Search for Light Neutral Bosons in the TREK/E36 Experiment at J-PARC

Dongwi H. Dongwi (on behalf of the TREK/E36 Collaboration)
Lawrence Livermore National Laboratory, 7000 East Ave., Livermore, CA 94550-9234
E-mail: dongwi1@llnl.gov

Abstract. The Standard Model (SM) represents our best description of the subatomic world and it has been very successful in explaining how elementary particles interact under the influence of the fundamental forces. Despite its far reaching success in describing the building blocks of matter, the SM is still incomplete; falling short to explain dark matter, baryogenesis, neutrino masses and much more. The E36 experiment conducted at J-PARC in Japan, allows for sensitivity to search for light $U(1)$ gauge bosons, in the muonic K^+ decay channel. Such $U(1)$ bosons could be associated with dark matter or explain established muon-related anomalies such as the muon $g_\mu - 2$ value, and the proton radius puzzle. A scintillating fiber target was used to stop a beam of positively charged K mesons. The K^+ products were detected with a large-acceptance toroidal spectrometer capable of tracking charged particles with high resolution, combined with a large solid angle CsI(TI) photon detector and particle ID systems. A realistic simulation was employed to search for these rare decays in the mass range of 20−100 MeV/c^2. Preliminary results of the upper limits for the A' branching ratio $\mathcal{B}r(A')$ extracted at 95% CL, will be discussed.

1. Introduction

The primary goal of the TREK/E36 experiment was to provide a high precision electroweak measurement in order to test lepton universality, which is expressed as an identical coupling constant of the charged lepton family (e, μ, and τ). Lepton universality is a staple of the Standard Model (SM) and any violation of this would be clear evidence of New Physics (NP) beyond the SM. E36 was designed to measure the ratio of the two-body decay widths $R_K = K_{e2}/K_{\mu 2}$ with high precision. In the SM, the value of R_K is very precise because to a first approximation the strong interaction dynamics cancel, leaving behind the expression 1 [1, 2]

$$\begin{aligned} R_K^{SM} &= \frac{\Gamma(K^+ \to e^+\nu_e)}{\Gamma(K^+ \to \mu^+\nu_\mu)} \\ &= \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1+\delta_r) \\ &= (2.477 \pm 0.001) \times 10^{-5} \end{aligned} \tag{1}$$

where m_K, m_e and m_μ are the masses of the K^+, e^+ and μ^+, respectively, and δ_r represents radiative corrections corresponding to IB. Detailed calculations have been carried out in [3].

This makes the SM value of $R_K^{SM} = 2.477 \times 10^{-5}$ very accurate and enhanced sensitivity through helicity suppression makes it possible to search for NP effects by conducting a precise measurement of R_K [1].

Additionally, the TREK/E36 experiment is sensitive to searches for light neutral particles in the exotic kaon decay modes of $K^+ \to \mu^+\nu_\mu A'$ and/or $K^+ \to \pi^+ A'$, followed by a prompt decay of the $A' \to e^+e^-$. The former decay mode is of interest. This A', often dubbed a dark photon, could also be considered as a light neutral $U(1)$ boson, and might be a hidden force carrier of the dark sector associated with dark matter [4]. An A' that is weakly coupled to the SM and is sufficiently light could decay into observable electron-positron pairs, which can be used to reconstruct its invariant mass. Furthermore, the A' could help resolve, simultaneously, the proton radius puzzle and anomalous magnetic moment of the muon $g_\mu - 2$ [5–8]. Such hypothetic particles can also be conceived without violating existing constraints if they are fine-tuned and non-universally coupled [6–11]. In this case there would be a pronounced signal over the calculable SM leptonic radiative mode $K^+ \to \mu^+\nu_\mu e^+e^-$ [7,8]. Figure 1 shows the Feynman diagram of muonic kaon decay involving an A' $K^+ \to \mu^+\nu_\mu A'$ followed promptly by $A' \to e^+e^-$.

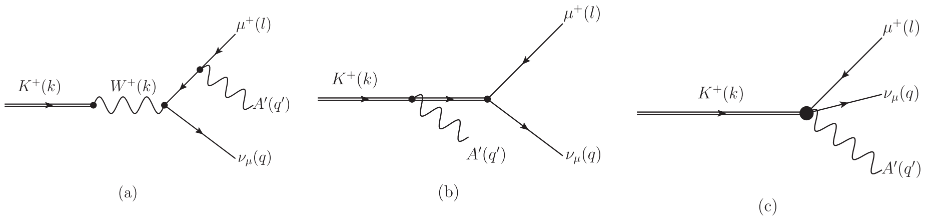

Figure 1: A' production amplitude. Feynman diagrams showing the channel of interest $K^+ \to \mu^+\nu_\mu A'$ [12].

Carlson and Rislow have calculated the branching ratio $\mathcal{B}r(K^+ \to \mu^+\nu_\mu A')$ to be of order 10^{-5} for polar and axial vector couplings. Their prediction of the aforementioned branching ratio as a function of m_{ee} indicates that a strong signal peak over the SM background would be observed experimentally in the invariant mass of the e^+e^- par, m_{ee}, as shown in Figure 2 [8] for an assumed mass $m_{A'} = 30$ MeV/c^2.

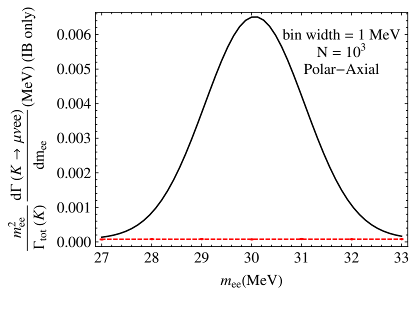

Figure 2: Strong signal to background prediction of the differential branching ratio as a function of m_{ee}. The QED background prediction for $K^+ \to \mu^+\nu_\mu e^+e^-$ (red dashed curve) and the prediction with a 30 MeV/c^2 lepton universality violating A' of the Carlson model [8].

Given the strong signal to background expectation of the Carlson model, the TREK/E36 experiment which is sensitive to light neutral bosons below 300 MeV would be able to test the efficacy of the Carlson model. The search would include a charged μ^+ that is detected in the spectrometer gap and two clusters in the CsI barrel from e^+e^- pairs, from which a peak search can be conducted in the invariant mass spectrum m_{ee}.

2. Light Neutral Boson Search with the TREK/E36 Detector Apparatus

TREK/E36 was conducted at the K1.1BR kaon beamline in the hadron hall facility at J-PARC using a stopped K^+ beam in conjunction with a 12-sector superconducting toroidal spectrometer [13, 14]. Figure 3 shows the end and side view of the E36 detector apparatus. Details of the experimental method and detector configuration have been described in Ref. [15].

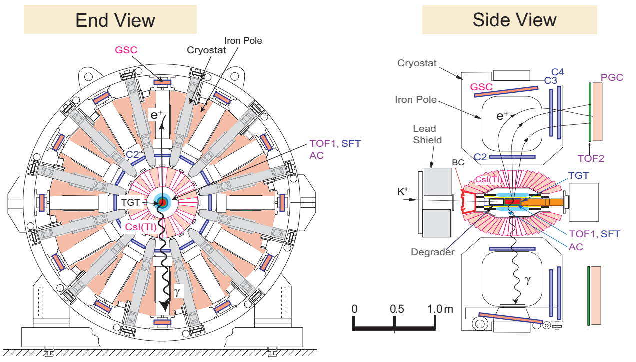

Figure 3: TREK/E36 apparatus. General end and side views of the detector system.

The incoming K^+ was tagged with a Fitch Čerenkov detector [13] in order to distinguish it from a π^+, before being slowed down by a BeO degrader and stopped in the active target (TGT). Charged K^+ decay products were tracked by using the spiral fiber tracker (SFT) [16] which surrounded the target, and three multi-wire proportional chamber (C2, C3, C4) in each spectrometer sector. The C2, and C3/C4 were placed at the entrance and exit of the magnet gaps, respectively. To suppress μ^+/e^+ mis-identification, redundancy was introduced into the particle identification detectors which was provided by time of flight detectors (TOF1, TOF2), aerogel Čerenkov, and lead glass Čerenkov counters (PGC). A highly segmented and large acceptance CsI(Tl) calorimeter barrel which consisted of 768 crystals and covered about 70% of 4π [17] was used to identify and correct for structure dependent (SD) background events and also to search for light neutral bosons A'. The A' search necessitated that a μ^+ is tracked in the gap, whose primary vertex lies within the fiducial volume of the target (*good gap event*) and two-clusters in the CsI calorimeter to detect the e^+e^- pair, along with at least 3 TOF1 counters that registered a charged particle hit.

3. Analysis and Preliminary Results

The aforementioned A' signal search required a TOF1 multiplicity of of at least 3, implying that three charged particles have passed through the TOF1 counters. Specifically the μ^+ is tracked in the magnet gap and the e^+e^- form clusters in the CsI(Tl) calorimeter, and an invariant mass m_{ee} distribution was reconstructed from the clusters. A Geant4 *Monte Carlo* was used to generate and reconstruct A' mass $M_{A'}$, whose reconstructed widths, corresponding to 2σ, were used as the search window in the m_{ee} spectrum, shown in Figure 4 [18].

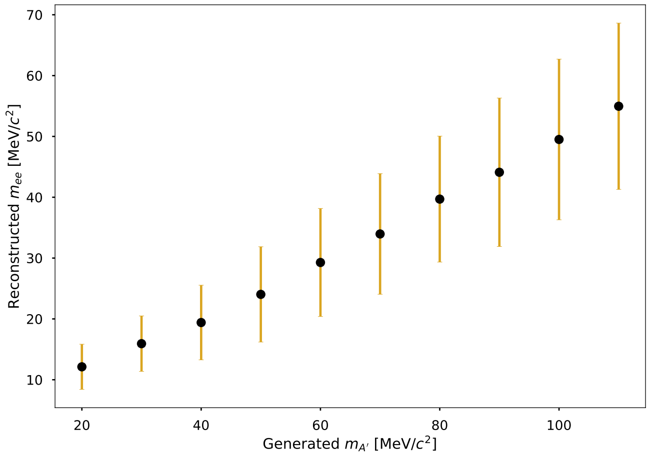

Figure 4: MC reconstructed invariant mass m_{ee} vs. generated A' mass. The horizontal bars represent a 2σ search window for a given A' mass. [18].

This analysis considered masses in the range of 20-110 MeV/c^2, in incremental step-sizes of 5 MeV/c^2. Several cut conditions in addition to the TOF1 multiplicity were employed in order to suppress the reducible background:

i. a momentum endpoint cut as a function of the generated $M_{A'}$
ii. a correlated angle cut between fired TOF1 counter and corresponding CsI(Tl) cluster
iii. a muon mass squared M_μ^2 cut for the charged particle in the gap.

A polynomial fit to the resulting invariant mass m_{ee} data can be seen in Figure 4 below. The bottom panel of Figure 5 shows the residual, which is defined as the relative difference between data and fit, normalized to the data.

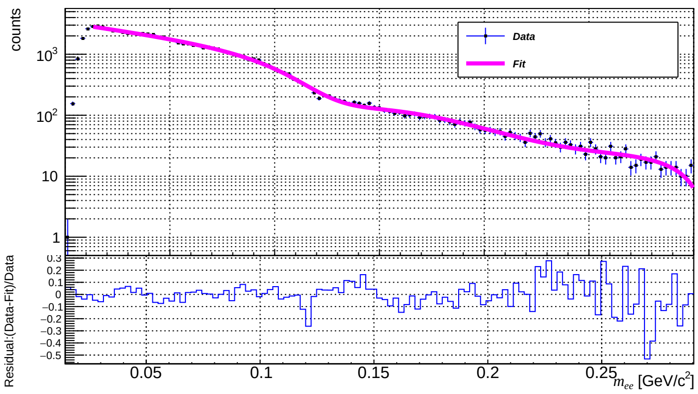

Figure 5: Invariant mass m_{ee} distribution with fit to data. The normalized residual is shown in the bottom plot.

The fit function from Figure 5 and the total number of stopped kaons N_K were used to extract the upper limits. The total number of stopped K^+ in the fiducial region of the active target was computed as follows

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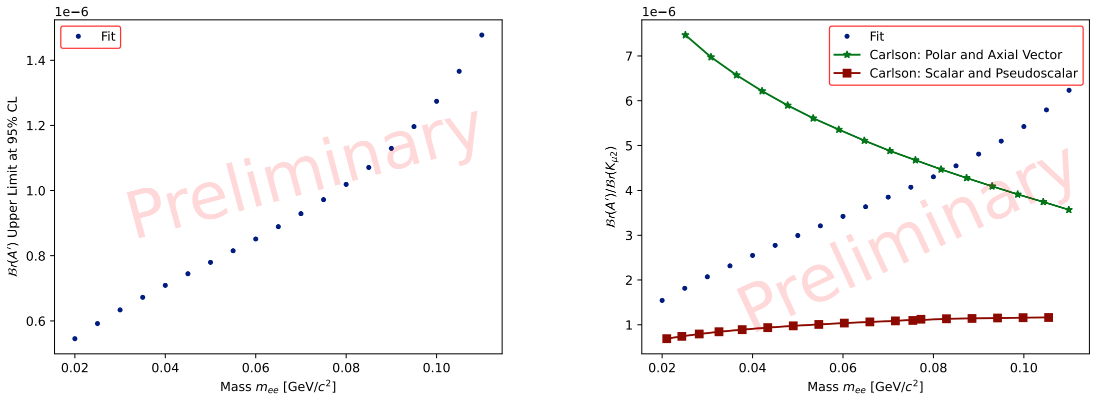
$$N_K = \frac{N_{\mu 2}}{\mathcal{B}r(K_{\mu 2})A_{\mu 2}} = 2.81 \times 10^9 \tag{2}$$

where $N_{\mu 2}$ is the number of tracked data candidates satisfying the $K_{\mu 2}$ decay momentum, $A_{\mu 2}$ is the acceptance fraction of the $K_{\mu 2}$ muons evaluated with the MC simulations and $\mathcal{B}r(K_{\mu 2})$ is the nominal branching ratio of the $K_{\mu 2}$ decay mode. Upper limits at 95% CL on the branching ratio of $Br(K^+ \to \mu^+ \nu_\mu A')$ for each A' mass corresponding to a 2σ limit for not observing the A' was computed for each aforementioned mass and corresponding search window of the invariant spectrum using the following relation

$$Br(K^+ \to \mu^+ \nu_\mu A') < \frac{2\sqrt{N_{\mu\nu ee}}}{N_K A_{A'} \cdot LT}. \tag{3}$$

where $N_{\mu\nu ee}$ is the number of candidate events within a given search window after applying all cuts to suppress the reducible background, $A_{A'}$ is the fractional acceptance of the signal process $K^+ \to \mu^+ \nu_\mu A'$, $A' \to ee$, and LT is the livetime fraction for candidate events. The upper limit as a function of the invariant mass m_{ee} is shown in Figure 6 (a). With $\sim 20\%$ of the data analyzed, the upper limit was found to be at $\mathcal{O}(10^{-6})$.



(a) (b)

Figure 6: Upper limit extraction (a) as a function of reconstructed invariant mass m_{ee}. Data (blue) and theory comparisons (b) on particles with scalar and pseudoscalar (squares), and polar and axial vector (stars) couplings. Particles with both polar and axial vector couplings appear to be excluded for masses below 80 MeV/c^2.

Experimental limits for the Carlson model for new light neutral bosons with polar (scalar) and axial vector (pseudoscalar) couplings are $\mathcal{O}(10^{-6})$. Whereas Figure 6 (b), shows the comparison between data and theory prediction of particles with scalar and pseudoscalar (green), and polar and axial vector (orange) couplings [7]. An A' particle with both polar and axial vector couplings, appears to be already excluded for masses below 80 MeV/c^2 with only $\sim 20\%$ of the data analyzed. However, an A' with scalar and pseudoscalar couplings is not yet excluded. With further development in reducible background suppression, and more data analysis, we are hoping to enhance the sensitivity and experimental reach. Presently PID cuts to suppress $e/\mu/\pi$ mis-identification have not been applied. These cuts would further reduce the reducible background, and would enhance our sensitivity to particles with scalar and pseudoscalar couplings.

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