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Measurements and prospects for K^0_S decays at LHCb

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Rare decays are fundamental probes for physics beyond the Standard Model, and the expanding LHCb programme on strange physics provides unique and complementary information with respect to the beauty and charm sectors. Recent results of rare kaon decays at LHCb are summarized as well as prospects for strange physics with the LHCb Upgrade.

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1. Introduction

Historically, Kaons have been crucial in developing and establishing the Standard Model (SM). Kaon decays are mediated by the $s \to d$ transition, which is a Flavor Changing Neutral Current (FCNC) and it is forbidden at tree level in the SM. It can only proceed at loop level via the creation of an Electro-weak gauge boson. This transition is suppressed due to the size of the CKM matrix elements involved, and the GIM mechanism. However, new particles could contribute to the transition via the loop and enhance the associated rare decays by up to two orders of magnitude [1]. Studying such rare Kaons decays allows us to test the SM, and also to perform indirect searches (appearing in the loop) of new particles probing much higher scales of energies than those achieved at current accelerators.

The LHCb detector [2] is designed as a single-arm forward spectrometer, optimized to study b- and d-decays. In addition to its primary objectives, the LHCb has proven capable of studying K^0_S and other hyperon decays thanks to its baseline, as shown in Fig. 1. Additionally, the LHC

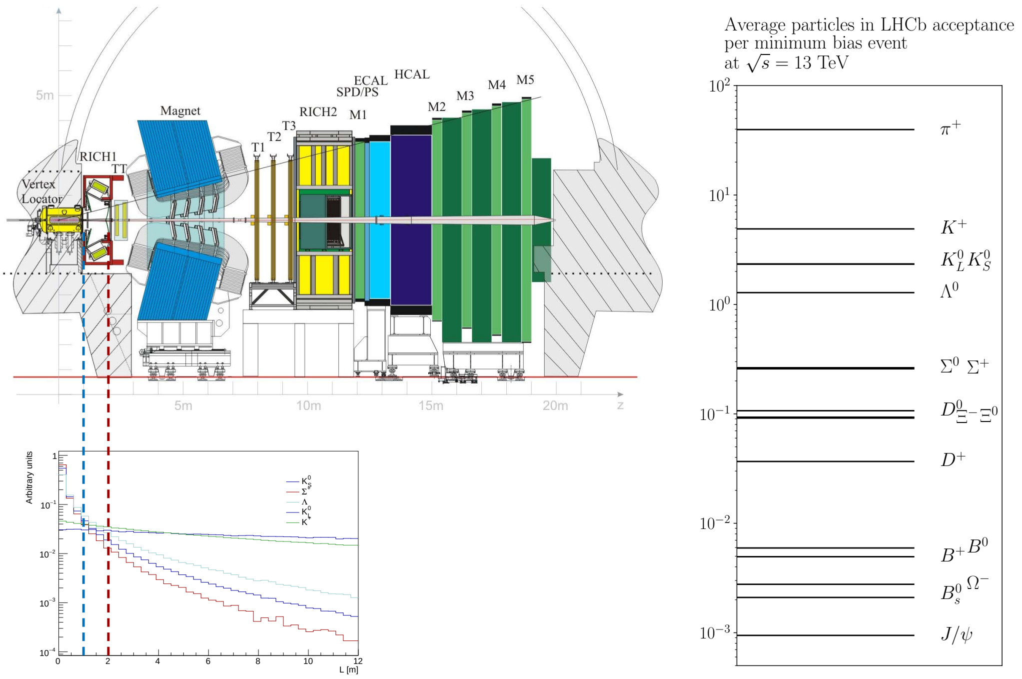

Figure 1: The LHCb detector scheme (left, top), compared to the decay length of strange hadrons produced in pp collisions at $\sqrt{s} = 13$ TeV (left, bottom). Average production multiplicity of different hadrons in the same kind of events (right). The plots are obtained with PYTHIA Monte Carlo simulations, and are from Ref [3].

conditions produce a high rate of strange hadrons, two orders of magnitude higher than for heavy hadrons. On average, one K^0_S meson is produced in each pp collision (for comparison, the B^0 meson production rate is 500 times lower). There are some challenges associated with the study of kaons at LHCb. The standard handle to discriminate signal and background at LHCb is the transverse momentum of the decay products. Due to kaon low mass, their decay products have low $p_T \sim O(100\,\text{MeV}/c)$. However, the naturally longer lifetime of strange hadrons provides them with longer flight distances. This feature is exploited to discriminate strange hadron decays from the background and analogous b-decays. The main bottleneck in kaon selection at LHCb has been its trigger, which selected events with $p_T > O(1\,\mathrm{GeV}/c)$ at hardware level. Additionally, the software level trigger did not consider kaon decays, producing an overall trigger efficiency during Run 1 (2011-2012) of $\varepsilon_{\mathrm{trig}} \sim 1\%$. For Run 2 (2015-2018), the software level triggers were optimized for decay products of kaon decays. This increased the trigger efficiency up to $\varepsilon_{\mathrm{trig}} \sim 18\%$ [4, 5]. Recently, the LHCb underwent a major upgrade, and, particularly, the hardware level trigger was completely removed. The current LHCb Upgrade is taking data with efficiency for kaons decays of $\varepsilon_{\mathrm{trig}} \sim 100\%$ [2]. The LHCb detector has collected $9\,\mathrm{fb}^{-1}$ during its Run 1 and 2. It is foreseen that with the upgraded detector Runs 3 and 4 (2023-2030) this number will reach $50\,\mathrm{fb}^{-1}$. After that, the LHCb will undergo the second phase of its Upgrade, in preparation for the High Luminosity era, when it is expected to collect up to $300\,\mathrm{fb}^{-1}$.

The LHCb collaboration has already published some results on kaons decays. The $K^0_S \to \mu^+\mu^-$ is sensitive to New Physics (NP) through short-distance contributions. However, the uncertainty from the SM prediction is dominated by Long-distance contributions. The interference between $K^0_S \to \mu^+\mu^-$ and $K^0_L \to \mu^+\mu^-$ would help to determine the sign of $\mathcal{A}(K^0_L \to \gamma\gamma)$ and, if NP is found, to distinguish models Beyond the SM (BSM) [6]. The LHCb collaboration recently published an updated $K^0_S \to \mu^+\mu^-$ search exploiting Run 1 and 2 datasets where no signal was found [7]. The stringiest upper limit at to date was set $\mathcal{B}(K^0_S \to \mu^+\mu^-) < 2.2 \times 10^{-10}$ at 90% confidence level (CL). This result is just two orders of magnitude over the SM prediction, meaning that LHCb will start exploring allowed BSM ranges.

A kind of decays with rising interest is kaon decays to four leptons, which rates are expected to be very low in the SM ($\mathcal{B}(K^0_S \to e^+e^-e^+e^-) \sim O(10^{-11})$, $\mathcal{B}(K^0_S \to e^+e^-\mu^+\mu^-) \sim O(10^{-12})$, $\mathcal{B}(K^0_S \to \mu^+\mu^-\mu^+\mu^-) \sim O(10^{-14})$). Any measurement approaching the SM prediction would be a probe for NP. Similarly, as to the $K^0_S \to \mu^+\mu^-$ case, the K^0_S and K^0_L decays are complementary, and their interference could be exploited to derive the sign of $\mathcal{A}(K^0_L \to \gamma\gamma)$ and to distinguish between BSM [8]. The pure muonic decay, $K^0_S \to \mu^+\mu^-\mu^+\mu^-$, has been searched by LHCb using Run 1 and 2 datasets. Thanks to the unique footprint of the decay, a clean sample was obtained, without contributions from the abundant $K^0_S \to \pi^+\pi^-$ physical background. No signal was found, and the upper limit $\mathcal{B}(K^0_S \to \mu^+\mu^-\mu^+\mu^-) < 5.1 \times 10^{-12}$ was set. Additionally, the data was re-analyzed under K^0_L assumption, and the upper limit $\mathcal{B}(K^0_L \to \mu^+\mu^-\mu^+\mu^-) < 2.3 \times 10^{-9}$ was also reported, constituting the fist LHCb results with from K^0_L decays. The prospects for this mode at LHCb are excellent and will allow us to scan most of the allowed range in BSM models and to get close to the SM prediction.

A clean probe to NP is the $K^0_L \to \pi^0\mu^+\mu^-$ decay. However, its SM prediction suffers from high uncertainty ($\mathcal{B}(K^0_L \to \pi^0\mu^+\mu^-) = 1.41^{+0.28}_{-0.26} \times 10^{-11}$ [9]. This prediction and, thus, its interpretation in terms of NP relies on two parameters, a_S and b_S, which can be extracted from $K^0_S \to \pi^0\mu^+\mu^-$ decays. A recent measurement by NA48/2 provides $\mathcal{B}$ ($K^0_S \to \pi^0\mu^+\mu^-$) with 50% which can be used to derive a single parameter, but not both at the same time. Using Vector-Meson Dominance one can relate a_S and b_S to extract $|a_S|$ from the single branching ratio measurement. The LHCb sensitivity the this decay has been studied [10], proving that the precision of the measurement could be improved. Furthermore, the differential branching ratio could be measured, which could be used to derive the a_S model independently, with similar precision to the current one with just Run 3 data [3]. The $K^0_S \to \pi^0\mu^+\mu^-$ analysis can be extended to a more general $K^0_S \to X^0\mu^+\mu^-$ analysis, where X^0 is any neutral particle (vector or scalar) [10]. The K^0_S mass resolution depends on the mass of the neutral particle. Sensitivity studies performed for LHCb [10] prove that even in the most unfavorable case, $K^0_S \to \gamma\mu^+\mu^-$, the resolution is still enough to differentiate the signal peak from the $K^0_S \to \pi^+\pi^-$ background.

Results on other hyperons have also been published by the LHCb collaboration, such as the search for $\Sigma^+ \to p\mu^+\mu^-$. This decay was first studied by the HyperCP collaboration finding a branching ratio of $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \times 10^{-8}$ [11] compatible with the SM prediction. Additionally, all the candidates analyzed shared a $\mu^+\mu^-$ invariant mass close to 214 MeV/c^2, compatible with the existence of a new neutral state. An equivalent analysis was done using Run 1 from LHCb. A branching ratio of $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (2.2^{+1.8}_{-1.3}) \times 10^{-8}$ [12] was measured with 4.1σ of significance, but the $m_{\mu\mu}$ spectrum was compatible with phase-space (*i.e.*, no intermediate state). A new analysis using Run 2 data is currently ongoing and it is expected to provide 10 times more candidates. Such precision will enable a direct CP symmetry test. Furthermore, the measurement can be extended to a differential branching ratio and forward-backward asymmetry with the luminosity and efficiency expected for the LHCb upgrades.

Semileptonic hyperon decays ($B_1 \to B_2\ell\overline{\nu}$) grant access to suppressed helicity contributions [13] and feature relatively high branching fraction ($\mathcal{B} \sim O(10^{-4})$). Currently, the muonic modes are reported with uncertainties ranging from 20% to 100%. Improving these results would be challenging due to the contamination from the physics background in the form of $B_1 \to B_2 h$, which usually features higher branching ratios. Despite the challenge, LHCb expects to achieve world-leading precision on branching ratio measurements of the $\Lambda \to p\mu^-\nu_\mu$, $\Xi^- \to p\mu^-\nu_\mu$ and $\Xi^- \to \Sigma^0\mu^-\nu_\mu$ decays. Lastly, LHCb could also contribute to Lepton Flavor Violation (LFV) tests. While the SM does not contemplate LFV, some models of BSM predict a non-zero rate for $K \to (\pi)\mu e$. No constraints have been set for K^0_S decays. The major contributor up-to-date for charge modes is NA62 setting upper limits of the order $\mathcal{B} < O(10^{-11})$. Assuming optimistic particle identification performance, LHCb should be able to improve the estimates from NA62 and even future HIKE [14].

The LHCb sensitivity to many other Kaon and hyperon decays has been studied, demonstrating that LHCb will be able to provide significant contributions to strange physics in the near future [3].

In summary, the LHCb experiment has proven suitable for the study of rare Kaon and hyperon decays, which are sensitive to NP. With the current Upgrade, the flexibility of the trigger, and the huge strangeness production, the LHCb is ready to provide unprecedented precision on strange physics measurements. A future Upgrade is also foreseen which will provide LHCb datasets big enough to reach SM sensitivities. It should be mentioned that just a few examples have been mentioned in this article, but new ideas may come to exploit the full potential of the data.

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