NEW PHYSICS FROM THE FIRST DETECTION OF COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING (CEνNS) WITH LIQUID ARGON

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INTRODUCTION

The CENNS-10 experiment of the COHERENT collaboration has recently reported the first detection of coherent-elastic neutrino-nucleus scattering (CEνNS) on liquid Argon with more than 3σ significance [1]. Through a dedicated statistical analysis of the new data, we derive a first measurement of the neutron rms charge radius of Argon, and also an improved determination of the weak mixing angle in the low energy regime. We also update the constraints on neutrino non-standard interactions, electromagnetic properties and light mediators with respect to those derived from the first COHERENT-CsI data.

CEνNS IN THE STANDARD MODEL

Proposed more than forty years ago by Freedman [2], the neutral current CEνNS cross section scales as N^2, with N being the number of neutrons in the nucleus:

$$\left(\frac{d\sigma}{dT_A}\right)_{\rm SM} = \frac{G_F^2 m_A}{2\pi}(Q_W^V)^2\left[2 - \frac{2T_A}{E_\nu} - \frac{m_A T_A}{E_\nu^2}\right], \tag{1}$$

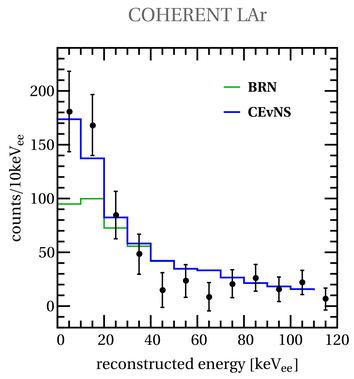
where G_F denotes the Fermi constant, T_A is the nucleus kinetic energy, E_ν the neutrino energy and Q_W^V the vector weak charge written in the form: $Q_W^V = \left[g_V^p Z F_p(Q^2) + g_V^n N F_n(Q^2)\right]$. Here, Z and N are the number of protons and neutrons in the nucleus while the neutral current vector couplings, $g_V^{p,n}$, are given by: $g_V^p = \frac{1}{2} - 2\sin^2\theta_W$, $g_V^n = -\frac{1}{2}$, with the weak mixing angle taken in the $\overline{\rm MS}$ scheme, i.e. $\sin^2\theta_W \equiv \hat{s}_Z^2 = 0.2312$.

Finally, $F_{p,n}(Q)^2$ stands for the nuclear form factors for protons and neutrons respectively, for which we employ the well-known Helm parametrization

$$F_{p,n}(Q^2) = 3\frac{j_1(QR_0)}{QR_0}\exp(-Q^2 s^2/2), \tag{2}$$

where the magnitude of the three-momentum transfer is $Q = \sqrt{2m_A T_A}$, while j_1 denotes the spherical Bessel function of order one and $R_0^2 = \frac{5}{3}(R_{p,n}^2 - 3s^2)$ with $R_n = 3.36$ fm ($R_p = 3.14$ fm) denoting the neutron (proton) rms radius and $s = 0.9$ fm.

FIGURE 1



Simulated number of events at the CENNS-10 LAr detector as a function of the reconstructed electron recoil energy. The beam related neutron (BRN) and the experimental data are also shown [3].

The differential number of events is given by

$$\frac{{\rm d}N_x}{{\rm d}T_A} = \eta\, N_{\rm target}\sum_{\nu_\alpha}\int_{\sqrt{\frac{m_A T_A}{2}}}^{E_\nu^{\rm max}} \mathcal{A}(T_A)\frac{{\rm d}\phi_{\nu_\alpha}}{{\rm d}E_\nu}\left(\frac{{\rm d}\sigma}{{\rm d}T_A}\right)_x {\rm d}E_\nu\,, \tag{3}$$

where ${\rm d}\phi_{\nu_\alpha}/{\rm d}E_\nu$ is the π-DAR neutrino spectrum, $N_{\rm target}$ is the number of nuclear targets in the CENNS-10 detector, and x = (SM, new) denotes the type of interaction. Here, η denotes a normalization factor given by $\eta = rN_{\rm POT}/4\pi L^2$, where L is the baseline, $N_{\rm POT}$ is the number of delivered POT, r is the number of produced neutrinos per POT and $\mathcal{A}(T_A)$ is the detector efficiency.

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SM PRECISION TESTS

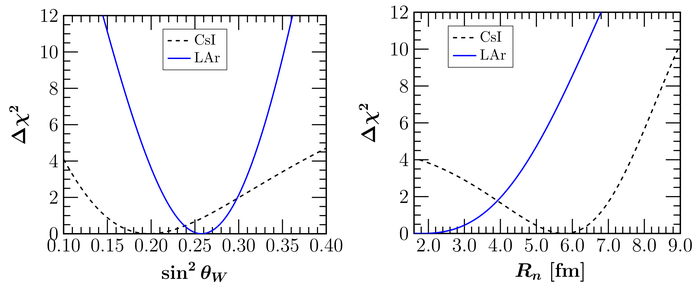
The weak mixing angle is measured with great accuracy at the Z peak. At low energies, however, the existing measurements are less precise but still very relevant given the prediction of an increase of about 3% in its value due to radiative corrections. The new measurement of the weak mixing angle, derived from the CENNS-10 data at 90% C.L. reads [3]

$$\sin^2\theta_W = 0.258^{+0.048}_{-0.050}\,. \tag{4}$$

Another very useful standard information that can be obtained from the CEνNS interaction is the neutron mean radius R_n for the Argon isotope, the determination of which can facilitate a better understanding of the CEνNS background at dark matter oriented experiments. Using CEνNS we obtained the first experimental determination of the neutron radius in Argon at 90% C.L. [3]

$$R_n < 4.33\ {\rm fm}\,. \tag{5}$$

FIGURE 2



Sensitivity on the weak mixing angle (left) and on the neutron rms radius (right) [3]. A comparison between the results obtained with LAr and CsI detectors is also shown.

ELECTROMAGNETIC NEUTRINO PROPERTIES

The non-vanishing neutrino mass implied by oscillation data points to the existence of non-trivial electromagnetic neutrino properties. Due to the helicity-violating nature of the neutrino magnetic moment cross section, there is no interference with the SM one given in Eq.(1) and yields an additive contribution of the form

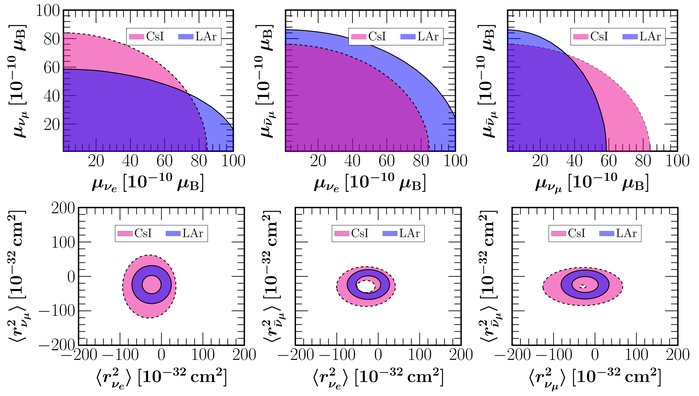
$$\left(\frac{d\sigma}{dT_A}\right)_{\rm EM} = \frac{\pi a_{\rm EM}^2 \mu_\nu^2 Z^2}{m_e^2}\left(\frac{1 - T_A/E_\nu}{T_A}\right)F_p^2(Q^2)\,. \tag{6}$$

Similarly, the impact of a non-zero neutrino charge radius to the SM cross section is simply taken as a shift on the weak mixing angle according to

$$\sin^2\theta_W \to \hat{s}_Z^2 + \frac{\sqrt{2}\pi\alpha_{\rm EM}}{3G_F}\langle r_{\nu_\alpha}^2\rangle\,. \tag{7}$$

While the current constraints are not stringent, CEνNS provides a new window to probe μ_{ν_μ} and $\langle r_{\nu_\mu}^2\rangle$

FIGURE 3



Upper panel: 90% C.L. allowed region in the parameter space of the neutrino magnetic moments ($\mu_{\nu_\alpha}, \mu_{\nu_\beta}$). Lower panel: 90% C.L. allowed region in the parameter space of neutrino charge radii ($\langle r_{\nu_\alpha}^2\rangle, \langle r_{\nu_\beta}^2\rangle$). The results are shown for different choices of neutrino flavours, with the undisplayed parameters in each case assumed to be vanishing [3]. For comparison, we show the results from the analysis of CsI and LAr data.

NON STANDARD INTERACTIONS (NSIS)

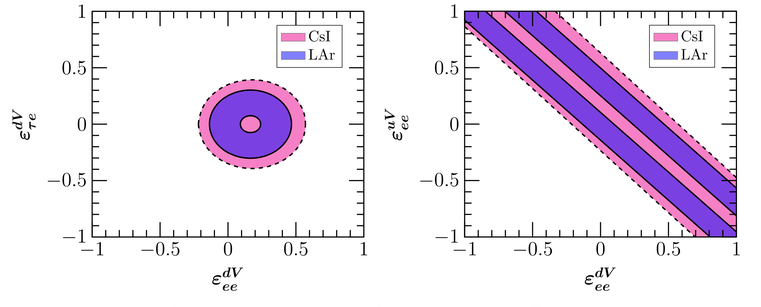
A large family of new physics models can be phenomenologically described using the formalism of NSI, that modify the neutral current SM Lagrangian through the contribution [4]

$$\mathcal{L}_{NC}^{NSI} = -2\sqrt{2}G_F\sum_{f,P,\alpha,\beta}\varepsilon_{\alpha\beta}^{fP}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu P_X f)\,. \tag{8}$$

The weak charge of the CEνNS reaction is modified according to the substitution $Q_W^V \to Q_{\rm NSI}^V$ in Eq. (1), with the NSI charge given by

$$\begin{aligned} Q_{\rm NSI}^V = &\left[\left(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}\right)ZF_p(Q^2) + \left(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV}\right)NF_n(Q^2)\right] \\ &+ \sum_\alpha\left[\left(2\varepsilon_{\alpha\beta}^{uV} + \varepsilon_{\alpha\beta}^{dV}\right)ZF_p(Q^2) + \left(\varepsilon_{\alpha\beta}^{uV} + 2\varepsilon_{\alpha\beta}^{dV}\right)NF_n(Q^2)\right]. \end{aligned} \tag{9}$$

FIGURE 4



90% C.L. allowed regions from the analysis allowing two NSI parameters at a time. The left panel considers the simultaneous presence of non-universal and flavor-changing NSI with d quark, while the right panel corresponds to the case of simultaneous non-universal NSI couplings with u and d quarks. A comparison is also given with the CsI data.

LIGHT MEDIATORS

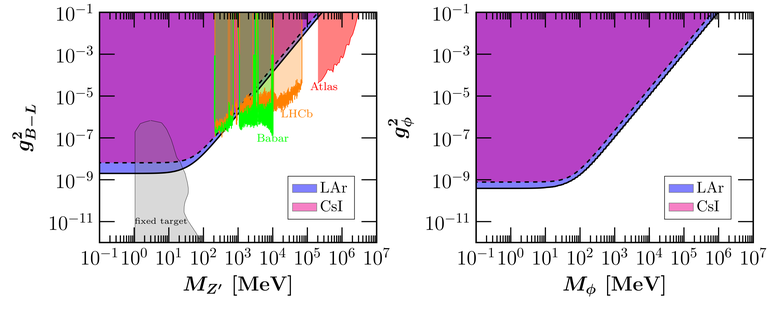
Simplified $U(1)'$ scenarios with an additional vector Z' or a scalar ϕ boson arise from [5]

$$\begin{aligned} \mathcal{L}_{\rm vector} &= Z'_\mu\left(g_{Z'}^{qV}\bar{q}\gamma^\mu q + g_{Z'}^{\nu V}\bar{\nu}_L\gamma^\mu\nu_L\right), \\ \mathcal{L}_{\rm scalar} &= \phi\left(g_\phi^{qS}\bar{q}q + g_\phi^{\nu S}\bar{\nu}_R\nu_L + {\rm H.c.}\right), \end{aligned} \tag{10}$$

with $M_{Z'}$ and M_ϕ being the mass of the vector and scalar mediators, whereas $g_{Z'}^{fV}$ and g_ϕ^{fS} are the respective vector and scalar couplings to the fermion $f = u, d, \nu$.

CEνNS searches are clearly complementary, excluding a large part of the parameter space probed by ATLAS, beam-dump experiments, LHCb and BaBar.

FIGURE 5



Excluded region at 90% C.L in the parameter space ($M_{Z'}, g^2_{B-L}$) for the vector mediator scenario (left) and (M_Φ, g^2_Φ) for the scalar mediator scenario (right), from the analysis of the recent LAr data [3]. A comparison is also given with the CsI data.

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