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Updating Hadron Production Models to Better Predict Neutrino Flux for DUNE

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I Introduction

The Deep Underground Neutrino Experiment (DUNE) is an ongoing project at Fermilab with international collaboration and over 190 institutions involved. DUNE has three primary science goals, one of which is searching for the origin of the imbalance of matter and antimatter in the universe. Accomplishing this goal will require the study of neutrinos and the phenomenon of neutrino oscillation.

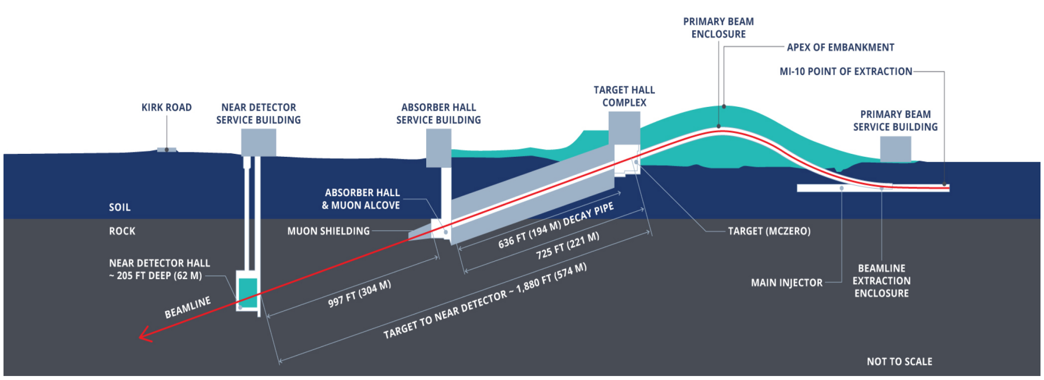
Neutrinos are elementary particles, which in the standard model have the characteristics of being massless, having no charge, and only interacting via the weak force. But there is now strong evidence collected from experiments from the past few decades which indicate that neutrinos do in fact have mass. There are three different flavors (types) of neutrinos, the electron neutrino, muon neutrino and tau neutrino. The different flavors are defined by their relationship with the associated charged lepton (electron, muon, or tau) e.g. in positive pion decay,

$$\pi^+ \rightarrow \mu^+ + \nu_\mu,$$

we know that the neutrino emitted was a muon neutrino because the decay also emitted an antimuon.

Neutrino oscillation is the phenomenon by which neutrinos change between their three different flavors. Neutrino oscillation can be expressed as a mixing matrix called the Pontecorvo–Maki–Nakagawa–Sakata matrix (PMNS matrix). Essentially the PMNS matrix is a way to mathematically express the probability of a neutrino being in one of the three flavor states. This is where DUNE comes in as we hope to learn more and make more accurate measurements of the parameters used in the PMNS matrix. These parameters are the mass of the neutrino flavors, the mixing angles, and the charge-parity symmetry violation phase. In fact, DUNE has been optimized to study the charge-parity symmetry violation in neutrino oscillation, because it could explain the preference for matter over antimatter in the universe.

The Long-Baseline Neutrino Facility (LBNF) is the facility that DUNE will be using to generate its neutrino beam.



The way that the neutrino beam will be generated is that a particle accelerator will accelerate protons to 120 GeV. Then the protons will be extracted and then directed into the LBNF beamline. After which the protons will then collide with a target. The LBNF target will be made of carbon, so the main interaction taking place is proton on carbon. The interaction of protons and carbon atoms can cause secondary particles, such as pions and kaons, to be created. The secondary particles then will escape the target and go through magnetic “horns”. These horns can be tuned to focus particles of a certain charge and defocus particles of the opposite charge i.e. the horn can focus positively charged particles and defocus negatively charged particles or vice versa. After passing through the horns the particles enter the decay pipe this is where some of the secondary particles created in the target will undergo decay processes and produce more particles. For example, positively charged pions will undergo decay via the weak force which will typically result in the creation of antimuons and muon neutrinos. The specific neutrino oscillations that DUNE will be studying is muon neutrino disappearance and electron neutrino appearance (muon neutrinos becoming electron neutrinos through the phenomenon of neutrino oscillation). Because of this the decay pipe length has been optimized to maximize the amount of decays that result in muon neutrinos, e.g. positively charged pion decay, and minimize the amount of decays that result in contamination of the beam, e.g. muon decay. At the end of the decay pipe there is shielding that is designed to stop particles such as muons from continuing past the decay pipe. This shielding doesn't affect the neutrinos in the beam however as neutrinos rarely interact and can travel through the shielding and the Earth's crust without issue. The beam then continues to the near detector located on site at Fermilab approximately 574 meters from the target. Then the neutrinos travel from the near detector to the far detector, approximately 1300 km away from the target, located at the Sanford Underground Research Facility (SURF) in South Dakota. There is an important reason that there are two detectors being using in this experiment. The purpose of the near detector is to measure the composition of the neutrino beam before any neutrino oscillation occurs. While the far detector is meant to measure the composition of the beam after oscillation occurs.

In order to study neutrino oscillation and perform any analysis related to the beam, it is critically important to know how many neutrinos of a certain flavor are in the beamline. Therefore, it is important to make measurements that will help improve the accuracy of neutrino flux predictions. For DUNE specifically we need to have accurate neutrino flux predictions of the LBNF beamline. Improving our neutrino flux predictions of the LBNF has been the purpose of my project. To that end I studied two hadron production models and compared those models with experimental data. The two hadron models I studied were QGSP_BERT and FTFP_BERT. QGSP_BERT is the hadron model that DUNE is currently using to simulate the physics of the LBNF beamline. FTFP_BERT is an alternative model that is currently being used in other experiments, such as NOvA, to simulate the physics of the NUMI beamline. I worked to characterize these models and compare them with an experiment conducted at CERN called NA49.

NA49 was an experiment that studied the cross-section of hadronic interactions on thin targets of different materials. In the case of DUNE, the target is made of carbon and NA49 has cross section data on proton on carbon interactions. However, DUNE is going to be using incident protons at 120 GeV while NA49 studied at 158 GeV.

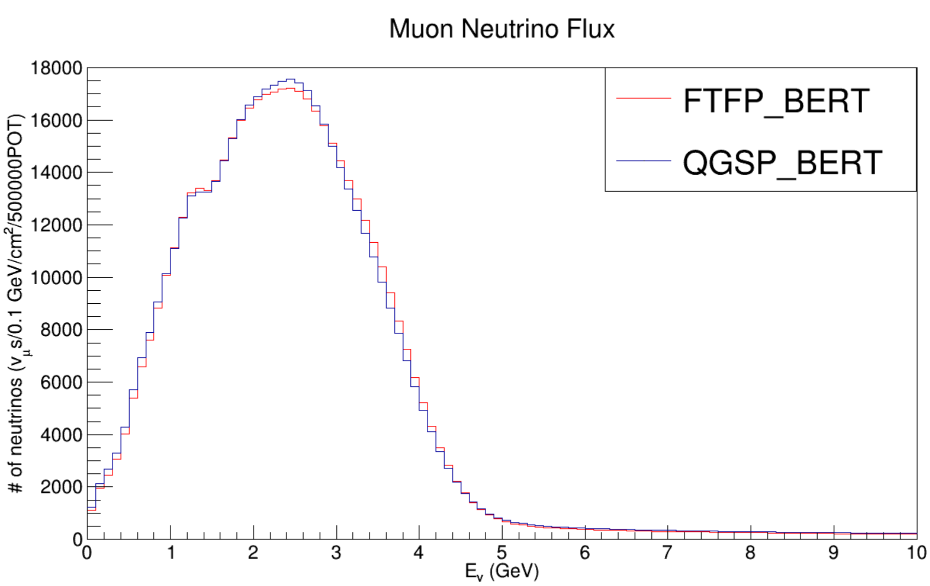
After having characterized the cross section for QGSP_BERT and FTFP_BERT the next step was to apply corrections to the models using the data from NA49 and see what effect there is on their neutrino flux predictions. This was done using a program called PPFX (package to predict the flux) which is used by many detectors such MINERvA, NOvA, MINOS, and MicroBooNE. PPFX has recently been modified and updated for the DUNE experiment. At this time, I have been able to apply corrections for proton on carbon interactions that produce pions and for the cumulative particles created. These corrections have been applied to QGSP_BERT for flux calculated at the near detector.

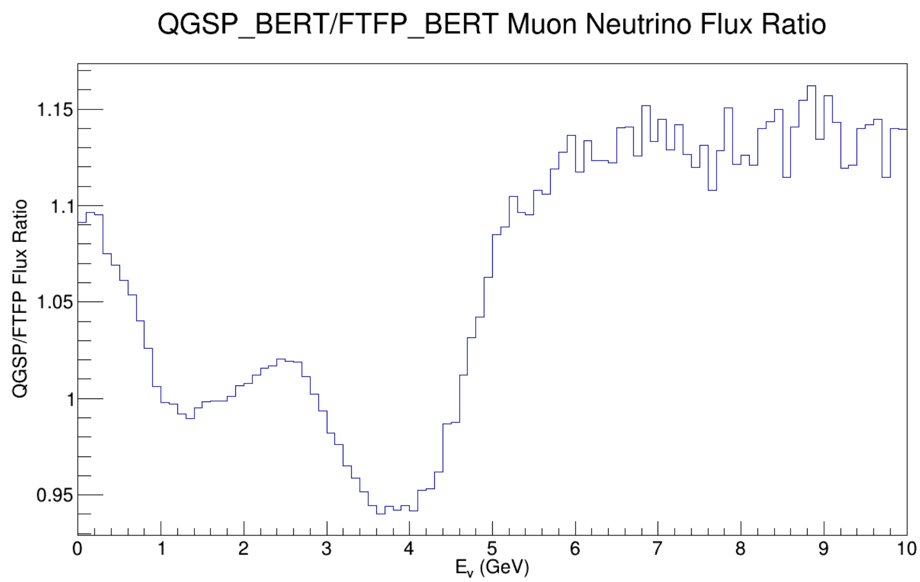
II Methods

To obtain the data required for my project several different programs were used. For creating the simulated data, I used geant4 version v4_10_3_p03b. The two geant4 programs I used for my project are called g4lbne and g4hp. The version of g4lbne I used was v3r5p7. Both g4lbne and g4hp can run on the Fermilab grid, which allows for hundreds of simulations to be run simultaneously. Being able to run many files simultaneously on the grid is crucial as running each file individually would take an enormous amount of time and being able to generate more files allows for a high degree of statistics and greater certainty in the data. G4lbne is a program that simulates the LBNF beamline. It does this by simulating the geometry and composition of the LBNF. It then simulates and tracks all of the initial protons fired at the target and the hadronic cascade that leads to a neutrino. For my project the data generated from g4lbne used 500,000 protons on target (POT) in each file. Using g4lbne on Fermilab's grid I was able to create 1000 files which when the files are compiled together amounts in 500 million POT in total. It stores a variety of information about the particles tracked such as their interaction and decay ancestry, the type of interaction taking place, volume in which the interaction takes place, it also stores data about position and momentum. G4hp is the program used to get the underlying cross section of the proton on carbon interaction used in the QGSP_BERT and FTFP_BERT models. What g4hp does is it simulates protons interacting on a thin carbon target (similar material to the LBNF target), and it tracks ancestry, position, and momentum. This simplified program allows for many more protons on target to be simulated, in a reasonable amount of time. Each g4hp simulation used 10,000,000 POT and since g4hp can also run on Fermilab's grid I was able to create 500 files of the simulation resulting in a total of 5 billion POT. To get the data from g4lbne and g4hp in a desirable form many ROOT macros were utilized. To create the histograms for the number of interactions taking place data from the g4lbne was run though a macro called ancestry_test. What the ancestry_test macro does is it checks whether the interaction in question occurs inside or outside of the target and records that data. Then if the interaction takes place in the target it checks what particle interaction is taking place and records that data. The histograms for the neutrino flux and pion kinematics were generated using a macro called nuinfo. Nuinfo took the data from the g4lbne simulation on momentum, neutrino energy, and the weighted importance of the interactions. Then it complies that information into histograms on flux and kinematics. To create the cross-section histograms from the simulated data of g4hp two macros called CreateYields and CreateInvXS were used. CreateYields generates histograms of the kinematic distributions of the produced particle yields. Those histograms are then put into CreateInvXS, which then takes the information from those histograms and creates the desired cross-section histograms. The reason that we need to use g4hp, CreateYields, and CreateInvXS to obtain the cross section is because the geant4 cross-section data is not directly available to users.

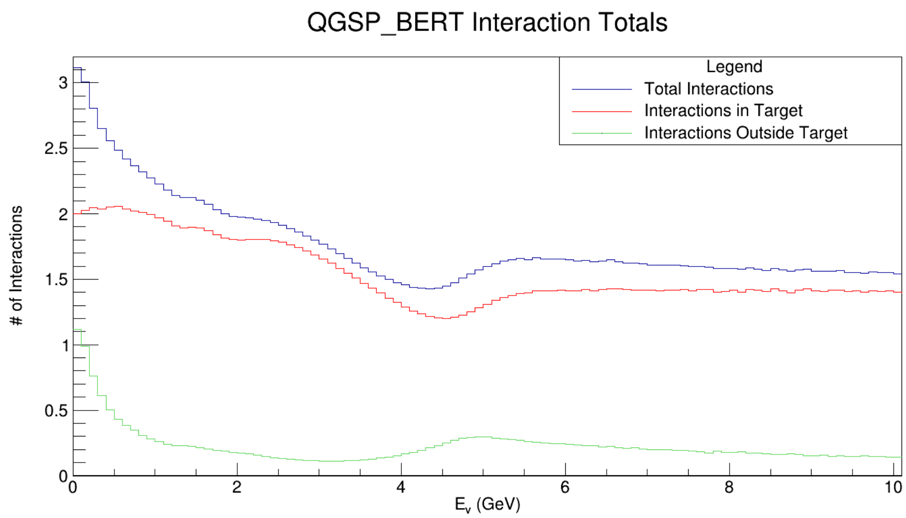
III Results & Discussion

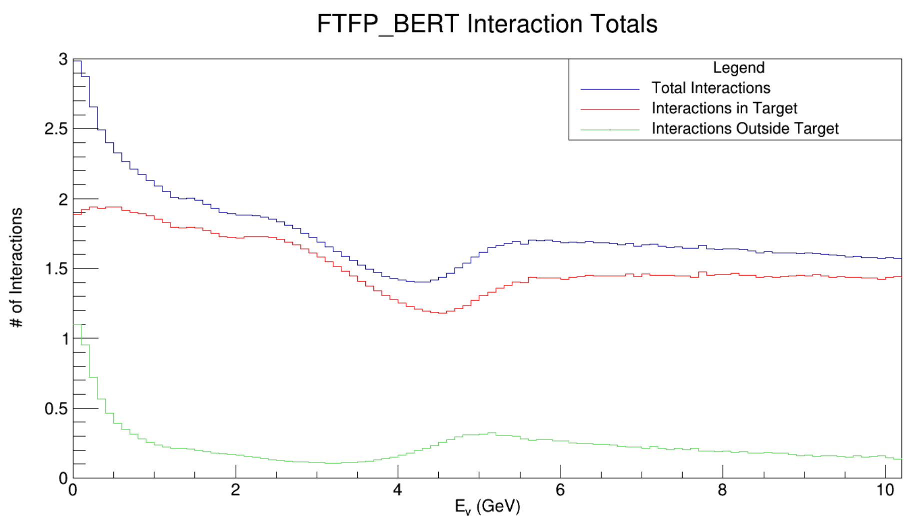
What we found for the uncorrected flux is that both QGSP_BERT and FTFP_BERT have a similar shape and agree that the flux has a wide band spectrum with a peak in the energy range of 0 to 5 GeV. We also see in that energy range QGSP_BERT and FTFP_BERT don't disagree by more than 10% and they typically disagree by around 5% or less. This is interesting as older versions of the models had much greater disagreement.





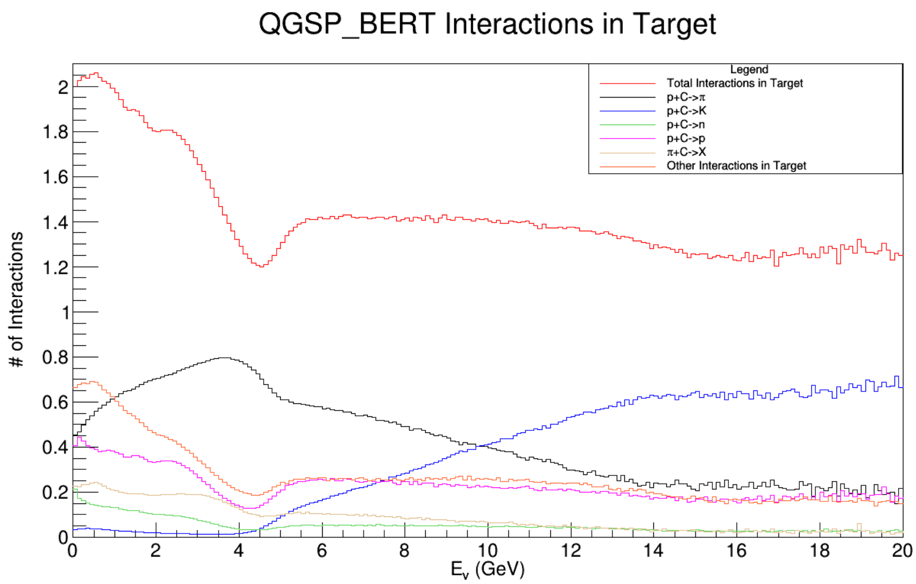
In order to identify the relevant hadronic interactions for the LBNF beam, I calculated the average number of total interactions with respect to the neutrino energy of a neutrino that passes through the DUNE near detector. What we find is that the average interactions of QGSP_BERT and FTFP_BERT are very similar in shape.

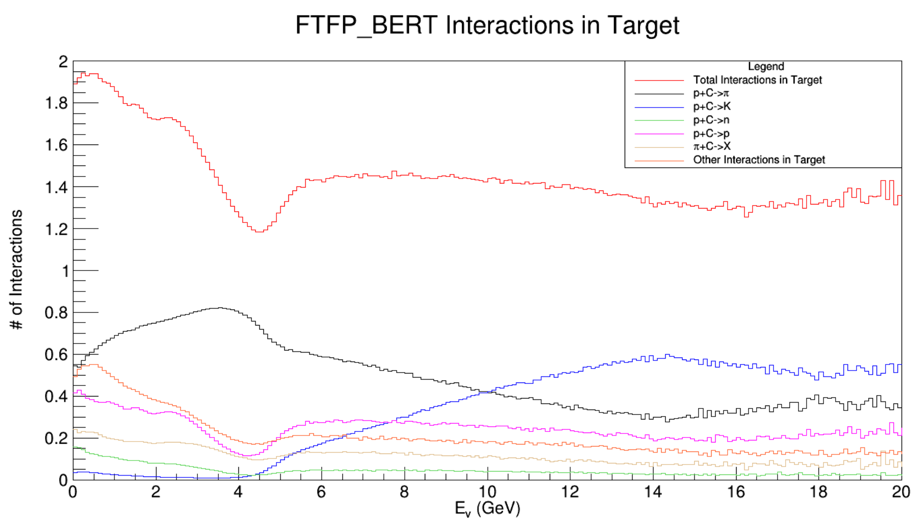




They also don't appear to differ very much from each other in the value of average number of interactions taking place. We also find both models agree most interactions are taking place inside of the target. In fact, on average less than 1 interaction takes place outside of the target, meaning that most particles in the beam don't interact outside of the target. The exception for this is when the neutrino energy is less than 0.5 GeV then we find that approximately 1 interaction on average is taking place outside the target. Inside of the target the average number of interactions varies from 1 to 2 interactions. Particles with lower energy tend to have more interactions, the reason for this is because at very low energies the particles have a more difficult time leaving the target, which increases the chance of an interaction occurring. Because we find that most interactions are happening inside the target, we split this total into different categories.

What we see for the breakdown of the interactions taking place in the target is for energies below 10 GeV proton on carbon interactions that produce pions ($p + C \rightarrow \pi$) is the dominant interaction taking place.

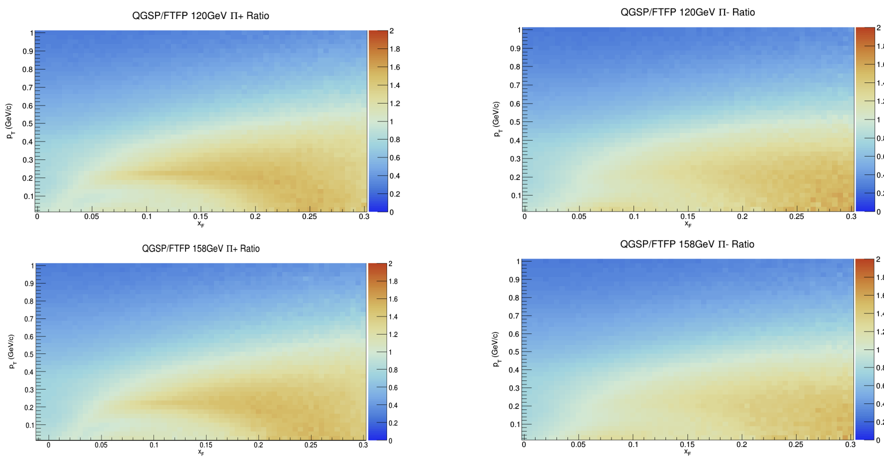




For energies above 10 GeV proton on carbon interactions that produce kaons ($p + C \to K$) become dominant. It appears that QGSP_BERT and FTFP_BERT don't have much disagreement on pions being dominant in the

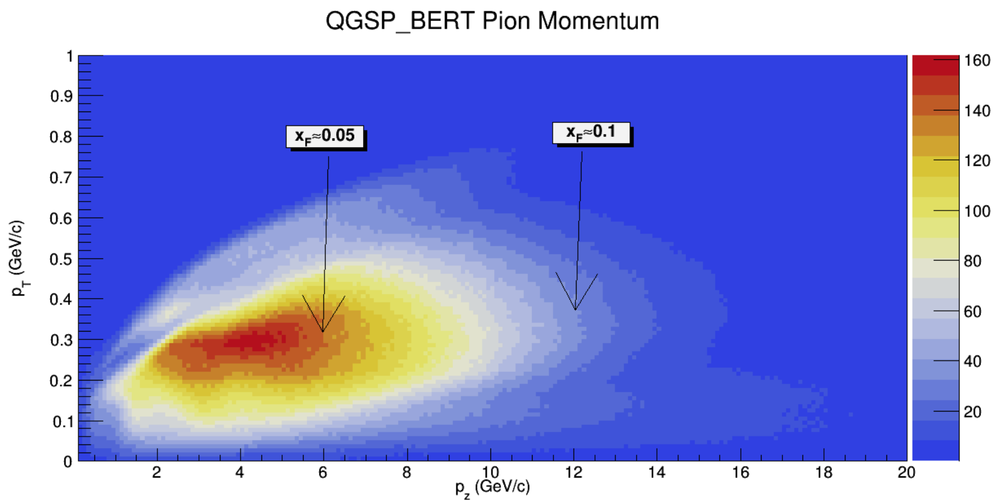
0-10 GeV range or kaons being dominant in the 10-20 GeV. But they do disagree on the nondominant interactions taking place in the target, especially at higher neutrino energies. For example, there is a difference in the ratio of pion to kaon production in the 10 to 20 GeV range. For the QGSP_BERT model the kaon production is much more dominant over every other interaction in that energy range. While FTFP_BERT also does have kaon production being dominant it is not as dominant. The difference appears to come from the fact that FTFP_BERT has a higher rate of $p + C \to \pi$ than QGSP_BERT in the 10 to 20 GeV range.

The next step was comparing the extracted pion production cross section from incident protons at 158 GeV and 120 GeV. The results I found were that the cross-section ratios of QGSP_BERT and FTFP_BERT are very similar for both positive and negative pions for both 120 and 158 GeV. Both models have a lot of agreement for values of Feynman-x (x_F) below 0.05 when the transverse momentum (p_T) is less than 0.5 GeV/c. When x_F is above 0.05 and transverse momentum is less than 0.5 GeV/c we find that QGSP_BERT has a larger cross section in this range. Also, FTFP_BERT has a larger cross section in all cases when p_T is greater than 0.5 GeV/c.



However, in the ranges where the models have the most disagreement, they appear to disagree by approximately 30% - 40%.

The plot below shows the positive pions produced in proton on carbon collisions in the target, with respect to the longitudinal and transverse momentum, that create neutrinos that pass through the DUNE near detector.

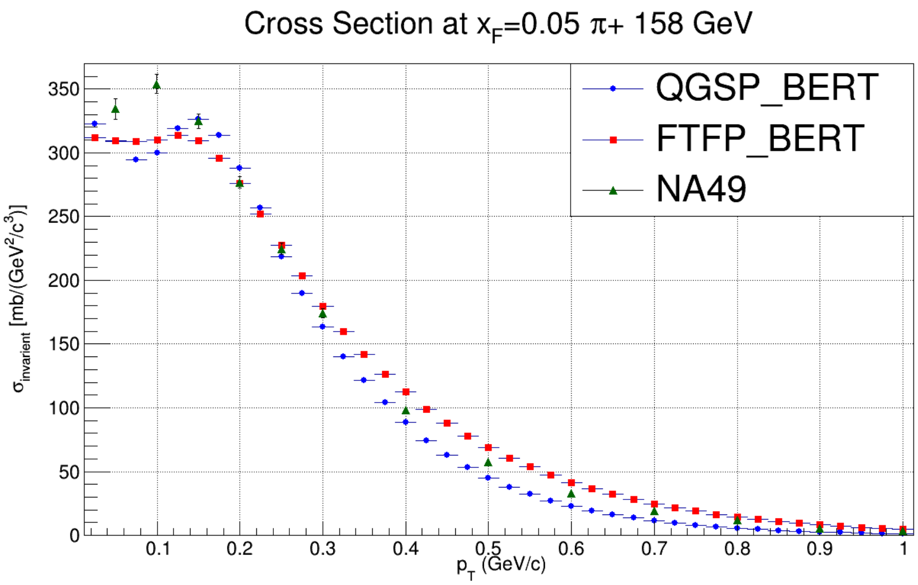


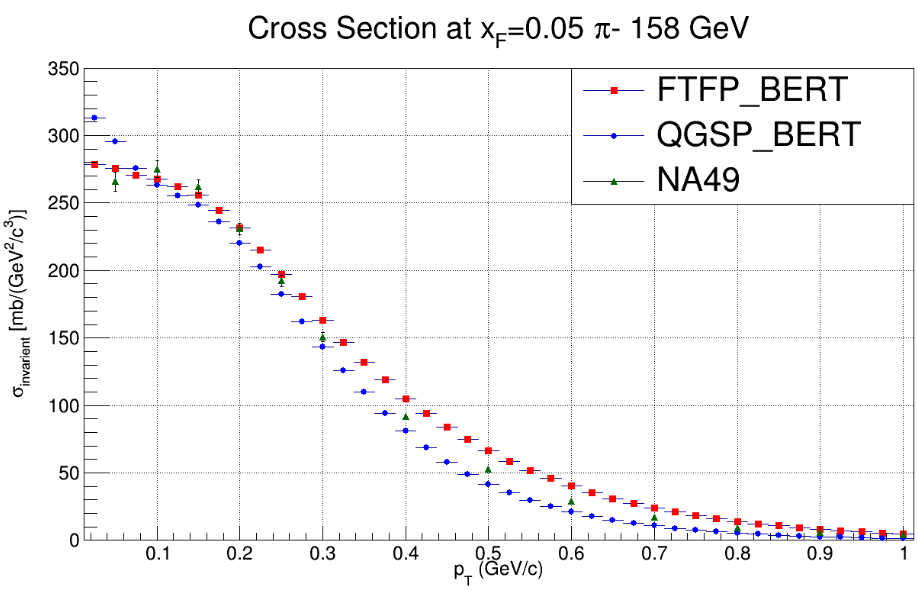
It is clear from the plot that most of the pion momentum is in the 1-10 GeV/c range. This plot also shows why the Feynman-x values presented in the below cross-section histograms were chosen. First, the equation for Feynman-x is

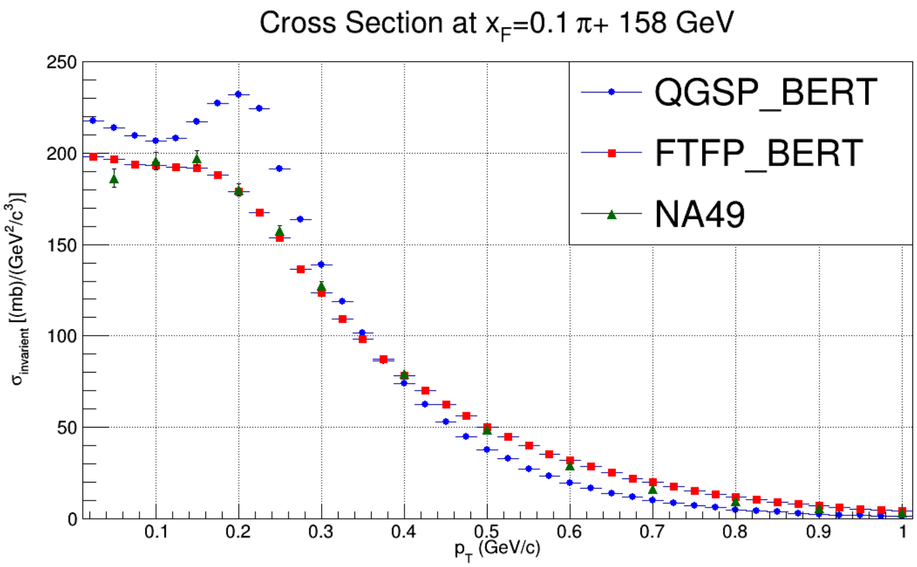
$$x_F \simeq \frac{p_L}{\sqrt{s}/2},$$

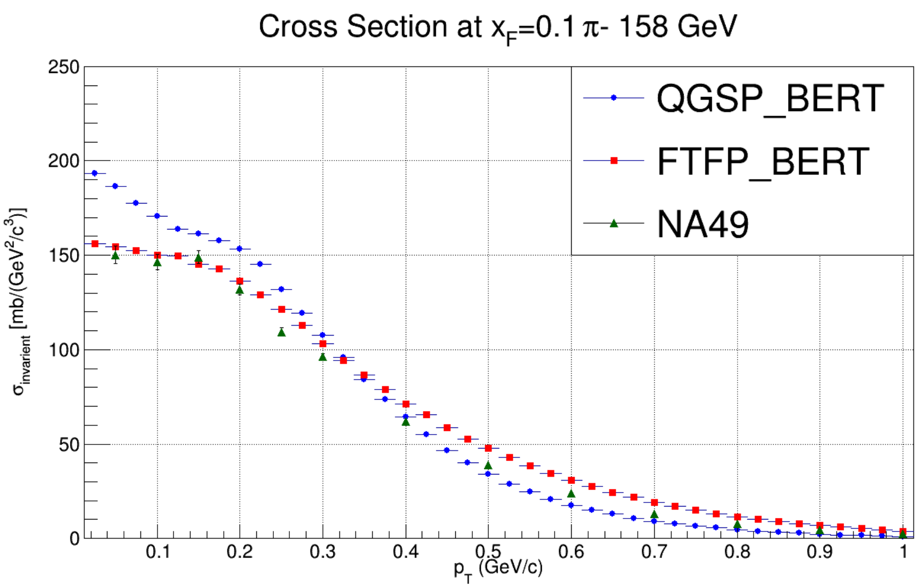
where p_L is the longitudinal momentum in the center of mass frame and $\sqrt{s}/2$ is the energy of the center of mass. As can be seen x_F of 0.05 is approximately equal to the longitudinal momentum of 6 GeV/c and x_F of 0.1 is approximately equal to the longitudinal momentum of 12 GeV/c. (Note: the arrows in the plot are there to show the region that the x_F value is associated with. It does not mean that only that specific point has that x_F value. The entire slice of the x-axis at 6 GeV/c corresponds to x_F=0.05 and the entire slice of the x-axis at 12 GeV/c corresponds to x_F=0.1). The reason that 0.05 and 0.1 were the Feynman-x values chosen was because x_F=0.05 is very close to the center of the 'hotspot' where most of the pions produced in the target will have similar kinematics. x_F=0.1 was chosen because it lies on the edge of the 'hotspot'.

The below plots show the results of the cross-sections for both positive and negative pions at Feynman-x of 0.05 and 0.1 with incident proton energy of 158 GeV. What we find is that, for both positive and negative pions, at low transverse momentum QGSP_BERT has a larger cross section compared to NA49. QGSP_BERT's cross section also generally decreases as the transverse momentum increases until the cross section for QGSP_BERT is smaller than the cross section for NA49. On the other hand, FTFP_BERT usually starts close to the NA49 data when transverse momentum is low and at higher transverse momentum it tends to have a larger cross-section compared to NA49.

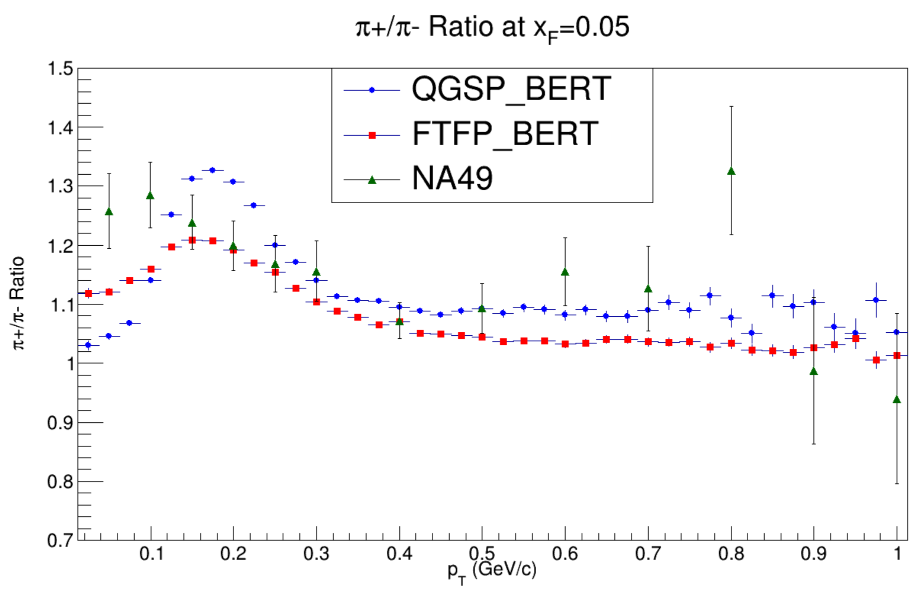

Cross Section at x_F=0.05 π+ 158 GeV
QGSP_BERT
FTFP_BERT
NA49
$\sigma_{invarient}$ [mb/(GeV^2/c^3)]
p_T (GeV/c)


Cross Section at x_F=0.05 π- 158 GeV
FTFP_BERT
QGSP_BERT
NA49
$\sigma_{invarient}$ [mb/(GeV^2/c^3)]
p_T (GeV/c)

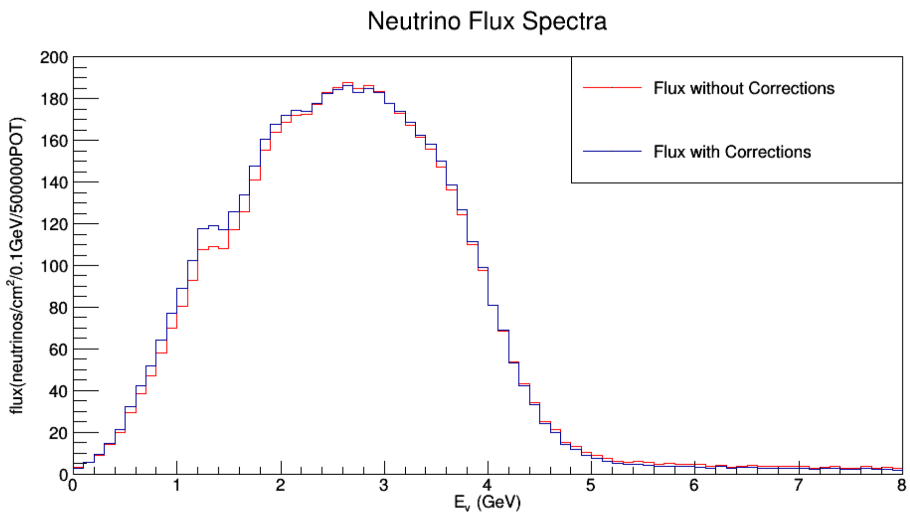




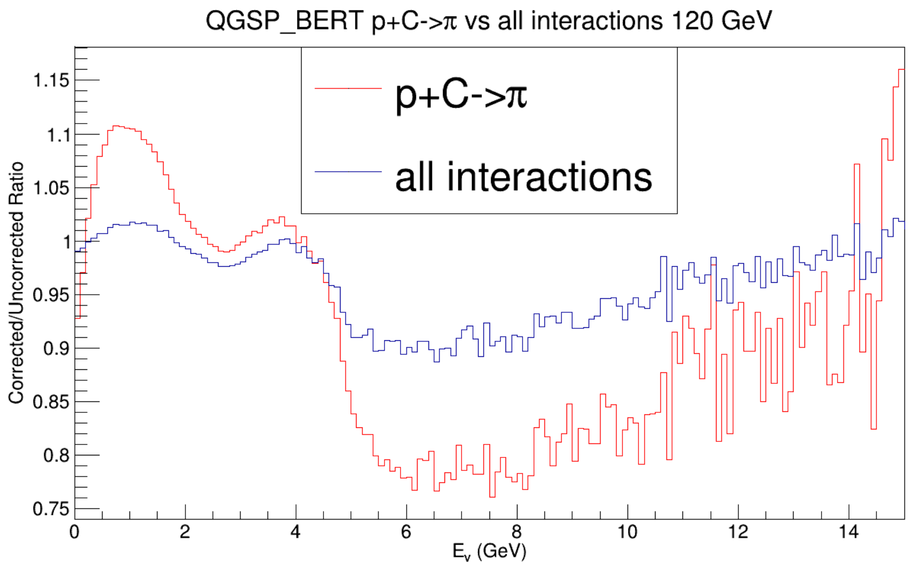
Also, of note is that the cross section of positive pions is greater than the cross section of negative pions. This is important to note because the LBNF has, the previously mentioned, magnetic focusing horns. Which have the functionality to focus charged particles we want in the beamline, and defocus charged particle we don't. However, there will still be some background of the particles we don't want that get past the magnets into the beamline. So knowing how many pions of both charges are created is important.



The final step of my project was to apply a correction to the QGSP_BERT model to match the NA49 data for the primary proton interactions producing pions in the target. Then evaluating the effect, it has on the muon neutrino flux predictions at the DUNE near detector.



What we find for the corrections applied to the neutrino flux is that the corrected and uncorrected flux have a similar shape. The difference between the flux is it also does not appear to be too dissimilar in the 0 to 5 GeV region. We also calculated the flux correction for a subset of the total flux corresponding to neutrinos produced from primary protons interacting with the target and creating a pion neutrino parent (that means, only those that can be corrected). This indicated to us the real impact of the corrections I applied (red line in the plot below).



What we find is a moderately large correction being applied in the 0 to 2 GeV region. The probable reason for this is because the correction is only applied to the initial proton and not any subsequent interactions that may have taken place and for low energies the chance for reinteraction is greater. The dip that then happens in the weight of the corrections does not currently have an explanation and will require further study.

IV Conclusion

FTFP_BERT on average does a better job of more closely following the NA49 data than QGSP_BERT. FTFP_BERT could possibly be used to simulate proton on carbon interactions that we have no experimental data for comparison. My project can also be used as a template to correct the flux for other particles, e.g. kaons. The next step to be taken with this data should be to apply corrections beyond primary proton (i.e. particles that reinteract in the target to obtain a better idea of the correction at lower neutrino energies).

V Acknowledgments

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VI References

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