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K^0_S decays at LHCb

C. Marin Benito(*) on behalf of the LHCb Collaboration
Universitat de Barcelona - Barcelona, Spain

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Summary. — K^0_S decays are a new area of interest for LHCb. Latest results on the $K^0_S \to \mu^+\mu^-$ search are reported using data collected by the LHCb experiment at a center-of-mass energy of $\sqrt{s} = 7\,\text{TeV}$, corresponding to an integrated luminosity of $1\,\text{fb}^{-1}$. The upper limit at 90% CL on the branching ratio of this decay is found to be 9×10^{-9}. This limit is 30 times lower than the previous world best. LHCb prospects for other K^0_S decays and other strange mesons decays are also reported.

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1. – Introduction

Strange mesons have played a major role in the history of particle physics. When first observed, back in the late 1940s, they triggered large interest. Experiments showed that kaons were produced through the strong force but they were not decaying through this interaction, thus being long-lived particles. This fact helped to understand in a better way the weak interaction, which was pretty unknown at that moment, and motivated the GIM mechanism and the prediction of the c quark [1].

Another key point in the history of kaon physics was the discovery of charge-parity (CP) violation. It was first observed in 1964 in the decay of $K^0_L \to \pi^+\pi^-$ at the Brookhaven National Laboratory [2]. Charge-parity violation was completely unexpected at that moment and its observation triggered many advances in the understanding of particle physics.

Strange meson decays are very interesting both from the theoretical and experimental point of view. On one side, they are theoretically clean and involve flavour changing neutral currents (FCNC) with the strongest Cabibbo-Kobayashi-Masakawa (CKM) suppression ($V_{ts}V_{td} \sim 10^{-4}$), making them very sensitive to New Physics (NP) effects. From the experimental side, there is a copious production of strange particles at the LHC and the number of possible final states is limited, allowing for clean studies of these decays.

(*) E-mail: carla.marin.benito@cern.ch

1˙1. *LHCb detector for strange decays.* – The LHCb detector is a single-arm forward spectrometer described in detail in ref. [3]. The detector is optimized for the study of b and c hadrons. Although strange mesons have in average lower masses and larger decay times, they are produced in copious amounts at the LHC. During 2011, at a center-of-mass energy of $\sqrt{s} = 7\,\text{TeV}$, the LHC produced $\sim 10^{13}$ K^0_S per fb^{-1} inside the LHCb acceptance [4].

Due to the larger decay times of strange mesons, many of them decay outside the vertex locator (VELO). This fact implies that the decay vertex is not directly observed and the daughter tracks are only detected in the subsequent subdetectors. These tracks are referred to as downstream tracks and have in average worse momentum resolution. Tracks that are detected also inside the VELO are referred to as long tracks.

When using downstream tracks to reconstruct the daughters of a decay, there is no information on the decay vertex. However, when the mother is a charged particle, it leaves also hits in the VELO that can be matched to the downstream tracks to extrapolate the position of the decay vertex. This technique helps to improve a lot the selection of these decays as shown in sect. **3**˙3.

1˙2. *LHCb trigger for strange decays.* – The LHCb trigger consists of a hardware stage, that selects high p_T and E_T signatures based on the information from the calorimeters and muon chambers, followed by a software stage that after selecting displaced tracks using tracking and vertexing information, performs a full event reconstruction.

The LHCb trigger is not designed to select strange decays, since it takes advantage of the distinct signatures of b and c hadron decays. Nevertheless, in 2011, around 1/3 of the events that passed the trigger contained a reconstructible $K^0_S \to \pi^+\pi^-$.

During 2011, the di-μ invariant mass requirement in the software trigger was incompatible with the K^0_S mass. Thus, only triggers selecting single muons were useful to select decays like $K^0_S \to \mu^+\mu^-$. In 2012, a low mass di-μ line compatible with the K^0_S mass was included. This resulted in an increase in the trigger efficiency for $K^0_S \to \mu^+\mu^-$ of a factor 3. Additional studies are ongoing to improve this efficiency for LHC Run 2.

2. – $K^0_S \to \mu^+\mu^-$

The $K^0_S \to \mu^+\mu^-$ decay is a FCNC with no tree-level contribution in the Standard Model (SM), with a predicted branching fraction (BR) of $(5.1 \pm 0.2) \times 10^{-12}$ [6]. Within the SM, there are two contributions to the amplitude of this process [5]: the long-distance contribution, which is mediated by virtual photons, and the short-distance, which is mediated by electroweak bosons. The last one is dominated by the CP-violating part of the quark level transition $s \to dll$, making this decay very sensitive to NP contributions.

From the experimental side, the previous best measurement dates from 1973 when the upper limit on the BR was set to 3.1×10^{-7} at 90% confidence level (CL) [7], far from the SM prediction.

2˙1. *LHCb analysis.* – The LHCb collaboration reported in 2012 an improved measurement of the BR limit for the decay $K^0_S \to \mu^+\mu^-$ [4]. The analyses used $1\,\text{fb}^{-1}$ of data collected at a center-of-mass energy of $\sqrt{s} = 7\,\text{TeV}$.

The K^0_S candidates were reconstructed using μ pairs from long tracks and selected by a multivariate algorithm, namely a Boosted Decision Tree (BDT). The BDT rejected candidates coming from random combination of two muons and muons resulting from

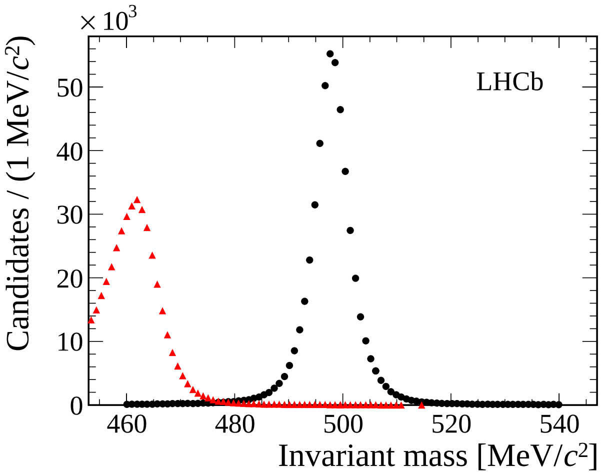

Fig. 1. – Mass spectrum for selected $K^0_S \to \pi^+\pi^-$ candidates. The points correspond to the mass reconstructed under the $\pi^+\pi^-$ mass hypothesis for the daughters, while the triangles correspond to the mass reconstructed under the $\mu^+\mu^-$ mass hypothesis.

the interaction of particles produced in the pp collision vertex with the material in the region of the VELO.

The $K^0_S \to \pi^+\pi^-$ channel was used as normalization channel. The separation of this decay from the signal channel was studied using $K^0_S \to \pi^+\pi^-$ decays reconstructed and selected in the same way as the signal channel, both in the $\pi^+\pi^-$ and $\mu^+\mu^-$ mass hypotheses. As shown in fig. 1, the two mass peaks are separated by $40\,\text{MeV}/c^2$. This separation, combined with the LHCb mass resolution of about $4\,\text{MeV}/c^2$ for such combination of tracks, was used to discriminate between the two channels.

The search region in the di-μ invariant mass was defined between $[492, 504]\,\text{MeV}/c^2$. The background level was calibrated by interpolating the observed yield in the mass side-bands to the signal region. A model with two components was used: a power law to describe the tail of $K^0_S \to \pi^+\pi^-$ decays where both pions are misidentified as muons and an exponential function describing the combinatorial background. Other sources of background were found to be negligible. The invariant mass distribution of selected candidates is shown in fig. 2.

To translate the number of $K^0_S \to \mu^+\mu^-$ signal decays into a branching fraction measurement a normalisation was performed in BDT bins. Using the value of the BR of $K^0_S \to \pi^+\pi^-$ from ref. [8], around 2×10^{-4} SM candidates were expected per BDT bin.

The modified frequentist approach (or CLs method) [9] was used to asses the compatibility of the observation with expectations as a function of the BR of $K^0_S \to \mu^+\mu^-$. The observed distribution of events was compatible with the background expectations, as shown in fig. 3. The measured upper limit is $11(9) \times 10^{-9}$ at 95(90)% confidence level, a factor of thirty below the previous world best limit.

2˙2. $K^0_S \to \mu^+\mu^-$ *prospects at LHCb*. – LHCb has improved by a factor of 30 the previous world best upper limit measurement but there is still need for improvement to get to the SM prediction of $(5.1 \pm 0.2) \times 10^{-12}$. The most interesting region is below the 10^{-10} limit where most new physics models arise.

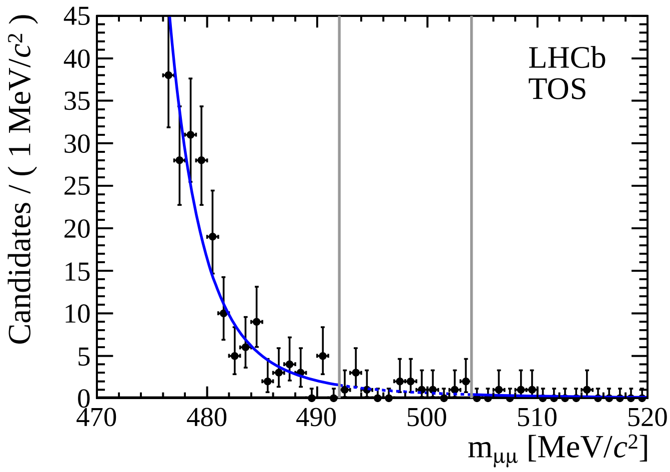

Fig. 2. – Background model fitted to data events which are triggered on the signal object (TOS), independently of the rest of the event. The vertical lines delimit the search region.

The current limit measurement makes use of only one third of the total amount of data recorded by the LHCb detector in Run 1. In addition, as mentioned in sect. **1**˙2 a threefold improvement in the trigger efficiency was already obtained from the adoption of new trigger strategies in 2012. Some extra improvement may be obtained by making use of downstream muon tracks. With these improvements, the LHCb collaboration expects to reach the 10^{-10} limit in its upgrade phase, with an accumulated luminosity of $40\,\text{fb}^{-1}$.

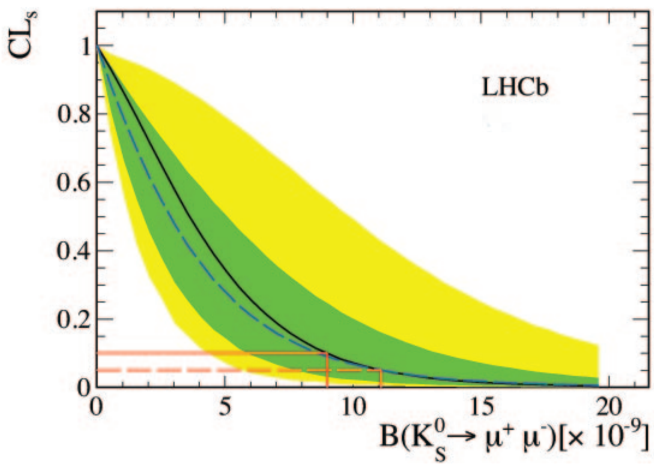

Fig. 3. – CLs curves. The solid line corresponds to the observed CLs. The dashed line corresponds to the median of the CLs for an ensemble of background-alone experiments. The dark band covers 65% (1σ) of the CLs curves obtained in the background only pseudo-experiments, while the light band covers 95% (2σ).

3. – Other rare strange prospects at LHCb

With the publication of the $K^0_S \to \mu^+\mu^-$ analysis, strange decays have become a new area of interest at LHCb with many ongoing studies on this field. A selection is reported here.

3˙1. $K^0_S \to \pi^0\mu^+\mu^-$. – The $K^0_S \to \pi^0\mu^+\mu^-$ decay measures the indirect CP violating component of the related $K_L \to \pi^0\mu^+\mu^-$ decay, allowing to extract the direct CP violating contribution of the last one. This can provide input to determine the imaginary part of the element V_{td} of the mixing matrix. Moreover, the $K^0_S \to \pi^0\mu^+\mu^-$ decay can be used to study the structure of the $K \to \pi\gamma^*$ form factor, as it is expected to be dominated by this contribution.

The NA48 collaboration reported in 2012 the first observation of this decay [10] and a BR measurement of $(2.9^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9}$ with an uncertainty of $\sim 50\%$.

The most challenging issue of this analysis at LHCb is the π^0 reconstruction. Different possibilities have been studied using simulated data and the most feasible option is the reconstruction of $\pi^0 \to \gamma\gamma$. Although few $K^0_S \to \pi^0\mu^+\mu^-$ events are expected in the $3\,\text{fb}^{-1}$ currently accumulated by the LHCb detector, this decay may be observed in the LHC Run 2 and surely after the LHCb upgrade.

3˙2. $K^0_S \to 4\ell$. – The predicted branching fraction of $K^0_S \to 4\ell$ in the SM are expected to be [11]

$$K^0_S \to eeee \sim 10^{-10},$$
$$K^0_S \to \mu\mu ee \sim 10^{-11},$$
$$K^0_S \to \mu\mu\mu\mu \sim 10^{-14}.$$

Any deviation from these values may hint to contributions from NP. No experimental results have been reported so far.

For those decays containing electrons in the final state, the reconstruction of these particles is the most challenging issue at LHCb. Studies on simulated data allow to extract an expected mass resolution of ~ 20 $(\sim 10)\,\text{MeV}/c^2$ for $K^0_S \to eeee$ $(K^0_S \to \mu\mu ee)$. These studies also show a clear displacement of the mass peak due to the energy loss of the electrons. However, the expected separation to the normalization channel $K^0_S \to \pi\pi ee$ with the two pions misidentified as electrons or muons, respectively, combined with the quoted mass resolution, should allow to discriminate between the different channels.

Using the well measured $K^0_S \to \pi\pi ee$ decay as normalization channel, the expected single event sensitivity, assuming no background in the search region, with the $3\,\text{fb}^{-1}$ of data accumulated by the LHCb detector is found to be $\sim 10^{-6}$ $(\sim 10^{-7})$ for the $K^0_S \to eeee$ $(K^0_S \to \mu\mu ee)$ channel. Similar studies are being performed with the $K^0_S \to \mu\mu\mu\mu$ channel.

3˙3. K^+ *mass prospects*. – Currently experimental results show a disagreement between the most precise measurements of the K^+ mass [12]. LHCb could give a competitive result on this puzzle by means of the $K^+ \to \pi\pi\pi$ decay.

The K^+ candidates are reconstructed combining 3 π from downstream tracks, which have no information from the decay vertex. Random combinations of 3 π not coming from a decay of a K^+ are easily selected if no requirement on the decay vertex is made. Studies using simulated data at LHCb show a great selection improvement when the tracks are

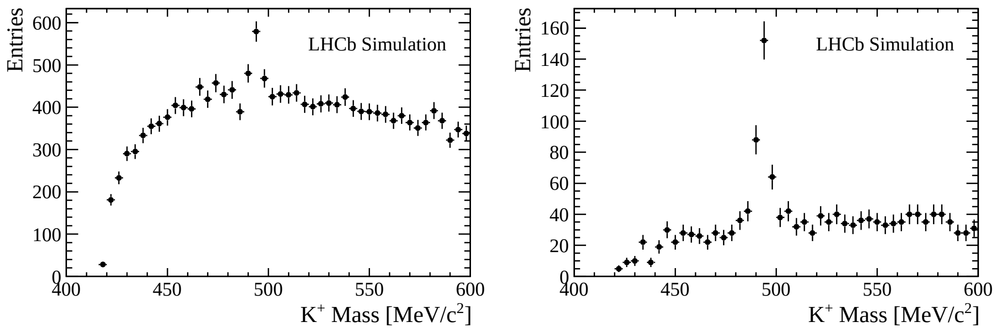

Fig. 4. – K^+ invariant mass distribution for simulated events. Left: no matching requirement applied. Right: after matching requirement.

required to be matched to the hits left by the K^+ in the VELO. Figure 4 shows the invariant mass distribution of the K^+ before and after the matching requirement. This technique rejects most of the background with high efficiency on the signal events. More information of this technique can be found in [13].

A rough estimate of systematic uncertainties shows that the precision on the mass measurement is limited at the moment by statistics. LHC Run2 may provide enough data to the LHCb detector to allow for a competitive measurement of the K^+ mass.

3·4. $\Sigma^+ \to p\mu^+\mu^-$ *prospects.* – The HyperCP collaboration at Tevatron reported the observation of 3 $\Sigma^+ \to p\mu^+\mu^-$ events with 0 background and a branching fraction for this decay of $(8.6^{+6.6}_{-5.4} \pm 5.5) \times 10^{-8}$ [14]. This evidence had wide relevance since all the three observed events lie within the expected di-μ mass resolution of $\sim 0.5\,\mathrm{MeV}/c^2$, possibly pointing towards a $\Sigma^+ \to pX^0(\to \mu^+\mu^-)$ decay. The new intermediate state would have a mass of $214.3 \pm 0.5\,\mathrm{MeV}/c^2$. The existence of a light neutral particle decaying to a muon pair would have many consequences and several experiments have performed specific tests of this hypothesis [15-18].

The LHCb collaboration aims for a direct search for the $\Sigma^+ \to p\mu^+\mu^-$ decay, taking advantage of the huge amount of Σ^+ produced at LHC pp collisions — approximately 40% of the events contain one. To increase the statistics, both long and downstream tracks are used for this analysis. In the case of downstreeam tracks, the matching technique explained in sect. **3**·3 is used to purify the selection. Studies on simulated data show a very good mass resolution for this decay, $\sigma \sim 2\,\mathrm{MeV}/c^2$. Using $\Sigma^+ \to p\pi^0(\to e^+e^-\gamma)$ with undetected photon as normalization channel, a single event sensitivity of $\sim 5\times10^{-9}$ can be reached with the current statistics ($3\,\mathrm{fb}^{-1}$).

4. – Conclusions

Although the LHCb detector is not designed for strange physics, it has the potential to significantly contribute in the study of this type of decays. A world best upper limit measurement was set for the branching fraction of $K_S^0 \to \mu^+\mu^-$ to 9.0×10^{-9} at 90% CL, improving in a factor 30 the previous world best result. After this analysis, strange physics have become a new area of interest for LHCb and several studies are being carried out to asses the sensitivity of some of the most relevant measurements in the field.

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