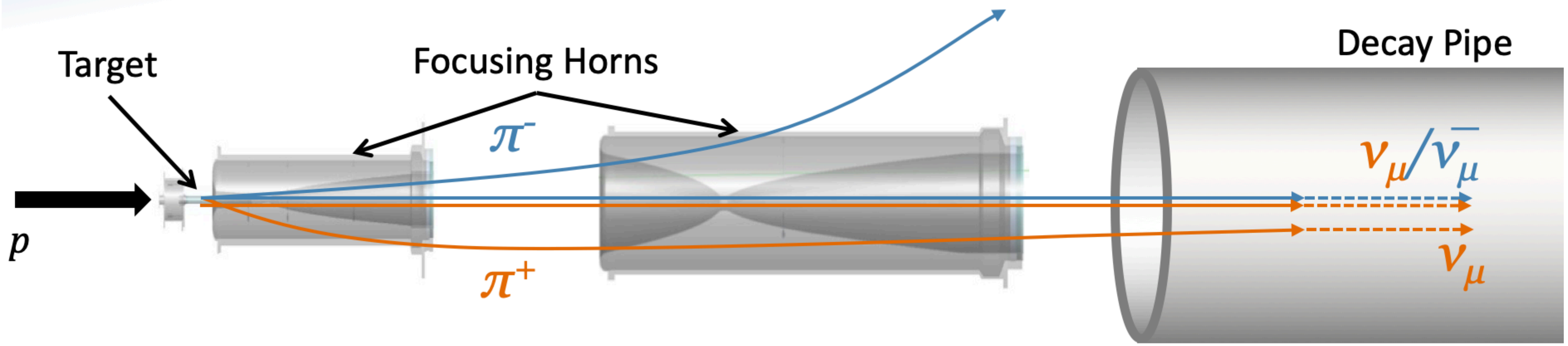
Fermilab long-baseline fluxes

Leo Aliaga

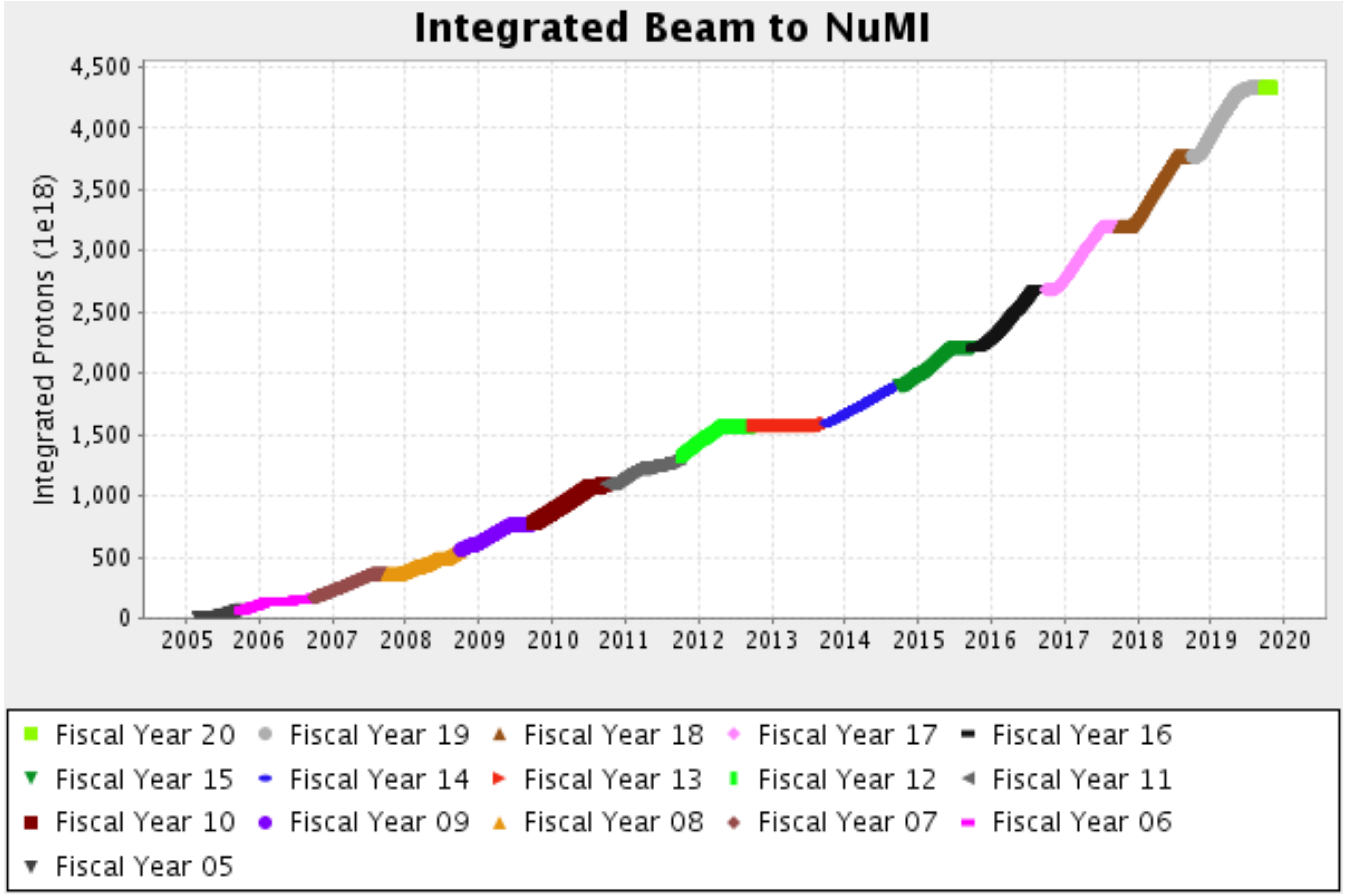
NA61/SHINE at Low Energy Workshop

December 10, 2020

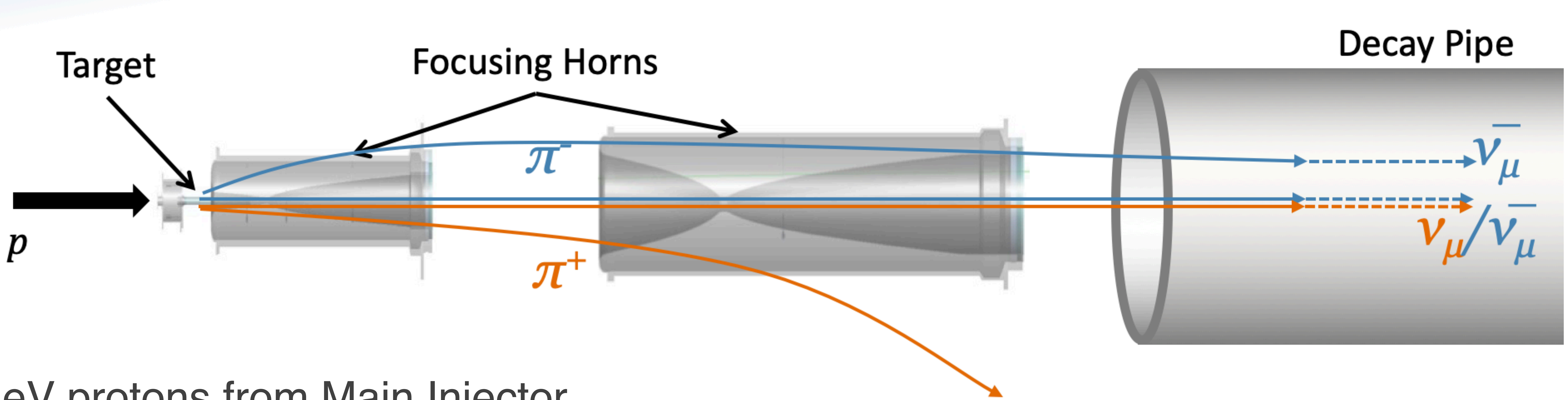
Neutrinos at the Main Injector



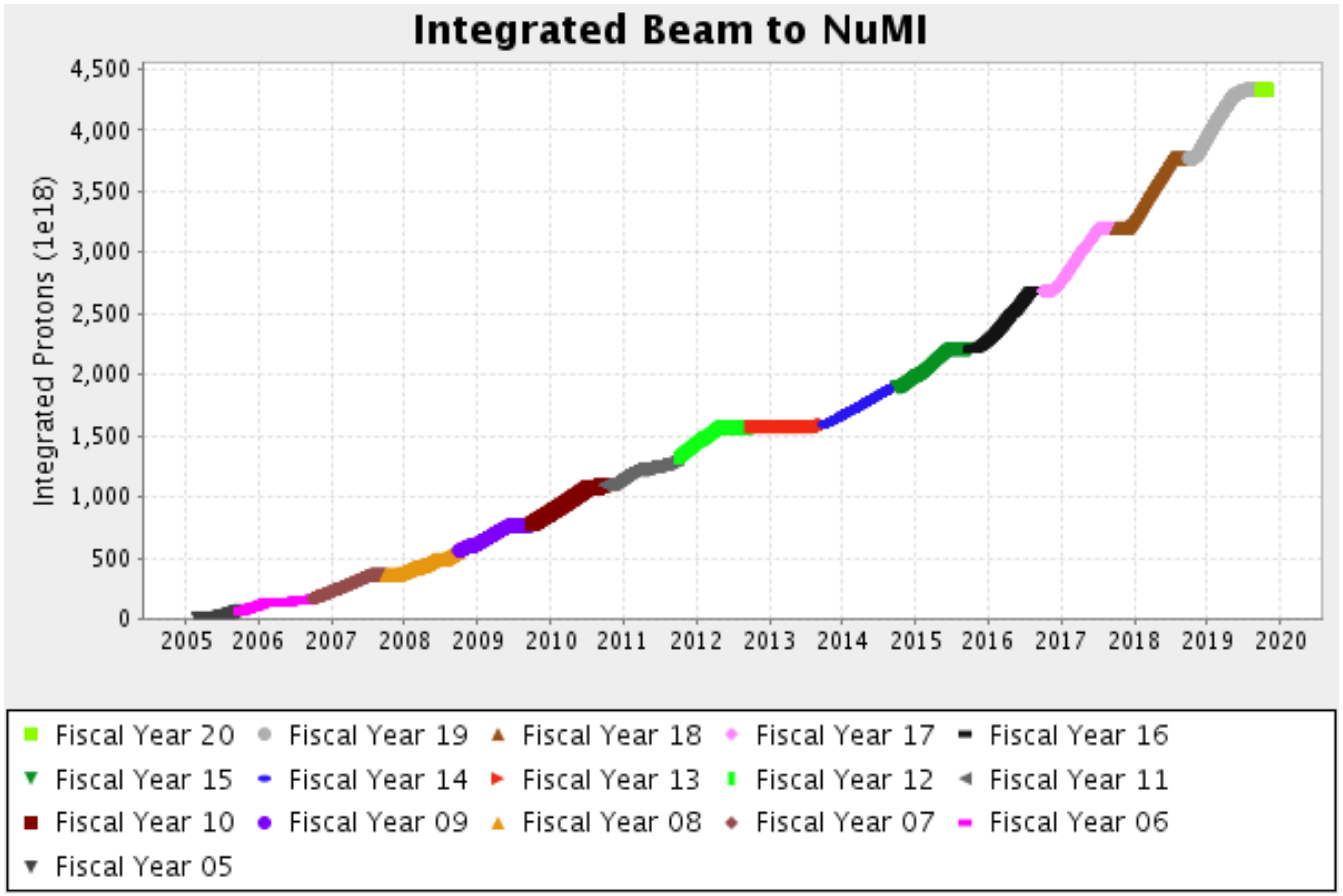
- 120 GeV protons from Main Injector.
- Graphite target
- 2 Magnetic horns
- Decay Pipe: 675 m filled with Helium.



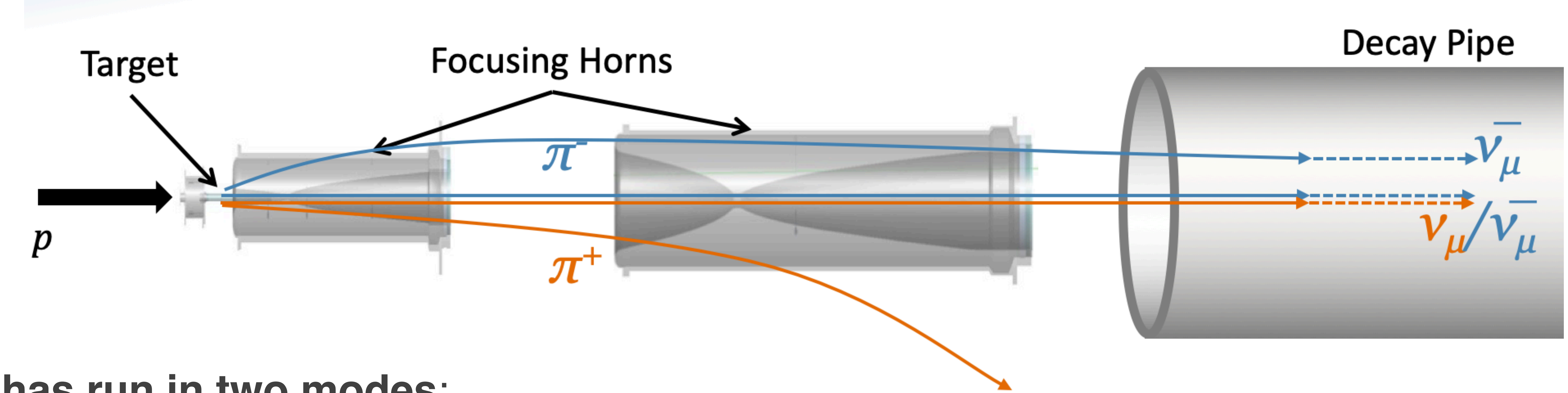
Neutrinos at the Main Injector



- 120 GeV protons from Main Injector.
- Graphite target
- 2 Magnetic horns
- Decay Pipe: 675 m filled with Helium.
- It can run in neutrino or antineutrino modes

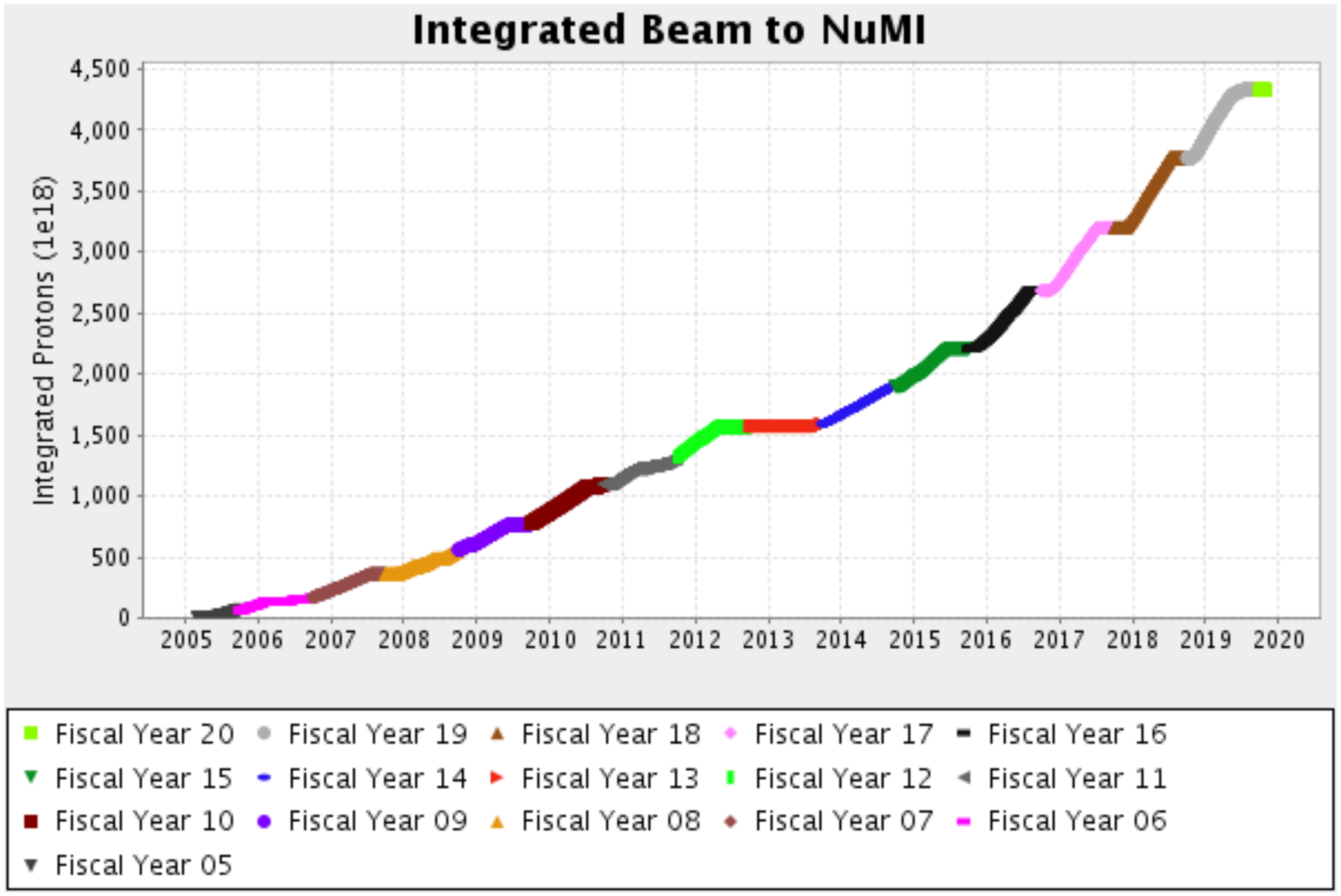


Neutrinos at the Main Injector



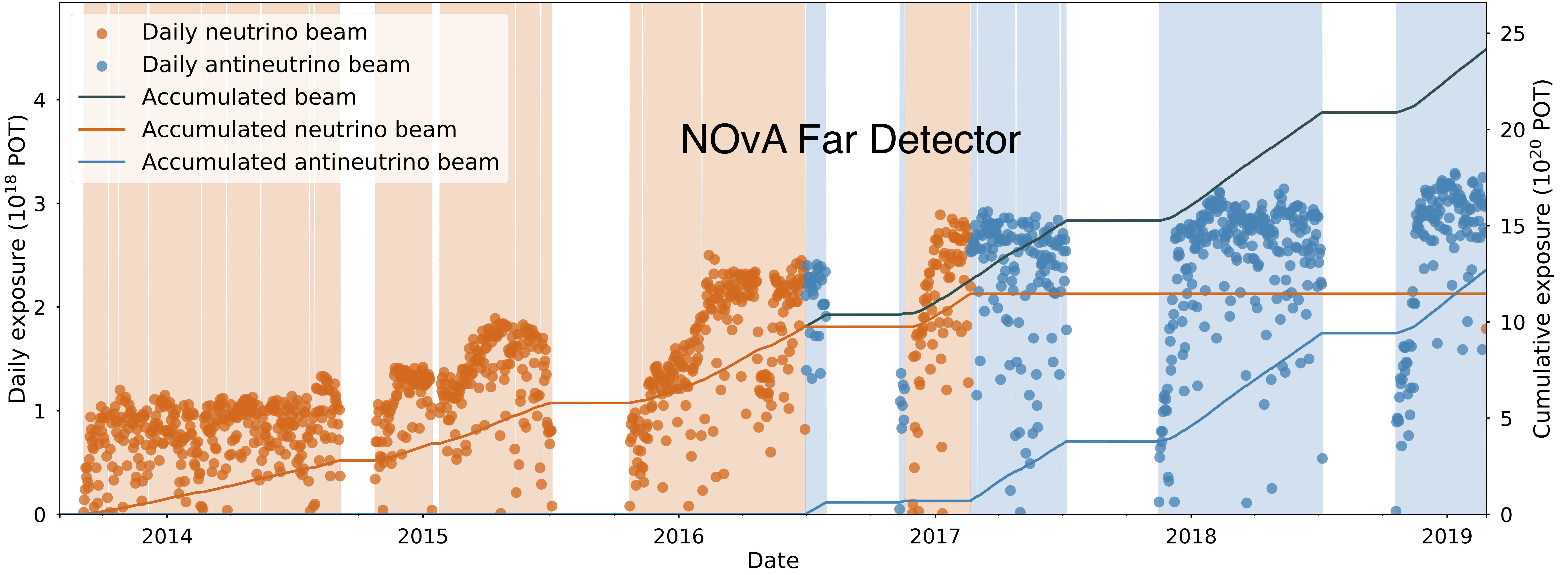
NuMI has run in two modes:

»	**Low energy**	2005 - 2012	MINOS era
»	**Medium energy**	2013 - present	NOvA era



- » Currently running with 10 µs spill every 1.33 s
- » **Achieved 750 kW power since early 2019**

NOvA Exposure to NuMI Beam



Collected data at NOvA ND to the present:

» 11 x 10^{20} POT of neutrino-mode data

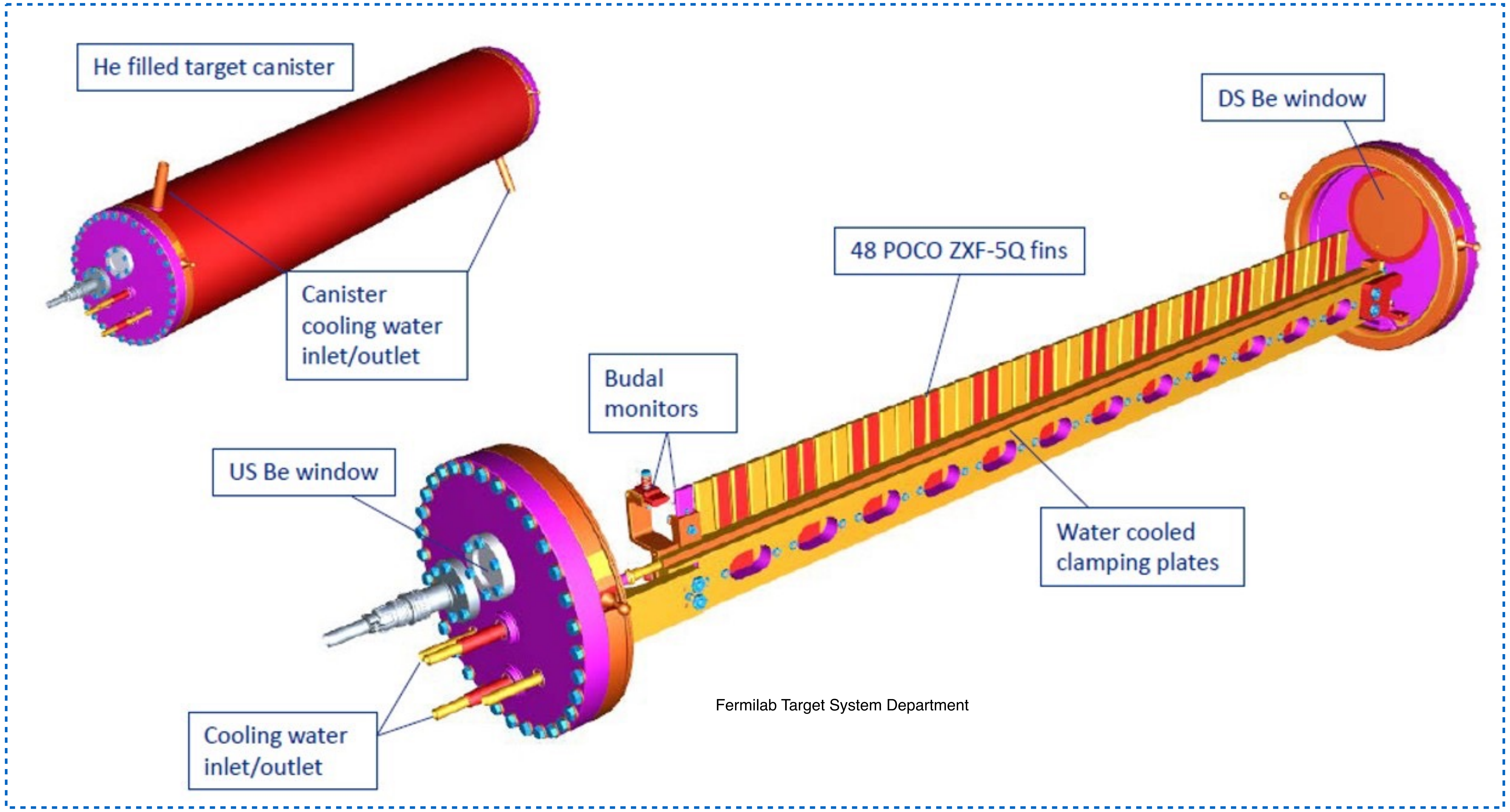
» 11.8 x 10^{20} POT of antineutrino-mode data collected in the NOvA near detector so far.

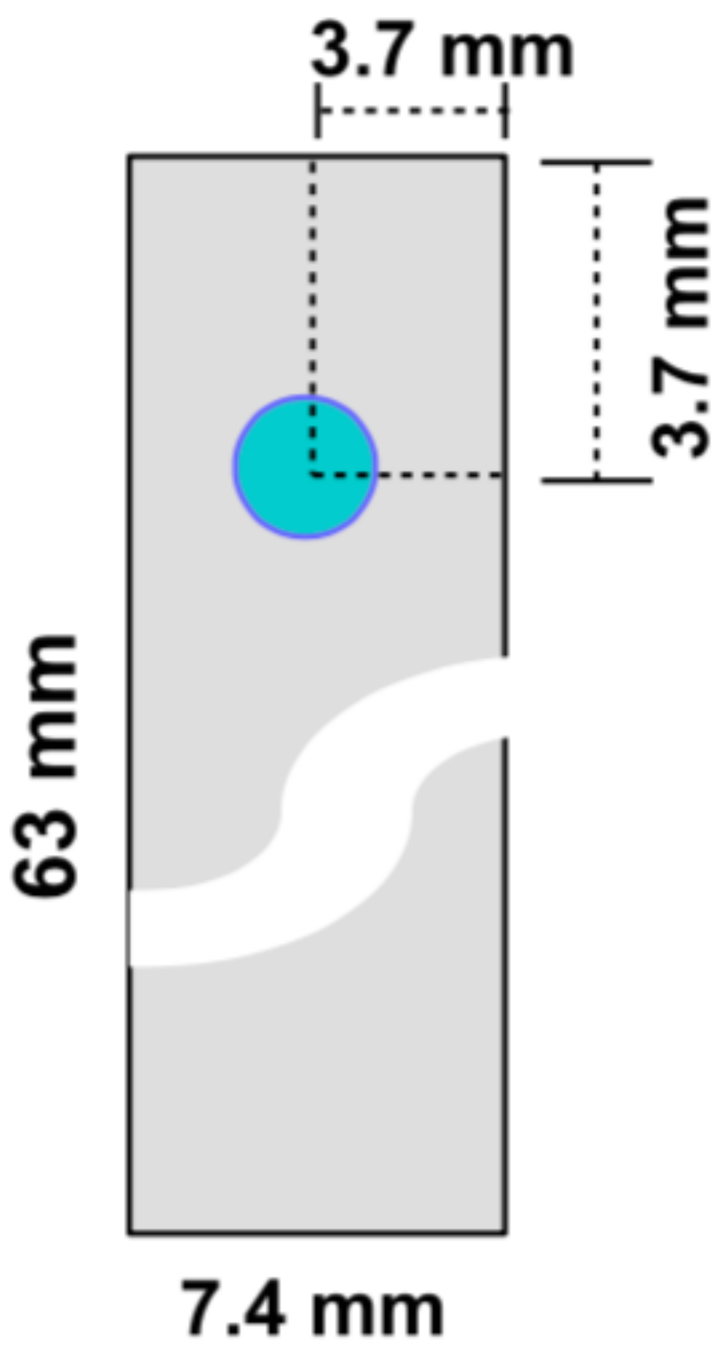
» More POT to come in the next years.

NuMI target

Rectangular graphite rode, segmented in rectangular pieces (“fins”).

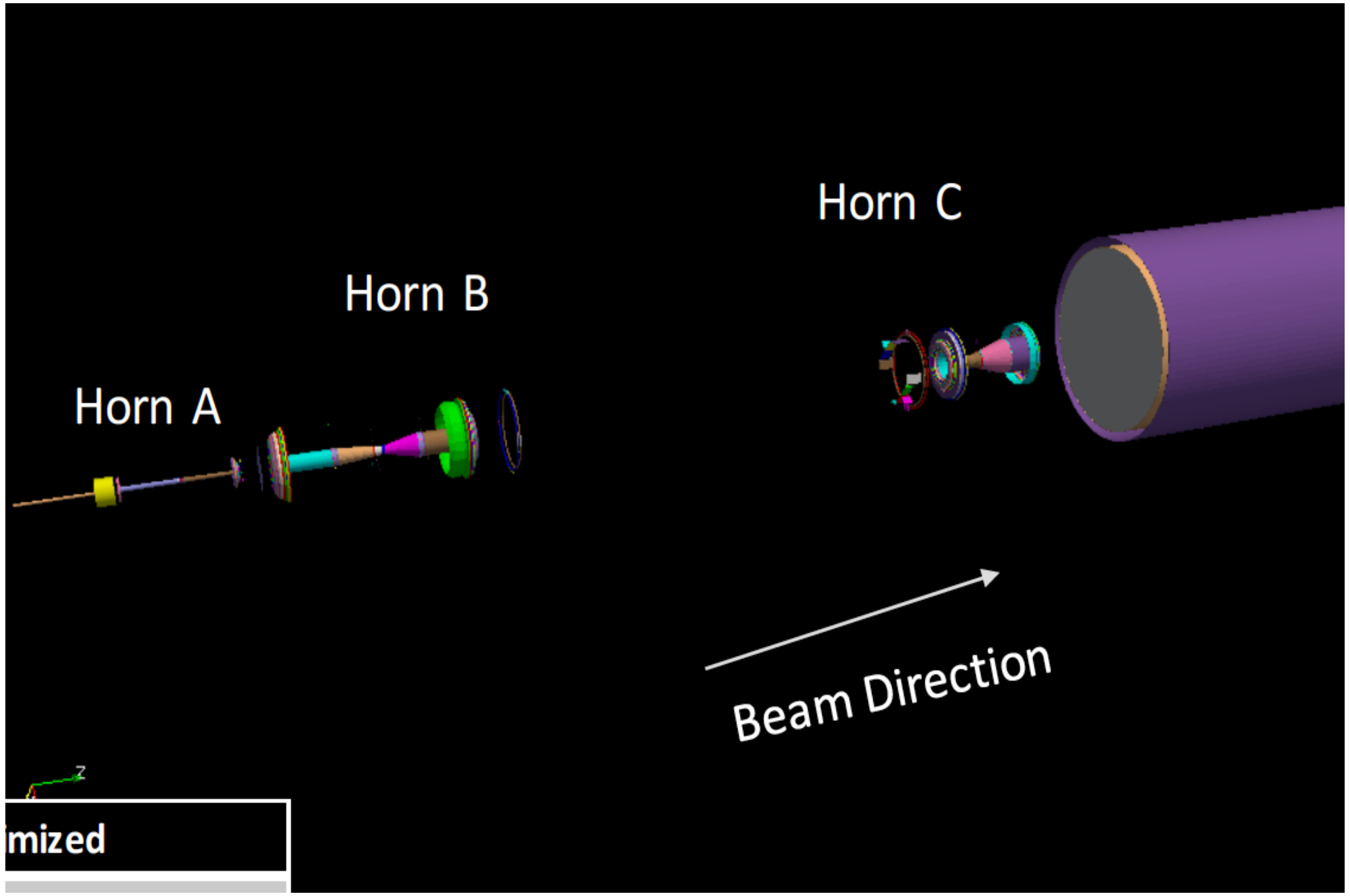
50 fins in total: 1.2 m (~2.5 λ).





Long-Baseline Neutrino Facility

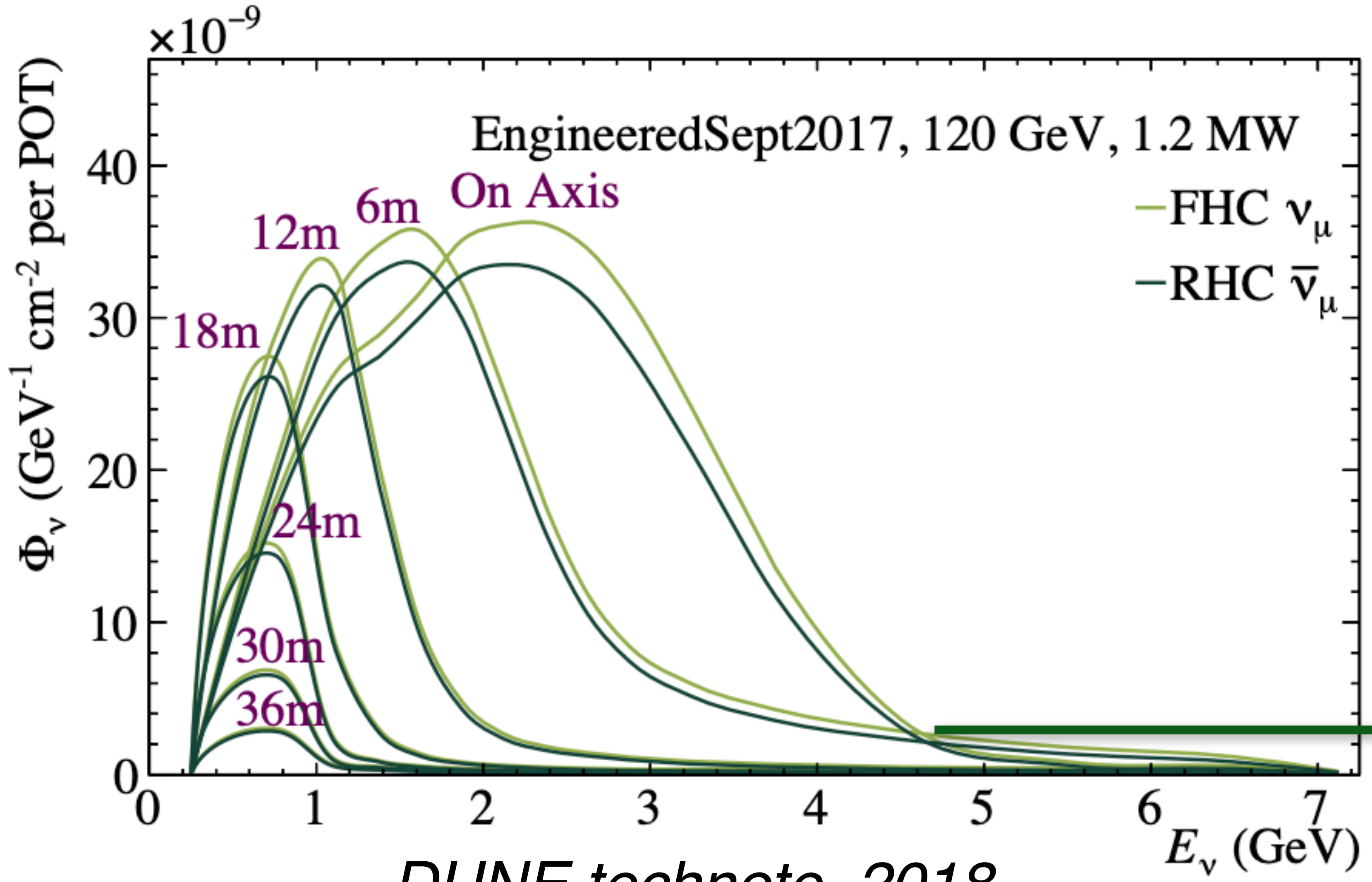
- Primary proton beam in 60-120 GeV.
- Initial 1.2 MW beam power, upgradable to 2.4 MW.
- Graphite target
- 3 Magnetic horns
- Extended Decay pipe, He filled.
- Experimental setup optimized for CP violation



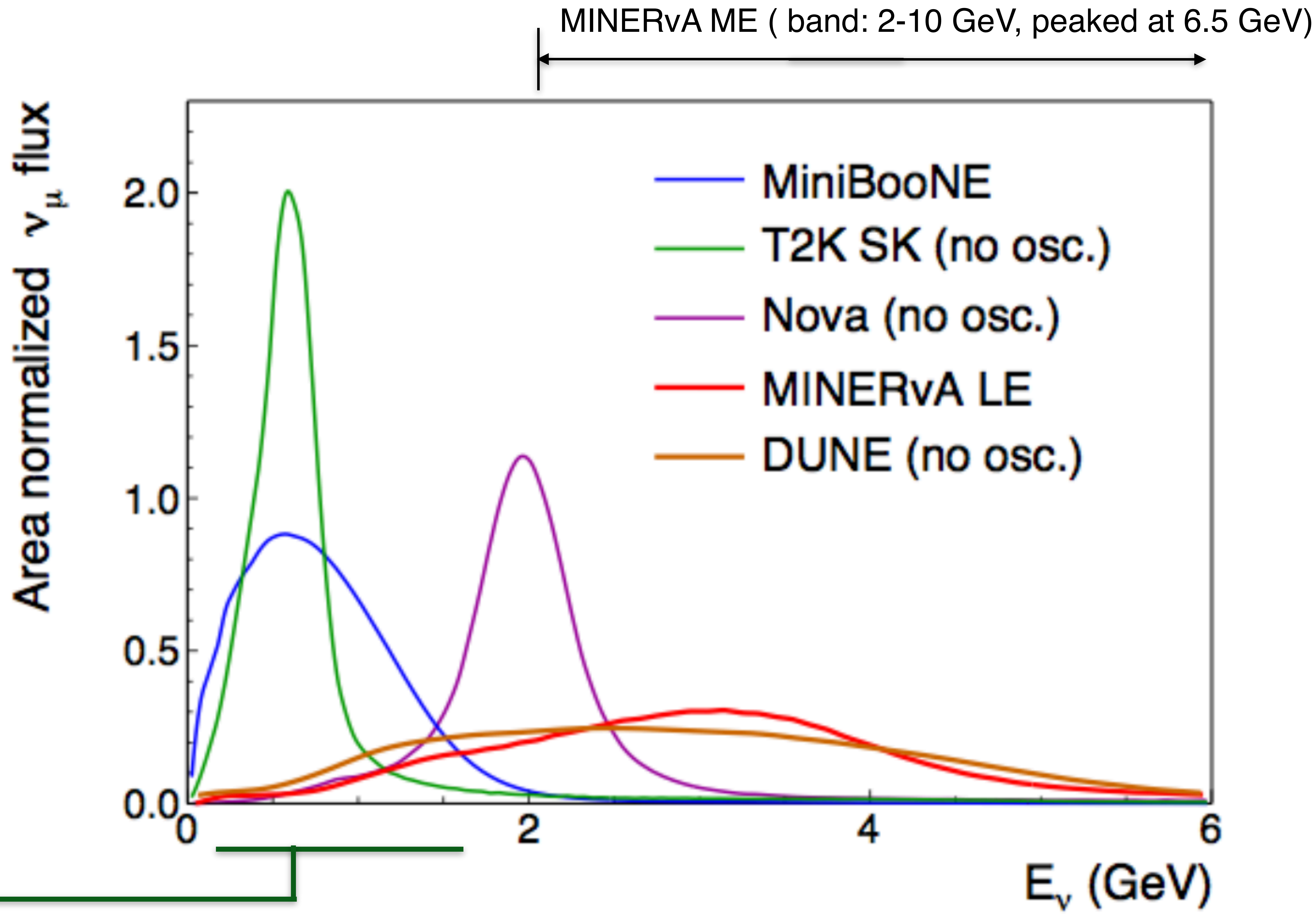
Neutrino Fluxes

» Not monocromatic: wide-band.
» A-priori shape and normalization are determined from simulation and hadron production constraints.

Flux at DUNE PRISM



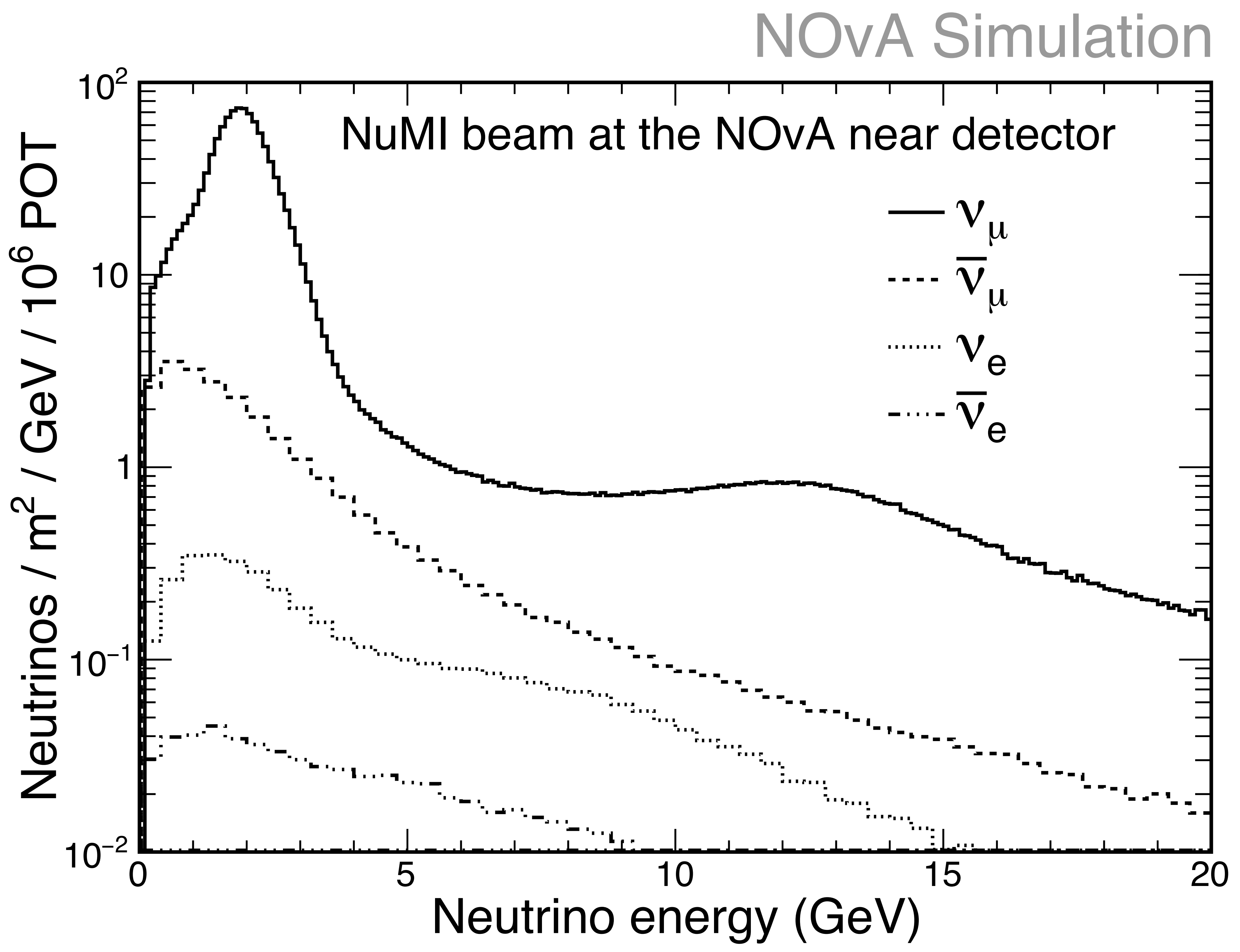
DUNE technote, 2018

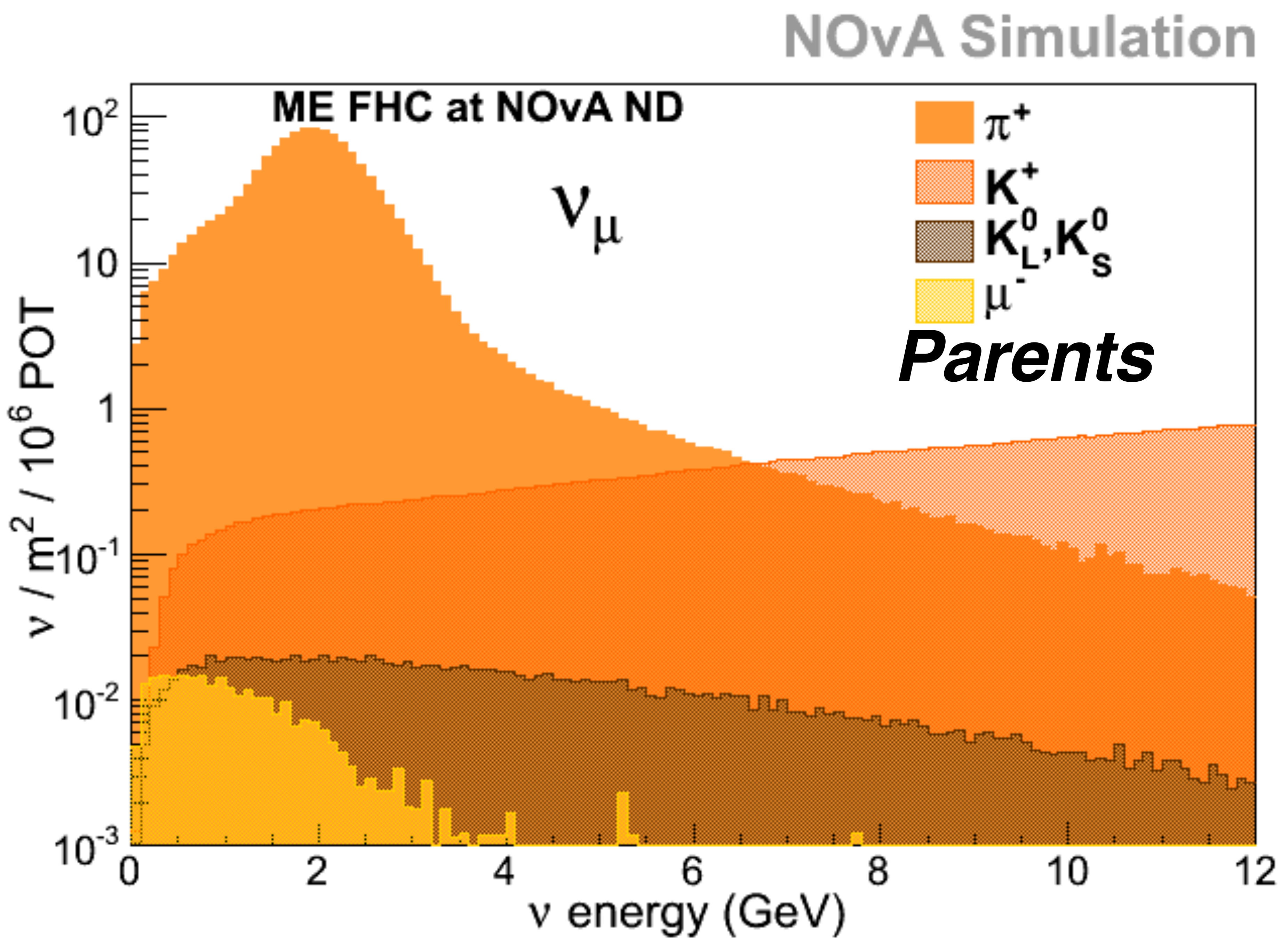


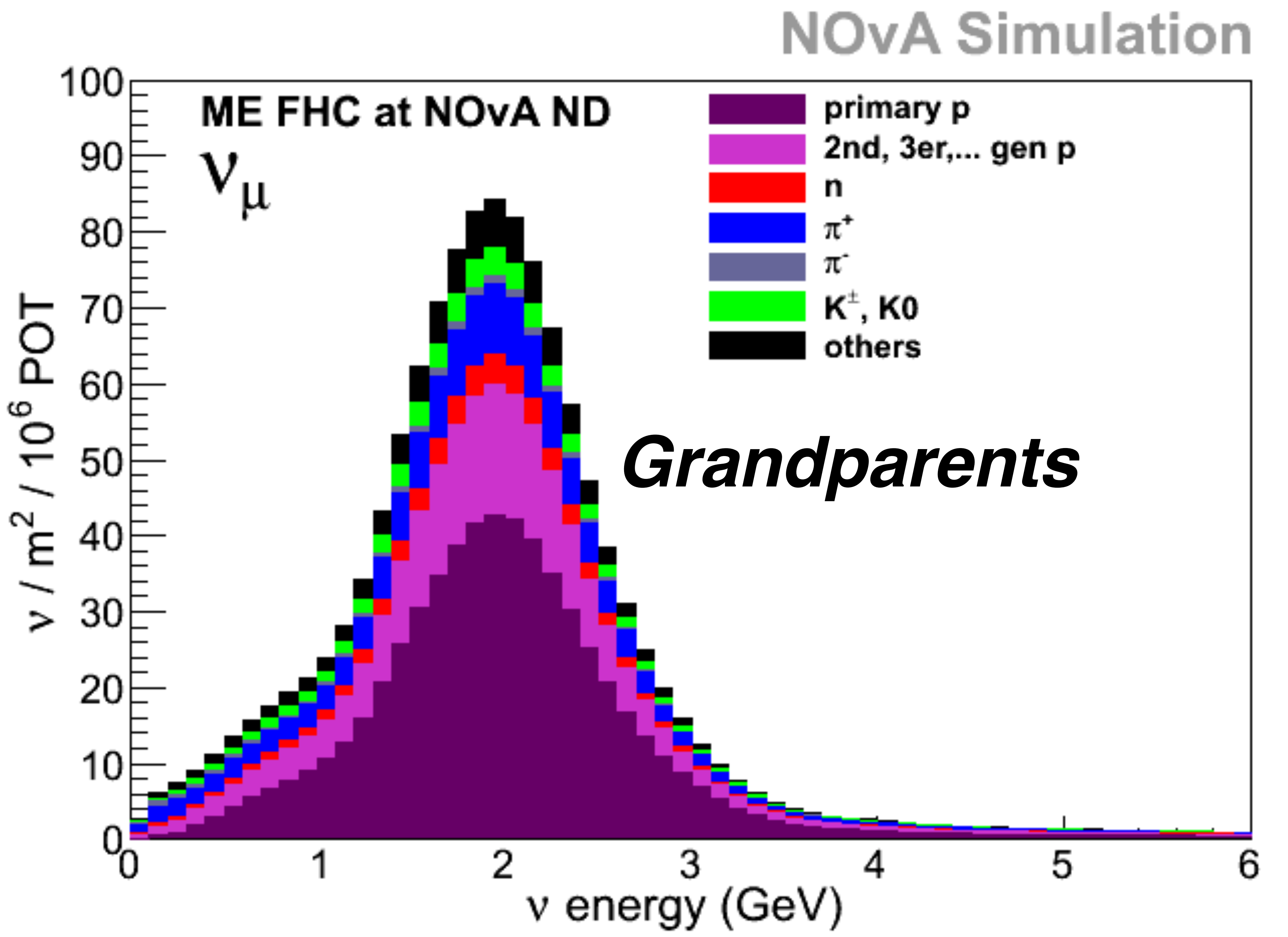
Fermilab JETP Seminar, Phil Rodrigues 2015

Neutrino flux at NOvA

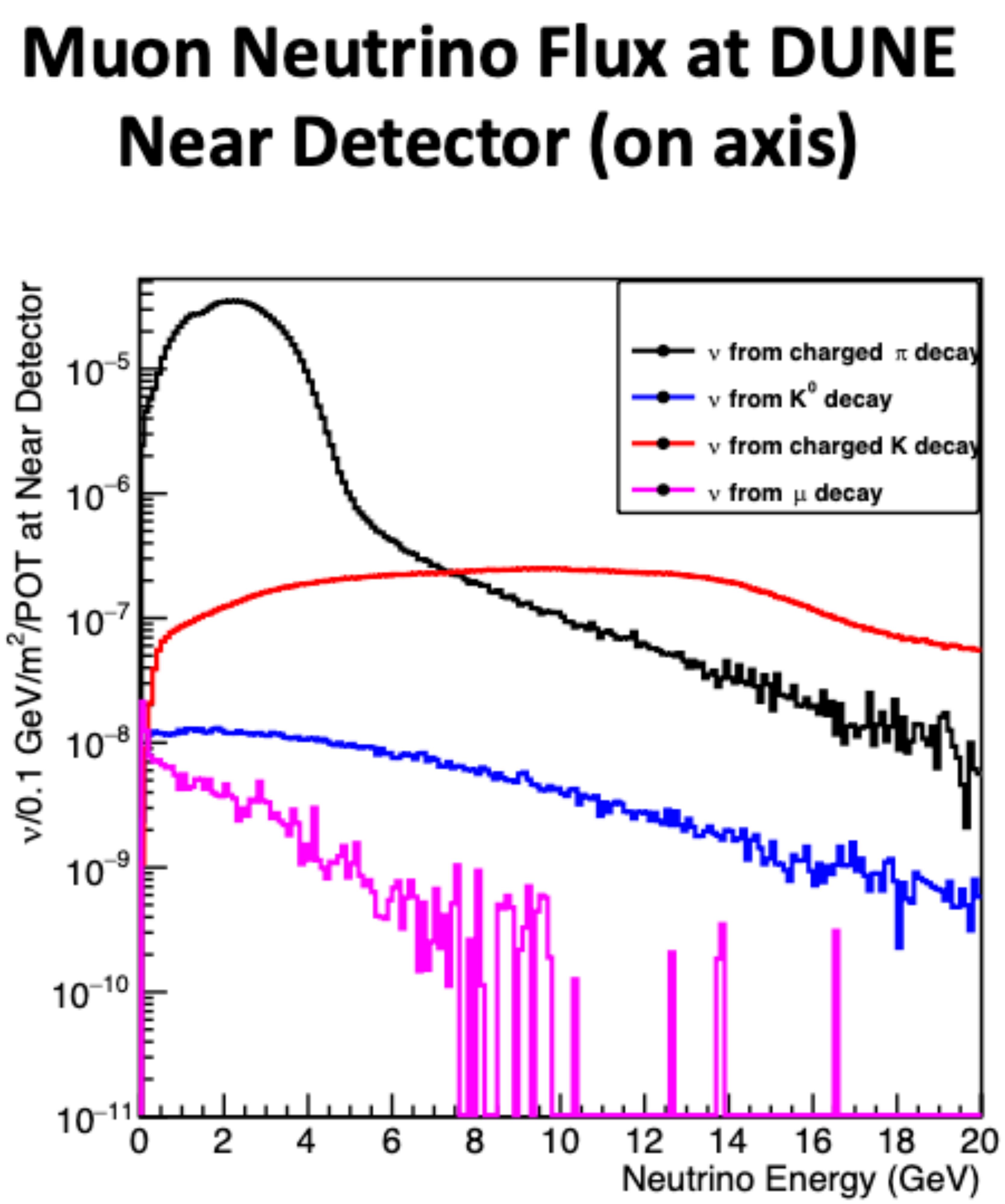
» 96% pure ν_μ beam, 1% ν_e and $\bar{\nu}_e$

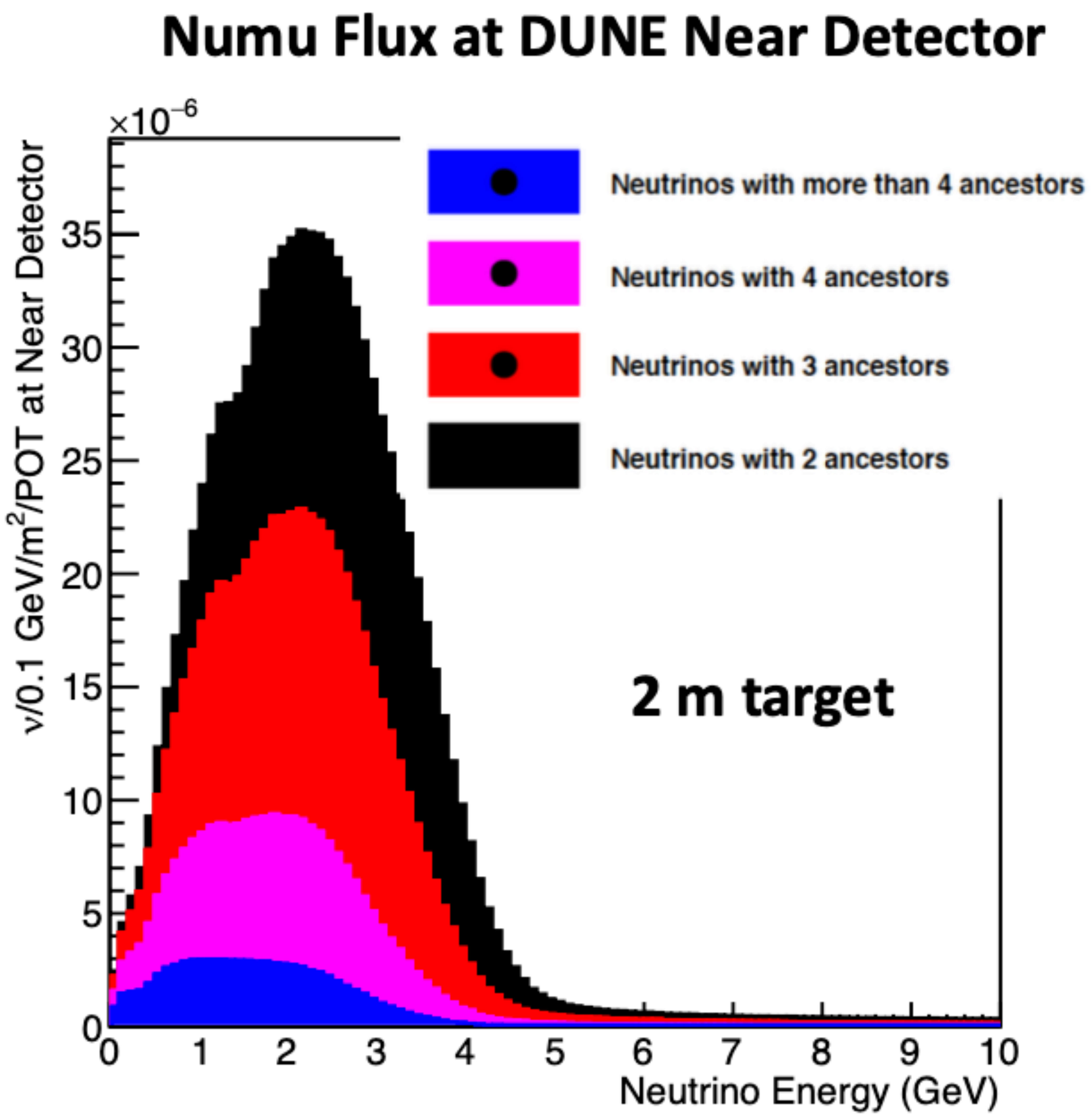






DUNE Flux

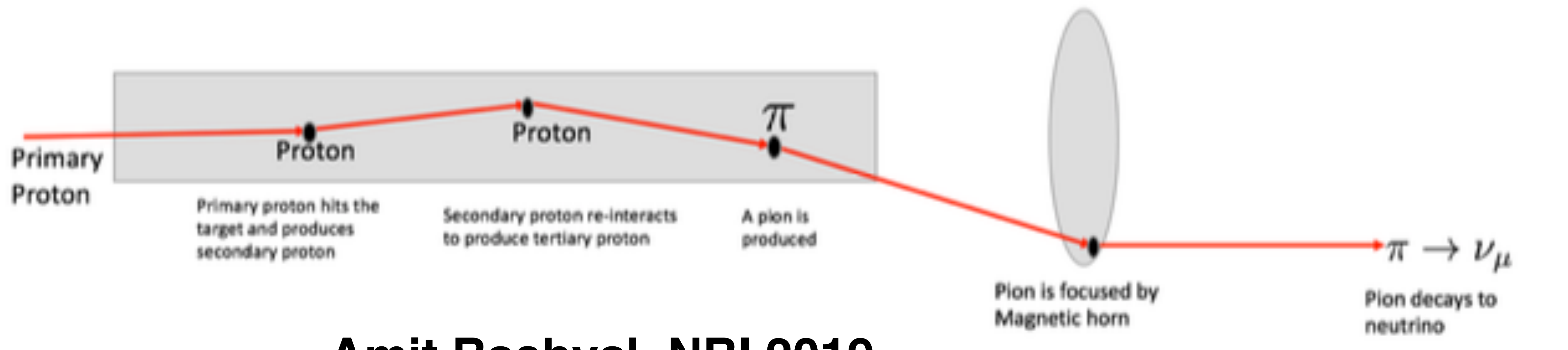




Amit Bashyal, NBI 2019

MINERvA strategy for predicting a-priori flux

Neutrino Flux Predictions for the NuMI Beam [Phys. Rev. D 94, 092005 (2016)]



Amit Bashyal, NBI 2019

Common framework is used for other long baseline neutrino experiments, such as NOvA and DUNE

» The beamline simulation is G4NuMI (geant4 based).

» The foundation is formed from **constraining** (correcting) the **interaction** and the **hadron production** with external measurements on **thick and thin targets**.

» It corrects the yields given by the model to match the measured data. If not data is available we extend the data coverage or assign a well-educated guess.

» It propagates the **underlying data correlations** to calculate the **neutrino interaction covariance (“multi-universe” technique)**.

- It requires the HP dataset bin-to-bin correlation

Hadron Production Corrections

Particle absorption

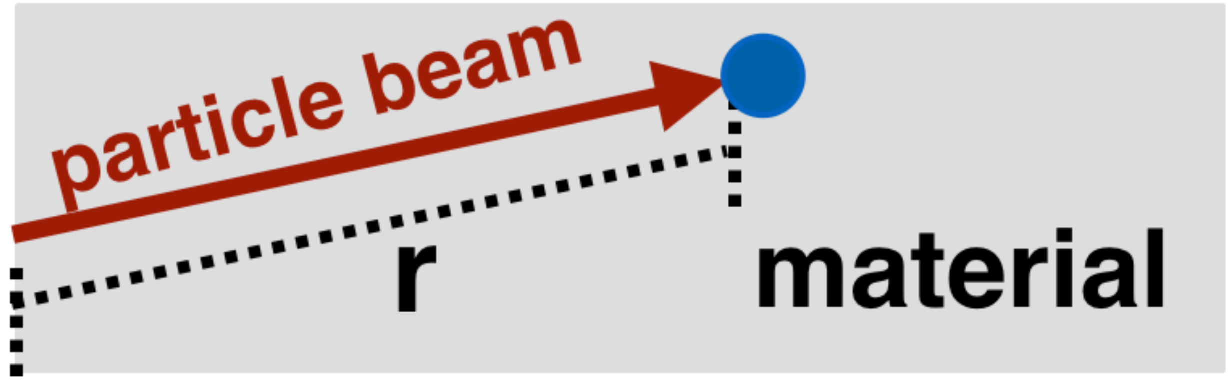
Neutrino Flux Predictions for the NuMI Beam [Phys. Rev. D 94, 092005 (2016)]

Particle absorption:

Interacting

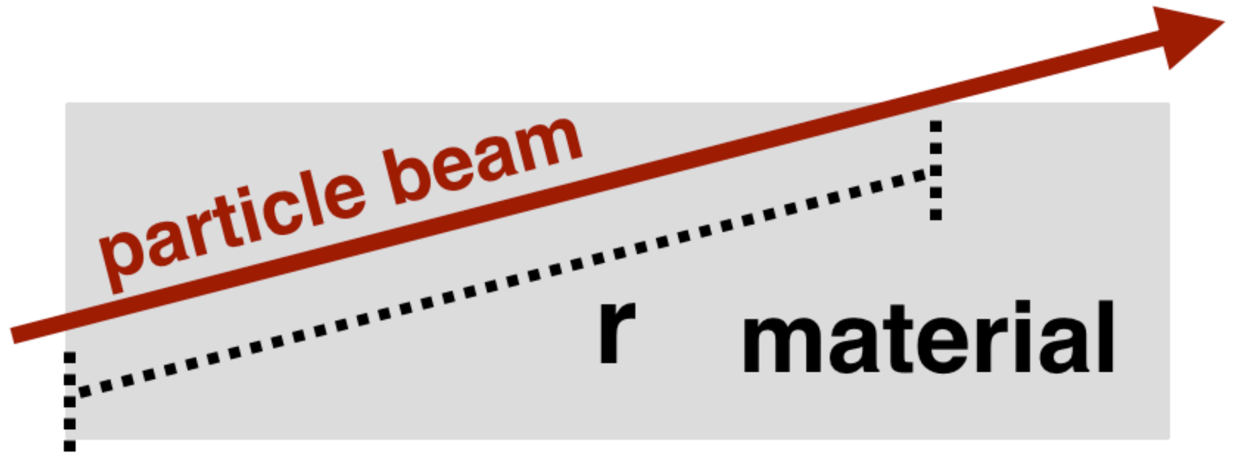
$$correction(r) = \frac{\sigma_{Data}}{\sigma_{MC}} e^{-r\frac{N_A \rho(\sigma_{Data}-\sigma_{MC})}{A}}$$

N_A: Avogadro Number, ρ: density, A: mass number



Not interacting

$$correction(r) = e^{-r\frac{N_A \rho(\sigma_{Data}-\sigma_{MC})}{A}}$$

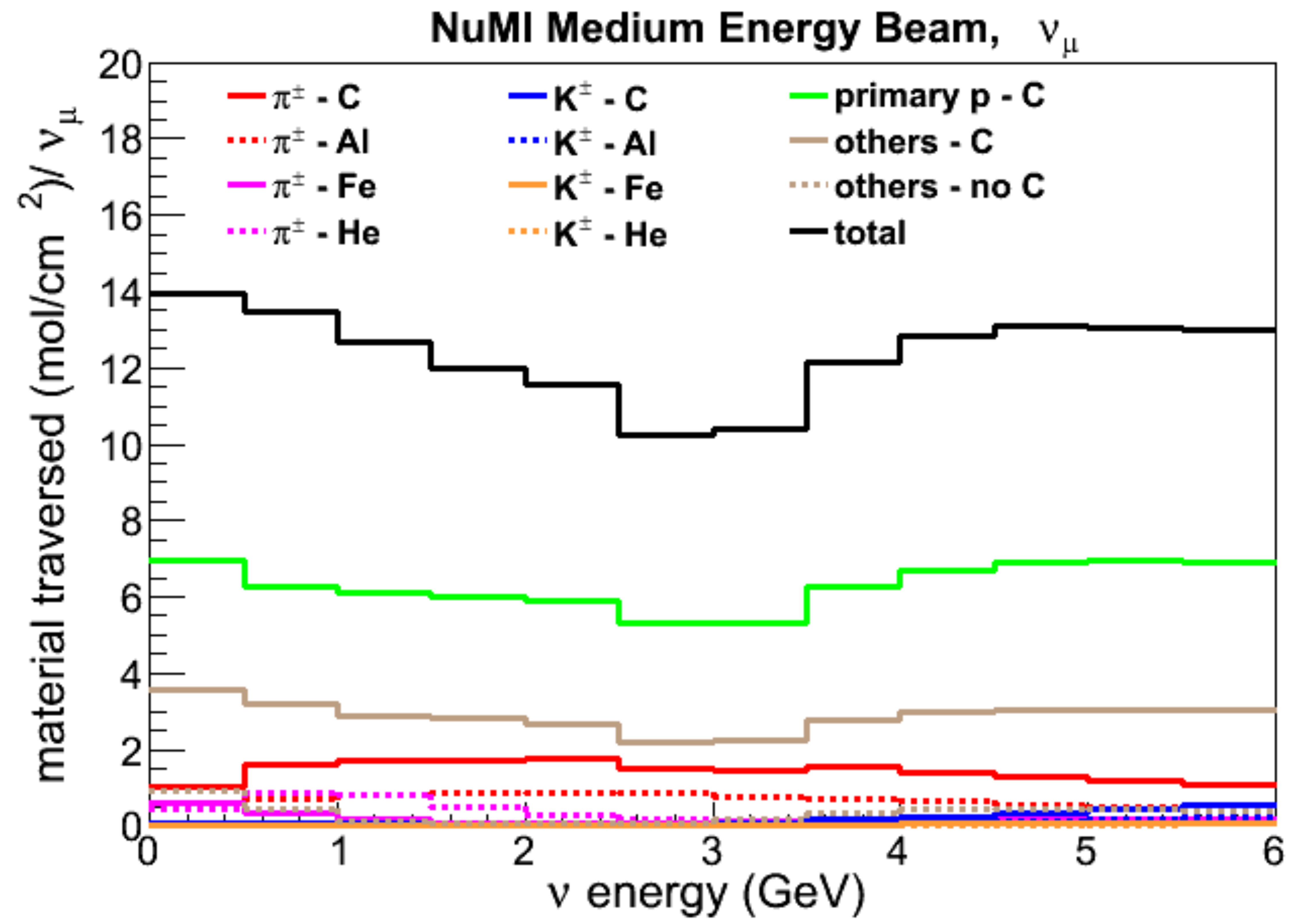


Two variables are important here:

- The amount of material: $\mathbf{rN_A\rho/A}$.
- The $\mathbf{\sigma_{Data}}$ and $\mathbf{\sigma_{MC}}$ disagreement .

Absorption correction

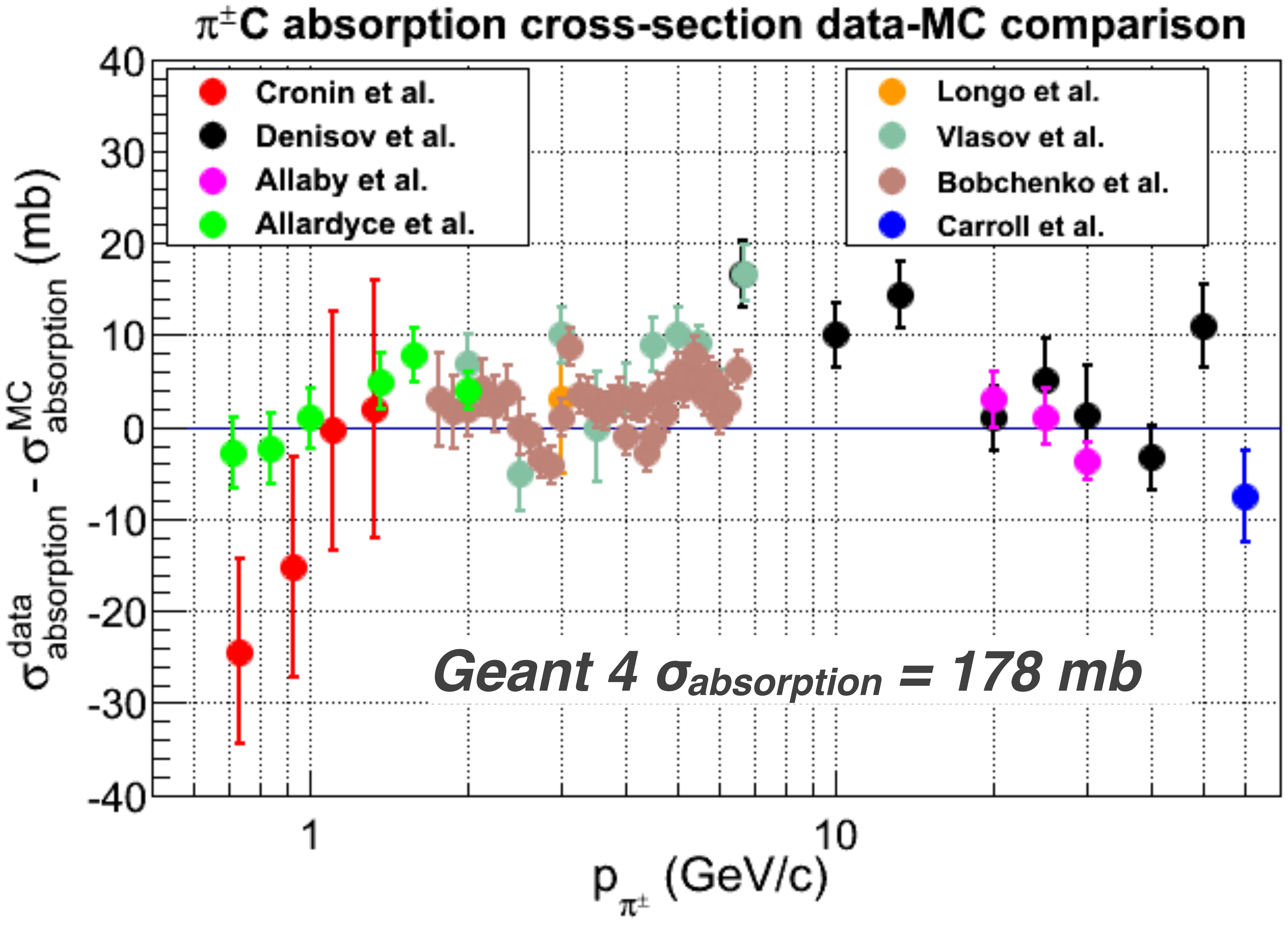
<rN$_A$ρ/A>



» C: 6 mol/cm² ≈ 40 cm

» Al: 1 mol/cm² ≈ 10 cm

» He: 1 mol/cm² ≈ 500 m



» We apply 10 mb uncertainty (~5%)

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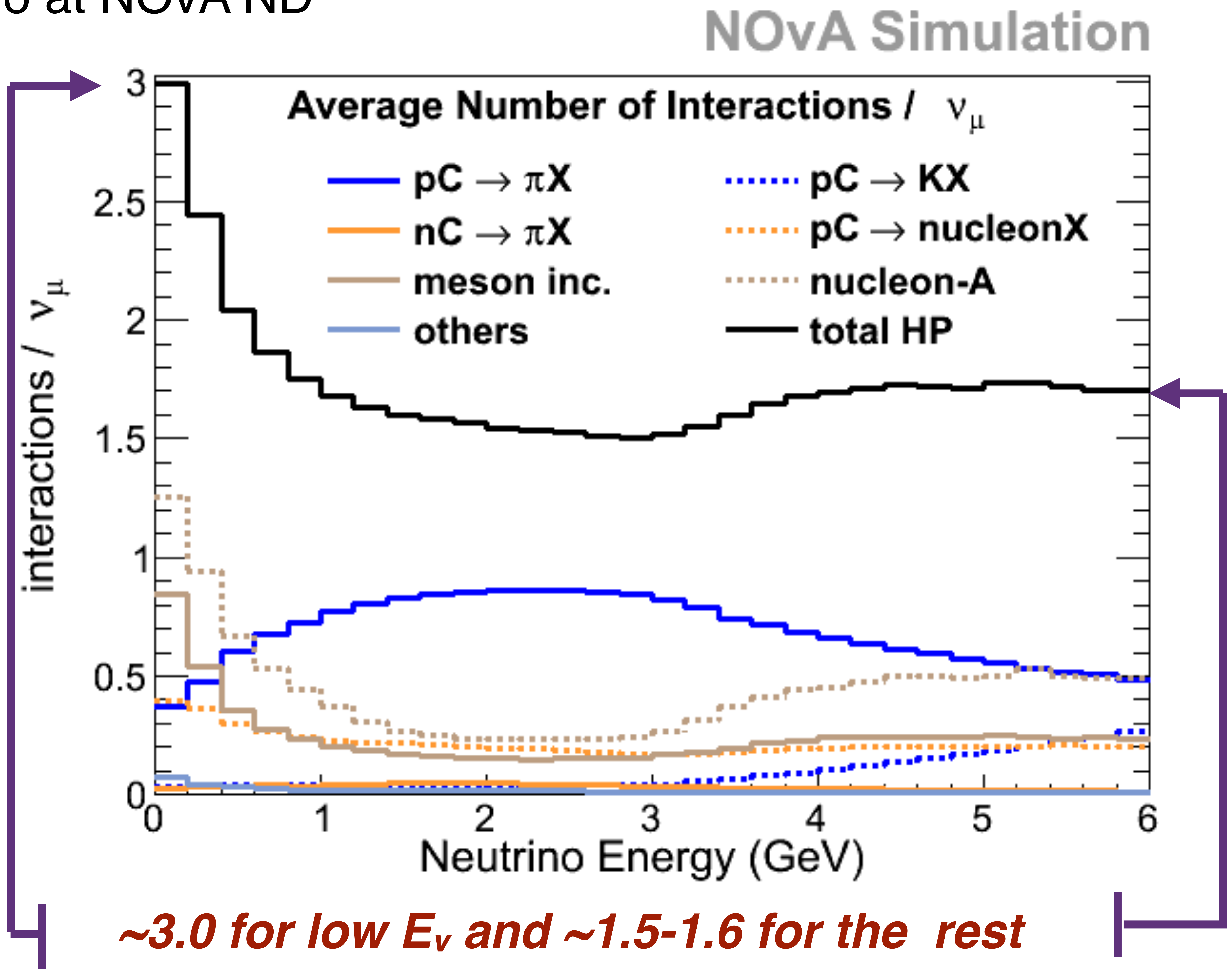
Hadronic interactions

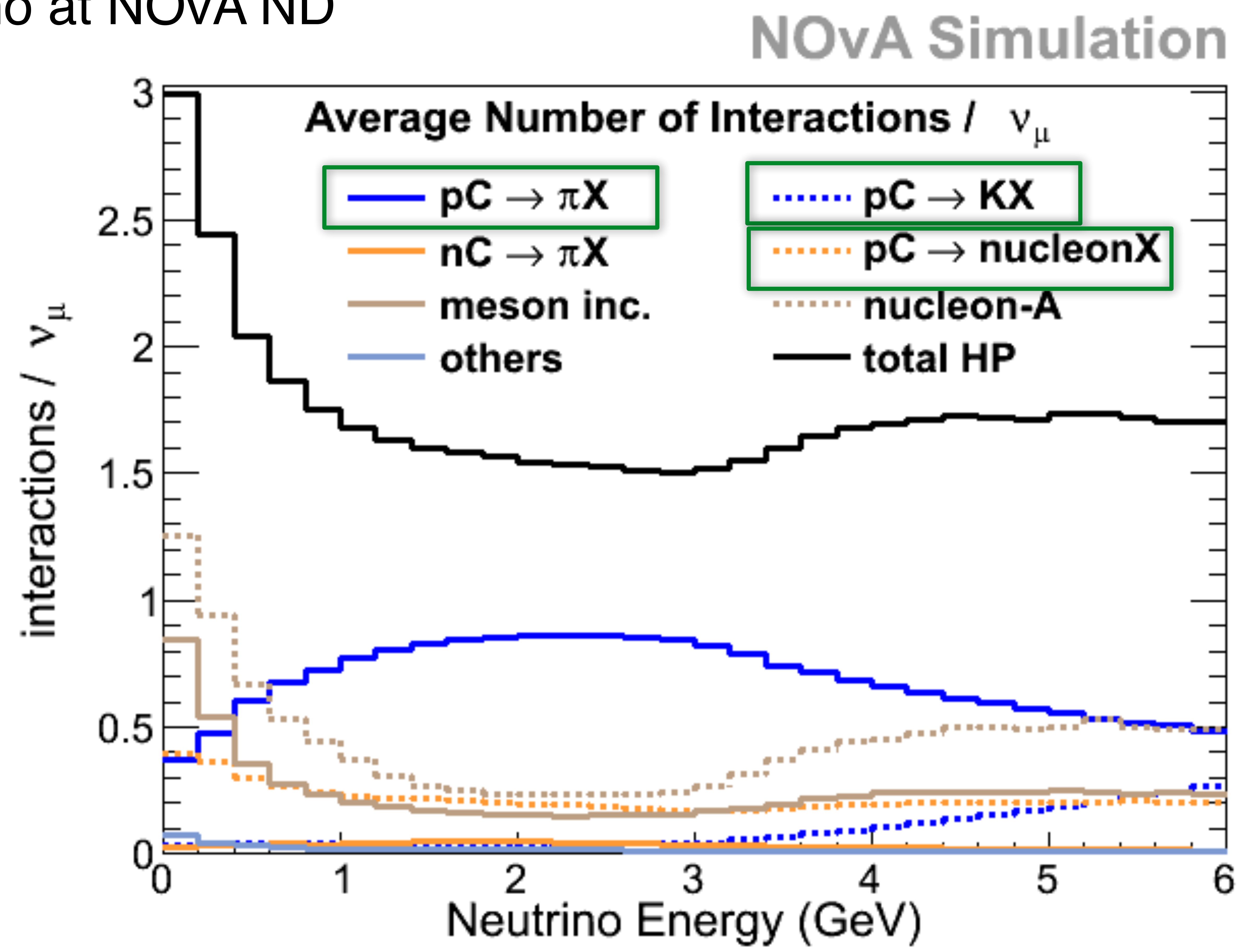
Average number of hadronic interactions per neutrino at NOvA ND



~3.0 for low E_ν and ~1.5-1.6 for the rest

Hadronic interactions

Average number of hadronic interactions per neutrino at NOvA ND



Based directly on data:

» Mostly NA49 proton on carbon producing charged pions, charged kaons, protons, neutrons,

Inclusive production of charged pions in p+C collisions at 158-GeV/c beam momentum

Eur.Phys.J.C 49 (2007) 897-917

Proton making pions

NA49 Data/MC comparison

Statistical:

» Closed circles: statistical error < 2.5%,

» Open circles: statistical error 2.5-5.0%,

» Crosses > 5%

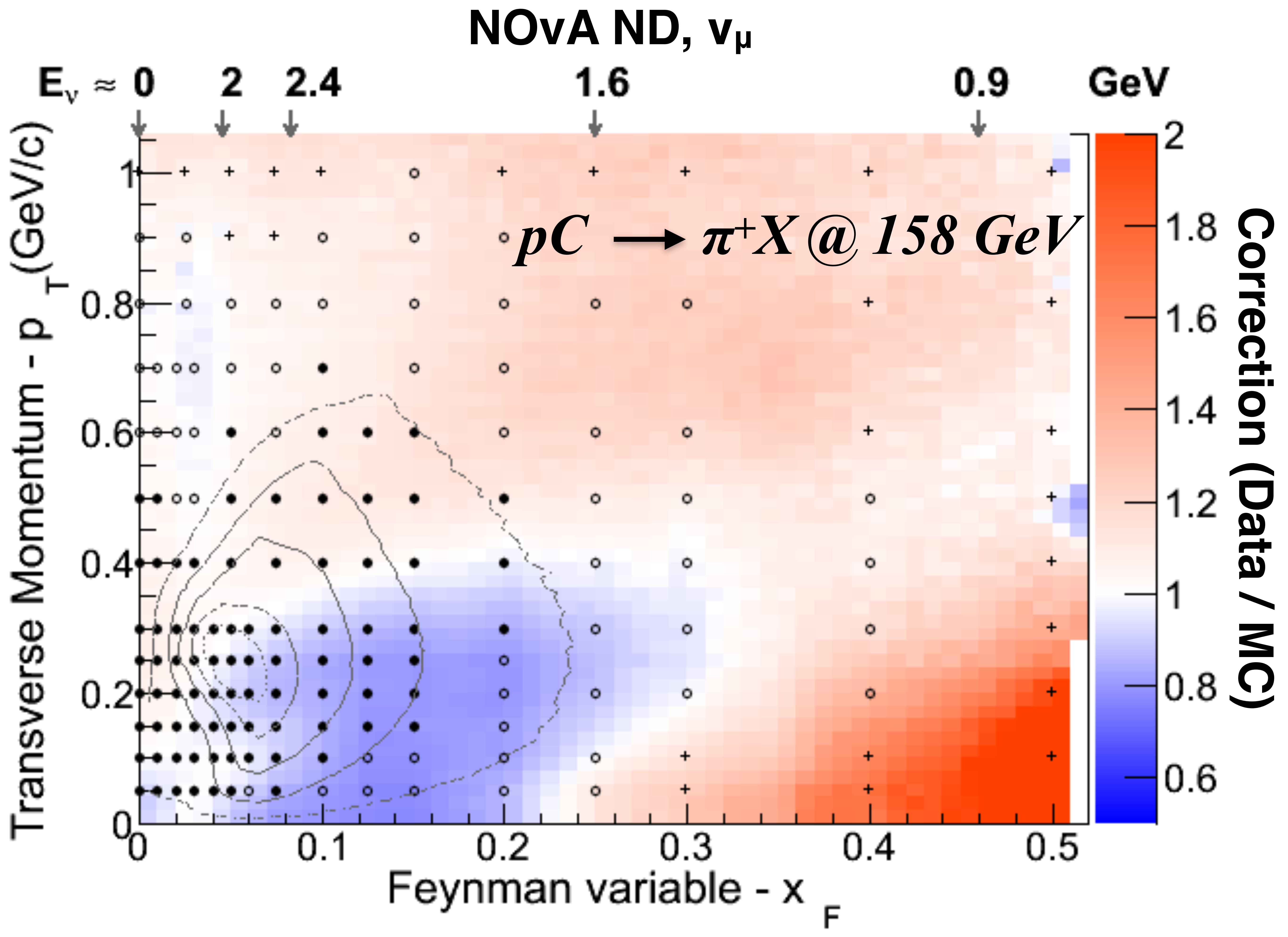
Systematics:

» 3.8% (added in quadrature).

» Highly correlated bin-to-bin (assumed 100%)

Contours:

» 2.5, 10, 25, 50 and 75 % of the π yields.



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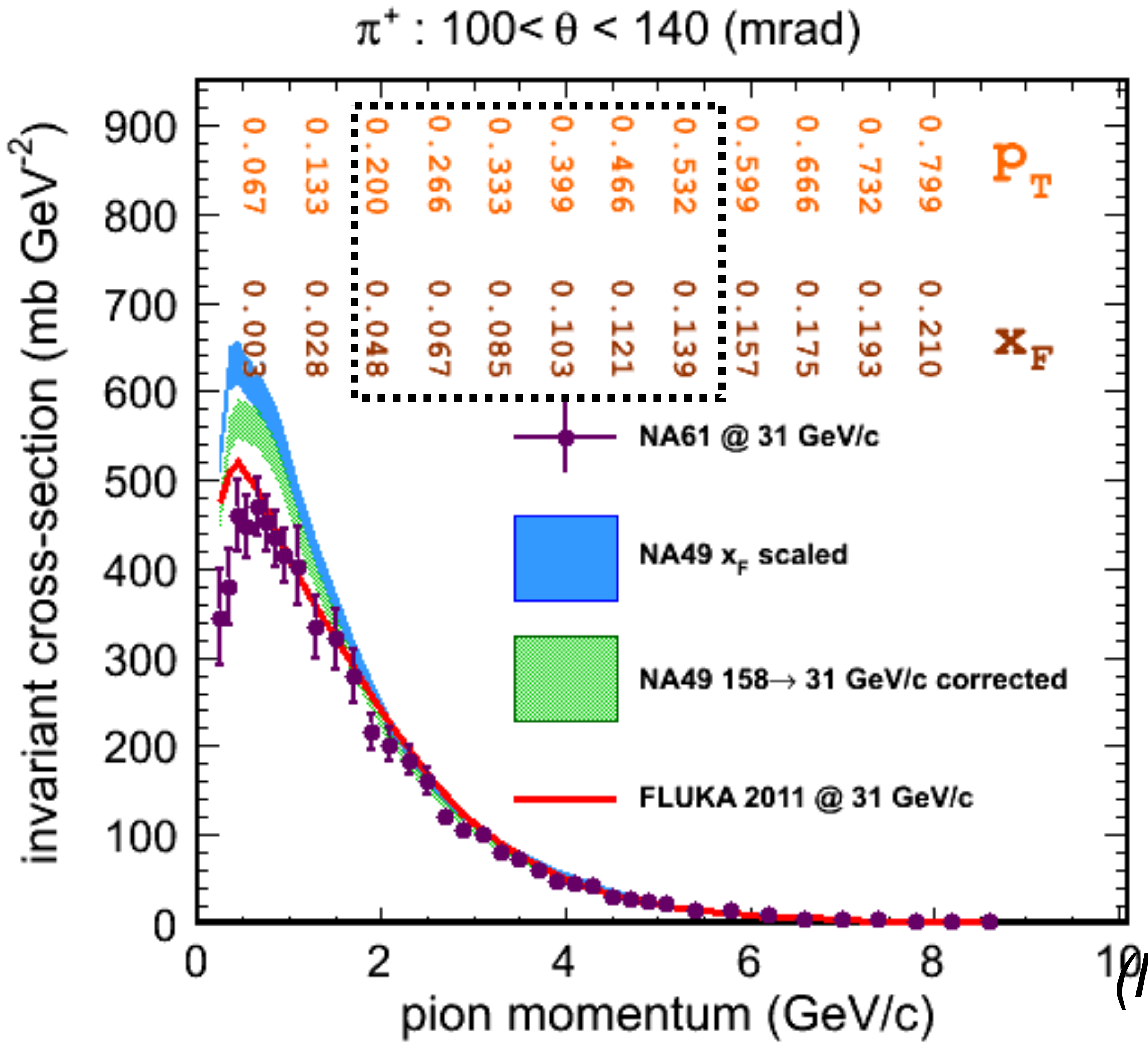
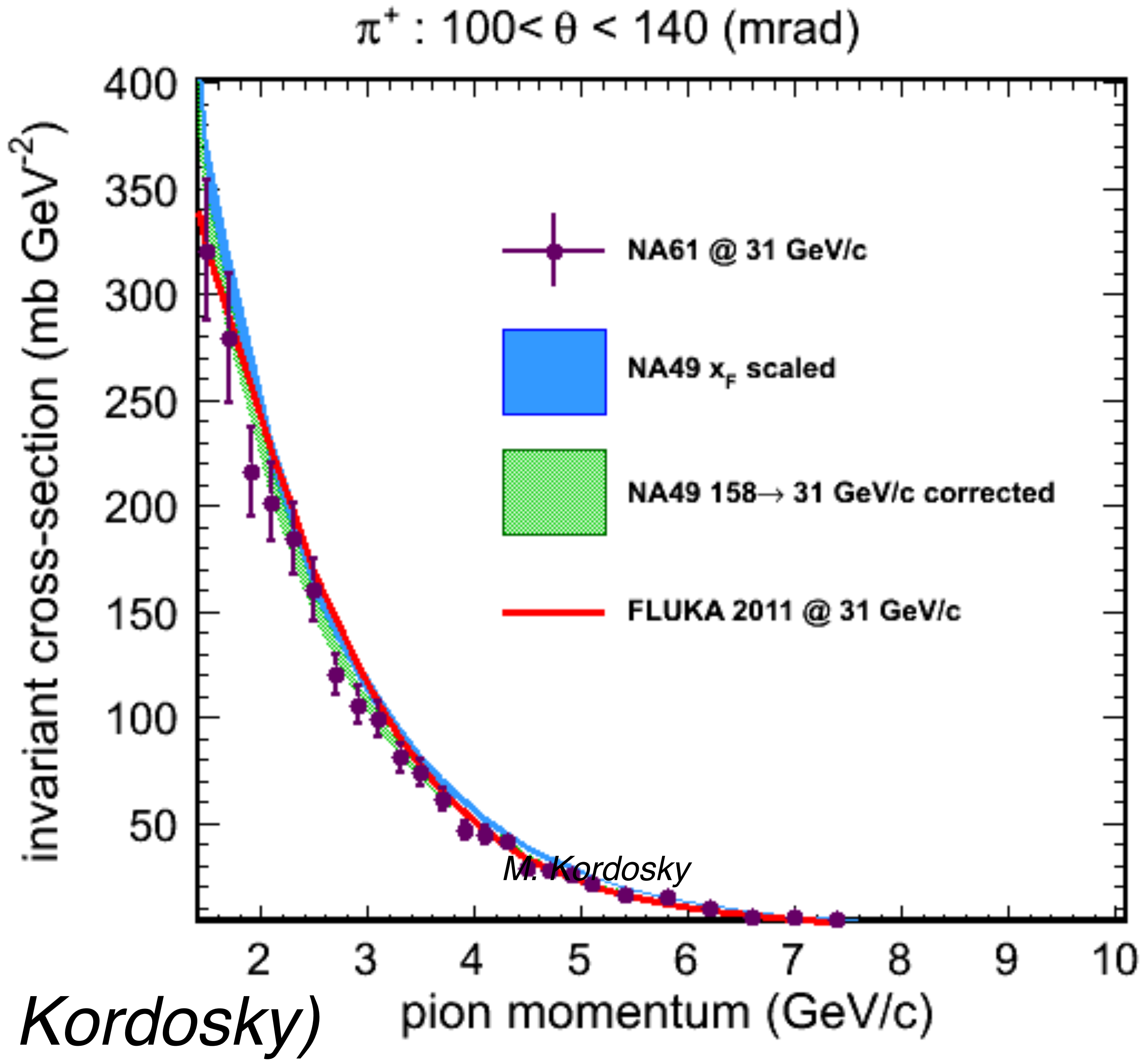
Using NA49 to correction proton - Carbon

$$correction(x_F,p_T,E) = \frac{f_{Data}(x_F,p_T,E=158GeV)\times scale(x_F,p_T,E)}{f_{MC}(x_F,p_T,E)}$$

- We use NA49 for proton-Carbon interactions in 12-120 GeV using Feynman-x scaling
- NA49 (158 GeV/c) and NA61 (31 GeV/c) look in good agreement in our region of interest.
- The violation of the scaling is calculated using FLUKA.





(M. Kordosky)

Nucleon - A

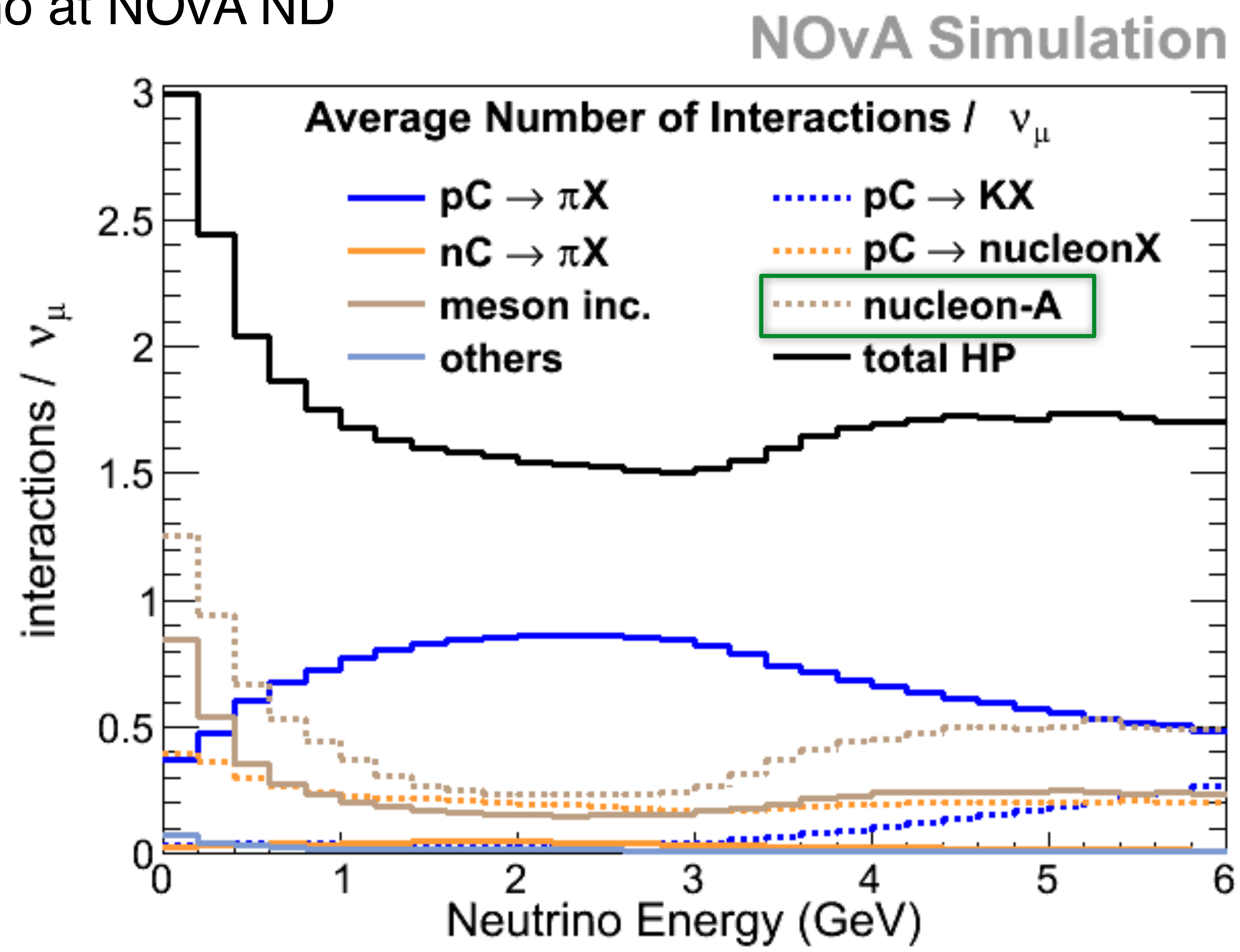
Average number of hadronic interactions per neutrino at NOvA ND

» **Quasi-elastic interactions**, selected as $x_F > 0.95$

- We assign a 40% uncertainty

» **Extension of NA49.**

- We extend NA49 to other materials than carbon adding an additional uncertainty.
- Additional uncertainty is calculated by looking at: K^0 and Λ^0 production at 300 GeV in Skubic and check with Barton at 100 GeV.



Fermilab

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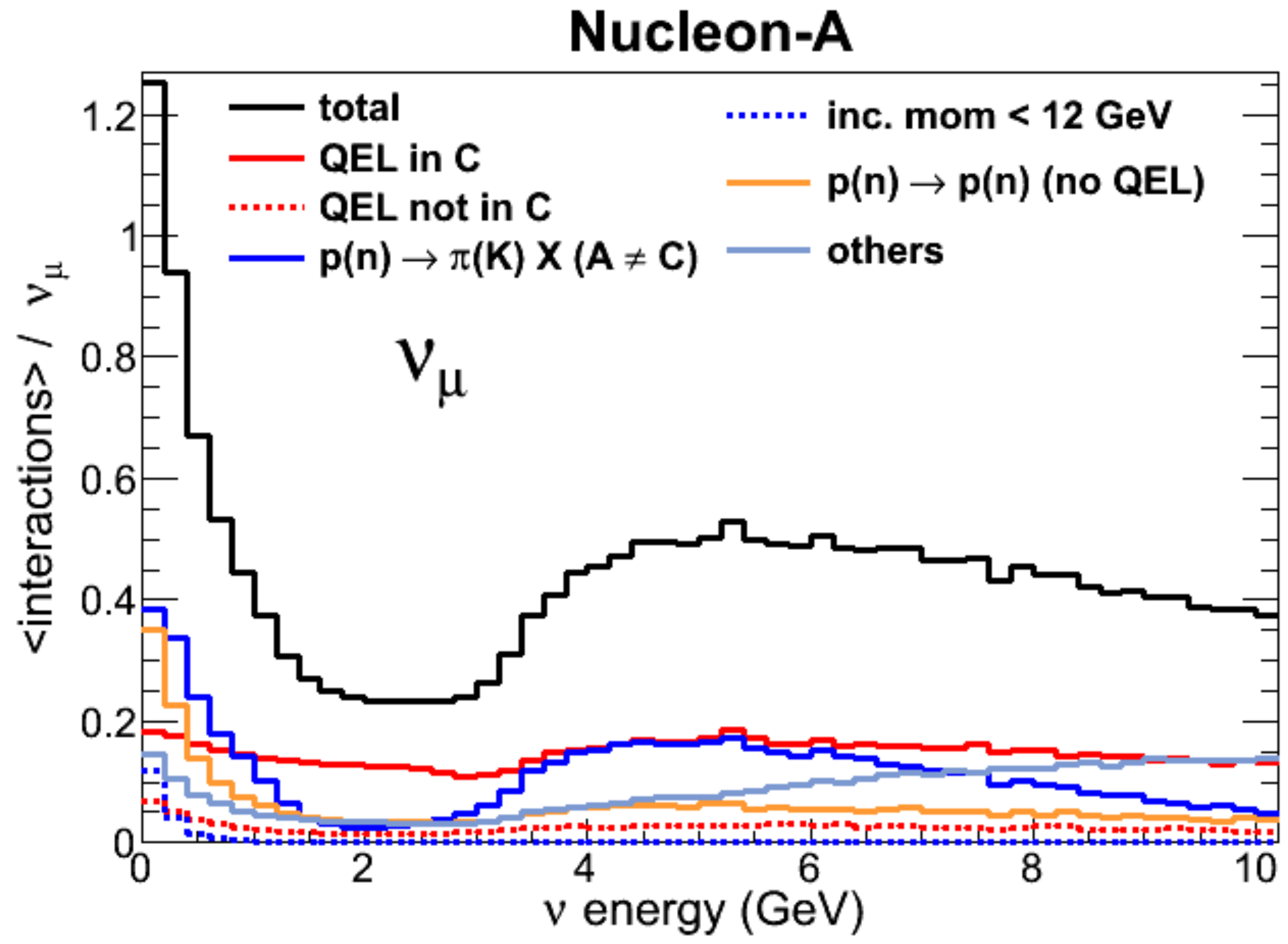

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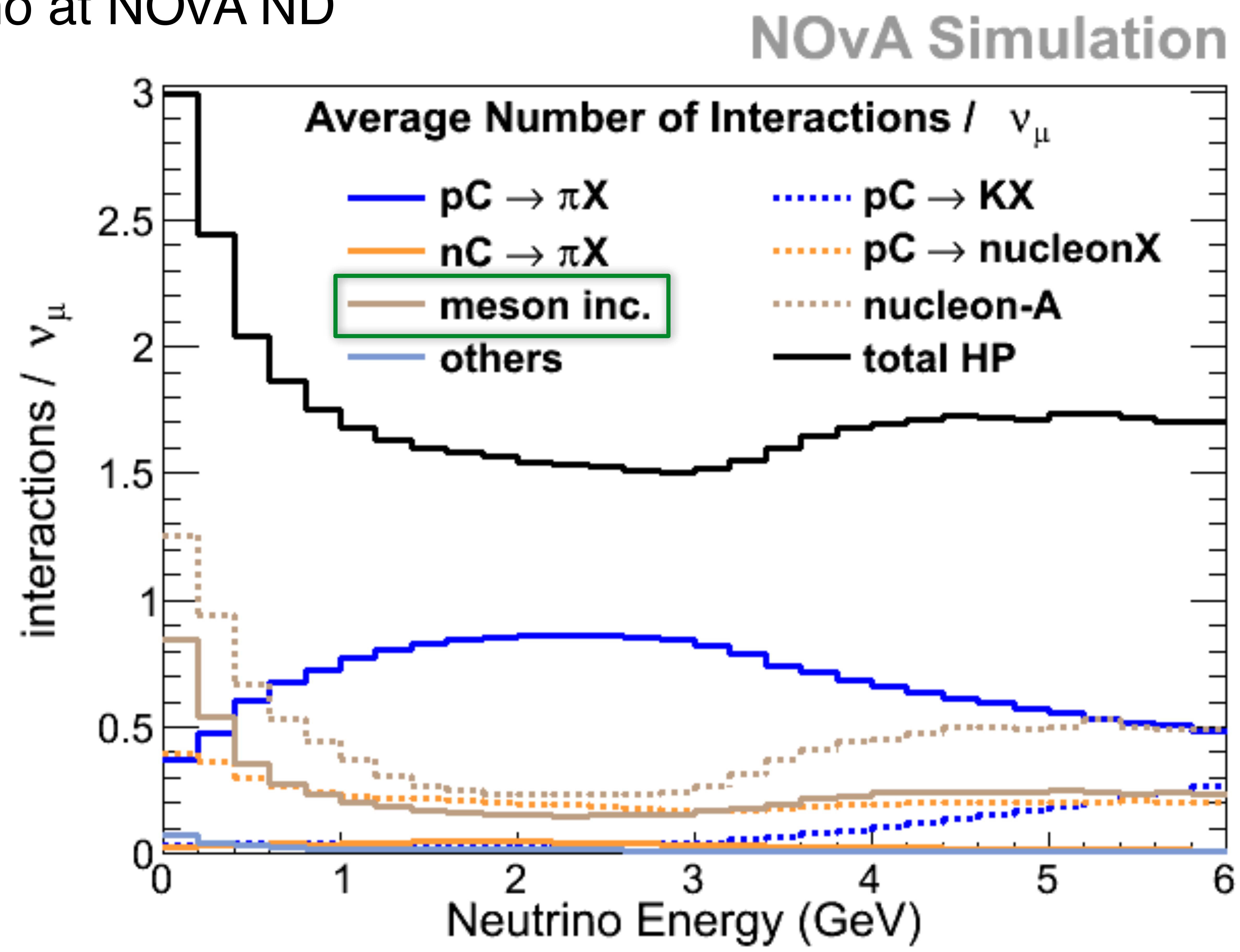
Incident meson

Average number of hadronic interactions per neutrino at NOvA ND

We assume large uncertainties for incident mesons: 40%



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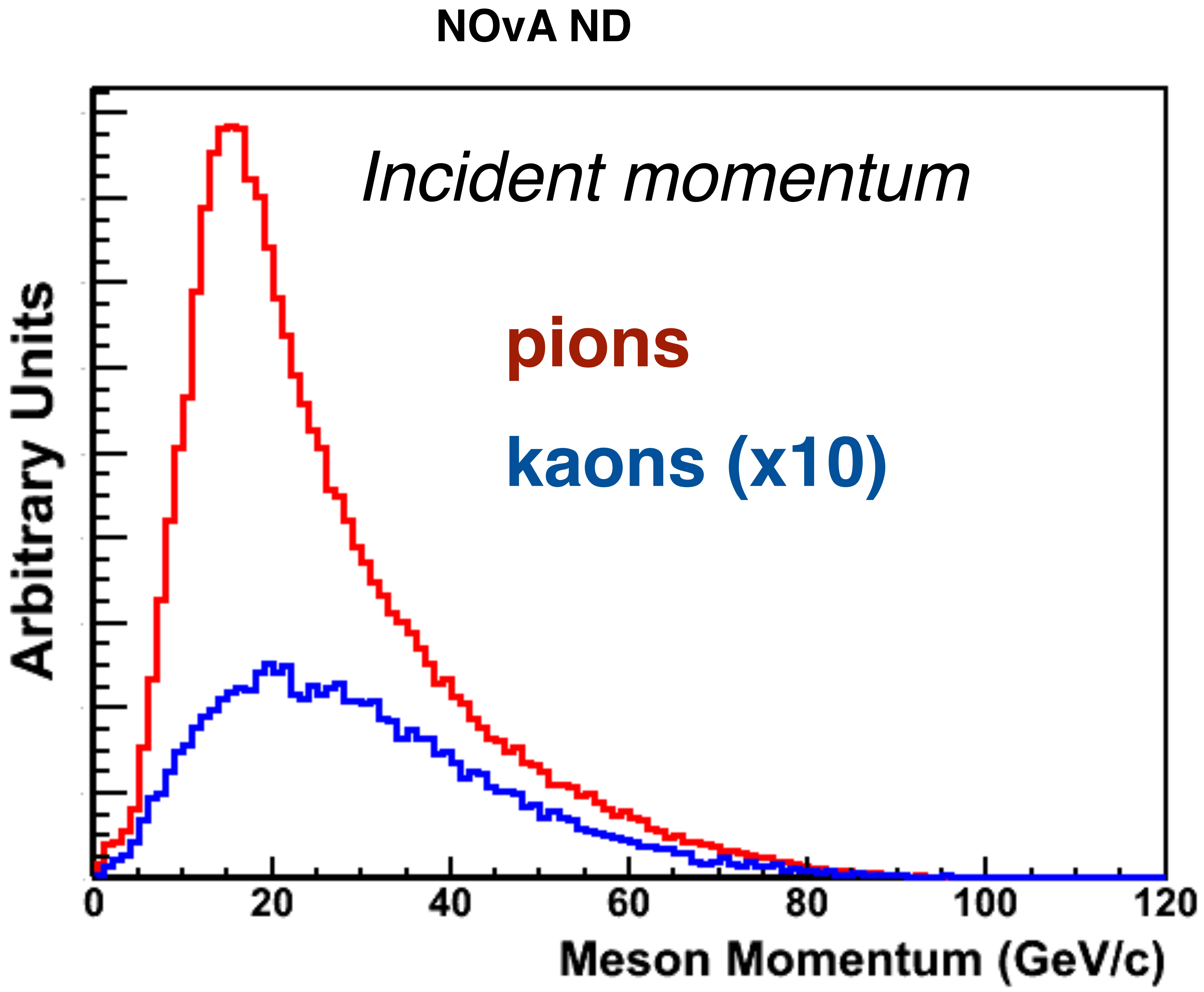
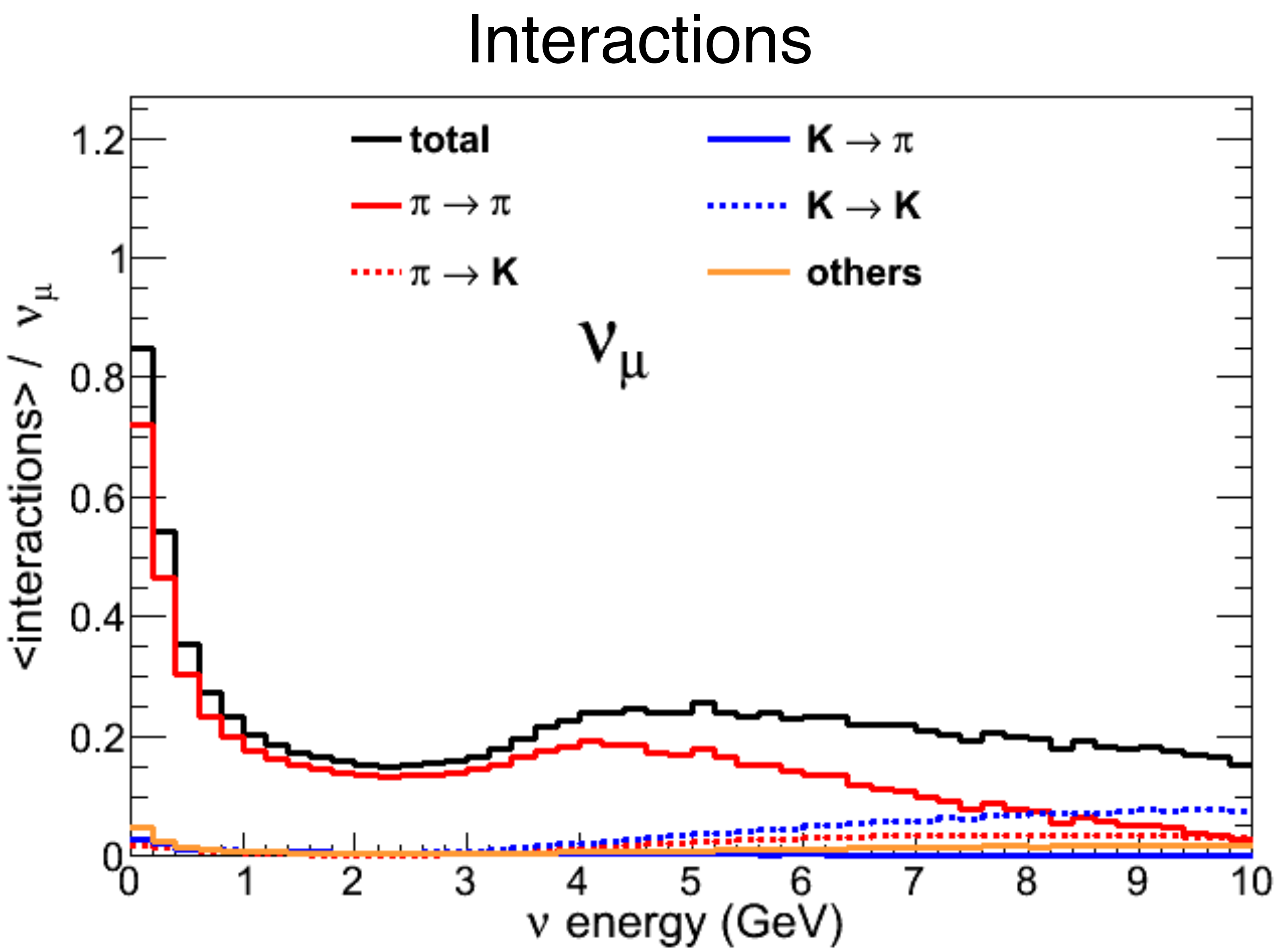
Incident meson





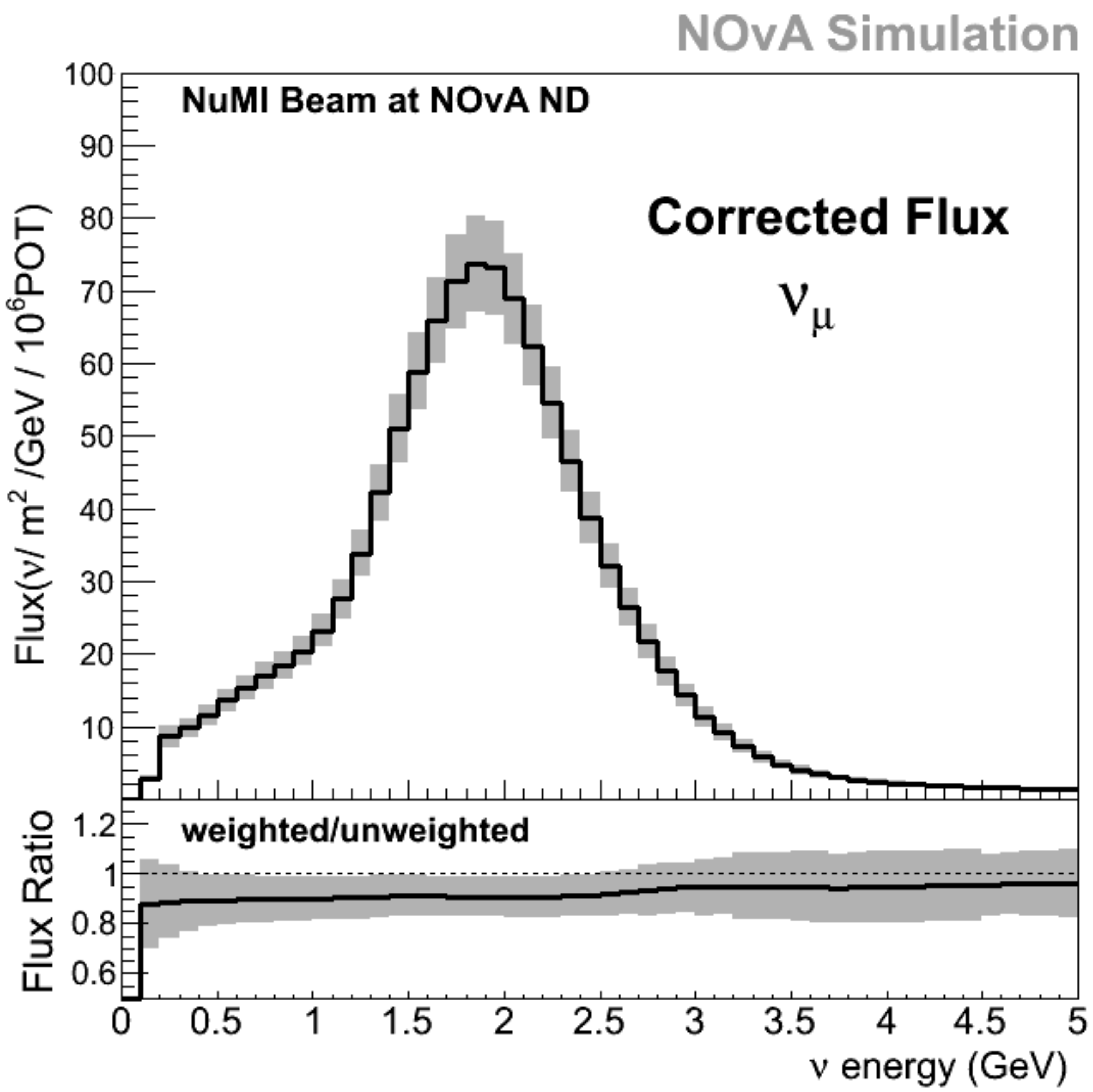
Main contribution from π ⟶ π in the whole neutrino energy spectrum

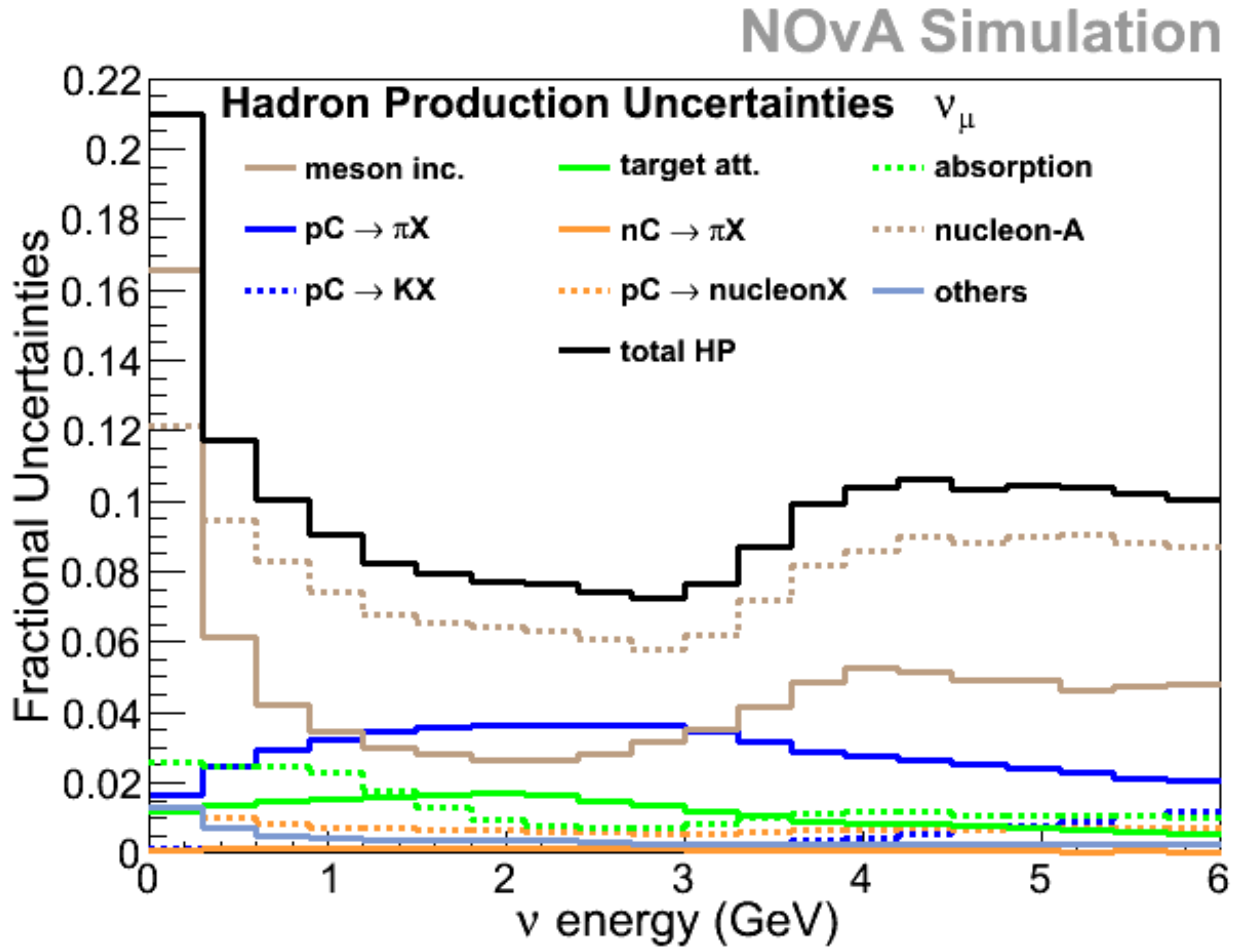
Currently we are working to include the NA61 incident pion on Be and C Phys. Rev. D 100, 112004 (2019)

Fermilab

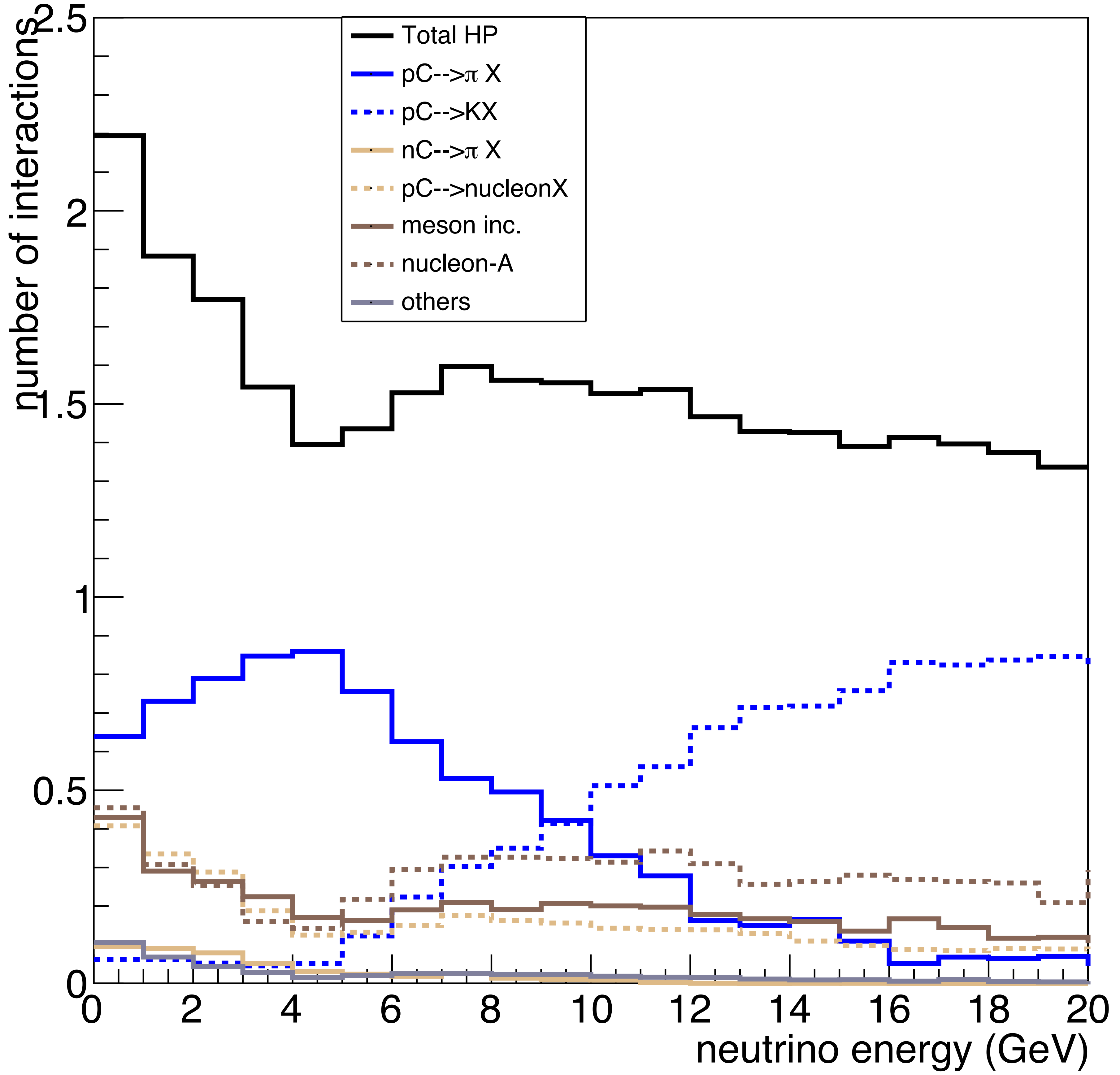
A Priori Flux Results for NOvA Near Detector

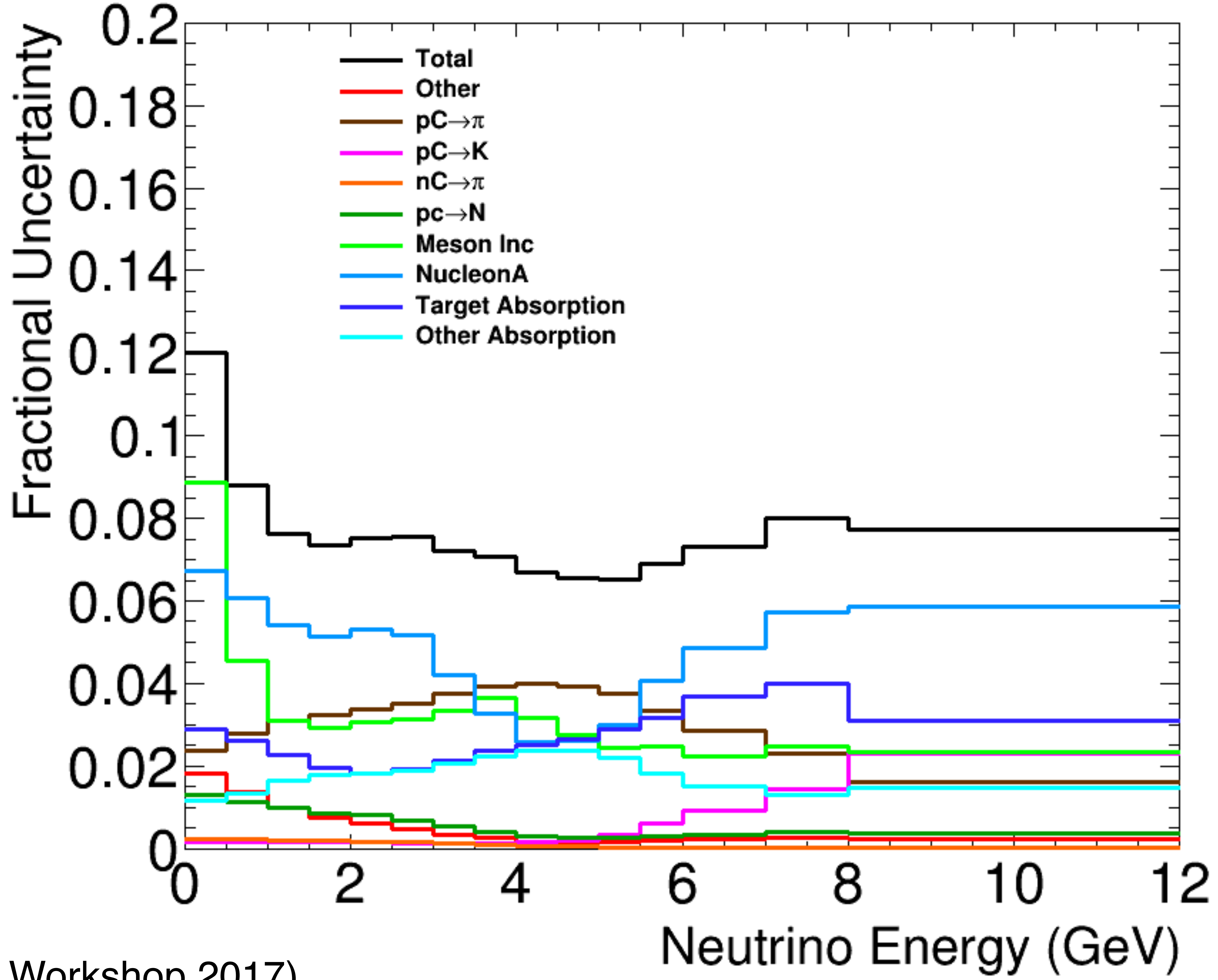
» A fully implemented a priori flux prediction in NOvA





A Priori Flux Results for DUNE Near Detector





L. Fields (NA61 Workshop 2017)

Summary

Summary

» Fermilab long baseline neutrino experiments, such as MINERvA, NOvA and DUNE use external hadron production data to predict the flux in their detectors. A common framework has been pioneer by MNERvA that allows to extend to the upcoming new data

» For interactions where we use HP data, the uncertainty associated to those interactions is relatively small. For instance, NA49 pion production: ~4% .

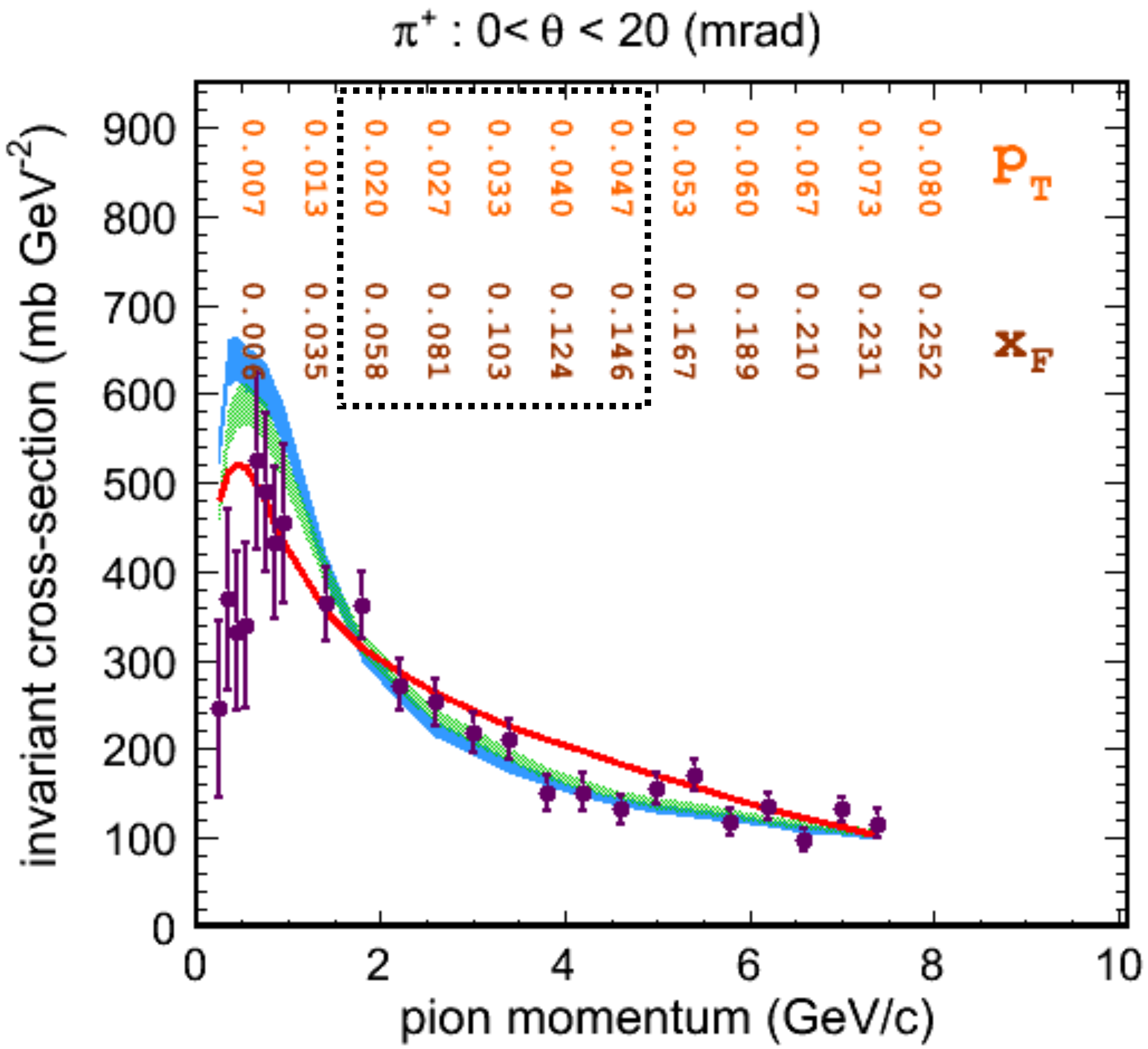
» New data is valuable (and crucial) for our physics program:

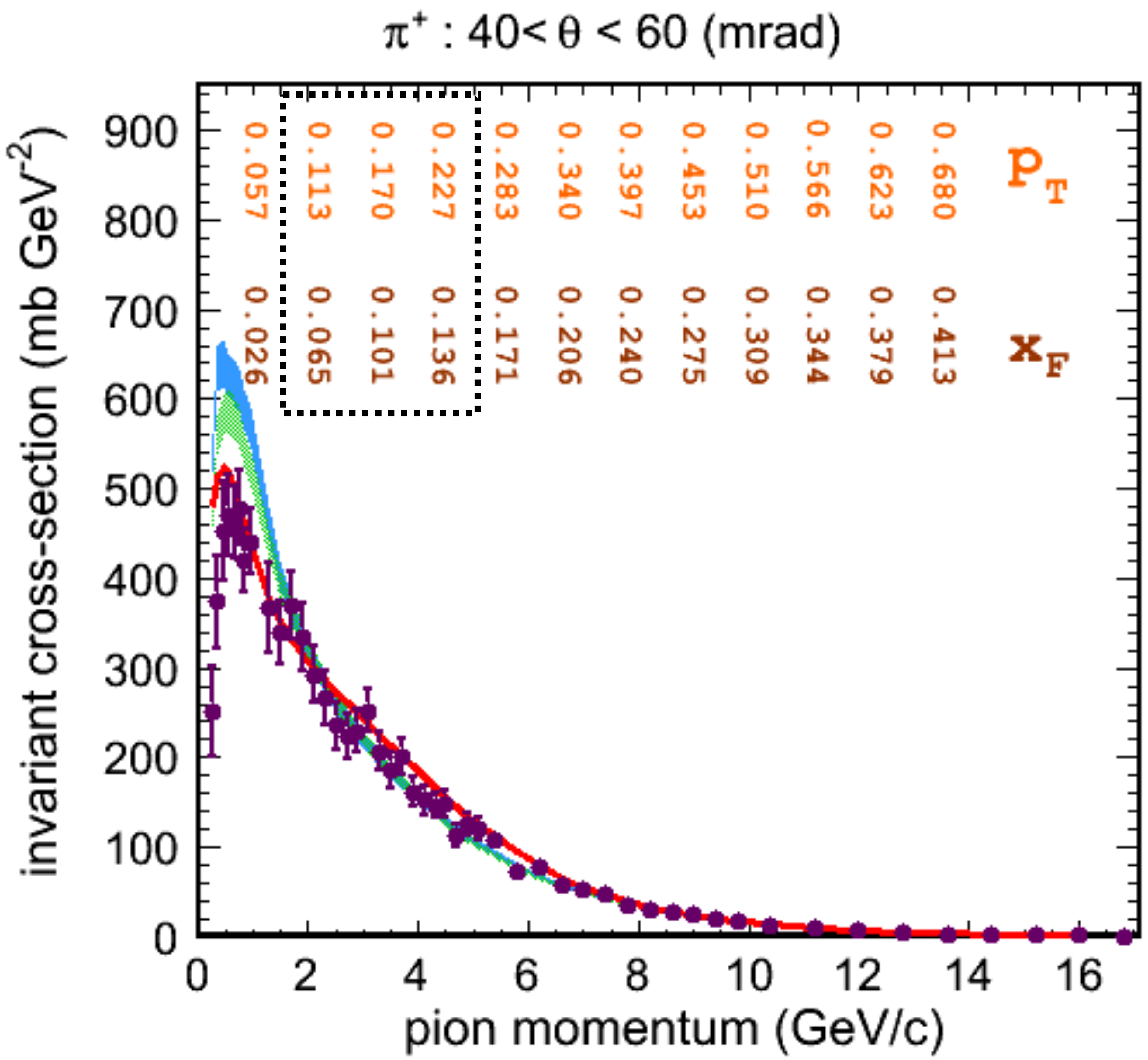
- The flux simulation is the starting point of the simulation chain for all analysis.
- The impact on the single detector analysis (such as cross section measurements) is direct

» New data will be incorporate in our framework to be used for the Fermilab long baseline experiments.

Backup

NA49 vs NA61


π+ : 0< θ < 20 (mrad)
invariant cross-section (mb GeV-2)
pion momentum (GeV/c)
pT
0.007 0.013 0.020 0.027 0.033 0.040 0.047 0.053 0.060 0.067 0.073 0.080
xF
0.035 0.058 0.081 0.103 0.124 0.146 0.167 0.189 0.210 0.231 0.252


π+ : 40< θ < 60 (mrad)
invariant cross-section (mb GeV-2)
pion momentum (GeV/c)
pT
0.057 0.113 0.170 0.227 0.283 0.340 0.397 0.453 0.510 0.566 0.623 0.680
xF
0.026 0.065 0.101 0.136 0.171 0.206 0.240 0.275 0.309 0.344 0.379 0.413