

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



NuCo 2021: Neutrinos en Colombia

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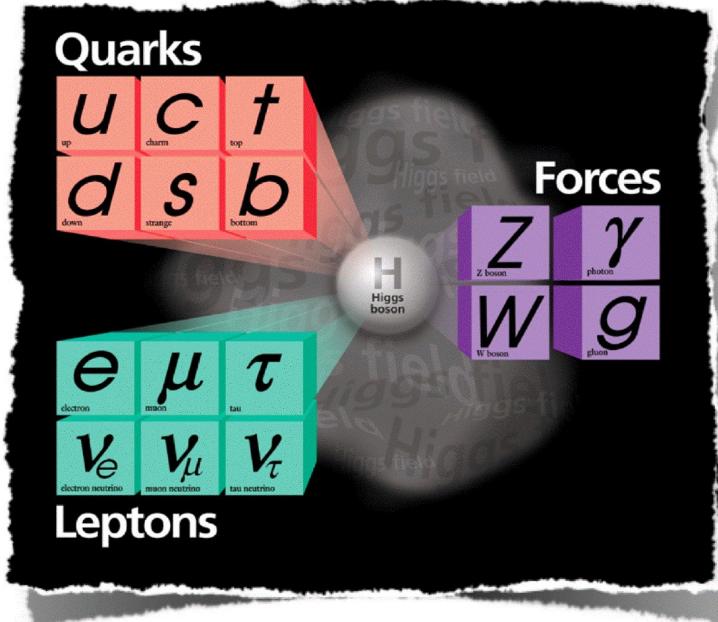
Outline

- Introduction.
- The neutrino electric millicharge (NEM).
- Bounds on NEM from ENES experiments of reactor antineutrinos.
- Constraints on NEM from CEvNS future experiments of reactor antineutrinos.
- Conclusions.



Introduction

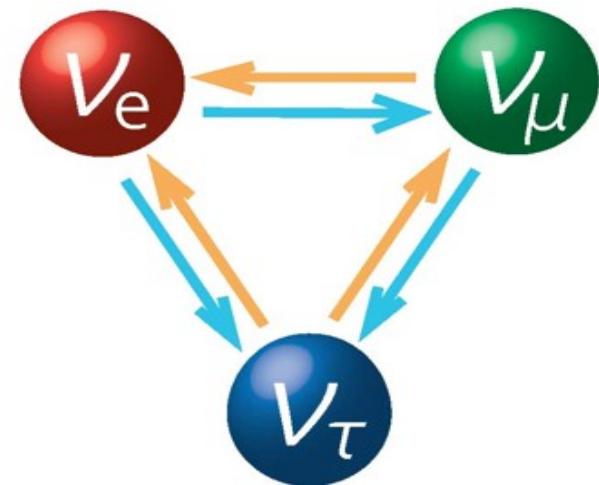
Standard Model (SM)



Fermi National Accelerator Laboratory

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

Neutrino Oscillations



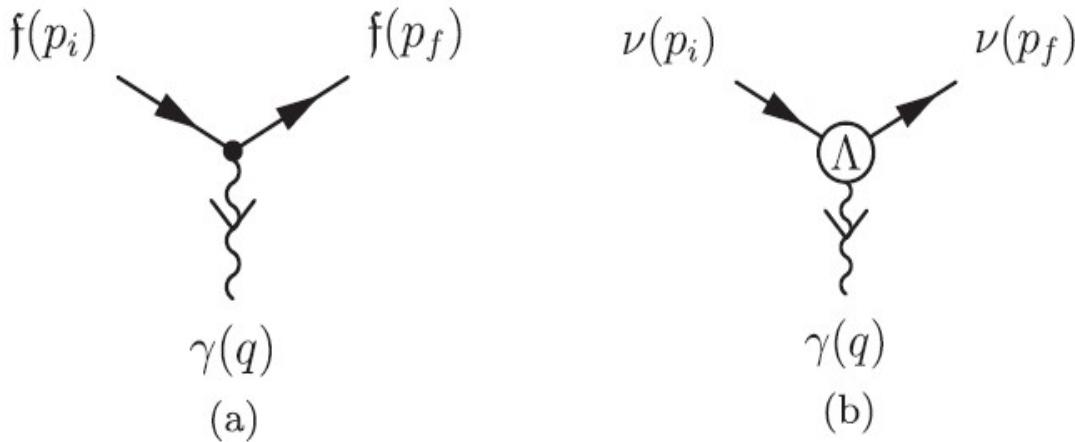
Neutrinos are massive particles



To extend the SM to explain the neutrino mass

Neutrino electric millicharge (NEM)

Tree level coupling $f - \gamma$



Amplitud de neutrino-photon electromagnetic interaction

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

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

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,

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

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

Some limits on NEM from different sources

- Based on the neutrality of matter [2] → $q_\nu \leq 3 \times 10^{-21} e$
- Neutrino Star Turning mechanism [3] → $q_\nu \leq 1.3 \times 10^{-19} e$
- Analysis of SN 1987 A neutrinos [4] → $q_\nu \leq 2 \times 10^{-15} e$
- From TEXONO experiment data [5] → $q_\nu \leq 3.7 \times 10^{-12} e$
- From GEMMA experiment data [6] → $q_\nu \leq 1.5 \times 10^{-12} e$
- Involving electron neutrino flavor
(from COHERENT experiment data)[7] → $q_{\nu x} \sim 1 \times 10^{-7} e \ (x = e, \mu, \tau)$

- [2] G. G. Raffelt, Physics Reports, vol. 320, no 1-6, pp. 319-327. 1999
- [3] A. I. Studenikin and I. Tokarev, Nuclear Physics B, vol 884, pp. 396-407, 2014.
- [4] G. Barbiellini and G. Cocconi, Nature, vol. 329, no. 6134, pp. 21-22, 1987.
- [5] S. N. Glinenko, N. V. Krasnikov and A. Rubbia, Phys. Rev. D 75, 075014 (2007).
- [6] A. Studenikin, EPL 107, no. 2, 21001 (2014) Erratum: [EPL 107, no. 3, 39901 (2014)].
- [7] 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

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

The Standard Model contribution

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

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

The Electromagnetic and interference contributions

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

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/>

MUNU experiment at Bugey NPP (France)



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

GEMMA at Kalinin nuclear power plant (Russia)



Kalinin-Nuclear-Power-Plant

TEXONO experiment at Kuo Sheng NPP(Taiwan)



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

Theoretical number of events (in the ith bin)

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

with the resolution function

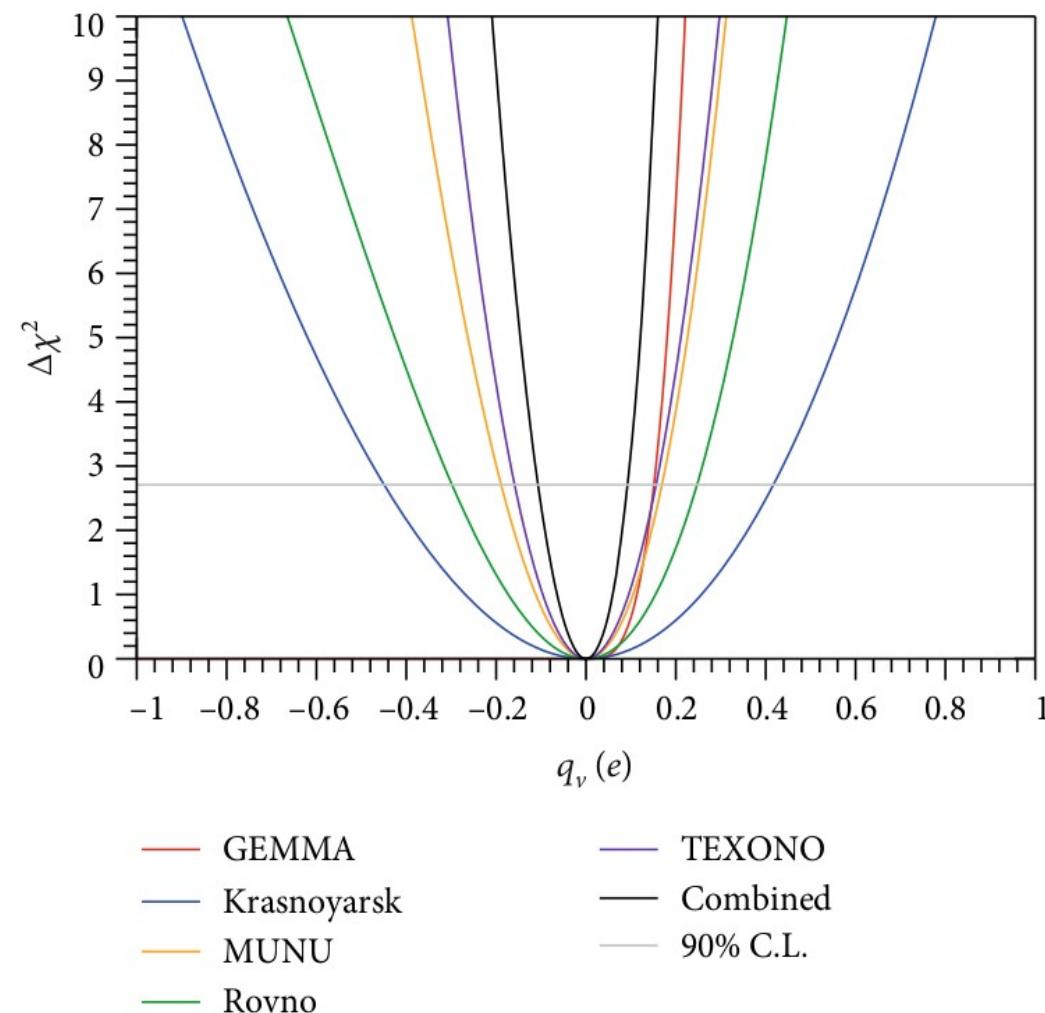
$$R(T_e, T'_e) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(\frac{-(T_e - T'_e)^2}{2\sigma^2}\right).$$

χ^2 Analysis

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

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:

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

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

Analysis from CEvNS experimental proposals of reactor antineutrinos

Cross section of CEvNS

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

Standard Model contribution

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

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

$$\left(\frac{d\sigma}{dT} \right)_{\text{EM}}^{\text{coh}} = \frac{2\pi Z^2}{MT^2} \left(1 - \frac{MT}{2E_\nu^2} \right) q_\nu^2$$

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

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-brasileña-construida-en-medio-de-un-paraiso/>

CONUS experiment at Brokdorf NPP (Germany)

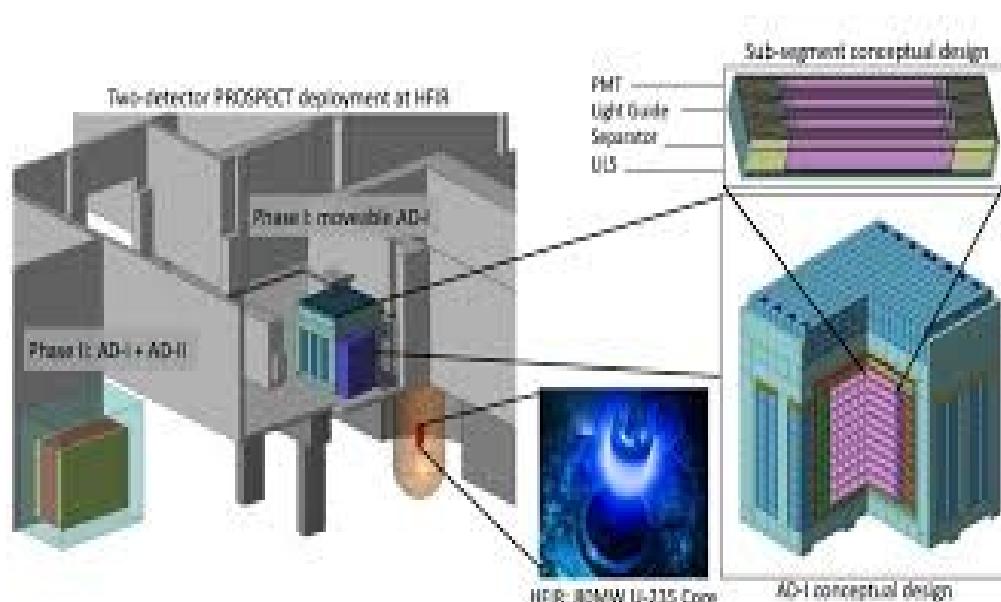


Kernkraftwerk Brokdorf.

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

[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

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

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

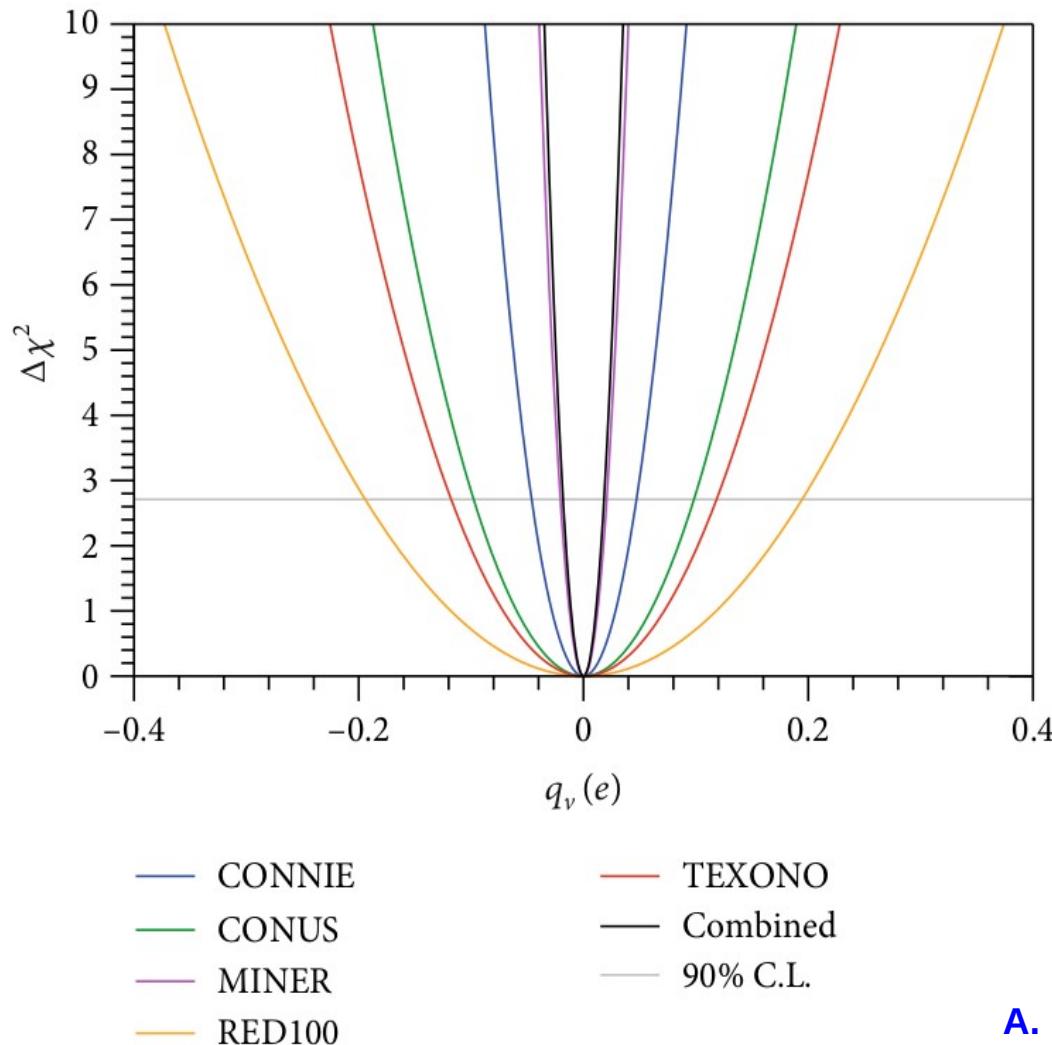
χ^2 statistical analysis

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

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

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:

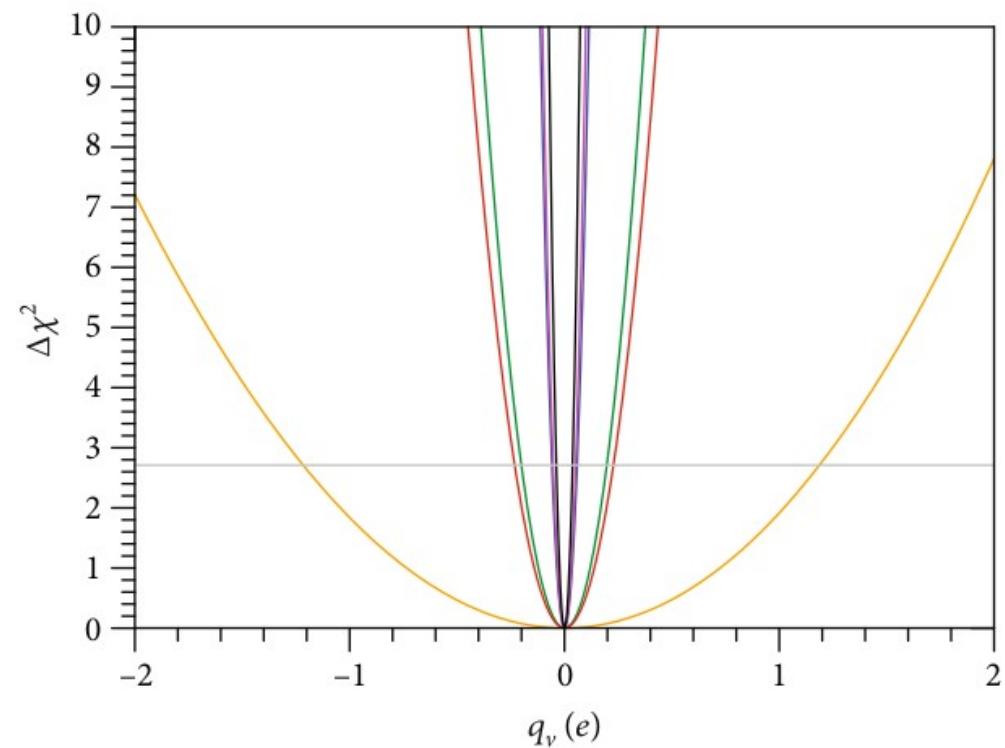
$$-1.8 \times 10^{-14}e < q_\nu < 1.8 \times 10^{-14}e$$

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

Results from CEvNS experiments

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

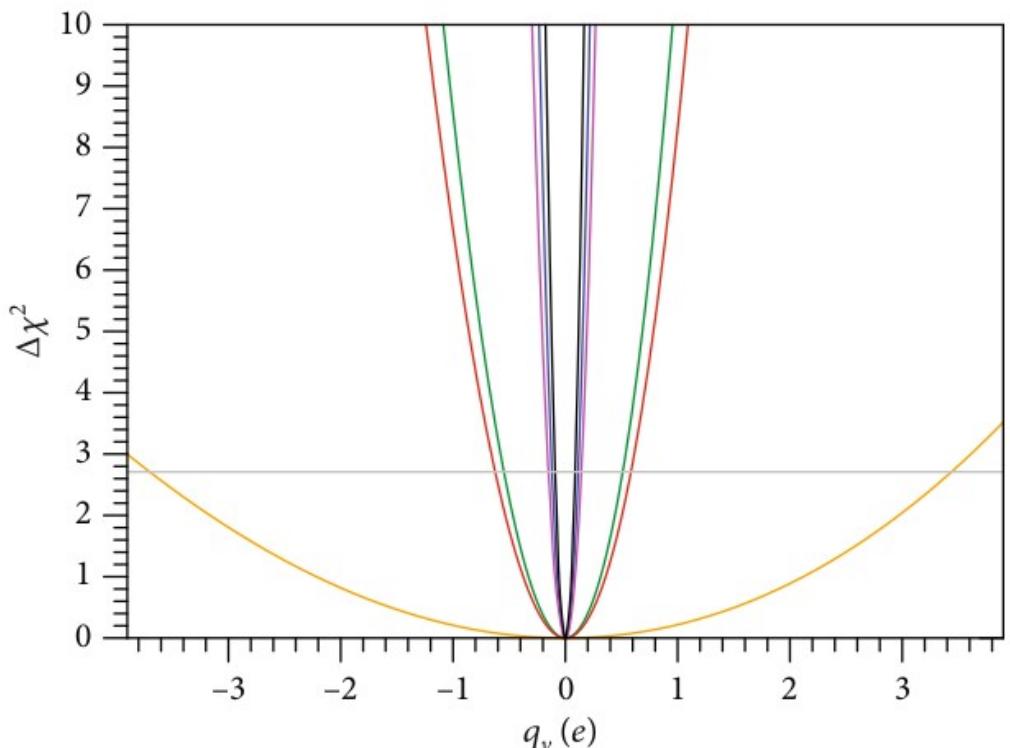
$$\sigma_{syst} = 1\%N^{\text{th}}$$



- CONNIE
- CONUS
- MINER
- RED100

- TEXONO
- Combined
- 90% C.L.

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



- CONNIE
- CONUS
- MINER
- RED100

- TEXONO
- Combined
- 90% C.L.

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

$$-9.0 \times 10^{-14}e < q_\nu < 8.8 \times 10^{-14}e$$

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.

