



Search for $K_{S(L)}^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ decays at LHCb

LHCb collaboration[†]

Abstract

A search for $K_{S(L)}^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ decays is performed using proton-proton collision data collected by the LHCb experiment at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 5.4 fb^{-1} . No $K_{S(L)}^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ signals are found and upper limits are set for the first time on the branching fractions $\mathcal{B}(K_S^0 \rightarrow \pi^+\pi^-\mu^+\mu^-) < 1.4 \times 10^{-9}$ and $\mathcal{B}(K_L^0 \rightarrow \pi^+\pi^-\mu^+\mu^-) < 6.6 \times 10^{-7}$, at the 90% confidence level.

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1 Introduction

Radiative decays of neutral kaons, in which a virtual photon converts into a Dalitz pair of leptons, provide a powerful laboratory for testing chiral perturbation theories and studying CP violation [1]. In particular, the $K^0 \rightarrow \pi^+ \pi^- \gamma^*$, with $\gamma^* \rightarrow \ell \ell$, decay proceeds through two different processes: inner bremsstrahlung, in which the virtual photon is emitted from the external charged pions; and direct emission, where the photon is generated at the weak vertex (Fig. 1). The CP information is encoded in the photon polarisation and, equivalently, in the distribution of the angle between the dipion and dilepton planes [2]. As the K_L^0 and K_S^0 mesons have opposite CP eigenvalues, the $K_L^0 \rightarrow \pi^+ \pi^- \gamma^*$ and $K_S^0 \rightarrow \pi^+ \pi^- \gamma^*$ decays provide complementary constraints. The short-lived mode is dominated by the $K_S^0 \rightarrow \pi^+ \pi^-$ process with inner bremsstrahlung and gives access to the long-distance (LD) chiral terms, while the long-lived mode is dominated by the direct emission (as the $K_L^0 \rightarrow \pi^+ \pi^-$ decay is heavily suppressed) and grants access to CP -violating terms [2].

Dalitz decays of the electron modes, $K_{S(L)}^0 \rightarrow \pi^+ \pi^- e^+ e^-$, have been observed by the NA48 collaboration. Their branching fractions $\mathcal{B}(K_L^0 \rightarrow \pi^+ \pi^- e^+ e^-) = (3.08 \pm 0.09 \pm 0.18) \times 10^{-7}$, and $\mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^- e^+ e^-) = (4.83 \pm 0.11 \pm 0.14) \times 10^{-5}$ [3, 4], differ by two orders of magnitude, as expected due to the opposite CP eigenvalues [2, 5].

The equivalent muonic mode, $K_{S(L)}^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$, probes higher values of the energy of the emitted photon (q), and thus has larger sensitivity to CP -violating observables where the direct emission contribution is enhanced with respect to the electron mode. The $K_{S(L)}^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ decay is highly suppressed in the Standard Model due to the phase-space limitations presented by the $\sim 7 \text{ MeV}/c^2$ difference in mass between the parent $K_{S(L)}^0$ and the four final-state particles. Theoretical calculations of $\mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-)$ are dominated by LD contributions to the $K_S^0 \rightarrow \pi^+ \pi^- \gamma^*$ decay, and give $\mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-) = (417.00 + 2.17 + 49.80) \times 10^{-16}$ [1], where the first term is due to a bremsstrahlung photon emitted by the pion, the second term accounts for the direct emission of the photon at the weak vertex, and the last term represents their interference. Theoretical calculations for $\mathcal{B}(K_L^0 \rightarrow \pi^+ \pi^- \ell^+ \ell^-)$ have been performed in Ref. [2, 5, 6] for $\ell = e$, but no specific prediction is given for $\mathcal{B}(K_L^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-)$. Experimentally, neither the $K_S^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ nor the $K_L^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ decays have been searched for before.

The LHCb experiment [7] has proven its strong capabilities to study rare kaon decays thanks to its excellent tracking and particle-identification (PID) performance, versatile trigger system and large hadron production rate. The LHCb collaboration has previously

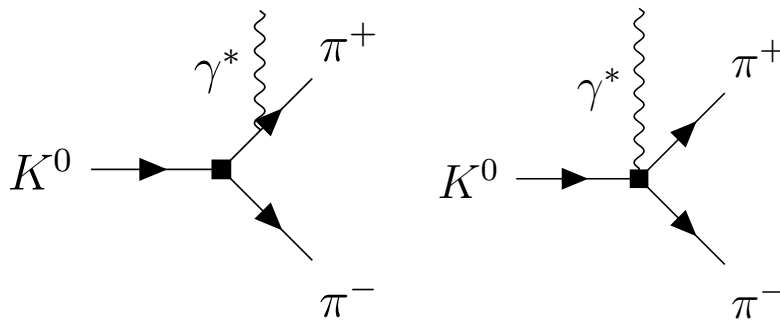


Figure 1: Tree-level diagrams in chiral perturbation theory for the $K^0 \rightarrow \pi^+ \pi^- \gamma^*$ decay with (left) inner bremsstrahlung and (right) direct emission of a γ^* photon.

set world-best upper limits on $\mathcal{B}(K_S^0 \rightarrow \mu^+ \mu^-)$ [8] and $\mathcal{B}(K_{S(L)}^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-)$ [9].

This paper presents the first-ever search for $K_{S(L)}^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$, using proton-proton (pp) collision data collected by the LHCb experiment during 2016–2018 at a centre-of-mass energy of 13 TeV, and corresponding to an integrated luminosity of 5.4 fb^{-1} .

2 Analysis strategy

The branching fractions are measured with respect to the $K_S^0 \rightarrow \pi^+ \pi^-$ decay, according to

$$\mathcal{B}(K_{S(L)}^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-) = \alpha_{S(L)} N_{\pi^+ \pi^- \mu^+ \mu^-}, \quad (1)$$

where the normalisation factor $\alpha_{S(L)}$, or single-event sensitivity,¹ is defined as

$$\alpha_{S(L)} \equiv \mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^-) \frac{\varepsilon_{K_S^0 \rightarrow \pi^+ \pi^-}}{N_{\pi^+ \pi^-} \varepsilon_{K_{S(L)}^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-}}. \quad (2)$$

The parameter $\varepsilon_{K_S^0 \rightarrow \pi^+ \pi^-} (\varepsilon_{K_{S(L)}^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-})$ represents the product of the reconstruction, trigger and selection efficiency of $K_S^0 \rightarrow \pi^+ \pi^-$ ($K_{S(L)}^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$) candidates. The observed number of $K_{S(L)}^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ candidates is $N_{\pi^+ \pi^- \mu^+ \mu^-}$, the observed number of $K_S^0 \rightarrow \pi^+ \pi^-$ candidates is $N_{\pi^+ \pi^-}$, and $\mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^-) = (69.20 \pm 0.05)\%$ [10] is the branching fraction of the normalisation channel. The $K_S^0 \rightarrow \pi^+ \pi^-$ normalisation channel is selected due to its abundant rate. Furthermore, it enables cancellation of the K^0 production rate and reduces systematic uncertainties related to final-state particle reconstruction.

At LHCb, the $K_L^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ and $K_S^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ decays are indistinguishable on an event-by-event basis [7]. For this reason, the K_L^0 contribution is not considered when setting the upper limit for $K_S^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$, and vice versa. As a consequence, the set upper limits are more conservative than they would be if the K_S^0 and K_L^0 modes could be distinguished. The LHCb acceptance for K_L^0 decays is $\sim 2 \times 10^{-3}$ times that of the K_S^0 modes [7]. The only relevant difference between $K_S^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ and $K_L^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ at reconstruction level is the lifetime. As a consequence, the selection strategy is optimized for $K_S^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ decays and then applied to $K_L^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ decays.

3 LHCb detector and trigger

The LHCb detector [11, 12] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector used for this analysis includes a high-precision tracking system consisting of a silicon-strip vertex detector (VELO) surrounding the pp interaction region [13], a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 T m, and three stations of silicon-strip detectors and straw drift tubes [14] placed downstream of the magnet. The tracking system provides a measurement of the momentum (p), of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV/ c . The minimum distance of a track to a pp collision vertex (PV), the impact parameter (IP), is measured with a resolution of $(15 + 29/p_T) \mu\text{m}$, where p_T is the

¹The value of $\mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-)$ corresponding to one signal event seen in the data sample.

component of the momentum transverse to the beam axis, in GeV/ c . Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov (RICH) detectors [15]. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers [16]. In addition, information from the tracking system, the calorimeter system and the RICH detectors is used to further improve the muon identification.

Events are first filtered by a hardware trigger, known as L0 [17], which uses information from the calorimeter and the muon system to select muon candidates with p_T above a few GeV/ c . Subsequently, a full event reconstruction is applied in the High Level Trigger (HLT), which is subdivided into two steps, HLT1 and HLT2. The HLT1 algorithms for strange decays were improved in 2016 [18, 19], boosting the efficiency of the $K_S^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ channel, amongst others. For this reason, only the 2016–2018 data is considered in this measurement. In the offline selection, trigger signals are associated with reconstructed particles. Selection requirements can therefore be made on the trigger selection itself and on whether the decision was due to the signal candidate (trigger on signal, TOS) or other particles produced in the pp collision (trigger independent of signal, TIS). To enhance the L0 trigger efficiency, events fulfilling either the TIS or TOS requirements are considered in this analysis. The $K_S^0 \rightarrow \pi^+\pi^-$ normalisation channel candidates are reconstructed from data selected by a trigger line requiring only the presence of a pp interaction, providing an unbiased representation of the collision. The triggered data further undergo a centralised, offline processing step [20].

Simulation is used to model the effects of the detector acceptance and selection requirements. In the simulation, pp collisions are generated using PYTHIA 8 [21, 22] with a specific LHCb configuration [23]. Decays of unstable particles are described by EVTGEN [24], in which final-state radiation is generated using PHOTOS [25]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [26, 27] as described in Ref. [28]. The simulated samples are corrected to account for known data-simulation differences in the K_S^0 production kinematics, as well as the track reconstruction and PID efficiencies. The analysis strategy is developed using $K_S^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ simulated samples. Given the K_L^0 decay only differs due to its lifetime, the $K_L^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ efficiency is obtained by weighting the decay time distribution of the simulated $K_S^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ sample to match that of the K_L^0 meson.

4 Signal selection

This measurement benefits from the large kaon production cross-section at the LHC, approximately 0.3 b for both K_S^0 and K_L^0 mesons [7], as well as from the forward production of kaons, which fall within the LHCb detector acceptance. The K_S^0 candidates from both the signal and the normalisation channels are required to originate from a PV. In case of multiple choices, the PV that fits best to the flight direction of the K_S^0 candidate is chosen as the associated PV. Candidate $K_S^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ decays are reconstructed by combining pairs of oppositely charged well-identified muons and pions originating from a common vertex, displaced from the PV. Candidates with an invariant mass in the region $490 < m(\pi^+\pi^-\mu^+\mu^-) < 600 \text{ MeV}/c^2$ are retained for further analysis. In order to avoid

experimenter's bias, selected candidates in the region $490 < m(\pi^+\pi^-\mu^+\mu^-) < 510 \text{ MeV}/c^2$, which contains approximately 97% of the signal, were removed from the data sample until the analysis procedure had been finalised.

Given the relatively long lifetime of the K_S^0 meson, only about a third of its decays occur inside the VELO, while the remainder take place downstream in the detector. Decays inside the VELO can be reconstructed with an invariant-mass resolution roughly twice as good as those outside. Moreover, the online event selection relies on tracks with hits in both the VELO and the downstream tracking stations. Consequently, only decays taking place inside the VELO are retained in this analysis.

Several selections are applied to reconstructed candidates in order to further reduce background contributions. These include requirements on the maximum distance of closest approach between any pair of the four signal tracks, the flight distance from the PV of the K_S^0 candidate on the plane transverse to the beam direction, the angles between the two muon and the two pion tracks, and PID variables of the final-state pions and muons.

The only non-negligible background source in the signal channel arises from random combinations of tracks, which originate from a pp interaction region or from inelastic interactions of the products of the pp collision with the detector material. A boosted decision tree (BDT) [29, 30] classifier implemented in the XGBOOST package [31] is used to further separate signal from combinatorial background. One BDT per trigger category (TIS and TOS) is used, each including as discriminating variables:

- the significance of the distance between the candidate decay vertex and any element of the VELO material [32];
- the smallest IP value of each of the muon and pion candidates with respect to any of the PVs reconstructed in the event;
- the smallest IP value of the K_S^0 candidate to any of the PVs reconstructed in the event;
- the difference in χ^2 of the PV fit when the K_S^0 candidate is or is not included;
- the transverse displacement of the K_S^0 decay vertex from the beam line;
- the maximum distance of closest approach between any pair of the four final-state tracks.

The BDT is trained with simulated $K_S^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ decays as a proxy for the signal, and $\pi^+\pi^-\mu^+\mu^-$ combinations with an invariant mass $m(\pi^+\pi^-\mu^+\mu^-) > 510 \text{ MeV}/c^2$ as a proxy for background. To mitigate the effects of statistical fluctuations and minimise overtraining, the k -fold method [33], with $k = 6$, is used during the training.

The BDT requirement is optimized for the best expected upper limit at the 90% confidence level (CL) using pseudoexperiments, performing fits as explained below. The BDT requirement corresponds to a signal efficiency of approximately 80% (95%) for the TIS (TOS) sample, and a background suppression above 99.9%. After the BDT selection requirement, in the case of multiple candidates per event, a single candidate is chosen arbitrarily.

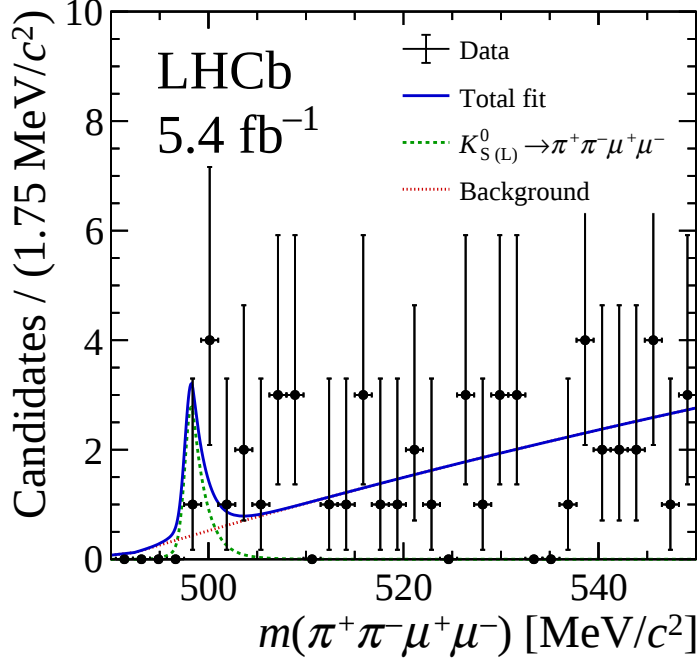


Figure 2: Invariant-mass distribution of selected $K_{S(L)}^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ candidates in the TIS and TOS trigger categories combined. The blue lines show the result of a simultaneous fit to both categories.

5 Fit model and normalisation decay mode

The signal yield $N_{\pi^+\pi^-\mu^+\mu^-}$ is obtained from a simultaneous, extended unbinned maximum-likelihood fit to the four-track invariant-mass distributions of the signal candidates in the two trigger categories. The invariant-mass distributions of the selected candidate events, and the result of the described mass fit are shown in Fig. 2. The kinematics of the $K_S^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ decay is such that no physical candidates below the production threshold of $\pi^+\pi^-\mu^+\mu^-$ can exist. To account for this, the invariant-mass distribution of the background follows the distribution of the available momentum in a two-body $K_S^0 \rightarrow (\pi^+\pi^-)(\mu^+\mu^-)$ decay. This distribution is modelled by a function with only one free parameter which dictates the kinematic threshold of the candidates,

$$Q(m, A) = \frac{[(m - A)^2 - (2m_\mu + 2m_\pi)^2][(m - A)^2 - (2m_\mu - 2m_\pi)^2]}{4(m - A)^3}, \quad (3)$$

where m is the four-track invariant mass $m(\pi^+\pi^-\mu^+\mu^-)$, and A is its minimum value, which can exceed the sum of the masses of the two pions and two muons due to the requirements on the minimum angle between the decay products. The background model is validated on background-enriched data obtained by loosening the BDT selection requirement. The $K_S^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ signal invariant-mass shape is parametrised by the sum of two Crystal Ball (CB) functions [34], with the same peak position, and power-law tails on opposite sides of the distribution. The parameter values of the signal distribution are obtained from simulated events with corrections obtained from a fit $K_S^0 \rightarrow \pi^+\pi^-$ decays in data, following Ref. [8].

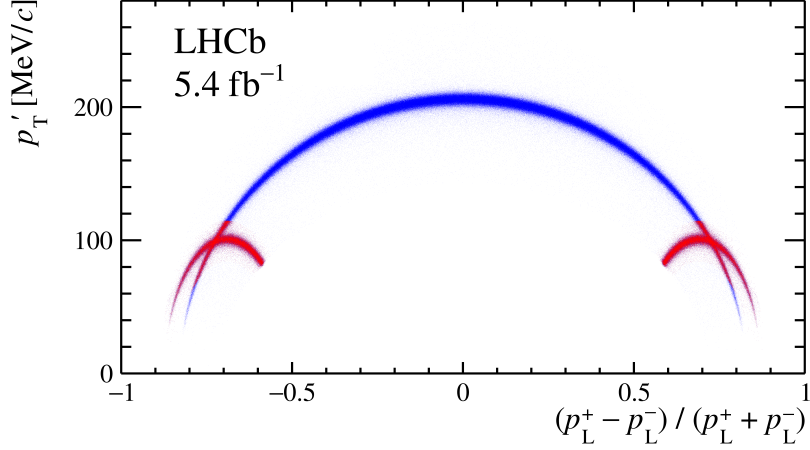


Figure 3: Distribution of selected $K_S^0 \rightarrow \pi^+\pi^-$ candidates in data in the Armenteros–Podolanski plane. The variables of the plane are the longitudinal momentum asymmetry between the positively (p_L^+) and negatively (p_L^-) charged pions, and the transverse momentum of the pions with respect to the K_S^0 flight direction, p_T' . The blue region, containing $K_S^0 \rightarrow \pi^+\pi^-$ decays, is accepted, while the red regions, containing background from $\Lambda \rightarrow p\pi^-$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ decays, are rejected.

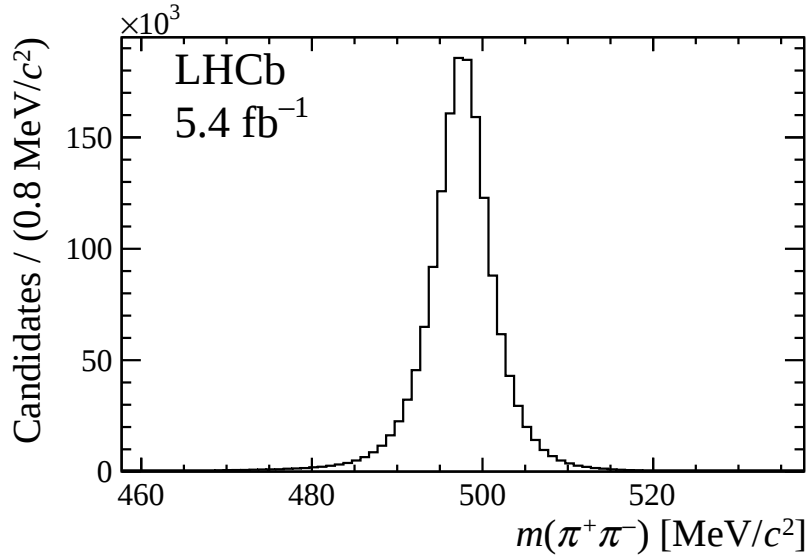


Figure 4: Invariant-mass distribution of the selected $K_S^0 \rightarrow \pi^+\pi^-$ candidates.

The $K_S^0 \rightarrow \pi^+\pi^-$ candidates, selected by combining two well-identified pions with opposite charge originating from a common vertex, are further restricted to specific regions of the Armenteros–Podolanski plane [35] in order to suppress contributions from $\Lambda \rightarrow p\pi^-$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ decays, as seen in Fig. 3. The $N_{\pi^+\pi^-}$ value is determined as the number of candidates in the mass range $400 < m(\pi^+\pi^-) < 600 \text{ MeV}/c^2$. Due to the negligible background contribution after the selection in the $K_S^0 \rightarrow \pi^+\pi^-$ sample, as illustrated by Fig. 4, no fit to the invariant-mass distribution is performed to determine the number of $K_S^0 \rightarrow \pi^+\pi^-$ decays.

The efficiencies are assumed to factorise according to

$$\varepsilon = \varepsilon^{\text{reco}} \varepsilon^{\text{sel/reco}} \varepsilon^{\text{trig/sel}}. \quad (4)$$

Here $\varepsilon^{\text{reco}}$ is the reconstruction efficiency, $\varepsilon^{\text{sel/reco}}$ is the selection efficiency for the reconstructed signal candidates, and $\varepsilon^{\text{trig/sel}}$ is the trigger efficiency. The $\varepsilon^{\text{reco}}$ efficiency includes track and vertex reconstruction effects and is estimated from simulation to be $\sim 0.2\%$ for $K_S^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ decays. The $\varepsilon^{\text{sel/reco}}$ efficiency includes the BDT and PID requirements and is estimated to be around 7% for $K_S^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ decays. Lastly, the $\varepsilon^{\text{trig/sel}}$ efficiency is determined to be around 1% for $K_S^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ decays. The efficiencies are calculated using simulation samples with corrections derived from $K_S^0 \rightarrow \pi^+\pi^-$ decays in data. The tracking efficiency is obtained using dedicated control samples of $J/\psi \rightarrow \mu^+\mu^-$ and $K_S^0 \rightarrow \pi^+\pi^-$ decays using a tag-and-probe method [36]. Similarly, PID efficiencies are obtained using calibration samples of low-momentum muons from $J/\psi \rightarrow \mu^+\mu^-$ decays collected concurrently with the data used for the analysis. The trigger efficiencies obtained in simulation are validated with $K^0 \rightarrow \pi^\pm \mu^\mp (\bar{\nu}_\mu)$ decays, by comparing the trigger efficiency in simulation and data, as described in Ref. [8]. The simulated samples used to compute the efficiencies are generated assuming the decay amplitude is uniform over the phase space of the K_S^0 particle without accounting for the presence of any intermediate resonances. The obtained efficiencies are verified to be independent of such effects. The efficiency for the $K_L^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ decay is derived using the same procedure applied to $K_S^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ simulated samples, weighted to reproduce the K_L^0 lifetime, as mentioned in Sec. 3.

6 Systematic uncertainties

Table 1 shows the sources of systematic uncertainty on α_S considered in this analysis. The systematic uncertainties are incorporated into the fit of the signal-candidate mass distribution as Gaussian priors on the single event sensitivity. For convenience, sources of systematic uncertainty are separated into those acting independently on each trigger category and those affecting the overall normalisation factor.

A 1% systematic uncertainty on the efficiencies accounts for minor modifications of the trigger selection criteria throughout the Run 2 data-taking period. These are

Table 1: Summary of the sources of systematic uncertainty, as well as their relative effect on the single event sensitivity, α_S .

Source	Relative effect (%)
Variations in data taking	1
Data/simulation differences	9
$K_S^0 \rightarrow \pi^+\pi^-$ yield	1
PID	2
Tracking	2
L0	9 (TIS), 11 (TOS)
HLT	13
Total	18 (TIS), 19 (TOS)

determined by comparing the yields of triggered $K^0 \rightarrow \pi^\pm \mu^\mp (\bar{\nu}_\mu)$ and $K_S^0 \rightarrow \pi^+ \pi^-$ decays from the trigger-unbiased data. To compute the systematic uncertainty associated with the corrections applied to the simulation, the efficiency ratio is recomputed with and without corrections on the kaon momenta. Half of the correction is taken as the systematic uncertainty and amounts to a 9% effect on $\alpha_{S(L)}$. The systematic uncertainty on the $K_S^0 \rightarrow \pi^+ \pi^-$ yield is evaluated by comparing the number of selected $K_S^0 \rightarrow \pi^+ \pi^-$ candidates in data with the yield obtained from a fit to the $\pi^+ \pi^-$ invariant mass with a floating background component modelled as an exponential function. A 1% systematic uncertainty contribution is found to cover any variation. The uncertainty on the PID efficiency corrections is propagated to the ratio of efficiencies and gives an additional 2% systematic uncertainty. The differences between data and simulation in the track reconstruction efficiencies, determined using control channels from data, are covered by a 2% systematic uncertainty. The L0 and HLT efficiencies for the $K_S^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ signal are determined using $K^0 \rightarrow \pi^\pm \mu^\mp (\bar{\nu}_\mu)$ decays as control modes. The efficiencies are found to be compatible between data and simulation, and their difference is used as the systematic uncertainty, following Ref. [8]. The $K^0 \rightarrow \pi^\pm \mu^\mp (\bar{\nu}_\mu)$ sample at LHCb is composed of K_S^0 and K_L^0 in similar amounts, due to a compensation between the different branching fractions [37–39], and the different reconstruction efficiency driven by the decay-time acceptance, which produces similar decay-time distributions for reconstructed K_L^0 and K_S^0 decays. A systematic uncertainty of 1.4% is added to the relative efficiency between $K_S^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ and $K_L^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ decays, when measuring $\mathcal{B}(K_L^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-)$. This systematic uncertainty covers the difference of the efficiency ratio across the data-taking period as well as uncertainties related to the limited simulation sample size. The systematic uncertainties from the signal and background invariant-mass models are negligible at the current level of precision. The uncertainty on the branching fraction $\mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^-) = (69.20 \pm 0.05)\%$ induces a 0.07% uncertainty on $\alpha_{S(L)}$, also considered negligible.

7 Results and conclusions

The number of selected $K_S^0 \rightarrow \pi^+ \pi^-$ decays is found to be $(8.79 \pm 0.11) \times 10^{12}$. The efficiency ratios, $\varepsilon_{K_S^0 \rightarrow \pi^+ \pi^-} / \varepsilon_{K_S^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-}$, are determined to be $(2.9 \pm 0.3) \times 10^3$ and $(5.4 \pm 0.5) \times 10^3$ for the TIS and TOS categories, respectively. The obtained normalisation factors are $\alpha_S^{\text{TIS}} = (2.27 \pm 0.42) \times 10^{-10}$ and $\alpha_S^{\text{TOS}} = (4.21 \pm 0.81) \times 10^{-10}$, assuming that the muons and pions are uniformly distributed in phase space for $K_S^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ decays. The normalisation factors, α_{TIS} and α_{TOS} , are derived for the $K_L^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ decay, using Eq. 2, and the efficiency for $K_L^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ decays, computed as described in Sec. 5.

The final data is consistent with the background-only hypothesis at the level of 1.9 standard deviations, showing no evidence for a signal. Upper limits are set, at 90% CL, by integrating the exponent of the negative profiled log-likelihood up to 90% of its total area, validated using pseudoexperiments. The upper limits are determined to be:

$$\begin{aligned} \mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-) &< 1.4 \times 10^{-9}, \\ \mathcal{B}(K_L^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-) &< 6.6 \times 10^{-7}, \end{aligned}$$

where the limit on each decay mode assumes the absence of the other.

In summary, a search for the $K_{S(L)}^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ decays has been performed using pp collision data recorded at LHCb between 2016 and 2018, corresponding to an integrated luminosity of 5.4 fb^{-1} . No evidence for signal is found, and an upper limit for each mode is reported for the first time.

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