Updated limit for the decay $K_S^0 \rightarrow \mu^+\mu^-$

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Abstract. A search for the decay $K_S^0 \rightarrow \mu^+\mu^-$ is performed using the data sample of pp collisions at $\sqrt{s} = 8$ TeV collected by the LHCb experiment at the Large Hadron Collider in 2012, corresponding to an integrated luminosity of $2.0\,fb^{-1}$. In the Standard Model, this decay is expected to be suppressed at a level below the current experimental sensitivity, but could be enhanced by new sources of CP violation. The observed number of candidates is compatible with the expected background and allows to set an upper limit $B(K_S^0 \rightarrow \mu^+\mu^-) < 6.9(5.8) \times 10^{-9}$ at 95 (90)% confidence level. This limit improves the result published by LHCb using 1.0 fb$^{-1}$ of collisions collected in 2011 at $\sqrt{s} = 7$ TeV.

1. Introduction
In the Standard Model (SM), the still unobserved $K_S^0 \rightarrow \mu^+\mu^-$ decay can proceed only through a Flavour-Changing Neutral-Current (FCNC) transition. This process cannot occur at tree level and is further suppressed by the small amount of CP violation in kaon decays, since the S-wave component of the decay is forbidden when CP is conserved. In the SM, the decay amplitude is expected to be dominated by long distance contributions, which can be precisely constrained using the observed decays $K_S^0 \rightarrow \gamma\gamma$ and $K_L^0 \rightarrow \pi^0\gamma\gamma$. This leads to the prediction $B(K_S^0 \rightarrow \mu^+\mu^-) = (5.0 \pm 1.5) \times 10^{-12}$ [2]. The corresponding branching fraction for the $K_L^0$ decay into two muons is $(6.85 \pm 0.32) \times 10^{-9}$ [3], in excellent agreement with the experimental world average $B(K_L^0 \rightarrow \mu^+\mu^-) = (6.84 \pm 0.11) \times 10^{-9}$ [4].

Due to its suppression in the SM, the $K_S^0 \rightarrow \mu^+\mu^-$ decay amplitude can be enhanced by possible New Physics (NP) contributions, notably from light scalars with CP-violating Yukawa couplings [1]. Contributions up to one order of magnitude above the SM expectation naturally arise in many models and would be compatible with the present bounds from other FCNC processes. An upper limit on $B(K_S^0 \rightarrow \mu^+\mu^-)$ close to $10^{-11}$ could be translated into model-independent bounds on the CP-violating phase of the $s \rightarrow d\ell^+\ell^-$ amplitude. This would be very useful to discriminate among NP scenarios in case other modes, such as $K^+ \rightarrow \pi^+\nu\bar{\nu}$, indicated a non-standard enhancement of such transitions [2].

2. Kaons at LHCb
The LHCb [5] experiment is mainly devoted to the study of flavour physics and CP violation in the $b$ and $c$ hadron decays. However, it can also be considered a kaon factory, since around $10^{13}/fb^{-1} K_S^0$ decay inside the LHCb acceptance.

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$. It is equipped with a high precision tracking system, providing a very good resolution in the measurements of the Impact Parameter (IP), momenta and mass. This allows to
reconstruct the invariant mass of $K^0_S \rightarrow \pi^+\pi^-$ events with a resolution of 4 MeV/c$^2$ (see Fig. 1). Another important feature of the LHCb detector is the very efficient particle identification. Most of the information used to do this task comes from two different Cherenkov detectors, complemented using other subdetectors. A new muon identification algorithm ($\mu$ID) for low transverse momentum ($p_T$) tracks has been explicitly developed for this analysis, reaching a fraction of pions misidentified as muons of $\sim 0.49\%$, while maintaining an efficiency of $95\%$ for the real muons. Most of the remaining misidentified pions come from $\pi \rightarrow \mu \nu$ decays inside the detector.

There are three different trigger systems to filter the large amount of data to be recorded by LHCb. The first level (L0), is implemented in hardware. Due to its $p_T$ cuts, optimized for the study of $b/c$ hadrons, it constitutes the biggest limiting factor in the study of kaons at LHCb. The two other trigger levels (Hlt1 and Hlt2) are implemented in software, being very flexible, so they can be optimized for any study. Although the L0 trigger could not be changed, the Hlt2 has been improved for kaon decays selection in the second part of the Run-I data-taking (2012). The trigger efficiency increased by a factor 2.5, leading to an overall trigger efficiency of $\sim 2.5\%$.

### 3. Analysis procedure

This document summarizes the preliminary results recently published by the LHCb collaboration [6]. The data used in this analysis corresponds to 2 fb$^{-1}$ collected in 2012 by LHCb. The events from the data sample inside the signal region $m_{\mu\mu} \in [492, 504]$ MeV/c$^2$ are blinded, and only used in the final fit.

In order to exploit the maximum capability of the LHCb trigger, three different trigger selections have been used. Taking into account the previous LHCb result $B(K^0_S \rightarrow \mu^+\mu^-) < 11 \times 10^{-9}$ [7], and considering the improvements coming from the optimization done for the 2012 data-taking period, the expected sensitivity of this analysis is $B(K^0_S \rightarrow \mu^+\mu^-) \sim 10^{-9}$.

The $K^0_S \rightarrow \mu^+\mu^-$ candidates are obtained from tracks with opposite charge identified as muons, forming a vertex with invariant mass in the range $m_{\mu\mu} \in [400, 600]$ MeV/c$^2$. Due to the large branching fraction and abundance of $K^0_S \rightarrow \pi^+\pi^-$ events, this decay mode is used as normalization channel. In the case where the two pions are identified as muons, the invariant mass of the candidate is underestimated on average by $\sim 40$ MeV/c$^2$, which corresponds to $\sim 10$
times the resolution in that mass region.

In order to remove combinatorial background events, a Multivariate Analysis (MVA) has been done. The search for the algorithm with the best performance for each trigger category, lead to the utilization of a Boosted Decision Tree (BDT) with the same input variables for each one. The variables used correspond to kinematical and reconstruction quality variables, carefully chosen in order not to distinguish $\mu^+\mu^-$ and $\pi^+\pi^-$ modes, and to avoid the correlation with the mass of the candidate. The samples used to train the BDT correspond to data, trigger unbiased $K_S^0 \rightarrow \pi^+\pi^-$ candidates for signal, and data $K_S^0 \rightarrow \mu^+\mu^-$ candidates from the far right sideband ($m_{\mu^+\mu^-} \in [600, 950]$ MeV/$c^2$) for background. Each background sample consists of $K_S^0 \rightarrow \mu^+\mu^-$ events passing the associated trigger conditions. Due to the presence of muon-ID cuts, and to avoid over-training effects, the different $K_S^0 \rightarrow \pi^+\pi^-$ samples are built applying cuts to emulate the trigger effects.

The analysis is performed in bins of the BDT distribution, chosen after a loose cut to remove most of the combinatorial background events. A simultaneous maximum likelihood fit is done to all the trigger categories and BDT bins. The normalization factors are included so the branching fraction can be extracted directly from the fit. A constraint is applied on this magnitude using the previous LHCb result [7]. In order to extract the limit, the integral of the probability calculated from the $-\log \mathcal{L}$ is used.

3.1. Backgrounds

The combinatorial background is made from candidates reconstructed from secondary hadronic collisions in the detector material, which generate fake secondary vertices. Its structure is expected to exhibit a smooth mass distribution, with no peak in the di-muon mass. This contribution has been reduced using the aforementioned BDT algorithm.

The decay $K_L^0 \rightarrow \mu^+\mu^-$ is probably the most dangerous background on the study of $K_S^0 \rightarrow \mu^+\mu^-$. It becomes indistinguishable from $K_S^0 \rightarrow \mu^+\mu^-$ at LHCb. However, due to the larger lifetime of $K_L^0$ and after applying a lifetime acceptance correction, it has been proved that its effective branching fraction is $B_{\text{eff.}} (K_L^0 \rightarrow \mu^+\mu^-) \sim 10^{-11}$, thus negligible for this study.

A study on Monte-Carlo samples shows that the amount of $K_{SL}^0 \rightarrow \pi^+\pi^-\nu\bar{\nu}$ events are also negligible. Contributions from $\omega \rightarrow \pi^0\mu^+\mu^-$ and $\eta \rightarrow \mu^+\mu^-\gamma$ are not expected to generate peaking structures in the di-muon spectrum either.

In conclusion, the main background remains $K_S^0 \rightarrow \pi^+\pi^-$ decays, where the two pions are misidentified as muons. In Fig. 2 the probability of misidentifying a pion as a muon is shown as a function of its momentum. This performance is obtained after a cut based on the muon-ID algorithm, so there is an efficiency of 90% for real muons. A similar cut is applied in this analysis to reduce the large amount of misidentified pions, considerably reducing the background events in the signal region.

3.2. Normalization

The calculation of the normalization factors ($\alpha$) has been done prior to the fit. Events from $K_S^0 \rightarrow \pi^+\pi^-$ have been used to calculate these numbers, taking into account the trigger, selection, BDT and muon-ID algorithm efficiencies. The magnitude of interest is computed as

$$B(K_S^0 \rightarrow \mu^+\mu^-) = B(K_S^0 \rightarrow \pi^+\pi^-) \cdot \frac{\epsilon_{\mu\mu}}{\epsilon_{\mu\mu}^{\text{sel}}} \cdot \frac{N_{\mu\mu}}{N_{\pi\pi}} \equiv \alpha N_{\mu\mu},$$

where

$$\frac{\epsilon_{\mu\mu}}{\epsilon_{\mu\mu}^{\text{sel}}} = \frac{\epsilon_{\mu\mu}}{\epsilon_{\mu\mu}^{\text{sel}}} \times \frac{\epsilon_{\mu\mu}^{\text{trig}}}{\epsilon_{\mu\mu}^{\text{trig}}} \times \frac{1}{\epsilon_{\mu\mu}^{\text{BDT}}} \times \frac{1}{\epsilon_{\mu\mu}^{\text{ID}}}.$$
Figure 2. Probability to misidentify a pion from $K_S^0 \rightarrow \pi^+\pi^-$ decays as a muon, as a function of its momentum, after applying a requirement based on the muon-ID having a 90% efficiency on real muons.

| Source          | TOS$_\mu$-TOS$_\mu$ | TOS$_\mu$-TOS$_{\mu\mu}$ | TOS$_{\mu\mu}$-TOS$_{\mu\mu}$ | TIS-TIS-TOS$_{\mu\mu}$ |
|-----------------|----------------------|--------------------------|--------------------------|-------------------------|
| Tracking        | 0.4%                 | 0.4%                     | 0.4%                     |                         |
| Selection       | 3.3%                 | 3.9%                     | 1.1%                     |                         |
| Trigger         | 8%                   | 11%                      | -                        |                         |
| K spectrum      | 3.3%                 | 3.3%                     | 3.3%                     |                         |
| Muon ID         | 0.2%                 | 0.3%                     | 0.8%                     |                         |

Table 1. Relevant systematic uncertainties considered in the analysis, split into relative uncertainties on the normalization factors. A relative uncertainty on the signal yield from the signal model used in the mass fit, and an uncertainty on the branching fraction, obtained combining the three categories, from the background model.

The equations (1) and (2) are applied to each of the trigger categories and BDT bins.

3.3. Systematic uncertainties

Several systematic effects contribute to the uncertainty on the normalization factors and the signal shape. In Tab. 1 the different uncertainties which have been taken into account in the fit are shown.

The biggest source of uncertainty comes from the trigger. This arises from the differences between data and Monte-Carlo samples in the transverse momentum of the kaon and its decay vertex radial position. For the category TIS-TIS-TOS$_{\mu\mu}$ no trigger systematic has been computed since the efficiency has been calculated directly from data.
3.4. Fit and limit calculation

A simultaneous maximum likelihood fit has been done to all the trigger categories and BDT bins. The normalization factors are included in the fit so the branching fraction becomes directly observable. The previous LHCb result [7] has been taken into account including a constraint on the branching fraction. There are three different contributions in the di-muon spectra:

- Combinatorial background: parametrized by an exponential function.
- \( K^0_S \rightarrow \pi^+\pi^- \) events with two misidentified pions: described by a power law function.
- \( K^0_S \rightarrow \mu^+\mu^- \) events: parametrized by an Hypatia function [8].

The parameters have been let free for the combinatorial background and the \( K^0_S \rightarrow \pi^+\pi^- \) shapes, while those describing the \( K^0_S \rightarrow \mu^+\mu^- \) peak have been fixed to values extracted from Monte-Carlo samples, leaving free only the yield. As can been seen in Fig. 3, no significant events have been observed in the signal region.

4. Results

Since the value obtained from the branching fraction was compatible with zero, a limit on the branching fraction is obtained. This quantity is computed integrating the posterior probability of the branching fraction, obtained from its – \( \log \mathcal{L} \) profile (see Fig. 4).

The result obtained was

\[
\mathcal{B} \left( K^0_S \rightarrow \mu^+\mu^- \right) < 6.9(5.8) \times 10^{-9} \text{ at } 95(90)\% \text{ CL},
\]

improving by a factor 1.6 the previous LHCb result [7].

Figure 3. Fit to the reconstructed kaon mass distributions for the most sensitive category and BDT bin. The fitted model is shown in blue, and the background components are overdrawn for (orange) combinatorial background and (green) \( K^0_S \rightarrow \pi^+\pi^- \) double misidentification. The pull plot is shown below.
Figure 4. Exclusion confidence level (CL) for each value of the $K^0_S \rightarrow \mu^+ \mu^-$ branching fraction. The regions corresponding to 90% and 95% CL are emphasised in magenta and blue, respectively.

5. Prospects for the Run-II and upgrade

Much effort is being put at LHCb to study strange decays. The new trigger lines for low $p_T$ processes included in the Run-II of the LHC are a benchmark for the study of strange decays using this detector. However, during the new run, the L0 hardware trigger remains unchanged, thus the major source of inefficiency is still present ($\text{eff}_{\text{trigger}} \sim 3\%$). This translates into a limit on the sensitivities of $10^{-10}$ for $K^0_S \rightarrow \mu^+ \mu^-$ during this period. After the LHCb upgrade, there will be no L0 trigger at all, thus efficiencies for strange decays up to $\sim 100\%$ can be reached. Therefore, the most interesting region for the studied decay $B(K^0_S \rightarrow \mu^+ \mu^-)$ will become accessible.

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