IL NUOVO CIMENTO **42 C** (2019) 218
DOI 10.1393/ncc/i2019-19218-3

COMMUNICATIONS: SIF Congress 2018

The Beam Dump eXperiment

L. MARSICANO([1])([2])

([1]) *INFN, Sezione di Genova - Genova, Italy*
([2]) *Università degli Studi di Genova - Genova, Italy*

received 16 February 2019

Summary. — The Beam Dump eXperiment (BDX), proposed at Jefferson Lab (JLab), will search for Light Dark Matter (LDM) particles in the Dark Photon scenario. In this model, the LDM interacts with the Standard Model via a new massive vector boson (Dark Photon or A'). The experiment uses the CEBAF (Continuous Electron Beam Accelerator Facility) 11 GeV electron beam impinging on the JLab Hall-A beam-dump, to produce a beam of LDM particles, detected by a $\sim m^3$ detector placed $\sim 20\,\mathrm{m}$ downstream. Receiving 10^{22} electrons on target in 285 days, the BDX will exceed the discovery potential of all existing experiments in the MeV-GeV LDM mass range.

1. – Introduction

The search for Dark Matter (DM) is one of the hottest topics of modern physics. Despite the various astrophysical and cosmological observations proving its existence, its elementary properties remain to date unknown [1]. Up to now, the experimental efforts have been focused on the WIMP (Weakly Interacting Massive Particle) paradigm, predicting heavy DM particles (10 GeV–10 TeV mass range) interacting with the Standard Model (SM) via weak force [2]. More recently, due to the lack of evidence of WIMPs, other models of DM gained the interest of the physics community. These models consider Light DM particles (LDM), in the MeV-GeV mass range. Among LDM theories, the Dark Photon theory predicts the existence of a dark sector interacting with the SM particles via a new massive vector boson (Dark Photon, Heavy Photon or A'), mediator of a new force [3]. This scenario, other than being theoretically motivated, is remarkably unexplored.

In the minimal paradigm of vector-mediated LDM, the interaction between the hidden sector and the SM is generated effectively by a kinetic mixing between the SM photon and the A':

$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\varepsilon}{2}F_{\mu\nu}F'^{\mu\nu} + \frac{m^2_{A'}}{2}A'_\mu A'^\mu + g_D A'_\mu J^\mu_D.$$

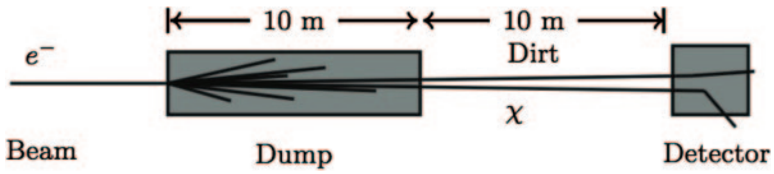

Fig. 1. – Schematic of the experimental setup. A high-intensity multi-GeV electron beam impinging on a beam-dump produces a secondary beam of dark sector states. In the basic setup, a small detector is placed downstream the beam-dump so that muons and energetic neutrons are entirely ranged out.

Here, $F'_{\mu\nu}$ is the A' field strength, g_D is the dark gauge coupling, J^{μ}_{D} is the current of DM fields and ε parameterizes the degree of kinetic mixing between dark and visible photons. The behavior of the A' depends on the $m_{A'}/m_\chi$ ratio (being χ the dark sector particle): if no dark sector particle with $2m_\chi < m_{A'}$ exists, A' decays dominantly into e^+e^- pairs (the so-called *visible* decay). Otherwise, the A' decays into a $\chi\bar{\chi}$ pair (*invisible* or *secluded* decay). In this work we will focus on the latter paradigm.

High intensity $\sim$ GeV electron-beam on thick-target experiment offer large sensitivity to the A' parameter space [4]. Figure 1 shows the generic BD experiment design: $\sim$ GeV electrons impinge on a thick target producing an A' beam; A' subsequently decay into a $\bar{\chi}\chi$ pair, which travels unaltered towards a detector placed downstream the BD. Here, χ can scatter off electrons in the detector volume giving rise to a detectable signal. Given that $m_e \ll m_\chi$, the typically scattered electron carries GeV-scale energy producing an electromagnetic shower in the detector. The *Beam Dump eXperiment* (BDX) [5] is a foreseen experiment at Jefferson Lab, aiming to produce and detect LDM making use of a high intensity 11 GeV electron beam impinging on the Hall A BD and a detector made of CsI(Tl) crystals.

2. – BDX experimental setup

BDX will make use of the CEBAF (Continuous Electron Beam Accelerator Facility) high intensity electron beam, impinging on the Jefferson Lab Hall-A beam dump, placed at the end of the beam transport line. CEBAF can provide 11 GeV electrons with a current of 65 μA, allowing to collect $\sim 10^{22}$ electrons on target (EOT) in 285 days. The BDX detector will be placed in a new underground facility, that will be built 20 m downstream of the Hall-A beam dump (see fig. 2).

The low signal rate expected, due to the weakness of the mixing between the SM photon and the A' makes background rejection a critical issue for BDX. To range out all the SM particles produced in the BD, except neutrinos, a passive shielding made of concrete and iron blocks will be located between the BD and the new facility; to reduce the beam-unrelated background, mainly due to cosmic neutrons and muons, the detector will be placed in a bunker 8 m underground with 10 meters of water equivalent overburden.

2·1. *BDX Detector*. – The BDX detector is composed of an electromagnetic calorimeter (ECAL) and an active veto system for cosmic background rejection. The ECAL is made of 800 CsI(Tl) crystals, arranged in 8 modules of 10×10 crystal each, for a total volume of $\sim$1 m^3. SiPMs are used as crystals readout. The calorimeter is enclosed into two layers of plastic scintillator, called Outer Veto (OV) and Inner Veto (IV). Light emitted by scintillator of both layers is collected by wavelength shifter (WLS) fibers and

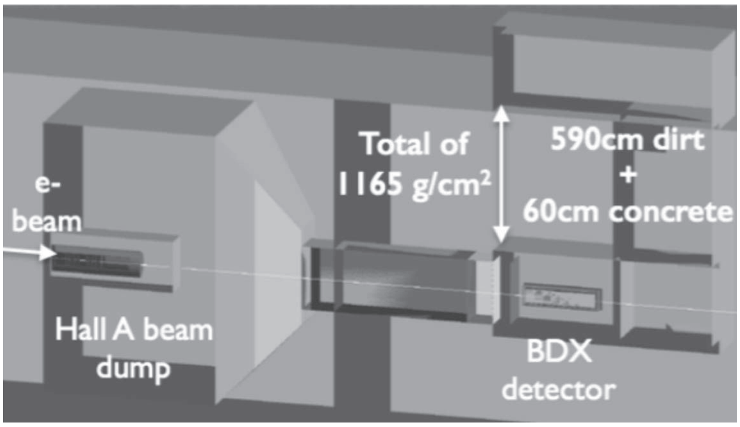

Fig. 2. – The BDX experimental setup.

conveyed to SiPMs, used as light sensors. A 5 cm thick lead layer is placed between the ECAL and the two vetos. In this configuration, the lead shielding prevents the electromagnetic shower produced by LDM scattering inside the ECAL from hitting the vetos, which would affect the whole detector signal efficiency.

The here presented detector setup was optimized and validated with both simulations and a measurement campaign with a prototype detector at Laboratori Nazionali del Sud (LNS) in Catania, described in the following section.

3. – Expected background

3˙1. *Cosmogenic background.* – Cosmogenic background consists mainly of muons and neutrons produced in the upper atmosphere. These particles can hit the detector, mimicking a LDM signal in the ECAL. This background has been evaluated by extrapolating the results obtained with the BDX prototype at LNS. This detector incorporates all the elements of the BDX detector: it is composed of a single CsI(Tl) crystal, two active veto layers and a lead shielding. The crystal and the inner veto layer are read with SiPMs, the outer veto is read by PMTs. The prototype was placed in a bunker at LNS, in order to match the overburden foreseen in the future BDX experimental hall. The measurement campaign started in April 2016; the data used to extrapolate cosmic background corresponds to about one month of data taking. The extrapolation has been performed by scaling the experimental rates of a single crystal to the 800 crystals constituting the full detector. This procedure gives an upper limit on the expected rates since this assumes crystal-to-crystal fully uncorrelated counts, leading to an overestimate of the number of events. Table I shows the number of cosmic background events expected for BDX: for detection energy thresholds higher enough, between 300 and 350 MeV, the number of cosmogenic background counts in the whole measurement run reduces to zero.

3˙2. *Beam related background.* – Beam related background was evaluated using massive FLUKA [6] Monte Carlo (MC) simulations. The geometry and materials of the existing Hall-A beam dump (provided by the Jefferson Lab Radiation Control Department) was included in FLUKA-2011.2c.5 together with the iron and concrete shielding and the other components of the foreseen BDX facility. We simulated the 11 GeV electron-

Table I. – *Number of expected cosmic background events as a function of the single crystal energy threshold.*

Energy threshold (MeV)	Expected counts (285 days meas.)
200	740 ± 300
250	57 ± 25
300	4.7 ± 2.2
350	0.037 ± 0.022

beam interacting with the beam-dump and we propagated all particles to the location of interest, sampling the flux in different locations. In order to crosscheck results we performed the same procedure using GEANT4 [7], obtaining good agreement between the two tools. Biasing techniques available in FLUKA were used in the simulation in order to obtain the highest statistics with the available computing resources. Biasing consists in a set of techniques that, artificially modifying the physics model used in the simulation, minimize the statistical fluctuations of scored quantities in a given region of interest (including both the energy range and the physical volume), while possibly increasing those elsewhere. For a detailed description of biasing techniques used, see [8]. The simulation was performed using ∼300 cores for about 3 months. The total number of simulated EOT is $N_0 \simeq 2 \times 10^{11}$. Given the heavy use of biasing, the equivalent number of EOT is much larger, as shown in fig. 3, right panel.

The left panel of fig. 3 shows the flux of different particles as a function of the depth in the shielding between the dump and the detector: all particles except neutrinos are ranged out before reaching the BDX experimental hall. Indeed, given a threshold of $O(300)$ MeV, neutrinos are the only source of beam-related background. These are mainly produced in muon decays and hadronic showers (pion decay); a non negligible fraction of this flux, due to in-flight pion and muon decay, experiences a significant boost to a several GeV energy. High energy ν interacting in the BDX detector can release a significant amount of energy, mimicking the signal. To quantify this background we followed a multi-step procedure:

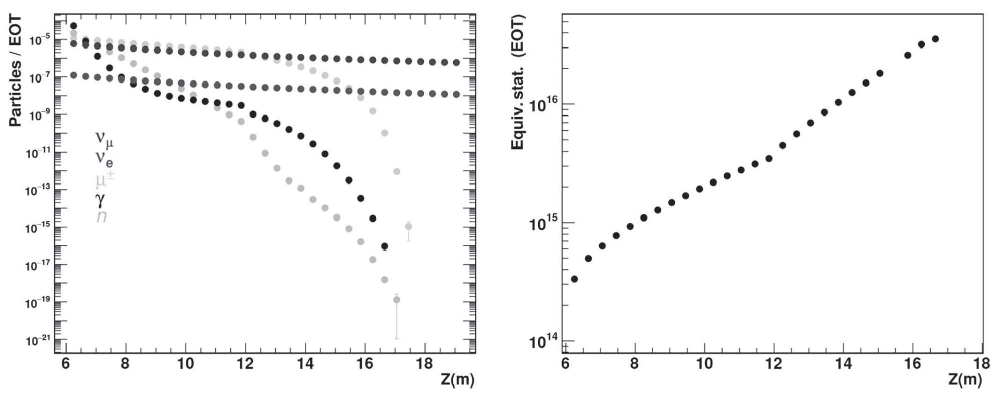

Fig. 3. – Left: particles fluxes per EOT at different depths in the shielding. Right: the equivalent number of electrons N_{equiv}^{EOT} in the biased simulation, as a function of the depth in the shielding.

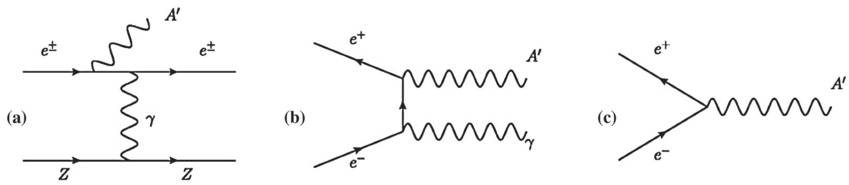

Fig. 4. – Three different A' production modes in lepton BD experiments: (a) A'-strahlung; (b) non-resonant e^+e^- annihilation; (c) resonant A' production in e^+e^- annihilation.

- The differential neutrino flux, with respect to energy, angle and species was sampled on the front wall of the BDX experimental hall. To perform this calculation, results from the FLUKA high-statistics simulation previously described were used.
- Neutrinos were propagated from the front-wall to the detector volume, where an interaction with the Cs/I nuclei was forced. Neutrino-nucleus interactions were simulated by using NUNDIS and NUNRES, the FLUKA internal neutrino-nucleon interaction generators.
- The secondary particles produced by the neutrino interaction were sampled and used as an input for a new simulation including the response of the detector.

This approach allowed us to study the variation of this background depending on the different selection cuts or detector configuration adopted [8]. We found that, given a $O(300)$ MeV detection threshold, the expected number of neutrino background events is $\sim$5.

4. – Light dark matter production processes

Dark photons can be generated in collisions of GeV electrons or positrons with a fixed target by the processes depicted in fig. 4. For electron BD experiments, such as BDX, only the so-called "*A'-strahlung*" (diagram (a)), analogous to ordinary photon bremsstrahlung, is usually included in A' production estimates. Nevertheless, the contribution from diagrams (b) and (c) can be relevant even for electron BD experiments, as proved in [9]. The electromagnetic shower resulting from the interaction of the primary electron beam in the dump produces indeed a large number of secondary positrons. As a result, for some selected kinematics, mechanism (b) and in particular (c) contribute significantly to the total A' yield of electron BD experiments.

To correctly evaluate the BDX reach, we calculated separately the contribution of the three different production mechanisms, using MC simulations. Starting from GEANT4 simulations of the electromagnetic shower propagation inside the dump, we used a modified Mad-Graph4 [10] version to simulate A'-strahlung events, and a custom event generator to estimate the contribution of the positron annihilation processes to the LDM beam generation. For a detailed description of the procedure adopted, see [5] and [9].

5. – BDX reach

Here we present the expected reach of BDX for the χ-e elastic scattering channel, in the minimal dark photon scenario. Result is reported as an upper limit on the exclusion

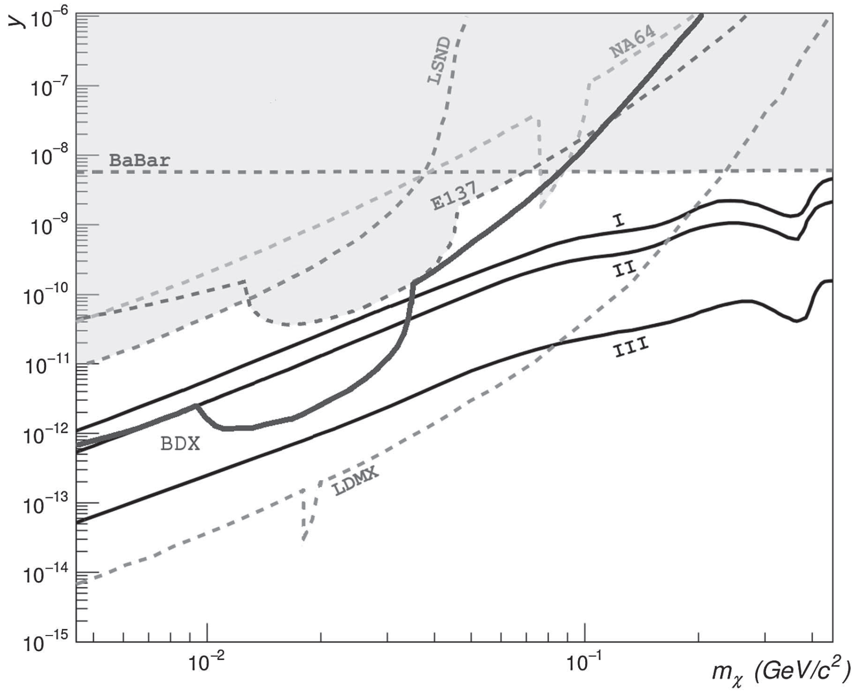

Fig. 5. – BDX reach together with exclusion limits of other past and foreseen experiments, for $\alpha_D = 0.5$ and $\frac{m_\chi}{m_{A'}} = \frac{1}{3}$. The gray region has already been excluded. The shape of the BDX reach curve is due to the different A' production processes involved: in particular, for χ with mass in the 10–35 MeV range the resonant annihilation of secondary positrons gives a relevant enhancement to the reach of the experiment.

plot in the y-m_χ plane, being m_χ the mass of LDM candidate and y an adimensional variable called *thermal target* [5]:

$$y = \alpha_D \varepsilon^2 \left(\frac{m_{A'}}{m_\chi}\right)^4 .$$

To evaluate the reach we estimated the number of expected signal events for a given value of the mixing parameter ε; the detection efficiency for χ-e scattering was evaluated through MC simulations. The line shown in fig. 5 represents the 90% Confidence Level exclusion limit set by BDX in case of no measured excess over the predicted background. For the calculation, we considered a 285 days measurement run with a 65 μA beam current, for total of 10^{22} EOT and a 350 MeV energy threshold on the single crystal of the detector. In this configuration, the expected background is of $\sim$5 events, coming from the interaction in the detector of high energy neutrinos produced in the dump. For a thorough description of the reach curve calculation, see [8]. If any excess is observed, a statistical analysis will be necessary to claim a positive result. In case of no positive observation, the accumulated data would provide very stringent limits on the DM parameter space, extending considerably the explored region with respect to previous experiments.

Fig. 6. – Schematic representation of the test locations. From left to right: the Hall-A aluminum-water beam dump, the concrete beam-vault walls, the dirt and the two vertical pipes.

6. – The BDX-Hodo measurement campaign

As seen in the previous sections, MC simulations are an essential tool for estimating beam-related backgrounds in BDX. A complete beam-on background assessment in the BDX detector, in fact, will only be possible when the new underground facility (including the additional iron shielding between the dump and the detector) will be built. Therefore, in order to validate our simulation tools and confirm that no other sources of unpredicted background are present, we performed an on-site measurement of the muon flux produced by the 11 GeV CEBAF beam in the Hall A dump. In the current configuration, there is no iron shielding and the radiation produced in the dump is only partially shielded by the dump vault concrete and $\sim$20 m of dirt. For this reason, a sizable muons flux can be measured at the location of the future BDX detector hall.

6˙1. *Masurement setup.* – The area downstream of Hall-A beam-dump is shown in fig. 6. Two wells have been dug in the positions marked as Well $-$ 1 and Well $-$ 2. To measure the flux of muons, we used a hodoscope, that was lowered to the beam height inside the wells. This detector, called the BDX-Hodo, is composed of a CsI(Tl) crystal sandwiched between a set of segmented 1–2 cm thick plastic scintillators. As in the case of BDX prototype in Catania, BDX-Hodo was built using the same technology proposed for the BDX detector, in order to validate the technical choices in a realistic background environment; the crystal is read with a SiPM and the plastic scintillators are read with SiPMs coupled to WLS fibers. Measurements were performed using the 10.6 GeV CEBAF electron beam with a steady current of 22 μA. During the test, the BDX-Hodo was lowered in both wells and the muon flux sampled at different heights with respect to nominal beam height. Measuring the flux vertical profile, at two different distances from the dump, allowed us to compare the data with the absolute and relative MC predictions. For a thorough overview of this measurement campaign see [11].

6˙2. *MC simulations.* – To simulate the production and the subsequent propagation of the muons in the dirt we used the same simulation framework based on FLUKA and

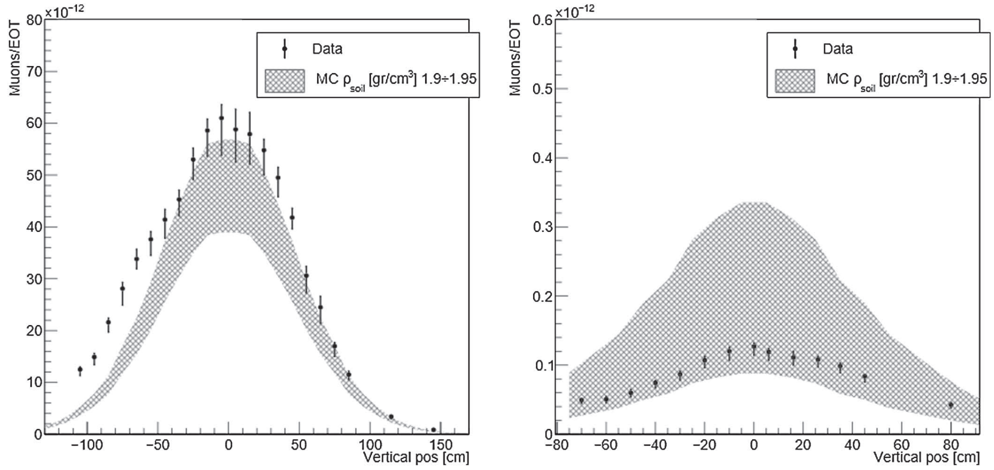

Fig. 7. – Comparison between simulated and measured muon rates. Well-1 (Well-2) is shown in the left (right) plot. The light gray error band includes the systematic error related to the density uncertainty as explained in the text.

GEANT4 used for the BDX beam-related background estimate, described in sect. 3.2. FLUKA was used to generate the muons in the BD and propagate them to a plane near the detector, and from there all particles were followed into the detector using GEANT4. This latter GEANT4 simulation included a detailed description of the detector response and was used to extract expected muon rates. The precise position of the two wells, the density of the dirt between the dump and the detector, as well as the beam parameters were included in the simulation. However, the uncertainty on the dirt density proved to be critical for the evaluation of the muon flux. The nominal density value, obtained by on site measurement, is $\rho_{dirt} \simeq 1.93\frac{\mathrm{g}}{\mathrm{cm}^3}$. According to simulations, a mere deviation of 2% from this value translates in a significant variation in the muon flux (up to a factor ∼2 in Well-2). To account for this effect, we performed simulations with different values of ρ_{dirt} and quoted the observed variation as a systematic error band.

6·3. *Results.* – Figure 7 shows the comparison of the measured rate profiles (as a function of the vertical height) with simulations. Measured fluxes present a suppression factor of $\sim$ 500 between the rates in the Well-1 and Well-2. This indicates that the position of the Well-2 is close to the edge of the muons range. Taking into account the large systematic error band due to the uncertainty on ρ_{dirt}, simulations are in reasonable agreement with the data: remarkably, they are able to reproduce the suppression factor between Well-1 and Well-2 as well as the Gaussian shape and width of the flux profile. This good agreement demonstrates that the simulation framework can be used to realistically estimate the beam-on background in the real BDX experiment configuration.

7. – Conclusions

BDX is an electron beam thick-target experiment at JLab aiming to search for LDM particles in the MeV-GeV mass range. It will make use of the CEBAF 11 GeV electron beam, collecting 10^{22} EOT in 285 days of measurement run. The BDX detector is composed of an electromagnetic calorimeter surrounded by active vetos and passive shielding;

it will be placed in a new underground facility located downstream of the Hall-A beam dump. The sensitivity of BDX was evaluated by measuring the cosmic background with a prototype detector under conditions similar to those proposed at JLab and estimating the beam-related background using FLUKA and GEANT4 MC simulations. An on-site measurement of the beam-related background with a dedicated detector has been performed to validate simulations: the results proved the robustness of the simulation framework used. In case of no measured excess over the expected background, BDX will be able to provide new stringent limits on the DM parameter space, exceeding the sensitivity of previous experiments by up to two orders of magnitude. BDX has been approved with maximum scientific rating by Jefferson Lab PAC46 in 2018.

REFERENCES

[1] Olive K. A. *et al.*, *Chin. Phys. C*, **38** (2014) 090001.
[2] Annika H. G. Peter, *Dark Matter: A Brief Review*, arXiv:1201.3942 (2012).
[3] Holdom B., *Phys. Lett. B*, **166** (1986) 196.
[4] Izaguirre E. *et al.*, *Phys. Rev. D*, **90** (2014) 014052.
[5] Battaglieri M. *et al.*, *Dark matter search in a Beam-Dump eXperiment (BDX) at Jefferson Lab*, arXiv:1607.01390v1.
[6] Bhlen T. T. *et al.*, *Nucl. Data Sheets*, **120** (2014) 211.
[7] Agostinelli S. *et al.*, *Nucl. Instrum. Methods A*, **506** (2003) 250.
[8] Battaglieri M. *et al.*, *Dark matter search in a Beam-Dump eXperiment (BDX) at Jefferson Lab - 2018 update to PR12-16-001* (2018).
[9] Marsicano L. *et al.*, *Phys. Rev. Lett.*, **121** (2018) 4.
[10] Alwall J., Demin P., de Visscher S., Frederix R., Herquet M. *et al.*, *JHEP*, **09** (2007) 028.
[11] Battaglieri M. *et al.*, *Nucl. Instrum. Methods A*, **925** (2019) 116.