COHERENT constraints after the Chicago-3 quenching factor measurement

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Recently an improved quenching factor (QF) measurement for low-energy nuclear recoils in CsI[Na] has been reported in arXiv:1907.04828 [nucl-ex]. The new energy-dependent QF is characterized by a reduced systematic uncertainty and leads to a better agreement between the experimental COHERENT data and the Standard Model (SM) expectation. In this work we report updated constraints on parameters that describe the process of coherent elastic neutrino-nucleus scattering within and beyond the SM and we also present how the new QF affects their interpretation.

1. INTRODUCTION

The first observation of coherent elastic neutrino-nucleus scattering (CEνNS) was made at the COHERENT experiment using a CsI[Na] detector at the Spallation Neutron Source (SNS) [1, 2], providing a novel powerful probe for a wide-range of low-energy physics searches. This motivated a large number of theoretical studies to analyze the recorded CEνNS signal for performing precision tests of the Standard Model (SM) [3] and for investigating possible signatures of new physics beyond the SM [4–7]. The subject became of intense interest during the latest period and a plethora of extensive studies constantly appear covering a wide spectrum of new physics phenomena such as non-standard interactions (NSI) [8–14], neutrino electromagnetic properties [15–18], sterile neutrinos [19–21], CP-violation [22] and new mediators [23–26]. Nuclear and atomic effects were also explored in Refs. [27–33] which may have direct implications to the neutrino-floor [34–36] and to dark matter searches [37, 38]. Moreover, from the perspective of experimental physics, several experimental proposals aim to measure CEνNS at the SNS [39] and at reactor facilities [40–47] (for a review see Ref. [48]).

Experiments looking for CEνNS and direct dark matter signals are typically based on accurate measurements of the nuclear response and are aiming to achieve keV or sub-keV threshold capabilities depending on the nuclear target. In such measurements, most of the nuclear recoil energy is dissipated as heat and ionization, while the recorded energy for the case of scintillator detectors is in reality an electron equivalent energy whose magnitude depends on the so-called quenching factor (QF) [49]. The QF is an energy-dependent quantity that is different for a given isotope and its calibration involves neutron scattering measurements [50]. Regarding the first observation of CEνNS at COHERENT with a 14.57 kg CsI[Na] detector, the first theoretical simulations adopted an energy-independent QF of 8.78 ± 1.66% in the search region 5–30 keVnr [51]. In this work we employ the new energy-dependent QF, namely Chicago-3 [52] that resulted from a refined analysis correcting systematic effects of previous measurements i.e. Chicago-1, Chicago-2, Duke.

We first show that the new QF measurement leads to a higher consistency between the SM expectation and the experimental data, a result that is in agreement with Ref. [52]. We then revisit various constraints on conventional and exotic parameters describing the CEνNS interaction and update their status. In the first stage, we explore the sensitivity to the weak mixing angle and to the average nuclear root-mean-square (rms) radius of CsI assuming purely SM interactions. Afterwards, we re-examine the sensitivity of COHERENT to phenomenological parameters in the framework of new physics interaction channels such as, vector NSIs, neutrino magnetic moments and charge-radii as well as in simplified scenarios with novel vector-Z’ and scalar mediators. The new constraints are obtained on the basis of an improved χ² fit analysis that incorporates the aforementioned quenching factor effects. We show that the new energy-dependent QF, combined with the reduced uncertainty, leads to stronger constraints compared to previous studies.

The paper is organized as follows: In Sect. 2 we provide all necessary ingredients to accurately simulate the observed CEνNS signal, in Sect. 3 we provide the numerical results of our sensitivity analysis and update the constraints on the parameters describing the studied conventional and exotic physics phenomena and, finally, in Sect. 4 we summarize the main outcomes of our work.

2. SIMULATION OF THE COHERENT CEνNS RATE

During the CEνNS interaction, a neutrino with energy $E_\nu$ scatters off a nuclear target $(A,Z)$ with Z protons and $N = A - Z$ neutrons which in turn produces a detectable nuclear recoil $T_A$. Focusing on the COHERENT experiment, after summing appropriately over the nuclear isotopes $x = Cs, I$ and all incident neutrino flavors $\nu_\alpha = (\nu_e, \nu_\mu, \bar{\nu}_\mu)$, the number of expected CEνNS events is given by
\[
N_{\text{theor}} = \sum_{\nu_\alpha} \sum_{x = \text{Cs}, \text{I}} N_{\text{tag}}^x \int_{T_{\text{th}}}^{T_{\text{max}}} \int_{E_{\nu_{\min}}}^{E_{\nu_{\max}}} f_{\nu_\alpha}(E_\nu) A(T_A) \left( \frac{d\sigma_x}{dT_A}(E_\nu, T_A) \right)_\lambda dE_\nu dT_A,
\]

and depends on the differential cross section \((d\sigma_x/dT_A)\)_\lambda that is relevant in the framework of a neutrino interaction channel \(\lambda\) within or beyond the SM. The number of target nuclei contained in the CsI detector with mass \(m_{\text{det}} = 14.57\ \text{kg}\) is determined by the Avogadro’s Number \(N_A\) and the stoichiometric ratio \(n_\text{Nu}\) through the relation \(N_{\text{tag}}^x = \frac{m_{\text{det}} n_\text{Nu}}{A_{\text{Nu}} n_\text{Nu}} N_A\). The neutrino energy flux at the SNS consists of a prompt and a delayed beam that is adequately described by the Michel spectrum [53].

\[
\begin{align*}
&f_{\nu_\alpha}(E_\nu) = N \delta \left( E_\nu - \frac{m_e^2 - m_\mu^2}{2m_\pi} \right) \quad (\text{prompt}), \\
&f_{\nu_\alpha}(E_\nu) = N \frac{64E_\nu^2}{m_\rho^4} \left( \frac{3}{4} - \frac{E_\nu}{m_\rho} \right) \quad (\text{delayed}), \\
&f_{\nu_\alpha}(E_\nu) = N \frac{192E_\nu^2}{m_\rho^4} \left( 1 - \frac{E_\nu}{m_\rho} \right) \quad (\text{delayed}),
\end{align*}
\]

normalized to \(N = r N_{\text{POT}}/4\pi L^2\), where \(L = 19.3\ \text{m}\) is the detector distance from the SNS source, and \(r = 0.08\) denotes the number of neutrinos per flavor produced for each proton on target (POT), i.e. \(N_{\text{POT}} = 1.76 \times 10^{23}\) for a period of 308.1 days. Assuming SM interactions the differential cross section with respect to the nuclear recoil energy is expressed as [54–56]

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

where \(m_A\) denotes the nuclear mass and \(G_F\) the Fermi coupling constant. The vector \(Q_W\) weak charge is given by [57]

\[
Q_W^V = \left[ 2 (g_u^L + g_d^R) + (g_d^L + g_u^R) \right] Z + \left[ (g_u^L + g_d^R) + 2(g_d^L + g_u^R) \right] N,
\]

while the P-handed couplings of \(u\) and \(d\) quarks to the \(Z\)-boson take the form

\[
\begin{align*}
&g_u^L = \rho_{\nu_\alpha}^{NC} \left( \frac{1}{2} - \frac{2}{3} \kappa_{\nu_\alpha} \delta Z^2 \right) + \lambda^{u,L}, \\
&g_d^L = \rho_{\nu_\alpha}^{NC} \left( \frac{1}{2} + \frac{1}{3} \kappa_{\nu_\alpha} \delta Z^2 \right) + \lambda^{d,L}, \\
&g_u^R = \rho_{\nu_\alpha}^{NC} \left( \frac{2}{3} \kappa_{\nu_\alpha} \delta Z^2 \right) + \lambda^{u,R}, \\
&g_d^R = \rho_{\nu_\alpha}^{NC} \left( \frac{1}{3} \kappa_{\nu_\alpha} \delta Z^2 \right) + \lambda^{d,R}.
\end{align*}
\]

Here, \(\delta Z^2 = \sin^2 \theta_W = 0.2382\) is the weak mixing-angle and \(\rho_{\nu_\alpha}^{NC} = 1.0082\), \(\kappa_{\nu_\alpha} = 0.9972\), \(\lambda^{u,L} = -0.0031\), \(\lambda^{d,L} = -0.0025\) and \(\lambda^{u,R} = 2\lambda^{u,R} = 3.7 \times 10^{-5}\) are the radiative corrections [58]. Due to their tiny contributions to the CEνNS rate, axial-vector interactions, incoherent interactions as well as contributions due to the Sodium dopant of the CsI[Na] detector are neglected.

The main source of theoretical uncertainty in the SM CEνNS process arises from the nuclear form factor that takes into account the finite nuclear size and depends on the variation of the momentum transfer \(Q^2 = 2m_A T_A\) [31]. Following the COHERENT Collaboration, in this work we adopt the Klein-Nystrand (KN) form factor parametrized as [59]

\[
F_{\text{KN}} = 3 \frac{J_1(QR_A)}{QR_A} \left[ 1 + (Qa_k)^2 \right]^{-1},
\]

where \(a_k = 0.7\ \text{fm}\) is the range of the Yukawa potential (over a Woods-Saxon distribution) in the hard sphere approximation with radius \(R_A = 1.23 \times A^{1/3}\). We note that regarding the old QF, slight differences from the corresponding results of Ref. [16] throughout the paper are due to the adoption of the KN form factor, the different neutrino-energy distribution considered and the different value of the weak mixing angle.

For a scintillation-based experiment, the measured quantity is the number of photoelectrons (PE) denoted here as \(n_{\text{PE}}\). To account for this mechanism, the CEνNS differential rate in events vs. nuclear recoil energy gets converted to an equivalent differential rate in events vs. electron recoil energy through the application of the QF function, \(Q_f(T_A)\), and that in turn gets converted to a PE spectrum via the light yield \(Y = 13.348\ \text{PE/keV}_{ee}\) measured for electron recoils, as

\[
n_{\text{PE}} = Q_f(T_A) L y T_A.
\]

In Eq.(1), the acceptance efficiency of the CsI detector is taken into account which in terms of the photoelectron content of the signal reads [2]

\[
A(n_{\text{PE}}) = \frac{k_1}{1 + e^{-k_2(n_{\text{PE}} - x_0)}} \Theta(n_{\text{PE}}),
\]

with \(k_1 = 0.6655\), \(k_2 = 0.4942\), \(x_0 = 10.8507\) and the modified Heaviside function

\[
\Theta(n_{\text{PE}}) = \begin{cases} 0 & n_{\text{PE}} < 5 \\ 0.5 & 5 \leq n_{\text{PE}} < 6 \\ 1 & n_{\text{PE}} \geq 6. 
\end{cases}
\]

Up to now, previous analyses adopted the energy-independent QF of 8.78 ± 1.66%, recommended by the

\footnote{Note that the efficiency function is instrumental and does not depend on the QF.}
COHERENT Collaboration. This QF carried a large uncertainty of 18.9%. In the present work we consider
the new energy-dependent QF which came out of the re-
ined Chicago-3 measurement with a reduced uncertainty
by about a factor-of-four at 5.8% (for more details see
Ref. [52]). The old vs. new QF measurements are repro-
duced from FIG.1 of Ref. [52] and are illustrated in the
left panel of Fig. 1 within $1\sigma$ boundaries. As can be seen,
the new QF is smaller within most of the recoil energy
range of interest and, therefore, predicts a lower number
of events. In agreement with Ref. [52], within the SM
the new calculation gives a theoretical value of $\sim 138$
events as compared to the $\sim 173$ events corresponding
to the old QF. At this point, it is rather important to
emphasize that a substantial agreement is now reached
with the 134 events observed in Ref. [1]. The correspond-
ing results are compared in the right panel of Fig. 1 as a
function of PE bins.

3. NUMERICAL RESULTS

In the present study, we perform a sensitivity analysis
for the parameter set $S$ in question (see below), that fol-
lows from a $\chi^2(S)$ fit that is relevant for the CsI detector
at the COHERENT experiment and reads

$$\chi^2(S) = \min_{a_1, a_2} \left[ \frac{N_{\text{meas}} - N_{\text{theor}}(S)[1 + a_1] - B_{0n}[1 + a_2]}{\sqrt{N_{\text{meas}} + B_{0n} + 2B_{ss}}} \right]^2 + \left( \frac{a_1}{\sigma_{a_1}} \right)^2 + \left( \frac{a_2}{\sigma_{a_2}} \right)^2, $$  \hspace{1cm} (10)

where the observed signal is $N_{\text{meas}} = 142$ events (547
beam ON minus 405 AC, see Ref. [1]) for PE in the
interval $6 \leq n_{\text{PE}} \leq 30$, while $B_{0n} = 6$ stands for the
beam-on prompt neutron background and $B_{ss} = 405$
denotes the steady-state background events. In Eq.(10),
a_1$ and $a_2$ are the corresponding systematic parameters
with fractional uncertainties $\sigma_{a_1} = 13.5\%$ (5% from signal
acceptance determination, 5% from form factor choice,
10% from neutrino flux and 5.8% from the new QF) and
$\sigma_{a_2} = 25\%$. Note that compared to $\sigma_{a_1} = 28\%$ \textsuperscript{2} given

\textsuperscript{2} This uncertainty was dominated by the large old QF uncertainty.

in Ref. [1] and adopted by all similar studies up to now,
the fractional uncertainty considered here is reduced by
about a factor-of-two [52]. This is also in agreement with
estimations of previous studies addressing possible future
experimental setups [17, 27, 31] and will have a direct im-
pact on the updated constraints presented below.

3.1. SM precision tests and nuclear physics

Assuming purely SM interactions, we first extract the
new sensitivity to the weak mixing angle that arises from
the new QF measurement. To this end, we evaluate
the $\chi^2(\sin^2 \theta_W)$ function and perform a sensitivity fit by varying around the central value $\sin^2 \theta_W = 0.2382$. The resulted sensitivity profiles are depicted in the left panel of Fig. 2. A comparison with the corresponding result assuming the old energy-independent QF is also shown. Indeed, this new calculation leads to reasonably improved results. From the fit we find the following constraints at 90% C.L.

$$\begin{align*}
\sin^2 \theta_W &= 0.197_{-0.080}^{+0.128} \text{ (old QF)}, \\
\sin^2 \theta_W &= 0.237_{-0.078}^{+0.098} \text{ (new QF)}. \tag{11}
\end{align*}$$

Evaluating the 1σ bands $\delta s^2_W$ according to the definition given in Ref. [15], we find the values $\delta s^2_W = (0.058, 0.047)$ for the (old, new) QF case which yield the corresponding percentage uncertainties $\delta s^2_W/\sin^2 \theta_W$ of (30%, 20%).

We then, devote an effort to explore the sensitivity to the nuclear rms radius that follows from the recent COHERENT measurement. To this purpose, we employ the refined QF resulting from the Chicago-3 dataset, while in this case we consider the Helm form factor [60]

$$F_{\text{Helm}}(Q^2) = 3j_1(QR_0) q R_0 e^{-\left(Q^2\right)/2},$$

where $j_1(x)$ is the spherical Bessel function of the first kind. Here, $\langle R^2_n \rangle^{1/2} = \sqrt{\frac{1}{2} R_0^2 + 3s^2}$ is the nuclear rms radius, $R_0 = 1.23 A^{1/3}$ fm is the diffraction radius and $s = 0.9$ fm quantifies the surface thickness (for more details see Refs. [30, 31]). The resulted sensitivity profile is presented in the right panel of the Fig. 2, showing that the constraints are now stronger than previously reported [27, 28, 31]. In particular at 90% C.L. we find the best fits

$$\begin{align*}
\langle R^{2}_{n} \rangle^{1/2} &= 5.8^{+1.5}_{-2.6} \text{ fm (old QF)}, \\
\langle R^{2}_{n} \rangle^{1/2} &= 5.1^{+1.3}_{-1.5} \text{ fm (new QF)}. \tag{13}
\end{align*}$$

In a similar manner, within 1σ error we find the bands $\delta \langle R^{2}_{n} \rangle^{1/2} = (1.11, 0.82)$ and the corresponding percentage uncertainties (19%, 16%) for the (old, new) QF measurement. We finally stress that the latter results remain essentially the same when considering the Klein-Nystrand form factor.

3.2. Non-standard interactions

Non-standard interactions has been a popular subject of extensive research during the last 15 years, with interesting applications in neutrino oscillations and low-energy neutrino physics (for a review see Refs. [61, 62]). For a neutrino with flavor $\alpha = \{e, \mu, \tau\}$ and a quark $q = \{u, d\}$, the vector-type NSI contributions that arise due to non-universal (NU) flavor-preserving and flavor-changing (FC) interactions are described in the NSI weak charge [63, 64]

$$\begin{align*}
Q_{\text{NSI}}^V &= (2e_{\alpha\alpha}^u V + \epsilon_{\alpha\beta}^d V + \eta_p) Z + (\epsilon_{\alpha\alpha}^e V + 2\epsilon_{\alpha\beta}^d V) N \\
+ \sum_{\alpha, \beta} [(2e_{\alpha\beta}^u V + \epsilon_{\alpha\beta}^d V) Z + (\epsilon_{\alpha\beta}^e V + 2\epsilon_{\alpha\beta}^d V) N]. \tag{14}
\end{align*}$$

In the context of NSI the expected CEνNS rate is modified according to the substitution $Q^V_W \rightarrow Q^V_{\text{NSI}}$ in the SM differential cross section of Eq.(3).

Assuming a single non-vanishing NSI parameter at a time, Fig. 3 illustrates the obtained sensitivity for the NU
\(\Delta \chi^2\) profiles for the NU NSIs from the analysis of the COHERENT data. A comparison of the obtained sensitivity using the old vs. the new QF is also shown.

FIG. 4: Allowed regions in the NU NSIs parameter space obtained from the analysis of the COHERENT data, for the old vs. the new QF measurement.

\(\epsilon_{ee}^{qV}\) couplings in the left (right) panel, while a useful comparison is also given for the case of the old QF. It becomes evident the impact of the new QF measurement on NSI constraints. The left and right panels of Fig. 4 show the allowed regions at 90\% C.L. in the \((\epsilon_{ee}^{dV}, \epsilon_{ee}^{uV})\) and the \((\epsilon_{\mu\mu}^{dV}, \epsilon_{\mu\mu}^{uV})\) parameter space respectively. We see that the bounds are now more restrictive than the corresponding results using the old QF.

3.3. Electromagnetic neutrino interactions

In this subsection we are interested to explore the possibility of probing non-trivial neutrino electromagnetic (EM) properties [65] and to revisit existing constraints from CE\(\nu\)NS [16]. The two main phenomenological parameters that arise in the framework of EM neutrino interactions are the neutrino magnetic moment and the neutrino charge-radius. For completeness, we mention that in the simplest Majorana neutrino case, the neutrino
magnetic moment $\mu_\nu$ is in reality expressed in terms of the neutrino transition magnetic moments $\Lambda_i$ of the neutrino magnetic moment matrix [66, 67] while constraints have been recently extracted from neutrino-electron scattering [68] and CE$\nu$NS [17]. Here, for simplicity we consider the effective neutrino magnetic moment in the helicity-violating EM cross section [69]

$$\left( \frac{d\sigma}{dT_A} \right)_{\text{EM}} = \frac{\pi a^2_{\text{EM}} \mu_\nu^2 Z^2}{m_e^2} \left( 1 - \frac{T_A/E_\nu}{T_A} \right) F^2(Q^2).$$

In Fig. 5 we present the updated constraint on $\mu_\nu$ from our analysis with the new QF which is also compared to the corresponding one that comes out from the old QF. The obtained upper limits at 90% C.L. read

$$\mu_\nu < 3.1 \times 10^{-9} \mu_B \quad (\text{old QF}) ,$$

$$\mu_\nu < 2.6 \times 10^{-9} \mu_B \quad (\text{new QF}) .$$

From the same plot it can be deduced that this difference is more pronounced at 99% C.L.

For a flavor neutrino $\nu_\alpha$ the associated neutrino charge radius $\langle r_{\nu_\alpha}^2 \rangle$ is another interesting phenomenological quantity which arises from the helicity-conserving charge form factor of the EM neutrino current [70]. The latter leads to a shift of the weak mixing angle as follows [71]

$$\sin^2 \theta_W \rightarrow \sin^2 \theta_W + \frac{\sqrt{2} \pi a_{\text{EM}}}{3 G_F} \langle r_{\nu_\alpha}^2 \rangle .$$

Note for the case of antineutrinos it holds $\langle r_{\bar{\nu}_\alpha}^2 \rangle = -\langle r_{\nu_\alpha}^2 \rangle$ [72]. We stress that, in Ref. [16] the shift considered was twice as large and also the sign flip was not taken into account. Here we follow the justification made by Ref. [72]. Neglecting transition charge radii and varying one parameter at a time, Fig. 6 shows the $\chi^2$ profiles of the neutrino charge radii $\langle r_{\nu_\alpha}^2 \rangle$ associated to the respective SNS neutrino flux, where the left (right) panels correspond to the old (new) QF measurement. The obtained constraints differ slightly due to the old vs. new QF data. The only noticeable difference is that by employing the new QF in the case of the prompt $\bar{\nu}_\mu$ beam, the resulted constraint on $\langle r_{\bar{\nu}_\mu}^2 \rangle$ is separated into two distinct regions at 90% C.L. It is now worthwhile to explore the simultaneous constraints that can be obtained. Figure 7 presents the allowed regions at 90% C.L. in the $(\langle r_{\nu_\alpha}^2 \rangle, \langle r_{\bar{\nu}_\alpha}^2 \rangle)$ parameter space. As expected the allowed parameter space in all cases is more restricted using the new QF data. We furthermore stress that due to the sign flip with respect to the neutrino vs. antineutrino charge radius, only the regions involving the prompt beam appear with a hole.

### 3.4. Simplified scenarios with light mediators

In addition to the NSIs discussed previously in Subsect. 3.3.2, we are now interested in simplified scenarios where the NSI is generated due to the presence of novel mediators.

In the first step we explore the case where the CE$\nu$NS rate is enhanced from contributions due to a vector $Z'$ mediator with mass $M_{Z'}$. The relevant cross section takes the form [73]

$$\left( \frac{d\sigma}{dT_A} \right)_{\text{SM}+Z'} = \mathcal{G}_{Z'}^2(T_A, g_{Z'}, M_{Z'}) \left( \frac{d\sigma}{dT_A} \right)_{\text{SM}} ,$$

with the $Z'$ factor defined as

$$\mathcal{G}_{Z'} = 1 + \frac{1}{\sqrt{2} G_F} \left( \frac{Q_{Z'}}{Q_{W}} \right) \frac{g_{Z'}^{\nu\nu}}{2M_{Z'} N + M_{Z'}^2} .$$

In the above expression, in order to reduce the number of model parameters, we consider the generalized coupling $g_{Z'}^\nu = g_{Z'}^{\nu\nu} Q_{Z'}/3 A$, that is expressed in terms of the vector $\nu_\alpha$-$Z'$ coupling times the respective vector charge $Q_{Z'}^{\nu\nu}$, under the assumption of universal quark-Z' couplings (for more details see Ref. [16]).

Concentrating our attention to the case of a new scalar boson $\phi$ mediating the CE$\nu$NS process, the cross section takes the form [74]

$$\left( \frac{d\sigma}{dT_A} \right)_{\text{scalar}} = \frac{G_{\phi}^2 m_\phi^2}{4 \pi} \frac{G_{Z'}^2 M_\phi^4 T_A}{E_\nu^2 \left( 2m_\phi T_A + M_{Z'}^2 \right)^2} F^2(T_A) ,$$

with the corresponding scalar factor being

$$\mathcal{G}_\phi = \frac{g_\phi^{\nu\nu}}{G_F M_\phi^2} .$$
In the same spirit of the discussion made above, for the sake of simplification our calculations involve the generalized scalar coupling $g_{\phi}^2 = g_{\phi S}^2 Q_{\phi} / (14A + 1.1Z)$.

The exclusion regions in the parameter space $(M_{Z'}, g_{Z'}^2)$ and $(M_{\phi}, g_{\phi}^2)$ for the vector and scalar scenarios respectively, are obtained from a two parameter analysis of the COHERENT data. For both old and new QF data the results are presented at 90% C.L. in the left (right) panel of Fig. 8 for vector (scalar) mediators. As in all previous cases, from this plot we conclude that the new QF data leads to generally more stringent bounds.

3 This result derives from the nuclear charge related to the scalar boson exchange see Ref. [16].

4. CONCLUSIONS

Focusing on the COHERENT experiment we have re-examined the results implied from coherent elastic neutrino-nucleus scattering (CEνNS) in the light of a new quenching factor (QF) measurement [52]. By using the new QF data we came out with improved constraints regarding all the cases analyzed in this work. A full summary is given in Table I. At first we have presented updated constraints focusing on important Standard Model (SM) parameters namely, the weak mixing angle and the average nuclear rms radius of CsI, and we have explicitly demonstrated the level of improvement. We have then concentrated on interesting phenomenological parameters beyond the SM and presented updated constraints...
FIG. 8: Left: exclusion curves in the $(g_Z^2, M_{Z'})$ parameter space and Right: in the $(g_\Phi^2, M_\Phi)$ parameter space from the analysis of the COHERENT data. The results are shown for the old and the new QF measurement.

| parameter          | old QF             | new QF             |
|--------------------|--------------------|--------------------|
| $\sin^2\theta_W$   | 0.117 – 0.325      | 0.189 – 0.282      |
| $\langle R_V^2 \rangle^{1/2}$ | -0.13 – 0.54 | -0.11 – 0.53 |
| $\epsilon_{\nu\nu}$ | -0.12 – 0.49      | -0.10 – 0.47       |
| $\epsilon_{\nu\mu}$ | -0.07 – 0.13 & 0.28 – 0.49 | -0.06 – 0.08 & 0.33 – 0.48 |
| $\epsilon_{\mu\mu}$ | -0.06 – 0.11 & 0.25 – 0.44 | -0.06 – 0.07 & 0.30 – 0.43 |
| $\mu_\nu$          | 31                 | 26                 |
| $\langle r_{\nu_e}^2 \rangle$ | -77 – 19 | -75 – 16 |
| $\langle r_{\mu_e}^2 \rangle$ | -91 – 32 | -92 – 33 |
| $\langle r_{\bar{\nu}_e}^2 \rangle$ | -13 – 72 | -11 – 16 & 43 – 70 |

TABLE I: Summary of constraints at 90% C.L. in the present work. The results are extracted assuming the old and the new QF data. The nuclear rms radius is in units of fm, the effective neutrino magnetic moment in $10^{-10} \, \mu_B$ and the neutrino charge radius in $10^{-32} \, \text{cm}^2$.

for non-universal NSIs as well as for electromagnetic neutrino properties including the effective neutrino magnetic moment and the neutrino charge radius. Finally we have revisited the sensitivity of COHERENT in the framework of simplified scenarios involving massive vector and scalar mediators. We conclude that a substantial improvement on SM parameters is reached, while the improvement of beyond the SM physics constraints is also evident.

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