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Nuclear Effects and CP Sensitivity at DUNE

University of Lucknow
Lucknow*

IIT Madras
Chennai

Presented by- Srishti Nagu*
Jaydip Singh*, Dr. Jyotsna Singh*

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Outline

Introduction

- Neutrino oscillation physics is entering into the era of precision measurement of known neutrino oscillation parameters and the estimation of unknown parameters.

- The known parameters i.e Δm^2_{21} , Δm^2_{31} , θ_{12} , θ_{13} , θ_{23} need to be explored with better precision while the unknown parameters are -
  1) CP violating phase δ_{CP}
  2) sign(Δm^2_{31}) i.e. neutrino mass ordering ($\Delta m^2_{31} > 0$:NH or $\Delta m^2_{31} < 0$: IH)
  3) octant of θ_{23} ($\theta_{23} > 45^0$:HO or $\theta_{23} < 45^0$:LO)

- We require neutrino oscillation experiments which are sensitive enough to capture them.

- DUNE, the upcoming long baseline neutrino experiment is a promising experiment aiming for discoveries of these unknown parameters.

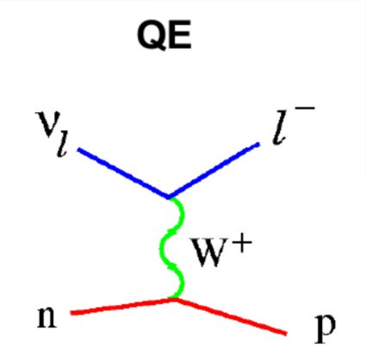
- DUNE plans to carry out a detailed study to resolve the neutrino mass ordering and search for CP violation in the lepton sector by studying the oscillation spectra of high-intensity ν_μ and (anti) ν_μ beams measured over a long baseline.

Nuclear Effects

- Modern experiments like DUNE, use heavy nuclear targets (eg. Argon, Calcium, Carbon) to get large event statistics. High event statistics, aid in reducing the statistical uncertainties.
- But we need to pin down the systematic uncertainties that arise due to the use of these heavy nuclear targets, as nuclear effects cannot be ignored .
- In neutrino-nucleus interactions, due to the nuclear effects many a times the particles emerging from the nucleus are different from the initially produced particles
- Since the nucleus containing nucleons undergo Fermi Motion- hadronic final states that are produced inside the nuclear medium- experience final state interactions (FSI) before exiting the nucleus, which alter their kinematics and identity.
- These effects can modify the final state of the particles emerging out of the detector from the initial states produced in neutrino-nucleus interactions.
- Understanding nuclear effects will help, to filter out true events from the fake events in a given neutrino nucleon interaction which will lead to an accurate measurement of neutrino oscillation parameters.

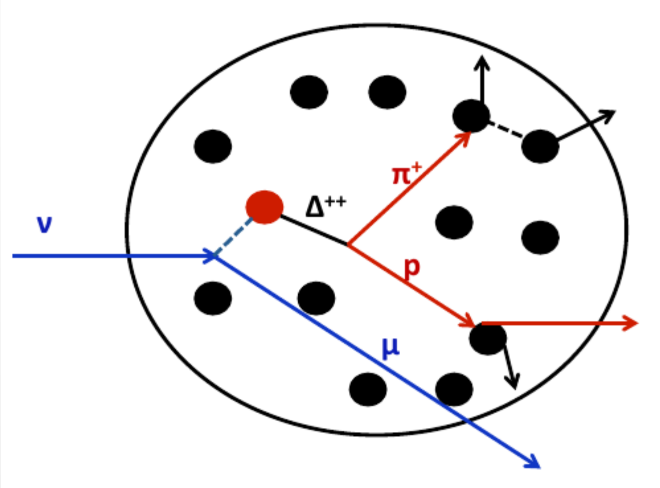
Difference between QE and QE like-

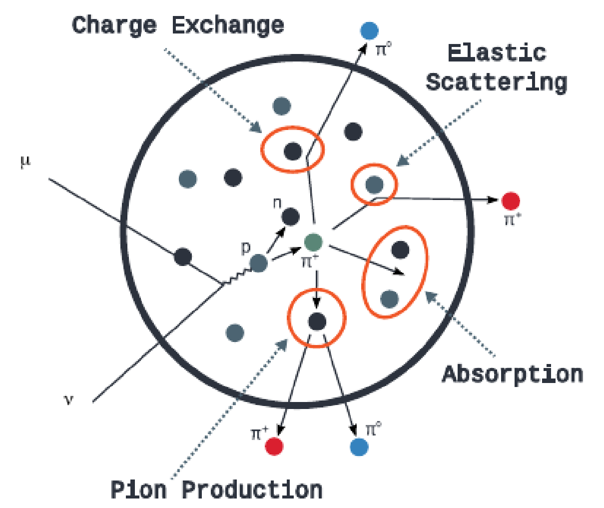
- Pure QE : $\nu n \rightarrow \mu^- p$



- QE like : $\nu p \rightarrow \mu^- p \, \pi^+$ - Stuck pion event : Pion is not seen in the final state.

  $\nu p \rightarrow \mu^- \Delta^{++}$





Uncertainties due to Nuclear Effects-

- Neutrino oscillation probabilities, which are being measured in long-baseline experiments, depend on neutrino energy.

$$P_{\mu\mu} = 1 - \sin^2\theta_{\mu\mu}\sin^2\left(\frac{\Delta m^2_{atm}L}{4E}\right) + \mathcal{O}(\Delta m^2_{21})$$

- Since neutrino beams are always produced as secondary decay products so the neutrino energy in a particular event is not directly known, but must be reconstructed from final state particles which are in turn effected by the nuclear effects. .
- Due to the mis-reconstruction of neutrino energy the quantitative estimation of neutrino oscillation parameters also carry some uncertainty.
- It is very difficult to quantify the “error” on models of nuclear effects, since they are generally not the result of a well-controlled expansion in some small parameter.

Neutrino Energy Reconstruction

- For QE scattering on a nucleon at rest the incoming neutrino energy is directly linked to the kinematics of the outgoing lepton and is thus known when lepton angle θ_μ and energy E_μ are measured.

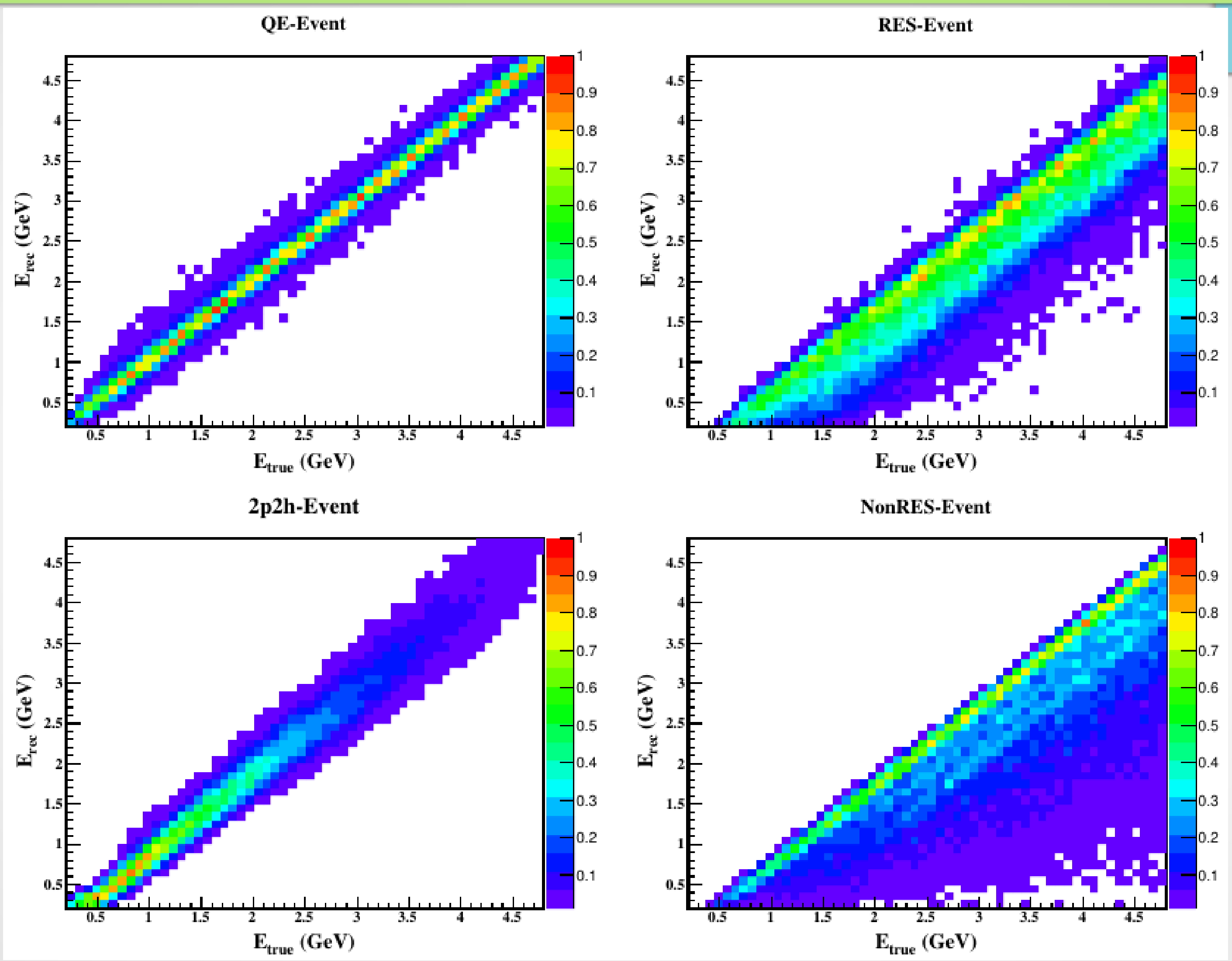
- The reconstructed (rec) neutrino energy is defined as -

$$E_\nu^{\text{rec}} = \frac{2(M_n - E_B)E_\mu - (E_B^2 - 2M_nE_B + m_\mu^2 + \Delta M^2)}{2\left[M_n - E_B - E_\mu + |\vec{k}_\mu| \cos\theta_\mu\right]}$$

- M_n is the mass of the neutron.
- $\Delta M^2 = M^2_n - M^2_p$
- E_B- Binding Energy
- $|k_\mu| = \sqrt{(E^2_\mu - m^2_\mu)}$
  absolute value of three momentum of outgoing muon.

- Ref. Neutrino energy reconstruction in quasi elastic-like scattering in the MiniBooNE and T2K experiments-O. Lalakulich, U. Mosel and K. Gallmeister-2012,arXiv:1208.3678v2.

Neutrino Energy Reconstruction



QE-Event

RES-Event

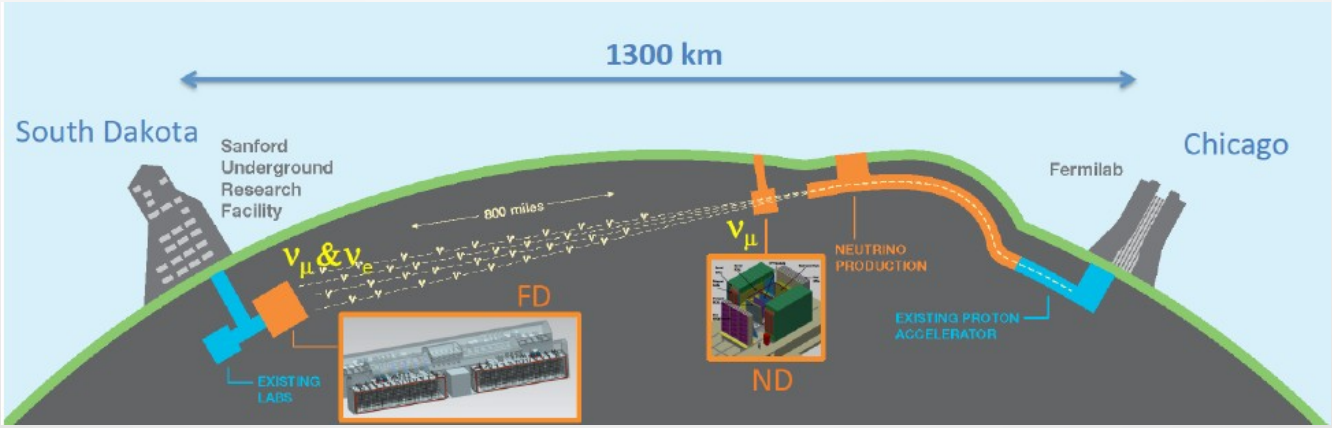
2p2h-Event

NonRES-Event

Fig. 3 Two-Dimensional Migration matrices for QE, RES, 2p-2h and Non-RES Events.

DUNE

- DUNE, will consist of two detectors- a near and a far detector.
- The Long-Baseline Neutrino Facility (LBNF) will provide the muon neutrino beam to both the near and the far detectors.
- The Far Detector(FD) will be placed at a distance of 1300 km to be built 1.5km underground at SURF, South Dakota.
- The near detector (ND) will be placed 600m away from the neutrino beamline.
- The FD will be composed of four gigantic 10kton LArTPC, using liquid argon as Target.



DUNE Flux

- For this work we have selected an optimized beam flux of 120 GeV.
- The DUNE-LBNF flux spreads in the energy range 0.5 to 10 GeV, having an average energy of 2.5 GeV.
- It is composed of QE, Resonance, DIS and Coherent neutrino-nucleon interaction processes each having a different energy dependent cross-section.

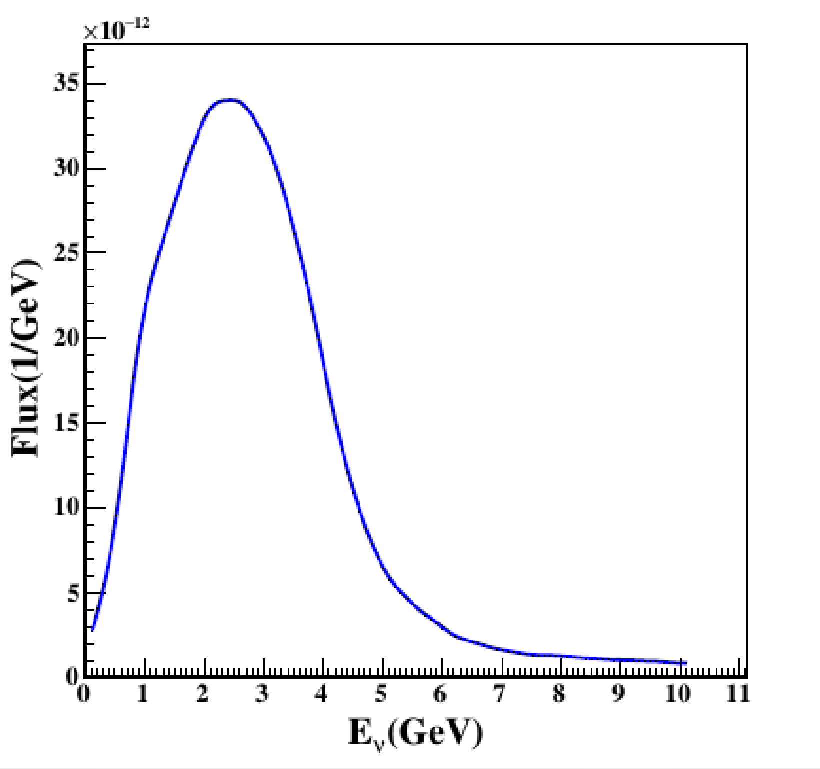


Fig. 1 DUNE-Flux Distribution in the energy range 0.5-10 GeV

Cross Section

- An understanding with sufficient accuracy of neutrino-nucleon cross section is essential for extraction of neutrino energy and neutrino oscillation parameters from the event rate.

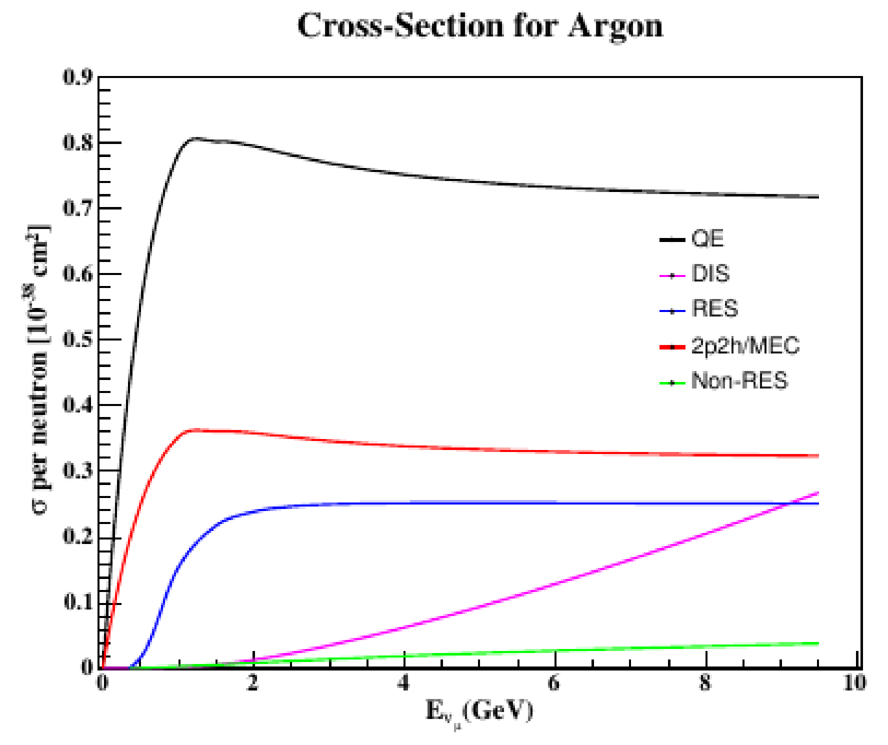


Fig. 2 Total cross-section per neutron as a function of true neutrino energy calculated for charged current processes for Argon target.

Parameter Inputs

- In this work we present the degenerate solution in the θ_{23} - δ_{CP} plane occurring due to nuclear effects.
- We have incorporated nuclear effects in our work by using migration matrices for QE and QE+RES+DIS events generated by GiBUU for roughly two lakh events using DUNE flux for muon disappearance channel.
- The true parameters opted for this work are-

  $\sin^2\theta_{12} = 0.306$, $\sin^2\theta_{13} = 0.085$, $\sin^2\theta_{23} = 0.5$, $\delta_{CP} = 180^0$,

  $\Delta^2 m_{21} = 7.50\text{x}10^{-5}$, $\Delta^2 m_{31} = 2.40\text{x}10^{-3}$.
- Running time considered here is (10+0) years.

Ref- Implications of the latest NOνA results- S. Goswami, N. Nath – 2017, arXiv:1705.01274v1

Preliminary Work with Quasi Elastic(QE+QE like) Events-

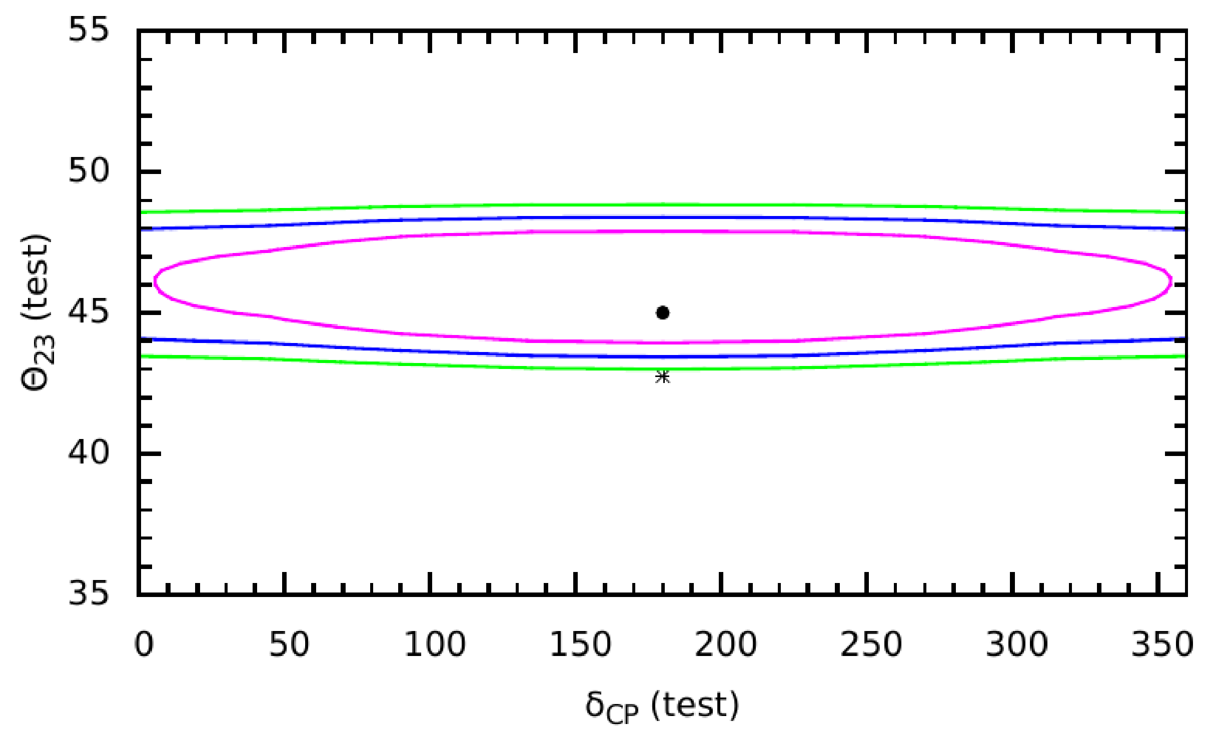


Fig. 4 Confidence regions in the (θ_{23} ,δ_{CP}) plane- obtained using the migration matrices of pure QE and QE like events.
The * point is the shift due to nuclear effects.

Preliminary Work with QE+RES+DIS Events-

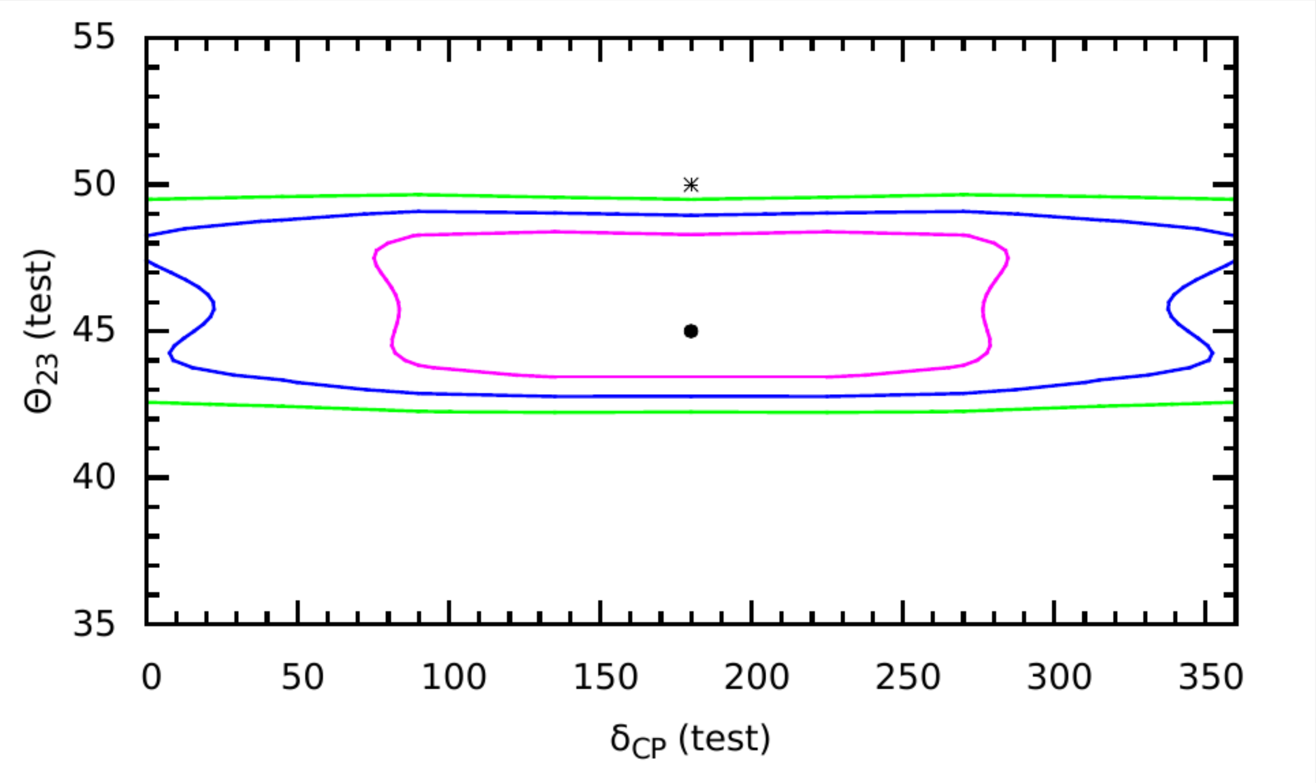


Fig. 5 Confidence regions in the (θ_{23} ,δ_{CP}) plane- obtained using the migration matrices of pure QE+RES+DIS and QE+RES+DIS like events.
The * point is the shift due to nuclear effects.

Conclusions-

- We present the position of the best fit corresponding to values

  of α taken as 0 and 1, by plugging them in this formula-

  $\mathbf{N_i^{test}\ (\alpha) = \alpha \times N_i^{QE} + (1 - \alpha) \times N_i^{QE\text{-}like}}$: N- Total number of events ----(1)

  1. When α = 1 (nuclear effects are completely disregarded)- without FSI

  2. When α = 0 (nuclear effect are perfectly known)- with FSI

  which is shown in Fig. 4
- We notice a 3σ shift in the best fit point value for Charged Current QE events.
- We notice a deviation of more than 3σ for QE, RES and DIS processes in Fig. 5.
- This work is in progress and we will report the results by considering different values of the parameter α as defined above.
- In an outlook of the study we can conclude that the best strategy for third generation neutrino-oscillation experiments seems to minimize detection thresholds of the employed detectors and to perform an extensive authentication of the accuracy of nuclear models employed in data analysis.

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Thank you!!