New Physics Searches in NA62 Experiment at CERN

PhD thesis project
New Physics Searches in NA62 Experiment at CERN

PhD thesis project

Mgr. Michal Kovaľ

Study field: 4.1.2 General Physics and Mathematical Physics
Study program: General Physics and Mathematical Physics

Supervisor: doc. RNDr. Tomáš Blažek, PhD.
Department of Theoretical Physics and Didactics of Physics

BRATISLAVA, 2014
License

Copyrighted by Michal Koval. Some rights reserved. This work is licensed under a Creative Commons Attribution 4.0 International License.

http://creativecommons.org/licenses/by/4.0/
Abstract

In this dissertation thesis project, possible searches for new physics in the CERN NA62 experiment are discussed. NA62 represents state-of-the-art kaon physics research. The experiment will study rare kaon decays, including the gold-plated $K^+ \rightarrow \pi^+ \nu \bar{\nu}$.

The physics goal of this work is to study $R_K$ measurement prospects in 2014/15 data and $\pi^0$ transition form factor measurement in 2007/08 data. The author also contributes to the operation of the experiment by development of the control software for the Local Trigger Unit. An introduction to the NA62 detector and physics program, some of the preliminary results and plans for the next two years are given, too.

Keywords: NA62 experiment, rare kaon decays
Acknowledgement

I would like to thank E. Goudovski, V. Černý, R. Lietava and T. Blažek for their valuable advice and guidance.

I declare that I have written this work on my own using the literature listed in the bibliography.

Bratislava 28.2.2014

............................

Mgr. Michal Kovaľ
Contents

1 Introduction 7

2 NA62 experiment 8
  2.1 $R_K$ measurement (2007-2008) .......................... 10
     2.1.1 Detector setup ........................................ 10
  2.2 Rare kaon decays (2014-2015) .............................. 12
     2.2.1 Detector setup ........................................ 13
     2.2.2 NA62 simulation software ............................ 14
     2.2.3 Other physics program ............................... 14

3 Aims of the dissertation thesis 15
  3.1 $R_K$ measurement .......................................... 16
     3.1.1 Theoretical framework ............................... 16
     3.1.2 Acceptance and momentum resolution ............... 18
     3.1.3 Muon polarization ................................... 24
  3.2 $\pi^0$ transition form factor measurement ................ 27
  3.3 Local Trigger Unit software development .................. 30
     3.3.1 NA62 trigger system overview ....................... 30
     3.3.2 LTU module ........................................... 32
     3.3.3 LTU current status and outlook ..................... 33
1 Introduction

The Standard Model (SM) of particle physics [1, 2, 3, 4] very successfully describes the electroweak and strong interactions of elementary particles. Recent discovery of the Higgs boson by the LHC experiments ATLAS and CMS [5, 6] has filled the last gap in the experimental evidence for the Standard Model. Despite of this great success, the SM is arguably not the final theory of particle physics. For example, it does not provide any dark matter candidate with properties compatible with astrophysical observations.

The main goal of particle physics today is the search for new physics beyond the Standard Model. There are many experiments which are trying to find any traces of such physics which would be demonstrated by disagreement between the SM prediction and experimental observation. The experiments can be divided into three main categories:

1. High energy frontier. Colliding particles at extremely high energies and trying to directly produce and observe new heavy states (e.g. experiments ATLAS and CMS at the LHC). No direct production of new particles has been observed so far in these experiments.

2. High precision frontier. High precision experiments are trying to find deviations from the SM at lower energies. Presence of new particles could be revealed indirectly through virtual quantum corrections. Representative field of this frontier, flavor physics, is looking for these effects in lepton flavor violating processes (LFV), flavor changing neutral current processes (FCNC), muon anomalous magnetic moment and so on.

3. Cosmic frontier. Astrophysical observations using underground experiments (dark matter searches) and both ground and space telescopes (e.g. the Hubble space telescope, Planck observatory). These observations are complementary to high-energy physics experiments.

One of the most important experiments at the high precision frontier today is the NA62 experiment\(^1\). The experiment represents the kaon physics research program at CERN and currently is in a state of preparation for the main phase of physics run which is scheduled for October 2014. Its main objective is to measure the branching ratio of the ultra-rare kaon decay \(K^+ \to \pi^+ \nu \bar{\nu}\).

\(^1\)https://na62.web.cern.ch/na62/
2 NA62 experiment

Kaons (also called K mesons) were discovered in cosmic rays in 1949 [7]. They are the lightest mesons with non-zero strangeness, a quantum number which was introduced in order to account for fast production and slow decay of new unstable particles [8, 9]. Experiments studying K mesons played a very important role in establishing the foundations of the Standard Model of elementary particles. The famous $\theta - \tau$ puzzle was resolved by the discovery of parity violation[10] in weak interactions. After the discovery of quarks, it was understood that strangeness of a particle comes from a strange quark content.

Neutral kaon systems\(^1\) provided another crucial discovery - CP-symmetry violation. CP-symmetry is the product of two symmetries, C - charge conjugation (particle/antiparticle transformation) and P - parity conversion ($\vec{r} \mapsto -\vec{r}$). After P symmetry was found to be violated by weak interactions, it was proposed that the interactions obey the CP-symmetry. Surprisingly few years later the CP violating decay $K^0_L \to 2\pi$ was observed[11].

Important results in kaon physics were obtained by the NA48 experiment at CERN. Precise measurement of direct CP violation in the system of neutral kaons has been performed [12]. Under the name NA48/1, the experiment continued to study rare decays of neutral $K^0_S$ meson, and finally as NA48/2, the experiment studied direct CP violation and various rare $K^\pm$ decays.

NA62 experiment is a successor to the NA48 series of kaon experiments. In the first phase (data taking took place in 2007 and 2008), the main objective was to measure ratio $R_K$ of the decay widths $\Gamma(K^+ \to e^+\nu)$ and $\Gamma(K^+ \to \mu^+\nu)$. The goal has been achieved and the experiment provided the most precise measurement of $R_K$[13, 14]. However, the collected data can be reanalyzed to perform more precise measurements and new physics searches. Some of the possibilities will be described in the following chapters.

The NA62 experiment is currently in a state of preparation for its second phase, in which the measurement of the $K^+ \to \pi^+\nu\bar{\nu}$ decay branching ratio will be the most important objective. Other rare decay processes are going to be studied as well.

---

\(^1\) $K^0_L$ (K-long) and $K^0_S$ (K-short) mesons are two weak eigenstates mixed from two strong eigenstates $K^0$ and $\bar{K}^0$. $K^0_L$ normally decays into $3\pi$, while $K^0_S$ into $2\pi$ mesons.
The NA62 experiment studies various decays of charged kaons. For reference, basic properties of positively charged kaon are summarized in the following table. In the second table six main decay modes of $K^+$ with their branching ratios are given.

<table>
<thead>
<tr>
<th>Particle symbol</th>
<th>$K^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quark content</td>
<td>$u\bar{s}$</td>
</tr>
<tr>
<td>Mass</td>
<td>$(493.677 \pm 0.016)$ MeV/c$^2$</td>
</tr>
<tr>
<td>Mean lifetime</td>
<td>$(1.2380 \pm 0.0021) \times 10^{-8}$ s</td>
</tr>
</tbody>
</table>

Table 2.1: Properties of charged kaon [15]

<table>
<thead>
<tr>
<th>Final state</th>
<th>Mode</th>
<th>Branching ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+\nu_\mu$</td>
<td>leptonic</td>
<td>$63.55 \pm 0.11%$</td>
</tr>
<tr>
<td>$\pi^+\pi^0$</td>
<td>hadronic</td>
<td>$20.66 \pm 0.08%$</td>
</tr>
<tr>
<td>$\pi^+\pi^+\pi^-$</td>
<td>hadronic</td>
<td>$5.59 \pm 0.04%$</td>
</tr>
<tr>
<td>$\pi^0\nu_e$</td>
<td>semileptonic</td>
<td>$5.07 \pm 0.04%$</td>
</tr>
<tr>
<td>$\pi^0\mu^+\nu_\mu$</td>
<td>semileptonic</td>
<td>$3.353 \pm 0.034%$</td>
</tr>
<tr>
<td>$\pi^+\pi^0\pi^0$</td>
<td>hadronic</td>
<td>$1.76 \pm 0.022%$</td>
</tr>
</tbody>
</table>

Table 2.2: $K^+$ main decay modes [15]

---

2.1 $R_K$ measurement (2007-2008)

In 2007 and 2008, NA62 used the existing NA48/2 apparatus and beamline in measurement of the ratio $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu2})$. Experimental conditions (e.g. Level-0 trigger setup) have been optimized for the measurement of $K_{e2}$ and $K_{\mu2}$ decays. The same data have been used in the recently published analysis of the $K^\pm \rightarrow \pi^\pm \gamma\gamma$ decays\cite{16} and also can be used in other future analyses.

2.1.1 Detector setup

The NA48/2 beamline and sub-detectors used in the $R_K$ measurement are briefly described in this section. For more details, see \cite{17, 18}. This experimental setup is also relevant to a future measurement of the $\pi^0$ transition form factor (see section 3.2).

![Figure 2.2: NA48/2 beamline and detector – schematic view](image)

The NA48/2 beam line (Fig. 2.2) was originally designed to deliver simultaneous unseparated $K^+$ and $K^-$ beams. The beams were produced by 400 GeV/c momentum protons (delivered from the SPS accelerator) impinging on a beryllium target. Both beams leave the target on axis at zero production angle. A system of dipole magnets (front-end achromat in Fig. 2.2) separates beams of opposite charges and selects kaons in a narrow momentum interval with a central momentum of 74.0 GeV/c and a spread of 1.4 GeV/c (RMS). The beams pass through a defining collimator and a series of four quadrupoles designed to produce horizontal
and vertical charge-symmetric focusing of the beams towards the detector. Finally the two beams are again split in the vertical plane and recombined by a second achromat. [17, 18]

In 2007 the muon sweeping system was optimized for the positive beam and the first measurement of the $R_K$ was performed only with the $K^+$ beam [13]. Simultaneous or single beams of positive and negative kaons were later used to study various systematic effects (e.g. muon halo background)[14].

After passing through the cleaning and final collimators, the beams entered the decay volume housed in a 114 m long cylindrical vacuum tank of 1.9 m to 2.4 m inner diameter.

![Figure 2.3: NA48 detector](image)

The momenta of charged decay products were measured by a magnetic spectrometer, housed in a tank filled with helium at approximately atmospheric pressure, placed downstream of the decay volume. The two tanks (vacuum - helium) were separated by a thin (~ 0.4% radiation lengths X0 ) Kevlar window (Fig. 2.3).
The spectrometer comprises four drift chambers (DCHs) two upstream and two downstream of a dipole magnet which gives a horizontal transverse momentum kick of 265 MeV/c to singly-charged particles.

The magnetic spectrometer was followed by a plastic scintillator hodoscope (HOD) used to produce fast trigger signals and to provide precise time measurements of charged particles. The HOD was followed by a liquid krypton electromagnetic calorimeter (LKr) used to detect electrons and photons. It is an almost homogeneous ionization chamber with an active volume of 7 m$^3$ of liquid krypton. The LKr is followed by a hadronic calorimeter (HAC) and a muon detector (MUV), both not used in the $R_K$ analysis.

2.2 Rare kaon decays (2014-2015)

The main physics run of the NA62 experiment aimed at study of ultra-rare and forbidden $K^+$ decays will start in October 2014. For this purpose almost all of the sub-detectors will be replaced and upgraded.

There are many rare flavor changing neutral current decays of $K$ and $B$ mesons. Among them, the ultra rare decays $K \rightarrow \pi \nu \bar{\nu}$ play a key role in the search for new physics beyond the Standard Model. The SM branching ratio has been computed to a very high degree of precision ([20], including two loop electroweak corrections):

$$BR_{SM}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (7.81 \pm 0.75 \pm 0.29) \times 10^{-11}.$$  \hfill (2.1)

The first error comes from the uncertainty of the CKM matrix elements, the second error is pure theoretical uncertainty. This decay is one of the best probes of the various models beyond the SM, including Minimal Supersymmetric Standard Model. Even deviations of the measurement from the SM prediction at the level of 20 % would be considered as a signal of new physics. The measurement of the branching ratio is the main goal of the NA62 experiment.

NA62 aims to collect of the order of 100 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events in about two years of data taking. To this purpose, at least $10^{13}$ $K^+$ decays are required (assuming 10% signal acceptance). The scheduled physics run starts in October 2014. In November 2012 NA62 took data during a technical run with partial detector configuration. The goals of this run were to test the final beam line and analysis of the time and spatial correlation between sub-detectors.
2.2.1 Detector setup

Here we briefly describe the NA62 layout designed for the $K^+ \to \pi^+ \nu \bar{\nu}$ measurement. The same CERN-SPS extraction line already used in the $R_K$ phase of NA62 can deliver the required proton intensity in order to produce sufficient number of kaons. The hadron beam contains $\pi^+$ (70%), protons (23%) and kaons (6%).

The CEDAR/KTAG identifies the $K^+$ component in the beam with respect to the other beam particles by employing an upgraded differential Cherenkov (CEDAR) counter from the SPS at CERN. The beam spectrometer, called Gigatracker (GTK) consists of three Si micro-pixel stations measuring time, direction and momentum of the beam particles before entering the decay region. The last GTK station is complemented by 6 stations of “guard-ring” counters called CHANTI to reduce critical background from inelastic interactions from beam particles in the last GTK station.

The STRAW Tracker measures the coordinates and momentum of secondary charged particles originating from the decay region. The RICH detector is required to improve the rejection of background from $K^+ \to \mu^+ \nu_\mu$ decays providing positive identification of the muon in the background events and an identification of the pion in the signal events. The charged-particle hodoscope (CHOD) will provide fast trigger signals.

The suppression of possible background from $K^+ \to \pi^+ \pi^0$ decays requires very high detection efficiency for high energy photons. A system of Photon-Veto
detectors provide hermetic coverage from zero to large angles (≈ 50 mrad) from the decay region. The Large Angle Veto (LAV) detector consists of 12 stations distributed along the decay volume. NA62 re-uses the Liquid Krypton Calorimeter (LKr) from NA48 as a veto for photons in the 1 – 10 mrad region. Two small calorimeters IRC and SAC cover very small angles near the beam pipe.

The muon veto system (MUV) consists of three sub-detectors, called MUV1, MUV2, and MUV3. The first two modules (MUV1 and MUV2) follow directly the LKr calorimeter and work as hadronic calorimeters for measurement of deposited energies and shower shapes of incident particles. The MUV3 detector is located after an additional Muon filter (80 cm of iron) serving as fast muon veto that can be used in the level-0 trigger.

A detailed description of the full system can be found in the technical design document of the NA62 experiment[21].

2.2.2 NA62 simulation software

Simulation of the new NA62 detector is performed in a Geant4 based simulation framework. The package NA62MC takes care of the generation and propagation of the particles along the NA62 volume. It also provides non-digitized signals as response from the various sub-detectors. NA62Reconstruction package takes care of the detector response: it simulates the signal digitization and performs the reconstructions of the sub-detectors. NA62Analysis package provides tools necessary to analyze the reconstructed data.

2.2.3 Other physics program

Large number of recorded $K^+$ decays and many high-precision sub-detectors in the NA62 experiment make possible to develop a very rich kaon physics program. Let us mention just two of the possibilities:

- new $R_K$ measurement
- search for Lepton Flavor Violation (LFV) in various processes (e.g. $K^+ \rightarrow \pi^+\mu^+\bar{e}^-$)

\[^3\text{http://sergiant.web.cern.ch/sergiant/NA62FW/html/}, \text{NA62 simulation framework}\]
3 Aims of the dissertation thesis

The presented work has been carried out within the NA62 experiment collaboration. The author’s work can be divided into three main categories. A short summary is given here, more detailed description with some preliminary results can be found in the following sections.

$R_K$ measurement

The experimental uncertainty of the $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu2})$ value is one order of magnitude larger than the theoretical prediction uncertainty. This motivates further precision measurement using the new NA62 detector. The author has developed a toy Monte-Carlo model with simulation of two-body decays which compares the geometrical acceptance and the momentum resolution of the 2007 detector setup with the new setup. He has contributed to the official NA62 simulation framework and included muon polarization into the framework. Detector resolution with realistic simulation software has been studied. Study of the background processes is ongoing. First data collected by the NA62 are going to be analyzed and compared with the simulation results. (section 3.1)

$\pi^0$ electromagnetic transition form factor measurement

Processes with electromagnetic interactions of hadrons, such as decays of neutral pion (e.g. Dalitz decay: $\pi^0 \rightarrow \gamma e^+ e^-$) can provide testing ground for any theory describing the structure of strongly interacting particles. Existing data collected by the NA62 experiment ($R_K$ phase) are going to be used in a measurement of the $\pi^0$ electromagnetic form factor. The measurement of the form factor is an inevitable prerequisite in a possible search for a dark photon $U$ in the decay channel $\pi^0 \rightarrow U\gamma \rightarrow e^+ e^- \gamma$. The author has studied the literature and acquired necessary skills to use the standard NA62 data analysis tools. (section 3.2).

Local Trigger Unit (LTU) software development

The author has participated in preparation of the new NA62 detector TDAQ system by development of the LTU controlling software. During the time spent at CERN he helped in testing of both LTU software and hardware. Maintenance and support during the physics run (starting in October 2014) will also be provided. (section 3.3)
3.1 $R_K$ measurement

3.1.1 Theoretical framework

Leptonic decays of pseudoscalar mesons are helicity suppressed in the Standard Model due to the V-A structure of charged current coupling. At tree level, decay width of two-body decays $P^\pm \rightarrow l^\pm \nu$ (denoted as $P_l^2$ in the following text) reads

$$\Gamma^{SM}_{P}(P^\pm \rightarrow l^\pm \nu) = \frac{G_F^2 M_P M_l^2}{8\pi} \left(1 - \frac{M_l^2}{M_P^2}\right) f_P^2 |V_{qq'}|^2,$$

(3.1)

where $G_F$ is the Fermi decay constant, $M_P$ and $M_l$ are the masses of the meson $P$ and lepton $l$, $f_P$ is the meson decay constant and $V_{qq'}$ is the corresponding CKM matrix element.

![Figure 3.1: Tree level Feynman diagram of a $K_{l2}$ decay](image)

Theoretical predictions for these decay widths are affected by hadronic uncertainties (determination of $f_P$). However specific ratios of the decay rates can be calculated very precisely, as the decay constant $f_P$ is canceled. The ratio $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu2})$ has been calculated within the Chiral Perturbation Theory framework to the order of $\epsilon^2 p^4$ and reads [22]

$$R_K^{SM} = \left(\frac{M_e}{M_\mu}\right)^2 \left(\frac{M_K^2 - M_e^2}{M_K^2 - M_\mu^2}\right)^2 (1 + \delta R_{QED})$$

(3.2)

$$= (2.477 \pm 0.001) \times 10^{-5},$$

where $\delta R_{QED} = (-3.79 \pm 0.04)\%$ is the electromagnetic correction. The predicted ratio value is inclusive of internal bremsstrahlung radiation (an extra photon is emitted by the charged lepton in Fig. 3.1).

Some extensions of the SM containing two Higgs doublets, for example Minimal Supersymmetric Standard Model (MSSM), introduce new source of lepton flavor...
violation which can contribute to the ratio $R_K$ via loop diagrams with an exchange of charged Higgs boson (see Feynman diagrams below).

![Feynman diagram](image)

Figure 3.2: Tree level MSSM diagram contributing to $\Gamma(K_{l2})$, this contribution does not depend on $M_l$ and is canceled in the $R_K$ ratio

![One-loop LFV diagrams](image)

Figure 3.3: One-loop LFV diagrams in MSSM contributing to $\Gamma(K_{l2})$.

A recent study [23] showed that the MSSM contribution can enhance $R_K$ by $\mathcal{O}(1\%)$ via Feynman diagrams in Fig. 3.3. Higgs mediated LFV processes are capable of providing an important contribution when the kaon decays into an electron plus a tau-neutrino. The enhancement is constrained by other observables such as $B_s \to \mu^+\mu^-$ and $B^+ \to \tau^+\nu$ decay rates[24], which are being studied in the B meson experiments like LHCb[25] or BaBar[26].

The most precise measurement to date has been performed by the NA62 experiment in its first phase of data taking in 2007-2008 (see section 2.2) [14]:

$$R_K = (2.488 \pm 0.010) \times 10^{-5} \quad (3.3)$$

The measurement is consistent with the Standard Model prediction and with previous measurements [27, 13]. However, the experimental uncertainty is still one order of magnitude larger than the uncertainty in the theoretical prediction (see equation 3.2), which motivates further measurement at improved precision.

The NA62 experiment in its second phase will be able to suppress various background contributions which were dominant in the previous measurement and thus
push the experimental uncertainty to the per-mill level. This will be possible due to the upgraded detector and a large number of recorded kaon decays (needed for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ study).

### 3.1.2 Acceptance and momentum resolution

In order to estimate the sensitivity of the new NA62 detector for a new $R_K$ measurement, various studies has to be done using simulation. As a first task of this PhD, a simple Monte Carlo program was developed. The goal was to compare the geometrical acceptance and the momentum resolution of the two NA62 detector setups.

The simulation program has been written from scratch within the ROOT framework\(^1\). Two-body kaon decays $K_{\mu2}$ and $K_{e2}$ with random decay vertex position and decay products are generated. The program takes into account the beam momentum and spread, the geometries of the two detector setups, uncertainties in determination of particle momenta in the sub-detectors, and the effect of the spectrometer magnet field. If the trajectory of a charged lepton ($\mu/e$) intersects all relevant sub-detectors, a “hit” is registered.

Generated data are divided into 11 bins based on the lepton momentum: $\text{bins} = \{ (10,15), (15,20), \ldots, (60,65) \}$ GeV. Geometrical acceptance in a momentum bin is defined as a ratio of events with lepton of a momentum $p_l \in \text{bin}(i)$ and a trajectory intersecting all the sub-detectors (in later denoted as hit) and all generated $K_{l2}$ decays in the decay region:

$$A_i(K_{l2}) = \frac{N_{i, \text{hit}}(K_{l2})}{N_{\text{all}}(K_{l2})}. \quad (3.4)$$

The choice of the acceptance definition in eq. (3.4) is given by the requirement that we want to measure the $R_K$ ratio independently in each of the momentum bins. In a very simplified situation with no trigger or detector inefficiencies, assuming no background processes, the ratio would be calculated from the recorded numbers of hits $N_{i, \text{hit}}(K_{l2})$ in the following way

$$R_K = \frac{N_{\text{all}}(K_{e2})}{N_{\text{all}}(K_{\mu2})} = \frac{N_{i, \text{hit}}(K_{e2})}{N_{i, \text{hit}}(K_{\mu2})} \frac{A_i(K_{\mu2})}{A_i(K_{e2})}, \quad (3.5)$$

where the ratio of the geometric acceptances is referred to as acceptance correction.

\(^1\)http://root.cern.ch/, ROOT, A Data Analysis Framework
in the following. The acceptance can be determined only by the simulation.

Here we present our results of geometrical acceptance study using the simple Monte Carlo program. The results were presented at the NA62 Physics Working Group meeting (10.04.2013). We see that there are only small differences between the two setups.

Figure 3.4: NA62 geometrical acceptance
2007 detector setup (top), 2014 detector setup (bottom)
The acceptance correction shows similar behavior for both setups (see plots below). The most significant difference is in the low momentum region, where the 2014 correction is slightly larger. This is caused by different length and position of the decay volume and dimensions of the sub-detectors.

Figure 3.5: NA62 acceptance correction
2007 detector setup (top), 2014 detector setup (bottom)
A basic variable reconstructed from the kaon decays with a charged track in the spectrometer is called *missing mass squared*. It is calculated as a difference between kaon four-momentum and a charged track four-momentum, squared. In the specific case of $K_{l2}$ decays, it reads

$$M_{\text{miss}}^2 = (P_K - P_l)^2.$$  

(3.6)

This variable represents *measured* mass of the neutrino, while the *physical* neutrino mass is practically zero. Therefore the histogram distribution of the $M_{\text{miss}}^2$ variable calculated from the reconstructed momenta tells us what is the momentum resolution of the detector. The distribution obtained from the simple Monte Carlo model is presented in the following plot, where we see a comparison between the two detector setups. In this figure, only the $K_{\mu2}$ data are shown, as the $K_{e2}$ distribution is very similar.

![Figure 3.6: Integrated distribution of $M_{\text{miss}}^2$ in $K_{\mu2}$](image)

From the value of root mean square (RMS), we see that the resolution of the new NA62 detector is expected to be approximately two times better. All events within the geometrical acceptance with lepton momentum from (10, 65) GeV interval are included in the plot. It is also interesting to look into the dependence of the resolution with respect to the lepton momentum. In the following plot $M_{\text{miss}}^2$ RMS values in momentum bins are shown. Again, only $K_{\mu2}$ data are presented.
Figure 3.7: Momentum resolution, $\sigma(M_{\text{miss}}^2)$ in momentum bins

We see that the $\sigma$ of the momentum resolution in the 2014 setup resolution slightly increases from low to high momenta, while in the 2007 setup the resolution was the best in the mid-momentum region. This is caused by the fact that in 2007 the momentum of each individual kaon was not measured. Only an average kaon momentum was known from analysis of fully-reconstructed $K^+ \rightarrow \pi^+\pi^+\pi^-$ decays. In 2014 there is going to be a dedicated sub-detector called Gigatracker (GTK) which will measure beam particle momenta.

A simplistic Model Carlo model is very useful in the first steps of a study but it has strong limitations as it can not realistically simulate interaction of particles passing through sub-detectors. After obtaining the results presented above, we started using the official NA62 Monte Carlo simulation framework described in subsection 2.2.2.

Data obtained from a real physics run or from a realistic simulation include events which are either misreconstructed (too few hits in a sub-detector) or involve a physics process like large angle scattering. One needs to find selection criteria in each of the sub-detectors which will exclude such events and keep the “good” events. Our most important recent contribution is the study of the track selection criteria in the STRAW spectrometer. Results were presented at the NA62 Physics Working Group meeting (18.12.2013).
Here we decided to show only two representative plots with $M_{\text{miss}}^2$ distribution with the comparison between data distribution before and after the “good track” selection. The plots are in the logarithmic scale.

![Plots of $M_{\text{miss}}^2$ distribution in $K_\mu^2$ (top) and $K_e^2$ decay (bottom)](image)

Figure 3.8: $M_{\text{miss}}^2$ distribution in $K_\mu^2$ (top) and $K_e^2$ decay (bottom)

We can see that it is really important to develop good selection criteria and suppress misreconstructed events which are easy to spot as “tails” in the $M_{\text{miss}}^2$ distribution. The tail in the positive $M_{\text{miss}}^2$ values in $K_e^2$ is not a reconstruction error but a physical effect of the bremsstrahlung radiation of electrons passing
through the STRAW spectrometer chambers.

The next step in the study of $R_K$ prospects will be an analysis of $K_{e2}$ background processes. One of the most important backgrounds will be $K_{\mu 2}$ decays with muon decays in flight.

### 3.1.3 Muon polarization

A muon coming from a $K_{\mu 2}$ decay is fully polarized ($K^+$ is spinless, $\nu_\mu$ is left-handed) and its polarization vector in the $K^+$ rest frame points in the direction opposite to the muon momentum (Fig. 3.9). In a subsequent muon decay $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu (\gamma)$, which represents an important background to $K_{e2}$ decays in the NA62 experiment, the positron distribution depends on the muon polarization. This was a motivation for us to study muon polarization effects and to modify the official NA62 Monte Carlo software in order to include polarization in it.\(^2\)

![Figure 3.9: Schematic view of a $K_{\mu 2}$ decay in the kaon rest frame](image)

We are interested in the positron distribution from fully polarized muon decay $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$. Assuming the Standard Model coupling, the tree level differential decay rate in the muon rest frame, in the limit $m_e/m_\mu \to 0$ takes the following form [15]:

$$\frac{d^2\Gamma}{dx \, d\cos \theta} = \frac{G_F^2 m_\mu^5}{192 \pi^3} \left[ 3 - 2x + (2x - 1) \cos \theta \right] x^2. \quad (3.7)$$

Here, $m$ is the muon mass, $x = E_e/\text{max}(E_e)$ is the reduced positron energy, $\theta$ is the angle between the muon polarization vector and the positron momentum direction. Integration of this distribution over positron energy gives the angular distribution of the positrons:

$$\frac{d\Gamma}{d\cos \theta} = \frac{G_F^2 m_\mu^5}{192 \pi^3} \left( \frac{1}{2} + \frac{1}{6} \cos \theta \right). \quad (3.8)$$

\(^2\)This subsection is a summary of the author’s NA62 internal note called *Muon Polarization in K\textsubscript{mu2} Decay* [28]. The changes to the official software have been reported at the NA62 Software Working Group meeting (28.08.2013).
Exact computation of the first order radiative corrections to the polarized muon decay spectrum can be found in [29], and leading second order corrections in [30].

We see that in order to know the positron spectrum in a polarized muon decay, we need to know the muon polarization vector in its rest frame. In the experimental situation of the NA62, we have kaon in the laboratory frame with four-momentum $p_k = (E_k, p_k)$, decaying into a muon $p_\mu = (E_\mu, p_\mu)$, and a muon neutrino $p_\nu = (E_\nu, p_\nu)$.

The easiest way how to calculate the muon polarization vector in the muon rest frame is to realize that the muon spin points in the direction of the neutrino momentum in all reference frames. In the muon rest frame it is identical to the direction of the kaon momentum. Therefore we just need to find the kaon momentum in the muon rest frame by a Lorentz transformation of $p_K$ into the muon rest frame.

$$E_k' = \frac{E_\mu}{m} \left( E_k - \frac{p_\mu \cdot p_k}{E_\mu} \right) = \frac{M^2 + m^2}{2m}$$

$$p_k' = p_k - \frac{M^2 + m^2 + 2mE_k}{2m(E_\mu + m)} p_\mu$$

The muon polarization is a unit vector, so in order to find it we need to normalize $p_k'$:

$$\xi = \frac{p_k'}{|p_k'|} = \frac{p_k'}{\frac{M^2 - m^2}{2m} p_k - \frac{1}{E_\mu + m} \left( 1 + \frac{2m}{M^2 - m^2} (E_k + m) \right) p_\mu},$$

This formula has been implemented in the NA62MC simulation framework together with a general polarization framework which can be reused for a different decay channel. It is important to note that without the inclusion of the polarization into the software, a wrong spectrum of positrons coming from $K_{\mu2}$ decays with muon decay in flight would be obtained.

In Fig. 3.10 we see the $M^2_{miss}$ distribution of positrons coming from $K_{\mu2}$ events which are in geometrical acceptance. Red (blue) line shows the positron distribution when we do (do not) take into account the muon polarization effect. This process is expected to be the dominant background to the $K_{e2}$ decays in the new $R_K$ measurement.
In the analysis of $R_K$ we are interested in the number of $K_{\mu 2}(\mu \rightarrow e)$ events with low missing mass (arrow in Fig. 3.10) as these events could mimic genuine $K_{\mu 2}$ decays and thus affect the measurement. We see that the muon polarization effect distinctly decreases the possible background to $K_{\mu 2}$. The study of this background is ongoing, but from our preliminary results we estimated the background to be:

\[
\frac{N_{\text{back}}(K_{\mu 2}(\mu \rightarrow e))}{N_{\text{hit}}(K_{\mu 2})} = (0.10 \pm 0.01)\%,
\]

while in the case of unpolarized muons, the background is approximately 10 times larger. In the previous NA62 $R_K$ measurement [14] the background was estimated as $(0.26 \pm 0.04)\%$. The difference is caused by different lengths of decay volumes in the two setups.
Neutral pion (also called pi meson) is the lightest meson and plays a very important role in study of low-energy properties of the strong nuclear force. Its basic properties are summarized in the following table.

<table>
<thead>
<tr>
<th>Particle symbol</th>
<th>( \pi^0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quark content</td>
<td>((u\bar{u} - d\bar{d})/\sqrt{2})</td>
</tr>
<tr>
<td>Mass</td>
<td>((134.9766 \pm 0.0006) \text{ MeV}/c^2)</td>
</tr>
<tr>
<td>Mean lifetime</td>
<td>((8.52 \pm 0.18) \times 10^{-17} \text{ s})</td>
</tr>
</tbody>
</table>

Table 3.1: \( \pi^0 \) properties [15]

\( \pi^0 \) decays almost instantaneously via electromagnetic interaction. The branching ratio of the \( \pi^0 \rightarrow 2\gamma \) decay is approximately 98.82 \%, the second most common decay, the Dalitz decay (\( \pi^0_D \)): \( \pi^0 \rightarrow e^+e^-\gamma \) proceeds via the same \( \pi^0\gamma\gamma \) vertex with probability 1.17 \%. Other decay channels are very rare (e.g. \( \pi^0 \rightarrow e^+e^-e^+e^- \) and \( \pi^0 \rightarrow e^+e^- \)). [15]

Figure 3.11: \( \pi^0 \) decays - Feynman diagrams

\begin{align*}
(3.11.1) \quad & \pi^0 \rightarrow 2\gamma, \text{ main decay channel} \\
(3.11.2) \quad & \pi^0 \rightarrow e^+e^-\gamma, \text{ Dalitz decay (}\pi^0_D\text{)}
\end{align*}

In the \( \pi^0_D \) Feynman diagram, one of the two photons from the \( \pi^0\gamma\gamma \) vertex is off-shell and decays to a \( e^+e^- \) pair. The amplitude for the process contains a form factor \( F(x) \):

\[ |M|^2 = |M_{QED}|^2 \times |F(x)|^2, \tag{3.12} \]

where \( M_{QED} \) is the scalar QED amplitude of point-like pion Dalitz decay and \( x \) is the invariant mass of the electron-positron pair divided by the pion mass, squared:

\[ x = \left( \frac{m_{e^+e^-}}{m_{\pi^0}} \right)^2 = \left( \frac{p_{e^+} + p_{e^-}}{m_{\pi^0}} \right)^2. \tag{3.13} \]
The form factor is called the $\pi^0$ electromagnetic transition form factor (TFF). In the real photon limit, value of $x$ goes to zero, and the form factor $F(x)$ is reduced to the pion decay constant, here denoted as $F$. $F(x)$ is generally expected to vary slowly in the available energy range ($4m_e^2/m_{\pi^0}^2 \leq x \leq 1$) and usually is approximated by the linear expansion

$$
F(x) = 1 + ax,
$$

where $a$ is called the slope parameter. This parameter can be compared with theoretical predictions of various hadron structure models. There is a general agreement between the simple vector meson dominance (VMD) model [31] and advanced calculations in the chiral perturbation theory framework [32] that the slope value is approximately $a \approx 0.03$.

The first measurement of the $\pi^0$ TFF which included $\pi^0_D$ radiative corrections (which play a very important role) was performed at CERN in 1977 [33]. The technique used in the measurement is very similar to the NA62 experiment approach. The $K^+ \to \pi^+\pi^0$ decay in flight was used to tag pions and momenta of charged particles were measured. The result was (only statistical error was given):

$$
a = 0.10 \pm 0.03.
$$

Two experiments used a different technique to produce neutral pions, i.e. charge exchange of negative pions with protons $\pi^-p \to \pi^0n$. The measurements are consistent with the theoretical predictions, but the error bars are very large.

$$
a = 0.026 \pm 0.024 \pm 0.048 \ [34]
a = 0.025 \pm 0.014 \pm 0.026 \ [35]
$$

Other experiments (CLEO [36] and Belle [37]) performed $\pi^0$ TFF measurements in the space-like region at much higher momentum transfers (large $x$ values) through the process $\gamma\gamma^* \to \pi^0$. The measurements are again consistent with the VMD and the error bars are much smaller. However the extrapolation from high energies to low values of $x$ (and determination of $a$) is model dependent. This motivates a new measurement of the $\pi^0$ TFF in the pion Dalitz decay.
The NA62 experiment with its high intensity kaon beam can be also viewed as a $\pi^0$ factory. Neutral pions are produced in four of the six main $K^+$ decay modes (see Table 2.2). The cleanest one for $\pi^0$ analysis purposes is the $K^+ \rightarrow \pi^+\pi^0 (K_{2\pi})$ decay. A neutral pion can be identified if missing mass calculated from the measured $\pi^+$ momentum corresponds to the mass of the neutral pion:

$$M_{\text{miss}}^2 = (P_K - P_{\pi^+})^2 \approx m_{\pi^0}^2. \quad (3.17)$$

Momenta of the charged particles are measured by the spectrometer (DCH in the 2007 NA62 setup). The form factor can be determined by comparing the Monte Carlo distribution of events with respect to $x$ generated with a constant value of $F$ to the data distribution.

The TFF measurement is also important in a possible search for a hypothetical dark photon. The idea of a new $U(1)$ gauge symmetry with a very light gauge boson, called a dark photon (or $U, \gamma'$, $A'$ boson) has been proposed [38, 39]. The dark photon could mediate the annihilation of Dark Matter particles and explain the excess of positrons in cosmic rays[40].

Dark photon presence would demonstrate itself in the NA62 data by the background process $\pi^0 \rightarrow U\gamma \rightarrow e^+e^-\gamma$ to the $\pi_0^D$ as an excess in the $\pi_0^D$ spectrum. The knowledge of the exact shape of the Dalitz decay distribution (given by the transition form factor) is crucial in the search for a contribution from the dark photon background.

The author has studied the literature and acquired necessary skills to access the existing data from the first phase of the NA62 experiment and to use standard NA62 data analysis tools. He will perform an analysis of the 2007-2008 NA62 data with the goal of measurement of the $\pi^0$ electromagnetic transition form factor.
3.3 Local Trigger Unit software development

In preparation for the new run of the NA62 experiment, Bratislava NA62 group took responsibility for development of control software and testing of Local Trigger Unit (LTU) module. The author participates in these activities. In the following sections a simple overview of the NA62 trigger system with some details on the LTU module are presented.

3.3.1 NA62 trigger system overview

The intense flux of the hadron beam in the NA62 experiment, necessary for rare decays study, yields very strong requirements for Trigger, and Data Acquisition (TDAQ) system. All systems (trigger distribution, sub-detector read-out) will have to deal with very high particle rates. The old TDAQ system used with the NA48 detector did not satisfy these requirements, therefore a new fully digital system has been developed (for full system overview, see chapter 4 in [21]).

Compared with the LHC experiments the NA62 TDAQ system is quite different, although it is based on the same technology developed at CERN. There are no tight space constraints, the sub-detectors are placed in 150 meter long area. The most important difference lies in the fact, that there is no bunch structure of the incoming beam. After protons from the SPS hit the target, the hadron beam comes in spills lasting few seconds, separated by inter-spill periods without beam lasting ∼ 10 s. This time is used for data retrieval and further processing.

Large distances between sub-detectors combined together with very high particle rates raise very important issue of precise time measurement and synchronization between the sub-detectors. A common coherent clock, with a frequency of approximately 40 MHz, generated centrally by a single free-running high-stability oscillator, will be distributed optically to all systems through the Timing, Trigger and Control (TTC) system designed and used for LHC experiments\(^3\). This “TTC clock” will be the common reference for time measurements.

\(^3\)http://ttc.web.cern.ch/ttc/, TTC: Timing, Trigger and Control Systems for LHC Detectors
The NA62 trigger system consists of multiple trigger levels. The first layer, a hardware trigger system, is called Level-0 (L0). A very simplified picture of the L0 trigger distribution network is presented in the figure above. The basic logic of the system can be described in the following way.

Sub-detectors involved in the L0 will provide “trigger primitives”, simple data containing information about the hits in the detector and the timestamp of the observed event. These data will be sent asynchronously to the L0 Trigger Processor (L0TP) over Gigabit Ethernet links. The data rates can reach more than 10 MHz, and have to be reduced to the nominal L0 read-out frequency 1 MHz by the L0TP.

L0 Trigger Processor will time-match L0 trigger primitives issued by different sub-detectors, select time slots with relevant events and appropriately generate a trigger signal. The signal is transmitted to the TTC partitions, each of them consisting of a Local Trigger Unit (LTU) module which serves as a master of a TTCex module. LTU encodes the trigger signal, TTCex converts the encoded electrical signal and sends it through the optical network to the sub-detector front-end electronics (FEE).

Data corresponding to the trigger signal are then sent from the sub-detector FEE to the PC farm where further data processing, selection (L1 and L2 trigger) and permanent storage takes place.
3.3.2 LTU module

Local Trigger Unit concept and design was originally created by P. Jovanovic for ALICE⁴. It was redesigned for NA62 purposes by M. Krivda⁵ (University of Birmingham, UK). In the normal (i.e. global) run of the experiment, it serves as a transparent interface between Level-0 Trigger Processor and sub-detector front-end electronics. Together with the TTCex module, it encodes the electrical input from the L0TP to the TTC optical network. It also provides useful monitoring tools and configuration options. [41]

![LTU and TTCex modules](image)

**Figure 3.13:** LTU (right) and TTCex (left) modules with highlighted connections

LTU has also a second mode of operation, called *standalone mode*, in which it can emulate a L0TP and send triggers by itself. This mode is very useful in a laboratory setup, where a L0TP is not present, so it can be used to debug sub-detector FEE in a preparatory phase. Or in the experimental setup during the “development phase” of the experiment when a specific sub-detector wishes to disconnect from the trigger chain and receive different trigger signals than others. A dedicated software for the controlling of the LTU module has been created by Vladimír Černý. Further development has been performed by both V. Černý and the author (M.Kovaľ).

⁴[http://cern.ch/alicestrigger](http://cern.ch/alicestrigger), Alice trigger web
3.3.3 LTU current status and outlook

In this section, contributions to the NA62 trigger system made by the author are presented. He has participated in three “dry runs” at CERN (July 2012, July 2013, November 2013), during which the trigger chain described in the previous sections has been tested and developed (without hadron beam from the SPS) and in a “technical run” (November 2012) with a low intensity hadron beam. Technical and software LTU related support to the NA62 users has been provided.

After the technical run, a major upgrade of the LTU firmware (M. Krivda) and software (M. Kovaľ) responsible for the L0TP emulation has been made. The new emulation provides many useful features, which are used by developers of the sub-detector FEE. A report on the upgrade has been given during TDAQ working group meeting at CERN (06.02.2013).

LTU modules proved to be very reliable in the first runs and tests. Most of the required features are ready for the physics run in October 2014. Bratislava NA62 group will participate in the run and provide support for the TTC partition.

![Figure 3.14: LTU software screen-shot, Top controller (left), L0TP emulation controller (right)](image)

LTU modules proved to be very reliable in the first runs and tests. Most of the required features are ready for the physics run in October 2014. Bratislava NA62 group will participate in the run and provide support for the TTC partition.
Bibliography

    arxiv:1101.4805.
    arxiv:1212.4012.
    arxiv:1205.1411.
    arxiv:1211.2674.


