Searching for neutrino electromagnetic properties with neutrino scattering experiments

Christoph Andreas Ternes

EPIC workshop

September 27th 2024

INFN
LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

Outline

Data condidered

- CEvNS: COHERENT, Dresden-II
- EvES: PandaX, LZ, XENON, DARWIN

Neutrino electromagnetic interactions and bounds

- Magnetic moments
- Electric charges
- Charge radii

Experimental data

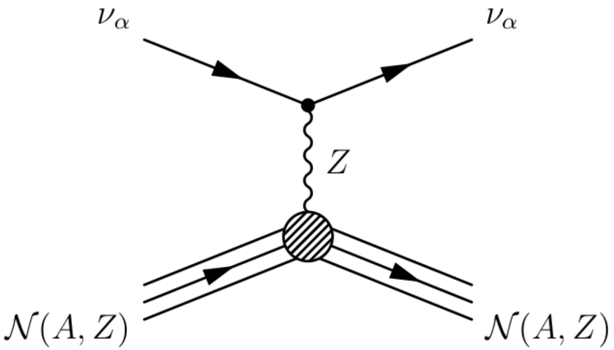
We will use data from several experiments to bound new physics scenarios

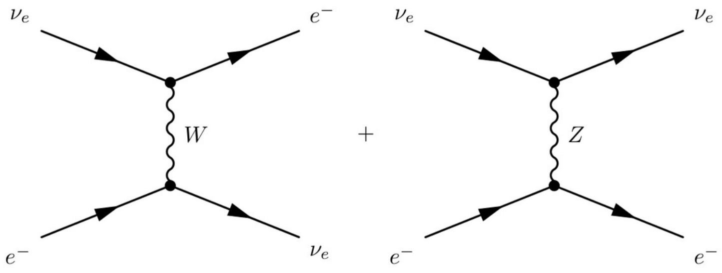
We use CEvNS data from

- COHERENT (CsI and Ar data)
- DRESDEN-II

We use EvES data from

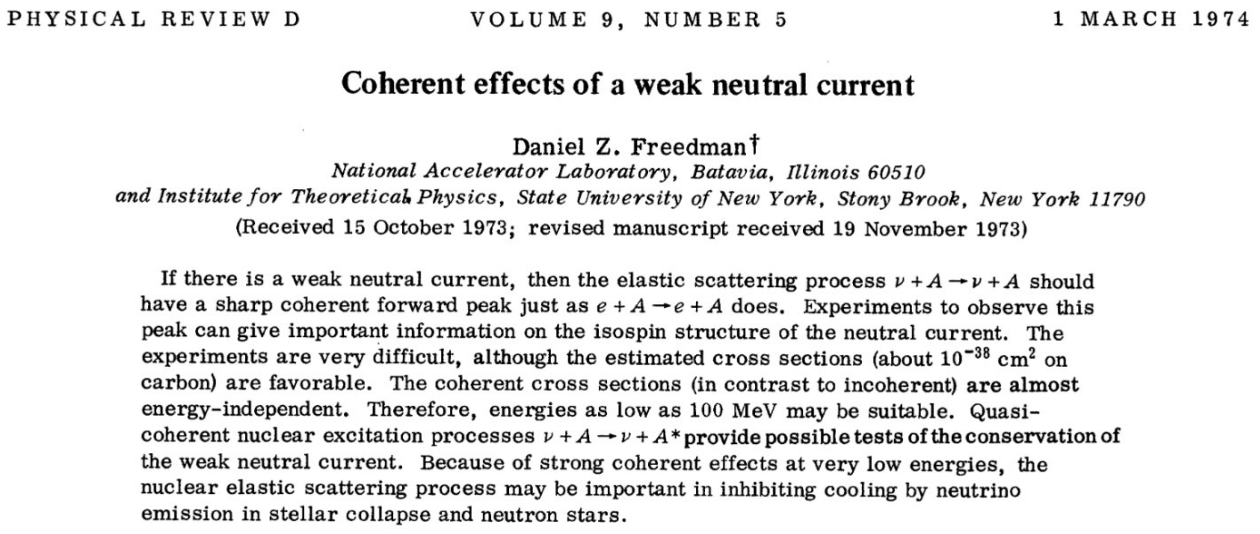
- PandaX-4T
- LUX-ZEPLIN
- XENONnT
- DARWIN (sensitivity)





Coherent elastic neutrino nucleus scattering

CEvNS was predicted in 1974!

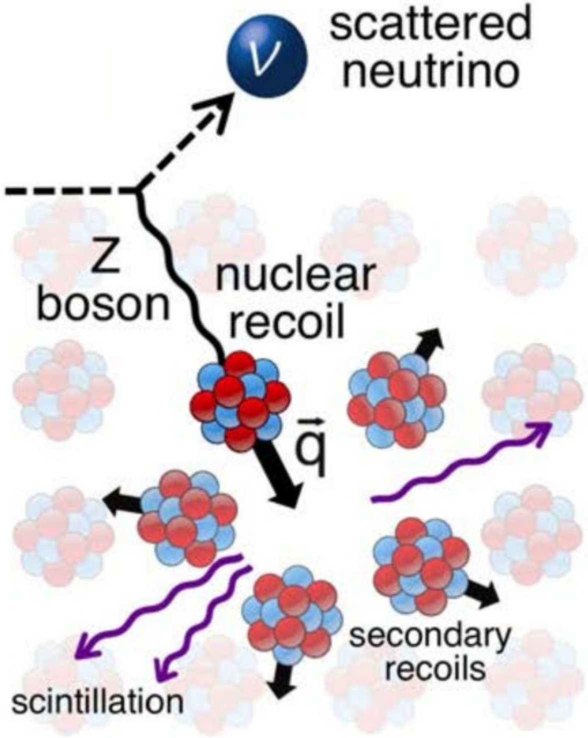


PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

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)

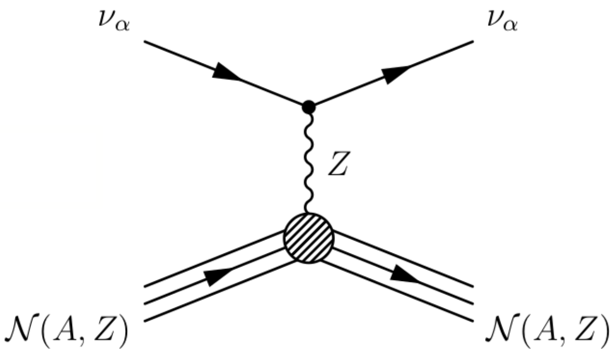
If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are 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.



Coherent elastic neutrino nucleus scattering

In the standard model we have

$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT_{\mathrm{nr}}}(E, T_{\mathrm{nr}}) = \frac{G_{\mathrm{F}}^2 M}{\pi}\left(1 - \frac{M T_{\mathrm{nr}}}{2E^2}\right)(Q^V_{\ell,\mathrm{SM}})^2$$



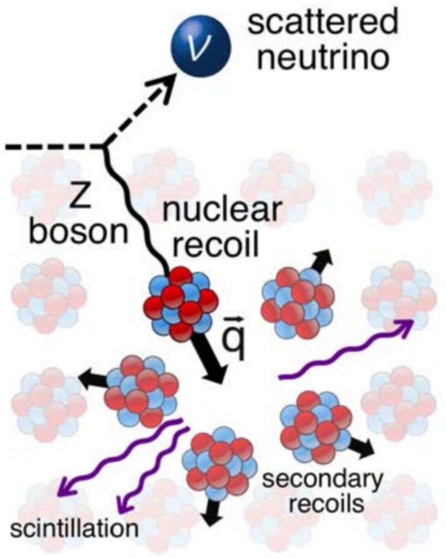
with the weak charge

$$Q^V_{\ell,\mathrm{SM}} = \left[g_V^p(\nu_\ell)\, Z F_Z(|\vec{q}|^2) + g_V^n N F_N(|\vec{q}|^2)\right]$$

$$g_V^p(\nu_e) = 0.0401, \qquad g_V^p(\nu_\mu) = 0.0318, \qquad g_V^n = -0.5094$$

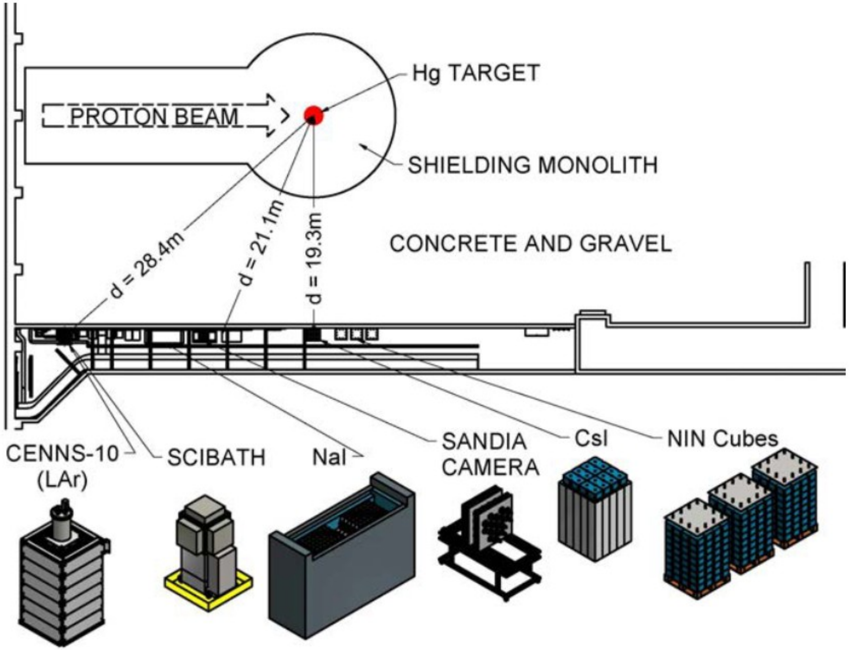
The cross section scales with the neutron number squared

The form factors describe the loss of coherence for large momentum transfer



COHERENT

Observed in 2017 in the COHERENT experiment!

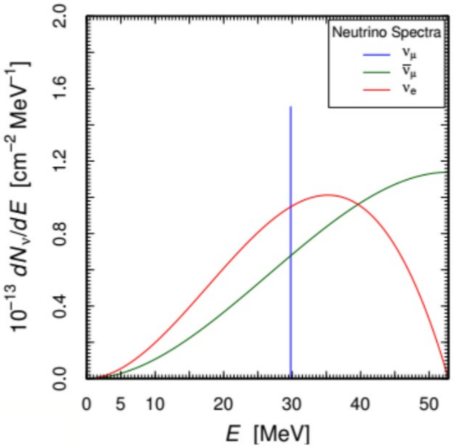


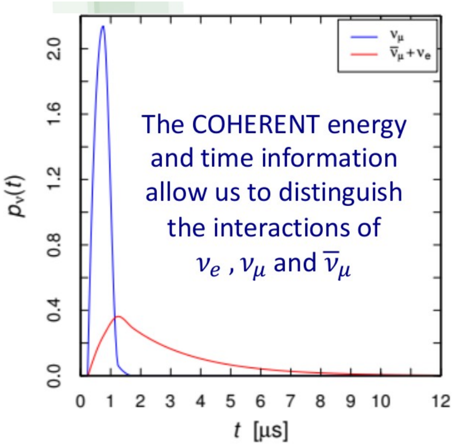
COHERENT, 1708.01294, Science 2017

COHERENT uses neutrinos from the decay of

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

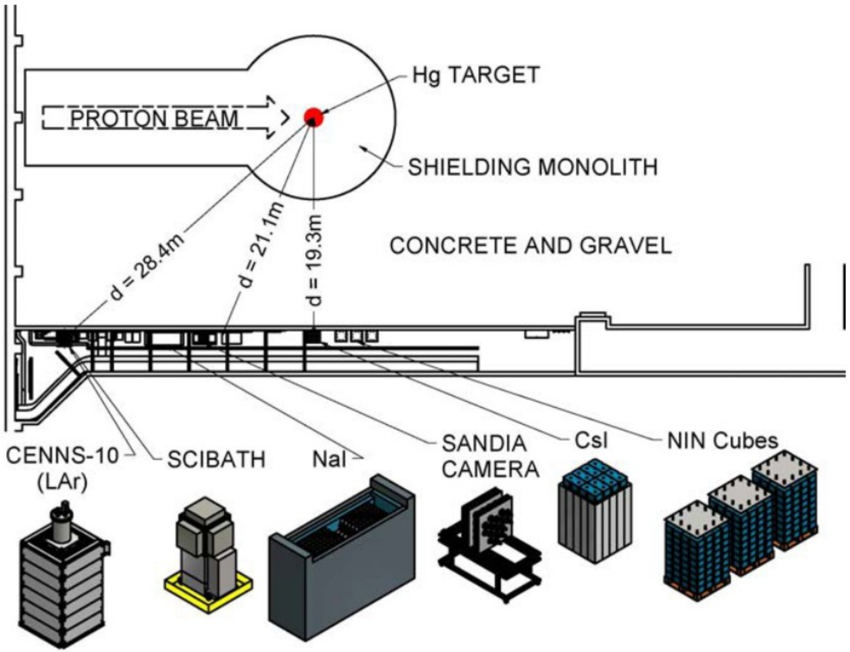


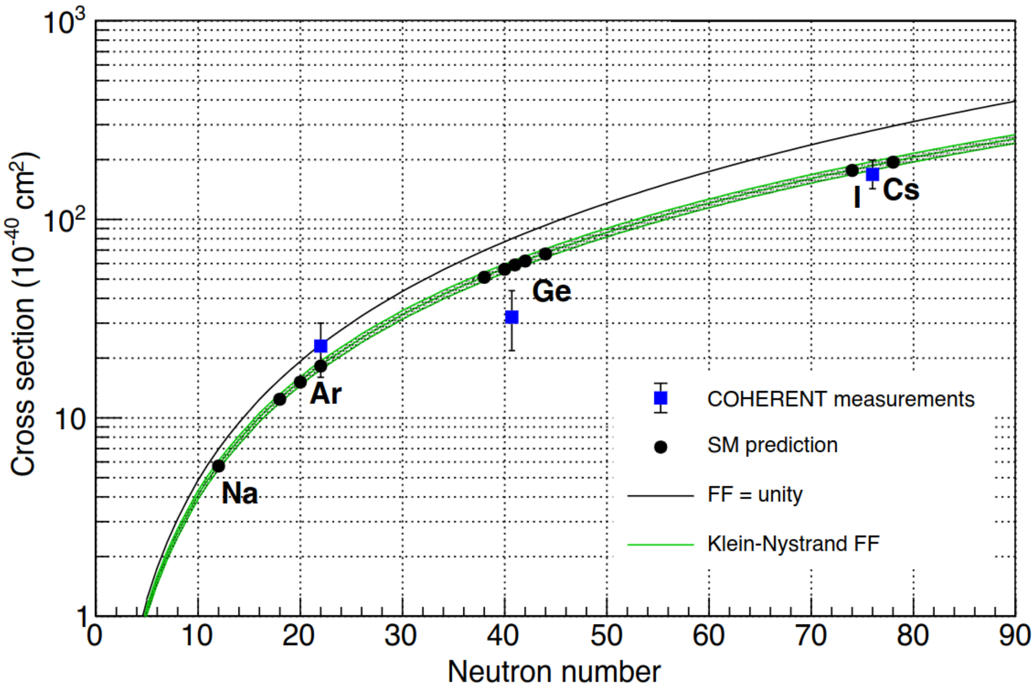


The COHERENT energy and time information allow us to distinguish the interactions of ν_e , ν_μ and $\bar{\nu}_\mu$

Cadeddu et al, 1810.05606, PRD 2018

COHERENT

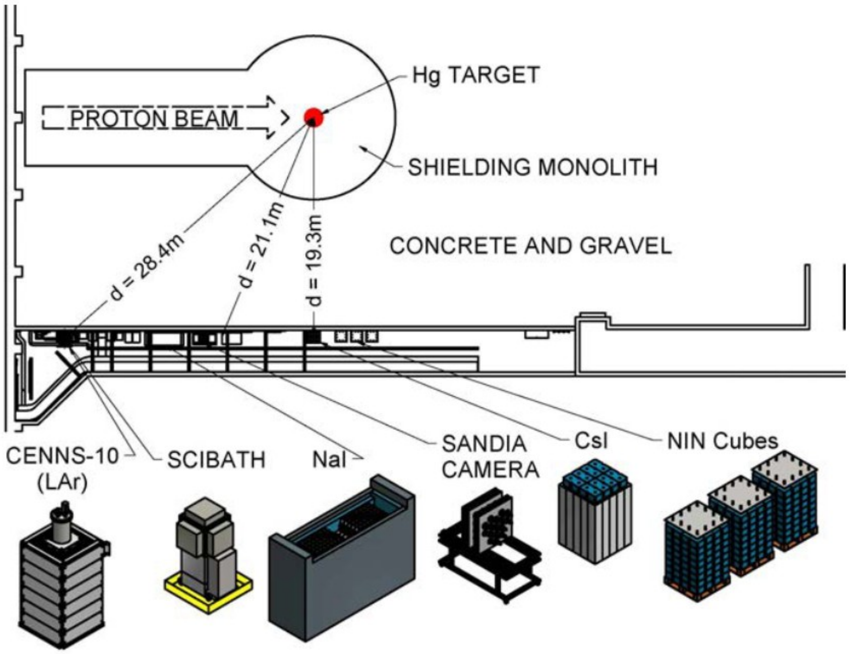




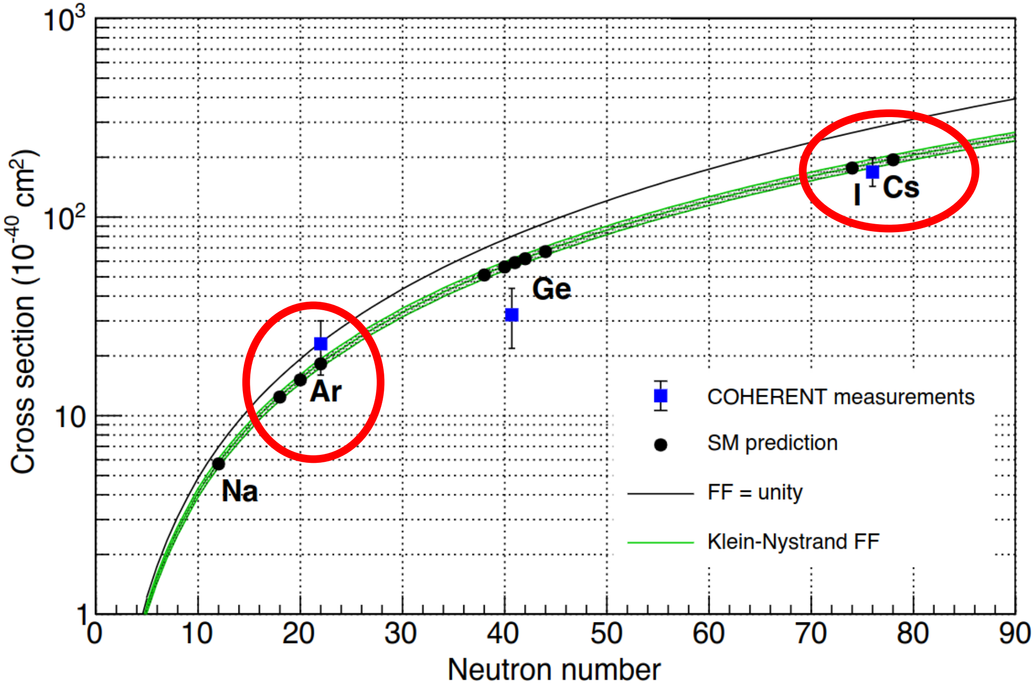
COHERENT, 1708.01294, Science 2017

Mathew Green @ Neutrino-2024

COHERENT



COHERENT, 1708.01294, Science 2017



Mathew Green @ Neutrino-2024

COHERENT

Data included

CEvNS on CsI scintillating crystal

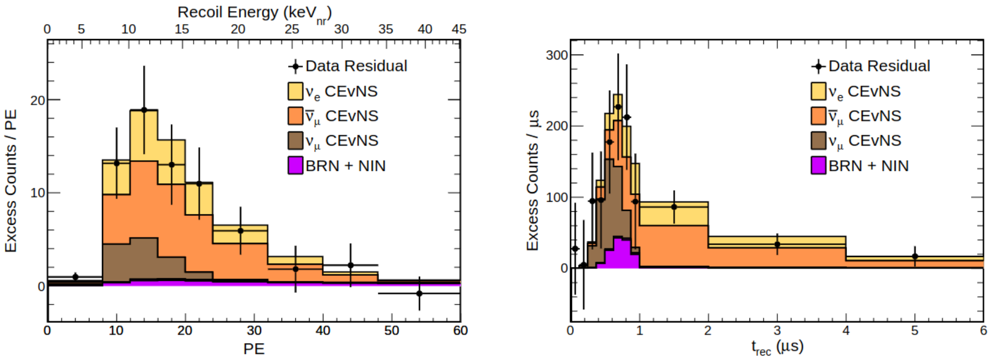
306 ± 20 events, $> 11\sigma$

consistent with SM

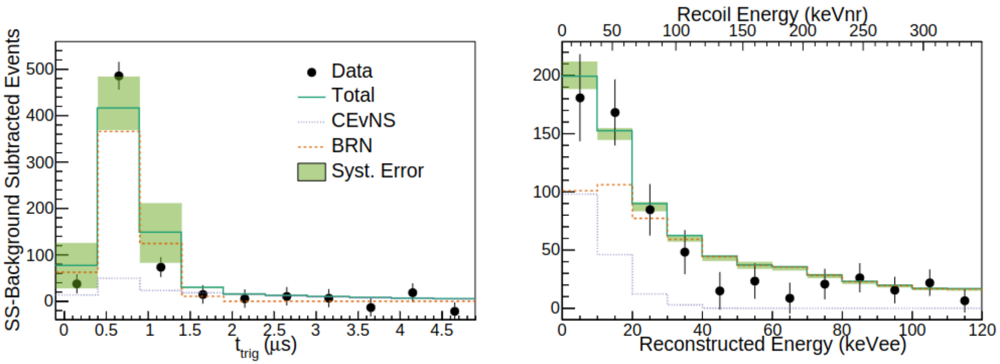
Data included

CEvNS on liquid argon

Still collecting data, more data expected to come soon



COHERENT, 2110.07730, PRL 2022

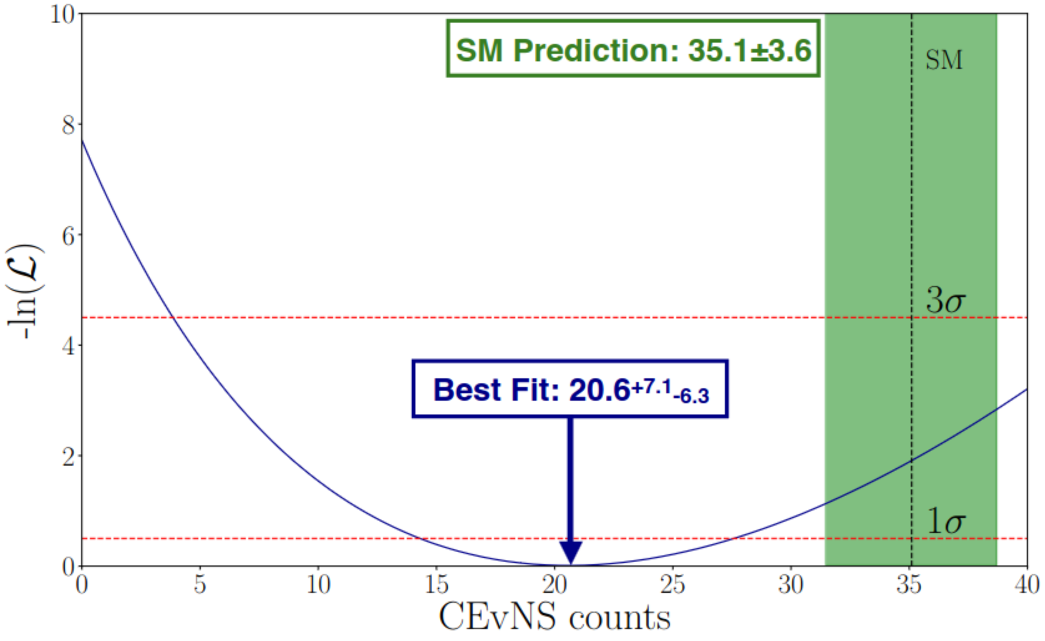


COHERENT, 2003.10630, PRL 2021

COHERENT

New results were presented at the Magnificent CEvNS workshop in Valencia this year!

These data are not included in the analyses discussed today



2D Unbinned Extended Likelihood Fit:

- Null Hypothesis rejected at 3.9σ
- Reduced X^2: 1.84 (p=0.40)
- 1.8σ separation from SM prediction

See:
COHERENT, 2406.13806

COHERENT

Calculation is more complicated

$$N_i^{\mathrm{CE}\nu\mathrm{NS}} = N(\mathcal{N}) \int_{T_{\mathrm{nr}}^{i}}^{T_{\mathrm{nr}}^{i+1}} dT_{\mathrm{nr}}\, A(T_{\mathrm{nr}}) \int_{0}^{T_{\mathrm{nr}}^{\prime\mathrm{max}}} dT_{\mathrm{nr}}^{\prime}\, R(T_{\mathrm{nr}}, T_{\mathrm{nr}}^{\prime}) \int_{E_{\mathrm{min}}(T_{\mathrm{nr}}^{\prime})}^{E_{\mathrm{max}}} dE \sum_{\nu=\nu_e,\nu_\mu,\bar{\nu}_\mu} \frac{dN_\nu}{dE}(E) \frac{d\sigma_{\nu-\mathcal{N}}}{dT_{\mathrm{nr}}}(E, T_{\mathrm{nr}}^{\prime})$$

Detector effects (resolution, efficiency, quenching) must be taken into account when calculating the expected number of events

In the statistical analysis we must consider several sources of background and associated systematic uncertainties

$$\chi^2_{\mathrm{CsI}} = 2 \sum_{i=1}^{9} \sum_{j=1}^{11} \left[\sum_{z=1}^{4} (1+\eta_z) N_{ij}^{z} - N_{ij}^{\mathrm{exp}} + N_{ij}^{\mathrm{exp}} \ln \left(\frac{N_{ij}^{\mathrm{exp}}}{\sum_{z=1}^{4} (1+\eta_z) N_{ij}^{z}} \right) \right] + \sum_{z=1}^{4} \left(\frac{\eta_z}{\sigma_z} \right)^2$$

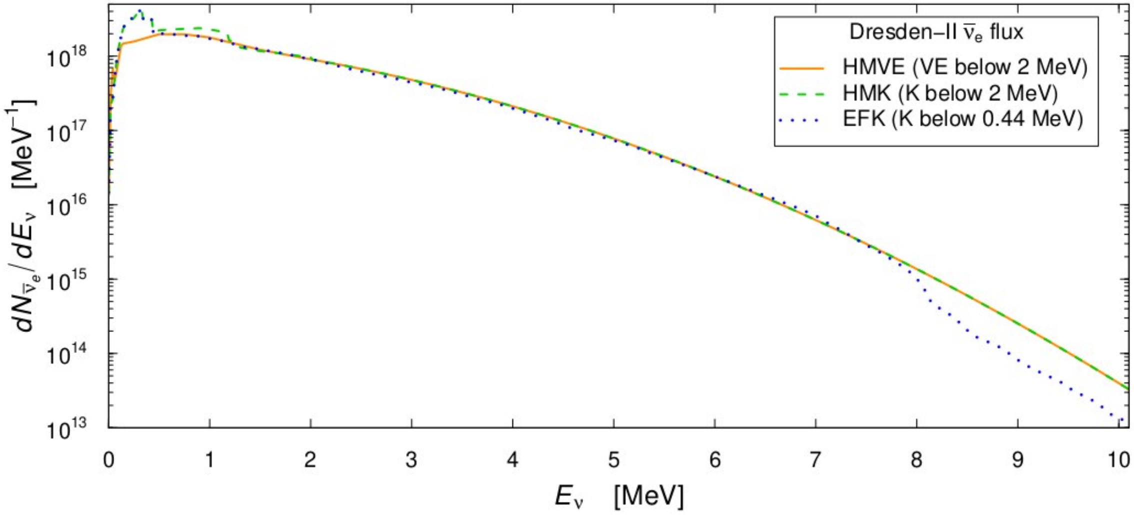
Atzori Corona et al, 2202.11002, JHEP 2022
Atzori Corona et al, 2205.09484, JHEP 2022

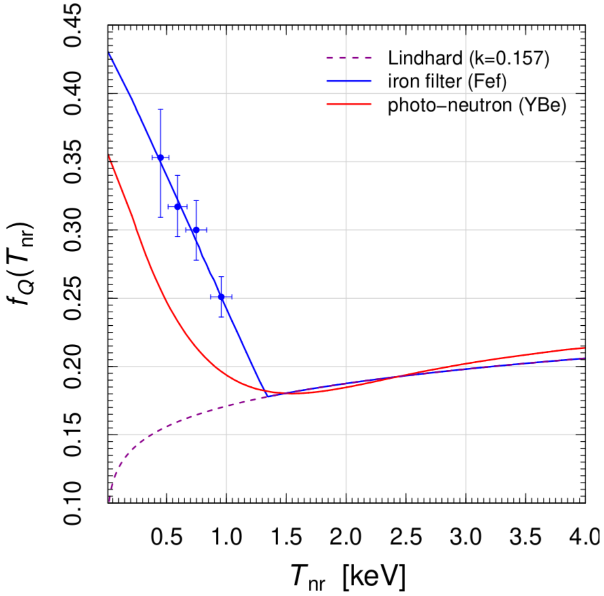
DRESDEN-II

CEvNS using (anti)neutrinos from a nuclear reactor

Depends on the reactor flux model under consideration

Depends on the exact form of the quenching factor



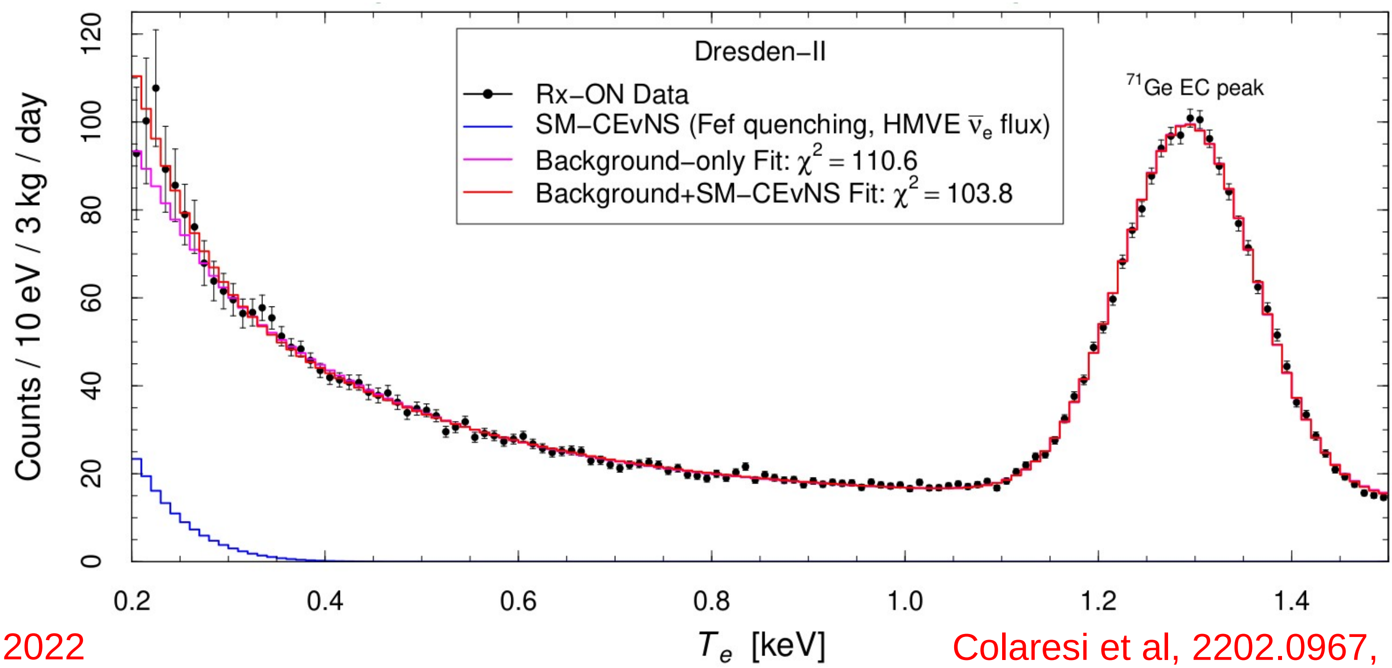


Giunti @ Neutrino 2022

Atzori Corona et al, 2205.09484, JHEP 2022

DRESDEN-II

Rather CEvNS “indication” than measurement

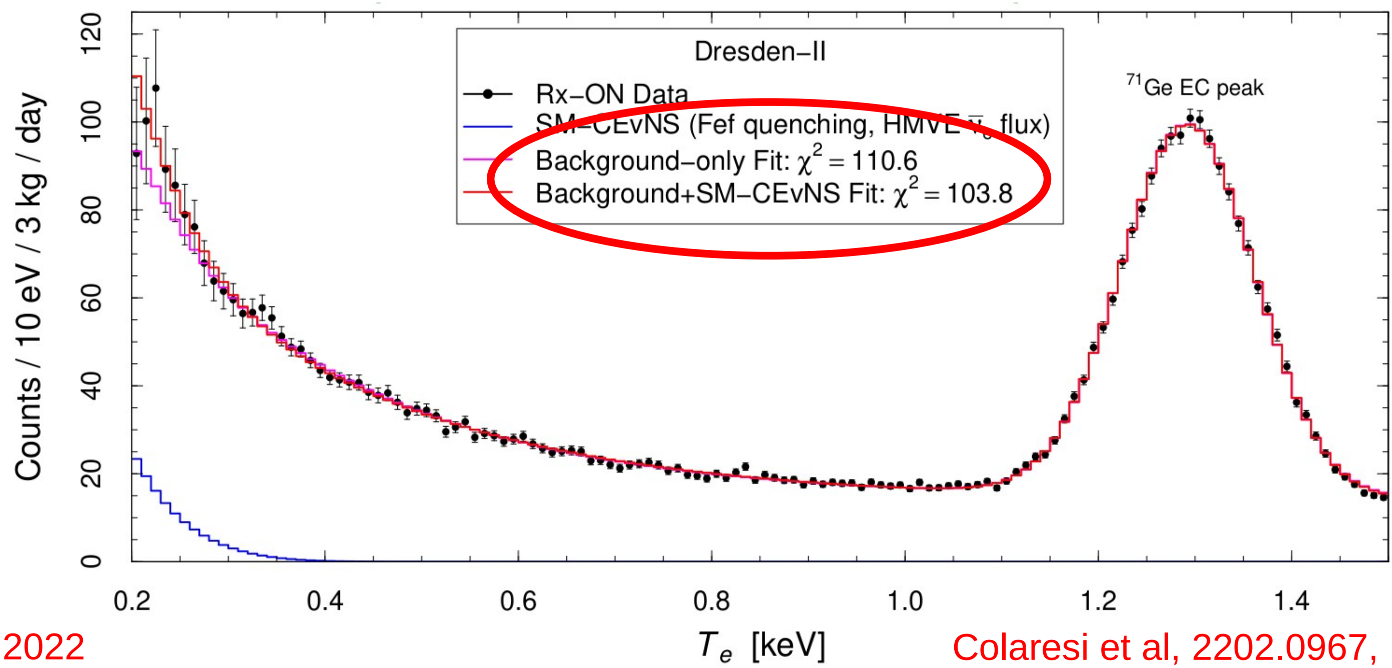


Giunti @ Neutrino 2022

Colaresi et al, 2202.0967, PRL 2022

DRESDEN-II

Rather CEvNS “indication” than measurement



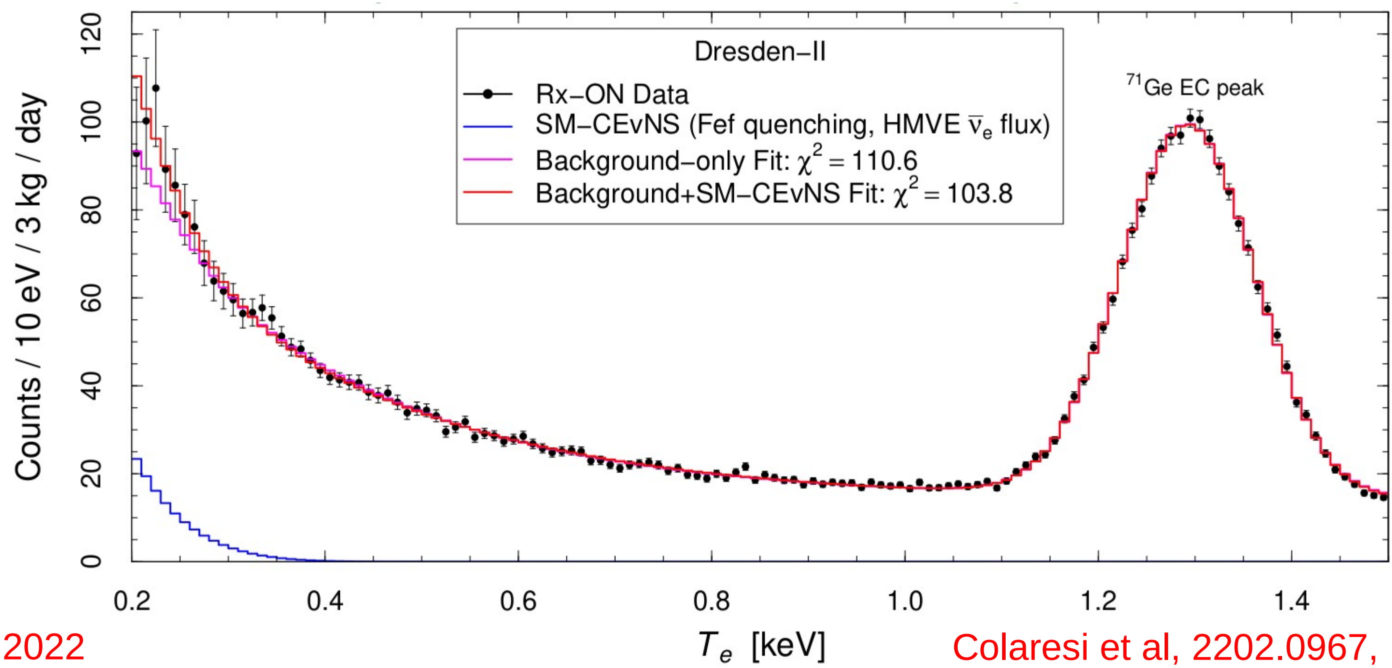
Giunti @ Neutrino 2022

Colaresi et al, 2202.0967, PRL 2022

DRESDEN-II

Rather CEvNS “indication” than measurement

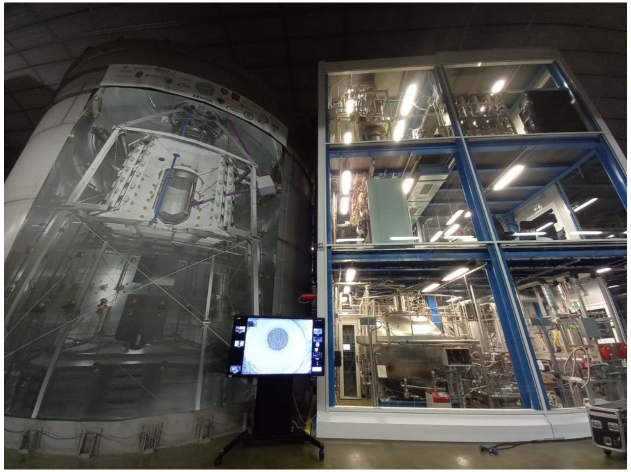
Results debated in the community



Giunti @ Neutrino 2022

Colaresi et al, 2202.0967, PRL 2022

Dark matter direct detection experiments



We will use data from several DMDD experiments

- PandaX-4T (China)
- LUX-ZEPLIN (USA)
- XENONnT (Gran Sasso)
- DARWIN (next generation experiment)

The original purpose of these experiments is to observe recoils induced by WIMP interactions

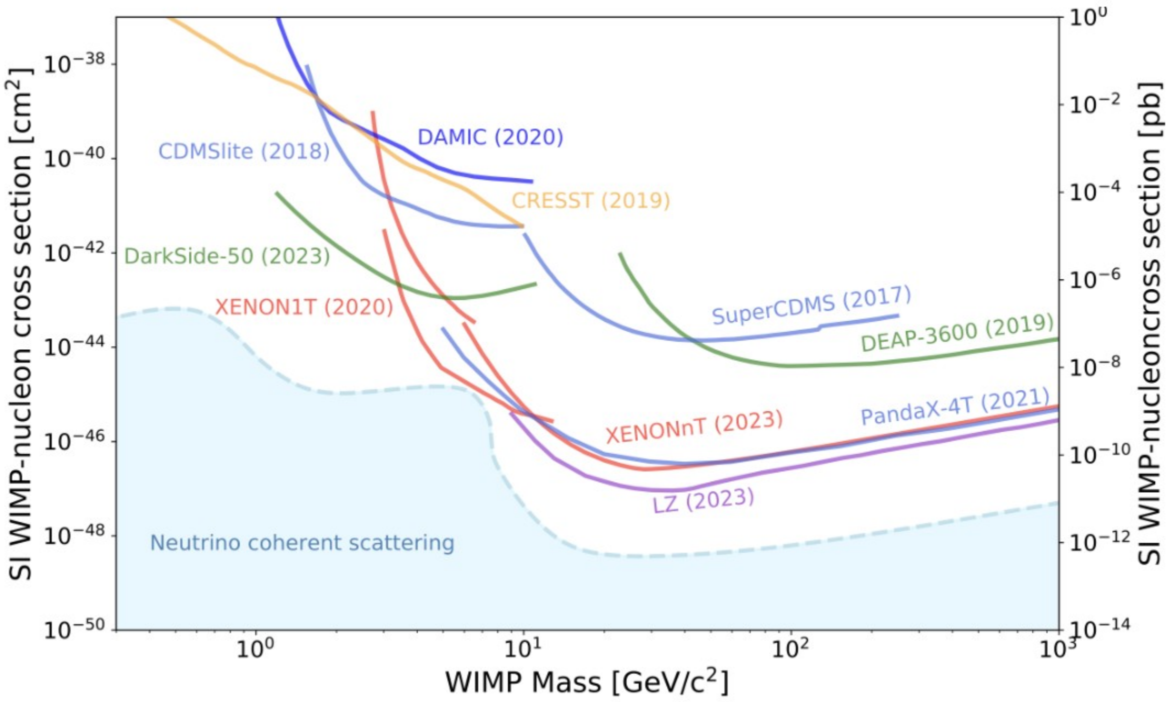
Solar neutrinos constitute an irreducible background for these experiments

These experiments can be used to measure nuclear and electron recoils!

Dark matter direct detection experiments

Direct detection experiments put stringent bounds on the WIMP parameter space

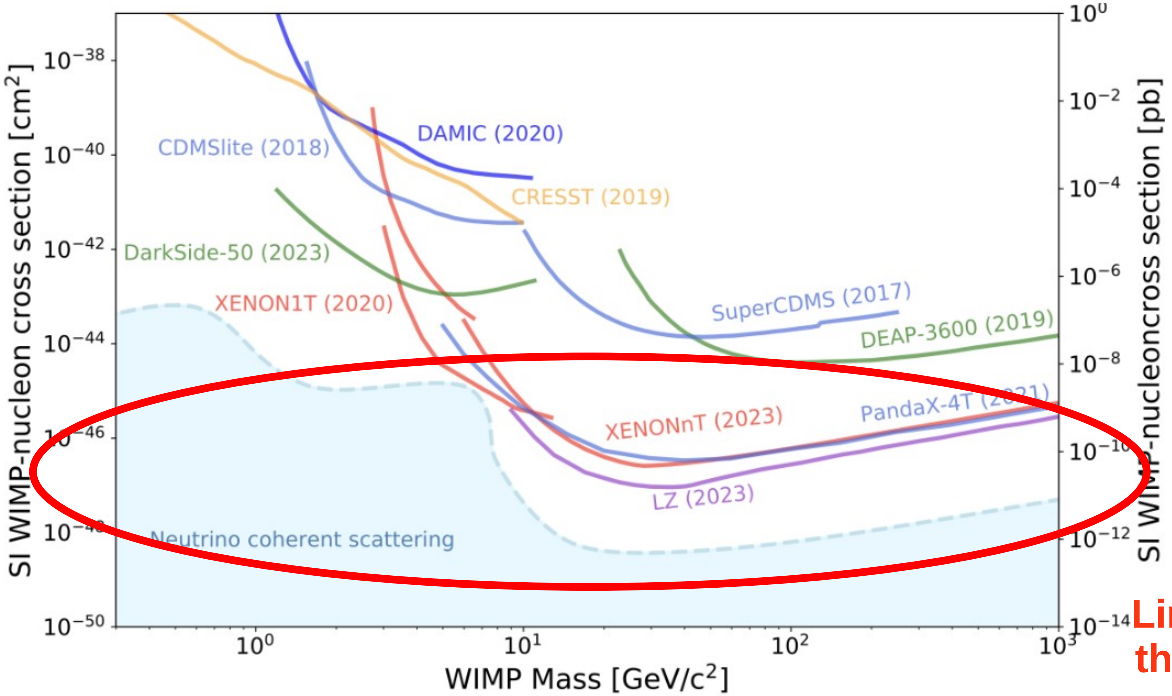
[Baudis & Profumo, PDG 2023]



Dark matter direct detection experiments

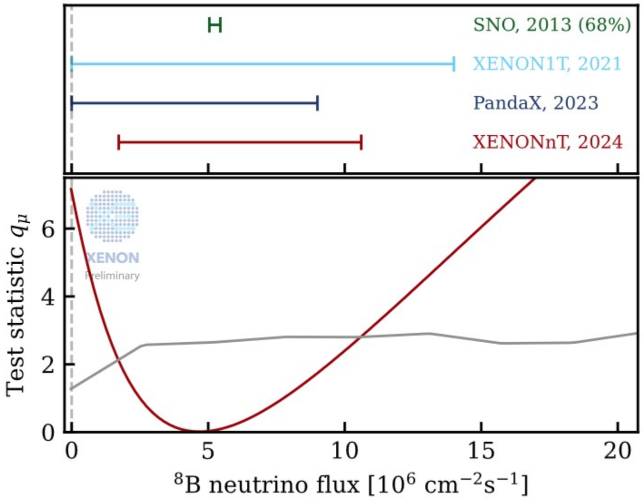
Direct detection experiments put stringent bounds on the WIMP parameter space

[Baudis & Profumo, PDG 2023]

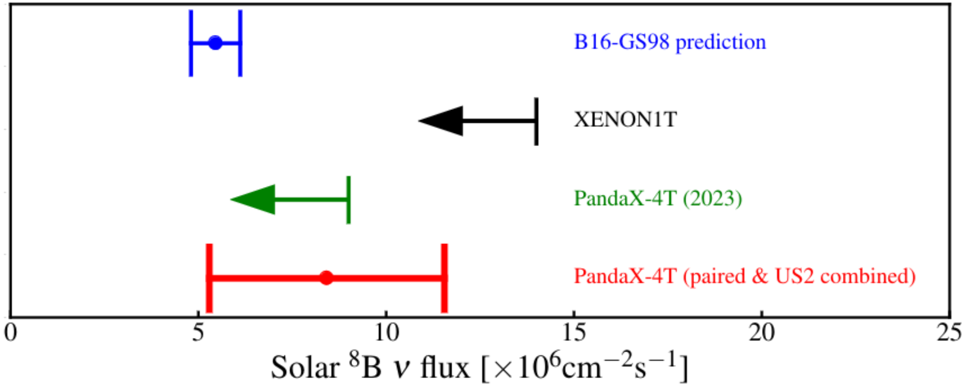


Limits are getting close to the so-called neutrino fog

Dark matter direct detection experiments



- We have measured the solar ^{8}B neutrinos via CEvNS in XENONnT at 2.73σ
- The first CEvNS measurement with Xe!
- The first astrophysical neutrino measurement via CEvNS



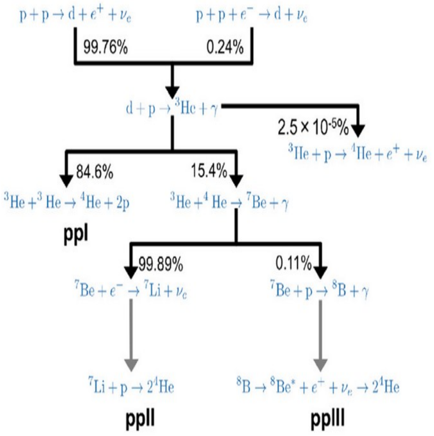
background-only hypothesis is disfavored at 2.64 σ significance.

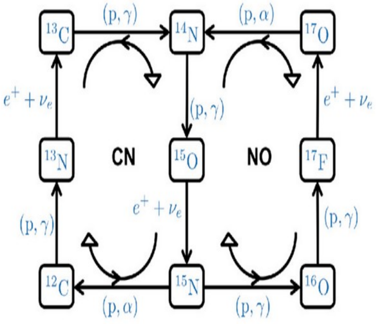
Fei Gao @ IDM 2024

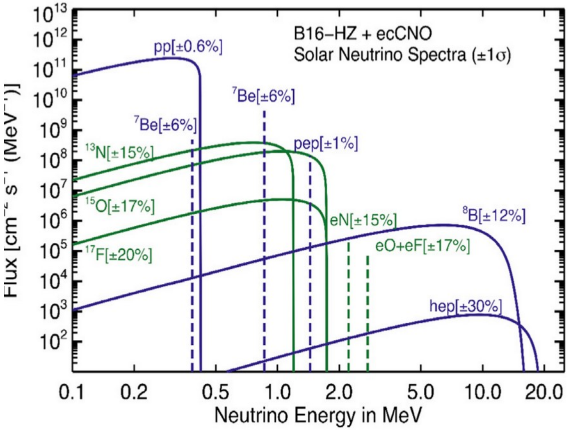
PandaX, 2407.10892

Dark matter direct detection experiments

Solar neutrinos oscillate and arrive at a detector on Earth as a mixture of ν_e , ν_μ , and ν_τ , whose fluxes are given by





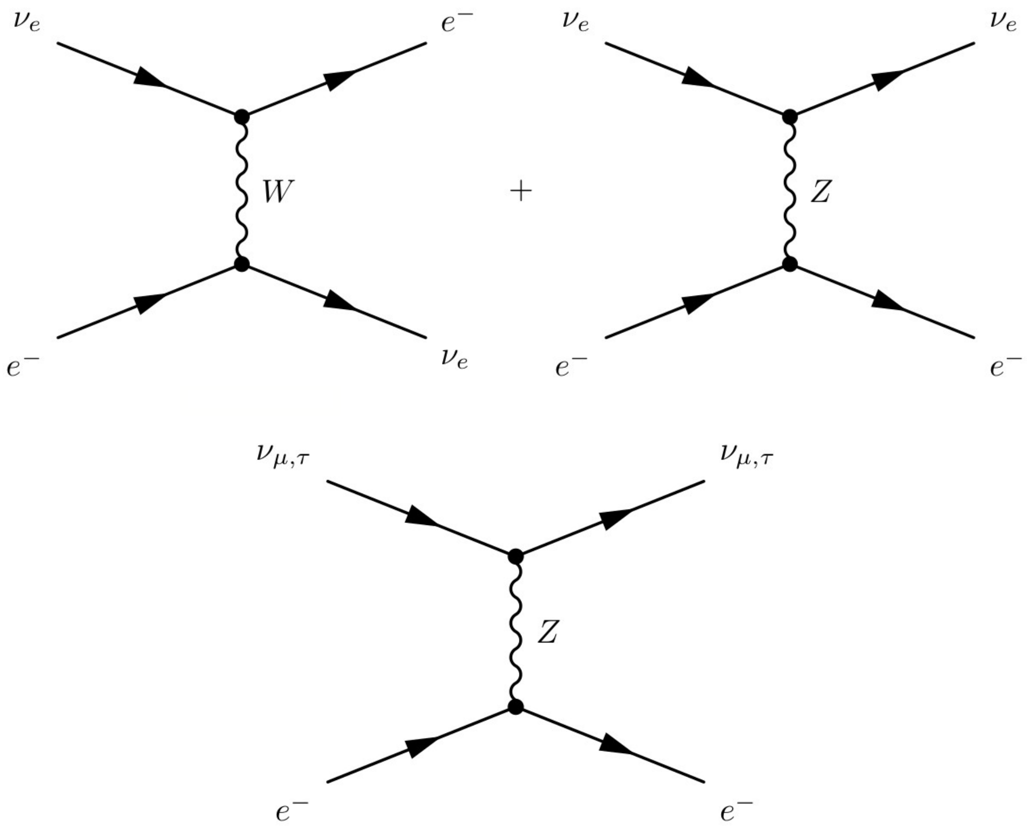


Flux	**B16-HZ**	**B16-LZ**
$\Phi(pp)$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$
$\Phi(pep)$	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$
$\Phi(hep)$	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$
$\Phi({}^7Be)$	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$
$\Phi({}^8B)$	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$
$\Phi({}^{13}N)$	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$
$\Phi({}^{15}O)$	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$
$\Phi({}^{17}F)$	$5.29(1 \pm 0.20)$	$3.26(1 \pm 0.18)$
$\Phi(eN)$	$2.20(1 \pm 0.15)$	$1.61(1 \pm 0.14)$
$\Phi(eO)$	$0.81(1 \pm 0.17)$	$0.57(1 \pm 0.16)$
$\Phi(eF)$	$3.11(1 \pm 0.20)$	$1.91(1 \pm 0.18)$

$$\Phi^i_{\nu_e} = \Phi^{i\,\odot}_{\nu_e} P_{ee}, \quad \Phi^i_{\nu_\mu} = \Phi^{i\,\odot}_{\nu_e} (1 - P_{ee}) \cos^2 \vartheta_{23}, \quad \Phi^i_{\nu_\tau} = \Phi^{i\,\odot}_{\nu_e} (1 - P_{ee}) \sin^2 \vartheta_{23}$$

Villante, Serenelli, 2101.03077, Frontiers 2021

Elastic neutrino electron scattering



Elastic neutrino electron scattering

In the standard model we have

$$\frac{d\sigma^{\text{SM}}_{\nu_\ell-\text{Xe}}}{dT_\text{e}}(E_\nu, T_\text{e}) = Z^{\text{Xe}}_{\text{eff}}(T_e)\,\frac{G_\text{F}^2 m_e}{2\pi}\left[(g_V^{\nu_\ell}+g_A^{\nu_\ell})^2 + (g_V^{\nu_\ell}-g_A^{\nu_\ell})^2\left(1-\frac{T_e}{E_\nu}\right)^2 - ((g_V^{\nu_\ell})^2-(g_A^{\nu_\ell})^2)\,\frac{m_e T_e}{E_\nu^2}\right]$$

with the couplings

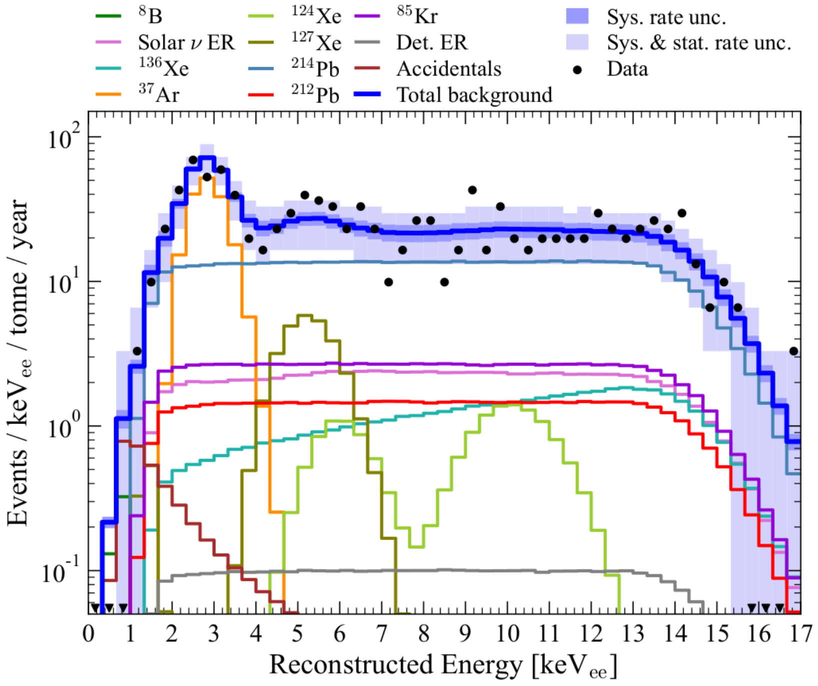
$$g_V^{\nu_e} = 2\sin^2\vartheta_W + 1/2, \qquad g_A^{\nu_e} = 1/2,$$

$$g_V^{\nu_{\mu,\tau}} = 2\sin^2\vartheta_W - 1/2, \qquad g_A^{\nu_{\mu,\tau}} = -1/2,$$

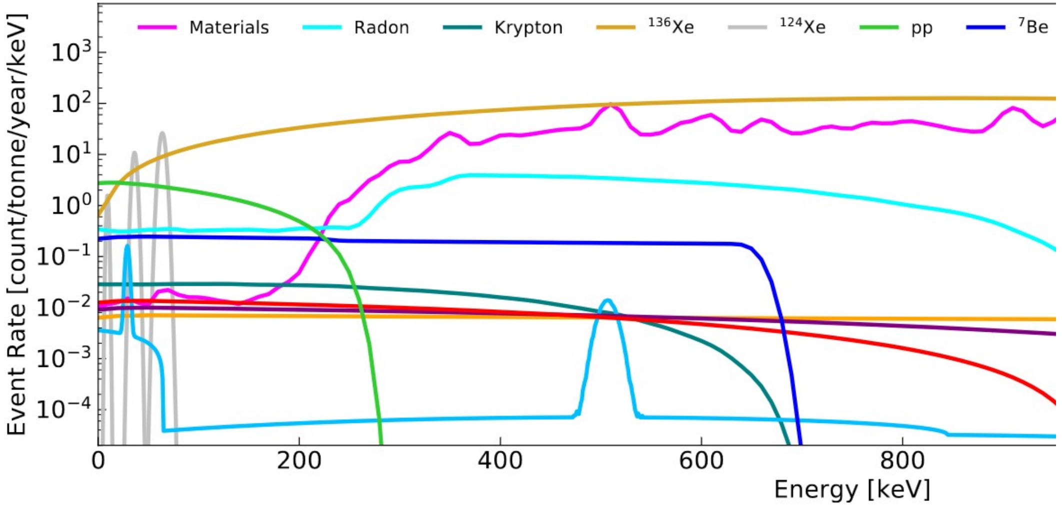
The first factor quantifies the effective number of electrons which can be ionized for a given recoil energy

Dark matter direct detection experiments

Solar neutrino EvES constitutes a subdominating (dominating) background component in current (future) experiment

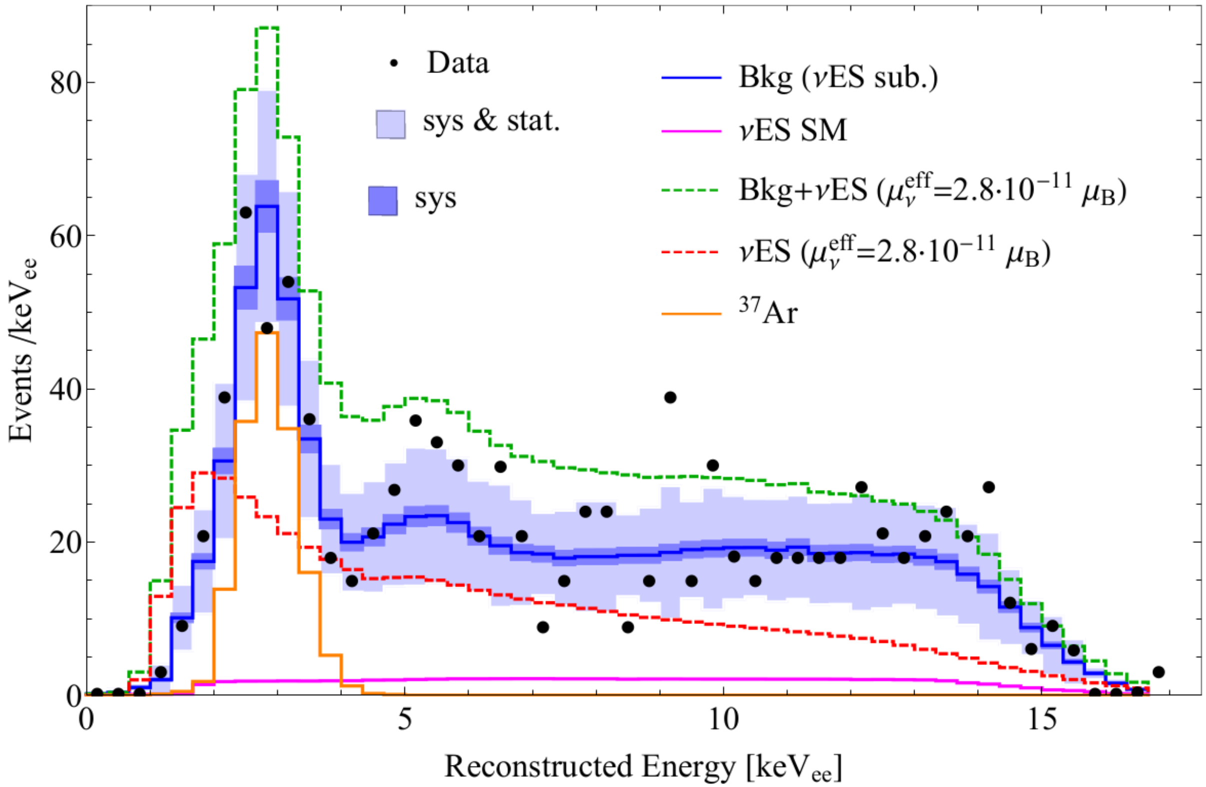


LZ, 2211.17120, PRD 2023



DARWIN, 2006.03114, EPJC 2020

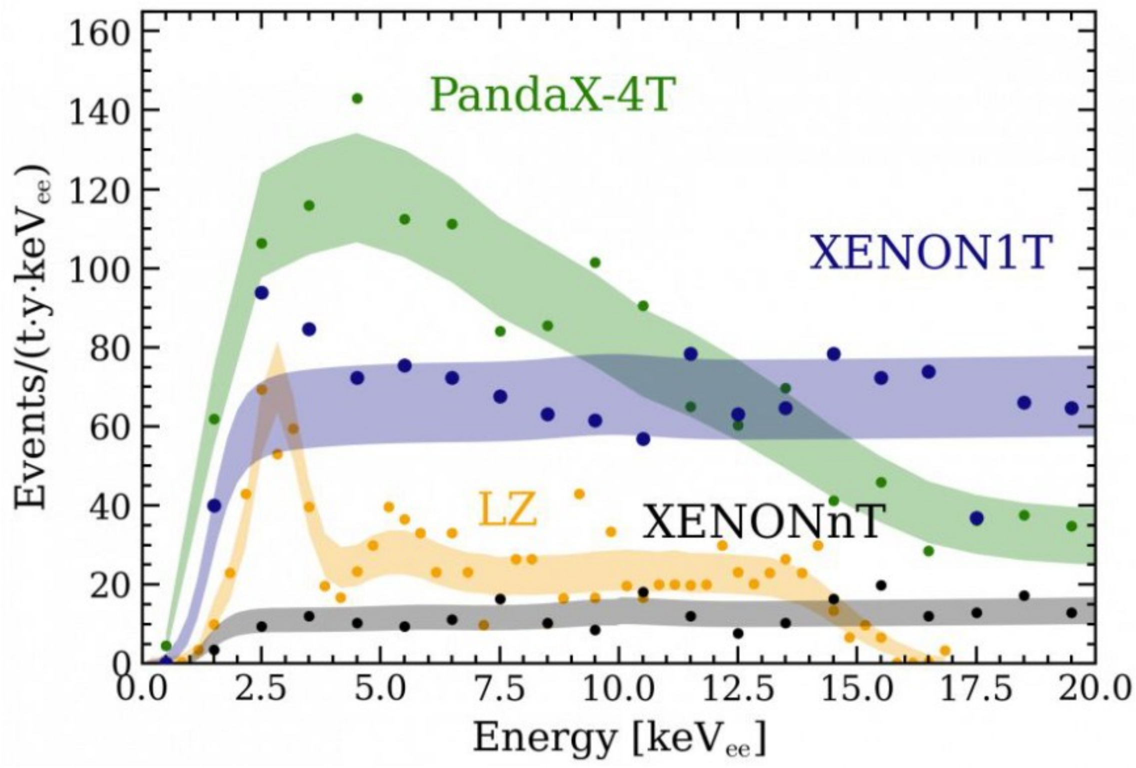
Dark matter direct detection experiments



Even though the EvES rate is very small in the SM, new physics can dramatically increase the cross section

Atzori Corona et al, 2207.05036, PRD 2023

Dark matter direct detection experiments



XENONnT has the lowest background rate

We can expect the strongest constraints on new physics from XENONnT data

PandaX-4T, 2206.02339, PRL 2022
LZ, 2207.03764, PRL 2023
XENON, 2207.11330, PRL2022

Angelino @ Neurino Telescopes 2022

Dark matter direct detection experiments

Again all background components with systematical uncertainties must be taken into account

$$R_k^X = R_k^{E\nu ES} + \sum_i R_k^i \qquad R_k^{E\nu ES} = N \int_{T_e^k}^{T_e^{k+1}} dT_e \int_0^\infty dT'_e \; R(T_e, T'_e) \; A(T'_e) \sum_{i=pp,{}^7\mathrm{Be}} \int_{E_\nu^{\min}}^{E_{\nu,i}^{\max}} dE_\nu \sum_\ell \Phi^i_{\nu_\ell}(E_\nu) \, \frac{d\sigma_{\nu_\ell}}{dT'_e}$$

$$\chi^2_X = \min_{\vec{\alpha},\vec{\beta}} \left\{ 2 \left(\sum_k R_k^X - D_k^X + D_k^X \; \log D_k^X / R_k^X \right) + \sum_i (\alpha_i/\sigma_{\alpha_i})^2 + \sum_i (\beta_i/\sigma_{\beta_i})^2 \right\}$$

We also perform a combined analysis of all DMDD experiments considering possible correlations among systematic uncertainties

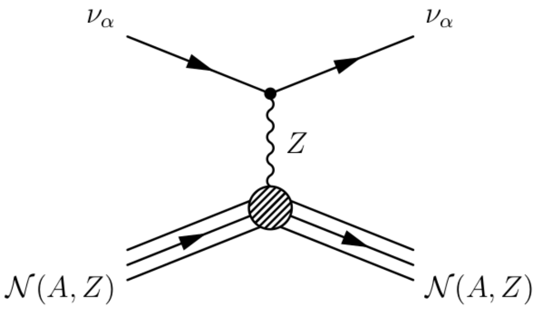
Giunti, Ternes, 2309.17380, PRD 2023

Possible new physics contributions

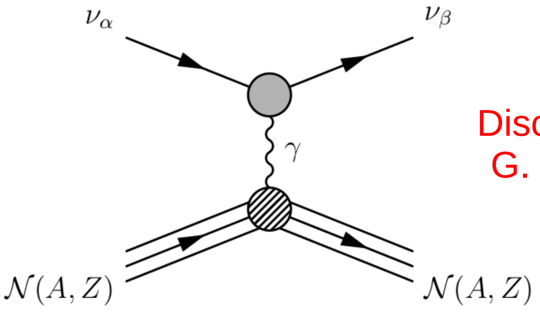
The process can be altered by many BSM scenarios

Discussed by
N.Cargioli
V. De Romeri
G. Sanchez
M. Atzori Corona
M. Giammei

Standard Model NC



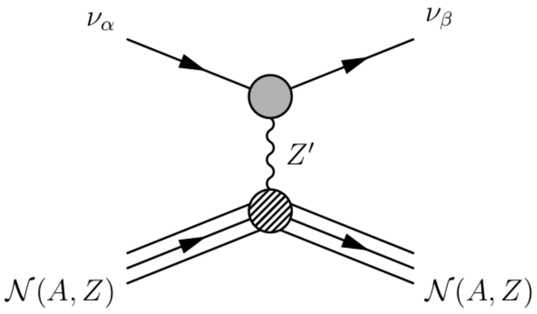
Electromagnetic Interactions



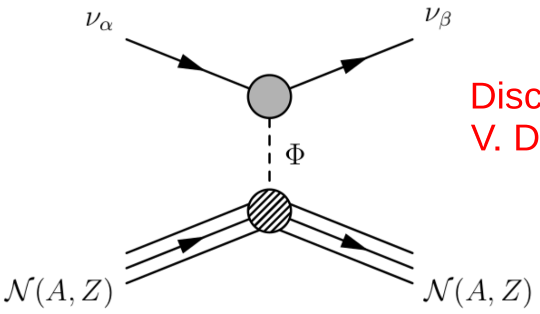
Discussed by
G. Sanchez

Discussed by
V. De Romeri
G. Sanchez

BSM Vector Mediator



BSM Scalar Mediator

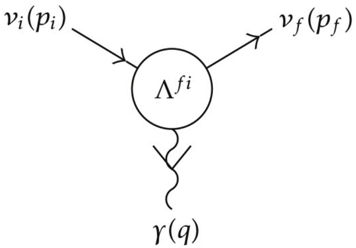


Discussed by
V. De Romeri

Giunti @ Neutrino 2022

Neutrino electromagnetic interactions

$$\mathcal{H}_{\text{em}}^{(\nu)} = j_{\lambda}^{(\nu)} A^{\lambda} = \sum_{j,k=1}^{3} \overline{\nu}_j \Lambda_{\lambda}^{jk} \nu_k A^{\lambda}$$



In some extensions of the Standard Model neutrinos acquire also electromagnetic properties through quantum loops effects

$$\Lambda_{\lambda}(q) = \left(\gamma_{\lambda} - \frac{q_{\lambda} \not{q}}{q^2}\right) \left[f_Q(q^2) + f_A(q^2) q^2 \gamma^5\right] - i\sigma_{\lambda\rho} q^{\rho} \left[f_M(q^2) + i f_E(q^2) \gamma^5\right]$$

Neutrino charge **Anapole** **Magnetic and electric moments**

See Broggini, Giunti, Studenikin, 1207.3980, Adv.HEP 2012
Kouzakov, Studenikin, 1703.00401, PRD 2017

Neutrino magnetic moments

In the minimal extended SM the magnetic moment is strongly suppressed by the small size of the neutrino mass

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

However, more complex models allow for larger magnetic moments, e.g. in left-right symmetric models

$$\mu_{\nu_l} = \frac{eG_F}{2\sqrt{2}\pi^2} \left[m_l \left(1 - \frac{m_{W_1}^2}{m_{W_2}^2} \right) \sin 2\xi + \frac{3}{4} m_{\nu_l} \left(1 + \frac{m_{W_1}^2}{m_{W_2}^2} \right) \right]$$

See Broggini, Giunti, Studenikin, 1207.3980, Adv.HEP 2012

Neutrino magnetic moments

Neutrino magnetic and electric dipoles contribute to CEvNS and EvES

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

Vogel, Engel, PRD 1989

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

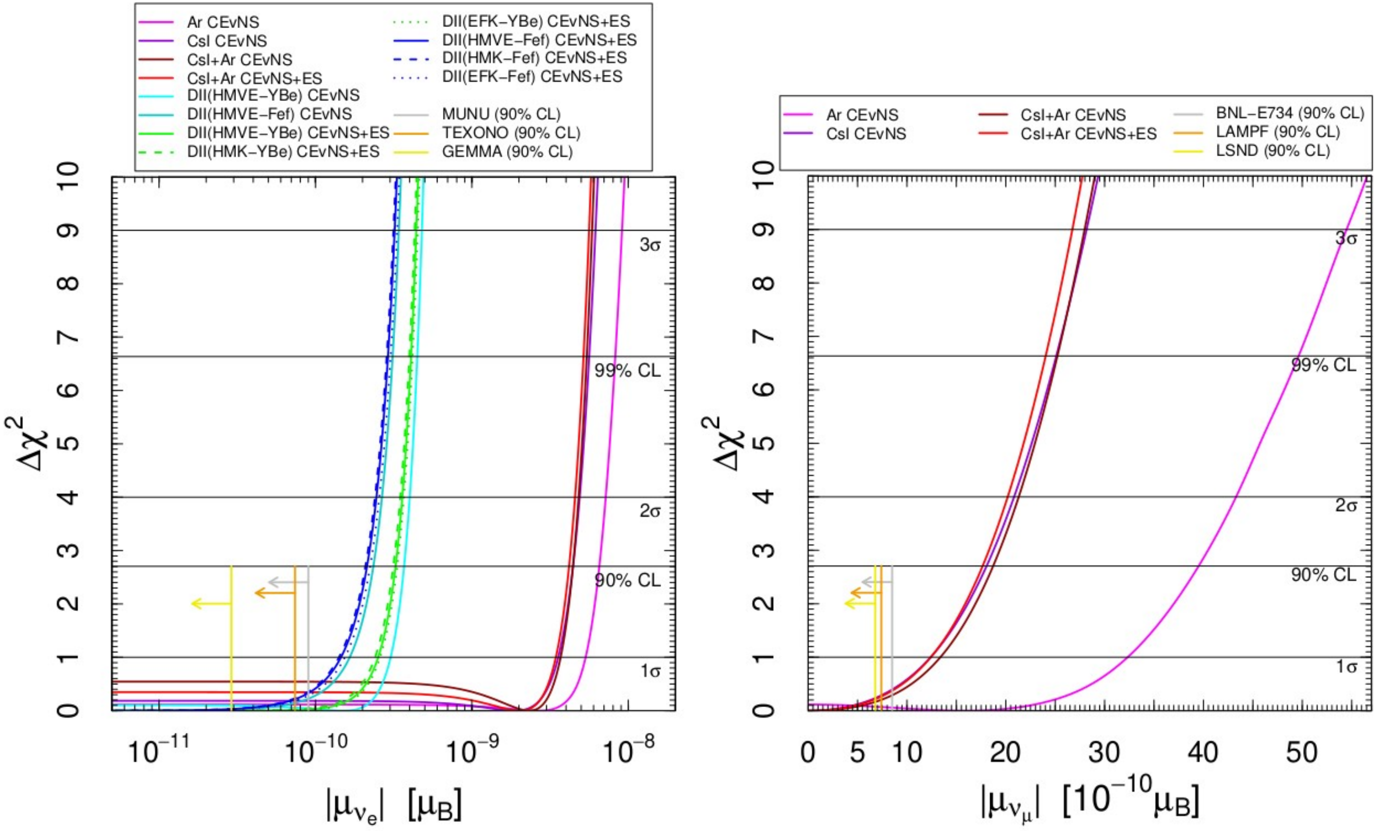
Care has to be taken when comparing bounds, the effective moment for solar neutrinos is not the same as for COHERENT

$$\lim_{L\to 0}|\mu_{\nu_l}(L,E))|^2 \to \sum_{l'}\left|\sum_{j,k}U^*_{lk}U_{l'j}(\mu_\nu)_{jk}\right|^2$$

$$\mu_\nu^2(\nu_\alpha,L,E) = \sum_j\left|\sum_k U^*_{\alpha k}e^{-im_k^2L/2E}(\mu_{jk}-i\epsilon_{jk})\right|^2.$$

$$\lim_{L\to\infty}|\mu_{\nu_l}(L,E))|^2 \to \sum_{j,k}|U_{lk}|^2|(\mu_\nu)_{jk}|^2$$

Neutrino magnetic moments

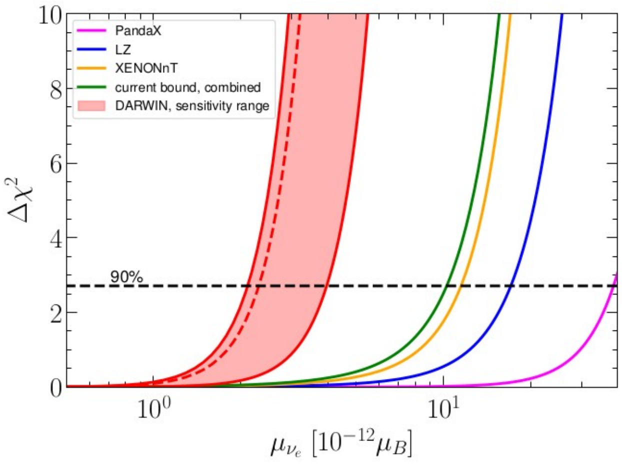


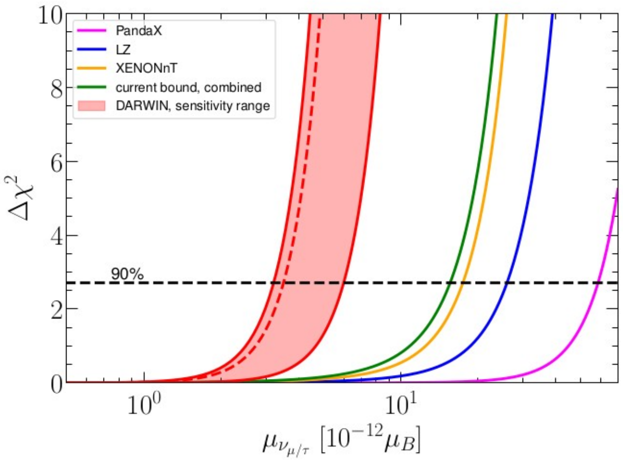
COHERENT and DRESDEN-II can be used to place bounds on the electron an muon sector

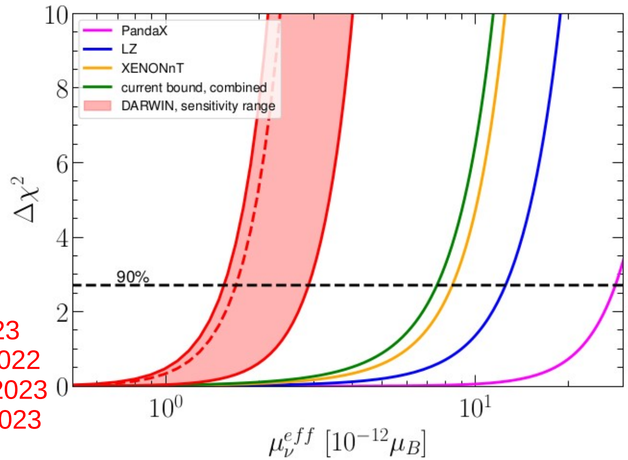
CEvNS bounds are not yet competitive with bounds from other probes

Atzori Corona et al, 2205.09484, JHEP 2022
See also: De Romeri et al, 2211.11905, JHEP 2023

Neutrino magnetic moments







DMDD can be used to place bounds also on the tau sector

These are the strongest laboratory bounds on neutrino magnetic moments

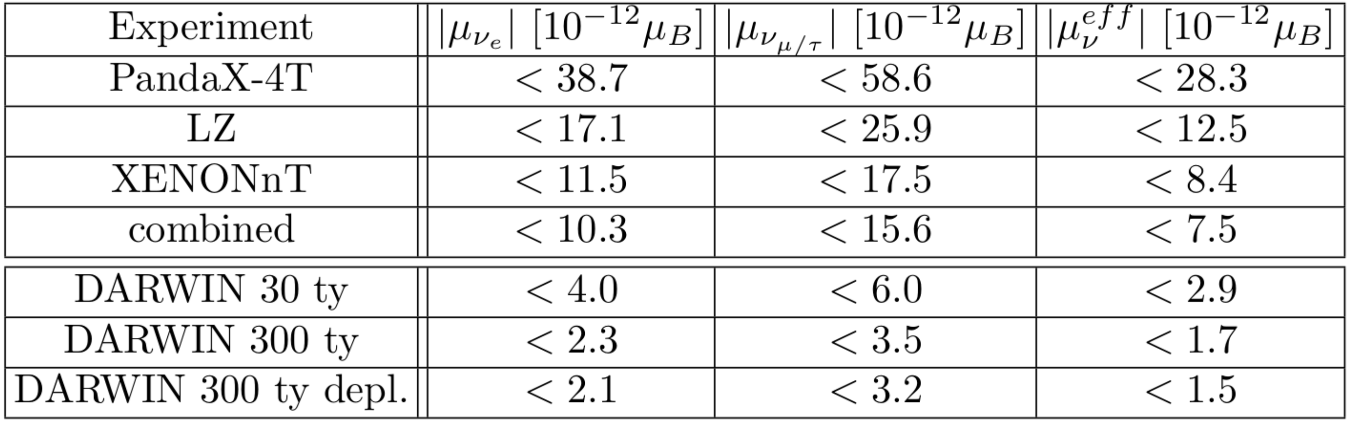
DARWIN will improve these bounds by up to a factor of 5

Giunti, Ternes, 2309.17380, PRD 2023
See also: XENON, 2207.11330, PRL 2022
Atzori Corona et al, 2207.05036, PRD 2023
ShivaSankar, et al, 2208.06415, PLB 2023

Neutrino magnetic moments

Giunti, Ternes, 2309.17380, PRD 2023

$(\Delta\chi^2 = 2.71)$



Experiment	$\lvert\mu_{\nu_e}\rvert\ [10^{-12}\mu_B]$	$\lvert\mu_{\nu_{\mu/\tau}}\rvert\ [10^{-12}\mu_B]$	$\lvert\mu_{\nu}^{eff}\rvert\ [10^{-12}\mu_B]$
PandaX-4T	< 38.7	< 58.6	< 28.3
LZ	< 17.1	< 25.9	< 12.5
XENONnT	< 11.5	< 17.5	< 8.4
combined	< 10.3	< 15.6	< 7.5
DARWIN 30 ty	< 4.0	< 6.0	< 2.9
DARWIN 300 ty	< 2.3	< 3.5	< 1.7
DARWIN 300 ty depl.	< 2.1	< 3.2	< 1.5

DMDD bounds are stronger than BOREXINO bounds:

$$\Delta\chi^2 = 1.64 \quad \mu_{\nu_e} < 3.7 \times 10^{-11}\mu_B\,, \qquad \mu_{\nu_\mu} < 5.0 \times 10^{-11}\mu_B\,, \qquad \mu_{\nu_\tau} < 5.9 \times 10^{-11}\mu_B$$

DARWIN would become competitive with astrophysical observations

$$\mu_\nu < 1.5 \times 10^{-12}\mu_{\mathrm{B}}\ (95\%\ \mathrm{CL})$$

Coloma et al, 2204.03011, JHEP 2022

Capozzi, Raffelt, 2007.03694, PRD 2020

Neutrino millicharges

In some BSM theories neutrinos may acquire small electric charges

The cross section receives extra contributions which add coherently (diagonal charges) and incoherently (non-diagonal charges) to the SM cross section

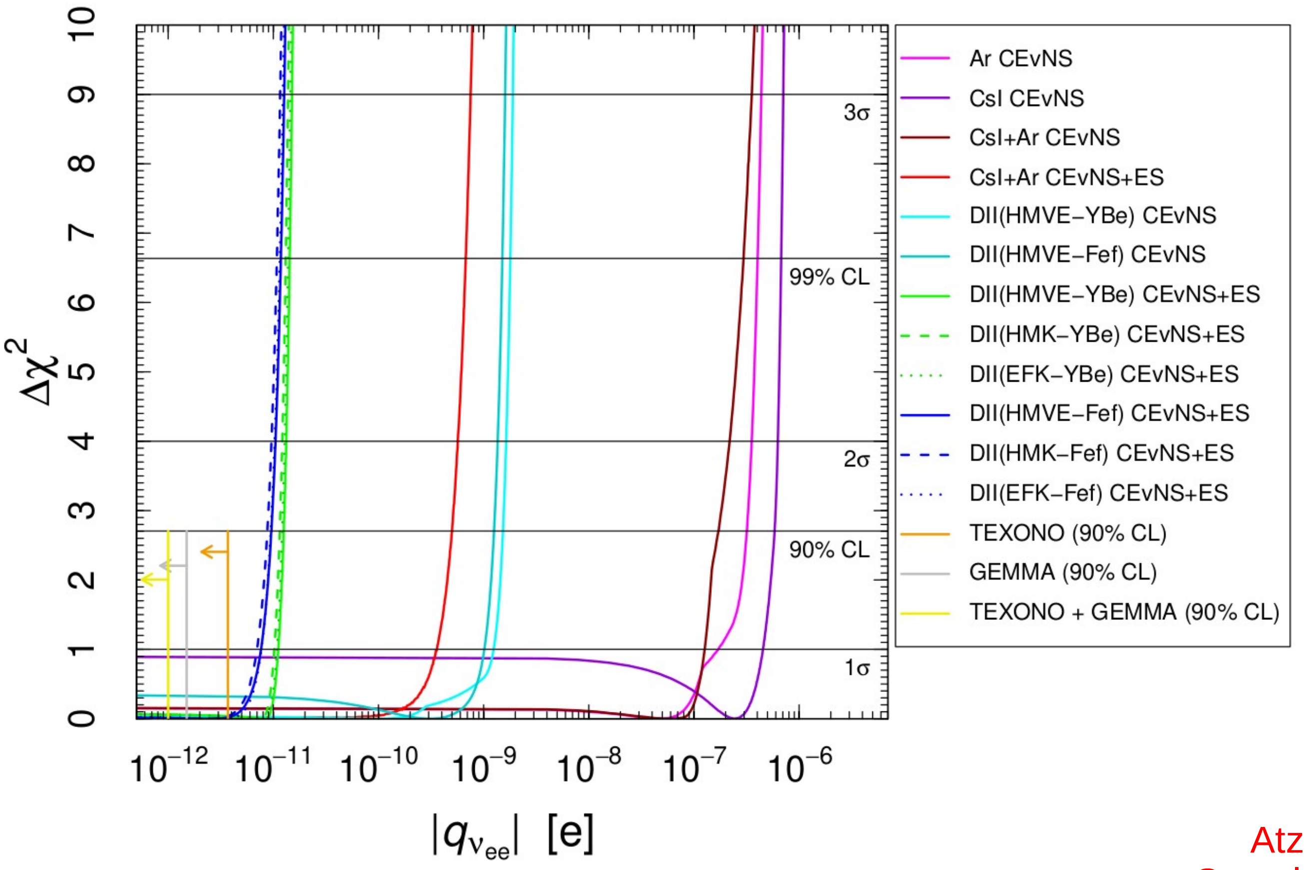
$$\frac{d\sigma^{\mathrm{SM+EC}}_{\nu_\ell-\mathrm{Xe}}}{dT_\mathrm{e}} = \left(\frac{d\sigma^{\mathrm{SM+EC}}_{\nu_\ell-\mathrm{Xe}}}{dT_\mathrm{e}}\right)_{q_{\nu_\ell}} + \sum_{\ell'\neq\ell}\left(\frac{d\sigma^{\mathrm{EC}}_{\nu_\ell-\mathrm{Xe}}}{dT_\mathrm{e}}\right)_{q_{\nu_{\ell\ell'}}}$$

$$g_V^{\nu_\ell} \to g_V^{\nu_\ell} - \frac{\sqrt{2}\pi\alpha}{G_\mathrm{F} m_e T_e} q_{\nu_\ell}$$

$$\left(\frac{d\sigma^{\mathrm{EC}}_{\nu_\ell-\mathrm{Xe}}}{dT_\mathrm{e}}\right)_{q_{\nu_{\ell\ell'}}} = Z^{\mathrm{Xe}}_{\mathrm{eff}}(T_e)\,\frac{\pi\alpha^2}{m_e T_\mathrm{e}^2}\left[1+\left(1-\frac{T_\mathrm{e}}{E_\nu}\right)^2 - \frac{m_e T_\mathrm{e}}{E_\nu^2}\right]|q_{\nu_{\ell\ell'}}|^2.$$

Kouzakov, Studenikin, 1703.00401, PRD 2017

Neutrino millicharges

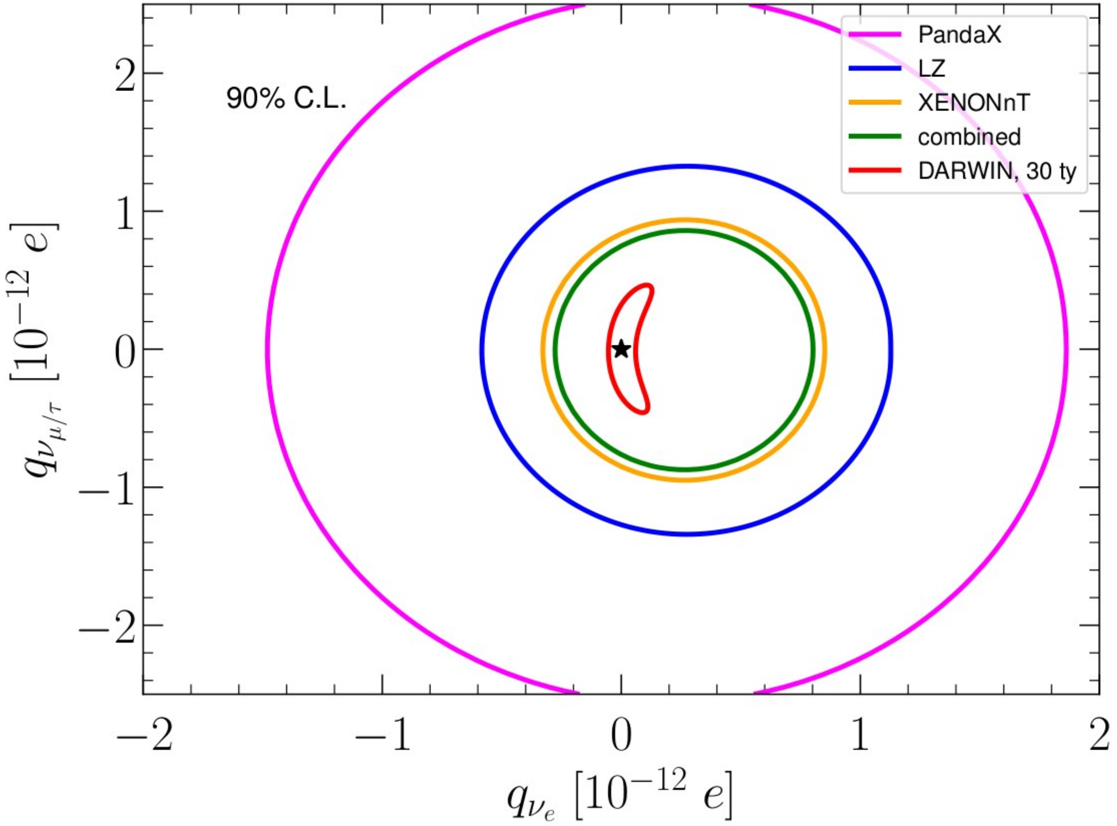


As previously, bounds from CEvNS experiments are not yet competitive with bounds from other experiments

(Similar strength for other charges)

Atzori Corona et al, 2205.09484, JHEP 2022
See also: De Romeri et al, 2211.11905, JHEP 2023

Neutrino millicharges

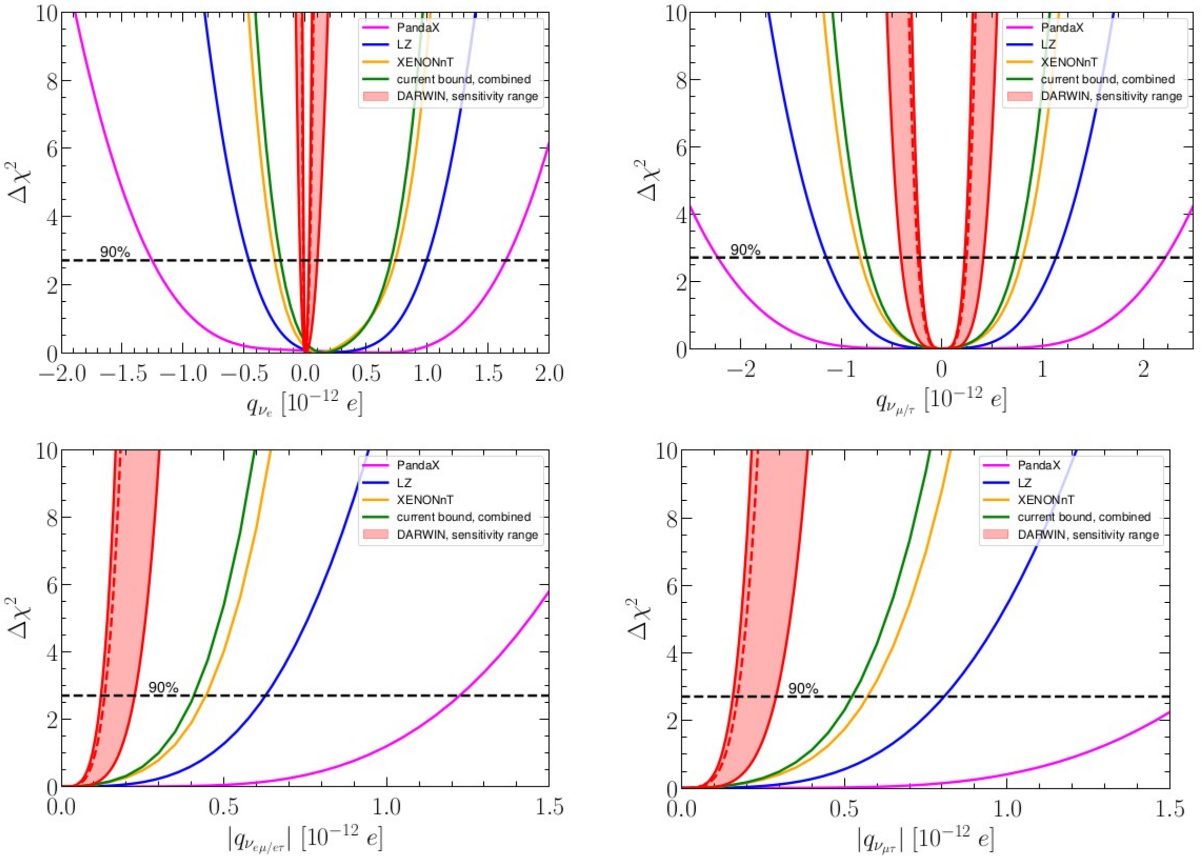


We obtain very strong bounds from DMDD experiments

Cancellations among parameters can occur and must be taken into account when deriving bounds

Giunti, Ternes, 2309.17380, PRD 2023

Neutrino millicharges



We obtain very strong bounds from DMDD experiments

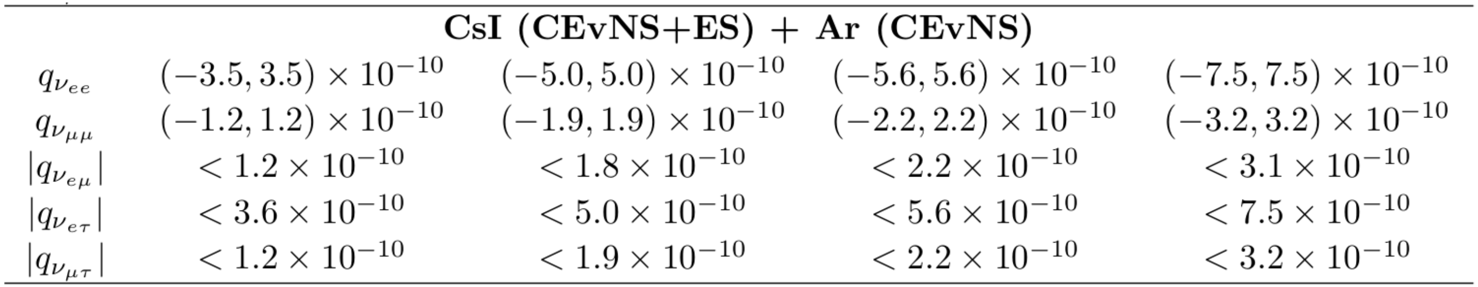
Cancellations among parameters can occur and must be taken into account when deriving bounds

Bounds can be significantly improved by DARWIN

Giunti, Ternes, 2309.17380, PRD 2023

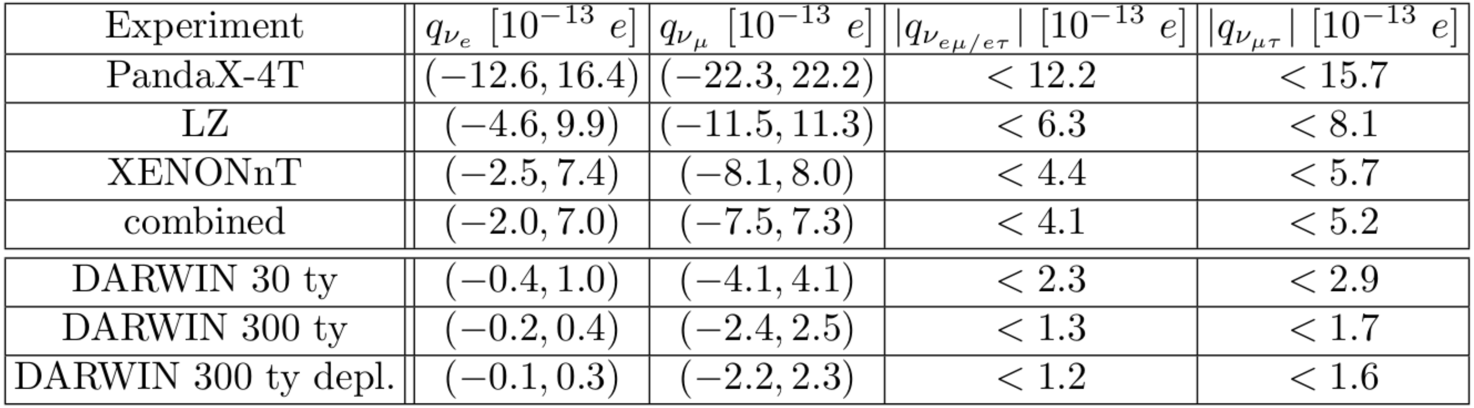
Neutrino millicharges

DMDD bounds are around 3 orders of magnitude more stringent than COHERENT bounds



CsI (CEvNS+ES) + Ar (CEvNS)

$q_{\nu_{ee}}$	$(-3.5, 3.5) \times 10^{-10}$	$(-5.0, 5.0) \times 10^{-10}$	$(-5.6, 5.6) \times 10^{-10}$	$(-7.5, 7.5) \times 10^{-10}$
$q_{\nu_{\mu\mu}}$	$(-1.2, 1.2) \times 10^{-10}$	$(-1.9, 1.9) \times 10^{-10}$	$(-2.2, 2.2) \times 10^{-10}$	$(-3.2, 3.2) \times 10^{-10}$
$\|q_{\nu_{e\mu}}\|$	$< 1.2 \times 10^{-10}$	$< 1.8 \times 10^{-10}$	$< 2.2 \times 10^{-10}$	$< 3.1 \times 10^{-10}$
$\|q_{\nu_{e\tau}}\|$	$< 3.6 \times 10^{-10}$	$< 5.0 \times 10^{-10}$	$< 5.6 \times 10^{-10}$	$< 7.5 \times 10^{-10}$
$\|q_{\nu_{\mu\tau}}\|$	$< 1.2 \times 10^{-10}$	$< 1.9 \times 10^{-10}$	$< 2.2 \times 10^{-10}$	$< 3.2 \times 10^{-10}$

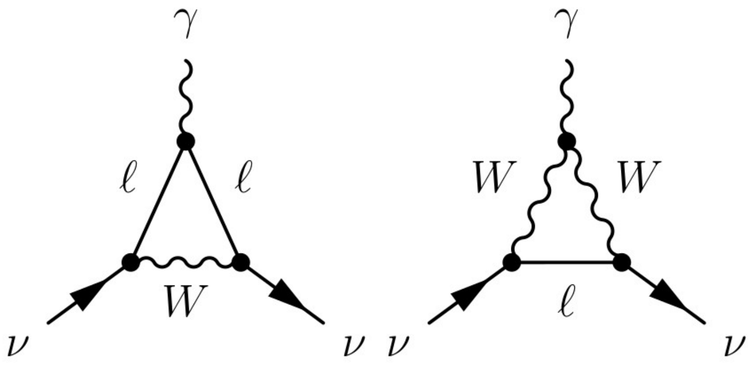


Experiment	q_{ν_e} $[10^{-13}\ e]$	q_{ν_μ} $[10^{-13}\ e]$	$\|q_{\nu_{e\mu/e\tau}}\|$ $[10^{-13}\ e]$	$\|q_{\nu_{\mu\tau}}\|$ $[10^{-13}\ e]$
PandaX-4T	$(-12.6, 16.4)$	$(-22.3, 22.2)$	< 12.2	< 15.7
LZ	$(-4.6, 9.9)$	$(-11.5, 11.3)$	< 6.3	< 8.1
XENONnT	$(-2.5, 7.4)$	$(-8.1, 8.0)$	< 4.4	< 5.7
combined	$(-2.0, 7.0)$	$(-7.5, 7.3)$	< 4.1	< 5.2
DARWIN 30 ty	$(-0.4, 1.0)$	$(-4.1, 4.1)$	< 2.3	< 2.9
DARWIN 300 ty	$(-0.2, 0.4)$	$(-2.4, 2.5)$	< 1.3	< 1.7
DARWIN 300 ty depl.	$(-0.1, 0.3)$	$(-2.2, 2.3)$	< 1.2	< 1.6

Neutrino charge radii

In the Standard Model neutrinos are neutral and there are no electromagnetic interactions at the tree-level

Radiative corrections generate an effective electromagnetic interaction vertex



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

$$\langle r^2_{\nu_e} \rangle_{\text{SM}} = -0.83 \times 10^{-32}\,\text{cm}^2,$$
$$\langle r^2_{\nu_\mu} \rangle_{\text{SM}} = -0.48 \times 10^{-32}\,\text{cm}^2,$$
$$\langle r^2_{\nu_\tau} \rangle_{\text{SM}} = -0.30 \times 10^{-32}\,\text{cm}^2.$$

Bernabeu, et al, hep-ph/0210055 , NPB 2004

Neutrino charge radii

The cross section receives extra contributions which add coherently (diagonal charge radii) and incoherently (non-diagonal charge radii) to the SM cross section

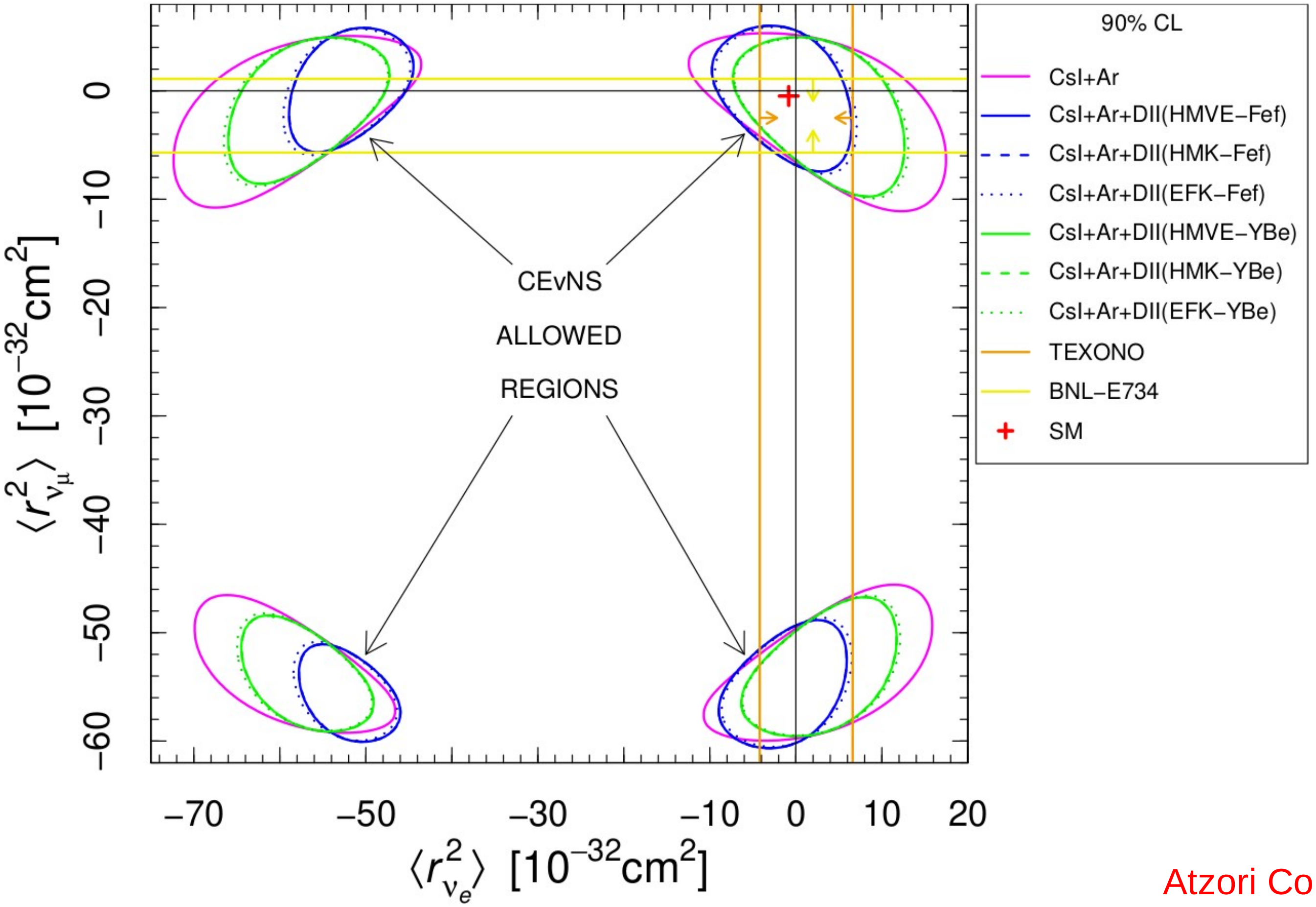
$$\frac{d\sigma^{\mathrm{SM+CR}}_{\nu_\ell-\mathrm{Xe}}}{dT_{\mathrm{e}}} = \left(\frac{d\sigma^{\mathrm{SM+CR}}_{\nu_\ell-\mathrm{Xe}}}{dT_{\mathrm{e}}}\right)_{\langle r^2_{\nu_\ell}\rangle} + \sum_{\ell'\neq\ell}\left(\frac{d\sigma^{\mathrm{CR}}_{\nu_\ell-\mathrm{Xe}}}{dT_{\mathrm{e}}}\right)_{\langle r^2_{\nu_{\ell\ell'}}\rangle}$$

$$g_V^{\nu_\ell} \to g_V^{\nu_\ell} + \frac{\sqrt{2}\pi\alpha}{3G_{\mathrm{F}}}\langle r^2_{\nu_{\ell\ell'}}\rangle$$

$$\left(\frac{d\sigma^{\mathrm{CR}}_{\nu_\ell-\mathrm{Xe}}}{dT_{\mathrm{e}}}\right)_{\langle r^2_{\nu_{\ell\ell'}}\rangle} = Z^{\mathcal{A}}_{\mathrm{eff}}(T_e)\,\frac{\pi\alpha^2 m_e}{9}\left[1+\left(1-\frac{T_e}{E_\nu}\right)^2-\frac{m_e T_e}{E_\nu^2}\right]|\langle r^2_{\nu_{\ell\ell'}}\rangle|^2$$

Kouzakov, Studenikin, 1703.00401, PRD 2017

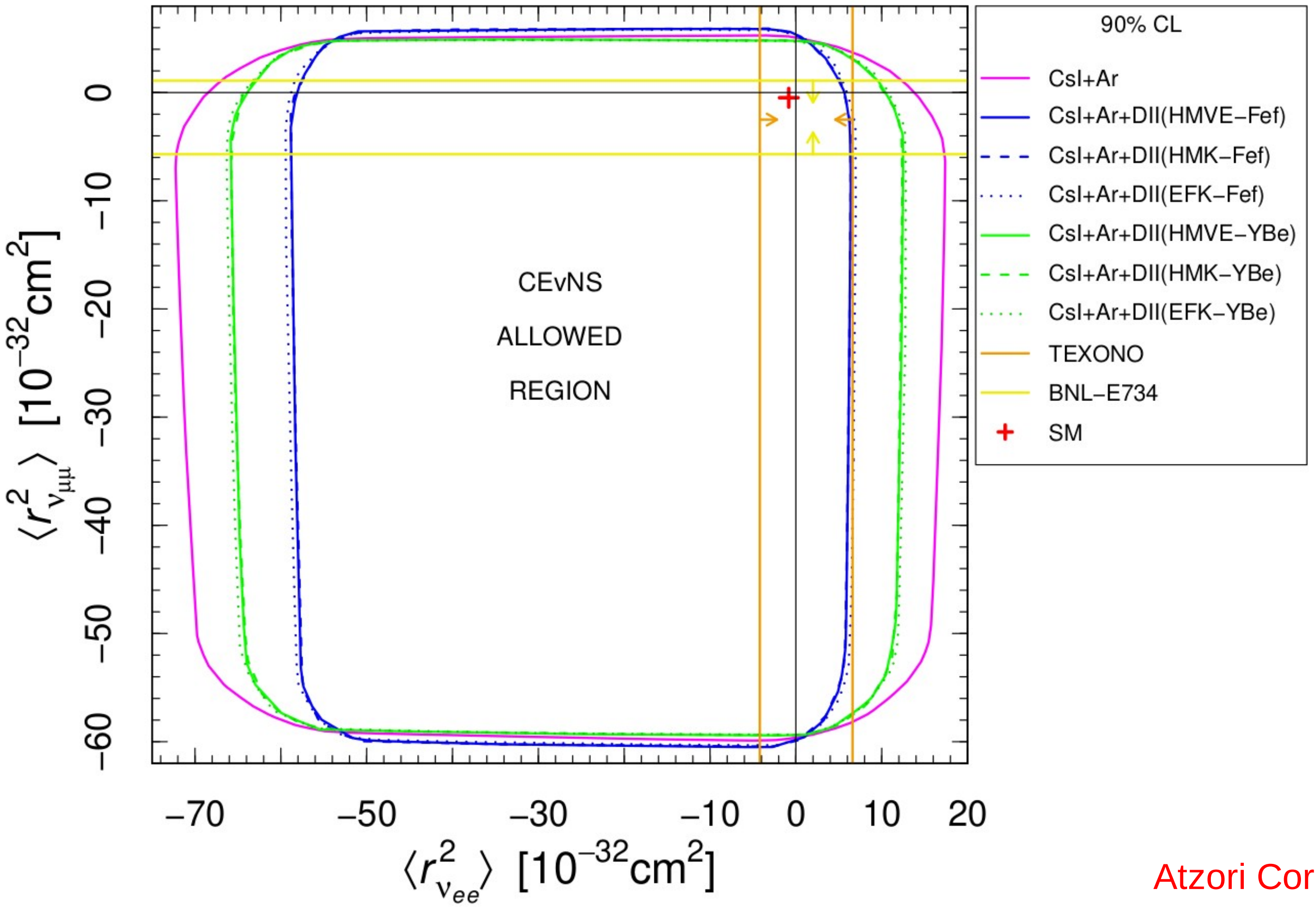
Neutrino charge radii



When allowing only for diagonal elements four separate regions are allowed

Atzori Corona et al, 2205.09484, JHEP 2022

Neutrino charge radii



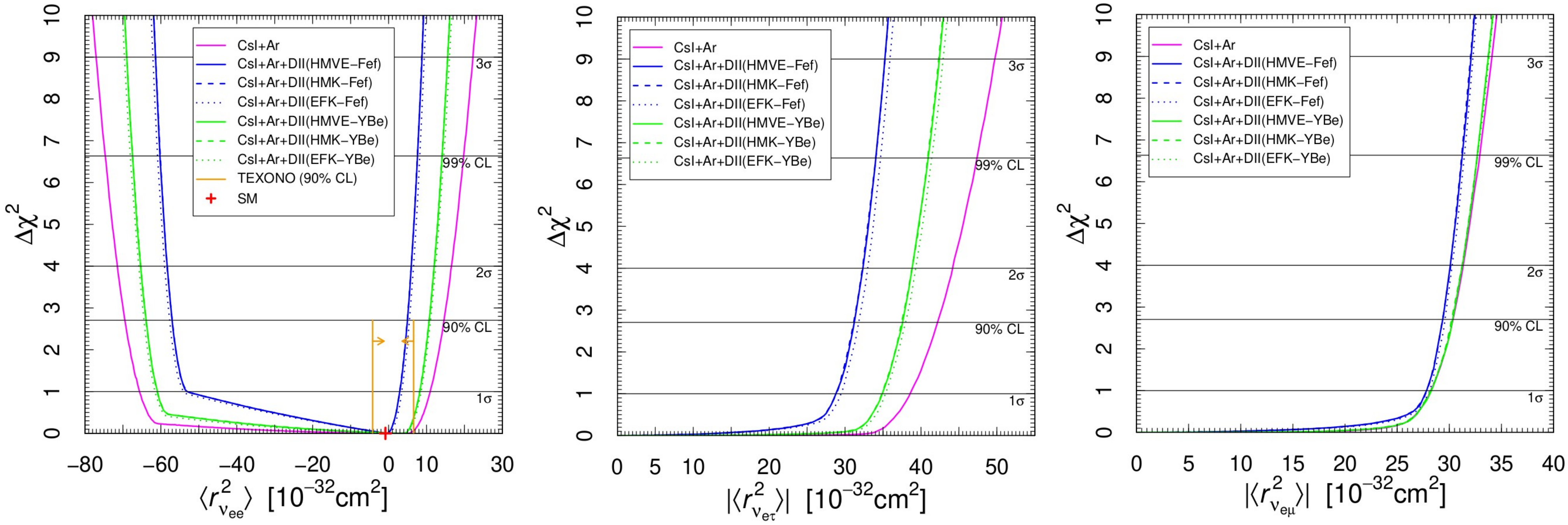
When allowing only for diagonal elements four separate regions are allowed

When marginalizing over the non-diagonal parameters the whole interior region remains allowed

Atzori Corona et al, 2205.09484, JHEP 2022

Neutrino charge radii

Leading bounds on transition charge radii

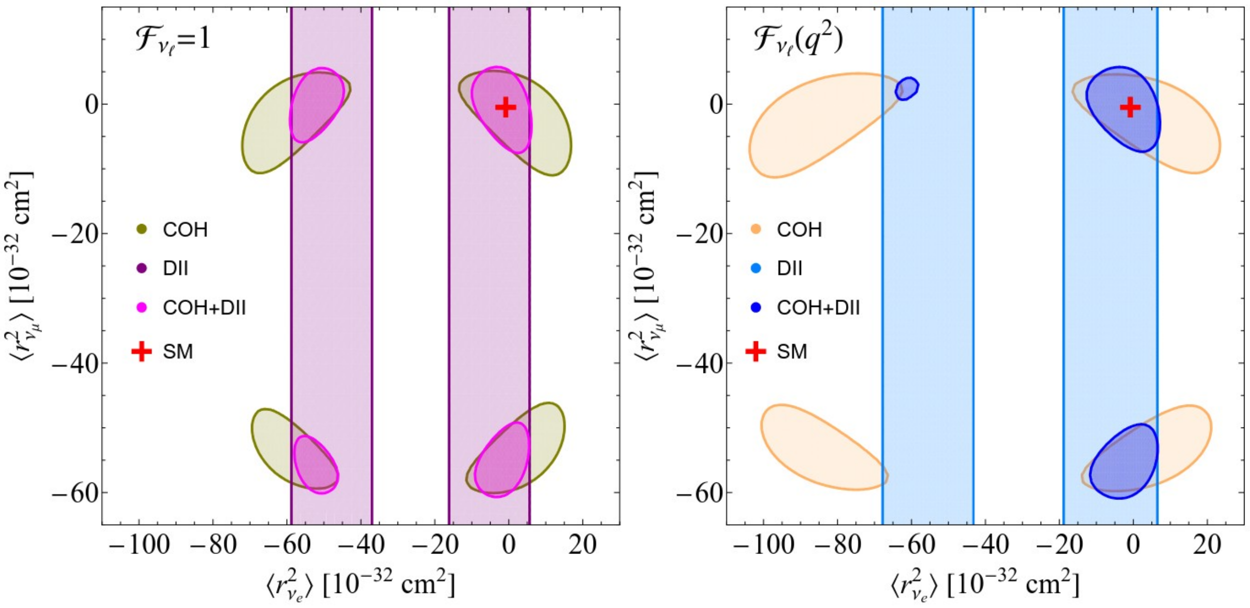


Atzori Corona et al, 2205.09484, JHEP 2022

Neutrino charge radii

$$g_V^p(\nu_\ell) = \rho\left(\frac{1}{2} - 2\sin^2\vartheta_{\rm W}\right) + 2\text{⧖}_{WW} + \square_{WW} - 2\phi_{\nu_\ell W} + \rho(2\boxtimes_{ZZ}^{uL} + \boxtimes_{ZZ}^{dL} - 2\boxtimes_{ZZ}^{uR} - \boxtimes_{ZZ}^{dR})$$

$$g_V^n = -\frac{\rho}{2} + 2\square_{WW} + \text{⧖}_{WW} + \rho(2\boxtimes_{ZZ}^{dL} + \boxtimes_{ZZ}^{uL} - 2\boxtimes_{ZZ}^{dR} - \boxtimes_{ZZ}^{uR}).$$

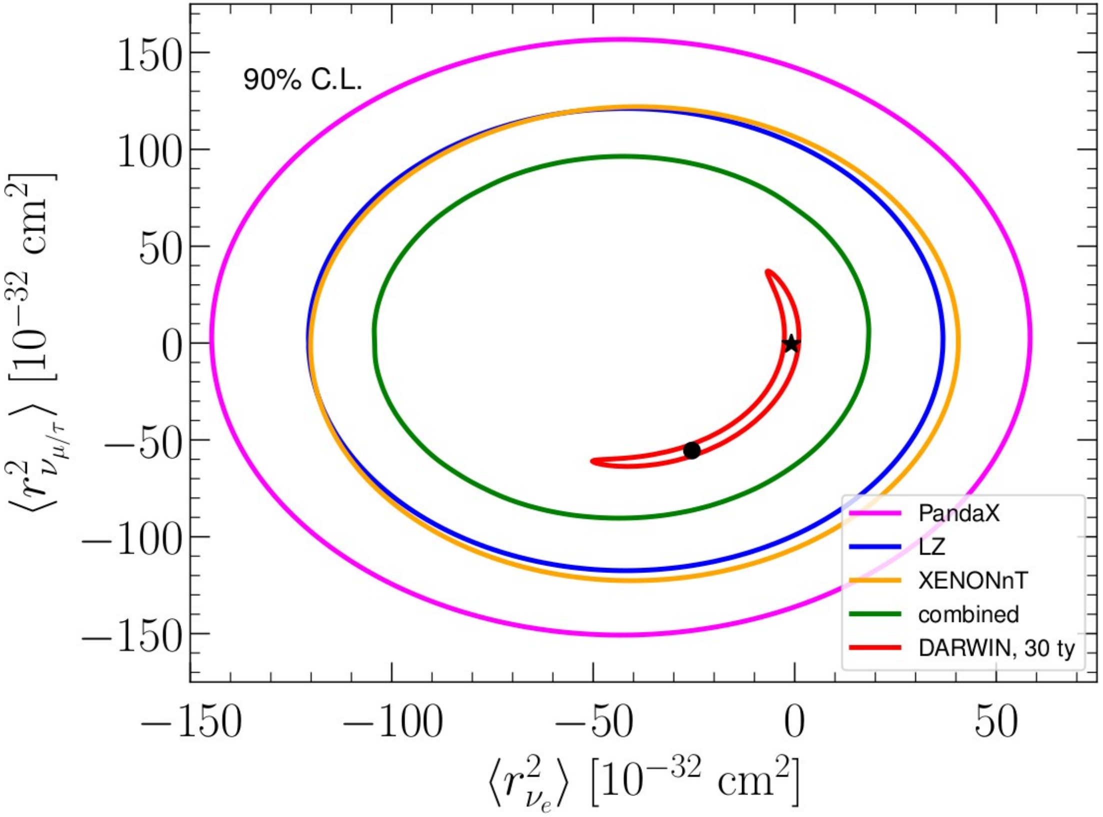


Including radiative corrections improves the combined fit

Since they are momentum dependent they affect the COHERENT analysis stronger

Atzori Corona et al, 2402.16709, JHEP 2024

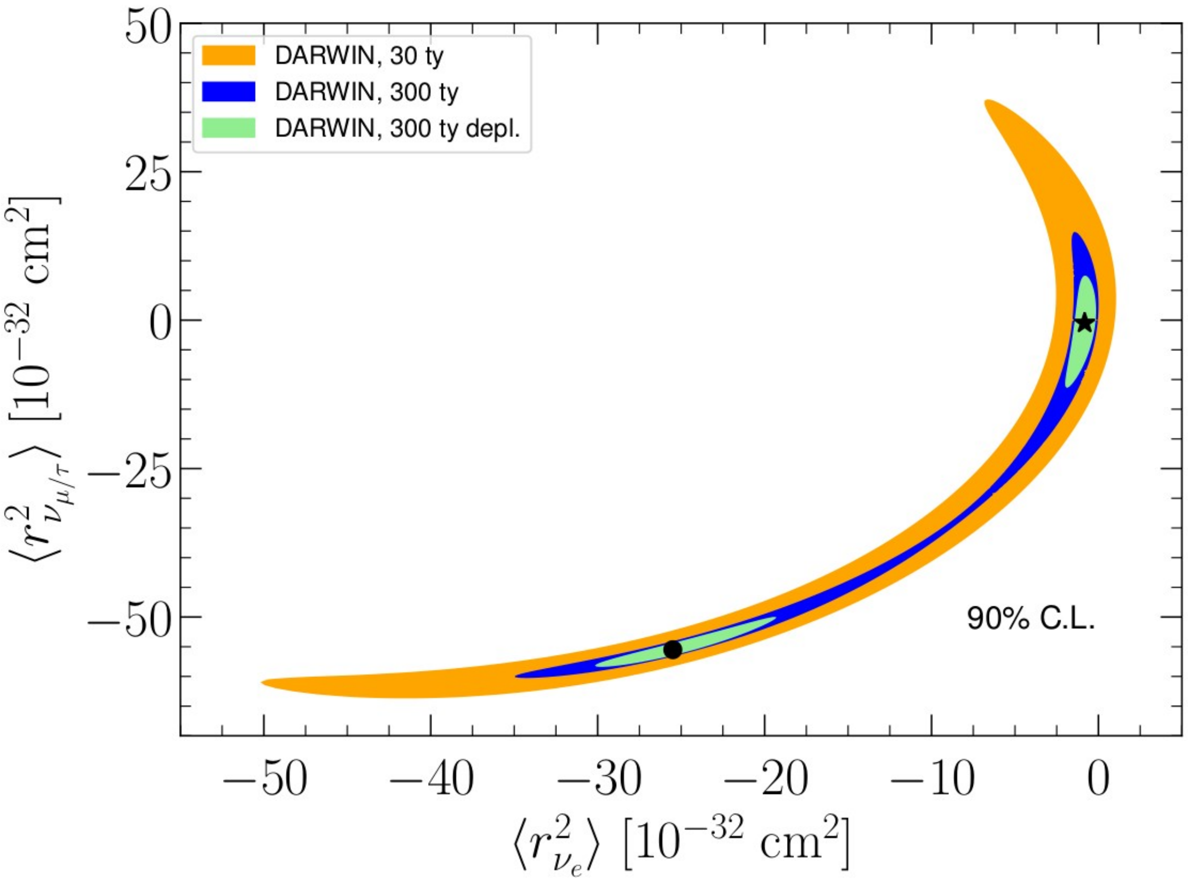
Neutrino charge radii



This time current DMDD experiments are not competitive with CEvNS experiments

Giunti, Ternes, 2309.17380, PRD 2023

Neutrino charge radii



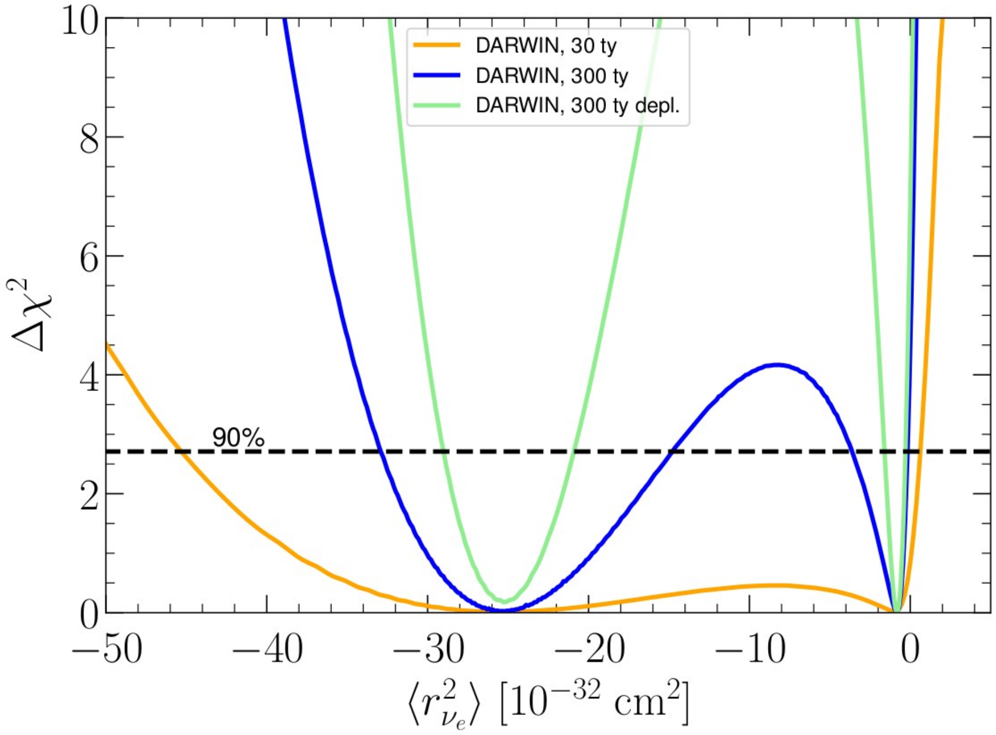
This time current DMDD experiments are not competitive with CEvNS experiments

Situation will dramatically improve with DARWIN

Giunti, Ternes, 2309.17380, PRD 2023

Neutrino charge radii

Giunti, Ternes, 2309.17380, PRD 2023



$$\langle r^2_{\nu_e}\rangle \in (-45.3, 0.6) \times 10^{-32}\ \mathrm{cm}^2,\ \text{DARWIN 30 ty},$$
$$\langle r^2_{\nu_e}\rangle \in \{(-32.9, -14.8)\ \&\ (-3.6, -0.2)\} \times 10^{-32}\ \mathrm{cm}^2,\ \text{DARWIN 300 ty},$$
$$\langle r^2_{\nu_e}\rangle \in \{(-29.1, -20.7)\ \&\ (-1.6, -0.3)\} \times 10^{-32}\ \mathrm{cm}^2,\ \text{DARWIN 300 ty, depleted}$$

This time current DMDD experiments are not competitive with CEvNS experiments

Situation will dramatically improve with DARWIN

DARWIN could provide the first ever measurement of one of the charge radii

Conclusions

Neutrino scattering experiments provide powerful tools for SM tests and BSM searches

Currently EvES provides stronger bounds on most light mediator models, on the (effective) neutrino magnetic moments and neutrino electric charges than CEvNS

Charge radii are better constrained using CEvNS data

DARWIN could provide the first measurement of one of the charge radii

Grazie!