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

李刚

中山大学物理与天文学院

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

第三届高能物理理论与实验融合发展研讨会

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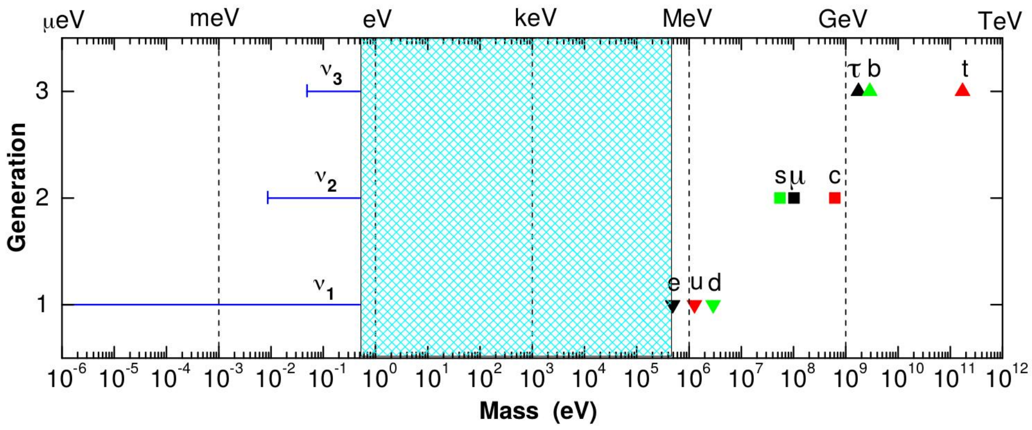
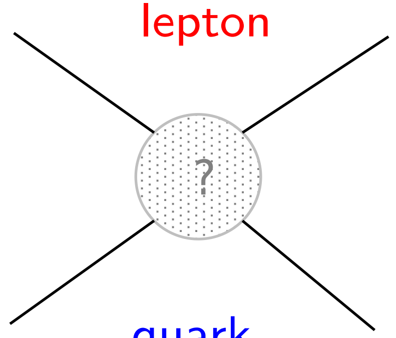
New physics

The Standard Model is successful but incomplete:

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



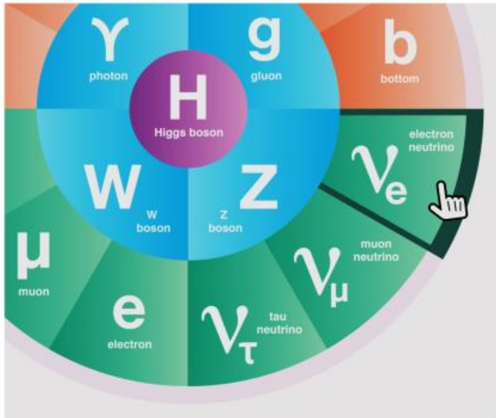
Z.-z. Xing, Phys.Rept. 854 (2020) 1-147



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 ($m_{\rm lightest} = 0$?)
- Majorana or Dirac Nature ($\nu = \nu^C$?)
- Majorana CP-Violating Phases (how?)



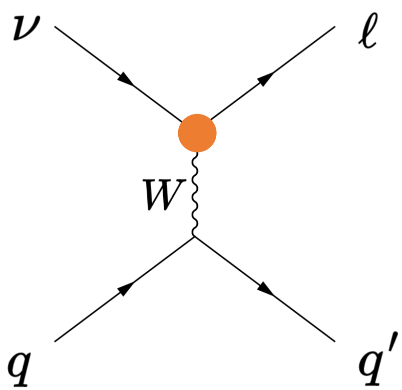
- Extra Neutrino Species
- ✔ Exotic Neutrino Interactions
- Various LNV & LFV Processes
- Leptonic Unitarity Violation

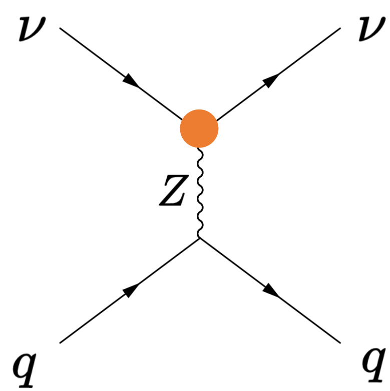
- **Origin of Neutrino Masses**
- Flavor Structure (Symmetry?)
- Quark-Lepton Connection
- Relations to DM and/or BAU

credit: Shun Zhou

Neutrino Interactions

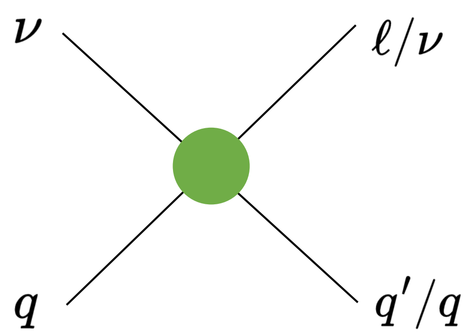
Neutrino Non-Standard Interactions:





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

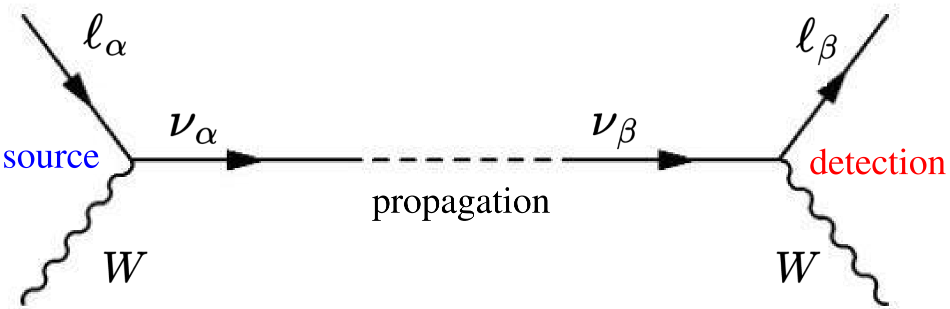
$\mu < M_W,\ M_Z$



semileptonic four-fermion operators

Neutrino Interactions

Charged-current interactions:



Neutrino CC NSIs affect the source (production) and detection (scattering) of neutrinos in oscillation experiments

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

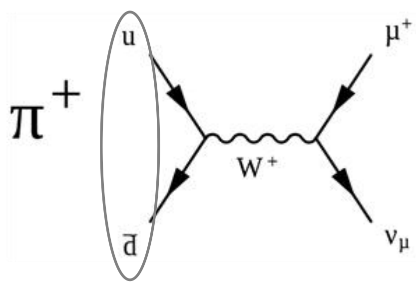
Neutrino Interactions

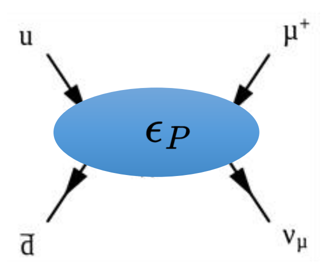
Neutrino production:

- Neutrinos from pion decays

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

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





Neutrino Interactions

Charged-current interactions:

- Chirality-flip four-fermion operator

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

$$\frac{C_{ledq}^{2211*}}{\Lambda^2} = \frac{-2V_{ud}}{v^2}[\epsilon_P]^{11}_{22}$$

Operator	T2HK limit (TeV)	DUNE limit (TeV)	JUNO limit (TeV)	T2HK and DUNE limit (TeV)	JUNO and TAO limit (TeV)
$\mathcal{O}_{ledq_{2211}}$	9.1	11.2	0.7	12.3	0.7

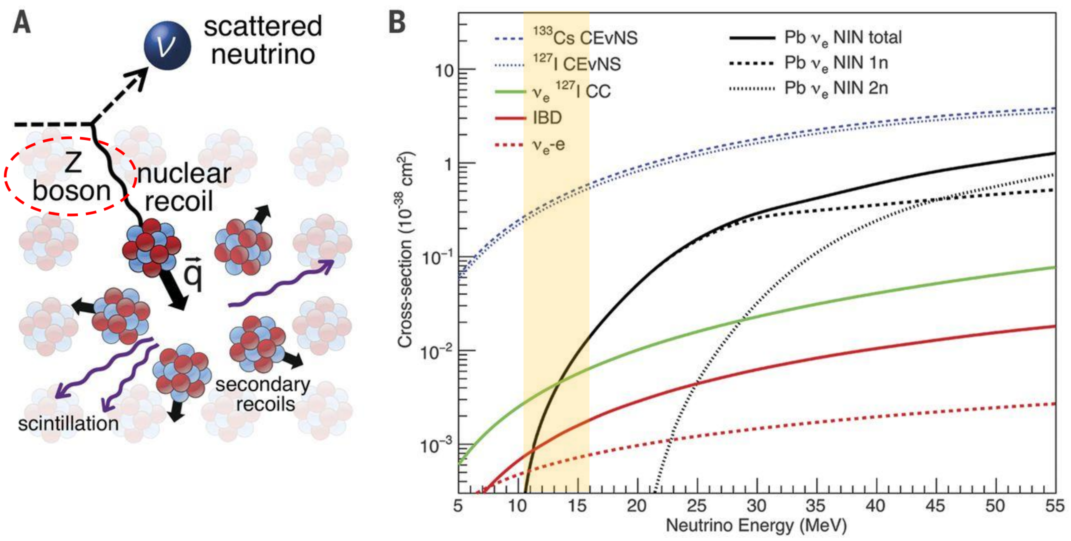
Best sensitivity among the flavor-conserving semileptonic four-fermion operators

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

For the study of chirality-flip four-fermion operator at the EIC, see **H.-L. Wang, X.-K. Wen, H. Xing, B. Yan, 2401.08419 (PRD)**

Neutrino Interactions

Neutral-current interactions:



Science 357 (2017) 6356, 1123

Coherent Neutrino-nucleus scattering (CEvNS)

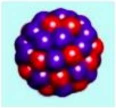
Neutrino Interactions

Neutrino scattering:

CEvNS: what's it good for? ① So ② Many ③ Things **!** (not a complete list!)

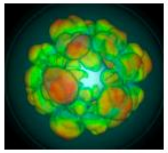
CEvNS as a **signal**
for signatures of *new physics*

CEvNS as a **signal**
for understanding of "old" physics

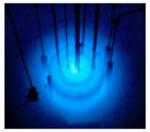


CEvNS as a **background**
for signatures of new physics

CEvNS as a **signal** for *astrophysics*



CEvNS as a **practical tool**

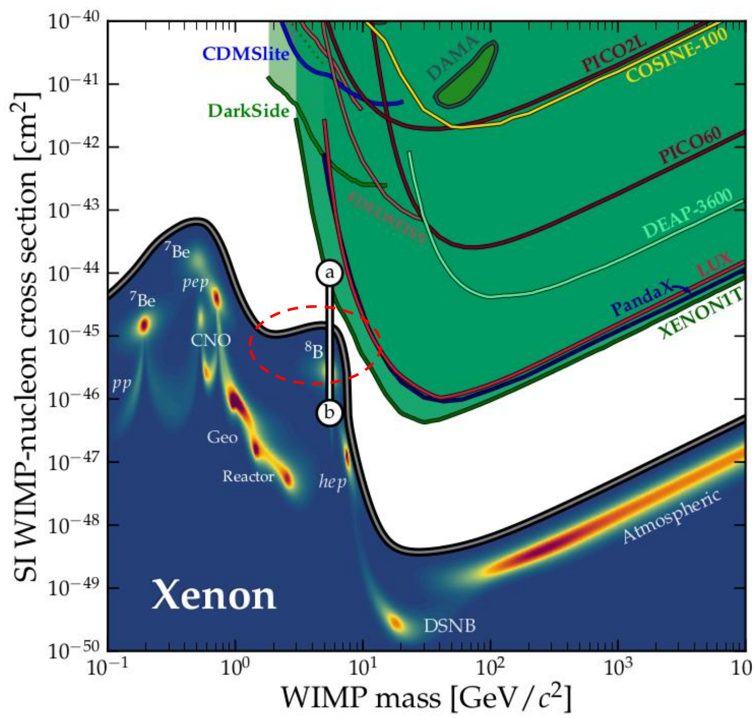


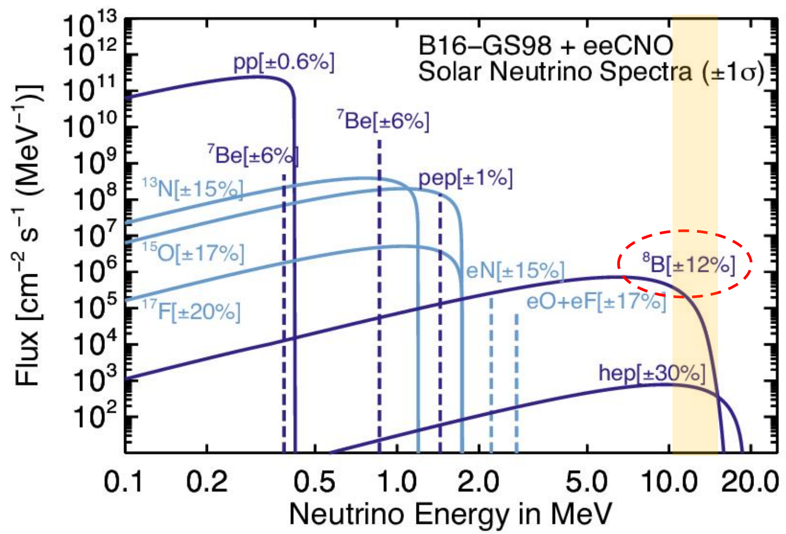
credit: Kate Scholberg

Neutrino NC NSIs affect the CEvNS

Neutrino Interactions

Neutrino scattering:



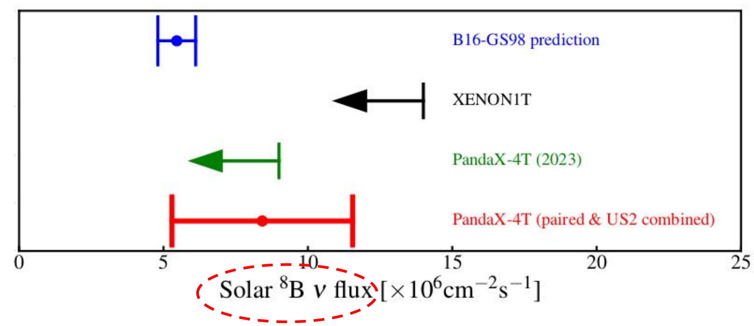


neutrino floor/frog

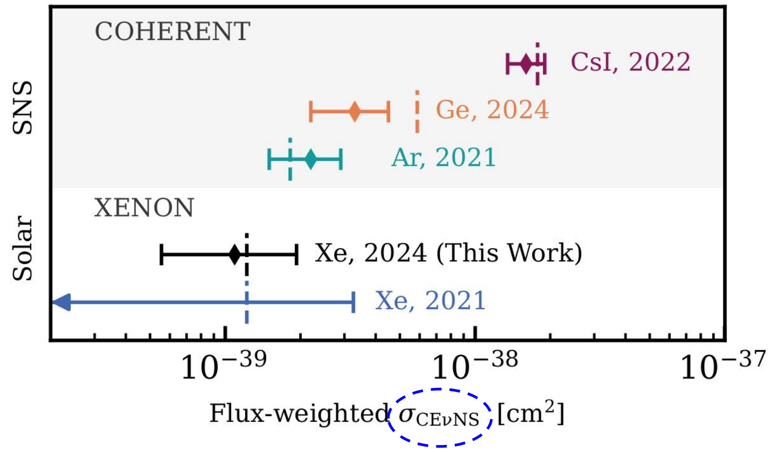
C. A. J. O'Hare, 2109.03116 (PRL)
J. Tang, B.-L. Zhang, 2304.13665 (PRD)

Neutrino Interactions

Neutrino scattering:



PandaX, 2407.10892 (PRL)



XENONnT, 2408.02877

Number of signal events

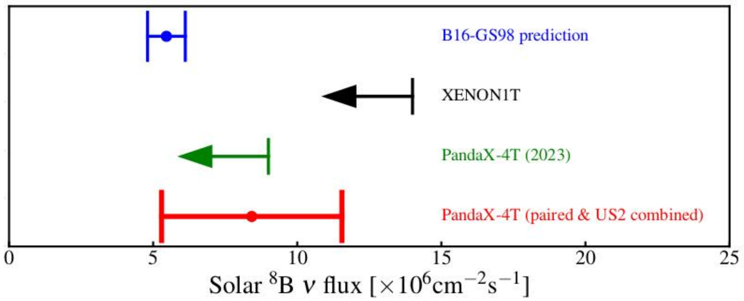
$=$ solar ^{8}B neutrino flux $\otimes$ CEvNS cross section

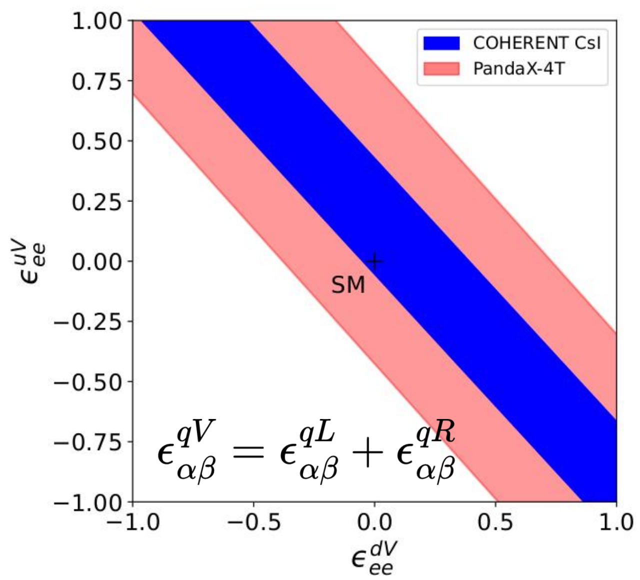
Neutrino NC NSIs

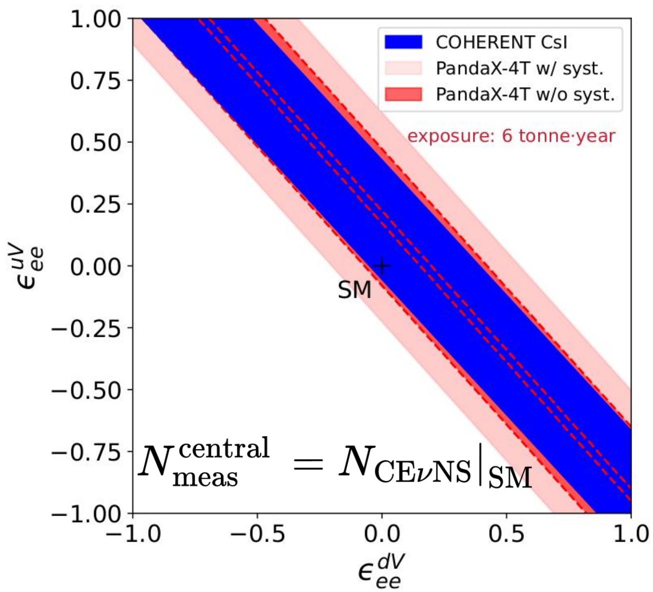
Neutrino Interactions

Neutral-current interactions:

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







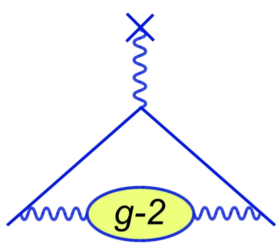
GL, C.-Q. Song, F.-J. Tang, J.-H. Yu, 2409.04703

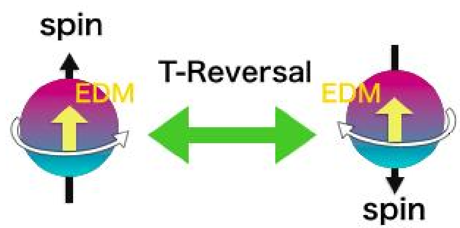
Charged lepton physics

Open questions:

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

see also Qiang Li's talk





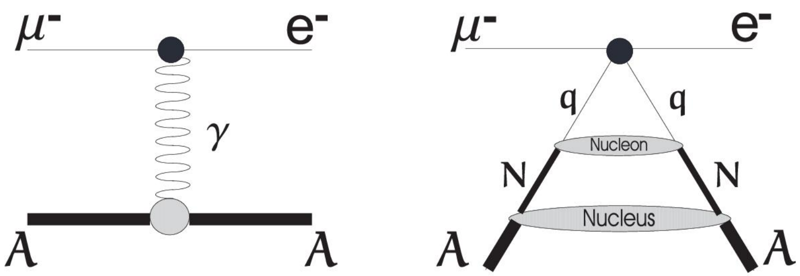
$$\mu \to e\gamma$$
$$\mu^- N \to e^- N$$
$$\mu^+ \to e^+ e^+ e^-$$

Large/Small

Yes/No

CLFV Interactions

$\mu \to e$ conversion:



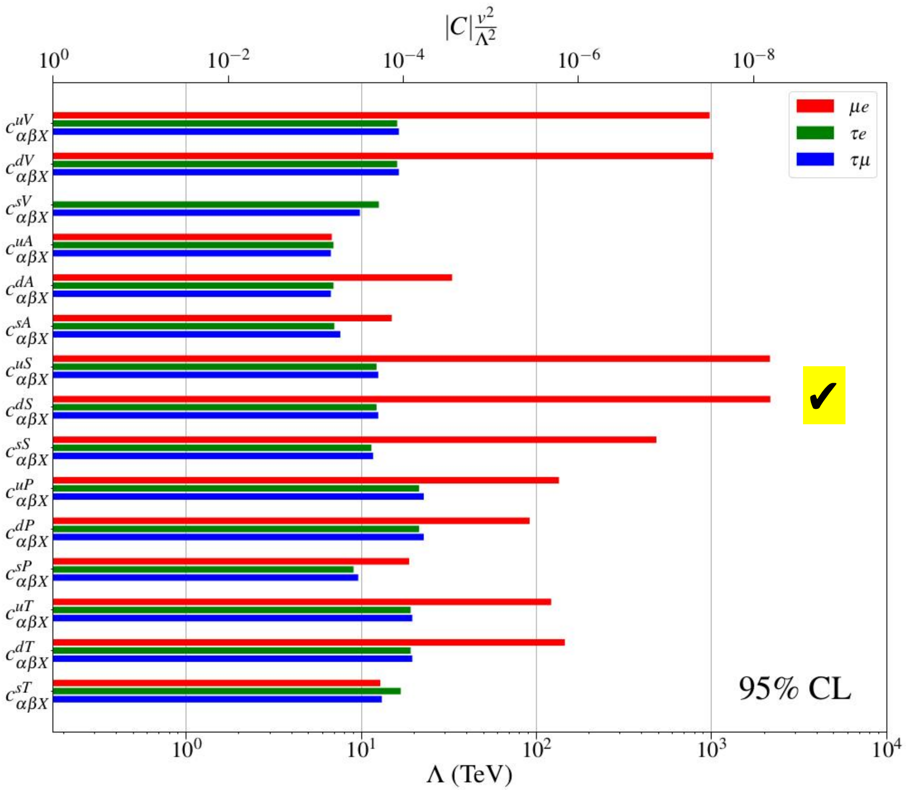
$$\mathrm{CR}\left(\mu^- + (A,Z) \to e^- + (A,Z)\right) \equiv \frac{\Gamma\left(\mu^- + (A,Z) \to e^- + (A,Z)\right)}{\Gamma\left(\mu^- + (A,Z) \to \text{ capture }\right)}$$

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

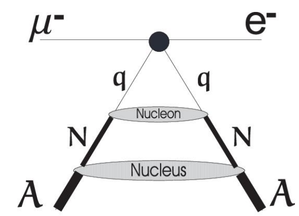
New experiments to start: COMET, Mu2e

CLFV Interactions

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



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



Chirality-flip four-fermion operator:

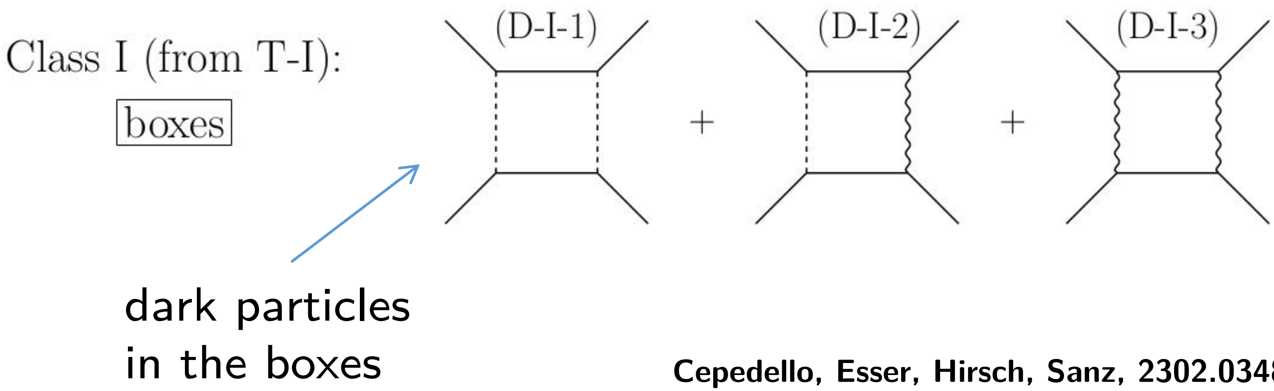
$$O^{\alpha\beta 11}_{ledq} = \left(\bar{L}^j_\alpha e_{R\beta}\right)\left(\bar{d}_R Q^j\right)$$

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

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

CLFV Interactions

- Given the severe CLFV constraints, is there *natural* scenario in which new physics is expected?
- Dark loop paradigm:

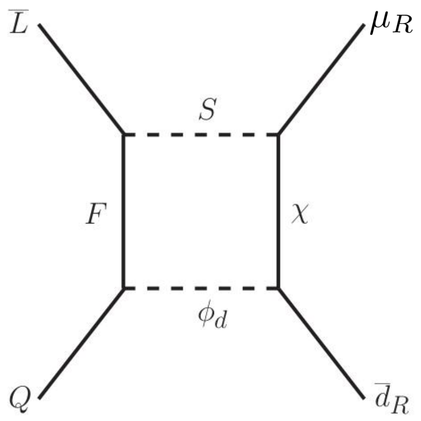


Cepedello, Esser, Hirsch, Sanz, 2302.03485 (JHEP)

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

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

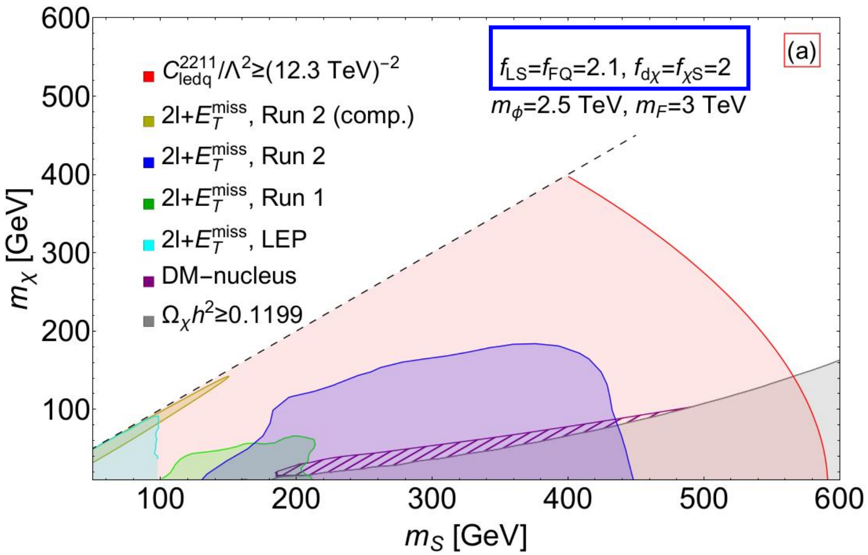
Majorana DM: χ
mediators: $S,\ \phi_d$
lepton: F

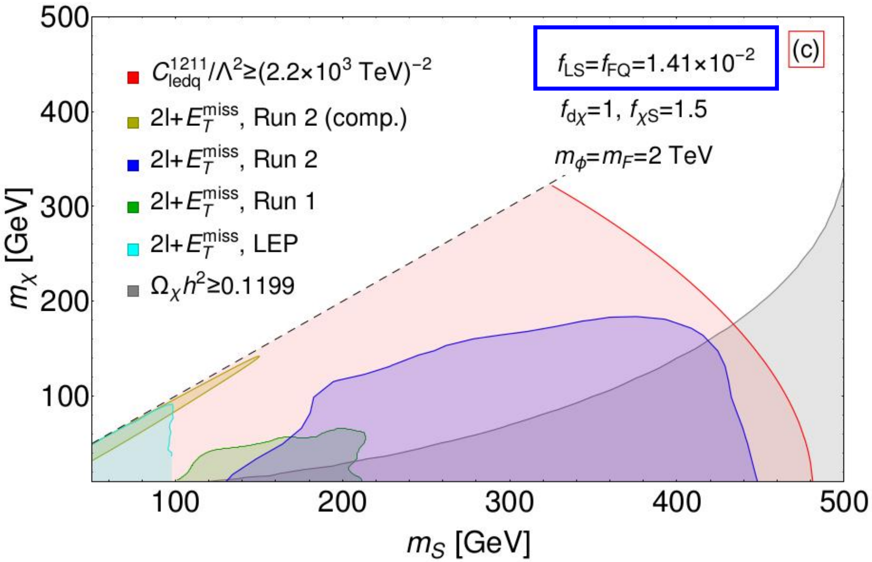
$$O_{ledq}^{\alpha\beta 11} = \left(\bar{L}_\alpha^j e_{R\beta}\right)\left(\bar{d}_R Q^j\right)$$

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

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 recent measurement of solar ^{8}B neutrinos via CEvNS by PandaX
- We show that both the neutrino CC NSI and charged-lepton-flavor-violation interaction can effectively probe dark matter

Thank you