SEARCHING FOR NEUTRINO ELECTROMAGNETIC SIGNATURES WITH CEVNS AND DARK MATTER DETECTORS DATA

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Neutrino Properties Session

Results in collaboration with:
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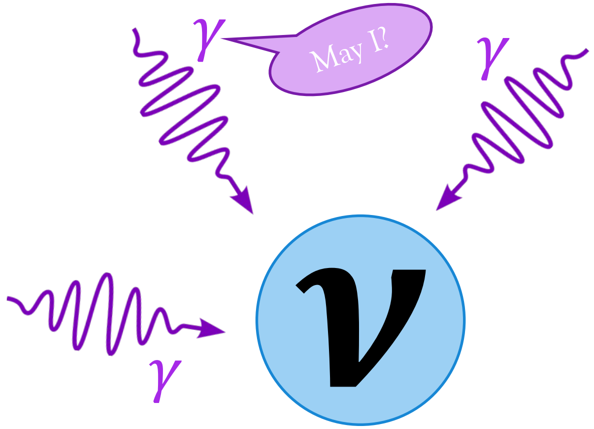
ELECTROMAGNETIC PROPERTIES

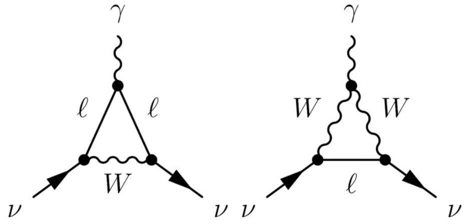
Neutrino electromagnetic properties: any property of the neutrino which makes it interact with a photon (electromagnetic interactions)



DISCLAMER: neutrinos are neutral particles in the SM:
no interaction with the photon

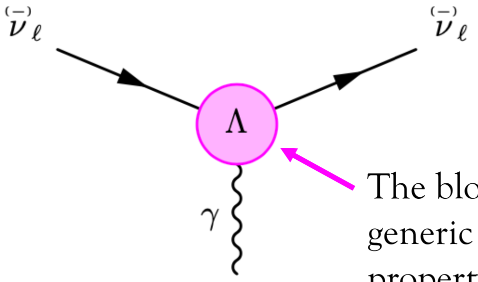
→ Can the neutrino have electromagnetic properties in the SM?
What about BSM theories?

- The neutrino charge radius (NCR):
  - The only electromagnetic neutrino property predicted by the SM
  - Flavor dependent
  - Treated as a radiative correction (but actually a gauge invariant quantity)



- The neutrino magnetic moment (MM)
- The neutrino electric charge (EC)

Beyond the Standard Model



The blob indicates a generic electromagnetic property, which generates the interaction

NEUTRINO MAGNETIC MOMENT

The **neutrino magnetic moment** (MM):

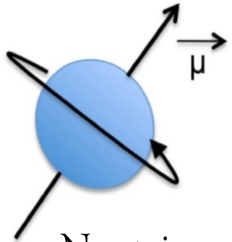
- In the minimal extension of SM in which neutrinos acquire Dirac masses through the introduction of right-handed neutrinos, they acquire a MM

https://neutrinos.fnal.gov/mysteries/mass/

C. Giunti and A. Studenikin
Rev.Mod.Phys. 87 (2015) 531

$$\mu_\nu = \frac{3\,e\,G_F}{8\sqrt{2}\pi^2} m_\nu \simeq 3.2 * 10^{-19} \left(\frac{m_\nu}{eV}\right) \mu_B$$

Considering $m_\nu \sim 1$ eV $\rightarrow \mu_\nu \simeq 10^{-19} \mu_B$
But in many models, "large" values of the MM are allowed



The magnetic moment interaction adds incoherently to the weak interaction because it flips helicity

Neutrinos are a mixture of mass eigenstates due to the phenomenon of oscillations; we can define an effective neutrino MM

C. Giunti and A. Studenikin
Rev.Mod.Phys. 87 (2015) 531

$$\mu_\nu^{2,\,\mathrm{eff}} = \sum_j \left| \sum_k \mu_{jk} A_k(E,L) \right|^2$$

where μ_{jk} is an element of the neutrino MM matrix and $A_k(E,L)$ is the amplitude of the k-mass state at the point of scattering

j=k, diagonal contribution: flavor conserving MMs

j≠k, off-diagonal contribution: transition (or flavor changing) MMs

For a Majorana neutrino, only the transition moments are nonzero (diagonal set to zero due to CPT conservation)

For the Dirac neutrino, all elements are potentially nonzero

Neutrino electric charge

The neutrino electric charge (EC):

- Similar to the MM structure
- Neutrinos could have a tiny electric charge
- Neutrality of matter: $q_\nu \lesssim 10^{-21} e_0$

C. Giunti and A. Studenikin
Rev.Mod.Phys. 87 (2015) 531

- The EC contribution is accounted as a modification of the SM couplings
- The coupling with neutrons in the case of CEvNS is not modified (no coupling with the photon)
- The correction depends on the momentum transfer

Neutrino interacting with electrons (**vES**) $g_V^{\nu_\ell e} \sim -\frac{1}{2} + 2\sin^2\theta_W + \frac{2\sqrt{2}\pi\alpha}{G_F q^2} q_{\nu_{\ell\ell}}$

Neutrino interacting with nuclei (**CEvNS**) $g_V^{\nu_\ell p} \sim \frac{1}{2} - 2\sin^2\theta_W - \frac{2\sqrt{2}\pi\alpha}{G_F q^2} q_{\nu_{\ell\ell}}$

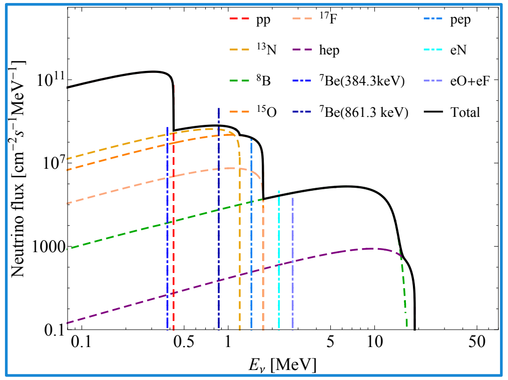
Similarly to the case of MM, one can think of a flavor structure behind the EC contribution:

$q_{\nu_{\ell\ell}}$: diagonal contribution: flavor conserving ECs

$q_{\nu_{\ell\ell'}}$: off-diagonal contribution: transition (or flavor changing) ECs

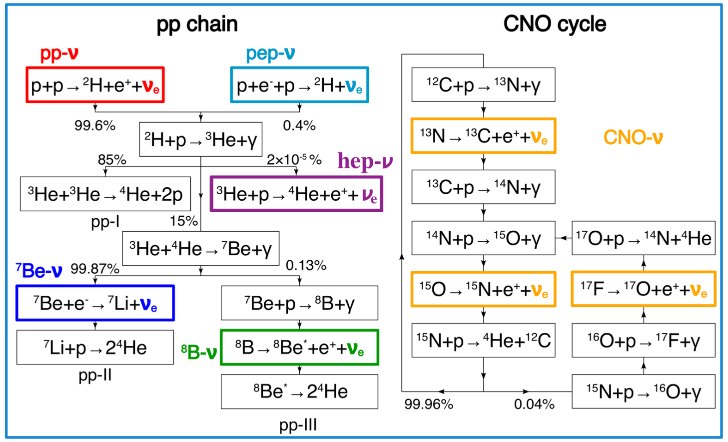
The transition ECs do not contribute as a shift to the coupling: incoherent contribution

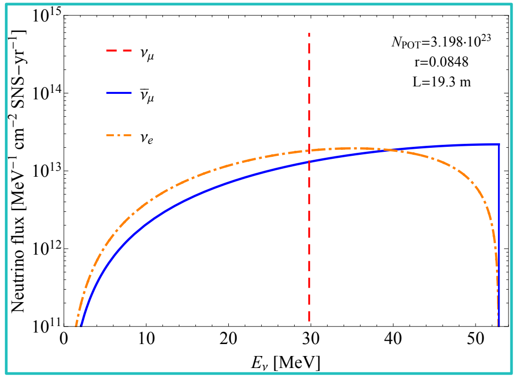
NEUTRINO SOURCES

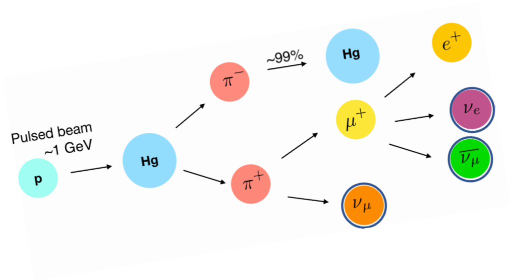


Solar Neutrinos

- High neutrino flux
- Various contributions with different end-point energies
- Neutrino oscillations

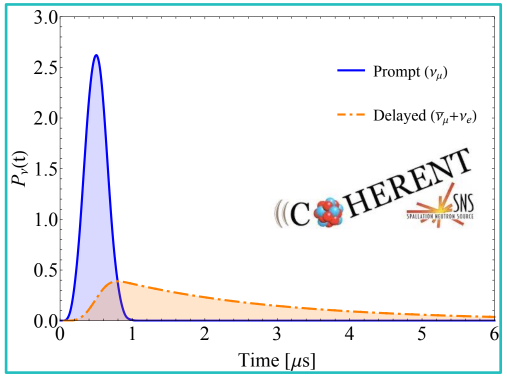


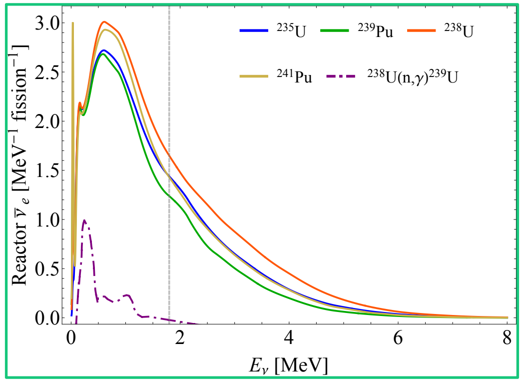




π-DAR

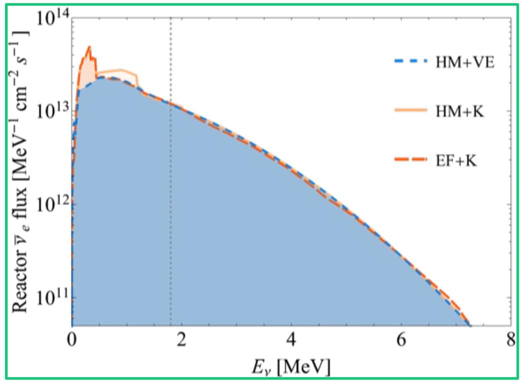
- Peaked around 30 MeV
- Maximum energy of ∼50 MeV
- $\tau_{\pi^+} = 26.033$ ns and $\tau_{\mu^+} = 2.197$ μs
- Both time and spectral information





Reactor Neutrinos

- Peaked around 1 MeV
- Only $\bar{\nu}_e$ neutrinos
- Different parametrizations



NEUTRINO INTERACTIONS

CEνNS: coherent elastic interaction of the neutrino with the nucleus via a purely NC process

Neutrino energy

Mass of the nucleus

SM vector proton coupling

$g_V^p(\nu_e) = 0.0382$
$g_V^p(\nu_\mu) = 0.0300$
$g_V^n = -0.5117$

SM vector neutron coupling

$$\frac{d\sigma_{\nu_\ell-\mathcal{N}}(E_\nu, T_{nr})}{dT_{nr}} \cong \frac{G_F^2\, m_N}{\pi}\left(1 - \frac{m_N T_{nr}}{2E_\nu^2}\right)\Big[\underbrace{g_V^p(\sin^2(\vartheta_W))Z\, F_Z(|\vec{q}|^2) + g_V^n\, N\, F_N(|\vec{q}|^2)}_{}\Big]^2$$

Nuclear weak charge Q_W

Nuclear recoil energy

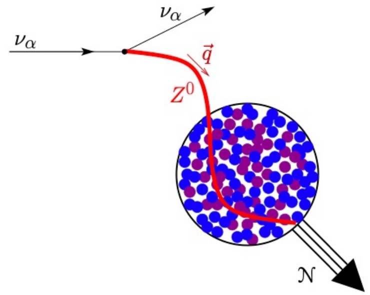
Weinberg angle

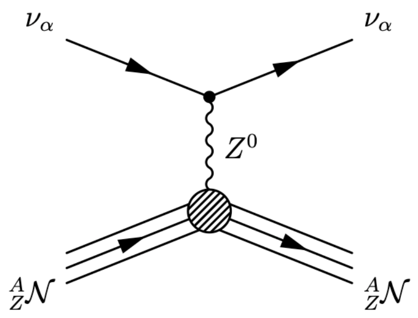
Proton Form Factor

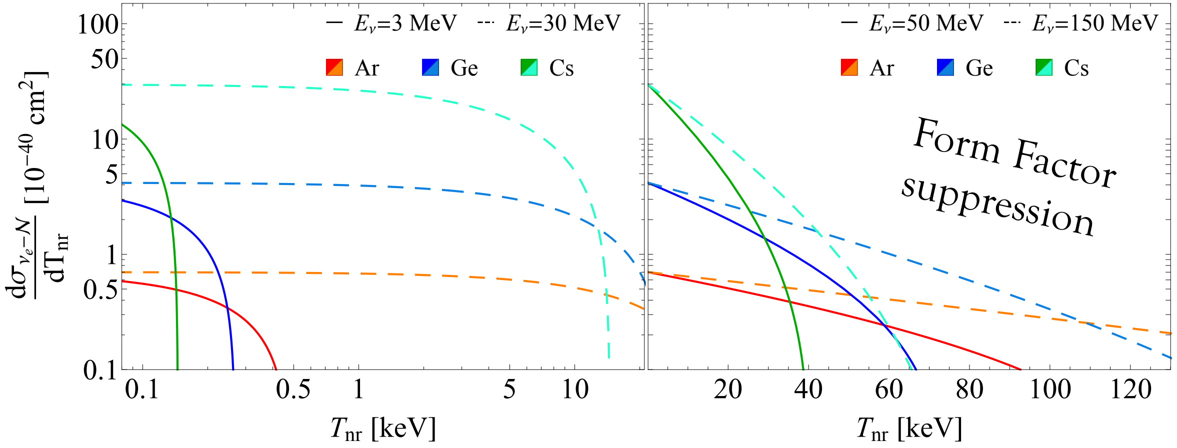
Neutron Form Factor

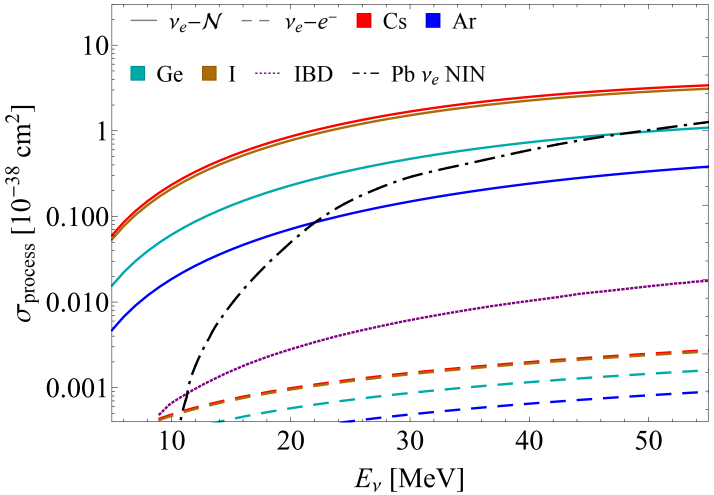
Elastic Coherent

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







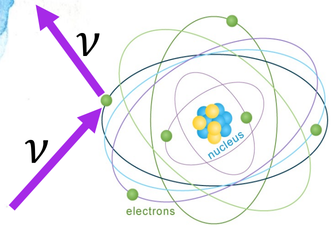


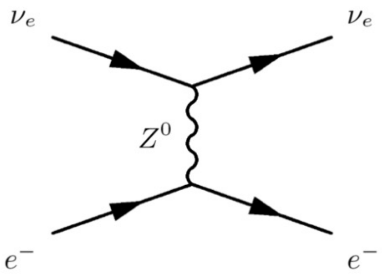
Large Cross section compared to other low energy neutrino processes

$\propto N^2$

NEUTRINO INTERACTIONS

νES: elastic scattering of neutrinos off atomic electrons





Electron mass

SM vector coupling

$g_V^{\nu_e e} = 0.9521$

$g_V^{\nu_\mu e} = -0.0397$

$$\frac{d\sigma^{\text{free}}_{\nu_\ell e}(E_\nu, T_e)}{dT_e} \cong \frac{G_F^2\, m_e}{2\pi}\left[\left(g_V^{\nu_\ell} + g_A^{\nu_\ell}\right)^2 + \left(g_V^{\nu_\ell} - g_A^{\nu_\ell}\right)^2\left(1 - \frac{T_e}{E_\nu}\right)^2 - \left(\left(g_V^{\nu_\ell}\right)^2 - \left(g_A^{\nu_\ell}\right)^2\right)\frac{m_e T_e}{E_\nu^2}\right]$$

Electron recoil energy

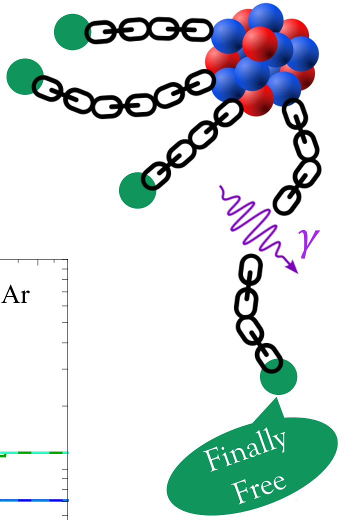
SM axial coupling

$g_A^{\nu_e e} = 0.4938$

$g_A^{\nu_\mu e} = -0.5062$

For free electrons $\longrightarrow$ multiplying for the atomic number Z

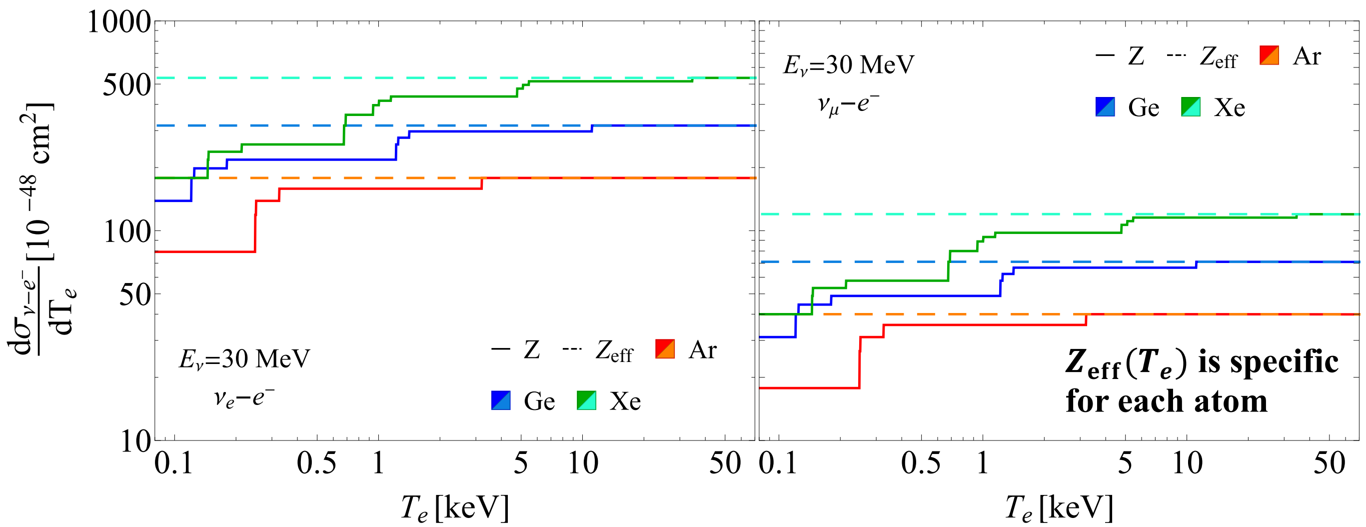
For bound electrons $\longrightarrow$?



Easiest approach: Free Electron Approximation (**FEA**) modified via a stepping function $Z_{\text{eff}}(T_e)$

This accounts for the effective number of electrons that can be ionized by a certain energy deposit T_e

$$\frac{d\sigma^{\text{FEA}}_{\nu_\ell e}}{dT_e}(E, T_e) = Z_{\text{eff}}(T_e)\frac{d\sigma^{\text{free}}_{\nu_\ell e}}{dT_e}(E, T_e)$$



MM AND EC IN CEVNS AND VES

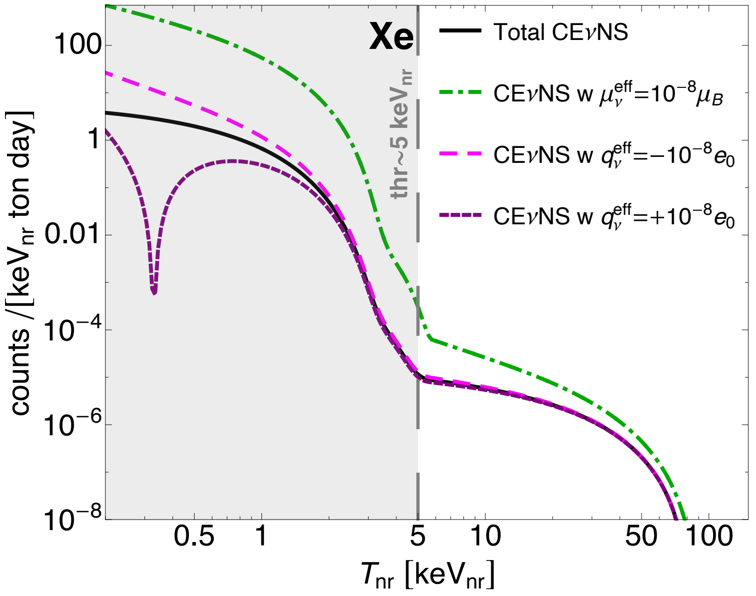
MM contribution to CEvNS cross section

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

MM contribution to vES cross section

$$\frac{d\sigma^{MM}_{\nu_\ell e}(E_\nu, T_e)}{dT_e} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)\left|\frac{\mu_{\nu_\ell}}{\mu_B}\right|^2$$

MM cross section $\propto$ **1/T**: "Explodes" for T→ **0**



EC contribution to CEvNS cross section

$$\frac{d\sigma^{EC}_{\nu_\ell-\mathcal{N}}(E_\nu, T_{nr})}{dT_{nr}} = \frac{G_F^2 m_N}{\pi}\left(1 - \frac{m_N T_{nr}}{2E_\nu^2}\right)\left\{\left[(g_V^p - Q_{\ell\ell})Z F_Z(|\vec{q}|^2) + g_V^n N F_N(|\vec{q}|^2)\right]^2 + Z^2 F_Z^2(|\vec{q}|^2)\sum_{\ell'\neq\ell}|Q_{\ell\ell'}|^2\right\}$$

EC contribution to vES cross section

$$\frac{d\sigma^{EC}_{\nu_\ell e}(E_\nu, T_e)}{dT_e} \cong Z_{eff}(T_e)\frac{G_F^2 m_e}{2\pi}\left[\left((g_V^{\nu_\ell}+Q_{\ell\ell}) + g_A^{\nu_\ell}\right)^2 + \left((g_V^{\nu_\ell}+Q_{\ell\ell}) - g_A^{\nu_\ell}\right)^2\left(1-\frac{T_e}{E_\nu}\right)^2 - \left((g_V^{\nu_\ell}+Q_{\ell\ell})^2 - (g_A^{\nu_\ell})^2\right)\frac{m_e T_e}{E_\nu^2}\right] +$$
$$+ Z_{eff}(T_e)\frac{\pi\alpha^2}{m_e T_e^2}\left[1 + \left(1-\frac{T_e}{E_\nu}\right)^2 - \frac{m_e T_e}{E_\nu}\right]\left|q_{\nu_{\ell\ell'}}\right|^2$$

where $Q_{\ell\ell'} = \frac{2\sqrt{2}\pi\alpha}{G_F q^2} q_{\nu_{\ell\ell'}}$

EC contribution $\propto$ **1/q²**: "Explodes" for small recoils ($q^2 \simeq 2mT$)

For the EC diagonal terms, the sign of the charge matters

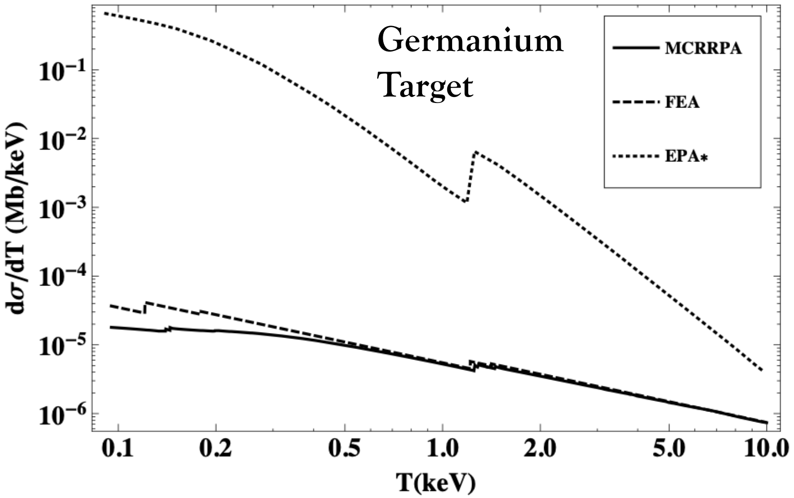
FEA VS EPA

RRPA: Relativistic Random-Phase Approximation, ab-initio approach able to improve the description of the atomic many-body effects

EPA: Equivalent Photon Approximation, relates the ionization cross section to the photo-absorption one

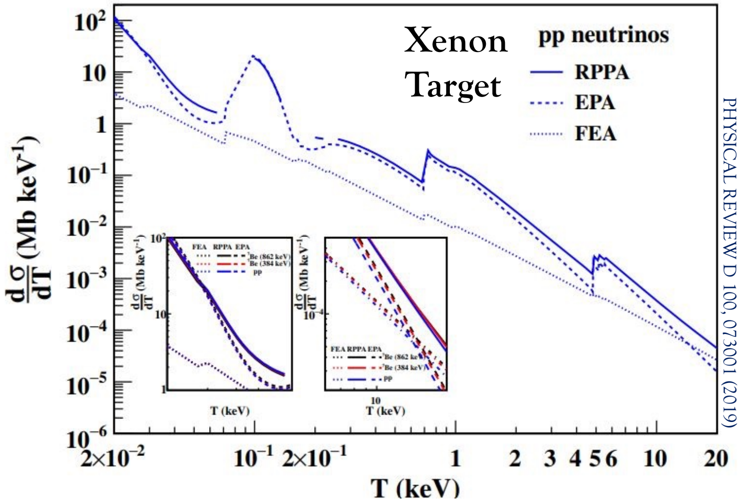
Neutrino Magnetic Moment

Phys.Rev.D 91 (2015) 1, 013005; ArXiv: 1411.0574



The FEA approach gives similar results to RRPA for the MM, while **EPA doesn't work well**

Neutrino Electric Charge



PHYSICAL REVIEW D 100, 073001 (2019)

The EPA approach gives similar results to RRPA for the EC, while **FEA doesn't work well**

- The EPA cross section depends on the neutrino mass ($m_\nu = 1\ eV$)
- **The sign doesn't matter**

$$\frac{d\sigma^{\text{EPA, EC}}_{\nu_\ell e}}{dT_e}(E, T_e) = \frac{2\alpha}{\pi}\frac{\sigma_\gamma(T_e)}{T_e}\log\left[\frac{E}{m_\nu}\right] q^2_{\nu_\ell}$$

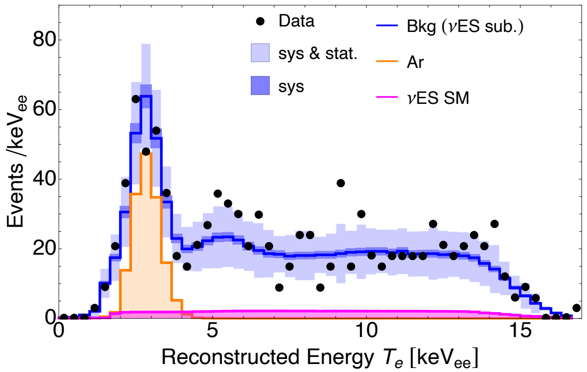
DETECTORS

Solar Neutrinos + νES

LZ dark matter detector

J. Aalbers et al., **Phys.Rev.Lett.** 131 (2023) 4,041002

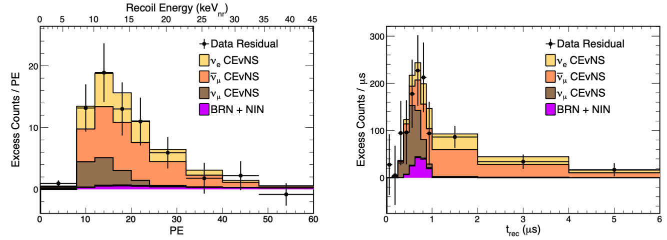
- Xenon dual-phase TPC at the Sandford Underground research facility, South Dakota
- 5.5 t fiducial volume
- Low threshold ~5 $\mathrm{keV_{nr}}$



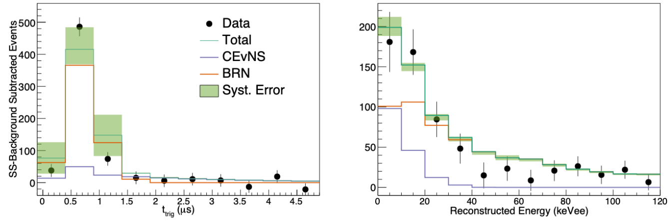
π-DAR + CEνNS (+ νES)

COHERENT experimental program

- CsI crystal: D. Akimov et al. **Phys.Rev.Lett.** 129 (2022) 8,081801
  - 14.6 kg scintillating crystal
  - 19.3 m away from the SNS target



- Ar single phase: D. Akimov et al. **Phys.Rev.Lett.** 126 (2021) 1, 012002
  - 24 kg of atmospheric argon
  - 27.5 m away from the SNS target



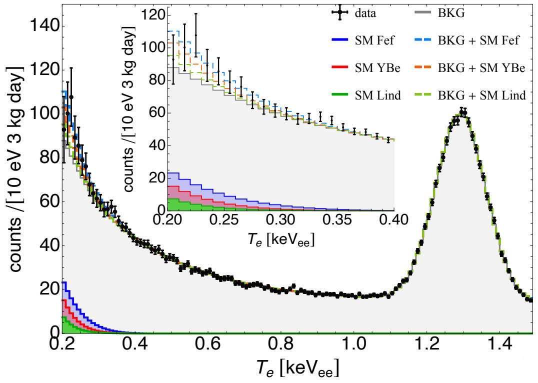
Reactor Neutrinos + CEνNS (+ νES)

NCC-1701 detector

J. Colaresi et al. **Phys.Rev.Lett.** 129 (2021) 21, 211802

- 3 kg ultra-low noise Ge crystal
- ~10 m away from the core of the Dresden-II nuclear reactor power plant, Illinois
- Quenching factor at low energy → Migdal effect?

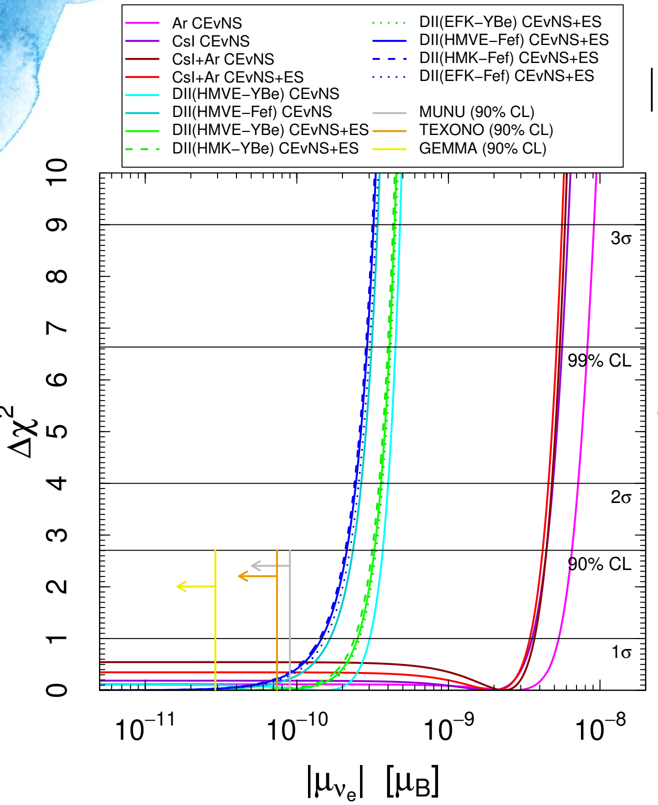
Check Arxiv:2307.12911



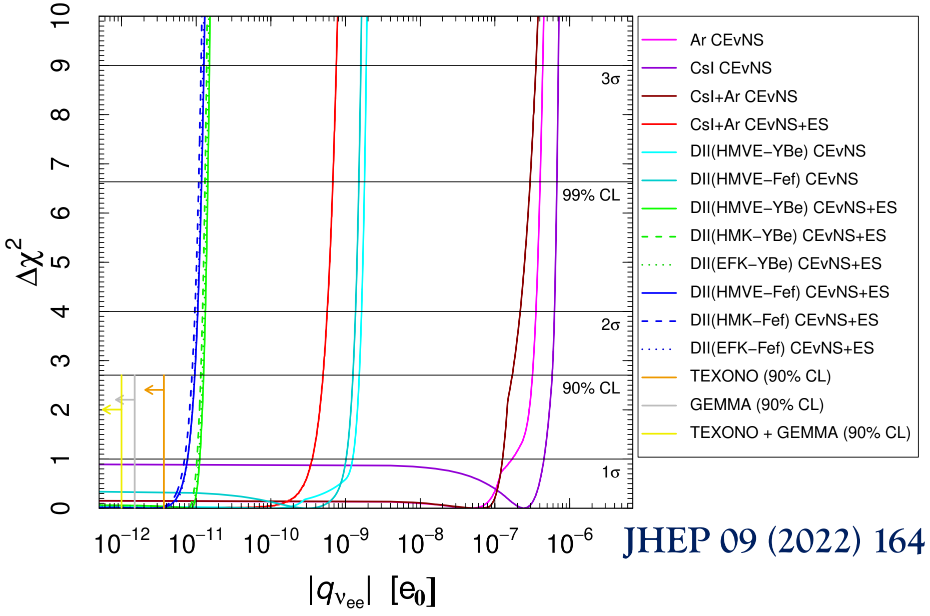
STATE OF THE ART

Results on the MM&EC from COHERENT+Dresden-II data

- Dresden-II data significantly improve the constraints
- The vES channel improves the constraints for CEvNS experiments
- COHERENT sets constraints also on the μ flavor
- Quenching factor for Dresden-II

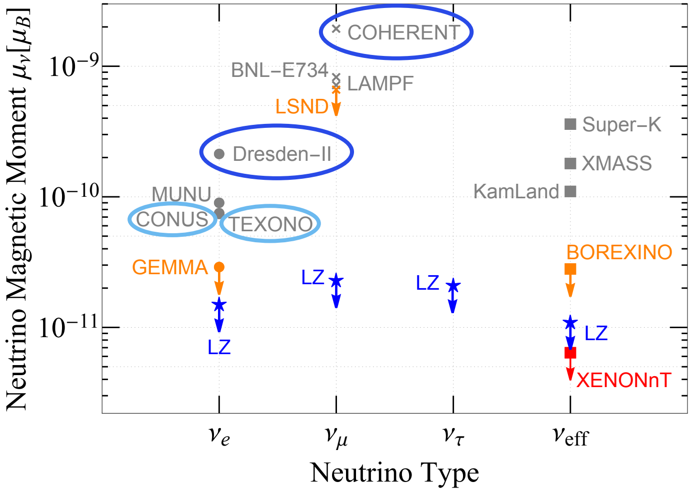


$$|\mu_{\nu_e}| < 2.13 \times 10^{-10} \mu_B \text{ Dresden-II (CEvNS+ES)}$$

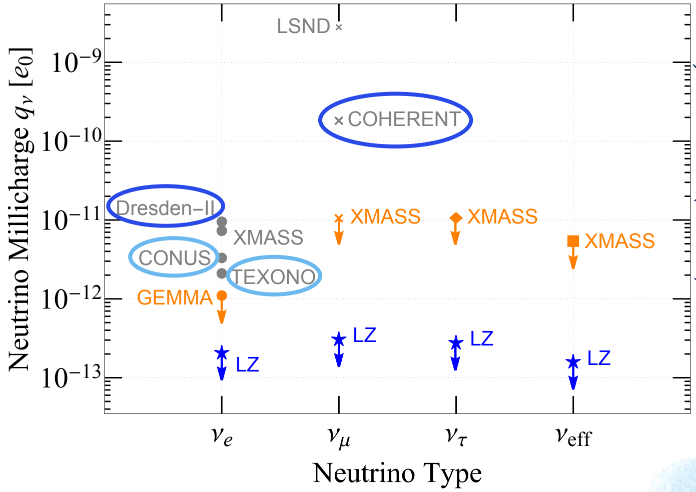


JHEP 09 (2022) 164

$$-9.3 < |q_{\nu_{ee}}| < 9.5 \times 10^{-12} e_0 \text{ Dresden-II (CEvNS+ES)+COHERENT}$$



Physical Review D 107, 053001(2023)

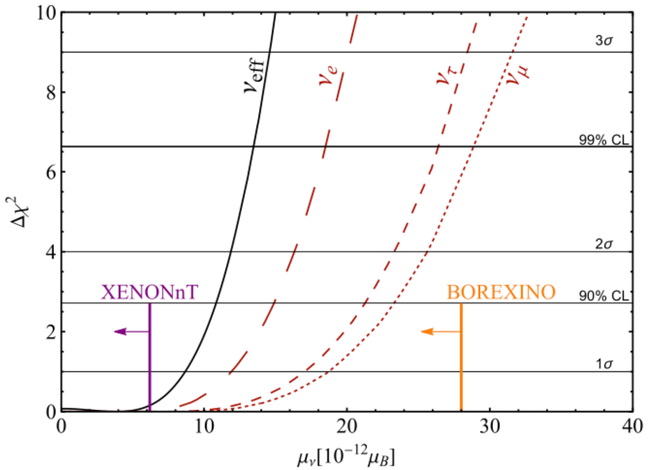


Physical Review D 107, 053001(2023)

STATE OF THE ART

Results on the MM&EC from LZ data

- Constraints about one order of magntitude more stringent than the Dresden-II ones
- Only vES channel contributes
- EPA gives a non negligible improvement in the constraints for the ECs
- Second best laboratory constraint on MM, after XENONnT



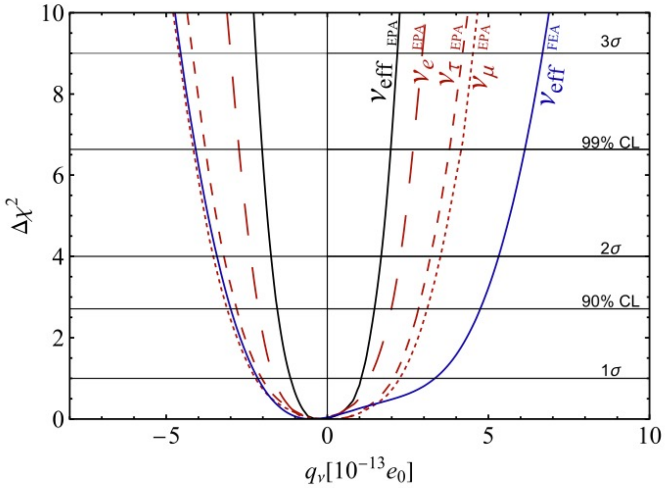


TABLE I. Limits on the neutrino magnetic moment and neutrino millicharge at 90% C.L. obtained with a χ^2 analysis as defined in Eq. (10). For the neutrino millicharge, the limits are reported for both the FEA and the EPA formalism.

Physical Review D 107, 053001(2023)

		$q_\nu[\times 10^{-13} e_0]$	
	$\lvert\mu_\nu\rvert[\times 10^{-11}\mu_B]$	FEA	EPA
ν_{eff}	<1.1	[−3.0, 4.7]	[−1.5, 1.5]
ν_e	<1.5	[−3.6, 6.5]	[−2.1, 2.0]
ν_μ	<2.3	[−8.9, 8.8]	[−3.1, 3.1]
ν_τ	<2.1	[−8.1, 8.1]	[−2.8, 2.8]

$\mu_\nu^{\text{eff}}(\text{XENONnT}) < 6.4\times10^{-12}\mu_B$

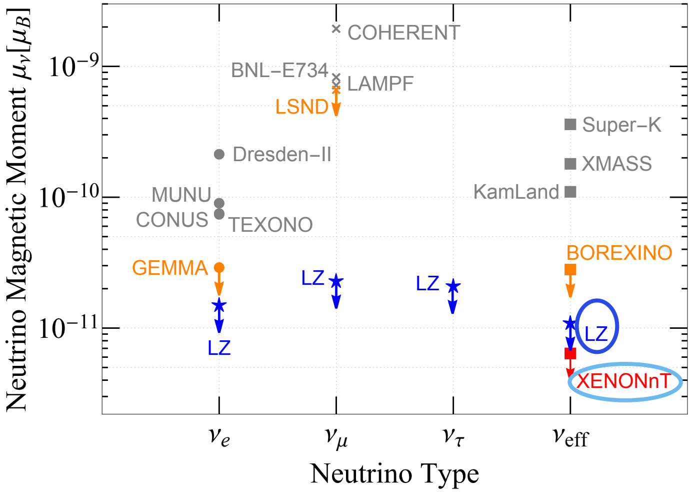
Phys. Rev. Lett. 129, 161805 (2022)

Official LZ analysis

$\nu_{\text{eff}}(\text{LZ}) < 1.36\times10^{-11}\mu_B$

$q_\nu(\text{LZ}) < 2.24\times10^{-13}e_0$

Phys. Rev. D 108.7 (2023), p. 072006



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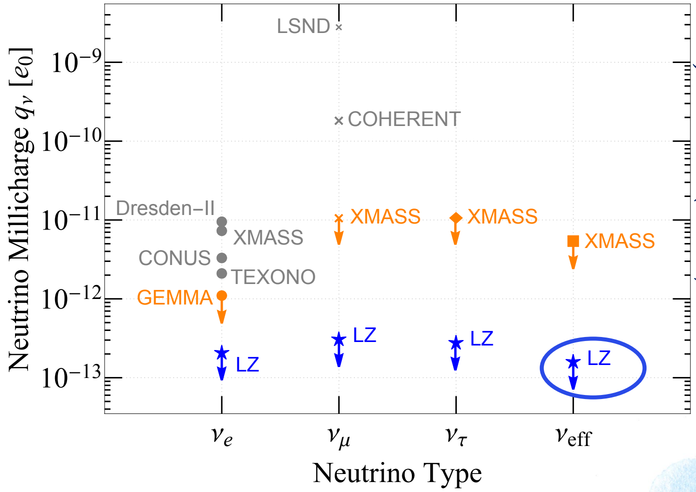
Astrophysical constraints on MM around $10^{-12}\mu_B$



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CONCLUSIONS

CEvNS experiments allow one to set constraints on neutrino electromagnetic properties
Direct dark matter detectors can also constraint neutrino electromagnetic properties considering the vES background as a signal

- The **neutrino magnetic moment** (MM):
  - The experimental threshold is the fundamental aspect for being sensitive to MMs
  - Dresden-II has a lower threshold than COHERENT, and sets more constraining bounds, but still one order of magnitude away from LZ bounds
  - Our LZ analysis: second best laboratory constraints $|\nu_{\mathrm{eff}}| < 1.1 \times 10^{-11} \mu_B$

- The **neutrino electric charge** (EC):
  - The experimental threshold is the fundamental aspect for being sensitive to ECs
  - Dresden-II has a lower threshold than COHERENT, and sets more constraining bounds, but still about two order of magnitude away from LZ bounds
  - Problem of the treatment of atomic electrons: EPA is closer to RRPA than FEA
  - Our LZ analysis: best laboratory constraints using EPA $|q_\nu| < 1.5 \times 10^{-13} e_0$

THANKS FOR LISTENING

Title: Searching for neutrino electromagnetic signatures with CEvNS and Dark Matter detectors data

Short Abstract: Neutrinos are the most elusive particles in the Standard Model, and many of their properties have not yet been fully understood. Among them, neutrino electromagnetic properties such as magnetic moment and millicharge have become objects of extensive research. Consequently, there is a pressing need for experiments capable of precisely probing them at a high precision level.

In this presentation, I will discuss the status of the constraints on such properties coming from experiments designed to measure coherent elastic neutrino-nucleus scattering (CEvNS) and xenon-based dark matter detectors, which are sensitive to the elastic scattering of solar neutrinos off atomic electrons. I will present the latest constraints obtained by the combined analysis of the COHERENT data on CsI and LAr detectors with the recent results from the CEvNS observation at the Dresden-II power plant site with a germanium detector [1]. Then, I will discuss the results from the LUX-ZEPLIN dark matter detector [2], focusing on the impact of adopting different theoretical descriptions for the interaction of neutrinos with atomic electrons.

Finally, I will show that the LUX-ZEPLIN data allows us to set the second best laboratory constraint (second only to the recent XENONnT result) namely $\mu_{eff} < 1.1\times10^{-11}\ \mu_B$ at 90% C.L., which improves by almost a factor of three the Borexino Collaboration limit. Moreover, exploiting the so-called equivalent photon approximation, we obtain the most stringent limit on the neutrino millicharge, namely $|q_{eff}| < 1.5\times10^{-13}\ e_0$ at 90% C.L., which represents a great improvement with respect to the previous laboratory bounds.

[1] M. Corona et al. JHEP 09 (2022) 164, 10.1007/JHEP09(2022)164

[2] M. Corona et al. Phys. Rev. D 107 (2023) 5, 053001, 10.1103/PhysRevD.107.053001

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