Constraints on neutrino nonstandard interactions from COHERENT, PandaX-4T and XENONnT

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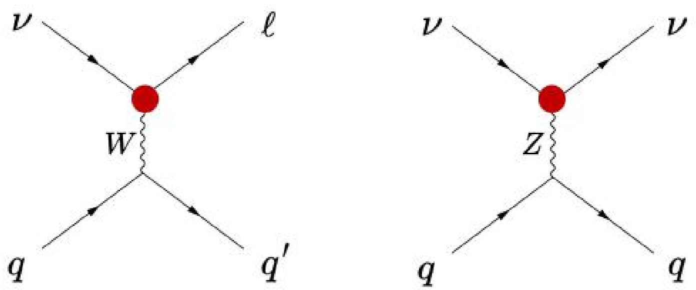
GL, Chuan-Qiang Song, Feng-Jie Tang, Jiang-Hao Yu, 2409.04703 (PRD)

22nd Lomonosov Conference on Elementary Particle Physics

Moscow, August 22, 2025

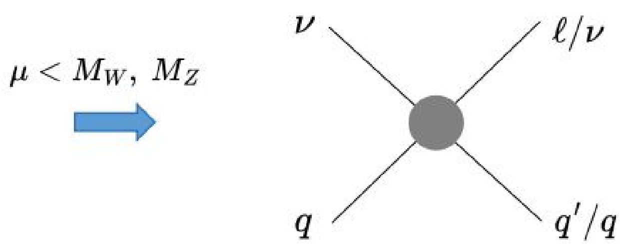
Neutrino Non-standard Interactions

Neutrino-quark interactions:



+

other contributions from BSM particles (W', Z', new scalar, leptoquark)



four-fermion interactions

Neutrino Non-standard Interactions

Parameterization of neutrino NSIs:

- charged current:

$$\mathcal{L}_{\rm CC} \supset -2\sqrt{2}G_F V_{ud}^{\rm SM}\Big\{[\mathbf{1}+\epsilon_L]_{\alpha\beta}^{ij}(\bar{u}_i\gamma^\mu P_L d_j)(\bar{\ell}_\alpha\gamma_\mu P_L \nu_\beta) + [\epsilon_R]_{\alpha\beta}^{ij}(\bar{u}_i\gamma^\mu P_R d_j)(\bar{\ell}_\alpha\gamma_\mu P_L \nu_\beta)$$
$$+\frac{1}{2}[\epsilon_S]_{\alpha\beta}^{ij}(\bar{u}_i d_j)(\bar{\ell}_\alpha P_L \nu_\beta) - \frac{1}{2}[\epsilon_P]_{\alpha\beta}^{ij}(\bar{u}_i\gamma_5 d_j)(\bar{\ell}_\alpha P_L \nu_\beta) + \frac{1}{4}[\epsilon_T]_{\alpha\beta}^{ij}(\bar{u}_i\sigma^{\mu\nu}P_L d_j)(\bar{\ell}_\alpha\sigma_{\mu\nu}P_L\nu_\beta) + {\rm H.c.}\Big\}$$

- neutral current:

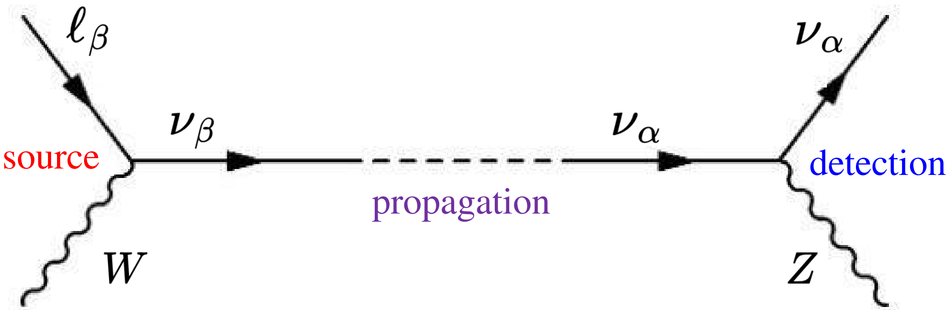
$$\mathcal{L}_{\rm NC} \supset 2\sqrt{2}G_F[\epsilon_{\alpha\beta}^{fL}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu P_L f) + \epsilon_{\alpha\beta}^{fR}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu P_R f)] + {\rm H.c.}$$

matched to dimension-6 operators in the SMEFT

Yong Du, Hao-Lin Li, Jian Tang, Sampsa Vihonen, Jiang-Hao Yu 2106.15800 (PRD)

Neutrino Non-standard Interactions

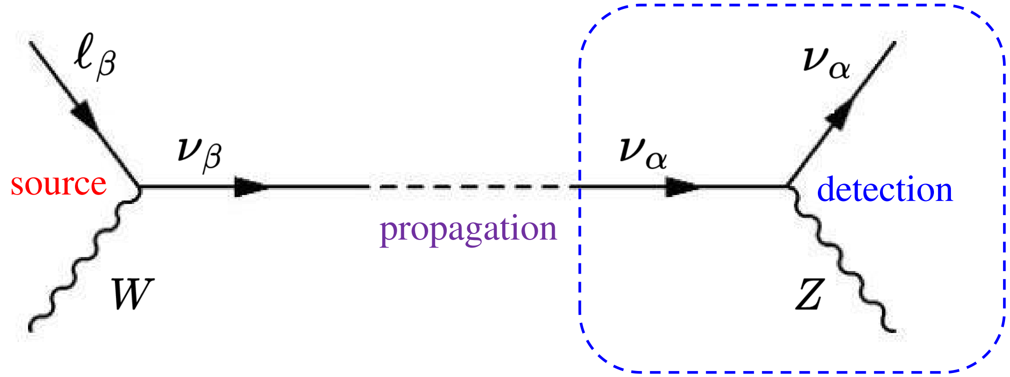
Measurements of neutrino NSIs in **oscillation** experiments:



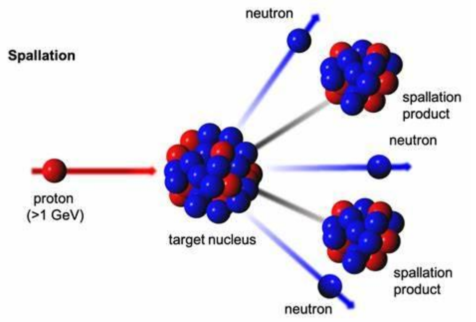
- Neutrino charged-current NSIs affect the source (production) and detection (scattering) of neutrinos
- Neutrino neutral-current NSIs affect the propagation of neutrinos

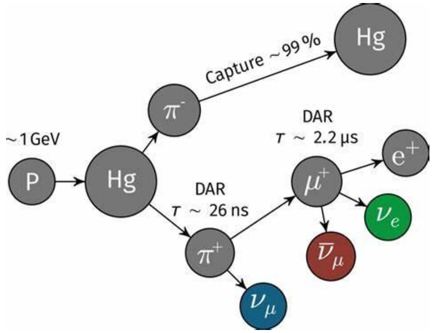
Neutrino Non-standard Interactions

Measurements of neutrino NSIs in **scattering** experiments:



- Neutrino neutral-current NSIs can also affect the detection (scattering) of neutrinos

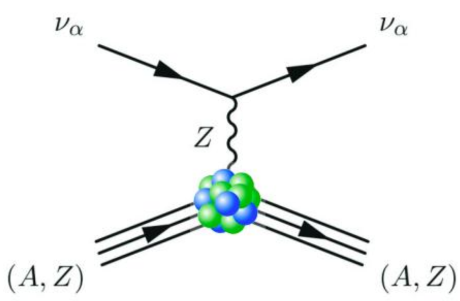


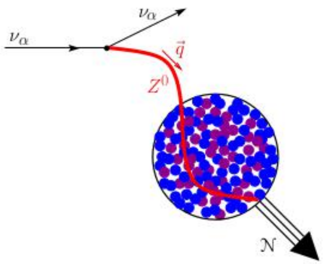


Neutrino source: Spallation Neutron Source

Coherent elastic neutrino-nucleus scattering

CEvNS: what is it?

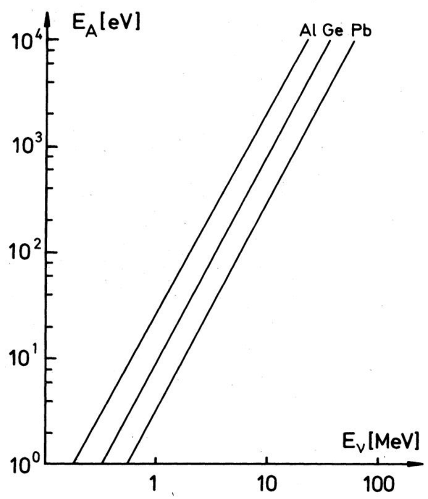




$$\frac{\mathrm{d}\sigma}{\mathrm{d}T_{\mathrm{nr}}} \propto Z^2$$

Z: atomic number

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



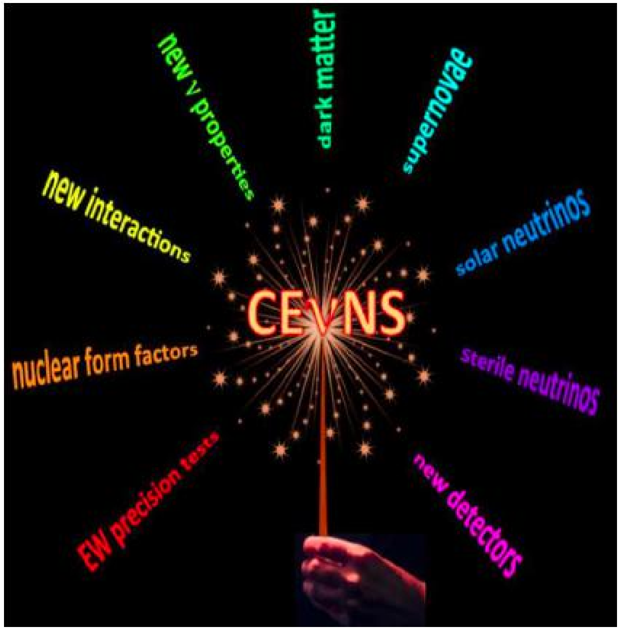
$$E_A = \frac{2}{3A}(E_\nu/1\ \mathrm{MeV})^2\ \mathrm{keV}$$

Drukier, Stodolsky, Phys.Rev.D 30 (1984) 2295

Coherent elastic neutrino-nucleus scattering

CEvNS: physical potential

- **EW precision tests:** weak mixing angle, electroweak charges;
- **Neutrino physics:** neutrino magnetic moment, charge radius, sterile neutrinos,
- **New interactions:** nonstandard interactions, light mediators, generalized interactions; light dark matter;
- **Nuclear Physics:** neutron radius, quenching factor, reactor neutrino flux;
- **Astroparticle physics:** supernova, solar, atmospheric neutrinos, DSNB;...

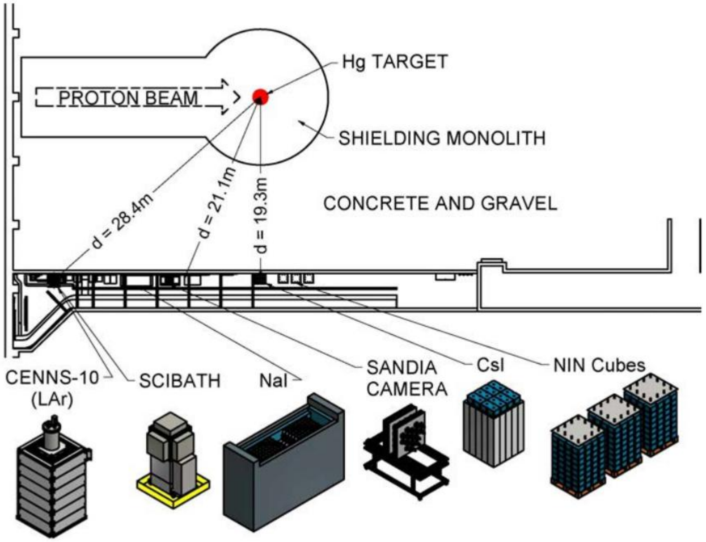


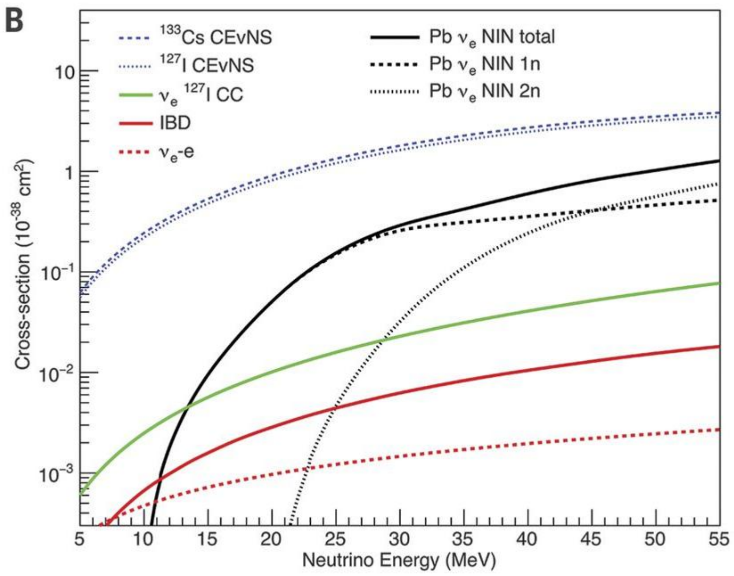
E. Lisi, Neutrino 2018

credit: Jiajun Liao

Coherent elastic neutrino-nucleus scattering

First observation of CEvNS by COHERENT:





CsI[Na] or CsI detector

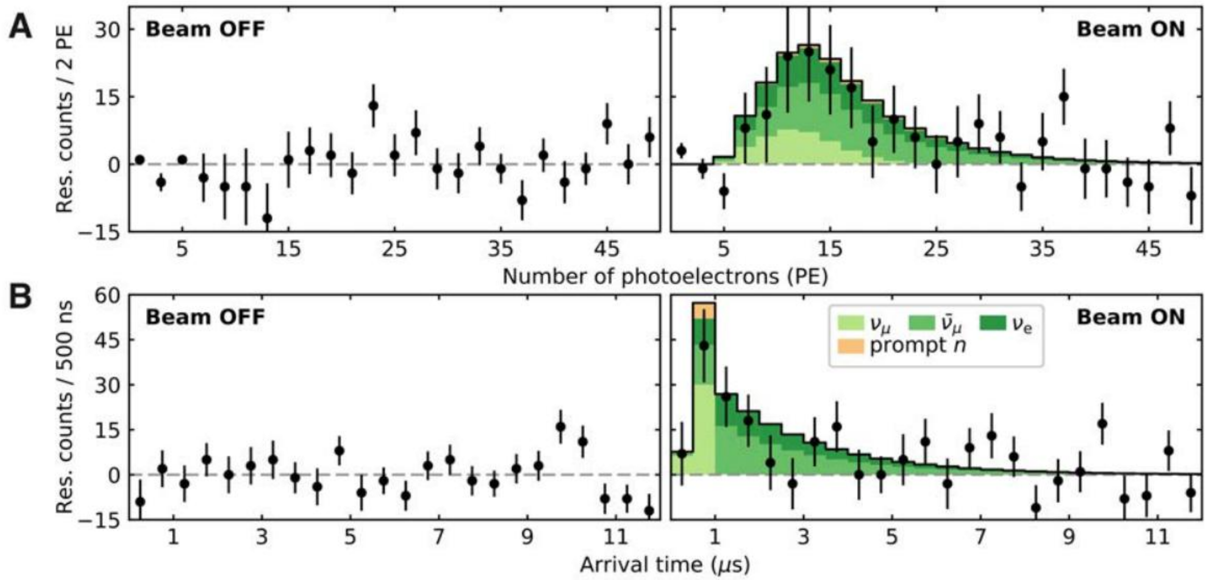
Science 357 (2017) 6356, 1123

neutrinos produced in

$$\pi^+ \to \nu_\mu(\mu^+ \to e^+ \nu_e \bar{\nu}_\mu)$$

Coherent elastic neutrino-nucleus scattering

First observation of CEvNS by COHERENT:



Science 357 (2017) 6356, 1123

$$n_{\rm PE} \longleftarrow T_{ee} \longleftarrow T_{\rm nr}$$

Constraint on NSIs from COHERENT

From CEvNS events to neutrino NSIs:

- Number of PEs in i-th bin

$$N^i_{\nu_\alpha} = n_N \sum_{x=\mathrm{Cs,I}} \eta_x \langle \varepsilon_T \rangle_{\nu_\alpha} \int_{n^i_{\mathrm{PE}}}^{n^{i+1}_{\mathrm{PE}}} \mathrm{d}n_{\mathrm{PE}} \varepsilon(n_{\mathrm{PE}}) \times \int_{T_{\mathrm{nr,min}}}^{T_{\mathrm{nr,max}}} \mathrm{d}T_{\mathrm{nr}} P(n_{\mathrm{PE}}) \frac{\mathrm{d}R_{\nu_\alpha}}{\mathrm{d}T_{\mathrm{nr}}}|_x$$

number of target nuclei: n_N

fraction of $\mathrm{Cs/I}$: η_x

average time efficiency: $\langle \varepsilon_T \rangle_{\nu_\alpha}$

detector efficiency: $\varepsilon(n_{\mathrm{PE}})$

detector energy resolution: $P(n_{\mathrm{PE}})$

- Differential event rate

$$\frac{\mathrm{d}R_{\nu_\alpha}}{\mathrm{d}T_{\mathrm{nr}}} = \int_{E_{\nu,\mathrm{min}}}^{E_{\nu,\mathrm{max}}} dE_\nu \Phi_{\nu_\alpha}(E_\nu) \frac{\mathrm{d}\sigma}{\mathrm{d}T_{\mathrm{nr}}}$$

total neutrino flux

$$\Phi_{\nu_e}(E_\nu) = \mathcal{N} \frac{192 E_\nu^2}{m_\mu^3} \left(\frac{1}{2} - \frac{E_\nu}{m_\mu} \right)$$

$$\Phi_{\bar{\nu}_\mu}(E_\nu) = \mathcal{N} \frac{64 E_\nu^2}{m_\mu^3} \left(\frac{3}{4} - \frac{E_\nu}{m_\mu} \right)$$

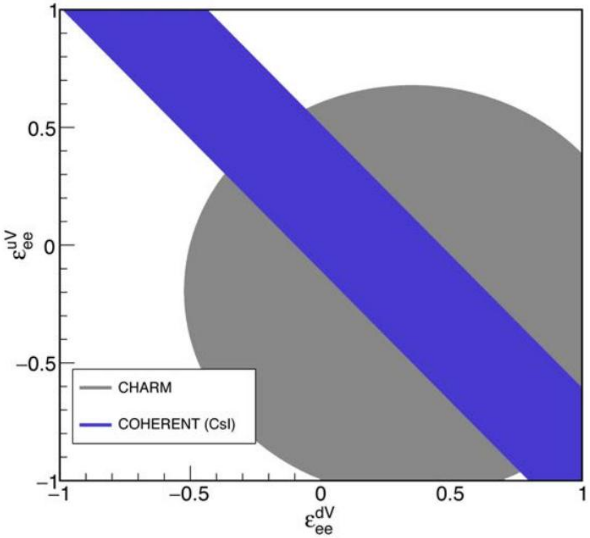
$$\Phi_{\nu_\mu}(E_\nu) = \mathcal{N} \delta \left(E_\nu - \frac{m_\pi^2 - m_\mu^2}{2 m_\pi} \right)$$

Constraint on NSIs from COHERENT

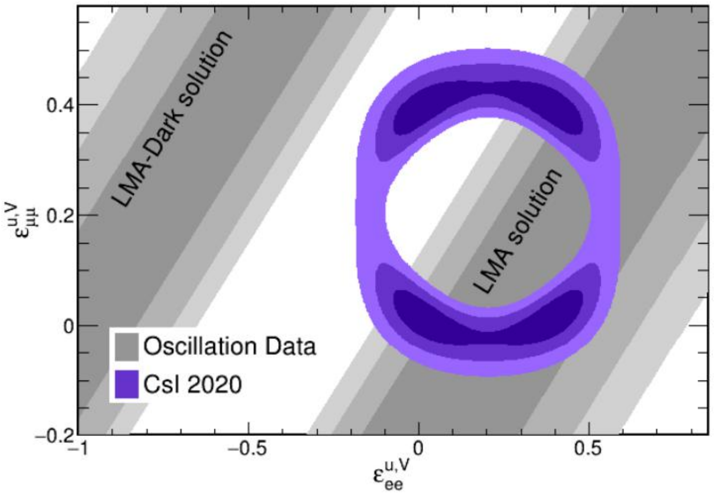
From CEvNS events to neutrino NSIs:

$$\mathcal{L}_{\rm NC} \supset -2\sqrt{2}G_F\left[\epsilon^{qL}_{\alpha\beta}\left(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta\right)\left(\bar{q}\gamma_\mu P_L q\right)+\epsilon^{qR}_{\alpha\beta}\left(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta\right)\left(\bar{q}\gamma_\mu P_R q\right)\right]$$

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



COHERENT, Science 357 (2017) 6356, 1123



COHERENT, 2110.07730 (PRL)

measurement by LAr detector **COHERENT, 2003.10630 (PRL)**

combined result of CsI+LAr **V. De Romeri, et al., 2211.11905 (JHEP)**

Experimental Synergy

From neutrino measurement to dark matter detection

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. 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 $\nu + A \to \nu + A^*$ 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.

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany
(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small ($10-10^3$ eV), however. We examine a

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

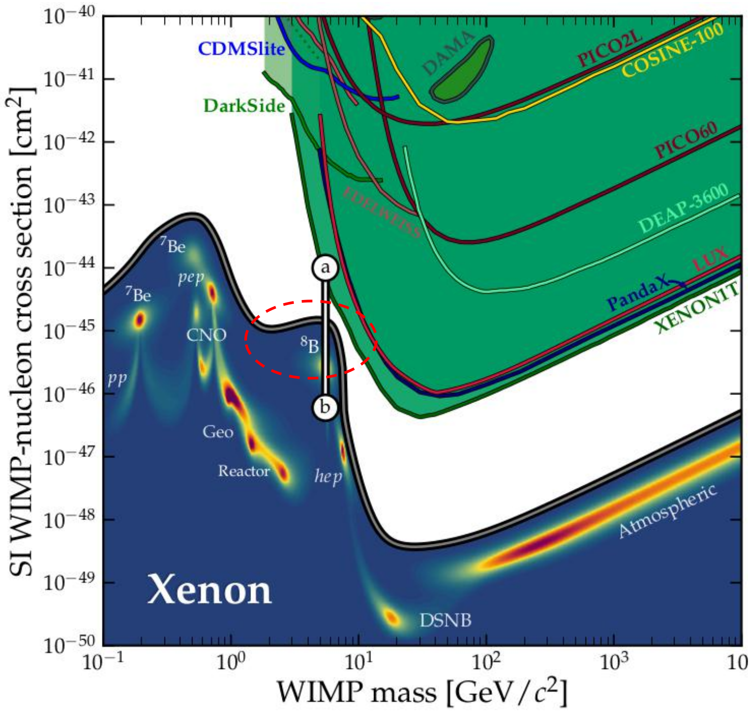
Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

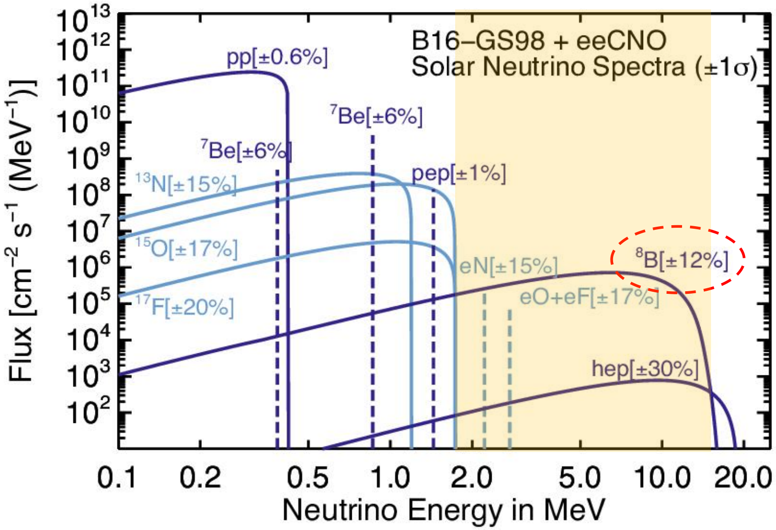
We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

credit: Jiajun Liao

Experimental Synergy

Neutrino floor/frog:



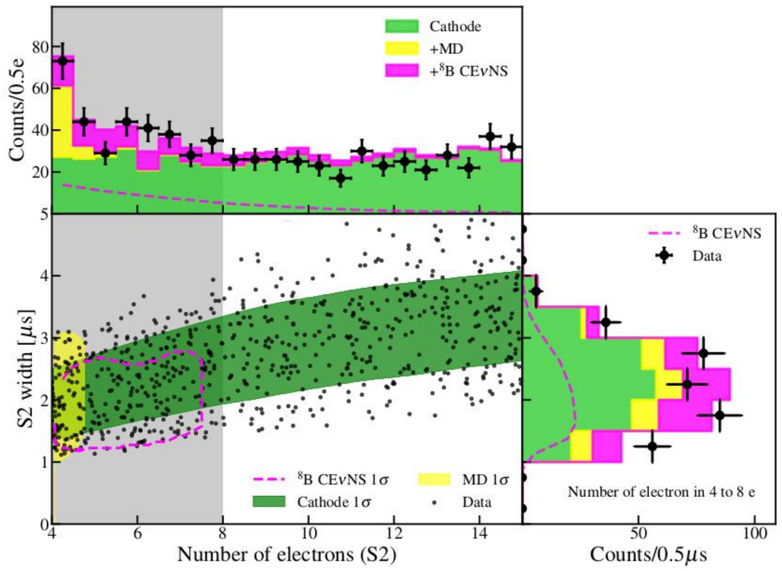


Neutrino source: sun

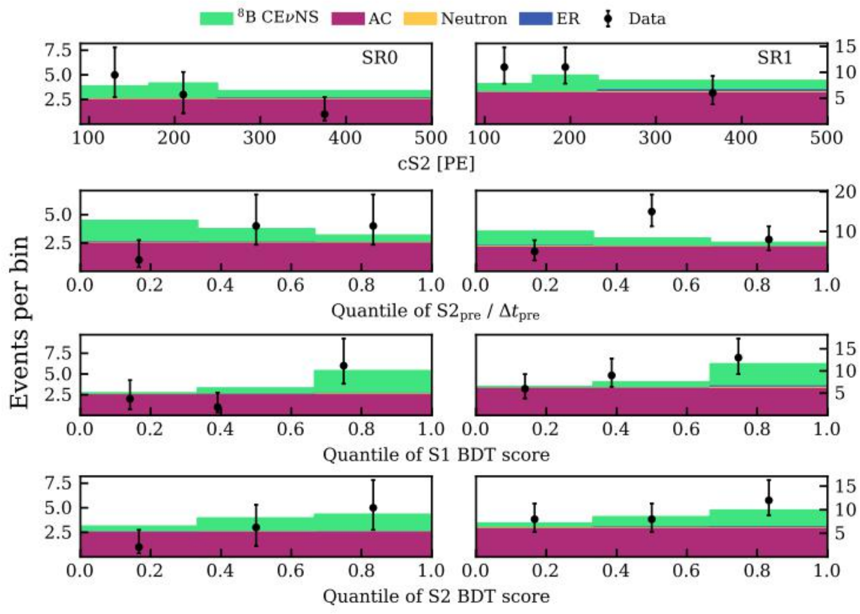
C. A. J. O'Hare, 2109.03116 (PRL)
J. Tang, B.-L. Zhang, 2304.13665 (PRD)

Solar ^{8}B neutrinos

First measurements of solar ^{8}B neutrinos via CEvNS:



PandaX-4T, 2407.10892 (PRL)



XENONnT, 2408.02877 (PRL)

US2 (75), pair (3.5) , background-only hypothesis is rejected with $2.64\ \sigma$

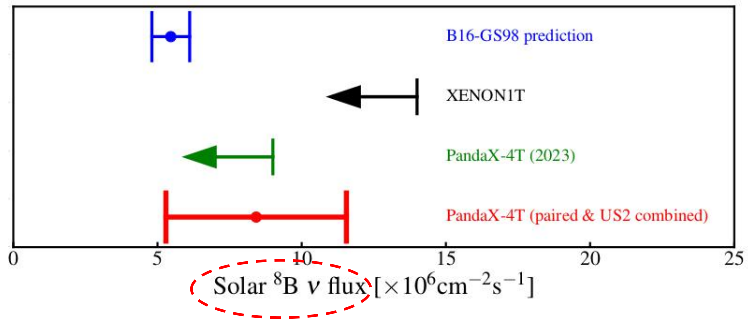
37 signal events, background-only hypothesis is rejected with $2.73\ \sigma$

Solar ^{8}B neutrinos

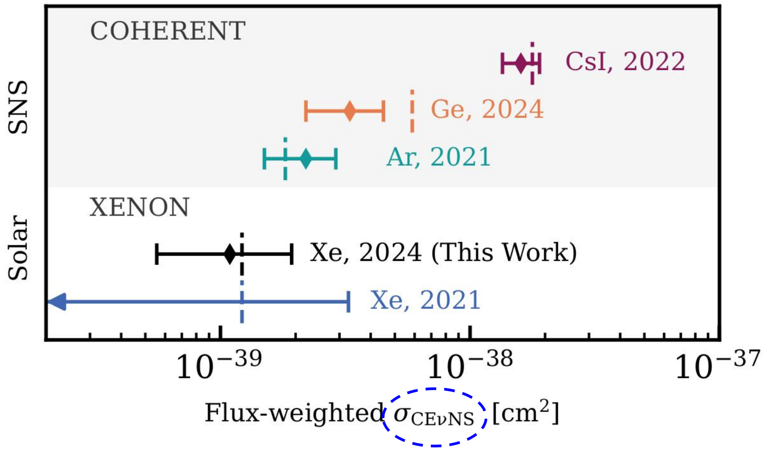
First measurements of solar ^{8}B neutrinos via CEvNS:

Number of signal events

= solar ^{8}B neutrino flux $\otimes$ CEvNS cross section



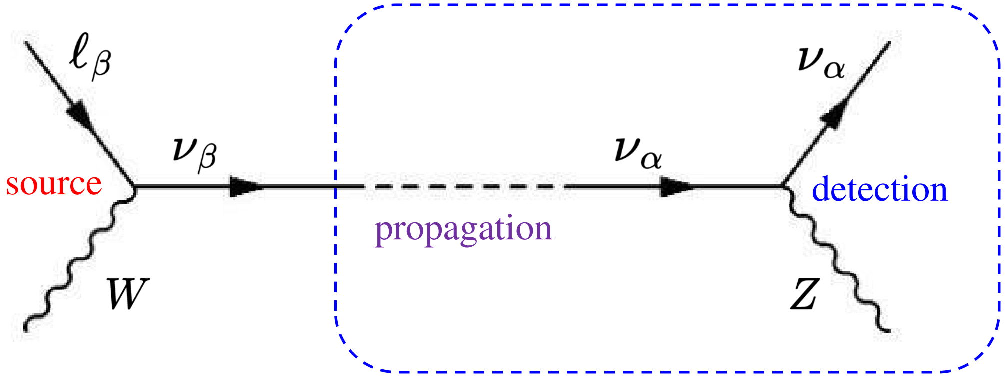
PandaX-4T, 2407.10892 (PRL)



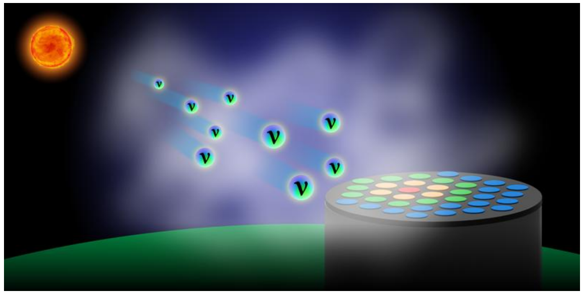
XENONnT, 2408.02877 (PRL)

Neutrino Non-standard Interactions

Measurements of neutrino NSIs in **scattering** experiments:



- Neutrino neutral-current NSIs can affect both the propagation and detection (scattering) of neutrinos



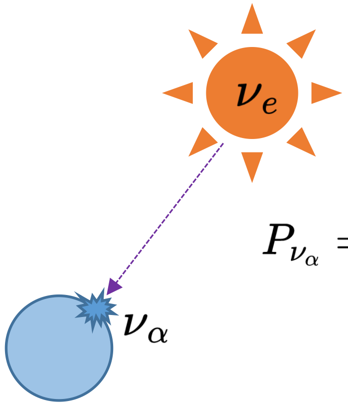
Neutrino source: sun

CEvNS events in PandaX-4T and XENONnT

From CEvNS events to neutrino NSIs:

- Number of signal events

$$N_{\nu_\alpha} = n_N \int_{T_{\rm nr,min}}^{T_{\rm nr,\,max}} {\rm d}T_{\rm nr}\, \varepsilon\left(T_{\rm nr}\right) \frac{{\rm d}R_\alpha}{{\rm d}T_{\rm nr}}$$



$$P_{\nu_\alpha} = \left|\langle \nu_e(t_0) | \nu_\alpha(t_E)\rangle\right|^2$$

- Differential event rate:

$$\frac{{\rm d}R_{\nu_\alpha}}{{\rm d}T_{\rm nr}} = \int_{E_{\nu,\rm min}}^{E_{\nu,\,\rm max}} dE_\nu \Phi_{\nu_\alpha}\left(E_\nu\right) \frac{{\rm d}\sigma}{{\rm d}T_{\rm nr}}$$

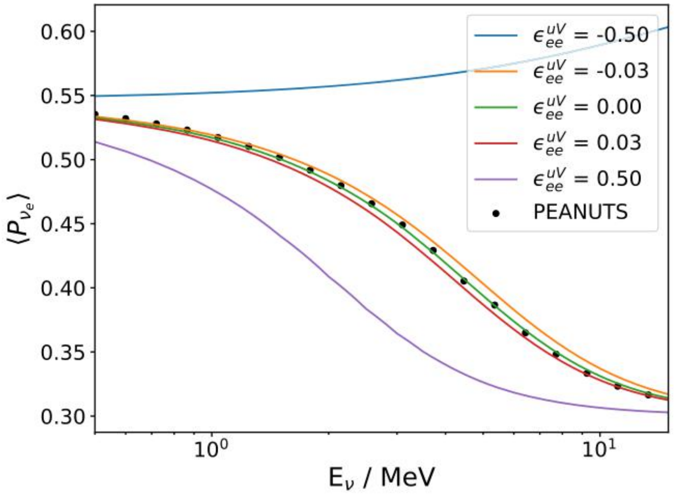
$$\Phi_{\nu_\alpha}\left(E_\nu\right) = \frac{\mathcal{E}}{M_{\rm det}} \langle P_{\nu_\alpha}\rangle \phi\left({}^8\,{\rm B}\right)$$

$$i\frac{d}{dr}|\nu\rangle = \left[\frac{1}{2E_\nu} U H_{\rm vac} U^\dagger + H_{\rm mat}\right]|\nu\rangle$$

$$\Delta H_{\rm mat} = \sqrt{2} G_F n_q \begin{pmatrix} \epsilon_{ee}^{qV} & \epsilon_{e\mu}^{qV} & \epsilon_{e\tau}^{qV} \\ \epsilon_{e\mu}^{qV*} & \epsilon_{\mu\mu}^{qV} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^{qV*} & \epsilon_{\mu\tau}^{qV*} & \epsilon_{\tau\tau}^{qV} \end{pmatrix}$$

CEvNS events in PandaX-4T and XENONnT

From CEvNS events to neutrino NSIs:



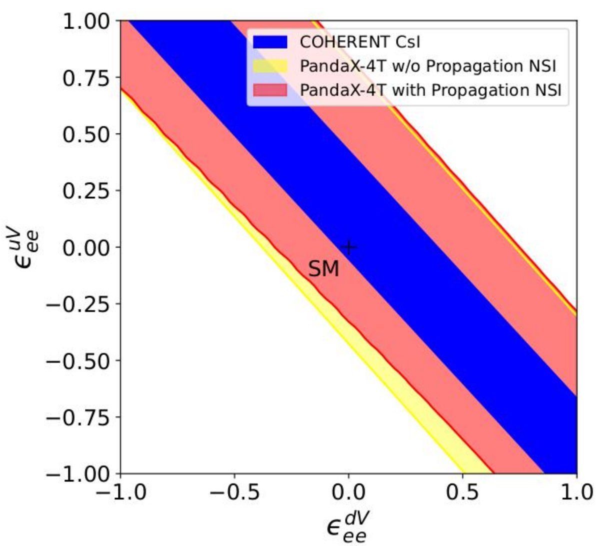
- The neutrino NSIs have substantial impact on the solar matter effect
- The averaged probabilities vary by a factor of 2 at most for $|\epsilon^{uV}_{ee}| \leq 0.5$

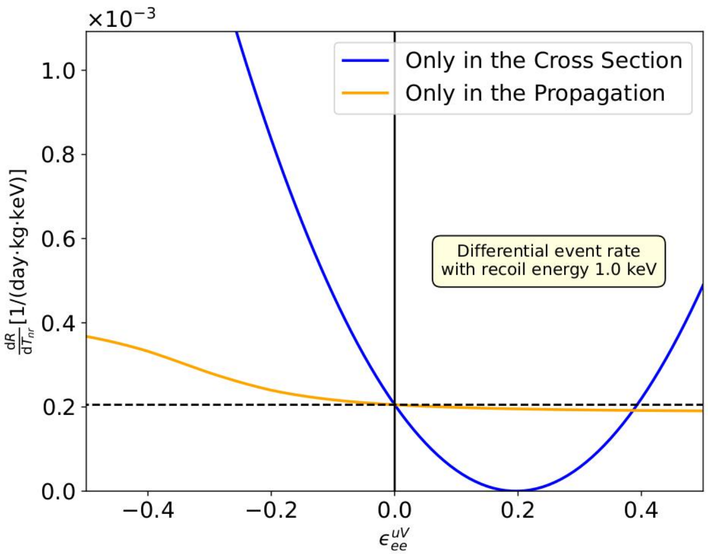
see also **Aristizabal Sierra, Mishra, Strigari, 2409.02003 (PRD)**

The neutrino neutral-current NSIs have impact on the solar matter effects (propagation) and CEvNS cross section (scattering)

CEvNS events in PandaX-4T and XENONnT

From CEvNS events to neutrino NSIs:





The effect of NSIs on neutrino propagation is weaker than that on scattering

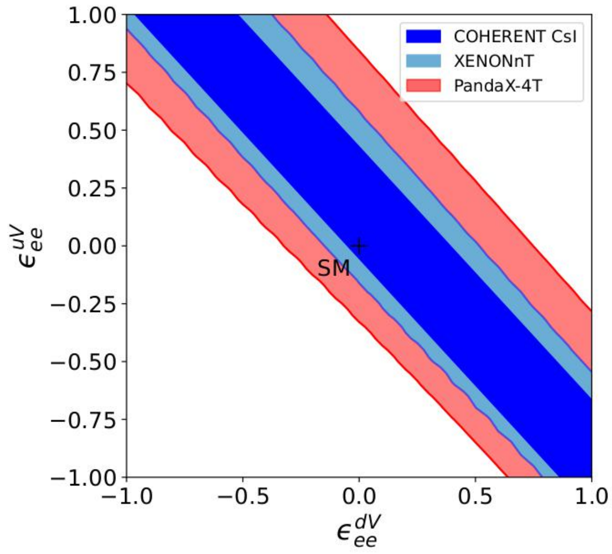
The cross section is approximated as quadratic polynomial of the NSI parameter

Constraint on NSIs from PandaX-4T and XENONnT

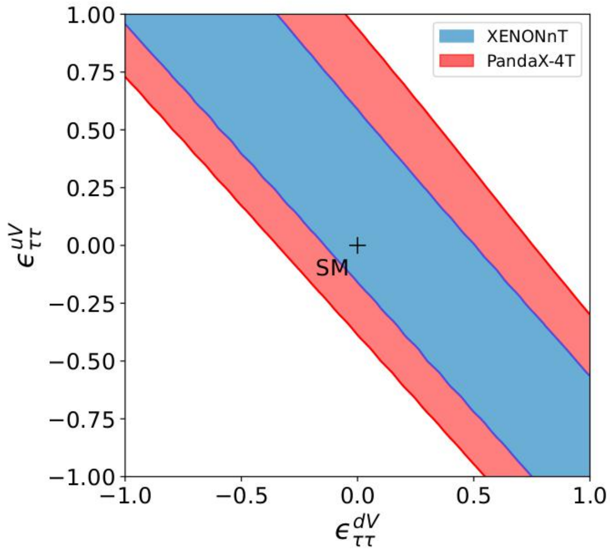
From CEvNS events to neutrino NSIs:

$$\mathcal{L}_{\rm NC} \supset -2\sqrt{2}G_F \left[\epsilon^{qL}_{\alpha\beta} \left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right)\left(\bar{q}\gamma_\mu P_L q\right) + \epsilon^{qR}_{\alpha\beta} \left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right)\left(\bar{q}\gamma_\mu P_R q\right)\right]$$

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



constraint from PandaX-4T (US2 data) is weaker than XENONnT



unique probe of tau-flavor NSIs

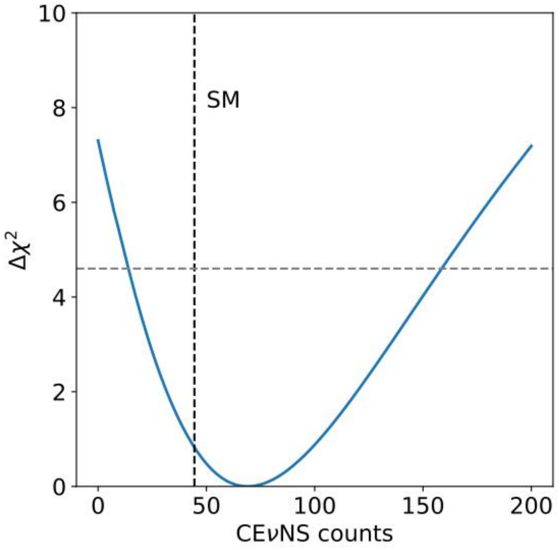
Prospects for PandaX-4T

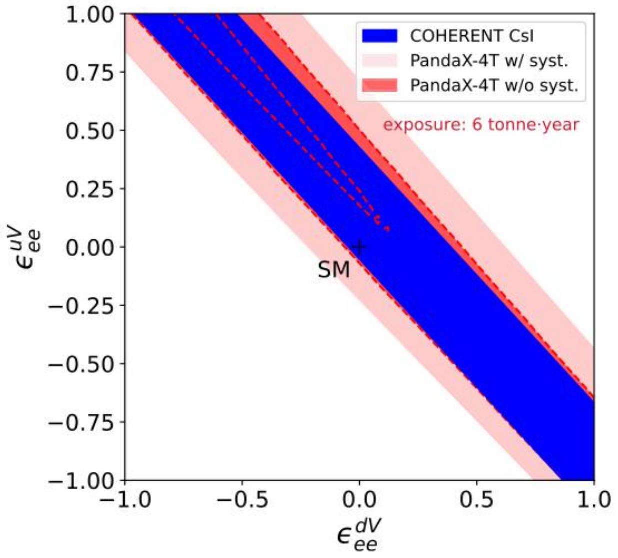
chi-square analysis:

$$\chi^2 = \frac{[N_{\text{meas}} - N_{\text{CE}\nu\text{NS}}(1+\alpha)]^2}{\sigma_{\text{stat}}^2} + \left(\frac{\alpha}{\sigma_\alpha}\right)^2$$

The sensitivity to NSIs is limited by

- central value (69.1)
- statistic uncertainties (37%)
- exposure (1.04 tonne · year)
- systematic uncertainties (24.5%)





Summary

- We investigate constraints on neutrino nonstandard interactions from COHERENT, PandaX-4T and XENONnT.
- We find that the costraints from PandaX-4T and XENONnT are weaker than that from COHERENT for e- and mu-flavor NSIs.
- PandaX-4T and XENONnT provide unique probes of tau-flavor NSIs.
- In the measurements of solar ^{8}B neutrinos, effect of NSIs on neutrino propagation is weaker than that on scattering.
- The sensitivity of PandaX-4T is primarily limited by the deviation of the central value from the SM prediction

Thank you