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Sensitivity of LHCb and its upgrade in the measurement of $\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-)$

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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 XXXX data and the oportunities of the full software trigger of 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 overtake current world best. Both approaches could be statisticaly combined.

1 TODO list

- Update with Sim09 MC
- Plots in LHCb style
- Some plots missing: Sensitifity for PARTIAL, fit for PARTIAL in the right format
- Fill appendices.

2 Introduction

The $s \to d$ processes have the strongest CKM suppression factor of all quark transitions (see Fig. 2). This makes them a central place to look for flavour violating sources different from those of the Standard Model. Indeed, flavour violation can induce detectable effects in flavour changing processes even if the scale of the new dynamics is heavy and well above direct production at accelerators. Among those transitions, the decay $K^0_{\mathrm{L}} \to \pi^0\mu^+\mu^-$ has been 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 (BSM) is limited by the lack of precision of its SM prediction:

$$\mathcal{B}(K^0_L \to \pi^0\mu^+\mu^-)_{\mathrm{SM}} = \{1.4 \pm 0.3; 0.9 \pm 0.2\} \times 10^{-11} \tag{1}$$

Such theory uncertainty is limited by the experimental precision on $\mathcal{B}(K^0_{\mathrm{S}} \to \pi^0\mu^+\mu^-)$ obtained by the NA48 experiment at CERN [2].

$$\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-) = 2.9^{+1.5}_{-1.2} \times 10^{-9} \tag{2}$$

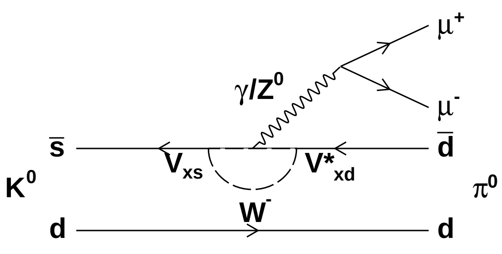

Figure 1: Feynman diagram of the process $K^0_{\mathrm{S}} \to \pi^0\mu^+\mu^-$

The LHCb experiment has shown a very good performance in searching for rare leptonic K^0_{S} decays [3]. In this note, we evaluate the potential sensitivity of LHCb and its upgrade to measure the $\mathcal{B}(K^0_{\mathrm{S}} \to \pi^0\mu^+\mu^-)$.

This document is organized as follows: in Sect. 3 the analysis strategy is sumarized, in Sect. 4, details on the signal reconstruction and selection are given, in Sect. **??** the expected background sources are studied, in Sect. 6 the likelihood fit is described, and in Sect. 7 the sensitivity to $\mathcal{B}(K^0_{\mathrm{S}} \to \pi^0\mu^+\mu^-)$ is obtained. Conclusions are drawn in Sect. 8.

3 Analysis strategy

Kaon decays in LHCb are characterized by decay vertices very well separated from the interaction point (*give range?*), and with tracks having a transverse momentum significantly lower than b and c decays .... This range is similar to average tracks generated in the proton-proton collision and hence has almost no dsicriminating power.

Muon candidates with transverse momentum greater than 80 MeV/c and a $XX\sigma$ detachment of the interaction point... are combined in $\mu^+\mu^-$ pairs. Then, the dimuon pair can be combined with a π^0 to make a fully reconstructed K^0_S decay. However, since the reconstruction efficiency and quality of the π^0 is limited, events in which no π^0 is found are also considered, based only on the dimuon information. This leads to two independent analyses: one for the events in which all the decay products are considered (hereafter FULL) and one in which only the dimuon pair is used (hereafter PARTIAL). The reconstructed candidates are then passed through a selection algorithm to reduce the amount of data to analyze, and then classified according to the response of a *Boosted Decission Tree* (BDT) trained to separate the signal from the combinatorial background.

The properties of the $K^0_\mathrm{S} \to \pi^0\mu^+\mu^-$ decays are studied using simulated samples *some more details*. The theoretical model for the differential decay rate [4] is used to generate the decays. The $\mu\mu$ mass distribution, $m_{\mu\mu}$ as well as the variation of (cosine of) the dimuon helicity angle (see the angle definitions in Fig. 3) are shown in Fig. 3.

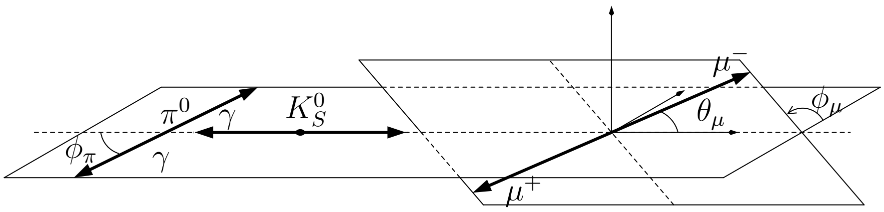

Figure 2: Definition of the helicity angles

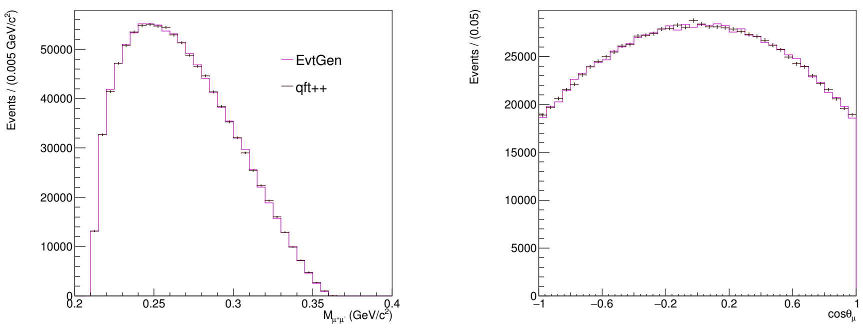

Figure 3: $\mu\mu$ mass distribution (left), and the variation of the dimuon helicity angle (right)

The BDT is trained with simulated signal and combinatorial background from the existing LHCb data. Since the main goal of this study is to evaluate the sensitivity for the LHCb upgrade, where the trigger efficiency is expected to be very high, the background is obtained from the *Trigger Independent of Signal*(TIS) [5] category of the LHCb trigger. That means the tracks and clusters of the reconstructed candidate are not needed for the event to fire the trigger. This ensures the events are almost trigger unbiased, while still providing a sample much larger than the minimum bias triggers.

The expected signal yield is obtained asuming the NA48 central value for $\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-)$, the observed $K^0_S \to \pi^+\pi^-$ yield in data and the efficiency ratio .... obtained in simulation (See (3)).

$$\frac{N(K^0_S \to \pi^0\mu^+\mu^-)}{N(K^0_S \to \pi^+\pi^-)} = \frac{\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-)\epsilon_{K^0_S\to\pi^0\mu^+\mu^-}}{\mathcal{B}(K^0_S \to \pi^+\pi^-)\epsilon_{K^0_S\to\pi^+\pi^-}} \tag{3}$$

The signal and background yields are then extrapolated for a desired expected luminosity and trigger efficiency. Then, pseudo-experiments are generated for those yields, and the precision of $\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-)$ is measured by fiting an invariant mass model to the K^0_S mass distribution of generated pseudo-experiments across the BDT categories.

4 Reconstruction and selection

The candidates are reconstructed ..... The mass resolution is then improved by constraining the mass of the π^0 to the PDG value, and by constraining the three-momentum vector of the K^0_S to point back to the production vertex. After reconstruction, some selection requirements are applied to reduce the amount of data to analyze and fulfill the rate requirements of LHCb offline processing. Those requirements include (.....).

The total reconstuction and selection efficiency for the FULL channel is $\approx 1 \times 10^{-3}$ *check/update* . Requiring a well reconstructed π^0 implies an inefficiency penalty of .... Thus, a strategy without using calorimeter information is also investigated. Indeed, the constraints on the π^0 mass and the K^0_S momentum are enough to get a peaking distribution if one has an estimate of the typical value of the π^0 momentum ($\approx 10\,\mathrm{GeV}/c$), as shown in Fig. 4. Hence, a second selection (PARTIAL) is designed without that requirement. On the contrary, some cuts have to be tightened (*say which*) to keep the background to a maneagable level. The total reconstruction and selection efficiency for the PARTIAL analysis is $\approx 5 \times 10^{-3}$ *check/update*

The total reconstuction and selection efficiency for the PARTIAL channel is ..., well above the FULL, but of course with a cost of an increased background yield.

A BDT is used .... prior to BDT training. The BDT response for signal and background for both FULL and PARTIAL is shown in Fig. 4. Signal and background are normalized to the same area.

The BDT response is binned in .... The signal yields are obtained via a simultaneous fit of the mass distribution in the different BDT bins, as described in the following sections.

5 Background sources

Several sources of background can a priori be relevant for a measurement of $\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-)$:

- Combinatorial...

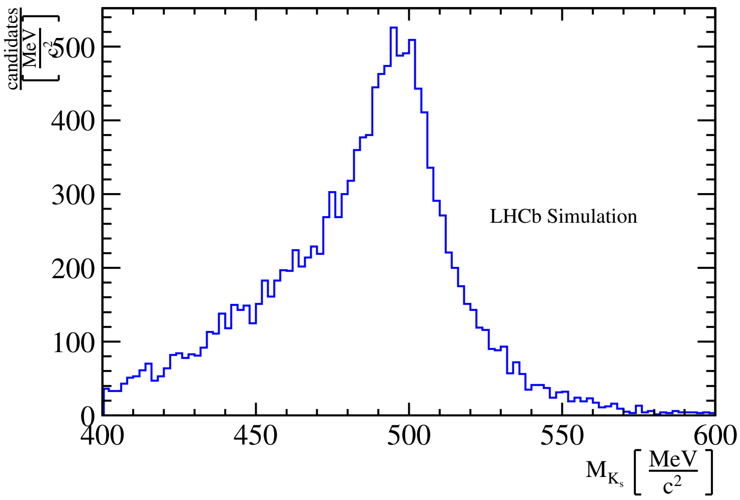

Figure 4: Reconstructed invariant mass of the dimuon pairs from $K^0_{\rm S} \to \pi^0\mu^+\mu^-$ decays when an artificial π^0 of 8.9 GeV/c momentum is added and the kinematic constraints applied.

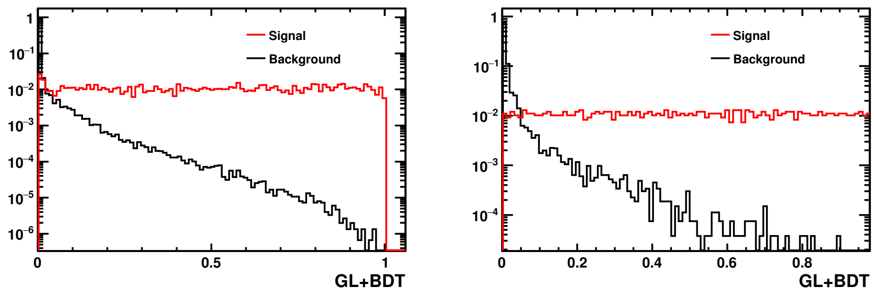

Figure 5: BDT response both for FULL (left) and PARTIAL (right) ...*DMS: Yo creo que esta mierda esta al revés*

- Misidentified $K^0_{\rm S} \to \pi^+\pi^-$ decays (combined with a combinatorial π^0 in the case of FULL). These decays have a mass larger than that of the $K^0_{\rm S}$ and do not enter the fit region, except of potential residual tails that effectively add up to the combinatorial.

- $K^0_{\rm L} \to \pi^0\pi^+\pi^-$ decays....

- $K^0 \to \mu^+\mu^-\gamma\gamma$ decays. These backgrounds were considered for the NA48 analysis, as $\mathcal{B}(K^0_{\rm L} \to \mu^+\mu^-\gamma\gamma)$ is $1.0^{+0.8}_{-0.6} \times 10^{-8}$. However, in LHCb are found to be negligible: the upper decay time acceptance introduces an effective 10^{-3} reduction of $K^0_{\rm L}$ with respect to $K^0_{\rm S}$ and hence the effective $\mathcal{B}(K^0_{\rm S} \to \mu^+\mu^-\gamma\gamma)$ becomes as low as 10^{-11}. There is no experimental measurement of $\mathcal{B}(K^0_{\rm S} \to \mu^+\mu^-\gamma\gamma)$, however, since the process is dominated by the two photon exchange[1], it can be estimated as:

$$\mathcal{B}(K^0_{\rm S} \to \mu^+\mu^-\gamma\gamma) = \mathcal{B}(K^0_{\rm S} \to \gamma\gamma)\frac{\mathcal{B}(K^0_{\rm L} \to \mu^+\mu^-\gamma\gamma)}{\mathcal{B}(K^0_{\rm L} \to \gamma\gamma)} \sim 4.81 \times 10^{-14} \tag{4}$$

[1]Isidori and D'Ambrosio, private comunication

and thus it is negligible.

6 Fit model

The model consits of a simultaneous fit of the mass distribution across the different BDT categories. The combinatorial background is described with an exponential PDF for both FULL and PARTIAL analysis, and the yield and decay constant of the exponential are floated independently on each BDT bin. The signal model is an Hypathia distribution [6], although with different configurations for FULL and PARTIAL (see Fig. **??**). The signal model parameters are independent in each BDT bin, and are obtained from simulation. The signal fraction that falls in each BDT bin is also fixed from the value obtained from simulation, and thus the signal yield is a single floating parameter that connects all the categories of the simultaneous fit. The signal yield is floated when fitting the model to data, although it is measured to be compatible with zero at one sigma, given the limited size of the data sample. The fits to the FULL and PARTIAL data are shown in Fig. **??** and Fig. 6, respectively.

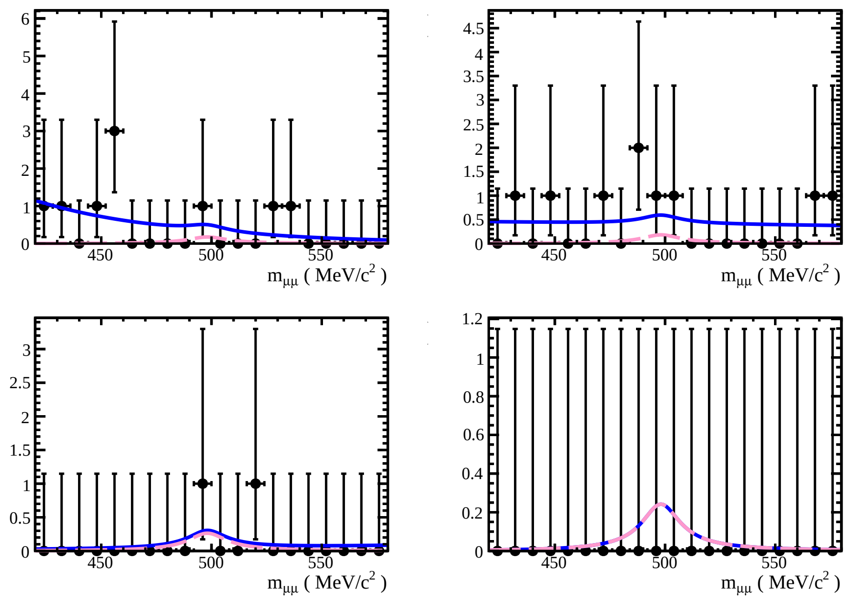

Figure 6: Fit to data for FULL category

7 Expected sensitivity

The expected statistical precision on $\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-)$ for integrated luminosities in the range of ... is estimated in this section.

The fit to the available data performed in Sect. 6 allows obtaining the model parameters of the background.

The TIS samples used are equivalent to a 100% trigger efficiency sample with an integrated luminosity of ... This effective luminosity, L^{dat}_{eff} has been estimated using the

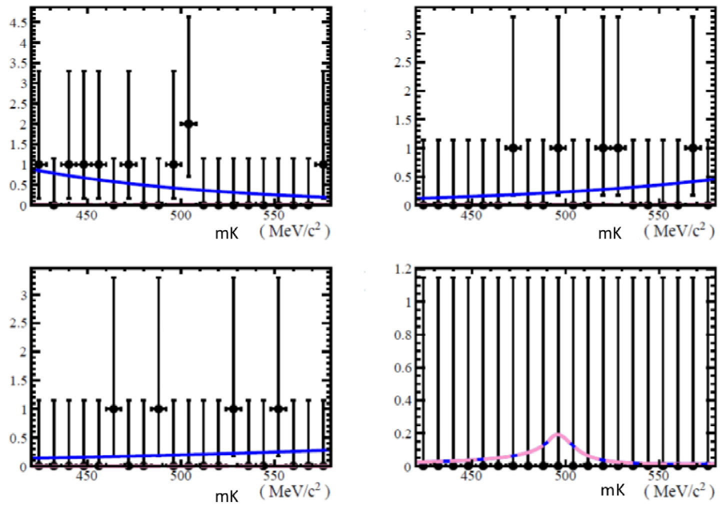

Figure 7: Fit to data for PARTIAL category *PUT CORRECT PLOT*

$K^0_\mathrm{S} \to \pi^+\pi^-$ decays present in the sample, as well as the $K^0_\mathrm{S} \to \pi^+\pi^-$ TIS efficiency, $\approx 2 \times 10^{-3}$ as measured using the TISTOS method [5]. is used to extrapolate the background yield to larger integrated luminosities, L, as:

$$N^L_{bkg} = N^{dat}_{bkg} \times \frac{L}{L^{dat}_{eff}} \tag{5}$$

For each integrated luminosity in the studied range, we generate sets of pseudo-experiments with the above background expectations, and with a signal expectation of:

$$N_{sig} = \frac{N(K^0_\mathrm{S} \to \pi^+\pi^-)}{\mathcal{B}(K^0_\mathrm{S} \to \pi^+\pi^-)} \frac{\epsilon_{K^0_S \to \pi^0\mu^+\mu^-}}{\epsilon_{K^0_S \to \pi^+\pi^-}} \mathcal{B}(K^0_\mathrm{S} \to \pi^0\mu^+\mu^-)_{NA48} \times L \tag{6}$$

The models described in Sect. 6 are fit to each pseudo-experiment with a floating $\mathcal{B}(K^0_\mathrm{S} \to \pi^0\mu^+\mu^-)$, and the uncertainties are obtained as the variations of $\mathcal{B}(K^0_\mathrm{S} \to \pi^0\mu^+\mu^-)$ that deviate the profile-likelihood value by half a unit. Finally, the uncertainties are averaged across the pseudo-experiments of the same integrated luminosity. The uncertainties on the background extrapolation are large and *blablabla.* the resulting sensitivity curves are shown in Fig. 7 and Fig. **??**. It can be seen that both the analyses of both PARTIAL and FULL categories can lead to a precision better than NA48 for the LHCb upgrade if the trigger efficiency is ... Studies of $K^0_\mathrm{S} \to \pi^0\mu^+\mu^-$ and minimum bias samples simulated with the LHCb upgrade detector and conditions show that the High Level Trigger rate can be kept low enough for a .... Timing studies are currently ongoing.

8 Conclusions

We are the champions

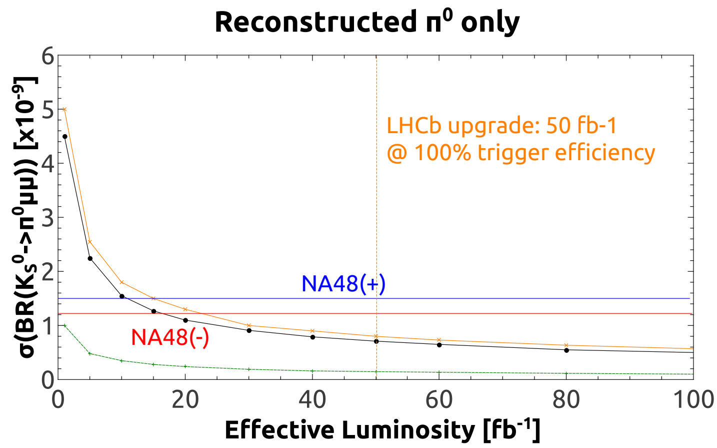

Figure 8: Expected precission on $\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-)$ as a function of the integrated luminosity times trigger efficiency, $L \times \varepsilon^{TRIG/SEL}$. *This and that line mean bla and bla-prime, etc...*

Acknowledgements

We would like to thank Gino Isidori and Giancarlo D'Ambrosio for their theoretical input. We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the scientifical, technical and administrative staff at the LHCb institutes. We acknowledge support from ERC, EPLANET, and Xunta de Galicia. We would like to dedicate this work to the memory of Pablo Rodríguez.

9 Samples used

The following samples were used for the preparation of this note:

- Signal MC sample of event type bla...
- Stripping 21 data, XX fb^{-1}.
- Stripping 25 data, YY fb^{-1}.
- Stripping 26 data, ZZ fb^{-1}.

10 Selection and BDT

Fill in the details of the stripping selection, fiducial cuts and BDT (RoC curves, signal and backgroung histrograms of input variables ...)

11 normalization

Give calculation of the efficiencies and other normalization related stuff.)

12 Peaking background studies

Give details on the K^0_L supression factor and on the $K^0_L \to \pi^0\pi^+\pi^-$)

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