# Search for the Hypothetical $\pi \to \mu$x Decay*

R. Bilger[a], H. Clement[a], A. Denig[b], K. Föhl[a], P. Hautle[c], W. Kluge[b], J. A. Konter[c], G. Kurz[a], S. Mango[c], D. Schapler[a], F. Schönleber[b], U. Siodlaczek[a], B. van den Brandt[c], G.J. Wagner[a], R. Wieser[b]

[a]Physikalisches Institut, Universität Tübingen, D-72076 Tübingen, Germany
[b]Institut für Experimentelle Kernphysik, Universität Karlsruhe, D-76021 Karlsruhe, Germany
[c]Paul Scherrer Institut, CH-5232 Villigen, Switzerland



**Abstract:** The KARMEN collaboration has reported the possible observation of a hitherto unknown neutral and weakly interacting particle $x$, which is produced in the decay $\pi^+ \to \mu^+ x$ with a mass $m_x = 33.9$ MeV. We have searched for this hypothetical decay branch by studying muons from pion decay in flight with the LEPS spectrometer at the $\pi E3$ channel at PSI and find branching ratios $BR(\pi^- \to \mu^- \bar{x}) < 4 \times 10^{-7}$ and $BR(\pi^+ \to \mu^+ x) < 7 \times 10^{-8}$ (95% C.L.). Together with the limit $BR > 2 \times 10^{-8}$ derived in a recent theoretical paper our result would leave only a narrow region for the existence of $x$ if it is a heavy neutrino.

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## 1. Introduction

The KARMEN collaboration, which studies nuclear interactions of neutrinos resulting from the decay of stopped $\pi^+$ and $\mu^+$ in the beam dump at the Rutherford Appleton Laboratory (RAL), recently reported [1] an anomaly in the time distribution of single prong events concerning the time interval corresponding to muon decay. The simultaneously observed energy deposit of these anomalous events in the KARMEN detector corresponds to that of neutrino interactions resulting in visible energies of typically $T_{vis} = 11-35$ MeV [1]. Hence this anomaly has been suggested to originate from the observation of a hitherto unknown weakly interacting neutral and massive particle, called $x$, which is produced in the decay $\pi^+ \to \mu^+ x$ in the beam dump, then travels with a velocity $v_x = c/60$ (corresponding to the anomaly at 3.6 $\mu$s in the time spectrum) and finally gets registered in the detector volume after passing a steel wall of more than 7 m thickness. The observed velocity and the two-body kinematics of the assumed pion decay branch lead to a mass of the $x$-particle of $m_x = 33.9$ MeV, which is just marginally below the kinematical limit and leaves a tiny reaction Q-value of 7 keV. Hence in the reference system of the decaying pion the kinetic energies of the decay products are $T_x \approx 5$ keV and $T_\mu \approx 2$ keV, respectively. A study of this particular branch by observing the associately produced muons in the pion decay at rest is therefore highly prohibitory. On the other hand the tiny Q-value is just ideal for the observation of this decay branch in the pion decay in flight.

## 2. The experiment

We exploit the fact of a tiny Q-value to search for muons from a possible $\pi \to \mu x$ decay in flight, taking advantage of the Lorentz boost. In a pion beam with momentum $p_\pi = 150$ MeV/c, a pion decay into $\mu$ and $x$ would result in a well-behaved muon "beam" with momenta in the range of $p_\mu = 112.8 - 114.4$ MeV/c and a divergence of $\Delta\Theta_\mu \leq 5$ mrad. In its chromatic mode the $\pi E3$ channel of the PSI delivers a pion beam at the position where usually the target is installed (pivot point), with a momentum resolution of $\Delta p/p \leq 0.3\%$ and a divergence $\Delta\Theta < 40$ mrad FWHM [2]. The Low Energy Pion Spectrometer (LEPS), a description of which is found in refs. [3,4], has a momentum resolution of $\Delta p/p \leq 0.1\%$ and an angular acceptance of 150 mrad. Hence the increase of divergence in the $\mu$ "beam" from the decay $\pi \to \mu x$ is small compared to the original beam divergence, whereas the increase in the momentum spread caused by this decay should be sizeable and easily detectable by LEPS.

The measurements have been carried out with two slightly different setups. The setup of the first measurement is shown in fig. 1, where LEPS is put "in the beam", i.e. at an angle of 0°. The beam is prepared in the Z-shaped $\pi E3$ channel containing two bending magnets for momentum selection. Slits S 1 and S 2, set to openings of 16 and 26 mm, respectively, in the central part of the channel as well as a collimator (C) with a diameter of 10 mm installed at the last quadrupole magnet of the beamline ensure a well-defined phase space of the beam, the properties of which were carefully studied with LEPS. The straight section of $l_x = 5.5$ m between the bending magnet D2 and the entrance into the split pole of LEPS serves as the decay path for $\pi \to \mu x$.

For this setup a beam momentum of $p = 150$ MeV/c has been chosen, which allows an efficient separation of the beam particles $(\pi, \mu, e)$ by time of flight (TOF) measurements. The number of pions at the exit of D2 with a phase space capable of passing the collimator and reaching LEPS is determined from the number of pions detected with LEPS at a magnetic field setting appropriate for the observation of the direct beam. The relative beam intensity is monitored continuously by a ring of $\mu$-telescopes [4] which are mounted near the position of the collimator and which register muons emerging from the conventional pion decay in the beam at the Jacobian angle of about 15°. The composition of the beam $(\pi, \mu, e)$ is determined by TOF measurements between the scintillators at the focal plane and the RF of the cyclotron. The reliability of the calibration of the momentum settings of beamline and LEPS has been checked to be better than 1% by observation of the direct beam ($p = 150$ MeV/c) as well as of the muons resulting from forward and backward (in the CM-system of the pion) decays of $\pi \to \mu\nu_\mu$ ($p_\mu = 162$ and 74.2 MeV/c, respectively). Muons originating from $\pi \to \mu x$ are expected just between these values at a central momentum of $p_\mu \approx p_\pi \cdot \frac{m_\mu}{m_\pi} = 113.6$ MeV/c.

At the $\pi E3$ channel the beam for positively charged particles also contains low-energy protons of high intensity. In order to avoid severe damage of the intermediate focus detector by these protons, we have carried out all measurements at this particular setup with a negatively charged beam, i.e. searching for a $\pi^- \to \mu^- \bar{x}$ decay.

In a second stage of the experiment we installed in addition superconducting Helmholtz coils at the pivot point of LEPS (position PP in fig. 1) supplying a vertical magnetic field up to 2.5 T. This way beam pions are separated from the muons (originating from the pion decay in flight) sufficiently in angle, in order to prevent them from entering LEPS. Thus muons originating from the pion decay within the dipole of LEPS do no longer contribute to the background at the focal plane. In contrast to the first setup, where we had a complete vacuum beamline between pion production target and LEPS, in this setup the vacuum systems of the $\pi E3$ channel, the superconducting magnet and LEPS had to be separated by thin foils. Upstream and downstream of the superconducting magnet these foils amount to a thickness of about 32 mg/cm$^2$ each. The energy straggling due to these foils has been small and tolerable, leading to a momentum resolution of still better than 0.5%.

The measurements with this setup have been carried out with the $\pi^-$ and $\pi^+$ beams of momentum $p_\pi = 140$ MeV/c and a magnetic field of about 1.6 T, which gives a deflection angle of 34° for pions and 45° for muons, respectively. Slits S1 and S2 have been set to openings of 44 mm to give maximum beam flux through the collimator of 10 mm at the position C (fig. 1). Further on a thick copper collimator with a diameter of 50 mm has been put on the entrance of LEPS, in order to block beam pions, which are separated from the muons by the superconducting magnet. In this setup the decay section for $\pi \to \mu x$ decay is the straight section between the bending magnet D2 and the entrance of the superconducting magnet, i.e. $l_x = 2.9$m.

### 3. Results

A very valuable feature of LEPS is its intermediate focus equipped with a 6-plane multiwire proportional chamber, which — together with the focal plane drift chamber — allows a detailed track reconstruction. Together with the timing information from the scintillator detector at the focal plane this leads to a very stringent background reduction in the recorded events. Fig. 2 shows the results from the measurements with the first setup. Plotted are the momentum spectra with cuts on phase space, TOF and energy loss ($\Delta E$) informations obtained from the intermediate and focal plane detectors. The inset in fig. 2 displays the measurement of the direct $\pi^-$ beam exhibiting a momentum resolution of better than 0.3%. This measurement also defines the intrinsic line shape as well as the cuts in the TOF, $\Delta E$ and phase space spectra of the individual LEPS detectors.

The main part of fig. 2 shows the $\mu^-$ spectrum in the momentum bite $p = 107 - 118$ MeV/c, i.e. in the range where we expect the associately produced muons from the decay $\pi^- \to \mu^- \bar{x}$ ($p_\mu = 112.8 - 114.4$ MeV). Here TOF, $\Delta E$ and phase space cuts have led to an overall reduction factor of 30 in the number of events.

These spectra correspond to an accumulated number of $1.5 \times 10^9$ pions entering the decay section $l_x = 5.5$m at the exit of D2. From the kinematics of the $\pi \to \mu x$ decay we expect a mainly rectangular shaped peak centered at $p = 113.6$ MeV/c with a width of 1.5 MeV/c. Folding this peak shape with the intrinsic line shape as observed with the direct $\pi$ beam (fig. 2, inset) produces an expected line shape for $\mu$ as shown in fig. 2 (bottom). We note that the expected line width is substantially larger than the momentum resolution observed with the direct beam. The measured $\mu$ spectrum (fig. 2, on the right) does not exhibit any statistically significant structure of the expected shape, in particular also not in the region around $p = 114$ MeV/c. Hence we associate the events registered in the constrained spectrum solely to background events arising from conventional $\pi$-decay etc. For a quantitative analysis of the spectrum we have first fitted the background spectrum by a smooth curve (polynomial of $4^{\text{th}}$ to $8^{\text{th}}$ degree) and next performed a $\chi^2$-fit where the expected response $R(x)$ was included and its amplitude varied to minimize $\chi^2$. As the first two lines of table 1 show, this inclusion did not improve the fit. The resulting number of events for $R(x)$ is $195 \pm 111(1\sigma)$ which corresponds to an upper limit of the branching ratio of

$$BR(\pi^- \to \mu^- \bar{x}) < 5 \times 10^{-7} \quad (95\% \text{ C.L.}) \quad . \tag{1}$$

The same limit was obtained with the $\pi^-$-beam using the second setup (lines 3 and 4 of table 1).

The results of the $\pi^+$-measurements, performed with the second setup only, are shown in fig. 3. Again the $\mu^+$ momentum spectrum is shown with cuts on phase space, TOF and $\Delta E$ informations from the intermediate and focal plane detectors. The shape of the constrained spectrum can be understood from the shape of the phase space accepted by LEPS, and is basically due to the circular collimator at the entrance of LEPS, which selects a bell-shaped momentum-bite of $\Delta p/p = 10\%$. We stress that the same shape of the momentum spectrum is obtained if we select electrons by a corresponding cut in the TOF spectrum. This suggests that the displayed $\mu^+$ spectrum arises primarily from background such as slit scattering.

At the initial pion momentum $p_\pi = 140$ MeV/c of this run we expect $x$-particles at a momentum around $p_\mu = 106$ MeV/c. Again no statistically significant structures are observed. The spectrum corresponds to an accumulated number of $2 \times 10^{10}$ pions entering the decay path $l_x = 2.9$m at the exit of D2. As table 1, line 6 shows, the fit to the expected response $R(x)$ yields $-553 \pm 432$ events. According to the recommendations of the Particle Data Group [5] only the physical region of positive values is considered. Then we obtain as an upper limit for the branching ratio

$$BR(\pi^+ \to \mu^+ x) < 7 \times 10^{-8} (95\% \text{ C.L.}) \quad . \tag{2}$$

In a recent paper [6] Barger, Phillips and Sarkar derive limits on the correlation between branching ratio and lifetime as given in fig. 4 of ref. [1] by assuming that $x$ is a massive neutrino underlying the standard weak interaction. From the absence of experimental evidence for anomalous contributions to $\mu \rightarrow e\nu\nu$ and $\pi \rightarrow e\nu$ decays they find the following limits for the branching ratio

$$2 \times 10^{-8} < BR(\pi \rightarrow \mu x) < 8 \times 10^{-5} \quad . \tag{3}$$

Our measurements lower this upper limit by three orders of magnitude. Together with the theoretical limits of expression (3) our measurements leave only a small region in the branching ratio for the existence of the $x$-particle.

## 4. Summary

Prompted by the reported anomaly in the time spectrum of single-prong events of KARMEN we have undertaken a first search for the hypothetical $\pi \rightarrow \mu x$ decay utilizing the LEPS-setup at the $\pi E3$ channel of PSI. This setup is very well suited for studying the pion decay in flight, in particular if the Q-value of the decay branch is very small as is the case for the postulated decay into the $x$-particle. Our first results give a branching ratio of less than $7 \times 10^{-8}$ at 95% C.L. for this decay branch, thus leaving only a narrow allowed region in the branching ratio if combined with the considerations of Ref. [6] based on standard weak interactions.

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**Figure Captions:**

Fig. 1: Schematical layout of the experimental setup. Perpendicular to the plane of the figure the proton beam hits the target PT for the production of $\pi, \mu$ and e. These are momentum and phase space selected in the $\pi E3$ beamline before being analysed in LEPS. D, Q and H denote dipole, quadrupole and hexapole magnets in the $\pi E3$ beamline, whereas $S_1$ and $S_2$ denote positions of slits, which may be varied both in horizontal and vertical directions. At the position of the last quadrupole magnet of the beamline, a 6 cm long copper collimator (C) with a diameter of 10 mm has been installed. PP denotes the pivot point of LEPS, where in the second stage of the experiment superconducting Helmholtz coils have been installed. 3Q denote the quadrupole triplet of LEPS, which focusses the beam onto the intermediate focus (IF) detector before it enters the split pole dipole of LEPS. At the focal plane FP a vertical drift chamber has been installed followed by scintillation detectors. The straight section between D2 and the entrance into the dipole of LEPS serves as decay path for $\pi \to \mu x$.

Fig. 2: Momentum spectra of pions (inset) and muons in the focal plane of the LEPS spectrometer obtained with a $\pi$ beam of $T_\pi$ = 150 MeV/c and the first setup. The events have been constrained by $\Delta E$, TOF and phase space information. Abscissa scales are identical. The solid curve is a $4^{\mathrm{th}}$ order polynomial fit to the data. Also indicated is the expected response to muons from $\pi^- \to \mu^- \bar{x}$ decay assuming as example a branching ratio $B = 2 \cdot 10^{-6}$.

Fig. 3: Momentum spectra of muons in the focal plane of LEPS obtained with a $\pi^+$ beam of $p_\pi$ = 140 MeV/c and the setup including superconducting Helmholtz coils. The solid curve represents a $6^{\mathrm{th}}$ order polynomial fit to the data. At the bottom we have indicated the expected response to $\pi^+ \to \mu^+ x$ decay with a branching ratio $B = 2 \cdot 10^{-6}$ as an example.

Table 1.

Summary of the statistical analysis of the measured muon spectra. $p^n$ denotes a polynomial of $n^{th}$ order, $R(x)$ is the expected response function for the $x$-particle, $DF$ are degrees of freedom in the fit and $N_x$ gives the number of counts (with $1\sigma$ uncertainty) in the $x$-region resulting from the fit. SHC = superconducting Helmholtz coil at pivot point (PP) of LEPS.

| channel setting | SHC | Analysis | $\chi^2(DF)$ | $N_x$ (counts) | $BR$ (95% C.L.) |
|---|---|---|---|---|---|
| $\pi^-$ | no | $p^4$ | 153.4 (143) | — | |
| 150 MeV/c | | $p^4 + R(x)$ | 150.3 (142) | $195 \pm 111$ | $< 5.0 \cdot 10^{-7}$ |
| $\pi^-$ | yes | $p^6$ | 110.8 (102) | — | |
| 140 MeV/c | | $p^6 + R(x)$ | 109.9 (101) | $170 \pm 171$ | $< 4.8 \cdot 10^{-7}$ |
| $\pi^+$ | yes | $p^6$ | 124.0 (113) | — | |
| 140 MeV/c | | $p^6 + R(x)$ | 122.4 (112) | $-553 \pm 432$ | $< 7 \cdot 10^{-8}$ |

Figure 1.

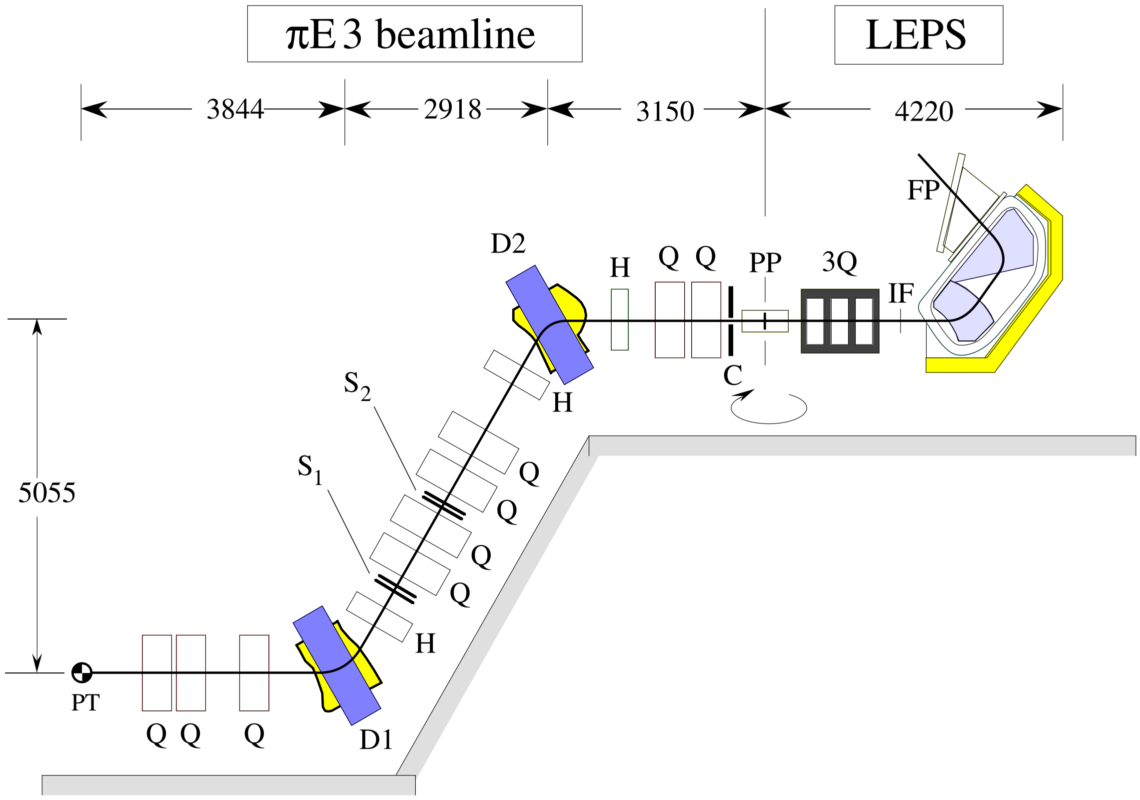
πE 3 beamline
LEPS
3844
2918
3150
4220
5055
FP
D2
H
Q
Q
PP
3Q
IF
C
H
S2
S1
Q
Q
Q
Q
H
PT
Q
Q
Q
D1

Figure 2.

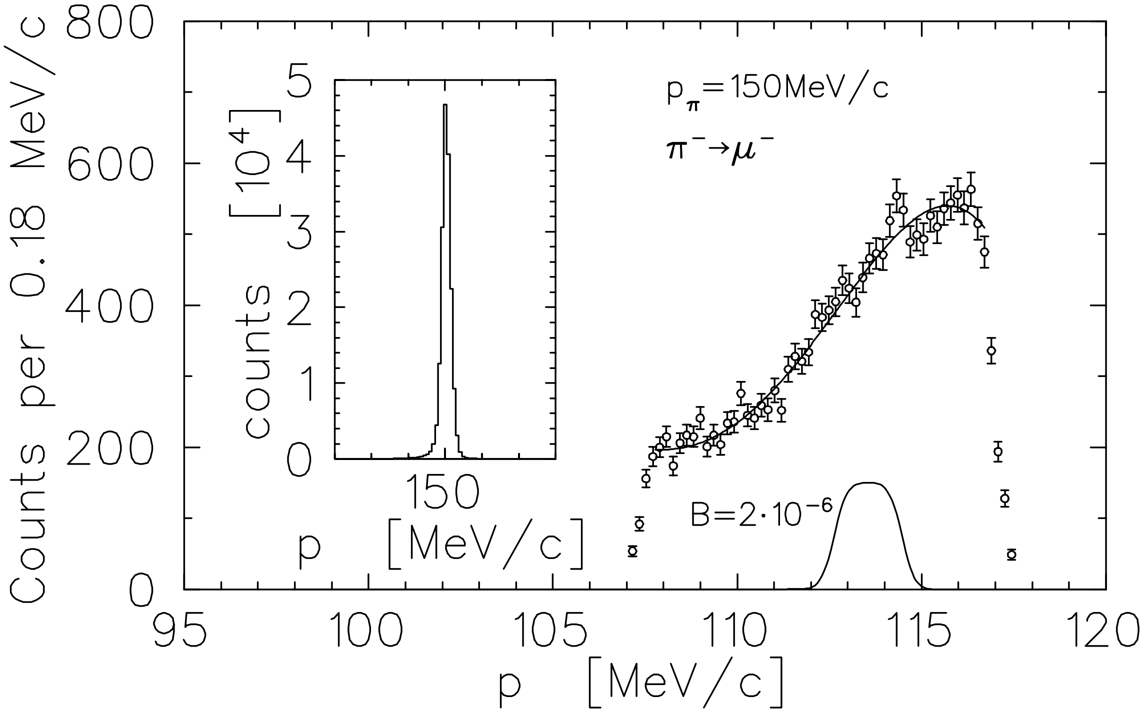


Figure 3.