EDELWEISS-III experiment: Status and first low WIMP mass results

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Abstract. The EDELWEISS-III collaboration is operating an experiment for the direct detection of Weakly Interacting Massive Particle (WIMPs) dark matter in the low radioactivity environment of the Modane Underground Laboratory. It consists of 24 advanced high-purity germanium detectors operating at 18 mK in a dilution refrigerator in order to identify rare nuclear recoils induced by elastic scattering of WIMPs from our Galactic halo. The current EDELWEISS-III program, including improvements of the background, data-acquisition and the current installation will be detailed. Sources of background along with the rejection techniques will be discussed. Detector performances and a first low WIMP mass (Boosted Decision Tree) BDT- based analysis of data acquired in a long-term campaign will be presented as well.

1. Introduction

There is strong observational evidence for the dominance of non-baryonic dark matter over baryonic matter in the universe [1]. Such evidence comes from many independent observations over different length scales. The most stringent constraint on the abundance of dark matter comes from the latest Planck results, pointing out that dark matter is contributing about 27% to the total energy density of the universe [2]. It is commonly believed that such a non-baryonic component could consist of new, as yet undiscovered, particles, usually referred to as WIMPs (Weakly Interacting Massive Particles). WIMPs are stable particles with unknown masses. Up until recently, many searches focused on the mass range from a few tens of GeV/c^2 to TeV/c^2 and a scattering cross-section wth nucleons below 10^{-42} cm^2. A number of theoretical models favoring lighter WIMP candidates have recently moved the interest of the community to the mass region below 10 GeV/c^2 and cross-sections as large as 10^{-37} cm^2. As such, light WIMPs produce only low-energy nuclear recoils O(keV), the challenge for their detection is to achieve a sufficiently low threshold, with enough background discrimination at these low energies.

2. The EDELWEISS-III Experiment

The EDELWEISS experiment is dedicated to the direct detection of WIMPs. It is designed to measure the energy released by nuclear recoils produced in an ordinary matter target by the elastic collision of a WIMP from the Galactic halo.

The main challenges are the relatively small deposited energy (<100 keV) and the expected extremely low event rate (<1 evt/kg/year), due to the very small interaction cross section of WIMPs with ordinary matter. Thus, efforts are made to ensure that the level of radioactivity of each component of the experimental setup is kept to the minimum, to shield the detectors from environmental natural radioactivity and to reduce the cosmic muon flux.

EDELWEISS-III is located in the Modane Underground Laboratory (LSM) in the Fréjus highway tunnel, where an overburden of about 1700 m of rock, equivalent to 4800 m of water, reduces the cosmic muon flux down to 5 $\mu/m^2/day$. The experimental setup is installed in a class 10000 clean room, and the immediate vicinity of the cryostat is surrounded by a constant flow of deradonised air which reduces the radon level down to $\sim$15 mBq/m^3. The flux of gamma-rays is attenuated by a 20 cm thick lead shielding around the cryostat (18 cm of lead followed by an internal 2 cm of ancient lead). An active muon veto with a geometrical coverage of 97.7% tags muons that can interact in the lead shielding producing neutrons [3]. Radiogenic neutrons coming form the rock are attenuated by more than five orders of magnitude by a 50 cm thick polyethylene shielding. To reduce the flux of neutrons arising from (α,n) reaction and fission occurring in the materials close to the detectors, an additional 10 cm polyethylene shielding has been installed between the detectors and the electronics, and the copper used in EDELWEISS-II has been replaced in large part by NOSV copper with better radiopurity (< 0.02 mBq/kg ^{238}U and ^{232}Th [4]).

To reduce environmental background, all materials used in the vicinity of the detectors have been tested for their radiopurity, using a dedicated HPGe detector [5]. In order to measure low energy recoils, EDELWEISS employs an array of twenty-four 800 g Fully Inter-Digitized (FID) cryogenic detectors (high purity Ge crystals) working at a temperature of 18 mK, with simultaneous measurements of phonon and ionization signals. The ionization signal, corresponding to the collection of electron-hole pairs on electrodes, depends on the particle type whereas the heat signal reflects the total energy deposit. The interleaved electrode design modifies the electric field lines near the surface [6], allowing to define a fiducial volume for each detector and to reject near-surface interactions. With the FID detector technology, surface events are tagged by the presence of charge on only one side of the detector: the charge collection is shared between one veto and its neighbor fiducial electrodes, whereas for events occurring in the bulk of the crystal, the charge is collected on fiducial electrodes of both sides. With a dedicated ^{210}Pb calibration, the surface event rejection factor of FID has been measured to be better than $4 \cdot 10^{-5}$ at 90% C.L., with a recoil energy threshold of 15 keV [7], leading to a fiducial volume fraction of 75%. The simultaneous measurement of two signals allows an event by event discrimination between electronic recoils caused by photons and beta decays, and nuclear recoils originated from neutrons and WIMPs. An extensive ^{133}Ba gamma calibration allows us to estimate the FID rejection power of the electronic recoils: no events with an ionization yield lower than 0.5 in a statistics of 4.1×10^5 gammas, leading to a γ rejection factor better than $6 \cdot 10^{-6}$ at 90% C.L., for a recoil energy threshold of 20 keV [8].

3. Low Mass WIMP Analysis

During 2014-2015 the collaboration operated an array of twenty-four high purity Ge detectors at 18 mK. Results from data recorded between July 2014 and April 2015 (Run308) will be discussed. We performed a blinded dedicated low threshold analysis to achieve better sensitivity to low-energy nuclear and electronic recoils, which might be induced by low mass WIMP particles. Data quality selection is based on having high sensitivity to the lowest WIMP mass achievable while keeping a good sensitivity for WIMPs with masses up to 30 GeV. The data acquisition triggers on the heat signal.The thresholds are adapted automatically online to ensure a constant trigger rate, corresponding to the lowest values achievable for each detector. The sensitivity to low mass WIMPs depends critically on the energy threshold and only periods of time where the online threshold of a given detector was below 1.5 keV$_{ee}$ are kept for the analysis. The analysis was restricted to the eight detectors with a significant exposure in these conditions. Out of these, for four detectors this heat threshold criterion could be reduced to 1 keV$_{ee}$, representing an energy

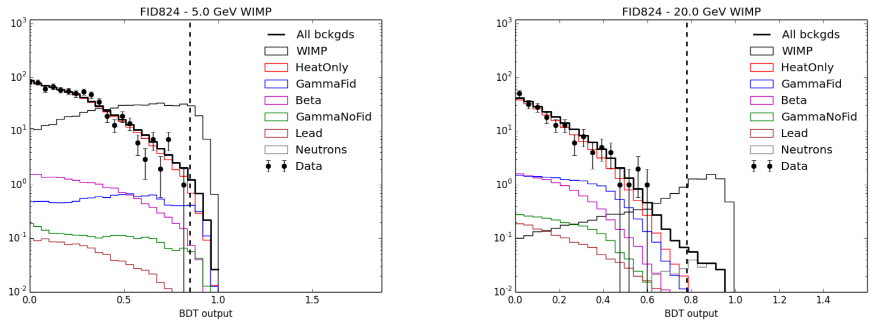

Figure 1. Simulated, pre-unblinding BDT score distributions for detector FID824 at 5 and 20 GeV WIMP mass (1 keV threshold). The histograms are normalized so that they correspond to the expected number of events given the selected data (except for the WIMP signal). The vertical dashed line shows the optimal, single-detector BDT score cut. Data points, in black, are added after BDT optimisation.

of 2.4 keV for a Ge nuclear recoil. Basic quality cuts in terms of baseline resolution, fiducial volume selection and ionization and heat signal χ^2 have been defined detector by detector and applied to the Run308 dataset. For the 582 kg·d fiducial exposure of the eight selected detectors a Boosted Decision Tree (BDT) [9] and a 2D profile likelihood analysis have been performed. The BDT analysis is detailed in the following.

Background modeling is data driven: regions without expected WIMP-signal (sidebands) are considered to build the model over the blinded dataset. Calibration data have been used for cross-checks. The considered backgrounds are: bulk gammas, surface events (betas and ^{206}Pb recoils from the ^{222}Rn decay chain and gammas), neutrons (both bulk and surface) as well as heat-only events. Heat-only events are the dominant background in FID detectors. They are probably of a mechanical origin and currently under investigation. The heat-only distribution is symmetric with respect to the fiducial ionization signal: we use the region of negative fiducial ionization signal as a clean signal to model the heat-only background, as the probability for a nuclear recoil above 1 keV$_{ee}$ to have a negative ionization measurement is negligible. Bulk gammas have been modeled over low background blinded data in the fiducial volume. A fit in the region [3-15] keV$_{ee}$ heat of the main cosmogenic K-shell lines ^{68}Ge, ^{68}Ga and ^{65}Zn has been performed. The flat Compton scattering component is extrapolated down to zero energy. Cosmogenic L-shell lines are modeled with an intensity derived from the fitted K-shell intensity [10]. For the surface events the background model is fitted for events in a non fiducial volume: the beta model consists of a spline function adjusted in the energy range [4-25] keV$_{ee}$ extrapolated down to zero energy. Recoils of ^{206}Pb are fitted by a flat component plus a gaussian peak in the heat energy region [10-35] keV$_{ee}$. Finally, surface gammas are modeled via a fit in [3,15] keV$_{ee}$ heat energy with a flat component plus K and L-shell cosmogenic lines. The intensity of the cosmogenic lines is scaled from intensity of the corresponding fiducial lines with fiducial mass fraction. For each of the aforementioned backgrounds, data-driven quenching factor models are used.

For each detector, a large set of events is drawn for all the background categories described above, as well as for simulated WIMP signals at different masses. A simulated event consists of six variables: the four ionization signals collected on fiducial and veto electrodes on both sides, a single (combined) heat signal and a time-related variable. For each simulation, the first five variables are drawn taking into account experimental resolutions and their correlation. For WIMPs, we use the standard formula [11] with standard halo model parameters: we consider

Journal of Physics: Conference Series **718** (2016) 042053 doi:10.1088/1742-6596/718/4/042053

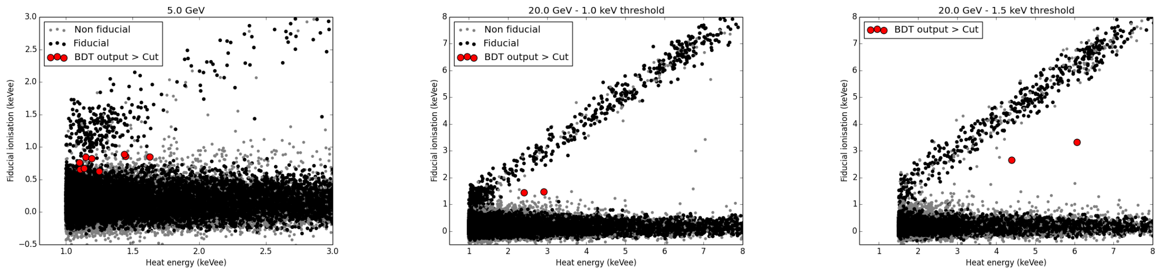

Figure 2. Candidate events are highlighted in red in the (E_{ion}, E_{heat}) plane. Black markers represent events passing the fiducial selection, grey markers failing the fiducial selection. Candidate events recorded in the four detectors with a threshold of, from left to right, 1 keV_{ee} for a 5 GeV WIMP mass, 1 keV_{ee} for a 20 GeV WIMP mass and 1.5 keV_{ee} for a 20 GeV WIMP mass.

only fiducial WIMPs and an ionization yield of $Y = 0.16 \cdot E_{rec}^{0.18}$, where E_{rec} is the energy deposit in the crystal.

A 'WIMP box' cut is then applied to both simulated and real events. It allows the BDT algorithm to focus on the region of interest. The box is defined as follows:

- Veto signals smaller than 5σ of the respective baseline resolutions, in order to remove obvious non-fiducial events.
- Positive ionization energy, allowing a clear separation between the heat-only sideband and the potential WIMP region.
- $E_{heat} < 15$ keV and $E_{ion} < 8$ keV.

A BDT is constructed for each of the eight detectors, and for each of the WIMP masses 3, 4, 5, 6, 7, 10, 15, 20 and 30 GeV. An example of a simulated BDT score distribution is shown in Fig. 1, for the WIMP masses 5 and 20 GeV. These distributions are very similar for all detectors, for a given threshold and WIMP mass. Among all modeled backgrounds, the most relevant for low-mass WIMP searches (5 GeV) are clearly fiducial gamma-rays and heat-only events. In all configurations, surface or surface-like events are subdominant, including at high values of the BDT score. At higher WIMP masses, the neutron background clearly becomes the dominant contribution. BDT score cuts are defined for each WIMP mass before unblinding, so that a WIMP limit is then obtained by Poisson statistics after these BDT cuts, without background subtraction. For all WIMP masses, the observed number of events after all cuts is always larger than expected according to the baseline background model. The excesses are associated with different events and detectors depending on the WIMP mass. The strongest excess is for a 7 GeV WIMP, for which 6 events are observed with respect to 1.77 expected.

All candidate events are located well within the fiducial nuclear recoil region, as shown in Fig. 2. The expected number of radiogenic neutron events in the 20 GeV analysis is two, with a large systematic error, and can explain the four events observed in the center and right panel of Fig. 2. For low mass WIMPs (e.g. 5 GeV, left panel of Fig. 2), the BDT ascribes relevant score to events below a few keV only, and the neutron background is expected to be negligible. All candidates lie close in-between the population due to the 1.3 keV L-line from cosmic activation and the abundant heat-only background. The three highest-energy events (heat signals in the energy region [1.4-1.8] keV_{ee}) come from the same detector, but no biases in the event reconstruction for this detector have been identified.

Figure 3 shows the derived limit. It results in an improvement of a factor of 40 at 7 GeV compared to EDELWEISS II [12], mostly due to a factor ~2 improvements in the heat threshold

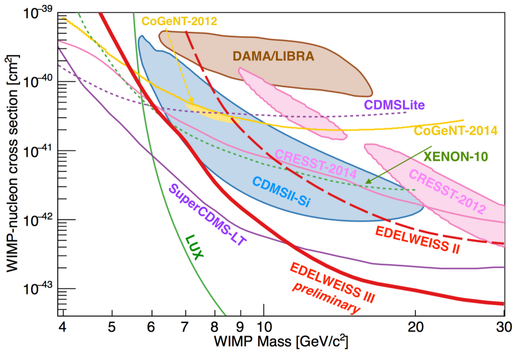

Figure 3. Preliminary limits on the cross-section for spin-independent scattering of WIMPs off nucleons as a function of WIMP mass.

and in the ionization resolution, the latter helping the discrimination against heat-only events.

4. Conclusion

Results of a blinded, low mass WIMP analysis performed for 582 kg·d (fiducial) have been presented. They show an improvement of a factor 40 (at 7 GeV WIMP mass) and a factor 8 (at 30 GeV), compared to the analysis of the previous generation of ID detectors performed with a fiducial exposure of 113 kg·d [12], see Fig. 3. A cross-check with a 2D profile likelihood analysis has been carried out and post-unblinding checks are ongoing. Papers detailing both analyses are in preparation.

The current ongoing runs focus on development aimed at reducing the thresholds for improved sensitivity for low-mass WIMPs, via the elimination of heat-only events, improved heat resolutions, and the amplification of the heat signal via the Luke-Neganov effect [13].

Acknowledgements

The help of the technical staff of the Laboratoire Souterrain de Modane and the participant laboratories is gratefully acknowledged. The EDELWEISS project is supported in part by the German ministry of science and education (BMBF Verbundforschung ATP Proj.-Nr. 05A14VKA), by the Helmholtz Alliance for Astroparticle Phyics (HAP), by the French Agence Nationale pour la Recherche (ANR) and the LabEx Lyon Institute of Origins (ANR-10-LABX-0066) of the Université de Lyon within the program "Investissements d'Avenir" (ANR-11-IDEX-00007), by the P2IO LabEx (ANR-10-LABX-0038) in the framework "Investissements d'Avenir" (ANR-11-IDEX-0003-01) managed by the ANR (France), by Science and Technology Facilities Council (UK), and the Russian Foundation for Basic Research (grant No. 15-02-03561).

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