Improved search for two body muon decay $\mu^+ \to e^+ X_H$

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Charged lepton flavor violating muon decay $\mu^+ \to e^+ X_H$, where X_H is a massive neutral boson, was sought by searching for extra peaks in the muon decay $\mu^+ \to e^+ \nu \bar{\nu}$ energy spectrum in the m_{X_H} mass region 47.8–95.1 MeV/c^2. No signal was found and 90% confidence level upper limits were set on the branching ratio $\Gamma(\mu^+ \to e^+ X_H)/\Gamma(\mu^+ \to e^+ \nu \bar{\nu})$ at the level of 10^{-5} for this region.

I. INTRODUCTION

Observations of neutrino oscillations have established that lepton flavor is not strictly conserved. In the context of

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the Standard Model (SM), however, charged lepton flavor violating (CLFV) effects are too small to be observed [1]. Massive or massless weakly interacting neutral bosons X such as axions [2–5] and majorons [6–8] have been suggested to extend the SM including models with dark matter candidates, baryogenesis, and solutions to the strong *CP* problem. Wilczek suggested such a model [9] which may lead to CLFV where the boson X can be emitted in flavor changing interactions. Such new bosons have been sought by experiments using kaon [10–15], pion [16,17], and muon decays [18–22].

When decay products from a massive boson X_H are not detected due to, for example, a long lifetime, CLFV two body muon decay involving a massive boson $\mu^+ \to e^+ X_H$ can be sought by searching for extra peaks in the muon decay $\mu^+ \to e^+ \nu \bar{\nu}$ positron energy spectrum. The mass of the boson m_{X_H} can be reconstructed using the equation
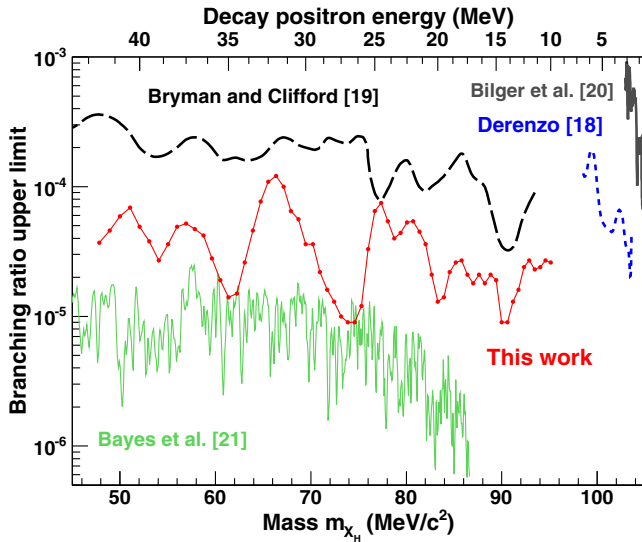
$$m_{X_H} = \sqrt{m_\mu^2 + m_e^2 - 2m_\mu E_e}, \qquad (1)$$

FIG. 1. Summary of the experimental upper limits on the $\mu^+ \to e^+ X_H$ branching ratio. The filled red circles with the thin solid red line show the results of this work. The limits represented by the dotted blue line, thick dashed black line, thick solid gray line, and thin solid green line are from Refs. [18–21], respectively.

where m_μ and m_e are the masses of the muon and the positron, respectively, and E_e is the total energy of the decay positron.

Two-body muon decays $\mu^+ \to e^+ X_H$ were searched for by Derenzo [18] using a magnetic spectrometer; experimental limits[1] on the branching ratio $\Gamma(\mu^+ \to e^+ X_H)/\Gamma(\mu^+ \to e^+ \nu\bar{\nu}) < 2 \times 10^{-4}$ were set in the mass region from 98.1 to 103.5 MeV/c^2. Exotic muon decays were also sought as a byproduct of the $\pi^+ \to e^+ \nu$ branching ratio measurement [23] by Bryman and Clifford [19] using a NaI(Tℓ) calorimeter, resulting in upper limits on the branching ratio $\lesssim 3 \times 10^{-4}$ in the mass range from 39.3 to 93.4 MeV/c^2. Muon decay in the mass region up to the kinetic limit was studied by Bilger *et al.* [20] using a germanium detector. The most sensitive experiment done so far by Bayes *et al.* [21] gave limits from 10^{-5} to 10^{-6} in the mass range from 3.2 to 86.6 MeV/c^2. Figure 1 shows a summary of the present status of the search for $\mu^+ \to e^+ X_H$ decay with upper limits in the mass region from 45 to 105 MeV/c^2. A massless boson X_0 was also searched for by Jodidio *et al.* [22], and the upper limit on the branching ratio was found to be $\Gamma(\mu^+ \to e^+ X_0)/\Gamma(\mu^+ \to e^+ \nu\bar{\nu}) < 2.6 \times 10^{-6}$.

The present work was carried out with data from the PIENU experiment principally designed to measure the branching ratio $\Gamma[\pi^+ \to e^+ \nu(\gamma)]/\Gamma[\pi^+ \to \mu^+ \nu(\gamma)]$ using pion decays at rest [24]. A 75 MeV/c π^+ beam from the TRIUMF M13 channel [25] was degraded by two thin

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plastic scintillator beam counters. Pion tracking was performed by two multiwire proportional chambers and two silicon strip detectors. The pion beam was stopped in an 8 mm thick plastic scintillator target. Positrons from $\pi^+ \to e^+ \nu$ decays and $\mu^+ \to e^+ \nu\bar{\nu}$ decays following $\pi^+ \to \mu^+ \nu$ decays were measured by two thin plastic scintillators used as telescope counters and a calorimeter consisting of a 48 cm(dia) $\times$ 48 cm (length) single crystal NaI(Tℓ) detector surrounded by pure CsI crystals [26]. A silicon strip detector and a multiwire proportional chamber were used to reconstruct tracks of decay positrons and define the acceptance. The energy resolution of the calorimeter was 2.2% (FWHM) for 70 MeV positrons. A total of 1.9×10^8 muon decays were used to search for the decay $\mu^+ \to e^+ X_H$ with lifetime $\tau_X > 10^{-9}$ s. The energy resolution is a factor of 2 improvement, and the statistics are an order of magnitude larger than the previous TRIUMF experiment [19]. The present experiment is also sensitive to a higher mass region than that of Ref. [21].
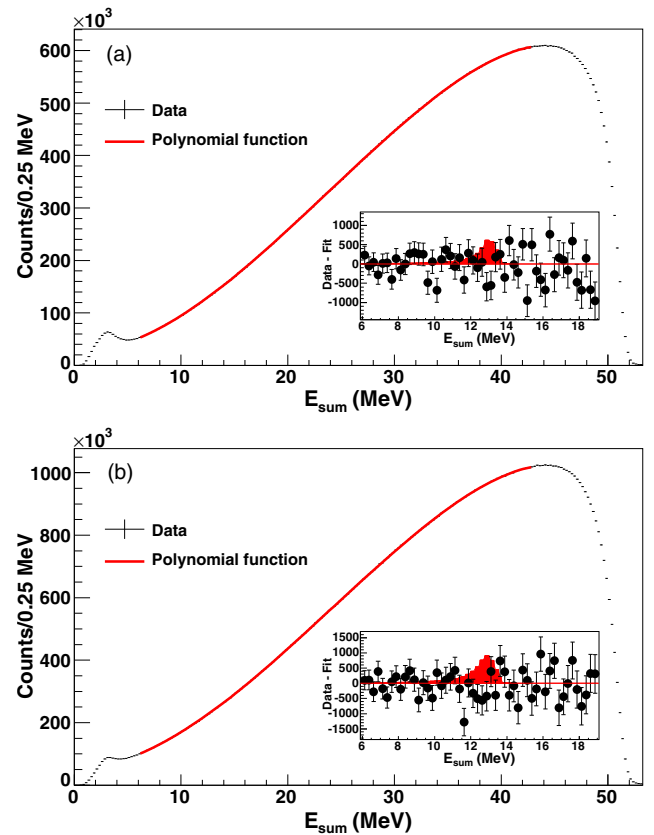

FIG. 2. The muon decay energy spectra from data taken before (a) and after (b) November, 2010 fit to polynomial functions (solid red line). The insert boxes show the residuals in the low energy region with statistical uncertainties (black circles) and a hypothetical signal (from MC) with the branching ratio 5.0×10^{-5} with $m_{X_H} = 90$ MeV/c^2 (red histograms). The bumps at 3 MeV were due to the low energy positrons that hit the telescope counters but did not reach the calorimeter (see text).

II. ANALYSIS

The data in the PIENU experiment were taken in runs occurring from 2009 to 2012. Because the energy calibration system for the CsI crystals was not available before November 2010, the data were divided into two sets, before and after that date. Pions were identified using energy loss information in the beam counters. Any events with extra hits in the beam and telescope counters were rejected. To ensure the events were from muon decay, the late time region > 200 ns after the pion stop was selected. A solid angle cut of about 15% was used for the dataset after November 2010. A tighter acceptance cut (corresponding to about 10% solid angle) was applied to the data taken before November 2010 to minimize electromagnetic shower leakage. Figure 2 shows the muon decay energy spectra for those two datasets where E_{sum} is the sum of energies observed in the calorimeter, telescope counters, and silicon strip detector including positron annihilation but excluding approximately 1.5 MeV energy loss in the target and inactive materials. The bumps at about 3 MeV in the low energy region of the spectra were due to positrons which hit the telescope counters but did not enter the calorimeter; positron annihilation in the last telescope scintillator resulted in one 0.511 MeV photon depositing energy in the calorimeter.

The two muon decay energy spectra were each fit to smooth sixth order polynomial functions in the energy region $E_{sum} = 6$ to 43 MeV but excluding a region from -1.75 to $+1.25$ MeV around a possible signal peak where the search was to be performed. Then, for each m_{X_H}, the spectra were fit simultaneously to the polynomial functions with fixed fitting parameters obtained in the initial procedure plus a peak signal shape for the decay $\mu^+ \to e^+ X_H$. To combine the two datasets, a common branching ratio was used as a free parameter in the fit. The validity of the fit procedure was confirmed using the simulated muon decay energy spectrum and the signal peak with the branching

ratio 1.0×10^{-4} at several energies. The polynomial function fit without any added signal shape resulted in $\chi^2/\mathrm{d.o.f.} = 1.09$ (d.o.f. = 282). The signal shapes were produced by a Monte Carlo (MC) simulation [27] that reproduced the peak of the decay $\pi^+ \to e^+ \nu$ at 69.8 MeV. This procedure was repeated in the range $E_{sum} = 8.5$ to 40.5 MeV (corresponding to the actual decay positron energy $E_e = 10$ to 42 MeV) with 0.5 MeV steps.

III. RESULTS AND CONCLUSION

No extra peaks due to CLFV muon decay $\mu^+ \to e^+ X_H$ with a lifetime $\tau_X > 10^{-9}$ s were observed and upper limits on the branching ratio $\Gamma(\mu^+ \to e^+ X_H)/\Gamma(\mu^+ \to e^+ \nu \bar{\nu})$ from 10^{-5} to 10^{-4} were set for the mass region $m_{X_H} = 47.8$ to 95.1 MeV/c^2 as shown in Fig. 1. Statistics were the dominant source of uncertainty on the branching ratios. Systematic uncertainties and acceptance effects were approximately canceled by taking the ratio of the fit amplitude of signal events to the number of total muon decays. Improved and new limits in the mass region from 87.0 to 95.1 MeV/c^2 were set.

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