How to predict the Neutrino Flux

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Neutrino Seminar Series
October 31, 2019

Goal of this talk

This seminar would like to be a discussion about flux **prediction and hadron production uncertainties.**

My focused will be on **NuMI**, with the eyes on **DUNE**.

- Are we understand everything to predict the beam with reasonable uncertainties?
- How far can we go to constrain the flux with existing data?
- What type of new experiments we should prioritize to constraint the flux for DUNE.

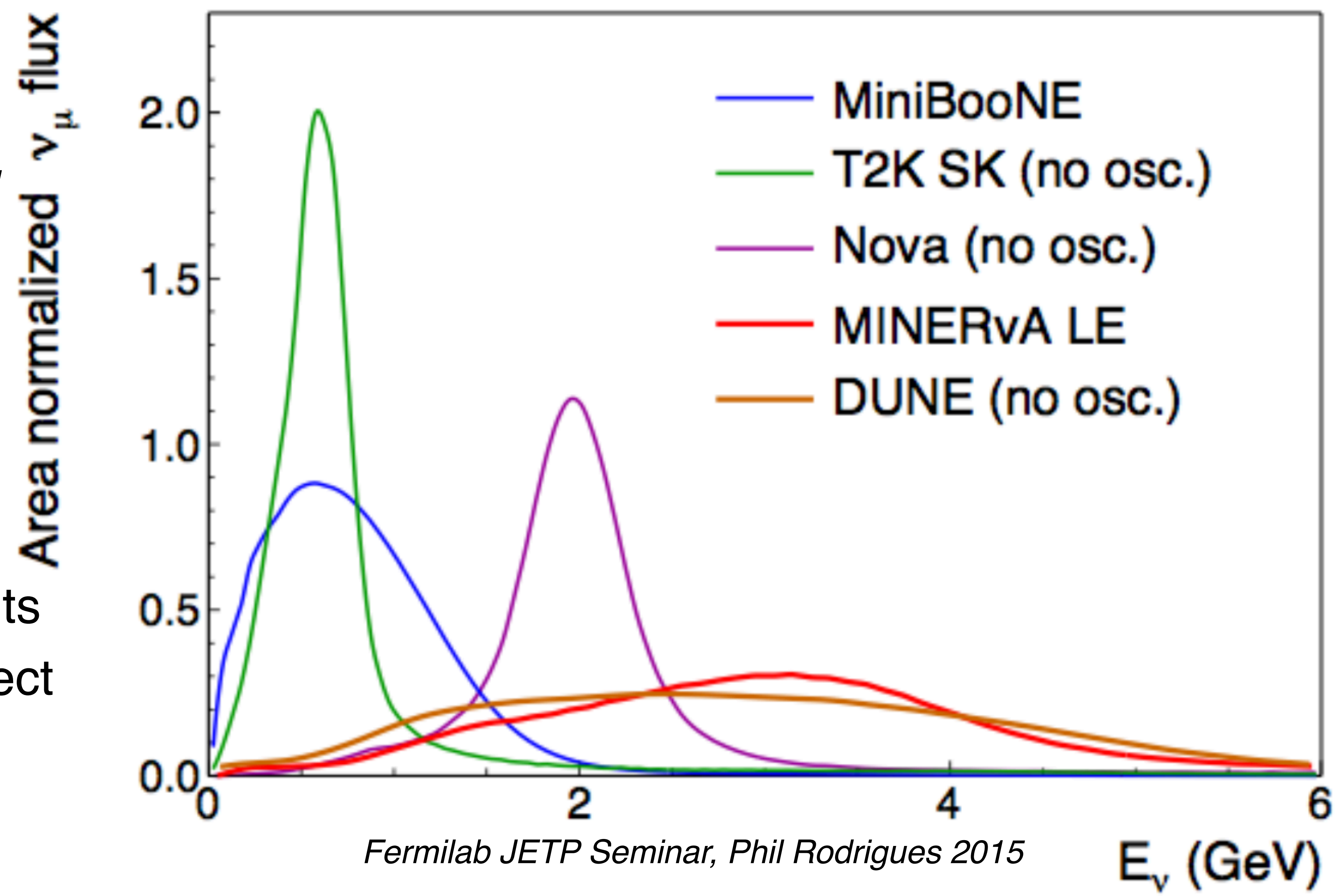
Challenges

- **Flux is not given:**

It is not monocromatic, wide-band and the shape and normalization are not determined.

- **Geometrical model:**

Simulation of the main components beam line. Allows study of the effect of focusing systematics.



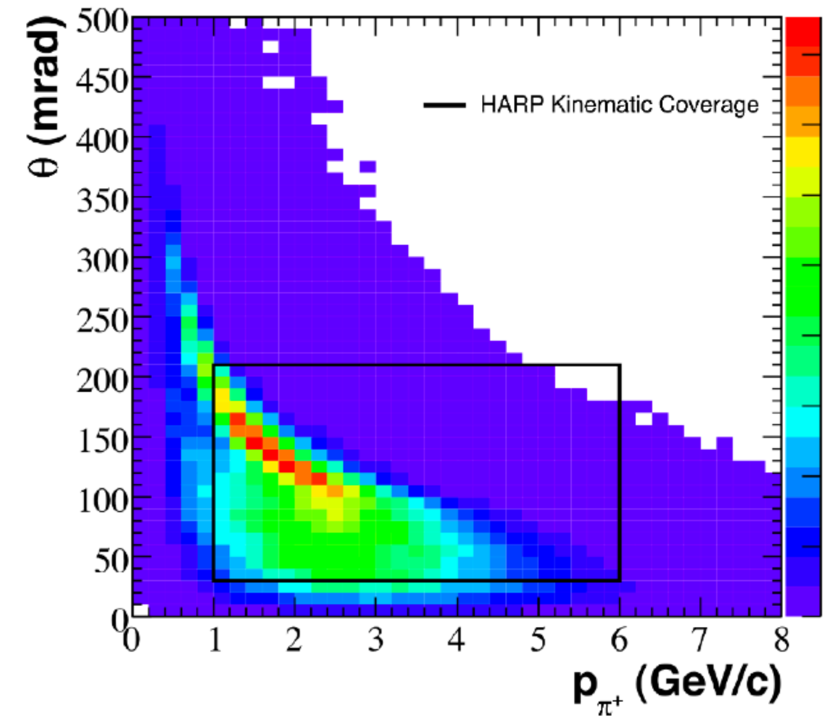
Fermilab JETP Seminar, Phil Rodrigues 2015

- **Hadron Production (HP):**

Physics behind the interactions in the hadronic cascade that follows the primary proton beam until the meson decay neutrino is not complete.

Strategies

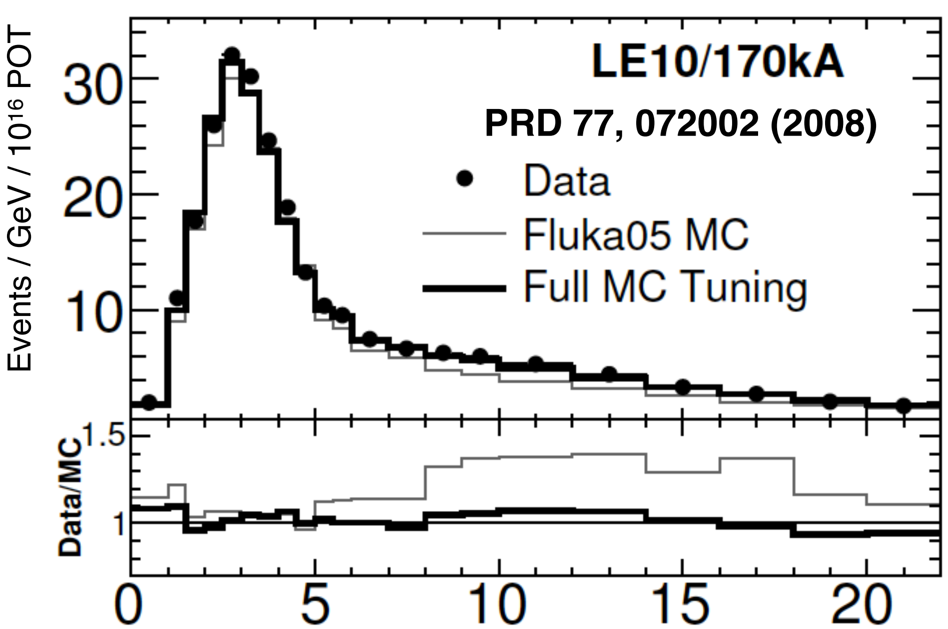
Eur. Phys. J. C 52, 29 (2007).



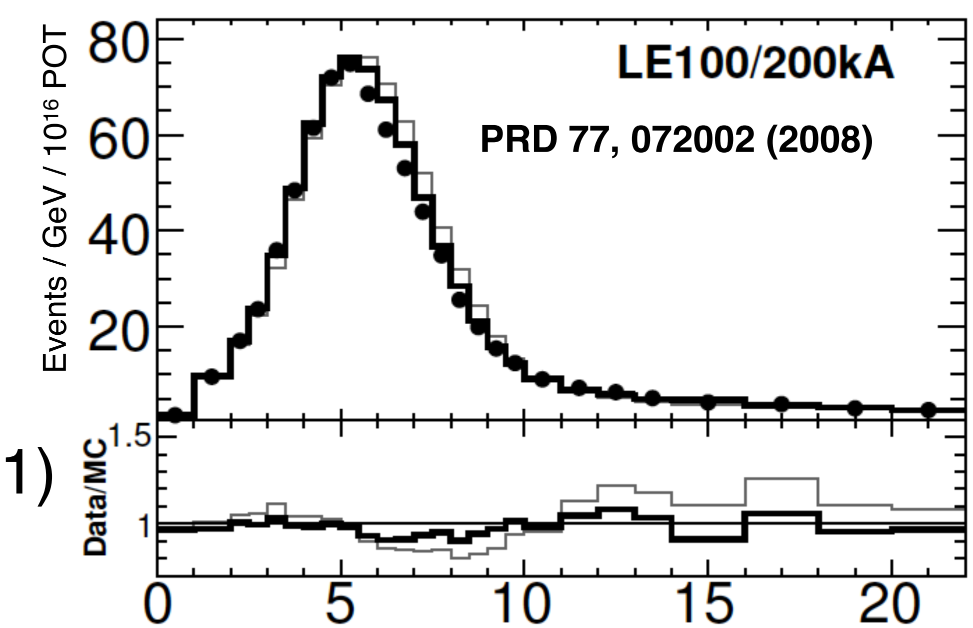
HP: to apply a constraint to the hadron production in the cascade that leads to a neutrino in the beam line simulation

Need to use dedicated HP experiment.
Example: Plot show π^+ produced on proton on Be (target) interactions (**black box is HARP coverage**).

Multi-beam fit: use data measured in the detector with different beam configuration: position of target, horn current, etc: **decouple hadron production and focusing system.**



It uses a parametrized HP out-of-target (BMPT, Eur.Phys.J.C20:13-27,2001)

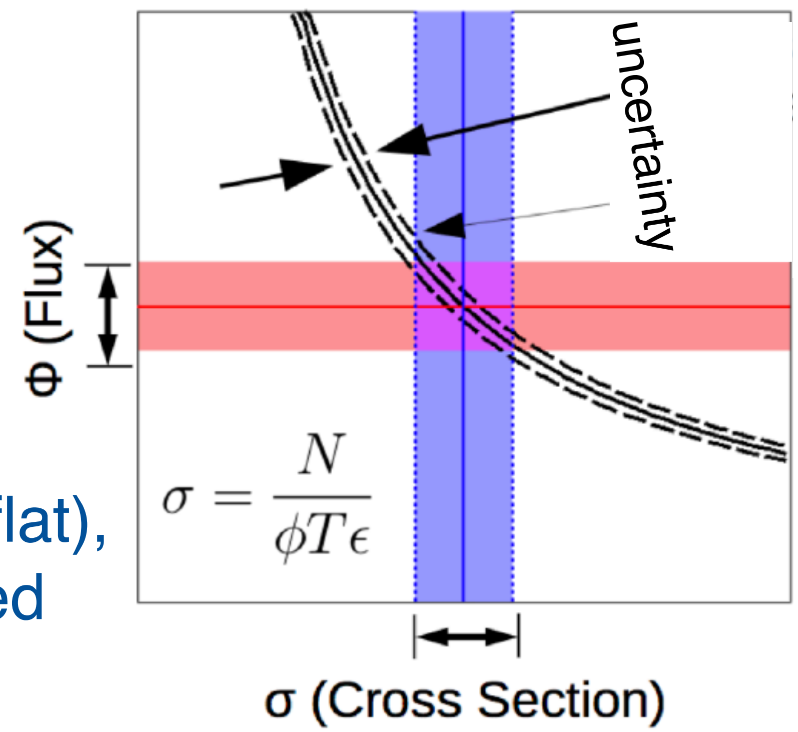


Strategies

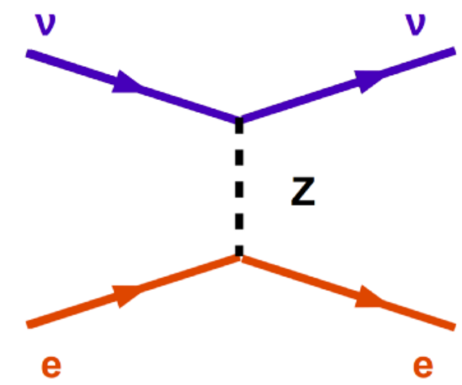
Standard candles

Low-nu: ν_μ ($\overline{\nu_\mu}$) - CC scattering events with low energy transfer to the target

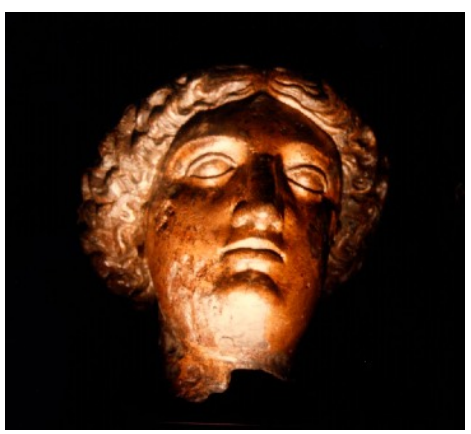
Cross-section shape is known (flat), then flux shape can be calculated



ν on e scattering events:



Cross-section is known: use as a normalization calculation



MINERvA approach

Determined a-priori flux based on correcting the physics model with external HP data.

- **On top on that, use in-situ measurements:**

  Low-nu: to check the consistency with the observed data.

  ν on e: to apply an additional constraint.

SBN HP (HARP)

PHYSICAL REVIEW D **79**, 072002 (2009)

Neutrino flux prediction at MiniBooNE

T2K HP (NA61)

PHYSICAL REVIEW D **87**, 012001 (2013)

T2K neutrino flux prediction

MINOS

PHYSICAL REVIEW D **77**, 072002 (2008)

Study of muon neutrino disappearance using the Fermilab Main Injector neutrino beam

Multi-beam fitting

PHYSICAL REVIEW D **81**, 072002 (2010)

Neutrino and antineutrino inclusive charged-current cross section measurements with the MINOS near detector

Low-nu

MINERvA

PHYSICAL REVIEW D **94**, 092005 (2016)

Neutrino flux predictions for the NuMI beam

HP (NA49 and MIPP)

PHYSICAL REVIEW D **93**, 112007 (2016)

Measurement of neutrino flux from neutrino-electron elastic scattering

nu-on-electron

PHYSICAL REVIEW D **94**, 112007 (2016)

Measurements of the inclusive neutrino and antineutrino charged current cross sections in MINERvA using the low-ν flux method

Low-nu

Constraint of the MINERvA Medium Energy Neutrino Flux using Neutrino-Electron Elastic Scattering

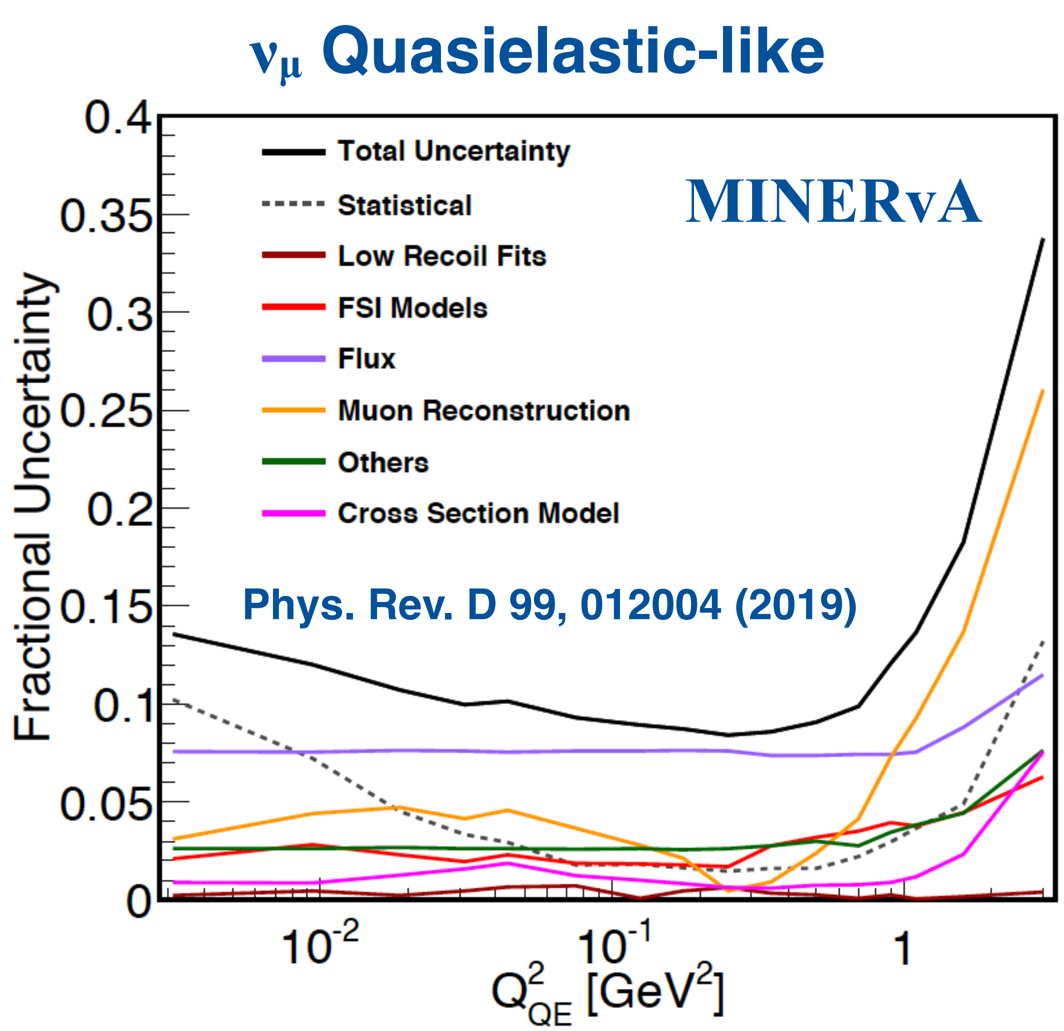
arXiv:1906.00111 [hep-ex]

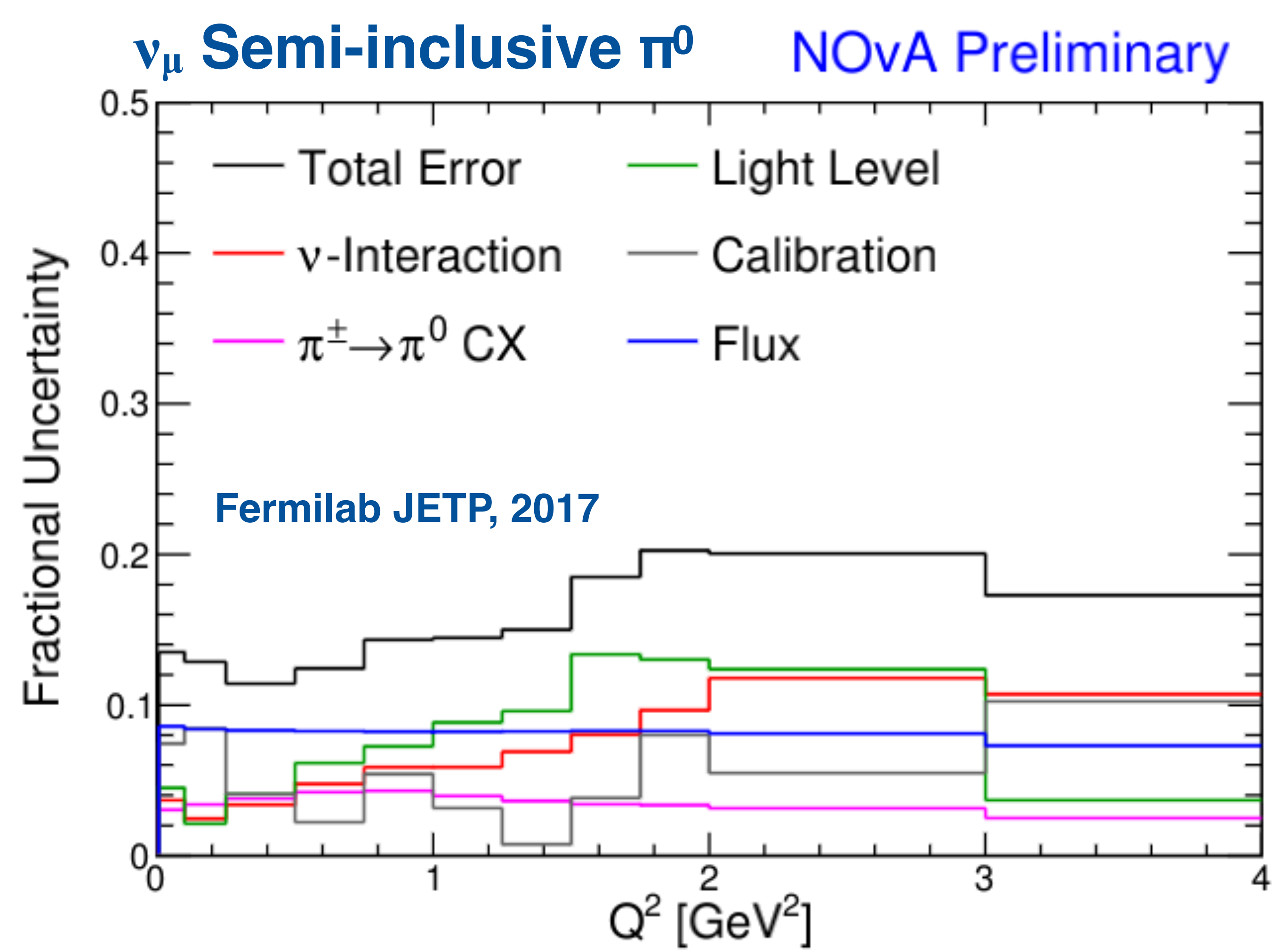
Low-nu

Why is predicting the neutrino flux important?

- The beam systematics enters into the ND measurements: signal, background, purity, etc.
- Flux central value is the starting point of the cross-section tune before extrapolation.
- Flux uncertainty enters directly into the cross-section measurement

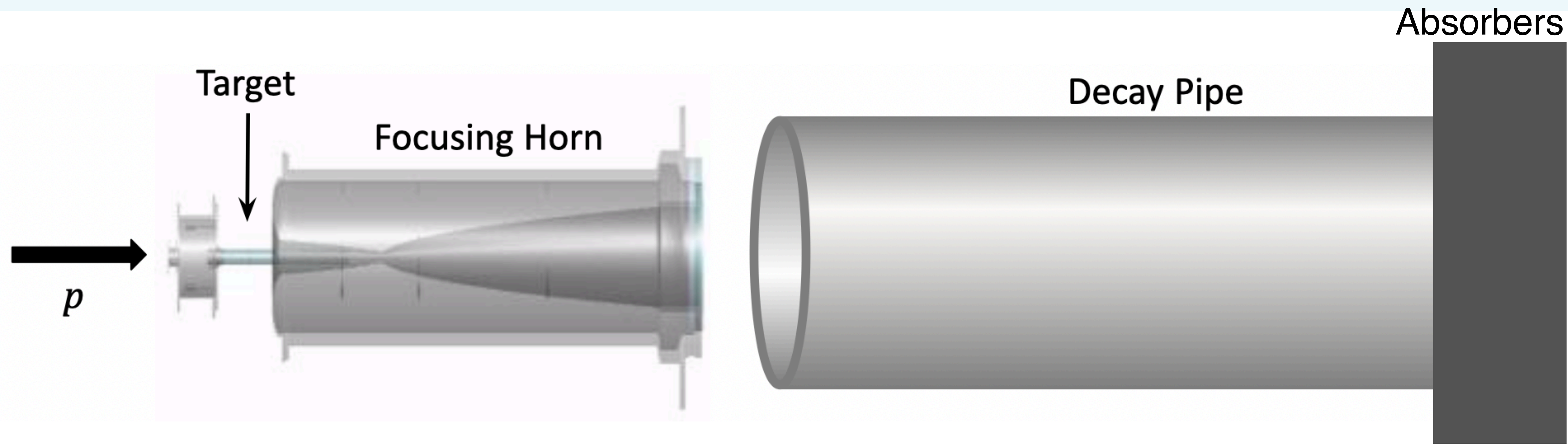
$$\sigma = \frac{N}{\phi T \epsilon}$$





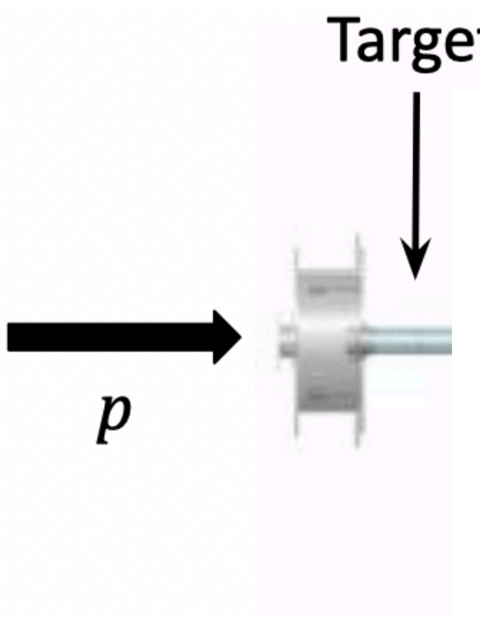
How to make a conventional neutrino beam

Recipe for a Conventional Neutrino Beam

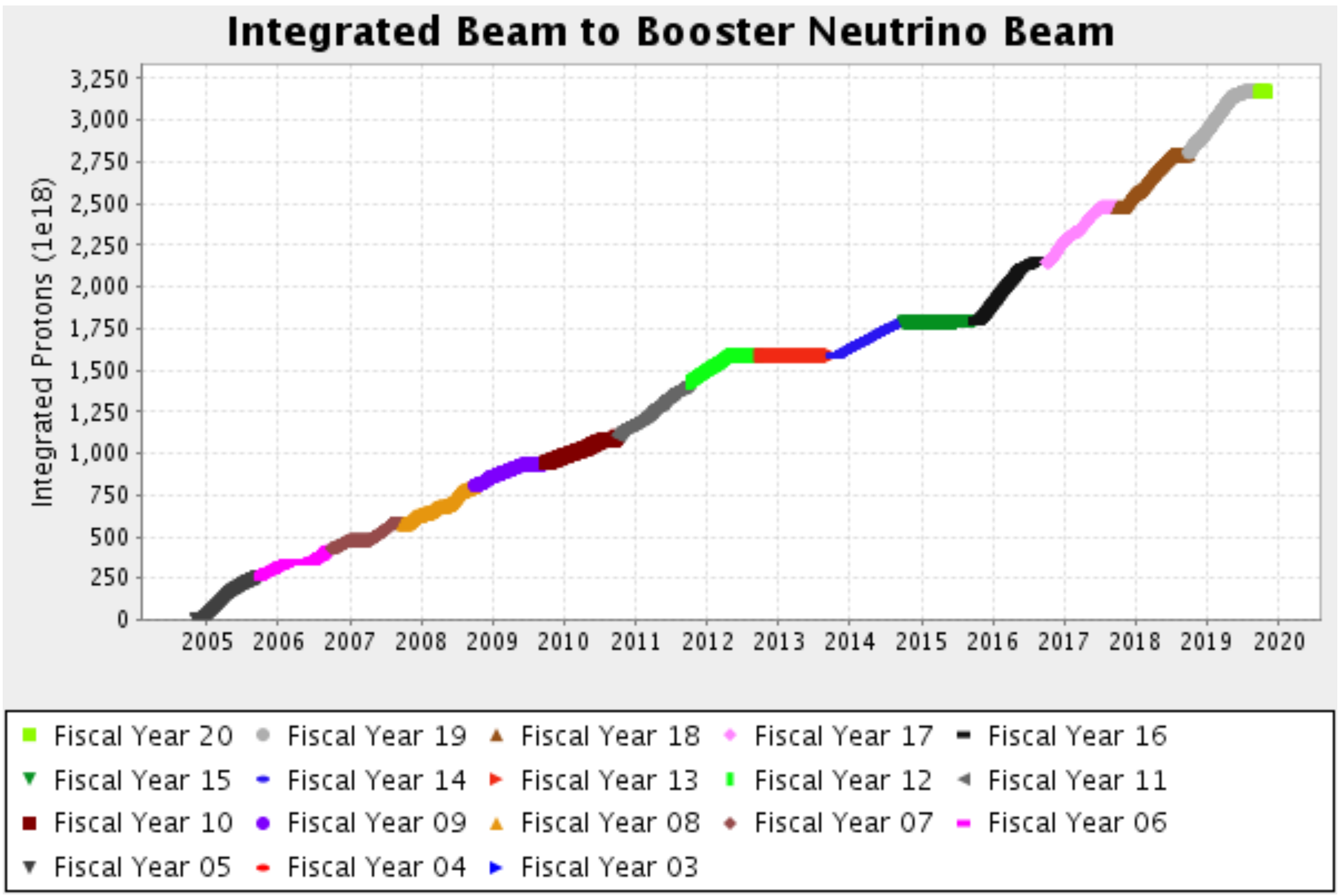


- A very intense proton beam from an accelerator striking a target.
- A production of short-lived particles like π's and K's.
- A system to focus π's and K's before they decay.
- An extended volume for the π's and K's decay.
- Absorbers for the remaining hadrons.

Recipe: Protons On Target

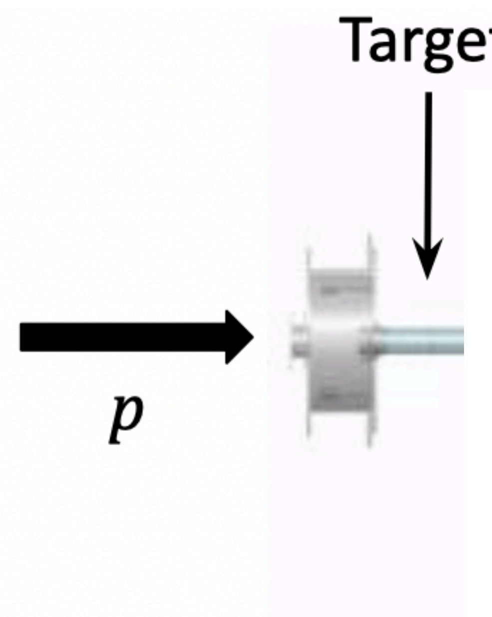


- Higher proton energy then, higher pion energy, then higher neutrino energy
- More particles on target, then more pions, then more neutrinos.



https://www-bd.fnal.gov/FixedTargetPlots/today/ProtonPlots.html

Recipe: Protons On Target



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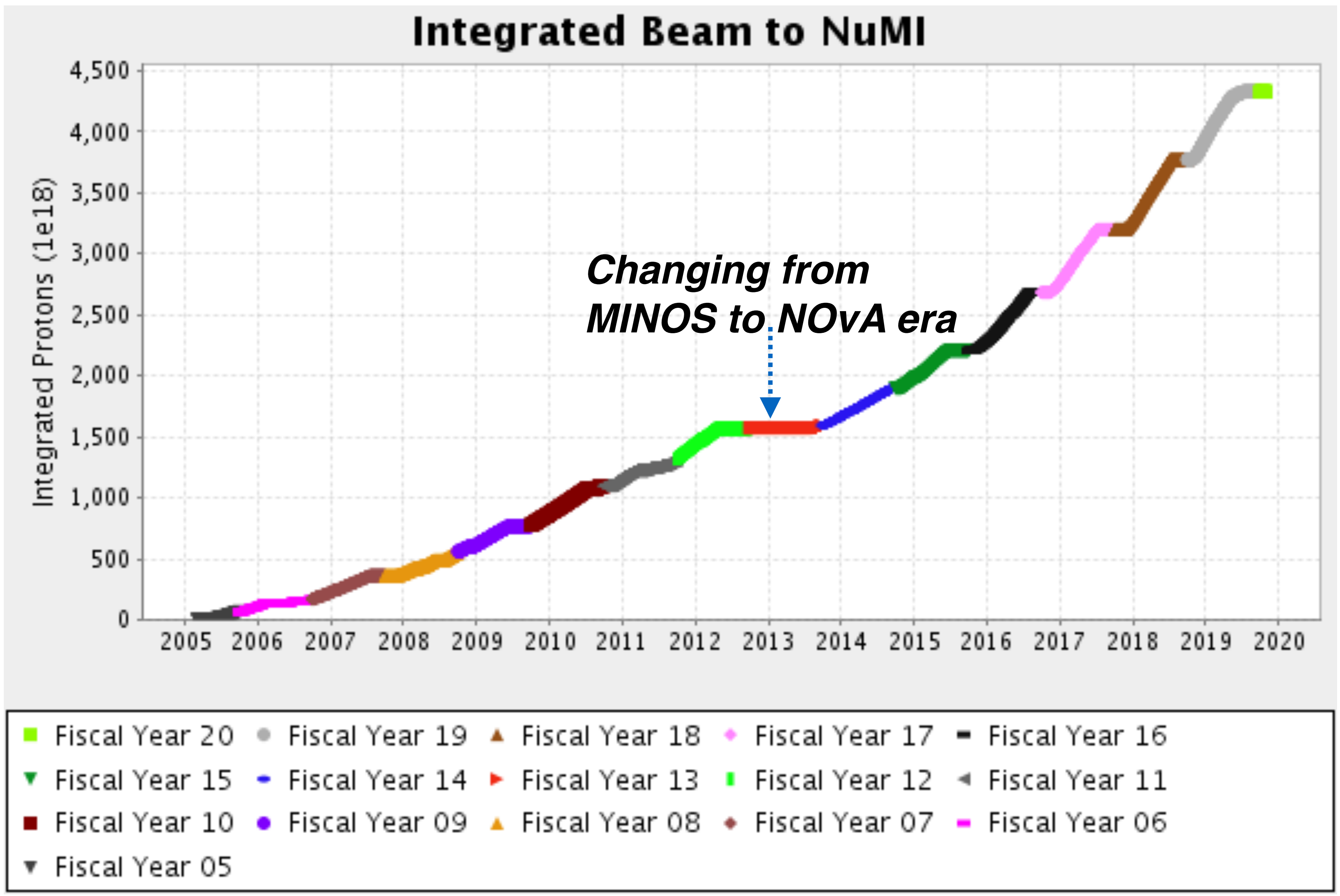
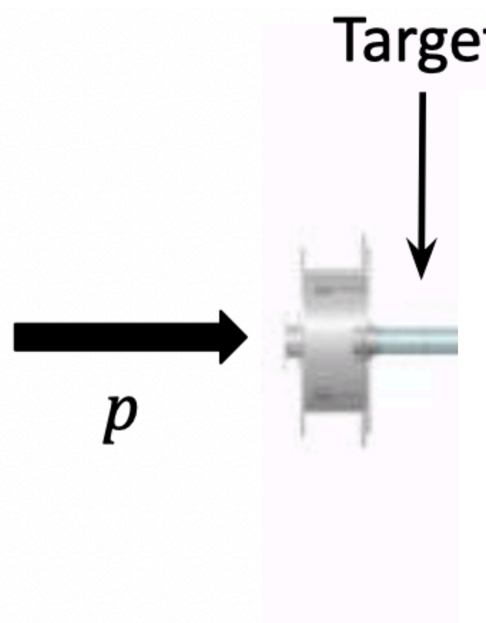


https://www-bd.fnal.gov/FixedTargetPlots/today/ProtonPlots.html

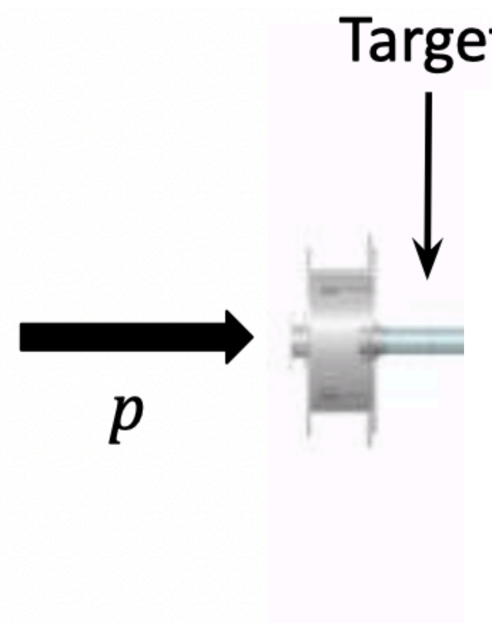
Recipe: Target



	Material	Shape	Length (cm)	Size (mm)
SBN	Be	cylinder	71	10
MINOS	Graphite	ruler	96	6.4x15
NOvA	Graphite	ruler	120	7.4x63
T2K	Graphite	cylinder	90	12-15
DUNE	Graphite	cylinder	150-200	2.67

- Longer the target, higher probability to interact.
- More protons interact, hotter the target gets.
- Segmentation design allows energy dissipation.
- Target N times wider the size of the beam.

Recipe: Target



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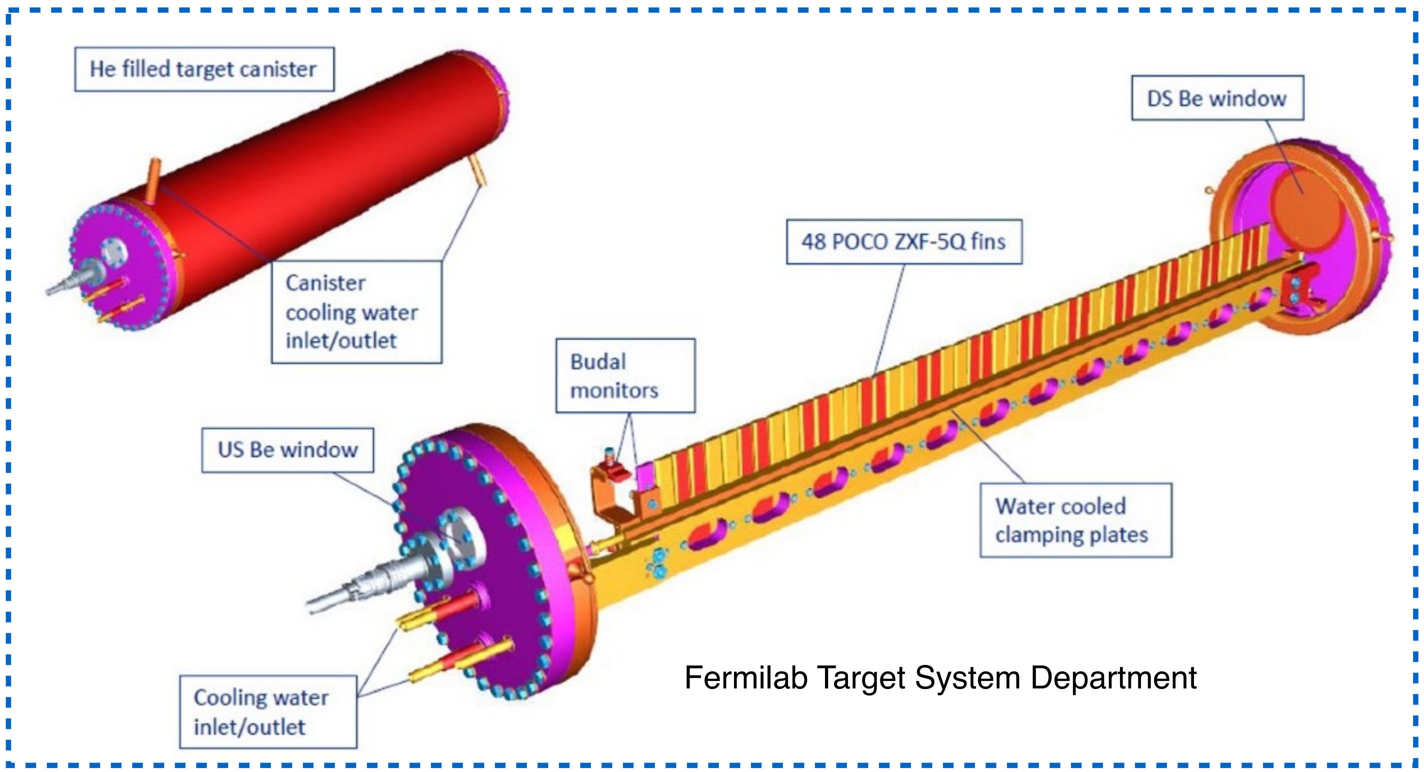
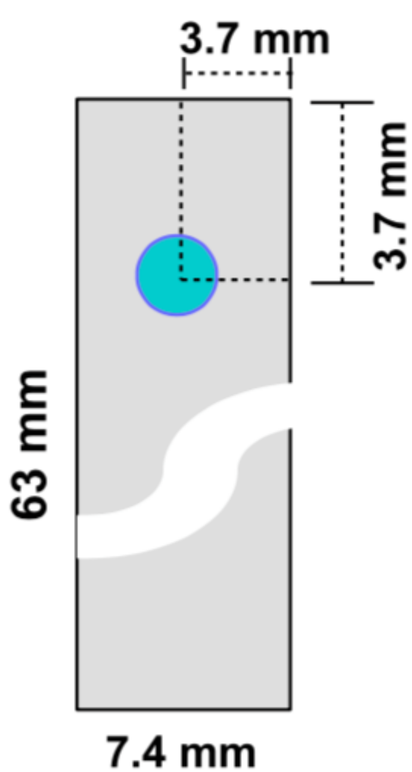
DUNE	Graphite	cylinder	150-200	2.67

NOvA Target

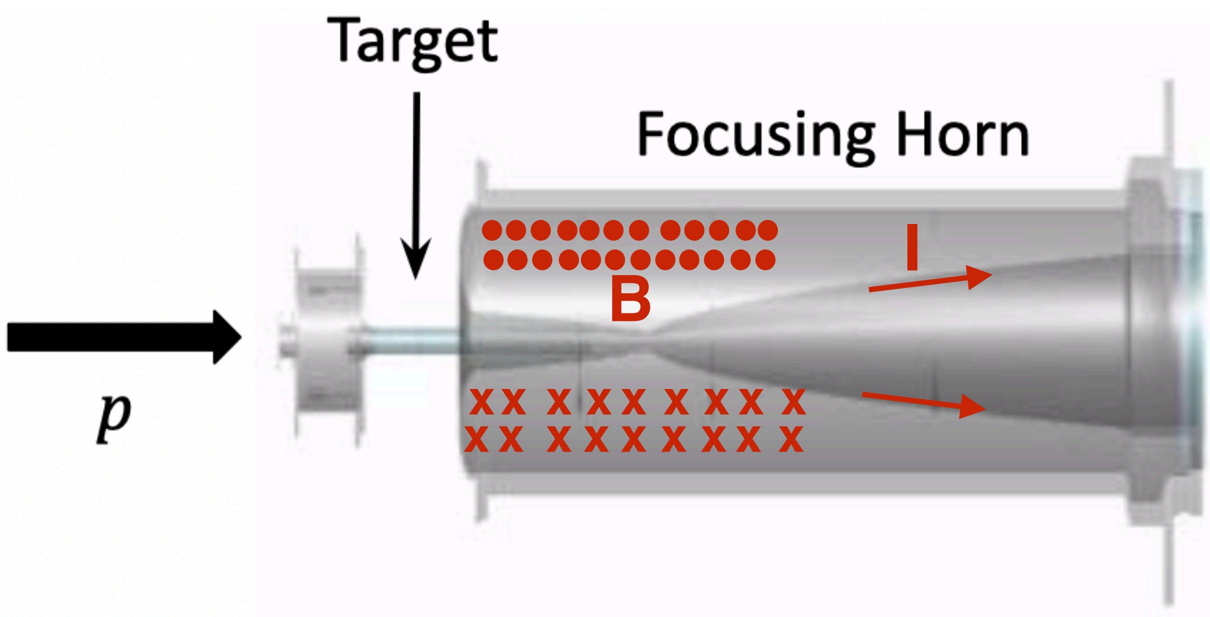


Rectangular graphite rode, segmented in rectangular pieces ("fins").

50 fins in total: 1.2 m (~2.5 λ).



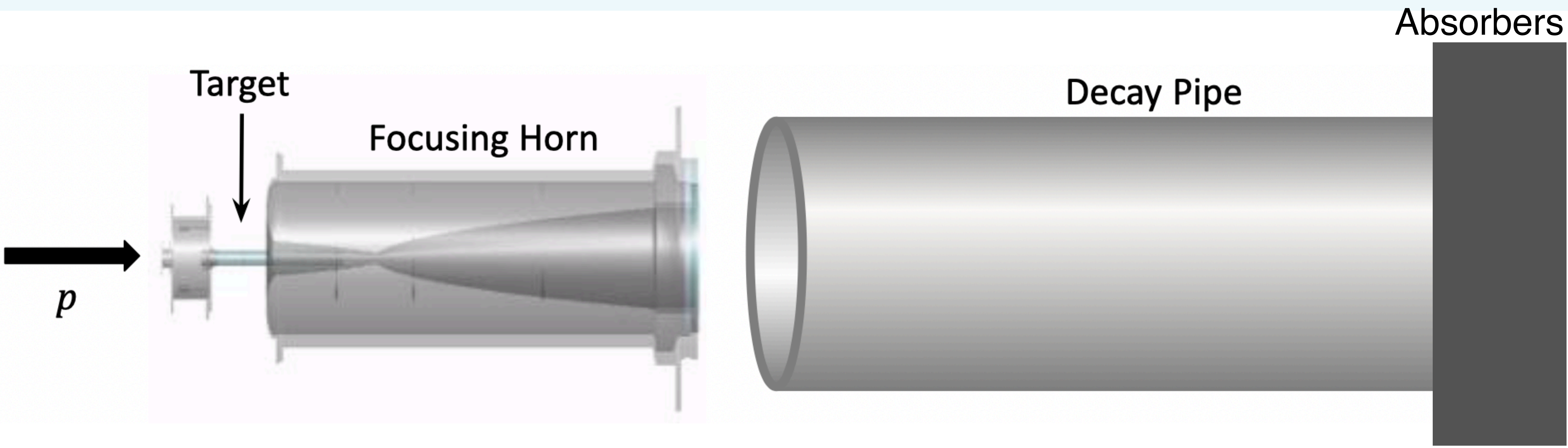
Recipe:Horns



	Number of Horns
SBN	1
NuMI	2
T2K	3
DUNE	3

- Focus as many π^{+-} with the wanted sign and deflect the unwanted sign
- Pions diverge from the target with: $\theta_\pi \sim p_T/p_\pi \sim \langle p_T \rangle/p = 280\ \text{MeV}/p_\pi = 2/\gamma$
- Neutrinos from pion decay: $\sim 1/\gamma$
- Parabolic shape horn inner conductor makes the horn behaves as lens (P_T proportional to the distance to the axis) with a focal length proportional to the pion momentum.

Recip: Decay Pipe



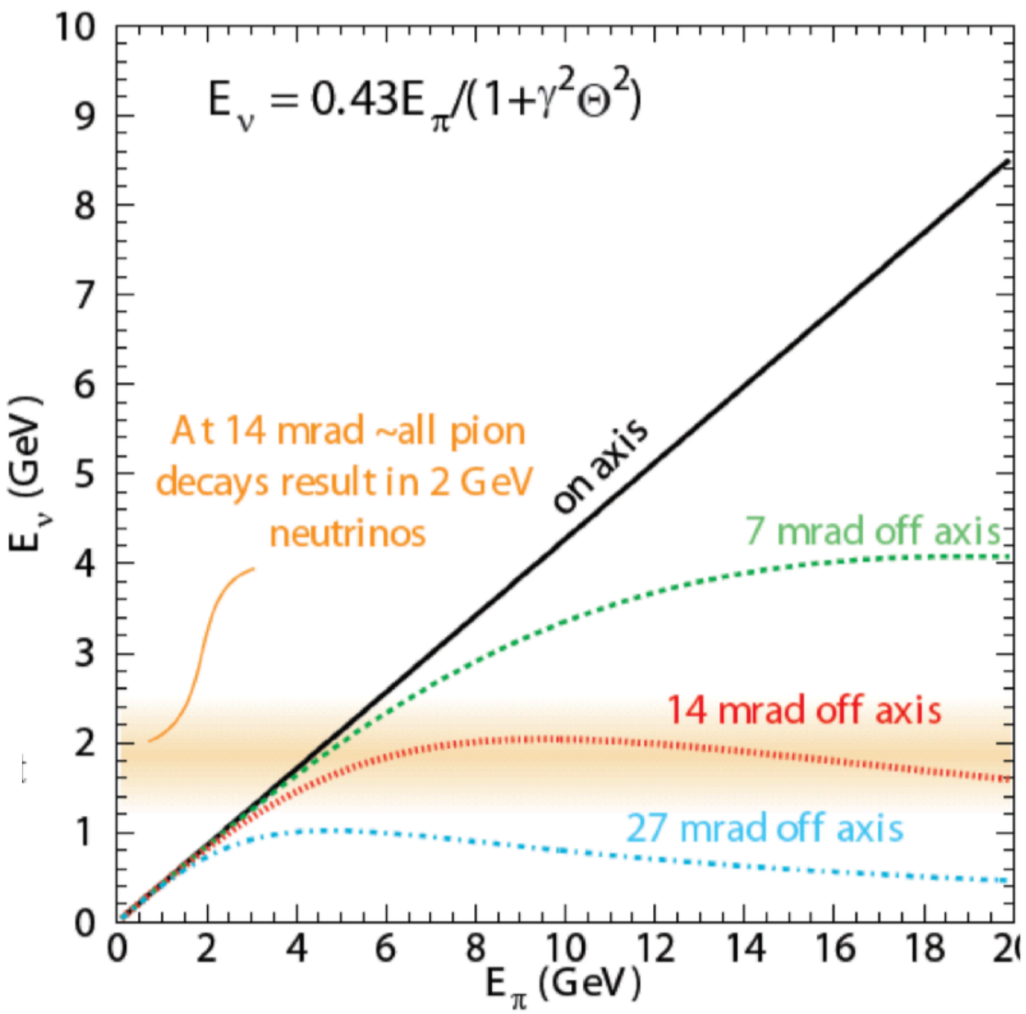
- Length and wide of the decay pipes depends on what pion energy you want to focus.
- Longer decay regions, more muon decays (more electron neutrinos)
- Evacuated decay regions is better… less beam absorption.. more dangerous.. Instead using He or air.

	Lenght (m)
SBN	50
MINOS/NOvA	675
T2K	130
DUNE	194

How to Make a Conventional Neutrino Beam

Neutrino decay:

- Main decay to neutrino mode for neutrino beam:

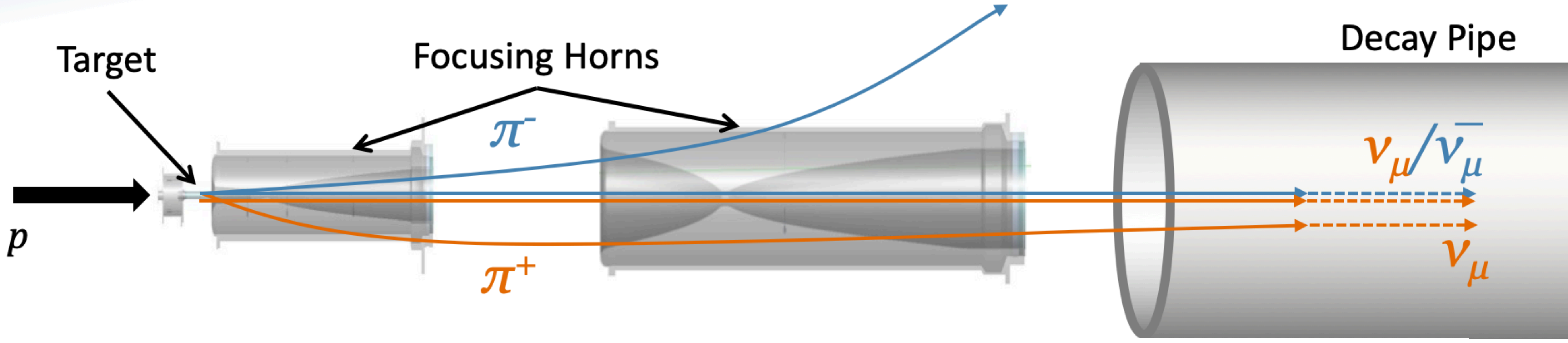


Decay	Chanel	Branching ratio (%)
1	$\pi^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$	99.9877
2	$\pi^\pm \to e^\pm + \nu_e(\bar{\nu}_e)$	0.0123
3	$K^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$	63.55
4	$K^\pm \to \pi^0 + e^\pm + \nu_e(\bar{\nu}_e)$	5.07
5	$K^\pm \to \pi^0 + \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$	3.353
6	$K^0_L \to \pi^\pm + e^\mp + \nu_e$	40.55
7	$K^0_L \to \pi^\pm + \mu^\mp + \nu_\mu$	27.04
8	$\mu^\pm \to e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$	100.0

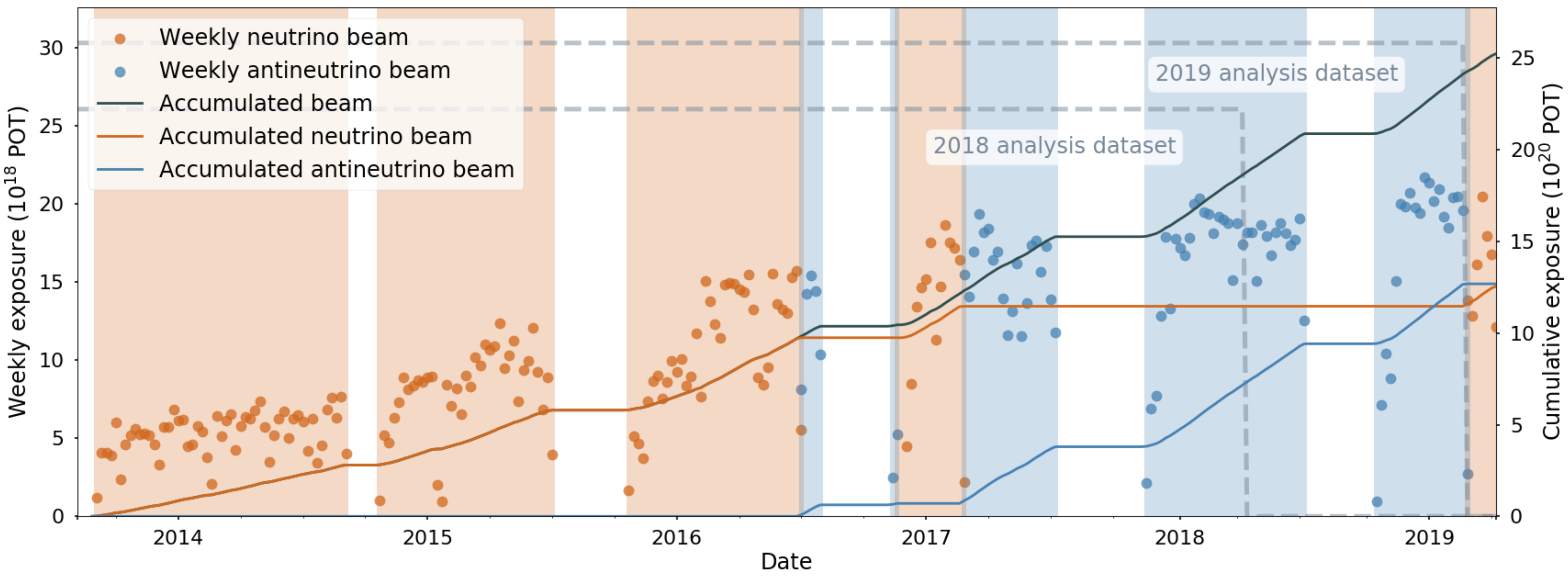
- From 2 pion body decay:

$$E_\nu \approx \frac{(1 - \frac{m_\mu^2}{M^2})E_{\pi(K)}}{1+\gamma^2\tan^2\theta_\nu}$$

NuMI Beam

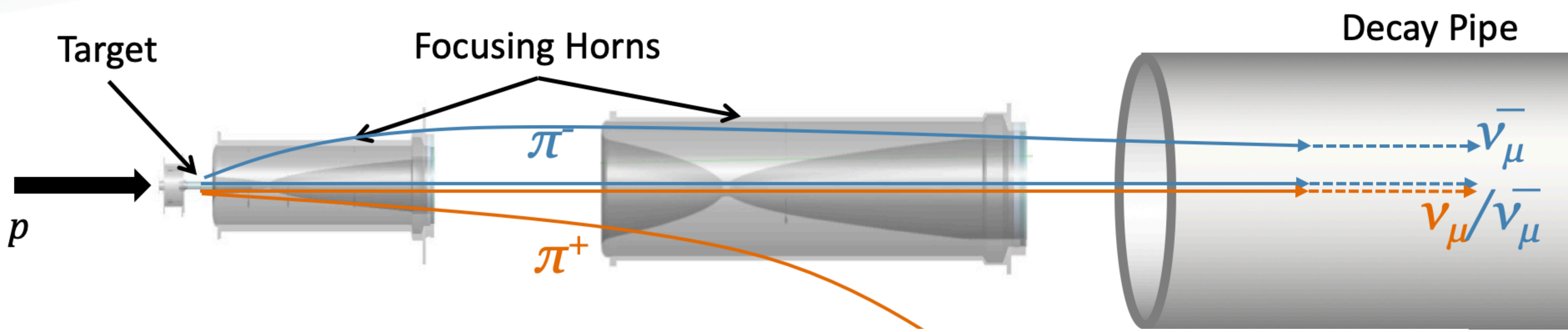


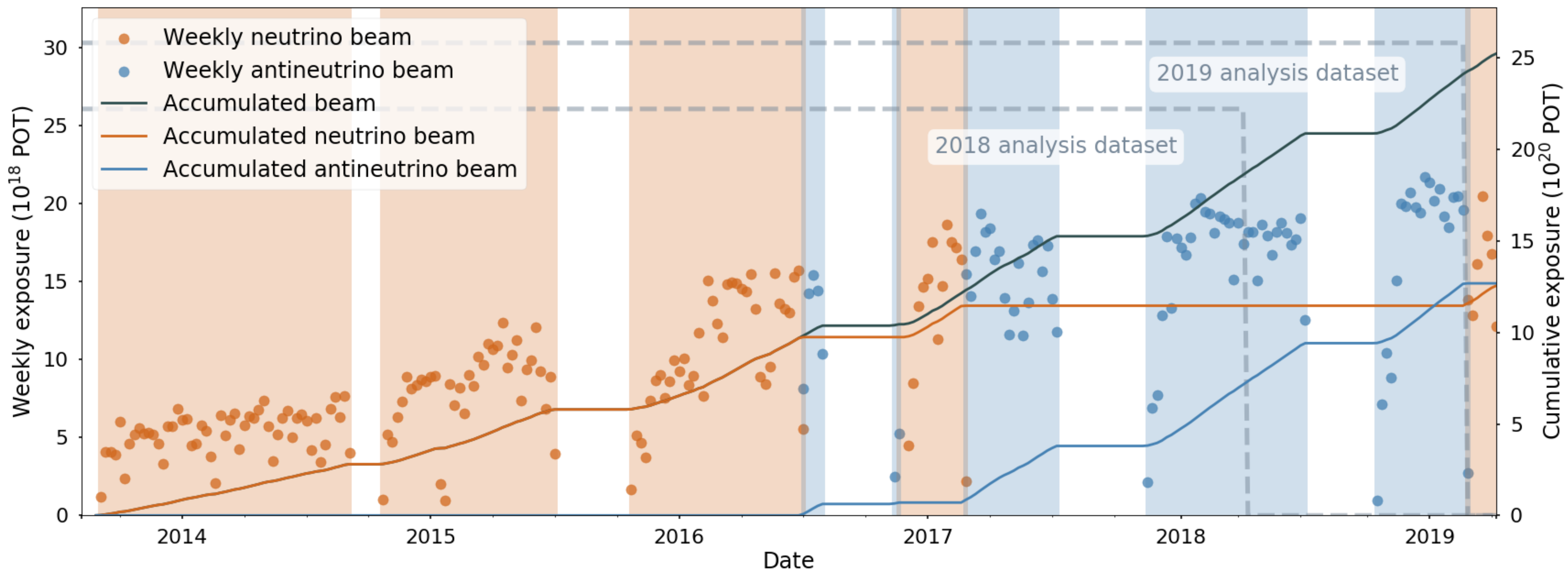
Target
Focusing Horns
Decay Pipe
p
π^-
π^+
$\nu_\mu/\bar{\nu}_\mu$
ν_μ



Weekly neutrino beam
Weekly antineutrino beam
Accumulated beam
Accumulated neutrino beam
Accumulated antineutrino beam
2019 analysis dataset
2018 analysis dataset
Weekly exposure (10^{18} POT)
Cumulative exposure (10^{20} POT)
Date
0
5
10
15
20
25
30
2014
2015
2016
2017
2018
2019

NuMI Beam


Target
Focusing Horns
Decay Pipe
p
π^-
π^+
$\bar{\nu}_\mu$
$\nu_\mu/\bar{\nu}_\mu$


Weekly neutrino beam
Weekly antineutrino beam
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Date
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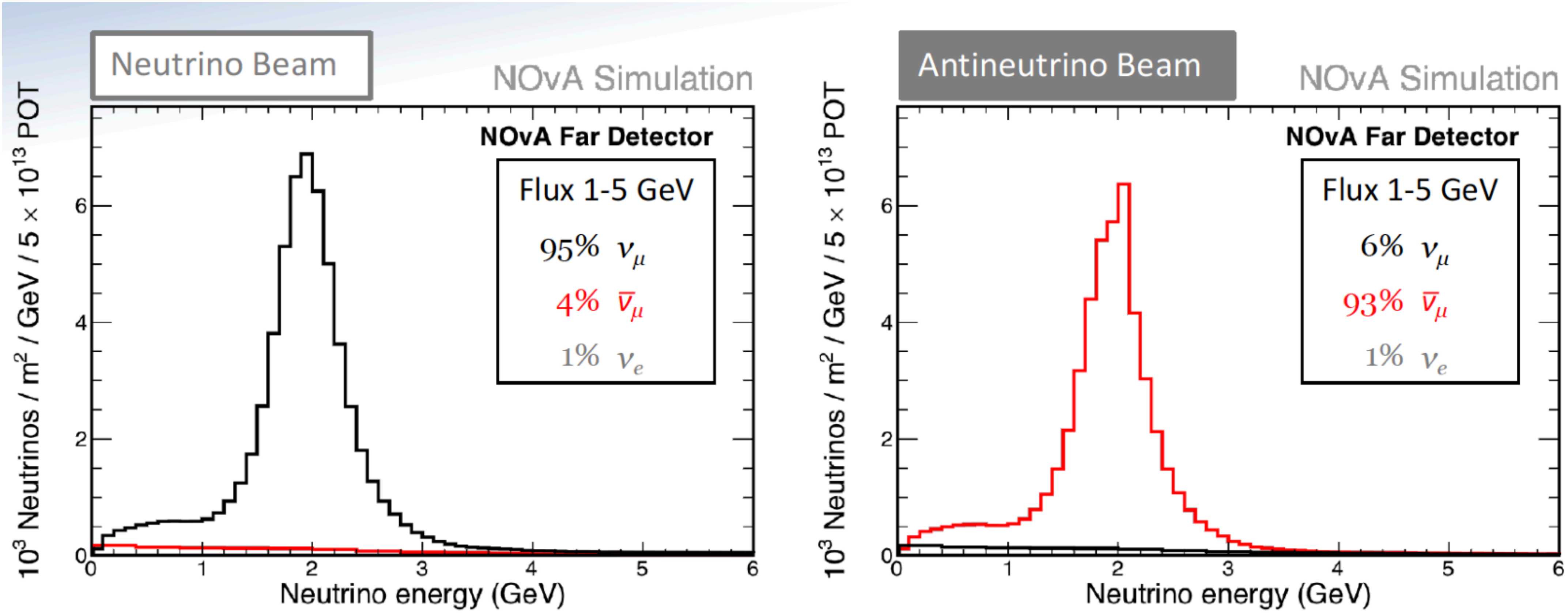
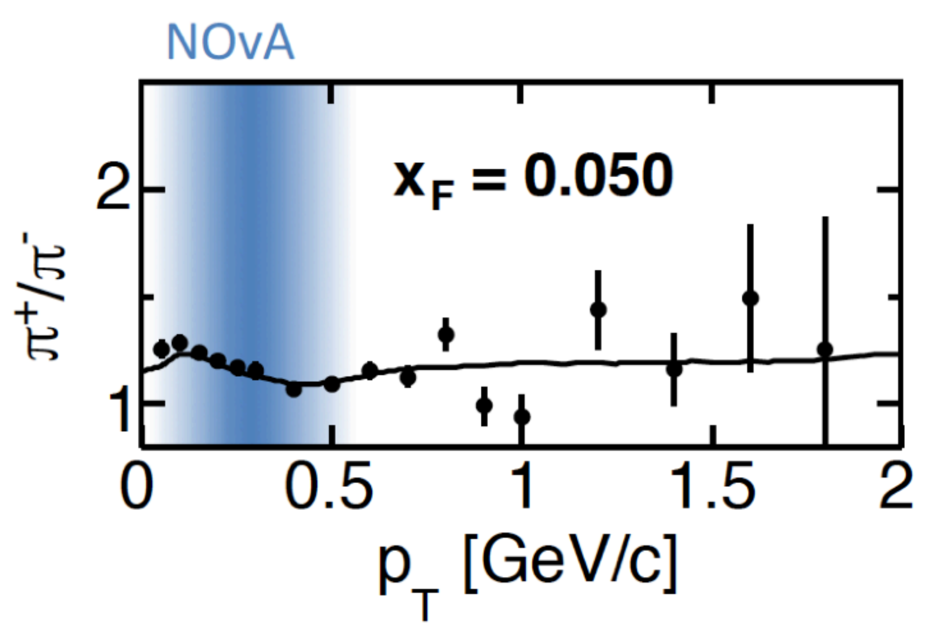
NOvA flux



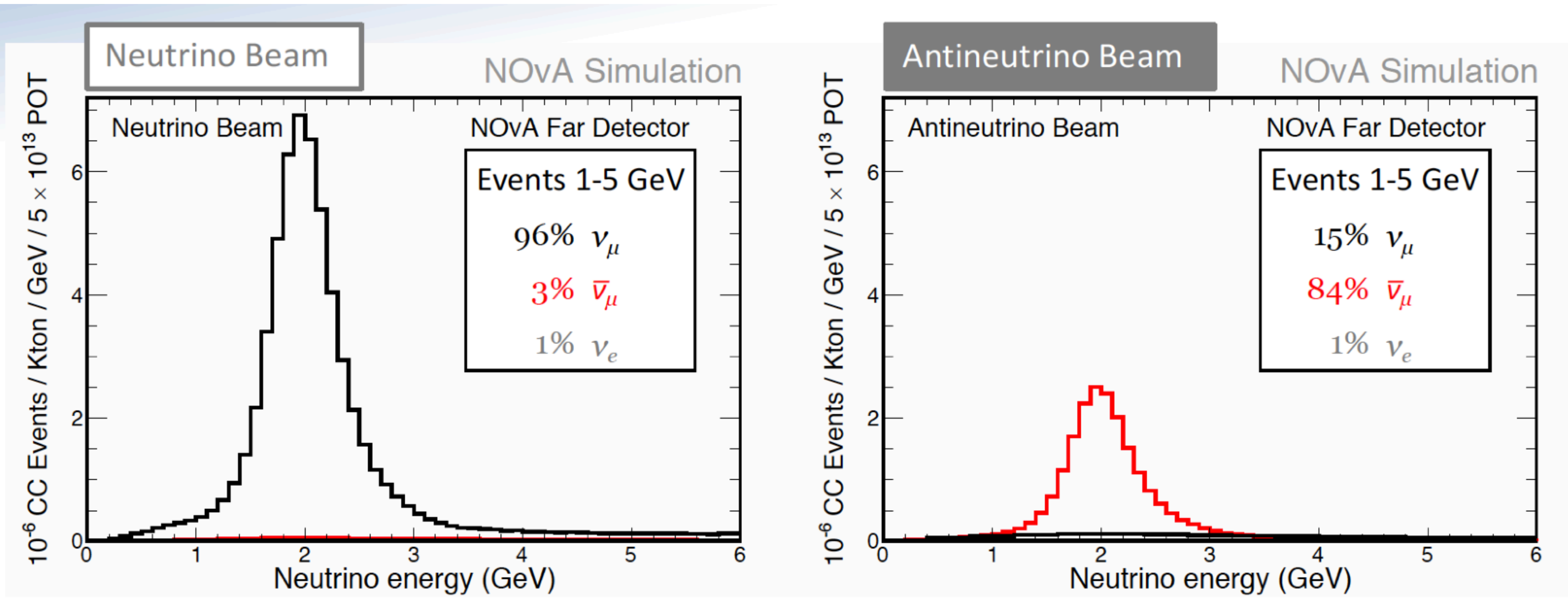
- Production cross section is a little higher for $\pi^+ \rightarrow \nu_\mu$ than for $\pi^- \rightarrow \bar{\nu}_\mu$
  - p^+ colliding with p^+ and n^0 in the target
- *Wrong-sign*: ν in the $\bar{\nu}$ beam (or vice versa).
- Off-axis beam reduces the wrong-sign.
  - WS primarily would primarily come from the unfocused high-energy tail.



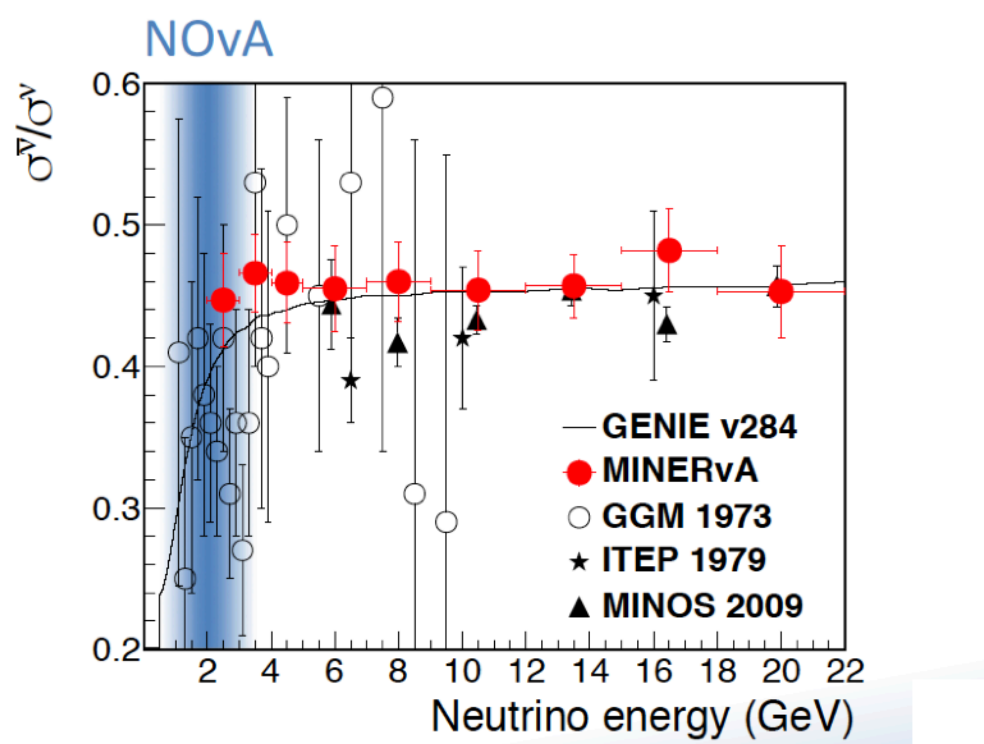
NA49, Eur. Phys. J. C 49 897 (2007)

A. Himmel, Fermilab JETP Seminar, June 2018

NOvA events



- The big difference is in the interaction: the cross section for antineutrinos is **~2.8 times lower** than for neutrinos.
- Antineutrinos also tend to have more lepton energy and less hadronic energy.
  - Lower kinematic y
  - More forward-going



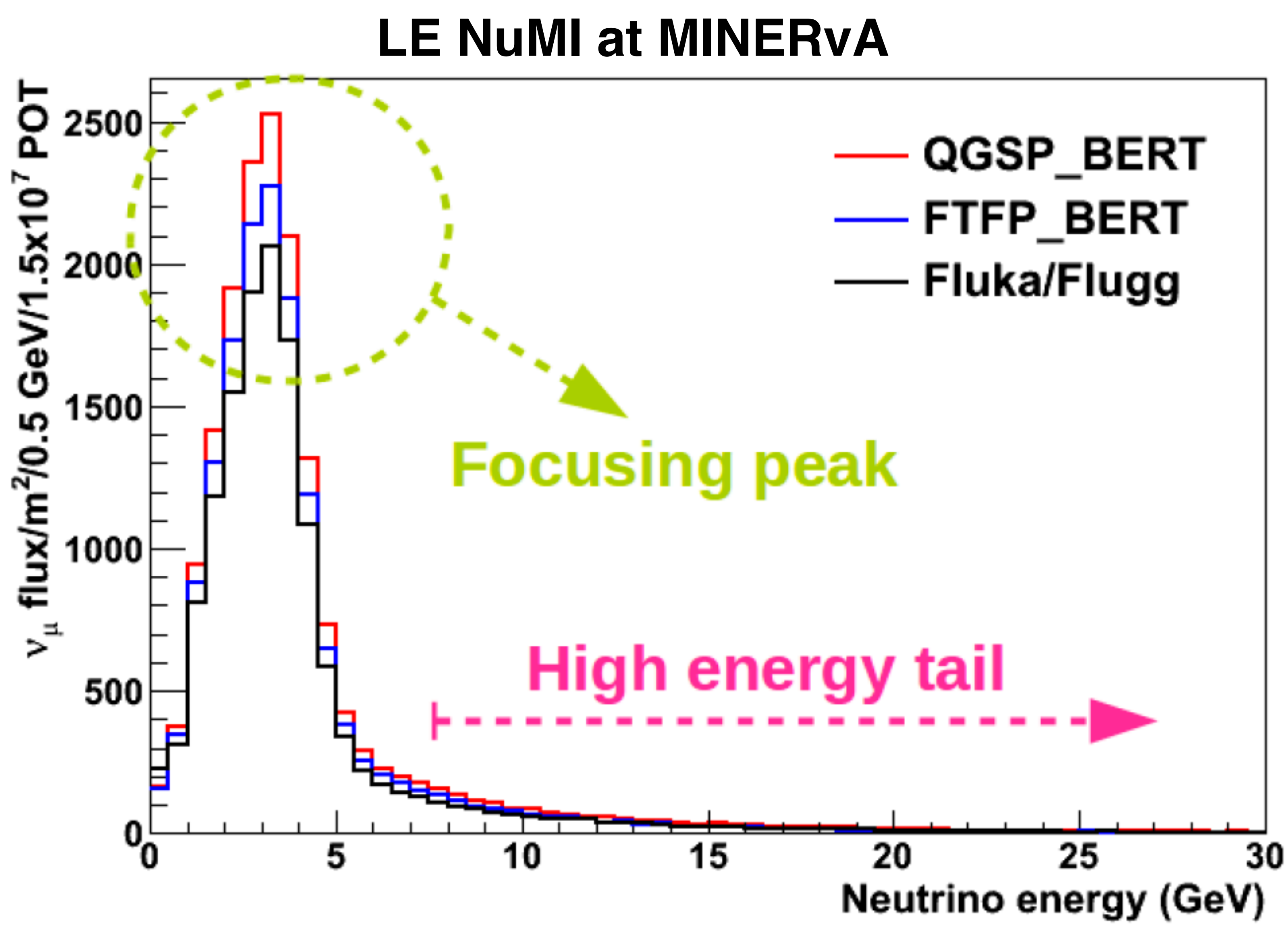
A. Himmel, Fermilab JETP Seminar, June 2018

MINERvA, Phys.Rev. D95 (2017) no.7, 072009

Predicting the A-priori flux

Model Predictions

- Models disagree at +-20%
- These are microphysical, first principle models of hadronic interactions.



- **Risk of using model spread** is to **under**/over estimate internal correlations.

Soft hadronic processes

Hadronic processes are tradionally classifed in:

- **Hard processes**. When $Q^2 \to \infty$ ($\geqslant 1GeV^2$), then $\alpha \to 0$ and pQCD can be used.

- **Soft processes**. Low Q^2 ($\sim$ few hunderd MeV)^2, then α too large to apply pQCD.
  - Phenomenological models has been developed.
  - Free parameters determined from the measured data.

The running strong coupling constant:

$$\alpha_s(Q^2) = \frac{4\pi}{(11 - \frac{2}{3}n_f)ln(\frac{Q^2}{\Lambda^2})}$$

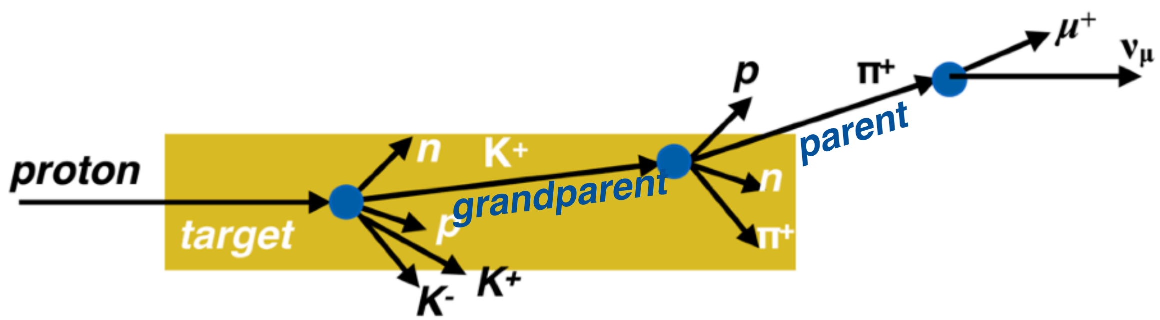
(One loop approximation. $\Lambda \sim 0.2GeV$. n_f: number of quarks flavors.)

The hadronic interactions in the target are non - perturbative QCD.

Neutrino Ancestry

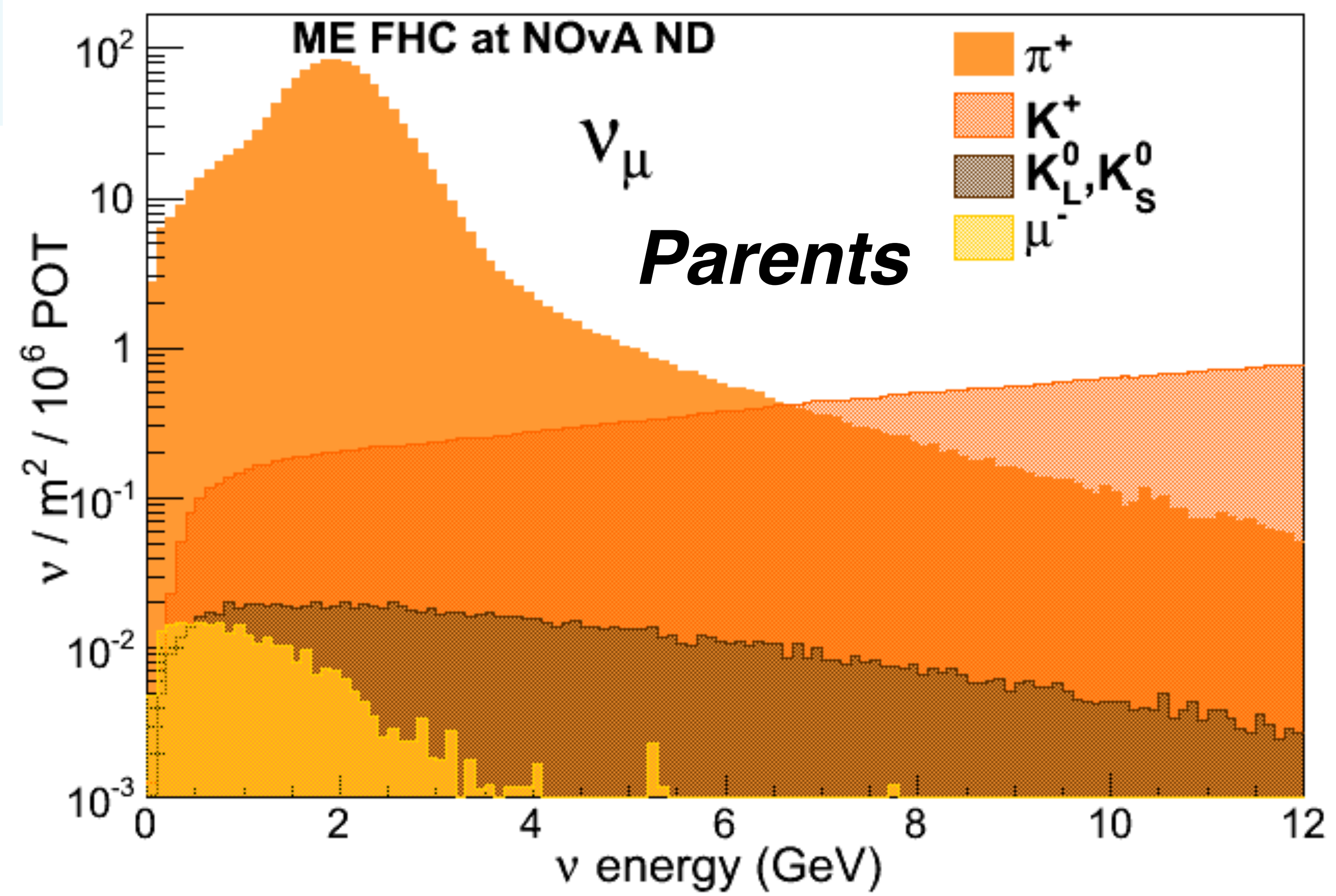
We will use ν_μ NOvA ND for the following slides.

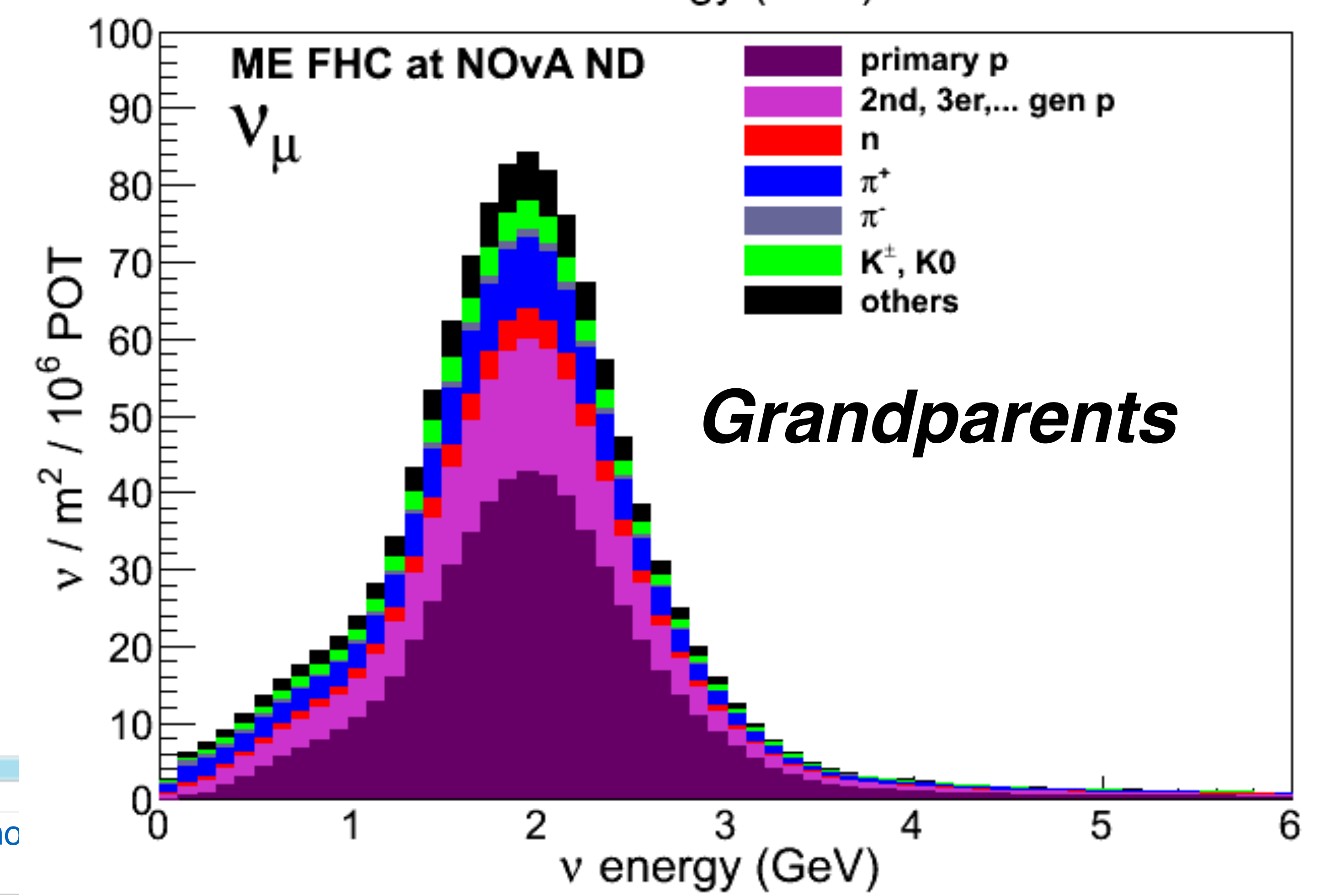
- ν_μ **parents:** *π's dominate up to 6-7 GeV and K beyond that.*



- ν_μ **grandparents:** *protons contribute the most.*

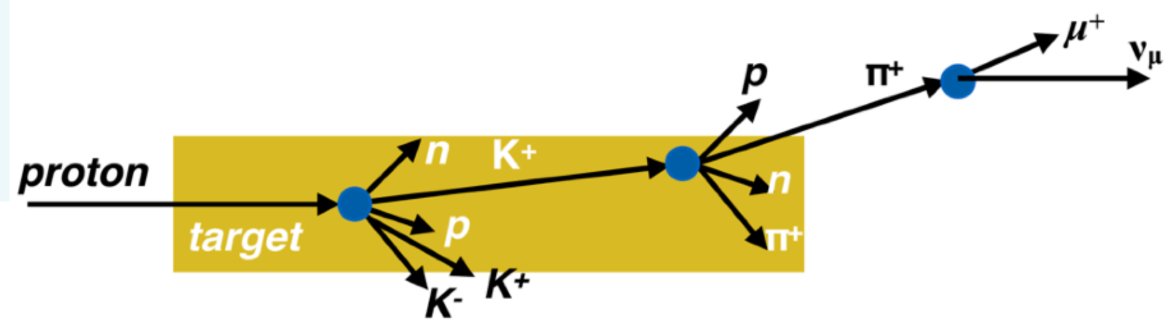
We use Geant4 to simulate the beamline and FTFP_BERT as hadronic model





Package to Predict the FluX (PPFX)

https://cdcvs.fnal.gov/redmine/projects/ppfx



- The beamline simulation is G4NuMI (geant4 based).
  - It stores the complete **neutrino ancestor information** in **dk2nu** format (MINOS-doc 9885, R. Hatcher). This is propagated event by event trough GENIE.

- **PPFX** is a package to calculate the a-priori flux:
  - The foundation is formed from **constraining** (correcting) the **interaction** and the **hadron production** with external measurements on **thick and thin targets**.
  - It was made originally for **MINERvA** using **all relevant data** to constraint the on-axis **NuMI** flux, currently used by **NOvA** and **DUNE**.
  - It corrects the yields given by the model to match the measured data. If not data is available PPFX try to extend the data coverage or assign a well-educated guess.
  - It propagates the **underlying data correlations** to calculate the **flux covariance (“multi-universe” technique)**.

Definitions for thin target experiments

Total Cross-section:

$$\sigma_{total} = \sigma_{elastic} + \underbrace{\sigma_{inelastic} + \sigma_{quasi-elastic}}_{\sigma_{absorption}}$$

- **Elastic component** ($h + A \to h + A$).
- **Inelastic component** ($h + A \to$ + mesons+ fragments of nucleus).
- **Quasi-elastic component** ($h + A \to$ + p + fragments of nucleus).

Lorentz invariant differential cross-section:

$$f = E_s \frac{d^3\sigma}{dp^3}.$$

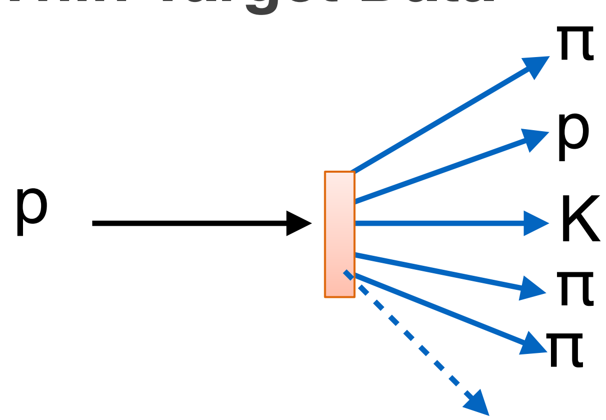
Feynman-x:

$$x_F \equiv \frac{p^*_{\parallel}}{P^*_{\parallel}(max)} \simeq \frac{2p^*_{\parallel}}{\sqrt{s}}$$

Experiments

- Hadron production data at the relevant energies for NuMI:

Thin Target Data



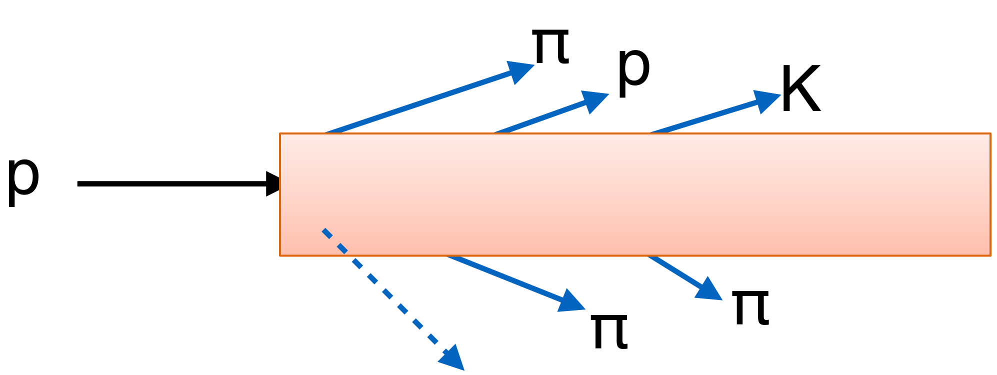
Inelastic/absoption cross section

- Belletinni, Denisov, etc. of p-C, π-C, π-Al etc. at different energies.
- NA61 and NA49 p-C at 31 and 158 GeV.

Hadron production

- NA49 π, K, p (x_F, p_T dependence) and n (x_F dependence) production @ 158 GeV and Barton π @100 GeV.
- NA61 π @ 31 GeV is used to validate scaling from NA49.
- MIPP π/K from pC @ 120 GeV for $P_Z > 20$ GeV.

Thick Target Data



MIPP: proton on a LE NuMI spare target @ 120 GeV

- π production up to 80 GeV/c.
- K/π for $P_Z > 20$ GeV/c.

We use this data to correct FTFP_BERT in geant4.9.2.p03.

1. Beam attenuation

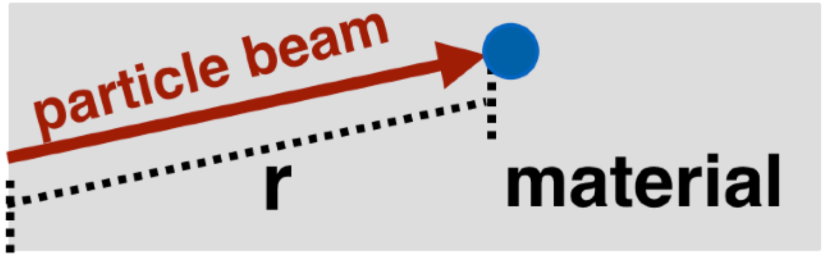
Correcting the probability that an interaction happened

2 scenarios, depending if the particle interact or passes without interacting in the volume

Interacting

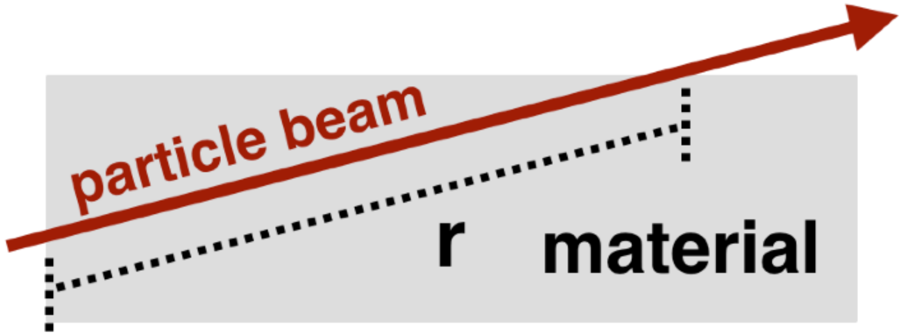
$$correction(r) = \frac{\sigma_{Data}}{\sigma_{MC}} e^{-r\frac{N_A \rho(\sigma_{Data}-\sigma_{MC})}{A}}$$

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



Not interacting

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



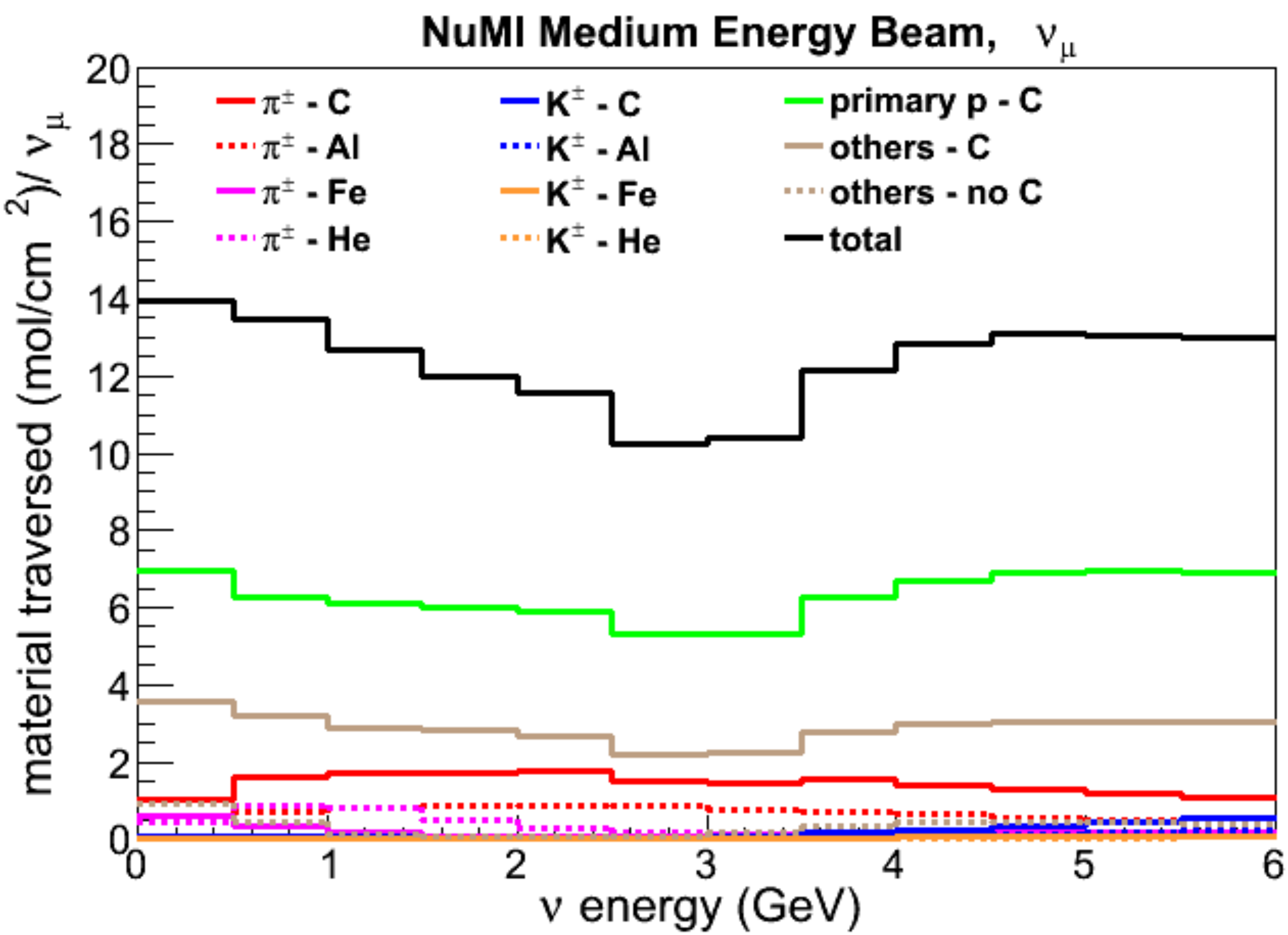
Two variables are important here:

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

Amount of Material Traversed

<rN$_A$ρ/A>

Average material traversed by a hadron per neutrino at NOvA ND



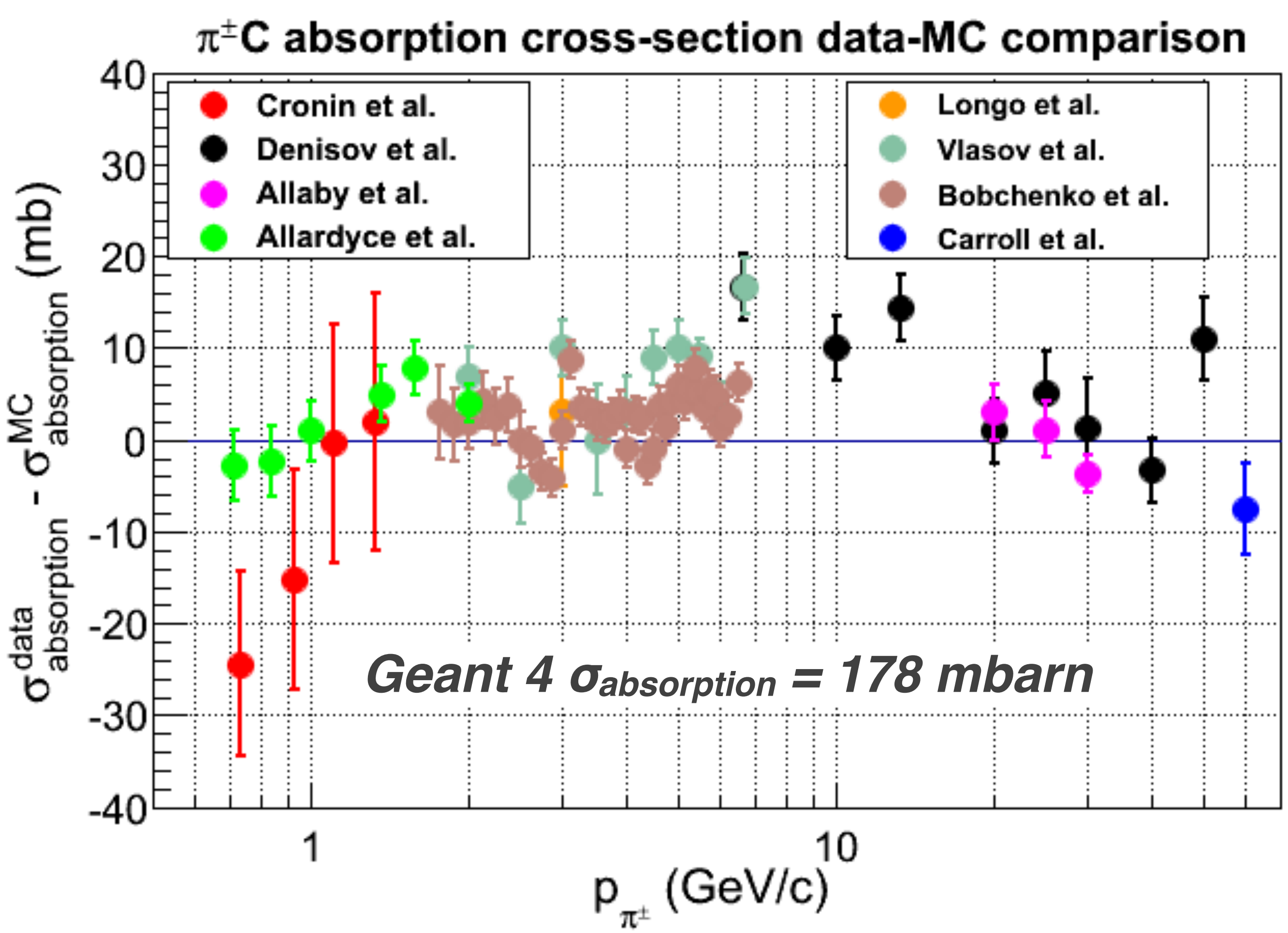
References:

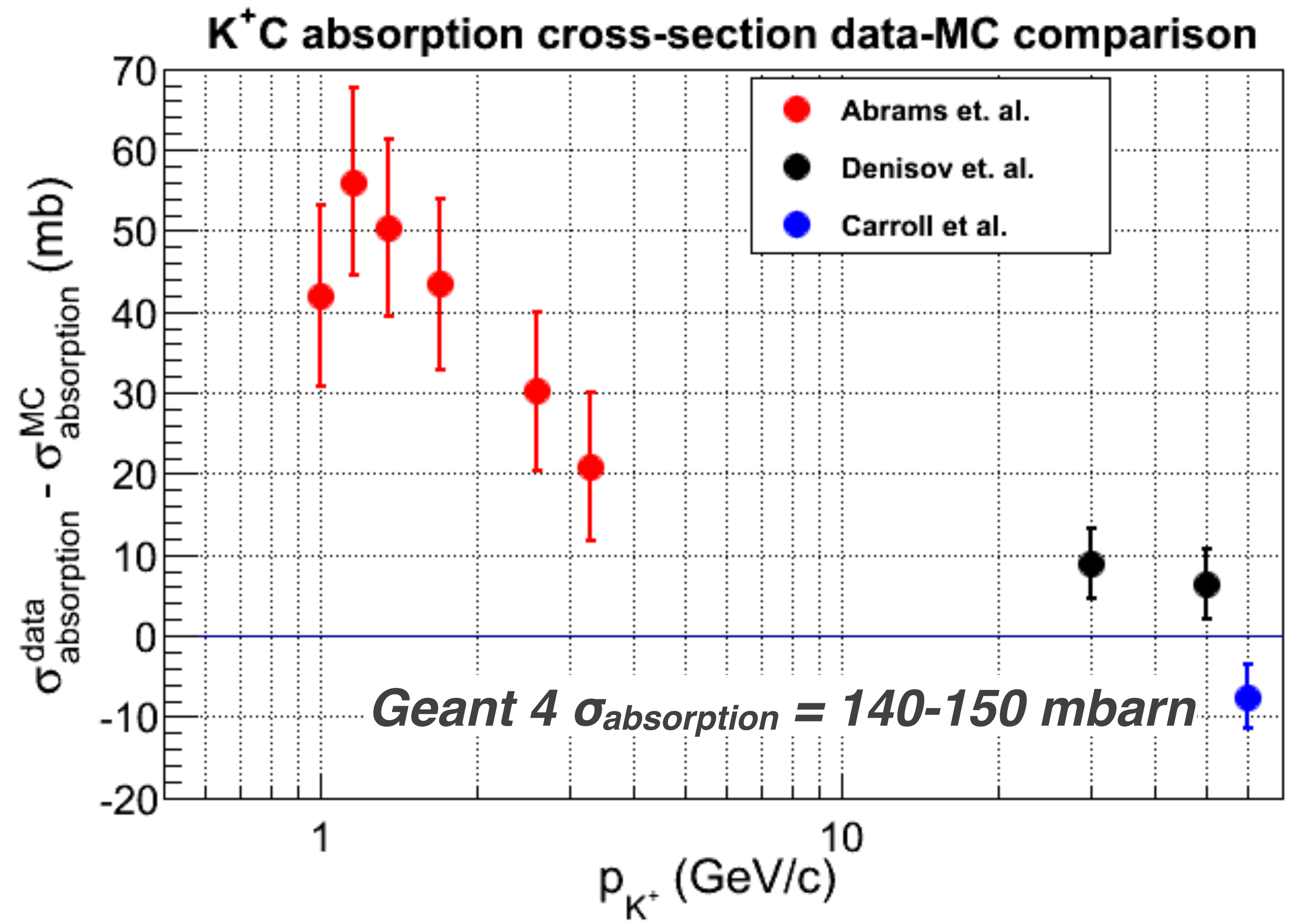
- ***C: 6 mol/cm² ≈ 40 cm***
- ***Al: 1 mol/cm² ≈ 10 cm***
- ***He: 1 mol/cm² ≈ 500 m***

Absorption cross section

rNAρ/A

Data - MC comparison of absorption cross section





We apply 10 mb uncertainty (~5%)

We apply 60-90 % for P < 4 GeV and 12% for P > 4 GeV.

2. Hadron production

Given that an interaction happened, it corrects the probability to produce a hadron in (x_F,p_T).

A. Using only thin-target data

For thin target data (NA49 for instance):

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

(**f=**invariant differential cross section)

- We **scaled** NA49 (**proton-Carbon at 158 GeV**) to **12-120 GeV** (calculated with FLUKA).
- It was compared with NA61 (**at 31 GeV**) (negligible difference in the region of interest).

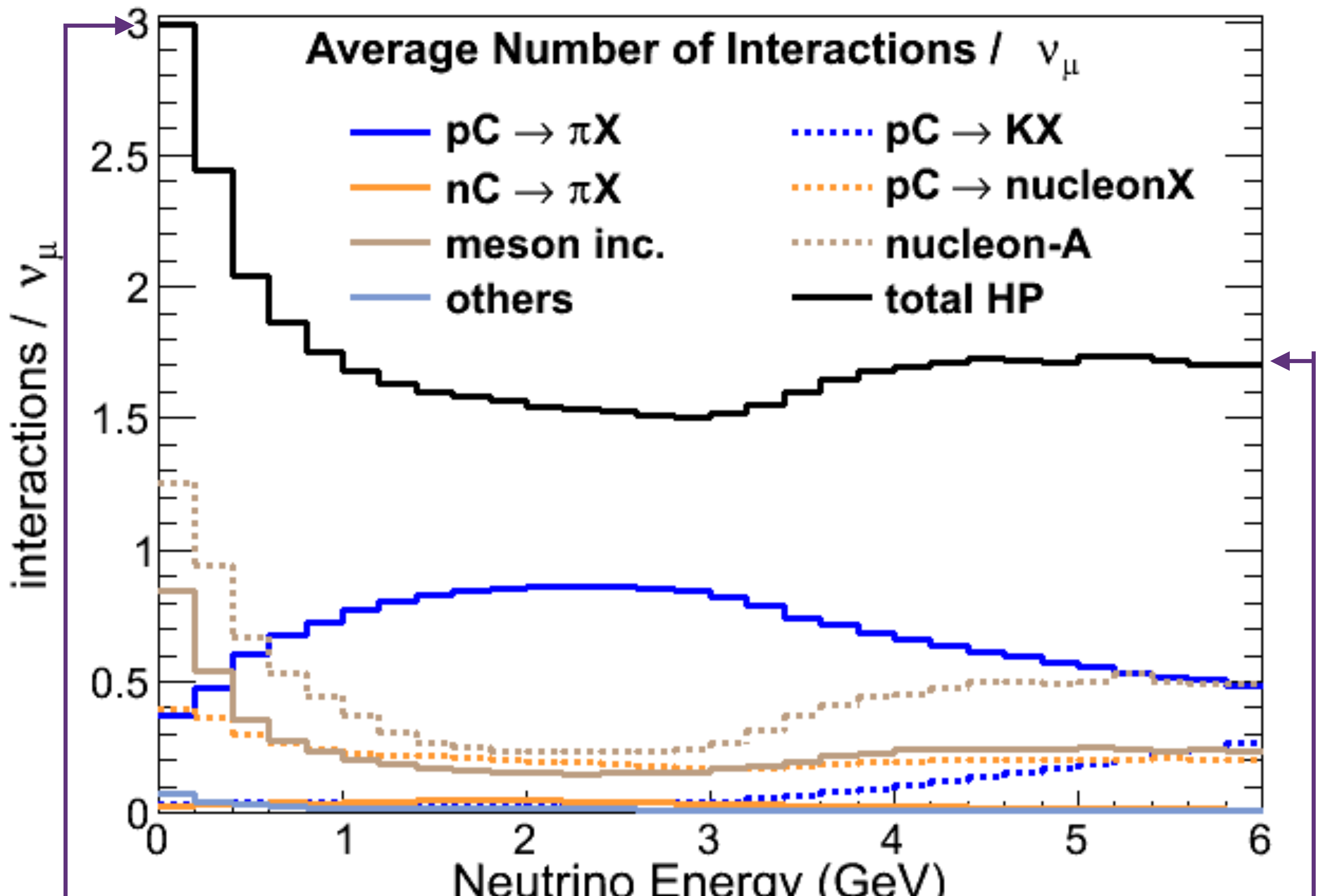
B. Using primarily thick-target data and then complete the constraint with thin-target data

For thick target data (MIPP MINOS target):

$$correction(p_Z, p_T) = \frac{n_{Data}(p_Z, p_T)}{n_{MC}(p_Z, p_T)}$$

Interactions

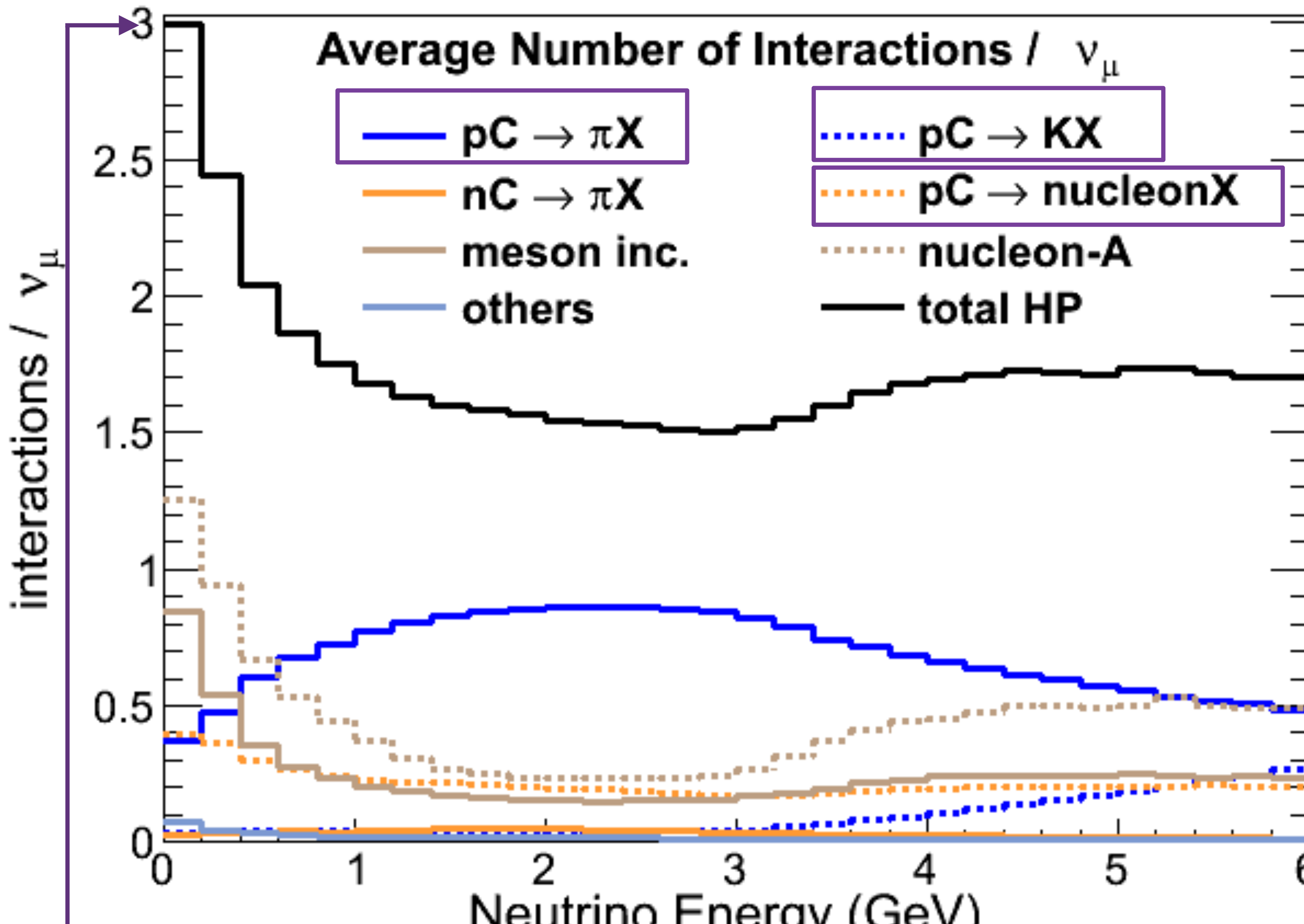
Average number of hadronic interactions per neutrino at NOvA ND



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

Interactions

Average number of hadronic interactions per neutrino at NOvA ND



Based directly on data (mostly NA49)

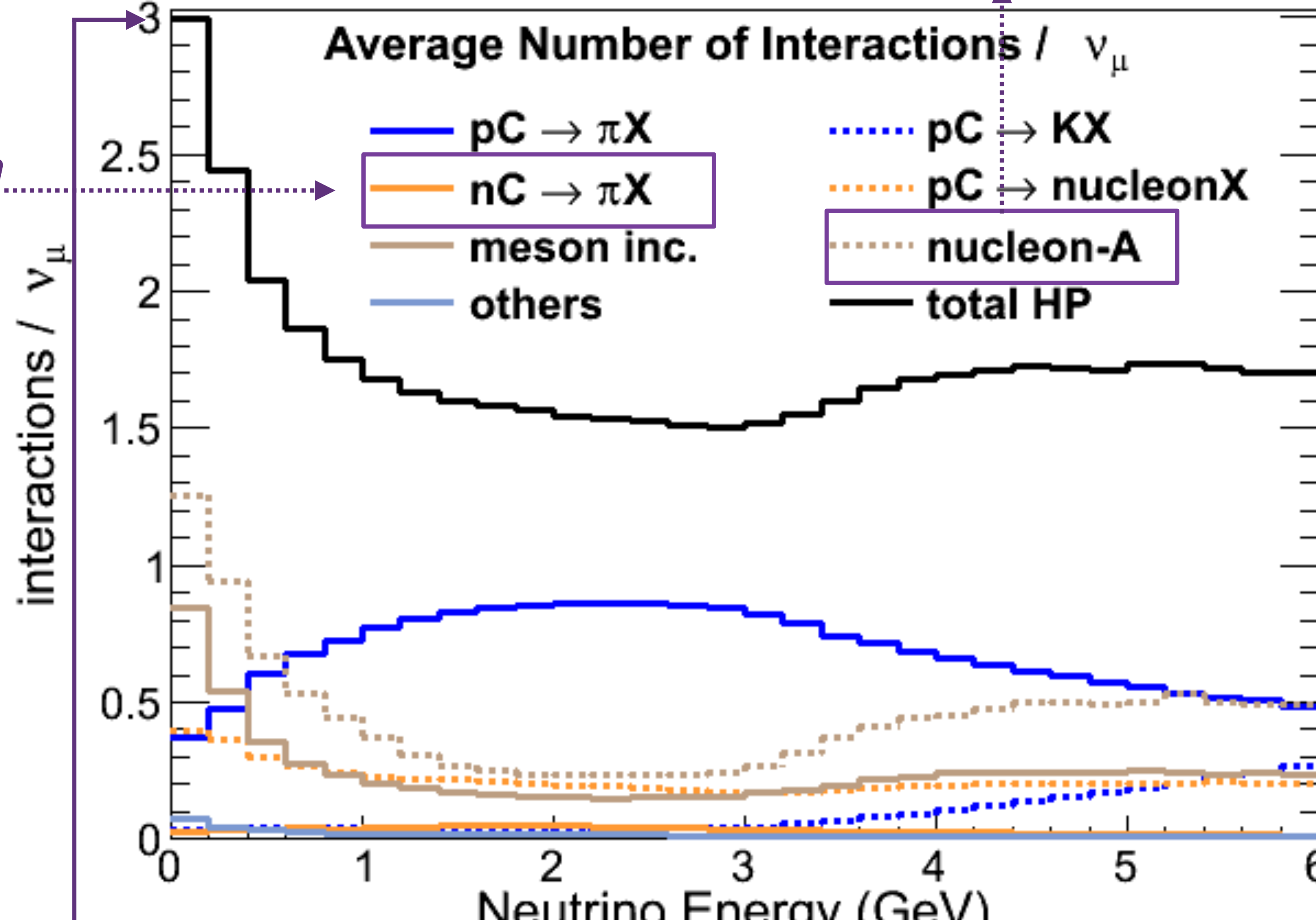
~3.0 for low E_ν and ~1.5-1.6 for the rest

Interactions

Average number of hadronic interactions per neutrino at NOvA ND

Quasi-elastics,
extension p-C to p-A (A!=C),
and interactions outside data coverage

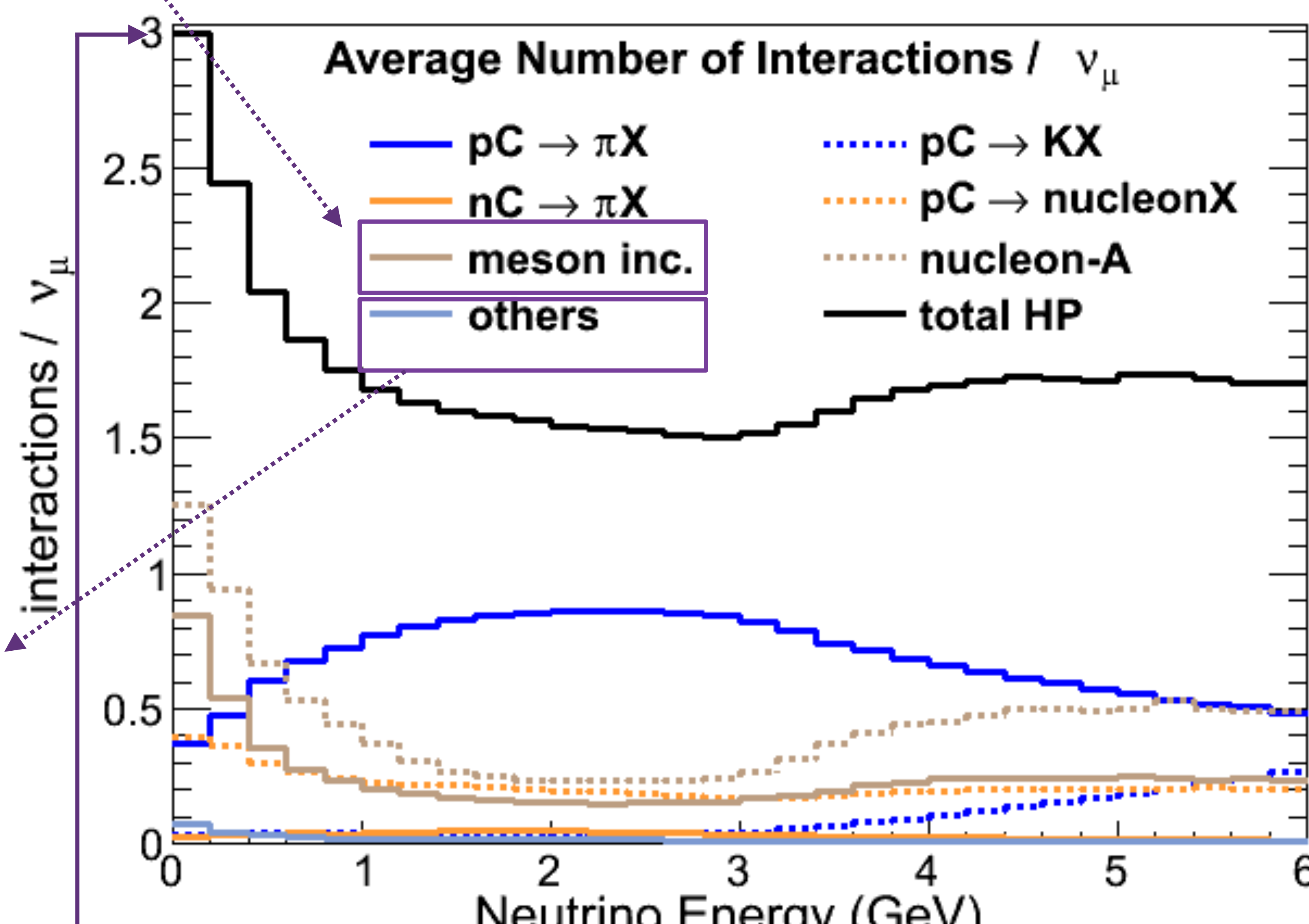
Extending based isospin symmetry



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

Average number of hadronic interactions per neutrino at NOvA ND

We assume large uncertainties for meson incident: 40%



Any additional interaction

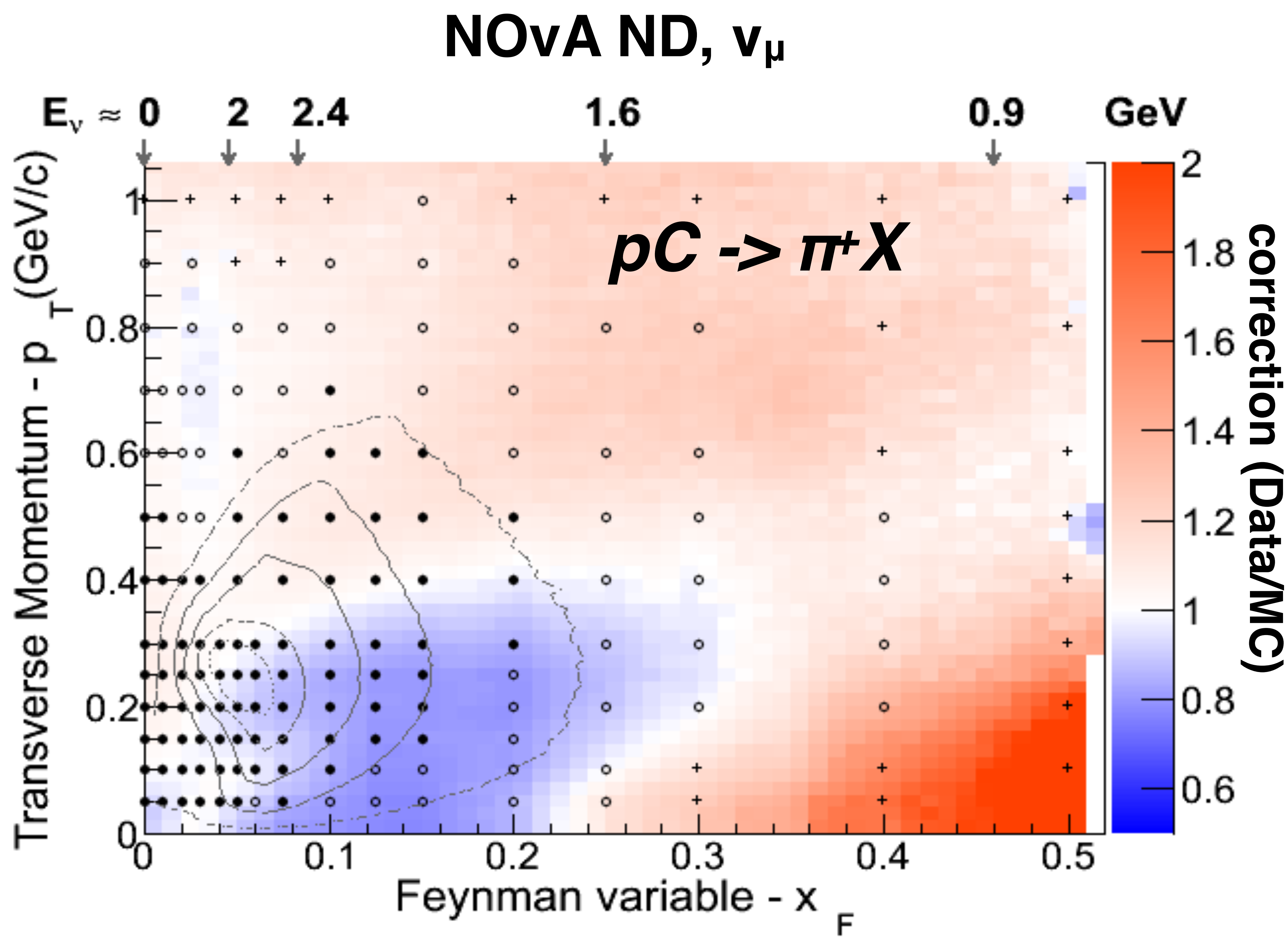
~3.0 for low E_ν and ~1.5-1.6 for the rest

Proton making pions

Example: NA49 Data/MC comparison (closed circles = statistical error < 2.5%, Open circles = statistical error 2.5-5.0%, Crosses > 5%).

Contours: 2.5, 10, 25, 50 and 75 % of the pion yields.

- Systematics are highly correlated bin-to-bin (assumed 100%): 3.8%.



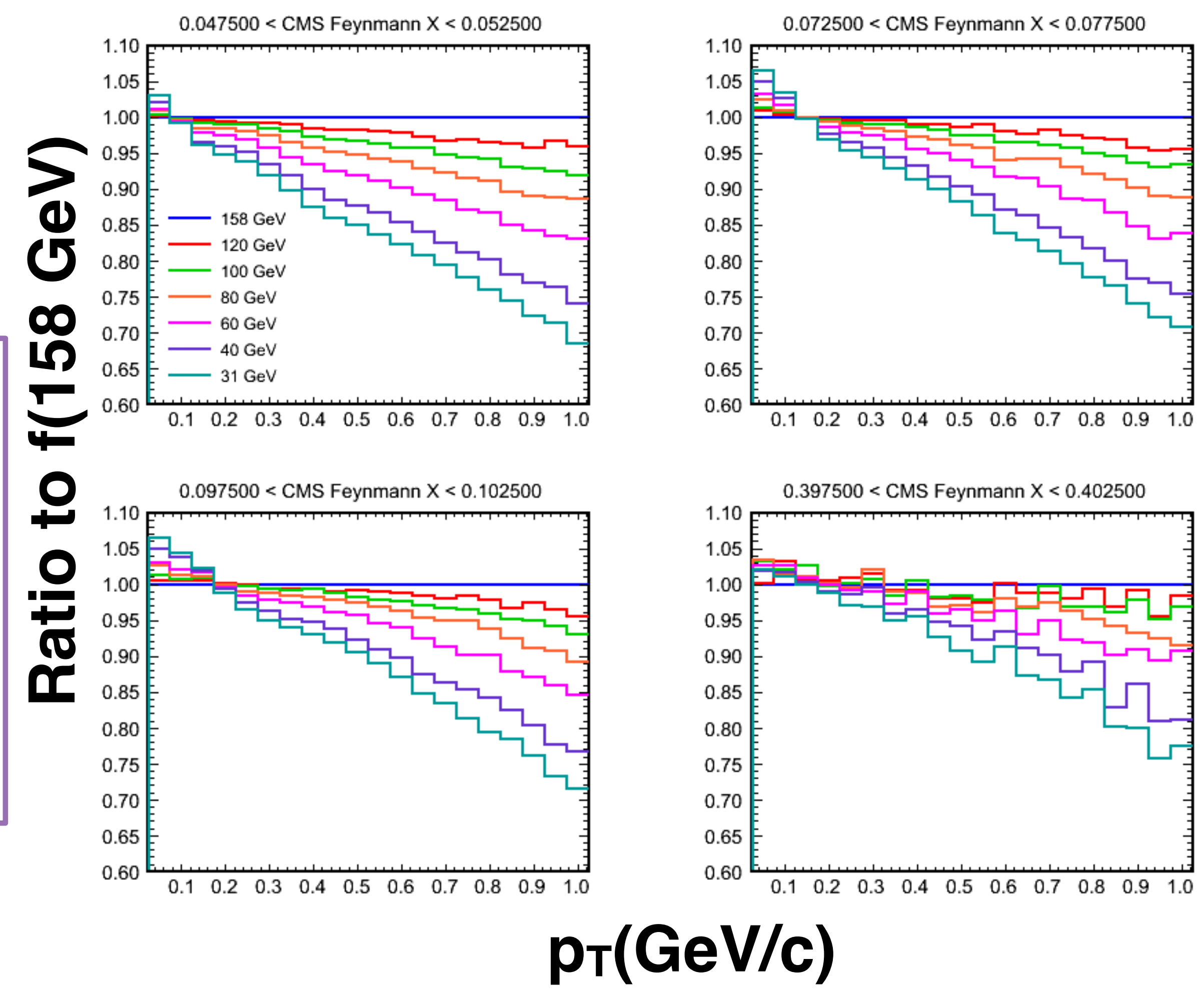
NA49 vs NA61

- NA49 reports invariant double differential cross-section, bin-center corrected): **(x_F, p_T) at 158 GeV**
- NA61 reports the cross section integrated over a kinematic bin: **([p_{low}, p_{high}], [θ_{low}, θ_{high}]) at 31 GeV**

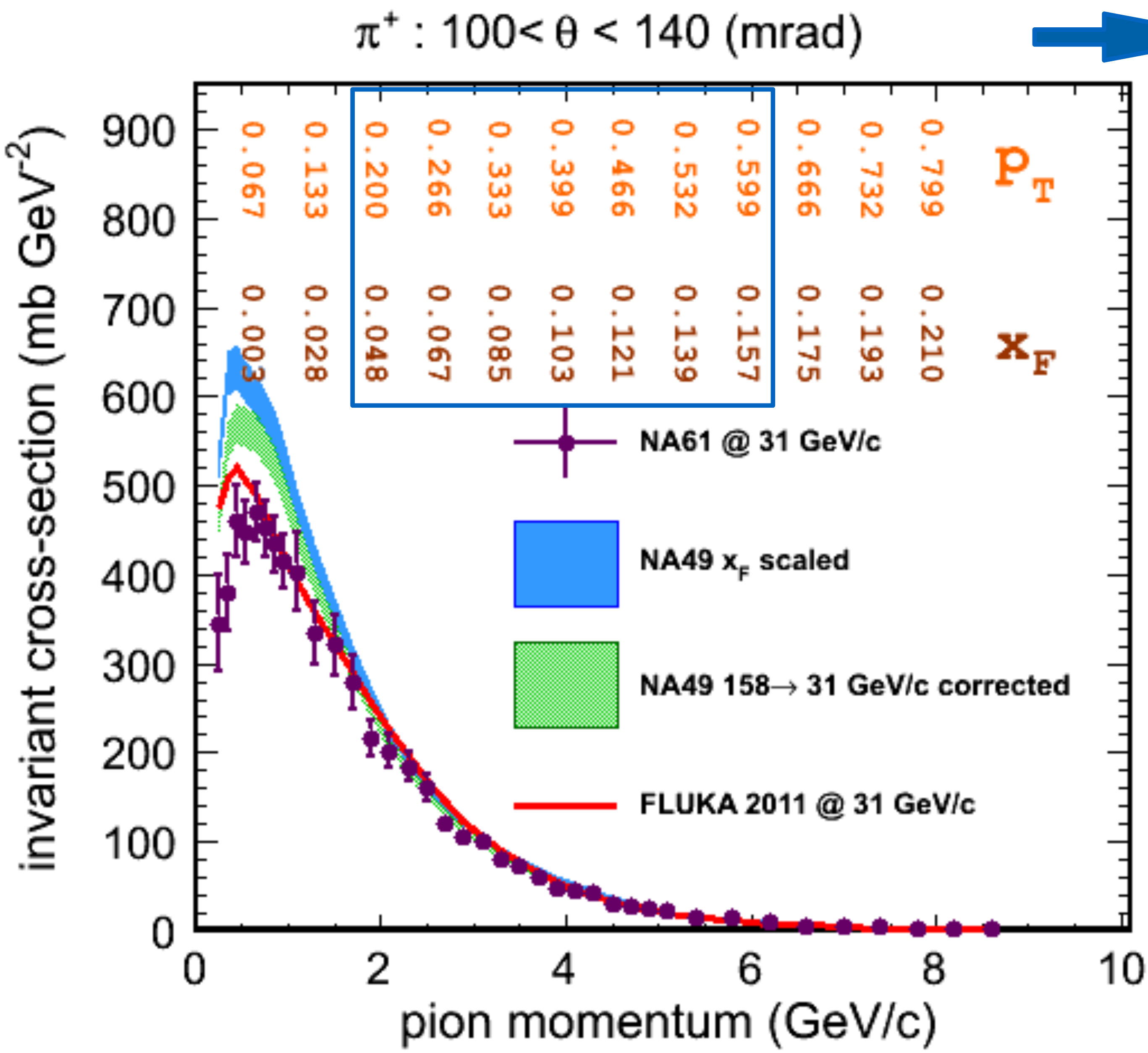
Is it possible to check the data energy scaling?

Procedure

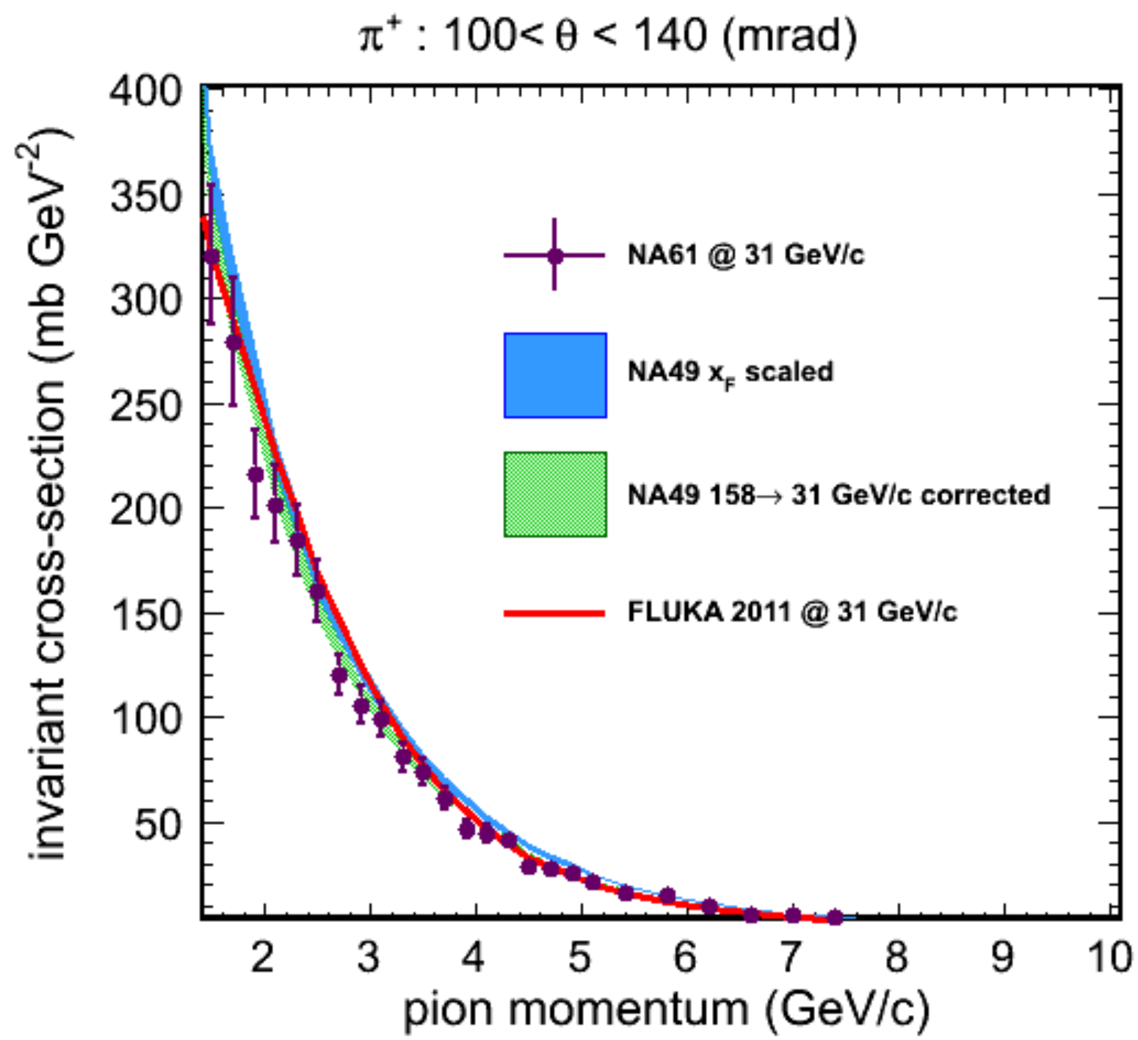
1. Use x_F scale to make f(NA49) to f(NA61 energy).
2. Account for the scaling difference with FLUKA.
3. Calculate NA61 bin-averaged invariant cross-section.



NA49 vs NA61

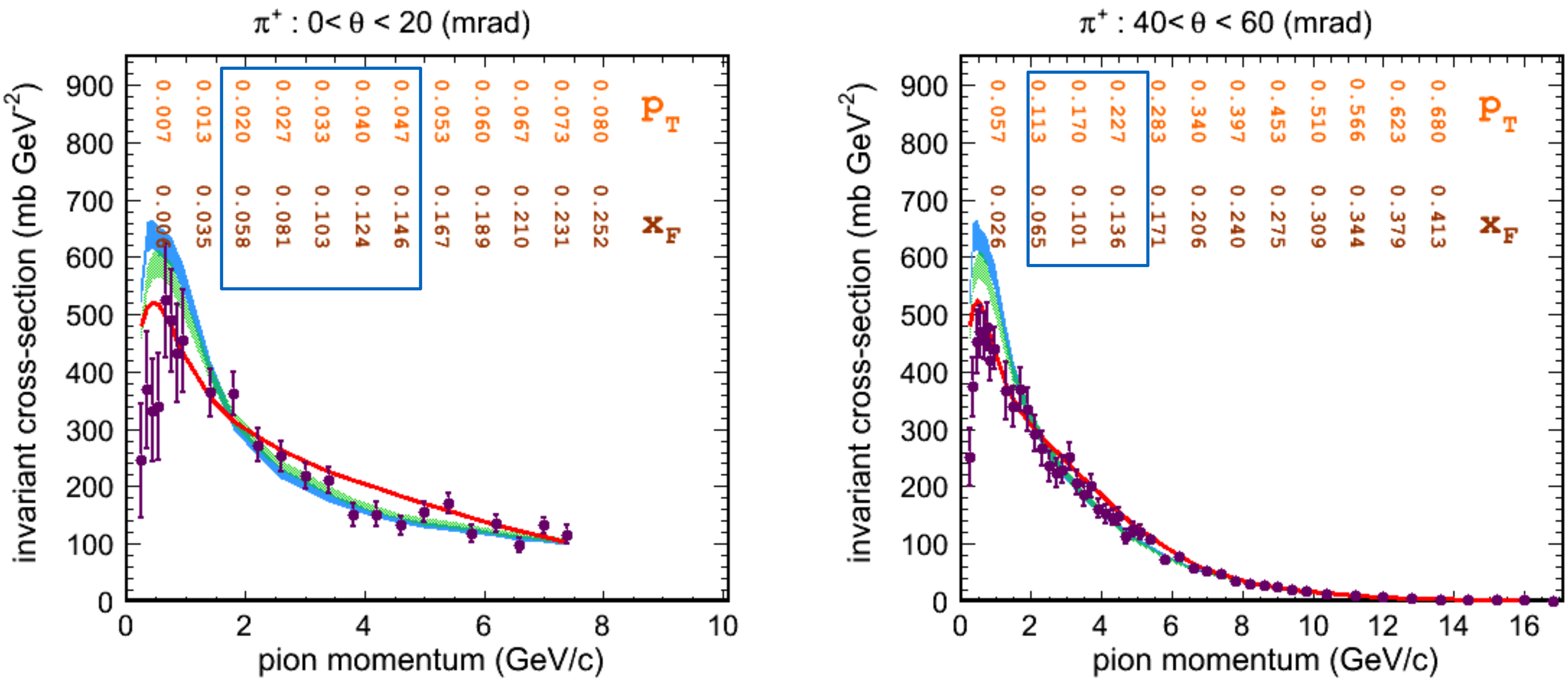


zooming the relevant region for NuMI flux



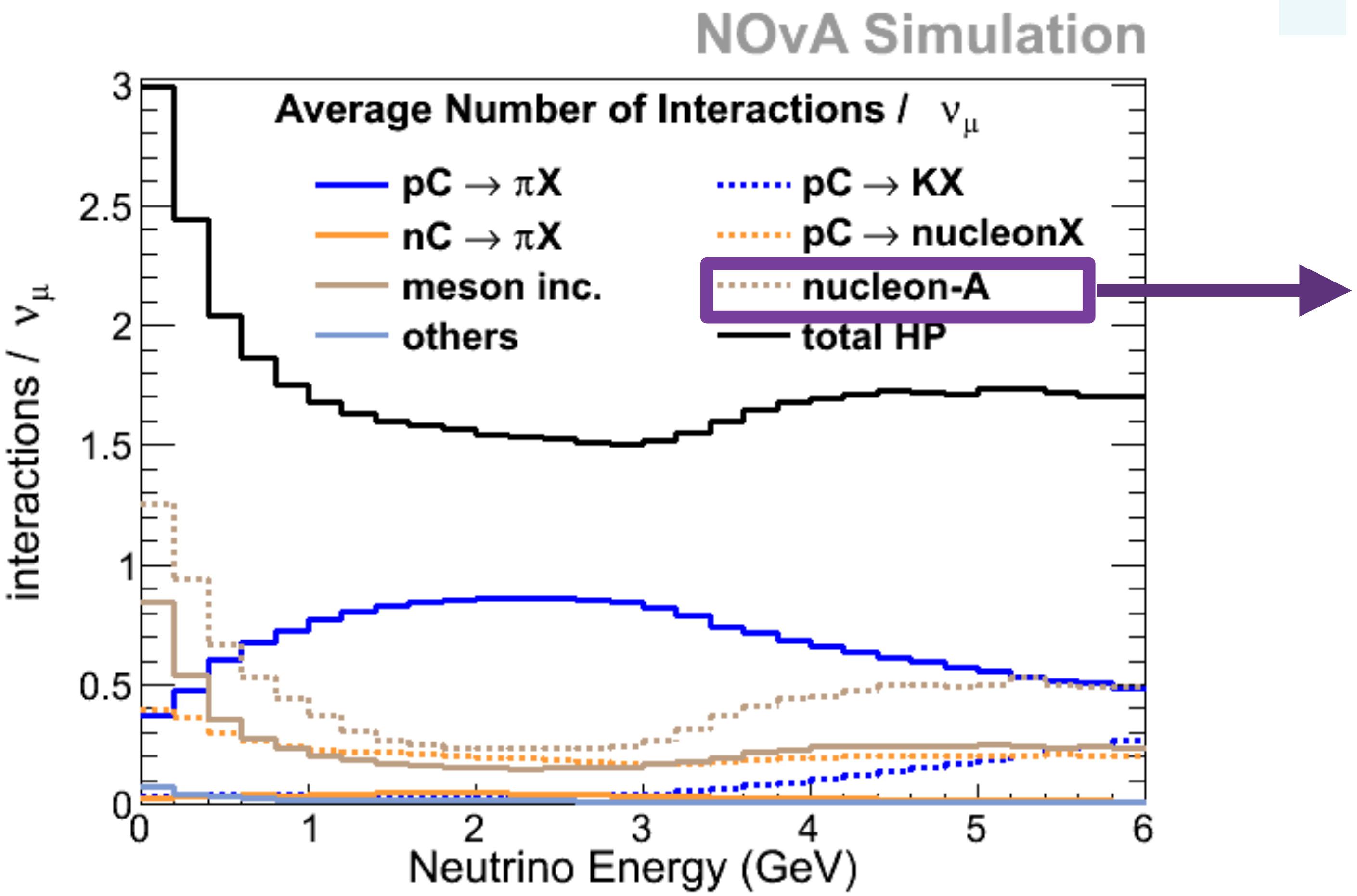
- Good agreement for medium and high pion energies
- Low pion energies are in disagreement.

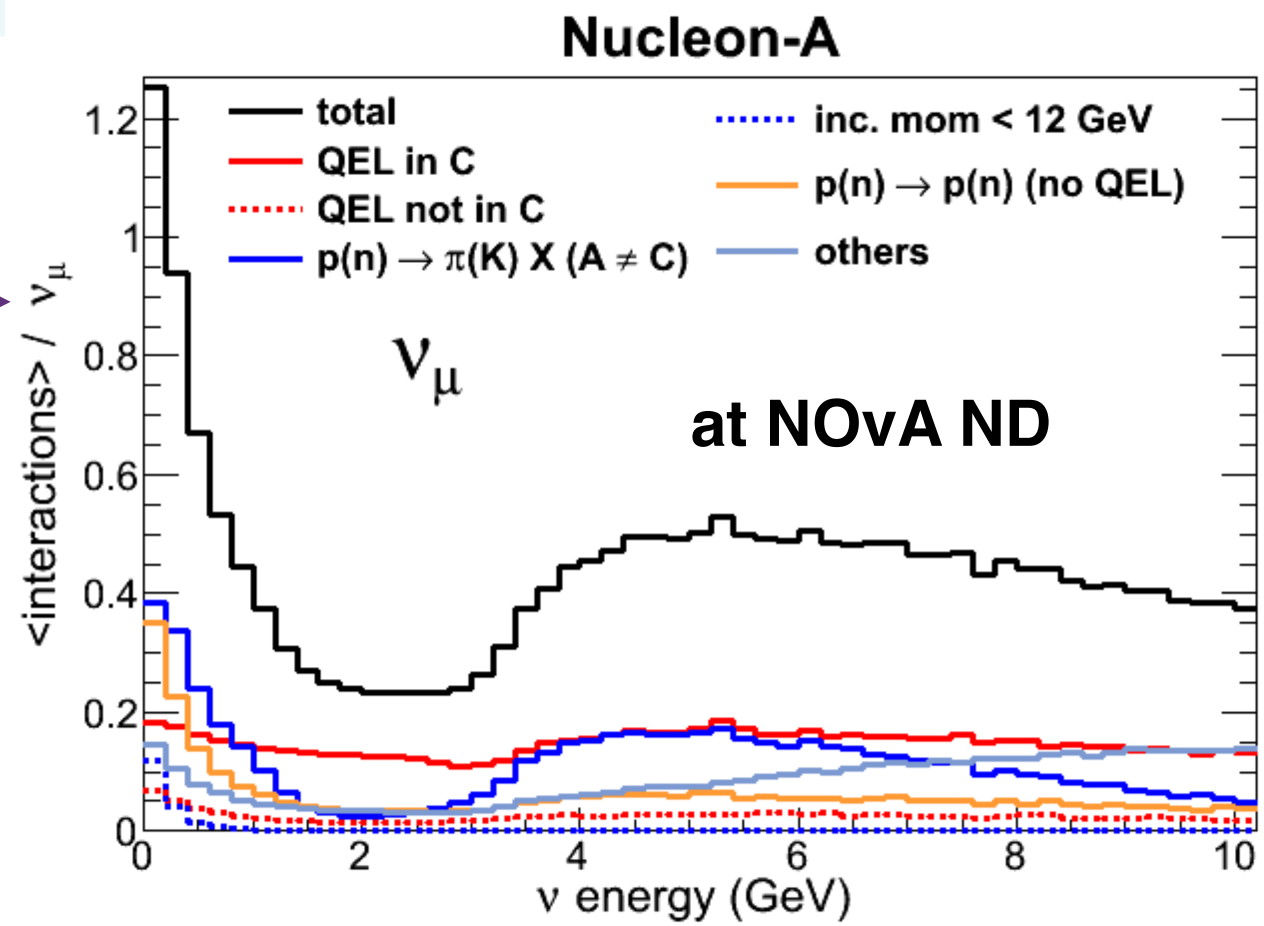
NA49 vs NA61



- Good agreement for medium and high pion energies
- Low pion energies are in disagreement.

Nucleon - A





QEL:

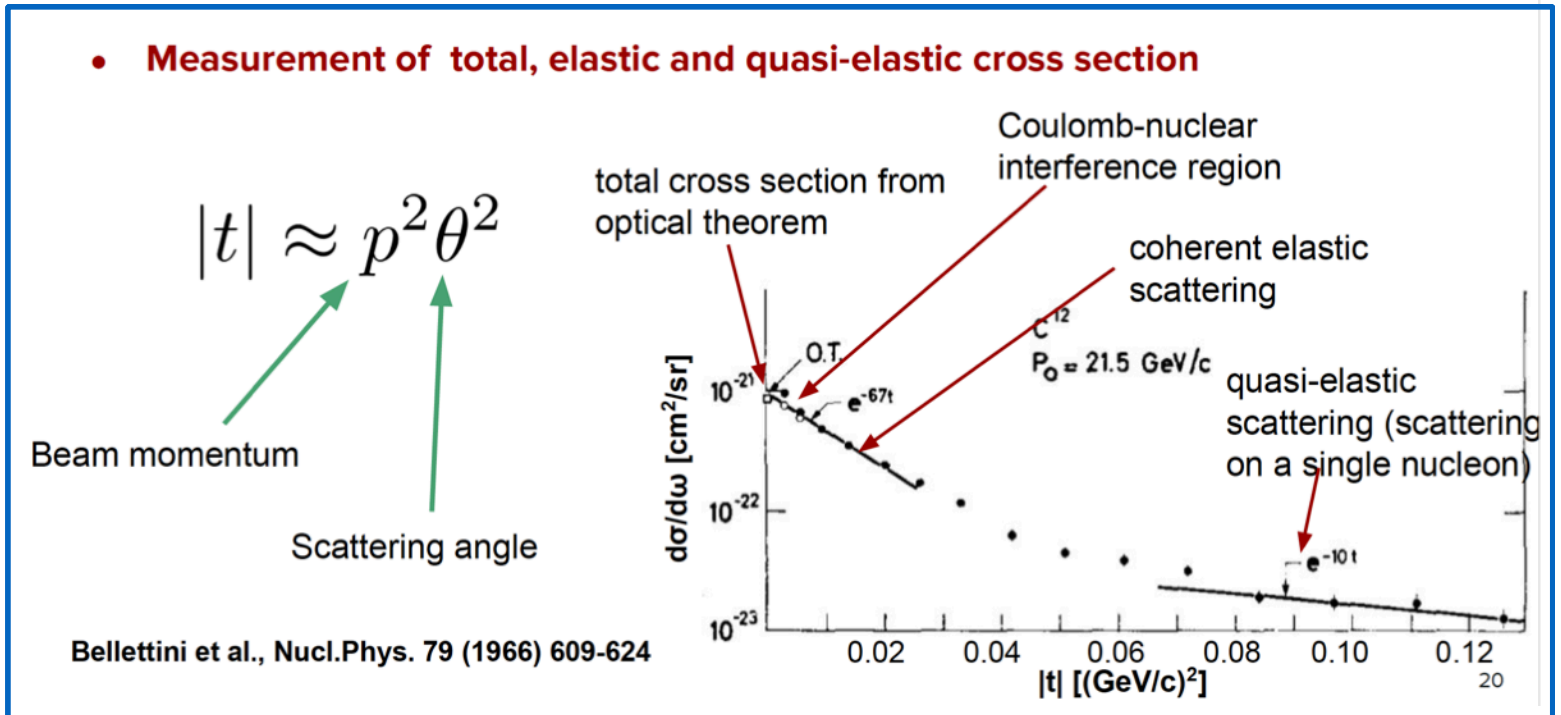
We select it as $x_F > 0.95$

p(n)->π(K)A (A!=C):

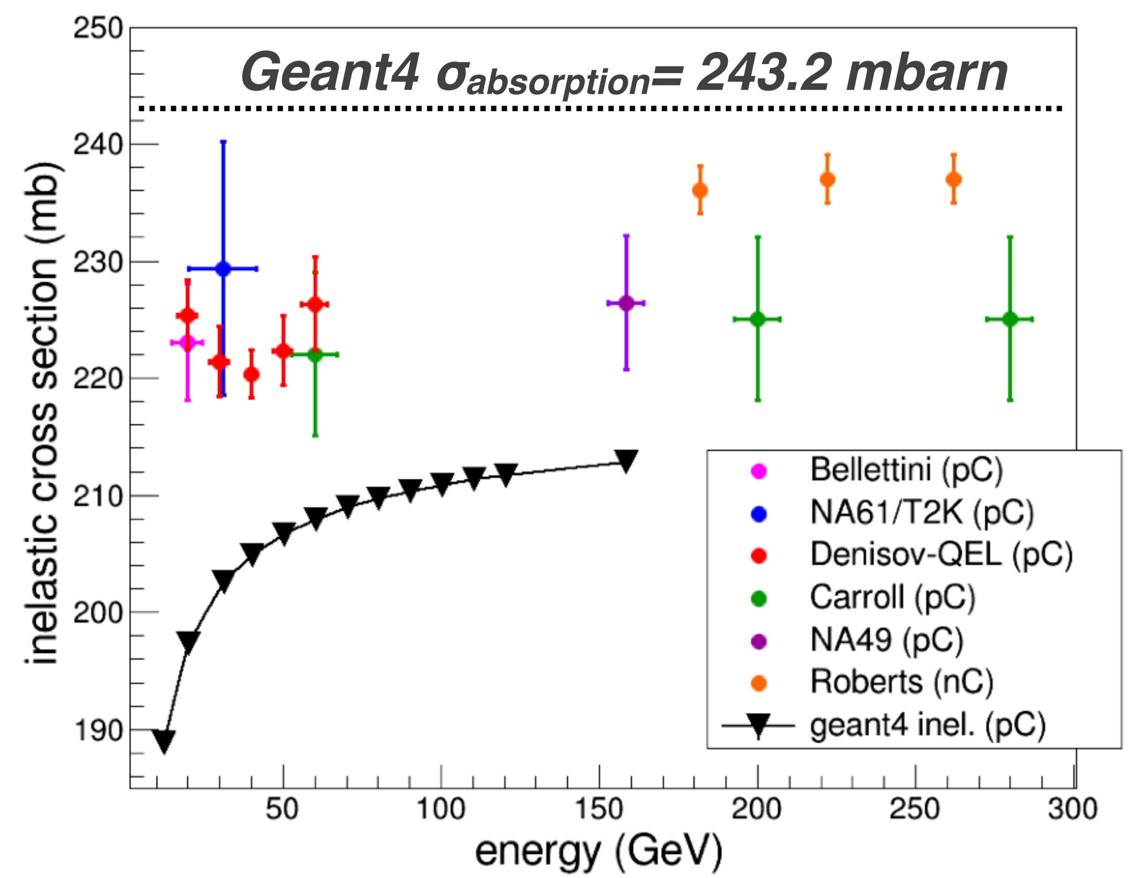
- **Extend NA49 pC adding an additional uncertainty to scale between materials.**
- **K^0 and Λ^0 production at 300 GeV in Skubic and check with Barton at 100 GeV.**

Quasi-elastic:

proton on Carbon -> proton (fast, $x_F > 0.95$) + fragments



Fermilab JETP Seminar, Matej Pavin 2019

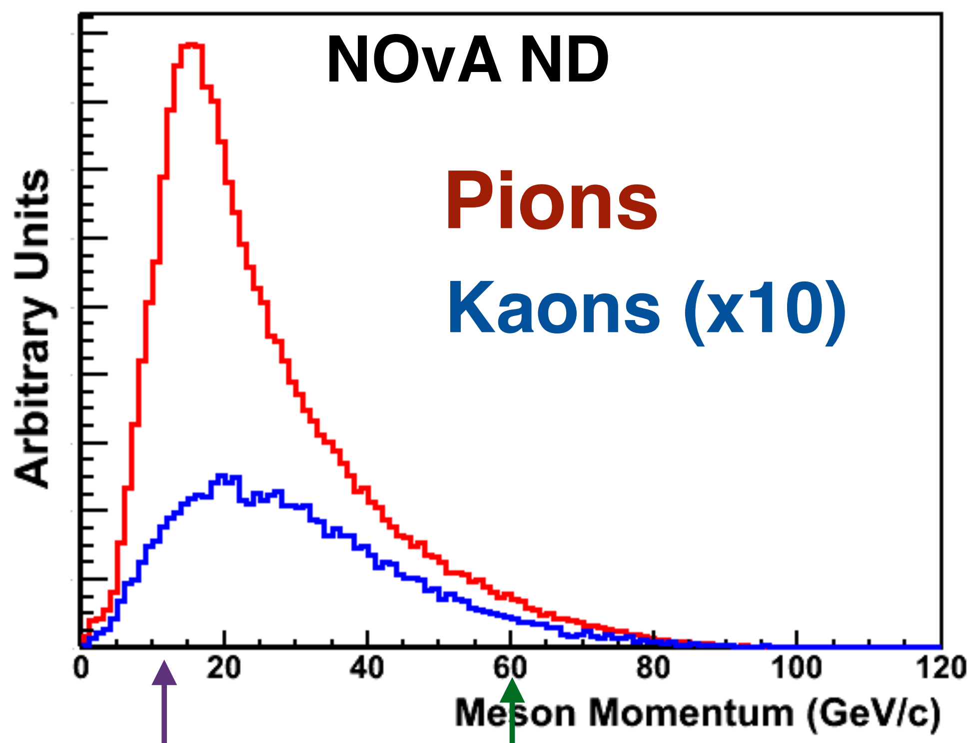


Belletini QEL of pC at 20 GeV: the only measured data for this channel.

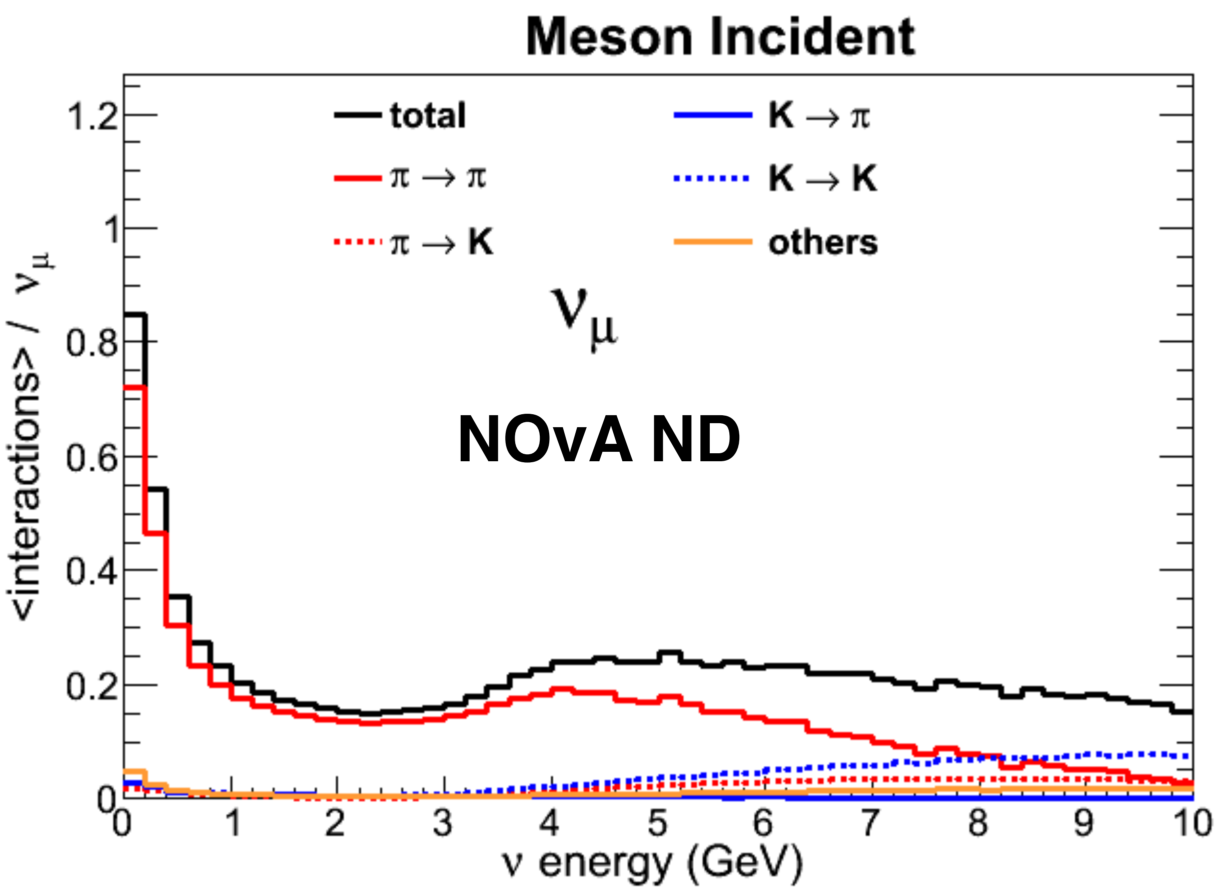
We assumed 40% uncertainty.

QEL-subtracted inelastic cross section in GEANT4: **energy dependence not in data**

Pion making pions



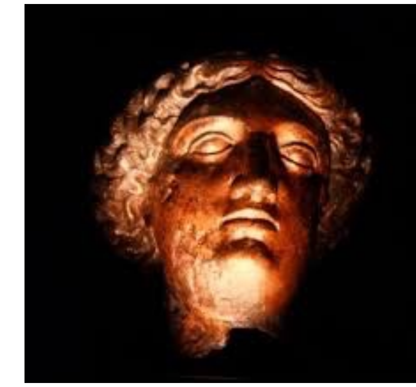
Main contribution from π -> π the whole neutrino energy spectrum



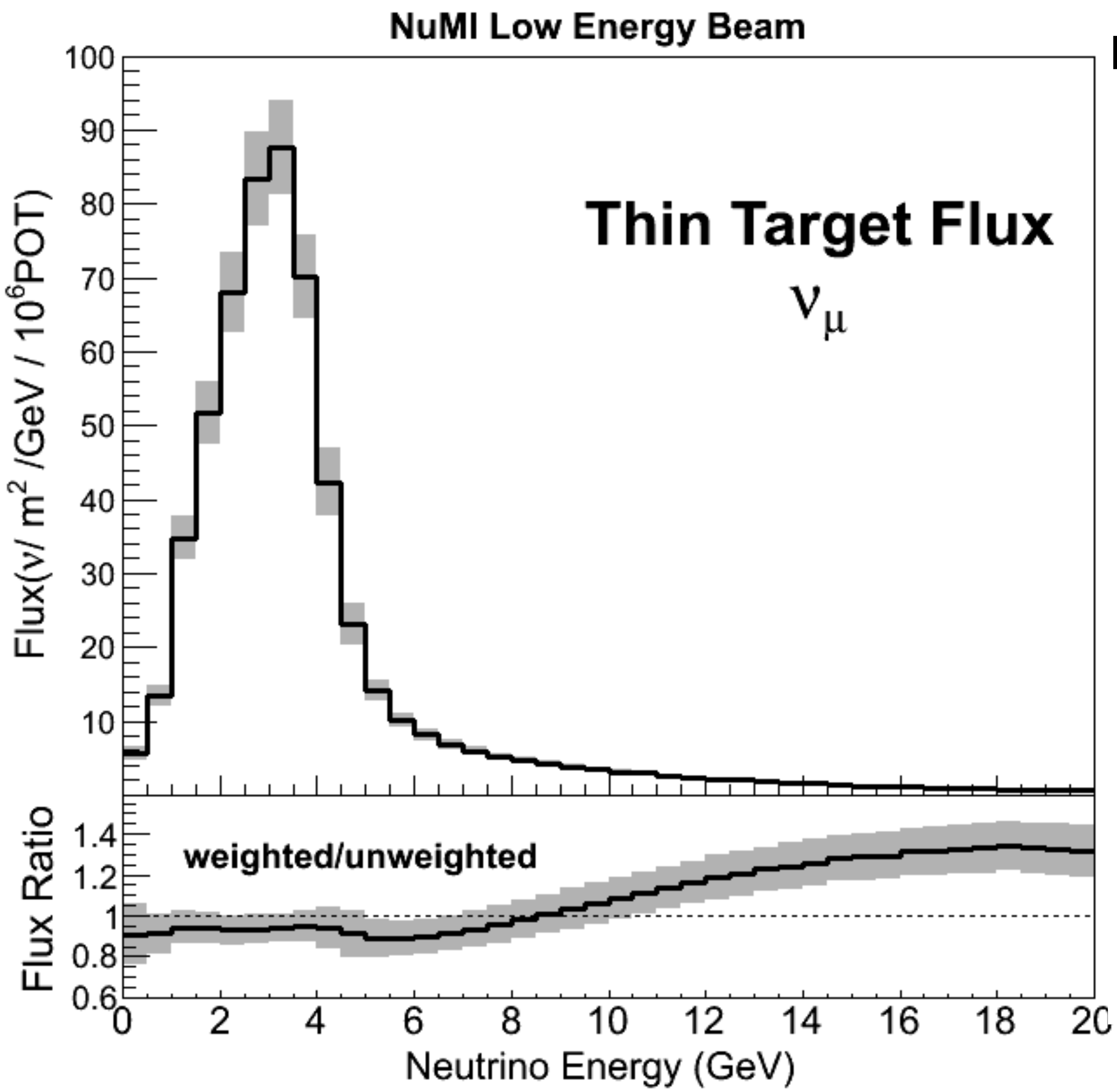
NA61 just released data for π+ on Be and C
arXiv:1909.06294

HARP measured π+- data on carbon and other materials but with limited coverage for from NuMI
Nucl.Phys.A 821:118-192, 2009

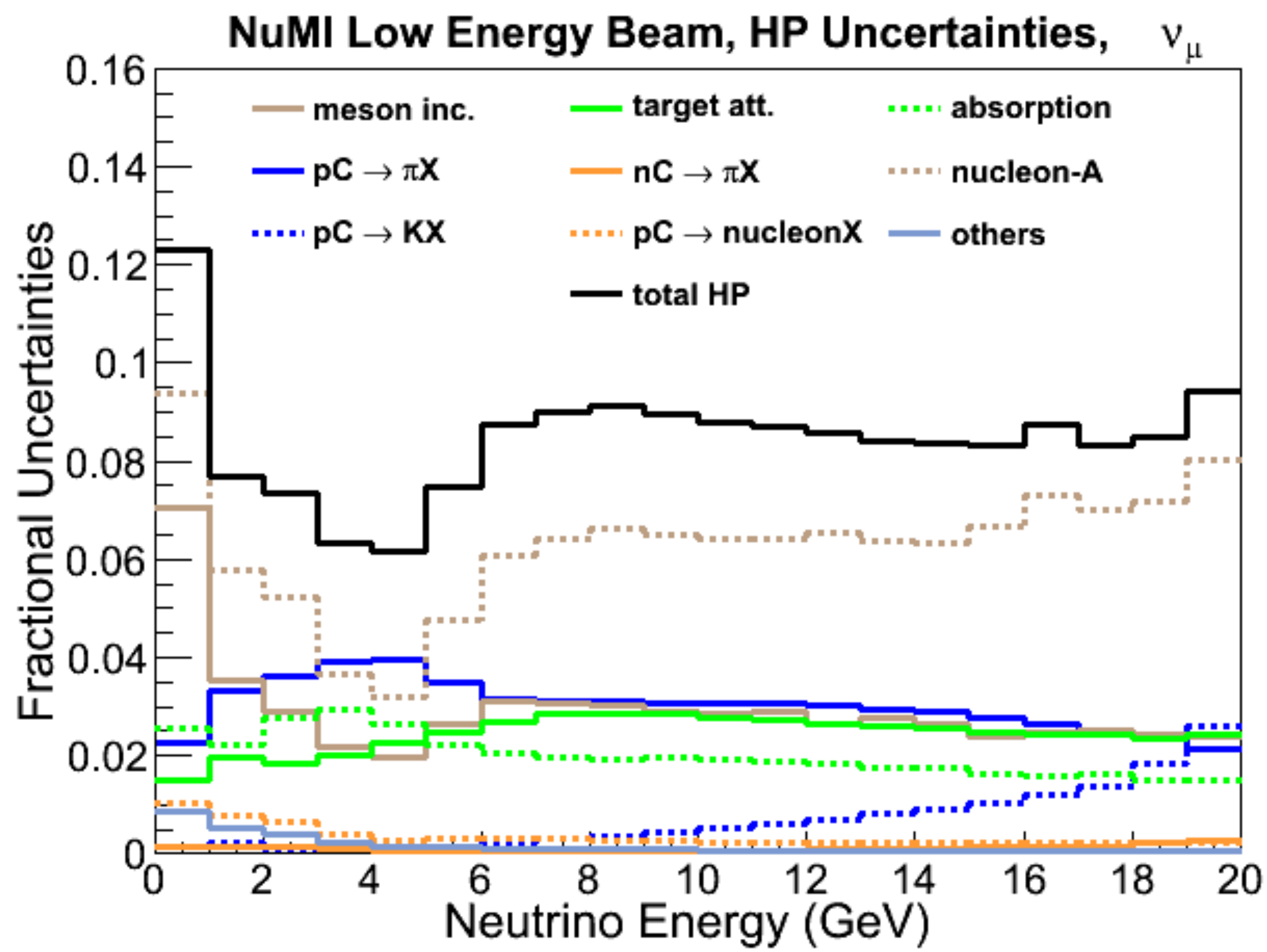
A Priori Flux Results for LE MINERvA



- MINERvA published the flux prediction for LE NuMI beam based on thin target data correction

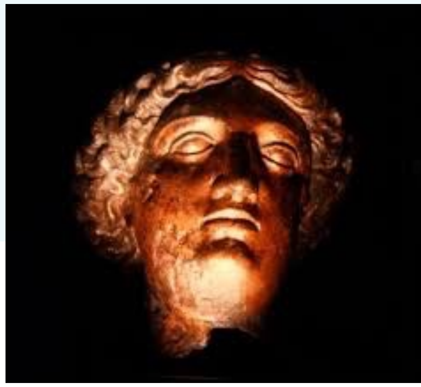


Phys. Rev. D 94, 092005 (2016)



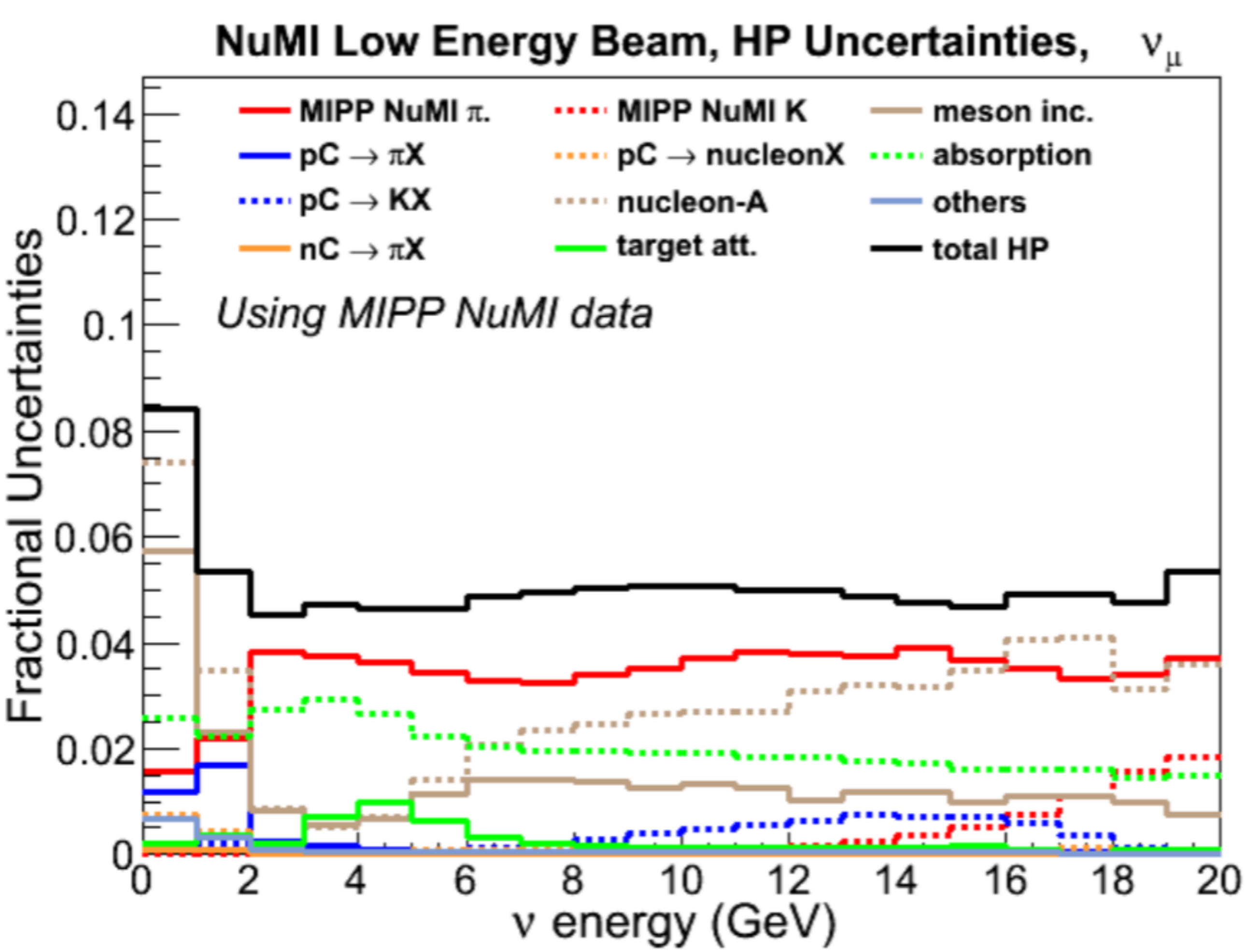
Results consistent with the nu-on-e scattering and low-nu flux.

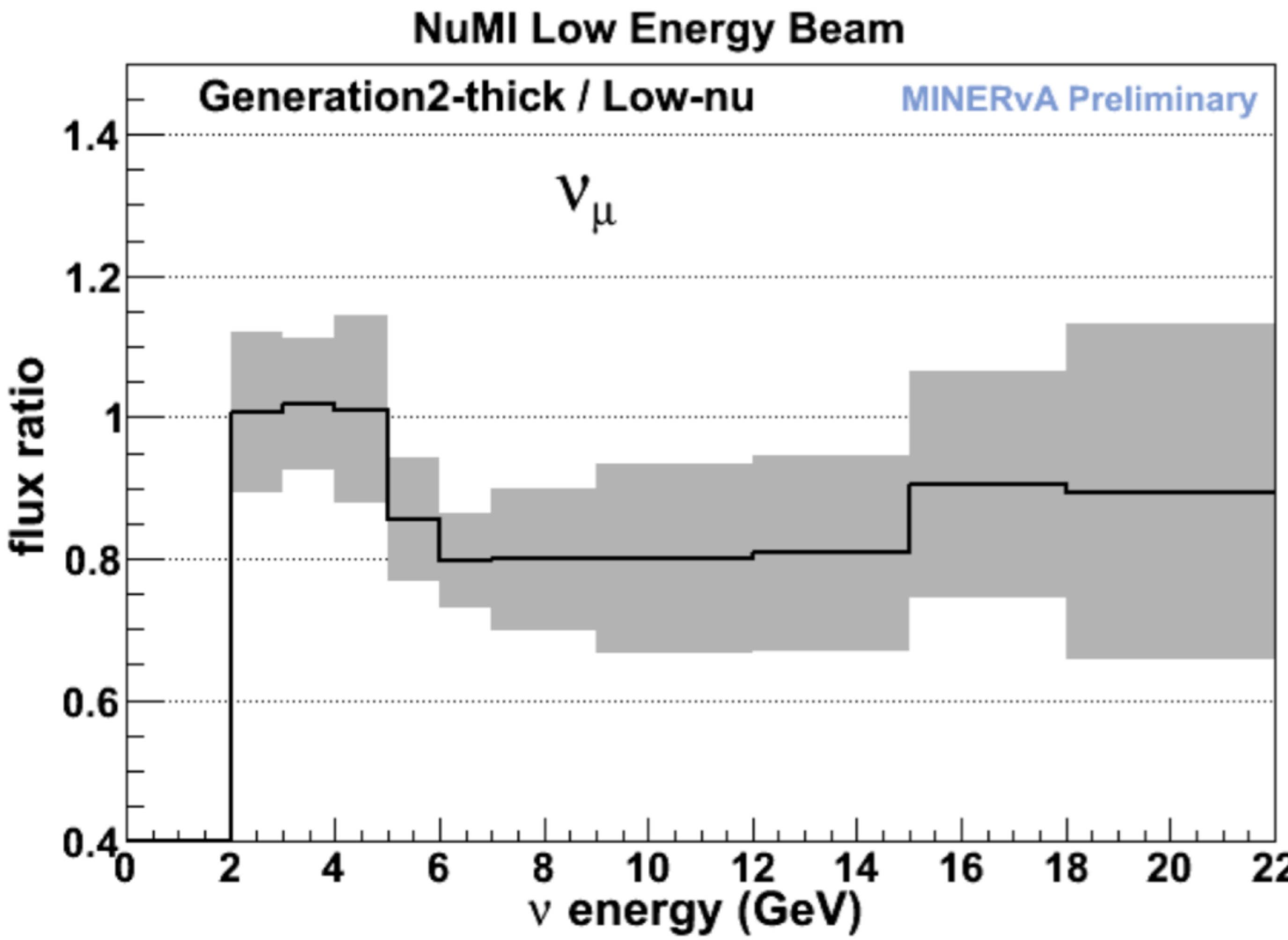
Thick Target fr MINERvA LE



Significant reduction of uncertainties by using thick tagets

Consistent with nu-on-e total flux but with the low-nu flux.

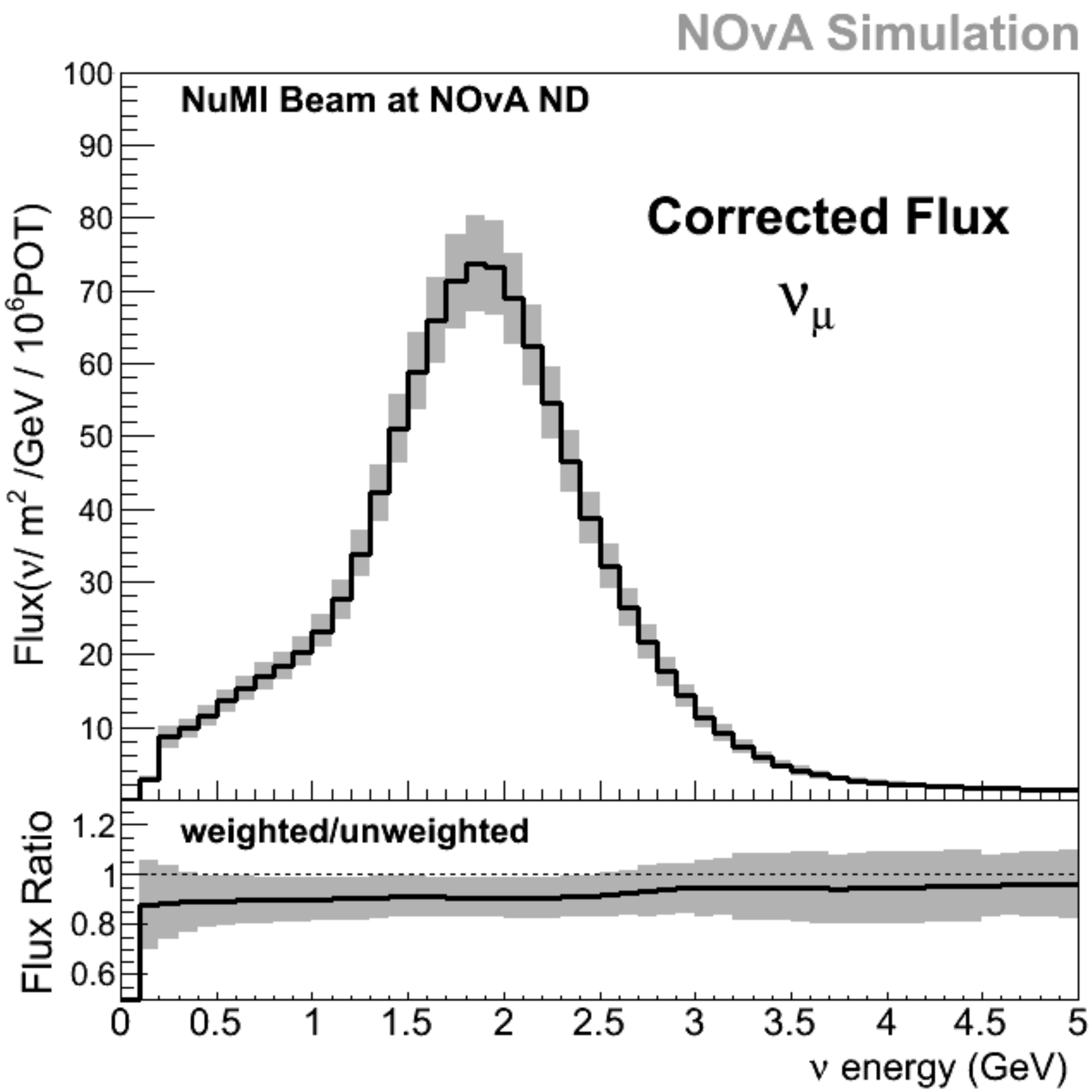


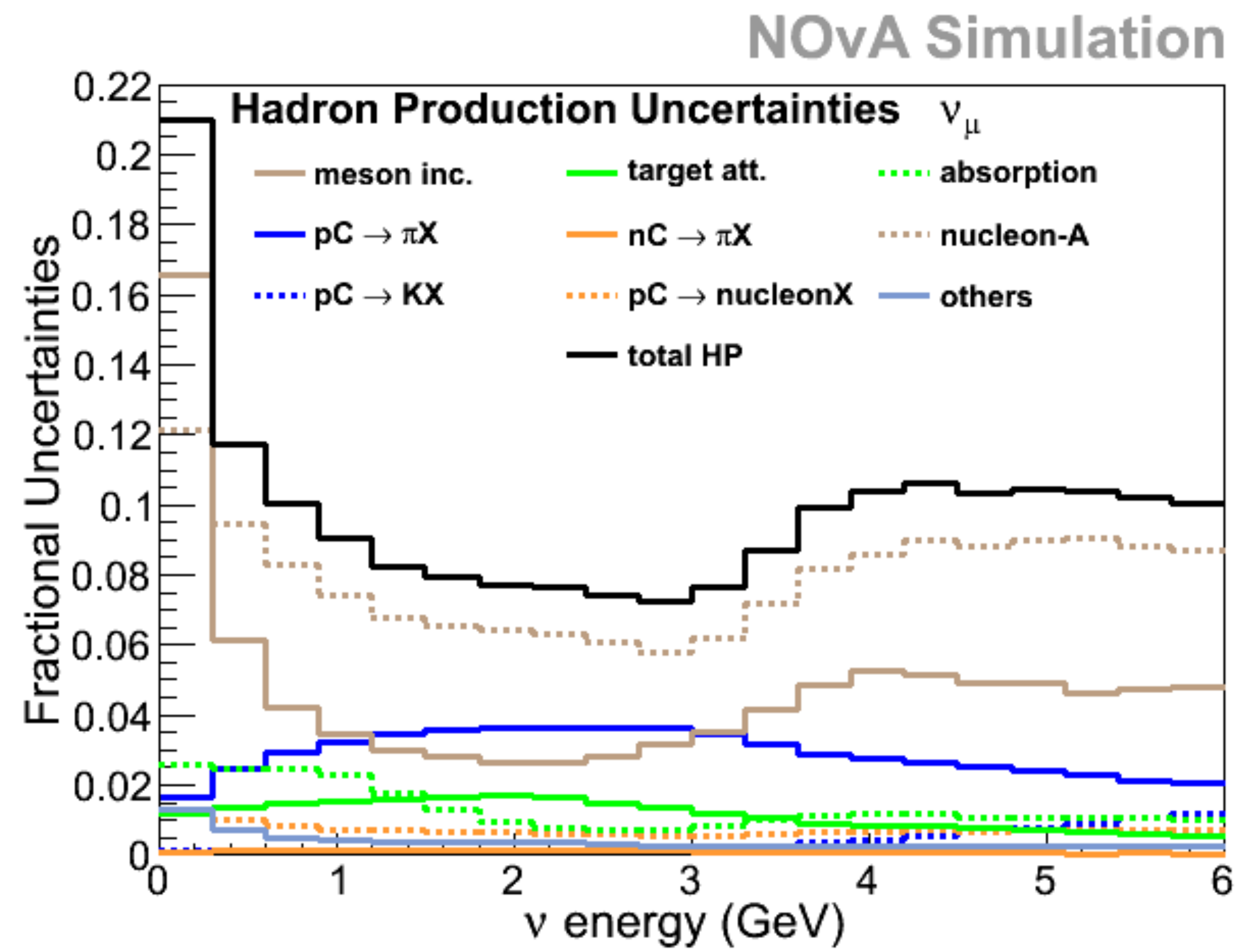


MINERvA decided to use thin-target flux production for all for its analyses.

A Priori Flux Results for NOvA Near Detector

- A fully implemented a priori flux prediction in NOvA

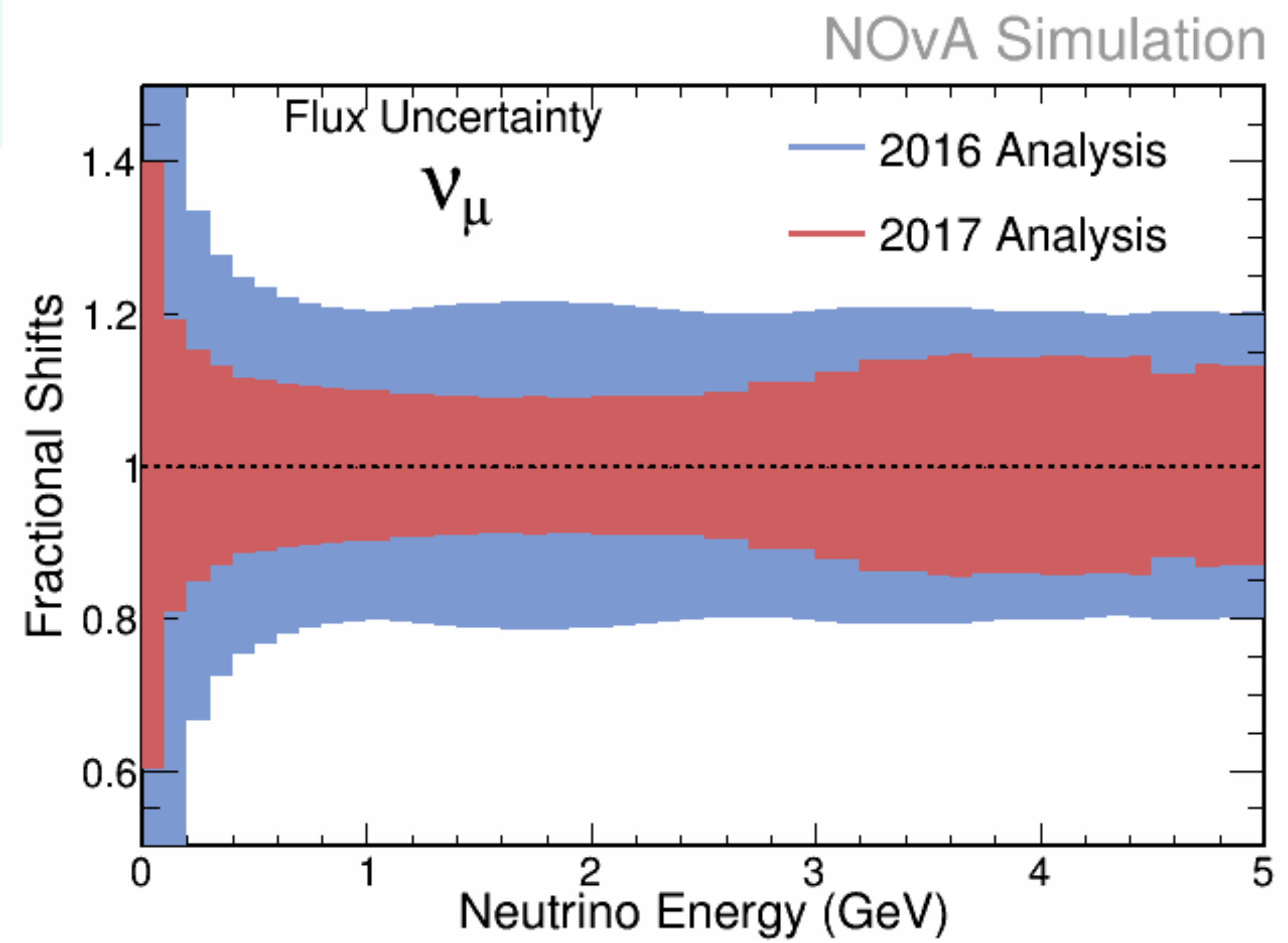


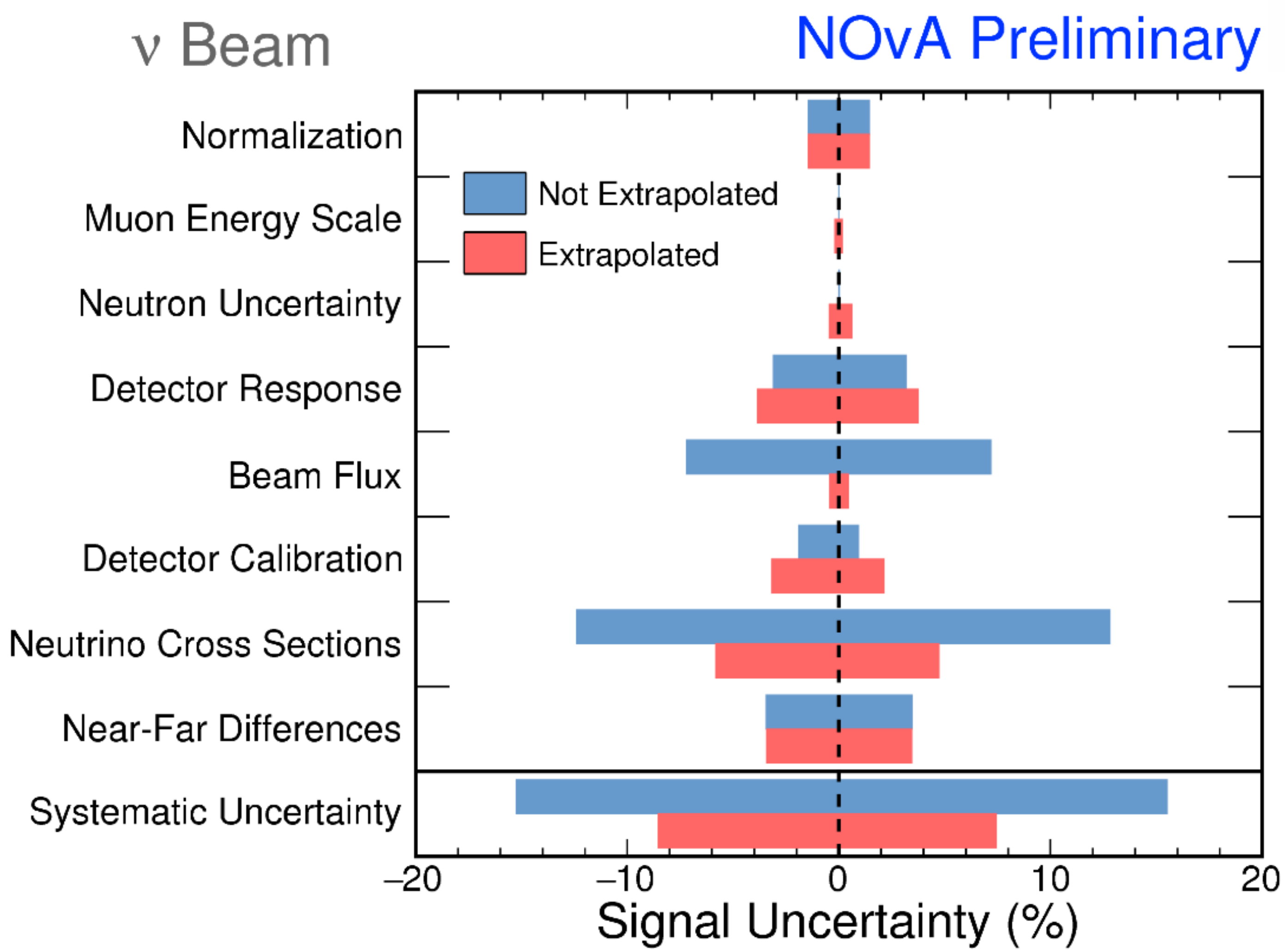


Effect on NOvA

ν_μ selection in the NOvA ND

Effects on using hard production data in constraining the flux



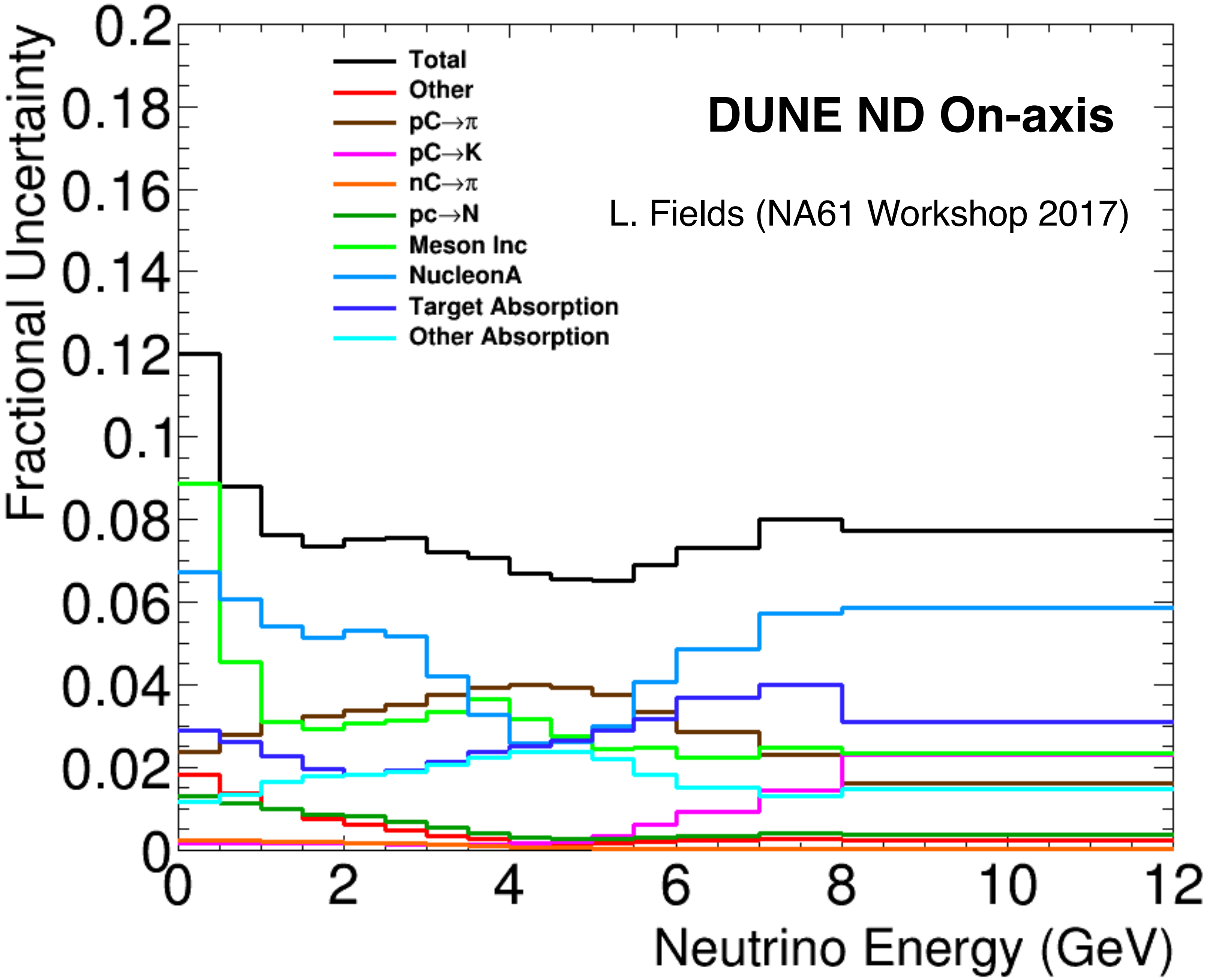


ν_e appearance systematics uncertainties

Comparison before and after extrapolation

DUNE HP Uncertainties

PPFX is used to calculate beam sensitivity in DUNE.



Conclusions

We calculated a beam uncertainty budget to ~7-8% including all data relevant for NuMI:

- MINERvA pioneered this work and use n all cross section analyses.
- NOvA is also using PPFX for its analysis program.

For DUNE, it also gets 8% uncertainty. A further improvement is possible (***target uncertainty at 3%?***)

- New HP data is needed.

Conclusions

Pion absorption cross section in carbon and aluminum

Differential cross section of of protons- and pion-incident cross-sections w.r.t (projectile energy, targets)

Proton quasielastic interactions w.r.t (projectile energy, Q^2, targets)

Thick target data

New data coming

EMPHATIC

Experiment to **M**easure the **P**roduction of **H**adron at a **T**est beam **I**n **C**hicagoland (Fermilab)

J. Paley, NBI 2019

Phase	Date	Subsystems	Momenta	Targets	Goals
1	Spring 2020	Beam Gas Ckov + Beam ACkov + FTBF SiStrip Detectors + Small-acceptance magnet (borrowed) + Downstream ACkov Time-of-flight	4, 8, 12, 20, 31, 60, 120	C, Al, Fe	Improved elastic and quasi-elastic scattering measurements, low-acceptance hadron production measurements
2	Spring 2021	Beam Gas Ckov + Beam ACkov + FTBF SiStrip Detectors + New Large-area SiStrip Detectors + Full-acceptance magnet + Downstream ACkov + Time-of-flight	4, 8, 12, 20, 31 60, 120	C, Al, Fe, H_2O, Be, B, BN, B_2O_3	Full-acceptance hadron production with PID up to 8 GeV/c
3	Spring 2022	Same as Phase 2 + Extended RICH	20, 31, 60, 80, 120	Same as Phase 2 + Ca, Hg, Ti	Full-acceptance hadron production with PID up to 15 GeV/c

SHINE

NA61/SHINE (CERN)

L. Fields, NBI 2019

Beam	Target	Year	Measurements
p@31 GeV/c	C	2007	$\pi^{\pm}$ [1], K^{+} [2], K^0_S, Λ^0 [3]
p@31 GeV/c	C	2009	$\pi^{\pm}$, $K^{\pm}$, p, K^0_S, Λ^0 [4]
π^+@31 GeV	C,Be	2015	Total Cross Section[5] (Magnet Off)
π^+@60 GeV	C,Be	2015	Total Cross Section[5] (Magnet Off)
K^+@60 GeV	C,Be	2015	Total Cross Section[5] (Magnet Off)
π^+@60 GeV	C,Be	2016	p, $\pi^{\pm}$, K^+, K^0_S, Λ [6]
p@60 GeV	C, Al, Be	2016	Total Cross Sections; Spectra Analysis in Progress
p@120 GeV	C, Be	2016	Total Cross Sections; Spectra Analysis in Progress

p @ 120 GeV/c of NOvA target, currently being analyzed

SPS **H**eavy **I**on and **N**eutrino **E**xperiment

backup

NOvA Beam Optics Uncertainties

This is calculated directly from the G4NuMI ntuples shifting components by their expected uncertainties and looking at the effect on the flux respect to neutrino energy.

Two assumptions:

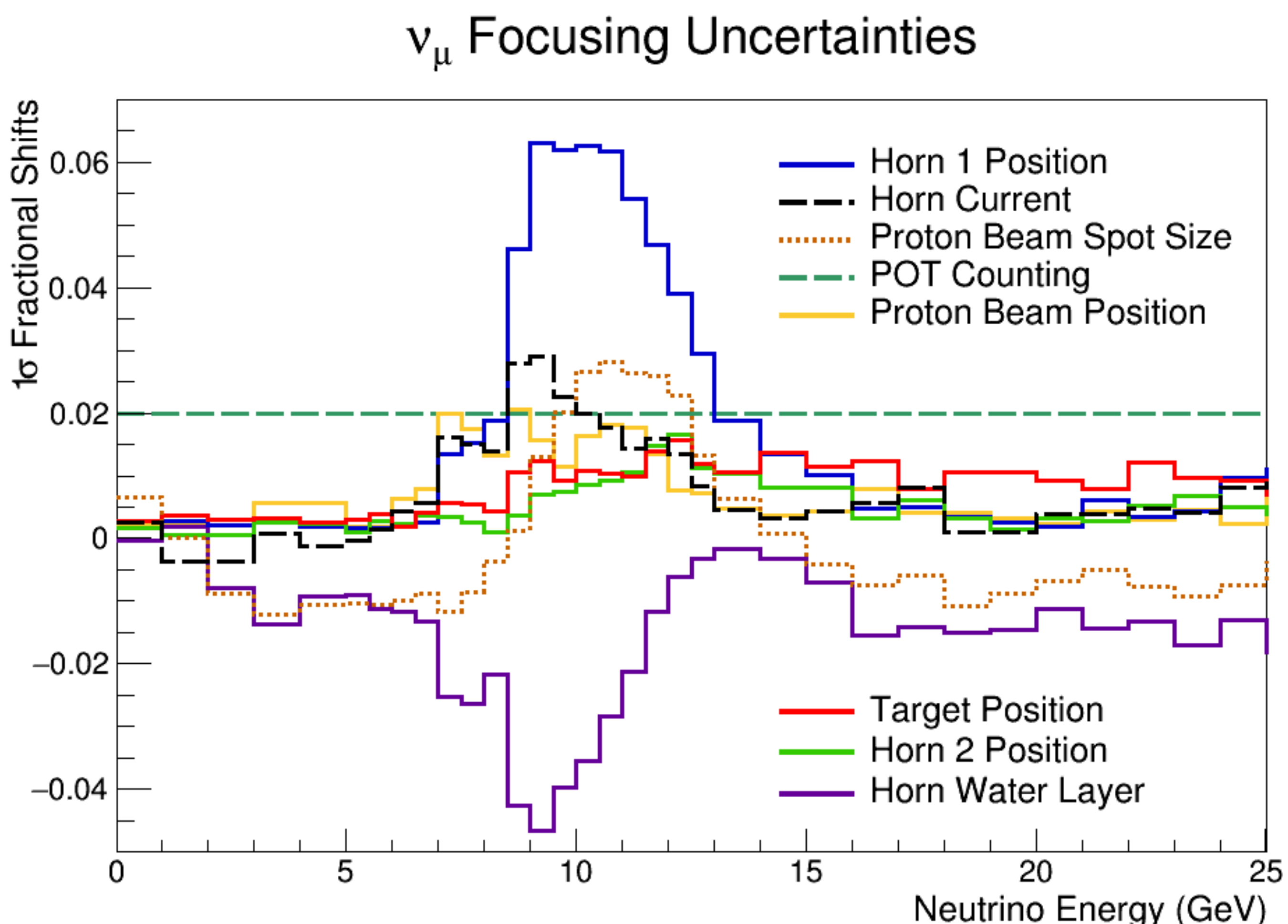
- We assumed that each systematics are independent each other.

- We only calculate +1 sigma shift (we assumed the beam shift and parameter misaligned have a linear relationship).

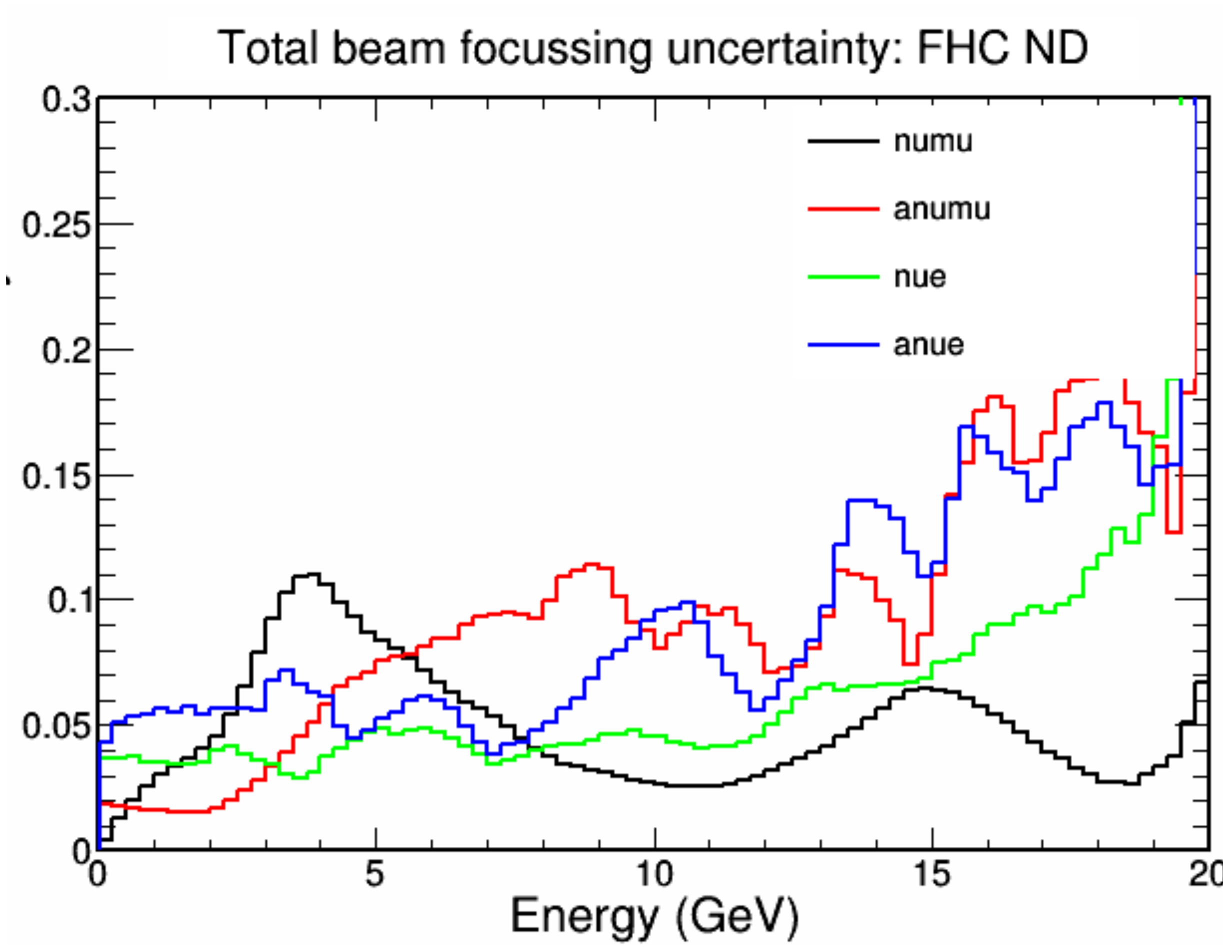
Horn Current $\pm$2kA
Horn1 X $\pm$ 3 mm
Horn1 Y $\pm$ 3 mm
Horn2 X $\pm$ 3 mm
Horn2 Y $\pm$ 3 mm
Beam position on the target $\pm$ 1 mm in X[1]
Beam position on the target $\pm$ 1 mm in Y
Beam spot size 1.1 to 1.5 mm
Horn1 water layers $\pm$ 1 mm
Horn1 finer geometry description
Target position Z $\pm$ 7 mm
Magnetic field

[1] Uncertainty is 1/6 of the difference

- **MINERvA Medium Energy**
- **NOvA**



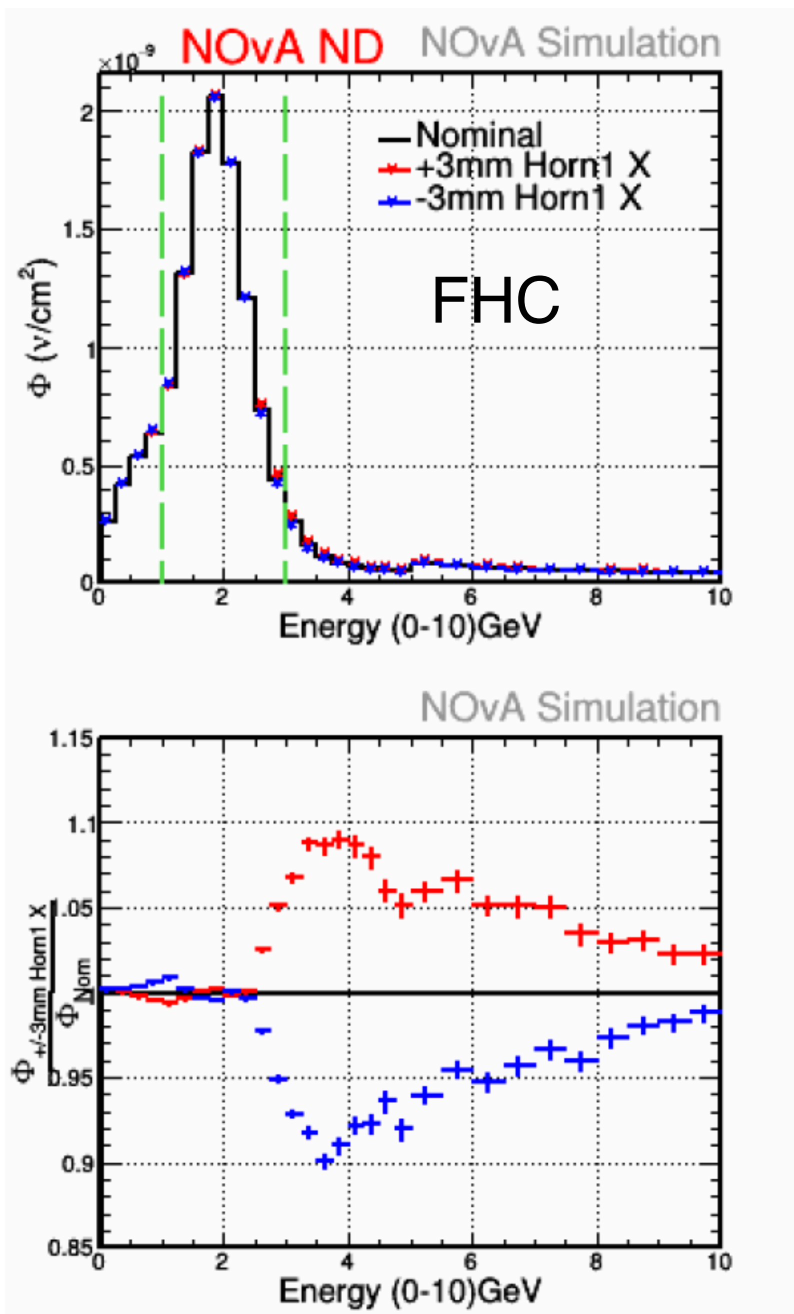
NBI 2019, Amit Bashyal

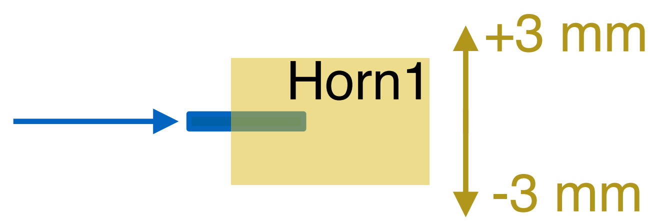


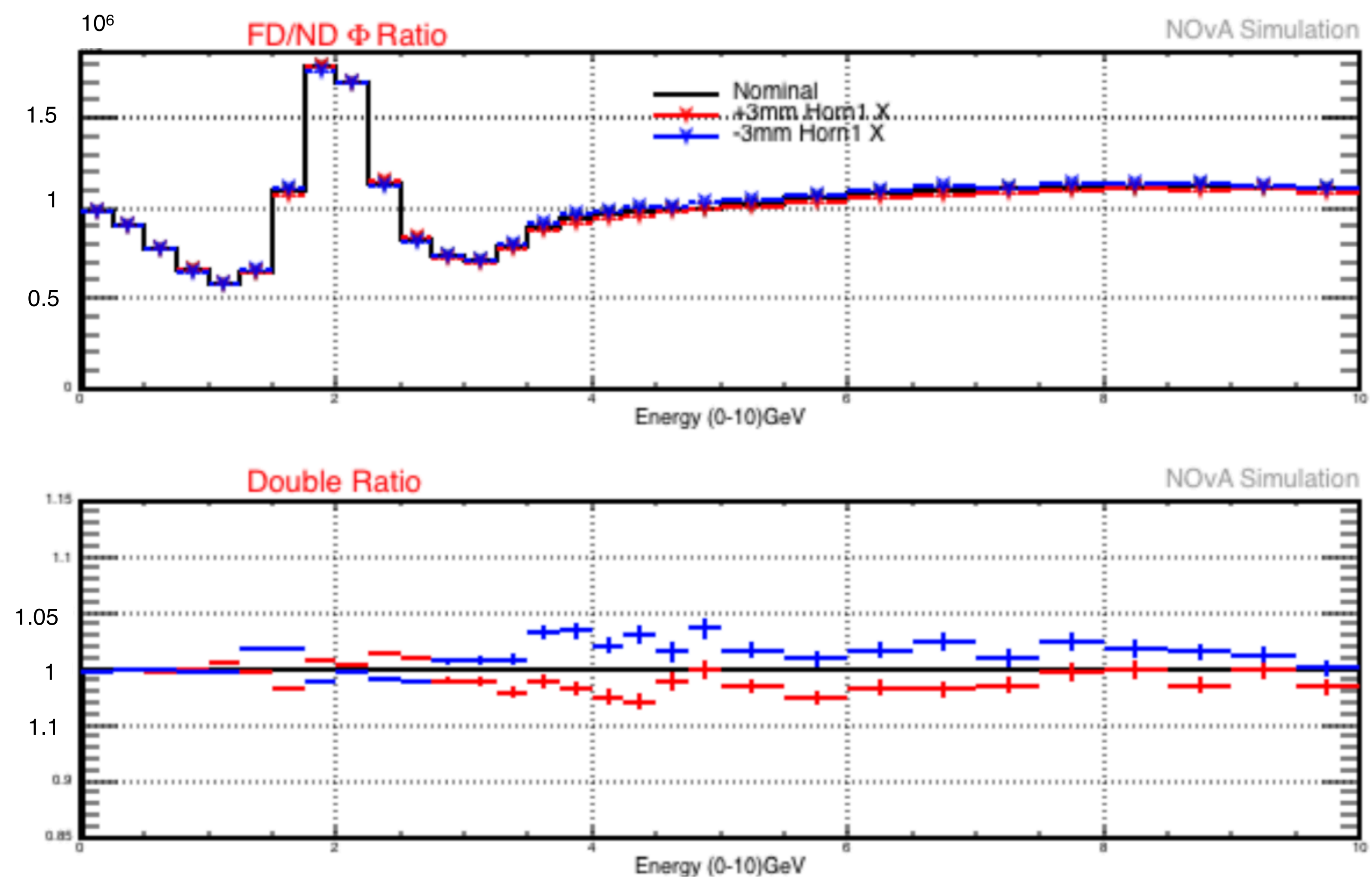
Beam Optics Uncertainties

- Biggest contribution comes from shifting the Horn 1 by +- 3 mm horizontally

NOvA ND



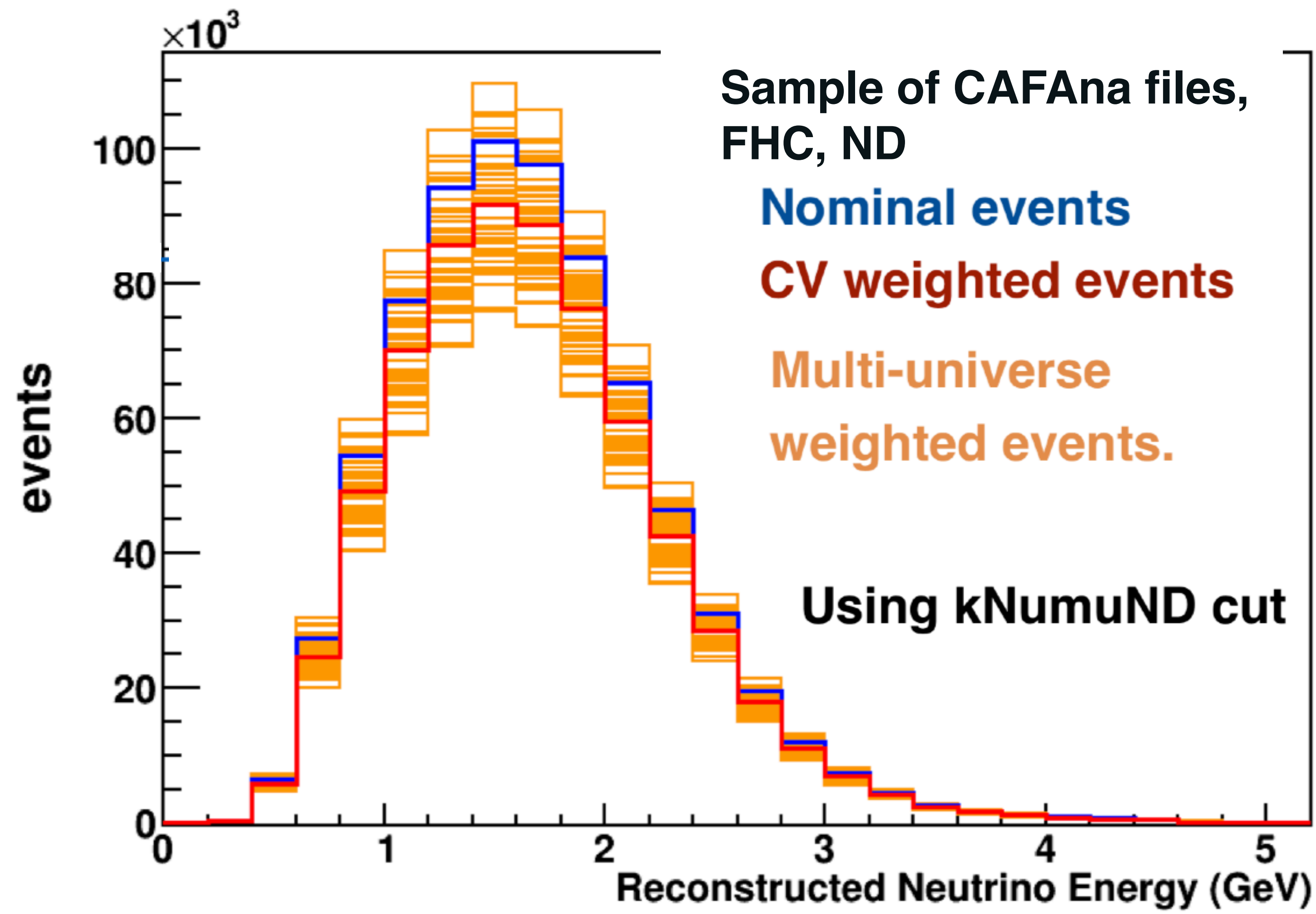




PPFX weights

- PPFX assigns a “central value” weight to each neutrino.
  - Filling a histogram (Spectrum) with these weights gives you the best guess prediction.
- PPFX assigns N additional “multi-universe” weights to each neutrino.

- Each universe has underlying data cross-sections shifted randomly according to joint covariance matrix.
  - A shift is made for a parameter with a determined random seed for a particular universe. This ensures repeatability.



If There is not Direct Data

Extending the data coverage

- Constrain pA interactions with pC adding an additional uncertainty found by comparing A dependence of Barton, Skubic and Eichten.

- Use theoretical guidance (isospin arguments, quark counting arguments, etc.)

What if data is not available?

- Guided by the agreement with other datasets: processes categorized by projectile and produced particle. 40% error assigned in 4 x_F bins, such us:

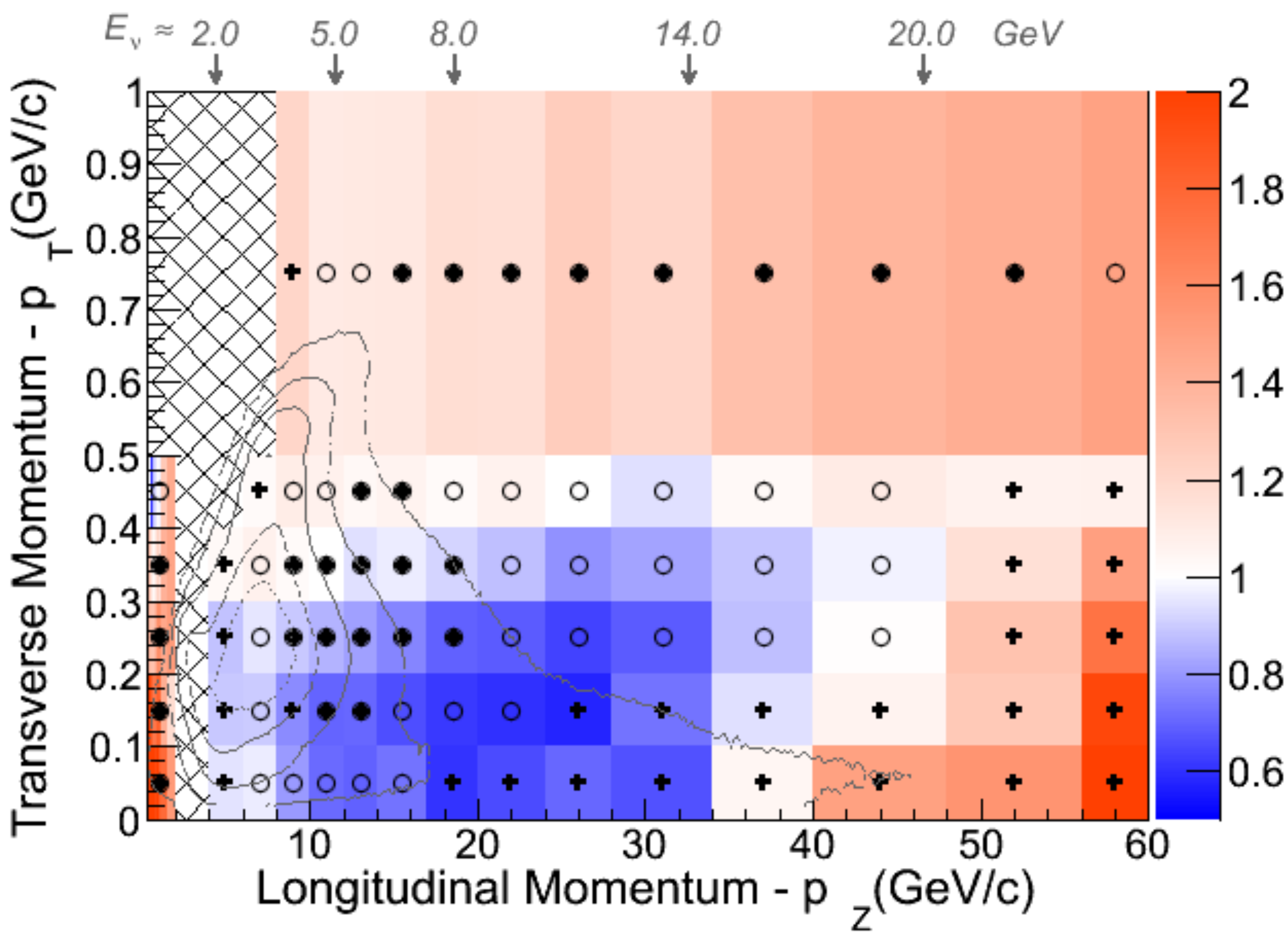
MIPP NuMI Data/MC comparison (closed circles = statistical error < 2.5%, Open circles = statistical error 2.5-5.0%, Crosses > 5%).

LE Mode On-Axis

Contours: 2.5, 10, 25, 50 and 75 % of the pion yields.

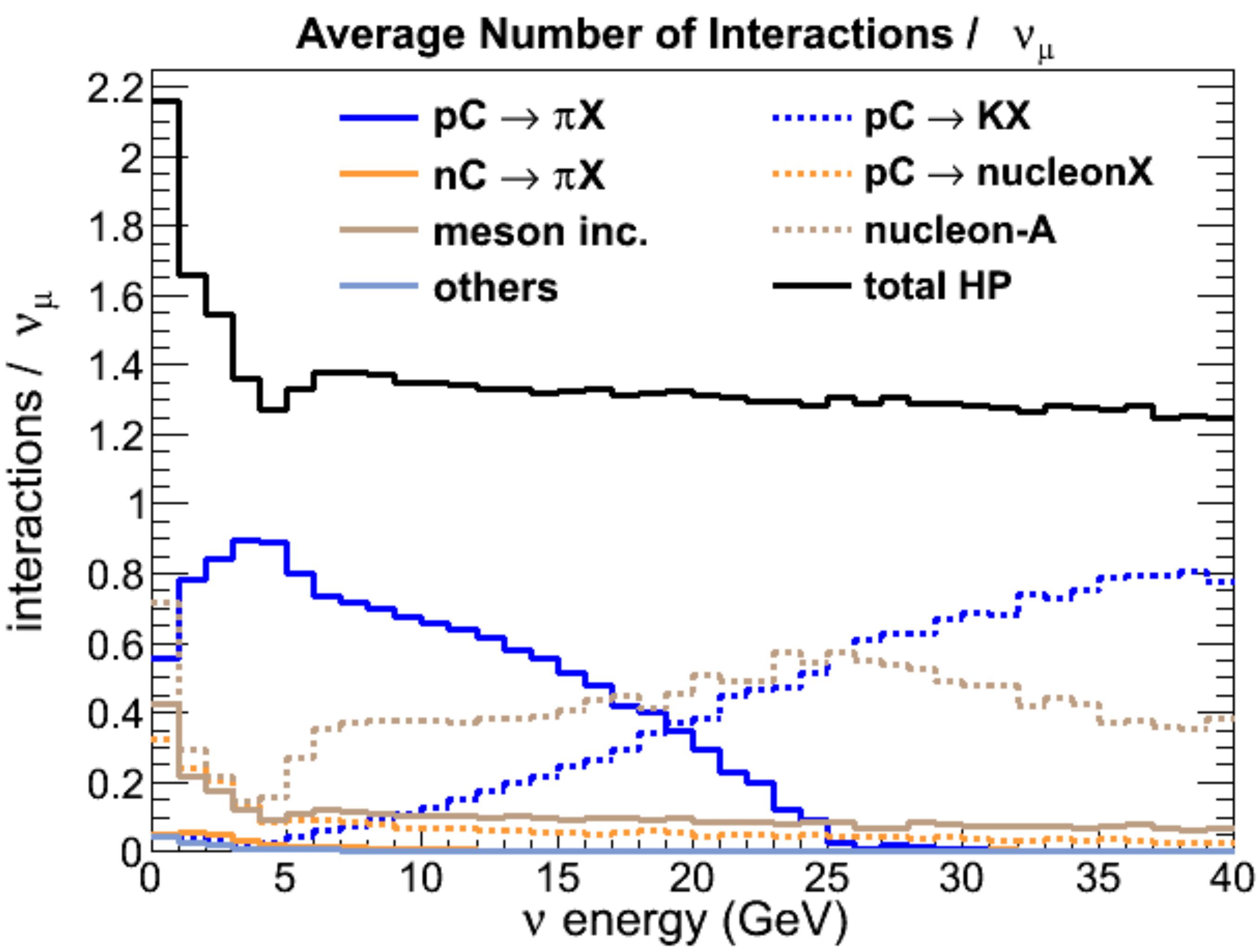
- Systematics are highly correlated bin-to-bin.
- Systematics and statistical errors are considered uncorrelated each other.

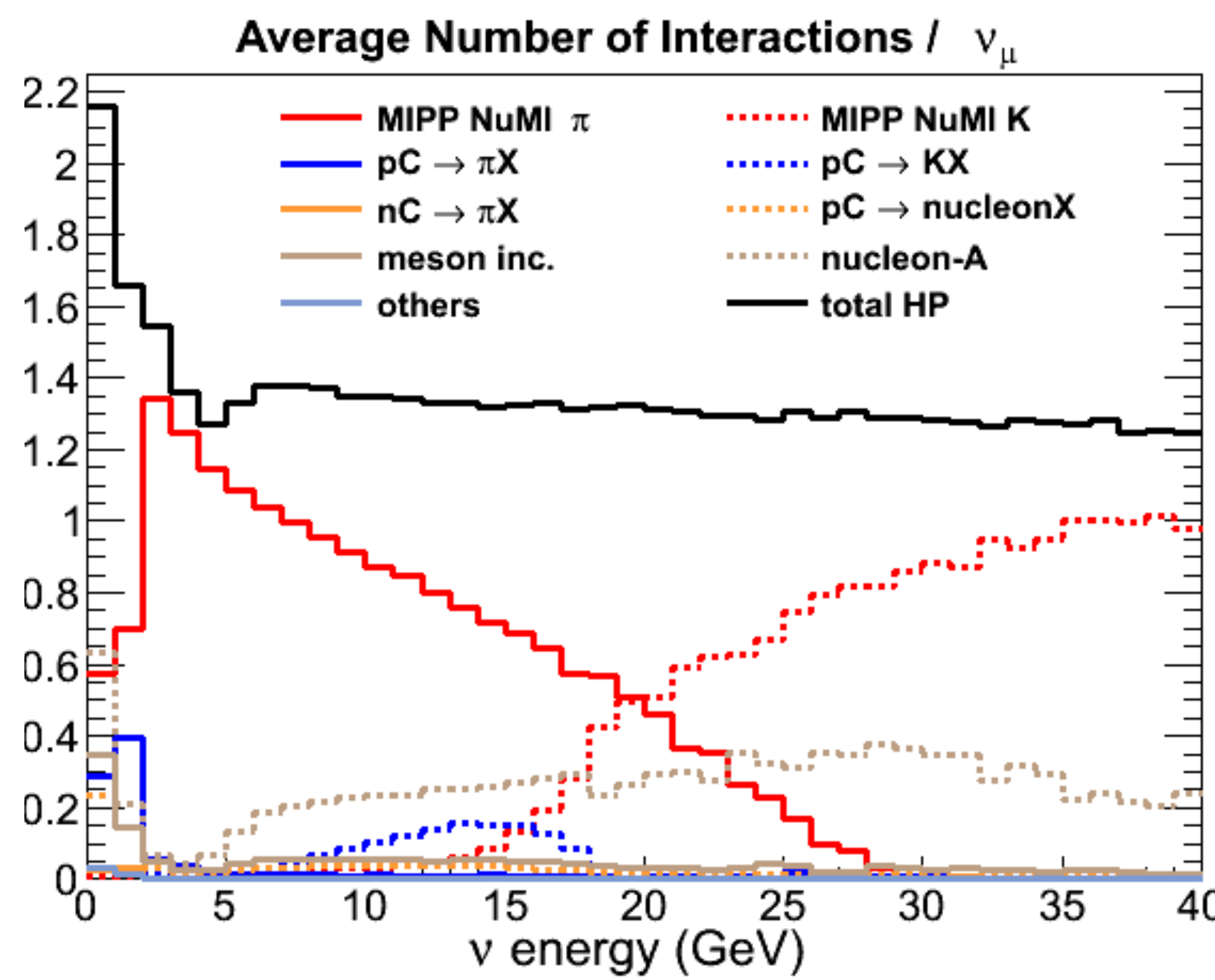
pNuMI -> π^+X



systematic uncertainties = 3.8% (added in quadrature).

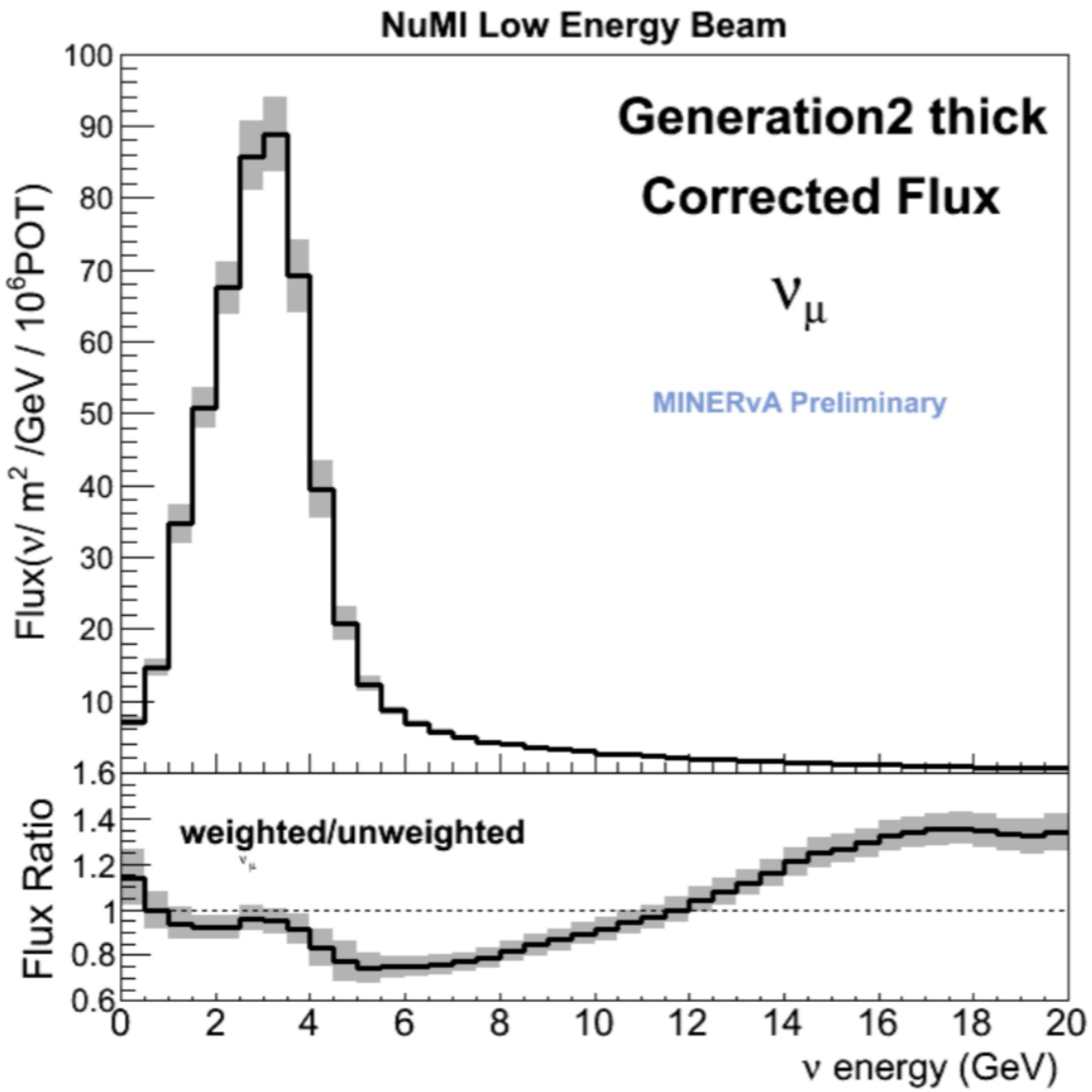
Advantage to use thick target data

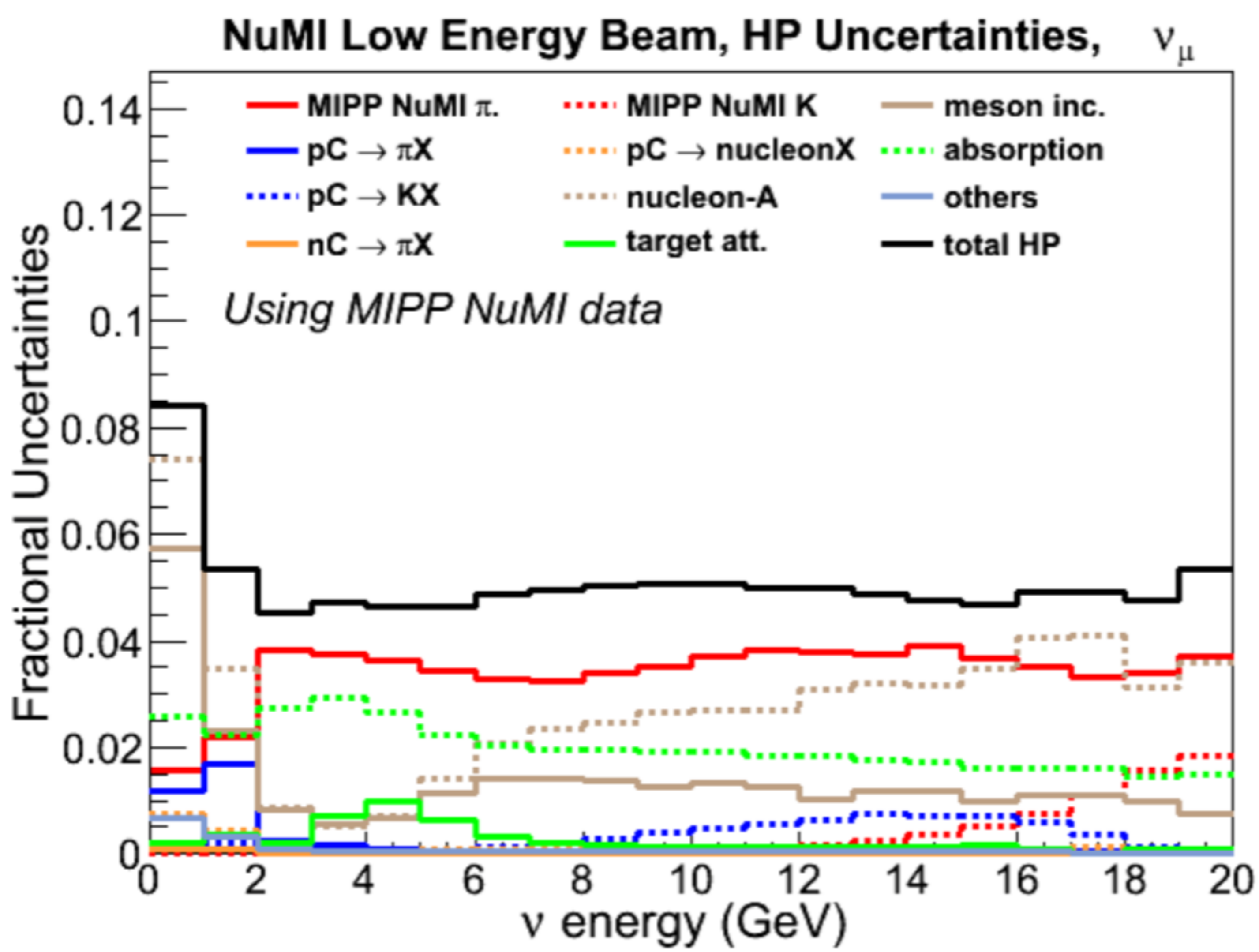




Thick Target Data Flux

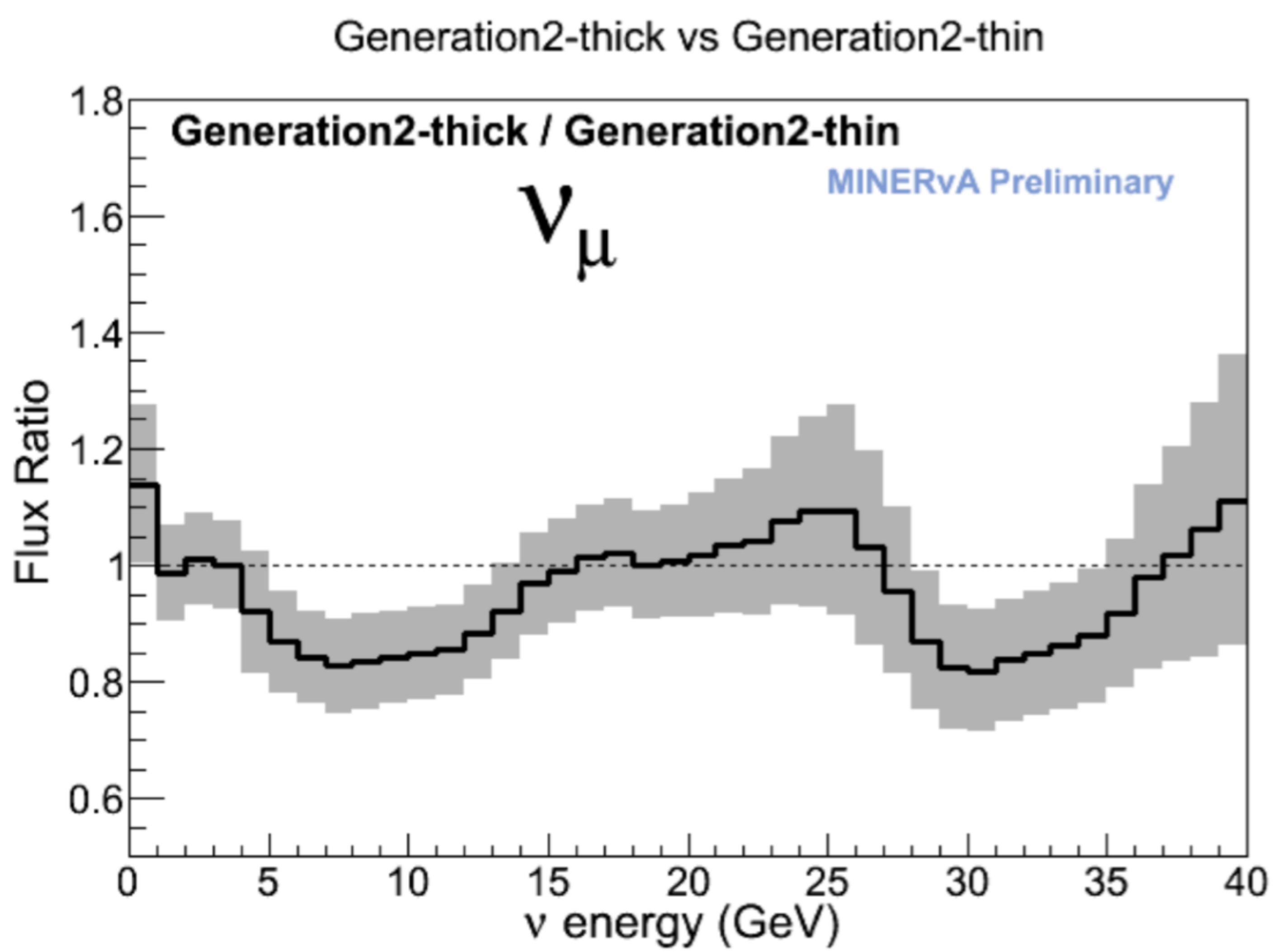
Gen2-thick





Thin - Thick Flux Comparison

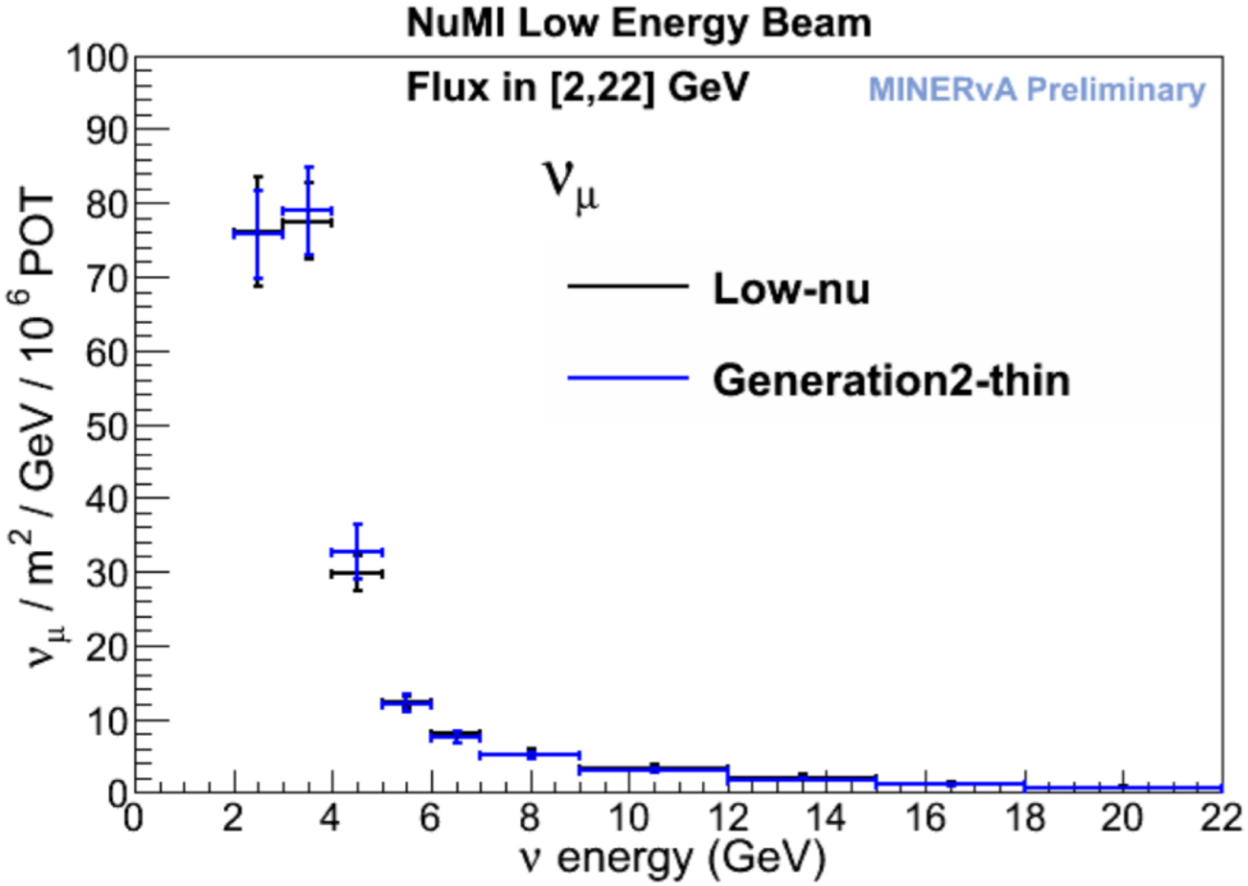
A comparison between these two predictions shows a significant disagreement.

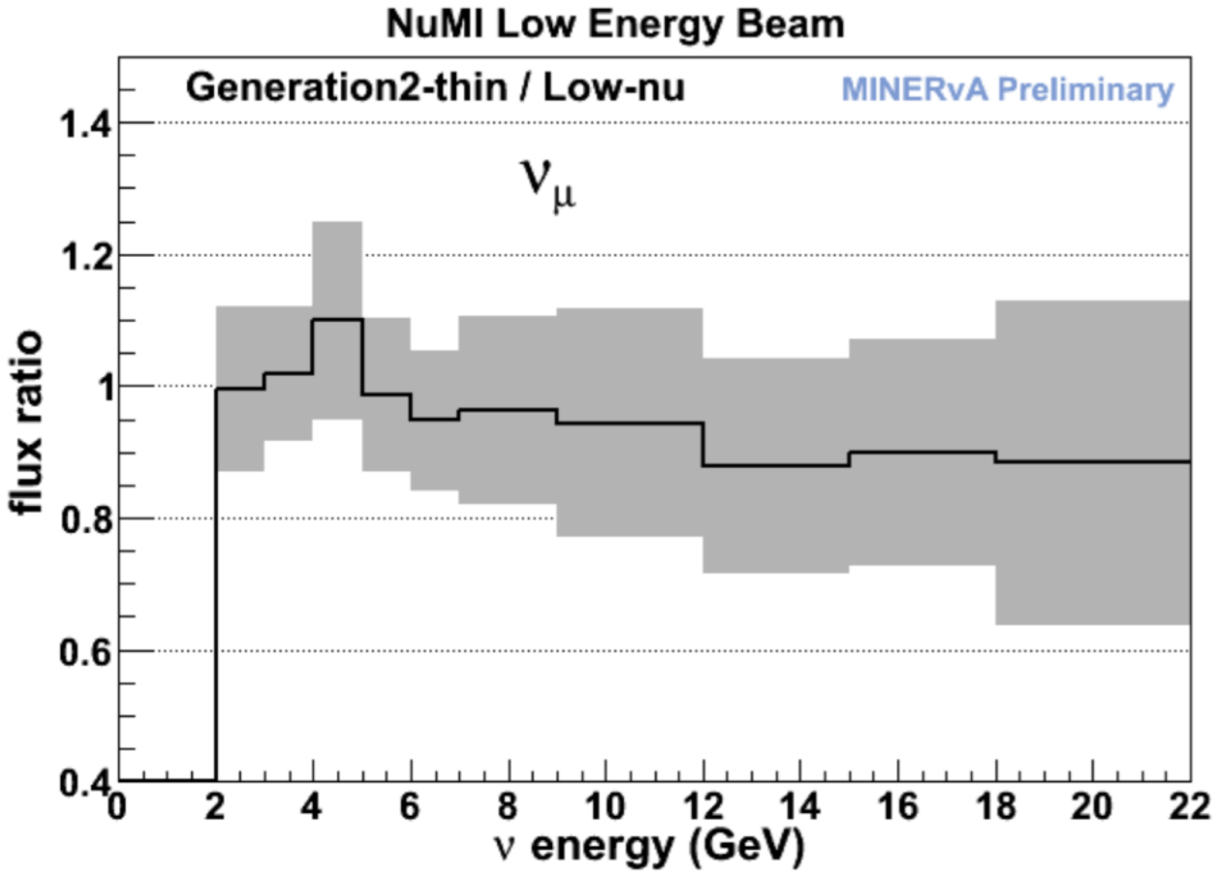


To decide between two a priori predictions, we compare to an in-situ measurement: **the "low-nu" technique**.

Thin Target Flux vs Low-nu

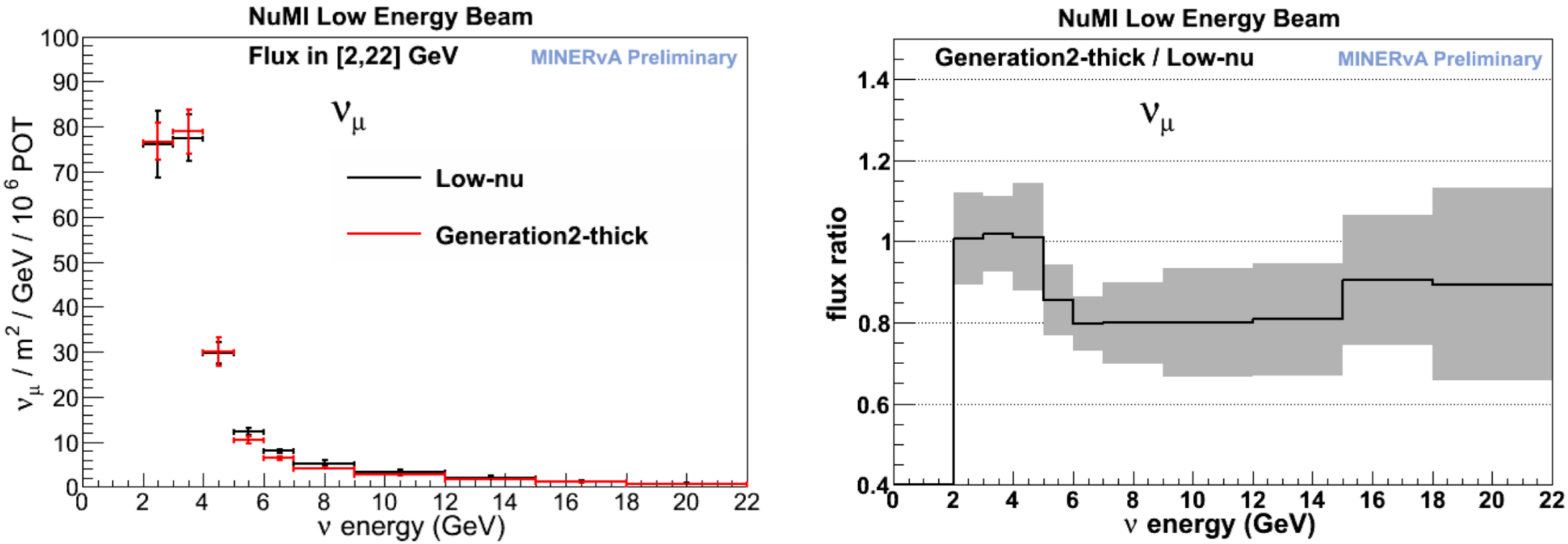
We see consistency along the whole neutrino energy range (low-nu flux predicts the flux for >2 GeV)





Thin Target Flux vs Low-nu

We see consistency in the peak but significant disagreement in the $5-15GeV$ regime.



Conclusions of Gen2 and Low-nu Comparison

- Full covariance comparison **Gen2** - **Low-nu** (2-22 GeV) gives as:

	Low-nu vs Gen2-thin	Low-nu vs Gen2-thick
χ^2	4.8/10	18.6/10

- Based on the agreement of Gen2-thin and low-nu, we recommend to MINERvA to use Gen2-thin for its next round of analysis and update the current MINERvA results.

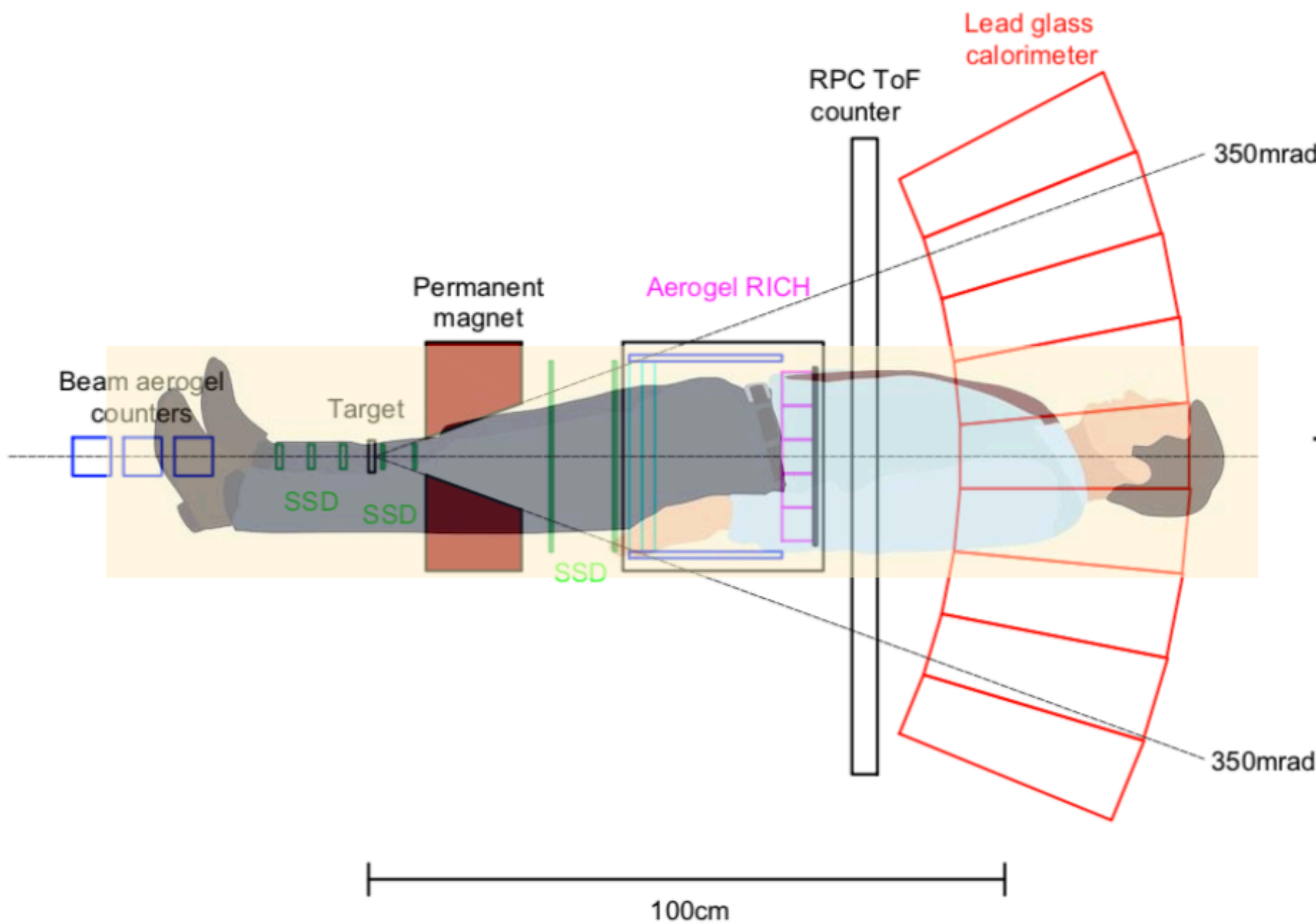
- Gen2-thick offers the prospect of significantly smaller errors: this validates the technique of measuring thick target data.

- Gen2-thin can be applied directly to the Medium Energy Flux.

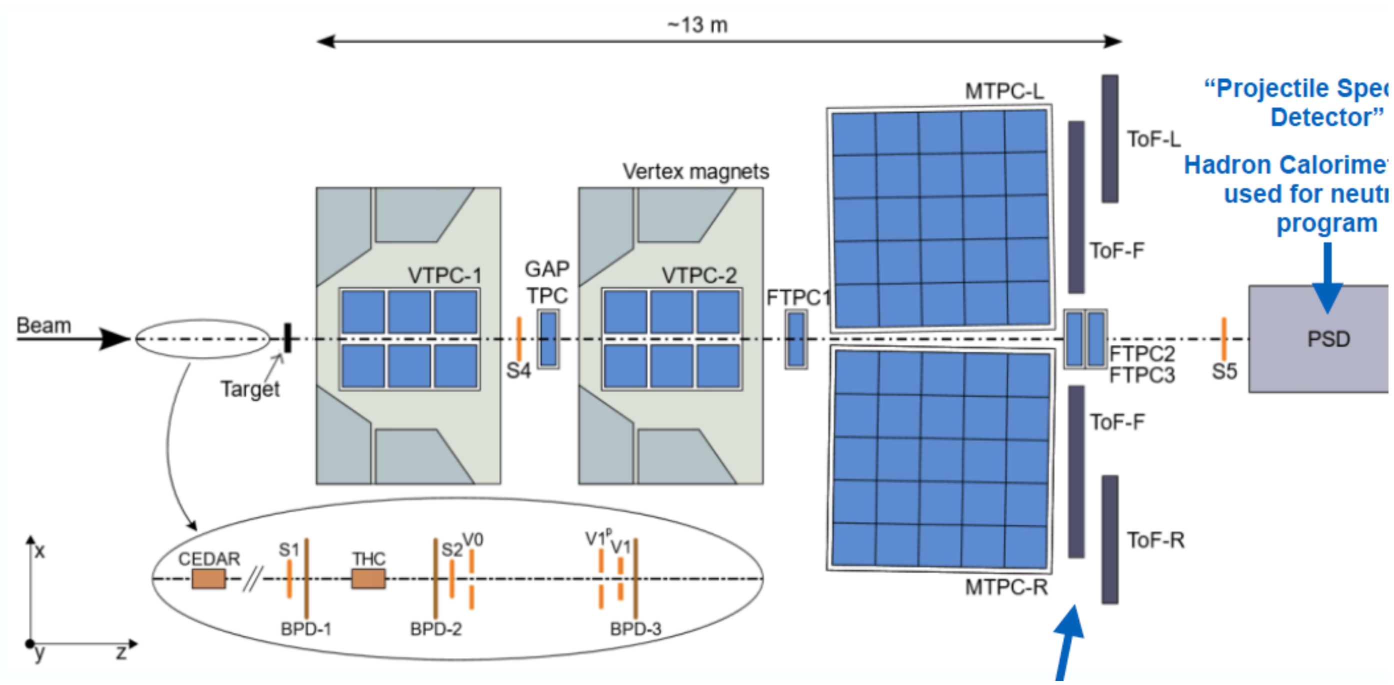
- Atop of the a priori flux, we apply an additional constraint of the flux with $\nu - e$ scattering measurements.

EMPHATIC

Experiment to **M**easure the **P**roduction of **H**adron at a **T**est beam **I**n **C**hicagoland (Fermilab)



NA61/SHINE has banked a large suite of thin-target measurements aimed at T2K and Fermilab flux predictions:



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K^+@60 GeV	C,Be	2015	Total Cross Section[5] (Magnet Off)
π^+@60 GeV	C,Be	2016	p, $\pi^{\pm}$, K^+, K^0_S, Λ [6]
p@60 GeV	C, Al, Be	2016	Total Cross Sections; Spectra Analysis in Progress
p@120 GeV	C, Be	2016	Total Cross Sections; Spectra Analysis in Progress