A liquid argon scintillating bubble chamber for CEνNS reactor neutrino detection and dark matter searches

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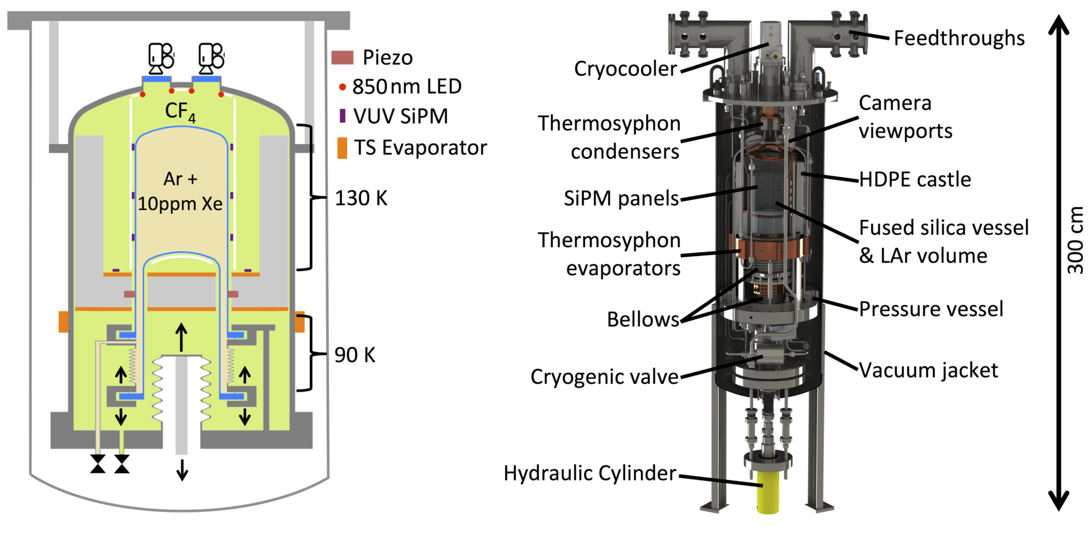
Introduction

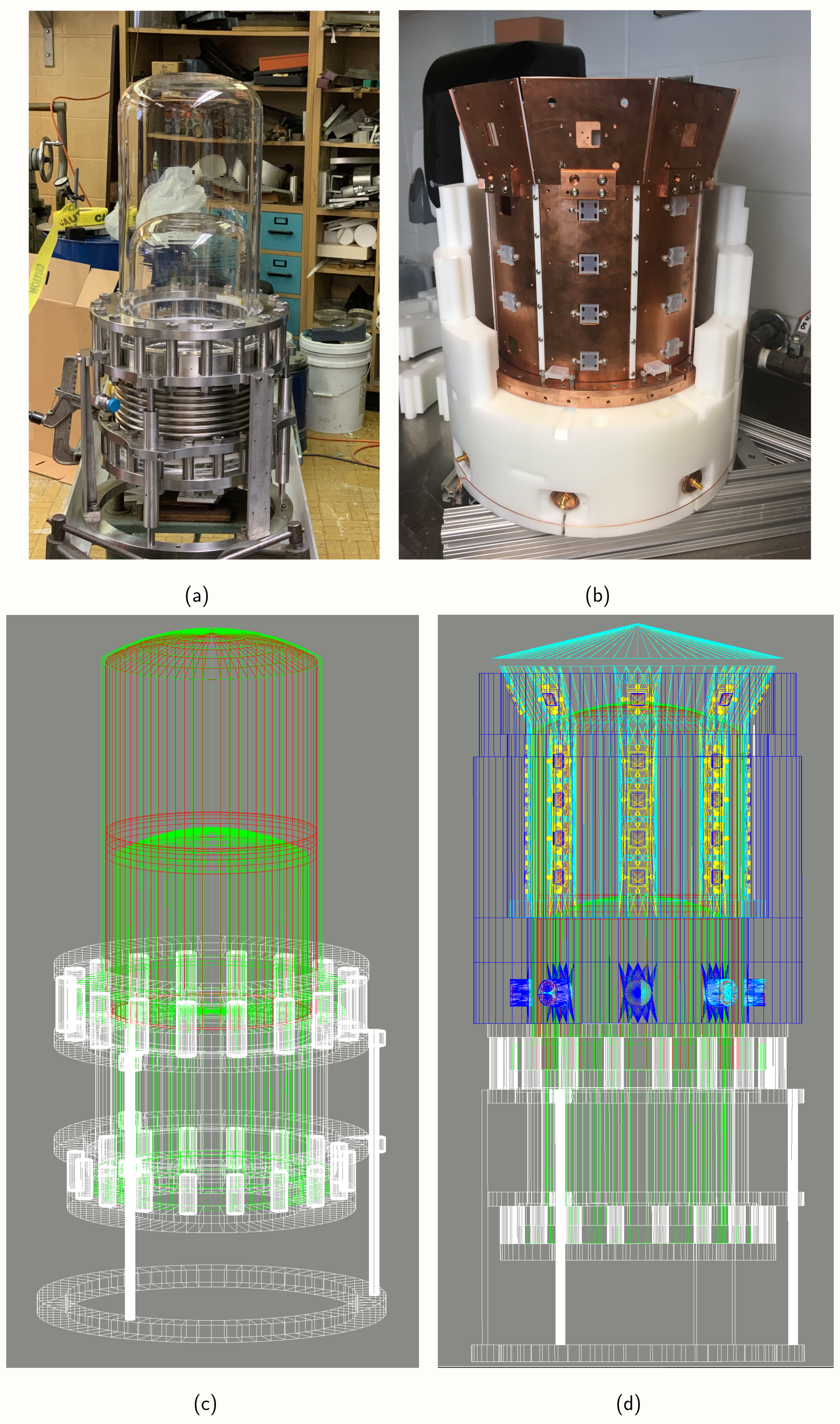
The Scintillating Bubble Chamber Collaboration (SBC) is developing a liquid-noble detector ideal for GeV-mass WIMP searches and coherent elastic neutrino-nucleus scattering (CEνNS) detection. The detector is now being commissioned at Fermilab and consists of a 10-kg bubble chamber using liquid argon (LAr) with the potential to reach and maintain sub-keV energy thresholds. This detector will combine the event-by-event energy resolution of a liquid noble scintillation detector with the world-leading electron-recoil discrimination capability of the bubble chamber.



Schematic (left) and annotated solid model (right) of the SBC-LAr Detector.

GEANT4 Model

The use of Monte Carlo simulations represents a valuable tool in the design and construction of the detector. The detector model is constantly being developed and updated, as part of the detector construction process. The model developed in this work, provides important information about the internal backgrounds generated by its different components.



(a) Test of the SBC-LAr "inner assembly" comprising the inner and outer fused silica vessels. (b) The partially-assembled HDPE "castle". (c) and (d) represents sections of the GEANT4 model equivalent to (a) and (b), respectively.

Detector Backgrounds

The SBC Collaboration has plans to use the detector to measure reactor neutrinos via CEνNS after finishing the commission and calibration of the chamber. The study of the background in the detector can be separated into two categories: internal and external backgrounds. The first ones come from the (α,n) and spontaneous fission reactions in the detector's components and can only be reduced by selecting low radioactive materials. After careful material selection, the internal backgrounds are under control, and less than one event per day is expected in the detector. External background come from cosmogenic muons and neutrons. Muons create neutrons via (μ,n) reactions in the materials of the detector and shielding.

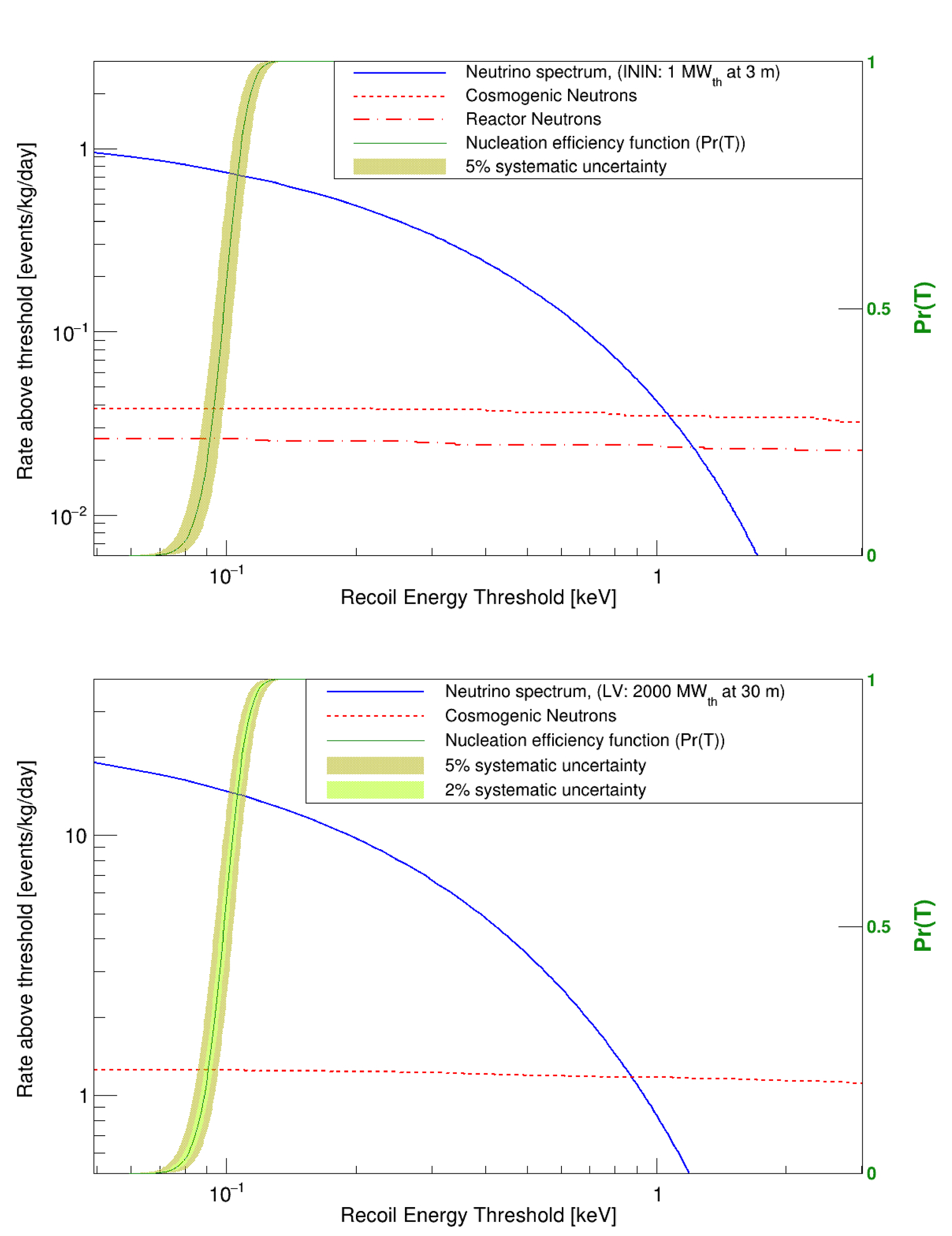
Physics Reach

Reactor´s neutrino detection via CEνNS presents a challenge because of the very low NR energy (sub keV range). The external backgrounds typically eclipsed the signal; these backgrounds are mainly generated by neutrons, γ-rays, and muons. Reactor neutrinos also provide an excellent opportunity to study CEνNS, and their observation is still an experimental competition within several detector technologies.

The study presented here considers three experimental configurations.

Setup	LAr mass (kg)	Power (MW_{th})	Distance (m)	$\bar{\nu}_e$ flux uncertainty (%)	Threshold uncertainty (%)
A	10	1	3	2.4	5
B	100	2000	30	2.4	5
B(1.5)	100	2000	30	1.5	2

Relevant parameters assumed for the setups considered in this work.

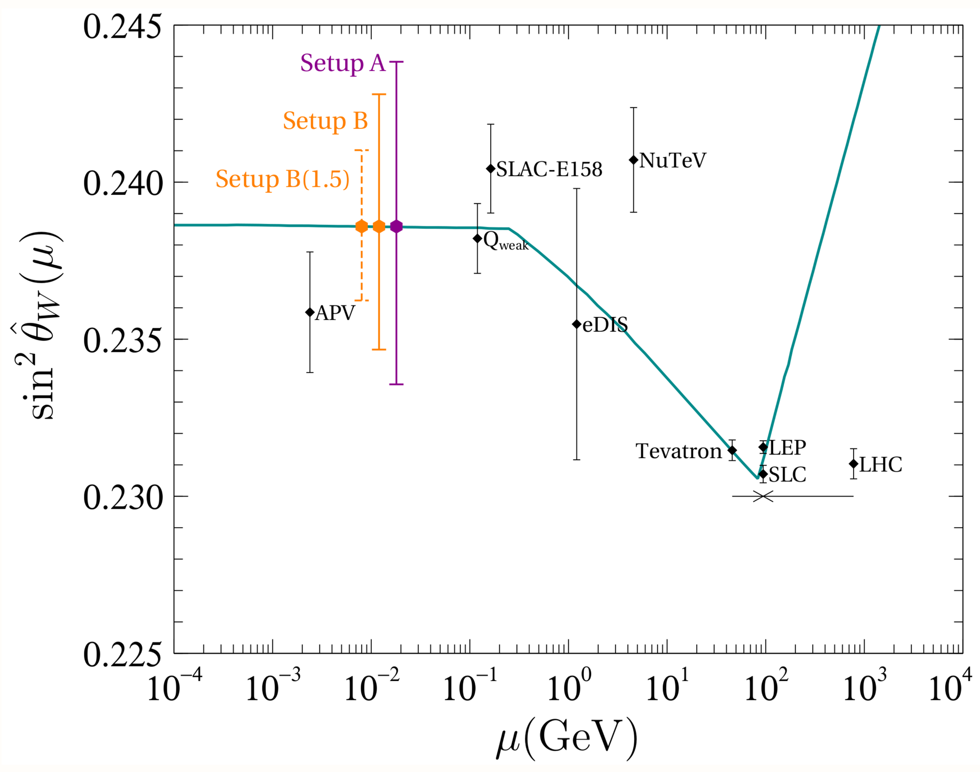


Expected neutrino signal and neutron background rates above threshold for setups A (top) and B (bottom).

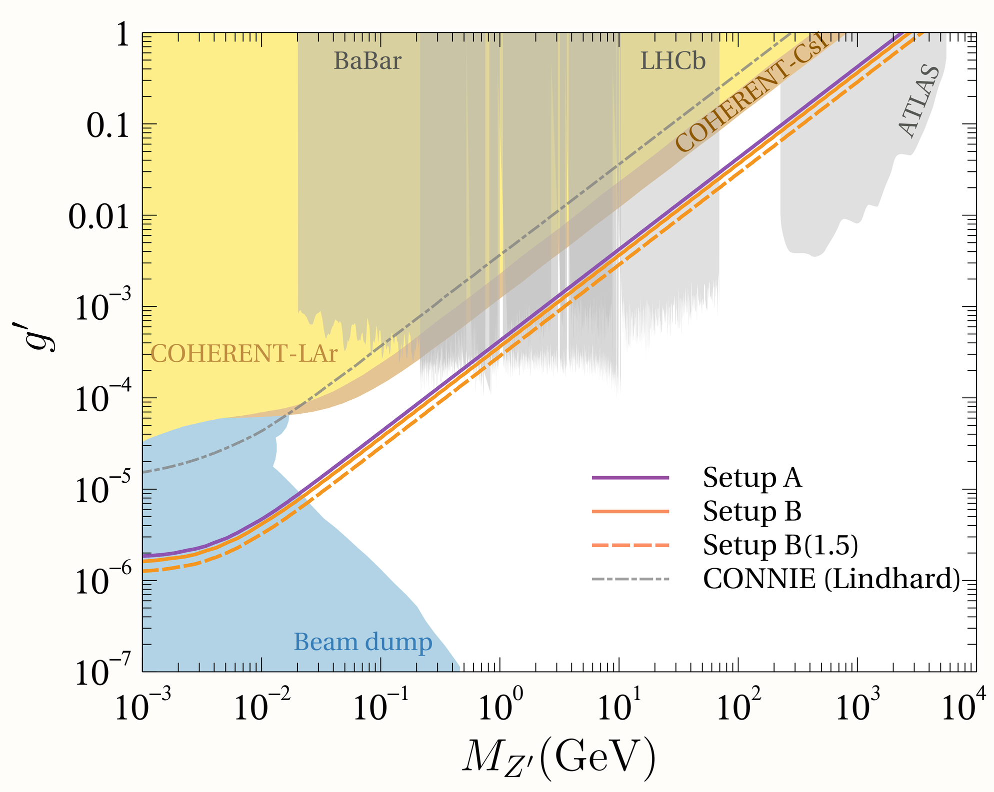
The physics reach of the setups described above is analyzed for a one-year exposure. The Standard Model (SM) cross-section employed for CEνNS, after neglecting the axial contribution, is:

$$\frac{d\sigma}{dT} = \frac{G_F^2}{2\pi} M_N Q_w^2 \left(2 - \frac{M_N T}{E_\nu^2}\right) F^2(q^2)$$

where $Q_w = Zg_p^V + Ng_n^V$ and m_N, Z, N are the nuclear mass, proton, and neutron number of the detector material.



RGE running of the weak mixing angle in the $\overline{MS}$ renormalization scheme, as a function of the energy scale μ.



Exclusion limits at 95% C.L. in the g'-$M_{Z'}$ plane.

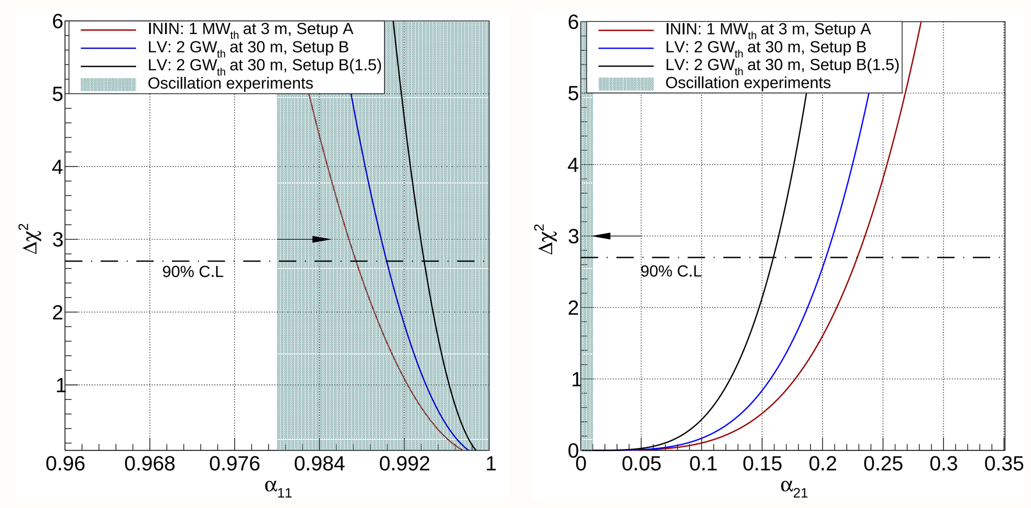
Under the assumption that the detector only measures the SM signal and using a χ^2 function, a fit is performed, and the value of the weak mixing angle at low energies is extracted with its corresponding uncertainty.

Among the extensions of the Standard Model, extra $U(1)'$ gauge symmetries are very popular, sometimes motivated by GUT's in the case of heavy Z'. In this analysis, a gauged $B - L$ symmetry is studied, namely that the extra gauge boson couples to quarks and leptons.

The measure of ν via CEνNS in reactors allows analysis of unitarity violation (UV) in the neutrino mixing matrix. In the case of heavy sterile neutrinos, constraints are set in the non-unitarity parameters through the neutral current. Adding extra heavy fermions provokes the non-unitarity of the 3×3 light neutrino mixing matrix. In this case, the generalized charged current weak interaction mixing matrix is written as

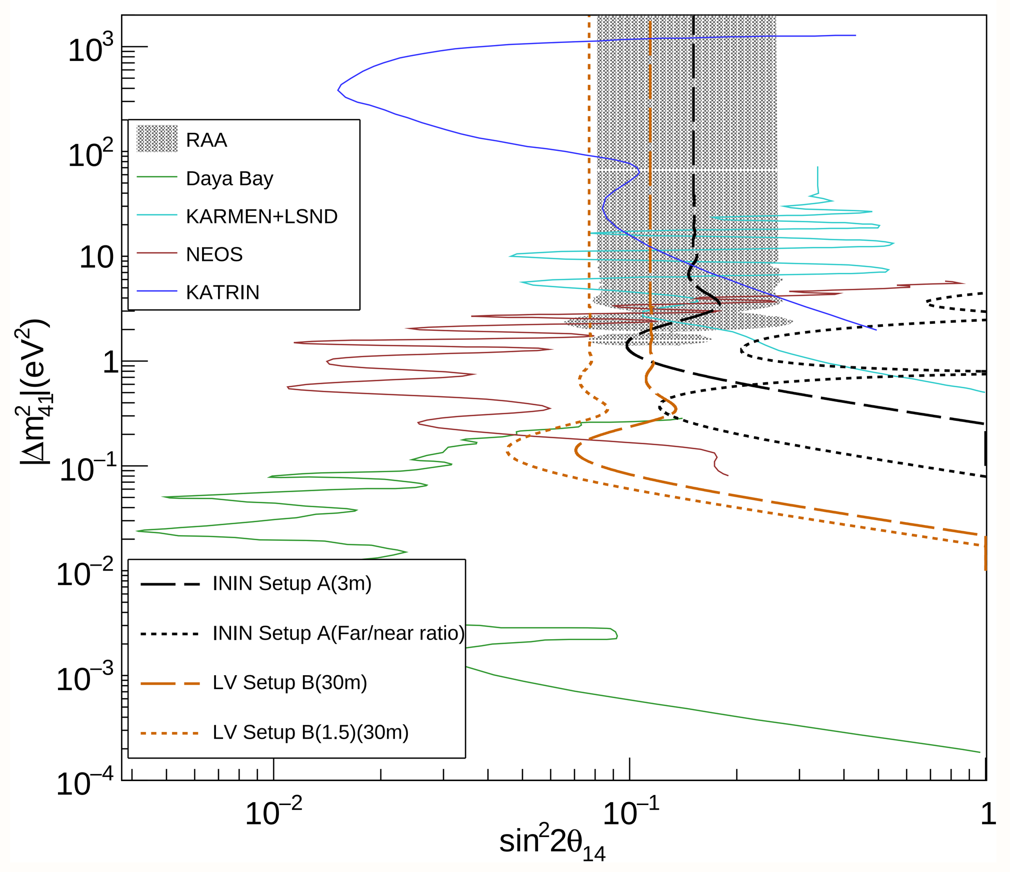
$$N = N^{UV} \cdot U^{3\times3} \to N^{UV} = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix}, \qquad (1)$$

The parameters α_{11}, α_{21}, and α_{31} are estimated with a χ^2 function identifying the optimal values of the parameters for setups A, B, and B(1.5).



(Left) Sensitivity of the diagonal parameter α_{11} for setups A (red), B (blue), and B(1.5) (black). The sensitivity from oscillation data is also presented (blue shaded region). (Right) Sensitivity of the non-diagonal parameter α_{21}. The projections for setups A, B, and B(1.5) are compared with upper limits from global oscillation fits (blue shaded region).

Many experiments with great success have confirmed the three neutrino oscillations model. Despite this, various experimental results could extend the current three flavor model, assuming the existence of at least one additional sterile neutrino. CEνNS offers a window to search for sterile neutrinos allowing to set constraints in different scenarios. A $3+1$ neutrino hypothesis is explored in this work, and sensitivity limits are established.



Expected 95% C.L. exclusion region from sterile neutrino searches. The expected limits from Setups A, B and, B(1.5) are compared with other experiments.

Conclusions

Studying backgrounds using simulations in GEANT4 is fundamental for designing and constructing the LAr scintillating bubble chamber. This novel bubble chamber technique has excellent discrimination for backgrounds generated by electromagnetic radiation. The SBC collaboration is now commissioning the detectors to study the NR and ER response (the goal is to reach a minimum threshold of 100 eV). The sensitivity of this detector for different physics cases, such as electroweak precision tests, new scalar mediators, unitarity violation, and sterile neutrino search, can be very competitive by controlling the systematic uncertainties in the anti-neutrino flux from the reactor and reducing environmental backgrounds.

References

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