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Detecting long-lived particles trapped in detector material at the LHC

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We propose to implement a two-stage detection strategy for exotic long-lived particles that could be produced at the CERN LHC, become trapped in detector material, and decay later. The proposed strategy relies on an array of metal rods, combined to form a high-density target. In a first stage, the rods are exposed to radiation from LHC collisions in one of the experimental caverns. In a second stage, they are individually immersed in liquid argon in a different experimental hall, where out-of-time decays could produce a detectable signal. Using a benchmark case of long-lived gluino pair production, we show that this experiment would be sensitive to a wide range of masses. Such an experiment would have unique sensitivity to gluino-neutralino mass splittings down to 3 GeV, in previously uncovered particle lifetimes ranging from days to years.

The search for new particles produced in proton-proton collisions is one of the main aspects of the physics program at the CERN LHC. One of the most intriguing scenarios explored in these searches for physics beyond the standard model is that of long-lived particles [1] produced in collisions and traveling in the detector before decaying. Depending on their lifetime and charge, these particles could generate a rich set of signatures in particle detectors: displaced vertices, track kinks, appearing jets, heavy muons, etc. These long-lived particles are being searched for with the ATLAS [2], CMS [3], and LHCb [4] detectors at the LHC, and also with dedicated detectors such as FASER [5, 6], milliQan [7], and the planned CODEX-b [8]. In one of the most extreme scenarios, heavy particles could be trapped in detector material and decay after some time. Typical examples of this kind include the production of long-lived sleptons in many SUSY scenarios, or long-lived gluinos ($\tilde{}$) [9] predicted by Split SUSY [10–12]. As a benchmark example, we consider pair-production of the latter in this study. In this scenario, each long-lived gluino decays to a gluon (g) and a neutralino ($\tilde{}^0$), or to a quark-antiquark pair and a neutralino. Decays of these kinds were searched for by the CMS [13, 14] and ATLAS [15, 16] Collaborations, using triggers that fired in absence of colliding beams. Gluino masses ( ) lighter than 1.4 TeV were excluded, for gluino proper lifetimes ( ) of $^{-5}$ to ^{3} s, assuming the gluinos decay to a quark-antiquark pair and a neutralino with a mass ($_0$) of about 100 GeV, with 100% branching fraction. Due to the nature of the trigger, these searches focused on large mass differences between the gluino and the neutralino.

In this Letter, we propose to probe very long-lived scenarios, e.g., compressed gluino-neutralino spectra, with a dedicated detection strategy, consisting of two stages:

- Trap: A removable inert material (RIM) is placed in the cavern of an LHC experiment. We assume that such a detector is CMS, which is the one with which we are most familiar. On the other hand, the strategy is general and could be adapted to other particle colliders and detectors at the collision points. For practical reasons, we consider brass rods, placed next to each other to form a block material with a shape optimized on specific aspects of the target scenarios, e.g., privileging coverage or absorption depth. Shielded by the particle detector, and by additional material if required, the RIM would receive only the most penetrating radiation, e.g. muons, neutrons, and potentially, new long-lived particles like gluinos. If the gluinos were moving sufficiently slowly, they could become trapped in the RIM.

- Detect: After the LHC run, the RIM is removed, the individual rods are separated, and they are placed in a cryostat filled with purified liquid argon (LAr). A voltage is applied to the rods, altering their polarity. We envision this basic LAr calorimeter setup, which could have simple readout electronics and is in line with current projects at CERN. Another potential detection setup could involve plastic scintillators and photosensors or similar calorimeter technologies. Fast muon timing detectors could be added to reject backgrounds from cosmic rays. When the long-lived gluinos decay, the energy of the decay products would be deposited in the LAr and the charge could be measured. We propose to use these technologies so that they could be shared or reused from ongoing CERN experiments.

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The detection strategy is similar to the approaches discussed in Refs. [17, 18], where the trapping of charged sleptons in water tanks is described. The main difficulties with proposals involving water or LAr as the stopping material, which we considered in an early stage of this study, are that a large volume is required to reach an acceptable stopping rate, and the logistics are challenging (impossible) in the CMS (ATLAS) cavern. The strategy highlighted in this Letter provides several advantages: it exploits a more compact design; it comes with a movable target, which could cover different acceptance ranges during different exposure campaigns targeting different new physics scenarios; and it builds on many detector activities already ongoing at CERN, notably at the Neutrino Platform [19]. A similar trapping detector concept is also used by the MoEDAL Collaboration to look for trapped monopoloes and long-lived particles [20, 21].

Gluinos, which are the benchmark target of this study, can form strongly produced hadronic states called R-hadrons [22]. We simulate gluino R-hadrons that travel through a rough approximation of the CMS detector and approach a brass RIM with GEANT4 [23]. We use the Regge model to generate the R-hadron strong interactions with matter [24, 25] and the FBERT physics list for the other processes. The CMS detector material is approximated with concentric cylinders. The innermost is made of air with a radius of 1 m to approximate the low-material silicon tracker, followed by led tungstate with a thickness of 20 cm to approximate the electromagnetic calorimeter, brass with a thickness of 1 m to approximate the hadronic calorimeter, and iron with a thickness of 2.9 m to approximate the iron in the CMS muon system. The RIM is modeled with 100 layers of brass, each of which are 2 cm thick in the direction and m in the - plane.

Neutral gluino R-hadrons are produced at the CMS beamspot and are shot directly at the brass RIM. Gluino masses from 5 GeV to 2 TeV are produced, and for each mass, we finely scan , which is the gluino velocity divided by the speed of light, from 0.0 to 1.0. In total, we simulate 160 million gluino R-hadrons. Gluinos with masses from about 5 GeV to 3 TeV can be absorbed by the brass RIM, with transverse momenta ranging from about 5 to 80 GeV. We find that if the brass RIM was replaced by the same volume of LAr, the absorption efficiency is reduced by about a factor of 2, while if the same volume of water is used, the absorption efficiency is at least two orders of magnitude smaller.

Stable gluinos and gluino R-hadrons are generated with PYTHIA 8.306 [26] in proton-proton collisions at a center-of-mass energy of 13 TeV, in a Split SUSY scenario. The gluinos are pair-produced through gluon-gluon fusion and quark-antiquark annihilation. We set the fraction of gluinos that hadronize into a gluino-gluon state, which is a free parameter in the hadronization model and determines the fraction of R-hadrons that are neutral at production, to be 0.1. We generate 100,000 events per gluino mass, which are the same masses as those that we simulate with GEANT4.

The smallest gluino masses we consider have maximum angular acceptance near and , while the largest gluino masses have the maximum acceptance near . Therefore, we consider two RIM absorber positions, just outside of the CMS detector: the first positioned at , covering ($_0$); and the second at , covering ($_1$).

We then convolve the R-hadron angular acceptance with the absorption efficiency in order to obtain the total efficiency times acceptance for the gluino R-hadrons to hit and be absorbed in the RIM, as shown as a function of in Fig. 1 for absorber $_0$ (top) and $_1$ (bottom). As a particle travels through CMS and the brass absorber, it will be slowed by material until it comes to a stop. For very small values, the particles are stopped before they reach the absorber, and for very large values the particles continue through the detector and the absorber without being stopped. Between these two extremes, there is a range of values for each that will come to a stop within the absorber and therefore be absorbed by the brass. There are clear maxima at different values for the different due to the absorption efficiency. For the absorber at $_0$, the angular acceptance times efficiency is largest for . For the absorber at $_1$, the acceptance times efficiency for gluinos with masses greater than about 300 GeV is roughly the same as for $_0$. However, there is a sharp increase in acceptance times efficiency for low mass gluinos, particularly for GeV. This is due to the low-mass gluinos having peak absorption efficiency at large values, which is where the angular acceptance is the highest for absorber at $_1$. For example, for the absorber at $_1$, gluinos with a mass of 5 GeV have a maximum acceptance times efficiency of 0.004 at . The total acceptance times efficiency ranges from about $^{-4}$ to $^{-3}$ for other .

We assume the detection setup is able to detect hadronic and electromagnetic activity with a total energy release of about 3 GeV and greater, as this is very well within the capabilities of typical LAr calorimeters. Further, we have verified in simulation that particles with momenta in the range of 100 MeV or higher can escape the rods and deposit energy in the sensitive material. The setup will be placed in an experimental hall with shielding from cosmic rays, but some muon showers from cosmic rays could still penetrate the setup.

Cosmic ray muons with energies between 1 GeV and 50 TeV are simulated and propagated diagonally through the GEANT4 implementation of the brass rods immersed in LAr, which maximizes the material the muons traverse and provides a conservative assumption. This simulation shows that highly energetic muons can leave about 1% of their energy in the LAr, for rod spacings of about 1 cm or more. We take the spectrum of vertical cosmic ray

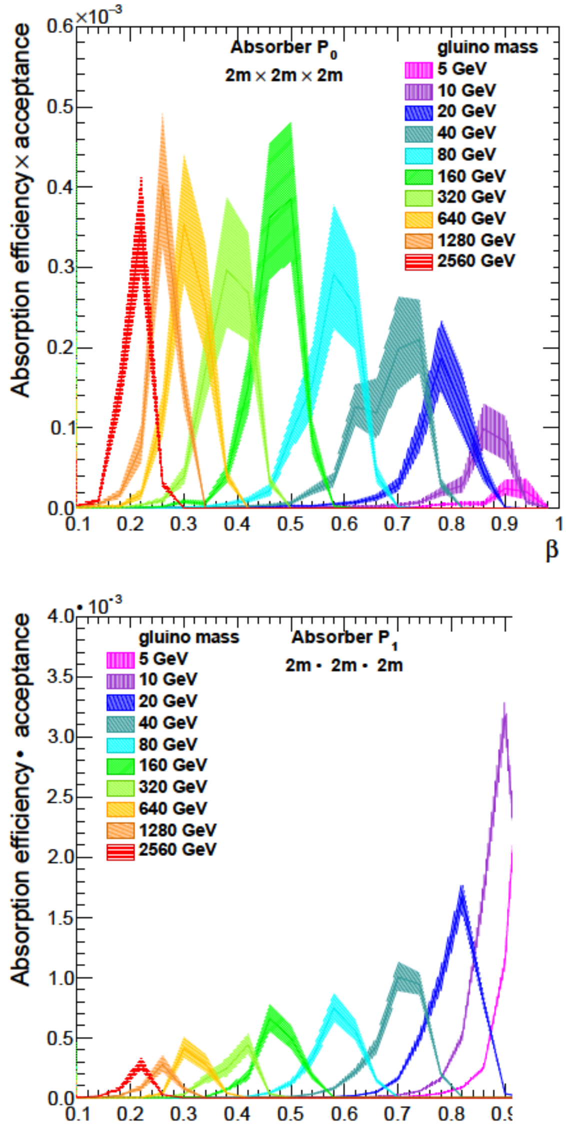

FIG. 1. Gluino R-hadron acceptance times the al efficiency as a function of β for different gluino mass (top) and P_1 (bottom). An absorber size of 2 m^3 is

muons at sea level from Ref. [27] as an upper limit on the total number of expected muons [28], and convolve it with the fraction of energy that the cosmic ray muons leave in the detection setup. We determine a cosmic ray muon background estimate by integrating the convolved muon spectrum over the momentum, starting from a threshold. We assume this threshold at which the cosmic ray muons could mimic the signal jet in the absence of other rejection methods is $\frac{\Delta m}{2}$, where $\Delta m = m_{\tilde{g}} - m_{\tilde{\chi}^0}$, as half the energy of the gluino R-hadron decaying at rest will be detectable.

To reject the background from cosmic ray muons, we assume that a muon veto system with a fast response would be put in place. A high rejection power could be achieved using the timing capabilities of multilayer resistive plate chambers (RPCs) or plastic scintillators. For example, two layers of RPCs could be placed above and below the brass rods and LAr as shown in Fig. 2, spaced d cm apart. A gluino decay is shown on the left side of the figure, and a muon from a cosmic shower is shown on the right. If the gluino decay produces a single shower, e.g., with a gluon in the final state, a signal would be easily distinguishable from a penetrating cosmic ray, since it would traverse the muon-veto system only once. If instead the gluino decay produces two showering quarks, particles from the two showers will interact with the innermost RPCs first and then the outermost RPCs, perhaps in the order as numbered in the figure. In contrast, a cosmic ray muon from the atmosphere will penetrate the setup from top to bottom, interacting with the RPCs in the order shown. Thus, if the RPCs have a timing resolution that is less than d divided by the speed of light, muons from cosmic rays could be distinguished from showers from

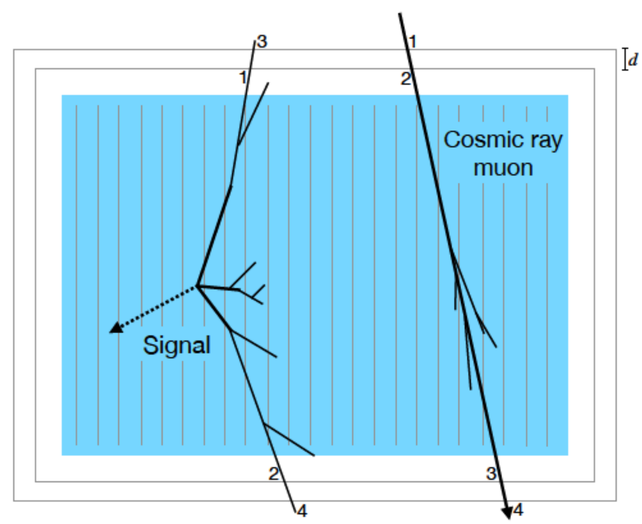

FIG. 2. The detection setup, with the brass rods shown with vertical gray lines, LAr shown in blue, and double layers of RPCs shown with the outermost gray lines. A sketch of a signal gluino decay is shown on the left, and a cosmic ray muon is shown on the right.

There are several methods available to perform estimates of the cosmic muon background from data. First, the unexposed RIM could be inserted within the detection setup and the rate of cosmic muons could be measured for a period of time. In addition, the exposed RIM rods could be placed horizontally within the LAr instead of vertically and the detector readout could be performed in layers. This readout method would allow one to more carefully measure the direction of each shower and to determine if it was produced within the grid of rods or if it came from above. Furthermore, one could rely on a signal shape analysis to distinguish signal from background on a statistical basis. This could be, for example, a one-dimensional fit of signal and background templates or a multivariate classifier based on deep neural networks. We do not consider these possibilities here. In this respect, the background estimate presented in this paper should be considered as a first, conservative approximation.

The sensitivity of this experiment to the benchmark gluino signal, given the cosmic ray muon background estimate and expected number of gluino signal events described earlier, is shown in Fig. 3. The sensitivity is quantified as , where and are the number of signal and background events, respectively. We assume 99% efficiency per muon detection layer, sufficient timing resolution with respect to the distance between each layer, and four layers in total. The minimum this experiment would be sensitive to is defined by how long it will take to remove the RIM from the LHC experimental cavern and set it up in the LAr cryostat. For this process, we estimate about a week. The maximum sensitivity is approximately how long we can run the detection for. As a result, the set of that this experiment is sensitive to is complementary to that of ATLAS and CMS; these two experiments can probe days. Furthermore, since the calorimeter-like detection setup is sensitive to a few GeV in momentum, this experiment will be able to probe values of a few GeV. Thus, this experiment will have complementary mass coverage with respect to ATLAS and CMS as well.

We envision a possibility to use longer detection phases to probe more rare signals, such as particles charged only under the electromagnetic force. There could be one exposure campaign per year, of progressively longer length, and an appropriate data-acquisition period.

We assume repurposing one of the existing facilities at the CERN Neutrino Platform to make use of existing cryostat, purification, and electronic systems. This would substantially reduce the overall cost of this experiment, which is mainly driven by the LAr, the brass for the target, and the muon-veto system. We estimate the cost of the LAr would be $\mathcal{O}$ CHF (24K CHF, assuming that 1 kg of LAr corresponds to 0.7 liters and costs 0.7 CHF). We again assume cm cm m rods and 200 rods in one dimension. Furthermore, we expect the price of the brass to be $\mathcal{O}$ CHF (assuming that the price of brass is 4 CHF/kg, the total cost of the brass rods for the configuration described above would be about 280K CHF). We estimate that the cost of streamer-mode RPCs will have a small impact on the total, even though a precise quantification is not easy at this stage. It might also be possible to further reduce this cost by recycling old RPCs or spares from other experiments. In conclusion, we estimate that this experiment would cost about $\mathcal{O}$ CHF, including a factor of 2 safety margin to cover adapting the cryostat, building the electronics, and other contingencies.

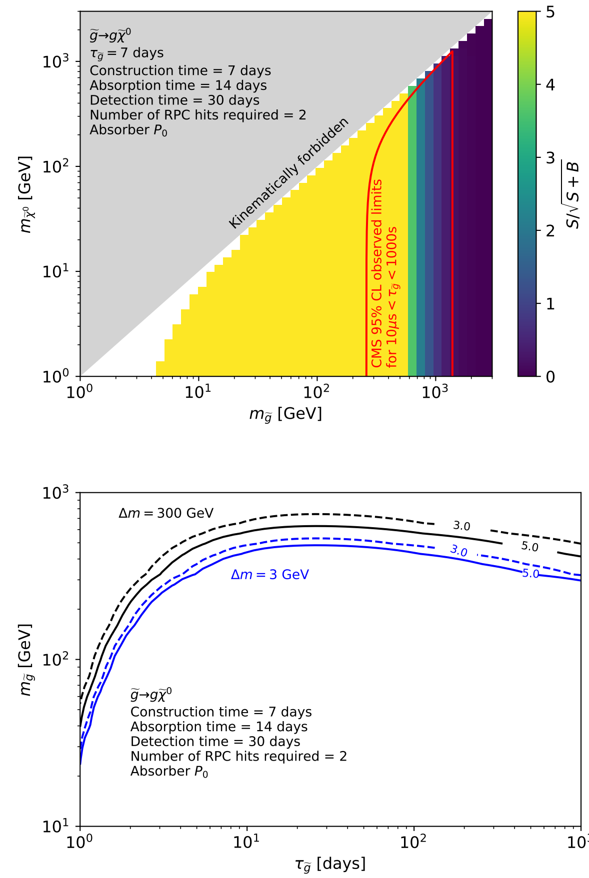

FIG. 3. The sensitivity of the experiment for a given neutralino mass and gluino mass is shown in the top plot. The grey area is kinematically forbidden. The 95% confidence level observed upper limits from CMS on the gluino cross section times branching fraction for s s [14] are shown with a red line. The sensitivity of the experiment for a given gluino mass and proper lifetime is shown in the bottom plot, for GeV (blue curves) and 300 GeV (black curves). The 3 and 5 standard deviation contours are shown with dashed and solid lines, respectively. In both plots, we assume a gluino proper lifetime of 7 days, 7 days to construct the detection setup, 14 days of absorption time, and 30 days of detection time. We also assume that 2 RPCs out of 4 detect the cosmic ray muons and that the absorber is in .

In summary, we have proposed a two-stage experiment to discover new long-lived particles that could be produced at the LHC, stop in detector material, and decay later. Compared to a typical high-energy physics experiment, this experiment has the advantage of a relatively low cost and the possibility of a discovery reach within a few months of operation. The construction could be carried out without interfering with the existing scientific operations at CERN. This experiment would bring unique sensitivity to the small mass splitting regime, that is, from about 3 to 100 GeV. It would also be uniquely sensitive to lifetimes on the order of days to years.

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SUPPLEMENTARY MATERIAL

An example of a gluino R-hadron originating from within the CMS detector and hitting a RIM detector is shown in Figure 4.

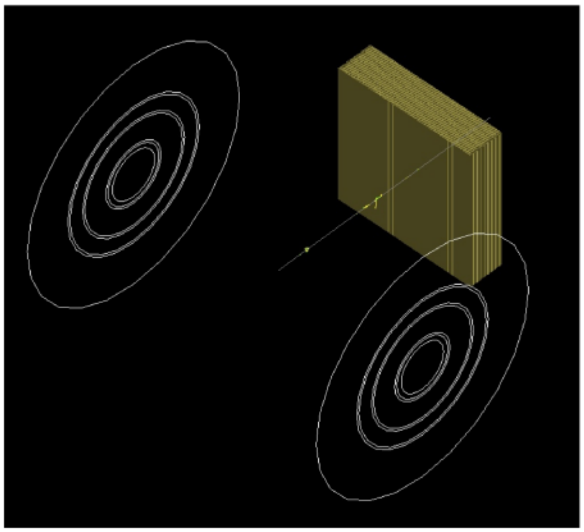

FIG. 4. Simulation showing a long-lived particle originating from within the CMS detector, hitting a RIM consisting of 100 layers of brass.

Figure 5 shows the efficiency for the gluino R-hadrons to be absorbed by the brass RIM as a function of β for different gluino masses. If the brass detector depth is increased, the absorption efficiency increases.

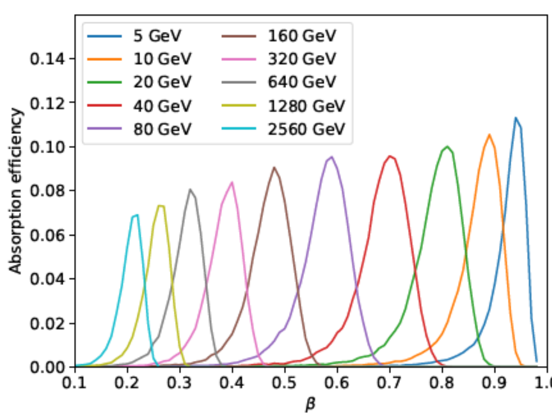

FIG. 5. Gluino R-hadron absorption efficiency for different gluino masses as a function of β.

Figure 6 shows the momentum, β and angular direction θ for the gluino R-hadrons. The angular acceptance for the two detector positions we consider are shown in gray hashed regions in the θ distribution.

The relative energy deposited in the LAr is plotted as a function of the spacing between the brass rods in Fig. 7. The cost of LAr as a function of the rod spacing is also indicated.

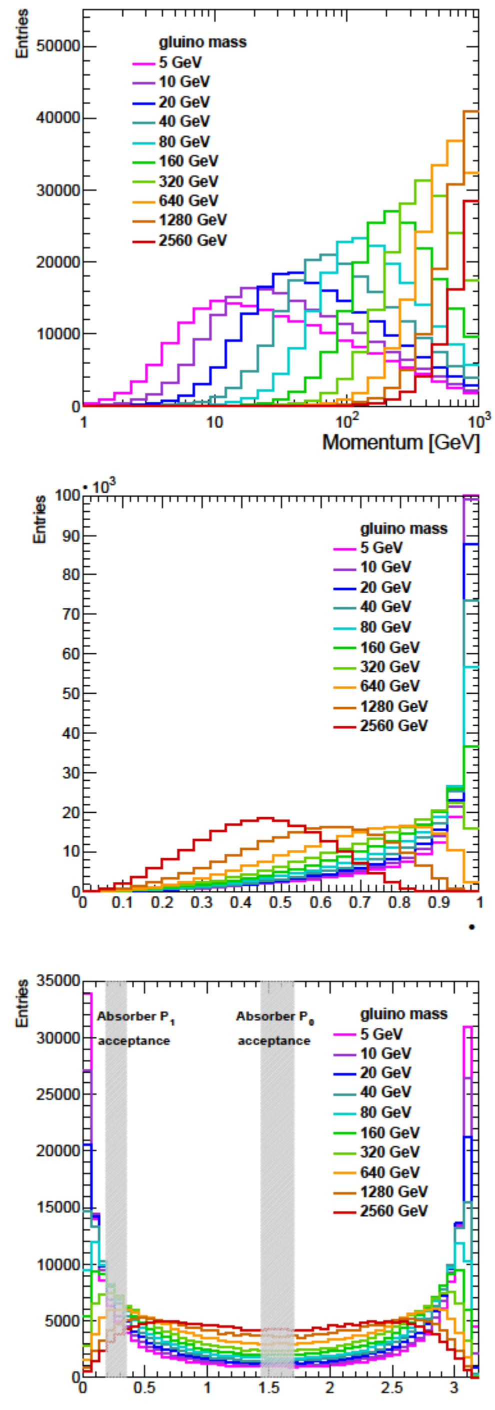

FIG. 6. Gluino R-hadron momentum (top), β (middle), and θ (bottom) for several choices of gluino mass.

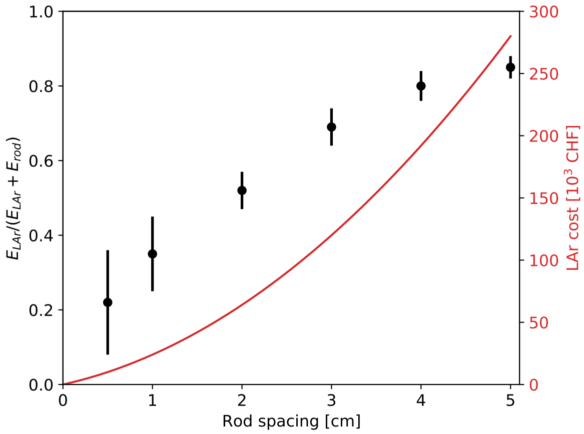

FIG. 7. The relative energy deposited in LAr with respect to that that is deposited in the LAr and the rods (black dots), as a function of the spacing between the brass rods. We assume cm cm m brass rods. The cost of LAr as a function of the rod spacing is also indicated with a red line.