Constraining new physics scenarios with COHERENT data

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Outline

- ✓ Introduction
- ✓ Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)
- ✓ The COHERENT Experiment
- ✓ Phenomenology of CEvNS
  - ✓ Non-Standard Interactions
  - ✓ Neutrino Magnetic Moment
  - ✓ Leptoquarks

Based on JHEP 04 (2023) 035
In collaboration with V. De Romeri, O.G. Miranda, D.K. Papoulias, GSG, M. Tórtola and J.W.F. Valle.

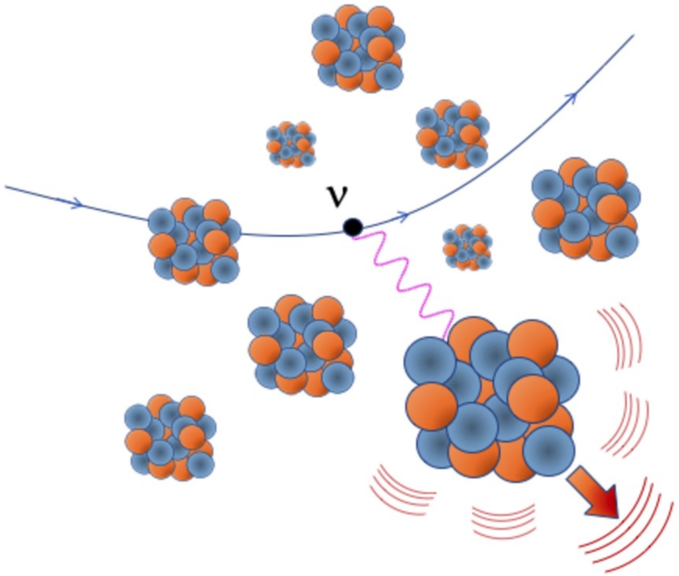
And arXiv 2307.13790
In collaboration with V. De Romeri, V. M. Lozano, and GSG

Coherent Elastic Neutrino-Nucleus Scattering

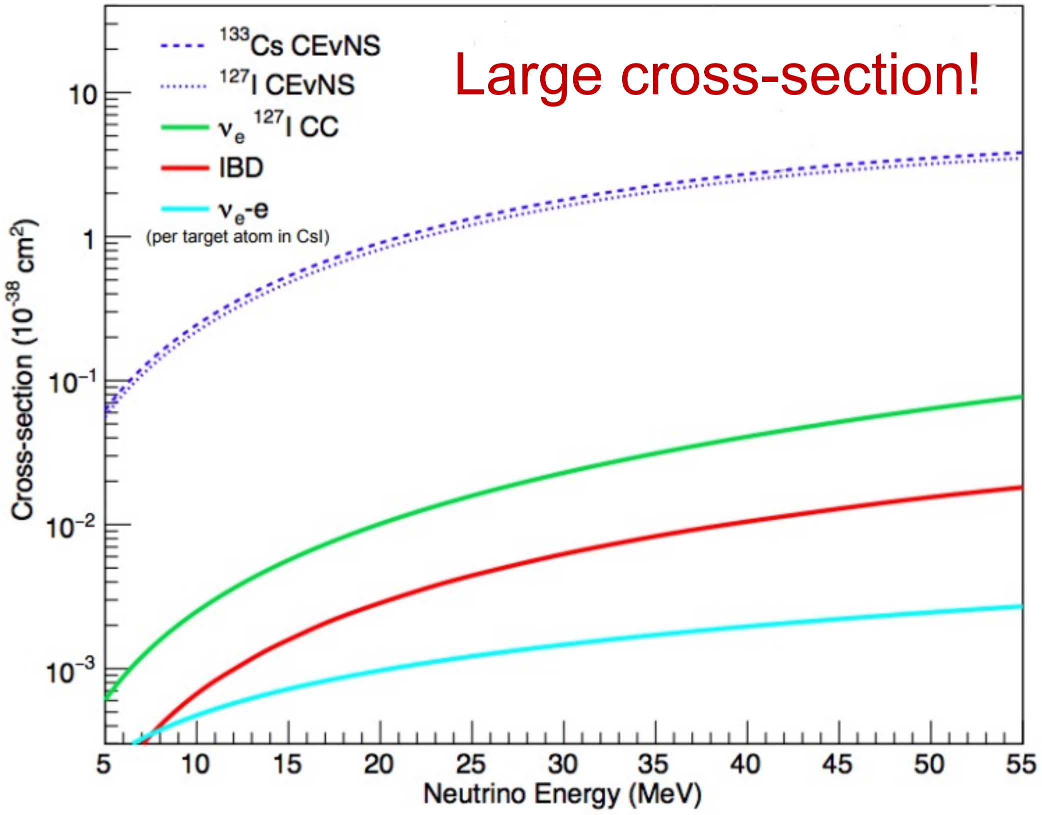
Neutral current process within the SM.

Neutrino interacts with a nucleus as a **whole.**

The nucleus acquires a kinetic recoil energy.



https://nucleus-experiment.org/main-topic-1



D. Akimov et al. Science, 357(6356) 1123–1126 (2017).

CEvNS cross section

$$\frac{d\sigma_{\nu\mathcal{N}}}{dE_{\mathrm{nr}}}\bigg|^{\mathrm{SM}}_{\mathrm{CE}\nu\mathrm{NS}} = \frac{G_F^2 m_N}{\pi} F_W^2(|\vec{q}|^2)\left(Q_V^{\mathrm{SM}}\right)^2\left(1 - \frac{m_N E_{\mathrm{nr}}}{2E_\nu^2}\right)$$

CEvNS cross section

$$\frac{d\sigma_{\nu\mathcal{N}}}{dE_{\mathrm{nr}}}\Big|_{\mathrm{CE}\nu\mathrm{NS}}^{\mathrm{SM}} = \frac{G_F^2 m_N}{\pi}\boxed{F_W^2(|\vec{q}|^2)}\left(Q_V^{\mathrm{SM}}\right)^2\left(1-\frac{m_N E_{\mathrm{nr}}}{2E_\nu^2}\right)$$

Form Factor

$$F_W(|\vec{q}|^2) = 3\frac{j_1(|\vec{q}|R_A)}{|\vec{q}|R_A}\left(\frac{1}{1+|\vec{q}|^2 a_k^2}\right)$$

Klein-Nystrand

CEvNS cross section

$$\left.\frac{d\sigma_{\nu\mathcal{N}}}{dE_{\rm nr}}\right|^{\rm SM}_{\rm CE\nu NS} = \frac{G_F^2 m_N}{\pi} F_W^2(|\vec{q}|^2)\left(Q_V^{\rm SM}\right)^2\left(1-\frac{m_N E_{\rm nr}}{2E_\nu^2}\right)$$

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Klein-Nystrand

SM weak charge

$$Q_V^{\rm SM} = g_V^p Z + g_V^n N\,,$$

$|g_V^p| \ll |g_V^n|$

The cross section
effectively scales as N^2

Why do we care about CEvNS?

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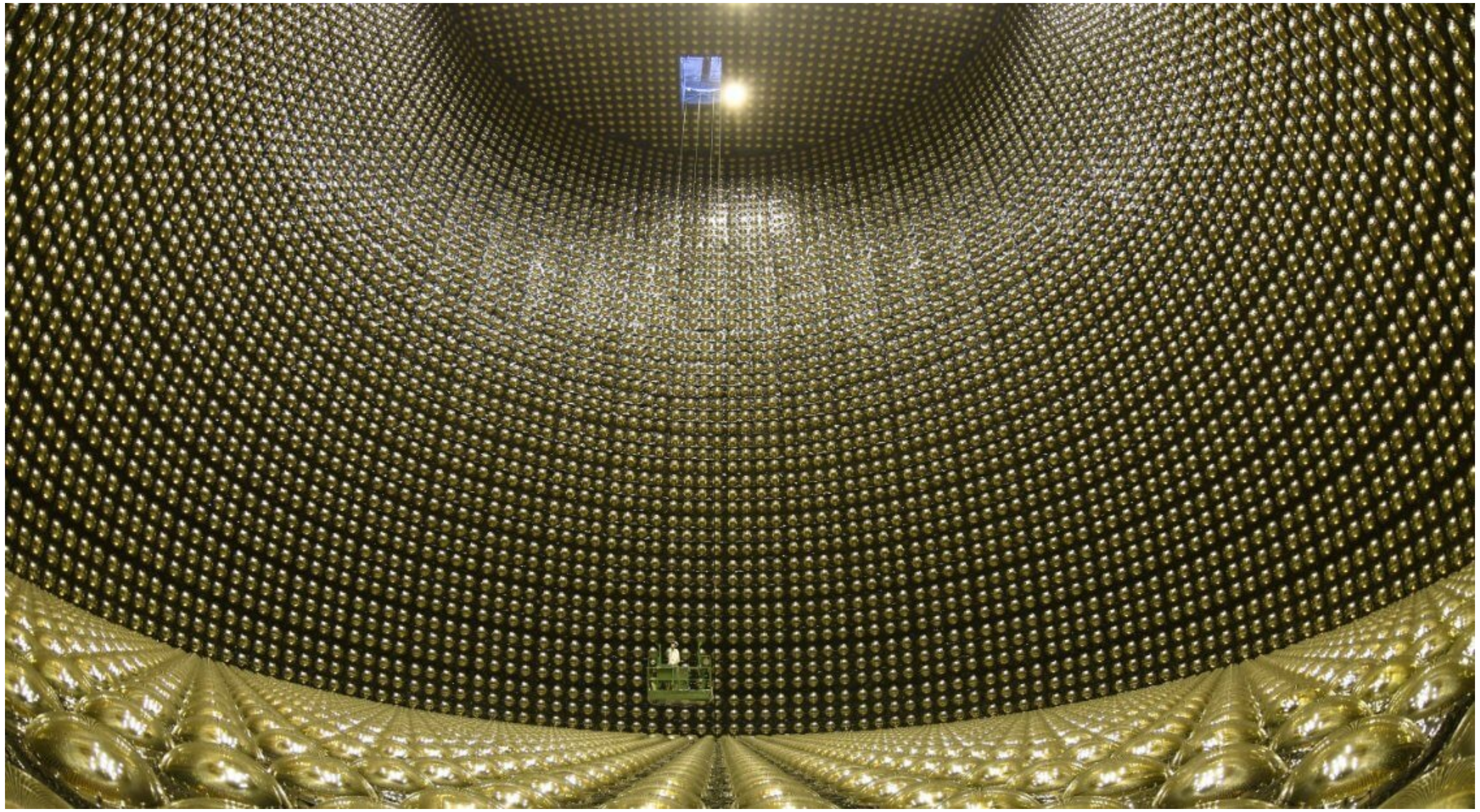
Usually, neutrino detectors are huge!



https://www-sk.icrr.u-tokyo.ac.jp/

Why do we care about CEvNS?

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The **characteristic N^2 dependence** allows to use small detectors!

https://sites.duke.edu/coherent/

Why do we care about CEvNS?

The **characteristic N^2 dependence** allows to use small detectors!

In addition:

We can perform tests to SM parameters.

Study the phenomenology of a variety of new physics scenarios!

https://sites.duke.edu/coherent/

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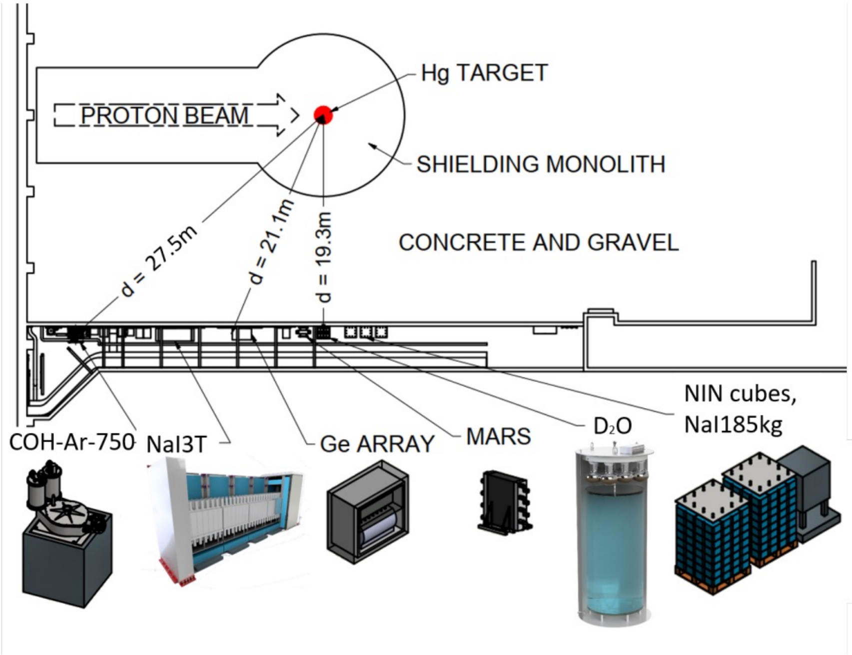
How to measure CEvNS?

The COHERENT experiment

$$\begin{array}{llllll} \pi^+ & \rightarrow & \mu^+ & + & \nu_\mu & \\ & & \downarrow & & & \\ & & e^+ & + & \nu_e & + \ \bar{\nu}_\mu \end{array}$$

Use of pion decay at rest neutrinos at the Spallation Neutron Source



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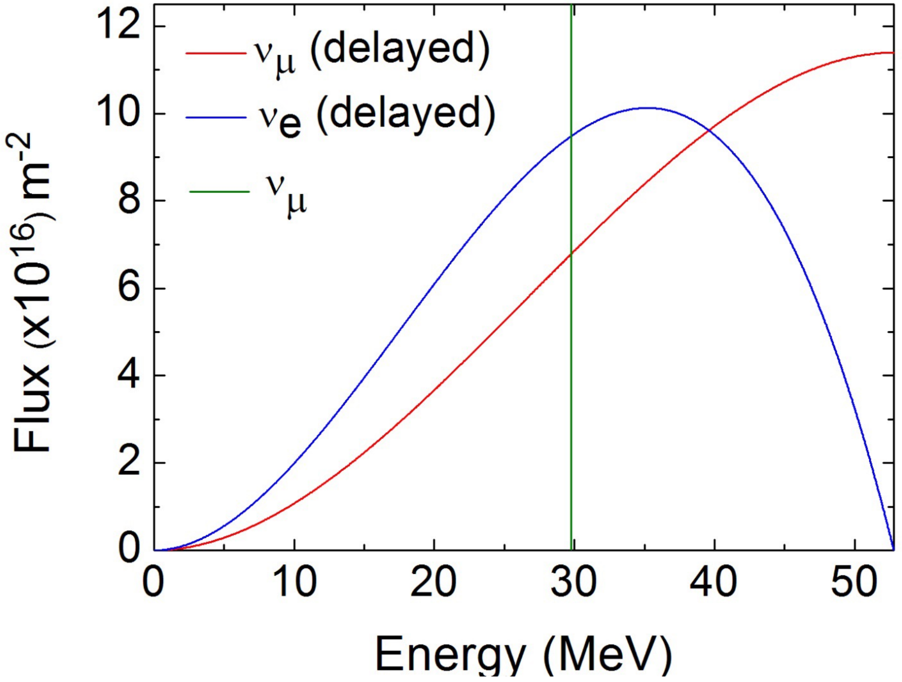

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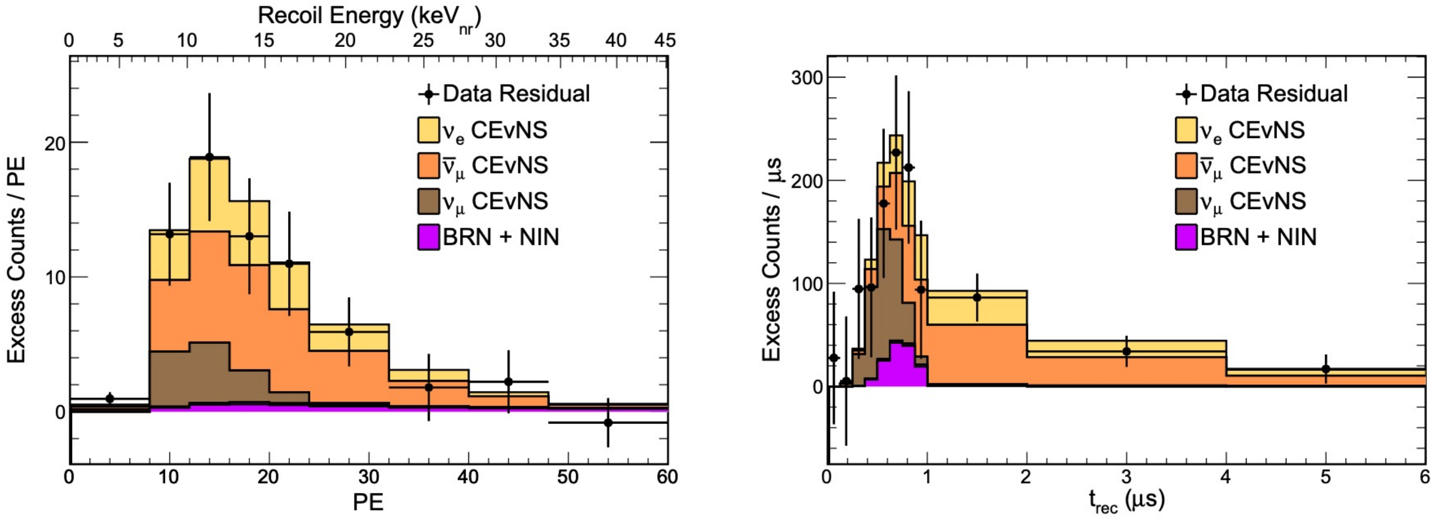
Status of the COHERENT experiment

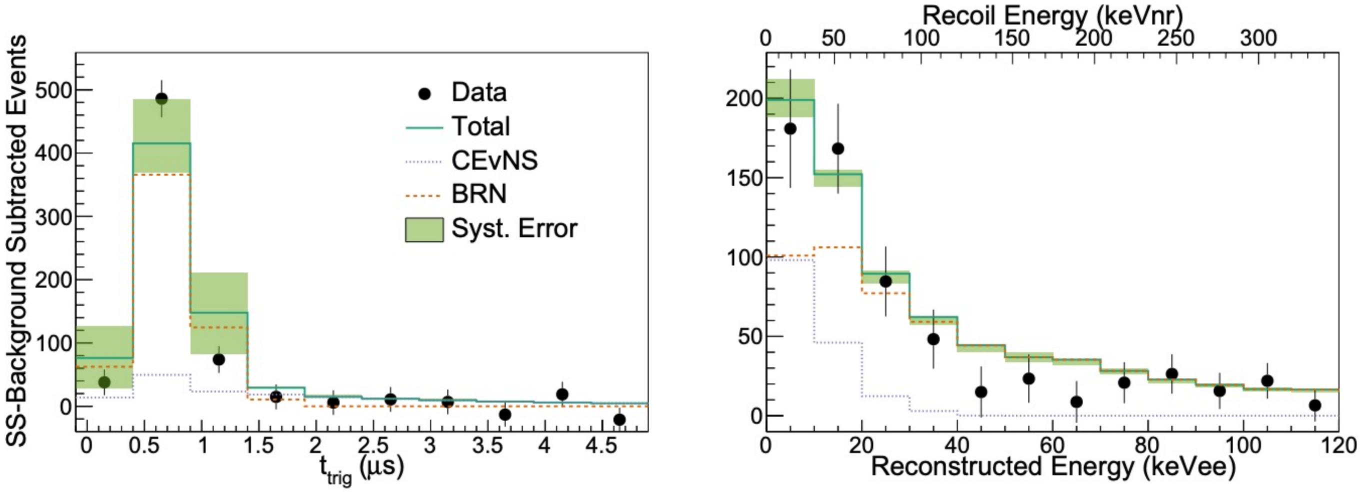
First observation with a CsI data set in 2017.

A second data set released in 2021.

Observation with a liquid argon detector in 2020.



D. Akimov et al., Phys.Rev.Lett. 129 (2022) 081801



D. Akimov et al. Phys.Rev.Lett. 126 (2021) 012002

Phenomenology with CEvNS

- Standard Model physics tests.

M. Cadeddu, et al. Phys. Rev. D 102 (2020)

- Neutron distribution of the target material.

M. Cadeddu, C. Giunti, et al. Rev. Lett. 120, 072501 (2018),

- Study new physics scenarios:
  - Non-Standard interactions.

    V. De Romeri, et al. arxiv 2211.11905, Coloma, et al Phys.Rev.D 96 (2017) 11, 115007, + …
  - Electromagnetic properties of neutrinos

    M. Atzori Corona, C. A. Ternes, et al. JHEP 09 (2022) 164, + …
  - Leptoquark models.

    Roberta Calabrese et al. Phys.Rev.D 107 (2023), V. De Romeri, et al., arXiv 2307.13790
  - Generalized neutrino interactions.

    M. Lindner et al. JHEP 03 (2017) 097, D. Aristizabal, et al. Phys.Rev.D 98 (2018) 075018, + ….
  - Light Mediators.

    O. G. Miranda, et al. JHEP 12 (2021) 191, + ….
  - Transition to sterile neutrinos.

And many more!

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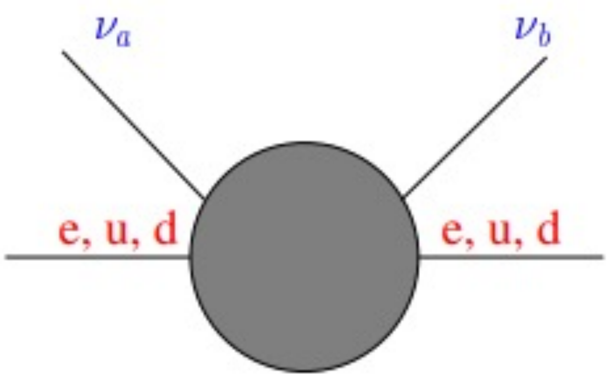
This talk!

And many more!

I) Non-Standard Interactions (NSI)



Neutral current Lagrangian allowing for non universal and flavor changing interactions

$$\mathcal{L}_{\rm NC}^{\rm NSI} = -2\sqrt{2}G_F \sum_{q,\ell,\ell'} \varepsilon_{\ell\ell'}^{qX} (\bar{\nu}_\ell \gamma^\mu P_L \nu_{\ell'})(\bar{f}\gamma_\mu P_X f)$$

ε_{ll}^{qX} ⇒ Non−universal

$\varepsilon_{ll'}^{qX}$ ⇒ Flavor changing

The weak charge is modified so we can test these NSI parameters.

$$Q_V^{\rm SM} = g_V^p Z + g_V^n N\,,$$

➡

$$Q_V^{\rm NSI\,2} = \left[\left(g_V^p + 2\varepsilon_{\ell\ell}^{uV} + \varepsilon_{\ell\ell}^{dV}\right) Z + \left(g_V^n + \varepsilon_{\ell\ell}^{uV} + 2\varepsilon_{\ell\ell}^{dV}\right) N\right]^2 + \sum_{\ell,\ell'} \left[\left(2\varepsilon_{\ell\ell'}^{uV} + \varepsilon_{\ell\ell'}^{dV}\right) Z + \left(\varepsilon_{\ell\ell'}^{uV} + 2\varepsilon_{\ell\ell'}^{dV}\right) N\right]^2.$$

J. Barranco, O. Miranda, and T. Rashba, JHEP 2005, 021 (2005)

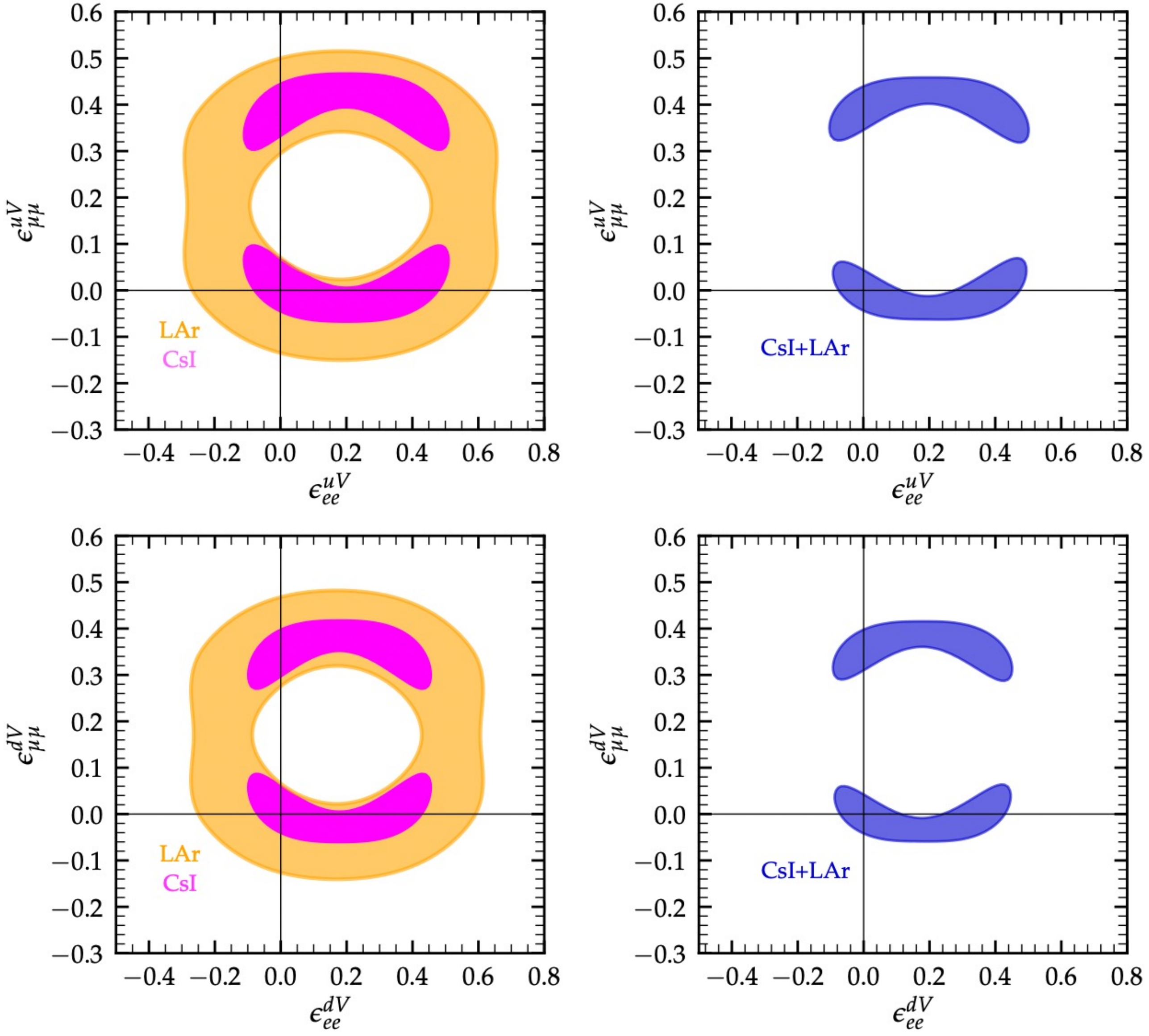
Non-Universal NSI

A **combined analysis** is dominated by CsI data.

Better bounds for muon related NSI than electron NSI

There is a degeneracy in the parameter space.

Second solution that reproduces the SM prediction for the number of events.



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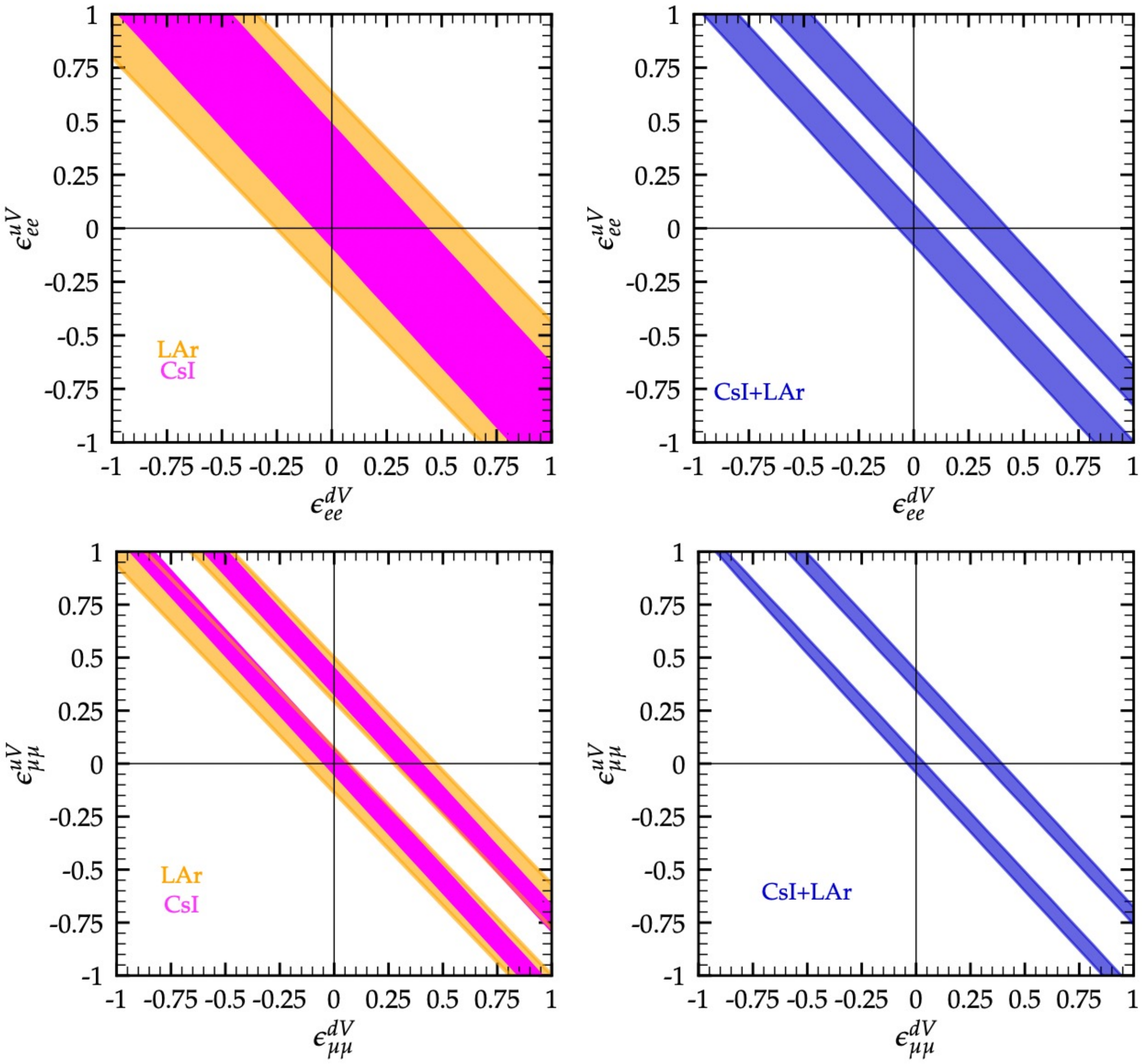

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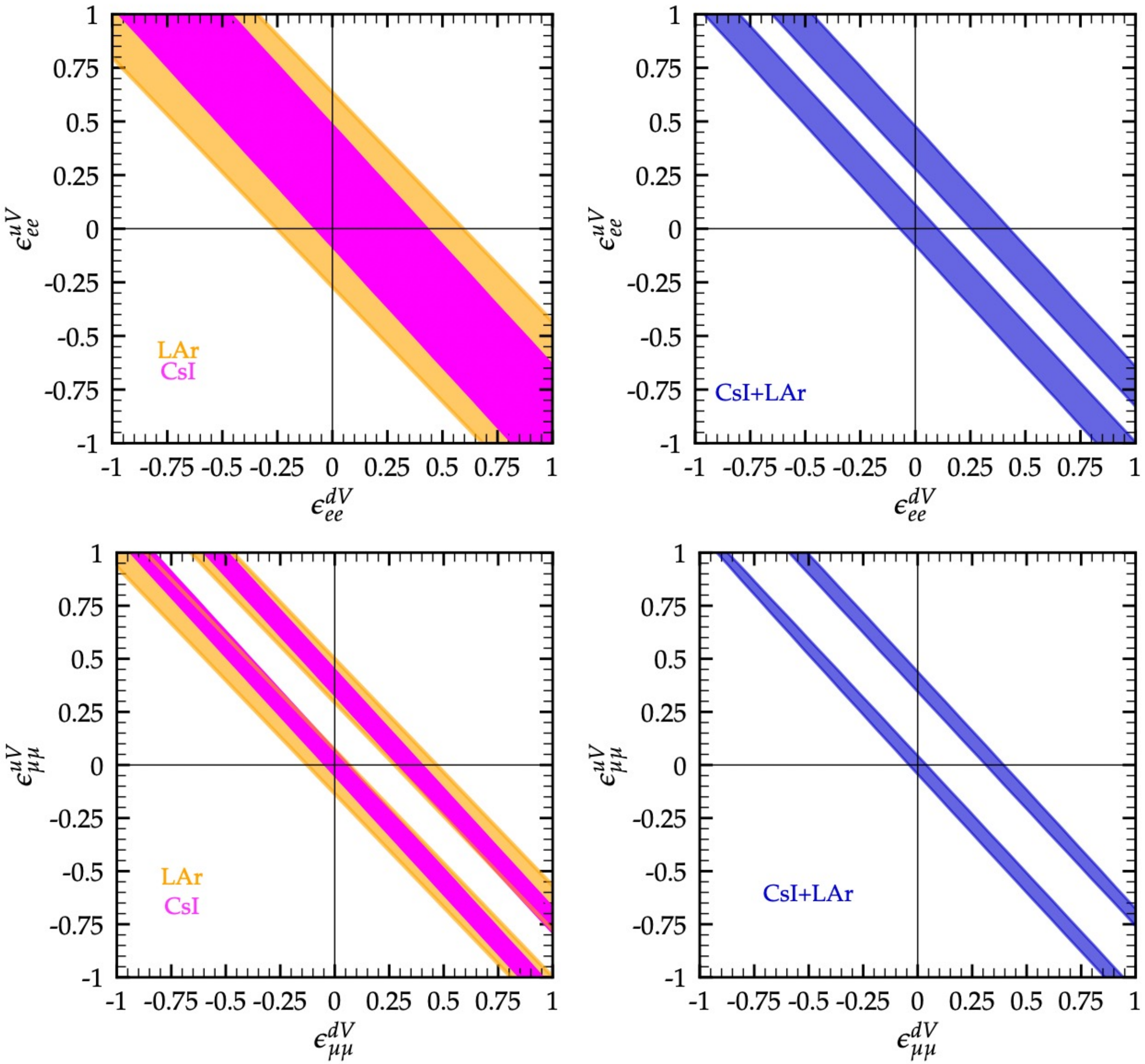
Second solution that reproduces the SM prediction for the number of events.

The slope depends on the ratio of protons to neutrons of the target material.

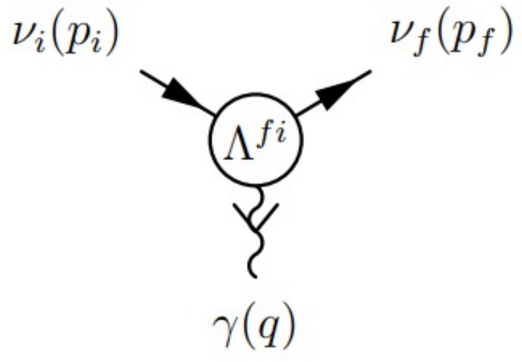
$$m = -\frac{2Z+N}{Z+2N}$$



V. De Romeri, O.G. Miranda, D.K. Papoulias, **GSG**, M. Tórtola and J.W.F. Valle JHEP 04 (2023) 035.

II) Electromagnetic properties of neutrinos

When massive neutrinos are considered, they can couple to photons at a loop level.



$$\mathcal{H}^{(\nu)}_{\rm em}(x) = j^{(\nu)}_{\mu}(x)A^{\mu}(x) = \sum_{k,j=1}^{N} \overline{\nu_k}(x)\Lambda^{kj}_{\mu}\nu_j(x)A^{\mu}(x)$$

In the most general form, consistent with Lorentz and gauge symmetries

$$\Lambda^{fi}_{\mu}(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right)\left[\mathbb{f}^{fi}_{Q}(q^2) + \mathbb{f}^{fi}_{A}(q^2)q^2\gamma_5\right] - i\sigma_{\mu\nu}q^{\nu}\left[\mathbb{f}^{fi}_{M}(q^2) + i\mathbb{f}^{fi}_{E}(q^2)\gamma_5\right]$$

$\mathbb{f}^{fi}_{Q}(0) = \mathbb{q}_{fi}$ Milicharge

$\mathbb{f}^{fi}_{M}(0) = \mathbb{\mu}_{fi}$ Magnetic dipole moment

$\mathbb{f}^{fi}_{E}(0) = \mathbb{e}_{fi},$ Electric dipole moment

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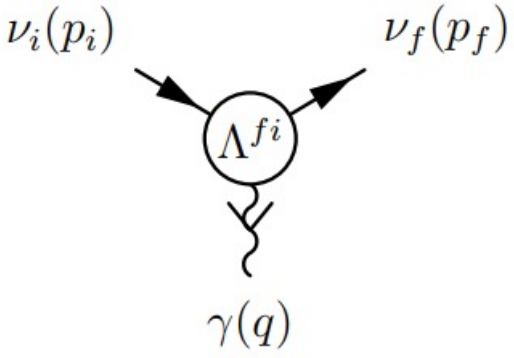

$$\mathcal{H}_{\mathrm{em}}^{(\nu)}(x) = j_\mu^{(\nu)}(x) A^\mu(x) = \sum_{k,j=1}^{N} \overline{\nu_k}(x) \Lambda_\mu^{kj} \nu_j(x) A^\mu(x)$$

$\mathfrak{f}_Q^{fi}(0) = \mathfrak{q}_{fi}$	Milicharge
$\mathfrak{f}_M^{fi}(0) = \mathfrak{\mu}_{fi}$	Magnetic dipole moment
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Neutrino magnetic moment

We add the magnetic moment contribution to the cross section

$$\left.\frac{d\sigma_{\nu_\ell\mathcal{N}}}{dE_{\rm nr}}\right|^{\rm MM}_{{\rm CE}\nu{\rm NS}} = \frac{\pi\alpha^2_{\rm EM}}{m_e^2}\left(\frac{1}{E_{\rm nr}} - \frac{1}{E_\nu}\right) Z^2 F_W^2(|\vec{q}|^2)\left|\frac{\mu^{\rm eff}_{\nu_\ell}}{\mu_{\rm B}}\right|^2 \qquad \mu^{\rm eff}_{\nu_\ell} = \sum_k \left|\sum_j U^*_{\ell k}\lambda_{jk}\right|^2$$

P. Vogel and J. Engel, Phys.Rev. D39 (1989) 3378

Neutrino magnetic moment

$$\lambda_{jk} = \mu_{jk} - i\epsilon_{jk}$$

We add the magnetic moment contribution to the cross section

$$\left.\frac{d\sigma_{\nu_\ell \mathcal{N}}}{dE_{\mathrm{nr}}}\right|_{\mathrm{CE}\nu\mathrm{NS}}^{\mathrm{MM}} = \frac{\pi\alpha_{\mathrm{EM}}^2}{m_e^2}\left(\frac{1}{E_{\mathrm{nr}}} - \frac{1}{E_\nu}\right) Z^2 F_W^2(|\vec{q}|^2)\left|\frac{\mu_{\nu_\ell}^{\mathrm{eff}}}{\mu_{\mathrm{B}}}\right|^2$$

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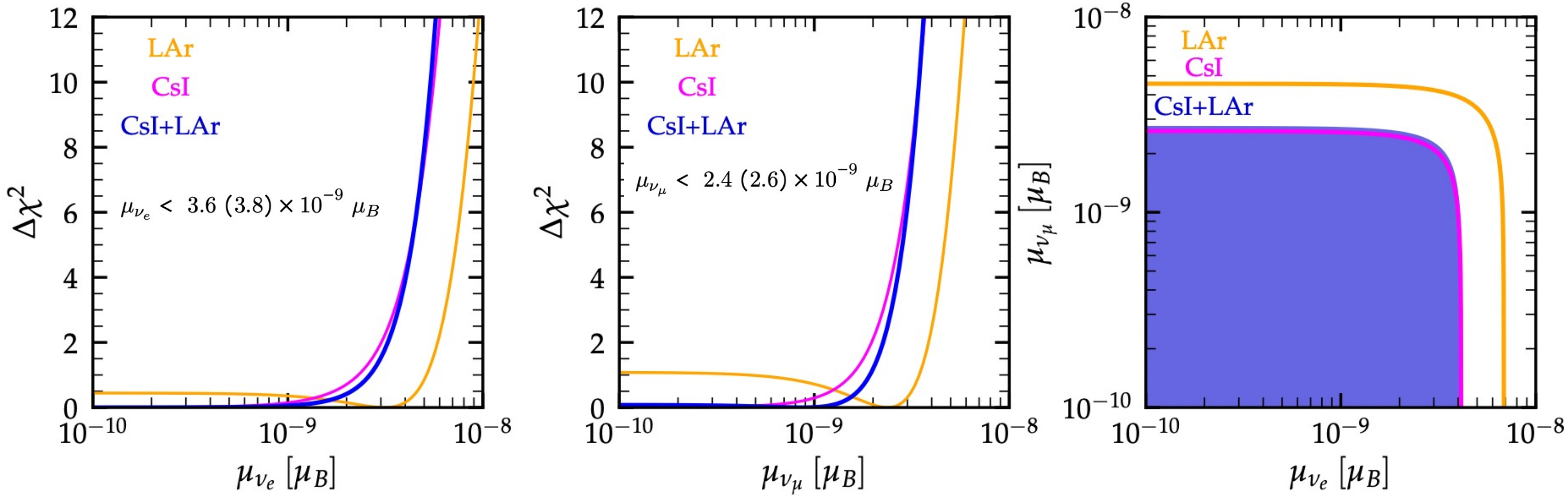
P. Vogel and J. Engel, Phys.Rev. D39 (1989) 3378

$$\mu^{\rm eff}_{\nu_\ell} = \sum_k \left|\sum_j U^*_{\ell k} \boxed{\lambda_{jk}}\right|^2$$



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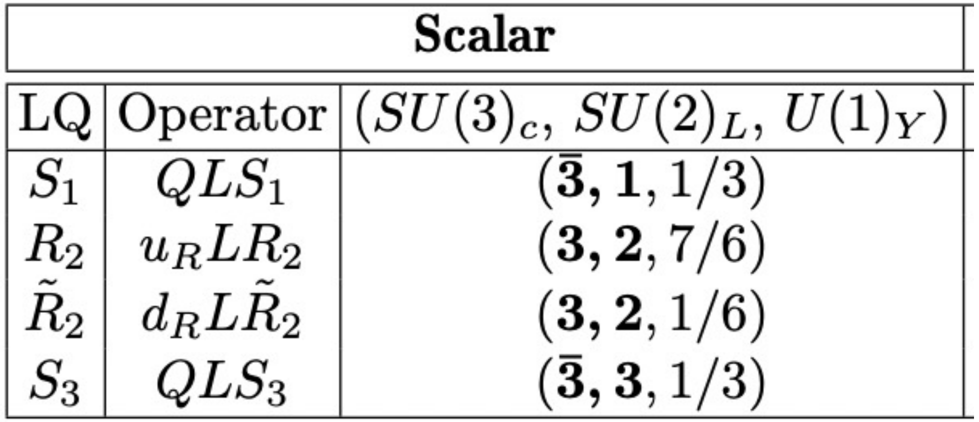
III) Leptoquark models

Hypothetical particles that simultaneously couple to leptons and quarks

Leptoquarks can be of either scalar or vector nature



Scalar		
LQ	Operator	$(SU(3)_c,\, SU(2)_L,\, U(1)_Y)$
S_1	QLS_1	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$
R_2	$u_R L R_2$	$(\mathbf{3}, \mathbf{2}, 7/6)$
$\tilde{R}_2$	$d_R L \tilde{R}_2$	$(\mathbf{3}, \mathbf{2}, 1/6)$
S_3	QLS_3	$(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$

A concrete LQ scenario: S_1

$$\mathcal{L} \subset \lambda_{ij} \bar{Q}^c_i i\tau_2 L_j S_1 + \text{h.c.} \quad \rightarrow \quad \mathcal{L} \subset (\lambda_{1j} \bar{u}^c P_L \ell_j - \lambda_{1j} \bar{d}^c P_L \nu_j) S_1^{-1/3} + \text{h.c.}\,,$$

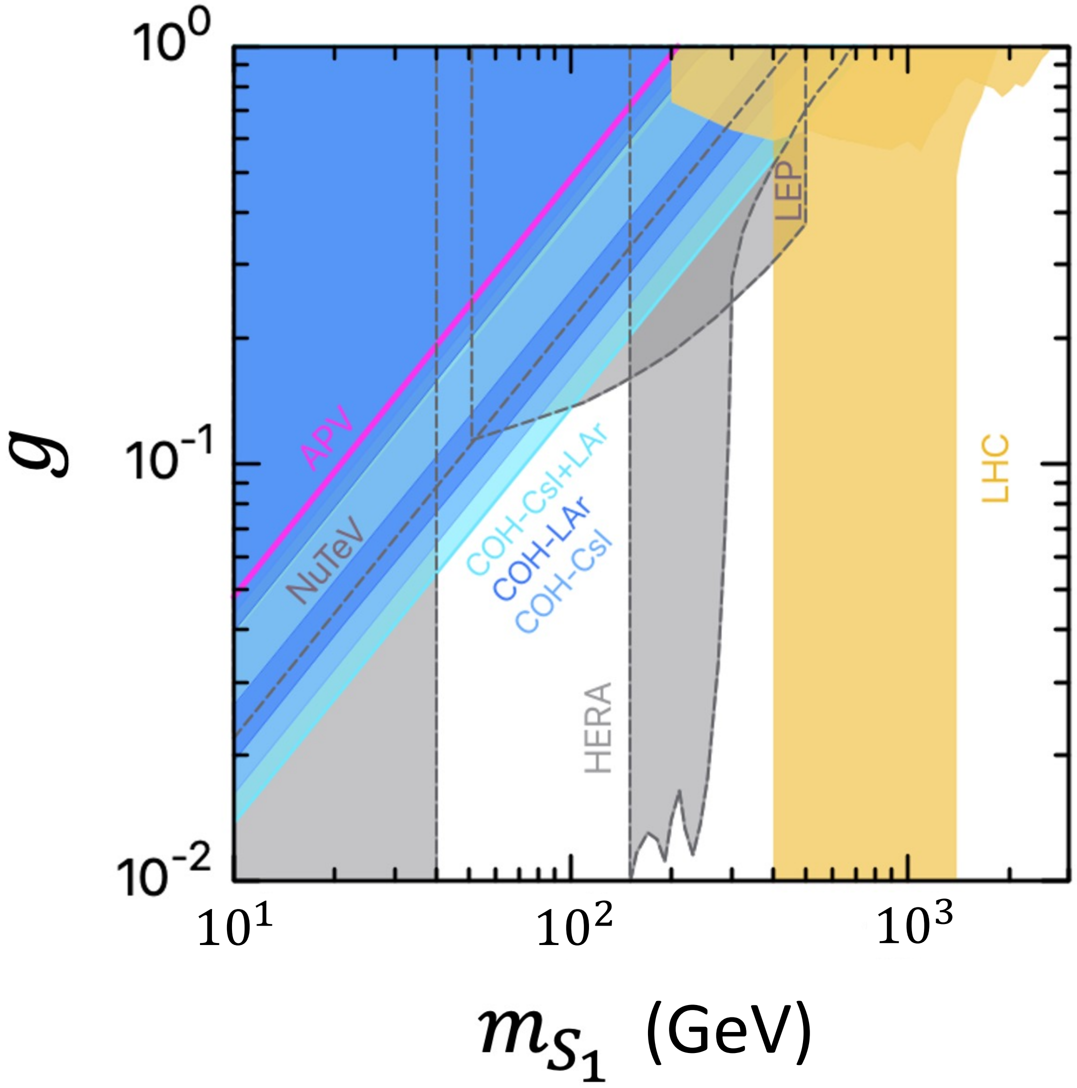
$$\lambda_{ij} = \begin{pmatrix} g & g & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

A concrete LQ scenario: S$_1$

The effect on the cross section is again a redefinition of the weak charge

$$(Q_W^{\rm SM})^2 \to (Q_i^{\rm LQ})^2 = \left(Q_W^{\rm SM} + Q_{ii,\rm LQ}\right)^2 + \sum_{i\neq j} Q^2_{ij,\rm LQ}\,,$$

$$Q^2_{ij,S_1} = \frac{g^2}{4\sqrt{2}G_F}\,\frac{ZF_Z(q^2) + 2NF_N(q^2)}{q^2 + m^2_{S_1}}\,,$$



V. De Romeri, V. M. Lozano and **GSG** arXiv 2307.13790

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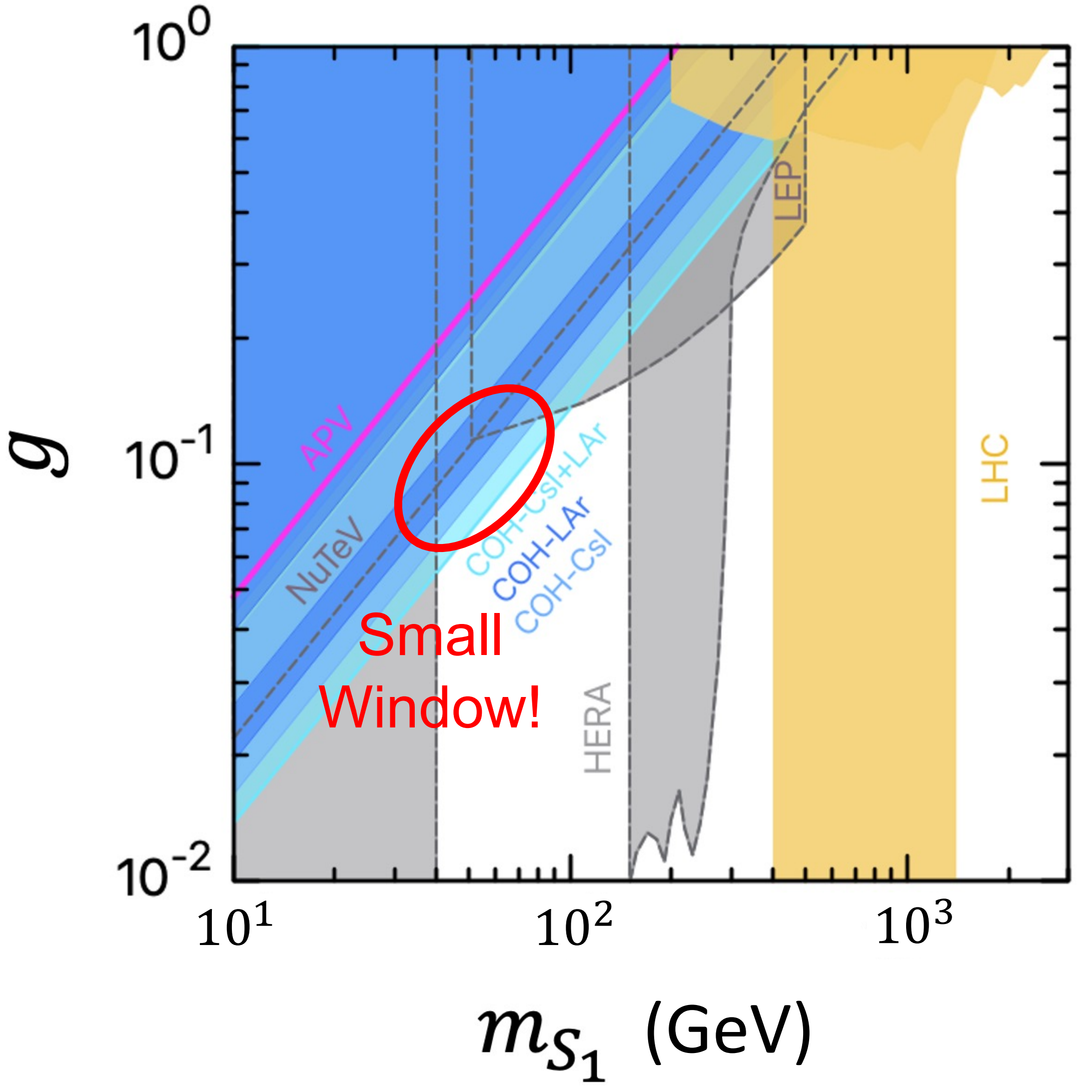

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The future of CEvNS

The future of CEvNS

Future upgrades for the SNS with NaI and Ge detectors.

The future of CEvNS

Future upgrades for the SNS with NaI and Ge detectors.

Other proposals with pion-decay at rest sources: ESS and Coherent Captain Mills

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The future of CEvNS

Future upgrades for the SNS with NaI and Ge detectors.

Other proposals with pion-decay at rest sources: ESS and Coherent Captain Mills

CEvNS using reactor neutrinos as a source?

Reactor neutrinos are not sensitive to nuclear information.

COHERENT SNS

ess EUROPEAN SPALLATION SOURCE

CO.νNie

CONUS

νGeN

RICOCHET
A Coherent Neutrino Scattering Program

Conclusions

- ✓ CEvNS provides a powerful tool to test different new physics scenarios.
- ✓ Degeneracies can be broken by using different target materials.
- ✓ Sensitivities can improve with better understanding of systematic uncertainties.
- ✓ Better bounds are expected with future experiments.

Thank you!

Backup

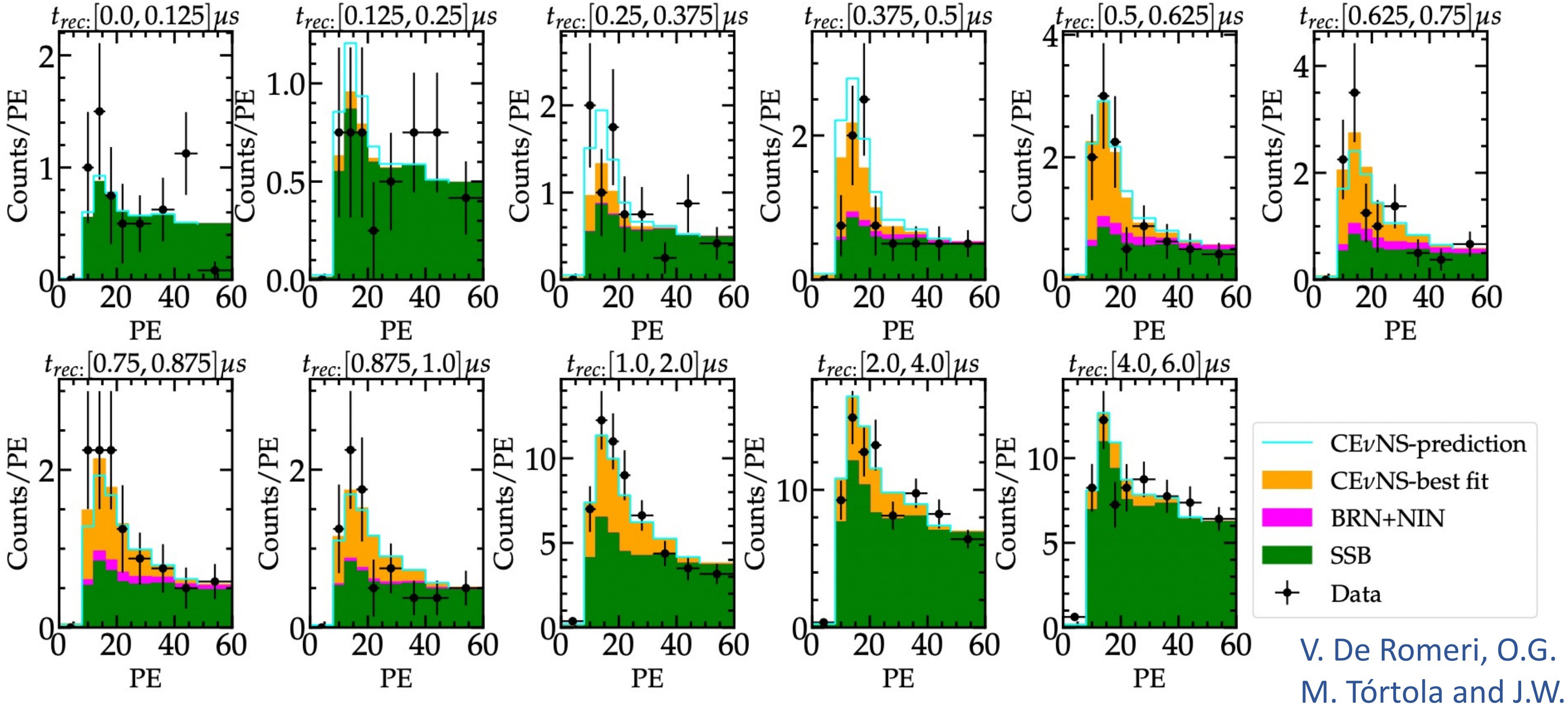
Predicted number of events

Nuclear recoil distribution

$$N_{i,n}^{\mathrm{CE}\nu\mathrm{NS},\mathcal{N}} = N_{\mathrm{target}} \int_{E_{\mathrm{nr}}^{i}}^{E_{\mathrm{nr}}^{i+1}} dE_{\mathrm{nr}}\, \epsilon_E(E_{\mathrm{nr}}) \int_0^{E_{\mathrm{nr}}^{\prime\mathrm{max}}} dE'_{\mathrm{nr}}\, P(E_{\mathrm{nr}}, E'_{\mathrm{nr}}) \times \int_{E_\nu^{\mathrm{min}}(E'_{\mathrm{nr}})}^{E_\nu^{\mathrm{max}}} dE_\nu \frac{dN_n}{dE_\nu}(E_\nu) \frac{d\sigma_{\nu_\ell \mathcal{N}}}{dE'_{\mathrm{nr}}}\bigg|_{\mathrm{CE}\nu\mathrm{NS}}(E_\nu, E'_{\mathrm{nr}}),$$

Timing distribution

$$N_{ij}^{\mathrm{CE}\nu\mathrm{NS},\mathcal{N}} = \sum_{n=\nu_e,\nu_\mu,\bar{\nu}_\mu} \int_{t_{\mathrm{rec}}^{j}}^{t_{\mathrm{rec}}^{j+1}} dt_{\mathrm{rec}} f_T^n(t_{\mathrm{rec}}, \alpha_6)\, \epsilon_T(t_{\mathrm{rec}})\, N_{i,n}^{\mathrm{CE}\nu\mathrm{NS},\mathcal{N}}.$$



V. De Romeri, O.G. Miranda, D.K. Papoulias, **GSG**, M. Tórtola and J.W.F. Valle JHEP 04 (2023) 035.

Statistical Analysis

$$\chi^2_{\mathrm{CsI}}\Big|_{\mathrm{CE}\nu\mathrm{NS(+ES)}} = 2\sum_{i=1}^{9}\sum_{j=1}^{11}\left[N_{\mathrm{th}}^{\mathrm{CsI}} - N_{ij}^{\mathrm{exp}} + N_{ij}^{\mathrm{exp}}\ln\left(\frac{N_{ij}^{\mathrm{exp}}}{N_{\mathrm{th}}^{\mathrm{CsI}}}\right)\right] + \sum_{k=0}^{4}\left(\frac{\alpha_k}{\sigma_k}\right)^2 .$$

$$\begin{aligned} N_{\mathrm{th}}^{\mathrm{CsI,CE}\nu\mathrm{NS+ES}} &= (1+\alpha_0+\alpha_5)N_{ij}^{\mathrm{CE}\nu\mathrm{NS}}(\alpha_4,\alpha_6,\alpha_7) + (1+\alpha_0)N_{ij}^{\mathrm{ES}}(\alpha_6,\alpha_7) \\ &+ (1+\alpha_1)N_{ij}^{\mathrm{BRN}}(\alpha_6) + (1+\alpha_2)N_{ij}^{\mathrm{NIN}}(\alpha_6) + (1+\alpha_3)N_{ij}^{\mathrm{SSB}} . \end{aligned}$$

Nuisance	**Source**
α_0	Flux + QF
α_1	BRN
α_2	NIN
α_3	SSB
α_4	RMS radius
α_6	Efficiency
α_7	Timing

All sources of systematics are included

Can we remove these degeneracies?

There is a proposal to measure CEvNS at the European Spallation Source (ESS).

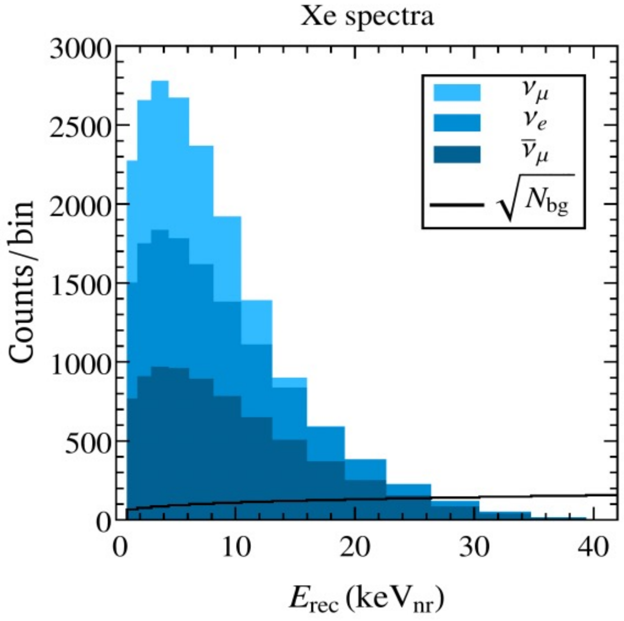
Expected to be the most intense pulsed neutron source.

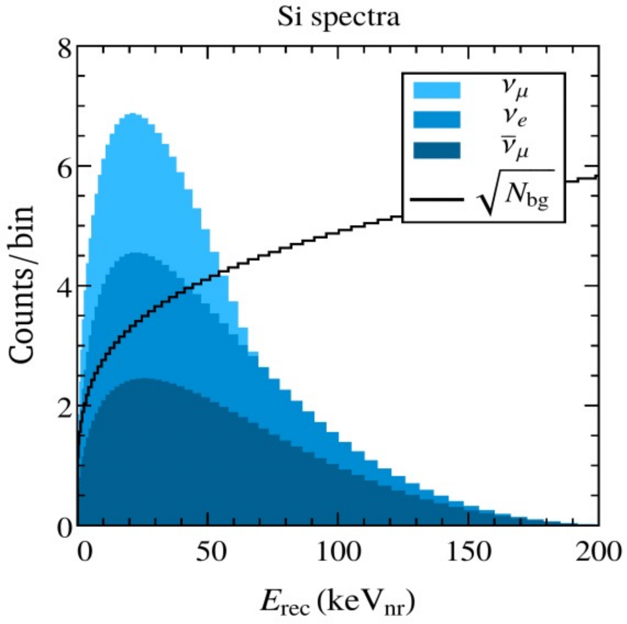
Advantage: Larger neutrino flux

Disadvantage: Larger SSB backgrounds expected

The proposal includes different detection technologies: *CsI, Xe, Ge, Si, Ar*.

D. Baxter et al JHEP 02 (2020) 123

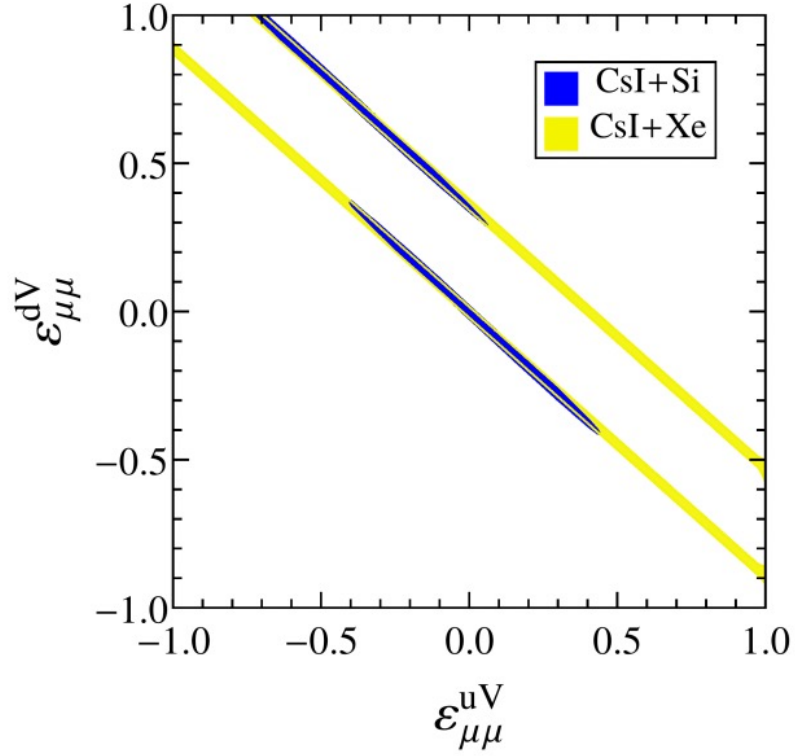


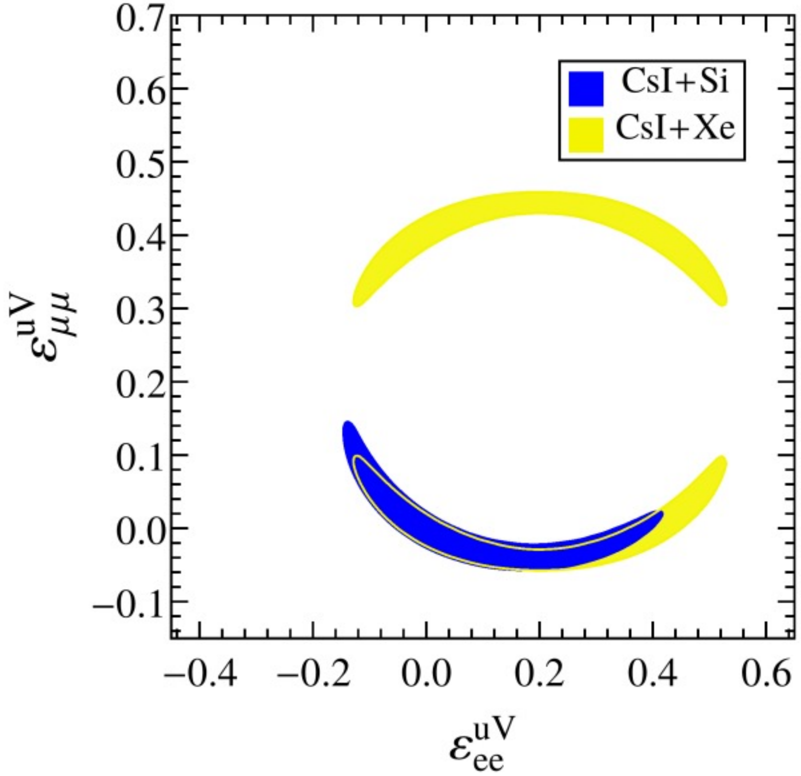


S. S. Chatterjee, S. Lavignac, O. G. Miranda, and **GSG** Phys.Rev.D 107 (2023) 5, 055019

Can we remove these degeneracies?

Both larger statistics and different detection technologies can contribute to break degeneracies

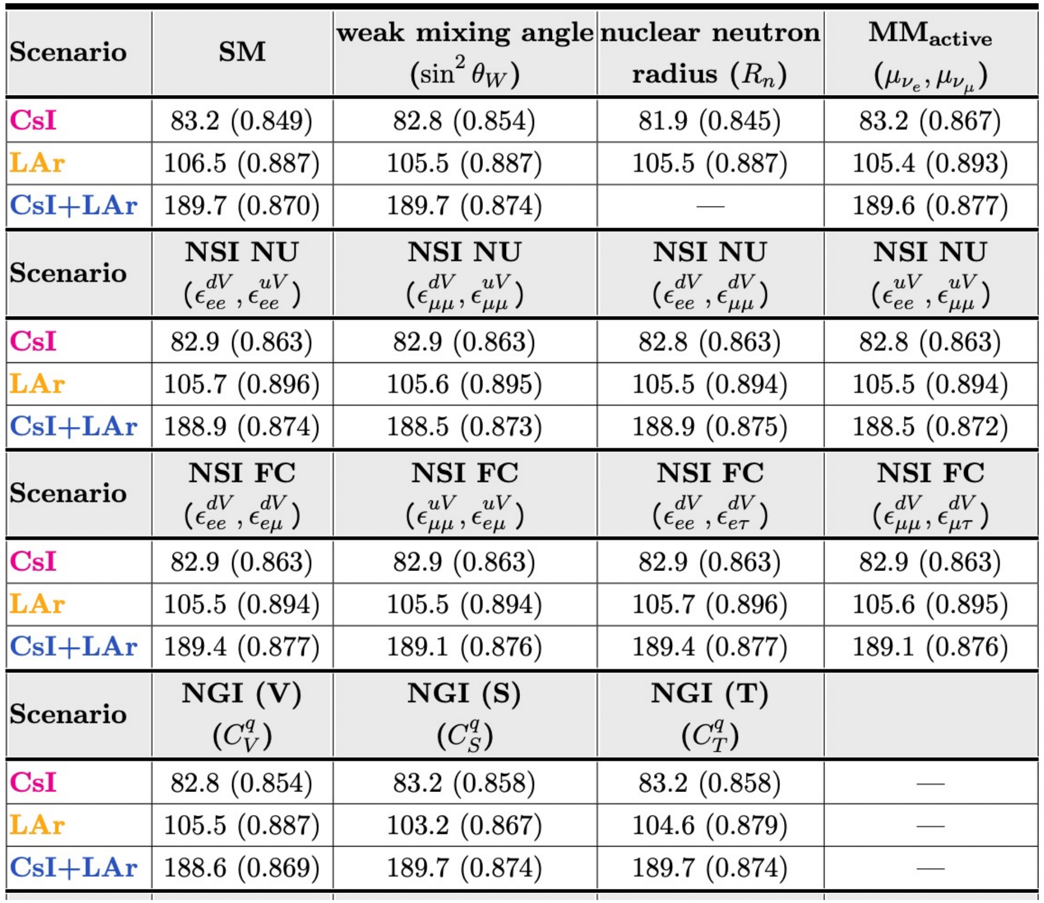




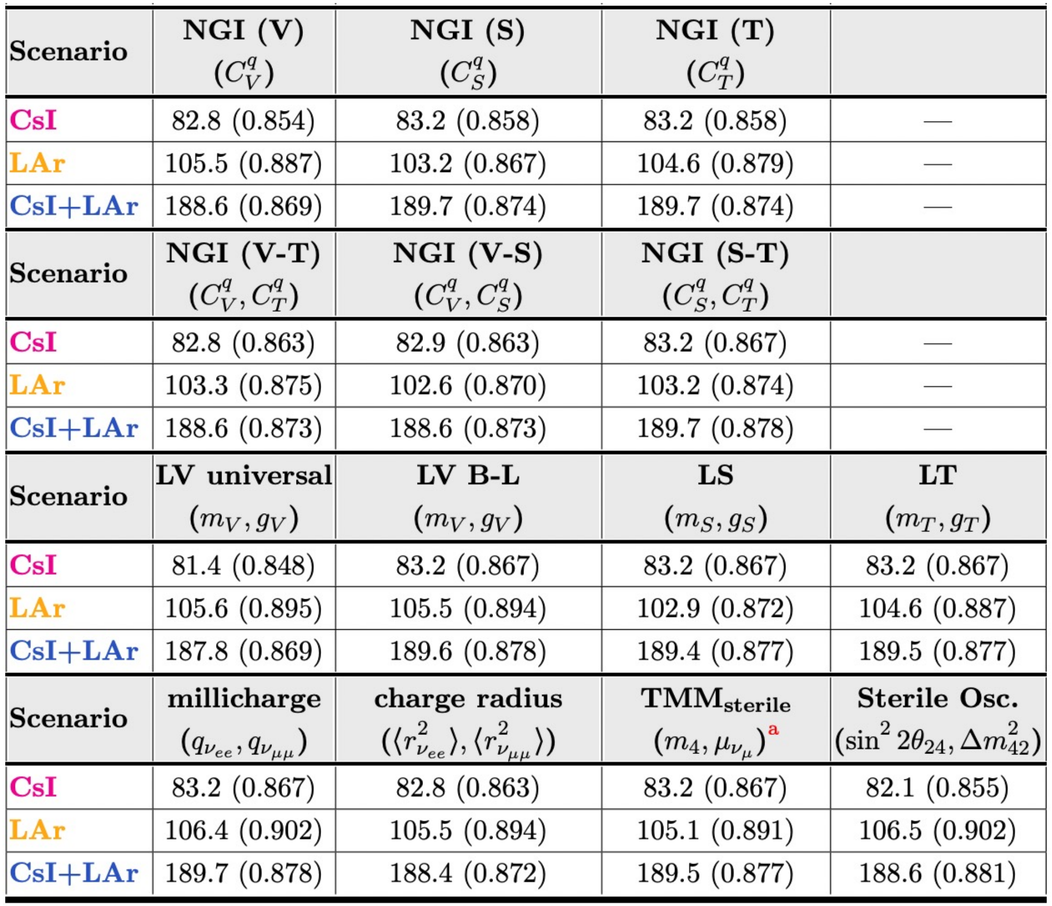
S. S. Chatterjee, S. Lavignac, O. G. Miranda, and **GSG** Phys.Rev.D 107 (2023) 5, 055019

Summary

Many different scenarios can be tested with CEvNS data



Scenario	**SM**	**weak mixing angle** ($\sin^2\theta_W$)	**nuclear neutron radius** (R_n)	**MM$_{\text{active}}$** ($\mu_{\nu_e}, \mu_{\nu_\mu}$)
CsI	83.2 (0.849)	82.8 (0.854)	81.9 (0.845)	83.2 (0.867)
LAr	106.5 (0.887)	105.5 (0.887)	105.5 (0.887)	105.4 (0.893)
CsI+LAr	189.7 (0.870)	189.7 (0.874)	—	189.6 (0.877)
Scenario	**NSI NU** ($\epsilon_{ee}^{dV}, \epsilon_{ee}^{uV}$)	**NSI NU** ($\epsilon_{\mu\mu}^{dV}, \epsilon_{\mu\mu}^{uV}$)	**NSI NU** ($\epsilon_{ee}^{dV}, \epsilon_{\mu\mu}^{dV}$)	**NSI NU** ($\epsilon_{ee}^{uV}, \epsilon_{\mu\mu}^{uV}$)
CsI	82.9 (0.863)	82.9 (0.863)	82.8 (0.863)	82.8 (0.863)
LAr	105.7 (0.896)	105.6 (0.895)	105.5 (0.894)	105.5 (0.894)
CsI+LAr	188.9 (0.874)	188.5 (0.873)	188.9 (0.875)	188.5 (0.872)
Scenario	**NSI FC** ($\epsilon_{ee}^{dV}, \epsilon_{e\mu}^{dV}$)	**NSI FC** ($\epsilon_{\mu\mu}^{uV}, \epsilon_{e\mu}^{uV}$)	**NSI FC** ($\epsilon_{ee}^{dV}, \epsilon_{e\tau}^{dV}$)	**NSI FC** ($\epsilon_{\mu\mu}^{dV}, \epsilon_{\mu\tau}^{dV}$)
CsI	82.9 (0.863)	82.9 (0.863)	82.9 (0.863)	82.9 (0.863)
LAr	105.5 (0.894)	105.5 (0.894)	105.7 (0.896)	105.6 (0.895)
CsI+LAr	189.4 (0.877)	189.1 (0.876)	189.4 (0.877)	189.1 (0.876)
Scenario	**NGI (V)** (C_V^q)	**NGI (S)** (C_S^q)	**NGI (T)** (C_T^q)	
CsI	82.8 (0.854)	83.2 (0.858)	83.2 (0.858)	—
LAr	105.5 (0.887)	103.2 (0.867)	104.6 (0.879)	—
CsI+LAr	188.6 (0.869)	189.7 (0.874)	189.7 (0.874)	—



Scenario	**NGI (V)** (C_V^q)	**NGI (S)** (C_S^q)	**NGI (T)** (C_T^q)	
CsI	82.8 (0.854)	83.2 (0.858)	83.2 (0.858)	—
LAr	105.5 (0.887)	103.2 (0.867)	104.6 (0.879)	—
CsI+LAr	188.6 (0.869)	189.7 (0.874)	189.7 (0.874)	—
Scenario	**NGI (V-T)** (C_V^q, C_T^q)	**NGI (V-S)** (C_V^q, C_S^q)	**NGI (S-T)** (C_S^q, C_T^q)	
CsI	82.8 (0.863)	82.9 (0.863)	83.2 (0.867)	—
LAr	103.3 (0.875)	102.6 (0.870)	103.2 (0.874)	—
CsI+LAr	188.6 (0.873)	188.6 (0.873)	189.7 (0.878)	—
Scenario	**LV universal** (m_V, g_V)	**LV B-L** (m_V, g_V)	**LS** (m_S, g_S)	**LT** (m_T, g_T)
CsI	81.4 (0.848)	83.2 (0.867)	83.2 (0.867)	83.2 (0.867)
LAr	105.6 (0.895)	105.5 (0.894)	102.9 (0.872)	104.6 (0.887)
CsI+LAr	187.8 (0.869)	189.6 (0.878)	189.4 (0.877)	189.5 (0.877)
Scenario	**millicharge** ($q_{\nu_{ee}}, q_{\nu_{\mu\mu}}$)	**charge radius** ($\langle r_{\nu_{ee}}^2\rangle, \langle r_{\nu_{\mu\mu}}^2\rangle$)	**TMM$_{\text{sterile}}$** (m_4, μ_{ν_μ})[a]	**Sterile Osc.** ($\sin^2 2\theta_{24}, \Delta m_{42}^2$)
CsI	83.2 (0.867)	82.8 (0.863)	83.2 (0.867)	82.1 (0.855)
LAr	106.4 (0.902)	105.5 (0.894)	105.1 (0.891)	106.5 (0.902)
CsI+LAr	189.7 (0.878)	188.4 (0.872)	189.5 (0.877)	188.6 (0.881)

V. De Romeri, O.G. Miranda, D.K. Papoulias, **GSG**, M. Tórtola and J.W.F. Valle JHEP 04 (2023) 035.

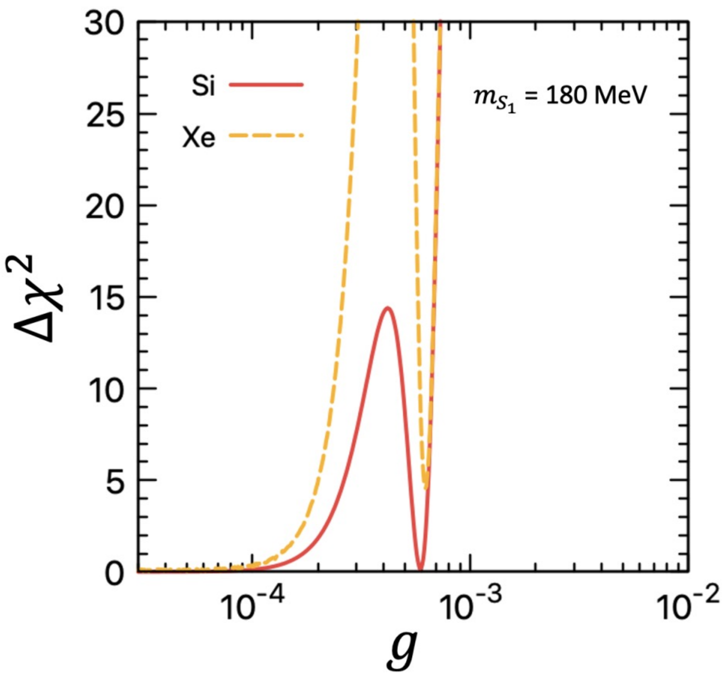
The allowed band can be explained when the mass of the LQ is large.

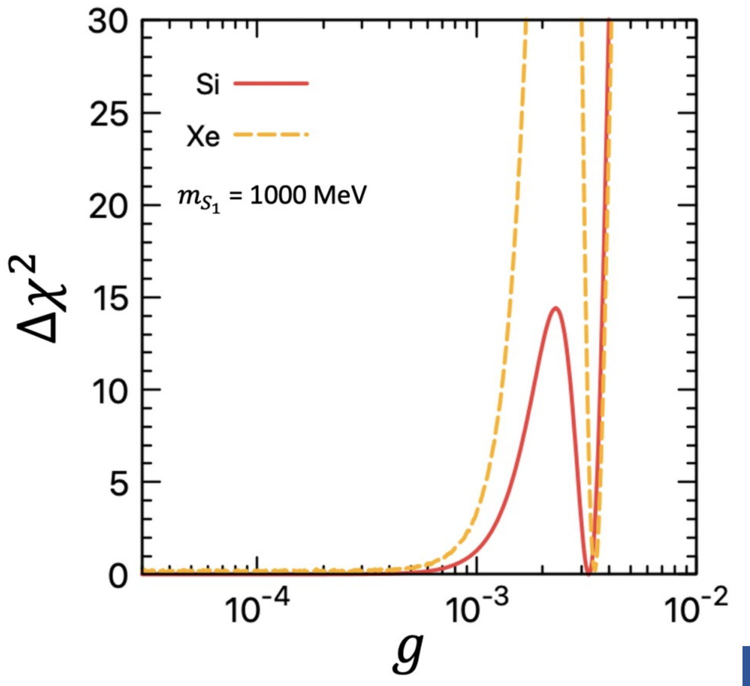
Indeed, we can reproduce the SM cross section when

$$(Q_W^{\rm SM} + Q_{ii,{\rm LQ}})^2 + Q_{ii,{\rm LQ}}^2 = (Q_W^{\rm SM})^2\,,$$

This condition is satisfied for

$$g^2 = \frac{4\sqrt{2}G_F\left(g_V^p Z + g_V^n N\right)\left(2m_N E_{\rm nr} + m_{\rm LQ}^2\right)}{\mathcal{C}_1 Z + \mathcal{C}_2 N}$$





V. De Romeri, V. M. Lozano and **GSG** arXiv 2307.13790

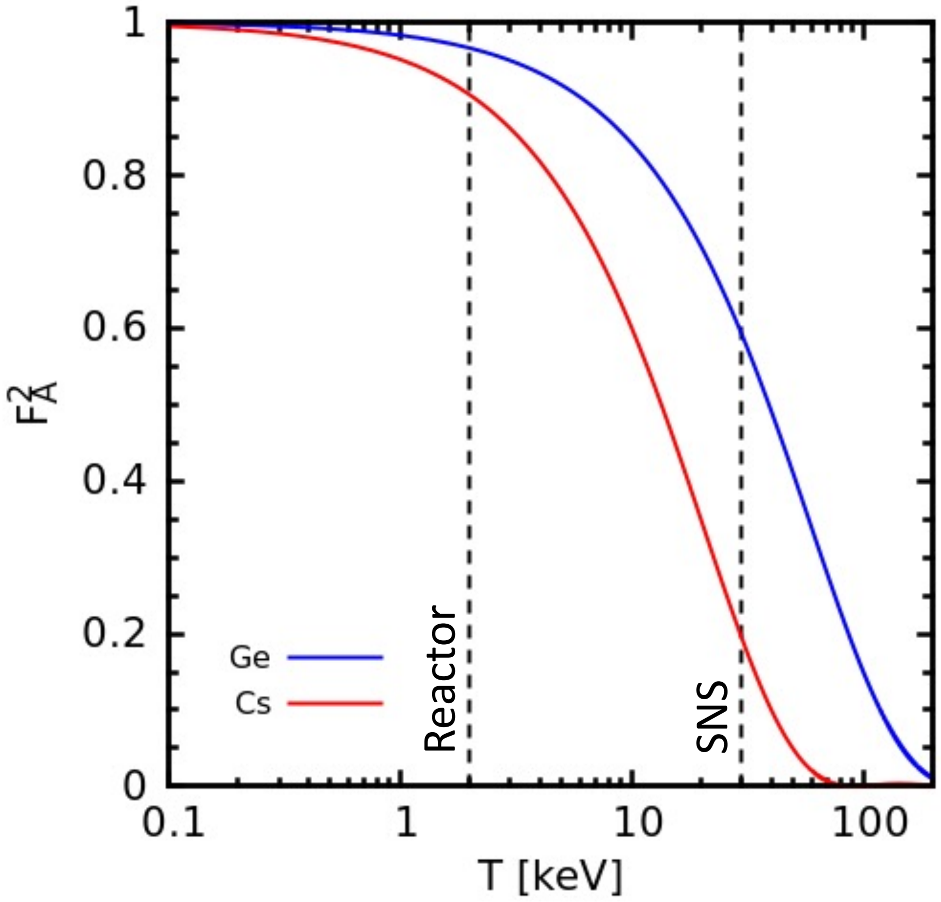
The future of CEvNS

Future upgrades for the SNS with NaI and Ge detectors.

Other proposals with pion-decay at rest sources: ESS and Coherent Captain Mills

CEvNS using reactor neutrinos as a source?

Reactor neutrinos are not sensitive to nuclear information.



νGeN

CONUS

RICOCHET
A Coherent Neutrino Scattering Program

CONνNIe