Cross Section Calculation Activity

Activity Summary

In this activity, you will learn the steps needed to calculate the neutrino interaction total cross section as a function of E_ν based on the experimental definition

$$\sigma_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N_{data,j}^{bkgd})}{A_\alpha \phi_\alpha T} \tag{1}$$

where j is the index of a reconstructed E_ν bin, $U_{j\alpha}$ is a function that accounts for unfolding from reconstructed bin j to true bin α, $N_{data,j}$ is the number of selected events, $N_{data,j}^{bkgd}$ is the estimated number of background events, A_α is the efficiency for reconstructing signal events, T is the number of target nucleons, and ϕ_α is the flux in bin i.

We will perform this calculation on a charged current neutrino interaction. This interaction has a charged lepton with matching lepton number in the final state. For ν_μ scattering, there will be a μ^- in the final state.

The background to this event sample are neutrino events of the wrong channel. These include neutral current events and wrong sign events (antineutrinos). A wrong sign (WS) event can be falsely accepted in the event sample when a charged-current interaction produces a muon whose charge is reconstructed as negative. Although a ν_μ event can lead to a μ^- through charm production, the vast majority of the WS background is the result of a reconstruction failure in MINOS. If the interaction is mediated by a $W^\pm (Z0)$ it is called a charged (neutral) current interaction. In neutral current interactions, the final state lepton is a neutrino that has the same favor as the incident neutrino.

There are three dominant interaction channels for neutrino-nucleon scattering neutrino energies: QuasiElastic scattering, Resonance production, and Deep Inelastic Scattering.

Figure 1 shows an event display of a CCQE two track interaction, where the muon is matched to MINOS and the short track is a proton.
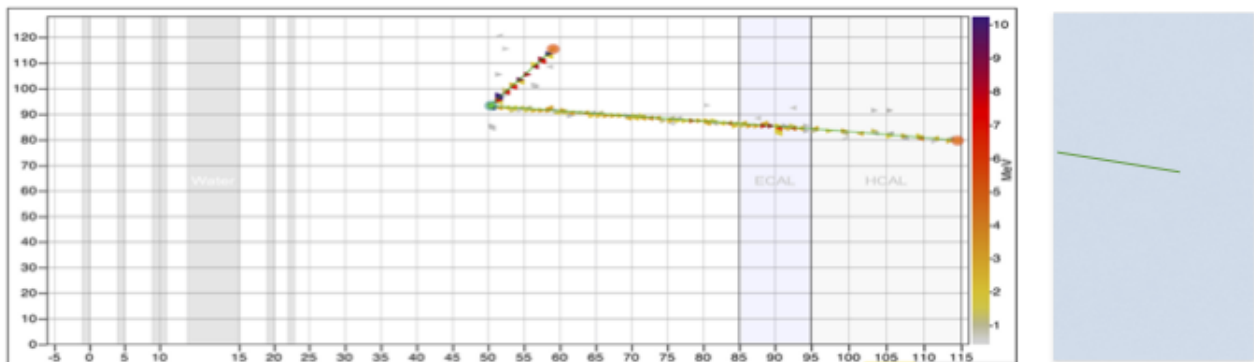

Figure 1: Event Display of CCQE Event

The input files for this activity can be found at
The Monte Carlo `http://home.fnal.gov/~betan009/CCInclusiveReco_MC_AnaTuple_minerva1.root`
The efficiency `http://home.fnal.gov/~betan009/Efficiency.root` and
the flux `http://home.fnal.gov/~betan009/Flux.root`

Event Selection

Select events for the muon neutrino Charged-Current interactions (quasi-elastic, resonance and deep inelastic). Fill a histogram of the MC for the reconstructed neutrino energy (`CCInclusiveReco_E`)
  HINT 1! The reconstruction cut used in this analysis:

- `CCInclusiveReco_nuHelicity == 1` (Event has the right helicity)

- `pass_canonical_cut==1` (Event has a fiducial vertex, an analyzable muon, significant curvature, matched to MINOS, plausible energy)

- `1 > phys_n_dead_discr_pair_upstream_prim_track_proj` (At least there's only 1 dead discr pairs upstream of the vertex of interaction/it removes event that can't be reconstructed due to the dead time)

- `CCInclusiveReco_E > 22.0` (Event has neutrino energy below 22 GeV)

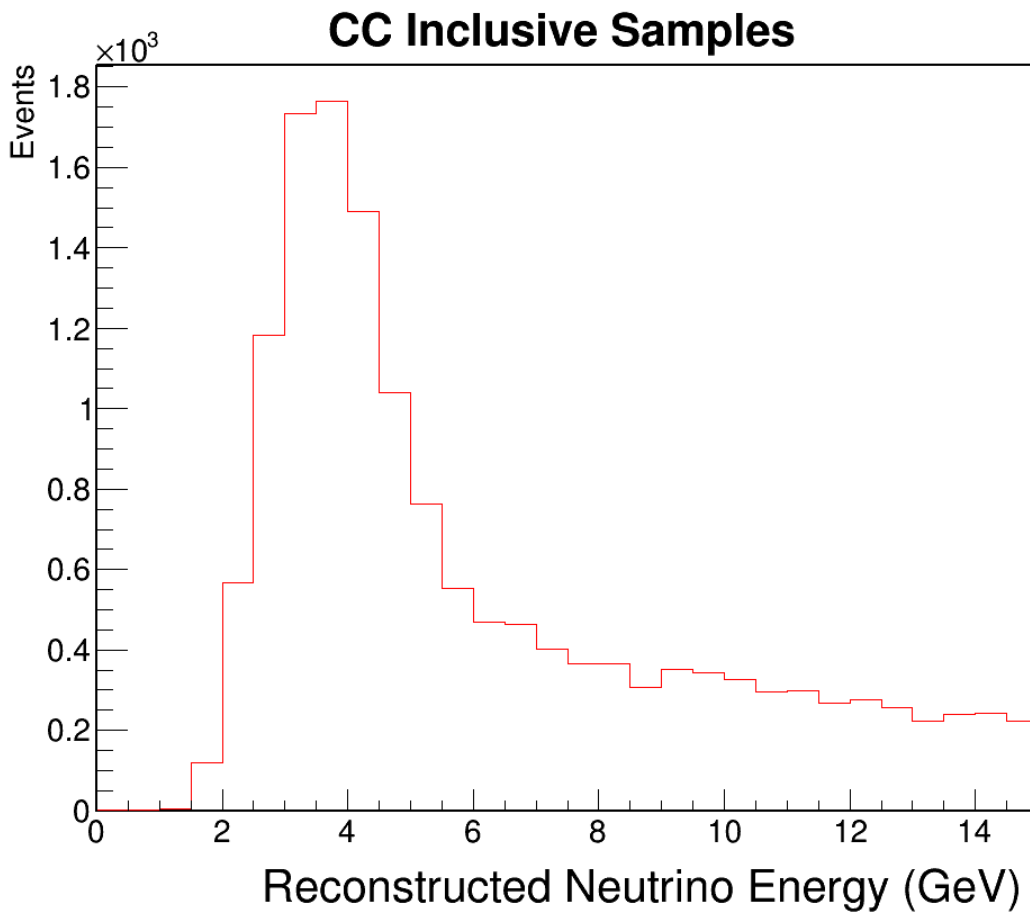The event sample distribution should look like Figure 2.

Figure 2: Event Sample Distribution

Background Subtraction

Any selected sample contains certain background, in this case the background is the neutral current events and wrong sign events (antineutrinos). We MUST constraint the background and subtract it from the data. Since the background for this sample is very small we do not have time do perform a background constraint, we are going to subtract the background prediction from genie simulation.

Fill a histogram with the prediction of the background events for the events passing the reconstruction cut (see Activity 1) but didn't pass the signal cuts according to the true information from the MC.
HINT!

- True energy cut is the same as the reco E cut: `mc_incomingE < 22.0`

- For MC, you can subtract the background from samples:

The background subtracted distribution for MC should look like Figure 3.
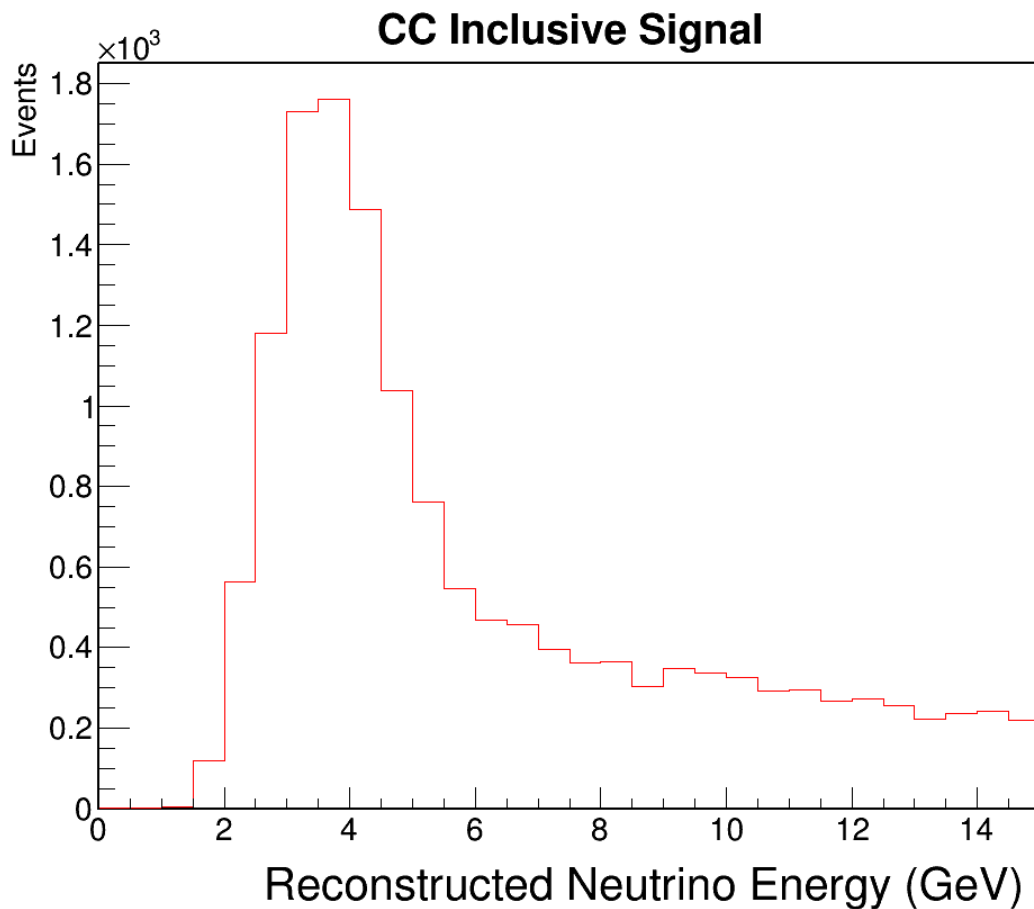

Figure 3: Background Sbtracted Distribution

Migration Matrix and True Neutrino Energy Distribution

$$\sigma_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N_{data,j}^{bkgd})}{A_\alpha \phi_\alpha T} \qquad (2)$$

The migration matrix is used for the unfolding, to fill the migration matrix define a 2 dimensional histogram, where x axis is the reconstructed neutrino energy `CCInclusiveReco_E` and the y is the true neutrino energy `mc_incomingE`. Fill the migration matrix with events that passed both the reconstruction cut and signal cut. Next, define a histogram for a true neutrino energy distribution, that also passed the reconstruction cut and signal cut. You will need these two histograms to unfold the reconstructed distribution to true distribution. The migration matrix of your event sample, should look like Figure 4.
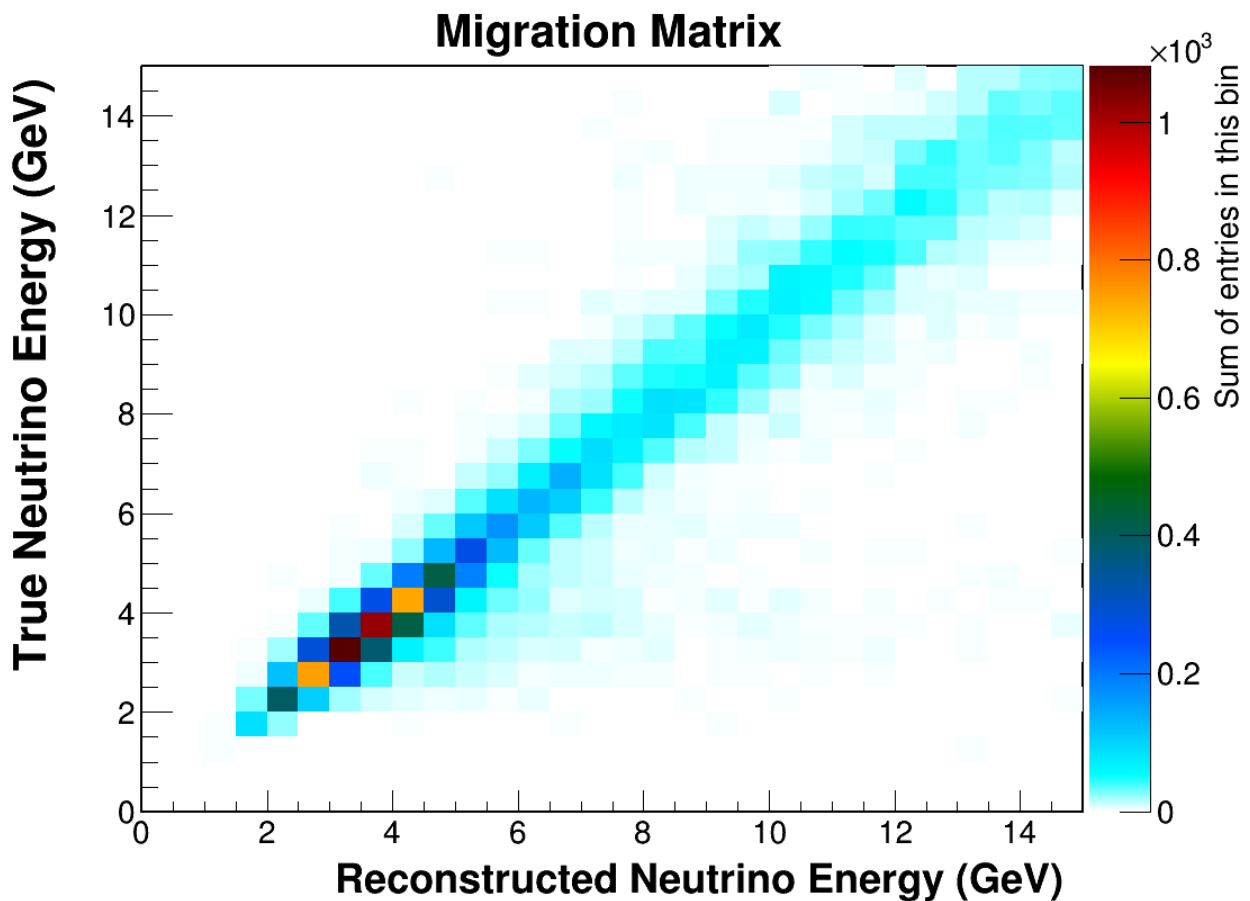

Figure 4: Migration Matrix

Unfolding

The unfolding uses the migration matrix from figure 4 and the background subtracted histogram from figure 3.

HINT! To unfold the distribution you will need to use the ROOT Unfolding Framework
http://hepunx.rl.ac.uk/ adye/software/unfold/RooUnfold.html
Download the RooUnfold-1.1.1.tar.gz
and follow the example at: examples/RooUnfoldExample.cxx
`RooUnfoldBayes unfold (&response, hMC_subtracted, 4);`
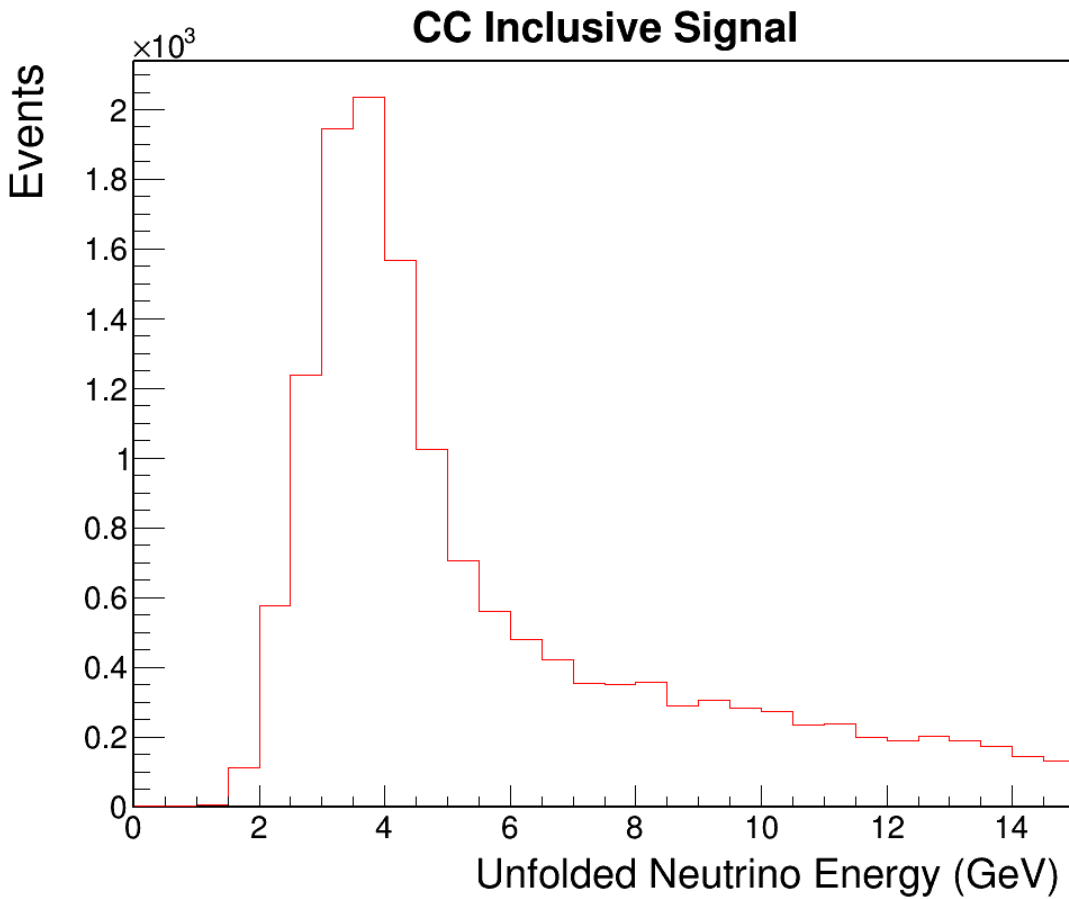The unfolded distribution should look like Figure 5.

Figure 5: Unfolded Neutrino Energy Distribution

Efficiency Correction

Due to the limitations of our detector technology and geometry and also because the neutrino event signature is difficult and challenging to identify, the signal cuts that we use are unable to reconstruct some fraction of our signal. Therefore, the cross section calculation needs to be corrected for its efficiency. The efficiency for true kinematics is measured in simulation as :

$$A_\alpha = Efficiency = \frac{N_{CCInclusive,\alpha}^{selected}}{N_{CCInclusive,\alpha}^{Total}} \tag{3}$$

where,

- $N_{CCInclusive,\alpha}^{selected}$ is the number of MC CC Inclusive signal events in the selected sample in the $\alpha - th$ neutrino energy bin. To get number of events for $N_{CCInclusive,\alpha}^{selected}$, apply the event selection cut described in Activity 1 and signal cut: `mc_current==1 and mc_incoming==14`

- $N_{CCInclusive,\alpha}^{selected}$ is the total number of CC Inclusive MC signal events generated in the $\alpha - th$ neutrino energy bin. To get the number of events for $N_{CCInclusive,\alpha}^{selected}$, apply the signal cuts and true energy cut: `mc_incomingE < 22`

HINT! Since we have to loop over the Truth tree entries to get $N_{CCInclusive,\alpha}^{selected}$, the code will take some time to run. To save time, we have provided the Efficiency histogram inside the code and you can use it to correct the unfolded neutrino energy histogram by: `h_CrossSection->Divide(h_unfold,h_Efficiency);`

The efficiency of the neutrino energy should look like Figure 6.
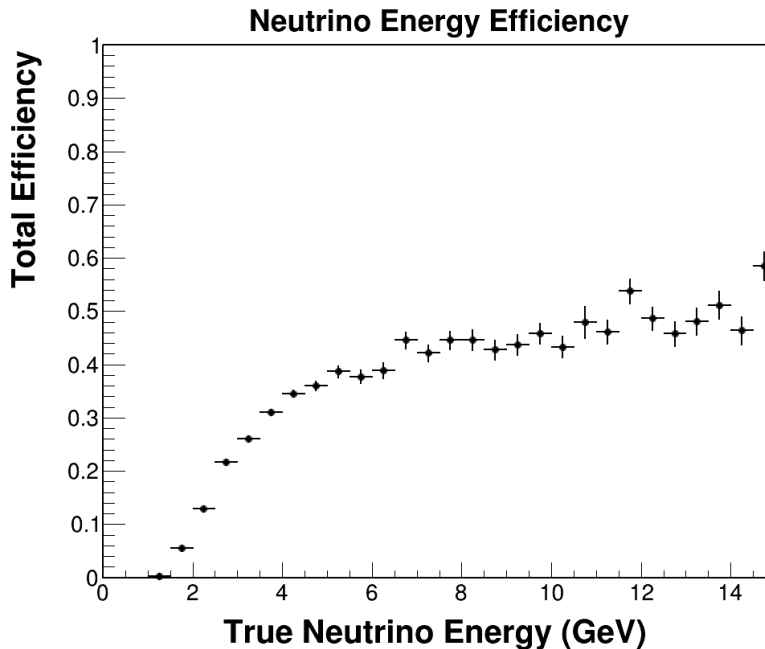

Figure 6: Neutrino Efficiency

Flux

The next step in calculating the cross section is dividing the efficiency corrected distribution by the flux in each neutrino energy bin and the width of the E_ν.

The flux we use for this calculation has finer binning compared to the E_ν binning that we have used so far. Since we need to divide the cross section by the flux, we need to rebin the original flux histogram to the binning we use for the E_ν histogram.

HINT! Rebin the flux histogram to the neutrino energy bins:

```
for(int j=1; j < h_flux_rebinned->GetNbinsX()+1; ++j ){
    double e_min = h_Eff_NeutrinoEnergy->GetBinLowEdge( j );
    double e_max = h_Eff_NeutrinoEnergy->GetBinLowEdge( j+1 );
    int b_min = flux->FindBin( e_min );
    int b_max = flux->FindBin( e_max ) - 1;
    double flux_cv =  flux->Integral( b_min, b_max, "width" );
    h_flux_rebinned->SetBinContent( j, flux_cv );
}
```

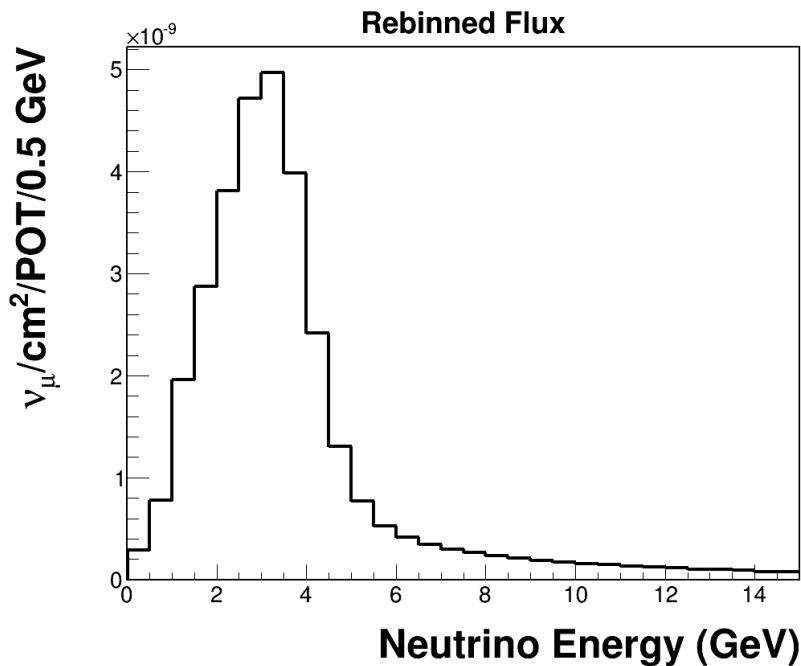The rebinned flux distribution should look like Figure 7 .

Figure 7: Rebinned Flux Histogram

Target Normalization and Cross Section Calculation

$$\sigma_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N_{data,j}^{bkgd})}{A_\alpha \phi_\alpha T} \tag{4}$$

The last step in calculating the cross section is dividing the unfolded, efficiency corrected distribution with the number of targets in CC Inclusive channel. The number of targets (nucleons) in the fiducial volume for the MINERvA experiment is 3.17846e+30
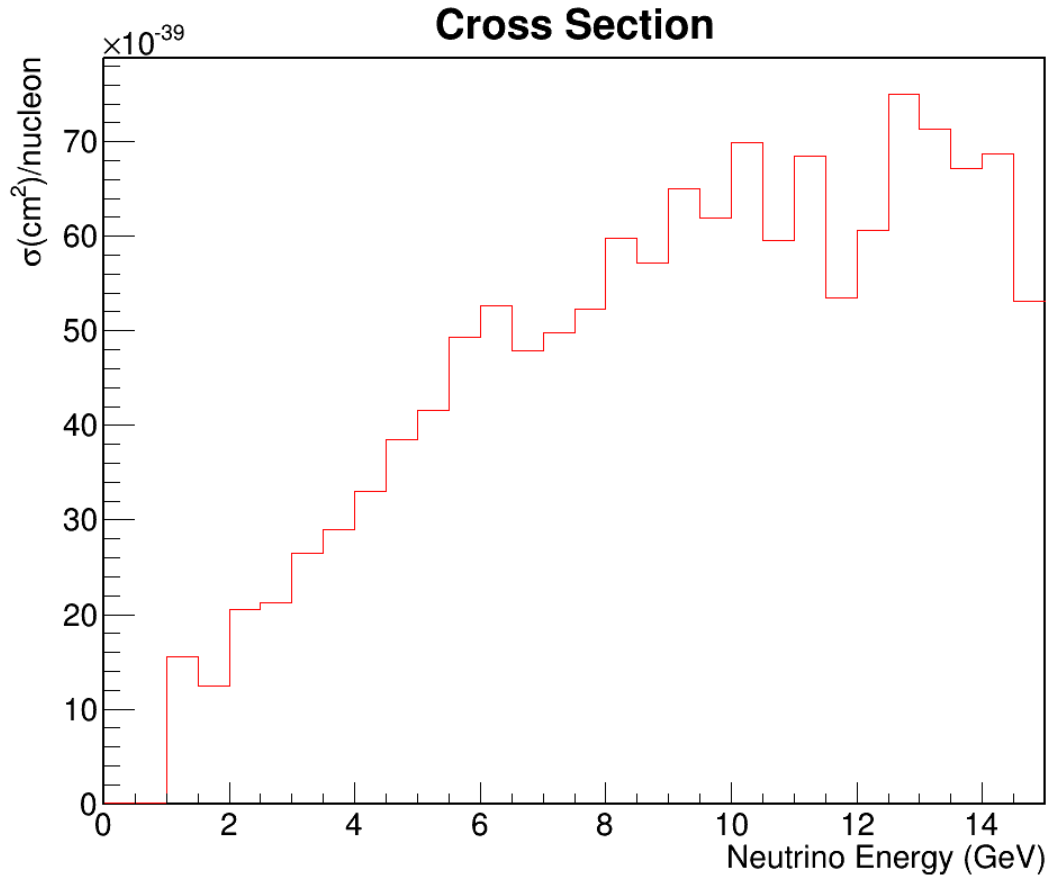
The cross section plot should look like Figure 8

Figure 8: The cross section of CC Inclusive Interaction