Probing lepton flavour violation with NA64 experiment
Исследование нарушения лептонного аромата в эксперименте NA64

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Нейтринные осцилляции являются доказательством нарушения закона сохранения аромата нейтральных лептонов, но в секторе заряженных лептонов такой процесс всё ещё не был обнаружен. Поиск такого нарушения среди заряженных лептонов является одной из наиболее интересных задач современной физики. Один из экспериментов, направленных на поиск данного процесса, NA64 - эксперимент на фиксированной мишени в ЦЕРНе. В статье рассматривается возможность поиска конверсии между заряженными лептонами. Приведены предварительные оценки чувствительности NA64 в электронном и мюонном пучках. Также обсуждается вероятность наблюдения процесса в эксперименте на основе текущей статистики.

Neutrino oscillations are evidence of flavor violation of neutral leptons, but such a process has not yet been discovered in the sector of charged leptons. The search for flavor violation of charged leptons is one of the most interesting problems in modern physics. One of the experiments aimed at searching for this process, NA64, is a fixed target experiment at CERN. In the article is discussed the possibility of searching for conversion between charged leptons. Preliminary estimates of the sensitivity of NA64 in electron and muon beams are presented. The probability of observing the process in an experiment based on current statistics is also discussed.

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Introduction

The phenomenon of Lepton Flavor Violation (LFV) is of interest in the study of the physics of flavor and its origin. Charged quarks mix their families according to the Cabibbo–Kobayashi–Maskawa matrix, and neutrinos, neutral leptons, mix through neutrino oscillations according to the Pontecorvo–Maki–Nakagawa–Sakata matrix. Unlike quarks and neutrinos, charged lepton mixing does not occur in the Standard Model (SM), even

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Process	Experiment	Branching ratio
$\mu \to e\gamma$	MEG (2016) [2]	4.2×10^{-13}
$\mu \to e\bar{e}e$	SINDRUM (1988) [3]	1.0×10^{-12}
$\mu N \to eN$	SINDRUM-II (2006) [4]	$6.1(7.1)\times10^{-13}$ Ti (Au)
$\tau \to e\gamma$	BaBar (2006) [5]	3.3×10^{-8}
$\tau \to \mu\gamma$	BaBar (2006) [5]	4.4×10^{-8}
$\tau \to eee$	Belle(2010) [6]	2.7×10^{-8}
$\tau \to \mu\mu\mu$	Belle(2010) [6]	2.1×10^{-8}
$\tau \to \mu ee$	Belle(2010) [6]	1.8×10^{-8}
$\tau \to e\mu\mu$	Belle(2010) [6]	2.7×10^{-8}
$\tau \to \mu\mu\mu$	Belle(2010) [6]	2.1×10^{-8}

Table 1. Current experimental bounds with 90% C.L. of CLFV processes for muons and some taus.

if neutrino mixing is taken into account. The probability of the transition among charged leptons, or Charged Lepton Flavor Violation (CLFV), is below $<$O(10^{-50}) [1]. However, many models beyond the SM (BSM) predict lepton conversion that doesn't conserve lepton family number.

The CLFV process of muon and tau leptons have been searched for a few decades [2–6]. Most experiments to search for the CLFV process use muon beams. Experimental bounds of the muon to electron conversion have better current sensitivity. For $\tau \to e(\mu)$ the upper limits are lower, but the phase space is larger. At the NA64 experiment, the research program is carried out using 100 GeV electron (NA64e) [7] and 160 GeV muon (NA64μ) [8] beams. This makes it possible to study the conversion of a lepton in both beams, for example, a muon or an electron to tau [9] and a muon and an electron into each other [10–12] in deep inelastic scattering (DIS) reactions. Current experimental upper limits of branching ratio suitable for our study are given in the Table 1.

The NA64 experiment was designed primarily to search for light dark photon or sub-GeV dark gauge boson Z′ in events with missing energy. Another physics goals are to explore light dark matter models and extensions of the BSM, such as axion-like particles, as well as test existing anomalies

Possibility of the CLFV study at NA64

Cross section of the $l \to l'$ conversion ($l = \tau, \mu(e)$) on a nucleus can be represented [9] in the form

$$\sigma(l + (A,Z) \to l' + X) = \sum_{I,if,XY} \frac{Q^A_{I,if,XY}}{\Lambda^4_{I,if,XY}} \tag{1}$$

where A, Z are mass and atomic numbers, $I = S, V, T$ are scalar, vector or tensor operators, $i, f = u, d, s, c, b, t$ are quark flavors and X, Y are left and right chiralities. $Q^A_{I,if,XY}$ is a double moment of quark parton distribution functions (PDFs) and $\Lambda^4_{I,if,XY} \equiv \Lambda$ is a mass scale parameter where new physics effects appear. Estimation of limits on the parameter Λ for $l \to l$ conversion for scalar, vector and tensor interactions were derived in [9]:

$$\mathrm{S-type}: \Lambda^{el} \geq 0.04 - 0.24 \text{ TeV}, \Lambda^{\mu l} \geq 0.56 - 3.05 \text{ TeV}, \tag{2}$$

$$\mathrm{V-type}: \Lambda^{el} \geq 0.05 - 0.44 \text{ TeV}, \Lambda^{\mu l} \geq 0.78 - 5.60 \text{ TeV}, \tag{3}$$

$$\mathrm{T-type}: \Lambda^{el} \geq 0.09 - 0.66 \text{ TeV}, \Lambda^{\mu l} \geq 1.45 - 10.06 \text{ TeV}. \tag{4}$$

Note that when estimating these parameters, the lepton masses were taken as zero compared to the large value of the initial lepton energy.

There are no known experimental limits for the $\mu \to \tau$ process yet. In the ZEUS experiment at HERA, constraints on the Λ for the $e \to \tau$ conversion [13] was obtained :

$$\Lambda^{e\tau}_{ZEUS} \geq 0.41 - 1.86 \text{ TeV}. \tag{5}$$

To estimate the probability of CLFV process at the NA64, the minimal values of the theoretical Λ values were taken from (2)–(4). The probability of the process at a step of 1 mm in a lead target depending on the beam energy for a 100 GeV electron beam is shown in Fig. 1. To simulate the number of events, the selection criteria used in NA64e to search for rare events were applied. The selection criteria were based on the following conditions: (i) The incoming track should have the momentum 100 ± 10 GeV; (ii) the detected synchrotron radiation (SR) energy should be within the range $\simeq 1-100$ MeV emitted by SR and in time with the trigger; (iii) single-hit per tracker before target; (iv) $E_{miss} = E_e - E_{ECAL} \geq 50$ GeV; (v) energy compatible with a minimum ionizing particle in the hadronic calorimeters and VETO.

Expected NA64 bound on minimal value of Λ is 0.13 TeV. For the statistics 2016 - 2022 with 10^{12} electrons on target (EOT) about 100 events for the vector operators can be used as candidate events. The initial candidate events (before cuts) were requested to have the missing energy $E_{miss} \gtrsim 50$ GeV.

The $\mu \to \tau(e)$ transition probability were calculated similarly to electron conversion (see Fig. 2). The NA64μ selection criteria were used for further simulation. It is only possible to consider $\mu \to \tau$ with subsequent decay $\tau \to \mu\nu\nu$ as a muon in the final state is required in the standard event selection. This simulation showed sensitivity of Λ is 0.095 TeV for the run 2022 with 2×10^{10} MOT (muons on target). The search for conversion requires some change in selection, for this reason it should be done as a separate analysis and not a direct recalculation.

Conclusion

Search for charged lepton conversion is one of the opportunity to explore new physics. The study of lepton conversion was started on the NA64 experiment. The probability of observing the process in the experiment on the

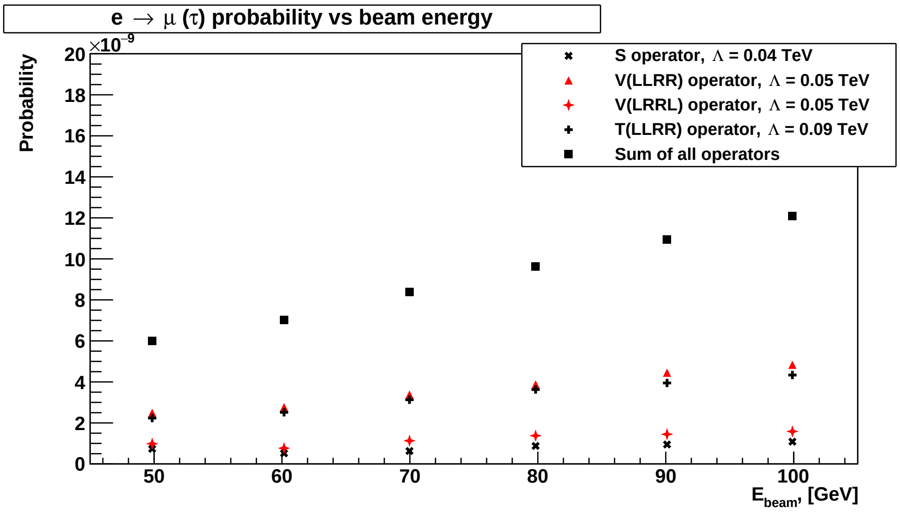

Fig. 1. The probability of e $\to \mu(\tau)$ conversion as a function of electron energy for scalar, vector (red points), tensor operators and their sum.

current statistics was studied. The expected sensitivity of the experiment to the Λ parameter is estimated for both beams. It is necessary to change the strategy for analysing the $\mu \to \tau(e)$ transition.

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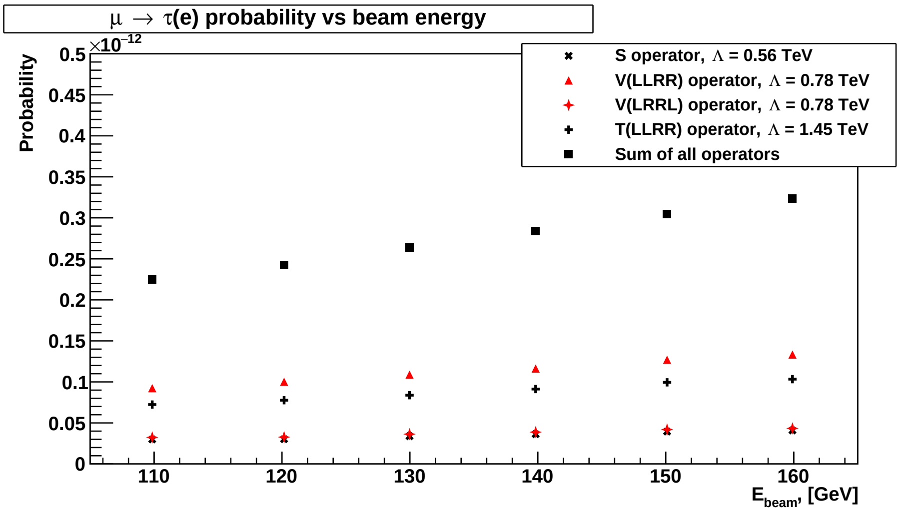

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