Forbidden Kaon and Pion Decays in NA62

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NA62, an experiment at the CERN SPS to measure the branching ratio for the decay $K^+ \to \pi^+\nu\bar{\nu}$ with ~10% precision, will observe $\sim 10^{13}$ K^+ decays in its fiducial volume, and will thus also be able to carry out a rich program to search for K^+ and π^0 decays that are forbidden in the Standard Model, including in particular K^+ decays that violate the conservation of lepton flavor and/or number. NA62's potential performance in searches for a number of forbidden K^+ and π^0 decays is discussed, with initial sensitivity estimates.

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1. Introduction

The goal of the NA62 experiment at the CERN SPS [1] is to measure the branching ratio (BR) for the decay $K^+ \to \pi^+ \nu \bar{\nu}$ with a precision of $\sim$10%. The Standard Model (SM) prediction $\mathrm{BR}(K^\pm \to \pi^\pm \nu \bar{\nu}) = (7.8 \pm 0.8) \times 10^{-11}$ [2] is quite precise, due in large part to the fact that the hadronic matrix element for the decay can be obtained from the experimentally determined rate for K_{e3} decays. The value of $\mathrm{BR}(K^\pm \to \pi^\pm \nu \bar{\nu})$ is therefore a sensitive probe for physics beyond the SM, but since this BR is so tiny, prodigious numbers of kaons are required for its measurement. NA62 is expected to begin running in late 2014; about 10^{13} K^+s will decay inside the NA62 fiducial volume in two years' equivalent of data taking. Obviously, this large sample of kaon decays provides an opportunity to perform various searches for novel phenomena in addition to $K^+ \to \pi^+ \nu \bar{\nu}$. In particular, NA62 should be well positioned to obtain competitive results on kaon decays with explicit violation of the conservation of lepton flavor or number (LFNV), as well as in related areas, such as the search for heavy neutrinos in decays such as $K_{\mu 2}$. In addition, since the decay mode $K^+ \to \pi^+ \pi^0$ accounts for $\sim$21% of K^+ decays, and since the detection of the π^+ monochromatic in the K^+ rest frame effectively tags the π^0 in such decays, NA62 should also be able to improve on searches for new physics in a number of π^0 decays as well.

2. Violation of lepton flavor and/or number conservation in kaon decays

Many attempts to improve upon the SM introduce new interactions that may give rise to violation of lepton flavor and/or number conservation in specific processes, including supersymmetry [3, 4], mechanisms for dynamical electroweak symmetry breaking with strong coupling such as extended technicolor [5], Little Higgs models [6], models that introduce heavy neutrinos into the SM [7], models featuring large extra dimensions [8, 9], and more. In the past, searches for LFNV in kaon decays have been able to place tight constraints on the parameter space for some of these models, for some very straightforward reasons. The availability of intense kaon beams has made it possible to design high-statistics experiments, while the relative topological simplicity of kaon decays (relatively few decay channels, low final-state multiplicities) and clear experimental signatures for the LFNV decays make efficient background rejection possible. As a result, kaon decay experiments have reached sensitivities to branching ratios as low as 10^{-12}, which, by simple dimensional arguments, can provide access to mass scales upwards of 100 TeV in the search for new physics at tree level (e.g., a new gauge boson mediating the tree-level $s \to d \mu e$ transition) [10]. Precisely because the results from searches for LFNV kaon decays up through the 1990s posed such stringent constraints on models such as technicolor, for the past decade or so, it appears to have been tacitly assumed that it would be very difficult to make any further progress with kaon decays [11]. However, interest in searches for LFNV in charged lepton decays has remained robust, as witness the interest in experiments such as MEG and Mu2e as well as in searches for $\tau \to \mu \gamma$, for example, at next-generation flavor factories [12]. In part this is because supersymmetric SM extensions that would explain the $> 3\sigma$ discrepancy between the measured and predicted values of the muon anomaly, $a_\mu \equiv (g_\mu - 2)/2$, predict some degree of charged LFV [13, 14]. In any case, there is certainly no lack of theories predicting observable LFNV phenomena. In this context, the next-generation experiments planned to measure the BRs for decays such as $K^+ \to \pi^+ \nu \bar{\nu}$ represent

Mode	UL at 90% CL	Experiment	Ref.
$K^+ \to \pi^+\mu^+e^-$	1.3×10^{-11}	BNL 777/865	[15]
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10}	BNL 865	[16]
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10}	BNL 865	[16]
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10}	BNL 865	[16]
$K^+ \to \pi^-\mu^+\mu^+$	1.1×10^{-9}	NA48/2	[17]
$K^+ \to \mu^-\nu e^+e^+$	2.0×10^{-8}	Geneva-Saclay	[18]
$K^+ \to e^-\nu\mu^+\mu^+$	no data		
$K_L \to \mu e$	4.7×10^{-12}	BNL 871	[19]
$K_L \to \pi^0\mu e$	7.6×10^{-11}	KTeV	[20]

Table 1: Current status of searches for selected LFV and LNV K^+ decays for which limits can potentially be improved by NA62. Two of the best results obtained with K_L decays are also listed for comparison.

real opportunities to push down the limits on LFNV phenomena through the study of charged kaon decays. Table 1 lists some LFNV K^+ decays (mainly those with three charged particles in the final state) and current limits on the corresponding BRs, as well as two of the best results obtained with K_L decays, for comparison. The NA62 experiment at the CERN SPS should be able to significantly improve on many, if not all, of the limits listed for the K^+ decays.

3. $K^\pm \to \pi^\mp\mu^\pm\mu^\pm$

The presence of the decay $K^+ \to \pi^-\mu^+\mu^+$ in Tab. 1 is particularly interesting for two reasons. On the theoretical side, as discussed in [21, 22], the lepton number violation in this decay would imply that the virtual neutrino exchanged is a Majorana fermion, i.e., it is its own antiparticle, as illustrated in Fig. 1. This is similar to the case of neutrinoless nuclear double beta decay, and is an intriguing possibility, because if the neutrino is a Majorana fermion, the see-saw mechanism provides a natural explanation for the lightness of the observed ν_e, ν_μ, and ν_τ flavor eigenstates. In this scenario, the existence of heavy-neutrino mass eigenstates that participate in the neutrino mixing to form sterile, right-handed neutrino flavor eigenstates would also be predicted. On the experimental side, the decay $K^+ \to \pi^-\mu^+\mu^+$ is interesting because NA62's prospects for measuring it can be accurately evaluated.

Until recently, the most stringent limit on the branching ratio for this decay was that from the E865 decay-in-flight experiment at Brookhaven [16]. This result was obtained from the analysis of a few hundred candidate events reconstructed in the magnetic spectrometer. Most of these are actually $K_{\pi3}$ decays; analysis of the invariant-mass distribution with assigned particle identification $M(\pi^-\mu^+\mu^+)$ gives 5 candidates in the signal window around $m_{K^\pm}$ with an expected background (from sidebands) of 5.3 events. This is used to set the limit $\mathrm{BR}(K^+ \to \pi^-\mu^+\mu^+) < 3.0\times10^{-9}$ (90% CL).

More recently, NA48/2 performed a similar analysis. The primary purpose of the NA48/2 experiment, which took data in 2003–2004, was to study direct CP violation in the K^+/K^- system. The experimental configuration is shown in Fig. 2. Simultaneous 60-GeV K^+ and K^- beams

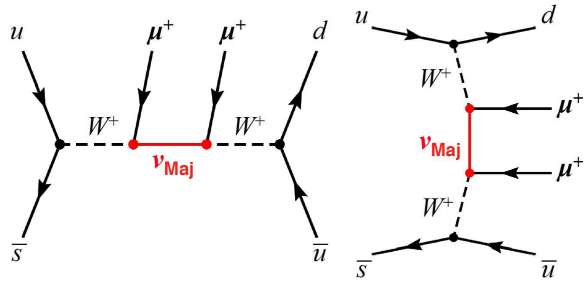

Figure 1: Lowest-order diagrams contributing to $K^+ \to \pi^- \mu^+ \mu^+$. The decay can proceed if the neutrino exchanged can annihilate itself, i.e., if it is its own antiparticle.

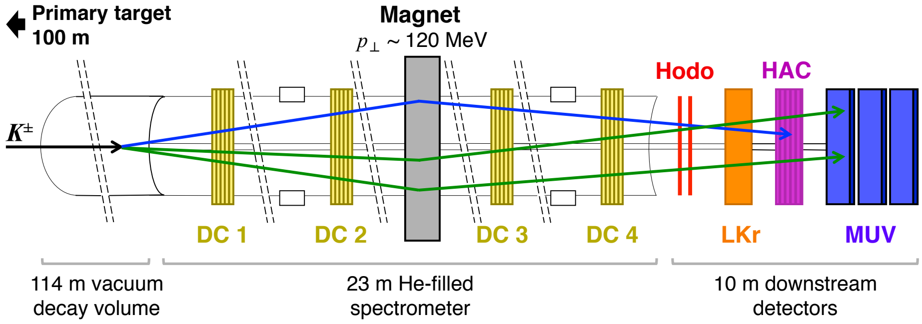

Figure 2: Schematic diagram of the NA48/2 experiment, showing drift chambers (DC1–4), trigger hodoscope (Hodo), NA48 liquid-krypton electromagnetic calorimeter (LKr), hadronic calorimeter (HAC), and muon vetoes (MUV).

entered a 114-m long vacuum decay tank, downstream of which, a 23-m long, helium-filled spectrometer consisting of four drift chambers (DC1–4) and an analyzing magnet with a $p_\perp$ kick of 120 MeV was used to track and analyze charged secondaries. Downstream of the spectrometer were located a scintillator hodoscope (Hodo) to provide a fast trigger, the high-performance NA48 liquid-krypton electromagnetic calorimeter (LKr), an iron/scintillator hadronic calorimeter (HAC), and a stack of muon-veto detectors (MUV). The $K \to \pi\mu\mu$ (signal) and $K \to \pi\pi\pi$ (normalization) samples were both collected with the same two-level trigger for three-track decays. For both signal and normalization events, reconstruction of the three-track vertex with strict quality criteria was required. For signal events, two tracks were further required to be identified as muons by hits in the MUV. The experimental configuration and the analysis are further described in [17].

Figure 3 shows the NA48/2 invariant-mass distributions for $K \to \pi\mu\mu$ candidate events with opposite-sign muons (left) and same-sign muons (right). The decay with opposite-sign muons ($K^\pm \to \pi^\pm \mu^\pm \mu^\mp$) conserves lepton number; it is a flavor-changing neutral-current decay for which there are form-factor predictions from chiral perturbation theory. NA48/2 sees about 3000 signal candidates, visible as the peak near $M(\pi\mu\mu) = m_{K^\pm}$ in Fig. 3, left. Normalized Monte Carlo (MC) distributions for signal and background are shown as the yellow- and green-shaded regions. In the distribution for events with like-sign muons, which violate lepton number conservation, the signal peak is largely absent (Fig. 3, right). There are 52 signal candidates in the region near $M(\pi\mu\mu) = m_{K^\pm}$ and 52.6 ± 19.8 background events expected from MC. This gives the upper limit

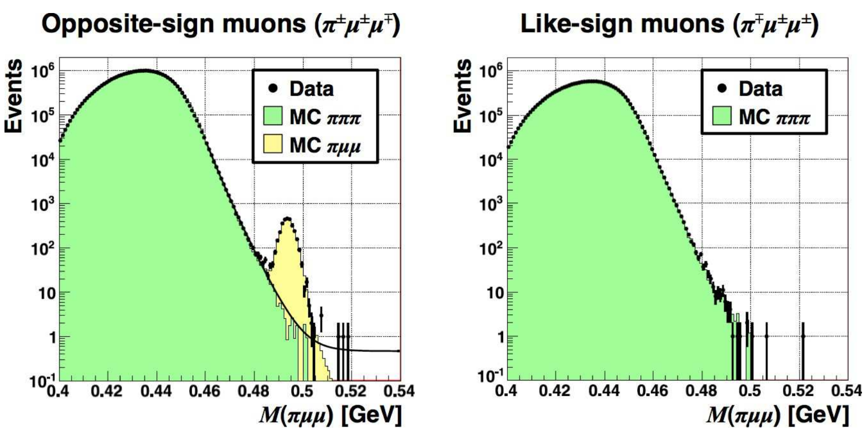

Figure 3: NA48/2 invariant-mass distributions for $K \to \pi\mu\mu$ candidates.

$\mathrm{BR}(K^\pm \to \pi^\mp\mu^\pm\mu^\pm) < 1.1 \times 10^{-9}$ (90% CL), which improves upon the E865 result by about a factor of three.

This analysis, however, was not fully optimized for the purposes of rejecting $K_{\pi3}$ background to $K^\pm \to \pi^\mp\mu^\pm\mu^\pm$. Subsequent analysis demonstrated that the $K_{\pi3}$ events with $M(\pi\mu\mu) \approx m_{K^\pm}$ are all of the type where two of the pions decay to muons, and one of the $\pi \to \mu$ decays occurs downstream of the spectrometer magnet and upstream of the last drift chamber. In this topology, the latter track (which is identified as a muon) is misreconstructed; this can increase the apparent value of $M(\pi\mu\mu)$. Requiring that the pion track have $p > 20$ GeV decreases the acceptance for signal events by 50%, but also eliminates all $K_{\pi3}$ events with $M(\pi\mu\mu) \approx m_{K^\pm}$. With the background thus reduced by at least an order of magnitude, the NA48/2 sensitivity is increased to $\sim 10^{-10}$.

4. NA62 prospects for searches for LFNV kaon decays

NA62 should be able to do better still. The experimental setup is illustrated schematically in Fig. 4. The basic infrastructure of the NA62 experiment is inherited from NA48, including some of the beamline elements, most of the vacuum tank, and most importantly, the LKr calorimeter, which will be used as a high-performance veto for forward photons in the measurement of $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})$. Most of the other detectors are either new or have been rebuilt. The current status of NA62 installation is summarized in [23].

The experiment makes use of an unseparated, 750-MHz, 75-GeV positive beam that is $\sim$6% K^+. The decay region, of fiducial length $\sim$65 m for the study of $K^+ \to \pi^+\nu\bar{\nu}$, is evacuated to 10^{-6} mbar. Inside the fiducial volume, there are $\sim$5 MHz of K^+ decays. With 1×10^6 live seconds per year (corresponding to 100 days of data taking, accounting for effective duty factor, uptime efficiency, etc.), in two years of data, there will be about 10^{13} K^+ decays in the NA62 fiducial volume. In addition to a 60-fold increase in statistics relative to NA48/2, NA62 will be able to take advantage of several of the upgrades critical to the success of the $K^+ \to \pi^+\nu\bar{\nu}$ measurement in its program to search for LFNV kaon decays. Among these, the improvement in kinematic reconstruction for charged tracks from fast and precise tracking of individual beam particles (with the Gigatracker), improved tracking for secondaries by four new straw chambers operated in vacuum, and a higher

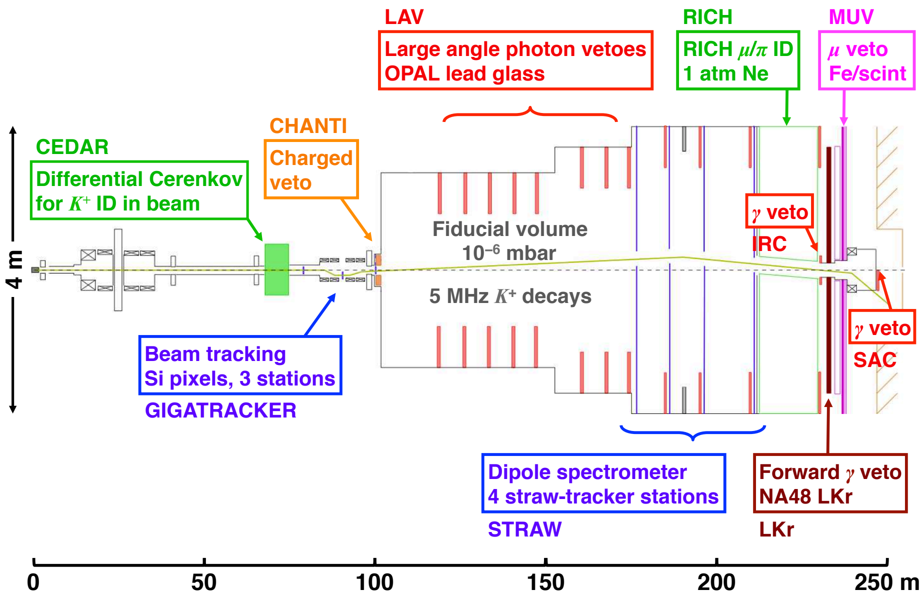

Figure 4: Schematic diagram of the NA62 experiment.

$p_\perp$ kick (270 MeV) from the spectrometer magnet will lead to improved invariant-mass resolution for three-track vertices (from 2–4 MeV to 1–2 MeV). Also important are NA62's redundant particle-identification systems, including a new RICH and a completely overhauled MUV system, which is highly segmented and included in the level-0 trigger.

In terms of the limit on BR($K^+ \to \pi^-\mu^+\mu^+$), the better kinematic reconstruction in NA62 should enable significant improvements. In particular, simulations show that with the higher field and better three-track invariant-mass resolution expected in NA62, the tail towards higher values of $M(\pi\mu\mu)$ from $K_{\pi3}$ seen in NA48/2 data (Fig. 3) is essentially eliminated, even without cuts on the momentum of the pion track. Thus it may be possible to reach the NA62 single-event sensitivity for $K^+ \to \pi^-\mu^+\mu^+$, which is 10^{-12}.

In a similar vein, preliminary studies have been performed for all of the decays listed in Tab. 1, focused mainly on trigger strategies (including rate and efficiency evaluation) and acceptance simulations. The trigger criteria, particularly at level 0, are a natural concern, because the use of a generic three-track trigger as in NA48/2 would consume a large part of the NA62 bandwidth (perhaps ~600 kHz, compared to the ~1 MHz design rate). Several primitives for the level-0 decision can be formed, including the following:

- $\mathrm{Q}_{\geq n}$: Hits in at least n hodoscope quadrants
- $\mathrm{LKR}_{\geq n}(x)$: At least n clusters with energy greater than x GeV in the LKr
- $\mathrm{MUV}_{\geq n}$: Hits in at least n MUV pads

On the basis of these, triggers for lepton pairs can be implemented:

- *ee* pairs: $\mathrm{Q}_{\geq 2} \cdot \mathrm{LKR}_{\geq 2}(15)$
- $e\mu$ pairs: $\mathrm{Q}_{\geq 2} \cdot \mathrm{LKR}_{\geq 1}(15) \cdot \mathrm{MUV}_{\geq 1}$

- $\mu\mu$ pairs: $Q_{\geq 2} \cdot MUV_{\geq 2}$

The exact criteria remain to be defined, of course, but studies indicate that all of the above triggers could be included at level 0 at the cost of a few tens of kHz of rate. The NA62 acceptance (including the trigger efficiency) for each of the K^+ decays in Tab. 1 has been preliminarily evaluated by fast MC simulation. As a general statement, the overall acceptances for final states containing ee, $e\mu$, and $\mu\mu$ pairs are respectively a few percent, about 10%, and about 20%, with the LKr energy threshold for $e^\pm$ identification responsible for the lower efficiency for the channels containing $e^\pm$. Considering the expected flux of $\sim 10^{13}$ K^+s, the NA62 single-event sensitivities are $\sim 10^{-12}$ for the K^+ decays. Assuming that the backgrounds can be tamed, NA62 is well positioned to improve significantly on the scenario in Tab. 1.

5. Searches for heavy neutrinos in $K_{\mu 2}$ decay

A related topic is the direct search for heavy-neutrino mass eigenstates ν_h among the decay products of dominant $K^\pm$ decays with final-state neutrinos. There are two types of searches. In production searches, one analyzes the momentum spectrum of a decay such as $K_{\mu 2}$ for kinematic evidence of the presence of a heavy particle. In decay searches, one attempts to exclusively reconstruct decays of the heavy neutrino itself in one or more hypothetical channels. Since decay searches focus on a particular topology, they usually obtain greater sensitivity, but only for the decay modes assumed. In addition, decay searches assume that the lifetime of the heavy neutrino is short enough so that the acceptance of the experiment for the decay of interest is not significantly affected. Since production searches are inclusive, the particular assumption on the lifetime is weaker, but it is generally assumed that the heavy neutrino will not decay inside the acceptance leaving signals that complicate the recognition of the parent decay (e.g., $K_{\mu 2}$). The current status of searches for heavy neutrinos in $K^\pm$ and $\pi^\pm$ decays is summarized in Fig. 5, which presents limits on the squared PMNS matrix element $|U_{\mu h}|^2$ that couples the heavy-neutrino mass eigenstate ν_h to the flavor eigenstate ν_μ as a function of m_h, the mass of ν_h.

NA62 has investigated the possibility of performing a production search for heavy neutrinos in $K_{\mu 2}$ decay with 40% of the 2007 $K_{\mu 2}$ sample used for the measurement of $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$, as in [29], corresponding to 18M $K_{\mu 2}$ events. In the absence of backgrounds, this would allow upper limits to be set on $|U_{\mu h}|^2$ of 10^{-7} for $100 < m_h < 400$ MeV. The main backgrounds are from events with muons from beam pions and the beam halo, $K_{\pi 2}$ and $K_{\pi 3}$ decays with missed photons and $\pi \to \mu$ decays or a π wrongly identified as a μ, $K_{\mu 2\gamma}$ and $K_{\mu 3}$ decays with missed photons, and $K_{\mu 2(\gamma)}$ decays with misreconstructed tracks. In the preliminary analysis, a single cleanly reconstructed track, identified as a μ on the basis of $E(\mathrm{LKr})/p(\mathrm{track})$ and confirmed by the MUV[1] is required. A veto is placed on the presence of any other photons in the LKr, and halo cuts (in the plane of track momentum vs. vertex position) are used to eliminate halo muons. Systematics are still under evaluation, but the preliminary results indicate that with the 2007 data alone, NA62 should be able to improve on the limits from production searches shown in Fig. 5 in the high-mass region ($300 < m_h < 350$ MeV). With the data from $K^+ \to \pi^+ \nu\bar{\nu}$ running, precise

[1]Where possible—not all NA48 detectors were available during 2007 running, as described in [29].

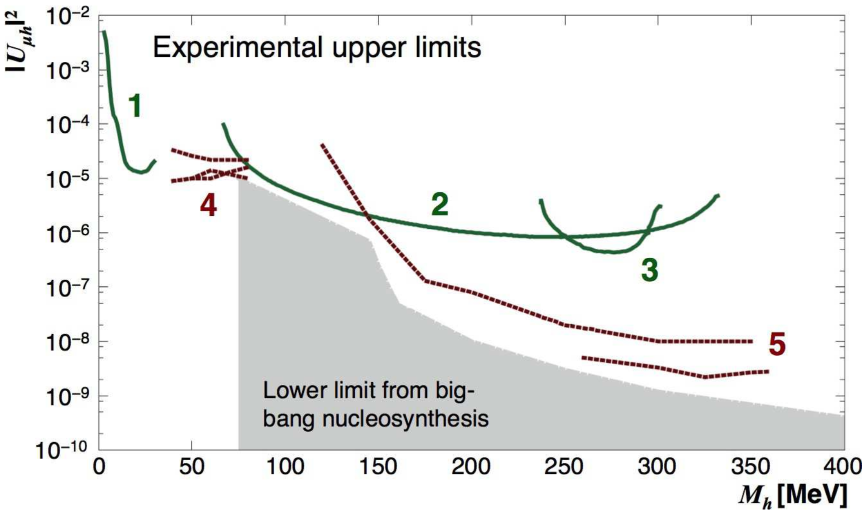

Figure 5: Searches for heavy neutrinos in $K^{\pm}$ decays. Limits in green are from production searches: 1) PSI 1981, $\pi_{\mu 2}$, [24]; 2) KEK 1982, $K_{\mu 2}$, [25]; 3) LBL 1973, calculated from limits on $K \to \mu\nu + \text{inv}$, [26]. Limits in red are from decay searches: 4) ISTRA+ 2012, $K_{\mu 2}$ with $\nu_h \to \nu\gamma$, $\tau_h = 10^{-9}$, 10^{-10}, and 10^{-11} s and Majorana statistics assumed [27]; 5) PS191 1988, $K_{\mu 2}$ with $\nu_h \to \mu^{\mp}e^{\pm}\nu$ (above), $\nu_h \to \mu^{\mp}\pi^{\pm}$ (below) [28]. The gray shaded region indicates a *lower* limit obtained from models for big-bang nucleosynthesis.

tracking (including beam tracking), and muon identification from the RICH and MUV in all data, NA62 should be able to improve on these results by orders of magnitude.

6. Searches for new physics in π^0 decays

The use of kaon decays as a source of π^0's to search for rare π^0 decays is well established. For example, KTeV used $K_L \to 3\pi^0$ decays to search for several rare π^0 decays, while E787/E949 at Brookhaven used $K^+ \to \pi^+\pi^0$ decays at rest as a source of tagged π^0's in searches for $\pi^0 \to \gamma X$ [30] and $\pi^0 \to \nu\bar{\nu}$ (see below). With 10^{13} K^+ decays in its fiducial volume from two years of data, NA62 will have $\sim 2.5 \times 10^{12}$ tagged π^0 decays from $K^+ \to \pi^+\pi^0$ with which to conduct various searches.

For example, NA62 should be able to improve on limits for the decays $\pi^0 \to 3\gamma$ and $\pi^0 \to 4\gamma$. The former violates C-parity conservation and cannot be accommodated in the SM at any observable level. The latter has an SM branching ratio on the order of 10^{-11} due mainly to higher-order electromagnetic contributions (light-by-light scattering) [31]; deviations from this prediction might provide evidence for new light scalars weakly coupled to the electromagnetic current. Current experimental limits for both BRs are at the level of 10^{-8}. At NA62, the primary challenge will be rejection of background from $K^+ \to \pi^+\pi^0(\gamma)$ and $K^+ \to \pi^+\pi^0\pi^0$, starting at the lowest trigger level. Studies indicate that a dedicated level-0 trigger such as $\mathrm{Q}_{=1} \cdot \mathrm{LKR}_{=3}(1) \cdot \overline{\mathrm{MUV}}$ can keep rates down to acceptable levels while maintaining reasonable efficiency, particularly if the trigger logic can exclude the π^+ cluster from the LKr cluster count. At level-1, the trigger would have to make kinematic cuts on the LKr clusters (e.g., in the space of $M(\gamma\gamma\gamma)$ vs. p^*_π). In the analysis (or possibly even at trigger level) the full complement of large- and small-angle photon veto detectors

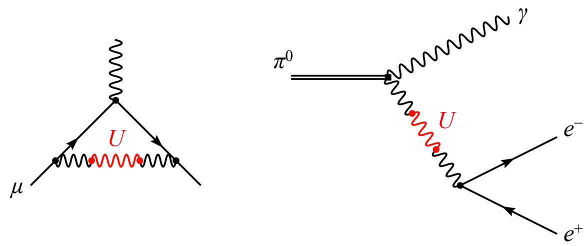

Figure 6: Amplitudes involving the U boson contributing to a_μ (left) and to the decay $\pi^0 \to e^+e^-\gamma$ (right).

can be used to reject events with additional photons, and a kinematic fit to the complete event can provide a background rejection factor of 10^{-4}. Then, NA62 should be able to obtain BR limits at the level of 10^{-10}, about two orders of magnitude better than present limits.

NA62 is also well positioned to use π^0 decays to search for a new, light vector gauge boson with weak couplings to charged SM fermions, a so-called U boson, or "dark photon". A hypothetical U boson could mediate the interactions of dark-matter constituents, as such providing explanations for various unexpected astrophysical observations and the results of certain dark-matter searches, and could also explain the $> 3\sigma$ discrepancy between the measured and predicted values for the muon anomaly, a_μ (see [32, 33] and references therein). A U boson with a mass of less than $m_{\pi^0}/2$ might be directly observable in $\pi^0 \to e^+e^-\gamma$ decays, as illustrated in Fig. 6. The current upper limit on $\mathrm{BR}(\pi^0 \to U\gamma)$ with $U \to e^+e^-$ is from the WASA-at-COSY experiment, and decreases from $\sim 1 \times 10^{-5}$ at $m_U = 30$ MeV to a little over 2×10^{-6} at 100 MeV [34]. This result was obtained with $\sim 5 \times 10^5$ $\pi^0 \to e^+e^-\gamma$ events. At NA62, with an *ee* pair trigger like that described in Sec. 4, $\sim 10^8$ $\pi^0 \to e^+e^-\gamma$ decays can be collected per year, with a mass resolution for the *ee* pair of $\sim$1 MeV (which can be improved by kinematic fitting), compared to several MeV in the case of WASA-at-COSY. As a result, NA62 should be able to improve on the current limit by at least two orders of magntiude.

As a final example, NA62 should be able to improve on limits for the invisible decay of the π^0. The least exotic decay to an invisible final state is $\pi^0 \to \nu\bar{\nu}$. This is forbidden by angular-momentum conservation if neutrinos are massless; for a massive neutrino ν of a given flavor and mass $m_\nu < m_{\pi^0}/2$ with standard coupling to the Z, the calculation of the decay rate is straightforward. The experimental signature $\pi^0 \to$ invisible could also arise from π^0 decays to other weakly interacting neutral states. The best direct experimental limit to date is $\mathrm{BR}(\pi^0 \to \text{invisible}) < 2.7 \times 10^{-7}$ (90% CL), from E949 at Brookhaven [35]. Neutrino-mass limits translate into limits on $\mathrm{BR}(\pi^0 \to \nu\bar{\nu})$ (though not on BRs to other invisible final states). The best limit on m_{ν_τ} (the neutrino mass for which the limits are least stringent), $m_{\nu_\tau} < 18.2$ MeV [36], implies $\mathrm{BR}(\pi^0 \to \nu\bar{\nu}) < 5 \times 10^{-10}$ (95% CL), while limits from astrophysics and cosmology imply $\mathrm{BR}(\pi^0 \to \nu\bar{\nu}) < 3 \times 10^{-13}$ [37, 38].

Experimentally, the process $K^+ \to \pi^+\pi^0$ with $\pi^0 \to$ invisible is very similar to $K^+ \to \pi^+\nu\bar{\nu}$, with the important difference that in the former case, the π^+ is monochromatic in the rest frame of the K^+. This means that there is no help from kinematics in identifying $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$ with two lost photons—the limit on $\mathrm{BR}(\pi^0 \to \text{invisible})$ essentially depends on the performance of the photon vetoes. At level 0, NA62 could use the same trigger criteria as for $K^+ \to \pi^+\nu\bar{\nu}$.

Inclusion at level 0 of information from the photon vetoes (in particular the LAVs) is already under consideration; for $\pi^0 \to$ invisible it might be important to keep the level-1 rate under control as kinematic cuts to exclude $K^+ \to \pi^+\pi^0$ events are loosened. The dominant contribution to the trigger rate is from events with one photon overlapping with the π^+ on the LKr calorimeter and one photon lost. With stringent track-quality cuts for the π^+ and additional cuts in the $(p_{\pi^+}, \theta_{\pi^+})$ plane to deselect events with low-energy, large-angle photons, the π^0 rejection can be increased by perhaps a factor of ten with respect to the NA62 baseline rejection of 10^{-8}. Then, NA62 would have the potential to set a limit on $\mathrm{BR}(\pi^0 \to \text{invisible})$ of $\sim 10^{-9}$, which is about 100 times better than present limits.

7. Conclusions

Next-generation experiments to measure $K^+ \to \pi^+\nu\bar{\nu}$ will be well adapted to carry out a rich program to search for very rare or forbidden K^+ and π^0 decays, because intense K^+ sources and robust background rejection (through precise tracking and particle identification and hermetic photon vetoes) are the defining features of such experiments. With $\sim 10^{13}$ K^+ and $\sim 2.5 \times 10^{12}$ π^0 decays in its fiducial volume after two years' worth of data taking, NA62 will have single-event sensitivities of $\sim 10^{-12}$ for a number of K^+ decays that violate lepton flavor and/or number conservation, as well as the potential to improve existing limits in a variety of searches for related phenomena.

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