Development of Run 3 HLT2 lines for $K_S^0 \to 2(e^+e^-)$ decays at LHCb

CERN Summer Student Proyect

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Abstract

This project focuses on developing trigger lines for the $K_S^0 \to 2(e^+e^-)$ decay considering the detectors and geometry of the LHCb. This type of decays constitute a strong test for the Standard Model, and could point to dark sector light-mass candidates. The implemented trigger line was run on MC signal and a HLT1-filtered Minimum Bias simulation samples in order to study the lines efficiency, which was of the order of 10^{-1} for the MC samples and 10^{-3} for Minimum Bias. Clear separation of the signal and the background was not achieved but clear ideas for further improvements were proposed

1 Introduction

For the last several decades particle physicist have tested and developed the now widely accepted Standard Model of elementary particle physics; a theoretical framework built from observation of particle interactions and phenomena [?]. In a general sense the Standard Model works as a periodic table for elementary particles by describing their interactions and ordering them according to certain intrinsic properties such as: mass, spin, charge, among others.

Nevertheless, the Standard Model is not able to accurately explain all observed phenomena in the universe, one of the most important flaw is its inability to provide a dark matter candidate. Several theories propose that these elusive dark particles could be light enough to be created by the pp collisions in the LHC. These particles would be able to escape the detectors without interacting due to their nature but being massive they would carry away energy and momentum. Certain light meson decay channels offer theoretical insight into the production of dark photons through dark Higgs and heavy neutral lepton decay [1].

For the purposes of the summer research project, the following decay channel was studied[1]:

$$K_S \rightarrow (XX \rightarrow 2(e^+e^-)) \tag{1}$$

where X represents a dark sector mediator particle.

The decay process in Eq. 1 represents a previously unstudied signature with a branching ration of the order of 10^{-10} as predicted by the Standard Model[2]. Nevertheless, Beyond Standard Model scenarios that incorporate the influence of dark sector mediators predict a branching ratio of the order of 10^{-8} [1].

Furthermore, it is important to consider that during Run 1 around 10^{13} K_s^0 per fb^{-1} were produced inside the LHCb acceptance[3], taking into account that the cross-section is almost constant with the collision energy it can be expected that for Run 3 the situation would be similar. The forward design of the LHCb is useful for the study of this decay due to the K_s^0 long decay length, and its ability to identify electrons from the tracker and calorimeter data. Therefore, it is important to study in depth the characteristics of this decay and the viability of its analysis in the LHCb. This project looks at the development of HLT2 lines in hopes of reconstructing these events within the specific geometry and detector array of the LHCb experiment.

2 Development of the line

2.1 High level Triggers

Every collision at LHCb produces an extremely large amount of data (around 1TB every second), making it impossible to store and process completely during the collider's runs. Therefore the development of trigger selections is essential to store the relevant data needed for the analysis.

The trigger of the LHCb experiment for Run 3 is fully based on software and thus referred to as a High Level Trigger (HLT). Two separate applications, HLT1 and HLT2, are used to select and reconstruct events based on certain conditions related to the LHCb detectors[4]. HLT1 run entirely on GPUs and works in real time to reconstruct the trajectories of charged particles that go through the entire series of detectors. The VELO information is used to reconstruct the initial track segments, these are extrapolated to the upstream tracker to create upstream tracks, and finally information of the SciFi is added to create long tracks [5]. It is important to notice that at the moment HLT1 is not able to identify any particles except for muons (even though there is work being done to include electrons), which have a clear signal from their detector.

Regarding HLT2, this trigger is implemented on CPUs and reconstructs charged and neutral particles, as well as identify them. In order to do this it uses the full data taken from the tracking sub detectors as well as the information from the calorimeter and RICH detectors for the particle identification.

2.2 Electron selection and vertex combination

The first step in the trigger selection consisted in implementing prefilters for the particles in the analyzed events. To achieve this, the upfront reconstruction was applied as well as requiring at least one primary vertex to be present.

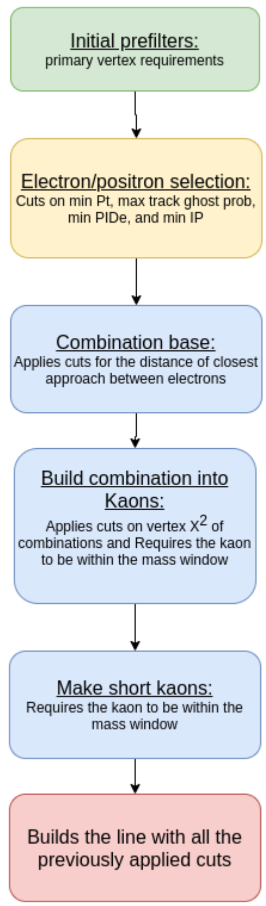

Figure 1: Flowchart describing the trigger selection

Next there is an electron selection in which several cuts are imposed in order to reduce the amount of data the line has to process. Long electrons with bremsstrahlung corrections were used because these contain the largest amount of information about the particle since they pass though the tracker and calorimeter. A minimum transverse momentum cut of 100MeV and a maximum ghost track probability of 0.5 was implemented in order to ensure that acceptable electrons were selected for the combinations step. This reduces the processing time of the combinatorics during the 4 electron combination base. The use of a particle identification cut aids in this procedure by comparing the logarithmic likelihood between electrons and pions, as it can be seen from equation 2 [1]. A value of $PIDe = 1$ was set for the line, as well as a minimum impact parameter of 0.2mm. Table **??** summarized the requirements imposed on the mentioned variables.

$$PIDe = log\left(\frac{\mathscr{L}_e}{\mathscr{L}_\pi}\right) \tag{2}$$

After the long electron selection the line goes intro the combination section, which is written as a python module and imported on all lines we developed for K_s to four lepton decays. Considering

Variable	Cut
Min pT	> 100MeV
Max Track Ghost Prob	< 0.5
Min PIDe	> 1.0
Min IP	> 0.2mm

Table 1: Variable requirements applied to the electron/positron selection

the topology of the decay of interest, the combiner focused on forming a detached vertex from a combination of 4 particles, in this case two electrons and two positrons. A combination base function takes as input the selected particles, and a decay descriptor and applied cuts by going through all combinations of electrons and requiring that the distance of closes approach (DOCA) between all of them is less than 1 mm. Following the DOCA requirement, a maximum value of 25 for the vertex χ^2 divided by the degrees of freedom is imposed, this enforces that the four particles come from the same vertex. This function then goes through combinations of electrons and requires that the distance of closes approach between all of them is less than 1 mm. Therefore, the return is a four body combiner functions with the applied cuts, a name, and a decay descriptor.

The next function in the line uses the previous combination base and applied cut to the combined elements as a whole. Minimum mass and transverse momentum were considered but in order not to restrict the line too much these values where set to zero, nevertheless it is useful to have them in the function for future line upgrades. However, there is an imposed limit to the chi^2 of vertex fits performed with the characteristics of the accepted pair of electron/positron pair. The function returns a particle filter with primary vertex with the applied cuts.

The last section of the basic combiner module makes the detached K_S, and requires that the reconstructed kaon has a mass withing the stipulated mass window and a transverse momentum larger than 0MeV. Furthermore a cut in the decay length significance with respect to the primary vertex is also included to ensure that the K_s^0 had a significant fly distance and reject background originating at the pp collision. The final step is to build the line with the electrons selected at the start and the appropriate decay descriptor, this is done with the *registerlinebuilder* decorator, which returns the Hlt2 line.

Variable	Cut
Max DOCA	< 1.0mm
K_s^0 Vertex χ^2 per dof	< 25.0
K_s^0 BPVDLS	> 2.0
K_s^0 invariant mass	± 200 MeV

Table 2: Cuts used for the 4-body combiner of electrons/positrons

3 Efficiencies and Rates

The described trigger line was run on three different data sets in order to compare the results. Initially a Minimum Bias Sample of filtered HLT1 MC data was used, this had a total of 14983 events and served as a way to simulate background and test lines reaction to a large number of different events. The other two data sets where Pythia8 Monte Carlo simulations consisting of pp collisions at $\sqrt{s} = 14TeV$ inside the LHCb acceptance, with the further requirement that in each event a $K_s^0 \to 2(e^+e^-)$ was present. The only difference between the two data sets was the magnet polarity (one pointing up and the other down), for the magnet down polarity the full data set contained 102017 events, whilst the one with magnet up contained 103423 events.

The trigger efficiencies where then calculated for the previously mentioned data sets using the MooreAnalysis tool, taking the total number of events as the denominator for one calculation, and the number of events with reconstructible children for the other. These values are summarized in Table 3. It is important to notice that the efficiency from the Miminum Bias sample had a comparable value to the ones calculated for the signal data sets, which alludes to a large presence of background events being picked up by the trigger.

Data Set	Efficiency (All Events)	Efficiency (CanRecoChildren)
MC (magnet down)	1.91×10^{-2}	3.9×10^{-2}
MC (magnet up)	1.93×10^{-2}	4.0×10^{-2}
Min Bias	9.3×10^{-3}	-

Table 3: Summary of calculated efficiencies for all the considered data sets.

Figure 2 shows the transverse momentum distribution of the K_s^0 and one of the produced e^- during the decay, with and overlay of the triggers efficiency in terms of such variable. These plots suggest that the efficiency is fairly constant for increasing values of pT for both particles, which is troublesome because it was expected that the efficiency would be small at the extremes of the pT spectrum.

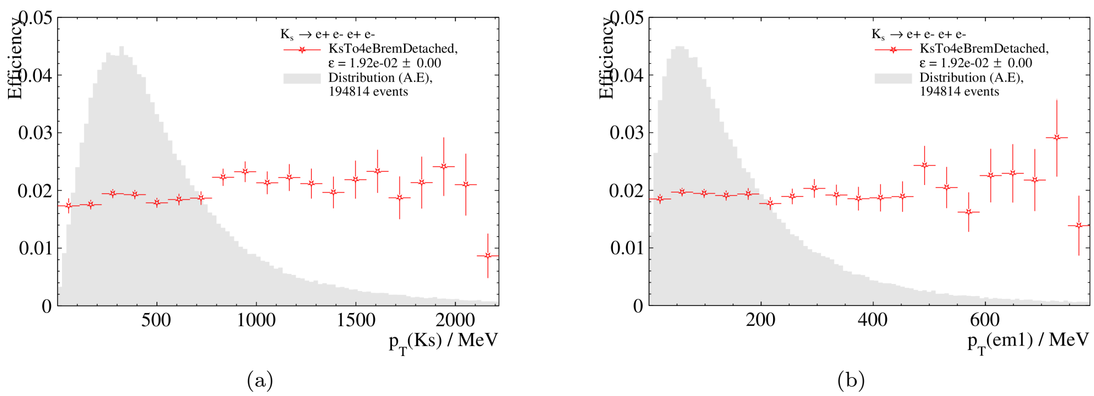

Figure 2: Plots showing the efficiency of the line and the pT distribution for the K_s^0 and one e^-

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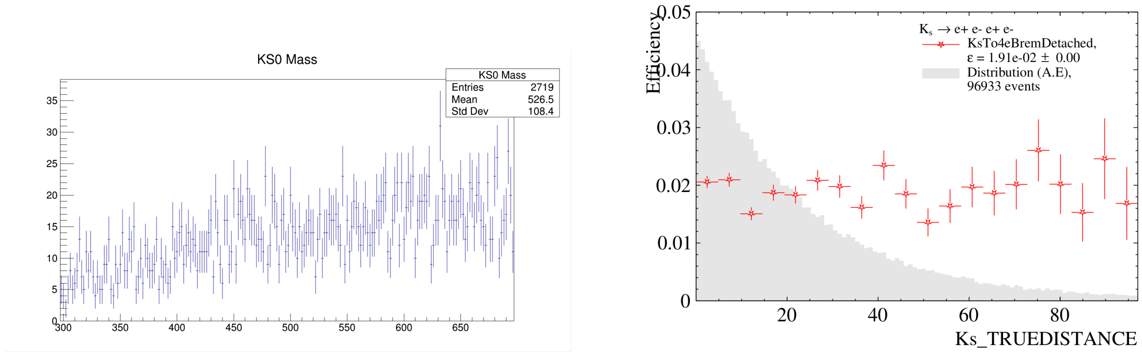
The problem persist for the results presented in Figure 3 where a) shows the mass of the reconstructed kaons that passed the trigger selection, and b) shows the efficiency in terms of the K_s^0 fly distance. These two plots show that the actual signal of $K_S^0 \to e^+e^-e^+e^-$ is lost within the background that is presents in the events, as can be seen from the lack of a peak at 497 MeV (Kaons invariant mass[]) in a). The presence of excess background signals also explains the constant efficiency distribution in b), it would be expected that this should actually decrease significantly as the fly distance increases because the electron candidates where required to have long tracks. These tracks possess VELO information, which could only be obtained if the K_S^0 decayed within this subdetector. The facts that this does not happens shows there is interference from other decay processes.

Looser cuts on the PIDe, IP, and MaxTrackGhost where explored in order to try and separate the signal from the background but all the combinations remained unsuccessful. Further work needs to be done in order to fix this issue with the electrons, maybe using some even looser cuts to first isolate the signal, or using downstream tracks to increase analyzed data and efficiency. It is importante to consider that work is being done to include electron identification in HLT1, which would be very useful for the present predicament in background elimination.

Some even further work could include the use of $K_s^0 \to \pi^+\pi^-e^+e^-$ lines in order to study their



(a) (b)

Figure 3: a)Mass distributions of reconstructed K_s^0. b)Trigger efficiency in terms of K_s^0 fly distance
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background contributions to the four electron signal. Because the electrons are identified using data from the tracker and calorimeter these are easily misidentifies as pions, thus creating the need to study their behaviour with a trigger line. As a final comment, a two vertex combiner was developed as a python module (same idea as the 4 body combiner currently used) which first combines separately the two electron/positron pairs, and the combines these into the K_s^0 candidate. This gives rise to the prospect of studying the dark matter mediator as a detached particle instead of a prompt one, as we have currently done.

4 Conclusions

The current project focused on developing a Run 3 HLT2 line for the $K_s^0 \to e^+e^-e^+e^-$ decay and studying its efficiency. The trigger line was successfully created and run within the Moore framework, considering the process topology and particular characteristic of the electrons/positrons. The efficiencies for the magnet up and magnet down MC samples where calculated, as well as a smaller Minimum Bias data set of filtered HLT1 events. These efficiencies where higher that expected due to background contributions which at the moment have not been able to filter out. This also meant that the mass reconstruction for the K_s^0 was not successful as the pertinent four electron signal was lost in the background. Ideas for improving this issue have been mentioned, and further work into HLT1 electron selection, downstream tracks reconstruction and possible $K_s^0 \to \pi^+\pi^-e^+e^-$ studies are proposed.

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References

[1] Hostert, M., Pospelov, M. (2020). Novel multi-lepton signatures of dark sectors in light meson decays. Journal of High Energy Physics. Published. https://arxiv.org/abs/2012.02142

[2] D'Ambrosio, G., Greynat, D., Vulvert, G. (2013). Standard model and new physics contributions to Kl and Ks into four leptons. The European Physical Journal C, 73(12). https://doi.org/10.1140/epjc/s10052-013-2678-1

[3] Dettori, F. (2010). First minimum bias physics results at LHCb. Nuclear Physics B - Proceedings Supplements, 207-208, 351–354. https://doi.org/10.1016/j.nuclphysbps.2010.10.089

[4] R. Hunter, O. Lupton, R. Matev, S. Stahl and M. Vesterinen, "An automated tool to facilitate con191 sistent test-driven development of trigger selections for LHCb's Run 3", EPJ Web of Conferences, 192 vol. 251, p. 04024, 2021. Available: 10.1051/epjconf/202125104024 [Accessed 2 September 2021].

[5] J. R. Aaij et al., "The LHCb trigger and its performance in 2011", Journal of Instrumentation, vol.183 8, no. 04, pp. P04022-P04022, 2013. Available: 10.1088/1748-0221/8/04/p04022 [Accessed 2 September 2021].