Constraining non-standard neutrino interactions via coherent elastic neutrino-nucleus scatteting at the ESS

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- non-standard neutrino interactions (NSIs)
- coherent elastic neutrino-nucleus scattering (CEvNS)
- bounds on NSIs from COHERENT
- expected sensitivity of the European Spallation Source (ESS)

based on S. Sachi Chatterjee, SL, O. Miranda and G. Sanchez Garcia [arXiv:2208.11771]

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Introduction

Why be interested in non-standard neutrino interactions (NSIs)?

Experimental opportunity: next generation of oscillation experiments (JUNO, DUNE, Hyper-Kamiokande), whose goal is to determine the mass ordering and establish CP violation in the lepton sector, will be sensitive to new physics (subleading effects in neutrino oscillations: NSIs, light sterile neutrinos…)

Also non-oscillation experiments like neutrinoless double beta decay, colliders (heavy neutral lepton searches), coherent elastic neutrino-nucleus scattering [CEvNS] (NSIs, neutrino magnetic moments, sterile neutrinos…)

CEvNS measured for the first time in 2017 by the COHERENT experiment
$\Longrightarrow$ bounds on NSIs

This talk: sensitivity to NSIs of precision CEvNS measurements at the European Spallation Source (ESS)

Non-standard neutrino interactions (NSIs)

Non-standard couplings to charged leptons and quarks described by the following [non-SU(2) invariant] 4-fermion operators: [Wolfenstein '78]

Charged-current NSIs (CC-NSIs)

$$\mathcal{L}_{\text{CC-NSI}} = -2\sqrt{2}\, G_F\, \varepsilon^{f f'}_{\alpha\beta} \left(\overline{\nu}_\alpha \gamma^\mu P_L l_\beta\right) \left(\overline{f'} \gamma_\mu P_{L/R} f\right) + h.c. \qquad f = u, \nu\,;\ f' = e, d$$

Neutral-current NSIs (NC-NSIs)

$$\mathcal{L}_{\text{NC-NSI}} = -2\sqrt{2}\, G_F\, \varepsilon^{f}_{\alpha\beta} \left(\overline{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right) \left(\overline{f} \gamma_\mu P_{L/R} f\right) \qquad f = u, d, e$$

NSIs can be flavour conserving ($\alpha = \beta = e, \mu, \tau$) or flavour violating ($\alpha \neq \beta$)

CC-NSIs are constrained by a variety of EW processes (muon decay, beta decay, meson and tau decays…)

$$|\varepsilon^{ud}_{\alpha\beta}|,\ |\varepsilon^{\mu e}_{\alpha\beta}| \lesssim \text{few}\, 10^{-2} \qquad (90\%\ \text{C.L.})$$ [Biggio et al., 0907.0097]

also affect neutrino production and detection (can induce the flavour-violating processes $\pi^+ \to \mu^+ \nu_e$ and $\bar{\nu}_\mu + p \to n + e^+$)

NC-NSIs are constrained by scattering of electrons and nucleons

$|\varepsilon^f_{\alpha\beta}| \lesssim \text{few}\,10^{-2} - \text{few}\,10^{-1}, \quad f = u, d, e \qquad (90\%\,\text{C.L.})$ [Biggio et al., 0907.0097]

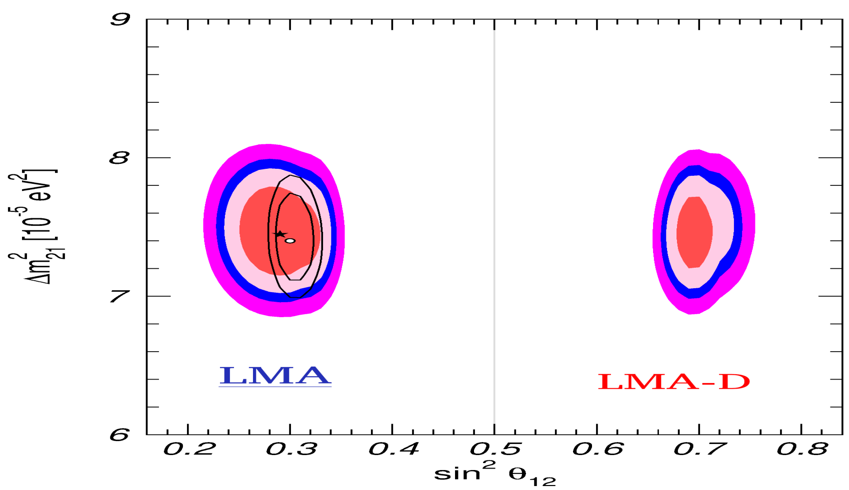
Also induce new flavour-conserving/violating contributions to coherent forward scattering of neutrinos on e, p, n ⇒ constrained by oscillation data

	LMA	LMA ⊕ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$[-0.072, +0.321]$	$\oplus[-1.042, -0.743]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$[-0.001, +0.018]$	$[-0.016, +0.018]$
$\varepsilon^u_{e\mu}$	$[-0.050, +0.020]$	$[-0.050, +0.059]$
$\varepsilon^u_{e\tau}$	$[-0.077, +0.098]$	$[-0.111, +0.098]$
$\varepsilon^u_{\mu\tau}$	$[-0.006, +0.007]$	$[-0.006, +0.007]$

from a global fit to oscillation data, assuming $\varepsilon^e_{\alpha\beta} = \varepsilon^d_{\alpha\beta} = 0$

[Esteban et al., 1805.04530]

in the presence of NSIs, a « LMA-Dark » region is allowed in the solar neutrino sector (with $\theta_{12} > 45°$ and opposite mass ordering), in addition to the standard LMA region



Since CEvNS is a neutral current process, it is also affected by (NC-)NSIs

[combination of oscillation data and CeVNS constraints on NSIs: Esteban et al. (1805.04530), Coloma et al. (1911.09109), Chaves and Schwetz (2105.11981)]

Warning note on NC-NSIs: if generated above the weak scale, SU(2) gauge invariance suggests the existence of similar operators involving charged leptons

$$-2\sqrt{2}\,G_F\,\varepsilon^f_{\alpha\beta}\left(\bar\ell_\alpha\gamma^\mu P_L\ell_\beta\right)\left(\bar f\gamma_\mu P_{L/R}f\right) \qquad (f=u,d,e)$$

⇒ strong bounds from charged lepton flavour violating (cLFV) processes like $\mu\to 3\,e,\ \mu - e$ conversion, $\tau\to 3\,e,\ \tau\to e\mu\mu$ (induced at tree level)

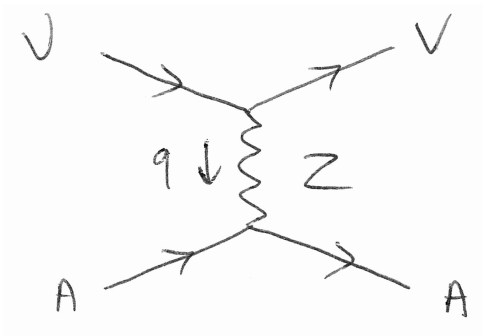
$$|\varepsilon^f_{e\mu}|\ \lesssim\ 10^{-6}\,, \qquad |\varepsilon^f_{e\tau}|\,|\varepsilon^f_{\mu\tau}|\ \lesssim\ 10^{-4}$$

[Bergmann et al., hep-ph/0004049
Berezhiani and Rossi, hep-ph/0111147
Antusch et al., 1005.0756]

Even if NC-NSIs arise from D=6 and D=8 SMEFT operators that do not induce cLFV at tree level, there are loop contributions and $\varepsilon^f_{e\mu}$ is too small to be observed, while $|\varepsilon^f_{e\tau}|, |\varepsilon^f_{\mu\tau}|\ <\ 0.1$ [Davidson and Gorbahn, 1909.07406]

Coherent elastic neutrino-nucleus scattering (CEvNS)

CEvNS = neutral current process in which the incoming neutrino scatters on the nucleus as a whole
$\Rightarrow$ large cross section $\propto N^2$ [Freedman '74]



Coherence condition: $|\vec{q}| \lesssim R^{-1}$ $|\vec{q}|$ = transferred momentum

R = nucleus size (typically, $R^{-1} \approx 20 - 150\,\mathrm{MeV}$)

Not observed until 2017 because very low nucleus recoil energy

$$T \equiv E_{\rm rec} \simeq |\vec{q}|^2/2M \sim (\text{few } 10 - \text{few } 100)\,\mathrm{keV}$$

SM cross section (for an incoming (anti-)neutrino of energy E_ν)

$$\frac{d\sigma}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right) F(|\vec{q}|^2)\; Q_W^2$$ [Freedman '74]

$F(|\vec{q}|^2)$ = nuclear form factor (accounts for loss of coherence for q > 1/R)

$(Q_W^2)_{\rm SM} = (Z\, g_V^p + N\, g_V^n)^2$ weak nuclear charge

$g_V^p = \frac{1}{2} - 2\sin^2\theta_W\,,\; g_V^n = -\frac{1}{2}$ vector neutral current coupling

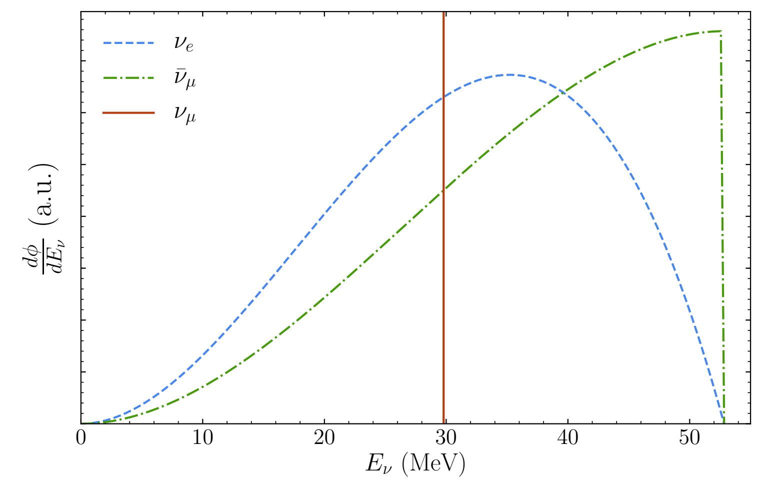
Z = number of protons, N = number of neutrons

CEvNS first observed by the COHERENT experiment (2017) at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory

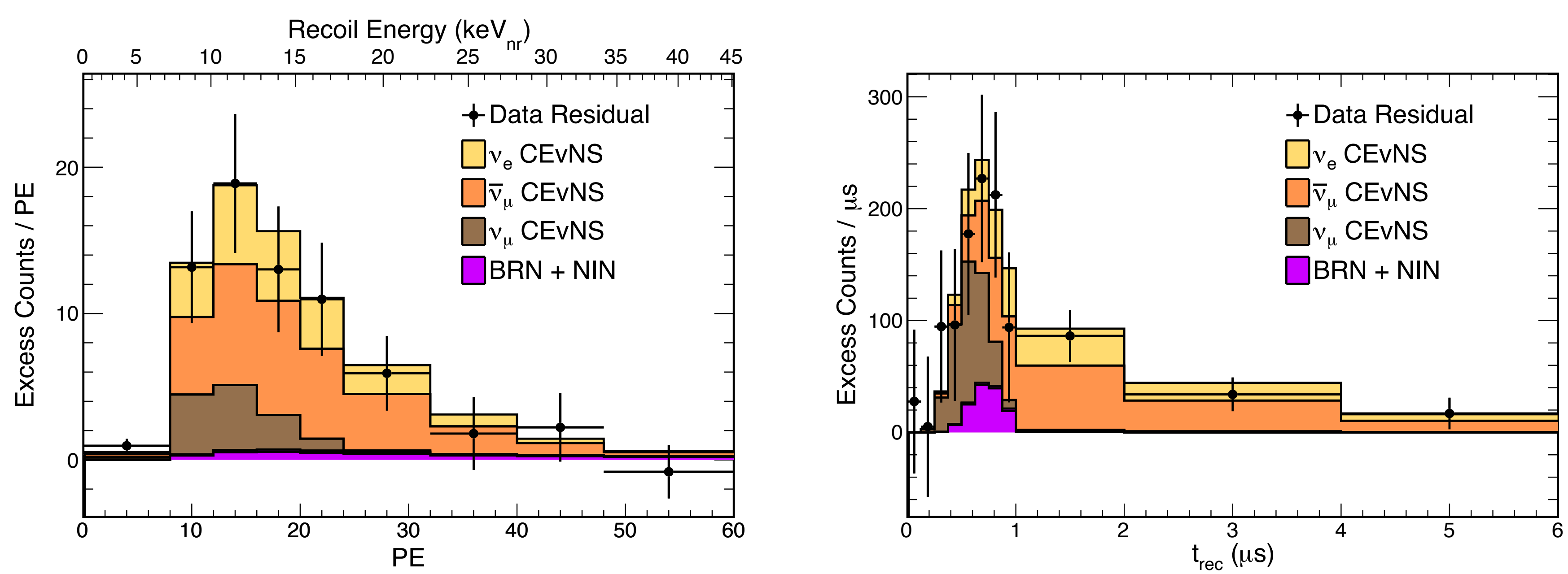
In addition to neutron beams, spallation sources produce a pulsed neutrino flux from charged pion decay at rest

$\pi^+ \to \mu^+ \nu_\mu$ prompt component

$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ delayed component



CEvNS on CsI detected with $11.6\,\sigma$ significance



[COHERENT collaboration, arXiv:2110.07730]

Figure 1. The data residual over SSBkg background compared to best fit CEvNS, BRN, and NIN predictions projected onto the PE (left) and t_{rec} (right) axes. The CEvNS distribution has been decomposed into each flavor of neutrino flux at the SNS.

In the presence of NSIs, the CEvNS cross section is modified and becomes flavour dependent [Barranco et al., hep-ph/0508299]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}T}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right) F(|\vec{q}|^2)\, Q_{W,\alpha}^2$$

$$\left(Q_{W,\alpha}^V\right)^2 = \left[Z\left(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}\right) + N\left(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV}\right)\right]^2 + \sum_{\beta\neq\alpha}\left|Z\left(2\varepsilon_{\alpha\beta}^{uV} + \varepsilon_{\alpha\beta}^{dV}\right) + N\left(\varepsilon_{\alpha\beta}^{uV} + 2\varepsilon_{\alpha\beta}^{dV}\right)\right|^2$$

flavour-diagonal NSIs interfere with the SM contribution

Using COHERENT data on CsI and Ar, can constrain the $\varepsilon_{\alpha\beta}^q$ parameters (q=u,d), except for $\varepsilon_{\tau\tau}^q$ (no tau neutrino in the flux)

[Coloma et al., Liao and Marfatia, esteban et al., Shoemaker, Giunti, Denton and Gehrlein, Miranda et al., Khan et al., De Romeri et al. …]

Recent analysis using energy spectrum and timing information (1σ bounds):

$\epsilon_{ee}^{dV} = [-0.027, 0.048] \cup [0.30, 0.39]\,,$
$\epsilon_{ee}^{uV} = [-0.024, 0.045] \cup [0.34, 0.43]\,,$
$\epsilon_{\mu\mu}^{dV} = [-0.012, 0.016] \cup [0.33, 0.37]\,,$
$\epsilon_{\mu\mu}^{uV} = [-0.002, 0.001] \cup [0.37, 0.41]\,.$

$\epsilon_{e\mu}^{dV} = [-0.071, 0.071]\,,$ $\epsilon_{e\mu}^{uV} = [-0.081, 0.081]\,,$
$\epsilon_{e\tau}^{dV} = [-0.12, 0.12]\,,$ $\epsilon_{e\tau}^{uV} = [-0.13, 0.13]\,,$
$\epsilon_{\mu\tau}^{dV} = [-0.087, 0.087]\,,$ $\epsilon_{\mu\tau}^{uV} = [-0.098, 0.098]\,.$

[De Romeri et al. , arXiv:2211.11905)]

Precision CEvNS measurements at the ESS

The European Spallation Source (ESS), under construction in Lund, Sweden, will provide a 10 x more intense neutrino flux as the SNS

ArXiv:1911.00762 (D. Baxter et al. , « coherent elastic neutrino-nucleus scattering at the European Spallation Source ») proposed to perform high-statistics CEvNS measurements at the ESS with advanced nuclear recoil detectors (w/ low threshold)

Detector Technology	Target nucleus	Mass (kg)	Steady-state background	E_{th} (keV_{ee})	QF (%)	E_{th} (keV_{nr})	$\frac{\Delta E}{E}$ (%) at E_{th}	E_{max} (keV_{nr})	CEνNS $\frac{NR}{yr}$ @20m, $>E_{th}$
Cryogenic scintillator	CsI	22.5	10 ckkd	0.1	$\sim$10 [71]	1	30	46.1	8,405
Charge-coupled device	Si	1	1 ckkd	0.007	4-30 [97]	0.16	60	212.9	80
High-pressure gaseous TPC	Xe	20	10 ckkd	0.18	20 [104]	0.9	40	45.6	7,770
p-type point contact HPGe	Ge	7	15 ckkd	0.12	20 [118]	0.6	15	78.9	1,610
Scintillating bubble chamber	Ar	10	0.1 c/kg-day	-	-	0.1	$\sim$40	150.0	1,380
Standard bubble chamber	C_3F_8	10	0.1 c/kg-day	-	-	2	40	329.6	515

6 detectors using different technologies and target material:
CsI (scintillator), Si and Ge (semiconductors), Xe (gaseous TPC), Ar and C_3F_8 (bubble chambers)

Expected future sensitivity to NSIs

Assume data (signal + background) = SM prediction (running time = 3 yr) and test against the SM + NSI hypothesis

Rely on arXiv:1911.00762 for the detector properties, background level and estimation of systematic uncertainties

Find improved sensitivity to individual NSI parameters wrt COHERENT (with a single detector)

More interesting: combining data from 2 detectors leads to improved bounds + regions of values leading to large cancellation between the NSI and SM contributions excluded at 90% CL or 2σ level (more than 3σ for $\varepsilon^u_{\mu\mu}$)

Target nucleus	Quark type	ε^{qV}_{ee}		$\varepsilon^{qV}_{\mu\mu}$	
		90% C.L.	2σ C.L.	90% C.L.	2σ C.L.
CsI + Si	u	$[-0.041, 0.042]$ –	$[-0.05, 0.052]$ $\cup\,[0.34, 0.39]$	$[-0.02, 0.016]$ –	$[-0.025, 0.022]$ –
	d	$[-0.038, 0.039]$ $\cup\,[0.31, 0.38]$	$[-0.046, 0.047]$ $\cup\,[0.30, 0.39]$	$[-0.018, 0.015]$ –	$[-0.023, 0.02]$ $\cup\,[0.34, 0.36]$

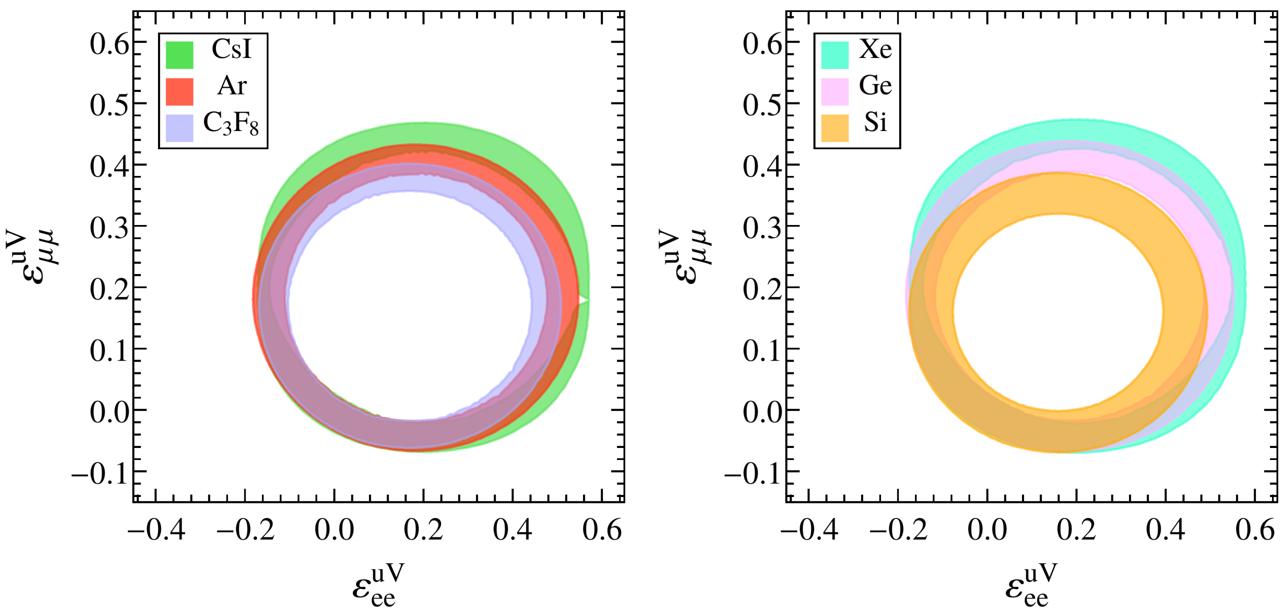
Need detectors with different Z/N ratios, such as CsI (0.7) and Si (1), as the cross section depends on the combinations $Z\varepsilon^p_{\alpha\alpha} + N\varepsilon^n_{\alpha\alpha} \quad (\alpha = e, \mu)$

Sensitivity to pairs of NSI parameters

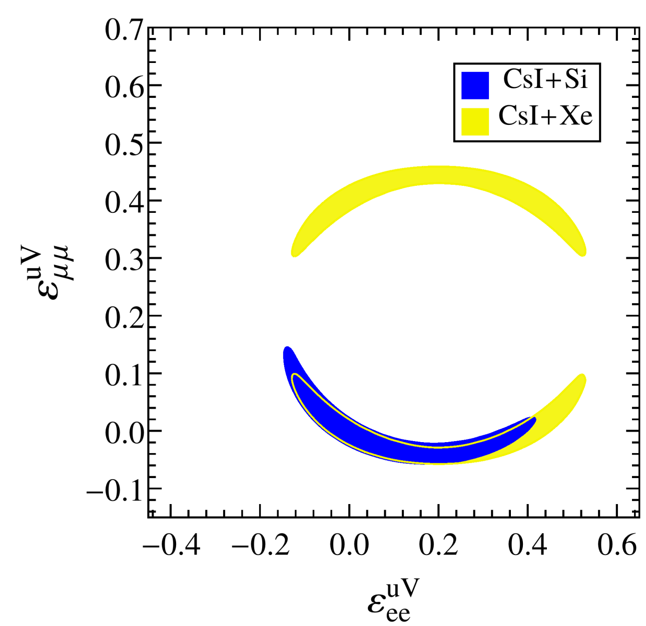
2 non-vanishing NSI parameters $\Rightarrow$ degeneracies

$$\left(Q^V_{W,\alpha}\right)^2 = \left[Z\left(g^p_V + 2\varepsilon^{uV}_{\alpha\alpha} + \varepsilon^{dV}_{\alpha\alpha}\right) + N\left(g^n_V + \varepsilon^{uV}_{\alpha\alpha} + 2\varepsilon^{dV}_{\alpha\alpha}\right)\right]^2$$
$$+ \sum_{\beta\neq\alpha}\left|Z\left(2\varepsilon^{uV}_{\alpha\beta} + \varepsilon^{dV}_{\alpha\beta}\right) + N\left(\varepsilon^{uV}_{\alpha\beta} + 2\varepsilon^{dV}_{\alpha\beta}\right)\right|^2$$

E.g. $(\varepsilon^u_{ee}, \varepsilon^u_{\mu\mu})$

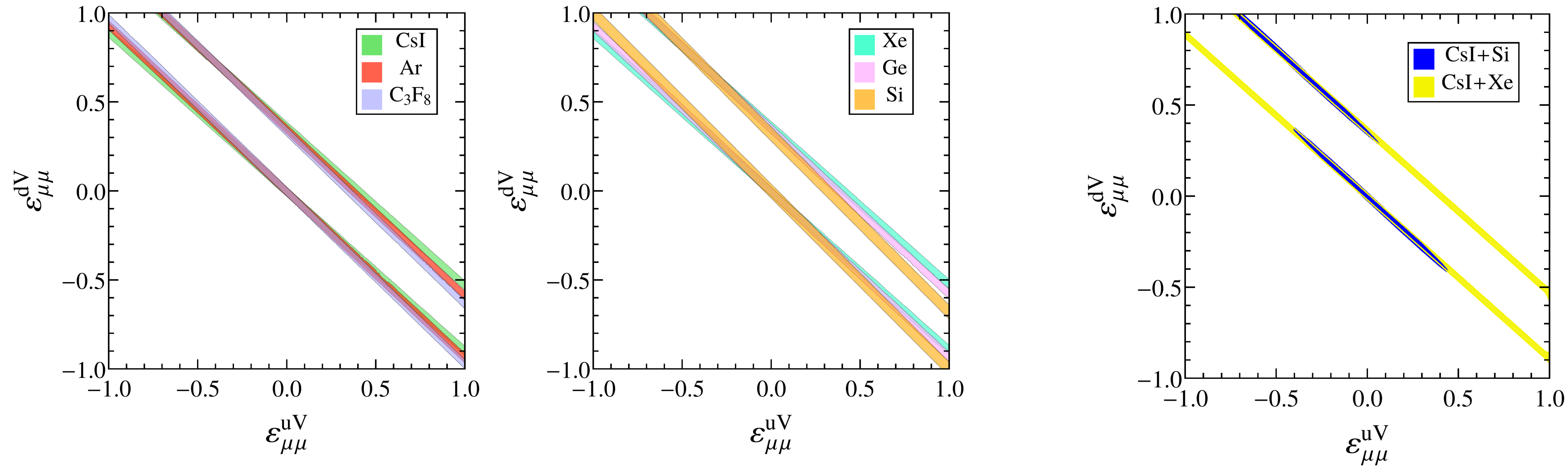


Combining the data from two detectors with different Z/N ratios leads to a partial breaking of the degeneracies



CS, I and Xe have similar Z/N ratios (0.7)

Other example: $(\varepsilon^u_{\mu\mu}, \varepsilon^d_{\mu\mu})$



<u>Other interesting combination</u>: NSI bounds from CEvNS and oscillations
[Esteban et al., 1805.04530; Coloma et al., 1911.09109; Chaves and Schwetz, 2105.11981]
(assume $\varepsilon^e_{\alpha\beta} = 0$ and $\varepsilon^u_{\alpha\beta} \propto \varepsilon^d_{\alpha\beta}$)

Chaves and Schwetz (arXiv: 2105.11981): LMA-Dark can be excluded at 4σ using CEvNS measurements at the ESS with a Z/N ratio close to 1, such as Si

Conclusions

CEvNS is a powerful probe of (neutral current) non-standard neutrino interactions (NSIs), complementary to neutrino oscillation data

CEvNS measurements at the European Spallation Source can improve current bounds on NSIs, especially if different detectors are operated

Combining the data of detectors whose target materials have different Z/N ratios is particularly efficient in reducing degeneracies between NSI parameters