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Sensitivity for new light, long-lived flavor-changing scalar bosons at DUNE and NA64μ

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Neutrino-oscillations motivate the search for new beyond-the-Standard-Model particles that might manifest as light scalar bosons mediating lepton-flavor-changing (LFC) interactions. In a certain class of theories, the light scalar boson could be produced at accelerator neutrino beams, where a high-intensity, high-energy muon flux is expected. An example of such a facility is the Deep Underground Neutrino Experiment (DUNE) using the high-power proton beam at LBNF. If such a particle exists, it could be produced after the DUNE LBNF beam target. If it is long-lived, it could travel a few hundred meters, and it could be detected at the DUNE Liquid Argon Near Detector. In parallel, the existence of such a new LFC scalar boson can also be tested using the 160-GeV muon beam at the fixed target NA64mu experiment at CERN, in a complementary way. In this talk, light long-lived LFC boson signatures and projected sensitivities at DUNE and NA64mu will be presented.

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Observations in cosmology and astrophysics imply the existence of a Dark Sector with new particles that could weakly couple to Standard Model (SM) particles [1]. Neutrino oscillations coupled with non-zero neutrino masses provide an experimental evidence of lepton-flavor violation. Furthermore, the existing discrepancy between the measured [2] and expected [3, 4] value of the muon anomalous magnetic moment provides a strong motivation for new physics searches with muons [5].

In this work [6], we study the sensitivity potential of μ-on-target experiments to new physics using a charged lepton flavor violation (CLFV) benchmark model, which uses a light, scalar boson associated with $\mu - \tau$ conversion. A class of new theories [7] proposes the search for CLFV, which is heavily suppressed in the SM. The effective Lagrangian interaction terms describe the coupling of the new scalar field with leptons,

$$\mathcal{L}_I = \phi\bar{\mu}(g_V + g_A\gamma^5)l + \phi^*\bar{l}(g_V^* - g_A^*\gamma^5)\mu \tag{1}$$

We explore two different experimental approaches to search for such a CLFV process:

- The proton beam at Fermilab, which is used to produce the neutrino beam for the Deep Underground Neutrino Experiment (DUNE) will produce a high-intensity muon beam dumped in an steel absorber. The system could be used to search for scalar boson particles at the Near Detector.
- The NA64μ experiment at CERN uses a 160-GeV energy muon beam with an active target to search for excess events with missing energy and momentum as a probe of new physics.

The DUNE [8] neutrino beam is produced by a 60-120 GeV proton beam hitting a graphite target [8], after which hadrons decay to leptons and neutrinos in a $\sim$ 220-m-long decay pipe. At the end of the pipe a dedicated $\sim$ 30-m-long stainless-steel structure acts as a beam-dump to stop all muons 300 m upstream from the Near Detector. New particles produced in the beam-dump could be detected at the Near Detector.

The NA64μ [9] is a fixed-target experiment at CERN looking for new particles of Dark Matter and portal interactions produced in electromagnetic showers. The experiment uses the 160-GeV muon beam from the CERN SPS. Beam scintillators, veto counters, low material-budget trackers and dipole magnets allow to precisely constrain the momentum of the incoming 160-GeV muons impinging on an active target. Missing energy/momentum carried away by the produced hypothetical, long-lived ϕ boson, leaves a scattered muon as experimental signature.

ϕ bosons are generated by the μ-on-target process, and a fraction of them decay and could be detected. The number of such signal events is

$$N_\phi = \int dE_\phi \Phi_\phi(E_\phi) \times \frac{l_{\text{det}}}{\gamma\beta c\tau_\phi}, \tag{2}$$

where $l_{\text{det}}/\gamma\beta c\tau_\phi$ is the fraction of bosons decaying in flight to produce a signal in the detector, and $\Phi_\phi(E_\phi)$ is the flux of ϕ bosons

$$\Phi_\phi(E_\phi) = \int dE\Phi_\mu(E) \times \int_{E_{\text{min}}}^{E} dE_l \frac{n_A}{-dE/dl} \int_0^{\theta_{\text{det}}} d\theta_\phi \sin\theta_\phi \frac{d^2\sigma(E_l, E_\phi)}{dE_\phi d\cos\theta_\phi}. \tag{3}$$

$\Phi_\mu(E)$ is the flux of the muon beam as a function of energy, n_A is the number of target atoms per volume, E_l is the muon energy after traveling a length l in the target and losing energy according to the stopping power $-dE/dl$, $E_{\rm min}$ is the energy of the muon at the end of the target, and $\theta_{\rm det}$ is the angular acceptance of the detector. In NA64μ, the production target thickness is small and the muon energy loss can be neglected. As a result we use the following expression to estimate the ϕ boson flux,

$$\Phi_\phi(E_\phi) = l_{\rm target} n_A \int dE \Phi_\mu(E) \int_0^{\theta_{\rm det}} d\theta_\phi \sin\theta_\phi \frac{d^2\sigma(E, E_\phi)}{dE_\phi d\cos\theta_\phi}, \quad (4)$$

where $l_{\rm target}$ is the thickness of the target.

The production cross-section for the ϕ boson [14] as a function of the incoming lepton is steeply rising above a threshold that is constrained by the tau mass. Assuming $m_\phi \simeq m_\tau$, the threshold for the production is given by $E_\mu > [(2m_\tau + m_N)^2 - m_\mu^2 - m_N^2]/2m_N \simeq 3.8$ GeV for a Pb target.

We estimated the sensitivity potential of DUNE and NA64μ to such a benchmark CLFV process proposed in [7]. We find that both experiments have complementary potential to cover a significant portion of the benchmark model parameter space, (m_ϕ, g_V), see Fig. 1. NA64μ with an optimized setup (a 5-m long target) could probe the coupling parameter down to $g_V \simeq 3 \times 10^{-3}$ in a few years of data taking, completely covering the muon $g_\mu - 2$ preferred region and thus providing a similar projected reach as SHiP. DUNE will also be able to cover unexplored parts of the parameter space, although requiring 10-20 years of data taking, but potentially improving on the obtained constraints from NuTeV.

Is it noted that a similar setup of NA64μ is capable of searching for other new scalar particle candidates using the same muon beam. The proposed Muon Missing Momentum (M^3) experiment at Fermilab [10] also plans to probe new physics with a dedicated muon beam. A number of experiments also have the potential to search for hidden-sector scalar particles, such as SHADOWS [11], HIKE [12], and ATLAS [13].

References

[1] G. Lanfranchi, M. Pospelov, and P. Schuster, The Search for Feebly Interacting Particles, Annual Review of Nuclear and Particle Science **71**, 279 (2021).

[2] B. Abi *et al.* (Muon g-2 Collaboration), Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm, Phys. Rev. Lett. **126**, 141801 (2021).

[3] T. Aoyama *et al.*, The anomalous magnetic moment of the muon in the Standard Model, Physics Reports **887**, 1 (2020).

[4] S. Borsanyi *et al.*, Leading hadronic contribution to the muon magnetic moment from lattice QCD, Nature **593**, 51 (2021).

[5] C.-Y. Chen, M. Pospelov, and Y.-M. Zhong, Muon beam experiments to probe the dark sector, Phys. Rev. D **95**, 115005 (2017).

[6] B. Radics, L. Molina-Bueno, L. Fields, H. Sieber and P. Crivelli, EPJ C **83**, 775 (2023).

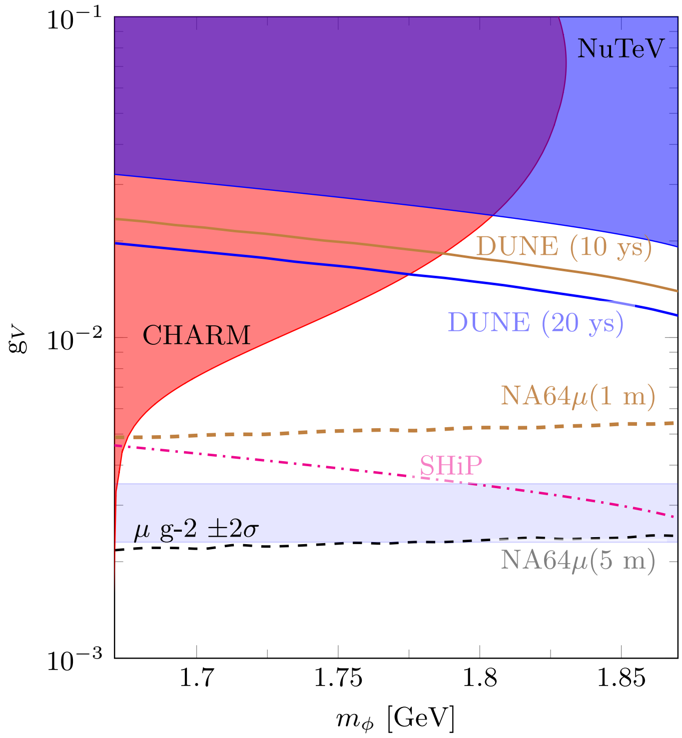

Figure 1: Sensitivity potential of DUNE and NA64μ shown as exclusion limits in the coupling strength vs mass parameter space. The limits are given for the case of no detected signal found at these experiments after a given exposure, see explanation in the text.

[7] Y. Ema, Z. Liu, K-F Lyu and M. Pospelov *JHEP* **135** (2023).

[8] B. Abi *et al.* (DUNE collaboration) (2020) arXiv:2002.03005 [hep-ex].

[9] H. Sieber *et al.*, Phys. Rev. D **105** (2022) 052006.

[10] Y. Kahn, G. Krnjaic, N. Tran, and A. Whitbeck, JHEP 09, 153 (2018), arXiv:1804.03144 [hep-ph].

[11] M. Alviggi *et al.*, CERN-SPSC-2022- 030/SPSC-I-256 (2022).

[12] E. Cortina Gil *et al.* (HIKE), HIKE, High Intensity Kaon Experiments at the CERN SPS: Letter of Intent, (2022), arXiv:2211.16586 [hep-ex].

[13] I. Galon, E. Kajamovitz, D. Shih, Y. Soreq, and S. Tarem, Phys. Rev. D **101**, 011701(R) (2020).

[14] J. D. Bjorken *et al.*, Phys. Rev. D **80** (2009) 070518.

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