INSTITUT DE FRANCE
Académie des sciences

Comptes Rendus
Physique

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Volume 21, issue 1 (2020), p. 75-92

Published online: 17 September 2020
Issue date: 17 September 2020

https://doi.org/10.5802/crphys.14

Part of Special Issue: A perspective of High Energy Physics from precision measurements
Guest editors: Stéphane Monteil (Clermont Université, CNRS/IN2P3, Clermont-Ferrand) and Marie-Hélène Schune (Université Paris-Saclay, CNRS/IN2P3, Orsay)

Les Comptes Rendus. Physique *sont membres du Centre Mersenne pour l'édition scientifique ouverte*
www.centre-mersenne.org
e-ISSN : 1878-1535

Comptes Rendus
Physique
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A perspective of High Energy Physics from precision measurements
La physique des Hautes Energies du point de vue des mesures de précision

Tau and charm decays

Les désintégrations du τ et du charme

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Abstract. A summary of recent precise results in tau and charm physics is presented. Topics include leptonic and hadronic tau decays, lepton flavour and lepton number violation, charm mixing and *CP* violation, leptonic and semileptonic charm decays, rare decays and spectroscopy.

Résumé. Nous présentons une sélection de mesures précises et récentes des physiques du lepton τ et du quark charmé et leur interprétation. Nous examinons en particulier les désintégrations hadroniques et leptoniques du τ, les recherches de violation du nombre leptonique et du nombre leptonique par famille, le mélange des mésons neutres charmés et l'observation de la brisure de la symétrie *CP*, les désintégrations leptoniques et semileptoniques des hadrons charmés, leurs désintégrations rares et les récentes découvertes spectroscopiques.

Keywords. Tau and charm physics, D^0 mixing, CP violation.

Mots-clés. La physique du charme et du tau, Oscillation du D^0, Violation de CP.

1. Introduction

The τ is a third generation lepton that decays into quarks and leptons of the first two families. A precision study of its dynamical properties could then shed some light in our understanding of the flavour problem: why fermions are replicated in three sequential generations with identical properties, except the values of their masses. Moreover, the τ lepton is heavy enough to have a rich variety of hadronic decays, providing a clean laboratory to tests QCD at low energies [1].

The charm is an up-type quark accessible to precision experiments. Being a member of the second family, it allows us to study the interplay of weak and strong interactions through its large diversity of weak decays: leptonic, semileptonic, Cabibbo favoured, Cabibbo suppressed,

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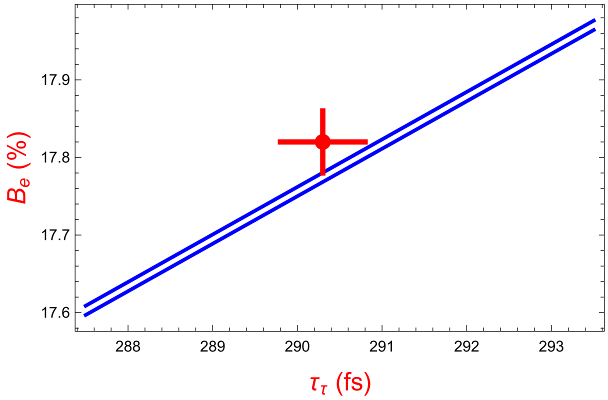

Figure 1. SM relation between the τ lifetime and $B_e \equiv B(\tau^- \to \nu_\tau e^- \bar{\nu}_e)$ (blue band), compared with the measured values (red cross). The band width reflects the current uncertainty on m_τ.

doubly Cabibbo suppressed, and rare decays that are very suppressed (radiative decays, flavour-changing neutral-current transitions) or even forbidden in the Standard Model (SM). The investigation of D^0-$\bar{D}^0$ mixing and *CP*-violation phenomena in the up-type sector is of enormous interest to test the CKM quark-mixing mechanism. The confinement properties of QCD can also be analysed through the spectroscopy of open charm mesons and charm baryons.

The τ mass, $m_\tau = (1776.86 \pm 0.12)$ MeV, is very close to the lightest charmed-particle mass, $m_{D^0} = (1864.83 \pm 0.05)$ MeV [2]. Therefore, both types of particles have similar production mechanisms at e^+e^- colliders, making the physics of τ and c a common objective in many experiments. The electromagnetic (or Z^0 exchange) production cross section is usually maximised by running at some resonance peak that, moreover, decays to quantum correlated $\tau^+\tau^-$, $D^0\bar{D}^0$ or D^+D^- pairs. The LEP-I experiments were running at the Z^0 peak, MARKIII (at SPEAR at SLAC), CLEO (at CESR-c) and BESIII (at BEPCII) utilise the $\psi(3770)$ resonance, and the $\Upsilon(4S)$ is the default choice at the b-factories, Belle (at KEKB) and BaBar (at PEP-II). The charm cross-sections at low-energy e^+e^- colliders are at the order few nb. The charm production at hadron colliders occurs in very asymmetric collisions due to the fact that the protons are no longer point-like particles. At hadron colliders experiments LHCb (at LHC) and CDF (at Tevatron), the cross-sections for prompt and secondary production (from B decays) are significantly higher: they can reach about 2 mb for prompt D^0 at 13 TeV [3].

2. Leptonic tau decays

The τ lepton decays through the emission of a virtual W^- boson, i.e., $\tau^- \to \nu_\tau W^{-*} \to \nu_\tau X^-$ with $X^- = e^-\bar{\nu}_e, \mu^-\bar{\nu}_\mu, d\bar{u}, s\bar{u}$. In the SM, the charged-current interaction has a universal strength that can be precisely measured in the analogous decay of the muon, $\mu^- \to \nu_\mu e^- \bar{\nu}_e$. Therefore, the leptonic decay width of the τ can be predicted with high accuracy or, equivalently, one gets a relation between the τ lifetime and its leptonic branching ratio that is in excellent agreement with the experimental values [2], shown in Figure 1. The main uncertainty originates in the current experimental error on the τ mass ($\Delta m_\tau / m_\tau = 0.7 \times 10^{-4}$) because $\Gamma_{\tau\to e}$ is proportional to m_τ^5.

Alternatively, one can use the leptonic decay widths of the τ and the μ to test the predicted flavour universality of the $W^\pm$ couplings, i.e., that $g_e = g_\mu = g_\tau \equiv g$. The ratio $\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$ is sensitive to $|g_\mu/g_e|$, while $\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$ tests $|g_\tau/g_\mu|$. Table 1 shows the current experimental

Table 1. Experimental determinations of the ratios $g_\ell/g_{\ell'}$ [1,2]

	$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$	$\Gamma_{\pi\to\mu}/\Gamma_{\pi\to e}$	$\Gamma_{K\to\mu}/\Gamma_{K\to e}$	$\Gamma_{K\to\pi\mu}/\Gamma_{K\to\pi e}$	$\Gamma_{W\to\mu}/\Gamma_{W\to e}$
$\lvert g_\mu/g_e\rvert$	1.0018 (16)	1.0021 (16)	0.9978 (20)	1.0010 (25)	0.996 (10)
	$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$	$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	$\Gamma_{W\to\tau}/\Gamma_{W\to\mu}$	
$\lvert g_\tau/g_\mu\rvert$	1.0011 (15)	0.9962 (27)	0.9858 (70)	1.034 (13)	
	$\Gamma_{\tau\to\mu}/\Gamma_{\mu\to e}$	$\Gamma_{W\to\tau}/\Gamma_{W\to e}$			
$\lvert g_\tau/g_e\rvert$	1.0030 (15)	1.031 (13)			

constraints, together with the most precise tests from leptonic π, K and $W^\pm$ decays. Charged-current universality has been successfully tested at low energies with a 0.15% precision. The direct leptonic decays of the $W^\pm$ suggest a slight excess of events in $W^-\to\tau^-\bar\nu_\tau$, implying a 2.5σ deviation from universality that is not compatible with the one order of magnitude more accurate constraints from W-mediated decays. Better $W^\pm$ data would be welcome.

The Lorentz structure of the $\ell^-\to\nu_\ell\ell'^-\bar\nu_{\ell'}$ interaction can be analysed in a model-independent way. The most general, local, derivative-free, lepton-number conserving, four-lepton interaction Hamiltonian, consistent with locality and Lorentz invariance contains ten possible structures with their corresponding complex couplings $g^n_{\epsilon\omega}$, where $n = S, V, T$ denotes the type of interaction (scalar, vector, tensor) and the subindices label the left or right chiralities of ℓ (ω) and ℓ' (ϵ) [1]. Taking out a common global factor that is determined by the total decay rate, the couplings are normalised so that they satisfy $|g^S_{\epsilon\omega}|\le 2$, $|g^V_{\epsilon\omega}|\le 1$ and $|g^T_{\epsilon\omega}|\le 1/\sqrt{3}$. In the SM, $g^V_{LL}=1$, while all other couplings are identically zero. Measuring the energy and angular distribution of the final charged lepton, complemented with polarisation information whenever available, it is possible to disentangle the contributions from the different operators.

In μ decay, where precise polarisation measurements have been performed of both μ and e, it has been experimentally proved that the bulk of the decay amplitude is indeed of the predicted $V-A$ type, $|g^V_{LL}| > 0.960$ (90% C.L.) [2] (one needs also information from the inverse transition $\nu_\mu e^-\to\mu^-\nu_e$), and upper bounds on all other couplings have been set. Owing to its much shorter lifetime, the analysis of the τ interaction is more challenging. It is still possible to get polarisation information about the initial τ, through the correlated distribution of $\tau^+\tau^-$ pairs produced in e^+e^- annihilation. However, the polarisation of the secondary charged lepton from the τ decay has never been measured. Since the data agree with the SM, there exist upper bounds on those couplings corresponding to an initial right-handed τ [2], but the Lorentz structure of a left-handed decaying τ remains undetermined.

3. Hadronic tau decays

A large set of kinematically-allowed semileptonic decays can be accessed with τ decay data. Contrary to e^+e^- annihilation that only tests the electromagnetic vector current, the decay $\tau^-\to\nu_\tau H^-$ probes the matrix elements of both vector and axial-vector currents between the vacuum and the given hadronic state H^-. Moreover, one can also disentangle the Cabibbo allowed ($\bar d u$) and suppressed ($\bar s u$) currents through the strangeness of the produced hadrons. The τ provides a very good data sample to investigate the dynamics of the QCD Goldstone bosons (π, K, η) in the resonance region, around 1 GeV.

For the lowest-multiplicity decays, $H^- = \pi^-, K^-$, the hadronic matrix elements are already known from $\pi^-\to\mu^-\bar\nu_\mu$ and $K^-\to\mu^-\bar\nu_\mu$, which makes possible to perform the universality tests in Table 1. One can also make a determination of $|V_{us}|$, but it is not yet competitive with those from $K\to\ell\nu$ and $K\to\pi\ell\nu$, owing to the currently larger uncertainties in $\tau^-\to K^-\nu_\tau$.

The $\pi^-\pi^0$, $\pi^-\bar{K}^0$ and $\pi^0 K^-$ final states give us access to an interesting variety of vector form factors with relevant dynamical information. The decay into the odd G-parity state $\pi^-\eta$ is strongly suppressed in the SM with an expected branching fraction around 10^{-5} [4, 5]; its observation above this level would imply new physics incorporating second-class currents. With the large data samples collected at the B factories, differential decay distributions with three hadrons in the final state have become available and branching ratios into high-multiplicity 3- and 5-prong decays have been measured [6]. However, several inconsistencies are known to exist in some branching fraction measurements [2] and errors are still large in the Cabibbo suppressed modes. Thus, there is ample room for improvements at Belle II.

The inclusive hadronic width of the τ can be rigorously computed in QCD. Its Cabibbo allowed component can be expressed in the form [7]

$$R_{\tau,V+A} \equiv \frac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons}\,[\bar{d}u])}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} = N_C\,|V_{ud}|^2 S_{\mathrm{EW}}\{1+\delta_P+\delta_{\mathrm{NP}}\}, \tag{1}$$

with $N_C = 3$ the number of QCD colours and $S_{\mathrm{EW}} = 1.0201 \pm 0.0003$ [8–10] the electroweak radiative corrections. The non-perturbative correction δ_{NP} is strongly suppressed by six powers of the τ mass [7] and, moreover, can be extracted from the invariant mass distribution of the final hadrons [11]. Detailed studies performed by ALEPH [12–16], CLEO [17] and OPAL [18] have confirmed that non-perturbative contributions are below 1%. The theoretical prediction of $R_{\tau,V+A}$ is then governed by the perturbative correction δ_P (∼20%), which is known to $O(\alpha_s^4)$ [19] and is very sensitive to the strong coupling, making possible a quite accurate determination of α_s [7, 20, 21]. The main theoretical uncertainty originates in the unknown higher-order perturbative corrections [22, 23].

The most precise experimental determination, extracted from the ALEPH τ decay distributions, gives $\delta_{\mathrm{NP}} = -0.0064 \pm 0.0013$ and $\alpha_s^{(n_f=3)}(m_\tau^2) = 0.332 \pm 0.005_{\mathrm{exp}} \pm 0.011_{\mathrm{th}}$ [24]. Taking as input the ALEPH value of δ_{NP}, the strong coupling can be also determined from the total τ hadronic width (and/or lifetime); one gets $\alpha_s^{(n_f=3)}(m_\tau^2) = 0.331 \pm 0.013$ [1], in perfect agreement with the ALEPH result. An exhaustive phenomenological re-analysis of the ALEPH data has been recently performed, exploring all strategies previously considered in the literature and several complementary approaches. The results from all adopted methodologies are in excellent agreement, leading to a very robust and reliable value of the strong coupling [25]:

$$\alpha_s^{(n_f=3)}(m_\tau^2) = 0.328 \pm 0.013. \tag{2}$$

After evolution up to the scale M_Z, it implies $\alpha_s^{(n_f=5)}(M_Z^2) = 0.1197 \pm 0.0015$, which agrees perfectly with the direct measurement at $s = M_Z^2$ from the Z^0 hadronic width, $\alpha_s^{(n_f=5)}(M_Z^2) = 0.1196 \pm 0.0030$ [26]. The comparison of these two determinations, provides a beautiful test of the predicted QCD running:

$$\alpha_s^{(n_f=5)}(M_Z^2)|_\tau - \alpha_s^{(n_f=5)}(M_Z^2)|_Z = 0.0001 \pm 0.0015_\tau \pm 0.0030_Z. \tag{3}$$

The ratio of the inclusive $|\Delta S| = 1$ and $|\Delta S| = 0$ τ decay widths (normalised to the electronic width), $R_{\tau,S}/R_{\tau,V+A}$, provides a clean determination of V_{us} [27, 28]. To a first approximation, the

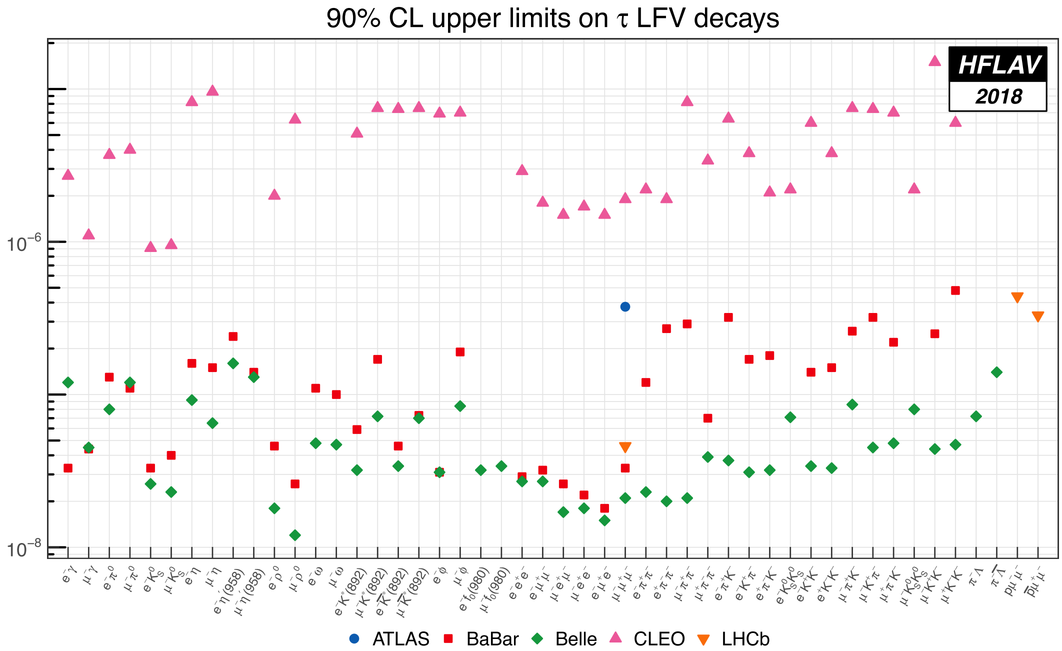

Figure 2. Experimental upper limits on τ LFV and LNV branching ratios [32].

experimental ratio directly measures $|V_{us}/V_{ud}|$. Taking into account the PDG value of V_{ud} and the small SU(3)-breaking correction $\delta R_{\tau,\mathrm{th}} = 0.242 \pm 0.033$ [29–31], one finds [32]

$$|V_{us}| = \left(\frac{R_{\tau,S}}{\frac{R_{\tau,V+A}}{|V_{ud}|^2} - \delta R_{\tau,\mathrm{th}}}\right)^{1/2} = 0.2195 \pm 0.0019, \tag{4}$$

which is 2.9σ lower than the unitarity expectation $|V_{us}|^{\mathrm{uni}} = \sqrt{1-|V_{ud}|^2-|V_{ub}|^2} = 0.2257 \pm 0.0009$. More precise measurements of the Cabibbo-suppressed τ branching fractions at Belle II are expected to clarify the current discrepancy [33].

4. Lepton flavour and lepton number violation in tau decays

The current experimental limits on neutrinoless lepton-flavour-violating (LFV) decays of the τ lepton are shown in Figure 2. Thanks to the large data samples collected at the B factories, sensitivities of a few times 10^{-8} have been achieved in many leptonic ($\tau \to \ell\gamma$, $\tau \to \ell'\ell^+\ell^-$) and semileptonic ($\tau \to \ell P^0$, $\tau \to \ell V^0$, $\tau \to \ell P^0 P^0$, $\tau \to \ell P^+ P'^-$) LFV decay modes. Competitive limits for some selected final states, such as $\tau \to 3\mu$, have been also set by LHCb. Belle II is expected to push these limits to the 10^{-9} level [33], increasing in a drastic way the sensitivity to new-physics scales.

Lepton-number violation (LNV) has been also searched for in τ decays. Very stringent upper limits in the range $(2.0-8.4)\times 10^{-8}$ (90% C.L.) have been set on the decay modes $\tau^- \to \ell^+ P^- P'^-$, with $\ell = e, \mu$ and $P, P' = \pi, K$ [34]. Worth mentioning is also the experimental limit $B(\tau^- \to \Lambda\pi^-) < 7.2\times 10^{-8}$ (90% C.L.), which tests the violation of both lepton and baryon numbers [35].

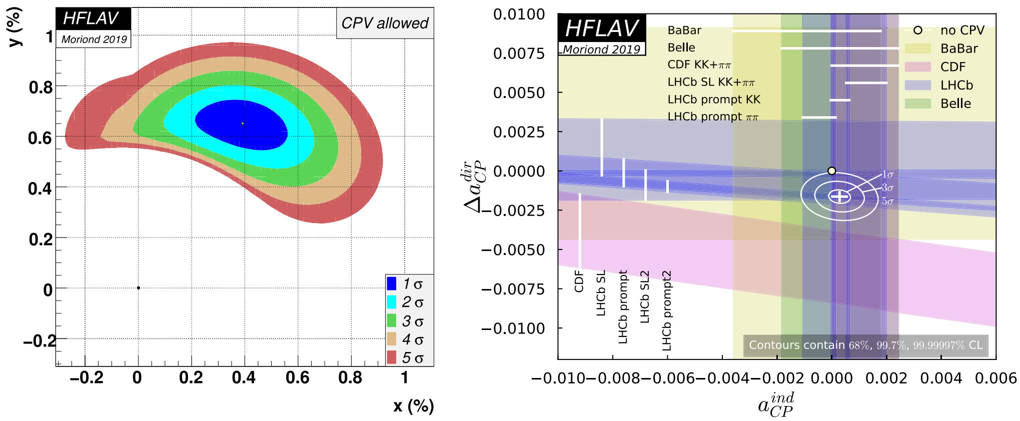

Figure 3. Left: The HFLAV averages for the mixing parameters x and y; Right: The combination plot of ΔA_{CP} and A_Γ. The point of no *CP* violation (0,0) is shown as a filled circle [32].

5. Mixing and *CP* violation in charm decays

The phenomenon of *CP* violation is one of the keys to uncover why there is an overwhelming amount of matter over antimatter in our Universe, as postulated by Sakharov in 1967 [36]. The *CP* symmetry applies to processes invariant under the combined transformation of charge conjugation (C) under which a particle is exchanged with its own anti-particle, and spatial inversion (parity, P). The SM accommodates *CP* violation in a single complex phase of the CKM matrix which only appeared after introducing the third family of quarks. The *CP* violation has been well established in decays of $K^0(\bar{s}d)$, $B^0(\bar{b}d)$, $B_s^0(\bar{b}s)$ and $B^+(\bar{b}u)$ mesons. Unlike for the b-system where we expect sizeable effects, for D meson decays, SM *CP* violation effects are expected to be tiny because of the smallness of the imaginary component of the CKM elements involved in the relevant processes. *CP* violation in charm was only recently observed in decays of $D^0(c\bar{u})$ to a pair of charged kaons and to a pair of charged pions [37] and there is no agreement whether its size is compatible with the SM predictions [38–42].[1]

Neutral charm mesons can periodically change into their antimatter counterparts and back – they oscillate. As a result, the mass eigenstates, with well-defined masses and lifetimes, are linear combinations of flavour eigenstates, with well-defined quark composition: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D^0}\rangle$. Here, q, p are complex numbers that are related by $p^2 + q^2 = 1$. The mixing parameters x and y are defined as $y \equiv \Delta\Gamma/(2\Gamma)$, where $\Delta\Gamma = \Gamma_2 - \Gamma_1$ is the width difference of the charm mesons, and $x \equiv \Delta m/\Gamma$, where Δm is their mass difference. The mixing process is suppressed in charm because the corresponding box diagrams contain down-type quarks in the internal lines: owing to the GIM cancellation, each virtual quark contribution is proportional to m_q^2, and the heaviest quark, b is not quite as heavy as the top quark (which plays an important role in the B meson mixing) and has very small couplings with c and u quarks. This leads to very slow oscillation of the D mesons, and to very small values of x and y, experimentally challenging to measure. The current world averages are displayed in Figure 3 (left) [32]. Including the latest LHCb result [43], the parameter x related to the mass difference between neutral charm-meson eigenstates is measured to be greater than 0 with a significance exceeding 3 standard deviations for the first time.

[1] The theory predictions for charm mesons are particularly difficult because of the intermediate mass of the c quark. Effective theories such as HQET (too light) and Chiral Perturbation Theory (too heavy) are not directly applicable.

The amplitude for the decay of a D hadron to a final state f can be expressed as A_f, and the amplitude of the charge-conjugated process as $\bar{A}_{\bar{f}}$. There are several ways to generate a *CP* asymmetry. Direct *CP* violation occurs for a non-zero asymmetry in the decay amplitudes. This type of *CP* violation depends on the decay mode, and it can involve either charged or neutral particles. In order for direct *CP* violation to be realised the amplitudes A_f and $\bar{A}_{\bar{f}}$ require interference of at least two different processes with different weak and strong phases, defined as the phase which changes its sign under *CP* transformation (the weak phase), and the one that does not (the strong phase). The indirect *CP* violation comprises the *CP* violation in mixing processes incorporating neutral particles, and *CP* violation in the interference between mixing and decay amplitudes. *CP* violation in mixing takes place if the transition probability of particles to antiparticles compared to the reverse process differs, and occurs when $|q/p| \neq 1$. This type of *CP* violation is universal and does not depend on the decay mode. *CP* violation in the interference between mixing and decay amplitudes is present if the imaginary part of $\lambda \equiv p\bar{A}_{\bar{f}}/(qA_f)$ is non-zero.

In two-body singly-Cabibbo-suppressed (SCS) charm decays, the direct *CP* violation is searched through measuring the time-integrated *CP* asymmetry in the decay rates of the charm mesons ($f = K^+K^-, \pi^+\pi^-$)

$$A_{CP} \equiv \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}, \tag{5}$$

where Γ denotes the partial decay rate. Taking the difference of the asymmetries in two different final states, $\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$, has two advantages: the nuisance asymmetries originating from production and detection cancel, and the sensitivity to *CP* violation is enhanced as the *CP* asymmetries in these two channels are expected to be of similar magnitude but with opposite signs. ΔA_{CP} is mostly a measure of direct *CP* violation in charm. A study using the full Run 1 and Run 2 data of LHC yields $\Delta A_{CP}^{\mathrm{exp}} = (-15.4 \pm 2.9) \times 10^{-4}$, with a significance of more than five standard deviations [37]. A range of new SM predictions for ΔA_{CP} [38–42] argue whether beyond the SM (BSM) physics is necessary to explain this result, or whether it originates in a mild non-perturbative enhancement due to rescattering effects or to the presence of a nearby 0^{++} resonance such as $f_0(1710)$. Some papers suggest that resolving this tension within an extension of the SM includes a flavour violating Z' that couples only to $\bar{s}s$ and $\bar{c}u$ quarks [38]. The value of ΔA_{CP} together with other experimental data can then be used to make predictions on CP violation in several $D^0 \to PP$ and $D^0 \to VP$ channels [42, 44].

This is the first observation of *CP* violation in the charm sector, and so far the only one. Several measurements in other two-body decays have greatly improved the precision of the asymmetries for the decay modes $D^0 \to K^0_S K^0_S$, $D^+_{(s)} \to K^0_S h^+$, $D^+_{(s)} \to \eta' h^+$, $D^+_{(s)} \to \pi^+\pi^0$, $D^0 \to \pi^0\pi^0$, $D^0 \to K^0_S\pi^0$, $D^0 \to K^0_S\eta^{(\prime)}$, etc. [32]. From the theoretical point of view, a promising two-body decay to probe for *CP* violating effects is $D^0 \to KK^*$ [45]. In addition, various model-dependent and model-independent techniques probe for *CP* violation in multibody decays but the experimental results are so far compatible with *CP* symmetry conservation [32].

The asymmetry between the effective lifetimes,[2] $\hat{\Gamma}$, of mesons initially produced as D^0 and $\bar{D}^0$ and decaying into the *CP*-even final states $D \to hh$, where $h = K, \pi$, is a measure of indirect *CP* violation. The current best results from LHCb, combining the full Run 1 and Run 2 statistics [46], $A_\Gamma(KK) = (-4.4 \pm 2.3 \pm 0.6) \times 10^{-4}$ and $A_\Gamma(\pi\pi) = (2.5 \pm 4.3 \pm 0.7) \times 10^{-4}$ are compatible with no *CP* violation in charm mixing or the interference between mixing and decay. These are yet the

[2]The effective lifetime is the lifetime obtained from a single exponential fit to the decay-time distribution.

most precise experimental measurements of *CP* asymmetries. The interplay between direct and indirect *CP* violation in two-body charm decays is presented in Figure 3 (right) combining the ΔA_{CP} and A_Γ results.

Two methods are employed in establishing mixing in charm decays. Firstly, the flavour of the neutral D meson at production has to be determined. Usually this is done by the charge of the pion in the strong decay of $D^{*+} \to D^0\pi^+$. Alternatively, the flavour of the secondary charm decays from $\bar{B} \to D^0\mu^-\nu_\mu X$ can be tagged by the charge of the muon. The second technique is used at the LHCb experiment only. Until 2012, the mixing in charm was established with more than 5 standard deviations significance only by a combination of three different experiments [47–50] done by HFLAV [32]. The mixing parameters can be extracted from the time-dependent ratio of $D^0 \to K^+\pi^-$ (also referred to as wrong-sign, WS) to $D^0 \to K^-\pi^+$ (also known as right-sign, RS) decay rates

$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} \approx R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2. \tag{6}$$

Here, t/τ is the decay time expressed in units of the average D^0 lifetime τ, and R_D is the ratio of doubly-Cabibbo-suppressed (DCS) to Cabibbo-favoured (CF) decay rates. Note that in (6), x' and y' are rotated by the strong phase difference between the CF and DCS amplitudes, δ, compared to the x, y parameters defined above. By observing a decay-time dependence of the ratio $R(t)$, and measuring the parameters y' and x'^2, the LHCb experiment reported a first observation of $D^0 - \bar{D}^0$ oscillations in a single measurement [51]. Since then, more precise measurements have been reported [52]. Following a similar strategy, $D^0 - \bar{D}^0$ oscillations were observed in $D^0 \to K3\pi$ decays as well [53].

These measurements have been extremely useful in establishing that the neutral charm mesons oscillate. However, the golden mode for measuring the mixing parameters x and y without the strong phase rotation is $D^0 \to K_S^0 hh$. This final state is accessible both through decays of D^0 and $\bar{D}^0$. The multiple CF and DCS interfering amplitudes enhance the sensitivity to x and y. There are two techniques that can be employed to analyse these decays: a model-independent one where the decay-time evolution in bins of similar strong phase difference is studied, and a model-dependent one where the effective lifetimes of individual resonances are measured. The model-dependent technique where time-dependent amplitude analysis of self-conjugated decays allows for a direct measurement of x and y, and a simultaneous search for *CP* violation in mixing, in the decay and in the interference between mixing and decay, was developed by the CLEO experiment [54], and was later extended by the BaBar and Belle experiments [55, 56]. The model-independent methods [57, 58] rely on external input for the strong phase differences between charm decay amplitudes from quantum correlated D^0 and $\bar{D}^0$ produced at threshold at the $\psi(3770)$ resonance at CLEO [59] or BESIII experiments. The most precise results come from BESIII [60, 61].[3] The latest LHCb measurement in [58], combined with previous measurements of the mixing parameters, yields the first evidence that the neutral charm meson masses are different, and x is positive. An overview of how complex the state-of-art of the theory predictions for x and y is can be found in [63]. The mixing parameters can be extracted for D^0 and $\bar{D}^0$ which probes *CP* violation in charm mixing. To date, all results are compatible with *CP* symmetry and agree with the SM predictions.

[3] The current best results are based on a data sample of about 3 fb^{-1} while the collaboration considers increasing this data sample to 20 fb^{-1}. In addition to improving our knowledge on charm mixing, these measurements play an important role in reducing systematic uncertainties on determinations of the CKM angle γ allowing for sub-degree precision [62].

6. Leptonic and semileptonic charm decays

Purely leptonic charm decays $D^+_{(s)} \to \ell^+\nu_\ell$, where ℓ is a lepton, proceed through a $W^\pm$ annihilation diagram. In the SM at tree level, the decay width is given by

$$\Gamma(D^+ \to \ell^+\nu_\ell) = \frac{G_F^2 f_{D^+}^2}{8\pi}|V_{cd}|^2 m_\ell^2 m_{D^+}\left(1-\frac{m_\ell^2}{m_{D^+}^2}\right)^2 \tag{7}$$

where G_F is the Fermi coupling constant, m_ℓ is the lepton mass, and m_{D^+} is the D^+-meson mass. All these quantities are known with a very good accuracy [2]. An experimental measurement of the decay width (or the branching fraction) allows for a determination of the product of the decay constant, f_{D^+}, and the CKM element V_{cd}. The unique tagging technique and the excellent performance of the BESIII detector allows to reconstruct these decays. BESIII measured $B(D^+ \to \mu^+\nu_\mu) = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$ [64]. This is the most precise result of this quantity to date, and determines $f_{D^+}|V_{cd}| = (45.75 \pm 1.20 \pm 0.39)$ MeV. The decay constant f_{D^+} is obtained using as input the CKM matrix element $|V_{cd}| = 0.22520 \pm 0.00065$ from the global fit in the SM [65]. Alternatively, $|V_{cd}|$ is determined using $f_{D^+} = (207 \pm 4)$ MeV from lattice QCD (LQCD) as input. The results are: $f_{D^+} = (203.2 \pm 5.3 \pm 1.8)$ MeV, and $|V_{cd}| = 0.2210 \pm 0.0058 \pm 0.0047$.

Recently, the decay $D^+ \to \tau^+\nu_\tau$ was observed for a first time by the BESIII collaboration [66]. Its branching fraction was determined to be $B(D^+ \to \tau^+\nu_\tau) = (1.20 \pm 0.24 \pm 0.12) \times 10^{-4}$. Taking the world average result for $B(D^+ \to \mu^+\nu_\mu) = (3.74 \pm 0.17) \times 10^{-4}$, a test for lepton flavour universality (LFU) was reported:

$$R(D^+)_{\tau/\mu} = \frac{\Gamma(D^+ \to \tau^+\nu_\tau)}{\Gamma(D^+ \to \mu^+\nu_\mu)} = 3.21 \pm 0.64 \pm 0.43, \tag{8}$$

which is consistent with the SM expectation $R(D^+)_{\tau/\mu} = 2.67$.

The decays $D_s^+ \to \ell^+\nu_\ell$ have been studied by BESIII [67, 68], as well as by its predecessor CLEO [69], Belle [70] and BaBar [71] experiments. Analogously to the case above, the values $f_{D_s^+}$ and $|V_{cs}|$ were extracted and the most precise values are $252.9 \pm 3.7 \pm 3.6$ MeV and $0.985 \pm 0.014 \pm 0.014$, respectively [67]. These results are important to calibrate various theoretical predictions [72].

Similarly to $R(D^+)_{\tau/\mu}$, $R(D_s^+)_{\tau/\mu} = 10.2 \pm 0.5$ [73] is in agreement with the SM expectation. With a future sample of 20 fb^{-1} of data at 3.773 GeV at BESIII, the precision on $R(D^+)_{\tau/\mu}$ will be statistically limited to about 8%. Increasing the data sample at 4.178 GeV to 6 fb^{-1}, the precision on $R(D_s^+)_{\tau/\mu}$ will be systematically limited to about 3%. The rate of the $D^+_{(s)} \to e^+\nu_e$ decay is helicity suppressed by a factor m_e^2 and is beyond the sensitivity of the BESIII experiment.

The measurements of $V_{cs(d)}$ from purely leptonic decays are the most precise ones. The projections with 20 fb^{-1} at BESIII [73] and 50 ab^{-1} of data at Belle II [74] indicate that their precision could be improved by an order of magnitude. An alternative way to measure $|V_{cs(d)}|$ is through the differential rate of semileptonic decays $D^0 \to K^-(\pi^-)\ell^+\nu_\ell$, which in the $m_\ell = 0$ limit takes the form

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3}|V_{cs(d)}|^2|p_{K^-(\pi^-)}|^3|f_+^{K^-(\pi^-)}(q^2)|^2, \tag{9}$$

where p is the three-momentum of the $K(\pi)$ meson in the rest frame of the D meson, and $f_+(q^2)$ represents the hadronic form factors which depend on the four-momentum transfer between the D meson and the final hadron. The form factors parameterise the strong interaction effects and can be calculated in LQCD. As the uncertainties in the predictions of the form factors shrink [75–77], experimental validation of the results becomes increasingly important. In [78, 79], using final states with electrons, the form factors are studied by fitting the differential decay rates with different shape parameters predicted by the various models, and the compatibility between the data and the calculations is interpreted. The best fit results in [79] for the form-factors at

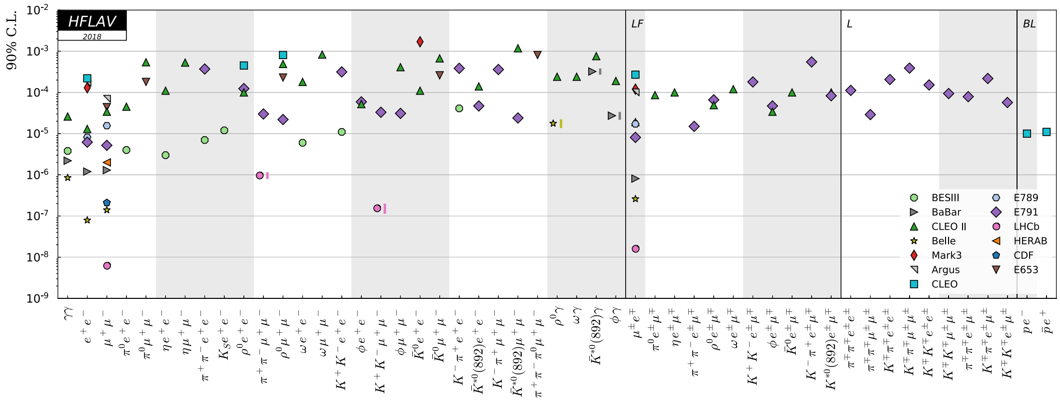

Figure 4. The current best 90% C.L. limits of rare D^0 decays. The different regions combine FCNC, LFV, LNV, BLN decays [32]. Similar summary plots for charged D mesons and charm baryons can be found in [32].

$q^2 = 0$ are $f_+^K(0) = 0.7368 \pm 0.0026 \pm 0.0036$ and $f_+^\pi(0) = 0.6372 \pm 0.0080 \pm 0.0044$. In analogy to the leptonic decays, $|V_{cs(d)}|$ are obtained using form-factor predictions as an input [75, 80] yielding $|V_{cs}| = 0.9601 \pm 0.0033 \pm 0.0047 \pm 0.0239$ and $|V_{cd}| = 0.2155 \pm 0.0027 \pm 0.0014 \pm 0.0094$.

The LFU tests with semileptonic decays indicate no deviation from the SM: $R_{\mu/e} = \Gamma(D^+ \to \bar{K}^0\mu^+\nu_\mu)/\Gamma(D^+ \to \bar{K}^0 e^+\nu_e) = 0.988 \pm 0.033$ [81] is consistent with the predicted value [82] within uncertainties; for $D^0 \to K^-\ell^+\nu_\ell$, the corresponding ratio $R_{\mu/e} = 0.974 \pm 0.007 \pm 0.012$ also agrees with the SM [77,83,84]; similarly, the ratios using $D^{0(+)} \to \pi^{-(0)} e^+\nu_e$ decays, $R^0_{\mu/e} = 0.922 \pm 0.030 \pm 0.022$ and $R^+_{\mu/e} = 0.964 \pm 0.037 \pm 0.026$, are in agreement with the SM [84] within 1.7σ and 0.5σ, respectively. All these measurements are currently statistically limited and will be significantly improved with 20 fb^{-1} of data taken at 3.773 GeV in the future, at BESIII [73], and 50 ab^{-1} of data which is being collected by Belle II [33].

7. Rare charm decays or searches for BSM particles

The studies of charm rare decays provide a unique probe of BSM physics in the flavour sector, complementary to studies in K and B systems. These comprise studies of lepton flavour violation (LFV), lepton number violation (LNV), baryon number violation (BNV), flavour-changing neutral-current (FCNC) transitions, vector-meson-dominated (VMD) and radiative decays. The expected rates of these processes vary vastly, from forbidden, FCNC (10^{-16} to 10^{-9}), VMD (10^{-8} to 10^{-6}) to the not-so-rare radiative decays (10^{-5} to 10^{-4}).

Examples for such processes can be seen on Figure 4, together with the limits from different experiments. The most stringent limit on FCNC decays comes from $D^0 \to \mu^+\mu^-$ [85]; on LFV from $D^0 \to e^\pm\mu^\mp$ [86]; on LNV from $D^+_{(s)} \to \pi^+\mu^-\mu^-$ [87], and on BNV from $D^0 \to pe$ [88].

The FCNC processes are heavily suppressed in the SM. Short distance contributions to effective $c \to u$ transitions are rather small, therefore the branching fractions are dominated by long distance contributions. An enhancement of the predicted decay rates could signal the presence of new physics.

In the future, many of these limits will be pushed further by the precision experiments LHCb (Upgrade I and II) and Belle II. The large production cross sections will likely translate into world's best measurements. The BESIII experiment is complementary for decays which are difficult for LHCb and Belle, with missing neutrinos, neutral particles, etc., due to its unique capability to identify the flavour of the D meson at production in quantum correlated decays, e.g. decays such as $D^0 \to \pi^0 \nu\bar{\nu}$ or $D^{\pm,0} \to \pi^{\pm,0} a$, where a is a light pseudoscalar. A future Super τ-charm factory in Novosibirsk (or China) could further help in pushing the limits for rare and forbidden charm decays.

The rarest charm decay observed to date is the $D^0 \to K^+K^-\mu^+\mu^-$, studied along with $D^0 \to \pi\pi\mu\mu$ decays. It is observed away from the known resonances $\rho^0/\omega,\phi,\eta$ and its branching fraction, $\mathscr{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}$ [89], is in agreement with the SM prediction [90,91]. The *CP* asymmetries in the non-resonance regions for these two decays were determined as well [92], $A_{CP}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (4.9 \pm 3.8 \pm 0.7)\%$ and $A_{CP}(D^0 \to K^+K^-\mu^+\mu^-) = (0 \pm 11 \pm 2)\%$, and also agree with the SM expectations, which in turn imposes constrains on several BSM models [90,91,93–97].

8. Charm spectroscopy

Charm spectroscopy provides an excellent ground to study the dynamics of light quarks in the environment of a heavy quark. The theoretical framework for analysing decays of hadrons with one heavy quark is the Heavy Quark Effective Theory (HQET), making use of the limit $m_Q \to \infty$. Many of the exited states predicted in the 80's have not yet been observed [98]. Two of the lowest-lying (1S) states and four (1P) orbital excitations of the open charm mesons are known [2], both for non-strange and strange mesons. Recent experimental effort allows to study the properties (masses, widths) and to determine the quantum numbers such as the total angular momentum and parity of some of the newly observed states. A prompt production of the excited states allows to establish whether a state is natural ($J^P = 0^+, 1^-, 2^+, \ldots$) or unnatural ($J^P = 0^-, 1^+, 2^-, \ldots$). A secondary production of charmed mesons allows for a full spin-parity analysis. The excited states $D_{s1}(2536)^+(1^+)$, $D^*_{s2}(2573)^+(2^+)$, $D^*_{s1}(2700)^+(1^-)$ and $D^*_{s3}(2860)^+(3^-)$ were observed by [99–103], yielding information on their properties, including spin-parity assignments. In addition to the states reported above, an enhancement around $D^*_{sJ}(3400)^+$ was seen [103]. The most recent results from charm meson spectroscopy report the resonance parameters, quantum numbers and partial branching fractions of the $D_1(2420)$, $D_1(2430)$, $D_0(2550)$, $D^*_1(2600)$, $D_2(2740)$ and $D^*_3(2750)$ resonances, which are measured for the first time in a four-body amplitude analysis of the $B^- \to D^{*+}\pi^-\pi^-$ decays [104].

Singly charmed baryons consist of one heavy charm quark and two light (u,d,s) quarks. The large mass difference between the charm quark and the lighter ones justifies the usage of HQET. Excited Λ_c, Σ_z and Ξ_c states have been well studied [2]. This was not the case for the heaviest of them, the Ω_c baryon with quark content css and quantum numbers $J^P = 1/2^+$, until not long ago. The first observed spin-excited Ω^*_c state was seen in a decay $\Omega^*_c \to \Omega_c\gamma$ [105,106], presumed to be a $J^P = 3/2^+$ state. The LHCb experiment has reported the discovery of five new excited Ω states decaying to $\Omega^{**0}_c \to \Xi_c K^-$, with $\Xi_c \to pK^-\pi^+$ [107]. These five new very narrow states (with widths $\leq$ 10 MeV) are $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, and $\Omega_c(3119)^0$ (see Figure 5, left). In addition, a broad structure around 3188 MeV has been identified, which could be resolved with more data. Since these baryons were reconstructed using a two-body decay, their quantum numbers are not determined, and their masses are not compared to the theoretical predictions. A possible analysis of three-body final states can provide additional information. The first four of these states were confirmed using a smaller data sample by the Belle experiment, reporting the first observation of these states in e^+e^- colliders [108]. These baryons have been interpreted as bound states of a c-quark and a P-wave ss-diquark [109]. An alternative interpretation is noted in which the heaviest two states are 2S excitations with $J^P = 1/2^+$ and $3/2^+$, while the lightest three are those with $J^P = 3/2^-, 3/2^-, 5/2^-$ expected to decay via D-waves. The lattice predictions of their masses are summarised in [110]. A molecular model has also been suggested for the interpretation of these states [111].

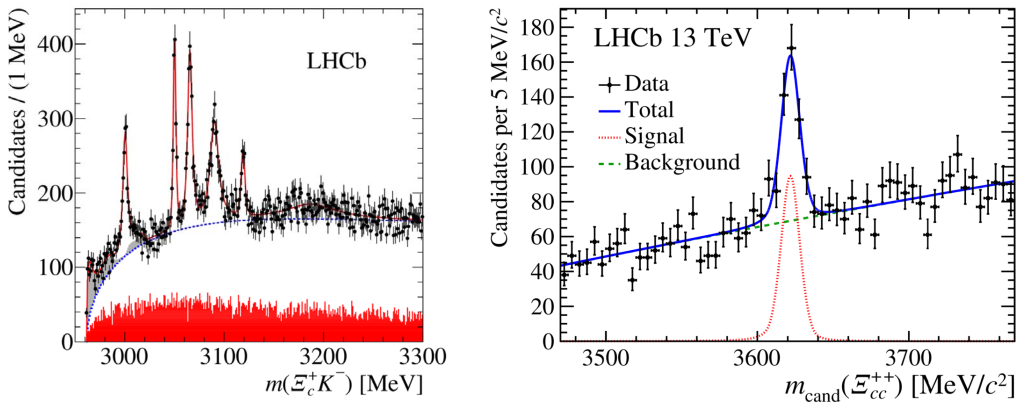

Figure 5. Left: The excited $\Omega_c(css)$ states observed by the LHCb collaboration [107]; Right: The first observation of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ [112].

The doubly charmed baryons are built of two c quarks and a lighter quark: these are Ξ_{cc}^{+}(ccd), Ξ_{cc}^{++}(ccu) and Ω_{cc}^{+}(ccs). The first two form an isospin doublet with quantum numbers $J^P = 1/2^+$ and $L = 0$. Many predictions of their masses in the range 3500 to 3800 MeV [113–124] and lifetimes from 0.1 to 1.5 ps [121, 122] exist. For the isospin doublet, the difference in the mass is not expected to exceed 1 MeV [120].

The SELEX collaboration [125, 126] observed a peak which was interpreted as a Ξ_{cc}^{+} baryon in the final states $\Lambda_c^+ K^- \pi^+$ and $pD^+ K^-$, with a measured mass of (3518.7 ± 1.7) MeV. The collaboration also reported a measurement of the Ξ_{cc}^{++} meson mass to be 3460 MeV [127]. The mass difference is in conflict with the expected mass splitting of isospin doublets. The Ξ_{cc}^{+} lifetime was experimentally measured to be less than 33 fs at the 90% C.L. which disagrees with the theoretical predictions. The Ξ_{cc}^{+} observation has not been confirmed in searches performed at the FOCUS [128], BaBar [129], Belle [130], and LHCb [112, 131] experiments.

The doubly-charmed baryon Ξ_{cc}^{++} was observed for the first time in the final state $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ by the LHCb experiment [112] (see Figure 5). Its mass was determined as $(3621.40 \pm 0.72^{+0.024}_{-0.27} \pm 0.14)$ MeV [112], and its lifetime was measured to be $(0.256 \pm 0.022 \pm 0.014)$ ps [132]. Since the first observation, Ξ_{cc}^{++} was also observed in the final state of $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ [133]. The production cross-section of Ξ_{cc}^{++} was determined relative to that of Λ_c baryons to be $(2.22 \pm 0.27 \pm 0.29) \times 10^{-4}$ [134]. Currently, other decay modes of Ξ_{cc}^{++} are investigated, and the searches for Ξ_{cc}^{+} (to confirm the SELEX result), and Ω_{cc}^{+} are ongoing.

Measurements of lifetimes play an important role in validating effective models such as HQET and can be used to search for deviations from the SM predictions. Recently, the LHCb experiment reported the most precise measurements of the lifetimes of the charm baryons Ω_c, Λ_c^+, Ξ_c^+ and Ξ_c^0 [135, 136]. While the last three agree with previous measurements, the lifetime of Ω_c^0 is about four times larger (see Figure 6). It has been argued that the expected lifetime hierarchy, due to the higher-order contributions discussed above, should be $\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$ [113,137–141]. The current best measurements are inconsistent with this hierarchy. Possible interpretations of this deviation include constructive interference between the s quark in the $c \to sW^+$ transition in the Ω_c^0 decay and the spectator s quark in the final state being smaller than expected, that the spin of the ss system plays a larger role, or that additional higher-order contributions in the HQET need to be considered. However, according to [138], Ω_c^0 can be either the most short-living or the most long-living among charmed baryons. For doubly charmed

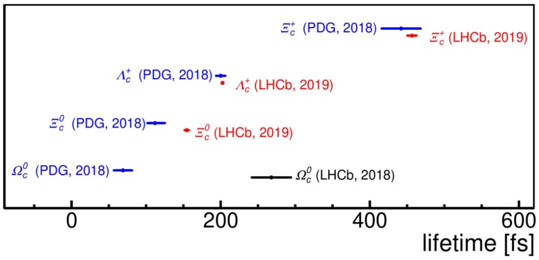

Figure 6. The tension in the charmed baryon lifetimes measurements [136].

baryons, the expected hierarchy is $\tau(\Xi_{cc}^{++}) \gg \tau(\Omega_{cc}^{+}) \approx \tau(\Xi_{cc}^{+})$ [137] which is why Ω_{cc}^{+} and Ξ_{cc}^{+} are more difficult to discover at LHCb.

9. Summary

The investigation of the τ lepton properties has provided many beautiful tests of the SM and strong constraints on new physics scenarios. Belle II will significantly improve the current sensitivity to LFV, LNV and *CP*-violating phenomena in τ decays. Moreover, its huge data sample should allow for a more accurate scrutiny of SM properties, such as lepton universality, Lorentz structure of the charged-current interaction, quark mixing and QCD in the non-perturbative regime. Meanwhile, the τ has also become a superb experimental tool in the search for new physics at the LHC. At long term, the TeraZ option of a future FCC-ee collider running at the Z^0 peak would produce an enormous data sample of 1.7×10^{11} $\tau^+\tau^-$ pairs in extremely clean kinematic (and background) conditions [142], opening a broad range of interesting opportunities in τ physics.

Charm physics covers a vast range of studies. In the past decade charm mixing and direct *CP* violation have been discovered. Intriguingly narrow excited Ω_c states have been seen and the doubly charmed baryons Ξ_{cc}^{++} have been observed. The rarest charm decay's branching fraction measured is of the order 10^{-7}. The LHCb experiment is currently undergoing its first major Upgrade. Several components of the detector will be replaced with new ones able to withstand the much higher rates and radiation doses in Run 3 of the LHC. A total of 300 fb^{-1} of data is planned to be recorded. Belle II is currently taking data and has planned to collect a total of 50 ab^{-1} of data. The BESIII experiment will increase its charm data samples at least by a factor 3. The longer term future of charm physics will be shaped by these three experiments and a possible Super Tau Charm factory.

Acknowledgements

This work was supported by the Royal Society, UK [grant DH160214], by the Spanish Government and ERDF funds from the EU Commission [grant FPA2017-84445-P], and by the Generalitat Valenciana [grant Prometeo/2017/053].

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