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**ν BDX: a Coherent Elastic Neutrino
Nucleus Scattering ($\text{CE}\nu\text{NS}$) experiment
at Jefferson Lab**

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1 Introduction

Particle physics is an ever-changing field seeking to explain phenomena that lie at the limits of our current knowledge. Among discovered and hypothesized interactions, Coherent Elastic Neutrino-Nucleus Scattering ($\text{CE}\nu\text{NS}$) stands out as a

fascinating and elusive phenomenon, offering a unique window into the nature of neutrinos and their interactions with matter.

$\text{CE}\nu\text{NS}$, a process predicted by the Standard Model, represents one of the subtle ways in which neutrinos can interact with atomic nuclei. Unlike other neutrino-nucleus interactions, $\text{CE}\nu\text{NS}$ occurs coherently, meaning that the entire nucleus collectively responds to the neutrino-mediated weak force, resulting in small energy transfers to the nucleus as a whole.

The extremely rare nature of $\text{CE}\nu\text{NS}$ events presents a formidable challenge to experimenters seeking to detect and study these interactions. Recent advances in detector technologies and the implementation of large-scale experiments, such as coherent neutrino scattering experiments at research facilities around the world, have opened up new avenues for exploring this elusive phenomenon. These experiments aim not only to observe $\text{CE}\nu\text{NS}$ directly but also to extract valuable information on neutrino properties, nuclear structure, and potential deviations from the Standard Model.

This thesis aims to study the feasibility of an experiment to study $\text{CE}\nu\text{NS}$ at The Thomas Jefferson National Accelerator Facility, Newport News, VA, USA. This would be an experiment that exploits the production of neutrinos by an electron beam dumped on a thick target (the beam dump). The large quantity of neutrinos produced and their energy profile are well suited to the purpose of studying the $\text{CE}\nu\text{NS}$. In my thesis, I will start from previous studies on $\text{CE}\nu\text{NS}$ and from theoretical considerations regarding the process, then quantify the expected events for a hypothetical experiment and possible backgrounds through simulations aimed at optimizing the geometry of the future detector. I will also show some tests on selected detector components that will be part of a first prototype.

2 Coherent elastic neutrino-nucleus scattering ($\text{CE}\nu\text{NS}$)

2.1 Neutrinos properties

Neutrinos are very special particles. It is known that their mass is different from zero, but until now, it has not been precisely measured. The lower limit put their masses several orders of magnitude lighter than all other fermions. Neutrinos have a neutral charge and are not subject to electromagnetic interactions. Being fermions, they are not subjected to strong interaction either and interact extraordinarily weakly with matter. Neutrinos with energy $E_\nu \sim \text{MeV}$ have a typical nucleon interaction cross-section of order $\sigma \sim 10^{-44} \text{ cm}^2$; this corresponds to a very little probability of interacting with a meter-long solid detector. Neutrinos are produced from different processes: thermal, solar, atmospheric, reactor, and accelerator neutrinos. Neutrinos are very abundant particles in the universe, so much that we are permeated by neutrinos produced when the universe was young and hot. Several billions of solar neutrinos, produced in the Sun's core by nuclear reactions, cross each square centimeter of our body every second. A large number of neutrinos is emitted in a few seconds following the gravitational collapse of a massive star that triggers one supernova explosion. Stars, supernovae, and other astrophysical objects can be “seen” with neutrinos. Thanks to their low interaction, they can be used as a precious “messenger” for studying distant objects. The neutrino cross section's very low intensity is also the biggest problem for detecting them since very massive detectors are required to have appreciable interaction event rates.

The existence of the electron neutrino was postulated in 1930 by Wolfgang Pauli [1] to explain the continuous spectrum of beta decay. It was also studied by Enrico

Fermi, who also coined the name at the Paris Conference in 1932 [2] but discovered only 24 years later, in 1956, by physicists Clyde Cowan and Fred Reines during a Nobel-prize experiment performed at the Savannah River fission reactor [3].

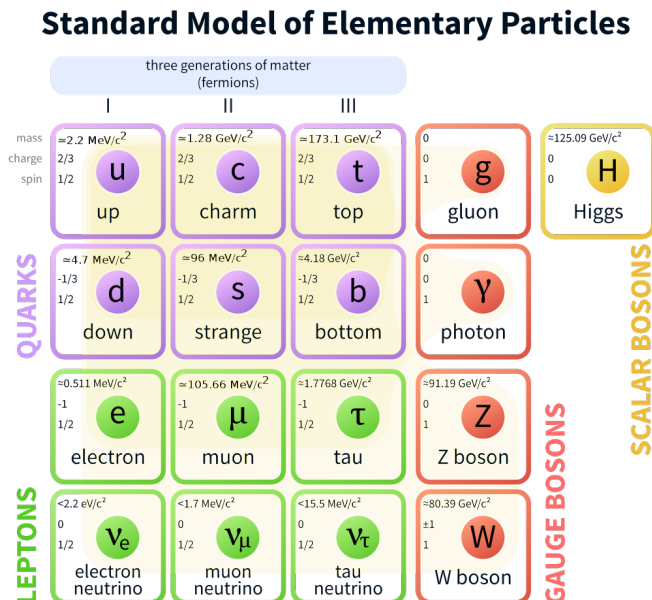


Figure 1: Summary view of the Standard Model

There are three different types of neutrino: electron ν_e , muonic ν_μ , and tauonic ν_τ , in direct relation respectively to the leptons of the standard model (electron, muon, and tau) (fig. 1). The existence of three families of neutrinos has been assessed at the Large Electron-Positron Collider, measuring the decay width of the Z_0 boson [4]. Neutrinos have two types of interactions: they can couple with a neutral Z_0 boson, changing their 4-momentum but keeping their identity (neutral current interactions) [5], or they can couple with a charged W boson “transforming” into one of the charged leptons e , μ or τ (charged current interactions) [6]. Several experiments (e.g. Super-Kamiokande [7], Sudbury Neutrino Observatory [8], and KamLAND [9]) proved the phenomenon known as “flavor oscillation” of neutrinos, that causes the particle to change from one “family” to another as already theor-

ized by the physicist Bruno Pontecorvo in 1957 [10]. Such flavor changes require that neutrino flavors have different masses. This, in turn, implies that neutrinos are not massless [11, 12]. The Standard Model of particles and their interactions (SM) provides the framework to describe how neutrinos interact with leptons and quarks through the weak force. However, some aspects of neutrinos are not very well explained in SM.

By observing neutrinos and their behavior in experiments such as neutrino oscillation experiments or neutrinoless double beta decay searches [13], scientists can uncover new physics phenomena that lie beyond the scope of the Standard Model [14]. Investigating neutrinos and their properties offers insights into some of the most pressing questions in modern physics, such as the nature of dark matter [15, 16], the matter-antimatter asymmetry in the universe [17], and the unification of fundamental forces [18]. These questions transcend the boundaries of the Standard Model and require the exploration of new theoretical frameworks and experimental approaches, in which neutrino physics plays a crucial role.

2.2 $\text{CE}\nu\text{NS}$

The low-energy, below MeV-scale, is especially important in elucidating the neutrino properties, such as their mass differences and mixing properties [11, 12]. Neutrinos can be detected via different processes. These include neutrino-electron elastic scattering ($\nu + e \rightarrow \nu + e$), as well as neutral and charged current inelastic interactions on nucleons and nuclei [19]. These interactions are often modeled as point-like interactions with fundamental particles. The neutrino can interact directly with individual particles such as electrons or nucleons (protons and neutrons) without considering their internal structure. As the energy of the neutrino

increases into the MeV range, its interactions with the nucleus become more prominent. Neutrino can interact coherently with the entire atomic nucleus as a single entity rather than with individual nucleons or electrons. This coherent interaction arises due to the weak nuclear force acting collectively on all the nucleons within the nucleus.

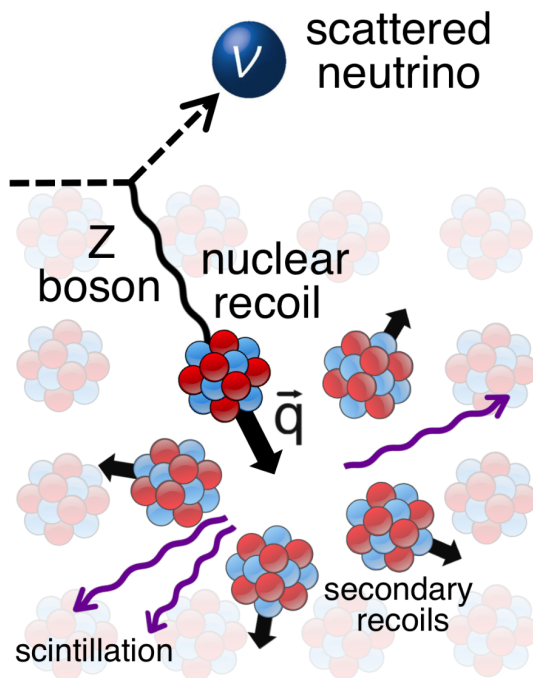


Figure 2: $\text{CE}\nu\text{NS}$ process schematic

Coherent elastic neutrino-nucleus scattering ($\text{CE}\nu\text{NS}$) is a process in which neutrinos scatter on a nucleus (fig. 2), which acts as a single particle [21]. When the neutrino-nucleus momentum transferred is small enough ($q < 200$ MeV), the individual nucleon amplitudes sum up coherently, enhancing the neutrino-nucleus cross-section. Within the SM, $\text{CE}\nu\text{NS}$ is described at a fundamental level by the neutral current interaction of neutrinos and quarks. The neutrino-nucleus scattering, mediated by Z_0 boson exchange, provides an excellent laboratory to test the basic principles of quantum physics and a bench test for the SM and

physics beyond.

Accounting for nucleus neutron and proton distributions independently and assuming that their root-mean-square(rms) radii are different, the Standard Model CE ν NS differential cross-section can be written as follows:

$$\frac{d\sigma}{dE_r} = \frac{m_N G_F^2}{2\pi} \left(2 - \frac{E_r m_N}{E_\nu^2} \right) Q_W^2$$

where G_F is the Fermi constant, E_r is nuclear recoil energy, m_N is nuclear mass, E_ν is neutrino energy, and Q_w is the weak charge of the nucleus. Q_w depends on neutron and proton number(N , Z), on proton/neutron couplings vector current (g_V^n , g_V^p), and proton/neutron form-factors of the nucleus.

$$Q_W^2 = [N g_V^n F_N(q) + Z g_V^p F_Z(q)]^2$$

The nucleon form factor takes into account that, at higher energies, the scattering is not completely coherent and encodes information about the nuclear densities through a Fourier transform, which in spherical nuclei takes the approximate form [22]:

$$F(q) = \int [\rho_n(r) - (1 - 4 \sin^2 \theta_w) \rho_p(r)] \times \frac{\sin(qr)}{qr} r^2 dr$$

where q is the 3-momentum transferred by the neutrino, $\rho_{n,p}(r)$ are neutron/proton densities, and θ_w is the weak mixing angle or Weinberg angle. The form factor is ~ 1 if $|q|R_A \ll 1$ being R_A the nucleus radius. The form factor vanishes at $|q| \rightarrow \infty$. As shown in the figure 3, it depends on the nucleus size, dropping rapidly for heavy nuclei.

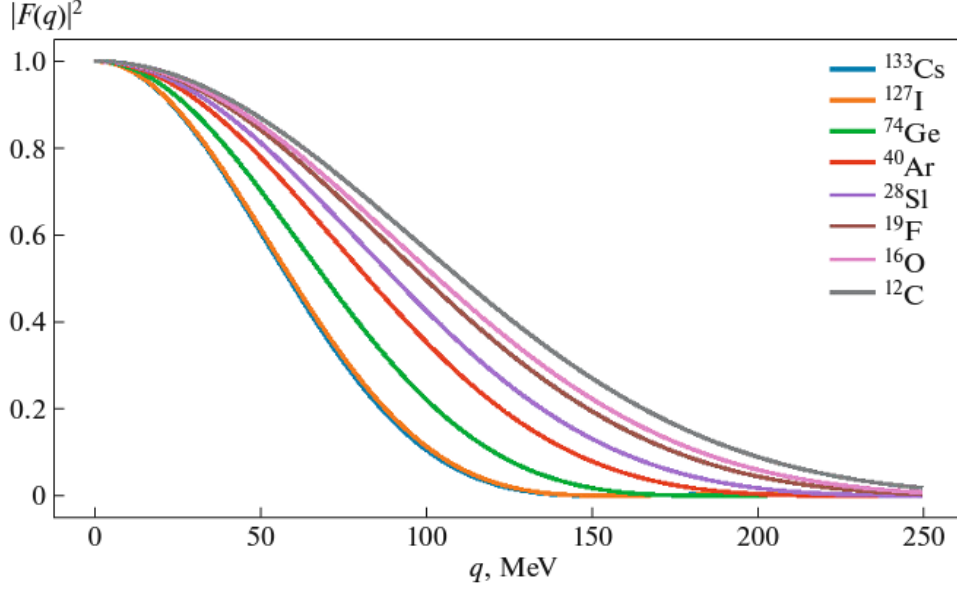


Figure 3: Form factor dependence to q from various nucleus

The proton and neutron vector coupling are determined by the up and down quark weak charges $g_V^p = 1/2 - 2 \sin^2 \theta_W$ and $g_V^n = -1/2$ [23]. Considering that $\sin^2 \theta_W \sim 1/4$, g_V^p is negligible with respect to g_V^n . Consequently, the cross-section of the CE ν NS is proportional to N^2 (fig. 4), and the nucleus form factor squared (normalized to 1), but the first behavior dominates on the form factor drop. Considering the dependence of the CE ν NS process on N^2 , heavy nuclei have a larger interaction cross-section.

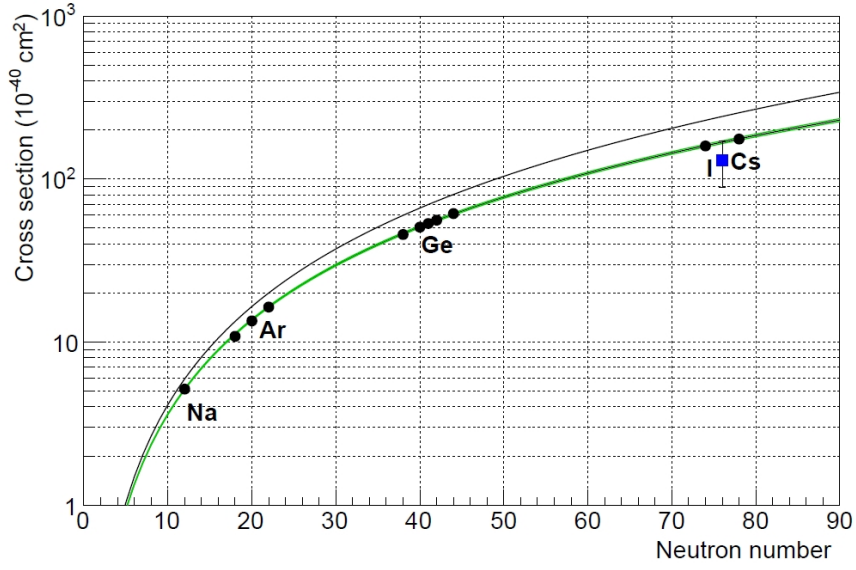


Figure 4: N^2 cross-section behavior for some neutrino scattering off nuclei

Inelastic or incoherent scattering, whose cross-section is proportional to $|1-F(q)|^2$, competes with $CE\nu NS$ at high energy while at low momentum transferred, where the form factor ~ 1 , coherent scattering dominates. In contrast, as the energy increases and the form factor decreases, inelastic scattering becomes more and more significant. Though the total cross section is large compared with neutrino interactions, $CE\nu NS$ has long proven difficult to detect since the energy transferred to the nucleus is quite small, in the range of a few keV.

2.3 Neutrino Artificial Source

Among artificial neutrino $O(1-100 \text{ MeV})$ sources, nuclear fission reactors play a significant role. During the fission reaction, several isotopes undergoing a decay β are formed, producing electrons and large fluxes of $\bar{\nu}_e$ [24] (fig. 5). A commercial fission reactor of $\sim \text{GW}$ electric power produces about 10^{20} anti-neutrinos per second. Unfortunately, the $\bar{\nu}_e$ energy has an upper bound of 7 MeV, limiting

their use to low-energy studies. Furthermore, these are steady-state sources, and backgrounds must be carefully kept under control.

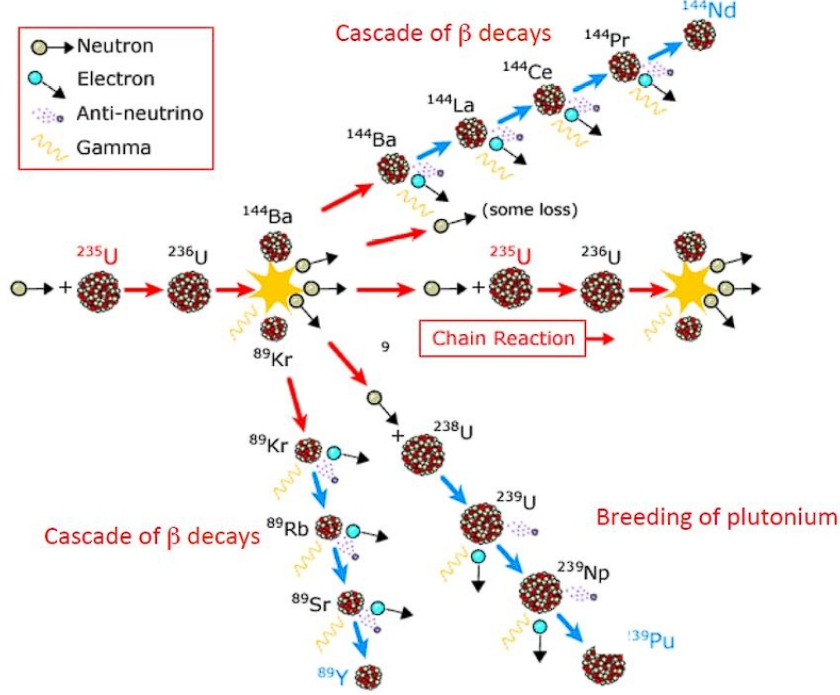


Figure 5: Reaction in a nuclear reactor. Particles production is shown, where purple flux corresponds to electron anti-neutrinos. In purple, anti-electron neutrinos

In recent years, the possibility of using the pion decay at rest (stopped-pion) as a neutrino source in beam facilities [25] has become of great interest. The idea is to irradiate a high-density nuclear target with a $\sim \text{GeV}$ proton beam or electron beam. In the interaction, a large number of pions are produced. Such low-energy pions mainly decay at rest, producing muon neutrinos, electrons, and muon anti-neutrinos with a well-defined energy spectrum. Compared to neutrinos produced in reactors, those stemming from pion decay typically exhibit a lower flux. However, their unique advantage lies in their ability to encompass all three neutrino flavors: electron neutrinos, muon neutrinos, and tau neutrinos (from neutrino-

oscillation processes). This diversity makes neutrinos from pion decay particularly well-suited for a wide array of studies and experimental investigations. In CE ν NS studies, accelerator-based neutrino sources offer several advantages compared to reactor-based sources, including controlled energy spectra, known neutrino flavor compositions, experimental flexibility, access to different neutrino energies, and opportunities for cross-verification.

2.4 COHERENT collaboration experiment

The COHERENT collaboration has assembled various kinds of detector technologies suitable for the first observation of CE ν NS at the Spallation Neutron Source (SNS) at ORNL Oak Ridge National Laboratory, a flux pulsed, stopped-pion neutrino source.

These experiments are located at a distance of 19-28 m from the target in the basement of the SNS, known as “Neutrino Alley” [26]. With a 1 GeV proton beam, the flux predicted is 4.7×10^7 neutrinos/(cm²s) 20m away from the target (fig. 6). Despite the proximity to the SNS beamline, beam-related neutrons are suppressed by a concrete fill between Neutrino Alley and the SNS target. An 8 m.w.e (meter water equivalent) of overburden materials reduces cosmogenic background.

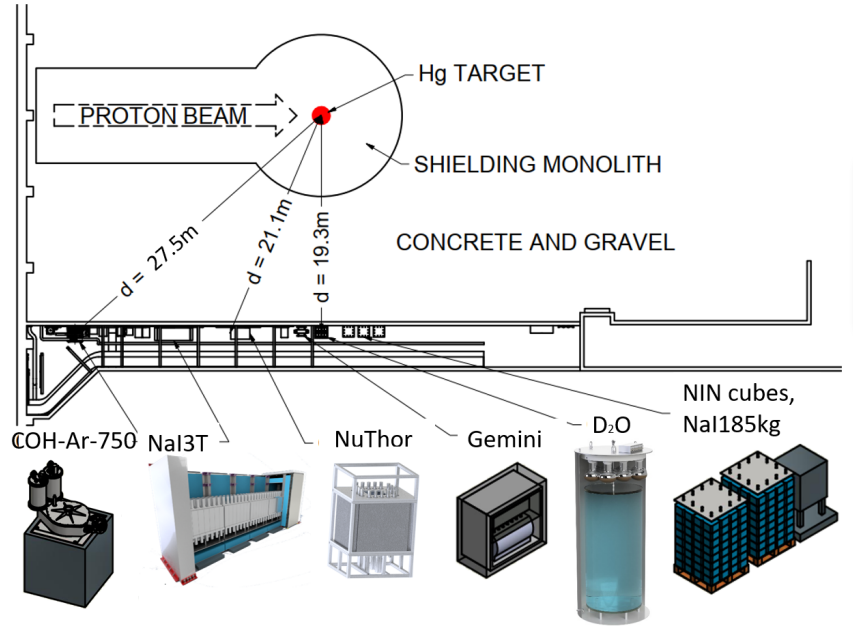


Figure 6: Location of Detector Systems in Neutrino Alley at SNS facility

The COHERENT collaboration used the technological development within the dark-matter direct-detection community over the last decade by deploying three mature low-threshold/low-background technologies capable of observing low-energy nuclear recoils: CsI(Na) scintillator, p-type point-contact(PPC) germanium detectors, and two-phase liquid xenon TPC. Using targets with different numbers of neutrons, the experiment provided a ready test of the N^2 nature of the cross-section. In contrast, the use of two different technologies for the heaviest targets(CsI(Na) and Xe) allows a convenient cross-check of the measured cross section for the two systems most susceptible to systematic errors related to detector response (quenching factor, QF). The three detector subsystems were installed in the SNS basement hallway, where a background measurement campaign indicated a very low beam-related neutron background. In 2017, the COHERENT collaboration announced the detection of $\text{CE}\nu\text{NS}$ using a stopped-pion source with a CsI(Na) scintillating crystal detector [27] (fig. 7).

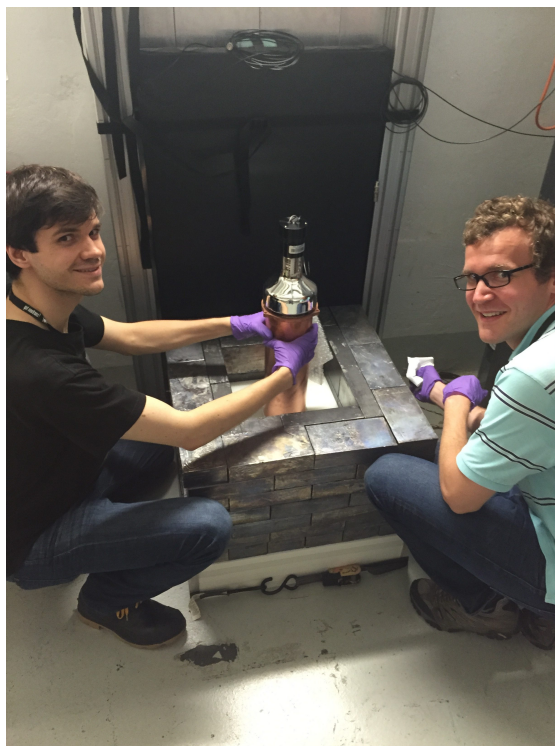


Figure 7: COHERENT collaboration CsI(Na) Detector

This was followed up by the detection of $\text{CE}\nu\text{NS}$ with a single-phase liquid argon target [29] and with a larger exposure of CsI(Na) [30]. The detection of $\text{CE}\nu\text{NS}$ has motivated a flurry of theoretical activity in high-energy physics, inspiring new constraints Beyond the Standard Model (BSM) physics. While the Standard Model of particle physics predicts $\text{CE}\nu\text{NS}$, the precision and sensitivity of experiments targeting this phenomenon also make them well-suited for probing potential deviations from the Standard Model. Any unexpected observations in $\text{CE}\nu\text{NS}$ experiments could be indicative of new physics, including interactions involving dark matter particles. This argument motivated the development of larger-scale detectors and technologies to extend current detector sensitivity into lower, sub-keV scale energy regimes. Therefore, in addition to providing a new channel for detecting neutrinos, there are many interesting physics applications of $\text{CE}\nu\text{NS}$ -based experiments. One such example is the search for low-mass, sub-

GeV-scale Dark Matter(DM) particles.

Searches for accelerator-produced DM are of particular interest. Experiments capable of seeing low-energy nuclear recoils associated with $\text{CE}\nu\text{NS}$ can search for an analogous coherent elastic DM-nucleus scattering process [31].

The previous experiments put some constraints on the coupling between DM and leptons. $\text{CE}\nu\text{NS}$ experiments can be sensitive to coherent DM-nucleus scattering, thus probing the quark coupling. This is important because the hadronic and leptonic DM couplings may differ radically. The COHERENT collaboration probed the potential of its experiments to shed light on DM succeeding in improving the interaction cross section upper limit in the mass range between 11 and 165 MeV/c^2 . Furthermore, $\text{CE}\nu\text{NS}$ experiments provide a means to precisely characterize background signals caused by neutrinos, which are notoriously difficult to detect due to their weak interactions with matter. By understanding and measuring $\text{CE}\nu\text{NS}$, researchers can refine their ability to distinguish neutrino-induced and potential signals from dark matter interactions. The sensitivity of dark matter detectors relies heavily on accurate calibration and validation. $\text{CE}\nu\text{NS}$ is an excellent calibration source for these detectors since it produces well-understood signals in a controlled environment. This allows researchers to fine-tune their detectors, ensuring that observed signals are more likely to be attributed to dark matter interactions rather than instrumental or environmental effects.

Beyond dark matter, $\text{CE}\nu\text{NS}$ -like experiments may be deployed to study long-sought-after particles such as axions [32].

2.4.1 CENNS-10

The pulsed beam in the SNS accelerator has a fine time structure, which consists of 695ns long mini-pulses separated by 250ns gaps in order to minimize transient beam losses in the accumulator ring, which could arise during the ring extraction kicker rise time [28]. Collaboration reported a 3σ CE ν NS signal using a LArTPC [29]. The detector was a compact single-phase liquid Argon TPC equipped with top and bottom PMTs (fig. 8), capable of measuring (only) the scintillation light produced by the nucleus recoil ionization. Using LAr pulse shape discrimination (PSD), it was possible to separate scattering on electrons (1.6 μ s) and nuclei (6 ns). PSD was also used to reduce some of the backgrounds. The primary background sources are related to cosmic rays, beam-related neutrons, and β emitted by ^{39}Ar contamination. Cosmic rays and ^{39}Ar backgrounds were reduced by requiring a tight time coincidence with the spill of the (pulsed) beam. Beam-related neutrons were reduced by water shielding. The remaining background was then subtracted by comparing beam-on and beam-off runs. The recoil energy threshold was set to 20 keVr, while the maximum energy detected was 120 keVr. In about a year run, CENNS-10 detected ~ 130 CE ν NS events. The collaboration is currently working on a new, larger detector. A new run is expected shortly.

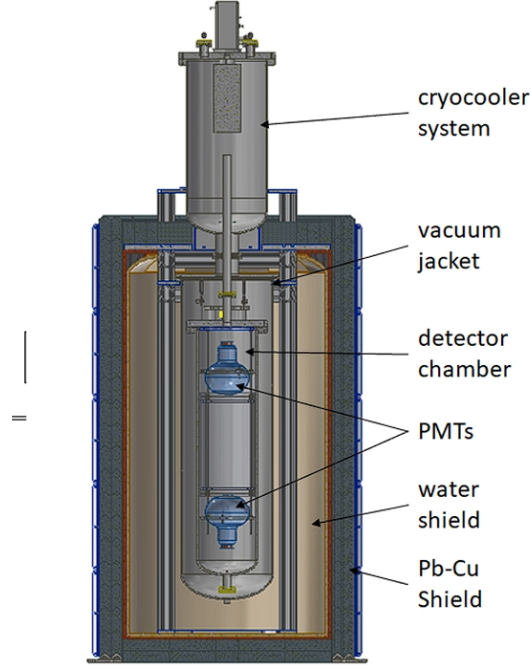


Figure 8: CENNS-10 Detector [29]

2.5 Physics interest

2.5.1 $\text{CE}\nu\text{NS}$ as a new probe

Measurements of the $\text{CE}\nu\text{NS}$ event spectrum can be used to extract information on the weak mixing angle and the rms radius of neutron distribution in nuclei.

The Weak Mixing Angle (WMA) is a parameter in the electroweak interaction theory, which is part of the SM. The WMA establishes the relationship between the neutral current(NC) and the electromagnetic interaction. It also shows the relationship between the masses of the W and Z bosons [33–35].

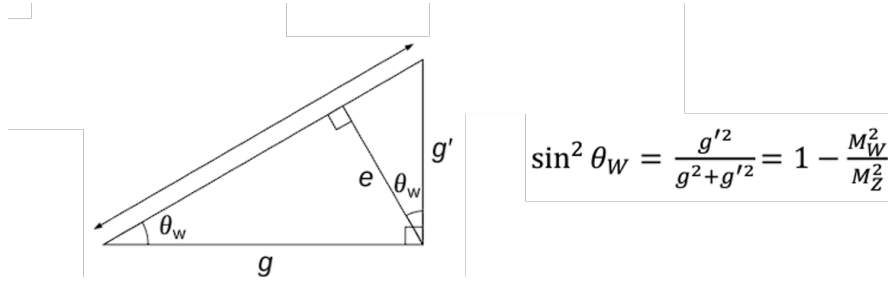


Figure 9: Weak Mixing angle relation with boson mass and coupling parameter [36]

The coupling parameters g and g' depend on the transferred momentum q and the WMA's value θ_W (fig. 9). The weak mixing angle has been measured with great precision at high energies [37, 38]. It comes from the right-left Z_0 pole production asymmetry measured at SLAC [37] and the $Z_0 \rightarrow b^- b$ forward-backward asymmetry measured at LEP1 [38]. At low energies, the measurement of WMA is demonstrated to be a difficult task. Low-energy measurements of $\sin^2 \theta_W$ at $q \ll m_Z$ include atomic parity violation in caesium at $q \simeq 2.4 \text{ MeV}$ [40, 41], electron-electron Møller scattering at $q \simeq 160 \text{ MeV}$ [42], and ν_μ -nucleus deep-inelastic scattering at $q \simeq 5 \text{ GeV}$ [43]. The $\text{CE}\nu\text{NS}$ process can be an additional and independent probe to extract this parameter. $\text{CE}\nu\text{NS}$ occurs at a low momentum transferred ($\leq 100 \text{ MeV}$), and its cross-section is directly related to WMA:

$$\sigma \propto Q_W^2 \propto (N - (1 - 4 \sin^2 \theta_W)Z)^2$$

In addition to the WMA, the $\text{CE}\nu\text{NS}$ cross section depends on the nucleus form factor f , which, in turn, depends on the neutron radius R_n . The measurement of neutron distribution rms radius in nuclei is relevant since, combined with the rms radius of the proton distribution, it defines the neutron skin thickness of a nucleus, $\Delta r_{np}(\text{nucleus}) = r_n^{\text{rms}} - r_p^{\text{rms}}$. This quantity is relevant in nuclear physics, and astrophysics [44]. For instance, nuclear physics plays an important role in

the nuclear energy density function [45]. At the same time, astrophysics allows the prediction of neutron star properties such as its density and radius [46]. A clean direct measurement of the neutron rms radius has been done only for ^{208}Pb by the PREX experiment at the Jefferson Laboratory [47]. The rms radii for other nuclides have been mapped using hadronic experiments and suffer from large uncontrolled uncertainties [48].

2.5.2 Neutrino Non-Standard Interaction (NSI)

Neutrino NSI is a four-fermion contact interaction that parametrizes a new hypothetical vector force relative to the electroweak interaction in terms of a set of flavored-dependent new parameters [49]. NSI is described by the effective four-fermion interaction Lagrangian:

$$\mathcal{L}_{\text{NSI}}^{\text{NC}} = -2\sqrt{2}G_{\text{F}} \sum_{\alpha,\beta=e,\mu,\tau} (\bar{\nu}_{\alpha L} \gamma^{\rho} \nu_{\beta L}) \sum_{f=u,d} \epsilon_{\alpha\beta}^{fV} (\bar{f} \gamma_{\rho} f),$$

where G_F is the Fermi constant, and the parameters $\epsilon_{\alpha\beta}^{fV}$ describe the size of non-standard interactions relative to standard neutral-current weak interactions. The axial current parameters generate spin-dependent interactions and are poorly constrained. From the hermiticity of the Lagrangian, we have $\epsilon_{\alpha\beta}^{fV} = \epsilon_{\beta\alpha}^{fV*}$. The strongest constraints on vector neutral-current neutrino non-standard interactions have been obtained from the data analysis of solar and atmospheric neutrino oscillation experiments [50].

If present, neutrino NSI would modify the $\text{CE}\nu\text{NS}$ differential cross-section. Being the interaction mediated by a vector field, the flavor diagonal couplings interfere with the SM contribution; the interference can be constructive or destructive depending on the sign the coupling comes along with. In contrast, off-diagonal

couplings always enhance the SM cross-section. Assuming equal rms radii for the proton and neutron distributions, the modified cross-section changes the coherent weak charge according to the relation:

$$\frac{d\sigma}{dE_r} = \frac{G_F^2 m_N}{2\pi} \left\{ (G_V + G_A)^2 + (G_V - G_A)^2 \left(1 - \frac{E_r}{E_\nu}\right)^2 - (G_V^2 - G_A^2) \frac{m_N E_r}{E_\nu^2} \right\}$$

$$G_V = \left[(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}) Z + (g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}) N \right] F_{nucl}^V(q),$$

$$G_A = \left[(g_A^p + 2\varepsilon_{ee}^{uA} + \varepsilon_{ee}^{dA}) (Z_+ - Z_-) + (g_A^n + \varepsilon_{ee}^{uA} + 2\varepsilon_{ee}^{dA}) (N_+ - N_-) \right] F_{nucl}^A(q)$$

where E_r is the nucleus recoil energy, $Z \pm (N \pm)$ is the number of protons(neutrons) with spin up (+) and spin down (-). The vector and axial nuclear form factors, $F_{nucl}^V(q)$ and $F_{nucl}^A(q)$, are usually assumed to be equal and of the order of unity in the limit of small energies, $q^2 \ll M^2$. It is possible to neglect the axial contribution in coherent neutrino-nuclei interaction since the ratio of axial to vector is expected to be of the order of $1/A$ for most of the nuclei. For example, cases where the axial contribution is important are scattering off hydrogen or nuclei with high spin [51].

Given this consideration, the cross-section of coherent scattering off a nucleus is in the low energy limit.

$$\frac{d\sigma}{dT}(E_\nu, E_r) = \frac{G_F^2 m_N}{\pi} \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) \times$$

$$\times \left\{ \left[Z(g_V^p + 2\varepsilon_{aa}^{uV} + \varepsilon_{aa}^{dV}) + N(g_V^n + \varepsilon_{aa}^{uV} + 2\varepsilon_{aa}^{dV}) \right]^2 + \right.$$

$$\left. + \sum_{a \neq b} \left[Z(2\varepsilon_{ab}^{uV} + \varepsilon_{ab}^{dV}) + N(\varepsilon_{ab}^{uV} + 2\varepsilon_{ab}^{dV}) \right]^2 \right\}.$$

This expression can be used to compute the expected number of NSI events for different detectors. NSI could affect the way neutrinos interact with nucleons and nuclei, including Coherent Elastic Neutrino-Nucleus Scattering (CE ν NS).

NSI could alter the expected $\text{CE}\nu\text{NS}$ signal by modifying the interaction between neutrinos and the target nuclei. This alteration could manifest as deviations from the expected $\text{CE}\nu\text{NS}$ event rate or energy spectrum.

Studying $\text{CE}\nu\text{NS}$ provides a unique opportunity to probe the standard and non-standard neutrino interactions with matter. By comparing experimental results with theoretical predictions, researchers can constrain or discover the presence of NSI.

2.5.3 Dark Matter

Several neutrino experiments have recently searched for light, sub-GeV dark matter [53]. The search for dark matter and $\text{CE}\nu\text{NS}$ takes place substantially in the same way, i.e., through the neutrino interaction with a target, which produces a nucleus recoil. This recoil can produce a signal which is then detectable. From the time and energy spectra of the interaction, it is possible to isolate the SM background dominated by the well-known pion's decay. For various types of Dark Matter interactions with scalars/gauge boson mediators, even without timing measurements, a dark matter signal can be distinguished from the Standard Model background by measuring the recoil spectra and angular distribution with a direction-sensitive detector [54].

The neutrino- (or dark matter-) nucleus scattering can produce heavier sterile neutrinos and heavier states in the inelastic dark matter scenario [55]. These heavy particles may decay within or outside the detector. If the decay occurs within the detector, the angular and recoil energy spectra would be able to distinguish this scenario from Standard Model background events.

3 CE ν NS at JLab

3.1 Jefferson Lab Accelerator facility

The Jefferson Lab, a US Department of Energy facility situated in Newport News, Virginia, hosts the Continuous Electron Beam Accelerator Facility (CEBAF). CEBAF operates as a continuous-wave electron accelerator, constructed with two 1-GeV LINACs (linear accelerators) and recirculating arcs, enabling it to achieve its maximum energy through five passes.

Presently, Jefferson Lab (JLab) hosts four experimental halls capable of simultaneously receiving a primary electron beam of 11 GeV (Halls A, B, and C) and up to 12 GeV (Hall D, which is subsequently converted into a secondary photon beam). These facilities conduct scattering experiments on nucleons and nuclei, contributing to research in the hadron spectrum, nucleon structure, nuclear interactions, and Beyond the Standard Model (BSM) physics.

Achieving typical luminosity of $10^{39} \text{ cm}^{-2} \text{ s}^{-1}$ necessitates high currents (ranging from 1 to 150 μA) on target, making Hall A, B, and D the optimal sources for secondary beams at Jefferson Lab.

While Hall A is planned for high-current experiments with long durations in the next decade, Hall C's operational days per year may become more sparse. Hall B and Hall D house large-acceptance spectrometers, such as CLAS12 and GlueX, based on toroidal and solenoidal magnetic fields, respectively. The almost 4π acceptance in these halls limits the current to hundreds of nA in Hall B and to a few μA in Hall D's radiator for generating Bremsstrahlung real-photon beams.

Dumping systems in Halls B and D are limited to approximately 100 kW, resulting in a reduction in the intensity of the incoming primary beam, rendering it

unsuitable for generating intense secondary beams. Presently, efforts are underway to increase the maximum beam energy of the CEBAF accelerator. Leveraging advancements in accelerator technologies, it will be possible to extend the energy reach of the CEBAF accelerator up to 22 GeV within the current tunnel footprint, utilizing the existing Superconducting RadioFrequency (SRF) cavity system.

3.2 First Evaluation

The idea of proposing a CE ν NS experiment at JLab comes from the first estimates of the neutrino flux produced in the beam dump by the intense electron beam. Compared to similar proposed experiments at proton-beam facilities (e.g. ν BDX-drift experiment [52] at FNAL), the JLab neutrino flux is about 1-2 orders of magnitude higher, making it attractive for a CE ν NS experiment (fig. 10).

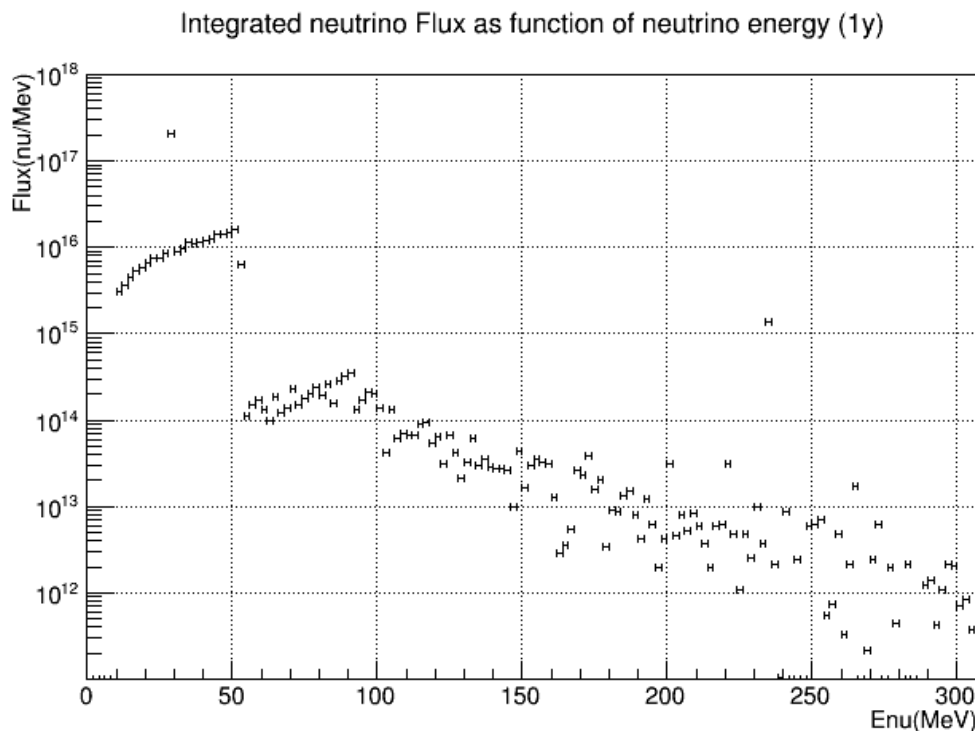


Figure 10: Simulated neutrino flux at JLab impinging in one year on a cube meter detector at 12 m distance from beam dump, perpendicular respect beam axis

Furthermore, neutrons produced by the electron beam in interaction with the target are expected to be fewer than those produced by proton beams. A detailed study based on FLUKA and GEANT simulations has been performed to quantify signal and background yields.

Surveying the neutrino production and fluxes at different positions (see section 3.5), it is found that at JLab it is possible to have about 10^{18} ν /year, competitive with other CE ν SN experiments. Another advantage over the COHERENT collaboration is the possibility of deploying a larger detector.

Based on positive preliminary results, we are considering a CE ν NS experiment at JLab using the same detection technique proposed by the COHERENT collaboration. As a cross-check with simulations, we calculated analytically the CE ν NS cross section and the expected yield for the estimated neutrino flux. The algorithm uses the target nucleus form factor [22] using the CE ν NS cross-section.

Provided the neutrino flux as a function of the energy, it is possible to estimate the yield for a given target as a function of the minimum detectable recoil energy. For a gaseous detector, it is possible to derive the dependence of the number of detectable events from the gas pressure. One of the main issues in using a gaseous detector in the low-recoil energy regime is connected to the fact that gaseous detectors must operate at low pressure to detect the recoil tracks produced by the interaction, meaning that the target material mass is lower, and therefore reducing the expected yield. However, this effect can be partially mitigated by using higher-energy neutrinos at the price of producing a larger background of non-coherent scattering events. Our investigation shows that the JLab energy spectrum is dominated by neutrinos produced by mesons decays at rest (DAR), with energies of a few tens of MeVs. If projected on a ν BDX-drift-like experiment, this would not

match the preferred detector sensitivity, resulting in only a few $\text{CE}\nu\text{NS}$ per year. This led us to evaluate the possibility of proposing an experiment with a denser target material such as LAr. We recalculated the yield considering an LArTPC detector. The preliminary estimates provided a few hundred $\text{CE}\nu\text{NS}$ scatterings per m^3 per year, providing a significant physics reach for the JLab experiment. Another option would be to use scintillating crystals as scattering targets. The advantage of this technique is that no cryogenic is involved, significantly simplifying the experimental setup. Moreover, the BDX experiment proposed at JLab to search for light dark matter is planning to use a CsI(Tl) crystals-based EM calorimeter and sharing R&D on crystals, photosensors, and front-end electronics may result in a significant advantage for a $\text{CE}\nu\text{NS}$ experiment. It is worth mentioning that the COHERENT collaboration reported the first $\text{CE}\nu\text{NS}$ observation by using a CsI(Na) detector.

3.3 νBDX

νBDX is a proposed experiment to study $\text{CE}\nu\text{NS}$ in CsI(Tl) crystals using DAR neutrinos generated by the interaction of the intense JLab electron beam with the experimental Hall-A beam dump. The final configuration of the detector is being designed, but some characteristics have been defined to be able to perform the simulations. It was decided to use CsI crystals as the main scintillating material due to their high light output and density, characteristics that make them ideal for $\text{CE}\nu\text{NS}$ experiments as already found by the COHERENT collaboration. The volume of crystals used for the simulations is a cube of 1 m^3 . Around this volume of crystals, some layers of plastic scintillators and lead screens are planned for background rejection.

The interest for a neutrino experiment at JLab derived from a study concerning the feasibility of a secondary muon beam produced in the same facility to be used for nucleon form factor's studies [56] .

3.3.1 Neutrino production from an electron beam

The electrons interact with the materials they pass through. Given their energy (11 GeV), one of the most relevant processes is the Bremsstrahlung photon emission (fig. 11). These photons of energies, of the order of a few GeV may interact with nucleons, producing excited baryons. The latter decays mainly in charged pions. Subsequently, the positive pions decay into muons and subsequently into electrons by emitting neutrinos.

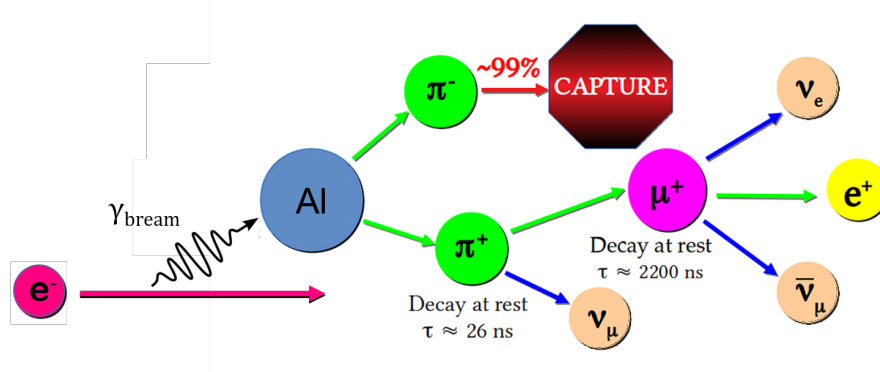


Figure 11: Scheme of neutrino production with electron beam

The neutrino energy spectrum obtained in the beam dump reflects the processes in which neutrinos are produced. Looking at figure 12 , it is evident that most neutrinos have energies between 10 and 50 MeV, while higher energies are suppressed [57]. Neutrinos with energy less than 50 MeV derive mainly from decays of pions at rest (DAR).

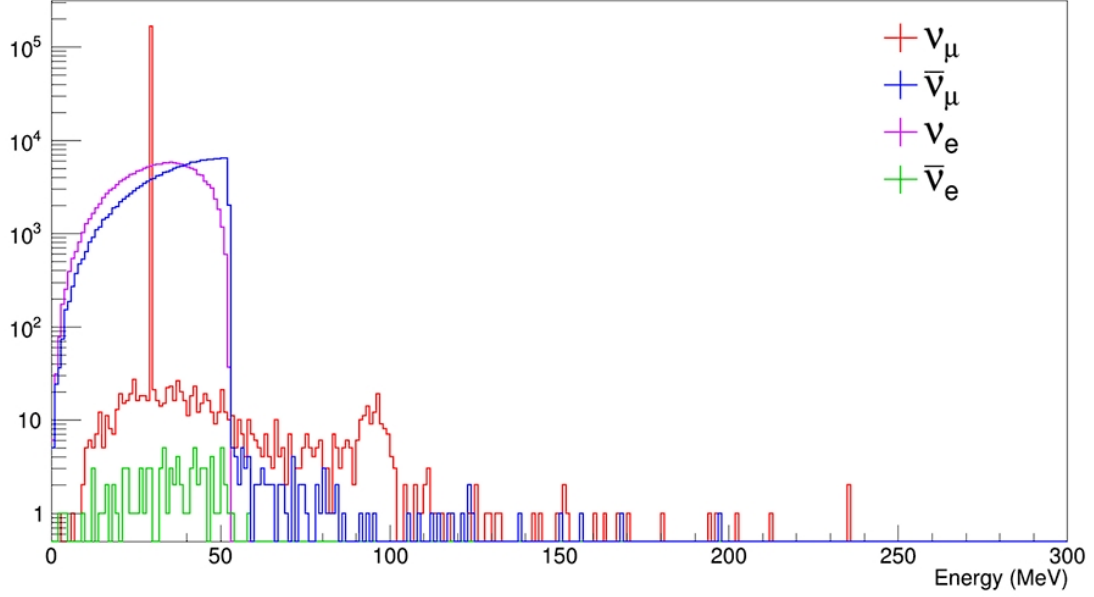


Figure 12: Neutrino family spectrum produced by 11 GeV electron beam at JLab [57].

The energy spectrum can be divided into pion-to-muon decay (in particular positive pions since negative pions are substantially absorbed before decaying), and muon-to-electron decay. The first process is a two-body decay, which produces a monochromatic muon neutrino of about 30 MeV (see peak in fig. 12) [57]. The second process is a three-body decay, which produces a continuous spectrum that ends at almost half the energy of the decaying muon. Analyzing the neutrino species (fig. 12), we have an evident prevalence of muon neutrinos, produced in the first decay, an equal number of muon antineutrinos and electron neutrinos, and an almost total absence of electron antineutrinos.

Negative pion (π^-) decay at rest can be suppressed by the capture of the pion by a nucleus. [58].

$$\begin{array}{l|l} \pi^+ \rightarrow \mu^+ + \nu_\mu & E_\nu \approx 30 \text{ MeV} \\ \mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu & 0 < E_\nu < 50 \text{ MeV} \end{array}$$

3.4 Simulation Framework

Two tools, FLUKA and GEMC, were used for the simulations. FLUKA was used to study the expected neutrino spectra at various locations around the dump. FLUKA simulation toolkit was used to derive the neutrino flux produced by the interaction of the primary electron beam with the beam dump. FLUKA [72–75] is a Monte Carlo program that simulates the interaction and transport of hadrons, leptons, and photons of energies from keV to TeV (except neutrons, tracked down to thermal energies). FLUKA is widely used in different fields: accelerator design and shielding, radiation protection, particle physics, dosimetry, detector simulation, and hadrontherapy. To simplify its usage, the graphical interface FLAIR [76] (FLUKA Advanced Interface), which provides an integrated development environment (IDE), was developed. Using FLUKA, it is possible to score the energy spectrum and the number of particles passing through a surface. Flux and cross sections are the basic ingredients to estimate the expected yield of a specific process and are therefore useful to extract the weak mixing angle or neutrino’s NSI.

GEMC (GEant4 Monte-Carlo) is a C++ framework that uses [80] GEANT4 simulation tool [81]. GEMC provides user-defined geometry and hit description. Detector and building structures can be implemented using the standard GEANT volume description. The program handles multiple input/output formats and provides a graphical interface to visualize the detector and the hits active and passive volumes. The ability to simulate the response of the detector and to trace the particles produced in a particular system are the elements that led to choosing GEMC to simulate the geometry of the shielding/veto around the detector. To better simulate the neutron interaction, the ENDF-VII.0 libraries [82, 83] were used. The library, released by the U.S. Cross Section Evaluation Working Group

(CSEWG) in December 2006, contains data for reactions with incident neutrons, protons, and photons on almost 400 isotopes based on experimental data and theoretical predictions.

3.5 Neutrino flux simulation

Several simulations were conducted using FLUKA to establish the number of muonic neutrinos and antineutrinos on different sampling surfaces at various distances from the beam dump. The simulations made use of the Hall-A beam dump geometry (fig. 13) and materials implemented in FLUKA-2011.2c.5 by the JLab Radiation Control Department (JRCD) and used in PR12-16-001 for the Beam-Dump eXperiment (BDX).

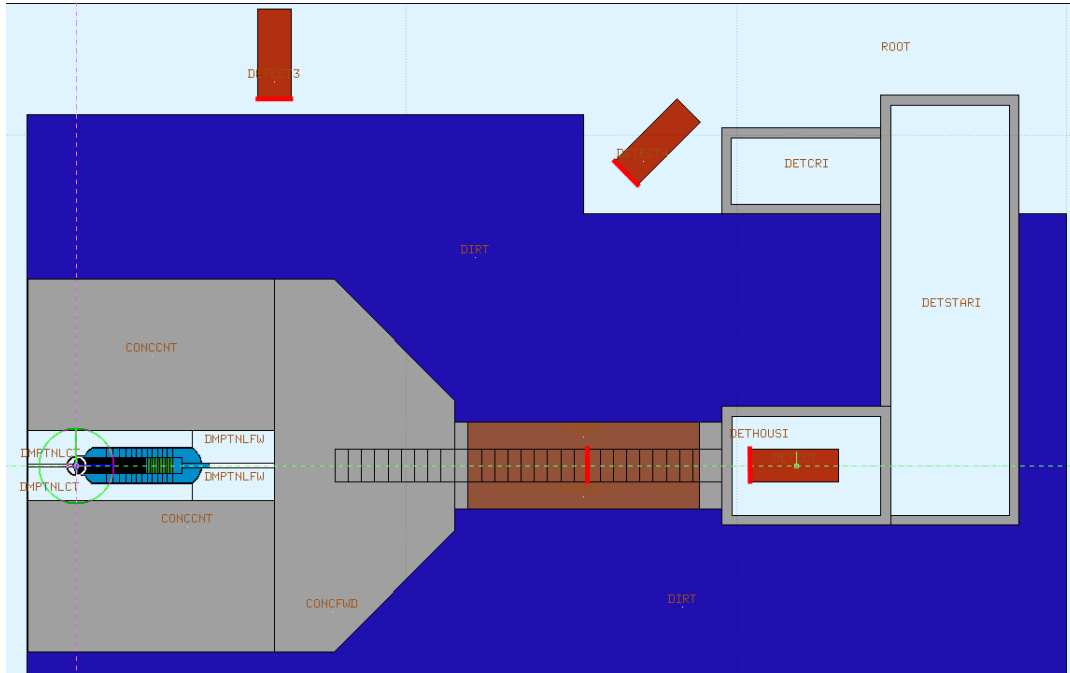


Figure 13: Simulation with BDX geometry [77]. Red lines marking the sampling surfaces that will be considered in this study

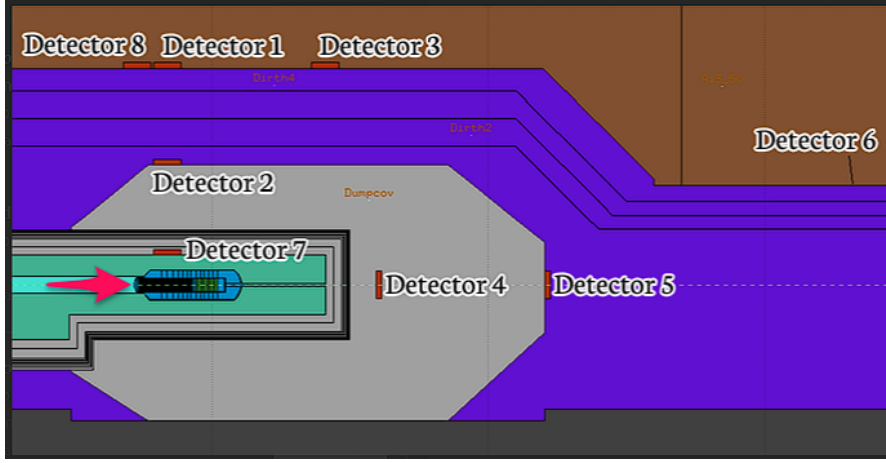


Figure 14: Simulation Geometry and possible detector sites

Following the optimization of simulation geometry, which included refining the description of the beam dump, concrete, and surrounding dirt, the neutrino and anti-neutrino fluxes were sampled across multiple surfaces, potentially housing the ν BDX detector(see figure 14). Assuming a detector area of approximately 1 m^2 and an operational period of roughly 1 year, we estimated the number of neutrinos projected to interact with the ν BDX detector.

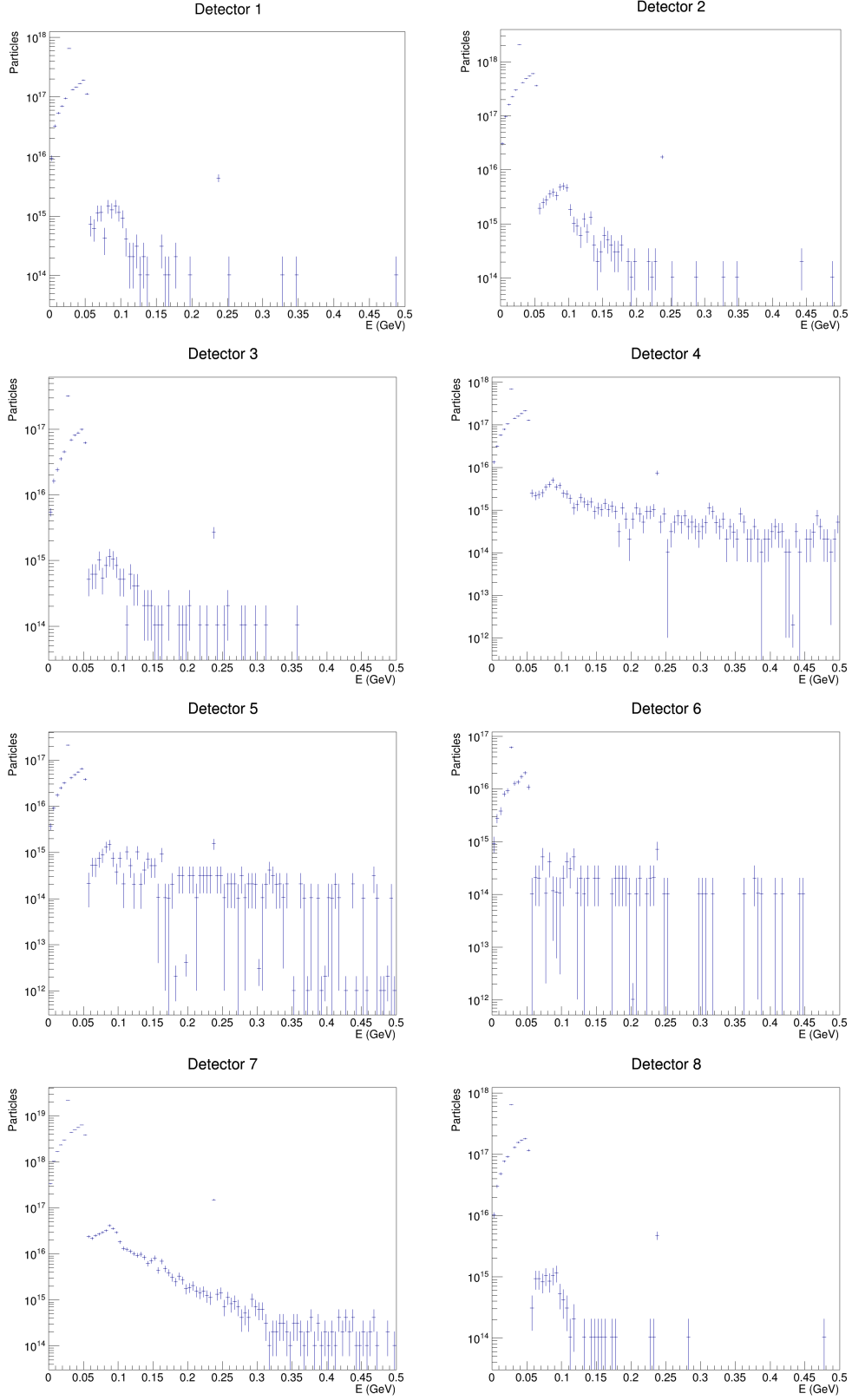


Figure 15: Simulated neutrino spectra at different detector positions, as shown in Fig. 14.

With 10^{23} EOT per year [77] and a beam energy of 11 GeV, the resulting integrated neutrino flux was found to be, on average, up to 10^{17} (detector 3,4,5,6,7 in fig. 15) and for some specific locations (detector 1,2,8 in fig. 15) up to 10^{18} . Based exclusively on these flow estimation data it can be concluded that these latter positions appear the most promising to host a possible CE ν NS experiment.

4 Background

In CE ν NS experiments, the background is associated both with the beam and produced within the detector by cosmic rays. The particle beam generates background, for example, through the production of neutrons in the beam dump, which is difficult to reduce. Cosmic rays introduce additional background, although they can be mitigated with appropriate shielding and event selection techniques. Unlike the COHERENT collaboration, the JLab beam is continuous in time (4ns intervals separate the bunches) rather than pulsed, which would allow the beam-uncorrelated background to be reduced by exploiting the timing coincidence with the frequency of the beam. In the context of the CE ν NS experiment, the background particles of concern are photons and neutrons. These can produce hits similar to signals, complicating the identification of CE ν NS events. Photons can interact with the nuclei of the medium, producing signals that may be confused with those from neutrino-nucleus interactions. Photons from the beam dump are partially shielded by materials placed between the dump and the experiment. Neutrons, similar to neutrinos, can penetrate through several meters of material and can originate from both the particle beam and cosmic radiation. Neutrons produced in the beam dump constitute an irreducible background, and an accur-

ate shielding/veto design is needed to reduce their contribution to detected events. Charged particles and muons, although capable of penetrating through material, are not a significant concern as they can be identified and rejected (at least, up to a certain level).

Considering the minimum visible energy deposited in CsI by a $\text{CE}\nu\text{NS}$ scattering to be 10 keV, a neutron should have a minimum energy of 330 keV to release the same visible energy. COHERENT collaboration quoted a similar neutron energy range for recoil energy of 8 keV in CsI (and similarly in LAr) [78].

4.1 Background Simulation

For background simulations, we used GEMC for its particle tracking characteristics and the optimal description of medium/high energy neutron interactions inside the detector. The main detector, as already described in paragraph 3.3, consists of a 1 m^3 cube of CsI crystals. As for shielding/veto, we considered a multi-layer system that surrounds the detector. The innermost part is made up of plastic scintillators capable of marking the particles that enter into the active part of the detector. Around this nucleus, we alternated passive shielding layers of heavy material (e.g., lead) to reduce the number of medium/high energy neutrons.

4.1.1 Bircks Law and quenching factor

To parameterize the detector response, one must start by estimating the energy deposited in active materials. In the case of a scintillator, the deposited energy is directly related to the amount of light produced. The passage of the particle through the crystal produces a local concentration of ionized molecules along its path. These molecules act as quenching agents for the 'excitons' the ionizing

particle produces. The number of 'excitons' produced per unit path length is proportional to the specific energy loss. The local concentration of ionized molecules at any point on the particle track is also proportional to the specific energy loss. Birks' law [84, 85] is an empirical formula that describes the light yield per path length as a function of the energy loss by a particle crossing a scintillator. It reads:

$$\frac{dL}{dr} = \frac{S \frac{dE}{dr}}{1 + kB \frac{dE}{dr}}$$

where L is the light yield, S is the scintillation efficiency, dE/dx is the specific energy loss of the particle per path length, k is the probability of quenching [85], and B is a constant parameter linking the local density of ionized molecules at a point along the particle's path to the specific energy loss. kB is also called Birks' coefficient, and its value depends on the scintillating material [86].

From this formula, it is also possible to obtain the *quenching factor*, defined as the ratio of the light yield for a generic crossing particle with respect to the light yield of an electron of the same energy [87].

$$Q_i(E) = \frac{L_i(E)}{L_e(E)} = \frac{L_i(E)/E}{L_e(E)/E} \simeq \frac{dL_i/dE}{dL_e/dE} \simeq \frac{1}{kB(dE/dr)_i}.$$

The quenching factor depends on the particle energy, reaching the minimum when $(dE/dr)_i$ is maximal and increases at low energies. This last feature shows why the quenching factor is critical for CE ν NS measures.

4.1.2 Hit definition

Particle detection is made by identifying hits in the active volume. Background hits can be removable or not removable. The first is associated with neutrons

and cosmic rays that, using the available information from veto and/or the whole detector, can be distinguished from $\text{CE}\nu\text{NS}$ events. The second represents an event that cannot be distinguished from $\text{CE}\nu\text{NS}$. Background can be suppressed by considering that background particles can interact with the plastic scintillator placed around the active volume (unlike neutrinos). The condition for defining a removable hit from crystal is that there is an event in which a hit is present both in the crystal and in the veto.

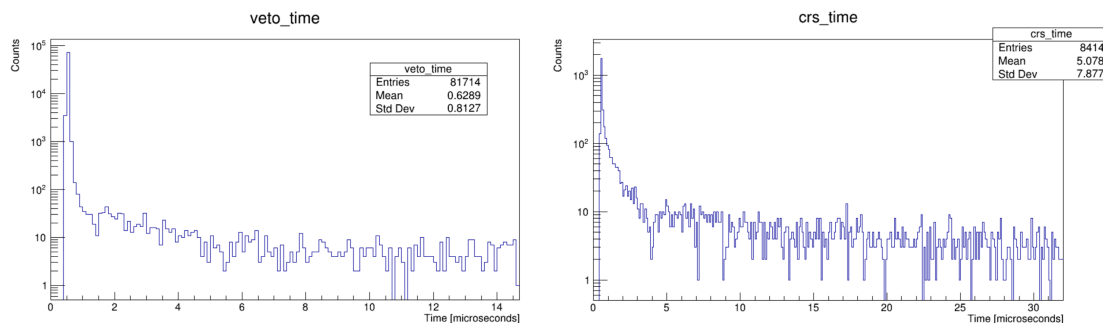


Figure 16: Time response of veto and crystal

To do this, it is necessary to define a coincidence window. The typical response and scintillation times of the individual elements must be taken into consideration. For plastic scintillators, the scintillation times are of the order of some hundred ns, while for the CsI crystal, they are of the order of $3\ \mu\text{s}$ (fig. 16). We can, therefore, define a reasonable time window in which the signal is contained. For scintillators is equal to $1\ \mu\text{s}$ and $4\ \mu\text{s}$ for the crystal. Given these considerations, we can define a reasonable coincidence window equal to $5\ \mu\text{s}$. GEMC also gives us the energy deposited by a particle in the matter, and that permits us to establish thresholds that define the hits in the various detector components (veto and crystal). This is particularly useful for the crystal as it allows us to identify neutron events that have deposited energy in the same range expected for the $\text{CE}\nu\text{NS}$ (10 keV-200

keV).

4.1.3 Veto Decision

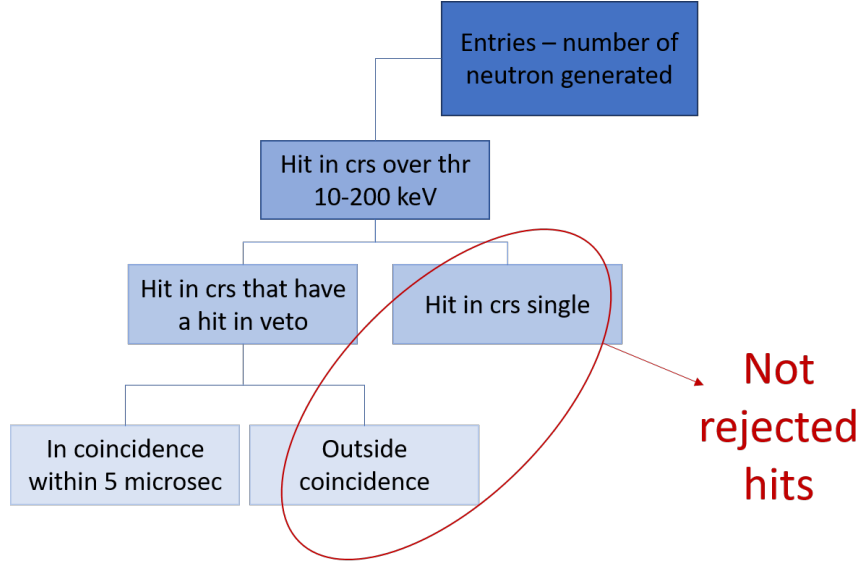


Figure 17: Veto Decision scheme

We can identify background events with the timing information and the threshold. However, this does not cover all possible cases. Neutrons, in particular, can produce hits outside the coincidence window or events with no hits in the veto but only in the crystal. These hits represent the irremovable background of the experiment. A scheme of veto decisions is shown in figure 17.

4.1.4 Passive shielding

Neutrons interact in matter through scattering and absorption. These interactions are used to shield and measure neutrons. However, unlike gamma radiation, which interacts primarily with the electrons in matter, neutrons interact with nuclei [88]. For many materials, the neutron cross-section is smaller than that for a photon. In general, high-energy neutrons scatter rather than be captured by the material (see

fig. 18). As the energy of neutrons reduces through scattering (thermalization or moderation), the probability of interaction increases, and capture becomes more relevant. Neutron scattering can be divided into elastic (the kinetic energy of the neutron-target system is conserved) and inelastic scattering (the kinetic energy of the neutron-target system is lowered through nucleus excitation). In neutron capture, a neutron and target nucleus collide and merge, forming a heavier nucleus. Depending on the energy of the incident neutron and the properties of the target nucleus, neutron capture may be followed by the emission of gamma radiation, atomic particles, and/or the fission of the compound nucleus. The probability of interaction between an incident neutron and a nucleus does not depend on the type of reaction and can be expressed by the total cross section θ_T , which is the sum of scattering, and absorption cross-sections θ_S and θ_A .

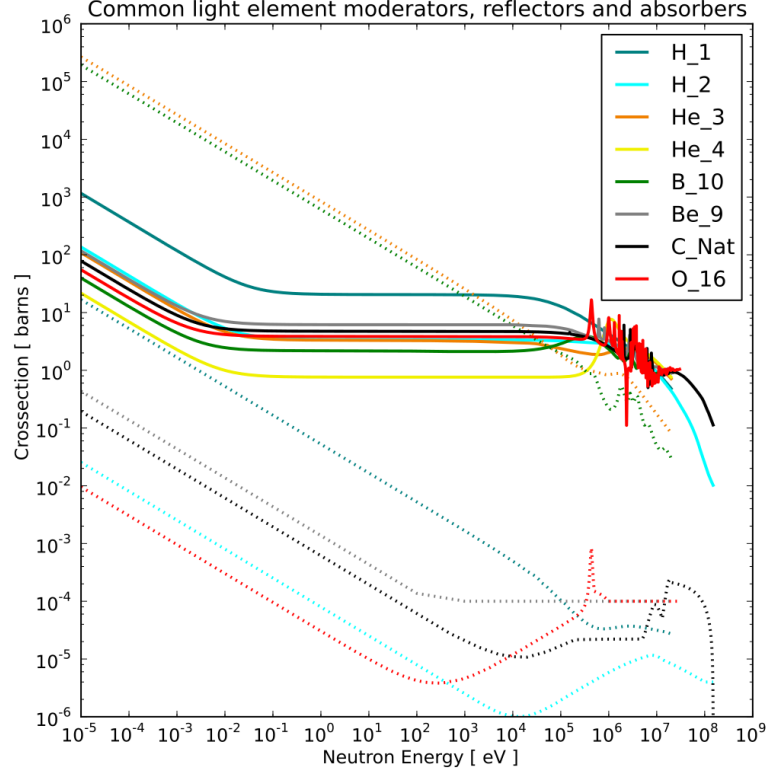


Figure 18: Scattering (full line) and absorption (dotted) crosssections of light elements commonly used as neutron moderators, reflectors and absorbers [89]

The Ramsauer Model provides a simple approximation of neutron total cross-section with energy dependence [90]:

$$\sigma_T = 2\pi(R + \lambda(E))^2(1 - \alpha \cos \beta)$$

where R is the radius of the nuclear potential, λ is thermal de Broglie wavelength, α is a parameter equal to one if no absorption is present and less than one if absorption occurs; β denotes the phase change of neutron passing through the nucleus.

Neutron shielding techniques depend on neutron energy [91, 92].

Materials used to moderate low-energy neutrons are typically made by low atomic number elements (hydrogen, carbon, and oxygen) with high scattering cross sections that moderate or thermalize incident neutrons. Shielding for small

sources is often made by polyethylene or paraffin, while shielding for large sources is made by concrete or large pools/tanks of water. Materials of high density and significant thickness, such as iron or lead, are instead used to slow down very fast neutrons and are put in front of the hydrogen-rich material. A schematic view of typical neutron shielding is shown in figure 28.

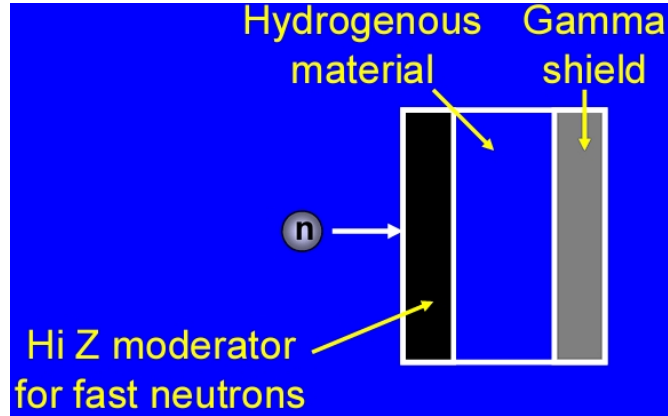


Figure 19: A schematic example of neutron shielding

Elements with a high capture cross section for thermal neutrons (boron, cadmium, and gadolinium) are used to capture moderated/thermalized neutrons. Borated polyethylene, layers of B_4C and aluminum, boron-aluminum alloys, and boric acid in water are examples of materials boron-rich with a high capture cross-section providing a lower energy gamma radiation than the radiative capture on hydrogen, oxygen, or carbon. Neutron shielding may also incorporate high atomic weight elements to shield from gamma radiation from neutron capture. Lead, bismuth, and tungsten are often used due to their high density, good gamma attenuation characteristics, and relatively neutral activation products.

The strategy in our simulation followed these guidelines by varying the thicknesses of materials and changing the order of layers of different elements to minimize the final number of non-removable events in the detector.

4.2 Cosmic Neutrons

4.2.1 Physics mechanism

The Earth is constantly hit by high-energy particles referred to as cosmic rays. These are high-energy particles consisting of approximately 89% protons, 10% helium ions, and 1% heavier nuclei, with energies up to approximately 1000 GeV [93]. These primary particles interact with air molecules. Target nuclei often undergo spallation, dividing into smaller and constituent nucleons. The cosmic-ray-induced neutrons are observable on the ground; they are produced through spallation reactions on primary nitrogen, oxygen, and argon nuclei in the air [94] and exhibit a broad energy range spanning from thermal energies up to several GeV (see fig. 20).

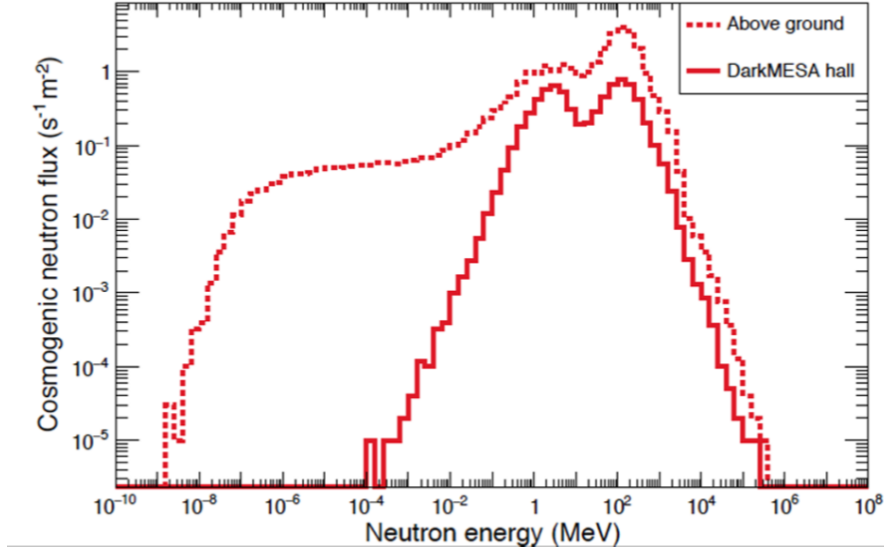


Figure 20: Cosmic neutron spectrum expected on the surface and at the DarkMesa site [95]

Neutrons penetrate much further into our atmosphere than the majority of electromagnetic components. As they propagate, they collide with atmospheric nuclei, liberating additional particles.

4.2.2 Cosmic neutrons shielding

In simulations, we varied the elements used to shield neutrons. In the case of cosmic neutrons, we considered the location of the detector, i.e., the top of the hill surrounding the beam dump and a thin concrete box of $600 \times 400 \times 600 \text{ cm}^3$ around the detector (see figure 21).

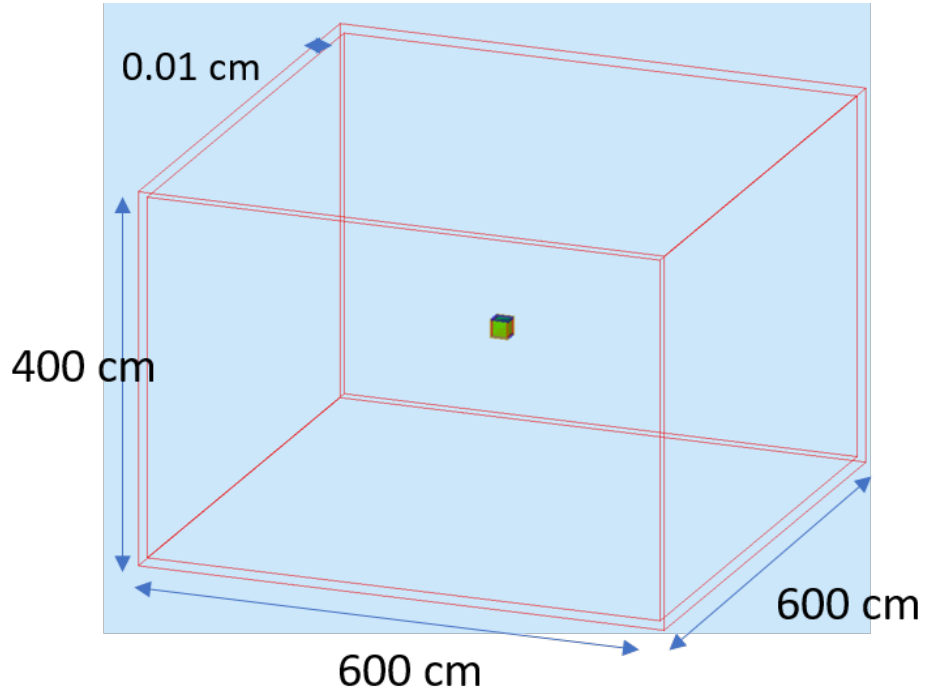


Figure 21: Concrete box view around the detector

To further shield the detector, we considered a veto composed of layers of plastic scintillators (active) and a heavy moderator (lead) to reduce the neutron energy (fig. 22). We also tested configurations with absorbing materials (Gadolinium).

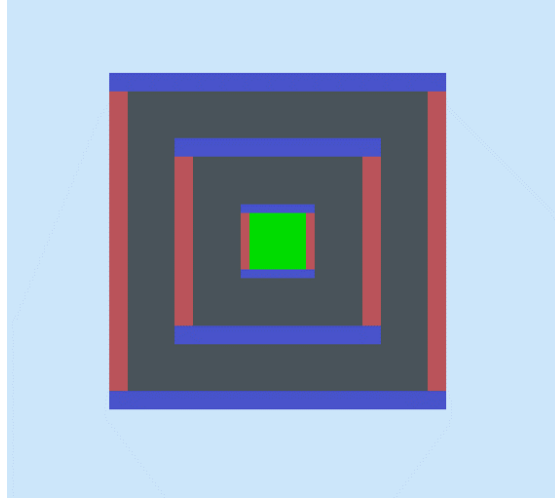


Figure 22: Simplify representation of initial geometry. In Green CsI crystal, in red and blue scintillating veto, and black lead

We initially changed the veto characteristics, keeping the lead thickness unchanged. We then tried to add other layers of lead. These tests showed (fig. 23) an increase in non-removable hits, which was different from what was expected.

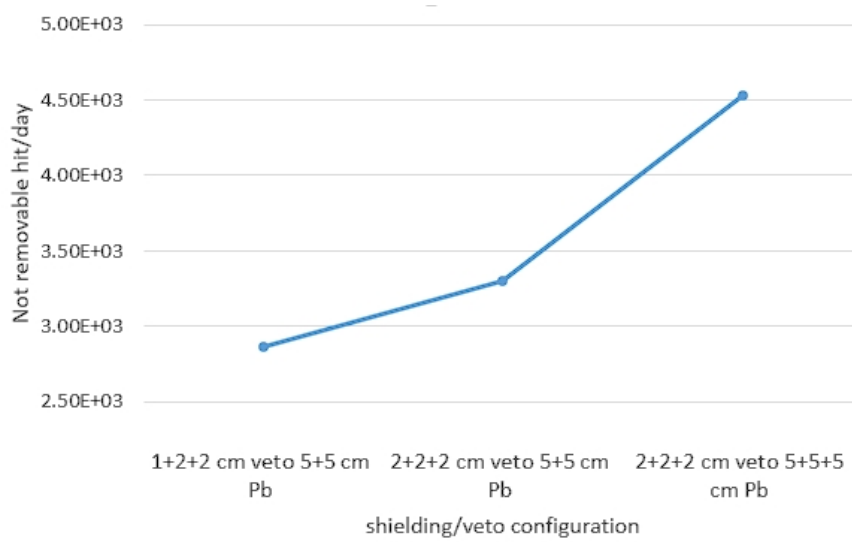


Figure 23: Plot with the result on first geometry varying veto thickness. As it can be seen, there is an increase in the number of non-removable hits increasing the veto thickness

To find a viable solution, we studied a simplified geometry with a single veto layer (right on fig. 24) of different thicknesses. In this case, the number of non-removable hits decreases as the veto thickness increases (plot on fig. 24). This was quite expected as the probability of neutrons interacting is expected to increase with the thickness crossed.

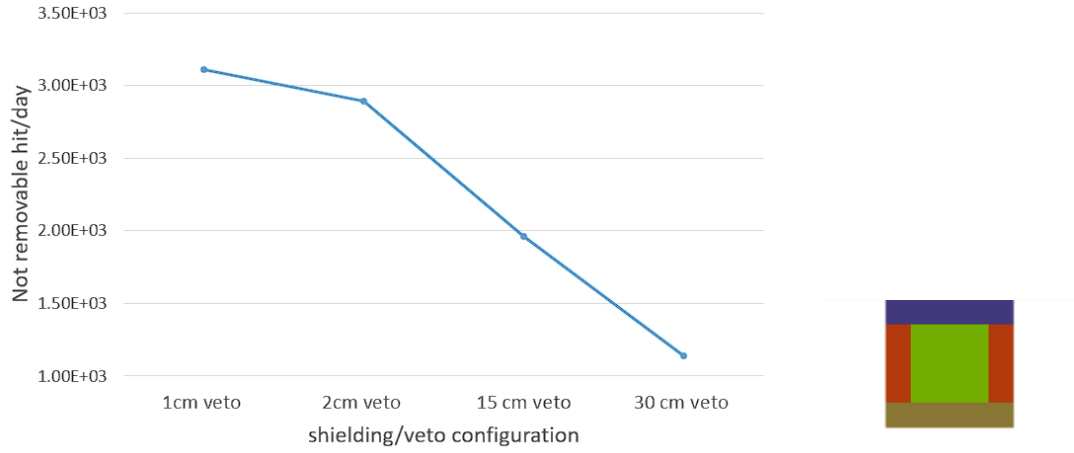


Figure 24: Left: Plot with the result from varying single veto thickness. Right: representation of geometry used

Fixed the thickness of the veto (6 cm); we then inserted layers of lead of different thicknesses (plot on fig. 25). We started by studying the effect of the shielding just placed on the top (right on fig. 25). Then we included a surrounding shielding.

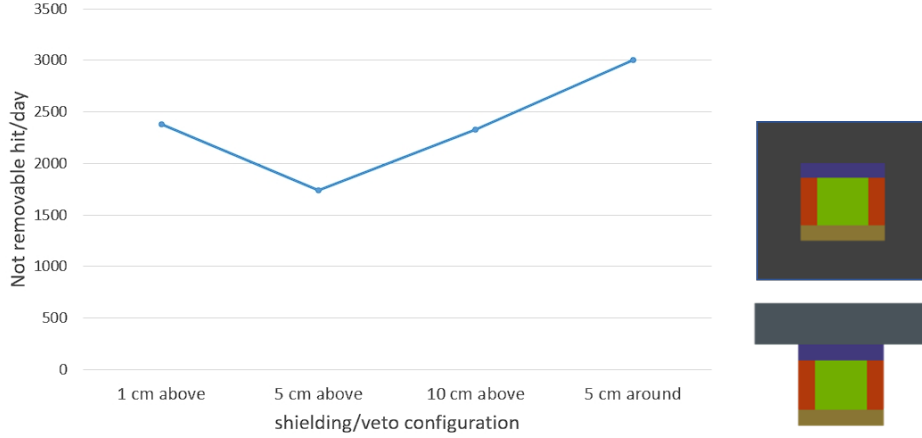


Figure 25: Left: Plot with the result from varying lead thickness. Right: representation of the two geometry used.

Results show a decrease in the number of non-removable events as the lead thickness increases, which, however, was followed by an increase of hits for a thickness of around 10 cm. Placing the lead all around the detector produced an increase in the number of neutron hits.

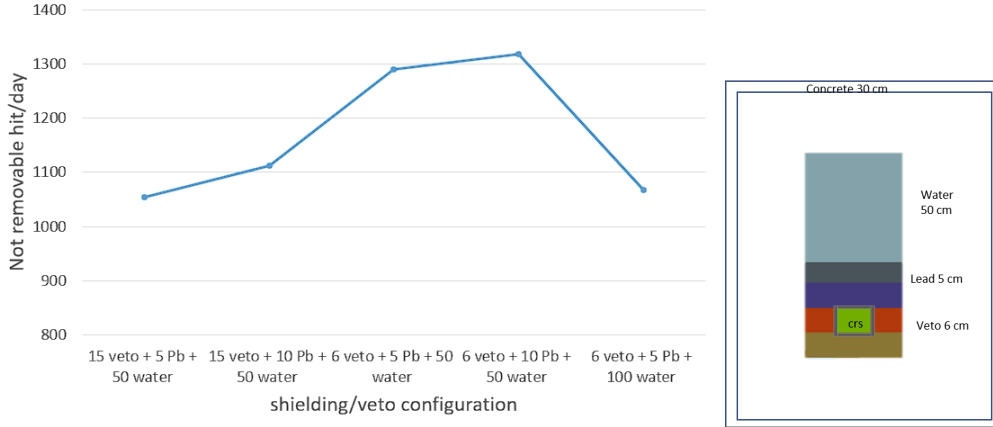


Figure 26: Left: Plot with the result from varying configurations of veto, water, and lead thickness. Right: representation of the geometry used.

Based on these results, we added a layer of water above the upper lead layer (right on fig. 26) in order to moderate the incoming neutrons, assuming that energetic neutrons create a multiplicative effect in the lead as the thickness increases.

Even if the effect of the water was found to be significant, the background remained almost the same. Changing the water with lead (right on fig. 27) we obtained a reduction of not-removable hits (plot on fig. 27). This can mean that the multiplicative effect can be due to some particles (photons) produced inside lead that are shielded if the lead thickness is enough. To better understand this behavior, we decided to investigate the effect of the various geometries on non-removable hits, studying neutrons and gammas separately. The scheme of this study is shown in figure 28. A larger thickness of lead decreased the number of neutrons but increased the gammas. The same behavior was observed after replacing the layer of water with some concrete. Increasing the layer of water, on the other hand, produced a decrease in both components.

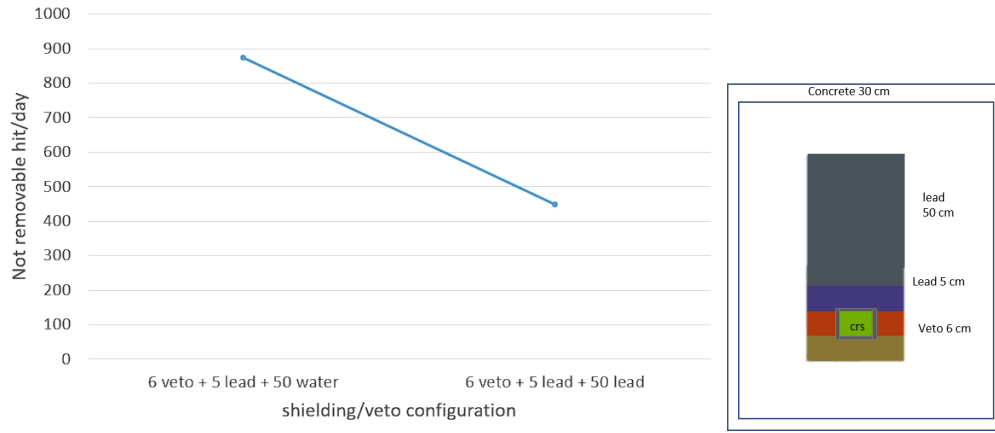


Figure 27: The result of the changing water layer to the lead layer

The large gamma hits we found suggested that they were produced in the lead layer band and were not adequately shielded. We then replaced the layer of water with a layer of lead. The effect of this change was to decrease the number of hits by about 50% compared to water. This last configuration, with 55 cm of lead above and 6 cm around the crystal, was chosen to shield the detector from cosmic neutrons. Scaling results to a full detector(of one cubic meter of crystal), provided

1.7×10^5 cosmic neutron hits/year.

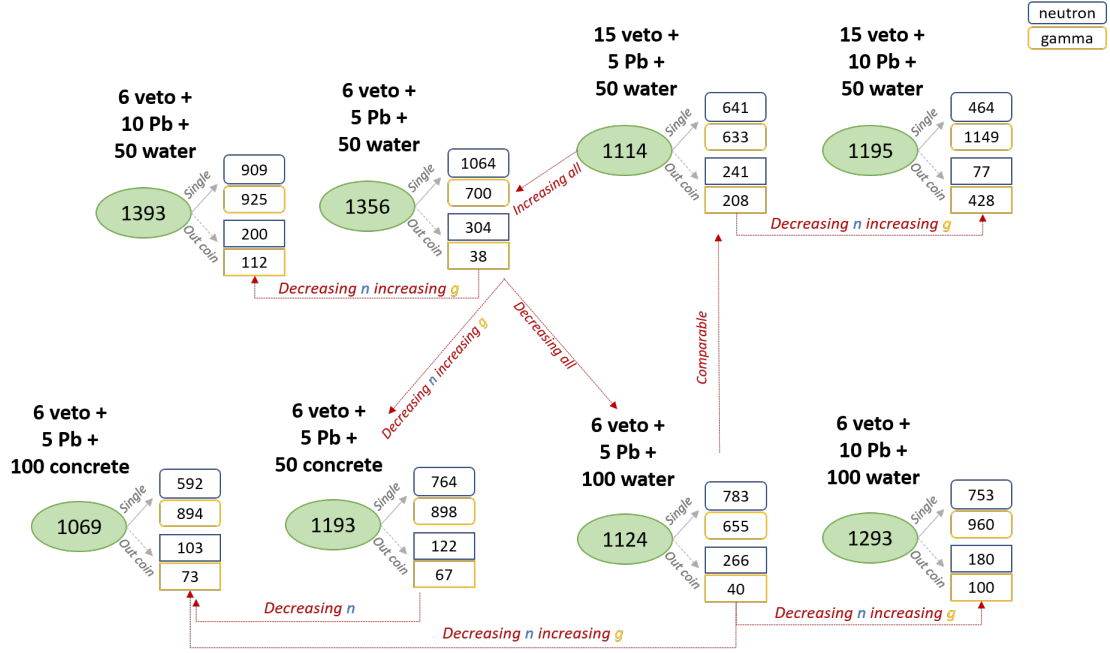


Figure 28: Survey of shield materials effect in our simulation

4.3 Beam-related neutrons

4.3.1 Production mechanisms

Electrons from the beam lose energy in the dump mainly by bremsstrahlung, producing a photon shower with a continuous energy spectrum whose endpoint is equal to the maximum electron energy. The produced photons can be absorbed by nuclei that decay to the fundamental state by emitting neutrons, according to the Dipole Giant Resonance mechanisms. Neutrons of higher energy are expected to be produced by the quasi-deuteron mechanism [96]. The emission of protons is also possible, but in the case of heavy nuclei, this channel is strongly suppressed due to the Coulomb barrier. The photon-neutron reaction has a threshold since a nucleon can be emitted only if the photon energy is greater than its binding energy. Heavy nuclei show a lower threshold and much higher photon-neutron

cross sections compared with light nuclei, making them a good choice for neutron photoproduction.

4.3.2 Beam-related neutron propagation

To optimize the shielding for neutrons produced by the interaction of the beam with the dump, we ran FLUKA simulations to evaluate the flux expected in the different locations of the experiment. The same geometry used to evaluate the neutrino flux was used, placing some flux detectors between the beam dump and the detector (see figure 29).

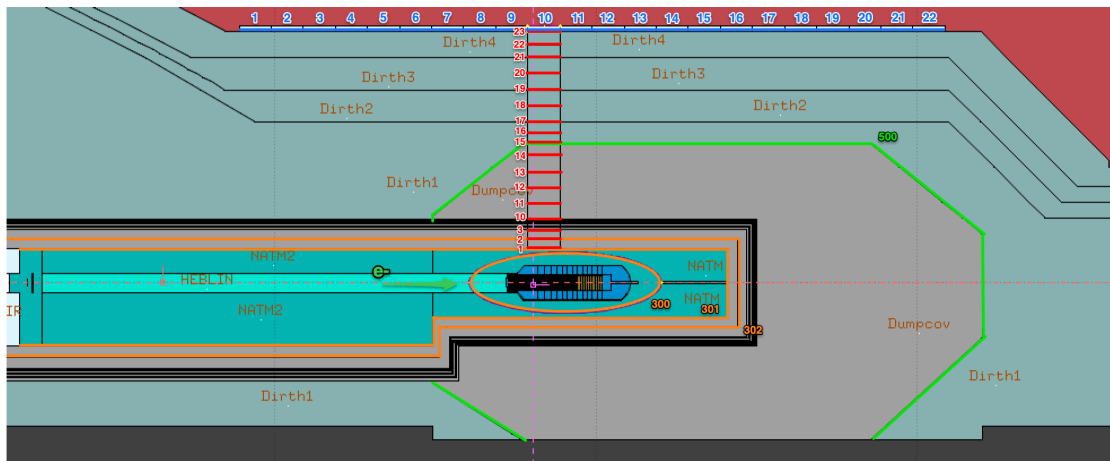


Figure 29: Simulation geometry indicating the location of the flux detector at a various distances from the beam dump (orange, red, and blue one)

Due to the large absorption of neutrons along the way, the classical 'brute force' approach did not work since the simulation time diverged to unsustainable values (fig. 30).

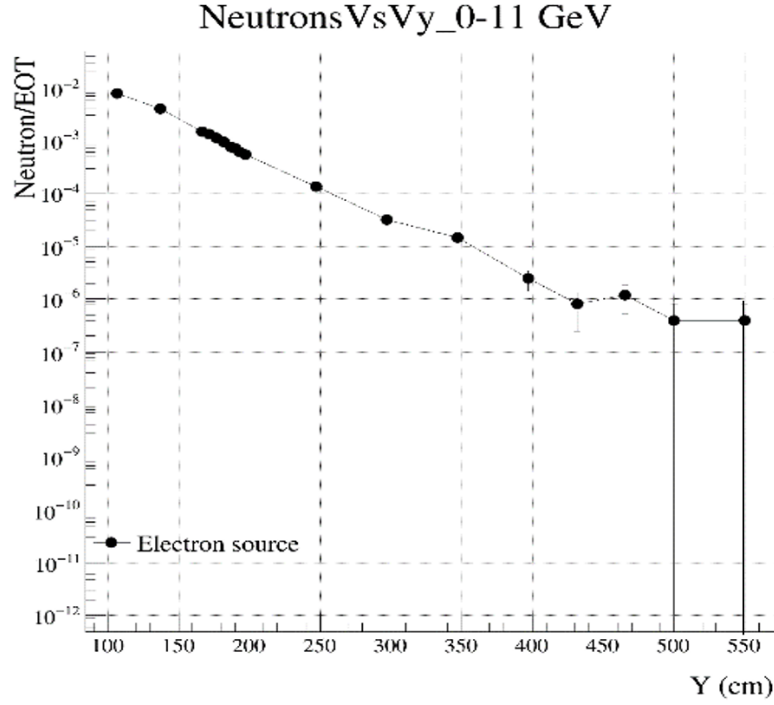


Figure 30: Neutron flux plot at different position distances from the dump in electron beam direct simulation. A low statistic is shown at a large distances from the beam dump

To generate large enough statistics on locations far from the dump, neutrons were sampled on a closer surface (for example, surfaces 300 and 500 shown in figure 31), and the yield was artificially scaled and used to re-generate a new (higher statistics) set of neutrons, propagate them to the next surface, and repeat the procedure. The scaling factors were recorded to extract, at the end of the procedure, the correct normalization. The statistics of the first sampling surface were used to associate the correct statistical error with the final neutron sample.

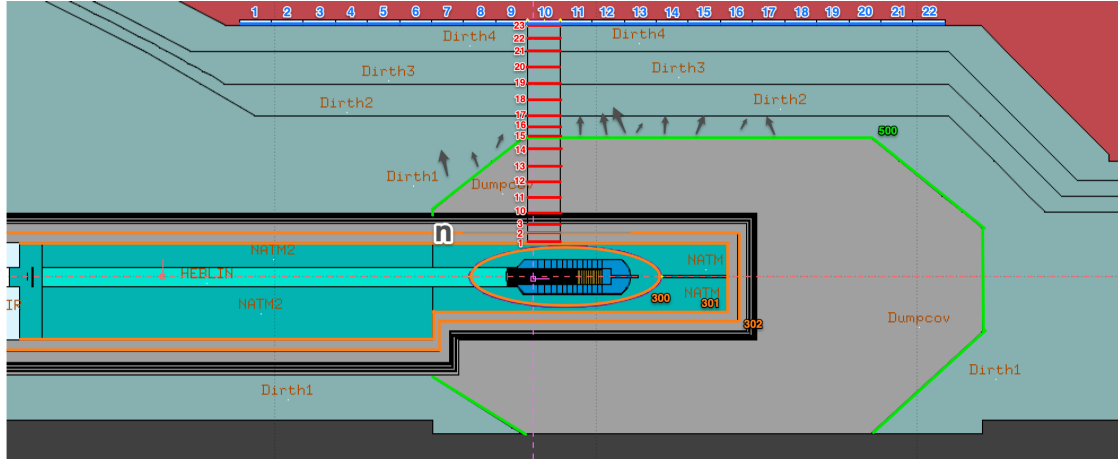


Figure 31: Surface 300 (orange around beam dump) and 500 (green around concrete) in which the neutron flux is sampled and subsequently used as generation surface

The results of this procedure are reported in figure 32, where the number of neutrons at different locations is shown.

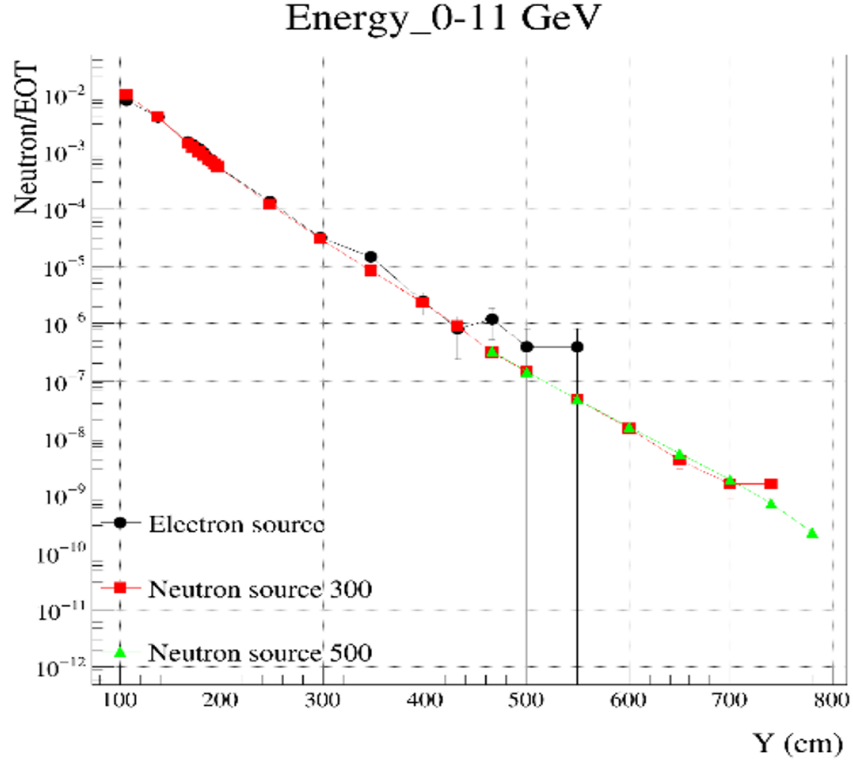


Figure 32: Neutron flux plot at different position distances using sampling surfaces. Comparison results with generation from different surfaces

The procedure was applied to estimate the neutron yield on different locations along the beam direction(Y coordinates) and perpendicular to it (Z coordinates). Results are reported in figure 32 for vertical and in figure 33 for horizontal. As expected, the neutron flux decreases moving away from the dump and is maximum perpendicular to it. The neutron flux was found to be similar in the longitudinal and perpendicular directions (with respect to the primary beam) and only dependent on the distance, suggesting an isotropic neutron propagation.

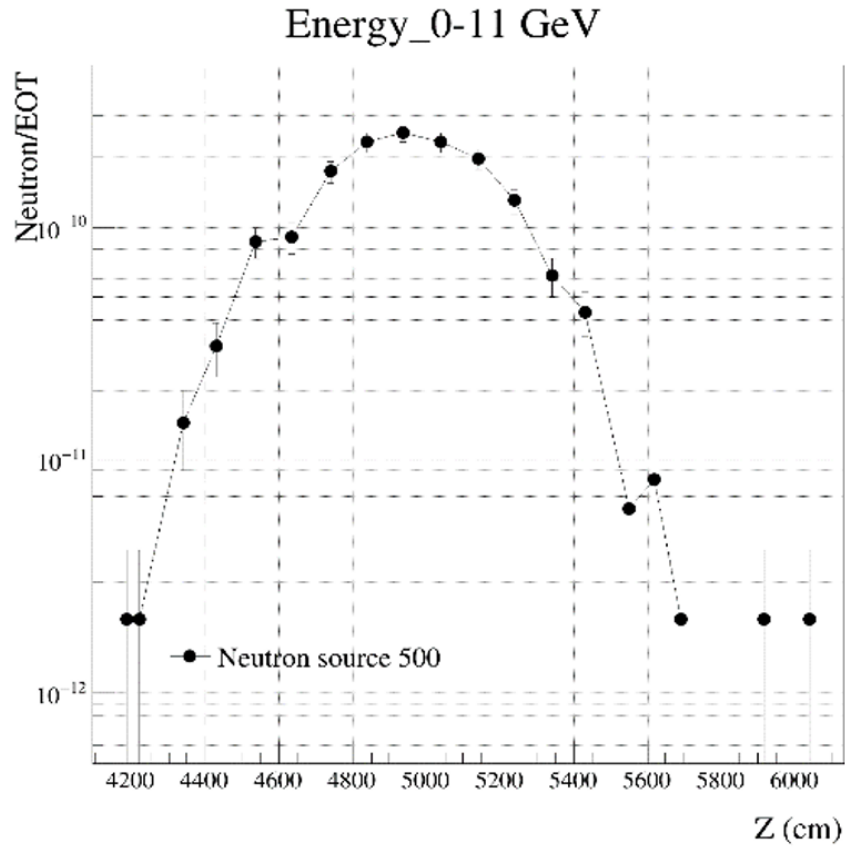


Figure 33: Neutron flux plot (using surface 500) at different position distances moving horizontally on the hill

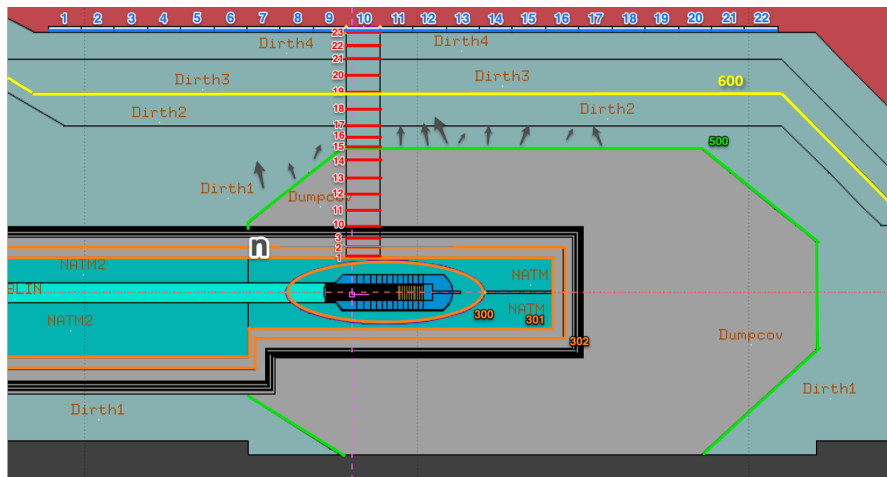


Figure 34: Surface 600, in which the neutron flux is sampled and subsequently used as a generation surface

To have sufficient statistics even in the positions suitable for the detector, we applied the sampling surface procedure to a surface (600) closer to the edge of the hill (yellow in figure 34). This procedure provided a significant neutron yield at the detector position; it was possible to derive the energy spectrum of neutrons in small energy intervals and scan different positions moving horizontally on the hill(fig. 35).

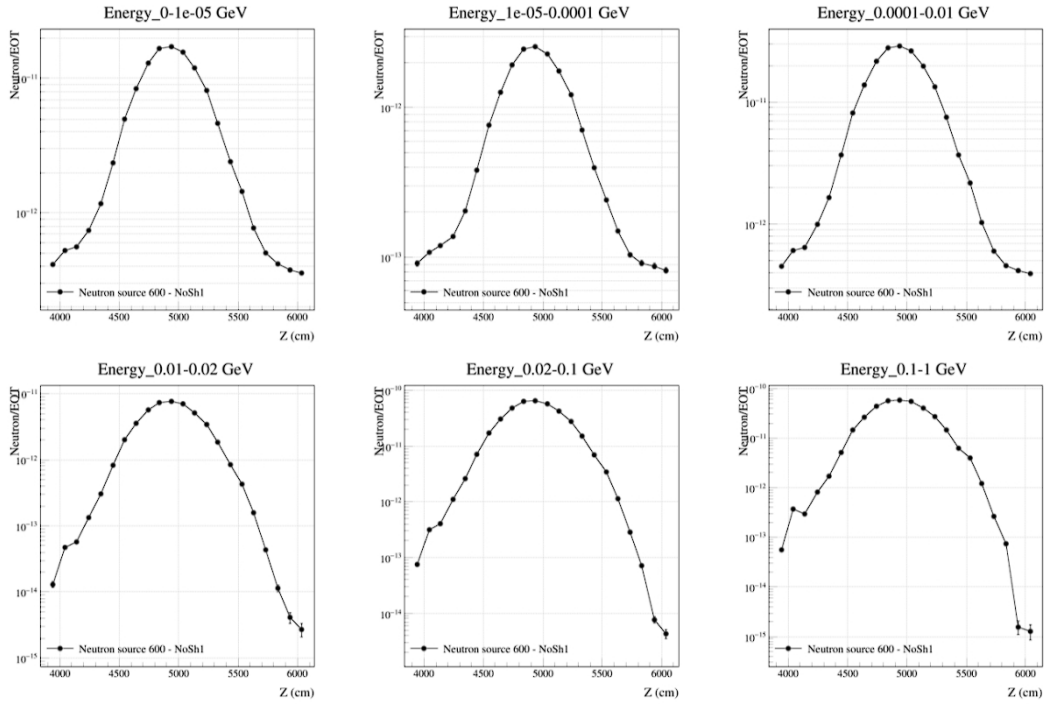


Figure 35: Neutron flux plot at different positions and different energy interval distances moving horizontally on the hill

The same positions are surveyed to obtain the neutrino flux and yield (fig 36) that are used in section 5 to evaluate $\text{CE}\nu\text{NS}$ yield, reach, and sensitivity of some physics quantities. As expected, it was not affected by the interleaved materials but only by the distance from the source.

Considering a hypothetical detector location at increasing distances from the dump, we found a reduction up to a factor of two of neutrino flux and up to two

orders of magnitude for neutrons.

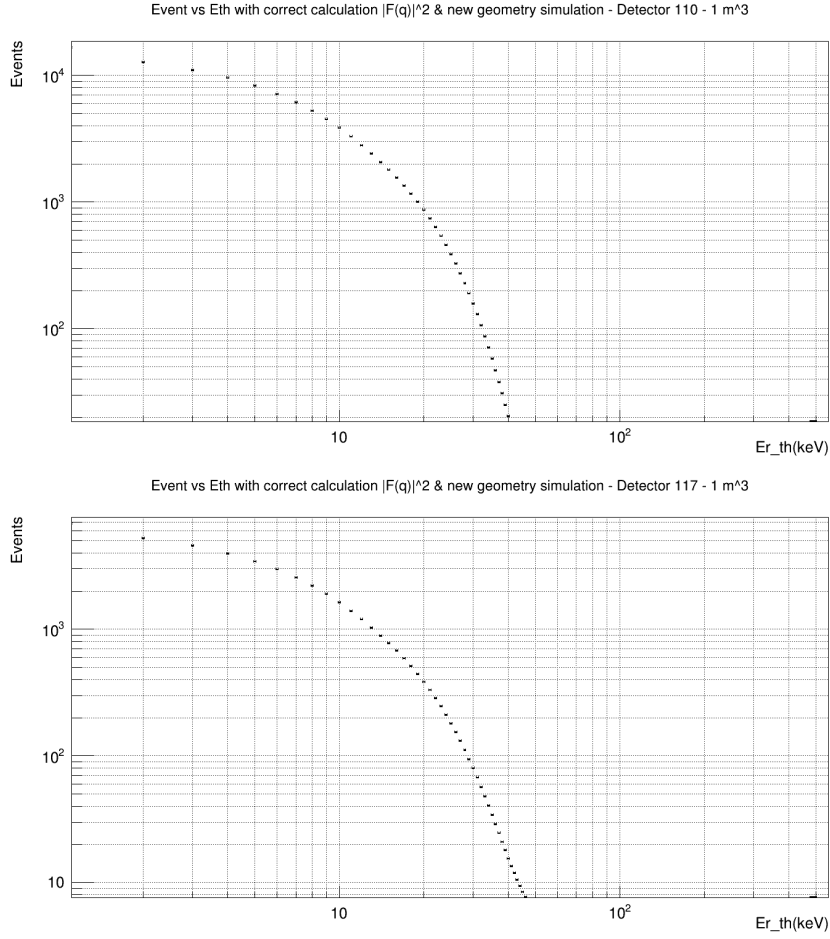


Figure 36: CE ν NS yield in position 110 (perpendicular to beam dump) and position 117 (far from beam dump and first favorable for neutron reduction)

4.3.3 Beam-related neutrons shielding

After having identified the best position that reduces the number of neutrons, we optimized the passive shielding around the detector. Since neutrons produced in the beam dump have a wide energy spectrum (0.01MeV-1GeV), it was necessary to consider a multi-layer setup. For slow neutrons, absorbing materials (Gd) or moderators (water) should be used to degrade their energy or fully absorb them. For fast neutrons, we relied on heavy materials (Pb) to provide the required shield-

Inspired by shielding configurations tested with GEMC during the cosmic neutron shielding design, we focused our studies around location 117 shown in figure 37. As in the previous case, we tested shielding configurations with 2-3 layers of lead and/or water placed below the detector, locating one shielding layer on the hill, and shifting the detector position in order to optimize the distance from the dump (sh5 and sh7 shown in figure 38).

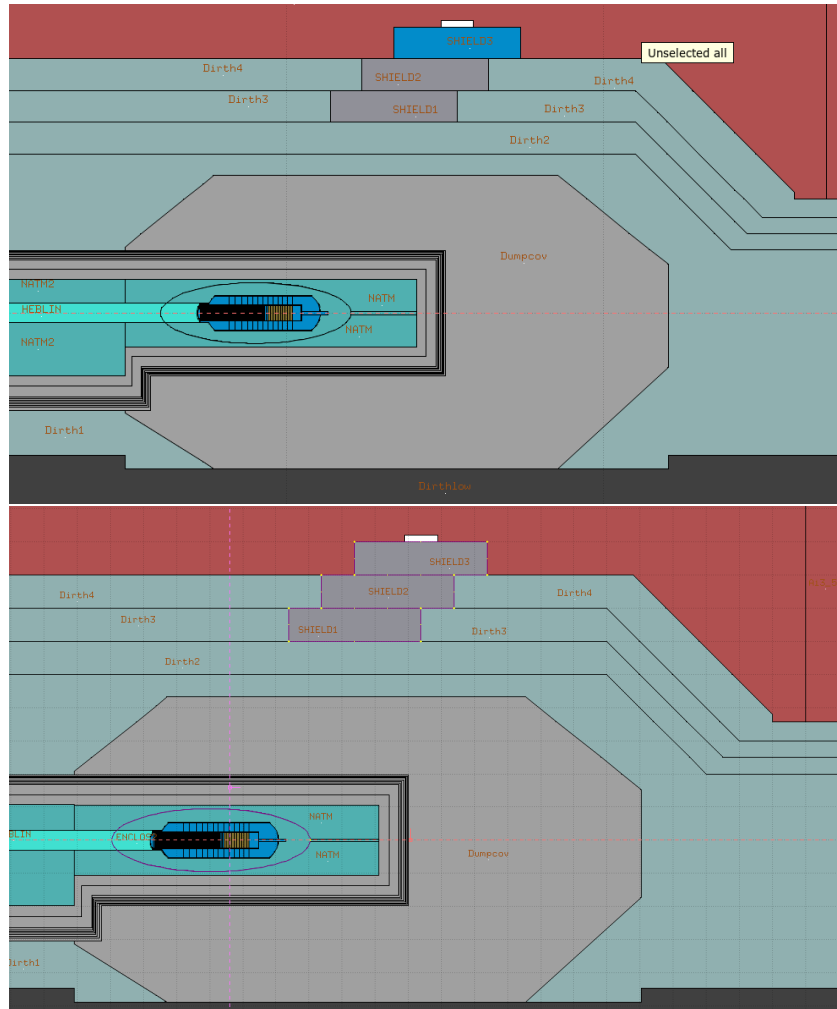


Figure 38: Simulation geometry for shielding studies around position 117. Shield configuration sh5 and sh7. In blue is indicated the water layer, and in gray is indicated the Pb layer

To identify the most effective shielding configuration for each setup, we derived

the number of neutrons expected in different energy intervals. The best configurations we found are sh3 and sh7. Both use 3 layers of lead (fig 37- 38), but in sh3, the shielding surfaces extend over all of the hill plateau; instead, in sh7, the shielding surfaces are limited in the area around position 117 and oriented in beam dump direction. Looking at the figure 39 in sh3, the shielding is more effective for energies below 10 keV. The two shields behave similarly for energies between 10 keV and 10 MeV. For energies above 10 MeV, sh7 is better than sh3 (1-2 orders of magnitude). In conclusion, this study showed that the best configuration to shield the detector from beam-related neutrons is to move it to a farther location (e.g. 117) rather than place it vertically and replace part of the dirt below this position with 3 layers of lead, 1 m thick each.

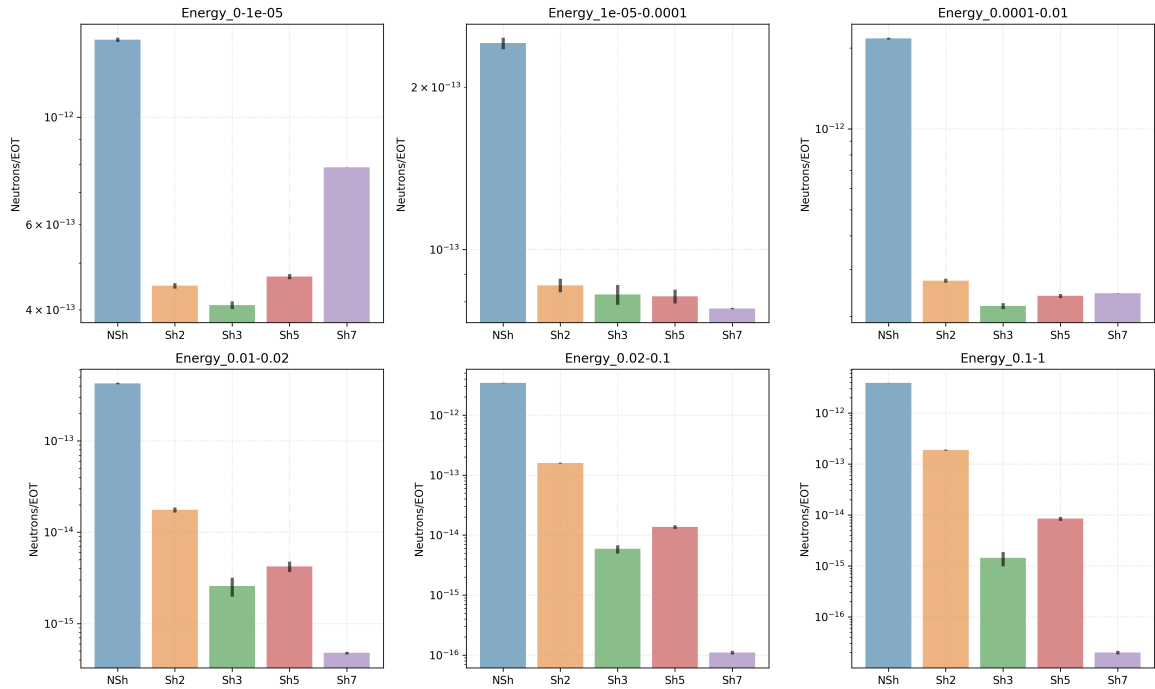


Figure 39: Comparison of the number of neutrons in different energy intervals for several shielding configurations

4.3.4 Detector shielding

As previously mentioned, the GEMC toolkit was used to optimize the detector shielding, while FLUKA was used to derive the particle flux and energy spectrum on the detector. The detector shielding optimization ran in parallel with the optimization of the detector location.

We started from the beam-related background on surface 600 with the shielding configuration optimized for cosmic neutrons, gradually increasing lead layer thickness. Since the low energy part of the neutron background was not affected by lead shielding, we inserted some water to moderate neutrons and cadmium to act as absorbers.

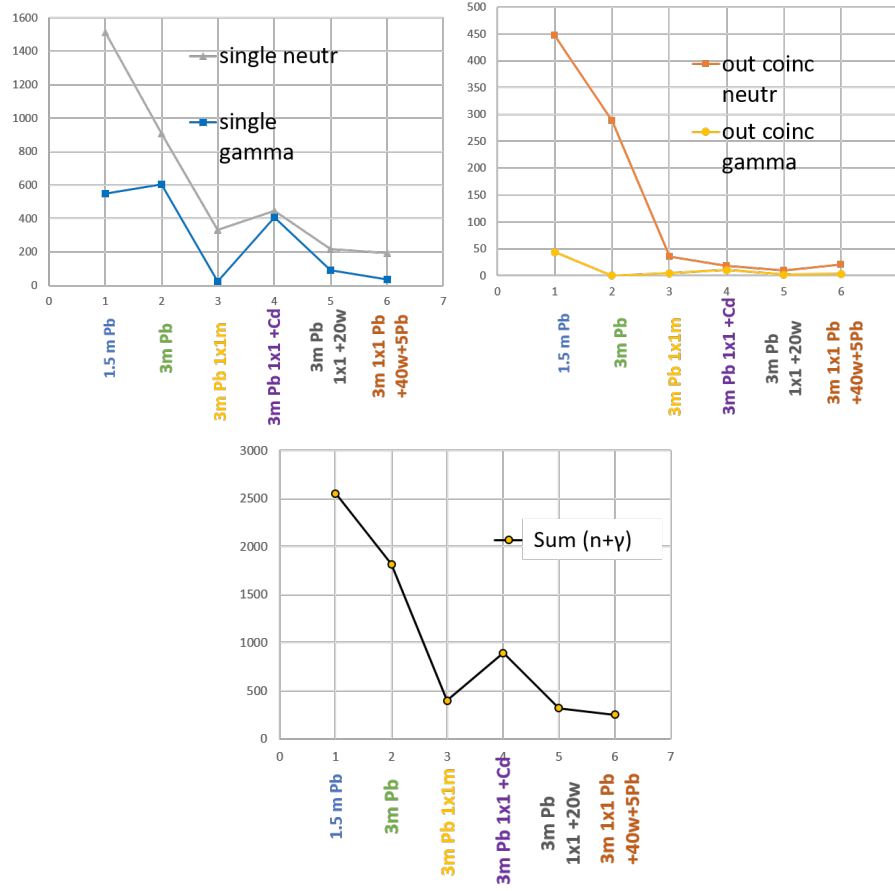


Figure 40: Summary plot of the behavior of several parameters (simulation entries number: 5.77×10^8) with different shielding configurations. On the upper-left are the numbers of the single hit detector generated by neutrons and gammas. In the upper-right: numbers of veto-detector coincidence hits outside the time window generated by neutron and gammas. On the lower: sum of all contributions of unremovable hits

Including Cd reduced the number of low-energy neutrons but increased the high-energy range of the spectrum. The configuration with water was found to be more effective. The configuration was optimized, adding a thin layer of lead immediately before the veto. Using the spectra obtained with FLUKA and normalizing to the number of EOTs corresponding to one year of the run, we calculated the ex-

pected non-removable hits generated by the beam background. With the optimal configuration, 40 cm of water and 5 centimeters of lead between the lead floor and vetoes, a total of 2×10^5 hits/year was found.

5 Physics sensitivity

5.1 Yield calculation

Coherent elastic neutrino-nucleus scattering (CE ν NS) occurs when a neutrino interacts coherently with the total nuclear weak charge. Considering that CE ν NS is an elastic scattering, it is enhanced at low momentum transfer. CE ν NS is the dominant interaction for neutrinos with energy below 100 MeV. ν BDX aims to repeat the COHERENT experiment with 1 m³ CsI crystals-based detector. We evaluated the sensitivity of such an experiment (the expected yield) relying on simulated neutrino flux shown before and an active volume reported above [79]. We assume the CsI density to be 4,51 g/cm³ and considered 78 (74) neutrons in Cs (I), respectively.

$$\frac{d\sigma_{\text{coh}}}{dT_A} \approx \frac{G_F^2 m_A}{\pi} \left(1 - \frac{T_A}{T_A^{\text{max}}} \right) |F_n|^2 (g_V^n)^2 N^2, \quad (52)$$

CE ν NS differential cross-section is proportional to neutron number squared (N^2), the nucleus recoil energy T_A , and Helm nucleus form factor F_n (that, in turn, depends on nucleus and momentum transfer q).

The nuclear form factor is the Fourier transform of the spatial charge distribution and describes the spatial extension of a nucleus.

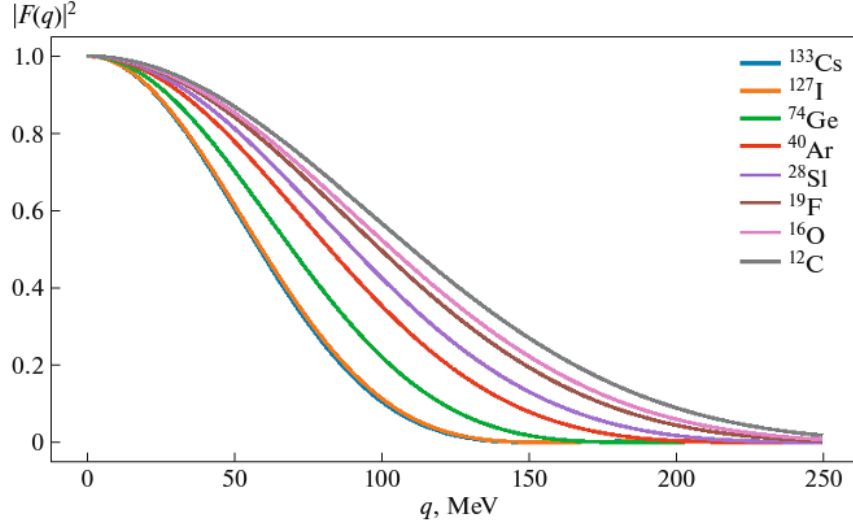


Figure 41: Helm nuclear form factor as a function of the absolute value of the 3-momentum transfer q .

Figure 41 shows the Helm parametrization of the form factor for different nuclei [22]. This figure demonstrates that, for $q \rightarrow 0$, the form factor tends to unity, $|F(q)|^2 \rightarrow 1$, with the result that the contribution of the incoherent cross-section (that is proportional to $1 - |F(q)|^2$) vanishes, leaving the coherent term to dominate. The coherent scattering term disappears in the opposite case (high q), leaving the incoherent piece to dominate.

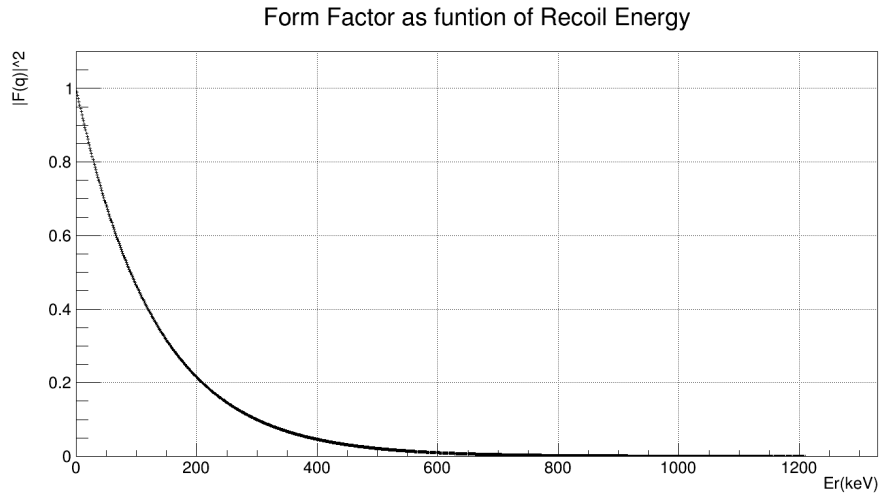


Figure 42: Helm nuclear form factor as a function of recoil nucleus energy.

Fixing parameters of the nucleus form factor makes it possible to calculate the CE ν NS differential cross-section as a function of the recoil energy of the scattered nucleus. Nucleus recoil energy T_A is related to the four-momentum transfer q , so we plot F as a function of T_A (or E_r)(fig. 42).

$$|q| = \left(E_\nu^2 + E_\nu'^2 - 2E_\nu E_\nu' \cos \theta \right)^{1/2} \simeq (2m_A T_A)^{1/2}, \quad (21)$$

$$T_A^{\max} = \lim_{\cos \theta \rightarrow -1} T_A \approx \frac{(2E_\nu - \Delta\varepsilon_{mn})^2}{2m_A}, \quad (29)$$

With this, we have all the ingredients to evaluate the cross-section for a given nucleus and calculate the number of expected events (yield) in the ν BDX experiment.

$$\frac{dR}{dE_r} = V_{\text{det}} \rho(P) \frac{N_A}{m_{\text{molar}}} \int_{E_\nu^{\min}}^{E_\nu^{\max}} \frac{d\sigma}{dE_r} \frac{d\Phi}{dE_\nu} dE_\nu$$

To do this, we must calculate the integral of the differential cross-section between $T_{\min}$ and $T_{\max}$ (for high E_ν is possible to limit the values corresponding at $T_{\max} = 500$ keV to accelerate the integration calculation), for each bin of neutrino energy spectrum (fig. 43), sum these integrate values for each interval of the spectrum and finally multiplied all for the mass of detector (Volume = 1 m³), the Avogadro number and divide for molar mass.

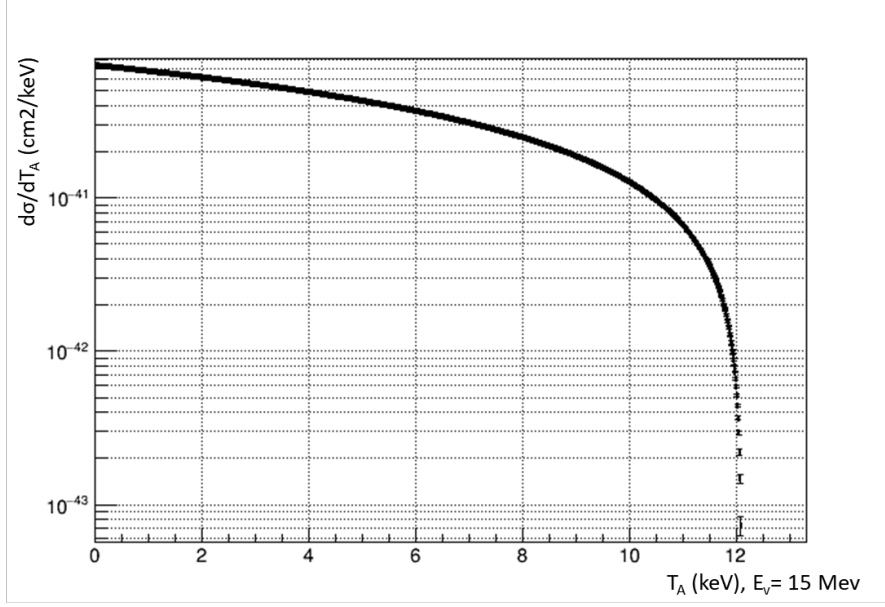


Figure 43: CE ν NS Differential cross-section at fixed neutrino energy

Finally, it is possible to plot the yield for a T_A (recoil energy threshold of the detector) by fixing the $T_{min} = T_A$ in the integration of differential cross-section. For a hypothetical threshold of 5 keVr, we obtained about 3.5×10^3 CE ν NS events per year (fig. 44). Another scintillating crystal that we potentially have available and whose performance we wanted to evaluate for CE ν NS measurement is lead tungstate (PbWO_4). Given the density equal to 8.28 g/cm^3 and N in the ranges 124-126 for Pb and 108-110 for tungsten, the number of CE ν NS events is expected to be greater than CsI. In fact, with the same volume, we would have approximately 4.5×10^4 CE ν NS events per year (fig. 44). Twice as much as CsI, however, PbWO_4 has a light output that is typically an order of magnitude less than CsI and is, therefore, more difficult to detect low recoil energies.

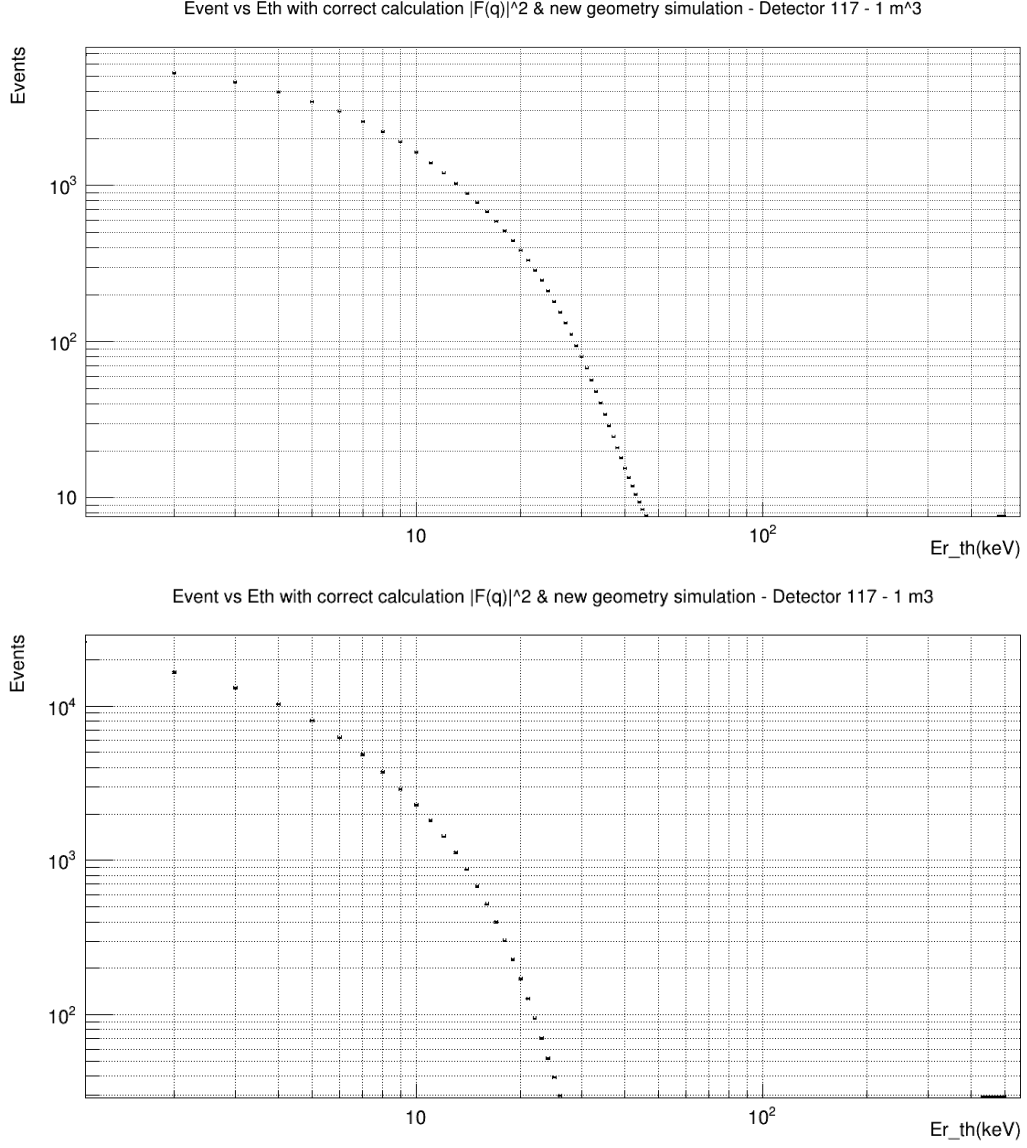


Figure 44: Yield of $CE\nu NS$ events for a 1 m^3 CsI detector(above) and $PbWO_4$ (below)

Based on the number of $CE\nu NS$ events, it is then possible to estimate the physics reach in extracting quantities such as the Weinberg angle and neutrino NSI.

5.2 Theta Weinberg

The Weinberg angle or weak mixing angle is a parameter of the Weinberg–Salam theory [59] of electroweak interaction. The measurement of the Weinberg angle is of great interest to JLab’s research activity.

5.2.1 Reach calculation

To determine the sensitivity to this quantity, a simple single-bin chi-square analysis was performed following the prescription reported in Ref. [60]:

$$\chi^2 = \left(\frac{N_{\text{Exp}} - (1 + \alpha)N_{\text{Theo}}(p)}{\sigma} \right)^2 + \left(\frac{\alpha}{\sigma_\alpha} \right)^2 ,$$

where N_{Exp} is assumed to be the SM prediction, N_{Theo} is based on the parameter(s) choice. The statistical uncertainty was assumed to be described by $\sigma = \sqrt{N_{\text{Exp}} + B}$. Here, B refers to the background, expressed as the fraction with respect to the signal: $B = N_{\text{Exp}} * f/100$.

To calculate the reach, it is necessary to consider the different parameters: signal yield, background, and quenching factor that is parametrized into term $(\alpha/\sigma_\alpha)^2$. The ionization quenching factor (QF) is the fraction of energy released by the nucleus recoil in a medium through ionization compared with its total kinetic energy. This last term seems to be critical for the Weinberg angle. The background estimate could be critical if its size becomes significantly larger (in order of magnitudes) than the signal.

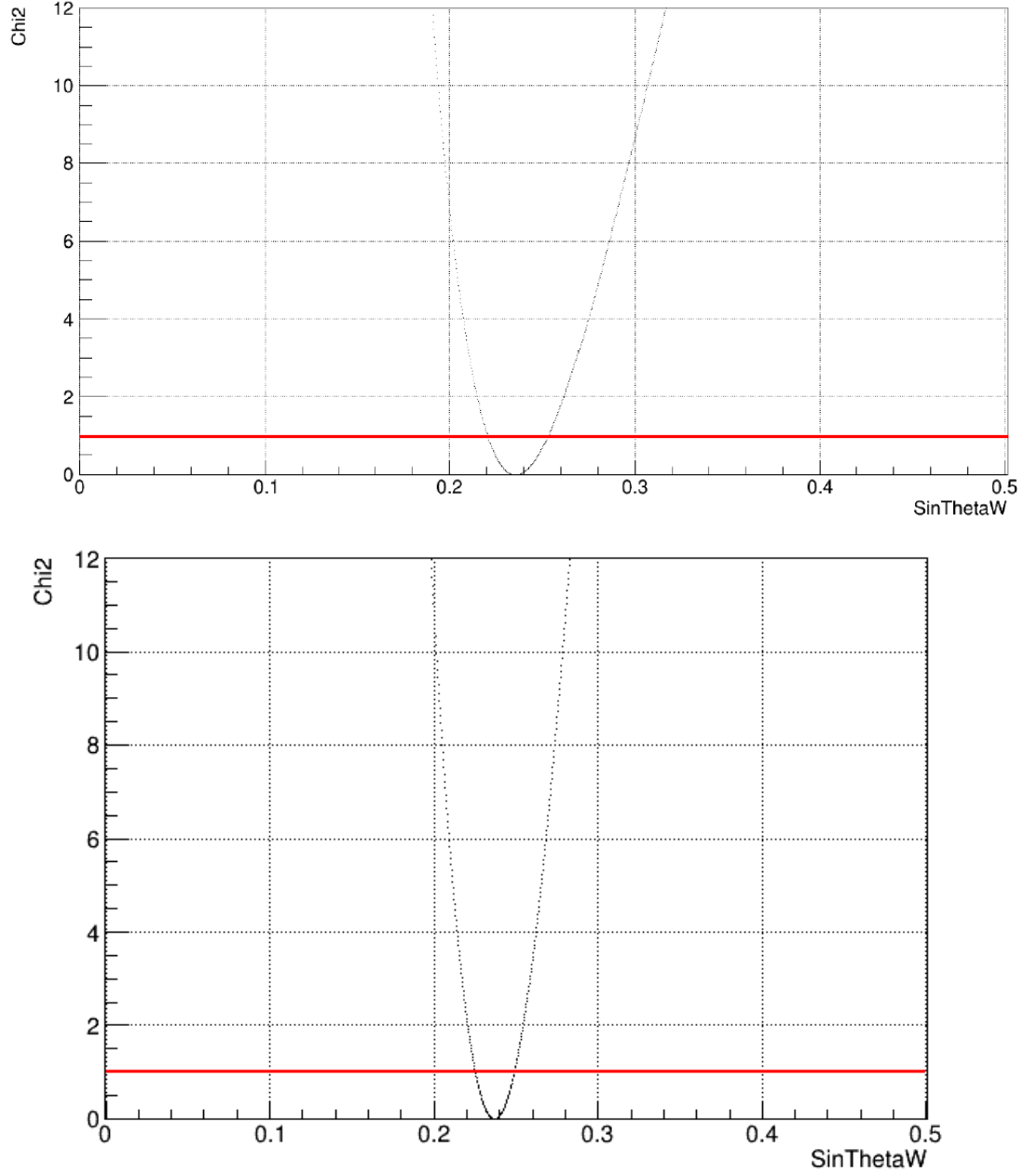


Figure 45: Reach for theta Weinberg in CsI(above) and PWO₄(below) with a background of 100 times large that the signal. Value estimate and uncertain are $\sin\theta_W = 0.2351^{+0.0162}_{-0.0142}$ for CsI and $\sin\theta_W = 0.2366^{+0.0126}_{-0.0114}$ for PWO₄

Using the same QF assumed by the COHERENT experiment and a background-to-signal ratio of 100 (as derived by simulations described in Chapter 4 comparing the number of expected CE ν NS and the total number of background events),

the uncertainty on the extracted sine of the Weinberg angle is expected to be 3 (4) times smaller than the COHERENT result when a calorimeter made of CsI ($PbWO_4$) is considered (fig. 45, 46).

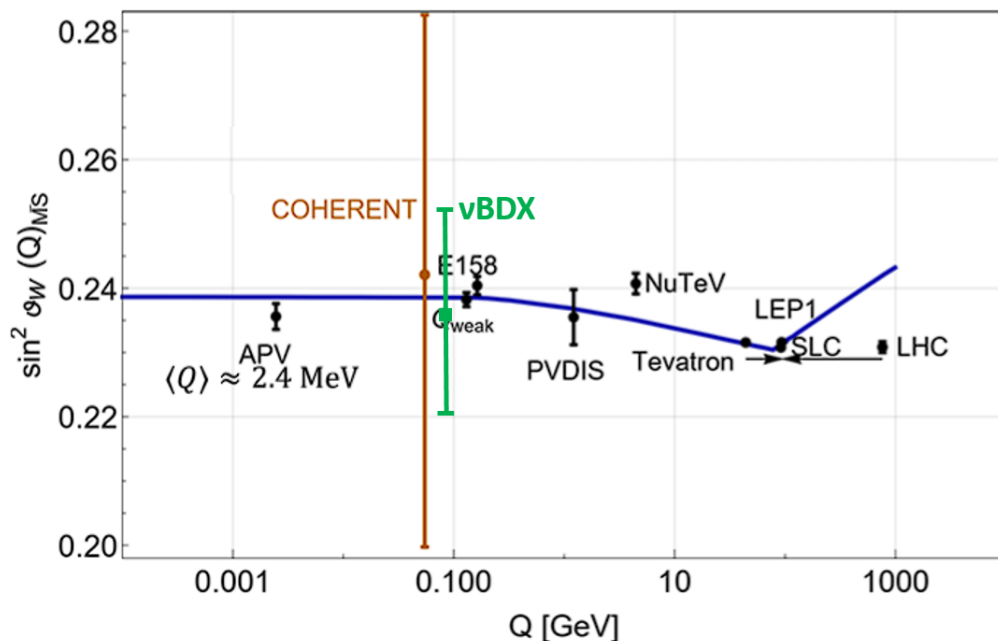


Figure 46: Comparison Weinberg angle sine for several experiments. In green, ν BDX-CsI estimation

5.2.2 Sensitivity

As already seen in the reach estimate, it is essential to have a solid estimate of the background. The sensitivity of ν BDX experiment can be evaluated in such conditions by estimating the irreducible background. Fluctuation of background contributes to the area where we expect $CE\nu$ NS signal. In the first approximation, we must be sure that the number of expected $CE\nu$ NS events is significantly greater than the standard deviation of the background. The latter goes like the square of the number of counts, making it easy to compare the two values. Considering an expected value of 3.5×10^3 $CE\nu$ NS events, the background events we can sustain

are about 7×10^6 (see fig. 47).

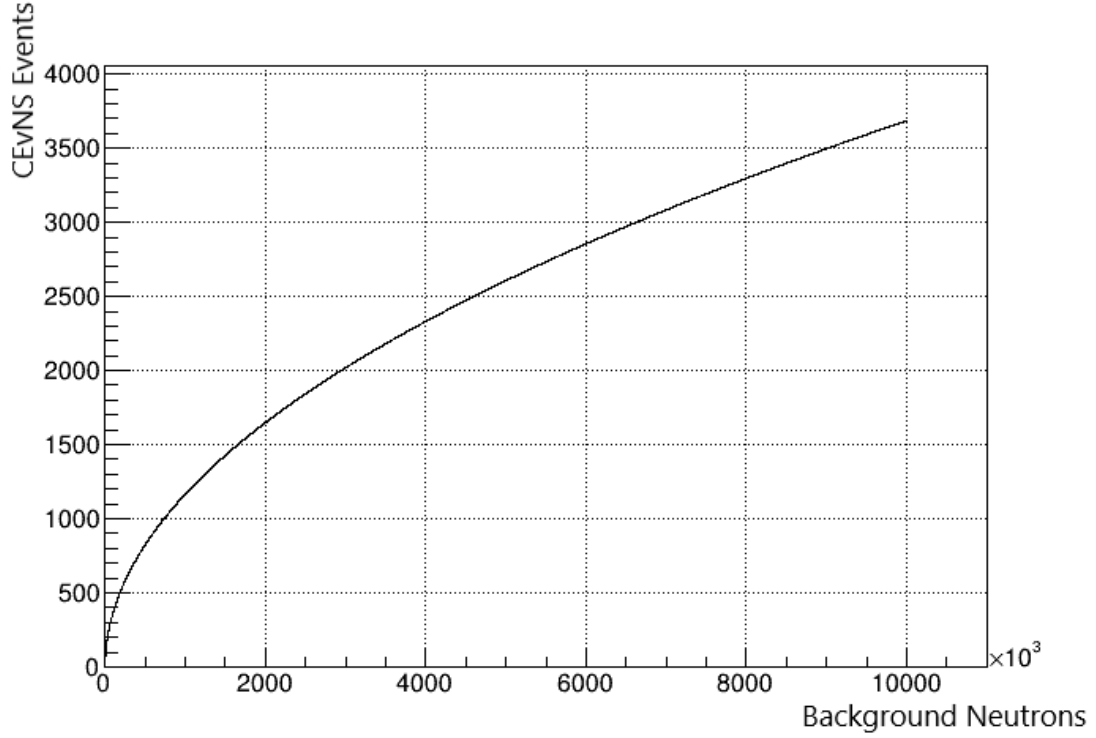


Figure 47: CEνNS events compared with maximum acceptable background events for sensibility estimation

5.3 Neutrino Non-Standard Interaction

Using the expression in the Par. 2.5.2 and the chi-square definition, it is possible to estimate the reach for neutrino NSI (fig. 48). Calculation of sensitivities is done assuming the variation of a parameter at a time. Our estimation of neutrino NSI coupling $\epsilon_{u\mu}^\mu$ ranges between $[-0.055, -0.025]$ and $[0.375, 0.404]$, slightly better than COHERENT results ($\epsilon_{u\mu}^\mu$ between $[-0.05, 0.03]$ and $[0.37, 0.44]$)

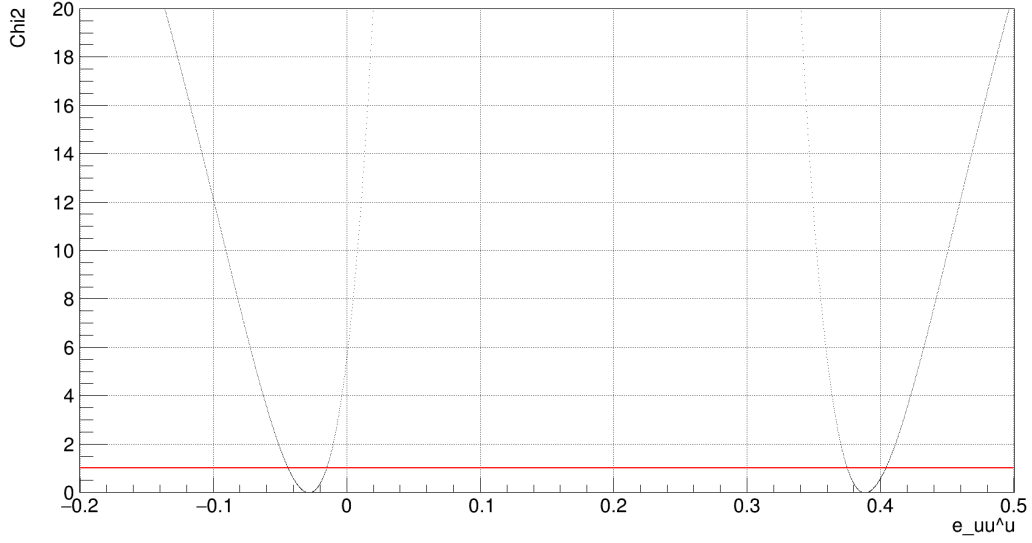


Figure 48: Reach for neutrino NSI with a background of 100 times the signal in the CsI detector. 1σ allowed ranges for neutrino NSI coupling $\epsilon_{u\mu}^\mu = [-0.055, -0.025]$ and $[0.375, 0.404]$

6 The experimental setup studies

6.1 $\text{CE}\nu\text{NS}$ events detections

The $\text{CE}\nu\text{NS}$ detection is essentially based on measuring ionization/excitation produced by the nucleus the neutrino interacted with. Different kinds of detectors can detect the energy transferred to the nucleus (fig. 49). There are several possible methods and technologies that can be used (49):

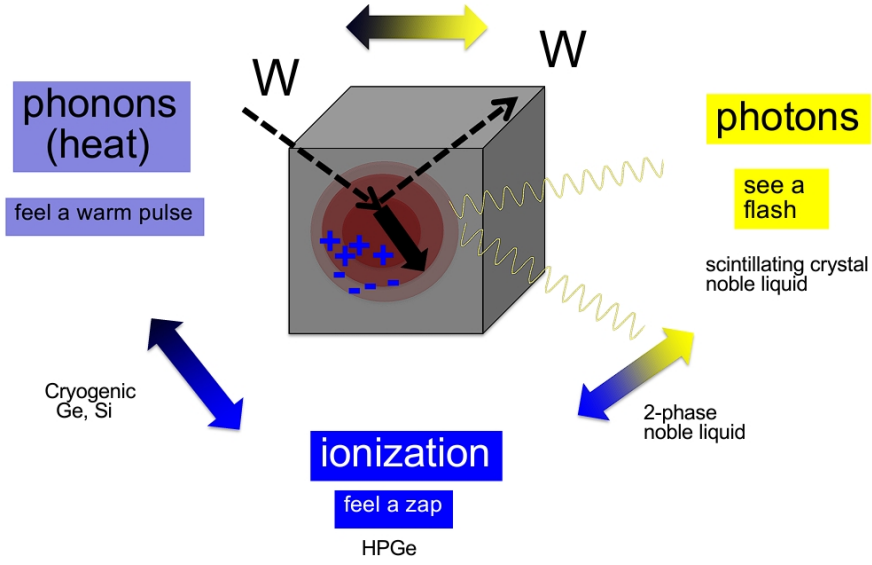


Figure 49: Scheme of main low-energy nuclear recoil detection strategies

6.1.1 Ionizing detector

The neutrino interaction generates a small ionization (a few eV), which can be detected in suitable ionization detectors such as Ge PPCs, Ar-Xe TPCs, and Si CCDs. Recoil energies of the order of keVr are easily detectable, while it is more difficult to go below 1 keVr. [61–63]

6.1.2 Scintillating detector

Similarly to ionization, the nucleus recoil energy that have interact may excite some levels of a crystal lattice, generating light. Given the energies involved (few keV), scintillators with a high light yield, such as CsI, NaI, and Ar-Xe TPCs, are necessary. As in the case of ionization, however, detectable energies are limited to $> \text{keV}$ due to light quenching [64–66].

6.1.3 Bubble chambers

The energy of recoiling nuclei can produce bubbles in a special chamber filled with Superheated liquids(C₃F₈, CF₃I, Xe, Ar). The energy range is analogous to the cases of ionization and scintillation. [67–69]

6.1.4 Phonon detector

The interaction of neutrinos within a crystal and the generated recoil nuclei can lead to the production of phonons. This results in a localized temperature difference that can be detected. Phonon readout is a promising technology to reach a threshold as low as < 100 eV. [70]

7 CsI(Tl) crystal characterization

For ν BDX, the method choice is a detector made by CsI(Tl) crystals of 1m^3 volume. We, therefore, studied in detail the response of CsI(Tl) crystals (about $5\text{x}5\text{x}30\text{cm}$) formerly used in the BaBar EM calorimeter [71], considering that a large number of crystals would be available for reuse and the volume thought to be instrumented (1m^3 for a total of more thousand crystals). Caesium Iodide has high γ -ray stopping power due to a relatively high density and large atomic number. It is used either in its undoped form or doped with sodium or thallium for scintillation counting. CsI is resistant to thermal and mechanical shock. The thallium-doped one is slightly hygroscopic so the contact with water or high humidity environment should be avoided. CsI(Tl) is one of the brightest scintillators ($50\text{k}\gamma/\text{MeV}$) with a maximum emission spectrum situated around 550nm (fig. 50). CsI(Tl) is a relatively slow scintillator with an average decay time of about some μs .

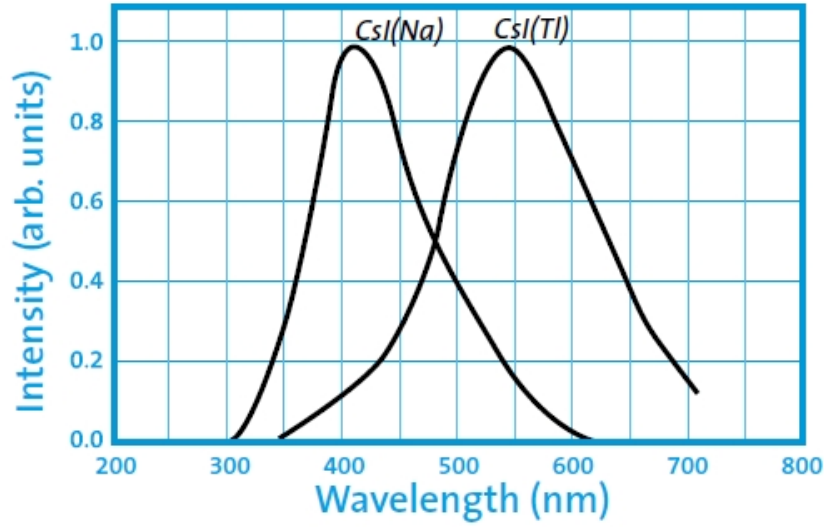


Figure 50: Scintillation emission spectrum of CsI crystal

The crystal wrapping is critical for collecting a large fraction of the light produced into the crystal. A thorough comparison of different materials (reflectors such as glued and un-glued VM2000 or diffusers) is then suitable.

Polishing is also a critical aspect of light collection efficiency. CsI(Tl) is slightly hygroscopic; therefore, if in contact with air, humidity gets collected on the surface, and the crystal becomes opaque. Age and storage are essential aspects that can negatively affect light output. To refurbish the 30-year-old BaBar crystals, a temperature annealing process has been tested. However, preliminary results do not show significant improvements.

7.1 The CsI(Tl) crystal

For the measurement of the $\text{CE}\nu\text{NS}$, we need a high energy resolution detector that allows to detect the small energies deposited by these processes. We also need to reduce the possible contribution due to other processes that imitate the signals we want to search for. Following the example of the COHERENT collaboration, we

focused on a detector based on Caesium's iodide crystals. The choice to focus on this type of scintillator is due to several factors: 1) large emission of photons for deposited energy; 2) easy to handle solid crystal; 3) availability of a large number of crystals available from the Babar experiment;

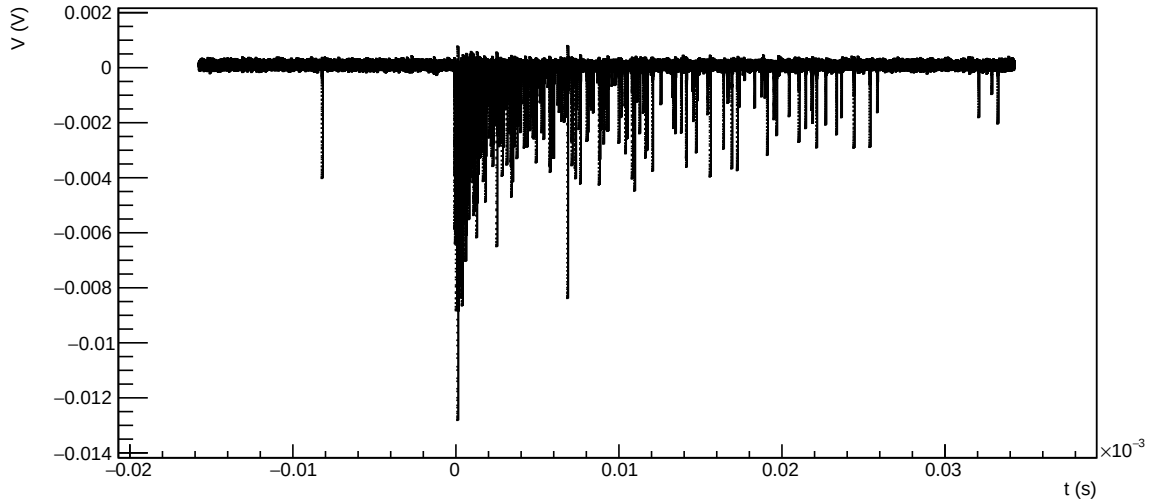


Figure 51: Signal produced by CsI scintillation

7.2 Integration time

The scintillation time of the CsI crystal is about few μs . By looking at the oscilloscope signals, we see a peak followed by a large number of events with few photoelectrons (see fig. 51). It is, therefore, important to evaluate the correct time interval to be used to integrate the collected charge. We then ran tests at different integration windows to assess the effect on the collected signal. These measurements tell us that we have a 20% increase of charge in the collected signal if we increase from a 2 μs window to a 4 μs window (fig. 52).

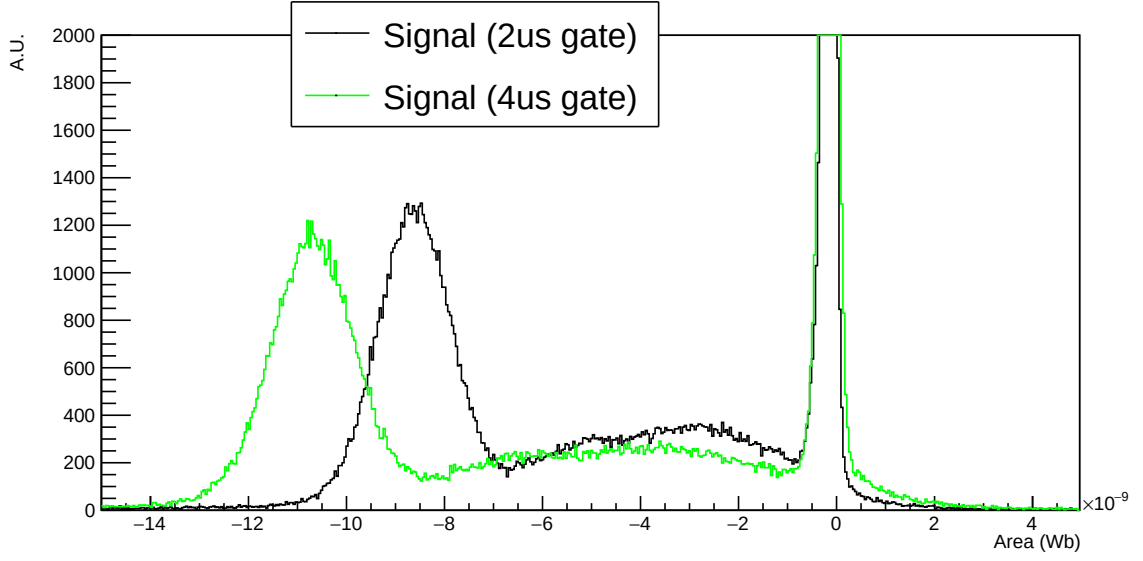


Figure 52: Cosmic ray signal comparison with different integration time

7.3 Light yield

One of the first necessary steps to proceed with the design of a prototype to measure the CE ν NS is to understand the characteristics of the chosen technology and, in particular, the light yield of the CsI crystals at our disposal. The Caesium Iodide crystal doped with Thallium (CsI(Tl)) has a moderate density (4.51 g/cm³). The CsI(Tl) is a scintillator with a high light output of about 51800–65000 photons for 1 MeV of deposited energy in the crystal. Given the age of the crystals at our disposal, it was necessary to verify that they had not changed their scintillation characteristics in terms of any impurities that have entered the crystal and aging due to the irradiation of the crystals used in former experiments. Studies were carried out using both PMT and SiPM. We used calibrated radioactive gamma sources (Cs137, Co60, Na22) to estimate the light yield of the crystals. Unfortunately, tests have shown us that the light yields of BaBar crystals are significantly lower than expected. We therefore tried to improve the light output through pol-

ishing, wrapping and heating interventions.

7.3.1 Polishing

The CsI(Tl) crystals we have examined from the Babar detector have a non-optimal state of conservation. Some parts of the crystal are yellow and of reduced transparency. This reduces the light that a photosensor can collect. Therefore, we investigated whether it was possible to partially restore the original transparency of the crystal. The opacity of the crystals is strongly related to the hygroscopicity of the same and consequently to the quantity of water penetrated in the crystal. How do you remove the water then? Much depends on how deep this has penetrated the crystal. If the penetration is only superficial, it may be sufficient to remove only a tiny layer through polishing. Conversely, if the penetration were deeper, it would be necessary to proceed with more invasive methods, such as cutting or trying to evaporate water with heat. Fortunately, Caesium iodine crystals are much less hygroscopic than other inorganic crystals such as NaI. We then initially proceeded to polish the two sides of the crystals manually. After a visual inspection of the polished crystals, the difference was quite evident(fig. 53,54).

To test the effect of the procedure more quantitatively, we proceeded to make two pre- and post-polishing measures using a source of Cs137 and measured the collected light from the crystal with a PMT.

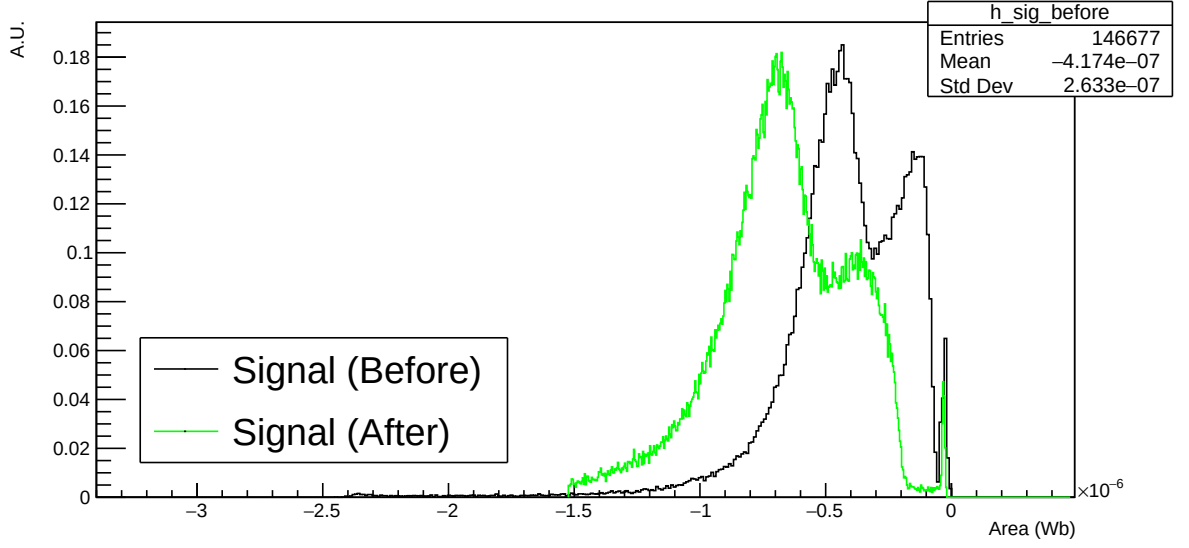


Figure 53: Comparison performance after and before polishing

These measurements show a clear improvement of the light collected by the photosensor of about 30 %.

7.3.2 Wrapping

Parallel to polishing studies, we evaluated the effect of wrapping on light yield. Initially, these crystals had a white diffusive envelope that reflected a part of the light produced behind them. We tested reflective wraps to replace the original diffuseness to increase the amount of collected light. In particular, we focused on the VM2000. We have two types of reflective VM2000: with glue or without. The version with glue might seem the best choice because it allows you to adhere the reflection perfectly to the surface of the crystal.

However, glue interacts with the crystal itself (slight corrosion), leading to opacification of the walls and favoring diffusive behavior. Therefore, we only worked with a reflective without glue.



Figure 54: Visual effect of polishing. On the left is polished crystal, and on the right, the original BaBar one

By comparing the measures, we evaluated the effectiveness of the wraps. Compared to a bare crystal with a white diffusive envelope, the improvement of the light collection is about 100% (fig. 55).

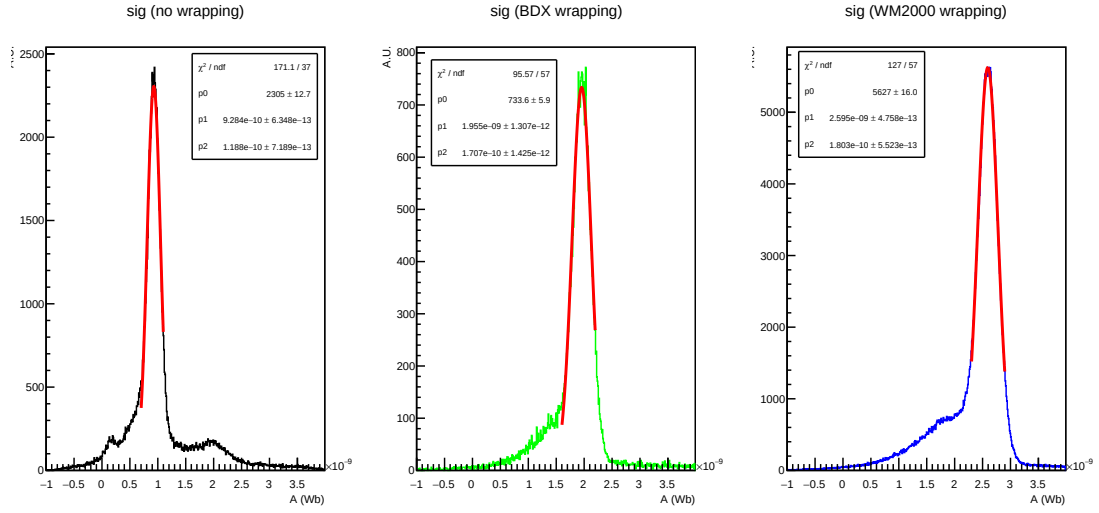


Figure 55: Wrapping effect. On the left, there is no wrapping. In the middle, the original white wrapping, and on the right VM2000 wrapping

The reflective envelope instead improves the collection of light of another 50%.

7.3.3 Air gap effect

Another element to consider in evaluating the number of photons collected is the effect of the interface between the crystal and the photosensor.

With some photosensors, it is not possible to put them on a crystal surface; it must stay at a distance of a few mm. Therefore, evaluating the effect of an air gap between the crystal and the photosensor becomes essential. During the tests, we tried to compare the amount of energy deposited in the case of a photosensor (EMI photomultiplier) perfectly attached to the crystal at a distance of 1 mm and 5 mm.

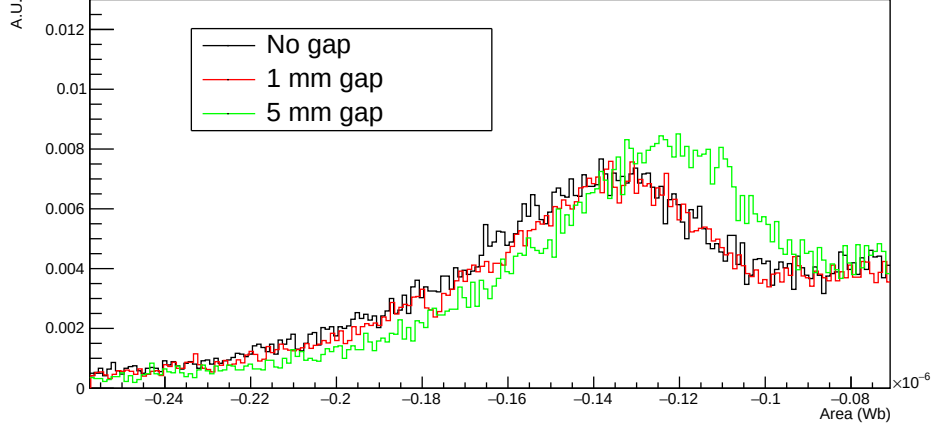


Figure 56: Effect of air gap

In these tests (fig. 56), we saw that if we put the photosensor at a 5 mm distance from the crystal, there is a signal loss of about 10-12%. Instead, the effect at a 1 mm distance is negligible.

7.3.4 Temperature Variation

To improve light emission, the response of crystals at cryogenic temperature is currently under investigation for some behavior promising for our purpose [97]. Under these conditions, CsI crystals show an increase in light yield that permits better energy resolution and reduced scintillating time, a critical factor in thallium doping. The tests, however, were not conclusive given the difficulty of maintaining the crystals at a uniform temperature for the tests before the used cryogenic liquid (liquid nitrogen) ran out. In the future we are thinking of instrumenting a cryostat to complete these tests.

7.3.5 Light attenuation

The light attenuation length in the crystal is an essential parameter for estimating the amount of collection by photosensors. The geometry of the CsI crystals we have studied is of a very elongated truncated pyramid, making it look like a right parallelepiped. Therefore, we have two small faces of different sizes.

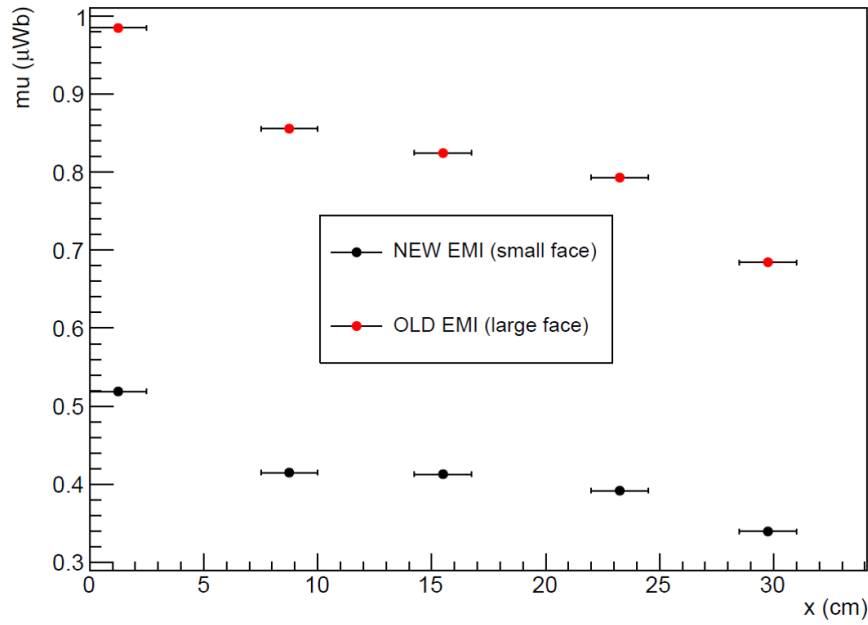


Figure 57: Plot of light attenuation for the crystal faces using 2 different phototubes

Considering the different gains of the phototubes used, it can be seen that on the small face, the optical attenuation reaches 40% for the more distinct signals, while for the large one, it seems to be only 30% (fig. 57). This discrepancy is due to the non-rectangularity of the crystal.

7.4 Photosensor

To detect recoil energies of the nuclei of the order of a few keV, it is necessary, in addition to scintillators crystals with a high number of photons emitted, photosensors capable of collecting as many photons from the crystal. Giving the dimension of crystals faces the readout system can consist of SiPM arrays or phototubes to cover a large area of faces. The phototubes has been beneficial in the crystal characterization tests but they are not a solution for the final prototype. The need for better quantum efficiency and a more straightforward system led us toward SiPM arrays. Given the possibility of working at cryogenic temperatures, we talked also to DarkSide colleagues, who designed their experiment using many SiPM arrays. The advantages would be in the size of the matrix (which is well suited to our crystal), the fact that it is designed to work at low temperatures, and the possibility of relying on the experience of the DarkSide group in Genoa.

7.4.1 Phototube

The phototubes (PMT) can easily be found with diameters such as to allow the trim surfaces of the CsI crystals of BaBar to be covered entirely. Another important feature is their response time, which will enable you to see the scattered emission of the crystal easily. On the other hand, they require high voltages and have dimensions comparable to crystals. One of the phototubes used for testing is Thorn EMI 9954B, a 51 mm (2 in.) diameter end window photomultiplier with an enhanced green sensitive bialkali photocathode and 12 BeCu dynodes. The PMT of this model has a total gain of $k=10^7$, a typical operative voltage of 1.8-2.3 kV, and a quantum efficiency of 28%. The transit time spread of the single p.e. response is 41 ns. The PMT has a good energy resolution characterized by the

manufacturer's peak-to-valley ratio.

7.4.2 DarkSide SiPM matrix

SiPMs are typically small in area (less than 100 mm^2); therefore, several dozen would be needed to cover a single face of the CsI crystal. If they were connected individually to the acquisition electronics, this would imply using many acquisition channels for a single crystal. It is, therefore, advisable to structure these SiPMs in matrices that allow the required surface to be easily covered, are readable with a single electronic channel, and have low noise to reduce the need for channels. The DarkSide group in Genoa has been working for years on a late-performance SiPM matrix (fig. 58) for their LArTPCs. The photosensor consists of 24 $10 \times 10 \text{ mm}^2$ SiPMs mounted on a substrate, referred to hereafter as a SiPM tile, mated to a board housing the front-end electronics. The 24 cm^2 SiPM tile is subdivided into 6 cm^2 quadrants, and each quadrant is read with an independent low-noise trans-impedance amplifier(TIA) based on an LMH6629 high-speed operational amplifier [98].

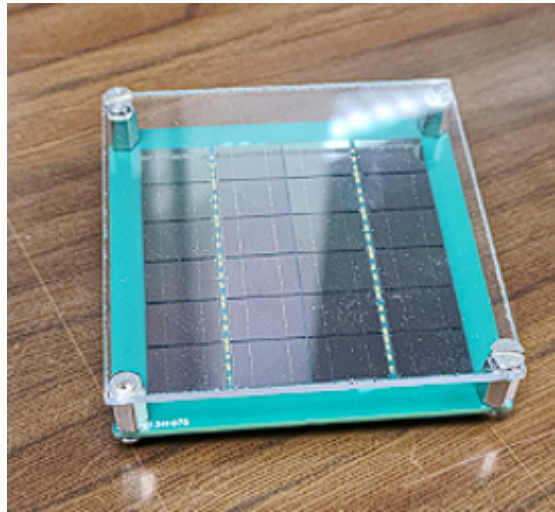


Figure 58: DarkSide Matrix

A second-stage amplifier then sums the four TIA outputs into a single analog output. The SiPM tile partitioning is driven by a compromise between a limit on the total power dissipation of the detector, equivalent to the total number of TIAs, and the bandwidth and SNR attainable for a given detector capacitance.

This SiPM tile is populated with 10×10 mm² NUVHD-LF SiPMs produced by Fondazione Bruno Kessler (FBK) for the DarkSide-20k collaboration [99]. NUVHD SiPMs have a peak efficiency of about 40% in the near-ultraviolet, between 400–420 nm (fig. 59), and are fabricated with a cell border structure that allows for high-density packing of small cell sizes [100]. The maximum efficiency range does not coincide with the maximum emission zone of the CsI crystal. However, it is still possible to achieve quantum efficiencies comparable to those of common SiPMs (25%) without acting on the over-voltage.

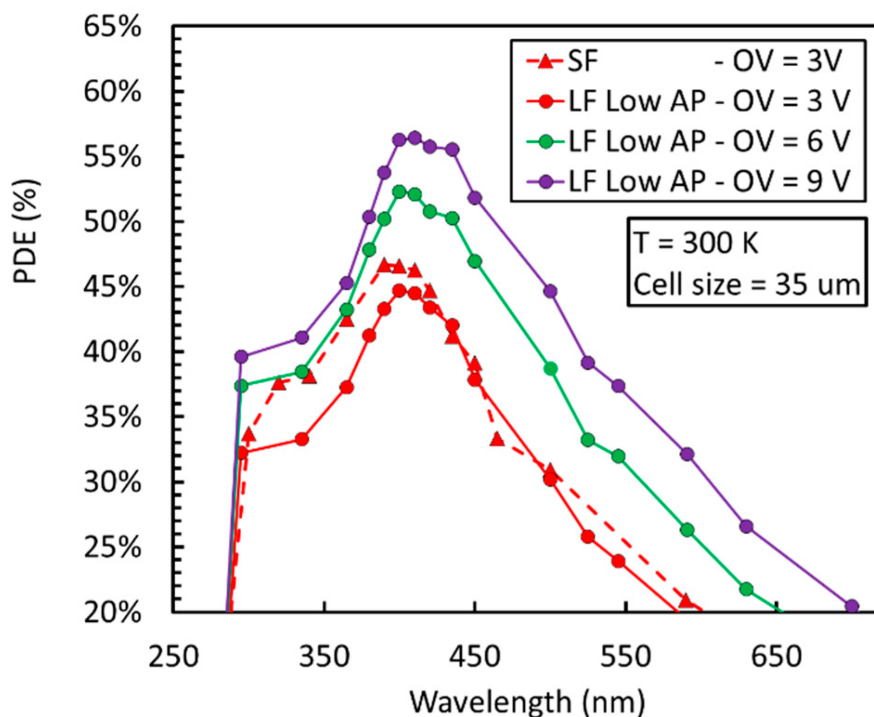


Figure 59: NUVHD quantum efficiency for different overvoltage

7.4.3 JLab EIC 3x3 SiPM matrix

During the collaboration with the JLab EIC group, it was possible to test a new SiPM matrix, which can also be very useful for ν BDX. The scintillator glasses being tested for EIC have a readable face of approximately 2x2 cm. Therefore a matrix was developed that completely covered this surface and is made up of 9 SiPMs (fig. 60). The matrix consists of a stack of two PCBs. The bottom board contains the SiPMs (S14161-6050HS) and a thermal correction circuit for the SiPM bias voltage. The top board has a pre-amplification circuit, coaxial connector, and 4-pin ribbon connectors for low voltage power and SiPM bias. Compared to the DarkSide matrix, this matrix would only cover 1/9 of the readable surface of the ν BDX crystal, but it can also work at room temperature and still allows a good gain of a factor of 8 compared to the single SiPM.



Figure 60: PCBA Bottom and top View

8 Streaming-ReadOut DAQ

We have said that the expected $CE\nu$ NS events will be in the order of a few thousand per year and that we should extract them from the neutron background. To avoid missing interesting events, it was decided to focus on Streaming-ReadOut

acquisition systems which allow the acquisition of enormous amounts of data that can be filtered at a later time. The Genoa section has great experience in this kind of system.

8.1 INFN-WaveBoard

For Beam Dump eXperiment (BDX) at Jefferson Laboratory (JLab) [101] is developed a triggerless highly configurable digitizer board (Waveboard) [102]. The board includes 12 complete acquisition channels dedicated to SiPM readout (fig. 61). The SiPM bias voltage is also generated and regulated on-board independently for each channel. The ADC can be tailored for applications ranging from 12-bit 65 MHz to 14-bit 250 MHz. The front end is now dedicated to the SiPM but can be easily reimplemented for other detectors.

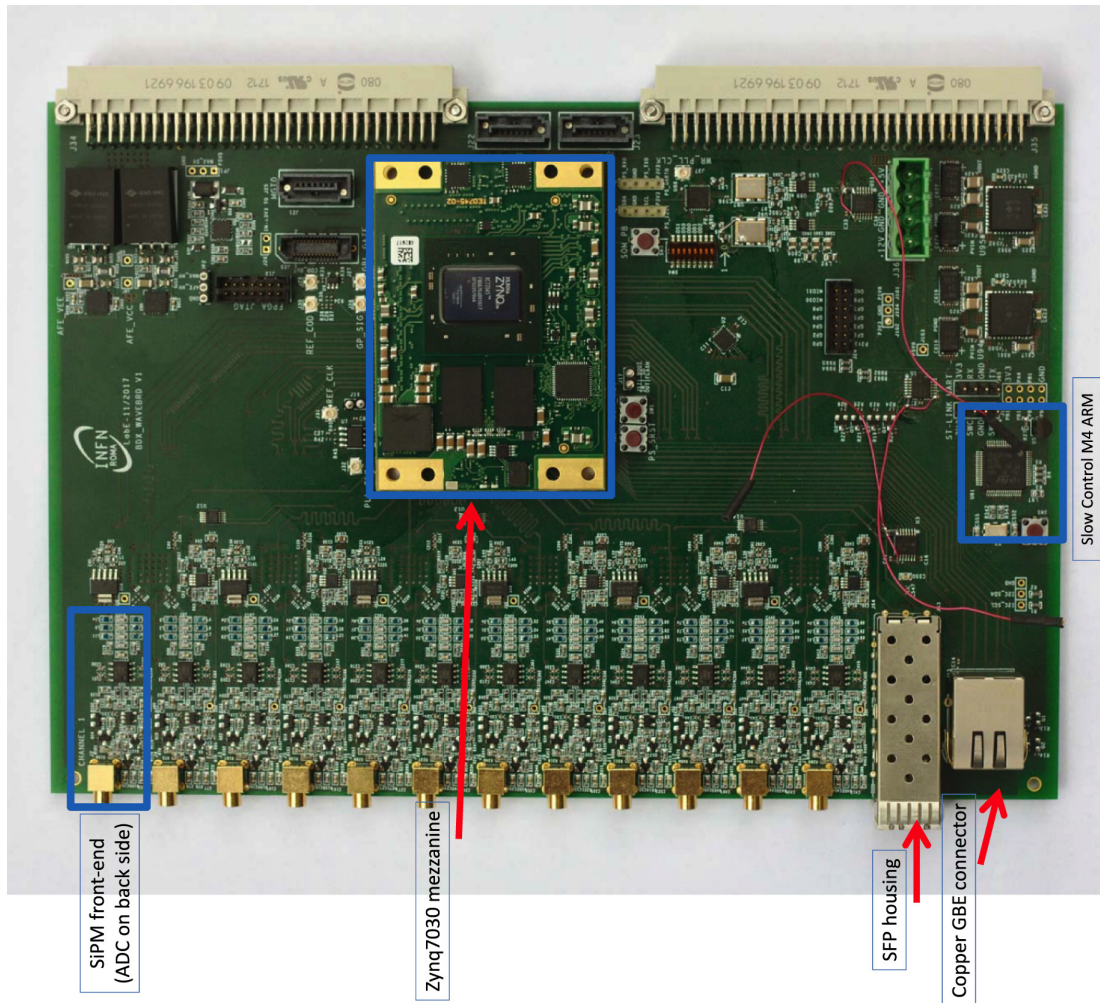


Figure 61: Schematic view of INFN-Waveboard

The board is controlled using a commercial FPGA module hosting a Xilinx Zynq device and all related peripherals, mainly memory and communication interfaces. The board is a triggerless system: all data passing some programmable selection criteria are sent out to a computing farm using gigabit Ethernet standard. The entire data acquisition system can be synchronized using GPS standard protocols (like NMEA [103] or IRIG [104]). The control of this board is done through an Ethernet connection sending commands directly on the board (EEE Testing Facility) or with a dedicated user-friendly interface (Astroplano).

8.1.1 EEE Testing Facility

The Extreme Energy Events (EEE) Project [105, 106] is designed to study high-energy Cosmic Rays (CR). It is a network of several muon telescopes based on Multigap Resistive Plate Chambers (MRPC) synchronized by GPS. The EEE network comprises 60 muon telescopes organized in clusters and single telescope stations installed in Italian High Schools, built and operated by students, and supervised by researchers. EEE Telescope comprises 3 Multigap Resistive Plate Chambers (MRPC), providing the impact coordinates of incoming muons and permitting the reconstruction of its track with high efficiency and good angular resolution. The time resolution is obtained using hit time on the top and bottom chambers to determine the expected time on the middle chamber.

The simultaneous presence of an EEE telescope and the INFN-Waveboard (WB) in the INFN section of Genova led to the creation of a collaboration. The result is the development of a detector test facility integrating the EEE extensive area detector tracking capabilities with the WB's multi-device simultaneous streaming data acquisition. In the CsI crystal test configuration, the reconstructed trajectories can be used to evaluate the hit point of the cosmic ray on the studied detector. A GPS provides a timestamp for each event in both systems. The antenna signal is the same (using a splitter) for both independent DAQ systems. Therefore, the two datasets are simultaneously analyzed, searching for coincidence events in a narrow time window for crystal characterization. It's possible to create a 2D-Map of these coincidence events (fig. 62). With this facility with a single measurement, it was possible to evaluate different parameters, such as optical attenuation, with a single measurement.

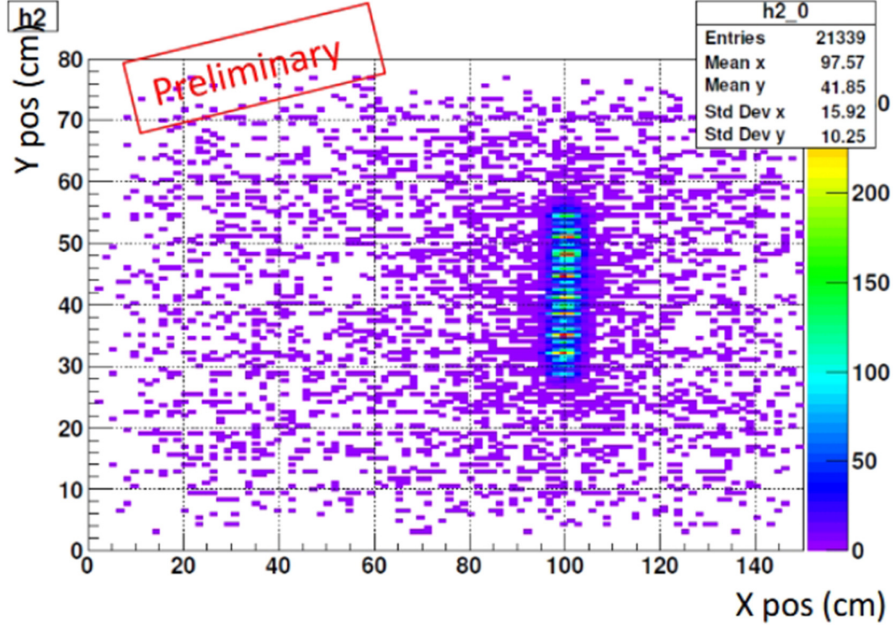
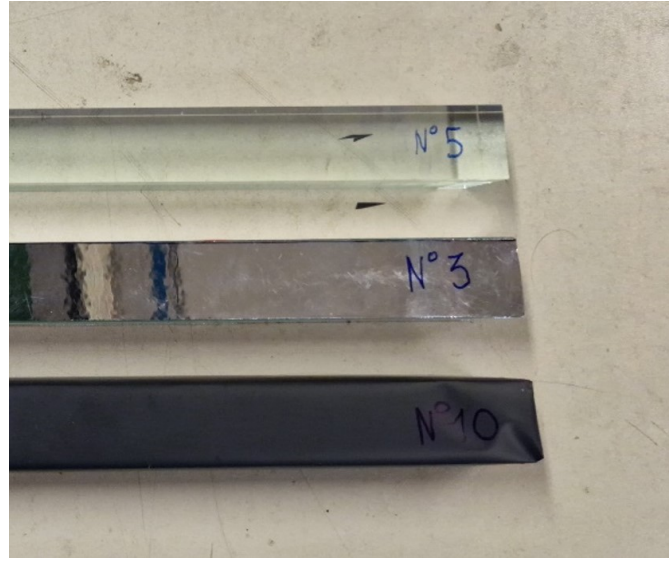


Figure 62: 2D-Map of cosmic-ray hits (in EEE telescope reference system) on a single crystal (blue–green points) by using EEE and WB data. The points outside the crystal are due to random coincidences between the two systems. The edges of the crystal do not appear clear due to the discretization of the EEE strips and the fact that the positional resolution of EEE is comparable with the size of the crystal.

The test facility of the EEE Telescope has proved to be highly valid for the study (particularly for attenuation length studies) of CsI crystals(see Paragraph 6.3.5) and other scintillating detectors. The facility was also used to test scintillator crystals (or glass) for experiments such as PPositron resonant annihilation into dark matter experiment (POKER) [107] and Electron-Ion Collider (EIC) [108]. Up to 25 scintillating devices are tested simultaneously.

8.1.2 JLab SciProto Test

In parallel with ν BDX activity, a Streaming-ReadOut system is tested using the INFN-Waveboard for the EIC calorimeter to permit calibration and data acquisition simultaneously. The Electron-Ion Collider (EIC) [108] is a particle accelerator collider designed to collide spin-polarized beams of electrons and ions to study the properties of nuclear matter in detail via deep inelastic scattering. EIC will allow probing of the substructure of protons and neutrons via a high-energy electron. The physics program of an EIC includes inclusive measurements, which require the detection of the scattered lepton and hadrons for which e - p is different from zero. Semi-inclusive processes, which require detection in coincidence with the scattered lepton of at least one (current or target region) hadron and exclusive processes which require detection of all particles in the reaction with high precision. The EIC requires electromagnetic calorimeters in the electron and hadron endpoint. Crystalline scintillators like $PbWO_4$ crystals have been used for high-resolution electromagnetic calorimeters, but crystals are expensive, and the production process is inflexible and slow.



CR Distribution signal on Sciglass 2_1

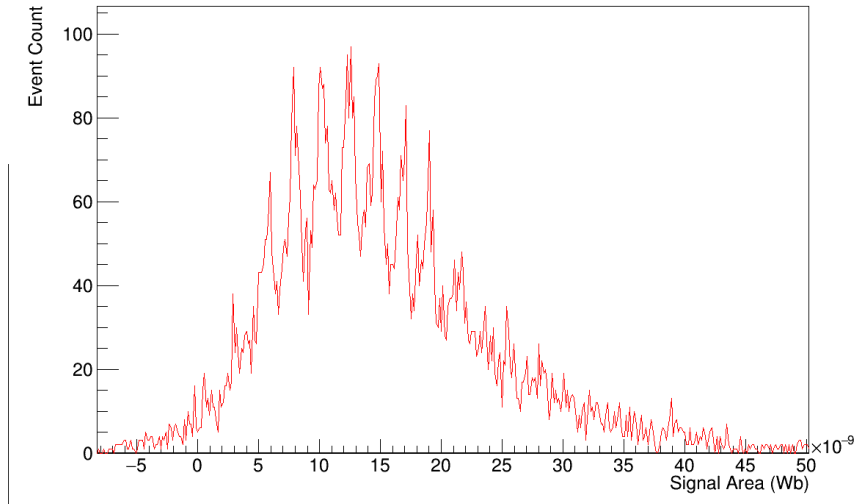


Figure 63: Above Sciglass wrapping. Below is the cosmic ray test for light yield estimation. The mean peak corresponds to about 6 pe, corresponding with the glass density of about 4.01 g/cm³ at about 13 MeV of energy. This corresponds to about 0.45 pe/MeV.

Scintillating glass is a new type of active material being engineered, in the context of calorimeter R&D for EIC, to have similar performance and radiation hardness to lead tungstate at a fraction of the cost. The SciGlass prototypes have grown from coin-sized samples to 40 cm bars representing 20 radiation lengths.

SciGlass is radiation hard to 1000 Gy and 10^{15} n/cm², has a response time of 20-50ns, and has a transmittance of 80% at the emission peak of about 440nm [109].

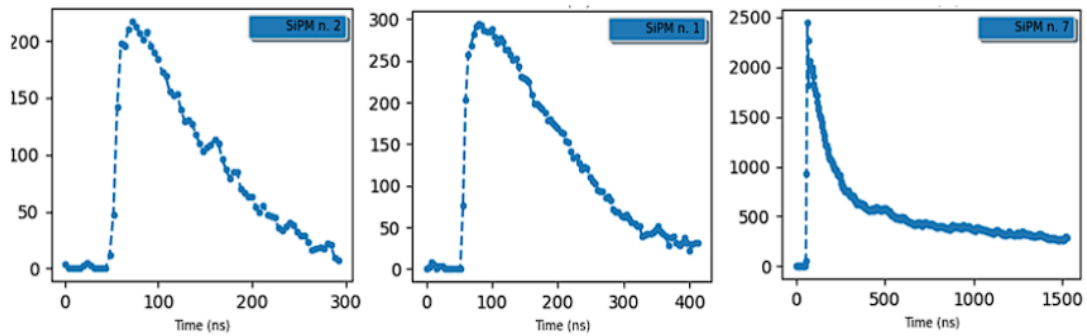
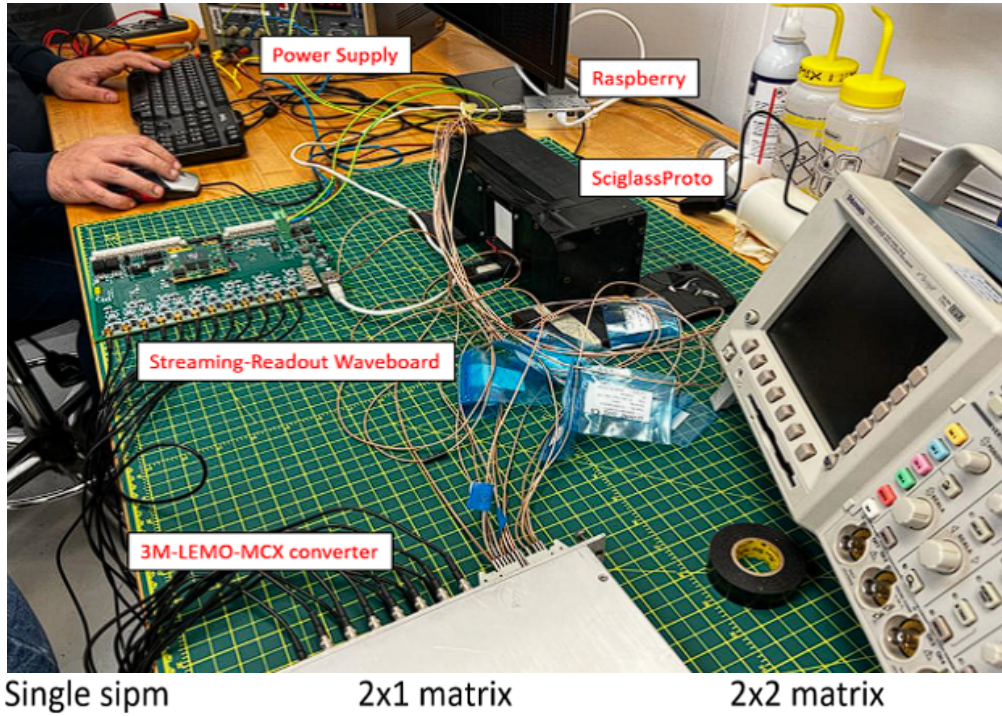


Figure 64: Above Sciglass Streaming-ReadOut test setup. Below: signal shape obtained with different readout and with Streaming-ReadOut

To proceed with the tests at the Jefferson Lab(fig. 64), the glasses were characterized at the INFN section of Genoa, and different signal reading configurations were prepared using combinations of SiPMs, single and in matrices of two or four elements. The light yield is measured using cosmic rays measure. With a dens-

ity of about 4.01 g/cm³, the mean energy deposited by cosmic rays is about 13 MeV(fig. 63). With a signal of about 6 pe, the light yield is 0.45 pe/MeV. The attenuation length of the glass was also measured using the EEE facility(fig. 65).

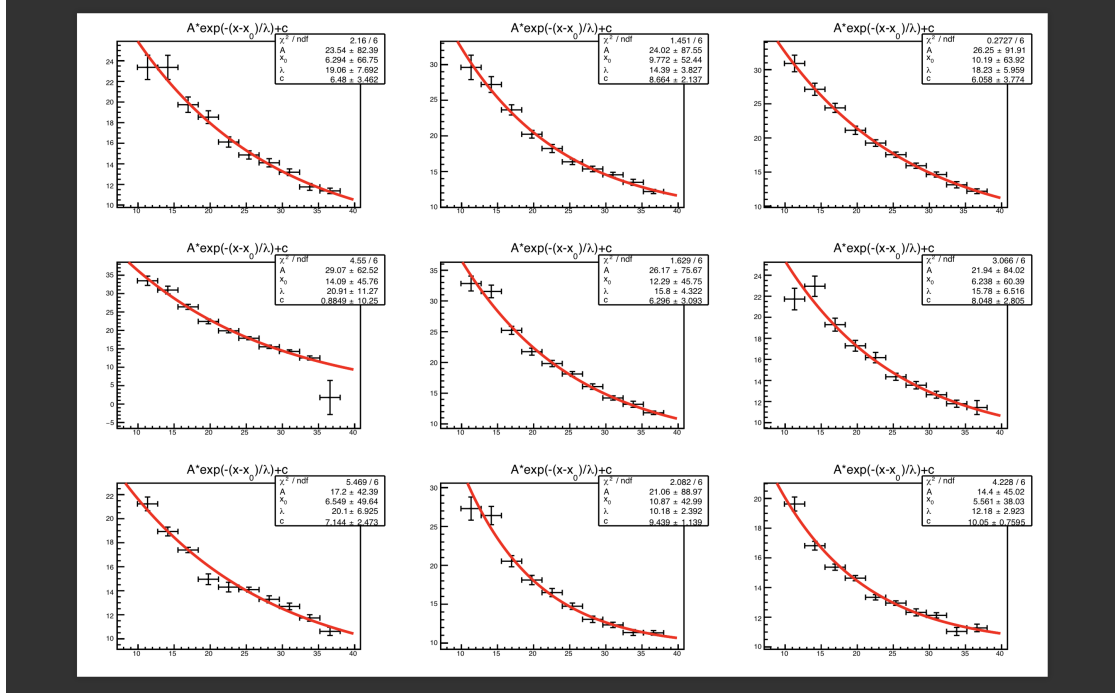


Figure 65: Sciglass attenuation measures results

These tests will help evaluate the veto capability of scintillator glass (Sciglass) and readout for the ν BDX prototype.

8.2 CAEN Digitalizer

The CAEN V1740 is a 1-unit wide VME 6U module housing a 64 Channel 12 bit 62.5 MS/s Flash ADC Waveform(fig. 66). Digitalizer with 2 Vpp input dynamic range on single-ended input connectors. The DC offset is adjustable via a 16-bit DAC on each channel in the full-scale range. Because of the high channel density and channel-to-ADC chip ratio, most settings are expected to "groups" of 8 adjacent channels. Considering the sampling frequency and bit number, these

digitizers are well suited for mid-slow signals like those from inorganic scintillators coupled with PMTs, gaseous detectors, and others. The acquisition trigger is common to all the channels, and it can be issued externally (on TRG-IN), via software, or upon the channel self-trigger (when the input signal goes under/over a programmable threshold). The board's common acquisition trigger can be propagated through a dedicated front panel connector (TRG-OUT). The data stream is continuously written in a circular memory buffer during acquisition. When the trigger occurs, the digitizer writes further samples for the post-trigger and freezes the buffer that can be read by one of the provided readout links.



Figure 66: View of CAEN V1740 VME, 64 Channel 12 bit

Each channel has an SRAM digital memory divided into buffers of programmable size (1-1024). The readout of a frozen buffer is independent of the write operations in the active circular buffer (ADC data storage). The V1740 is well suited for multi-board synchronization, where all V1740 can be synchronized to a common clock source, coherently ensuring Trigger Time Stamps and data alignment across multiple V1740 boards. Clock distribution is supported by a daisy chain on front panel connectors (CLK-IN / CLK-OUT).

V1740 is equipped with a VME64 interface where the data readout can be per-

formed in Single Data Transfer (D32), 32/64-bit Block Transfer (BLT, MBLT, 2eVME, 2eSST) and 32/64-bit Chained Block Transfer (CBLT). The module houses an Optical Link interface (CAEN proprietary CONET protocol) supporting transfer rate up to 80 MB/s and offers daisy chain capability. Therefore, it is possible to connect up to 8 ADC modules to a single A2818 Optical Link Controller, or up to 32 using a 4-link A3818 version (Mod. A2818/A3818, see Tab. 1.1).

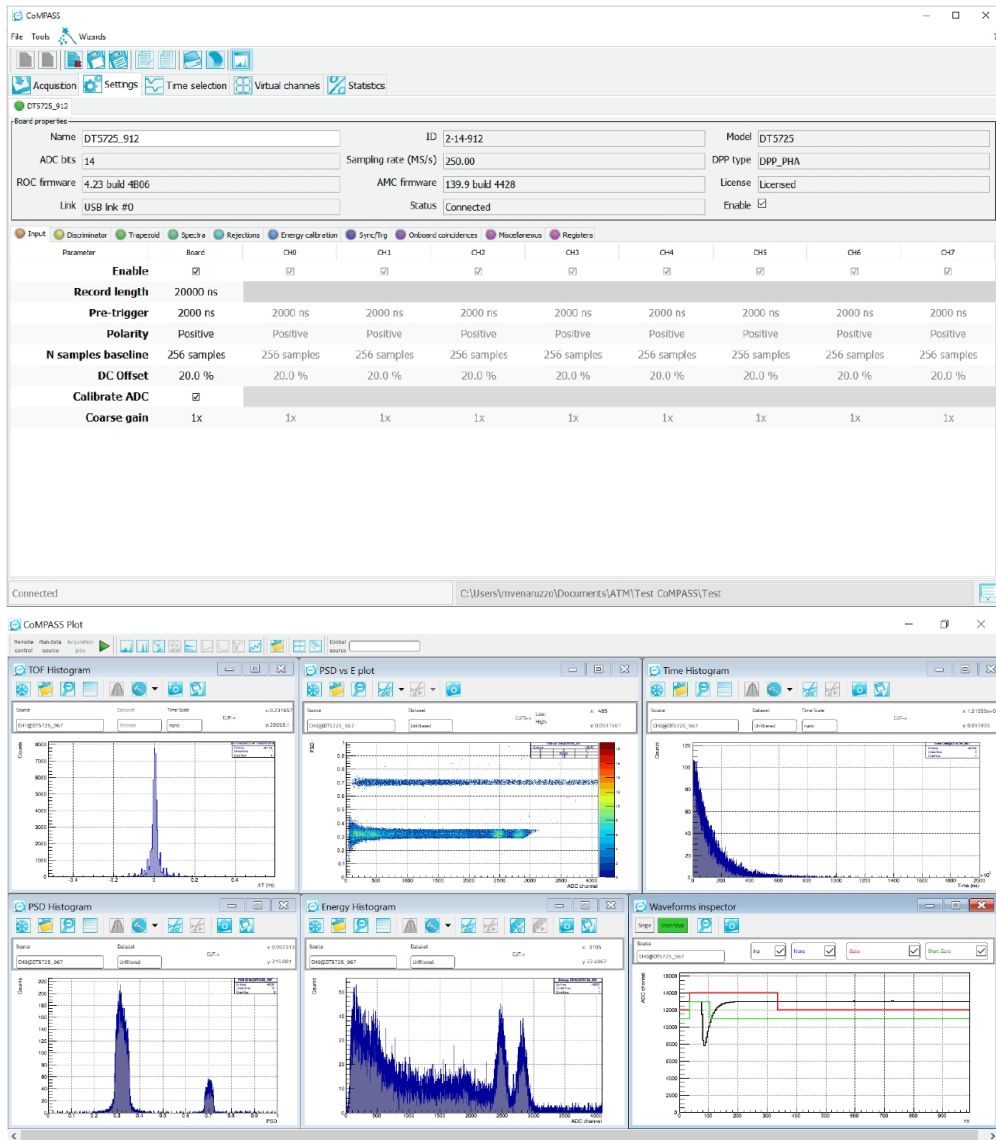


Figure 67: View of CAEN CoMPASS Software

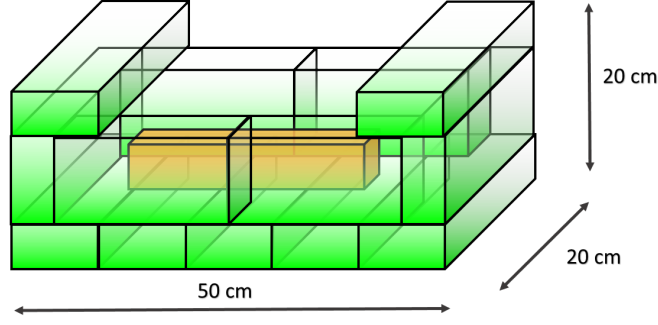
VME and Optical Link accesses take place on independent paths and are

handled by the on-board Therefore, when accessed through Optical Link, the board can be operated outside the VME Crate. The acquisition is managed by CoMPASS software from CAEN (fig. 67), which can implement a Multi-parametric DAQ for Physics Applications, where the detectors can be connected directly to the digitizer inputs, and the software acquires energy, timing, and PSD spectra. CoMPASS can manage multiple boards, even in synchronized mode, and the event correlation between different channels (in hardware and software), apply energy and PSD cuts, calculate and show the statistics (trigger rates, data throughput, etc...), save the output data files (raw data, lists, waveforms, spectra) and use the saved files to run off-line with different

The 64-channel CAEN Digitizer and CoMPASS Software allow the management of many channels in a streaming mode without using multiple modules and to set up the acquisition parameter easily, thanks to its Plotter. These features will be helpful for the small-scale prototype of ν BDX and for testing the requirements for the final detector acquisition system.

9 Prototype

To test the reliability of the simulations and begin concrete work on a functioning detector, a small prototype was decided to be tested. The initial idea was to use a single crystal of CsI(Tl) surrounded by plastic vetoes and lead tiles(fig. 68).



2

Figure 68: First prototype geometry

Starting from the simulations done for the 1 m^3 detector, we worked to implement them also for this reduced configuration. Later, it was decided to replace the lead casing with a metal (and tungsten) one derived from the BDX-Mini [110] detector(fig. 69). This second casing consists of two layers of plastic scintillators (an external cylindrical one and an internal parallelepiped with an octagonal base) with the crystal inside. All are enclosed in a metal casing. Studies on crystal light yield optimization are used on the prototype.

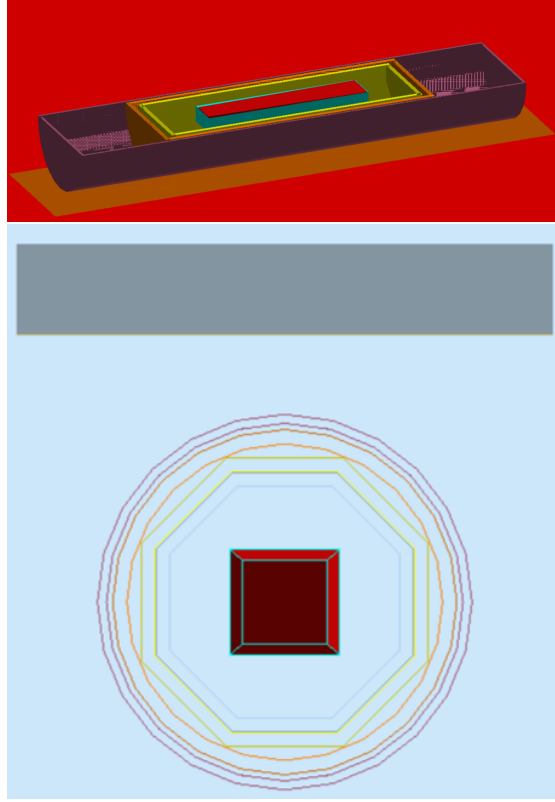


Figure 69: Prototype in BDX-Mini geometry and shield configuration in simulation

This prototype detector will initially be tested using cosmic rays and calibrated radioactive sources (es.: Cs137). Later is thinking to use some neutron sources (Am+Be). The shielding simulations were done to evaluate the best configuration and the effect of the tungsten that can be inserted inside the metal casing (fig. 70). The tests are being prepared and will be carried out in the coming months in various configurations (vertical and horizontal), photosensor (single or multiple SiPMs), different shielding (with or without tungsten), and with different sources (cosmic or Am+Be) to validate the simulations and optimize the acquisition system.

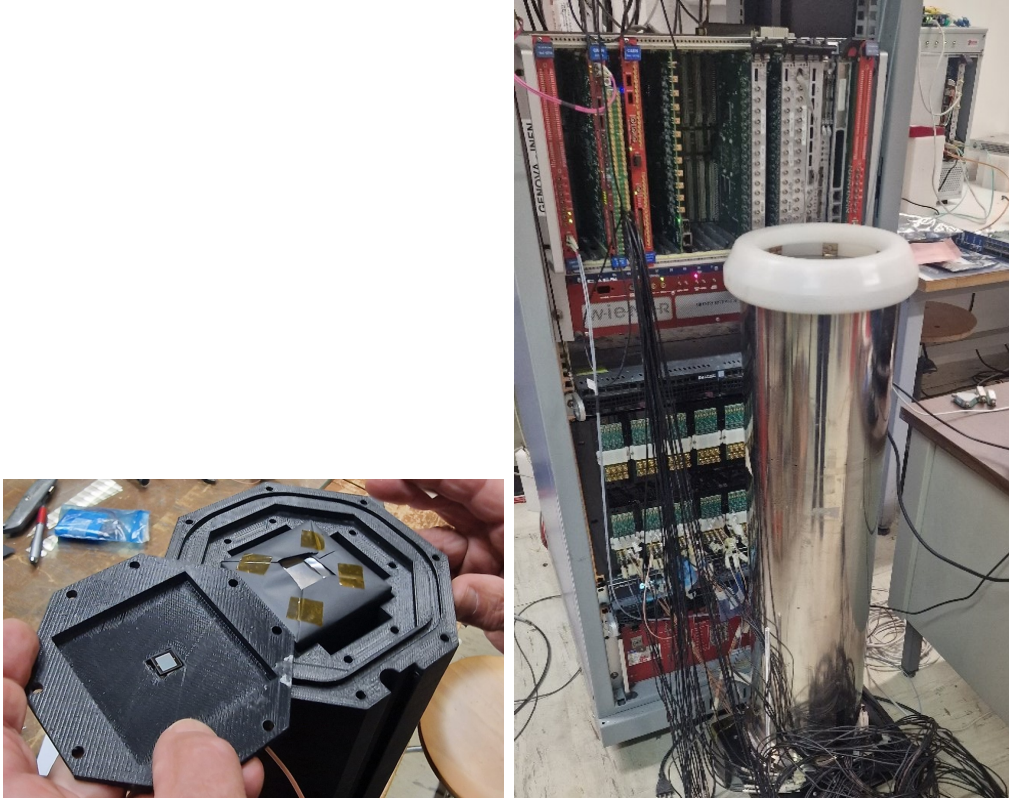


Figure 70: Prototype in first functionality test

In the first tests with the prototype, we used a single SiPM s13360-6075 and CAEN V1740 Digitalizer with the aim of finding the simplest readout configuration. We, therefore, tried to test the spectroscopic capabilities in this configuration using a Cs137 source, in particular for the low-energy component (see the Barium Ka-line at 35 keV). Unfortunately, the energy resolution in this configuration did not prove to be good enough, allowing only the peak of Cs137 (662 keV) to be distinguished. We, therefore, tried to use the JLab EIC 3x3 SiPM matrix, which guaranteed us larger coverage of the reading face.

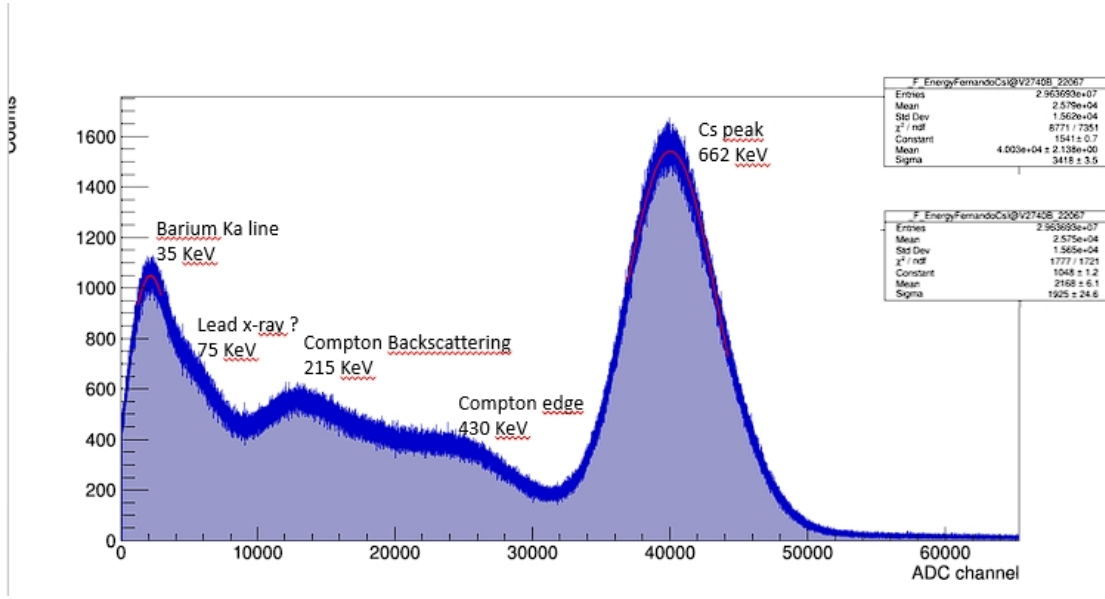


Figure 71: Cs137 spectrum obtain reading the CsI(Tl) crystal with JLab EIC 3x3 SiPM matrix

As can be seen in the figure(fig. 71), the spectrum is quite detailed, allowing us to see the Compton peaks and that of the barium line (that is in the range of interested energies), although still with a non-optimal resolution.

10 Conclusion

In conclusion, the feasibility of conducting a Coherent Elastic Neutrino-Nucleus Scattering ($\text{CE}\nu\text{NS}$) experiment at Jefferson Lab presents a compelling opportunity to enhance the results obtained by the COHERENT collaboration while also facilitating a diverse range of studies focused on the weak mixing angle and neutron skin of atomic nuclei. Leveraging the unique capabilities of Jefferson Lab's high-energy electron accelerator, such an experiment holds significant promise for advancing our understanding of $\text{CE}\nu\text{NS}$ phenomena and their broader implications for particle physics and nuclear structure.

By harnessing the precision and tunability of Jefferson Lab’s accelerator, researchers can design a $\text{CE}\nu\text{NS}$ experiment optimized to probe the weak mixing angle with unprecedented sensitivity. The ability to precisely control the energy spectrum of the neutrino beam allows for targeted investigations into the behavior of neutrinos interacting coherently with atomic nuclei, shedding light on the weak interaction dynamics and providing valuable constraints for theoretical models.

Furthermore, the feasibility of testing a small-scale prototype at Jefferson Lab represents a crucial next step in the experimental process. By optimizing the experimental configuration and validating the performance of detector systems in a controlled environment, will be possible to ensure the success of larger-scale $\text{CE}\nu\text{NS}$ experiments and maximize their scientific output. This iterative approach allows for the refinement of experimental techniques and the identification of potential challenges or limitations, ultimately leading to more robust and reliable results.

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