PROCEEDINGS OF SCIENCE

Rare strange decays at LHCb

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Due to the high suppression of $s \to d$ transitions, the sector of rare strange decays is a particularly powerful probe for New Physics. Assuming non-minimal flavour-violation, bounds from strange decays go up to a scale of $\mathcal{O}\left(10^5\right)$ TeV. Taking advantage of the high production rate of strange hadrons at the LHC, the LHCb detector is able to perform competitive measurements on decays like $K_S^0 \to \mu^+\mu^-$, $\Sigma^+ \to p\mu^+\mu^-$, $K_S^0 \to \pi^0\mu^+\mu^-$ or $K_S^0 \to l^+l^-l^+l^-$. These proceedings summarize recent results on searches for rare strange decays by the LHCb collaboration.

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1. The strange decays sector

Contributions beyond the Standard Model (SM) at $\mathscr{O}(\text{TeV})$ might only be visible if there are new sources of flavour violation. Rare strange decays profit from the high suppression of $s \to d$ transitions in the SM, due to the loop suppression and the small size of the involved CKM matrix elements $V_{td}V_{ts}^{*} \sim 10^{-4}$. Assuming non-minimal flavour-violation, they allow to probe New Physics (NP) contributions up to a scale of $\mathscr{O}\left(10^{5}\right)$ TeV.

2. Strange decays at LHCb

The LHCb detector [1] is mainly devoted to the study of b and c hadron decays. The design has been thus optimized to the topology of those processes, resulting in excellent vertexing, particle identification and mass resolution. Strange hadrons typically emerge from the proton-proton collision point with a very low angle with respect to the beam pipe, where soft QCD background dominates.

Efficiencies to detect such processes were proved to be high enough already in 2011, in the study of the $K^0_S \to \mu^+\mu^-$ decay [2]. Some improvements were implemented at the trigger level and on particle identification for the 2012 data taking, leading to an increase of the efficiency. For the Run-II of the LHC, a big step forward has been made to study strange decays, developing algorithms exclusively devoted to analyze these processes. After the LHCb upgrade, efficiencies are expected to increase even more with the removal of the hardware trigger, which currently constitutes the main bottleneck to study strange decays, due to its high transverse-momentum requirements.

3. $K^0_S \to \mu^+\mu^-$

This decay is a flavour-changing-neutral-current (FCNC) process, dominated by a $K^0_S \to \gamma\gamma$ transition. Although the measurement of the corresponding K^0_L decay is in agreement with the SM expectations [3], new scalars could affect the K^0_S exclusively. Furthermore, the study of the $K^0_S \to \mu^+\mu^-$ decay would allow to put model-independent bounds on the CP-violating phase of the $s \to dl^+l^-$ amplitude [4, 5].

An update on the measurement of the $K^0_S \to \mu^+\mu^-$ branching fraction is made using the 2012 data sample [6], combining it with the previous result published by LHCb [2]. The normalization is done with respect to the $K^0_S \to \pi^+\pi^-$ decay mode, which is also the main source of background. Contributions from $K^0_L \to \mu^+\mu^-$, $K^0 \to \pi^+\mu^-\bar{\nu}$ or $\eta \to \mu^+\mu^-\gamma$ are shown to be negligible. The analysis is performed using two different trigger selections. A multivariate analysis (MVA) technique is used to remove the remaining combinatorial background, and a muon identification algorithm allows to reduce the amount of doubly misidentified $K^0_S \to \pi^+\pi^-$ decays. Finally, a combined maximum likelihood fit is performed in bins of the MVA output, simultaneously for the two trigger categories, where the previous result is included as a prior. As can be seen in Fig. 1, no significant candidates from the $K^0_S \to \mu^+\mu^-$ decay are found, therefore a limit is set using the likelihood profile of the branching fraction in the signal region,

$$\mathscr{B}\left(K^0_S \to \mu^+\mu^-\right) < 0.8(1.0) \times 10^{-9} \text{ at } 90(95)\% \text{ CL}$$

which constitutes the new world-best measurement.

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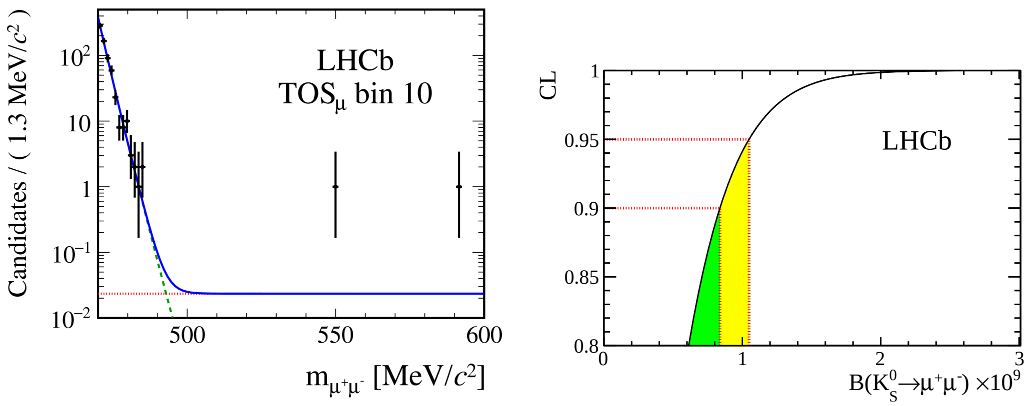

Figure 1: Left: mass distribution with the fit result overlaid (blue), for the most sensitive MVA bin. The contributions are $K^0_S \to \pi^+\pi^-$ doubly misidentified (dashed green) and combinatorial background (dotted red). Right: confidence level as a function of the branching fraction, extracted from the likelihood profile. The green and yellow areas correspond to the 90 % and 95 % confidence levels, respectively.

4. $\Sigma^+ \to p\mu^+\mu^-$

The interest on this decay originates from the observation of three candidates at a mass of ~ 214 MeV by the HyperCP experiment [7]. The three candidates would suggest an intermediate resonance

$$\Sigma^+ \to pX^0\,(\to \mu\mu)\,.$$

At LHCb, the full Run-I data-sample is used to search for this decay [8], adopting two different trigger strategies:

- Full: any event selected by the LHCb trigger is retained. Normalization is very complex, and relies on the collected luminosity and on Monte Carlo simulations.
- TIS: the event is triggered by an object other than the signal candidate. The decay $\Sigma^+ \to p\pi^0$ is used as normalization mode.

The study concludes with a 4σ evidence of the $\Sigma^+ \to p\mu^+\mu^-$ decay in the Full strategy, with $12.9^{+5.1}_{-4.2}$ fitted candidates. As can be seen in Fig. 2, no significant peaks appear in the dimuon mass, so there is no confirmation of any intermediate resonance. Since no signal candidates are observed using the TIS strategy, a limit on the branching fraction is set

$$\mathscr{B}\left(\Sigma^+ \to p\mu^+\mu^-\right) < 6.3\times 10^{-8} \text{ at 95\% CL.}$$

5. $K^0_S \to \pi^0\mu^+\mu^-$

In models with extra dimensions, the $K^0_L \to \pi^0\mu^+\mu^-$ branching fraction can have a variation of one order of magnitude [9]. Its theoretical expression can be written as

$$\mathscr{B}\left(K^0_L \to \pi^0 l^+ l^-\right)_{\rm SM} = \left(C^l_{\rm dir} \pm C^l_{\rm int}|a_S| + C^l_{\rm mix}|a_S|^2 + C^l_{\gamma\gamma} + C^l_S\right)\times 10^{-12}$$

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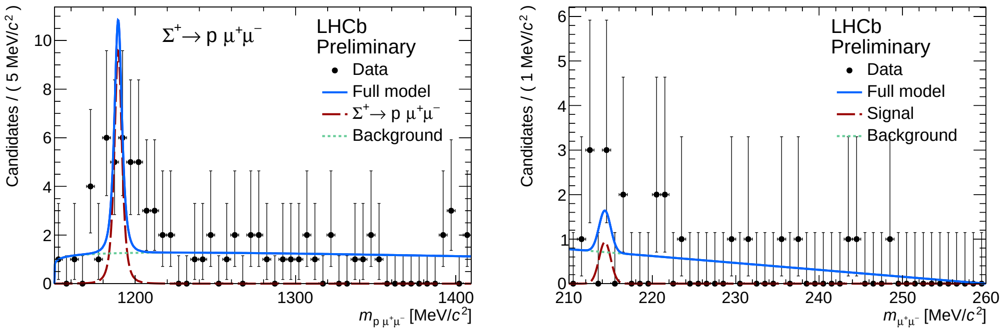

Figure 2: Left: three-body invariant mass distribution of the $\Sigma^+ \to p\mu^+\mu^-$ candidates. Right: dimuon invariant mass distribution, extracted from the candidates within two times the invariant mass resolution around the Σ^+ nominal mass. The different components are: main fit model (blue), background (green) and the signal distribution (dark red). Both plots correspond to the Full strategy.

where $|a_S| = 1.2 \pm 0.2$ dominates the theoretical uncertainty, and comes from the measurements of the $K^0_S \to \pi^0 l^+ l^-$ modes, like $\mathscr{B}\left(K^0_S \to \pi^0\mu^+\mu^-\right) = 2.9^{+1.5}_{-1.2} \times 10^{-9}$ [10].

A study of the decay $K^0_S \to \pi^0\mu^+\mu^-$ is performed to determine the sensitivity at LHCb after the upgrade [11]. At LHCb, the π^0 reconstruction is challenging. The efficiencies are very low for the two main ways of π^0 reconstruction: $\pi^0 \to \gamma\gamma$ and $\pi^0 \to e^+e^-e^+e^-$. However, it is proved that the K^0_S mass does not depend too much on the π^0 reconstruction, as it can be seen in Fig. 3. Therefore, two different strategies are adopted, and a different data-sample is used for each of them:

- Full: full reconstruction of the K^0_S. The π^0 is reconstructed as $\pi^0 \to \gamma\gamma$. The study uses the full Run-I statistics.

- Partial: the K^0_S is partially reconstructed from the two muons, and a virtual particle, with a momentum of $\sim$ 10 GeV/c, is added afterwards to emulate the π^0 inclusion effect on the three-body invariant mass. The value of the momentum of the virtual particle is optimized to provide the best mass resolution. The study uses 0.3 fb^{-1} of the Run-II statistics.

The main source of background is purely combinatorial and no peaking backgrounds from other decays, like $K^0_S \to \pi^+\pi^-$, $X^0 \to \pi^+\pi^-\pi^0$ or $K^0 \to \mu^+\mu^-\gamma$ are found. The best sensitivity is achieved without reconstructing the π^0, which leads to the conclusion that a precision measurement will be possible in the upgrade, as seen in Fig. 3.

6. $K^0_S \to l^+l^-l^+l^-$

The decays of a K^0_S to four leptons are highly suppressed in the SM [12], resulting in predic-

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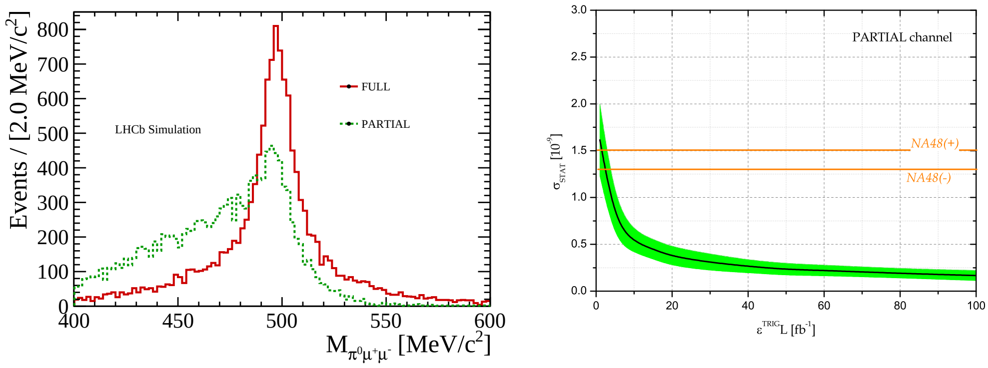

Figure 3: Left: three-body invariant mass distribution for the Full (red) and Partial (green) strategies. Right: statistical uncertainty as a function of the effective luminosity for the Partial strategy. The current expectation is drawn in black, with the 1σ interval displayed in green. The statistical uncertainties of the NA48 measurement are drawn in orange.

tions of

$$\mathscr{B}\left(K_S^0 \to e^+e^-e^+e^-\right) \sim 10^{-10}$$
$$\mathscr{B}\left(K_S^0 \to \mu^+\mu^-e^+e^-\right) \sim 10^{-11}$$
$$\mathscr{B}\left(K_S^0 \to \mu^+\mu^-\mu^+\mu^-\right) \sim 10^{-14}$$

They are therefore very sensitive to NP contributions. Furthermore, interference between $K_S^0 \to l^+l^-l^+l^-$ and $K_L^0 \to l^+l^-l^+l^-$ decays would allow to put strong constraints on the CKM matrix elements. Since the reconstruction and the selection of electron modes is challenging at LHCb, first a study of the $K_S^0 \to \pi^+\pi^-e^+e^-$ decay is needed to be used as normalization and control channel. Its branching fraction has been measured by the NA48 collaboration [13], and the current world average is [14]

$$\mathscr{B}\left(K_S^0 \to \pi^+\pi^-e^+e^-\right) = (4.79 \pm 0.15) \times 10^{-5}$$

A sensitivity study of this decay on the current and incoming data-samples is done at LHCb [15]. The analysis is based on Monte Carlo simulation and data in 2012 conditions (2 fb^{-1} at 8 TeV). No peaking structures are expected in the four-body spectrum, as can be seen in Fig. 4. The results from pseudo-experiments show that an observation of this decay is already possible with the Run-I data-sample. The number of $K_S^0 \to \pi^+\pi^-e^+e^-$ candidates expected in the Run-II is $\mathrm{N}^{\mathrm{exp}}_{\mathrm{Run\text{-}II}} = 120^{+280}_{-100}/\mathrm{fb}^{-1}$, whereas assuming a trigger efficiency of 100% for the upgrade, this number grows up to $\mathrm{N}^{\mathrm{exp}}_{\mathrm{up}} = (5.0 \pm 0.3) \times 10^4/\mathrm{fb}^{-1}$.

7. Conclusions

The strong suppression of the $s \to d$ transitions, makes the study of rare strange decays a

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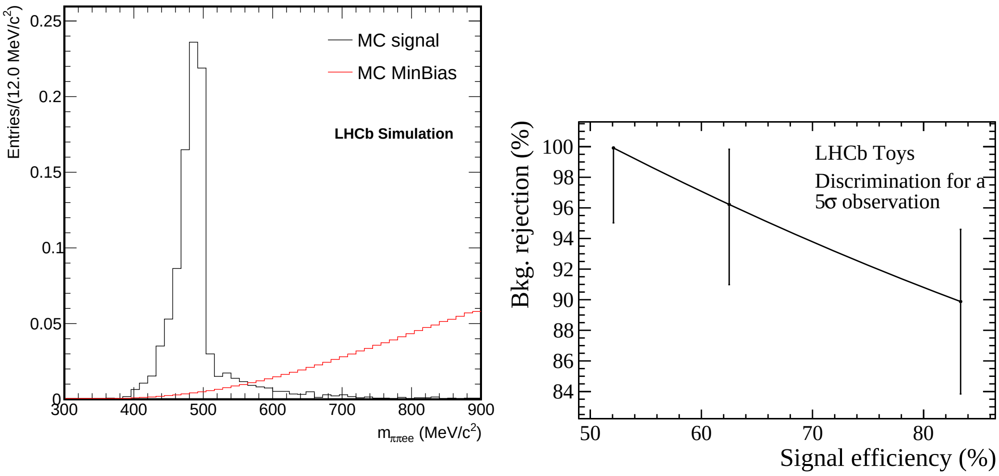

Figure 4: Left: four-body invariant mass distribution for simulated signal (black) and background (red) candidates. Right: background rejection as a function of the signal efficiency for a 5σ observation of the $K^0_S \to \pi^+\pi^-e^+e^-$ decay at LHCb.

good probe to search for NP. The high production rate of strange hadrons at the LHC, and the features of the LHCb detector, constitute a suitable environment to study rare strange decays. The improvements on trigger, reconstruction and particle identification open a wide program at LHCb to search for these decays. Updates on $K^0_S \to \mu^+\mu^-$, $\Sigma^+ \to p\mu^+\mu^-$ and $K^0_S \to \pi^0\mu^+\mu^-$ analyses are expected to be performed within the following years, as well as the studies of the $K^0_S \to l^+l^-l^+l^-$ modes, which might provide the first measurements of these decays.

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