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Prospects for the search of $K^0_S \to \pi^0\mu^+\mu^-$ at LHCb

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Abstract. The sensitivity of the LHCb experiment to $\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-)$ is analyzed in light of the 2011, 2012 and 2016 data and the oportunity of having a full software trigger with the LHCb upgrade. Two strategies are considered: the full reconstruction of the decay products and the partial reconstruction using only the dilepton pair and kinematic constraints. In both cases, the sensitivity achieved can surpass the world's current best measurement. Both approaches could be statistically combined to further improve the result.

1. Physics Motivation

Kaons play a major role in particle physics, both for Standard Model (SM) and for New Physics searches. If this New Physics stands at energies higher than the TeV its effect in quark flavour physics would be visible only with new sources of Flavour Violation not originating from the Yukawa couplings (non Minimal Flavour Violating, non-MFV). In this scenario, the $s \to d$ decay processes (see Fig. 1) play a central role. This is because they have the strongest CKM suppression factor of all quark transitions, which makes them particularly sensitive to non-MFV sources. Among these transitions, the decay ($K^0_L \to \pi^0\mu^+\mu^-$) is shown to be sensitive to, for example, models with extra dimensions [1]. However, the potential for this decay to constrain scenarios beyond the Standard Model is limited by the large SM uncertainty on its branching fraction prediction [1]:

$$\mathcal{B}(K^0_L \to \pi^0\mu^+\mu^-)_{\mathrm{SM}} = 1.4 \pm 0.3 \times 10^{-11} \quad (1)$$

$$\mathcal{B}(K^0_L \to \pi^0\mu^+\mu^-)_{\mathrm{SM}} = 0.9 \pm 0.2 \times 10^{-11} \quad (2)$$

The two values correspond to two theoretical solutions, depending on whether constructive or destructive interference between the contributing waves is present. The large theoretical uncertainty on $\mathcal{B}(K^0_L \to \pi^0\mu^+\mu^-)_{\mathrm{SM}}$ arises from the large uncertainty on one of the parameters involved in the calculation. An improved measurement of $\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-)$ will reduce this uncertainty. The only measurement of $\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-)$ was performed by the NA48 experiment at CERN [2], which obtained:

$$\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-) = (2.9^{+1.5}_{-1.2}(\mathrm{stat}) \pm 0.2(\mathrm{syst})) \times 10^{-9}. \quad (3)$$

Current and planned kaon experiments are not expected to improve $\mathcal{B}(K^0_L \to \pi^0\mu^+\mu^-)$. Thus, a sensitivity study is performed to assess if it could be done at LHCb [4].

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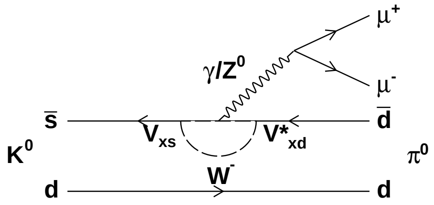

Figure 1. Feynman diagram of the process $K_S^0 \to \pi^0\mu^+\mu^-$.

2. Analysis Strategy

Decays of the K_S^0 in LHCb are characterized by decay vertices separated from the interaction point[1], and with tracks having an average transverse momentum significantly lower than those from the decay of b- or c-hadrons. Muon candidates are combined into $\mu^+\mu^-$ pairs. Then a π^0 can be added to the dimuon pair to make a fully reconstructed K_S^0 decay. However, due to the kinematic constraints the K_S^0 mass resolution does not depend much on the information of the reconstructed π^0. Indeed, a peaking distribution is found using only the constraints on the π^0 mass and the K_S^0 momentum, with an estimate of the typical value of the π^0 momentum ($\sim$ 10GeV/c) (Fig. 2). Therefore, since the reconstruction efficiency of the π^0 is limited, events without reconstructed π^0's are also considered. This leads to two independent analyses: one for the events in which all decay products are considered (hereafter FULL) and one in which only the dimuon pair is used (hereafter PARTIAL). More details on the procedure can be found in [4]. For the FULL analysis, data from Run I is used, corresponding to a luminosity of 3 fb^{-1}.

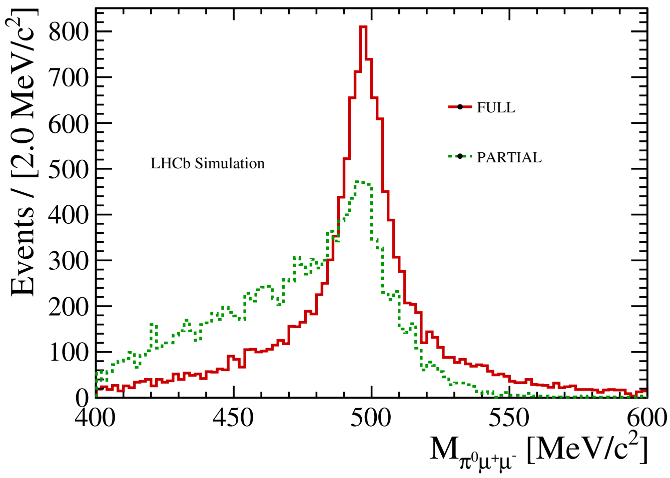

Figure 2. Comparison between the FULL (solid red) and PARTIAL (dashed green) kaon candidate mass distributions.

In the PARTIAL case, data from 2016 is analyzed, with an integrated luminosity of 0.3 fb^{-1}.

[1] The K_S at LHC typically decays after traversing tens of centimeters to several meters.

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3. Reconstruction and selection

Pairs of muon candidates are reconstructed combining opposite-charged tracks with hits in the vertex locator, tracker stations, and muon chambers. In addition, the tracks are required to be separated by at least 6σ (impact parameter significance) from any $p-p$ collision point in the event. Tracks with transverse momentum lower than 80 MeV/c are ignored. Neutral pion candidates are reconstructed from γ candidate pairs that correspond to two independent clusters in the calorimeter. Each photon candidate is required to have a transverse momentum of at least 200 MeV/c. The pion candidate is required to have a mass within 30 MeV/c of the world average π^0 mass. The mass resolution is then improved by constraining the π^0 candidate mass to the world average π^0 mass, and by constraining the three-momentum vector of the K^0_S to point back to the production vertex. The PARTIAL selection does not require any information about a reconstructed π^0.

A multivariate classifier (MVA) is used to separate signal from combinatorial background. It is trained with simulated events and a fraction of the data not used afterwards in the analysis. The MVA input variables contain information about the geometrical properties of the events, kinematics, track quality, and muon identification quality. First, they are divided into continuous variables and discrete variables. The continuous variables are gaussianized, decorrelated, and gaussianized again. Then the gaussianized and the discrete variables are inputs for a boosted decision tree (BDT) training. The BDT response for signal and background for both FULL and PARTIAL are shown in Fig. 3. The analysis is then performed in the BDT region [0.6,1.0], with

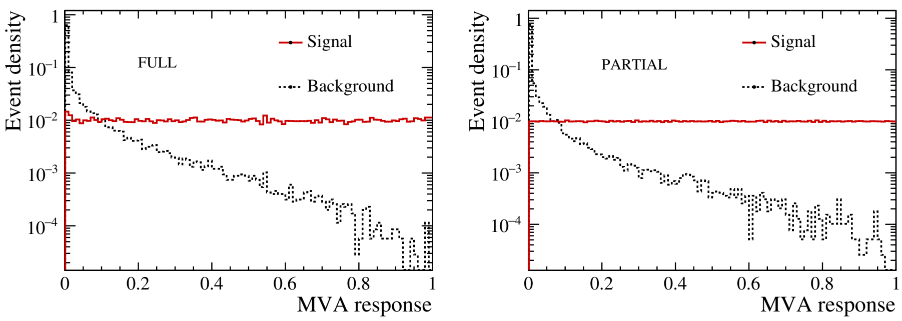

Figure 3. BDT response both for signal (solid red) and background (dashed black). Right: FULL channel. Left: PARTIAL channel. Signal and background are normalized to the same area.

a signal efficiency of 40% for both FULL and PARTIAL and a background rejection of 99.3% for FULL and 99.8% for PARTIAL.

4. Background sources

Several sources of background are investigated to assess their relevance:

- $K^0_S \to \pi^+\pi^-$ decays, where both pions are misidentified as muons, and in the case of the FULL category, combined with a random π^0 from the underlying event. These decays have a mass larger than that of the K^0_S and do not enter the fit region, except for potential residual tails that effectively add up to the combinatorial background. No evidence for $K^0_S \to \pi^+\pi^-$ background is seen for the BDT region fitted.
- $K^0 \to \mu^+\mu^-\gamma\gamma$ decays. This background was considered in the NA48 analysis [2]. However, its contribution at LHCb is found to be negligible. Further details on this study are given in [4].

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- $K_L^0 \to \pi^+\pi^-\pi^0$ decays. Since there is no evidence of this background in the data, it is neglected. Including a $K_L^0 \to \pi^+\pi^-\pi^0$ component to the observed background does not change significantly the sensitivity estimates. The K_S^0 counterpart has a branching fraction of 3.5×10^{-7} and thus is about four orders of magnitude smaller than $K_L^0 \to \pi^+\pi^-\pi^0$. In general, no sign of a resonant structure in the $\pi^+\pi^-\pi^0$ is seen on data.
- Combinatorial background. It is considered to be composed by random combination of tracks, including those generated by pseudo-random combinations of hits during the pattern recognition. It has a monotonic shape across the studied invariant mass range.

5. Fit model
Only events in the BDT range [0.6,1] are considered in the fit to the data. A simultaneous fit to the mass distribution across four equally-sized independent bins of the BDT response is performed. The combinatorial background is described with an exponential PDF for both FULL and PARTIAL analysis, with independent floating yields and decay constants in each BDT bin. The signal model is an Hypathia distribution [3] with different configurations for FULL and PARTIAL (see Fig. 4). The signal model parameters are independent in each BDT bin and are obtained from simulation. The fractions of signal events allotted to each BDT bin are also fixed from values obtained from simulation. The total signal yield is left floating free in the simultaneous fit. The signal yield is floated in the fit to the data. It is measured to be compatible with zero within one sigma for the FULL case and two sigma for the PARTIAL case. The fit projections to the FULL and PARTIAL data are shown in Fig. 5.

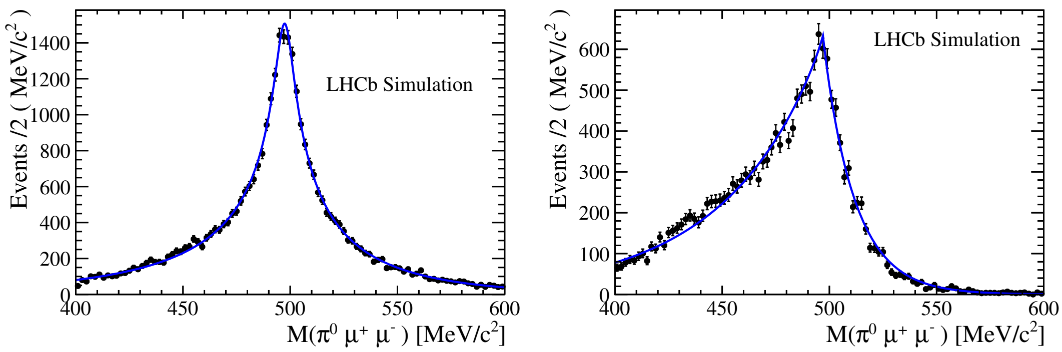

Figure 4. Invariant mass distribution fot $\pi^0\mu^+\mu^-$ events (black dots). The fit result is shown in blue for FULL (left) and PARTIAL (right) categories.

6. Expected sensitivity
The expected statistical precision on $\mathcal{B}(K_S^0 \to \pi^0\mu^+\mu^-)$ for multiple values of the integrated luminosity up to 100 fb^{-1} is estimated. The expected background yield is extrapolated from the current data fit result, where the signal yield is consistent with zero. The background yield is scaled linearly for larger integrated luminosities. For each integrated luminosity in the studied range, sets of pseudo-experiments are generated with the above background expectations, and with a signal yield expectation of

$$N_{sig} = \frac{\mathcal{B}(K_S^0 \to \pi^0\mu^+\mu^-)\epsilon(K_S^0 \to \pi^0\mu^+\mu^-)}{\mathcal{B}(K_S^0 \to \pi^+\pi^-)\epsilon(K_S^0 \to \pi^+\pi^-)} N(K_S^0 \to \pi^+\pi^-)\frac{\mathcal{L}_{fut}}{\mathcal{L}_{curr}}, \tag{4}$$

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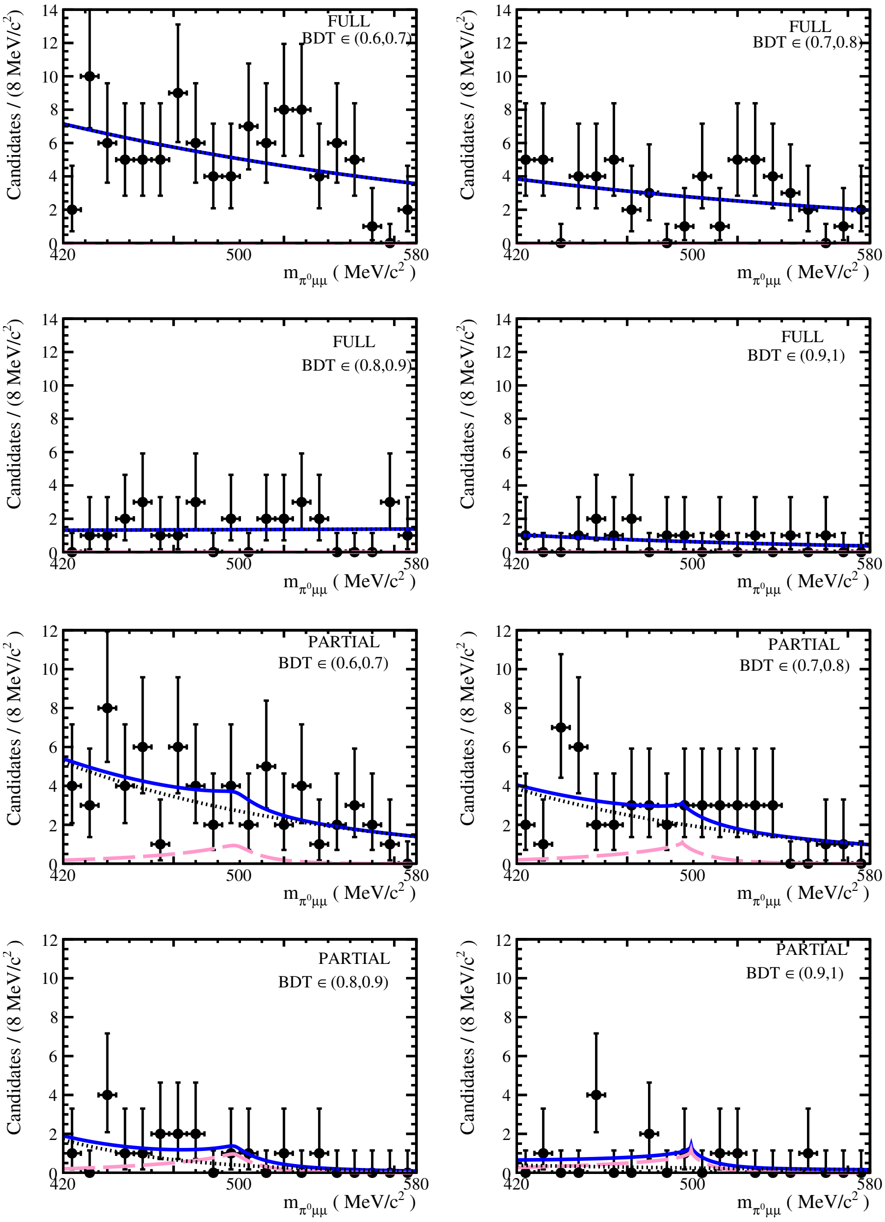

Figure 5. Fit to data for FULL (top) and PARTIAL (bottom) categories. The magenta dashed line shows the signal contribution, the dotted black line the background, and the solid blue line the prediction from the total fit model.

where L_{fut} and L_{curr} are the future and current luminosities, respectively, and $K_S^0 \to \pi^+\pi^-$ is used as normalisation channel. The models described in the previous section are fitted to each pseudo-experiment with a floating $\mathcal{B}(K_S^0 \to \pi^0\mu^+\mu^-)$. The background model parameters used are the ones obtained from the fit to the data. The statistical uncertainties are obtained as the variations of $\mathcal{B}(K_S^0 \to \pi^0\mu^+\mu^-)$ that deviate from the minimum of the log-likelihood profile by half a unit. Finally, the uncertainties are averaged across the set of pseudo-experiments for a given integrated luminosity. The resulting sensitivity curves are shown in Fig. 6. Since both of them enter values for $\sigma_{\rm STAT}$ lower than those measured by NA48 (horizontal orange lines) [2], it can be seen that the analyses of both PARTIAL and FULL categories can lead to a precision better than NA48 for the LHCb upgrade if a trigger efficiency above $\approx 50\%$ (corresponding to $\varepsilon^{TRIG}\mathcal{L} \approx 50\text{fb}^{-1}$) can be maintained.

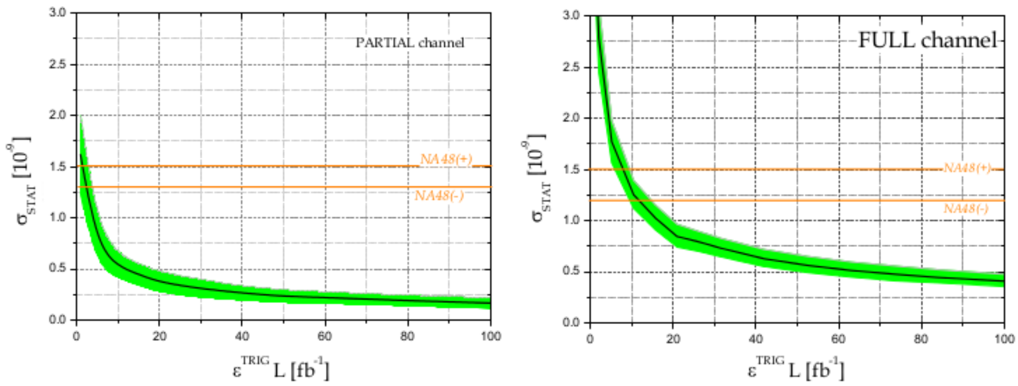

Figure 6. Expected precision on $\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-)$ for the FULL (top) and PARTIAL (bottom) channels, as a function of the integrated luminosity times trigger efficiency, $L \times \varepsilon^{TRIG/SEL}$. The horizontal orange lines represent the statistical errors measured by NA48 [2], both positive (+) and negative (-)

7. Summary and Outlook

A precise measurement of the $K^0_S \to \pi^0\mu^+\mu^-$ branching fraction is crucial for a precise $\mathcal{B}(K^0_L \to \pi^0\mu^+\mu^-)$ SM theoretical prediction and the search for physics beyond the SM. The sensitivity of the LHCb experiment to $\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-)$ was studied using the 3 fb^{-1} of data recorded at 7 and 8 TeV center-of-mass energy during 2011 and 2012, and on 0.3 fb^{-1} of data recorded at 13 TeV center-of-mass energy during 2016. Full and partial decay reconstruction algorithms were considered, provided that the efficiency for reconstructing kaons is higher for the LHCb upgrade. The sensitivity study was performed using pseudo-experiments by extrapolating signal yield results based on the currently available data to expected future integrated luminosities. If a trigger efficiency of at least 50% can be assured in the future, LHCb can determine $\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-)$ with a precision significantly better than that of NA48.

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