Indirect probes of new physics with non-standard interactions of leptons

李刚

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

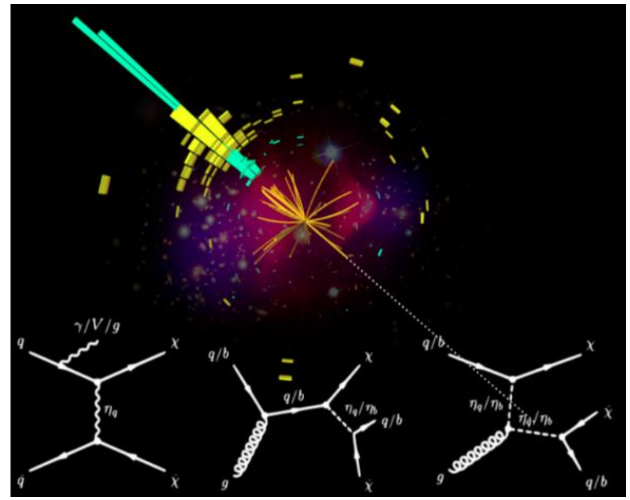
29th Mini-workshop on the frontier of LHC

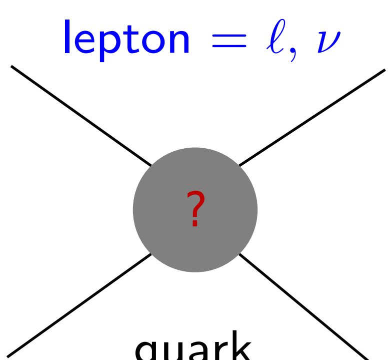
福州，2024年12月14日

New physics

The Standard Model is successful but incomplete:

- neutrino masses
- baryon asymmetry
- dark matter
- strong CP problem
- flavor structure
- ....



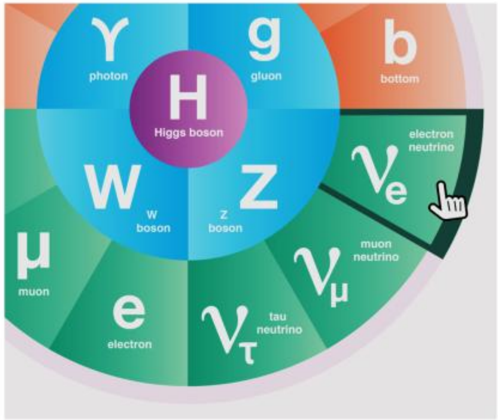


Indirect probes of new physics via precise measurements of lepton interactions

Neutrino physics

Open questions:

- **Normal or Inverted (sign of Δm^2_{31}?)**
- **Leptonic CP Violation (δ = ?)**
- **Octant of θ_{23} (> or < 45°?)**
- **Absolute Neutrino Masses ($m_{\text{lightest}} = 0$?)**
- **Majorana or Dirac Nature ($\nu=\nu^c$?)**
- **Majorana CP-Violating Phases (how?)**



- **Extra Neutrino Species**
- ✔ **Exotic Neutrino Interactions**
- **Various LNV & LFV Processes**
- **Leptonic Unitarity Violation**

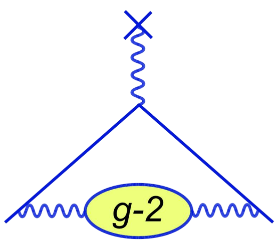
- **Origin of Neutrino Masses**
- **Flavor Structure (Symmetry?)**
- **Quark-Lepton Connection**
- **Relations to DM and/or BAU**

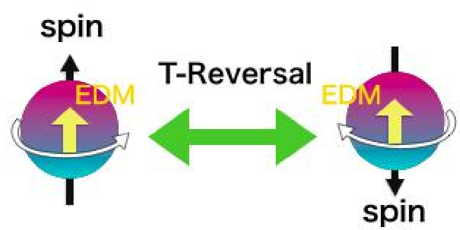
credit: Shun Zhou

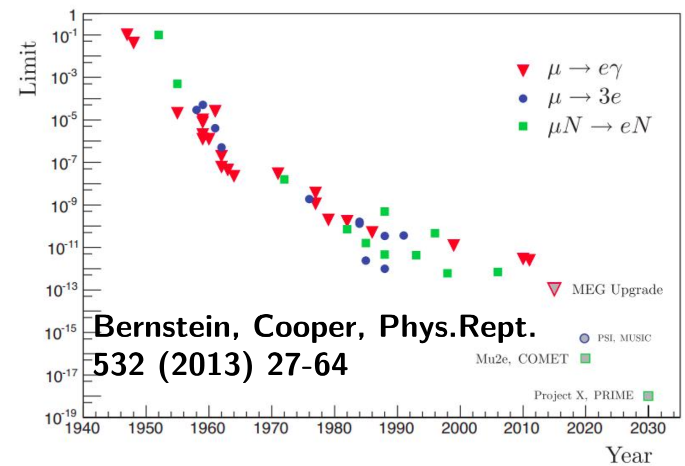
Charged lepton physics

Open questions:

- muon anomalous magnetic moment (g-2)
- electron electric dipole moment (EDM)
- charged lepton flavor violation (CLFV) ✔
- ...







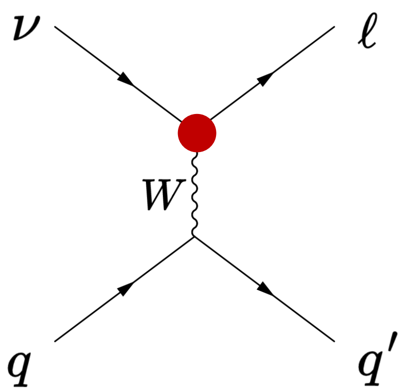
also $\mu^+ e^- \to \ell^+ \ell^-$ proposal by PKMu group

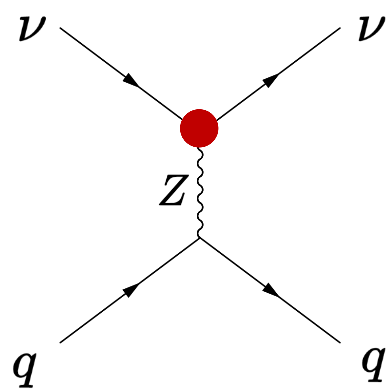
Outline

- Neutrino non-standard interactions (NSI): charged currents and neutral currents
- Constraints on neutrino neutral-current NSIs using the first measurements of solar ^{8}B neutrinos
- UV completion of neutrino charged-current NSI and CLFV interaction with dark matter

Neutrino Interactions

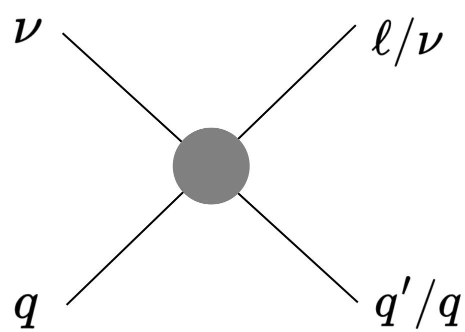
Neutrino Non-Standard Interactions:





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

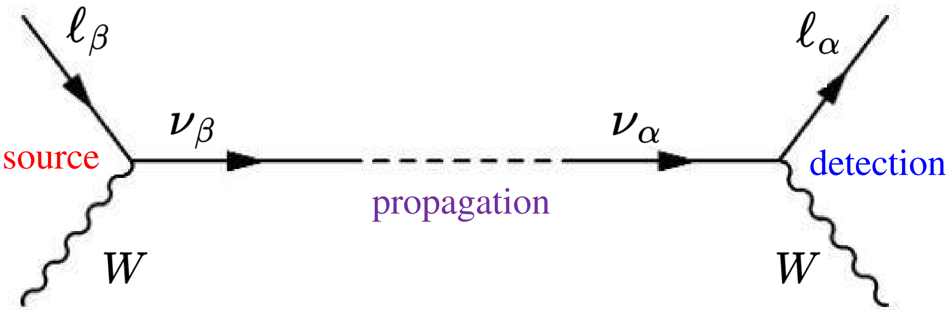
$\mu < M_W,\ M_Z$



semileptonic four-fermion operators

Neutrino Interactions

In neutrino 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 Interactions

Future neutrino oscillation experiments:

$O_{lq}^{(1)prst}$: $\left(\bar{l}_p \gamma_\mu l_r\right)(\bar{q}_s \gamma^\mu q_t)$ →

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

Operator	T2HK limit (TeV)	DUNE limit (TeV)	JUNO limit (TeV)	T2HK and DUNE limit (TeV)	JUNO and TAO limit (TeV)
$\mathcal{O}^{(1)}_{lq_{1111}}$	0.3	0.7	0.2	0.7	1.3
$\mathcal{O}_{ledq_{2211}}$	9.1	11.2	0.7	12.3	0.7

chirality-flip operator

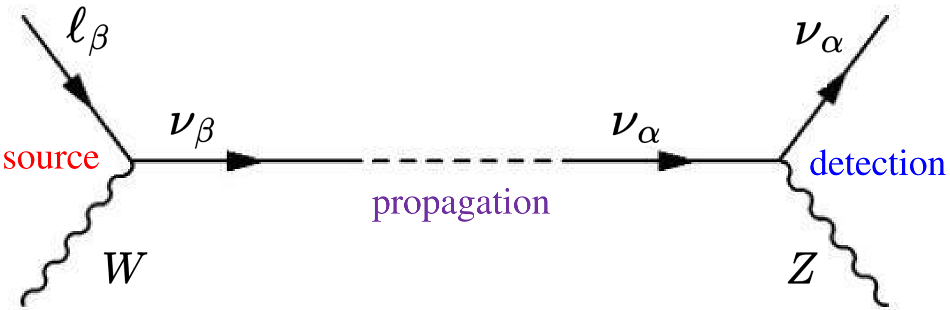
Y. Du, H.-L. Li, J. Tang, S. Vihonen, J.-H. Yu 2106.15800 (PRD)

$$\mathcal{L}_{\rm CC} \supset -2\sqrt{2}G_F V_{ud}^{\rm SM}\Big\{[\mathbf{1}+\epsilon_L]^{ij}_{\alpha\beta}(\bar{u}_i\gamma^\mu P_L d_j)(\bar{\ell}_\alpha\gamma_\mu P_L \nu_\beta) + [\epsilon_R]^{ij}_{\alpha\beta}(\bar{u}_i\gamma^\mu P_R d_j)(\bar{\ell}_\alpha\gamma_\mu P_L \nu_\beta)$$

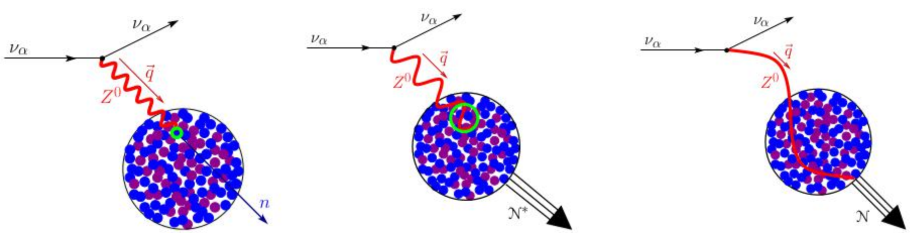
$$+\frac{1}{2}[\epsilon_S]^{ij}_{\alpha\beta}(\bar{u}_i d_j)(\bar{\ell}_\alpha P_L \nu_\beta) - \frac{1}{2}[\epsilon_P]^{ij}_{\alpha\beta}(\bar{u}_i\gamma_5 d_j)(\bar{\ell}_\alpha P_L \nu_\beta) + \frac{1}{4}[\epsilon_T]^{ij}_{\alpha\beta}(\bar{u}_i\sigma^{\mu\nu} P_L d_j)(\bar{\ell}_\alpha\sigma_{\mu\nu} P_L \nu_\beta) + \text{H.c.}\Big\}$$

Neutrino Interactions

In neutrino scattering experiments:



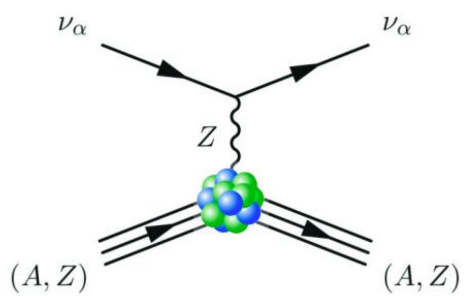
- Neutrino neutral-current NSIs can affect both the propagation and detection (scattering) of neutrinos

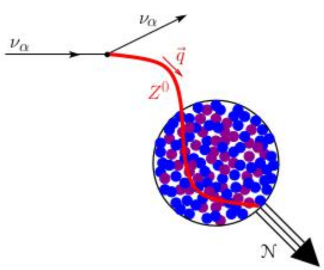


Inelastic incoherent $\lambda_{Z^0} \ll 2R$ Elastic incoherent $\lambda_{Z^0} \lesssim 2R$ Elastic coherent (CEνNS) $\lambda_{Z^0} \gtrsim 2R$

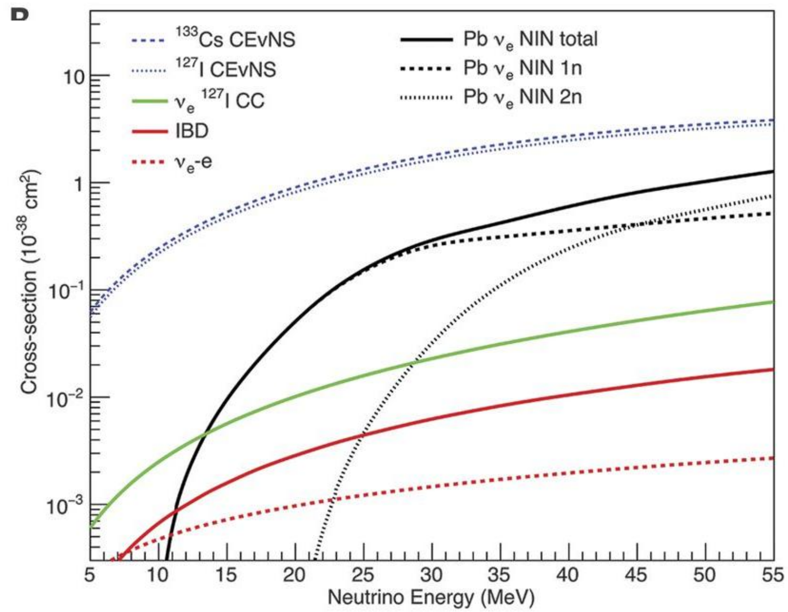
Neutrino NC Interactions

Coherent Neutrino-nucleus scattering (CEvNS):





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



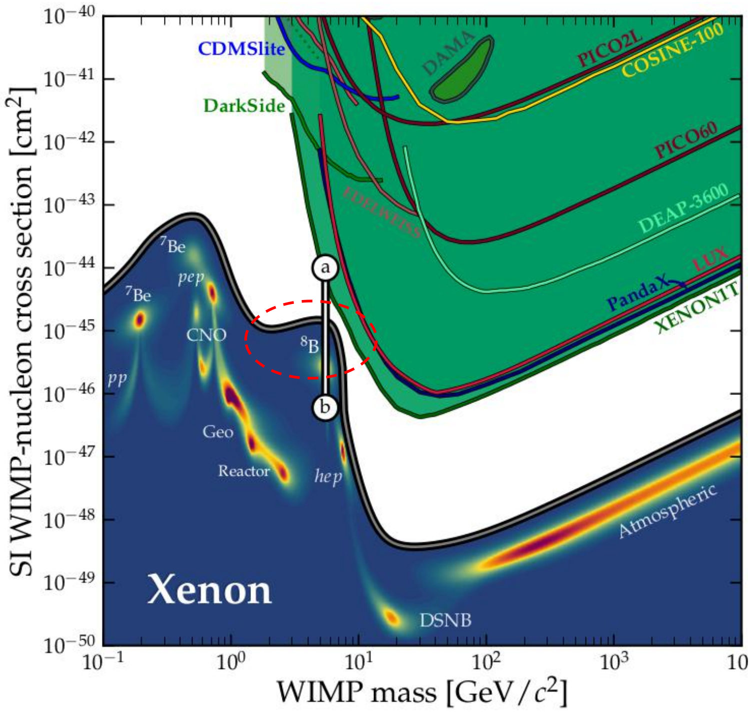
Science 357 (2017) 6356, 1123

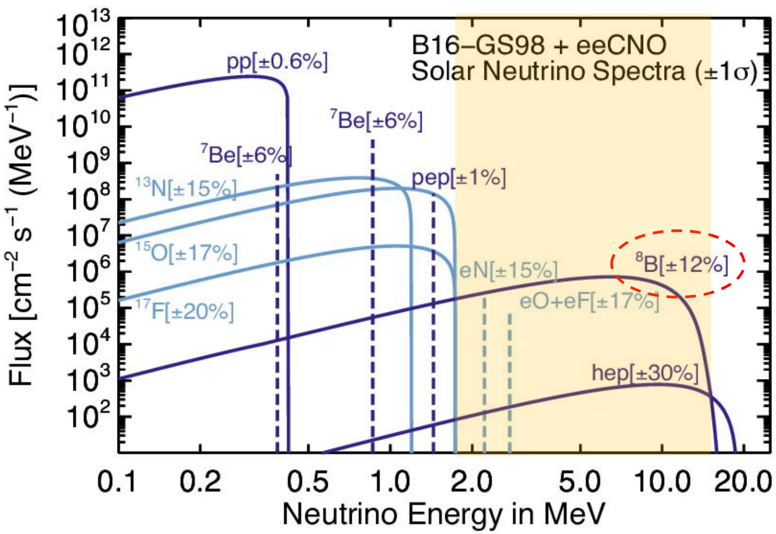
D. Z. Freedman, Phys. Rev. D 9, 1389 (1974)

Neutrino source: spallation neutron source

Neutrino NC Interactions

From neutrino to DM: neutrino floor/frog



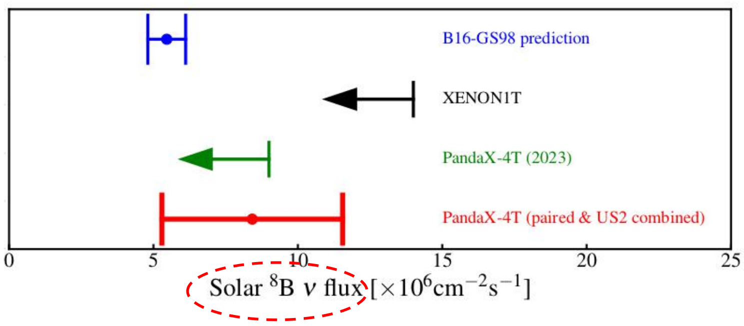


Neutrino source: sun

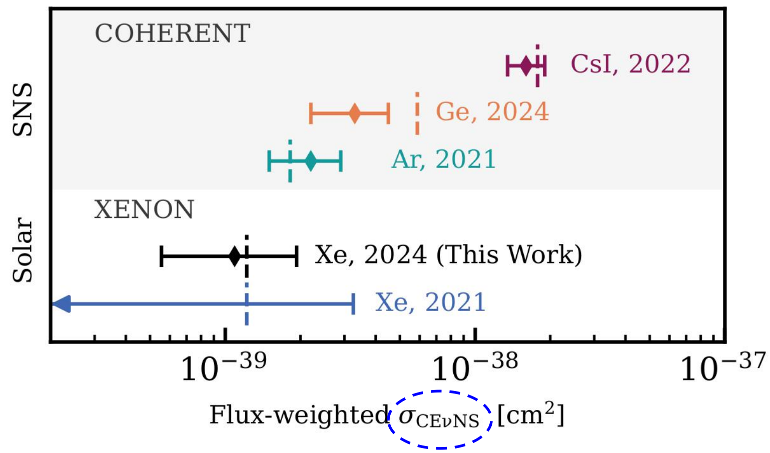
C. A. J. O'Hare, 2109.03116 (PRL)
J. Tang, B.-L. Zhang, 2304.13665 (PRD)

Neutrino NC Interactions

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



PandaX, 2407.10892 (PRL)



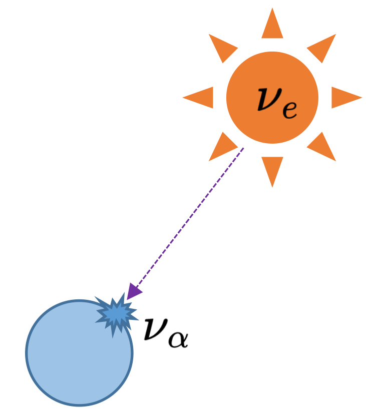
XENONnT, 2408.02877 (PRL)

Number of signal events

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

Neutrino NC Interactions

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



Number of signal events:

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

Differential event rate:

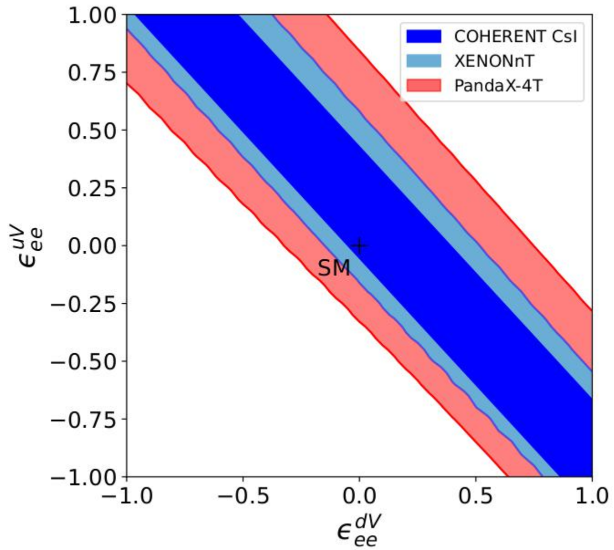
$$\frac{\mathrm{d}R_{\nu_\alpha}}{\mathrm{d}T_{\mathrm{nr}}} = \int_{E_{\nu,\mathrm{min}}}^{E_{\nu,\,\mathrm{max}}} dE_\nu \Phi_{\nu_\alpha}\left(E_\nu\right) \frac{\mathrm{d}\sigma}{\mathrm{d}T_{\mathrm{nr}}} \qquad \Phi_{\nu_\alpha}\left(E_\nu\right) = \frac{\mathcal{E}}{M_{\mathrm{det}}} \langle P_{\nu_\alpha} \rangle \phi\left({}^{8}\,\mathrm{B}\right)$$

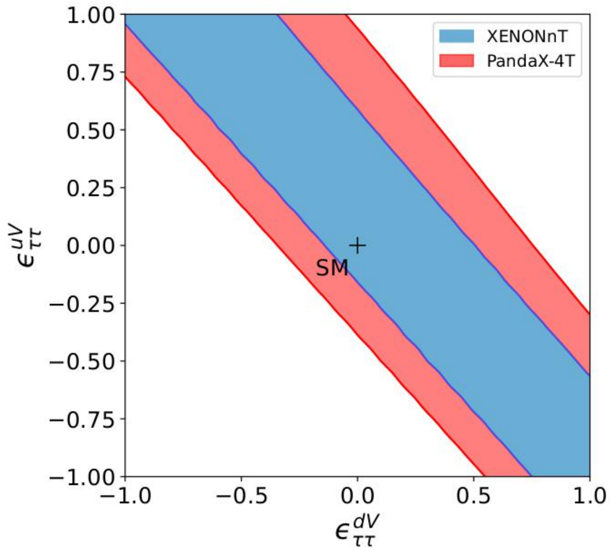
- The neutrino NC NSIs have impact on the solar matter effects (propagation) and CEvNS cross section (scattering)
- We find that the NSI impact on the neutrino propagation is milder than that on the scattering

Neutrino NC Interactions

Neutral-current interactions:

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





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

GL, C.-Q. Song, F.-J. Tang, J.-H. Yu, 2409.04703

Outline

- Neutrino non-standard interactions (NSI): charged currents and neutral currents
- Constraints on neutrino neutral-current NSIs using the first measurements of solar ^{8}B neutrinos
- UV completion of neutrino charged-current NSI and CLFV interaction with dark matter ✔

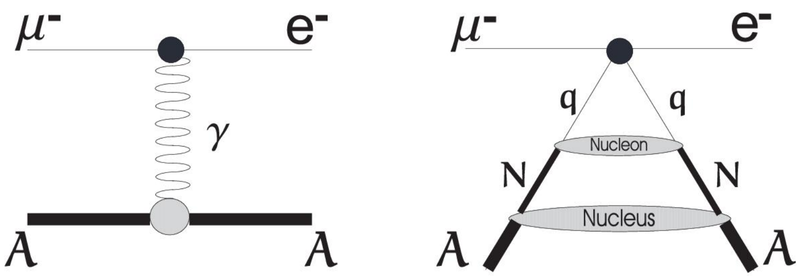
Semileptonic four-fermion operator:

$$O_{ledq}^{\alpha\beta 11} = \left(\bar{L}_\alpha^j e_{R\beta}\right)\left(\bar{d}_R Q^j\right) \qquad L_\alpha = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_\alpha \qquad \alpha, \beta = 1, 2$$

The unbroken $SU(2)_L$ symmetry relates neutrino physics to charged lepton physics

CLFV Interactions

$\mu \to e$ conversion:

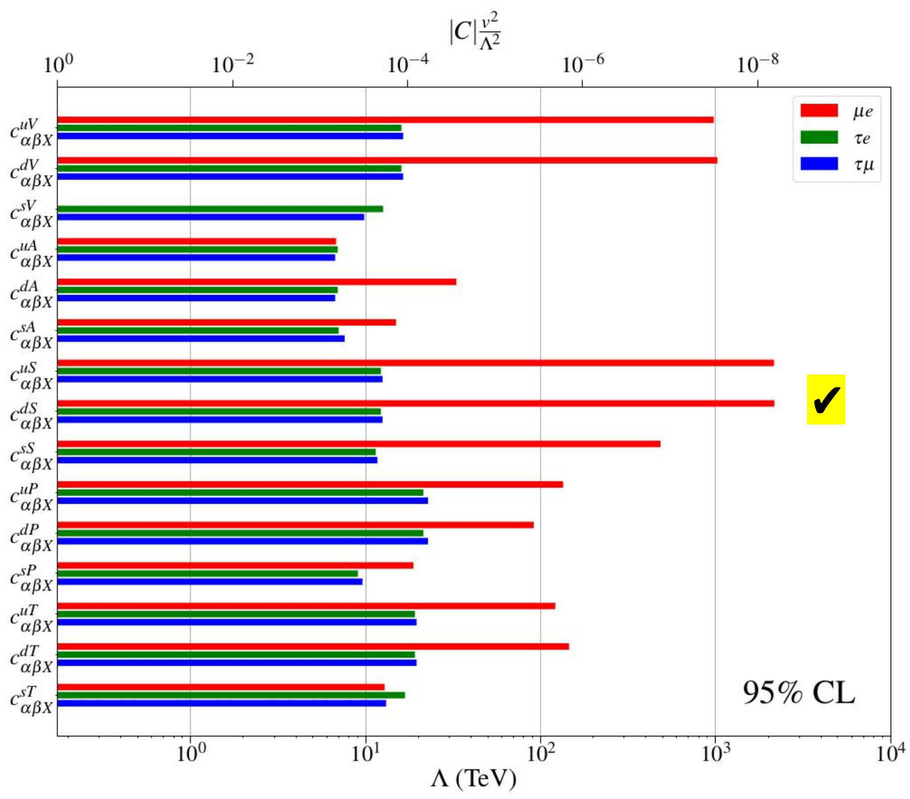


$$\text{CR}\left(\mu^- + (A,Z) \to e^- + (A,Z)\right) \equiv \frac{\Gamma\left(\mu^- + (A,Z) \to e^- + (A,Z)\right)}{\Gamma\left(\mu^- + (A,Z) \to \text{ capture }\right)}$$

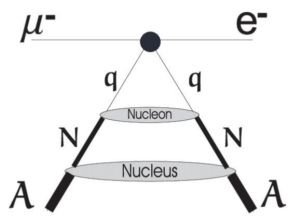
	cLFV obs.	Present upper bounds (90% CL)	
	$\text{CR}(\mu \to e, \text{S})$	7.0×10^{-11}	Badertscher *et al.* (1982)
	$\text{CR}(\mu \to e, \text{Ti})$	4.3×10^{-12}	SINDRUM II (1993)
	$\text{CR}(\mu \to e, \text{Pb})$	4.6×10^{-11}	SINDRUM II (1996)
✔	$\text{CR}(\mu \to e, \text{Au})$	7.0×10^{-13}	SINDRUM II (2006)

New experiments to start: COMET, Mu2e

$\mu \to e$ conversion to probe semileptonic four-fermion operators



Fernández-Martínez, et al., 2403.09772 (EPJC)



Chirality-flip four-fermion operator:

$$O^{\alpha\beta 11}_{ledq} = \left(\bar{L}^j_\alpha e_{R\beta}\right)\left(\bar{d}_R Q^j\right)$$

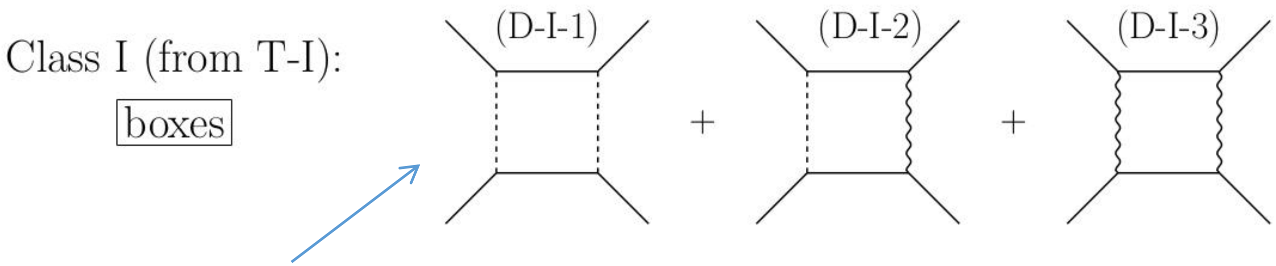
$$c^{dS}_{\alpha\beta R} = \frac{v^2}{2\Lambda^2} C^{\alpha\beta 11}_{\ell edq}$$

$$C^{1211}_{ledq}/\Lambda^2 < \left(2.2 \times 10^3 \text{ TeV}\right)^{-2}$$

CLFV Interactions

- Considering the stringent CLFV constraints, is there a plausible scenario where new physics is anticipated?

- Dark loop paradigm:



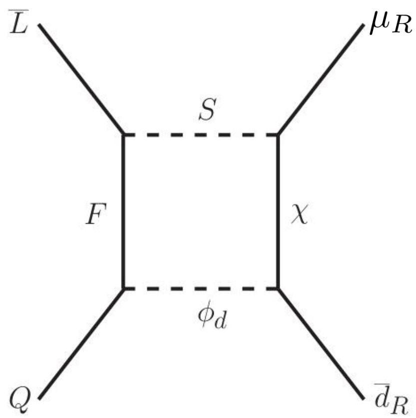
dark particles in the boxes

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

The dark symmetry guarantees that CLFV is naturally suppressed, which is forbidden at tree-level

Fermion portal dark matter

One-loop realization of the semileptonic four-fermion operator:



new fields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Z_2
χ	$\mathbf{1}$	$\mathbf{1}$	0	-1
F	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	-1
S	$\mathbf{1}$	$\mathbf{1}$	1	-1
ϕ_d	$\mathbf{3}$	$\mathbf{1}$	$-\frac{1}{3}$	-1

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

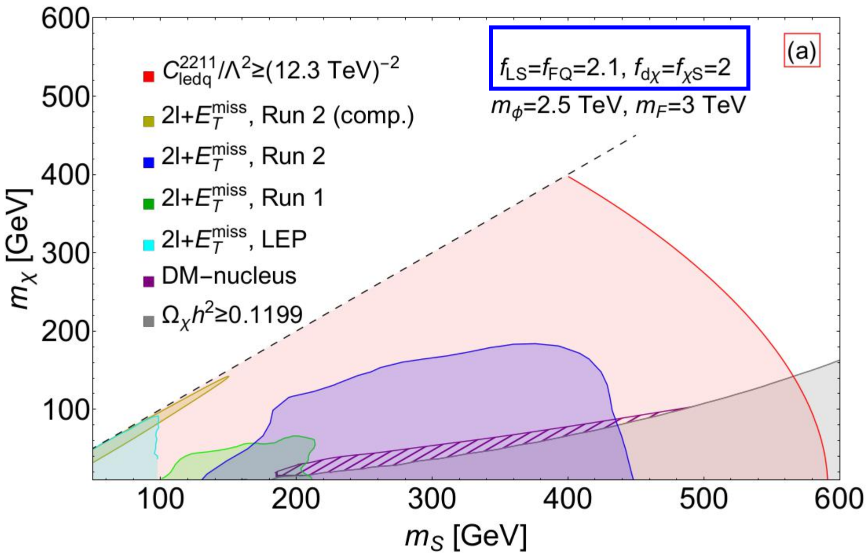
Majorana DM: χ
mediators: $S,\ \phi_d$
lepton: F

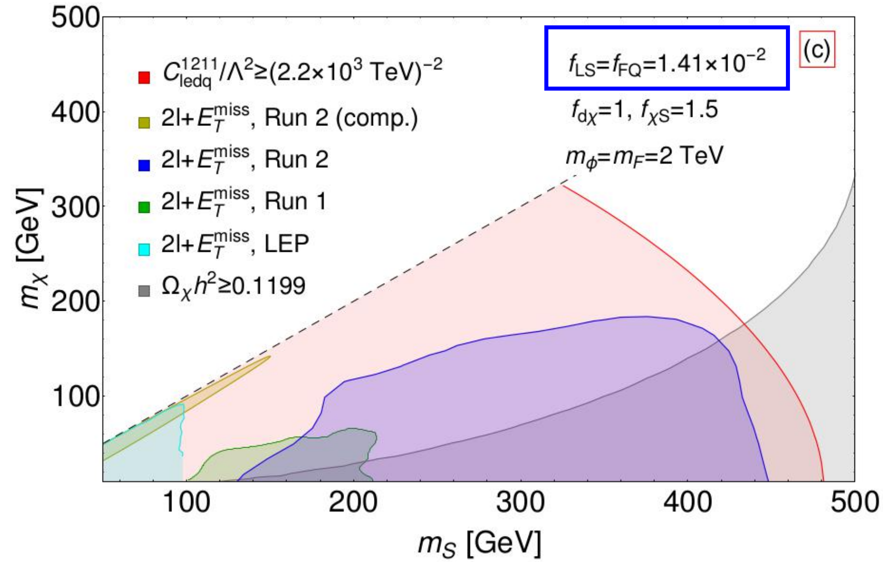
$$O_{ledq}^{\alpha\beta 11} = \left(\bar{L}_\alpha^j e_{R\beta}\right)\left(\bar{d}_R Q^j\right)$$

Cepedello, Esser, Hirsch, Sanz, 2302.03485 (JHEP)
An, Wang and Zhang, 1308.0592 (PRD)
Bai, Berger, 1308.0612 (JHEP); 1402.6696 (JHEP)
DiFranzo, Nagao, Rajaraman, Tait, 1308.2679 (JHEP)

Fermion portal dark matter

Indirect probes of dark matter with the NSIs of leptons:





Red: Neutrino CC NSI

Red: CLFV interaction

Exclude the compressed region that is beyond the reach of the LHC

Y. He, GL, J.Liu, X.-P. Wang, X. Zhao, 2407.06523

Summary

- Non-standard interactions (NSIs) of leptons are sensitive to new physics
- We investigate constraint on the neutrino NC NSI using the first measurements of solar ^{8}B neutrinos via CEvNS by PandaX and XENONnT
- We show that both the neutrino CC NSI and charged-lepton-flavor-violation interaction can effectively probe dark matter

Thank you

Neutrino CC Interactions

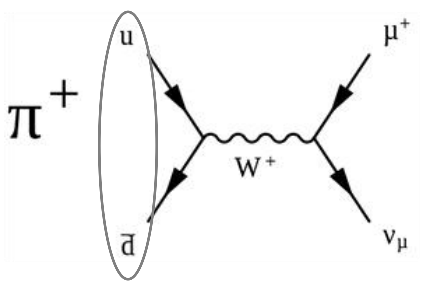
Future neutrino oscillation experiments:

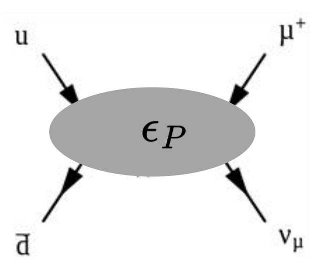
$$O_{lq}^{(1)prst}: \left(\bar{l}_p \gamma_\mu l_r\right)\left(\bar{q}_s \gamma^\mu q_t\right)$$

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

Operator	T2HK limit (TeV)	DUNE limit (TeV)	JUNO limit (TeV)	T2HK and DUNE limit (TeV)	JUNO and TAO limit (TeV)
$\mathcal{O}_{lq_{1111}}^{(1)}$	0.3	0.7	0.2	0.7	1.3
$\mathcal{O}_{ledq_{2211}}$	9.1	11.2	0.7	12.3	0.7

Y. Du, H.-L. Li, J. Tang, S. Vihonen, J.-H. Yu 2106.15800 (PRD)





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

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

Neutrino NC Interactions

From neutrino 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

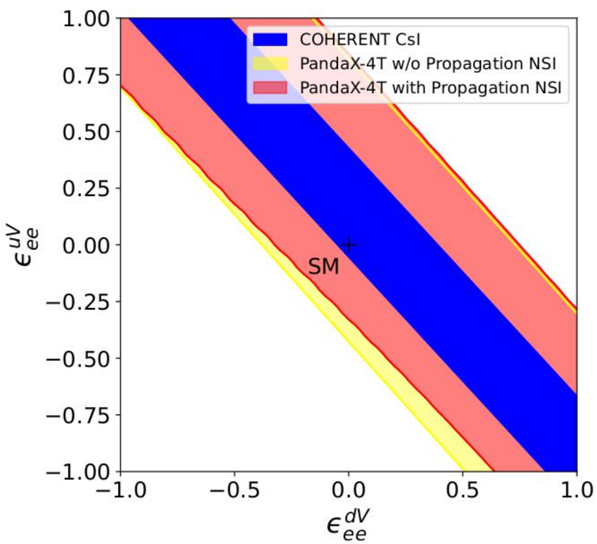
Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

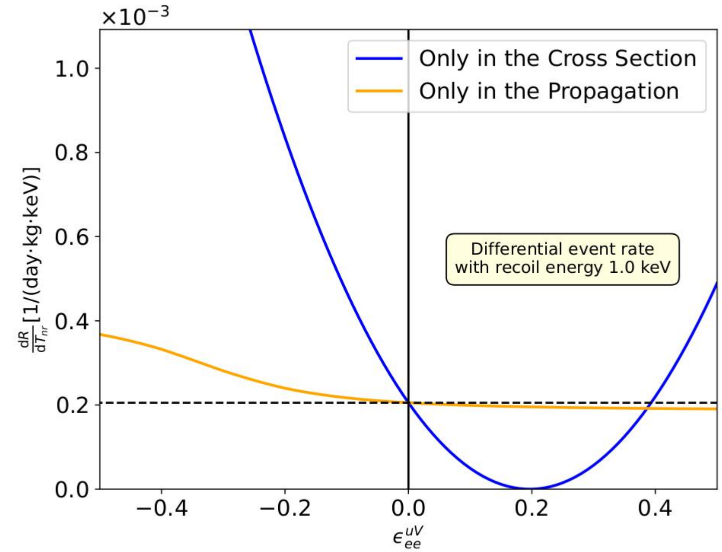
We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and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

Neutrino NC Interactions

Neutral-current interactions:





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

quadratic polynomial of the NSI parameter

GL, C.-Q. Song, F.-J. Tang, J.-H. Yu, 2409.04703