Strange decays at the LHC

Letter of interest for SnowMass 2021

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1 Motivation

The study of strange-hadron decays has fuelled discoveries in particle physics for the past seventy years. For instance, experimental anomalies in the strange sector motivated the prediction of the charm quark via the Glashow-Iliopoulos-Maiani (GIM) mechanism. The discovery of CP-symmetry violation prompted the postulation of the beauty and top quarks within the Cabibbo-Kobayashi-Maskawa (CKM) description; all now key ingredients of the Standard Model (SM). Presently, strange-hadrons decays are valuable probes in the search for dynamics Beyond the Standard Model (BSM), particularly in searches for sources of quark flavour violation beyond the CKM matrix. Since $s \to d$ transitions have the strongest suppression factor, they can typically probe energy scales higher than those accessible in charm or beauty-hadron decays for couplings of comparable size [1], and well above those directly attainable for direct production of new particles. Nevertheless, flavour physics experiments have greatly enhanced such knowledge from charm and beauty decays in recent years, while few measurements of strange-hadron decays have been updated or performed for the first time. The LHCb experiment has the capacity, both in terms of detector performance and statistics, to produce leading measurements exploiting almost all strange-hadron species, particularly in the search for their rare decays.

2 Existing LHCb results

The LHCb collaboration has provided so far world leading results in two rare strange decays: $K^0_S \to \mu^+\mu^-$ and $\Sigma^+ \to p\mu^+\mu^-$. Both channels are flavour changing neutral currents and highly suppressed in the SM. The SM prediction of $K^0_S \to \mu^+\mu^-$ is $\mathcal{B}(K^0_S \to$

$\mu^+\mu^-) = (5.18 \pm 1.50_{\text{LD}} \pm 0.02_{\text{SD}}) \times 10^{-12}$ [2,3], where the first uncertainty comes from long-distance (LD) contributions, while the second from short-distance ones (SD). The $K^0_S \to \mu^+\mu^-$ decay is sensitive to contributions from the Minimal Supersymmetric SM (MSSM) particles [4] or leptoquarks (LQ) [5,6]. LHCb has searched for this signal and found no evidence so far, setting an upper limit on the branching fraction:

$$\mathcal{B}(K^0_S \to \mu^+\mu^-) < 2.1 \times 10^{-10}\,, \tag{1}$$

at 90% confidence level (CL) [7], which excludes part of the MSSM and LQ parameter space that was previously allowed. This result uses the full existing datasets.

A predicted branching fraction of the $\Sigma^+ \to p\mu^+\mu^-$ decay is $1.2 \times 10^{-8} < \mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) < 10.2 \times 10^{-8}$ [8,9], dominated by LD contributions. This decay gained attention when the HyperCP collaboration published an evidence for it [10], with a hint of a structure in the dimuon invariant-mass distribution. This decay has been searched at LHCb with the full Run 1 statistics [11]. A strong evidence for this decay has been seen, with a 4.1σ significance. The fitted signal branching fraction is

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (2.2\,^{+\,1.8}_{-\,1.3}) \times 10^{-8}\,, \tag{2}$$

which is consistent with the SM prediction. An explicit search for a putative X^0 new particle in the dimuon mass found no significant signal and an upper limit on the branching fraction of the resonant decay was set at

$$\mathcal{B}(\Sigma^+ \to pX^0(\to \mu^+\mu^-)) < 1.4 \times 10^{-8}\ (1.7 \times 10^{-8})\,, \tag{3}$$

at 90% (95%) CL. This excludes the central value of the HyperCP result in the X^0 hypothesis reported above, although not the full range yet given the large uncertainties.

3 LHCb potential

The LHCb experiment will re-start operation in 2021 with an upgraded detector and trigger. The efficiency for strange decays into dimuons is expected to increase about one order of magnitude compared to Run 2 [12,13], and hence nearly two orders of magnitude compared to Run 1 data. This will boost the sensitivity for rare decays such as $K^0_S \to \mu^+\mu^-$, $\Sigma^+ \to p\mu^+\mu^-$, $K^0_S \to \gamma\mu^+\mu^-$, and $K^0_S \to \pi^0\mu^+\mu^-$. LHCb has the potential to become the world leading experiment on K^0_S and hyperon rare decays [14,15]. However LHCb can also provide world best results in other strange decays. This includes semileptonic hyperon decays, dielectron modes, or LFV modes such as $K^+ \to \pi^+ e\mu$ and $K^0_S \to e\mu$. A review of those capabilities can be found in [14]. In addition, LHCb has access to the full spectrum of hyperons, whose decays can be studied in detail, *e.g.*, $\Delta S = 2$ decays. While the acceptance is severely limited in lifetime, with the Run 3 statistics available LHCb will possibly be able to contribute also on the physics of charged kaons and on that of K^0_L mesons, possibly in interference with the K^0_S [3,4], as well as to semimuonic hyperon decays.

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