Synergies in the Searches for Neutrino NSIs and Dark Matter

李刚

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GL, Chuan-Qiang Song, Feng-Jie Tang, Jiang-Hao Yu, 2409.04703 (PRD)
Yuxuan He, **GL**, Jia Liu, Xiao-Ping Wang, Xiang Zhao, 2407.06523

2025粒子物理标准模型及新物理精细计算研讨会

河北大学，保定，2025年3月30日

Deep seek for new physics

What Deepseek says:

这句话 **"Synergies in the Searches for Neutrino NSIs and Dark Matter"** 的含义是：

1. 核心含义

它强调 **"中微子非标准相互作用（NSI）和暗物质（DM）的探测研究之间存在协同效应"**，即两者的研究可以相互促进，而非孤立进行。具体表现为：

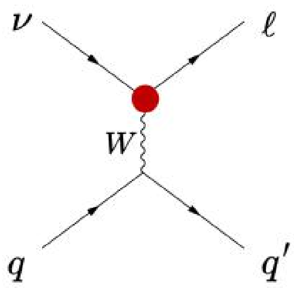
- **实验协同**：同一实验装置（如地下探测器）可能同时探测NSI和DM信号（如暗物质-中微子散射）。
- **理论协同**：某些新物理模型（如轻暗物质通过新玻色子与中微子耦合）可能同时解释NSI异常和暗物质观测。
- **数据分析协同**：NSI的测量结果可约束暗物质参数空间，反之亦然。

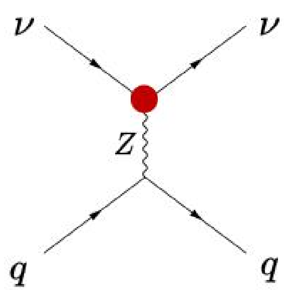
2. 隐含的深层信息

- **资源共享**：减少实验成本（例如利用中微子实验的设施兼作暗物质探测）。
- **交叉验证**：通过多信使（neutrino + DM）方法提高新物理发现的可信度。
- **模型构建**：若NSI和DM的观测数据存在关联，可能指向同一扩展理论（如超出标准模型的轻子味对称性破缺机制）。

Neutrino Non-standard Interactions

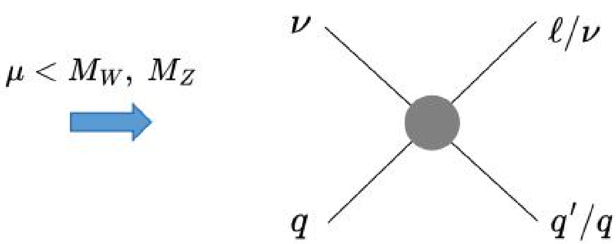
Origin of neutrino-quark NSIs:





+

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



four-fermion interactions

Note: **neutrino-electron** interactions in elastic scattering process (water Cherenkov solar neutrino detectors)

Neutrino Non-standard Interactions

Parameterization of neutrino NSIs:

- neutral current:

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

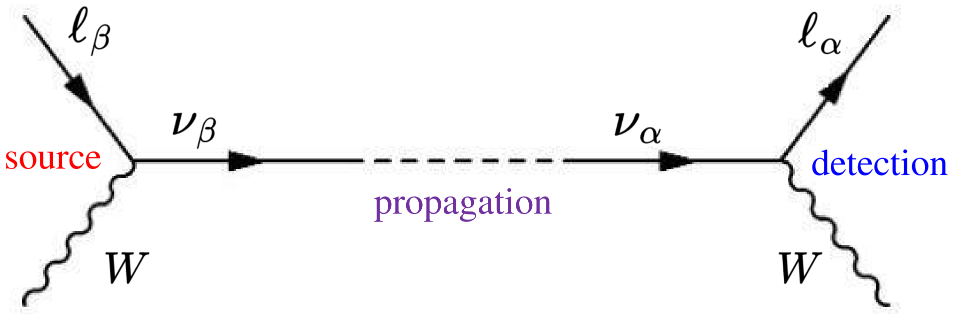
- charged current:

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

matched to dimension-6 operators in LEFT or SMEFT

Neutrino Non-standard Interactions

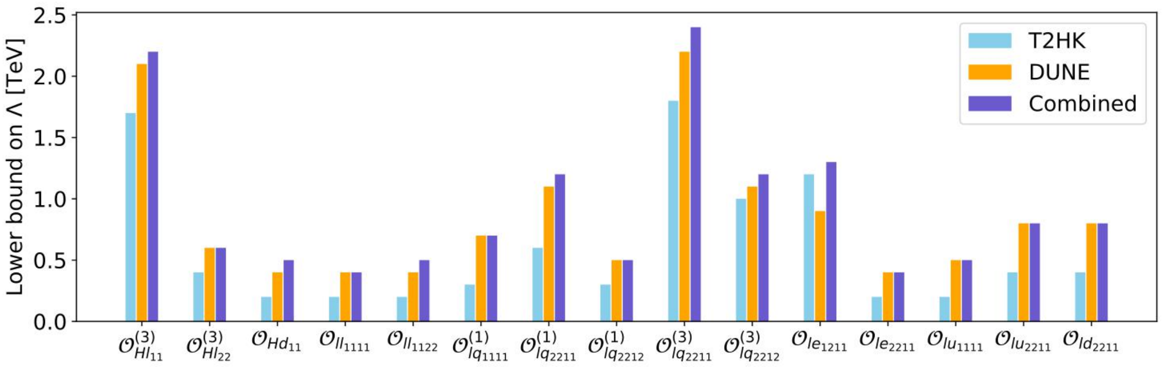
Measurements of neutrino NSIs in **oscillation** experiments:



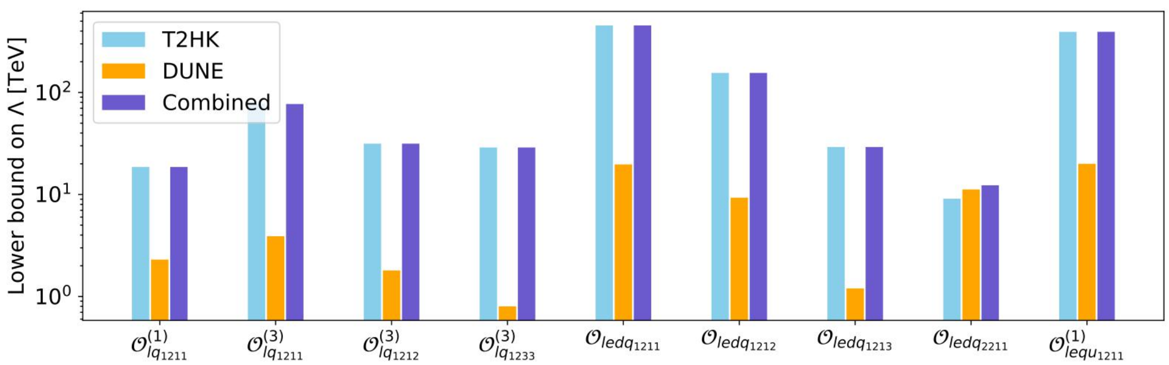
- Neutrino charged-current NSIs affect the source (production) and detection (scattering) of neutrinos
- Neutrino neutral-current NSIs affect the propagation of neutrinos

Neutrino Non-standard Interactions

Global fits in the SMEFT using long-baseline expts:



~ 1 TeV

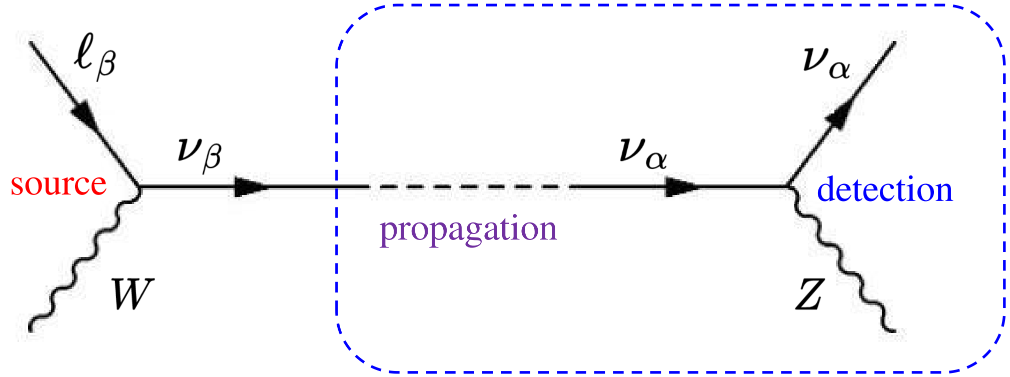


~ 10 TeV

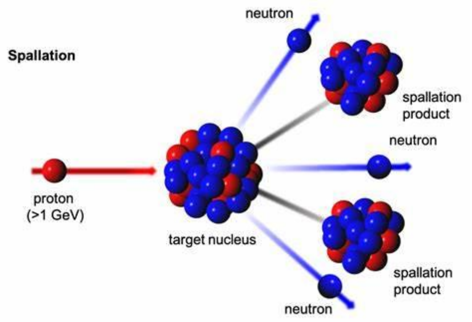
Yong Du, Hao-Lin Li, Jian Tang, Sampsa Vihonen, Jiang-Hao Yu 2106.15800 (PRD)

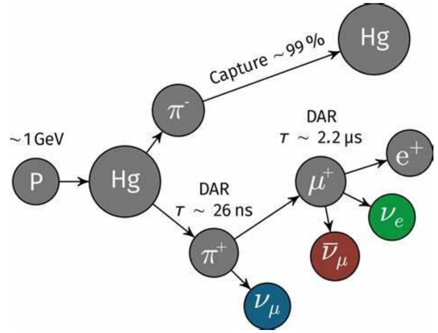
Neutrino Non-standard Interactions

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



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

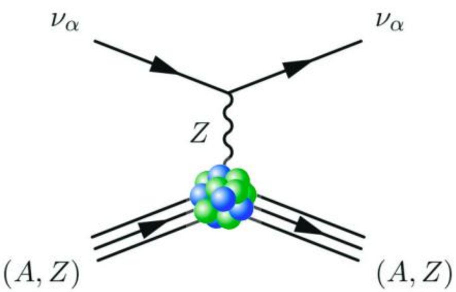


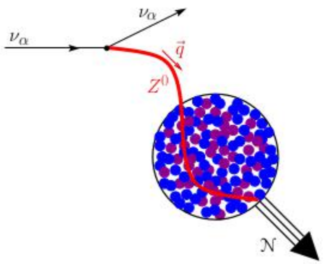


Neutrino source: Spallation Neutron Source

Neutrino Non-standard Interactions

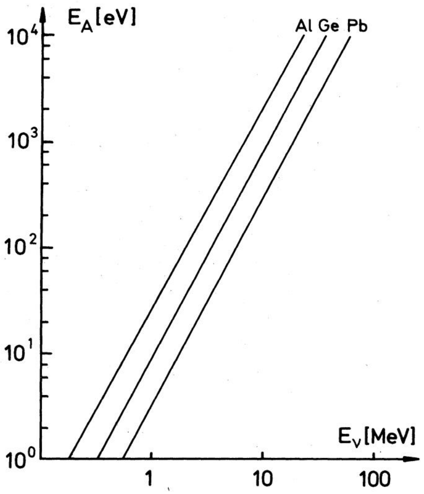
Coherent elastic neutrino-nucleus scattering (CEvNS):





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

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

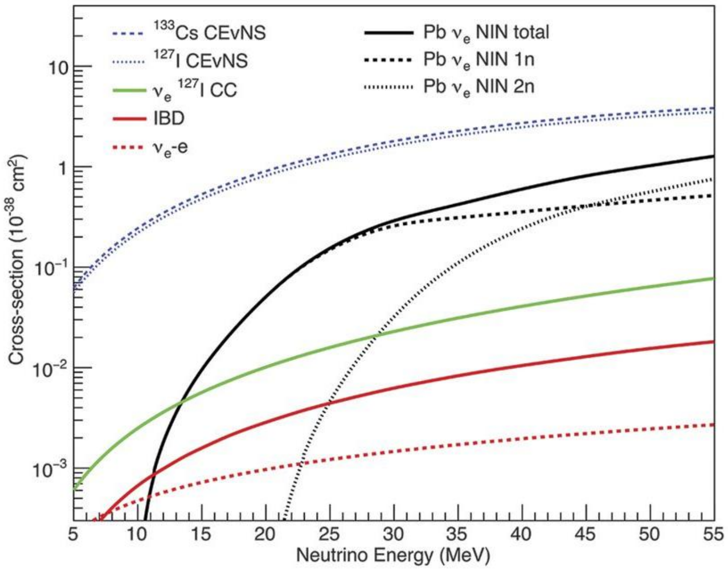


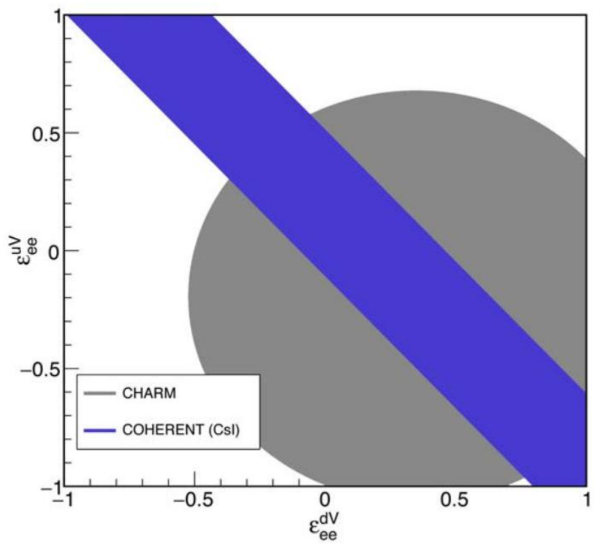
$$E_A = \frac{2}{3A}(E_\nu/1 \text{ MeV})^2 \text{ keV}$$

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

Neutrino Non-standard Interactions

Coherent elastic neutrino-nucleus scattering (CEvNS):



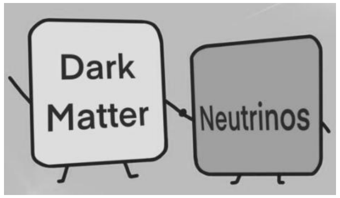


Science 357 (2017) 6356, 1123

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

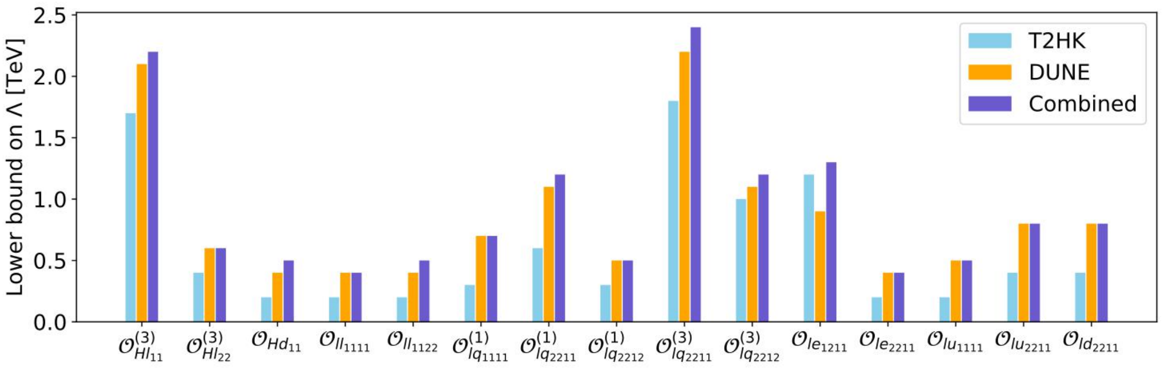
$$\epsilon^{qV}_{\alpha\beta} = \epsilon^{qL}_{\alpha\beta} + \epsilon^{qR}_{\alpha\beta}$$

理论协同

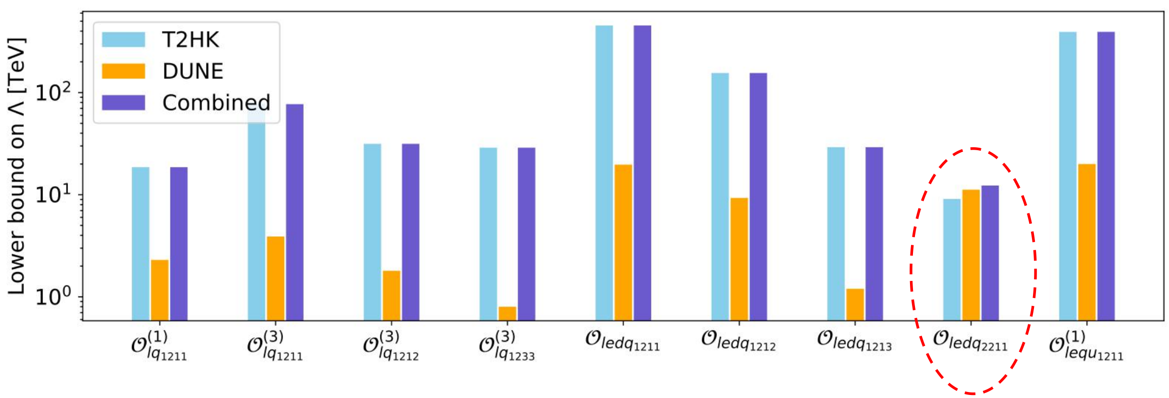


Neutrino Non-standard Interactions

Global fits in the SMEFT using long-baseline expts:



~ 1 TeV



~ 10 TeV

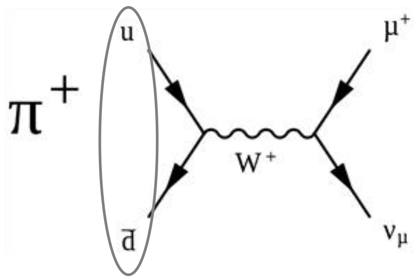
Yong Du, Hao-Lin Li, Jian Tang, Sampsa Vihonen, Jiang-Hao Yu 2106.15800 (PRD)

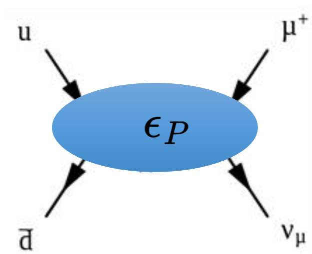
The most tightly constrained **lepton-flavor-conserving** operator

Neutrino Non-standard Interactions

Neutrino charged-current NSI arising from chirality-flip operator:

$$\mathcal{O}_{ledq}^{prst} : \left(\bar{l}_p^j e_r\right)\left(\bar{d}_s q_t^j\right) \quad \Longrightarrow \quad \mathcal{L}_{\rm CC} \supset -\frac{1}{2}\left[\epsilon_P\right]_{\alpha\beta}^{ij}\left(\bar{u}_i \gamma_5 d_j\right)\left(\bar{\ell}_\alpha P_L \nu_\beta\right)$$





The ϵ_P term modifies the neutrino source:

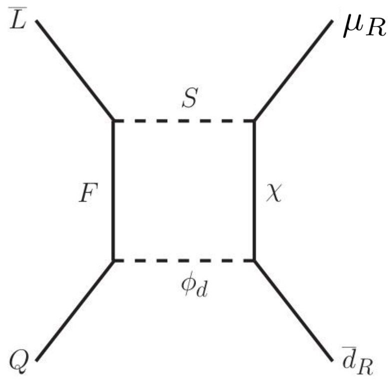
$$\delta\Gamma\left(\pi^+ \to \mu^+ \nu_\mu\right) \simeq \frac{\left(\left(m_\pi^2 - m_\mu^2\right)^2 m_\mu^2\right)^2 f_\pi^2}{64\pi m_\pi^3}\left|J_{\pi\mu}\left(\frac{V_{ud}}{v^2}\left[\epsilon_P\right]_{22}^{11}\right)^2\right|^2$$

$$J_{\pi\mu} = \frac{m_\pi^2}{m_\mu\left(m_u + m_d\right)} \sim 20$$

Theoretical Synergy

Dark-loop paradigm:

one-loop realization of four-fermion operators with **dark** particles



$$\mathcal{O}_{ledq}^{prst} : (\bar{l}_p^j e_r) \left(\bar{d}_s q_t^j\right)$$

$$prst = 2211$$

$$\mathcal{L} = f_{LS} \left(\bar{L} F_R\right) S^* + f_{\chi S} \left(\bar{\chi}_L \mu_R\right) S + f_{FQ} \left(\bar{F}_R Q\right) \phi_d^* + f_{d\chi} \left(\bar{d}_R \chi_L\right) \phi_d + \text{ h.c.}$$

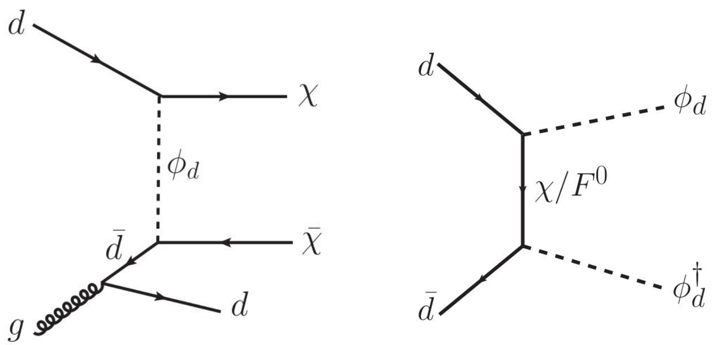
Z_2-odd

Majorana DM:	χ
mediators:	$S,\ \phi_d$
lepton:	F

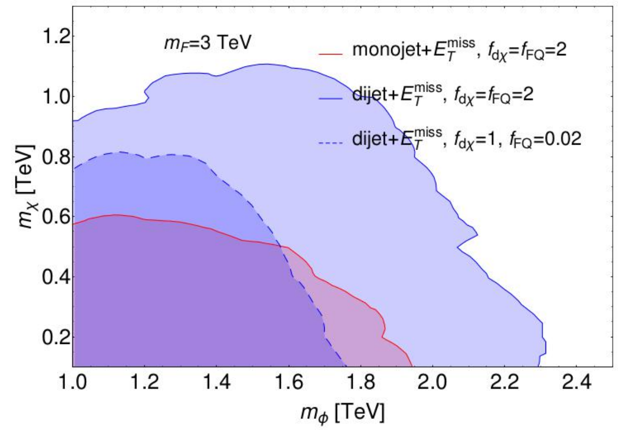
Cepedello, Esser, Hirsch, Sanz, 2302.03485 (JHEP)

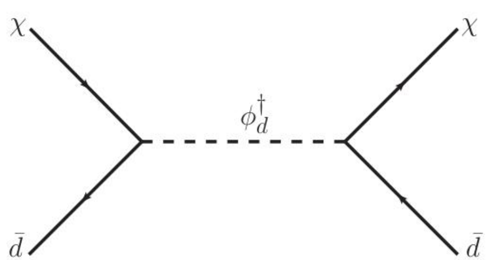
Fermion portal dark matter

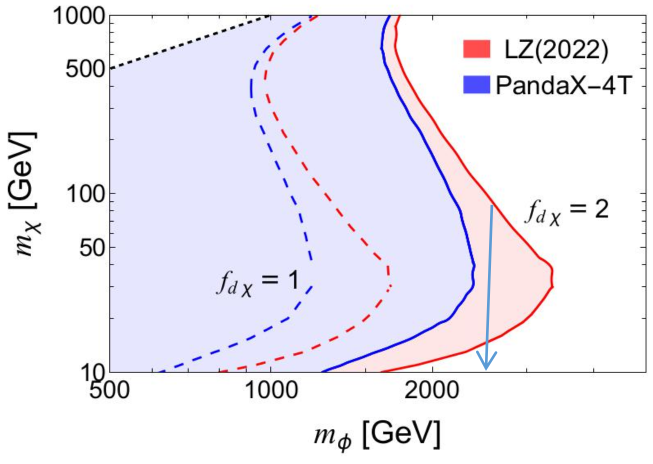
Constraints from LHC and direct detection



$$\phi_d^{\pm 1/3} \to \chi j$$

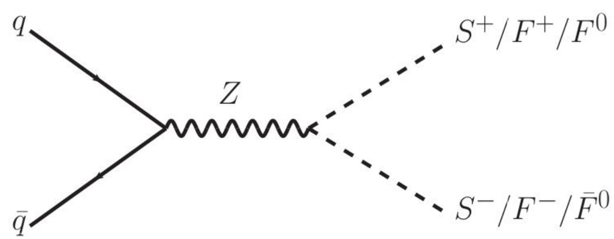




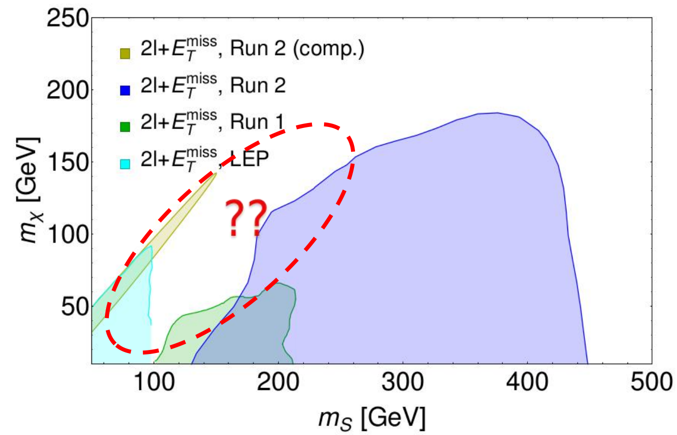


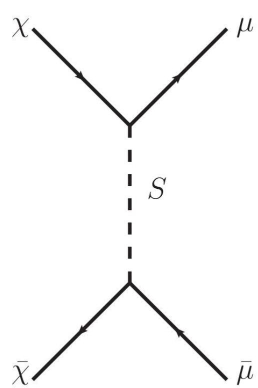
Fermion portal dark matter

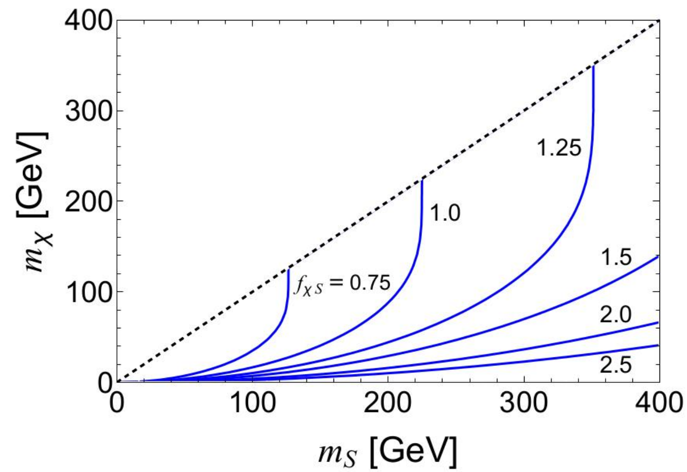
Constraints from LHC and relic density



$$S^{\pm} \to \mu^{\pm}\chi$$

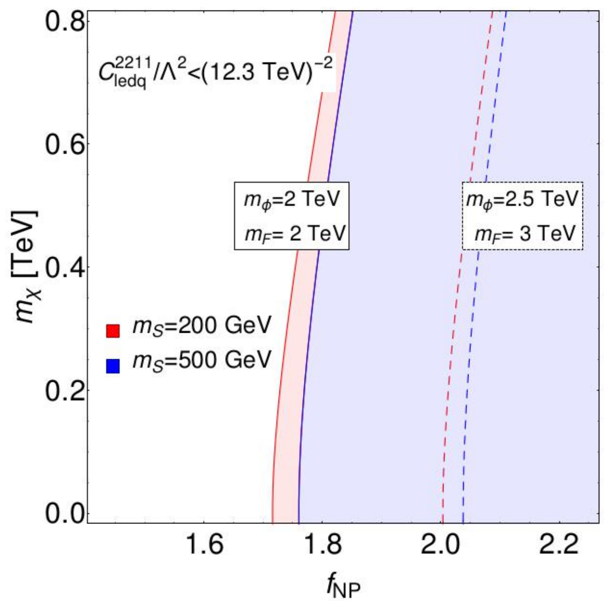




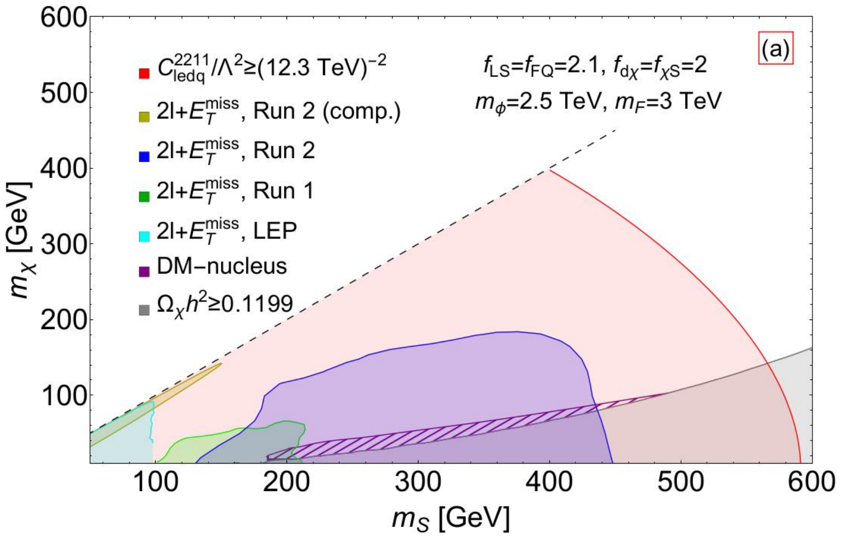


Fermion portal dark matter

Constraint from neutrino NSI

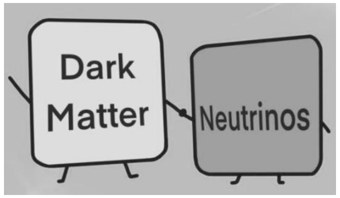


$$f_{\rm NP} = (f_{LS} f_{\chi S} f_{FQ} f_{d\chi})^{1/4}$$



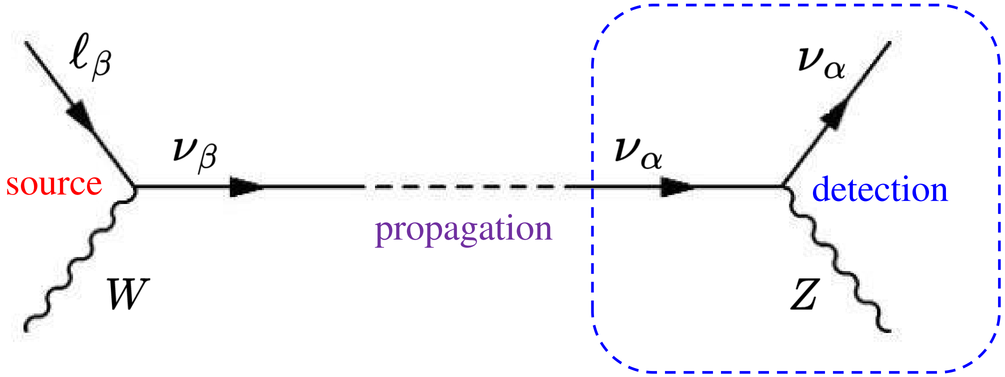
Note: sensitivity of direct detection via DM-nucleus scattering, which is suppressed by the relic density for $f_{\chi S} = 2$, is rather weak

实验协同

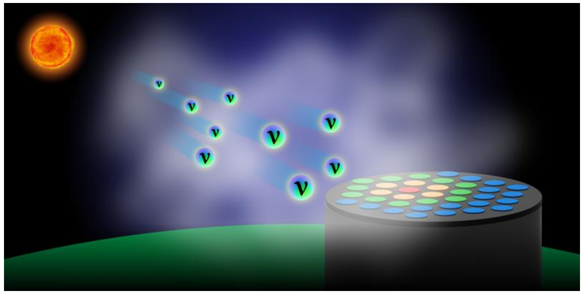


Neutrino Non-standard Interactions

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



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



Neutrino source: sun

Experimental Synergy

From neutrino neutral current to DM 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

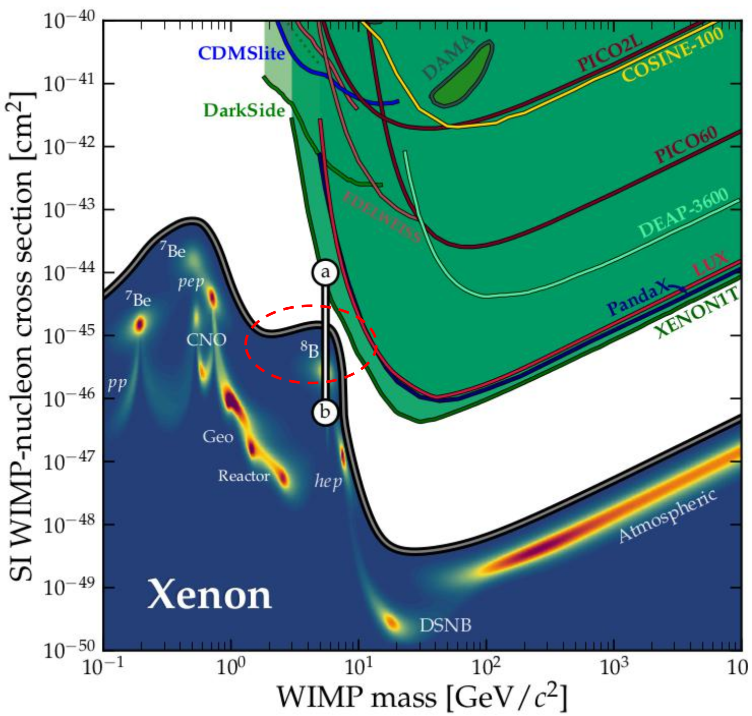
Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

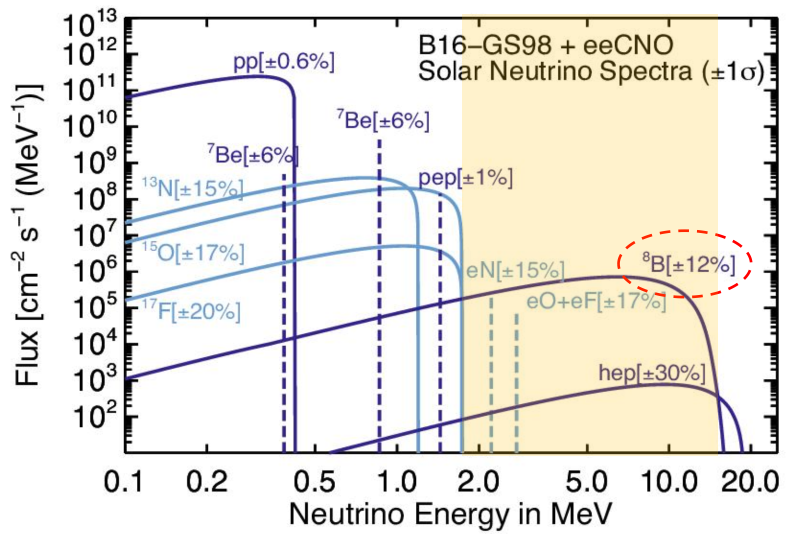
We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and 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

Solar ^{8}B neutrinos

Neutrino floor/frog:





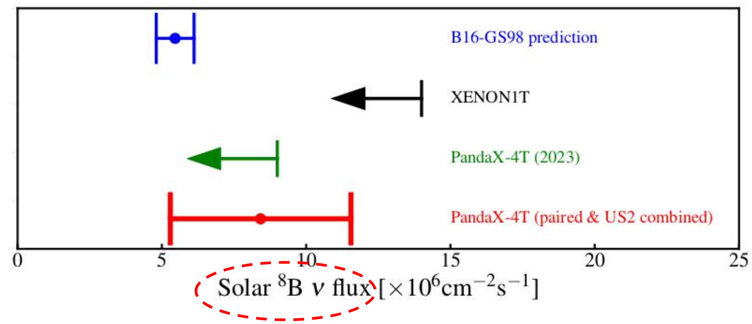
Neutrino source: sun

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

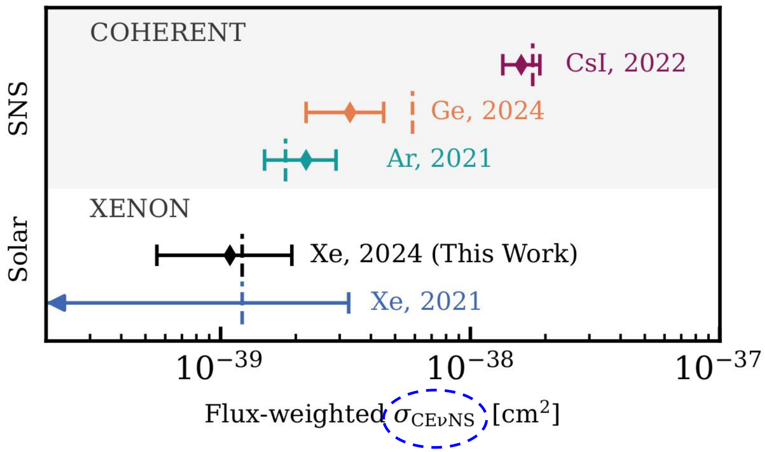
Solar ^{8}B neutrinos

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

经过多年无果的探索，暗物质搜寻实验可能终于捕捉到了一个真实信号……2024年，PandaX和XENON实验组独立报告称，他们的探测器很可能已初步观测到这一“中微子迷雾”。尽管长期来看，中微子迷雾可能对暗物质探测构成干扰，但学界普遍认为，其影响至少要到十年后下一代实验启动时才会显现。更重要的是，暗物质实验装置或可转型为多功能探测器，用于探索中微子物理的诸多奥秘。
来源：https://physics.aps.org/articles/v17/181



PandaX-4T, 2407.10892 (PRL)



XENONnT, 2408.02877 (PRL)

Number of signal events

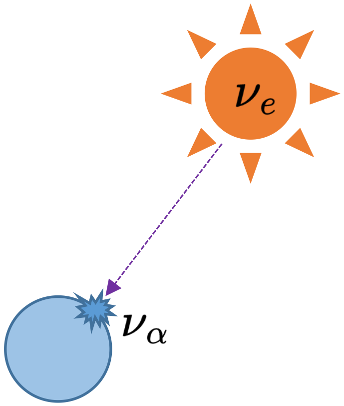
= solar ^{8}B neutrino flux $\otimes$ CEvNS cross section

Neutrino neutral-current NSIs

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

Number of signal events:

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



Differential event rate:

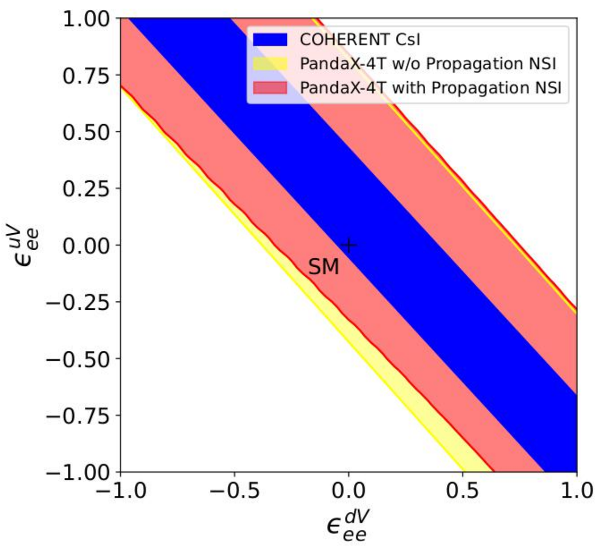
$$\frac{\mathrm{d}R_{\nu_\alpha}}{\mathrm{d}T_{\rm nr}} = \int_{E_{\nu,\rm min}}^{E_{\nu,\,\rm max}} dE_\nu \Phi_{\nu_\alpha}\left(E_\nu\right) \frac{\mathrm{d}\sigma}{\mathrm{d}T_{\rm nr}}$$

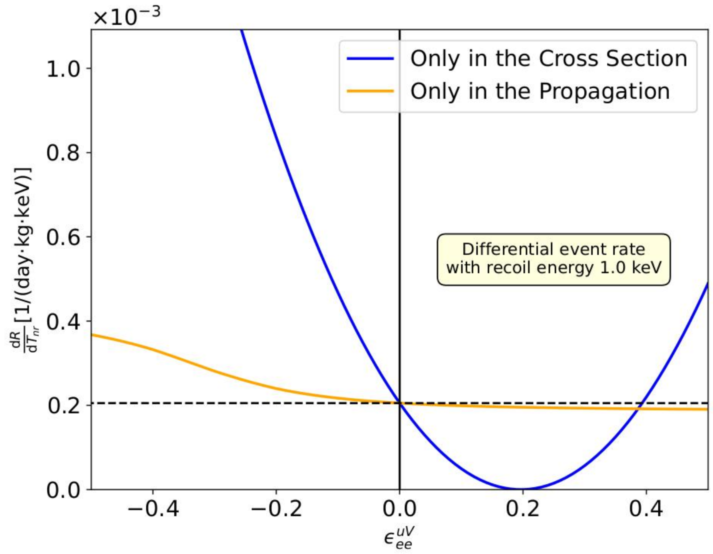
$$\Phi_{\nu_\alpha}\left(E_\nu\right) = \frac{\mathcal{E}}{M_{\rm det}} \langle P_{\nu_\alpha} \rangle \phi\left(^8\,\mathrm{B}\right)$$

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

Neutrino neutral-current NSIs

The impact on neutrino propagation is milder than that on scattering





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

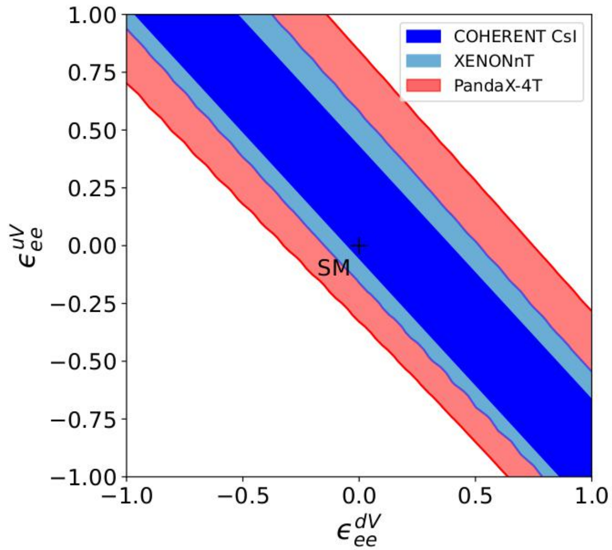
quadratic polynomial of the NSI parameter

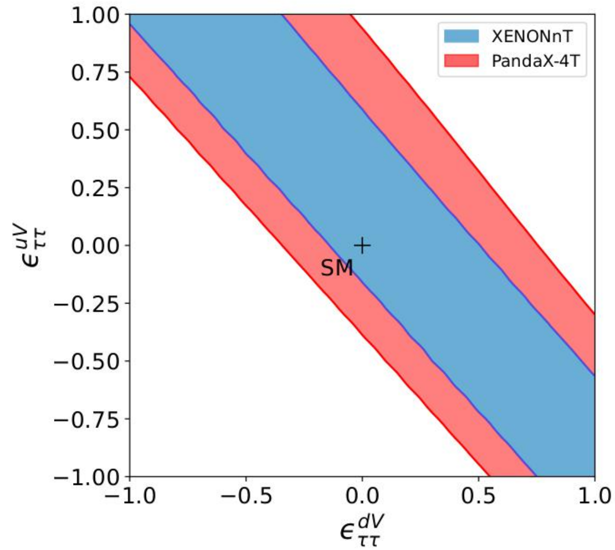
GL, Chuan-Qiang Song, Feng-Jie Tang, Jiang-Hao Yu, 2409.04703 (PRD)

Neutrino neutral-current NSIs

Neutral-current interactions:

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





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

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Summary

- We investigate the synergies between searches for neutrino NSIs and dark matter from both theoretical and experimental perspectives.

- From theoretical aspect, the neutrino **charged-current** NSI constraint can effectively probe fermion portal dark matter model beyond collider searches as well as direct/indirect detection.

- From experimental aspect, constraint on the neutrino **neutral-current** NSI using the first measurements of the solar ^{8}B neutrinos via CEvNS by PandaX-4T and XENONnT is derived.

Thank you