Charm mixing and CP violation in LHCb

Thomas R. Hampson, on behalf of the LHCb Collaboration
H H Wills Physics Laboratory, University of Bristol, BS8 1TL, UK

The vast samples of charm hadron decays collected by the LHCb experiment have enabled the study of charm physics with unprecedented precision. We present the latest charm mixing and CP violation results using $1.0\,\mathrm{fb}^{-1}$ of $\sqrt{s} = 7\,\mathrm{TeV}$ pp collision data, as well as recent searches for rare charm decays.

1 Introduction

The LHCb detector [1] is a single-arm, forward spectrometer designed to exploit the copious production of $b\bar{b}$ quark pairs at the LHC. Many characteristics of $b-$hadrons are also shared by charmed particles, making the LHCb detector ideally suited for charm physics. The charm cross-section has been measured as $1419 \pm 134\,\mu\mathrm{b}$ in the forward region [2], ~ 20 times larger than the b production cross-section [3]. This has allowed for the accumulation of vast samples of charm hadron decays. All results presented here use $1.0\,\mathrm{fb}^{-1}$ of pp collision data collected in 2011 with a centre-of-mass energy of 7 TeV.

2 Observation of D^0–$\overline{D}^0$ oscillations

Mixing occurs because the mass eigenstates of a neutral meson system differ from the flavour eigenstates. It is parameterised by the dimensionless quantities $x \equiv \Delta m/\Gamma$, and $y \equiv \Delta\Gamma/2\Gamma$, where Δm and $\Delta\Gamma$ are the mass and width differences of the two mass eigenstates, and Γ is the average of their widths.

Here, neutral D meson oscillations are studied by measuring the time dependent ratio of $D^0 \to K^+\pi^-$ to $D^0 \to K^-\pi^+$ decay rates. The former, Wrong Sign (WS), rate is highly suppressed with respect to the latter, Right Sign (RS) rate. The RS decay is completely dominated the the Cabibbo Favoured (CF) amplitude, while the WS decay may proceed either directly via the DCS amplitude or via an oscillation followed by the CF decay. To determine the initial state flavour of the D mesons, they are reconstructed from the strong decay $D^{*+} \to D^0\pi_s^+$, where the charge of the slow pion ($\pi_s^\pm$) determines the flavour of the D.

Assuming negligible CP violation, and $|x|, |y| \ll 1$, the time dependent ratio of WS/RS decay rates can be approximated as

$$R(t) \approx R_D + \sqrt{R_D}\,y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2 \qquad (1)$$

where R_D is the ratio of DCS to CF decay rates, t is the measured D decay time, τ is the average D lifetime, and x' and y' are the mixing parameters rotated by the strong phase difference between CF and DCS decays, δ.

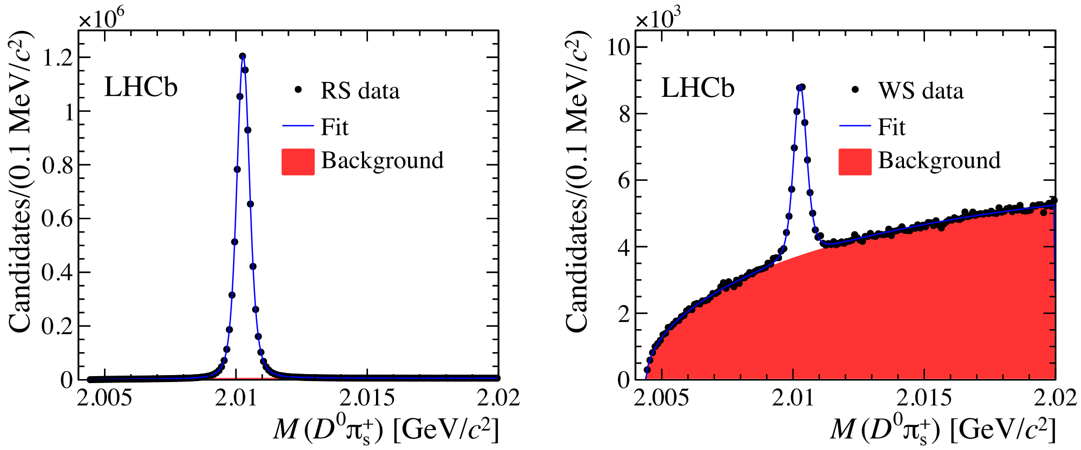

Figure 1: Fit to the D^{*+} invariant mass distribution for RS (left) and WS (right) candidates.

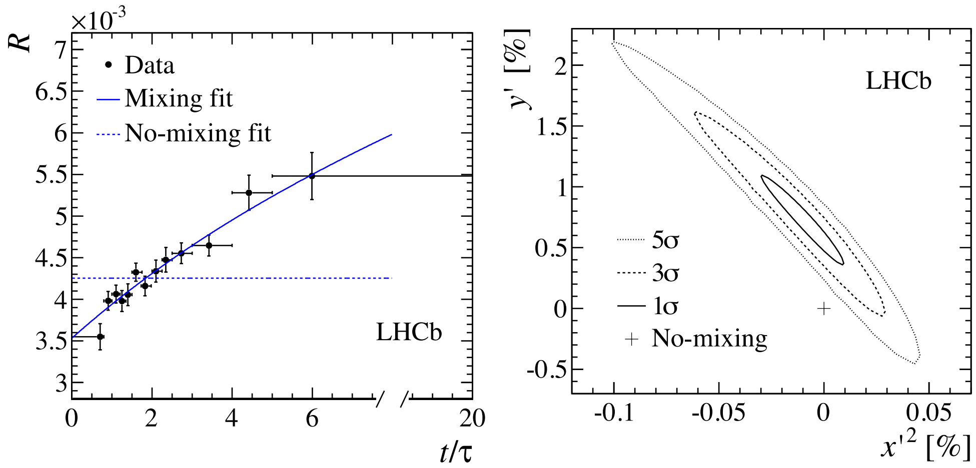

Figure 2: Fit to the time dependent WS/RS ratio (left), and contours in the $x'^2 - y'$ plane compared with the no-mixing point (right).

Fig. 1 shows fits to the D^{*+} invariant mass spectrum for RS and WS decays [4]. We find 3.6×10^4 WS and 8.4×10^6 RS signal candidates. The data sample is divided into thirteen decay time bins, each with a similar number of candidates. The ratio of WS/RS decays is measured in each bin, and the mixing parameters are determined using a binned χ^2 fit to the time dependence of the ratio (see Fig. 2). The fit results are $R_D = (3.52 \pm 0.15) \times 10^{-3}$, $y' = (7.2 \pm 2.4) \times 10^{-3}$, and $x'^2 = (-0.09 \pm 0.13) \times 10^{-3}$.

In addition, the time dependent ratio is fit with a zeroth order polynomial to test the significance of the mixing result. The no-mixing hypothesis is excluded at 9.1 standard deviations (illustrated in Fig. 2). Although $D-$mixing is well established [5], this is the first single $> 5\sigma$ observation of neutral charm meson mixing.

3 Model independent search for CP violation in multibody D decays

Singly Cabibbo Suppressed (SCS) decays can occur via tree and penguin processes, and are sensitive to CP violating phases. However, CP violation in charm decays is expected to be small (lower than $\mathcal{O}(10^{-3})$), but could be significantly enhanced by physics beyond the Standard Model [6]. We present results using the SCS decay $D^0 \to \pi^-\pi^+\pi^-\pi^+$ to search for local CP asymmetries across the phase space [7], which is a five-dimensional generalisation of a Dalitz plot.

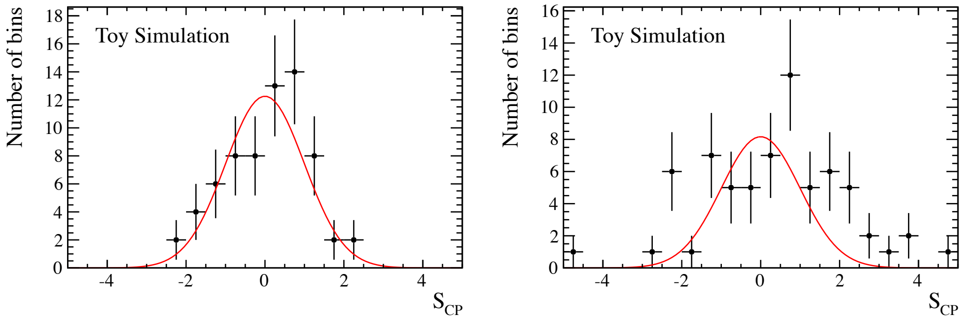

Figure 3: Toy Monte Carlo simulation of the S^i_{CP} variable for no CP violation (left) and a phase difference of $10°$ between D^0 and D^0 decays via the $\rho^0\rho^0$ intermediate resonant state. A Gaussian of mean 0 and width 1 (shown in red), is drawn for comparison with the data points.

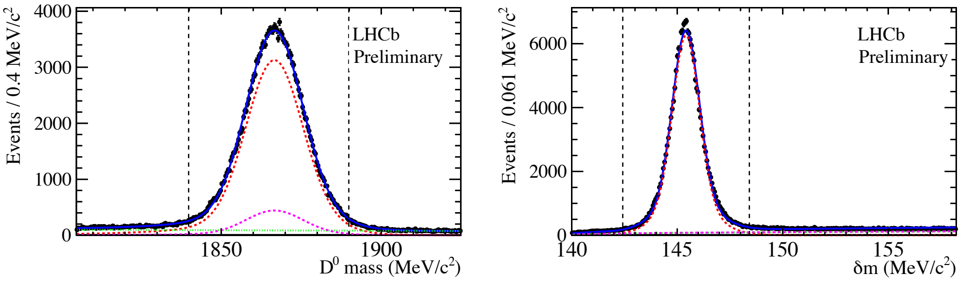

Figure 4: Projections of the two-dimensional fit to the m_{D^0} vs. δm plane. The signal component of the fit is shown as a red dashed line. Windows around the m_{D^0} and δm peaks are shown as vertical dashed lines.

The CP asymmetry variable is defined [8] as

$$S^i_{CP} = \frac{N^i\left(D^0\right) - \alpha N^i\left(\bar{D}^0\right)}{\sqrt{N^i\left(D^0\right) + \alpha^2 N^i\left(\bar{D}^0\right)}}, \qquad \alpha = \frac{\sum N^i\left(D^0\right)}{\sum N^i\left(\bar{D}^0\right)} \tag{2}$$

where $N^i\left(D^0\right)$ and $N^i\left(\bar{D}^0\right)$ are the number of D^0 and $\bar{D}^0$ events in bin i, and α is a normalisation factor that removes sensitivity to any global asymmetry. The flavour of the D is tagged using the charge of the slow pion from $D^{*+} \to D^0\pi^+_s$ decays. In the absence of any CP violation, S^i_{CP} is Gaussian distributed with a mean of 0 and a width of 1. The 5D Dalitz space is divided using an adaptive approach which aims to uniformly populate the bins (all bins contain a number of events within a defined minimum and maximum). This results in fine binning in highly populated ares of phase space, and coarse binning in more sparsely populated regions. A χ^2 is defined as

$$\chi^2/N_{\text{dof}} = \sum \left(S^i_{CP}\right)^2 / \left(N_{\text{bins}} - 1\right) \tag{3}$$

from which a probability value is calculated to quantify the degree of asymmetry.

The decay $D^0 \to \pi^-\pi^+\pi^-\pi^+$ can proceed via different intermediate resonances, most prominently $D^0 \to \rho^0\rho^0$ and $D^0 \to a_1\left(1260\right)^+\pi^-$. Toy Monte Carlo studies show that, for example, the method is sensitive to a $10°$ phase difference between D^0 and $\bar{D}^0$ decaying via the $\rho^0\rho^0$ resonances (illustrated in Fig. 3).

A two-dimensional fit to the $m\left(D^0\right)$ vs. $\delta m = m\left(D^{*+}\right) - m\left(D^0\right)$ plane is performed to estimate the signal yield and purity in the data sample (projection of the fit are shown in Fig. 4). After the $m\left(D^0\right)$ and δm mass window requirements, we are left with $\sim$ 180k signal candidates with a purity of 95.8%.

Probability values for the no-CP violation hypothesis are calculated for three different binning schemes: 15, 29, and 66 phase space bins. They are found to be 97.1%, 95.6%, and 99.8% respectively; all consistent with no CP violation.

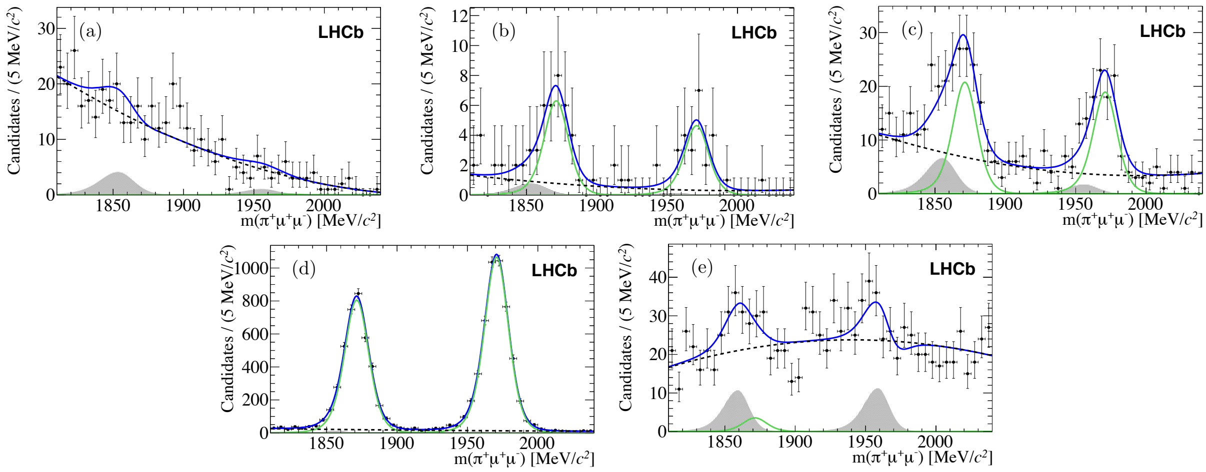

Figure 5: Invariant $D^+_{(s)}$ spectra for (a) low-q^2, (b) η, (c) ρ/ω, (d) ϕ, and (e) high-q^2 regions. In each case, the shaded grey component represents misidentified $D^+_{(s)} \to \pi^+\pi^+\pi^-$ decays, the dashed black line represents the non-peaking background, and the signal component is shown as a solid green line.

4 Search for rare D decays and lepton number violation

4.1 Search for non-resonant $D^+_{(s)} \to \pi^+\mu^+\mu^-$ decays

Flavour-Changing Neutral Current (FCNC) decays can only occur at the loop level, and are highly suppressed by the GIM mechanism. Although they are well established in $B^+ \to K^+\mu^+\mu^-$ and $K^+ \to \pi^+\mu^+\mu^-$ decays [9,10], branching fractions for $c \to u\mu^+\mu^-$ transitions are predicted to be much smaller in the Standard Model [11,12,13] ($\sim 1 \times 10^{-9}$). We present a search [14] for the rare decays $D^+_{(s)} \to \pi^+\mu^+\mu^-$. The best previous branching fraction upper limits (at 90% confidence) are $\mathcal{B}(D^+ \to \pi^-\mu^+\mu^+) < 3.9 \times 10^{-6}$ and $\mathcal{B}(D^+_s \to \pi^-\mu^+\mu^+) < 2.6 \times 10^{-5}$, published by the D0 [15] and FOCUS [16] Collaborations respectively.

For the analysis presented here, the data are split into five bins of $q^2 = m(\mu^+\mu^-)$ in order to separate the decays that proceed via $\mu^+\mu^-$ resonances (η, ω, ρ, ϕ) from the non-resonant high-q^2 ($1250 - 2000\,\mathrm{MeV}/c^2$) and low-$q^2$ ($250 - 525\,\mathrm{MeV}/c^2$) regions. The resonant decays $D^+_{(s)} \to \pi^+\phi$ with $\phi \to \mu^+\mu^-$ are used as normalisation modes. Fits to the $D^+_{(s)}$ invariant mass spectra in the five q^2 bins are shown in Fig. 5, where the main peaking background is identified as $D^+_{(s)} \to \pi^+\pi^+\pi^-$ decays where two oppositely charged pions are misidentified as muons. No significant signals are found in the low- and high-q^2 regions. When extrapolating to the full phase space for the non-resonant decays, we obtain 90 (95)% confidence limits on the branching fractions of

$$\mathcal{B}\left(D^+ \to \pi^+\mu^+\mu^-\right) < 7.3\,(8.3) \times 10^{-8},$$
$$\mathcal{B}\left(D^+_s \to \pi^+\mu^+\mu^-\right) < 4.1\,(4.8) \times 10^{-7}.$$

4.2 Search for the lepton number violating decay $D^+_{(s)} \to \pi^-\mu^+\mu^+$

Lepton Number Violation (LNV) is forbidden in the Standard Model, and may only proceed via lepton mixing (mediated by a Majorana neutrino [17], for example). We present a search for the LNV violating decays $D^+_{(s)} \to \pi^-\mu^+\mu^+$. The previous best 90% confidence limits are $\mathcal{B}(D^+ \to \pi^-\mu^+\mu^+) < 2 \times 10^{-6}$ and $\mathcal{B}(D^+_s \to \pi^-\mu^+\mu^+) < 1.4 \times 10^{-5}$, which were published by the BaBar Collaboration [18].

Here, the search is performed [14] by fitting the invariant mass of $\pi^-\mu^+\mu^+$ combinations. The data are divided into four regions of $m(\pi^-\mu^+)$ in order to increase the statistical significance

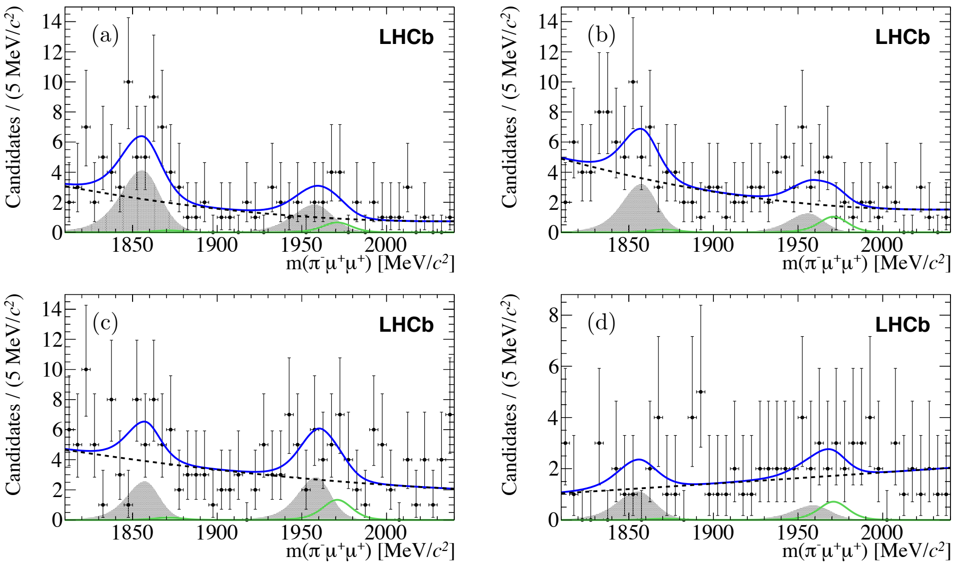

Figure 6: Invariant mass distributions for $\pi^-\mu^+\mu^+$ combinations in regions (a) $250 < m\left(\pi^-\mu^+\right) < 1140\,\mathrm{MeV}/c^2$, (b) $1140 < m\left(\pi^-\mu^+\right) < 1340\,\mathrm{MeV}/c^2$, (c) $1340 < m\left(\pi^-\mu^+\right) < 1540\,\mathrm{MeV}/c^2$, (a) $1540 < m\left(\pi^-\mu^+\right) < 2000\,\mathrm{MeV}/c^2$. The peaking background is shown as solid grey, the non-peaking background as a dashed black line, and the signal as a green line.

of any observed signal peak, because we expect the Majorana neutrino to appear in only one region. The region boundaries are defined as 250, 1140, 1340, 1540, and 2000 MeV/c^2. Invariant mass fits are shown in Fig. 6, where the main peaking backgrounds are misidentified $D^+_{(s)} \to \pi^+\pi^+\pi^-$ decays. No significant signal is observed in any of the $m\left(\pi^-\mu^+\right)$ bins, which allows the determination of 90 (95)% confidence limits on the branching fractions of

$$\mathcal{B}\left(D^+ \to \pi^-\mu^+\mu^+\right) < 2.2\,(2.5) \times 10^{-8},$$
$$\mathcal{B}\left(D^+_s \to \pi^-\mu^+\mu^+\right) < 1.2\,(1.4) \times 10^{-7}.$$

5 Conclusions

The LHCb experiment has recorded some of the world's largest samples of charm hadron decays, allowing the study of charm physics with unprecedented precision. Here we have presented the latest charm results using $1.0\,\mathrm{fb}^{-1}$ of data collected in 2011 at $\sqrt{s} = 7\,\mathrm{TeV}$.

By fitting the time dependent ratio of WS/RS $D \to K\pi$ decays, neutral D meson oscillations are observed for the first time in a single measurement with a significance of 9.1 standard deviations. Comparing the five-dimensional Dalitz space of D^0 and $\overline{D}^0$ decays to $\pi^-\pi^+\pi^-\pi^+$ reveals no evidence of local CP asymmetries. We find no evidence of the rare decays $D^+_{(s)} \to \pi^+\mu^+\mu^-$ and significantly improve the upper limits of their branching fractions. In addition, a search for the LNV processes $D^+_{(s)} \to \pi^-\mu^+\mu^+$ is performed. The data are found to be consistent with the background-only hypothesis which leads to an improvement on the upper limits of the branching fractions by a factor of ~ 100.

References

1. R. Aaij *et al.* (LHCb Collaboration), "The LHCb detector at the LHC", JINST **3**, S08005 (2008).
2. R. Aaij *et al.* (LHCb Collaboration), "Prompt charm production in *pp* collisions at $\sqrt{s} = 7$ TeV", *Nucl. Phys.* **B871**, 1-20 (2013).

3. R. Aaij *et al.* (LHCb Collaboration), "Measurement of $\sigma\left(pp \to b\bar{b}X\right)$ at $\sqrt{s} = 7$ TeV", *Phys. Lett.* **B694**, 209-216 (2010).
4. R. Aaij *et al.* (LHCb Collaboration), "Observation of D^0–$\overline{D}^0$ oscillations", *Phys. Rev. Lett.* **110**, 101802 (2013).
5. Heavy Flavour Averaging Group, "D mixing results allowing for CPV", 2012, www.slac.stanford.edu/xorg/hfag/charm/March12/results_mix+cpv.html
6. Y. Grossman, A. L. Kagan, and Y. Nir, "New physics and CP violation in singly Cabibbo suppressed D decays", *Phys. Rev.* **D75**, 036008 (2007).
7. R. Aaij *et al.* (LHCb Collaboration), "Search for CP violation in $D^0 \to \pi^-\pi^+\pi-\pi^+$ decays", LHCb-CONF-2012-019.
8. I. Bediaga *et al.*, "On a CP anisotropy measurement in the Dalitz plot", *Phys. Rev.* **D80**, 096006 (2009).
9. K. Abe *et al.* (Belle Collaboration), "Observation of the decay $B \to Kl^+l^-$", Phys. Rev. Lett. **88**, 021801 (2002).
10. H. Park *et al.* (HyperCP Collaboration), "Observation of the decay $K^- \to \pi^-\mu^+\mu^-$ and measurements of the branching ratios for $K^\pm \to \pi^\pm\mu^+\mu^-$", Phys. Rev. Lett. **88**, 021801 (2002).
11. S. Fajfer, S. Prelovsek, and P. Singer, "Rare charm meson decays $D \to Pl^+l^-$ and $c \to ul^+l^-$ in SM and MSSM", Phys. Rev. **D64**, 114009 (2001).
12. S. Fajfer, N. Kosnik, and S. Prelovsek, "Updated constraints on new physics in rare charm decays", Phys. Rev. **D76**, 074010 (2007).
13. A. Paul, I. I. Bigi, and S. Recksiegel, "On $D \to X_u l^+l^-$ within the Standard Model and frameworks like the littlest Higgs model with T parity", Phys. Rev. **D83**, 114006 (2011).
14. R. Aaij *et al.* (LHCb Collaboration), "Search for $D^+_{(s)} \to \pi^+\mu^+\mu^-$ and $D^+_{(s)} \to \pi^-\mu^+\mu^+$", arXiv:1304.6365v1.
15. V. Abazov *et al.* (D0 Collaboration), "Search for flavour-changing-neutral-current D meson decays", Phys. Rev. Lett. **100**, 101801 (2008)
16. J. Link *et al.* (FOCUS Collaboration), "Search for rare and forbidden three body dimuon decays of the charmed mesons D^+ and D^+_s, Phys. Lett. **B572**, 21 (2003)
17. E. Majorana, "Teoria simmetrica dellelettrone e del positrone", Nuovo Cim. **14**, 171 (1937)
18. J. Lees *et al.* (BaBar Collaboration), "Searches for rare or forbidden semileptonic charm decays", Phys. Rev. **D84**, 072006 (2011)