Indirect searches, and in particular rare decays, have proven to be a fruitful field to search for New Physics beyond the Standard Model. While the down-quark sector (B and K) have been studied in detail, less attention was devoted to charm decays due to the smaller expected values and higher theoretical uncertainties of their observables. Recently a renewed interest is growing in rare charm searches. In this article we review the current experimental status of searches for rare decays in charmed hadrons. While the Standard Model rates are yet to be reached, current experimental limits are already putting constraints on New Physics models.
1 Introduction

The Standard Model (SM) of particle physics is an exceptionally precise theory and up to now is able to describe all the available experimental information, with really few exceptions. Therefore deviations from this theory belong either to non-explored energy regimes or to extremely small effects. While direct searches at current accelerators have not yet led to New Physics (NP) discoveries, hints of new effects might hide in rare processes.

Due to the flavour structure of the SM, flavour changing neutral currents (FCNC) are only allowed at loop level, giving the possibility to explore effects where the dominant tree level is forbidden. Furthermore they give access, through the virtual loops, to higher energy ranges than those accessible to direct searches. FCNC and rare decays in general have been extensively studied in the down-type quark sector, *i.e.* in B and K meson decays, and have proven to constrain tightly New Physics possibilities. Less attention was devoted in the past to the charm sector, mainly due to the fact that SM values of FCNC for charmed hadrons are very small. In fact, the absence of a heavy down-type quark which would decouple the short distance effects (as the top quark does for the $B$ and $K$ decays) implies that the Glashow-Iliopoulos-Maiani (GIM) mechanism [1] is extremely effective for charmed hadrons. On one side this leads to the advantage that NP effects can be orders of magnitude larger than the SM ones; however it also implies that SM predictions can be dominated by long distance contributions due to the propagation of light quarks intermediate states. Unfortunately long distance contributions, being non perturbative, carry large theoretical uncertainties.

Many New Physics scenarios can enhance these processes, like Supersymmetry (with or without $R$-parity violation) [2], Littlest Higgs model [3, 4] and Leptoquarks [5]. Furthermore some models lead to enhancements only in the up sector, and therefore can only be probed in charm decays.

As the experimental results improve a renewed interest in the charm sector has grown, also due to the recent measurements of CP violation in D decays by the LHCb [6] and CDF experiments [7], stimulating the theoretical work.

We will review in the following the current status of experimental searches for rare charm decays. In particular in §2 we will treat the FCNC $c \to u\ell^+\ell^-$ transitions for charged (§2.1) and neutral charm hadrons (§2.2). Radiative processes will not be treated in the following as the high theoretical uncertainties make them less interesting [2], though recently it has been proposed that their study could shed light on charm CP violation [8]. In sections 3 and 4 we will describe the di-photon and di-lepton $D^0$ decays. Finally a brief overview of the current searches for SM forbidden decays will be given in section 5.

*Here and in the rest of this article we always imply charge conjugation unless otherwise stated.*
As far as the future prospects are concerned, we will not discuss them in this article as they are subject of another report at this same conference.

2 \[ c \to u\ell^+\ell^- \] transitions

We start from the \[ c \to u\ell^+\ell^- \] transitions as they are the most probable to be observed at currently running experiments. Short distance contributions for transitions of the type \[ c \to u\ell^+\ell^- \] are heavily suppressed by the GIM mechanism. In particular, the inclusive branching fractions calculated for the mesonic modes to electrons are [2]:

\[ B_{D^+ \to Xe^+e^-} \approx 2 \times 10^{-8} \quad B_{D^0 \to Xe^+e^-} \approx 8 \times 10^{-9}, \]

which would be out of present experimental reach. However, as already said, short distance contributions are shaded by the long distance ones. Long distance (LD) processes can be represented in the form \[ D \to XV \to X\ell\ell \] where \( V = \phi, \rho, \omega \) is the intermediate resonance. Typical exclusive branching fractions of the resonant processes are at the level of \( \mathcal{O}(10^{-6}) \) [2, 9]. As an example the branching fraction for \[ D^+ \to \pi^+e^+e^- \] is \( B \approx 2 \times 10^{-6} \) dominated by the \( \pi^+\phi \) intermediate state.

However long distance processes, being non-perturbative in nature, carry also large theoretical uncertainties so that they make more difficult the comparison between SM and New Physics predictions and between these and the experimental results.

Different New Physics scenarios can enhance \[ c \to u\ell^+\ell^- \] transitions. Already the Minimal Supersymmetric Standard Model (MSSM) with R-parity conservation could give contributions to \[ c \to u\ell^+\ell^- \] processes. These would come from one-loop diagrams with gluino and squarks in the loop [2, 10] and would increase the decay rate at low di-lepton invariant mass. However when including bounds from \( D^0 - \bar{D}^0 \) oscillations these enhancements are reduced. Furthermore when considering the hadronic decay \( D \to X\ell^+\ell^- \) the rate is decreased by a factor \( m_{\ell\ell}^2 \) when \( X \) is a pseudoscalar meson and hidden by long distance contributions when \( X \) is a vector meson [11].

On the other hand the MSSM with R-parity violation (\( \tilde{R}_p \)) is not so constrained and can give large contributions via a tree-level exchange of squarks. Enhancement of a factor \( \sim 3 \) are possible, for example, in the \( D^+ \to \pi^+\mu^+\mu^- \) decay [11]. In particular, as shown in Fig. 1(a), at low and high di-muon invariant mass (or \( q^2 = m_{\ell\ell}^2 \)), i.e. far from the resonances, there is a possible high sensitivity to the MSSM \( \tilde{R}_p \).

Similar increases in the branching fraction can appear also in the \( D \to \rho\mu^+\mu^- \) channel; in this channel in addition to the branching fraction also angular observables, such as the forward-backward asymmetry for the leptons are thought to be sensitive to NP effect, even if only reachable at high yields [2, 11].

Other possible contributions to \[ c \to u\ell^+\ell^- \] can come from new physics leptoquarks. In particular it has been shown that the \( D^+ \to \pi^+\mu^+\mu^- \) decay is sensitive also to couplings which cannot be limited by constraints on the branching fraction.
Figure 1: Differential rate as a function of invariant mass squared of the two muons in the $D^+ \to \pi^+ \mu^+ \mu^-$ decay for the SM long distance (LD) prediction, and compared with (a) MSSM$_p$ and (b) Leptoquarks new physics model. The Leptoquark contribution is saturated to the experimental limit on the total branching fraction.

of $D^0 \to \mu^+ \mu^-$ [3]. In Fig. 1(b) the differential branching fraction of $D^+ \to \pi^+ \mu^+ \mu^-$ is shown in the hypothesis of saturating its experimental limit with Leptoquarks coupling, showing that large room for a distinction between this and the LD SM contribution is still present at large and low $q^2$.

In the next two sections we will review the experimental searches for $c \to u \ell^+ \ell^-$ transitions divided for simplicity into charged and neutral hadron decays.

2.1 Searches for $X_c^\pm \to h^\pm \ell^+ \ell^-$

The current limits on rare decays of charged charm hadrons are nicely summarized by the Heavy Flavour Averaging Group (HFAG) plots shown in Fig. 2.

None of the listed channels have been observed up to now and the limits on the decays branching fractions are at the level of $10^{-6}$ or higher. With few exceptions the best limit for all of these decay modes come from a comprehensive analysis of the BABAR experiment, described in Ref. [14], which we review in the following.

2.1.1 Search for $X_c^\pm \to h^\pm \ell^+ \ell^-$ at BaBar

A search for rare decays in the form $X_c^\pm \to h^\pm \ell^+ \ell^-$ was conducted by the BaBar collaboration [14] exploiting data collected at the PEP-II at SLAC. A dataset of 347 fb$^{-1}$ of $e^+e^-$ collisions at the $\Upsilon(4S)$ and of 37 fb$^{-1}$ just below it was used. We will not describe the BaBar detector and the reader should refer to Ref. [15].
Figure 2: Summary of the upper limits on charged charm hadron rare decays compiled by the HFAG group. [13]
Pairs of tracks identified as leptons and a track identified as a charged hadron (pion, kaon or proton) were used to build charm hadron candidates. The candidate momentum in the $e^+e^-$ center of mass ($p^*$) was required to be larger than 2.5 GeV/$c^2$ to remove a large combinatorial background in those regimes. QED background was rejected requiring a multiplicity larger than 5. The residual combinatorial background, mainly from charm and beauty semi-leptonic decays, was reduced with cuts on the $\chi^2$ of the vertex fit and on the distance of closest approach between the leptons. Finally the $\phi$ region was rejected from the invariant mass of the di-lepton in order to exclude the resonant (and long distance) part of the decay. After this first selection a likelihood ratio was used to further discriminate the signal from combinatorial background. The likelihood was built from information on the $p^*$ of charmed candidate, total energy in the event and flight length significance. The PDFs for the signal were built using Monte Carlo (MC) simulations while for the background data events in the invariant mass sidebands were used. The cut value on the likelihood was optimized independently for each decay mode in order to provide the lowest expected upper limit.

Extended, unbinned maximum-likelihood fits to the invariant mass distributions were used in order to extract the number of signal events. The signal pdf was parametrized as a Crystal Ball function while the combinatorial background as a first order polynomial. For some channels an additional component to take into account background from mis-identified non leptonic charm decays was included. In Fig. 3 the invariant mass distribution of some of the studied channels is shown together with the fit.

The signal yields were normalized to known hadronic charm decays in order to compute the branching fractions: $D^+_c(s)$ mesons channels were normalized to the $D^+_c(s) \to \phi(\to KK)\pi^+$ channel while $\Lambda_c^+ \to pK^-\pi^+$ decay was used for the $\Lambda_c^+$ decays.

No significant signal was observed in any of the channels. A $2\sigma$ fluctuation was seen in the $\Lambda_c^+ \to p\mu^+\mu^-$ decay which however has a 25% probability to occur when looking at 35 different channels. Therefore upper limits were put on the decay branching fractions using a Bayesian approach with flat prior for the event yield in the physical region. The obtained upper limits on the branching fractions at 90% CL are between $1 \cdot 10^{-6}$ and $44 \cdot 10^{-6}$ depending on the decay mode and are the best limits up to now for most of the channels.

### 2.1.2 $D^+ \to \pi^+\mu^+\mu^-$ at $D\bar{O}$

One of the channels in which the best limit does not come from BABAR is the $D^+ \to \pi^+\mu^+\mu^-$ decay were a strongest limit was put by the $D\bar{O}$ collaboration [12]. This search was conducted with 1.3 fb$^{-1}$ of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV collected at Tevatron with the $D\bar{O}$ detector.

Tracks identified as muons were used as starting point after a cut on the transverse
Figure 3: Invariant mass distributions for $X_c^\pm \rightarrow h^\pm \ell^+\ell^-$ candidates in the analysis performed by BaBar [14].
momentum \((2 \text{ GeV/c})\) and on the momentum \((3 \text{ GeV/c})\). Two oppositely charged muons were combined requiring to form a well reconstructed vertex and to have an invariant mass lower than \(2 \text{ GeV/c}^2\). The \(\phi\) invariant mass region of the di-muon system was excluded from the search of the non-resonant \(D^+ \rightarrow \pi^+\mu^+\mu^-\) system and used to study the \(D^+ \rightarrow \phi\pi^+\) decay, with \(\phi \rightarrow \mu^+\mu^-\). The di-muon system was combined with an additional track passing requirements on its impact parameter significance and on its transverse momentum, and the three body invariant mass was required to be in the \(1.4 - 2.4 \text{ GeV/c}^2\) range. Further selection criteria were applied based on the significance of the transverse flight distance of the \(D^+\) candidate and on the collinearity angle, \(i.e.\) the angle between the \(D^+\) momentum and the line between primary and secondary vertices. After this selection the \(\pi^+\mu^+\mu^-\) invariant mass for events in the \(\phi\) di-muon mass region is shown in Fig. 4(a), where the two signals of \(D^+\) and \(D^+_s \rightarrow \phi\pi^+\) can be seen. The \(D^+ \rightarrow \phi\pi^+ \rightarrow \mu^+\mu^-\pi^+\) branching fraction was measured to be \((1.8 \pm 0.5\text{ (stat)} \pm 0.6\text{ (syst)}) \times 10^{-6}\). Before considering the non-resonant part of the di-muon invariant mass, tighter cuts were applied based on the already mentioned variables and on the pion transverse momentum and the isolation of the \(D^+: I = p_D/\sum p_{\text{cone}}\) where the sum of the momenta is extended to a cone around the \(D^+\) candidate. The criteria were optimized in order to obtain the best upper limit on the branching fraction. The invariant mass distribution of the remaining events is shown Fig. 4(b). No signal above the combinatorial background was observed and the following upper limit on the branching fraction was estimated:

\[
\mathcal{B}(D^+ \rightarrow \pi^+\mu^+\mu^-) < 3.9 \times 10^{-6} \text{ at 90\% CL.}
\]

While this limit is still more than 2 orders of magnitude from the Standard Model expected rate it constraints already the parameter space of R-parity violating SUSY \([2]\); on the other hand the little Higgs models are an order of magnitude below this level and therefore are still not constrained by this measurement \([4]\).

### 2.2 Searches for \(X^0_c \rightarrow h^0\ell^+\ell^-\)

Results on rare decays from \(D^0\) decays are all at least 10-years old, with the exception of di-lepton and di-photon decays which will be treated separately. A summary of the upper limits on the various decay modes is shown in Fig. 5 from the HFAG group \([13]\). With few exceptions, all the limits on \(D^0 \rightarrow X\ell\ell\) decays come from two analyses by the E791 and CLEOII collaborations which will be discussed in the following.

#### 2.2.1 Search for \(D^0 \rightarrow X\ell\ell\) decays at E791

The E791 collaboration reported in 2001 a search for decays in the forms \(D^0 \rightarrow V\ell^+\ell^-\), with \(V = \rho^0, K^{*0}, \phi\) and \(D^0 \rightarrow hh\ell^+\ell^-\), with \(h = \pi, K\) \([16]\) based on \(2 \times 10^{10}\) events of a \(400 \text{ GeV/c} \pi^-\) beam on fixed target. Events with secondary vertex well separated from the primary one and from the detector material were selected. A blind
Figure 4: Invariant mass distribution of $D^+ \to \pi^+ \mu^+ \mu^-$ candidates for events with the di-muon (a) in the $\phi$ mass region and (b) outside of it [12].

Figure 5: Summary of upper limits on branching fraction of FCNC $D^0$ decays [13].
analysis was optimized exploiting MC simulations of the signal channels and using background from the invariant mass sidebands. All the channels were normalized to topologically similar hadronic decays to which the very same selection, with the exception of particle identification, was applied. MC simulations were used in order to calculate the signal and normalization selection efficiencies, while the muon and electron identification efficiencies were measured on data. After unblinding the signal invariant mass regions no significant signal was found in any of the channels, as can be seen from the invariant mass distributions shown in Fig. 6(a). After subtracting the combinatorial background, estimated from the sidebands, and the mis-identification background, upper limits on the number of signal events were calculated with the Feldman-Cousins method and translated into branching fractions with the normalization channels.

The upper limits on the branching fractions vary between 3.0 and \(55.3 \times 10^{-5}\) at 90\% CL depending on the channel, most of which are the best results to date.

2.2.2 Search for \(D^0 \rightarrow X\ell\ell\) decays at CLEOII

A similar study was conducted by the CLEO collaboration with the CLEOII detector at CESR \cite{17}. A dataset of 3.87 fb\(^{-1}\) of \(e^+e^-\) collisions at the \(\Upsilon(4S)\) and just below it was used to search for events in the form \(D^0 \rightarrow X\ell\ell\) where \(X = \pi^0, K^0_S, \eta, \rho^0, \omega, K^{*0}, \phi\). In order to build the signal candidates, charged tracks were required to come from the primary interaction, with the exception of the ones for the \(K^0_S\). Particle identification of pions and kaons was based on \(dE/dx\) and time-of-flight information, while calorimeter and muon chambers information was additionally exploited for the lepton candidates. Electrons coming from photon and \(\pi^0\) decays were rejected. The various employed mesons were reconstructed in the following final states: \(K^0_S \rightarrow \pi^+\pi^-\), \(\rho^0 \rightarrow \pi^+\pi^-\), \(\omega \rightarrow \pi^+\pi^-\pi^0\), \(K^{*0} \rightarrow K^-\pi^+\), \(\phi \rightarrow K^+K^-\), and \(\pi^0\) and \(\eta\) into \(\gamma\gamma\).

The so constructed \(D^0\) candidate was required to come from a \(D^{*+} \rightarrow D^0\pi^+\) decay, in order to reduce the combinatorial background, imposing a cut on the \(D^{*+} - D^0\) mass difference (\(\Delta M\)) at 2.0 MeV/c\(^2\) from the nominal value. Cuts on the scaled momentum of the \(D^*(p_{D^*}/\sqrt{E^2_{beam} - M^2_{D^*}})\) and on the angle between the daughter tracks and the \(D^0\) momentum were also applied.

After this selection the invariant mass distributions of the studied decay modes are shown in Fig. 6(b). No signals were observed over the small expected combinatorial background and a 90\% poissonian upper limit was put on the number of signal events. This limit was translated in a branching fraction by normalizing to the total number of produced \(D^0\), measured in data in the \(K^-\pi^+\) final state, and correcting for the efficiency of each channel, obtained from simulations. The upper limits on the branching fractions of the various modes are in the range between few in \(10^{-5}\) to \(10^{-4}\) depending on the channels and are the best limits to date for most of them.
Figure 6: Invariant mass distributions for (a) the search of signals in the form $D^0 \to X\ell\ell$ performed by the E791 collaboration [16] and (b) candidates in the form $D^0 \to X\ell\ell$ in the search performed by the CLEO collaboration [17].
3 \( D^0 \to \gamma \gamma \)

The Standard Model prediction for the short-distance contribution to the \( D^0 \to \gamma \gamma \) decay leads to a branching fraction of \( 3 \times 10^{-11} \), which however is completely shaded by the long distance contributions \[10\]. Calculations done for the Vector Meson Dominance mechanism give a long distance contribution to the branching fraction of \( 3.5^{+0.6}_{-2.0} \times 10^{-8} \), and other calculations which exploit the Heavy Quark Chiral Perturbation Theory lead to similar results \[10, 18\].

In various new physics scenarios this process could be enhanced and it has been pointed out that within the MSSM scenario gluino exchange could enhance the SM rate of more than 2 orders of magnitude \[19\].

3.1 Search for \( D^0 \to \gamma \gamma \) at BaBar

The present best limit on the \( D^0 \to \gamma \gamma \) branching fraction is due to an analysis performed at BaBar and reported in Ref. \[20\]. This analysis is based on 470.5 fb\(^{-1}\) of \( e^+ e^- \) collisions at \( \sqrt{s} = 10.58 \) GeV and 10.54 GeV. The search for \( D^0 \to \gamma \gamma \) was done in parallel with a measurement of the \( D^0 \to \pi^0 \pi^0 \) branching fraction which is also the main background for the di-photon final state. As normalisation channel was chosen the \( D^0 \to K_S^0 \pi^0 \) decay for its well known branching fraction.

MC simulations were used to optimize the search for \( D^0 \to \gamma \gamma \) decays. \( D^0 \to \gamma \gamma \) (\( D^0 \to \pi^0 \pi^0 \)) candidates were formed with pairs of photons (pions) required to have an invariant mass between 1.7 and 2.1 GeV/c\(^2\) (1.65 and 2.05 GeV/c\(^2\)). Photons were required to have a CM energy between 0.74 and 4 GeV. The \( D^0 \) candidates were required to come from a \( D^{*+} \to D^0 \pi^+ \) decay and therefore kinematically fitted, together with a \( \pi^+ \), to a common vertex constrained to be within the beam spot.

Background from B decays was rejected with a 2.85 (2.4) GeV/c momentum threshold on the \( D^* \) candidate for \( D^0 \to \gamma \gamma \) (\( D^0 \to \pi^0 \pi^0 \)), while the large QED background was removed with a cut on the tracks and neutrals multiplicity of the events. Finally the \( D^0 \to \pi^0 \pi^0 \) background to \( D^0 \to \gamma \gamma \) was rejected with an ad-hoc \( \pi^0 \)-veto which required the photons not to be consistent with coming from a \( \pi^0 \) decay after being combined with other photons of the same event.

The invariant mass of \( D^0 \to \pi^0 \pi^0 \) candidates is shown in Fig. 7(a); the superimposed fitted PDF is composed of a 3\(^{rd}\) order Chebychev polynomial for the background and of a signal PDF which is the sum of a Crystal Ball, a gaussian and a bifurcated gaussian function. A signal yield of about 26k events was estimated which led to a branching fraction measurement of: \( \mathcal{B}(D^0 \to \pi^0 \pi^0) = (8.4 \pm 0.1 \pm 0.3) \times 10^{-4} \). On the other hand a negative signal yield, consistent with zero, was estimated from the fit to the \( D^0 \to \gamma \gamma \) invariant mass distribution, shown in Fig. 7(b). The measured upper limit on the branching fraction of this decay was estimated to be: \( \mathcal{B}(D^0 \to \gamma \gamma) < 2.2 \times 10^{-6} \) at 90\% confidence level. While this result is not yet
approaching the SM rate, it limits the branching fraction to, at most, $\sim 70$ times the SM levels, tightly constraining New Physics models.

4. $D^0 \rightarrow \ell^+ \ell^-$

While the two-body leptonic signature of the $D^0 \rightarrow \ell^+ \ell^-$ decays is more appealing from the experimental point of view, theoretically they are foreseen to be even more rare than $c \rightarrow u \ell^+ \ell^-$ processes, due to the helicity suppression of the phase space. The Standard Model short distance contribution for $D^0 \rightarrow \mu^+ \mu^-$ is at the level of $10^{-18}$ and even less for $D^0 \rightarrow e^+ e^-$. The long distance contributions are relevant in the SM branching fraction and in particular the dominant one is due to the two-photon intermediate state and the following expression can be derived for the di-muon final state [2]:

$$B(D^0 \rightarrow \mu^+ \mu^-) \approx 2.7 \times 10^{-5} B(D^0 \rightarrow \gamma \gamma)$$

which leads to an estimate of a minimum theoretical contribution to the branching fraction of $B(D^0 \rightarrow \mu^+ \mu^-) \gtrsim 10^{-13}$. However equation [1] could also be exploited to estimate a rough upper limit to this contribution: together with the experimental limit on $D^0 \rightarrow \gamma \gamma$ set by BaBar [20] described earlier, this gives $B(D^0 \rightarrow \mu^+ \mu^-)_{\gamma\gamma} \lesssim 6 \times 10^{-11}$.

Many NP models can instead enhance the $D^0 \rightarrow \ell^+ \ell^-$ branching fraction by various orders of magnitude. Moreover it has been noted that the $D^0 \rightarrow \mu^+ \mu^-$ decay can be related directly to the couplings involved in the $D^0 - \bar{D}^0$ mixing [21] so that limits on one of the two processes can be used to constrain evaluations of the other.
As an example one of the largest contributions is from $R_p$ SUSY and gives an estimate of \cite{21}:

$$B_{D^0 \rightarrow \mu^+ \mu^-}^{R_p} \approx 4.8 \times 10^{-7} x_D \left( \frac{300 \text{ GeV}}{m_{\tilde{d}_k}} \right)^2 \leq 4.8 \times 10^{-9} \left( \frac{300 \text{ GeV}}{m_{\tilde{d}_k}} \right)^2$$ (2)

which is dependent on the mass of the down type quarks super partners.

Finally, also contributions from Leptoquarks were found to be relevant, and predicted branching fractions at the level of $5 \times 10^{-7}$ \cite{22} and are being already strongly constrained by experimental limits.

In the following we will present a preliminary result of the LHCb experiment on the $D^0 \rightarrow \mu^+ \mu^-$ decay, which is the strongest limit up to date, and the results obtained by the Belle collaboration on all the $D^0 \rightarrow \ell^+ \ell^-$ decays.

### 4.1 Search for $D^0 \rightarrow \mu^+ \mu^-$ at LHCb

The search for the $D^0 \rightarrow \mu^+ \mu^-$ decay at LHCb is based on a dataset of 0.9 fb$^{-1}$ of $pp$ collisions in LHC at $\sqrt{s} = 7$ TeV \cite{23}. An additional sample of about 79 pb$^{-1}$ was also used in order to optimize the selection but not used in the final analysis.

Pairs of opposite side muons were selected to form $D^0$ candidates, which were required to come from a $D^{*+} \rightarrow D^0 \pi^+$ decay. After a first selection based on standard geometrical and kinematic variables, a Boosted Decision Tree (BDT) was built in order to reject the combinatorial background, combining information from the following variables: $\chi^2$ of the impact parameter of the $D^0$ candidate and pointing angle of the $D^0$ with respect to the primary vertex, minimum transverse momentum of the two muons, minimum $\chi^2$ of impact parameter of the two muons, angle of the positive muon in the $D^0$ candidate rest frame with respect to the $D^0$ flight direction. In Fig. 8 is shown the distribution of the BDT output for signal MC events and for events in the di-muon invariant mass sidebands. The final cut value on the BDT was chosen in order to have the best expected upper limit on the $D^0 \rightarrow \mu^+ \mu^-$ branching fraction. A large background to this decay is the $D^0 \rightarrow \pi^+ \pi^-$ with both pions mis-identified into muons. This background was estimated by measuring the mis-ID probability directly on data $D^0 \rightarrow K^- \pi^+$ decays. The double mis-ID probability was estimated to be $p(D^0 \rightarrow \pi^+ \pi^- \rightarrow \mu \mu) = (27.3 \pm 3.4 \pm 2.0) \cdot 10^{-6}$. The $D^{*+} \rightarrow D^0(\rightarrow \pi^+ \pi^-) \pi^+$ decay was also exploited as normalisation channel, after being selected with the same selection as the signal, with the exception of the muon identification. The $D^0 \rightarrow \pi^+ \pi^-$ yield was estimated with a 2-dimensional fit to the distribution in the $\Delta M$ versus invariant mass plane. A projection of this distribution together with the fit is shown in Fig. 8(b). The signal and normalisation channel efficiencies were estimated from MC simulations and corrected for data-MC discrepancies. The estimate of the $D^0 \rightarrow \mu^+ \mu^-$ signal yield was also done in the 2D $\Delta M-M_{D^0}$ plane. The data distribution was fitted
with a PDF built upon the following components: the signal was parametrised as a gaussian (in M) times a double gaussian ($\Delta M$), the $D^0 \to \pi^+\pi^-$ mis-ID as Crystal Ball (M) times a double gaussian ($\Delta M$), the $D^0 \to K^-\pi^+$ tail mis-ID as a gaussian in both M and $\Delta M$ and the combinatorial background as an exponential (in M) times the following function: $f(\Delta M) = (\frac{\Delta M}{a})^2 (1 - e^{\frac{\Delta M - \Delta M_0}{c}}) + b \cdot (\frac{\Delta M}{d} - 1)$. The projection of this fit along the $D^0$ candidate invariant mass is shown in Fig. 9(a). As no significant signal was observed, the upper limit to the $D^0 \to \mu^+\mu^-$ branching fraction was estimated with the CLs method to be: $\mathcal{B}(D^0 \to \mu^+\mu^-) < 1.3(1.1) \times 10^{-8}$ at 95 (90)% CL. In Fig. 9(b) is shown the CLs value as a function of the $D^0 \to \mu^+\mu^-$ branching fraction and the expected values and bands. This limit is still several orders of magnitude far from the SM predictions but constraints various NP models.

4.2 Search for $D^0 \to \ell^+\ell^-$ at Belle

Another search for di-leptonic $D^0$ decays was done by the Belle collaboration and reported in Ref. [24]. This analysis was based on 660 fb$^{-1}$ of $e^+e^-$ collisions at the $\Upsilon(4S)$ and just below it, collected with the Belle detector at KEKB. $D^0$ candidates were built from two opposite side leptons in the $D^0 \to \mu^+\mu^-$, $D^0 \to e^+e^-$ and $D^0 \to e^+\mu^\pm$ final states. Only $D$ mesons from $e^+e^- \to c\bar{c}$ were used, excluding those from $B$ decays because of the higher combinatorial background; these were removed by requiring a maximum allowed missing energy which is high in events with $B$ semileptonic decays due to missing neutrinos. The $D^0 \to \pi^+\pi^-$ final state was also reconstructed as normalisation and control channel. Standard particle identification criteria, based on $dE/dx$, TOF, Cherenkov light and muon detectors information, were exploited in
Figure 9: (a) Invariant mass distribution for $D^0 \rightarrow \mu^+\mu^-$ candidates, projected from the $M_D, \Delta M$ plane, and the fit to the distribution: the black line is the total fit function composed of the combinatorial background (light grey dashed line), $D^0 \rightarrow \pi^+\pi^-$ mis-identified background (dark dashed line), $D^0 \rightarrow K^-\pi^+$ mis-identified background (dash-dotted line) and the signal $D^0 \rightarrow \mu^+\mu^-$ (light grey continuous line). In (b) the CLs value as a function of the $D^0 \rightarrow \mu^+\mu^-$ branching fraction as obtained with the CLs method is shown; the red line shows the upper limit to the branching fraction at 95 % CL [23].
order to select pions, electrons and muons. The $D^0$ candidate was required to come from a $D^{*+} \rightarrow D^0 \pi^+$ decay from the vertex of the $e^+e^-$ interaction point. Further rejection of combinatorial background and of B-decays was achieved by requiring a $D^{*+}$ candidate momentum in excess of 2.5 GeV/c. Candidates were selected to be in a region of the $D^0$ candidate invariant mass between 1.81 and 1.91 GeV/c$^2$ and with $q < 20$ MeV, where $q = (M_{D^{*+}} - M_{D^0} - m_\pi)c^2$. Further selection criteria, based on the missing energy, lepton identification and signal region in the mass versus $q$ plane, were optimized differently for each final state with a blind analysis. Residual combinatorial background was estimated from the sideband region of the $M - q$ plane, while the mis-identified $D^0 \rightarrow \pi^+\pi^-$ background was evaluated from the decay itself reconstructed in data, re-weighted for momentum dependent mis-identification probabilities. The invariant mass distributions after the final selection criteria are shown in Fig. 10. No events in excess of the estimated background are observed in any of the final states. A binned maximum likelihood fit to the invariant mass distribution was used to estimate the yield of the normalisation channel $D^0 \rightarrow \pi^+\pi^-$. Efficiencies were estimated from tuned MC samples. Finally the following upper limits were derived on the signal channels branching fractions: $\mathcal{B}(D^0 \rightarrow \mu^+\mu^-) < 1.4 \times 10^{-7}$, $\mathcal{B}(D^0 \rightarrow e^+e^-) < 7.9 \times 10^{-7}$, $\mathcal{B}(D^0 \rightarrow e^\pm\mu^{\mp}) < 2.6 \times 10^{-7}$ at 90% CL.

The ones on $D^0 \rightarrow e^+e^-$ and $D^0 \rightarrow e^\pm\mu^{\mp}$ are the best limits on these channels to date and limit further the parameter space for NP models.

5 Forbidden decays

While rare decays are often dominated by the theoretical uncertainties, an unambiguous sign of New Physics would be to observe one of the decays which in the Standard Model are forbidden because of violation of one or more conservation laws. In particular here we consider decays which do not conserve the Lepton Family Number, the total Lepton Number, the Baryon Number or more than one of these.

Experimentally none of these decays has ever been observed, and therefore limits on the branching fractions are set. A summary of the current situation for the neutral sector, i.e. for $D^0$ decays, can be seen in Fig. 11 where is shown a collection of the various limits on branching fractions compiled by the HFAG group [13]. These upper limits have been set, with few exceptions, by the already mentioned experiments: E791 [16] and CLEOII [17].

Analyses of $D^0 \rightarrow X\ell\ell$ LFV decays were performed in the very same way as described in §2.2.1 and §2.2.2 for the E791 and CLEOII experiments respectively. The invariant mass distributions for some of the analysed final states are shown in Fig. 13. None of the searched decays was observed and the limits on the branching fractions are between $10^{-5}$ and few in $10^{-4}$.

One of the exceptions in this sector is the already mentioned limit on $D^0 \rightarrow e^\pm\mu^{\mp}$
Figure 10: Invariant mass distributions for $D^0 \to \ell^+\ell^-$ candidates in the analysis performed by the Belle Collaboration [24].
Figure 11: Summary of branching fraction upper limits on $D^0$ forbidden decays, compiled by the HFAG group [13].

which has been set by the Belle collaboration [24] and described in §4.2.

The BaBar collaboration has instead the almost absolute monopoly on the limits on the charged sector as can be seen by the HFAG summary plots in Fig. 2. Most of the limits on LFV and BV decays for $D^+, D_s^+$ and $\Lambda_c^+$ come in fact from the already discussed Ref. [20] (Cfr. §2.1.1). The analysis of forbidden $X^\pm \to h^\pm \ell^+ \ell^-$ final states was the same as for the FCNC ones. Invariant mass distributions of some of the analysed states are shown in Fig. 12 where it can be seen that no signal was observed. The upper limits on the branching fractions are all of the order of $10^{-5}$.

6 Conclusion

We have given a broad overview of the current experimental status of searches for charm rare decays. While in the past less interest was devoted to these decays than to the $B$ and $K$ correspondent ones, a renewed effort is going on both on the theoretical and experimental side. This is partially motivated by the recent measurement in the other charm processes but also due to new experimental searches going on at LHC and B-factories.

The most stringent limits are still not approaching the Standard Model predictions and large theoretical errors still dominate the calculations of SM long distance
Figure 12: Invariant mass distributions of charged charm hadron decays into SM forbidden final states [20].
contributions. Nevertheless these searches are already constraining the parameter space of various New Physics models.

Furthermore, as we have seen, there is a large playground of searches, especially in the neutral charm sector, which are more than ten years old and could be repeated and updated in current experiments, improving the knowledge of this interesting field.

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