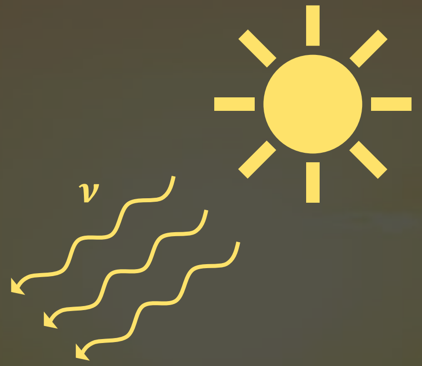
IDM2026

Zaragoza, 1-5 Jun 2026



Turning background into signal: solar neutrinos in xenon dark matter detectors

Michela Sestu

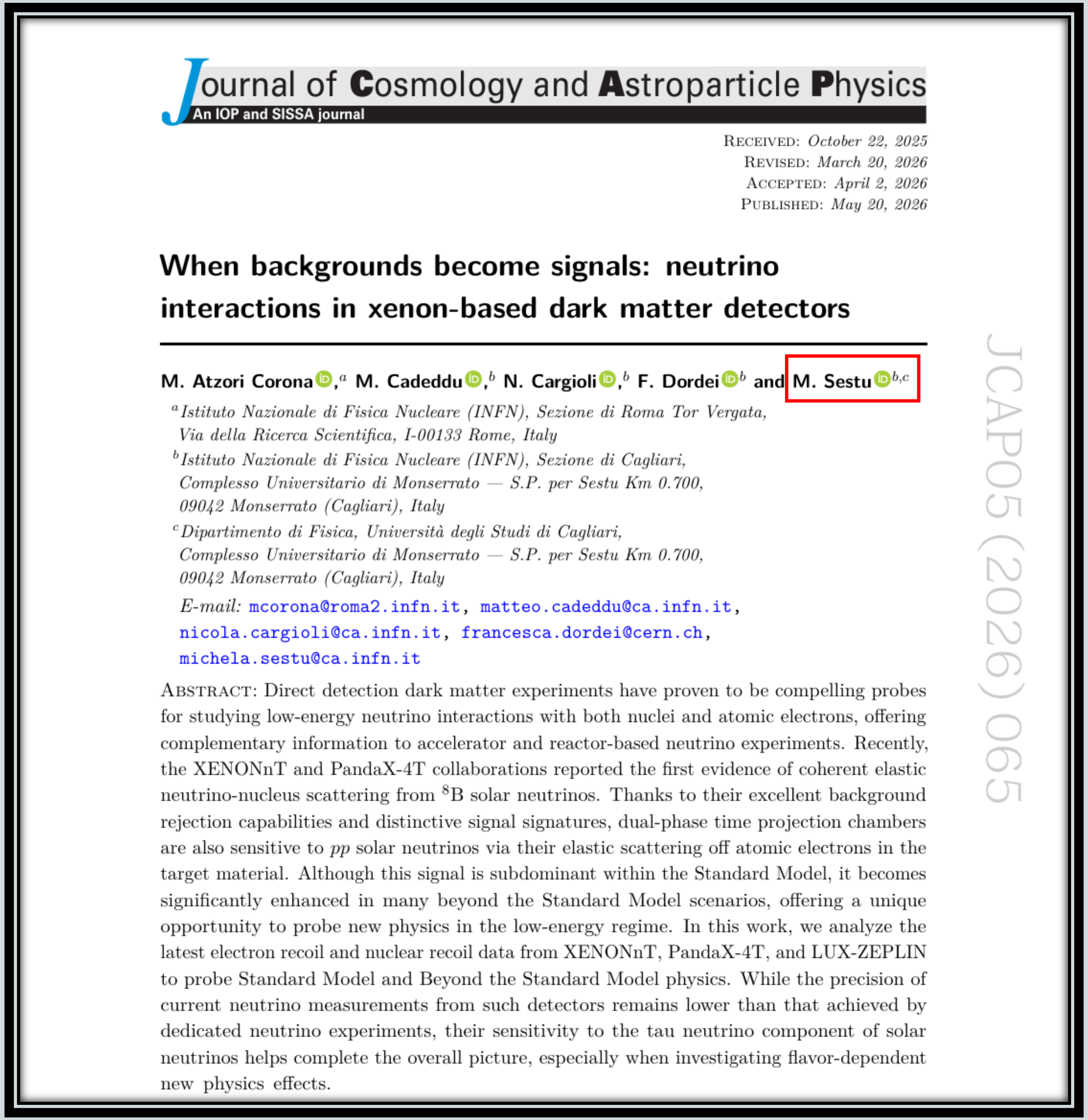
michela.sestu@ca.infn.it

University of Cagliari & INFN Cagliari

Presentation based on

JCAP05(2026)065
https://doi.org/10.1088/1475-7516/2026/05/065

In collaboration with:
M. Atzori Corona, M. Cadeddu, N. Cargioli and F. Dordei



Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Received: *October 22, 2025*
Revised: *March 20, 2026*
Accepted: *April 2, 2026*
Published: *May 20, 2026*

When backgrounds become signals: neutrino interactions in xenon-based dark matter detectors

M. Atzori Corona,[a] **M. Cadeddu**,[b] **N. Cargioli**,[b] **F. Dordei**[b] and **M. Sestu**[b,c]

[a] *Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Roma Tor Vergata,*
Via della Ricerca Scientifica, I-00133 Rome, Italy
[b] *Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Cagliari,*
Complesso Universitario di Monserrato — S.P. per Sestu Km 0.700,
09042 Monserrato (Cagliari), Italy
[c] *Dipartimento di Fisica, Università degli Studi di Cagliari,*
Complesso Universitario di Monserrato — S.P. per Sestu Km 0.700,
09042 Monserrato (Cagliari), Italy

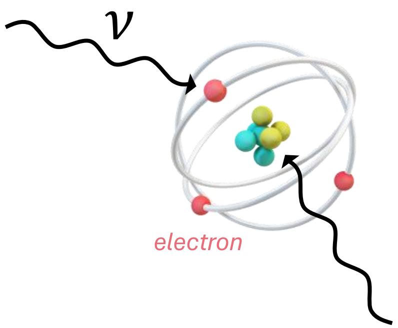
E-mail: mcorona@roma2.infn.it, matteo.cadeddu@ca.infn.it, nicola.cargioli@ca.infn.it, francesca.dordei@cern.ch, michela.sestu@ca.infn.it

Abstract: Direct detection dark matter experiments have proven to be compelling probes for studying low-energy neutrino interactions with both nuclei and atomic electrons, offering complementary information to accelerator and reactor-based neutrino experiments. Recently, the XENONnT and PandaX-4T collaborations reported the first evidence of coherent elastic neutrino-nucleus scattering from ^{8}B solar neutrinos. Thanks to their excellent background rejection capabilities and distinctive signal signatures, dual-phase time projection chambers are also sensitive to pp solar neutrinos via their elastic scattering off atomic electrons in the target material. Although this signal is subdominant within the Standard Model, it becomes significantly enhanced in many beyond the Standard Model scenarios, offering a unique opportunity to probe new physics in the low-energy regime. In this work, we analyze the latest electron recoil and nuclear recoil data from XENONnT, PandaX-4T, and LUX-ZEPLIN to probe Standard Model and Beyond the Standard Model physics. While the precision of current neutrino measurements from such detectors remains lower than that achieved by dedicated neutrino experiments, their sensitivity to the tau neutrino component of solar neutrinos helps complete the overall picture, especially when investigating flavor-dependent new physics effects.

JCAP05(2026)065

Neutrino interactions

Neutrino scattering at **low** neutrino **energies** (< **100 MeV**)

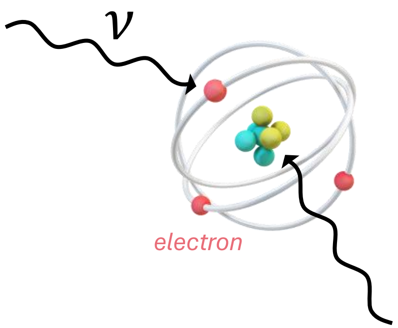


Neutrino interactions

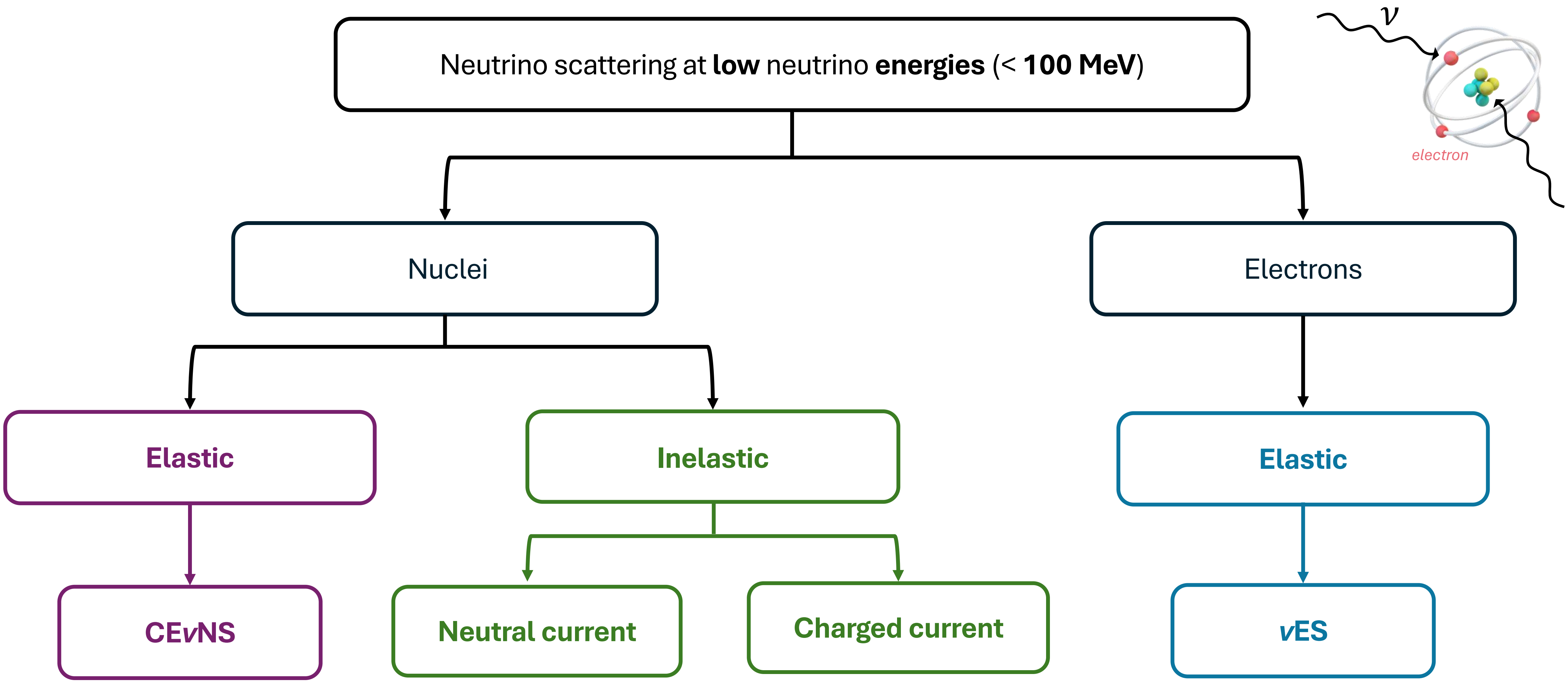
Neutrino scattering at **low** neutrino **energies** (< **100 MeV**)

Nuclei

Electrons



Neutrino interactions



Neutrino scattering at **low** neutrino **energies** (< **100 MeV**)

Nuclei

Electrons

Elastic

Inelastic

Elastic

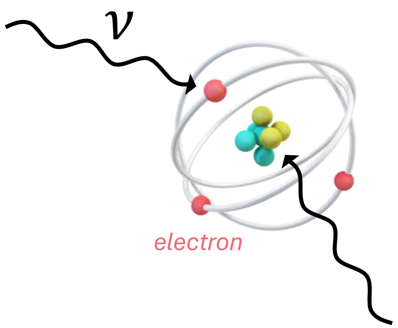
CEνNS

Neutral current

Charged current

νES

Neutrino interactions



- Neutrino scattering at **low** neutrino **energies** (< **100 MeV**)
  - Nuclei
    - **Elastic**
      - **CEνNS**
    - **Inelastic**
      - **Neutral current**
      - **Charged current**
  - Electrons
    - **Elastic**
      - **νES**

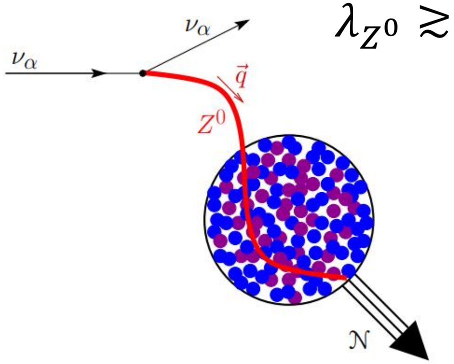
CEνNS → **Coherent Elastic Neutrino-Nucleus Scattering**

νES → **Neutrino-Electron Scattering**

CEνNS: Coherent Elastic Neutrino-Nucleus Scattering

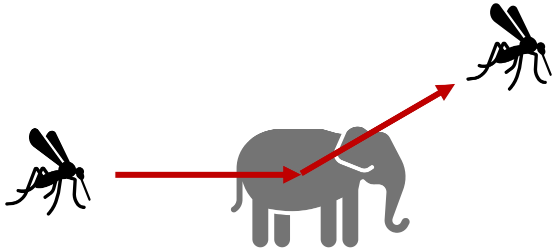
- **Neutral current** process mediated by a Z^0 boson

- **Coherent** scattering: the nucleus recoils as a whole



$\lambda_{Z^0} \gtrsim 2R$

M. Cadeddu et al., EPL 143 34001



Very tiny nuclear recoil
$\boldsymbol{T \lesssim 10\ \mathrm{keV}}$

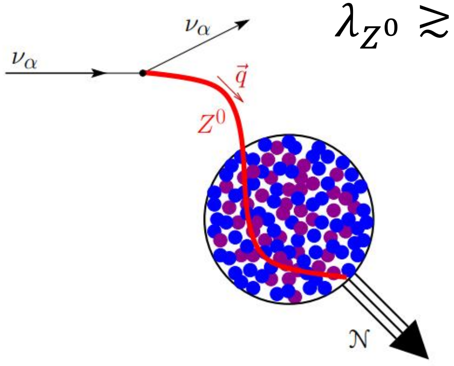
☹

CEνNS: Coherent Elastic Neutrino-Nucleus Scattering

- **Neutral current** process mediated by a Z^0 boson

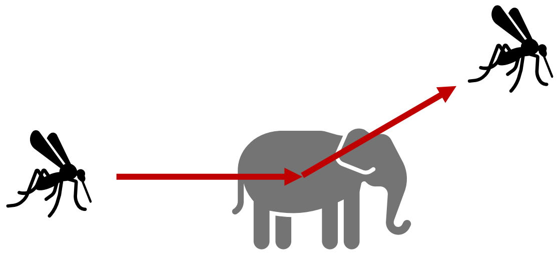
- **Coherent** scattering: the nucleus recoils as a whole

- **Larger cross section** compared to those of other ν-nucleus interactions (at the same energy)



$\lambda_{Z^0} \gtrsim 2R$

M. Cadeddu et al., EPL 143 34001



Very tiny nuclear recoil
$T \lesssim 10$ **keV**

☹

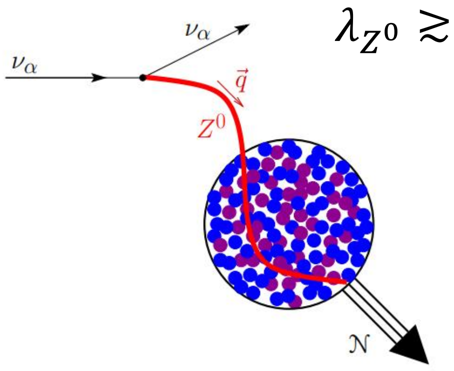
Neutrino energy

$$\frac{d\sigma_{\nu_\ell \mathcal{N}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\left[g_V^n \, N F_N^{\mathcal{N}}(|\vec{q}|) + \; g_V^p \, Z F_Z^{\mathcal{N}}(|\vec{q}|) \right]^2$$

Nuclear recoil energy

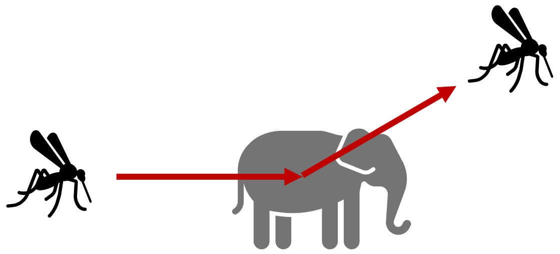
CEvNS: Coherent Elastic Neutrino-Nucleus Scattering

- **Neutral current** process mediated by a Z^0 boson
- **Coherent** scattering: the nucleus recoils as a whole
- **Larger cross section** compared to those of other ν-nucleus interactions (at the same energy)



$\lambda_{Z^0} \gtrsim 2R$

M. Cadeddu et al., EPL 143 34001



Very tiny nuclear recoil
$\boldsymbol{T \lesssim 10\ \mathrm{keV}}$

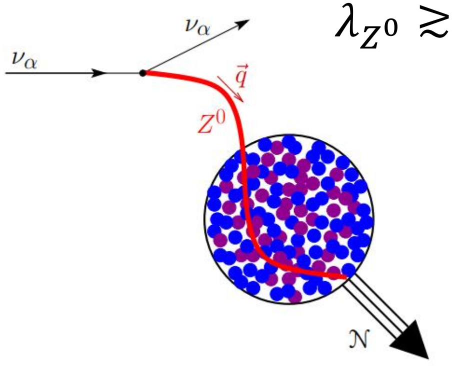
Neutrino energy

$$\frac{d\sigma_{\nu_\ell \mathcal{N}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\overbrace{\left[g_V^n\, N F_N^{\mathcal{N}}(|\vec{q}|) + g_V^p\, Z F_Z^{\mathcal{N}}(|\vec{q}|)\right]}^{Q_W^{\mathcal{N}}(|\vec{q}|)\text{: weak charge of the nucleus}}{}^{2}$$

Nuclear recoil energy

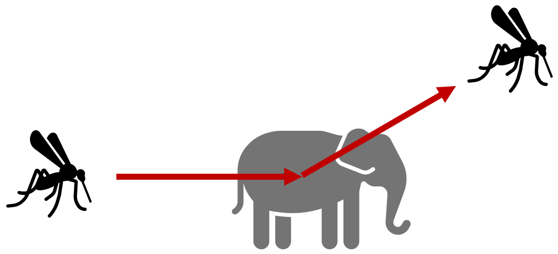
CEνNS: Coherent Elastic Neutrino-Nucleus Scattering

- **Neutral current** process mediated by a Z^0 boson
- **Coherent** scattering: the nucleus recoils as a whole
- **Larger cross section** compared to those of other ν-nucleus interactions (at the same energy)



$\lambda_{Z^0} \gtrsim 2R$

M. Cadeddu et al., EPL 143 34001



Very tiny nuclear recoil
$T \lesssim 10\ \mathrm{keV}$

☹

$Q_W^{\mathcal{N}}(|\vec{q}|)$**: weak charge of the nucleus**

Neutrino energy

$$\frac{d\sigma_{\nu_\ell \mathcal{N}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\overbrace{\left[\boldsymbol{g_V^n}\, N \boldsymbol{F_N^{\mathcal{N}}}(|\vec{q}|) + \boldsymbol{g_V^p}\, Z \boldsymbol{F_Z^{\mathcal{N}}}(|\vec{q}|)\right]}^{}{}^{2}$$

Nuclear recoil energy

Neutron form factor

Proton form factor

Neutrino couplings with protons and neutrons

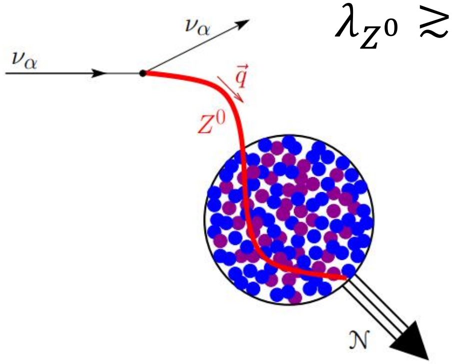
$$\begin{cases} g_V^n = -0.5117 \\ g_V^p(\nu_e) = 0.0381 \\ g_V^p(\nu_\mu) = 0.0299 \\ g_V^p(\nu_\tau) = 0.0255 \end{cases}$$

M. Atzori Corona et al., JHEP 05 (2024) 271

M. Atzori Corona et al., Phys. Rev. D 112, 015007 (2025)

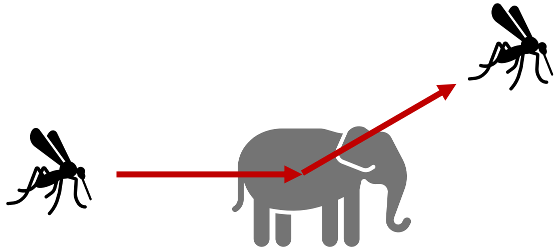
CEνNS: Coherent Elastic Neutrino-Nucleus Scattering

- **Neutral current** process mediated by a Z^0 boson
- **Coherent** scattering: the nucleus recoils as a whole
- **Larger cross section** compared to those of other ν-nucleus interactions (at the same energy)



$\lambda_{Z^0} \gtrsim 2R$

M. Cadeddu et al., EPL 143 34001



Very tiny nuclear recoil
$\boldsymbol{T \lesssim 10\ \mathrm{keV}}$

Neutrino energy

$$\frac{d\sigma_{\nu_\ell \mathcal{N}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\Big[\overbrace{g_V^n\, N F_N^{\mathcal{N}}(|\vec{q}|) + g_V^p\, Z F_Z^{\mathcal{N}}(|\vec{q}|)}^{Q_W^{\mathcal{N}}(|\vec{q}|)\text{: weak charge of the nucleus}}\Big]^2$$

Nuclear recoil energy

Neutron form factor

Proton form factor

The neutron contribution is much larger than the proton contribution!

Neutrino couplings with protons and neutrons

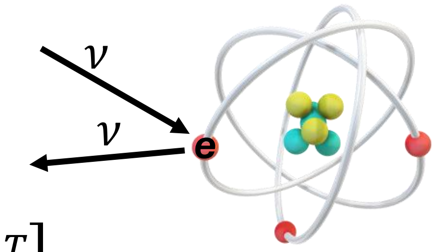
$$\begin{cases} \boldsymbol{g_V^n = -0.5117} \\ g_V^p(\nu_e) = 0.0381 \\ g_V^p(\nu_\mu) = 0.0299 \\ g_V^p(\nu_\tau) = 0.0255 \end{cases}$$

M. Atzori Corona et al., JHEP 05 (2024) 271
M. Atzori Corona et al., Phys. Rev. D 112, 015007 (2025)

Cross section scales as $\displaystyle \frac{d\sigma_{\nu\mathcal{N}}}{dT} \propto N^2$

νES: Neutrino-Electron Scattering

Elastic scattering of neutrinos off **atomic electrons**:



Electron mass

$$\frac{d\sigma_{\nu_\ell e}}{dT}(E_\nu, T) = Z_{\text{eff}}\frac{G_F^2 m_e}{2\pi}\left[\left(g_V^{\nu_\ell}+g_A^{\nu_\ell}\right)^2 + \left(g_V^{\nu_\ell}-g_A^{\nu_\ell}\right)^2\left(1-\frac{T}{E_\nu}\right)^2 - \left(\left(g_V^{\nu_\ell}\right)^2-\left(g_A^{\nu_\ell}\right)^2\right)\frac{m_e T}{E_\nu^2}\right]$$

Electron recoil energy

Accounts for the number of electrons that can be ionized for a given energy deposit T

Adv. High Energy Phys. 2014 (2014) 569409
Atomic Data and Nuclear Data Tables 54.2 (1993), p. 181

Vector coupling

$g_V^{\nu_e} = 0.9524$
$g_V^{\nu_\mu} = -0.0394$
$g_V^{\nu_\tau} = -0.0350$

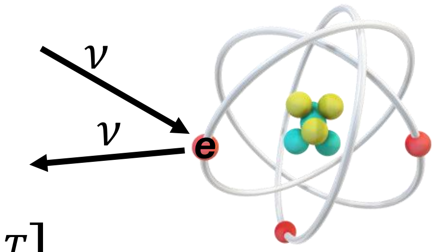
Axial coupling

$g_A^{\nu_e} = 0.4938$
$g_A^{\nu_{\mu,\tau}} = -0.5062$

M. Atzori Corona et al., Phys.Rev.D 107 (2023) 5, 053001
M. Atzori Corona et al., Phys. Rev. Lett. 135, 231803 (2025)

νES: Neutrino-Electron Scattering

Elastic scattering of neutrinos off **atomic electrons**:



Electron mass

$$\frac{d\sigma_{\nu_\ell e}}{dT}(E_\nu, T) = Z_{\text{eff}}\frac{G_F^2 m_e}{2\pi}\left[\left(g_V^{\nu_\ell}+g_A^{\nu_\ell}\right)^2 + \left(g_V^{\nu_\ell}-g_A^{\nu_\ell}\right)^2\left(1-\frac{T}{E_\nu}\right)^2 - \left(\left(g_V^{\nu_\ell}\right)^2-\left(g_A^{\nu_\ell}\right)^2\right)\frac{m_e T}{E_\nu^2}\right]$$

Electron recoil energy

Accounts for the number of electrons that can be ionized for a given energy deposit *T*

Adv. High Energy Phys. 2014 (2014) 569409
Atomic Data and Nuclear Data Tables 54.2 (1993), p. 181

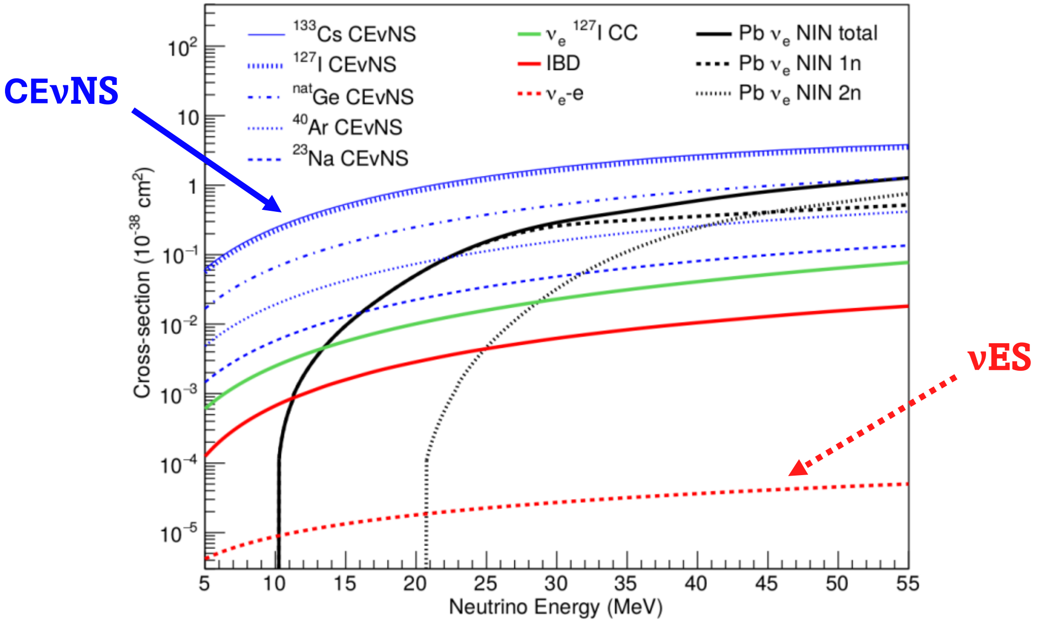
Vector coupling

$$g_V^{\nu_e} = 0.9524$$
$$g_V^{\nu_\mu} = -0.0394$$
$$g_V^{\nu_\tau} = -0.0350$$

Axial coupling

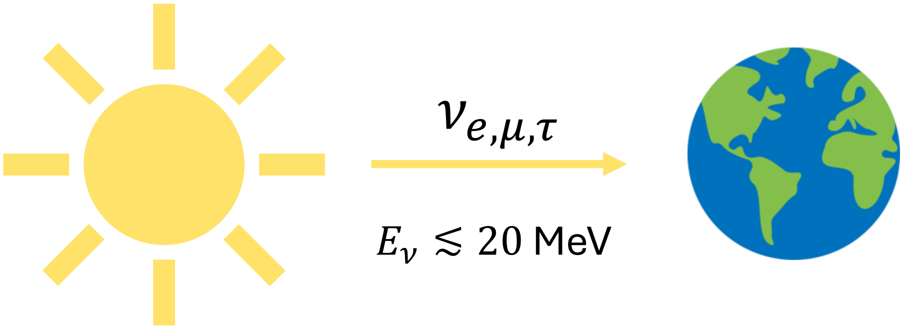
$$g_A^{\nu_e} = 0.4938$$
$$g_A^{\nu_{\mu,\tau}} = -0.5062$$

M. Atzori Corona et al., Phys.Rev.D 107 (2023) 5, 053001
M. Atzori Corona et al., Phys. Rev. Lett. 135, 231803 (2025)



arXiv:1803.09183v2

The Sun as a neutrino source

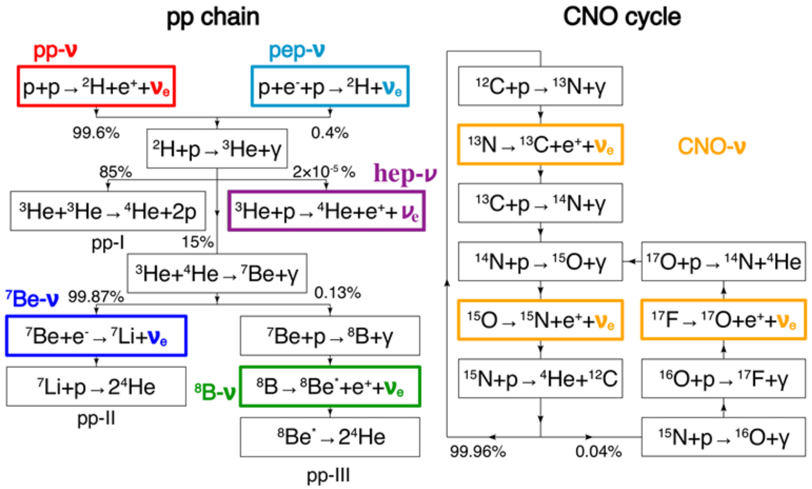


$\nu_{e,\mu,\tau}$

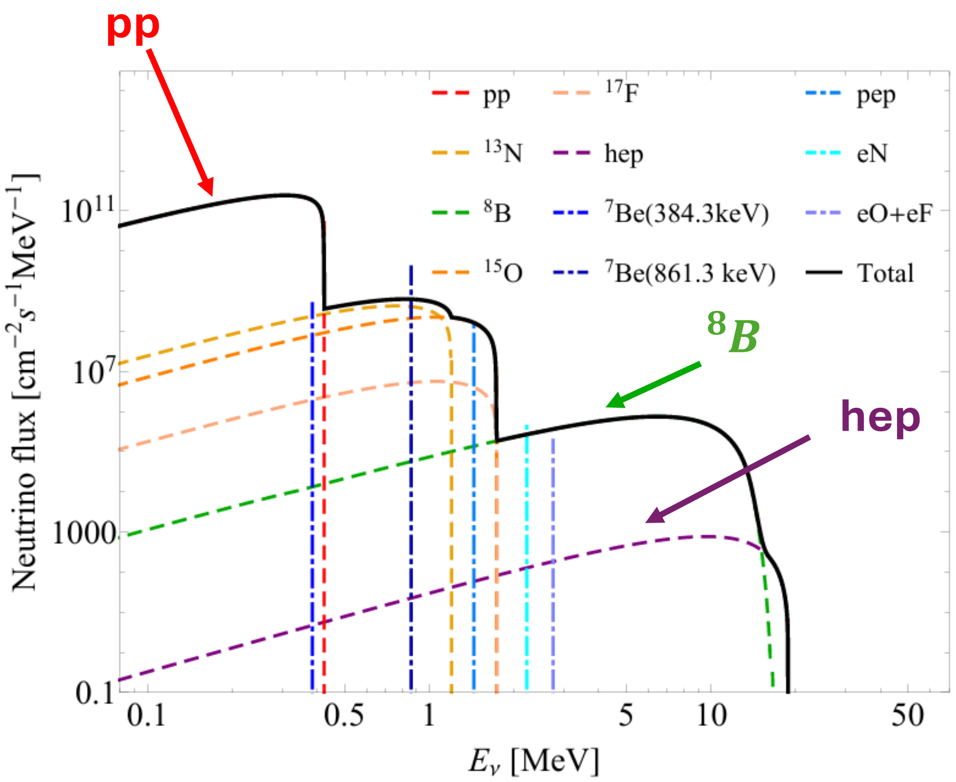
$E_\nu \lesssim 20$ MeV

- Neutrinos of **all flavours** are produced
- **Suitable energies** for CEνNS and νES

Solar neutrinos are produced through two thermonuclear reactions: the **pp chain** and the **CNO cycle**



Universe 2021, 7, 231



Nicola Cargioli, PhD Thesis

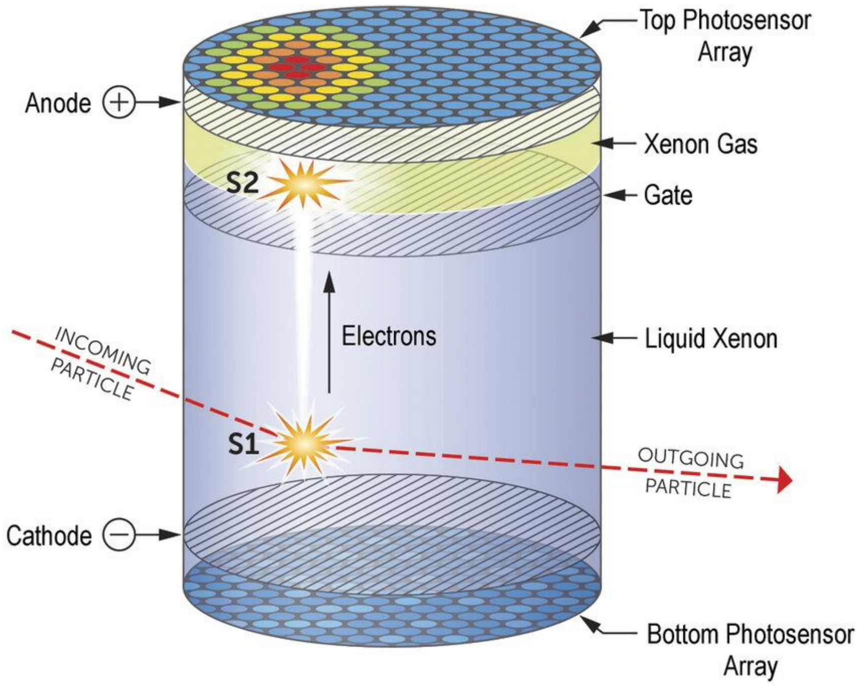
From backgrounds…

- **Direct detection dark matter** experiments search for **nuclear recoil** signals from **WIMPs**

- Irreducible **backgrounds**:
  nuclear recoils (NR) from **CEνNS** + electron recoils (ER) from **νES**

J. Phys. G: Nucl. Part. Phys. 50 (2023) 013001

Dual-phase time projection chamber (TPC)



S1: primary scintillation
S2: ionization signal

From backgrounds… to signals

- **Direct detection dark matter** experiments search for **nuclear recoil** signals from **WIMPs**

- Irreducible **backgrounds**:
  nuclear recoils (NR) from **CEνNS** + electron recoils (ER) from **νES**

LATEST AVAILABLE DATA

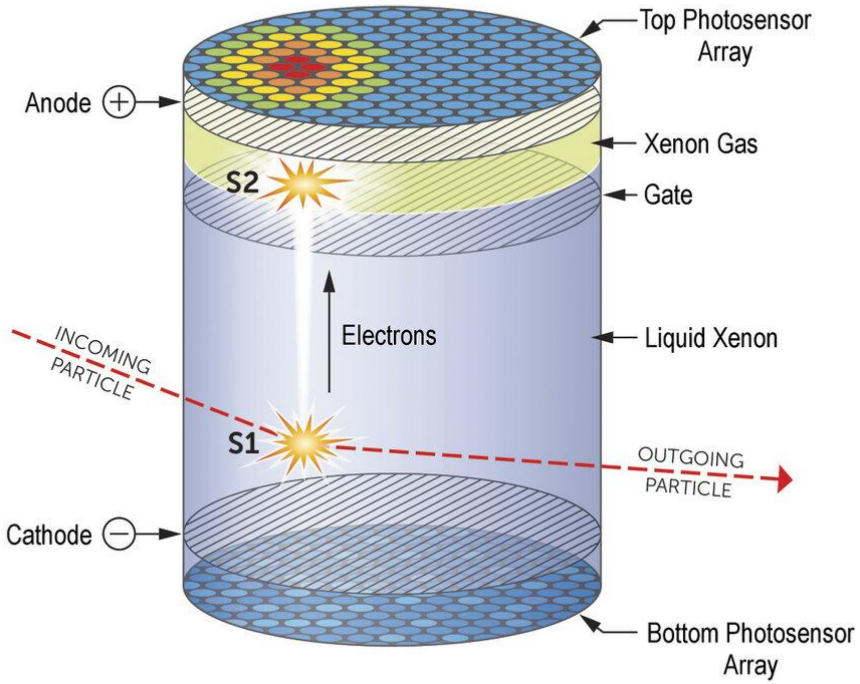
XENONnT	**PandaX-4T**	**Lux-Zeplin**
νES (2022) Phys. Rev. Lett. 129, 161805	**νES (2025)** Phys. Rev. Lett. 134, 041001	**νES (2025)** Phys. Rev. Lett. 135, 011802
CEνNS (2024) Phys. Rev. Lett. 133, 191002	**CEνNS (2024)** Phys. Rev. Lett. 133, 191001	**CEνNS (2025)** arXiv:2512.08065v2

First evidence of CEνNS from solar neutrinos!

Not considered in our analysis

J. Phys. G: Nucl. Part. Phys. 50 (2023) 013001

Dual-phase time projection chamber (TPC)

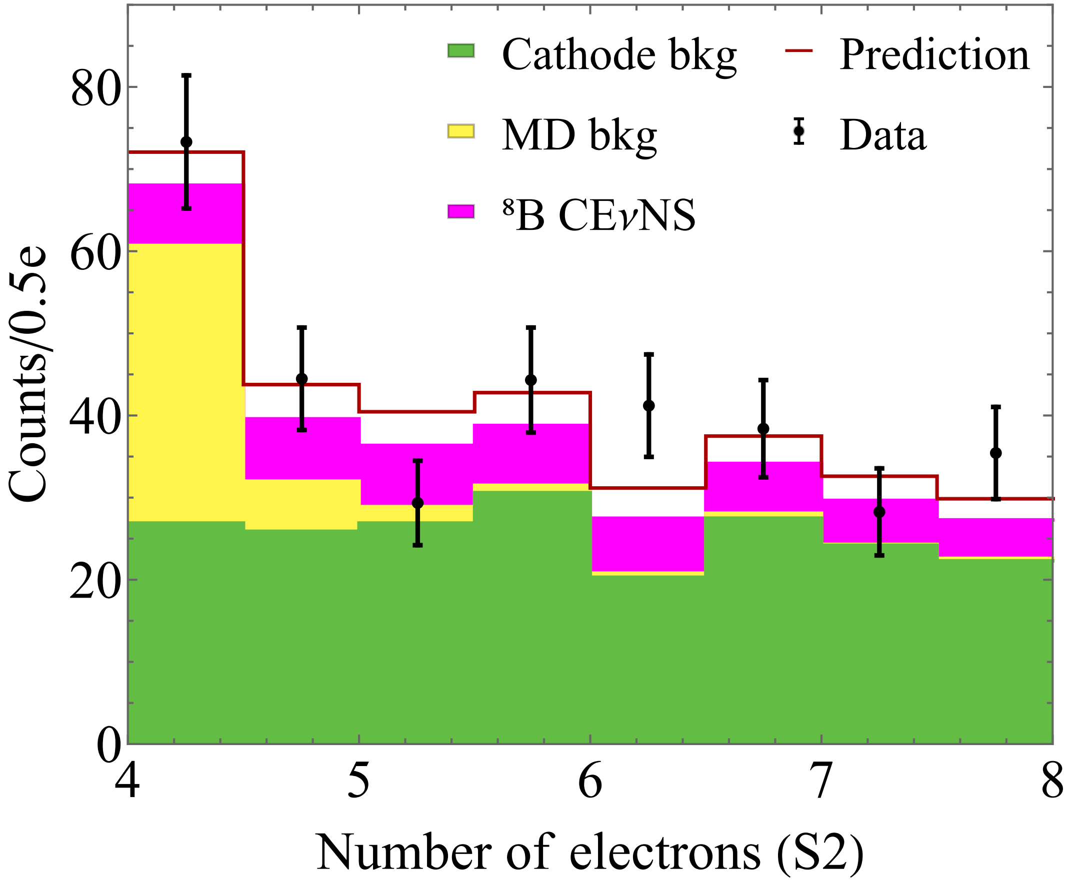


S1: primary scintillation
S2: ionization signal

See also G. Volta's, X. Zhou's and A. Uson's talks!

Data analysis

CEνNS data from PandaX-4T



Phys. Rev. Lett. 133, 191001

We compare the **theoretical number** of predicted events to the **experimental data**:

CEνNS: **Gaussian** least-squares function

νES: **Poissonian** least-squares function

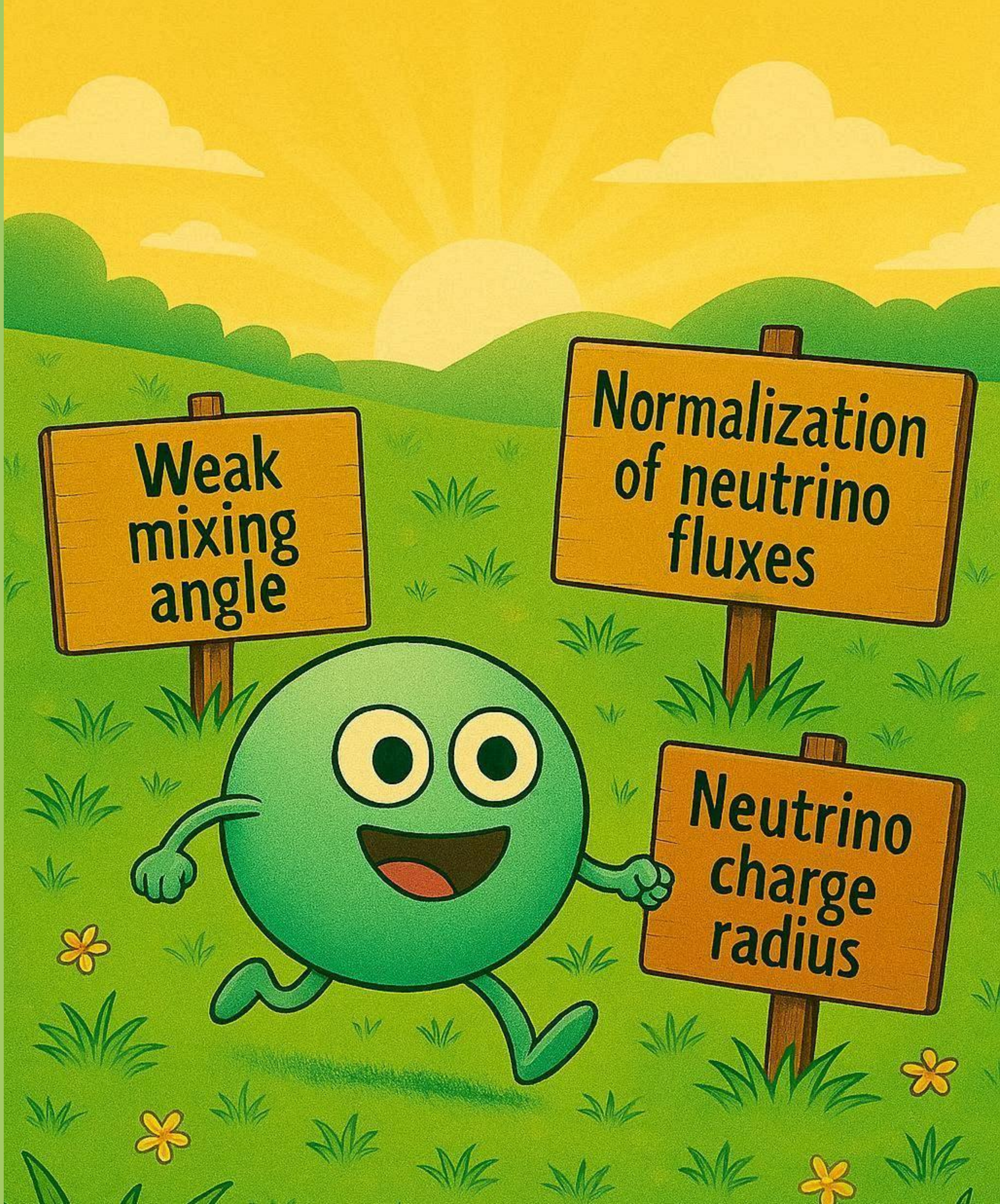
By **varying theoretical parameters**, the prediction changes

The χ^2 comparison shows which values best describe the data

Standard Model tests

Beyond the Standard Model scenarios

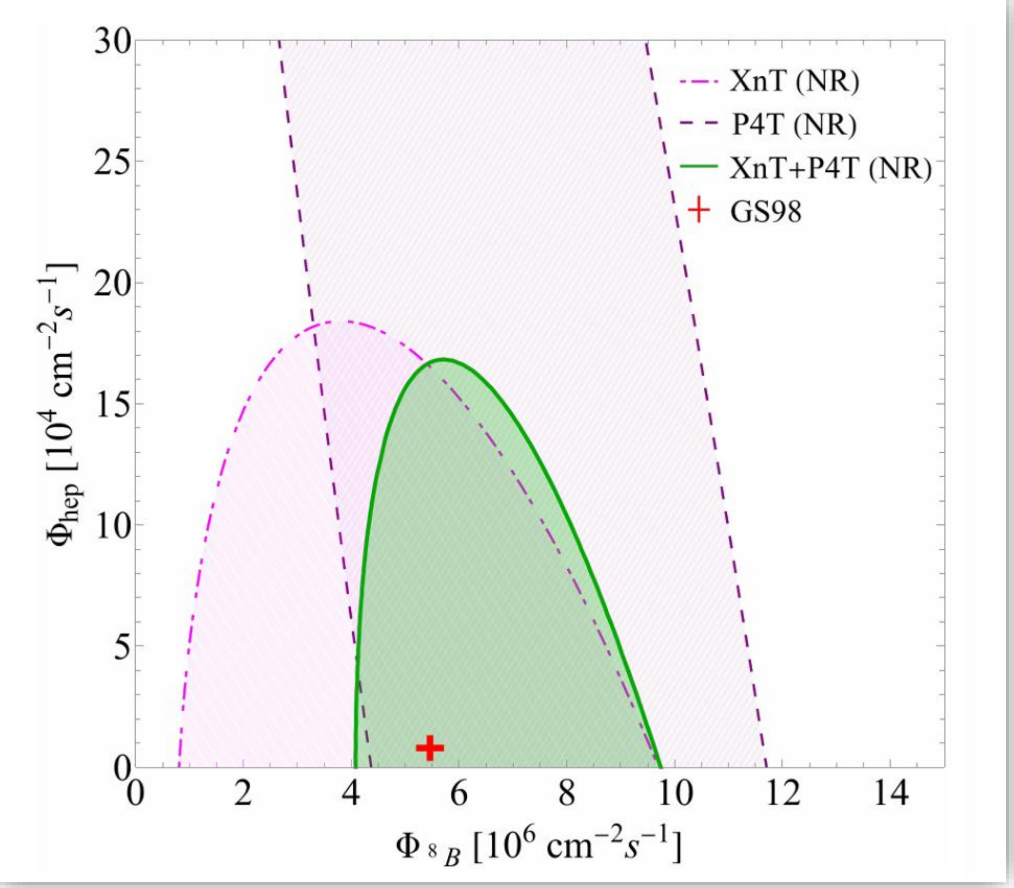
STANDARD MODEL TESTS

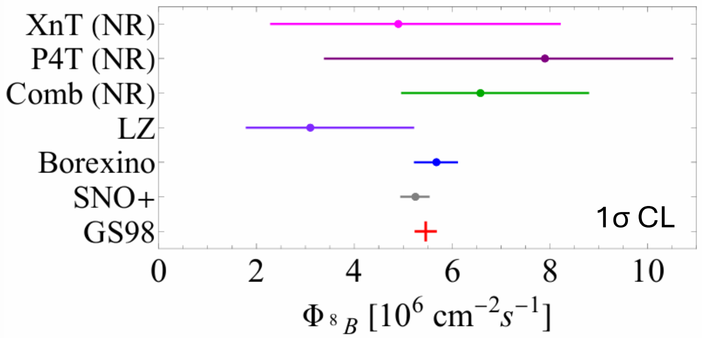


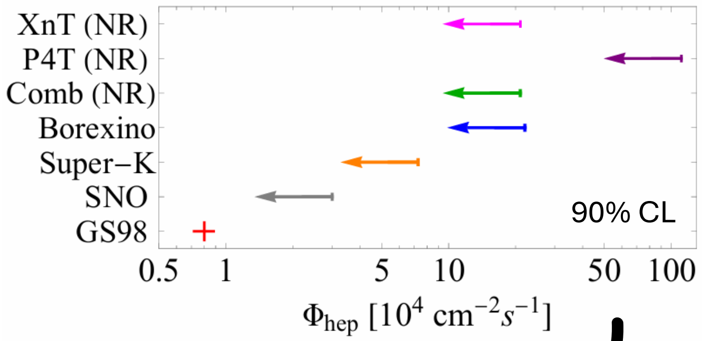
Normalization of neutrino fluxes

- Only **CEνNS** data (**XENONnT** and **PandaX-4T**)
- Main contribution from $^8\boldsymbol{B}$ neutrinos, **hep** flux subdominant

	$\Phi_{^8B}(\text{Comb})$ $[10^6\text{cm}^{-2}\text{s}^{-1}]$	$\Phi_{hep}(\text{Comb})$ $[10^4\text{cm}^{-2}\text{s}^{-1}]$
Our work	$6.7^{+2.1}_{-1.7}$ $(1\sigma\ \text{CL})$	< 19 $(90\%\ \text{CL})$
GS98 *(Rev. Mod. Phys. 92, 45006 (2020))*	5.46	0.8





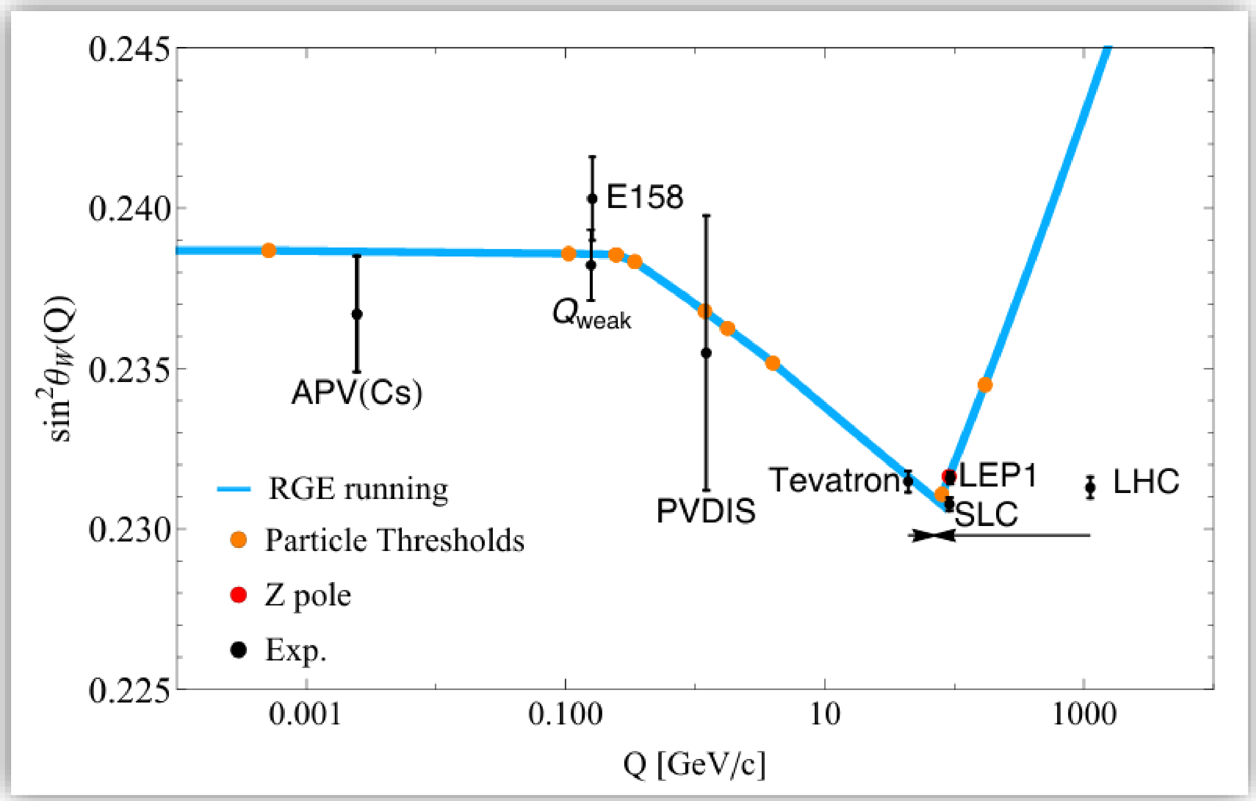


Best limit: $\boldsymbol{\Phi_{hep}(\text{SNO}) < 3 \times 10^4\text{cm}^{-2}\text{s}^{-1}}$

Phys. Rev. D 102, 062006 (2020)

See also *V. De Romeri et al., JCAP 05 (2025) 012*

Weak mixing angle



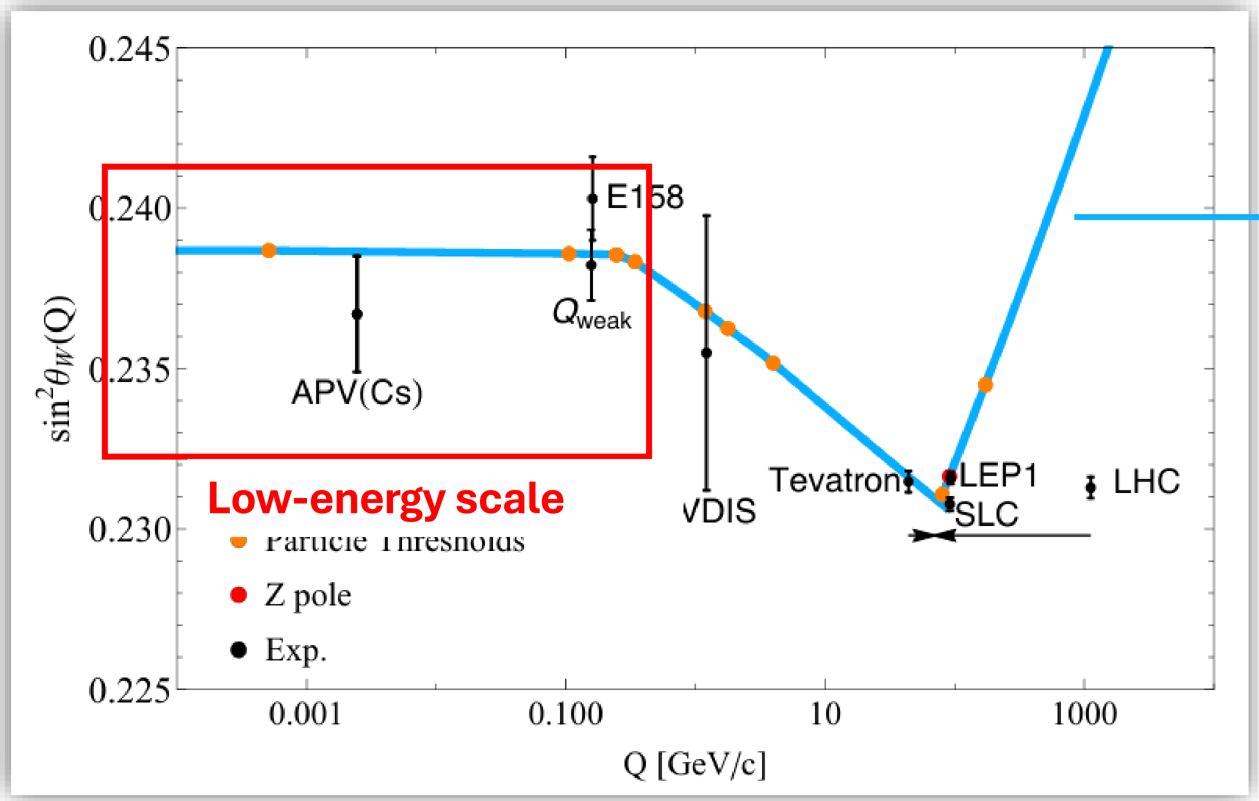
It describes the electroweak coupling

Fundamental test of Standard Model

Well predicted by theory

$\sin^2\vartheta_W$

Weak mixing angle



Low-energy scale

It describes the electroweak coupling

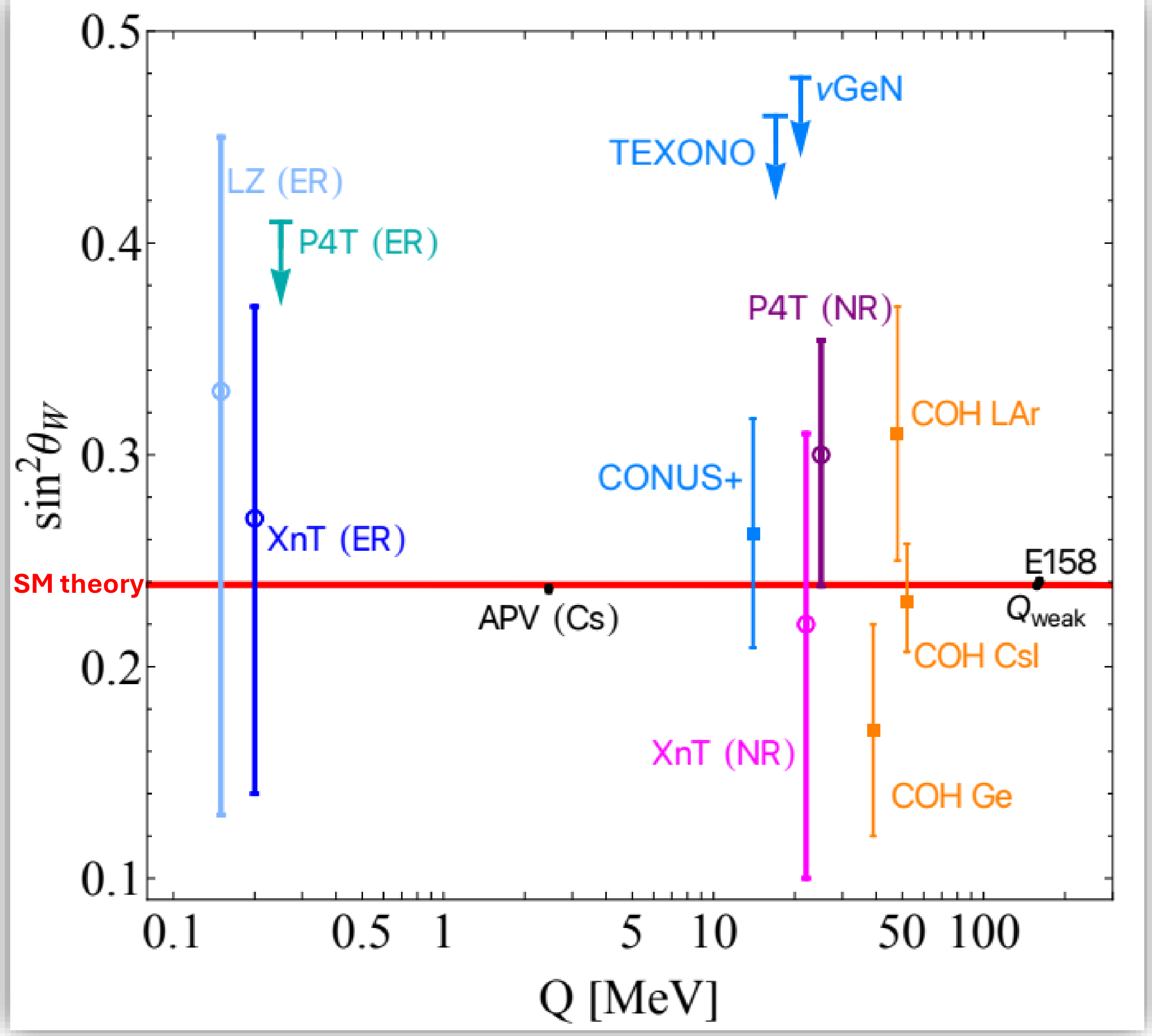
Fundamental test of Standard Model

Well predicted by theory $\simeq \mathbf{0.23873}$

$sin^2\vartheta_W$

Phys. Rev. D 110, 030001 (2024)

Weak mixing angle



It describes the electroweak coupling

Fundamental test of Standard Model

Well predicted by theory $\simeq 0.23873$

$\sin^2\vartheta_W$

Phys. Rev. D 110, 030001 (2024)

CEνNS:

$$g_V^p \simeq \frac{1}{2} - 2\,\sin^2\vartheta_W$$

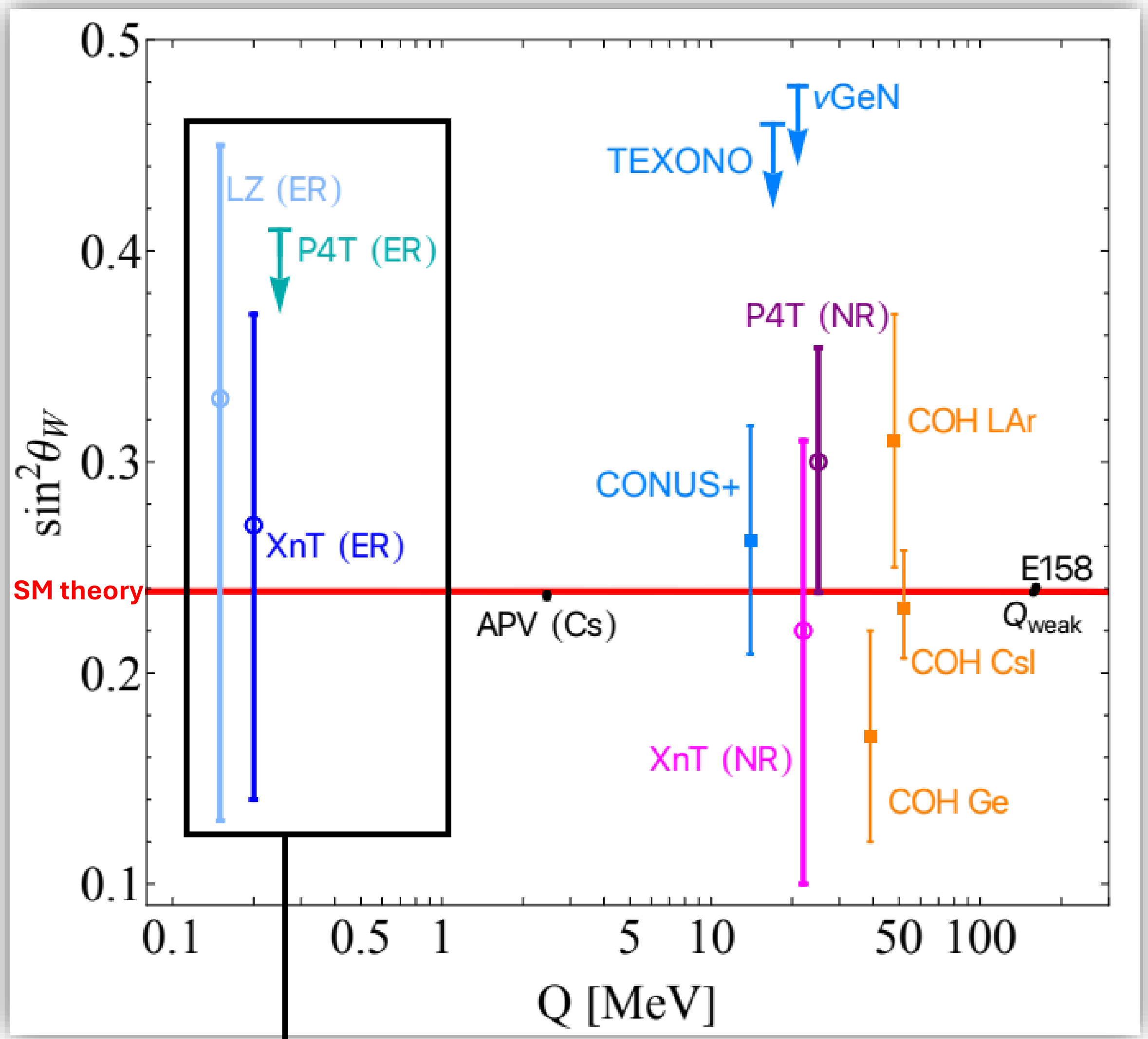
νES:

$$g_V^{\nu_e} \simeq \frac{1}{2} + 2\,\sin^2\vartheta_W$$

$$g_V^{\nu_{\mu,\tau}} \simeq -\frac{1}{2} + 2\,\sin^2\vartheta_W$$

See also *V. De Romeri et al., JCAP 05 (2025) 012,*
T.N. Maity and C. Boehm, Phys. Rev. D 112 (2025) 053001
M. Atzori Corona et al., arXiv:2605.07975v2

Weak mixing angle



Electron recoil data (**lowest energy measurement!**)

It describes the electroweak coupling

Fundamental test of Standard Model

Well predicted by theory $\simeq 0.23873$

$$\boldsymbol{sin^2\vartheta_W}$$

Phys. Rev. D 110, 030001 (2024)

CEνNS:

$$g_V^p \simeq \frac{1}{2} - 2\,\boldsymbol{sin^2\vartheta_W}$$

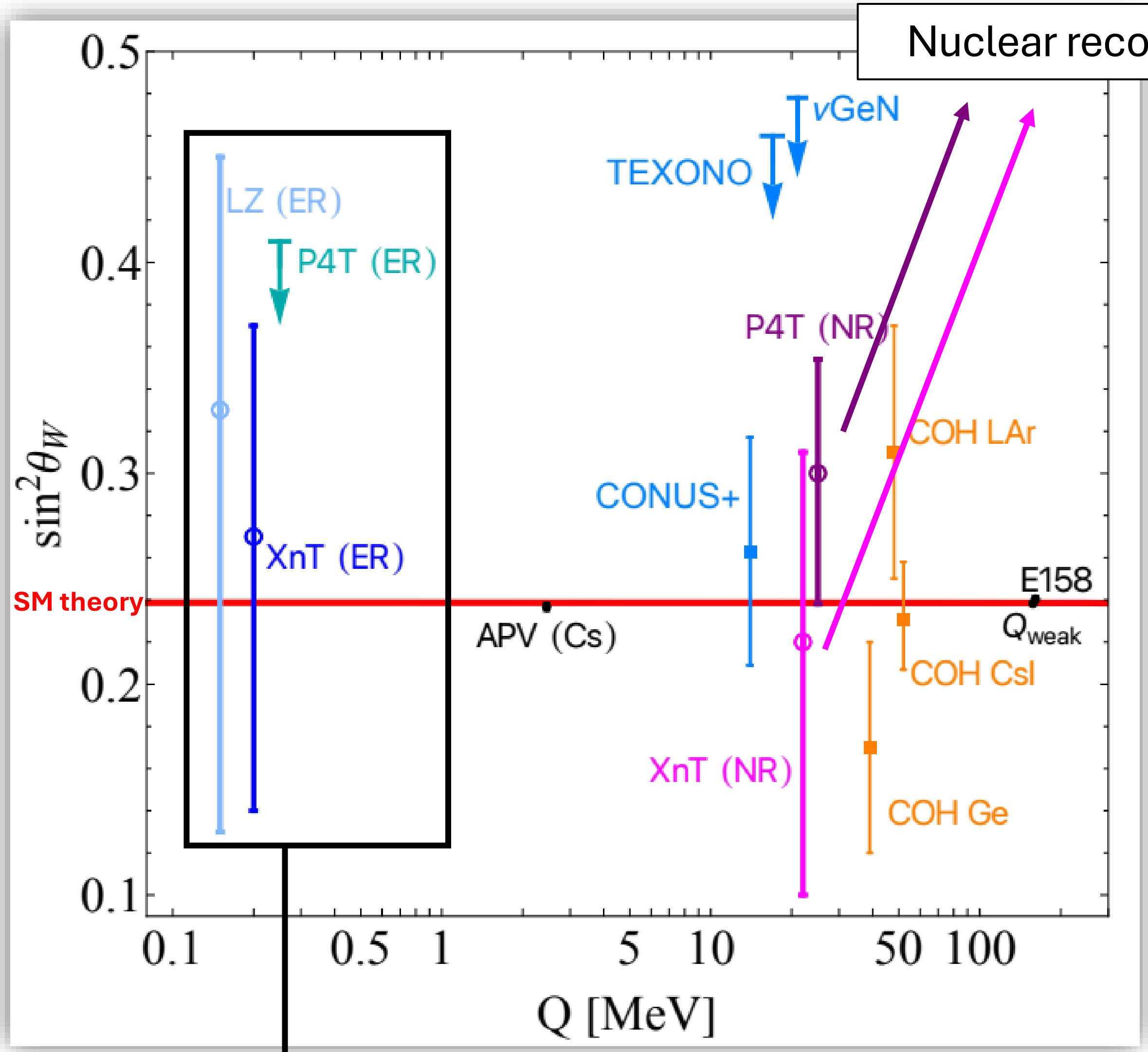
νES:

$$g_V^{\nu_e} \simeq \frac{1}{2} + 2\,\boldsymbol{sin^2\vartheta_W}$$

$$g_V^{\nu_{\mu,\tau}} \simeq -\frac{1}{2} + 2\,\boldsymbol{sin^2\vartheta_W}$$

See also *V. De Romeri et al., JCAP 05 (2025) 012,*
T.N. Maity and C. Boehm, Phys. Rev. D 112 (2025) 053001
M. Atzori Corona et al., arXiv:2605.07975v2

Weak mixing angle



Nuclear recoil data

Electron recoil data (**lowest energy measurement!**)

It describes the electroweak coupling

Fundamental test of Standard Model

Well predicted by theory $\simeq$ 0.23873

$$\left.\begin{array}{l}\\ \\ \\ \end{array}\right\} \boldsymbol{sin^2\vartheta_W}$$

Phys. Rev. D 110, 030001 (2024)

CEνNS:

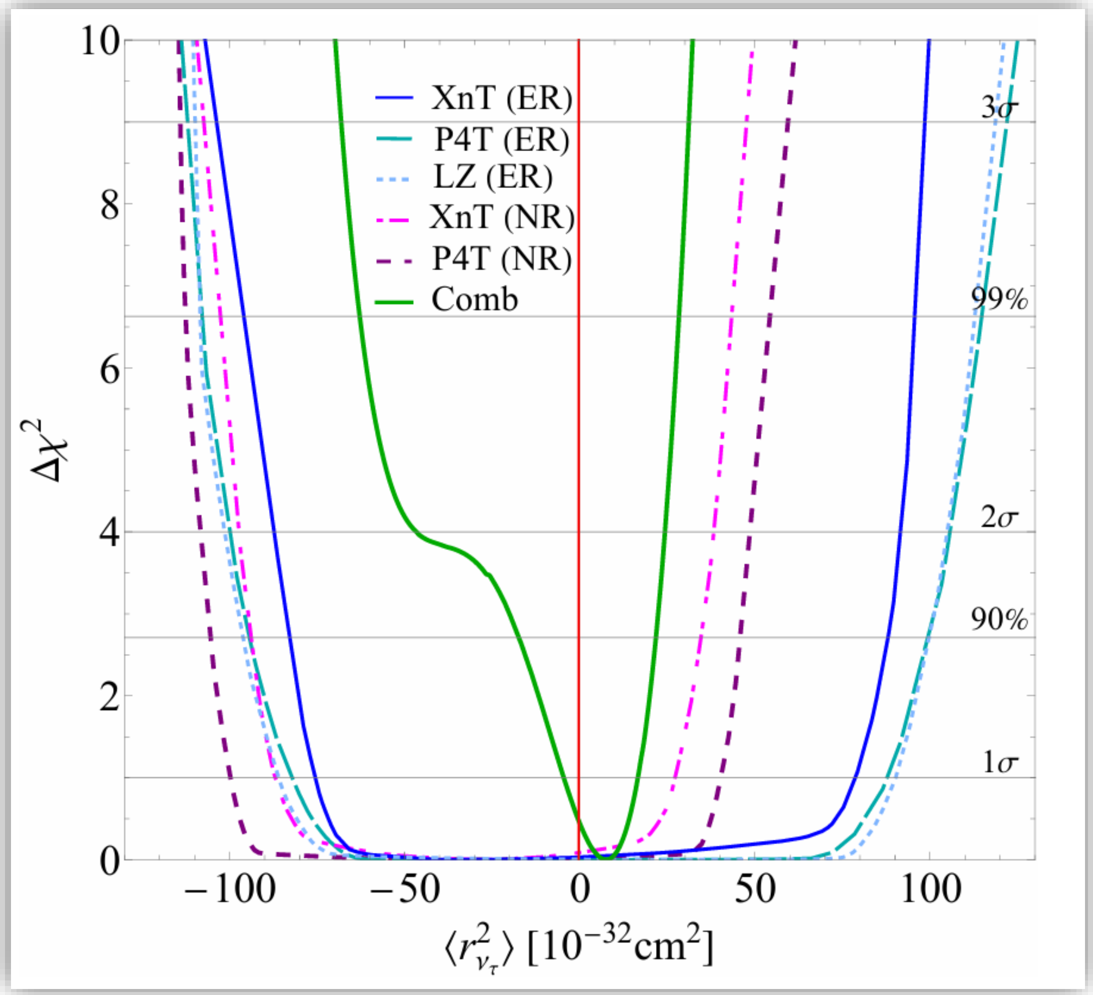
$$\boxed{g_V^p \simeq \frac{1}{2} - 2\,\boldsymbol{sin^2\vartheta_W}}$$

νES:

$$\boxed{\begin{array}{l} g_V^{\nu_e} \simeq \frac{1}{2} + 2\,\boldsymbol{sin^2\vartheta_W} \\ g_V^{\nu_{\mu,\tau}} \simeq -\frac{1}{2} + 2\,\boldsymbol{sin^2\vartheta_W} \end{array}}$$

***See also** V. De Romeri et al., JCAP 05 (2025) 012,*
T.N. Maity and C. Boehm, Phys. Rev. D 112 (2025) 053001

Neutrino charge radius



In the SM neutrinos are neutral, but tiny **charge radii** are generated by radiative corrections to the vector couplings:

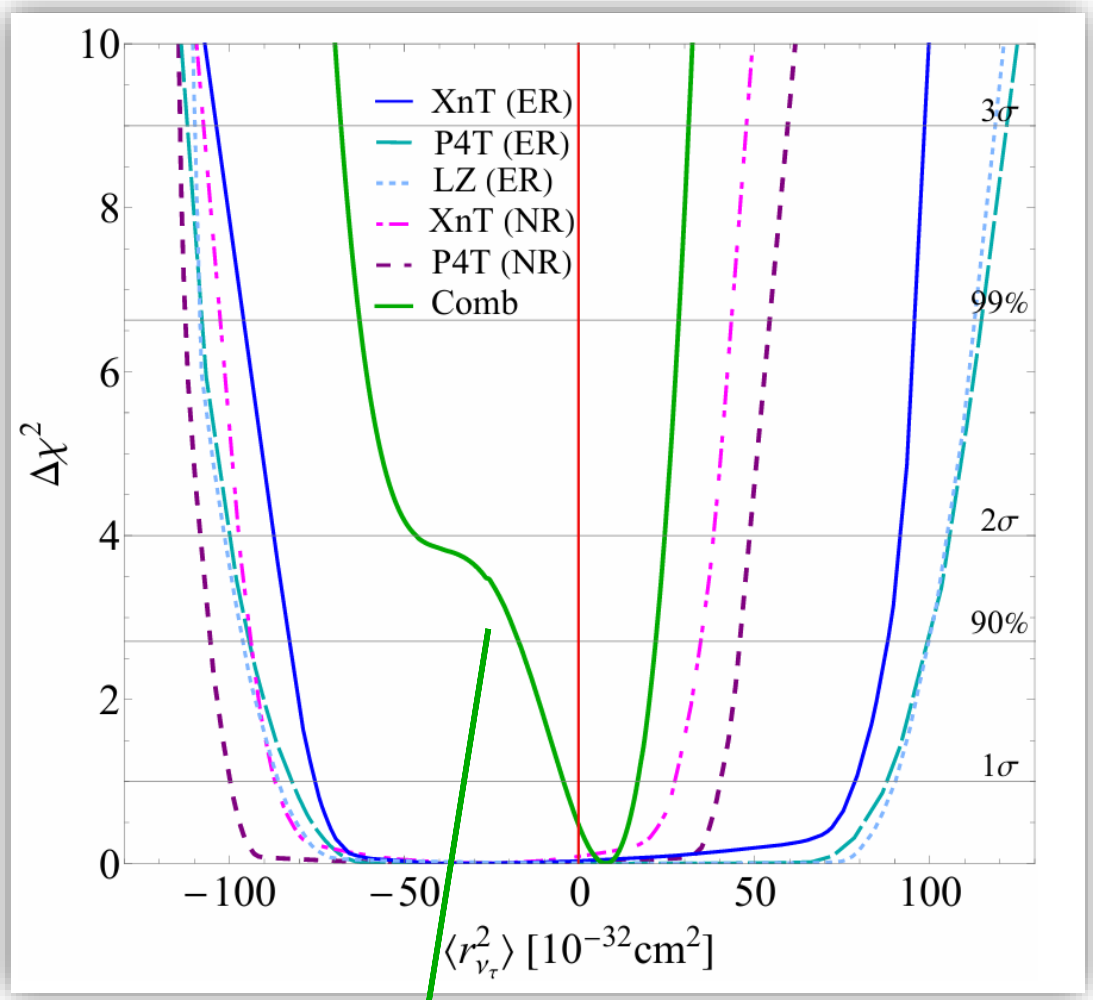
CEνNS:

$$\boxed{g_V^p = \tilde{g}_V^p - \frac{\sqrt{2}\pi\alpha}{3G_F}\langle \boldsymbol{r^2_{\nu_\ell}}\rangle}$$

νES:

$$\boxed{g_V^{\nu_\ell} = \tilde{g}_V^\nu + \frac{\sqrt{2}\pi\alpha}{3G_F}\langle \boldsymbol{r^2_{\nu_\ell}}\rangle}$$

Neutrino charge radius



Global fit

In the SM neutrinos are neutral, but tiny **charge radii** are generated by radiative corrections to the vector couplings:

CEνNS:

$$g_V^p = \tilde{g}_V^p - \frac{\sqrt{2}\pi\alpha}{3G_F}\langle \boldsymbol{r^2_{\nu_\ell}} \rangle$$

νES:

$$g_V^{\nu_\ell} = \tilde{g}_V^\nu + \frac{\sqrt{2}\pi\alpha}{3G_F}\langle \boldsymbol{r^2_{\nu_\ell}} \rangle$$

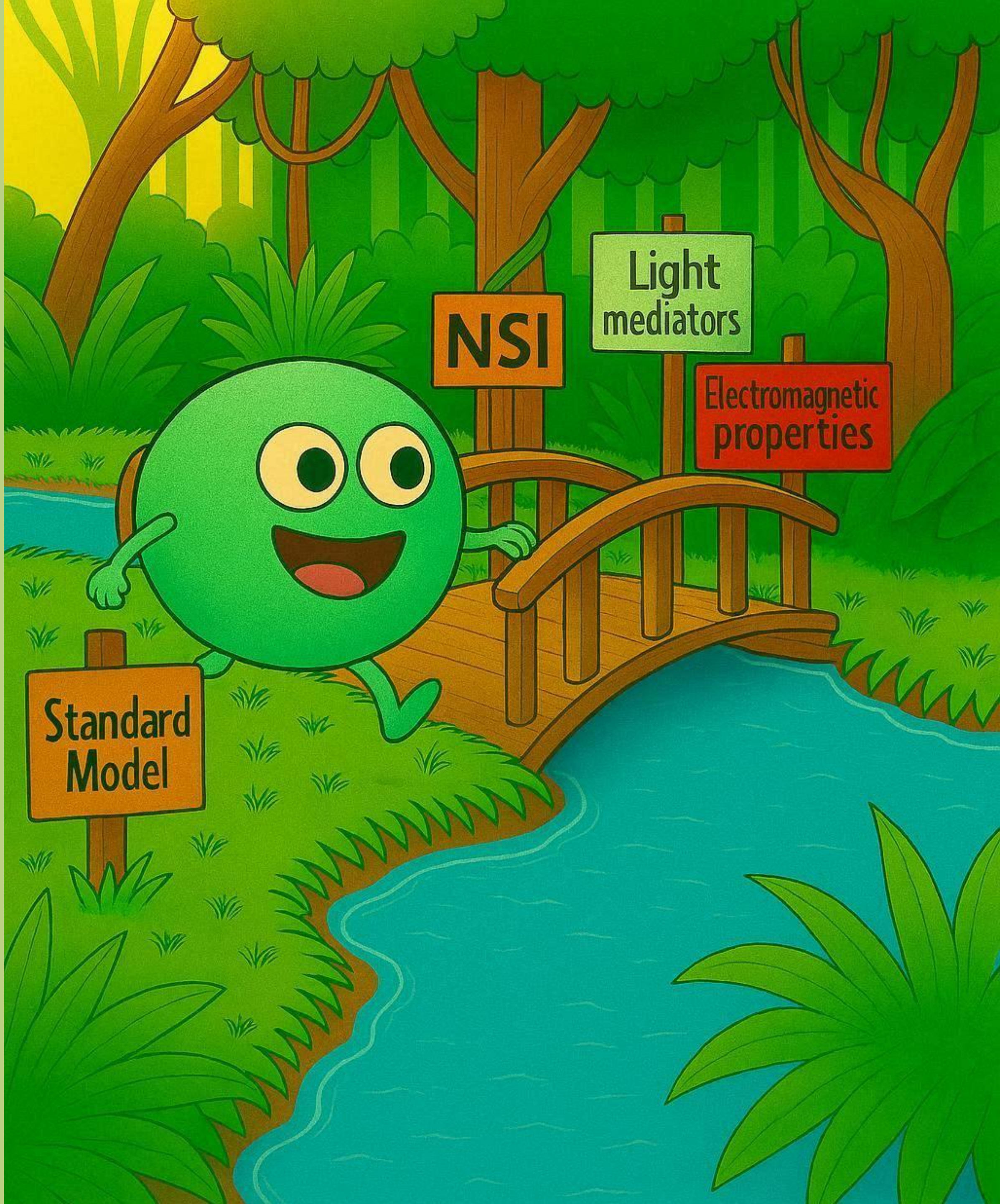
$\langle r^2_{\nu_\tau}\rangle(\text{Global fit}) = 7.5^{+9.5}_{-11.7} \times 10^{-32}\text{cm}^2$ 1σ CL

$\langle r^2_{\nu_\tau}\rangle(\text{Predicted}) \simeq -0.30 \times 10^{-32}\text{cm}^2$

Most stringent constraints on $\langle r^2_{\nu_\tau}\rangle$
from neutrino scattering experiments

🔍 ***See also*** *M. Demirci et al.*, Phys. Rev. D 112 (2025) 095035

BEYOND THE STANDARD MODEL SCENARIOS



Neutrino electromagnetic properties

Magnetic moment

- In the simplest extension of Standard Model:

$$\mu_\nu \lesssim 3.2 \times \mathbf{10^{-19}} \left(\frac{m_k}{\mathrm{eV}}\right) \mu_\mathrm{B}$$

7 orders of magnitude difference between theory and experiments!

- Best upper limit on solar neutrinos : $\mu_{\nu_s} \lesssim 6.4 \times \mathbf{10^{-12}} \mu_B$

XENON Collaboration, *Phys. Rev. Lett. 129, 161805*

CEνNS:

$$\boxed{\frac{d\sigma^{\mathrm{MM}}_{\nu_\ell\text{-}\mathcal{N}}}{dT_\mathrm{nr}} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_\mathrm{nr}} - \frac{1}{E_\nu}\right) Z^2 F_Z^2(|\vec{q}|^2) \left|\frac{\mu_{\nu_\ell}}{\mu_\mathrm{B}}\right|^2}$$

νES:

$$\boxed{\frac{d\sigma^{\mathrm{MM}}_{\nu_\ell\text{-}\mathcal{A}}}{dT_\mathrm{e}} = Z^{\mathcal{A}}_{\mathrm{eff}}(T_\mathrm{e}) \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_\mathrm{e}} - \frac{1}{E}\right) \left|\frac{\mu_{\nu_\ell}}{\mu_\mathrm{B}}\right|^2}$$

Neutrino electromagnetic properties

Magnetic moment

- In the simplest extension of Standard Model:

$$\mu_\nu \lesssim 3.2 \times 10^{-19} \left(\frac{m_k}{\mathrm{eV}}\right) \mu_{\mathrm{B}}$$

7 orders of magnitude difference between theory and experiments!

- Best upper limit on solar neutrinos : $\mu_{\nu_s} \lesssim 6.4 \times 10^{-12} \mu_B$

XENON Collaboration, *Phys. Rev. Lett. 129, 161805*

CEνNS:

$$\frac{d\sigma^{\mathrm{MM}}_{\nu_\ell\text{-}\mathcal{N}}}{dT_{\mathrm{nr}}} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_{\mathrm{nr}}} - \frac{1}{E_\nu}\right) Z^2 F_Z^2(|\vec{q}|^2) \left|\frac{\mu_{\nu_\ell}}{\mu_{\mathrm{B}}}\right|^2$$

Strongly depends on recoil energy!

νES:

$$\frac{d\sigma^{\mathrm{MM}}_{\nu_\ell\text{-}\mathcal{A}}}{dT_{\mathrm{e}}} = Z^{\mathcal{A}}_{\mathrm{eff}}(T_{\mathrm{e}})\frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_{\mathrm{e}}} - \frac{1}{E}\right)\left|\frac{\mu_{\nu_\ell}}{\mu_{\mathrm{B}}}\right|^2$$

Neutrino electromagnetic properties

Magnetic moment

- In the simplest extension of Standard Model:

$$\mu_\nu \lesssim 3.2 \times \mathbf{10^{-19}} \left(\frac{m_k}{\mathrm{eV}}\right) \mu_\mathrm{B}$$

7 orders of magnitude difference between theory and experiments!

- Best upper limit on solar neutrinos : $\mu_{\nu_s} \lesssim 6.4 \times \mathbf{10^{-12}} \mu_B$

XENON Collaboration, *Phys. Rev. Lett. 129, 161805*

CEνNS:

$$\frac{d\sigma^{\mathrm{MM}}_{\nu_\ell\text{-}\mathcal{N}}}{dT_\mathrm{nr}} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_\mathrm{nr}} - \frac{1}{E_\nu}\right) Z^2 F_Z^2(|\vec{q}|^2) \left|\frac{\mu_{\nu_\ell}}{\mu_\mathrm{B}}\right|^2$$

Strongly depends on recoil energy!

νES:

$$\frac{d\sigma^{\mathrm{MM}}_{\nu_\ell\text{-}\mathcal{A}}}{dT_\mathrm{e}} = Z^{\mathcal{A}}_{\mathrm{eff}}(T_\mathrm{e}) \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_\mathrm{e}} - \frac{1}{E}\right) \left|\frac{\mu_{\nu_\ell}}{\mu_\mathrm{B}}\right|^2$$

Millicharge

- In some BSM scenarios neutrinos can acquire a small **electric charge q_ν** (millicharge)

- Strongest constraint from neutrality of matter :

$$q_\nu < 10^{-21}\, e_0$$

JHEP 05 (2000) 003

CEνNS:

$$g_V^p = g_V^p - \frac{2\sqrt{2}\pi\alpha}{G_F\, q^2} q_{\nu_\ell}$$

νES:

$$g_V^{\nu_\ell} = g_V^{\nu_\ell} + \frac{2\sqrt{2}\pi\alpha}{G_F\, q^2} q_{\nu_\ell}$$

Neutrino electromagnetic properties

Magnetic moment

- In the simplest extension of Standard Model:

$$\mu_\nu \lesssim 3.2 \times \mathbf{10^{-19}} \left(\frac{m_k}{\mathrm{eV}}\right) \mu_\mathrm{B}$$

7 orders of magnitude difference between theory and experiments!

- Best upper limit on solar neutrinos : $\mu_{\nu_s} \lesssim 6.4 \times \mathbf{10^{-12}} \mu_B$

XENON Collaboration, *Phys. Rev. Lett. 129, 161805*

CEνNS:

$$\boxed{\frac{d\sigma^{\mathrm{MM}}_{\nu_\ell\text{-}\mathcal{N}}}{dT_\mathrm{nr}} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_\mathrm{nr}} - \frac{1}{E_\nu}\right) Z^2 F_Z^2(|\vec{q}|^2) \left|\frac{\mu_{\nu_\ell}}{\mu_\mathrm{B}}\right|^2}$$

Strongly depends on recoil energy!

νES:

$$\boxed{\frac{d\sigma^{\mathrm{MM}}_{\nu_\ell\text{-}\mathcal{A}}}{dT_\mathrm{e}} = Z_\mathrm{eff}^{\mathcal{A}}(T_\mathrm{e}) \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_\mathrm{e}} - \frac{1}{E}\right) \left|\frac{\mu_{\nu_\ell}}{\mu_\mathrm{B}}\right|^2}$$

Millicharge

- In some BSM scenarios neutrinos can acquire a small **electric charge q_ν** (millicharge)
- Strongest constraint from neutrality of matter :

$$q_\nu < 10^{-21}\, e_0$$

JHEP 05 (2000) 003

CEνNS:

$$\boxed{g_V^p = g_V^p - \frac{2\sqrt{2}\pi\alpha}{G_F\, \boldsymbol{q^2}} q_{\nu_\ell}}$$

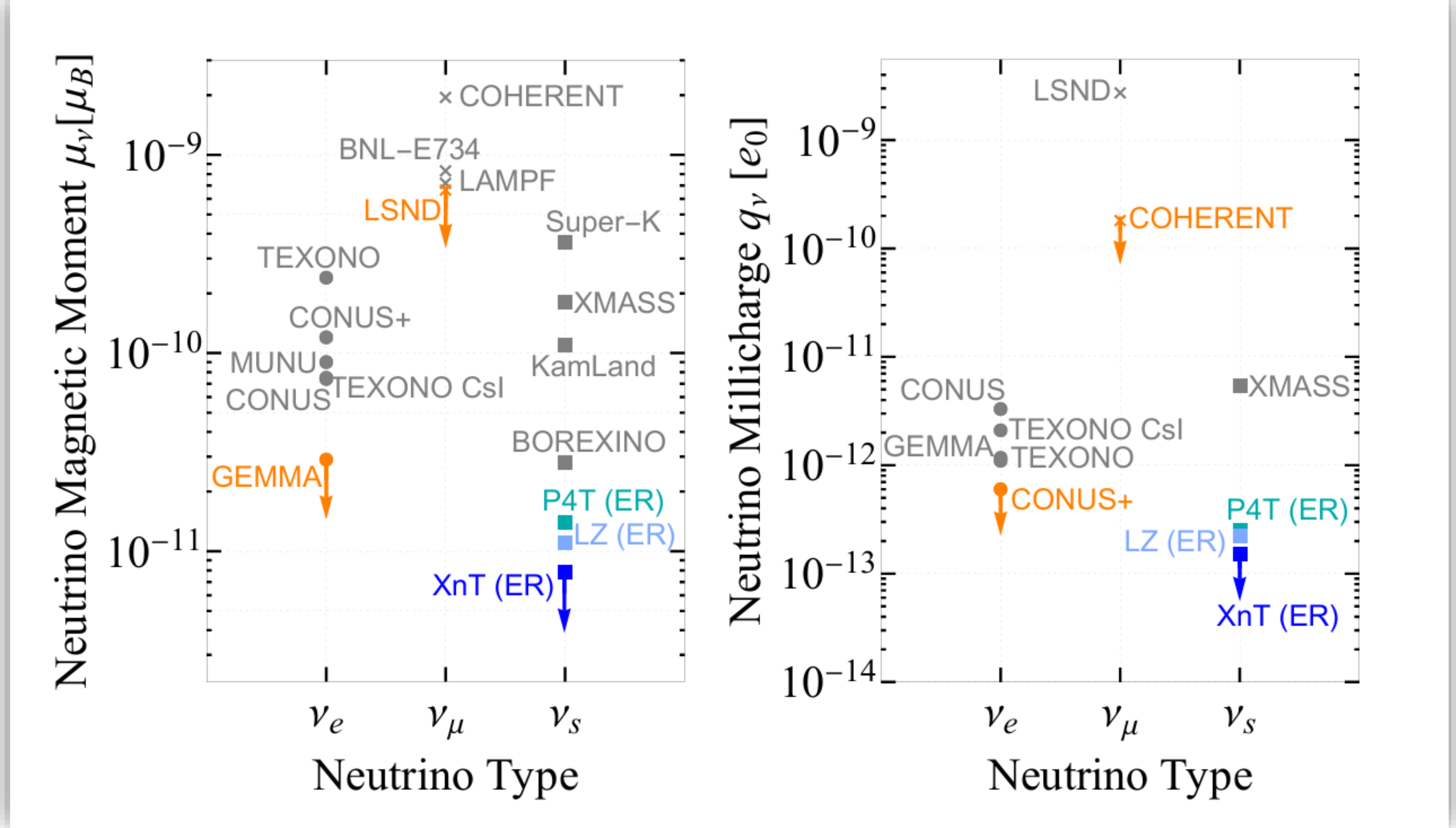
νES:

$$\boxed{g_V^{\nu_\ell} = g_V^{\nu_\ell} + \frac{2\sqrt{2}\pi\alpha}{G_F\, \boldsymbol{q^2}} q_{\nu_\ell}}$$

$|\vec{q}| \simeq \sqrt{2MT}$ **Strongly depends on recoil energy!**

Neutrino electromagnetic properties

Magnetic moment **Electric charge**



Magnetic moment

$$\mu_{\nu_s}(\mathrm{XnT-ER}) < 7.8 \times 10^{-12}\mu_B,$$
$$\mu_{\nu_s}(\mathrm{P4T-ER}) < 14 \times 10^{-12}\mu_B,$$
$$\mu_{\nu_s}(\mathrm{LZ-ER}) < 11 \times 10^{-12}\mu_B.$$

Electric charge

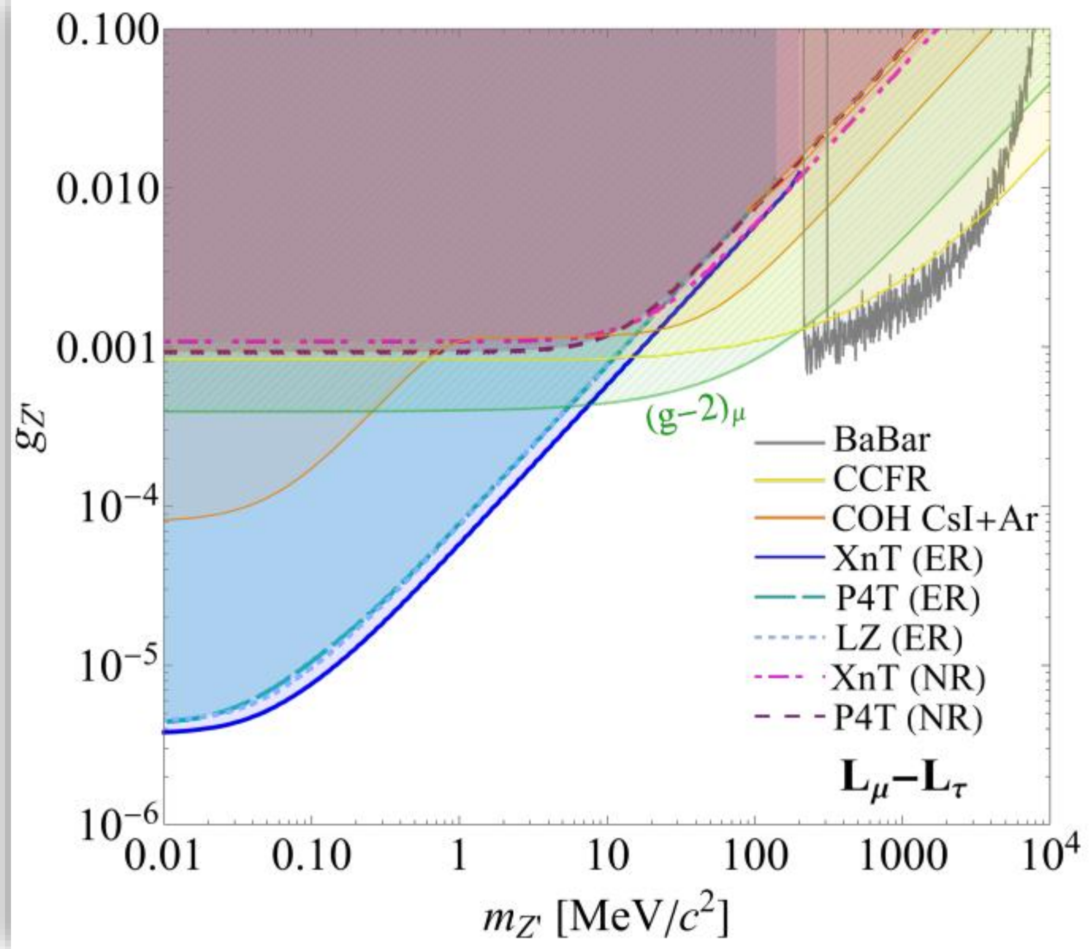
$$-1.4 < q_{\nu_s}(\mathrm{XnT-ER})\,[10^{-13}e_0] < 1.7,$$
$$-2.5 < q_{\nu_s}(\mathrm{P4T-ER})\,[10^{-13}e_0] < 2.5,$$
$$-2.3 < q_{\nu_s}(\mathrm{LZ-ER})\,[10^{-13}e_0] < 2.2,$$

Strongest laboratory constraints!

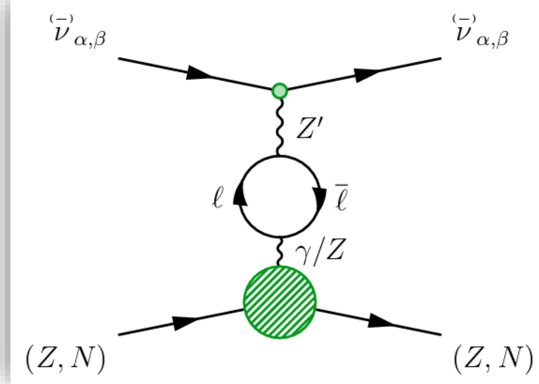
See also *M. Demirci et al.*, Phys. Rev. D 112 (2025) 095035

Light mediators

$L_\mu - L_\tau$



- **New** vector mediator $\boldsymbol{Z'}$, similar to the Z boson but lighter
- The new boson couples directly only with **$\boldsymbol{\mu}$ and $\boldsymbol{\tau}$ flavours**



N. Cargioli, PhD Thesis

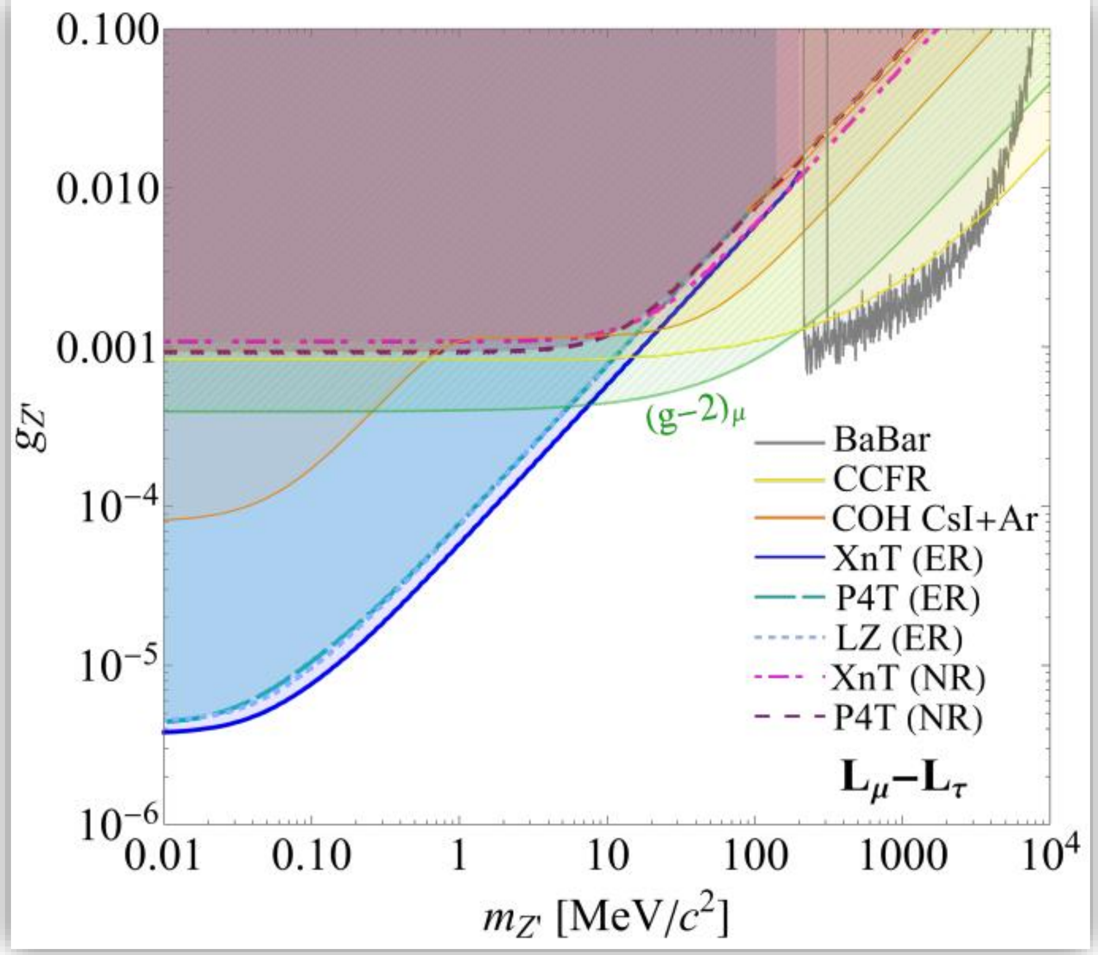
CEνNS: $$g_V^p(\nu_\ell) \to g_V^p(\nu_\ell) + \frac{\sqrt{2}\alpha g_{Z'}^2 \left(\delta_{\ell\mu}\varepsilon_{\tau\mu}(|\vec{q}|) + \delta_{\ell\tau}\varepsilon_{\mu\tau}(|\vec{q}|)\right)}{\pi G_F \left(|\vec{q}|^2 + M_{Z'}^2\right)}$$

νES: $$g_V^{\nu_\ell} \to g_V^{\nu_\ell} - \frac{\sqrt{2}\alpha g_{Z'}^2 \left(\delta_{\ell\mu}\varepsilon_{\tau\mu}(|\vec{q}|) + \delta_{\ell\tau}\varepsilon_{\mu\tau}(|\vec{q}|)\right)}{\pi G_F \left(|\vec{q}|^2 + M_{Z'}^2\right)}$$

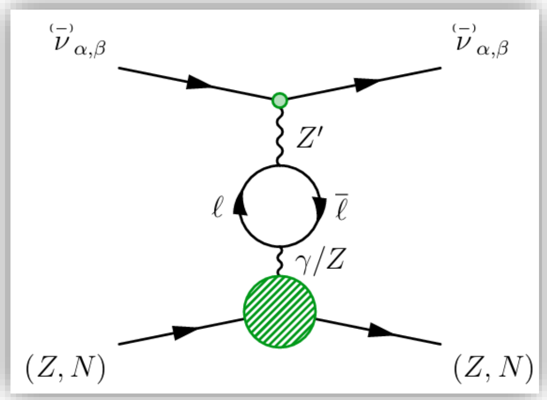
***See also** M. Demirci et al.,* Phys. Rev. D 111 (2025) 055032

Light mediators

$L_\mu - L_\tau$



- **New** vector mediator Z', similar to the Z boson but lighter
- The new boson couples directly only with **μ and τ flavours**



N. Cargioli, PhD Thesis

CEνNS: $$g_V^p(\nu_\ell) \to g_V^p(\nu_\ell) + \frac{\sqrt{2}\alpha g_{Z'}^2 (\delta_{\ell\mu}\varepsilon_{\tau\mu}(|\vec{q}|) + \delta_{\ell\tau}\varepsilon_{\mu\tau}(|\vec{q}|))}{\pi G_F (|\vec{q}|^2 + M_{Z'}^2}$$

Z' coupling constant

Z' mass

νES: $$g_V^{\nu_\ell} \to g_V^{\nu_\ell} - \frac{\sqrt{2}\alpha g_{Z'}^2 (\delta_{\ell\mu}\varepsilon_{\tau\mu}(|\vec{q}|) + \delta_{\ell\tau}\varepsilon_{\mu\tau}(|\vec{q}|))}{\pi G_F (|\vec{q}|^2 + M_{Z'}^2}$$

See also *M. Demirci et al.*, Phys. Rev. D 111 (2025) 055032

Conclusions and outlooks

- **Direct detection dark matter experiments** provide a powerful tool to probe low-energy neutrino interactions with nuclei and atomic electrons

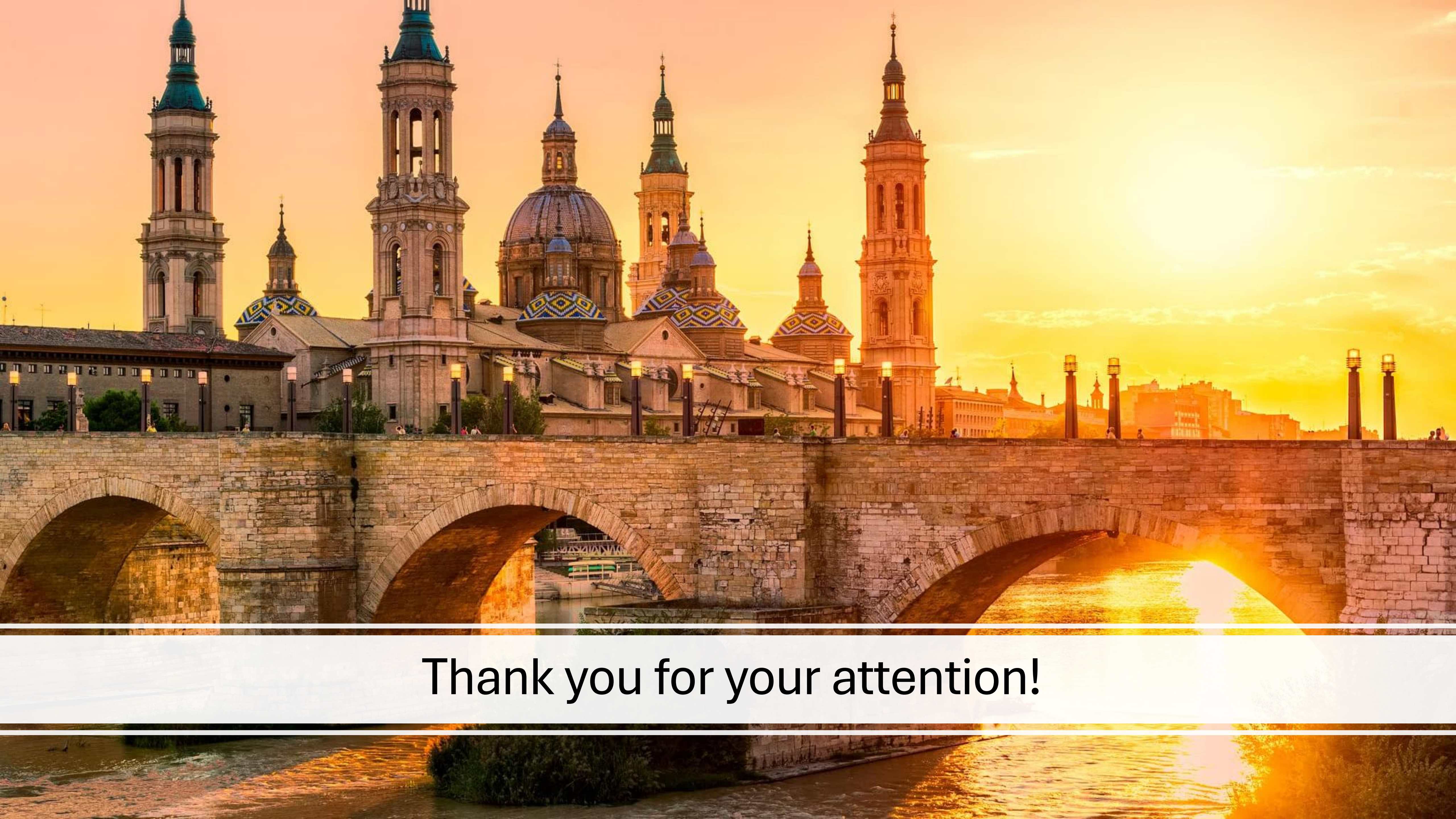
- **CEνNS** and **νES** data enable tests of SM and the exploration of BSM scenarios

- Main results: upper limit on **hep flux**, lowest energy determination of **weak mixing angle**,
  strongest laboratory constraints on **electromagnetic properties**

What's next?

- The current analysis could be revisited with **upcoming dark matter data**
  ↳ **CEνNS data** from **Lux-Zeplin** and from **XENONnT's SR2 data** (**see G. Volta's talk**)

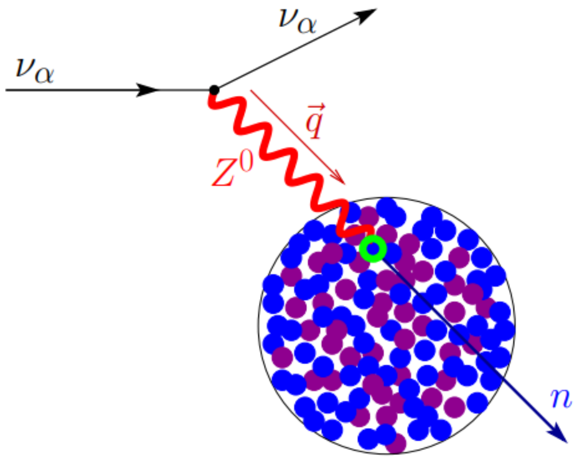
- Including **inelastic channels** for a more comprehensive picture
  ↳ **First evidence of neutrino absorption** on argon with solar neutrinos by **DEAP-3600** Collaboration (**see G. Vera Díaz's talk**)



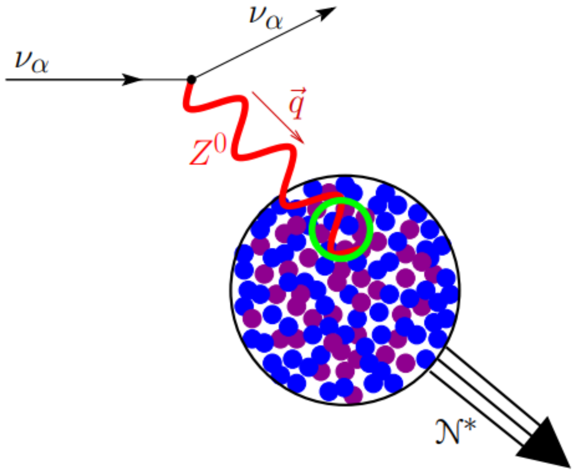
Thank you for your attention!

Neutrino interactions with nuclei at low energies

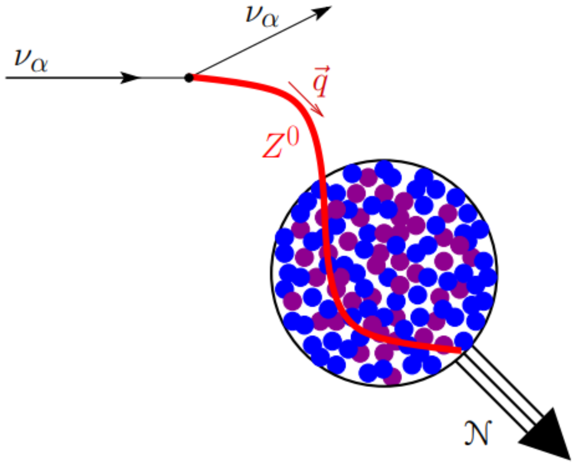
The spatial scale that can be probed is determined by the de Broglie wavelength of the mediator $\lambda_{Z^0} = \frac{h}{|\vec{q}|}$



Inelastic incoherent
$\lambda_{Z^0} \ll 2R$



Elastic incoherent
$\lambda_{Z^0} \lesssim 2R$



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

EPL 143 34001

Form factors

The proton and neutron **form factors** account for the **spatial distribution** of **protons** and **neutrons** inside the nucleus

$$F_Z^{\mathrm{SF}}(q^2) = \frac{3}{qc\left[(qc)^2 + (\pi qa)^2\right]}\left[\frac{\pi qa}{\sinh(\pi qa)}\right]\left[\frac{\pi qa\sin(qc)}{\tanh(\pi qa)} - qc\cos(qc)\right]$$

Symmetrized Fermi parameterization

$\boldsymbol{c}$: half density radius, $\boldsymbol{a}$: diffuseness parameter, $\boldsymbol{t}$: thickness [$t = 4aln(3)$)]

t defines the distance between points where the proton density drops from 90% to 10% of the plateau value

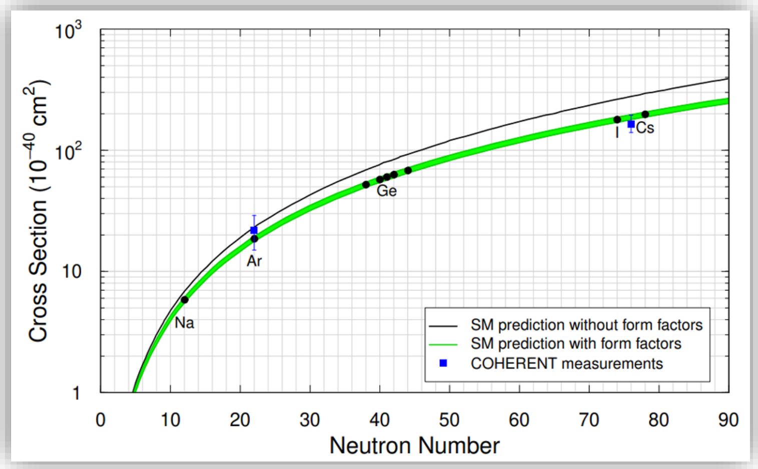
$$F^{\mathrm{Helm}}\left(|\vec{q}|^2\right) = 3\frac{j_1(qR_0)}{qR_0}e^{-|\vec{q}|^2 s^2/2}$$

Helm parameterization

$\boldsymbol{j_1}$: first-order spherical Bessel functions

$\boldsymbol{s}$: surface thickness

$\boldsymbol{R_0}$: box (or diffraction) radius

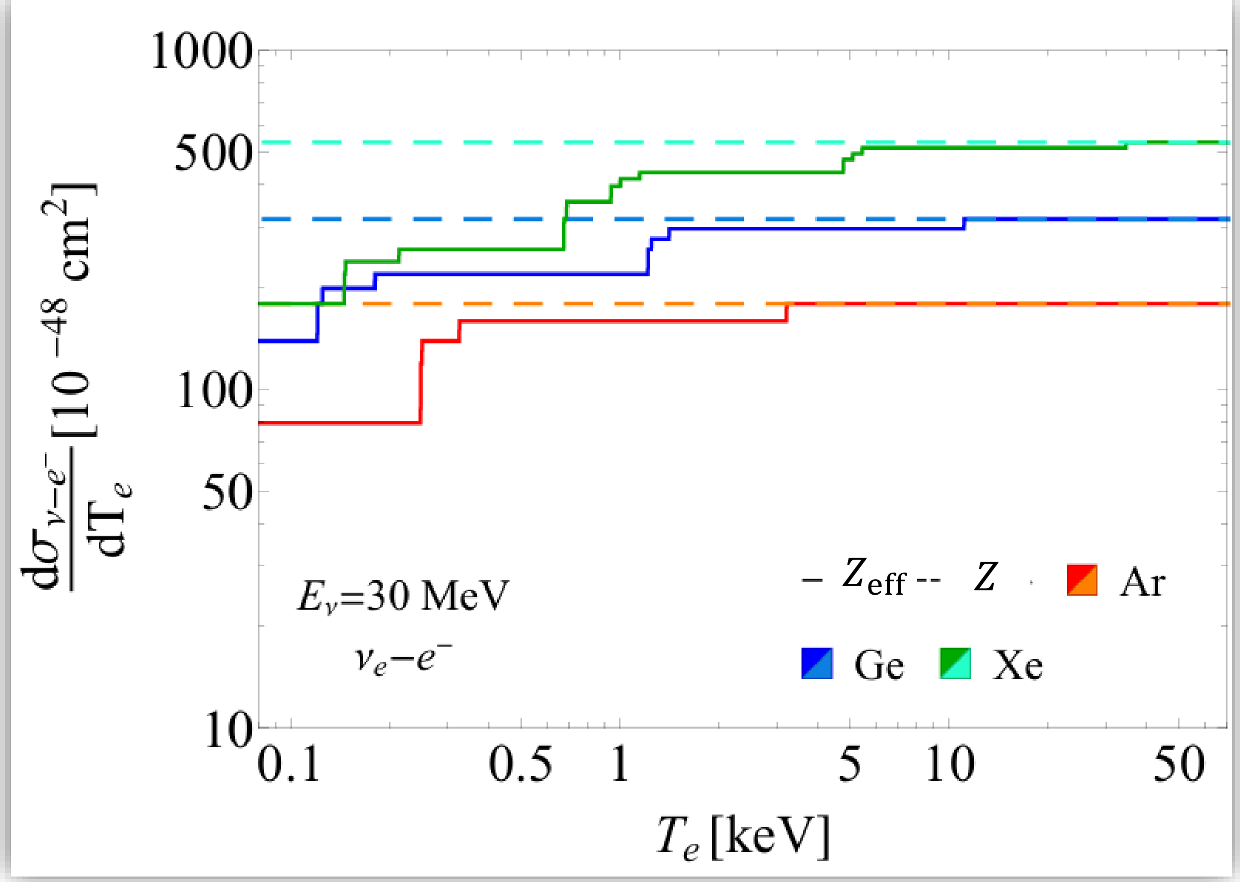


EPL 143 34001

Effective electron charge Z_{eff}

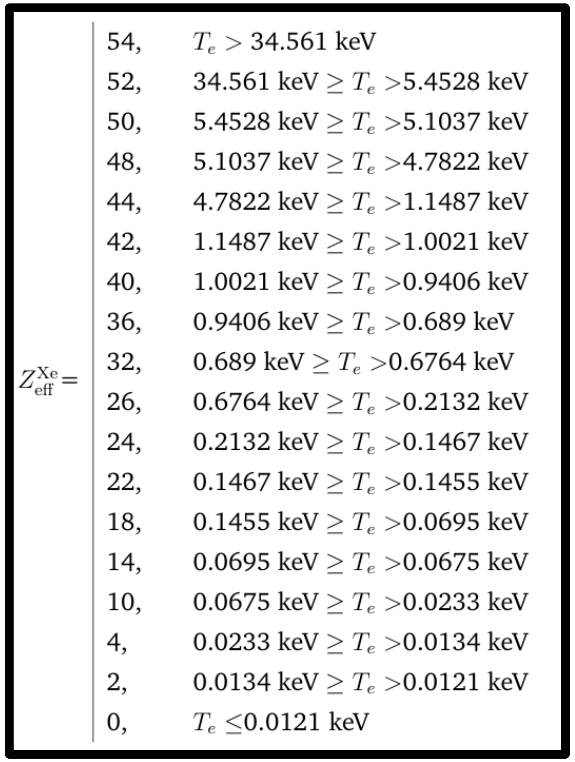
Z_{eff} is obtained by using the **binding energies** of the atomic shells, extracted from photo-absorption data

Atomic Data and Nuclear Data Tables 54.2 (1993), p. 181



Stronger effect for heavier atoms!

$Z_{\text{eff}}^{\text{Xe}}$



$$Z_{\text{eff}}^{\text{Xe}} = \begin{cases} 54, & T_e > 34.561\ \text{keV} \\ 52, & 34.561\ \text{keV} \geq T_e > 5.4528\ \text{keV} \\ 50, & 5.4528\ \text{keV} \geq T_e > 5.1037\ \text{keV} \\ 48, & 5.1037\ \text{keV} \geq T_e > 4.7822\ \text{keV} \\ 44, & 4.7822\ \text{keV} \geq T_e > 1.1487\ \text{keV} \\ 42, & 1.1487\ \text{keV} \geq T_e > 1.0021\ \text{keV} \\ 40, & 1.0021\ \text{keV} \geq T_e > 0.9406\ \text{keV} \\ 36, & 0.9406\ \text{keV} \geq T_e > 0.689\ \text{keV} \\ 32, & 0.689\ \text{keV} \geq T_e > 0.6764\ \text{keV} \\ 26, & 0.6764\ \text{keV} \geq T_e > 0.2132\ \text{keV} \\ 24, & 0.2132\ \text{keV} \geq T_e > 0.1467\ \text{keV} \\ 22, & 0.1467\ \text{keV} \geq T_e > 0.1455\ \text{keV} \\ 18, & 0.1455\ \text{keV} \geq T_e > 0.0695\ \text{keV} \\ 14, & 0.0695\ \text{keV} \geq T_e > 0.0675\ \text{keV} \\ 10, & 0.0675\ \text{keV} \geq T_e > 0.0233\ \text{keV} \\ 4, & 0.0233\ \text{keV} \geq T_e > 0.0134\ \text{keV} \\ 2, & 0.0134\ \text{keV} \geq T_e > 0.0121\ \text{keV} \\ 0, & T_e \leq 0.0121\ \text{keV} \end{cases}$$

Nicola Cargioli, PhD Thesis

Neutrino charge radius

- In the SM neutrinos are neutral and there are no electromagnetic **interactions at tree-level**

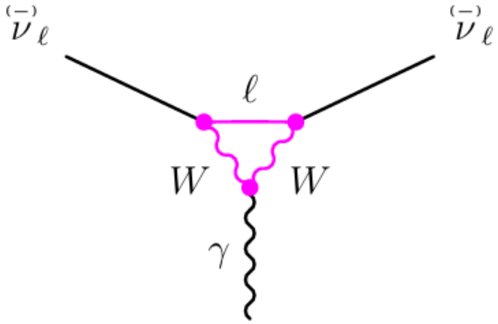
- A neutral particle can be seen as a **superposition** of two **charge distributions** of opposite signs:

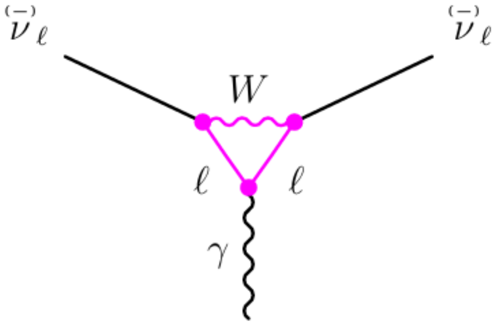
Neutrino charge radius

$$\mathbb{f}_Q(q^2) = \cancel{\mathbb{f}_Q(0)} + q^2 \frac{d\mathbb{f}_Q(q^2)}{dq^2}\bigg|_{q^2=0} + \ldots \quad \longrightarrow \quad \boxed{\langle r^2 \rangle = 6 \frac{d\mathbb{f}_Q(q^2)}{dq^2}\bigg|_{q^2=0}}$$

In the SM:

$$\boxed{\langle r^2_{\nu_\ell} \rangle_{\text{SM}} = -\frac{G_{\text{F}}}{2\sqrt{2}\pi^2}\left[3 - 2\ln\left(\frac{m_\ell^2}{m_W^2}\right)\right]}$$





$$\langle r^2_{\nu_e} \rangle \simeq -8.3 \times 10^{-33}\,\text{cm}^2\,,$$
$$\langle r^2_{\nu_\mu} \rangle \simeq -4.8 \times 10^{-33}\,\text{cm}^2\,,$$
$$\langle r^2_{\nu_\tau} \rangle \simeq -3.0 \times 10^{-33}\,\text{cm}^2\,.$$

τ neutrino charge radius

Marginal $\Delta\chi^2$ for the τ neutrino charge radius from each solar neutrino dataset:

$$
\begin{aligned}
&-83 \leq \langle r^2_{\nu_\tau} \rangle\,(\mathrm{XnT-ER}) \leq 88\,, \qquad -95 \leq \langle r^2_{\nu_\tau} \rangle\,(\mathrm{XnT-NR}) \leq 35\,,\\
&-94 \leq \langle r^2_{\nu_\tau} \rangle\,(\mathrm{P4T-ER}) \leq 99\,, \qquad -105 \leq \langle r^2_{\nu_\tau} \rangle\,(\mathrm{P4T-NR}) \leq 46\,,\\
&-96 \leq \langle r^2_{\nu_\tau} \rangle\,(\mathrm{LZ-ER}) \leq 100\,.
\end{aligned}
$$

90% CL

We consider **constraints** on the muon and electron **neutrino charge radii** from a global fit of neutrino data to **strenghthen the precision** on the τ flavor:

$$\langle r^2_{\nu_e} \rangle\,(\text{Global Fit}) = 2.2^{+2.4}_{-2.3} \times 10^{-32}\,\mathrm{cm}^2\,, \quad \langle r^2_{\nu_\mu} \rangle\,(\text{Global Fit}) = -0.19^{+0.55}_{-0.56} \times 10^{-32}\,\mathrm{cm}^2$$

M. Atzori Corona et al., Phys. Rev. Lett. 135, 231803

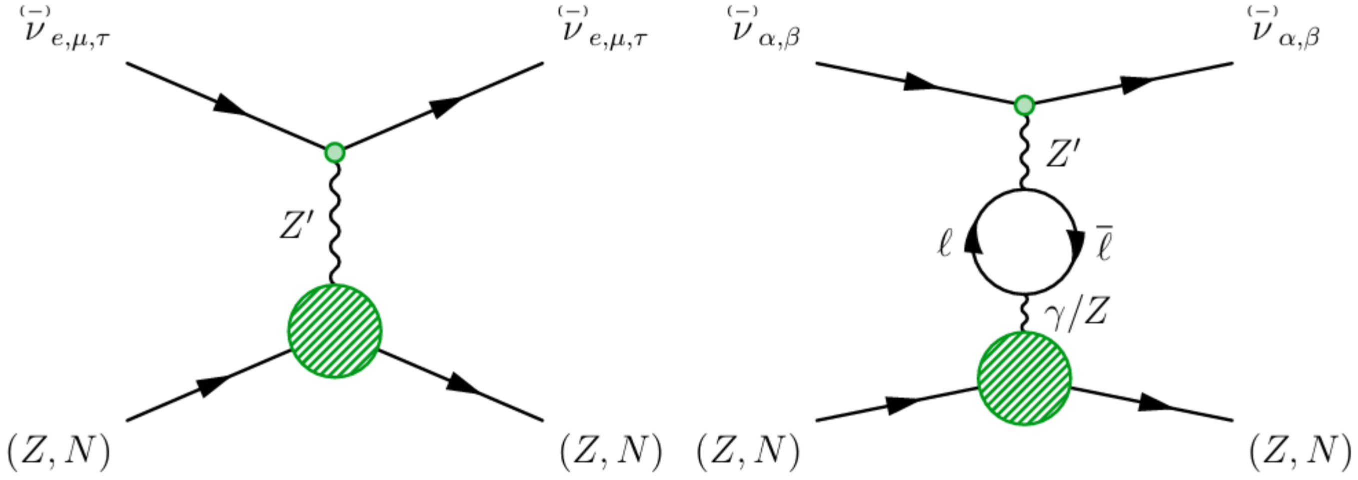
$$\boxed{\langle r^2_{\nu_\tau} \rangle\,(\text{Global Fit}) = 7.5^{+9.5}_{-11.7} \times 10^{-32}\,\mathrm{cm}^2}$$

1σ CL

Light vector mediators

Extended SM gauge group: $SU(3)_C \times SU(2)_L \times U(1)_Y \longrightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$

Diagrams contributing to CEνNS



Tree-level

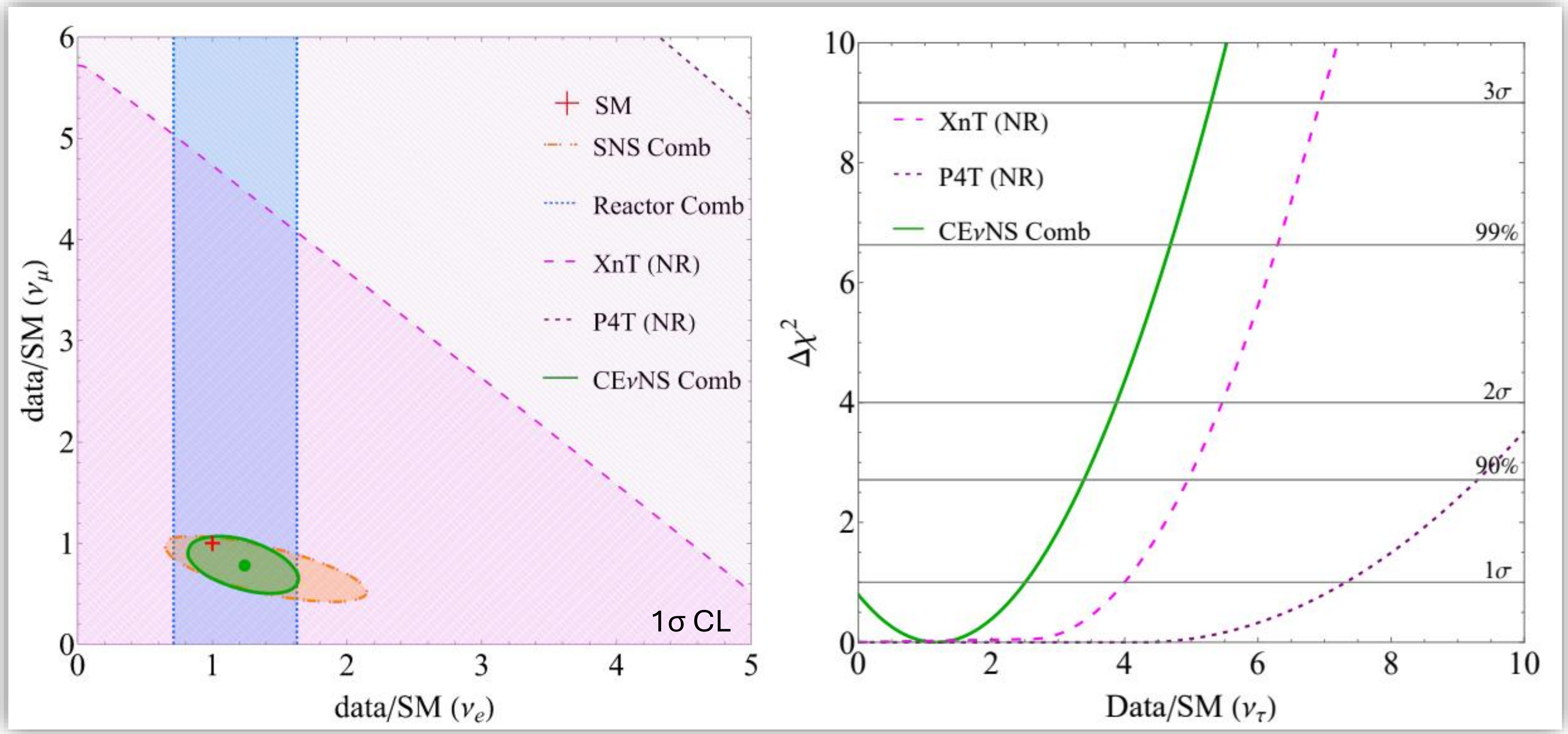
One-loop level

	Model	Q'_u	Q'_d	Q'_e	Q'_μ	Q'_τ
	universal	1	1	1	1	1
Tree-level	$B-L$	$1/3$	$1/3$	-1	-1	-1
	$B-3L_e$	$1/3$	$1/3$	-3	0	0
	$B-3L_\mu$	$1/3$	$1/3$	0	-3	0
	$B-2L_e-L_\mu$	$1/3$	$1/3$	-2	-1	0
	$B-L_e-2L_\mu$	$1/3$	$1/3$	-1	-2	0
	$B_y+L_\mu+L_\tau$	$1/3$	$1/3$	0	1	1
One-loop level	L_e-L_μ	0	0	1	-1	0
	L_e-L_τ	0	0	1	0	-1
	$L_\mu-L_\tau$	0	0	0	1	-1

Nicola Cargioli, PhD Thesis

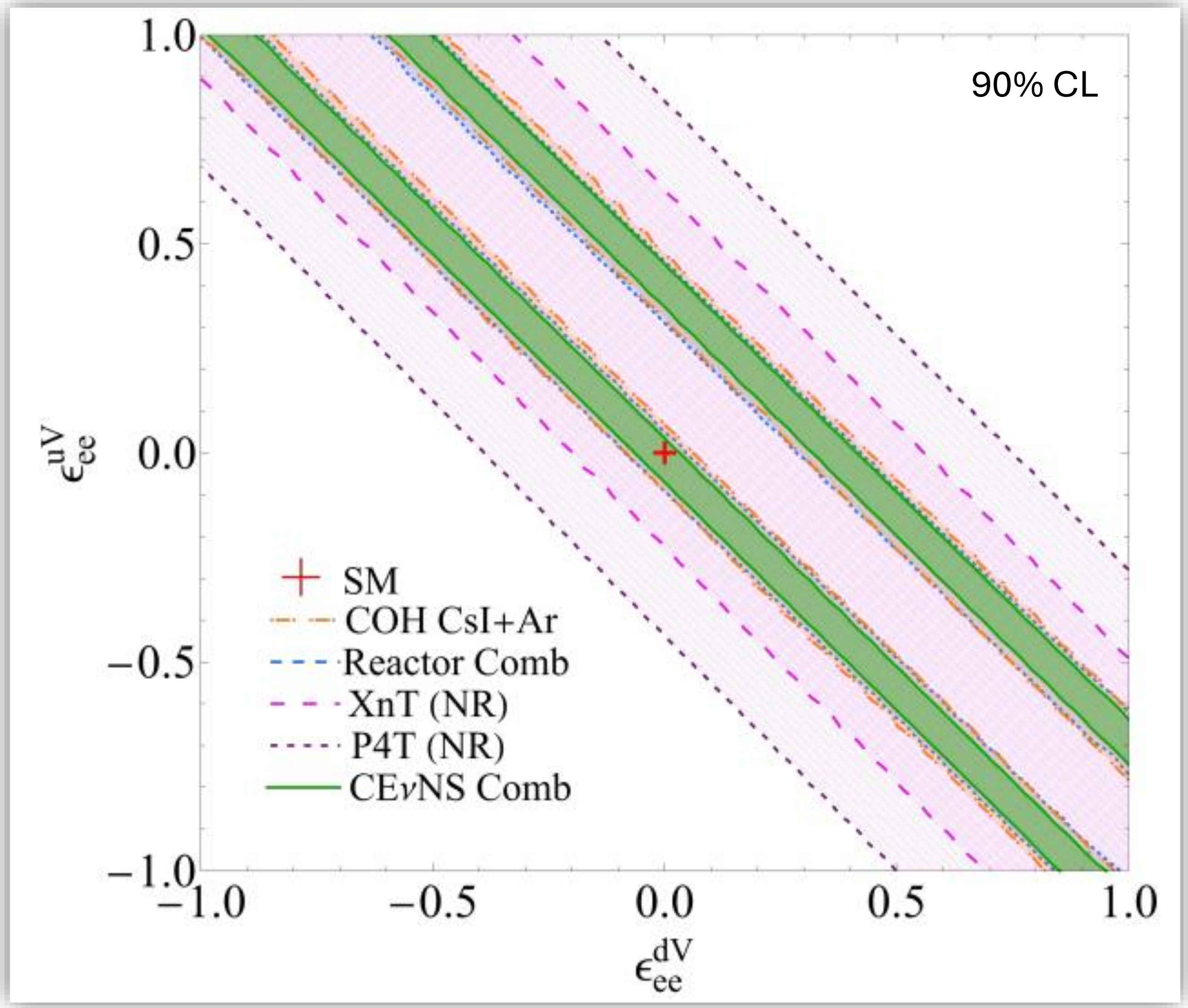
Other results: Standard Model tests

Consistency between the available CEνNS data and theoretical predictions



$\boxed{\text{Data/SM } (\nu_\tau) < 2.5 \text{ at } 1\sigma \text{ CL}}$

Other results: non-standard neutrino interactions (NSI)



A heavy mediator modifies the **neutrino-quark coupling** by an energy independent contribution:

Modified weak charge of the nucleus

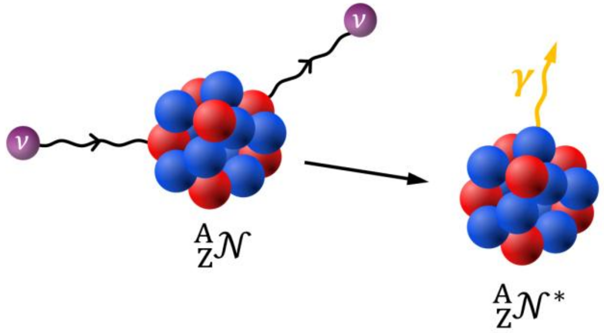
$$Q^V_{\ell,\mathrm{NSI}} = \left(g_V^p(\nu_\ell) + \boxed{2\varepsilon_{\ell\ell}^{uV} + \varepsilon_{\ell\ell}^{dV}}\right) Z F_Z(|\vec{q}|^2) + \left(g_V^n + \boxed{\varepsilon_{\ell\ell}^{uV} + 2\varepsilon_{\ell\ell}^{dV}}\right) N F_N(|\vec{q}|^2)$$

- Simplified scenario with only two nonzero NSI parameters, only involving the **electronic** neutrino **flavor**
- **vES** cross section is **not affected**

Inelastic interactions with nuclei

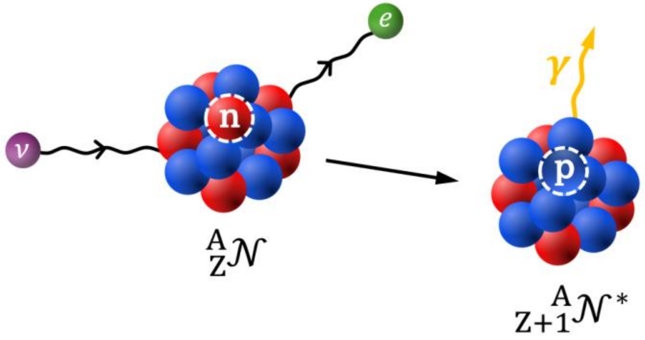
Neutral Current (NC)

$$\boxed{\nu_e + {}^{A}_{Z}\mathcal{N} \longrightarrow \nu_e + {}^{A}_{Z}\mathcal{N}^*}$$



Charged Current (CC)

$$\boxed{\nu_e + {}^{A}_{Z}\mathcal{N} \longrightarrow e^- + {}^{\;A}_{Z+1}\mathcal{N}^*}$$



Inelastic interactions are subdominant with respect to CEνNS, but…

- Can constitute a **background** for neutrinos and dark matter experiments
- Are useful to detect **solar** and **supernovae** neutrinos
- Can provide a better understanding of the **nuclear structure**

Data analysis

Poissonian least-squares function:

$$\chi^2_{\mathrm{ER}} = 2\sum_i \left[(1+\alpha)N_i^{\mathrm{bkg}} + (1+\beta)N_i^{\nu\mathrm{ES}} - N_i^{\mathrm{exp}} + N_i^{\mathrm{exp}} \ln\left(\frac{N_i^{\mathrm{exp}}}{(1+\alpha)N_i^{\mathrm{bkg}} + (1+\beta)N_i^{\nu\mathrm{ES}}}\right)\right] + \left(\frac{\alpha}{\sigma_\alpha}\right)^2 + \left(\frac{\beta}{\sigma_\beta}\right)^2, \tag{2.8}$$

Gaussian least-squares function:

$$\chi^2_{\mathrm{NR}} = \sum_i \left(\frac{N_i^{\mathrm{exp}} - (1+\eta)N_i^{\mathrm{CE}\nu\mathrm{NS}} - \sum_j (1+\rho_j)N_i^{\mathrm{bkgj}}}{\sigma_{\mathrm{exp}}}\right)^2 + \left(\frac{\eta}{\sigma_\eta}\right)^2 + \sum_j \left(\frac{\rho_j}{\sigma_{\rho_j}}\right)^2$$

Gaussian least-squares function used for US2+paired data from P4T(NR):

$$\chi^2_{\mathrm{US2+paired}} = \left(\frac{N_{\mathrm{US2}}^{\mathrm{exp}} - (1+\eta)N_{\mathrm{US2}}^{\mathrm{CE}\nu\mathrm{NS}}}{\sigma_{\mathrm{exp}}^{\mathrm{US2}}}\right)^2 + \left(\frac{N_{\mathrm{paired}}^{\mathrm{exp}} - (1+\eta)N_{\mathrm{paired}}^{\mathrm{CE}\nu\mathrm{NS}}}{\sigma_{\mathrm{exp}}^{\mathrm{paired}}}\right)^2 + \left(\frac{\eta}{\sigma_\eta}\right)^2$$