Sensitivity to the neutrino electric millicharge of experiments involving elastic neutrino-electron and coherent elastic neutrino-nucleus processes

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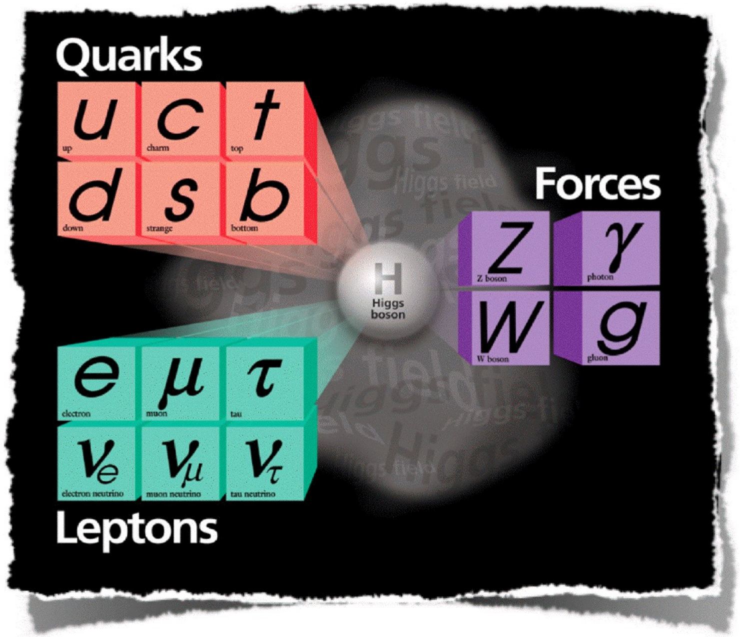
Outline

- Introduction
- Elastic neutrino-electron scattering (ENES)
- Coherent elastic neutrino-nucleus scattering (CEvNS)
- Bounds on NEM from ENES experiments of reactor antineutrinos.
- Constraints on NEM from CEvNS future experiments of reactor antineutrinos.
- Conclusions.

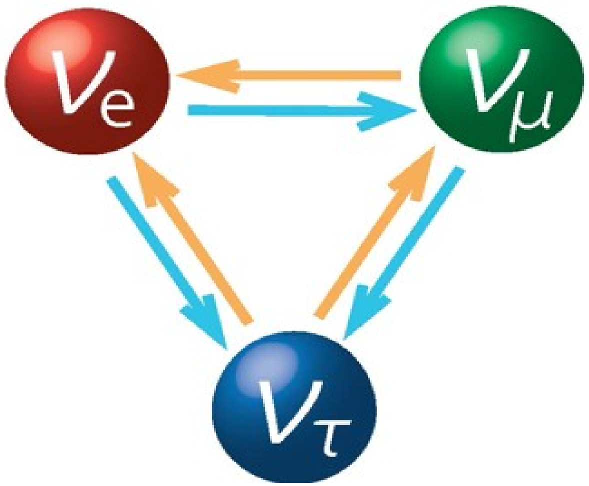
Introduction

Standard Model (SM)



Fermi National Accelerator Laboratory

Neutrino Oscillations



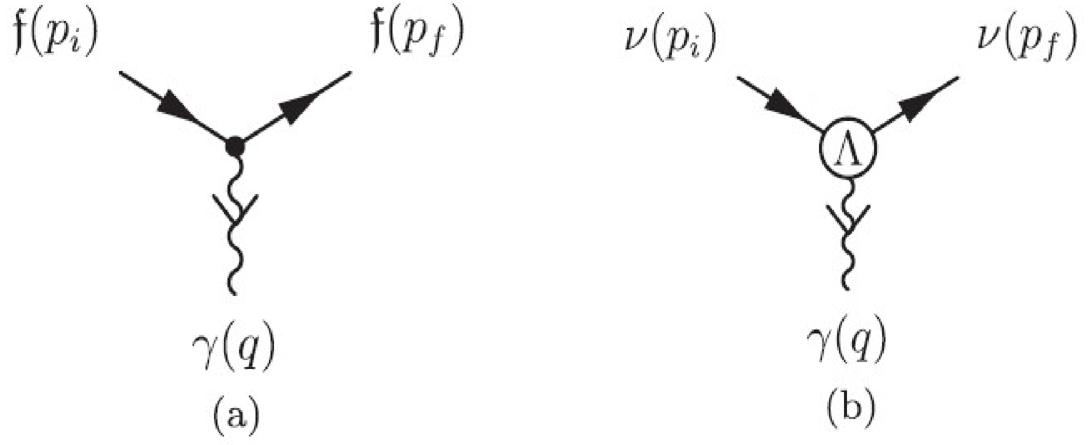
Neutrinos are massive particles

Neutrinos are massless, electrically neutral, and only interact weakly with charged leptons.

To extend the SM to explain the neutrino mass

Neutrino electric millicharge (NEM)

Tree level coupling $f - \gamma$



Effective one-photon coupling $\nu - \gamma$

Amplitud of neutrino-photon electromagnetic interaction

$$\langle \nu(p_f, s_f)| J_\mu^{EM} |\nu(p_i, s_i)\rangle = i\bar{u}_f \Lambda_\mu(q) u_i$$

The vertex function includes four form factors,

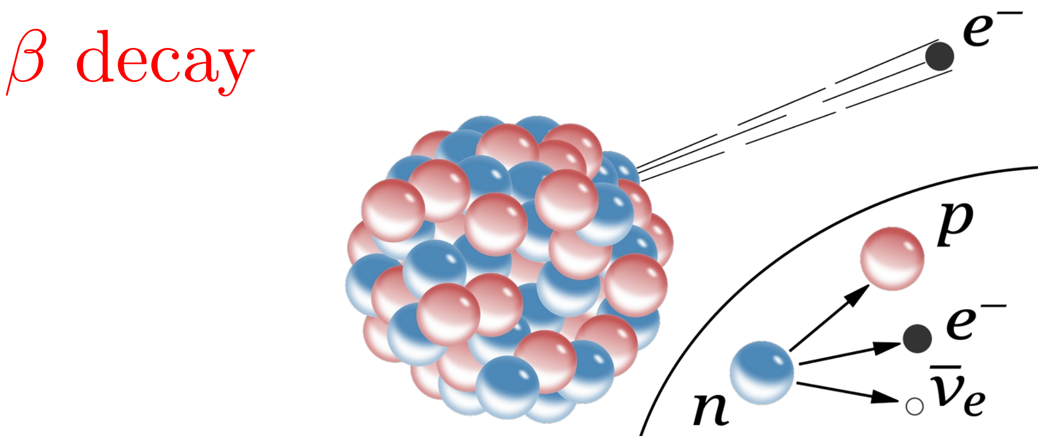
$$\Lambda_\mu(q) = \mathbf{F_D}(q^2)\gamma_\mu + \mathbf{G_D}(q^2)(q^2\gamma_\mu - 2miq_\mu)\gamma_5 + \mathbf{M_D}(q^2)\sigma_{\mu\nu}q_\nu + \mathbf{E_D}(q^2) i\sigma_{\mu\nu}q_\nu\gamma_5.$$

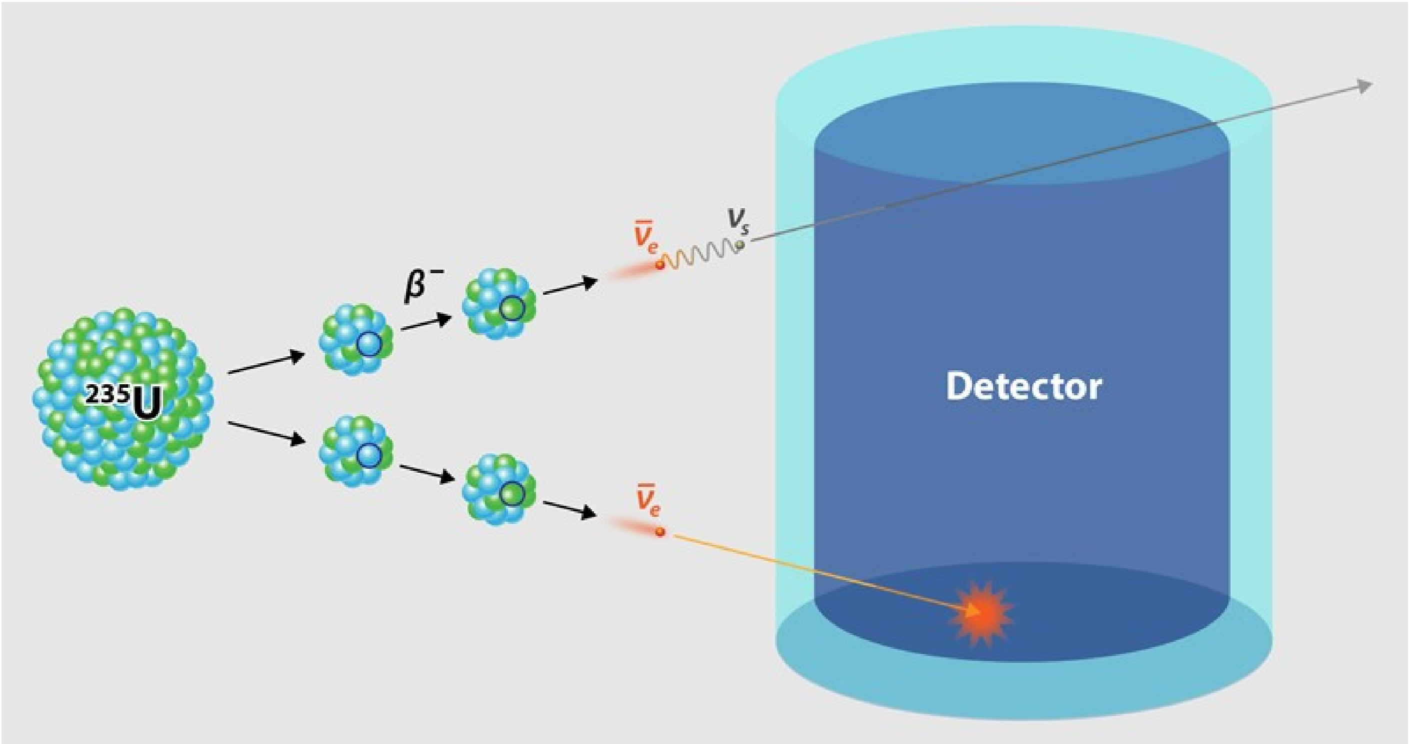
Considering couplings with real photons,

$$\mathbf{F_D}(\mathbf{0}) = \mathbf{q}_\nu,\ G_D(0) = a,\ M_D(0) = \mu_\nu,\ E_D(0) = d,$$

[1] C. Giunti and A. Studenikin, Rev. Mod. Phys., 87, 531 (2015).

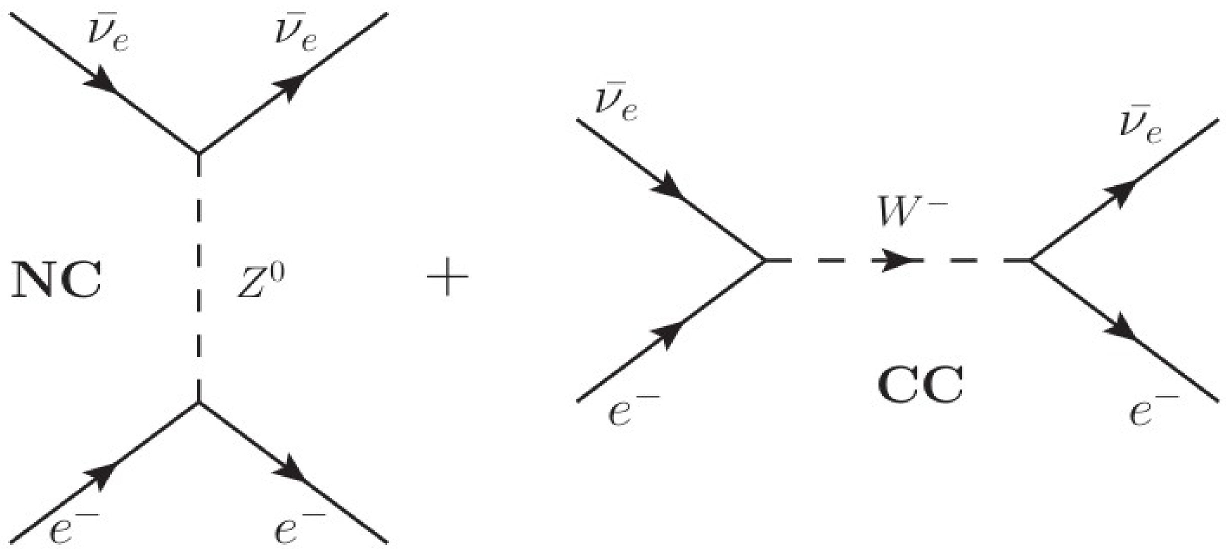
Antineutrinos from reactor experiments





https://physics.aps.org/articles/v10/66

Elastic neutrino-electron scattering (ENES)



Antineutrino-electron cross section

$$\left(\frac{d\sigma}{dT_e}\right)^{\bar{\nu}e}_{\mathbf{SM}} = \frac{2\mathrm{G}_{\mathrm{F}}^2 m_e}{\pi}\left[g_L^2 + g_R^2\left(1-\frac{T_e}{E_\nu}\right)^2 - g_L g_R\left(\frac{m_e T_e}{E_\nu^2}\right)\right],$$

$g_L = \sin^2\theta_W$ and $g_R = sin^2\theta_W + 1/2$ $\rightarrow$ standard coupling constants.

$$\sigma_{\bar{\nu}-e} \sim 10^{-45}\mathrm{cm}^2/\mathrm{MeV}$$

Coherent elastic neutrino-nucleus scattering (CEvNS)

1974: Theoretical prediction

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 $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does".

"**The experiments are very difficult**, although the estimated cross sections (about 10^{-38} cm^2 on Carbon) are favorable".

[2] D. Z. Freedman, Phys. Rev. D 9, 1389 (1974)

2017: Observation of CEvNS by COHERENT Collaboration

RESEARCH

NEUTRINO PHYSICS

Observation of coherent elastic neutrino-nucleus scattering

"**We observed this process at a 6.7σ confidence level**, using a low background, 14.6-Kilogram CsI[Na] scintillator exposed to the neutrino emissions from the Spallation Neutron Source at Oak Ridge National Laboratory".

[3] D. Akimov et al., Science 357, no. 6356, 1123 (2017)

2020: Detection of CEvNS on Argon

"**We report the first detection of CEvNS on argon** using the CENNS-10 liquid argon detector at the Oak Ridge National Laboratory Spallation Neutrino Source".

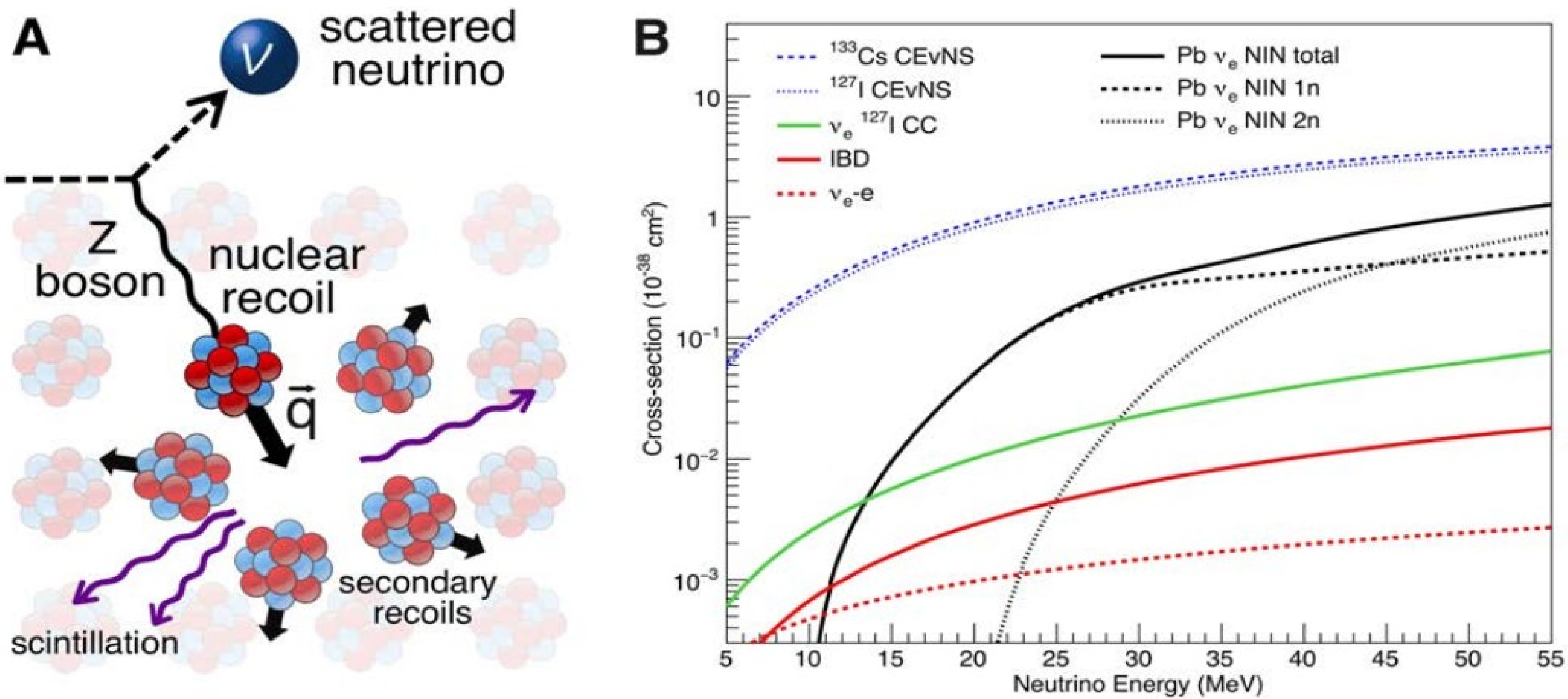
[4] D. Akimov et al, arXiv: 2003.10630

Neutral Current (NC) interaction

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

The momentum exchanged is smaller than the inverse of the nuclear size

$$\mathbf{qR \leq 1} \qquad \mathbf{E_\nu \leq 100}\mathrm{MeV}$$

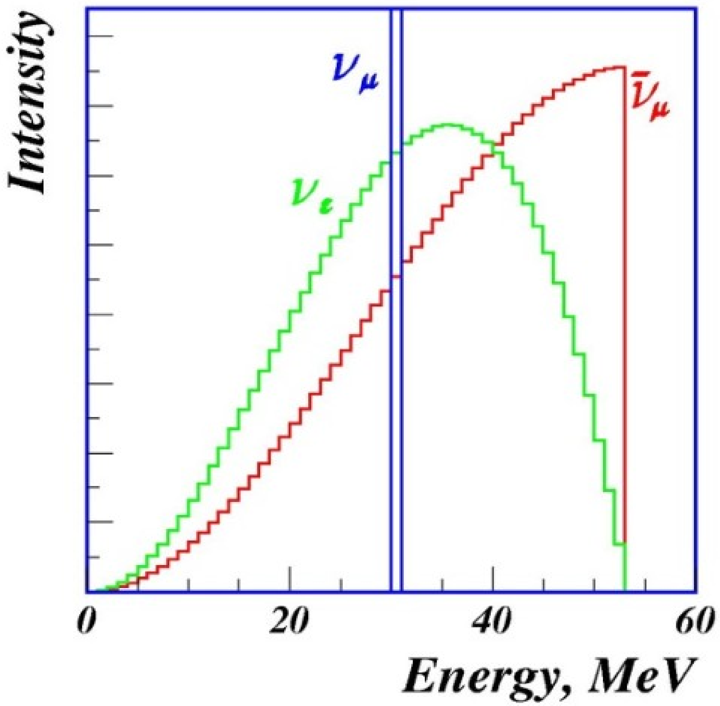


$$\sigma_{\nu_\alpha - \mathbf{N}} \sim \mathbf{10^{-38}}\mathrm{cm}^2$$

D. Akimov et al., Science 357, no. 6356, 1123 (2017)

Neutrinos production at the SNS

arXiv: 1211.5199v1



$$\frac{\mathrm{dN}_{\nu_\mu}}{\mathrm{d}E} = \eta\delta\left(E - \frac{m_\pi^2 - m_\mu^2}{2m_\pi}\right)$$

$$\frac{\mathrm{dN}_{\nu_e}}{\mathrm{d}E} = \eta\frac{192E^2}{m_\mu^3}\left(\frac{1}{2} - \frac{E}{m_\mu}\right)$$

$$\frac{\mathrm{dN}_{\bar{\nu}_\mu}}{\mathrm{d}E} = \eta\frac{64E^2}{m_\mu^3}\left(\frac{3}{4} - \frac{E}{m_\mu}\right)$$

Perspectives for exploring new physics in CEvNS

- NSI Interactions
- Sterile neutrinos
- Neutrino magnetic moment
- Neutrino couplings to new massive or light scalars (vector) mediators
- Leptoquarks
- Neutrino electric millicharge

ArXiv: 1805.01798, **arXiv:** 1907.04942, **arXiv:** 2003,12050, and references therein.

Some limits on NEM from different sources

- Based on the neutrality of matter [5] → $q_\nu \leq 3 \times 10^{-21} e$
- Neutrino Star Turning mechanism [6] → $q_\nu \leq 1.3 \times 10^{-19} e$
- Analysis of SN 1987 A neutrinos [7] → $q_\nu \leq 2 \times 10^{-15} e$
- From TEXONO experiment data [8] → $q_\nu \leq 3.7 \times 10^{-12} e$
- From GEMMA experiment data [9] → $q_\nu \leq 1.5 \times 10^{-12} e$
- Involving electron neutrino flavor (from COHERENT experiment data) [10] → $q_{\nu x} \sim 1 \times 10^{-7} e \, (x = e, \mu, \tau)$

[5] G. G. Raffelt, Physics Reports, vol. 320, no 1-6, pp. 319-327. 1999
[6] A. I. Studenikin and I. Tokarev, Nuclear Physics B, vol 884, pp. 396-407, 2014.
[7] G. Barbiellini and G. Cocconi, Nature, vol. 329, no. 6134, pp. 21-22, 1987.
[8] S. N. Gninenko, N. V. Krasnikov and A. Rubbia, Phys. Rev. D 75, 075014 (2007).
[9] A. Studenikin, EPL 107, no. 2, 21001 (2014) Erratum: [EPL 107, no. 3, 39901 (2014)].
[10] M. Cadeddu, F. Dordei, C. Giunti, Y. Li, and Y. Zhang, Physical Review D, 101, no. 3, 033004, 2020.

Analysis from ENES experiments of reactor antineutrinos

Antineutrino-electron cross section

$$\left(\frac{d\sigma}{dT_e}\right)^{\bar{\nu}e}_{\mathbf{tot}} = \left(\frac{d\sigma}{dT_e}\right)^{\bar{\nu}e}_{\mathbf{SM}} + \left(\frac{d\sigma}{dT_e}\right)^{\bar{\nu}e}_{\mathbf{EM}} + \left(\frac{d\sigma}{dT_e}\right)^{\bar{\nu}e}_{\mathbf{INT}}$$

The Standard Model contribution

$$\left(\frac{d\sigma}{dT_e}\right)^{\bar{\nu}e}_{\mathbf{SM}} = \frac{2\mathrm{G}_{\mathrm{F}}^2 m_e}{\pi}\left[g_L^2 + g_R^2\left(1 - \frac{T_e}{E_\nu}\right)^2 - g_L g_R\left(\frac{m_e T_e}{E_\nu^2}\right)\right],$$

$g_L = \sin^2\theta_W$ and $g_R = sin^2\theta_W + 1/2$ are de standard coupling constants.

The Electromagnetic and interference contributions

$$\left(\frac{d\sigma}{dT_e}\right)^{\bar{\nu}e}_{\mathbf{EM}} \simeq \frac{2\pi\alpha}{m_e T_e^2} q_\nu^2, \qquad \left(\frac{d\sigma}{dT_e}\right)^{\bar{\nu}e}_{\mathbf{INT}} = \frac{2\sqrt{2}\alpha G_F}{T_e} q_\nu$$

Reactor antineutrino experiments

Rovno nuclear power plant (Ukraine)
Krasnoyarsk nuclear power plant (Russia)


https://uatom.org/index.php/en/general-information/rivne-npp/
http://large.stanford.edu/courses/2017/ph241/buttinger2/

GEMMA at Kalinin nuclear power plant (Russia)

Kalinin-Nuclear-Power-Plant

MUNU experiment at Bugey NPP (France)

https://www.entrepriseetdecouverte.fr/property/edf-bugey-nuclear-power-plant/?lang=en

TEXONO experiment at Kuo Sheng NPP(Taiwan)

https://www.taiwannews.com.tw/en/news/3406044

Features of the reactor experiments

Experiment	Baseline (m)	Mass (Kg)	Material	Cross section/ Events
Rovno [11]	15	75	Silicon	$12.6 \times 10^{-45} cm^2/fission$
Krasnoyarsk [12]	–	103	Fluororganic scintillator	$4.5 \times 10^{-45} cm^2/fission$
MUNU [13]	18	-	CF_4	$1.07\, evt \cdot day^{-1}$
TEXONO [14]	28	187	CsI(Tl)	$0.7\, evt \cdot day^{-1}$
GEMMA [15]	13.9	1.5	Germanium	–

[11] A. Aguilar-Arevalo, et al, Journal of Instrumentation, vol 11, no 7, 012057, 2016.

[12] Y. Farzan, et al., Journal of High Energy Physics, vol 2018, no 5, 66, 2018.

[13] G. Agnolet, et al., Nuclear Instruments and Methods in Physics Research, vol 853, pp. 53-60, 2017

[14] D. Y. Akimov, et al., Journal of Instrumentation, vol 12, no. 6, C06018, 2017

[15] H. T. Wong, Nuclear Physics A, Vol. 844, no. 1-4, pp. 229C-233c, 2010.

Theoretical number of events (in the ith bin)

$$N^{\rm th} = \kappa \int_{E_{\nu_{\rm min}}}^{E_{\nu_{\rm max}}} \int_{T_i}^{T_{i+1}} \int_{T_{\rm min}}^{T_{\rm max}} \lambda(E_\nu) \left(\frac{d\sigma}{dT_e}\right)^{\bar{\nu}e}_{\rm tot} \times R(T_e, T'_e) dT_e dT'_e dE_\nu,$$

where the resolution function corresponds to

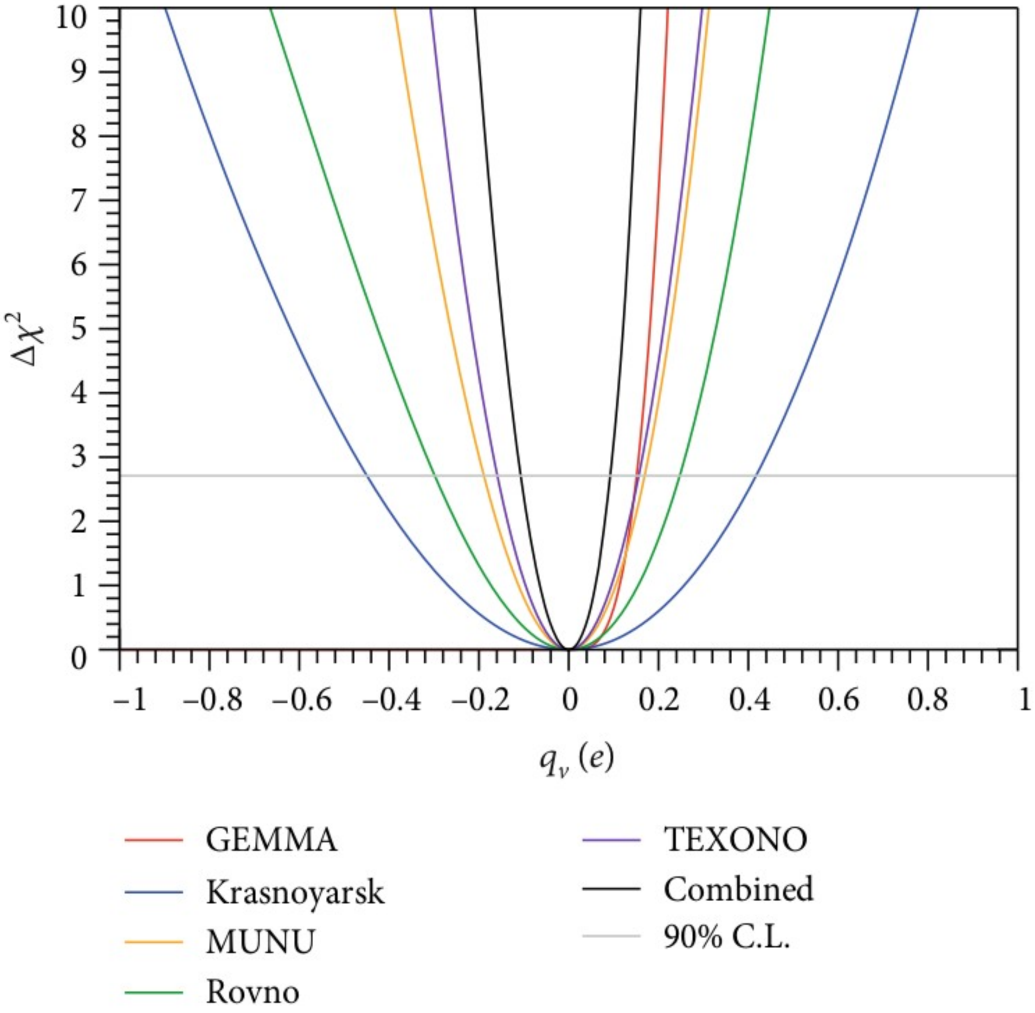
$$R(T_e, T'_e) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(\frac{-(T_e - T'_e)^2}{2\sigma^2}\right).$$

χ^2 Analysis

$$\chi^2 = \sum_{i=1}^{N_{\rm bin}} \frac{(N^{\rm SM} - N^{\rm th}(q_\nu))^2}{\Delta_i^2}$$

Results from ENES experiments

$\Delta\chi^2$ sensitivity profile for q_ν (in units of $10^{-11}e$)



90% C.L. Limits on q_ν (in units of $10^{-12}e$)

Experiment	Limit
Rovno	$-3.0 < q_\nu < 2.5$
Krasnoyarsk	$-4.5 < q_\nu < 4.2$
MUNU	$-1.9 < q_\nu < 1.7$
TEXONO	$-1.6 < q_\nu < 1.6$
GEMMA	$q_\nu < 1.5$
Combined	$-1.1 < q_\nu < 0.93$

Combined limit:

$$-1.1 \times 10^{-12}\mathrm{e} < q_\nu < 9.3 \times 10^{-13}\mathrm{e}$$

[16] A. Parada, Adv. High Energy Phys. 2020 (2020) 5908904.

Analysis from CEvNS experimental proposals of reactor antineutrinos

Cross section of CEvNS

$$\left(\frac{d\sigma}{dT}\right)^{\text{coh}}_{\textbf{tot}} = \left(\frac{d\sigma}{dT}\right)^{\text{coh}}_{\textbf{SM}} + \left(\frac{d\sigma}{dT}\right)^{\text{coh}}_{\textbf{EM}} + \left(\frac{d\sigma}{dT}\right)^{\text{coh}}_{\textbf{INT}}$$

Standard Model contribution

$$\left(\frac{d\sigma}{dT}\right)^{\text{coh}}_{\textbf{SM}} = \frac{G_{\text{F}}^2 M}{\pi}\left[1 - \frac{MT}{2E_\nu^2}\right]\left(g_V^p Z + g_V^n N\right)^2 F(Q^2),$$

where g_V^p and g_V^n represent the vector couplings,

$$\begin{aligned} g_V^p &= \rho_{\nu N}^{NC}\left(\frac{1}{2} - 2\hat{\kappa}_{\nu N}\hat{S}_Z^2\right) + 2\lambda^{uL} + 2\lambda^{uR} + \lambda^{dL} + \lambda^{dR}, \\ g_V^n &= -\frac{1}{2}\rho_{\nu N}^{NC} + \lambda^{uL} + \lambda^{uR} + 2\lambda^{dL} + 2\lambda^{dR} \end{aligned}$$

$F(Q^2)$ corresponds to the nuclear form factor.

Electromagnetic and interference contributions

$$\left(\frac{d\sigma}{dT}\right)^{\text{coh}}_{\textbf{EM}} = \frac{2\pi Z^2}{MT^2}\left(1-\frac{MT}{2E_\nu^2}\right)q_\nu^2 \qquad \left(\frac{d\sigma}{dT}\right)^{\text{coh}}_{\textbf{INT}} = \frac{\sqrt{8}G_F C_V Z}{T}\left(1-\frac{MT}{2E_\nu^2}\right)q_\nu$$

$$\text{with } C_V = g_V^p Z + g_V^n N$$

CEvNS experiments

TEXONO experiment at Kuo Sheng NPP(Taiwan)

http://wikimapia.org/197066/Kalinin-Nuclear-Power-Plant

CONNIE experiment at Angra NPP (Brasil)

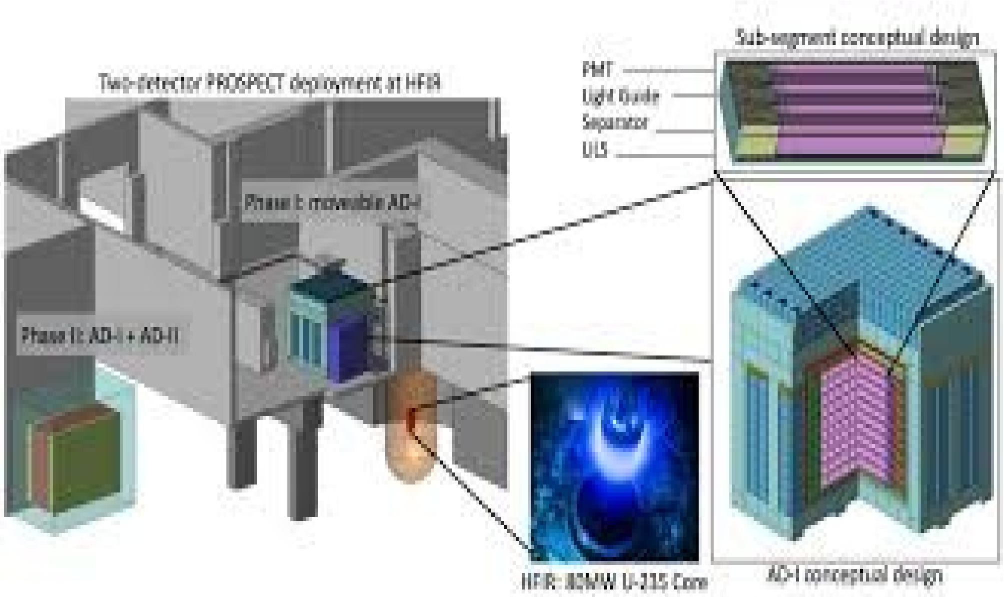
https://elperiodicodelaenergia.com/la-central-nuclear-brasilena-construida-en-medio-de-un-paraiso/

CONUS experiment at Brokdorf NPP (Germany)

Kernkraftwerk Brokdorf.

RED100 experiment at Kalinin NPP (Russia)

Kalinin-Nuclear-Power-Plant



MINER experiment at the Nuclear Science Center at Texas A&M University.

Experiment's characteristics

Experiment	**Baseline (m)**	$\bar{\nu}_e$**flux**$(\mathbf{cm^{-2}s^{-1}})$	**Mass (Kg)**	**Material**	**Events expected**
CONNIE [9]	30	7.8×10^{12}	1	Silicon	$16.1\ evt \cdot Kg^{-1} \cdot day^{-1}$
CONUS [10]	17	2.5×10^{13}	4	Germanium	$31200\ evt \cdot day^{-1}$
MINER [11]	1	2.5×10^{13}	4	^{72}Ge and ^{28}Si	$5 - 20\ evt \cdot Kg^{-1} \cdot day^{-1}$
RED100 [12]	19	1.35×10^{13}	100	^{136}Xe	$1020\ evt \cdot day^{-1}$
TEXONO [13]	28	1×10^{13}	1	Germanium	$27962\ evt \cdot year^{-1}$

[9] A. Aguilar-Arevalo, et al, Journal of Instrumentation, vol 11, no 7, 012057, 2016.

[10] Y. Farzan, et al., Journal of High Energy Physics, vol 2018, no 5, 66, 2018.

[11] G. Agnolet, et al., Nuclear Instruments and Methods in Physics Research, vol 853, pp. 53-60, 2017

[12] D. Y. Akimov, et al., Journal of Instrumentation, vol 12, no. 6, C06018, 2017

[13] H. T. Wong, Nuclear Physics A, Vol. 844, no. 1-4, pp. 229C-233c, 2010.

Theoretical number of events

$$N^{\text{th}} = t\phi_0 \frac{M_{\text{detector}}}{M} \int_{E_{\nu\text{min}}}^{E_{\nu\text{max}}} \lambda(E_\nu) dE_\nu \int_{T_{\text{min}}}^{T_{\text{max}}(E_\nu)} \left(\frac{d\sigma}{dT}\right)_{\text{tot}}^{\text{coh}} dT$$

$t \rightarrow$ experiment's exposure time, $\phi_0 \rightarrow$ antineutrino flux from the reactor

χ^2 statistical analysis

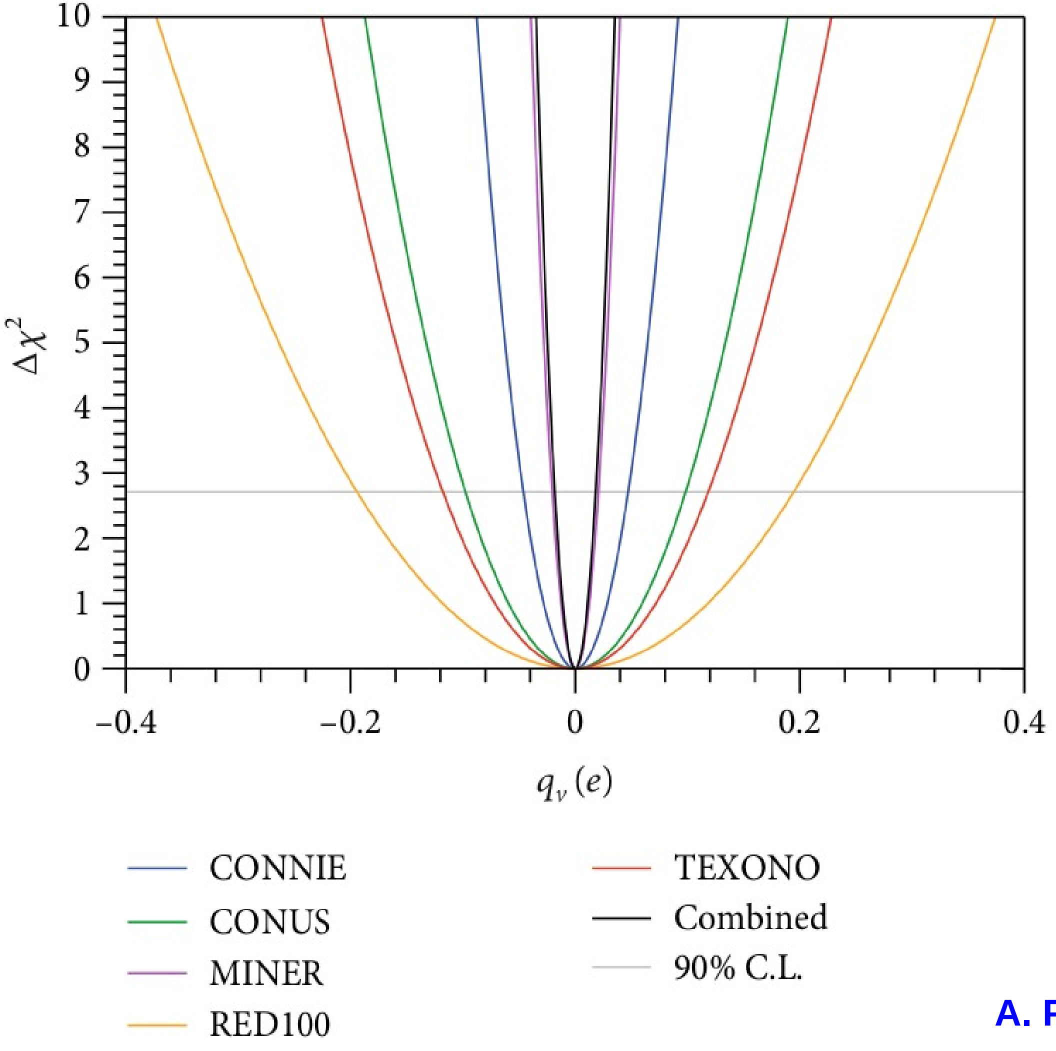
$$\chi^2 = \frac{(N^{\text{SM}} - N^{\text{th}}(q_\nu))^2}{\sigma_{\text{stat}}^2 + \sigma_{\text{syst}}^2}$$

- Only statiscal errors ($\sigma_{\text{stat}} = \sqrt{N^{SM}}$)
- By including statistical and systematic uncertainties ($\sigma_{syst} = pN^{th}$)

Results from CEvNS experiments

$\Delta\chi^2$ **sensitivity profile for** q_ν **(in units of** $10^{-12}e$**)**

Only statistical errors



90% **C.L. Limits on** q_ν **(in units of** $10^{-14}e$**)**

Experiment	Limit
CONNIE	$-4.6 < q_\nu < 4.7$
CONUS	$-9.8 < q_\nu < 9.8$
MINER	$-2.0 < q_\nu < 2.1$
RED100	$-19 < q_\nu < 19$
TEXONO	$-12 < q_\nu < 12$
Combined	$-1.8 < q_\nu < 1.8$

Combined limit:

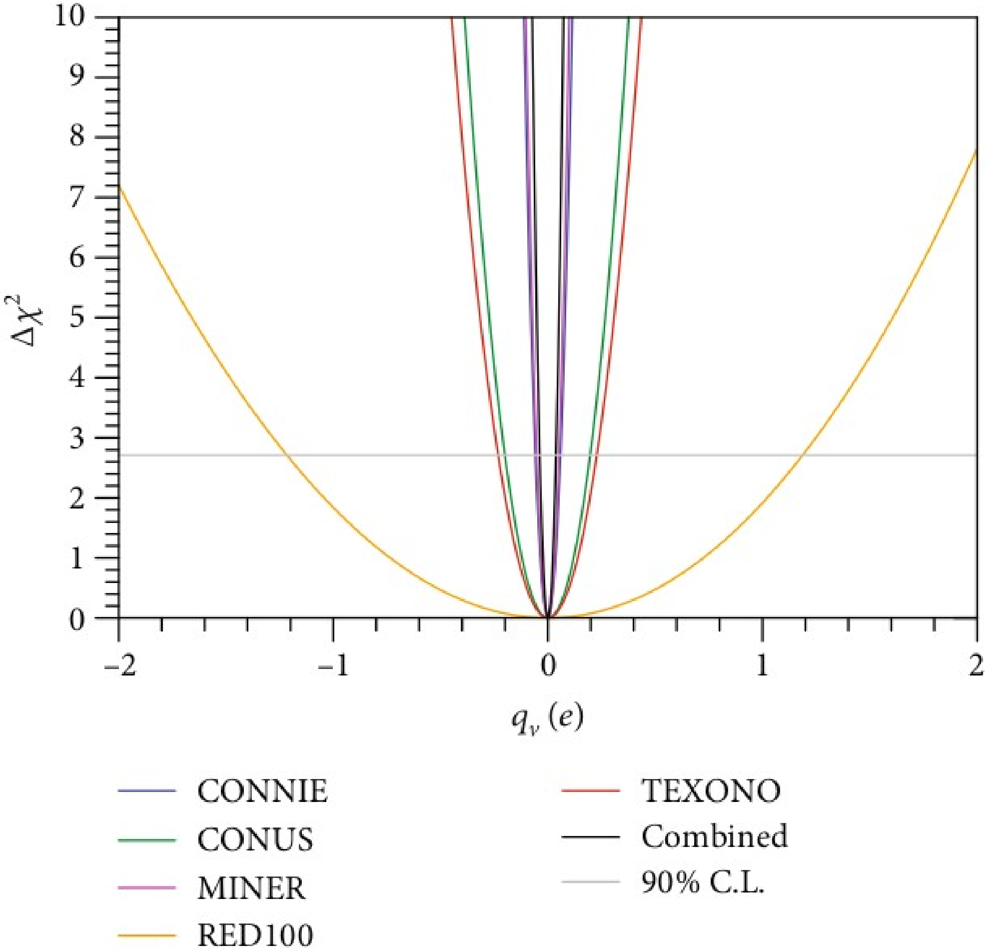
$$-1.8 \times 10^{-14}\mathrm{e} < q_\nu < 1.8 \times 10^{-14}\mathrm{e}$$

A. Parada, Adv. High Energy Phys. 2020 (2020) 5908904.

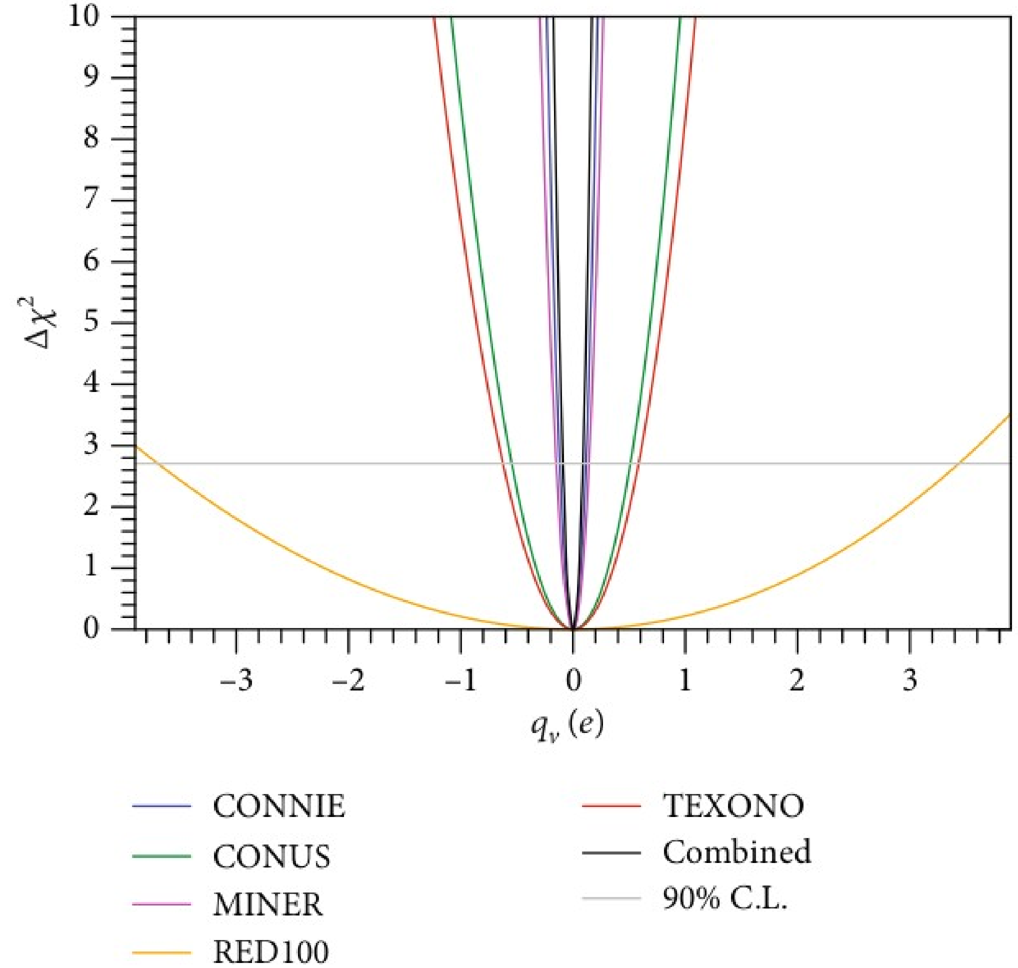
Results from CEvNS experiments

$\boldsymbol{\Delta\chi^2}$ **sensitivity profile for** q_ν **(in units of** $10^{-12}e$**)**

$\sigma_{syst} = 1\% N^{\mathbf{th}}$



$\sigma_{syst} = 3\% N^{\mathbf{th}}$



A. Parada, Adv. High Energy Phys. 2020 (2020) 5908904.

Results from CEvNS experiments

90% **C.L. Bounds on** q_ν **(in units of** $10^{-14}e$**)**

Experiment	Limit ($p = 1\%$)	Limit ($p = 3\%$)
CONNIE	$-5.9 < q_\nu < 5.9$	$-12 < q_\nu < 12$
CONUS	$-20 < q_\nu < 20$	$-55 < q_\nu < 51$
MINER	$-5.3 < q_\nu < 5.2$	$-15 < q_\nu < 14$
RED100	$-120 < q_\nu < 120$	$-370 < q_\nu < 340$
TEXONO	$-23 < q_\nu < 23$	$-63 < q_\nu < 59$
Combined	$-3.8 < q_\nu < 3.8$	$-9.0 < q_\nu < 8.8$

Combined limit for $\sigma_{\mathrm{syst}} = 3\%\mathrm{N}^{\mathrm{th}}$

$$-9.0 \times 10^{-14}\mathrm{e} < \mathrm{q}_\nu < 8.8 \times 10^{-14}\mathrm{e}$$

A. Parada, Adv. High Energy Phys. 2020 (2020) 5908904.

Conclusions

- We carried out a phenomenological study to constraint the neutrino electric millicharge by using data from ENES and CEvNS experimental proposals of reactor antineutrinos.
- In the context of ENES experiments, we obtained combined limits: $-1.1 \times 10^{-12}e < q_\nu < 9.3 \times 10^{-13}e$ at 90% C.L.
- Regarding CEvNS proposals, we achieved combined bounds: $-9.0 \times 10^{-14}e < q_\nu < 8.8 \times 10^{-14}e$ at 90% C.L, including statistical and systematic uncertainties.
- In the near future CEvNS experiments of reactor antineutrinos would be an important option to probe the neutrino electric millicharge.


感謝你
Danke
Gracias
Grazie
Merci
Thanks!
THANK
YOU!