Neutrino flux prediction for DUNE

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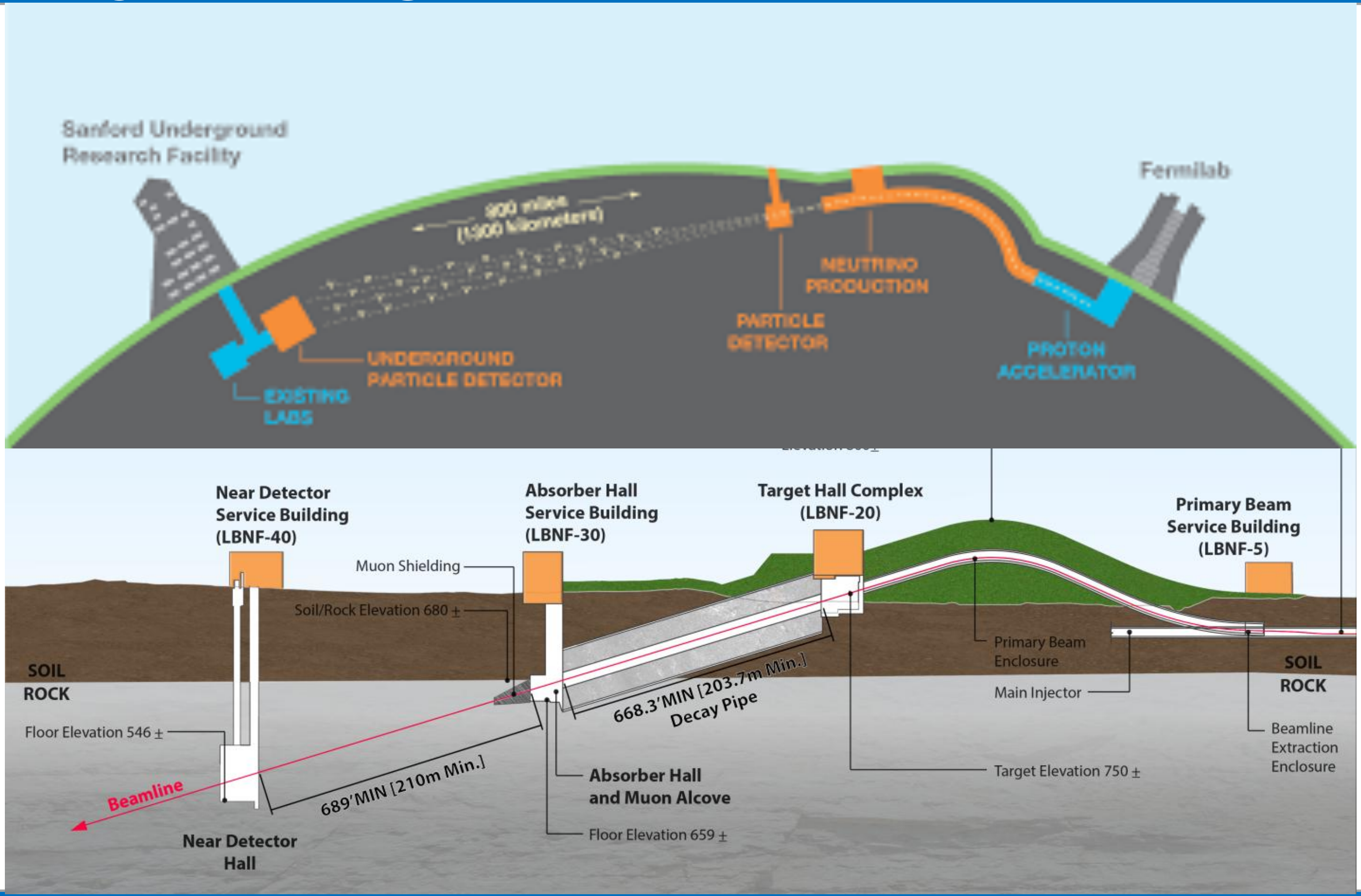
On behalf of
Deep Underground Neutrino Experiment (DUNE)
Collaboration

Deep Underground Neutrino Experiment (DUNE)

- DUNE is a future long baseline neutrino experiment

- Neutrino oscillation studies to test CP violations in lepton sector and mass ordering

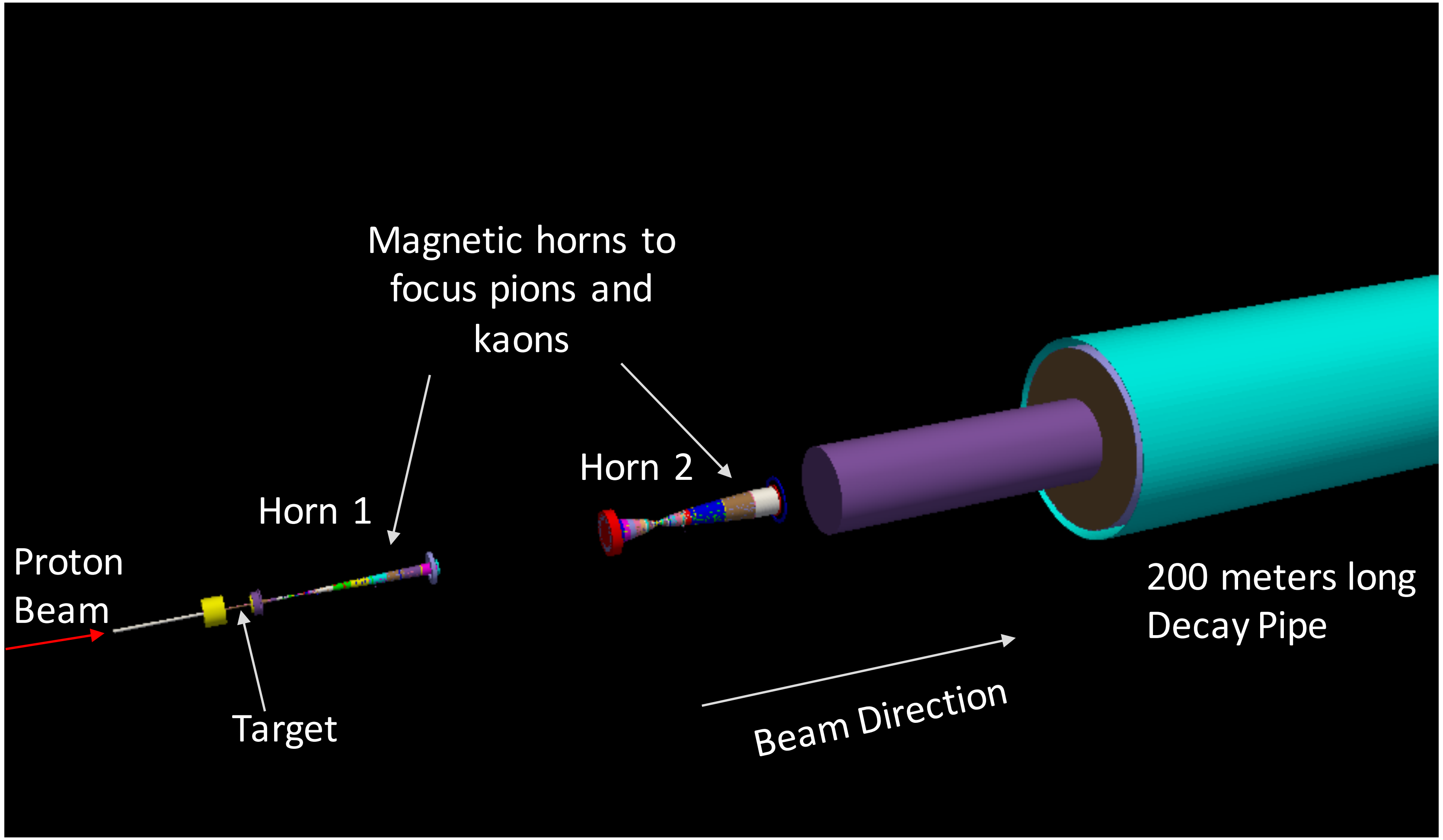
- Near Detector will be at 574 m from the start of first focusing horn
- Far Detector at 1300 km in Sanford, South Dakota



DUNE Beam Simulation

- LBNF beam line (g4lbnf) written with GEANT4 package
- Detailed simulation of particle production, transportation and decay leading to the neutrino flux production
- Produced neutrinos are projected at the Far and Near Detector locations for physics studies
  - Reliable neutrino flux prediction depends on:
    - Understanding the flux at near and far detector and their correlations
    - Understanding the systematics in the neutrino flux from focusing and hadron production uncertainties

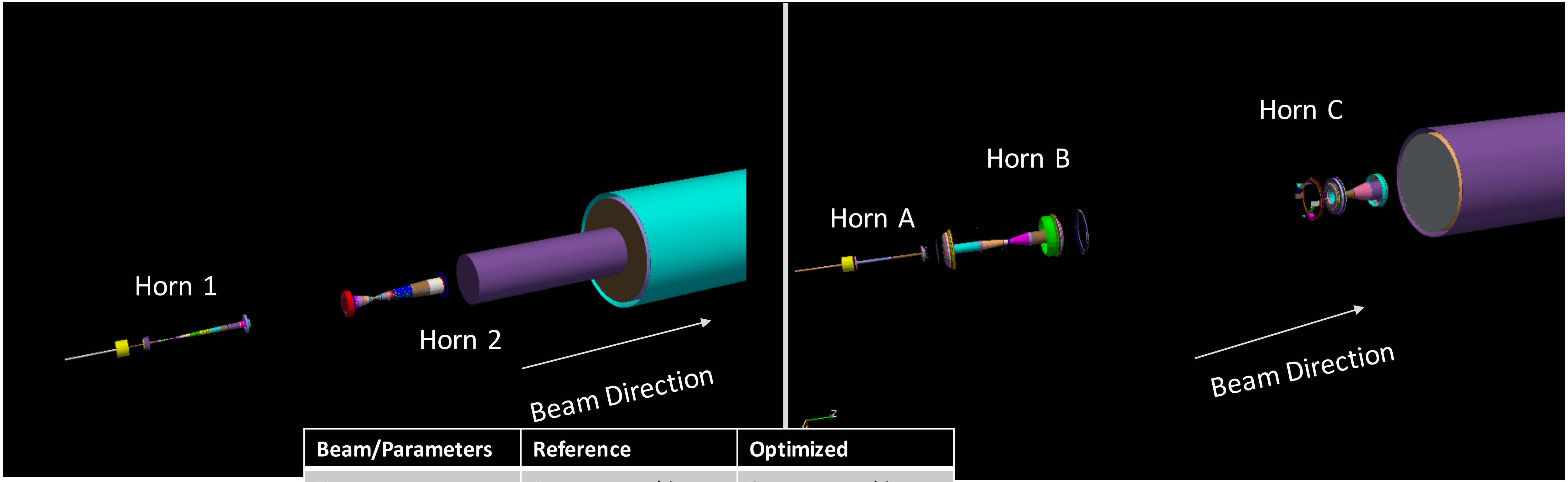
DUNE Beamline (Nominal)



Simulation starts from proton beam hitting the target to neutrino production

- Proton Beam hits the target
- Charged pions and kaons are produced which in turn are focused by magnetic horns
- 200 meters long decay pipe to let focused pions and kaons decay to produce neutrinos

DUNE Beamline (Nominal & Optimized)



Nominal

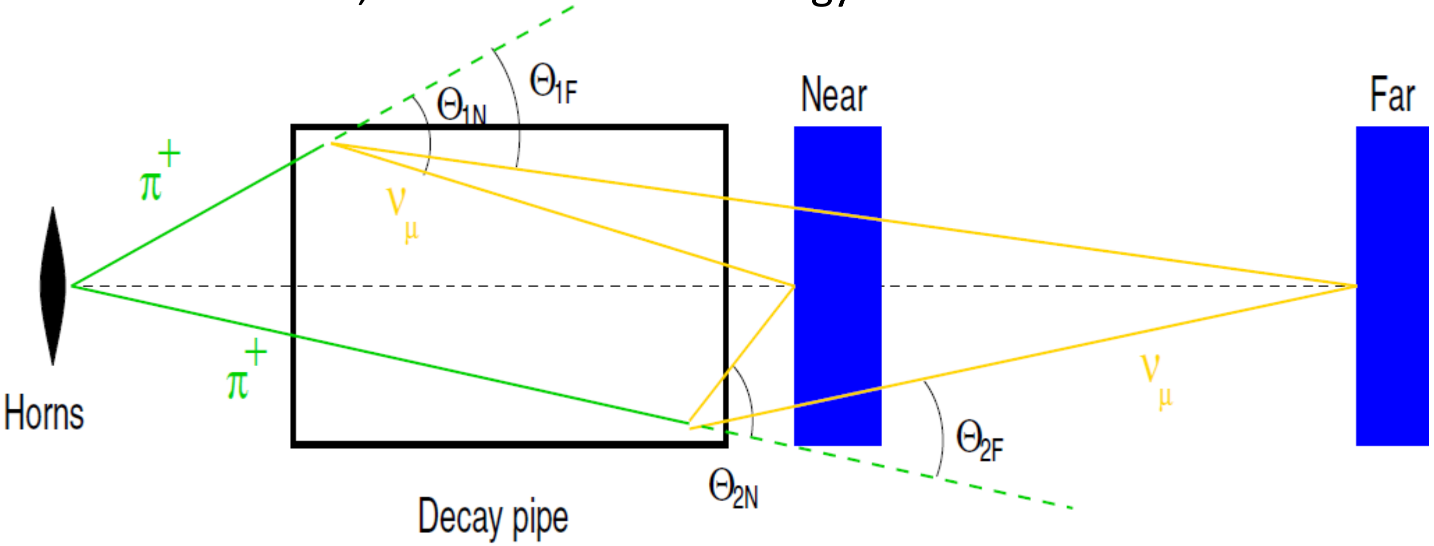
Optimized

Beam/Parameters	Reference	Optimized
Target	1 meter graphite	2 meter graphite
Horns	2 horn (Numi Style)	3 Horn (Ideal, no Eng. Constraints)
Current	230 kA	298 kA
Proton Energy	120 GeV	120 GeV

Near to Far Flux Extrapolation for DUNE

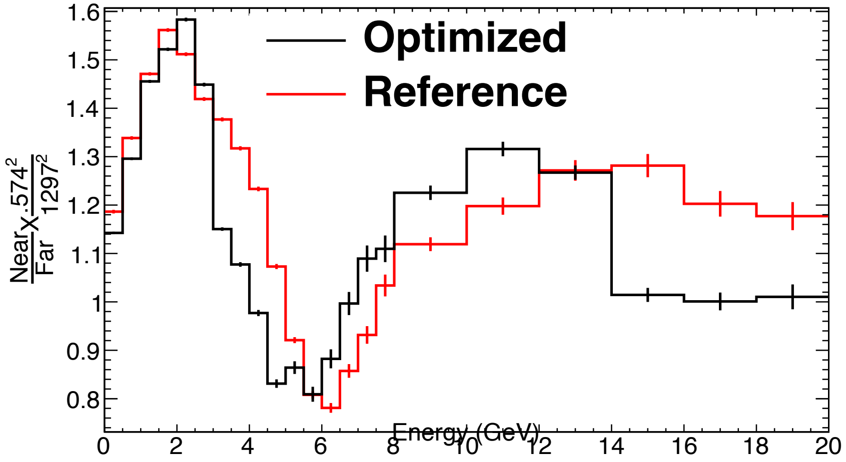
$E_\nu = \frac{0.43\ E_\pi}{1 + \gamma^2\theta^2}$ Θ → decay angle

- Decay angle as seen by near and far detector are different
- Strong dependence for high energy pions
- For same neutrino:
  - At near detector, it will have lower energy than that in far detector

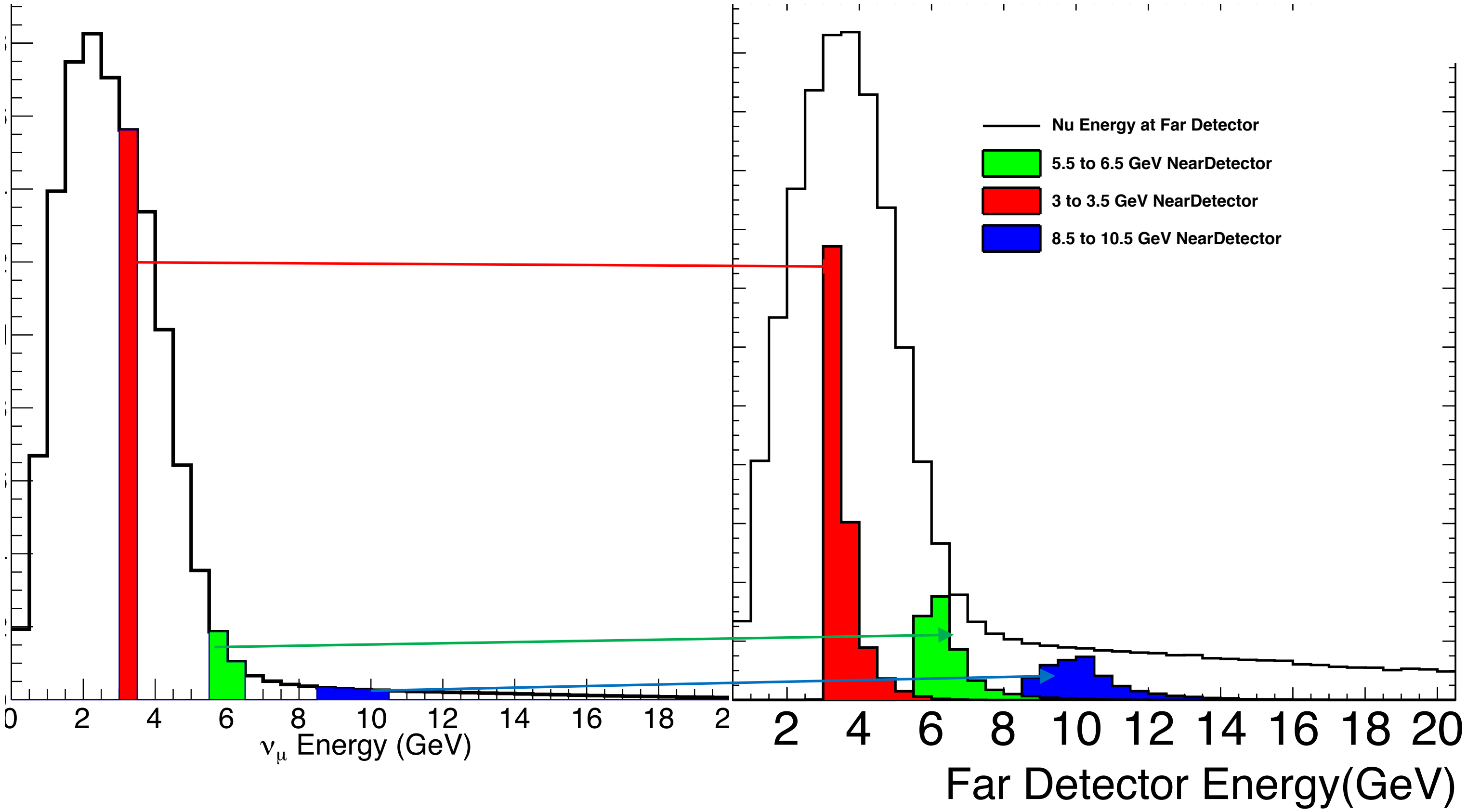


- Near detector being near to beamline, sees it as a line source of neutrinos
- Far detector sees it as a point source

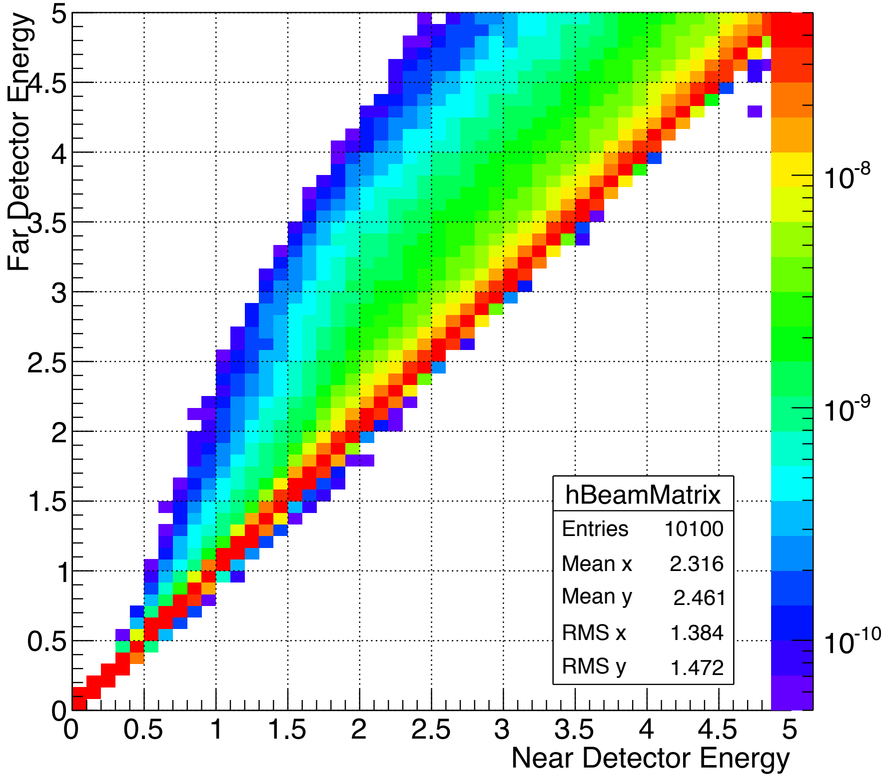
- Besides the R^2 effect, this effect also needs to be considered for an accurate neutrino flux prediction



Near to Far Flux Extrapolation for DUNE

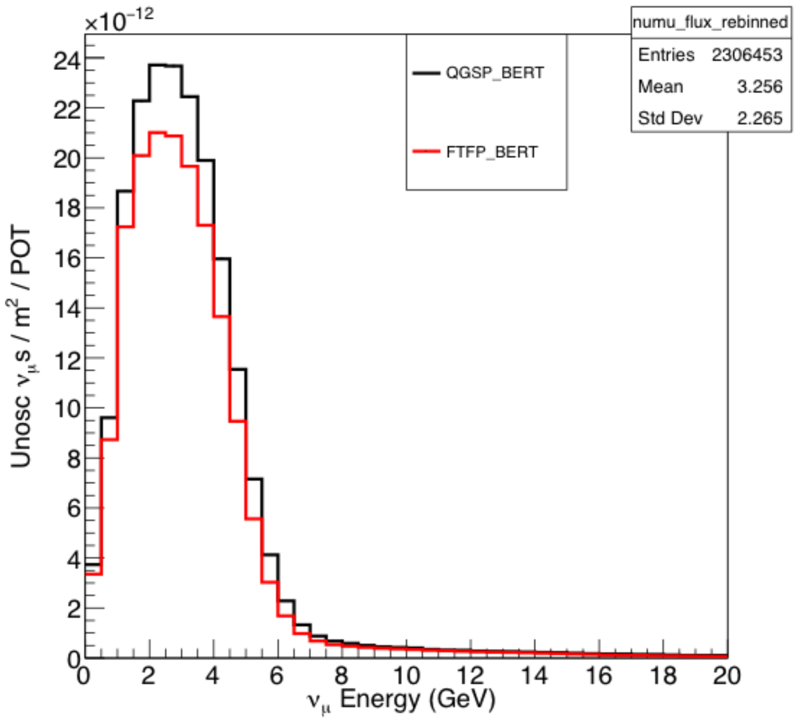


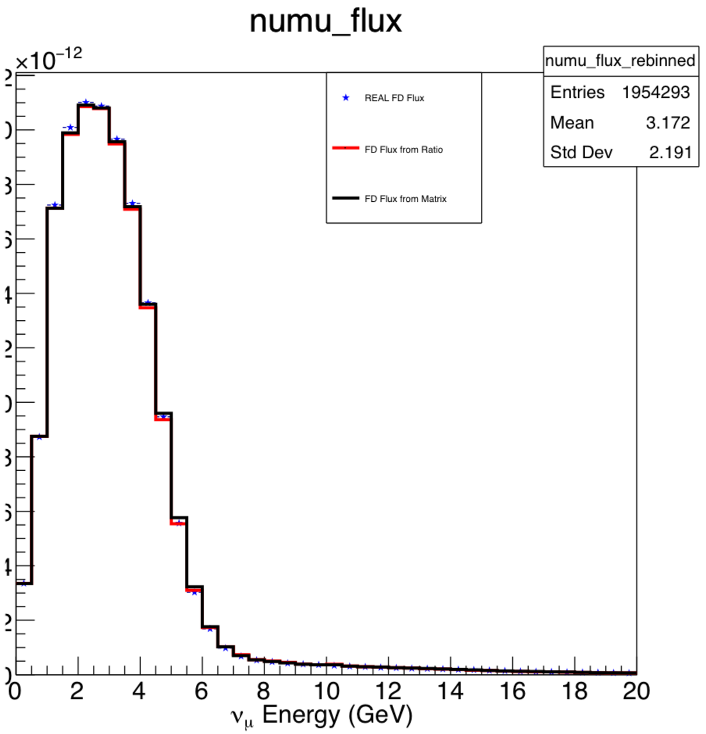
Mapping of neutrino energies from Near to Far Detector

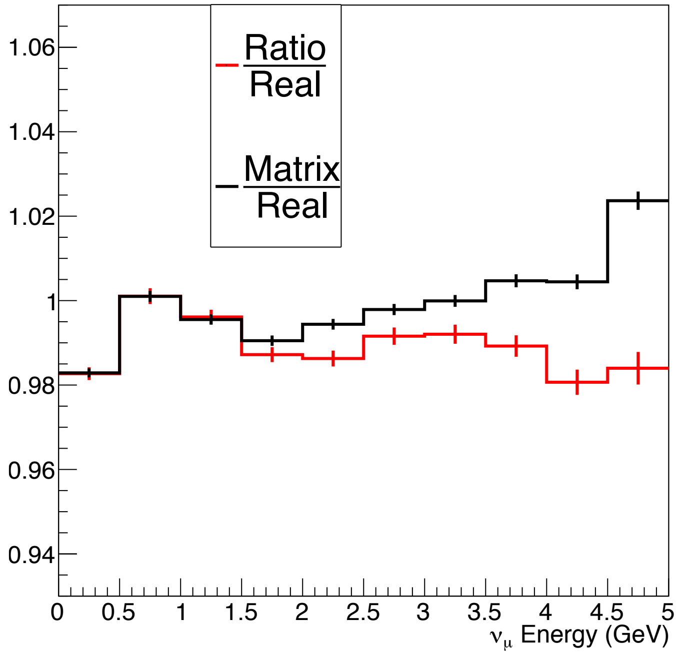


Near Far Correlation with the Matrix

Near to Far Flux Extrapolation for DUNE







- $\emptyset^{FTFP}_{v\ i(Far)} = \frac{\emptyset^{QGSP}_{v(Far)}}{\emptyset^{QGSP}_{v(Near)}} \ \emptyset^{FTFP}_{v(Near)}$ (Ratio Method)

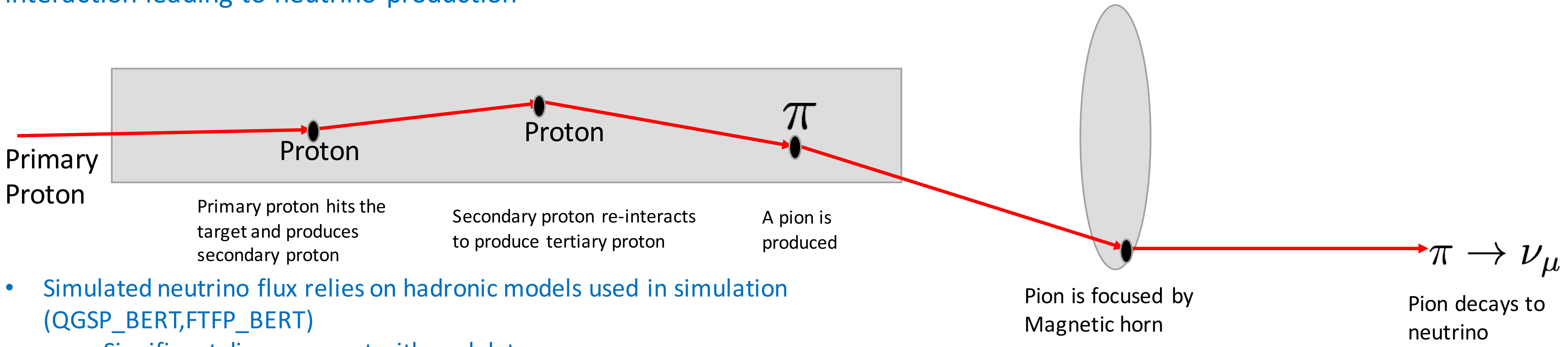
$\emptyset^{FTFP}_{v\ i(Far)} = \Sigma_j \ M_{ji} \emptyset^{FTFP}_{v(Near)}$ (Matrix Method) $M_{ji} = \frac{\emptyset^{QGSP}_{ji(Far)}}{\emptyset^{QGSP}_{j(Near)}}$

Flux Uncertainties in DUNE Neutrino Beam

- Accurate prediction of neutrino flux also relies on understanding the systematics in the flux
  - Uncertainties in 2 broad categories:
  - Focusing
    - Uncertainties in beamline parameters → Position of horns, current in horns,target density
    - Uncertainty in number of protons on Target
  - Hadron Production
    - Due to uncertainties in Geant4 models of pions and kaons produced in the target and other beam line materials

Neutrino Flux Uncertainties

Accurate neutrino flux prediction relies on detailed modeling and understanding of processes starting from primary proton on carbon interaction leading to neutrino production



- Simulated neutrino flux relies on hadronic models used in simulation (QGSP_BERT,FTFP_BERT)
  - Significant disagreement with real data
    - Constrain the hadron production models by external data

- Focusing uncertainties from the fact that simulation has an idealized beamline geometry and doesn't account for geometrical mismodeling

Package to Predict the Flux (PPFX)*

- An experiment independent neutrino flux determination package for the NuMI beam
- Correction for hadron production uncertainties using existing thin target data sets
- Developed by Leo Aliaga for the MINERvA collaboration

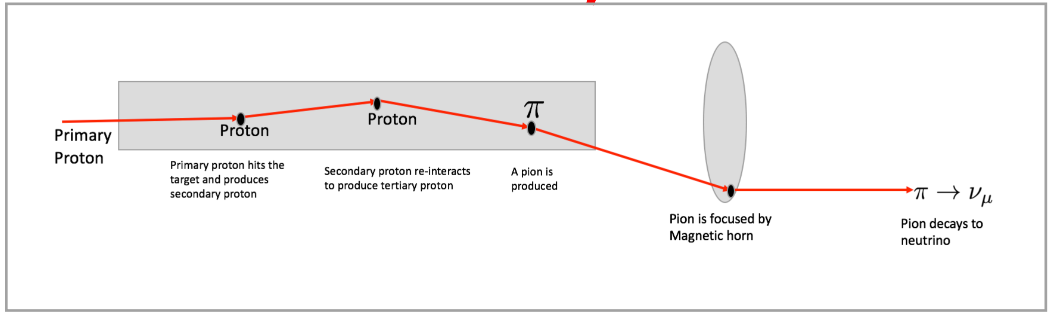
*L. Aliaga Soplin, *Neutrino Flux Prediction for the NuMI Beam*, URL: https://arxiv.org/pdf/1607.00704.pdf

Neutrino Flux Uncertainties from Hadron Production

Simulation → Full Neutrino Ancestry → For Each interaction in an ancestry →

Coverage of interaction by Existing Data sets

- Direct Coverage
- Coverage By Extension
- No Coverage at all



Full ancestry of a neutrino event (from primary proton hitting target to neutrino production)

***Coverage by Extension of Data Sets**

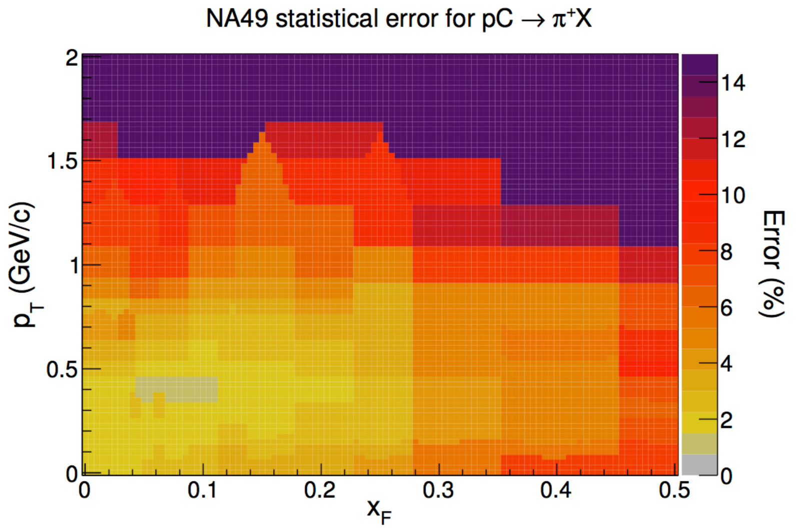
Extend the coverage for interactions that are not covered directly wherever possible

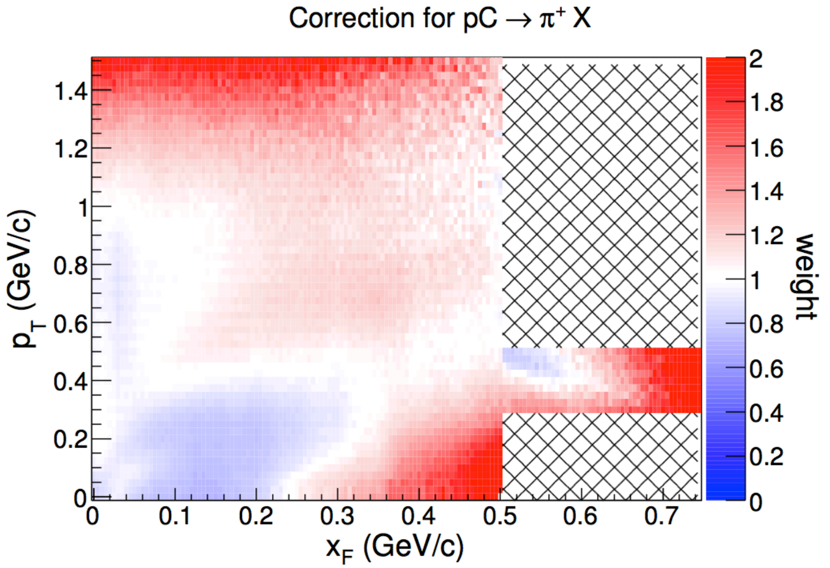
***No Coverage at All**

Apply uncertainties based on best estimation from current physics models if an interaction is not covered directly or indirectly

Hadron Production Data Sets

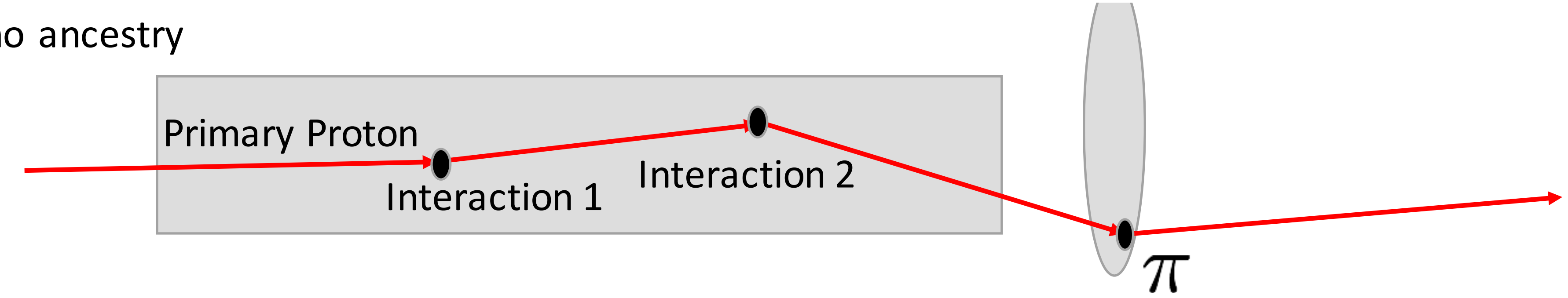
- Thin target data sets from *NA49*
- x_F →(-0.1,0.5) and p_T →(0,2 GeV/c)
  - Include *Barton* data to extend the coverage
  - x_F →(0.3,0.88) and p_T →(0.3,0.5 GeV/c)





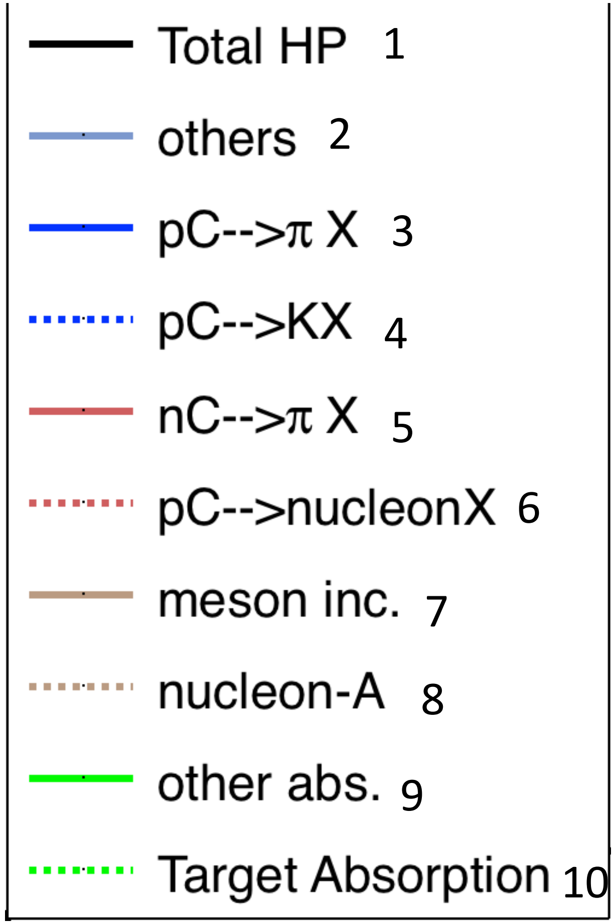
Applying these data sets means:

- Looking back at neutrino ancestry
- For an interaction:
  - Covered directly
  - Covered indirectly
  - Or not at all



* NA49 Collaboration, Eur. Phys. J. C49, 897 (2007).
* NA49 Collaboration, Eur. Phys. J. C73, 2364 (2013).
* D. S. Barton et al., Phys. Rev. D 27, 2580 (1983).

How Uncertainties are Categorized

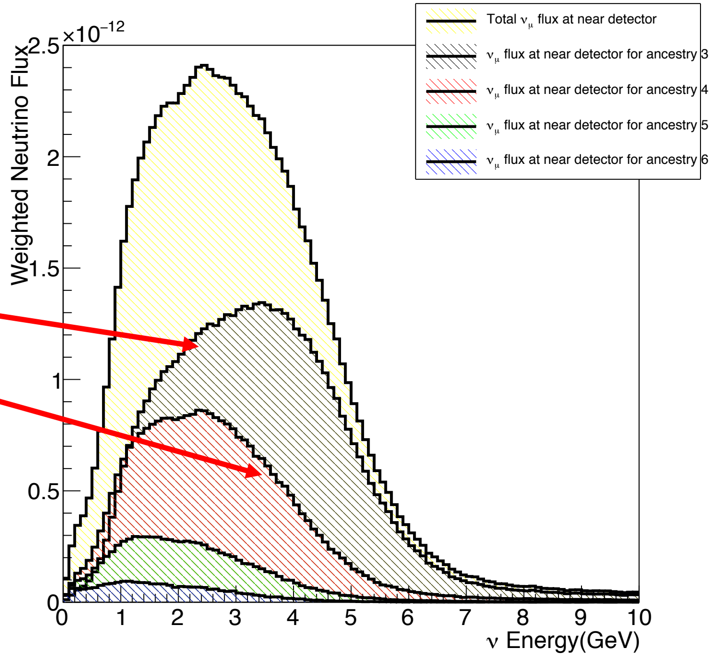


1. **Total Hadron Production Interactions**
2. **Interactions (excluding 8. interactions) not covered by any of the below categories.**
3. **Pion production in proton Carbon Interaction**
4. **Kaon production in proton Carbon Interaction**
5. **Pion production in neutron Carbon Interaction**
6. **Nucleon production in proton Carbon Interaction**
7. **Meson incident Interactions**
8. **Nucleon Incident interactions not covered by any data**
9. **Absorption outside the target**
10. **Absorption inside the target**

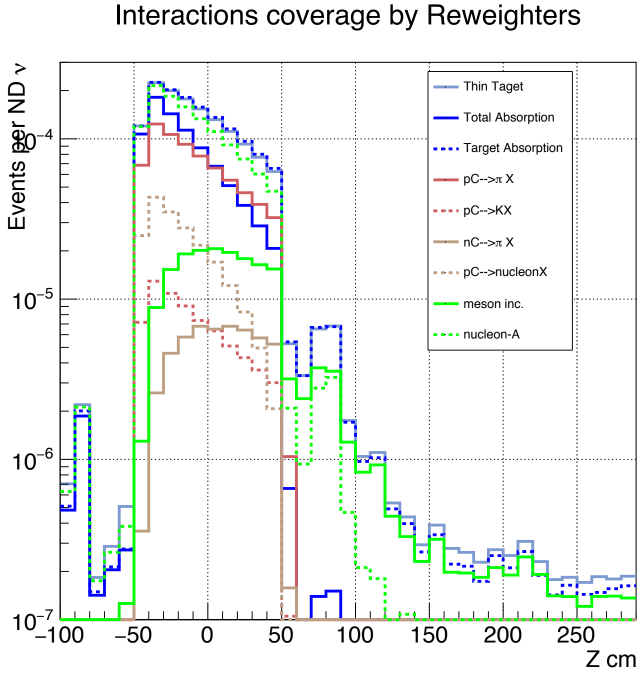
2 contains the interactions 3,4,5,6,7,9 and 10 category interactions that are not covered by thin target data.

Neutrino Ancestry and Hadronic Interaction in DUNE Flux

- To apply the constraints from Hadron production Data sets:
  - Need to understand the ancestry of the neutrino
    - Ancestry 3: p→X→ν
    - Ancestry 4: p→X→Y→ ν
    - And so on
  - Need to categorize interactions based on coverage by hadron production data set

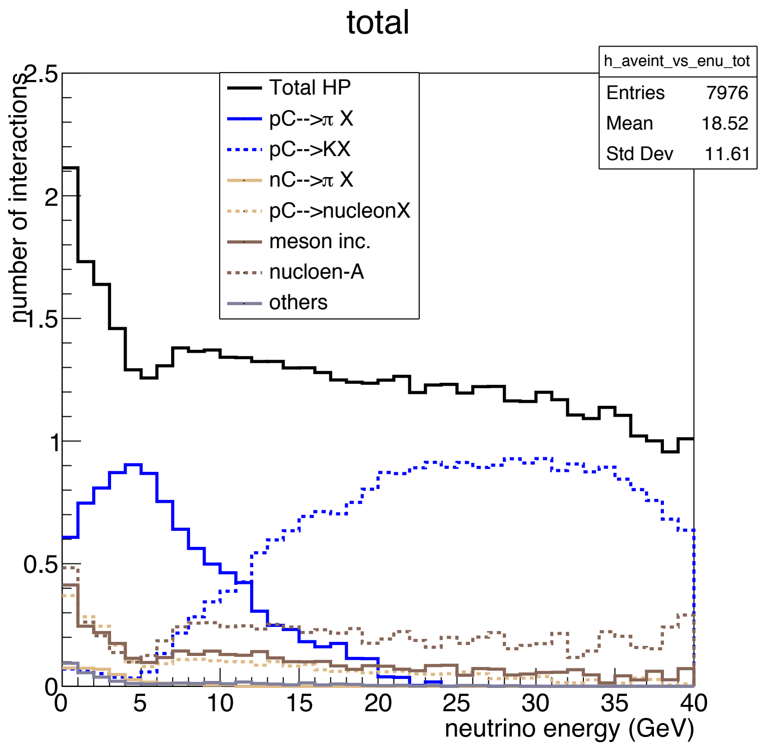


DUNE neutrino flux at ND for 80 GeV proton beam reference design as a function of ancestry length (not a stacked plot)

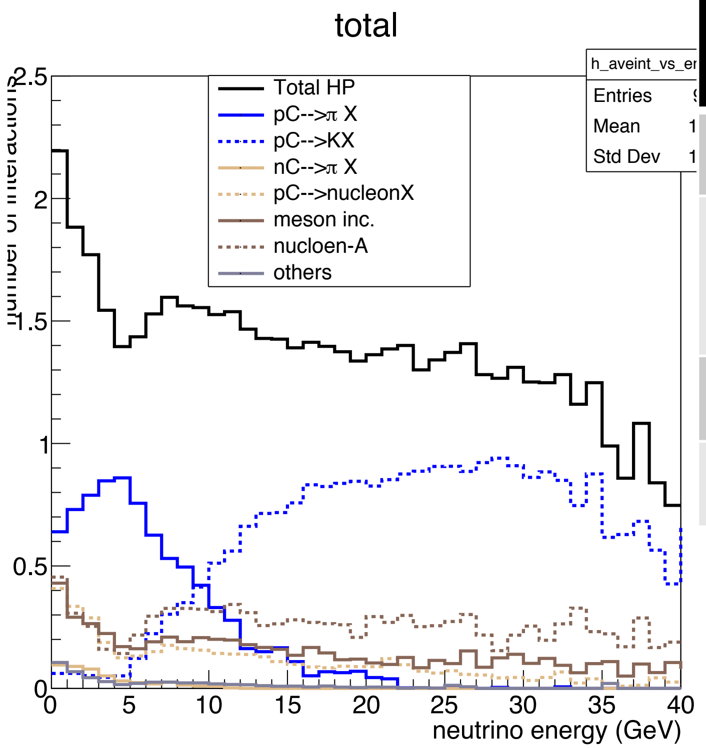


Hadron production location and coverage by ppfx reweighters

Interactions Per Near Detector Neutrino



Reference: 120 GeV

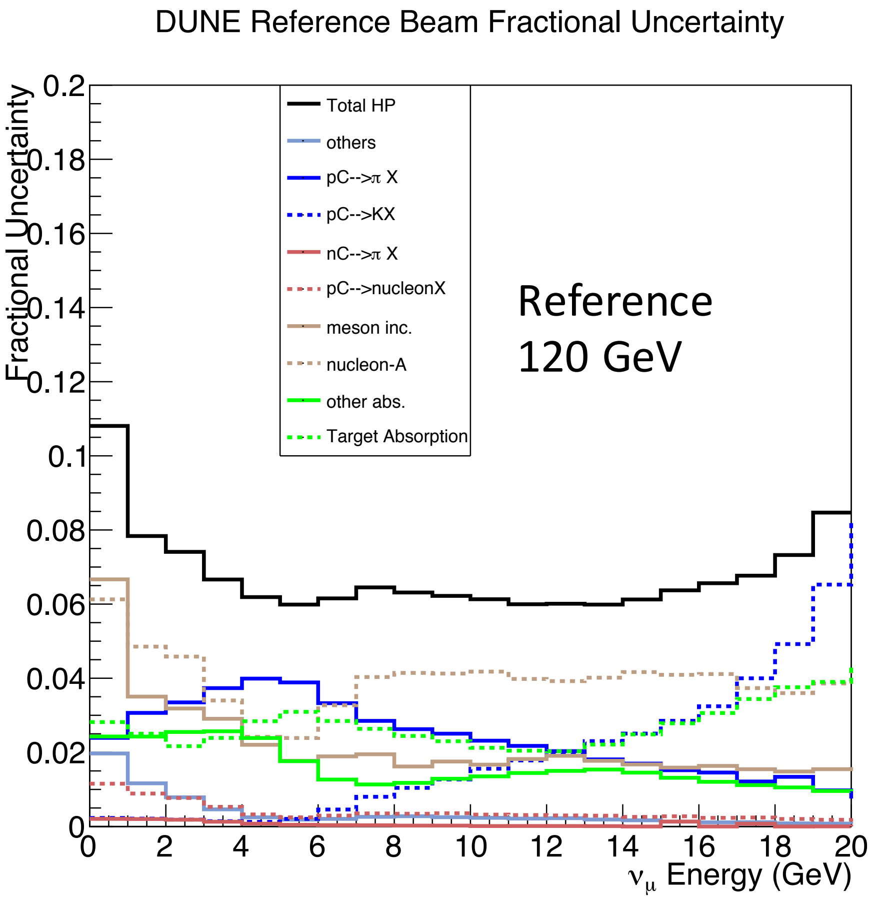


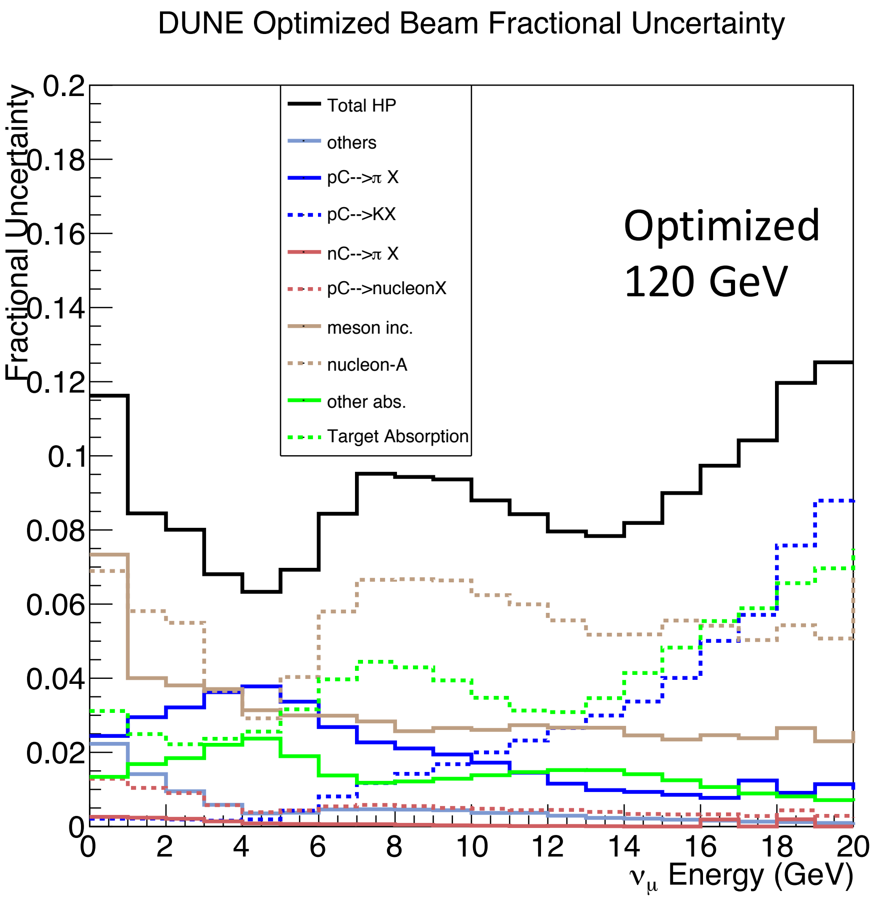
Optimized: 120 GeV

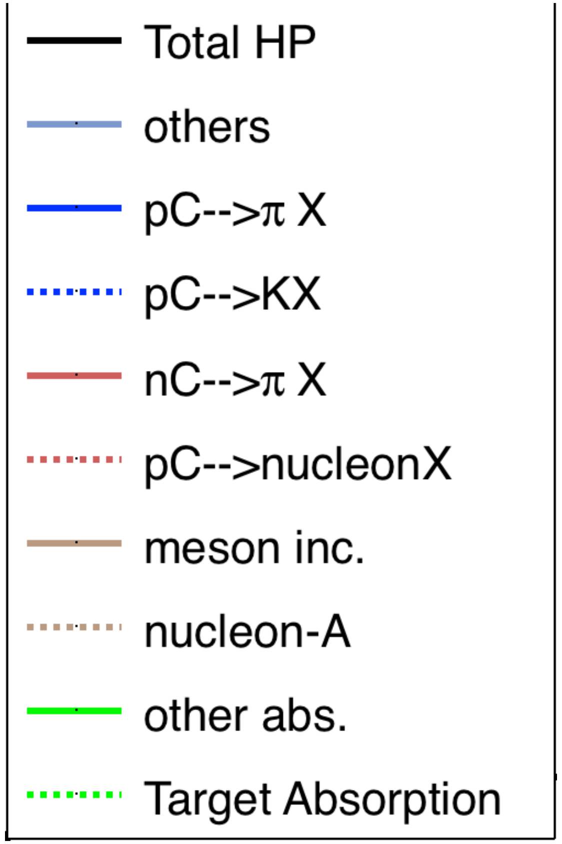
Beam/Parameters	Reference	Optimized
Target	1 meter graphite	2 meter graphite
Horns	2 horn (Numi Style)	3 Horn (Ideal, no Eng. Constraints)
Current	230 kA	298 kA
Proton Energy	120 GeV	120 GeV

Number of interactions per near detector neutrino covered by various ppfx reweighters for 2 different beamline design

Fractional Uncertainties

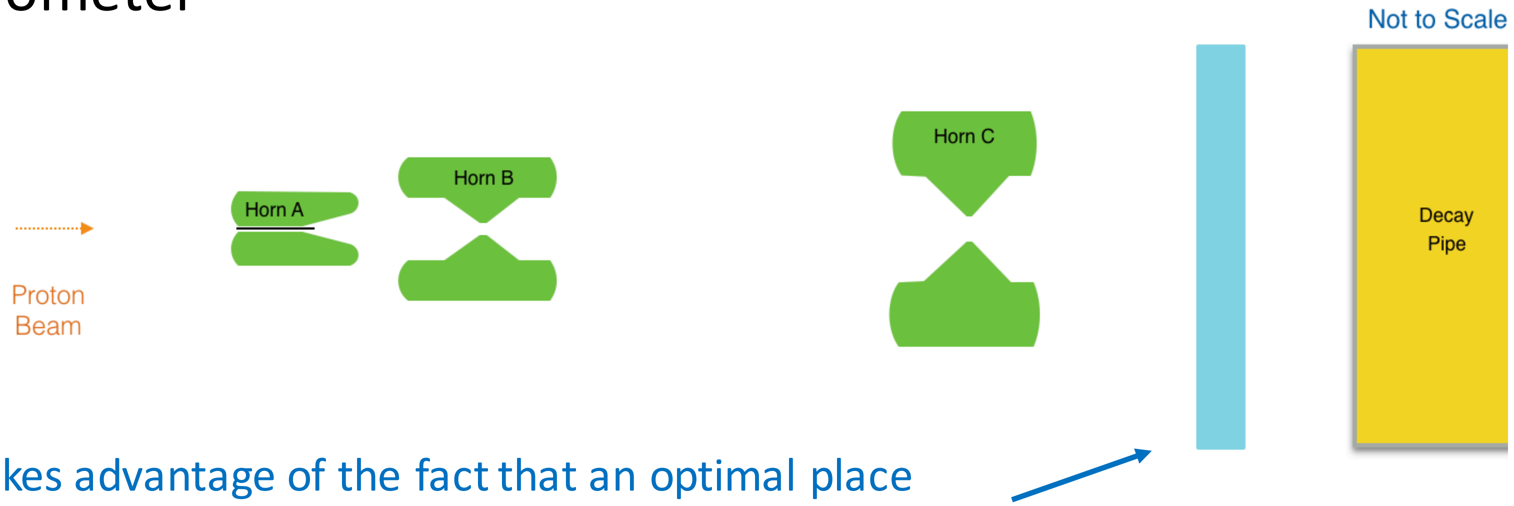






Spectrometer

- Uncertainties will be further lowered by current and future NA61 thin target measurements (and potentially thick targets too)
- Another possible way to lower DUNE flux uncertainties is the “Flux Spectrometer”

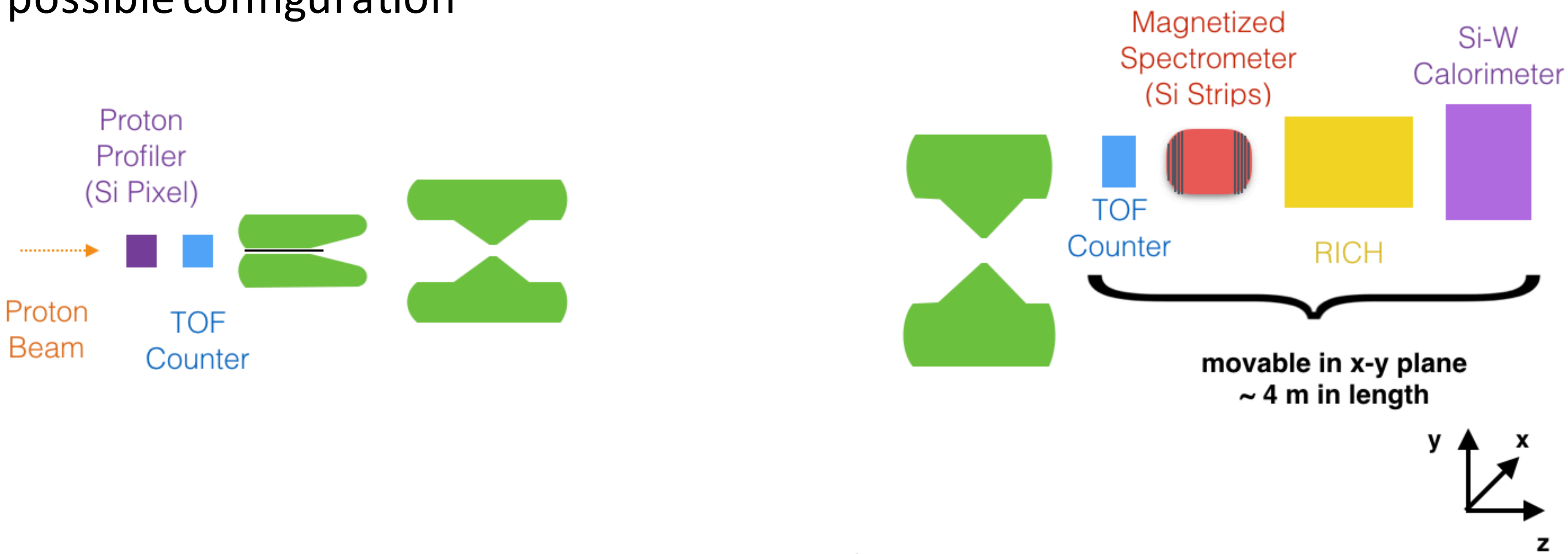


Would require: id and energy/position measurement of everything that decays to neutrinos (pions, muons & kaons)

This concept takes advantage of the fact that an optimal place to measure hadron production is after they have been focused by horns and before they have decayed

Spectrometer

- One possible configuration



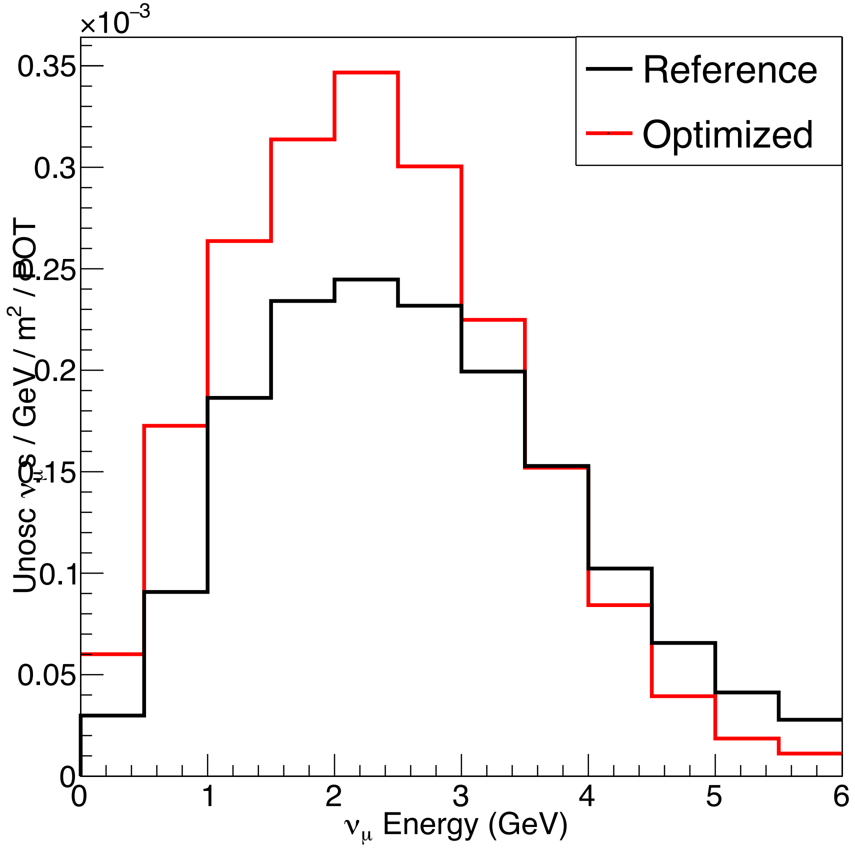
- A replica of the LBNF beam (using spare horns/target) would be placed in a low intensity proton beamline at Fermilab
- In early stages of development -- currently being developed into a full proposal

Summary

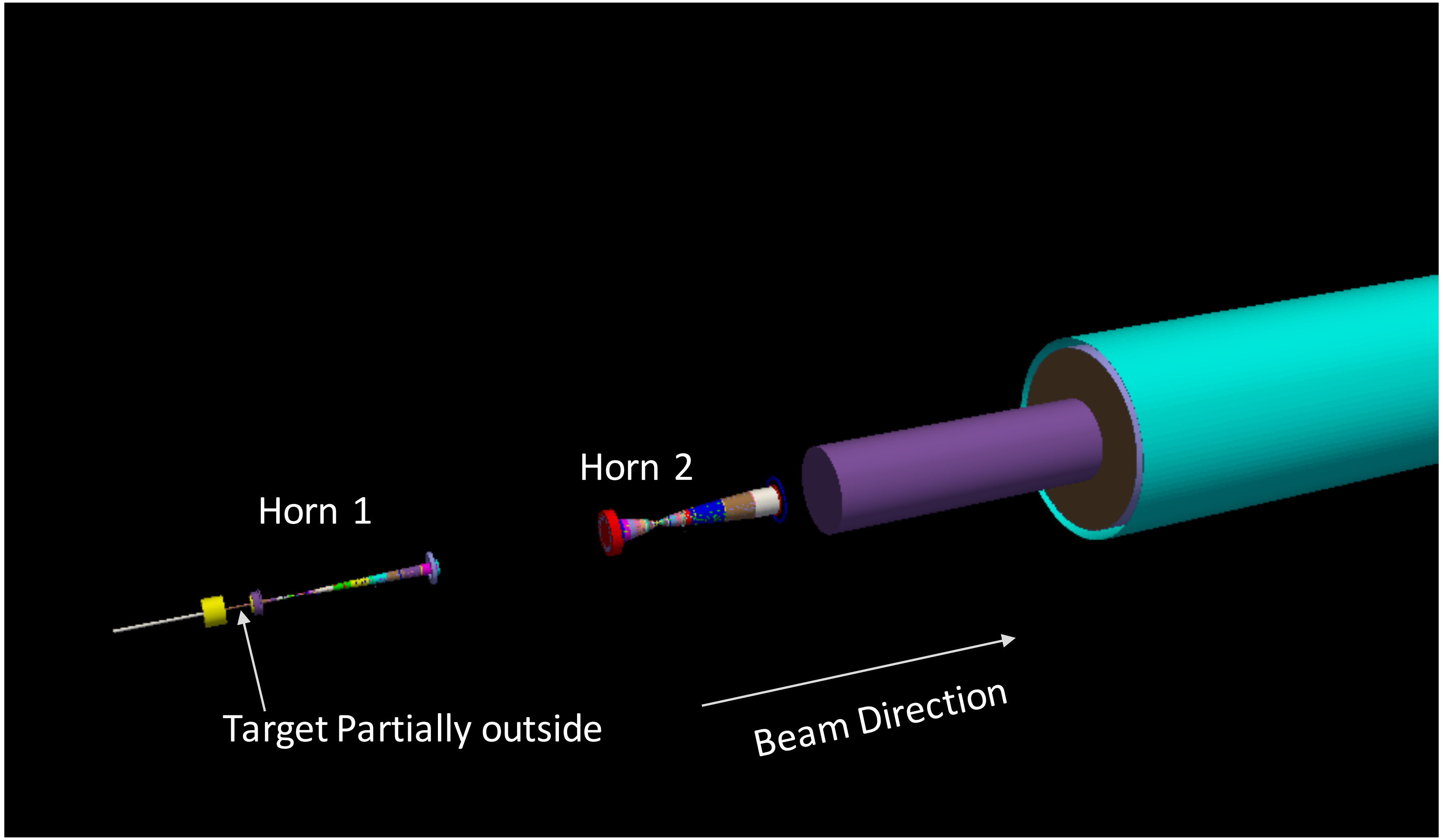
- Study of 2 different methods to extrapolate the neutrino flux at Far Detector
- Implementation of uncertainties due to hadronic interactions in the DUNE flux
  - Current estimation shows an uncertainty in the flux of 8% for both reference and optimized design beam in focusing peak
  - Future plan is to implement NA61/SHINE data sets to extend the coverage of interactions
  - Further constraining of uncertainties is achievable by flux spectrometer by measuring the hadron flux in real time

BACK UP SLIDES

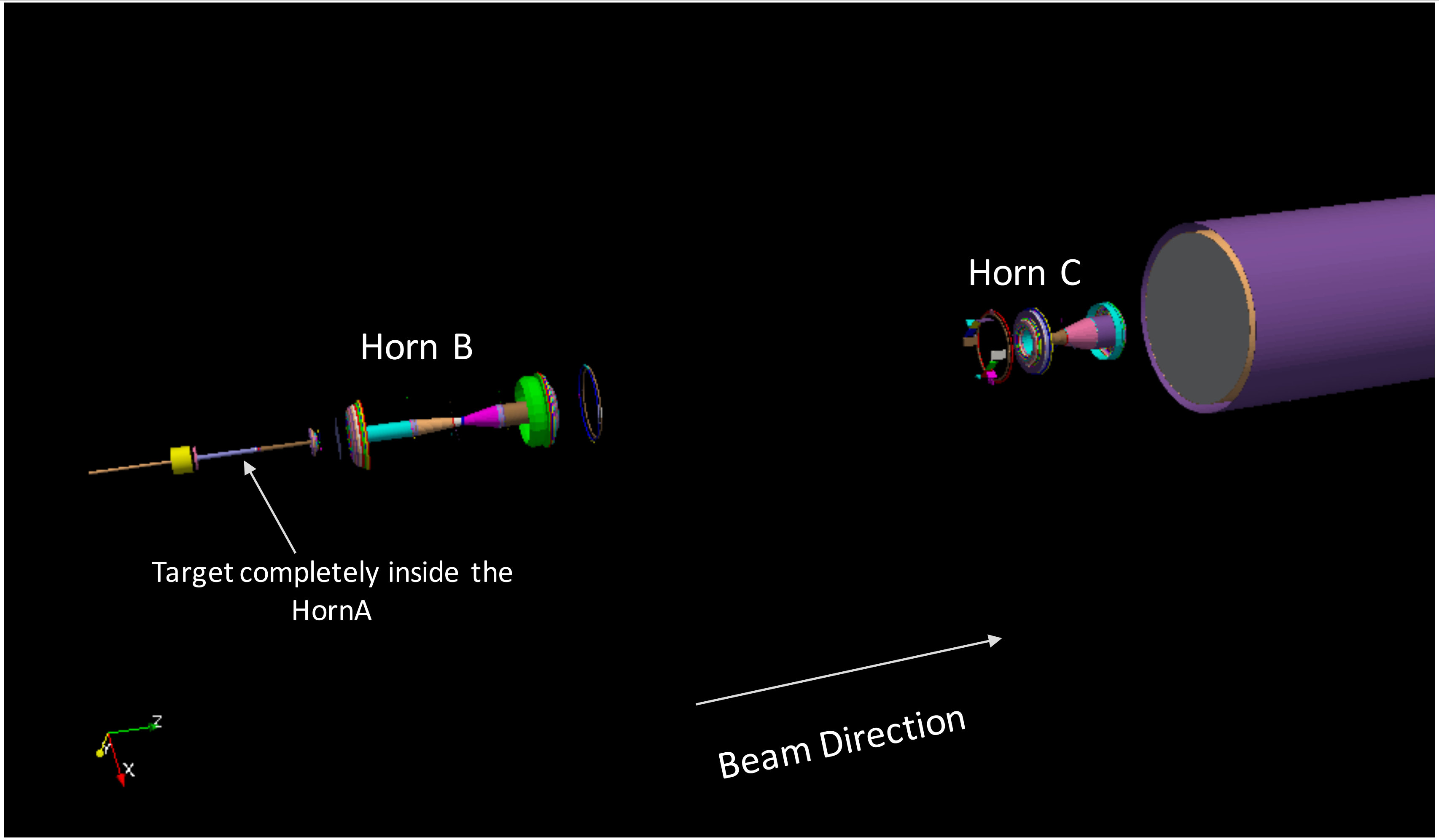
Neutrino Flux: Nominal & Optimized



Nominal



Optimized/Engineered



How is an interaction Handled by PPFX

I. Direct Data Coverage

UNDERSTANDING PPFX: *Covered by Data*

- When an interaction happens, a correction value is determined for each interaction:
- $c_i = \frac{N_i^{Data}}{N_i^{MC}}$ $for\ any\ i^{th}\ interaction.$ [1]
- $c_i\ is\ the\ central\ value\ correction\ for\ the\ interaction\ that\ falls\ in\ the\ i^{th}$ *bin of the Hadron Production Data Set.*
- *Each bin has an associated uncertainty* σ_i and a covariance with other bins j, V_{ij}.

Covered By Data

- When a particle traverses through the volume, correction is:
  - $c(r) = e^{-\frac{N_A \rho (\sigma_{Data} - \sigma_{MC})}{A}}$ [1]
- When an interaction happens inside a volume:
  - $c(r) = \frac{\sigma_{Data}}{\sigma_{MC}} e^{-\frac{N_A \rho (\sigma_{Data} - \sigma_{MC})}{A}}$ [1]
  - Here:
  - C(r) is the central value correction
  - N_A is the number of atoms with atomic number A seen by the particle when it traverses the volume

When a Particle is Produced:

- When a particle is produced the correction is given by:
- $c(x_F, p_T, E) = \frac{f_{Data}(x_F, p_T, 158\ GeV)}{f_{MC}(x_F, p_T, E)} \times Scale(x_F, p_T, E)$ [1]
- Scaling done for 12,20,31,40,60,100,110,120 GeV [1]
- Linear interpolation for the intermediate energies
- $\Delta x_F = 0.005$ [1]
- $\Delta p_T = 0.025\ GeV/c$ [1]

Uncertainties for Each bin

- Since we use NA49 and Barton Data sets, the closest of the uncertainties from either data set is applied where the data sets overlap.
- Systematic uncertainties are 100% correlated between all bins
- Total systematic uncertainties are added by quadrature

How is an interaction Handled by PPFX

II. Extension of Data Coverage

Extension of Data Coverage

- Interaction outside the target in IC and Decay Pipe Wall
  - Parameterization of invariant cross section
  - $$\frac{f(A_1, x_F, p_T)}{f(A_2, x_F, p_T)} = \frac{A_1^{\propto(x_F, p_T)}}{A_2}$$ [1]
    - If A_1 is atomic number of Carbon and A_2 is the atomic number of other materials, $\propto$ is determined by independent fit of skubic data. [1,2]

Extension of Data Coverage

- Cross section of proton on carbon producing pions is extended to neutron on carbon producing pions using iso scalar symmetry

- Charged kaon production is extended to neutral kaon production by quark parton model.

How is an interaction Handled by PPFX

Covered by Data
(Directly or by Extension)

Interactions not covered by Data

- Incident Mesons
- Particle produced in or out of target by re interacting proton

- Particle production in target by primary proton but outside the x_F range of Data (> .5 for pions and >.2 for kaons)
- For more info:
  - M. Jerkins, **MINERvA-docdb 7633-v1**, *Using Monte Carlo Models to Determine A Priori Flux Uncertainties*

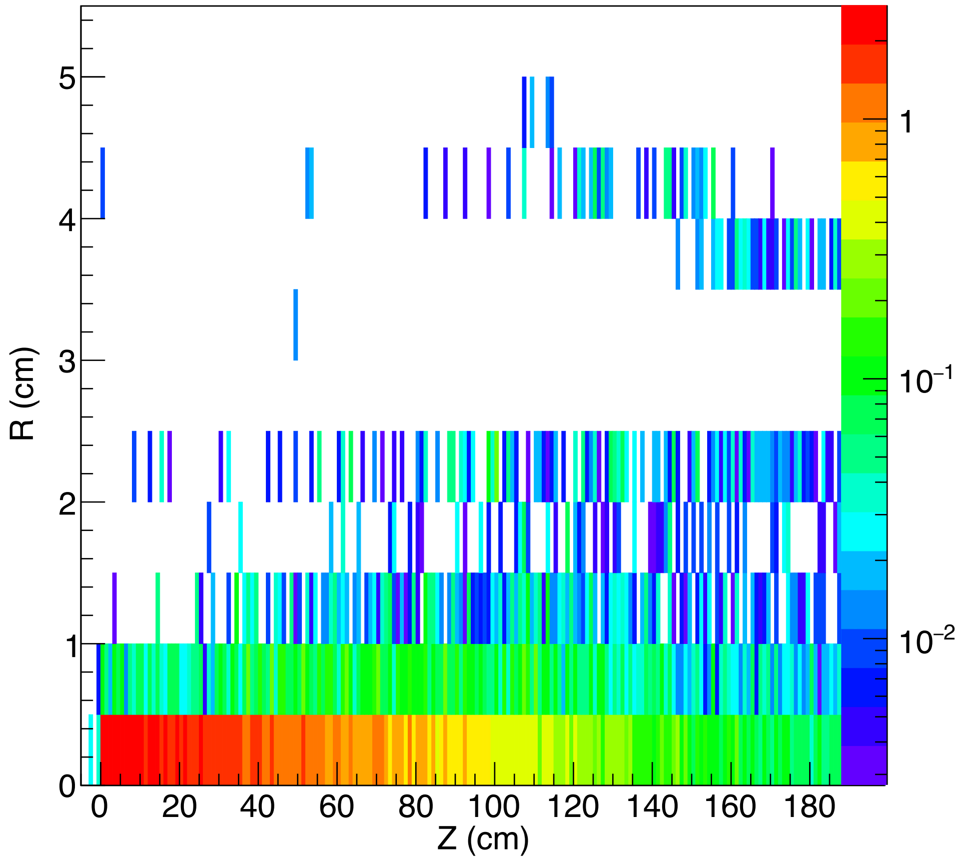
Interaction Not Covered by Data: Uncertainties

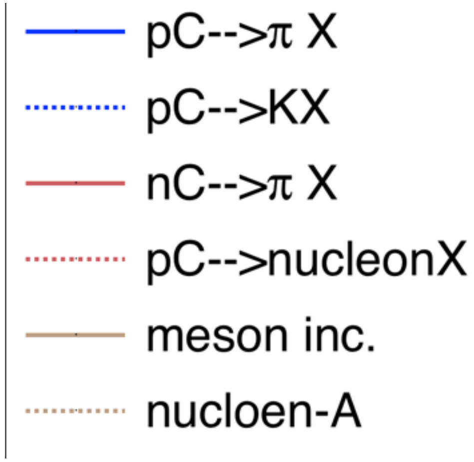
- Uncertainty for these interactions is assigned 40% and they are un correlated.

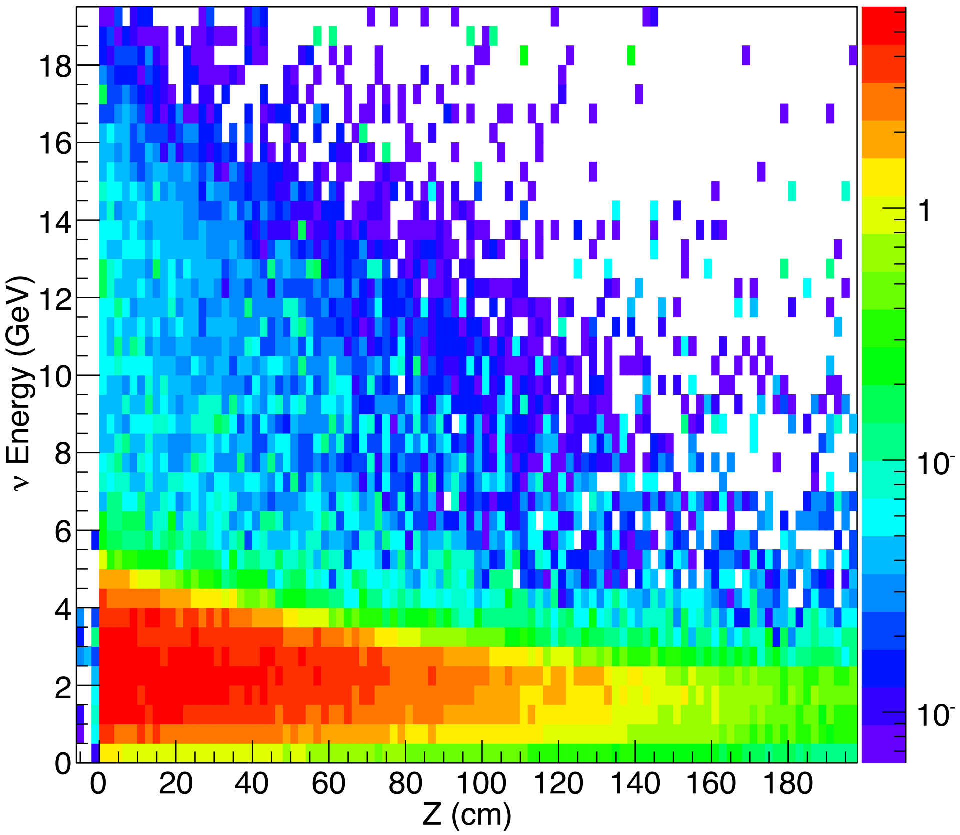
Error Propagation by Multi Universe Method [1][3]

- When uncertainties are correlated:
  - N universes
  - Parameters and matrix of Parameters
  - Covariance matrix of parameters
  - Decomposition of Covariannce matrix by Chloskey method into upper and lower triangular matrix
  - Use lower triangular matrix to create the vector of deviates
  - Use the deviates to create N flux histograms for N universe
  - Use multi-variate Gaussian to get the final systematic uncertainty

Thin Target Coverage

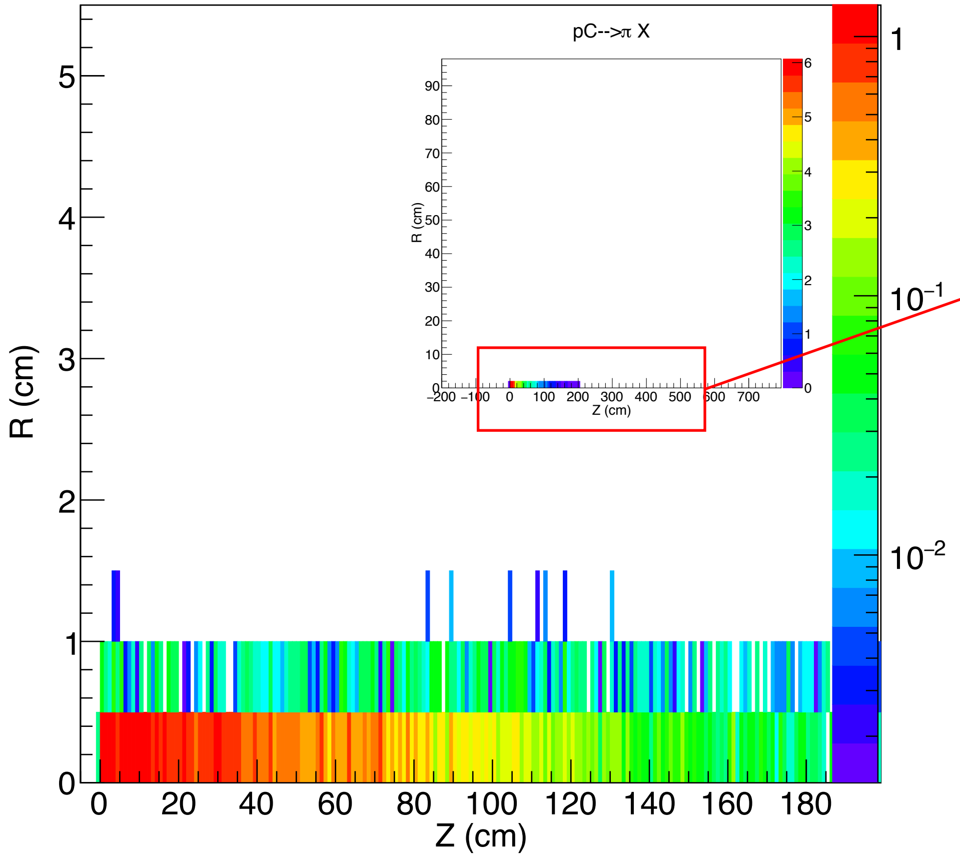






pc→pion X

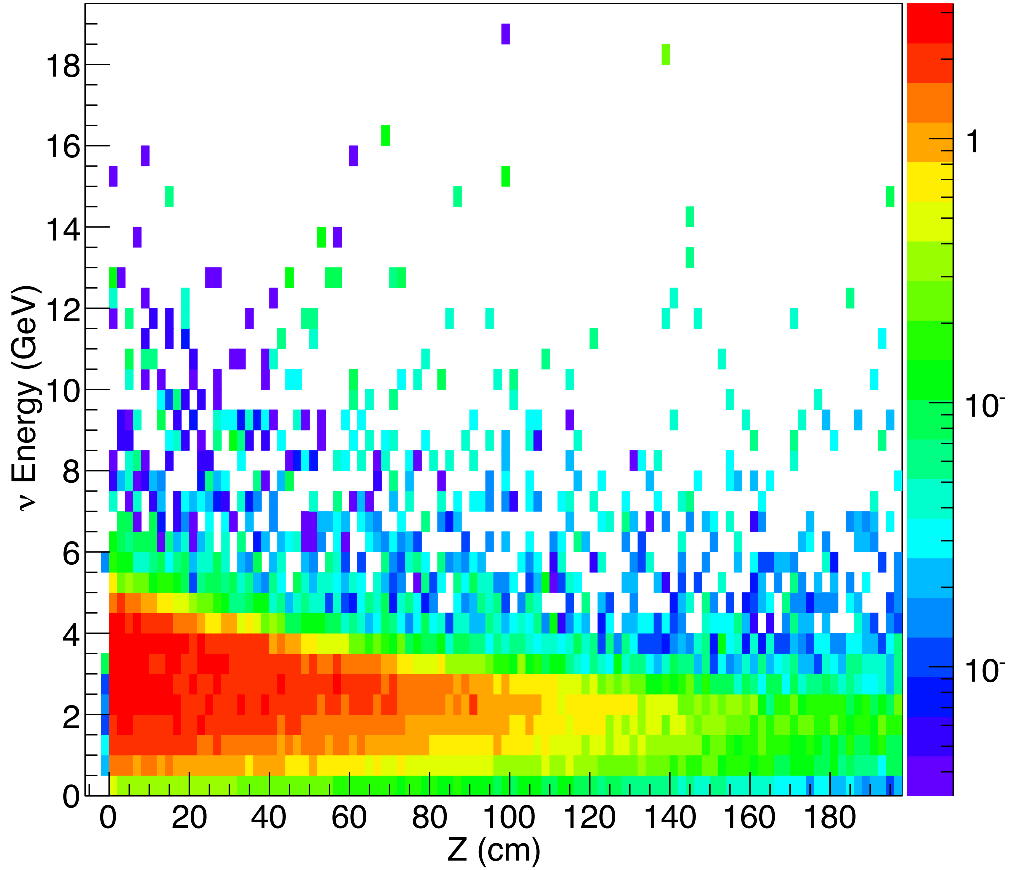
pC-->π X



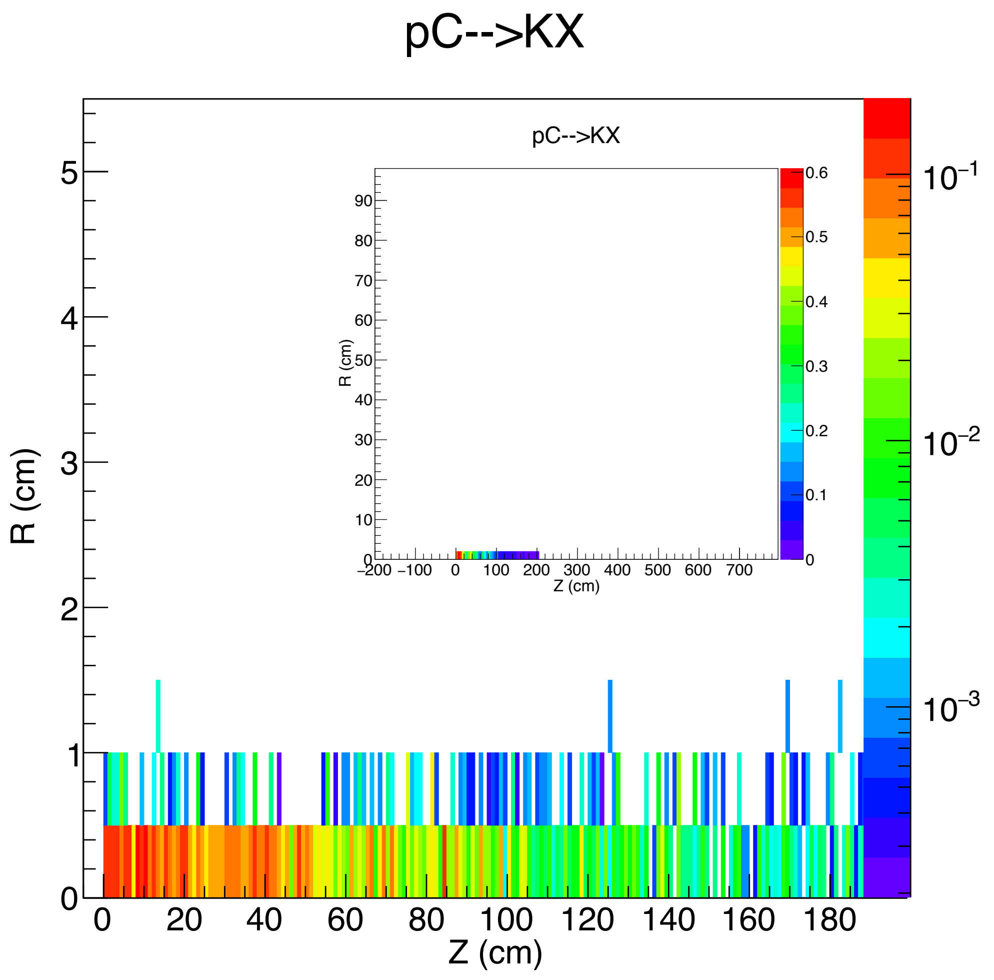
Notice that all interactions are limited inside target.

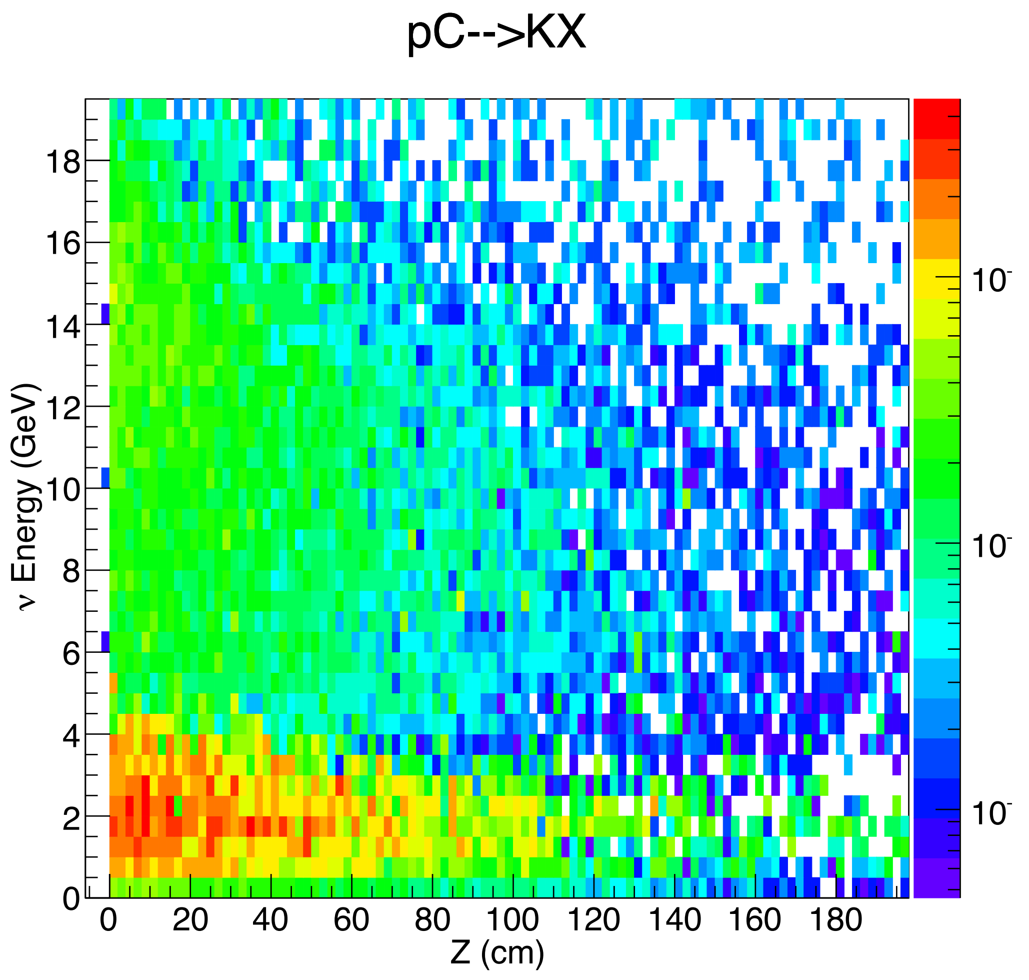
Our cross check that reweighters are doing their jobs

pC-->π X

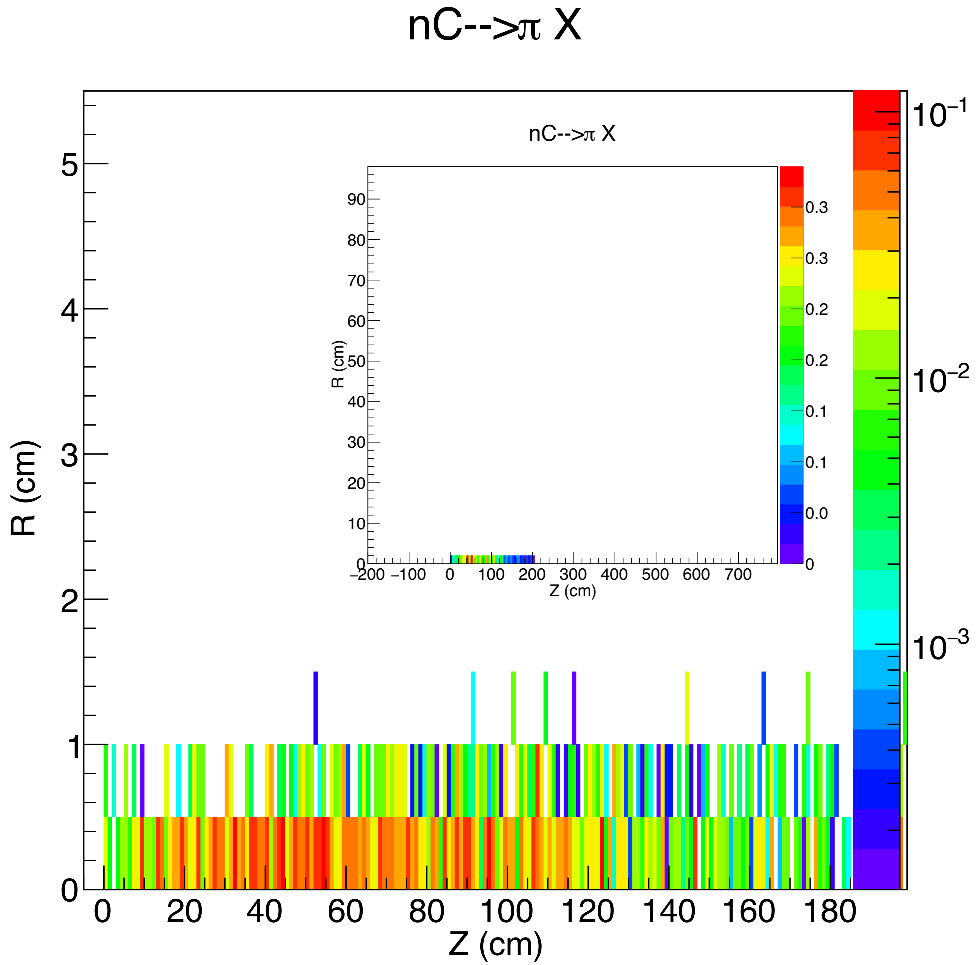


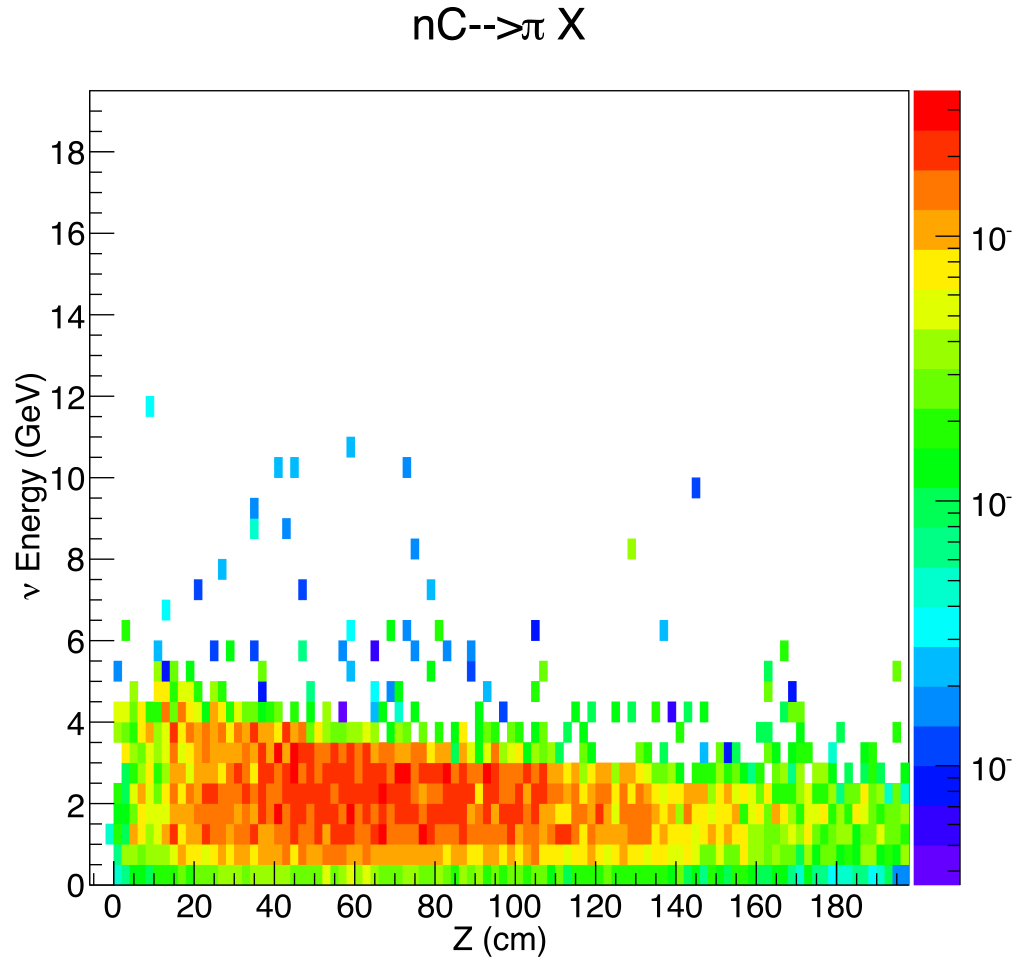
pc→kaon X


pC-->KX
R (cm)
Z (cm)
0
20
40
60
80
100
120
140
160
180
1
2
3
4
5
10^{-1}
10^{-2}
10^{-3}
pC-->KX
R (cm)
Z (cm)
−200
−100
0
100
200
300
400
500
600
700
10
20
30
40
50
60
70
80
90
0.1
0.2
0.3
0.4
0.5
0.6

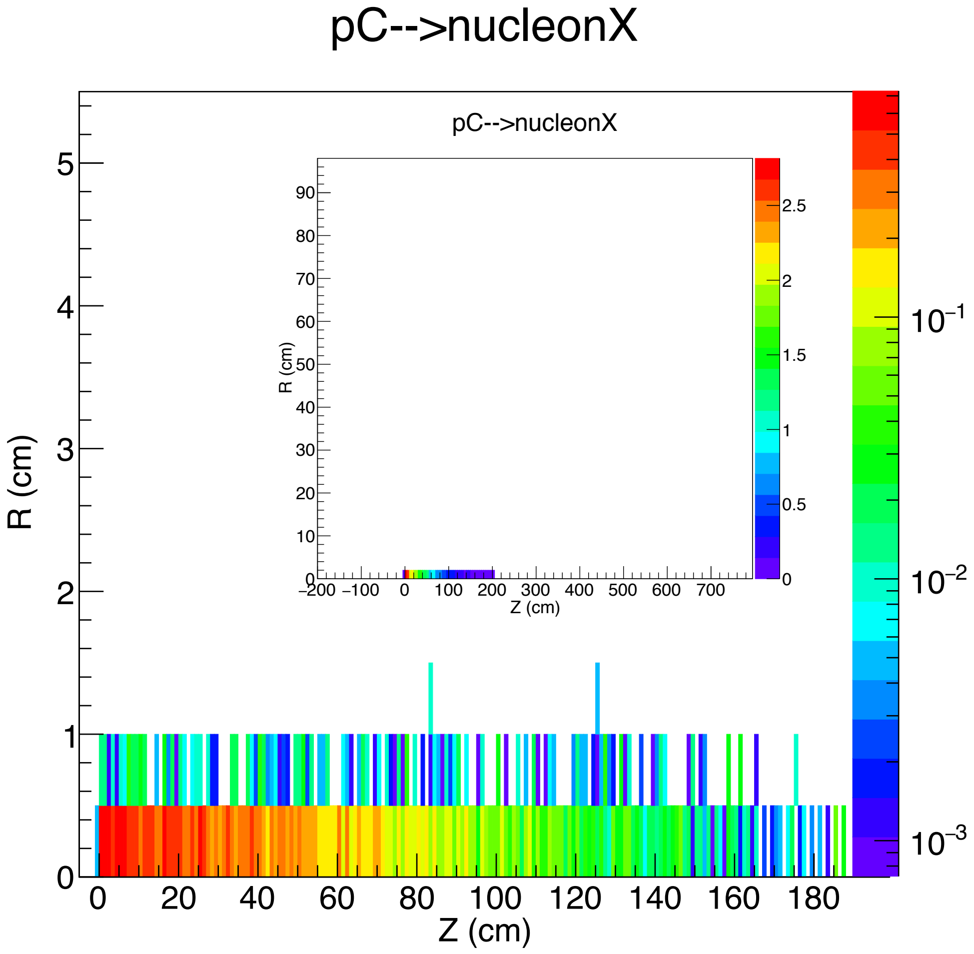

pC-->KX
ν Energy (GeV)
Z (cm)
0
20
40
60
80
100
120
140
160
180
2
4
6
8
10
12
14
16
18

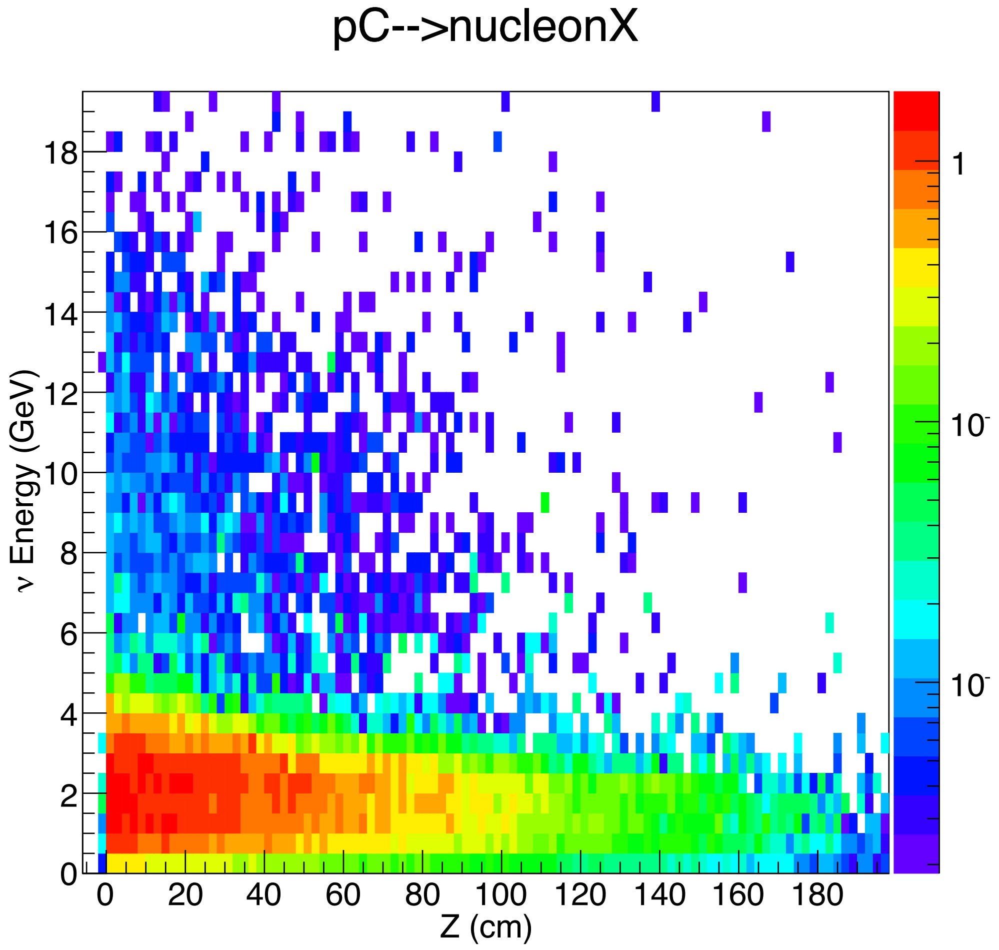
nc→ pion X



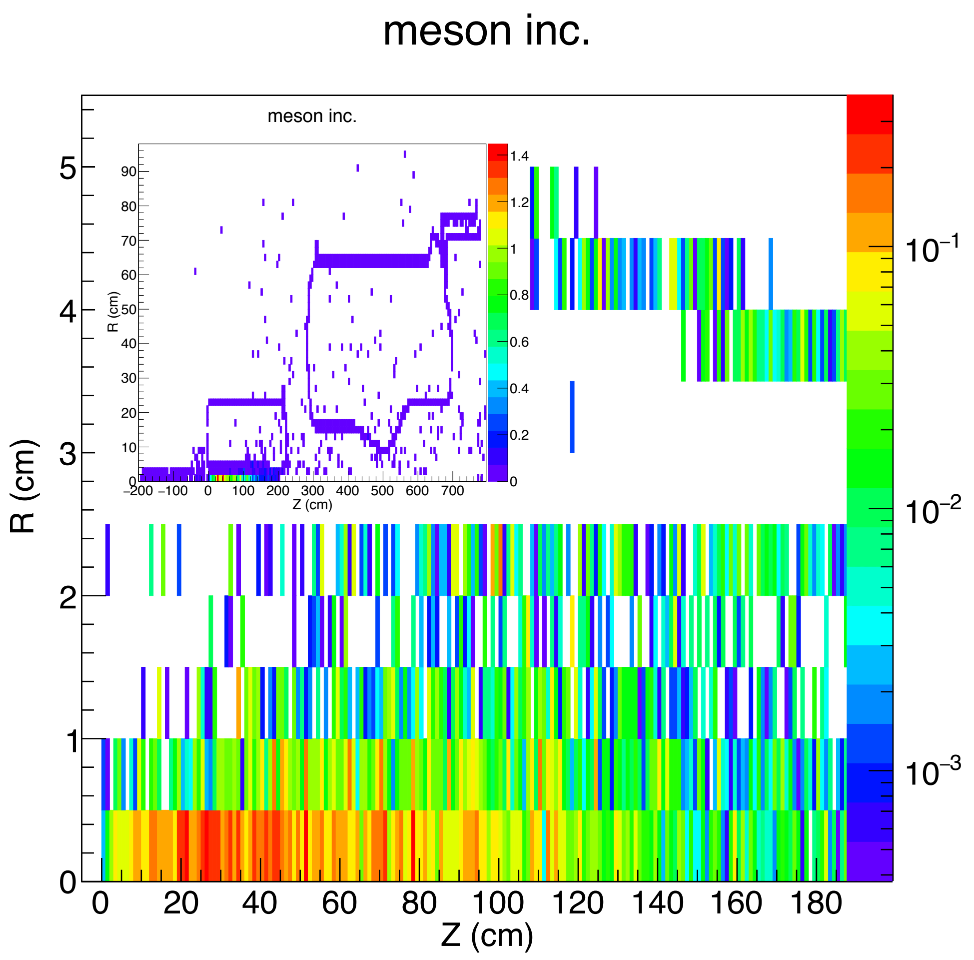


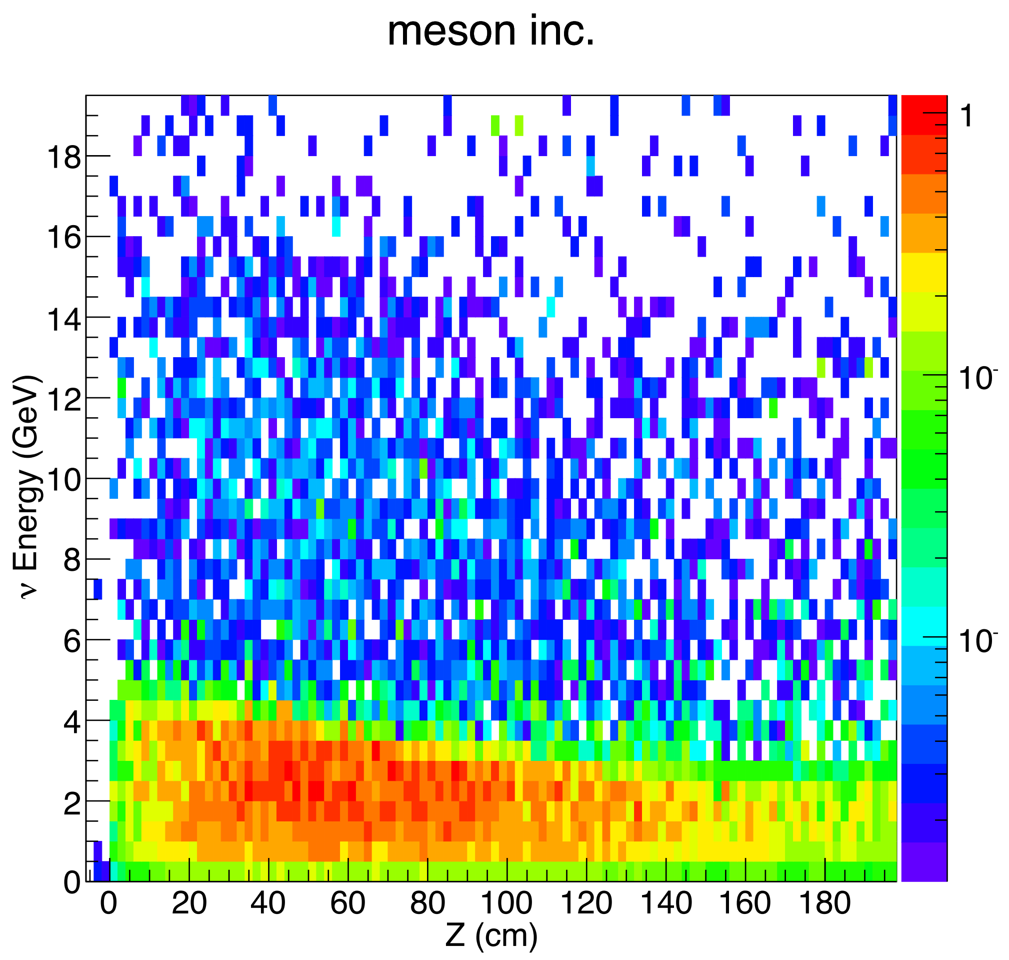
pc→nucleon X


pC-->nucleonX
pC-->nucleonX
R (cm)
Z (cm)
R (cm)
Z (cm)

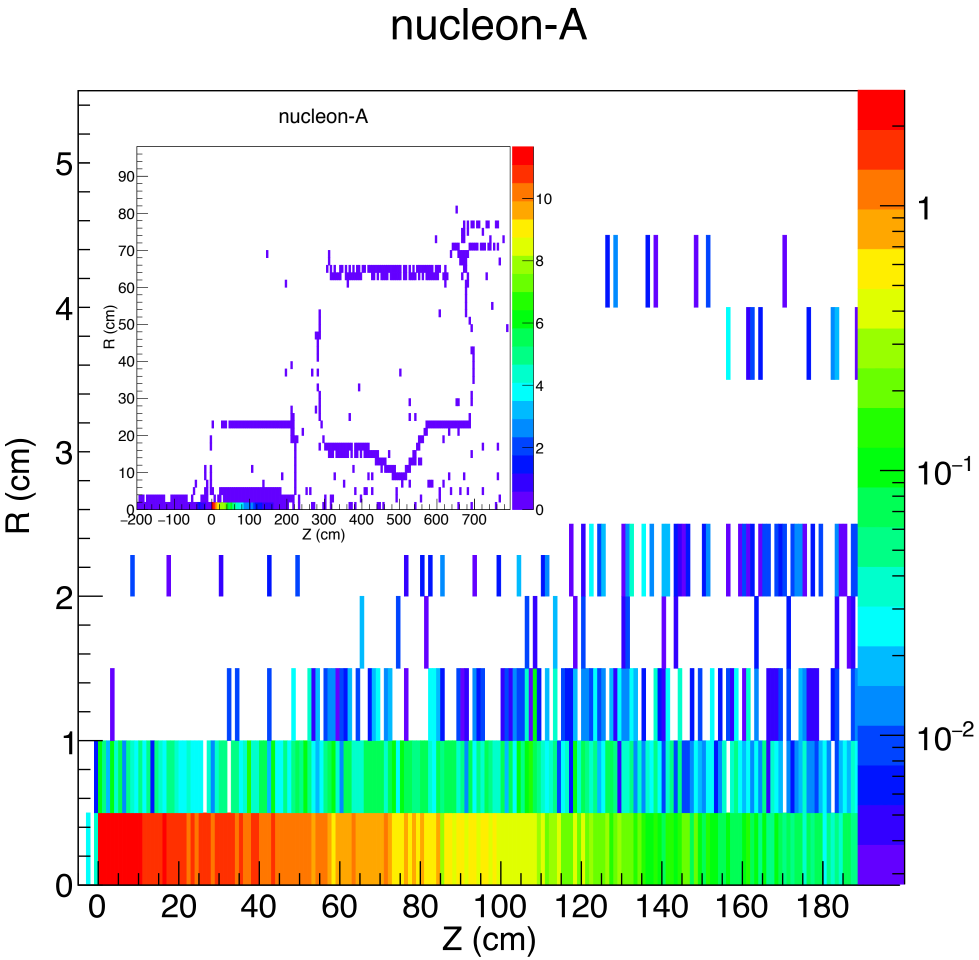

pC-->nucleonX
ν Energy (GeV)
Z (cm)

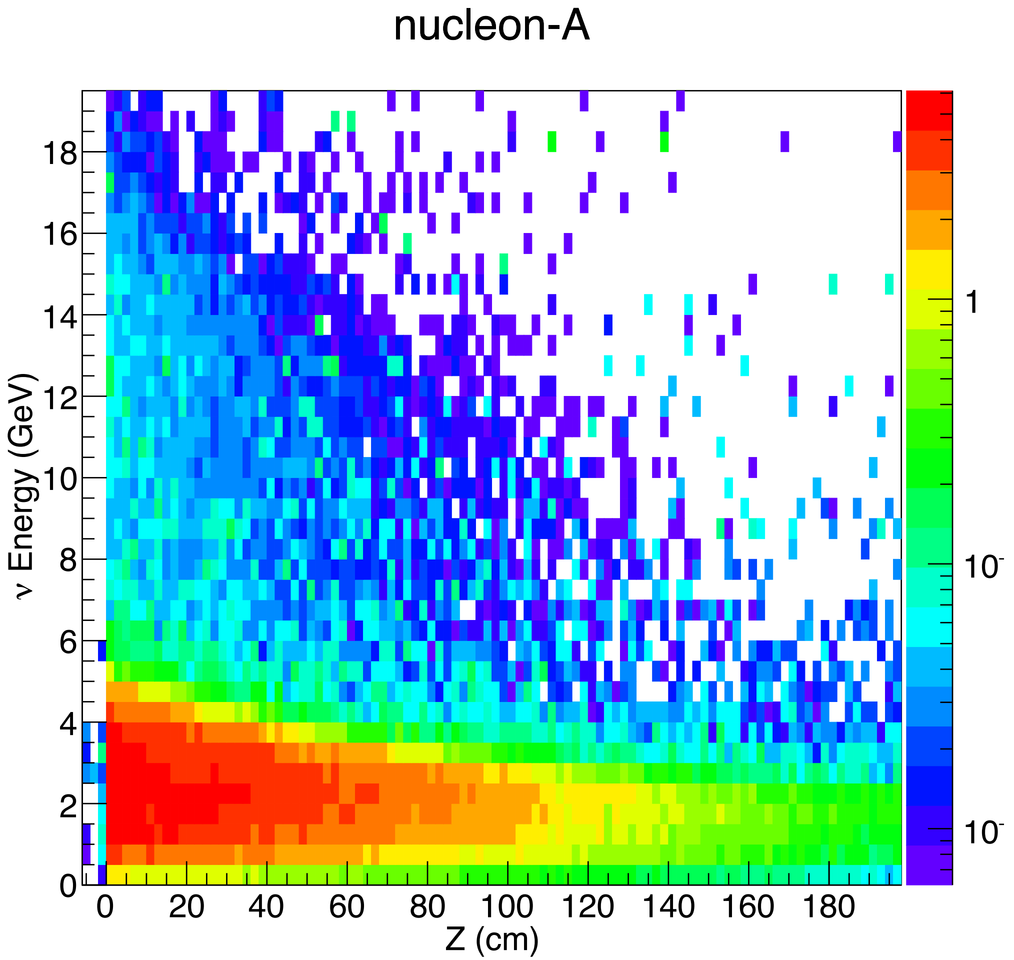
Meson Incident





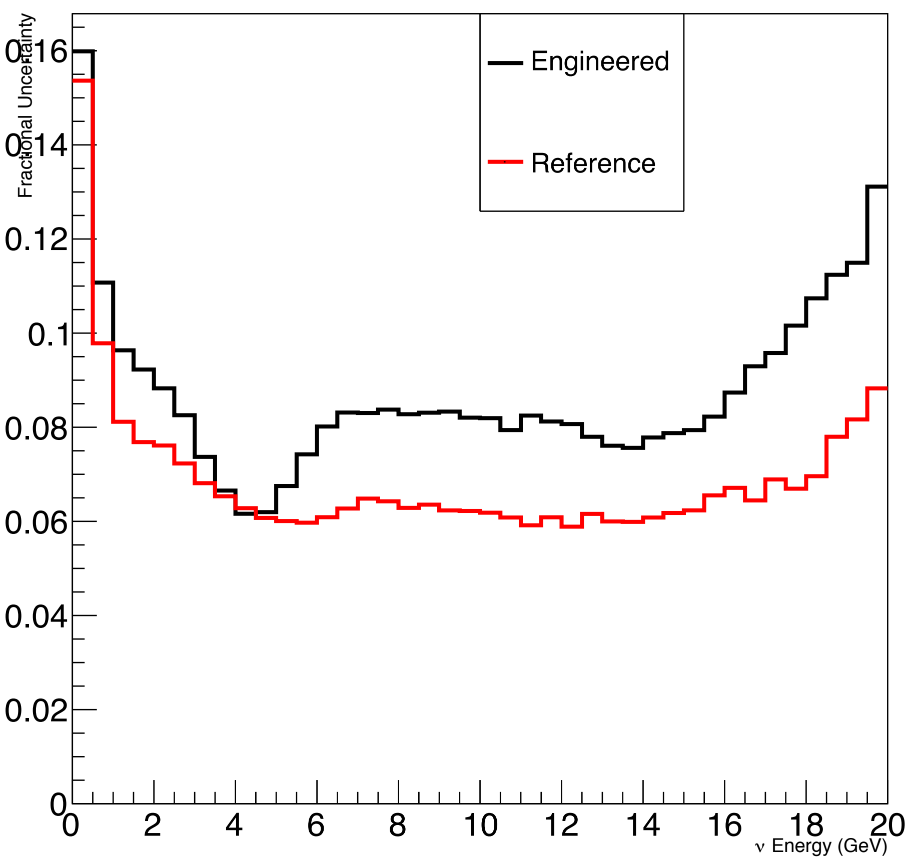
nucleon-A

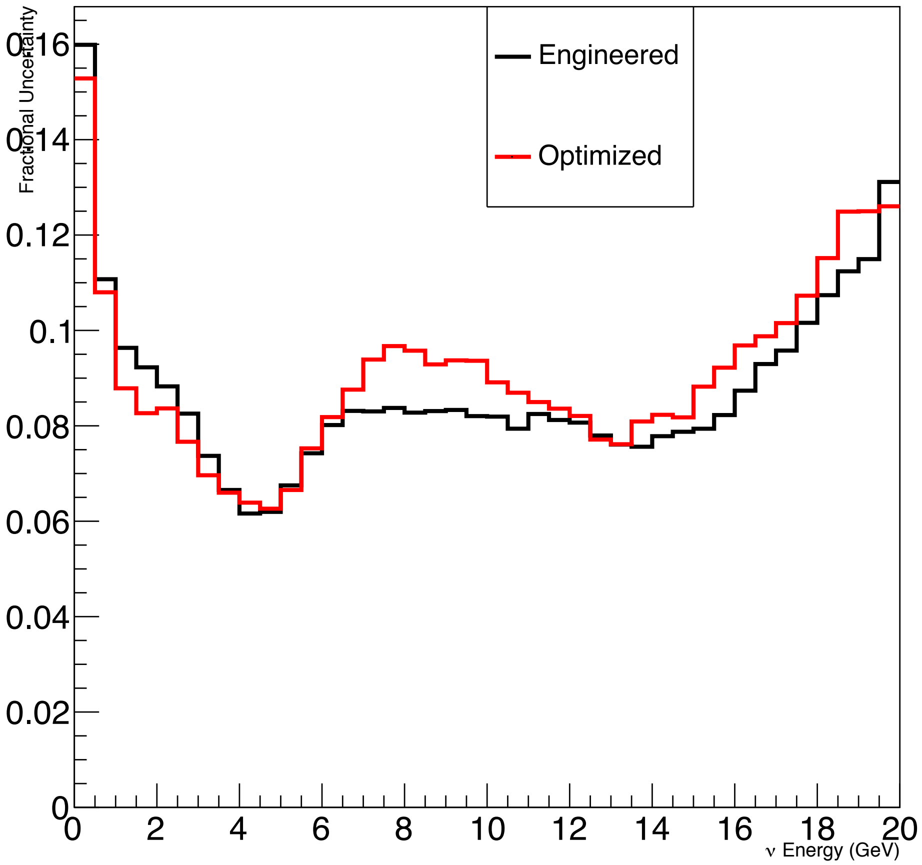

nucleon-A
R (cm)
Z (cm)
nucleon-A
R (cm)
Z (cm)
1
10^{-1}
10^{-2}


nucleon-A
ν Energy (GeV)
Z (cm)
1
10⁻
10⁻

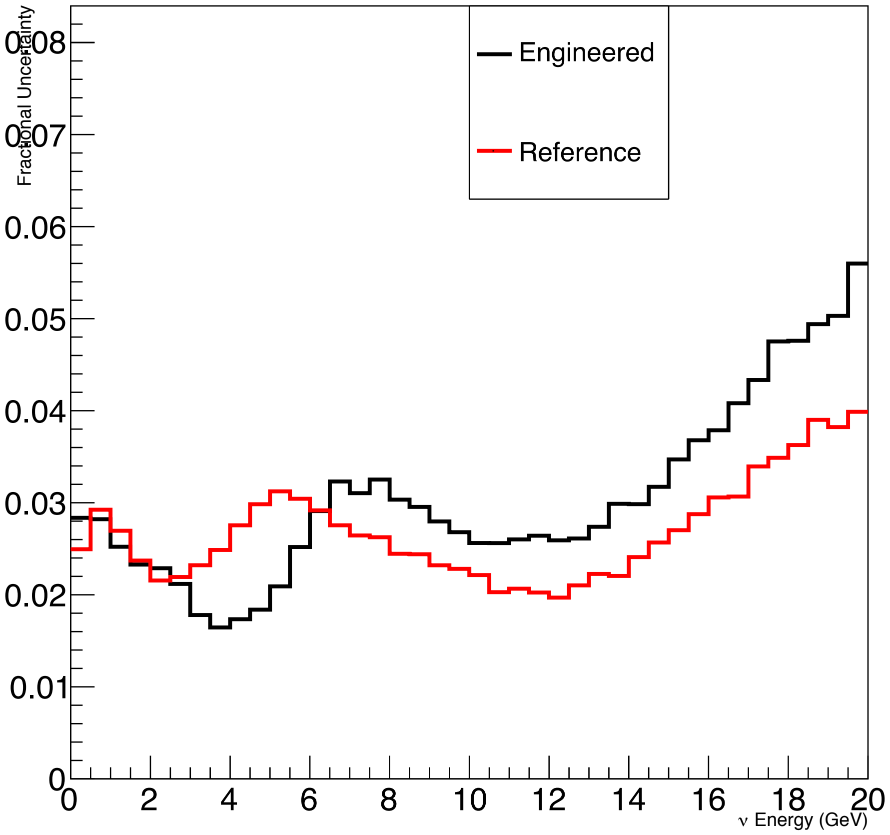
Comparison Plots

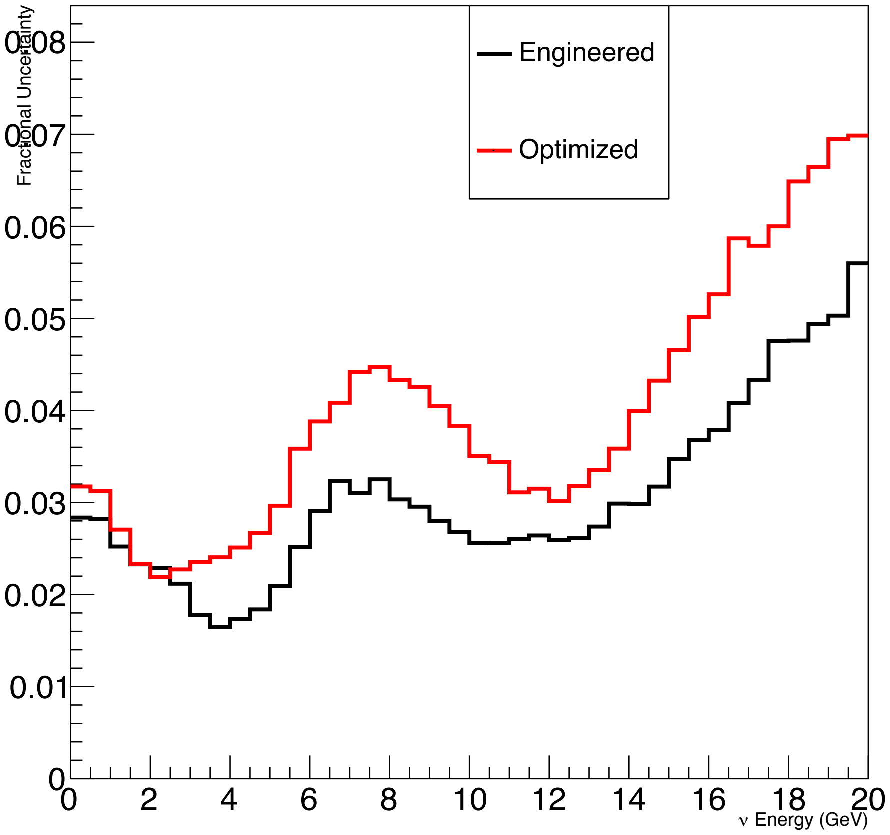
Total Uncertainty



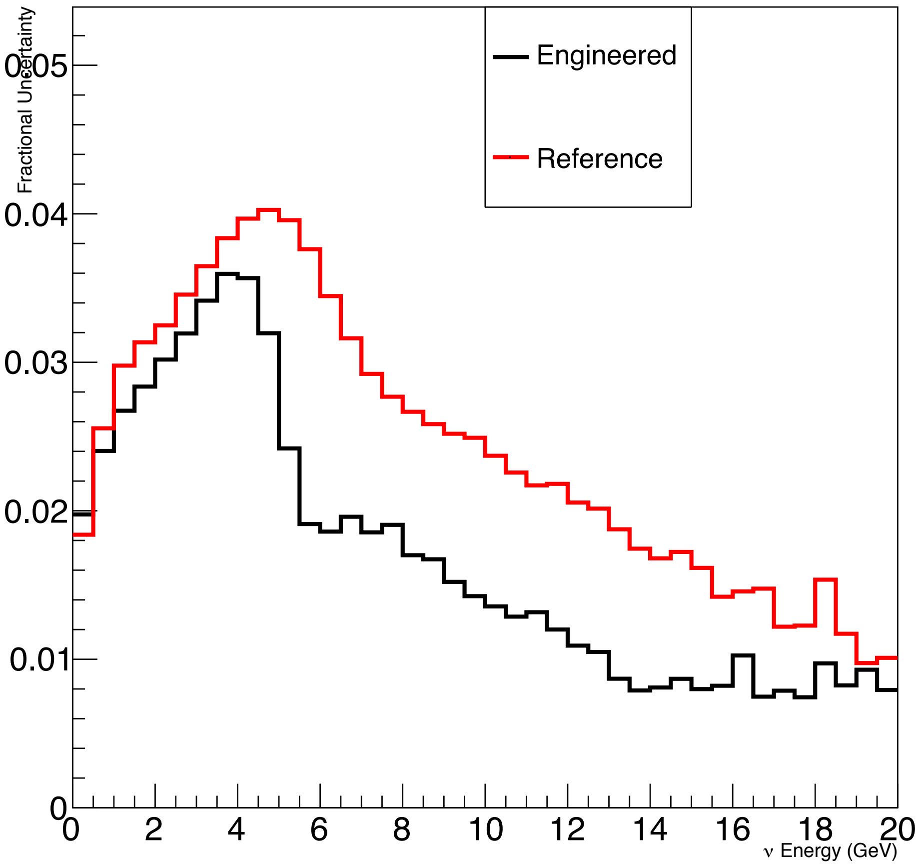


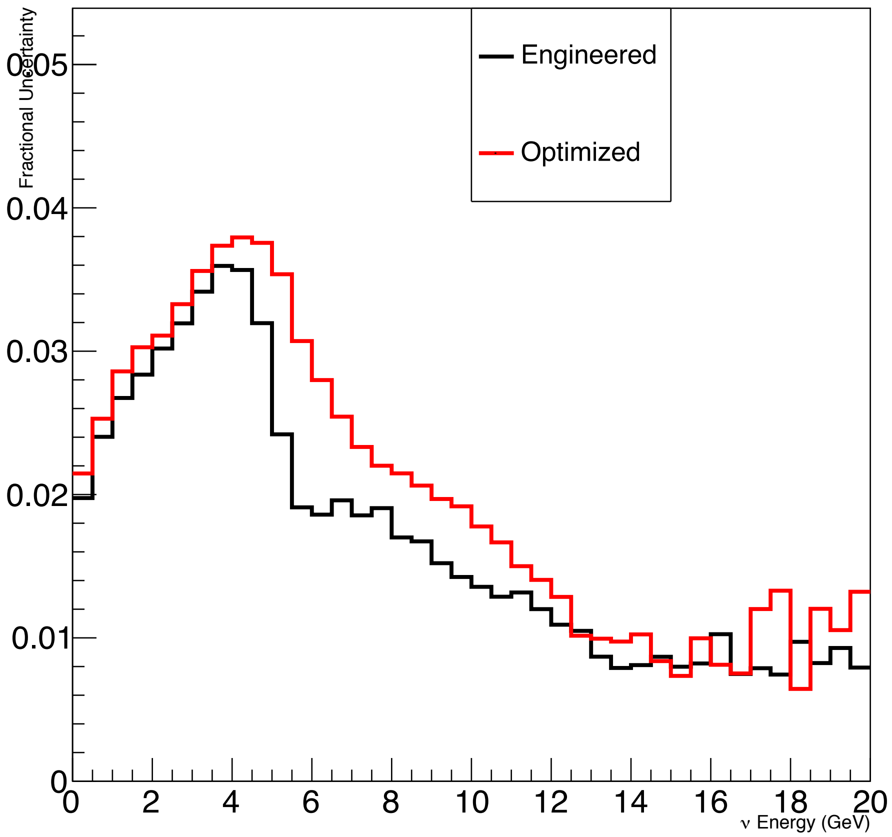
Target Absorption



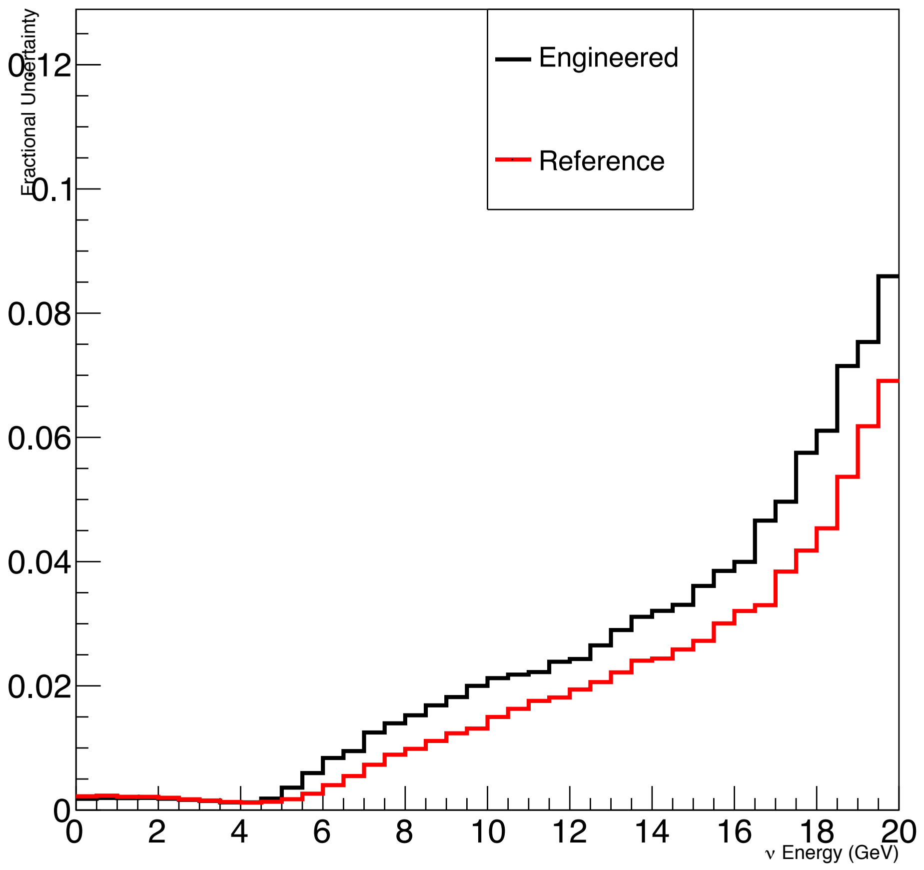


pc→pi X

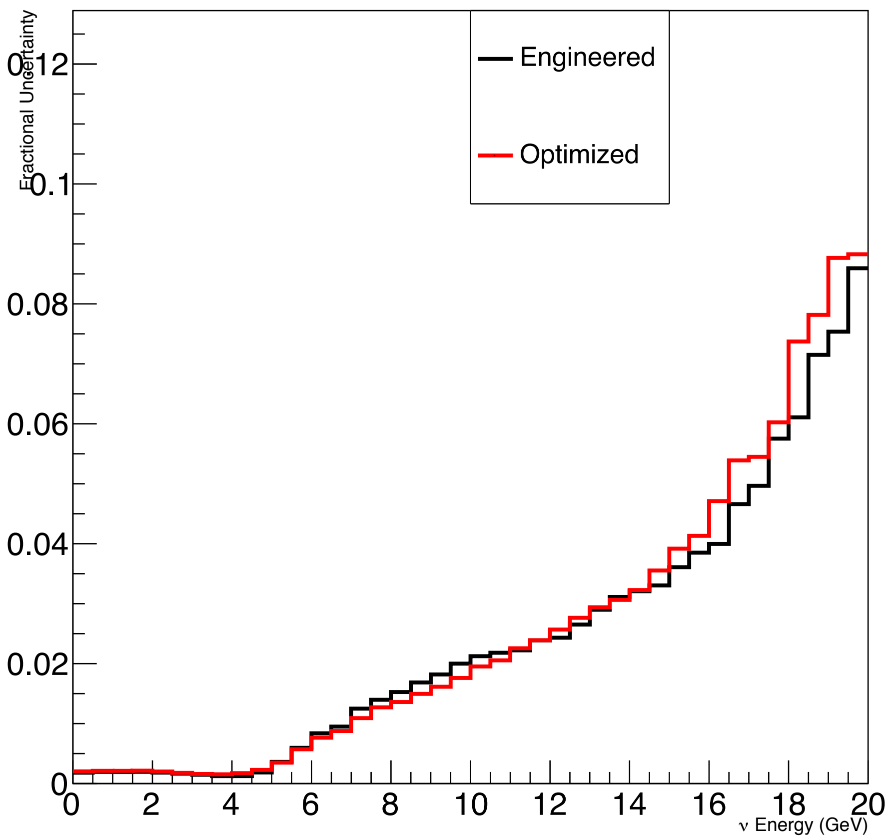

Engineered
Reference
Fractional Uncertainty
0.05
0.04
0.03
0.02
0.01
0
0 2 4 6 8 10 12 14 16 18 20
ν Energy (GeV)


Engineered
Optimized
Fractional Uncertainty
0.05
0.04
0.03
0.02
0.01
0
0 2 4 6 8 10 12 14 16 18 20
ν Energy (GeV)

pc→K X

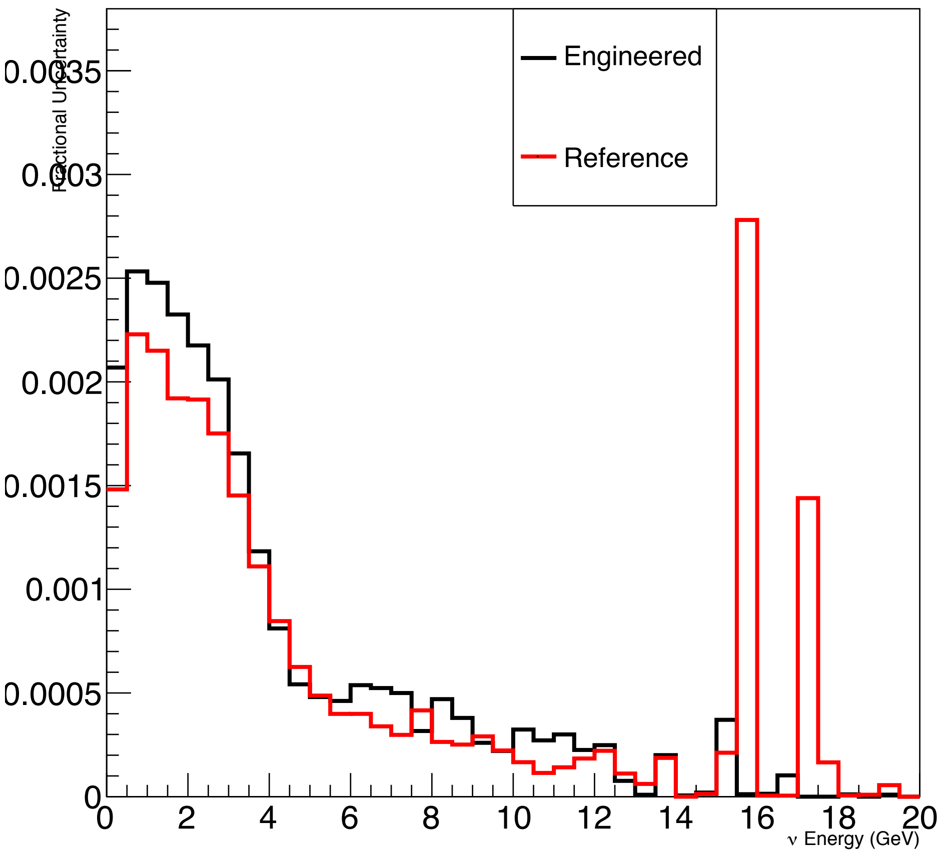


Engineered
Reference
Fractional Uncertainty
0.12
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
10
12
14
16
18
20
ν Energy (GeV)

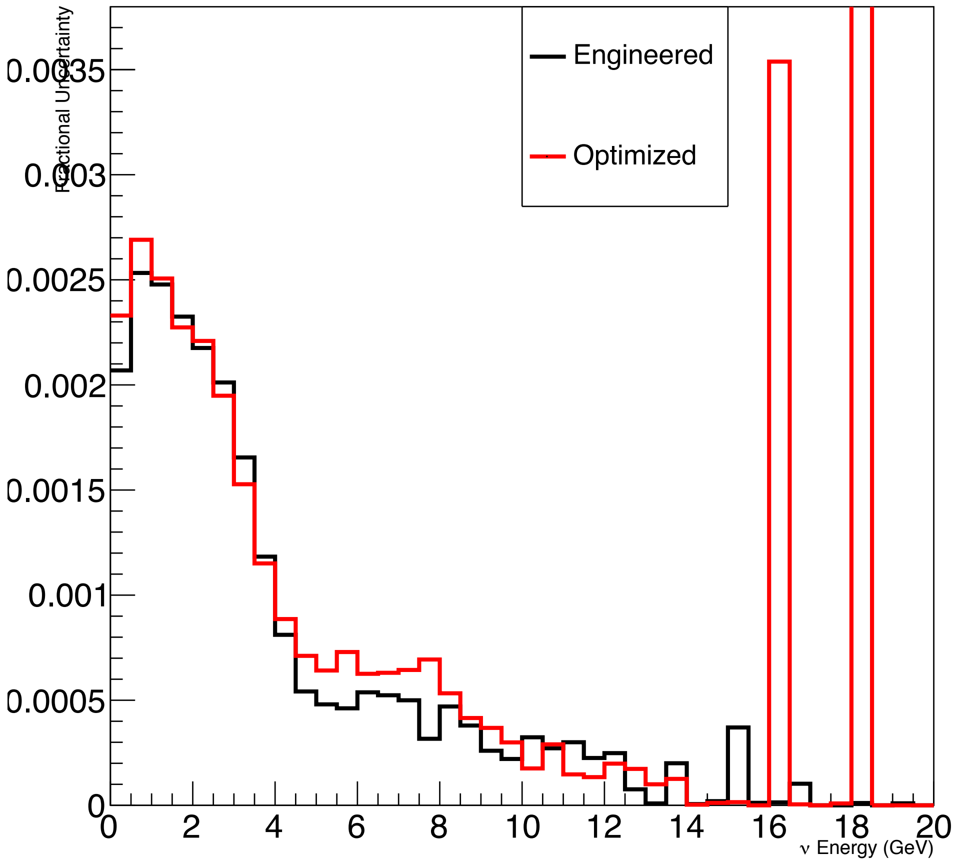


Engineered
Optimized
Fractional Uncertainty
0.12
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
10
12
14
16
18
20
ν Energy (GeV)

nc→pi X

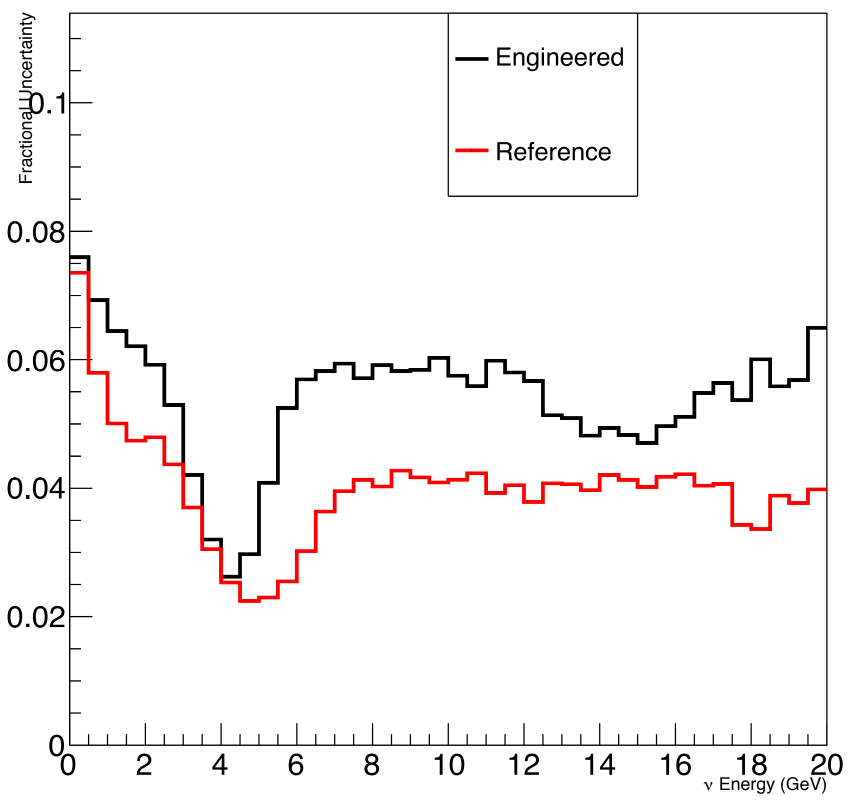


Fractional Uncertainty
Engineered
Reference
0
0.0005
0.001
0.0015
0.002
0.0025
0.003
0.0035
0 2 4 6 8 10 12 14 16 18 20
ν Energy (GeV)

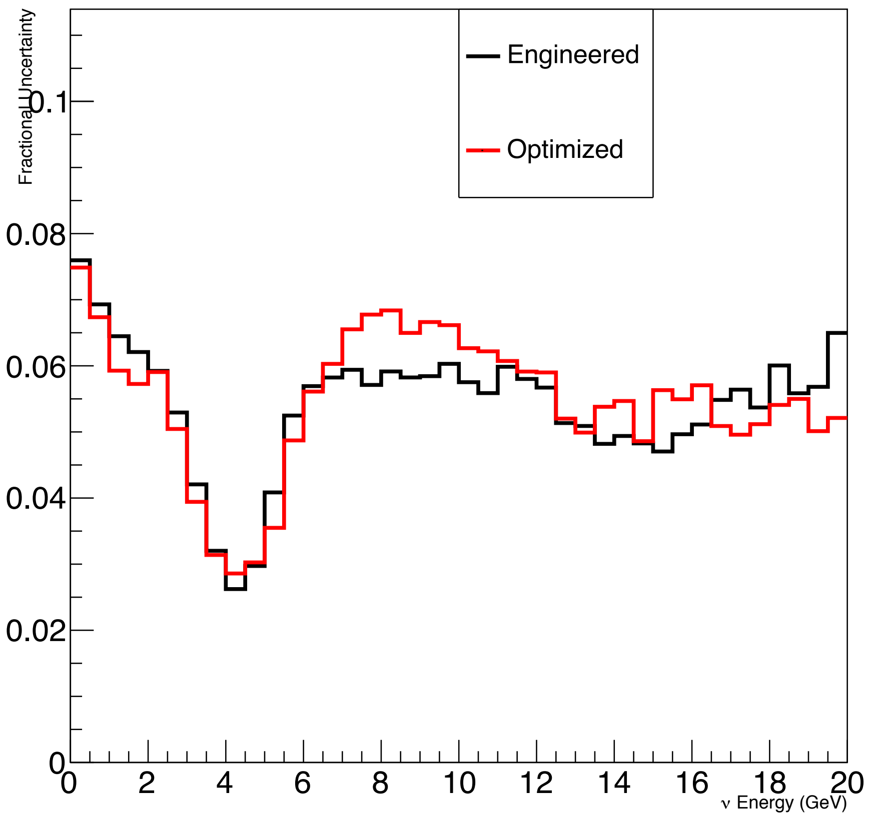


Fractional Uncertainty
Engineered
Optimized
0
0.0005
0.001
0.0015
0.002
0.0025
0.003
0.0035
0 2 4 6 8 10 12 14 16 18 20
ν Energy (GeV)

nucleon-A

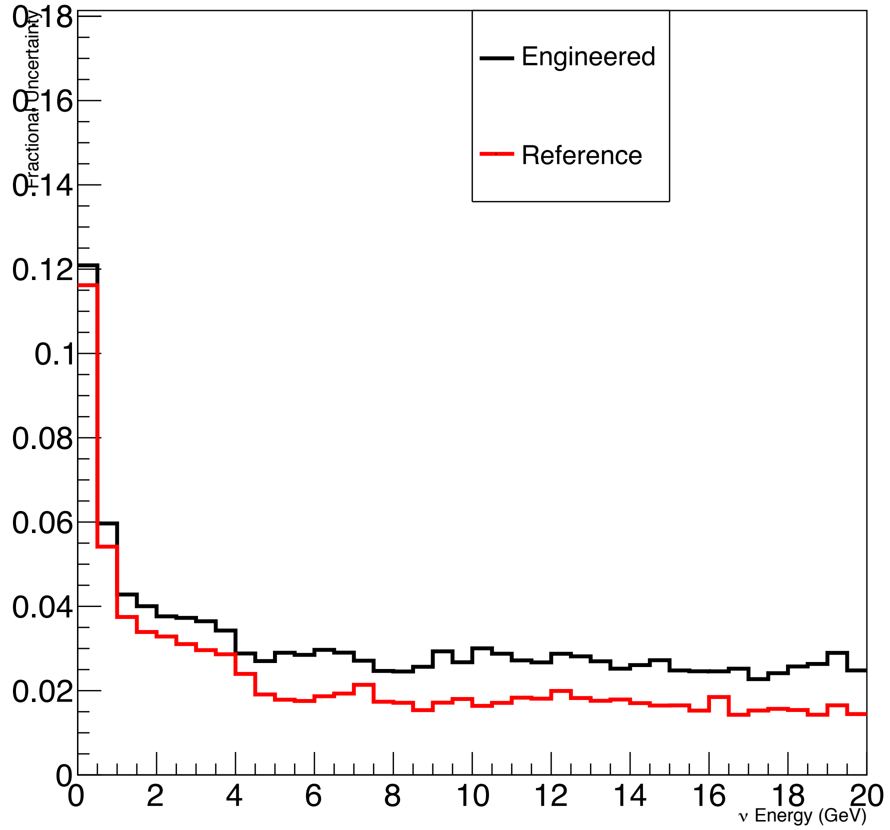


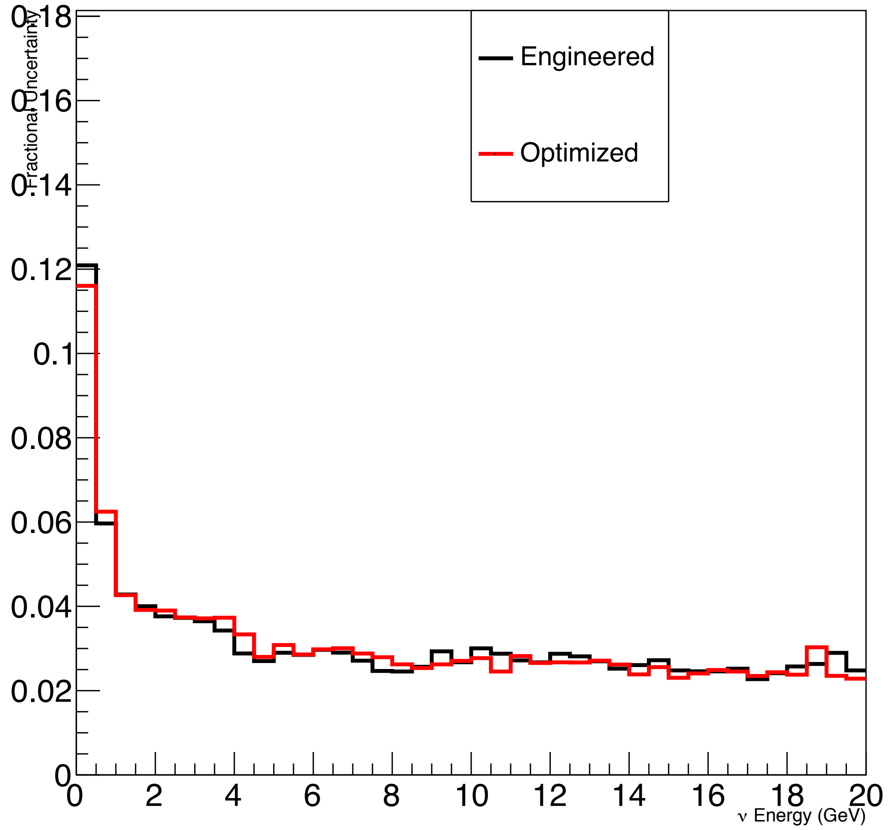
Fractional Uncertainty
Engineered
Reference
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
10
12
14
16
18
20
ν Energy (GeV)



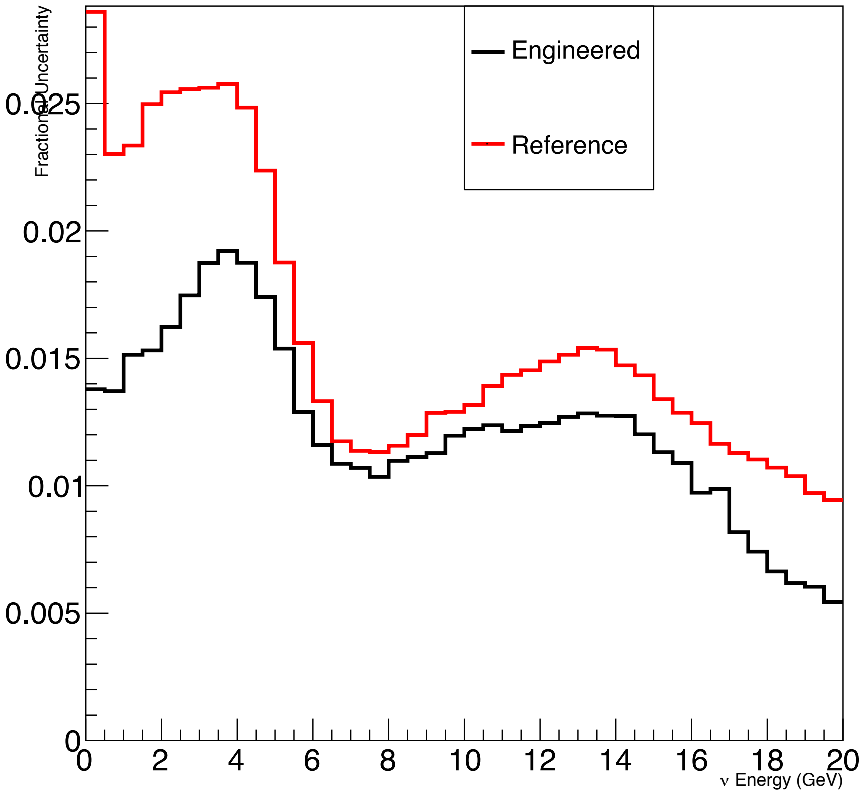
Fractional Uncertainty
Engineered
Optimized
0.1
0.08
0.06
0.04
0.02
0
0
2
4
6
8
10
12
14
16
18
20
ν Energy (GeV)

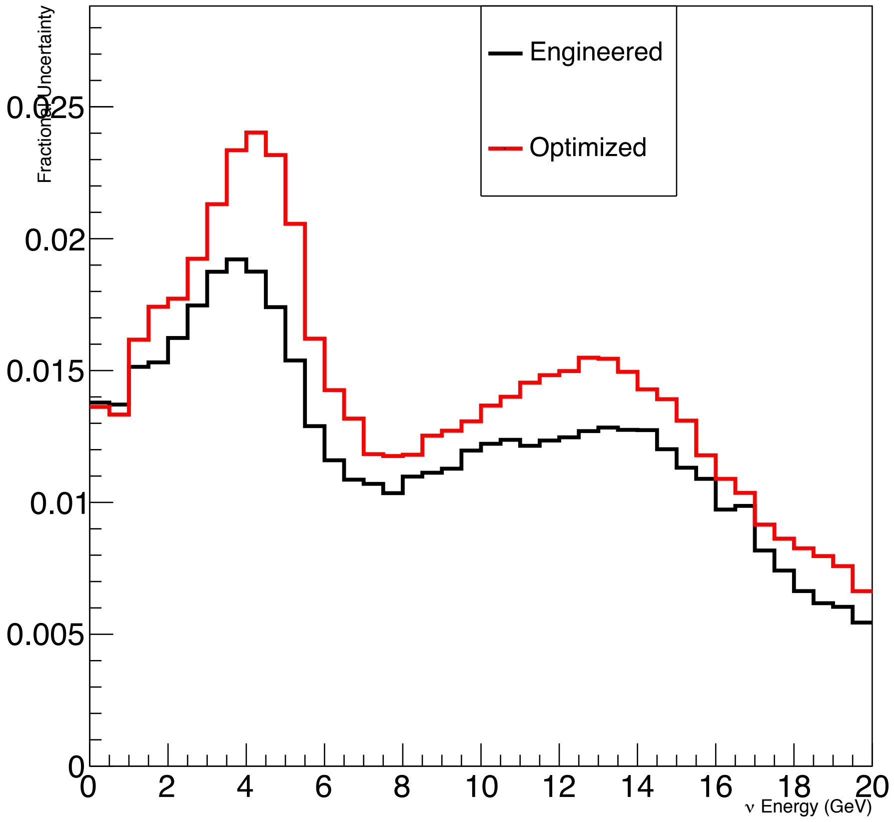
Target Meson Incident



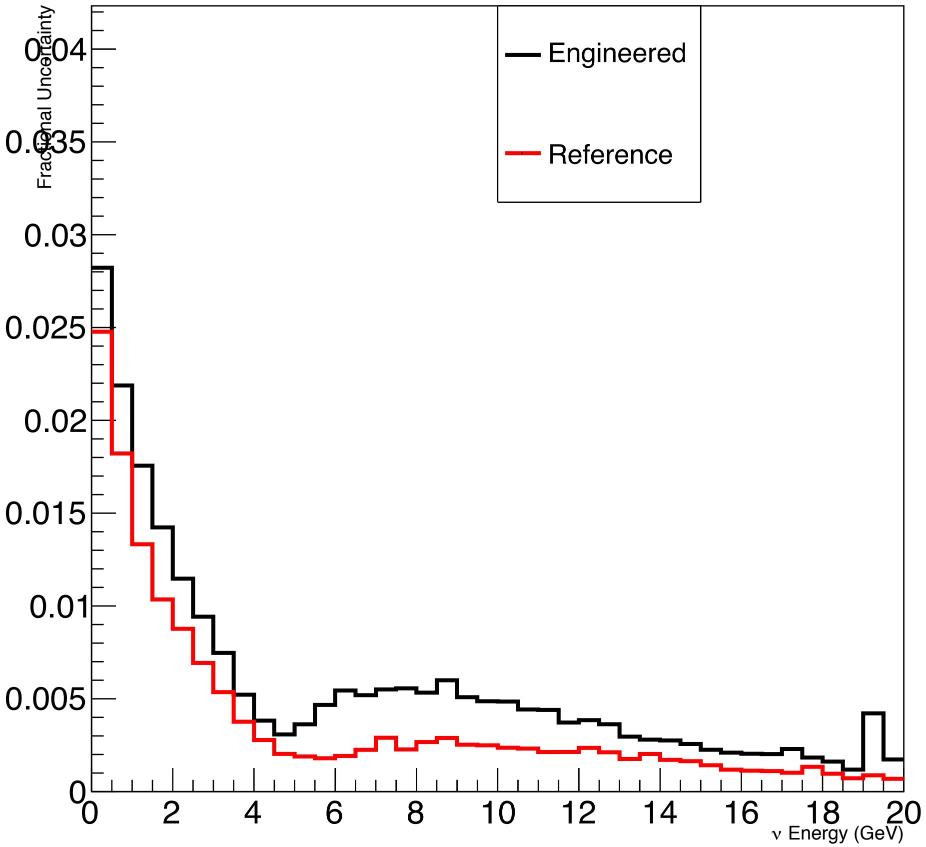


Total Absorption

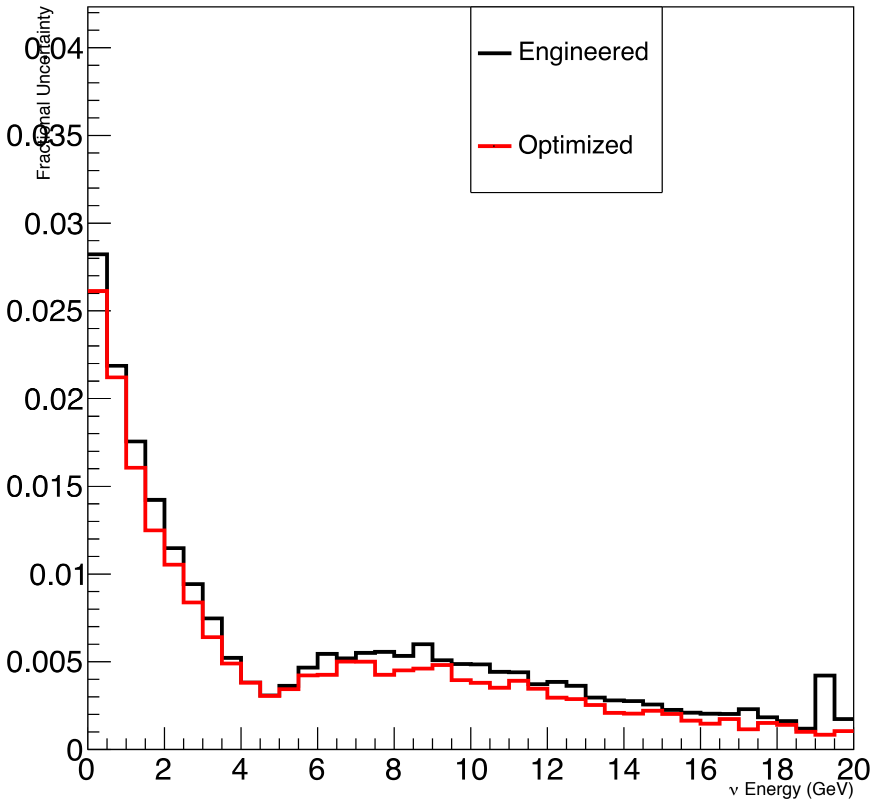




Others



Fractional Uncertainty
Engineered
Reference
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
2
4
6
8
10
12
14
16
18
20
ν Energy (GeV)



Fractional Uncertainty
Engineered
Optimized
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
2
4
6
8
10
12
14
16
18
20
ν Energy (GeV)

REFERENCES AND FURTHER READING

- [1] **Neutrino Flux Prediction for the NuMI BeamLine**, Leonidas Aliaga Soplin, arXiv.org

- [2] T. Golan, **MINERvA –doc-11150-v1** (*For detailed skubic data fitting*)

- [3]. M. Kordosky, **MINERvA-doc-7433-v1** (*For detailed multi universe method for error propagation)*