

Sensitivity of Coherent Elastic Neutrino-Nucleus Scattering experiments to Non-Standard Interactions

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Outline

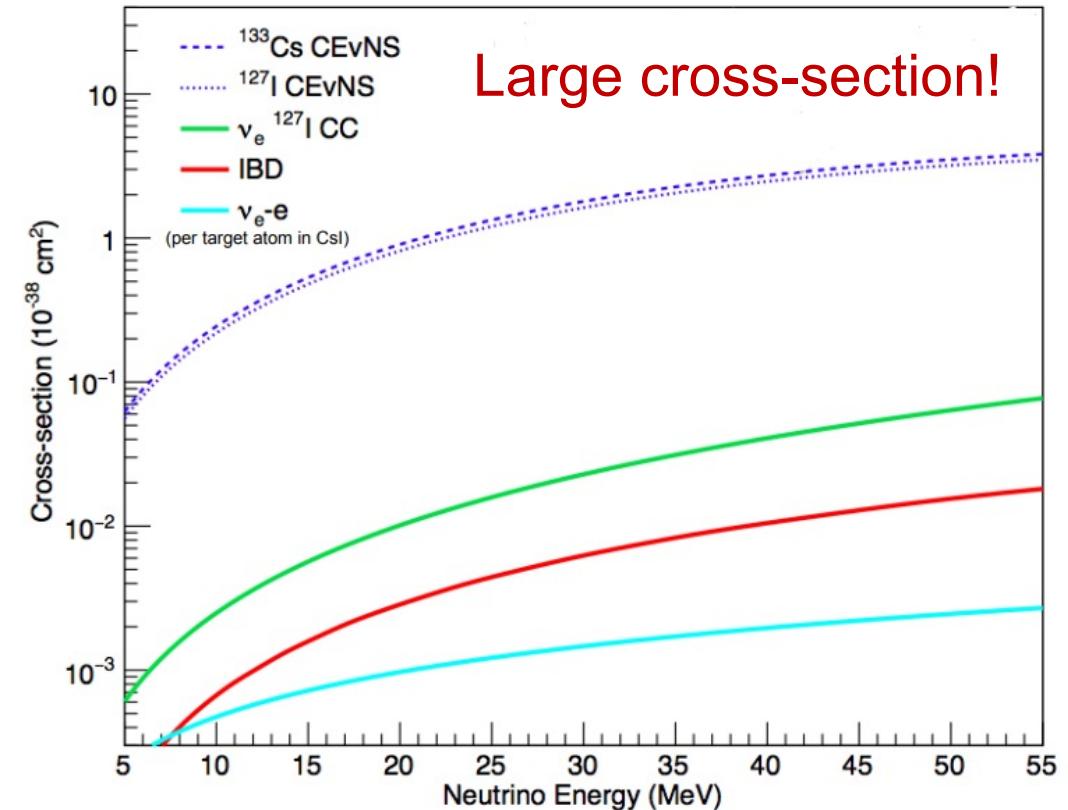
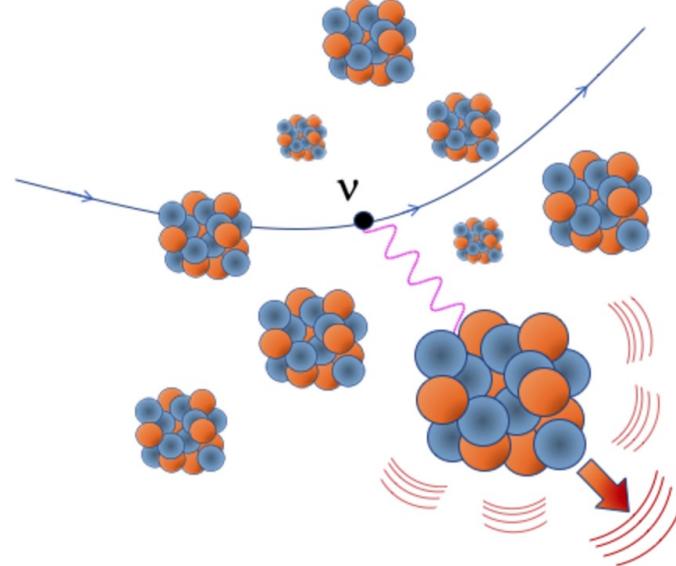
- ✓ Introduction
- ✓ Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)
- ✓ The COHERENT Experiment
- ✓ Phenomenology of CEvNS
 - ✓ Non-Standard Interactions
 - ✓ Leptoquarks

Coherent Elastic Neutrino-Nucleus Scattering

Neutrino interacts with a nucleus as a whole.

Neutral current process within the SM.

The nucleus acquires a kinetic recoil energy.



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

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

CEvNS cross section

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

CEvNS cross section

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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

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

Form Factor

SM weak charge

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

Klein-Nystrand

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

The cross section
effectively scales as N^2

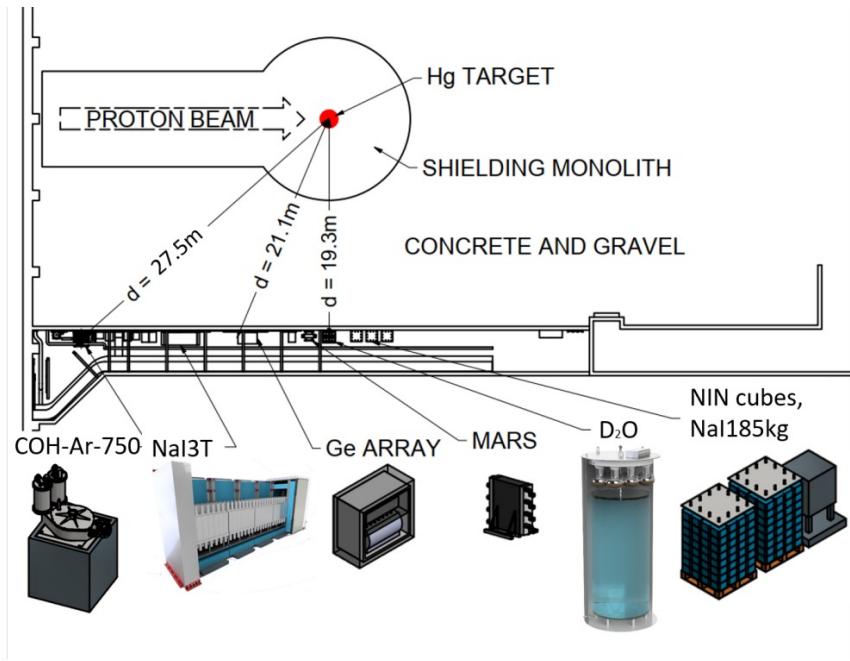
$$|g_V^p| \ll |g_V^n|$$

Small detectors
can be used!

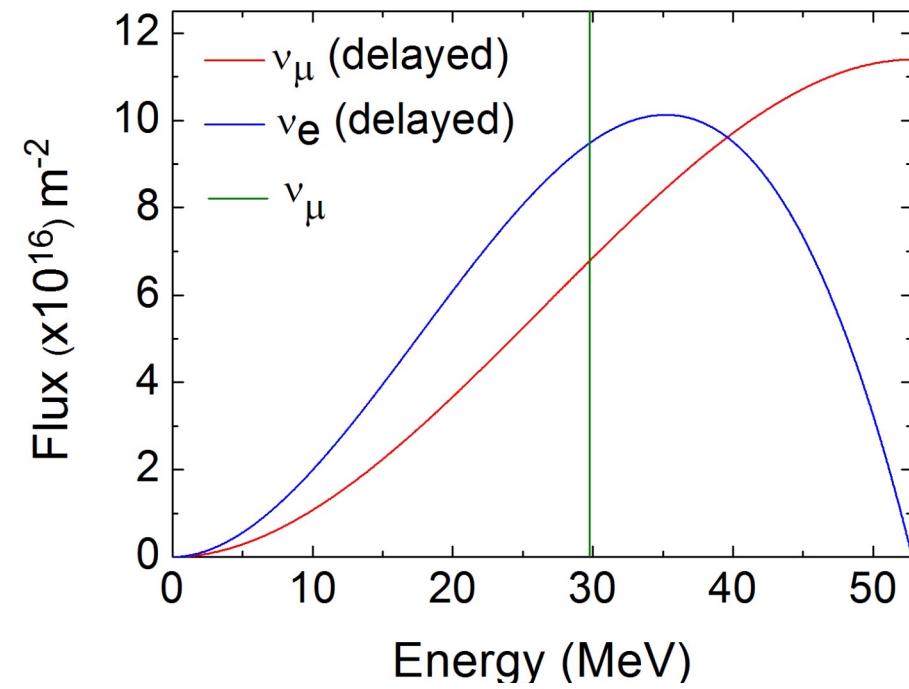
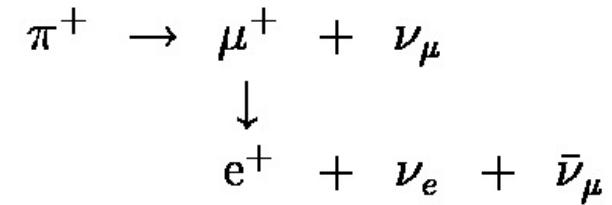
How to measure CEvNS?

The COHERENT experiment

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



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

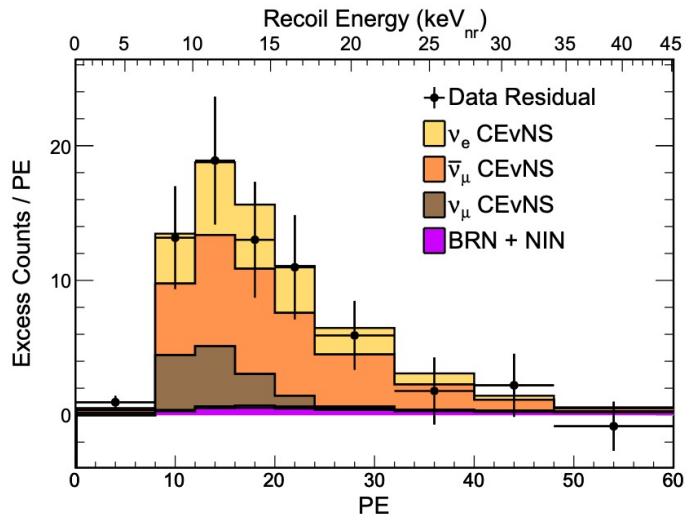


Status of the COHERENT experiment

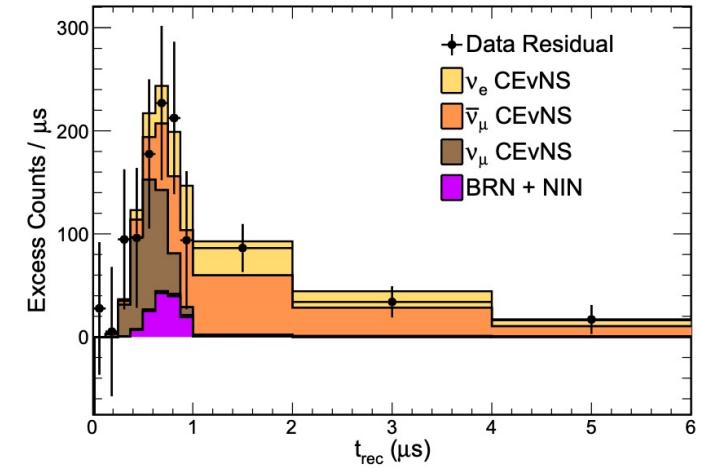
First observation with a CsI
data set in 2017.

A second data set released in
2021.

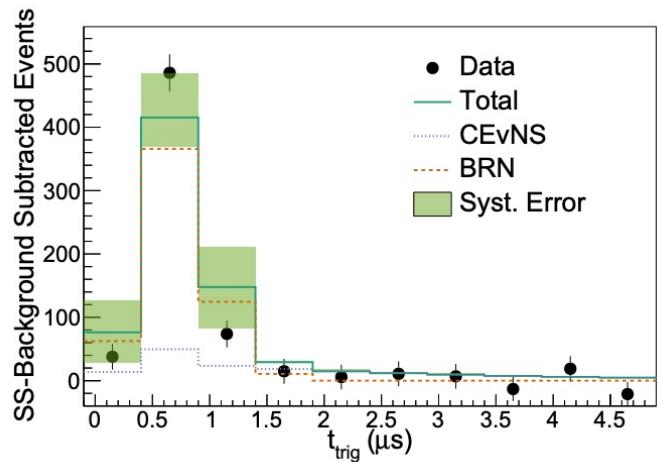
Observation with a liquid
argon detector in 2020.



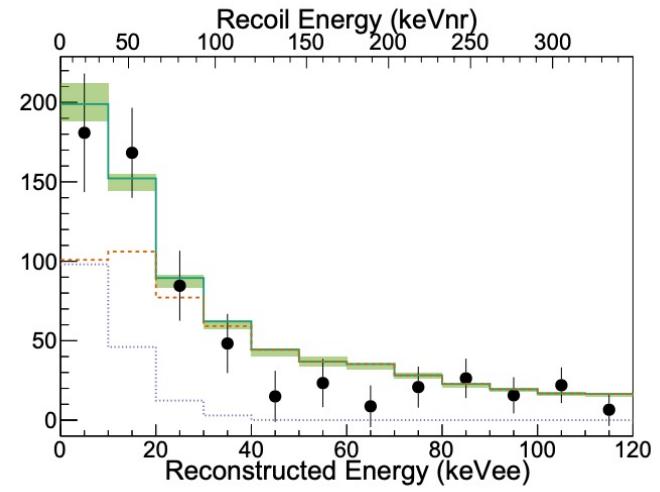
D. Akimov et al., Phys.Rev.Lett. 129 (2022) 081801



D. Akimov et al., Phys.Rev.Lett. 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. S. S. Chatterjee, et al. Phys. Rev. D 107 (2023)
 - Leptoquark models.
Roberta Calabrese et al. Phys.Rev.D 107 (2023)
 - Generalized neutrino interactions.
O. G. Miranda, D. K. Papoulias, et al. JHEP 07, 103 (2019)
 - Electromagnetic properties of neutrinos.
M. Atzori Corona, C. A. Ternes, et al. JHEP 09 (2022) 164
 - Light Mediators.
O. G. Miranda, et al. JHEP 12 (2021) 191
 - Transition to sterile neutrinos.

And many more!

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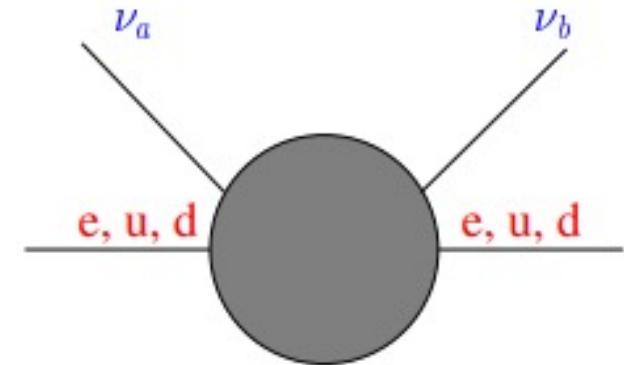
This talk!

And many more!

Non-Standard Interactions (NSI)

Neutral current Lagrangian allowing for non universal and flavor changing interactions

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



$\varepsilon_{ll}^{qX} \Rightarrow \text{Non-universal}$

$\varepsilon_{ll'}^{qX} \Rightarrow \text{Flavor changing}$

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

$$Q_V^{\text{SM}} = g_V^p Z + g_V^n N, \quad \rightarrow$$

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

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

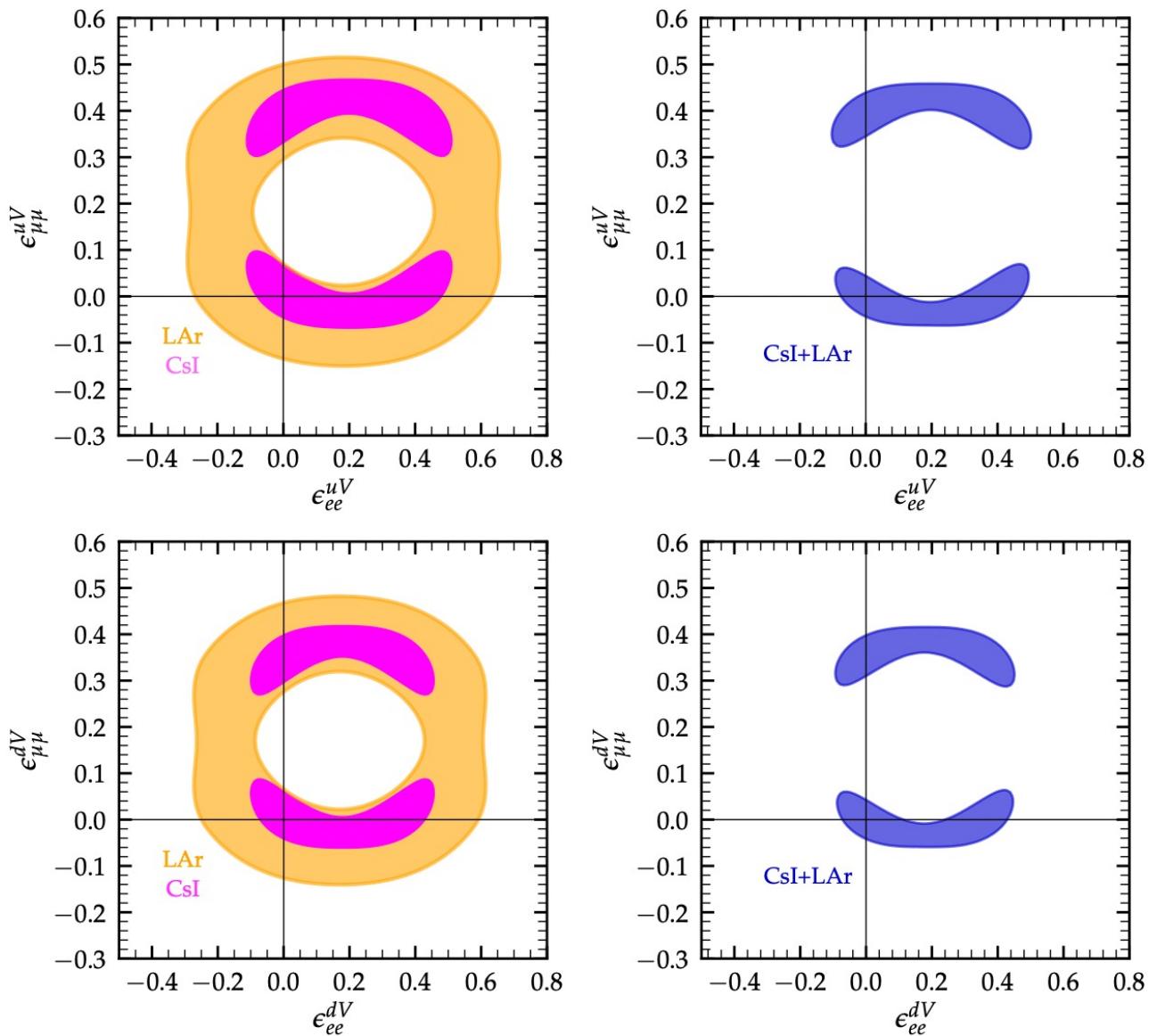
Non-Universal NSI

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.



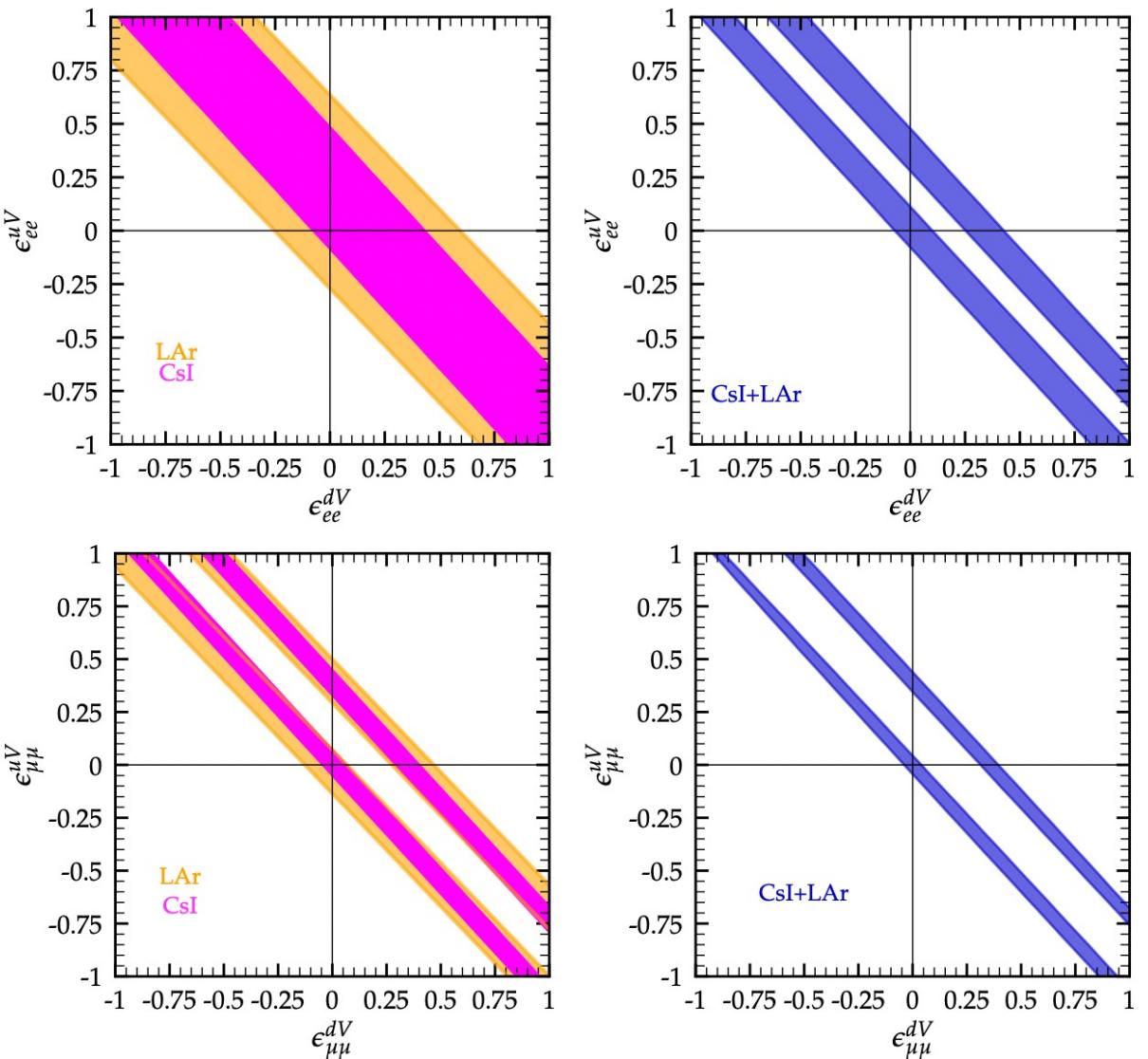
V. De Romeri, O.G. Miranda, D.K. Papoulias, **GSG**, M. Tórtola and J.W.F. Valle
JHEP 04 (2023) 035.

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Non-Universal NSI

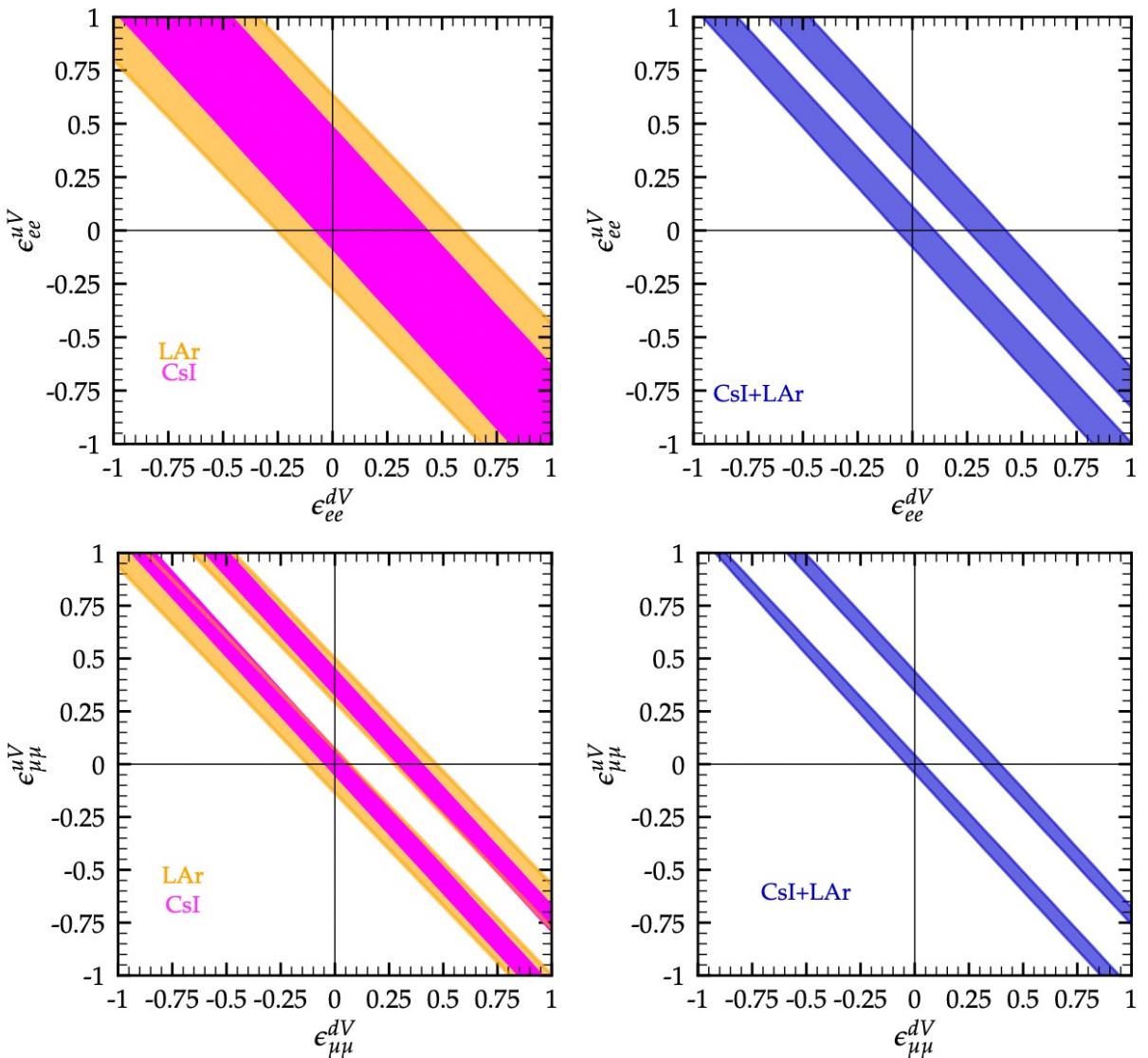
A combined analysis is dominated by CsI data.

There is a degeneracy in the parameter space.

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.

Can we remove these degeneracies?

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

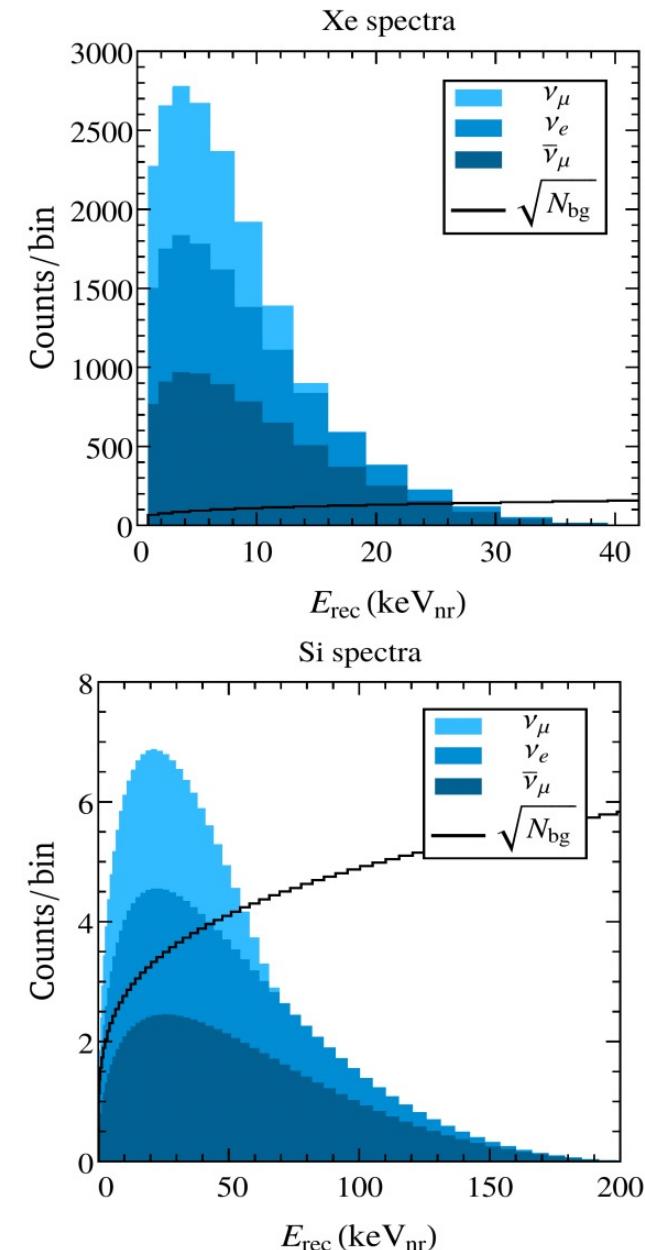
Expected to be the most intense pulsed neutron source.

Advantage: Larger neutrino flux

Disadvantage: Larger SSB backgrounds expected

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

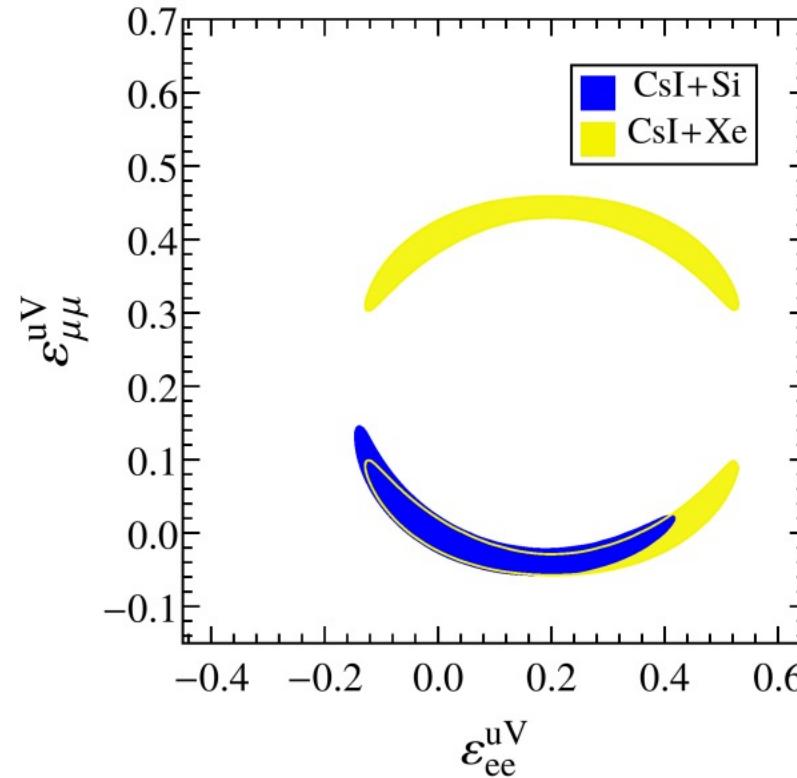
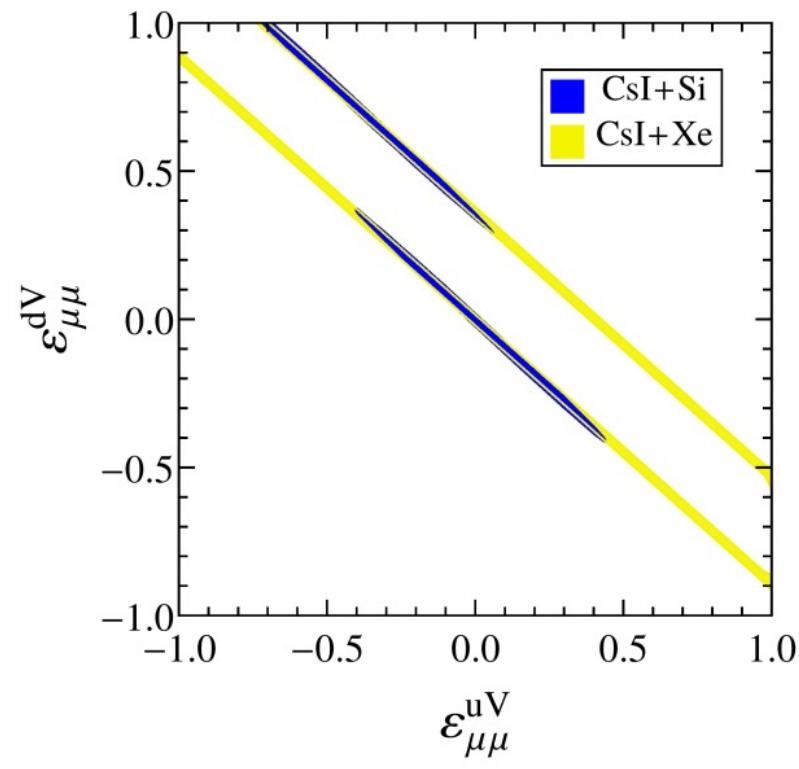
D. Baxter et al JHEP 02 (2020) 123



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

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

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

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

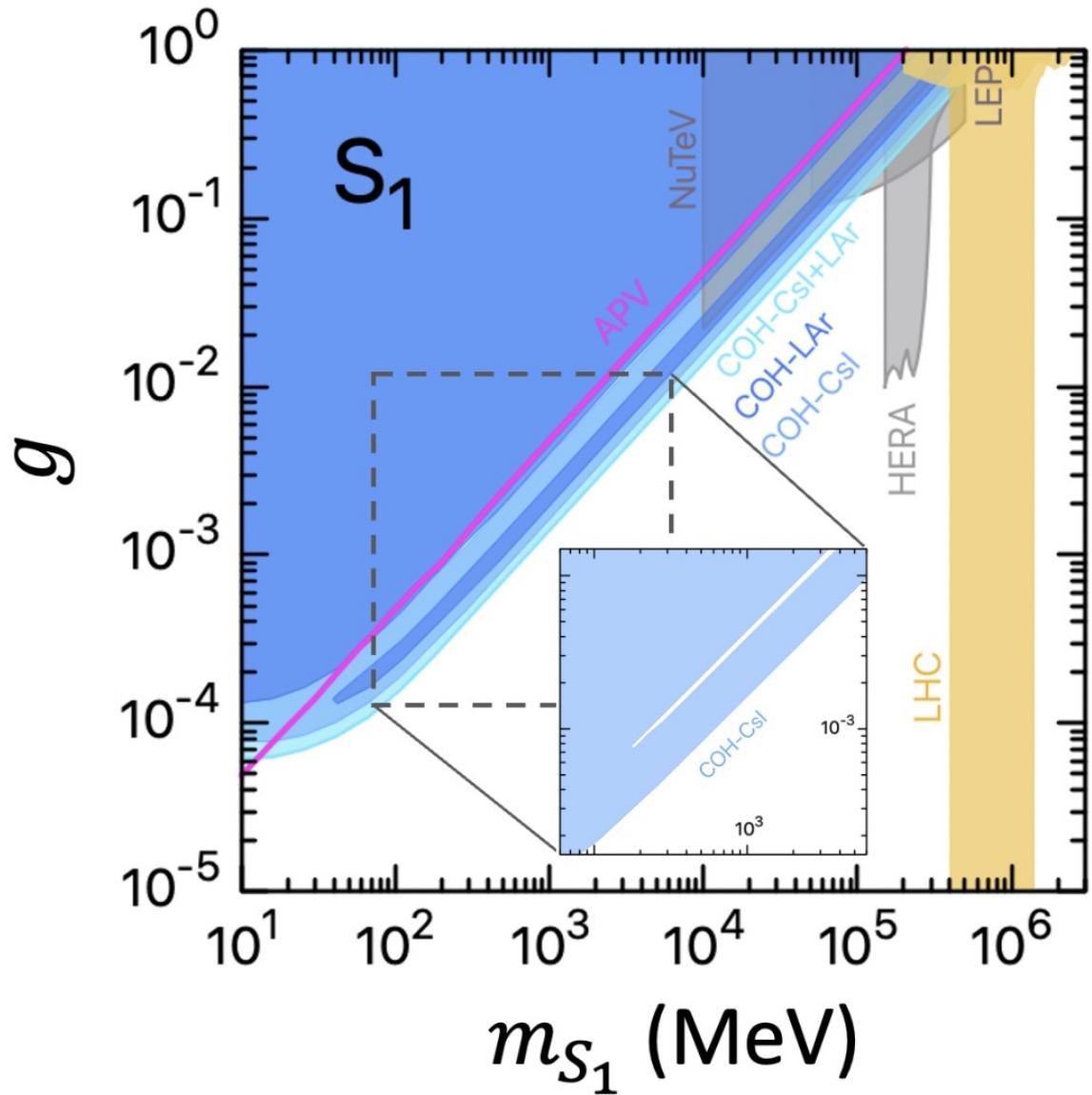
A concrete LQ scenario: S_1

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

$$(Q_W^{\text{SM}})^2 \rightarrow (Q_i^{\text{LQ}})^2 = (Q_W^{\text{SM}} + Q_{ii,\text{LQ}})^2 + \sum_{i \neq j} Q_{ij,\text{LQ}}^2$$

Where

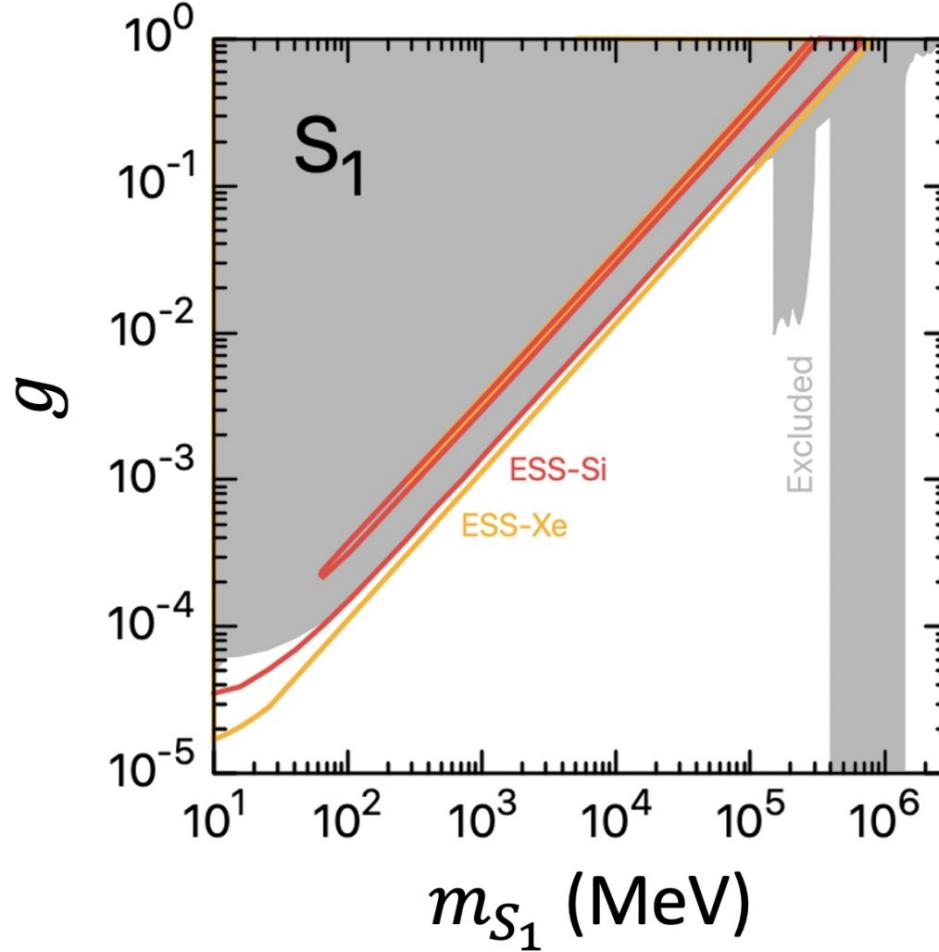
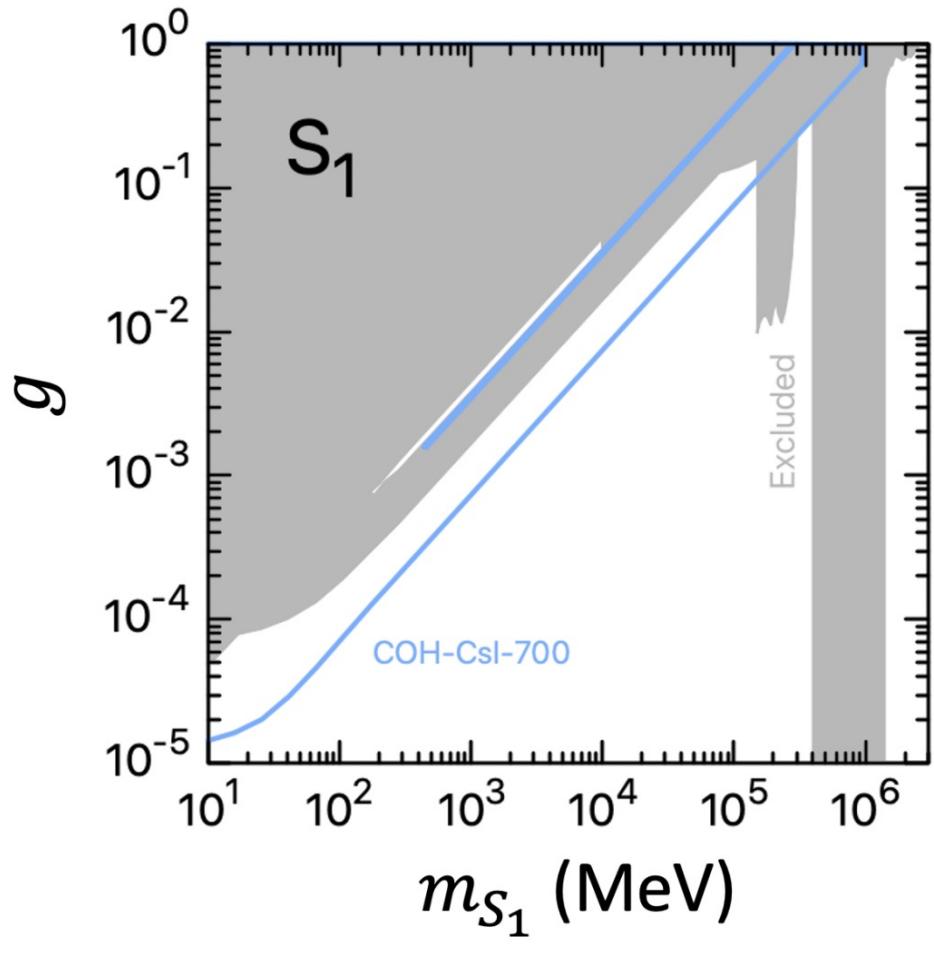
$$Q_{ij,S_1}^2 = \frac{g^2}{4\sqrt{2}G_F} \frac{Z F_Z(q^2) + 2N F_N(q^2)}{q^2 + m_{S_1}^2}$$



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

Can we improve on these bounds?

Future COHERENT upgrades and ESS detectors will be sensitive to LQ scenarios



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

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.

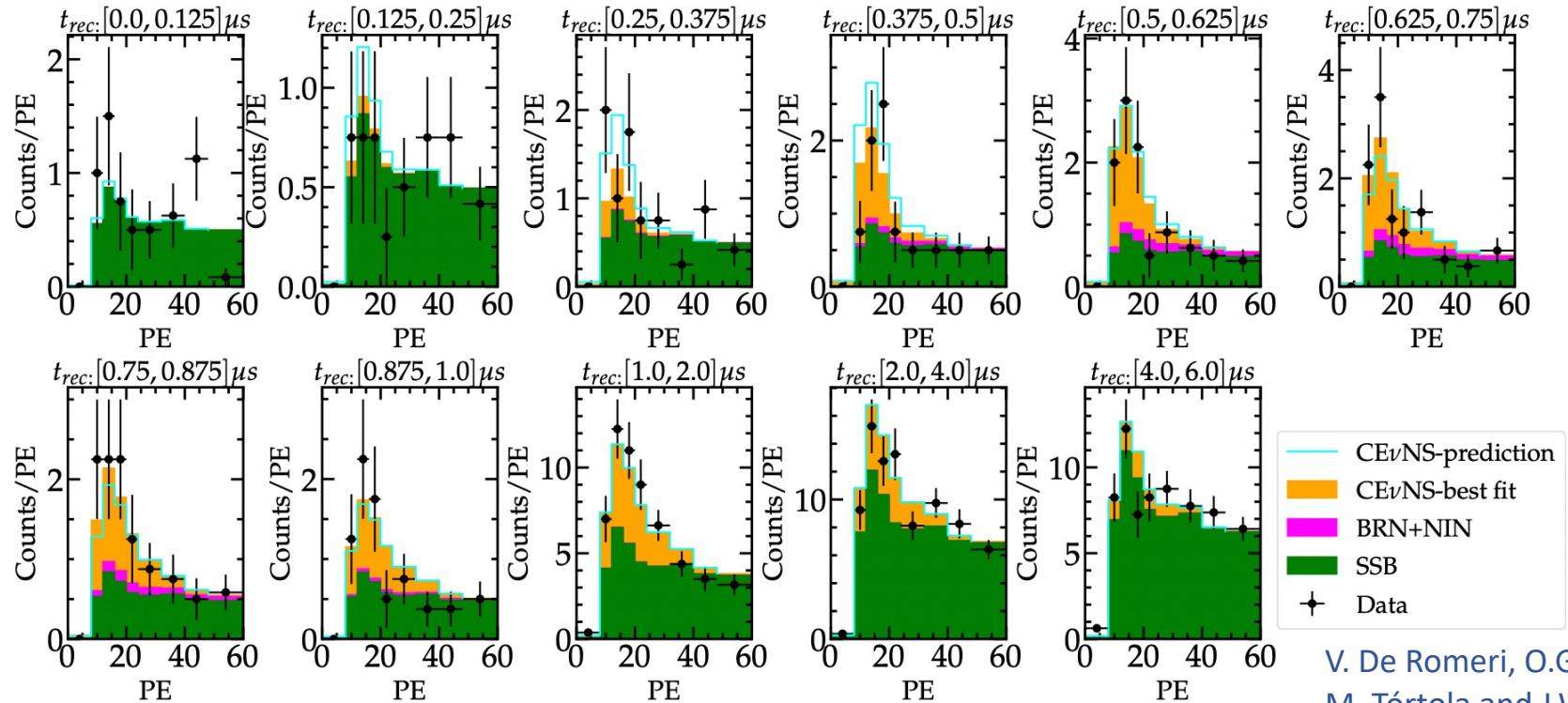
Thank you!

Backup

Predicted number of events

Nuclear recoil distribution

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



Timing distribution

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

- CEvNS-prediction
- CEvNS-best fit
- BRN+NIN
- SSB
- Data

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

Statistical Analysis

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

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

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

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 _{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 _{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)

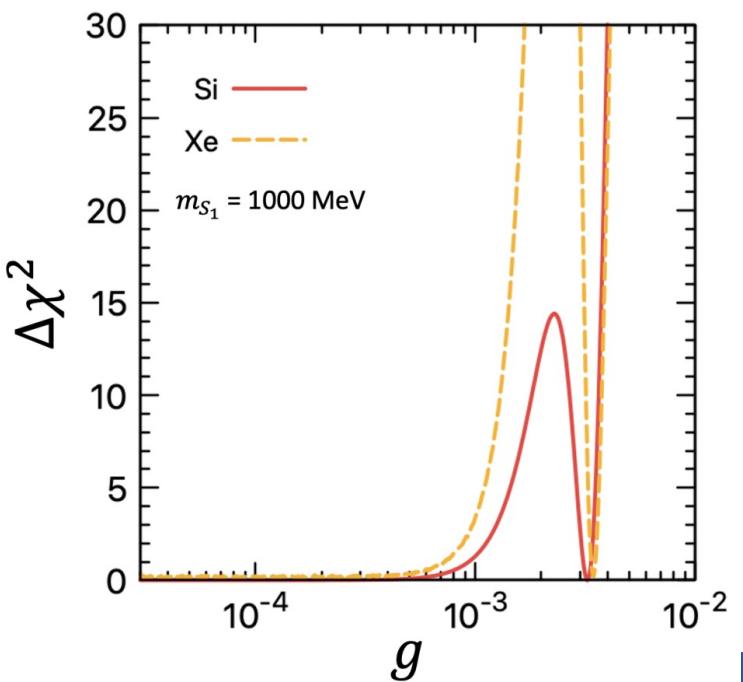
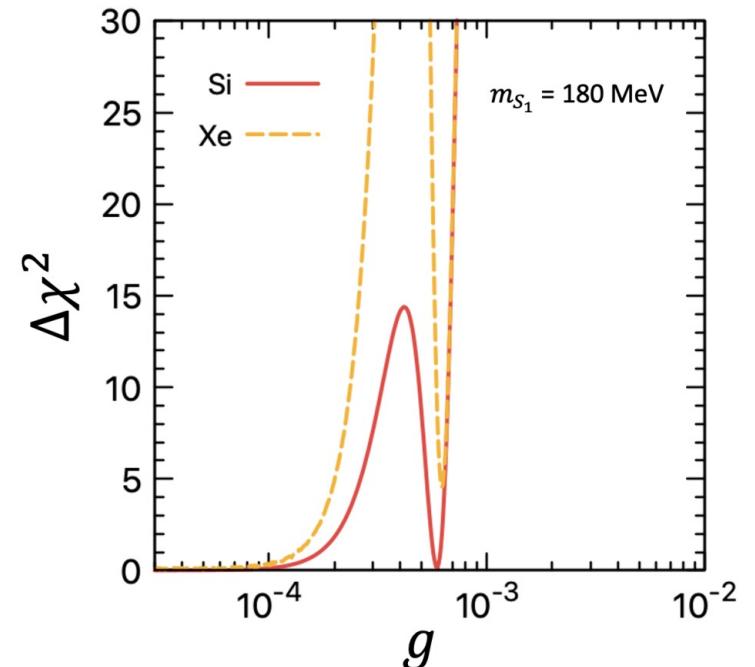
The allowed band can be explained when the mass of the LQ is large.

Indeed, we can reproduce the SM cross section when

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

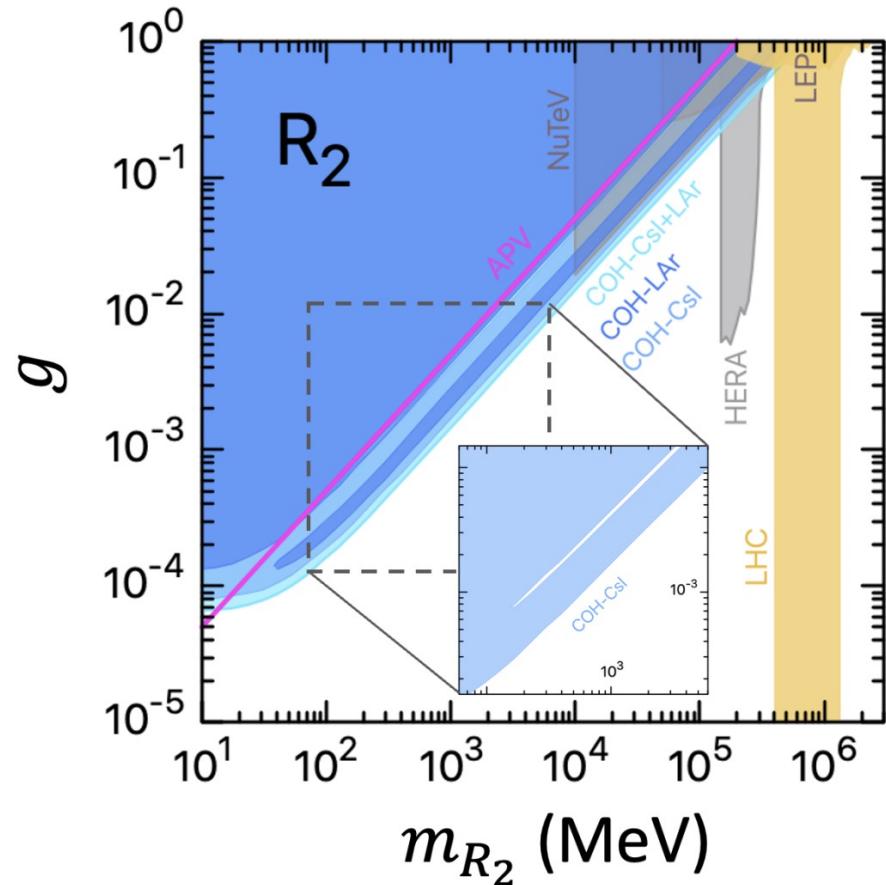
This condition is satisfied for

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



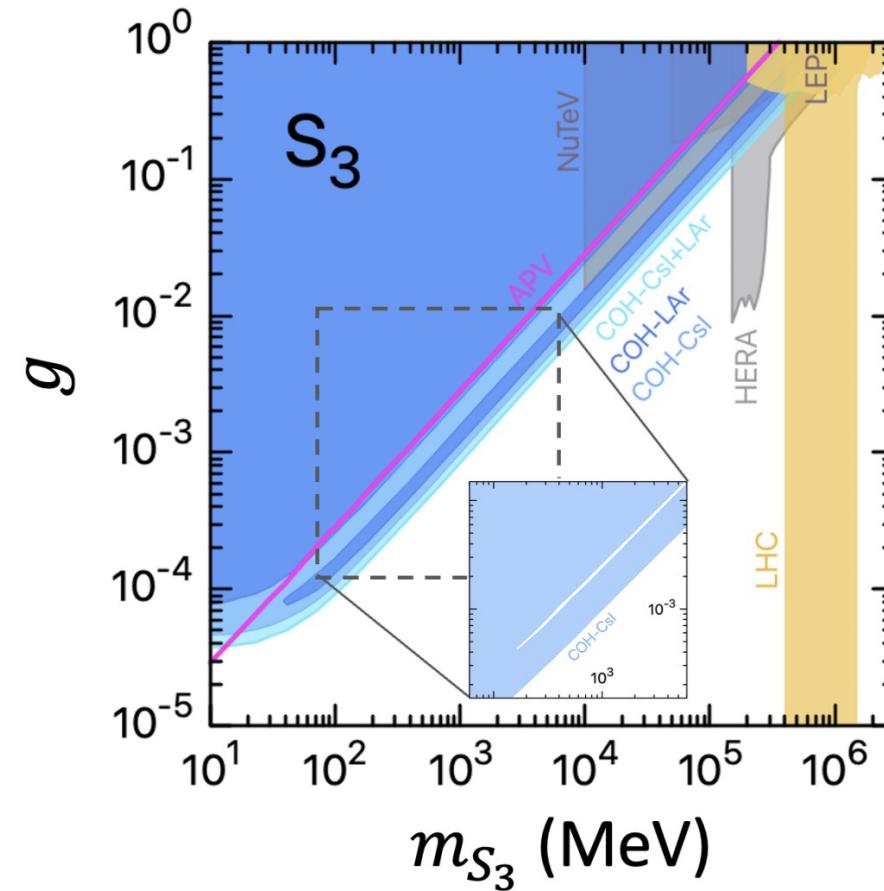
Scalar R_2

$$Q_{ij,R_2}^2 = \frac{g^2}{4\sqrt{2}G_F} \frac{2ZF_Z(q^2) + NF_N(q^2)}{q^2 + m_{R_2}^2}$$



Scalar S_3

$$Q_{ij,S_3}^2 = \frac{g^2}{4\sqrt{2}G_F} \left[\frac{5ZF_Z(q^2) + 4NF_N(q^2)}{q^2 + m_{S_3}^2} \right]$$



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