A STUDY OF CABIBBO ANGLE FAVORED DECAYS: $D_s \to VP$

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We have studied Cabibbo angle favored decays of D_s (old F) into a vector and a pseudo-scalar meson (VP modes) in factorization of the hadron currents approximation. The technique and the model were applied and tested, in the past, for the calculation of several two body decays of hadrons. The branching ratio for the decays $D_s \to \phi\pi$, $D_s \to K^*K$ and $D_s \to \rho\eta$ (η') are estimated. The results are found to be in general agreement with the experimental values and consistent with few other theoretical values. We also estimate the branching ratio for the decay $D_s \to \rho\pi$, which can occur only via quark flavor annihilation process and found it to be in agreement with the recent data by ARGUS at the DORIS II e^+e^- storage ring at DESY.

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1. *Introduction*

Non-leptonic weak decays are of particular interest because of the interplay of weak and strong interactions. Recently [1–5] the branching ratios for D_s^+ (old F^+) $\to \phi\pi^+$ and $D_s^+ \to \overline{K}^{*0}K^+$ have been measured. In this paper we have studied Cabibbo angle favored D_s^+ decays into a vector and a pseudo-scalar meson ($D_s^+ \to VP$).

The influence of short and long range QCD (quantum chromodynamics) forces on weak amplitudes makes detailed predictions of non-leptonic decays very difficult. For example, the $\Delta I = 1/2$ enhancement in strange particle decays has always been considered a difficult problem and never been understood in a very satisfactory way. However, for energetic two-body decays of heavy mesons (e.g. D, D_s etc.) the situation is less difficult. It appears to be possible that the factorization approximation of the hadron currents [6] can be used to analyse the two-body decays [7]. We adopt the technique used successfully in Ref. [7] to discuss the two-body D-decays. The D_s^+-decays have been discussed in Refs [8–12] adopting different approaches.

2. $D_s^+ \to VP$

2.1. $D_s^+ \to \phi\pi^+$

We use the weak Hamiltonian

$$H_w = \frac{G_F}{\sqrt{2}} \cos^2 \theta_C \left[\frac{(C_+ + C_-)}{2} (\bar{u}d)^\mu (\bar{s}c)_\mu + \frac{(C_+ - C_-)}{2} (\bar{u}c)^\mu (\bar{s}d)_\mu\right] \tag{1}$$

where $(\bar{u}d)^\mu$ etc. represent the left-handed hadronic currents and C_+ and C_- are the quantum chromodynamics (QCD) coefficients. In the factorization approximation the amplitude for $D_s^+ \to \phi\pi^+$ is given by [7] (upto an overall constant),

$$A(D_s^+ \to \phi\pi^+) = C_1 \langle \pi^+ | (\bar{u}d) | 0 \rangle \langle \phi | (\bar{s}c)_\mu | D_s^+ \rangle, \tag{2}$$

where $C_1 = (2C_+ + C_-)/3$. This is a pure spectator process. Using

$$\langle \pi^+ | (\bar{u}d)^\mu | 0 \rangle = -i\sqrt{2} f_\pi p_\pi^\mu \tag{3}$$

and Partially Conserved Axial Vector Current (PCAC) hypothesis,

$$\partial_\mu A_\mu^{13+i14} = m_{D_s}^2 f_{D_s} P^{13+i14}, \tag{4}$$

we obtain

$$A(D_s^+ \to \phi\pi^+) = -2\sqrt{2} (\varepsilon \cdot k) C_1 f_\pi f_{D_s} g_{VPP}, \tag{5}$$

where k is the pion 4-momentum and we have used a $V_i \to P_j P_k$ vertex

$$g_{ijk} = f_{ijk} \varepsilon \cdot (p_j - p_k) g_{VPP}. \tag{6}$$

We use $g_{VPP}^2/4\pi \simeq 3$ from $\varrho \to \pi\pi$ width.

We can normalize $D_s^+ \to \phi\pi^+$ amplitude to that for $D^+ \to \overline{K}^0 \varrho^+$ and extract the branching ratio for $D_s^+ \to \phi\pi^+$. $D^+ \to \overline{K}^0 \varrho^+$ is also a pure spectator process with a decay amplitude [7] (k is the kaon 4-momentum),

$$A(D^+ \to \overline{K}^0 \varrho^+) = 2\sqrt{2} (\varepsilon \cdot k) C_1 g_V f_+^{D_s^*}(m_\varrho^2) - \frac{C_2 f_K f_D m_D^2}{m_D^2 - m_K^2} g_{VPP}. \tag{7}$$

$f_+^{D_s^*}(m_\varrho^2)$ is the form factor defined by following matrix element:

$$\langle P_i | V_j^\mu | P_k \rangle = i f_{ijk} [(p_k + p_i)^\mu f_+(q^2) + (p_k - p_i)^\mu f_-(q^2)]. \tag{8}$$

D_s^* (old F^* at 2.1 GeV) contributes to this form factor. g_V is defined [7] through

$$\langle 0 | V_i^\mu | V_j \rangle = \delta_{ij} g_V \varepsilon^\mu \tag{9}$$

and $g_V = 0.12$ GeV^2 is determined from $g_V = m_\varrho^2/f_\varrho$ with $f_\varrho^2/4\pi = 2.0$ (from $\varrho \to e^+e^-$ rate). $f_+^{D_s^*}(q^2)$ in the pole approximation is given by [7]

$$f_+^{D_s^*}(q^2) = 1 \Big/ \left(1 - \frac{q^2}{m_{D_s^*}^2}\right). \tag{10}$$

The QCD coefficient $C_2 = (2C_+ - C_-)/3$.

The QCD coefficients (C_1 and C_2) are obtained from the analysis of Cabibbo angle favored D-decays and Cabibbo angle suppressed D-decays [13] as $C_1/C_2 = -(3.0)$. To estimate $B(D_s^+ \to \phi\pi^+)/B(D^+ \to \bar{K}^0\varrho^+)$ we need the knowledge of f_D and f_{D_s}. f_D and f_{D_s} are not known experimentally and the theoretical predictions are varying in a wide range [14]. Therefore, we use few different values in our numerical estimations.

With $m_{D_s^*} = 2.1$ GeV and $f_K = 0.12$ GeV for $f_K = f_D$ and $f_D/2$ we find

$$\frac{B(D_s^+ \to \phi\pi^+)}{B(D^+ \to \bar{K}^0\varrho^+)} = 0.09, \quad (f_{D_s} = 0.12 \text{ GeV and } f_K = f_D)$$

$$= 0.11, \quad (f_K = f_D/2)$$

$$= 0.23, \quad (f_{D_s} = 0.18 \text{ GeV and } f_K = f_D)$$

$$= 0.26, \quad (f_K = f_D/2)$$

$$= 0.41, \quad (f_D = 0.24 \text{ GeV and } f_K = f_D)$$

$$= 0.46, \quad (f_K = f_D/2), \tag{11}$$

where we have used [15] $\tau_{D_s^+}/\tau_{D^+} = 0.55$. Since $B(D^+ \to \bar{K}^0\varrho^+)$ is 12% or 17% (Ref. [16]) the experimental value [1–5] of $B(D_s^+ \to \phi\pi^+) \simeq (2\text{–}4)\%$ can be obtained from (11) with $f_{D_s} \simeq (1.5\text{–}2)f_K$, which is a reasonable theoretical value [14]. Furthermore, the errors in [15] $\tau_{D_s^+}$ and in [16] $B(D^+ \to \bar{K}^0\varrho^+)$ could also be considered to affect our estimate.

2.2. $D_s^+ \to \bar{K}^{*0}K^+$ and $\bar{K}^0K^{*+}$

The decay amplitude for $D_s^+ \to \bar{K}^{*0}K^+$ in the factorization approximation is

$$A(D_s^+ \to \bar{K}^{*0}K^+) = C_1\langle K^+\bar{K}^{*0}|\,(\bar{u}d)\,|0\rangle\,\langle 0|\,(\bar{s}c)\,|D_s^+\rangle + C_2\langle\bar{K}^{*0}|\,(\bar{s}d)\,|0\rangle\,\langle K^+|\,(u\bar{c})\,|D_s^+\rangle. \tag{12}$$

The spectator term (second term) in (12) is calculated using (8) and (see Eq. (9))

$$\langle\bar{K}^{*0}|\,(\bar{s}d)\,|0\rangle = \sqrt{2}\,g_V\varepsilon_\mu. \tag{13}$$

We obtain for the spectator term (k is the kaon 4-momentum)

$$\langle\bar{K}^{*0}|\,(\bar{s}d)\,|0\rangle\,\langle K^+|\,(u\bar{c})\,|D_s^+\rangle = 2\sqrt{2}\,(\varepsilon\cdot k)g_V f_+^{D^*}(m_{K^*}^2). \tag{14}$$

The annihilation term in (12) is parametrized, as was done in Ref. [7] for D → VP decays, as follows

$$\langle K^+\bar{K}^{*0}|\,(\bar{u}d)\,|0\rangle\,\langle 0|\,(\bar{s}c)\,|D_s^+\rangle = \sqrt{2}f_{D_s}(\varepsilon\cdot k)\hat{R}. \tag{15}$$

The naive PCAC value of $\hat{R}$ is

$$(\hat{R})_{\text{naive PCAC}} = 2f_\pi\,\frac{m_\pi^2}{m_{D_s}^2 - m_\pi^2}\,g_{VPP}. \tag{16}$$

This naive PCAC value of $\hat{K}$ suppresses the annihilation term. However, since the amplitude is required at $q^2 = m^2_{D_s}$, the naive PCAC extrapolation is bound to fail as was the case in $D \to VP$ decays [7].

The decay amplitude for $D_s^+ \to \bar{K}^{*0}K^+$ is finally given by

$$A(D_s^+ \to \bar{K}^{*0}K^+) = \sqrt{2}\,(\varepsilon \cdot k)\,[2C_2 g_V f_+^{D^*}(m^2_{K^*}) + C_1 f_{D_s}\hat{K}]. \tag{17}$$

As in the discussion [7] of $D \to VP$ decays we treat the annihilation parameter K as a free parameter to be determined from data. From (5) and (17) we can evaluate the ratio $B(D_s^+ \to \bar{K}^{*0}K^+)/B(D_s^+ \to \phi\pi^+)$. This ratio is quoted [4] to be 1.44 ± 0.37. In Table I we tabulate

TABLE I

$B(D_s^+ \to \bar{K}^{*0}K^+)/B(D_s^+ \to \phi\pi^+)$ vs $\hat{K}$. Columns (a), (b) and (c) use f_{D_s} = 0.12 GeV, 0.18 GeV and 0.24 GeV respectively

$\hat{K}$ (GeV)	(a)	(b)	(c)
−0.8	1.10	0.84	0.73
−1.0	1.47	1.18	1.04
−1.2	1.90	1.56	1.40
−1.4	2.38	2.00	1.83

this ratio for three different values of f_{D_s}. It is clear that $\hat{K} \simeq -1.0$ GeV is required to fit the experimental [4] value of this ratio. We note that the analogous annihilation parameter K appearing [7] in $D \to VP$ decays was considerably larger. We wish to point out at this stage that without the annihilation term, i.e. if $\hat{K} = 0$ in (17), one obtains $B(D_s^+ \to \bar{K}^{*0}K^+)/B(D_s^+ \to \phi\pi^+) \simeq 0.07$, in strong disagreement with the data [4].

We now turn to the decay $D_s^+ \to K^{*+}\bar{K}^0$, which in the naive diagramatic approach would not differ from $D_s^+ \to \bar{K}^{*0}K^+$. However, the spectator terms in these two modes involve somewhat different physics. In the former decay mode the vector particle results from the hadronization of the *spectator* $\bar{s}$ with u while in the latter the vector particle results from the hadronization of the *decay* s with $\bar{d}$. One should expect these two processes to be not the same because of the expected differences in the distribution functions of the spectator quark and the decay quark. This difference is reflected in our approach.

In the factorization approximation we obtain

$$A(D_s^+ \to K^{*+}\bar{K}^0) = C_1\langle K^{*+}\bar{K}^0|\,(\bar{u}d)\,|0\rangle\,\langle 0|\,(s\bar{c})\,|D_s^+\rangle$$
$$+ C_2\langle \bar{K}^0|\,(\bar{s}d)\,|0\rangle\,\langle K^{*+}|\,(\bar{u}c)\,|D_s^+\rangle. \tag{18}$$

The spectator term (second term) in (18) can be evaluated by using PCAC hypothesis (4) with SU(4) labels (9+i10) for D^0-meson with the result (k is the kaon 4-momentum),

$$\langle \bar{K}^0|\,(\bar{s}d)\,|0\rangle\,\langle K^{*+}|\,(\bar{u}d)\,|D_s^+\rangle = -2\sqrt{2}\,(\varepsilon \cdot k) f_K f_D \frac{m_D^2}{m_D^2 - m_K^2}\, g_{VPP}. \tag{19}$$

TABLE II

$B(D_s^+ \to \overline{K}^{*0}K^+)/B(D_s^+ \to K^{*+}\overline{K}^0)$ vs $\hat{K}$. Columns (a), (b) and (c) use f_{D_s} = 0.12 GeV, 0.18 GeV and 0.24 GeV, respectively

$\hat{K}$ (GeV)	(a)	(b)	(c)
−0.8	1.32	1.23	1.18
−1.0	1.27	1.19	1.15
−1.2	1.23	1.16	1.13
−1.4	1.20	1.14	1.11

A comparison of (14) and (19) shows that structurally the spectator terms in $D_s^+ \to \overline{K}^{*0}K^+$ and $D_s^+ \to K^{*+}\overline{K}^0$ are different reflecting the difference in the physics involved. The annihilation term in (18) can be parametrized the same way as in (15). Our final result for the decay amplitude is

$$A(D_s^+ \to K^{*+}\overline{K}^0) = -\sqrt{2}\,(\varepsilon \cdot k)\left[2C_2 f_K f_D \frac{m_D^2}{m_D^2 - m_K^2}\, g_{VPP} + C_1 f_{D_s}\hat{K}\right]. \tag{20}$$

The sign difference between (17) and (20) arises from the SU(4) Clebsch–Gordan coefficients. In Table II we have listed the ratio $B(D_s^+ \to \overline{K}^{*0}K^+)/B(D_s^+ \to K^{*+}\overline{K}^0)$ for different values of f_{D_s} and $\hat{K}$. We have used $f_K = f_D = 0.12$ GeV. We notice that with $\hat{K}$ around 1.0 GeV this ratio is between 1.15 and 1.25.

2.3. $D_s^+ \to \varrho^+\eta$ and $\varrho^+\eta'$

Consider $D_s^+ \to \varrho^+\eta$ first. In the factorization approximation the decay amplitude is

$$A(D_s^+ \to \varrho^+\eta) = C_1[\langle\varrho^+|(\bar{u}d)|0\rangle\langle\eta|(\bar{s}c)|D_s^+\rangle$$
$$+\langle\varrho^+\eta^0|(\bar{u}d)|0\rangle\langle 0|(s\bar{c})|D_s^+\rangle]. \tag{21}$$

The second term in (21), the annihilation term, vanishes for the following reasons. Only the axial vector part of $(\bar{u}d)$ can contribute to the matrix element. If the axial vector current is a first class current, it has an odd G-parity. This will forbid its coupling to the $\varrho\eta$ system which has an even G-parity. It is also easy to check that an F-type coupling of the divergence of the axial $(\bar{u}d)$ current to $\varrho\eta$ system vanishes. Hence only the first term in (21) survives. It is evaluated by using (8) and (9) with the result (k is the η-meson 4-momentum),

$$A(D_s^+ \to \varrho^+\eta) = -\frac{4}{\sqrt{3}}C_1(\varepsilon \cdot k)g_V f_+^{D_s^*}(m_\varrho^2). \tag{22}$$

The amplitude for $D_s^+ \to \varrho^+\eta'$ is evaluated analogously to be

$$A(D_s^+ \to \varrho^+\eta') = 2(\tfrac{2}{3})^{1/2}C_1(\varepsilon \cdot k)g_V f_+^{D_s^*}(m_\varrho^2). \tag{23}$$

Thus from (22) and (23) it is evident that the ratio $B(D_s^+ \to \varrho^+\eta')/B(D_s^+ \to \varrho^+\eta)$ is determined entirely by the Clebsch–Gordan coefficients and the phase space. We obtain

$$B(D_s^+ \to \varrho^+\eta')/B(D_s^+ \to \varrho^+\eta) \simeq 0.13. \tag{24}$$

Furthermore from (5) and (22) we can evaluate $B(D_s^+ \to \varrho^+\eta)/B(D_s^+ \to \phi\pi^+)$. Using $f_\pi = 0.093$ GeV, $f_K = 0.12$ GeV, $g_V = 0.12$ GeV^2 and $f_+^{D_s^*}(m_\varrho^2)$ from (10) we obtain

$$B(D_s^+ \to \varrho^+\eta)/B(D_s^+ \to \phi\pi^+) = 2.8, \quad f_{D_s} = 0.12 \text{ GeV}$$
$$= 1.2, \quad f_{D_s} = 0.18 \text{ GeV}$$
$$= 0.70, \quad f_{D_s} = 0.24 \text{ GeV}. \tag{25}$$

Thus $B(D_s^+ \to \varrho^+\eta)$ should be comparable to $B(D_s^+ \to \phi\pi^+)$. $B(D_s^+ \to \varrho^+\eta')$ should be almost an order of magnitude lower.

2.4. $D_s^+ \to \varrho^0\pi^+$

This is a pure annihilation process. The decay amplitude in the factorization approximation is given by (k is the pion 4-momentum)

$$A(D_s^+ \to \varrho^0\pi^+) = C_1\langle\varrho^0\pi^+|(\bar{u}d)|0\rangle\langle 0|(\bar{s}c)|D_s^+\rangle$$
$$= -2C_1 f_{D_s}(\varepsilon\cdot k)\hat{K}. \tag{26}$$

We normalize $B(D_s^+ \to \varrho^0\pi^+)$ to $B(D^0 \to \phi\bar{K}^0)$ — another pure annihilation process. The decay amplitude for $D^0 \to \phi\bar{K}^0$ is [7] (k is the kaon 4-momentum)

$$A(D^0 \to \phi\bar{K}^0) = \sqrt{2}\,(\varepsilon\cdot k)C_2 f_D K. \tag{27}$$

Here K is the annihilation parameter introduced in Ref. [7] whose naive PCAC value is

$$(K)_{\text{naive PCAC}} = \frac{2f_K m_K^2}{m_D^2 - m_K^2}\, g_{VPP}. \tag{28}$$

It was found that $D \to VP$ data required $K \simeq -10$ GeV. From (26) and (27) we find

$$B(D_s^+ \to \varrho^0\pi^+)/B(D^0 \to \phi\bar{K}^0) = (65\pm15)\left[\frac{f_{D_s}\hat{K}}{f_D K}\right]^2 \tag{29}$$

Where we have used [15] $\tau_{D_s^+}/\tau_{D^0} = 1.0\pm0.2$. $\hat{K}/K \cong 0.1$ and $f_{D_s} = f_D$ then

$$B(D_s^+ \to \varrho^0\pi^+)/B(D^0 \to \phi\bar{K}^0) \simeq (0.65\pm0.15). \tag{30}$$

Since $B(D^0 \to \phi\bar{K}^0)$ is about 1% we find $B(D_s^+ \to \varrho^0\pi^+)$ to be about (0.65 ± 0.15)%. This is in agreement with the recent experimental values ($B(D_s \to \varrho^0\pi) < 0.7$%) of ARGUS group [17], and with the calculated value ($B(D_s^+ \to \varrho^0\pi^+) \simeq 0.5$%) of Ref. [11], where different technique has been used. If we invoke the experimental errors in $B(D_s^+ \to \bar{K}^{*0}K^+)/$ $/B(D_s^+ \to \phi\pi^+)$, in $\hat{K}$ and in the D_s life time and flexibility in the theoretical values of f_{D_s} and f_D then these can also affect our estimate. We would like to mention that we have normalised $B(D_s^+ \to \varrho^0\pi^+)$, a pure annihilation process, to another pure annihilation process

$B(D^0 \to \phi \bar{K}^0)$ *only*. A careful analysis of multichannel final state interactions also suggests that comparision of an annihilation process ($D_s^+ \to \varrho^0\pi^+$) with another annihilation process ($D^0 \to \phi\, 2\bar{K}^0$) is phenomenologically more realistic [18, 19]. This may be probably due to the similar nature of approximation involved in the parametrization in these annihilation process. The other charged mode $D_s^+ \to \varrho^0\pi^0$ would have an equal branching ratio.

A recent paper by Kamal et al [20], has discussed the Cabibbo angle favored $D_s \to PP$ decays using techniques of the present paper. They have successfully explained the recent MARK II and MARK III data [21] and found an excellency of our technique over others in the case of $D_s \to PP$ decays. Furthermore, Kamal et al. have calculated the QCD parameters C_1 and C_2 from next-to-leading-log perturbation theory with $m_c = 1.5$ GeV, $m_t = 50$ GeV and $\Lambda_{QCD} = (0.1 \sim 0.3)$ GeV and obtained $C_1/C_2 \simeq (3.2 \sim 2.4)$. This gives $B(D_s \to \varrho\pi) \simeq (0.4 \sim 0.7)\%$, a nice agreement with the experimental results ($<0.7\%$) [17].

Finally $D_s^+ \to \omega\pi$ is forbidden in the limit of ideal mixing. In the case of an ideal mixing an annihilation diagram can seemingly be drawn. However, the first class axial $\bar{u}d$ current with an odd G-parity will not couple to the $\omega\pi$ system with an even G-parity. One can check that the F-type Clebsch–Gordan coefficient also vanishes thereby forbidding the annihilation amplitude.

3. *Discussion*

We normalized $B(D_s^+ \to \phi\pi^+)$ to $B(D_s^+ \to \bar{K}^0\varrho^+)$, both spectator process. We found that $B(D_s^+ \to \phi\pi^+) \simeq 2$–$4\%$ can be obtained with the value of $f_{D_s} = (1.5 \sim 2) f_K$. We also found that the measured ratio [4] $B(D_s^+ \to \bar{K}^{*0}K^+)/B(D_s^+ \to \phi\pi^+) \simeq 1.44 \pm 0.37$ can be fitted with an annihilation parameter $\hat{K} \simeq -1.0$ GeV. In the absence of annihilation process we find this ratio to be $\simeq 0.07$, much below the measured ratio. Furthermore, we found $B(D_s^+ \to K^{*0}K^+)/B(D_s^+ \to K^{*+}\bar{K}^0)$ to be between 1.15 and 1.25 depending on the value of f_{D_s}. We agree here with Stech and his co-workers [11, 8]. We find the ratio $B(D_s^+ \to \varrho^+\eta)/B(D_s^+ \to \phi\pi^+)$ to depend rather strongly on f_{D_s}. For $f_{D_s} \simeq 0.12$ GeV this ratio is 2.8 while for $f_{D_s} \simeq 0.24$ GeV this ratio is 0.7. We find $B(D_s^+ \to \varrho^+\eta')/B(D_s^+ \to \varrho^+\eta)$ to be 0.13.

Finally we discuss the pure annihilation process $D_s^+ \to \varrho^0\pi^+$ (and $D_s^+ \to \varrho^+\pi^0$). If the naive PCAC is used this process is all but disallowed since the naive PCAC value of the annihilation parameter $\hat{K}$ is very small (see Eq. (16)). Analogously $D^0 \to \bar{K}^0\phi$ is a pure annihilation process which would also be suppressed if the naive PCAC value of the annihilation parameter K were used (see Eq. (28)). However, when a particular attention is paid to the annihilation term, the annihilation parameter can go up. Our estimation of $B(D_s^+ \to \varrho^0\pi^+)$ is in agreement with the recent experimental value [17] and with the theoretical value of Bauer, Stech and Wirbel [11]. We also note that multichannel final state strong interactions and phases are subtle and difficult problems [11–12, 19]. At present a full knowledge of the strong interaction S-matrix elements of these rescattering effects for the calculation of D_s-decays are very little known. Furthermore recently Stech and Kamal et al. [11, 20] have pointed out that the final state interactions for some two-body D_s-decays are not likely to be very large. The agreement of the measured decay rates with our predictions approximately support their analysis [18]. Thus, it appears that the technique and the model explain almost *all* the two body D and D_s decays successfully. We also argue that the present paper represents *a fair objective studies and the present state-of-affairs of* $D_s^+ \to VP$ decays by the use of limited available experimental results.

In summary, we have outlined a general method for a study of all the Cabibbo-angle favored decays of $D_s \to VP$. The results are found to be in general agreement with the available experimental values and the results of some other calculations. However, few of our results are in a range rather than fixed one due to the non-availability of the experimental values of D and D_s decay constants and due to the large experimental errors in some of the input decay rates and life times. Better statistics in future data especially expected from ARGUS, CLEO, FNAL E691, MARK II and MARK III groups will be help and guide in the theoretical analysis and it will serve to constrain the parameters of the model.

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