^+\pi^-}$ axis, (d) taken from sidebands of δm and projected on the $m_{K^+\pi^-}$ axis; and (b), the difference between (c) and (d), showing the signal of 14.9 events.

Having established the signal, the particle ID cuts are relaxed to get a measure of the branching ratio. The result is:

$$R \equiv \frac{\Gamma(D^0\{\rightarrow\overline{D}^0\}\rightarrow K^+\pi^-)}{\Gamma(D^0\rightarrow K^-\pi^+)} = [0.77 \pm 0.25 \pm 0.25]\% \quad (8)$$
$$= (2.92 \pm 0.95 \pm 0.95)\tan^4\theta_c \quad (9)$$

where θ_c is the Cabibbo angle.

Absolute D^0 and D^+ Branching Ratios

CLEO-II has also used the soft pions D^* decays to provide the normalization in new, precise measurements of the absolute branching ratios for $D^0\rightarrow K^-\pi^+$ and $D^+\rightarrow K^-\pi^+\pi^+$. The possibility of soft pions from $\overline{\Sigma}^0\rightarrow\pi^-\overline{\Lambda}_c^-$ has been excluded in a Monte Carlo independent way. The result for the D^0, where the tags are only π^+ from the D^{*+}, is:

$$\mathcal{B}(D^0\rightarrow K^-\pi^+) = (3.912 \pm 0.082 \pm 0.17)\% \qquad (10)$$

The largest contribution to the systematic error results from uncertainty in track reconstruction efficiency.

For the D^+ decay, the soft π^0 from the D^{*+} must be be used, and that bring in background from $D^{*0}\rightarrow D^0\pi^0$. The analysis is specially designed to suppress systematic uncertainty from the D^* branching ratios. The result is:

$$\mathcal{B}(D^+\rightarrow K^-\pi^+\pi^+) = (10.0 \pm 0.5 \pm 0.7 \pm 1.4)\% \quad (11)$$

The second systematic error results only from uncertainty on the relative efficiency of soft π^0 to soft π^+ reconstruction.

Conclusions

CLEO-II's large data sample has been exploited to further understanding of a number of hadronic weak decays of heavy mesons. There is clear evidence that a number of two body branching ratios for the B^- are larger than the analogous branching ratios for the $\overline{B^0}$. It remains to be seen whether, nevertheless, $\tau_0 < \tau_-$.

Acknowledgements

Many thanks to John Carr for his tolerance and persistence.

References

[1] M. Bauer, B. Stech, and M. Wirbel, *Z. Phys. C* **29**, (1985) 637; *ibid* **34**, (1987) 103; *ibid* **42**, (1989) 671.