CERN

NA62 Experiment

CERN Summer student project report

The preliminary study of RICH detector usage in $K_L^0 \to \mu^{\pm}e^{\mp}$ decay with the NA62 experiment at CERN

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Abstract

During my work I performed statistical analysis data received from the NA62 simulations of $K^+ \to e^+\nu$ and $K^+ \to \mu^+\nu$ processes. The goal was to measure NA62 RICH detector efficiency and its capability to distinguish between muons and electrons in specific momentum bins. The separation between electrons and muons would be useful in future to study of rare lepton flavor violating process $K_L^0 \to \mu^\pm e^\mp$.

1 Introduction

1.1 The NA62 Experiment

NA62 is a fixed target experiment and is connected to CERN Super Proton Synchrotron [1]. The CERN SPS provides protons at the energy of 400 GeV/c, which collide with the target and produce secondary hadron beam with the energy of 75 GeV/c. During each 3 s SPS spill, the particle rate in the NA62 positive secondary hadronic beam is 750 MHz. From all created particles only about 6% are K^+. From this K^+ only about 25% decay early enough to be detected, rest hits the dump at the end of the beam line. The layout of the NA62 beam line and detectors is shown in Fig. 1.1

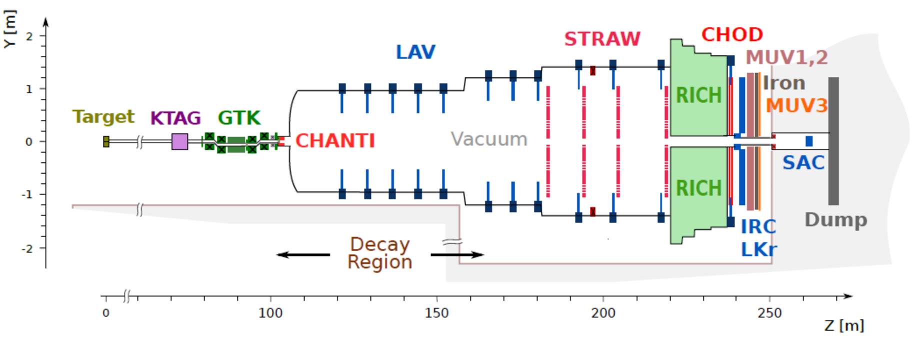

Figure 1.1: NA62 experimental setup, with a beam traveling in a positive Z direction. The RICH detector is light green colored part.

It is designed for branching ratio measurement of very rare kaon decay $K^+ \to \pi^+\nu\overline{\nu}$ with a Standard Model branching ratio $BR = (8.4 \pm 1.0) \times 10^{-11}$. This process was chosen for the purpose of studying Standard Model symmetry violation sector. The goal is to collect ~100 of this events assuming the SM branching ratio and 10% detector acceptance. To achieve this goal 10^{13} kaon decays are needed and the rejection factor for the other decays must be on the order of 10^{12}.

A slightly modified NA62 apparatus with a high energy neutral kaon beam could reach sensitivity to branching ratio as low as 10^{-12}. This would allow to study lepton flavor violating process $K^0_L \to \mu^\pm e^\mp$ with a branching ratio $BR \sim 1 - 5 \times 10^{-12}$.

1.2 RICH detector

One of the main backgrounds for $K^+ \to \pi^+\nu\overline{\nu}$ decay comes from $K^+ \to \mu^+\nu_\mu$. Even though pions and muons can be distinguished by different stopping power (measured in MUV1, MUV2 and MUV3), with RICH detector further rejection of muon background in pion sample can be achieved [2]. The contamination is reduced by a factor of at least ∼100 in the momentum range from 15 GeV/c and 35 GeV/c.

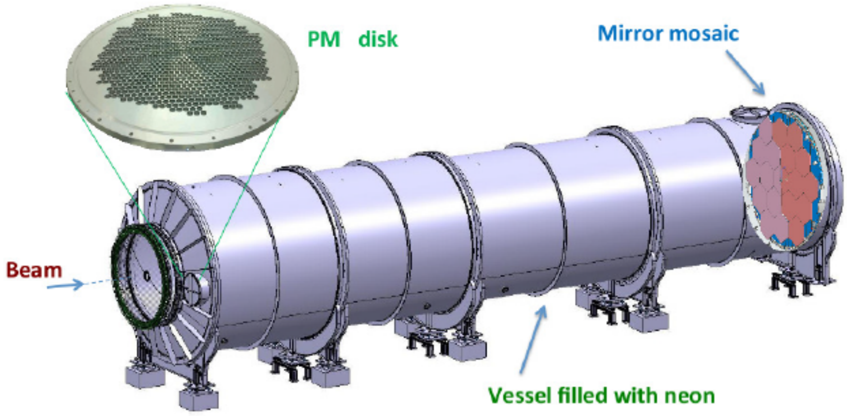

Figure 1.2: RICH detector layout. On figure there are shown one of two photomultiplier detectors, vessel filled with neon gas and composite mirror that focuses light on PM detectors.

As shown in Fig. 1.2, the RICH detector is a pipe filled with neon gas. On the opposite side of the beam entry point it has a mirror composed out of 18 hexagonal mirrors with a 350 mm side that are distributed around 2 two semi-hexagonal mirrors in the center. The semi-hexagonal mirrors have hole in the middle, so the beam pipe can travel through them. The whole mirror is split in half (Jura and Saleve side), where each half focuses on one of two photomultiplier disks. They are located at about 1.5 m away from the beam pipe, away from the area illuminated by charged particles. Each disks has diameter of about 600mm and contain 976 photomultiplier tubes.

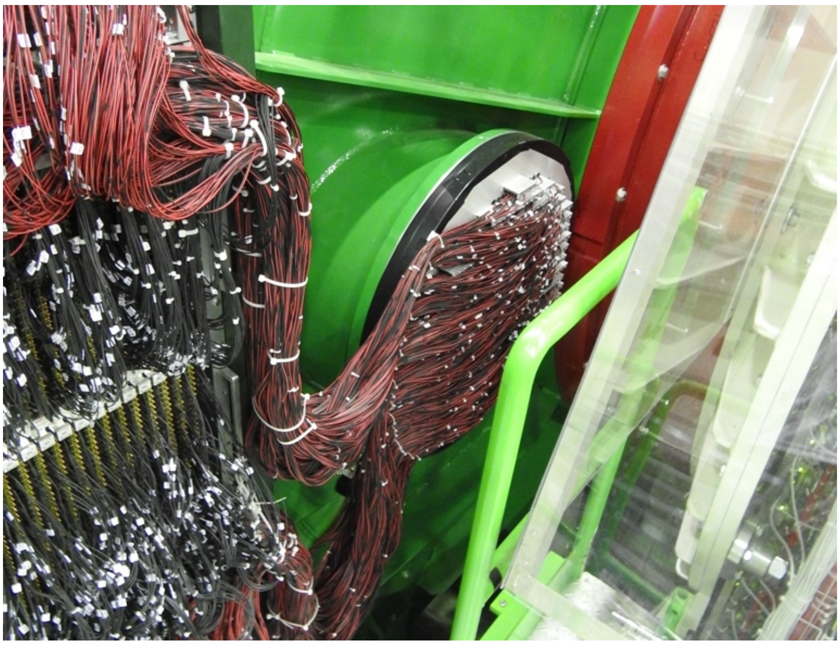

Figure 1.3: Back side of connected Jura photomultiplier disk.

1.3 Project goal

The goal of the project is to test if a slightly modified NA62 machine can be used for the study of $K_L^0 \rightarrow \mu^{\pm} e^{\mp}$ process. Focus is on capability of RICH detector to distinguish between electrons and muons. For this, cuts must be applied on RICH sensitive variables such as reconstructed mass of particles and likelihoods. For the test case 90% muon signal efficiency and 1% electron contamination thresholds will be tested.

2 Analysis and results

The sample data sets used for the analysis are Monte Carlo simulations of $K^+ \rightarrow e^+\nu$ and $K^+ \rightarrow \mu^+\nu$ processes created for the NA62 experiment. The first step of processing is performed such that charged particle track coincide with geometrical acceptance of the detector and cover a momentum range between 10 GeV and 40 GeV. In addition to this other constraints, such a number of tracks, charge of particles and track times need to be invoke, so that only good tracks can be selected. The further procedure involves binning in momentum bins of 5 GeV. In each of the momentum bins the statistical analysis of reconstructed mass and RICH likelihoods is performed. This variables are described later. For the purpose of the study muons are used as a signal, while electrons as a background. Two thresholds are taken to get the efficiency. The first one is 90% muon signal efficiency, the other is electron noise contamination at the level of 1%. The mass is obtained combining measurements of the Cherenkov ring radius by the RICH, and the measurement of the charged particle momentum by the STRAW spectrometer. The mass is then received from the equation:

$$m^2_{RICH}(p, R) = p^2 \cdot \left(\frac{F^2 \cdot n^2}{F^2 + R^2} - 1\right), \tag{2.1}$$

where F=17020 mm is the focal length and n=1.000062 is the refractive index of the neon gas in the RICH.

The track-centered mass is calculated from the track-centered ring. The size of the ring depends on the type of the particle. The single ring reconstruction is performed in the annulus between 80 mm and 200 mm. Because of only one parameter, only two hits are needed to perform the fit.

The track seeded mass works similarly track centered mass. The difference is that the center is only used to open the annulus, which limits area of hits. It then calculates the center of the ring from best fit of the hits, independently from the center of the annulus.

In the figures 2.1 and 2.2 are shown plots of track centered mass squared and track seeded mass squared. The mass squared value is used to prevent double peak in electron mass distribution that arises as an artifact from the dat processing. Using mass squared gives possibility of quick comparison of two graphs of different particles. Comparison of plots of same particle in 2.1 and 2.2 shows that track centered mass has much wider tails than track seeded mass. Comparing this with the tables 2.1-2.6 implies, that we have a smaller signal to noise ratio when we fix low background contamination (in this case $\epsilon_e = 1\%$). On the other hand we see that with the same amount of entries we have a higher track centered mass squared peak, so the rase of the values is much faster, giving us higher signal efficiency in proximity of the mean value.

The likelihood values are computed comparing the hits in the RICH and the expected rings. The center for those rings come from spectrometer. The most probable hypothesis value receives likelihood 1, all the other values are than rescaled to this value. There are five different hypotheses: noise, electron, muon, pion, kaon. In this case the value of the highest non-muon likelihood will be used. In the figure 2.3 are shown the distributions of particle not being muon. The likelihood value goes from 0 to 1, but in the case of non-muon hypothesis the value 0 represents the muon and moving toward 1 means reduction of likelihood that the particle is muon. Better that is a distinction between searched particle hypothesis and second best hypothesis, more events will be located in 0 and 1 peaks reducing number of events in the middle. Ideally there would be only one peak exactly at 0 and one at 1.

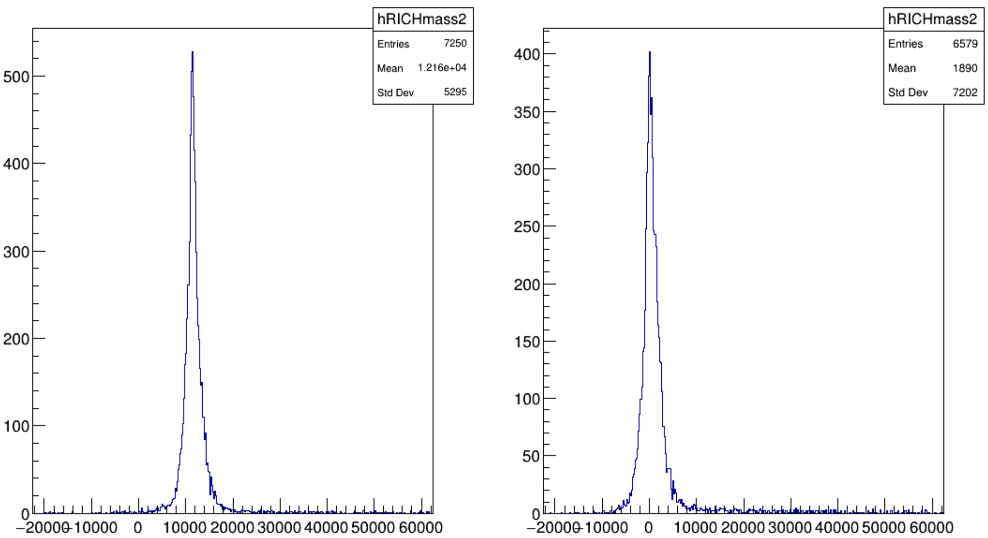

Figure 2.1: Comparison between track centered masses squared. On the left we have mass of muons, while on the right mass of electrons.

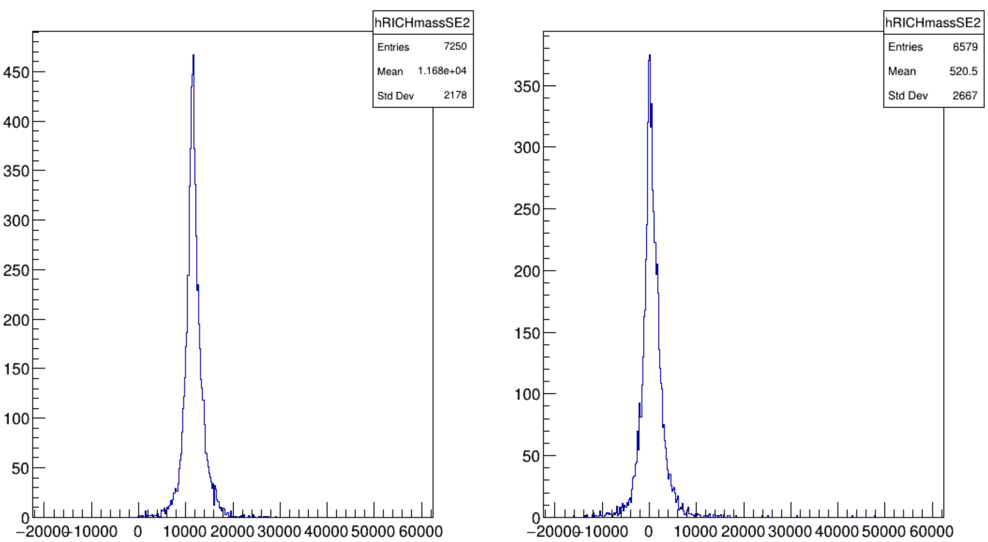

Figure 2.2: Comparison between track seeded masses squared. On the left we have mass of muons, while on the right mass of electrons.

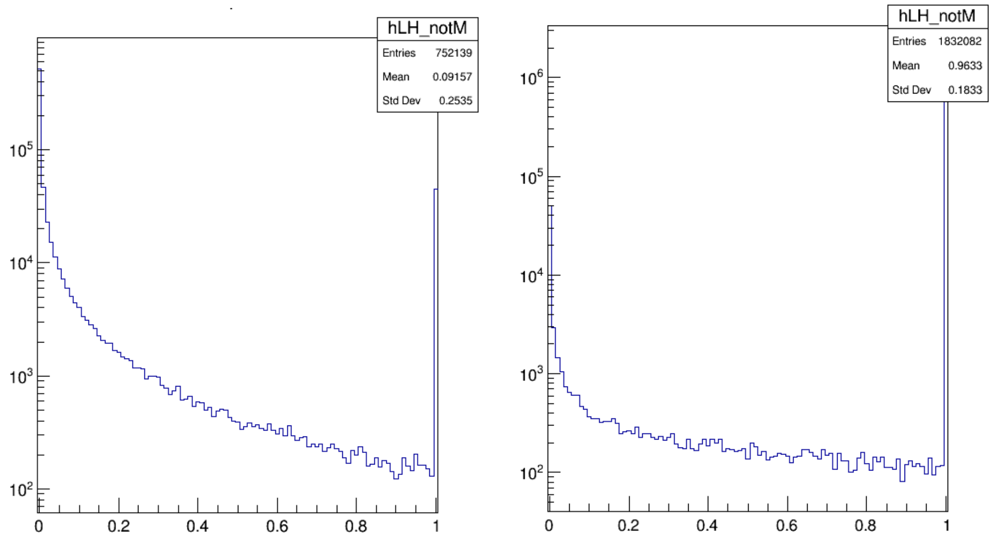

Figure 2.3: Comparison of likelihoods that the particle is not a muon. On left we have analysis performed on muon sample (thus large peak at 0), on the right we have analysis of electron sample (Large peak at 1). The y-axis scale is logarithmic.

Each of the tables 2.1-2.6 shows a value of the parameter (track centered mass, track seeded mass or likelihood) in a specific momentum bin, for the given threshold, where the cut is performed, to obtain such ϵ_μ or ϵ_e. The events are selected as muons if $m > m^{cut}$ and $LH < LH^{cut}$ The units of mass parameter value are in MeV, while likelihood is without units. In addition to the parameter there is added electron background contamination (for muon cuts) and muon signal (for electron cuts) both in %. When there is a blank space in the tables, the fixed cut efficiency could not be achieved.

Table 2.1: Table of the muon masses and likelihood with electron background, where m$_{tc}$ is track centered mass and m$_{ts}$ is track seeded mass, both in MeV, while the likelihood is in %. This table is for momentum bin between 10 GeV and 15 GeV.

Pbin = 10 GeV-15 GeV				
Threshold	$\epsilon_\mu = (90 \pm 0.23)\%$ **Parameter**	$\epsilon_\mu = (90 \pm 0.23)\%$ **e Background** [%]	$\epsilon_e = (1 \pm 0.08)\%$ **Parameter**	$\epsilon_e = (1 \pm 0.08)\%$ μ **signal** [%]
m$_{tc}$ [MeV]	100	1.4±0.06	103	83±0.3
m$_{ts}$ [MeV]			38	70±0.4
Likelihood	0.01	0.7±0.04	0.37	91.3±0.2

Table 2.2: Table of the muon masses and likelihood with electron background, where m_{tc} is track centered mass and m_{ts} is track seeded mass, both in MeV. This table is for momentum bin between 15 GeV and 20 GeV.

Pbin = 15 GeV-20 GeV				
Threshold	$\epsilon_\mu = (90 \pm 0.18)\%$ **Parameter**	$\epsilon_\mu = (90 \pm 0.18)\%$ **e Background** [%]	$\epsilon_e = (1 \pm 0.06)\%$ **Parameter**	$\epsilon_e = (1 \pm 0.06)\%$ μ **signal** [%]
$\mathbf{m}_{tc}$ **[Mev]**	101	4.6±0.08	141	1±0.06
$\mathbf{m}_{ts}$ **[MeV]**			54	86±0.2
Likelihood	0.01	0.5±0.03	0.99	91.8±0.2

Table 2.3: Table of the muon masses and likelihood with electron background, where m_{tc} is track centered mass and m_{ts} is track seeded mass, both in MeV. This table is for momentum bin between 20 GeV and 25 GeV.

Pbin = 20 GeV-25 GeV				
Threshold	$\epsilon_\mu = (90 \pm 0.15)\%$ **Parameter**	$\epsilon_\mu = (90 \pm 0.15)\%$ **e Background** [%]	$\epsilon_e = (1 \pm 0.06)\%$ **Parameter**	$\epsilon_e = (1 \pm 0.06)\%$ μ **signal** [%]
$\mathbf{m}_{tc}$ **[MeV]**	99	6.1±0.08	175	1±0.06
$\mathbf{m}_{ts}$ **[MeV]**			68	89.8±0.1
Likelihood	0.01	0.4±0.02	0.99	92.3±0.1

Table 2.4: Table of the muon masses and likelihood with electron background, where m_{tc} is track centered mass and m_{ts} is track seeded mass, both in MeV. This table is for momentum bin between 25 GeV and 30 GeV.

Pbin = 25 GeV-30 GeV				
Threshold	$\epsilon_\mu = (90 \pm 0.13)\%$ **Parameter**	$\epsilon_\mu = (90 \pm 0.13)\%$ **e Background** [%]	$\epsilon_e = (1 \pm 0.03)\%$ **Parameter**	$\epsilon_e = (1 \pm 0.03)\%$ μ **signal** [%]
$\mathbf{m}_{tc}$ **[MeV]**	98	6.1±0.07	208	1±0.04
$\mathbf{m}_{ts}$ **[MeV]**	89	0.5±0.02	79	91.4±0.1
Likelihood	0.03	0.4±0.02	0.99	92.6±0.1

Table 2.5: Table of the muon masses and likelihood with electron background, where m_{tc} is track centered mass and m_{ts} is track seeded mass, both in MeV. This table is for momentum bin between 30 GeV and 35 GeV.

Pbin = 30 GeV-35 GeV				
Threshold	$\epsilon_\mu = (90 \pm 0.13)\%$ **Parameter**	$\epsilon_\mu = (90 \pm 0.13)\%$ **e Background** [%]	$\epsilon_e = (1 \pm 0.03)\%$ **Parameter**	$\epsilon_e = (1 \pm 0.03)\%$ μ **signal** [%]
$\mathbf{m}_{tc}$ **[MeV]**	96	6.2±0.07	242	1±0.03
$\mathbf{m}_{ts}$ **[MeV]**	84	1.5±0.03	91	87.4±0.1
Likelihood	0.45	0.9±0.02	0.49	90.2±0.1

Table 2.6: Table of the muon masses and likelihood with electron background, where m_{tc} is track centered mass and m_{ts} is track seeded mass, both in MeV. This table is for momentum bin between 35 GeV and 40 GeV.

Pbin = 35 GeV-40 GeV				
Threshold	$\epsilon_\mu = (90 \pm 0.13)\%$ **Parameter**	$\epsilon_\mu = (90 \pm 0.13)\%$ **e Background** [%]	$\epsilon_e = (1 \pm 0.03)\%$ **Parameter**	$\epsilon_e = (1 \pm 0.03)\%$ μ **signal** [%]
$\mathbf{m}_{tc}$ **[MeV]**	92	6.6±0.07		
$\mathbf{m}_{ts}$ **[MeV]**	75	5.3±0.07	102	67±0.2
Likelihood			0.19	71.7±0.2

3 Conclusion

For the purpose of analysis we used simulated data from $K^+ \rightarrow e^+\nu$ (Ke2) and $K^+ \rightarrow \mu^+\nu$ (Kmu2) decays to test the NA62 RICH detector capabilities to distinguish between muons and electrons for possibility of studying $K^0_L \rightarrow \mu^\pm e^\mp$ decay. The study was performed on three parameters (track centered mass, track seeded mass and Likelihood) to see if the distinction is possible. On those data the 90% muon signal efficiency and 1% electron contamination thresholds were tested. For the muon signal efficiency we can see that we mostly have best performance with likelihood, except in the last momentum bin, where the electron-muon separation is worse even with other two parameters, which implies that the upper momentum limit for the muon-electron distinction should be lower than 35 GeV. Comparing tables 2.1-2.6 with each other, we can see that highest efficiency with lowest background contamination can be achieved in momentum bins between 15 GeV and 30 GeV as expected.

In this momentum interval likelihood achieved 90% signal efficiency and only $(0.4 \pm 0.02)\%$ background contamination. When setting Background contamination to 1% level the signal efficiency raised to approximately 92%.

On the other hand we found out that the track centered mass does not perform well, when the threshold contamination is set to 1% due to the long tails of the electron mass distribution. In this case the signal efficiency soon drops to the level of background noise and muons can not be distinguished from the electrons only by this parameter.

The track centered mass performs quiet well when the signal efficiency is set to 90%. The background noise is in low momentum bins in the order of 1%, but increases when we increase momentum of particles, reaching almost 7% in upper analysis. The track seeded mass performs better when moving to momentum between 25 GeV and 35 GeV, but never reaches values above 90% efficiency for momentum smaller than 25 GeV.

This is only preliminary analysis and was performed on each of the variables separately. In future analysis combination of multiple variables is possible, which will further increase efficiency of cuts. It is also possible to add other parameters (such as radius), which will increase discrimination between muons and electrons. Even though the analysis was performed on the simulation data of $K^+ \rightarrow e^+\nu$ and $K^+ \rightarrow \mu^+\nu$ decays the results show clear possibility of distinguishing muons from electrons with high signal to noise ratio. For the future, more complex analysis the $K^0_L \rightarrow \mu^\pm e^\mp$ simulated data would be recommended in order to take into account the different geometry and two-tracks event topology.

Bibliography

[1] The NA62 collaboration, 2017 JINST 12 P05025, *The beam and detector of the NA62 experiment at CERN* Jurnal of Instrumentation (2017)

[2] V. Duk et al, *Precise mirror alignment and basic performance of the RICH detector of the NA62 experiment at CERN*, IOP Publishing for Sissa Medialab (2018)