Effect of systematic uncertainties on NOνA Far/Near extrapolation using FNEX

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Abstract

The long baseline NOνA experiment (NuMI Off-axis ν_e Appearance) has been designed to provide a proof of neutrino oscillations in the channel $\nu_\mu \to \nu_e$ and even $\bar{\nu}_\mu \to \bar{\nu}_e$. It also aims to gain a more precise measurement of all the neutrino oscillation parameters, mainly θ_{13} and δ_{CP}.
In order to reach this goal, a new framework for data analysis has been conceived, namely FNEX or the so called Far/Near Extrapolation package, which is in continuos improvement. This program provides to the user general tools to perform not only analysis cuts, but also a Far/Near complete extrapolation and generator of confidence level contours as full systematic uncertainty, which is ultimately responsible for making the measurement of neutrino oscillation parameters.
My work activities within this Summer Internship at Fermilab have been focused on testing the effect of systematics on the data set concerning the NOνA ν_μ first analysis.
This report consists of four sections, organized in the following way:

- The first section describes in detail the main features of FNEX, the tools of the package and the way it actually deals with: a Far/Near extrapolation, best-fit oscillation parameters, confidence interval estimation.
- In the second section the analysis aims are carefully explained, especially focusing the attention on the systematic errors, whose effect has been tested and further investigated.
- The third section is principally devoted to the explanation of the results from the testing of systematics. Moreover, the need for an Unbinned Likelihood best-fit is also introduced, then the final results presented.
- The fourth section provides a description of the software improvements that have been implemented in FNEX, namely the class *OscPlots*, which provides all the neutrino oscillation probability plots as a function of energy.

1 FNEX package

1.1 Introduction

The Far/Near Extrapolation analysis package, namely called FNEX [1], is a software used within the NOνA experiment to generate full confidential level contours in an arbitrary parameters space, without loss of information on the events. Written in C++ language, it works in the ART framework, producing as output of running jobs both ART and ROOT files.
FNEX provides all the necessary tools for the user to select personal features on the data set of the NOνA ν_μ disappearance very first analysis, simply interfacing with FNEX *.fcl configuration files. Indeed, for every job it is possible to select not only your own variables, or the number of total events to be analyzed, but also the kinematic cuts, to get a complete best-fit estimation of neutrino oscillation parameters. Furthermore, if selected by the user,

this software produces the related star plots and even the gaussian-distributed confidence level contours. However, the interesting feature explored in this paper lies in the possible application of the known systematic uncertainties, called here *shifts*, and consequently in seeing how the final plots are affected by them. Finally, with more expertise FNEX provides a method to get the Feldman-Cousin confidence intervals, based upon the event selection.

1.2 Far Detector/Near Detector extrapolation

In a long baseline neutrino experiment, the role covered by the Near Detector (ND) is substantial for the evaluation of any discrepancy between data and predictions. The ND high-statistics data are used to estimate the main value of the difference between the number of expected neutrino events and the number of events actually reconstructed as a function of some reconstructed variable. Indeed, considering a simulated energy spectrum in the ND, named $\mathrm{N}_{ND,MC}$, and the reconstructed energy spectrum, $\mathrm{N}_{ND,DATA}$, then the uncertainty on the content of the neutrino beam in each bin can be fixed just by counting how big is the deviation between the expected and the reconstructed events. As a result, the prediction for the expected number of events is adjusted for the FD. In other words, for every reconstructed energy bin i, the simulated MC predictions for the FD are revised bin-by-bin this way:

$$N_{(FD,Corrected),i} = \frac{N_{(ND,DATA),i}}{N_{(ND,MC),i}} \times N_{(FD,MC),i}.$$

The ratio $\mathrm{N}_{(ND,DATA),i}/\mathrm{N}_{(ND,MC),i}$ represents a new weight for FD neutrino events in bin i, while the quantity $\mathrm{N}_{(FD,Corrected),i}$ is consequently called the *extrapolated* energy spectrum, referring to the *extrapolation* of deviations from the Near Detector to the Far Detector (fig. 1).

There are several steps to be taken into account to perform a full, final extrapolation with the FNEX package. The first one is strongly related to the neutrino event types identification. As a consequence, it is of the upmost importance to tag at first the *neutrino type*, i.e. ν_e, ν_μ, ν_τ, and then to identify the *interaction type*, e.g. "Quasi-elastic Charged Current (QECC)", "Neutral Current (NC)", "Resonant Elastic Scattering (RES)", "Deep Inelastic Scattering (DIS)" events. Indeed, they will produce a different reconstructed energy spectrum and, according to this, distinct extrapolated weights. Thus, after the initial setup function, FNEX provides the feature of tagging properly every neutrino interaction. In this way, user gets an FNESpectrum object that stores the values for each variable, that belongs to a specific neutrino interaction type: namely, the *true* energy, the *reconstructed* energy, start and stop position of the longest track identified by the Kalman filter, and much more. All of those information are saved both as TObjects in ROOT files, or as FNESpectrum objects in an ART file.

Once the FNESpectrum object has been built up properly by the running job, it is used by the Analysis Module to pull out of it every useful information. Among the leading functions of this class, one could point out *ApplyCuts()* and *ApplyWeights()*: they both

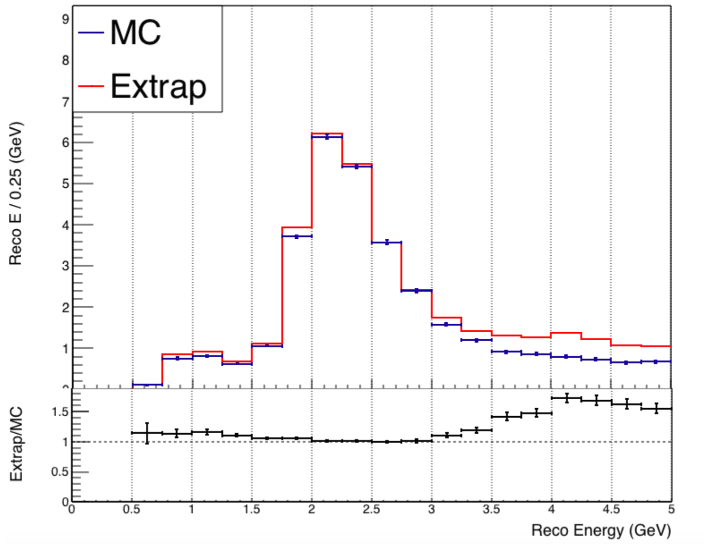


Figure 1: The red distribution represents the extrapolated reconstructed energy, while the blue one the Monte Carlo predictions, both in the Far Detector.

loop on all the events, applying the cuts and evaluating the weights, respectively, according to the user's selections from the configuration files, *fnespectrumanajob.fcl* and *FNESpectrumAna.fcl*. What is more, each event weight is adjusted by the neutrino oscillation probability, according to the neutrino type, and also by the value of the scaling factor for the total number of protons on target (POT).
The very last step is then represented by the class *FNESpectrum Extrapolator*, responsible for the fulfillment of the final extrapolation. In FNEX the user is allowed to choose between several kind of extrapolation:

- **Basic Extrapolation**: this is the standard one, that keeps the reconstructed energy spectra from the beam data events;
- **MC 1 to 1 Extrapolation**: this one is performed by setting data equal to MC ("in-out test");
- **Extrapolation MC-Poisson**: in this case the data reconstructed energy spectrum is cleared and then simulated by Poisson-distributed MC predictions.

The analysis presented in this paper has been conducted adopting the Basic Extrapolation and the setup shown in fig. 2. After passing through all these steps, FNEX package yields the complete FD/ND extrapolation and all the wanted plots.

1.3 Best-fit oscillation parameters

The very ultimate goal of the NOνA experiment is to find the best-fit neutrino oscillation rates, namely the set of parameters producing the best agreement between data (reconstructed events) and simulations (MC predictions) in the Far Detector. In the first

```
standard_fnespectrumana_numu_firstana:
{

 module_type:      FNESpectrumAna

 # Main job options
 #-----------------------------------

Jobs:
{
  MakeBasicExtrap:            true   # Make a basic extrapolation
  MakeBestFitPlots:           true   # Find the best-fit oscillation parameters
  MakeBestFitPoints:          true   # Make best-fit points for hi/lo shift values
  MakeGausContours:           true   # Make Gaussian CL contours
  MakeGausContours_WithSyst:  true  # Make Gaussian CL contours with syst. unc.
  MakeFCContours:             false  # Make Feldman-Cousins contours
  DrawFCContours:             false  # Draw Feldman-Cousins contours (you don't always want both! Trust.)
}


EventCap:                 10000            # if 0, use all events; else up to EventCap of each type

IgnoreCuts:               true
IgnoreWeights:            false

TrueEnergyBinLowest:          0.0              # TrueE bin range
TrueEnergyBinHighest:         5.0              # " "
TrueEnergyBinIncrement:       0.25             # TrueE bin increment

Target:                   "kRecoE"            # What variable are we extrapolating?
TargetTitle:              "Reco E"            # What do we want it to appear as? (Latex is fine)
TargetUnits:              "GeV"               # Units
TargetBinLowest:          0.0                 # Target bin range
TargetBinHighest:         5.0                 #
TargetBinIncrement:       0.25                # Target bin increment
```

```
# Cut configurations
#-----------------------------------

fne_var_configs:
    {
      kRecoE:
          {
          keep_lo:  0.0
          keep_hi:  10.0
          }
       kNumuDecafCut:
          {
          cut_lo: -0.5
          cut_hi:  1.5
          }
       kNumu:
          {
          cut_lo:  0.5
          cut_hi:  1.5
          keep_lo:  0.5
          keep_hi:  1.5
          }
       kNumuQE:
          {
          cut_lo:  -0.5
          cut_hi:  1.5
          }
       kNumuNonQE:
          {
          cut_lo:  -0.5
          cut_hi:  1.5
          }

       }
```

Figure 2: Basic setup of the file *FNESpectrumAna.fcl*, used in this analysis.

ν_μ disappearance analysis, the parameters we are most interested to determine are Δm^2_{32} and $\sin^2\theta_{23}$; hence we only allow them to vary in their bounded range, setting all the others as constants.

In order to accomplish this task, after the extrapolation procedure the FNEX class *FNESpectrumBestFit* leads to a minimization routine of the χ^2, defined as follows [2]:

$$\chi^2 = \sum_{all\,bins,i}\left(N_{MC,i} + b_i - N_{DATA,i} + N_{DATA,i}\ln\frac{N_{DATA,i}}{N_{MC,i}+b_i}\right) + \sum_k\left(\frac{(\epsilon_k - <\epsilon_k>)^2}{\sigma^2_{\epsilon_k}}\right), \quad (1)$$

where the first sum accounts for the χ^2 for Poisson-distributed data, while $N_{DATA,i}$ is the number of data events seen in bin i with relative expected background b_i, and $N_{MC,i}$ accounts for the number of predicted events in the same bin. The parameters ϵ_k represent the systematic uncertainties in the predicted number of neutrino events, and are expected to be Gaussian distributed; therefore the discrepancy between the main and the assumed value contributes to χ^2 as $\frac{(\epsilon_k - <\epsilon_k>)^2}{\sigma^2_{\epsilon_k}}$.

FNEX basic χ^2 minimization routine in based on the Minuit2 minimizer [1] and starts with two initial guesses: they are symmetrically placed below and above the value $\sin^2\theta_{23} = 0.5$. In general, there are two minima in χ^2 in $(\sin^2\theta_{23}, \Delta m^2_{32})$ space, one on each side of $\sin^2\theta_{23} = 0.5$. Earlier studies showed that Minuit2 tends to choose the minimun at $\sin^2\theta_{23} > 0.5$, whether or not it was correct, if given an initial guess of $\sin^2\theta_{23} = 0.5$.

1.4 Confidence intervals

Once the minimization routine produces convergence to the best-fit neutrino oscillation parameters, the very next step consists in the determination of the range of values with the same statistical significance, namely the *Confidence Interval.* In a case of bounded physical parameters, such as those used in neutrino oscillation analysis, the standard method of estimating the confidence region does not work properly. Consequently, a possible solution is represented by the Gaussian approximation or the method developed by Feldman and Cousins [2]. However, this work is limited at the former in a two dimensional parameter space, as we are especially interested in the $(\sin^2\theta_{23}, \Delta m^2_{32})$.
Firstly assume that the Likelihood function $\mathscr{L}(\sin^2 2\theta, \Delta m^2)$ could be approximated as a two dimensional Gaussian, and then that the couple of oscillation parameters could be scaled in this way:

$$x = \frac{(\sin^2 2\theta - \sin^2 2\theta_{best})}{\sigma_{\sin^2 2\theta}}, \qquad y = \frac{(\Delta m^2 - \Delta m^2_{best})}{\sigma_{\Delta m^2}}$$

where the subscript *best* refers to the best-fit value, while σ represents the RMS.
According to this, the Likelihood function becomes

$$\mathscr{L} = Ae^{-\frac{(x^2+y^2)}{2}}$$

and the χ^2 for a given set of x and y is

$$\chi^2 = -2\ln\mathscr{L} = (x^2+y^2) + \chi^2_{min},$$

where χ^2_{min} stands for the minimum value of χ^2.
In the individual case of physical boundary, the normalization condition becomes:

$$\Gamma = \int_{-\infty}^{+\infty}\int_{-\infty}^{b} \mathscr{L}(x,y)\, dxdy \ < 1.$$

If the minimum value of χ^2 on the physical boundary, i.e. at a given point $(b, 0)$, is expressed as:

$$\chi^2_b = \chi^2_{min} + b$$

then, the $\Delta\chi^2$ in the entire space is given by

$$\Delta\chi^2 = \chi^2_b - \chi^2_{min}.$$

From this, the confidence interval λ could be simply determined, as it is strongly dependent on the value of $\Delta\chi^2$:

$$\lambda = 1 - \int_{-\infty}^{+\infty}\int_{-\infty}^{\sqrt{\Delta\chi^2}} \frac{e^{-\frac{(x^2+y^2)}{2}}\Theta\big(\chi^2(x,y) - \chi^2(x',y')\big)\, dxdy}{\Gamma}$$

where $\Theta(u) = 0$ for $u < 0$ and $\Theta(u) = 1$ for $u \geq 0$, while Γ is the normalization factor.
In case the best fit point of the $(\sin^2\theta, \Delta m^2)$ space is inside the physical region, then the 68% *confidence level* (CL) includes all the points with $\left(\chi^2_{(x,y)} - \chi^2_{min}\right) < 2.28$; the same is for 90% and 99% CL, with a $\Delta\chi^2$ of 4.61 and 9.21, respectively. In practice, this is what we find for our best-fit point in the $\nu_\mu \to \nu_\mu$ disappearance analysis.

2 Systematic uncertainties on NOνA first analysis

The following section describes the main systematic uncertainties, that have been taken into account in the NOνA ν_μ disappearance first analysis [3]. They have been implemented in the FNEX package and then translated as systematic shifts, to be applied to data or even MC events. Assuming that the systematics cover the whole size of the following shifts:

- Hadronic Absolute Shift ($\pm$ 21%), that involves the hadronic deposit of energy of both ND and FD;

- Hadronic Relative Shift ($\pm$ 6%), to be applied only in the Far Detector and is related to the supposed difference in the reconstructed hadronic energy in the FD compared to the ND;

- Hadronic Relative Normalization ($\pm$ 2.2%), that increases or decreases the normalization of the FD.

This analysis aims to figure out how big some of our uncertainties are, their consequent effect on the final extrapolation and on the evaluation of best-fit neutrino oscillation rates.

2.1 Hadronic energy correction

The biggest among the NOνA systematics has been uncovered by seeing a large discrepancy between data and MC, mostly in the number of hits and total energy. When reconstructing a ν_μ CC event in the detector, since the muon track parameters and the average energy per hit seem to match with MC predictions, it is assumed that the problem derives from the hadronic sector, i.e. it is caused by mis-modeling of the hadrons produced in the neutrino interaction. Consequently, an empirical correction has been applied to data, shifting the reconstructed hadronic energy. The size of this uncertainty can be determined simply by minimizing the χ^2 difference between the corrected data and MC. The hadronic systematic error can be split in two effects: the *absolute* and the *relative* one, respectively. Absolute shifts are assumed to be identical and are referred to as relative shifts. They exist both in the ND and FD; further differences between them have to be assigned to the difference in the fiducial volume of the two detectors.

2.2 Normalization correction

This systematic error has two main sources: the first one lies in the uncertainty on the fiducial volume of the detector in its entirety (optic fibers, scintillators, extrusions, glue), deduced from the average unit of mass . The last could be derived from the inconstant exposure (namely, the total POT) in the oscillation analysis.

3 Effect of systematics on $\nu_\mu \to \nu_\mu$ disappearance First Analysis

The aim of this analysis has been to figure out how adding systematic uncertainty affects the best-fit point and 68% and 98% CL contours in the $\nu_\mu \to \nu_\mu$ disappearance First Analysis (fig. 3). In this report the result of applying systematic shifts to the MC sample is introduced; moreover, it has been discovered that the biggest contribution comes from the hadronic correction.
Thus, the first shown and to be taken into account is the Hadronic Absolute Shift *Low*[1], whose result is shown in this paper in fig. 4. The new CL contours shrink and shift upwards; furthermore, it causes an increase in the best-fit value of Δm^2_{32}, indicating less oscillations. Even if the result is affected a lot by applying this shift, it still looks reasonable, as the new best fit point is included in the 68% CL region of the results without any systematics. This points out the goodness of the initial confidence interval estimation.
The second among the main shifts to be investigated is the Hadronic Absolute Shift *High*, whose related plots are shown in fig. 5. This time the new CL contours look wider than before, and they shift downwards, too. As a result, the best-fit point corresponds to an increase in the value of Δm^2_{32}, suggesting even more oscillations.
Finally, the last shift here reported is the Hadronic Relative *Low*, the effect of which looks really irrelevant compared to the previous ones (fig. 6). Indeed, the new CL contours basically match with those without systematics, even if a small reduction could be observed. Furthermore, the same tiny effect involves the estimation of the new best-fit point, that leads to very similar values of the two parameters Δm^2_{32} and $\sin^2\theta_{23}$ to the ones without shifts.

3.1 Comparison between FNEX and CAFAna results

A further step of this analysis has been devoted to the study of the differences between FNEX and CAFAna[1] final results, namely the estimation of the best-fit oscillation parameters, CL contours and FD reconstructed energy spectrum (recoE). The aim is to figure out why the 90% CL contours between the two results look slightly shifted (fig. 7).
In order to accomplish this task, a new method has been implemented in the class FNESpectrum of the FNEX package. The standard FNEX approach is to reweight the contribution of *each event* to the recoE spectrum, based upon that event's true MC energy. Substantially we add a new option to revaluate the weights of the FD recoE spectrum, miming CAFAna's approach: firstly, the program finds the bin whose energy equals the MC True Energy, determining the bin center for each event. Then, that value, together with the features of the neutrino interaction (that is the initial and final state flavour) is passed to the class OscCalculator[2] to evaluate the new weights.

[1] *High* shift means that the hadronic energy of each bin i of the spectrum has been shifted upwards, while *Low* shift refers to the specular situation, that is the shifting downwards of the content in energy of each bin.

[1] The Common Analysis Format (CAFAna) is a general framework for physics analysis, widely used in the NOνA experiment, too.

[2] http://nusoft.fnal.gov/nova/novasoft/doxygen/

According to those changes the recoE spectrum in the FD (fig. 8) looks really similar to the previous one, got with the old weights. Therefore, the conclusion that any difference between the two methods must be due to two main reasons: a different approach to the minimization procedure and a different extrapolation technique.

3.2 The Unbinned Likelihood Best Fit

Another point of this work activities has been conceived to figure out how much are the NOνA $\nu_\mu to \nu_\mu$ first analysis results reliable and whether the implementation of the *Unbinned Likelihood Best Fit* is a necessary step to get an overall answer.
A way to do this is then represented by the so called method of *Walking Bins*, in which each bin of the target variable (recoE) is shifted by the same constant amount. In this analysis, three shifts have been considered:

- 100 MeV
- 200 MeV
- 300 MeV

The result for the best fit point and CL interval in the space $(\sin^2\theta_{23}, \Delta m^2_{32})$ is reported in fig. 9: the 90% CL contours look basically the same as those gained without shifting the bin range, even if they are wider than expected. Interesting is to notice that, although the best-fit points are really affected by the shifts, they are still included in the confidence interval. As a consequence, we are confident in our answer, however we would like to free from the costraint of binning that seems to affect so much the final parameters evaluation.
In order to perform the Extended Unbinned Likelihood Best Fit, it is required to minimize the espression of the following Likelihood function:

$$UBL = \sum_i -\log f_i(x_i, \vec{\theta}) + A(\bar{p})$$

where f_i is the predicted target (recoE) spectrum as a function of the point x_i and of a certain set of parameters $\vec{\theta}$, and $A(\bar{p})$ is the total predicted event count. We generate f_i using a bin simulation that is small enough that no bin contains more than one data event, to maximize the advantages of a UBL.
The preliminary result for the implementation of the UBL fit in FNEX is shown in fig. 10: the black lines refer to the 33 tagged ν_μ events found in the FD, while the purple distribution stands for the simulated MC PDF in a range between 0 and 5 GeV. Here the CL contours are not really different for both UBL fit (blue line) and Binned χ^2 fit (red line), although the ones got by performing a UBL look wider, and the its best fit point shows a decrease in the value of $\sin^2\theta_{23}$.

4 Software improvements

The second half of this work has been devoted to a personal contribution to the implementation of a new class in FNEX called *OscPlots*, that has been introduced and written: it produces all the neutrino oscillation probability plots, for each neutrino type (ν_e, ν_μ, ν_τ) and oscillation channel. Every time the FNEX minimization routine leads to a new set of best-fit neutrino oscillation parameters, the output changes, according to it.
In the *OscPlots* class, three methods have been defined:

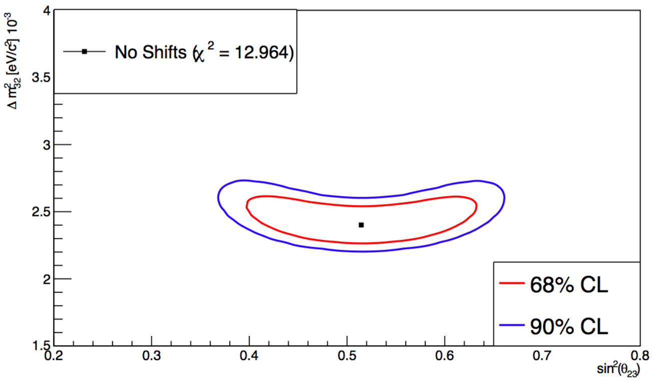
- **OscPlots::SetOscillationParametersBF**(), which provides a link between this current class and the one producing the best-fit parameters, i.e. FNEXFit. In the latter, by means of a new function called *PassValues*(), the final array of parameters produced in the minimization routine is passed to OscPlots. Furthermore, they are set up as default parameters and passed to the class *osc::OscCalculator*() to determine the oscillation rates.

- **OscPlots::MakeHisto**(). This method produces as output all the neutrino oscillation probability individual distributions (fig. 11), according to the calculation derived from OscCalculator. Then, they are saved in a subfolder of the directory *OscPlots*, called *IndividualPlots*.

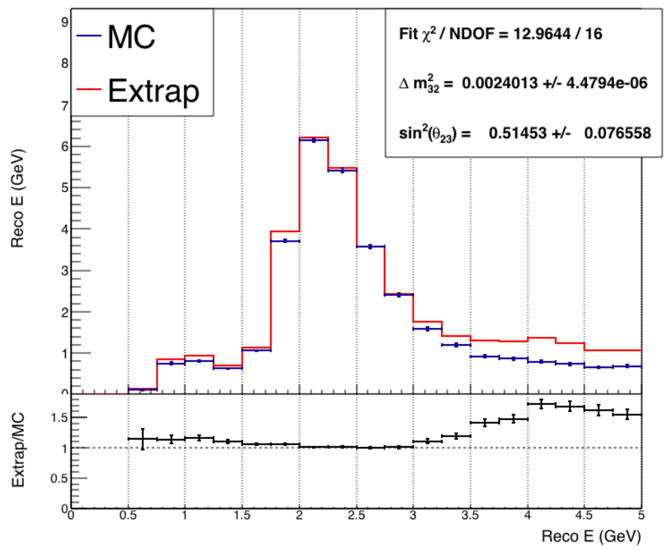
- **OscPlots::MakeStacks**(). This function provides the final stacks containing all the distributions, even split for each neutrino oscillation channel: ν_e, ν_μ, ν_τ in fig. 12. Then, they are saved in the subfolder *FinalResults*, belonging to the *OscPlots* directory.

Conclusions

The NOνA experiment has recently provided a irrefutable proof of the neutrino oscillations in the channel $\nu_\mu \to \nu_e$, as a result of the First ν_μ disappearance analysis.
Through the use of the Far/Near Extrapolation package (FNEX), the effect of systematic uncertainties has been tested on the first analysis $\nu_\mu \to \nu_\mu$, to figure out their relative prominence in the final evaluation of best-fit points and of CL contours in the space $(\sin^2\theta_{23}, \Delta m^2_{32})$. It has been uncovered that the main affection is due to the Hadronic Absolute Shift *Low* and *High*, and to the Hadronic Relative Shift *Low*; however, despite the CL contours being affected by these shifts, all the best-fit points related to each systematic effect are still included in the 90% confidence region, giving in this way great trust on FNEX achievements.
Furthermore, it has been realized the study of *walking bins*, to quantify the dependency of the final best-fit plots on the selected binning, discovering a need for an Unbinned Likelihood fit in order to get a very inclusive outcome.
Finally, the new class *OscPlots* has been implemented in the NOνA software, to provide to the user all the neutrino oscillation probability plots, helping in this way in the comprehension of all the outcoming results of a FNEX running job.

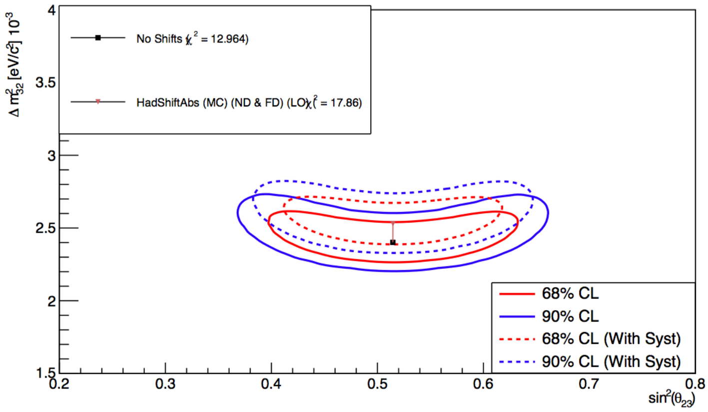


(a) *Confidence intervals gained as output of a $\nu_\mu \to \nu_\mu$ oscillation first analysis job in FNEX, without any systematic shift applied.*

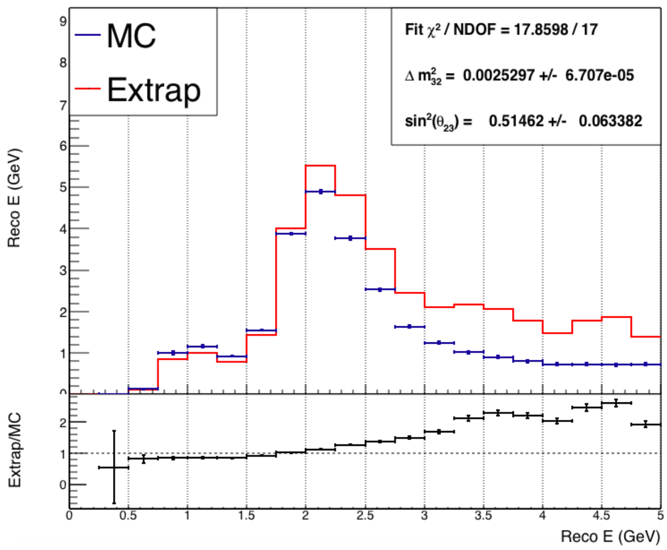


(b) *Reconstructed energy spectrum in the Far Detector, without any systematics. The red line represents the result of the extrapolation, while the blue dots are the MC predictions.*

Figure 3: Final plots produced after a full extrapolation and evaluation of best-fit oscillation parameters in FNEX, without applying systematic shifts.

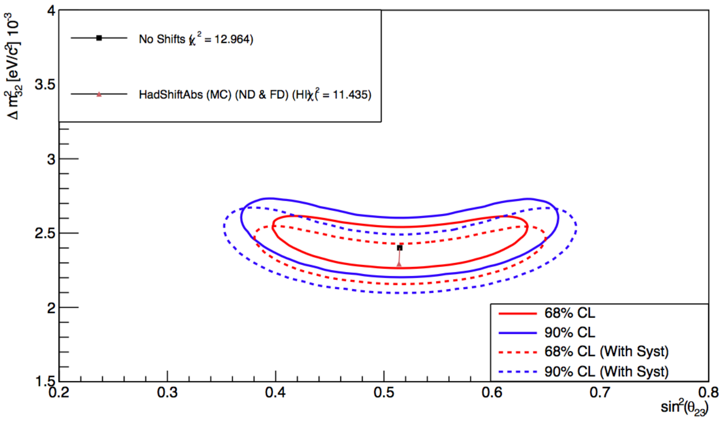


(a) *Confidence level contours before (continuous line) and after (dashed lines) the application of the Hadronic Absolute Shift Low. The new best fit point is placed inside the confidence region.*

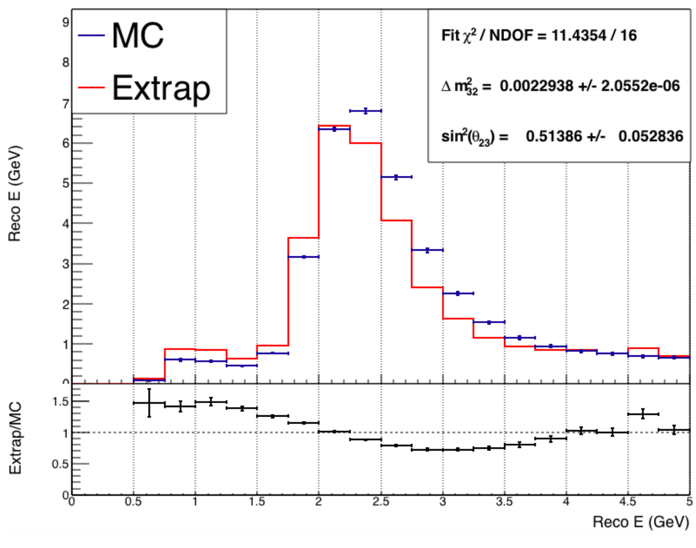


(b) *Reconstructed energy spectrum in the FD, related to the Hadronic Absolute Shift Low.*

Figure 4: Final plots produced after having applied the Hadronic Absolute Shift Low to MC events.

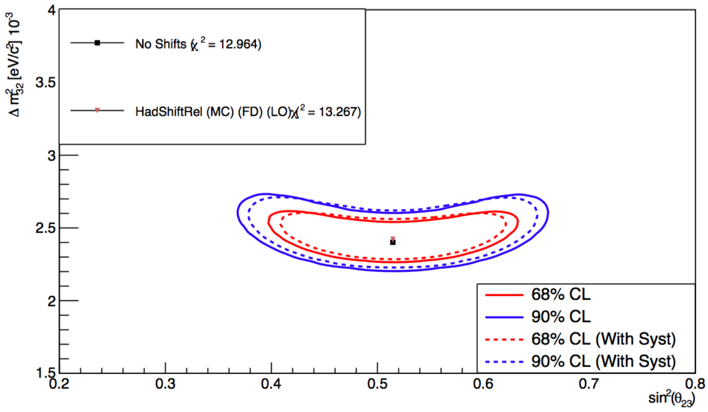


(a) *Confidence level contours before (continuous lines) and after (dashed lines) having applied the Hadronic Absolute Shift High. The new best-fit point is still placed inside the confidence region.*

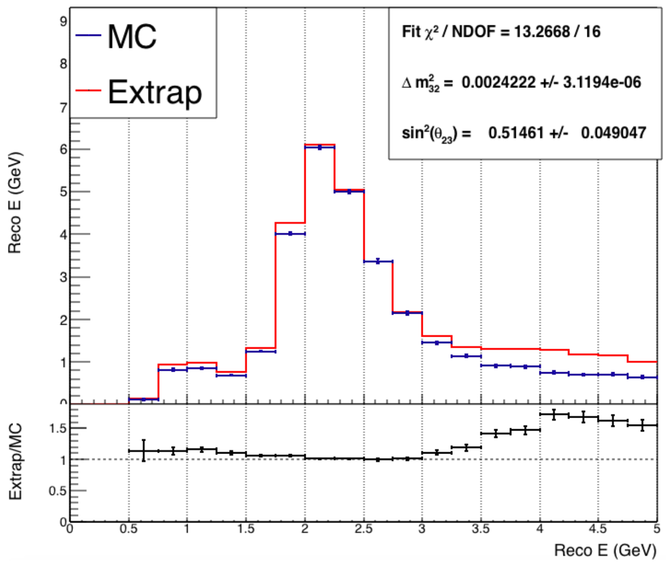


(b) *Reconstructed energy spectrum in the FD after applying the Hadronic Absolute Shift High.*

Figure 5: Final plots related to the application of the Hadronic Absolute Shift High to MC events.



(a) *Confidence level contours before (continuos lines) and after (dashed lines) applying the Hadronic Relative Shift Low.*



(b) *Reconstructed energy spectrum in the FD, after the application of the Hadronic Relative Shift Low.*

Figure 6: Final plots related to the application of the Hadronic Relative Shift Low to MC events.

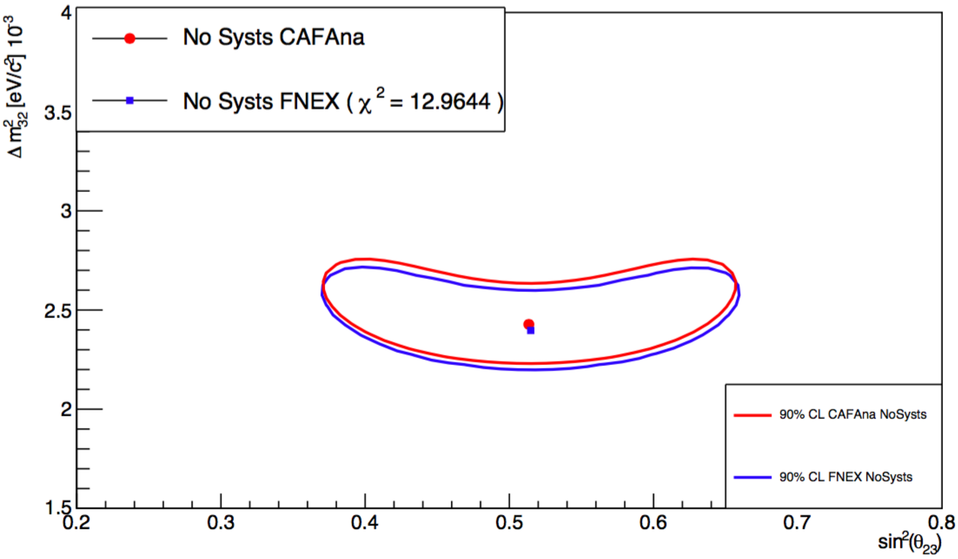
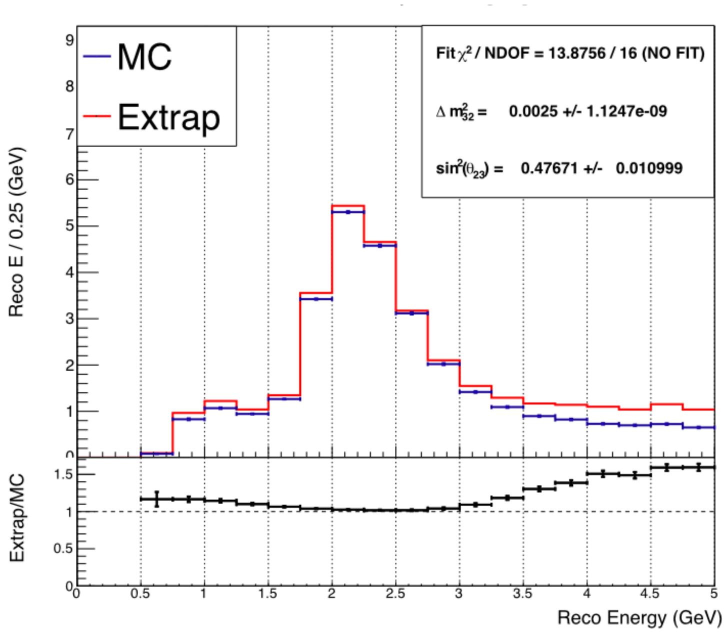
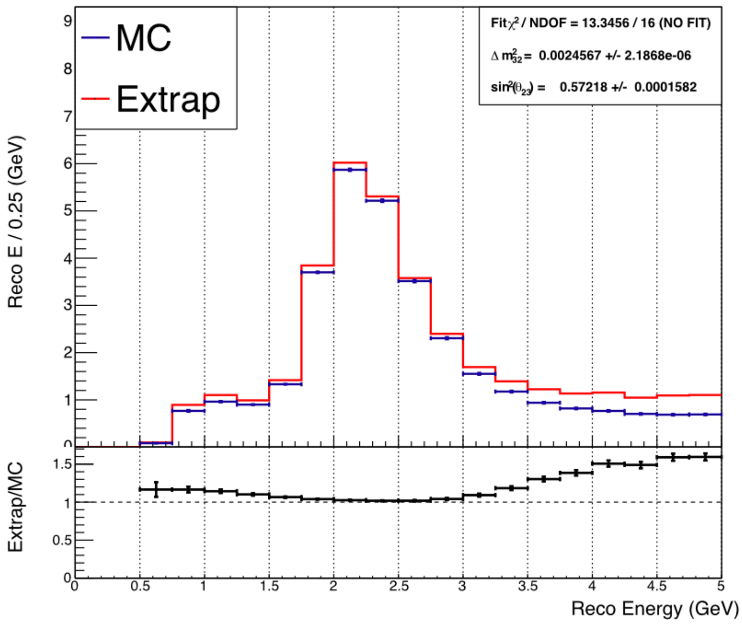


Figure 7: 90% Confidence intervals, gained with the CAFAna approach (red line) and the FNEX one (blue line). The direct comparison between them shows a tiny relative shift.



(a) *FD RecoE spectrum produced without any systematics and with the FNEX default method for the weights estimation. The contribution of each event to the recoE spectrum is weighted by its true energy.*



(b) *FD RecoE spectrum gained with the new weights, that have been evaluated miming the CAFAna approach of finding the bin center.*

Figure 8: RecoE spectra comparison for finding any difference between the old approach and the new one, namely evaluating the weights of each event with the bin center of the true energy bin, containing this event's true energy value (similar to the histogram-bared approach of CAFAna).

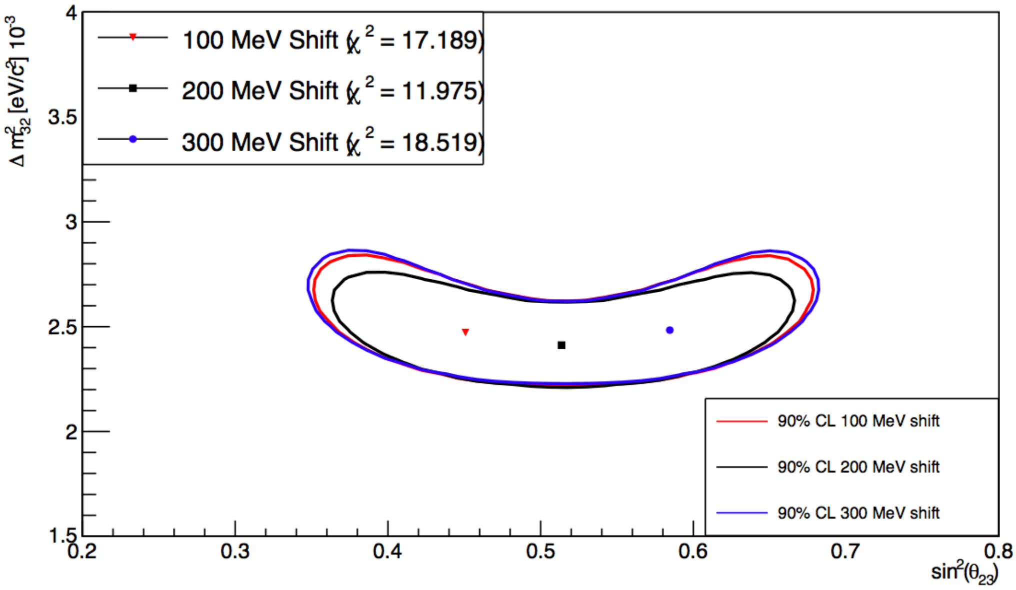
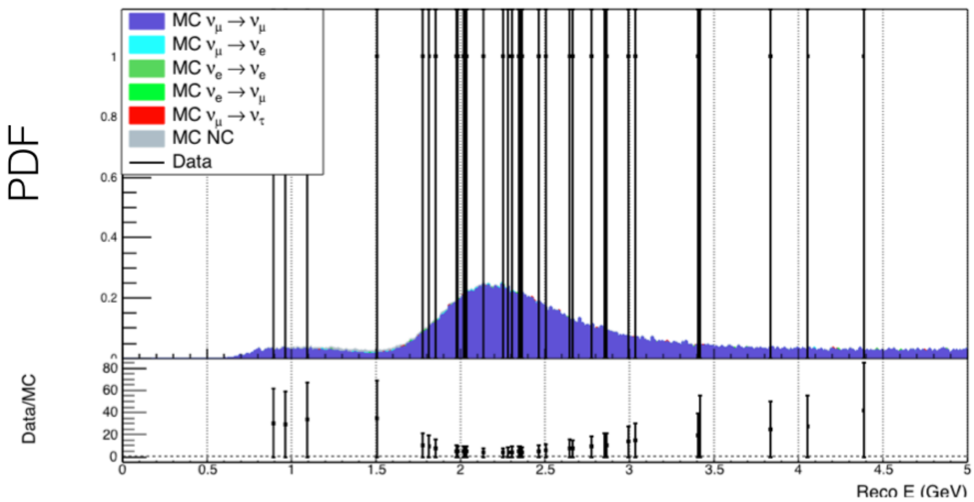
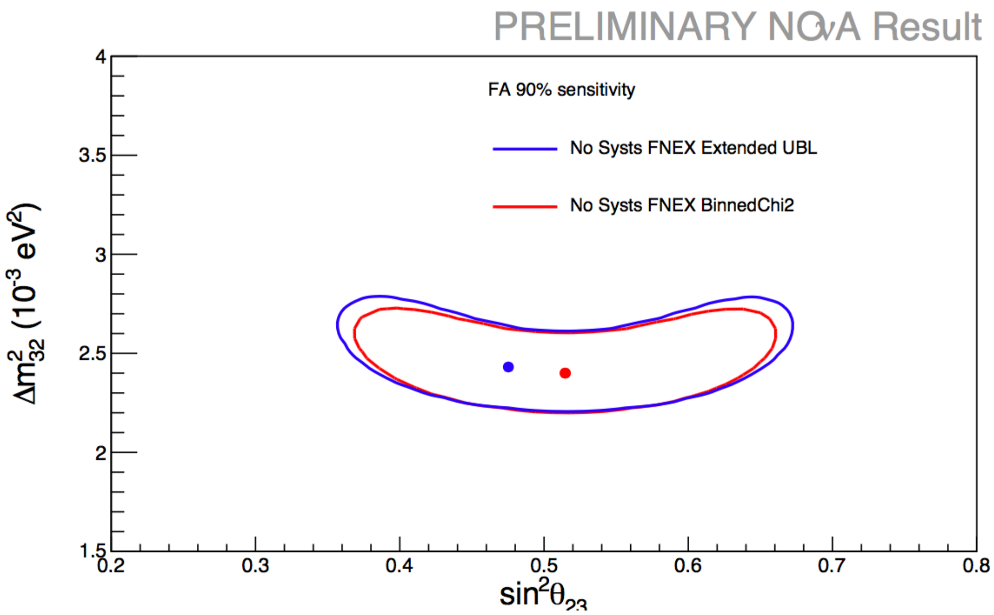


Figure 9: 90% Confidence level contours and best-fit points, as a result of the 100, 200, 300 MeV shifts applied to the target bin range (Walking bins).

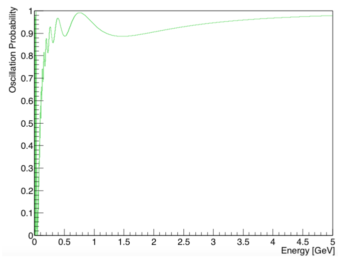


(a) *Preliminary result for a simulated Probability Density Function (PDF), defined for use by a more general Unbinned Likelihood best fit. The black lines represent the collected data of the first ν_μ disappearance analysis, and the corresponding value of the PDF related to their energy.*

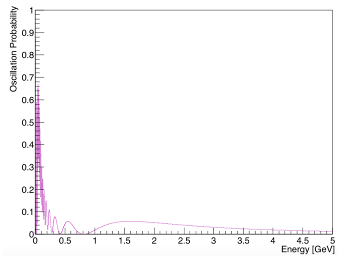


(b) *Confidence level contours comparison without systematics, between the FNEX Binned χ^2 fit (red line) and the FNEX Unbinned Likelihood fit (blue line). The latter looks wider and the new best-fit point is shifted to a lower value of $\sin^2\theta_{23}$.*

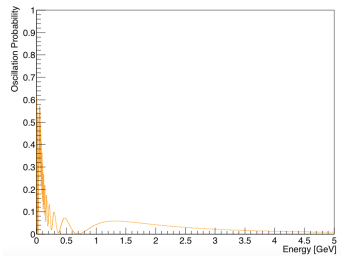
Figure 10: Preliminary NOνA results for the Unbinned Likelihood fit.



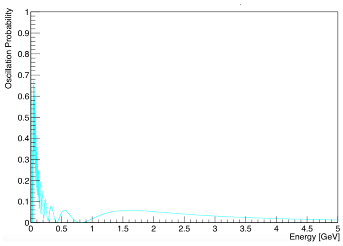
(a) $P(\nu_e \to \nu_e)$



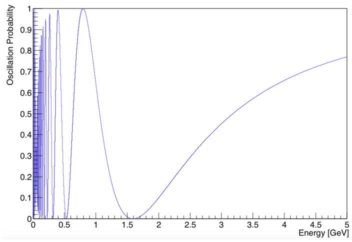
(b) $P(\nu_e \to \nu_\mu)$



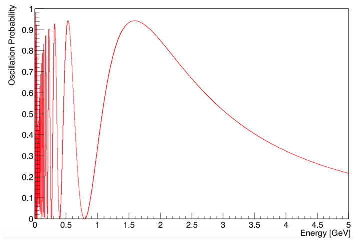
(c) $P(\nu_e \to \nu_\tau)$



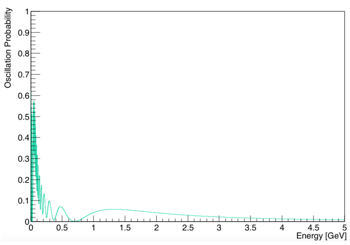
(d) $P(\nu_\mu \to \nu_e)$



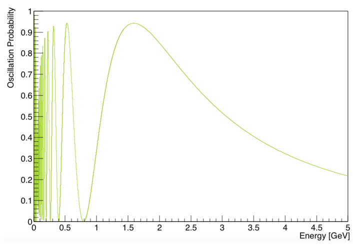
(e) $P(\nu_\mu \to \nu_\mu)$



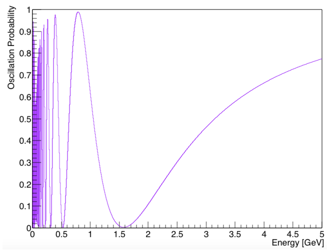
(f) $P(\nu_\mu \to \nu_\tau)$



(g) $P(\nu_\tau \to \nu_e)$

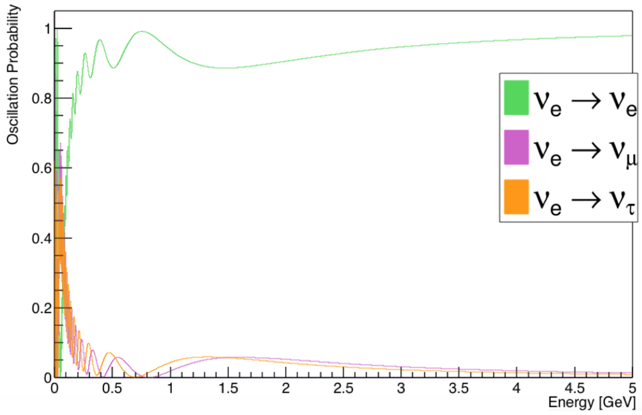


(h) $P(\nu_\tau \to \nu_\mu)$

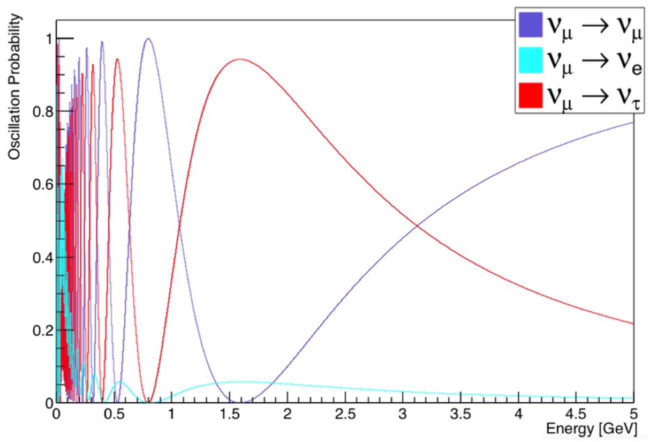


(i) $P(\nu_\tau \to \nu_\tau)$

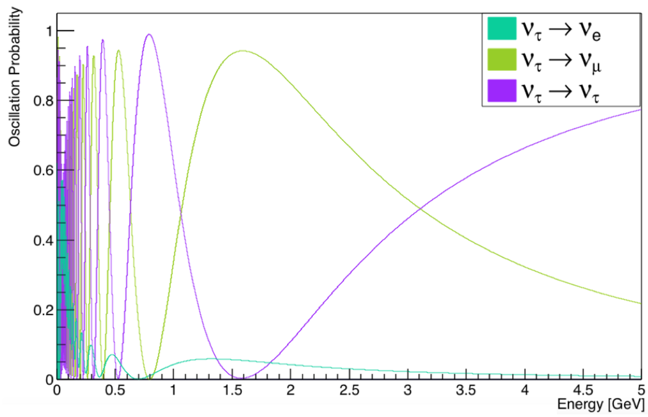
Figure 11: Individual plots for neutrino oscillation probability, produced as output of the function *OscPlots::MakeHisto*() without any applied shift.



(a) *Oscillation Probability stack for* ν_e.



(b) *Oscillation Probability stack for* ν_μ.



(c) *Oscillation Probability stack for* ν_τ.

Figure 12: Final stacks for neutrino oscillation probability, produced as output of the function *OscPlots::MakeStacks*() without any applied shift.

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[1] K. Matera, *FNEX tech note*, NOVA-doc-13749-v4.

[2] B. J. Rebel, *Neutrino - Induced Muons in the MINOS Far Detector*, FERMILAB-THESIS-2004-33, UMI-31-52825-MC.

[3] J. Paley, G. Pawloski, K. Bays, N. Raddatz, S. Lein, L. Suter for the ν_μ CC Working Group, *Executive Summary of the 2015 ν_μ Disappearance Analysis*, NOVA-doc-13641-v2.