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Improving the precision in low-energy neutrino detection using silicon and neon isotopic detectors

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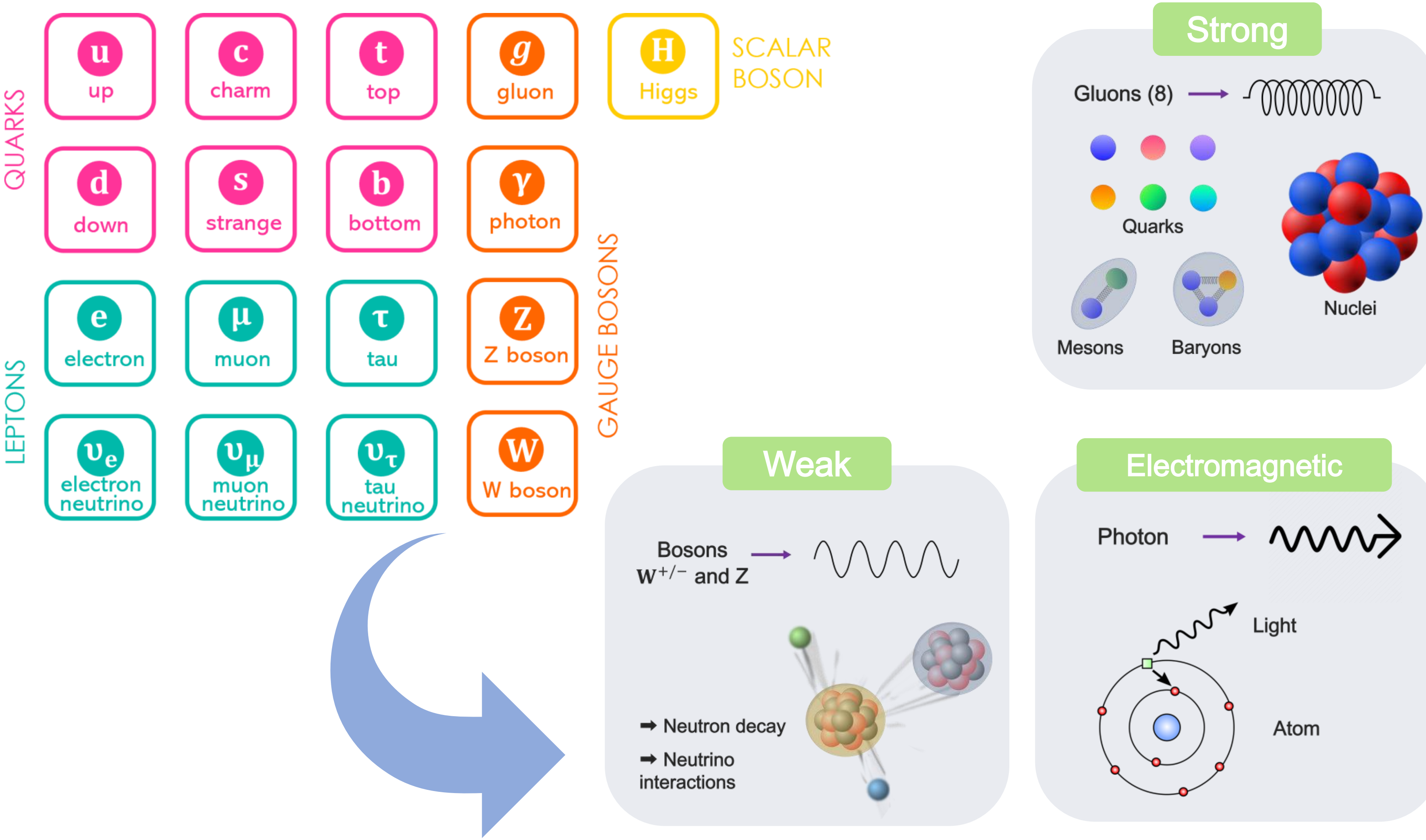
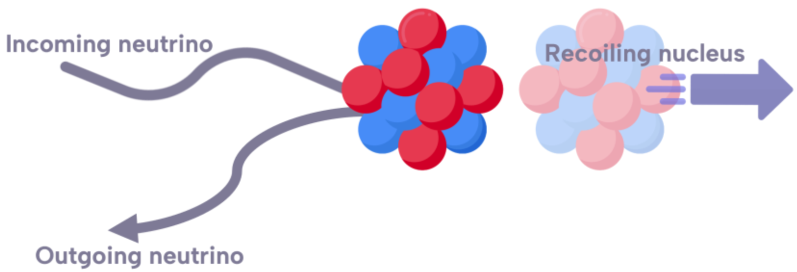
Standard Model of Elementary Particles



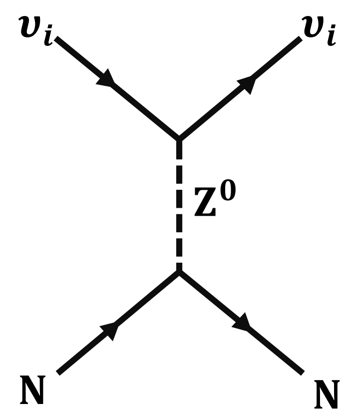
Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)



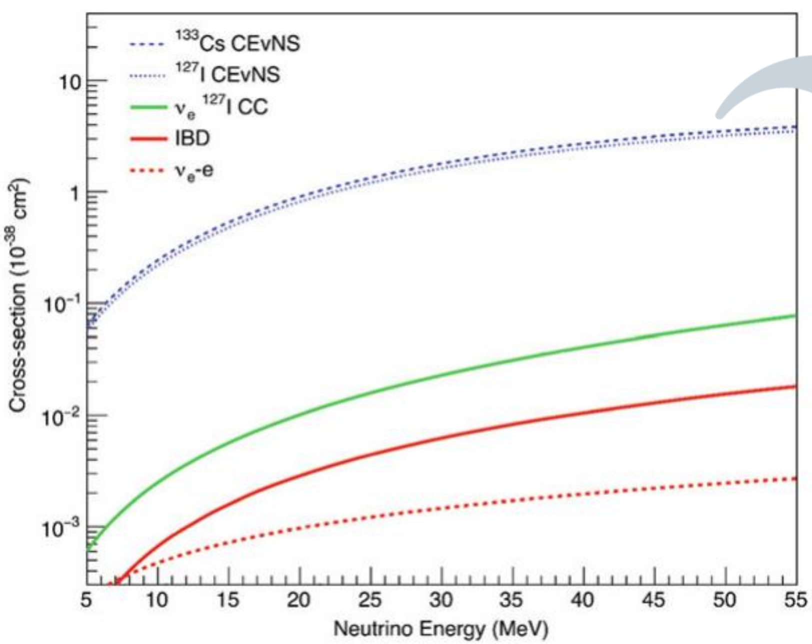
Coherence condition

Low energies~ KeV-50 MeV

$$Q \ll \frac{1}{R}$$



$$\nu + N \rightarrow \nu + N$$



D. Akimov et al. Science 357,1123-1126 (2017)

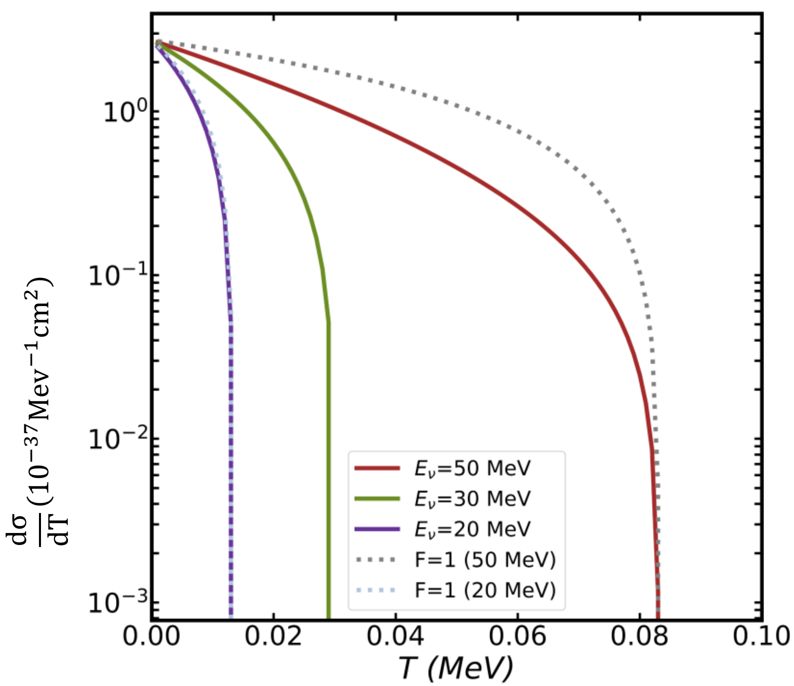
Large cross section (by neutrino interactions standards)

- Proposed in 1974 by Daniel Z. Freedman
- Observed by the COHERENT collaboration.
  - In 2017 with CsI detector.
  - In 2020 with Liquid Argon detector.
  - In 2024 with Ge detector.

CEνNS Cross Section

$$\frac{d\sigma}{dT} = \frac{G_f^2}{2\pi} \mathcal{Q}_W^2 F^2(Q^2)\left(2 - \frac{MT}{E_\nu^2}\right)$$

$\mathbf{E_\nu}$ → Incident neutrino energy
$\mathbf{T}$ → Nuclear recoil energy
$\mathbf{M}$ → Nuclear mass
$\mathbf{G_f}$ → Fermi constant



Weak nuclear charge

$$\mathcal{Q}_W^2 = (\mathbf{Z}\ \mathbf{g_p^V} + \mathbf{N}\ \mathbf{g_n^V})^2$$

$$g_p^V = \frac{1}{2} - 2\mathrm{sen}^2\theta_W \quad \rightarrow \quad \mathrm{sen}^2\theta_W = 0.23867$$

$$g_N^V = -\frac{1}{2}$$

Proton coupling is small so:

$\mathcal{Q}_W^2 \propto N^2$ → $\sigma \propto N^2$

Form factor evaluated at
$Q^2 = 2MT$ → Momentum transfer

- Symmetrized Fermi
- Helm
- Klein-Nystrand

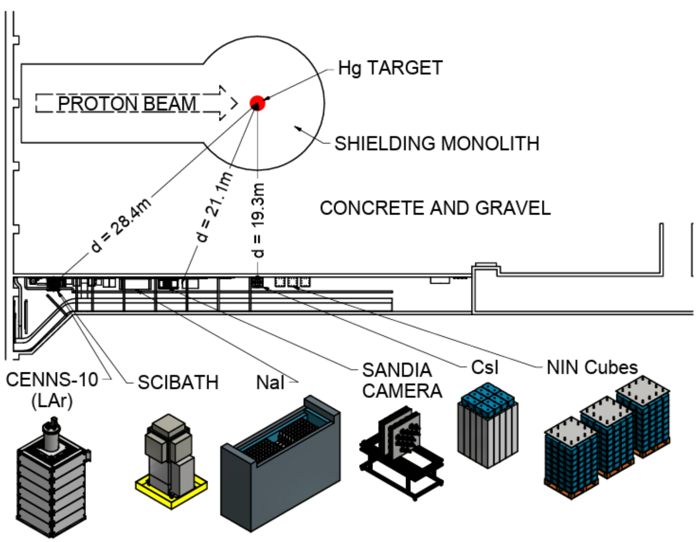
CEνNS detection

- Spallation Neutron Source in Oak Ridge National Laboratory, USA.
- CsI, Liquid Argon and Germanium detectors…

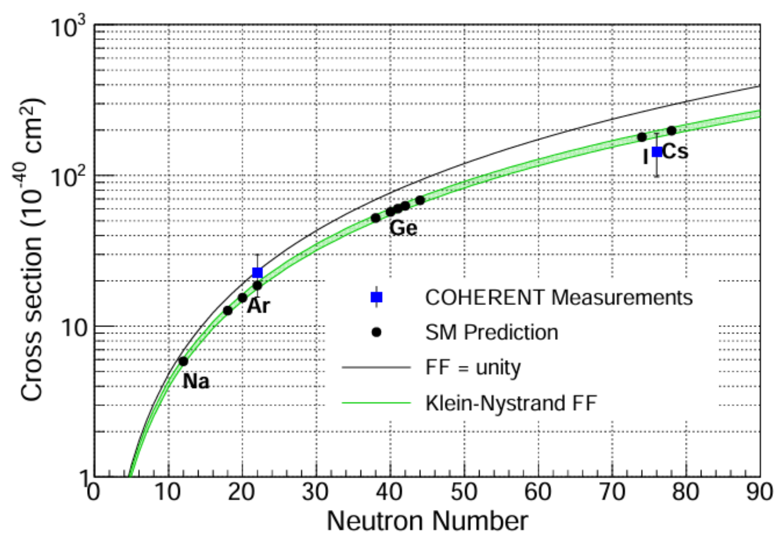
CsI $T_{th} \sim 4.5$ KeV Mass=14.6 Kg

LAr $T_{th} \sim 20$ KeV Mass=24 Kg

Ge $T_{th} \sim 1.5$ KeV Mass=8 x 2.2 Kg



D. Akimov et al. (COHERENT Collaboration)
Science 357,1123-1126 (2017)



D. Akimov et al. (COHERENT Collaboration)
Phys. Rev. Lett. 126, 012002 (2021)

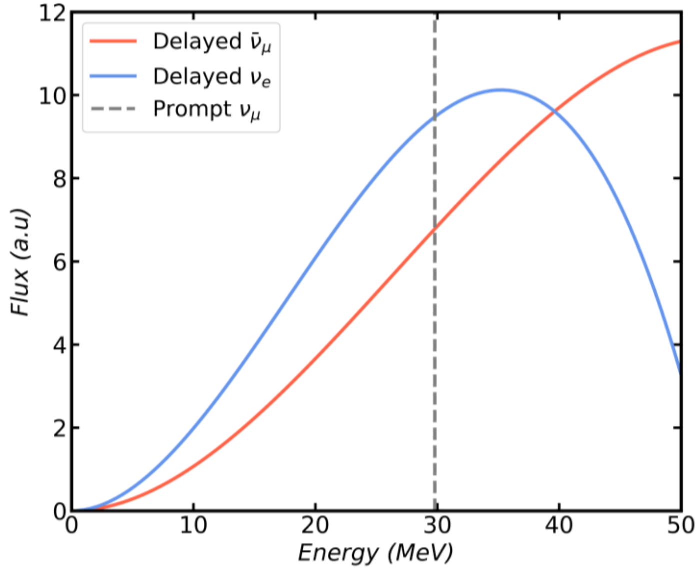
Neutrino Flux

Spallation Neutron Source (SNS)

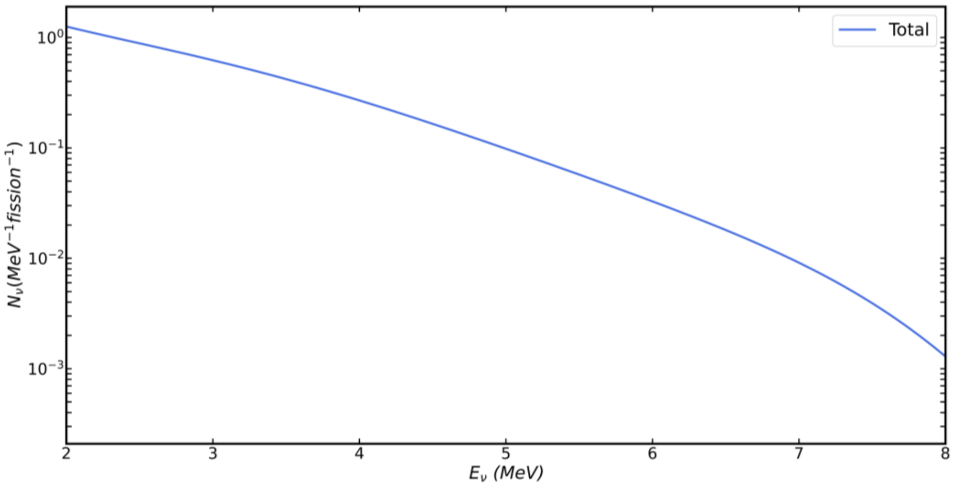
π-DAR Neutrinos (Pion Decay At Rest)

$\pi^+ \longrightarrow \mu^+ + \nu_\mu$ — Prompt component of ν_μ

$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$ — Two delayed components of $\bar{\nu}_\mu$ y ν_e



Antineutrinos from reactors



Phenomenological parametrization:

$$S(E_\upsilon) = \exp\left(\sum_{p=1}^{6} \alpha_p E_\upsilon^{p-1}\right)$$

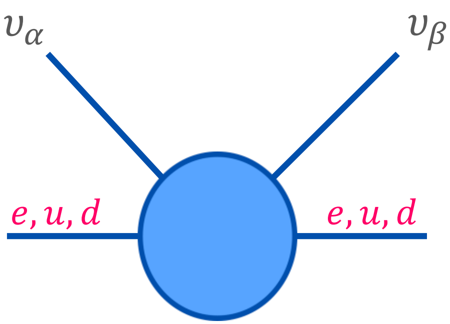
α coefficients are determined by a fit to the data

A. Mueller et al. Phys. Rev. C 83, 054615 (2011)

Non-Standard Interactions (NSI)

NSI's provide a general framework to quantify new physics in the neutrino sector. And for neutral currents it can be described with the following effective four fermion Lagrangian

$$\mathcal{L}^{NSI-NC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon_{\beta\alpha}^{fP}(\bar{\nu}_\alpha\gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)$$



$\varepsilon_{\alpha\alpha}^{fP}$ → Non-universal parameter

$\varepsilon_{\beta\alpha}^{fP}$ → Flavor-changing parameter

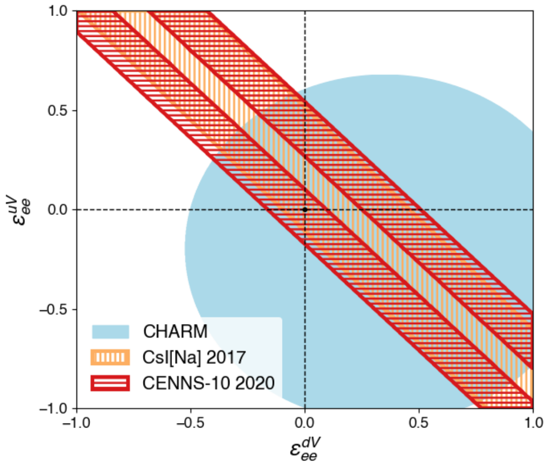
$$\varepsilon_{\beta\alpha}^{qV} = \varepsilon_{\beta\alpha}^{qL} + \varepsilon_{\beta\alpha}^{qR}$$

The weak nuclear charge is modified so that the cross-section is now flavor dependent.

$$\frac{d\sigma}{dT} \simeq \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\upsilon^2}\right) F^2(q^2)\left\{\left[Z\left(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}\right) + N\left(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV}\right)\right]^2 + \sum_{\beta\neq\alpha}\left[Z\left(2\varepsilon_{\beta\alpha}^{uV} + \varepsilon_{\beta\alpha}^{dV}\right) + N\left(\varepsilon_{\beta\alpha}^{uV} + 2\varepsilon_{\beta\alpha}^{dV}\right)\right]^2\right\}$$

Juan Barranco et al JHEP12(2005)021

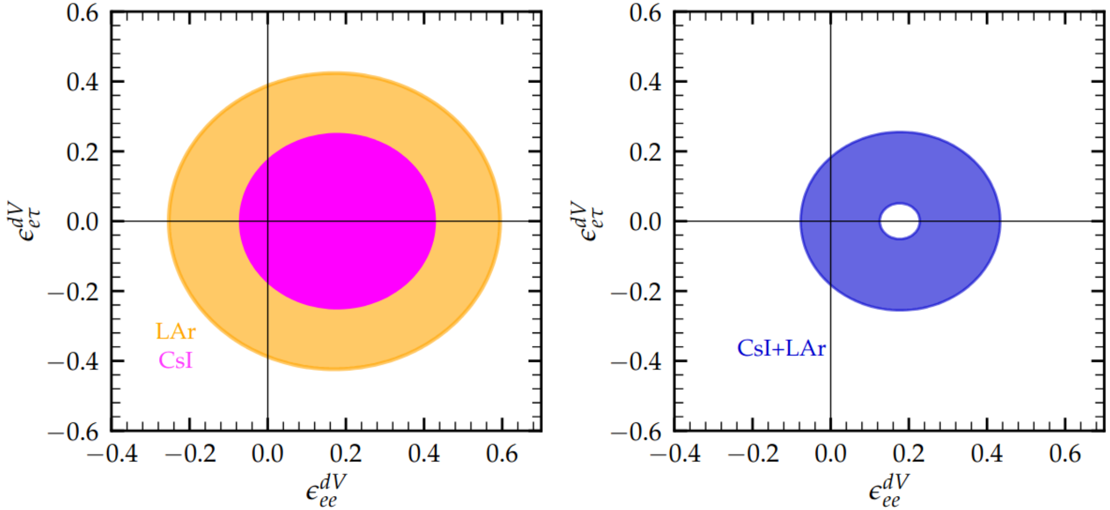
- **Non-universal parameters**



CHARM Experiment : Deep Inelastic Scattering with muon neutrinos.

B. Batell et al. (2022) 2207.06898

- **Flavor-changing parameters**



With updated **CsI** data (2021)

V. De Romeri, O.G. Miranda, D.K. Papoulias, G. Sanchez, M. Tórtola, JHEP 04 (2023) 035

Isotopic detectors

Silicon

^{28}Si | ^{30}Si

Mass of each detector:

→ 1 Kg

→ 5 Kg

Neon

^{20}Ne | ^{22}Ne

Mass of each detector:

→ 20 Kg

A. Galindo et al. Phys. Rev. D 105, 033001 (2022)

χ^2 analysis

$$\chi^2 = \sum_{ij} \left(\mathcal{N}_i^{\text{theo}} - \mathcal{N}_i^{\text{exp}}\right) \left[\sigma_{ij}^2\right]^{-1} \left(\mathcal{N}_j^{\text{theo}} - \mathcal{N}_j^{\text{exp}}\right)$$

σ^2 is the covariant matrix that is related to the statistical and systematic uncertainties

$$\sigma^2 = \begin{pmatrix} {\sigma_l^{\text{stat}}}^2 + {\sigma_l^{A}}^2 + {\sigma_l^{B}}^2 & \sigma_l^{\text{stat}}\sigma_m^{\text{stat}} + \sigma_l^{A}\sigma_m^{A} + \sigma_l^{B}\sigma_m^{B} \\ \sigma_l^{\text{stat}}\sigma_m^{\text{stat}} + \sigma_l^{A}\sigma_m^{A} + \sigma_l^{B}\sigma_m^{B} & {\sigma_m^{\text{stat}}}^2 + {\sigma_m^{A}}^2 + {\sigma_m^{B}}^2 \end{pmatrix}$$

where

σ^A → Quenching factor

σ^B → Form factor

For π-DAR neutrinos

σ^A → Quenching factor

σ^B → Neutrino Flux

For reactor neutrinos

A. Galindo et al. Phys. Rev. D 105, 033001 (2022)

Silicon isotopic detectors

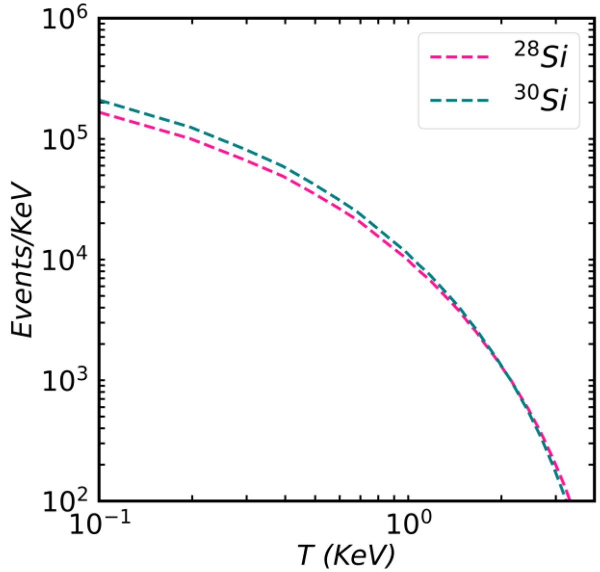
^{28}Si : 14 protons and 14 neutrons

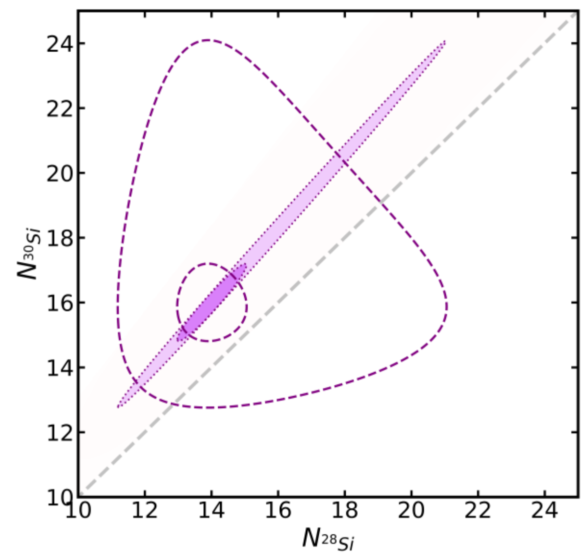
^{30}Si : 14 protons and 16 neutrons

Reactor neutrino flux

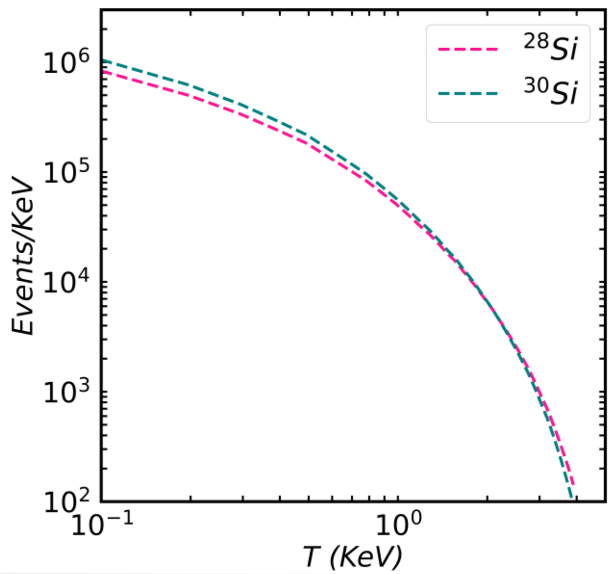
1 year of exposition

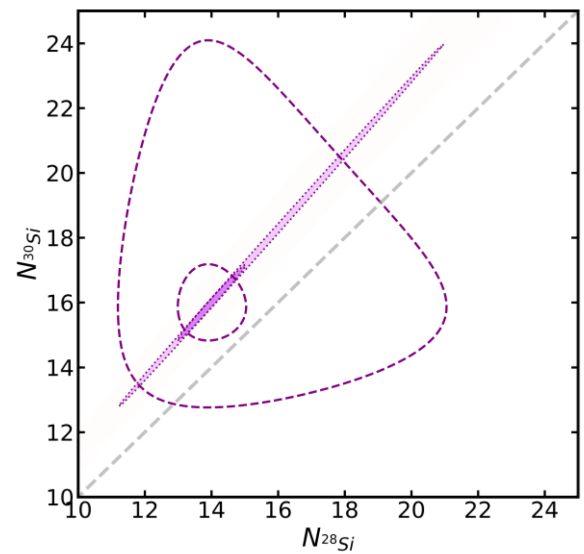
1 Kg



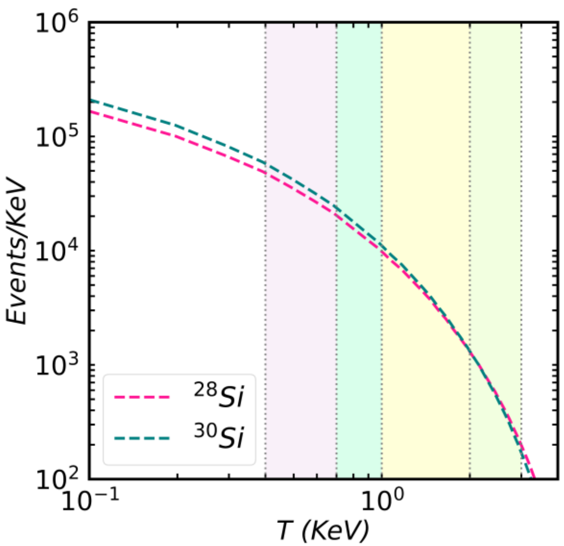


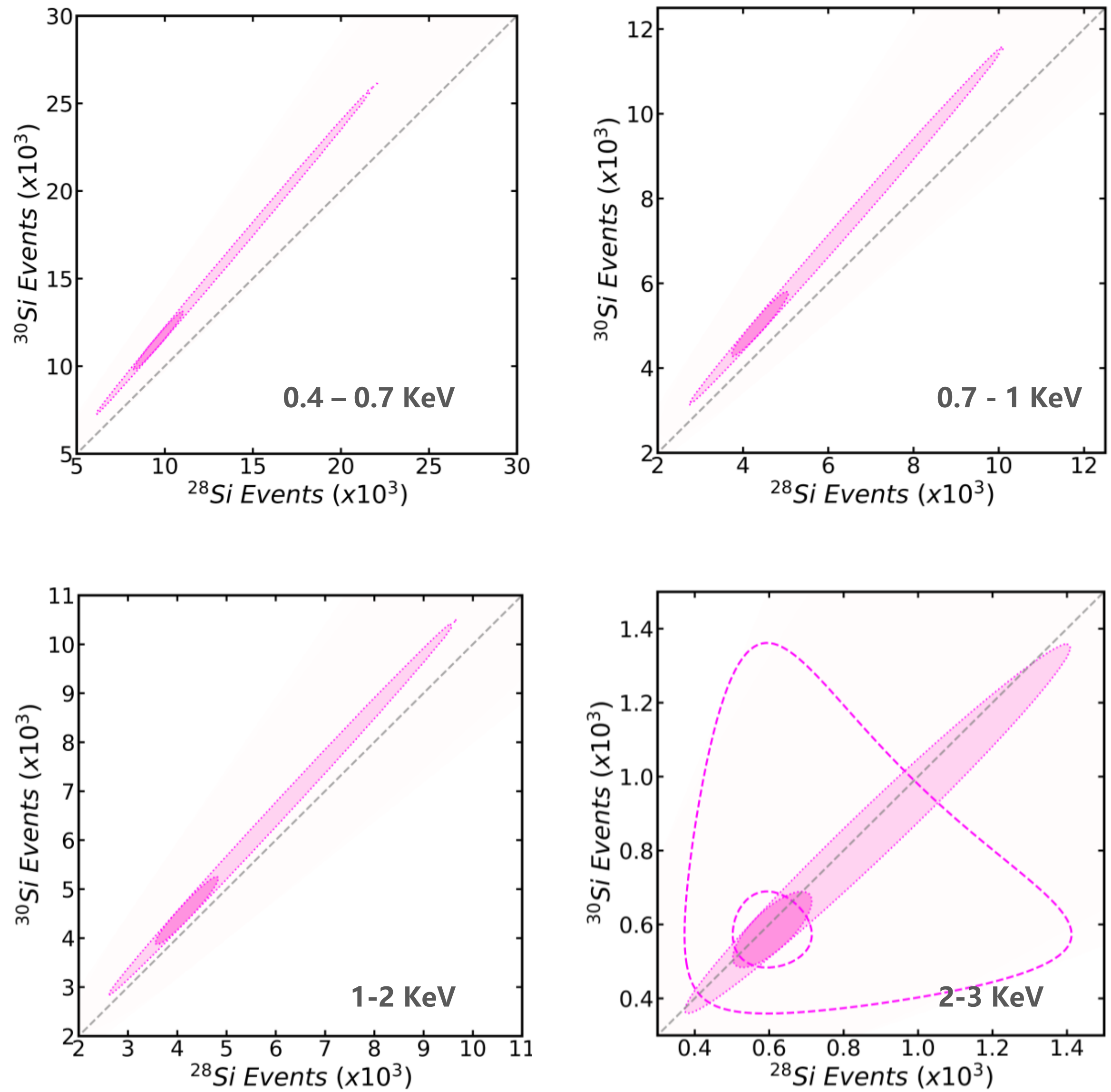
5 Kg





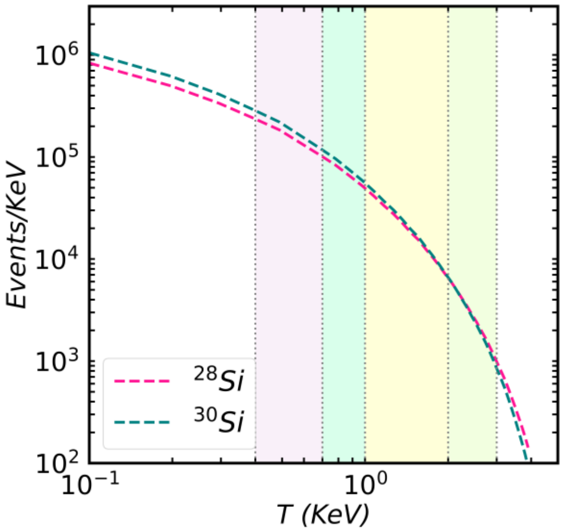
Si
1 Kg

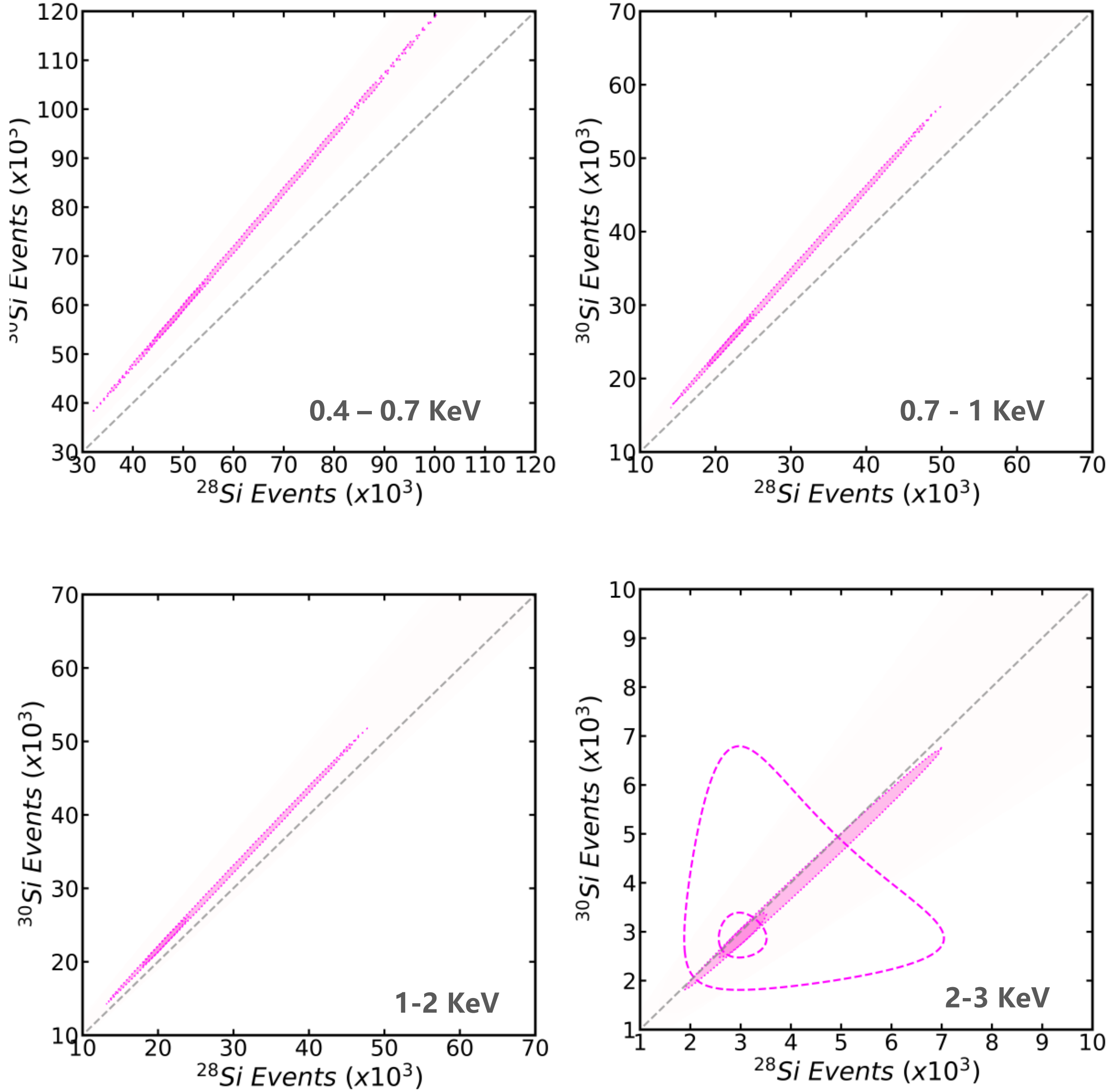




Dashed lines: No-correlated case
Colored regions: Correlated case

Si
5 Kg





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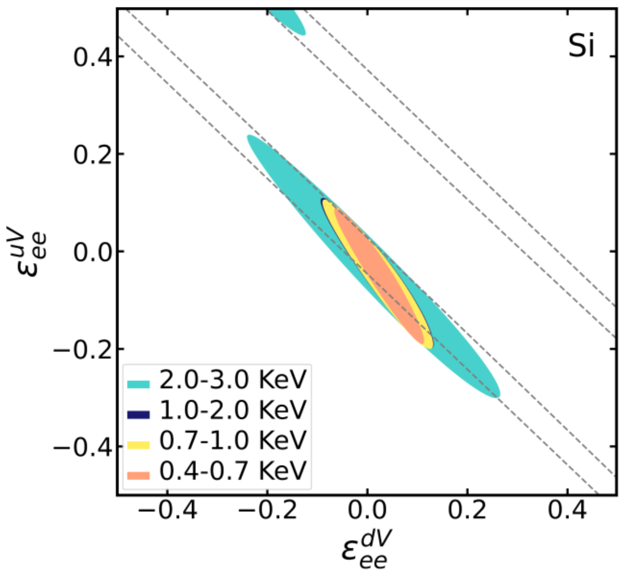
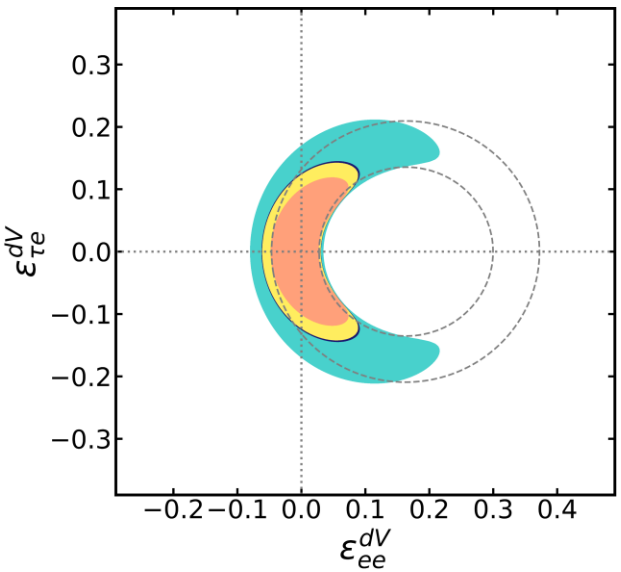
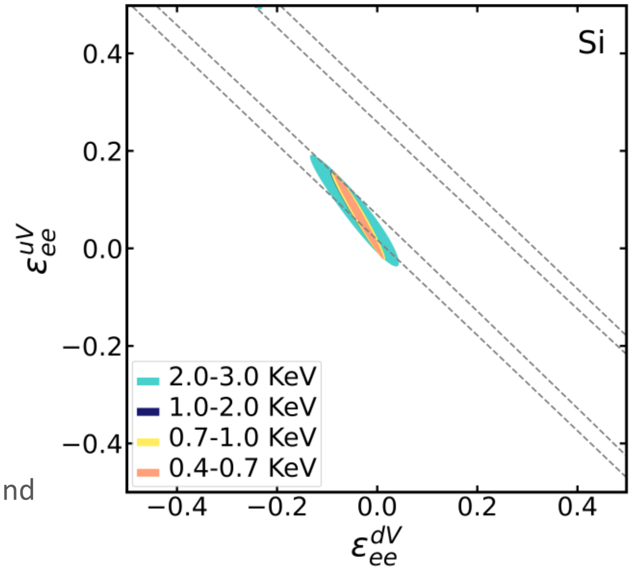
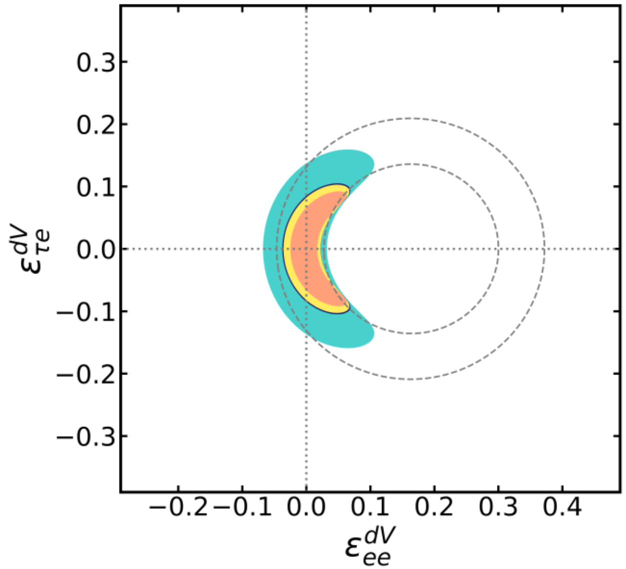




Reactor 1 Kg

Reactor 5 Kg





Systematic Uncertainties: σ_a=25% and σ_b=10%

Dashed lines: No-correlated case
Colored regions: Correlated case

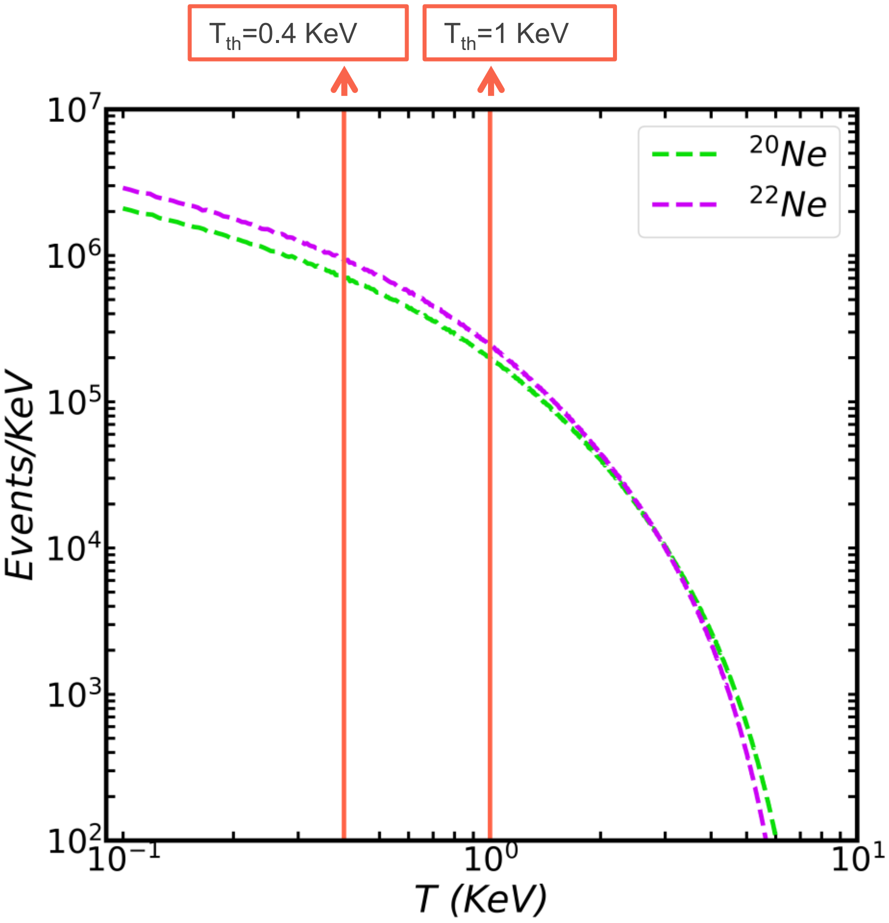
Neon isotopic detectors

Reactor neutrino flux

$^{20}\mathrm{Ne}$: 10 protons and 10 neutrons

$^{22}\mathrm{Ne}$: 10 protons and 12 neutrons

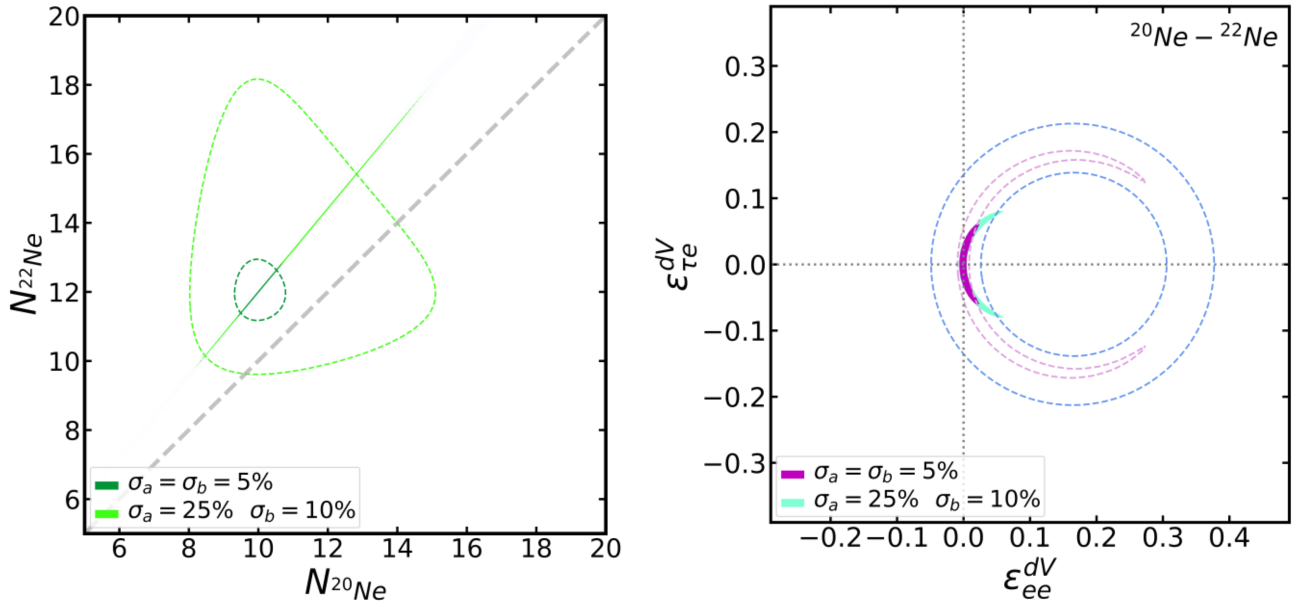
- 20 Kg detectors
- 1 year of exposition



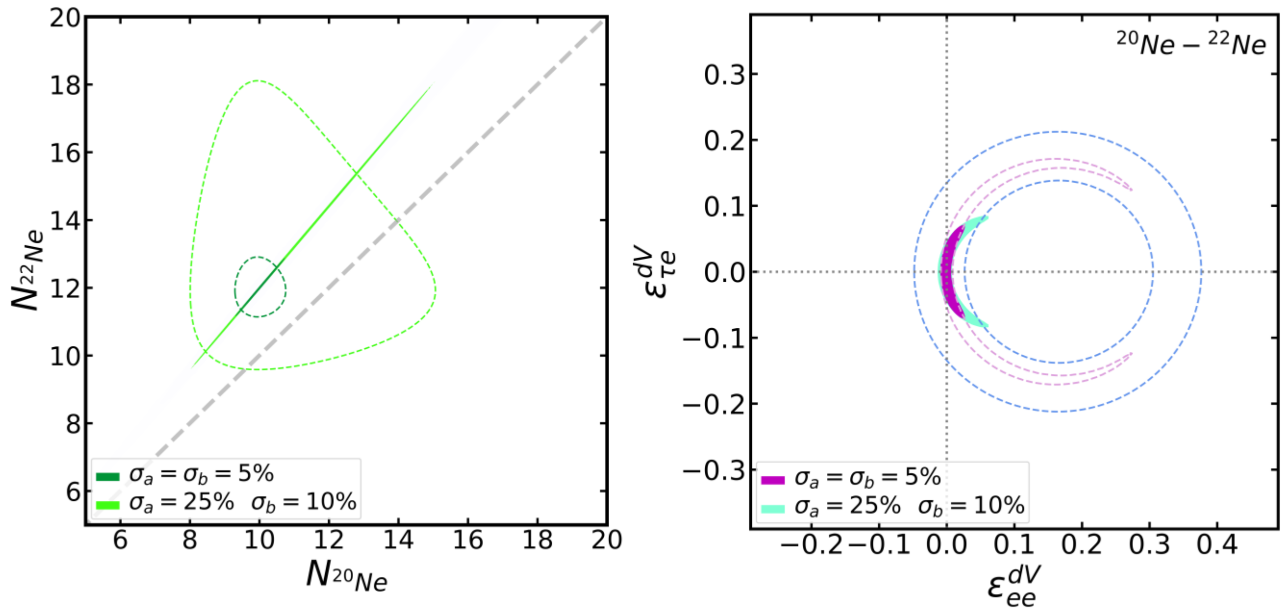
Systematic Uncertainties: σ_a and σ_b

Dashed lines: No-correlated case
Colored regions: Correlated case

T_{th}=0.4 KeV



T_{th}=1 KeV



Conclusions

- The correlation between different isotope detectors can help to break degeneracies in the NSI parameters for the reactor antineutrino flux, besides improving the sensitivity to these NSI parameters.

- The increase in experimental capability for the development of larger isotope detectors may have a significant impact on the improvement of accuracy.

- This is a preliminary analysis that is expected to be refined to further study the capabilities of these detector arrays.

Thank you!

Back Up

Weak Mixing Angle

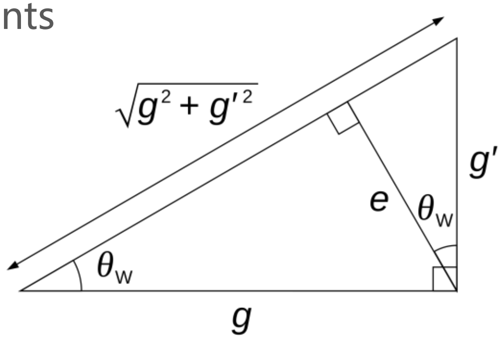
Angle by which spontaneous symmetry breaking rotates the original W^3 and B vector boson plane, producing as a result the Z boson, and the photon γ

$$\begin{pmatrix}\gamma \\ Z\end{pmatrix} = \begin{pmatrix} cos\theta_W & sen\theta_W \\ -sen\theta_W & cos\theta_W \end{pmatrix}\begin{pmatrix} B \\ W^3 \end{pmatrix}$$

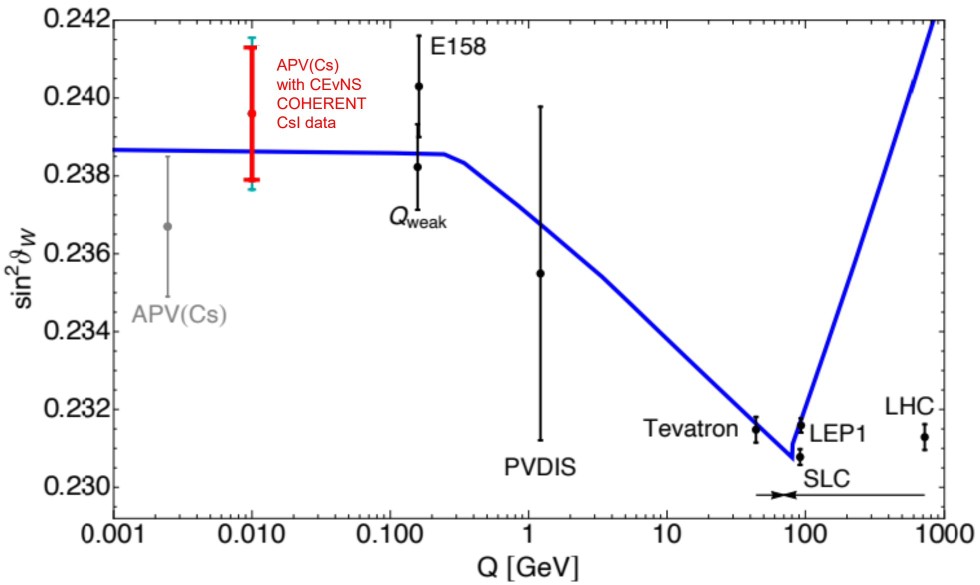
Is related to the masses of the Z and W bosons

$$M_z = \frac{M_W}{cos\theta_W}$$

Determines the connection between the **electric charge** through the coupling constants



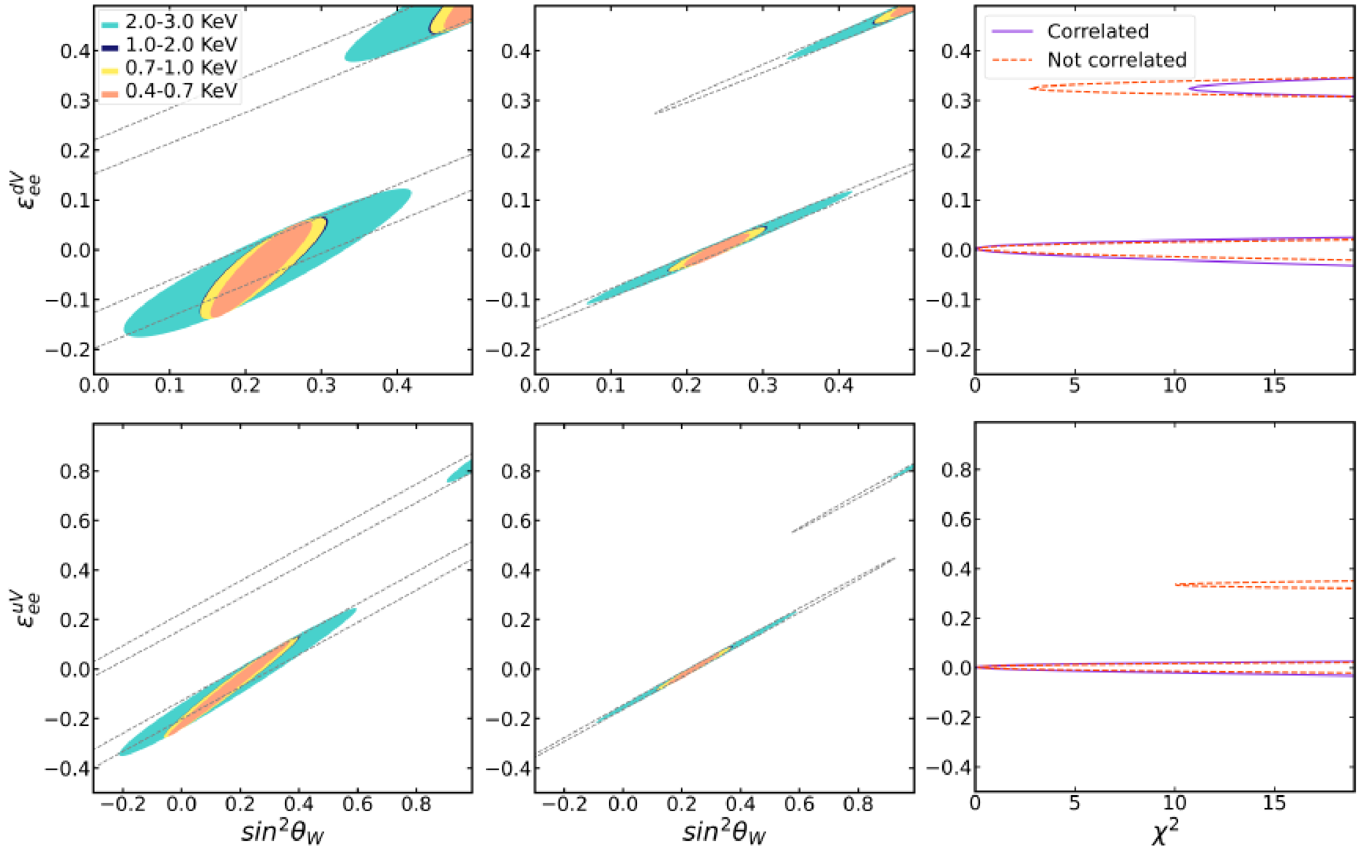
$e = gsen\theta_W = g'cos\theta_W$



M. Atzori Corona, M. Cadeddu, N. Cargioli, F.Dordei, and C. Giunti. Phys. Rev. D 110, 033005 (2024)

$SU(2)_L \rightarrow g$ $\qquad$ $U(1)_Y \rightarrow g'$

$$cos\theta_W = \frac{g}{\sqrt{g^2 + g'^2}} \qquad sen\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}$$



2.0-3.0 KeV
1.0-2.0 KeV
0.7-1.0 KeV
0.4-0.7 KeV
Correlated
Not correlated
ϵ_{ee}^{dV}
ϵ_{ee}^{uV}
$sin^2\theta_W$
$sin^2\theta_W$
χ^2

Form factor

- Klein-Nystrand distribution

$$F_{KN} = 3\frac{j_1(QR_A)}{QR_A}[1 + (Qa_k)^2]^{-1}$$

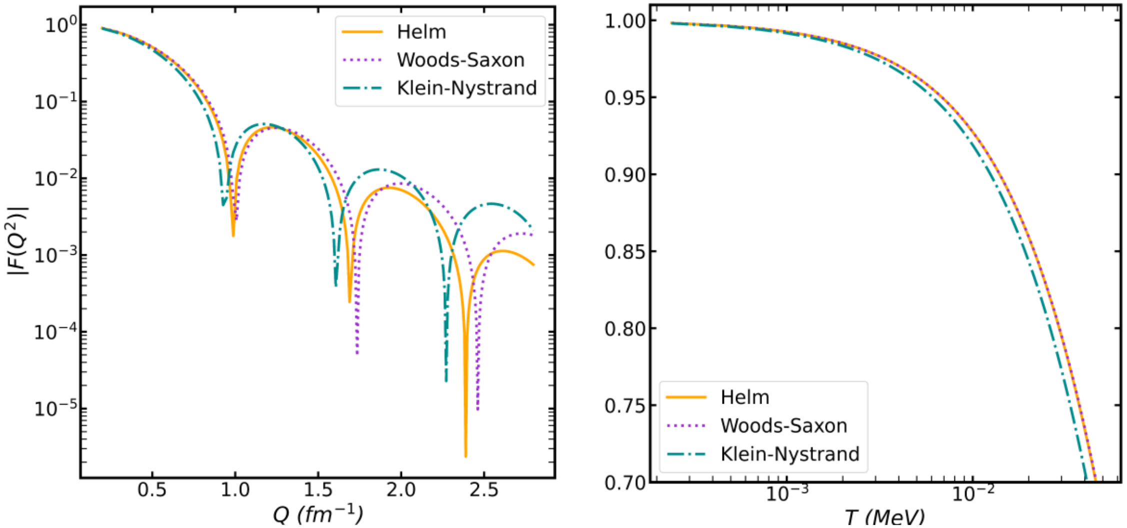
$$j_1 = \frac{sen(x)}{x^2} - \frac{cos(x)}{x}$$

- Symmetrized Fermi distribution

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

- Helm distribution

$$F_{Helm} = 3\frac{j_1(QR_0)}{QR_0}e^{-(Qs)^2/2}$$



Events

$$\frac{dR}{dT} = t_{run} N_{targ} \int_{E_{\nu,min}}^{E_{\nu,max}} \frac{dN_\nu}{dE} \frac{d\sigma}{dT} \, dE$$

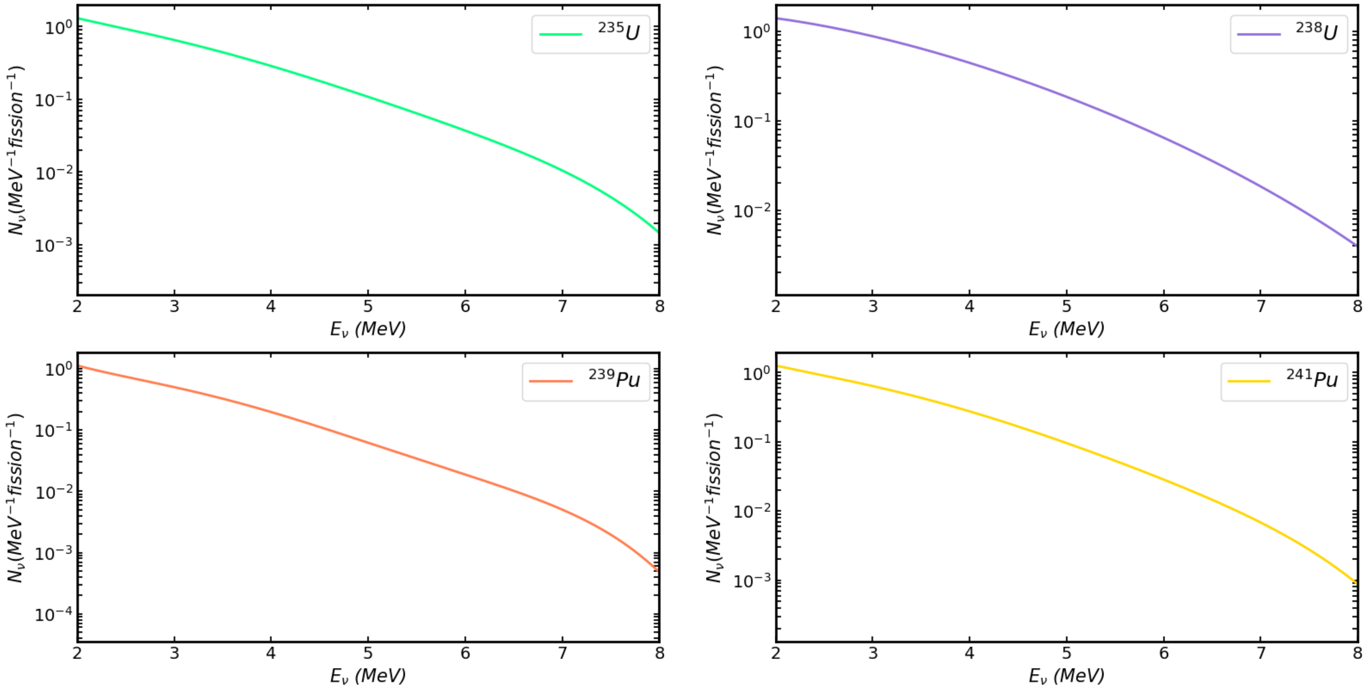
$$E_{\nu,min} \simeq \sqrt{\frac{M\,T}{2}} \rightarrow E_{\nu,max} \begin{cases} \frac{m_\mu}{2} \simeq 52.8 \text{ MeV} \\ 8 \text{ MeV} \end{cases}$$

For π-DAR neutrinos

For reactor neutrinos

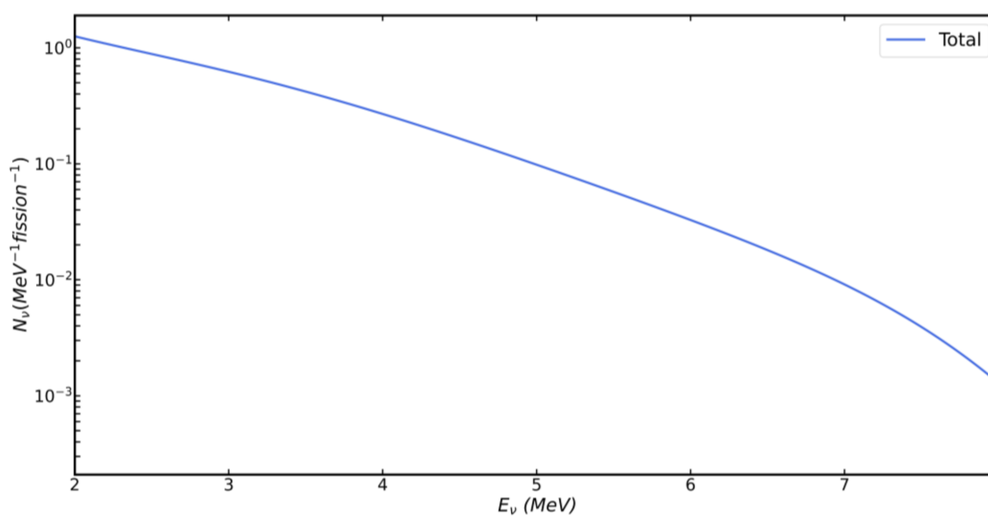
Total number of events:

$$T_{thres} \rightarrow T_{max} \simeq \frac{2\,E_{\nu,max}^2}{M}$$



Total spectra:

- 55% ^{235}U
- 32% ^{239}Pu
- 7% ^{238}U
- 6% ^{241}Pu



Neutrino generalized interactions (NGI)

$$\mathcal{L}^{NGI} = \frac{G_F}{\sqrt{2}} \sum_X \bar{\nu}\, \Gamma^X \nu \bar{q} \Gamma_X \left(C_X^q + i\gamma_5 D_X^q \right) q$$

$X = S, \quad P, \quad V, \quad A, \quad T$

- S → Scalar
- P → Pseudo-scalar
- V → Vectorial
- A → Axial
- T → Tensorial

$$\Gamma^X = \left\{ \mathbb{I}, i\gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu} \equiv \frac{i}{2}[\gamma^\mu, \gamma^\nu] \right\}$$

D. Aristizabal Sierra, Valentina De Romeri, and N. Rojas
Phys. Rev. D 98, 075018 (2018)