Constraining NSIs through CEνNS measurements at the European Spallation Source

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Based on **PRD 107 (2023) 5, 055019** by
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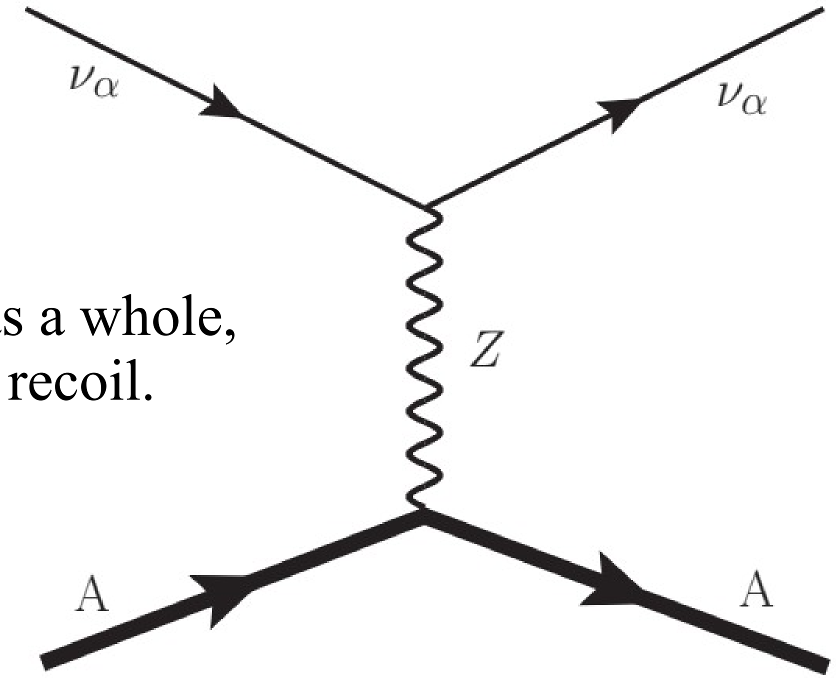
Outline

- Brief introduction to Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)
- Introduction to Non-Standard Interaction
- Exploring the sensitivities of European Spallation Source (ESS) to NSI through CEvNS measurements.

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

$$\nu_\alpha + \mathrm{A} \rightarrow \nu_\alpha + \mathrm{A}$$



A neutrino of any flavor scatters-off a nucleus as a whole, transferring some energy in the form of nuclear recoil.

Condition: $\mathrm{QR} \leq 1$

Q→ three momentum transfer
R→ radius of the nucleus

The nucleon wave functions are in phase with each other. The cross-sections of the individual nucleons added coherently.

The differential cross-section for this process:

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

$$\left(Q_{W,\mathrm{SM}}^V\right)^2 \quad = [(Z\, g_V^p + N\, g_V^n)]^2$$ → Weak vector Charge in SM.

$$\mathrm{g}_V^p = \tfrac{1}{2} - 2\sin^2\theta_W \ \text{ and } \ \mathrm{g}_\mathrm{V}^\mathrm{n} = -\tfrac{1}{2}$$ → Neutral current vector couplings

T → Nuclear recoil energy

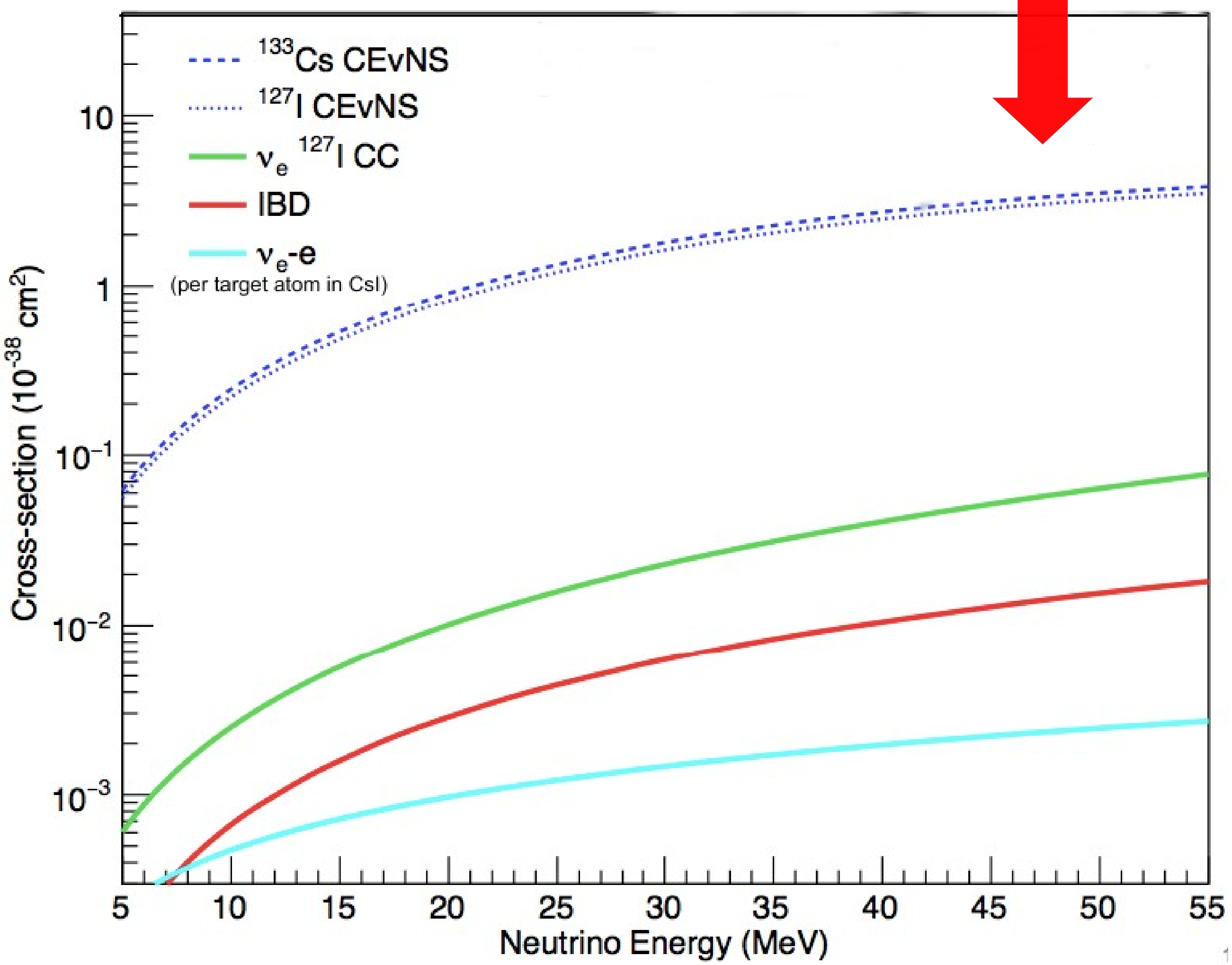
$F(|\vec{q}|^2)$ → Nuclear form factor, we use Helm parametrization.

For, $\sin^2\theta_W \sim \frac{1}{4}$,

$$\sigma \propto N^2$$

So, the cross-section is large in compared to other neutrino interactions !

Large cross-section



A trade-off between the large cross-section and the small-ness of the recoil energy!

Why do we study CEνNS ?

1. As a probe of SM physics:
   - Weak mixing angle
   - Neutron *rms* radius

2. Physics beyond the SM:
   - Non-standard interactions (NSIs) of neutrinos
   - Generalized neutrino interactions
   - Neutrino electromagnetic properties
   - Light NC mediators
   - New tool to probe sterile neutrinos and non-unitarity of the PMNS matrix

A lot more !

Where do we study CEνNS ?

Tremendous progress has been made for the measurement of CEνNS !

COHERENT SNS

Spallation Neutron Sources:

- COHERENT
- European Spallation Sources (ESS)
- Captain Mills Experiment

Reactor Sources:

- CONUS
- CONNIE
- NUCLEUS
- nuGeN
- RED-100
- RICOCHET

And many more!

In 2017 only, the COHERENT collaboration reported the first measurement of CEνNS, 43 yrs after its proposal !

This talk will cover NSI at ESS

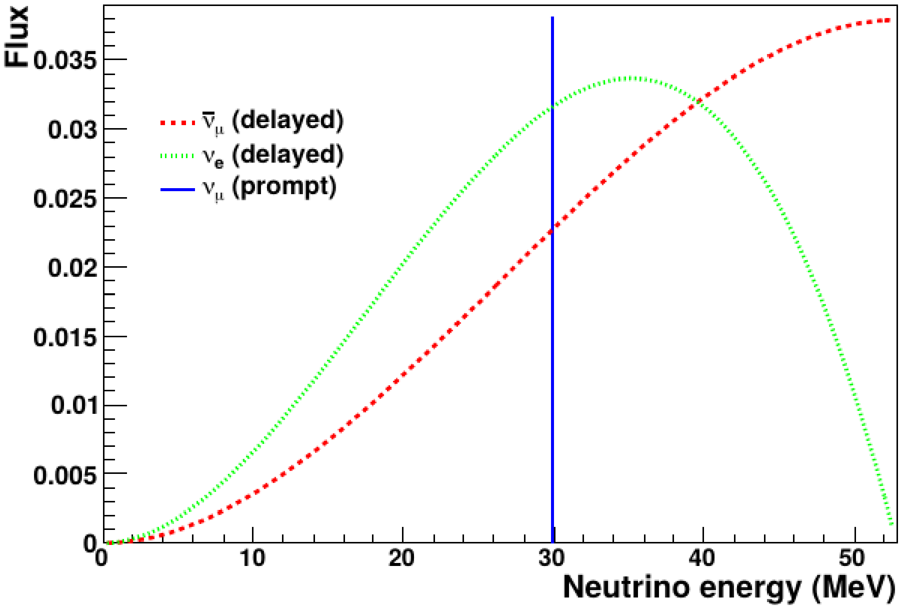
Flux at the Spallation Neutron Sources

Pion decay at rest:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

Scholberg, hep-ex/0511042



The differential fluxes are given as:

$$\frac{dN_{\nu_\mu}}{dE_\nu} = \xi\,\delta\left(E_\nu - \frac{m_\pi^2 - m_\mu^2}{2m_\pi}\right),$$

→ Prompt component

$$\frac{dN_{\bar{\nu}_\mu}}{dE_\nu} = \xi\frac{64\,E_\nu^2}{m_\mu^3}\left(\frac{3}{4} - \frac{E_\nu}{m_\mu}\right),$$

$$\frac{dN_{\nu_e}}{dE_\nu} = \xi\frac{192\,E_\nu^2}{m_\mu^3}\left(\frac{1}{2} - \frac{E_\nu}{m_\mu}\right).$$

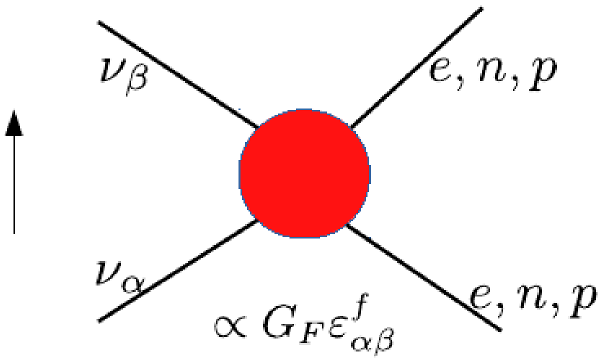
→ Delayed components

$$\xi = rN_{\mathrm{POT}}/4\pi L^2$$

Non-Standard Interactions (NSIs)

The presence of the effective 4-Fermi neutral current non-standard interactions (NSI) can be realized through the dimension-six operators as,

$$-\mathcal{L}_{\mathcal{NSI}} = \frac{G_F}{\sqrt{2}} \sum_{\alpha,\beta,f} \varepsilon_{\alpha\beta}^{fC} \left[\bar{\nu}_\alpha \gamma^\mu \left(1-\gamma^5\right) \nu_\beta\right] \left[\bar{f}\gamma_\mu P_C f\right]$$

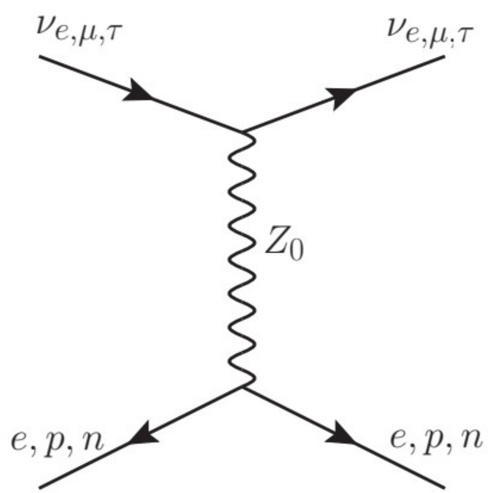


C=L, R

$\alpha,\ \beta = e,\ \mu,\ \tau$ and $f = e, u, d$

For CEvNS :

$$\varepsilon_{\alpha\beta}^{qV} \equiv (\varepsilon_{\alpha\beta}^{qL} + \varepsilon_{\alpha\beta}^{qR}),\ q = u,\ v$$



NC-interaction

L. Wolfenstein PRD 17, 2369 (1978)

CEvNS cross-section changes in presence of NSI

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

$$\begin{aligned}\left(Q_{W,\mathrm{NSI}}^V\right)^2 \quad &= \left[Z\left(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}\right) + N\left(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV}\right)\right]^2 \\ &+ \sum_{\beta\neq\alpha} \left|Z\left(2\varepsilon_{\alpha\beta}^{uV} + \varepsilon_{\alpha\beta}^{dV}\right) + N\left(\varepsilon_{\alpha\beta}^{uV} + 2\varepsilon_{\alpha\beta}^{dV}\right)\right|^2.\end{aligned}$$

Possibilities to explore:

- Bound on the NSI parameters using the available data
- Expected sensitivities of the NSI parameters using the future data

Brief description of the European Spallation Source (ESS) setup

The European Spallation source (ESS) is a highly ambitious and multi-disciplinary research facility. Apart from producing the World`s most intense pulsed neutron beams, it will also generate neutrino fluxes from low energy to high energy suitable for exploring neutrino oscillation and Coherent Elastic Neutrino Nucleus Scattering (CEvNS).

ESS (Sourced at Lund, Sweden)	
Baseline	20 m
Proton Energy	2 GeV
Average Beam Power	5 MW
Protons on target (POT) Per year	$\mathbf{2.8 \times 10^{23}}$

One order of magnitude increase in flux w.r.t. the COHERENT SNS experiment

A number of detectors have been proposed

For more details, see JHEP 02 (2020) 123, arXiv: 2211.10396

Properties of the detector materials

Detectors proposed for the study of CEvNS: CsI, Si, Ge, Xe, Ar, C_3F_8

Target nucleus	**Z**	**N**	**Z/N**	**M (a.m.u)**	**R (fm)**
Cs	55	78	0.71	132.91	4.83
I	53	74	0.72	126.90	4.83
Xe	54	78	0.69	131.29	4.79
Si	14	14	1	27.98	3.12
Ge	32	40	0.8	72.00	4.06
Ar	18	22	0.81	39.95	3.43
C	6	6	1	12.01	2.47
F	9	10	0.9	19.00	2.90

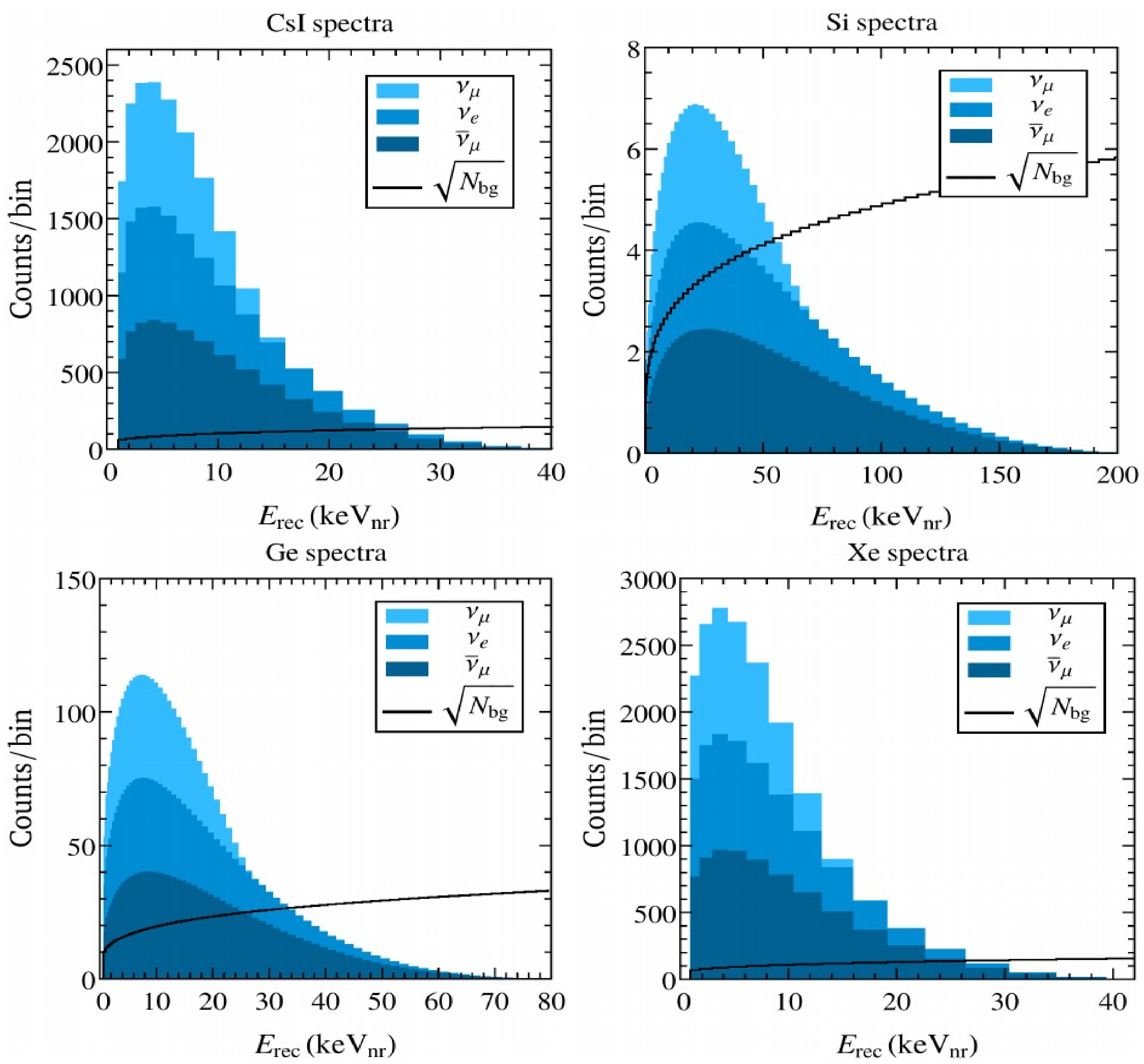
Suitable combination of different detectors (different n/p ratio) can help breaking the degeneracies arise naturally when considering the single or multiple NSI Couplings with up or down type of quarks !

Proposed detectors properties

Detector technology	Target nucleus	Detector mass (kg)	Steady-state background	E_{th}^{ee} ($\mathrm{keV_{ee}}$)	QF (%)	T_{th} ($\mathrm{keV_{nr}}$)	$\frac{\Delta E}{E}$(%) at T_{th}	σ_0 (keV)
Cryogenic scintillator	CsI	22.5	10 ckkd	0.1	10	1	30	0.3
High-pressure gaseous TPC	Xe	20	10 ckkd	0.18	20	0.9	40	0.36
Charge-coupled device	Si	1	1 ckkd	0.007	20	0.16	60	0.096
p-type point contact HPGe	Ge	7	15 ckkd	0.12	20	0.6	15	0.09
Scintillating bubble chamber	Ar	10	0.1 c/kg-day	–	–	0.1	40	0.04
Standard bubble chamber	C_3F_8	10	15 c/kg-day	–	–	0.2	40	0.08

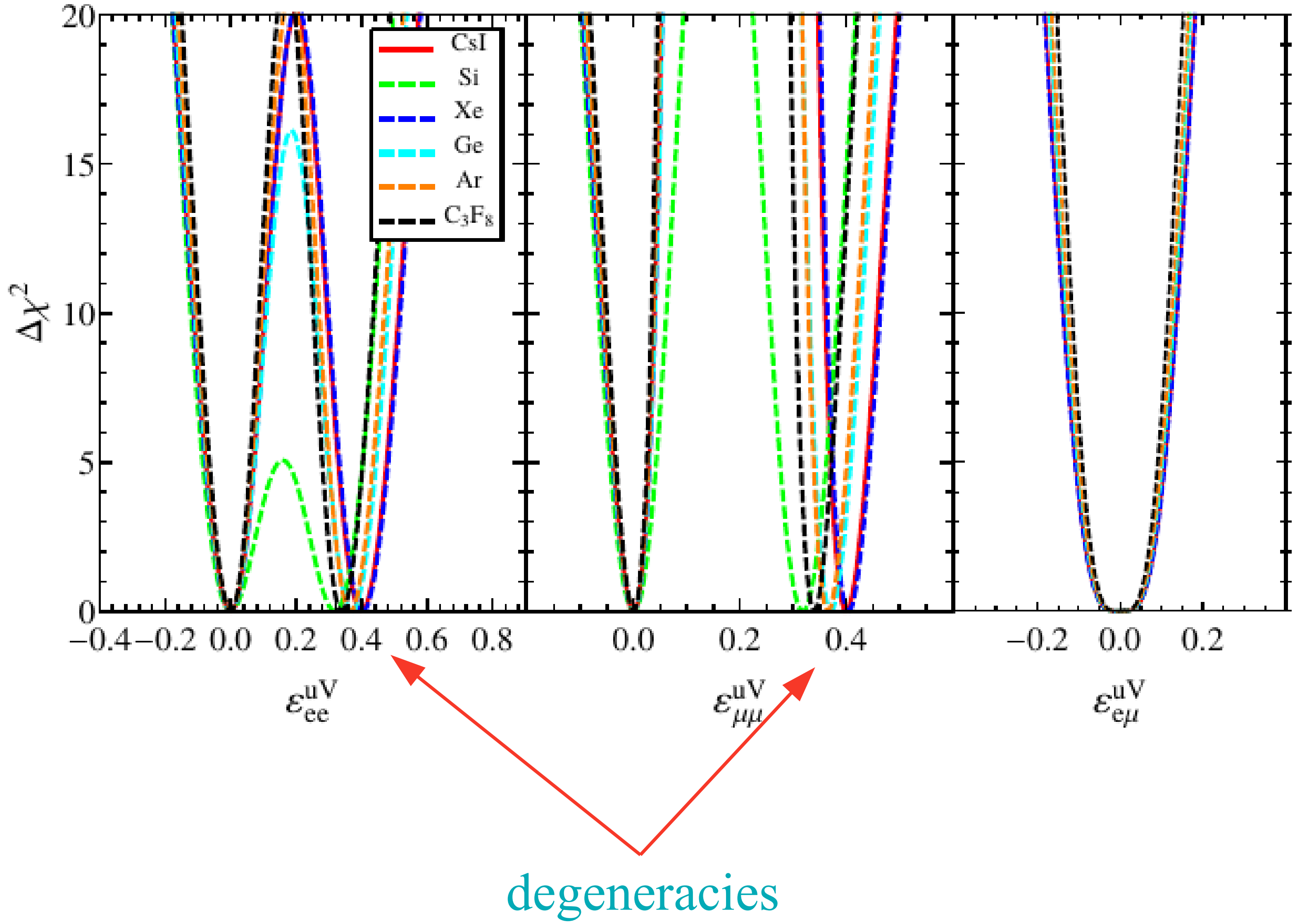
See also, JHEP 02 (2020) 123

Run time : 3 yrs



Single detector analysis

One NSI at a time

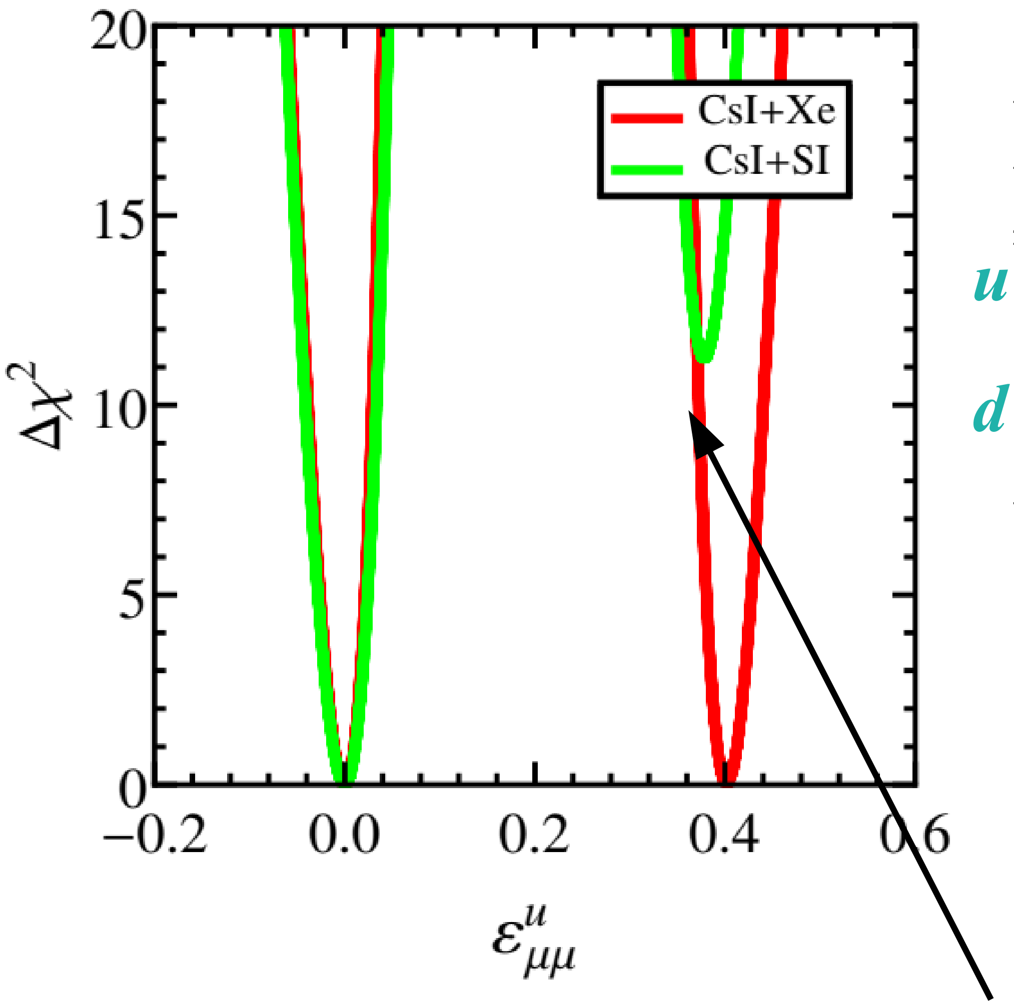


Constraints on the NSI parameters

Target nucleus	Quark type	ε_{ee}^{qV}		$\varepsilon_{\mu\mu}^{qV}$	
		90% C.L.	2σ C.L.	90% C.L.	2σ C.L.
CsI	u	$[-0.055, 0.051] \cup [0.35, 0.45]$	$[-0.067, 0.064] \cup [0.34, 0.47]$	$[-0.027, 0.023] \cup [0.38, 0.43]$	$[-0.034, 0.028] \cup [0.37, 0.43]$
	d	$[-0.040, 0.047] \cup [0.31, 0.41]$	$[-0.061, 0.057] \cup [0.30, 0.42]$	$[-0.024, 0.020] \cup [0.34, 0.38]$	$[-0.031, 0.024] \cup [0.33, 0.39]$

Target nucleus	Quark type	$\varepsilon_{e\mu}^{qV}$		$\varepsilon_{e\tau}^{qV}$		$\varepsilon_{\mu\tau}^{qV}$	
		90% C.L.	2σ C.L.	90% C.L.	2σ C.L.	90% C.L.	2σ C.L.
CsI	u	$[-0.089, 0.089]$	$[-0.1, 0.1]$	$[-0.16, 0.16]$	$[-0.18, 0.18]$	$[-0.11, 0.11]$	$[-0.12, 0.12]$
	d	$[-0.08, 0.08]$	$[-0.09, 0.09]$	$[-0.14, 0.14]$	$[-0.16, 0.16]$	$[-0.096, 0.096]$	$[-0.11, 0.11]$

Combination of two detectors



Disallowed at 3sigma C.L.

(CsI+Si)

	$\varepsilon^{qV}_{\mu\mu}$		$\varepsilon^{qV}_{e\mu}$	
	90% C.L.	2σ C.L.	90% C.L.	2σ C.L.
u	$[-0.02, 0.016]$	$[-0.025, 0.022]$	$[-0.074, 0.074]$	$[-0.081, 0.081]$
	–	–		
d	$[-0.018, 0.015]$ –	$[-0.023, 0.02]$ $\cup [0.34, 0.36]$	$[-0.068, 0.068]$	$[-0.075, 0.075]$

Not only constrain the parameter space but also break the degeneracy!

Current constraints using CsI + LAr data

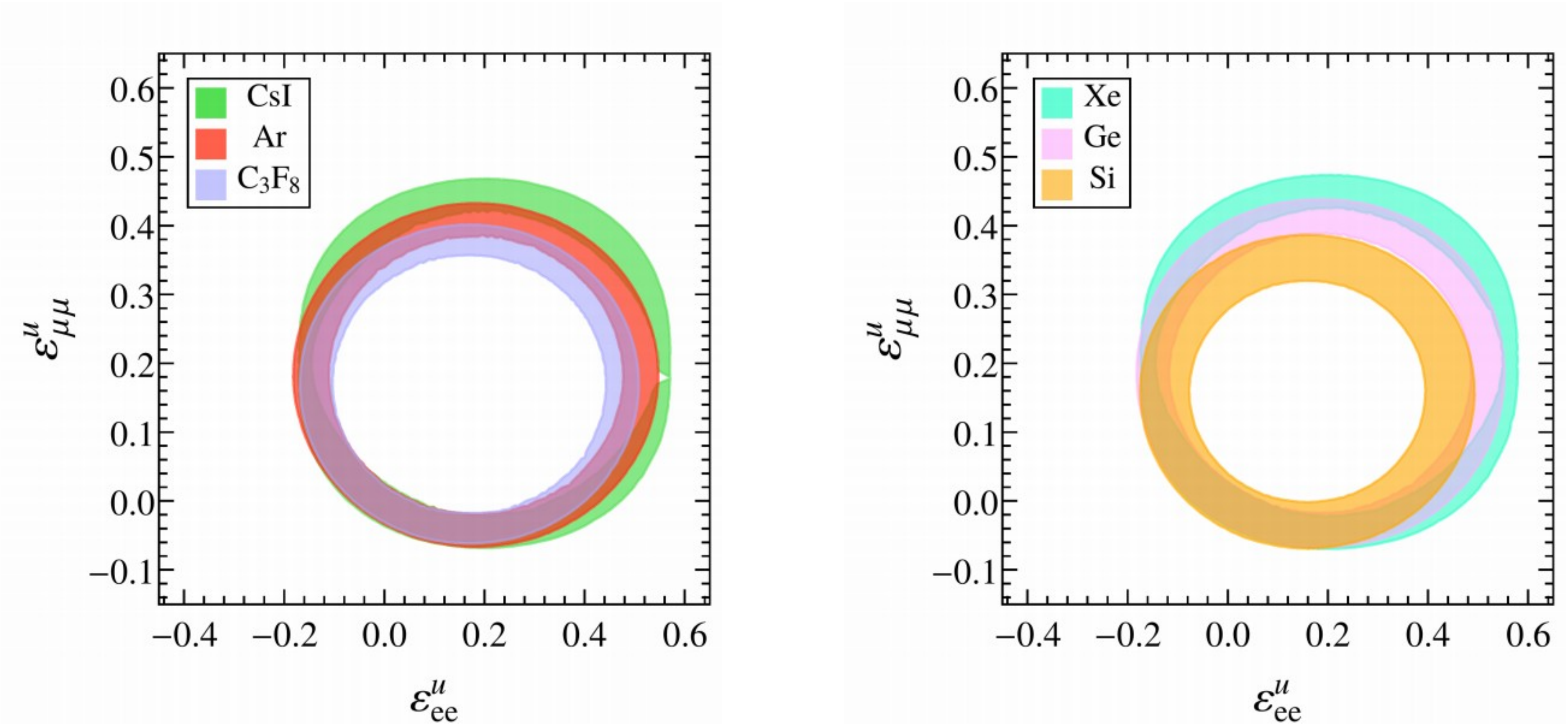
$$\epsilon_{ee}^{dV} = [-0.027, 0.048] \cup [0.30, 0.39]\,,$$
$$\epsilon_{ee}^{uV} = [-0.024, 0.045] \cup [0.34, 0.43]\,,$$
$$\epsilon_{\mu\mu}^{dV} = [-0.012, 0.016] \cup [0.33, 0.37]\,,$$
$$\epsilon_{\mu\mu}^{uV} = [-0.002, 0.001] \cup [0.37, 0.41]\,.$$

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

JHEP 04 (2023) 035 by V. D. Romeri, O. G. Miranda, D. K. Papoulias, G. S. Garcia, M. Tortola, and J.W.F. Valle

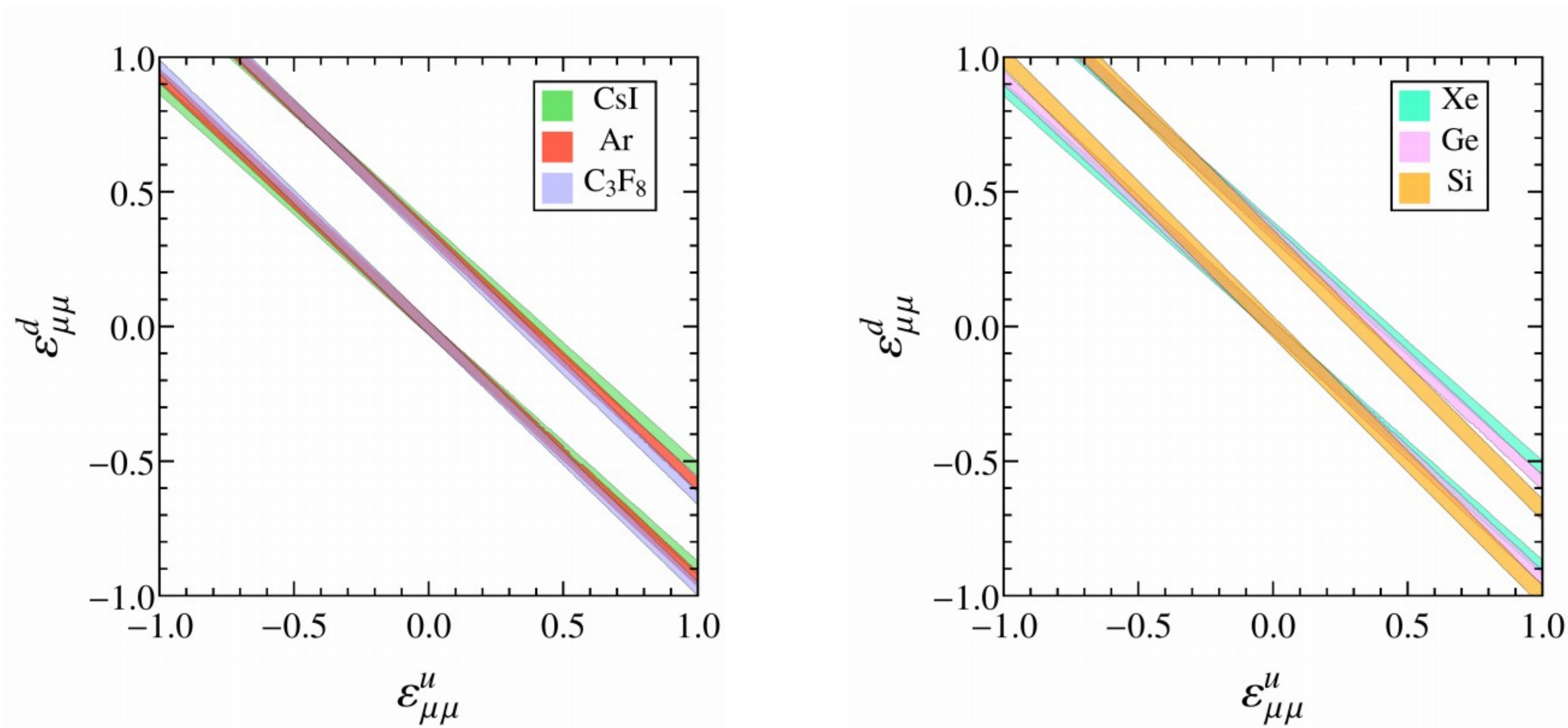
So, ESS will further improve the bounds !

Single detector analysis of two non-zero NSI parameters



$$N_{th} = C_e\,(2Z+N)^2\left(\varepsilon^{uV}_{ee} + \frac{Zg^p_V + Ng^n_V}{2Z+N}\right)^2 + C_\mu\,(2Z+N)^2\left(\varepsilon^{uV}_{\mu\mu} + \frac{Zg^p_V + Ng^n_V}{2Z+N}\right)^2$$

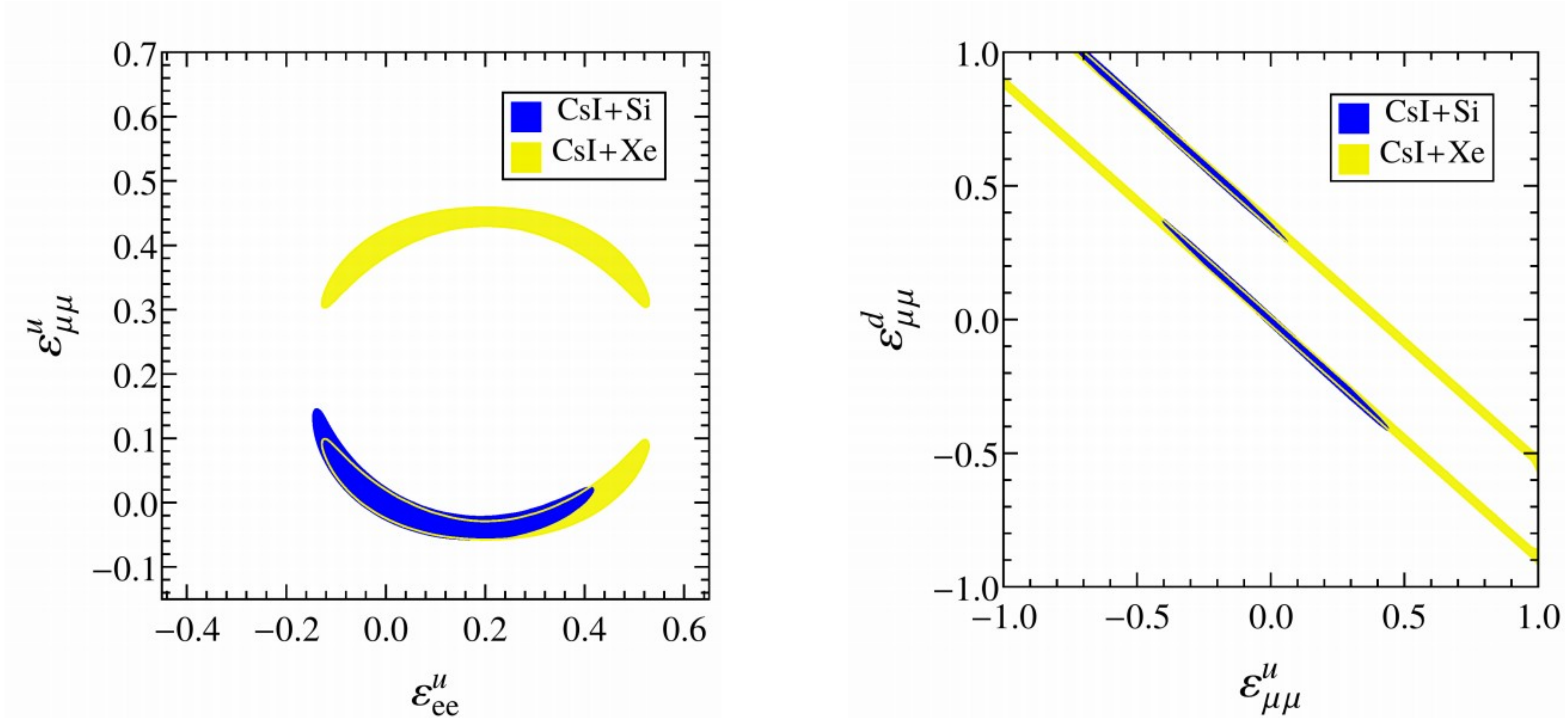
Characterises elliptical shape



$$N_{th} = \left[Z g_V^p + N g_V^n + (2Z + N)\, \varepsilon_{ee}^{uV} + (Z + 2N)\, \varepsilon_{ee}^{dV} \right]^2 C_e + \left[Z g_V^p + N g_V^n \right]^2 C_\mu$$

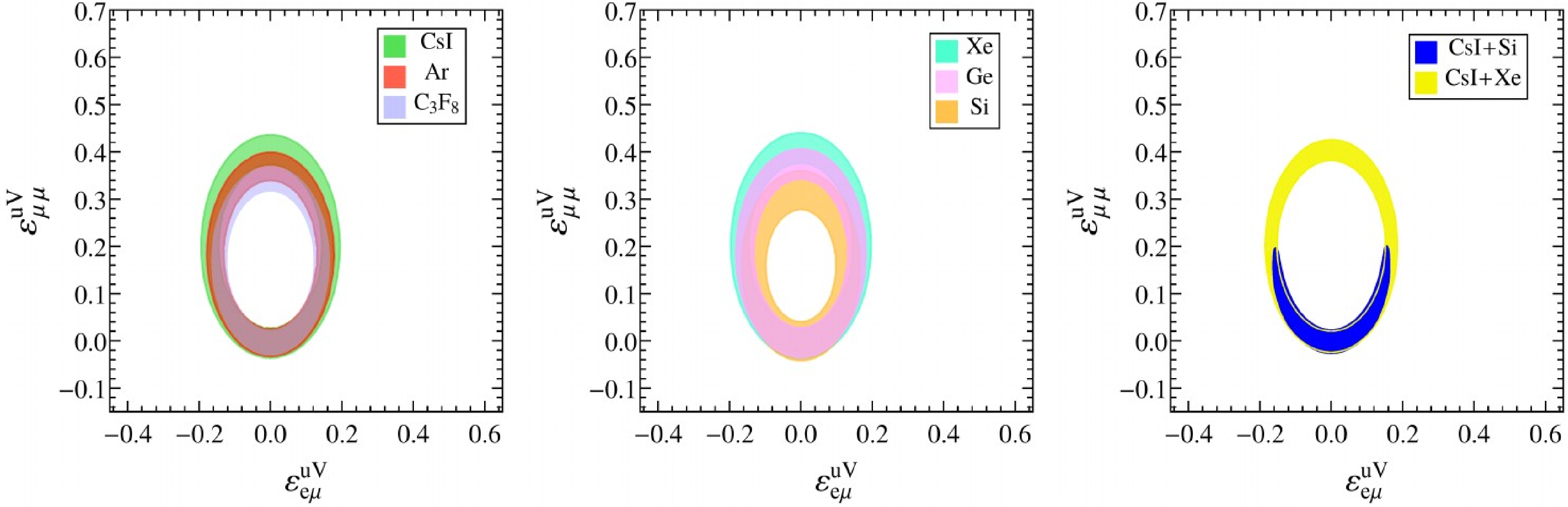
Characterises two linear bands

Combined analysis of two non-zero NSI parameters



Breaking some part of the degeneracies

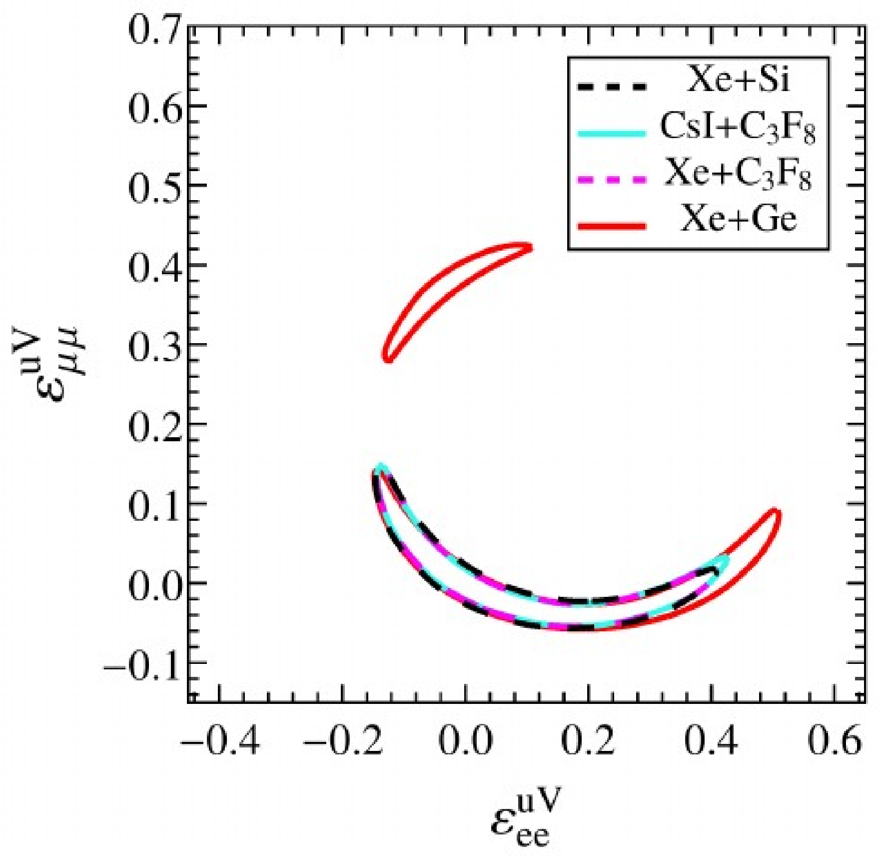
Combined analysis of two non-zero NSI parameters

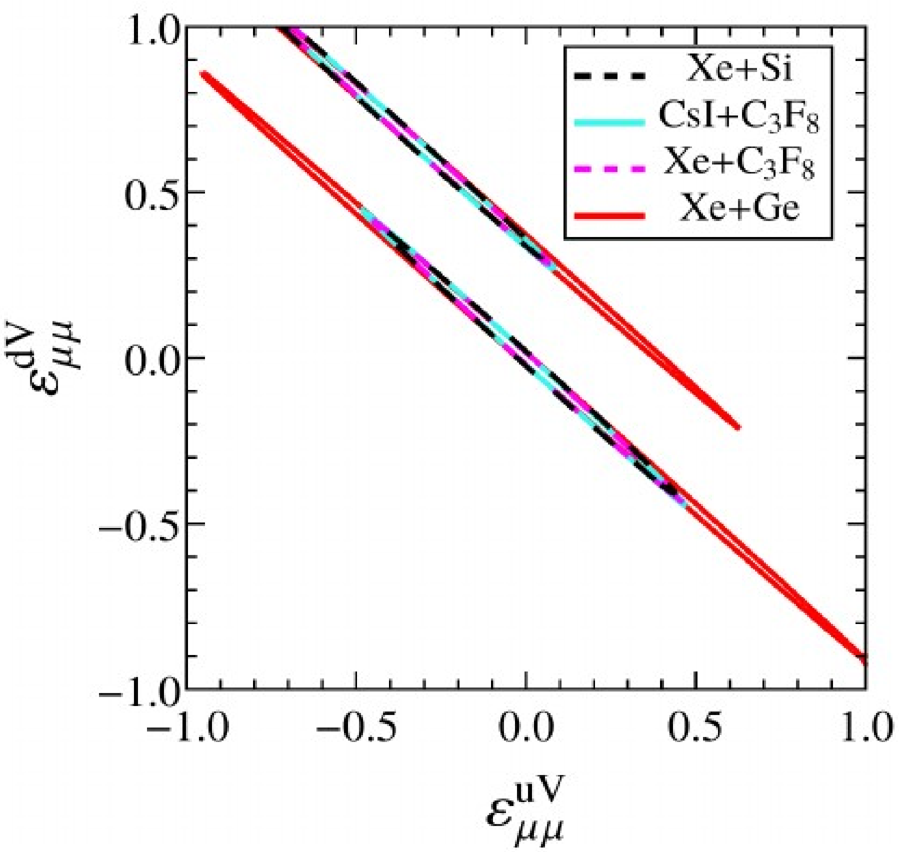


Degeneracy broken in a large parameter spaces with suitable combinations of the different target materials of the detectors.

Combined analysis of two non-zero NSI parameters

A few more examples:





Summary

- The measurement of CEvNS has opened a new window to test SM as well as beyond SM physics opportunities.

- We have explored the physics potential of European Spallation Source in constraining the NC-NSI.

- The combined analysis of two ESS detectors significantly enhance the sensitivities and partially break degeneracies of the NSI parameters taken one at a time. CsI+Si provides one of the best sensitivities.

- The combined analysis of two detectors becomes even more powerful reducing the degeneracies arising naturally when considered two at a time. We identify CsI+Si, Xe+Si, Csi+C3F8, and Xe+C3F8 as the best possible combinations in this regard.

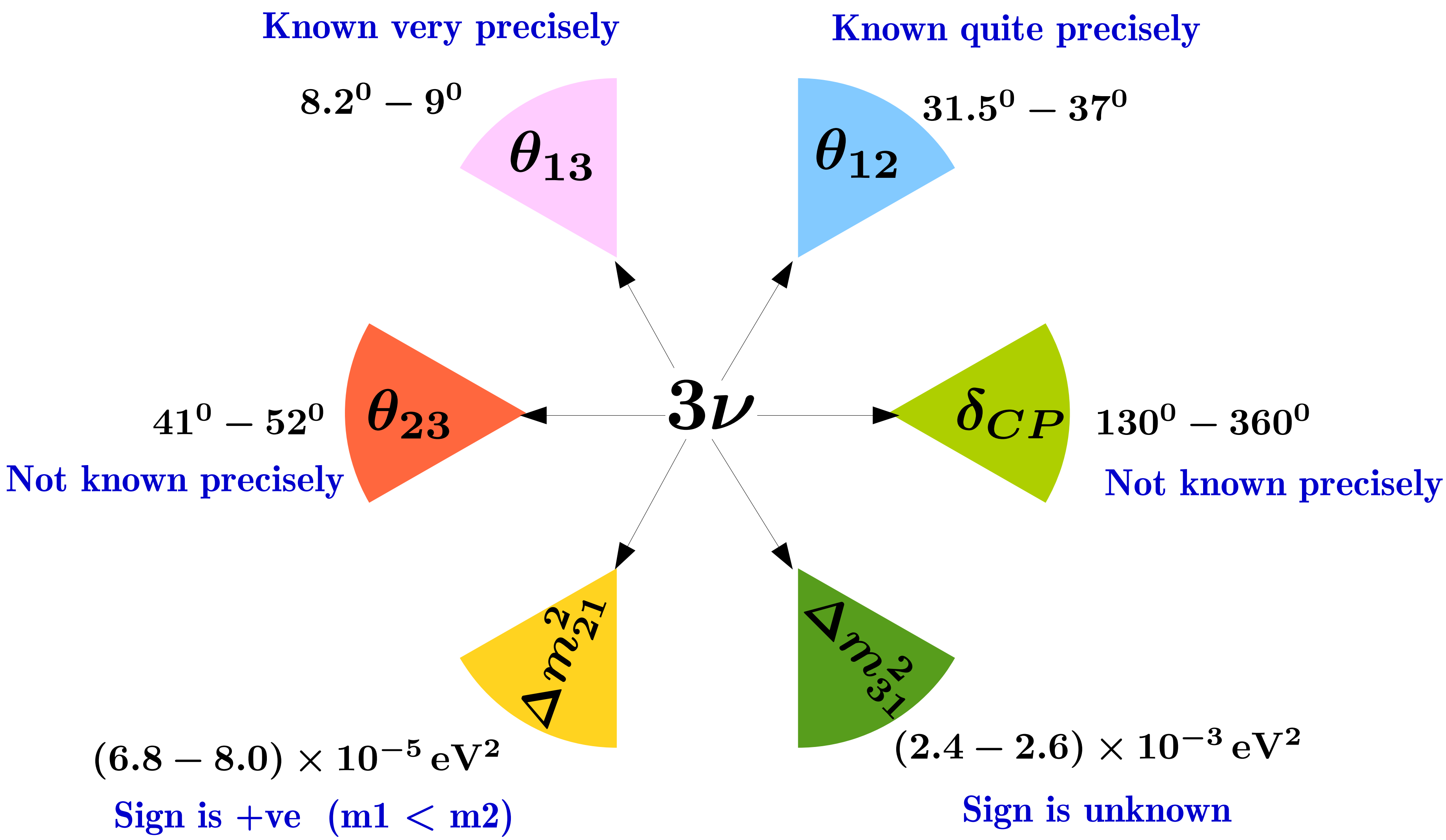
- Hope the sensitivities will further improve with more runtime and with better systematic uncertainties.

Thank You !

We use the following chi-squared function for the analysis at ESS

$$\chi^2(\kappa) = \min_{\xi} \left[\sum_i 2 \left\{ N_i(\kappa,\xi) - \tilde{N}_i + \tilde{N}_i \ln\left(\frac{\tilde{N}_i}{N_i(\kappa,\xi)} \right) \right\} + \left(\frac{\xi_{sig}}{\sigma_{sig}} \right)^2 + \left(\frac{\xi_{bg}}{\sigma_{bg}} \right)^2 \right]$$

Current status of 3ν parameters (3σ bound)



ArXiv: 2006.11237 by P. Salas et al., arXiv: 2007.14792 by Esteban et al., and arXiv: 2107.00532 by F. Capozzi et al.

Neutrino flavor eigenstates are related to the mass eigenstates as

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}^{*} |\nu_i\rangle,$$

Where,

$$U = R(\theta_{23})\, R(\theta_{13}, \delta_{\mathrm{CP}})\, R(\theta_{12})$$

$$= \begin{pmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta_{\mathrm{CP}}} \\ -s_{12}\, c_{23} - c_{12}\, s_{23}\, s_{13}\, e^{i\delta_{\mathrm{CP}}} & c_{12}\, c_{23} - s_{12}\, s_{23}\, s_{13}\, e^{i\delta_{\mathrm{CP}}} & s_{23}\, c_{13} \\ s_{12}\, s_{23} - c_{12}\, c_{23}\, s_{13}\, e^{i\delta_{\mathrm{CP}}} & -c_{12}\, s_{23} - s_{12}\, c_{23}\, s_{13}\, e^{i\delta_{\mathrm{CP}}} & c_{23}\, c_{13} \end{pmatrix}$$