Exploring the New Physics at the Neutrino facilities of the European Spallation Source

Sabya Sachi Chatterjee

Planck 2022, old Ecole Polytechnique, Paris

May 30 – June 3

01.06.2022

Outline

First part

1). Brief introduction to Non-Unitarity in the neutrino oscillation.

2). Brief description of the ESSnuSB setup.

3). Discussion of the numerical results in the context of Non-Unitarity.

Second part

4). Brief introduction to the Coherent Elastic Neutrino-Nucleus Scattering.

5). Discussion of the numerical results in the context of Neutrino Non-Standard Interactions.

6). Conclusions.

Over the past few years tremendous efforts and invaluable contributions from the neutrino experiments established the standard three-neutrino framework beyond any doubt.

However the standard interpretation of that framework might not be the ultimate picture. There may exist many new physics scenarios for which we will need to invoke new interpretation on top of the standard interpretation.

New Physics ?

Presence of Sterile Neutrino, Long-Range forces, Non-Unitary of the leptonic PMNS matrix, CPT violation, Non-Standard Neutrino interactions, and many others.

In this talk I will discuss two such new physics scenarios namely, the **Non-Unitarity of the PMNS matrix** in the context of oscillation physics and the **Non-Standard Interactions of Neutrinos (NSI)** using the Coherent Elastic Neutrino-Nucleus Scattering at the European Spallation Source facility.

Non-Unitarity at the Oscillation Framework

In presence of Non-Unitarity, the effective Hamiltonian in the flavor basis is given by

$$H_{Mat} = \left[\underbrace{\frac{1}{2E} N \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix}}_{\text{Vacuum}} N^\dagger + (NN^\dagger) \underbrace{\begin{pmatrix} V_{CC} + V_{NC} & 0 & 0 \\ 0 & +V_{NC} & 0 \\ 0 & 0 & +V_{NC} \end{pmatrix}}_{\text{Matter}} (NN^\dagger) \right]$$

$\mathrm{V}_{CC} = \sqrt{2}\, G_F\, N_e$ **CC-potential for neutrino,** $\mathrm{V}_{CC} \rightarrow -V_{CC}$ **For antineutrino**

$\mathrm{V}_{NC} = -\frac{G_F\, N_n}{\sqrt{2}}$ **NC-potential for neutrino,** $\mathrm{V}_{NC} \rightarrow -V_{NC}$ **For antineutrino**

The Non-Unitary matrix N is parametrized as

$$N = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U^{PMNS}$$

Where, $\alpha_{ij}|_{i \neq j} = |\alpha_{ij}|\, e^{i\phi_{ij}}$

The probability for one flavor ν_α transforming to another flavor ν_β is calculated as

$$\mathrm{P}(\nu_\alpha \rightarrow \nu_\beta) = |S_{\beta\alpha}(L)|^2 = |(e^{-iH_{Mat}L})_{\beta\alpha}|^2$$

In presence of NU, the $\nu_\mu \rightarrow \nu_e$ appearance probability can be written approximately as,

$$P_{\mu e} = \alpha_{11}^2 |\alpha_{21}|^2 - 4 \sum_{j>i}^{3} Re\left[N_{\mu j}^* N_{ej} N_{\mu i} N_{ei}^*\right] \sin^2\left(\frac{\Delta m_{ji}^2 L}{4E}\right)$$

$$+2 \sum_{j>i}^{3} Im\left[N_{\mu j}^* N_{ej} N_{\mu i} N_{ei}^*\right] \sin\left(\frac{\Delta m_{ji}^2 L}{2E}\right)$$

In vacuum,

$$P_{\mu e} = (\alpha_{11}\alpha_{22})^2 P_{\mu e}^{3\times 3} + \alpha_{11}^2 \alpha_{22} |\alpha_{21}| P_{\mu e}^I + \alpha_{11}^2 |\alpha_{21}|^2$$

$$P_{\mu e}^I = -2\Bigg[\sin(2\theta_{13}) \sin\theta_{23} \sin\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) \times \sin\left(\frac{\Delta m_{31}^2 L}{4E_\nu} + \delta_{\mathrm{CP}} - \phi_{21}\right)\Bigg] + \cos\theta_{13} \cos\theta_{23} \sin 2\theta_{12} \sin\phi_{21} \sin\left(\frac{\Delta m_{21}^2 L}{2E_\nu}\right)$$

Brief description of the ESSnuSB 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).

ESSnuSB (Sourced at Lund, Sweden)	
Baseline	540 km, 360 km, 200km
Detector mass	500 Kt
Detector type	Water Cherenkov
Proton Energy	2 GeV
Average Beam Power	5 MW
Protons on target (POT) Per year	2.7×10^{23}
Run time	2 yrs ν + 8 yrs $\bar{\nu}$

The flux peaks around 0.3 GeV

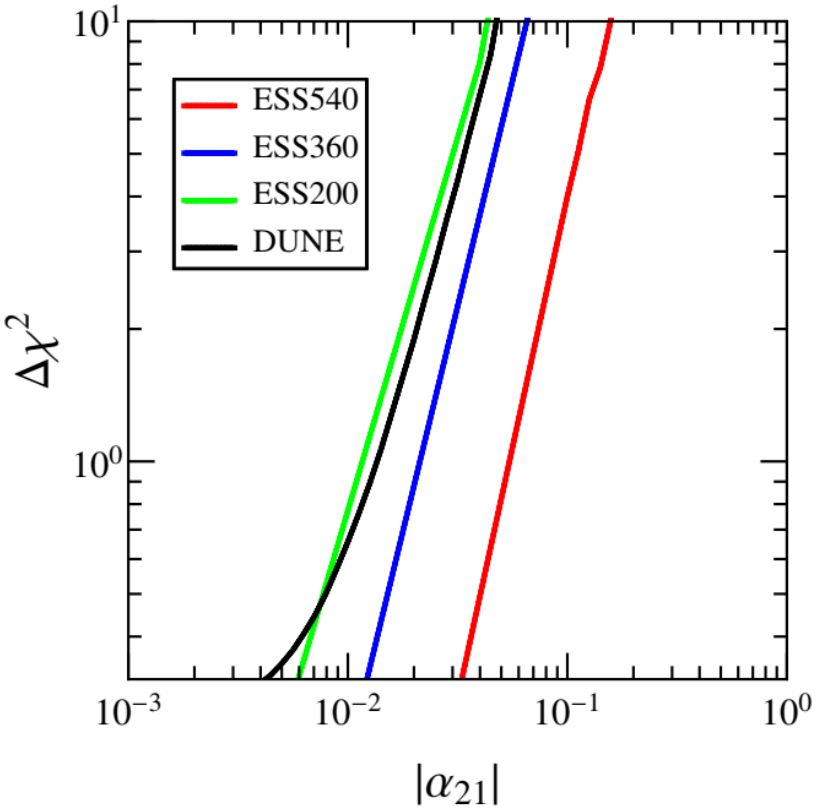
baseline (km)	1st osc. max. (GeV)	2nd osc. max. (GeV)
540	1.05	0.35
360	0.70	0.23
200	0.39	0.13

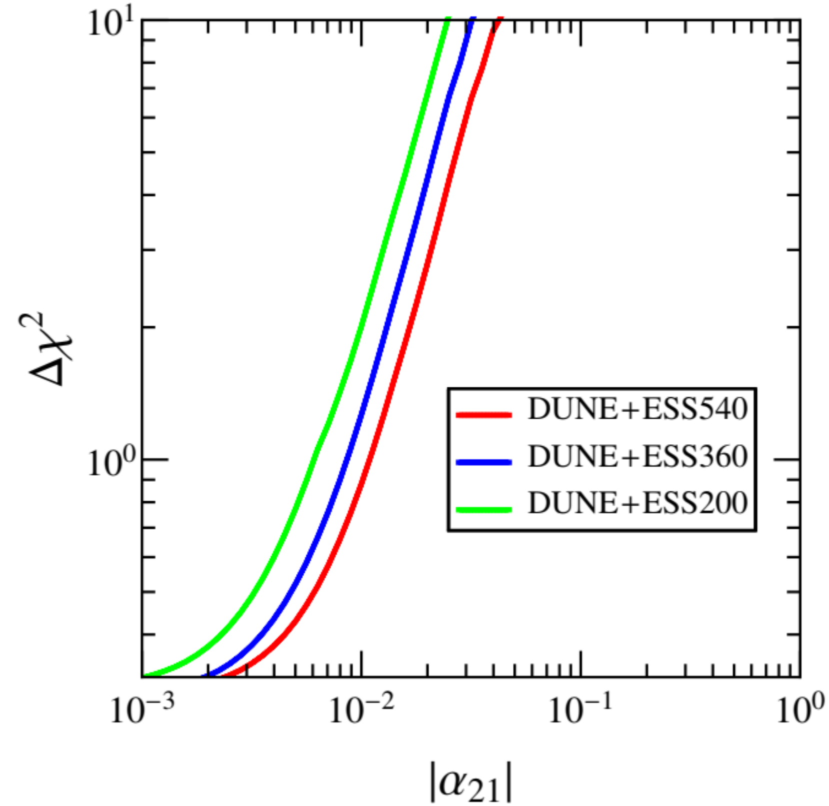
For the oscillation analysis we use the above information.

Current Bounds

NU parameters	$\|\alpha_{21}\|$	$\|\alpha_{31}\|$	$\|\alpha_{32}\|$	α_{11}	α_{22}	α_{33}
3σ bounds	< 0.025	< 0.075	< 0.02	> 0.93	> 0.98	> 0.72

Future Sensitivities





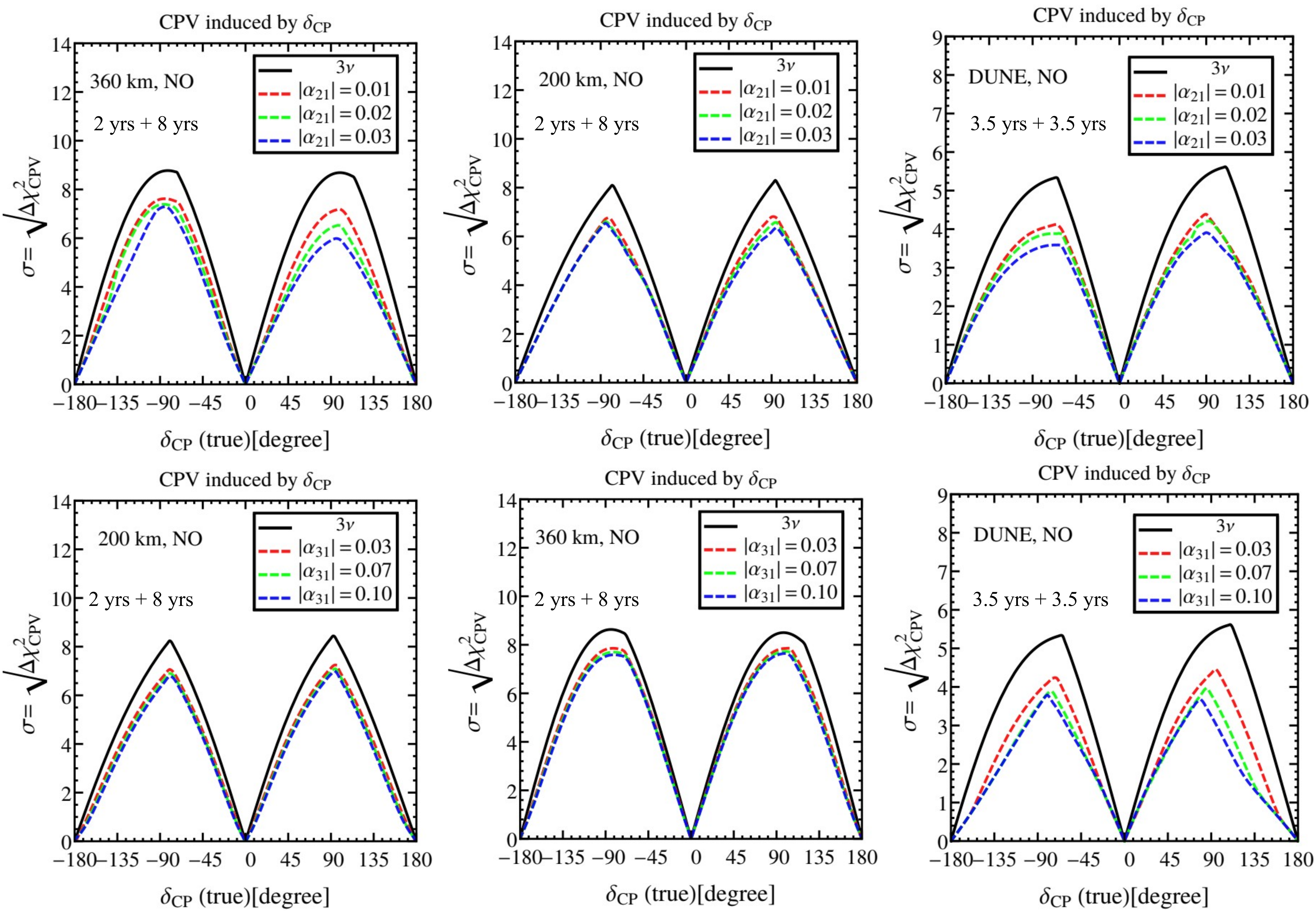
Expt. Setups	ESS540	ESS360	ESS200	DUNE	DUNE+ESS540	DUNE+ESS360	DUNE+ESS200
3σ bounds ($\|\alpha_{21}\|$)	< 0.16	< 0.06	< 0.04	< 0.045	< 0.04	< 0.03	< 0.022

DUNE & ESSnuSB plays a complementary role with each other

Improved over the current bound

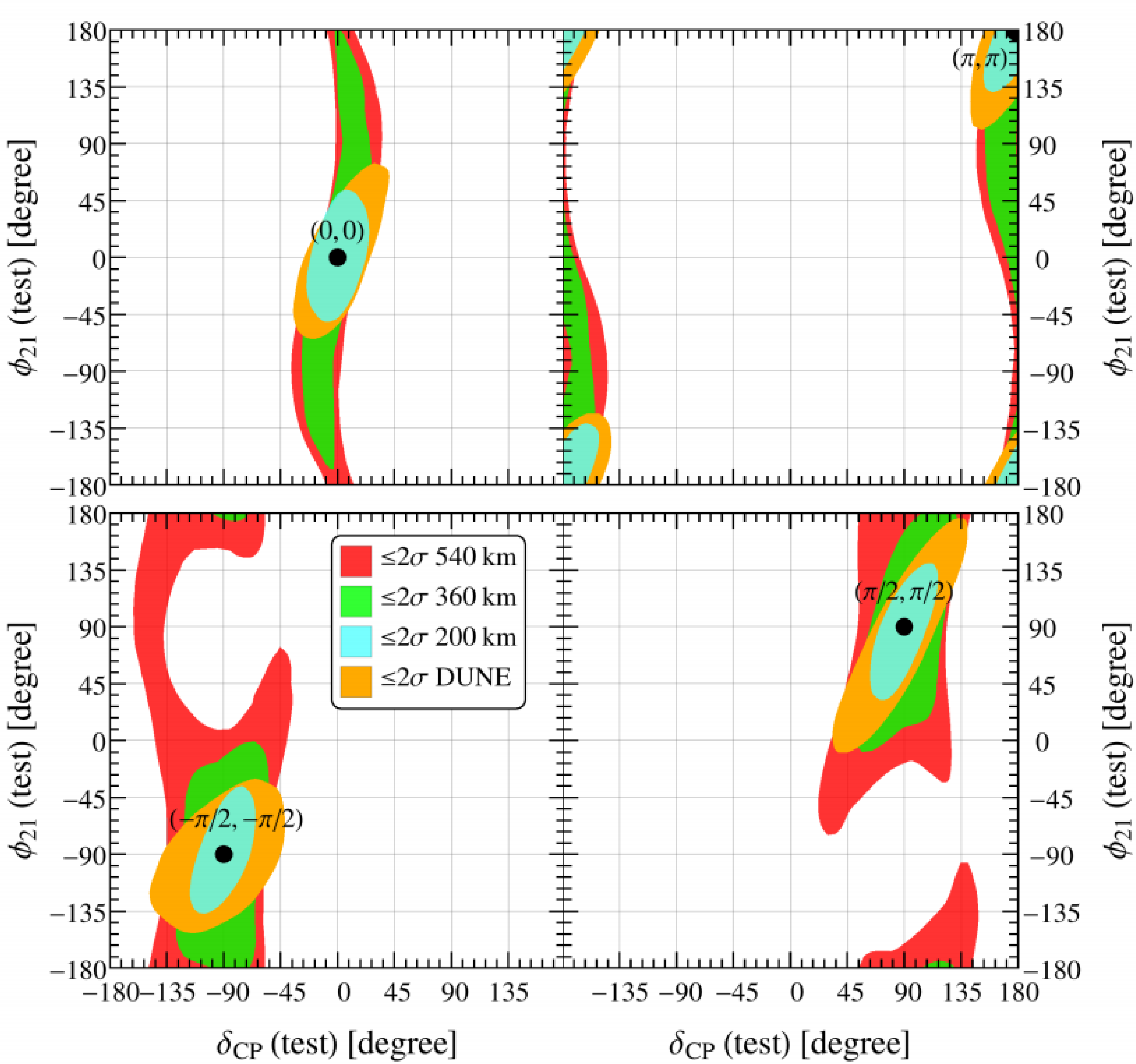
ArXiv: 2111.08673, by S. S. Chatterjee, O. G. Miranda, M. Tortola, and J. W. F. Valle

CP-violation discovery in presence of Non-Unitarity



ArXiv: 2111.08673, by S. S. Chatterjee, O. G. Miranda, M. Tortola, and J. W. F. Valle

CP-reconstruction potential



ArXiv: 2111.08673, by S. S. Chatterjee, O. G. Miranda, M. Tortola, and J. W. F. Valle

ESSnuSB offers an excellant opportunity to measure both the standard & new CP-phases

Coherent Elastic Neutrino-Nucleus Scattering

Decay at rest:

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

$$\downarrow$$

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

The differential fluxes are given as:

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

$$\left.\begin{aligned} \frac{dN_{\bar{\nu}_\mu}}{dE_\nu} &= \xi\,\frac{64\,E_\nu^2}{m_\mu^3}\left(\frac{3}{4} - \frac{E_\nu}{m_\mu}\right), \\ \frac{dN_{\nu_e}}{dE_\nu} &= \xi\,\frac{192\,E_\nu^2}{m_\mu^3}\left(\frac{1}{2} - \frac{E_\nu}{m_\mu}\right). \end{aligned}\right\} \longrightarrow \text{Delayed components}$$

The differential cross-section of a neutrino interacting with a nucleus of mass M is,

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

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

T → Nuclear recoil energy

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

Now, in presence of Neutrino Non-Standard Interactions (NSI), the waek charge modified as,

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

Where we have defined, $\varepsilon_{\alpha\beta}^{fV} \equiv \varepsilon_{\alpha\beta}^{fL} + \varepsilon_{\alpha\beta}^{fR}$

Using ESS as a probe of CEvNS events

How the suitable combination of different detectors can help breaking the degeneracies arise naturally when considering the single or multiple NSI Couplings with up or down type of quarks.

POT: 2.8×10^{23} **Run time: 3 yrs**

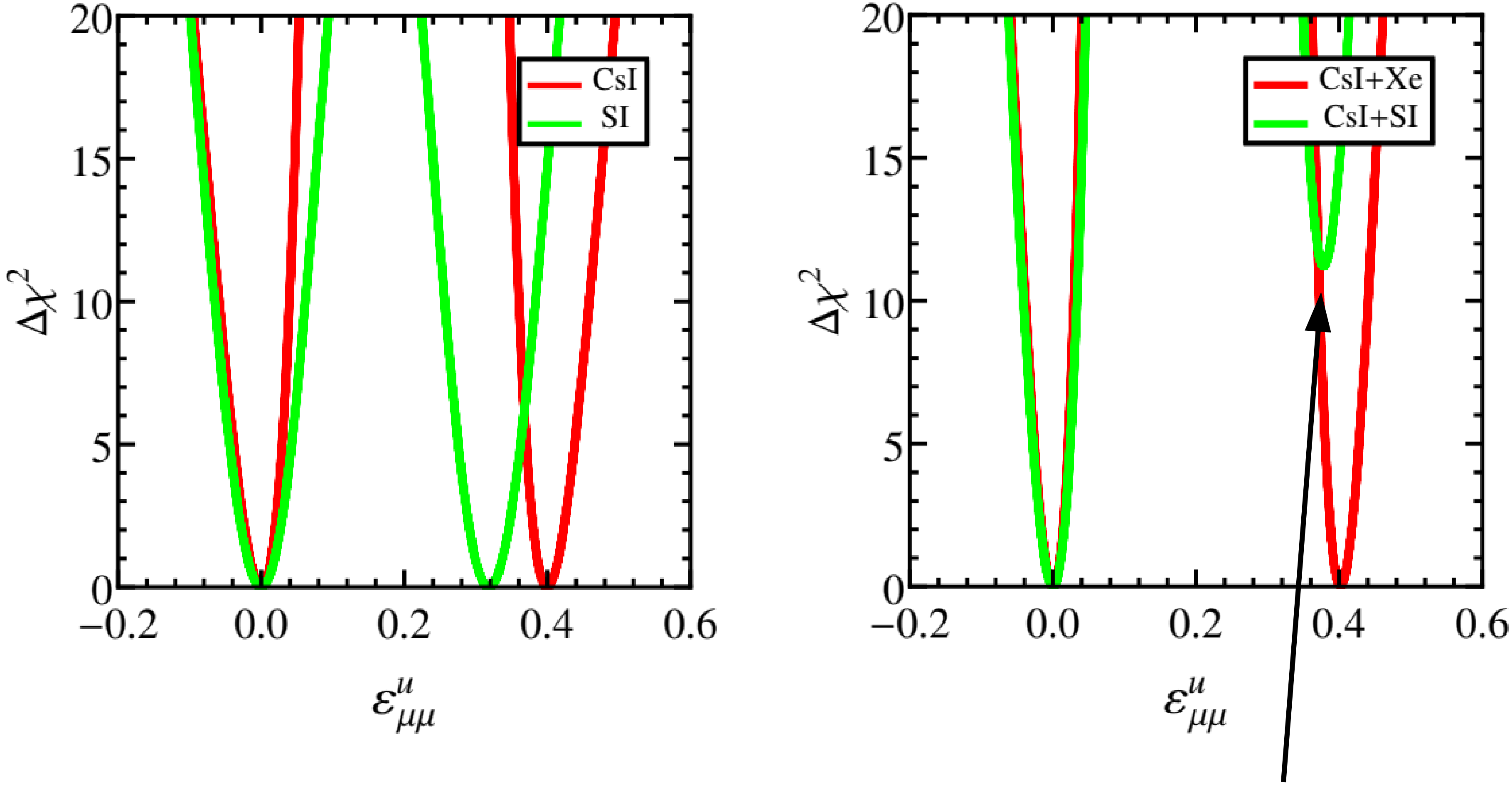
Properties of the detector materials

Target nucleus	Z	n/p	Mass No.	R (fm)
Xe	54	0.69	131.29	4.79
Cs	55	0.71	132.91	4.83
I	53	0.72	126.90	4.83
Ge	32	0.8	72.0	4.06
Si	14	1	27.98	3.12
Ar	18	0.81	39.95	3.43
F	9	0.9	19.00	2.90
C	6	1	12.01	2.47

Detectors used: CSI, Si, Ge, Xe, Ar, C_3F_8

For details, see, arXiv: 1911.00762

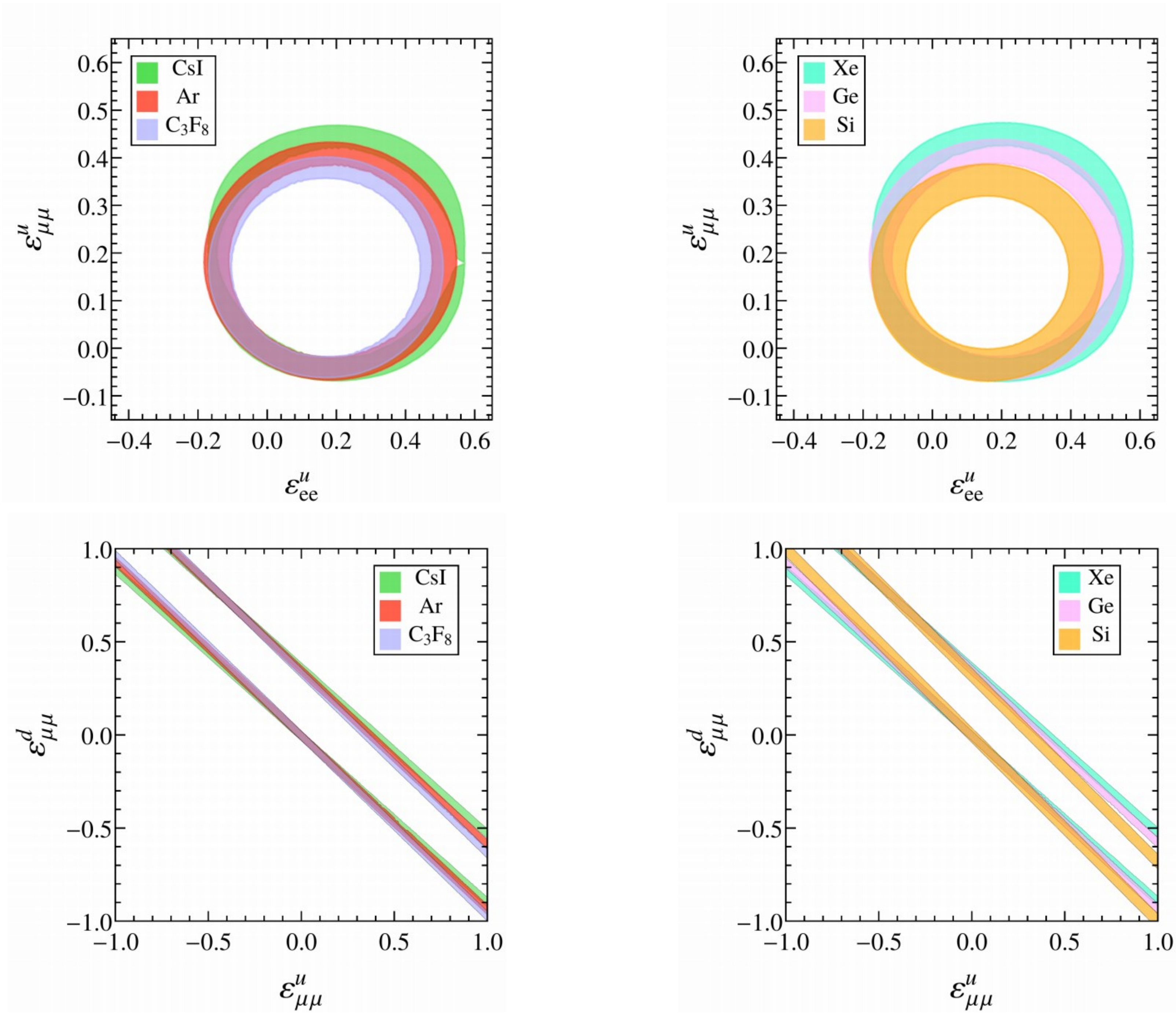
1D projections



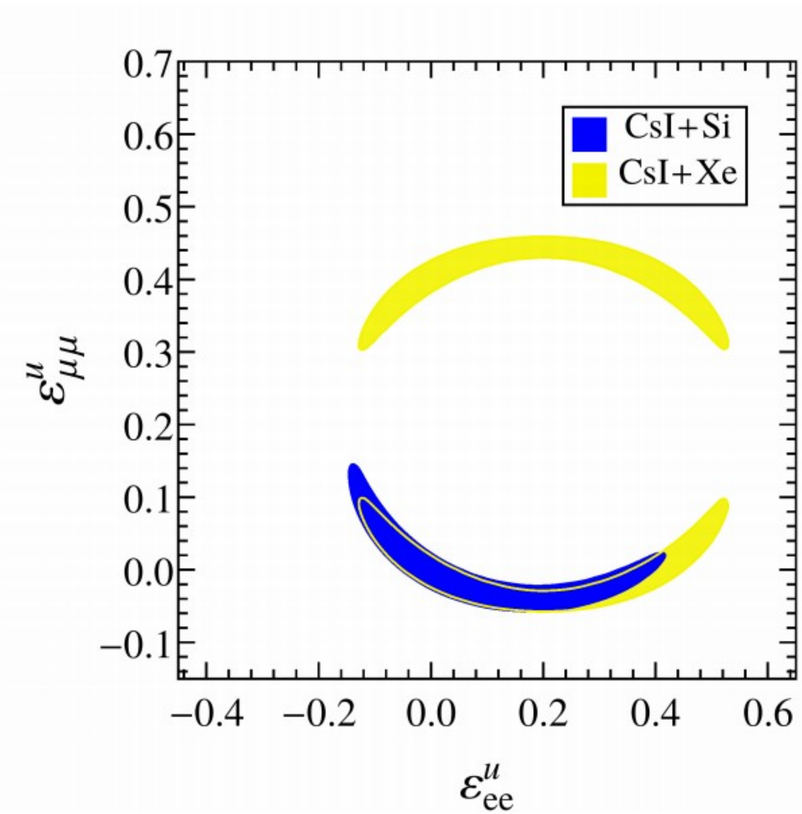
Disallowed at 3sigma C.L.

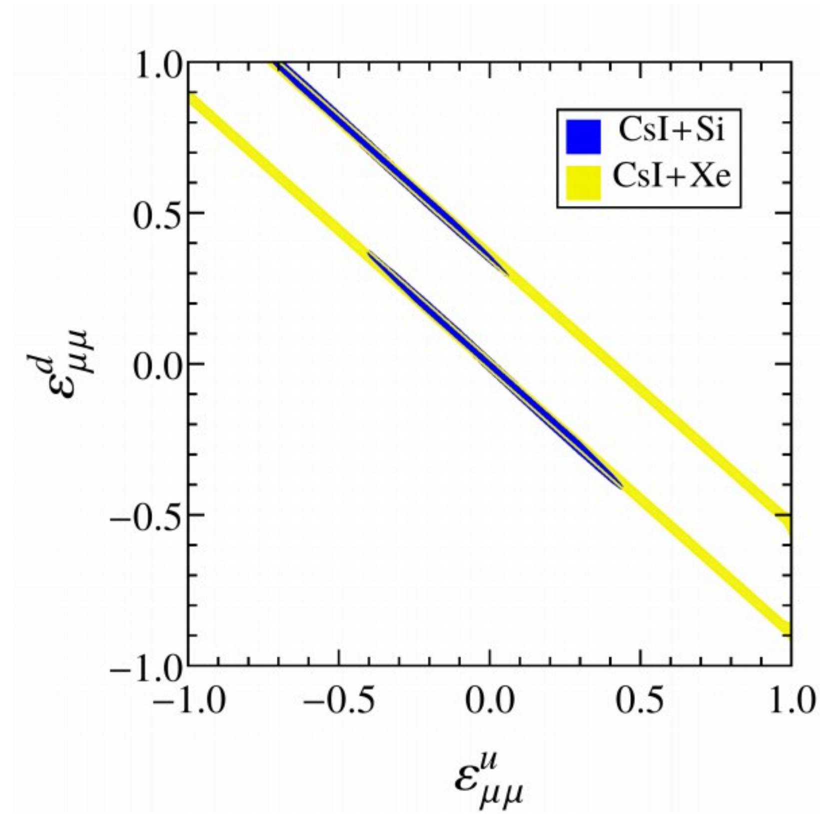
Not only constrain the parameter space but also break the degeneracy!

Ongoing work by S. S. Chatterjee, G. S. Garcia, S. Lavignac, and O. G. Miranda



Ongoing work by S. S. Chatterjee, G. S. Garcia, S. Lavignac, and O. G. Miranda





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

Ongoing work by S. S. Chatterjee, G. S. Garcia, S. Lavignac, and O. G. Miranda

Conclusion

- We have investigated the possibilities of exploring the Non-Unitarity and its impact in the long-baseline experiments like ESSnuSB and DUNE.

- We have shown that ESSnuSB and DUNE both can place competitive and complementary Constraint on the NU parameter $|\alpha_{21}|$. In fact the combined analysis of both this Experiments can give improved bound over the current bound.

- The CPV discovery potential of ESSnuSB gets degraded only slightly in presence of Non-Unitary parameters $|\alpha_{21}|$ or $|\alpha_{31}|$ The CPV discovery potential of DUNE gets degraded more in presence of $|\alpha_{31}|$. So in this case both the experiments will play a complementary role with each other.

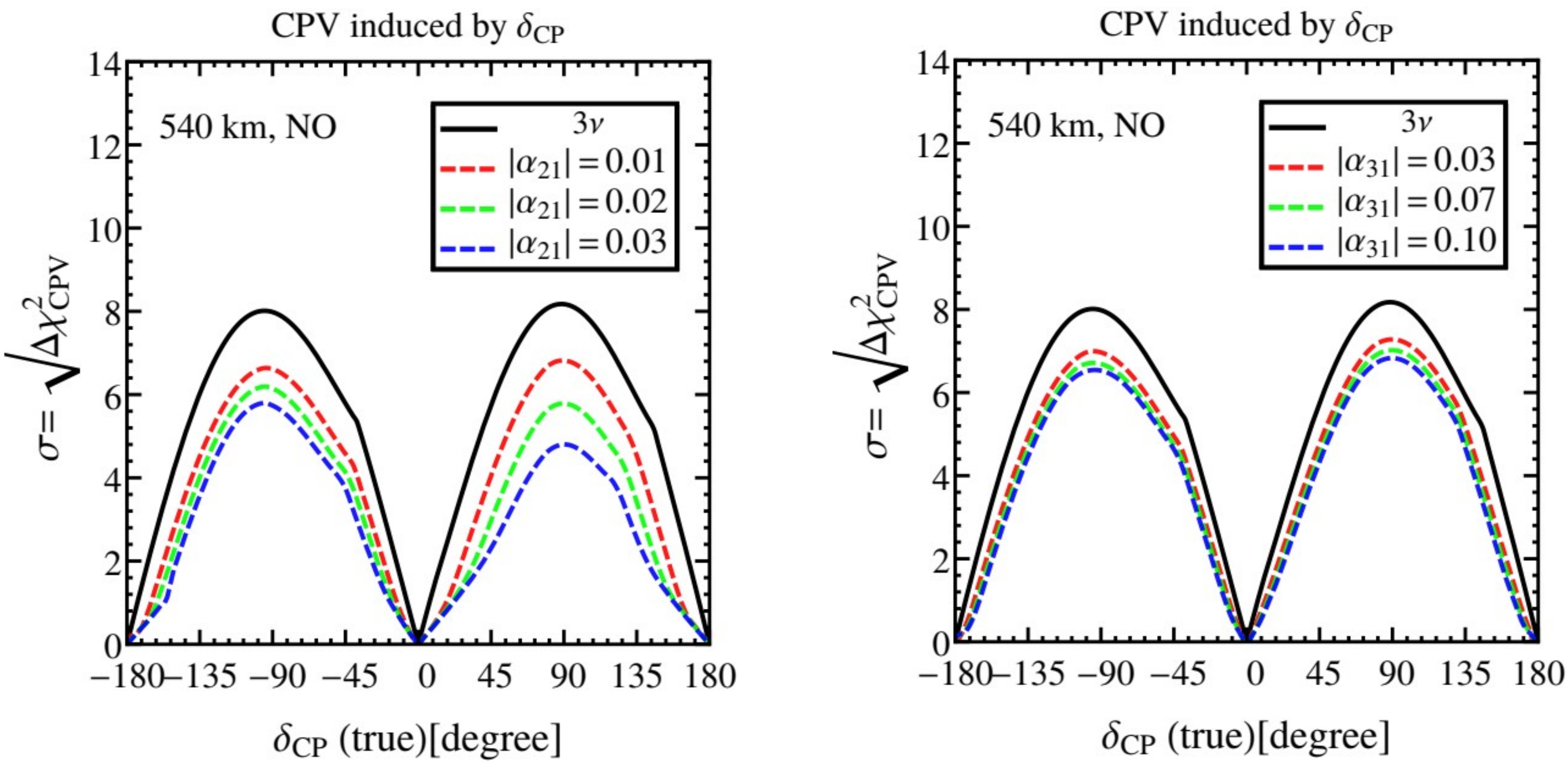
- ESSnuSB also provide a promising CP-reconstruction potential both for the standard as well as for the CP-phase associated with the non-unitarity. In some cases it performs better than DUNE

- We have also shown that the European Spallation Source facilities provides an excellant opportunity to explore new physics scenarios using Coherent Elastic Neutrino-Nucleus Scattering events.

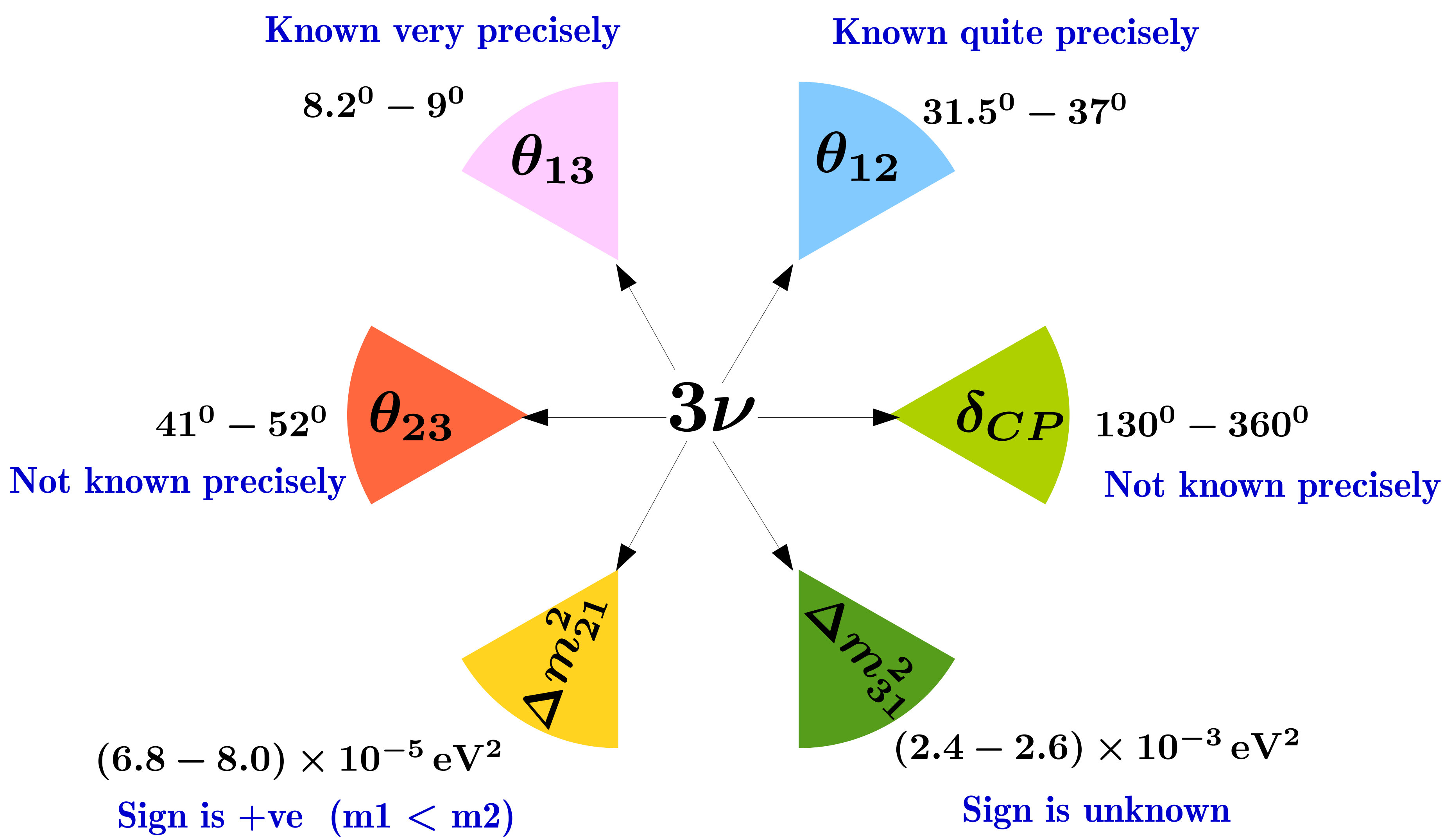
- ✯ We have shown that the suitable combinations of the different target materials helps not only constraining the NSI couplings but also it helps to remove the degeneracies of the NSI parameters with up or down type quarks.

- ✗ We hope our analyses will help more to explore the standard and new physics capabilities of the European Spallation Source.

Thank you for your kind attention!


CPV induced by δ_{CP}
540 km, NO
3ν
$|\alpha_{21}| = 0.01$
$|\alpha_{21}| = 0.02$
$|\alpha_{21}| = 0.03$
$\sigma = \sqrt{\Delta\chi^2_{CPV}}$
δ_{CP} (true)[degree]
CPV induced by δ_{CP}
540 km, NO
3ν
$|\alpha_{31}| = 0.03$
$|\alpha_{31}| = 0.07$
$|\alpha_{31}| = 0.10$
$\sigma = \sqrt{\Delta\chi^2_{CPV}}$
δ_{CP} (true)[degree]

Current status of 3ν parameters (3σ bound)



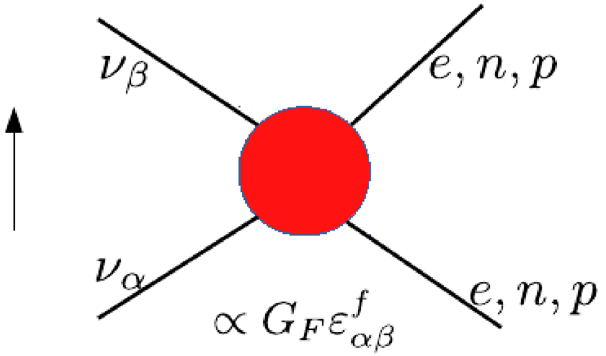
ArXiv: 2006.11237 by P. Salas et al., arXiv: 2007.14792 by Esteban et al., and arXiv: 2107.00532 by F. Capozzi et al.

NSI and its impact in the neutrino oscillation

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

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

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

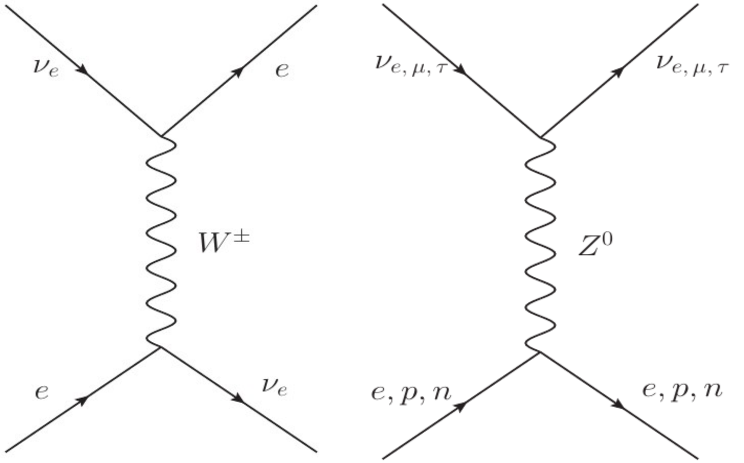


$$\varepsilon_{\alpha\beta} \equiv \sum_{f=e,u,d} \varepsilon^f_{\alpha\beta} \frac{N_f}{N_e}$$

N is the number density of fermions

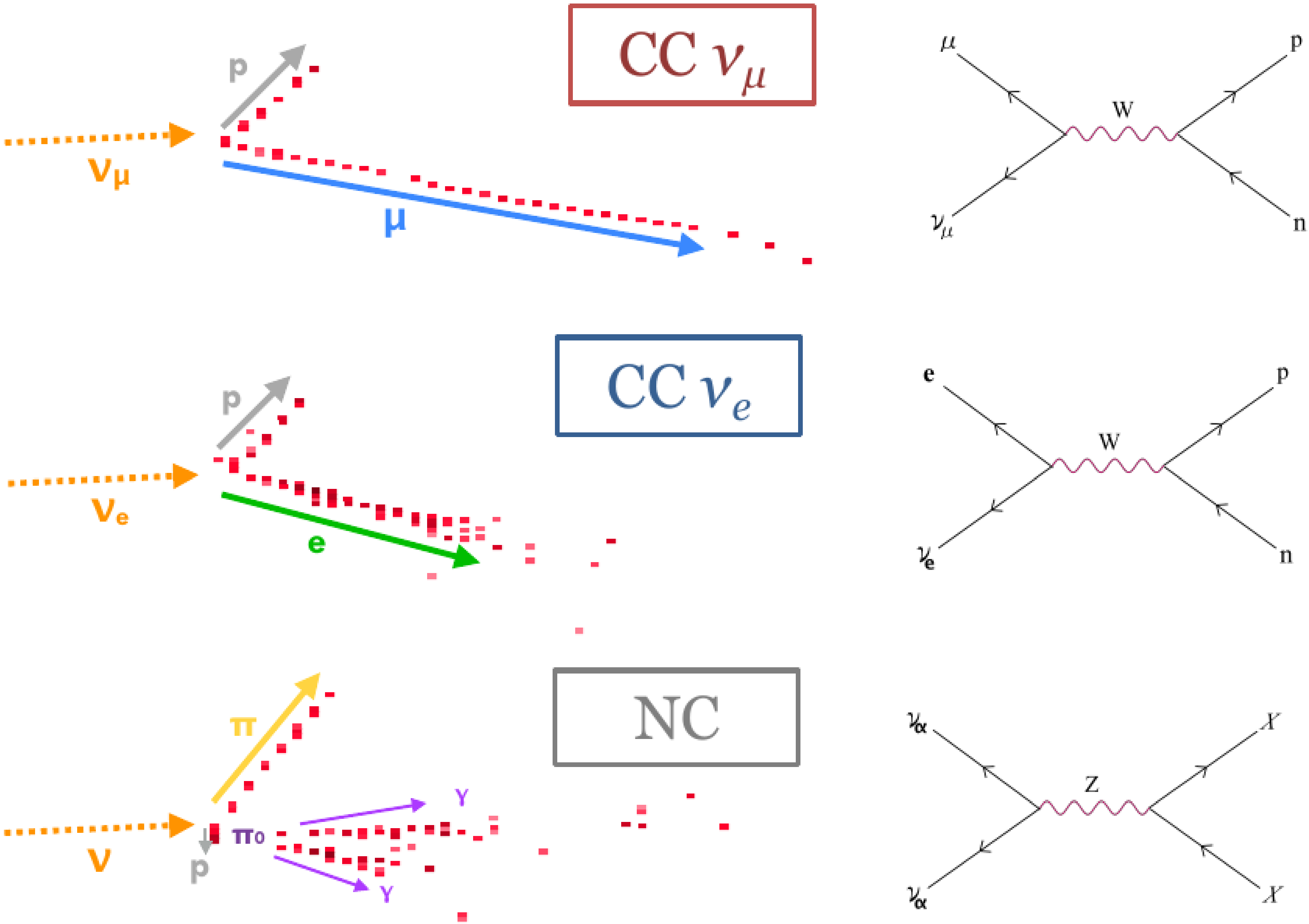
$$\varepsilon_{\alpha\beta} \simeq \varepsilon^e_{\alpha\beta} + 3\,\varepsilon^u_{\alpha\beta} + 3\,\varepsilon^d_{\alpha\beta}$$

→ Strength of NSIs



CC-interaction **NC-interaction**

L. Wolfenstein PRD 17, 2369 (1978)



$\alpha = e,\ \mu,\ \tau$

For antineutrinos (inverse beta-decay)

$$\bar{\nu}_l + p \rightarrow l^+ + n$$

In Liquid Ar detector

$$\nu_l + Ar \rightarrow l^- + K$$

Neutrino flavor eigenstates are related to the mass eigenstates as

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

Where,

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

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