Charm Physics: another route towards New Physics

A. J. SCHWARTZ

Physics Department, University of Cincinnati, Cincinnati, Ohio 45221 USA

We summarize recent results for charm physics. These results span several categories: charm mixing, indirect (time-dependent) \( CP \) violation, direct (time-integrated) \( CP \) violation, \( T \) violation, semileptonic and leptonic decays, and decays of charm baryons.

PACS numbers: 11.30.Er, 13.20.Fc, 13.25.Ft, 14.20.Lq

1. Introduction

Many new measurements of \( D \) meson decays and charm baryon decays have been performed by the Belle, BaBar, LHCb, and BESIII experiments. Each experiment has unique advantages: Belle and BaBar produce boosted charmed hadrons in a low-background \( e^+e^- \) environment; LHCb produces very large event samples due the large \( c\bar{c} \) production cross section in hadron collisions; and BESIII produces \( D\bar{D} \) meson pairs in a quantum-correlated state at threshold with very little background. Here we review recent results from all four experiments. The measurements can be grouped into six areas: measurements of charm mixing, indirect (time-dependent) \( CP \) violation, direct (time-integrated) \( CP \) violation, \( T \) violation, semileptonic and leptonic decays, and charm baryon decays. Our review highlights results that are sensitive to New Physics and thus can constrain extensions to the Standard Model (SM).

2. Mixing and indirect \( CP \) violation

Measurements of mixing and \( CP \) violation require accurate flavor tagging and precise measurement of decay times. The former is usually achieved by reconstructing neutral \( D \) mesons originating from \( D^{*+} \rightarrow D^0\pi^+ \) and

* Present at the XXIV Cracow Epiphany Conference on Advances in Heavy Flavor Physics
$D^{*-} \to \overline{D}^0 \pi^-$ decays$^1$ the charge of the accompanying $\pi^\pm$ tags the flavor of the $D$. The latter is achieved by measuring the displacement $\vec{\ell}$ between the $D^{*+}$ and $D^0$ decay vertices and dividing by the $D^0$ momentum: 
\[ t = (\vec{\ell} \cdot \hat{p}_{D})(M_{D^0}/p_{D}), \]
where $M_{D^0}$ is the $D^0$ mass$^1$. The $D^{*+}$ vertex position is taken to be the intersection of $\vec{p}_D$ with the beam spot profile for $e^+e^-$ experiments, and at the primary interaction vertex for $\bar{p}p$ and $pp$ experiments.

$\text{CP}$ violation ($\text{CPV}$) arises from interference between two or more decay amplitudes. When one of these amplitudes arises from mixing, then the resulting $\text{CPV}$ is called indirect. Otherwise, when no mixing is involved, the $\text{CPV}$ is called direct. Current measurements of charm mixing and indirect $\text{CPV}$ determine mixing parameters $x$, $y$, or $x' = x\cos \delta + y\sin \delta$, $y' = y\cos \delta - x\sin \delta$, where $\delta$ is a strong phase; $\text{CPV}$ parameters $|q/p|$ and $\text{Arg}(q/p)$ = $\phi$; and “mixed” observables $y_{CP} = y\cos \phi - (|q/p| - |p/q|)x\sin \phi/2$ and $A_{\Gamma} = (|q/p| - |p/q|)y\cos \phi/2 - x\sin \phi$. A value $|q/p| \neq 1$ gives rise to $\text{CPV}$ in mixing, and a value $\phi \neq 0$ gives rise to $\text{CPV}$ resulting from interference between a mixed amplitude and a direct decay amplitude. For further details of these quantities, see the review by the Heavy Flavor Averaging Group (HFLAV)$^2$. Here we present recent measurements of $A_{\Gamma}$, $x'^2$, $y'$, and $|q/p|$ by LHCb$^3$, and results of a global fit for mixing and $\text{CPV}$ by HFLAV.

2.1. LHCb measurements

LHCb recently measured $A_{\Gamma}$ using their full Run I dataset of 3.0 fb$^{-1}$$^3$. This parameter is defined as 
\[ A_{\Gamma} = \frac{\tau_{\overline{D}^0 \to f} - \tau_{D^0 \to f}}{\tau_{\overline{D}^0 \to f} + \tau_{D^0 \to f}}, \]
where $\tau$ is the effective exponential lifetime of $D^0 \to f$ or $\overline{D}^0 \to f$ decays. This parameter can also be measured via the time-dependent $\text{CP}$ asymmetry 
\[ A_{\text{CP}}(t) = \frac{\Gamma(D^0(t) \to f) - \Gamma(\overline{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\overline{D}^0(t) \to f)} \approx a_{\text{direct}}^f - A_{\Gamma}\left(\frac{t}{\tau_D}\right), \]
where $a_{\text{direct}}^f$ represents the amount of direct $\text{CPV}$ in the decay, and $\tau_D$ is the $D^0$ lifetime. This is the method used by LHCb. Here one fits for $D^0$ and $\overline{D}^0$ yields in bins of decay time and calculates the difference in yields over the sum; the resulting background-free distribution is fit to Eq. (1). The method is much less sensitive to the decay time resolution function, which can be difficult to determine to high precision. The LHCb distribution is shown in Fig.1. The fit results are $A_{\Gamma}(K^+K^-) = (-0.030 \pm 0.032 \pm 0.010)\%$

---

$^1$ Throughout this paper, charge-conjugate modes are implicitly included unless stated otherwise.
and $A_T(\pi^+\pi^-) = (0.046\pm 0.058\pm 0.012)\%$, where the first error is statistical and the second is systematic. Combining these gives $A_T = (-0.013\pm 0.028\pm 0.010)\%$, which is the most precise result for $A_T$ to-date.

LHCb also recently measured mixing parameters $x'\times$, $y'\times$, and the CPV parameter $|q/p|$ using “wrong-sign” $D^0 \to K^+\pi^-$ decays and 3 fb$^{-1}$ of data [4, 5]. Two separate analyses were performed, both using $D^{*+} \to D^0\pi^+$ decays to tag the flavor of the $D^0$. However, the second analysis required the $D^*$ to originate from a $B \to D^{*+}\mu^-\nu$ decay, and thus the $D^0$ flavor was also tagged by the $\mu^+$. The signal yield of the first analysis is 720,000 events, while the yield for the “double-tagged” analysis is much less, 6,680 events. However, upon combining the measurements, the latter adds $\sim 10\%$ in sensitivity due to very low background and increased acceptance at low $D^0$ decay times.

The ratio of wrong-sign $D^0 \to K^+\pi^-$ decays to Cabibbo-favored “right-sign” decays $D^0 \to K^-\pi^+$, and the ratio for $\overline{D}^0 \to K^-\pi^+$ to $\overline{D}^0 \to K^+\pi^-$, are respectively [6]

$$R^+(t) = R_D + \left|\frac{q}{p}\right| \sqrt{R_D(y'\cos \phi - x'\sin \phi)} (\Gamma t) + \left|\frac{q}{p}\right|^2 \frac{(x'^2 + y'^2)}{4} (\Gamma t)^2$$

$$R^-(t) = \overline{R}_D + \left|\frac{p}{q}\right| \sqrt{R_D(y'\cos \phi + x'\sin \phi)} (\Gamma t) + \left|\frac{p}{q}\right|^2 \frac{(x'^2 + y'^2)}{4} (\Gamma t)^2,$$

Fig. 1. $A_{CP}(t)$ for $D^0 \to K^+K^-$ (top) and $D^0 \to \pi^+\pi^-$ (bottom), from LHCb [3].
where \( R_D \) is the ratio of amplitudes squared \( |A(D^0 \rightarrow K^+\pi^-)|^2/|A(D^0 \rightarrow K^-\pi^+)|^2 \), and \( \overline{R}_D = |A(D^0 \rightarrow K^+\pi^-)|^2/|A(D^0 \rightarrow K^-\pi^+)|^2 \). This measurement, like that for \( A_\Gamma \), is also performed in bins of decay time. For each bin, signal yields are obtained by fitting to variables \( M_D \) and \( \Delta M = M_D + M_D' \), and the ratios \( R^+ \) and \( R^- \) calculated. The resulting (background-free) decay time distributions are shown in Fig. 2. Simultaneously fitting these distributions to Eqs. (2) and (3) gives \( x' = (0.039 \pm 0.023 \pm 0.014) \times 10^{-3} \) and \( y' = (0.528 \pm 0.045 \pm 0.027) \). From the single-tagged analysis alone, a loose constraint \( |q/p| \in [0.82, 1.45] \) at 95% CL is obtained.

![Fig. 2. Ratios \( R^+(t) \) and \( R^-(t) \) for singly tagged (left) and doubly tagged (right) \( D^0 \rightarrow K^+\pi^- \) decays, from LHCb [4, 5].](image)

### 2.2. HFLAV global fit

HFLAV calculates world average values of \( A_\Gamma \) and also \( y_{CP} \), and inputs all \( D^0, \overline{D}^0 \) mixing measurements into a global fit to determine world average values for 10 parameters: \( x, y, |q/p|, \phi, R_D \), direct CPV parameters \( A_D, A_K \), and \( A_\pi \), and strong phase differences \( \delta \) and \( \delta_{K\pi\pi} \). The fit uses 49 observables from measurements of \( D^0 \rightarrow K^+\ell^-\nu, D^0 \rightarrow K^+K^-, D^0 \rightarrow \pi^+\pi^-, D^0 \rightarrow K^+\pi^-, D^0 \rightarrow K^+\pi^-\pi^0, D^0 \rightarrow K_S^0\pi^+\pi^-, D^0 \rightarrow \pi^0\pi^+\pi^- \),
$D^0 \rightarrow K_S^0 K^+ K^-$, and $D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$ decays, and double-tagged branching fractions measured at the $\psi(3770)$ resonance. Details are given in Ref. [2].

The results of the fit are listed in Table 1. Several fits are performed: (a) assuming $CP$ conservation by fixing $A_D=0$, $A_K=0$, $A_\pi=0$, $\phi=0$, and $|q/p|=1$; (b) assuming no direct $CPV$ in doubly Cabibbo-suppressed (DCS) decays ($A_D=0$); (c) assuming no direct $CPV$ in DCS decays and fitting for parameters $x_{12} = 2 |M_{12}|/\Gamma$, $y_{12} = \Gamma_{12}/\Gamma$, and $\phi_{12} = \text{Arg}(M_{12}/\Gamma_{12})$, where $M_{12}$ and $\Gamma_{12}$ are the off-diagonal elements of the $D^0\bar{D}^0$ mass and decay matrices, respectively; and (d) allowing full $CPV$ (floating all parameters).

For fit (b), in addition to $A_D=0$ we impose the constraint \[ \tan \phi = \frac{1 - |q/p|^2}{1 + |q/p|^2} \times \frac{x}{y}, \] which reduces four independent parameters to three\(^2\). This constraint is imposed in two ways: first floating $x$, $y$, and $\phi$ and from these deriving $|q/p|$; and alternatively floating $x$, $y$, and $|q/p|$ and from these deriving $\phi$. The central values obtained from the two fits are identical, but the first fit yields (MINOS) errors for $\phi$, while the second fit yields errors for $|q/p|$. For fit (c), we float parameters $x_{12}$, $y_{12}$, and $\phi_{12}$ and from these calculate \[ x, y, |q/p|, \] and $\phi$; these are then compared to measured values. The $1\sigma - 5\sigma$ contours in the two-dimensional parameter spaces ($|q/p|, \phi$) and ($x_{12}, \phi_{12}$) are shown in Fig. 3. The HFLAV fit excludes the no-mixing point $x = y = 0$ at $>11.5\sigma$, but the fit is consistent with $CP$ conservation ($|q/p| = 1$, $\phi = 0$).

\(^2\) One can also use Eq. (15) of Ref. [9] to reduce four parameters to three.

Fig. 3. Confidence contours resulting from the HFLAV global fit to 49 observables, from Ref. [2].
No method used is similar to that used for earlier measurements of \(D\) and \(LHCb\) (Ref. [D]) measurements, i.e., they do not require measuring decay times. However, π needs to be corrected for small systematic effects such as a possible charge flavor-tagging is important and, for high precision measurements, usually Table 3 for \(D\) decays. The results to-date are listed in Table 2 for \(±\) [15]). In all cases the results are consistent with no \(CPV\) (\(BaBar\) [41], \(LHCb\) [42]) and
\[
0 \rightarrow \pi^- \bar{\pi}^+ [10], \quad D^0 \rightarrow \rho^+ / \phi / K^0 \gamma [11], \quad D^+ \rightarrow \pi^+ \pi^0 [12]
\] and \(LHCb\) \(D^0 \rightarrow \pi^+ \pi^- [13], \quad D^0 \rightarrow K^+ K^- [13], \quad D^0 \rightarrow \pi^+ \pi^- \pi^0 [14], \quad D^0_{(s)} \rightarrow \eta' \pi^+ [15])\). In all cases the results are consistent with no \(CPV\).

### 3. Direct \(CP\) violation

In addition to searches for indirect \(CPV\) in \(D\) decays, there have been many searches for direct \(CPV\). Such searches consist of time-integrated measurements, i.e., they do not require measuring decay times. However, flavor-tagging is important and, for high precision measurements, usually needs to be corrected for small systematic effects such as a possible charge asymmetry in the reconstruction of the low momentum \(\pi^\pm\) originating from \(D^{*\pm} \rightarrow D_{\pi^\pm}\). The results to-date are listed in Table 2 for \(D^0\) decays, Table 3 for \(D^+\) decays, and Table 4 for \(D^0_s\) decays. There are recent results from Belle \((D^0 \rightarrow K^0_S K^0_S [10], \quad D^0 \rightarrow \rho^0 / \phi / K^0 \gamma [11], \quad D^+ \rightarrow \pi^+ \pi^0 [12])\) and \(LHCb\) \((D^0 \rightarrow \pi^+ \pi^- [13], \quad D^0 \rightarrow K^+ K^- [13], \quad D^0 \rightarrow \pi^+ \pi^- \pi^0 [14], \quad D^0_{(s)} \rightarrow \eta' \pi^+ [15])\) in all cases the results are consistent with no \(CPV\). Several measurements have a precision of 0.2% or smaller.

### 4. \(T\) violation

Belle recently measured the \(T\)-violating parameter \(a_T\) for Cabibbo-favored \(D^0 \rightarrow K^0_S \pi^+ \pi^- \pi^0\) decays using their full dataset of 966 fb\(^{-1}\) [10]. The method used is similar to that used for earlier measurements of \(D^0 \rightarrow K^+ K^- \pi^\pm\) decays (\(BaBar\) [31], \(LHCb\) [42]) and \(D^0_{(s)} \rightarrow K^+ K^0_S \pi^+ \pi^-\) de-
| Decay                  | Channel            | World avg. or most precise (%) | Most precise measurement |
|-----------------------|--------------------|--------------------------------|--------------------------|
| Cabibbo-favored       | $D^0 \to K^-\pi^+$ | 0.3 ± 0.7                      | CLEO 2014 [16]           |
|                       | $D^0 \to K^0_S\pi^0$ | −0.20 ± 0.17                   | Belle 2014 [17]          |
|                       | $D^0 \to K^-\pi^+\pi^0$ | 0.1 ± 0.5                      | CLEO 2014 [18]          |
|                       | $D^0 \to K^0_S\pi^+\pi^-$ | −0.08 ± 0.77                   | CDF 2012 [19]           |
|                       | $D^0 \to K^-\pi^+\pi^-\pi^+$ | 0.2 ± 0.5                      | CLEO 2014 [20]          |
|                       | $D^0 \to \eta K^0_S$ | 0.54 ± 0.53                    | Belle 2011 [21]          |
|                       | $D^0 \to \eta' K^0_S$ | 0.98 ± 0.68                    | Belle 2011 [21]          |
| Singly Cabibbo-suppressed | $D^0 \to \pi^+\pi^-$ | 0.00 ± 0.15                    | LHCb 2017 [13]          |
|                       | $D^0 \to \pi^0\pi^0$ | −0.03 ± 0.64                   | Belle 2014 [17]          |
|                       | $D^0 \to \pi^+\pi^-\pi^0$ | 0.32 ± 0.42                   | LHCb 2015 [22]          |
|                       | $D^0 \to K_S^0K^0_S$ | −0.02 ± 1.54                   | Belle 2017 [10]          |
|                       | $D^0 \to K^+K^-$ | −0.16 ± 0.12                   | LHCb 2017 [13]          |
|                       | $D^0 \to K^+K^-\pi^0$ | −1.00 ± 1.69                   | BaBar 2008 [23]         |
|                       | $D^0 \to K^0_SK^+\pi^+$ | -                              | LHCb 2016 [24]          |
|                       | $D^0 \to \pi^+\pi^-\pi^+\pi^-$ | -                             | LHCb 2017 [14]         |
|                       | $D^0 \to K^+K^-\pi^+\pi^-$ | -                              | LHCb 2013 [25]          |
| Doubly Cabibbo-suppressed | $D^0 \to K^+\pi^-\pi^0$ | −0.14 ± 5.17                   | Belle 2005 [26]         |
|                       | $D^0 \to K^+\pi^-\pi^+\pi^-$ | −1.8 ± 4.4                     | Belle 2005 [26]         |
| Radiative             | $D^0 \to \rho^0\gamma$ | 5.6 ± 15.2                     | Belle 2017 [11]         |
|                       | $D^0 \to \phi\gamma$ | −9.4 ± 6.6                     | Belle 2017 [11]         |
|                       | $D^0 \to K^*\cdot\gamma$ | −0.3 ± 2.0                     | Belle 2017 [11]         |

Table 2. Time-integrated $CP$ asymmetries for hadronic $D^0$ decays. The world averages are from HFLAV [27].

(cays (BaBar [43]). This method is as follows. From the momenta of the daughter particles, one calculates the $T$-odd quantities

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

(4)

for $D^0 \to K^0_S \pi^+\pi^-\pi^0$ decays, and

$$\overline{C}_T \equiv \vec{p}_{K_S} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+})$$

(5)
Table 3. Time-integrated CP asymmetries for hadronic $D^+$ decays. The world averages are from HFLAV [27].

| Decay                  | Channel                  | World avg. or most precise (%) | Most precise measurement |
|------------------------|--------------------------|-------------------------------|--------------------------|
| **Cabibbo-favored**    | $D^+ \rightarrow K_S^0 \pi^+$ | $-0.41 \pm 0.09$ | Belle 2012 [28] |
|                        | $D^+ \rightarrow K_S^0 \pi^+\pi^0$ | $-0.1 \pm 0.7$ | CLEO 2014 [29] |
|                        | $D^+ \rightarrow K_S^0 \pi^+\pi^-$ | $0.0 \pm 1.2$ | CLEO 2014 [29] |
|                        | $D^+ \rightarrow K^-\pi^+\pi^+$ | $-0.18 \pm 0.16$ | DO 2014 [30] |
|                        | $D^+ \rightarrow K^-\pi^+\pi^+\pi^0$ | $-0.3 \pm 0.7$ | CLEO 2014 [29] |
| **Singly Cabibbo-suppressed** | $D^+ \rightarrow \pi^+\pi^0$ | $2.3 \pm 1.3$ | Belle 2017 [12] |
|                        | $D^+ \rightarrow \pi^+\pi^+\pi^-$ | - | LHCb 2014 [31] |
|                        | $D^+ \rightarrow K_S^0 K^+$ | $0.11 \pm 0.17$ | LHCb 2014 [32] |
|                        | $D^+ \rightarrow K_S^0 K^+\pi^+\pi^-$ | $-4.2 \pm 6.8$ | FOCUS 2005 [33] |
|                        | $D^+ \rightarrow K^+ K^-\pi^+$ | $0.32 \pm 0.31$ | BaBar 2013 [34] |
|                        | $D^+ \rightarrow \eta\pi^+$ | $1.0 \pm 1.0$ | Belle 2011 [35] |
|                        | $D^+ \rightarrow \eta'\pi^+$ | $-0.61 \pm 0.90$ | LHCb 2017 [15] |
| **Doubly Cabibbo-suppressed** | $D^+ \rightarrow K^+\pi^0$ | $-3.5 \pm 10.7$ | CLEO 2010 [36] |

for $D^0 \rightarrow K_S^0 \pi^-\pi^+\pi^0$ decays. One integrates these quantities to construct the $T$-odd observables

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

(6)

for $D^0$ decays, and

$$\tilde{A}_T \equiv \frac{\Gamma(-C_T > 0) - \Gamma(-C_T < 0)}{\Gamma}$$

(7)

for $\overline{D}^0$ decays. As illustrated in Fig. 4, these observables correspond to the difference between the $K_S^0$ momentum projecting above the $(\pi^+, \pi^-)$ decay plane, and the momentum projecting below. Both $A_T$ and $\tilde{A}_T$ may be nonzero due to either interference between strong phases in the decay amplitude, or $T$ violation. A difference due to strong phases would be the same for $A_T$ and $\tilde{A}_T$, and thus the difference $a_T \equiv (A_T - \tilde{A}_T)/2$ isolates the $T$-violating effect [44]. (This asymmetry is also CP-violating, so CPT conservation implies $T$ violation.)
| Decay                  | Channel                          | World avg. or most precise (%) | Most precise measurement |
|-----------------------|----------------------------------|--------------------------------|---------------------------|
| **Cabibbo-favored**   | $D_s^+ \rightarrow K_S^0 K^+$    | 0.08 ± 0.26                    | BaBar 2013 [37]            |
|                       | $D_s^+ \rightarrow K_S^0 K^+\pi^0$ | −1.6 ± 6.1                    | CLEO 2013 [38]             |
|                       | $D_s^+ \rightarrow K_S^0 K_S^+\pi^+$ | 3.1 ± 5.2                     | CLEO 2013 [38]             |
|                       | $D_s^+ \rightarrow K^+ K^-\pi^+$  | −0.5 ± 0.9                     | CLEO 2013 [38]             |
|                       | $D_s^+ \rightarrow K^+ K^-\pi^+\pi^0$ | 0.0 ± 3.0                     | CLEO 2013 [38]             |
|                       | $D_s^+ \rightarrow K^- K_S^0\pi^+\pi^+$ | 4.1 ± 2.8                     | CLEO 2013 [38]             |
|                       | $D_s^+ \rightarrow K^0 K^+\pi^+\pi^-$ | −5.7 ± 5.4                    | CLEO 2013 [38]             |
|                       | $D_s^+ \rightarrow \eta\pi^+$     | 1.1 ± 3.1                      | CLEO 2013 [38]             |
|                       | $D_s^+ \rightarrow \eta\pi^+\pi^0$ | −0.5 ± 4.4                     | CLEO 2013 [38]             |
|                       | $D_s^+ \rightarrow \eta'\pi^+$    | −0.82 ± 0.50                   | LHCb 2017 [15]             |
|                       | $D_s^+ \rightarrow \eta'\pi^+\pi^0$ | −0.4 ± 7.6                     | CLEO 2013 [38]             |
| **Singly Cabibbo-suppressed** | $D_s^+ \rightarrow K_S^0\pi^+$ | 0.38 ± 0.49                    | LHCb 2014 [39]             |
|                       | $D_s^+ \rightarrow K^+\pi^0$     | −27 ± 24                       | CLEO 2010 [36]             |
|                       | $D_s^+ \rightarrow K^+\pi^+\pi^-$ | 4.5 ± 4.8                      | CLEO 2013 [38]             |
|                       | $D_s^+ \rightarrow \eta K^+$      | 9.3 ± 15.2                     | CLEO 2010 [36]             |
|                       | $D_s^+ \rightarrow \eta'K^+$      | 6 ± 19                         | CLEO 2010 [36]             |
| **Annihilation**      | $D_s^+ \rightarrow \pi^+\pi^-\pi^0$ | −0.7 ± 3.1                     | CLEO 2013 [38]             |

Table 4. Time-integrated $CP$ asymmetries for hadronic $D_s^+$ decays. The world averages are from HFLAV [27].

Fig. 4. Decay topology for $D^0 \rightarrow K_S^0\pi^+\pi^-\pi^0$.

The Belle measurement for $D^0 \rightarrow K_S^0\pi^+\pi^-\pi^0$ has good precision, as the signal yield is large and backgrounds are low. Belle fits for the signal yields of four independent subsamples: $\{D^0, C_T > 0\}$, $\{D^0, C_T < 0\}$, $\{\bar{D}^0, C_T > 0\}$, and $\{\bar{D}^0, C_T < 0\}$. The resulting yields give $a_T = (-0.028 \pm 0.138^{+0.023}_{-0.076})\%$, which is consistent with zero. As the four-body final state re-
results mainly from two- and three-body intermediate states, Belle also divides the event sample into ranges of \( M(\pi^+\pi^-\pi^0) \), \( M(\pi^+\pi^0) \), and \( M(K^0_S\pi^\pm) \) invariant masses to isolate \( K^0_S \omega \), \( K^0_S \eta \), \( K^*-\rho^+ \), \( K^*+\rho^- \), \( K^*+\pi^+\pi^0 \), \( K^*+\pi^-\pi^0 \), \( K^*+\pi^+\pi^- \), and \( K^0_S \rho^+\pi^- \) intermediate states. For these subsamples, \( a_T \) is recalculated. The results are listed in Table 5 and are all consistent with zero, i.e., no \( T \) violation is seen. Previous measurements of \( a_T \) for \( D^0 \to K^+K^-\pi^+\pi^- \) \([41, 42]\) and \( D^+_s \to K^+ K^0_S \pi^+\pi^- \) \([43]\) also show no evidence for \( T \) violation.

| Resonance | Invariant mass range (GeV/c^2) | \( A_T \) \((\times 10^{-2})\) | \( a_T \) \((\times 10^{-3})\) |
|-----------|-------------------------------|-----------------|-----------------|
| \( K^0_S \omega \) | \( 0.762 < M_{\pi^+\pi^-\pi^0} < 0.802 \) | 3.6 ± 0.5 ± 0.5 | -1.7 ± 3.2 ± 0.7 |
| \( K^0_S \eta \) | \( M_{\pi^+\pi^-\pi^0} < 0.590 \) | 0.2 ± 1.3 ± 0.4 | 4.6 ± 9.5 ± 0.2 |
| \( K^*-\rho^+ \) | \( 0.790 < M_{K^0_S\pi^+} < 0.994 \) | 6.9 ± 0.3 ± 1.6  | 0.0 ± 2.0 ± 1.4 |
| \( K^*+\rho^- \) | \( 0.610 < M_{\pi^+\pi^0} < 0.960 \) | 22.0 ± 0.6 ± 0.3 | 1.2 ± 4.4 ± 0.3 |
| \( K^*+\pi^+\pi^0 \) | \( 0.790 < M_{K^0_S\pi^-} < 0.994 \) | 25.5 ± 0.7 ± 0.5 | -7.1 ± 5.2 ± 1.3 |
| \( K^*+\pi^-\pi^0 \) | \( 0.790 < M_{K^0_S\pi^+} < 0.994 \) | 24.5 ± 1.0 ± 2.4  | -3.9 ± 7.3 ± 1.2 |
| \( K^*0\pi^+\pi^- \) | \( 0.790 < M_{K^0_S\pi^0} < 0.994 \) | 19.7 ± 0.8 ± 1.1  | 0.0 ± 5.6 ± 0.9 |
| \( K^0_S \rho^+\pi^- \) | \( 0.610 < M_{\pi^+\pi^0} < 0.960 \) | 13.2 ± 0.9 ± 0.2  | 7.6 ± 6.1 ± 0.0 |
| Rest | | 20.5 ± 1.0 ± 2.1  | 1.8 ± 7.4 ± 5.3 |

Table 5. Values of \( A_T \) and \( a_T \) for different regions of \( D^0 \to K^0_S \pi^+\pi^-\pi^0 \) phase space, from Belle \([41]\). \( M_{i|j|k} \) indicates the invariant mass of mesons \( i \) and \( j \) [and \( k \)].

### 5. Semileptonic and leptonic decays

Semileptonic and leptonic \( D \) decays are easier to understand theoretically than hadronic decays. Their decay rates are parameterized as

\[
\frac{d\Gamma(D \to P\ell^+\nu)}{dq^2} = \frac{G_F^2}{24\pi^3} |f^+(q^2)|^2 |V_{cs,cd}|^2 \left( 1 + \frac{m_\ell^2}{m_{P}^2} \right)^2
\]

and

\[
\Gamma(D^+_s \to \ell^+\nu) = \frac{G_F^2}{8\pi} f_{D^+_s}^2 |V_{cs,cd}|^2 m_D^2 m_{\ell}^2 \left( 1 - \frac{m_\ell^2}{m_D^2} \right)^2,
\]
where $V_{cs}$ and $V_{cd}$ are CKM matrix elements, $p^*$ is the magnitude of the momentum of the final state hadron in the $D$ rest frame, $f^+(q^2)$ is a form factor evaluated at $q^2 = (P_D - P_P)^2 = (P_\ell + P_\nu)^2$, and $f_{D(s)}$ is the $D(s)$ decay constant. Thus, with knowledge of $f^+(q^2)$ or $f_{D(s)}$ (e.g., from lattice QCD calculations), semileptonic and leptonic decay rates determine $|V_{cd}|$ and $|V_{cs}|$. Alternatively, assuming values of $|V_{cd}|$ and $|V_{cs}|$ (e.g., from CKM unitarity), the decay rates determine $f^+(q^2)$ and $f_{D(s)}$. These form factor and decay constant values can be compared to theory predictions.

5.1. BESIII results

BESIII has recently presented new measurements of $D^+ \rightarrow K^0 e^+ \nu$ and $D^+ \rightarrow \pi^0 e^+ \nu$ decays using hadronic tagging and 2.93 fb$^{-1}$ of data [45]. The decay rates are measured in bins of $q^2$, as shown in Fig. 5. The data points are fit to Eq. (8) using several theoretical models for $f^+(q^2)$; the floated parameters are the normalizations $f^K_+(q^2 = 0) \cdot |V_{cs}|$ and $f^\pi_+(q^2 = 0) \cdot |V_{cd}|$. Taking the form factor normalizations $f^K_+(0)$ and $f^\pi_+(0)$ from lattice QCD calculations [46, 47], one obtains $|V_{cs}| = 0.944 \pm 0.005 \pm 0.024$ and $|V_{cd}| = 0.210 \pm 0.004 \pm 0.001 \pm 0.009$, where the third error is due to theoretical uncertainty in the lattice calculations. These values are consistent with CKM unitarity (see below).

![Fig. 5. BESIII results](image)

Several other semileptonic decays have also been measured by BESIII,
although no form factor calculations for these exist: $D^+ \to \phi(\mu^+, e^+)\nu$ \cite{15}, $D^+ \to \eta(\mu^+)\nu$ \cite{15}, $D^+ \to \eta(\epsilon^+)\nu$ \cite{19}, $D^+ \to \overline{K}^0\mu^+\nu$ \cite{50}, and the radiative leptonic decay $D^+ \to \gamma e^+\nu$ \cite{51}. BESIII results for purely leptonic decays $D_s^+ \to \mu^+\nu$ and $D_s^+ \to \tau^+\nu$ are given in Ref. \cite{52}.

5.2. HFLAV world averages

HFLAV has calculated world averages for the product $f_D |V_{cd}|$ measured using $D^+ \to \mu^+\nu$ decays, and for the product $f_{D_s} |V_{cs}|$ measured using $D_s^+ \to e^+\nu/\mu^+\nu/\tau^+\nu$ decays \cite{2}. In the former case, inserting the lattice result $f_D = 212.15 \pm 1.45$ MeV \cite{53} gives $|V_{cd}| = 0.2164 \pm 0.0050 \pm 0.0015$, which is consistent with the unitarity constraint $|V_{cd}| = 0.22492 \pm 0.00050$ \cite{54}. Averaging this result with the corresponding value from semileptonic $D \to \pi \ell \nu$ decays gives a world average of 0.216 \pm 0.005, as shown in Fig. 6. This value is also consistent with unitarity. Alternatively, inserting the unitarity value for $|V_{cd}|$ gives $f_D = 203.7 \pm 4.9$ MeV, which is 1.7\sigma lower than the lattice QCD prediction.

For $D_s^+ \to \ell^+\nu$ decays, using the lattice result $f_{D_s} = 248.83 \pm 1.27$ MeV \cite{53} gives $|V_{cs}| = 1.006 \pm 0.018 \pm 0.005$, which is consistent with the unitarity constraint $|V_{cs}| = 0.97351 \pm 0.0013$ \cite{54}. Averaging this result with the corresponding value from $D \to K \ell \nu$ decays gives a world average of 0.997 \pm 0.017 (see Fig. 6), which is also consistent with unitarity. Alternatively, inserting the unitarity value for $|V_{cs}|$ gives $f_{D_s} = 257.1 \pm 4.6$ MeV, which is 1.7\sigma higher than the lattice QCD prediction.

![Fig. 6. HFLAV world average values for $|V_{cd}|$ (left) and $|V_{cs}|$ (right), from Ref. \cite{2}.](image-url)
6. Charm baryons

There has recently been a profusion of new measurements of charm baryon decays. Belle, BESIII, and LHCb dominate these measurements, and their most recent results are listed in Table 6.

An interesting result from Belle is that of a search for a “hidden-strangeness” pentaquark ($P_c^+$) with quark content $s\bar{s}uud$ [59]. This state would be analogous to the “hidden charm” pentaquark $P_c^+ = c\bar{c}uud$ observed by LHCb [77]. For this analysis Belle reconstructed $\Lambda_c^+ \to \phi p\pi^0$ decays and fitted for the signal yield in bins of $M(\phi p)$ invariant mass. Plotting these yields gives a background-free $M(\phi p)$ distribution; a peaking structure would indicate an intermediate $P_c^+ \to \phi p$ decay. The resulting distribution is shown in Fig. 7. There is an excess of events ($78 \pm 28$) at $M_{\phi p} = 2.025 \pm 0.005$ GeV/$c^2$, but the significance is only $2.7\sigma$. The future Belle II experiment [78], with much higher statistics, should be able to clarify whether this excess is the
first hint of a $P_s^{+}$ state.

Fig. 7. Background-free $M(\phi p)$ invariant mass distribution for $D^0 \rightarrow \phi p\pi^0$ decays, from Belle [59].

Another interesting result comes from both LHCb [68] and Belle [58] and concerns excited $\Omega_c^*$ states, which have a valence quark content of $css$. LHCb observed five new excited states by reconstructing $\Xi_c^{++} \rightarrow pK^-\pi^+$ decays, pairing the $\Xi_c^{++}$ with well-identified $K^-$ tracks, and calculating the $M(\Xi_c^{++}K^-)$ invariant mass. The resulting distribution is shown in Fig. 8. Five narrow peaks are observed, clearly indicating $\Omega_c^* \rightarrow \Xi_c^{++}K^-$ decays. This result was recently confirmed by Belle (see Fig. 9), although the Belle statistics are significantly lower and only sufficient to identify four of the five $\Omega_c^*$ states.

Fig. 8. $M(\Xi_c^{++}K^-)$ invariant mass distribution, from LHCb [68].
Fig. 9. Belle measurement \cite{57} of excited $\Omega_c^+$ states. Top: $M(\Xi_c^+ K^-)$ invariant mass distribution. Middle: wrong-sign $M(\Xi_c^+ K^+) \text{ mass distribution, which nominally contains only background.}$ Bottom: $M(\Xi_c^+ K^-)$ mass distribution in which the $\Xi_c^+$ is taken from the $M(pK^-\pi^+)$ sideband. The solid (blue) curves show the overall fit projections.

7. Summary

Recent world averages for $D^0\bar{D}^0$ mixing and indirect CPV parameters as calculated by HFLAV are summarized in Table 1. Results for searches for direct CPV are summarized in Tables 2, 3, and 4. The most recent world averages for $|V_{cd}|$ and $|V_{cs}|$ as calculated from measurements of semileptonic and leptonic decays are plotted in Fig. 6; the resulting values are consistent with CKM unitarity. Finally, the most recent results for charm baryon decays are listed in Table 6. Although no statistically significant anomaly or “smoking gun” of new physics is seen, the precision of these results will be significantly improved with the analysis of LHCb Run 2 data and the large $e^+e^-$ dataset to be collected by Belle II. Many new charm baryon measurements are expected, well beyond those listed in Table 6.

We thank the workshop organizers for hosting a productive meeting with excellent hospitality. The author also thanks Andrea Contu for reviewing this manuscript.
REFERENCES

[1] C. Patrignani et al. (Particle Data Group), Chin. Phys C, 40, 100001 (2016) and 2017 update.
[2] Y. Amhis et al. (Heavy Flavor Averaging Group), Eur. Phys. Jour. C 77, 895 (2017) [arXiv:1612.07233].
[3] R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 118, 261803 (2017).
[4] R. Aaij et al. (LHCb Collaboration), Phys. Rev. D 97, 031101 (2018).
[5] R. Aaij et al. (LHCb Collaboration), Phys. Rev. D 95, 052004 (2017).
[6] S. Bergmann, Y. Grossman, Z. Ligeti, Y. Nir, and A. A. Petrov, Phys. Lett. B 486, 418 (2000).
[7] M. Ciuchini et al., Phys. Lett. B 655, 162 (2007).
[8] A. Kagan and M. D. Sokoloff, Phys. Rev. D 80, 076008 (2009).
[9] Y. Grossman, Y. Nir, and G. Perez, Phys. Rev. Lett. 103, 071602 (2009).
[10] N. Dash, et al. (Belle Collaboration), Phys. Rev. Lett. 119, 171801 (2017).
[11] T. Nanut et al. (Belle Collab.), Phys. Rev. Lett. 118, 051801 (2017).
[12] V. Babu, et al. (Belle Collab.), Phys. Rev. D 97, 011101 (2018).
[13] R. Aaij et al. (LHCb Collab.), Phys. Lett. B 767, 177 (2017).
[14] R. Aaij et al. (LHCb Collab.), Phys. Lett. B 769, 345 (2017).
[15] R. Aaij et al. (LHCb Collab.), Phys. Lett. B 771, 21 (2017).
[16] G. Bonvicini et al. (CLEO Collab.), Phys. Rev. D 89, 072002 (2014).
[17] N. K. Nisar et al. (Belle Collab.), Phys. Rev. Lett. 112, 211601 (2014).
[18] G. Bonvicini et al. (CLEO Collab.), Phys. Rev. D 89, 072002 (2014).
[19] T. Aaltonen et al. (CDF Collab.), Phys. Rev. D 86, 032007 (2012).
[20] G. Bonvicini et al. (CLEO Collab.), Phys. Rev. D 89, 072002 (2014).
[21] B. R. Ko et al. (Belle Collab.), Phys. Rev. Lett. 106, 211801 (2011).
[22] R. Aaij et al. (LHCb Collab.), Phys. Lett. B 740, 158 (2015).
[23] B. Aubert et al. (BABAR Collab.), Phys. Rev. D 78, 051102 (2008).
[24] R. Aaij et al. (LHCb Collab.), Phys. Rev. D 93, 052018 (2016).
[25] R. Aaij et al. (LHCb Collab.), Phys. Lett. B 726, 623 (2013).
[26] X. C. Tian et al. (Belle Collab.), Phys. Rev. Lett. 95, 231801 (2005).
[27] Heavy Flavor Averaging Group, http://www.slac.stanford.edu/xorg/hflav/charm/index.html.
[28] B. R. Ko et al. (Belle Collab.), Phys. Rev. Lett. 109, 021601 (2012).
[29] G. Bonvicini et al. (CLEO Collab.), Phys. Rev. D 89, 072002 (2014).
[30] V. M. Abazov et al. (D0 Collab.), Phys. Rev. D 90, 111102 (2014).
[31] R. Aaij et al. (LHCb Collab.), Phys. Lett. B 728, 585 (2014).
[32] R. Aaij et al. (LHCb Collab.), JHEP 1410, 025 (2014).
[33] J. M. Link et al. (FOCUS Collab.), Phys. Lett. B 622, 239 (2005).
[34] J. P. Lees et al. (BaBar Collab.), Phys. Rev. D 87, 052010 (2013).
[35] E. Won et al. (Belle Collab.), Phys. Rev. Lett. 107, 221801 (2011).
[36] H. Mendez et al. (CLEO Collab.), Phys. Rev. D 81, 052013 (2010).
[37] J.P. Lees et al. (BaBar Collab.), Phys. Rev. D 87, 052012 (2013).
[38] P.U.E. Onyisi et al. (CLEO Collab.), Phys. Rev. D 88, 032009 (2013).
[39] R. Aaij et al. (LHCb Collab.), JHEP 1410, 025 (2014).
[40] K. Prasanth et al. (Belle Collab.), Phys. Rev. D 95, 091101(R) (2017).
[41] P. del Amo Sanchez et al. (BaBar Collab.), Phys. Rev. D 81, 111103 (2010).
[42] R. Aaij et al. (LHCb Collab.), JHEP 10, 5 (2014).
[43] J.P. Lees et al. (BaBar Collab.), Phys. Rev. D 84, 031103 (2011).
[44] See, e.g., W. Bensalem and D. London, Phys. Rev. D 64, 116003 (2001).
[45] M. Ablikim et al. (BESIII Collab.), Phys. Rev. D 96, 012002 (2017).
[46] H. Na et al. (HPQCD Collab.), Phys. Rev. D 82, 114506 (2010).
[47] H. Na et al. (HPQCD Collab.), Phys. Rev. D 84, 114505 (2011).
[48] M. Ablikim et al. (BESIII Collab.), Phys. Rev. D 97, 012006 (2018).
[49] M. Ablikim et al. (BESIII Collab.), Phys. Rev. D 94, 112003 (2016).
[50] M. Ablikim et al. (BESIII Collab.), EPJC 76, 369 (2016).
[51] M. Ablikim et al. (BESIII Collab.), Phys. Rev. D 95, 071102(R) (2017).
[52] M. Ablikim et al. (BESIII Collab.), Phys. Rev. D 94, 072004 (2016).
[53] S. Aoki et al. (FLAG Working Group), EPJC 77, 112 (2017).
[54] A. Ceccucci, Z. Ligeti, and Y. Sakai, “CKM Quark-Mixing Matrix,” in C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016) and 2017 update.
[55] M. Berger et al. (Belle Collab.), arXiv:1802.03421.
[56] Y. B. Li et al. (Belle Collab.), Eur. Phys. Jour. C 78, 252 (2018).
[57] J. Yelton, et al. (Belle Collab.), Phys. Rev. D 97, 032001 (2018).
[58] J. Yelton, et al. (Belle Collab.), Phys. Rev. D 97, 051102 (2018).
[59] B. Pal, A.J. Schwartz et al. (Belle Collab.), Phys. Rev. D 96, 051102(R) (2017).
[60] M. Niiyama et al. (Belle Collab.), arXiv:1706.06791.
[61] J. Yelton, et al. (Belle Collab.), Phys. Rev. D 94, 052011 (2016).
[62] Y. Kato, et al. (Belle Collab.), Phys. Rev. D 94, 032002 (2016).
[63] S.B. Yang, et al. (Belle Collab.), Phys. Rev. Lett. 117, 011801 (2016).
[64] R. Aaij et al. (LHCb Collab.), arXiv:1712.07938.
[65] R. Aaij et al. (LHCb Collab.), arXiv:1712.07051.
[66] R. Aaij et al. (LHCb Collab.), JHEP 1803, 043 (2018).
[67] R. Aaij et al. (LHCb Collab.), Phys. Rev. Lett. 119, 112001 (2017).
[68] R. Aaij et al. (LHCb Collab.), Phys. Rev. Lett. 118, 182001 (2017).
[69] M. Ablikim et al. (BESIII Collab.), arXiv:1803.04299.
[70] M. Ablikim et al. (BESIII Collab.), Phys. Lett. B 772, 388 (2017).
[71] M. Ablikim et al. (BESIII Collab.), Phys. Rev. D 95, 111102(R) (2017).
[72] M. Ablikim et al. (BESIII Collab.), Phys. Lett. B 767, 42 (2017).
[73] M. Ablikim et al. (BESIII Collab.), Phys. Rev. Lett. 118, 112001 (2017).
[74] M. Ablikim et al. (BESIII Collab.), Phys. Rev. Lett. 117, 232002 (2016).
[75] M. Ablikim et al. (BESIII Collab.), Phys. Rev. Lett. 116, 052001 (2016).
[76] M. Ablikim et al. (BESIII Collab.), Phys. Rev. Lett. 115, 221805 (2015).
[77] R. Aaij et al. (LHCb Collab.), Phys. Rev. Lett. 115, 072001 (2015).
[78] https://www.belle2.org/