

Prospect of the NUCLEUS experiment at Chooz for coherent elastic neutrino-nucleus scattering and new physics searches

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The NUCLEUS experiment aims to measure coherent elastic neutrino–nucleus scattering (CE ν NS) at unprecedentedly low nuclear recoil energies using gram-scale cryogenic calorimeters operated at the Chooz nuclear power plant in France. Access to recoil energies at the $\mathcal{O}(10\text{ eV})$ scale enables CE ν NS studies at extremely low momentum transfer and provides enhanced sensitivity to new physics. In this work, we present sensitivity projections for the upcoming NUCLEUS technical and physics runs, incorporating a data-driven treatment of the low-energy excess (LEE) observed during commissioning. We develop a likelihood framework that exploits reactor-power variation to disentangle signal and background in a low signal-to-background regime and to assess the impact of the dominant systematic uncertainties. For the *Technical Run* with a 7 g CaWO₄ target, we find competitive sensitivity to several scenarios beyond the Standard Model, which do not require a CE ν NS observation. For the *Physics Run*, assuming complete

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suppression of the LEE, we project a 4.7σ observation of $\text{CE}\nu\text{NS}$ with a statistical precision of about 20% in 1 year, enabling a determination of the weak mixing angle at the lowest momentum transfer probed to date with $\text{CE}\nu\text{NS}$ and leading $\text{CE}\nu\text{NS}$ -based constraints on the neutrino charge radius and new mediator models.

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I. INTRODUCTION

Neutrinos interact extremely weakly with matter, making them notoriously difficult to detect. Yet, coherent elastic neutrino-nucleus scattering ($\text{CE}\nu\text{NS}$), occurring at neutrino energies below ~ 50 MeV, offers a rare opportunity to observe neutrino interactions through a purely weak neutral-current process. Predicted by Freedman in 1974 [1], and further studied in Refs. [2,3], $\text{CE}\nu\text{NS}$ is a Standard Model (SM) process involving the coherent scattering of a neutrino off an entire nucleus via Z^0 exchange. Its relatively large cross-section compared to other low-energy neutrino interactions makes it a powerful tool for exploring a broad range of physics scenarios, from nuclear structure and electroweak parameters to physics beyond the SM (BSM).

The COHERENT Collaboration provided the first experimental observation of this process using a cesium-iodine (CsI) detector and neutrinos from the Spallation Neutron Source (SNS) [4,5], followed by measurements on argon nuclei [5,6] and more recently on germanium [7,8]. Complementary searches have also emerged in the dark-matter community, where experiments such as PandaX [9], XENONnT [10], and LUX-ZEPLIN [11] have begun probing $\text{CE}\nu\text{NS}$ from solar neutrinos. Within this framework, reactor-based $\text{CE}\nu\text{NS}$ measurements play a crucial role: nuclear power plants provide intense, continuous, and well-localized sources of low-energy $\bar{\nu}_e$, enabling measurements deep in the fully coherent regime. Recently, CONUS+ reported a 3.7σ $\text{CE}\nu\text{NS}$ detection using high-purity germanium detectors near a commercial reactor [12]. Several other $\text{CE}\nu\text{NS}$ experiments are operating at reactor facilities [13–18], with the objective of precision measurements.

The NUCLEUS Collaboration aims to measure the $\text{CE}\nu\text{NS}$ cross section in the fully coherent regime with high precision by deploying gram-scale cryogenic calorimeters in close proximity to the Chooz nuclear power plant in France [19]. NUCLEUS will employ CaWO_4 target crystals operated at 10 mK and instrumented with tungsten transition-edge sensors (W-TES), targeting nuclear-recoil energy thresholds down to $\mathcal{O}(10)$ eV thanks to the excellent intrinsic energy resolution of cryogenic calorimetry [20]. This detector concept builds directly on the technology developed by the CRESST experiment for low-mass dark-matter searches, also employing CaWO_4 targets and TES-based cryogenic calorimetry [21,22]. A precise measurement of reactor $\text{CE}\nu\text{NS}$ with NUCLEUS will also provide important input for future dark-matter searches with similar detectors, as coherent neutrino

scattering will ultimately constitute an irreducible background once sensitivities reach the neutrino fog [23].

The experiment will be hosted in Chooz at the so-called very near site (VNS), an ~ 24 m² experimental room located between the two reactor cores at distances of 72 and 102 m, respectively. Each core operates at a nominal thermal power of 4.25 GW_{th} and is shut down for refueling for approximately one month per year. For the reactor antineutrino flux prediction, we adopt the model of Ref. [24] and the average fission fractions reported therein, obtaining an integrated flux at the VNS of $(2.15 \pm 0.08) \times 10^{12} \text{ cm}^{-2} \text{ s}^{-1}$ when both reactors are operated at full power. Being located in the basement of a five-story office building, the modest overburden of the VNS corresponds to about 3 m water-equivalent. As a consequence, the experiment operates in an environment with significant exposure to cosmic-ray-induced backgrounds, requiring a dedicated and highly optimized shielding strategy. The background mitigation concept combines passive shielding with multiple active veto systems, whose performance and interplay have been extensively studied using detailed Monte Carlo simulations [25]. In particular, muon-induced backgrounds are suppressed by a muon-veto system [26] that includes a cryogenic muon veto [27], while external γ rays and secondary particles are further mitigated by a cryogenic outer veto based on high-purity Ge detectors providing close to 4π coverage of the cryogenic target [28,29]. Together, these systems are designed to compensate for the limited overburden at the VNS and to suppress particle-induced backgrounds in the $\text{CE}\nu\text{NS}$ region of interest to a level that preserves sensitivity to the expected signal.

A simplified version of the NUCLEUS experiment was commissioned in 2024 at the Technical University of Munich (TUM) [30], demonstrating simultaneous operation of all components with stable performance over about two months.

Building on this milestone, the experiment will be relocated to Chooz in 2026 and operated in two successive phases. An upcoming *Technical Run* will deploy four CaWO_4 detectors, each instrumented with two TESs, with a total target mass of about 7 g. The primary goals of this phase are to validate detector performance under VNS conditions and to characterize the particle background in situ. Based on the commissioning results, the sensitivity during the *Technical Run* is expected to remain limited by the low-energy excess (LEE), an excess of sub-keV events not explained by known backgrounds or detector noise [31–33]. One leading hypothesis is that a significant

fraction of the LEE is stress-induced, arising from relaxation processes in the detector crystal or surrounding mechanical structures. The double-TES technology, pioneered by CRESST and TESSERACT [33,34] and implemented in NUCLEUS during the commissioning run [30], has demonstrated the capability to discriminate a distinct LEE component that predominantly couples to the sensor rather than to the absorber phonon system. This supports a detector-intrinsic origin for at least part of the LEE. Nevertheless, additional components remain, and a comprehensive study of their origin and mitigation is presented in Ref. [35]. The *Technical Run* will be followed by a *Physics Run* with the same CaWO_4 target mass, in which the detectors will be integrated into an instrumented holder (inner veto) currently under development within the Collaboration [36,37]. This represents a key upgrade with respect to the *Technical Run*, as the inner veto is expected to provide additional event rejection capabilities, in particular mitigating LEE contributions arising from holder-related or external stress on the crystals [36,37]. In parallel, complementary strategies to further reduce the LEE are under investigation, including approaches exploiting its time dependence and the detector cooling conditions [35].

The goal of this paper is to assess the physics potential of NUCLEUS at the Chooz VNS during the upcoming *Technical Run* and subsequent *Physics Run*, and to quantify its reach for the SM CE ν NS signal and selected BSM scenarios enabled by the unprecedentedly low recoil-energy threshold. The phenomenological LEE model adopted for the sensitivity studies of the *Technical Run* is introduced in Sec. III A 2. Importantly, the two-reactor configuration at Chooz naturally induces reactor-power variation over time through scheduled outages and periods of reduced power. As discussed in Sec. III B, this time dependence can be exploited to enhance sensitivity in the low signal-to-background regime encountered during this phase. For the *Physics Run*, we consider an optimistic scenario in which the LEE is suppressed to a negligible level, such that the dominant background is given by the particle-induced component estimated from simulations [25]. Under this assumption, a measurement of the SM CE ν NS signal becomes feasible, with a significantly improved sensitivity to BSM scenarios. For both runs, a total measurement period of one year is assumed. If the LEE cannot be fully suppressed, but is nevertheless reduced compared to the currently observed level, an intermediate physics reach between the *Technical Run* and *Physics Run* scenarios can be expected. A quantitative assessment of such intermediate scenarios is beyond the scope of this work, as it would require a more detailed understanding of the LEE properties and of the effectiveness of the ongoing mitigation strategies.

The paper is structured as follows. In Sec. II, we describe the theoretical framework considered in this work. In Sec. III, we present the sensitivity strategy, including a

likelihood framework that incorporates the anticipated reactor power variation. In Sec. IV, we report the projected sensitivities, and we conclude in Sec. V. The Appendixes provide details on the validation of the statistical framework (Appendix A) and on the treatment of systematic uncertainties (Appendix B).

II. CE ν NS THEORY FRAMEWORK

A. Standard model CE ν NS cross section

The coherent elastic scattering of a neutrino ν_ℓ ($\ell = e, \mu, \tau$) off a nucleus $\mathcal{N}$ is described, within the SM, by the differential cross section [1–3,38]

$$\frac{d\sigma_{\nu_\ell-\mathcal{N}}}{dT_{\text{nr}}} = \frac{G_F^2 M}{\pi} \left(1 - \frac{T_{\text{nr}}}{E_\nu} - \frac{MT_{\text{nr}}}{2E_\nu^2} \right) (Q_{\ell,\text{SM}}^V)^2, \quad (1)$$

where G_F is the Fermi constant, M is the nuclear mass, E_ν is the neutrino energy, and T_{nr} denotes the nuclear recoil energy. The effective weak nuclear charge, which parametrizes the strength of the neutrino-nucleus coupling, is given by

$$Q_{\ell,\text{SM}}^V = [g_V^p(\nu_\ell)ZF_Z(|\vec{q}|^2) + g_V^n NF_N(|\vec{q}|^2)], \quad (2)$$

where Z and N are the proton and neutron numbers of the nucleus, g_V^p and g_V^n represent the weak neutral-current couplings of neutrinos with protons and neutrons, and $F_Z(q^2)$ and $F_N(q^2)$ are the corresponding nuclear form factors, describing the loss of coherence at high momentum transfer $|\vec{q}| \simeq \sqrt{2MT_{\text{nr}}}$ [39]. To account for the isotopic composition of the target nuclei, a weighted sum over the CE ν NS cross sections of the individual isotopes is performed, specifically

$$\left\langle \frac{d\sigma_{\nu_\ell-\mathcal{N}}}{dT_{\text{nr}}} \right\rangle = \sum_i f_i \frac{d\sigma_{\nu_\ell-\mathcal{N}_i}}{dT_{\text{nr}}}, \quad (3)$$

where f_i is the isotopic abundance of the i th isotope of the $\mathcal{N}$ nuclear species. The isotopic abundances of Ca, W, O, and their respective masses are taken from Refs. [40,41]. At the sub-keV recoil energies relevant for NUCLEUS, the momentum transfer is sufficiently small that nuclear coherence is essentially preserved and the form factors are very close to unity. Nevertheless, we model both proton and neutron distributions using the Helm parametrization [42], with nuclear radii following the prescription of Lewin and Smith [43].

In the SM, the coefficients g_V^p and g_V^n , including radiative corrections under the so-called minimal subtraction scheme ($\overline{\text{MS}}$) [44], are given by [39,45–47]

$$g_V^p(\nu_e) = 0.0379, \quad g_V^n = -0.5117, \quad (4)$$

which should be compared with the tree-level (TL) predictions of $g_{V,\text{TL}}^p = 1/2 - 2\sin^2\theta_W \simeq 0.0225$ and

$g_{V,TL}^n = -0.5$ respectively. The strong suppression of g_V^p relative to g_V^n originates from the weak mixing angle, whose low-momentum-transfer value is $\sin^2 \vartheta_W(|\vec{q}| \rightarrow 0) = 0.23873(5)$ [48]. As a consequence, CE ν NS predominantly probes the neutron content of the nucleus, making the nuclear weak charge highly sensitive to variations of $\sin^2 \vartheta_W$ at low momentum transfer, a regime where only few experimental measurements exist. The extraction of the weak mixing angle from CE ν NS data is typically affected by a degeneracy with the average neutron radius of the target nucleus [39], which must be inferred from nuclear-structure models in the absence of precise experimental measurements. At the very low nuclear recoil energies probed by NUCLEUS, however, the momentum transfer is sufficiently small that nuclear-structure effects play only a marginal role, enabling a cleaner sensitivity to electroweak parameters.

In Eq. (4), the values for the neutrino-proton coupling are derived by taking into account their flavor dependence. In fact, radiative corrections induce a flavor-dependent contribution to the neutrino-proton coupling through the neutrino charge radius $\langle r_{\nu_e}^2 \rangle$ (NCR), which represents the only non-vanishing electromagnetic property of neutrinos within the SM. For the electronic flavor, this is equal to $\langle r_{\nu_e}^2 \rangle \simeq -0.83 \times 10^{-32} \text{ cm}^2$ [49]. The NCR modifies the effective proton coupling as [49–51]

$$\begin{aligned} g_V^p(\nu_\ell) &\rightarrow \tilde{g}_V^p - \frac{2}{3} M_W^2 \langle r_{\nu_\ell}^2 \rangle \sin^2 \vartheta_W \\ &= \tilde{g}_V^p - \frac{\sqrt{2} \pi \alpha_{\text{EM}}}{3 G_F} \langle r_{\nu_\ell}^2 \rangle, \end{aligned} \quad (5)$$

where M_W is the mass of the $W^\pm$ boson, and α_{EM} is the electromagnetic fine structure constant. At the same time, $\tilde{g}_V^p \simeq 0.0184$ is the neutrino-proton coupling without the contribution of the SM NCR, but including the other radiative corrections as described in Ref. [39]. In this work, we also account for the energy dependence of the NCR-related radiative corrections [45]. In this study, we consider only the diagonal neutrino charge radius $\langle r_{\nu_e}^2 \rangle$, neglecting possible BSM effects that could induce off-diagonal, or so-called transition NCRs in which the neutrino changes flavor during the interaction [49]. Any deviation of the NCR from its SM prediction would therefore constitute a clear signal of BSM physics. Although the allowed parameter space is tightly constrained around the SM values [52], a precise determination of the NCR is still lacking. Future high-precision CE ν NS measurements thus offer a promising avenue to probe this fundamental neutrino property.

Figure 1 illustrates the expected CE ν NS recoil spectrum in CaWO₄ for the SM (solid green) and for an enhanced value of the NCR (dot-dashed blue). The NCR enters as a correction to the neutrino-proton coupling and can therefore interfere

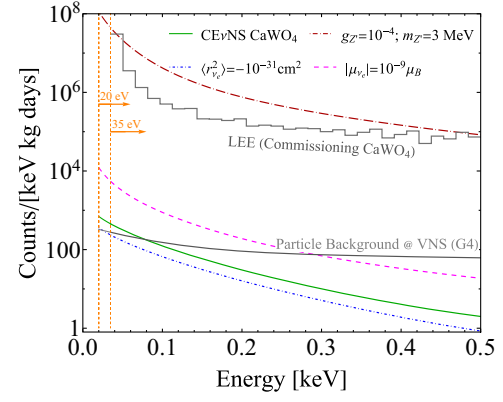


FIG. 1. Expected event rate in the NUCLEUS CaWO₄ target at Chooz as a function of the observed energy for different physics scenarios. The green line shows the SM CE ν NS prediction, while the dashed and dot-dashed curves correspond to a representative value of neutrino magnetic moment (magenta), modified neutrino charge radius (blue), and the presence of a new light universal mediator (red). The theoretical predictions are qualitatively compared with the LEE background measured during the NUCLEUS commissioning run at TUM [30] (dark gray line), and the particle background contribution estimated for the NUCLEUS detectors at VNS from Geant4 (G4) simulations [25] (light gray line). Vertical lines mark recoil-energy thresholds of 20 and 35 eV.

either constructively or destructively with the SM weak charge. For a single nuclear target probed at very low momentum transfer, such an effect would largely manifest as an overall rescaling of the CE ν NS rate when the form factors approach unity. In contrast, for a multicomponent target such as CaWO₄, the different nuclear species contribute with distinct weights and recoil-energy distributions, leading to a nontrivial distortion of the observed spectrum rather than a simple normalization shift.

B. Beyond the Standard Model scenarios

The ultralow nuclear recoil energy threshold targeted by NUCLEUS provides enhanced sensitivity to new physics scenarios that modify the CE ν NS spectrum at low energies. In this work, we consider two well-motivated classes of BSM scenarios: nonstandard neutrino interactions (NSI) and the neutrino magnetic moment.

Nonstandard neutrino interactions with quarks can be parameterized at low energies through effective four-fermion operators. Assuming flavor-conserving neutral-current interactions, the corresponding NSI Lagrangian term can be written as [53–55]

$$\mathcal{L}_{\text{NSI}}^{\text{NC}} = -2\sqrt{2}G_F \sum_{\ell=e,\mu} (\bar{\nu}_{\ell L} \gamma^\rho \nu_{\ell L}) \sum_{f=u,d} \epsilon_{\ell\ell}^{fV} (\bar{f} \gamma_\rho f), \quad (6)$$

where $\nu_{\ell L}$ and f represent the neutrino and the fermion fields, respectively. The parameters $\epsilon_{\ell\ell}^{fV}$, where $f = u, d$

stands for the flavor of the quark and $\ell = e, \mu$ is the neutrino flavor, describe the strength of non-standard interactions relative to standard neutral-current weak interactions. This NSI Lagrangian modifies the weak charge in Eq. (2), which becomes [53]

$$Q_{\ell, \text{NSI}}^V = (g_V^p(\nu_\ell) + 2\epsilon_{\ell\ell}^{uV} + \epsilon_{\ell\ell}^{dV})ZF_Z(|\vec{q}|^2) + (g_V^n + \epsilon_{\ell\ell}^{uV} + 2\epsilon_{\ell\ell}^{dV})NF_N(|\vec{q}|^2). \quad (7)$$

In this work, we investigate the sensitivity to NSI parameters in the flavor-preserving framework, where neutrino flavor remains unchanged during scattering, and the parameters ϵ_{ee}^{uV} and ϵ_{ee}^{dV} are allowed to vary simultaneously. This approach enables a direct comparison with existing studies and sets the stage for the physics reach of the experiment under alternative NSIs frameworks, e.g., [54,56,57].

A particularly well-studied realization of NSIs arises when they are mediated by a light vector boson Z' , associated with an additional $U(1)'$ gauge symmetry. In this case, the NSI parameters acquire a momentum-dependent form [58,59]:

$$\epsilon_{\ell\ell}^{fV} = \frac{g_{Z'}^2 Q'_\ell Q'_f}{\sqrt{2}G_F(|\vec{q}|^2 + m_{Z'}^2)}, \quad (8)$$

where $m_{Z'}$ and $g_{Z'}$ denote the mediator mass and coupling strength, respectively, and Q' are the fermion charges under the new gauge symmetry. As a reference scenario, in this work, we consider a universal model with $Q'_\ell = Q'_f = 1$, which, while not gauge invariant without additional field content [60], provides a convenient reference for comparison with existing experimental constraints. Other gauge structures, such as $B - L$ or $B - 3L_e$ [59,61,62], or scenarios with a scalar mediator [63], can be straightforwardly accommodated once experimental data become available. Owing to the $1/(|\vec{q}|^2 + m_{Z'}^2)$ enhancement of the mediator propagator at low momentum transfer, light vector mediator scenarios are particularly sensitive to the ultralow recoil energy regime probed by NUCLEUS. This is illustrated in Fig. 1, where the red dot-dashed curve shows the theoretical prediction for a representative point in the $(g_{Z'}, m_{Z'})$ parameter space, which features a strong enhancement at low recoil energies. This allows NUCLEUS to set competitive constraints on light mediator models even in the absence of a direct CE ν NS observation.

A fundamental BSM neutrino property is provided by the neutrino magnetic moment (μ_ν), which is expected to arise because neutrinos are massive [49,64,65]. In the minimally extended SM, the expected value of the neutrino magnetic moment for Dirac neutrinos is of the order of $\mu_\nu \sim 10^{-19} \mu_B$ [65], which lies far below current experimental sensitivities. Therefore, any positive experimental observation would constitute an unambiguous signal of new physics, demanding further theoretical investigation to clarify its origin. The magnetic-moment contribution does

not interfere with the SM CE ν NS amplitude and adds incoherently to Eq. (1), namely,

$$\frac{d\sigma_{\nu_\ell - N}^{\text{MM}}}{dT_{\text{nr}}} = \frac{\pi\alpha_{\text{EM}}^2}{m_e^2} \left(\frac{1}{T_{\text{nr}}} - \frac{1}{E_\nu} \right) Z^2 F_Z^2(|\vec{q}|^2) \left| \frac{\mu_{\nu_\ell}}{\mu_B} \right|^2, \quad (9)$$

where μ_{ν_ℓ} is the effective magnetic moment of the neutrino flavor ν_ℓ and μ_B is the Bohr magneton [49]. Owing to its characteristic $1/T_{\text{nr}}$ enhancement, this contribution is particularly relevant at very low recoil energies, making NUCLEUS sensitive to competitive constraints despite its small target mass. An example of the corresponding theoretical prediction, assuming a neutrino magnetic moment of $\mu_{\nu_e} = 10^{-9} \mu_B$, is shown in Fig. 1.

In this work, we restrict the study of neutrino magnetic moment to the CE ν NS channel. This additional interaction channel is particularly relevant in scenarios predicting an enhanced low-energy signal, and has been successfully exploited in several experiments employing Ge [66–69], CsI [50,69,70], and Xe [71,72] targets. In fact, the neutrino-electron scattering (ν ES) signal in the $\mathcal{O}(\text{keV})$ recoil range and can be modeled with good theoretical control by scaling the free electron-neutrino cross section by the number of ionized electrons for a given energy deposit [73]. In contrast, for the $\mathcal{O}(10 \text{ eV})$ energy scale relevant for NUCLEUS, a reliable calculation of neutrino-electron scattering in CaWO_4 is hindered by poorly known atomic many-body effects. For this reason, we do not consider the ν ES channel further in this analysis.

III. SENSITIVITY STRATEGY

In this section, we describe the strategy adopted to derive sensitivity projections for the different phases of the NUCLEUS experiment at the Chooz site. The analysis framework accounts for the distinct detector configurations and background conditions expected during the upcoming *Technical Run* and the subsequent *Physics Run*.

A. Signal prediction and background model

The signal and background models used in the sensitivity studies depend on the specific detector configuration considered. In this work, we distinguish between two main running phases: the initial *Technical Run* at Chooz and the following *Physics Run*.

1. CE ν NS signal prediction

The expected CE ν NS recoil spectrum is obtained by convolving the differential cross section with the reactor antineutrino flux, integrating over all possible neutrino energies, and folding in the detector energy response. The resulting differential event rate is given by

$$\frac{dR}{dT_{\text{nr}}} = N_T \sum_{\mathcal{N}} \int_0^{T'_{\text{nr}}^{\text{max}}} dT'_{\text{nr}} \mathcal{R}(T_{\text{nr}}, T'_{\text{nr}}) \int_{E_{\nu}^{\text{min}}(T'_{\text{nr}})}^{E_{\nu}^{\text{max}}} dE_{\nu} \times \frac{d\Phi}{dE_{\nu}}(E_{\nu}) \left\langle \frac{d\sigma_{\bar{\nu}_e - \mathcal{N}}}{dT'_{\text{nr}}}(E_{\nu}, T'_{\text{nr}}) \right\rangle, \quad (10)$$

where the sum runs over the nuclear species $\mathcal{N}$ in CaWO_4 , and N_T denotes the number of target nuclei in the detector. The maximum recoil energy is $T'_{\text{nr}}^{\text{max}} \simeq 2(E_{\nu}^{\text{max}})^2/M$, with $E_{\nu}^{\text{max}} = 12$ MeV [24], while the minimum neutrino energy required to produce a recoil T'_{nr} is $E_{\nu}^{\text{min}}(T'_{\text{nr}}) \simeq \sqrt{MT'_{\text{nr}}/2}$.

The detector response function $\mathcal{R}$ is modeled as a Gaussian, with an energy-dependent width $\sigma(T_{\text{nr}})$, parametrized following Ref. [74]:

$$\sigma(T_{\text{nr}}) = \sqrt{\left(\frac{\eta}{e_{\text{ath}}}\right)^{-1} T_{\text{nr}} + (\beta T_{\text{nr}})^2 + \sigma_0^2}. \quad (11)$$

Here $\eta/e_{\text{ath}} = 0.0045 \pm 0.0016$ meV^{-1} denotes the ratio between the athermal phonon collection efficiency and the mean energy of an athermal phonon, while $\beta = 0.013 \pm 0.0011$ encodes systematic effects such as nonuniformities and position-dependence effects [74]. We assume a baseline resolution of $\sigma_0 = 4$ eV, consistent with the energy-threshold targets considered in this work. Owing to the excellent intrinsic energy resolution of NUCLEUS detectors, the impact of the energy response on the total event rate is at the subpercent level and constitutes a negligible source of systematic uncertainty. Since the trigger threshold is typically set at five times the detector's baseline resolution, the finite energy resolution also determines the effective trigger efficiency near threshold: for an optimal-filter trigger, the efficiency follows the Gaussian smearing and is therefore 50% at the trigger threshold by construction [75]. This behavior was experimentally validated in the commissioning run analysis [30]. No additional energy-dependent trigger efficiency is applied beyond this resolution folding; only a flat overall efficiency factor is included in the overall analysis efficiency quoted below (Sec. IV).

2. Technical Run

During the *Technical Run* at Chooz, the detector module will consist of four CaWO_4 double-TES detectors, for a total target mass of 7 g. In this configuration, the $\text{CE}\nu\text{NS}$ region of interest is expected to be dominated by the LEE, while the particle-induced background estimated from simulations is negligible in comparison (see Fig. 1).

The rate and spectral shape of the LEE are modeled using data from the NUCLEUS commissioning run [30]. Since an energy threshold of 35 eV was achieved during commissioning, the same analysis threshold is adopted for the technical-run sensitivity projections. The analysis range extends up to 500 eV. Within this range, the LEE spectral

shape is parametrized by a double-exponential function,

$$S_{\text{LEE}}(T_{\text{nr}}) = B \times [f e^{-T_{\text{nr}}/\varepsilon_1} + (1-f) e^{-T_{\text{nr}}/\varepsilon_2}], \quad (12)$$

where $S_{\text{LEE}}(T_{\text{nr}})$ describes the normalized energy distribution of LEE events in the analysis window. The normalization constant B is chosen such that $\int S_{\text{LEE}}(T_{\text{nr}}) dT_{\text{nr}} = 1$ over the 35–500 eV range. The parameters $f \simeq 0.99$, $\varepsilon_1 \simeq 28$ eV, and $\varepsilon_2 \simeq 320$ eV are obtained from fits to the CaWO_4 commissioning data over the wider 35–7000 eV energy range [30], where the fit model includes an additional constant component that becomes relevant only well above 500 eV and is therefore neglected in the present analysis.

In addition, a time-dependent decay of the LEE rate was observed during the commissioning run and is modeled by a power-law function,

$$R_{\text{LEE}}(t) = R_{0,\text{LEE}}(t - t_0)^{-k}, \quad (13)$$

where $R_{0,\text{LEE}}$ is the initial LEE rate and k is the exponent governing the temporal decay. The parameter t_0 denotes a common reference time defined as the moment when the detectors reach 4 K, which is used to parametrize the onset of the LEE decay. During the commissioning run, this occurred after approximately 9 days, and a similar time-scale is expected at Chooz. Further details on the definition of t_0 and the LEE time evolution are provided in Ref. [35]. When the time difference $t - t_0$ is expressed in days, the exponent was found to be $k \simeq 0.59$ during the commissioning run, and was observed to consistently describe multiple runs with a different NUCLEUS detector [35]; the same functional form is therefore adopted in this work. The initial LEE rate observed in the commissioning CaWO_4 detector, operated as a single-TES device, between 35 and 500 eV is 3650 events/day. In this work, this rate is directly adopted for the *Technical Run* detectors. Although these will be operated with a double-TES configuration, which is expected to provide additional discrimination against the LEE, we conservatively do not assume any suppression from this technique. The same initial rate is therefore assigned to each of the four detectors. Furthermore, despite the smaller target mass of the commissioning detector (0.76 g) compared to the 1.75 g of each *Technical Run* detector, we assume that the LEE rate does not scale with detector mass. This assumption is supported by observations from other cryogenic experiments operating at comparable energy thresholds [32,35,76].¹ In addition, the same initial rate is adopted for the Chooz site despite the different overburden with respect to the shallow underground

¹We note that the phenomenological assumptions adopted for the LEE model in this work represent one possible, conservative scenario motivated by the currently available data. The scaling of the LEE with detector mass, material, and detector design will need to be validated experimentally with dedicated measurements using the *Technical Run* detectors.

commissioning setup. This assumption is motivated by dedicated studies within NUCLEUS, which did not observe a correlation between the LEE rate and variations in the ambient particle background or shielding conditions, thereby disfavoring a dominant cosmogenic origin of the LEE [35].

3. Physics Run (LEE-free)

The *Physics Run* is expected to start immediately after the *Technical Run* and will employ the same total CaWO_4 target mass of about 7 g. In this phase, the detectors will be integrated into an instrumented holder (inner veto) [36,37], representing a key upgrade aimed at enhancing the rejection of the LEE background, in particular for contributions arising from holder-related or external stress on the crystals. Complementary mitigation strategies, such as exploiting the time dependence of the LEE and optimizing detector cooling conditions, are also under investigation. For the sensitivity projections presented in this work, we consider an optimistic scenario in which the LEE is suppressed to a negligible level, such that the dominant background during the *Physics Run* is given by the particle-induced component estimated from simulations [25]. Because the detectors are located at distances of order 70–100 m from the reactor cores, reactor-correlated particle backgrounds are expected to be negligible, and this component is therefore assumed to be constant in time.

An improved recoil-energy threshold of 20 eV is considered achievable and is adopted for the physics-run sensitivity projections. This lower threshold does not rely on a modified detector design, but on already demonstrated energy resolutions [20] and on improved analysis methods developed within the Collaboration [77]. The analysis range extends up to 500 eV, and the expected signal and background rates [25] in this range are summarized in Table I.

B. Reactor-power variation analysis

At the Chooz nuclear power plant, periods in which both reactor cores are simultaneously OFF are unlikely, meaning background subtraction based solely on dedicated reactor-OFF data is not possible. However, scheduled maintenance shutdowns of individual reactors and periods of reduced reactor power naturally induce a variation of the total

thermal power, and hence of the antineutrino flux impinging on the detector.

The total antineutrino flux at the VNS can be expressed in terms of a single source characterized by an effective thermal power and distance. For the two Chooz cores, this is given by

$$\frac{1}{L_{\text{eff}}^2} = \frac{1}{L_1^2} + \frac{1}{L_2^2}, \quad P_{\text{eff}} = \frac{P_1 L_2^2 + P_2 L_1^2}{L_1^2 + L_2^2}, \quad (14)$$

where $L_1 = 72$ m and $L_2 = 102$ m are the distances to reactor cores B1 and B2, respectively, and P_1 and P_2 denote their thermal powers. This yields an effective distance of $L_{\text{eff}} \simeq 58.8$ m. Each reactor operates at a nominal thermal power of 4.25 GW_{th}, such that the effective power varies between zero, when both cores are OFF, and 4.25 GW_{th}, when both cores are ON. Intermediate effective powers amount to approximately one-third of the maximum power when B1 is OFF and two-thirds when B2 is OFF.

The time dependence of the effective reactor power induces a corresponding variation of the antineutrino flux, which can be exploited to identify signal and background in the time domain. This strategy was successfully employed by the Double Chooz experiment to obtain a background-model-independent measurement of the mixing angle θ_{13} with a precision comparable to that achieved using full spectral information [78]. In that case, the method benefited from a very high signal rate and a large signal-to-background ratio (approximately 1000 signal events per day at full power compared to fewer than 20 background events per day, corresponding to S/B ~ 50). In contrast, the situation for NUCLEUS is markedly different. When the LEE is taken into account, the signal-to-background ratio in the CE ν NS recoil-energy region of interest is S/B $\ll 1$, and even under the ideal background conditions of the *Physics Run*, the total event rate at full reactor power remains below one count per day.² To retain sensitivity in this low-rate, background-dominated regime, we develop a likelihood-based analysis framework that exploits both the time dependence induced by reactor power variation and the recoil energy information of individual events.

The unbinned log-likelihood function ($\mathcal{L}$) used in this work is defined as

$$-\log \mathcal{L} = \left[\alpha \int_{T_1}^{T_2} P(t) dt + \int_{T_1}^{T_2} \beta(t) dt \right] - \sum_i \log [\alpha P(t_i) f_s(E_i) + \beta(t_i) f_b(E_i)], \quad (15)$$

TABLE I. Expected signal and background rates for the NUCLEUS *Physics Run* with a 7 g CaWO_4 target, assuming complete suppression of the LEE. The signal rates correspond to operation at maximum reactor power. The quoted background rate includes all background components considered in Ref. [25], and is derived from the corresponding background simulations.

T_{nr} range (eV)	Rate (events/day)	
	CE ν NS signal	Background
20–200	0.214	0.209
200–500	0.019	0.167

²The much lower event rate in NUCLEUS is primarily a consequence of the gram-scale target mass, in contrast to the ~ 8.3 t liquid scintillator target mass of each Double Chooz detector [79], even though the CE ν NS cross section at reactor energies is orders of magnitude larger than the one of the inverse beta decay.

where each term has a well-defined physical interpretation:

- (i) α is the rate of the CE ν NS signal, expressed in counts per day per MW_{th};
- (ii) $P(t)$ is the time-dependent reactor power, proportional to the instantaneous antineutrino flux at the detector, and t_i denotes the timestamp of the i th event;
- (iii) $f_s(E)$ is the CE ν NS recoil-energy probability density function (PDF) within the analysis window, including detector response effects;
- (iv) $\beta(t)$ is the rate of the background component, in counts per day. In the *Technical Run*, $\beta(t)$ follows the temporal decay of the LEE as introduced in Sec. III A 2, while in the *Physics Run* it is assumed to be constant; and
- (v) $f_b(E)$ is the background recoil-energy PDF. It corresponds to the LEE spectral shape for the *Technical Run* and to the particle-induced background spectrum estimated from simulations for the *Physics Run*.

The first term in square brackets in Eq. (15) represents the Poisson expectation value for the total number of events in the observation time window $[T_1, T_2]$, given by the sum of the signal contribution, proportional to the time-integrated reactor power, and the time-integrated background rate. The second term describes the likelihood of the observed dataset, where each event (t_i, E_i) is assigned a probability composed of a time-modulated signal component and a background component whose rate may vary in time but whose spectral shape is assumed to be stationary. Figure 2 illustrates the reactor-power configuration adopted for the sensitivity study, constructed assuming a realistic one-year data-taking period. During this time, the reactor operational schedule includes two single-core refueling and maintenance shutdowns, each lasting approximately one month, during which one of the two reactors (B1 or B2) is OFF while the other operates at nominal thermal power. In addition, a two-week period in which both reactors are simultaneously OFF is assumed. For the remainder of the year, both reactors are taken to operate at nominal power. This results in an overall effective reactor duty cycle of approximately 85%. The assumed schedule is representative of typical Chooz operating conditions and is consistent with historical reactor operation patterns inferred from publicly available electricity production records averaged over the past decade [80]. This structured variation of the antineutrino flux provides time intervals with enhanced signal-to-background contrast, despite the presence of the dominant LEE component. In the present study, stable detector operation after the initial cooldown is assumed, such that the LEE time evolution can be described by a single power-law behavior over the full data-taking period. Possible interruptions requiring a warm-up and subsequent cooldown cycle could be incorporated into the phenomenological LEE model and included in the likelihood analysis if needed.

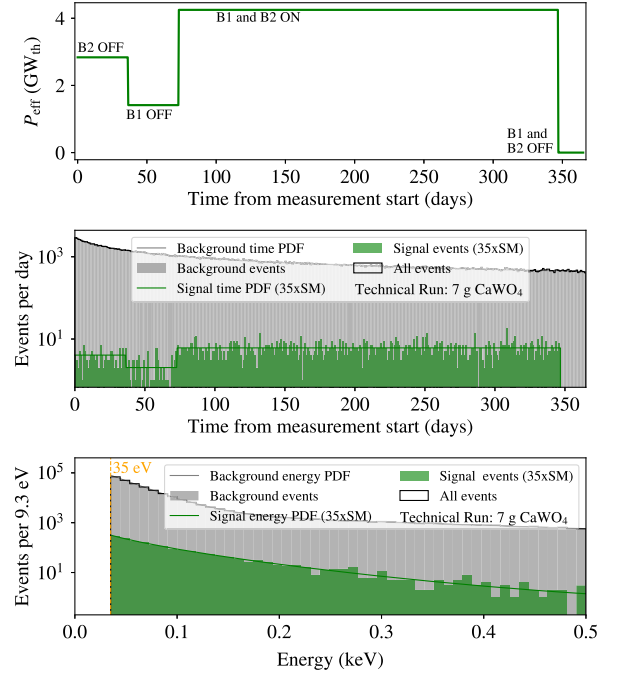


FIG. 2. Top: assumed time evolution of the effective reactor thermal power [Eq. (14)] at the Chooz VNS over one year, reflecting realistic operational conditions. The two reactor cores are treated as a single effective source at an effective distance of $L_{\text{eff}} \simeq 58.8$ m. Middle: representative Monte Carlo pseudo-experiment for the *Technical Run* configuration, generated assuming a CE ν NS signal normalized to 35 times the SM prediction for illustrative purposes. Time distribution of events over one year, showing the signal and background components separately, together with their expected PDFs. The signal follows the reactor-power variation, while the background reflects the time decay of the LEE. Bottom: recoil-energy spectrum of the same pseudo-experiment, displaying the signal and background contributions and their corresponding energy PDFs.

Monte Carlo pseudo-experiments are generated by randomly sampling Poisson-distributed toy datasets from the signal and background PDFs defined above, accounting for the time dependence of the reactor power and, where applicable, of the background rate. Figure 2 shows an example pseudo-experiment for the *Technical Run* configuration, illustrating the resulting time and energy distributions of signal and background events. For each pseudo-experiment, parameter inference is performed using a profile likelihood ratio test statistic [81],

$$q(\theta) = -2 \log \frac{\mathcal{L}(\theta, \hat{\hat{\nu}})}{\mathcal{L}(\hat{\theta}, \hat{\nu})}, \quad (16)$$

where θ denotes the parameter of interest (e.g., the CE ν NS signal normalization or a BSM coupling), ν represents the set of nuisance parameters, $\hat{\hat{\nu}}$ are the values of the nuisance parameters that maximize the likelihood for fixed θ , and $(\hat{\theta}, \hat{\nu})$ correspond to the global maximum of the likelihood.

All relevant nuisance parameters are profiled in the fit. These include the normalization of the background component, as well as the parameters describing the background energy spectrum and, for the *Technical Run*, the temporal evolution of the LEE rate. No external constraints are imposed on these parameters. The distributions of the test statistic obtained from ensembles of pseudo-experiments are used to determine median expected discovery significances for the SM CE ν NS signal or, in the absence of a signal, to derive projected upper limits on the parameters of interest at the desired confidence level. Additional details on the statistical procedure and its validation are provided in Appendix A.

IV. RESULTS

In this section, we present the results of the sensitivity studies described above. Unless otherwise stated, all projections assume one year of data acquisition with an overall 80% efficiency, which accounts for detector live time and analysis efficiency. Illustrative examples on the extraction of median expected upper limits, confidence intervals, and discovery significances are presented in Appendix A.

A. Sensitivity to Standard Model CE ν NS

Owing to the presence of the LEE, which exceeds the expected CE ν NS signal by several orders of magnitude, a detection of the SM CE ν NS signal is not expected during the upcoming *Technical Run*. Using the reactor power variation analysis introduced in Sec. III B, together with the signal and background models described in Sec. III A 2, we obtain a median 90% confidence level (CL) sensitivity corresponding to a signal normalization approximately 35 times larger than the SM prediction. To put this number into context, we can compare it with results obtained from other reactor CE ν NS experiments. At 90% CL, CONNIE [82] and RED-100 [17] reported observed upper limits around 70 and 60 times the SM expectation, respectively, while MINER [18] currently stands at roughly 1500 times the predicted SM value. In contrast, the CONUS+ experiment reported a 3.7σ observation of reactor CE ν NS with a total uncertainty of about 27% on the extracted neutrino signal [12]. For comparison, a likelihood analysis based solely on spectral-shape information yields a substantially weaker sensitivity, at the level of about 200 times the SM rate, due to the strong degeneracy between the CE ν NS spectrum and the LEE shape. An analysis based only on the time variation of the total event rate performs better, reaching a sensitivity of roughly 50 times the SM expectation at the 90% CL. These results highlight the substantial gain achieved by combining temporal and spectral information in the likelihood, as illustrated in Fig. 10 of Appendix A. Because the sensitivity of the *Technical Run* is limited by the dominant LEE background, it

improves only slowly with exposure, and extending the data-taking period beyond one year would not lead to a substantial gain in sensitivity within realistic timescales.

In contrast, during the *Physics Run*—where the LEE contribution is assumed to be suppressed to negligible levels—a clear observation of the SM CE ν NS signal becomes feasible. For the reference configuration considered here, a median discovery significance of 4.7σ is expected, corresponding to approximately 58 expected CE ν NS events and a statistical uncertainty of around 20% on the measured cross section. This precision enables a competitive determination of the weak mixing angle at low momentum transfer, with $\sin^2 \theta_W$ treated as the only free electroweak parameter in the fit. We obtain an expected 1σ (68.27% CL) interval of

$$0.187 < \sin^2 \theta_W(|\vec{q}| \sim 5 \text{ MeV}) < 0.286, \quad (17)$$

where the quoted momentum transfer corresponds to the characteristic scale probed by NUCLEUS. This would represent the lowest momentum-transfer determination of the weak mixing angle to date from a CE ν NS experiment. A comparison with existing measurements is shown in Fig. 3. The impact of the dominant systematic uncertainties on these results has also been evaluated. Their contribution is found to be at the level of a few percent and therefore subdominant with respect to the statistical uncertainty. Details of this study are provided in Appendix B.

In Fig. 4, we present the projected sensitivities to the neutrino charge radius. For the *Physics Run*, NUCLEUS is

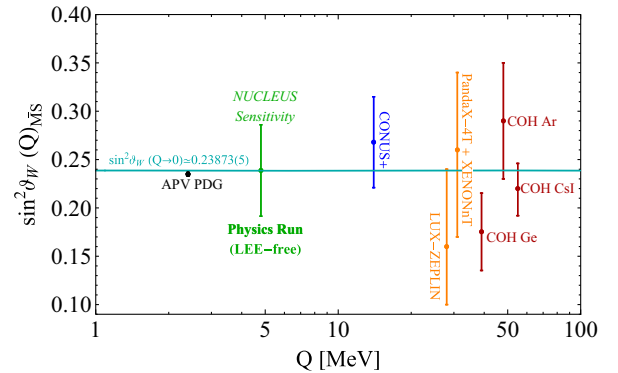


FIG. 3. Projected sensitivity of the NUCLEUS experiment to the weak mixing angle $\sin^2 \theta_W(Q)_{\overline{\text{MS}}}$ as a function of the momentum transfer $|\vec{q}| \doteq Q$. The solid line represents the latest theoretical determination at zero momentum transfer [48]. The green point indicates the expected precision for the *Physics Run*, assuming complete suppression of the LEE. This is compared to the precision from atomic parity violation (APV) on cesium [48] and existing measurements from CE ν NS experiments, specifically CONUS+ [83], COHERENT CsI [84], Ar [85], Ge [86], a combined analysis of XENONnT [10] and PandaX [9] data [87], and the determination from LUX-ZEPLIN [11].

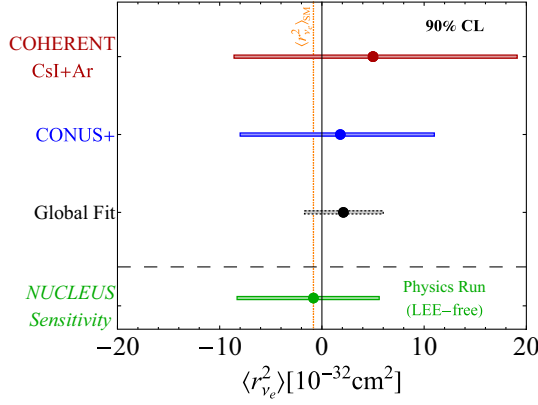


FIG. 4. Projected sensitivity of the NUCLEUS experiment to the diagonal electronic neutrino charge radius $\langle r_{\nu_e}^2 \rangle$. The green point indicates the expected precision for the *Physics Run*, assuming complete suppression of the LEE, compared to the precision from CONUS+ [68] and COHERENT CsI + Ar [45], and a global fit of existing neutrino data [52].

expected to constrain the NCR within³

$$(-8.3 < \langle r_{\nu_e}^2 \rangle < 5.6) \times 10^{-32} \text{ cm}^2 \quad (18)$$

at 90% CL. This would represent one of the most stringent constraints to date, when compared to the existing CE ν NS measurement shown in Fig. 4. We note that while at the SNS it is possible to simultaneously constrain both the electronic and muonic flavors, an intrinsic degeneracy between the two parameters weakens the sensitivity on the electronic flavor. Furthermore, since the neutrino flux at COHERENT is dominated by ν_μ , reactor neutrinos offer a highly complementary probe, exceptionally sensitive to the electronic flavor. This complementarity helps to break degeneracies when combining data from different neutrino sources.

B. Sensitivity to physics beyond the Standard Model

Figure 5 shows the projected sensitivity of NUCLEUS to a universal light vector mediator, parametrized according to Eq. (8), for both the *Technical Run* and the *Physics Run*, compared with existing constraints from other CE ν NS experiments. Despite the presence of the dominant LEE background, competitive sensitivities are already achieved during the *Technical Run*, owing to the strong enhancement of light-mediator effects at low momentum transfer and the exploitation of reactor-power variation. The *Physics Run* significantly extends the reach of NUCLEUS, allowing

³In this study, we do not extend the fit to the degenerate solution appearing at large and negative values of $\langle r_{\nu_e}^2 \rangle$, as this region has been ruled out by a recent global analysis of neutrino data [52].

previously unexplored regions of the parameter space to be probed, particularly for mediator masses between approximately 0.1 and 10 MeV when compared to existing CE ν NS experiments. The sensitivity exhibits a characteristic degeneracy band, corresponding to regions where destructive interference occurs between the SM nuclear weak charge and the contribution from the new vector mediator [59].

The right panel of Fig. 5 shows the projected NUCLEUS sensitivity in the $(\epsilon_{ee}^{uV}, \epsilon_{ee}^{dV})$ plane achievable during the *Physics Run*, compared with 90% CL constraints from a selection of existing CE ν NS experiments. The NUCLEUS sensitivity bands display a pronounced anticorrelation between the up- and down-quark vector NSI couplings, arising from the phenomenology of the model and from the different proton and neutron contributions of the target nuclei. Again, the precision foreseen is comparable, or even better, than that from leading CE ν NS experiments, highlighting the capability of NUCLEUS to test subleading non-standard interaction effects and to help resolve degeneracies present in existing measurements.

In addition to this, already during the *Technical Run*, NUCLEUS is expected to place a constraint on the effective electron-flavor neutrino magnetic moment that is more stringent than the current limit obtained from the combined COHERENT CsI + Ar dataset [50,61], namely, $\mu_{\nu_e} < 22.3 \times 10^{-10} \mu_B$ at 90% CL as shown in Fig. 6. This sensitivity is driven by the characteristic $1/T_{\text{nr}}$ enhancement of the magnetic-moment contribution at low recoil energies, which compensates for the small target mass of the experiment. For the *Physics Run*, an additional improvement of approximately one order of magnitude is expected, yielding a projected sensitivity of $\mu_{\nu_e} < 2.0 \times 10^{-10} \mu_B$ at 90% CL. This places NUCLEUS among the most sensitive CE ν NS-based probes of the effective electron neutrino magnetic moment, even though CONUS+ constraints remain stronger when ν ES is included on top of the CE ν NS signal. We note, however, that direct constraints on μ_{ν_e} exploiting reactor neutrino–electron scattering data at $\sim$ MeV recoil energies currently provide constraints that are approximately one order of magnitude stronger [66,93–95].

In addition, the effective neutrino magnetic moment can be tightly constrained using solar-neutrino data. However, due to the phenomenon of neutrino oscillations, the extracted constraints for solar neutrino magnetic moments correspond to different combinations of the magnetic contributions relative to the mass eigenstate [97]. For this reason, the resulting limits from solar neutrinos are not directly comparable to those derived in this work and are therefore not shown in Fig. 6. For a qualitative comparison, the strongest constraints on the effective solar magnetic moment (μ_{ν_s}) have been obtained by XENONnT, $\mu_{\nu_s} \lesssim 6.4 \times 10^{-12} \mu_B$ [98], LUX-ZEPLIN, $\mu_{\nu_s} \lesssim 8.3 \times 10^{-12} \mu_B$ [99], and BOREXINO, $\mu_{\nu_s} \lesssim 2.8 \times 10^{-11} \mu_B$ [100], all of which rely on the ν ES channel.

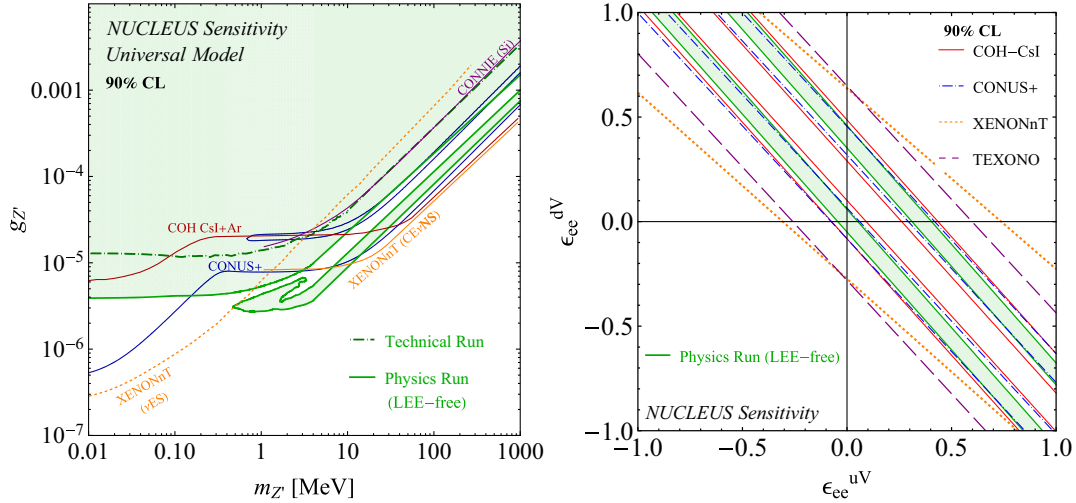


FIG. 5. Projected sensitivity of the NUCLEUS experiment to a universal light mediator model (left) and to a flavor preserving NSI scenario (right). The green regions indicate the parameter space that can be probed by NUCLEUS at 90% CL, with curves corresponding to the *Technical Run* (only for the light mediator case) and *Physics Run* (filled region), assuming complete suppression of the LEE for the latter. Left: sensitivity to the light mediator model is compared to existing constraints at the 90% CL from CONUS+ [68,88], COHERENT CsI + Ar [61], CONNIE [82], XENONnT electron recoil (ν ES) [89], and CE ν NS data [90]. Right: we compare the sensitivity to NSI with the results from COHERENT CsI [84], TEXONO [91], CONUS+ [88], and XENONnT [92] at 90% CL.

C. Impact of increased target mass

The results presented above highlight the distinctive strength of the NUCLEUS detector concept: thanks to its ultralow nuclear recoil energy threshold, competitive sensitivity to CE ν NS and to several BSM scenarios can be achieved with a target mass at the gram scale. In particular, a CE ν NS observation with a statistical uncertainty of about 20% is possible with only 7 g of CaWO₄, a mass up to several orders of magnitude smaller than that employed

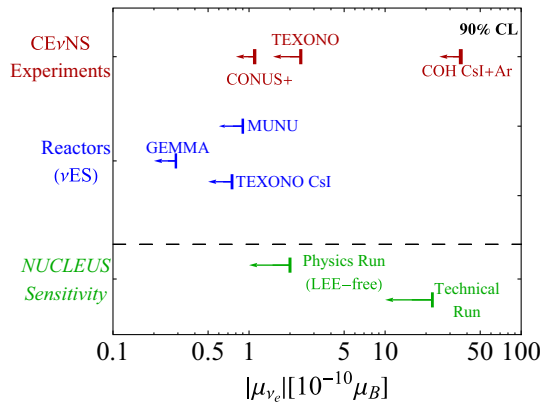


FIG. 6. Projected sensitivity of the NUCLEUS experiment to the effective electronic neutrino magnetic moment μ_{ν_e} at 90% CL. The green arrows indicate the expected precision for the *Technical Run* and *Physics Run*, assuming complete suppression of the LEE for the latter. The results of the sensitivity are compared to existing constraints on μ_{ν_e} from CE ν NS experiments [COHERENT CsI + Ar [61], TEXONO [68], and CONUS+ [96]] and data that exploit ν ES at the $\sim$ MeV range at reactor plants [MUNU [93], GEMMA [94] and TEXONO CsI [95]].

by other CE ν NS experiments operating at higher recoil-energy thresholds. For comparison, experiments such as COHERENT and CONUS+ achieved comparable statistical precision using target masses at the kilogram scale or above, reflecting the strong dependence of CE ν NS sensitivity on the accessible recoil-energy threshold. However, increasing the CaWO₄ target mass offers substantial margin to improve the precision of the CE ν NS cross section measurement. Such improvements would directly enhance the experiment's sensitivity to the physics parameters considered in this work, making higher-precision measurements particularly valuable. To quantify this potential, we examine how the statistical sensitivity scales with target mass under the assumptions of the *Physics Run*, considering statistical uncertainties only. This projection is intended as a simplified estimate of the achievable statistical improvement and does not account for possible changes in detector design, background composition, or mitigation strategies that could accompany a scaling to significantly larger target masses. The results are shown in Fig. 7, which reports the 1σ median statistical precision obtained through the sensitivity procedure described in Sec. III B. We find that improving the statistical precision of the SM CE ν NS measurement by a factor of two, to reach similar precision as that of current COHERENT measurements [84], requires an increase in target mass by approximately a factor six (about 40 g of CaWO₄). Pushing the precision further will eventually bring the experiment into a regime where systematic uncertainties dominate over the statistical ones. In the configuration considered here, this transition occurs for a CaWO₄ target mass of approximately 340 g (see Fig. 7), at which point the statistical

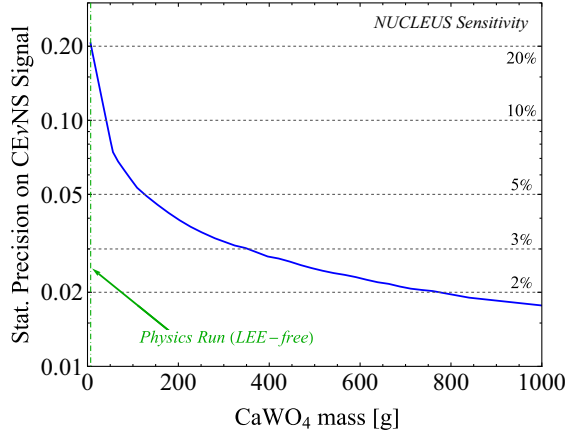


FIG. 7. Median statistical precision on the SM CE ν NS signal as a function of the total CaWO₄ target mass, assuming the configuration of the *Physics Run* with negligible LEE background, 20 eV threshold, and 1 year of exposure. The blue curve shows the median expected 1σ statistical uncertainty obtained from ensembles of pseudo-experiments. The green dashed line indicates the nominal 7 g target mass for the *Physics Run* assuming complete suppression of the LEE. Horizontal dashed lines mark representative precision levels (20%, 10%, 5%, 3%, 2%).

precision reaches about 3%, becoming comparable to reactor-related systematic uncertainties (see Appendix B).

V. CONCLUSIONS

In this work, we have presented a comprehensive sensitivity study for the NUCLEUS experiment at the Chooz VNS, focusing on its physics reach during the upcoming technical and physics runs. The study exploits two key features of the experiment: an unprecedentedly low nuclear recoil energy threshold enabled by cryogenic calorimetry, and the use of reactor-power variation to disentangle signal and background in a challenging low signal-to-background environment.

During the *Technical Run*, the sensitivity is limited by the presence of the LEE, which dominates the recoil energy spectrum at sub-keV energies. Nevertheless, by combining recoil energy information with the time dependence induced by reactor power variation, NUCLEUS is expected to reach competitive sensitivity to several BSM scenarios, including light vector mediators and the neutrino magnetic moment, even in the absence of a SM CE ν NS observation.

In view of the subsequent *Physics Run*, the collaboration is currently pursuing a dedicated program to suppress the LEE background. This includes the integration of the detectors into an instrumented inner veto, as well as studies of its time evolution and dependence on detector cooling conditions. Assuming that these mitigation strategies will reduce the LEE contribution to negligible levels compared to the particle-induced background estimated from simulations, NUCLEUS is expected to achieve a clear observation of SM CE ν NS with a statistical uncertainty of about

20% using only 7 g of CaWO₄. This measurement would enable a competitive determination of the weak mixing angle at the lowest momentum transfer probed to date by CE ν NS experiments and to put leading constraints on the neutrino charge radius. At the same time, the ultralow recoil-energy threshold provides strong sensitivity to new physics effects that modify the CE ν NS spectrum at low energies, allowing NUCLEUS to explore previously unexplored regions of light-mediator parameter space. Overall, this study demonstrates that the NUCLEUS experiment occupies a unique position in the landscape of CE ν NS measurements. By accessing the lowest nuclear recoil energies achieved to date, NUCLEUS can compensate for its small target mass and provide competitive sensitivity to both SM and new physics scenarios. These results highlight the strong complementarity between ultralow-threshold cryogenic detectors and larger-mass experiments operating at higher recoil energy thresholds, and establish NUCLEUS as a powerful probe of CE ν NS and low-energy neutrino physics at nuclear reactors.

ACKNOWLEDGMENTS

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX A: VALIDATION OF THE STATISTICAL FRAMEWORK

In this appendix, we validate the likelihood-based inference framework described in Sec. III B and illustrate the construction of upper limits, confidence intervals, and discovery significances used throughout this work.

1. Fit parameter reconstruction

To validate the fit procedure based on the likelihood defined in Eq. (15), we use ensembles of pseudo-experiments generated from the nominal signal and background

model. For each pseudo-experiment, the full likelihood is maximized and the reconstructed best-fit parameters and their uncertainties are recorded. This procedure allows us to assess unbiasedness, parameter correlations, and the overall behavior of the likelihood in the relevant regions of parameter space.

As a representative example, Fig. 8 shows the distributions of the reconstructed best-fit parameters and their pairwise correlations for the *Technical Run* configuration, assuming an injected signal strength $\alpha_{\text{true}} = 35 \times \alpha_{\text{SM}}$, where α_{SM} denotes the normalization of the SM CE ν NS signal, and the LEE background model defined in Sec. III A 2. The distributions peak at the injected (true) values (red dashed lines), demonstrating unbiased parameter reconstruction. The one-dimensional projections are approximately symmetric and show no secondary modes or visible distortions, indicating that the likelihood is well behaved in the explored parameter region.

The off-diagonal panels reveal the correlation structure among the fitted parameters. A pronounced anticorrelation is observed between the signal normalization α and the overall background normalization β , reflecting their partial spectral degeneracy in the low-energy region where both contribute. Strong correlations are also visible among the parameters governing the LEE model. In particular, the spectral shape parameters ϵ_1 , ϵ_2 , and f exhibit correlations, consistent with their coupled role in defining the LEE spectral behavior. The parameter k , which controls the time decay of the LEE component, shows correlations with both the signal and background normalization. These arise from the interplay between spectral and time-dependent components of the likelihood, as variations in the time evolution of the background can partially mimic changes in normalization.

The observed correlation pattern is well understood and fully accounted for in the analysis through likelihood profiling.

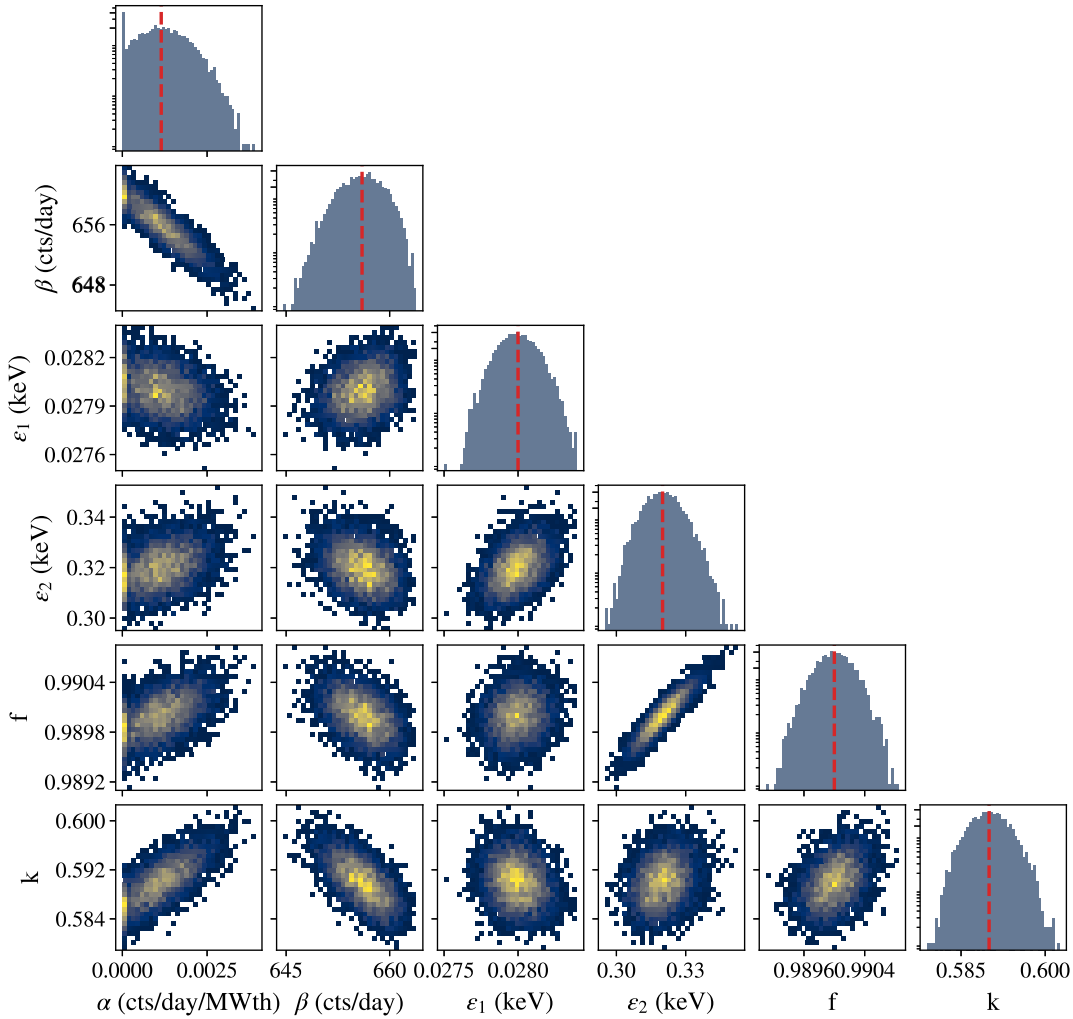


FIG. 8. Distributions of reconstructed best-fit parameters and their pairwise correlations for the *Technical Run* configuration, obtained from ensembles of ~ 5000 pseudo-experiments generated with fixed injected values. The red dashed lines indicate the injected (true) parameter values.

2. Test statistic distribution

Confidence intervals in this work are derived from the profile-likelihood ratio test statistic defined in Eq. (16). Under regularity conditions and for sufficient large event counts, Wilks' theorem predicts that the test statistic evaluated at the true parameter value follows a χ^2 distribution with one degree of freedom [81,101]. In this section, we examine the behavior of the test statistic in both the *Technical Run* and *Physics Run* configurations using ensembles of pseudo-experiments.

The distribution of the test statistic $q(\alpha_{\text{true}})$, with $\alpha_{\text{true}} = 35 \times \alpha_{\text{SM}}$, for the *Technical Run* configuration is shown in the left panel of Fig. 9. The distribution is obtained from the same ensemble of ~ 5000 pseudo-experiments used for the parameter-reconstruction study described above, with the injected signal strength of $\alpha_{\text{true}} = 35 \times \alpha_{\text{SM}}$. For each pseudo-experiment, the profile-likelihood ratio is evaluated at the injected parameter value, and the resulting values of $q(\alpha_{\text{true}})$ are collected.

The empirical 90% quantile of the simulated distribution is found to be 2.67 ± 0.04 , compared to the asymptotic expectation of 2.71 for a χ^2 distribution with one degree of freedom. The observed agreement is satisfactory within statistical precision in the region relevant for limit construction and indicates that the use of asymptotic thresholds provides an adequate approximation for the *Technical Run* sensitivity projections presented in this work.

Figure 10 illustrates the procedure used to extract upper limits on the CE ν NS signal strength in the *Technical Run* configuration. For each signal hypothesis, ensembles of 500 pseudo-experiments are generated and analyzed with the corresponding likelihood model. The profile likelihood ratio $q(\alpha)$ is constructed for every pseudo-experiment, and the median value is reported. This corresponds to the standard definition of expected sensitivity, i.e., behavior

of the test statistic in 50% of repeated experiments under the assumed signal hypothesis [81].

Three analysis strategies are compared: an energy-only likelihood, a time-only likelihood, and the combined time-energy likelihood adopted in the main analysis. For all injected signal strengths, the combined likelihood yields the largest median test statistic, reflecting the complementarity of spectral and reactor-power information. The energy-only analysis exploits differences in recoil spectra between signal and background, while the time-only analysis relies on the distinct time dependence of signal and background, with only the former correlated with reactor power. Their combination reduces parameter degeneracies and produces a steeper increase of the test statistic with signal strength.

The intersection with $q(\alpha) \simeq 2.71$ defines the expected median 90% CL upper limit. The more stringent upper limit obtained in the combined analysis directly quantifies the gain achieved by exploiting both observables in the *Technical Run* scenario.

We now consider the *Physics Run* configuration. Ensembles of $\sim 10^4$ pseudo-experiments are generated assuming an injected signal strength $\alpha_{\text{true}} = \alpha_{\text{SM}}$ and the background model defined in Sec. III A 3. The distribution of the test statistic $q(\alpha_{\text{true}})$ is shown in the right panel of Fig. 9, together with the χ^2 distribution with one degree of freedom. The empirical 68.27% (1σ) quantile of the simulated distribution is found to be 1.009 ± 0.019 , in good agreement with the asymptotic expectation of unity. This level of agreement indicates that the asymptotic thresholds provide an adequate approximation for the sensitivity projections of the *Physics Run* configuration presented in this work.

To illustrate how confidence intervals on a measured parameter are extracted in this work, Fig. 11 shows the median profile-likelihood ratio test statistic as a function of

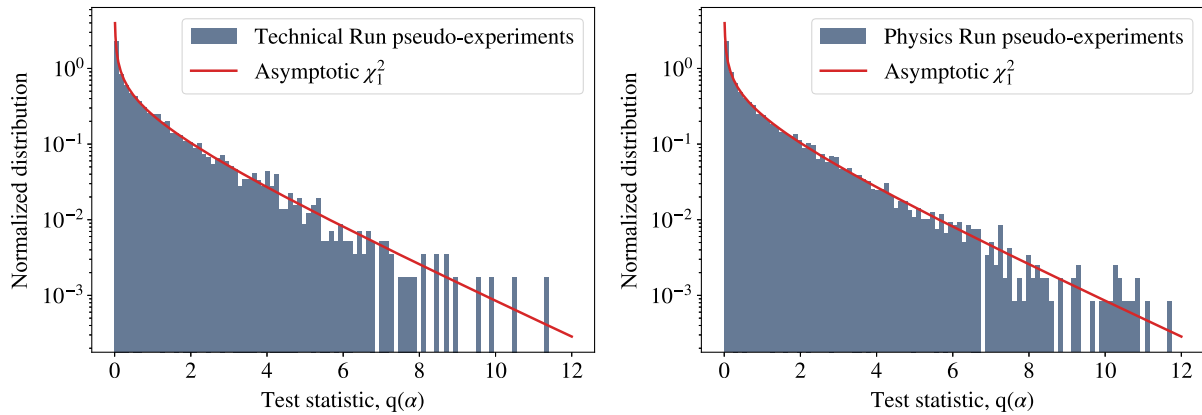


FIG. 9. Left: distribution of the profile-likelihood ratio test statistic for the *Technical Run* configuration, obtained from ~ 5000 pseudo-experiments generated with an injected signal strength $\alpha_{\text{true}} = 35 \times \alpha_{\text{SM}}$. Right: same distribution for the *Physics Run* configuration, obtained from $\sim 10^4$ pseudo-experiments generated with an injected signal strength $\alpha_{\text{true}} = \alpha_{\text{SM}}$. The histogram shows the normalized empirical distribution, while the red curve represents the asymptotic χ^2 distribution with one degree of freedom (χ^2_1).

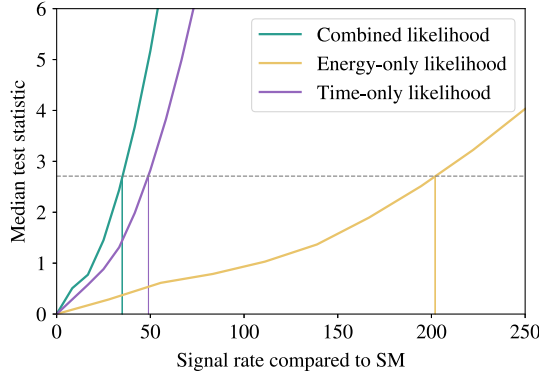


FIG. 10. Median profile-likelihood ratio test statistic as a function of the injected CE ν NS signal strength (expressed relative to the SM prediction) for the *Technical Run* configuration. For each signal hypothesis, the median value of $q(\alpha)$ is obtained from ensembles of 500 pseudo-experiments fitted with the energy-only, time-only, and combined likelihoods. 90% CL upper limits are determined from the intersection of the curves with the asymptotic threshold $q = 2.71$ (gray dashed line).

the weak mixing angle $\sin^2 \theta_W$ for the *Physics Run* configuration. The curve is obtained from an ensemble of 10^4 pseudo-experiments generated under the SM hypothesis. For each pseudo-experiment, the profile likelihood ratio $q(\sin^2 \theta_W)$ is evaluated on a fixed grid in $\sin^2 \theta_W$, and the median value at each grid point is reported. The minimum of the median curve coincides with the injected SM value within statistical precision, and the likelihood is approximately quadratic in its vicinity. The intersections with $q(\sin^2 \theta_W) = 1$ define the expected (median) 1σ confidence interval.

In addition to interval estimation, we evaluate the expected discovery significance for the SM CE ν NS signal in the *Physics Run* configuration. For this purpose, we

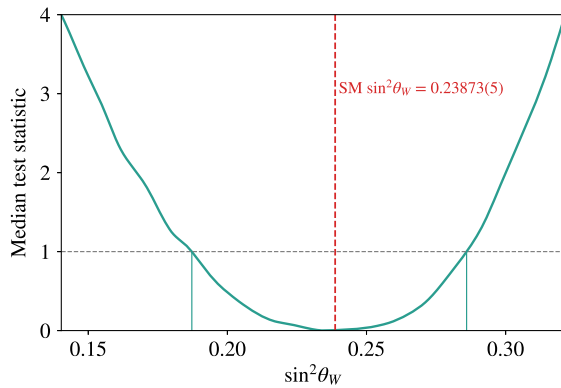


FIG. 11. Median profile-likelihood ratio test statistic as a function of the weak mixing angle $\sin^2 \theta_W$ for the *Physics Run* configuration. The median is obtained from $\sim 10^4$ pseudo-experiments generated under the SM hypothesis. The expected 1σ confidence interval is determined from the intersection with $q = 1$ (gray dashed line).

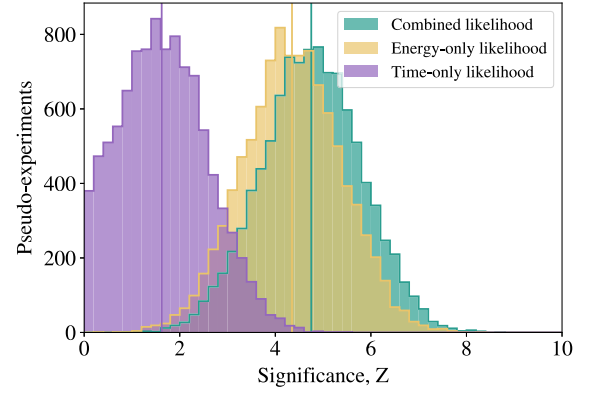


FIG. 12. Distribution of the discovery significance $Z = \sqrt{q_0}$ for the SM CE ν NS signal in the *Physics Run* configuration. Results are obtained from ensembles of $\sim 10^4$ pseudo-experiments generated under the SM hypothesis and analyzed with the energy-only, time-only, and combined likelihoods. The median of each distribution defines the expected discovery significance.

determine the distribution of the test statistic $q_0 = q(\alpha = 0)$ using ensembles of pseudo-experiments generated under the SM hypothesis. The significance is then defined as $Z = \sqrt{q_0}$, corresponding to the asymptotic relation for a one-sided test in the regime where the profile-likelihood ratio follows the expected χ^2 behavior [81].

Figure 12 shows the resulting distribution of the significance Z , obtained from ensembles of $\sim 10^4$ pseudo-experiments generated under the SM hypothesis. The median of this distribution defines the expected discovery significance, corresponding to the sensitivity achieved in 50% of repeated experiments under the SM hypothesis. Again, the three analysis strategies are compared: an energy-only likelihood, a time-only likelihood, and the combined time-energy likelihood adopted in the main analysis. In contrast to the *Technical Run* configuration, the *Physics Run* sensitivity is primarily driven by spectral information, reflecting the stronger separation between signal and background once the overall background level is reduced. The time-only analysis provides a comparatively weaker constraint; however, its inclusion in the combined likelihood increases the median significance by further constraining background components not correlated with reactor power.

APPENDIX B: SYSTEMATIC UNCERTAINTIES

In this appendix, we evaluate the impact of the dominant sources of systematic uncertainty on the projected sensitivities, focusing in particular on the nuclear recoil energy scale and the reactor antineutrino flux. We first consider the uncertainty associated with the absolute energy calibration at low recoil energies, which is a known challenge for experiments operating at ultralow thresholds. The NUCLEUS Collaboration is addressing this issue through dedicated calibration campaigns, including measurements

with controlled nuclear recoils using the CRAB facility [102,103] and low-energy X-ray calibration sources [74]. These approaches are pursued in addition to the LED calibration based on Poisson statistics [30], with the goal of cross-checking the energy scale and constraining the associated systematic uncertainties. In particular, CRAB provides a direct calibration of nuclear recoils in CaWO_4 , thereby avoiding model-dependent assumptions and offering a robust handle on the nuclear-recoil energy scale. Current CRAB measurements are performed offsite [103], and studies are ongoing to assess the feasibility of an onsite calibration at the VNS, which would allow a direct in-situ determination of the nuclear recoil response and is expected to significantly reduce the associated systematic uncertainty. During the commissioning run, a discrepancy at the level of 25% was observed between the LED calibration based on Poisson statistics and the position of the copper X-ray line at 8.04 keV [30]. Although this uncertainty is expected to be reduced in future runs, we conservatively assume a 25% uncertainty on the absolute energy scale in the present study.

Unlike ionization- or scintillation-based detectors, cryogenic calorimeters measure almost the entire nuclear recoil energy as heat. As a result, they do not rely on quenching-factor models, which constitute a major source of systematic uncertainty in other CE ν NS experiments—particularly at the very low recoil energies where the CE ν NS signal is concentrated and where quenching effects are poorly constrained experimentally [104]. This feature is further reinforced by calibration approaches such as CRAB, which directly probe nuclear recoils and are intrinsically insensitive to quenching effects. Consequently, the dominant detector-related systematic uncertainty for NUCLEUS arises from the absolute calibration of the energy scale rather than from energy-dependent quenching effects.

The impact of the energy-scale uncertainty is modeled by introducing a linear relation between the observed and true recoil energies:

$$T_{\text{nr,obs}} = T_{\text{nr,true}}(1 + \delta). \quad (\text{B1})$$

For the evaluation of this systematic effect, the transformation is applied to the CE ν NS signal prediction in Eq. (10) and to the background model only when generating pseudo-experiments. The fits to these pseudo-datasets are performed with the nominal (unshifted) energy model. Since the differential rate and the analysis threshold depend explicitly on the recoil energy, the shifted model differs from the nominal prediction both in spectral shape and in the total number of events above threshold. Pseudo-experiments are generated under two scenarios,

corresponding to energy-scale shifts of $\delta = +25\%$ and $\delta = -25\%$, and then fitted using the nominal energy model ($\delta = 0$). The reconstructed signal normalization is compared to that obtained from pseudo-experiments both generated and fitted with the nominal model, yielding an asymmetric systematic bias of $^{+0.5}_{-4.0}\%$ on the reconstructed CE ν NS signal, with a similar variation observed in the median expected discovery significance. This bias therefore quantifies the impact of the energy scale uncertainty on the extracted SM normalization, including the change in the predicted event rate induced by the shift.

A similar procedure is used to estimate the systematic uncertainty associated with the reactor antineutrino flux. Propagating the 1σ flux uncertainty reported in Ref. [24] to the CE ν NS signal model results in a relative uncertainty of $\pm 2\%$ on the extracted signal normalization. Both systematic effects are therefore subdominant compared to the expected $\sim 20\%$ statistical uncertainty of the CE ν NS measurement in the *Physics Run* and have a negligible impact on both the SM observables presented in Sec. IV A and on the projected sensitivities to the BSM scenarios discussed in Sec. IV B.

In addition, the uncertainty on the reactor thermal power determination has been considered. The Double Chooz collaboration reports an uncertainty of 0.5% on the instantaneous thermal power at full reactor power when using operator-provided EDF data [105]. In the present study, we rely on publicly available reactor power information, for which the estimated uncertainty is approximately 5%. This larger value reflects the use of public data in the current sensitivity study rather than an intrinsic limitation: access to operator-provided reactor information would allow a determination at the $\sim 0.5\%$ level. However, this refinement is not required for the projected sensitivity of the *Physics Run*, as the overall signal normalization uncertainty remains subleading compared to the expected $\sim 20\%$ statistical uncertainty. For future higher-exposure phases and mass scaling, the use of operator-provided reactor information and a detailed treatment of the fission inventory evolution will become necessary and will be addressed at that stage.

Finally, we do not assign an additional theoretical uncertainty to the CE ν NS cross section prediction. As discussed in Sec. II A, nuclear form-factor effects are negligible in the recoil-energy range relevant for NUCLEUS, and the uncertainty on the SM value of the weak mixing angle induces only a subpercent variation in the normalization. These effects are therefore negligible compared to the statistical and experimental systematic uncertainties considered above.

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