



JOINT INSTITUTE FOR NUCLEAR RESEARCH
Dzhelepov Laboratory of Nuclear Problems

**FINAL REPORT ON THE
SUMMER STUDENT PROGRAM**

The study of muon neutrino disappearance in $NO\nu A$

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Contents

Abstract	2
1 Neutrino	3
1.1 Brief neutrino history	3
1.2 Unresolved problems around neutrino.	4
1.3 Neutrino oscillations and mixing	5
2 The $\text{NO}\nu\text{A}$ experiment	9
2.1 Measurement of oscillation parameters	10
3 Working with $\text{NO}\nu\text{A}$ software	11
3.1 Common setup for $\text{NO}\nu\text{A}$ software.	11
3.2 EventGenerator package	13
3.3 TrackFit package	17
Conclusion	19

Abstract

In the present report following topics are considered: a brief history of neutrino, main problems connected with modern neutrino physics, an elementary theory of neutrino oscillations in vacuum, the $\text{NO}\nu\text{A}$ experiment , experimental analysis technics and several tools for $\text{NO}\nu\text{A}$ (EventGenerator and TrackFit packages).

Chapter 1

Neutrino

Neutrino physics researches are among the most important and perspective researches in modern physics. Neutrino is one of the most abundant particles in our universe. Flux of neutrinos is the most intensive of all fluxes of other particles passing through the Earth – about $10^{13} - 10^{14} \text{cm}^{-2} \text{s}^{-1}$. Neutrinos are coming from different sources such as stars, quasars, supernovas, galaxy cores, pulsars. Also there are so-called relict neutrinos [1] which were produced with the galaxy formation. The feature of neutrinos is that their interaction with the matter is very weak and that allows them to travel very long distances without losing any energy. That makes neutrinos valuable for fundamental researches: their study can give us a possibility to get information about different remote parts of our galaxy or about it's primary states during it's formation. On the other hand the feature makes it very hard to detect these particles. So all of the experiments devoted to neutrino detection require long-term data retrieval. But how do we know about neutrino if it's interaction with the matter is very weak? The first idea of neutrino existence appeared in 1930.

1.1 Brief neutrino history

The idea belonged to Wolfgang Pauli, a german physicist, in order to explain a spectrum of electrons in beta-decay. According to experimental data the spectrum is continuous which didn't correspond to experimental data about alpha and gamma rays, where spectrum had a monochromatic nature. Pauli assumed that beta-decay is accompanied by emitting a particle which takes a part of the whole energy, which interaction with the matter is very weak and which would never be detected. He informed a scientific community about his assumption in his famous letter "to radioactive ladies

and gentlemen” from December, 4th , 1930. Despite of Pauli’s belief after 26 years an electron antineutrino was detected by two American physicists F. Reines and J Cowan in consequence of reactions:

$$\bar{\nu}_e + p \rightarrow e^+ e^- \rightarrow \gamma\gamma \rightarrow +Cd \rightarrow \gamma + ... \quad (1.1)$$

Further experiments held in next years led to discovery of neutrinos antineutrinos of all known types nowadays. All of these particles are divided into three generations (these generations are also called flavors), represented in table 1. The existence of three neutrino flavors is approved by LEP experiment devoted to measurement of decay width of $Z \rightarrow \nu_1 + \bar{\nu}_1$. Global fit of all the LEP’s data provides a number of existing flavors $n = 2,984 \pm 0,008$. Also there is an assumption based on experimental data of WMAP collaboration devoted to measurement of anisotropy of temperature of relict photons that one more type of neutrino exists. That neutrino is called “sterile” and does not interact with the matter at all. This hypothesis explains results of many experiments in neutrino physics and answers several questions connected with baryon asymmetry and dark matter. Result of WMAP data provides next value for a number of neutrino flavors:

$$n = 4,34 \pm 0,87 \quad (1.2)$$

Several experiments are held in the meantime in order to check the result.

1.2 Unresolved problems around neutrino.

In the modern neutrino physics the main phenomenon researched is neutrino oscillations - a property of neutrinos to change their flavor with travelled distance in vacuum or in matter. The property is the result of hypothesis of neutrino mixing. Description of neutrino mixing is given below. For a modern state of neutrino physics there are several problems which require further research:

1. What are the values of neutrino masses? According to theoretical evaluations neutrinos are the lightest particles ever detected. Top border for neutrino mass is 0,28 eV. But science didn’t manage to get any specific values yet.
2. Is CP-invariance violated in leptonic sector?
3. Updating parametres of mixing matrix
4. Are there any more neutrino flavors?

5. Are neutrinos Majorana or Dirac particles?
6. Study of neutrino from supernova flashlights.
7. Study neutrino of ultrahigh energy and search of their sources.

The goal of my research work during summer student program was to explore several methods used to solve the third problem from the list in long-baseline accelerative neutrino experiment NO ν A (NuMI Off-Axis ν_e Appearance). Determination of oscillation parameters can be done by measuring probability of neutrino interaction with matter and comparing this probability with theoretical predictions. Further is given a simplest model of neutrino oscillations in vacuum which demonstrates the main idea of oscillation parameters retrieval.

1.3 Neutrino oscillations and mixing

Modern study of neutrino oscillations is based on two main assumptions [2]:

1. All of the data received so far including results of very precise measurements in LEP experiment confirms that neutrino interactions with other particles is described by Standard model of electroweak interaction.
2. Only three flavors exist in nature (sterile neutrinos are excluded from the following model).

Neutrino mixing phenomenon is based on a hypothesis that neutrino mass addendum is being generated in complete Lagrangian describing neutrino interaction with other particles. There are several possible addendums:

1. Dirac mass addendum

$$L^D = -\bar{\nu}'_R M^D \nu_L h.c., \quad (1.3)$$

where

$$\nu'_L = \begin{pmatrix} \nu_{e,L} \\ \nu_{\mu,L} \\ \nu_{\tau,L} \end{pmatrix}, \nu'_R = \begin{pmatrix} \nu_{e,R} \\ \nu_{\mu,R} \\ \nu_{\tau,R} \end{pmatrix}, \quad (1.4)$$

and M^D is a complex non-diagonal matrix. After diagonalisation of the matrix we receive next expression for flavor neutrino fields:

$$\nu_{l,L} = \sum_i U_{li} \nu_{i,L} \quad (1.5)$$

The complete Lagrangian is invariant to global calibrating transformation:

$$\nu'_i \rightarrow e^{i\alpha}\nu'_i, \nu'_R \rightarrow e^{i\alpha}\nu'_R, l \rightarrow e^{i\alpha}l \quad (1.6)$$

where α is any real number. The result of the invariance is law of full leptonic number conservation and in that case ν_i a field of Dirac neutrinos and antineutrinos ($L(\nu_i)=1, L(\bar{\nu}_i)=-1$).

2. Majorana mass addendum

$$L^{Mj} = -\frac{1}{2}(\bar{\nu}'_L)^c M^{Mj} \nu'_L + h.c., \quad (1.7)$$

where M^{Mj} is a complex non-diagonal symmetrical matrix, $(\nu'_L)^c = C\nu'^T_L$, where C is unitary matrix of charge conjugation. After diagonalisation of M^{Mj} we receive next expression for flavor fields:

$$\nu_i = \nu_i^c = C\nu'^T_i \quad (1.8)$$

As we can see in that case ν_i is a field of Majorana particles and complete Lagrangian is not invariant to global calibrating transformation thus neutrinos and antineutrinos are true-neutral particles. They do not have any electric or leptonic charges so neutrinos and antineutrinos are the same particles.

Neutrino oscillations is the result of an assumption about neutrino mixing:

$$\nu_{\alpha,L} = \sum_i U_{\alpha i} \nu_{i,L} \quad (1.9)$$

In that case for a state vector of neutrino we have next expression:

$$|\nu_\alpha \rangle = \sum_i U_{\alpha i}^* |\nu_i \rangle \quad (1.10)$$

Probability of neutrino transition from flavor α to flavor α' :

$$P(\nu_\alpha \rightarrow \nu_{\alpha'}) = \left| \delta_{\alpha'\alpha} + \sum_i U_{\alpha'i} U_{\alpha i}^* \left[\exp\left(-j\Delta m_{i1}^2 \frac{L}{2E}\right) - 1 \right] \right|^2 \quad (1.11)$$

where j is an imaginary unit, $\delta_{\alpha'a}$ - Kronecker's delta, E - energy of neutrino, L - distance travelled by neutrino in vacuum, $\Delta m_{i1}^2 = m_i^2 - m_1^2$. The same expression for oscillation probabilities of antineutrinos:

$$P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_{\alpha'}) = \left| \delta_{\alpha'\alpha} + \sum_i U_{\alpha'i}^* U_{\alpha i} \left[\exp\left(-j\Delta m_{i1}^2 \frac{L}{2E}\right) - 1 \right] \right|^2 \quad (1.12)$$

Main features of neutrino oscillations in vacuum are:

- Probabilities of transitions depend on $\frac{L}{E}$
- Oscillations observe is possible in case at least for one i the next condition is satisfied:

$$\Delta m_{i1}^2 \frac{L}{E} \gtrsim 1 \quad (1.13)$$

-

$$P(\nu_\alpha \rightarrow \nu_{\alpha'}) = P(\bar{\nu}_{\alpha'} \rightarrow \bar{\nu}_\alpha) \quad (1.14)$$

The last expression is the result of CPT-invariance which is typical for each local quantum field theory.

Next a minimal scheme of mixing - mixing of three neutrinos - is observed:

$$\nu_{\alpha,L} = \sum_{i=1}^3 U_{\alpha i} \nu_{i,L} \quad (1.15)$$

In that case matrix U is called Pontecorvo-Maki-Nakagawa-Sakata matrix. The scheme contains two independent δm^2 and allows to explain oscillations data referenced to solar and atmospheric neutrinos. The primary interest for the experiment described below is represented by the second category. There are two capabilities within the scope of described model [6]: 1) Normal hierarchy of neutrino masses:

$$\Delta m_{32}^2 \simeq \Delta m_{sol}^2, \Delta m_{21}^2 \simeq \Delta m_{atm}^2, \Delta m_{32}^2 \ll \Delta m_{21}^2 \quad (1.16)$$

2) Reversed hierarchy:

$$\Delta m_{21}^2 \simeq \Delta m_{sol}^2, \Delta m_{32}^2 \simeq \Delta m_{atm}^2, \Delta m_{21}^2 \ll \Delta m_{32}^2 \quad (1.17)$$

Considering the first case we have next condition for atmospherical of Δm_{21}^2 :

$$\Delta m_{21}^2 \frac{L}{E} \lesssim 1 \quad (1.18)$$

We can neglect the value of addendum with Δm_{21}^2 in 1.11. In that case the probability of transition $\nu_\alpha \rightarrow \nu_{\alpha'}$:

$$P(\nu_\alpha \rightarrow \nu_{\alpha'}) \simeq \left| \delta_{\alpha'\alpha} + U_{\alpha'3} U_{\alpha 3}^* \left[\exp\left(-j \Delta m_{i1}^2 \frac{L}{2E}\right) - 1 \right] \right|^2 \quad (1.19)$$

As the result probability of transitions in atmospherical interval is determined only by Δm_{32}^2 and the third column of PMNS matrix which link flavor

neutrino fields $\nu_{\alpha L}$ with the field of the most heavy neutrino ν_{3L} .
If $\alpha \neq \alpha'$:

$$P(\nu_{\alpha} \rightarrow \nu_{\alpha'}) = \frac{1}{2} A_{\alpha, \alpha'} \left[1 - \cos \left(\Delta m_{32}^2 \frac{L}{2E} \right) \right], \quad (1.20)$$

where

$$A_{\alpha, \alpha'} = 4 |U_{\alpha' 3}|^2 |U_{\alpha 3}|^2 \quad (1.21)$$

An expression for probability of neutrino ‘‘survival’’:

$$P(\nu_{\alpha} \rightarrow \nu_{\alpha}) = 1 - \sum_{\alpha \neq \alpha'} P(\nu_{\alpha} \rightarrow \nu_{\alpha'}) = 1 - \frac{1}{2} B_{\alpha, \alpha} \left[1 - \cos \left(\Delta m_{32}^2 \frac{L}{2E} \right) \right]^2 \quad (1.22)$$

From unitarity of PMNS matrix for amplitude $B_{\alpha, \alpha}$ we have:

$$B_{\alpha, \alpha} = \sum_{\alpha \neq \alpha'} A_{\alpha', \alpha} = 4 |U_{\alpha 3}|^2 (1 - |U_{\alpha 3}|^2) \quad (1.23)$$

For reversed hierarchy we receive expressions for oscillation probabilities by doing next substitution:

$$\begin{aligned} \Delta m_{32}^2 &\rightarrow \Delta m_{21}^2 \\ |U_{\alpha 3}|^2 &\rightarrow |U_{\alpha 1}|^2. \end{aligned}$$

Usually PMNS matrix is used in parameterised form:

$$\begin{aligned} U_{\mu 3} &= (1 - |U_{e3}|^2)^{\frac{1}{2}} \sin \theta_{23}, \\ U_{\tau 3} &= (1 - |U_{e3}|^2)^{\frac{1}{2}} \cos \theta_{23} \end{aligned} \quad (1.24)$$

where parameter θ_{23} is called mixing angle.

Then for probability amplitudes we have

$$\begin{aligned} A_{\tau, \mu} &= (1 - |U_{e3}|^2)^2 \sin^2 2\theta_{23}, \\ A_{e, \mu} &= 4 |U_{e3}|^2 (1 - |U_{e3}|^2)^2 \sin^2 2\theta_{23} \end{aligned} \quad (1.25)$$

All mentioned expressions are rough. More precise equations are used in the NO ν A experiment for calculating the parameters. general form of PMNS matrix parameterised by θ_{13} , θ_{23} , θ_{12} angles:

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{\frac{i\alpha_1}{2}} & 0 & 0 \\ 0 & e^{\frac{i\alpha_2}{2}} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad (1.26)$$

where $s_{ij} = \sin \theta_{ij}$, $c_{ij} = \cos \theta_{ij}$

Chapter 2

The NO ν A experiment

The NO ν A experiment[4] is a long-baseline neutrino experiment with two functionally identical detectors. Energy spectrum of neutrinos is produced by NuMI beam at the Fermilab national accelerator laboratory is measured by the Near Detector (ND) located 1 km away from the NuMI target [5]. The neutrinos are subsequently detected 810 km away in the Far Detector (FD) near Ash River, Minnesota. The 14-kton FD is located on the surface while the 290-ton ND is 100 m underground. Both detectors are sited off the central beam axis. The FD is 14.6 mrad off-axis so that the resulting narrow neutrino-energy spectrum peaks around 2 GeV, near the first oscillation maximum. The ND is positioned to maximize the similarity between the neutrino energy spectra observed at the two detectors. The flavor composition of beam neutrinos interacting in the ND (FD) is estimated from simulation to be 97.5% (97.8%) ν_μ , 1.8 % (1.6%) $\bar{\nu}_e$ and 0.7% (0.6%) $\nu_e + \bar{\nu}_e$ between 1-3 GeV, assuming no oscillations. Both detectors are segmented, tracking calorimeters with organic scintillator constituting 62% of their fiducial mass. Reflective polyvinyl chloride cells of length 15.5 m (3.9 m) in the FD (ND) with a $3.9 \times 6.6 \text{ cm}^2$ cross section are filled with liquid scintillator. The cells are arranged in 896 (214) planes in the FD (ND) and alternate between vertical and horizontal orientations to allow three-dimensional reconstruction. Muon containment is improved at the downstream end of the ND by ten layers of 10-cm-thick steel. Each layer of steel is interleaved with two planes of scintillator, one in each orientation. Light produced by charged particles is collected by a loop of wavelength-shifting optical fiber in each cell and measured with an avalanche photodiode (APD). APD signals within a 550- μs time windows centered on the 10- μs NuMI beam spill are stored. Other time windows are also recorded for calibration and background measurements.

2.1 Measurement of oscillation parameters

Neutrino energy spectra in both detectors is measured by registering neutrino charged current events (CC-events). Flavor of interacted neutrino is determined by flavor of a lepton appeared as the result of interaction. Primary energy of neutrino is defined by a sum of energies of all the interaction products. Measurement of oscillation parameters is done by measuring probability of oscillations as a function of energy with further fitting the function by a theoretical predicted formula. That can be done by changing values of Δm_{32} and θ_{23} in theoretical model. The process continues till the best correspondance is achieved. Parameters providing such correspondance are acknowledged as true values.

Chapter 3

Working with NO ν A software

My task on the summer program was to learn to use several instruments applied in the NO ν A experiment . These instruments are simulation and analysis tools withing software called Nova-Art [8].

3.1 Common setup for NO ν A software.

I was working on cloud machines provided by the Laboratory of Information Technologies, JINR. Connection establishment with the machines was performed through ssh-protocol with the use of Linux terminal. Example off the log-in procedure and tools adjustment is represented below:

```
[ user@nova ~ ] $ ssh cldvm121.jinr.ru
[ user@cldvm121 ~ ] $ setup_nova -r S17-06-19
Nova Offline Environment Enabled (CVMFS Base)
Appending LIBRARY_SHIM_SL6_LIB_PATH to LD_LIBRARY_PATH
nutools version v1_21_11 NOT GREATER THAN v2_02_00; DO NOTHING
/cvmfs/nova.opensciencegrid.org/externals/art/v1_17_06/slf6.x86_64.e9.nu.debug/bin/checkClassVersion

Release: S17-06-19
Build: debug
Build Date: 2017-06-19 11:22:54

PWD: /afs/jinr.ru/user/

[ user@cldvm121 ~ ] $ cd /mnt/nova/user/S17-06-19/
[ user@cldvm121 S17-06-19] $ srt_setup -a
[ user@cldvm121 S17-06-19] $
```

To start working with NO ν A software after connection to the machine one should download required release of the software from the Fermilab database.

After connecting download is available and can be initialized by a following command:

```
newrel -t <release version> <directory>
```

This procedure is done once. There is no need to download files after each connection. The files are stored on the cloud machine. Other following procedures should be done each time one connects to cldvm.

Next, required release should be initialized at the common (public) directory for that release by a command:

```
setup_nova -r S<date of release>
```

Release initialization can be done before downloading. Downloaded release files do not influence the initialization anyhow. All instruments for it are already installed on cldvm. Next step is to set a folder from where NO ν A instruments will be launched. For that we need to change a directory to the folder of downloaded release by a command:

```
cd <directory>
```

The following command initiates instruments from the current local release directory:

```
srt_setup -a
```

After that the software is ready for use for both public and local environment. NO ν Asoft basic idea is to use all the modules from local release first, then if they are missing they are being initiated from the public area. These modules can for NO ν Asoft can be downloaded from the Fermilab database by a command

```
addpkg_svn <name of the module>
```

I worked with EventGenerator and KalmanTrackFit packages. The first one allows to generate different particles with given parameters in the detectors' volumes in order to study their movement inside the detectors and interaction with the scintillator. The second one allows to reconstruct energy of particles left inside the detectors.

3.2 EventGenerator package

EventGenerator allows to generate single and multiple particles at one time. I was working only with single muons. Setup of particle's parameters is done in SingleGen.fcl file. On the fig 3.1 one can see the full list of applying parameters. The parameters can be set definitely or they can be set as a random number from a set interval. In case of random parameters possibility of each value can be set to be governed by Gauss or uniform distribution. After all of the parameters is set the file should be saved and the package should be compiled. For that one needs to change directory to the folder with the package and initiate a command:

```
make EventGenerator.all
```

Now the package is ready for launch. A command:

```
nova -c prodsingle.fcl -n <number of events>
```



```
amvrosov@cldvm121:/mnt/nova/amvrosov/S16-06-01
BEGIN_PROLOG
standard_singlep:
{
  module_type: SingleGen
  PDG: [13] # Particle data group particle code
  P0: [2.0] # Central momentum in GeV
  SigmaP: [2.0] # Variation in momentum in GeV
  PDist: [0] # How to vary momentum (0=uniform, 1=gaussian)
  X0: [0.0] # central position in cm
  Y0: [0.0] # central position in cm
  Z0: [150.0] # central position in cm
  T0: [14005.0] # central time in ns
  SigmaX: [100.0] # variation in x in cm
  SigmaY: [100.0] # variation in y in cm
  SigmaZ: [100.0] # variation in z in cm
  SigmaT: [0.0] # variation in time in ns
  PosDist: [0] # How to vary positions (0=uniform, 1=gaussian)
  CosZ0: [0.9] # Central value of cosine theta wrt z-axis
  SigmaCosZ: [0.1] # Variation in cosine theta
  PhiXY0: [0] # Central angle in xy plane (degrees)
  SigmaPhiXY: [180] # Variation in phi (degrees)
  AngleDist: [0] # How to vary angular parameters (0=uniform, 1=gaussian)
}
1,1 Top
```

Figure 3.1: An example of SingleGen.fcl file

```

amvrosov@cldvm121:/mnt/nova/amvrosov1/amvrosov/S16-06-01
File Edit View Search Terminal Help

PionMinusInelastic Models:          QGSP: Emin(GeV)= 12  Emax(GeV)= 100000
                                     G4LEPionMinusInelastic: Emin(GeV)= 9.5  Emax(GeV)= 25
                                     BertiniCascade: Emin(GeV)= 0  Emax(GeV)= 9.9

PionMinusInelastic Crs sctns:      G4CrossSectionPairGG: Emin(GeV)= 0  Emax(GeV)= 100000
                                     G4CrossSectionPairGG: G4PiNuclearCrossSection cross sections
                                     below 91 GeV, Glauber-Gribov above
                                     GheishaInelastic: Emin(GeV)= 0  Emax(GeV)= 100000

hBertiniCaptureAtRest

Hadronic Processes for <proton>
-----
hadElastic Models:                  hElasticCHIPS: Emin(GeV)= 0  Emax(GeV)= 100000

hadElastic Crs sctns:              ChipsProtonElasticXS: Emin(GeV)= 0  Emax(GeV)= 100000
                                     GheishaElastic: Emin(GeV)= 0  Emax(GeV)= 100000

ProtonInelastic Models:           QGSP: Emin(GeV)= 12  Emax(GeV)= 100000
                                     G4LEProtonInelastic: Emin(GeV)= 9.5  Emax(GeV)= 25
                                     BertiniCascade: Emin(GeV)= 0  Emax(GeV)= 9.9

ProtonInelastic Crs sctns:        Barashenkov-Glauber: Emin(GeV)= 0  Emax(GeV)= 100000
                                     GheishaInelastic: Emin(GeV)= 0  Emax(GeV)= 100000

=====
### NovaG4EmSaturation::FindBirksCoefficient Birks coefficient for Scintillator 0.465658 mm/MeV
%MSG-i NoiseMaker: ReadoutSim:daq 31-Aug-2017 18:14:51 MSK run: 1000001 subRun: 1 event: 1
rsim::NoiseMaker Initializing...
%MSG
%MSG-i NoiseMaker: ReadoutSim:daq 31-Aug-2017 18:14:51 MSK run: 1000001 subRun: 1 event: 1
rsim::NoiseMaker: equivalent noise charge (current) = 488.611 electrons
%MSG
%MSG-i NoiseMaker: ReadoutSim:daq 31-Aug-2017 18:14:51 MSK run: 1000001 subRun: 1 event: 1
rsim::NoiseMaker: equivalent noise charge (voltage) = 33.1035 electrons
%MSG
%MSG-i NoiseMaker: ReadoutSim:daq 31-Aug-2017 18:14:51 MSK run: 1000001 subRun: 1 event: 1
rsim::NoiseMaker: nominal threshold (4*sigma_dcs) = 44.4722
%MSG
Begin processing the 2nd record. run: 1000001 subRun: 1 event: 2 at 31-Aug-2017 18:14:53 MSK
Begin processing the 3rd record. run: 1000001 subRun: 1 event: 3 at 31-Aug-2017 18:14:58 MSK
Begin processing the 4th record. run: 1000001 subRun: 1 event: 4 at 31-Aug-2017 18:15:02 MSK
Begin processing the 5th record. run: 1000001 subRun: 1 event: 5 at 31-Aug-2017 18:15:05 MSK
Begin processing the 6th record. run: 1000001 subRun: 1 event: 6 at 31-Aug-2017 18:15:09 MSK

```

Figure 3.2: An example of EventGenerator working.

starts generation of events with particles inside the chosen detector (fig. 3.2). The process of generation is longstanding: 1000 events with single muons are being generated over 40 minutes. And usually we require at least 10000 events to get enough statistics. The result of working of EventGenerator is performed by 2 ROOT (it is a common high energy physics analysis tools [9]) files: `single_gen.root` and `single_hist.root`. The first file contains all the information about generated events. The second one is empty by default. But one can modify a module file `SingleGen_module.cc` to create different trees (TTree class objects) to write all the parameters we need for histograms into them. After the modification is complete the package should be compiled to read last changes (actually each time package's files are modified the package should be compiled, this note refers to all of the packages in NOVA software). My first task was to perform such a modification. The result of the modification is show on fig. 3.3. In the example I added energies, impulse projections, mass of each particle and a counter «npart» to the tree called `Single_Gen_tree`. All of the events generated in the `single_gen.root`

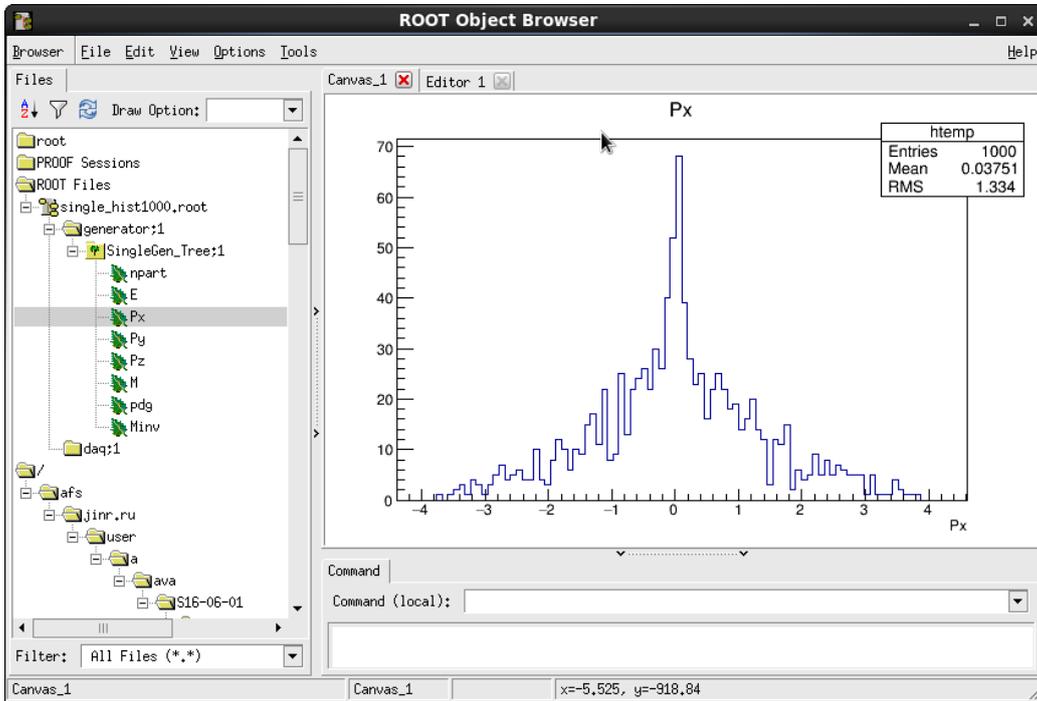


Figure 3.3: An example of single_hist.root file

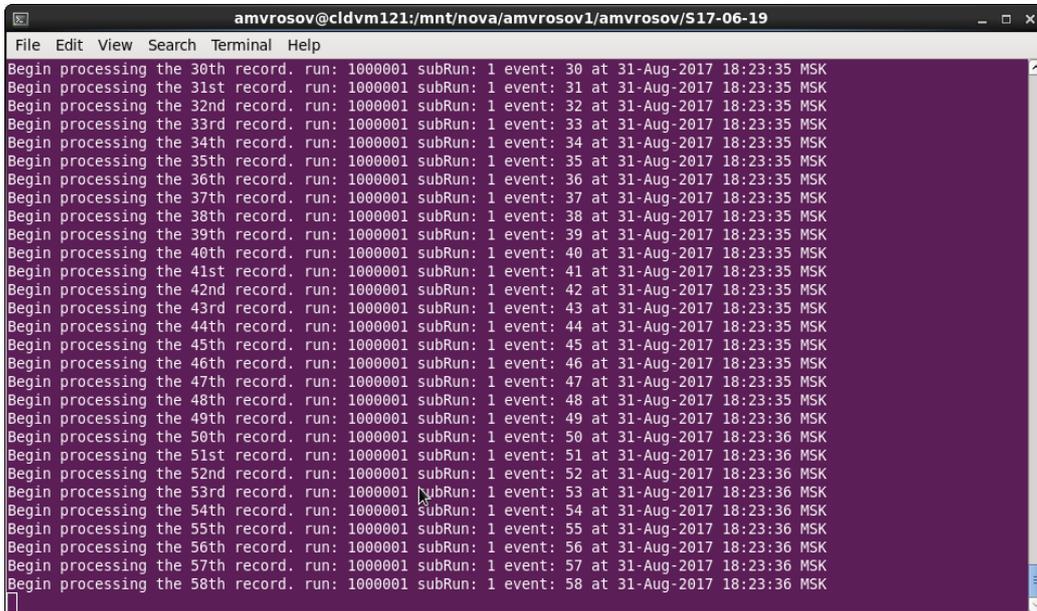


Figure 3.4: An example of analyzer working.

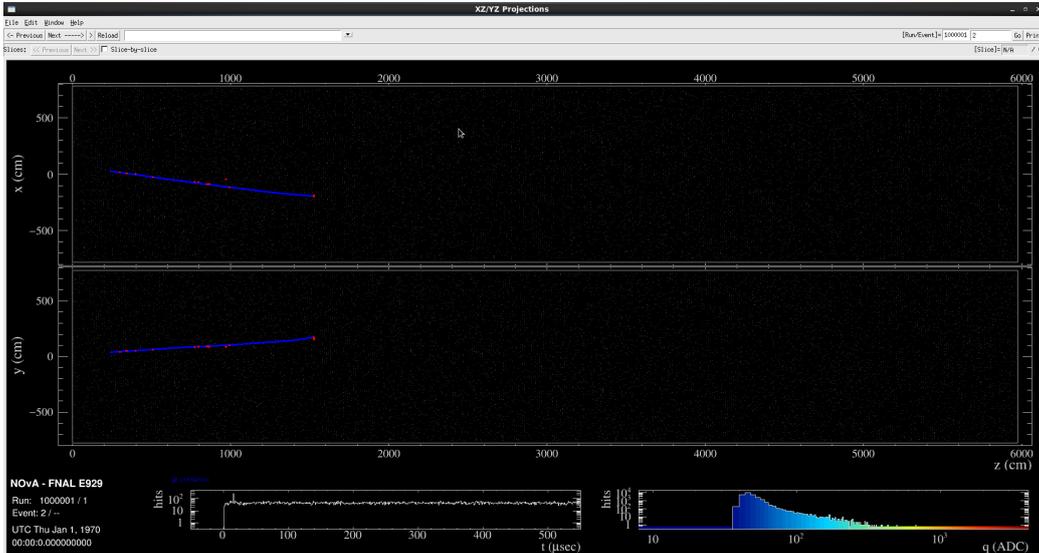


Figure 3.5: An example of analyzer output file.

file can be visualized by an EventDisplay module. To run the module one can execute evd.fcl by a following command:

```
nova -c evd.fcl <file with events' information>
```

An example of EventDisplay working is shown on a fig. 3.5.

Such an output like in single_hist.root is very useful because we can analyze simulated events using parameters received in simulation. The method of getting information about events described above is very inconvenient for the analysis because we need to run EventGenerator each time we add new parameters to the module file for output because they are being written during the generation. And as it was mentioned before each generation takes very much time. Besides it is also unnecessary work because all of the information we might need is contained in the single_gen.root file. The only thing that is needed to be done is to create a program which reads the information. Such programs are called analyzers. My second task was to create a new analyzer using existing carcass. The simplest analyzer contains several files so it should be treated like any NOVA soft package. Among these files there is a module file (<name_of_file>_module.cc) which I edited the same way as SingleGen file to get the same output. After compiling of the analyzer one can launch main executable file muonanajob.fcl to run the analyzer by a following command (fig. 3.4):

```
nova -c muonanajob.fcl <name of the file>
```

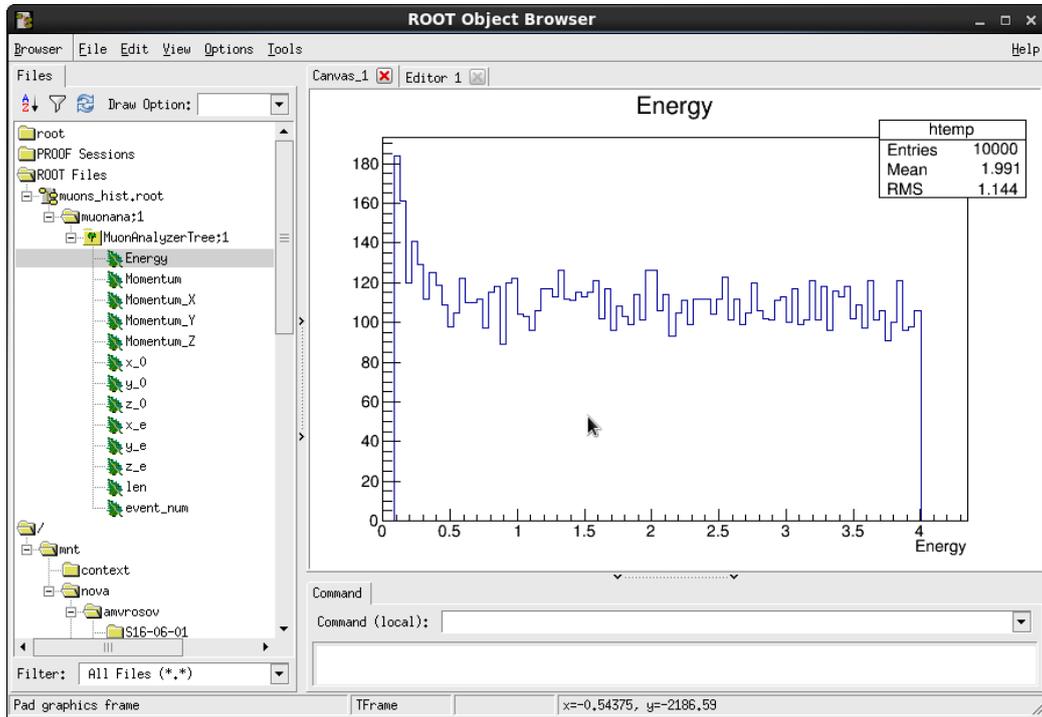


Figure 3.6: An example of EventDisplay working.

The last argument is an output file of EventGenerator (in the previous example it was `single_gen.root`). An output file of analyzer is a root file containing output parameters (example is shown on fig 3.6).

The method of using analyzer instead of writing different parameters during generation gives a big advantage in time. For instance generation of 10000 events with parameters' output takes about seven hours while analyzer needs about a minute to read the whole information from the file.

3.3 TrackFit package

After I was done with events simulation and creating analyzer I began working with TrackFit package. What does TrackFit do?

Spectra of muon neutrino from two detectors are measured in the experiment. The difference between them gives us the probability of oscillations of the particles. As it was mentioned before flavor of interacted neutrino by charged current is determined by a flavor of lepton which appeared as the result of interaction. In case of muon neutrino it is a muon that we should look for in the statistics. But there a not only muons from the neutrino that appear

in the detector. They can also come with cosmic rays or other interactions outside the detectors. In order to understand if the detected muon is the result of neutrino interaction within the detector volume or not we should determine the muons' trajectory. That is the purpose TrackFit was created for. The package handles the information about hits in detectors and tries to find (reconstruct) trajectories of particular particles among the hits. It is also a first step to reconstruction of primary energy of the particle. By default there are no parameters in the output represented by histograms. But as in the case of EventGenerator package one can modify a module file to create the output. In contrast to EventGenerator TrackFit package has its own analyzer. To launch the package you need to initiate the following command:

```
nova -c kalmantrackana.fcl -s <name of the file>
```

where the last argument is the file containing information about detected events. I tested TrackFit on previously simulated events by EventGenerator (fig. ??). The output file is `kalman_reco.root`. It contains information about reconstructed parameters. After that we need to create a file with histograms to analyze the received data. That can be done by the next command:

```
nova -c kalmantrackanajob.fcl -s kalman_reco.root
```

The output information has the same structure as in case of EventGenerator.

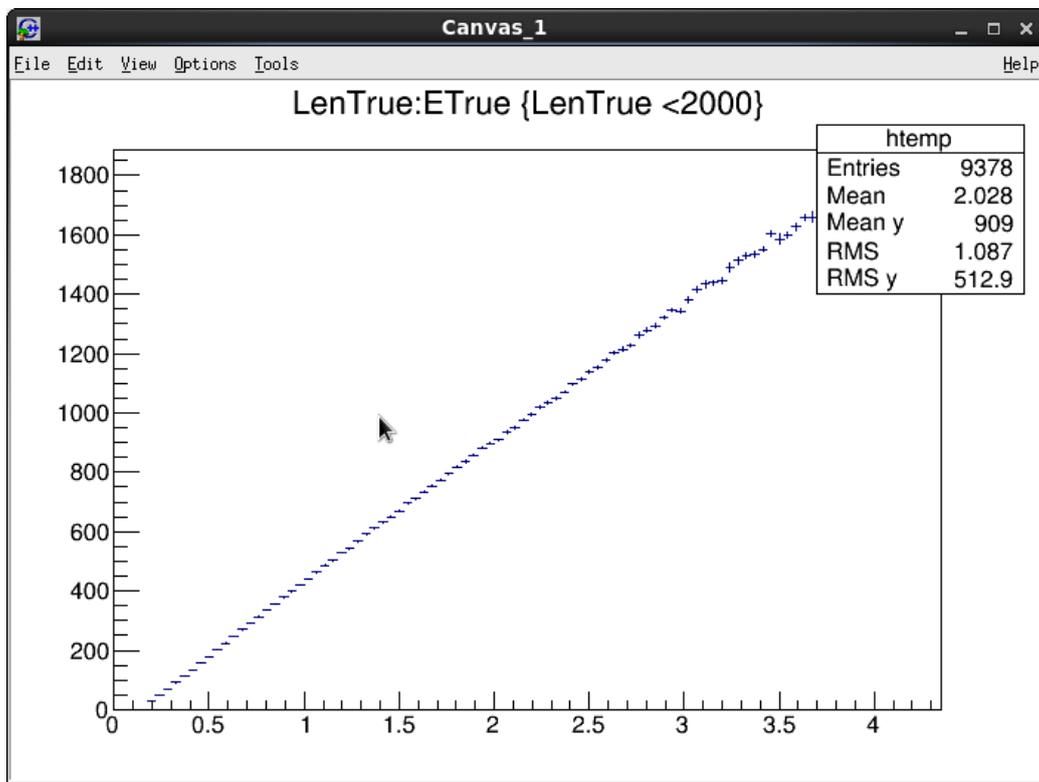


Figure 3.7: An example of analyzer output file.

Conclusion

Neutrino oscillations is a phenomenon lying beyond the Standard Model thus researches in this field are so important. NO ν A is a long-baseline neutrino experiment aimed to measure oscillation parameters Δm_{32}^2 and θ_{23} using muon disappearance channel. During my summer program I learned to use two modules of NO ν A software: EventGenerator and TrackFit. In future I plan to continue working at this vector in order to perform analysis of neutrino events in NO ν A.

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