

## First Results in the Search for Dark Sectors at NA64 with the CERN SPS High Energy Muon Beam

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We report the first search for dark sectors performed at the NA64 experiment employing a high energy muon beam and a missing energy-momentum technique. Muons from the M2 beamline at the CERN Super Proton Synchrotron with a momentum of 160 GeV/c are directed to an active target. The signal signature consists of a single scattered muon with momentum  $< 80$  GeV/c in the final state, accompanied by missing energy, i.e., no detectable activity in the downstream calorimeters. For a total dataset of  $(1.98 \pm 0.02) \times 10^{10}$  muons on target, no event is observed in the expected signal region. This allows us to set new limits on the remaining  $(m_{Z'}, g_{Z'})$  parameter space of a new  $Z'$  ( $L_\mu - L_\tau$ ) vector boson which could explain the muon  $(g - 2)_\mu$  anomaly. Additionally, our study excludes part of the parameter space suggested by the thermal dark matter relic abundance. Our results pave the way to explore dark sectors and light dark matter with muon beams in a unique and complementary way to other experiments.

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In this Letter, we present the first results of the NA64 experiment muon program, dubbed NA64 $\mu$ , employing a novel missing energy-momentum technique to look for sub-GeV gauge bosons coupled to muons [1]. Dark sectors (DS) are a promising paradigm to address open questions of the standard model (SM) such as the origin of dark matter (DM) [2]. In this framework, one postulates a new sector of

particles below the electroweak scale that are not charged under the SM but could have a phenomenology of their own [3–8]. In addition to gravity, the interactions between DS states and the SM could proceed through portal mediators. If one assumes that DM is made of the lightest stable DS particles, the resulting feeble interaction between the two sectors can be compatible with cosmological observations and, thus, would accommodate a solution to the DM problem [9–12]. DS models became an extremely fertile domain of exploration with many different techniques tackling the very large parameter space of possible DM candidates (see e.g., for recent reviews [13–16]). From the broad DS landscape, many scenarios suggest new feeble interactions with muons mediated by scalar, pseudoscalar or vectorlike particles. The new feebly interacting mediator,  $X$ , could be produced in the bremsstrahlung-like reaction of 160 GeV/ $c$  muons with a target ( $N$ ) followed by its subsequent invisible decay,  $\mu N \rightarrow \mu NX$ ;  $X \rightarrow$  invisible (see Fig. 1).

Even though our results are model independent, to demonstrate the potential of our experiment to search for DS, we use as a benchmark scenario a new sub-GeV  $Z'$   $L_\mu - L_\tau$  boson arising by gauging the difference of the lepton number between the muon and tau flavor. Interestingly, this model could explain the origin of DM and, at the same time, the long-standing  $g - 2$  muon anomaly in terms of new physics [17]. The current bounds for  $m_{Z'} > 2m_\mu$  arise from direct searches, sensitive to the kinematically allowed visible decay channel  $Z' \rightarrow \mu^+\mu^-$  [18–21]. Neutrino scattering experiments [22,23] and missing energy searches through  $Z' \rightarrow \bar{\chi}\chi$  [24,25] provide constraints for  $m_{Z'} < 2m_\mu$ . The lower bound is set through the  $Z'$  contribution to the radiation density of the Universe through  $\Delta N_{\text{eff}}$ , with its value being defined from both the CMB spectrum [12] and big Bang nucleosynthesis (BBN) [21,26,27] to  $m_{Z'} > 3\text{--}10$  MeV [28] and  $g_{Z'} \sim 10^{-4}\text{--}10^{-3}$ . If a  $Z'$  boson exists, it could be produced in the reaction depicted in Fig. 1,  $\mu N \rightarrow \mu NZ'$ ;  $Z' \rightarrow$  invisible. In the *vanilla* model, the  $Z'$  can only decay invisibly to neutrinos,  $Z' \rightarrow \bar{\nu}\nu$ , while in extended models, it can additionally decay to DM candidates,  $Z' \rightarrow \bar{\chi}\chi$ , [29–31]. For a value of  $g_\chi = 5 \times 10^{-2}$  one can accommodate in the same parameter space the muon  $g - 2$  and the DM relic prediction [32]. For a viable DM candidate (below  $m_\chi < 1$  GeV)  $g_\chi \gg g_{Z'}$ , the branching ratio to DS invisible final states can be assumed to be  $\text{Br}(Z' \rightarrow \bar{\chi}\chi) \simeq 1$ , while the ones in visible states ( $Z' \rightarrow \mu^+\mu^-$ ) and neutrinos can be neglected.

The search for signal events in NA64 $\mu$  consists of the detection of a primary beam muon with a momentum of 160 GeV/ $c$  in the initial state and a single muon that scatters off the active target with missing momentum  $> 80$  GeV/ $c$  in the final state, accompanied by missing energy, i.e., no detectable electromagnetic or hadronic activity in the downstream calorimeters. The working

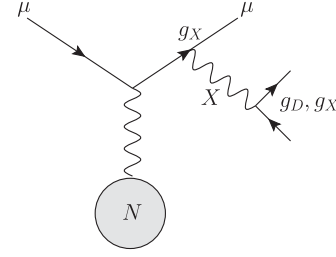


FIG. 1. Production of a generic  $X$  boson through a bremsstrahlunglike reaction, followed by its prompt invisible decay,  $\mu N \rightarrow \mu NX$ ;  $X \rightarrow$  invisible. The interaction strength of the  $X$  boson with SM particles and DM candidates is regulated by the couplings  $g_X$  and  $g_D$  respectively. The nucleus is assumed to recoil elastically leaving only the outgoing muon and invisible energy in the detector.

principle and experimental setup are schematically shown in Fig. 2. The 160 GeV/ $c$  muons are delivered by the M2 beamline at the CERN SPS accelerator [33]. The beam optics comprises a series of quadrupoles (QPLs) focusing the beam before the target with a divergency  $\sigma_x \sim 0.9$  and  $\sigma_y \sim 1.9$  cm [34]. The incoming muon momentum is reconstructed through a magnetic spectrometer (MS1) consisting of three 5 T · m bending magnets, together with four  $8 \times 8$  cm<sup>2</sup> micromesh gas detectors (micromegas, MM<sub>1–4</sub>), two  $20 \times 20$  cm<sup>2</sup> straw tubes chambers (ST<sub>5,4</sub>) and six variable-sized scintillator (Sc) hodoscopes, the beam momentum stations (BMS<sub>1–6</sub>). The obtained momentum resolution is  $\sigma_{p_{\text{in}}}/p_{\text{in}} \simeq 3.8\%$ . The target is an active electromagnetic calorimeter (ECAL) composed of Shashlik-type modules made of lead-scintillator layers resulting in 40 radiation lengths ( $X_0$ ). The ECAL has an asymmetric  $5 \times 6$  lateral segmentation and a resolution of  $\sigma_E/E = 8\%/\sqrt{E} \oplus 1\%$ . The target is followed by a large  $55 \times 55$  cm<sup>2</sup> high-efficiency veto counter (VETO) and a 5 nuclear interaction lengths ( $\lambda_{\text{int}}$ ) copper-scintillator hadronic calorimeter (VHCAL) with a hole in its middle. The outgoing muon momentum is reconstructed through a second magnetic spectrometer consisting of a single 1.4 T · m bending magnet (MS2) together with four  $10 \times 10$  cm<sup>2</sup> gaseous electron multiplier trackers (GEM<sub>1–4</sub>), two additional straw chambers (ST<sub>2,1</sub>) and three  $25 \times 8$  cm<sup>2</sup> micromegas (MM<sub>5–7</sub>) yielding a resolution of  $\sigma_{p_{\text{out}}}/p_{\text{out}} \simeq 4.4\%$ . To identify and remove any residuals from interactions in the detectors upstream of MS2 and ensure maximal hermeticity, two large  $120 \times 60$  cm<sup>2</sup>,  $\lambda_{\text{int}} \simeq 15$  iron-Sc HCAL modules (HCAL<sub>1,2</sub>), with energy resolution  $\sigma_E/E = 65\%/\sqrt{E} + 6\%$ , are placed at the end of the setup together with a  $120 \times 60$  cm<sup>2</sup> straw tube chamber, ST<sub>11</sub>. Further details about calorimeters and tracking detectors can be found in [35] and in [36].

The trigger system is defined by a veto counter with a hole ( $V_1$ ) and a set of 42 mm diameter plastic scintillator counters ( $S_{0–1}$ ) before the target, together with two  $20 \times 20$

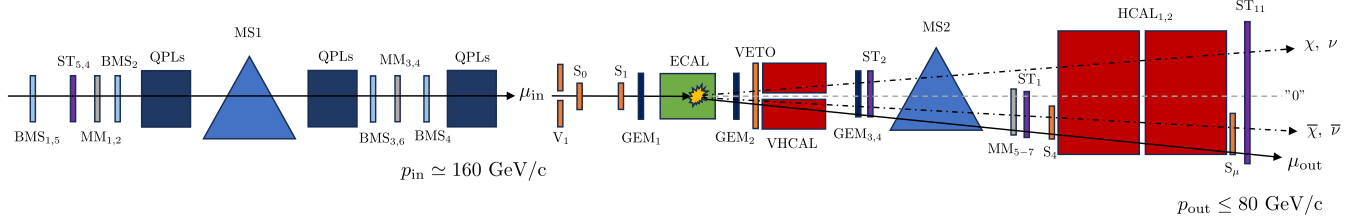


FIG. 2. Schematic illustration of the NA64 $\mu$  setup and of a signal event topology. Well-defined incoming muons with momentum  $p_{\text{in}} \simeq 160 \text{ GeV}/c$  are reconstructed in the first magnet spectrometer and tagged by a set of scintillator counters before arriving at the active target (ECAL). In the collision of muons with the target nuclei the bremsstrahlunglike reaction and subsequent invisible decay,  $\mu N \rightarrow \mu N(Z' \rightarrow \text{invisible})$  is produced. The resulting scattered muon with momentum  $p_{\text{out}} \leq 80 \text{ GeV}/c$  is measured in the second spectrometer (MS2).

and  $30 \times 30 \text{ cm}^2$  counters ( $S_4$  and  $S_\mu$ ) sandwiching the HCAL modules, shifted from the undeflected beam axis (referred to as *zero line*) to detect the scattered muons. The data were collected in two trigger configurations ( $S_0 \times S_1 \times \overline{V}_1 \times S_4 \times S_\mu$ ) with different  $S_\mu$  distances to the zero line along the deflection axis  $\hat{x}$ , namely,  $S_\mu \hat{x} = -152$  and  $S_\mu \hat{x} = -117 \text{ mm}$  and with  $S_4 \hat{x} = -65 \text{ mm}$ . The corresponding measured rate is 0.04% and 0.07% of the calibration trigger ( $S_{0,1} \times \overline{V}_1$ ) coincidences at a beam intensity of  $2.8 \times 10^6 \mu/\text{spill}$ . In each configuration, we recorded, respectively,  $(11.7 \pm 0.1) \times 10^9$  and  $(8.1 \pm 0.1) \times 10^9$  muons on target (MOT) yielding a total accumulated dataset of  $(1.98 \pm 0.02) \times 10^{10}$  MOT.

A detailed GEANT4 [37,38] Monte Carlo (MC) simulation is performed to study the main background sources and the response of the detectors and the muon propagation. In the latter case, the full beam optics developed by the CERN BE-EA beam department is encompassed in the simulation framework using separately both the TRANSPORT, HALO, and TURTLE programs [39–41], as well the GEANT4 compatible beam delivery simulation (BDSIM) program [42–44] to simulate secondaries interactions in the beamline material. The signal acceptance is carefully studied using the GEANT4 interface DMG4 package [45,46], including light mediators production cross-section computations through muon bremsstrahlung [31]. The placements of  $S_4$  and  $S_\mu$  are optimized to compensate for the low signal yield at high masses,  $\sigma_{Z'} \sim g_{Z'}^2 \alpha Z^2 / m_{Z'}^2$ , with  $\alpha$  the fine structure constant and  $Z$  the atomic number of the target, through the angular acceptance being maximized for a scattered muon angle  $\psi'_\mu \sim 10^{-2}$  rad after the ECAL. In addition, the trigger counters downstream of MS2 account for the expected 160 GeV/ $c$  mean deflected position at the level of  $S_4$ , estimated at  $\langle \delta x \rangle \simeq -12.0 \text{ mm}$  from a detailed GenFit-based [47,48] Runge-Kutta extrapolation scheme.

The signal region,  $p_{\text{out}}^{\text{cut}} \leq 80 \text{ GeV}/c$  and  $E_{\text{CAL}}^{\text{cut}} < 12 \text{ GeV}$ , is optimized with simulations and data-driven background estimations to maximize the sensitivity. The cut on the total energy deposit in the calorimeters,  $E_{\text{CAL}}^{\text{cut}}$ , is defined by fitting

the minimum ionizing particle (MIP) spectra obtained from the sum of the energy deposit in the ECAL, VHCAL, and HCAL modules.

To minimize the background, the following set of selection criteria is used. (i) The incoming momentum should be in the momentum range  $160 \pm 20 \text{ GeV}/c$ . (ii) A single track is reconstructed in each magnetic spectrometer (MS1 and MS2) to ensure that a single muon traverses the full setup. (iii) At most one hit is reconstructed in MM<sub>5–7</sub> and ST<sub>1</sub> (no multiple hits) and the corresponding extrapolated track to the HCAL face is compatible with a MIP energy deposit in the expected cell. This cut verifies that no energetic enough secondaries from interactions upstream of MS2 arrive at the HCAL. (vi) The energy deposit in the calorimeters and the veto should be compatible with a MIP. This cut enforces the selection of events with no muon nuclear interactions in the calorimeters. The aforementioned cut flow is applied to events distributed in the outgoing muon momentum and total energy deposit plane,  $(p_{\text{out}}, E_{\text{CAL}})$ , as shown in Fig. 3.

Region A is inherent to events with MIP-compatible energy deposits in all of the calorimeters, resulting in  $p_{\text{in}} \simeq p_{\text{out}} \simeq 160 \text{ GeV}/c$ . By design, most unscattered beam muons do not pass through the  $S_4$  and  $S_\mu$  counters, however, the trigger condition can be fulfilled by sufficiently energetic residual ionization  $\mu N \rightarrow \mu N + \delta e$  originating from the downstream trackers MM<sub>5–7</sub> or last HCAL<sub>2</sub> layers. The accumulation of events in region C is associated with large energy deposition of the full-momentum scattered muon in the HCAL, while region B corresponds to a hard scattering or bremsstrahlung in the ECAL, with a soft outgoing muon and full energy deposition in either the active target or HCAL. The small number of events between  $p_{\text{out}} \geq 50 \text{ GeV}/c$  and  $p_{\text{out}} \leq 100 \text{ GeV}/c$  are associated with hard muon bremsstrahlung events,  $\mu N \rightarrow \mu N + \gamma$ , with  $\psi'_\mu \ll 10^{-2}$  rad, as a result of the trigger optimization for signal events emitted at larger angles. The events in the region D are associated with muon nuclear interactions in the ECAL,  $\mu N \rightarrow \mu + X$ , with  $X$  containing any combination of  $\pi$ 's,  $K$ ,  $p$ ,  $n$ , ..., with low-energy charged hadrons being deflected away in MS2,

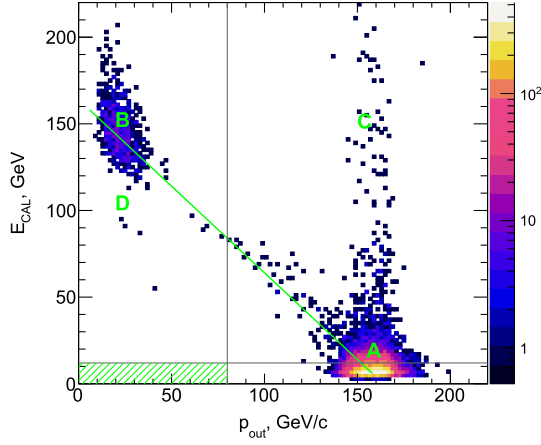


FIG. 3. Event distribution in the  $(p_{\text{out}}, E_{\text{CAL}})$  plane before the MIP-compatible requirement selection criterion. The signal region is defined as the shaded green rectangular area and the controlled region labeled with A through D (see text).

going out of the detector acceptance (typically the HCAL modules).

An exhaustive discussion of background sources is given in [1,34]. The main processes are summarized in Table I, with the dominant background contribution being associated with (I) momentum misreconstruction of the scattered muon in MS2. An incoming muon with 160 GeV/c is reconstructed after the target with momentum  $\leq 80$  GeV/c, whereas it truly is 160 GeV/c. This background is evaluated from data by selecting a sample of muons with  $p_{\text{in}} = 160 \pm 2\sigma_{p_{\text{in}}}$  GeV/c measured in MS1, and a MIP-compatible energy deposit in the ECAL. The tails of the measured momentum distribution in MS2,  $p_{\text{out}}$ , are then extrapolated to the blinded signal region at 80 GeV/c to estimate the number of expected background events. The second most important background process is (II) kaon decays to (semi-)leptonic final states with muons,  $K \rightarrow \mu\nu, \dots$ , before the ECAL target. Because of the level of hadron contamination in the M2 beamline,  $P_h \simeq 5 \times 10^{-5}$  [33], incoming kaons could be reconstructed through MS1 with a momentum passing the selection criterion (i) and subsequently decaying to muons with energy  $\leq 80$  GeV, with the neutrino carrying away the remaining energy. This contribution is estimated from MC with the hadron contamination being extracted from existing data [33]. Pion decays do not contribute to this background, since due to kinematics, the muon momentum is always  $\geq 80$  GeV. Another background source is associated with (III) non-Hermiticity in the calorimeters due to muon nuclear interactions in the target. As such, a leading hadron with energy  $E_h \geq 80$  GeV could be produced and escape the ECAL with lesser energetic charged secondaries and the scattered muon. Because of the nonzero charge of the particles and the trigger acceptance, low-energy secondaries are deflected away through MS2 resulting in

TABLE I. Expected main background level within the signal region, together with its statistical error, for the accumulated dataset of  $\sim 2 \times 10^{10}$  MOT.

Background source	Background, $n_b$
(I) Momentum misreconstruction	$0.05 \pm 0.03$
(II) $K \rightarrow \mu + \nu, \dots$ in-flight decays	$0.010 \pm 0.001$
(III) Calorimeter non-Hermiticity	$< 0.01$
Total nb (conservatively)	$0.07 \pm 0.03$

missing energy events. This background is extrapolated to the signal region from region D of Fig. 3. After applying all selection criteria (I–IV) and summing up the processes contributing to the background, the expected background level is found to be  $0.07 \pm 0.03$  for the total dataset of  $\sim 2 \times 10^{10}$  MOT.

The upper limits on the coupling  $g_{Z'}$  as a function of its mass  $m_{Z'}$  are estimated at 90% confidence level (C.L.) following the modified frequentist approach. In particular, the RooFit/RooStats-based [49–51] profile likelihood ratio statistical test is used in the asymptotic approximation [52]. The total number of signal events falling within the signal region is given by the sum of the two trigger configurations  $t$

$$N_{Z'} = \sum_{t=1,2} N_{Z'}^t = \sum_{t=1,2} N_{\text{MOT}}^t \times \epsilon_{Z'}^t \times N_{Z'}^t(m_{Z'}, g_{Z'}), \quad (1)$$

where  $N_{\text{MOT}}^t$  is the number of MOT for trigger configuration  $t$ ,  $N_{Z'}^t$  the number of signals per MOT produced in the ECAL target, depending on the mass or coupling parameters  $m_{Z'}$  and  $g_{Z'}$ , and  $\epsilon_{Z'}^t$  the trigger-dependent signal efficiency.

The main systematic effects contributing to the signal yield defined in Eq. (1) are studied in detail. The uncertainty on  $N_{\text{MOT}}^t$  is conservatively set to 1%. The systematics associated with the  $Z'$  production cross section are extracted from the uncertainty introduced by the Weizsäcker-Williams (WW) approximation and from QED corrections to the exact tree-level (ETL) expression. In the former case, the relative error in assessing the number of produced  $Z'$  ( $N_{Z'}^t$ ) is found to be 2% [30,31]. In the latter case both the running of  $\alpha$  at the upper bound  $Q^2 \simeq m_{Z'}^2 \sim \mathcal{O}(1)$  GeV and higher order corrections from soft photon emissions, are estimated to contribute through respectively  $\Delta N_{Z'} \sim \alpha^2 g_{Z'}^2 Z^2$  and through the Sudakov factor  $\Delta N_{\text{soft}} \sim \exp(-\alpha/\pi)$  at the level of 2.4% and 1.4%. Uncertainties relative to the lead purity of the ECAL target are addressed at the level of 1%. The systematics on  $\epsilon_{Z'}^t$  are evaluated by comparing the detector responses in MC and data around the MIP-compatible peak, in particular in the ECAL and HCAL. Through comparisons between spectra integration and the corresponding peak ratio, it is found that the related cumulative uncertainty does

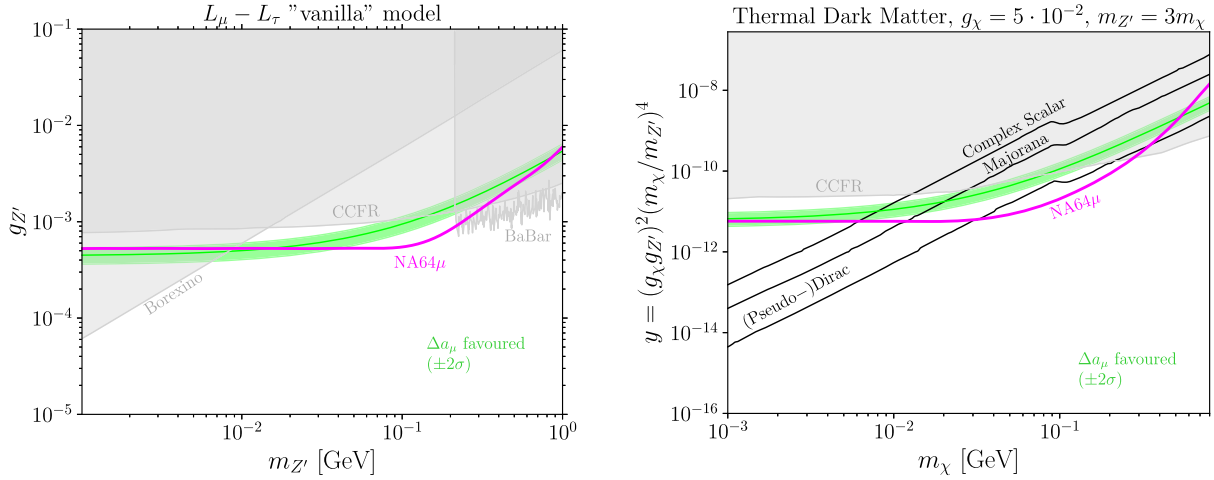


FIG. 4. Left: NA64 $\mu$  90% C.L. exclusion limits on the coupling  $g_{Z'}$  as a function of the  $Z'$  mass,  $m_{Z'}$ , for the vanilla  $L_\mu - L_\tau$  model. The  $\pm 2\sigma$  band for the  $Z'$  contribution to the  $(g-2)_\mu$  discrepancy is also shown. Existing constraints from *BABAR* [58,59] and from neutrino experiments such as *BOREXINO* [21,60,61] and *CCFR* [22,62] are plotted. Right: The 90% C.L. exclusion limits obtained by the NA64 $\mu$  experiment in the  $(m_\chi, y)$  parameters space for thermal dark matter charged under  $U(1)_{L_\mu - L_\tau}$  with  $m_{Z'} = 3m_\chi$  and the coupling  $g_\chi = 5 \times 10^{-2}$  for  $2 \times 10^{10}$  MOT. The branching ratio to invisible final states is assumed to be  $\text{Br}(Z' \rightarrow \text{invisible}) \simeq 1$  (see text for details). Existing bounds obtained through the *CCFR* experiment [22,62] are shown for completeness. The thermal targets for the different scenarios are taken from [63].

not exceed 4%. Because of the strong dependence of the efficiency  $\epsilon_{Z'}^t$  on the trigger configuration  $t$ , in particular, on the distance from the zero line, additional uncertainties due to  $S_4$  and  $S_\mu$  misalignment are studied through the change in efficiency as a response to small displacements of the  $S_c$  counters. Because of the  $m_{Z'}$  mass dependence of the trigger rate [34], the resulting uncertainty reaches up to  $\leq 5\%$ . As such the total systematic in the signal yield of Eq. (1) is  $\leq 8\%$ . The acceptance loss due to accidentals (pile-up events,  $\sim 13\%$ ) entering the trigger time window is taken into account in the final efficiency computations. The signal efficiency peaks at its maximum of  $\sim 12\%$  for the mass range  $\mathcal{O}(100 \text{ MeV} - 1 \text{ GeV})$ .

After unblinding, no event compatible with  $Z'$  production is found in the signal region. This allows us to set the 90% C.L. exclusion limits on  $g_{Z'}$  which are plotted in Fig. 4, left, in the  $(m_{Z'}, g_{Z'})$  parameter space, together with the values of  $\Delta a_\mu$  compatible with the muon  $g-2$  anomaly, within  $\pm 2\sigma$ . The band is computed using the latest results of the Muon  $g-2$  Collaboration,  $a_\mu(\text{Exp}) = 116\,592\,059(22) \times 10^{-11}$  [53] and the SM prediction of  $a_\mu(\text{SM}) = 116\,591\,810(43) \times 10^{-11}$  from the Muon  $g-2$  theory initiative (TI) [54]. It is worth noting that the extraction of the hadronic vacuum polarization contribution using the latest results from the CMD-3 Collaboration [55,56] disagree within the  $2.5\text{--}5\sigma$  level with the TI value. Note that the recent lattice QCD computations from the BMW Collaboration [57] are also in tension with the TI value by  $2.1\sigma$ .

Our results, excluding a previously unexplored parameter space with masses  $m_{Z'} \gtrsim 40 \text{ MeV}$  and coupling

$g_{Z'} \gtrsim 5 \times 10^{-4}$ , are the first search for a light  $Z'$  (*vanilla*  $L_\mu - L_\tau$  model) with a muon beam using the missing energy-momentum technique (see Fig. 4, left). Figure 4, right, shows the obtained limits at 90% C.L. in the target parameter space  $(m_\chi, y)$  with freeze-out parameter  $y = (g_\chi g_{Z'})^2 (m_\chi / m_{Z'})^4$  for accelerator-based experiments probing thermal DM for  $m_{Z'} = 3m_\chi$ , away from the resonant enhancement  $m_{Z'} \simeq 2m_\chi$ , and  $g_\chi = 5 \times 10^{-2}$ . The thermal targets for favored  $y$  values are plotted for scalar, pseudo-Dirac, and Majorana DM candidate scenarios, and obtained from the integration of the underlying Boltzmann equation [63]. The results indicate that NA64 $\mu$  excludes a portion of the  $(m_\chi, y)$  parameter space, below the current *CCFR* [22,62] limits, constraining for a choice of masses  $m_\chi \lesssim 40 \text{ MeV}$  the dimensionless parameter to  $y \lesssim 6 \times 10^{-12}$ .

In summary, for a dataset of  $(1.98 \pm 0.02) \times 10^{10}$  MOT, no event falling within the expected signal region is observed. Therefore, 90% C.L. upper limits are set in the  $(m_{Z'}, g_{Z'})$  parameter space of the  $L_\mu - L_\tau$  vanilla model, constraining viable mass values for the explanation of the  $(g-2)_\mu$  anomaly to  $6\text{--}7 \text{ MeV} \lesssim m_{Z'} \lesssim 40 \text{ MeV}$ , with  $g_{Z'} \lesssim 6 \times 10^{-4}$ . New constraints on light thermal DM for values  $y \gtrsim 6 \times 10^{-12}$  for  $m_\chi \gtrsim 40 \text{ MeV}$  are also obtained. The use of a muon beam demonstrated in this work opens a new window to explore other well-motivated scenarios such as benchmark dark photon models in the mass region  $(0.1\text{--}1) \text{ GeV}$  [64], scalar portals [31], millicharged particles [65] or  $\mu \rightarrow e$  or  $\mu \rightarrow \tau$  processes involving lepton flavor conversion [66–68], complementing the DS quest world

wide effort [13–16]. Improvements in the experimental setup such as an additional magnetic spectrometer to reduce by more than an order of magnitude the background from momentum misreconstruction, and new detectors able to cope with rates up to  $10^8$   $\mu$ /spill available at the SPS M2 beamline, would allow NA64 $\mu$  to collect up to 3 orders of magnitude more data. With such statistics, NA64 $\mu$  can probe unequivocally a variety of muon-philic DS scenarios complementing present experiments such as Belle-II [25] or FASER [69], and future projects as  $M^3$  [32].

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