Summary of Muon Beam-Dump Searches

Chien-Yi Chen, Maxim Pospelov, and Yi-Ming Zhong

The persistence of several anomalies in low-energy muon experiments, such as the muon anomalous magnetic moment (a_μ) [1] and the muonic hydrogen Lamb shift [2–4] might be implications of new light particles beyond the Standard Model.

A minimal model to explain the a_μ anomaly can be achieved by introducing a new light scalar S that predominantly couples to the muons. The model is characterized by two parameters: the mass of the dark scalar m_S, and its coupling to the muons g_μ. We further restrict the scalar-quark couplings to be zero to evade constraints from meson decays and the dark scalar-charged lepton couplings to be proportional to the lepton masses (model A) or to be zero for electrons and taus (model B). References [5] and [6] have discussed the phenomenology of such model and choose different types of UV complete scenarios with vector-like fermions and multiple Higgs states, respectively. Within the mass range around MeV$\leq m_S \leq 2m_\mu$, the coupling $g_\mu \sim \mathcal{O}(10^{-4})$ is preferred to explain the a_μ anomaly. In this part of the parameter space, S dominantly decays into e^+e^- ($\gamma\gamma$) for model A (model B) with a displaced decay length of ~ 25 cm (~ 20 m).

Muon beam-dump experiments can effectively probe the dark scalars with sizable displaced decays. The dark scalars can be abundantly produced through bremsstrahlung of the intensive incident muons. We propose two particular experimental setups:

1. NA64 missing momentum search: NA64 is a fixed-target experiment at CERN [7, 8]. It can be run in the muon mode with a beam energy of 160 GeV. The signal of the search will be a recoiled muon with large missing energy ($\gtrsim 50$ GeV) together with a negligible amount of energy deposited in the electric and hadronic calorimeters. We sketch the setup in Fig. 1 (left) and list relevant parameters in Tab. I.

2. Fermilab displaced decay search: a muon beam source with energy around 3 GeV for precision measurements [9] is available at Fermilab. We intend to use the existing setup at Fermilab with minimal modification to probe the light dark scalar S. The signal would be a displaced vertex reconstructed from electron/photon trackers or anomalous energy deposit with a sizable distance. Relevant setup and parameters are shown in Fig. 1 (right) and Tab. I, respectively.

	NA64-type	Fermilab
Incident muon beam energy, $E_{\mu,\mathrm{beam}}$	160 GeV	3 GeV
Total number of incident muons, N_μ	8×10^{12} (3-month run)	3×10^{14} (1-year run)
Target material	Tungsten (W)	Lead (Pb)
Atomic number density, n_{atom}	$3.3 \times 10^{22}/\mathrm{cm}^3$	$6.3 \times 10^{22}/\mathrm{cm}^3$
Muon energy loss per unit length, $\langle \mathrm{d}E_\mu/\mathrm{d}y \rangle$	12.7×10^{-3} GeV/cm	22.1×10^{-3} GeV/cm
Target Length, L_{tg}	0.2 m	1.5 m
Detector Length, L_{dec}	5 m	4.5 m
Min fiducial range for the decay, z_{min}	$L_{\mathrm{tg}} + L_{\mathrm{dec}} - \Delta y(E_\mu)$	$L_{\mathrm{tg}} - \Delta y(E_\mu)$
Max fiducial range for the decay, z_{max}	∞	$L_{\mathrm{tg}} + L_{\mathrm{dec}} - \Delta y(E_\mu)$

TABLE I: Parameters for the proposed muon beam-dump experiments at NA64 and Fermilab.

We project exclusions with 95% confidence level (CL) for the two proposed experiments for model A and B in Fig. 2. The orange and cyan contours represent constraints from NA64 and Fermilab respectively. For model A, muon beam-dump constraint is largely covered by existing electron beam-dump searches except for the range of 50 MeV $\leq m_S \leq 2m_\mu$ with $g_\mu \sim 10^{-4}$. As for model B, *both* muon beam-dump experiments at Fermilab and NA64 can place strong limits and completely exclude the parameter space favored to explain a_μ anomaly below the di-muon threshold. For the NA64 setup, we can also explore models with S couples to a light fermionic dark matter χ. The result is shown in Fig. 3 with a particular choice of the dark matter mass m_χ and its coupling g_χ.

[1] Muon g-2, G. W. Bennett *et al.*, Phys. Rev. **D73**, 072003 (2006), hep-ex/0602035.

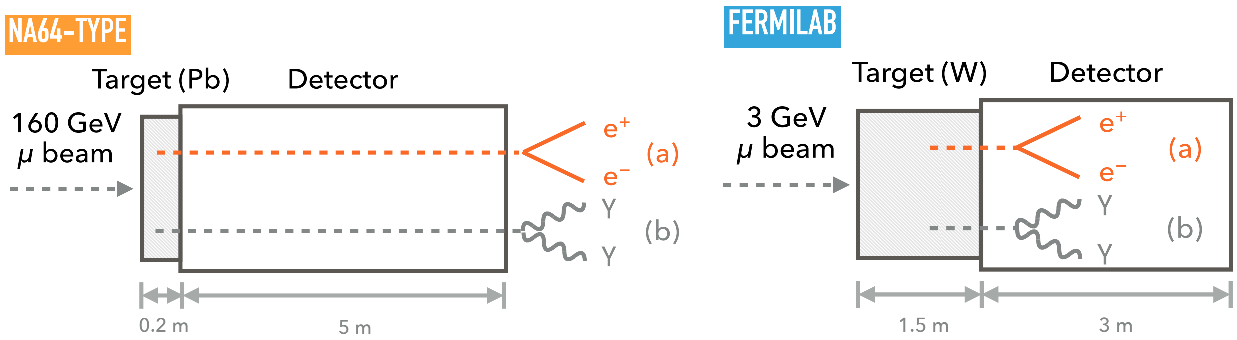

FIG. 1: Setups for muon beam-dump experiments at NA64 (left) and Fermilab (right). For the NA64 experiment, the muon beam energy is ∼160 GeV and the target material is lead. We focus on the missing energy searches with S decays into e^+e^- or $\gamma\gamma$ (also for decays to fermionic dark matter pairs $\chi\bar{\chi}$). For Fermilab experiment, the muon beam energy is ∼3 GeV and the target material is tungsten. We focus on the decays with displaced vertices of S to e^+e^- or $\gamma\gamma$. The lengths of the targets and the detectors are shown in the plot and listed in Tab. I.

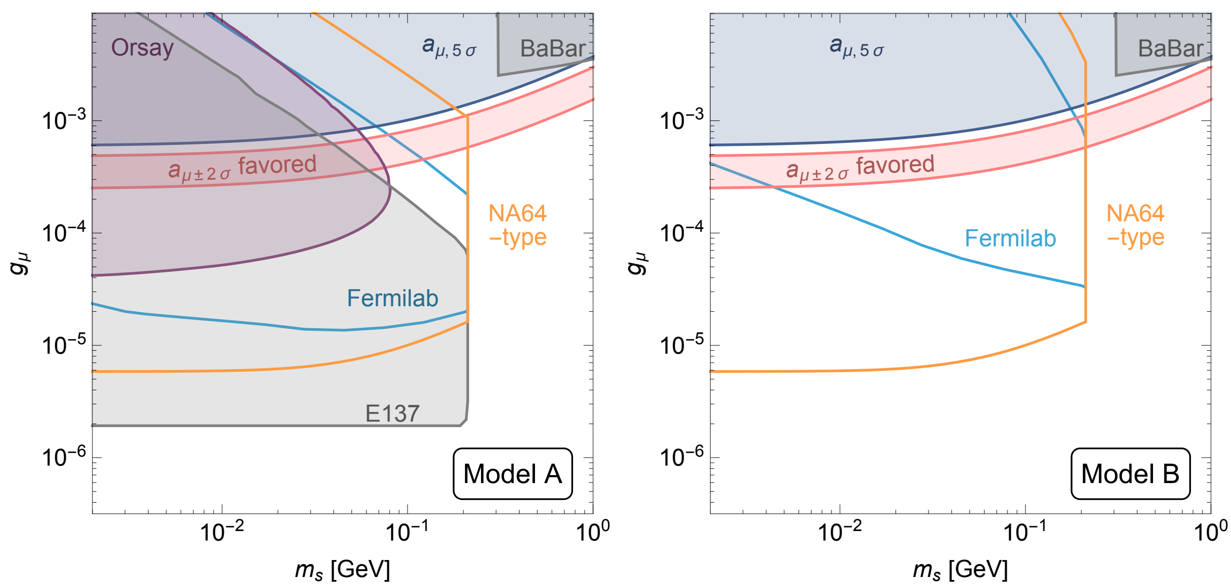

FIG. 2: 95 % CL prospects and constraints in the m_S vs. g_μ plane for model A (left) and model B (right) respectively. The orange and cyan contours show the projected constraints from NA64-type and Fermilab muon beam-dump experiments respectively. We include the 2σ CL favored region and the 5σ CL exclusions of a_μ [10, 11], and BaBar constraints [12] for both models. For model A (left), we also include constraints from Orsay [13] and E137 [14].

[2] R. Pohl *et al.*, Nature **466**, 213 (2010).
[3] A. Antognini *et al.*, Science **339**, 417 (2013).
[4] CREMA, R. Pohl1 *et al.*, Science **353**, 669 (2016).
[5] C.-Y. Chen, H. Davoudiasl, W. J. Marciano, and C. Zhang, (2015), 1511.04715.
[6] B. Batell, N. Lange, D. McKeen, M. Pospelov, and A. Ritz, (2016), 1606.04943.
[7] S. Andreas *et al.*, (2013), 1312.3309.
[8] S. N. Gninenko, N. V. Krasnikov, and V. A. Matveev, Phys. Rev. **D91**, 095015 (2015), 1412.1400.
[9] A. Chapelain, The Muon g-2 experiment at Fermilab, 2017, 1701.02807.
[10] Muon g-2, J. Grange *et al.*, (2015), 1501.06858.
[11] J-PARC g-2, T. Mibe, Chin. Phys. **C34**, 745 (2010).
[12] BaBar, J. P. Lees *et al.*, Phys. Rev. **D94**, 011102 (2016), 1606.03501.
[13] M. Davier and H. Nguyen Ngoc, Phys. Lett. **B229**, 150 (1989).
[14] J. D. Bjorken *et al.*, Phys. Rev. **D38**, 3375 (1988).

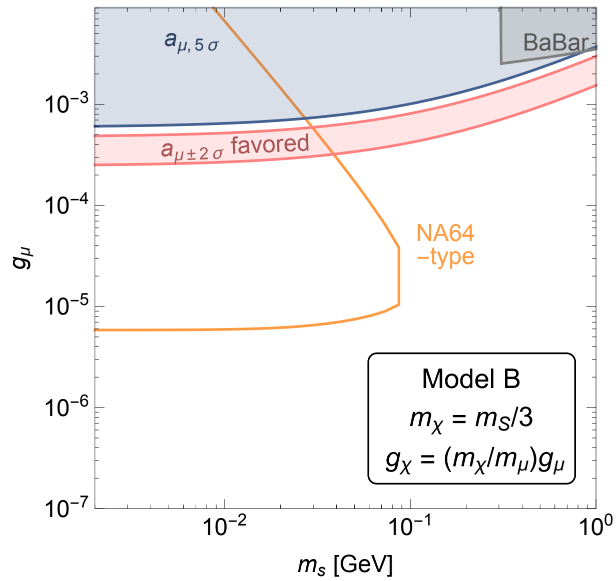

FIG. 3: 95 % CL prospects in the m_χ vs. g_χ plane for NA64 missing momentum search for light dark matter. Based on the model B, we introduce a light fermionic dark matter χ that couples to S with a coupling g_χ. In addition, we restrict $m_\chi = m_S/3$ and $g_\chi = (m_\chi/m_\mu)g_\mu$ to project the parameter space. We also show the a_μ favored regions and exclusions as before.