Novel constraints on neutrino physics beyond the standard model of elementary particles from the CONUS experiment

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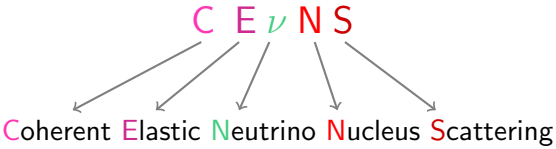
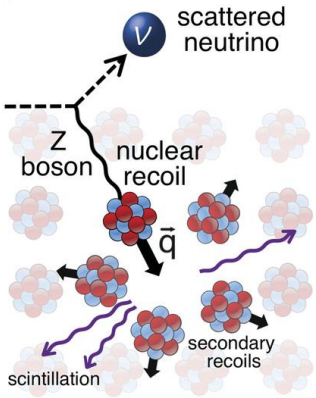
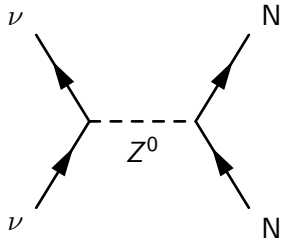
NBIA Summer School, 09/07/2025

Introduction Part 1



Coherent Elastic Neutrino Nucleus Scattering





Coherence condition: $qR \lesssim 1 \Rightarrow$ at small momentum transfer + low E_ν (wavelength bigger than nucleus)

Coherent Elastic Neutrino Nucleus Scattering

➢ Weak charge: $Q_W = g_V^p Z + g_V^n N = \left(\frac{1}{2} - 2\sin^2\theta_W\right) Z - \frac{1}{2} N \approx -\frac{1}{2} N$ ($\sin^2\theta_W \approx 1/4$)

➢ Cross section: $\frac{d\sigma}{dT} \sim \frac{G_F^2 M}{2\pi} \frac{N^2}{4} F^2(q) \left(2 - \frac{MT}{E_\nu^2}\right)$

$$T_{max}(E_\nu) = \frac{2E_\nu^2}{M + 2E_\nu}$$

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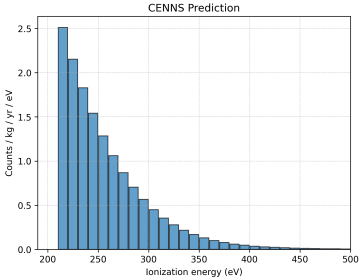
- Need high cross section and low threshold
- Additional challenge: quenching



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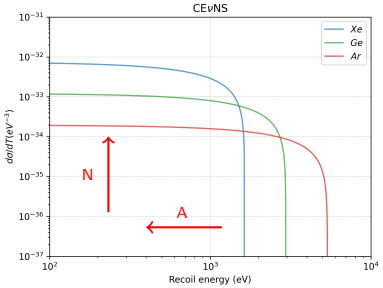

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Medium mass of Ge isotopes

- Why is this interaction interesting?
  - $\Rightarrow$ High cross section.
  - $\Rightarrow$ Experimental setups do not need to have the huge masses of inverse beta decay or elastic neutrino electron scattering experiments.

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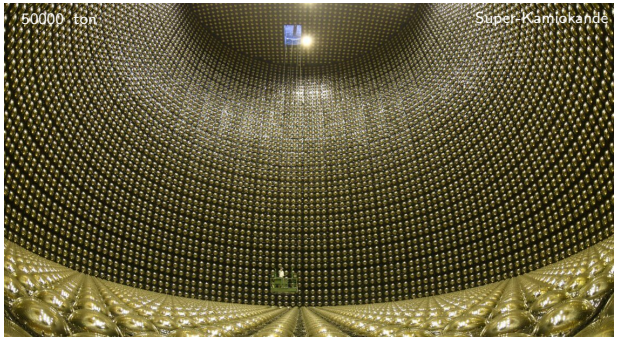


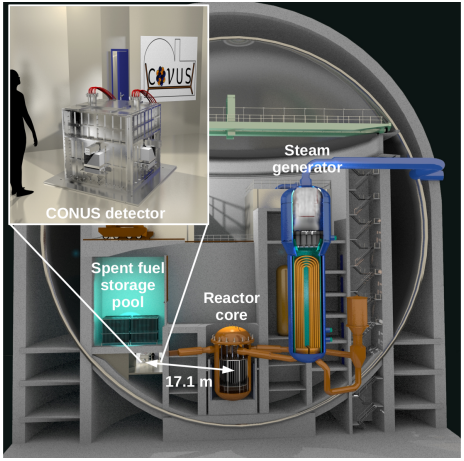
Introduction Part 2

- Why is this interaction interesting?
  - $\Rightarrow$ High cross section.
  - $\Rightarrow$ Experimental setups do not need to have the huge masses of inverse beta decay or elastic neutrino electron scattering experiments.
  - $\Rightarrow$ Clean channel that is very sensitive to new physics.
  - $\Rightarrow$ Test the SM for BSM effects.

Timeline of CEνNS

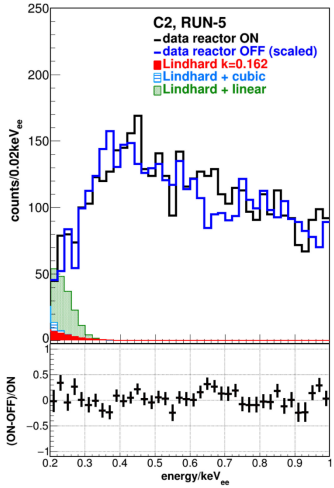
1974	CEνNS predicted by D. Freedmen.
2017	First observation at the COHERENT experiment (CsI detector).
2021	Follow-up detection in Argon at the COHERENT experiment.
2024	Follow-up detection in Germanium at the COHERENT experiment.
2024	First indication of solar neutrinos at XENONnT (T 41.3) and PandaX-4T.
2025	First observation of antineutrinos in reactors in the CONUS+ experiment.
More	TEXONO, CONNIE, RICOCHET, NUCLEUS, νGeN, Dresden-II, MINER and other running experiments.

CONUS Experiment



Location: Nuclear Power Plant in Brokdorf, Germany
Thermal Power: 3.9 GW
Detectors: four 1 kg Germanium crystals
Shield: layered lead, borated and non-borated polyethylene, plastic scintillator plates with PMTs (muon veto)
Overburden: 24 m of water equivalent average
Data acquisition during reactor ON and OFF periods
Run 5: 05/2021 - 07/2022.

CONUS final results



210 eV_{ee} threshold detectors

Detector	Reactor on (kg d)	Reactor off (kg d)
C1	141.5	40.2
C2	145.5	130.3
C4	139.0	101.6
Total	426	272

arXiv: 2401.07684

➢CEνNS $<$ 0.34 signal events/kg/day

➢Brokdorf power plant ended operations in 2021

Almost 1 yr of reactor OFF data collected

Log-Likelihood procedure:

$$-2\log\mathcal{L} = -2\log\mathcal{L}_{\mathrm{ON}} - 2\log\mathcal{L}_{\mathrm{OFF}} + 2\sum_i \frac{(\Theta_i - \Theta_i^*)^2}{2\sigma_i^2}$$

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ON and OFF data simultaneously fitted

Analysis Method

Log-Likelihood procedure:

$$-2\log\mathcal{L} = -2\log\mathcal{L}_{\mathrm{ON}} - 2\log\mathcal{L}_{\mathrm{OFF}} + 2\sum_i \frac{(\Theta_i - \Theta_i^*)^2}{2\sigma_i^2}$$

$$\mathcal{L}_{ON}(\Theta_{add}, \Theta_{MC}, \Theta_{LEAK1,2}, \Theta_{reactor}, \Theta_{det}, \Theta_{\Delta E})$$

Log-Likelihood procedure:

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$$\mathcal{L}_{OFF}(\Theta_{MC}, \Theta_{LEAK1,2}, \Theta_{det}, \Theta_{\Delta E})$$

Analysis Method

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Additional knowledge: Gaussian pull terms

BSM Studies

- ✓ Vector NSI
- ✓ Light mediators

BSM Studies

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- ✓ Light mediators
  - Light Scalar
  - Light Vector

BSM Studies Part 1 (NSI)

New vector neutrino-quark interaction $\mathcal{O}_{NSI}^{qV} = (\bar{\nu_\alpha}\gamma^\mu L\nu_\beta)(\bar{q}\gamma_\mu Pq) + h.c.$

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Vector NSI weak charge: $\mathcal{Q}_{NSI}^{qV} = (g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV})Z + (g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV})N$

$$+ \sum_{\alpha,\beta} \left[\left(2\varepsilon_{\alpha\beta}^{uV} + \varepsilon_{\alpha\beta}^{dV} \right) Z + \left(\varepsilon_{\alpha\beta}^{uV} + 2\varepsilon_{\alpha\beta}^{dV} \right) N \right]$$

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Only ν_e ($\bar{\nu}_e$) and no oscillation

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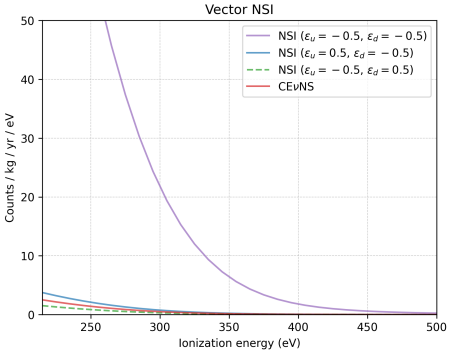
Potential destructive interference

Vector NSI weak charge: $\mathcal{Q}_{NSI}^{qV} = (g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV})Z + (g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV})N$



Total exposure (kg d): 426 (ON), 272 (OFF)

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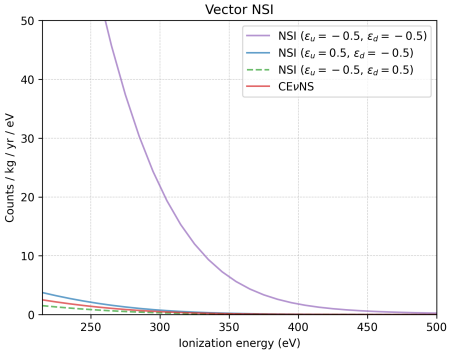

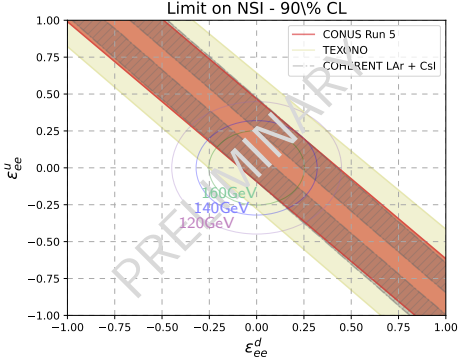

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Sensitivity to new mediator mass: $\varepsilon \approx \frac{g_X^2}{g^2}\frac{M_W^2}{M_X^2}$

≈ 140 GeV

Light scalar mediator:

$$\mathcal{L}_\phi = \phi \left(g_\phi^{qS} \bar{q} q + g_\phi^{eS} \bar{e} e + g_\phi^{\nu S} \bar{\nu}_R \nu_L + \text{h.c.} \right) - \frac{1}{2} m_\phi^2 \phi^2$$

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Universal couplings assumed

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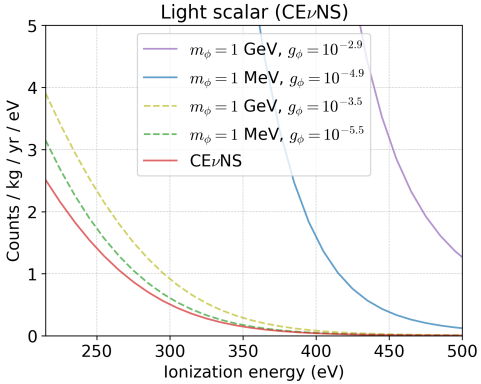

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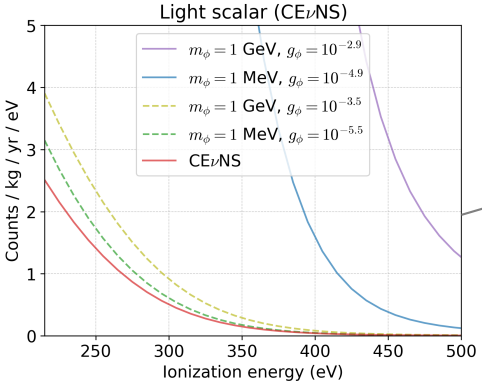

No destructive interference

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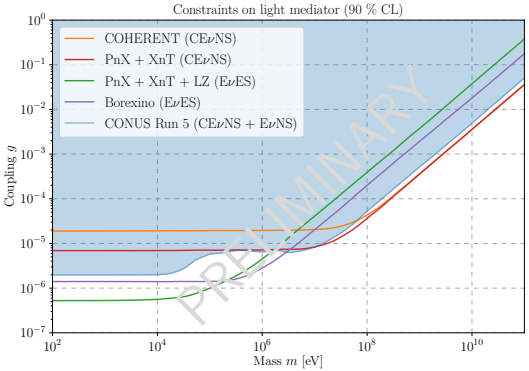

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$$\mathcal{L}_{Z'} = Z'_\mu \left(g_{Z'}^{qV} \bar{q} \gamma^\mu q + g_{Z'}^{eV} \bar{e} \gamma^\mu e + g_{Z'}^{\nu V} \bar{\nu}_R \gamma^\mu \nu_L \right) + \frac{1}{2} m_{Z'}^2 Z'_\mu Z'^\mu$$

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Universal couplings: $g_{Z'}^{qV} = g_{Z'}^{eV} = g_{Z'}^{\nu V} \equiv g$

B-L coupling: $g_{Z'}^{eV} = g_{Z'}^{\nu V} = -3 g_{Z'}^{qV} \equiv g$

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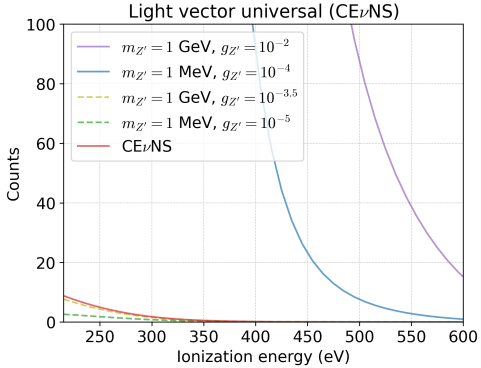

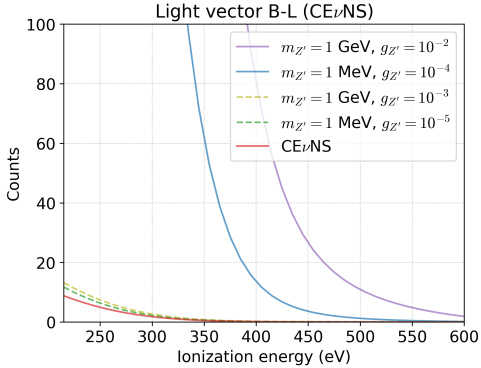

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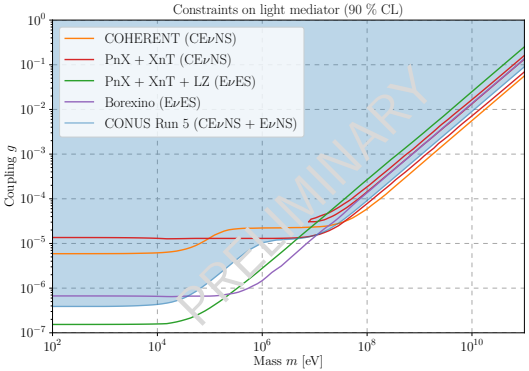

Universal

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B-L

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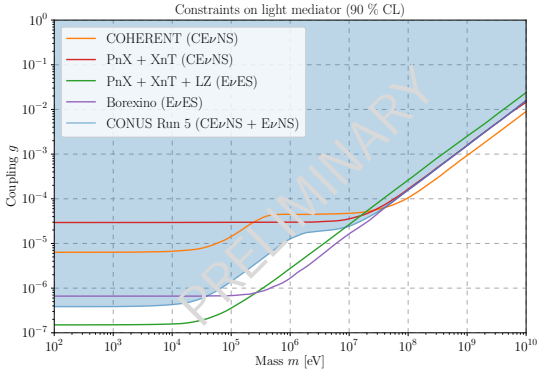

Outlook

Ongoing: BSM analysis of new data from the CONUS+ experiment.

Outlook

CONUS+ ⟶ New location: Leibstadt, Switzerland. 3.6 GW reactor.

Outlook

CONUS+ → New location: Leibstadt, Switzerland. 3.6 GW reactor.

CONUS+ → Run 1 with four 1 kg HPGe detectors

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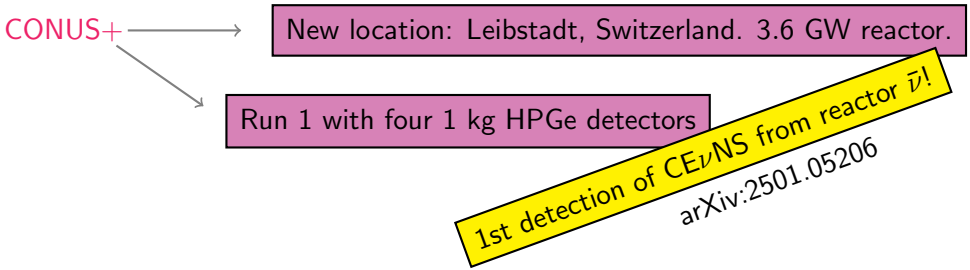
CONUS+ → Run 1 with four 1 kg HPGe detectors

Improved detectors: lower threshold

Outlook

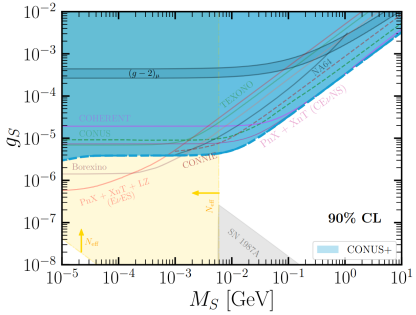

CONUS+
New location: Leibstadt, Switzerland. 3.6 GW reactor.
Run 1 with four 1 kg HPGe detectors
1st detection of CEνNS from reactor $\bar{\nu}$!
arXiv:2501.05206

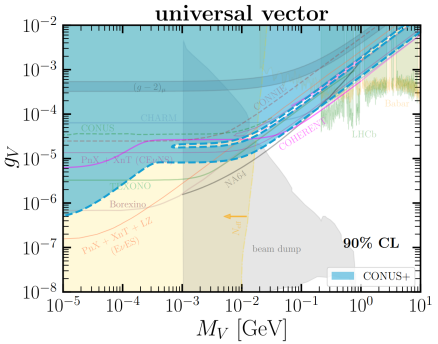
Outlook

CONUS+ → New location: Leibstadt, Switzerland. 3.6 GW reactor.

→ Run 1 with four 1 kg HPGe detectors

BSM studies:





V. De Romeri et al.

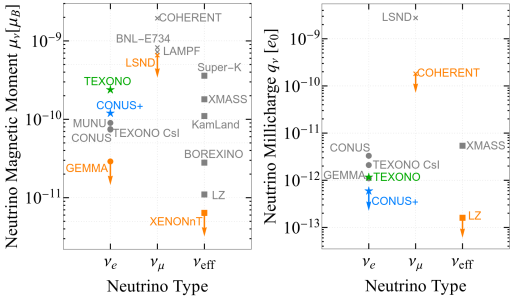
arXiv:2501.17843v2

Outlook

CONUS+ → New location: Leibstadt, Switzerland. 3.6 GW reactor.

→ Run 1 with four 1 kg HPGe detectors

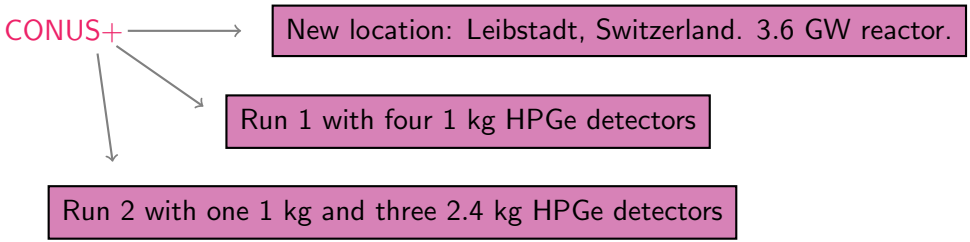
BSM studies:



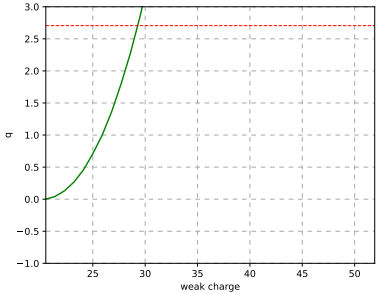
M. Atzori Corona et al.

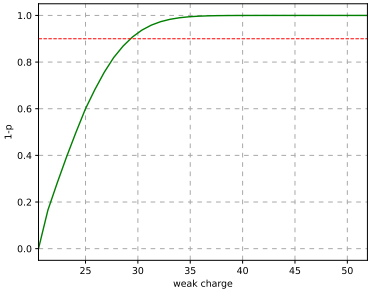
arXiv:2501.18550v2

Outlook

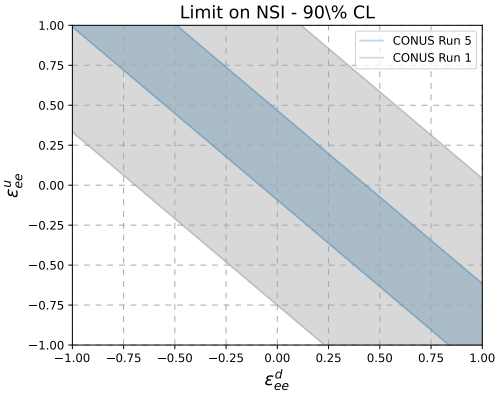

CONUS+
New location: Leibstadt, Switzerland. 3.6 GW reactor.
Run 1 with four 1 kg HPGe detectors
Run 2 with one 1 kg and three 2.4 kg HPGe detectors

Vector NSI

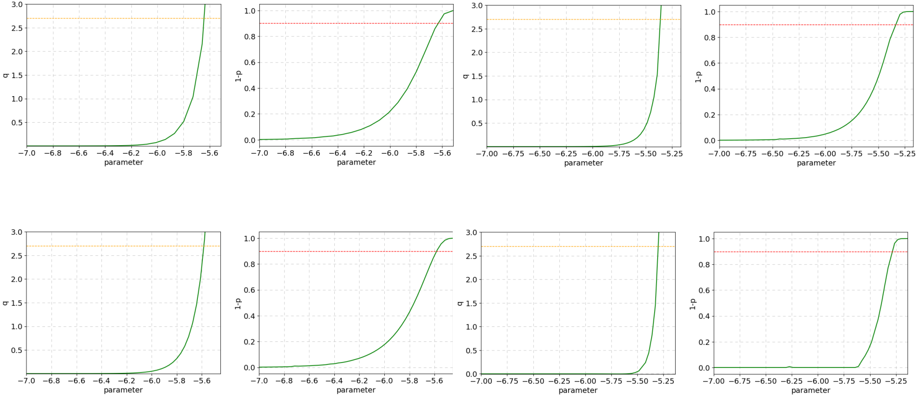




BACKUP


Limit on NSI - 90\% CL
CONUS Run 5
CONUS Run 1
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
ε^u_{ee}
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
ε^d_{ee}

BACKUP



Electromagnetic properties

- In SM neutrinos have no electromagnetic properties.
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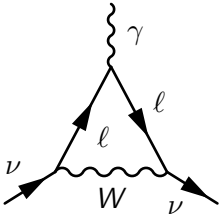

Cross section in elastic neutrino electron scattering (EνNS):

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[J. Hempfling, PhD thesis, 2024]