CHARM PHYSICS: STATE OF THE ART AND PROSPECTS

B. F. Viaud

Laboratoire de l'Accélérateur Linéaire, CNRS, Orsay, France

The goal of this document is to provide a brief overlook of the present status of charm physics. Since most of the physicists attending the NPAE conference are not experts in particle physics, an introduction to flavor physics and CP violation is given so that the interest of charm can be understood, and basics of charm physics are presented. A brief introduction to the experiments involved in this field is also given. In the second part of this document, a collection of important results is presented, along with the improvements that can be expected, in particular from the LHCb experiment which started taking data six month ago and will soon provide the largest charmed particles sample ever.

1. Introduction: CP violation and Flavor Physics

The Standard Model (SM) of particle physics describes accurately the results of all the experiments carried out so far. However, there are reasons to think that it's only the low energy (~100 GeV) manifestation of a more fundamental physics. Among them, the fact that the intensity of the CP violating phenomena it predicts is ways to low to explain the quasi-absence of antimatter in the present Universe. That's why we think an extensive and precise study of CP violation is one of the keys to the discovery and characterization of physics beyond the SM (NP). The most promising way to study CP violation is to measure the behavior of *beauty* mesons, often referred to as "B" mesons, a bound state of a b quark and another quark. Charm mesons, containing a charm quark, although more difficult to describe theoretically and less sensitive to CP violation, are complementary to B's, as will be shown below. They're the subject of an intense theoretical and experimental activity which main aspects will be presented here.

Ref. [1] contains reviews that can be a good introduction to the SM and to CP violation. We just give here a few basic elements. The gauge invariant SM Lagrangian is built in terms of quark fields in their weak *interaction* state. CP violation is introduced by assuming that the observable states (ie the mass states) don't coincide with them, and are derived from them via the Cabibbo - Kobayashi - Maskawa matrix (V_{CKM}) [1]. The quark charged current sector of the electroweak Lagrangian takes the form:

$$L = ... + \frac{g}{2\sqrt{2}}\left(\bar{u},\bar{c},\bar{t}\right)\gamma^{\mu}\left(1-\gamma^{5}\right)\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}\begin{pmatrix} d \\ s \\ b \end{pmatrix} W_{\mu} \qquad (1)$$

In the SM with 3 generations of quarks, V_{CKM} depends on 4 independent parameters, including a complex phase. In practice, this weak phase is shared among V_{td} and V_{ub}. Thanks to these complex elements, CP-conjugate decay amplitudes can sometimes differ: this is how CP violation is possible in the SM. This is no accident if the complex elements concern the coupling between the third and the first generation of quarks. If there were only 2 quark generations, V_{CKM} would depend on only one, real, parameter.

Quark mixing allows transitions at first order between different generations of quarks (ex: b→u), with a probability proportional to the V_{ij}'s, which are not predicted by the SM, and have to be measured. However, certain logic seems at work. The transition between 2 generations is not forbidden like in the lepton sector but it is still easier for a quark to interact within its own generation: the values of the V_{ij}'s [1] are such that transitions are suppressed by λ between the first 2, and by λ^3 between the first and the much heavier third generation (λ~0.22).

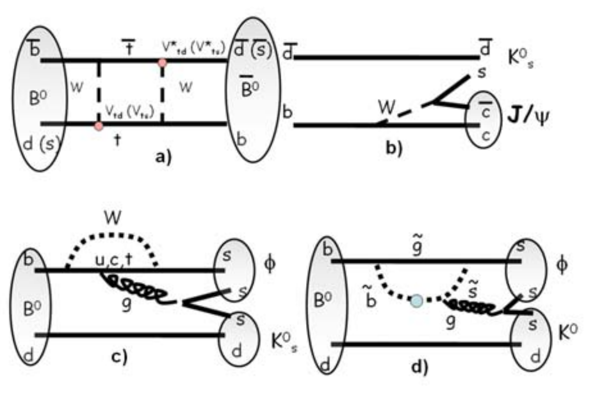


Fig. 1. Interplay of oscillation (*a*), and decay into $B^0 \rightarrow J/\psi K^0$ (*b*), Penguin contribution to the $B \rightarrow \phi K^0$ (*c*) and NP contribution (*d*).

CP violation can be observed if an asymmetry is measured between 2 CP-conjugate processes. Their amplitudes need a least to have at 2 contributions of similar size, carrying different weak phases. The interference between these 2 amplitudes makes the rate sensitive to the weak phase difference, and the rate of the decay does differ from that of its CP-conjugate since it involves opposite weak phases (V_{ij}^* instead of V_{ij}). Such interference is hard to find in practice! It is easier to observe it in B mesons (like $B^0(b\bar{d})$, $B_s^0(b\bar{s})$) which have the ability to oscillate into their antiparticle, with a probability which depends on time. It is illustrated in Fig. 1 in the case of $B^0 \rightarrow J/\psi K^0$. The oscillation provides interference between the amplitude for a direct decay and that for a decay preceded by an oscillation. Because the oscillation diagram involves V_{td} while the decay involves no complex element, the time-dependent decay rate is sensitive to phase of V_{td} and CP violation is observed. This is why this phenomenon is so crucial: it makes CP violation easier to detect. It can also help discovering NP by enhancing CP violation due to NP amplitudes involving particles and weak phases beyond the SM (Fig. 1, *d*).

The "box" of Fig. 1, *a* is a Flavor Changing Neutral Current (FCNC), made possible by the quark mixing introduced by the CKM matrix. One has to take into account all the amplitudes, with all the combinations of quarks (u, c and t) circulating in the loop. The only difference between them lies in the mass of the quarks and the V_{CKM} elements to which they're proportional. If all the quarks had the same mass, they would cancel each other (GIM mechanism [12]). This suppression is broken by the mass of the quarks: the amplitude is proportional to their squared mass, and finally dominated by the contribution of the heavy top quark. We'll see below this suppression is far stronger in the D system: the *c* quark, unlike the *b*, is not coupled to the GIM-breaking t quark. FCNC also happen in decays, like the "penguin" contribution of Fig. 1, *c*. This provides rare decays, for which the SM contributions can't overwhelm that of NP, which becomes detectable (Fig. 1, *d*). Loops, as that of this penguin, are often the best place for NP particles to appear. The $1/M^2$ factors associated with the propagation of particles makes "tree" diagrams, like that of Fig. 1, *b*, very suppressed when the propagating particle is a heavy NP particle. This suppression is weaker in the case of loop diagrams since one integrates over all momenta.

The large B mass (>5GeV) is an advantage concerning QCD long distance (LD) effects. Quarks in Fig. 1 are actually confined within hadrons and permanently interact by strong interaction, exchanging many gluons. Those of low energy cannot be treated perturbatively since the QCD coupling constant is too close to unity in this regime. The many delicate theoretical approaches, like lattice QCD, developed to address those effects are beyond the scope of my presentation. Important is to know that they're often based on assumptions and approximations which yield important uncertainties, difficult to evaluate reliably. The higher the available energy, the lower the contribution of LD effects to the total amplitude. That's why heavy hadrons like B's are a privileged place: NP in weak interactions is less clouded by LD effects.

Charm mesons are lighter and not coupled to the t quark: they're a priori less promising. Nevertheless, they also bring precious inputs in the search for NP. Some decays, ruled by LD effects, are a unique laboratory to better understand them, what will help to interpret the signal found in B decays. Moreover, NP models sometimes impact D's more than B's, making the former indispensable.

2. Charm physics

This section provides basic notions about charm physics. Again, $D^0-\overline{D}^0$ mixing plays a central role. A good introduction to the corresponding formalism and phenomenology can be found in [11]. Fig. 3 shows Feynman diagrams making it possible.

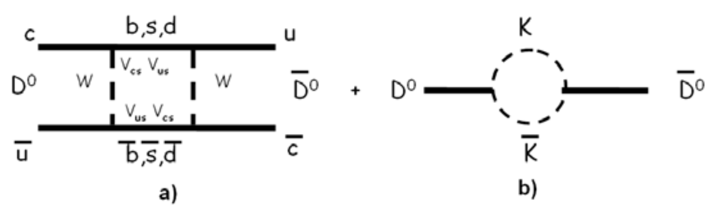


Fig. 3. *a* - box diagram; *b* - LD diagram involved in the neutral D mixing.

A neutral D meson is created by strong interaction in the $\left|D^0(c\bar{u})\right\rangle$ or $\left|\overline{D}^0(\bar{c}u)\right\rangle$ flavor eigenstate. Weak interaction then rules its time evolution: decay and oscillation. The probability to find this meson, a time t after its creation, in the state $\left|D^0\right\rangle$ or $\left|\overline{D}^0\right\rangle$, can be derived from a Schrodinger equation involving an effective Hamiltonian:

$$i\frac{d}{dt}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = H_{eff}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} \quad (1)$$

with

$$H_{eff} = M - i\frac{\Gamma}{2} = \begin{pmatrix} M_{11} - i\frac{\Gamma_{11}}{2} & M_{12} - i\frac{\Gamma_{12}}{2} \\ M_{12}^{*} - i\frac{\Gamma_{12}^{*}}{2} & M_{22} - i\frac{\Gamma_{22}}{2} \end{pmatrix} \quad (2)$$

Its eigenstates are the physical states D_1 and D_2:

$$\left|D_{1,2}\right\rangle = \frac{1}{\sqrt{|q|^2+|p|^2}}\left(p\left|D^0\right\rangle \pm q\left|\overline{D}^0\right\rangle\right) \quad (3)$$

The time evolution of this system is ruled by the corresponding eigenvalues ω_1 and ω_2 in terms of which is expressed the state of a mesons initially created as a $\left|D^0\right\rangle$ or a $\left|\overline{D}^0\right\rangle$:

$$\left|D^0(t)\right\rangle = g_+(t)\left|D^0\right\rangle + \frac{q}{p}g_-(t)\left|\overline{D}^0\right\rangle,$$
$$\left|\overline{D}^0(t)\right\rangle = \frac{p}{q}g_-(t)\left|D^0\right\rangle + g_+(t)\left|\overline{D}^0\right\rangle. \quad (4)$$

With $g_\pm(t) = \frac{1}{2}\left(\exp(-i\omega_1 t) \pm \exp(-i\omega_2 t)\right)$ and $\omega_{1,2} = m_{1,2} - i\frac{\Gamma_{1,2}}{2}$ we can see two parameters characterize the mixing: the mass difference and width difference between the 2 physical eigenstates that we normalize to the average width $\Gamma = \frac{\Gamma_1+\Gamma_2}{2}$:

$$x = \frac{m_2-m_1}{\Gamma} = -\frac{2}{\Gamma}\mathrm{Re}\left[\frac{q}{p}\left(M_{12}-i\frac{\Gamma_{12}}{2}\right)\right], \quad y = \frac{\Gamma_2-\Gamma_1}{2\Gamma} = -\frac{1}{\Gamma}\mathrm{Im}\left[\frac{q}{p}\left(M_{12}-i\frac{\Gamma_{12}}{2}\right)\right]. \quad (5)$$

As we will see, CP violation is expected to be much suppressed in the SM. If we neglect it, M_{ij} and Γ_{ij} are real, and x is determined by M_{12} while y is by Γ_{12}. The first receives contributions form the box diagrams in Fig. 3, *a*. It also receives contributions both from LD (Fig. 3, *b* with virtual intermediate state). The second receives contributions from the diagrams of Fig. 3, *b*, where the intermediate states are decay modes common to both $\left|D^0\right\rangle$ and $\left|\overline{D}^0\right\rangle$ and are real.

The box diagram undergoes a very efficient GIM suppression: one could expect the b quark in the loop to dominate due to its ~4 GeV mass. However, being proportional to $(V_{cb}V^*_{ub})^2$, it very "CKM suppressed". The s-quark dominates, but its low mass yields a contribution to x as low as 10^{-6} - 10^{-5}. The LD contributions in Fig. 3, *b* dominate, but are, as many LD effects, very hard to evaluate. Reference [11] explains how theorists predict $x \sim 10^{-3}$ and $y \sim 10^{-2}$. Measuring $x >> y$ would then be a sign of NP, with new particles circulating in the loop of the box diagram. However, those predictions are subject to large uncertainties. Values (see next sections) found around 1 % both for x and y are actually not really conclusive NP-wise.

It is however crucial to measure this mixing since it could reveal CP violation effects, the same way we mentioned in section 3. D meson oscillation or decays involve almost only the first two quark generations, where CP is essentially absent. Any sign of CP violation above 0.1% would signal the presence of NP, in the form of new particles in the loops of these diagrams, with new complex coupling. Despite the clouding to the large LD effects inherent to D mesons, the CP violation effects they would generate might be large enough to be detected. Another crucial point can be seen in Fig. 3, *a*: the quarks circulating in the loop are of down-type. This is also true for all the diagrams describing the decays sensitive to new physics presented here. In the B system, only up-type quarks appear in such diagrams. These up-type FCNC's, in many models, are not affected by NP in the same way than down-type FCNC's. Not the same new particles and coupling are involved in the NP loop diagrams. That's another reason why charm physics is an important aspect of Flavor Physics. It can help detecting NP effects B physics would miss.

The measurements that will be presented in this document require the selection and reconstruction of signals such as $D^0 \to K^+\pi^-$, $D^0 \to K^+K^-$ or $D^0 \to K^0_s\pi^+\pi^-$. Next section is an introduction of the experimental techniques used for that purpose.

3. Experimental arsenal

Fig. 4 shows the LHCb [4] detector. The other main experiments involved in flavor physics are: Babar [3], Belle [5], CLEO-c [6], BESIII [7], D0 [8] and CDF [9]. They all share the same goals when it comes to D physics: reconstructing the largest possible D sample, while maintaining the backgrounds low. Of primary importance is the reconstruction of the meson's decay time since they aim at measuring time-dependent rates generated by the mixing. Distinction between charged kaons and pions is another angular stone. Signal identification and Dalitz studies also require a precise mass (ie momentum) reconstruction. The references given above can be consulted to discover in deeper detail how those experiments achieve those goals.

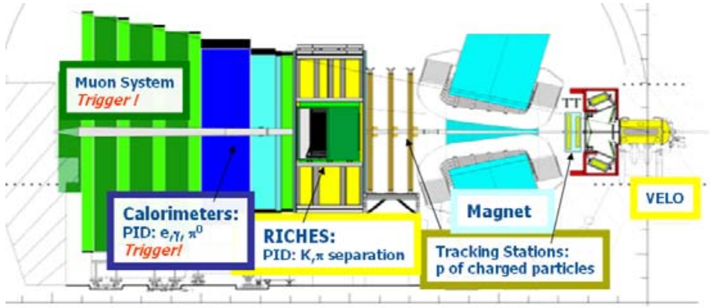


Fig. 4. The LHCb experiment's detector.

BESIII and CLEO-c have been designed for charm physics. They're installed on e^+e^- colliders. The luminosity delivered at the BESIII interaction point reaches 0.3 × 10^{33} $cm^{-2}s^{-1}$ at the energy of the $\Psi(3770)$ $c\bar{c}$ resonance. It will accumulate 3.2 fb^{-1} by late 2012 [10], corresponding ~20 million $D - \bar{D}$ pairs. It's 4 times higher than for CLEO-c, a less recent facility. Depending on the scientific priorities of the collaboration, it could then be extended to 10fb^{-1} [11]. When this resonance decays, nothing more than the D mesons we look for is present in the detector: the backgrounds are kept low.

These experiments also share many common points with Babar and Belle, which were designed for B-physics. The center of mass energy was tuned this time to the $\Upsilon(4S)$ mass, but the charm cross section was still high (~1.3nb): the cumulated luminosity integrated by these B-factories gave birth to ~1 billion $c\bar{c}$ pairs. They also provide very clean background conditions although at this √s, other particles are created along with the D's.

The LHCb experiment could be the leading experiment in charm physics in the years to come. It was also designed for B physics but is very well suited to charm physics. Installed on the LHC, it will record 1fb^{-1} of 3.5 + 3.5 TeV pp collisions by the end of 2011. In such hadron collisions the charm production cross-section is far higher and several 10^{12} $c\bar{c}$ pairs will be created. On the other end, dozens of other particles are created in each pp collision. The control and understanding of the background is one of the key-point of any analysis in LHCb. Note that the charm production rate is 1 order of magnitude above that of b mesons. That's another reason to study D decays: then can be studied with high precision.

The most striking difference between these experiments is the one-harm forward geometry of LHCb. It is adapted to the fact that most of the *b* and *c* quarks are produced less than 300 mrad away from the beam line. The full solid angle coverage of the flavor factories is one of their main strengths: the reconstructed energy-momentum can be compared to that, very well known, of the beams, to improve the reconstruction of the signal decays. Also, only one pp collision out of ~10(~100) produced a $c\bar{c}$ ($b\bar{b}$) pair. One of the keys of LHCb resides in its performance trigger system. Partly hardware (Front End Electronics), partly software (Event Farms) it's able to reduce online the event rate from 40 MHz to 2kHz of useful data, but the selection cuts necessary for that sacrifice a substantial part of the produced c-quark pairs.

Reconstruction performance varies in the same ballpark between experiments: for most of tracks of interest, the momentum resolution is below 1%, the kaon and pion identification and reconstruction efficiency exceed 95 %, the D meson invariant mass is reconstructed with a resolution of ~10 MeV, the lateral position of the vertices is reconstructed with an error of a few dozens μms, ten times less than the longitudinal one. This allows, at LHCb, a precision of 0.04 ps, ie 10%, on the D^0 lifetime. It's ~5 times better than at B-factories thanks to a larger boost. No boost exists at charm factories, which are then less equipped to measure time-dependent decay rates

4. Neutral D mixing measurements

One way to measure the $D^0 - \bar{D}^0$ mixing consists on looking for the decay of a meson initially tagged as D^0, into a final state forbidden to him, but into which $\bar{D}^0$ can decay, and vice versa. If such decay is found, it proves that D^0 changed into $\bar{D}^0$ between its creation and its decay. The first evidence for the existence of mixing in the D system was found this way in 2007. $D^0 \to K^+\pi^-$ and $\bar{D}^0 \to K^-\pi^+$ are doubly Cabbibo suppressed (DCS); their branching fraction is two order of magnitudes below that of the Cabbibo favored decays (CF) $\bar{D}^0 \to K^+\pi^-$ and $D^0 \to K^-\pi^+$, which BF is ~4 % [1]. From Eq. 4, one can derive, assuming CP conservation, the time-dependent decay rate into a DCS mode of a D initially tagged as $\bar{D}^0$ or D^0 :

$$r(t)=\bar{r}(t)=e^{-\Gamma t}\left[R_D+\sqrt{R_D}\,y'\Gamma t+\frac{\left((x')^2+(y')^2\right)}{4}(\Gamma t)^2\right] \quad (6)$$

with $\frac{A_f}{\bar{A}_f}=\frac{\langle f\,|\,H\,|\,D^0\rangle}{\langle f\,|\,H\,|\,\bar{D}^0\rangle}=\frac{\bar{A}_{\bar{f}}}{A_{\bar{f}}}=-\sqrt{R_D}e^{-i\delta_f}$, where δ_f is the relative strong phase between the CF and DCS channels. The first term in the right-hand side of (6) shows that at t = 0, before any possible oscillation, the decay we look for is possible only via a direct decay, suppressed by the ratio between the DCS and CF amplitudes. The two next terms show how easier it becomes as the oscillation becomes more and more probable with time.

The relative strong phase is responsible for one of the limitations of the method: the interference between both decay amplitudes makes the rate sensitive to this phase in such ways that no direct access to x and y is possible. We measure instead:

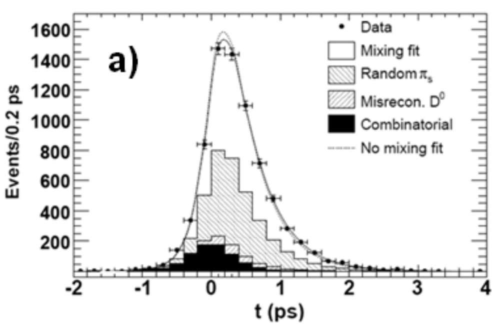
$$x'=x\cos\delta_{K\pi}+y\sin\delta_{K\pi} \text{ and } y'=y\cos\delta_{K\pi}-x\sin\delta_{K\pi}.$$

When CP violation is not neglected, new factors appear in (6) in front of each term of the right-hand-side to correct in opposite ways $r(t)$ and $\bar{r}(t)$. They account for the fact that A_f and $\bar{A}_{\bar{f}}$ are no longer equal due to the contribution to the decay of NP amplitudes involving new particles and weak phases. The third term is also corrected since additional box diagrams due to NP could contribute to the mixing. These terms involve Φ_M, the weak phase appearing in the mixing and Φ_D, that which appears in decays. These parameters can be measured as we look for NP by measuring $r(t)$ and $\bar{r}(t)$ separately.

Babar analyzed a 384 fb^{-1} sample corresponding to ~500 million $c\bar{c}$ pairs [12]. That sample corresponding to seven years of data taking was necessary to select ~1 million $\bar{D}^0\to K^+\pi^-$ and $D^0\to K^-\pi^+$ and 4000 wrong sign decays. That statistics was necessary to be sensitive to the slight departure from an exponential shape caused by the mixing on the decay time distribution (Fig. 5, *a*). Two separate fits are performed to look also for CP violation. The following values for x' and y'(*10^{-3}) are obtained:

$$x'^{2+}=-0.24\pm0.43\pm0.30 \quad y'^{-}=9.8\pm6.4\pm4.5 \quad x'^{2-}=-0.20\pm0.41\pm0.29 \quad y'^{+}=9.6\pm6.1\pm4.3.$$

No CP violation effect is found. However, with a 94 % correlation between the x' and y' found by the fit, this provides a 4.1 σ evidence for the existence of mixing. Similar results were obtained by Belle. LHCb expects 10 times more statistics by the end of 2010 [13]. It will allow a significant reduction of the statistical uncertainty. The errors will also be reduced by the improved decay time resolution.



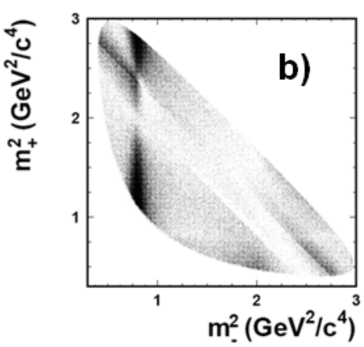


Fig. 5. *a* - decay rate distribution used in [12]. The 2 curves fit to the data (mixing/no mixing hypothesis) show the precision necessary to discover the mixing; *b* - dalitz plot of reference [15].

Babar used the same sample as for the wrong-sign analysis to measure y_{CP} [11,14]:

$$y_{CP}=\frac{<\tau_{K\pi}>}{<\tau_{KK}>}-1=\frac{\left|\frac{q}{p}\right|+\left|\frac{p}{q}\right|}{2}y\cos\Phi-\frac{\left|\frac{q}{p}\right|-\left|\frac{p}{q}\right|}{2}x\sin\Phi.$$

It leads to y_{CP} = [1.12 ± 0.26 ± 0.22] %, and give additional constraint on x and y. Again, LHCb will improve this significantly with ten times more statistics as soon as the end 2010 [13].

To extract directly x and y (with no complication due to a strong phase), one can measure the $K^0_s\pi^+\pi^-$ decay mode instead of $K^-\pi^+$. $D^0 \to K^0_s\pi^+\pi^-$ has a resonant substructure:

$$\left|K^0_S\pi^+\pi^-\right\rangle = a\left|K^{*-}\pi^+\right\rangle + b\left|K^{*-}_{1430}\pi^+\right\rangle + \ldots + j\left|K^{*+}\pi^-\right\rangle, \tag{7}$$

where, for instance, $K^{*-} \to K^0_s\pi^-$. The time-dependent decay rate does not involve only 2 amplitudes, like $\overline{A}_{K^+\pi^-}$ or $A_{K^+\pi^-}$, but 18 amplitudes, along with the corresponding relative weak and strong phases. The latter can this time be extracted using another observable: the decay rate can be measured as function of (m^2_-, m^2_+), where $m^2_\pm = m^2(K^0_s\pi^\pm)$. The sizes of the amplitudes vary along the (m^2_-, m^2_+) distribution (ie along the Dalitz plot-DP). Their relative contributions also vary with time, since some of the intermediate states are accessible only after an oscillation. These variations and the phases determine the shape of the DP as a function of time. Fitting the DP and decay time distributions simultaneously disentangles everything and we gives a direct access to x and y.

Belle carried out this measurement using a 540 fb^{-1} sample (~650 million $c\overline{c}$ pairs) [15]. It obtains: $x = 0.81 \pm 0.30^{+0.10}_{-0.07}{}^{+0.09}_{-0.16}$ %, $y = 0.37 \pm 0.25^{+0.07}_{-0.13}{}^{+0.07}_{-0.08}$ %, $\phi_M = (14 \pm 18^{+5}_{-3}{}^{+2}_{-4})^o$. Babar, with a similar statistics also find results consistent with no CP violation. No public results exist so far for LHCb. With 10 times more statistics in 2010, the uncertainty should again be significantly reduced.

The second way to measure directly x and y is to exploit the fact that the D created in the $\Psi(3770) \to D^0\overline{D}^0$ are in a coherent quantum state due to the conservation of C-parity and angular momentum. If one of the 2 is identified as a D_2 state by its decay into a CP = -1 eigenstate (assuming CP conservation), then it tags the second one as a D_1. Since $\left|D_1\right\rangle = a\left|D^0\right\rangle + b\left|\overline{D}^0\right\rangle$, the rate of "double tag "$\left(D_2 \to f_{CP-}, D_1 \to K^-\pi^+\right)$ events involves an interference between the CF and DCS decays, thus an access to $\cos\delta_{K\pi}$.

CLEO-c accumulated 1 million such decays, and the following yields for single tags [16]: The double tag yields are: $N_{K-\pi+,K+K-}$ = 71 ± 8, $N_{K+\pi-,K+K-}$ = 54 ± 7, $N_{K-\pi+,\pi+\pi-}$ = 24 ± 5 and $N_{K+\pi-,\pi+\pi-}$ = 25 ± 5. These small yields required a delicate analysis but allowed to extract $\cos\delta_{K\pi}$= 1.10 ± 0.35 ± 0.07. It should be greatly improved by BES in the years to come, with the 10 million $D^0\overline{D}^0$ pairs they expect at $\Psi(3770)$ in two year from now.

The HFAG group [17] collected and combined the results from all experiments. Fig. 6 shows the averages obtained for the mixing and CP violation parameters. The no-mixing hypthesis is now excluded at 10 sigmas. Those results should be seen as a great achievement. The diffuculty of finding such a subtle effect can be understood by comparing the intensity of the mixing in this system to that in the $B^0\overline{B}^0$ system, where it is 100 times larger: x_{B0} = 0.776 [1]. In a few years from now, LHCb and BESIII should reduce the statistical uncertainties on x and y to the level of the systematics, and will improve a lot the sensitivity to CP violation in the mixing.

Parameter	No CPV	No direct CPV	CPV-allowed	CPV-allowed 95% C.L.
x (%)	$0.61^{+0.19}_{-0.20}$	0.59 ± 0.20	0.59 ± 0.20	[0.19, 0.97]
y (%)	0.79 ± 0.13	0.81 ± 0.13	0.80 ± 0.13	[0.54, 1.05]
δ (°)	$26.6^{+11.2}_{-12.1}$	$28.3^{+11.3}_{-12.2}$	$27.6^{+11.2}_{-12.2}$	[0.7, 49.5]
R_D (%)	$0.3317^{+0.0080}_{-0.0081}$	$0.3316^{+0.0080}_{-0.0081}$	0.3319 ± 0.0081	[0.316, 0.348]
A_D (%)	–	–	-2.0 ± 2.4	[−6.7, 2.7]
$\|q/p\|$	–	$0.98^{+0.15}_{-0.14}$	$0.91^{+0.19}_{-0.16}$	[0.60, 1.29]
ϕ (°)	–	$-2.9^{+6.4}_{-6.6}$	$-10.0^{+9.3}_{-8.7}$	[−26.9, 8.4]
$\delta_{K\pi\pi}$ (°)	$21.6^{+22.1}_{-23.2}$	$23.4^{+22.2}_{-23.3}$	$23.2^{+22.3}_{-23.3}$	[−23.2, 66.4]

Fig. 6. Current world averaged knowledge on neutral D mixing.

7. CP asymmetries and rare decays measurements

Another way to look for CP violation is measure time-integrated CP asymmetries like:

$$a_f = \frac{\Gamma(\overline{D}^0 \to \overline{f}) - \Gamma(D^0 \to f)}{\Gamma(\overline{D}^0 \to \overline{f}) + \Gamma(D^0 \to f)}. \tag{8}$$

The K^+K^- and $\pi^+\pi^-$ modes are of particular interest since they are the only modes accessible via penguin diagrams, in the loop of which a NP particle can intervene. That's not possible for $K\pi$ modes which have no $q\overline{q}$ pair in the final state but 3 quarks of different flavors. Ref. [18] predicts $a^d{}_f$ could reach O(1%) in some NP scenarios, far above the SM predictions.

The asymmetry measured by Belle with 540 fb^{-1} and 120.10^3 (51.10^3) KK ($\pi\pi$) signal events [19] finds no NP: a_{KK} = 0.42 ± 0.30 ± 0.11. Again, we can expect 10 times more statistics at the end of 2010 and far more in 2015 at LHCb. The uncertainty will be reduced to the systematic part. With a lot of work, we might be 5 times more sensitive in the end.

Comparing differential decay rate could be a more powerful way to track down very small NP effects. Indeed, the relative difference between a decay and its CP conjugate could be sensible only in some particular regions of the phase space, and be hidden once we have integrated over it. That's why attempts are done to look for NP in the final state distributions. It can be based on a Dalitz plot analysis. Babar recently measured T-odd distributions built from the $D^0 \to K^+K^-\pi^+\pi^-$ final state particles momenta and found no sign T-violation [20]. LHCb as planned to improve this measurement.

Looking for CP violation is not the only approach to look for NP effects. One can also simply seek a deviation in the branching ratio with respect to the SM predictions. The best decays for that are those which are much suppressed in the SM, like $D^+ \to \pi^+ l^+ l^-$ and $D^0 \to \mu^+\mu^-$. The SD contributions to these decays are again topologies with a loop that undergo a very efficient suppression. The latter is further suppressed by helicity suppression and the annilation topology (both quarks of the meson have to annihilate to be left with only leptons). Here again, LD effects will dominate. Their SM BR's are estimated around 10^{-6} and 10^{-13}, respectively. NP particles in the loop might increase them and become detectable.

The current best constraints on these channels are due to CDF [21]. With 1.3 fb^{-1} of data at √s = 1.96 TeV: $B(D^+ \to \pi^+ l^+ l^-) < 3.9 \cdot 10^6$. LHCb should collect between 2013 and 2016 more data (5 fb^{-1}) at √s = 14 TeV. The charm production cross section being ~linear in the energy, LHCb being more adapted to the low polar angle production of the D's and its trigger favoring muon pairs, improving that upper limit by more than two orders of magnitude might be possible. CDF also obtains: $B(D^0 \to \mu^+\mu^-) < 4.3 \cdot 10^7$. It should be improved by LHCb by again ~2 orders of magnitude, while BESIII claims it can improve it by a factor 3 [11].

5. Charmonia

Study of charmonia ($c\overline{c}$ bound states) became a very active area in the few past years at flavor factories and Tevatron experiments. Their mass, natural width and production rates in e^+e^-, $p\overline{p}$ or pp collisions, as well as their hadronic decays BR's, are described by the delicate non perturbative approaches designed to treat LD effects [11]. They're a precious laboratory to test and validate those methods. Fig. 7 shows the map of charmonia according to their mass and quantum numbers. This physics is one of the main aims of the BES experiment [10, 11]. LHCb will should be performant at measuring rare hadronic decays. Fig. 7, *b* shows the yields expected by late 2010 in the J/Ψ, h_c and χ_{ci} states decaying into $p\overline{p}$ (BR~10^{-3}) [13].

6. Outlook

We presented a short introduction to charm physics for non expert physicists. Although a priori less promising that B decays in the quest for New Physics due to the weakness of CP violation in this system and the large contributions due to LD effects, they have an important potential. Any substantial CP violation detected in the mixing or in some decays would immediately prove the existence of NP. In some NP scenarios affecting more up-type than down-type FCNC's, D decays are more sensitive to NP than B decays. The existence of very rare decays gives NP a chance to be detected. Some charm mesons, like charmonia, are ruled by LD strong interaction and provide a precious laboratory for its study. The many experiments already devoted to charm physics, as well as the advent of the LHC, where the production cross sections are very high, make the experimental situation ideal.

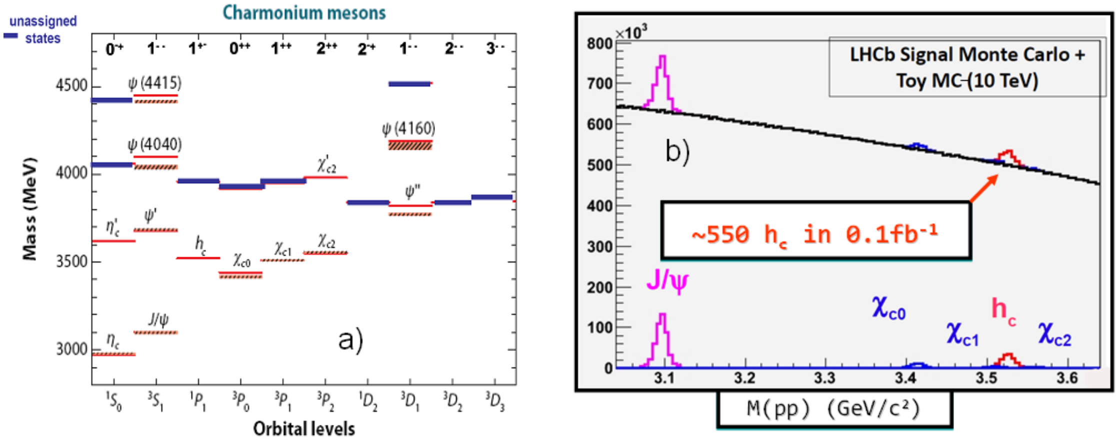


Fig. 7. *a* - map of the Charmonia; *b* - expectation at LHCb with the 2010 sample.

REFERENCES

1. *Amsler C. et al.* Review of Particle Physics // Phys. Lett. - 2008. - Vol. B667. - P. 1.
2. *Glashow S.L., Iliopoulos J., Maiani L.* // Phys. Rev. - 1970. - Vol. D2. - P. 1285.
3. *The Babar* collaboration // http://www.slac.stanford.edu/babar
4. *The LHCb* collaboration. The LHCb detector at the LHC // JINST. - 2008. - Vol. 3. - P. S08005.
5. *The Belle* collaboration // arXiv:0704.1000v2, 2007.
6. *The CLEO-c* collaboration // http://www-cdf.fnal.gov/
7. *The BESIII* collaboration // Nucl. Instrum. Meth. - 2010. - Vol. A614. - P. 345 - 399.
8. *The D0* collaboration // http://www-d0.fnal.gov/
9. *The CDF* collaboration // http://www-cdf.fnal.gov/
10. *Hai-Bo Li.* The First Results from BESIII // Proc. of the FPCP Conf. (Torino, 2010).
11. *The BESIII* Collaboration // IHEP-Physics-Report-BES-III-2008-001-v1, 2008, P-651.
12. *Aubert B. et al.* Evidence for D0-D0bar Mixing // SLAC-PUB-12385, 2008.
13. *Marks J.* Charm Physics Results and Prospects at LHCb // Conf. Physics at LHC, 06-2010.
14. *Aubert B. et al.* Measurement of D^0-D^0bar Mixing using the Ratio of Lifetimes for the Decays D0→K-π+ and K+K− // SLAC-PUB-13737, 2009.
15. *Zhang et al.* Measurement of D^0-D^0bar Mixing in $D^0 \rightarrow K^0{}_S\pi^+\pi^-$ // arXiv:0704.1000v2, 2007.
16. *Rosner J.L. et al.* (CLEO Collab.) // Phys. Rev. Lett. - 2008. - Vol. 100. - P. 221801.
17. *Heavy Flavor Averaging Grou* // http://www.slac.stanford.edu/xorg/hfag/charm
18. *Grossman Y. et al* // arXiv:hep-ph/0609178v1.
19. *Staric M. et al* // arXiv:0807.0148v1.
20. *Del Amo Sanchez P. et al.* // SLAC-PUB-13996.
21. *Kuhr T.* Rare B and Charm decays at the Tevatron // arXiv:0804.2743v1.