Neutrino Flux Requirements for DUNE

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WG1: Neutrino Flux

October 16, 2017

Outline

- LBNF beamline designs.
- Current flux uncertainties.
- Reducing the flux uncertainties

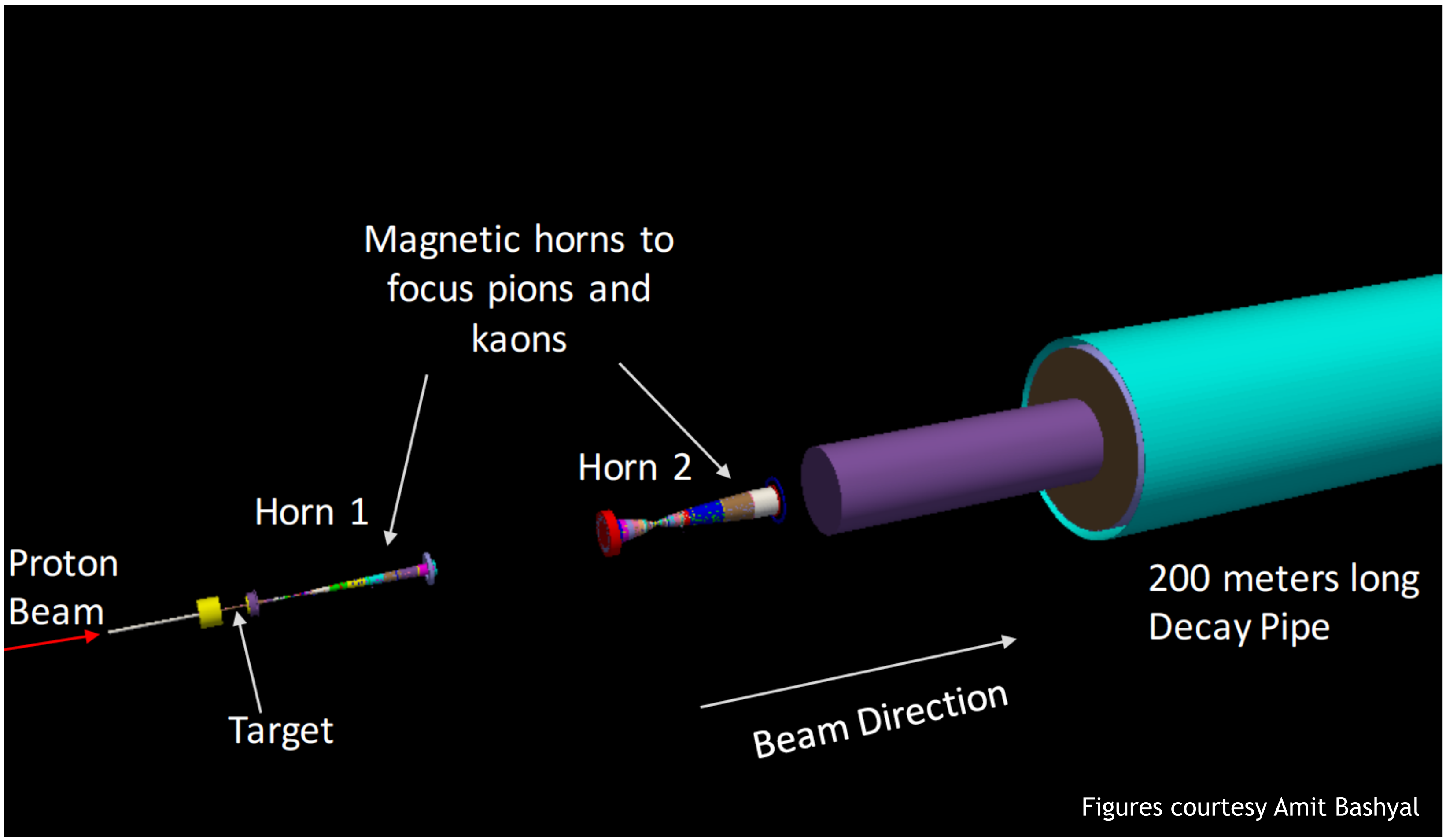
LBNF Beamline Designs

LBNF Beamline

- Primary proton beam in 60-120 GeV.
- Initial 1.2 MW beam power, upgradable to 2.4 MW.
- Wide-band beam on-axis with tunable energy spectrum.
- Decay pipe ~ 200 m long, He filled.
- Currently considering two different beamline designs:
  - Reference (NuMI-like).
  - Optimized (for CP violation).
- ***Decision regarding which one will go forward to preliminary design will be made soon.***

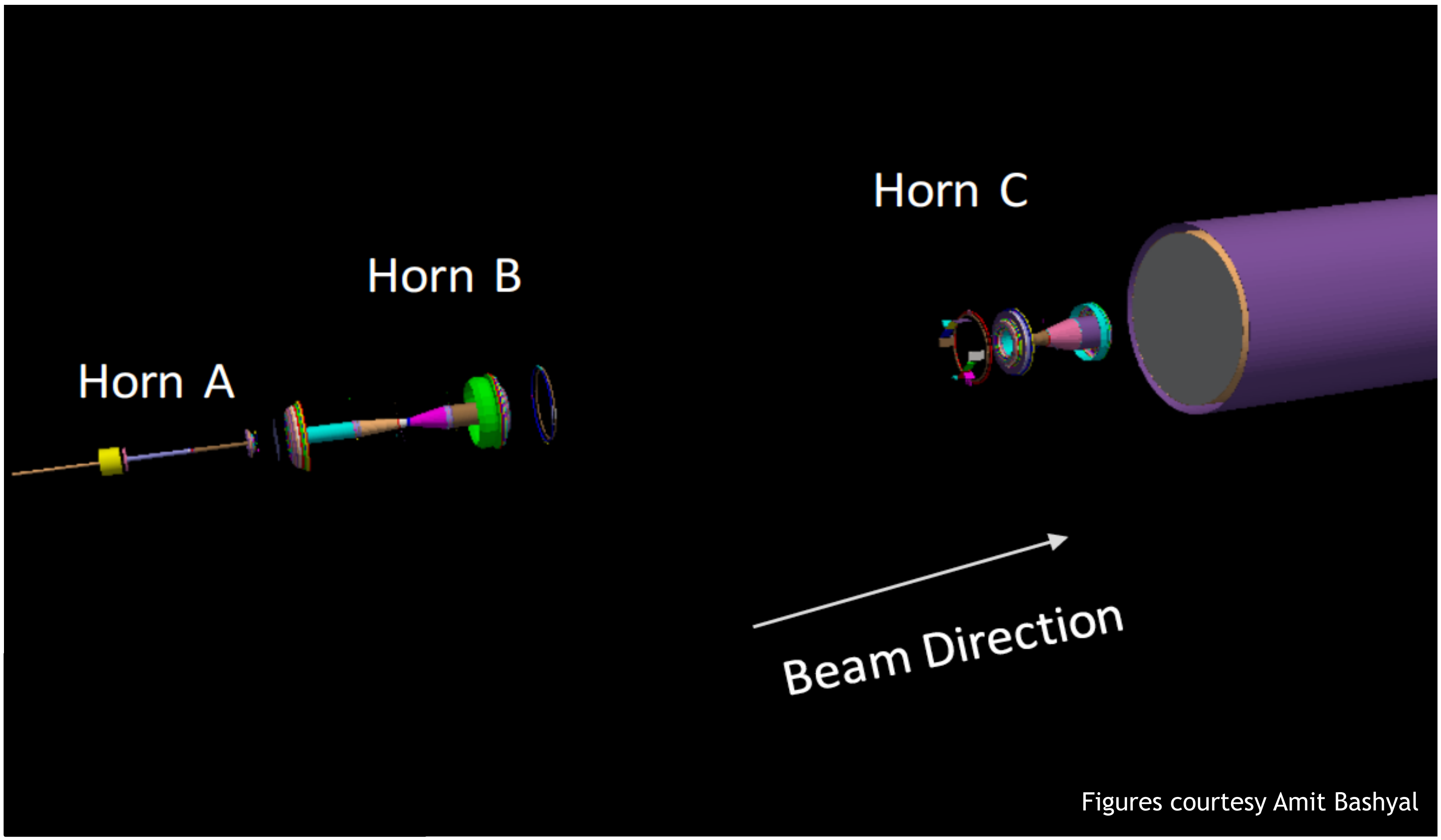
LBNF Reference Beamline

- Two horns, nearly identical to those used in NuMI, run at slightly higher current (230 kA).
- 1 m long graphite fin target, similar to but not identical to NuMI target

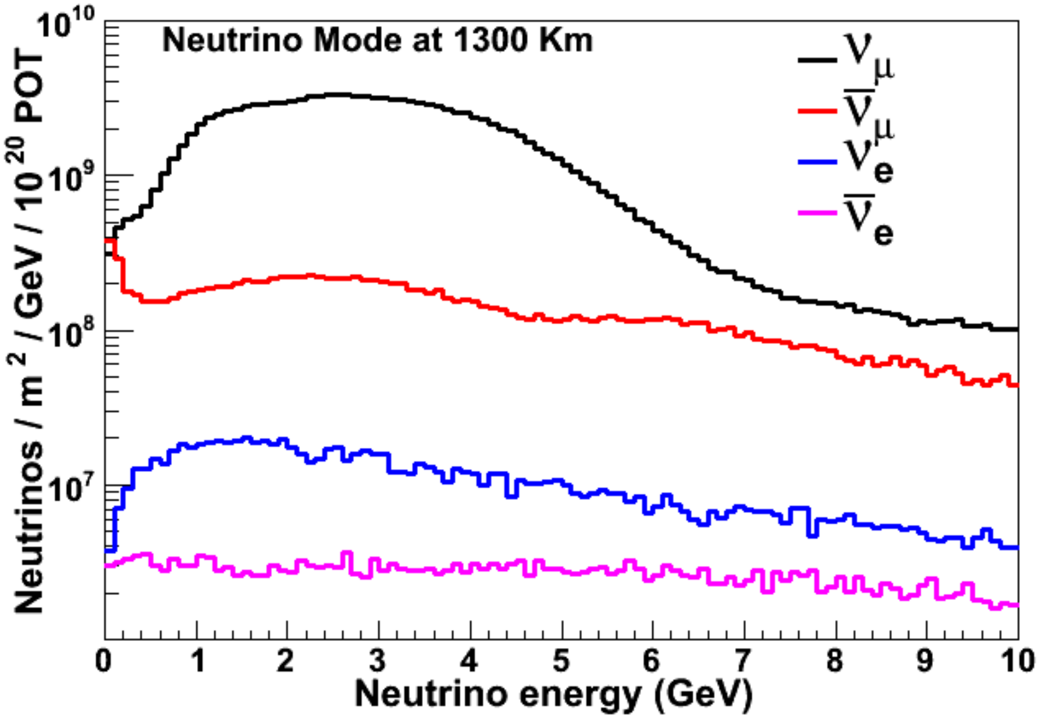


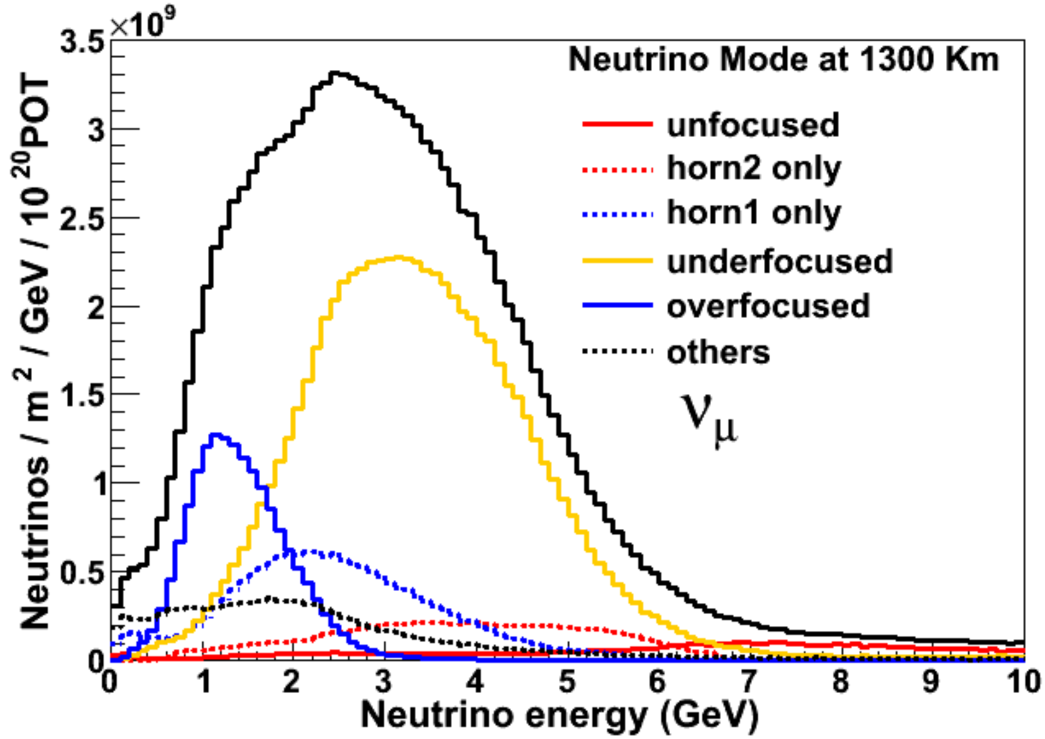
LBNF Optimized Beamline

- Three horns, not similar to NuMI, run at 300 kA
- 2 m long graphite fin target, but development of alternative graphite cylindrical target design is ongoing at RAL

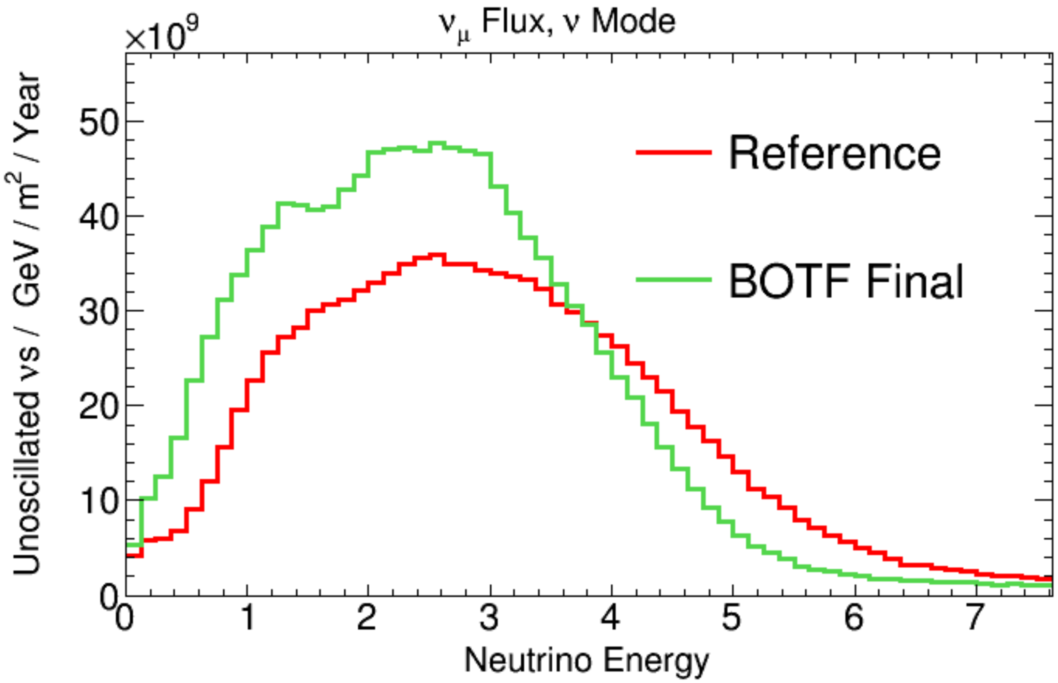


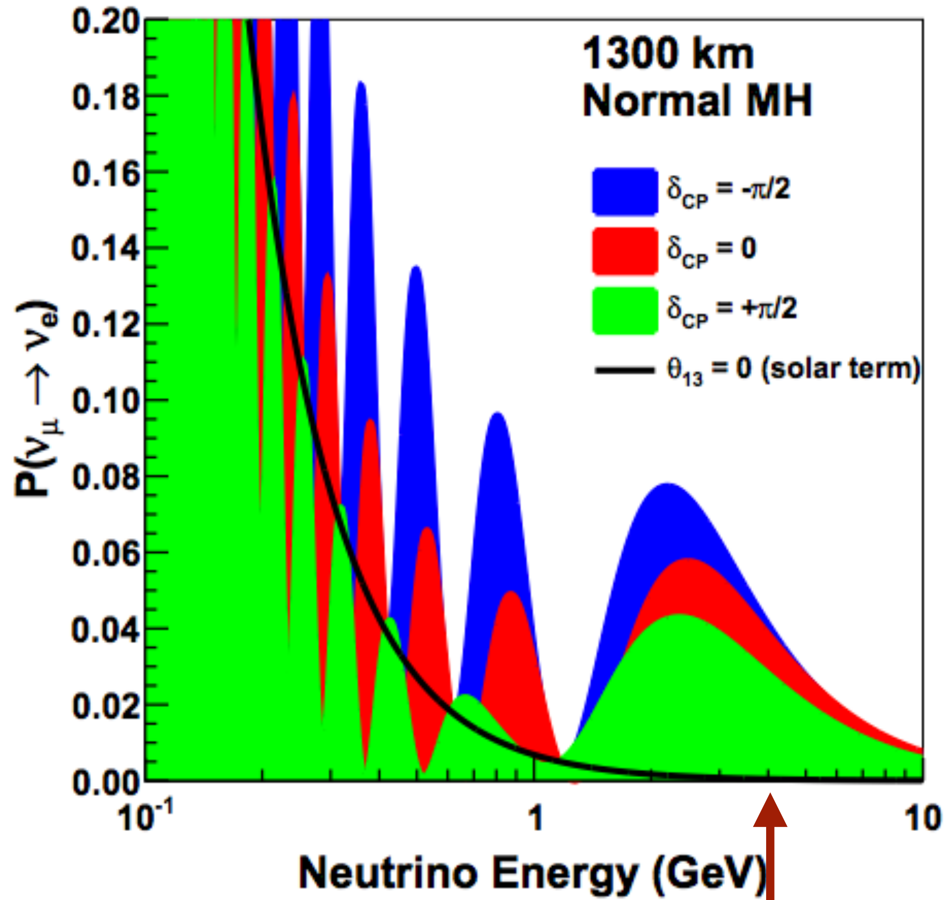
LBNF Reference Beamline





LBNF Beamline Options





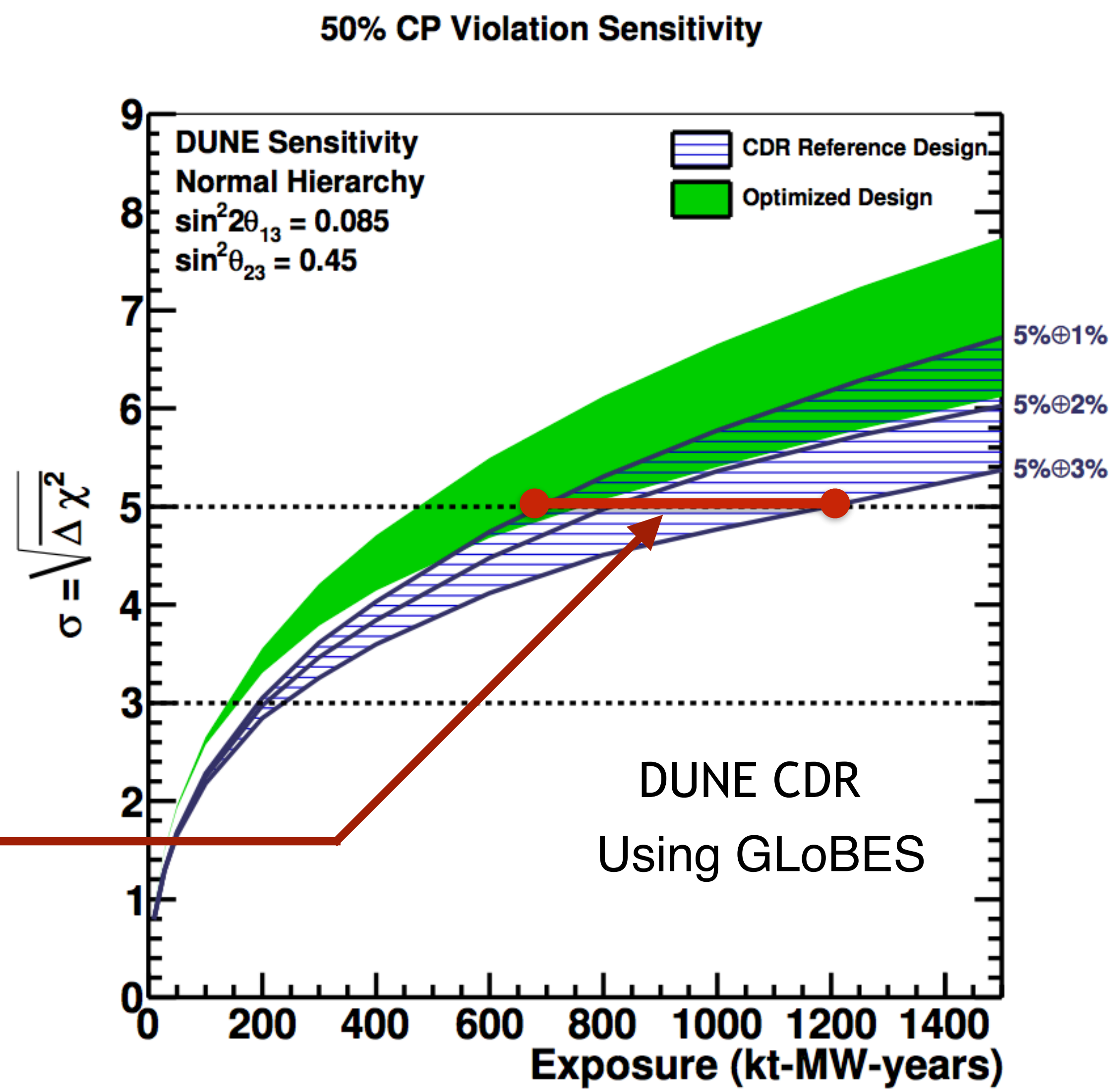
LBNF/DUNE Long Baseline Physics

Assuming:

1. 5% uncertainties on the normalizations of the ν_e appearance correlated with the ν_μ disappearance.

2. Additional uncertainties of 1%, 2% or 3% that are uncorrelated with the ν_μ spectrum

- Going from 3% vs 1% uncertainty is equivalent to nearly doubling exposure time.



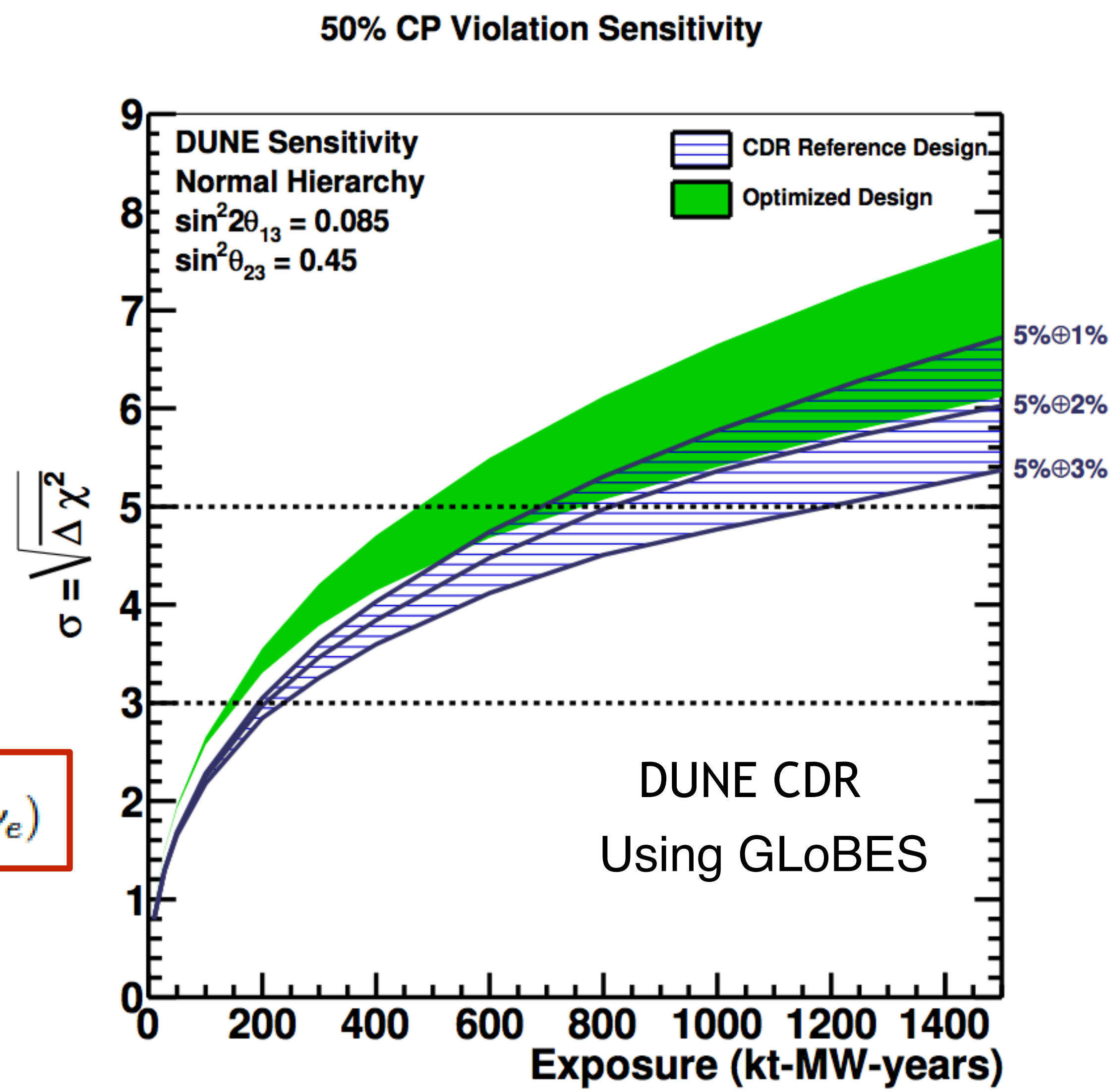
LBNF/DUNE Long Baseline Physics

Flux uncertainties enter:

1. **Directly** (after constraint by the near detector) the uncertainty 1, that is correlated between ν_e and ν_μ,

2. **Indirectly** to the uncertainty 2, since flux uncertainties couple to uncertainties in cross sections:

$$N_{\nu_e}(E_\nu) = \phi_{\nu_\mu} \times \sigma(\nu_e) \times \epsilon(\nu_e) \times P(\nu_\mu \to \nu_e)$$

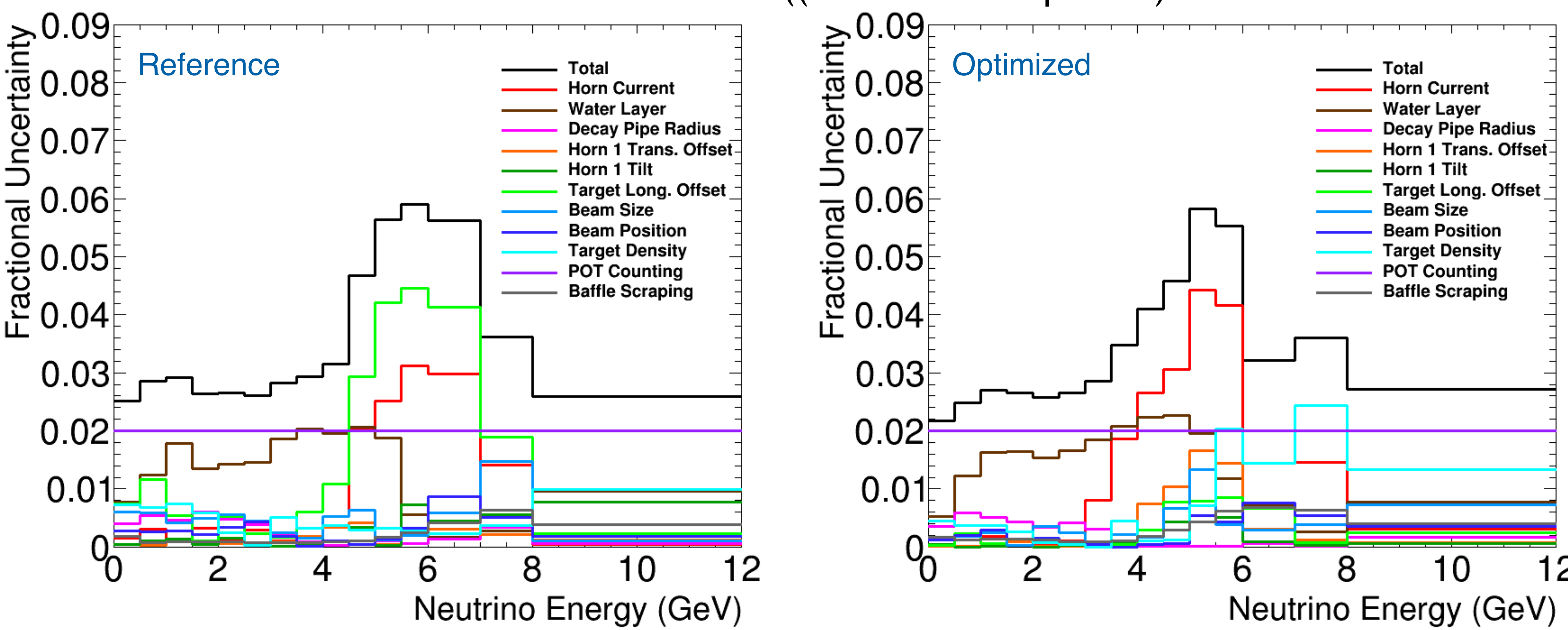


Final uncertainties should include the flux shape uncertainty as well.

Current Flux Uncertainties

Focusing Uncertainties

L. Fields ((NA61 Workshop 2017)



- **POT counting** and **water layer** are the most significant at the peak.
- **Horn current** and **target longitudinal offset** are the most significant at the falling edge for the reference design.

HP Uncertainties

- DUNE uses PPFX (Package to Predict the Flux) developed by MINERvA that uses all relevant HP data (currently it corrects FTFP_BERT G4 model).

- DUNE uses QGSP hadronic model and then only the uncertainties can be calculated using PPFX.

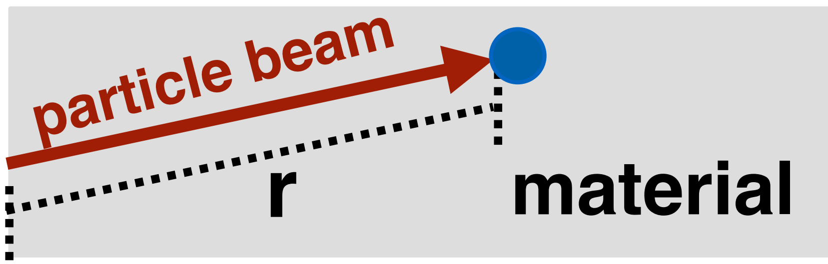
- PPFX calculates two kind of uncertainties related to the corrections of the HP:

  1. ***Beam attenuation.***

  2. ***Hadron production.***

1. Beam Attenuation

When the particle interacts in a volume

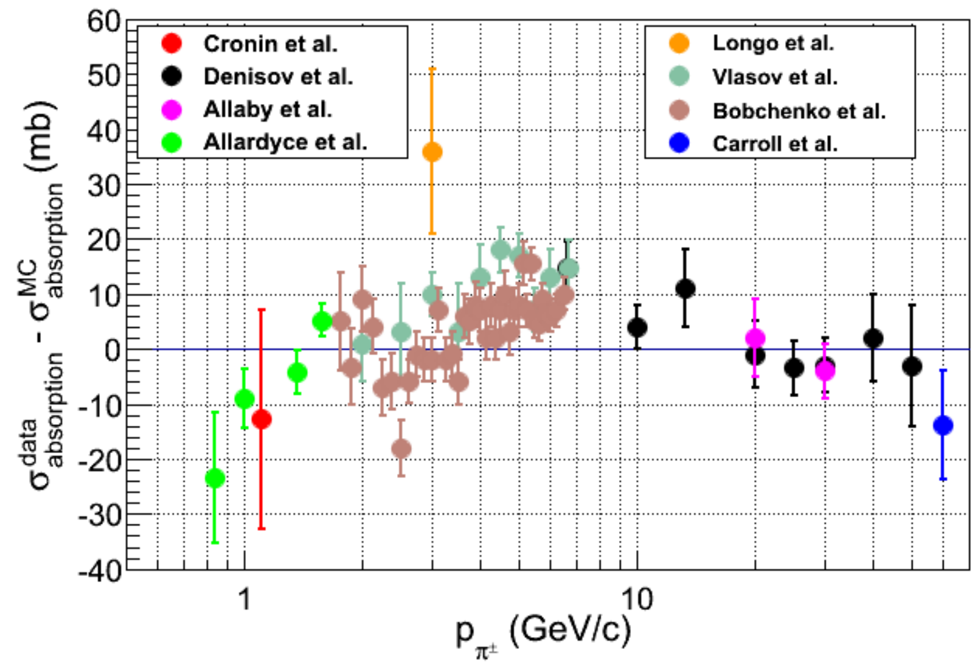


$$correction(r) = \frac{\sigma_{Data}}{\sigma_{MC}} e^{-r\frac{N_A \rho(\sigma_{Data}-\sigma_{MC})}{A}}$$

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

When the particle passes through the volume without interacting the survival probability is calculated.

- **Example: Absorption cross section of pion on Aluminum**



Reference (Geant4):

$\sigma_{absorption}$ = 344 mbar

- Most of the cross-section discrepancies are less than 6%.

2. Hadron Production

For thin target data (NA49 for instance):

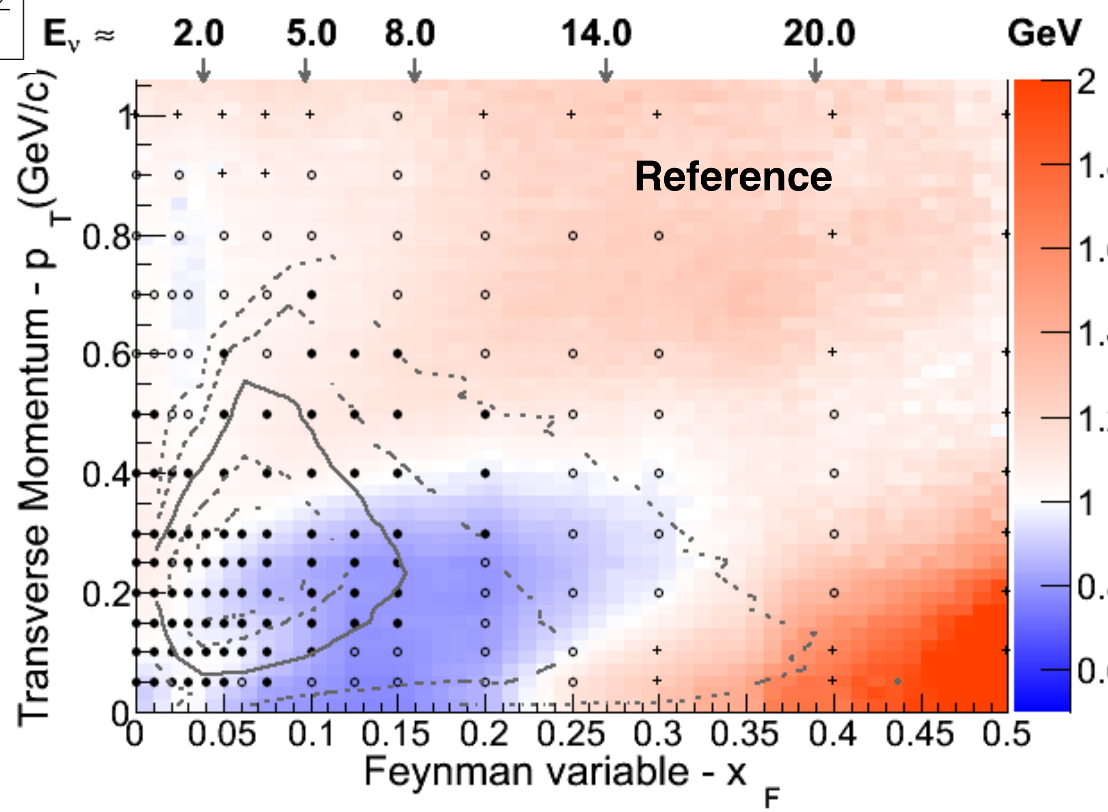
$$correction(x_F, p_T, E) = \frac{f_{Data}(x_F, p_T, E = 158GeV) \times scale(x_F, p_T, E)}{f_{MC}(x_F, p_T, E)}$$

*(**f=Ed³σ/dp³**: invariant production cross section)*

- The **scale** allows us to use NA49 for proton on carbon in 12-120 GeV (calculated with FLUKA).
- It was checked by comparing with NA61 at 31 GeV (negligible difference).

pC -> π⁺X

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



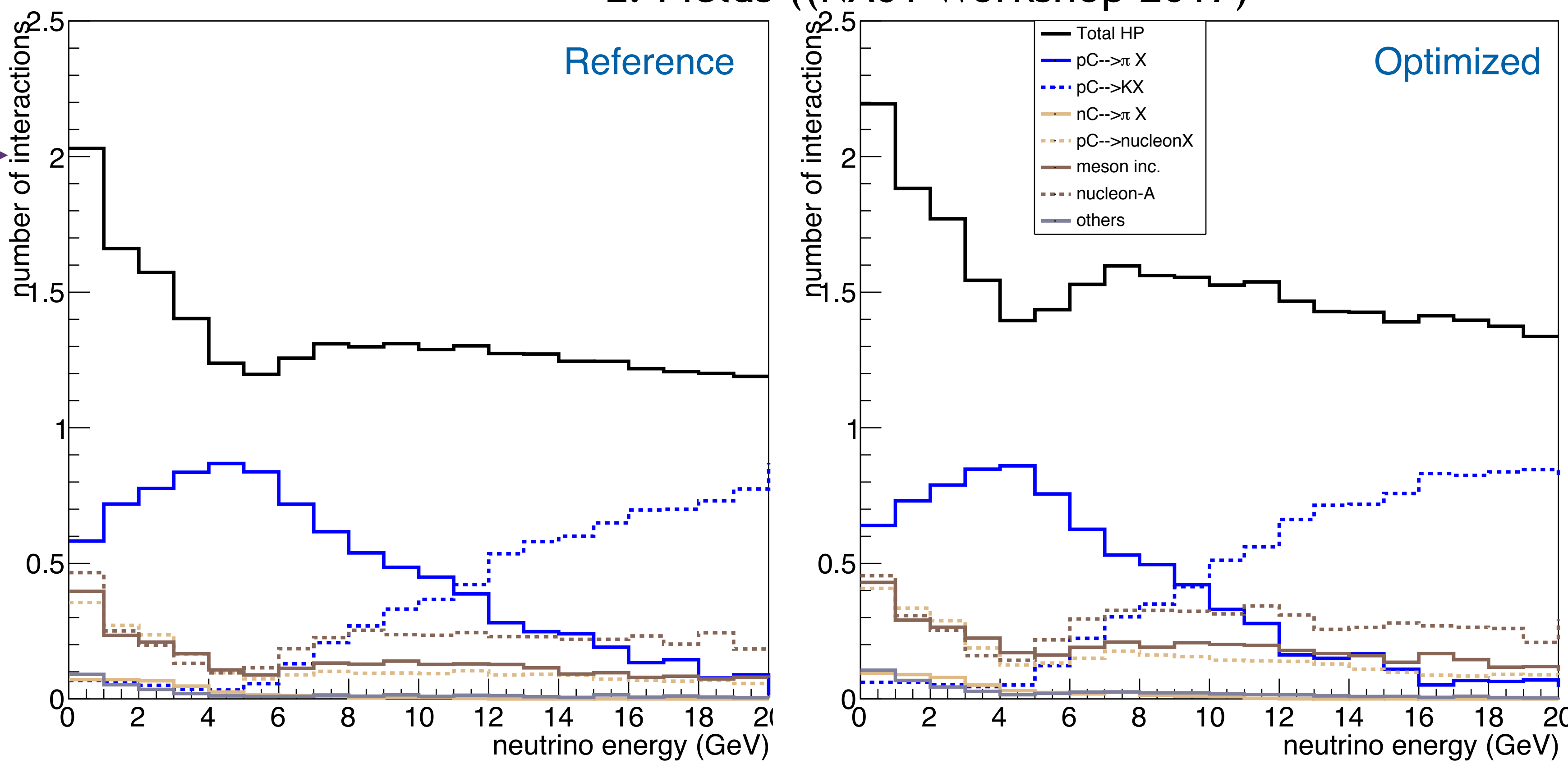
$$x_F = \frac{2p_L^*}{\sqrt{s}}$$

Systematic uncertainties = 3.8% (added in quadrature).

Hadron Production Needs

- ***π**, **K** and **nucleons** productions from **pC** based on data (mainly NA49).*
- **nucleon-A:** quasi-elastics, extension from carbon to other materials, etc.
- *No data applied to meson incidents: assuming large uncertainties.*

L. Fields ((NA61 Workshop 2017)



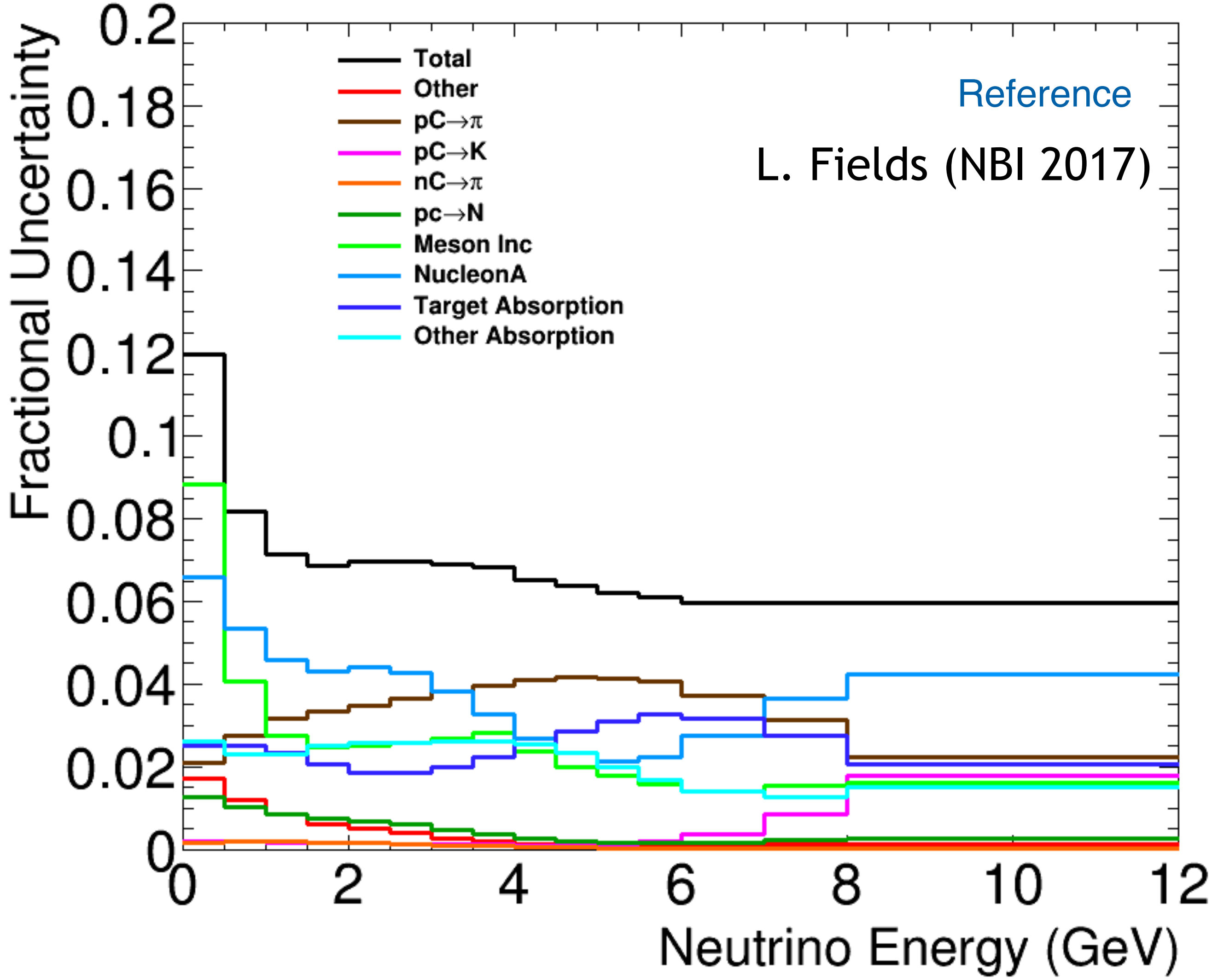
> 2.2 for very low E_ν and 1.2-1.5 for the rest

Fermilab

Hadron Production Uncertainties

- Same procedure as MINERvA applied to DUNE beam simulation

- Total HP uncertainty ~7% in the peak and 12% for very low energies.



Hadron Production Uncertainties

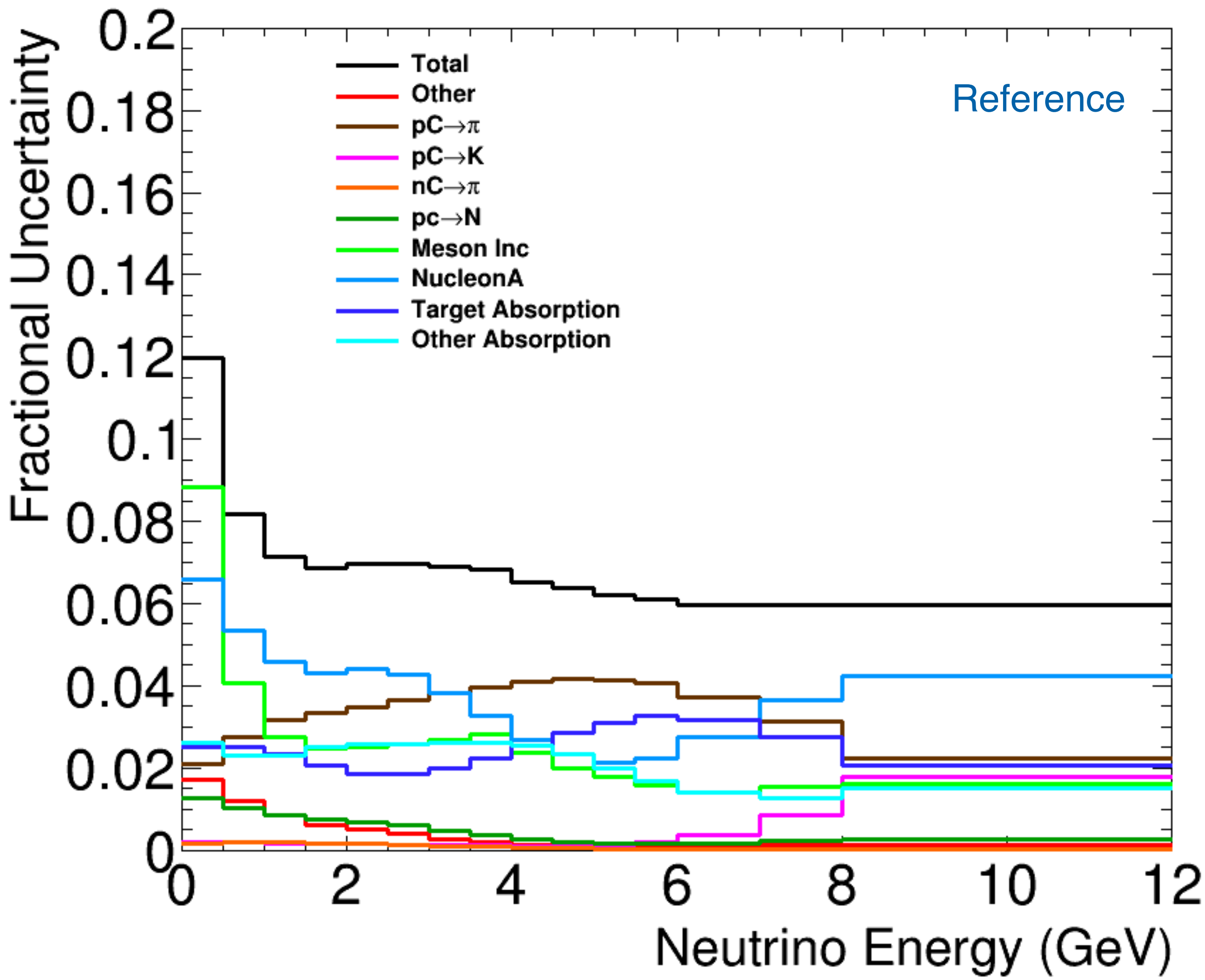
Particle production in proton carbon interactions:

- **Pions (pC -> π)**
- **Kaons (pC -> K)**
- **Nucleons (pC -> N)**

All covered by external data (mainly NA49).
(for high energy kaons, a combination of NA49 + MIPP k/π)

The magnitude of this uncertainty depends both on uncertainties reported by experiments.

The correlations of the datasets are not reported by experiments. We assumed 100% for the systematics (conservative approach from MINERvA).



Hadron Production Uncertainties

Extending the data coverage:

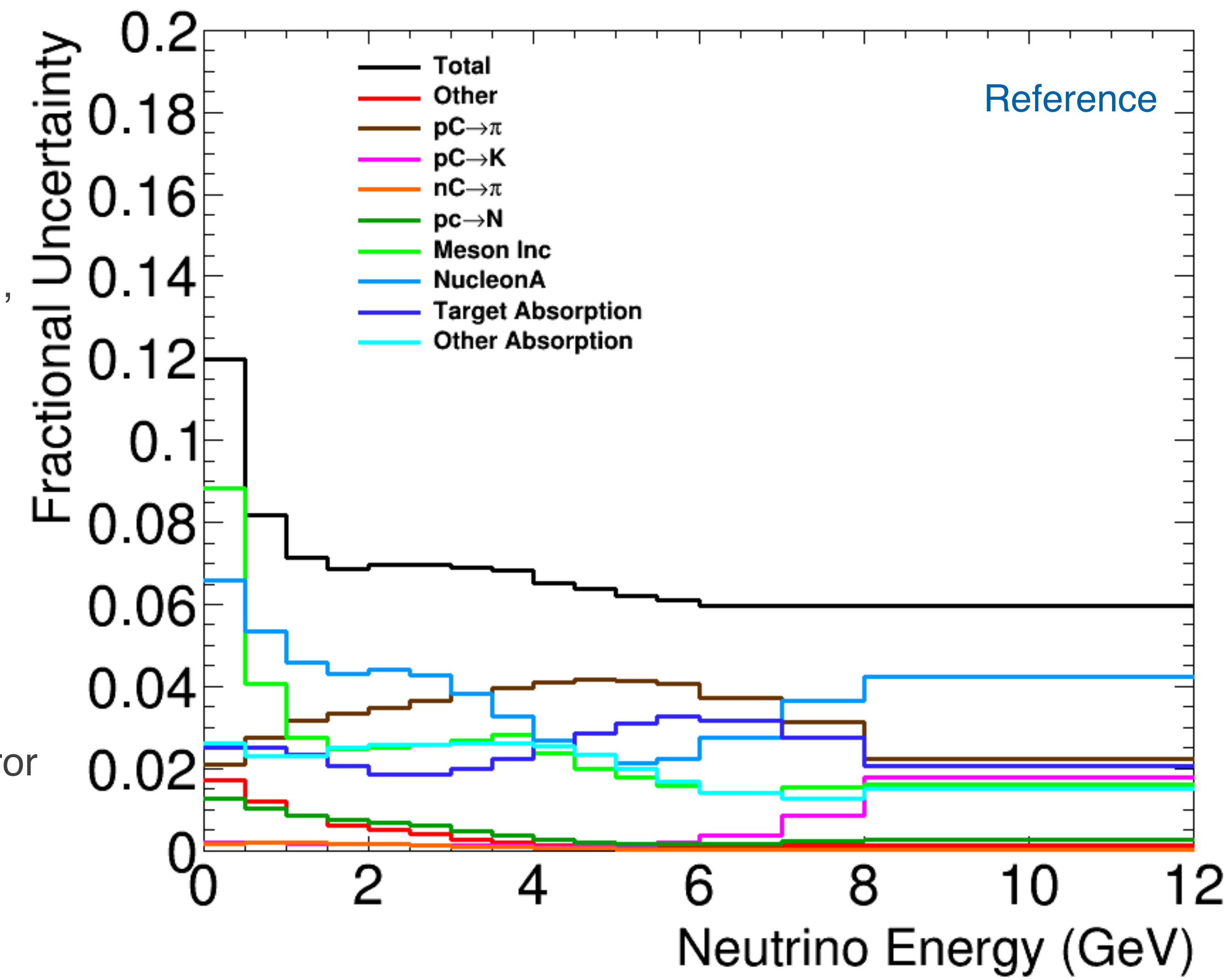
- **Nucleon interactions (NucleonA)**

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

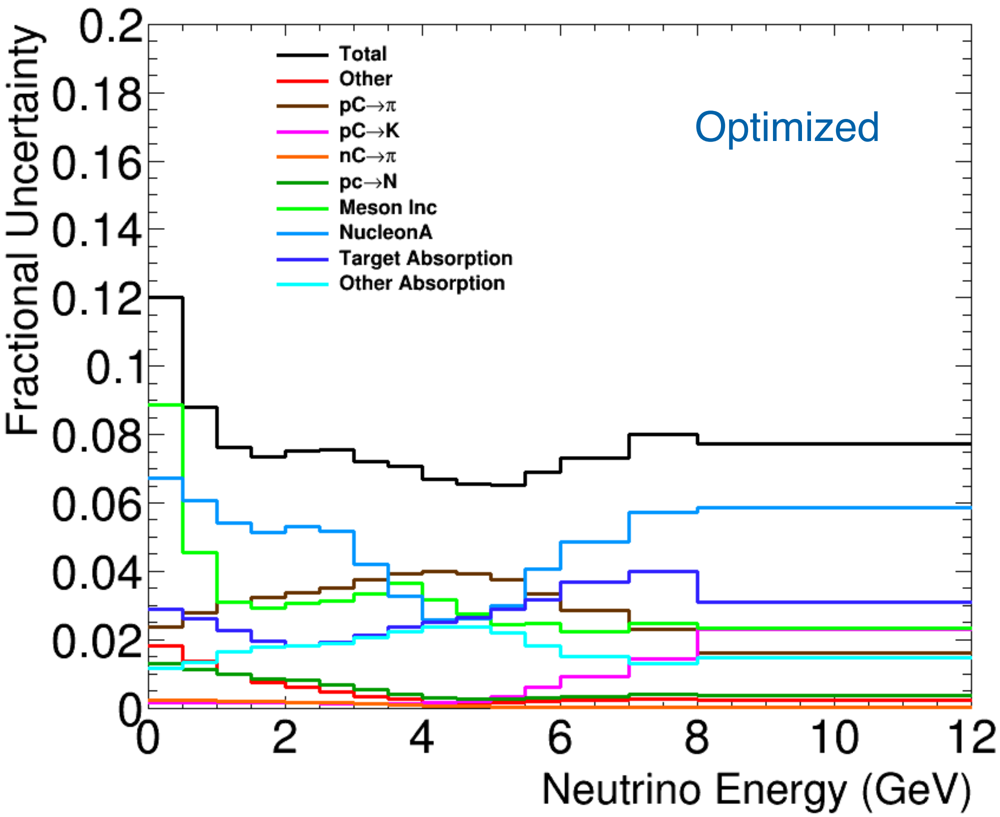
When there is not data coverage, like:

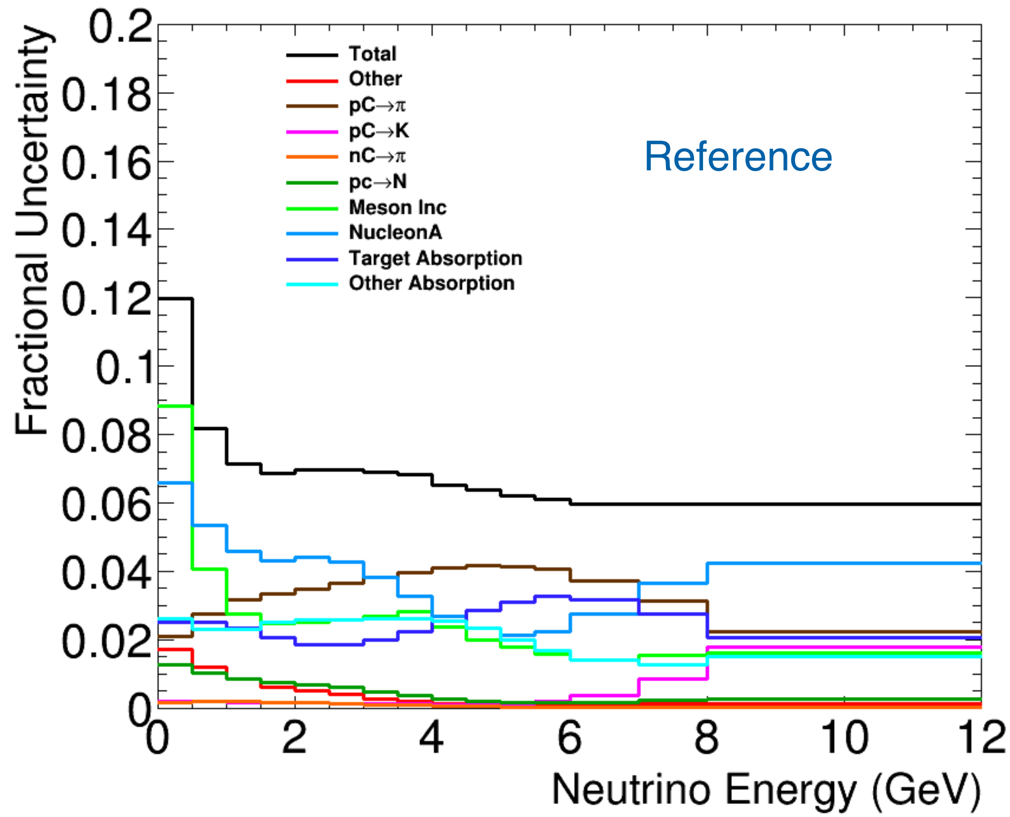
- **Incident Mesons (Meson Inc)**

Guided by the agreement with other datasets: processes categorized by meson and produced particle. 40% error assigned in 4 x_F bins.



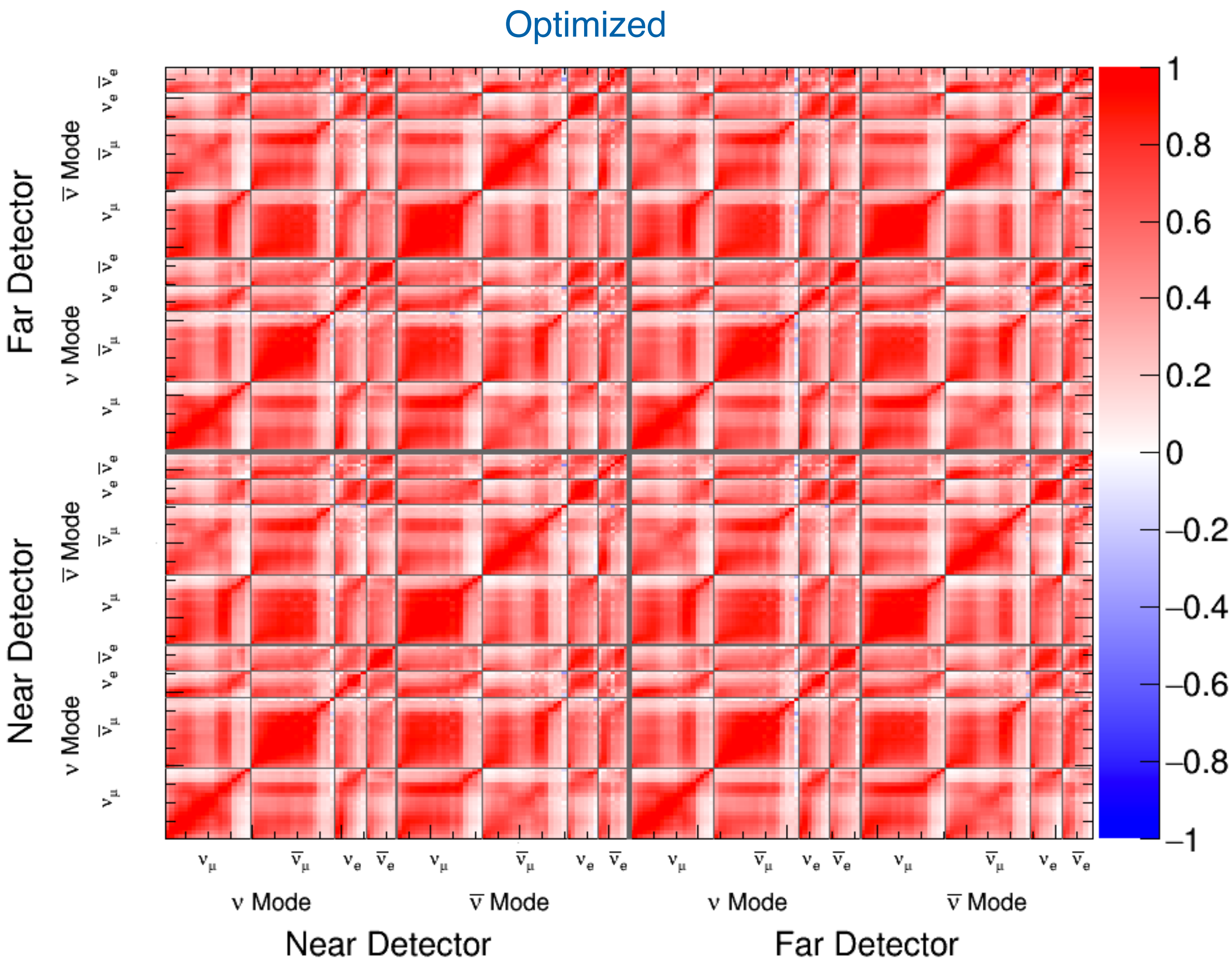
Reference and Optimized Beam Uncertainties





Very similar in focusing peak; Optimized has slightly larger uncertainties at high energy, primarily due to having more interactions not covered by data

Beam Uncertainty Correlation Matrix for the Optimized beam



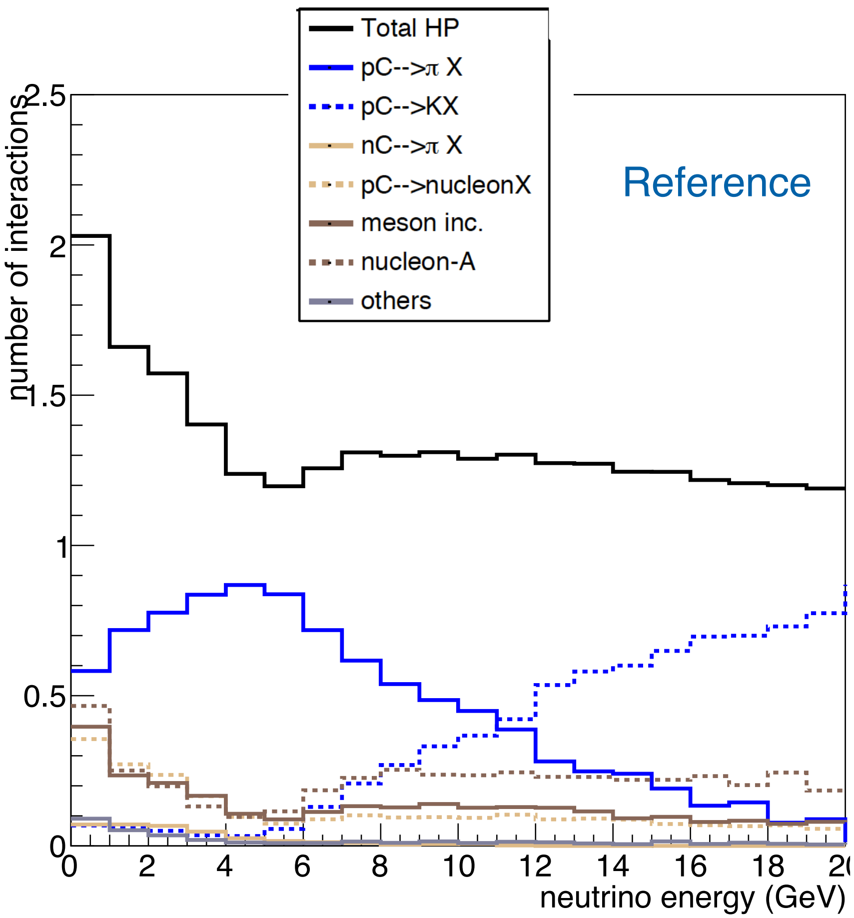
L. Fields (NA61 Workshop 2017)

- Fluxes are **highly correlated** across most bins
- **Focusing regions and high energy bins** are the exceptions
- Depends strongly on **correlations of underlying datasets**; in many cases, we have to guess at these.

Reducing the flux uncertainties

How can we reduce the a priori uncertainties

More thin target data



- **Inelastic cross-sections** of π, K and protons in different materials (C, Fe, Al, He).
- **Differential cross-sections** in different materials
  - π -> π at a wide range 10-60 GeV.
  - pA-> π (K) X, where X != C
- **Proton quasi elastic cross-sections**

How can we reduce the a priori uncertainties

Replica target data: MINERvA experience.

- ~ 5% using MIPP NuMI target data primarily.

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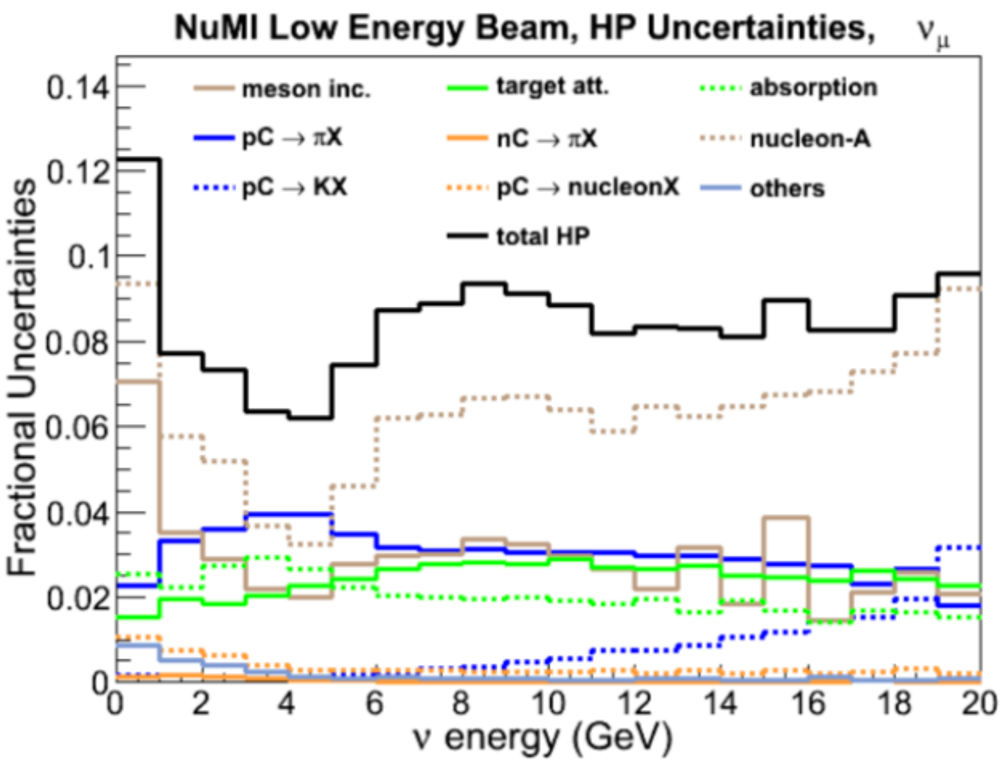
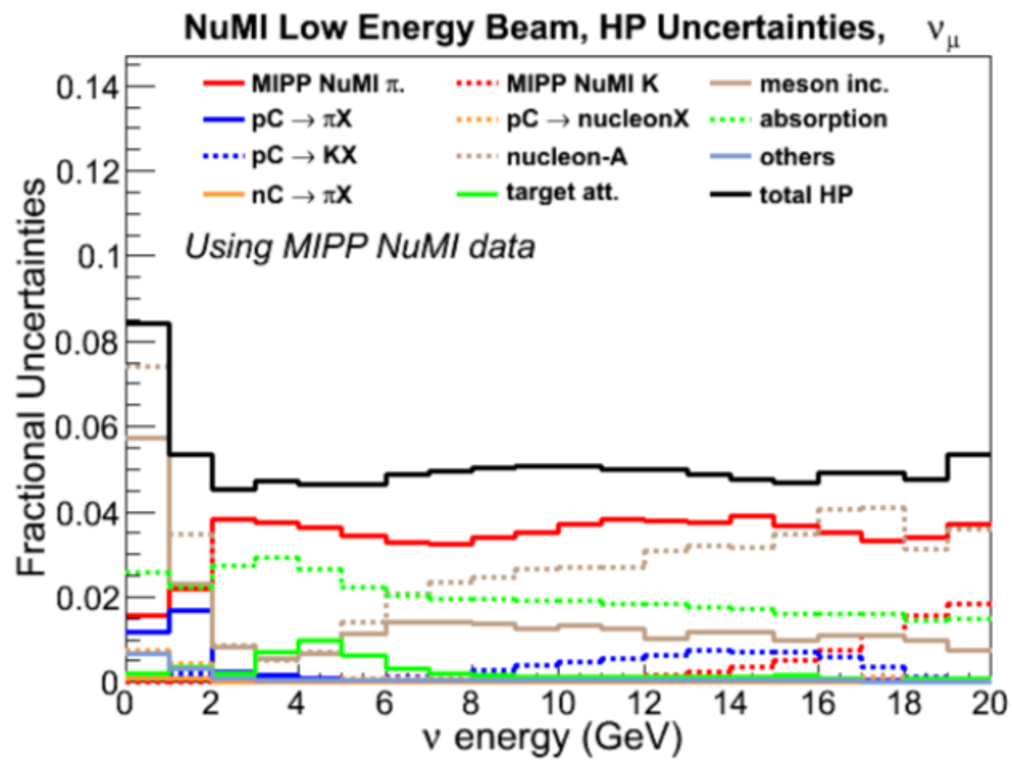




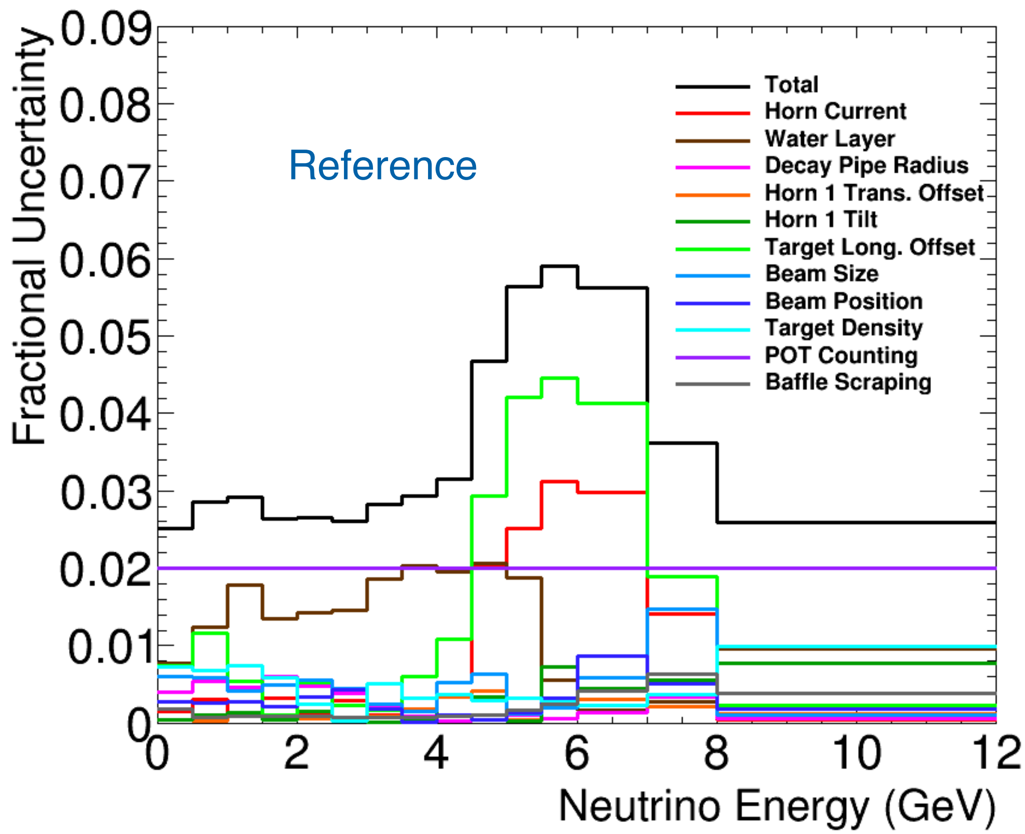
Checking the consistency with the low-nu measurement, MINERvA decided to use a prediction based only on thin target corrections

LBNF Flux Spectrometer

A concept to measure hadron production after the horns (See Paul Le Brun’s talk)

Reducing the Focusing Uncertainties

After reducing the HP, the focusing uncertainties will become dominant.



- **POT counting** and **water layer** are the most significant at the peak.

- **Horn current** and **target longitudinal offset** are the most significant at the falling edge for the reference design.

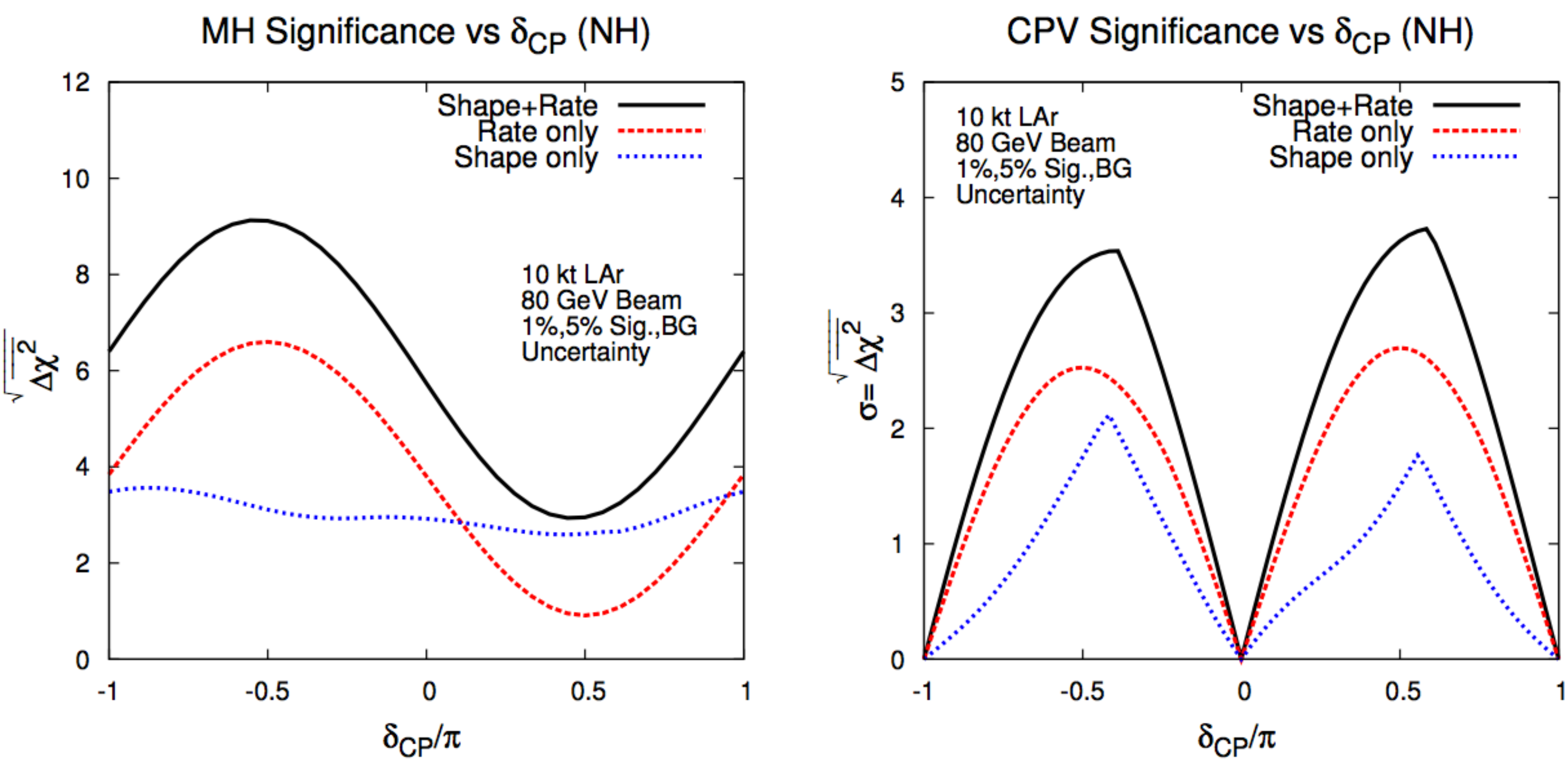
Conclusions

- Reducing the HP uncertainties is possible with dedicated experiments:
  - **Replica target data** would be the best option but **timescale** is a challenge (DUNE expects to receive beam in 2026) and it is likely that no replica will be available.
  - **Thin target data** would likely to have big impact on DUNE.

backup

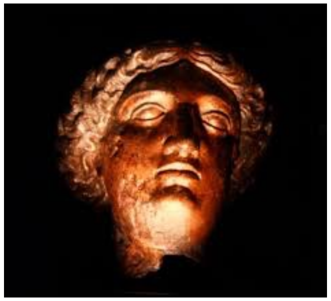
LBNF/DUNE Long Baseline Physics

Respect to the shape (flux shape can have a big impact):



LBNE Physics Book

This omission means that systematics likely have **an even bigger impact** than shown on previous page (which is already impressive!)



MINERvA Strategy for Predicting the Flux

1. Calculate an a-priori flux

Accounting for every optical modeling uncertainty.

Correcting the hadron production in the beam line to constrain to external hadron production data.

2. Use in-situ measurements

Checking our results with the low recoil event rates (low-nu method): flux shape measurement.

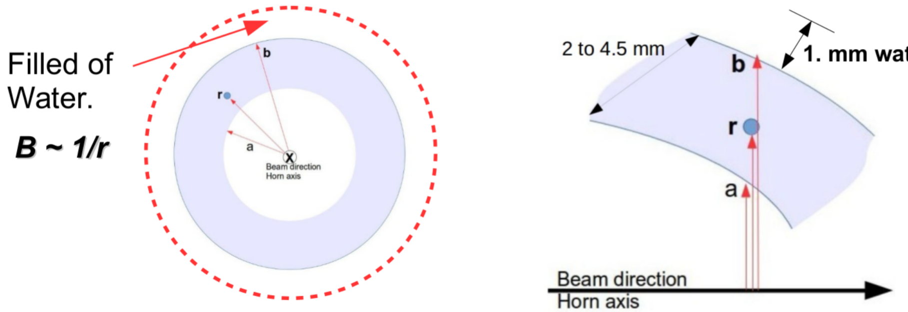
Applying an additional constraint from the neutrino - electron scattering events.

3. Package to Predict the FluX

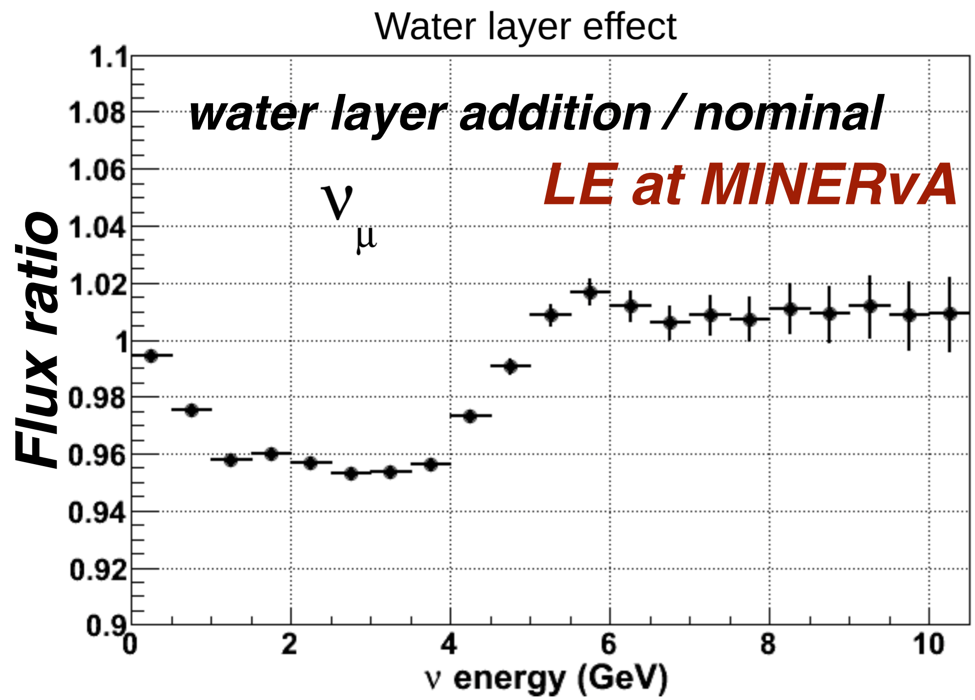
Develop every tool in such a way they can be used by any experiment at NuMI (PPFX).

Some geometrical improvements

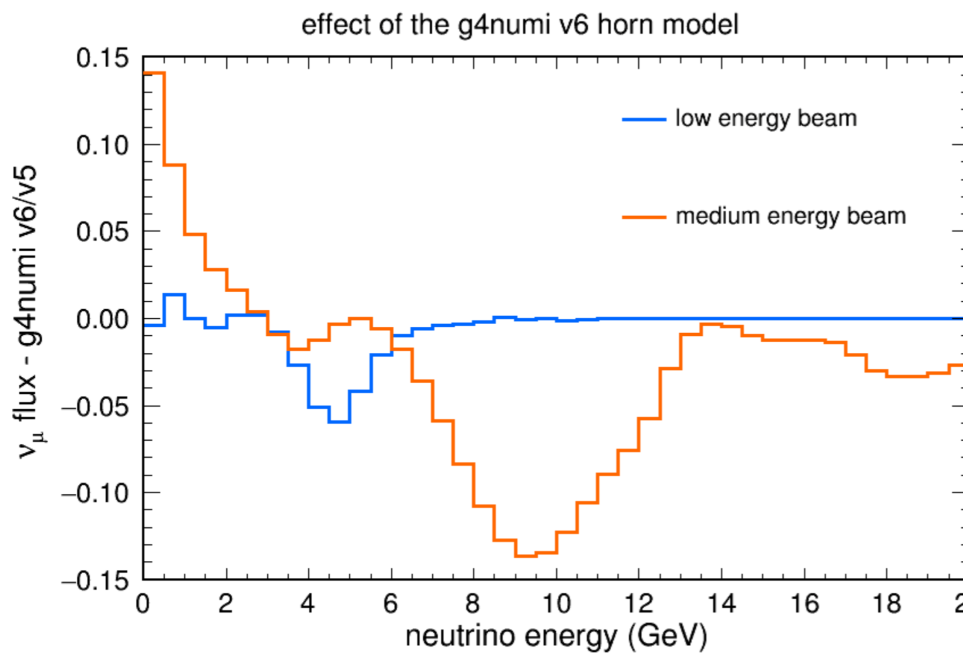
Effect of 1mm water layer around the Horn 1 inner conductor



- 4% effect around the LE flux peak.



- More accurate description of the inner conductor (IC) of Horn 1 designed for LBNF
  - Improved segmentation of the IC surface
  - Check the neck shape (cylinder).
- 5% (14%) effect in the LE (ME) falling edge of the flux peak at MINERvA.

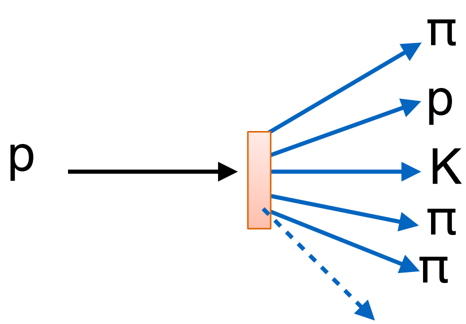


(Implemented by Paul Le Brun)

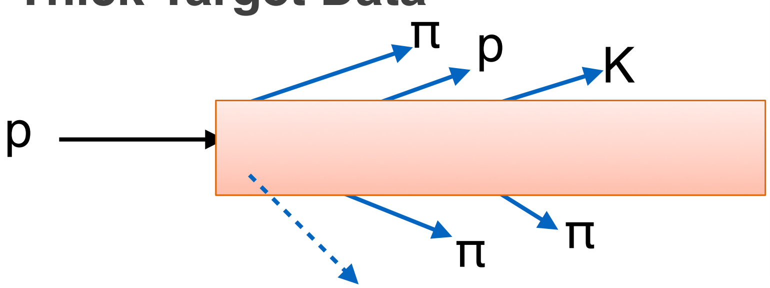
External Data? What Sort of Data is Available?

- Hadron production data at the relevant energies for NuMI (references in the backup slides):

Thin Target Data



Thick Target Data



- Inelastic/absorption
  - Belletinni, Denisov, etc. cross sections of pC, πC, πAl etc.
  - **NA49: pC @ 158 GeV.**
  - NA61 pC @ 31 GeV.
- Hadron Production:
  - Barton: $pC \to \pi^{\pm} X$ @ 100 GeV $x_F > 0.3$.
  - **NA49: $pC \to \pi^{\pm} X$ @ 158 GeV $x_F < 0.5$.**
  - NA49: $pC \to n(p) X$ @ 158 GeV for $x_F < 0.95$.
  - NA49: $pC \to K^{\pm} X$ @ 158 GeV for $x_F < 0.2$.
  - NA61: $pC \to \pi^{\pm} X$ @ 31 GeV .
  - MIPP: π / K from pC at 120 GeV for $p_Z > 20 GeV/c$.
- MIPP: proton on a spare NuMI target at 120 GeV:
  - $\pi^{\pm}$ up to 80 GeV/c.
  - K/π for $p_Z > 20 GeV/c$.

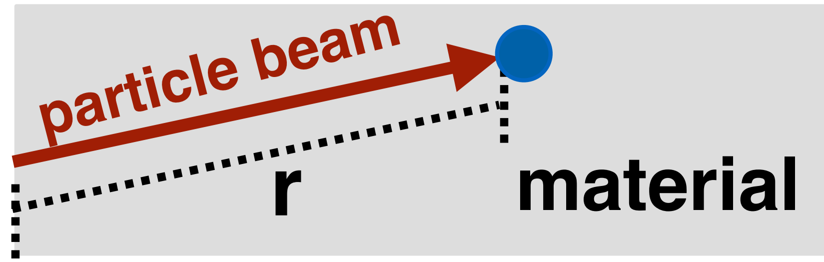
Checking the consistency with the MINERvA low-nu measurement, we decided to use a prediction based only on thin target correction

1. Beam Attenuation

When the particle interacts in a volume

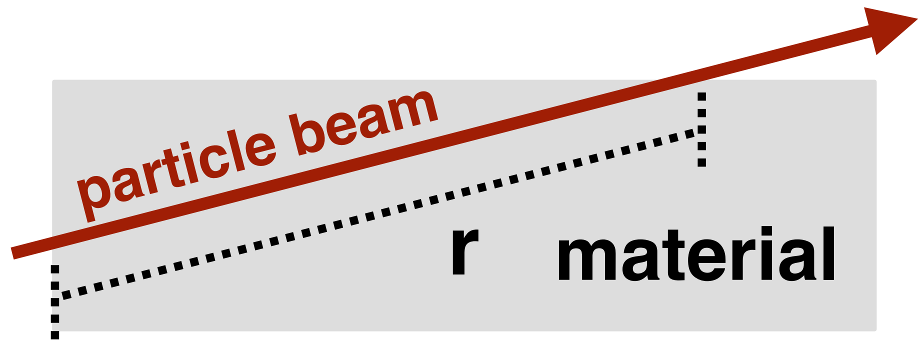
$$correction(r) = \frac{\sigma_{Data}}{\sigma_{MC}} e^{-r\frac{N_A \rho(\sigma_{Data} - \sigma_{MC})}{A}}$$

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



When the particle passes through the volume without interacting

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

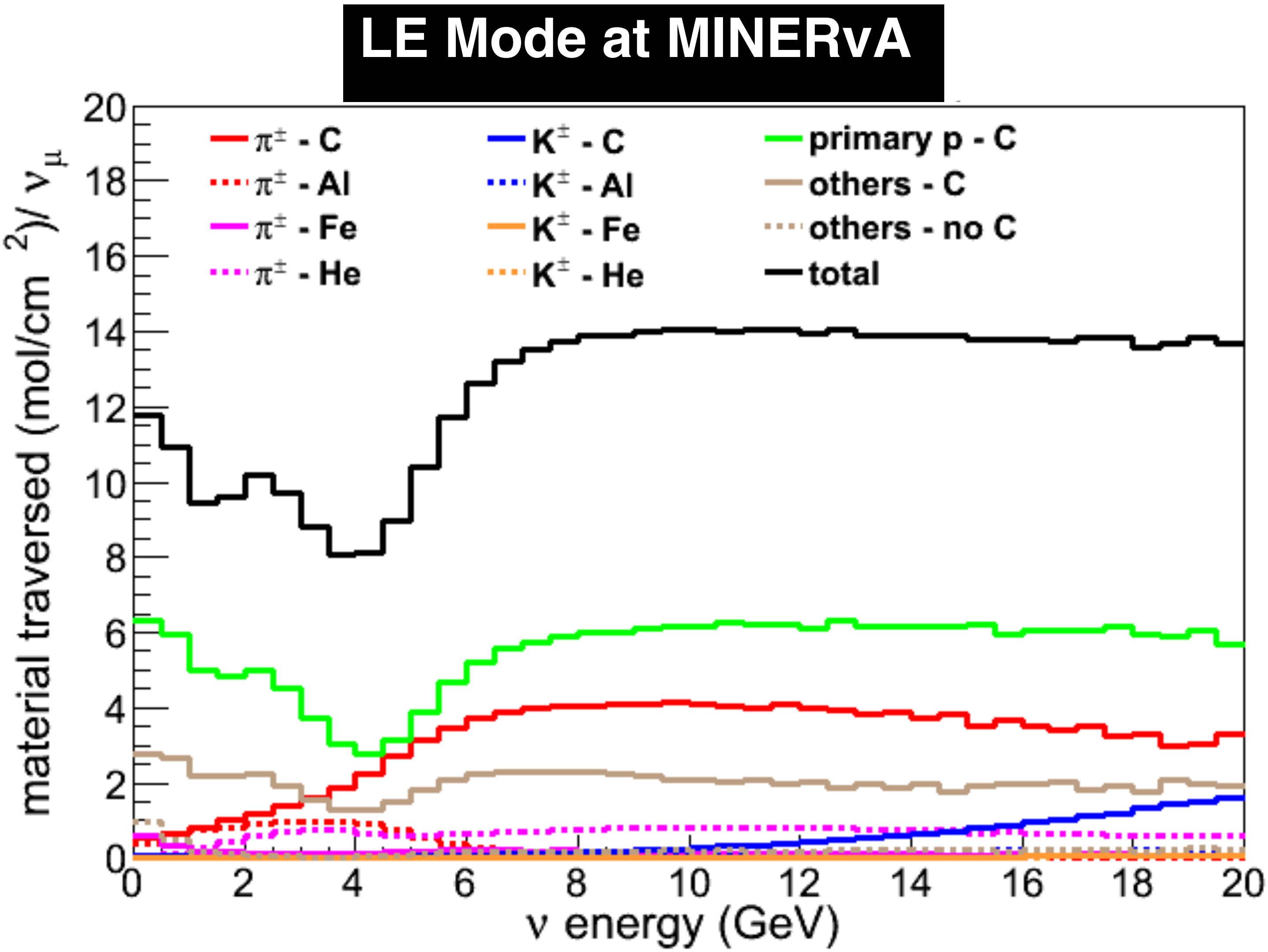


Two variables are important here:

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

Amount of Material Traversed

- Muon neutrino parent:



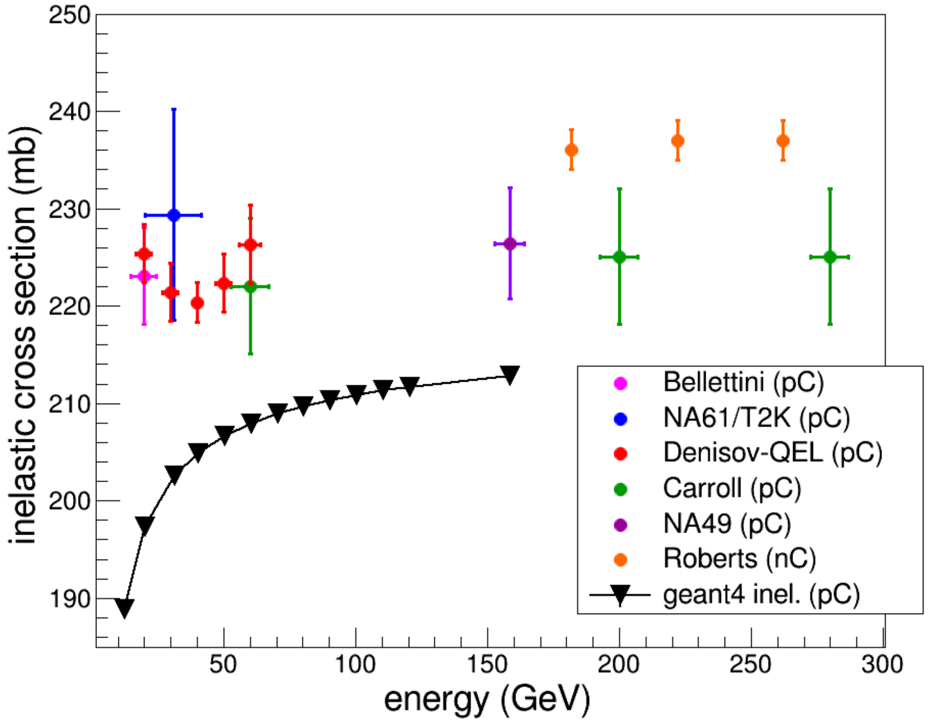
References:

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

Data - MC Comparison

- **Inelastic cross section**

Proton on Carbon

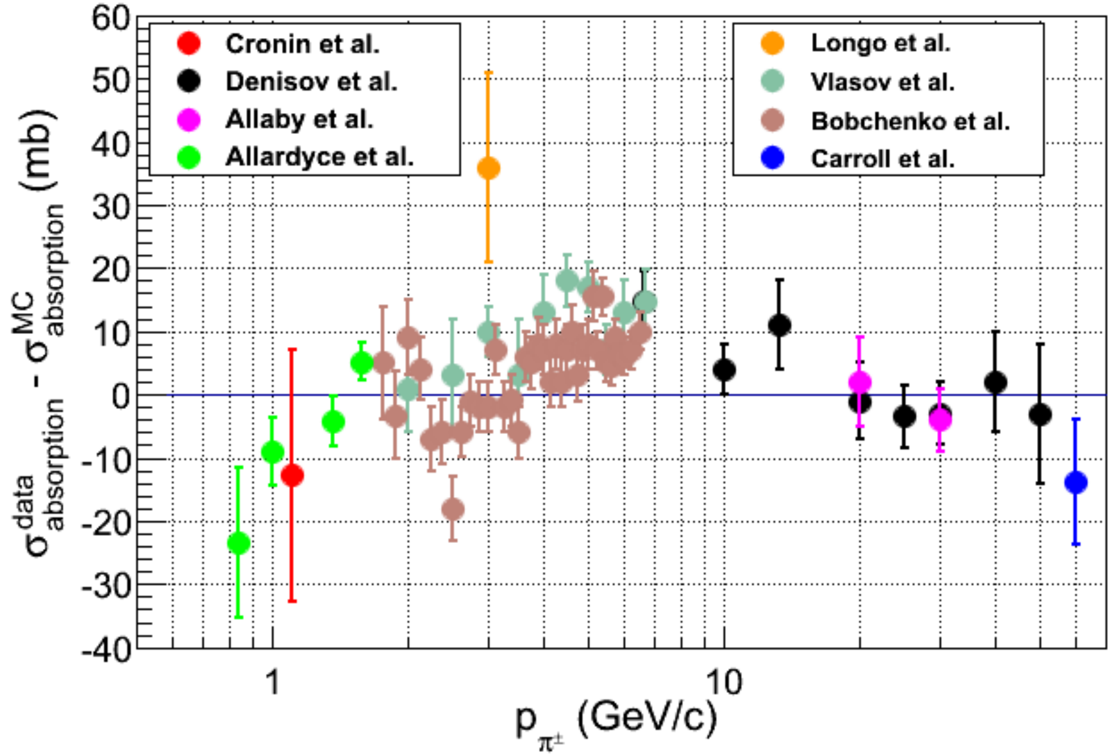


Reference (Geant4):

$\sigma_{absorption}$ = 243.2 mbar

- **Absorption cross section**

Pion on Aluminum



Reference (Geant4):

$\sigma_{absorption}$ = 344 mbar

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

2. Hadron Production

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=Ed³σ/dp³***: *invariant production cross section)*

- The **scale** allows us to use NA49 for proton on carbon in 12-120 GeV (calculated with FLUKA).
- It was checked by comparing with NA61 at 31 GeV (negligible difference).

For thick target data (MIPP):

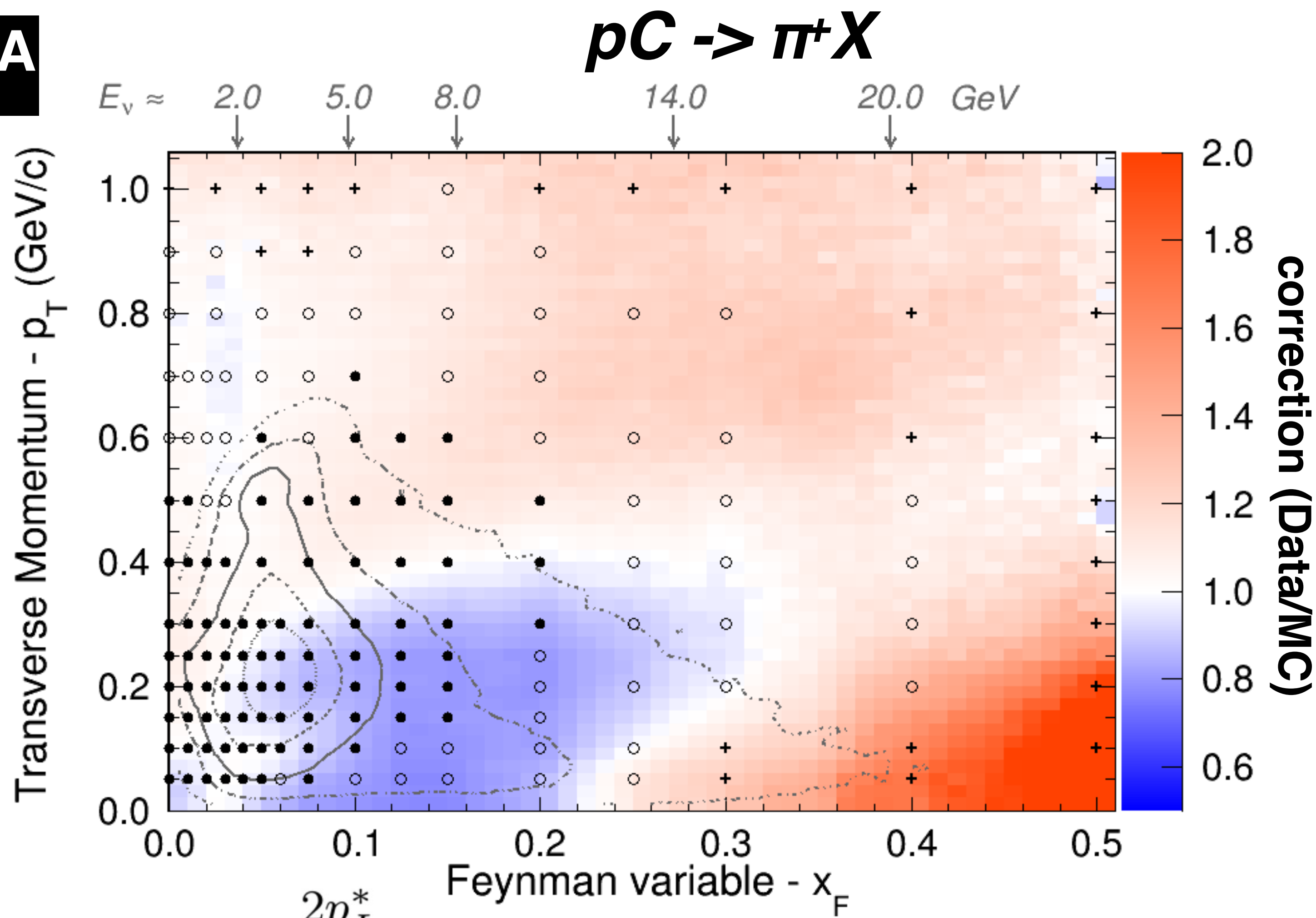
$$correction(p_Z, p_T) = \frac{n_{Data}(p_Z, p_T)}{n_{MC}(p_Z, p_T)}$$

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

LE Mode at MINERvA

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.



$$x_F = \frac{2p_L^*}{\sqrt{s}}$$

Systematic uncertainties = 3.8% (added in quadrature).

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.

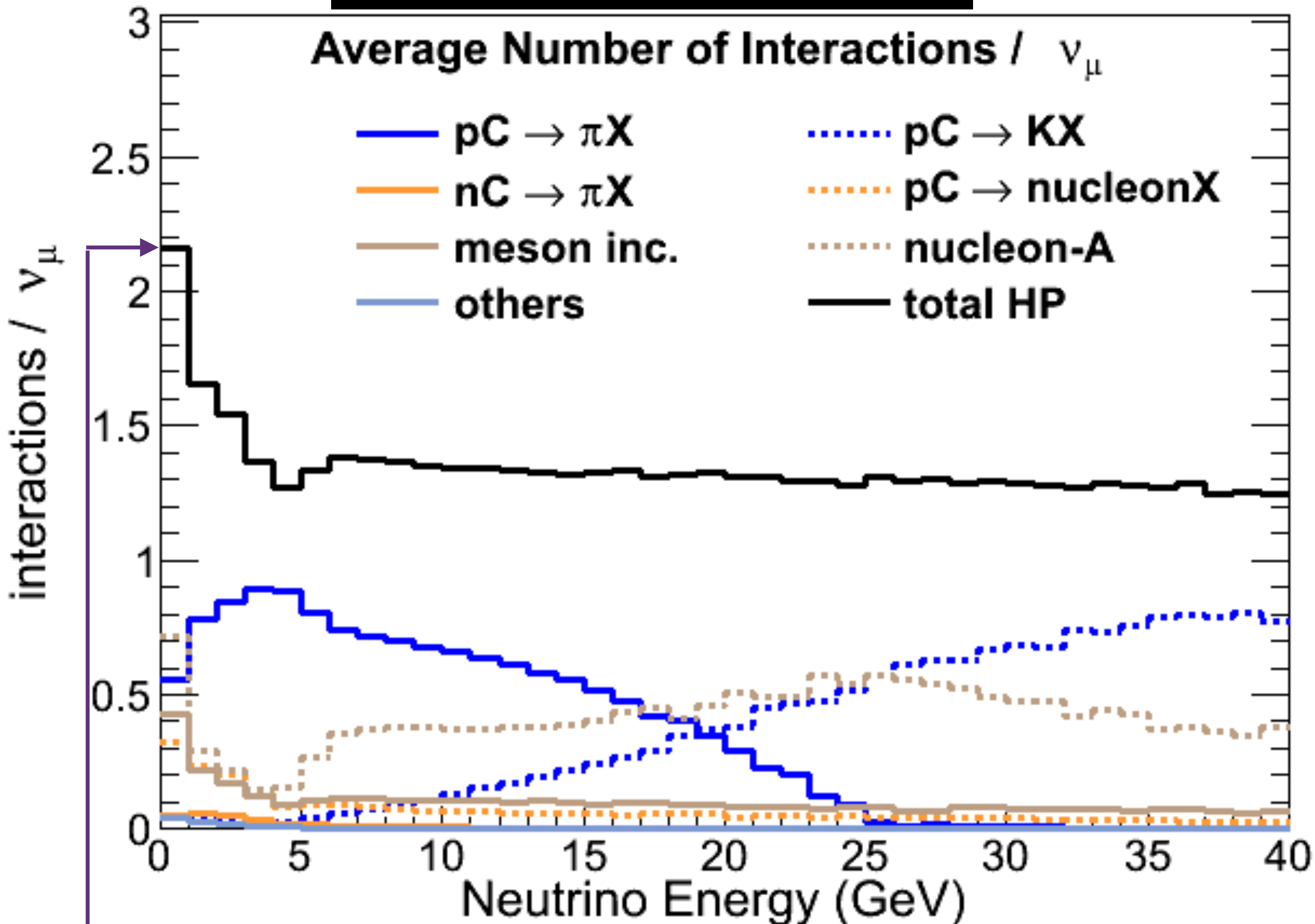
- Use theoretical guidance (isospin arguments, quark counting arguments, etc.)

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.

Average Number of Interactions

LE Mode at MINERvA



~2.2 for very low E_ν and ~1.4 for the rest

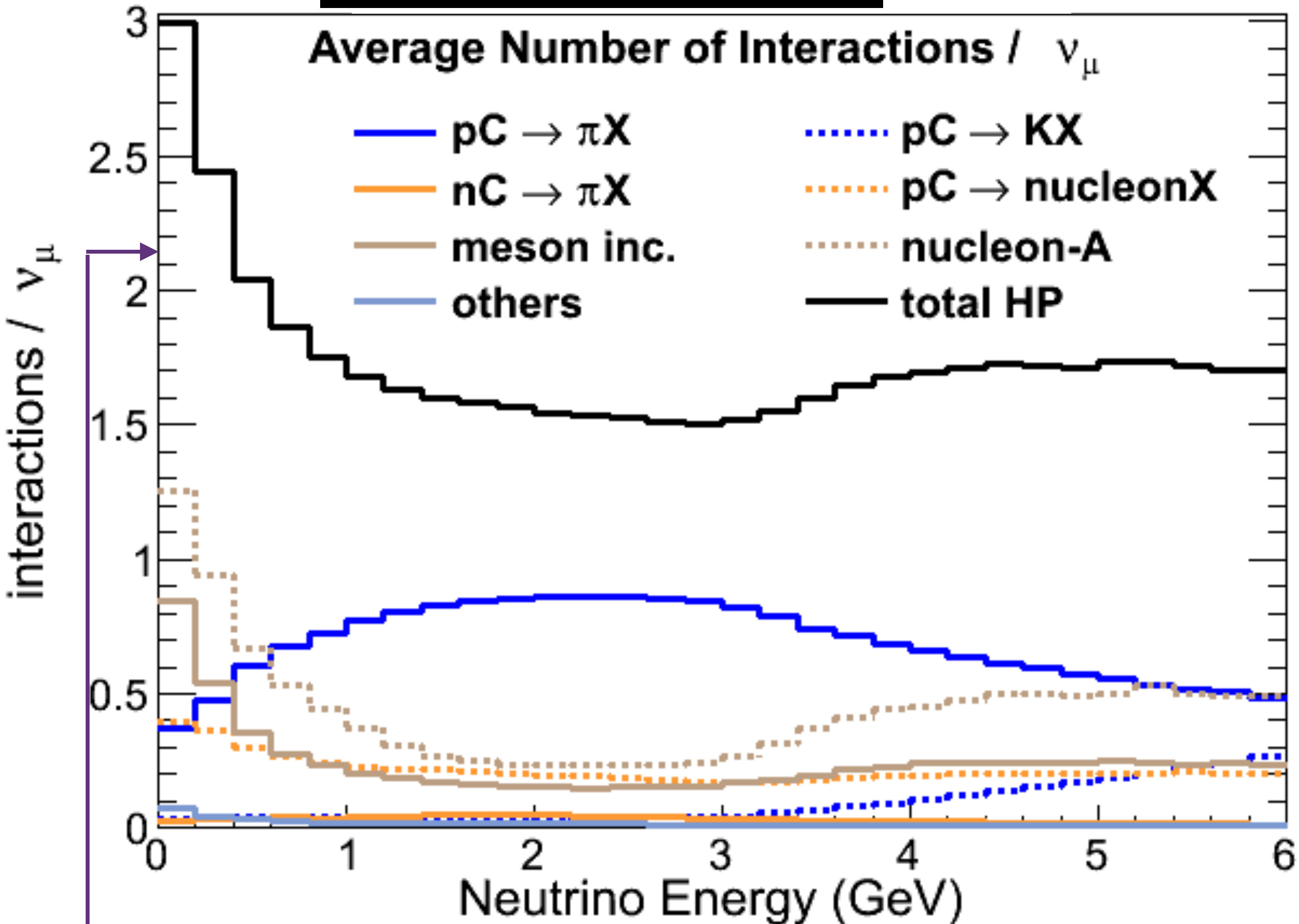
***π*, *K* and *nucleons* productions from *pC* based on data (mainly NA49).**

We assume large uncertainties for meson incident.

- **nucleon-A** (quasi-elastics, extension from carbon to other materials, production outside data coverage, etc).

Average Number of Interactions

At NOvA

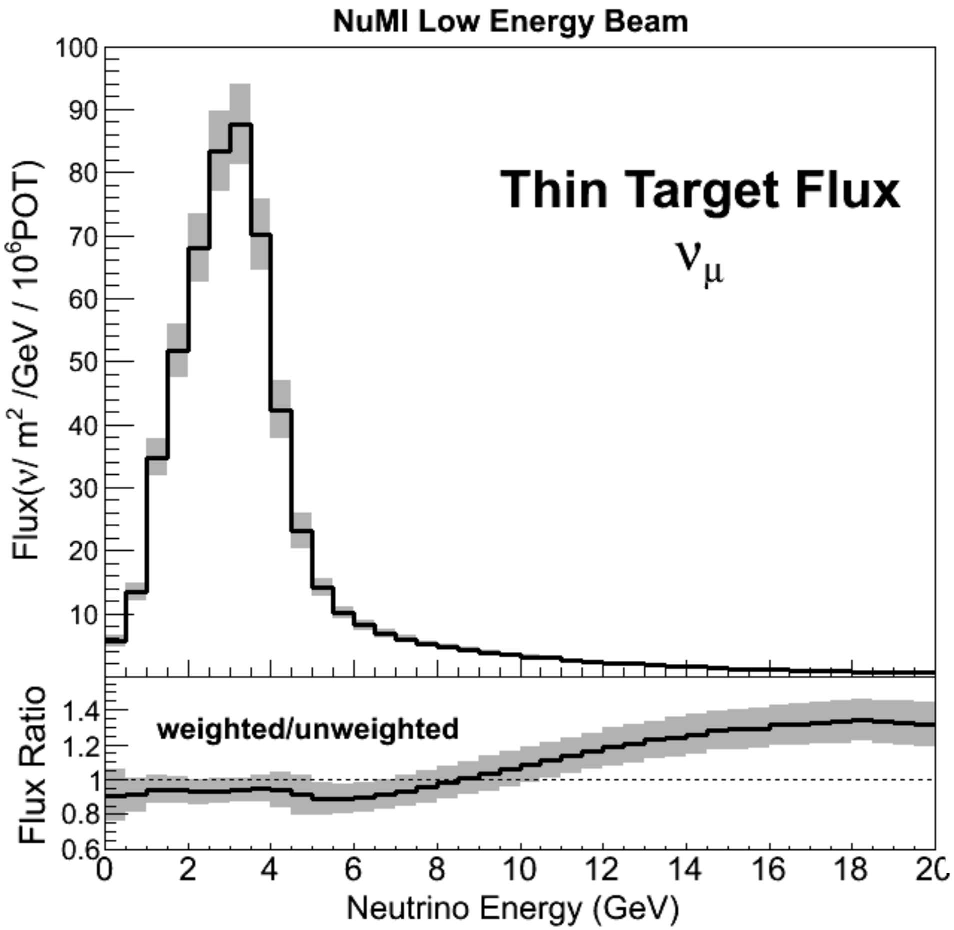


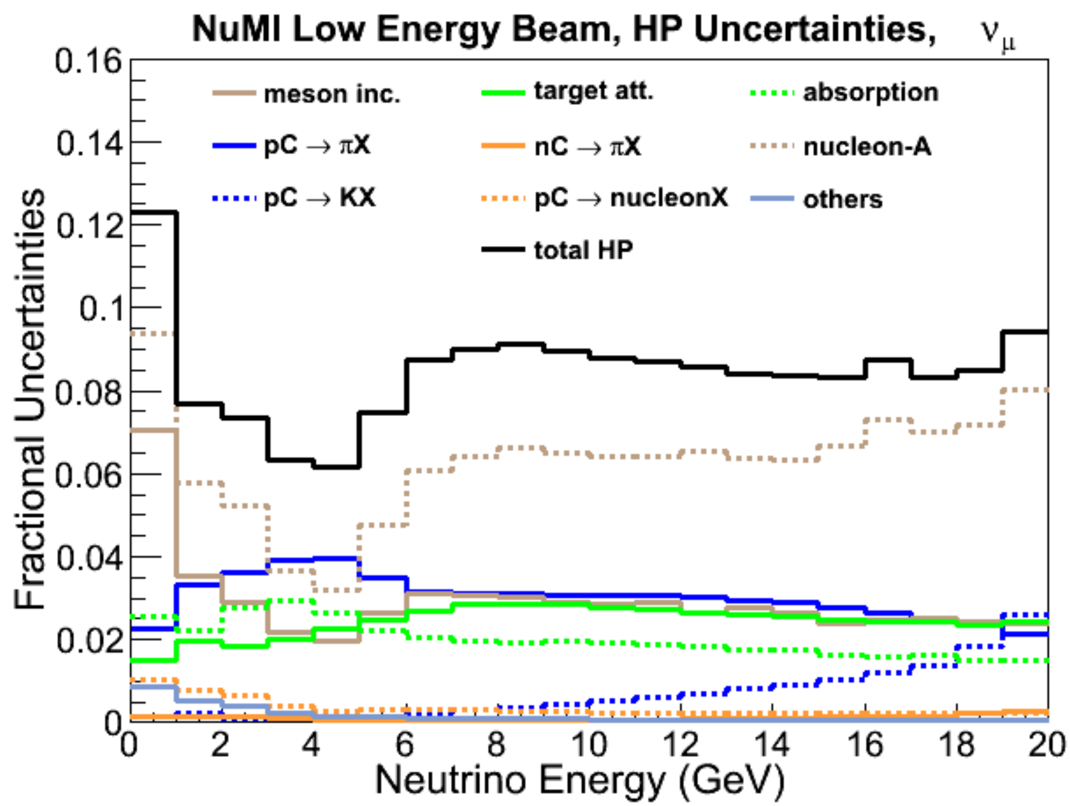
~3.0 for low E_ν and ~1.5-1.6 for the rest

Fermilab

A Priori Flux Results for LE MINERvA

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





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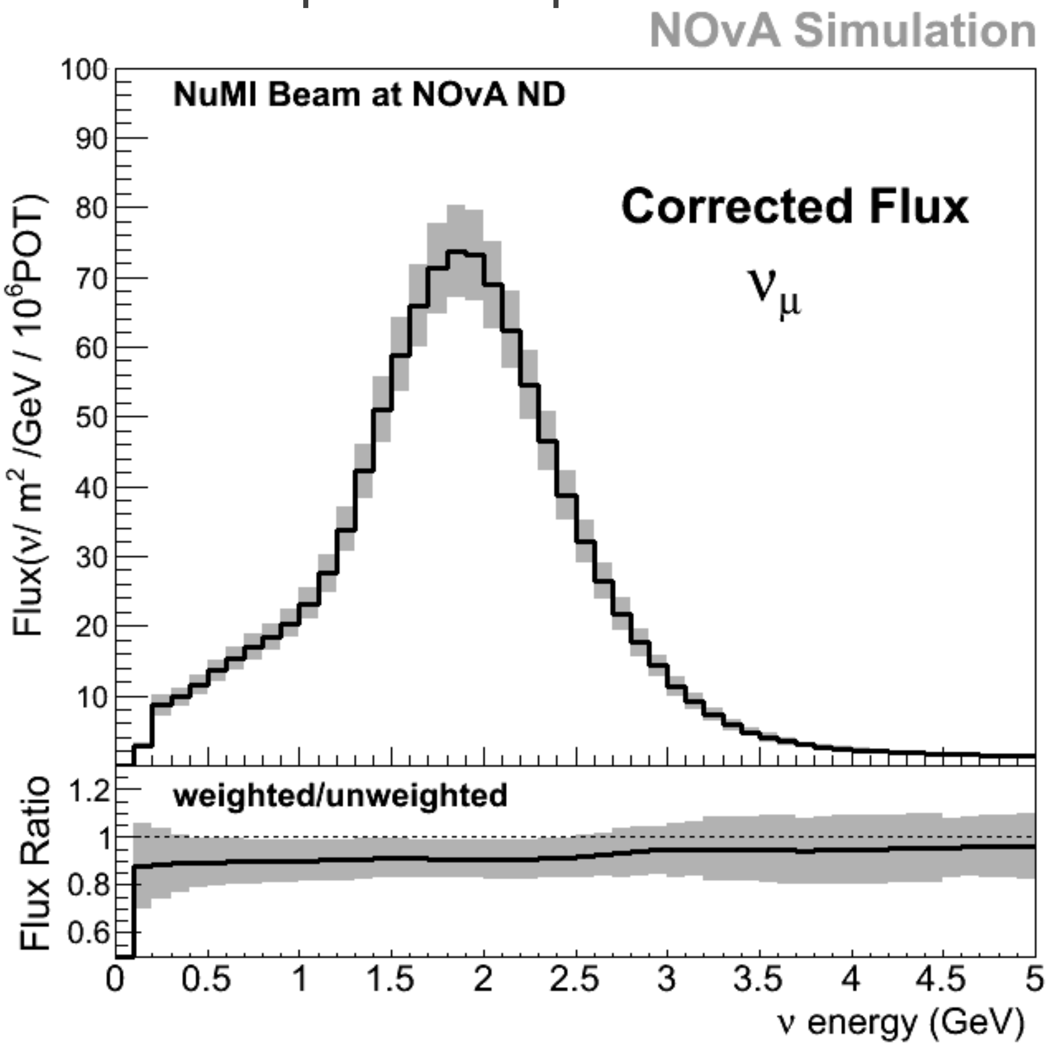
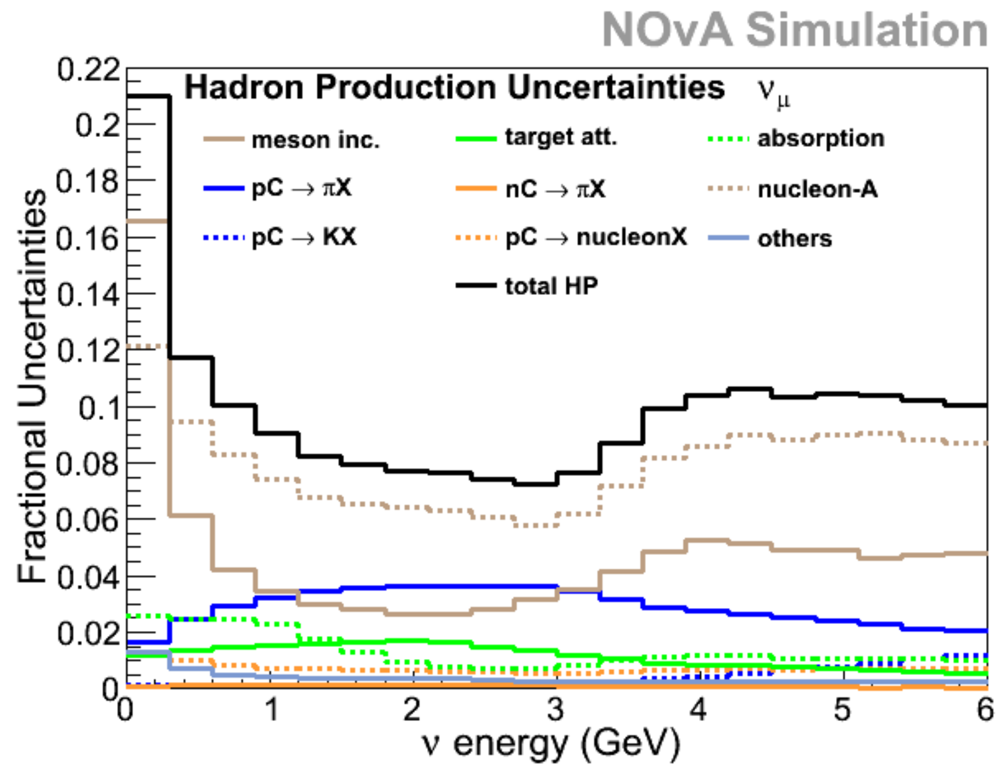
A Priori Flux Results for NOvA Near Detector

- The same procedure has been fully implemented by NOvA for its a priori flux prediction in NOvA





Conclusions

- For NOvA, MINERvA (and MINOS+) and other experiments it is crucial to have a precise measurement of the flux with small uncertainties.

- The hadron production is the main source of uncertainties. Applied all relevant existing data to constrain the flux reduce the uncertainties.

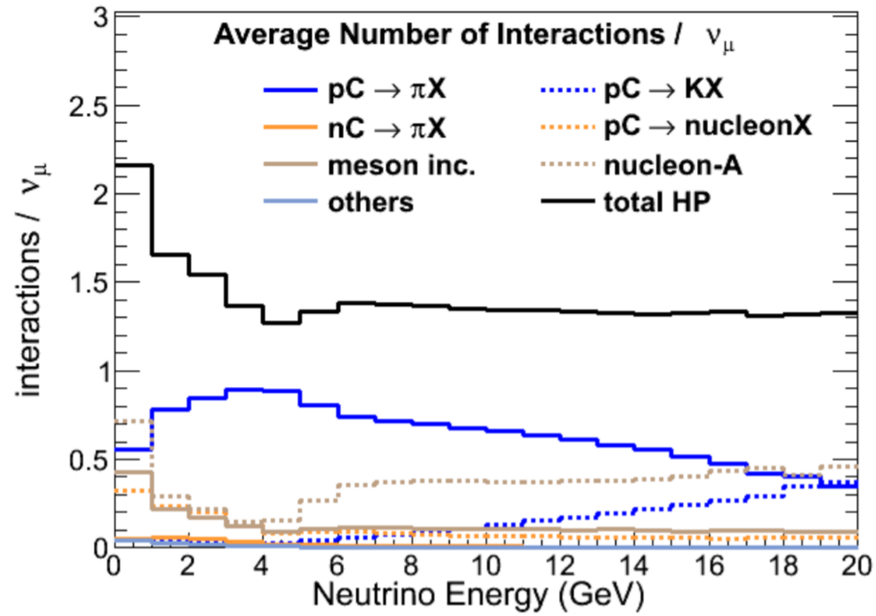
- We develop an open and free computational tool called **PPFX** to share our result with other NuMI experiments.

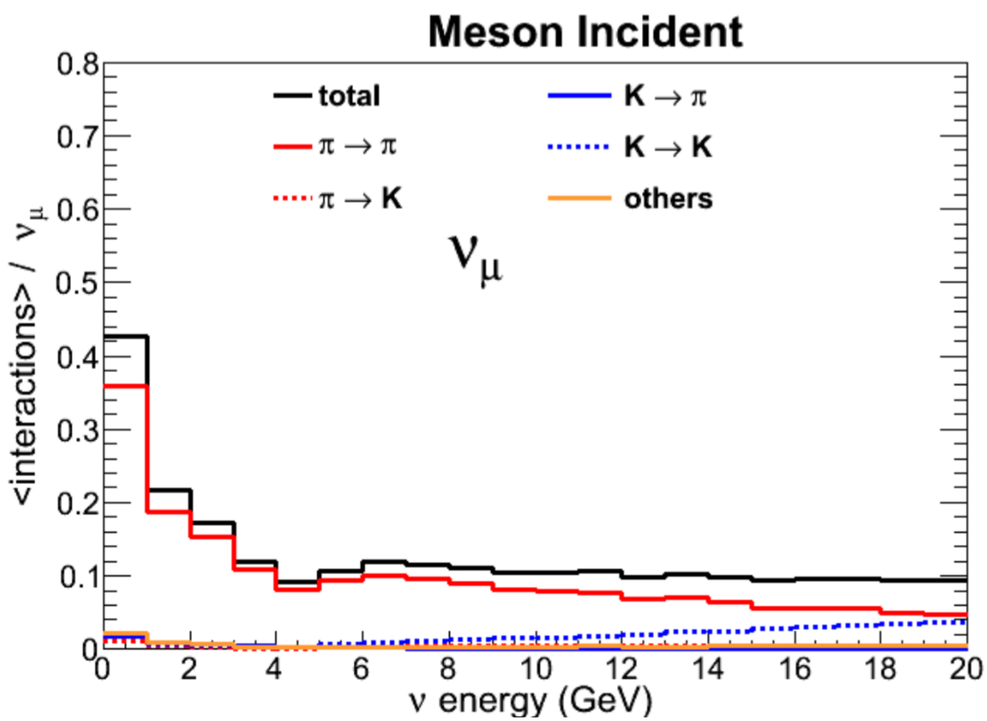
    - Currently use by MINERvA and NOvA .

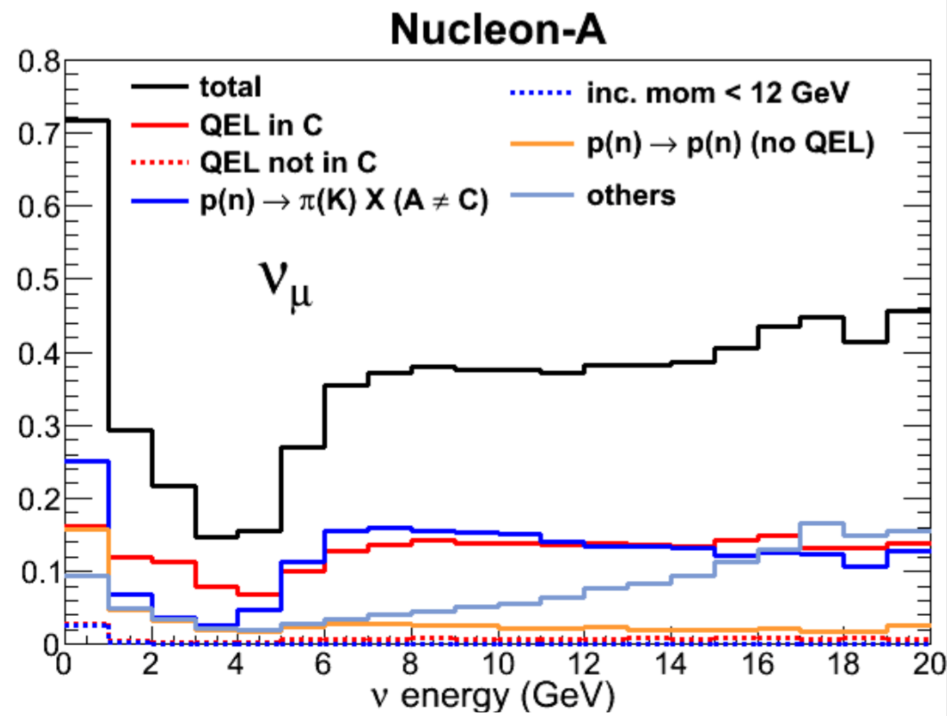
    - It has been adapted for DUNE and it is being used by the ND systematics

Conclusions FOR MINERvA

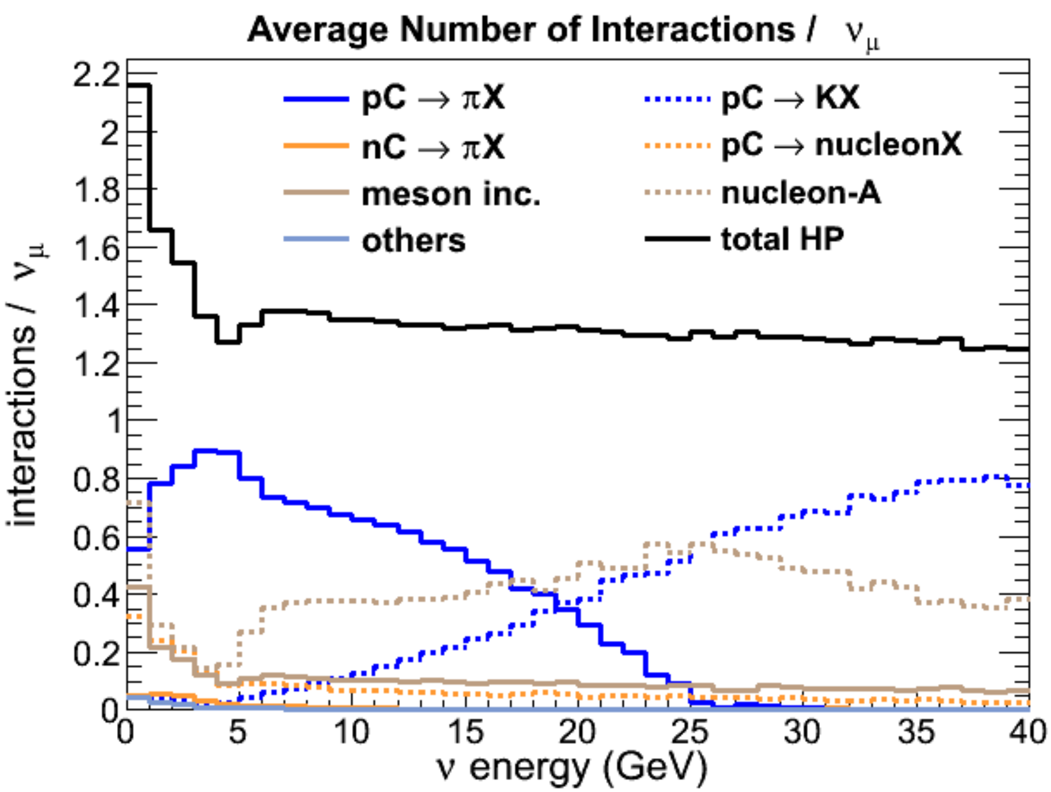
- This work also indicates where additional data is needed
  - π -> π at 30 GeV.
  - proton quasi-elastic cross section.
  - pX->π (K)X (A not C).

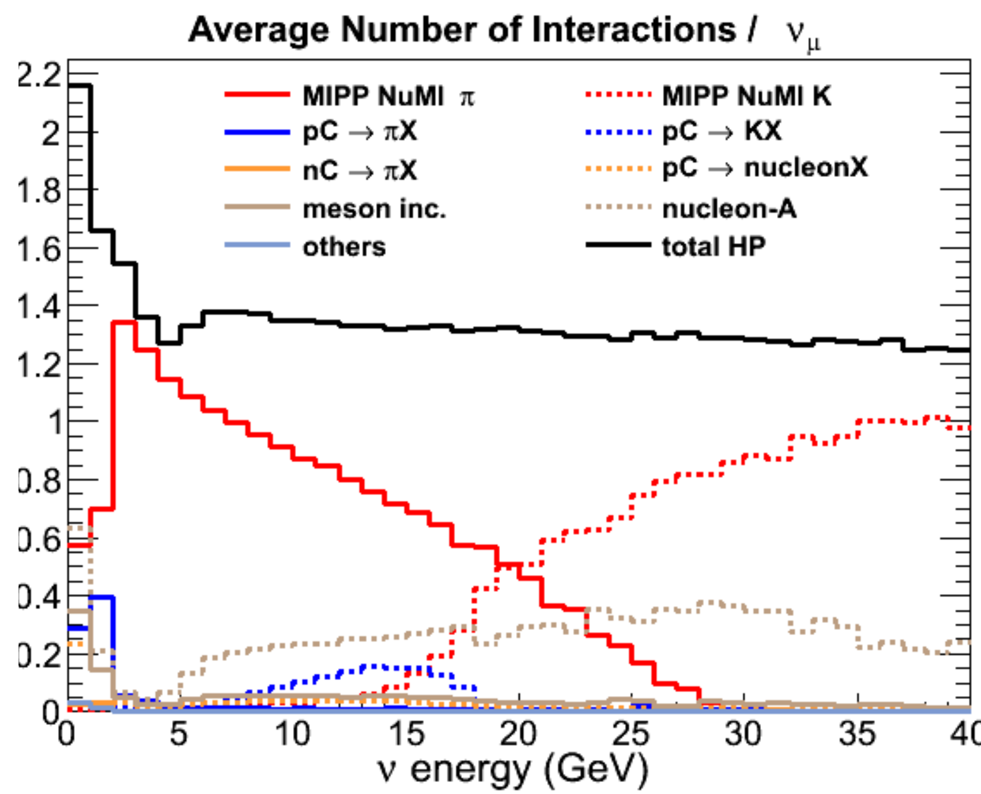






Advantage to use thick target data





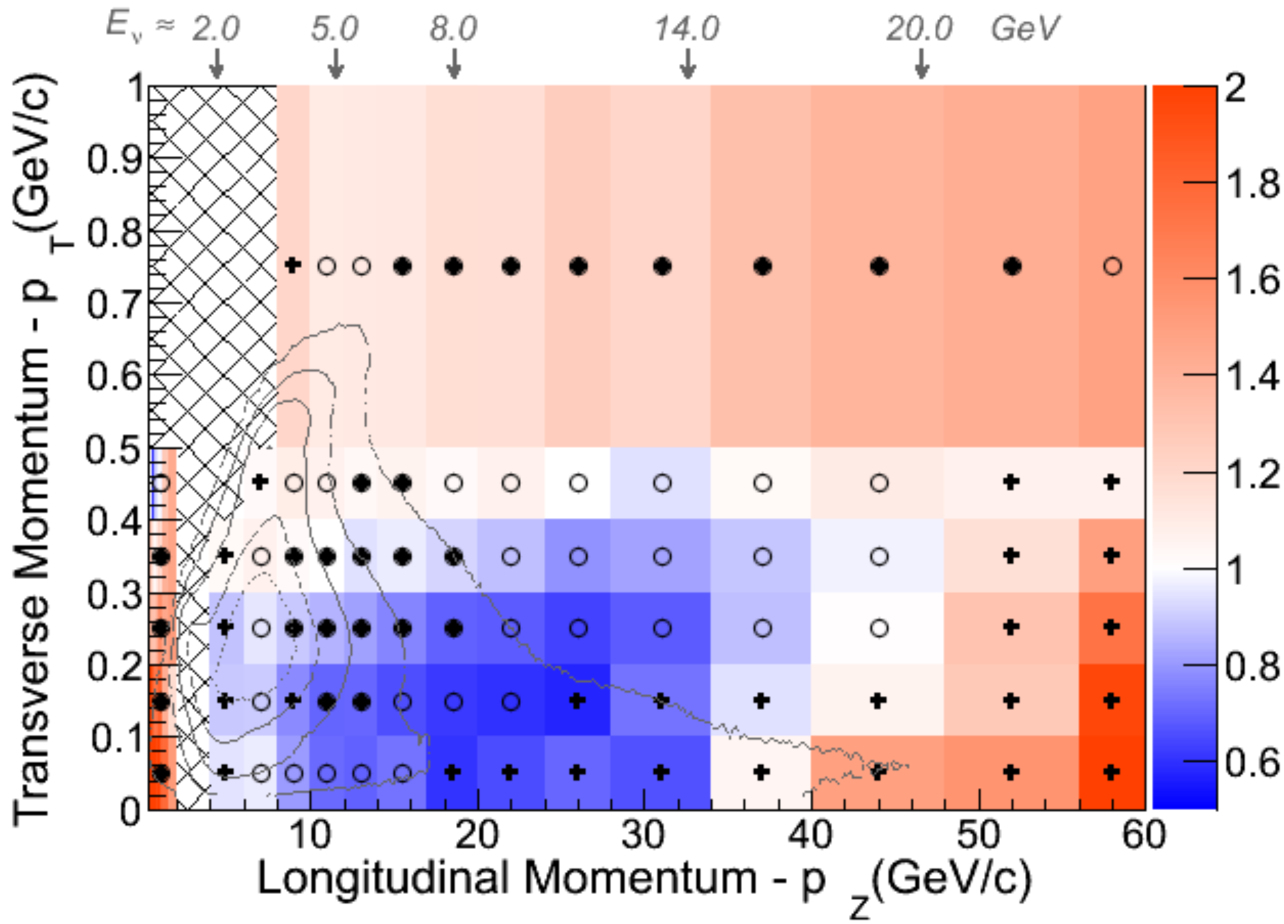
MIPP NuMI Data/MC comparison **(closed circles = statistical error < 2.5%, Open circles = statistical error 2.5-5.0%, Crosses > 5%).**

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).

Focusing Components