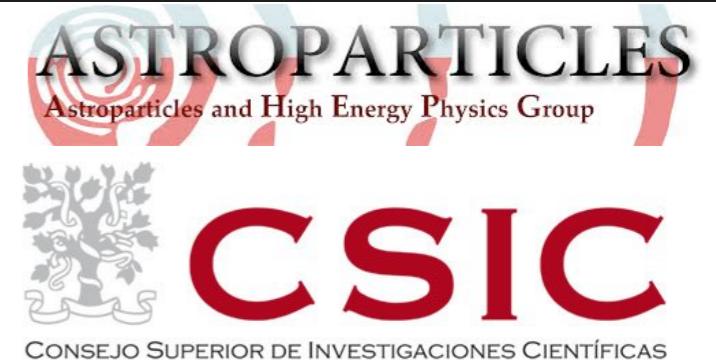




Gen=T



Valentina De Romeri

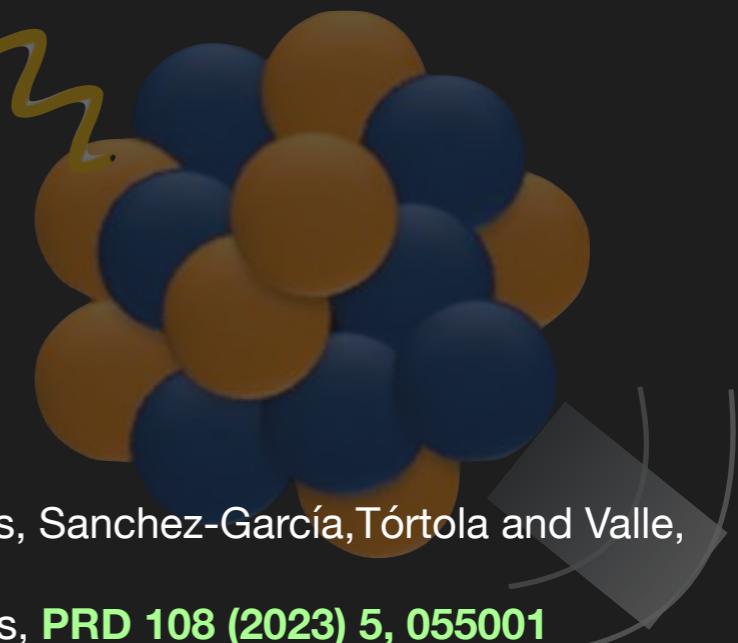
(IFIC Valencia - UV/CSIC)

New physics implications of COHERENT data



Based on:

- ▶ VDR, Miranda, Papoulias, Sanchez-García, Tórtola and Valle,
JHEP 04 (2023) 035
- ▶ VDR, Candela, Papoulias, **PRD 108 (2023) 5, 055001**
- ▶ VDR, Martín-Lozano, Sanchez-García, **2307.13790**



Coherent Elastic Neutrino-Nucleus Scattering

- Neutral-current process: $\nu + N(A,Z) \rightarrow \nu + N(A,Z)$
- CE ν NS occurs when the neutrino energy E_ν is such that nucleon amplitudes sum up coherently ($|\vec{q}| \leq 1/R_{\text{nucleus}}$):
=> cross section enhancement $\sigma \sim (\# \text{scatter targets})^2$
=> upper limit on neutrino energy (up to $E_\nu \sim 100$ MeV)

- Total cross section scales approximately like N^2

$$\frac{d\sigma}{dE_R} \propto N^2$$

- Can be ~ 2 orders of magnitude larger than inverse beta decay process used to first observe neutrinos

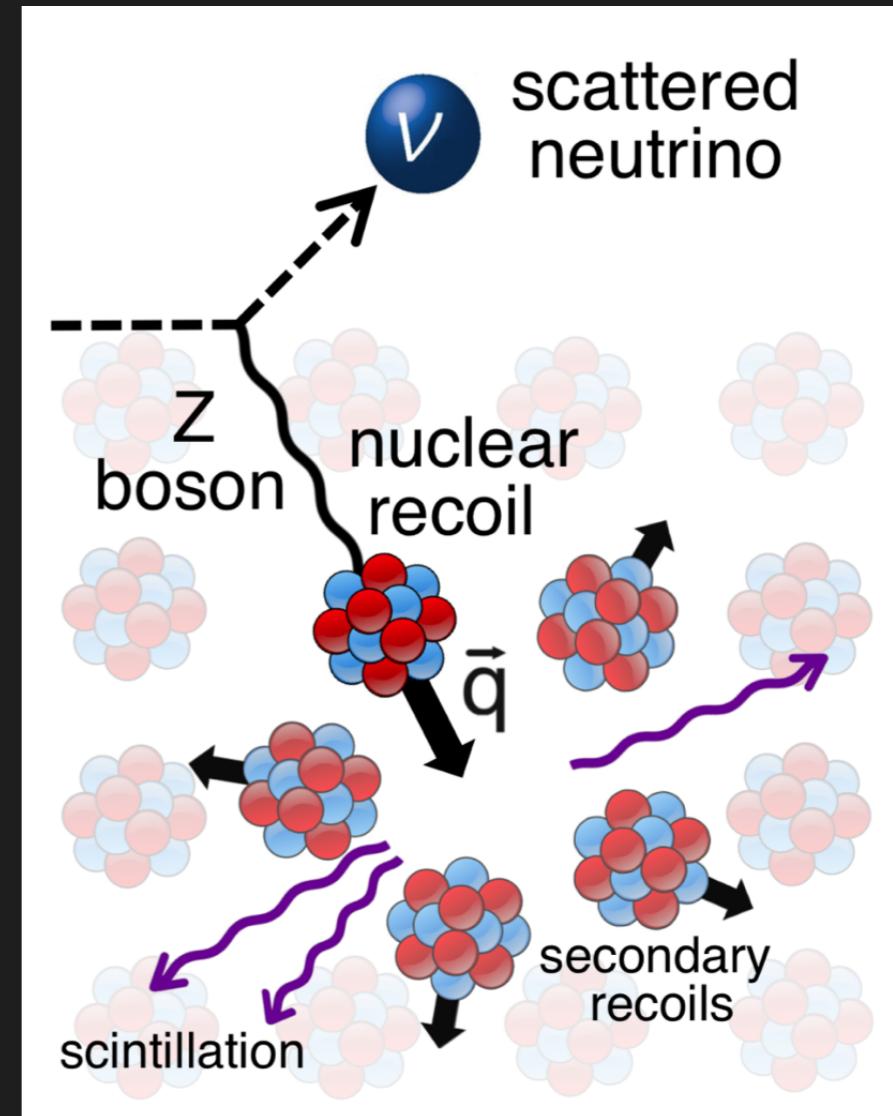


Image adapted from COHERENT exp.

D.Z. Freedman, Phys. Rev. D 9 (1974)
V.B. Kopeliovich and L.L. Frankfurt, ZhETF Pis. Red. 19 (1974)

Coherent Elastic Neutrino-Nucleus Scattering

CEvNS has a well-calculable cross-section in the SM:
(probability of kicking a nucleus with nuclear recoil energy T)

Fermi constant (SM parameter)	Kinematics	Nuclear Form Factor: $F=1$ full coherence
$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi} \left(1 - \frac{MT}{2E_\nu^2} - \frac{T}{E_\nu} \right) Q_w^2 [F_w(q^2)]^2 + \frac{G_F^2 M}{4\pi} \left(1 + \frac{MT}{2E_\nu^2} - \frac{T}{E_\nu} \right) F_A(q^2)$		
	Weak nuclear charge	

$$Q_w = [Z(1 - 4 \sin^2 \theta_W) - N] \quad s w^2 = 0.23 \rightarrow \text{protons unimportant}$$

Neutron contribution dominates

- E_ν : is the incident neutrino energy
- M : the nuclear mass of the detector material
- 3-momentum transfer $q^2 = 2MT$

Axial contribution is small for most nuclei, spin-dependent.
It vanishes for nuclei with even number of protons and neutrons

Freedman, PRD 9 (1974) 1389; Drukier, Stodolsky, PRD 30 (1984) 2295; Barranco, Miranda, Rashba, hep-ph/0508299

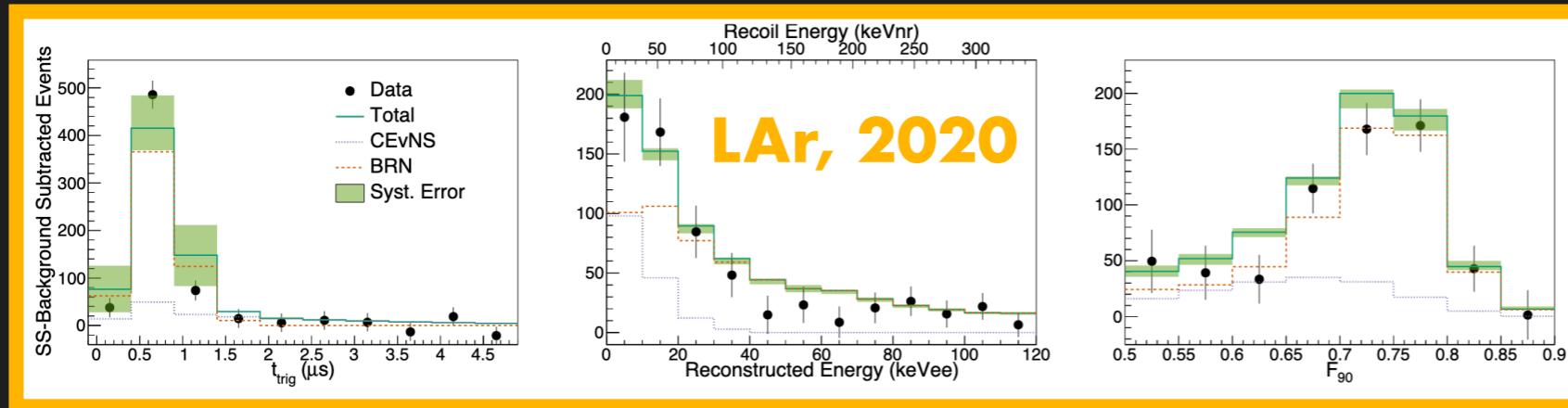
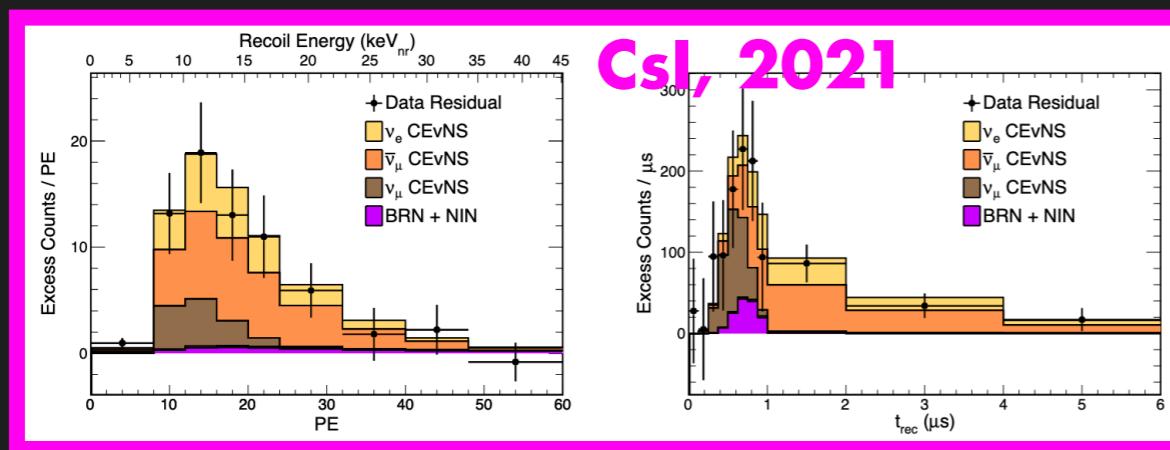
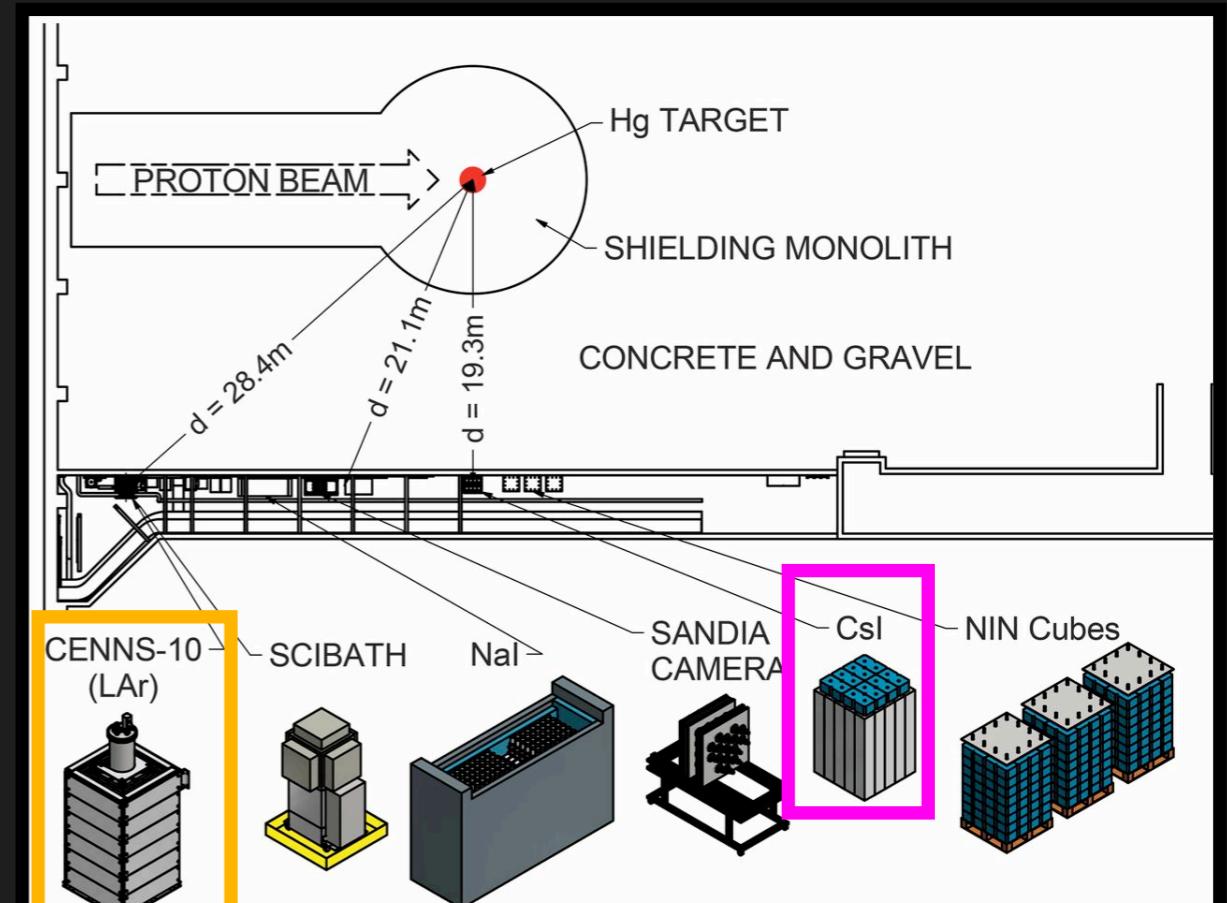
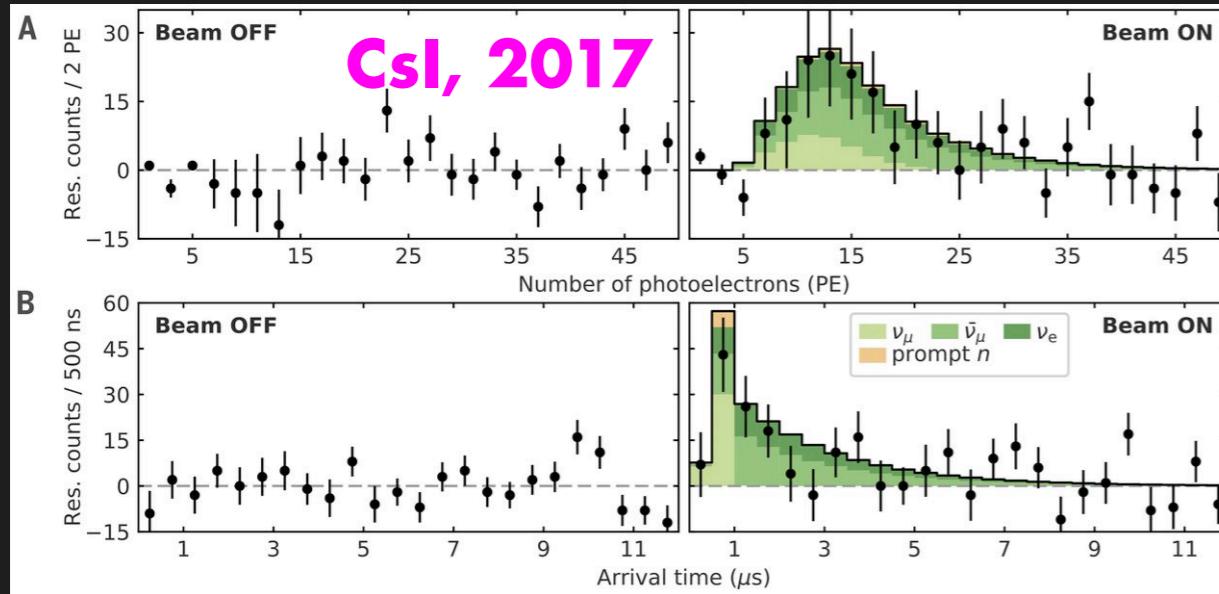


CEvNS experiments worldwide



+ SBC (Mexico), NEON (Corea), JSNS² (Japan) ...

Observation of CE ν NS by COHERENT



D. Akimov et al. (COHERENT). Science 357, 1123–1126 (2017)
 D. Akimov et al. (COHERENT). 2110.07730
 D. Akimov et al. (COHERENT). Phys. Rev. Lett. 126, 012002 (2021)
 Daughhetee, BNL Physics Seminar 2020

Physics potential of CE_vNS

- ▶ EW precision tests
 - Weak mixing angle

- ▶ Nuclear physics
 - Nuclear form factors
 - Neutron radius and “skin”
- ▶ Supernovae
- ▶ Solar neutrinos

THIS TALK

- ▶ New neutrino interactions
 - Non-standard interactions
 - Generalised interactions
 - New light mediators
- ▶ Neutrino electromagnetic properties
 - Neutrino charge radius
 - Magnetic moments
- ▶ Sterile neutrinos
- ▶ Dark matter/dark sectors

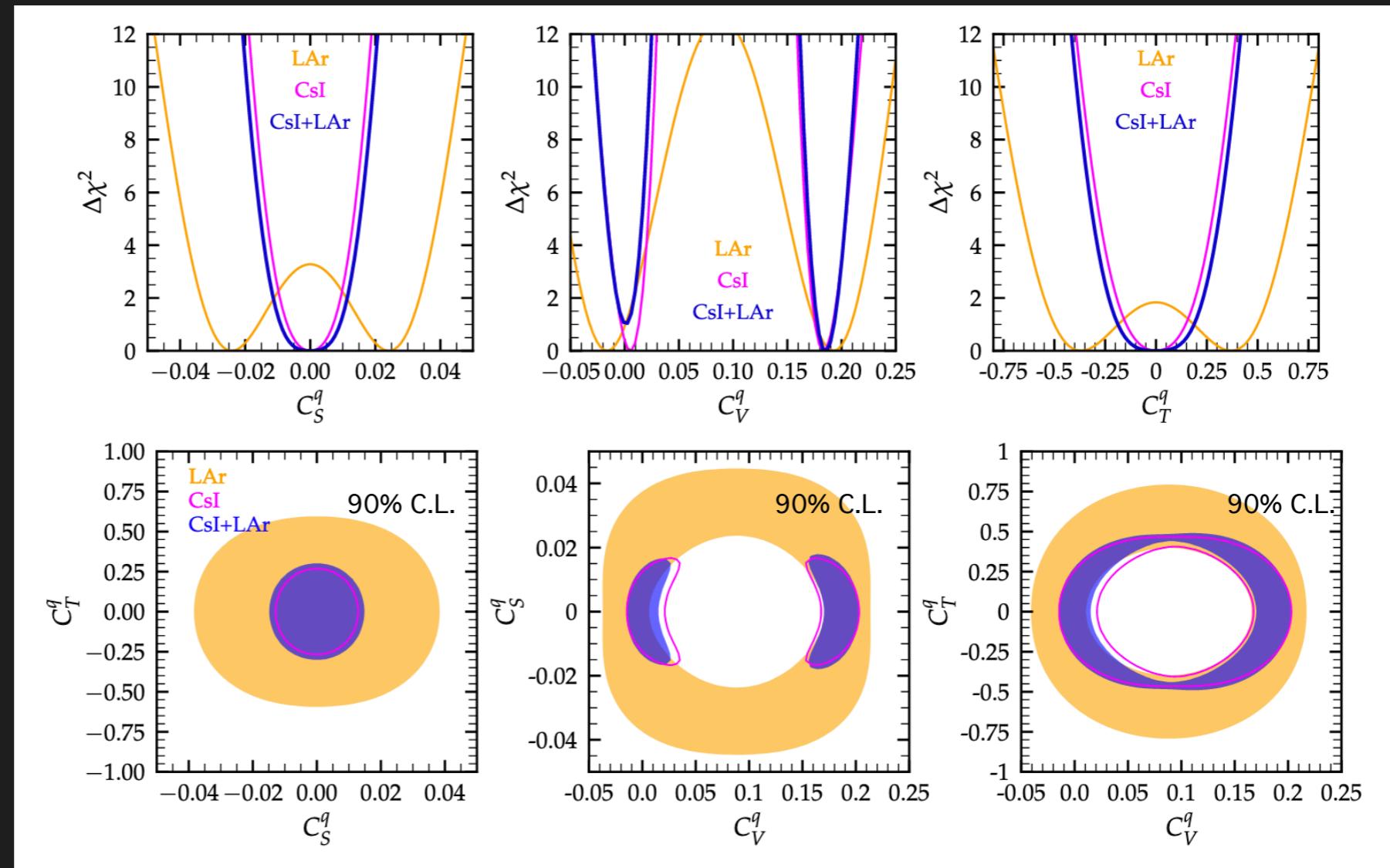
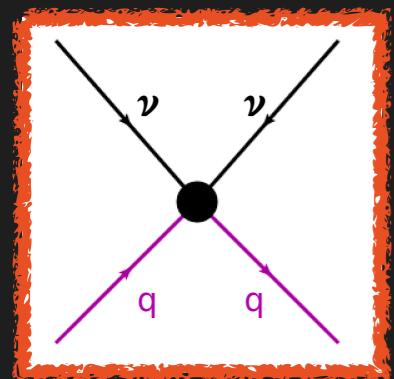


New neutrino interactions: NGI

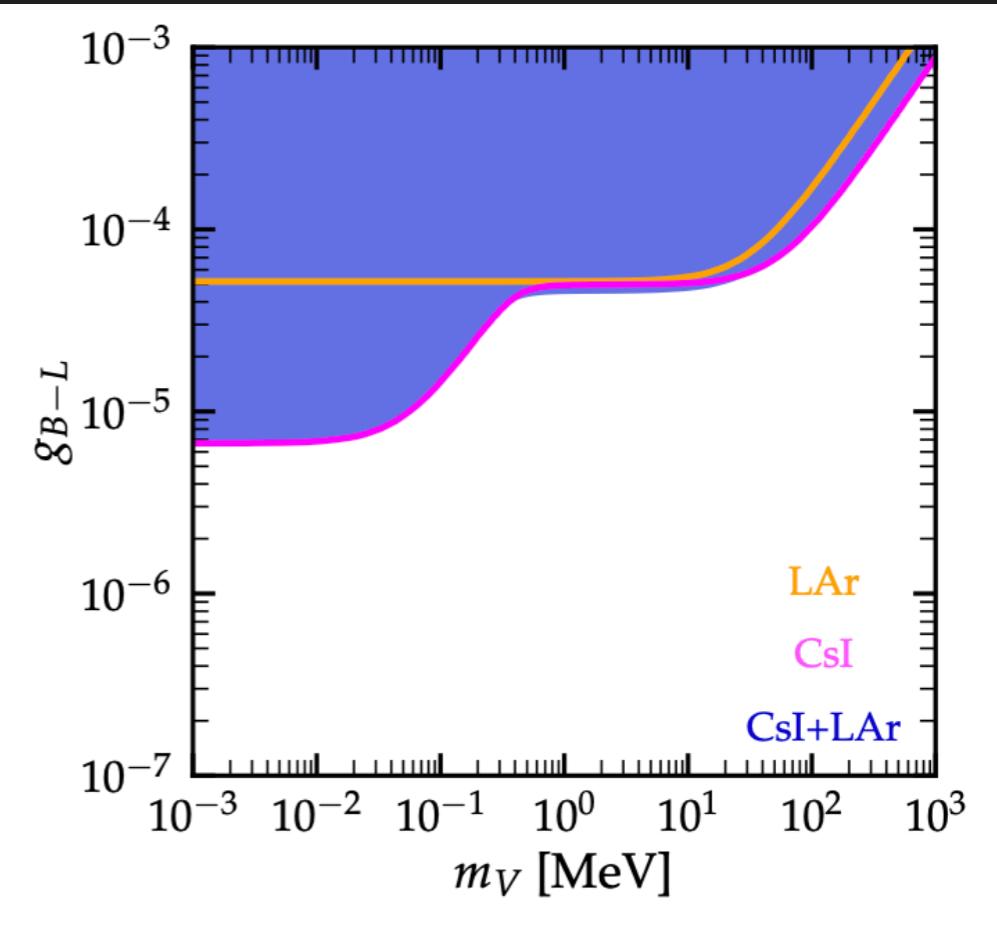
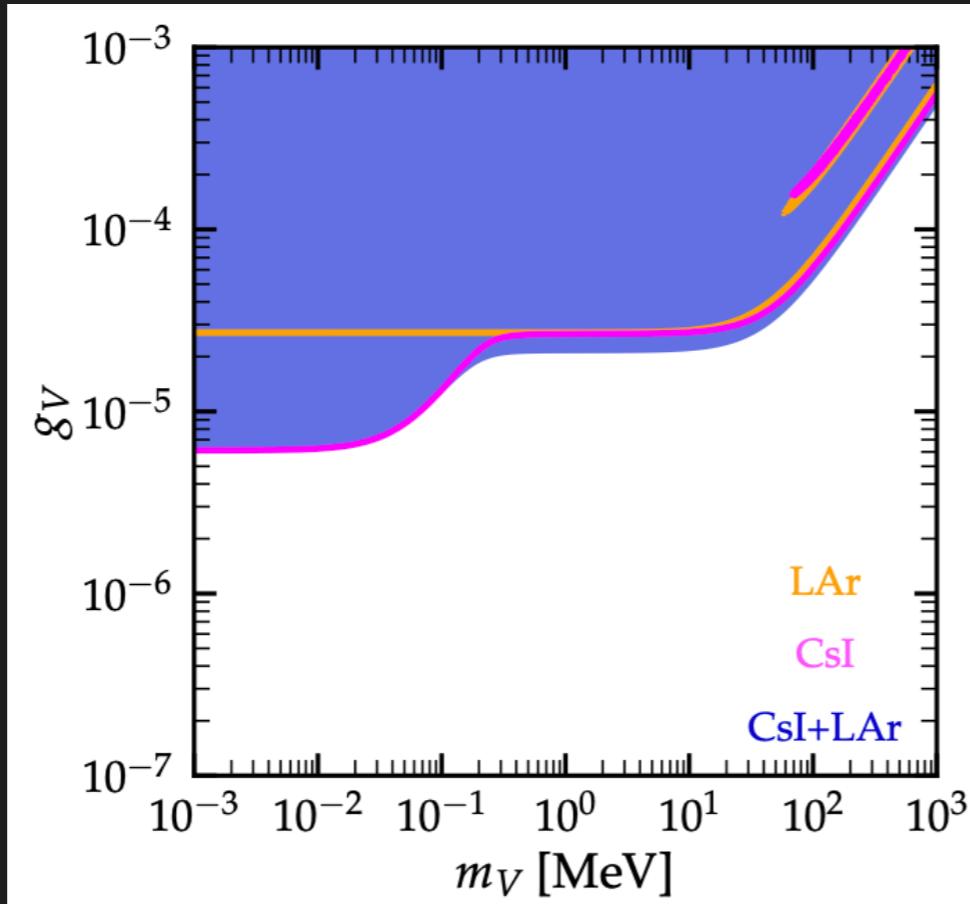
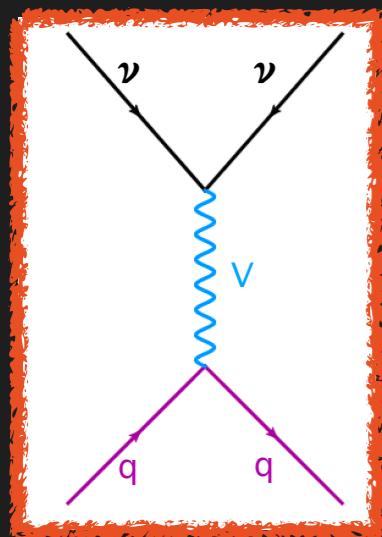
Additional types of Lorentz-invariant interactions involving scalar, vector and tensor terms

$$\mathcal{L}_{\text{eff}}^{\text{NGI}} = \frac{G_F}{\sqrt{2}} \sum_{X=S,P,V,A,T} [\bar{\nu} \Gamma^X \nu] [\bar{q} \Gamma_X (C_X^q + i\gamma_5 D_X^q) q]$$

Lee & Yang, Phys. Rev. 104 (1956) 254-258
 Lindner et al., JHEP 03 (2017) 097
 Aristizabal, VDR, Rojas Phys. Rev. D 98 (2018) 075018
 Flores et al. Phys. Rev. D 105 no. 5, (2022) 05501
 ...



New neutrino interactions: light vector mediator

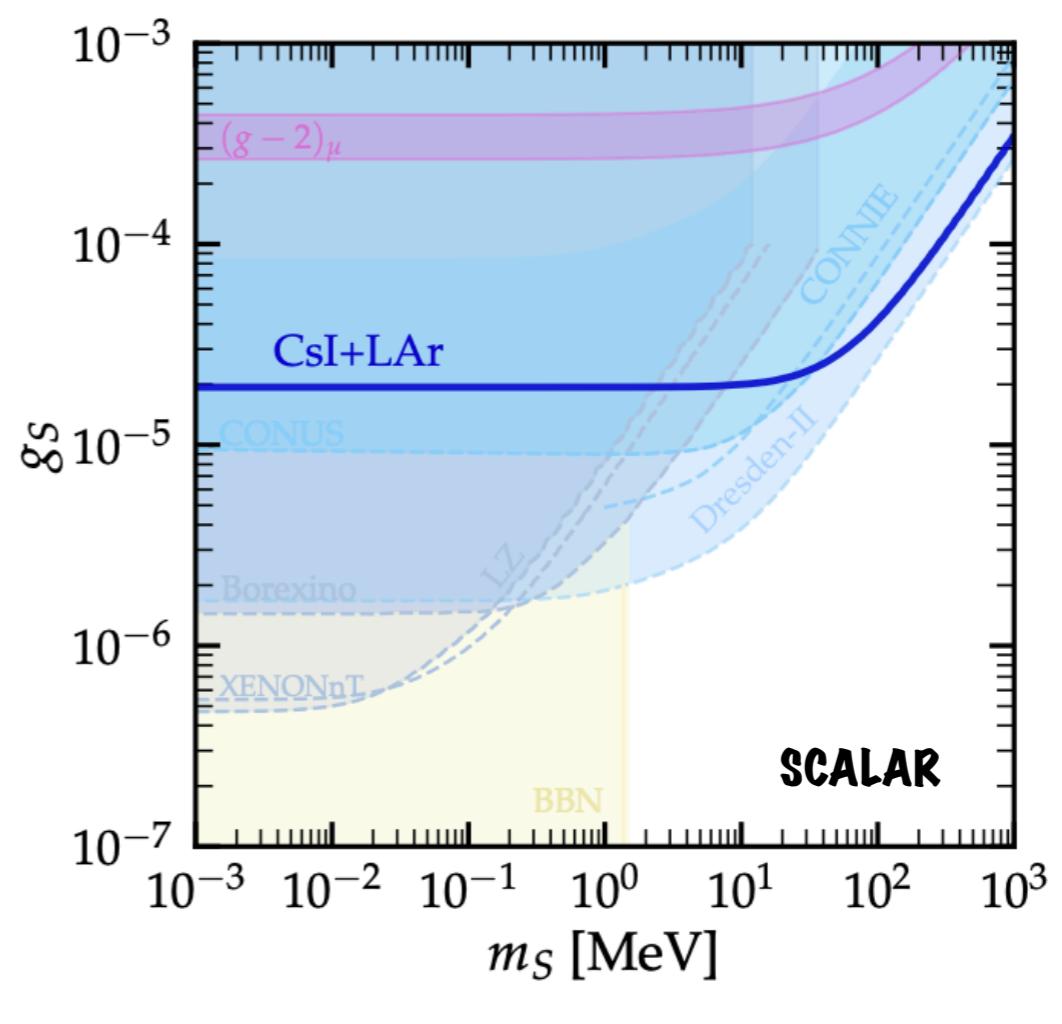
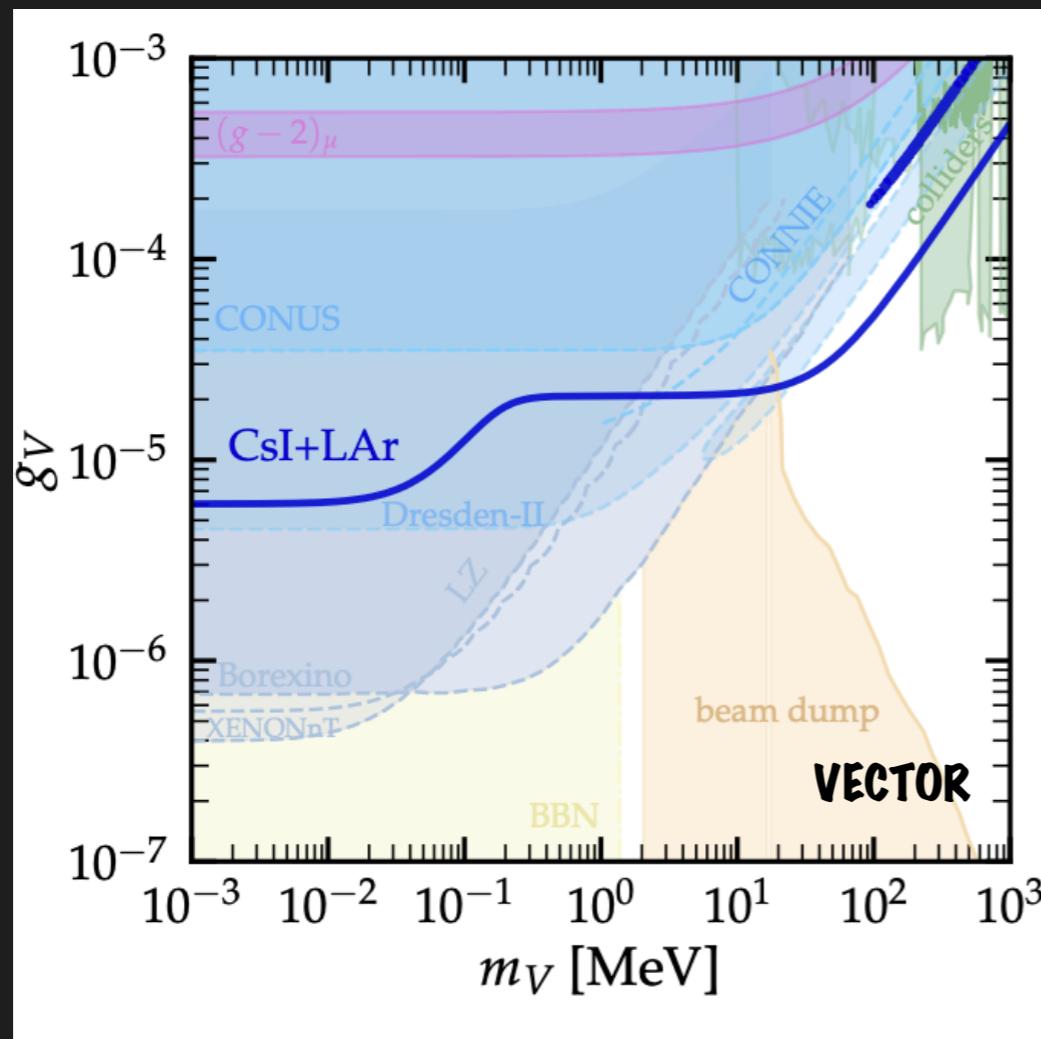
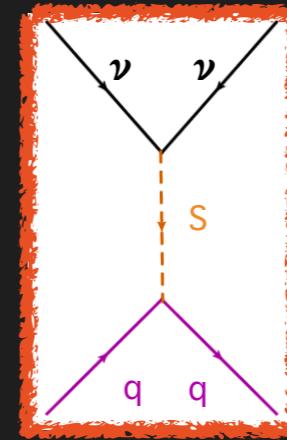
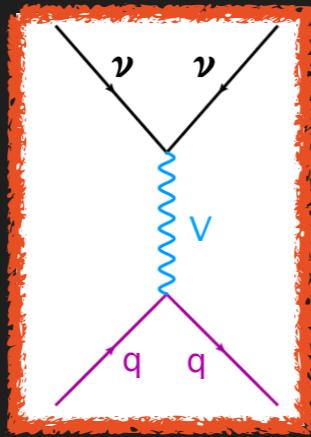


VDR, Miranda, Papoulias, Sanchez-García, Tórtola and Valle, JHEP 04 (2023) 035

- Complementary analyses in: Coloma et al. 2202.10829, Atzori-Corona et al. 2205.09484



New light mediators: summary

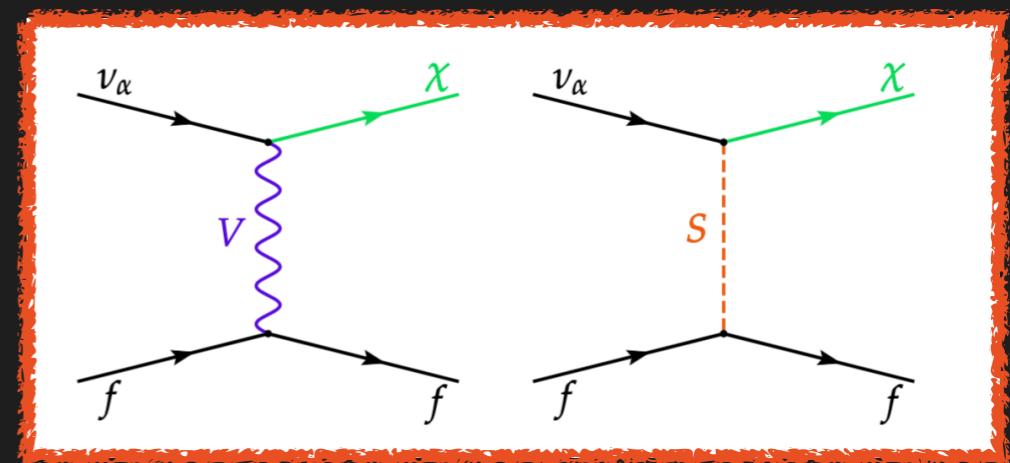


VDR, Miranda, Papoulias, Sanchez-García, Tórtola and Valle, JHEP 04 (2023) 035

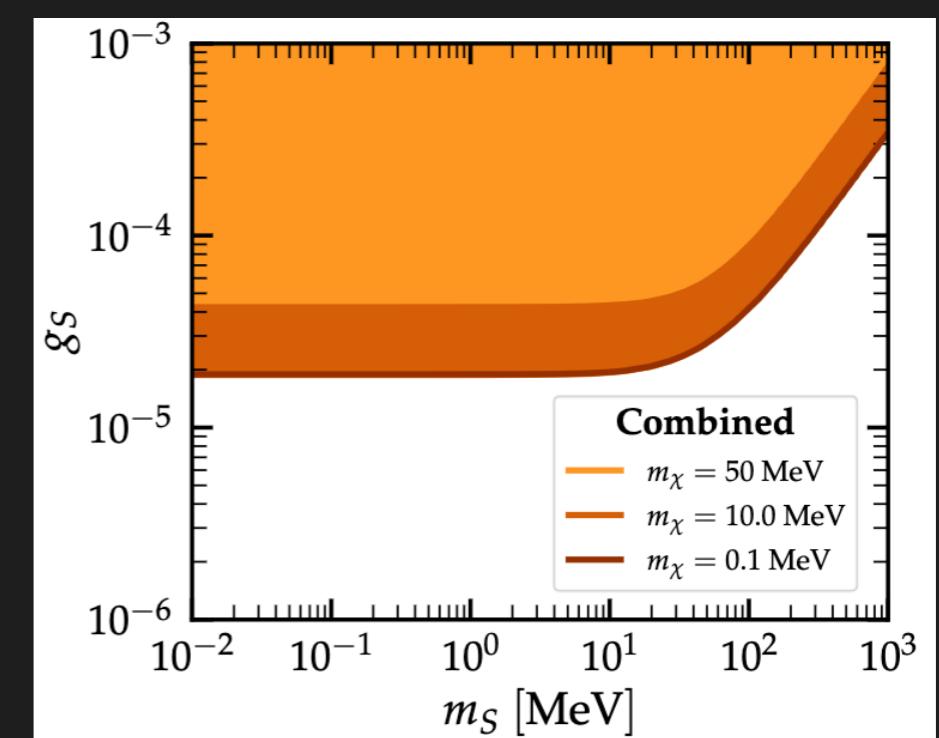
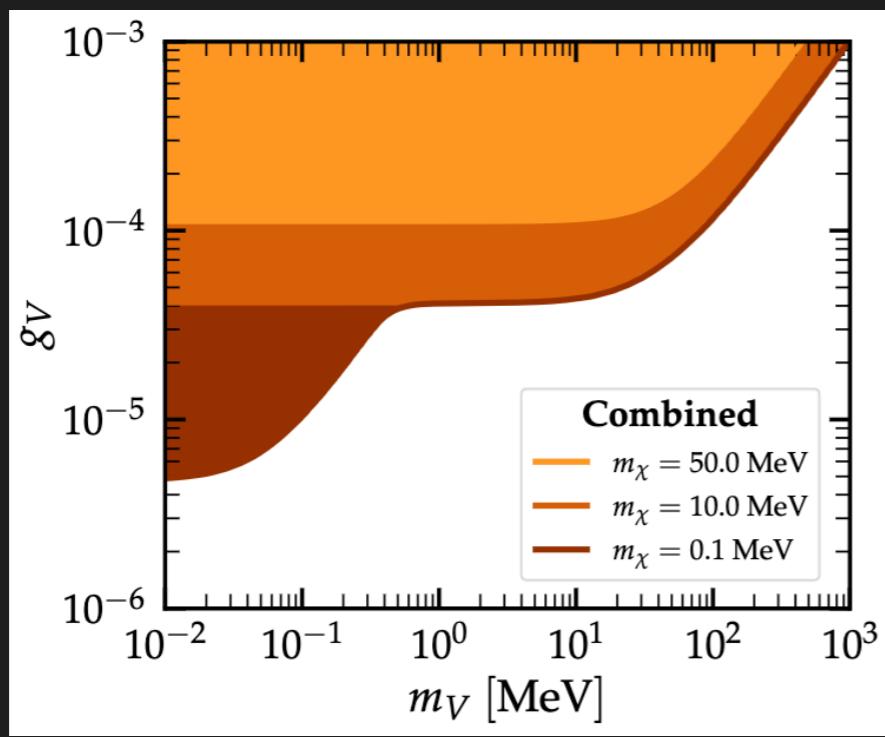


Production of new particles: dark fermion

Possible production of a new MeV-scale fermion through the **up-scattering process** of neutrinos off the nuclei and the electrons of the detector material, via the exchange of a light vector or scalar mediator.



VDR, Muñoz-Candela, Papoulias 2305.03341

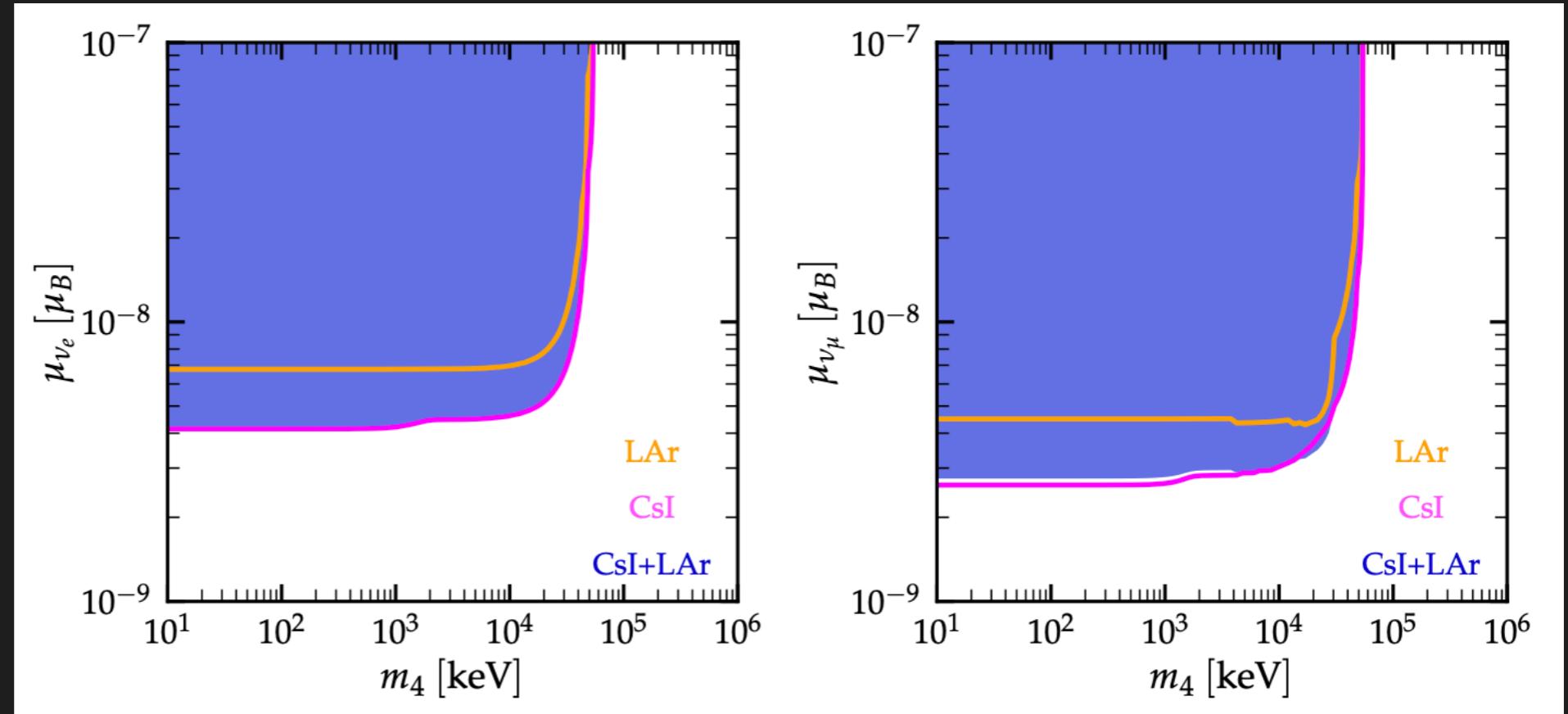
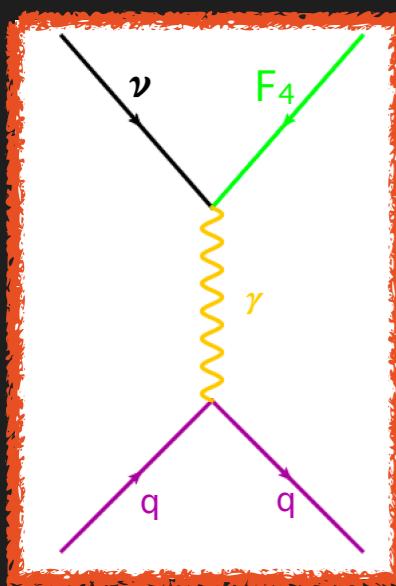


Production of new particles: sterile neutrino dipole portal

Transition of an active neutrino to a massive sterile state, induced by a magnetic coupling: $\nu_L + N \rightarrow F_4 + N$

$$\mathcal{L} = \bar{\nu} \sigma_{\mu\nu} \lambda \nu_R F^{\mu\nu} + H.c.$$

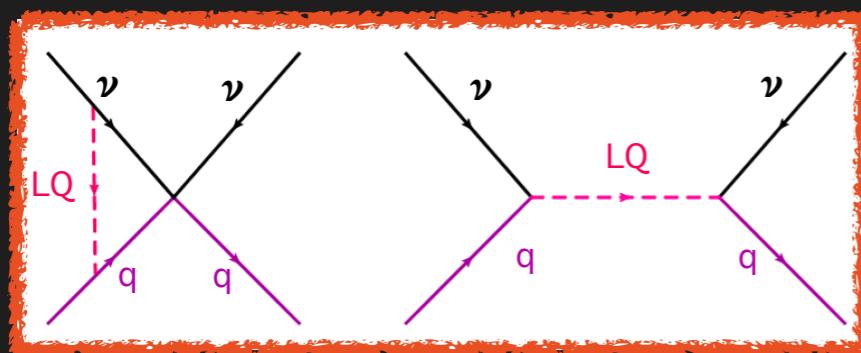
$$m_4^2 \lesssim 2m_N E_r \left(\sqrt{\frac{2}{m_N E_r}} E_\nu - 1 \right)$$



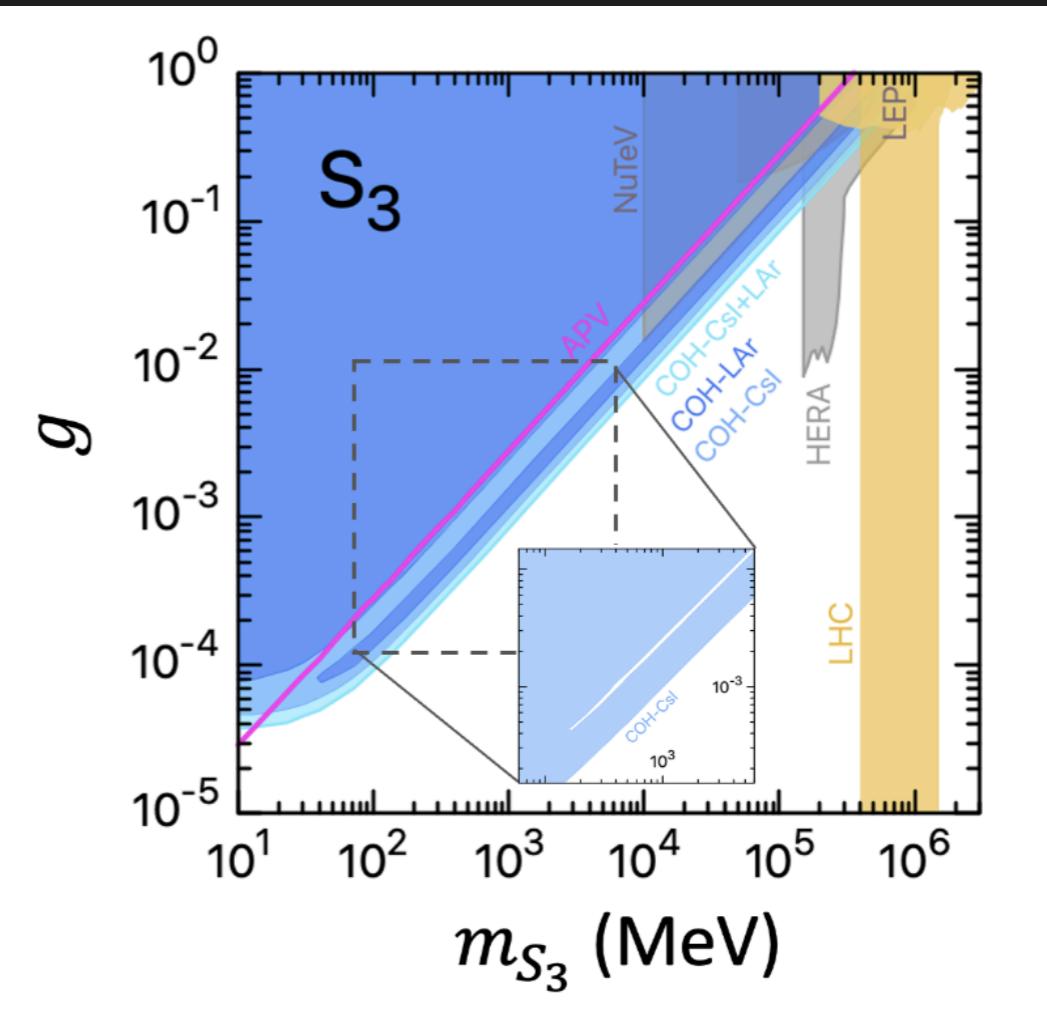
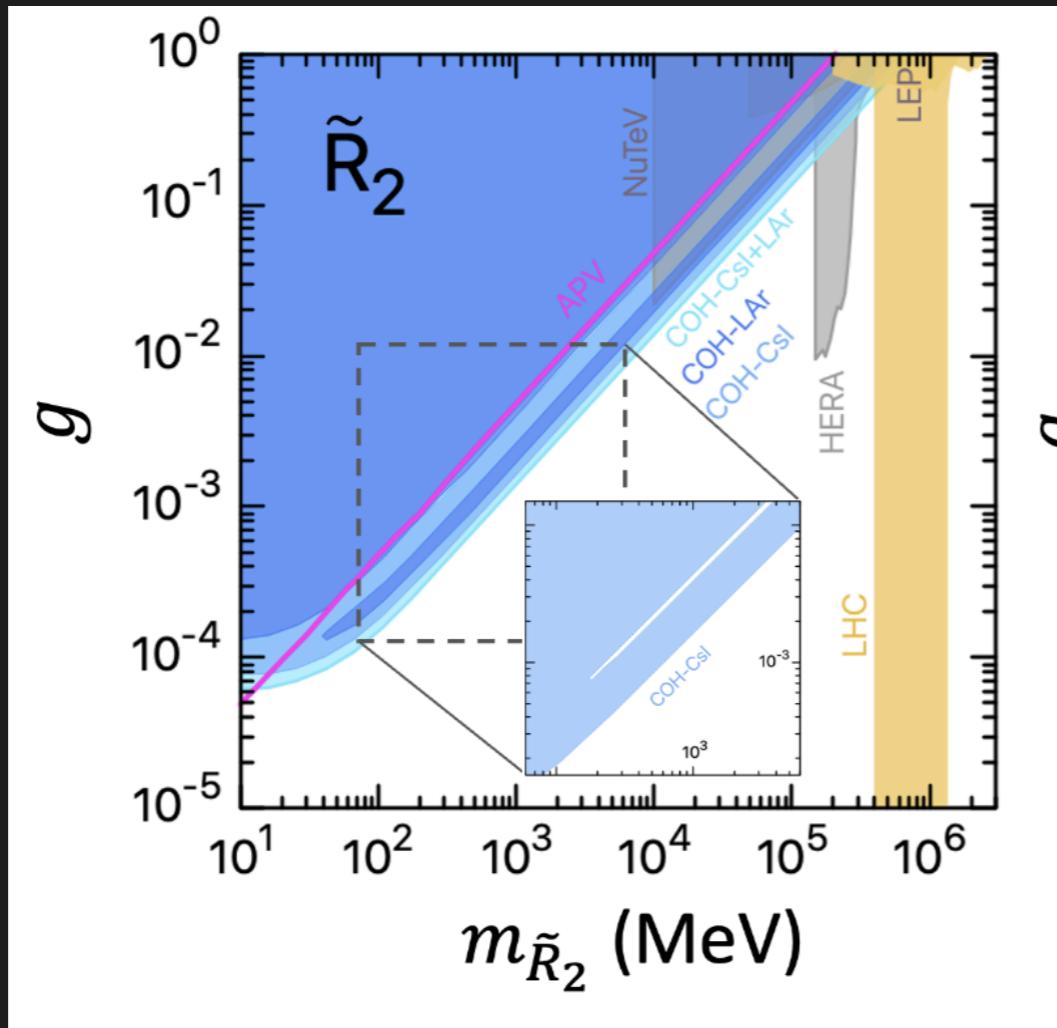
VDR, Miranda, Papoulias, Sanchez-García, Tórtola and Valle, JHEP 04 (2023) 035



Scalar leptoquarks coupling to neutrinos



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	$(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$

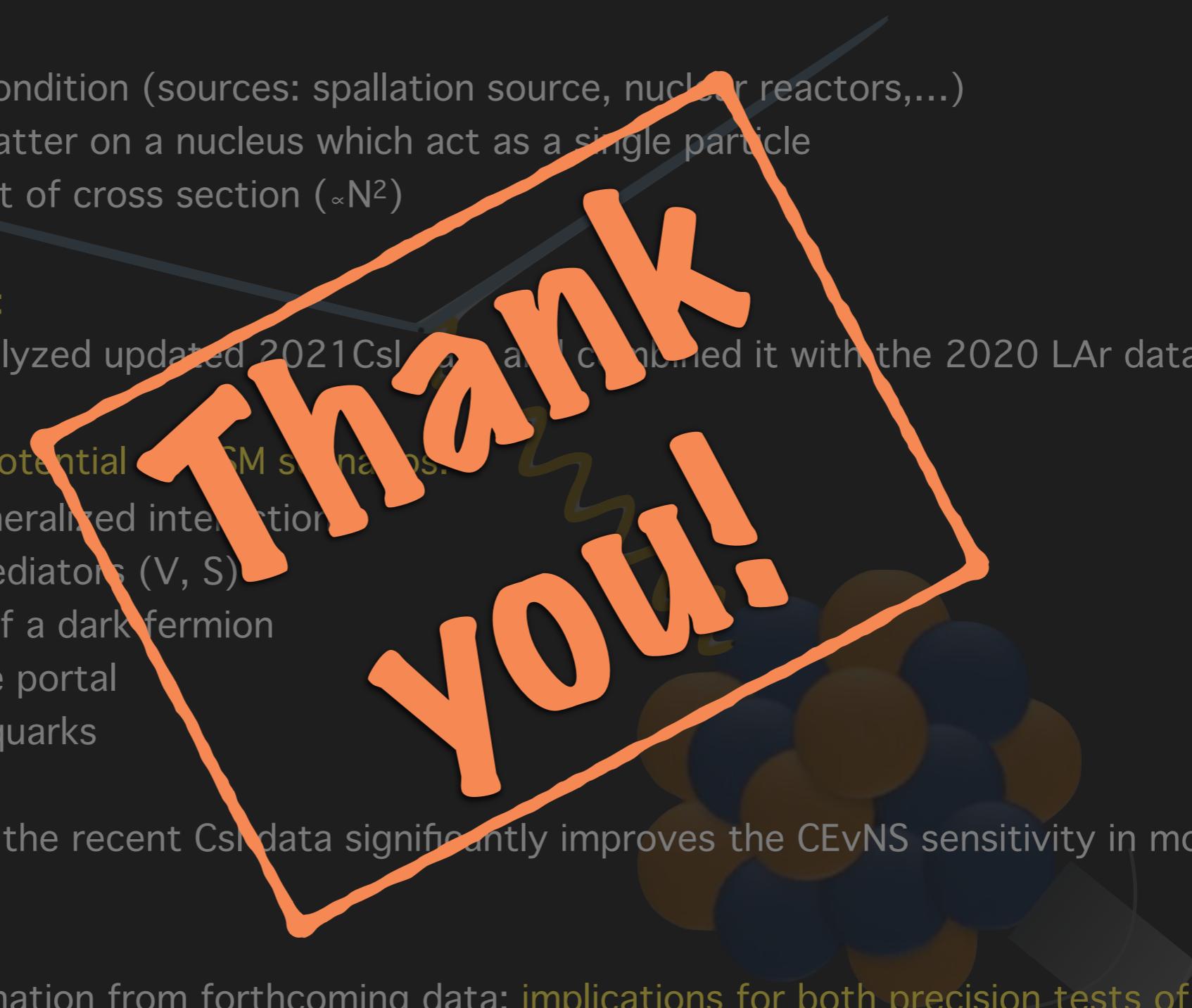


Summary

- ▶ CE_νNS process:
 - coherency condition (sources: spallation source, nuclear reactors,...)
 - neutrinos scatter on a nucleus which act as a single particle
 - enhancement of cross section ($\sim N^2$)
- ▶ COHERENT data:
 - We have analyzed updated 2021 CsI data and combined it with the 2020 LAr data set.
- ▶ CE_νNS physics potential on BSM scenarios:
 - Neutrino generalized interactions
 - New light mediators (V, S)
 - Production of a dark fermion
 - Sterile dipole portal
 - Scalar leptoquarks
- ▶ The inclusion of the recent CsI data significantly improves the CE_νNS sensitivity in most of these physics cases.
- ▶ Wealth of information from forthcoming data: implications for both precision tests of the Standard Model and for new physics in the neutrino sector!



Summary

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- 

Statistical analysis

CsI

$$\chi^2_{\text{CsI}} \Big|_{\text{CE}\nu\text{NS}(\text{+ES})} = 2 \sum_{i=1}^9 \sum_{j=1}^{11} \left[N_{\text{th}}^{\text{CsI}} - N_{ij}^{\text{exp}} + N_{ij}^{\text{exp}} \ln \left(\frac{N_{ij}^{\text{exp}}}{N_{\text{th}}^{\text{CsI}}} \right) \right] + \sum_{k=0}^{4(5)} \left(\frac{\alpha_k}{\sigma_k} \right)^2.$$

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

- $\sigma_0 = 11\%$ efficiency + flux
- $\sigma_1 = 25\%$ BRN
- $\sigma_2 = 35\%$ NIN
- $\sigma_3 = 2.1\%$ SSB
- $\sigma_5 = 3.8\%$ QF
- $\sigma_4 = 5\%$ ($R_A = 1.23 A^{1/3}(1 + \alpha_4)$)
- α_6 beam timing (no prior)
- α_7 CEvNS efficiency

• COHERENT Collaboration Phys.Rev.Lett. 129 no. 8, (2022) 081801

LAr

- $\sigma_0 = 13\%$ normal. CEvNS
- $\sigma_3 = 0.79\%$ SS
- $\sigma_8 = 100\%$ delayed BRN
- $\sigma_4 = 32\%$ prompt BRN
- $\beta_1, \beta_2, \beta_5, \beta_6$ and β_7 shape uncertainties

$$\chi^2_{\text{LAr}} = \sum_{i=1}^{12} \sum_{j=1}^{10} \frac{1}{\sigma_{ij}^2} \left[(1 + \beta_0 + \beta_1 \Delta_{\text{CE}\nu\text{NS}}^{F_{90+}} + \beta_1 \Delta_{\text{CE}\nu\text{NS}}^{F_{90-}} + \beta_2 \Delta_{\text{CE}\nu\text{NS}}^{t_{\text{trig}}}) N_{ij}^{\text{CE}\nu\text{NS}} \right. \\ \left. + (1 + \beta_3) N_{ij}^{\text{SSB}} \right. \\ \left. + (1 + \beta_4 + \beta_5 \Delta_{\text{pBRN}}^{E_+} + \beta_5 \Delta_{\text{pBRN}}^{E_-} + \beta_6 \Delta_{\text{pBRN}}^{t_{\text{trig}}^+} + \beta_6 \Delta_{\text{pBRN}}^{t_{\text{trig}}^-} + \beta_7 \Delta_{\text{pBRN}}^{t_{\text{trig}}^w}) N_{ij}^{\text{pBRN}} \right. \\ \left. + (1 + \beta_8) N_{ij}^{\text{dBRN}} - N_{ij}^{\text{exp}} \right]^2 \\ + \sum_{k=0,3,4,8} \left(\frac{\beta_k}{\sigma_k} \right)^2 + \sum_{k=1,2,5,6,7} (\beta_k)^2,$$

• Atzori-Corona et al. 2205.09484, COHERENT Collaboration arXiv:2006.12659



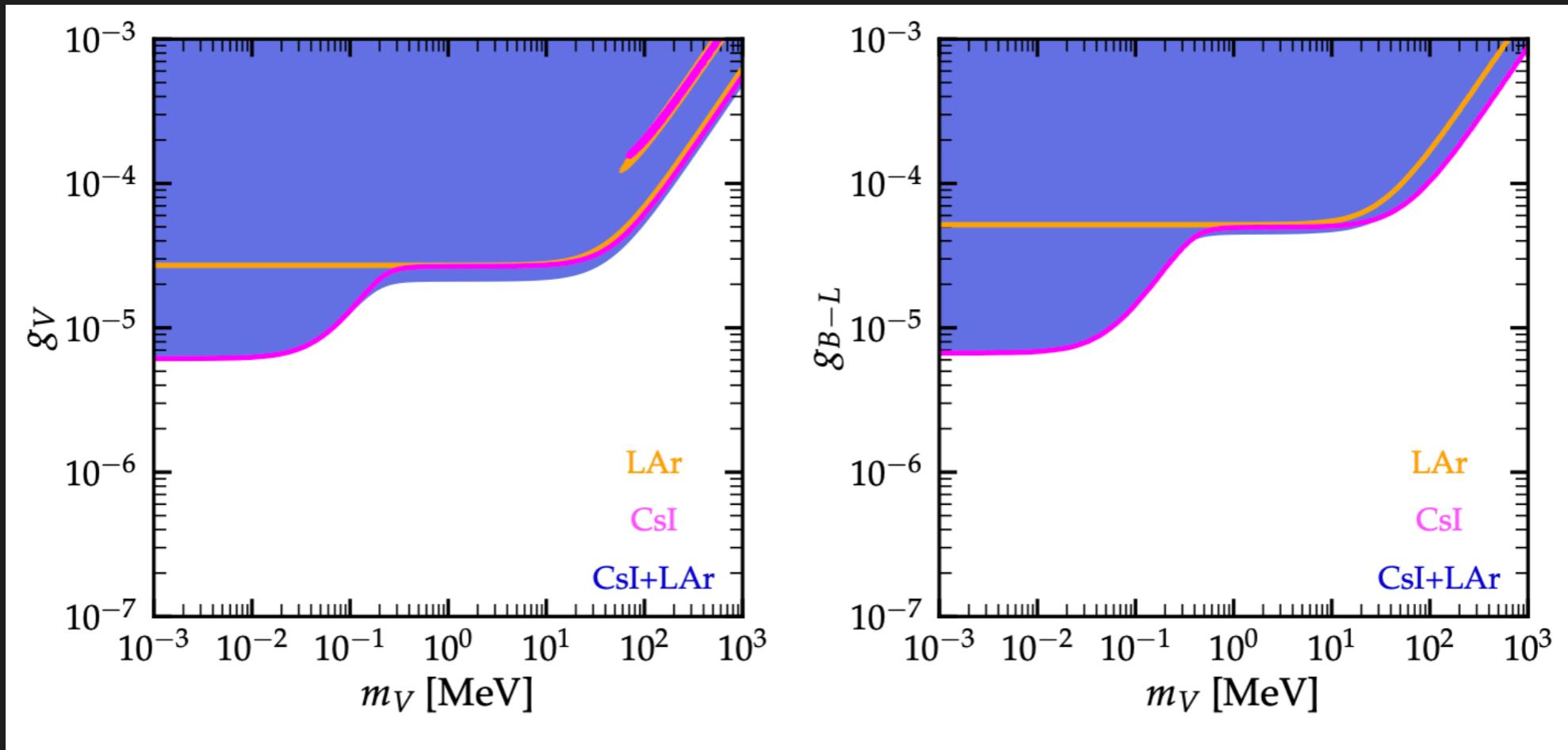
New neutrino interactions: LV

$$\frac{d\sigma_{\nu_\ell N}}{dE_{\text{nr}}} \Big|_{\text{CE}\nu\text{NS}}^{\text{LV}} = \left(1 + \kappa \frac{C_V}{\sqrt{2}G_F Q_V^{\text{SM}} (2m_N E_{\text{nr}} + \boxed{m_V^2})} \right)^2 \frac{d\sigma_{\nu_\ell N}}{dE_{\text{nr}}} \Big|_{\text{CE}\nu\text{NS}}^{\text{SM}}$$

$$C_V = g_{\nu V} [(2g_{uV} + g_{dV}) Z + (g_{uV} + 2g_{dV}) N]$$

$$g_X = \sqrt{g_{\nu X} g_{fX}}; f = \{u, d\}$$

$\kappa = 1$ for universal couplings and $\kappa = -1/3$ in the B – L model



VDR, Miranda, Papoulias, Sanchez-García, Tórtola and Valle, JHEP 04 (2023) 035

- Complementary analyses in: Coloma et al. 2202.10829, Atzori-Corona et al. 2205.09484

See also talk by
T. Rink 30/08

New neutrino interactions: LS and LT

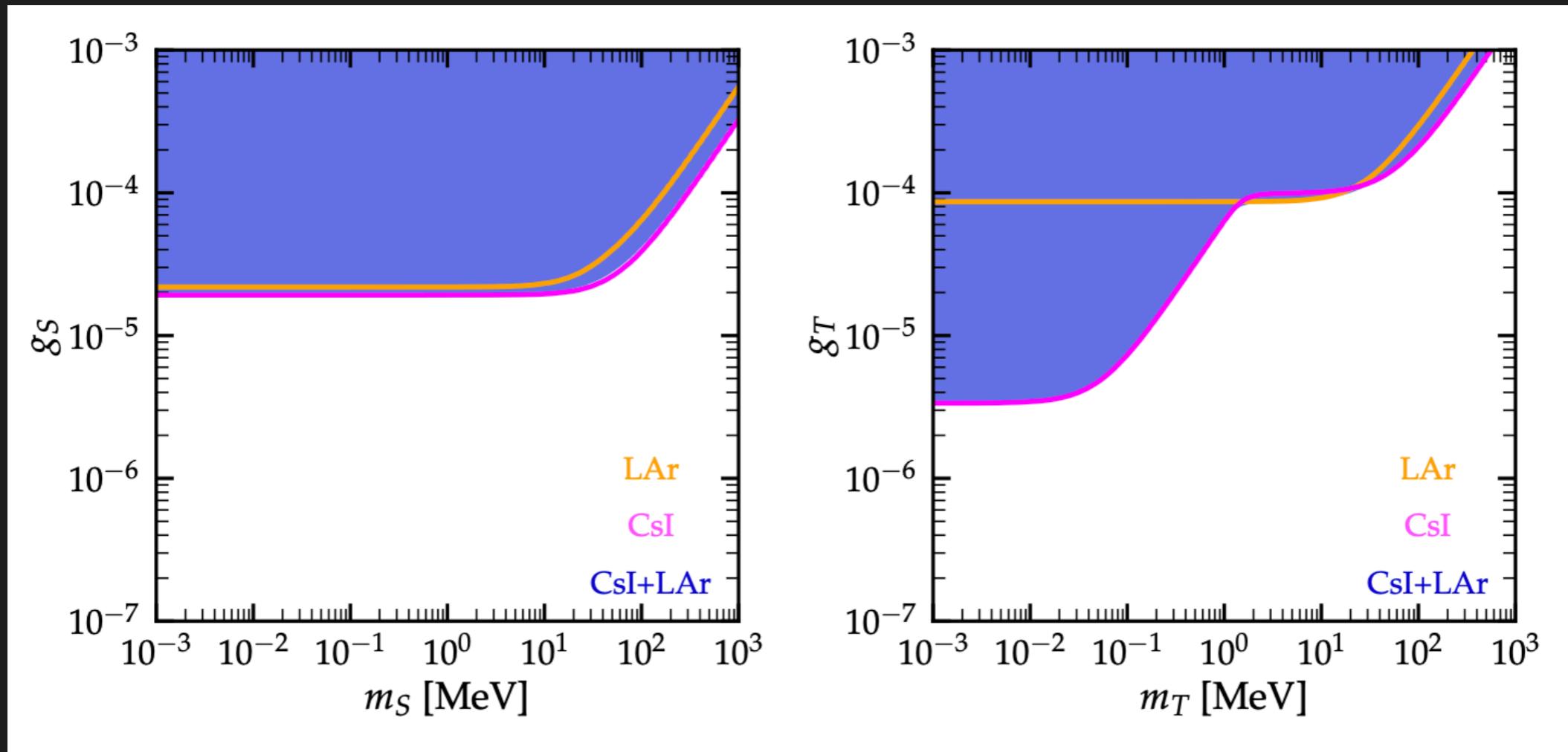
$$\frac{d\sigma_{\nu_\ell N}}{dE_{\text{nr}}} \Big|_{\text{CE}\nu\text{NS}}^{\text{LS}} = \frac{m_N^2 E_{\text{nr}} C_S^2}{4\pi E_\nu^2 (2m_N E_{\text{nr}} + m_S^2)^2} F_W^2(|\vec{q}|^2)$$

$$C_S = g_{\nu S} \left(Z \sum_q g_{qS} \frac{m_p}{m_q} f_q^p + N \sum_q g_{qS} \frac{m_n}{m_q} f_q^n \right)$$

$$\frac{d\sigma_{\nu_\ell N}}{dE_{\text{nr}}} \Big|_{\text{CE}\nu\text{NS}}^{\text{LT}} = \frac{m_N (4E_\nu^2 - m_N E_{\text{nr}}) C_T^2}{2\pi E_\nu^2 (2m_N E_{\text{nr}} + m_T^2)^2} F_W^2(|\vec{q}|^2)$$

$$C_T = g_{\nu T} \left(Z \sum_q g_{qT} \delta_q^p + N \sum_q g_{qT} \delta_q^n \right)$$

$$g_X = \sqrt{g_{\nu X} g_{fX}}$$



New neutrino interactions: NSI

Neutrino NSI can be formulated in terms of the effective four-fermion Lagrangian:

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

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

The NSI couplings quantify the relative strength of the NSI in terms of G_F and can be either flavour preserving (non-universal, $\alpha = \beta$) or flavor changing ($\alpha \neq \beta$).

VDR, Miranda, Papoulias, Sanchez-García, Tórtola and Valle, 2211.11905 [hep-ph]

