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Strange physics at LHCb

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Despite being designed primarily for the study of *beauty* and *charm* decays, the LHCb experiment has provided world-leading results on kaon and hyperon physics. In this proceeding, some of the most recent LHCb results on kaon a hyperon decays are reviewed, and the prospects for future measurements with data already collected by LHCb as well as planned future Upgrades are discussed.

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The LHCb experiment [1] at the LHC is optimized primarily for the study of decays of the short-lived *beauty* and *charm* hadrons. In addition to its primary objectives, LHCb has proven to be suitable for strange physics. Studying kaon and hyperon decays at LHCb, however, is challenging for several reasons. At the typical LHC energies, the average K^0_S and hyperons decay length is about one meter, while K^0_L and K^+ are considered stable for LHCb with decay lengths of tens to hundreds of meters (see Figure 1). The transverse momentum (p_T), which is used as a standard handle at the LHC to separate signal from generic proton-proton collisions, is also not effective for strange decays due to the very low p_T of the decay products $O(100\ \mathrm{MeV}/c)$. This can be partially mitigated by requiring a large separation between the proton-proton collision and the kaon decay points. In Run 1 (2010-2012) the main bottleneck for strange physics at LHCb was the trigger system, which was selecting only events with $p_T > O(\mathrm{GeV})$ resulting in a trigger efficiency of $\epsilon_{\mathrm{trig}}(\mathrm{Run\ 1}) \sim 1-2\%$. In Run 2 (2015-2018), a significantly modified software trigger enabled an improvement of the trigger efficiency by about an order of magnitude $\epsilon_{\mathrm{trig}}(\mathrm{Run\ 2}) \sim 18\%$ with further improvements limited by the hardware trigger system. In Run 3, which started in 2022, the upgraded LHCb detector is equipped with an entirely software-based trigger system which will boost significantly the sensitivity to kaon and hyperon decays with trigger efficiencies close to 100%. Furthermore, the huge strangeness production cross-section at the LHC, two to three orders of magnitude larger than that of heavy flavours, makes strange-hadron physics an increasingly-exciting field at LHCb [2], with several world-leading results already published and more in the pipeline.

The reconstruction of strange hadrons in LHCb is limited by the tracking of their decay products and by the trigger. Obtaining the highest tracking performance for a charged particle in LHCb usually requires the particle to produce hits either in all of the tracking stations (long track) or in all but the VErtex LOcator (VELO) (See Fig. 1) tracking stations (downstream track). The former limits the decay length to less than a meter while the second allows up to two meters. Decays further downstream, albeit reconstructible, would not allow a momentum measurement of the tracks. In addition to this, the trigger imposes constraints on the transverse momenta of the particles in an event. In particular, during Run 1 and Run 2, typical thresholds at the level of $p_T > 1-5\ \mathrm{GeV}/c$ were required for at least a muon or a hadron in the event in the first hardware level of the LHCb trigger (L0). Strange hadrons are often too soft for these L0 thresholds but given the high production rates it is sufficient that a small fraction of the events are triggered by the signal in question (Triggered On Signal, TOS). Furthermore, one can exploit events triggered by other particles in the same event (Triggered Independently of Signal, TIS). On top of L0, LHCb has two software trigger layers, HLT1 and HLT2, which perform a coarse and a more refined event reconstruction and select interesting events for subsequent offline analysis. These layers are more customizable than the L0, albeit having to respect tight rate requirements. During Run 1 no dedicated trigger was present for strange physics at HLT1 and only part of Run 1 data-taking had a dedicated HLT2 line for $K^0_S \to \mu^+\mu^-$ decays. In Run 2, different inclusive and exclusive lines were studied and included in both HLT1 and HLT2 [3] allowing about an order of magnitude increase in trigger efficiency for strange decays.

The data collected so far by LHCb in Run 1 and 2 correspond to 9 fb^{-1}. About 50 fb^{-1} are expected to be collected after LHCb Run 3 and 4 and there is interest to continue the experiment at high luminosity with a future Upgrade, possibly reaching 300 fb^{-1} [13] after Run 5 and 6. This will allow unprecedented statistics to be collected for heavy flavours. The highly-customisable software

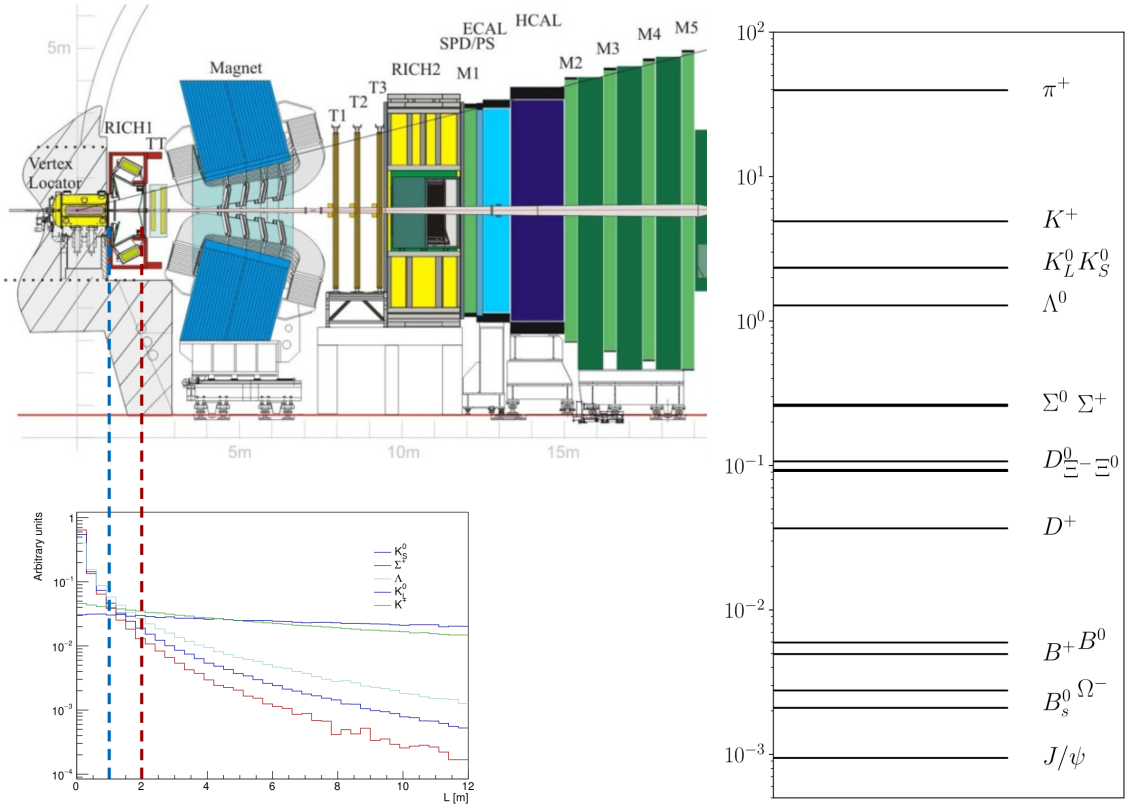

Figure 1: Left: The LHCb detector scheme (top), compared to the decay length of strange hadrons produced in pp collisions at $\sqrt{s}$ = 13 TeV (bottom). Right: Average production multiplicity of different hadrons in the same kind of events. The plots are obtained with PYTHIA Monte Carlo simulations, and are from Ref [2].

trigger available in Run 3 and beyond will also allow targeting all interesting strange decays with exclusive lines, reaching efficiencies up to 100% evaluated on top of the offline signal selection. Therefore, prospects for different analyses have been prepared taking into account the possible luminosities and efficiencies and some of these will be presented in the following.

The LHCb collaboration has already published several world-leading results in strange physics: the strongest bound on the branching fraction of $K^0_S \to \mu^+\mu^-$ decays [10], the first 4.1 standard deviation evidence for the rare $\Sigma^+ \to p\mu^+\mu^-$ decay [11], and best upper limit on the branching fraction of $K^0_{S(L)} \to \mu^+\mu^-\mu^+\mu^-$ reaching $O(10^{-12})$ level for the K^0_S mode [12].

One of the most interesting decays in the short term will be the $K^0_S \to \pi^0\mu^+\mu^-$ decay. Its long-lived partner $K^0_L \to \pi^0\mu^+\mu^-$ decay is a very sensitive probe of physics Beyond the Standard Model (BSM) and has been studied in models with extra dimensions [4]. Furthermore, correlations between a $K^0_L \to \pi^0\mu^+\mu^-$ branching fraction measurement and the CP-violating observables ϵ'/ϵ, ϵ_K as well as the $K^0 - \bar{K^0}$ mass difference, ΔM_K, will help disentangle the nature of possible New Physics (NP) [5]. However, the SM prediction still suffers from a large uncertainty $\mathcal{B}_{SM}(K^0_L \to \pi^0\mu^+\mu^-) = \{1.4 \pm 0.3, 1.0 \pm 0.2\} \times 10^{-11}$. The uncertainty stems from a limited knowledge of the Chiral Perturbation Theory parameter $|a_S|$. The two different predictions are due to the unknown sign of the interference between CP violation in mixing and decay [6, 7]. The parameter a_S can be extracted from a measurement of the $K^0_S \to \pi^0\mu^+\mu^-$

branching fraction, which is known to about 50% precision from a measurement by the NA48 collaboration, $\mathcal{B}_{SM}(K_L^0 \to \pi^0\mu^+\mu^-) = (2.9^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9}$ [8]. A more precise measurement of this branching fraction will result in an improved prediction of $K_L^0 \to \pi^0\mu^+\mu^-$ and ultimately in improved BSM constraints that can be derived from it. The sensitivity of LHCb to $K_S^0 \to \pi^0\mu^+\mu^-$ decays has been studied extensively, demonstrating that significant improvements are possible depending on the trigger efficiency already with 10 fb^{-1} of Upgrade data [9].

A second group of decays which is gradually becoming more promising is the set of 4-body leptonic decays of the neutral kaon. Here again, it is the K_L^0 modes that are the more interesting because the short-distance contribution to $K^0 \to l^+l^-l^+l^-$ decays is sensitive to NP with the caveat that the sensitivity is reduced by the uncertainty of the long-distance contribution prediction. A measurement of the interference between $\mathcal{A}(K_S^0 \to l^+l^-l^+l^-)$ and $\mathcal{A}(K_L^0 \to l^+l^-l^+l^-)$ will give a measurement of the sign of $\mathcal{A}(K_L^0 \to \gamma\gamma)$ and provide a stringent CKM test [14, 15]. While the $K_L^0 \to l^+l^-l^+l^-$ decays were studied by different experiments, no experimental constraints are present on the K_S^0 modes except for the recent limit on the $K_S^0 \to \mu^+\mu^-\mu^+\mu^-$ mode provided by LHCb [12]. Even though the rates for these decays are expected to be very low ($\mathcal{B}(K_S^0 \to e^+e^-e^+e^-) \sim 10^{-10}, \mathcal{B}(K_S^0 \to \mu^+\mu^-e^+e^-) \sim 10^{-11}, \mathcal{B}(K_S^0 \to \mu^+\mu^-\mu^+\mu^-) \sim 10^{-14}$) any sensitivity approaching the SM rates would be a test of new physics. The prospects for such decays at LHCb are excellent and will allow us to scan most of the allowed range in BSM models and get very close to the SM sensitivity if no signal is found.

Semileptonic hyperon decays ($B_1 \to B_2 l \nu_l$) can also be studied at LHCb. Many muonic modes still have poor precision with uncertainties on the branching fractions in the 20 – 100% range. The decays profit from the relatively-high branching fractions, around $\mathcal{B} \sim O(10^{-4})$, which, coupled with the large strange hyperon production rates at the LHC, result in huge yields at LHCb. An improved measurement of these modes will be challenging due to the high levels of contamination from physics backgrounds but will offer high sensitivity to helicity-suppressed NP contributions [16]. Despite the challenges, LHCb is expecting to achieve world-leading precision on the branching fraction measurements of $\Lambda \to p\mu^-\nu_\mu$, $\Xi^- \to \Lambda\mu^-\nu_\mu$, and $\Xi^- \to \Sigma^0\mu^-\nu_\mu$ decays. More comprehensive studies assessing the prospects for measurements with strange hadrons at LHCb have been done [2], using approximate simulations of the LHCb detector. Dozens of decays have been studied from K_S^0 to hyperons showing that LHCb will be in a position to give significant contributions to strange-hadron physics in the near future.

In summary, the LHCb experiment has demonstrated the capability to study rare decays of K_S^0 and strange hyperons and has the possibility to provide improved measurements of many processes sensitive to new physics, complementary to other state-of-the-art kaon experiments. With the current Upgrade, the flexibility of the new software trigger allows unprecedented rates for different decays, possibly establishing LHCb as a strange factory. It should be underlined, that the decay modes mentioned in this contribution are just examples of the possibilities and benchmarks; however new ideas are always welcome to exploit the full potential of the data.

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