Predicting the Flux: Models and Simulation for NOvA

Elise Chavez, Florida State University – SIST
Supervisor: Leo Aliaga, Fermilab

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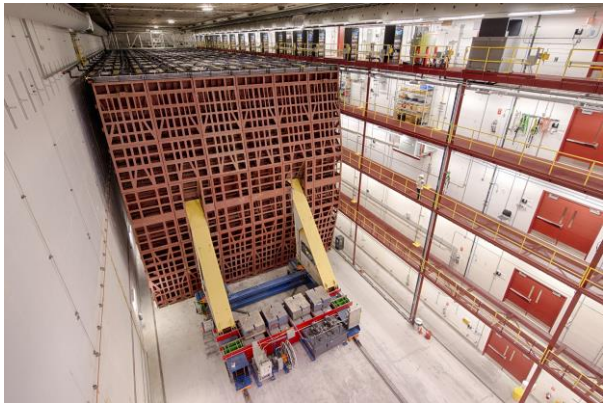
A Brief Introduction

- Neutrinos, elusive as they are, provide unique ways of studying the sub-atomic world
  - Charge-Parity(CP) Violation
  - Mass Hierarchy
  - Precise measurement of oscillation parameters
- Several experiments here at Fermilab, and around the world, work to study neutrinos for these reasons
  - NuMI Off-axis ν_e Appearance (NOvA)
  - Upcoming Deep Underground Neutrino Experiment (DUNE)
  - MicroBooNE
  - MINERvA
  - Super Kamiokande
  - Ice Cube
- The main experiments of interest for this project are NOvA and DUNE

NOvA

- Receives neutrinos from the NuMI (Neutrinos from the Main Injector)
- Consists of two detectors approximately 810 kilometers apart
  - NOvA Near
    - 300 metric-tons
    - Fermilab
  - NOvA Far
    - 14 metric-kilotons
    - Ash River, Minnesota



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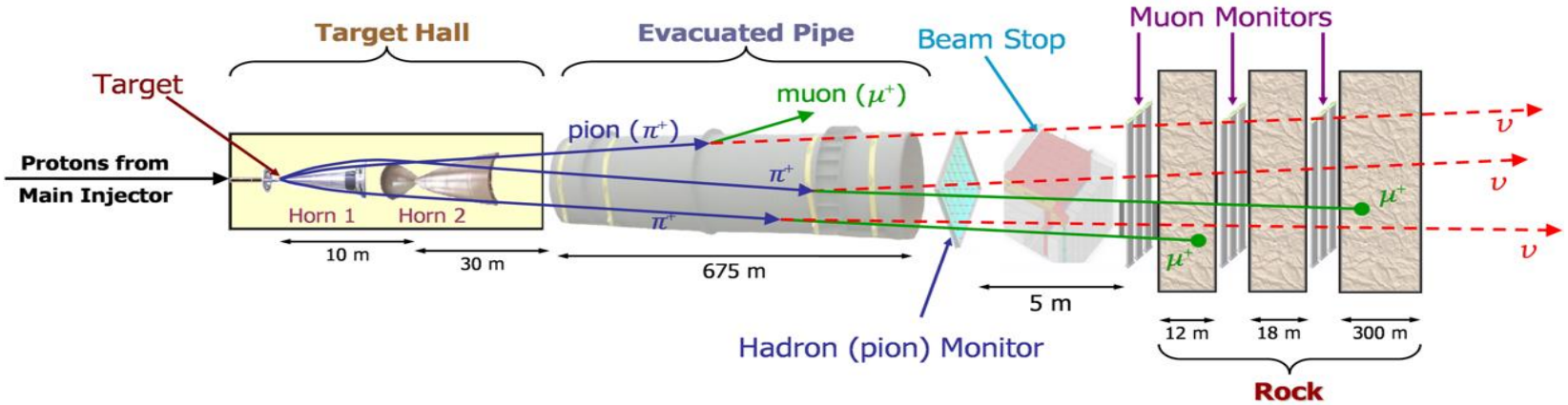
The NuMI Beam

- Protons extracted from Main Injector at 120 GeV and aimed at a 1.2-meter graphite target
- Protons interact with the target
  - Produce short-lived secondary particles (pions and kaons)
- Horns focus the charged secondaries
- Secondaries decay to neutrinos



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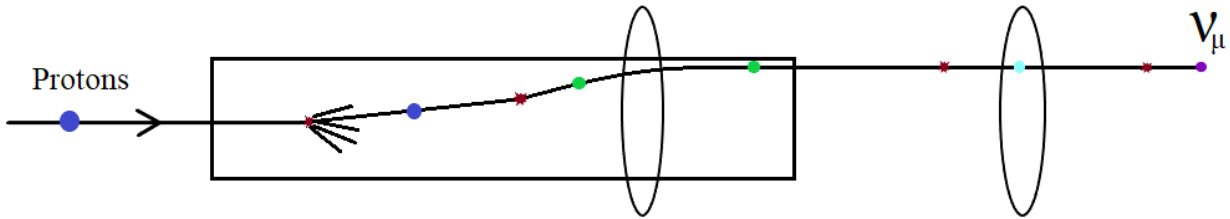
Neutrino Flux

- Several important pieces
  - Interactions and beam simulated using g4numi (geant4 based simulation with FTFP_BERT hadronic model)
  - Simulation output processed using PPFX (Package to Predict the Flux)
    - Corrects simulation hadron production using measured data and extended data based on physics when there is none
- Two main challenges
  - Geometry
  - Hadronic Model



The Goal

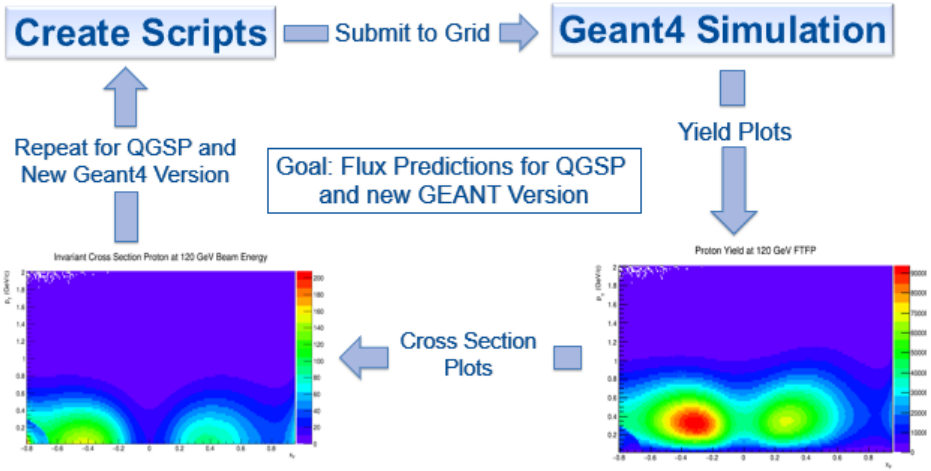
- Automate updating Geant4 and changing the hadronic model
  - Make tools to make the update easier
  - geant4.9.2p03 → geant4 v4_10_3_p03b
    - NOVA uses the old version, DUNE uses the new one
  - FTFP_BERT → QGSP_BERT
    - NOVA uses FTFP, DUNE uses QGSP
- Obtain yield and cross section plots to analyze the changes
- Obtain neutrino flux predictions for the update and model change
- PPFX, currently, only corrects FTFP_BERT for geant4.9.2p03

Current Progress

- The process of updating GEANT4 and extracting the cross sections from the hadronic model is largely automated
  - Tested for geant4.9.2p03 and FTFP_BERT and geant4.9.2p03 and QGSP_BERT
  - The GEANT4 version update has been completed, but the data has not been analyzed at this time
- Extracted yields and cross sections for particles produced in proton interactions in carbon for QGSP_BERT
  - Compared it with FTFP_BERT

The Process

- Differential cross section not available to users
  - Start by making a simulation of projectile colliding with a thin target
  - Store the kinematic information
  - This simulation is called G4HP and produces event by event ntuples
- Script called CYhA creates yield distributions from the G4HP ntuples and stores them in histograms
- Then a script called CreateInvXS-ha takes in these histograms and calculates the final invariant double differential cross sections



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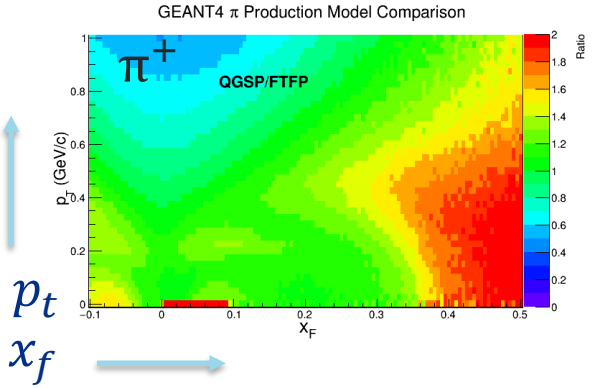
The Process for Changing Hadronic Models

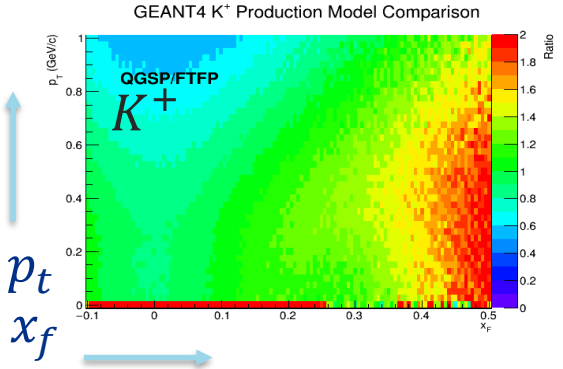
- Setup a compatible version of ROOT and GEANT4
  - Script: setupold_g4hp.sh
  - GEANT4 Version: 09-02-patch-03
  - ROOT Version: 5.34/32
- Change the hadronic model with “QGSP_BERT* physicsList = new QGSP_BERT;” in the g4hp.cc file
- Run ProcessG4HP.py with the appropriate grid instructions
  - --n_jobs=1000 --particle proton --nevts=25000000 --target=C --numrun=6 --outdir=/pnfs/nova/persistent/users/elisec/g4hp/QGSPTest in my case
  - Will run for 13 energies each job (12, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 158)

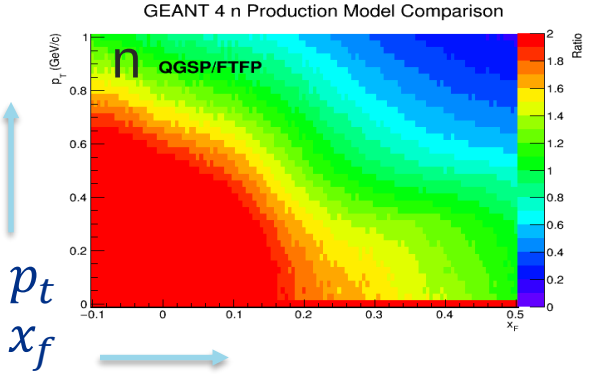
The Process for Changing Hadronic Models (cont.)

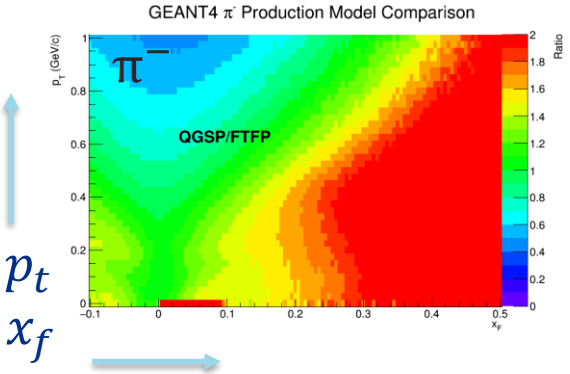
- Run haddscript.sh once the grid run is complete with the appropriate directory name
  - In this example, QGSPTest
  - haddscript.sh hadds together Yield histograms created during the grid job
- Run CreateInvXS_hA.C for each hadded file (13 total)
- After this, there will be cross section plots that can be used to update PPFX and create a new flux prediction

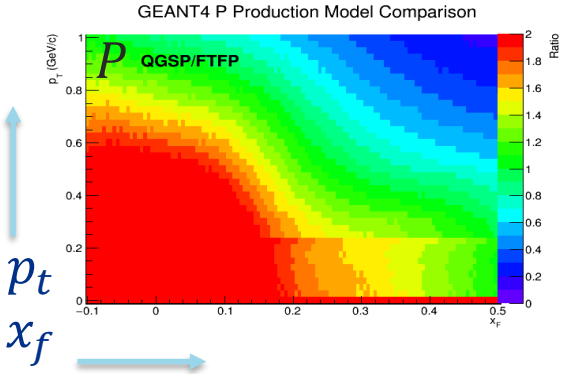
FTFP_BERT vs. QGSP_BERT

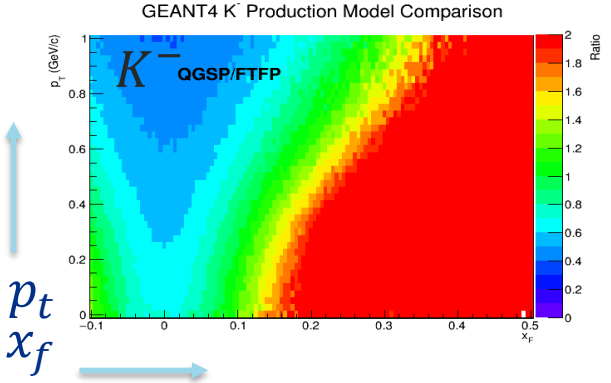












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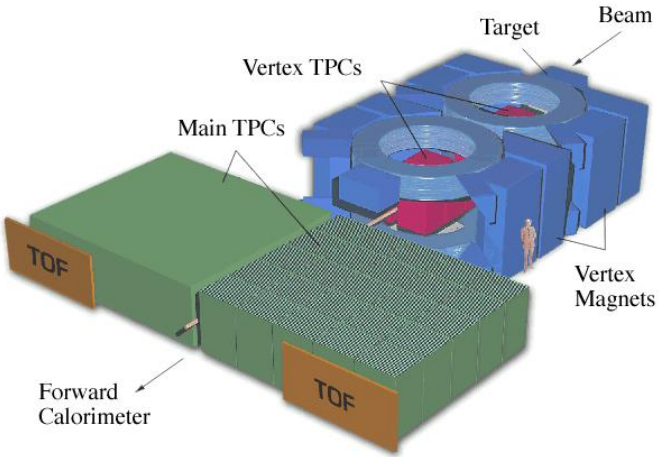
NA49 Experiment

- CERN Experiment on hadron production
- Study cross sections for various proton on target interactions
- Have studied proton on carbon at 158 GeV
  - Cross section data for this energy



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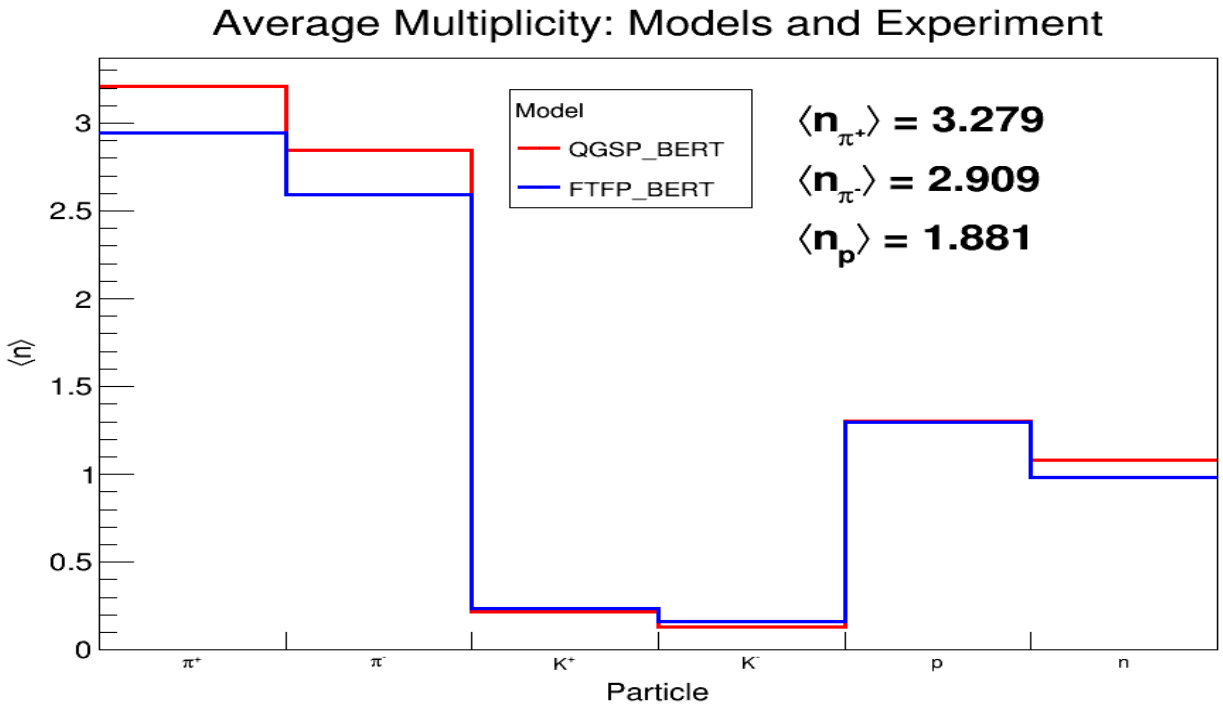
FTFP, QGSP, and Data: Pion Ratios



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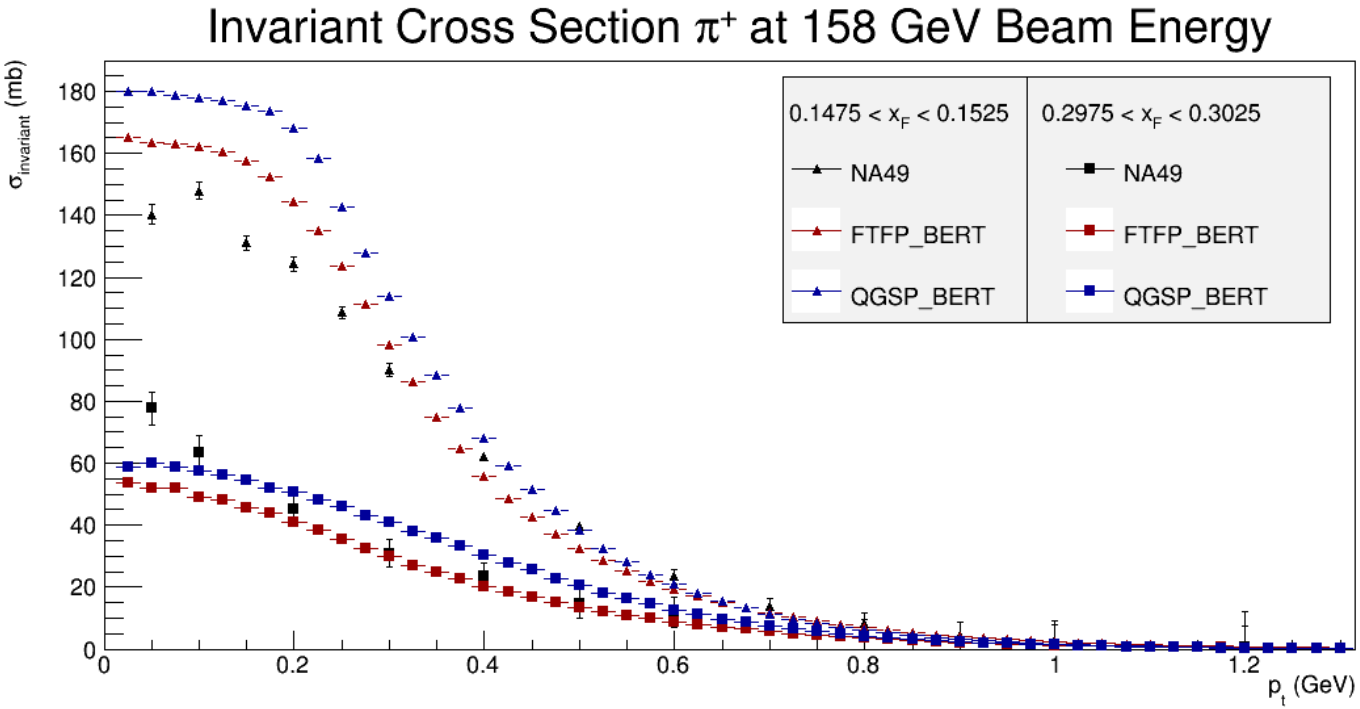
FTFP_BERT, QGSP_BERT, and NA49 Experimental Data for Pion Plus



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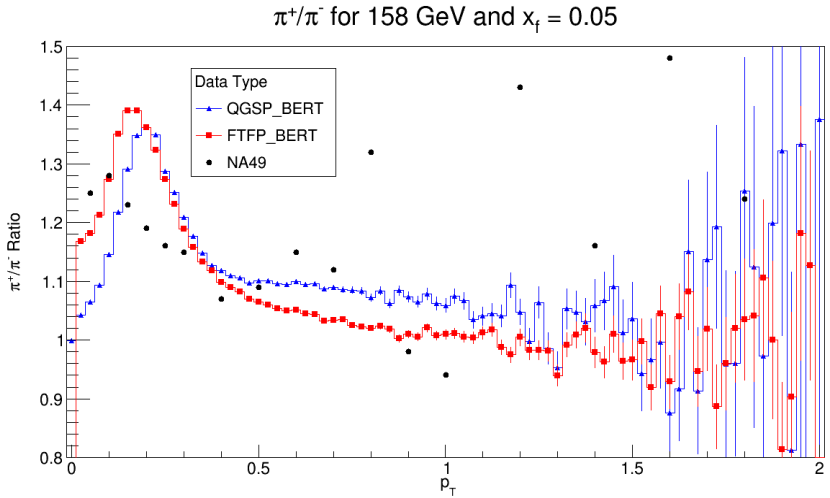
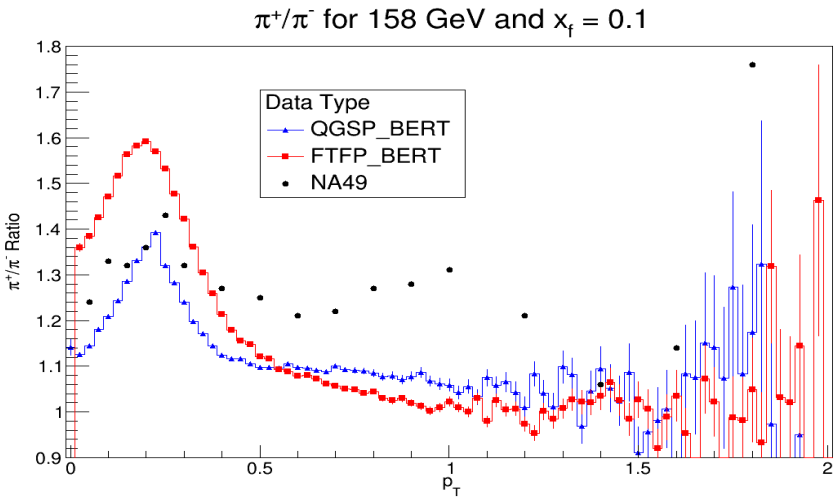
π^+/π^- Ratios for Two Different Values of x_f





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GEANT4 Update

- The GEANT4 update was completed but the data was not available for analysis before this presentation
  - The process is automated and we look forward to viewing the results
- The change occurs in the setup script that runs when the simulation is sent to the grid
  - Once the entire run is analyzed and the process finalized, the change from one version to another should be as easy as switching out setup scripts

Conclusions

- Need further studies of hadronic cross sections
  - EMPHATIC
- The hadronic models are indeed incomplete
- NOvA's use of FTFP is appropriate for their version of GEANT4
- Updating is far easier
  - NOvA can use it now
  - DUNE should be able to mimic this for their experiment

Thank you!

- My Supervisor: Leo Aliaga
- My Mentors: Camille, Donovan, and Arden
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- Laura Fields, Sandra Charles, and Judy Núñez
- NOvA
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- The Bison