PROCEEDINGS OF SCIENCE

Rare charm and strange decays at LHCb

Francesco Dettori[*]

[a] *Università degli Studi di Cagliari and INFN Cagliari,*
Cittadella Universitaria - S.P. Sestu km 0.700 Monserrato (CA), Italy

E-mail: francesco.dettori@cern.ch

Recent results by the LHCb collaboration in charm and strange-hadrons rare decays are summarised. A short summary of the related discussion at the ICHEP2024 conference is reported.

42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic

[*]Speaker

https://pos.sissa.it/

PoS(ICHEP2024)435

1. Overview of the presented results

Since the discovery of charm quarks with $K^0_L \to \mu^+\mu^-$ decays [1], rare decays have always been an important tool to search for new physics effects. In particular, Flavour Changing Neutral Currents (FCNC) are a tool to probe the symmetries of the Standard Model (SM) and beyond. The LHCb collaboration has a large program of searches in beauty, charm and strange hadron decays. Here the latest results on charm and strange rare decays are briefly summarised and a glimpse of the related discussion at ICHEP2024 is given at the end.

1.1 Search for $D^0 \to \mu^+\mu^-$ decays

The $D^0 \to \mu^+\mu^-$ decay is a very rare FCNC, additionally suppressed by helicity. In the SM this would have a short-distance branching fraction in the 10^{-18} order, however, its amplitude is dominated by long-distance contributions from $D^0 \to \gamma\gamma$, resulting in a branching fraction of $\mathcal{B}(D^0 \to \mu^+\mu^-) \simeq 2.7 \cdot 10^{-5} \cdot \mathcal{B}(D^0 \to \gamma\gamma)$. Using the experimental limit on the two-photon decay [12, 13] this results in $\mathcal{B}(D^0 \to \mu^+\mu^-) \lesssim 2.3 \cdot 10^{-11}$. Hence, any branching fraction measurement in excess of this order of magnitude would be a unequivocal sign of new physics contributions. In fact this decay leads to the most-stringent constraints on pseudoscalar, scalar and axial vector contributions in the $c\bar{u}\mu\bar{\mu}$ four-fermion coupling. In particular, many new physics models that allow to explain the so-called “b-anomalies” in the b-quark sector [19], would predict large (up to tree-level) contributions in the charm quark sector. This makes $D^0 \to \mu^+\mu^-$ decays branching fraction constraints pre-requisites for model-building [2].

The latest measurement by the LHCb experiment uses the full Run 1 and 2 data sample [2], with a total integrated luminosity of 9 fb^{-1} of pp collision data at 7, 8 and 13 TeV. The search is performed using D^0 from $D^{*+} \to D^0\pi^+$ decays to reject a large fraction of the background. Run 2 conditions are considerably harsher in terms of multiplicity and thus combinatorial background with respect to Run 1. Therefore, compared to the first LHCb measurement [10] better multivariate methods against both combinatorial and misidentified background are employed. After full selection the residual background is mostly combinatorial and due to the misidentified $D^{*+} \to D^0(\to \pi^+\pi^-)\pi^+$: a component of irreducible $\pi \to \mu$ decays in flight needs to be taken into account, but could be rejected with improved particle identification in future analyses. This residual background is precisely calibrated and constrained with control channels. The signal is normalised both to $D^0 \to \pi^+\pi^-$ and $D^0 \to K^-\pi^+$ decays, such that a check on the ratio of the normalisation channels branching fractions can be performed, and is consistent with PDG average.

A simultaneous two-dimensional unbinned fit is performed to search for the signal, in the dimuon invariant mass and in the $\Delta m = m(\pi\mu\mu) - m(\mu\mu)$ variable. Six search regions are used, employing three intervals of the multivariate operator’s output, and analysing the two Runs in parallel. No evidence for an excess of events above the background expectation is seen, thus an upper limit of $\mathcal{B}(D^0 \to \mu^+\mu^-) < 3.1(3.5) \times 10^{-9}$ at 90% (95%) CL is set, which is the most stringent published result on this channel.

During this conference, a new search for this decay has been presented by the CMS collaboration, improving this limit [11] by 35%. Additional searches are very welcome on this channel, as it keeps being the cornerstone of constraints on new physics models for what concerns up-sector FCNCs.

1.2 Search for $D^{*0}(2007) \to \mu^+\mu^-$ decays

The $D^{*0}(2007) \to \mu^+\mu^-$ decay is very similar to $D^0 \to \mu^+\mu^-$, with the exception of the spin of the initial meson. This removes the helicity suppression in the decay, making it sensitive to vector couplings rather than axial-vector ones. However, given that the D^* (here and in the following D^* represents the $D^{*0}(2007)$), can decay via strong and electromagnetic interactions, the branching fraction of any weak decay will be very suppressed. The SM branching fraction for $D^{*0}(2007) \to \mu^+\mu^-$ decays is tiny, at the 10^{-19} level [7], however its experimental value is unconstrained. A limit on the corresponding electron channel at $\mathcal{B}(D^* \to e^+e^-) < 1.7 \times 10^{-6}$ [9] has been set by the CMD-3 collaboration, but no limit on the muonic channel is present.

The presented search at LHCb [3] is based on data corresponding to 9fb^{-1} of integrated luminosity, as for the $D^0 \to \mu^+\mu^-$ analysis. The search is performed with the method outlined in Ref. [8], i.e. searching for the cascade $B^+ \to D^*(\to \mu^+\mu^-)\pi$ decays. In practice the signature would correspond to a D^* peak in the dimuon invariant mass of $B^+ \to \pi^+\mu^-\mu^+$ decays. The decay branching fraction is normalised to $B^+ \to J/\psi K^+$ decays, where the J/ψ decays into muons.

After a standard selection and a multivariate selection, the main background left is combinatorial. In addition, non-resonant $B^+ \to \pi^+\mu^-\mu^+$ decays are present. The $B^+ \to D^*(\to \mu^+\mu^-)\pi^+$ signal yield is obtained from a two-dimensional unbinned fit to the dimuon invariant mass and the $\pi^+\mu^+\mu^-$ invariant mass . A yield consistent with zero is measured, consequently an upper limit on the signal branching fraction is set at $\mathcal{B}(D^{*0}(2007) \to \mu^+\mu^-) < 2.6(3.4) \times 10^{-8}$ at 90 (95)% CL, which is the world first result on this channel.

1.3 Search for $\Lambda_c^+ \to p\mu^+\mu^-$ decays

The non-resonant $\Lambda_c^+ \to p\mu^+\mu^-$ decays are very rare in the SM, with a predicted branching fraction around 10^{-8} for short-distance contributions, enhanced up to 10^{-6} from long-distance contributions due to intermediate vector resonances [12, 13]. In particular, $\Lambda_c^+ \to pV$ with $V = \phi, \rho, \eta$ and ω, decaying to two muons, can contribute. The analysis presented here [4] therefore divides the dimuon invariant mass in 6 regions, of which only the low invariant mass one (below $m_{\mu\mu} < 507.86$ MeV/c^2) and the high-mass one ($m_{\mu\mu} > 1059.46$ MeV/c^2) are used to search for the non-resonant $\Lambda_c^+ \to p\mu^+\mu^-$ decay. This analysis uses pp collision data at 13 TeV corresponding to 5.4fb^{-1} of integrated luminosity acquired in Run 2. As often for rare decays, a standard selection plus a multivariate classifier are employed to reject most of the background. After that, the residual background is mostly combinatorial plus a small irreducible component due to misidentified $\Lambda_c^+ \to p\pi^+\pi^-$ decays.

The search is then performed through an unbinned fit to the $p\mu^+\mu^-$ in regions of the dimuon invariant mass . No amplitude analysis is performed, hence interferences between resonances or with the non-resonant part are not considered. Significant signals are obtained in the ρ, ω and ϕ regions. An evidence (significance of 3σ) is also obtained in the η region. The corresponding branching fractions are determined to be

$$\mathcal{B}(\Lambda_c^+ \to p\omega) = (9.82 \pm 1.23\ (\text{stat.}) \pm 0.73\ (\text{syst.}) \pm 2.79\ (\text{ext.})) \times 10^{-4},$$

$$\mathcal{B}(\Lambda_c^+ \to p\rho) = (1.52 \pm 0.34\ (\text{stat.}) \pm 0.14\ (\text{syst.}) \pm 0.24\ (\text{ext.})) \times 10^{-3},$$

$$\mathcal{B}(\Lambda_c^+ \to p\eta) = (1.67 \pm 0.69\ (\text{stat.}) \pm 0.23\ (\text{syst.}) \pm 0.34\ (\text{ext.})) \times 10^{-3}.$$

No evidence for $\Lambda_c^+ \to p\mu^+\mu^-$ decays is instead obtained in the non-resonant regions, and an upper limit of $\frac{\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-)}{\mathcal{B}(\Lambda_c^+ \to p\phi)\mathcal{B}(\phi\to\mu^+\mu^-)} < 0.09\ (0.10)$ at 90% (95%) CL is obtained for a non-resonant $\Lambda_c^+ \to p\mu^+\mu^-$ extrapolated to the full dimuon invariant mass with a phase space model. This, using the values of the branching fractions for $\Lambda_c^+ \to p\phi$ and $\phi \to \mu^+\mu^-$ decays from PDG, corresponds to $\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 2.9\ (3.2) \times 10^{-8}$ at 90% (95%) CL which is the most stringent to date.

1.4 First observation of $\Sigma^+ \to p\mu^+\mu^-$ decays

The LHCb collaboration has also an expanding program of rare strange-hadrons decays. The $\Sigma^+ \to p\mu^+\mu^-$ is a very rare FCNC: contrary to the $\Lambda_c^+ \to p\mu^+\mu^-$ just described, there cannot be resonances in the $\Sigma^+ \to p\mu^+\mu^-$ due to the small dimuon invariant mass , hence this decay has only non-resonant (rare) contributions. In particular, the short-distance SM prediction for its branching fraction is around 10^{-12}, while the long-distance one, dominating the decay, leads to a branching fraction of $1.2 \cdot 10^{-8} < \mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) < 10.2 \cdot 10^{-8}$ [14, 15, 18]. This decay gained attention when the HyperCP experiment saw an evidence for it with three background-free events [16], for a branching fraction $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \cdot 10^{-8}$. While the integrated branching fraction was compatible with the SM, the dimuon invariant mass of the three events was very similar, rather than distributed along the phase space. This pointed towards a possible $\Sigma^+ \to pX^0(\to \mu\mu)$ decay with X^0 being a particle beyond the SM, with a mass $m_X^0 = 214.3 \pm 0.5$ MeV/c^2. Many new physics explanations were proposed for this possible particle and searches were conducted in different final states including a dimuon pair. While no other evidence was found, before LHCb no other experiment could search for $\Sigma^+ \to p\mu^+\mu^-$ decays. At LHC pp collision energies naturally a large production of hyperons is present, with about one per every minimum bias collision. The long hyperon lifetime, while reducing considerably the prompt background, together with the small p_t reduces also the efficiency considerably. A search for $\Sigma^+ \to p\mu^+\mu^-$ decays was performed already with Run 1 data [5], which produced an evidence for this decay with about ten events and a branching fraction compatible with the SM. No structure in the dimuon invariant mass was seen excluding the central value of the HyperCP branching fraction under the X^0 hypothesis.

With Run 2 data, a significantly improved trigger with dedicated lines for soft dimuons and rare strange decays was deployed [17], bringing a factor 10 larger trigger efficiency. Adding to the increased cross-section and integrated luminosity this brings almost two orders of magnitude of improvement. The Run 2 analysis [6] is based on 5.4fb^{-1} of pp collisions at 13 TeV. The search is based on a standard selection and a multivariate classifier to reject most of the combinatorial background, which is the main background source. A second background is due to $\Lambda \to p\pi^-$ decays where the pion is misidentified as a muon, and the pair is associated with an unrelated muon. This background is rejected through a veto on the $p\mu^-$ invariant mass in the $p\pi^-$ hypothesis around the Λ known mass, and stringent particle identification criteria. No other background is present, due to the tight phase space and small mass of the Σ^+ hyperon. As an example the $\Sigma^+ \to p\pi^+\pi^-$ decay is kinematically forbidden.

The signal yield is obtained, after full selection, with an unbinned fit to the $p\mu^+\mu^-$ invariant mass . A clear peak is observed with very large significance and $N(\Sigma^+ \to p\mu^+\mu^-) = 279 \pm 19$ signal events are found. This constitutes the first observation of this channel, which is the rarest hyperon and possibly the rarest baryon decay ever observed. The dimuon invariant mass distribution is also examined: no evidence of any structure is present and the distribution is found very compatible with the SM prediction. An article is in preparation where the signal yield will be also normalised to $\Sigma^+ \to p\pi^0$ decays in order to measure its branching fraction. Beyond the integrated and differential rate, this signal yield will allow for a measurement of the violation of Charge-Parity symmetry and possibly of other observables such as the forward-backward asymmetry.

2. Discussion and outlook

There was some discussion at the conference, around the physics interest on the $D^{*0}(2007) \to \mu^+\mu^-$ decay. It was pointed out, that given the large amplitude of the strong and electromagnetic decays of the D^*, any other decay would have an insignificantly low branching fraction, hence invalidating the presented search. This argument seems to miss that what is relevant is the modification of the amplitude, by possible new physics terms, and not the absolute value of the branching fraction, which is scaled by the large intrinsic width of the D^*. Clearly measuring the $D^{*0}(2007) \to \mu^+\mu^-$ branching fraction, especially at the SM level, will be challenging, as many rare decay searches are, however assuming to reach that experimental sensitivity, the physics interest does not depend on the branching fraction per se, but on its modification w.r.t the SM prediction. Furthermore, assuming a branching fraction enhanced by NP, the experimental observation would be very clean, with a dimuon peak in an already background-free B decay, and an easy normalisation to a decay with the same signature ($B^+ \to J/\psi K^+$). In any case, the interplay between several rare charm decays with complementary couplings could corner also small new physics signals, in the same way as current sensitivity on B FCNC is cornering the different couplings involved in the "b-anomalies".

All the mentioned rare decays measurements presented here are limited mostly by statistical uncertainties, hence the data currently being acquired with the LHCb upgraded detector in Run 3 will allow to improve all these searches and measurements, particularly thanks to the improved trigger. The removal of the hardware trigger, which was limiting the efficiency of the charm and strange physics programs, opens room for large improvements.

References

[1] S. L. Glashow, J. Iliopoulos and L. Maiani, Phys. Rev. D **2** (1970), 1285-1292 doi:10.1103/PhysRevD.2.1285

[2] LHCb Collaboration, R. Aaij *et al.*, *Search for Rare Decays of D0 Mesons into Two Muons*, Phys. Rev. Lett. **131** (2023) no.4, 041804 doi:10.1103/PhysRevLett.131.041804 [arXiv:2212.11203 [hep-ex]].

[3] LHCb Collaboration, R. Aaij *et al.*, *Search for* $D^*(2007)^0 \to \mu^+\mu^-$ *in* $B^- \to \pi^-\mu^+\mu^-$ *decays*, Eur. Phys. J. C **83** (2023) no.7, 666 doi:10.1140/epjc/s10052-023-11759-6 [arXiv:2304.01981 [hep-ex]].

[4] LHCb Collaboration, R. Aaij *et al.*, *Search for the rare* $\Lambda_c^+ \to p\mu^+\mu^-$ *decay*, [arXiv:2407.11474 [hep-ex]].

[5] LHCb Collaboration, R. Aaij *et al.*, *Evidence for the rare decay* $\Sigma^+ \to p\mu^+\mu^-$, Phys. Rev. Lett. **120** (2018) no.22, 221803 doi:10.1103/PhysRevLett.120.221803 [arXiv:1712.08606 [hep-ex]].

[6] LHCb Collaboration, R. Aaij *et al.*, *Observation of the* $\Sigma^+ \to p\mu^+\mu^-$ *rare decay at LHCb*, LHCb-CONF-2024-002.

[7] A. Khodjamirian, T. Mannel and A. A. Petrov, *Direct probes of flavor-changing neutral currents in* e^+ e^-*-collisions*, JHEP **11** (2015), 142 doi:10.1007/JHEP11(2015)142 [arXiv:1509.07123 [hep-ph]].

[8] F. Abudinén, T. Blake, U. Egede and T. Gershon, *Prospects for studies of* $D^{*0} \to \mu^+\mu^-$ *and* $B^{*0}_{(s)} \to \mu^+\mu^-$ *decays*, Eur. Phys. J. C **82** (2022) no.5, 459 doi:10.1140/epjc/s10052-022-10369-y [arXiv:2202.03916 [hep-ex]].

[9] D. N. Shemyakin [CMD-3], *Search for the Process* $e^+e^- \to D^*(2007)^0$ *with the CMD-3 Detector*, Phys. Atom. Nucl. **83** (2020) no.6, 954-957 doi:10.1134/S1063778820060277

[10] R. Aaij *et al.* [LHCb], *Search for the rare decay* $D^0 \to \mu^+\mu^-$, Phys. Lett. B **725** (2013), 15-24 doi:10.1016/j.physletb.2013.06.037 [arXiv:1305.5059 [hep-ex]].

[11] CMS Collaboration, *Search for Rare Charm Decays Into Two Muons*, CMS-PAS-BPH-23-008.

[12] S. Fajfer, S. Prelovsek and P. Singer, *Rare charm meson decays D —> P lepton+ lepton- and c —> u lepton+ lepton- in SM and MSSM*, Phys. Rev. D **64** (2001), 114009 doi:10.1103/PhysRevD.64.114009 [arXiv:hep-ph/0106333 [hep-ph]].

[13] G. Burdman, E. Golowich, J. L. Hewett and S. Pakvasa, *Rare charm decays in the standard model and beyond*, Phys. Rev. D **66** (2002), 014009 doi:10.1103/PhysRevD.66.014009 [arXiv:hep-ph/0112235 [hep-ph]].

[14] X. G. He, J. Tandean and G. Valencia, *The Decay Sigma+ —> p l+ l- within the standard model*, Phys. Rev. D **72** (2005), 074003 doi:10.1103/PhysRevD.72.074003 [arXiv:hep-ph/0506067 [hep-ph]].

[15] X. G. He, J. Tandean and G. Valencia, *Decay rate and asymmetries of* $\Sigma^+ \to p\mu^+\mu^-$, JHEP **10** (2018), 040 doi:10.1007/JHEP10(2018)040 [arXiv:1806.08350 [hep-ph]].

[16] H. Park *et al.* [HyperCP], *Evidence for the decay Sigma+ —> p mu+ mu-*, Phys. Rev. Lett. **94** (2005), 021801 doi:10.1103/PhysRevLett.94.021801 [arXiv:hep-ex/0501014 [hep-ex]].

[17] F. Dettori, D. Martinez Santos and J. Prisciandaro, *Low-*p_T *dimuon triggers at LHCb in Run 2*, LHCb-PUB-2017-023.

[18] A. Roy, J. Tandean and G. Valencia, *The decays* $\Sigma^+ \to p\ell^+\ell^-$ *within the standard model and beyond*, [arXiv:2404.15268 [hep-ph]].

[19] T. Hurth, F. Mahmoudi and S. Neshatpour, Phys. Rev. D **108** (2023) no.11, 115037 doi:10.1103/PhysRevD.108.115037 [arXiv:2310.05585 [hep-ph]].