Sensitivity study within and beyond the SM using neutrino elastic scattering

Pantelis Melas, Dimitris Papoulias

National and Kapodistrian University of Athens

H.F.R.I.
Hellenic Foundation for Research & Innovation

DUNE

Outline

- Introduction to PMNS
- Non-unitary models
- χ^2 analysis
- Probing the weak mixing angle
- Summary

Introduction

The standard unitary lepton mixing matrix (PMNS) is:

$$U_{\text{PMNS}} = \overbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}^{\text{Neutrino Mixing Matrix}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric Sector}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor Sector}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar Sector}}$$

Many Questions

$\delta_{CP} \approx$??

$\theta_{23} \approx 45^\circ$

$\theta_{13} \approx 8.5^\circ$

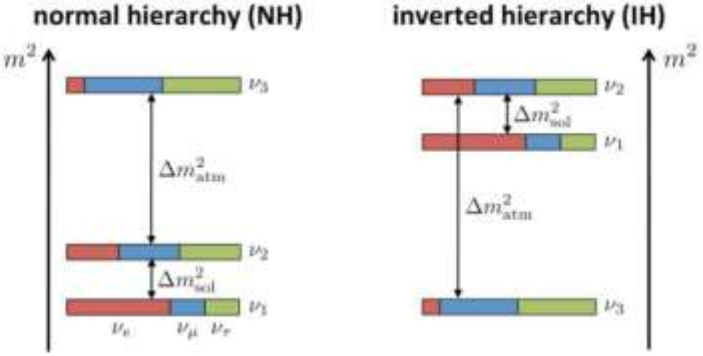
$\theta_{12} \approx 34^\circ$

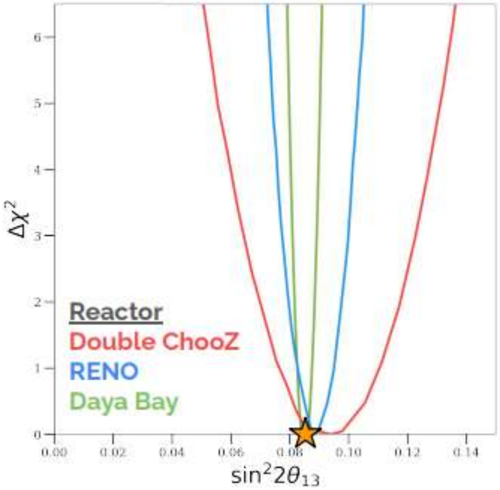
Is there **CP violation** in neutrino sector (do neutrinos and antineutrinos behave differently?)

What's the **octant** of of θ_{23}? Measured with $\sin^2(2\theta_{23})$

$$|\Delta m^2_{32}| = 2.5 \times 10^{-3} eV^2$$

What's the **sign** of Δm^2_{32}? The "Mass Ordering" problem





Non-unitary models

One more question: Is PMNS unitary?

For the case **existence of a sterile neutrino** -> the PMNS matrix is non-unitary

The (3+1) model consist 3 original neutrino flavors + 1 sterile neutrino.
The neutrino mixing can be expressed by **a 4-generation PMNS matrix**:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Models like **type-I seesaw (linear or invert)** can accommodate several **new heavy neutral leptons**, leading to **violation of lepton unitarity**.

Non-unitary models

The New PMNS matrix for the type-I seesaw model

- Takes the form: **K = (N S),** where **N is a 3×3 matrix**, while **S is a 3× m matrix**, with m the number of fermionic singlets that mix with the active neutrinos.

- The small block **S ~ O (ε) is the seesaw expansion matrix**.

A systematic approach to **the (non-unitary) matrix N** can be derived from the seesaw expansion, as the lower triangular **parameterization**

$$N = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{31} & \alpha_{33} \end{pmatrix} \cdot U^{\,3\times 3}$$

,where $U^{\,3\times3}$ is the PMNS

A viable way to study the non-unitarity is by using neutrino-electron elastic scattering events (EνES).

DOI: 10.1103/PhysRevD.109.115007

DOI: 10.1103/PhysRevD.92.053009

χ^2 Analysis

For that case, the new EνES cross section can be expressed as

$$\left[\frac{d\sigma_{\nu_\ell}}{dT_e}\right]_{\mathrm{NU}} = (2a_{11}^2 - a_{22}^2)\left[\frac{d\sigma_{\nu_\ell}}{dT_e}\right]_{\mathrm{SM}} + \mathcal{O}(\varepsilon^4), \qquad \nu_\ell = \nu_e,\ \bar{\nu}_e$$

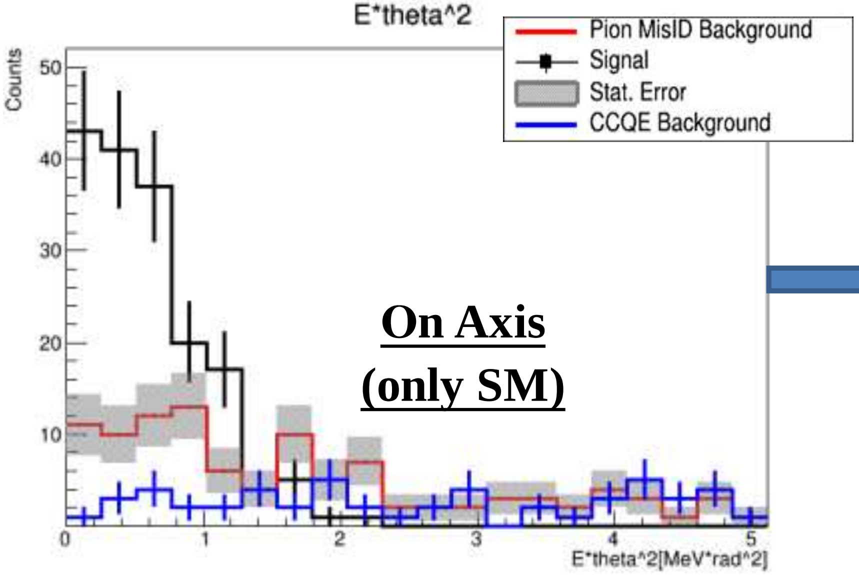
$$\varepsilon \equiv \mathcal{O}(Yv/M)$$

$$\left[\frac{d\sigma_{\nu_\ell}}{dT_e}\right]_{\mathrm{NU}} = (2a_{22}^2 - a_{11}^2)\left[\frac{d\sigma_{\nu_\ell}}{dT_e}\right]_{\mathrm{SM}} + \mathcal{O}(\varepsilon^4), \qquad \nu_\ell = \nu_\mu,\ \bar{\nu}_\mu$$

DOI: 10.1103/PhysRevD.92.053009

DOI: 10.1103/PhysRevD.109.115007

From the previous collaboration meeting:
https://indico.fnal.gov/event/60082

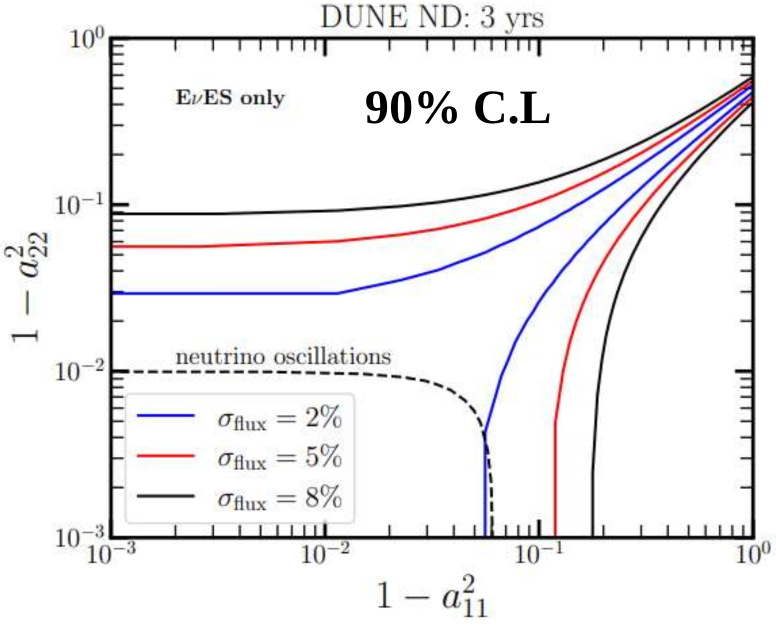


On Axis
(only SM)

Thus we can rescale the EνES spectra by a factor $(2a_{22}^2 - a_{11}^2)$

https://doi.org/10.3390/ particles7030035

χ^2 Analysis



$$\chi^2 = 2 \sum_{i=1}^{20} \left[N_{\text{exp}}^{ijk} - N_{\text{obs}}^{ijk} + N_{\text{obs}}^{ijk} \log \frac{N_{\text{obs}}^{ijk}}{N_{\text{exp}}^{ijk}} \right] + \left(\frac{\alpha_1}{\sigma_{\alpha_1}} \right)^2 + \left(\frac{\alpha_2}{\sigma_{\alpha_2}} \right)^2$$

$$N_{\text{obs}} = N_{\text{SM}}\,(a_{11}, a_{22}) + N_{\text{bkg}}$$

$$N_{\text{exp}} = N_{\text{SM}} \cdot (1+\alpha_1) + N_{\text{bkg}} \cdot (1+\alpha_2)$$

$$N_{\text{bkg}} = N_{\pi^0}^{\text{missID}} + N_{\text{CCQE}}$$

https://doi.org/10.3390/ particles7030035

- We consider two nuisance parameters α_1 and α_2 (which were minimized) with $\sigma_{\alpha 1}$=8% (5%, 2%) and $\sigma_{\alpha 2}$ = 10% to account for the normalization uncertainties of the DUNE neutrino flux and background.

- We ignore the non-unitarity effects that are expected to affect the CCQE background rate; given the very low statistics of CCQE combined with the large assigned uncertainty of σ_{bkg} = 10%, we find this to be a valid assumption.
- The performed statistical analysis proceeds under the assumption that the EνES rate is induced by muon neutrinos only.

Probing the weak mixing angle

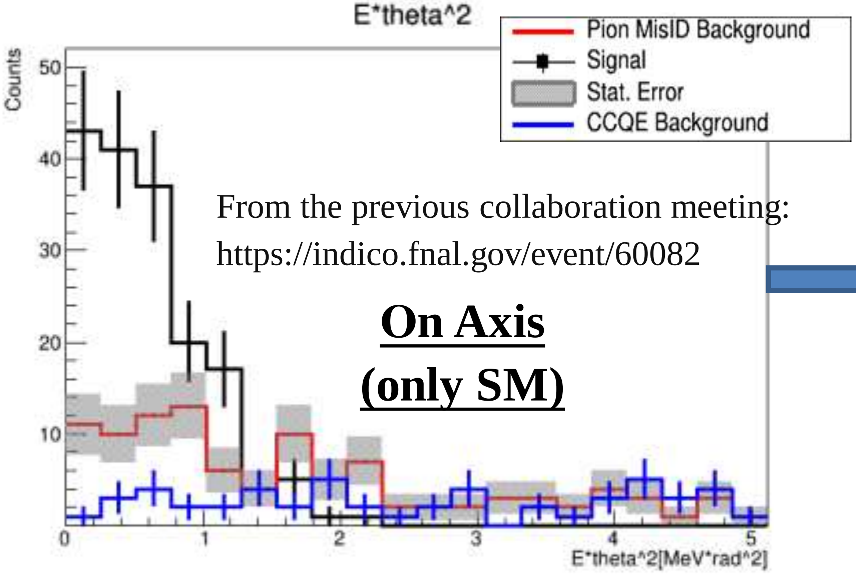
We now turn our attention on estimating the capabilities of DUNE-ND in probing the weak mixing angle within the SM via the exploitation of EνES events.

The EνES cross section for $E_\nu >> m_e$ can be expressed as

$$\sigma_{\nu_\ell - e^-}(E_\nu) \approx \frac{G_F^2 m_e E_\nu}{2\pi}\left(A + \frac{1}{3}B\right)$$

,where $A = (g_V^{\nu_\ell} + g_A^{\nu_\ell})^2$ and $B = (g_V^{\nu_\ell} - g_A^{\nu_\ell})^2$

Assuming muon neutrinos, the couplings are $g_V^{\nu_\mu} = -\frac{1}{2} + 2\sin^2\theta_W$ and $g_A^{\nu_\mu} = -\frac{1}{2}$



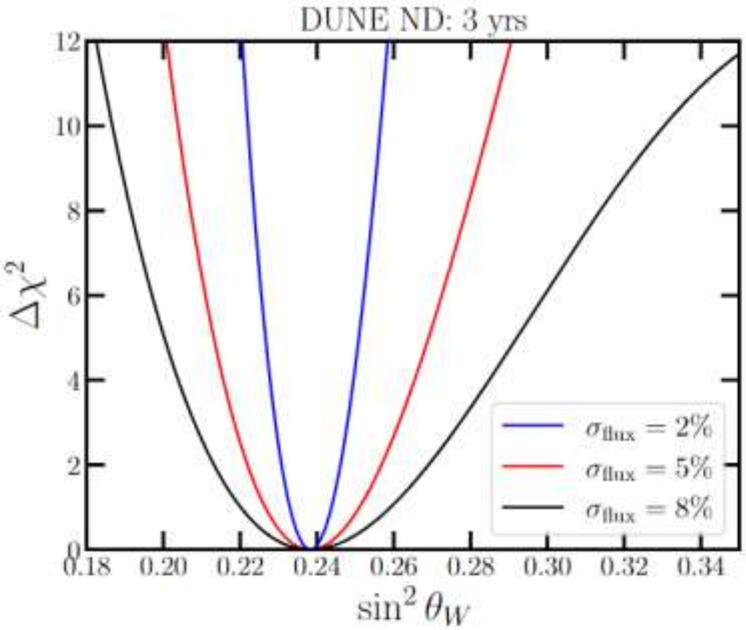
From the previous collaboration meeting:
https://indico.fnal.gov/event/60082

On Axis
(only SM)

DOI: 10.1103/PhysRevLett.125.051803

Thus we can rescale the EνES spectra by a factor (A+(1/3)B) / (A′+(1/3)B′), where A, B are allowed to vary with the weak mixing angle, while A′, B′ are fixed assuming $\sin^2\theta_W = 0.2386$

χ^2 Analysis



$$\chi^2 = 2\sum_{i=1}^{20}\left[N^{ijk}_{\rm exp} - N^{ijk}_{\rm obs} + N^{ijk}_{\rm obs}\log\frac{N^{ijk}_{\rm obs}}{N^{ijk}_{\rm exp}}\right] + \left(\frac{\alpha_1}{\sigma_{\alpha_1}}\right)^2 + \left(\frac{\alpha_2}{\sigma_{\alpha_2}}\right)^2$$

$$N_{\rm obs} = N_{\rm SM}(\sin^2\theta_W) + N_{\rm bkg}$$

$$N_{\rm exp} = N_{\rm SM}\cdot(1+\alpha_1) + N_{\rm bkg}\cdot(1+\alpha_2)$$

$$N_{\rm bkg} = N_{\pi^0}^{\rm missID} + N_{\rm CCQE}$$

- We consider two nuisance parameters α_1 and α_2 (which were minimized) with $\sigma_{\alpha 1}$=8% (5%, 2%) and $\sigma_{\alpha 2}$ = 10% to account for the normalization uncertainties of the DUNE neutrino flux and background.

- We ignore the effects that are expected to affect the CCQE background rate; given the very low statistics of CCQE combined with the large assigned uncertainty of $\sigma_{\rm bkg}$ = 10%, we find this to be a valid assumption.

- The performed statistical analysis proceeds under the assumption that the EνES rate is induced by muon neutrinos only.

Summary – Publication Plans

- We have explored the utility of elastic neutrino-electron scattering (EνES) events within and beyond the Standard Model (BSM) searches.
- The analysis is based of EνES and relevant background events using parameterized reconstruction techniques.
- The result indicates that the DUNE-ND sensitivity will be particularly relevant if the flux uncertainty will be under control.
- Should we consider publishing this with the full DUNE-ND event reconstruction?

Thank you for your kind attention

National and Kapodistrian
University of Athens

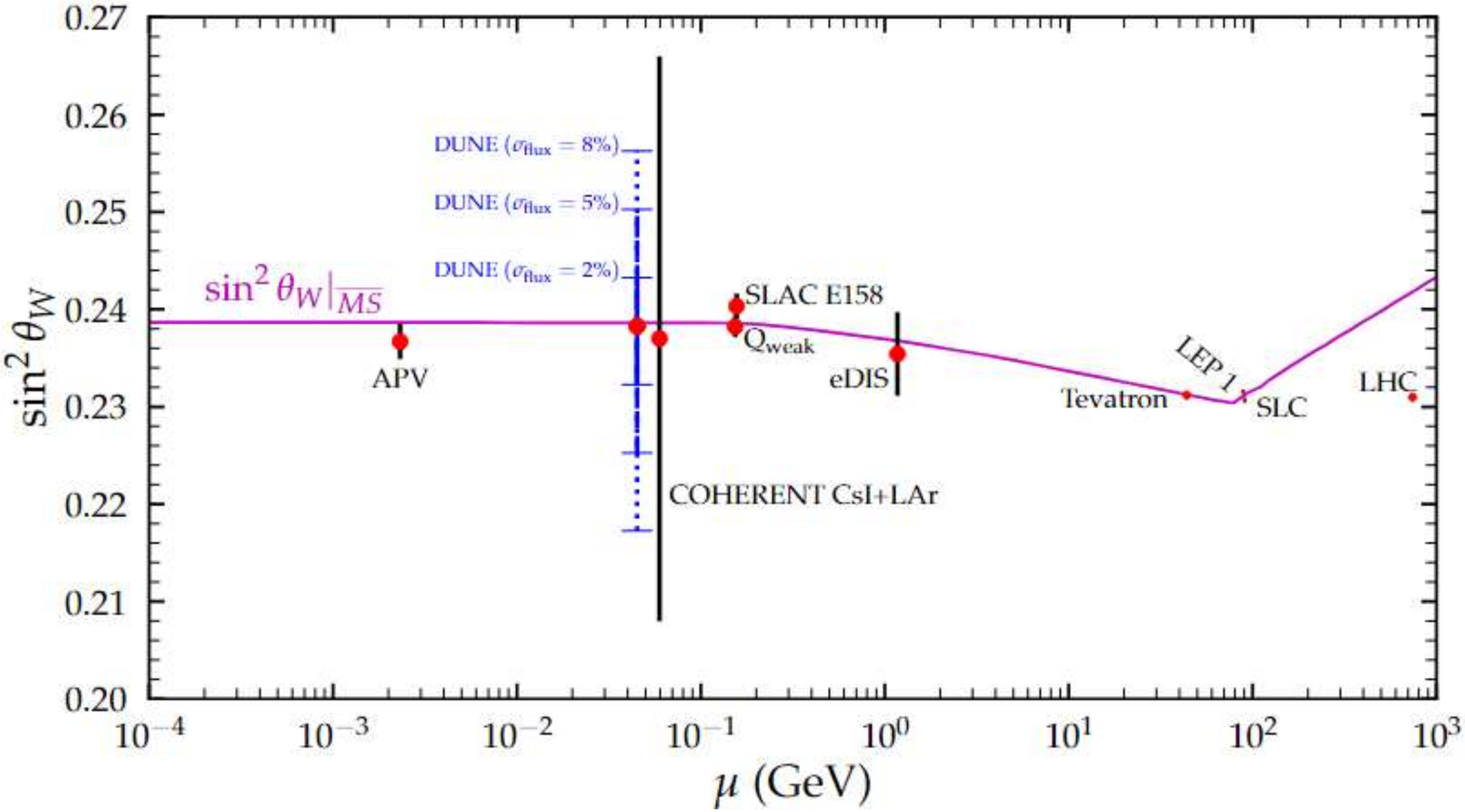
H.F.R.I.
Hellenic Foundation for
Research & Innovation

The research project was supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "3rd Call for H.F.R.I. Research Projects to support Post-Doctoral Researchers"

(Project Number: 7036)

BACK-UP

Probing the weak mixing angle



EνES measurements at DUNE-ND can place competitive constraints in the low-energy regime and complementary to existing results from the analysis of COHERENT experiment