PROCEEDINGS OF SCIENCE

EFT analysis of CEνNS data

Víctor Bresó-Pla[a,*]

[a] *Departament de Física Teòrica, IFIC, Universitat de València - CSIC, Apt. Correus 22085, E-46071 València, Spain*

E-mail: victor.breso@ific.uv.es

We examine the latest measurements coming from the COHERENT experiment within a fully realized effecyive field theory framework. To do so, we put forward a formalism which for the first time models correctly within the quantum field theory environment the interplay between production and detection. We use it to perform a complete phenomenological analysis for coherent elastic neutrino-nuclei scattering data measured at the COHERENT experiment on Argon and Cesium-Iodium nuclei considering as observables not only the total number of events but also the recoil energy and timing distributions.

International Conference on High Energy Physics - ICHEP 2022
6th-13th July 2022
Bologna, Italy

*Speaker

PoS(ICHEP2022)579

1. Neutrino oscillation observables in quantum field theory

The main purpose of this work is to properly formulate neutrino oscillation observables within the quantum field theory (QFT) framework, and then apply it to perform a complete phenomenological analysis on real data. To fulfill the first step, we will start by characterizing the oscillation observables through an inseparable combination of three phenomena, following closely the study presented in [1]. Examining them separately, first we have the neutrino production process, generally described through $S \to X_\alpha \nu_k$, where S is the neutrino source, X_α is a one- or more-body final state that contains a charged lepton $\ell_\alpha = e, \mu, \tau$, and ν_k is a neutrino-mass eigenstate. Then, we have the neutrino oscillation, wherein the produced neutrinos propagate a distance L until they are detected. The third phenomenon is the neutrino detection process $\nu_k T \to \nu_j Y$, where j is again a mass index, T is the initial state of the neutrino target prior to its arrival and Y is again a one- or more-body final states. We are going to be focusing on final states containing one neutrino and no charged leptons because we are interested in examining detection processes mediated by neutral current (NC) interactions. The case where the detection is carried out through a charged current (CC) interaction has already been studied in detail in [1].

Taking all these ingredients into account, the key to integrate the oscillation observables into the QFT framework is the consideration of the neutrino production and detection processes not as separate entities, but as constituents of a single process. We can enforce that condition by combining the pieces in the following way

$$ST \to X_\alpha Y \nu_j \ , \tag{1}$$

where the ν_k neutrino will be considered just as an intermediate particle in the amplitude. Using this as a starting point, it can be proven that the differential event rate per target particle $R_\alpha \equiv \frac{dN_\alpha}{N_T dt dE_\nu}$ is given by

$$R_\alpha = \frac{N_S}{32\pi L^2 m_S m_T E_\nu} \sum_{j,k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} \int d\Pi_{P'} \mathcal{M}^P_{\alpha k} \bar{\mathcal{M}}^P_{\alpha l} \int d\Pi_{D'} \mathcal{M}^D_{jk} \bar{\mathcal{M}}^D_{jl} \ , \tag{2}$$

where complex conjugation is denoted with a bar, N_S is the number of source particles, $m_{S,T}$ are the masses of the source and target particles respectively and $\Delta m^2_{kl} \equiv m^2_k - m^2_l$ is the mass squared difference between neutrino mass eigenstates, which appears in the formula through the $e^{-i\, L\Delta m^2_{kl}/(2E_\nu)}$ oscillatory factor. Additionally, $\mathcal{M}^{\rm P}_{\alpha k} \equiv \mathcal{M}(S \to X_\alpha \nu_k)$ and $\mathcal{M}^{\rm D}_{jk} \equiv \mathcal{M}(\nu_k T \to \nu_j Y)$ are the production and detection amplitudes, which encode the fundamental physics taking place at both those contexts and which can be calculated in terms of nuclear and hadronic parameters. These quantities can be made to include whichever non-standard interactions (NSIs) we may want inside our observable.

The phase space elements for the production and detection processes, $d\Pi_P$ and $d\Pi_D$, are defined as: $d\Pi \equiv \frac{d^3k_1}{(2\pi)^3 2E_1} \dots \frac{d^3k_n}{(2\pi)^3 2E_n} (2\pi)^4 \delta^4(\mathcal{P} - \sum k_i)$, where k_i are the 4-momenta of the final states and $\mathcal{P}$ is the total 4-momentum of the initial state, which includes the neutrino phase space, and we define $d\Pi_P = d\Pi'_P dE_\nu$. The integral sign involves both integration as well as sum and averaging over all unobserved degrees of freedom.

This result differs from the one obtained in Ref. [1] because in a NC interaction we will have no information about the neutrino final mass eigenstate. As a consequence, we need to sum over the corresponding mass index j to properly define the observable.

When comparing our formalism with a "factorized" approach where this specific interplay between the production and detection processes is dismissed, such a description will suffice in most NP setups, but when flavour violating couplings are included and new physics is assumed to be present at production and detection simultaneously it will lead to non-physical predictions.

2. Coherent elastic neutrino-nuclei scattering in the COHERENT experiment

We now move on to try exploiting this formalism to aid us in the phenomenological analysis of data coming from neutrino experiments. In particular, we will focus on the COHERENT experiment, which is an experiment built to measure coherent elastic neutrino-nucleus scattering (CEνNS). This interaction takes place when a neutrino scatters elastically with the whole nucleus, and it is a very attractive outlet to study neutrino interactions because its cross section scales with the number of nuclear constituents squared A^2.

The COHERENT experiment has been the first to measure this type of interactions. Consisting of a Spallation Neutron Source (SNS) that produces a neutrino flux made to interact with nuclear targets, it has been able to register the process for cesium/iodine [2, 3] and argon [4] nuclei. The neutrino fluxes are produced by pion decay at rest $\pi^+ \to \mu^+\nu_\mu$ and the subsequent three-body decay of the muon $\mu^+ \to \bar{\nu}_\mu e^+ \nu_e$. Hence, the detector receives a monoenergetic prompt flux of ν_μ followed by a delayed flux of $\bar{\nu}_\mu$ and ν_e.

Given this experimental setup, it is clear that we can apply our formalism to describe the observables that COHERENT measures. There are only two modifications that we need to consider for our master formula (2). First, given the low baseline of the experiment, we can set the oscillation length L to zero and neglect the effects coming from neutrino oscillations. Second, we will need to model how the number of source particles N_S changes over time in order to capture properly the time dependence of the observable.

Using the information coming from the three datasets provided by COHERENT, our plan is to use our framework to extract limits for the NP parameters that may be linked to the observables measured at COHERENT. We will do so not only looking at the total number of events measured in each instance, but also at their decomposition in recoil energy and timing distributions. These additional inputs will let us to access a larger multiplicity of NP parameter combinations, which in turn will allow us to confidently analyze scenarios where multiple BSM contributions are present at the same time.

3. New physics parameter space and early results

The next step in our analysis is to quantitatively identify the new physics (NP) effects that may be present in these observables. To that end, we will be working with effective field theories (EFTs). EFTs have proven themselves to be an excellent tool for analyzing precision measurements in beyond the SM (BSM) physics searches, providing an organized and minimally specific characterization for NP contributions through high-dimensional effective operators. Among them, the Standard Model Effective Field Theory (SMEFT) [6, 7] is specially well suited for NP searches, since it only assumes the existence of a large gap between the electroweak scale and the BSM degrees of freedom.

This framework is very well suited to analyze NP effects that lie outside of the SM scale, but since CEνNS is a low energy process, it will be better to work with the Weak Effective Field Theory (WEFT) instead [8]. This EFT can be accessed from the SMEFT by integrating out electroweak gauge bosons, the Higgs boson and the top quark, and it is more convenient for this context because it will be able to capture NP contributions that may lie below the electroweak scale.

Out of the WEFT lagrangian, we will focus on the lepton-number-conserving parts that are relevant for COHERENT physics, namely the NC interactions mediating CEνNS and the CC interactions involved in pion and muon decay. Let us first present the NC interactions between neutrinos and quarks:

$$\mathcal{L}_{\rm WEFT} \subset -\frac{2}{v^2}\left\{[g_V^{qq}+\epsilon_V^{qq}]_{\alpha\beta}\,(\bar q\gamma^\mu q)\left(\bar\nu_\alpha\gamma_\mu P_L\nu_\beta\right)+[g_A^{qq}+\epsilon_A^{qq}]_{\alpha\beta}\left(\bar q\gamma^\mu\gamma^5 q\right)\left(\bar\nu_\alpha\gamma_\mu P_L\nu_\beta\right)\right\}, \tag{3}$$

where $P_{L,R} = \left(1\mp\gamma^5\right)/2$ are the chirality projection operators, the quarks q are summed over their possible flavours and the $\epsilon_{V,A}^{qq}$ matrices are hermitian (in the neutrino indices), standing as corrections to the SM couplings $[g_V^{qq}]_{\alpha\beta}$. COHERENT sensitivity to axial-vector interactions is very small due to the spinless status of the target nuclei, so we can neglect it and stick to just with the vector Wilson coefficients.

Next, let us introduce the interaction terms that mediate neutrino production at COHERENT. Starting with pion decay

$$\begin{aligned}\mathcal{L}_{\rm WEFT} \subset -\frac{2V_{ud}}{v^2}\Big\{&[1+\epsilon_L^{ud}]_{\alpha\beta}\,(\bar u\gamma^\mu P_L d)\left(\bar l_\alpha\gamma_\mu P_L\nu_\beta\right)+[\epsilon_R^{ud}]_{\alpha\beta}\,(\bar u\gamma^\mu P_R d)\left(\bar l_\alpha\gamma_\mu P_L\nu_\beta\right)+\\ &+\frac{1}{2}\left[\epsilon_S^{ud}\right]_{\alpha\beta}(\bar u d)\left(\bar l_\alpha P_L\nu_\beta\right)-\frac{1}{2}\left[\epsilon_P^{ud}\right]_{\alpha\beta}\left(\bar u\gamma^5 d\right)\left(\bar l_\alpha P_L\nu_\beta\right)+\\ &+\frac{1}{4}\left[\epsilon_T^{ud}\right]_{\alpha\beta}(\bar u\sigma^{\mu\nu}P_L d)\left(\bar l_\alpha\sigma_{\mu\nu}P_L\nu_\beta\right)\Big\},\end{aligned} \tag{4}$$

where V_{ud} is the (1,1) element of the Cabibbo–Kobayashi–Maskawa (CKM) matrix. Last, the WEFT interactions describing muon decay are:

$$\mathcal{L}_{\rm WEFT} \subset -\frac{2}{v^2}\left\{\left(\delta_{\alpha a}\delta_{\beta b}+[\rho_L]_{a\alpha\beta b}\right)\left(\bar l_a\gamma^\mu P_L\nu_\alpha\right)\left(\bar\nu_\beta\gamma_\mu P_L l_b\right)-2\,[\rho_R]_{a\alpha\beta b}\left(\bar l_a P_L\nu_\alpha\right)\left(\bar\nu_\beta P_R l_b\right)\right\}, \tag{5}$$

where $[\rho_L]^*_{a\alpha\beta b} = [\rho_L]_{b\beta\alpha a}$ so that the Lagrangian is hermitian. In all these expressions particle fields are in the basis where their kinetic and mass terms are diagonal except for the neutrino fields ν_α which are taken in the flavour basis.

Finally, v denotes the vacuum expectation value (VEV) of the Higgs doublet (in the presence of WEFT operators), which is related with the phenomenological value of the Fermi constant G_F as follows

$$G_F = \frac{1}{\sqrt{2}v^2}\left(1+\frac{\delta G_F}{G_F}\right), \tag{6}$$

where $G_F \approx 1.166\times10^{-5}\ \mathrm{GeV}^{-2}$ is the Fermi constant extracted from muon decay using the SM expression and $(\delta G_F)/G_F$ contains the nonstandard contributions to muon decay, which in our case are captured by the $[\rho_L]_{\mu\alpha\beta e}$ and $[\rho_R]_{\mu\alpha\beta e}$ couplings in Eq. (5). Likewise one should take into account that NP effects in Eq. (4) affect the extraction of the CKM factor V_{ud}. This contribution

PoS(ICHEP2022)579

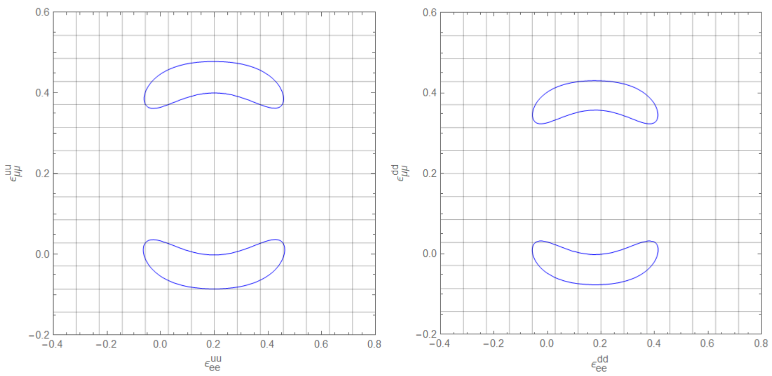

Figure 1: 90% CL allowed regions for the flavour diagonal NP couplings ϵ_{ll}^{qq} with up (left) and down quarks (right) in the nonlinear regime based on the CsI-1, CsI-2 and Ar datasets. For these bounds all NP couplings except the ones displayed in the figures are set to zero.

will be captured through the introduction of the SM decay widths for the pion and the muon in our expressions. The use of these inputs will render much of the NP contributions coming from production heavily suppressed, leaving the indirect contributions coming from $(\delta G_F)/G_F$ at the detection piece as the main probing point for the production parameters. Separately, one should also be considering the indirect NP effects that will enter the observable through the weak angle input present in the SM interaction terms in Eq. (3).

Once we use the WEFT formalism to derive the production and detection amplitudes, we are ready to start extracting limits for the WEFT Wilson coefficients. We will do so by constructing fully fledged theoretical predictions within our NP framework for the observables measured at COHERENT, featuring a complete implementation of resolution and detector effects, and comparing them to the corresponding data via a Poissonian χ^2 test statistic.

Making a small selection of our preliminary results, Fig. 1 displays the allowed regions in parameter space when only some select pairs of detection parameters are allowed to be non-zero. This plot can be compared to Fig. 3 in Ref. [5], and it illustrates that our approach is at least as competitive as the current methods that are used in the literature.

4. Conclusions

In this work, we have developed an EFT based formalism for the description of NP affecting neutrino oscillation observables which involve NC interactions at detection. This setup allows us to understand the ultraviolet meaning and limitations of the production and detection NSIs, include NP affecting the SM input and connect with specific NP models or interactions such as leptoquarks.

We have successfully applied this framework for the description of BSM physics at the COHERENT experiment, recovering previous results and highlighting the impact of NP coming from production and its interplay with the NP couplings linked to detection. In our final work, we expect to attain results which are able to compete and in some instances improve upon the previous analyses that have been made in this matter [5, 9–12]. Additionally, we also intend to connect the limits within the WEFT with the corresponding bounds for SMEFT parameters and integrate them into the electroweak global fit [13, 14].

References

[1] A. Falkowski, M. González-Alonso, Z. Tabrizi, *Consistent QFT description of non-standard neutrino interactions*, *JHEP* **11** (2020) 048 [hep-ph/1910.02971].

[2] D. Akimov and others for the COHERENT collaboration, *General COHERENT constraints on neutrino nonstandard interactions*, *Phys. Rev. D* **101** (2020) 35–39 [hep-ph/1909.00466].

[3] D. Akimov and others for the COHERENT collaboration, *Measurement of the Coherent Elastic Neutrino-Nucleus Scattering Cross Section on CsI by COHERENT*, *Phys. Rev. D* **129** (2022) 8, 081801 [hep-ex/2110.07730].

[4] D. Akimov and others for the COHERENT collaboration, *First Measurement of Coherent Elastic Neutrino-Nucleus Scattering on Argon*, *Phys. Rev. Lett.* **126** (2021) 1, 012002 [nucl-ex/2003.10630].

[5] P. Coloma, I. Esteban, M. C. Gonzalez-Garcia, L. Larizgoitia, F. Monrabal, S. Palomares-Ruiz, *Bounds on new physics with data of the Dresden-II reactor experiment and COHERENT*, *JHEP* **05** (2022) 037 [hep-ph/2202.10829].

[6] C. N. Leung, S. T. Love, S. Rao, *Low-energy manifestations of a new interactions scale: Operator analysis*, *Z. Phys. C - Particles and Fields* **31** (1986) 433-437.

[7] W. Buchmüller, D. Wyler, *Effective lagrangian analysis of new interactions and flavour conservation*, *Nuclear Physics B* **268** (1986) 3, 621-653.

[8] V. Cirigliano, J. Jenkins, M. Gonzalez-Alonso, *Semileptonic decays of light quarks beyond the Standard Model*, *Nuclear Physics B* **830** (2010) 3, 95–115 [hep-ph/0908.1754].

[9] P. Coloma, I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, *Improved global fit to Non-Standard neutrino Interactions using COHERENT energy and timing data*, *JHEP* **02** (2020) 023 [hep-ph/1911.09109].

[10] C. Giunti, *General COHERENT constraints on neutrino nonstandard interactions*, *Phys. Rev. D* **101** (2020) 3, 035039 [hep-ph/1909.00466].

[11] O. G. Miranda, D. K. Papoulias, G. Sanchez-Garcia, O. Sanders, M. Tórtola, J. W. F. Valle, *Implications of the first detection of coherent elastic neutrino-nucleus scattering (CEvNS) with Liquid Argon*, *JHEP* **05** (2020) 130 [hep-ph/2003.12050].

[12] M. Atzori Corona, M. Cadeddu, N. Cargioli, F. Dordei, C. Giunti, Y. F. Li, C. A. Ternes, Y. Y. Zhang, *Impact of the Dresden-II and COHERENT neutrino scattering data on neutrino electromagnetic properties and electroweak physics*, *JHEP* **09** (2022) 164 [hep-ph/2205.09484].

[13] Z. Han, W. Skiba, *Effective theory analysis of precision electroweak data*, *Phys. Rev. D* **71** (2005) 075009 [hep-ph/0412166].

[14] V. Bresó-Pla, A. Falkowski, M. González-Alonso A_{FB} *in the SMEFT: precision Z physics at the LHC*, *JHEP* **08** (2021) 021 [hep-ph/2103.12074].

PoS(ICHEP2022)579