Search for a Light Higgs Boson in the Decay $K^+ \to \pi^+ H$, $H \to \mu^+\mu^-$

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An upper limit on the branching ratio of the decay $K^+ \to \pi^+ H$, $H \to \mu^+\mu^-$ is set at 1.5×10^{-7} at the 90% confidence level, for a Higgs-boson mass in the interval $220 < m_H < 320$ MeV/c^2. In addition, 90%-confidence-level upper limits on the branching ratios of the decays $K^+ \to \pi^+\mu^+\mu^-$ and $K^+ \to \mu^+\nu\mu^+\mu^-$ are set at 2.3×10^{-7} and 4.1×10^{-7}, respectively.

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In the minimal standard model of electroweak interactions, there is no theoretical lower bound[1,2] on the mass of the scalar Higgs boson provided the mass of the top quark is > 80 GeV/c^2. The possibility of a light Higgs boson has recently been explored by several authors,[3-5] who conclude that a light Higgs boson has not been ruled out experimentally and may be produced in kaon decays.

The decay $K^+ \to \pi^+ H$, $H \to \mu^+\mu^-$ is expected to be a particularly attractive process in which to search for a light Higgs particle, because the branching ratio[6] for $H \to \mu^+\mu^-$ is close to unity for a Higgs-boson mass in the interval $2m_\mu < m_H < 2m_\pi$ and remains substantial (approximately 0.1) for $2m_\pi < m_H < m_K - m_\pi$. As the expected lifetime of a Higgs boson is $< 10^{-14}$ s in the mass region in which this experiment has good acceptance ($220 < m_H < 320$ MeV/c^2), the topology for $K^+ \to \pi^+ H$ is the same as for $K^+ \to \pi^+\mu^+\mu^-$, which is predicted[7] at a level of about 5×10^{-8}, far below the sensitivity of previous searches.

The experiment utilizes a low-energy separated kaon beam produced by the BNL Alternating Gradient Synchrotron. The apparatus was designed to measure the rare decay $K^+ \to \pi^+\nu\bar{\nu}$, and a more detailed description is presented elsewhere.[8,9] Figures 1(a) and 1(b) show schematic side and end views of the detector, which is located inside a 1-T, 3-m-diam, conventional solenoidal magnet. A 775-MeV/c K^+ beam is degraded in BeO and stopped in a segmented scintillating fiber target located in the center of the cylindrically symmetric detector. The target consists of 379 triangular clusters, each containing six 2-mm fibers, and is surrounded by six 6-mm-thick I counters that define the kaon stopping volume. Charged particles from the K^+ decay that enter the 2π-sr fiducial region of the detector, defined by the T counters, are momentum analyzed by a cylindrical drift chamber and are subsequently stopped in a segmented scintillator range stack. There is little dead ma-

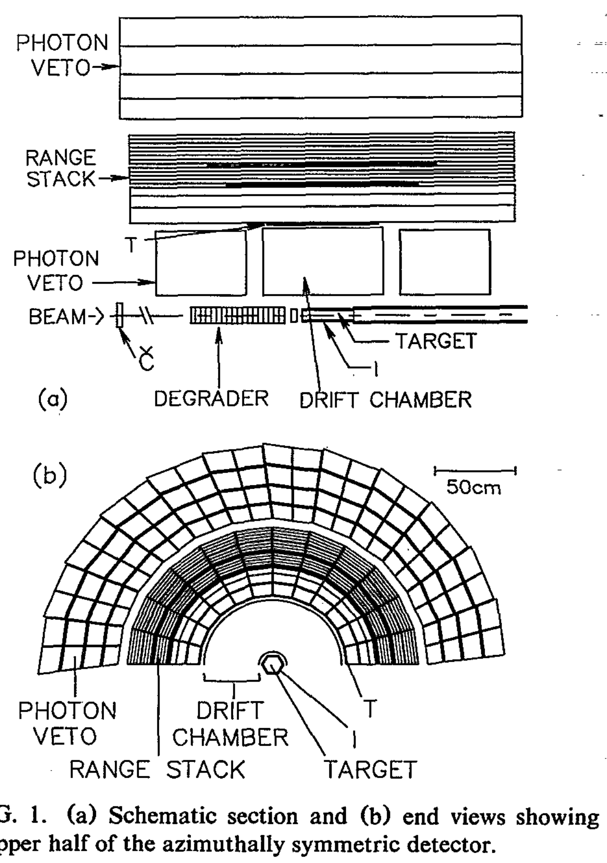

FIG. 1. (a) Schematic section and (b) end views showing the upper half of the azimuthally symmetric detector.

terial in any of these systems, facilitating the measurement of total energy, range, and momentum of the decay particles. Deployed radially outside the range stack and covering either end of the cylindrical detector is an electromagnetic calorimeter twelve to fifteen radiation lengths thick, consisting of many thin alternating layers of lead and plastic scintillator. The calorimeter provides the highly efficient 4π-sr photon detection necessary to suppress the background arising from $K^+ \rightarrow \pi^+\pi^0$ and other decays involving photons.

The trigger selects $K^+ \rightarrow \pi^+ H$, $H \rightarrow \mu^+\mu^-$ candidates based on the requirements that at least two charged tracks enter the range stack and that these tracks do not penetrate deeper than the first three radial layers. The trigger also requires that the beam particle be identified as a kaon by the Cherenkov counter, that there be a delay of at least 2 ns between the entering beam kaon and the emerging decay particles, that there be more than one track in the target, and that no significant energy be present in the electromagnetic calorimeter. The resulting trigger rate was about seven $K^+ \rightarrow \pi^+ H$, $H \rightarrow \mu^+\mu^-$ triggers per spill of 10^5 kaons stopped in the fiducial target volume.

The analysis was performed on a sample resulting from an exposure of 7.6×10^9 stopped kaons. Reconstruction required that one negative and two positive tracks be successfully fit to hits in the x-y plane of the cylindrical drift chamber. The drift-chamber tracks were extrapolated back into the target, taking into account energy loss, and a fit was made to a common vertex. Loose cuts were then placed on the quality of the vertex fit and on the three-track vector momentum at the vertex.[10] Events were rejected if they had a fitted vertex more than 2 cm outside the target, or were inconsistent with a three-track event in the target or I counters.

Kinematic and photon veto cuts were used to eliminate backgrounds that can satisfy the track-reconstruction requirements such as $K^+ \rightarrow \pi^+\pi^- e^+\nu$ and $K^+ \rightarrow \pi^+\pi^0$ with $\pi^0 \rightarrow \gamma e^+e^-$ or $\pi^0 \rightarrow \gamma\gamma$ followed by $\gamma \rightarrow e^+e^-$. We required the momentum of each track to be less than 150 MeV/c, the range stack energy of each track to be less than 120 MeV, and the total energy in the range stack to be less than 175 MeV. Requiring the minimum opening angle between any two of the three tracks to be greater than 20° removed e^+e^- pairs. Energy not associated with a reconstructed track was required to be less than 1 MeV in the range stack and the photon vetoes and less than 20 MeV in the target.

Finally, events were eliminated if any track had an energy deposition in the I counters or range stack consistent with that expected for an electron. Low-momentum tracks that reentered the target were rejected if the time of flight between I-counter hits was consistent with that of an electron.

After imposing the above cuts on the 658 226 events surviving the trigger, we are left with the three events shown in Fig. 2 with $\pi^+\mu^+\mu^-$ and $\mu^+\mu^-$ masses given in Table I. The final-state muons and pions are identified by comparing drift-chamber momentum to range stack energy where possible, a process that is correct approximately 90% of the time, according to our simulation. All three candidates have reconstructed invariant masses, vertices, and total momentum consistent with the continuum decay $K^+ \rightarrow \pi^+\mu^+\mu^-$. The uncertainties in the $\pi^+\mu^+\mu^-$ and $\mu^+\mu^-$ masses are 7.5 and 5.0 MeV/c^2, respectively.

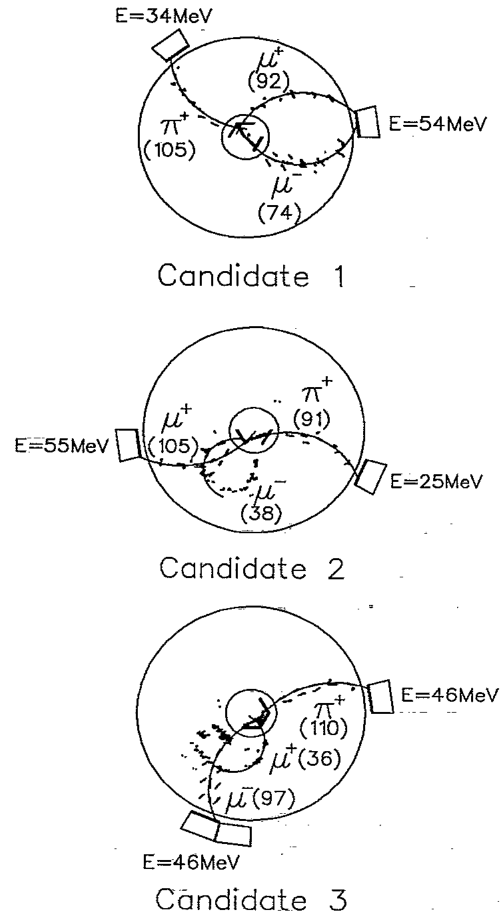

FIG. 2. End-view detector displays of the three $K^+ \rightarrow \pi^+\mu^+\mu^-$ candidates, showing the struck target, I counter, range stack elements, the reconstructed drift-chamber tracks, and the particle identification. The numbers in parentheses are the track momenta in MeV/c. Energy deposited in the range stack is also shown.

TABLE I. The $\pi^+\mu^+\mu^-$ and $\mu^+\mu^-$ masses of the three $K^+ \rightarrow \pi^+\mu^+\mu^-$ candidates. The errors in $M_{\pi\mu\mu}$ and $M_{\mu\mu}$ are 7.5 and 5.0 MeV/c^2, respectively.

Candidate No.	$M_{\pi\mu\mu}$ (MeV/c^2)	$M_{\mu\mu}$ (MeV/c^2)
1	498.4	298.7
2	495.0	255.6
3	491.0	256.1

Table II shows a summary of the acceptance of the trigger and analysis. As an example, the results for continuum (direct) $K^+ \to \pi^+\mu^+\mu^-$ events are given. Figure 3(a) shows how the total acceptance varies with the Higgs-boson mass for $K^+ \to \pi^+ H$, $H \to \mu^+\mu^-$. The acceptance is calculated using a Monte Carlo simulation of the detector.[8,12] Elements of the calculation have been verified by using calibration data taken during the run to measure the branching ratios for $K^+ \to \mu^+\nu$ and $K^+ \to \pi^+\pi^0$. The results agree to better than 2% with the established values. The acceptance of the trigger and reconstruction are limited by the radius of the target and high magnetic field, which make it unlikely for two of the three charged particles to reach the range stack and for the third to be analyzable in the drift chamber.

Background to the decay $K^+ \to \pi^+ H$, $H \to \mu^+\mu^-$ comes from both misanalyzed $K^+ \to \pi^+\pi^- e^+\nu$ and $K^+ \to \pi^+\pi^0$, as well as direct $K^+ \to \pi^+\mu^+\mu^-$. As discussed below, the observed rate represented by the three candidates is consistent with these non-Higgs-boson sources. We can conservatively use the three remaining events to calculate the upper limit on the decay $K^+ \to \pi^+ H$, $H \to \mu^+\mu^-$ as a function of the Higgs-boson mass in the interval $220 < m_H < 320$ MeV/c^2. As shown in Fig. 3(b), this limit never exceeds 1.5×10^{-7} at the 90% confidence level. This result can be compared with the limits of a previous inclusive search[11] for the process $K^+ \to \pi^+ X^0$, shown as the dashed line in Fig. 3(b).

Our data can also be used to study the direct decay $K^+ \to \pi^+\mu^+\mu^-$, for which the previous branching ratio upper limit[13] is 2.4×10^{-6}. The largest expected background for $K^+ \to \pi^+\mu^+\mu^-$ is the decay $K^+ \to \pi^+\pi^- e^+\nu$, which has a similar signature and which produces an effective $\pi^+\mu^+\mu^-$ mass broadly peaked at the K^+ mass from 450 to 525 MeV/c^2. Using the procedure discussed above, 10^6 Monte Carlo–generated $K^+ \to \pi^+\pi^- e^+\nu$ events were analyzed. From this analysis and the measured[14] $K^+ \to \pi^+\pi^- e^+\nu$ branching ratio of $(3.90\pm0.15)\times10^{-5}$, we expect <0.3 of these events in the final sample. Other background decays, such as $K^+ \to \pi^+\pi^-\mu^+\nu$, $K^+ \to \pi^+\pi^+\pi^-$, and $K^+ \to \pi^+\pi^0$, were considered; however, they each lead to estimated backgrounds of <0.1 event and to effective $\pi^+\mu^+\mu^-$ masses much different from the K^+ mass. We therefore estimate the total background to the decay $K^+ \to \pi^+\mu^+\mu^-$ to be 0.3 ± 0.3 event.

With a total acceptance given in Table II, the three candidate events occur at a rate[15] consistent with the theoretically predicted branching ratio[7] for $K^+ \to \pi^+\mu^+\mu^-$. However, because we have not yet established a statistically significant signal for this decay mode above the backgrounds,[16] we deduce an upper limit on the branching ratio of 2.3×10^{-7} (90% confidence level). This improves on the previous limit by a factor of 10.

We also have studied the decay $K^+ \to \mu^+\nu\mu^+\mu^-$, for which no previous published data exist. Using the same three candidates and an estimated total acceptance[8] of $(2.2\pm0.3\pm0.6)\times10^{-3}$, we conclude that the branching ratio for this decay is $<4.1\times10^{-7}$ at 90% confidence level. This process constitutes another way to search for the Higgs boson through the decay $K^+ \to H\mu^+\nu$, $H \to \mu^+\mu^-$, which has an expected branching ratio[17] of the order of 10^{-9}. This is thought to be free of some of the theoretical uncertainties affecting $K^+ \to \pi^+ H$.[3]

TABLE II. The calculated acceptance for continuum $K^+ \to \pi^+\mu^+\mu^-$ events. In the total acceptance, the first error is the statistical error of the Monte Carlo simulation and the second is the estimated systematic error, resulting primarily from uncertainties in the drift-chamber reconstruction efficiency and in the thickness and density of the target.

Constraint	Acceptance
Hardware trigger	0.114
Reconstruction	0.057
Kinematic and photon cuts	0.88
Accidental losses	0.80
Electron rejection	0.89
Total	$0.0040\pm0.0005\pm0.0010$

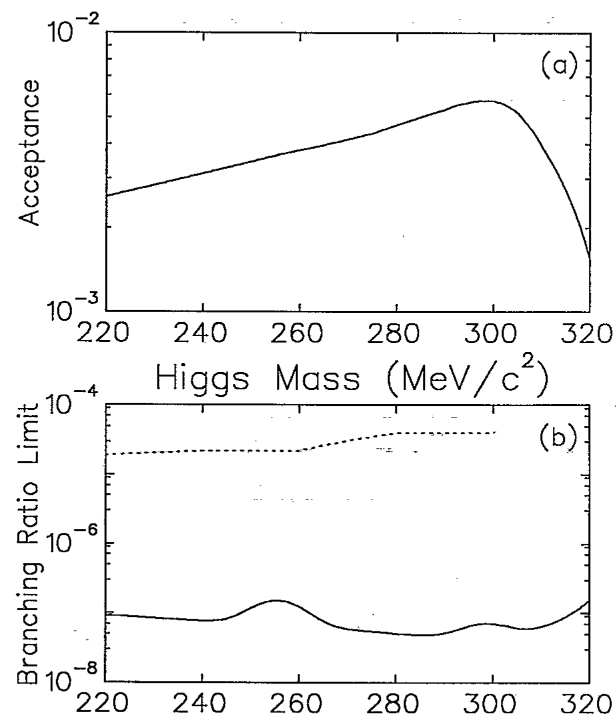

FIG. 3. (a) The total acceptance for the decay $K^+ \to \pi^+ H$, $H \to \mu^+\mu^-$ as a function of m_H. The magnitude of the acceptance has an error of 28% (statistical plus systematic). (b) The 90%-confidence-level upper limits of the branching ratio for the decay $K^+ \to \pi^+ H$, $H \to \mu^+\mu^-$ as a function of m_H (solid line). Also shown (dashed line) is the result of an inclusive search for $K^+ \to \pi^+ X^0$ (Ref. 11).

In conclusion, we have observed three candidate events consistent with the continuum decay mode $K^+ \to \pi^+\mu^+\mu^-$. We calculate an upper limit on the branching ratio of the decay $K^+ \to \pi^+ H$, $H \to \mu^+\mu^-$ of 1.5×10^{-7} at the 90% confidence level, for a Higgs-boson mass in the interval $220 < m_H < 320$ MeV/c^2. In addition, 90%-confidence-level upper limits on the branching ratios of the decays $K^+ \to \pi^+\mu^+\mu^-$ and $K^+ \to \mu^+\nu\mu^+\mu^-$ are set at 2.3×10^{-7} and 4.1×10^{-7}, respectively.

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[10]The sum of the squared distance of closest approach of each track to the vertex was required to be less than 5 cm^2, and the magnitude of the total momentum vector in the *x-y* plane was less than 40 MeV/*c*. All possible mass assignments were examined for each track.

[11]T. Yamazaki *et al.*, Phys. Rev. Lett. **52**, 1089 (1984); V. Bisi *et al.*, Phys. Lett. **25B**, 572 (1967), may also be applicable, but, since no acceptance for the process $K^+ \to \pi^+ H$, $H \to \mu^+\mu^-$ is given, we cannot infer a limit.

[12]A matrix element of unity was assumed when generating both $K^+ \to \pi^+\mu^+\mu^-$ and $K^+ \to \mu^+\nu\mu^+\mu^-$ Monte Carlo decays.

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[15]Assuming a signal of 3 events, an estimated background of 0.3 event, and using the calculated acceptance, one would arrive at a branching ratio of $(9\pm6)\times10^{-8}$.

[16]The confidence level for observing 3 or more events with an average of 0.3 ± 0.3 event is greater than 0.5%. (This corresponds to less than 3 Gaussian standard deviations.)

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