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Searches for rare charm decays at LHCb

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Prompted by hints of deviations from the Standard Model in the beauty sector, the interest on charm hadron rare decays is growing, with LHCb playing a major role. We present results on $D^0 \to hh\mu\mu$, $D^0 \to e\mu$, charmonium decays and discuss the LHCb potential for the next decade.

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1. Introduction

Rare decays of charmed hadrons comprises a wide variety of physics topics that range from completely forbidden to relatively frequent radiative transitions. In particular, this paper will concentrate on Flavour Changing Neutral Currents (FCNC) and Lepton Flavour Number Violation (LFV) mediated decays, for which the LHCb experiment is particularly well suited. FCNC processes of the type $D^0 \to h^+h^-\mu^+\mu^-$ can only occur at loop level in the Standard Model (SM) and are highly suppressed via the Glashow-Iliopoulos-Maiani (GIM) mechanism, which is particularly effective for $c \to u$ transitions. The branching fraction of these decays is dominated by Long Distance (LD) contributions, with the two muons originating from a vector resonance such as ρ/ω and ϕ, and usually yield branching fractions of $\mathcal{O}(10^{-6})$. On the other hand Short Distance (SD) contributions, accessible in the regions away from resonances, are expected to be $\mathcal{O}(10^{-9})$ or below [1] in the Standard Model(SM). The SD contribution is accessible in regions free from dimuon resonances and is potentially extremely sensitive to contributions from physics beyond the SM (BSM). In addition, in certain SM extensions CP and forward-backward asymmetries in multibody rare charm decays can be expected at the level of a few percent (depending on the decay mode) [1, 2]. The only known process that could result in LFV decays involves neutrino flavour oscillation, as a consequence these decays are extremely suppressed, well beyond any experimental sensitivity. However, these are predicted to occur at a sizeable level in R-parity violating MSSM models [3, 4]. Another area of interest is the study of charmonium decays which are proven to be a remarkable laboratory for gathering information on quantum chromodynamics in the non-perturbative regime. Exploiting B decays into final states containing charmonium states, LHCb is an excellent environment to investigate the properties of these states.

It is finally emphasised the complementarity of of charm hadrons which are the only bound systems where an up-type quarks can be investigated similarly to what is done for down-type quarks in beauty and strange sectors.

2. Search for the rare decay $D^0 \to \pi^+\pi^-\mu^+\mu^-$

LHCb searched for the $D^0 \to \pi^+\pi^-\mu^+\mu^-$ decay using $1\,\text{fb}^{-1}$ of pp collision data collected at $\sqrt{s} = 7\,\text{TeV}$ [5]. The analysis strategy is based on reconstructing $D^{*\pm} \to D^0\pi^\pm$ to suppress combinatorial background and the normalisation is done with respect to the LD decay channel $D^0 \to \pi^+\pi^-\phi(\to \mu^+\mu^-)$. The D^0 candidates mass distributions in four dimuon mass bins are shown in Figure 1. A limit for the SD contribution (assuming a phase-space like decay) was set at 5.5×10^{-7} at 90% CL which is the current world's best limit and a factor of about 50 better than previous searches, which is a statement of the huge potential for these studies in LHCb. One of the main limitations to the result is the branching fraction for the normalisation that had to be derived from an amplitude analysis of $D^0 \to K^+K^-\pi^+\pi^-$ performed by the CLEO collaboration [6]. This resulted in a large systematic uncertainty of about $\sim 20\%$. In order to overcome this issue for future updates of this measurement, some time has been invested in finding a better normalisation, as described in the next section.

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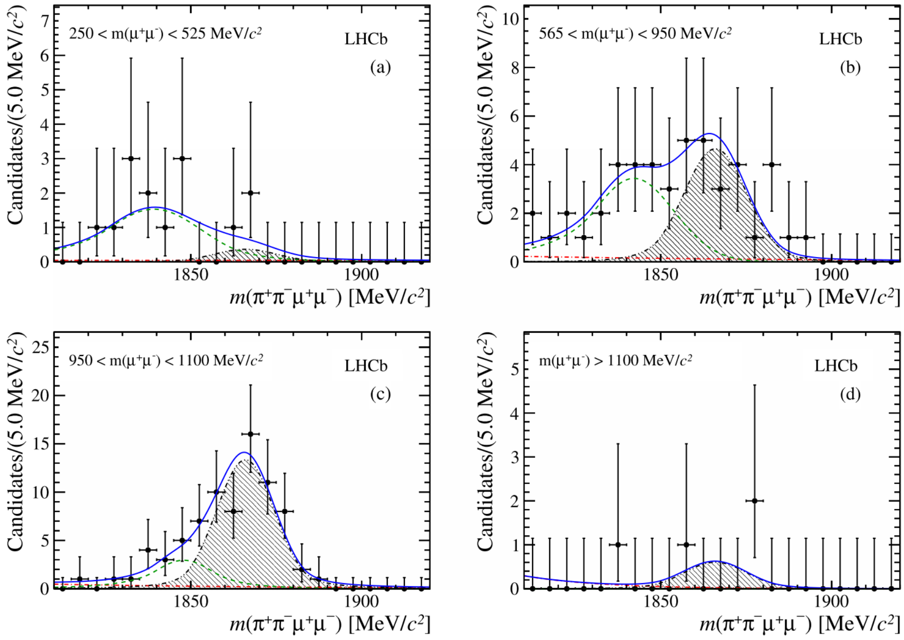

Figure 1: Distributions of $m(\pi^+\pi^-\mu^+\mu^-)$ candidates in the (a) $[250, 525]$ MeV, (b) $[525, 950]$ MeV (corresponding to the ρ/ω), (c) $[950, 1100]$ MeV (corresponding to the ϕ), and (d) high dimuon mass regions. All spectra correspond to mass difference between the $D^{*\pm}$ and the D^0 candidate in the range $[144.4, 146.6]$ MeV. The data are shown as points (black) and the fit result (dark blue line) is overlaid. The components of the fit are also shown: the signal (filled area), the $D^0 \to \pi^+\pi^-\pi^+\pi^-$ background (green dashed line) and the non-peaking background (red dashed-dotted line).

3. First observation of the decay $D^0 \to \pi^+K^-\mu^+\mu^-$ in the ρ^0/ω region

At first order the $D^0 \to \pi^+K^-\mu^+\mu^-$ decay does not need to proceed through a FCNC process and therefore its sensitivity BSM physics is limited. On the other hand, this final state has a relatively high branching fraction (LD-dominated) which makes it an ideal normalisation and control mode for other four-body rare decays. LHCb measured the $D^0 \to \pi^+K^-\mu^+\mu^-$ branching fraction with the dimuon pair in the ρ^0/ω mass region using $D^0 \to \pi^+K^-\pi^+\pi^-$ as normalisation channel. The measurement has been performed using untagged D^0 decays collected in 2012 at $\sqrt{s} = 8\,\text{TeV}$ ($2\,\text{fb}^{-1}$) [7]. The mass distribution for signal and normalisation modes are shown in Figure 2. The branching fraction is measured to be $(4.12 \pm 0.12 \pm 0.38) \times 10^{-6}$ where the first uncertainty is statistical and the second one systematic. This result are in agreement with theoretical predictions [1] and will be used to normalise all rare four body modes in future LHCb measurements. A first investigation of the $m(K\pi)$ and $m(\mu\mu)$ spectra is shown in Figure 3. Although these distributions are sculpted by kinematic cuts, the presence of resonances can be clearly inferred.

4. Search for the $D^0 \to e^\pm\mu^\mp$ decay

The potential observation of the LVF decay $D^0 \to e\mu$ would be a clear sign of NP. Up until 2016, the best limit was set by the Belle collaboration at 2.6×10^{-7} at 90% CL [8]. LHCb recently searched for this decay using the full Run I dataset of $3\,\text{fb}^{-1}$ [9]. The analysis exploits tagged D^0

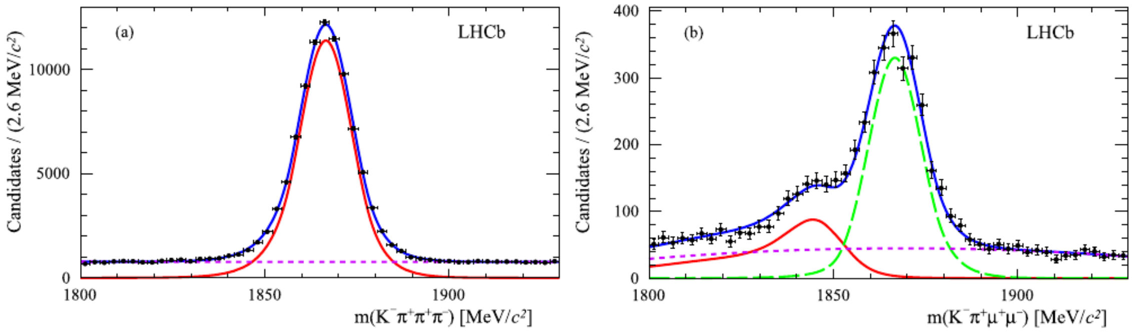

Figure 2: Invariant mass spectra for selected D^0 candidates in (a) the normalisation channel and (b) the signal channel. The $\pi^+K^-\mu^+\mu^-$ component is shown in dashed green, the $\pi^+K^-\pi^+\pi^-$ in solid red and the combinatorial background in dotted magenta.

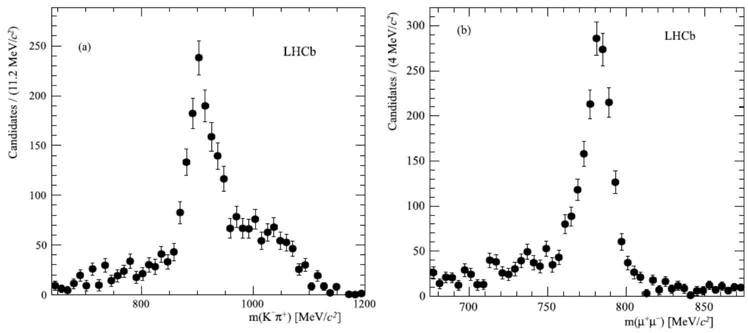

Figure 3: Background subtracted invariant mass of the (a) πK system and (b) dimuon system for selected $D^0 \to \pi^+K^-\mu^+\mu^-$ candidates.

mesons from the decay $D^{*\pm} \to D^0\pi^\pm$ with $D^0 \to K^-\pi^+$ used as normalisation channel. The main systematics in this analysis is attributed to the bremsstrahlung radiation from the electron, which makes the discrimination against the peaking $D^0 \to \pi^+\pi^-$ challenging, as shown in Figure 4. The

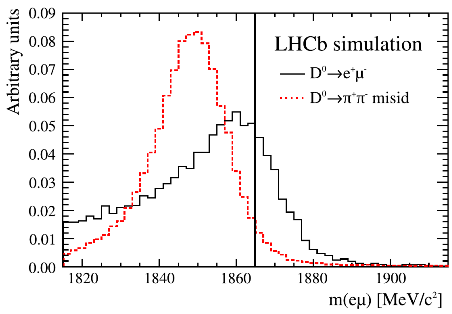

Figure 4: Simulated invariant mass spectra for $D^0 \to e\mu$ and $D^0 \to \pi^+\pi^-$ under the e,μ mass hypothesis for the two final state particles.

two-dimensional fit to the $m(e\mu)$ distribution is shown in Figure 5. The fitted yields for signal and backgrounds components translate into a limit of 1.3×10^{-8} at 90% CL which is the currently the best upper limit on this branching fraction.

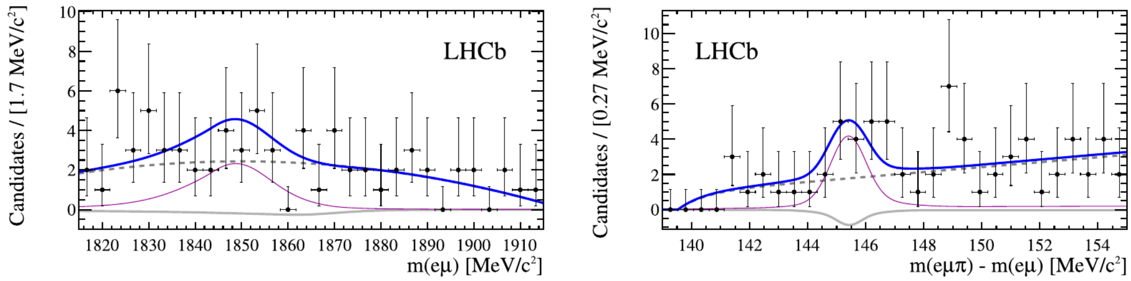

Figure 5: Distribution of (a) $m(e\mu)$ and (b) $m(e\mu\pi) - m(e\mu)$ with the result of the two dimensional fit superimposed. The components of the fit are also shown: the signal (thick grey line), the $D^0 \to \pi^+\pi^-$ background (thin magenta line) and the combinatorial background (dark grey dashed line).

5. Observation of $\eta_c(2S) \to p\bar{p}$ and search for the $X(3872) \to p\bar{p}$ decays

Using the full Run I dataset, a search for decays of charmonium states into a $p\bar{p}$ pair [10] was performed by LHCb. The analysis is based on the study of contributions to the $p\bar{p}$ spectrum in $B^\pm \to p\bar{p}K^\pm$ decays, shown in Figure 6. The first observation of the decay $\eta_c(2S) \to p\bar{p}$ is reported with a significance of about 6σ while no evidence is found for other charmonium states decaying into the same final state.

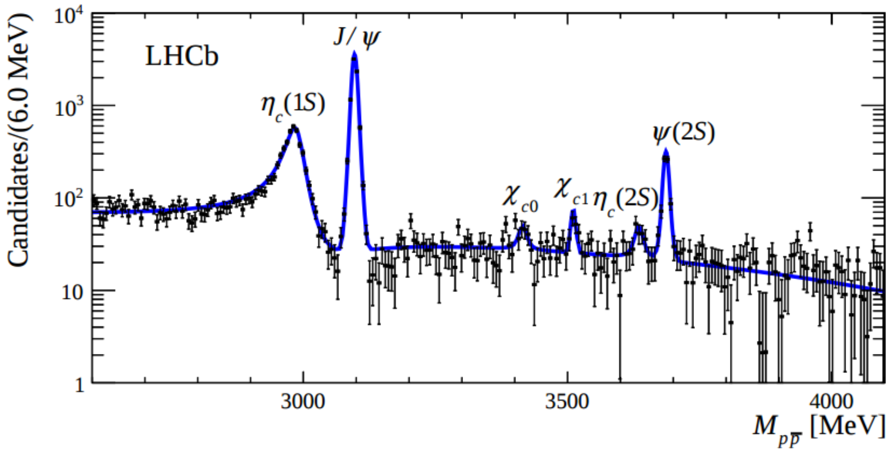

Figure 6: Distribution of $m(p\bar{p})$ in selected $B^\pm \to p\bar{p}K^\pm$ candidates.

6. Conclusions and prospects

A collection of results on charm hadrons rare decays is presented. Thanks to the large charm cross section at the LHCb [11, 12] unprecedented charm yields could be collected at LHCb, a golden mine for rare decay searches. All measurements in this area performed at LHCb generally improve over the previous results, even by orders of magnitude. In particular, first observations of a decays with two muons in the final state were performed for the first time both in three- and four body final states. In the next decade, thanks to an ambitious LHCb upgrade plan, the charm datasets recorded will grow by two orders of magnitude and therefore the SM SD contribution for these channels could be potentially be probed. More interestingly, *CP* and forward backward asymmetries measurements will also be investigated at the percent level (tens of percent in by the end of 2017), allowing to confirm or exclude new physics scenarios.

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