NO\nu\Lambda A Far Detector $\nu_e$ Sideband Study Technical Note

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Abstract

Till now the NO\nu\Lambda A experiment has used the Far Detector (FD) electron neutrino (antineutrino) events in the energy range $1 < E_\nu < 4$ GeV in 3-flavor neutrino oscillation analysis, to constraint the neutrino oscillation parameters. In this study, we have used the high-energy neutrino (sideband) sample with $4 < E_\nu < 12$ GeV, dominated heavily by the beam electron neutrino/anti-neutrino background events to constrain the neutrino oscillation parameters. This was done to figure out if an additional power can be obtained in constraining the oscillation parameters by adding this sample to the analysis. This technote discusses the modifications done in the existing framework to add the sideband sample to the standard FD $\nu_e$ predictions and its impact on the neutrino oscillation parameters sensitivity of the NO\nu\Lambda A experiment. Results from the statistics only study and the study including all the existing systematic shifts are reported separately.

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1 Introduction

Traditionally, we have been using neutrino events in the energy range $1 < E_\nu < 4$ GeV, measured in the Far Detector (FD), for 3-flavor neutrino oscillation analyses. This is done because the high energy neutrino event sample is heavily dominated by the beam electron neutrino component\cite{1}. In this study, we have added high-energy $\nu_e$ ($\bar{\nu}_e$) events with $4 < E_\nu < 12$ GeV in our analysis, primarily to see if an additional power can be obtained to constrain the neutrino oscillation parameters. Section 2 of this technote shows a few of the sideband plots made with events in the range $4 < E_\nu < 12$ GeV. We have added high energy $\nu_e$ ($\bar{\nu}_e$) events to the standard FD $\nu_e$ ($\bar{\nu}_e$) predictions modifying the existing framework and then used these new predictions, instead of the standard 3-flavor predictions, to find the constraints on the neutrino oscillation parameters. The relevant technical information e.g. the changes made in the framework, MC file definitions, etc. of the study are discussed in section 3 of this technote. The statistics only study and the study with existing systematic shifts were done separately. The new FD statistics only predictions and sensitivities, including the sideband sample, are shown in section 4 and section 5 of this technote respectively. Finally, sections 6 and 7 show FD predictions and sensitivities including existing systematic shifts, respectively. The key takeaways of this study are concluded in section 8 of this technote.

2 Sideband Plots

The sideband plots are the FD $\nu_e$ event spectra outside the signal region\footnote{The signal region energy range is $1 < E_\nu < 4$ GeV} i.e. $E_\nu > 4.0$ GeV. This sample was one of the cross-checks used to ensure the data quality in the 2020 analysis \cite{1}. The idea was to compare the data and the MC events in a region outside the signal region to gain more confidence in the analysis and perhaps to constrain the neutrino oscillation parameters better. We wished to include the “core high energy (CoreHE)” sample in the standard 3-flavor predictions for our study and decided to look at this sample first. This part of our study is based on the analysis presented in ref \cite{2}, with one major change in the energy range of the neutrino events. Previously, the cut selected all neutrino events with $E_\nu > 4.5$ GeV. The cut has been modified to include neutrino events in the energy range $4.0 < E_\nu < 12.0$ GeV \cite{3}, shown in table 1. In total, 26 variables have been selected to generate the sideband plots. A brief description of each variable is given in table 2.
<table>
<thead>
<tr>
<th>Cut</th>
<th>$E_\nu$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old</td>
<td>&gt; 4.5</td>
</tr>
<tr>
<td>New</td>
<td>&gt; 4.0</td>
</tr>
</tbody>
</table>

Table 1: Neutrino energy selection cuts.

A few sideband plots for the neutrino and anti-neutrino beams, respectively, are shown in Figures 1 and 2 respectively. It is important to note that the beam electron neutrino (anti-neutrino) component of the background dominates this sideband sample, which may be helpful in limiting this specific background component.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Variable Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>kShwDirX</td>
<td>X projection of the primary shower at the starting point</td>
</tr>
<tr>
<td>2</td>
<td>kShwDirY</td>
<td>Y projection of the primary shower at the starting point</td>
</tr>
<tr>
<td>3</td>
<td>kShwDirZ</td>
<td>Z projection of the primary shower at the starting point</td>
</tr>
<tr>
<td>4</td>
<td>kShwCosNumi</td>
<td>Projection of the primary shower along the NuMI beam direction</td>
</tr>
<tr>
<td>5</td>
<td>en</td>
<td>Reconstructed Neutrino Energy</td>
</tr>
<tr>
<td>6</td>
<td>en_custom</td>
<td>Reconstructed Neutrino Energy in customised binning scheme</td>
</tr>
<tr>
<td>7</td>
<td>id_cvne</td>
<td>CVN Classifier</td>
</tr>
<tr>
<td>8</td>
<td>cosmic_core_bdt</td>
<td>Cosmic rejection criteria for Core sample</td>
</tr>
<tr>
<td>9</td>
<td>cosmic_peri_bdt</td>
<td>Cosmic rejection criteria for Peripheral sample</td>
</tr>
<tr>
<td>10</td>
<td>shw_e</td>
<td>Primary shower calorimetric energy (based on summed calibrated deposited charge)</td>
</tr>
<tr>
<td>11</td>
<td>vtx_x</td>
<td>X position of the vertex in detector (cm)</td>
</tr>
<tr>
<td>12</td>
<td>vtx_y</td>
<td>Y position of the vertex in detector (cm)</td>
</tr>
<tr>
<td>13</td>
<td>vtx_z</td>
<td>Z position of the vertex in detector (cm)</td>
</tr>
<tr>
<td>14</td>
<td>inelast</td>
<td>Reconstructed inelasticity</td>
</tr>
<tr>
<td>15</td>
<td>had_e_2020</td>
<td>Total CalE of hadronic showers</td>
</tr>
<tr>
<td>16</td>
<td>shw_e_2020</td>
<td>Total CalE of the EM showers</td>
</tr>
<tr>
<td>17</td>
<td>distAllFront</td>
<td>Minimum distance of all prongs to the front of detector</td>
</tr>
<tr>
<td>18</td>
<td>distAllBack</td>
<td>Minimum distance of all prongs to the back of detector</td>
</tr>
<tr>
<td>19</td>
<td>distAllTop</td>
<td>Minimum distance of all prongs to the top of detector</td>
</tr>
<tr>
<td>20</td>
<td>distAllBottom</td>
<td>Minimum distance of all prongs to the bottom of detector</td>
</tr>
<tr>
<td>21</td>
<td>distAllEast</td>
<td>Minimum distance of all prongs to the East of detector</td>
</tr>
<tr>
<td>22</td>
<td>distAllWest</td>
<td>Minimum distance of all prongs to the West of detector</td>
</tr>
<tr>
<td>23</td>
<td>shwMaxY</td>
<td>Maximum Y of all start and stop points</td>
</tr>
<tr>
<td>24</td>
<td>sparsnessAsym</td>
<td>Sparsness asymmetry</td>
</tr>
<tr>
<td>25</td>
<td>shwPtp</td>
<td>Event transverse momentum fraction</td>
</tr>
<tr>
<td>26</td>
<td>id_cvn-zoom</td>
<td>Output from CVN- Loose Presel Plus Ptp cut</td>
</tr>
</tbody>
</table>

Table 2: A brief description of the variables used in generating the sideband plots.
Figure 1: Sideband plots for the neutrino beam.
Figure 2: Sideband plots for the anti-neutrino beam.
3 Technical Information

3.1 Workflow

The sideband sample was included in the standard 3-flavor FD predictions with the help of a newly defined HistAxis kNue2020AxisIncludingSideband that adds the sample between the High PID and the Peripheral bins [4]. The Pt-extrapolated [5] FD $\nu_e$ predictions were generated using the existing macro\(^2\) with the following changes:

- HistAxis kNue2020AxisIncludingSideband was used instead of the standard HistAxis kNue2020Axis
- A new $\nu_e$ selection cut, kNue2020FDAllSamplesNew, was used
- Only the Nominal systematic shift was used to generate the statistics only predictions

The cosmic background [6] and rock events were also redistributed according to the new axis before merging them into the FD $\nu_e$ predictions. Finally, some new methods were defined in the PredictionExtendToPeripheral class to incorporate the new axis while copying over the decomposition weights from the high PID bins to the peripheral bins [7]. All the existing 2020 analysis systematic shifts were used in this study.

3.2 Concat File Definitions

The $\nu_e$ concat file definitions used in generating the FD predictions including the sideband sample are the same as 2020 analysis file definitions [8].

3.2.1 Far Detector Monte Carlo (MC) - Nominal

- Forward Horn Current (FHC)
  - prod_sumdecaf_R19-11-18-prod5reco.f_fd_genie_N1810j0211a_nonswap_fhc_nova_v08_full_v1_nue2020
  - prod_sumdecaf_R19-11-18-prod5reco.f_fd_genie_N1810j0211a_fluxswap_fhc_nova_v08_full_v1_nue2020
  - prod_sumdecaf_R19-11-18-prod5reco.f_fd_genie_N1810j0211a_tau_fhc_nova_v08_full_v1_nue2020

\(^2\)https://cdcvs.fnal.gov/redmine/projects/novaart/wiki/Reproducing_the_2020_joint_analysis
• Reverse Horn Current (RHC)
  - prod_sumdecaf_R19-11-18-prod5reco.f_fd_genie_N1810j0211a_nonswap_rhc_nova_v08_full_v1_nue2020
  - prod_sumdecaf_R19-11-18-prod5reco.f_fd_genie_N1810j0211a_fluxswap_rhc_nova_v08_full_v1_nue2020
  - prod_sumdecaf_R19-11-18-prod5reco.f_fd_genie_N1810j0211a_tau_rhc_nova_v08_full_v1_nue2020

3.2.2 Near Detector Monte Carlo - Nominal
• Forward Horn Current (FHC)
  - prod_sumdecaf_R19-11-18-prod5reco.d.h.l_nd_genie_N1810j0211a_nonswap_fhc_nova_v08_full_v1_nue2020
  - prod_sumdecaf_R19-11-18-prod5reco.d.h.l_nd_genie_N1810j0211a_nonswap_fhc_nova_v08_full_v1_numu2020
• Reverse Horn Current (RHC)
  - prod_sumdecaf_R19-11-18-prod5reco.d_nd_genie_N1810j0211a_nonswap_rhc_nova_v08_full_v1_nue2020
  - prod_sumdecaf_R19-11-18-prod5reco.d_nd_genie_N1810j0211a_nonswap_rhc_nova_v08_full_v1_numu2020

3.2.3 Far Detector Monte Carlo - Rock
• Forward Horn Current (FHC)
  - prod_sumdecaf_R19-11-18-prod5reco.o_fd_genie_N1810j0211a_nonswap_fhc_nova_v08_full_v1_nue2020
  - prod_sumdecaf_R19-11-18-prod5reco.o_fd_genie_N1810j0211a_fluxswap_fhc_nova_v08_full_v1_nue2020
• Reverse Horn Current (RHC)
  - prod_sumdecaf_R19-11-18-prod5reco.o_fd_genie_N1810j0211a_nonswap_rhc_nova_v08_full_v1_nue2020
  - prod_sumdecaf_R19-11-18-prod5reco.o_fd_genie_N1810j0211a_fluxswap_rhc_nova_v08_full_v1_nue2020
4 Far Detector Statistics Only $\nu_e$ Predictions

Figure 3 and 4 respectively shows the comparison of the new FD predictions including the sideband sample and the standard 3-flavor predictions, at the 2020 best fit values [9], given in table 3, for the neutrino and the anti-neutrino beam. The predictions on the left are the new predictions including the sideband sample whereas the predictions on the right are the standard 3-flavor predictions. The event counts corresponding to the new predictions including the sideband sample are compared to the event counts of the standard 3-flavor predictions for the neutrino beam and the anti-neutrino beam and is given in table 4 and 5 respectively. It can be observed clearly that the new event counts are in a good agreement with the standard 3-flavor event counts for almost all of the PID bins, except that some minor differences in the event counts still exist for the Peripheral PID bin, but these differences won’t affect the sensitivities much and hence can be ignored.

<table>
<thead>
<tr>
<th>$\sin^2 \theta_{23}$</th>
<th>$\Delta m^2_{32}$ (eV$^2$)</th>
<th>$\delta$ ($\pi$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.568</td>
<td>$2.41 \times 10^{-3}$</td>
<td>0.82</td>
</tr>
</tbody>
</table>

Table 3: The 2020 best fit values of the oscillation parameters [9].

![Figure 3: A comparison of the new FD statistics only predictions including the sideband sample (on the left) and the standard statistics only 3-flavor predictions (on the right) for the neutrino beam.]

(a) Including Sideband  

(b) Standard 3-Flavor
<table>
<thead>
<tr>
<th>Sample</th>
<th>Low PID</th>
<th>High PID</th>
<th>Peripheral</th>
<th>Sideband</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New</td>
<td>Old</td>
<td>New</td>
<td>Old</td>
<td></td>
</tr>
<tr>
<td>Signal</td>
<td>10.06</td>
<td>10.06</td>
<td>41.55</td>
<td>41.55</td>
<td>60.23</td>
</tr>
<tr>
<td>Beam Nue</td>
<td>2.33</td>
<td>2.33</td>
<td>7.72</td>
<td>7.72</td>
<td>13.24</td>
</tr>
<tr>
<td>WS</td>
<td>0.19</td>
<td>0.19</td>
<td>0.66</td>
<td>0.66</td>
<td>1.08</td>
</tr>
<tr>
<td>NC</td>
<td>3.74</td>
<td>3.75</td>
<td>1.03</td>
<td>1.03</td>
<td>6.05</td>
</tr>
<tr>
<td>Numu</td>
<td>0.71</td>
<td>0.71</td>
<td>0.21</td>
<td>0.21</td>
<td>1.39</td>
</tr>
<tr>
<td>Nutau</td>
<td>0.17</td>
<td>0.17</td>
<td>0.29</td>
<td>0.29</td>
<td>0.37</td>
</tr>
<tr>
<td>Cosmics</td>
<td>1.28</td>
<td>1.28</td>
<td>0.21</td>
<td>0.21</td>
<td>3.22</td>
</tr>
</tbody>
</table>

Table 4: Bin-wise PID comparison of the event counts corresponding to the new statistics only predictions including the sideband sample and the standard 3-flavor predictions for the neutrino beam.

Figure 4: A comparison of the new FD predictions including the sideband sample (on the left) and the standard 3-flavor predictions (on the right) for the anti-neutrino beam.

5 Statistics Only $\Delta \chi^2$ Surfaces and Sensitivities

The statistics only sensitivities are produced using new statistics only FD $\nu_e$ predictions including the sideband sample and the fake FD data generated at the 2020 best fit oscillation parameter values. The 2020 best fit values are given in table 3. The FD $\nu_\mu$ predictions were left untouched. The 2020 analysis $\nu_\mu$ predictions were used for generating the sensitivities. The philosophy behind generating the sensitivities remains the same. More details on the procedure to generate the sensitivities are available in ref [10]. The new sensitivities, includ-
Table 5: Bin-wise PID comparison of the event counts corresponding to the new statistics only predictions including the sideband sample and the standard 3-flavor predictions for the anti-neutrino beam.

The ∆χ² surfaces and the overlay sensitivities are shown in the upcoming sections of this tech-note. Please note that the surfaces and the sensitivities correspond to joint FHC and RHC analysis i.e. ν_e/ν̄_e appearance and ν_µ/ν̄_µ survival combined analysis.

5.1 ∆χ² Surfaces

The ∆χ² surfaces generated using the FD predictions including sideband are compared to the standard 3-flavor ∆χ² surfaces in this section of the tech-note. The ∆χ² surfaces for ∆m²_{32} vs sin²θ_{23} surfaces are compared in figs. 5 and 6 for normal and inverted hierarchy respectively. The sin²θ_{23} vs δ joint ∆χ² are compared in figs. 7 and 8 respectively for the normal and inverted hierarchy. It can been seen clearly that the ∆χ² surfaces including the sideband sample don’t differ much from the standard 3-flavor ∆χ² surfaces for both the normal hierarchy (NH) and the inverted hierarchy (IH).

---

3These sensitivities were also generated at the 2020 best fit values instead of the 2019 best fit values for a one to one comparison of the sensitivities.
Figure 5: $\Delta m_{32}^2$ vs $\sin^2 \theta_{23}$ statistics only $\Delta \chi^2$ surfaces for Normal Hierarchy.

Figure 6: $\Delta m_{32}^2$ vs $\sin^2 \theta_{23}$ statistics only $\Delta \chi^2$ surfaces for Inverted Hierarchy.
Figure 7: $\sin^2 \theta_{23}$ vs $\delta$ statistics only $\Delta \chi^2$ surfaces for Normal Hierarchy.

Figure 8: $\sin^2 \theta_{23}$ vs $\delta$ statistics only $\Delta \chi^2$ surfaces for Inverted Hierarchy.

5.2 Sensitivities

5.2.1 $\nu_e$ Only Sensitivities

Overlay of $\nu_e$ only $\Delta m^2_{32}$ vs $\sin^2 \theta_{23}$ and $\sin^2 \theta_{23}$ vs $\delta$ sensitivities for both mass hierarchies are shown in figs. 9 and 10. The colored sensitivities are the new sensitivities including the sideband sample whereas the gray ones are the standard 3-flavor sensitivities. The new sensitivities including the sideband sample overlap exactly with the standard 3-flavor sensitivities signifying that there are no major changes in the neutrino oscillation parameter constraints after including the sideband sample.
Figure 9: Overlay of $\nu_e$ only $\Delta m^2_{32}$ vs $\sin^2 \theta_{23}$ sensitivities for both mass hierarchies. The colored sensitivities are the new sensitivities including the sideband sample whereas the gray ones are the standard 3-flavor sensitivities.

Figure 10: Overlay of $\nu_e$ only $\sin^2 \theta_{23}$ vs $\delta$ sensitivities for both mass hierarchies. The colored sensitivities are the new sensitivities including the sideband sample whereas the gray ones are the standard 3-flavor sensitivities.

5.2.2 Joint Sensitivities

Overlay of statistics only $\Delta m^2_{32}$ vs $\sin^2 \theta_{23}$ and $\sin^2 \theta_{23}$ vs $\delta$ sensitivities for both mass hierarchies are shown in figs. 11 and 12 respectively. The colored sensitivities are the new sensitivities including the sideband sample whereas the gray ones are the standard 3-flavor sensitivities. The new sensitivities with sideband sample overlap exactly with the standard 3-flavor sensitivities signifying that there are no major changes in the neutrino oscillation parameters by including the sideband sample.
Figure 11: Overlay of statistics only $\Delta m^2_{32}$ vs $\sin^2 \theta_{23}$ sensitivities for both mass hierarchies. The colored sensitivities are the new sensitivities with sideband sample whereas the gray ones are the standard 3-flavor sensitivities.

Figure 12: Overlay of statistics only $\sin^2 \theta_{23}$ vs $\delta$ sensitivities for both mass hierarchies. The colored sensitivities are the new sensitivities with sideband sample whereas the gray ones are the standard 3-flavor sensitivities.

6 Far Detector $\nu_e$ Predictions with Systematics

Figures 13 and 14 shows comparison of new FD predictions, including the sideband sample and existing systematic shifts, with the standard 3-flavor predictions, at the 2020 best fit values, for the neutrino and the anti-neutrino beam respectively. The predictions on the left are the new predictions including the sideband sample whereas the predictions on the right are the standard 3-flavor predictions. The event counts corresponding to the new predictions including the sideband sample are compared to the event counts of the standard 3-flavor predictions.
predictions for the neutrino beam and anti-neutrino beams in table 6 and 7 respectively. It can be observed clearly that the new event counts are in a good agreement with the standard 3-flavor event counts for almost all of the PID bins, except for some minor differences in the event counts for the Peripheral PID bin, but these differences won’t affect the sensitivities much and hence can be ignored.

Figure 13: A comparison of new FD predictions using all existing systematics including the sideband sample (on the left) and the standard 3-flavor predictions (on the right) for the neutrino beam.

Figure 14: A comparison of new FD predictions using all existing systematics including the sideband sample (on the left) and the standard 3-flavor predictions (on the right) for the anti-neutrino beam.
### FHC

<table>
<thead>
<tr>
<th>Sample</th>
<th>Low PID</th>
<th>High PID</th>
<th>Peripheral</th>
<th>Sideband</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New</td>
<td>Old</td>
<td>New</td>
<td>Old</td>
<td>New</td>
</tr>
<tr>
<td>Signal</td>
<td>10.23</td>
<td>10.23</td>
<td>40.72</td>
<td>40.72</td>
<td>8.30</td>
</tr>
<tr>
<td>Beam Nue</td>
<td>2.35</td>
<td>2.35</td>
<td>7.86</td>
<td>7.86</td>
<td>3.70</td>
</tr>
<tr>
<td>WS</td>
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<td>0.63</td>
<td>0.63</td>
<td>0.19</td>
</tr>
<tr>
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<td>1.18</td>
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<td>0.81</td>
<td>0.27</td>
<td>0.27</td>
<td>0.28</td>
</tr>
<tr>
<td>Nutau</td>
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<td>0.16</td>
<td>0.26</td>
<td>0.26</td>
<td>0.10</td>
</tr>
<tr>
<td>Cosmics</td>
<td>1.28</td>
<td>1.28</td>
<td>0.21</td>
<td>0.21</td>
<td>1.64</td>
</tr>
</tbody>
</table>

Table 6: Bin-wise PID comparison of event counts corresponding to the new FD predictions including the sideband sample and the standard 3-flavor predictions for the neutrino beam using existing systematics.

### RHC

<table>
<thead>
<tr>
<th>Sample</th>
<th>Low PID</th>
<th>High PID</th>
<th>Peripheral</th>
<th>Sideband</th>
<th>Total</th>
</tr>
</thead>
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<td></td>
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<td>Old</td>
<td>New</td>
<td>Old</td>
<td>New</td>
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<td>2.30</td>
<td>14.66</td>
<td>14.66</td>
<td>2.92</td>
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<tr>
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<td>1.05</td>
<td>3.67</td>
<td>3.67</td>
<td>1.87</td>
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<tr>
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<td>1.47</td>
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<tr>
<td>NC</td>
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<td>1.47</td>
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</tr>
<tr>
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<td>0.05</td>
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<td>0.43</td>
<td>0.14</td>
<td>0.14</td>
<td>0.98</td>
</tr>
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</table>

Table 7: Bin-wise PID comparison of event counts corresponding to the new FD predictions including the sideband sample and the standard 3-flavor predictions for the anti-neutrino beam using existing systematics.

## 7 Sensitivities with Systematics Included

Overlay of joint $\Delta m_{32}^2$ vs $\sin^2 \theta_{23}$ and $\sin^2 \theta_{23}$ vs $\delta$ sensitivities including all existing systematic shifts for both mass hierarchies are shown in figure 15. The colored sensitivities are the new sensitivities including the sideband sample whereas the gray ones are the standard 3-flavor sensitivities. The new sensitivities and best fit values including the sideband sample overlap exactly with the standard 3-flavor sensitivities and best fit values as was the case for the
statistics only study. In essence, there is almost no improvement in the neutrino oscillation parameters due to sideband sample even after including all existing sensitivities.

![Figure 15: Overlay of $\Delta m^2_{32}$ vs $\sin^2 \theta_{23}$, NH and $\sin^2 \theta_{23}$ vs $\delta$, NH](image)

8 Conclusions

We have successfully added the sideband (high energy neutrino/anti-neutrino) events in our standard FD predictions by making suitable changes in the existing CAFAna framework. The gain in signal events, after adding the sideband events, is minimal. Most of the sideband events contribute to beam $\nu_e/\bar{\nu}_e$ component of the background. We then used these new predictions, including sideband, to find new constraints on the neutrino oscillation parameters. We don’t observe any major changes in the neutrino oscillation parameter constraints after including the sideband sample events in the standard 3-flavor predictions. More importantly, the framework to include the sideband sample events in the predictions and then
using these new predictions to generate sensitivities is now ready.

9 Acknowledgments

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References


