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HAS THE CHARM DEFICIT REALLY VANISHED ?

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ABSTRACT

Many experiments have observed charmed particles inclusively in e^+e^- annihilation, hadro-, photo-, and neutrino- production, and recently in the direct cascade process from B meson decay. The scale of these measurements is set largely by the branching ratios $\mathrm{B}(D^0 \to K^-\pi^+)$ and $\mathrm{B}(D^+ \to K^-\pi^+\pi^+)$. These branching fractions have been measured by attributing the enhancement in the total hadronic cross section at the $\psi(3770)$ resonance to $D\bar{D}$ production, and normalizing the rates for $K^-\pi^+$ and $K^-\pi^+\pi^+$ accordingly. These height measurements however exhibit a wide variance. Two years ago a new technique for measuring branching fractions was introduced by the Mark III, which largely avoided the cross section normalization. The result, however, yielded significantly larger values for all branching ratios while leaving their relative values unchanged. In turn, it created a problem for subsequent high statistics inclusive measurements of charm (in particular the continuum e^+e^- production rate and B cascade decay rates) where an $\sim 50\%$ "deficit" of charm was claimed to exist by CLEO. With the rescaling downward by 24 % (21 %) of the Mark III D^0 (D^+) values, the so-called "charm deficit" is again addressed in this review. Also introduced here are new measurements from ARGUS and HRS which also directly address the issue of charm normalization with statistics comparable to other measurements. Finally, an attempt is made to understand the whole body of $\psi(3770)$ resonance data.

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1. INTRODUCTION TO THE DEFICIT PROBLEM

The first[1] direct determination of charmed D meson branching ratios (B_i), led to values $\sim 50\%$ greater than those determined by dividing charm production rates ($\sigma_D \cdot B$) at the $\psi(3770)$ by the resonance height, (σ_D) determined in the most recent scans.[2] Large variations in σ_D from the numerous scans[2][3] of the $\psi(3770)$ confused the early picture. While the hadronic widths (Γ_h) were similar, suggesting a strong decay to $D\bar{D}$ pairs, the leptonic widths (Γ_e) had a large variance. The direct method,[1] yielding a subtantially smaller value for σ_D, suggested the possibility of a large non-$D\bar{D}$ partial width of the $\psi(3770)$ contrary to the naive assumption. This has however been ruled out by examination of the x distribution of tracks at the $\psi(3770)$ resonance.[4] Recently, the issue was reopened by the high statistics results of CLEO[5] measuring D meson production in the continuum and from the cascade of B decays. Using latest[1] B_i, they interpret their results as indicating an $\sim 50\%$ "deficit" of charm.[5][6] I detail here a reanalysis of Mark III data that reflects corrections for contamination in ref.[1], by known Cabibbo suppressed decays (CSD), and previously unmeasured multi-π^0 decays. The size of the corrections (21 to 24 %) in the new analysis cannot fully account for the CLEO charm deficit. In light of these results and new ARGUS[7] and HRS[8] results, I re-examine the charm deficit issue in a statistically rigorous manner, showing that a sizeable part of the original "deficit" cannot be attributed to the Mark III analysis.

2. DETAILS OF THE NEW ANALYSIS

The new analysis utilizes the same data sample (9.56 pb^{-1}), particle identification and kinematic fitting previously employed. Briefly, the exclusive production of D^+D^- and $D^0\bar{D}^0$ at the $\psi(3770)$ allows the isolation of two classes of events: *single tags*, wherein only one D of a pair is reconstructed, and *double tags* wherein both D mesons are reconstructed through kinematic fitting of the reaction $e^+e^- \rightarrow X\bar{X} \rightarrow$ final state, with the constraint $M_X = M_{\bar{X}}$. By comparing the number of single and double tag events, individual B_i are determined *independent of* σ_D. The single tags, having smaller statistical errors, determine relative B_i, while double tags establish the absolute scale. As the issue is one of normalization, establishing the purity of the double tag sample is essential. The focus then is on backgrounds to this sample escaping the original *sideband* subtraction. That is, those backgrounds which peak at the D mass, and have similar width.

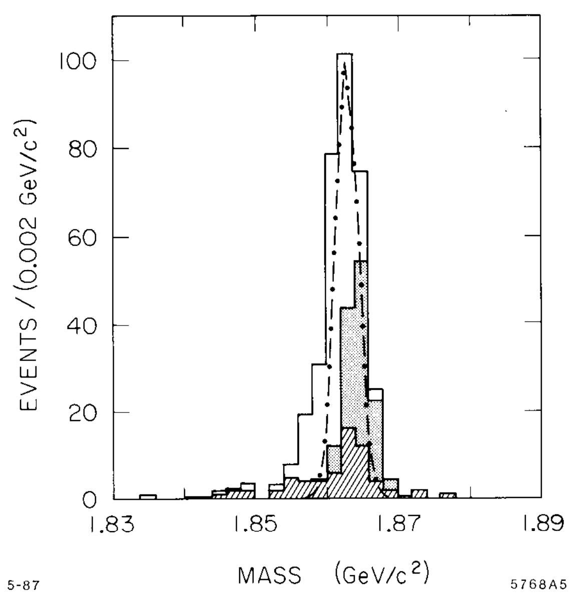

Fig. 1 M_X from fits to $K^-\pi^+$ *vs.* $K^+\pi^-$(dot-dash), $K^-\pi^+$ *vs.* ($\pi^+\pi^-$ (shaded), $K^+\pi^-\pi^0$ (hatched), and K^+K^-(solid)).

Monte Carlos (MC) of all known D decays that pass the original χ^2 cut on the kinematic fit, indicate that such backgrounds come exclusively from true $D\bar{D}$ pairs where *only* one D is correctly identified. Such errors arise from either (*i*) a single particle misidentification, or (*ii*) the loss of one soft π^0.

Background (*i*) comes from CSD having the correct P_D, but incorrect E_D after $\pi^\pm \rightleftharpoons K^\pm$ interchange. Background (*ii*) comes from higher multiplicity Cabibbo allowed channels with one or more soft π^0's, where one π^0 is lost. Large E_γ errors allow such losses within the χ^2 cut on the fit. When one D is correctly identified, the fit cannot reject a second erroneous D with the original χ^2 cut. The M_X distributions from MC (Fig. 1) for both the signal ($K^-\pi^+$ *vs.* $K^+\pi^-$) and the background ($K^-\pi^+$ *vs.* (K^+K^- or $\pi^+\pi^-$ or $K^+\pi^-\pi^0$)), indicate how these decays produce peaks similar to a true signal.

To remove these backgrounds an additional kinematic cut on ***each*** D meson of a double tag is imposed; the ***unfitted*** invariant mass (M_{inv}) is compared with the beam constrained mass (M_{bc}).[9] The differences, $\Delta M \equiv M_{bc} - M_{inv}$, are shown in Fig. 2 for the $K^-\pi^+$ mode of the original analysis and for MC of the signal ($K^-\pi^+$) and the dominant backgrounds (K^-K^+, $\pi^-\pi^+$, and $K^-\pi^+\pi^0$). Requiring $|\Delta M| \leq 60$ MeV, ($-120 \leq \Delta M \leq 100$ MeV), for modes containing only charged particles (containing π^0's), removes all background with a $\leq 5\%$,($\leq 30\%$) loss in efficiency.

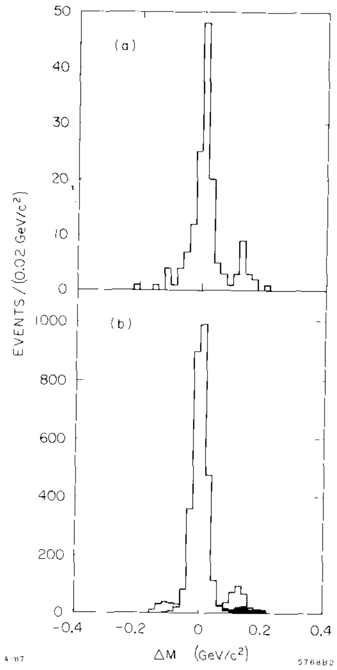

Fig. 2 ΔM for (a) data, (b) MC of:(i) signal ($K^-\pi^+$ *vs.* $K^+\pi^-$), and (ii) backgrounds ($K^-\pi^+$ *vs.* $\pi^-\pi^+$ (hatched), $K^-\pi^+$ *vs.* $K^+\pi^-\pi^0$ (solid), and $K^-\pi^+$ *vs.* K^-K^+ (shaded)).

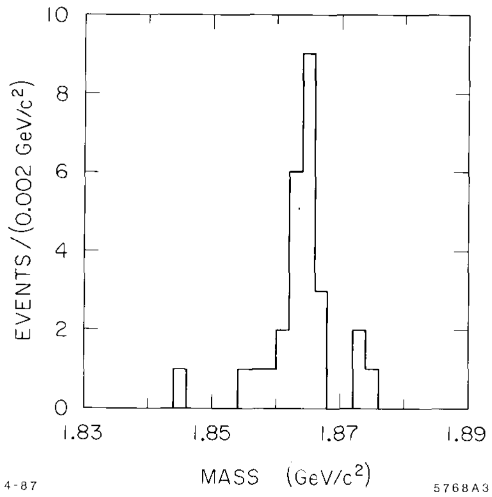

Fig.

To demonstrate that the ΔM cut provides adequate background suppression ***regardless of the source***, MC of all contributing topologies were generated and compared with the data. Measurements of many CSD[10] and of several modes containing one π^0 exist;[1] no data has previously been available on multi-π^0 decays. Examination of the double tags containing candidates for $D^0 \to K^-\pi^+\pi^0$ indicates, however, the presence of an additional π^0 in a subset of events that survive the kinematic fit but fail the ΔM cut. These events, which form the largest background to $K^-\pi^+\pi^0$ in the previous analysis, arise from the multi-π^0 decay $D^0 \rightarrow K^-\pi^+\pi^0\pi^0$. We observe 24 ± 5 events in fully reconstructed $D^0\bar{D}^0$ events along with $K^+\pi^-$ (see Fig. 3).

Table I. Signal Events Lost by the ΔM Cut

Double Tag Channels	Predicted Loss	Obs. Loss
$K^-\pi^+$ *vs.* $K^+\pi^-$	6±2	11±4
$K^-\pi^+$ *vs.* $K^+\pi^-\pi^0$	48±6	50±8
$K^-\pi^+$ *vs.* $K^+\pi^-\pi^-\pi^+$	11±2	13±5
$K^-\pi^+\pi^0$ *vs.* $K^+\pi^-\pi^0$	49±9	34±14
$K^-\pi^+\pi^0$ *vs.* $K^+\pi^-\pi^-\pi^+$	40±6	53±10
$K^-\pi^+\pi^+\pi^-$ *vs.* $K^+\pi^-\pi^-\pi^+$	2±1	1±3
$K^-\pi^+\pi^+$ *vs.* $K^0\pi^-$	2±1	2±1
$K^-\pi^+\pi^+$ *vs.* $K^+\pi^-\pi^-$	4±1	8±3
$K^-\pi^+\pi^+$ *vs.* $K^0\pi^-\pi^0$	6±2	4±4
Total Events Rejected	168±13	176±21

To further test our rejection of backgrounds, Table I summarizes a MC study of the absolute number of signal events removed by the ΔM cut. The loss of 176 ± 21 original events by the cut agrees with that predicted (168±13) from all known D background sources. As the ΔM cut is more general, this implies that all major backgrounds must now be accounted for. The sideband subtraction is applied and the results combined with the single tags allowing separate fits to the D^0 and D^+ samples.[1] The B_i are given in Table II, where they are seen to be reduced from those reported in ref. [1] by 21% $\rightarrow$ 24%. The cross-sections $\sigma_{D^0} = (5.8 \pm 0.5 \pm 0.6)$ n b and $\sigma_{D^+} = (4.2 \pm 0.6 \pm 0.3)$ nb are obtained from the fitted number of produced events ($27.7 \pm 2.4 \pm 2.6$ K $D^0\bar{D}^0$ and $20.3 \pm 2.9 \pm 1.1$ K D^+D^-) and the luminosity. The ratio $\sigma_{D^0}/\sigma_{D^+} = 1.36 \pm 0.23 \pm 0.14$ remains largely unchanged from the previous result.[1] This cross section ratio agrees well with the expectation from the coupled channel potential models[11] which predict a ratio of $\sim$ 1.36. More importantly, the agreement is further evidence that the new analysis is correct, since substantially larger corrections were applied to the D^0, and the fits for D^0 and D^+ are completely independent. A new HRS measurement[8] of $B(D^0 \rightarrow K^-\pi^+) = 4.0 \pm 0.6^{+0.7}_{-0.6}$ using daughter $\pi^\pm$ from D^* decay to tag charm, also confirms our new analysis.

Table II. D^0 and D^+ Branching Fractions

Decay Mode	Branching Fraction (%)
$D^0 \rightarrow K^-\pi^+$	$4.2 \pm 0.4 \pm 0.4$
$D^0 \rightarrow K^-\pi^+\pi^-\pi^+$	$9.1 \pm 0.8 \pm 0.8$
$D^0 \rightarrow K^-\pi^+\pi^0$	$13.3 \pm 1.2 \pm 1.3$
$D^+ \rightarrow K^-\pi^+\pi^+$	$9.1 \pm 1.3 \pm 0.4$
$D^+ \rightarrow \bar{K}^0\pi^+$	$3.2 \pm 0.5 \pm 0.2$
$D^+ \rightarrow \bar{K}^0\pi^+\pi^0$	$10.2 \pm 2.5 \pm 1.6$
$D^+ \rightarrow \bar{K}^0\pi^+\pi^-\pi^+$	$6.6 \pm 1.5 \pm 0.5$
$D^0 \rightarrow K^-\pi^+\pi^0\pi^0$	$14.9 \pm 3.7 \pm 3.0$

3. THE CHARM DEFICIT REVISITED

The HRS result,[8] provides the first direct confirmation of the correction to the scale for charmed B_i. The continuum production of charm in e^+e^-, cascade charm from B decay, and the $\psi(3770)$ height are the three additional primary pieces of physics evidence testing the this scale. To compute new values for $\mathrm{Br}(B \rightarrow D + X)$ and $\mathrm{R}(e^+e^- \rightarrow D + X)$ requires that we return to the original product branching fractions,[12] and $\sigma \cdot Br$ for each process. Table III summarizes the results from CLEO[5] and ARGUS,[7] using the B_i from Table II. Care has been taken to exclude where appropriate, common scale uncertainties (either the B_i or σ_c) to allow a proper comparison between experiments. Table III is very illustrative since two comparisons are possible: between experiments measuring the same quantity, and between experiment and theory. Moreover, two separate but similar *quantities* are available for each of those cases - namely, cascade charm from B decays and charm from the e^+e^- continuum.

Table III. Charm from B Decay and Continuum[†]

Measured	ARGUS	CLEO	Difference
$B(B \to D^0 + X)B(D^0 \to K\pi)$	$(2.6 \pm .30) \times 10^{-2}$	$(2.1 \pm .26) \times 10^{-2}$	$+1.3\sigma$
$B(B \to D^+ + X)B(D^+ \to K\pi\pi)$	$(2.3 \pm .40) \times 10^{-2}$	$(1.9 \pm .45) \times 10^{-2}$	$+0.7\sigma$
$B(B \to D^0 + X)$	0.63 ± 0.07	0.50 ± 0.06	$+1.3\sigma$
$B(B \to D^+ + X)$	0.25 ± 0.04	0.20 ± 0.05	$+0.7\sigma$
Total $B(B \to D + X)$	0.88 ± 0.08	0.70 ± 0.08	$+1.5\sigma$
Theoretical Expectation[††]	0.95	0.95	
Deviation from Theory[‡]	-0.6σ	-2.4σ	
$R(e^+e^- \to D^0 + X)$[♮]	0.52±0.065	0.41±0.042	$+1.4\sigma$
$R(e^+e^- \to D^+ + X)$[♮]	0.17±0.023	0.19±0.030	-0.5σ
Total $R(e^+e^- \to D + X)$	0.69±0.069	0.60±0.049	$+1.1\sigma$
Theoretical Expectation[♯]	0.70	0.70	
Deviation from Theory[‡♭]	-0.1σ	-1.0σ	

[†] Common errors associated with B_i are excluded except where noted. [††] Assumes 1.15 charmed particles per B decay, where 0.20 is accounted as $c\bar{c}$ states, D_s, D_s^* and c-baryons.[5] [‡] Includes 13% (15%) error for $K\pi$ ($K\pi\pi$) branching fractions. [♮] ARGUS (CLEO) results at $\sqrt{s}$ =10.23 (10.55) GeV, use $\sigma_c = 2.83 \pm 0.04 \pm 0.18 (2.66 \pm 0.04 \pm 0.17)$, respectively. Common errors in σ_c and R_c are removed. [♯] Assumes R(D_s)≈R(c-baryons)≈0.15. [♭] Stat. and syst. error in σ_c are added in quadrature.

Table III indicates that when errors common to ARGUS and CLEO are removed, (*eg:* the B_i and the charm cross section, σ_c), allowing a direct comparison to be made, the agreement between experiments is poor. Three of the four independent CLEO values lie below those of ARGUS by 1.4σ, 1.3σ, and 0.7σ. The probability that these experiments are sampling the same parent distribution is 2.7%. This suggests a systematic error which is not related to the charm B_i normalization. *The sign is such that CLEO measures less charm than ARGUS, which itself could account for slightly less than one half of the original charm deficit, claimed by CLEO.*

The next step is to divide out the charm meson branching ratios and compare to theoretical expectations. At this stage, errors are propagated from the B_i and σ_c. We observe that while the two independent ARGUS results are close to the theoretical prediction (-0.6 and -0.1 σ), the CLEO results fall systematically lower, in one case (charm from B decay), by as much as 2.4σ and in the other (continuum charm), about 1.0σ. The probability of all four measurements being negative is $\sim$ 6.3%, while the probability of observing the values reported is $\sim$ 1.3%. Of course, in neither case are *theoretical uncertainties* included. These come from unknown quark masses effecting the expected value of 1.15 charm particles per B decay, the fraction of D_s, $c\bar{c}$ bound states and baryons (charmed and uncharmed) in B decay, and charm fragmentation (the influence of states such as D^{**}). Many of these uncertainties are also present in the continuum analysis.

4. THE $\psi(3770)$ SCANS REVISITED - AN ATTEMPT TO UNDERSTAND σ_D

The comparison of old $\psi(3770)$ scans and the direct σ_D of ref. [1], was the source of much initial confusion. To reconcile our new σ_D value with the scans is difficult in part because early scan measurements didn't include the necessary τ subtractions. Table IV attempts to correct the problem by applying the τ corrections suggested by later papers.[2,3] [13] Also included in the last row is a new and speculative ansatz. I assume that the direct (tagged) measurement of the average semileptonic D branching ratio at the $\psi(3770)$ ($< B_e >$) can be taken as a weighted average of the MKII and Mark III values, namely $B(D \to e + X) = 11.5 \pm 1.0$ %. Both DELCO and LGW measured leptons directly from the $\psi(3770)$ and divided by the total resonance height to get the weighted average $< B_e >$ for D mesons. If we assume the lepton rate was correct, then then another correction to Γ_h for DELCO and LGW ought to be made bringing their $< B_e >$ into agreement with the direct (MKII and MKIII) measurements. CB and MKII do not need the τ correction, nor do they measure leptons inclusively. I leave them unchanged in the table. One observes that parity between experiments can then be nearly achieved after these two systematic corrections. This provides further, albeit weaker evidence for the validity of the new B_i scale.

Table IV. Charm Cross Sections at the $\psi(3770)$ (nanobarns)

Experiments.	LGW	MKII	DELCO	CB	MarkIII
$\sqrt(s)$(GeV)	3.774	3.771	3.770	3.771	3.768
Measurement	10.3 ± 1.6	7.0 ± 1.1	6.0 ± 1.2	6.4 ± 0.9	$5.1 \pm 0.4 \pm 0.5$
$\tau\bar{\tau}$ – corrected	9.1 ± 1.4	7.0 ± 1.1	5.3 ± 1.1	6.4 ± 0.9	$5.1 \pm 0.4 \pm 0.5$
B_e – corrected	6.0 ± 2.4	7.0 ± 1.1	3.7 ± 0.8	6.4 ± 0.9	$5.1 \pm 0.4 \pm 0.5$

5. CONCLUSIONS

The original results[1] of MarkIII on charmed branching fractions have been revised downward by 21 to 24 %, but leave relative branching ratios intact. This correction is attributable to two backgrounds feeding into the signal. The first, from known Cabibbo suppressed decays, and the second from previously unobserved multi-π^0 decays; the latter having a large branching ratio. This correction is consistent with the subsequent HRS result on $B(D^0 \to K^-\pi^+)$, which has somewhat larger errors.

The shift of the branching ratios that we observe is unable to fully account for the large (~ 50% "charm deficit" in the e^+e^- continuum and B decay, originally claimed by CLEO.[5,6] Recent results by ARGUS appear to exhibit systematically larger values for charmed D meson production *both* in the continuum and from cascade B decay, than CLEO. They are in closer agreement with naive theoretical expectations for these processes.

An interesting facet of this picture, is to try to understand the original $\psi(3770)$ scan data which also sets the scale on B_i. I have shown that with some concrete corrections for $\tau\bar{\tau}$ production, and some speculative corrections based on their lepton measurements, it is possible to bring the measurements into line with σ_D from the direct measurement.

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