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Search for $K^+ \to \pi^+ \nu\bar{\nu}$ at the NA62 experiment at CERN

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The flavor physics sector allows us to explore the possible extensions of the Standard Model (SM) in a complementary approach to the direct searches conducted i.e. at the Large Hadron Collider (LHC). New physics contributions at high energy scales can manifest themselves in low energy phenomena provided that the observables are carefully chosen, precisely measured and compared to accurate predictions. A stringent test of the SM predictions is the observation of the rare decay $K^+ \to \pi^+ \nu\bar{\nu}$. The NA62 experiment at CERN is designed to measure the branching ratio (BR) of this decay with 10% precision. NA62 has been successfully launched in October 2014, took data in pilot runs in 2014 and 2015 achieving the commissioning of the detectors and the designed beam intensity. The NA62 experimental setup is described and the quality of data collected in view of the final measurement is reported.

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1. The NA62 experiment

The study of flavour changing neutral current (FCNC) meson decays, forbidden at tree level by the SM, allows one to test the SM and to search for signals of new physics in a way complementary to the study of the processes at very high energies, where the possible contribution of new particles is expected to manifest itself already at "leading order". In this context, the NA62 experiment at CERN [1] has the main purpose to measure with 10% precision the branching fraction of the rare decay $K^+ \to \pi^+\nu\bar{\nu}$. NA62 is a fixed target experiment at CERN using protons from the Super-Proton-Synchrotron (SPS) facility hitting a beryllium target to produce an intense secondary beam of positive particles of 75 GeV/c momentum. The goal of the experiment is to observe about 80 SM events of $K^+ \to \pi^+\nu\bar{\nu}$ in two years of data taking, by studying the decay in flight of the K^+ produced in the secondary beam.
The NA62 experiment had a first pilot run in October-November 2014. Data collected in the pilot run had been used to study the detector performance and to validate the analysis method. The NA62 experiment plans to collect data each year until 2018, when the second long shutdown of the LHC machine is foreseen.

2. Branching ratio of the $K^+ \to \pi^+\nu\bar{\nu}$

The transitions $K^+ \to \pi^+\nu\bar{\nu}$ and $K^0 \to \pi^0\nu\bar{\nu}$ are very interesting in SM because the measurement of their decay rates provides important information about some of the less well-known fundamental physics parameters of the model. In fact, for these transitions the branching ratios are theoretically predicted in the SM and the purely theoretical (i.e. not related to experimentally measured quantities) relative uncertainties are well known, both for BR($K^+ \to \pi^+\nu\bar{\nu}$) and for BR($K^0 \to \pi^0\nu\bar{\nu}$) [2]. The calculations show the sensitivity of these decay rates to the magnitude of the V_{td} element of Cabibbo-Kobayashi-Maskawa (CKM) matrix, which can be determined with few percent accuracy without relying on unitarity constraints. Moreover simultaneous BR measurements of $K^+ \to \pi^+\nu\bar{\nu}$ and $K^0 \to \pi^0\nu\bar{\nu}$ decays provide determinations of CKM parameters and the unitarity triangle in a complementary and independent way with respect to the study of B decays. In the SM the quark level process that contributes to the $K^+ \to \pi^+\nu\bar{\nu}$ decay is the flavour changing quark transition $s \to d\nu\bar{\nu}$ described, at first non-null order, by the one-loop diagram shown in Figure 1: penguin diagrams with Z exchange and box diagrams with W exchange. In fact neutral flavour-changing transitions such as $s \to d\nu\bar{\nu}$ are forbidden at tree-level. The u, c and t quarks, that appear as internal lines, contribute to the amplitude with terms which are positive power of their own mass. Because of its mass, the top-quark contribution becomes the dominant term and the transition $s \to d\nu\bar{\nu}$ is described by short-distance quark dynamics. Using the value of

Perez Gomez, M. Perrin-Terrin, L. Peruzzo, P. Petrov, F. Petrucci, R. Piandani, M. Piccini, D. Pietreanu, J. Pinzino, I. Polenkevich, L. Pontisso, Yu. Potrebenikov, D. Protopopescu, F. Raffaelli, M. Raggi, P. Riedler, A. Romano, P. Rubin, G. Ruggiero, V. Russo, V. Ryjov, A. Salamon, G. Salina, V. Samsonov, C. Santoni, G. Saracino, F. Sargeni, V. Semenov, A. Sergi, M. Serra, A. Shaikhiev, S. Shkarovskiy, I. Skillicorn, D. Soldi, A. Sotnikov, V. Sugonyaev, M. Sozzi, T. Spadaro, F. Spinella, R. Staley, A. Sturgess, P. Sutcliffe, N. Szilasi, D. Tagnani, S. Trilov, M. Valdata-Nappi, P. Valente, M. Vasile, T. Vassilieva, B. Velghe, M. Veltri, S. Venditti, P. Vicini, R. Volpe, M. Vormstein, H. Wahl, R. Wanke, P. Wertelaers, A. Winhart, R. Winston, B. Wrona, O. Yushchenko, M. Zamkovsky, A. Zinchenko.

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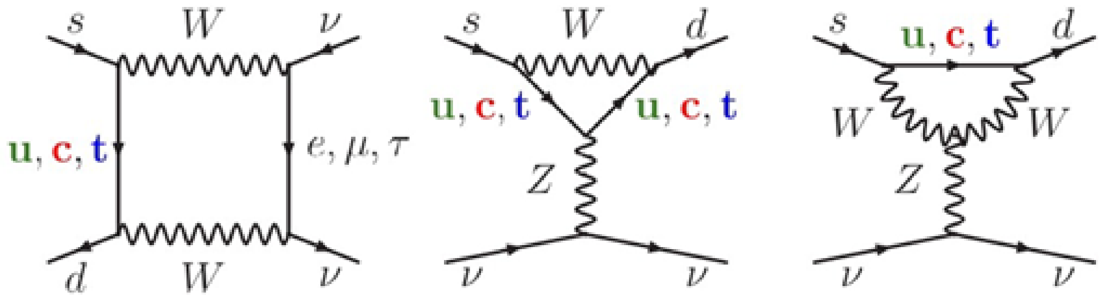

Figure 1: Box diagram and Z-penguin diagrams contributing to the process $K \to \pi\nu\bar{\nu}$.

tree-level elements of the CKM as external inputs, the SM predicts [3][4]:

$$\begin{aligned} \mathrm{BR}\left(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}\right) &= (8.4 \pm 1.0) \times 10^{-11} \\ \mathrm{BR}\left(\mathrm{K}^0 \to \pi^0\nu\bar{\nu}\right) &= (3.4 \pm 0.6) \times 10^{-11} \end{aligned} \tag{2.1}$$

Results from LHC direct searches strongly limit the range of variation mainly in supersymmetric models [5][6]. In any case, thanks to the SM suppression and to the existing weak experimental constraints from kaon physics, significant variations of the $K \to \pi\nu\bar{\nu}$ BRs' from the SM predictions induced by new physics at mass scales up to 100 TeV are still possible providing a measurement with 10% precision at least.
At present only seven events of the charged mode have been observed by the experiments E797 and E949 at BNL, while an upper limit has been set on the BR of the neutral mode by the E391a collaboration. The experimental status for the two BR is [7][8][9]

$$\begin{aligned} \mathrm{BR}\left(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}\right) &= 1.73^{+1.15}_{-1.05} \times 10^{-10} \\ \mathrm{BR}\left(\mathrm{K}^0 \to \pi^0\nu\bar{\nu}\right) &< 2.6 \times 10^{-8} \quad 90\%\mathrm{CL} \end{aligned} \tag{2.2}$$

3. Measurement strategy and NA62 experimental apparatus

A measurement of the BR of the $K^+ \to \pi^+\nu\bar{\nu}$ decay with 10% precision or better is the main goal of the NA62 experiment at CERN[1][10]. The experiment plans to collect about 10^{13} kaon decays in few years using 400 GeV/c protons from SPS. As a consequence 10% signal acceptance and of the order of 10% signal to background ratio are required to obtain the design precision[11]. Twelve orders of magnitude of background rejection requires the use of as much as possible independent experimental techniques to suppress unwanted final states. The experiment consists in generating a high intensity unseparated hadron beam and to detect both the decaying kaon and the final pion coming from a big fiducial volume (∼60 m), and to exclude all the other channels. The hadron beam arises from a 400 GeV proton beam hitting on a beryllium target (CERN T10 line). The beam optics selects particles with an average momentum of 75 GeV/c producing a 750 MHz unseparated positive hadron beam with a 6% kaon component. Because of the beam intensity, a precise timing (level 100 - 150 ps) of the K^+ and π^+ is needed in order to allow precise matching of the particles in the decay. The high momentum of the incoming beam improves the background

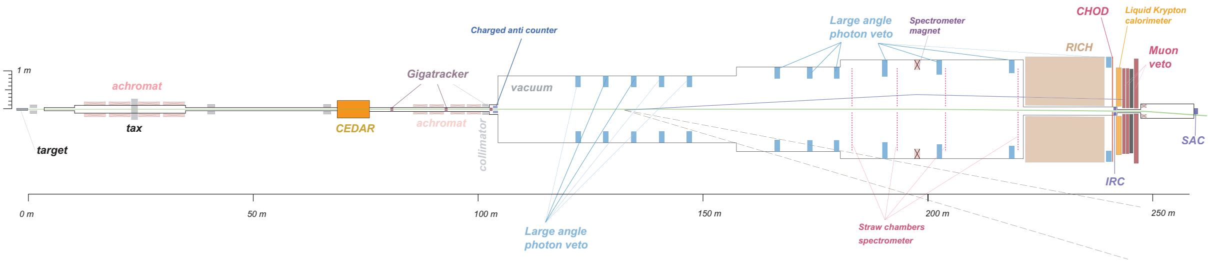

Figure 2: Layout of the NA62 experimental setup.

rejection and sets the longitudinal scale of the experiment (see Figure 2). The signature of the signal is one π^+ track in the final state matched with one K^+ track in the beam. Only the momentum of the incoming kaon and of the daughter pion can be measured respectively by means of a beam spectrometer (named Gigatracker) and a spectrometer placed downstream of the decay region (the straw chamber spectrometer in Figure 2). Let P_K and P_{π^+} denote the 4-momenta of the kaon and the charged particles produced from kaon decay under the π^+ mass hypothesis, respectively. The squared missing mass distribution of the signal, $m^2_{miss} = (P_K - P_{\pi^+})^2$, has a three body decay shape. This distribution allows a separation of the signal from the main K^+ decay modes by defining two signal regions (named region I and II, around the $K^+ \to \pi^+\pi^0$ peak) where a limited background coming from the kinematically constrained decays of K^+ is expected (Figure 3).

Nevertheless, the total background in region I and II is still several order of magnitude larger

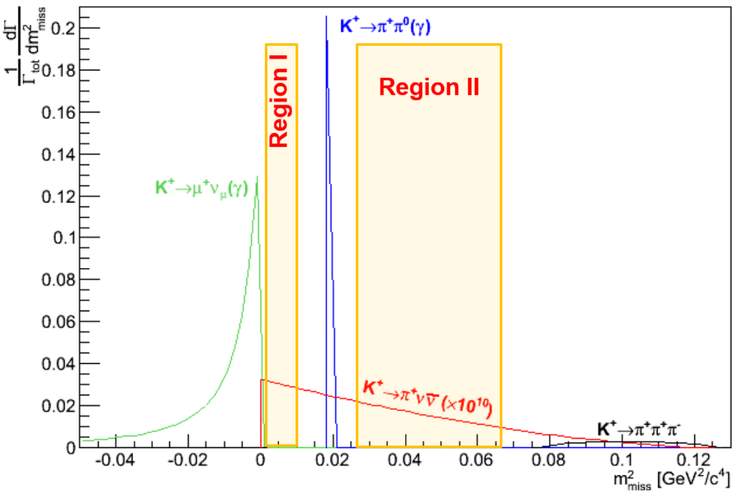

Figure 3: Distributions of the m^2_{miss} variable under the hypothesis that the detected charged particle in the final state is a pion, for the signal and kaon kinematically constrained decays. The latter represents 92% of the total backgrounds for the $K^+ \to \pi^+\nu\bar{\nu}$ process. The $K^+ \to \pi^+\pi^0$ background forces the analysis region to be split into two regions.

than the signal, as a consequence of the main decay modes leaking there via resolution effects and radiative tails, semi-leptonic decays and even rare decays whose kinematics cannot be constrained by the m^2_{miss} variable (see Figure 4). Information from other detectors has to be collected in order to reduce background in the two signal regions.

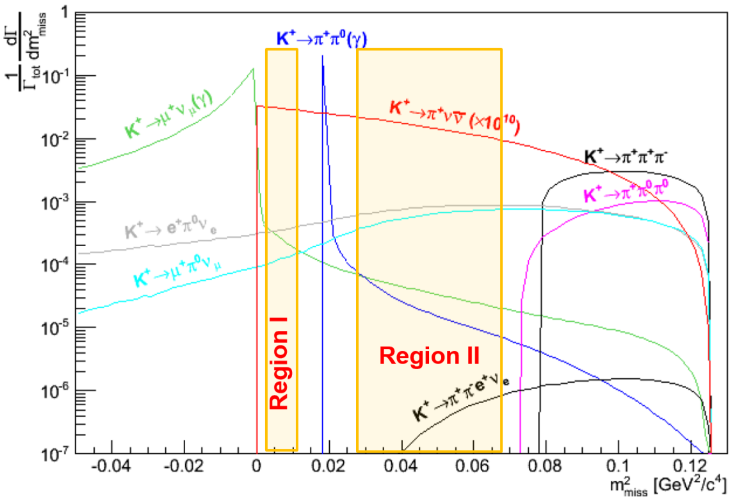

Figure 4: Distributions of the m^2_{miss} variable under the hypothesis that the detected charged particle in the final state is a pion, for the signal and backgrounds. The two analysis regions are named I and II.

A signal in the Cherenkov counter on the beam line (named KTAG) ensures the presence of a kaon in time with the tracks in beam spectrometer and in the downstream spectrometer; the timing of the downstream particle is provided by the CHOD hodoscope. The KTAG signal also allows the suppression of most of the accidental tracks coming from the interactions of the pions in the beam with the material along the beam line. The presence of one track reconstructed in the downstream spectrometer matched in space and time with one kaon track reconstructed in the beam spectrometer is the second requirement for a signal selection. A set of criteria for pion identification allows the suppression of the decay modes with muons and positrons, by means of a RICH counter filled with Ne and hadronic calorimeters MUV1-2, that are made of two modules of iron-scintillator sandwiches. The same requirements are also effective for controlling the backgrounds with more than one charged track in the final state. A fast scintillator array (MUV3) identifies and triggers muons with sub-nanosecond time resolution. A hermetic photon veto system is also important to suppress decay modes with photons in the final state (like $K^+ \to \pi^+\pi^0$):

- Large angle annular electromagnetic calorimeters (LAV) made of lead glass blocks surround the decay and downstream volumes to catch up to 50 mrad.
- The NA48 LKr calorimeter detects forward γ and complements the RICH for particle identification.
- A shashlik small-angle annular calorimeter (IRC) in front of LKr detects efficiently γ directed on the inner edges of the LKr hole around the beam axis.
- A shashlik calorimeter (SAC) placed on the beam axis downstream to a dipole magnet bending off-axis the undecayed beam particles, detects γ down to zero angle.

The interaction of the beam with the GTK is itself a possible source of background. In particular, kaon inelastic scattering events can mimic the signal if a produced pion falls into the RICH and

STRAW acceptance, if it is badly reconstructed inside the fiducial volume and if no other tracks are detected. The charged anti counter (CHANTI) is a detector placed in vacuum just after the GTK (27 mm) to help the rejection of this background, by covering hermetically the region between 49 mrad and 1.34 rad wrt the third (last) Gigatracker station.
A multi-level trigger architecture is used. Timing information from CHOD, RICH and MUV3 and calorimetric variables from electromagnetic and hadronic calorimeters are build up on FPGAs' memories mounted on the readout TEL62 boards[12] to issue level zero trigger conditions. Software-based variables from KTAG, LAV and magnetic spectrometer provide higher level trigger requirements. Two global requirements are applied in the analysis:

- the kaon decay has to take place in the first 60m of the decay volume (fiducial volume)
- the measured momentum of the downstream π^+ must be between 15 GeV/c and 35 GeV/c in order to achieve the desired background rejection

4. Data Quality in 2015 and perspective for the $K^+ \to \pi^+ \nu\bar{\nu}$ analysis

The following selection is applied to study the quality of the data for the $K^+ \to \pi^+ \nu\bar{\nu}$ BR measurement. Tracks reconstructed in the straw spectrometer matching in space energy depositions in calorimeters and signals in CHOD are selected. Matched CHOD signals define the time of the tracks with 200 ps resolution. A track not forming a common vertex within the decay region with any other in-time track defines a single track event. The last Gigatracker station and the first plane of the straw spectrometer bound the decay region. A vertex is defined as the average position of two tracks projected back in the decay region at the distance of closest (CDA) approach less than 1.5 cm. In order to select a single track event originated from kaon decays, a Gigatracker track is required to match the downstream track both in time and space, forming a vertex in the decay region with it, and to be in-time also with a kaon-like signal in KTAG.

Figure 5 (left) shows the m^2_{miss} versus the spectrometer track momentum for 2015 data recorded at low intensity. The time resolutions of the KTAG and of a Gigatracker track has been measured in the range of 100 and 200 ps, respectively, matching the design values. The KTAG is also used in anti-coincidence with a Gigatracker track to select single track events not related to kaons (Figure 5 right). This technique shows that decay from beam π^+, elastic scattering of beam particles in the material along the beam line (KTAG and Gigatracker stations) and inelastic scatterings in the last Gigatracker station are the main sources of tracks downstream originated from beam related activity. The sample of single track events from kaon decays selected above is used to study kinematic resolution, particle identification and rejection. The resolution of the m^2_{miss} measured from the width of the $K^+ \to \pi^+\pi^0$ peak is in the range of $1.2 \times 10^{-3}\mathrm{GeV}^2/\mathrm{c}^4$, close to the $10^{-3}\mathrm{GeV}^2/\mathrm{c}^4$ design value, as shown in Figure 6. This resolution is a factor of 3 larger if the nominal kaon momentum is taken, instead of the event by event Gigatracker measured value (see Figure 7) .

The tracking system of NA62 is also designed to provide a rejection factor in the range of $10^4 \div 10^5$ for $K^+ \to \pi^+\pi^0$ and $K^+ \to \mu^+\nu_\mu$ using m^2_{miss} to separate signal from backgrounds, respectively. The $K^+ \to \pi^+\pi^0$ kinematic suppression is measured using a sub-sample of single track events from kaon decays selected by requiring the additional presence of two γ compatible with a π^0 in the LKr calorimeter. This constraint defines a sample of $K^+ \to \pi^+\pi^0$ with negligible

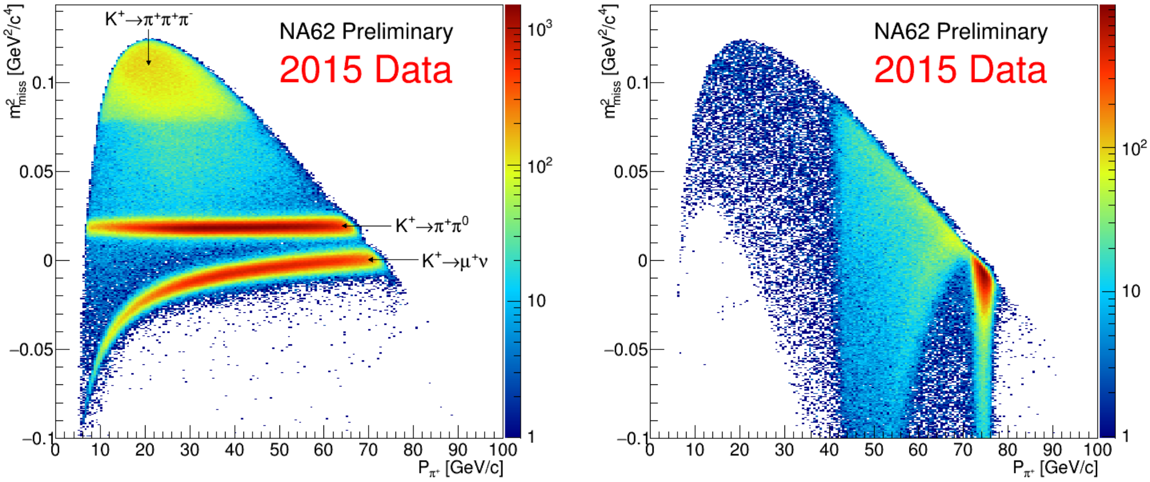

Figure 5: Distribution of the m^2_{miss} variable under π^+ mass hypothesis as a function of the momentum of the track measured in the straw spectrometer after selection for single track from kaon decays (left). Same distribution as left-side picture, but asking for single track without a positive kaon tag in time in KTAG (right).

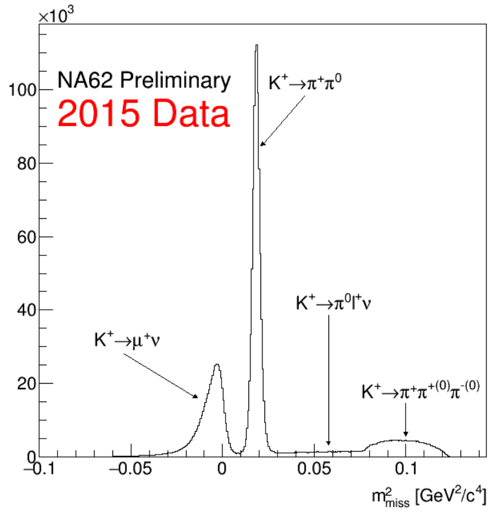

Figure 6: Distribution of the m^2_{miss} variable after the signal event selection. The kaon decays contributing to the distribution are indicated.

background even in the signal m^2_{miss} regions, allowing the study of the far tails of the m^2_{miss}. The measured $K^+ \to \pi^+\pi^0$ suppression factor is of the order of 10^3. The partial hardware Gigatracker arrangement used in 2015 mainly limits the suppression because of m^2_{miss} tails due to beam track mis-reconstruction.

The particle identification of NA62 is designed to separate π^+ from μ^+ and e^+ in order to guarantee at least 7 order of magnitude suppression of $K^+ \to \mu^+\nu_\mu$ in addition to the kinematic rejection. RICH and calorimeters together are employed to this purpose. In Figure 8 the Cherenkov ring radius of RICH as a function of momentum is shown without any selection on the type of particle:

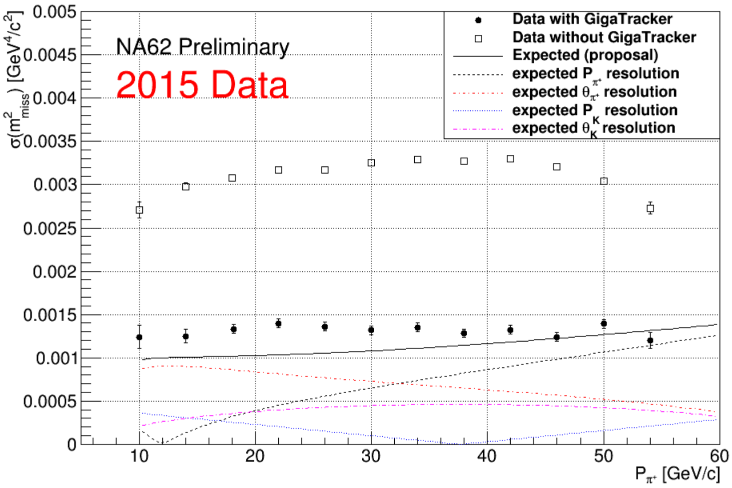

Figure 7: Resolution of the m^2_{miss} as a function of the candidate pion momentum obtained with kaon momentun information from GTK (black points) and with nominal value (empty squares). Expected resolutions are also shown.

electrons, muons, charged pions and scattered charged kaons can be clearly seen. The pure samples

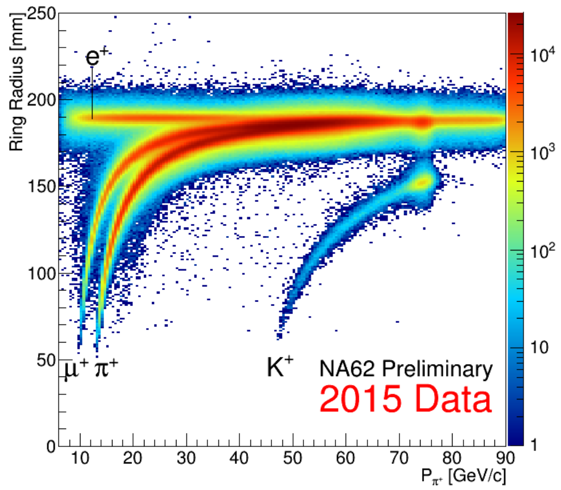

Figure 8: Cherenkov ring radius as a function of particle momentum; electrons, muons and charged pions can be clearly seen; charged kaons from the scattered beam can also be seen.

of $K^+ \to \pi^+\pi^0$ used for kinematic studies and an additional sample of $K^+ \to \mu^+\nu_\mu$ selected among the single track events from kaon decays by requiring the presence of signals in MUV3 are used to study the π^+ / μ^+ separation in the RICH. About 10^2 muon suppression for 80% π^+ efficiency is measured in a track momentum region between 15 and 35 GeV/c. Above 35 GeV/c the separation degrades quickly as expected from the Cerenkov threshold curves for π^+ and μ^+ in neon. As a by-product the RICH provides an even better separation between π^+ and e^+. The same π^+ and

μ^+ samples allow the calorimetric muon-pion separation to be investigated. Simple cut and count analysis provide a muon suppression factor within $10^4 \div 10^6$ for a π^+ efficiency in a 90%÷50% range. Several analysis techniques are under study to get the optimal separation.
The layout of NA62 is designed to suppress $K^+ \to \pi^+\pi^0$ by 8 orders of magnitude by detecting at least one photon from π^0 decay in one of the electromagnetic calorimeters, LAV, LKr, IRC and SAC covering an angular region between 50÷8.5 mrad, 8.5÷1 mrad, < 1 mrad, respectively. The π^0 suppression profits from the angle-energy correlation of the two π^0 photons and the cut at 35 maximum π^+ momentum at analysis level. This allows the above suppression factor to be reached by requiring single photon detection inefficiencies within the reach of the calorimeters and not below 10^{-5} for γ above 10 GeV. The suppression of π^0 from $K^+ \to \pi^+\pi^0$ is measured on data looking directly at the scaling of the $K^+ \to \pi^+\pi^0$ m^2_{miss} peak after applying conditions for photon rejection on the sample of single track events from kaon decays selected above. The measured π^0 veto inefficiency on the 2015 data, shown in Figure 9, is statistically limited at 10^{-6} (90% CL) as an upper limit. The signal efficiency is within 90% as measured on samples of muons from $K^+ \to \mu^+\nu_\mu$ and events with a single 75 GeV/c π^+ in the final state entering in the downstream detector acceptance via beam elastic scattering upstream. To conclude, the preliminary analysis of

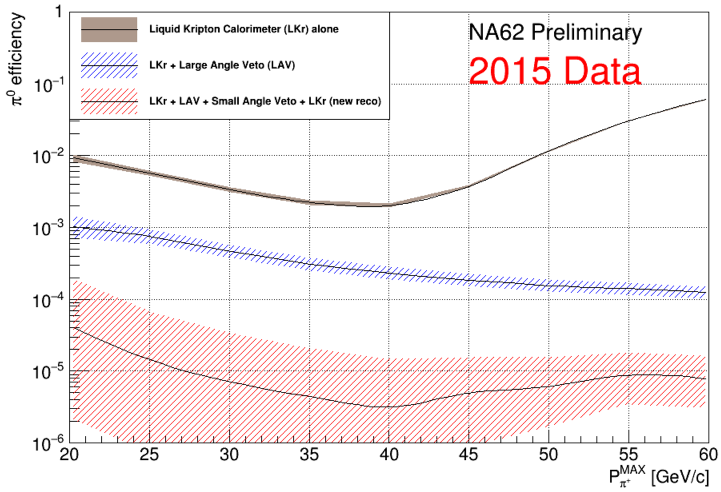

Figure 9: Veto inefficiency of the π^0 rejection for different combinations of the calorimeters information..

the low intensity 2015 data shows that NA62 is approaching the design sensitivity for measuring $K^+ \to \pi^+ \nu \bar{\nu}$.

5. NA62 physics program beyond $K^+ \to \pi^+ \nu \bar{\nu}$

The NA62 apparatus allow us to perform a compelling physics program beyond $K^+ \to \pi^+ \nu \bar{\nu}$. The main kaon decays can be studied with an unprecedented precision with the opportunity to stress once more the SM predictions. The level of single event sensitivity offers the possibility to further improve the limits on lepton flavour and number violation processes. The π^0 physics program can take advantage of the efficient photon detection system to search decays in 3γ or 4γ, invisible or dark photon production. The quality of the kinematics reconstruction allows us to extend the search for heavy neutrinos in the mass range 100-380 MeV via the $K^+ \to l^+ \nu$ decay, improving the existing limits. The longitudinal scale of the apparatus and the resolutions of the detectors open the possibility to search for long-lived particles through their decays, like dark photon decaying to $l^+ l^-$ or axion-like particles decaying to $\gamma\gamma$ pairs and produced at the target or in beam dump configurations.

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