Reactor Neutrinos on Model Independent New Physics Studies with CEvNS

Yong Du（杜勇）

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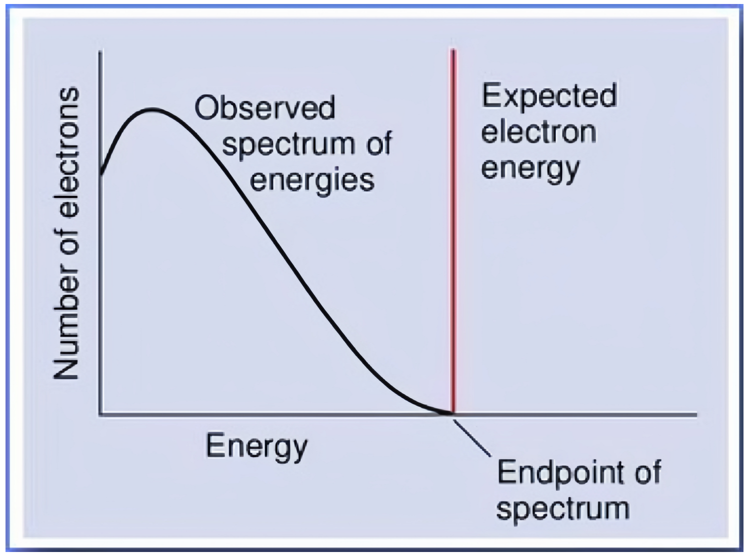
Dark Matter and Neutrino Focus Week
TDLI SJTU, Aug 23, 2025

Based on ongoing work with

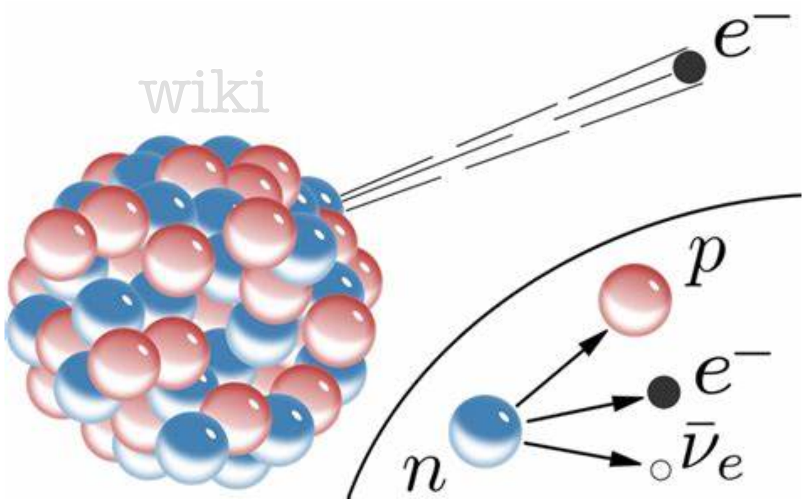
Adam Falkowski, Martin Gonzalez-Alonso, Leïla Haegel, Suraj Prakash

IMP 中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

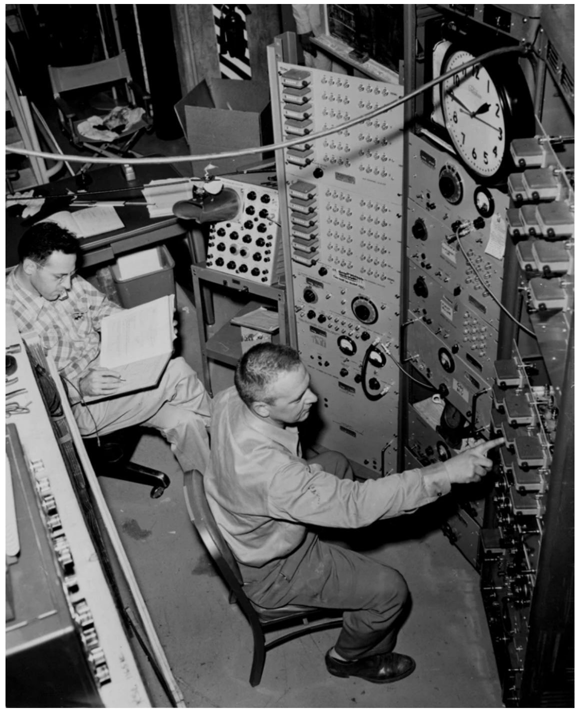
Introduction



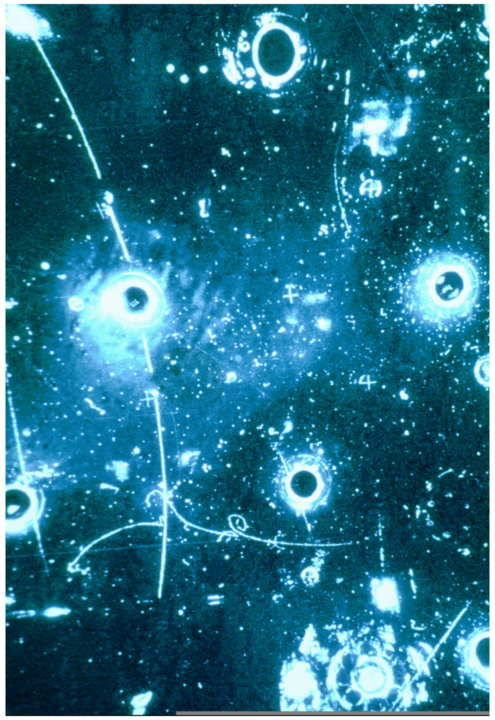
1930, Pauli



1933, Fermi



1956, Cowan-Reines



July 19,1973, Gargamelle

Introduction

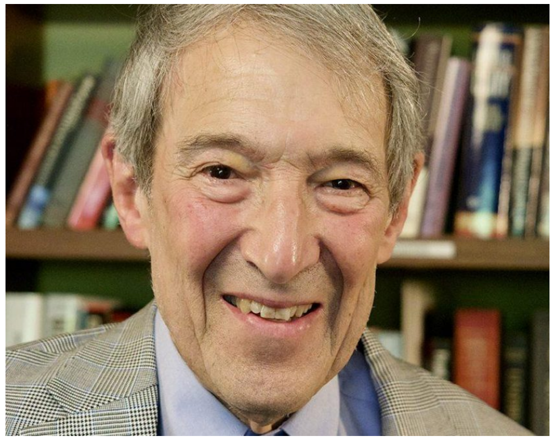
PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

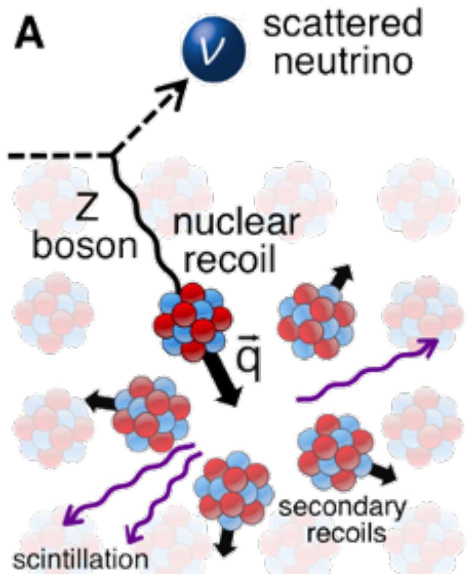
Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \rightarrow \nu + A$ should have a sharp coherent forward peak just as $e + A \rightarrow e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \rightarrow \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.





$$\nu_\alpha + N(A,Z) \rightarrow \nu_\alpha + N(A,Z)$$

$$\lambda_\nu \simeq \frac{1}{|\vec{q}|} \gtrsim r_N \simeq 5\ \text{fm} \simeq \frac{1}{197.3\text{MeV}} \qquad \text{for } N \simeq 100$$

thus the momentum transfer is of $\mathcal{O}(10)$ MeV, such that the recoil energy is

$$E_r \simeq \frac{q^2}{2M_N} = \mathcal{O}(1 \sim 10)\,\text{keV}$$

✓ early 2000s

Introduction

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REPORT

Observation of coherent elastic neutrino-nucleus scattering

D. Akimov[1,2], J. B. Albert[3], P. An[4], C. Awe[4,5], P. S. Barbeau[4,5], B. Becker[6], V. Belov[1,2], A. Brown[4,7]…

+ See all authors and affiliations

Science 15 Sep 2017:
Vol. 357, Issue 6356, pp. 1123-1126
DOI: 10.1126/science.aao0990

Article | Figures & Data | Info & Metrics | eLetters | PDF

Science
Vol 357, Issue 6356
15 September 2017

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First Measurement of Coherent Elastic Neutrino-Nucleus Scattering on Argon

D. Akimov *et al.* (COHERENT Collaboration)

Phys. Rev. Lett. **126**, 012002 – Published 7 January 2021

Introduction

Observation of Coherent Elastic Neutrino-Nucleus Scattering

COHERENT Collaboration • D. Akimov (Moscow, ITEP and Moscow Phys. Eng. Inst.) Show All(81)

Aug 3, 2017

10 pages

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e-Print: 1708.01294 [nucl-ex]

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Experiments: ORNL-SNS-COHERENT

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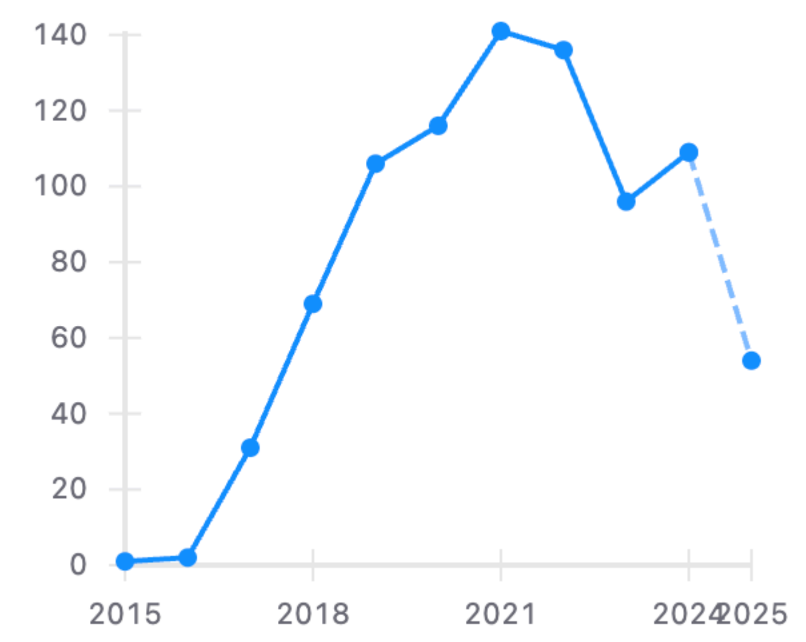
Citations per year



Constrain TEXONO

Shao-Feng Ge[a]

Probing ge lepton char long-baselin

Tobias Felkl,[a] To

Exploring SMI Interactions fr Oscillations

Yong Du,[a] Hao-Lin Li,[a]

EFT a

Víctor Bresó-Pla[a], Adam Falkowski[b], Martín González-Alonso[a] Monsálvez-Pozo[a]

Constraints on neutrino non-standard i and X

Gang Li,[2,*] Chuan-Qiang Song,[1,3,4,†] Fe

+ ⋯

Formalism

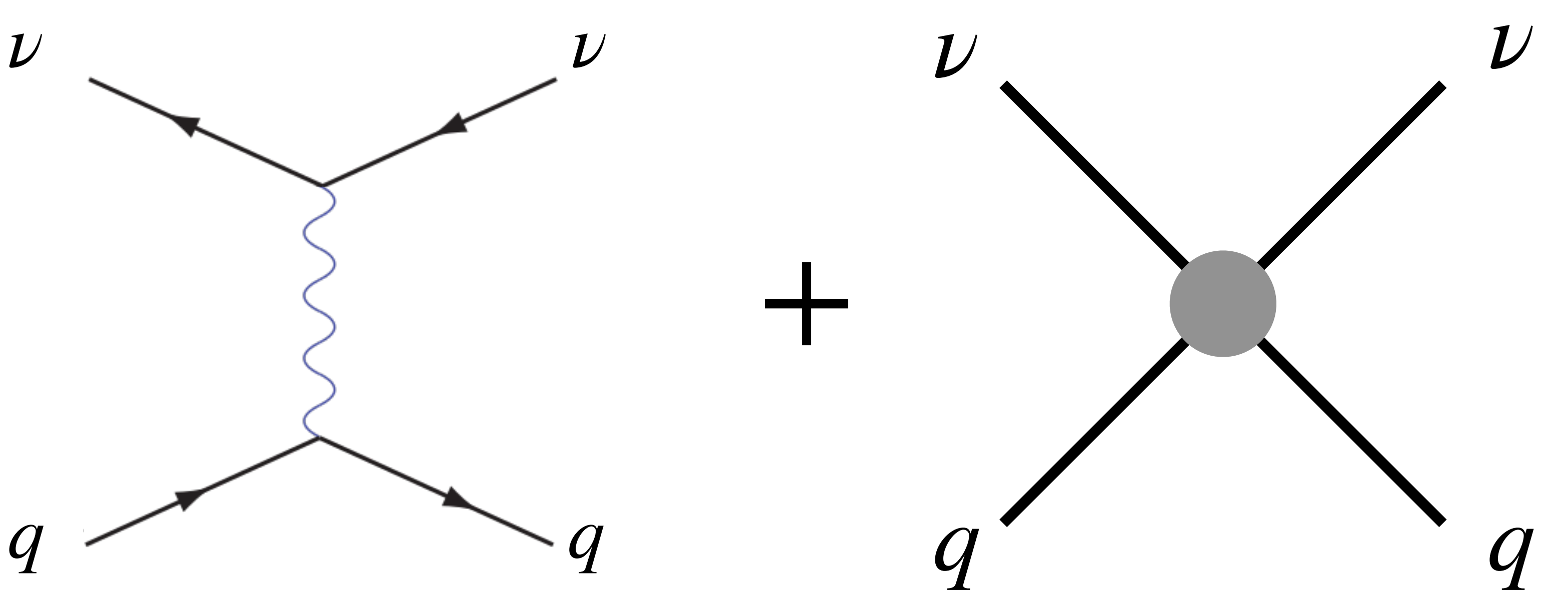
The standard event rate per nuclear recoil energy (after integrating over the time for simplicity)

$$\frac{d\sigma_{\nu_\alpha N}}{dE_r} = \frac{G_F^2 M_N}{4\pi}\left(1-\frac{M_N E_r}{2E_{\nu_\alpha}^2}\right)\left[ZQ_pF_p\left(q^2\right)+NQ_n^VF_n\left(q^2\right)\right]^2$$

with the SM proton and the neutron weak charges being (tree-level)

$$Q_p^{\rm SM} = 1-4\sin^2\theta_W \approx 0, \qquad Q_n^{\rm SM} = -1$$

Clearly, these charges will be modified in the presence of new physics/interactions, and it's often seen in literature to consider the neutral current 4-fermion operators



$$Q_p = Q_p^{\rm SM} + \sum_i \#_1^i\, c^i_{\nu\nu qq}$$

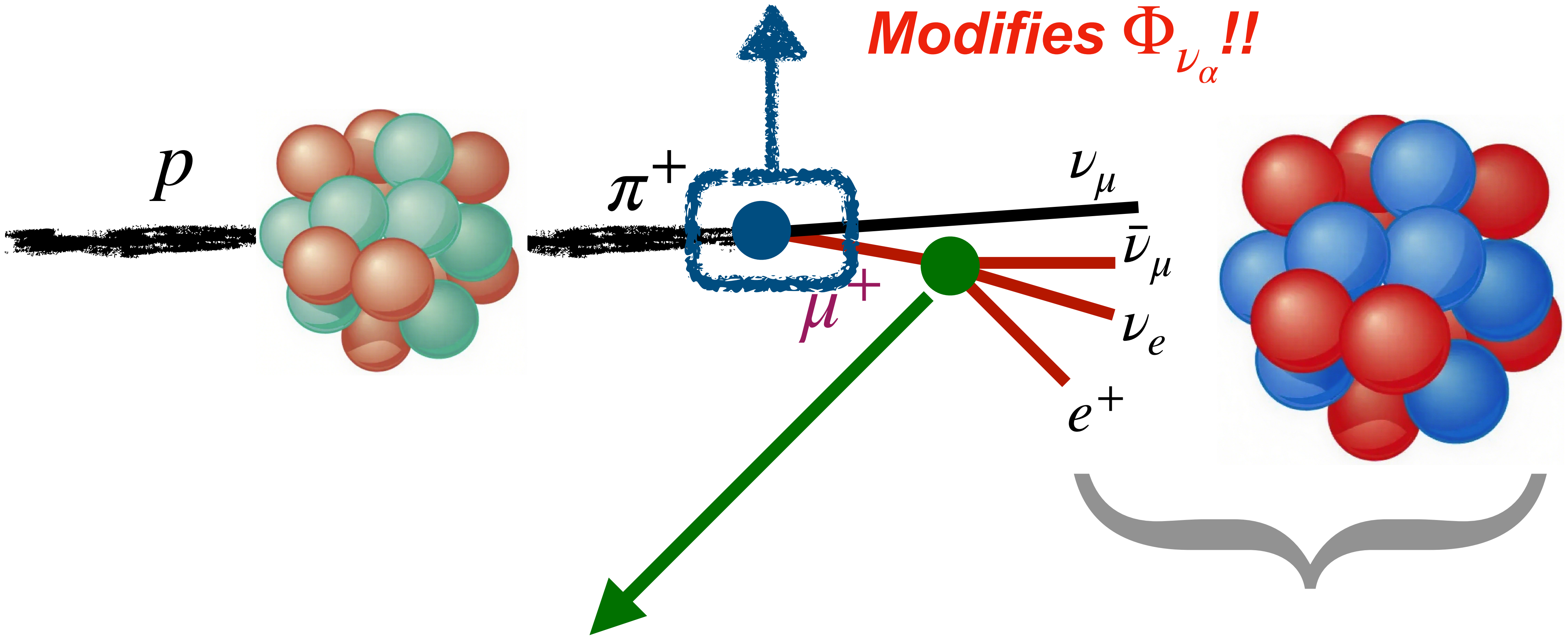
$$Q_n = Q_n^{\rm SM} + \sum_i \#_2^i\, c^i_{\nu\nu qq}$$

Q: Full story?

Formalism

$$\mathscr{L} \supset -\frac{2V_{ud}}{v^2}\Big\{ \left[1+\epsilon_L\right]_{\alpha\beta}\left(\bar{u}\gamma^\mu P_L d\right)\left(\bar{\ell}_\alpha\gamma_\mu P_L \nu_\beta\right) + \left[\epsilon_R\right]_{\alpha\beta}\left(\bar{u}\gamma^\mu P_R d\right)\left(\bar{\ell}_\alpha\gamma_\mu P_L \nu_\beta\right) + \frac{1}{2}\left[\epsilon_S\right]_{\alpha\beta}\left(\bar{u}d\right)\left(\bar{\ell}_\alpha P_L \nu_\beta\right)$$

$$-\frac{1}{2}\left[\epsilon_P\right]_{\alpha\beta}\left(\bar{u}\gamma_5 d\right)\left(\bar{\ell}_\alpha P_L \nu_\beta\right) + \frac{1}{4}\left[\epsilon_T\right]_{\alpha\beta}\left(\bar{u}\sigma^{\mu\nu} P_L d\right)\left(\bar{\ell}_\alpha \sigma_{\mu\nu} P_L \nu_\beta\right) + \text{h.c.} \Big\}$$



Modified by $\mathscr{O}_{\mu\nu_\mu e\nu_e}$ operators, but absorbed in G_F

$$\left(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta\right)\left(\bar{\nu}_\lambda\gamma^\mu P_L\ell_\xi\right), \left(\bar{\ell}_\alpha P_L\nu_\beta\right)\left(\bar{\nu}_\lambda P_R\ell_\xi\right)$$

Interactions of $\mathscr{O}_{\nu\nu qq}$ type on last page

$$\left(\bar{q}\gamma_\mu q\right)\left(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta\right), \left(\bar{q}\gamma_\mu\gamma_5 q\right)\left(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta\right)$$

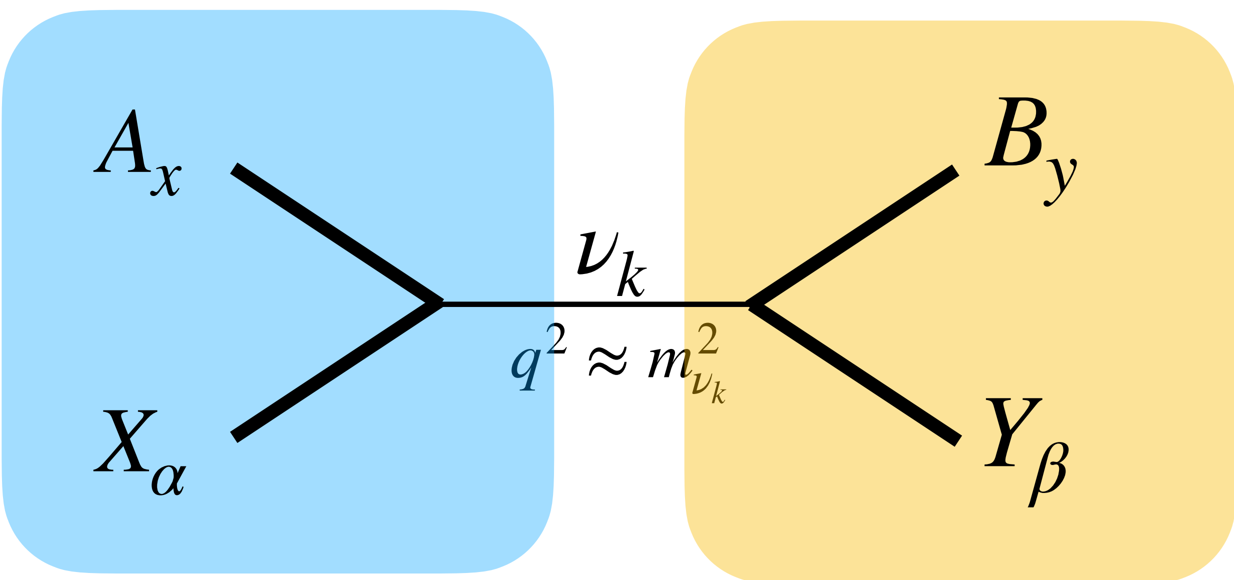
Formalism

A consistent treatment on new physics modifications to neutrino production and detection is outlined earlier Falkowski, Gonzalez-Alonso, Tabriziet, 1910.02971

Dobrev, Melnikov, Schwetz, 2504.10600

$$A_x \to X_\alpha \nu, \quad \nu B_y \to Y_\beta$$

$$\mathscr{M}^P_{\alpha k} = U^*_{\alpha k} A^P_L + \sum_X \left[\epsilon_X U\right]^*_{\alpha k} A^P_X$$



$$\mathscr{M}^D_{\beta k} = U_{\beta k} A^D_L + \sum_X \left[\epsilon_X U\right]_{\beta k} A^D_X$$

CEvNS: $L = \mathcal{O}(10)\,m$, $E_\nu = \mathcal{O}(10)\,\mathrm{MeV}$ ≈ 1

$$R^S_\alpha = \frac{N_S(t)}{32\pi L^2 m_S m_{\mathcal{N}} E_\nu} \sum_{j,k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} \times \int \frac{d\Pi_P}{dE_\nu} \mathscr{M}^P_{\alpha k} \overline{\mathscr{M}}^P_{\alpha l} \int \frac{d\Pi_D}{dE_r} \mathscr{M}^D_{jk} \overline{\mathscr{M}}^D_{jl}$$

$N_S(t)$ number of source particle ($\pi^\pm$ for example), the time info is also largely ignored in previous analyses, but it *allows distinguishing prompt vs delayed weak charges*

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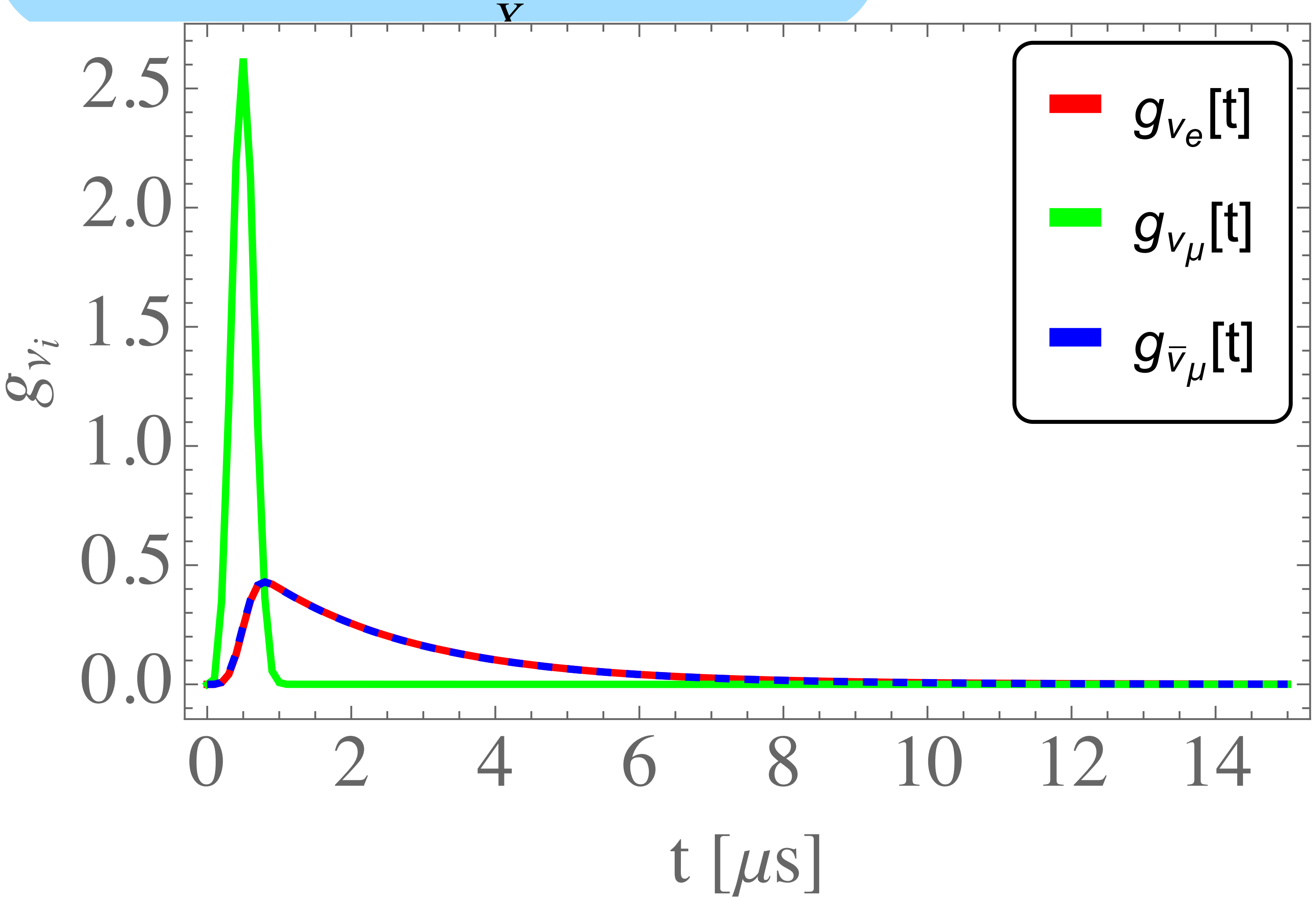


$$R^S_\alpha = \frac{N_S(t)}{32\pi L^2 m_S m_{\mathcal{N}} E_r} \sum_{j,k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} \times \int \frac{d\Pi_P}{dE_\nu} \mathcal{M}^P_{\alpha k} \overline{\mathcal{M}}^P_{\alpha l} \int \frac{d\Pi_D}{dE_r} \mathcal{M}^D_{jk} \overline{\mathcal{M}}^D_{jl}$$

$N_S(t)$ number of source particle ($\pi^\pm$ for example), the time info is also largely ignored in previous analyses, but it *allows distinguishing prompt vs delayed weak charges*

Formalism

For example, for π^+ decay,

$$\mathscr{L} \supset -\frac{2V_{ud}}{v^2}\Big\{ [1+\epsilon_L]_{\alpha\beta}(\bar{u}\gamma^\mu P_L d)\left(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta\right) + [\epsilon_R]_{\alpha\beta}(\bar{u}\gamma^\mu P_R d)\left(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta\right) + \frac{1}{2}[\epsilon_S]_{\alpha\beta}(\bar{u}d)\left(\bar{\ell}_\alpha P_L \nu_\beta\right) - \frac{1}{2}[\epsilon_P]_{\alpha\beta}(\bar{u}\gamma_5 d)\left(\bar{\ell}_\alpha P_L \nu_\beta\right) + \frac{1}{4}[\epsilon_T]_{\alpha\beta}(\bar{u}\sigma^{\mu\nu} P_L d)\left(\bar{\ell}_\alpha \sigma_{\mu\nu} P_L \nu_\beta\right) + \text{h.c.} \Big\}$$

the modified amplitudes are

$$\mathscr{M}^{P,\pi}_{\alpha k} = -\, i m_{\ell_\alpha} f_{\pi^\pm} \frac{V_{ud}}{v^2}[CU]^*_{\alpha k}\left(\bar{u}_{\nu_k} P_L v_{\ell_\alpha}\right)$$

$$\int \frac{d\Pi_P}{dE_\nu} \mathscr{M}^{P,\pi}_{\mu k} \overline{\mathscr{M}}^{P,\pi}_{\mu l} = 2 m_{\pi^\pm} \Gamma_{\pi\to\mu\nu} \frac{[CU]_{\mu l}[U^\dagger C^\dagger]_{k\mu}}{[CC^\dagger]_{\mu\mu}} \delta\left(E_\nu - E_{\nu,\pi}\right)$$

plug in

$$R^S_\alpha = \frac{N_S(t)}{32\pi L^2 m_S m_{\mathcal{N}} E_\nu} \sum_{j,k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} \times \int \frac{d\Pi_P}{dE_\nu} \mathscr{M}^P_{\alpha k} \overline{\mathscr{M}}^P_{\alpha l} \int \frac{d\Pi_D}{dE_r} \mathscr{M}^D_{jk} \overline{\mathscr{M}}^D_{jl}$$

Modified prompt neutrino flux from NP!

$$C_{\alpha\beta} \equiv \delta_{\alpha\beta} + \left[\epsilon^{ud}_L\right]_{\alpha\beta} - \left[\epsilon^{ud}_R\right]_{\alpha\beta} - \left[\epsilon^{ud}_P\right]_{\alpha\beta} \frac{m^2_{\pi^\pm}}{m_{\ell_\alpha}(m_u + m_d)}$$

$$\frac{dN_{\text{prompt}}}{dT} = n_{\text{POT}} f^\pi_{\nu/p} \frac{N_T F(q^2)^2 (m_N + T)}{32\pi^2 v^4 L^2} f_\mu(T) \tilde{Q}^2_\mu$$

$$\tilde{Q}^2_\mu = Q^2_{SM} + 2Q_{SM}[\delta\mathcal{Q}]_{\mu\mu}$$

$$\delta\mathcal{Q}^{\text{LO}}_{\mu\mu} = 2\left((A+Z)\epsilon^{uu}_{\mu\mu} + (2A-Z)\epsilon^{dd}_{\mu\mu}\right)$$

Results: *Accelerator ones*

Given the limited number of signal events, Poissonian likelihoods are constructed for CsI and LAr detectors *based on the 2D datasets released*

$$\chi^2 = \sum_{i,j} 2\left(-N_{ij}^{\text{exp}} + N_{ij}^{\text{th}}\left(\overrightarrow{Q}_N^2;\vec{x}\right) + N_{ij}^{\text{exp}}\ln\left(\frac{N_{ij}^{\text{exp}}}{N_{ij}^{\text{th}}\left(\overrightarrow{Q}_N^2;\vec{x}\right)}\right)\right) + \sum_n\left(\frac{x_n}{\sigma_n}\right)^2$$

Marginalizing over the nuisance parameters, accelerator results (CsI + LAr) lead to

Flavor general

$$\begin{pmatrix} 0.63 & -0.70 & -0.22 & 0.24 \\ 0.21 & -0.24 & 0.63 & -0.70 \\ -0.68 & -0.61 & 0.30 & 0.27 \\ 0.30 & 0.27 & 0.68 & 0.61 \end{pmatrix}\begin{pmatrix} \epsilon_{ee}^{dd} \\ \epsilon_{ee}^{uu} \\ \epsilon_{\mu\mu}^{dd} \\ \epsilon_{\mu\mu}^{uu} \end{pmatrix} = \begin{pmatrix} 2.0 \pm 5.7 \\ -0.2 \pm 1.7 \\ -0.037 \pm 0.042 \\ -0.004 \pm 0.013 \end{pmatrix}$$

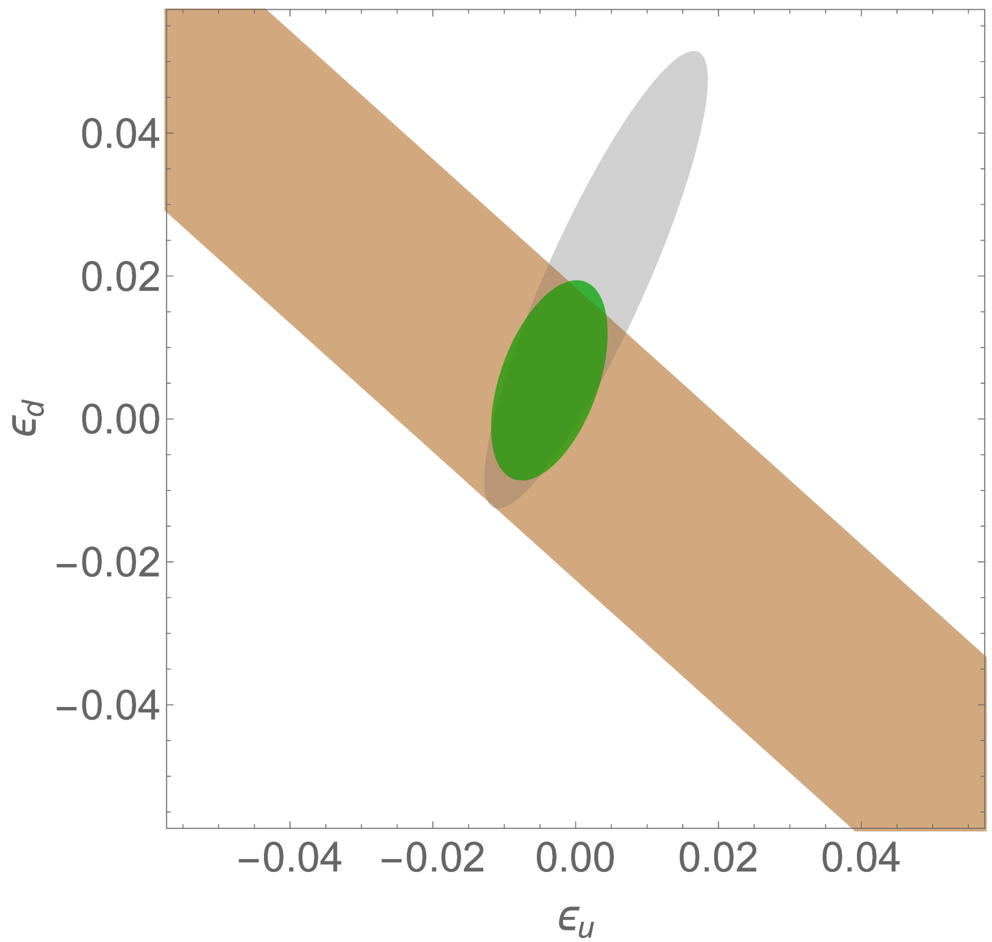
Flavor universal

$$0.67\epsilon_u + 0.74\epsilon_d = -0.002 \pm 0.010$$
$$0.74\epsilon_u - 0.67\epsilon_d = 0.0 \pm 1.3$$

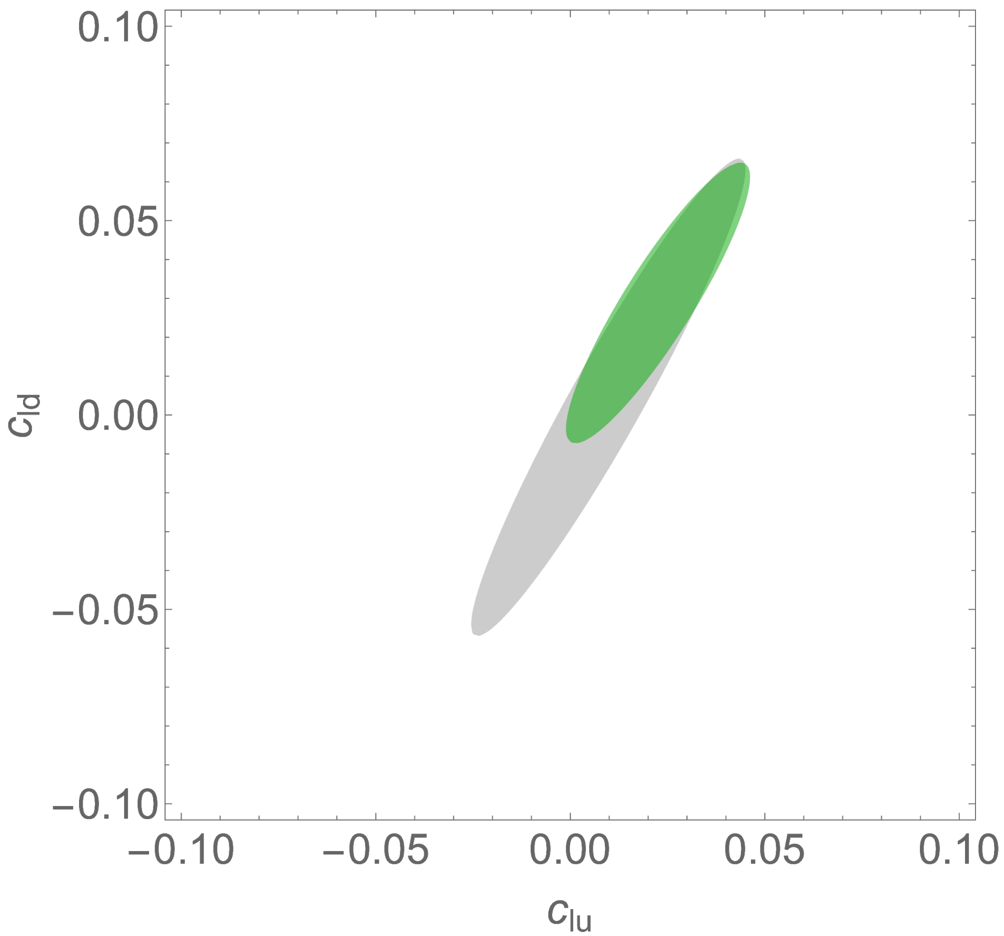
Bresó-Pla, Falkowski, González-Alonso, Monsálvez-Pozo, 2301.07036

Results: *Accelerator ones*

Flavor universal (LEFT)



Flavor universal (SMEFT)



$$\epsilon^{uu}_{\alpha\alpha} = \delta g_L^{Zu} + \delta g_R^{Zu} + \left(1 - \frac{8s_\theta^2}{3}\right)\delta g_L^{Z\nu_\alpha} - \frac{1}{2}\left[c_{lq}^{(1)} + c_{lq}^{(3)} + c_{lu}\right]_{\alpha\alpha 11}$$

$$\epsilon^{dd}_{\alpha\alpha} = \delta g_L^{Zd} + \delta g_R^{Zd} - \left(1 - \frac{4s_\theta^2}{3}\right)\delta g_L^{Z\nu_\alpha} - \frac{1}{2}\left[c_{lq}^{(1)} - c_{lq}^{(3)} + c_{ld}\right]_{\alpha\alpha 11}$$

Bresó-Pla, Falkowski, González-Alonso, Monsálvez-Pozo, 2301.07036

Article | Open access | Published: 30 July 2025

Direct observation of coherent elastic antineutrino–nucleus scattering

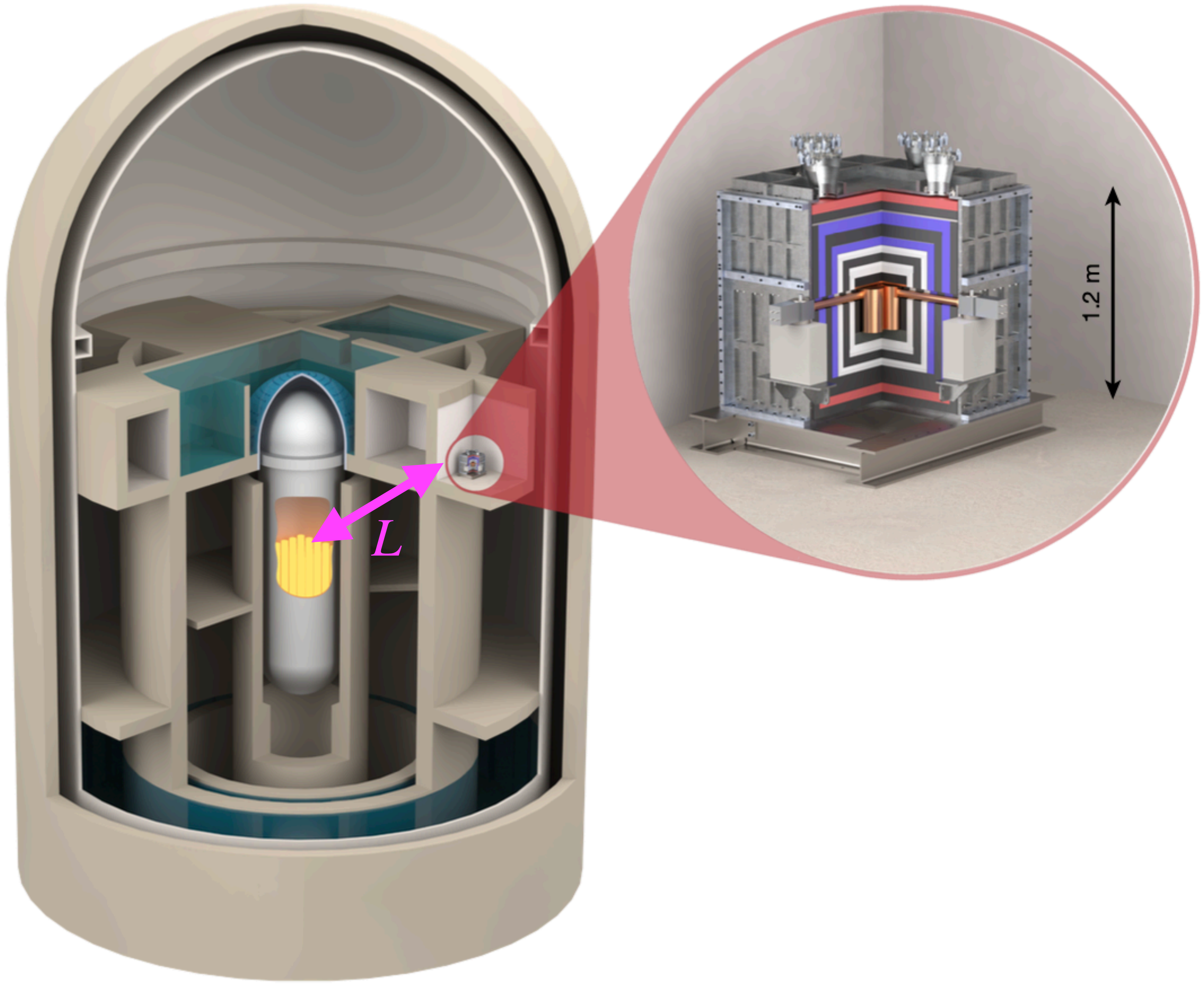
N. Ackermann, H. Bonet, A. Bonhomme, C. Buck, K. Fülber, J. Hakenmüller, J. Hempfling, G. Heusser, M. Lindner, W. Maneschg, K. Ni, M. Rank, T. Rink, E. Sánchez García, I. Stalder, H. Strecker, R. Wink & J. Woenckhaus

Nature **643**, 1229–1233 (2025) | Cite this article

Abstract

Neutrinos are elementary particles that interact only very weakly with matter. Neutrino experiments are, therefore, usually big, with masses in the multi-tonne range. The thresholdless interaction of coherent elastic scattering of neutrinos on atomic nuclei leads to greatly enhanced interaction rates, which allows for much smaller detectors. The study of this process gives insights into physics beyond the Standard Model of particle physics. The CONUS+ experiment[1] was designed to first detect elastic neutrino–nucleus scattering in the fully coherent regime with low-energy neutrinos produced in nuclear reactors. For

Results: *Adding CONUS+*



Data: [2018 - 2022] → 2023 [119 days]

Location: Germany → Switzerland

Distance: 20.7m

Flux: $1.5 \times 10^{13} \bar{\nu}_e / \mathrm{cm}^2 \cdot s$

Detector: HPGe

Operation time:

327 kg·day [On]

60 kg·day [Off]

# of Events:

(395 ± 106) kg·day [Observed]

(347 ± 59) kg·day [Off]

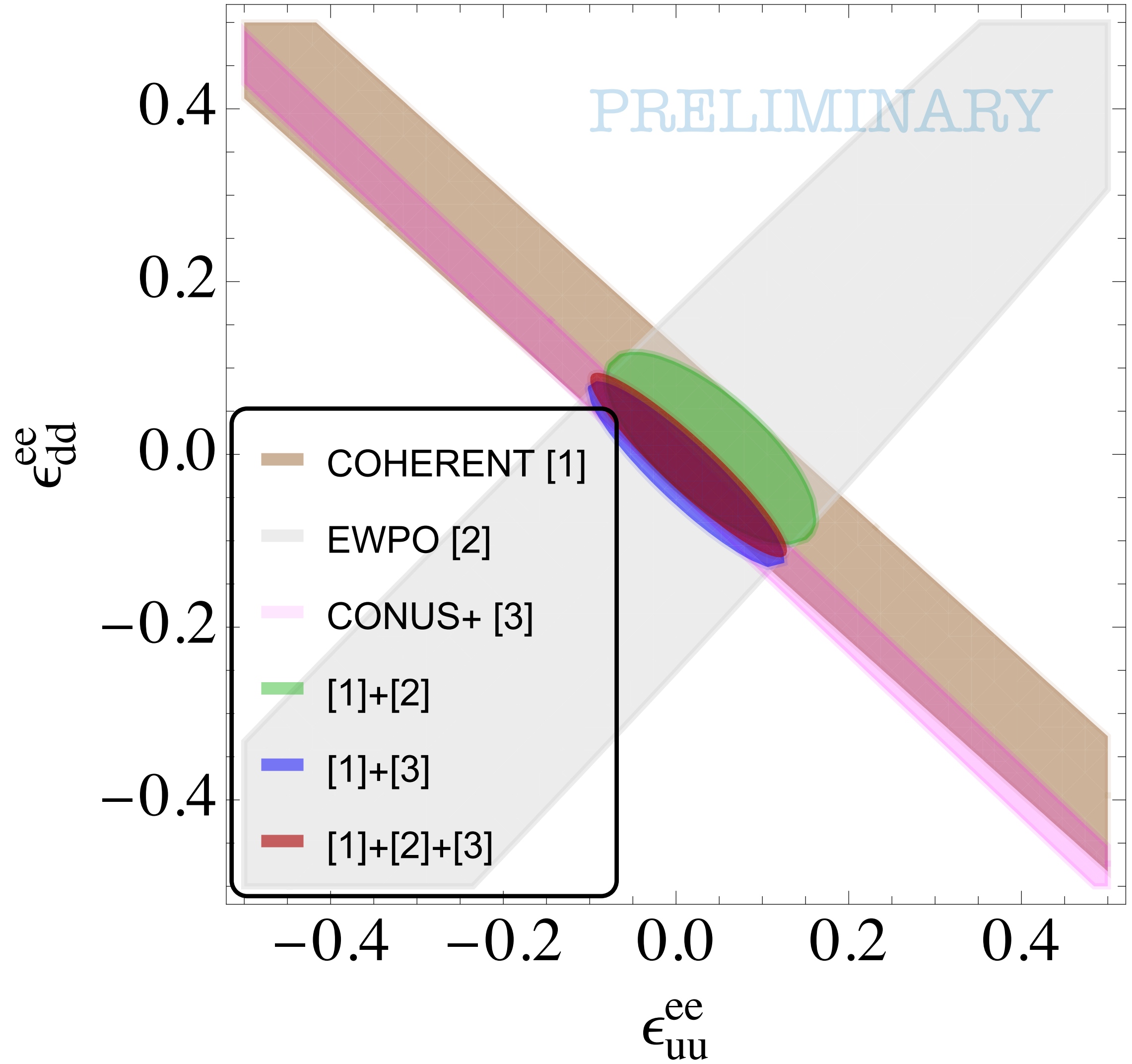
Results: *Adding CONUS+*

Reactor-type CEvNS are special since one only has $\bar{\nu}_e$ from $n \to p + e^- + \bar{\nu}_e$. Based on a similar computation, one has only one generalized weak charge, given by

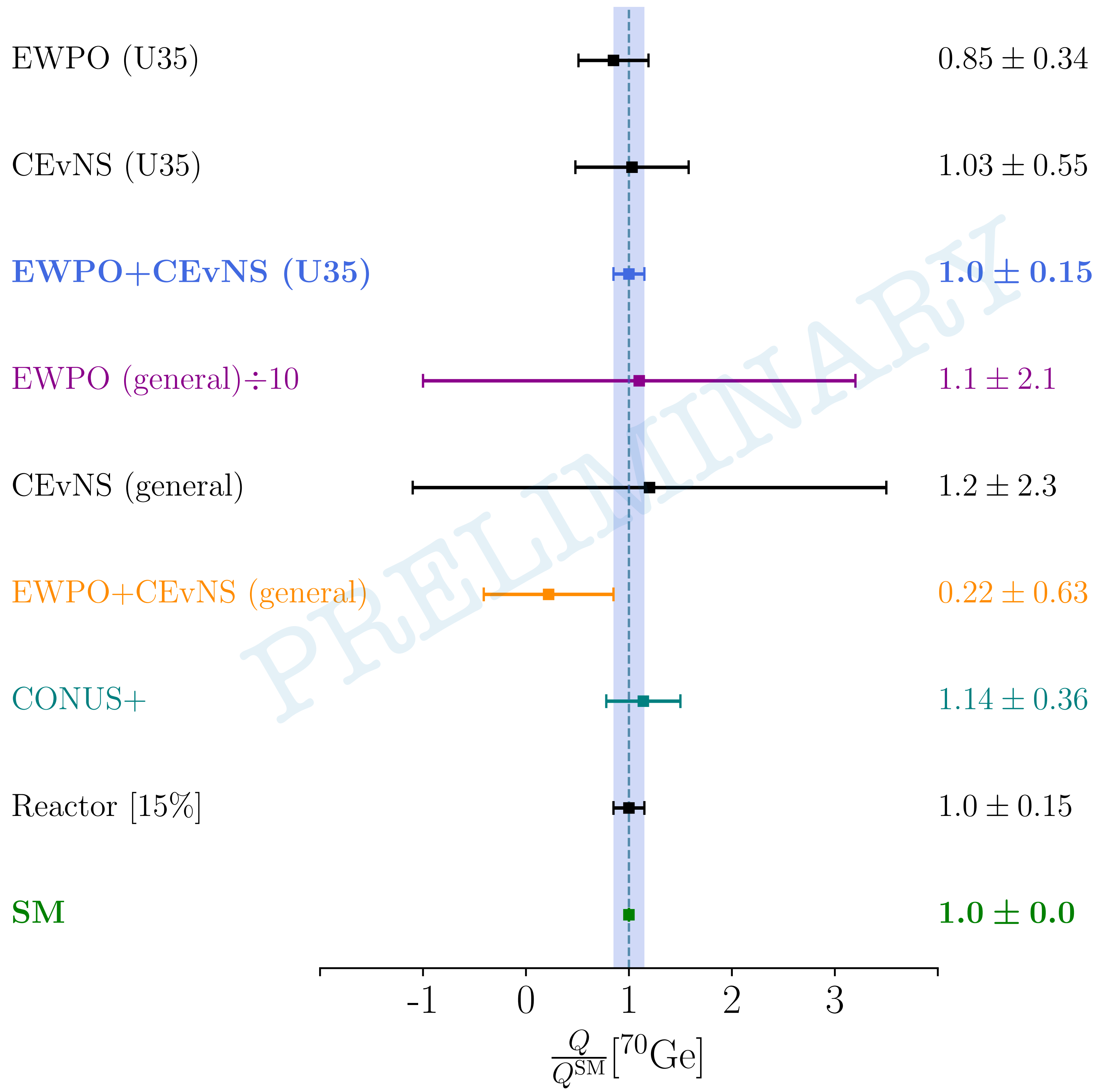
$$\tilde{Q}_e^2[\mathrm{Ge}] = Q_{SM}^2 + 2Q_{SM}[\delta\mathbb{Q}]_{ee}\Big|_{\mathrm{Ge}} \qquad \delta\mathbb{Q}_{ee}^{\mathrm{Ge}} = 2\left((A+Z)\epsilon_{ee}^{uu} + (2A-Z)\epsilon_{ee}^{dd}\right)\Big|_{\mathrm{Ge}}$$

These parameters are already constrained (though only strongly in one direction) by accelerator-type experiments.

What is the gain then from CONUS+?



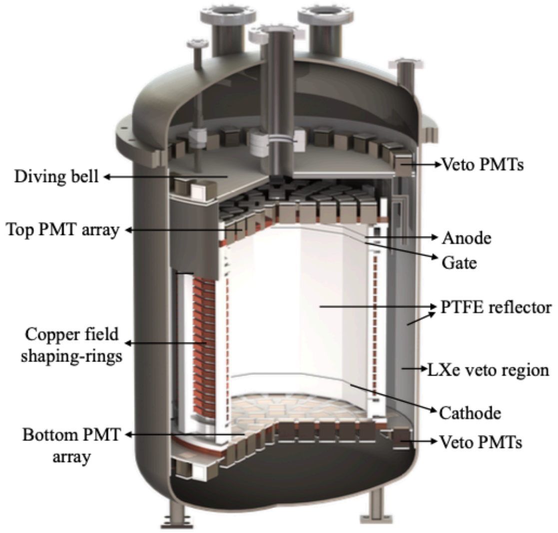
Results: *Adding CONUS+*



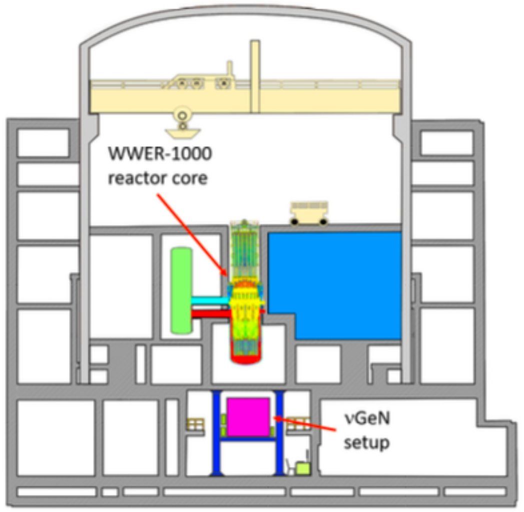
Upcoming: *More reactors*

Global efforts: several more proposals/on-going projects (*just to name a few*)

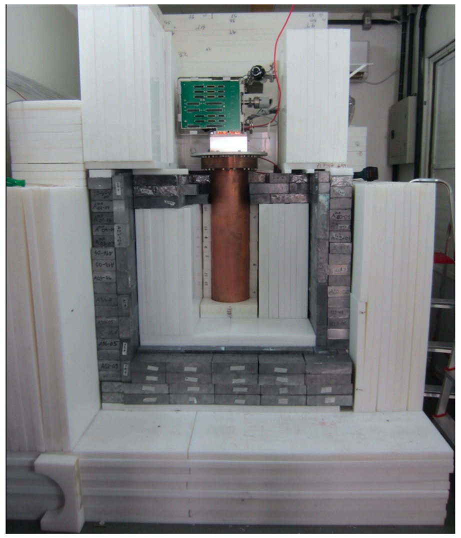
RICOCHET w/ HPGe@ ILL, France



RELICS w/ LXe@ Sanmen, China



vGen w/ HPGe@ Kalinin, Rusia



CONNIE w/ Si@ Angra 2, Brazil

Summary

- The observation of CEvNS has motivated tremendous studies within/beyond the SM. We highlight the consistent treatment on NP-modified event rates.

- Reactor-type CEvNS events are found to significantly improve the determination of the generalized weak charge:

  - *15% (30% now) relative precision* matches that from the U35 global fit (*Preliminary, subject to change*).

- More results to come very soon…

Backup