Recent charm physics results from \textit{BABAR}

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Abstract. In this proceeding, recent charm physics results from the \textit{BABAR} experiment are discussed. The studies include a Dalitz plot and partial-wave analysis of the decay $D_s \rightarrow K^+K^+\pi^-$, a recent measurement of the leptonic decay constant $f_{D_s}$, the precision mass and width measurements of the $D_s(2535)$ meson, searches for new resonances in inclusive $e^+e^-$ collisions, searches for flavor changing neutral currents, lepton-flavor and lepton-number violating decays, and searches for CP violation.

1. Introduction

The Charm physics studies discussed in this proceeding make use of the $\Upsilon(4S)$ data set with an integrated luminosity of $\sim 480$ fb$^{-1}$ collected by the \textit{BABAR} detector. The \textit{BABAR} detector is described in detail elsewhere \cite{1}. The components that are important to the analyses described here follows. Charged particle tracks are detected, and their momenta measured, with a cylindrical drift chamber (DCH) and a silicon vertex tracker (SVT), both operating inside a 1.5 T solenoidal magnetic field. Photon energies are measured with a CsI(Tl) electromagnetic calorimeter (EMC). Identification of charged particle species is determined from information collected from a ring-imaging Cherenkov detector (DIRC) and specific energy-loss measurements in the SVT and DCH. Additionally, muons are identified with information collected from a instrumented flux return (IFR) which is made of layers of iron, brass, limited streamer tubes (LSTs), and resistive plate chambers (RPCs).

2. Dalitz plot and Partial Wave Analysis of the Decay $D_s \rightarrow K^+K^-\pi^+$ [2]

Scalar mesons are still a puzzle in light meson spectroscopy. New claims for the existence of broad states close to threshold such as $\kappa(800)$ \cite{3} and $f_0(600)$ \cite{4}, have reopened discussion about the composition of the ground state $J^{PC} = 0^{++}$ nonet, and about the possibility that states such as the $a_0(980)$ or $f_0(980)$ may be 4-quark states, due to their proximity to the $K\bar{K}$ threshold \cite{5}. This hypothesis can be tested only through accurate measurements of the branching fractions and the couplings to different final states. It is therefore important to have precise information on the structure of the $\pi\pi$ and $K\bar{K}$ $S$-waves. In this context, $D_s^+$ mesons can shed light on the structure of the scalar amplitude coupled to $s\bar{s}$. The understanding of the $K\bar{K}$ $S$-wave is also of great importance for the precise measurement of $CP$-violation in $B_s$ oscillations using $B_s \rightarrow J/\psi\phi$ \cite{6, 7}.

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The $D_{s}^{+}$ meson decay to $K^{+}K^{-}\pi^{+}$ is studied to determine the $S$-wave structure in the vicinity of the $\phi(1020)$ resonance using a partial wave analysis technique. The results of this study are used in the Dalitz plot analysis to determine the resonant structure of this decay.

Model-independent information of the $K^{+}K^{-}$ $S$-wave in the vicinity of the $\phi(1020)$ resonance is obtained by performing a partial wave analysis in the threshold region. We measure the fraction of $S$ and $P$-wave in various $K^{+}K^{-}$ mass regions, shown in table 1. We then extract a phenomenological description of the $S$-wave, assuming that it is dominated by the $f_{0}(980)$. We fit the $|S|$, $|P|$, and $\phi_{SP}$ distributions (figure 1), where we assume empirically a Breit-Wigner (BW) to parameterize the $f_{0}(980)$ and the spin-1 Relativistic Breit-Wigner (RBW) for the $\phi(1020)$. The resulting mass and width, $m_{0} = (0.922 \pm 0.003_{\text{stat}})$ GeV/c$^{2}$ and $\Gamma_{0} = (0.24 \pm 0.08_{\text{stat}})$ GeV/c$^{2}$, are used to parameterize the $f_{0}(980)$ in the Dalitz plot analysis, where an unbinned maximum likelihood (ML) fit of the events is performed to determine the resonant contributions of this decay.

The decay is found to be dominated by the $\phi(1020)$ resonance in $K^{+}K^{-}$ and the $\bar{K}^{*0}(892)$ resonance in $K^{-}\pi^{+}$, although $S$-wave contributions exist as well. The magnitudes and phases of each resonance are measured relative to the $\bar{K}^{*0}(892)$. In addition to the magnitudes and phases as parameters in the fit, the $\bar{K}^{*0}(892)$ and the $f_{0}(1370)$ masses and widths are free to float. The results of the fit are shown in figure 2. The magnitudes, phases, and fit fractions of the resonances in the decay model are shown in table 2.

The fitted parameters for the $\bar{K}^{*0}(892)$ are:

$$m_{\bar{K}^{*0}(892)} = (895.6 \pm 0.2_{\text{stat}} \pm 0.3_{\text{sys}}) \text{ MeV/c}^{2}$$

$$\Gamma_{\bar{K}^{*0}(892)} = (45.1 \pm 0.4_{\text{stat}} \pm 0.4_{\text{sys}}) \text{ MeV}$$

and for the $f_{0}(1370)$

$$m_{f_{0}(1370)} = (1.22 \pm 0.01_{\text{stat}} \pm 0.04_{\text{sys}}) \text{ GeV/c}^{2}$$

$$\Gamma_{f_{0}(1370)} = (0.21 \pm 0.01_{\text{stat}} \pm 0.03_{\text{sys}}) \text{ GeV}$$

### Table 1

| $m_{K^{+}K^{-}}$ range(MeV/c$^{2}$) | $f_{S}$-wave(%) | $f_{P}$-wave(%) |
|-----------------------------------|-----------------|-----------------|
| 1019.456 ± 5                     | 3.5 ± 1.0       | 96.5 ± 1.0      |
| 1019.456 ± 10                     | 5.6 ± 0.9       | 94.4 ± 0.9      |
| 1019.456 ± 15                     | 7.9 ± 0.9       | 92.1 ± 0.9      |

The curves result from the fit.

3. Absolute Branching Fractions of Leptonic Decays of the $D_{s}$ and a Measurement of the Leptonic Decay Constant $f_{D_{s}}$ [8]

The $D_{s}^{-}$ meson can decay purely leptonically via annihilation of the $c$ and $s$ quarks into a $W^{-}$. In the Standard Model (SM), the leptonic partial width $\Gamma(D_{s}^{-} \rightarrow \ell^{-}\bar{\nu}_{\ell})$ is given by...
Figure 2. $D_s^+ \to K^+ K^- \pi^+$: Dalitz plot projections. The data are represented by points with error bars, the fit results by the histograms.

| Decay Mode      | Decay fraction(%) | Amplitude         | Phase(radians) |
|-----------------|-------------------|-------------------|----------------|
| $K^*(892)^0 K^+$| 47.9 ± 0.5 ± 0.5  | 1. (Fixed)        | 0. (Fixed)     |
| $\phi(1020)\pi^+$| 41.4 ± 0.8 ± 0.5 | 1.15 ± 0.01 ± 0.26| 2.89 ± 0.02 ± 0.04|
| $f_0(980)\pi^+$ | 16.4 ± 0.7 ± 2.0 | 2.67 ± 0.05 ± 0.20| 1.56 ± 0.02 ± 0.09|
| $K_0(1430)^0 K^+$| 2.4 ± 0.3 ± 1.  | 1.14 ± 0.06 ± 0.36| 2.55 ± 0.04 ± 0.22|
| $f_0(1710)\pi^+$ | 1.1 ± 0.1 ± 0.1 | 0.65 ± 0.02 ± 0.06| 1.36 ± 0.05 ± 0.20|
| $f_0(1370)\pi^+$ | 1.1 ± 0.1 ± 0.2 | 0.46 ± 0.03 ± 0.09| -0.45 ± 0.11 ± 0.52|
| $\chi^2/NDF$    | 1.24              |                   |                |

Table 2. Results from the $D_s^+ \to K^+ K^- \pi^+$ Dalitz plot analysis. Quoted uncertainties are statistical and systematic, respectively. The error on each fit fraction is obtained by propagating the full covariance matrix from the fit.

$$
\Gamma = \frac{G_F^2 M_{D_s}^3}{8\pi} \left( \frac{m_\ell}{M_{D_s}} \right)^2 \left( 1 - \frac{m_\ell^2}{M_{D_s}^2} \right)^2 |V_{cs}|^2 f_{D_s}^2, \tag{1}
$$

where $M_{D_s}$ and $m_\ell$ are the $D_s^-$ and lepton masses, respectively, $G_F$ is the Fermi coupling constant, and $V_{cs}$ is an element of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix. These decays provide a clean probe of the pseudoscalar meson decay constant $f_{D_s}$.
Within the SM, $f_{D_s}$ has been predicted using several methods [9, 10]; the most precise method uses unquenched LQCD calculations. As of 2008, experimental averages [11] were significantly larger than the theoretical predictions at that time. Models of new physics (NP), including a two-Higgs doublet [12] and leptoquarks [13], may have explained this difference. In addition, $f_{D_s}$ measurements provide a cross-check of QCD calculations which predict the impact of NP on $B$ and $B_s$ meson decay rates and mixing. High precision determinations of $f_{D_s}$, both from experiment and theory, are necessary in order to discover or constrain effects of NP.

We measure the absolute branching fractions of leptonic $D_s^+$ decays with a method similar to the one used by the Belle Collaboration [14, 15]. An inclusive sample of $D_s^+$'s is obtained by reconstructing the rest of the event in reactions of the kind $e^+ e^- \rightarrow c \bar{c} \rightarrow D K X D_s^-$, where $D_s^- \rightarrow D_s^+ \gamma$. Here, $D$ represents a charmed hadron ($D^0$, $D^+$, $D^*$, or $\Lambda_c^+$), $K$ represents the $K^0$ or $K^+$ required to balance strangeness in the event, and $X$ represents additional pions produced in the $c\bar{c}$ fragmentation process. When the charmed hadron is a $\Lambda_c^+$ an additional anti-proton is required to assure baryon number conservation. No requirements are placed on the decay products of the $D_s^+$ so that the selected events correspond to an inclusive sample. The 4-momentum of each $D_s^-$ candidate, $p_r$, is measured as the difference between the momenta of the colliding beam particles and the fully reconstructed $D K X \gamma$ system: $p_r = p_{e^+} + p_{e^-} - p_D - p_K - p_X - p_\gamma$. The inclusive $D_s^-$ yield is obtained from a binned fit to the distribution in the recoil mass $m_r(D K X \gamma) \equiv \sqrt{p_r^2}$ shown in figure 3. Within this inclusive sample, we determine the fraction of events corresponding to $D_s^- \rightarrow \mu^- \bar{\nu}_\mu$, $D_s^- \rightarrow e^- \bar{\nu}_e$, and $D_s^- \rightarrow \tau^- \bar{\nu}_\tau$ decays (fits shown in figure 4) by extracting the yield from a binned likelihood fit. In the $D_s^- \rightarrow \mu^- \bar{\nu}_\mu$ and $D_s^- \rightarrow e^- \bar{\nu}_e$ channels, the signal yield is extracted from $m^2_r(D K X \gamma (\mu e))$. Since the $D_s^- \rightarrow \tau^- \bar{\nu}_\tau$ events contain more than one neutrino $E_{\text{extra}}$ is used to extract the signal yield, where $E_{\text{extra}}$ is defined as the total energy of the EMC clusters with individual energy greater than 30 MeV and not overlapping with the $D K X \gamma$ candidates. In the SM, ratios of the branching fractions for these decays are $e^- \bar{\nu}_e : \mu^- \bar{\nu}_\mu : \tau^- \bar{\nu}_\tau = 2 \times 10^{-5}$: 1 : 10, due to helicity and phase-space suppression.

Using the measured branching fractions, we determine the $D_s^-$ decay constant using Eq. (1) and the known values for $m_{\ell}$, $m_{D_s}$, $|V_{ud}|$ (we assume $|V_{cs}| = |V_{ud}|$), and the $D^+$ lifetime [16]. The $f_{D_s}$ values are listed in table 3; the systematic uncertainty includes the uncertainties on these parameters (1.9 MeV). Finally, we obtain the error-weighted average $f_{D_s} = (258.6 \pm 6.4 \text{(stat)} \pm 7.5 \text{(syst)})$ MeV. The precise determination of $f_{D_s}$ from BABAR updates the HFAG average of $f_{D_s} = 257.3 \pm 5.3$ MeV [11], which is 1.6$\sigma$ larger than the current theoretical prediction [9].

![Figure 3](image-url)
4. Precision Mass and Width Measurement of the $D_{s1}(2535)$ Meson [17]

Unlike $D$ mesons, the theoretical description of $D_s^+$ mesons is problematic because the masses and widths of the $D_{s0}^+(2317)^+$ and $D_{s1}(2460)^+$ states [18, 19, 20, 21, 22, 23] are not in agreement with potential model calculations based on HQET [24]. Theoretical explanations for the discrepancy invoke $D^{(*)}K$ molecules [25], chiral partners [26, 27], unitarized chiral models [28, 29], tetraquarks [30, 31], and lattice calculations [32, 33], but a satisfactory description is still lacking (see [34, 35] for more details). Improved measurements of the $D_{s1}(2536)^+$ meson parameters can lead to a better understanding of these states.

In this analysis a precise measurement of the $D_{s1}(2536)^+$ mass and decay width is performed based on a high statistics data sample. The $D_{s1}^+$ is reconstructed via its decay mode $D^{*+}K_S^0$, with $K_S^0 \to \pi^+\pi^-$ and $D^{*+} \to D^0\pi^+$. The $D^0$ is reconstructed through two decay modes, $K^-\pi^+$ and $K^-\pi^+\pi^-\pi^+$, which will be labeled $K4\pi$ and $K6\pi$, respectively, in the following. To improve
the mass resolution, the mass difference $\Delta m(D_{s1}^+) = m(D_{s1}^+) - m(D^{*+}) - m(K^0_s)$ is examined. The fit to $\Delta m(D_{s1}^+)$ (figure 5), is parameterized with a signal function that consists of a RBW shape numerically convolved with a $p^*(D_{s1}^+)$-dependent Gaussian resolution function, where $p^*$ is the momentum in the CM, and a linear function is used to describe the background. The resolution model is derived from $D_{s1}^+$ signal Monte Carlo (MC) by studying the difference $\Delta m_{res}$ between the reconstructed and generated $D_{s1}^+$ mass values. The detector resolution is found to have a half-width-at-half-max (HWHM) of about 0.55 MeV/c$^2$. We determine from the fit of $\Delta m(D_{s1}^+)$ the mean mass differences to be:

$$\begin{align*}
\Delta m(D_{s1}^+) &= 27.231 \pm 0.020 \text{ MeV}/c^2 \quad (K4\pi), \\
\Delta m(D_{s1}^+) &= 27.205 \pm 0.018 \text{ MeV}/c^2 \quad (K6\pi),
\end{align*}$$

and total width values

$$\begin{align*}
\Gamma(D_{s1}^+) &= 1.000 \pm 0.049 \text{ MeV} \quad (K4\pi), \\
\Gamma(D_{s1}^+) &= 0.941 \pm 0.045 \text{ MeV} \quad (K6\pi).
\end{align*}$$

The fitted values for the two $D^0$ decay modes agree within the statistical errors. The signal yield is 3704 ± 71 for $K4\pi$ and 4334 ± 78 for $K6\pi$. Combining these results, and adding the $D^{*+}$ and $K^0_s$ masses, the final value for the $m(D_{s1}(2536)^+)$ = (2535.08 ± 0.01 ± 0.15) MeV/c$^2$ and for the width, $\Gamma(D_{s1}^+) = (0.92 \pm 0.03 \pm 0.04) \text{ MeV}$.

5. Search for New Resonances Decaying to $D\pi$ and $D^*\pi$ in Inclusive $e^+e^-$ Collisions near $\sqrt{s} = 10.58$ GeV [36]

The spectrum of quark-antiquark systems was predicted using a relativistic chromodynamic potential model [37], yet experimentally little is known of the spectrum of mesons consisting of a charm quark and an up or down quark. The low mass spectrum of the $c\bar{u}$ or $cd$ systems consists of the ground states (1S), orbital excitations with angular momentum $L = 1, 2$ (1P,1D), and the first radial excitations (2S). Besides the ground state mesons $D$ and $D^*$, only two 1P states have been well-established experimentally [16], known as the $D_1(2420)$ and the $D_2^*(2460)$. 

Figure 5. Fit of a RBW convolved with the resolution function to the $D_{s1}^+$ candidate mass difference spectra in data, for the (left) $K4\pi$ and (right) $K6\pi$ modes. The dotted line indicates the background line shape. The upper parts of the figures show the normalized fit residuals.
and width values differ by 2.6 and 1.5 $\sigma$ this region [37], but only two are expected to decay to $D^+\pi^-$ (right) candidates. Points correspond to data, with the total fit overlaid as a solid curve. The lower solid curves are the backgrounds, and the dotted curves are the signal components. The inset plots show the background-subtracted distributions.

The measurement of these states is possible due to their narrow widths ($\sim 30$ MeV), while other 1P states have broad widths on the order of $\sim 300$ MeV, making them difficult to detect.

To search for additional states that have not been observed, the inclusive production of $D^+\pi^-$, $D^0\pi^+$, and $D^{*+}\pi^-$ final states in the reaction $e^+e^- \rightarrow \bar{c}c \rightarrow D^{(*)}X$, where X is any additional system, is analyzed. In order to measure the resonance parameters, the mass difference is examined, where $M(D^+\pi^-) = m(K^-\pi^+\pi^+\pi^+) - m(K^-\pi^+\pi^+) + m_{D^+}$, $M(D^0\pi^+) = m(K^-\pi^+\pi^+) - m(K^-\pi^+) + m_{D^o}$, and $M(D^{*+}) = m(K^-\pi^+(\pi^+\pi^-)\pi^+_K\pi^-) - m(K^-\pi^+(\pi^+\pi^-)\pi^+_K\pi^-) + m_{D^{*+}}$, where $m_{D^{*+}}$, $m_{D^o}$, and $m_{D^+}$ are the nominal mass values [16]. The mass spectrum is modeled with a smooth background function, BW functions convolved with resolution and bias functions for peaking backgrounds, and RBW functions to describe the signal resonances. The signal RBW shapes are corrected for the mass resolution by convolving them with the detector resolution. The detector resolution using the mass variables is about 3 MeV/$c^2$. The masses and widths of resonances determined from fits to the various final states are found in table 5, and the fits to the data are shown in figure 6.

Due to the vector nature of the $D^{*+}$, the $D^{*+}\pi^-$ final states contain resonances with different spin-parity ($J^P$) which have different helicity-angle distributions. The helicity angle $\theta_H$ is defined as the angle between the primary pion and the slow pion from the $D^{*+}$ decay. To extract the signal resonances in the $D^{*+}\pi^-$ distribution, the fit is performed for $|\cos \theta_H| > 0.75$ and for $|\cos \theta_H| < 0.5$ separately. Using the signal parameters determined from these two fits, the final parameters for the $D^{*+}\pi^-$ are determined by fitting the entire sample, fixing the parameters from the previous fit (indicated in table 5).

Further information as to the spin-parity nature of some of these states is accessible by studying the helicity distributions (figure 7) of the $D^{*+}\pi^-$ final state. The $D^{*+}\pi^-$ data is divided into 10 sub-samples corresponding to $\cos \theta_H$ intervals of 0.2 from -1 to +1. Each sample is fit with the shape parameters fixed to the values determined in the final fit of the entire sample. The yields are extracted from these fits and the resulting distributions are fit to various Y functions, indicated in the plots.

We observe for the first time four signal peaks, which we denote $D(2550)^0$, $D^*(2600)^0$, $D(2750)^0$, and $D^*(2760)^0$. We also observe the isospin partners $D^*(2600)^+$ and $D^*(2760)^+$. The $D(2550)^0$ and $D^*(2600)^0$ have mass values and helicity-angle distributions that are consistent with the predicted radial excitations $D_{1}^0(2S)$ and $D_{1}^0(2S)$. The $D^*(2760)^0$ signal observed in $D^+\pi^-$ is very close in mass to the $D(2750)^0$ signal observed in $D^{*+}\pi^-$; however, their mass and width values differ by 2.6$\sigma$ and 1.5$\sigma$, respectively. Four $L = 2$ states are predicted to lie in this region [37], but only two are expected to decay to $D^+\pi^-$. This may explain the observed features.
The recent observation of $D^0 - \bar{D}^0$ mixing [44, 45] has increased interest in FCNC processes in the charm sector. Of particular interest is the source of $D^0 - \bar{D}^0$ mixing. If the mixing is due to physics beyond the SM, it could also give rise to measurable effects in FCNC charm decays. In the SM, the FCNC decays $X^+ \rightarrow h^+ \ell^+\ell^-$ are expected to be heavily suppressed due to cancellations of amplitudes through the Glashow-Iliopoulos-Maiani (GIM) mechanism. For example, the $c \rightarrow u\ell^+\ell^-$ transitions illustrated in figure 8 yield branching fractions for $D \rightarrow X_u\ell^+\ell^-$ of $O(10^{-8})$ [46, 47]. These decays are masked by the presence of long-distance contributions from intermediate vector resonances such as $D \rightarrow X_u V$, $V \rightarrow \ell\ell$, which are predicted to have branching fractions of $O(10^{-6})$ [46, 47]. The effect of these resonances can be separated from short-distance contributions by studying the invariant mass of the $\ell^+\ell^-$ pair. In radiative charm decays, $c \rightarrow w\gamma$, uncertainties in calculating the long-distance terms make it impossible to study the underlying short-distance physics [48]. The decay $D^0 \rightarrow \gamma\gamma$ is dominated by long-distance contributions and the theoretical branching fraction is estimated to be $O(10^{-11}$ to $10^{-8})$ [46]. However, in the context of the Minimal Supersymmetric Standard Model, gluino exchange can enhance the SM rate by up to a factor of 200 [52].

### Table 4.

| Resonance $| (2420) \rangle$ | Channel $D^+\pi^-$ | Yield $(x10^3)$ | Mass MeV/$c^2$ | Width MeV |
|-------------------------|---------------------|-----------------|-----------------|-----------|
| $D_1(2420)^+$ | $D^+\pi^-$ | 102.8±1.3±2.3 | 2420.1±0.1±0.8 | 31.4±0.5±1.3 |
| $D^+\pi^-$ | 214.6±1.2±6.4 | 2420.1(fixed) | 31.4(fixed) |

$D_2^*(2600)^0$ | $D^+\pi^- - 10$ | 242.8±1.8±3.4 | 2462±0.1±0.8 | 50.5±0.6±0.7 |
| $D^+\pi^- - 10$ | 136±2±13 | 2462.2(fixed) | 50.5(fixed) |

$D(2550)^0$ | $D^+\pi^-$ | 34.3±6±9.2 | 2539±4±5±6.8 | 130±12±13 |
| $D^+\pi^- - 10$ | 98.4±8.2±38 | 2539.4(fixed) | 130(fixed) |

$D^*(2600)^0$ | $D^+\pi^- - 10$ | 26.0±1.4±6.6 | 2608.7±2.4±2.5 | 93±6±13 |
| $D^+\pi^- - 10$ | 50.2±3.0±6.7 | 2608.7(fixed) | 93(fixed) |
| $D^+\pi^- - 10$ | 71.4±1.7±7.3 | 2608.7(fixed) | 93(fixed) |

$D(2750)^0$ | $D^+\pi^- - 10$ | 23.5±2.1±5.2 | 2752.4±1.7±2.7 | 71±6±11 |

$D^*(2760)^0$ | $D^+\pi^- - 10$ | 11.3±0.8±1.0 | 2763±2±3±2.3 | 60.9±5.1±3.6 |

$D_2^*(2460)^+$ | $D^*\pi^+$ | 110.8±1.3±7.5 | 2465±0.2±1.1 | 50.5(fixed) |

$D^*(2600)^+$ | $D^*\pi^+$ | 13.0±1.3±4.5 | 2621.3±3.7±4.2 | 93(fixed) |

$D^*(2760)^+$ | $D^*\pi^+$ | 5.7±0.7±1.5 | 2769.7±3.8±1.5 | 60.9(fixed) |

Figure 7. Distribution in $\cos\theta_H$ for each signal in $D^+\pi^-$. The error bars include statistical and correlated systematic uncertainties. The curve is a fit using the function $Y$ shown in the plot; $\varepsilon_H$ is the efficiency as a function of $\cos\theta_H$.

6. Search for Rare and Forbidden Charm Decays

Flavor changing neutral current (FCNC) processes have been studied extensively for $K$ and $B$ mesons, in $K^0 - \bar{K}^0$ and $B^0 - \bar{B}^0$ mixing, and in rare FCNC decays such as $s \rightarrow d\ell^+\ell^-$, $b \rightarrow s\gamma$ and $b \rightarrow s\ell^+\ell^-$ decays. The results agree with expectations within the framework of the SM. There are ongoing efforts to improve the measurements and the theoretical predictions, and to measure new effects, such as CP violation, in FCNC processes.
6.1. Search for Flavor Changing Neutral Current, Lepton-Flavor Violating, and Lepton-Number Violating Semileptonic Charm Decays [38]

BABAR searched for semileptonic charm hadron decays that are either forbidden or heavily suppressed in the SM of particle physics. The decays are of the form $X_c^+ \rightarrow h^{\pm} \ell^{\mp} \ell^{(i)^+}$, where $X_c^+$ is a charm hadron ($D^+$, $D_s^+$, or $\Lambda_c^+$), $h$ is a pion, kaon, or proton, and $\ell^{(i)}$ is an electron or muon. The decay modes with oppositely charged leptons but same lepton flavor are examples of FCNC processes, which are expected to be very rare because they cannot occur at tree level in the SM. The decay modes with two oppositely charged leptons of different flavor correspond to lepton-flavor violating (LFV) decays and are essentially forbidden in the SM because they can occur only through lepton mixing. The decay modes with two leptons of the same charge are lepton-number violating (LNV) decays and are forbidden in the SM. Hence, decays of the form $X_c^+ \rightarrow h^{\pm} \ell^{\mp} \ell^{(i)^+}$ provide a sensitive tool to investigate physics beyond the SM. The most stringent existing upper limits [39, 40, 41, 42, 43] on the branching fractions for $X_c^+ \rightarrow h^{\pm} \ell^{\mp} \ell^{(i)^+}$ decays range from 1 to $700 \times 10^{-6}$ and do not exist for most of the $\Lambda_c^+$ decays.

Charm hadron candidates are formed from one track identified as either a pion, kaon, or proton ($h$) and two tracks, each of which is identified as an electron or a muon ($\ell \ell^{(i)}$). The final candidate selection is performed using a likelihood ratio test, combining probability distribution functions (PDFs) from the following three variables: the charm hadron candidate $p^*$, the total energy in the event, and the flight significance which is the ratio of the signed flight length to its uncertainty. The signed flight length is the scalar product between the direction of the charm-hadron candidate and the position vector that points from the beam spot to the charm-hadron decay vertex. The total energy in an event is calculated as the sum of the energies of all reconstructed tracks (assuming each track to be a charged pion) and neutral energy EMC clusters.

An extended, unbinned, ML fit is applied to the invariant-mass distributions for the $h^{\pm} \ell^{\mp} \ell^{(i)^+}$ candidates. The PDF we use for signal events is the so-called Crystal Ball function [49], which has an asymmetric component to describe the radiative tail in the mass distribution. The shape parameters of the signal PDF are determined from fits to signal MC candidates and are fixed to these values in the fits to data, with only the overall normalization as a free parameter. The width of the Gaussian component ($\sigma$) is found to lie between 5 and 10 MeV/$c^2$, depending on the decay mode. The invariant mass distributions of the combinatoric background events for the signal modes are described by first-order polynomials. The background slope is a free parameter in all fits.

No signals are observed, yet for 32 of the 35 decay modes, this analysis is more sensitive than existing measurements. In most cases, the improvement is significant (factor of 2 to 60). The biggest improvements are seen for the lepton-flavor violating decays, which are all improved by
at least a factor of 10. The only $\Lambda_c^+$ decay with a pre-existing limit is $\Lambda_c^+ \rightarrow p\mu^+\mu^-$, for which we improve the limit by roughly a factor of 8. For all other $\Lambda_c^+$ decays this study presents the first limits. The only modes that do not provide a more sensitive limit are $D^+ \rightarrow \pi^-e^+e^+$, $D^+ \rightarrow \pi^+\mu^+\mu^-$, and $D_s^+ \rightarrow \pi^+\mu^+\mu^-$ where existing limits [39, 42, 43] are about a factor of two lower than the $\text{BaBar}$ measurements (see table 5).

6.2. Search for the Decay $D^0 \rightarrow \gamma\gamma$ [50]

The only previous search of a neutral D meson into two photons was conducted by the CLEO collaboration in 2002 using 13.8 fb$^{-1}$ [51]. The large number of charm decays contained in the $\text{BaBar}$ dataset provide the opportunity to probe the upper limit of NP enhancements in this decay.

$D^0$ candidates are formed by combining pairs of photon candidates. A photon candidate is defined as energy deposited in the EMC, which is not associated with the trajectory of any charged track and exhibits the appropriate shower characteristics. The photon candidates are constrained to have a CM momentum between 0.74 and 4 GeV/c.

The signal yield is obtained using an unbinned ML fit to the $D^0$ mass distribution. The overall PDFs are sums of functions describing signal and background distributions obtained from MC studies. The relative normalization of these functions are free parameters while the shapes are fixed. The $D^0 \rightarrow \gamma\gamma$ signal PDF is the sum of a Crystal Ball function and a bifurcated Gaussian distribution. The background PDF is described by a second-order Chebychev polynomial.

![Figure 9](image-url)

**Figure 9.** The full $D^0 \rightarrow \gamma\gamma$ PDF fit to the data showing the combinatoric background (long-dashed red), the combinatoric background plus $D^0 \rightarrow \pi^0\pi^0$ background shape (small-dash red), and both backgrounds and signal component (solid blue) which results in a negative signal. The fit is determined by unbinned maximum likelihood but the $\chi^2$ value is determined from binned data and is provided as a goodness-of-fit measure. The pull distribution shows the differences between the data and the solid blue curve above with values and errors normalized to the Poisson error.

The invariant mass distribution of $D^0 \rightarrow \gamma\gamma$ is shown in figure 9 together with projections of the likelihood fit and the individual signal and background combinations. The signal yield is $-6 \pm 15$ events. Including systematic uncertainties the upper limit for the branching ratio of the decay $D^0 \rightarrow \gamma\gamma$ is determined to be $B(D^0 \rightarrow \gamma\gamma) < 2.4 \times 10^{-6}$. 


Table 5. Signal yields for the fits to the 35 $X^+_c \rightarrow h^+\ell^+\ell'^+(l')^+$ event samples. The first error is the statistical uncertainty and the second is the systematic uncertainty. The third column lists the estimated signal efficiency. The fourth column gives for each signal mode the 90% CL upper limit (UL) on the ratio of the branching fraction of the signal mode to that of the normalization mode (BR). The last column shows the 90% CL upper limit on the branching fraction for each signal mode (BF). The upper limits include all systematic uncertainties.

| Decay Mode | Yield (events) | Eff. (%) | BR UL | BF UL |
|------------|----------------|----------|-------|-------|
| $D^+ \rightarrow \pi^+ e^+ e^-$ | $-3.9 \pm 1.6 \pm 1.7$ | 1.56 | 3.9 | 1.1 |
| $D^+ \rightarrow \pi^+ \mu^+ \mu^-$ | $-0.2 \pm 2.8 \pm 0.9$ | 0.46 | 24 | 6.5 |
| $D^+ \rightarrow \pi^+ e^+ \mu^-$ | $-2.9 \pm 3.4 \pm 2.4$ | 1.21 | 11 | 2.9 |
| $D^+ \rightarrow \pi^+ \mu^+ e^-$ | $3.6 \pm 4.3 \pm 1.3$ | 1.54 | 13 | 3.6 |
| $D^+ \rightarrow \pi^+ e^+ e^-$ | $8 \pm 34 \pm 8$ | 6.36 | 5.4 | 13 |
| $D^+ \rightarrow \pi^+ \mu^+ \mu^-$ | $20 \pm 15 \pm 4$ | 1.21 | 18 | 43 |
| $D^+ \rightarrow \pi^+ e^+ \mu^-$ | $-3 \pm 11 \pm 3$ | 2.16 | 4.9 | 12 |
| $D^+ \rightarrow \pi^+ \mu^+ e^-$ | $9.3 \pm 7.3 \pm 2.8$ | 1.50 | 8.4 | 20 |
| $D^+ \rightarrow K^+ e^+ e^-$ | $-3.7 \pm 2.9 \pm 3.3$ | 2.88 | 3.7 | 1.0 |
| $D^+ \rightarrow K^+ \mu^+ \mu^-$ | $-1.3 \pm 2.8 \pm 1.1$ | 0.65 | 16 | 4.3 |
| $D^+ \rightarrow K^+ e^+ \mu^-$ | $-4.3 \pm 1.8 \pm 0.6$ | 1.44 | 4.3 | 1.2 |
| $D^+ \rightarrow K^+ \mu^+ e^-$ | $3.2 \pm 3.8 \pm 1.2$ | 1.74 | 9.9 | 2.8 |
| $D^+ \rightarrow K^+ e^+ e^-$ | $-5.7 \pm 5.8 \pm 2.0$ | 3.20 | 1.6 | 3.7 |
| $D^+ \rightarrow K^+ \mu^+ \mu^-$ | $4.8 \pm 5.9 \pm 1.2$ | 0.85 | 9.1 | 21 |
| $D^+ \rightarrow K^+ e^+ \mu^-$ | $9.1 \pm 6.0 \pm 2.8$ | 1.74 | 5.7 | 14 |
| $D^+ \rightarrow K^+ \mu^+ e^-$ | $3.4 \pm 6.4 \pm 3.5$ | 2.08 | 4.2 | 9.7 |
| $\Lambda_c^+ \rightarrow p e^+ e^-$ | $4.0 \pm 6.5 \pm 2.8$ | 5.52 | 0.8 | 5.5 |
| $\Lambda_c^+ \rightarrow p \mu^+ \mu^-$ | $11.1 \pm 5.0 \pm 2.5$ | 0.86 | 6.4 | 44 |
| $\Lambda_c^+ \rightarrow p e^+ \mu^-$ | $-0.7 \pm 2.9 \pm 0.9$ | 1.10 | 1.6 | 19 |
| $\Lambda_c^+ \rightarrow p \mu^+ e^-$ | $6.2 \pm 4.6 \pm 1.8$ | 1.37 | 2.9 | 19 |
| $D^+ \rightarrow \pi^- e^+ e^+$ | $4.7 \pm 4.7 \pm 0.5$ | 3.16 | 6.8 | 1.9 |
| $D^+ \rightarrow \pi^- \mu^+ \mu^+$ | $-3.1 \pm 1.2 \pm 0.5$ | 0.70 | 7.5 | 2.0 |
| $D^+ \rightarrow \pi^- \mu^+ e^+$ | $-5.1 \pm 4.2 \pm 2.0$ | 1.72 | 7.4 | 2.0 |
| $D^+ \rightarrow \pi^- e^+ e^+$ | $-5.7 \pm 14 \pm 3.4$ | 6.84 | 1.8 | 4.1 |
| $D^+ \rightarrow \pi^- \mu^+ \mu^+$ | $0.6 \pm 5.1 \pm 2.7$ | 1.05 | 6.2 | 14 |
| $D^+ \rightarrow \pi^- \mu^+ e^+$ | $-0.2 \pm 7.9 \pm 0.6$ | 2.23 | 3.6 | 8.4 |
| $D^+ \rightarrow K^- e^+ e^+$ | $-2.8 \pm 2.4 \pm 0.2$ | 2.67 | 3.1 | 0.9 |
| $D^+ \rightarrow K^- \mu^+ \mu^+$ | $7.2 \pm 5.4 \pm 1.6$ | 0.80 | 37 | 10 |
| $D^+ \rightarrow K^- e^+ e^+$ | $-11.6 \pm 4.0 \pm 3.1$ | 1.52 | 6.8 | 1.9 |
| $D^+ \rightarrow K^- \mu^+ \mu^+$ | $2.3 \pm 7.9 \pm 3.3$ | 4.10 | 2.1 | 5.2 |
| $D^+ \rightarrow K^- \mu^+ e^+$ | $-2.3 \pm 5.0 \pm 2.8$ | 0.98 | 5.3 | 13 |
| $D^+ \rightarrow K^- \mu^+ e^+$ | $-14.0 \pm 8.4 \pm 2.0$ | 2.26 | 2.4 | 6.1 |
| $\Lambda_c^+ \rightarrow \bar{p} e^+ e^+$ | $-1.5 \pm 4.2 \pm 1.5$ | 5.14 | 0.4 | 2.7 |
| $\Lambda_c^+ \rightarrow \bar{p} \mu^+ \mu^+$ | $0.0 \pm 2.1 \pm 0.6$ | 0.94 | 1.4 | 9.4 |
| $\Lambda_c^+ \rightarrow \bar{p} \mu^+ e^+$ | $10.1 \pm 5.8 \pm 3.5$ | 2.50 | 2.3 | 16 |
7. Searches for CP Violation

In the SM, CP violation (CPV) arises from the complex phase of the CKM quark-mixing matrix [54]. Measurements of the CPV asymmetries in the K and B meson systems are consistent with expectations based on the SM and, together with theoretical inputs, lead to the determination of the parameters of the CKM matrix. CPV has not yet been observed in the charm sector, where the theoretical predictions based on the SM for CPV asymmetries are at the level of $10^{-5}$ or below [55].

7.1. Search for CP Violation in the decay $D^+ \to K_s^0\pi^+$ [53]

BABAR searched for CPV in the decay $D^\pm \to K_s^0\pi^\pm$ by measuring the CPV parameter $A_{CP}$ defined as:

$$A_{CP} = \frac{\Gamma(D^+ \to K_s^0\pi^+)-\Gamma(D^- \to K_s^0\pi^-)}{\Gamma(D^+ \to K_s^0\pi^+)+\Gamma(D^- \to K_s^0\pi^-)},$$

(2)

where $\Gamma$ is the partial decay width for this decay. This decay mode has been chosen because of its clean experimental signature. Although direct CP violation due to interference between Cabibbo-allowed and doubly Cabibbo-suppressed amplitudes is predicted to be negligible within the SM [56], $K^0 - \bar{K}^0$ mixing induces a time-integrated CP violating asymmetry of $(-0.332 \pm 0.006)\%$ [60]. Contributions from non-SM processes may reduce the value of the measured $A_{CP}$ or enhance it up to the level of one percent [56, 57]. Therefore, a significant deviation of the $A_{CP}$ measurement from pure $K^0 - \bar{K}^0$ mixing effects would be evidence for the presence of new physics beyond the SM. Due to the smallness of the expected value, this measurement requires a large data sample and precise control of the systematic uncertainties. Previous measurements of $A_{CP}$ have been reported by the CLEO-c ($(-0.6 \pm 1.0\text{(stat)} \pm 0.3\text{(syst)})\%$ [58]) and Belle collaborations ($(-0.71 \pm 0.19\text{(stat)} \pm 0.20\text{(syst)})\%$ [59]).

We select $D^\pm \to K_s^0\pi^\pm$ decays by combining a $K_s^0$ candidate reconstructed in the decay mode $K_s^0 \to \pi^+\pi^-$ with a charged pion candidate. A $K_s^0$ candidate is reconstructed from two oppositely charged tracks with an invariant mass within $\pm 10$ MeV/$c^2$ of the nominal $K_s^0$ mass [60]. To obtain the final candidate events, a Boosted Decision Tree (BDT) algorithm [61] is constructed from seven discriminating variables for each $D^\pm$ candidate: the measured proper decay time $\tau(D^\pm)$, the decay distance in the transverse plane $L_{xy}(D^\pm)$, the CM momentum magnitude $p^*(D^\pm)$, the momentum magnitudes and transverse components with respect to the beam axis for both the $K_s^0$ and pion candidates.

A binned ML fit to the $m(K_s^0\pi^\pm)$ distribution for the retained $D^\pm$ candidates is used to extract the signal yield. The total PDF is the sum of signal and background components. The signal PDF is modeled as a sum of three Gaussian functions, the first two of them with common mean. The background PDF is taken as a sum of two components: a background from $D_s^\pm \to K_s^0 K^\pm$, where the $K^\pm$ is misidentified as $\pi^\pm$, and a combinatorial background from other sources. The data and the fit are shown in figure 10. All of the fit parameters are extracted from the fit to the data sample apart from the normalization of the $D_s^\pm \to K_s^0 K^\pm$ background, which is fixed to the value predicted by the MC simulation. We determine $A_{CP}$ by measuring the signal yield asymmetry $A$ defined as:

$$A = \frac{N_{D^+} - N_{D^-}}{N_{D^+} + N_{D^-}},$$

(3)

where $N_{D^+}(N_{D^-})$ is the number of fitted $D^+ \to K_s^0\pi^+(D^- \to K_s^0\pi^-)$ decays. The quantity $A$ is the result of two other contributions in addition to $A_{CP}$. There is a physics component due to the forward-backward (FB) asymmetry ($A_{FB}$) in $e^+e^- \to c\bar{c}$, arising from $\gamma^*Z^0$ interference and high order QED processes in $e^+e^- \to c\bar{c}$. This asymmetry will create a difference in the number of reconstructed $D^+$ and $D^-$ decays due to the FB detection asymmetries arising
Figure 10. Invariant mass distribution for $K^0\pi^\pm$ candidates in the data (black points). The solid curve shows the fit to the data. The dashed line is the sum of all backgrounds, while the dotted line is combinatorial background only. The vertical scale of the plot is logarithmic.

from the boost of the CM system relative to the laboratory frame. There is also a detector-induced component due to the difference in the reconstruction efficiencies of $D^+ \to K^0\pi^+$ and $D^- \to K^0\pi^-$ generated by differences in the track reconstruction and identification efficiencies for $\pi^+$ and $\pi^-$. While $A_{FB}$ is measured together with $A_{CP}$ using the selected dataset, we correct the dataset itself for the reconstruction and identification effects using control data sets. BABAR developed a data-driven method to determine the charge asymmetry in track reconstruction as a function of the magnitude of the track momentum and its polar angle which is shown along with the associated errors in figure 11.

Neglecting the second-order terms that contain the product of $A_{CP}$ and $A_{FB}$, the resulting asymmetry can be expressed simply as the sum of the two. The parameter $A_{CP}$ is independent of kinematic variables, while $A_{FB}$ is an odd function of $\cos \theta^*_D$, where $\theta^*_D$ is the polar angle of the $D^\pm$ candidate momentum in the $e^+e^-$ CM frame. If we compute $A(\pm |\cos \theta^*_D|)$ for the $D^\pm$ candidates in a positive $|\cos \theta^*_D|$ bin and $A(-|\cos \theta^*_D|)$ for the candidates in its negative counterpart, the contribution to the two asymmetries from $A_{CP}$ is the same, while the contribution from $A_{FB}$ has the same magnitude but opposite sign. Therefore $A_{CP}$ and $A_{FB}$ can be written as a function of $|\cos \theta^*_D|$ as follows:

$$A_{FB}(|\cos \theta^*_D|) = \frac{A(\pm |\cos \theta^*_D|) - A(-|\cos \theta^*_D|)}{2}$$

and

$$A_{CP}(|\cos \theta^*_D|) = \frac{A(\pm |\cos \theta^*_D|) + A(-|\cos \theta^*_D|)}{2}.$$  

The selected sample is divided into ten subsamples corresponding to ten $\cos \theta^*_D$ bins of equal width and a simultaneous binned ML fit is performed on the invariant mass distributions of $D^+$ and $D^-$ candidates for each subsample to extract the signal yield asymmetries. Using the asymmetry measurements in five positive and in five negative $\cos \theta^*_D$ bins, we obtain five $A_{FB}$ and five $A_{CP}$ values. As $A_{CP}$ does not depend upon $\cos \theta^*_D$, we compute a central value of this parameter using a $\chi^2$ minimization to a constant. The $A_{CP}$ and $A_{FB}$ values are shown in
Figure 11. Map of the ratio between detection efficiency for $\pi^+$ and $\pi^−$ (top) and the corresponding statistical errors (bottom). The map is produced using the numbers of $\pi^−$ and $\pi^+$ tracks in a control sample in data.

Figure 12, together with the central value and $\pm 1\sigma$ confidence interval for $A_{CP}$. We determine $A_{CP}$ to be:

$$A_{CP} = (-0.39 \pm 0.13 \pm 0.10)\%$$

where the first error is statistical and the second systematic.

7.2. Search for T-Violation using T-Odd Correlation in $D_{(s)}^+ \rightarrow K^0_S K^+ \pi^+ \pi^−$

A search for $CP$ violation in the decays $D^+ \rightarrow K^+ K^0_S \pi^+ \pi^−$ and $D_{(s)}^+ \rightarrow K^+ K^0_S \pi^+ \pi^−$ using $T$-odd correlations is described here. We define a kinematic triple product that is odd under time reversal using the vector momenta of the final state particles in the $D_{(s)}^+$ rest frame as

$$C_T \equiv \mathbf{p}_{K^+} \cdot (\mathbf{p}_{\pi^+} \times \mathbf{p}_{\pi^-})$$

(7)

Under the assumption of $CPT$ invariance, $T$ violation is equivalent to $CP$ violation.

We study the $T$-odd correlations by measuring the observable expressed in Eq. (7) and then evaluating the asymmetry

$$A_T \equiv \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)},$$

(8)

where $\Gamma$ is the decay rate for the process under study. The observable defined in Eq. (8) can have a non-zero value due to final state interactions even if the weak phases are zero [62]. The
the background is parametrized by a first-order polynomial in regions. For each region, the signal is described by the superposition of two Gaussian functions using the events with at least five charged particles. To obtain the final set of signal candidates, the likelihood-ratio test. Figure 13 shows the resulting region is the ±1σ interval, both obtained from a χ² minimization assuming no dependence on ∣cosθD∣.

T-odd asymmetry measured in the CP-conjugate decay process, AT, is defined as:

\[ \bar{A}_T \equiv \frac{\Gamma(-\bar{C}_T > 0) - \Gamma(-\bar{C}_T < 0)}{\Gamma(-\bar{C}_T > 0) + \Gamma(-\bar{C}_T < 0)}, \]

where \( \bar{C}_T \equiv \vec{p}_K^- \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+}) \). We can then construct:

\[ A_T \equiv \frac{1}{2} (A_T - \bar{A}_T), \]

which is an asymmetry that characterizes T-violation in the weak decay process [63, 64, 65].

At least four different particles are required in the final state so that the triple product may be defined using momentum vectors only [66]. The D meson decays suitable for this analysis method are \( D^+ \rightarrow K^+K_0^{*0}\pi^+\pi^- \), \( D^+ \rightarrow K^+K_0^{*0}\pi^+\pi^- \) and \( D^0 \rightarrow K^+K^-\pi^+\pi^- \). The search for CP violation using T-odd correlations in \( D^0 \rightarrow K^+K^-\pi^+\pi^- \) has recently been carried out by the BABAR Collaboration, and no evidence of CP violation has been observed [67].

The \( D^+ \) and \( D_s^+ \) meson decay candidates are reconstructed in the production and decay sequence:

\[ e^+e^- \rightarrow XD^+_\text{(s)}, D^+_\text{(s)} \rightarrow K^+K_0^{*0}\pi^+\pi^-; K_0^{*0} \rightarrow \pi^+\pi^-, \]

using the events with at least five charged particles. To obtain the final set of signal candidates, the \( p^* \) (\( D^+_\text{(s)} \)), the difference in vertex probabilities that the parent meson originates from a common vertex and the primary vertex, and the signed transverse decay length are combined in a likelihood-ratio test. Figure 13 shows the resulting \( K^+K_0^{*0}\pi^+\pi^- \) mass spectra in the \( D^+ \) and \( D_s^+ \) regions. For each region, the signal is described by the superposition of two Gaussian functions with a common mean value. The background is parametrized by a first-order polynomial in the \( D^+ \) region, and by a second-order polynomial in the \( D_s^+ \) region. We extract the integrated yields \( N(D^+) = 21210 \pm 392 \) and \( N(D_s^+) = 29791 \pm 337 \) from the fits, where the uncertainties are statistical only.

We next divide the data sample into four sub-samples depending on \( D^+_\text{(s)} \) charge and whether \( C_T \) (\( \bar{C}_T \)) is greater or less than zero, and fit the corresponding mass spectra simultaneously to extract the yields and the values of the asymmetry parameters \( A_T \) and \( \bar{A}_T \). The T-violating parameter \( A_T \) is then computed using Eq. (10). We obtain the T violation parameter values:

\[ A_T(D^+) = (-12.0 \pm 10.0_{(\text{stat})} \pm 4.6_{(\text{syst})}) \times 10^{-3} \]
The $K^+ K^0_S \pi^+ \pi^-$ mass spectrum a) in the $D^+$, and b) in the $D_s^+$ mass region. The curves result from the fits described in the text. The distributions of the Pull values are also shown.

and

$$A_T(D_s^+) = (-13.6 \pm 7.7_{(\text{stat})} \pm 3.4_{(\text{syst})}) \times 10^{-3}. \quad (13)$$

For comparison, the value obtained for $D^0$ decay was [67]

$$A_T(D^0) = (+1.0 \pm 5.1_{(\text{stat})} \pm 4.4_{(\text{syst})}) \times 10^{-3}. \quad (14)$$

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9. References

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