The Need for an Early Anti-neutrino Run in NOνA

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(Prakash, UR, Sankar, arXiv:1306.4125)

[http://www.sciencecartoonsplus.com/gallery/physics/galphys2h.php]

The Neutrino Mixing Parameters

- $|\nu_e\rangle$, $|\nu_\mu\rangle$, $|\nu_\tau\rangle$ are flavor states / interaction states
- $|\nu_i\rangle$s are the mass eigen states / propagation states, where i=1, 2, 3
- $|\nu_\alpha\rangle = U|\nu_i\rangle$
- $U = \begin{bmatrix} c_{13}c_{12} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - s_{13}c_{12}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{13}c_{23}s_{12}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$
- Oscillation probabilities depend on 3 mixing angles, two independent mass-squared differences $\Delta_{21} = m_2^2 - m_1^2$, $\Delta_{31} = m_3^2 - m_1^2$ and one CP violating phase δ.

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The Parameter Space Before Reactor Neutrino Results ($bfp \pm 1\sigma$)

- $\sin^2\theta_{12} = 0.30 \pm 0.013$
- $\sin^2\theta_{23} = 0.41^{+0.037}_{-0.025} \bigoplus 0.59^{+0.021}_{-0.022}$
- $\Delta_{21} = (7.50 \pm 0.185) \times 10^{-5} eV^2$
- $|\Delta_{31}| = (2.47^{+0.069}_{-0.067}) \times 10^{-3} eV^2$

[Table 1 of Gonzalez-Garcia, Maltoni, Salvado, Schwetz, arXiv:1209.3023]

- $\alpha = \frac{\Delta_{21}}{\Delta_{31}}$ and θ_{13} very small
- P_{ee} and $P_{\mu\mu}$ generally can be written in effective two-flavor form.
  $P_{\overline{ee}} = 1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta_{21}L}{4E}$ (KamLAND)
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$|\nu_\mu\rangle \longrightarrow |\nu_e\rangle$ Oscillation with Matter Effect in Long Baseline Experiments

- $$\begin{aligned} P_{\mu e} &= \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2 \hat{\Delta}(1-\hat{A})}{(1-\hat{A})^2} \\ &+ \alpha \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\hat{\Delta} + \delta_{CP}) \\ &\quad \frac{\sin \hat{\Delta}\hat{A}}{\hat{A}} \frac{\sin \hat{\Delta}(1-\hat{A})}{1-\hat{A}} \\ &+ \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{13} \cos^2\theta_{23} \frac{\sin^2 \hat{\Delta}\hat{A}}{\hat{A}^2} \end{aligned} \tag{0.1}$$

  [Cervera et al., arXiv: hep-ph/0002108]
- $\hat{\Delta} = \Delta_{31}L/4E$, $\hat{A} = A/\Delta_{31}$, $\alpha = \Delta_{21}/\Delta_{31}$, $A = 0.000076\rho E$ has energy dependence and hence can create matter effect.

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- Δ_{31} +ve for NH and -ve for IH
- A +ve for ν and -ve for $\bar{\nu}$
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Eight -fold Degeneracy

[Barger et al., arXiv: hep-ph/0112119]

- The (hierarchy-δ_{CP}) degeneracy:$P_{\mu e}(\theta_{13}, \mathrm{NH}, \delta_{CP})(\theta_{13}, \mathrm{NH}, \delta_{CP}) = P_{\mu e}(\theta_{13}, \mathrm{IH}, {\delta_{CP}}')$
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Recent Reactor Neutrino Experiments

- $\sin^2 2\theta_{13} = 0.089$
  [An et al., arXiv: 1203.1669; Ahn et al., arXiv: 1204.0626; Abe et al., arXiv: 1207.6632]
- $\sin^2 \theta_{13} = 0.023 \pm 0.0023$
  [Table 1 of Gonzalez-Garcia, Maltoni, Salvado, Schwetz, arXiv:1209.3023]
- Daya Bay will reduce the error in $\sin^2 2\theta_{13}$ from 10% to 5% at the end of its running.
  [Dwyer (Daya Bay collaboration), talk given at the Neutrino 2012 conference, June 3-9, 2012, Kyoto, japan, http://neu2012.kek.jp]
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- δ_{CP}, Sign of Δ_{31}, octant of θ_{23}
- Reactor experiments result on θ_{13} allows mass hierarchy to be determined by current experiment
  [An et al., arXiv: 1203.1669; Ahn et al., arXiv: 1204.0626; Abe et al., arXiv: 1207.6632]
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The Hierarchy-δ_{CP} Degeneracy

[Barger et al., arXiv: hep-ph/0112119; Mena, Parke, arXiv: hep-ph/040870]

- $$\begin{aligned} P_{\mu e} &= \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 \hat{\Delta}(1-\hat{A})}{(1-\hat{A})^2} \\ &+ \alpha \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\hat{\Delta}+\delta_{CP}) \\ &\frac{\sin \hat{\Delta}\hat{A}}{\hat{A}} \frac{\sin \hat{\Delta}(1-\hat{A})}{1-\hat{A}} \end{aligned} \qquad (0.3)$$

- $P_{\mu e}$ (NH) $> P_{\mu e}$ (IH), for ν: consequences of $\hat{A}$ dependence
- At oscillation maxima $\hat{\Delta} \simeq 90°$
- $\cos(\hat{\Delta}+\delta_{CP})$ is 1 for $\delta_{CP} = -90°$ and -1 for $\delta_{CP} = 90°$

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The Hierarchy-δ_{CP} Degeneracy in NOνA

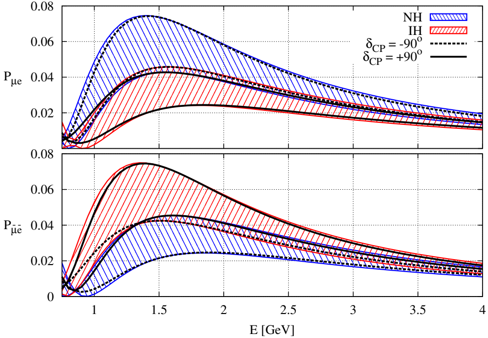

Figure: $P_{\mu e}$ (top panel) and $P_{\bar{\mu}\bar{e}}$ (bottom panel) vs. energy for NOνA. Variation of δ_{CP} leads to the blue (red) bands for NH (IH). The plots are drawn for maximal θ_{23} and other neutrino parameters given as the central value in slide 3.

[Prakash, Raut, Sankar, arXiv: 1201.6485v3]

- $P_{\mu e}(NH, -180^\circ < \delta_{CP} < 0) > P_{\mu e}(IH, \text{any } \delta_{CP})$
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- For these two cases NOνA can determine hierarchy if statistics is large enough.
- $P_{\mu e}(NH, 0 < \delta_{CP} < 180^\circ) \simeq P_{\mu e}(IH, -180^\circ < {\delta_{CP}}' < 0)$
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  DEGENERATE solutions- (true hierarchy, δ_{CP}) and (wrong hierarchy, ${\delta_{CP}}'$) for each measurement, no hierarchy determination

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- (NH, δ_{CP} in LHP) and (IH, δ_{CP} in UHP) are favorable combinations for hierarchy determination in NOνA.
- (NH, δ_{CP} in UHP) and (IH, δ_{CP} in LHP) are unfavorable combinations for hierarchy determination in NOνA.
- We have confined ourselves in the favorable combinations in this work [Prakash, Raut, Sankar, arXiv: 1201.6485v3]

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Potential for NOνA

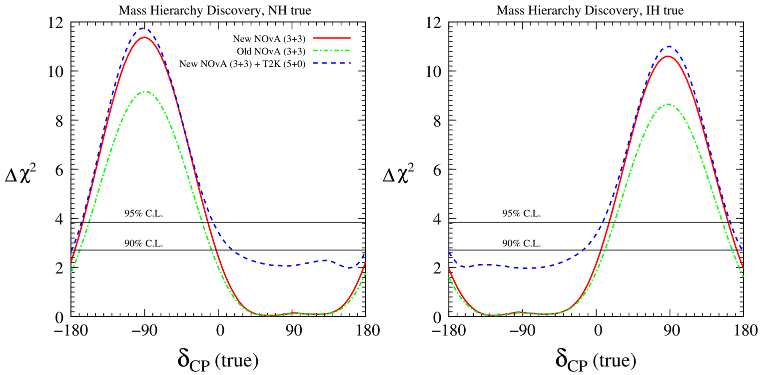

Figure: Hierarchy sensitivity for NOνA after complete run. In the left (right) panel, the true hierarchy is taken to be NH (IH).

[Agarwalla, Prakash, Raut, Sankar, arXiv: 1208.3644v2]

Aim of the Work

What can we learn in first 3 years of NOνA, if we have favorable hierarchy-δ_{CP} combinations as true combinations?
Consider two possibilities.

- 3 year of ν run
- 1.5 year ν run + 1.5 year $\bar{\nu}$ run

WHY?

Originally first 3 year ν run was considered to discover non-zero θ_{13}, in case it was small. But now $\theta_{13} \simeq 8^\circ$, other possibilities can be considered.

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Simulations

NOνA Experiment

[Ayres et al., NOνA, Tech. Rep. (2007), Fermilab-Design-2007-01]

- 14 kiloton TASD
- 810 km away from Fermilab
- Detector locaton: $0.8°$ off axis from the NuMI beam
- ν flux peaks sharply at 2 GeV, oscillation maximum energy 1.5 GeV
- Equal ν and $\bar{\nu}$ run of 3 years each
- NuMI beam power 700 kW, corresponding to 6×10^{20} protons on target per year
- We have used retuned signal acceptance and background factor [Agarwalla, Prakash, Raut, Sankar, arXiv: 1208.3644]

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- $\sin^2\theta_{12} = 0.30$, $\Delta_{21} = 7.5 \times 10^{-5}\ eV^2 \longrightarrow$ kept fixed
- $\sin^2 2\theta_{13} = 0.089$, $\sigma(\sin^2 2\theta_{13}) = 10\%$, in preliminary calculations, 5% in later calculations, marginalization done over 2σ range.
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Simulations

- For maximal mixing, $\sin^2\theta_{23} = 0.5$
- For non-maximal mixing, $\sin^2\theta_{23} = 0.41$ for θ_{23} in lower octant and $\sin^2\theta_{23} = 0.59$ for θ_{23} in higher octant
- Marginalization range of $\sin^2\theta_{23}$ is [0.35, 0.65]- 3 σ range of global fit
- Marginalization of δ_{CP} is full range- $[-180°, 180°]$

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- For non-maximal mixing, $\sin^2\theta_{23} = 0.41$ for θ_{23} in lower octant and $\sin^2\theta_{23} = 0.59$ for θ_{23} in higher octant
- Marginalization range of $\sin^2\theta_{23}$ is [0.35, 0.65]- 3 σ range of global fit
- Marginalization of δ_{CP} is full range- $[-180°, 180°]$

Simulations

Event number simulations and the $\Delta\chi^2$ calculations are done by using GLoBES
[Huber et al., arXiv: hep-ph/0407333, Huber et al., arXiv: hep-ph/0701187]
Minimum $\Delta\chi^2$ is calculated by doing a marginalization over the above mentioned parameters.

Effect of Precision of $\sin^2 2\theta_{13}$

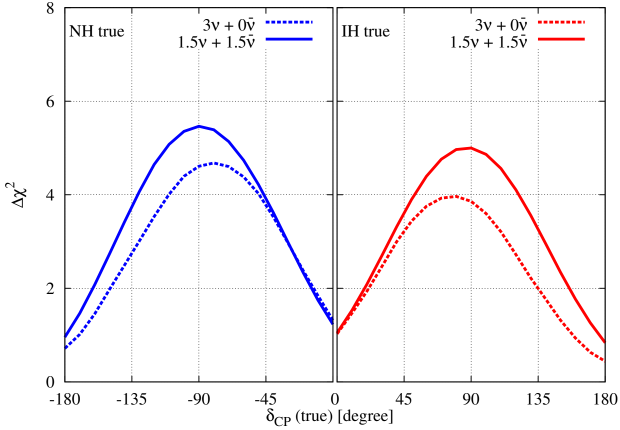

Figure: Hierarchy sensitivity assuming 10% uncertainty in $\sin^2 2\theta_{13}$ and maximal θ_{23}. In the left (right) panel, the true hierarchy is taken to be NH (IH).

Effect of Precision of $\sin^2 2\theta_{13}$

10% uncertainty in $\sin^2 2\theta_{13}$

- 2 σ hierarchy determination is possible in 1.5 year ν run + 1.5 year $\bar{\nu}$ for about 50% of the favorable half plane.
- 2 σ hierarchy determination is possible over a very small range (no δ_{CP}) if NH,LHP (IH,UHP) is true in 3ν run

WHY?

- The lower sensitivity of 3ν run is due to hierarchy-$\sin^2 2\theta_{13}$ degeneracy.
- If the value of $\sin^2 2\theta_{13}$ is not precisely known it is possible to fake the probability value with a wrong hierarchy and with a wrong $\sin^2 2\theta_{13}$.
- This wrong value of $\sin^2 2\theta_{13}$ is different for ν and $\bar{\nu}$.
- Because hierarchy affects ν and $\bar{\nu}$ in different ways but changing $\sin^2 2\theta_{13}$ in same way.

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- Pure ν is sensitive to this degeneracy but a combination of ν and $\bar{\nu}$ not.
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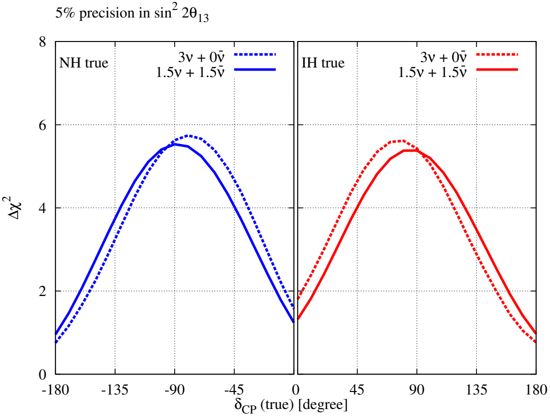
Effect of Precision of $\sin^2 2\theta_{13}$

If the uncertainty in $\sin^2 2\theta_{13}$ is reduced to 5%, the hierarchy reach for 3ν does improve and becomes equal to that of $1.5\nu + 1.5\bar{\nu}$ run.



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Non-maximal θ_{23}

- Recent hint of non-maximal θ_{23}
  [Nichol, talk given at the Neutrino 2012 conference, June 3-9, 2012, Kyoto, japan, http://neu2012.kek.jp]
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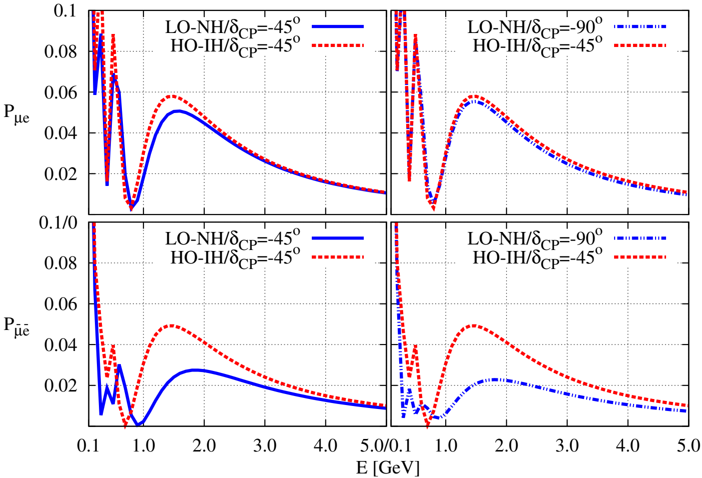

Figure: Illustration of degenerate $P_{\mu e}$ and non-degenerate $P_{\bar{\mu}\bar{e}}$ for the following two cases. Left: (LO-NH, $\delta_{CP} = -45°$) and (HO-IH, $\delta_{CP}' = -45°$), Right: (LO-NH, $\delta_{CP} = -90°$) and (HO-IH, $\delta_{CP}' = -45°$).

Non-maximal θ_{23}

- Dominant term in $P_{\mu e}$ proportional to $\sin^2 2\theta_{13} \sin^2 \theta_{23}$
- Matter effect in NH makes it larger and HO makes it even larger.
- $P_{\mu e}$(HO-NH, δ_{CP} in LHP) $>>$ $P_{\mu e}$(IH) , for any values of neutrino parameters $\Rightarrow$ statistics for HO-NH will be quite large.
- Similarly, $P_{\mu e}$(LO-IH, δ_{CP} in UHP) $<<$ $P_{\mu e}$(NH)
- NO degeneracy for HO-NH and LO-IH

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Non-maximal θ_{23}

- For LO-NH, LO decreases $P_{\mu e}$, NH increases it.
- For HO-IH, HO increases $P_{\mu e}$, IH lowers it.
- Marginalization over θ_{23} an$\delta_{CP} \Rightarrow P_{\mu e}$(LO-NH,$\delta_{CP}$) $\simeq P_{\mu e}$(HO-IH,$\delta_{CP}{}'$), δ_{CP} and $\delta_{CP}{}'$ may or may not be equal
- For $\bar{\nu}$, both LO and NH decreases $P_{\bar{\mu}\bar{e}}$
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ν and $\bar{\nu}$ data have different dependence on hierarchy-octant degeneracy $\Rightarrow$ a combination of both will help to solve this degeneracy in case of LO-NH and HO-IH.

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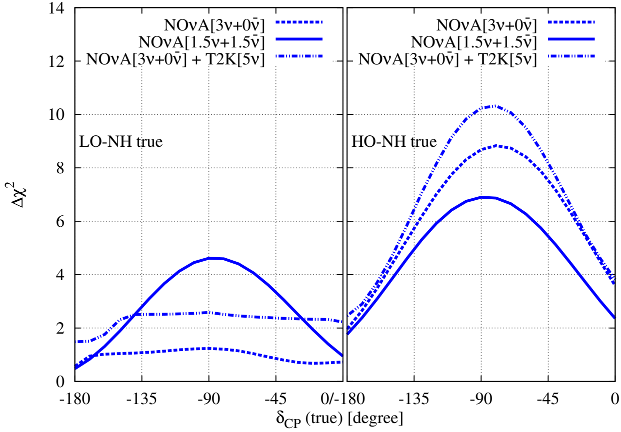

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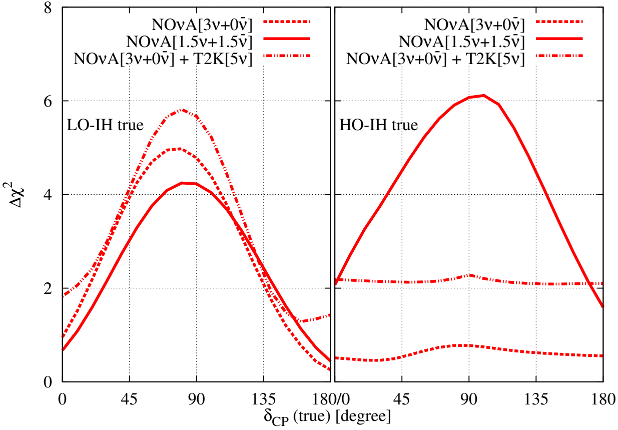

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Non-maximal θ_{23}

- HO-NH combination has a 2σ hierarchy discrimination for 80% (70%) of the favorable half plane for 3ν ($1.5\nu + 1.5\bar{\nu}$)
- LO-IH combination has a 2σ hierarchy discrimination for 40% (20%) of the favorable half plane for 3ν ($1.5\nu + 1.5\bar{\nu}$)
- For HO-NH and LO-IH$1.5\nu + 1.5\bar{\nu}$ is slightly worse than 3ν.
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Conclusions

- $1.5\nu + 1.5\bar{\nu}$ has far better hierarchy sensitivity than 3ν, if $\sigma(\sin^2 2\theta_{13}) = 10\%$, if δ_{CP} is in favorable half plane, 3ν run fails to give any hierarchy discrimanation.
- After Daya Bay reduces $\sigma(\sin^2 2\theta_{13})$ to 5%, $1.5\nu + 1.5\bar{\nu}$ has 2σ hierarchy sensitivity in all possible hierarchy-octant combinations for a satisfying range of δ_{CP} in favorable half plane, where as 3ν has no sensitivity at all for LO-NH and HO-IH
- Addition of T2K data does not help much, because we are confined in favorable region.
- It is imperative for NOνA to plan on early $\bar{\nu}$ run to get a quick hint of hierarchy.

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"Quarks. Neutrinos. Mesons. All those damn particles you can't see. That's what drove me to drink. But now I can see them!"

[http://www.sciencecartoonsplus.com/gallery/physics/galphys2b.php]

THANK YOU

Re-optimizing NOνA

- Relaxed energy cut allowing more signal events $\Rightarrow$ more backgrounds as well
- Signal efficiencies in new NOνA (45% for both neutrino and anti-neutrino) is 2 times the old one (26% for neutrino and 40% for anti-neutrino) for neutrino
- NC background $\Rightarrow$ about 7 times (2% vs 0.3%) for ν and 3 times (3% vs 0.9%) for $\overline{\nu}$ than the old one.
- Misidentified muons $\Rightarrow$ 6 time (0.83% vs 0.13%) for ν and 2 times (0.22% vs 0.13%) than the old one
- Earlier the number of NC background events were moderate. For that case assuming a Gaussian energy resolution function to smear the background events was a good approximation. But at present the NC backgrounds are higher by a factor 5. But their measured energy range in is much below the range of large flux. The NC spectrum shift to measured energies is implemented through migration matrices.

- We have considered the neutrino contamination in the anti-neutrino beam in both appearance and disappearance channels. While the anti- neutrino contamination in the neutrino beam can be ignored, the reverse is not true.
- The above optimization criteria was developed in the case of $\nu_\mu \longrightarrow \nu_e$ vacuum oscillation with $\delta_{cp} = 0$ and maximizing signal events while keeping the background events relatively small.