

Prospects for the search of $K_S^0 \rightarrow \pi^+ \pi^- e^+ e^-$ at LHCb

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Abstract. The feasibility of observing the $K_S^0 \rightarrow \pi^+ \pi^- e^+ e^-$ decay at LHCb is studied using simulated and real data. During the Run I of LHC, the yield of events expected per fb^{-1} of pp collisions at $\sqrt{s} = 8$ TeV is found to be $N_{RunI}(K_S^0 \rightarrow \pi^+ \pi^- e^+ e^-) = 120_{-100}^{+280}$. A dedicated trigger selection has been developed for the 2016 data-taking. A large signal yield, $N_{Upgrade}(K_S^0 \rightarrow \pi^+ \pi^- e^+ e^-) = (5.0 \pm 0.3) \times 10^4$ per fb^{-1} , is expected in the LHC upgrade phase. Pseudoexperiments have been run to assess the feasibility of discovering evidence for the observation of the signal already in the Run I data-set.

1. Introduction

LHCb has proved to be very competitive in the search for rare strange decays, the most recent proof of this being the new results and prospects presented at this conference. Among the decays of interest one can find $K_S^0 \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$ where $\ell^{(\prime)}$ can be either an electron or a muon.

These decays have never been observed and no experimental limits are available in the literature [1]. The predicted branching fractions in the Standard Model (SM) are of the order [2]:

$$\begin{aligned} \mathcal{B}(K_S^0 \rightarrow e^+ e^- e^+ e^-) &\sim 10^{-10} \\ \mathcal{B}(K_S^0 \rightarrow \mu^+ \mu^- e^+ e^-) &\sim 10^{-11} \\ \mathcal{B}(K_S^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-) &\sim 10^{-14} \end{aligned} \quad (1)$$

The introduction of possible New Physics (NP) terms in the amplitude calculation could lead to dominant contributions. Therefore, any experimental deviation from the SM predicted values would be a hint of contributions from NP. Moreover, the measurement of the time interference of $K_L^0 \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$ with $K_S^0 \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$ would allow stringent CKM tests.

For those decays containing electrons in the final state the reconstruction of the electrons is the most challenging issue at LHCb, due to the low momentum they have in this decay and the large energy loss they suffer by bremsstrahlung.

Preliminary analysis on simulated data allow to study the expected mass resolution and displacement of the mass peak due to the energy loss of the electrons. For $K_S^0 \rightarrow \mu^+ \mu^- e^+ e^-$, $K_S^0 \rightarrow \pi^+ \pi^- e^+ e^-$ events are used as a proxy given the similar topology. A simple fit with a double sided Crystal-Ball [3] to $K_S^0 \rightarrow e^+ e^- e^+ e^-$ and $K_S^0 \rightarrow \pi^+ \pi^- e^+ e^-$ simulated events is shown in Figure 1.

In addition to the mass resolution, the expected overlap with the copious background $K_S^0 \rightarrow \pi^+ \pi^- e^+ e^-$ with the two pions misidentified as electrons or muons is also checked. For this, $K_S^0 \rightarrow \pi^+ \pi^- e^+ e^-$ simulated events are reconstructed changing the mass hypothesis of the two pions to two electrons and two muons, respectively. Figure 2 shows these distributions



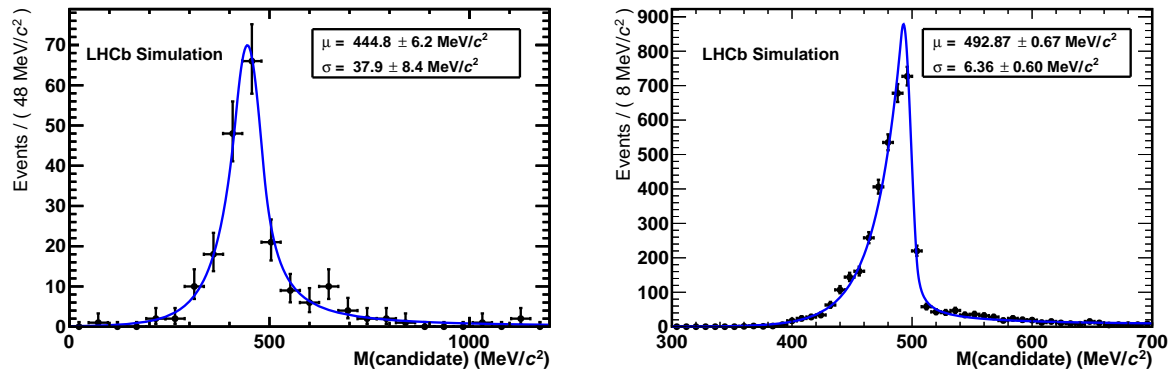


Figure 1. Mass distributions for reconstructed $K_S^0 \rightarrow e^+e^-e^+e^-$ (left) and $K_S^0 \rightarrow \pi^+\pi^-e^+e^-$ (right) simulated events. The continuous line shows a fit with a double sided Crystal-Ball function.

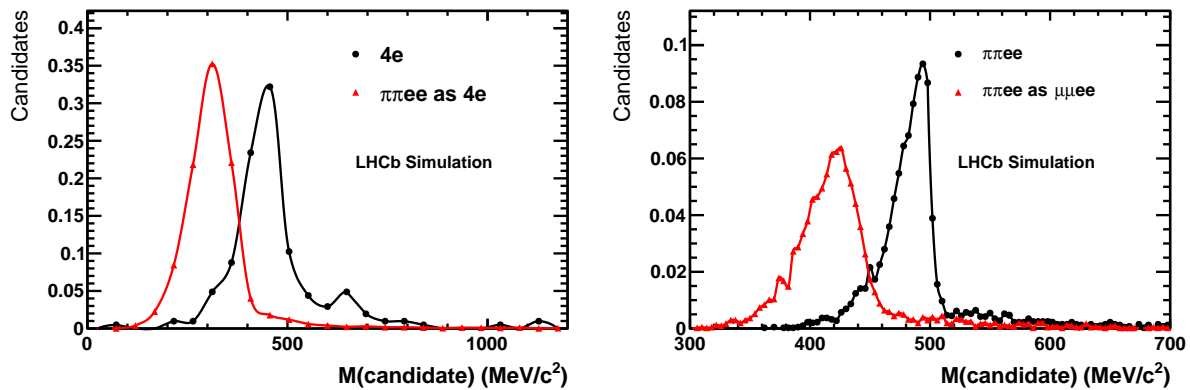


Figure 2. Mass distributions for reconstructed $K_S^0 \rightarrow e^+e^-e^+e^-$ and $K_S^0 \rightarrow \pi^+\pi^-e^+e^-$ simulated events under the $e^+e^-e^+e^-$ mass hypothesis (left) and reconstructed $K_S^0 \rightarrow \pi^+\pi^-e^+e^-$ simulated events under the $\pi^+\pi^-e^+e^-$ and $\mu^+\mu^-e^+e^-$ mass hypothesis (right).

overlaid with the $K_S^0 \rightarrow e^+e^-e^+e^-$ and $K_S^0 \rightarrow \pi^+\pi^-e^+e^-$ reconstructed mass. It can be seen that the signal peaks can be discriminated from the $K_S^0 \rightarrow \pi^+\pi^-e^+e^-$ one thanks to the good mass resolution. Nevertheless, the tails of the distributions overlap and therefore it becomes necessary to have this decay under complete control before being able to set a limit on the signal channels.

In addition, the $K_S^0 \rightarrow \pi^+\pi^-e^+e^-$ decay is the most obvious candidate as normalisation channel for the leptonic 4-body final states, given the similar topology to the signal channels with four tracks including a di-electron in the final state. Moreover, this channel is interesting by itself as a place to look for new light dark matter states decaying dominantly to a pair of leptons that would peak in the di-electron invariant mass [4]. An example could be the search for dark photons using a strategy similar to the one proposed in [5], which has become of great interest after recent hints of a light new boson decaying to a e^+e^- pair [6]. The feasibility of observing the $K_S^0 \rightarrow \pi^+\pi^-e^+e^-$ decay at LHCb is presented in this study.

The NA48 collaboration has observed and measured the $\mathcal{B}(K_S^0 \rightarrow \pi^+\pi^-e^+e^-)$. The current world average for this observable, $\mathcal{B}(K_S^0 \rightarrow \pi^+\pi^-e^+e^-) = (4.79 \pm 0.15) \times 10^{-5}$ [1], is used in this study to assess the feasibility of observation at LHCb.

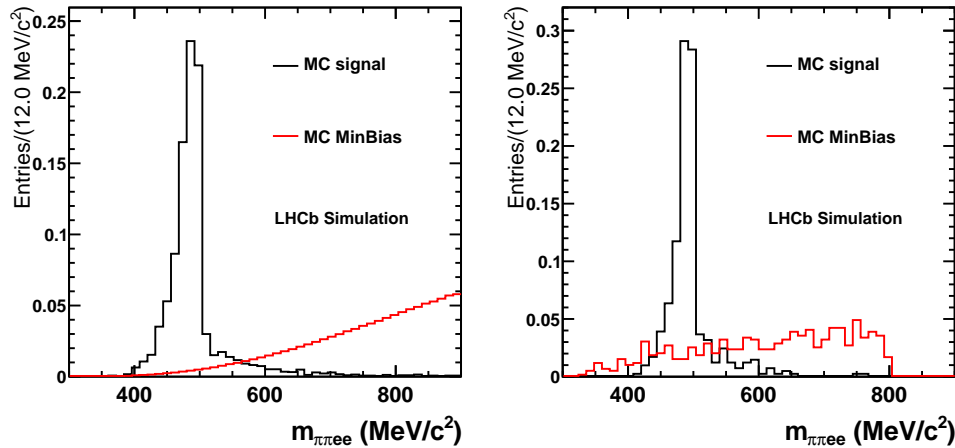


Figure 3. Invariant $\pi^+\pi^-\mathrm{e}^+\mathrm{e}^-$ mass distribution for $\mathrm{K}_\mathrm{s}^0 \rightarrow \pi^+\pi^-\mathrm{e}^+\mathrm{e}^-$ (grey) and minimum bias (red) reconstructed MC candidates before (left) and after (right) the offline selection.

2. $\mathrm{K}_\mathrm{s}^0 \rightarrow \pi^+\pi^-\mathrm{e}^+\mathrm{e}^-$ at LHCb

This study is based on simulated data reproducing the conditions of the 2012 LHCb data-taking. Moreover, some studies are also performed on a data sample corresponding to 2 fb^{-1} of integrated luminosity at $\sqrt{s} = 8 \text{ TeV}$ collected by LHCb during 2012. The efficiency of the reconstruction, the selection and the trigger is obtained from the MC sample. This allows to extract the expected signal yield while the background level is estimated from data. Possible improvements on the trigger side are studied for Run II of the LHC and beyond and the expected signal yield is recomputed taking them into account. Finally, we assess the feasibility of observing this decay at LHCb already with Run I data.

2.1. Reconstruction, selection and trigger

The reconstruction performance for this decay is evaluated by requiring the reconstructed particles to match the MC generated signal. The efficiency of this matching is found to be $\epsilon_{\text{reco}}^{\text{sig}} = (0.134 \pm 0.002) \%$. The $\pi\pi\mathrm{e}\mathrm{e}$ invariant mass distribution for reconstructed signal and background MC is shown in Figure 3 left. An offline selection based on linear cuts is defined exploiting the topology of the decay. Loose momentum and transverse momentum and large displacement from the interaction vertex are combined with track quality and particle identification requirements. The full selection is detailed in [7] and the invariant mass distribution for candidates fulfilling it can be found in the right plot of Figure 3. The selection efficiency for signal and minimum bias MC samples is $\epsilon_{\text{sel}}^{\text{sig}} = (10.1 \pm 0.5) \times 10^{-2}$ and $\epsilon_{\text{reco,sel}}^{\text{bkg}} = (2.95 \pm 0.12) \times 10^{-5}$, respectively. In the second case, the reconstruction efficiency is included here.

No specific trigger selection was present during the Run I data-taking to select $\mathrm{K}_\mathrm{s}^0 \rightarrow \pi^+\pi^-\mathrm{e}^+\mathrm{e}^-$ decays. Thus, the LHCb trigger efficiency to select this decay is evaluated on signal and minimum bias simulated events that satisfy the offline selection as an OR of all the physics selections that were present in the trigger in Run I [8]. The total trigger efficiency is found to be $\epsilon_{\text{trig}}^{\text{sig}} = (0.24^{+0.56}_{-0.20}) \%$ and $\epsilon_{\text{trig}}^{\text{bkg}} < 0.51 \%$ for signal and background, respectively. In the second case, since no events are selected in the MC sample a limit is set on the efficiency assuming the number of selected events is < 3 at 90 % CL.

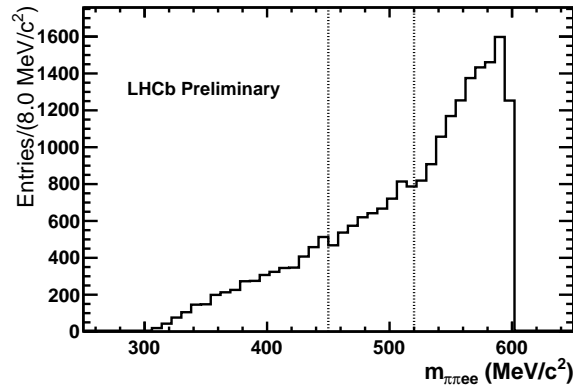


Figure 4. Invariant $\pi^+\pi^-e^+e^-$ mass distribution for candidates satisfying the offline selection and trigger requirements. The signal region, $450 - 520 \text{ MeV}/c^2$, is delimited by dashed lines.

2.2. Expected yields in Run I

The expected yields are obtained in a tight mass window, $450 - 520 \text{ MeV}/c^2$, selecting $(76.9 \pm 1.8) \%$ of the signal and $(4.33 \pm 0.02) \%$ of the background. The expected signal yield can be computed from the following expression:

$$N_{exp}^{sig} = N(K_S^0/\text{fb}^{-1}) \cdot \mathcal{B}(K_S^0 \rightarrow \pi^+\pi^-e^+e^-) \cdot \epsilon^{sig} \quad (2)$$

where $N(K_S^0/\text{fb}^{-1}) \sim 10^{13}$ is the number of K_S^0 mesons decaying inside the LHCb acceptance [9], $\mathcal{B}(K_S^0 \rightarrow \pi^+\pi^-e^+e^-) = (4.79 \pm 0.15) \times 10^{-5}$ [1] is the world average branching ratio for this decay and $\epsilon^{sig} = \epsilon_{reco}^{sig} \cdot \epsilon_{sel}^{sig} \cdot \epsilon_{trig}^{sig} \cdot \epsilon_{mass}^{sig}$. The expected signal yield per fb^{-1} of LHCb data at 8 TeV is found to be:

$$N_{exp}^{sig} = 120_{-100}^{+280}$$

where the uncertainty is dominated by the MC statistics.

A similar technique can be used to estimate the expected background yield from MC:

$$N_{exp}^{bkg} = \sigma_{tot} \cdot \epsilon^{bkg} \quad (3)$$

where $\sigma_{tot} = (94.6 \pm 0.3) \text{ mb}$ is the total cross-section simulated in the MC minimum bias sample and $\epsilon^{bkg} = \epsilon_{reco,sel}^{bkg} \cdot \epsilon_{trig}^{bkg} \cdot \epsilon_{mass}^{bkg}$. The expected background yield after the full selection is:

$$N_{exp}^{bkg} < 6.1 \times 10^5$$

per fb^{-1} at 90 % CL.

2.3. Studies on data

The full selection defined in Section 2.1 is applied to the 2012 LHCb dataset corresponding to an integrated luminosity of 2 fb^{-1} . The resulting $\pi^+\pi^-e^+e^-$ invariant mass distribution is shown in Figure 4. Since no evidence for a signal peak is observed, this contribution is assumed to be negligible. With this assumption the background level in the signal region amounts to:

$$N_{obs}^{bkg} \sim 6 \times 10^3$$

which is compatible with the expectations from the MC study.

2.4. Expected yields in Run II and beyond

A new trigger selection has been developed in order to inclusively select K_S^0 decays into a di-electron pair. The requirements follow the offline selection presented in Section 2.1. This configuration started running in the LHCb trigger at the beginning of the 2016 data-taking.

The efficiency of the new configuration is estimated on the MC sample in 2012 conditions since no sample in Run II conditions is available. The total trigger efficiency with the new selection is $\epsilon_{trig}^{sig} = (0.24_{-0.20}^{+0.56})\%$.

Assuming no other improvements have been achieved in Run II and also neglecting the increase in the K_S^0 production cross section and flight distance from 8 to 13 TeV, the expected yield per fb^{-1} in Run II is:

$$N_{RunII}^{sig} = 120_{-100}^{+280}$$

where the uncertainty is dominated by the MC statistics.

Although the Run I and Run II trigger selections have the same efficiency selecting the signal channel, they use complementary approaches. Thus combining both would lead to an increase in the trigger efficiency for this decay.

Beyond the LHC Run II, during its upgrade phase, the LHCb trigger will be fully based on software [10]. This will allow to have many exclusive selections exploiting the full event reconstruction at trigger level. In the ideal scenario a signal efficiency of $\sim 100\%$ can be achieved. With this assumption, the yield of $K_S^0 \rightarrow \pi^+ \pi^- e^+ e^-$ per fb^{-1} is expected to be:

$$N_{upgrade}^{sig} = (5.0 \pm 0.3) \times 10^4$$

2.5. Observation feasibility with Run I data

Taking into account the expected signal, $N_{exp}^{sig} \sim 240$, and observed background, $N_{obs}^{bkg} \sim 6 \times 10^3$, in the 2012 LHCb dataset it might be possible to observe this decay with the current data sample by means of a high-efficiency large-rejection further selection. A multivariate (MVA) selection would be appropriate in this case. Other dedicated tools for the selection of low momentum electrons could help to further discriminate signal from background.

In order to study the possibility of an observation or evidence in a more quantitative way, a study based on pseudoexperiments has been performed. It is based on the expected signal and observed background yields in the signal region, together with the corresponding mass Probability Density Functions (PDFs). A detailed description of the study is presented in [7]. The main result can be found in Figure 5, where the signal efficiency vs. background rejection curves needed to obtain a 3σ evidence or 5σ observation of the decay are represented. Notice that the working point for the selection presented in Section 2.1, corresponding to 100% signal efficiency and 0% background rejection, is found way below the curves, confirming the selected data sample is not statistically significant. However, both curves are well within the usual discrimination achieved by standard MVA selections, which reinforces the conclusion that an evidence or observation could be possible using only Run I data.

3. Conclusions

The feasibility of observing the $K_S^0 \rightarrow \pi^+ \pi^- e^+ e^-$ decay at LHCb has been studied using MC and data samples in Run I conditions. The expected signal yield per fb^{-1} of data at 8 TeV is found to be:

$$N_{RunI}^{exp}(K_S^0 \rightarrow \pi^+ \pi^- e^+ e^-) = 120_{-100}^{+280} \quad (4)$$

where the uncertainty is dominated by the MC statistics.

No hint of signal is observed in the 2012 LHCb dataset corresponding to an integrated luminosity of 2 fb^{-1} while the total background amounts to:

$$N_{RunI}^{obs}(bkg) \sim 6 \times 10^3 \quad (5)$$

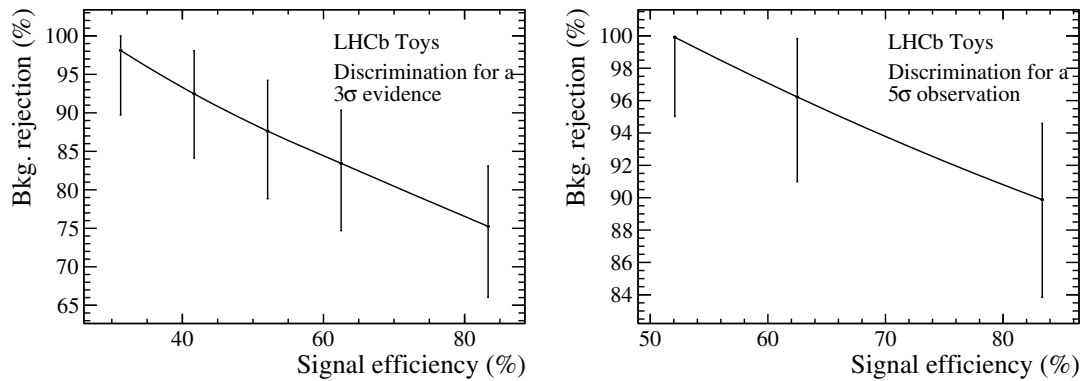


Figure 5. Signal efficiency vs. background rejection curves needed to obtain a 3σ evidence (left) or 5σ observation (right) of $K_S^0 \rightarrow \pi^+\pi^-e^+e^-$ using the 2012 LHCb dataset. The error bars correspond to 68% C.L. variation in the toys for each expected signal yield.

A dedicated trigger selection has been developed for the 2016 data-taking. Its efficiency is expected to be the same as in Run I. Since a complementary approach is used, the combination of both could improve the efficiency for Run II.

In the LHC upgrade phase with a full software trigger at LHCb, a signal efficiency of $\sim 100\%$ can be achieved. Under this assumption the signal yield per fb^{-1} is expected to be:

$$N_{U\text{pgrade}}(K_S^0 \rightarrow \pi^+\pi^-e^+e^-) = (5.0 \pm 0.3) \times 10^4$$

Pseudoexperiments have been run with the expected signal and observed background yields in the 2012 data-set to obtain the signal efficiency vs background rejection curves needed in order to assess an evidence or observation for this decay. Both are well within the usual discrimination achieved by standard MVA selections, which reinforces the conclusion that an evidence or observation could be possible using only Run I data. During the upgrade phase the large expected signal yield would allow to set stringent constraints in the $K_S^0 \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ decays and search for peaks in the di-electron invariant mass distribution of the signal.

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