Experimental search for muonic photons

CHARM II Collaboration

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We report new limits on the production of muonic photons in the CERN neutrino beam. The results are based on the analysis of neutrino production of dimuons in the CHARM II detector. A 90% CL limit on the coupling constant of muonic photons, $\alpha_\mu/\alpha < (1.5 \div 3.2) \times 10^{-6}$ is derived for a muon neutrino mass in the range $m_{\nu_\mu} = (10^{-20} \div 10^5)$ eV. This improves the limit obtained from a precision measurement of the anomalous magnetic moment of the muon $(g-2)_\mu$ by a factor from 8 to 4.

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1 Introduction

The possible existence of massless vector particles (extra photons) coupled to the baryonic number [1] and to the leptonic number [2]–[7] has been under discussion for several decades. In particular, three types of these photons — electronic γ_e, muonic γ_μ, and tauonic γ_τ, — have recently been considered [3]. A possible search for muonic photons in high-energy neutrino experiments and calculations of the muonic photon flux and of event rates were published recently [8]. In the present paper we describe a search for γ_μ in the CERN SPS neutrino beam using the full data set of the CHARM II detector [9].

The beam of muonic neutrinos of the CERN SPS is formed in a 300 m long decay tunnel, where positive or negative pions and kaons produced in interactions of 450 GeV protons can be selected. The main decay modes are:

$$\pi^+ \to \mu^+ + \nu_\mu \ , \quad \pi^- \to \mu^- + \bar{\nu}_\mu \tag{1}$$

$$K^+ \to \mu^+ + \nu_\mu \ , \quad K^- \to \mu^- + \bar{\nu}_\mu \ . \tag{2}$$

The decay tunnel is followed by a shielding consisting of 185 m of iron, then 173 m of earth, another 20 m of iron, and 15 m of concrete [10]. This shielding absorbs muons and all secondary particles (hadrons and photons).

The production of muonic photons in the neutrino beam could be possible by two distinct mechanisms. The first mechanism is the internal radiation of muonic photons in the decays of pions and kaons:

$$\pi \to \mu + \nu_\mu + \gamma_\mu \tag{3}$$

$$K \to \mu + \nu_\mu + \gamma_\mu \ . \tag{4}$$

The yield of muonic photons from this process of internal bremsstrahlung is proportional to the coupling of muonic photons to the muon and to the muon neutrino α_μ. It has the typical spectrum of internal bremsstrahlung. Another important feature of internal bremsstrahlung is its logarithmic increase with the decreasing mass of the muon neutrino. Thus, in the lucky case of discovering muonic photons one can also measure the mass of the muon neutrino.

The second production mechanism is the external bremsstrahlung of muonic photons by muons on the iron nuclei of the neutrino beam muon shielding:

$$\mu + \mathrm{Fe} \to \mu + \gamma_\mu + \mathrm{Fe} \ . \tag{5}$$

This cross-section is also proportional to α_μ, but contrary to processes (3–4) it does not depend on the ν_μ mass.

A limit of the ratio of the coupling constant of the muonic photons α_μ to that of normal photons, $\alpha = 1/137$,

$$\alpha_\mu/\alpha < 1.2 \times 10^{-5} \; . \tag{6}$$

(at 90 % CL) has been derived [2,3] from precision measurements of the $(g-2)_\mu$ anomalous magnetic moment of the muon [11]. If they exist, muonic photons should increase the value of the anomalous magnetic moment of the muon $a_\mu = (g-2)/2$ by $\alpha_\mu/(2\pi)$. Using the experimental value of $a_\mu^{\rm exp} = (1165.9230 \pm 0.0084) \times 10^{-6}$ and the theoretical prediction $a_\mu^{\rm th} = (1165.9202 \pm 0.0020) \times 10^{-6}$ one obtains for the possible contribution of muonic photons $\delta(a_\mu) = (0.0028 \pm 0.0086) \times 10^{-6}$, which leads to the upper limit [Eq. (6)] at 90% CL. This value of α_μ is small enough to allow the muonic photons to penetrate the muon shielding of the neutrino beam without any important losses and is big enough to produce a sizeable amount of muon pairs in the Coulomb field of a nuclei with charge Z in the detector

$$\gamma_\mu + Z \to \mu^+ + \mu^- \; + Z \; . \tag{7}$$

The main background for the process (7) is the so-called trident process:

$$\nu_\mu + Z \to \nu_\mu + \mu^+ + \mu^- + Z \; . \tag{8}$$

The dimuon invariant mass distribution for tridents [8] is broader, and these dimuons have much larger p_t-unbalance than in process (7); this may help to separate process (7) from the trident background.

2 Experimental results

A search for muonic photons was made in the full data set obtained by the CHARM II detector in the neutrino Wide Band Beam (WBB) of the CERN 450 GeV SPS. It consists of a fine-grained tracking calorimeter with 420 glass plates as a target and plastic streamer tubes as a detector. After the calorimeter there is a muon spectrometer which consists of six magnetized iron toroids interspaced with drift chambers. The small longitudinal sampling of onehalf radiation length (4.8 cm of glass) and the fine transversal granularity of the streamer tubes (1 cm pitch) allows events with electromagnetic or hadronic activities at the vertex, down to a few hundred MeV to be rejected. The CHARM II neutrino detector is described in detail in Ref. [9].

In five years of data-taking a total flux of $20.0 \times 10^{11} \nu$ cm^{-2} was collected in neutrino and antineutrino beams. Since the muonic gamma production and detection are similar in both beams the data were combined.

Dimuon events with their vertex between plates 4–390 and transversal coordinates inside a square of ± 160 cm were selected. This target volume contains 1.63×10^{31} nuclei. Both muons were required to pass through the muon spectrometer with reconstructed muon momenta above 4 GeV/c. The muon pairs were required to have opposite charge and to have less than four additional hits in the first five planes after the vertex plane. Events with a dimuon invariant mass $W_{\mu^+\mu^-}$ of less than 0.5 GeV were retained.

The distribution of the missing transverse momentum with respect to the neutrino beam direction $p_t^{\rm miss} = |\overrightarrow{p_T^{\mu^+}} + \overrightarrow{p_T^{\mu^-}}|$ is shown in Fig. 1 for the selected events. The Monte Carlo prediction for muonic photons including the measurement errors is shown by the continuous curve. The expectation of the background from trident events is shown with dots.

In order to suppress the background from trident production and other sources we applied a cut on the missing transverse momentum of 0.12 GeV/c. After these cuts we are left with two candidates. The kinematical properties of the two selected candidates are presented in Table 1.

These two candidates are consistent with the background from trident events, diffractive charged pion production with decay in flight into a muon, and charm production decaying in the muon channel with low hadron energy.

The trigger and reconstruction efficiency of muonic gamma events was estimated with a realistic Monte Carlo simulation to be 0.09 ± 0.02.

The expected number of events for a muon neutrino mass of 10^{-10} eV and a muonic photon coupling of $\alpha_\mu/\alpha = 10^{-5}$ is 80 events/$10^{11}\nu$ cm^{-2} for internal bremsstrahlung and 20 events/$10^{11}\nu$ cm^{-2} for external bremsstrahlung [8]. The expected background from trident events [12] is 1.6 events. For a conservative upper limit we neglect other types of background. Subtracting 1.6 background events from two observed events we get a 90% CL limit of 4.1 events of muonic photons. For this case the upper limit on the coupling constant of muonic photons at the 90% CL is $\alpha_\mu/\alpha < 1.5 \times 10^{-6}$ for small values of neutrino mass $m_\nu = 10^{-20}$ eV.

In Fig. 2 the upper limit on the coupling constant of the muonic photon is presented as a function of the mass of the muon neutrino.

One can see that for all the allowed masses of the muon neutrino, below the direct limit of 170 keV [11], the CHARM II experiment improves the upper limit on the coupling constant from the $(g-2)_\mu$ experiment by a factor from

8 to 4.

3 Conclusions

The search for muon pairs from the conversion of muonic photons in the CHARM II detector allows us to put an upper limit on the coupling constant of the muonic photons as a function of the mass of the muon neutrino. For the high value of the neutrino mass $m_\nu =$ 170 keV the upper limit is $\alpha_\mu/\alpha < 3.2 \times 10^{-6}$, whilst for small values of the neutrino mass $m_\nu = 10^{-20}$ eV the upper limit is $\alpha_\mu/\alpha < 1.5 \times 10^{-6}$.

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Table 1: Kinematical quantities of the two selected candidates for muonic photons.

Table 1

Quantity	Event 1	Event2
Run number	1163	3717
Event number	105120	122326
Vertex plate	337	348
y-vertex	1 cm	–9 cm
z-vertex	–70 cm	–38 cm
p_{μ^-}	24.1 GeV/c	13.4 GeV/c
p_{μ^+}	6.7 GeV/c	13.9 GeV/c
θ_{μ^-}	0.0062	0.0107
θ_{μ^+}	0.0130	0.0052
$\pi - \phi_{\mu^+\mu^-}$	0.3342	0.3927
$M_{\mu^+\mu^-}$	0.352 GeV	0.301 GeV
Add.hits in 5 planes	0	0

Figure 1: Distribution of the selected dimuon events on the missing transversal momentum. The prediction for muonic photons is shown as a continuous curve. The dots show the Standard Model Monte Carlo prediction for trident background events.

Figure 2: Upper limit on the muonic photon coupling constant as a function of the muon neutrino mass.

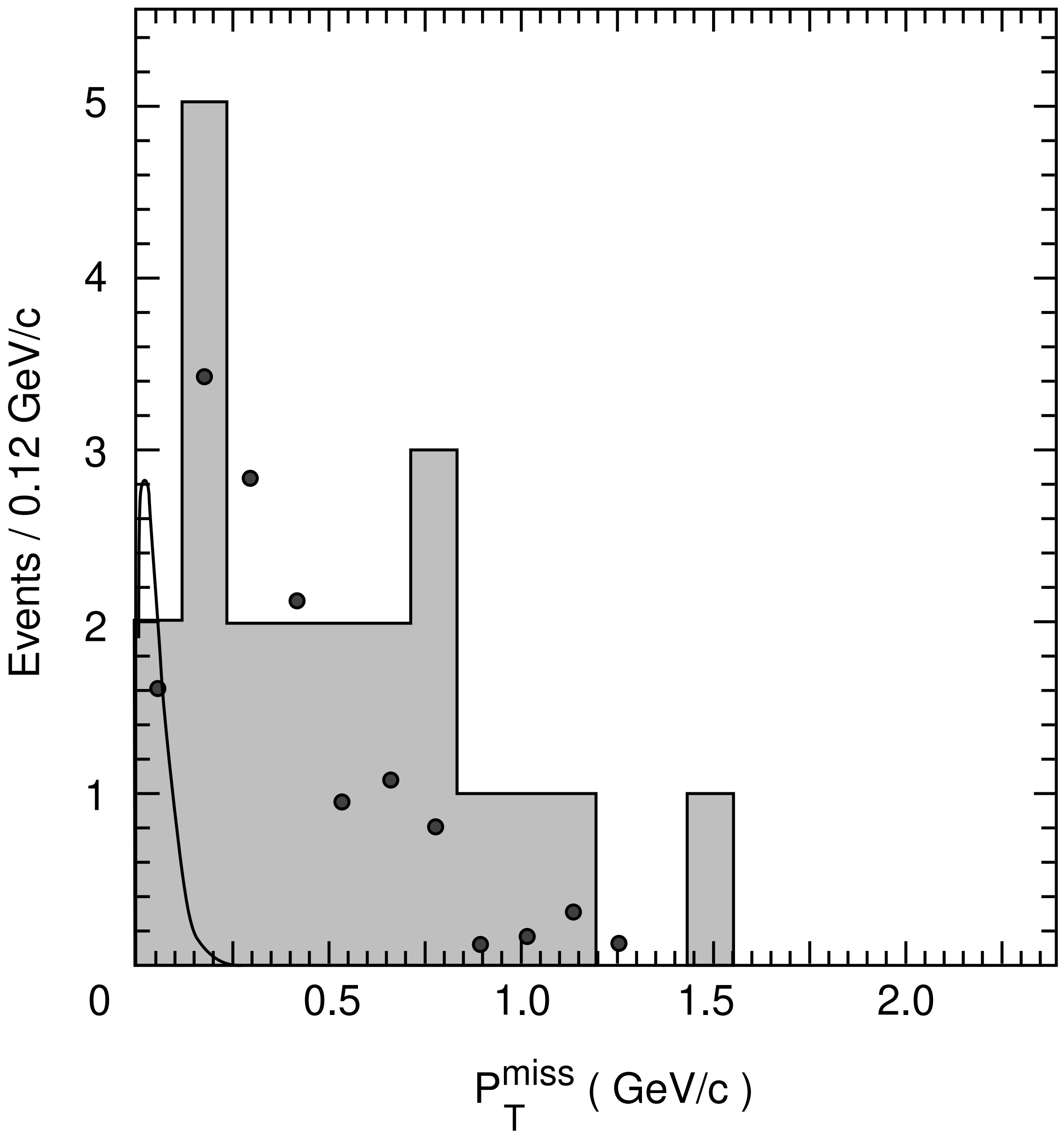

Figure 1

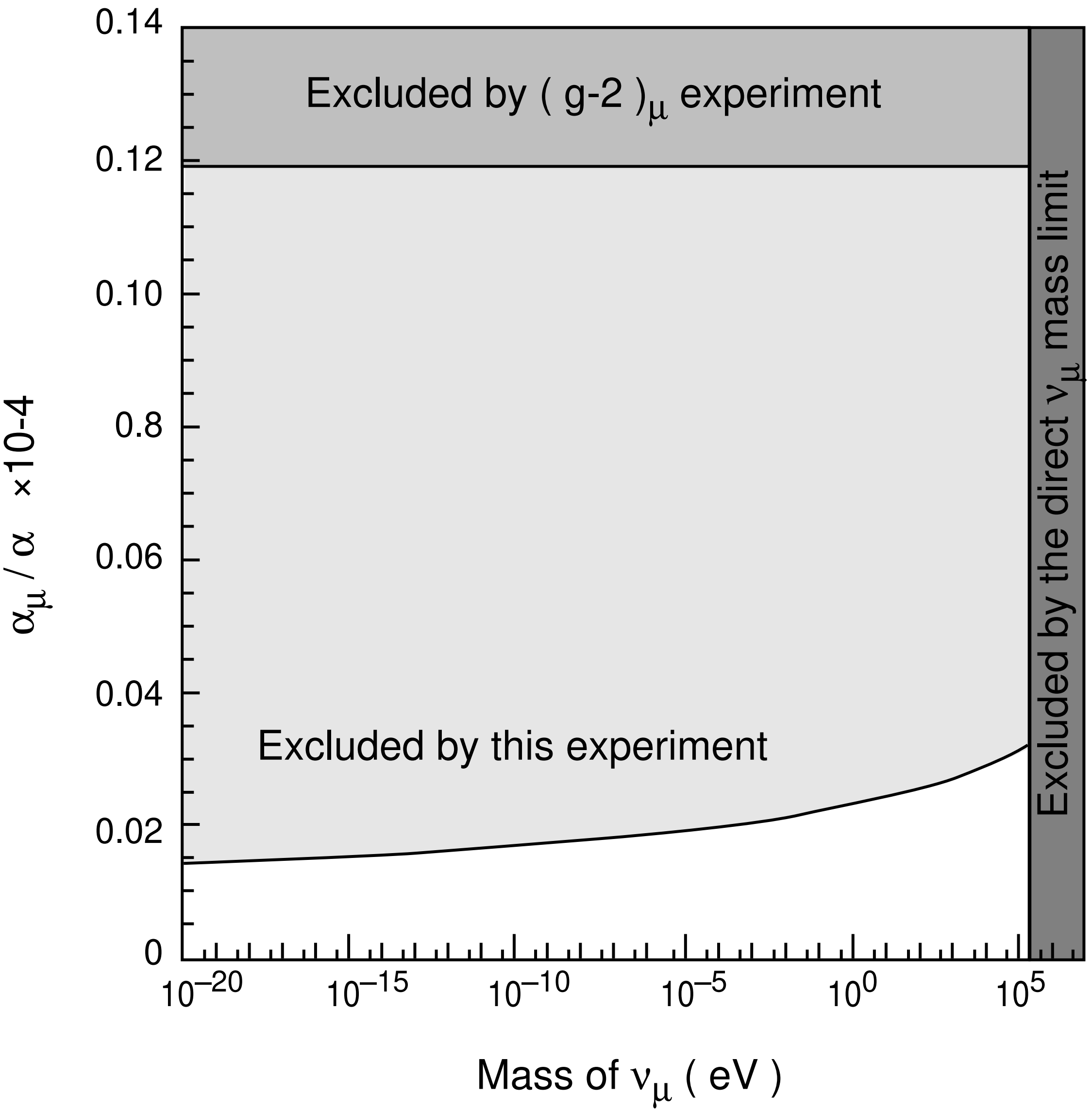
Excluded by (g-2)$_\mu$ experiment
Excluded by this experiment
Excluded by the direct ν_μ mass limit
0.14
0.12
0.10
0.8
0.06
0.04
0.02
0
$\alpha_\mu / \alpha \times 10\text{-}4$
10^{-20}
10^{-15}
10^{-10}
10^{-5}
10^{0}
10^{5}
Mass of ν_μ (eV)

Figure 2