JOINT INSTITUTE FOR NUCLEAR RESEARCH

Dzhelepov Laboratory of Nuclear Problems

# FINAL REPORT ON THE SUMMER STUDENT PROGRAM

*Searching for the optimal parameters to cut background events in the JUNO experiment*

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**Abstract**

During the time of practicing a principle of the JUNO neutrino detector work was studied, also a method of cutting a background noise from the vessel capacity while a muon moving through it was invented. The method was checked on muons generated with a Monte-Carlo simulation. In this report next topics are mentioned: a brief history of a neutrino research and nowadays perspectives, a basic theory of neutrino oscillations, a description of the JUNO experiment, a description of the work made by an author.

## 1 Introduction

One of the large projects of the DLNP is the neutrino oscillations research. In the framework of this study a Jiangmen Underground Neutrino Observatory, more known as JUNO is being built. An aim of this experiment is the determination of the neutrino mass hierarchy by detecting reactor antineutrinos from two nuclear power plants (NPPs) and to perform precision measurements of the Pontekorvo-Maki-Nakagava-Sakata (PMNS) matrix.[1] A building process is going to come to its end in 2020. The detector will be situated equidistantly from Taishan and Yangjiang NPPs (53 km) that is shown in Fig. 1. The thermal power and baselines are listed in Table 1

| Cores | YJ-C1 | YJ-C2 | YJ-C3 | YJ-C4 | YJ-C5 | YJ-C6 |
|---|---|---|---|---|---|---|
| Power (GW) | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 | 2.9 |
| Baseline(km) | 52.75 | 52.84 | 52.42 | 52.51 | 52.12 | 52.21 |
| Cores | TS-C1 | TS-C2 | TS-C3 | TS-C4 | DYB | HZ |
| Power (GW) | 4.6 | 4.6 | 4.6 | 4.6 | 17.4 | 17.4 |
| Baseline(km) | 52.76 | 52.63 | 52.32 | 52.20 | 215 | 265 |

Table 1: Summary of the thermal power and baseline to the JUNO detector for the Yangjiang (YJ) and Taishan (TS) reactor cores, as well as the remote reactors of Daya Bay (DYB) and Huizhou (HZ).

The main detector consists of a PMMA sphere, containing 20 tons of linear alkylbenzene liquid scintillator. It is surrounded by inox steel truss, supporting approximately 53000 PMTs.[2]

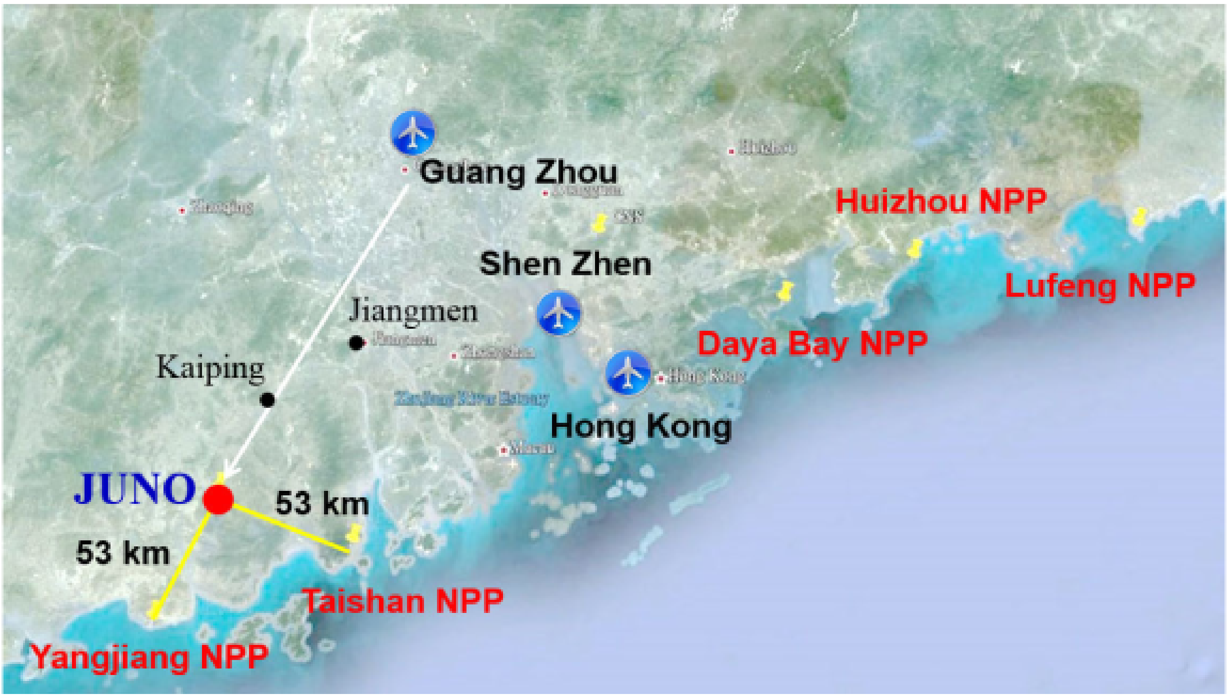


Fig.1 Location of the JUNO, NPPs and nearby objects

## 2 Reactor neutrinos and background

### 2.1 Classification

Reactor neutrinos are electron antineutrinos emitted from $\beta$-decays. In reactors close to JUNO four types of fuel are used: $^{235}$U, $^{238}$U, $^{239}$Pu and $^{241}$Pu. Their fission rates can be predicted via core simulation and thermal power measurements. The reactor neutrino flux can be estimated as

$$\Phi(E_\nu) = \frac{W_{th}}{\Sigma_i f_i e_i} \cdot \sum_i f_i \cdot S_i(E_\nu)$$

Here $W_{th}$ is the thermal power of the reactor, $f_i$, $e_i$ and $S_i(E_\nu)$ are fission fraction, the thermal energy released in each fission and the neutrino flux per fission for the $i$-th isotope, respectively. Such a prediction is expected to carry an uncertainty of 2-3%.

JUNO measures the reactor antineutrino signal via the inverse beta decay reaction

$$\overline{\nu}_e + p \rightarrow e^+ + n \ .$$

A positron quickly annihilates creating two 511-keV photons, which give a signal while the neutron scatters in the detector until being thermalized. ~200 $\mu$s later it is captured by a proton and releases a 2.2-MeV photon. A scheme of this process is shown in Fig. 2

The major backgrounds for the reactor neutrino analysis are the accidental background, $^8$He/$^9$Li, fast neutron and ($\alpha$, n) background. Fiducial volume cut reduces the accidental and ($\alpha$, n) backgrounds.

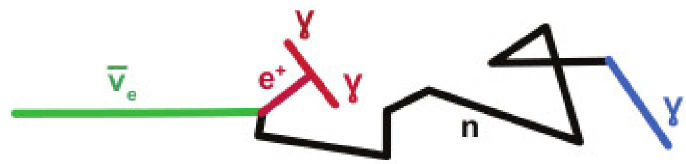


Fig 2. The scheme of processes happening after the inverse $\beta$-decay.

To reject the cosmogenic backgrounds such as $^8$He/$^9$Li and fast neutron muon veto cuts are necessary and they need to be minimized to reduce the loss of the live time of the detector. Here is listed a set of antineutrino selection criteria.[3]

1. Fiducial volume $r < 17m$.
2. The prompt energy 0.7 MeV $< E_p <$ 12 MeV.
3. The delayed energy 1.9 MeV $< E_d <$ 2.5 MeV.
4. Time between prompt and delayed signals $\Delta$T $<$ 1.0 ms.
5. The prompt – delayed distance $R_{p-d} <$ 1.5 m.
6. The muon veto criteria.

## 2.2 Background estimation

### 2.2.1 Accidental background

For suppressing background this one fiducial volume cut is the most important one. The total rate of accidental backgrounds is expected to be about 0.9 per day after taking into account the efficiency of muon veto. The uncertainty of accidental background rate can be controlled within 1% and the uncertainty of spectrum shape is negligible due to the large statistics of prompt-like singles [3]

### 2.2.2 $^8$He/$^9$Li

This type of background is estimated to be the most correlated to reactor antineutrinos. The cross section of these ions is usually thought as a proportion to an energy of a muon at the detector. The cross section was measured in the KamLAND[4] detector as $2.2 \cdot 10^{-7} \mu^{-1} g^{-1} cm^2$ for $^9$Li and $0.7 \cdot 10^{-7} \mu^{-1} g^{-1} cm^2$ for $^8$He. Thus the production rate for these ions at JUNO is expected to be 150 and 50 day$^{-1}$, respectively. In practice, the rate of $^8$He/$^9$Li can be measured from the distribution of the time since the last muon using the known decay times for these isotopes[3].

The $^8$He/$^9$Li background is correlated with the parent muon in time and space. The lateral distance between the muon-induced isotopes and the parent muon trajectory is roughly exponential. The most effective approach to reject $^8$He/$^9$Li background is to veto a sufficient detector volume along the muon trajectory for a relative long time, e.g, a few times of the isotope's lifetime. Muons that are accompanied by electromagnetic or hadronic showers, usually named as showering muons, are the dominant producers ($>$85%) of the radioactive isotopes. The simulation for JUNO also suggests that after producing a shower, the muon still survives and its direction changes negligibly.

### 2.2.3 Fast neutrons

The cosmic muons that only passing the surrounding rock of the water pool, as well as the corner clipping muons with very short track length in water, are not able to be tagged. The energetic neutrons produced by those muons can form a fast neutron background by scattering off a proton and then being captured in the LS detector. The rate of fast neutrons is expected to be $\sim 0.1$ per day. The signals produced by the energetic neutrons are found to be concentrated at the top of detector and near the equator where the water shielding is minimum.

For the analysis, we assume the relative rate uncertainty is 100%. The prompt energy spectrum is consistent with a flat distribution. The tagged fast-neutrons can actually provide good information about the energy spectrum. In this analysis, we assume the shape uncertainty is 20%.[3]

# 3 Algorithm of $^8$He/$^9$Li cut

## 3.1 Ions production

During muon deep inelastic scettering (DIS) it produces a great number of particles along its trajectory. Most of them are $\pi^\pm$ and $\pi^0$ objects. $^8$He and $^9$Li are produced when pions interact with nuclei of scintillator. These reactions usually happen near a muon track. Fig. 3 shows their production probability distribution depending on a distance from a muon track. It is well-seen that probability hyperbolically decreases with increasing distance.

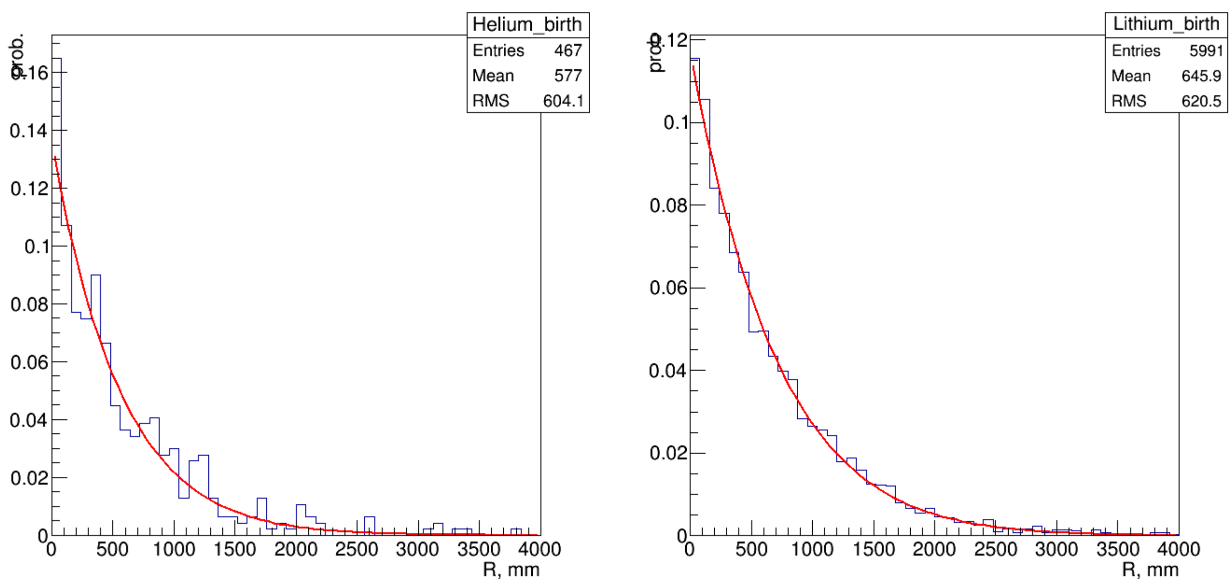


Fig 3. The graph of $^8$He/$^9$Li production probability. R is a distance from the muon track.

According to a simulation, helium fraction of the total number of particles is estimated to be ~7.2%; lithium fraction is ~92.8%.

When muon interacts with scintillator producing pions, a big splash of energy is released. It may be seen on a histogram of energy release shown on Fig. 4.

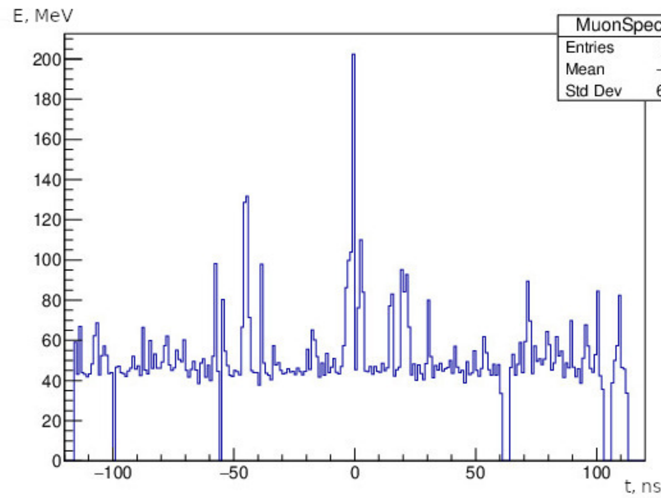


Fig 4. The release of energy during the muon pass the fiducial volume. t is time with a zero at the peak of histogram.

The peak of this histogram means a moment of time when a number of pions was produced. They move in all directions and interact with nuclei around them. So $^{8}$He and $^{9}$Li ions appear. Computer simulation confirm this.

After the producing ions muon continues moving in another direction. So the distribution of ion events is estimated to look like an abrupt change in quantity of particles and then a return to an ordinary level. Such a result can be seen in Fig. 7 where a histogram of events is shown. It represents a number of produced ions depending on from the point of interaction between the muon and some nucleus and a distance from a muon track. Summing up, a muon moves along a straight line, then it interacts with the scintillator, producing ions and changes its direction. So the diagram of the producing particles looks plainly, then leaps and returns to plain line. It is shown on Fig. 5.

### 3.2 Selection of the cut form

First variants of muon cut looked like a simple cylinder with a main axis coincided with a muon track. It worked but a problem was that too much space was cut out and a live time was lost.

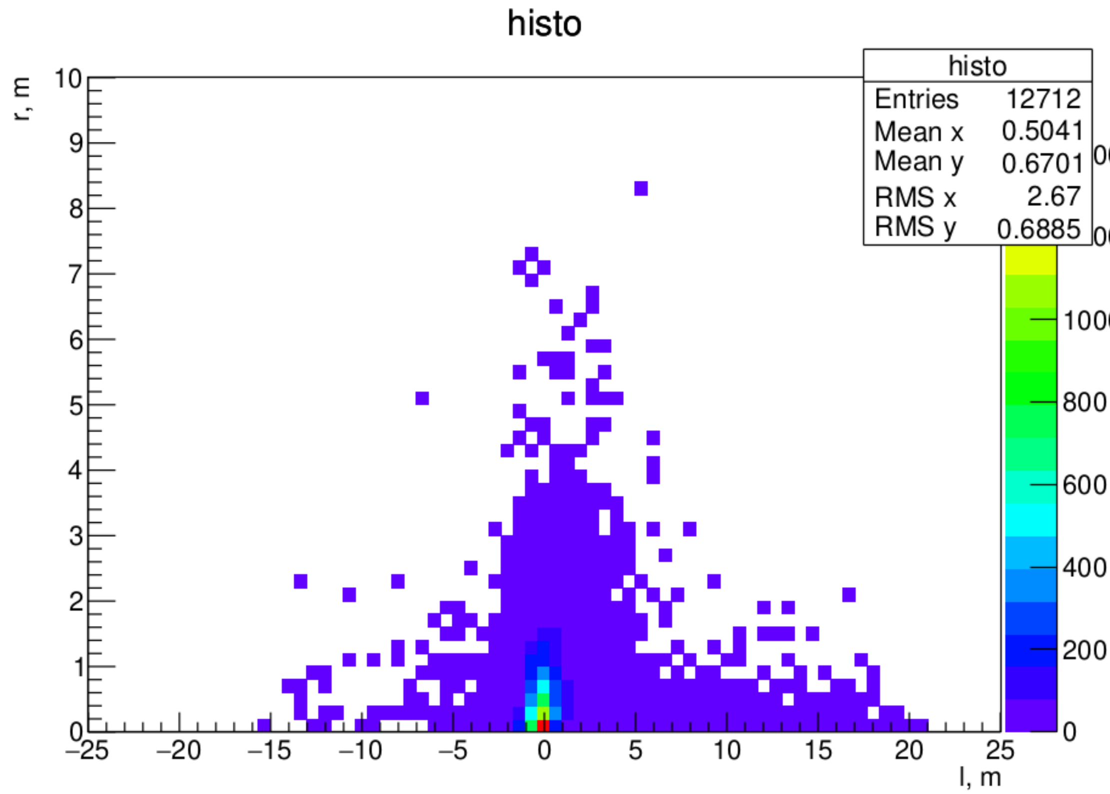


Fig 5. A distribution of $^8He/^9Li$ production depending on d - distance from the maximum energy release point and r - distance from the muon track

So an idea appeared to complicate a cut form to impose it better on a diagram of events. According to a diagram on Fig. 5 was chosen a figure of rotation which projection contains two rectangles and a normal distribution between them.

The final formula looked so:

$$R(d) = \begin{cases} r_1, & d < d_{min} \\ H \cdot e^{-\frac{(d-b)^2}{2\sigma^2}} + r_2, & d_{min} < d < d_{max} (1) \\ r_2, & d_{max} > d \end{cases}$$

Here $r_1$, $r_2$, $h$, $d_{min}$, $d_{max}$, $\sigma$, $b$ are parameters. By selecting their values we are able to modify the cut line.

- $d_{min}$ and $d_{max}$ define cross-linking points of lines and gauss.
- $r_1$ and $r_2$ define the level of ascent of lines.
- $H$ defines the highness of gauss line.
- $\sigma$ is a parameter that varies a form of the gauss.
- $b$ is a shift of gauss relatively to a zero.

Initial values of these variables were selected randomly (see Fig. 6) and after that the formula (1) was analysed by MINUIT, a numerical minimization computer program.

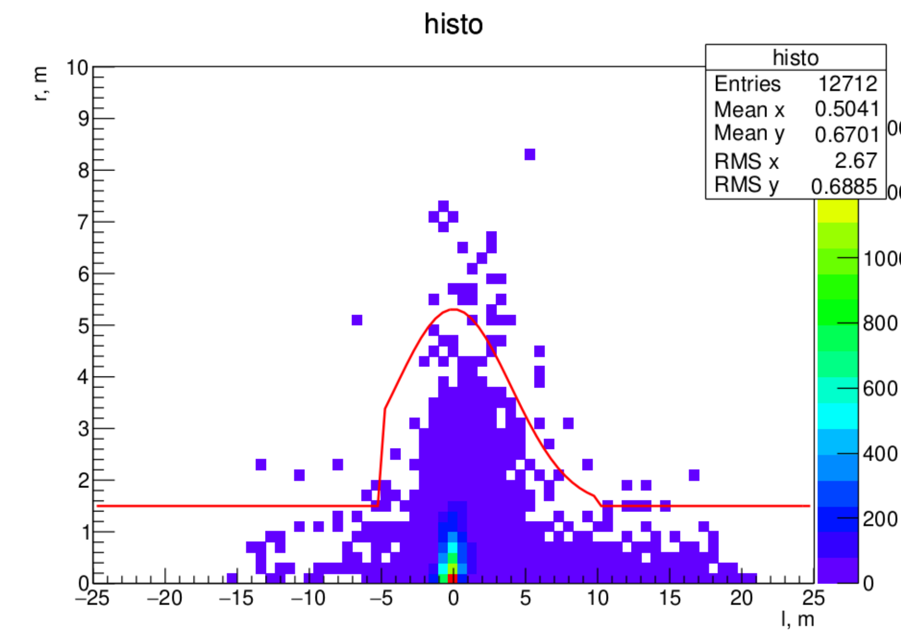


Fig 6. Initial cut line selected randomly.

### 3.3 Results

MINUIT ended its work with a good result. The program varied parameters in order to minimize cut volume while there was set a precise value efficiency (acceptable percent of events left uncut). Wherein the greatest interest was the range of 0.95 - 0.99 efficiency as most precise. Program was able to decrease cut volume to 10%, which is a better result. The graph on Fig. 7 is far from a monotonous curve. It is referred to a small sample of events used in an analyse leading to a very good local form matching between events diagram and a curve (e.g. at 0.983 efficiency).

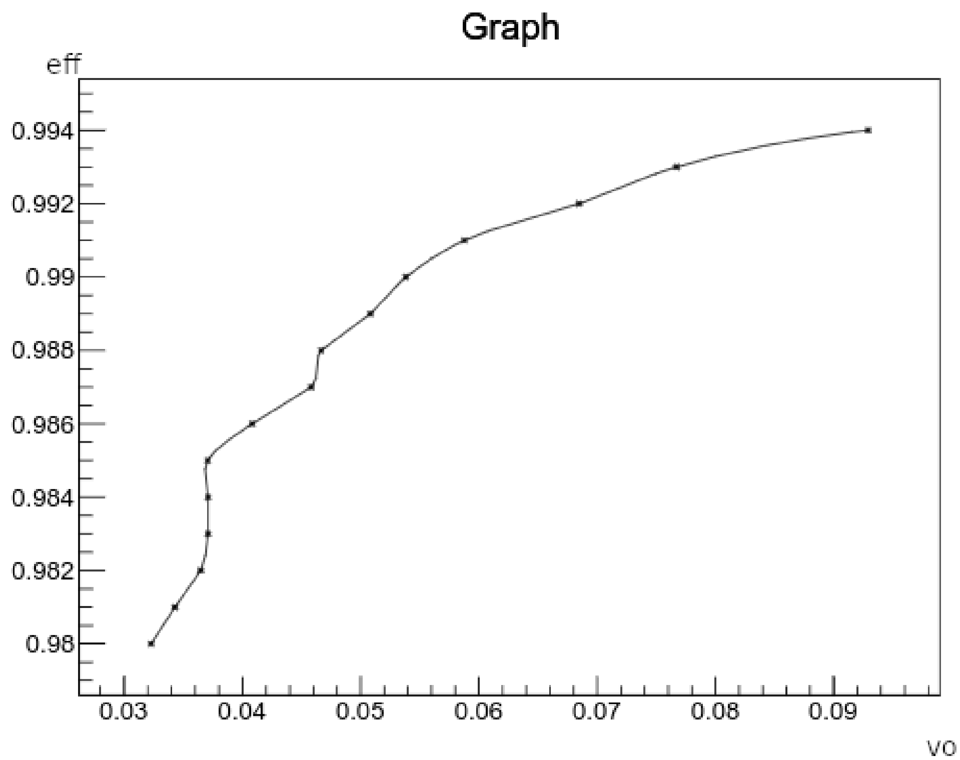


Fig 7. Volume is a volume cut by a program. Efficiency is a minimal fraction of events that should be cut out.

## Conclusion

To sum up all the topics mentioned, a few inferences might be done. Main of them is that the search is not ended. Actually only one formula was checked and the sample was much less than estimated in working detector. But now there is a base to continue the research, because a computing algorithm is not tied to a certain formula (1).

Anyway, a good result was achieved. In case of muons passing through a fiducial volume of a detector an existing algorithm allows to cut out up to 99% of events that refer to them with losing not more than 10% of live time.

## References

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