Constraints on nonstandard interactions and the neutron radius from coherent elastic neutrino-nucleus scattering experiments

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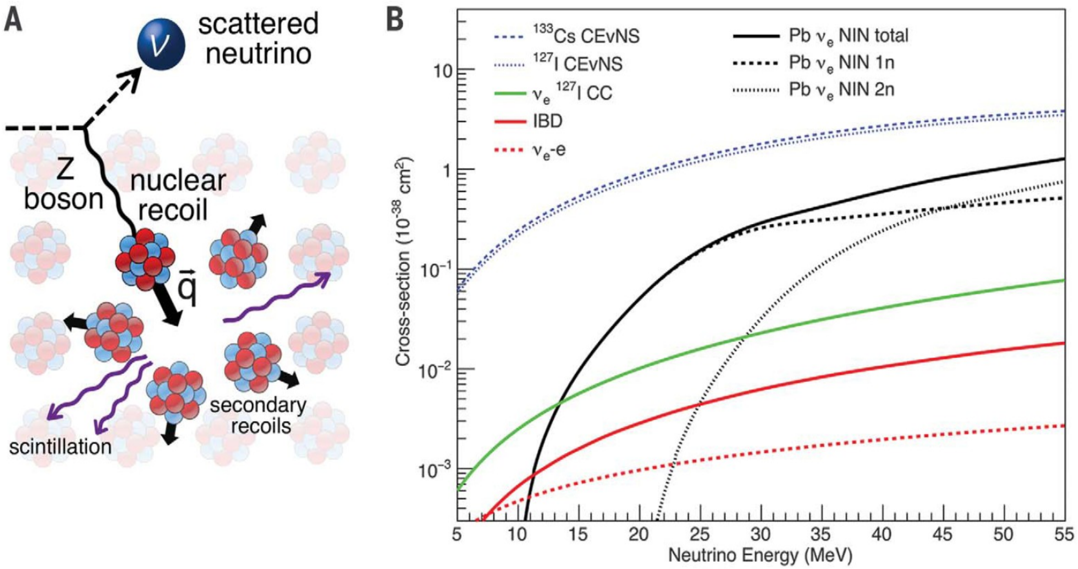
Outline

- Introduction
- CEvNS and Nonstandard Interactions (NSI)
- CEvNS experiments with Spallation Neutron Source (SNS)
- Conclusions

Introduction

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)



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

The coherence condition: $Q \leq 1/R$

Talk ICHEP 2020: The COHERENT Experiment at the Spallation Neutron Source (Alexey Konovalov)

CEvNS was proposed by Daniel Freedman (1974)
[2] D. Z. Freedman, Phys. Rev. D 9, 1389 (1974)

CEvNS observation for the first time: COHERENT Collaboration (2017)
[1] D. Akimov et al., Science 357, no. 6356, 1123 (2017)

CEvNS detection on argon: COHERENT Collaboration (2020)
[3] D. Akimov et al.,arXiv:2003.10630.

CEvNS in the Standard Model (SM) and beyond SM

- Nonstandard Interactions [4]
- Searches for sterile neutrinos [5,6]
- Measurements on weak mixing angle [7]
- Nuclear density distributions [8,9,10]
- Neutrino electromagnetic properties [11]
- Neutrino couplings to light scalars [12]

The main idea

Studying the future sensitivity of CEvNS experiments to nuclear physics and nonstandard parameters.

[4] J. Barranco, et al., JHEP 0512, 021 (2005)
[5] B. C. Cañas, et al., Phys. Lett. B 776, 451 (2018)
[6] Bhaskar Dutta, et al.,Phys. Rev. D 94, 093002 (2016)
[7] B. C. Cañas, et al., Phys. Lett. B 784, 159 (2018)
[8] M. Cadeddu, et al., Phys. Rev. Lett. 120, 072501 (2018)
[9] Pilar Coloma, arXiv:2006.08624
[10] K. Patton, et al., Phys. Rev. C 86, 024612 (2012)
[11] T. S. Kosmas, et al.,, Phys. Rev. D 92, no. 1, 013011 (2015)
[12] Y. Farzan, et al., JHEP 1805, 066 (2018)

SM cross section of CEνNS

$$\left(\frac{d\sigma}{dT}\right)^{\mathrm{coh}}_{\mathrm{SM}} = \frac{G_F^2 M}{\pi}\left[1-\frac{MT}{2E_\nu^2}\right]\left[Z g_V^p F_Z(q^2) + N g_V^n F_N(q^2)\right]^2.$$

$F_{Z,N}(q^2) \rightarrow$ Nuclear form factors.

Neutral current vector couplings

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

$\rho_{\nu N}^{NC} = 1.0086$, $\hat{s}_Z^2 = \sin^2\theta_W = 0.2312$, $\hat{\kappa}_{\nu N} = 0.9978$, $\lambda^{uL} = -0.0031$, $\lambda^{dL} = -0.0025$,

and $\lambda^{dR} = 2\lambda^{uR} = 7.5 \times 10^{-5}$

[13] C. Patrignani et al. (Particle Data Group), Chin. Phys. C 40, 100001 (2016).

NSI in future reactor experimental proposals of CEvNS

Cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}T}(E_\nu,T) \simeq \frac{G_F^2 M}{\pi}\left(1-\frac{MT}{2E_\nu^2}\right)\left\{\left[Z\left(g_V^p+2\varepsilon_{ee}^{uV}+\varepsilon_{ee}^{dV}\right)F_Z^V(Q^2)+N\left(g_V^n+\varepsilon_{ee}^{uV}+2\varepsilon_{ee}^{dV}\right)F_N^V(Q^2)\right]^2 + \sum_\alpha \left[Z\left(2\varepsilon_{\alpha e}^{uV}+\varepsilon_{\alpha e}^{dV}\right)F_Z^V(Q^2)+N\left(\varepsilon_{\alpha e}^{uV}+2\varepsilon_{\alpha e}^{dV}\right)F_N^V(Q^2)\right]^2\right\},$$

$\varepsilon_{\alpha\beta}^{qV}$ (with $q = u, d, V = L, R$ and $\alpha, \beta = e, \mu, \tau$) are the NSI parameters.

And $F_{Z,N}^V(Q^2) \simeq 1$

Theoretical number of events

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

$\lambda(E_\nu)$ → Antineutrino energy spectrum
ϕ_0 → Total antineutrino flux
t → Exposure time

$$\lambda(E_\nu) = \Sigma_l f_l \lambda_l(E_\nu) = \Sigma_l f_l \exp\left[\Sigma_{k=1}^{6}\alpha_{kl}E_\nu^{k-1}\right]$$

[14] T. Mueller *et al.*, Phys.Rev. C83,054615 (2011)

Statistical analysis

$$\chi^2 = \frac{(N^{\text{SM}}_{\text{events}} - N^{th})^2}{\sigma^2_{stat} + \sigma^2_{syst}}$$

σ^2_{stat} → Statistical uncertainty.

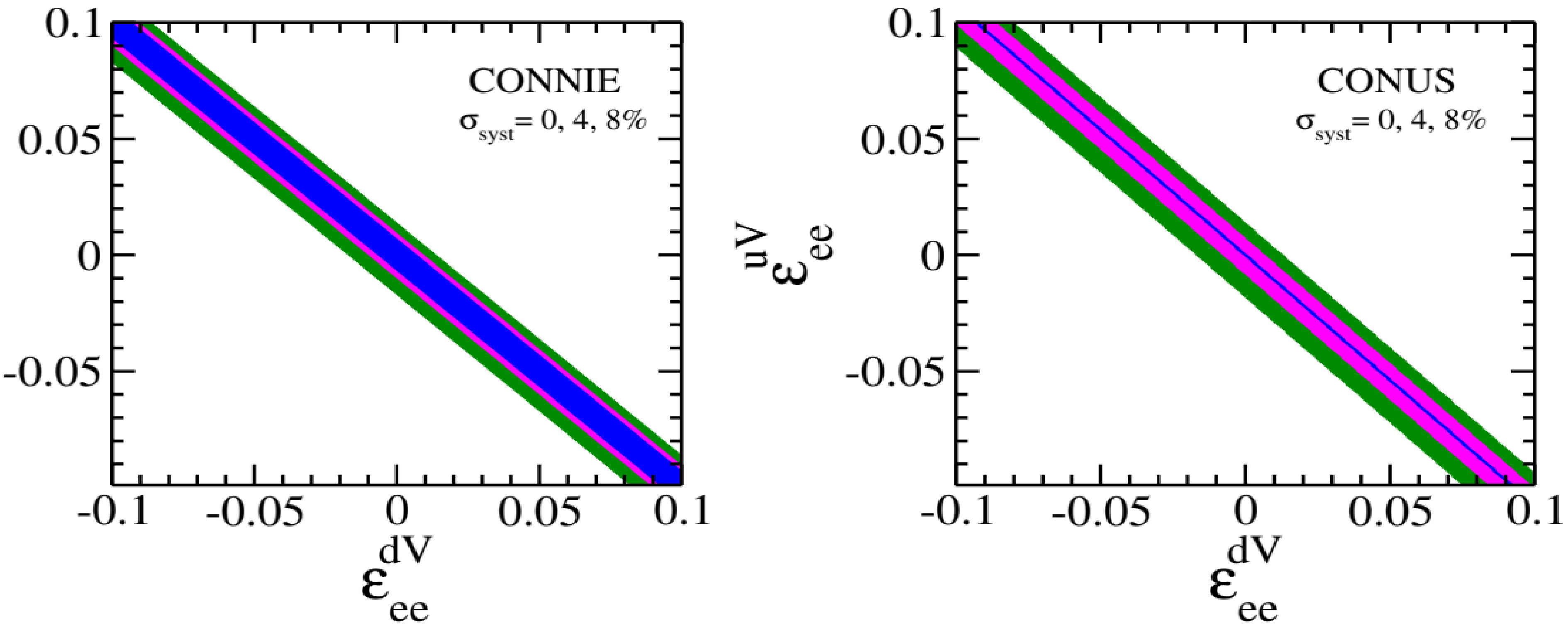
σ^2_{syst} → Systematic error.

CEvNS experimental proposals

	T_{thres}	Baseline	Z/N	Det. Tec.	Fid. Mass
CONNIE [15]	28 eV	30 m	1.0	CCD (Si)	0.1 – 1 kg
CONUS [16]	100 eV	10 m	0.79	HPGe	4 – 100 kg

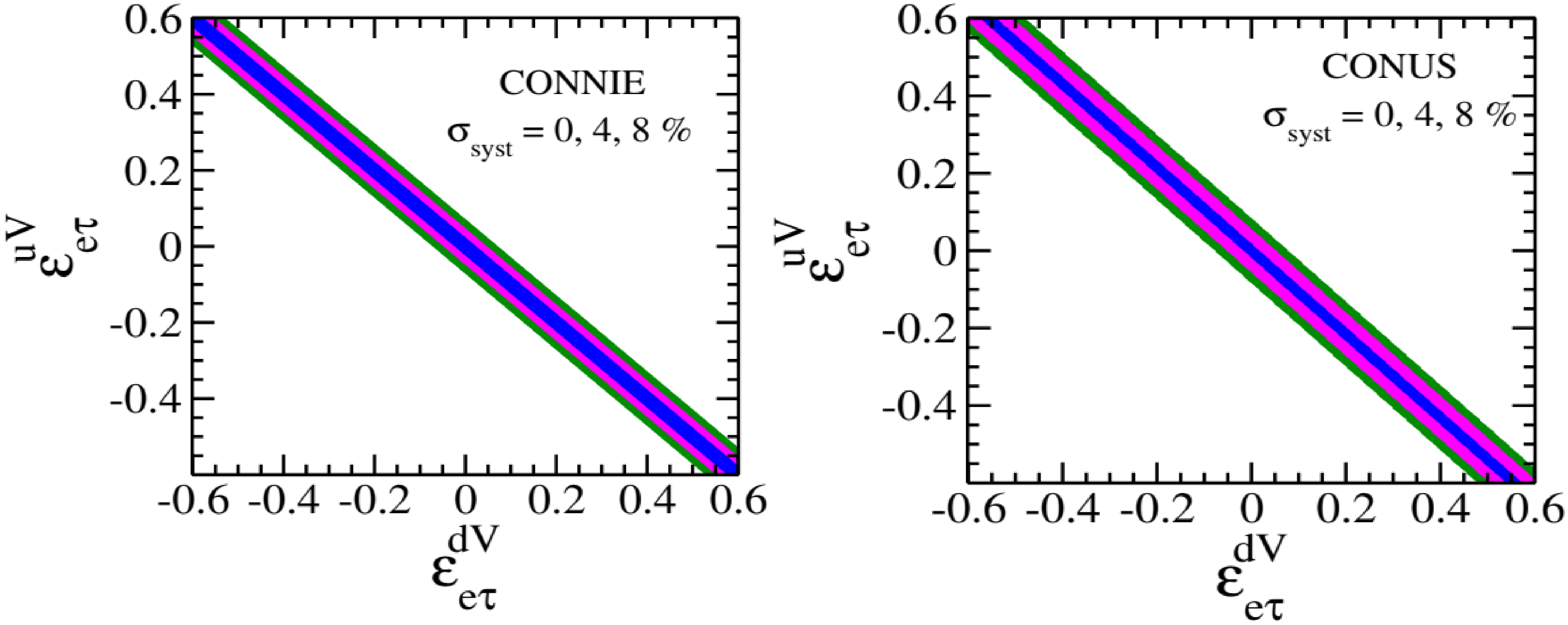
[15] A. Aguilar-Arevalo et al. (CONNIE), JINST 11, P07024 (2016)
[16] M. Lindner, W. Rodejohann, and X.-J. Xu, JHEP 03, 097 (2017)

Future sensitivity to nonuniversal NSI parameters



B. C. Cañas *et al*., Phys. Rev. D 101, 0351012 (2020)

Future sensitivity to flavor changing NSI parameters



B. C. Cañas *et al*., Phys. Rev. D 101, 0351012 (2020)

These results in a future would improve current limits obtained from other experiments.

[17] Y. Farzan and M. Tortola, Front. Phys. 6, 10 (2018)
[18] O. G. Miranda and H. Nunokawa, New J. Phys. 17, 095002 (2015)
[19] T. Ohlsson, Rep. Prog. Phys. 76, 044201 (2013)

Future combined analysis (CONNIE + CONUS)

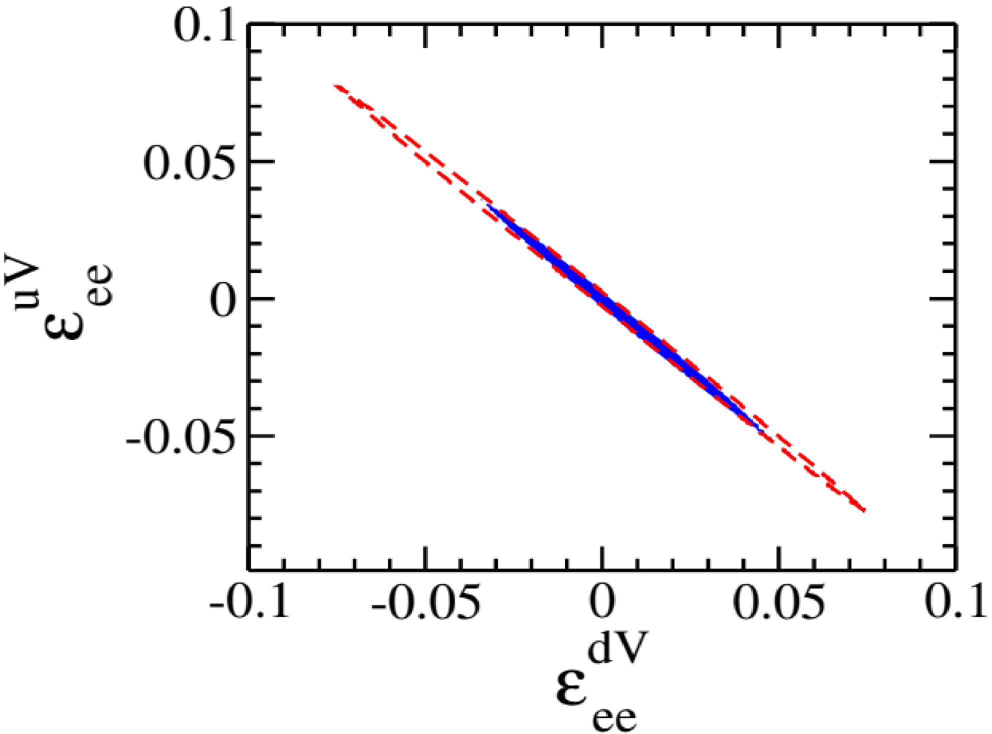
$$\chi^2 = \sum_{ij} \frac{(N_i^{theo} - N_i^{exp})(N_j^{theo} - N_j^{exp})}{\sigma_{ij}^2}.$$

Covariance matrix: $\sigma_{ij}^2 = \Delta_i^2 \delta_{ij} + \sum_l \delta N_i^l \delta N_j^l.$

$\Delta_i^2 \rightarrow$ Statistical uncertainty.

$\delta N_i^l \rightarrow$ Systematic error due to l isotope.

[20] P. Huber *et al*, Phys. Rev. D70, 053011 (2004)



B. C. Cañas *et al*., Phys. Rev. D 101, 0351012 (2020)

Dashed red line: 2% of systematic error (without correlations).

CEvNS experiments with SNS

COHERENT experiment

[21] https://sites.duke.edu/coherent/sns-aerial_0/

Neutrinos from SNS

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

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Total neutrino flux

$$\frac{\mathrm{dN}_\nu}{\mathrm{d}E} = \frac{\mathrm{dN}_{\nu_\mu}}{\mathrm{d}E} + \frac{\mathrm{dN}_{\bar{\nu}_\mu}}{\mathrm{d}E} + \frac{\mathrm{dN}_{\nu_e}}{\mathrm{d}E}$$

$$\frac{\mathrm{dN}_{\nu_\mu}}{\mathrm{d}E} = \eta\delta\left(E - \frac{m_\pi^2 - m_\mu^2}{2m_\pi}\right), \quad \frac{\mathrm{dN}_{\bar{\nu}_\mu}}{\mathrm{d}E} = \eta\frac{64E^2}{m_\mu^3}\left(\frac{3}{4} - \frac{E}{m_\mu}\right), \quad \frac{\mathrm{dN}_{\nu_e}}{\mathrm{d}E} = \eta\frac{192E^2}{m_\mu^3}\left(\frac{1}{2} - \frac{E}{m_\mu}\right).$$

$\eta \to$ Normalization factor.

Neutron and proton form factors

$$\frac{\mathrm{d}\sigma}{\mathrm{d}T}(E_\nu, T) \simeq \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\left\{\left[Z\left(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}\right)F_Z^V(Q^2) + N\left(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}\right)F_N^V(Q^2)\right]^2 + \sum_\alpha \left[Z\left(2\varepsilon_{\alpha e}^{uV} + \varepsilon_{\alpha e}^{dV}\right)F_Z^V(Q^2) + N\left(\varepsilon_{\alpha e}^{uV} + 2\varepsilon_{\alpha e}^{dV}\right)F_N^V(Q^2)\right]^2\right\}.$$

$E_\nu \sim 52\mathrm{MeV},$ $\quad Q^2 = 2MT,$ $\quad F_{Z,N}^V(Q^2) \neq 1$

Symmetrized Fermi form factor

$$F_A^{SF}(Q^2) = \frac{3}{Qc_A\left[(Qc_A)^2 + (\pi Qa)^2\right]}\left[\frac{\pi Qa}{\sinh(\pi Qa)}\right]\left[\frac{\pi Qa \sin(Qc_A)}{\tanh(\pi Qa)} - Qc_A\cos(Qc_A)\right].$$

$A = Z, N$ $\quad \mathbf{R_A^2} = \frac{\mathbf{3}}{\mathbf{5}}\mathbf{c_A^2} + \frac{\mathbf{7}}{\mathbf{5}}(\pi\mathbf{a})^{\mathbf{2}},$

$a = 0.5233fm.$

[22] J. Piekarewicz, et al., Phys. Rev. C94, 034316 (2016)

Statistical analysis from CsI COHERENT data

Theoretical number of events

$$N^{th} = N_D \int_T A(T)dT \int_{E_{min}}^{52.8MeV} dE \sum_a \frac{\mathrm{d}N_a}{\mathrm{d}E} \frac{\mathrm{d}\sigma_a}{\mathrm{d}T}.$$

Acceptance function

$$A(x) = \frac{a}{1 + \exp(-k(x - x_0))} \Theta(x - 5)$$

[23] D. Akimov et al. (COHERENT) (2017), 1708.01294

$$\chi^2 = \left(\frac{N^{exp} - (1+\alpha)N^{th}(X) - (1+\beta)N^{bg}}{\sigma_{stat}} \right)^2 + \left(\frac{\alpha}{\sigma_\alpha} \right)^2 + \left(\frac{\beta}{\sigma_\beta} \right)^2$$

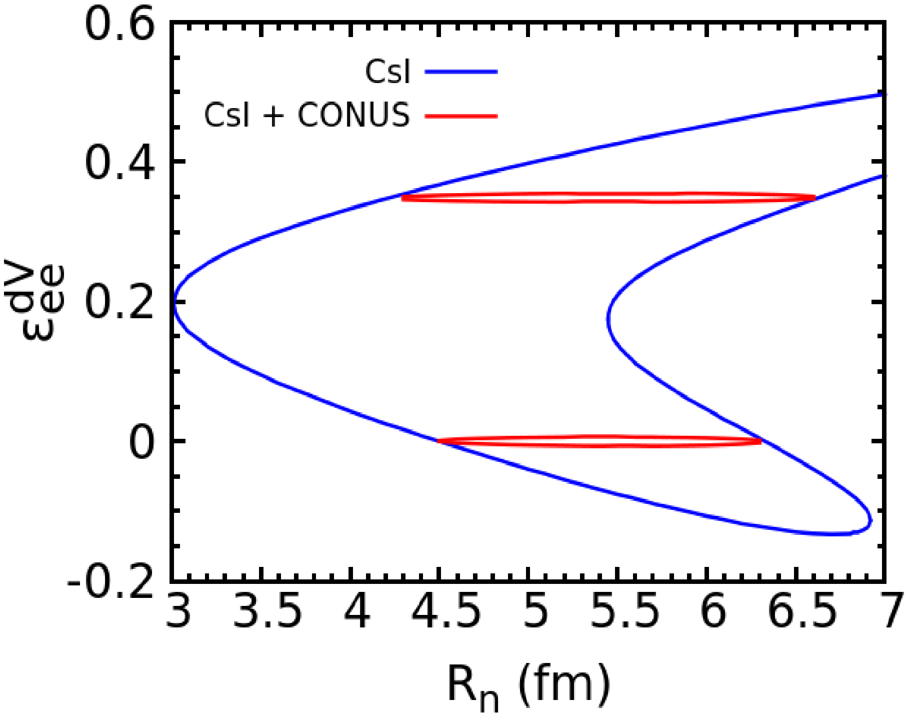
$X = \{\epsilon_{ee}^{dV}, R_n\}$ $\qquad$ N^{bg} $\rightarrow$ Background events number.

α $\rightarrow$ Systematic error of the signal rate.

β $\rightarrow$ Systematic error of the background rate.

Allowed region (ε_{ee}^{dV} vs R_n) from CsI COHERENT data (1σ)

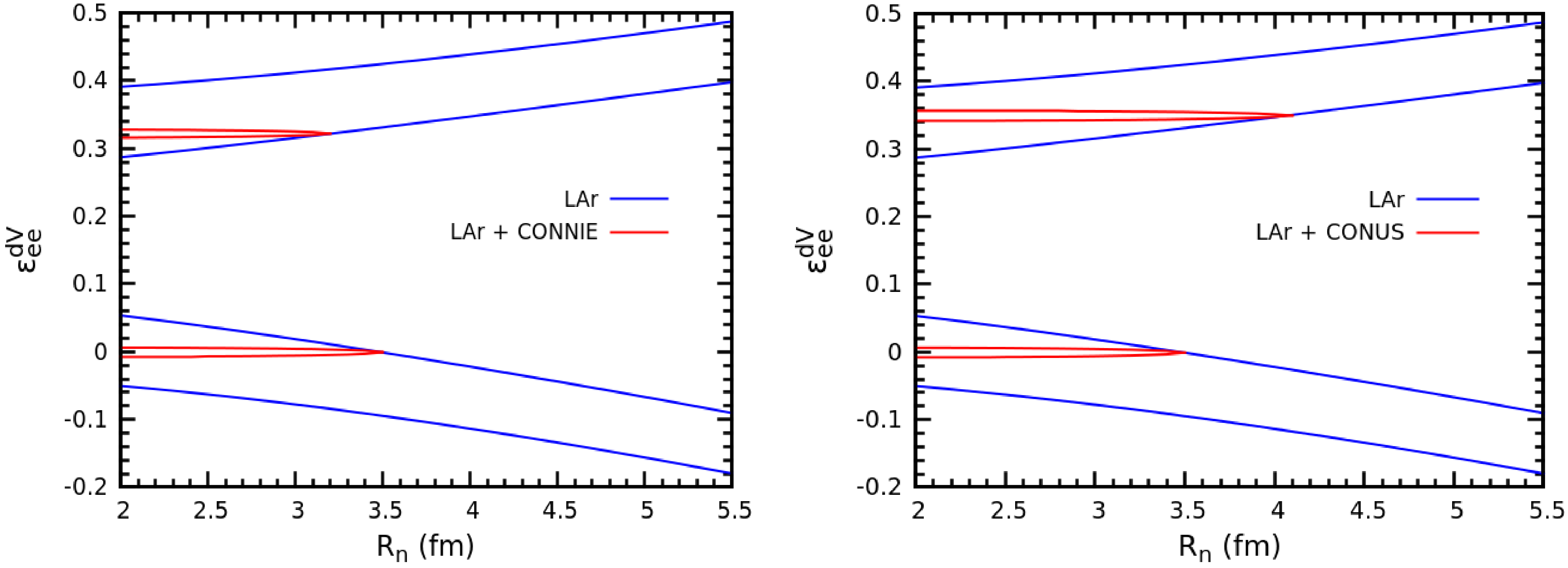
Constant QF (COHERENT Collaboration)
$\sigma_\alpha = 0.28$, $\sigma_\beta = 0.25$



Taken 8% of systematic error for the CONUS experiment.

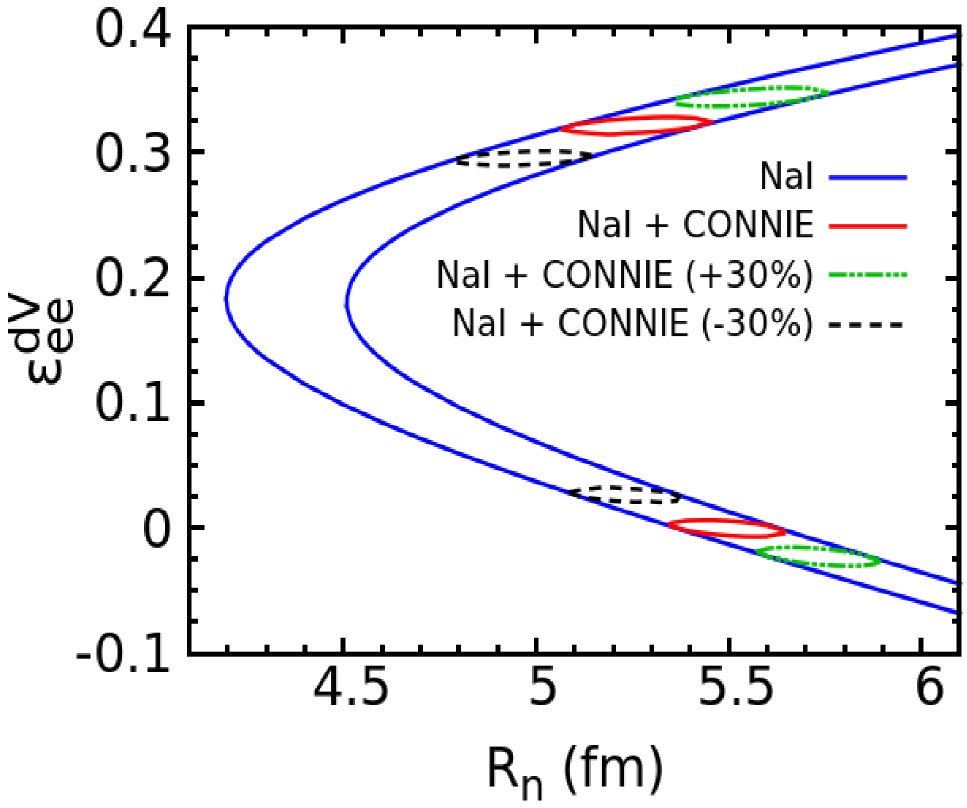
B. C. Cañas *et al*., Phys. Rev. D 101, 0351012 (2020)

Allowed region (ε_{ee}^{dV} vs R_n) from LAr COHERENT data (1σ)



Based on O. G. Miranda et al., JHEP 05 (2020) 130, 2003.12050

ε_{ee}^{dV} vs R_n from future NaI COHERENT data



Detector's features taken from **D. Akimov et al, arXiv: 1803.09183.**

$$A(T) = 1,\ \sigma_\alpha = 0.05 \text{ and } \sigma_\beta = 0.10$$

$\pm 30\%$ of deviation from the SM prediction.

B. C. Cañas *et al*., Phys. Rev. D 101, 0351012 (2020)

Conclusions

- *Future detections of CEvNS in reactor antineutrino experiments and new measurements of this process involving neutrinos from SNS can give rise to precise estimations of the nuclear physics parameters and NSI interactions.*

- *CEvNS combined analysis from nuclear reactors and SNS leads to better constraints on the mean neutron radius and NSI parameters, and produces complementary information.*

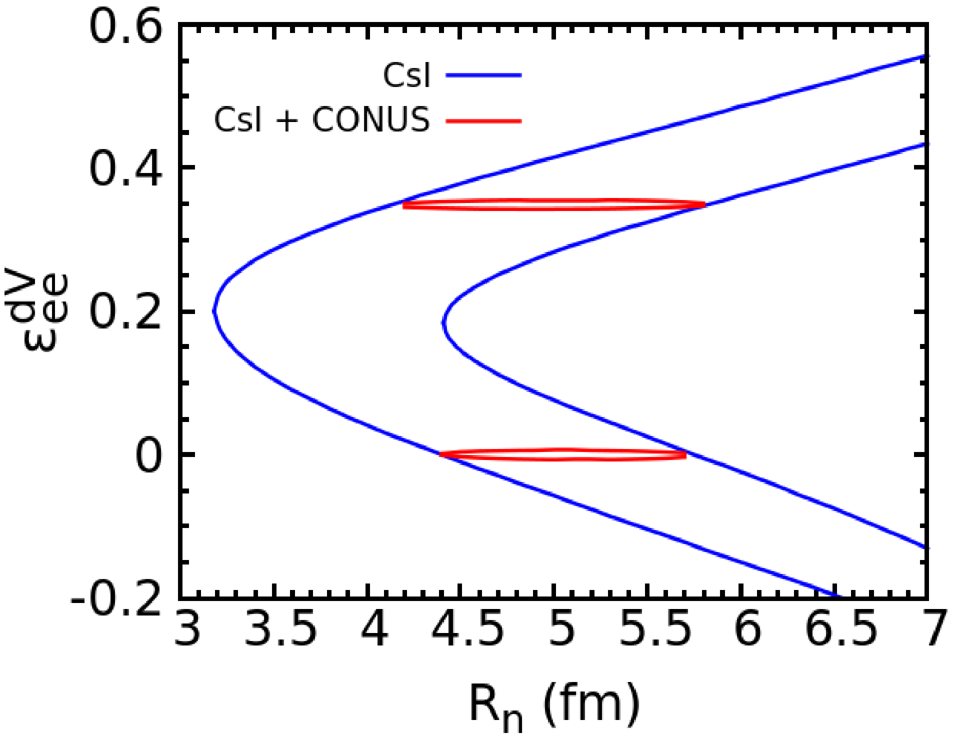

感謝你
Danke
Gracias
Grazie
Merci
Thanks!
THANK
YOU!

Backup

Allowed region (ε_{ee}^{dV} vs R_n) from CsI COHERENT data (1σ)

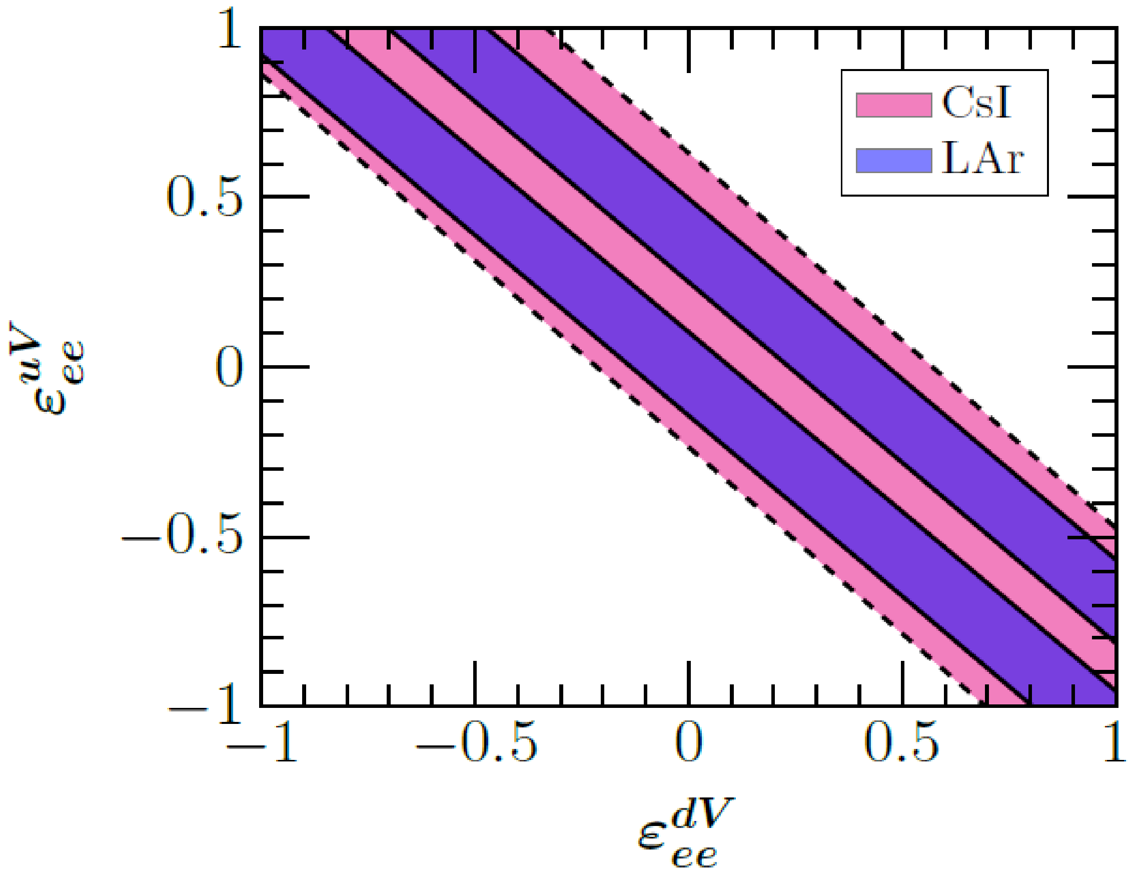
$$\mathrm{QF}(T), \sigma_\alpha = 0.135 \text{ and } \sigma_\beta = 0.25$$

J. I. Collar, et al., Phys. Rev. D100, 033003 (2019)



Backup

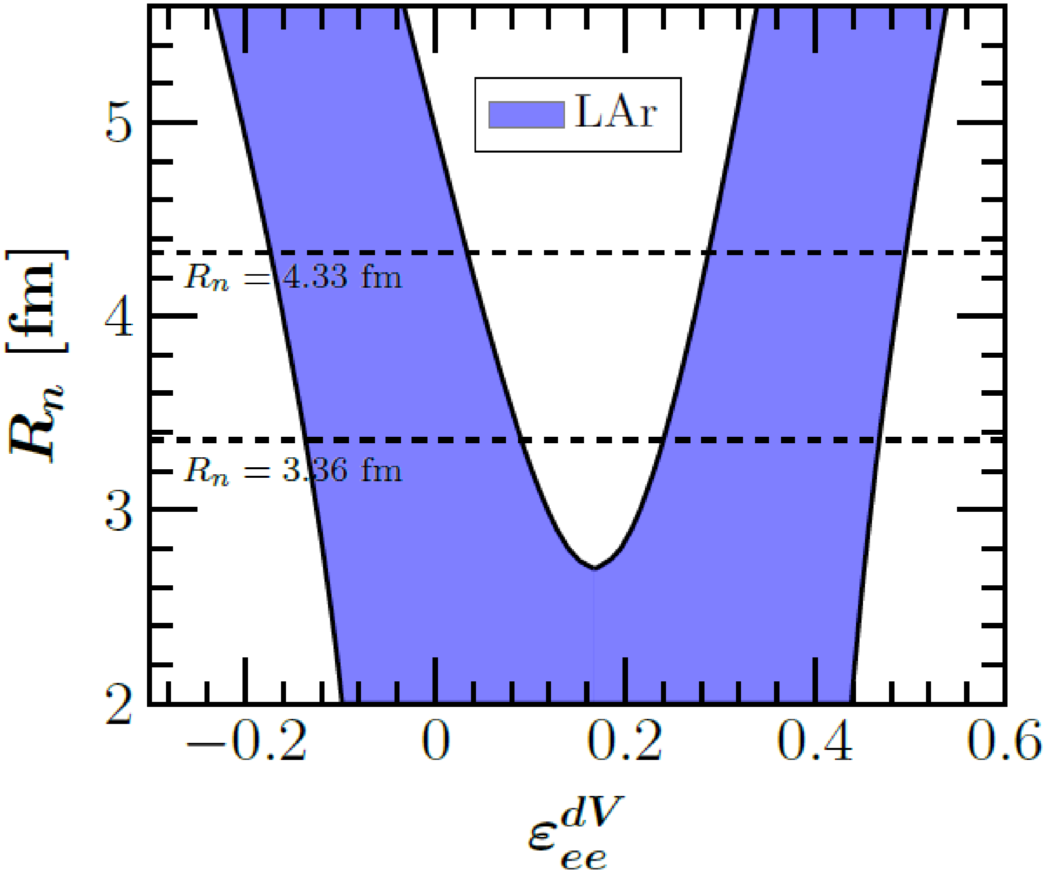
Current constraints on nonuniversal NSI parameters (90% C.L.)



Taken from: O. G. Miranda et al., JHEP 05 (2020) 130, 2003.12050

Current constraints

Allowed region (R_n vs ε_{ee}^{dV}) from LAr COHERENT data (90% C.L.)



Taken from: O. G. Miranda et al., JHEP 05 (2020) 130, 2003.12050