Joint Institute for Nuclear Research

Dzhelepov Laboratory of Nuclear Problems

FINAL REPORT ON THE START PROGRAMME

Determining the number of resonant events in the SAND Experiment

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Contents

1 Abstract

This work investigates resonances, focusing on selection criteria for registration, a methodology for determining the number of events, and numerical characteristics of their outputs. The study provides insights into the properties and behavior of Δ^{++} resonances through rigorous analysis and experimental techniques. The established selection criteria ensure accurate registration, and the methodology outlines further research. Numerical characteristics shed light on their behavior and potential applications. Additionally, the demonstrated method for predicting the resonance process on hydrogen.

2 Introduction

Neutrinos are among the most abundant particles in the universe, and yet we still know relatively little about their properties. By studying neutrinos in greater detail, we can deepen our understanding of the fundamental nature of matter and the universe.

Neutrinos have some unique properties that make them difficult to detect and study. For example, they interact very weakly with matter and can pass through vast amounts of material without being absorbed or scattered. Neutrinos play an important role in astrophysics, as they are produced in large numbers by processes such as nuclear fusion in the sun and supernova explosions. By studying neutrinos from these sources, we can learn more about the inner workings of stars and other astrophysical objects.

Neutrinos have been implicated in a number of unsolved puzzles in physics, such as the origin of the matter-antimatter asymmetry in the universe and the nature of dark matter. By studying neutrinos in greater detail, we may be able to shed light on these mysteries.

The T2K experiment in Japan has recently published new results that suggest a discrepancy between the behavior of neutrinos and antineutrinos, which could be an indication of new physics beyond the Standard Model[1].

The MINOS+ and Daya Bay experiments have made precise measurements of the mixing angle that governs the oscillation of neutrinos between different flavors, confirming the previous measurements by other experiments[2].

The IceCube experiment at the South Pole has detected a high-energy neutrino that appears to have originated outside of our galaxy, providing new insights into the sources and properties of these elusive particles[3].

Despite the large number of neutrino experiments currently in progress, the need for new ones cannot be denied. Firstly, with the improvement of technology, we can reach new capacities and work with a large amount of data. Secondly, check and confirm the hypotheses put forward earlier, as well as agree on the results of previous experiments. One of the upcoming and promising experiments is the experiment DUNE[4].

2.1 DUNE experiment

The Deep Underground Neutrino Experiment (DUNE) is a planned experiment to study muon neutrino oscillations into other types of neutrinos. The start of work is planned for the end-2020s. The Joint Institute for Nuclear Research and the laboratories representing it are direct participants in this experiment and take an active part in the development and improvement of technical and experimental methods.

It will use the neutrino beam generated by the proton accelerator at the Fermilab laboratory. Then the properties of this neutrino beam will be studied by two complexes neutrino detectors: a near one, also located at Fermilab, and a far one, located at a distance of 1300 km at the Sanford Laboratory. The objectives of the experiment are: to study the mass hierarchy of the three neutrino states; study of the mechanism by which neutrinos acquire mass; search for manifestations of violation of CP invariance.

One of the main advantages of the experiment is the number of recorded events. As discussed earlier, a neutrino-weakly interacting particle, but due to special technical solutions and the design of detectors, in this experiment will be fixed up to $5.5 * 10^6$ charge current events per year.Such a number of events is an order of magnitude greater than in previous experiments and will make it possible to observe rare processes

Overall, the DUNE experiment is an important step forward in our quest to understand the nature of the universe and the fundamental building blocks of matter.

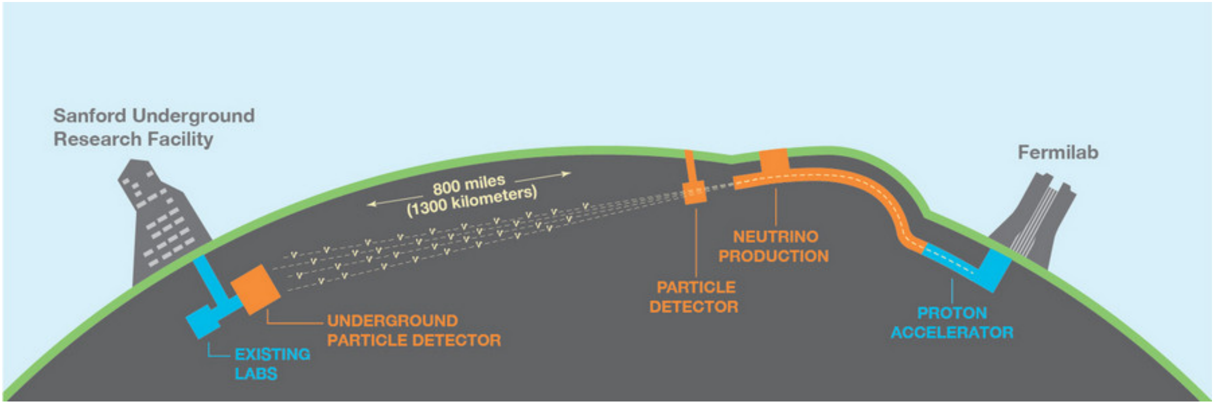


Figure 1: Neutrino production associated with DUNE

2.2 Near detector design

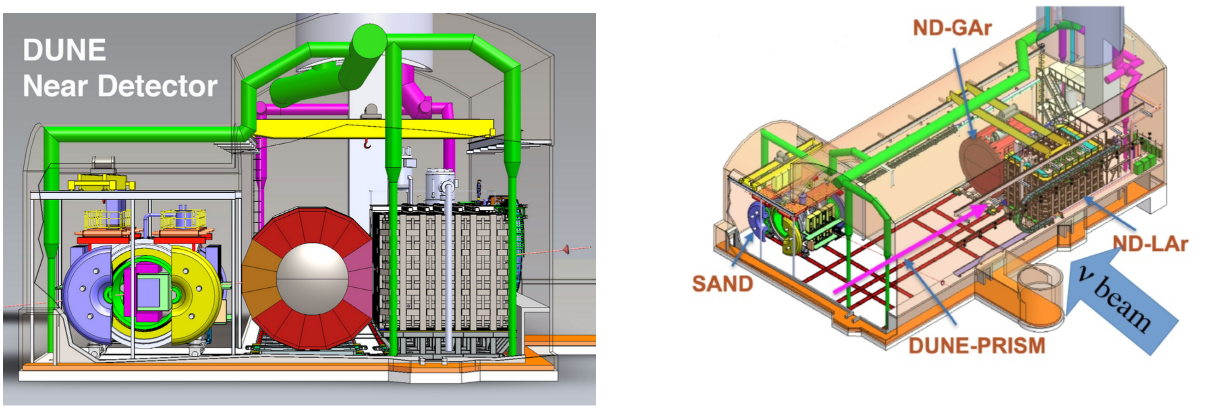


Figure 2: Near detector design

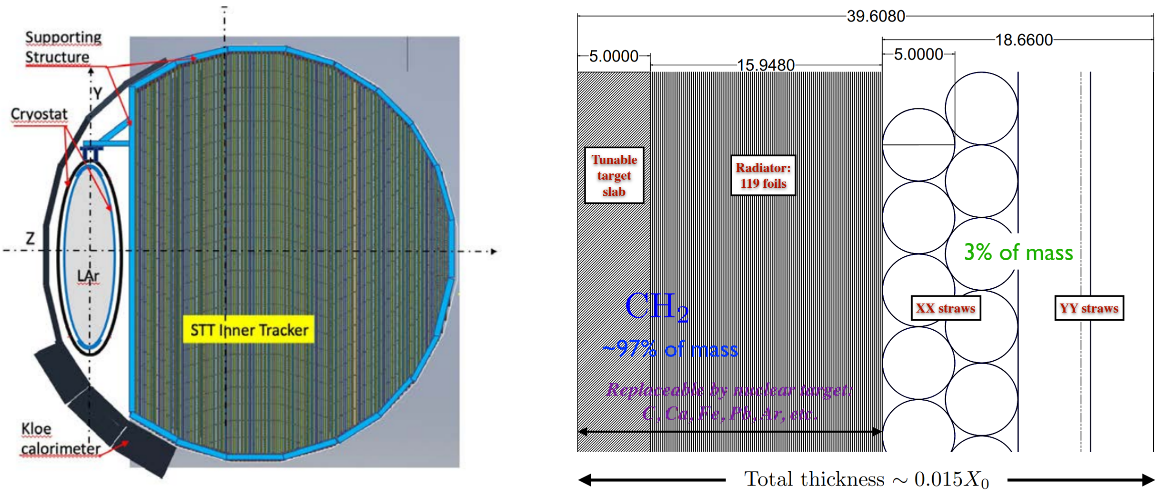
The DUNE near detector will be situated on the Fermilab site, downstream of LBNF, approximately 600 meters away from the point of neutrino production[5]. It consists of several detectors that will be positioned side by side. One of these detector (SAND) will be installed along the neutrino beam axis, while the others (NDLAr and NDGar) will be movable and can be shifted in a direction perpendicular to the beam to detect neutrinos produced at different angles.

2.3 Detector SAND

SAND (System for on-Axis Neutrino Detection) is the permanently on-axis component of the Near Detector, placed downstream of ND-GAr and ND-LAr in a dedicated alcove of the ND hall. SAND consists of an inner tracker surrounded by an electromagnetic calorimeter inside a large solenoidal magnet.

The SAND-track detector is capable, due to its design features, particularly straw tubes, of reducing the effect of rescattering. Furthermore, this detector allows us to change the target and observe processes on nuclei of particular interest, such as hydrogen.(Fig.3)

The main task of the SAND detector is to monitor the beam in real time and study changes in the beam parameters. The detector is stationary and collects more statistics than NDLAr and NDGar. Also, one of the advantages of the SAND detector is the ability to accurately detect individual tracks and accurately calculate the cross section capability.



1) SAND detector detection

2) Straw tubes in SAND

Figure 3: SAND detector construction

3 Theory

3.1 Type of events

As part of the experiment, we can observe many processes associated with neutrino scattering. The most common processes are presented below(Fig. 4).

-Quasi-elastic scattering(QE) In the neutrino energy range less than 2 GeV, the QE interaction is the dominant one in the neutrino hadron interactions. These reactions can be written in a reaction style equation

$$\nu + n \to l^- + p$$

$$\overline{\nu} + p \to l^+ + n$$

-Resonant scattering (RES): In this process, when enough energy is given to a neutrino, it can excite the target nucleon to an excited state producing a baryon resonance. This baryon resonance decays quickly

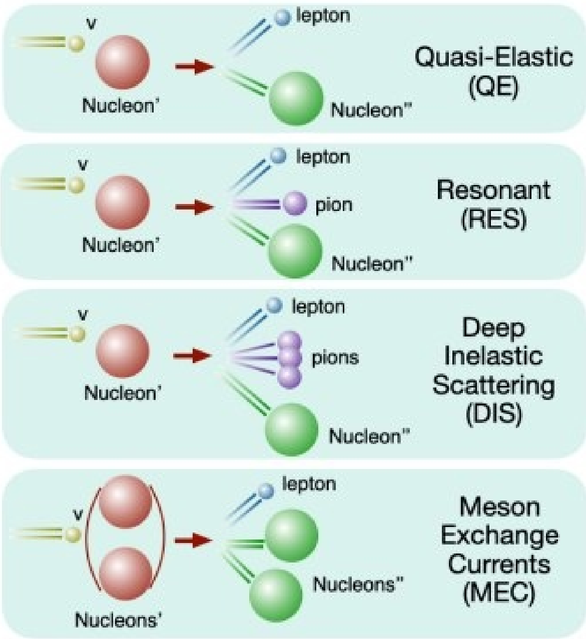


Figure 4: Types of CC events

to a nucleon and a single pion (meson) in the final state:

$$\overline{\nu} + N \rightarrow l + \pi + N^{'} \tag{1}$$

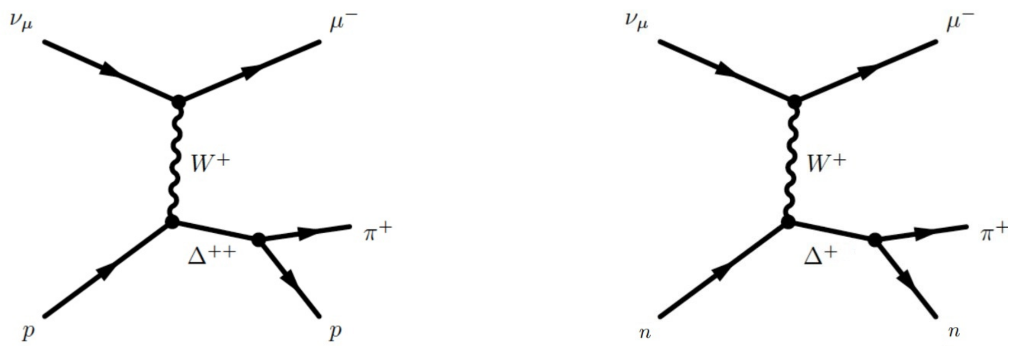
-Deep inelastic scattering(DIS) The neutrino can scatter off a quark in the nucleon exchanging a virtual or boson with a lepton and a hadronic system in the final state. It is termed as “deep” as the neutrino has enough energy to interact with the quark in the nucleon (as the neutrino with very high energy will have smaller wavelength). DIS energy range is beyond resonance interaction range. In this interaction both CC and NC channels are possible.

-Scattering by clusters of nucleons bound through the exchange of charged mesons (MEC) In this process, a neutrino interacts with nucleons inside the nucleus by exchanging a W boson. This results in the absorption of the neutrino by nucleons, which knocks out two-particle and two-hole pairs (2p-2h) through an exchange of a meson. Additionally, there is a possibility of knocking out 3-particle 3-hole pairs, producing 3p-3h in the final state, which can be generally termed as np-nh or multi-nucleon excitation.

Each of these processes is of great interest to physicists. For example, DIS allows us to study of nucleon clusters, while RES is of particular interest and was not practically studied in previous experiments due to low statistics. Many previous works were based on manual selection of these types of events[6]. As part of our task, we will try to develop a method for the automatic detection and analysis of resonant events.

3.2 Resonant scattering

Delta resonance production is more complicated than the QE process. The proton and neutron are bound states of three quarks. The proton is composed of an *uud* configuration while the neutron is *udd*. These



1) Types of processes that we can detect 2) Types of processes that we cannot detect

Figure 5: Feyman diagrams for resonant scattering

represent the ground states of any three quark system. The delta particles are the first excited states of three quark systems comprised of up and down quarks.

The delta baryon comes in four different types, corresponding to charges of +2(uuu), +1 (uud), 0 (udd) and -1 (ddd). Figure 5 shows one mode of delta production, where a neutrino scatters off a neutron or proton to produce a Δ^+ and Δ^{++} particle.

The delta particle cannot be observed directly because it decays in the nucleus.The troubling feature of the delta is its short lifespan. The delta particle decays with a mean lifetime on the order of 10^{-24} seconds, which does not give the delta enough time to escape the nucleus. The result is that delta resonance production is identified by the delta decay products.

It should be noted that only the decay of Δ^{++} resonance will be studied in this work. This is primarily due to the fact that the decay processes for Δ^+ and baryons contain neutral particles that are difficult to identify in the detector.

4 Studies of delta resonances in the process of resonant scattering

4.1 Invarian mass

The decay products of the delta particle will have the same invariant mass as the delta particle. Invariant mass is the mass in the rest frame of a particle. If a particle decays, the invariant mass can be computed from the decay products. Measuring the latter is one way to confirm the production of a delta particle. The invariant mass squared, M^2_{inv}, is defined as the sum of the squared energies minus the sum of the squared momenta of the decay products[7].

$$M^2_{inv} = (\sum_i E_i)^2 - ||\sum_i P_i||^2 \tag{2}$$

In our case, the invariant mass calculation procedure is implemented in the ROOT software package.

4.2 Delta resonance identification

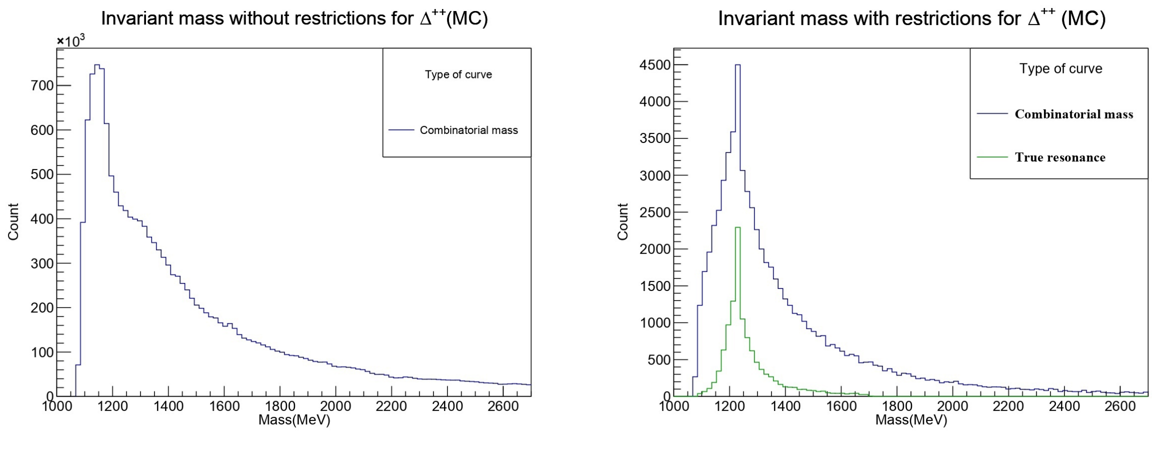
One of the key stages in the identification of delta resonances is the selection of events in which the birth event occurred. To do this, we imposed a number of restrictions on the selected particles:

1) The presence of a muon in our event, since the muon is a well identified particle, then there is no need to introduce additional conditions for the reconstruction of the muon track when using the reconstruction program.

2) An important condition is that the particle tracks come out of the primary vertex. Within the framework of the experimental approach, this is determined by the fact that the distance from the event to the particle does not exceed 5 cm (in the future, this condition is subject to correction)

4) Tracks must be charged and reconstructed. The presence of a charge is a necessary condition for the decays we are considering. Without the condition that the track has been reconstructed, we will not be able to work with the results from the experiment. The condition for the reconstruction of the track is the number of hits greater than 6 in OZY plane.

3) The number of reconstructed tracks (in addition to the muon) for an event originating from the primary vertex should not exceed two. Separately, it should be noted that the condition for two reconstructed tracks is subject to discussion. For more accurate detection under ideal conditions (for example, Monte Carlo data) for Δ^{++}, Δ^{+}, the limit on the number of tracks should correspond to two, in further works $(\Delta^{++})^{*}$ the constraint matches three. At the same time, it is clear that in the case of a real experiment, such conditions are difficult to implement, since we do not have real ones, we will artificially worsen the conditions.



1) Invariant mass without using selection criteria 2) Invariant mass with using selection criteria

Figure 6: Application demonstration of selection criteria

4.3 Reconstructed data

The next stage of work was the transition from Monte Carlo to reconstruction. It is important to note that this is not exactly a reconstruction program in the usual sense, but rather its simulation. Essentially, it takes data from Monte Carlo and "smeares" it by a percentage corresponding to the expected errors on the SAND detector.

By combining data from simulation and reconstruction, we can determine background and actual birth events. Background events arise as a result, when we choose as pairs for the invariant mass either particles not related to the Δ^{++} resonance creation process. This curve is called the combinatorial mass.

In this figure 7, we see three curves. The first(blue) corresponds to the invariant masses of the selected pairs. The second(orange) is for background events and the third(green) is for pure resonant events.

It is important to note that in all the following graphs we have normalized the curves corresponding to our method, as well as pure and false resonances, to the combinatorial background. Energy interval for which normalization was performed: [1787.5 ; 2400] MeV

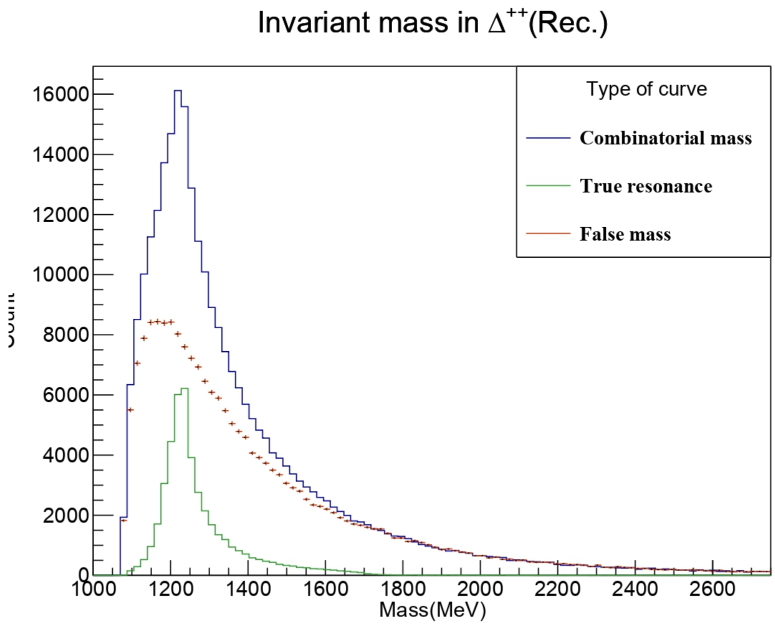


Figure 7: Data from the reconstruction program

4.4 Background calculation

To estimate the background, we selected several methods and applied them to solve the problem. Thanks to the use of computer simulations, we can still tell the origin of the particle and also accurately identify it.

4.4.1 Polynomial approximation

In problems related to resonances, the polynomial approximation method has been widely used and has proven itself well as one of the main ones. The essence of this method is that the combinatorial background can be described by any function of the form:

$$f_{bg}(M_{inv}) = P_n(M_{inv} - M_{min}) * T(M_{inv}) \tag{3}$$

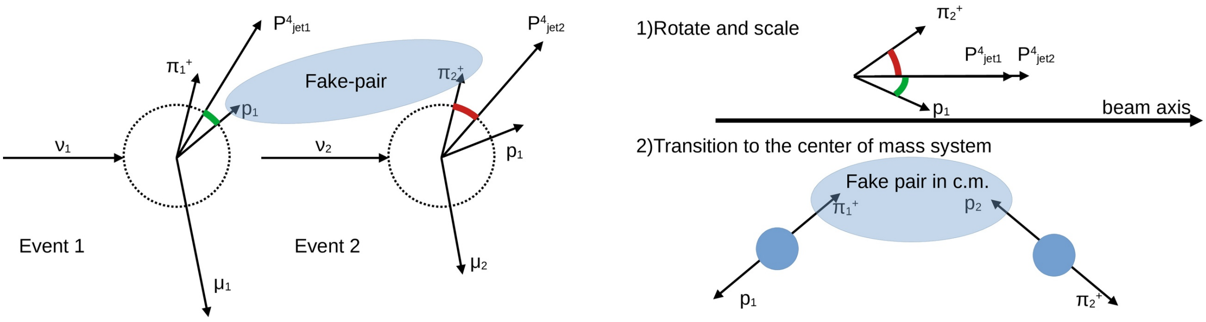
where $P_n(M_{inv} - M_{min})$ - polynomial n-th order, vanishing at $M_{inv} = M_{min}$, M_{min} - threshold mass distribution and $T(M_{inv})$ - any function tending to zero as $M_{inv} \to \inf$ faster than corresponding growth

P_n. Unfortunately, this method is not suitable for assessing the background within our task, since we cannot clearly distinguish the signal from the background, so we will consider other methods.

4.4.2 Fake-pair method

The next option was also adopted and tested by the scientific community[8] - the method of fake-pair.

Its essence is to artificially create a background curve. To do this, we collect a pair of two different events. We tried several ways to work with such pairs(Fig. 8):



1) Principle of fake-pair method

2) Variations of the false pair method that we tried in our work

Figure 8: Fake-pair method

1-method) It consists in turning the resulting tree momentum vector of the hadron jet to a certain axis. The axis itself can be arbitrary, but we have chosen the beam axis. It is important that in this method, in order to preserve the kinematics of the process when turning to the axis, all angles between the tree momenta vectors of our particles (hadrons in the jet) and the resulting three momenta vector were preserved.

Next, we equate the energies of the hadron jets by applying a single factor. And we recalculate the rotated momenta, since within the framework of the task we clearly indicate the particle, then we have the value of the mass. There are uncertainties in this method. In which jet to equate (to a jet with more energy or less?). We have considered both options.

2-Method) In this case, in each event, we go to the system of the center of mass of the hadron jet and make pairs from this system. In this case, we do not need to think about kinematics. The invariant mass is preserved during transitions between frames of reference.

All of these options yielded bad results and are not suitable for fitting the background curve. This is clearly visible in the figure 9, as they do not fit the curve's shape due to the shifted peak. Additionally, they do not converge at the tail, .

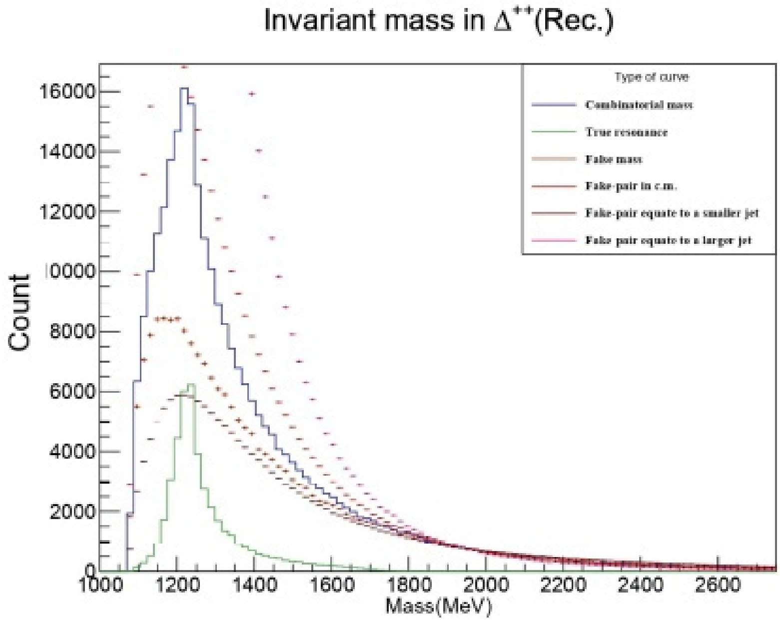


Figure 9: Background curves with different variants of the fake-pair method

4.4.3 Fake-pair method with momentum averaging

To find ways to estimate the background, we decided to modify the method with rotation of the hadron jet vector.We have noticed that this method is very sensitive to the average value of the momentum of the products.

Now we have found the average energy of the hadron jets and equated both jets to this value. We linearly transformed the momentum in proportion to the new energy. In addition, the momentum were multiplied by a coefficient that we determined visually. This coefficient is selected manually for the low-energy region, where there are still no pure delta resonances, until the first bins for the fake-pair graph and the combinatorial background constructed by us coincide. Conceptually, this coefficient can be justified as a normalization to the left end of the graph. Unfortunately, we do not yet know how to determine this coefficient without using Monte Carlo. Further work involves finding ways to determine it.The coefficient selection technique is shown in figure 10.

In order to obtain a curve of pure resonances obtained by the pulse averaging method, it is necessary to subtract from the combinatorial mass the background curve that created by our method.

Why do we think that this method is needed in further research? Because it performs even better than the Monte Carlo background curve we normalized to. This can be clearly seen in the presented figure 11.

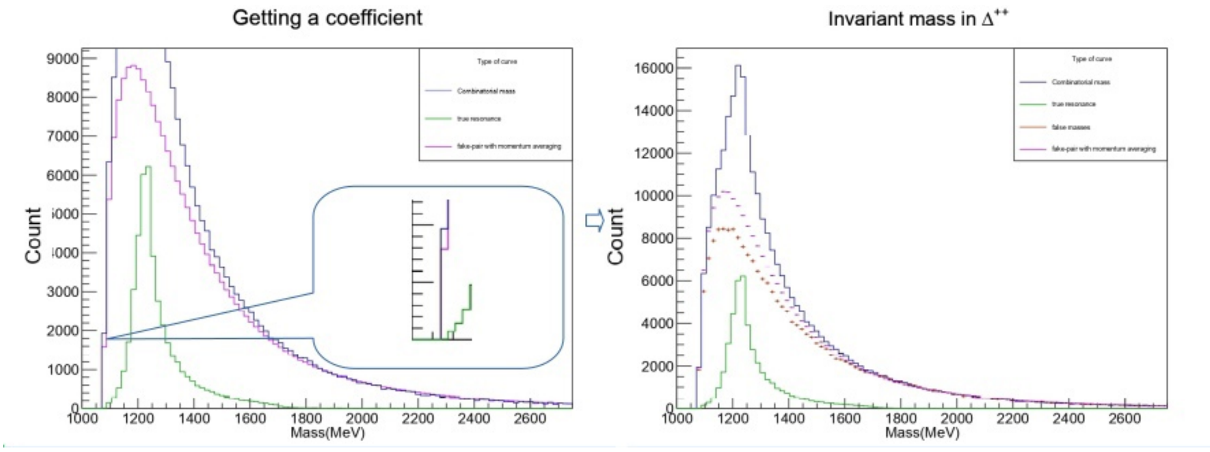


Figure 10: Technique for visually obtaining the conversion coefficient of averaged pulses

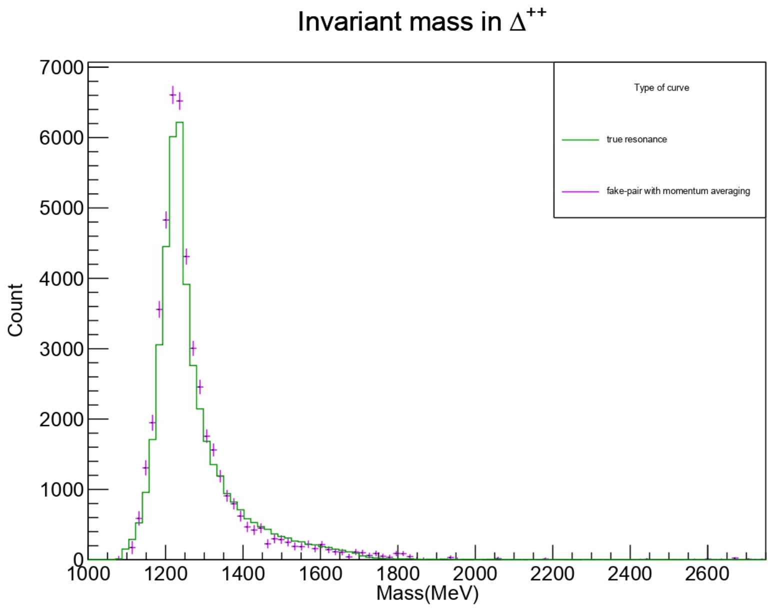


Figure 11:

4.5 Identification efficiency for Δ^{++}

To complete our analysis, we decided to find the efficiency value and the relative number of outputs for Δ^{++} in the process $\nu p \to \Delta^{++}\mu^{-}$, intermediate values are presented on the table 1. As we can see the values are not "impressive". We explain this by the fact that the reconstruction program is not yet ready. Therefore, as we see, we have a neutrino reconstruction efficiency of 93%, which is associated with a bad reconstruction of protons. The relative frequency of Δ++ yields was about 20%.

Table 1: Numerical characteristics in the process $\nu p \to \Delta^{++}\mu^-$

Meaning	Symbol	Value
Number of simulated cc processes	N_ν^{sim}	980063
Number of reconstructed cc processes	N_ν^{rec}	919704
Neutrino reconstruction efficiency	$\epsilon_\nu = N_\nu^{rec}/N_\nu^{sim}$	0.9384
Number of simulated Δ^{++} events	$N_{\Delta^{++}}^{sim}$	211852
Number of identified Δ^{++} events	$N_{\Delta^{++}}^{id}$	45770
Efficiency of identification in process $\nu p \to \Delta^{++}\mu^-$	$\epsilon = N_{\Delta^{++}}^{rec}/N_{\Delta^{++}}^{sim}$	0.2075
Relative number of yields in process $\nu p \to \Delta^{++}\mu^-$	$P = N_{\Delta^{++}}^{sim}/N_\nu^{sim}$	0.2046

4.6 Δ^{++} on a hydrogen target

Although our proposed method is in good agreement with Monte Carlo simulations, it is not without drawbacks. In particular, we cannot determine which event corresponds to the birth of Delta resonances. Therefore, it is suitable for evaluating reaction cross sections. In theoretical tasks, there is a demand for accurate knowledge of the process to further refine models.

Thanks to the ability to change the target, as noted in paragraph 2.3. We can experimentally determine the interaction on hydrogen. This can be obtained by comparing the results on C and CH_2 targets. In our work, we considered production on a hydrogen target. In this case, the number of tracks emerging from the primary vertex should be equal to 2. Figure 12 shows that if we set the energy condition to no more than 1400 MeV, we will register only the resonant event with a 92% success rate.

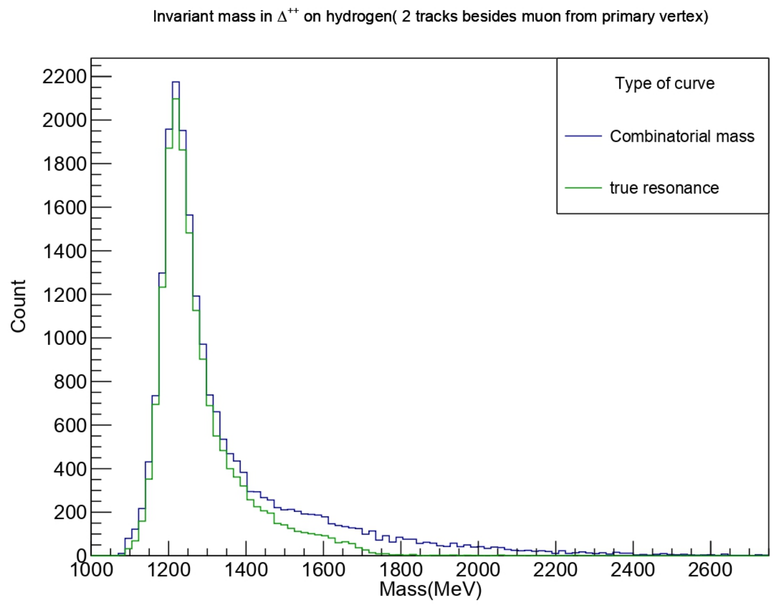


Figure 12:

5 Conclusion

Highlight the main results of the work:

1) Selection criteria for registration of Δ^{++} resonances were determined.

2) A methodology for determining the number of events of Δ^{++} resonances has been obtained and a vector for further research has been outlined.

3) Determined numerical characteristics of Δ^{++} resonance outputs.

4)A method for predicting the resonance process on hydrogen is demonstrated.

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