JOINT INSTITUTE FOR NUCLEAR RESEARCH
Dzhelepov Laboratory of Nuclear Problem

FINAL REPORT ON THE
INTEREST PROGRAMME

Analysis and interactive visualization of neutrino event topologies registered in the OPERA experiment

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Abstract

In this project, various software tools were used to analyze and visualize event data obtained from the OPERA experiment. This experiment was designed to investigate neutrino oscillation (in this case it was the transmutation of muon neutrinos into tau neutrinos). Datasets from the experiment are published on the CERN Open Data portal. C++ and ROOT were used to construct 1D and 2D histograms in the first two tasks of the project, and the third one included using HTML, CSS, and Javascript for interactive visualization of tau neutrino event topologies.

Acknowlegement

I am grateful to the organizers of the INTEREST program for the unique opportunity to gain new knowledge both in the field of physics and in the field of data analysis and apply them in practice. The workflow of this online program is designed very conveniently and allowed me to participate in the project even though I had another time commitments.
I would like to express special gratitude to the mentor of the project in which I took part, Dr Sergey Dmitrievsky. His passion for work and passion for the subject of the project motivated me to put more effort into the tasks and helped me dive deeper into the field of study.

Introduction

Neutrino and its oscillations

Neutrino is a general name for neutral fundamental particles belonging to the class of leptons. Currently, three types of neutrinos are known: electron, muon and tau neutrinos. Also, each of them corresponds to an antineutrino.

Different types of neutrinos can transform into each other: these are the so-called neutrino oscillations. The idea of neutrino oscillations was first put forward by the Soviet-Italian physicist Bruno Pontecorvo in 1957, and in 2015 Takaaki Kajita and Arthur B. McDonald received the Nobel Prize in Physics for experimental confirmation of this phenomenon. Neutrino oscillations are evidence of a non-zero neutrino mass, which is inconsistent with the Standard Model of particle physics. This phenomenon has attracted the interest of many studies, and one of the consequences of that was the creation of the OPERA experiment.

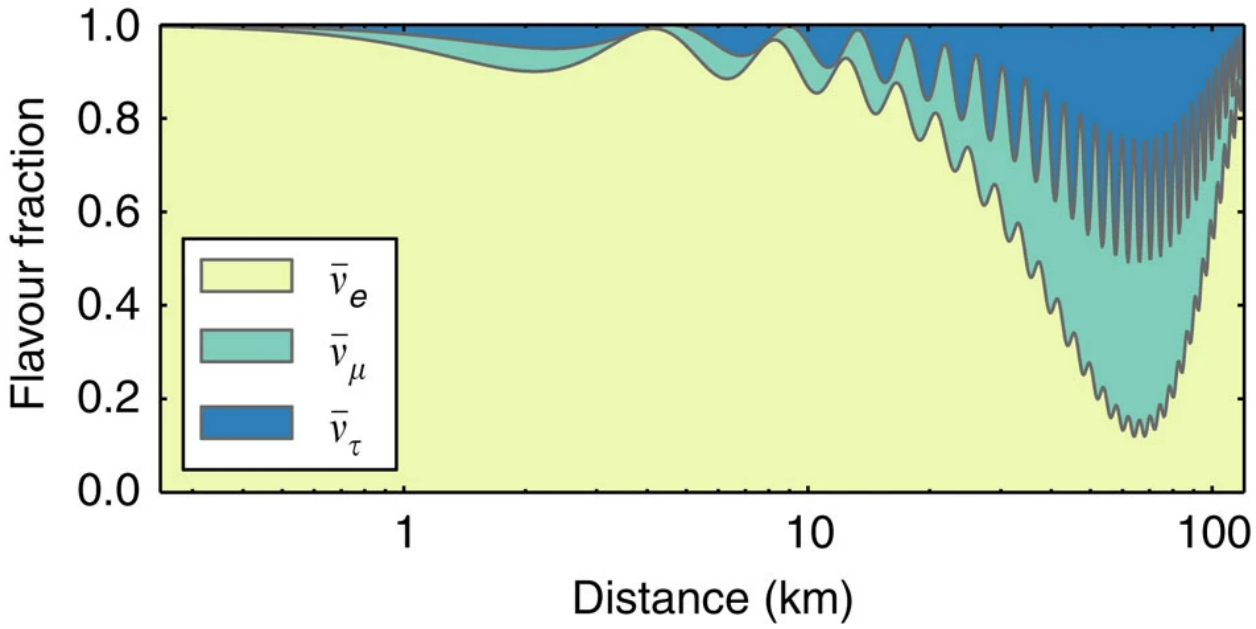
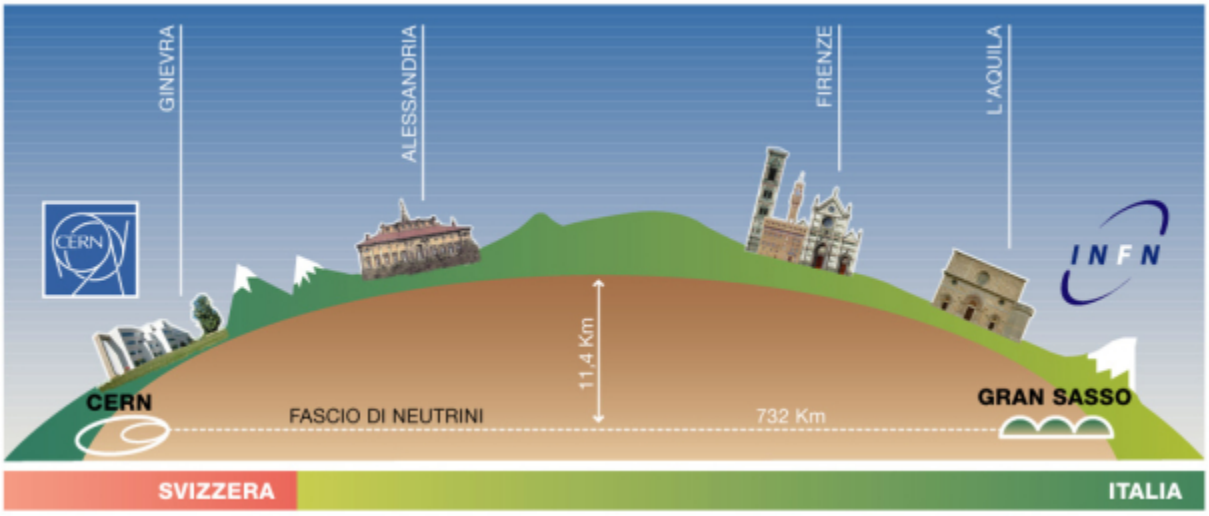


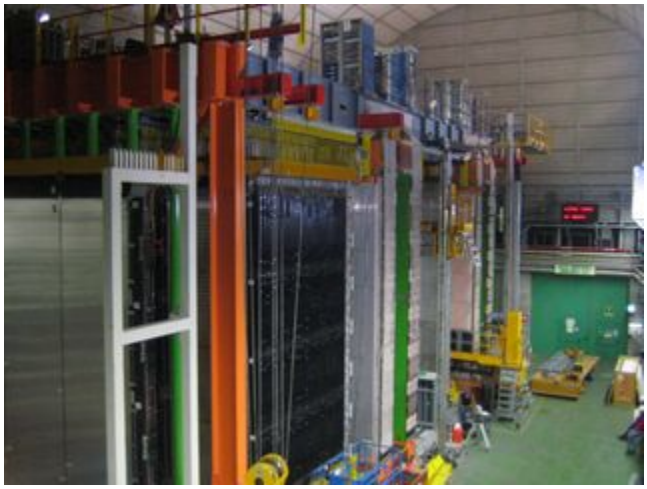
Illustration of neutrino oscillations from Wikimedia.

The OPERA experiment

The **Oscillation Project with Emulsion-tRacking Apparatus** (**OPERA**) was an instrument for investigation of the transmutation of muon neutrinos into tau neutrinos. It was a collaboration between CERN in Geneva, Switzerland, and the Laboratori Nazionali del Gran Sasso in Gran Sasso, Italy. Intensive beam of muon neutrinos was being produced in CERN and moving to Gran Sasso where OPERA was detecting the first appearance of tau neutrinos as a result of oscillation.



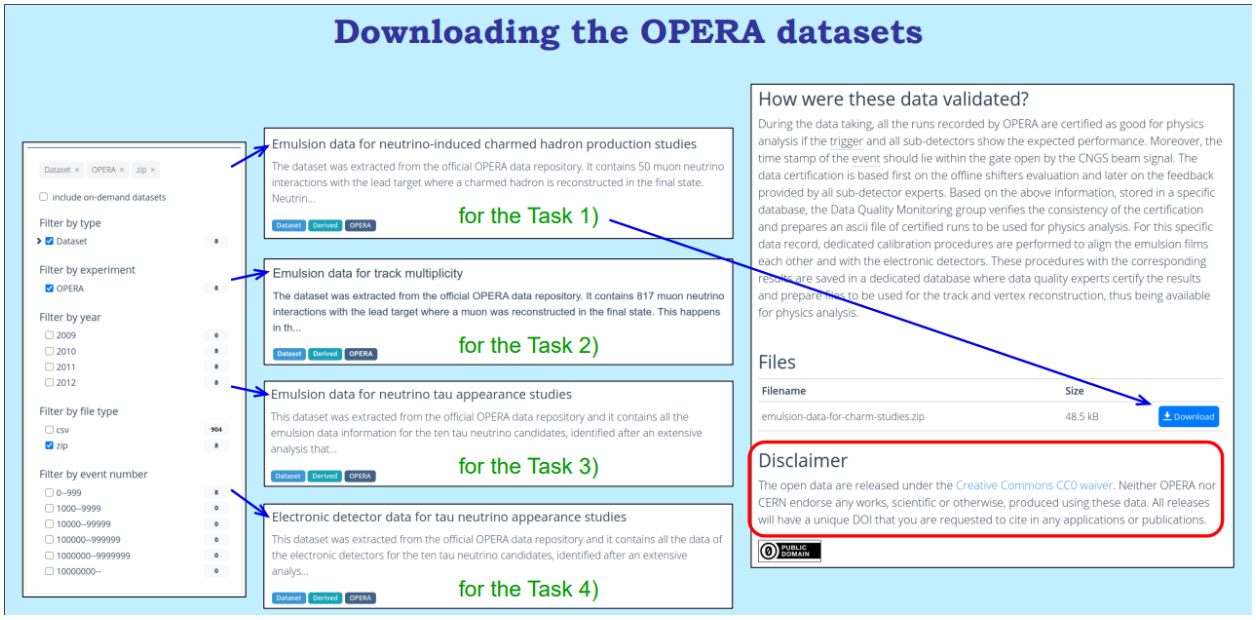
OPERA was a hybrid detector: it included a target part consisting of 150,000 emulsion blocks and electronic detectors that served to register the time of arrival of events, to determine the location of the vertex of an event and to identify particles.



General view of the OPERA Detector from Wikimedia

The CERN Open Data portal

CERN makes publicly available the data it has collected, including those collected at OPERA. The CERN Open Data portal is used as a repository. Here can be found a large number of different datasets, both from real experiments and simulated ones, as well as accompanying software and documentation. The information storage system is designed conveniently with the ability to search for data and filter it by type, experiment, year, and so on. In the project, we used the datasets from the illustration below.



Project tasks

Task 1

“Download OPERA emulsion dataset for the neutrino-induced charmed hadron production studies from the Open Data Portal. Develop a C++ program for analysis of the dataset. Read the positions of the primary and the secondary interaction vertices as well as the parameters of the charm decay daughter particle tracks. Calculate and save to histograms a) flight lengths of charmed hadrons and b) impact parameters of the daughter particle tracks with respect to the primary neutrino interaction vertices. Save the histograms to a ROOT or to an image file. Compare the results with the ones published in the corresponding OPERA paper”

For the task *a)* we needed to apply the formula for finding the distance between two points (the vertices of neutrino representation):

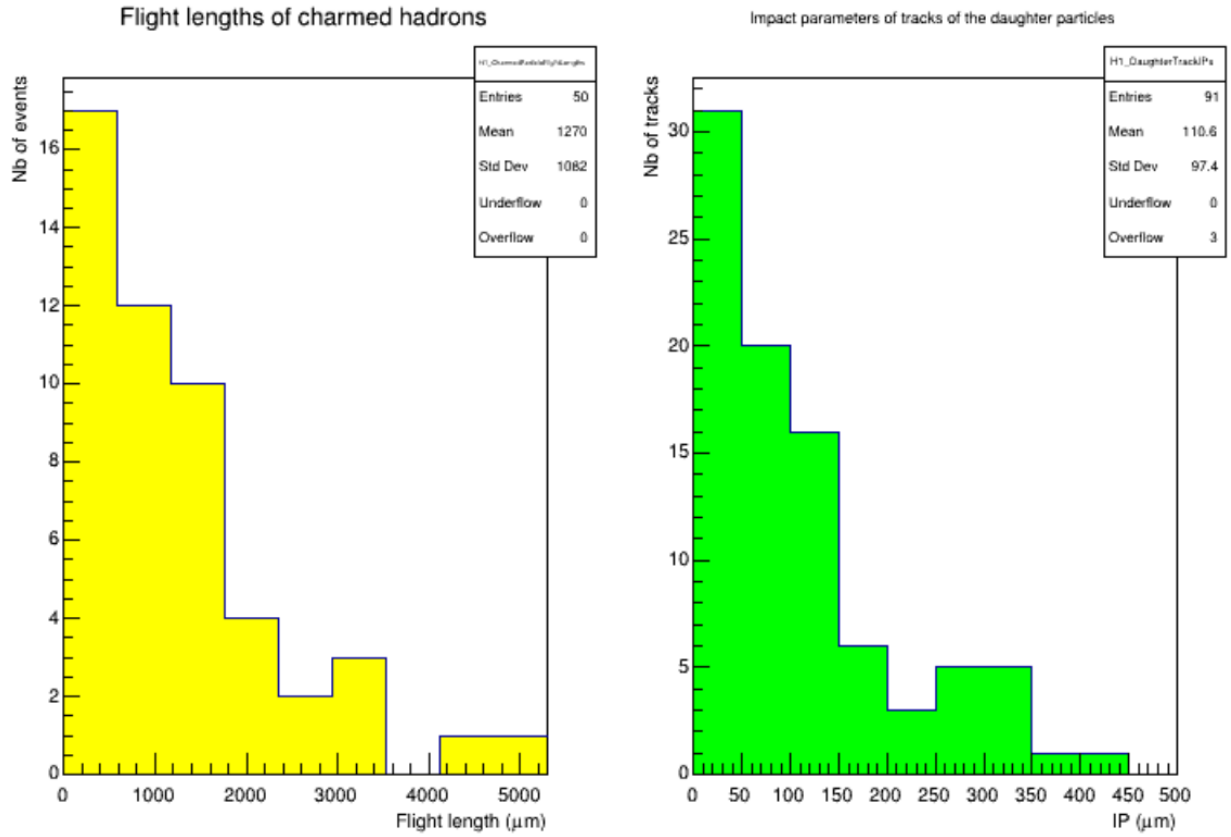
$$D = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}$$

For the task *b)* the formula for finding the distance between a point (here it is the primary neutrino interaction vertex) and a line (the track’s line) was used:

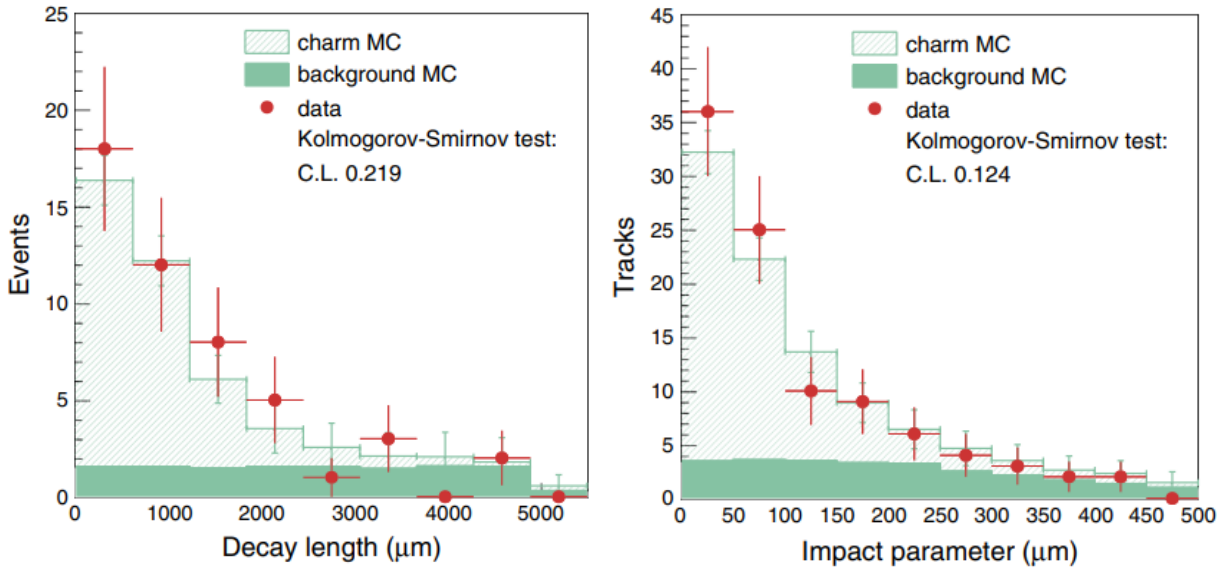
$$IP = \frac{|\overline{V_0V_1} \times \overline{V_1P_2}|}{|\overline{V_1P_2}|} = \frac{\begin{vmatrix} \bar{i} & \bar{j} & \bar{k} \\ dx_{10} & dy_{10} & dz_{10} \\ dx_{21} & dy_{21} & dz_{21} \end{vmatrix}}{\sqrt{dx_{21}^2 + dy_{21}^2 + dz_{21}^2}} =$$

$$= \sqrt{\frac{(dy_{10}dz_{21} - dy_{21}dz_{10})^2 + (dx_{10}dz_{21} - dx_{21}dz_{10})^2 + (dx_{10}dy_{21} - dx_{21}dy_{10})^2}{dx_{21}^2 + dy_{21}^2 + dz_{21}^2}}$$

The following pictures were obtained as a result:



It is comparable enough with the results from the corresponding [paper]():

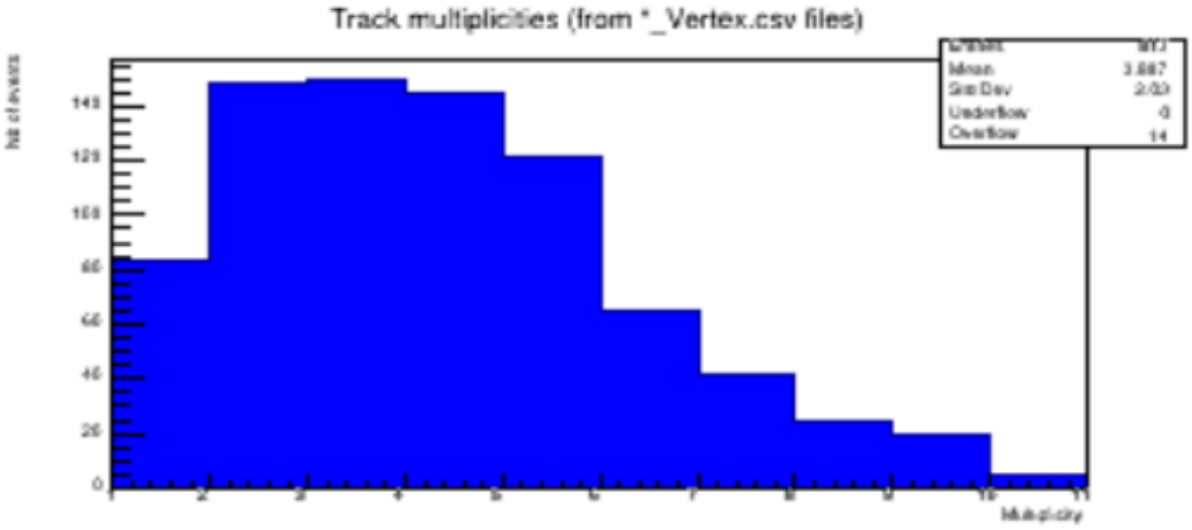


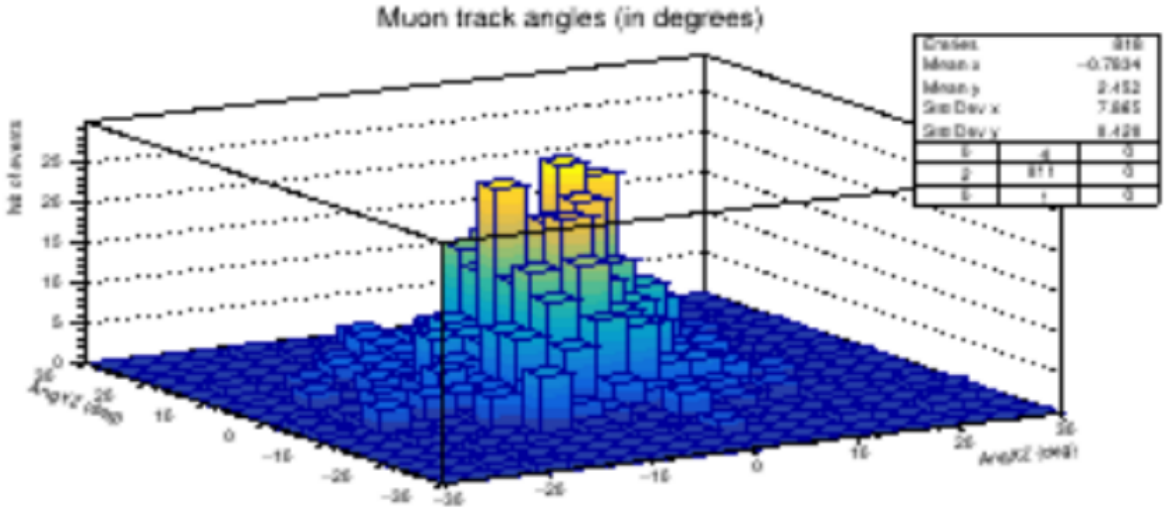
Task 2

“Download OPERA emulsion dataset for the charged hadron multiplicity studies from the Open Data Portal. Develop a C++ program for analysis of the dataset. Read the positions of the primary neutrino-lead interaction vertices as well as the parameters of the secondary charged particle tracks. Find and save to histograms a) multiplicities of all produced charged particles and b) angles of the muon tracks. Save the histograms to a ROOT or to an image file. Compare the results with the ones published in the corresponding OPERA paper”

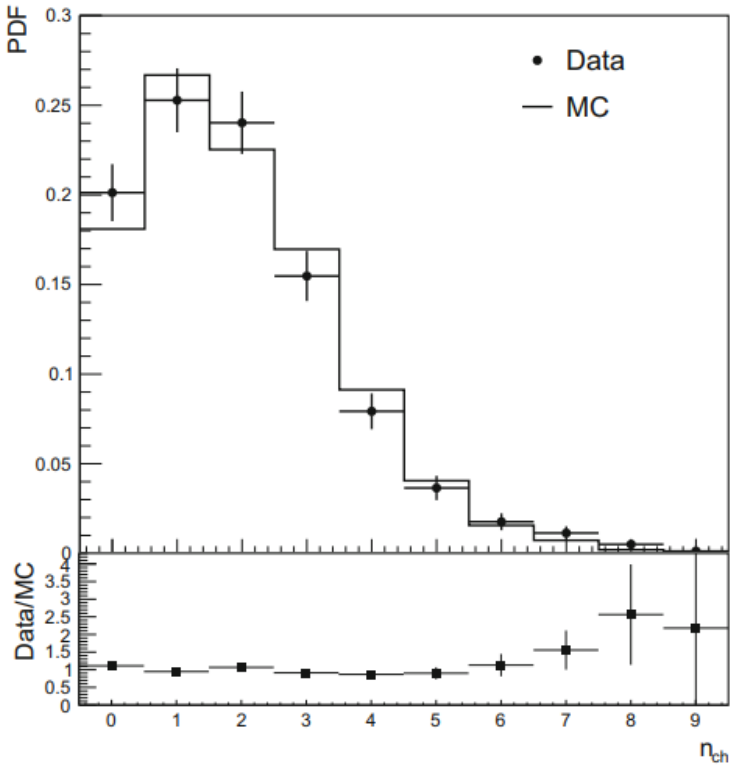
For the task *a)* it was needed to draw an 1D histogram.
For the task *b)* the *atan()* function was used for calculations. In this case the histogram is 2D.

The result is following:





Here is a picture from the paper for comparison:

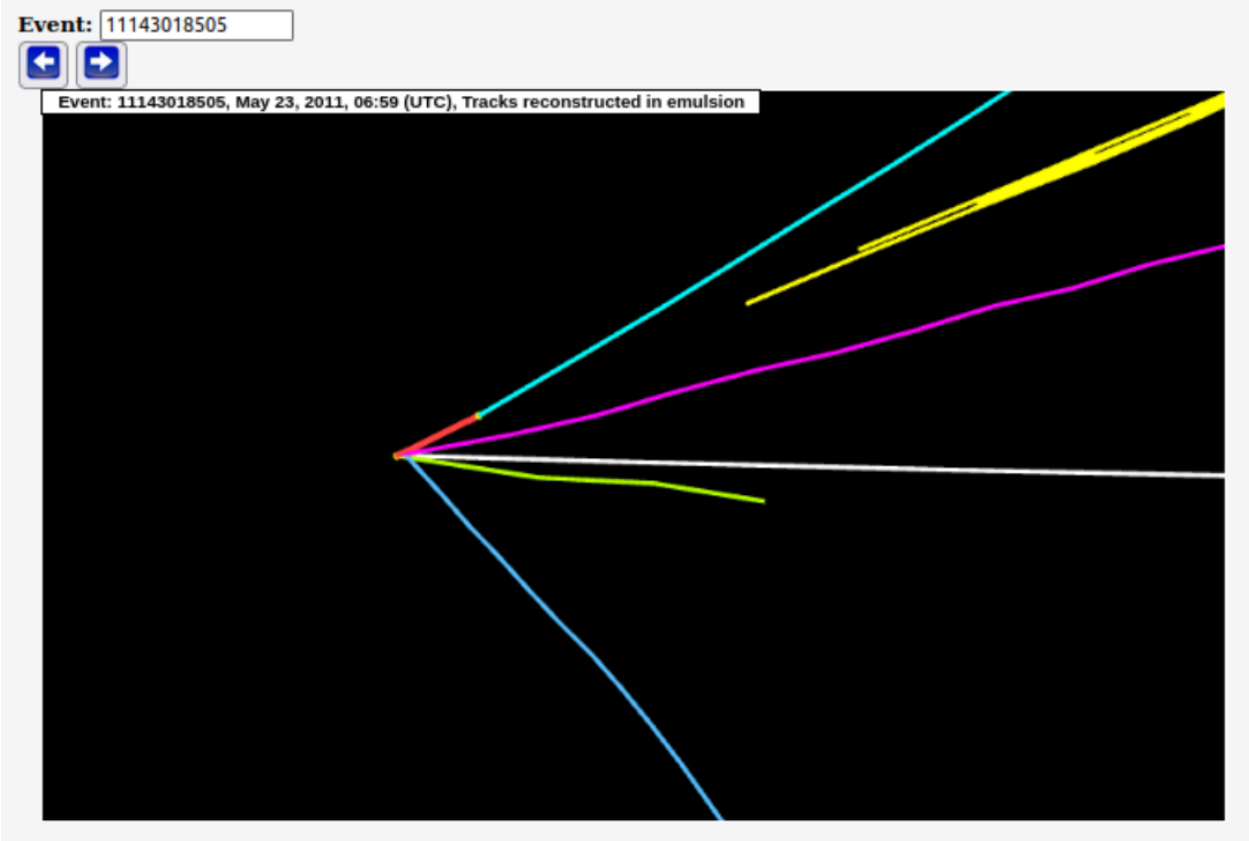


The histogram above is also comparable enough.

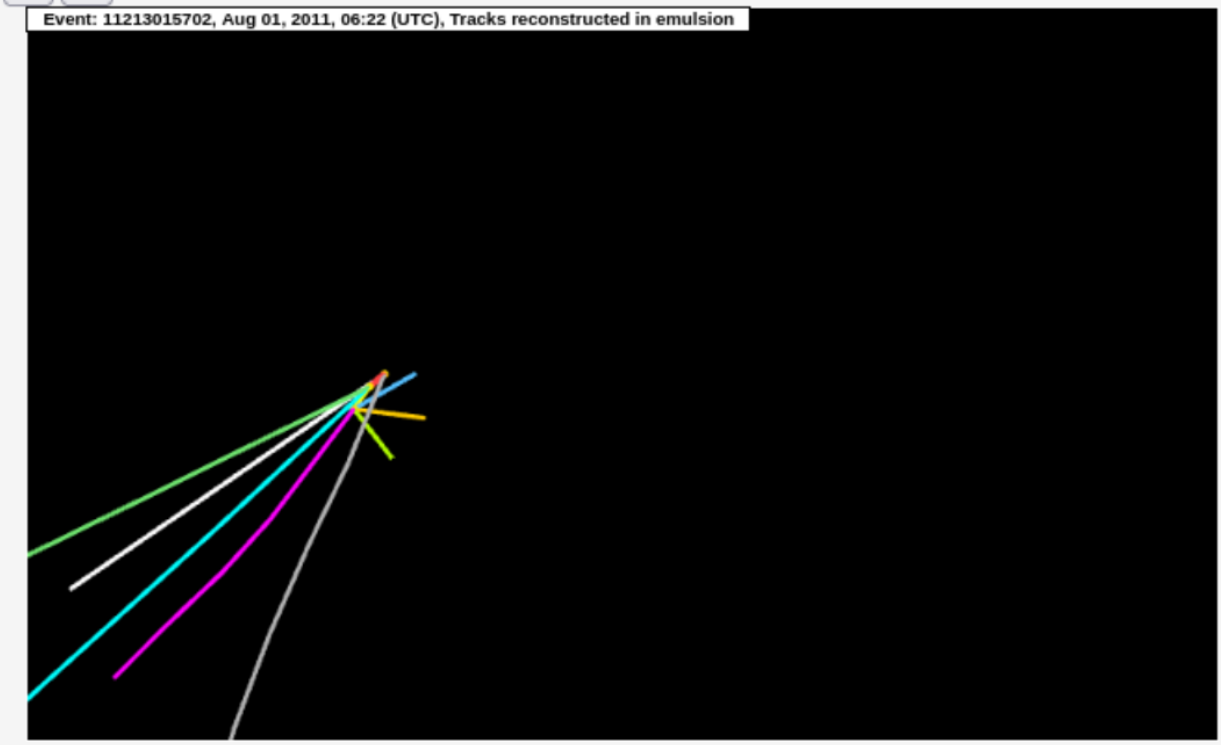
Task 3

“In this task OPERA emulsion dataset for the tau neutrino appearance studies from the Open Data Portal will be used. A simplified version of a browser based 3D event display that uses the THREE.js graphics library will be provided with missing parts of the source code. It will be suggested to recover the code in order to display tracks and vertices reconstructed in nuclear emulsions in the 10 tau neutrino candidate events”

In this task it was needed to fill in the missing code snippets in the browser project. As a result, we got an browser-based application that allows to interactively look at tracks and vertices of an event. For example, here two events, 11143018505 and 11213015702, are displayed below:



Event: 11213015702



Conclusion

In this project, I and other participants under the guidance of our mentor tried some data analysis and visualization tools, including such development stacks as C++/ROOT and HTML/CSS/JavaScript with libraries. As a result, it became possible to recreate some graphs from the original scientific papers. This is an infinitely valuable experience for further immersion in this area.

Bibliography

1) About OPERA (https://opendata.cern.ch/docs/about-opera)
2) CERN Open Data Portal (https://opendata.cern.ch)
3) CERN ROOT online manual (https://root.cern)
4) The OPERA experiment in the CERN to Gran Sasso neutrino beam (https://iopscience.iop.org/article/10.1088/1748-0221/4/04/P04018/pdf)
5) “Поиск осцилляций нейтрино в канале $\nu_\mu \rightarrow \nu_\tau$ с помощью гибридного детектора эксперимента OPERA”, Физика элементарных частиц и атомного ядра, 2013, т. 44, вып. 4