FERMILAB-SLIDES-22-041-LBNF

Application of hadron production data to Fermilab neutrino beam simulations

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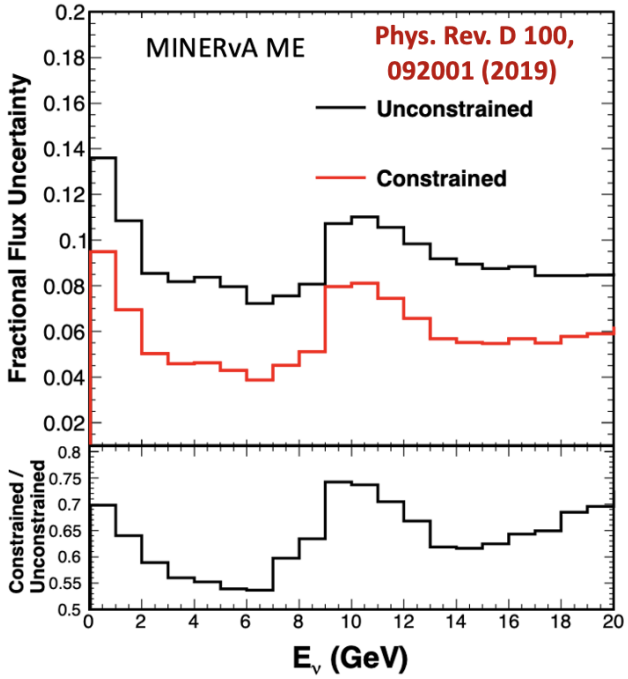
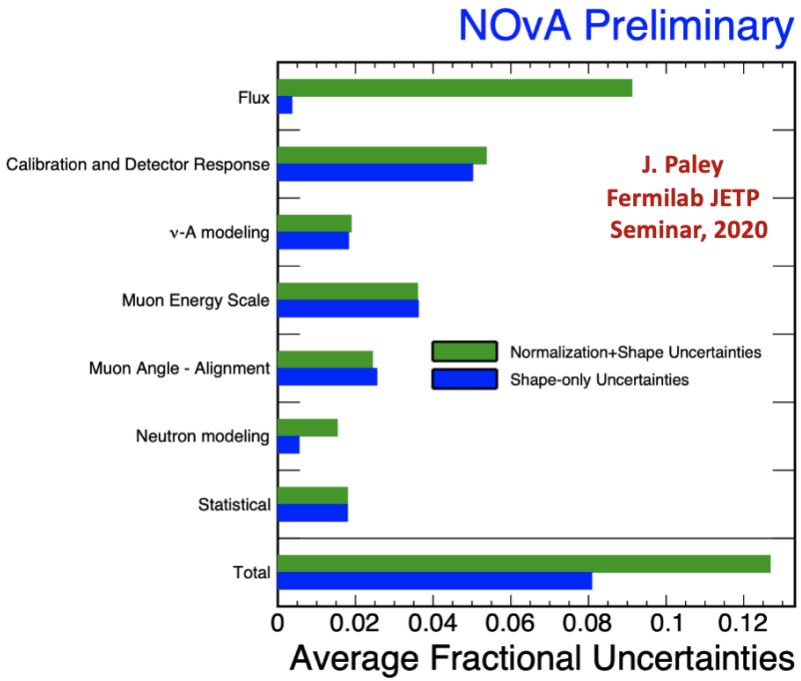
prepared for the New Perspectives 2022

Why is the Flux important? "*Flux is a dominant normalisation uncertainty*"

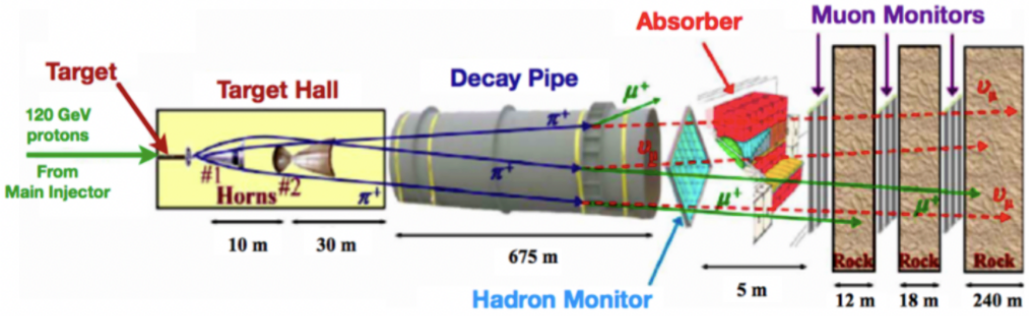
⋆ Left plot: Frac. unc. on the predicted ν_μ flux in bins of E_ν, before and after constraining the *a priori* flux model using the neutrino-electron scattering data measured by MINERvA, ⋆ Right plot: Sources of Systematic Uncertainty for NOvA.

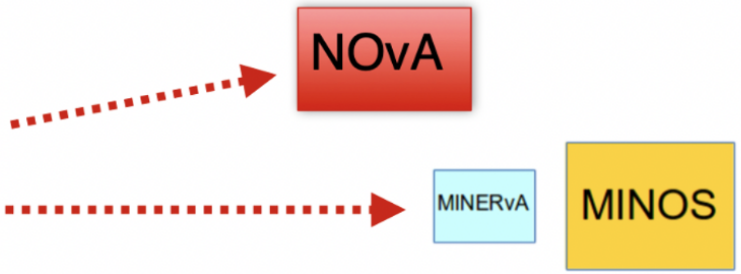


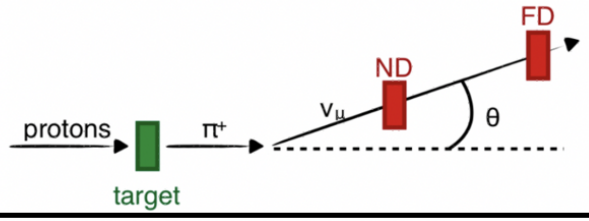


- Flux is the dominant uncertainty in neutrino-nucleus cross-section measurements (one-detector measurement).
- Flux systematics in oscillation experiments are sub-dominant, however, it is important to have a good prediction for the baseline simulation.

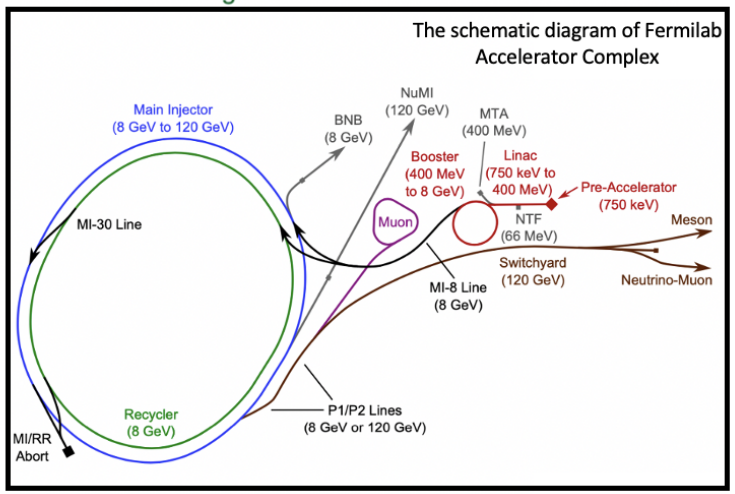
NuMI and Neutrino Experiments



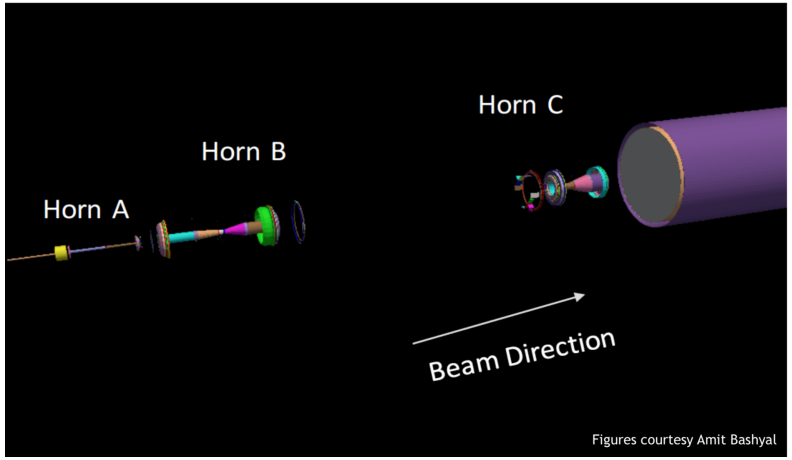


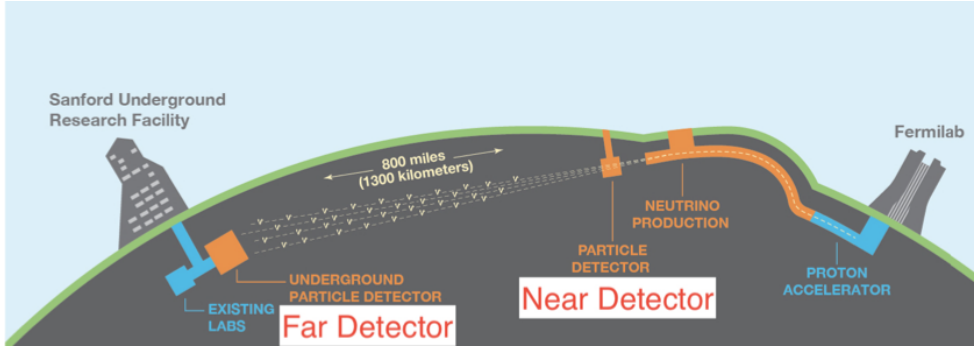


- 120 GeV protons hit the target and π^+ produced
- Magnetic horns to focus π^+
- π^+ decay to $\mu^+\nu$ in long low-density He-filled pipe
- ν beam travels through earth to experiment
- MINERvA (Main Injector Experiment for ν - A)
  - → On-axis experiment located at Fermilab
  - → It completed physics run in 2019
- NOvA (NuMI Off-axis ν_e Appearance)
  - → Off-axis angle 14.6 mrad
  - → Near Detector at Fermilab and Far Detector at Ash River



LBNF Optimized beamline

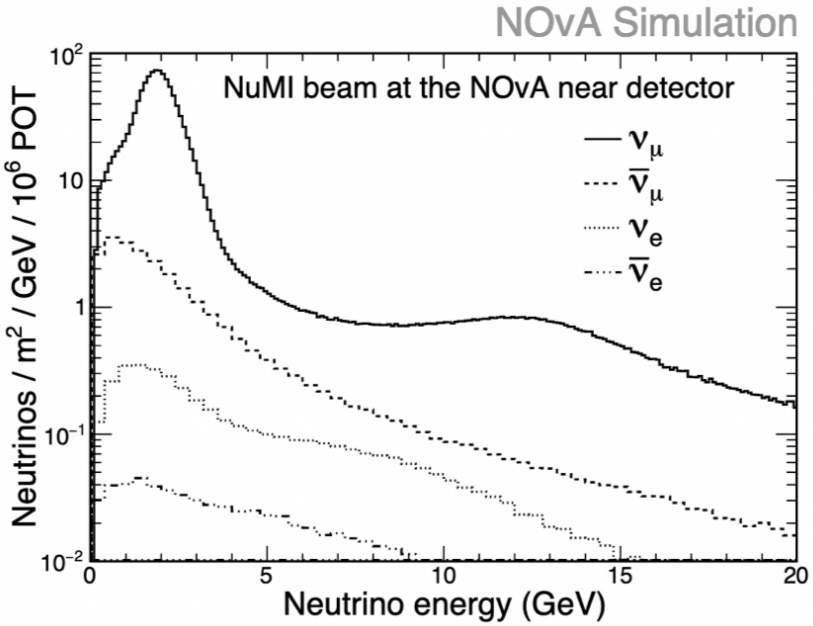


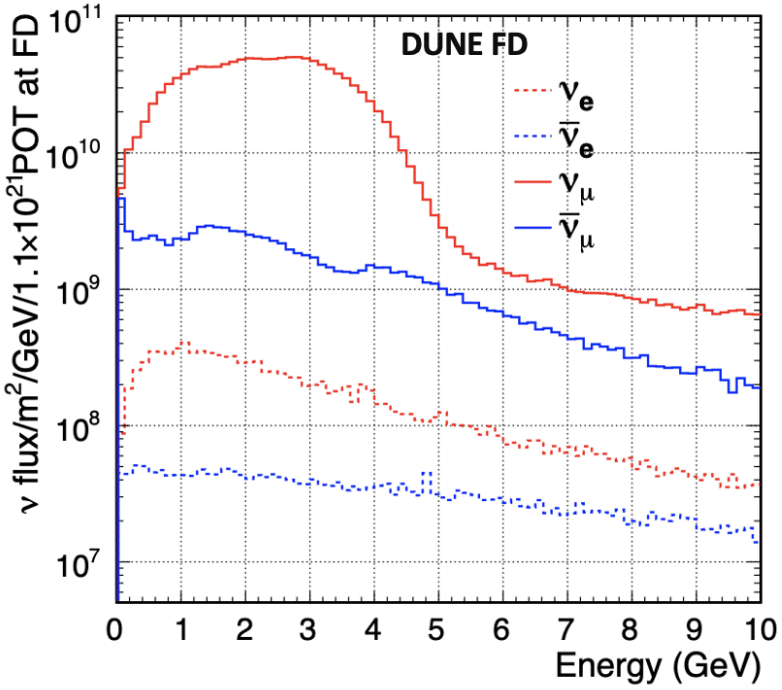


- Primary proton beam in 60-120 GeV
- Initial 1.2 MW beam power, upgradable to 2.4 MW
- Graphite target, 3 Magnetic horns
- He-filled Decay pipe
- Experimental setup optimized for δ_{CP} measurement
- Near detector at Fermilab and Far detector at South Dakota
- A baseline is $\sim$ 1300 km

NOvA and DUNE Fluxes

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

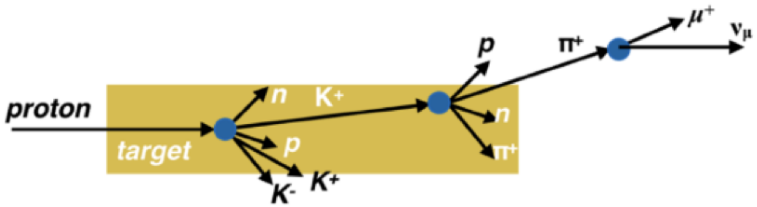




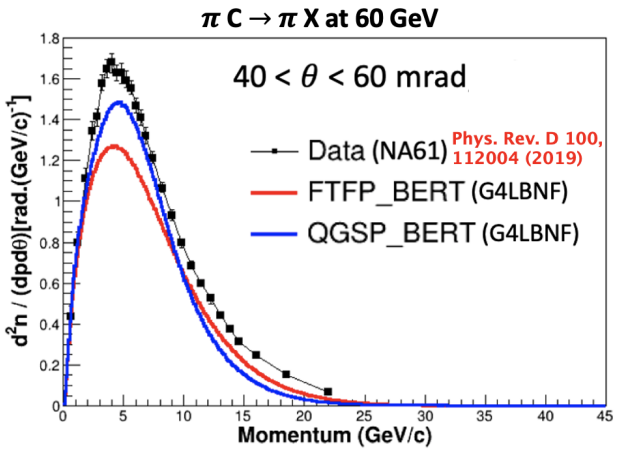
- NuMI simulation (G4NuMI): GEANT4 v4.9.2.p03 with FTFP_BERT
- LBNF simulation (G4LBNF): GEANT4 v4.10.3.p03b with QGSP_BERT
- Currently, NuMI and DUNE fluxes are constrained using HP data of particle production off of thin targets mainly from the NA49 experiment.

But Hadron Production models differ significantly from the data

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

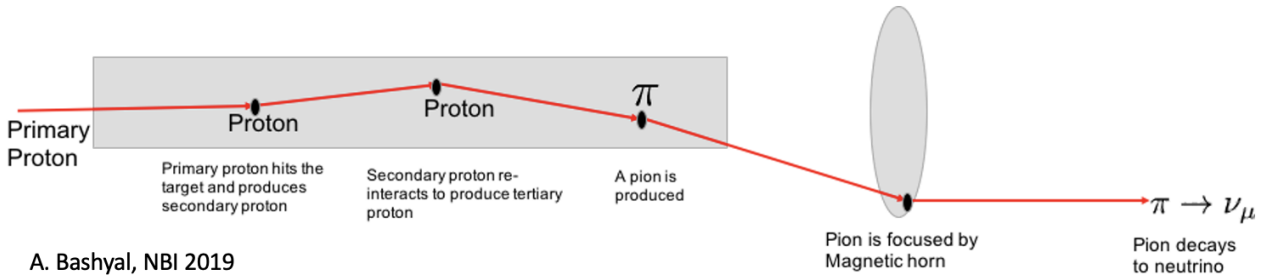


- Simulated neutrino flux relies on HP model used in the simulation. But, a significant discrepancy between data and simulation:



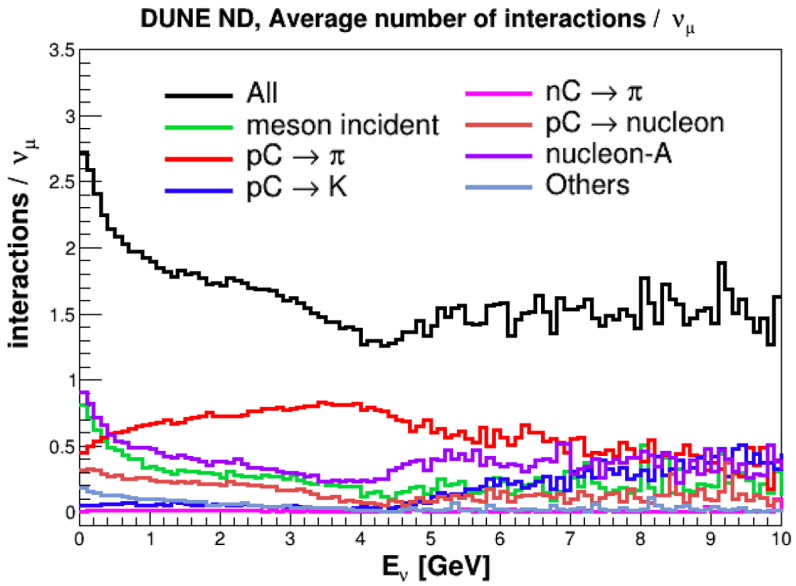
- *So, neutrino experiments need to use external data to constrain their hadron production models.*

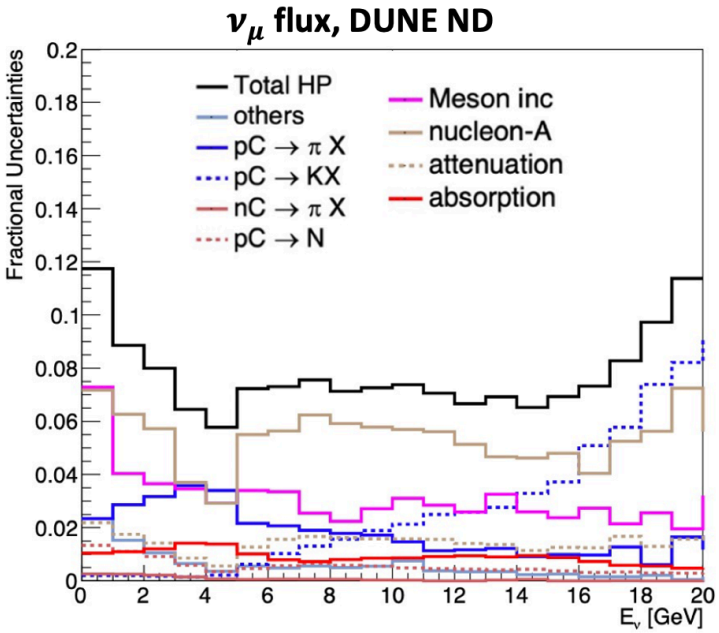
Our strategy for correcting the NuMI and DUNE fluxes: PPFX *[Phys. Rev. D 94, (2016)]*



- Currently, NuMI and DUNE fluxes are predicted using the Package to Predict the FluX (PPFX).
- *The main idea is constraining the interactions and the hadron productions using external measurements on thick and thin targets.*
- It corrects the yields given by the hadronic model to match the external data. If there is no available data, we extend the data coverage or assign a well-educated guess for these interactions.
- **It propagates the underlying data correlations** to calculate the neutrino interaction covariance ("multi-universe" technique).
  $\rightarrow$ It requires the hadron production datasets bin-to-bin correlation.

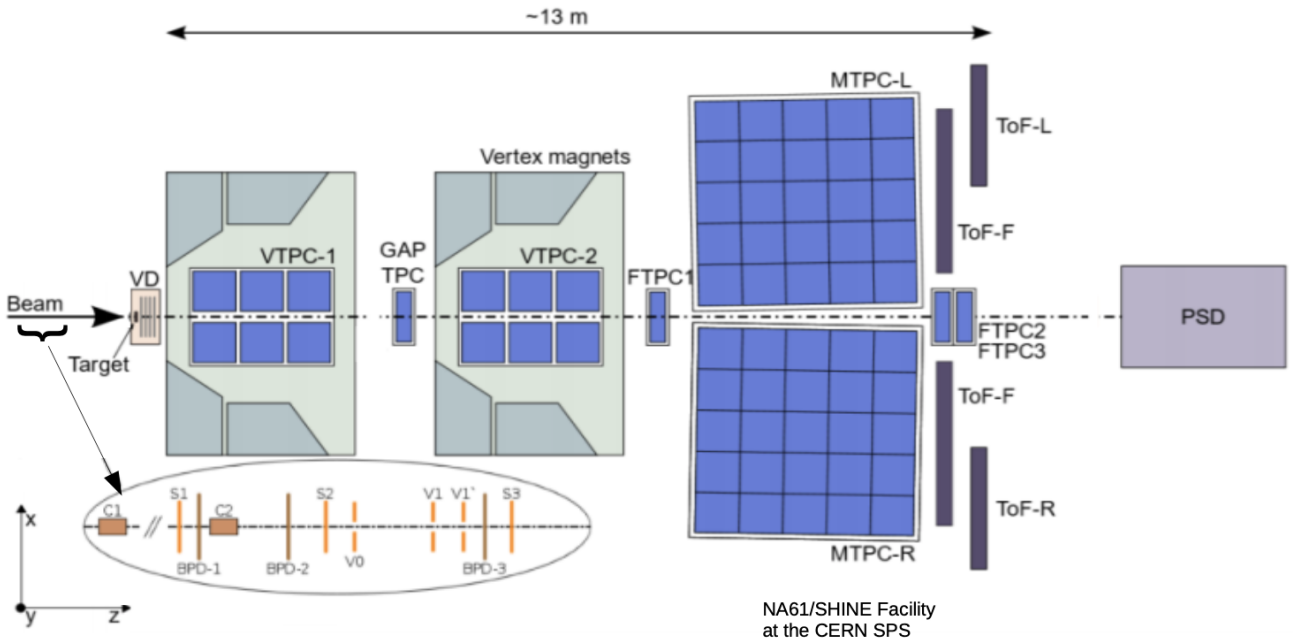
Interactions and uncertainties on the DUNE flux





- Mostly based directly on NA49 data for $pC \to \pi X$, $pC \to KX$ and $pC \to N$.
- Meson interactions are not constrained by data and we assume 40% uncertainty for these interactions for DUNE and NuMI.
- These plots have similar patterns and values for MINERvA and NOvA.
- **NA61/SHINE (CERN) and EMPHATIC (Fermilab) experiments are working to make *new* hadron production measurements to reduce the flux uncertainties for neutrino experiments.**

NA61/SHINE at CERN's Super Proton Synchrotron (SPS)



- Receives secondary beam initiated by 400 GeV/c SPS protons
- Series of magnets selects desired momentum from 13-350 GeV/c range
- Target options: Thin ($\sim$ 2 cm) targets, any material, neutrino experiment targets (T2K, NOvA etc.)
- NA61/SHINE has a rich physics program including ***hadron production measurements to constrain flux uncertainties***
- *Large acceptance and good momentum for charged particles*
- Also, *good resolution* for the particle identification

Recent NA61/SHINE measurements for neutrino flux predictions

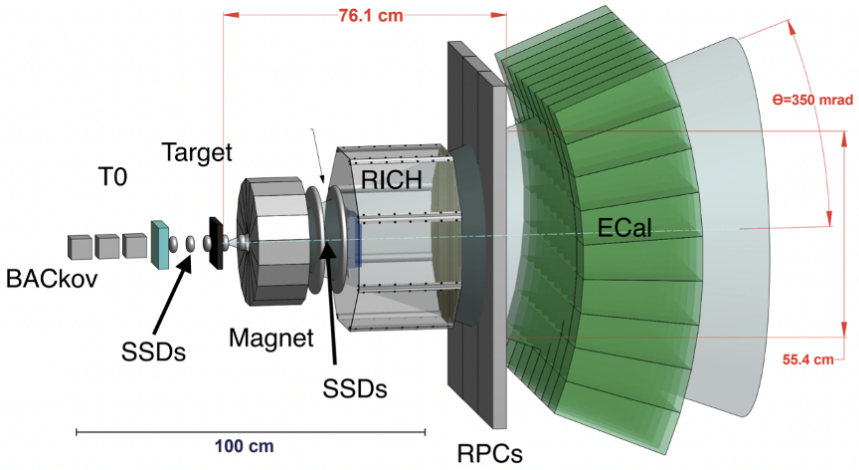
List from B. Rumberger, DUNE Collaboration Meeting, May, 2022

Year	Reaction		Number of Triggers
2016	π^+ + C 60 GeV/c	Multiplicity Analysis Published	3.0 Million
2016	π^+ + Be 60 GeV/c	Multiplicity Analysis Published	2.7 Million
2016	p + C 120 GeV/c	Multiplicity Analysis Publication Pending	4.6 Million
2016	p + Be 120 GeV/c	Cross-Section Analysis Published	2.5 Million
2016	p + C 60 GeV/c	Multiplicity Analysis Publication Pending	3.1 Million
2016	p + Al 60 GeV/c	Multiplicity Analysis Finalized	3.5 Million
2016	p + Be 60 GeV/c	Cross-Section Analysis Published	2.2 Million
2017	π^+ + Al 60 GeV/c		2.5 Million
2017	π^+ + C 30 GeV/c		2.1 Million
2017	π^- + C 60 GeV/c		3.5 Million
2017	p + C 120 GeV/c	Multiplicity Analysis Publication Pending	2.5 Million
2017	p + Be 120 GeV/c		3.9 Million
2017	p + C 90 GeV/c	Calibration In Progress	3.1 Million
2018	p + NuMI-ME Target	Calibration In Progress	21.3 Million

→ ***Proposed low energy beamline relevant to DUNE second oscillation maximum (allow for < 13 GeV/c)***

→ **Plan for the future LBNF replica target data**

EMPHATIC at Fermilab

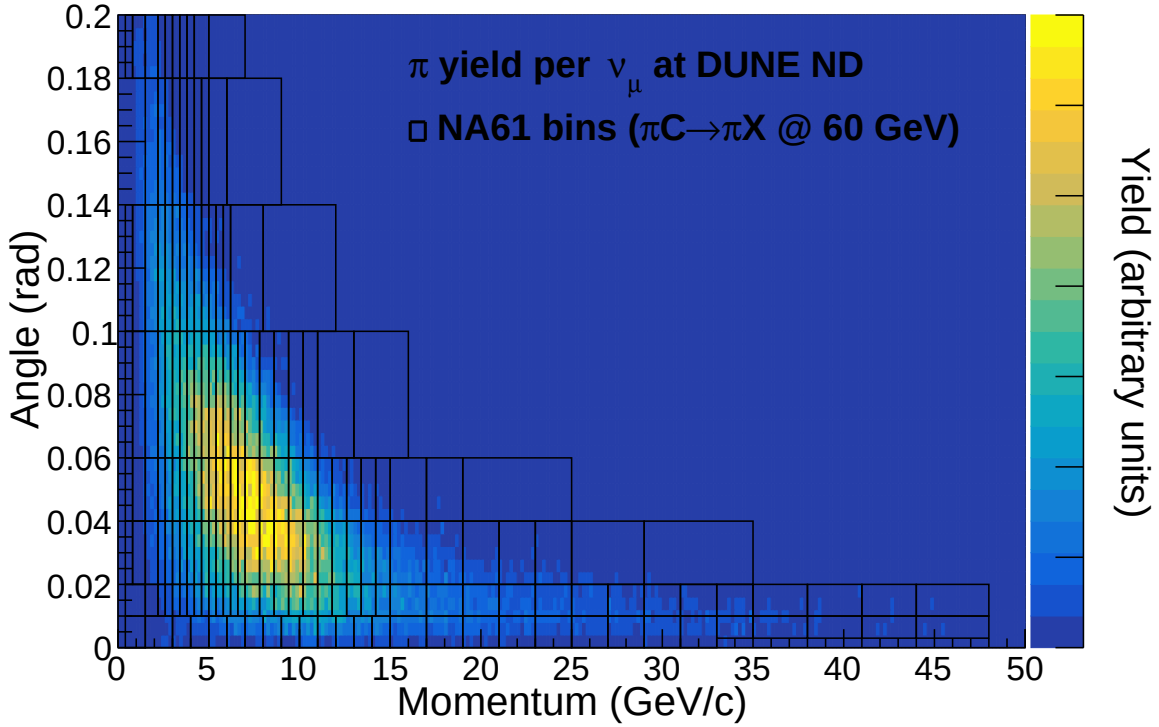


- EMPHATIC at Fermilab Test Beam Facility

- Measurements of the hadronic interactions using different projectiles, targets, and energies *relevant for the neutrino flux predictions*
- Table-top size experiment, focused on regions *currently* inaccessible to NA61, $p < 15$ GeV/c but measurements with beam from 20-120 GeV/c
- Recently released data for forward proton scattering at 20, 30, and 120 GeV/c using Carbon target *[arXiv: 2106.15723]*
- It will also provide data for *larger acceptance with a permanent magnet*
- The experimental setup will include Silicon Strip Detectors, (Aerogel) RICH counters, RPC (ToF) counters and the lead-glass calorimeter

One of the efforts of the PPFX group

→ One of the efforts of the PPFX group is to implement the NA61/SHINE pion projectiles at 60 GeV/c data for LBNF and NuMI



This data covers the region of interest to constrain the neutrino flux with small uncertainties (typically statistical $\sim 2\%$ and systematic $\sim 5\%$) *[Phys. Rev. D 100, (2019)]*

Conclusions

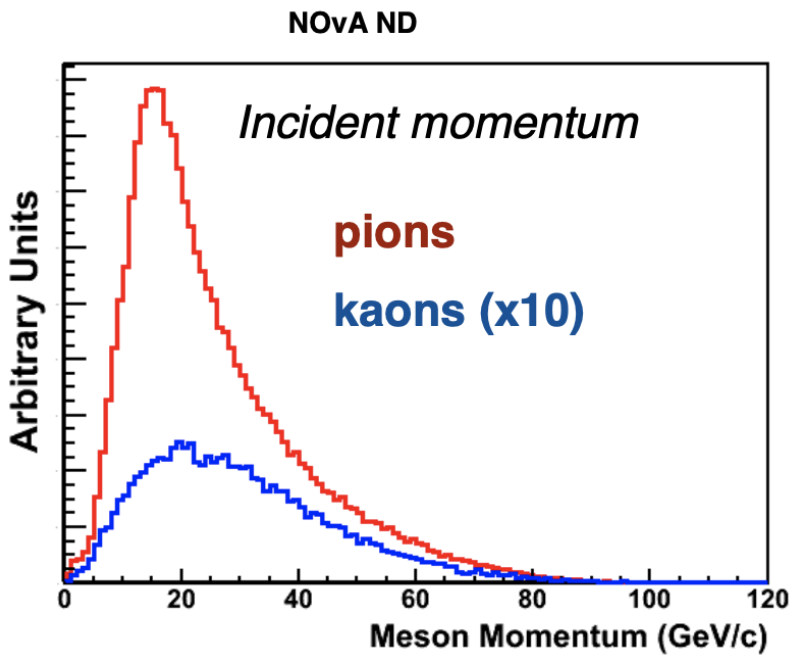
- Flux uncertainties have improved importantly in recent years using the NA61/SHINE hadron production measurements.
- Currently, NA61/SHINE and EMPHATIC experiments are working to make new hadron production measurements at different energies with different targets.
- PPFX group is dedicated to the implementation of the current new measurements from hadron production experiments to constrain the flux uncertainties.
- We expect that flux prediction will improve significantly after these implementations. This will contribute to the physics programs for the neutrino experiments.

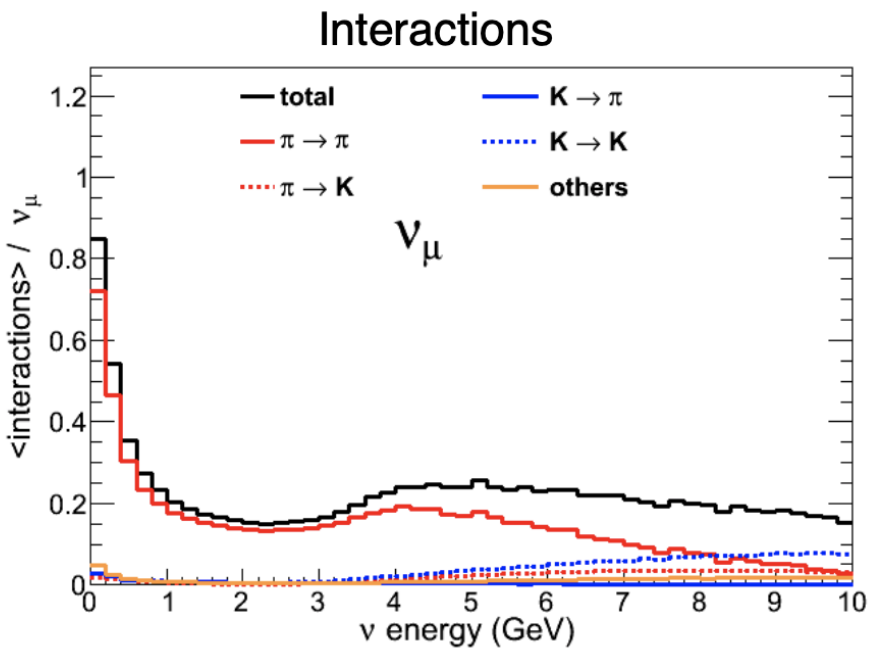
Thank you very much for listening & Stay tuned

Contact information: `ppfx@listserv.fnal.gov`

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

Incident mesons





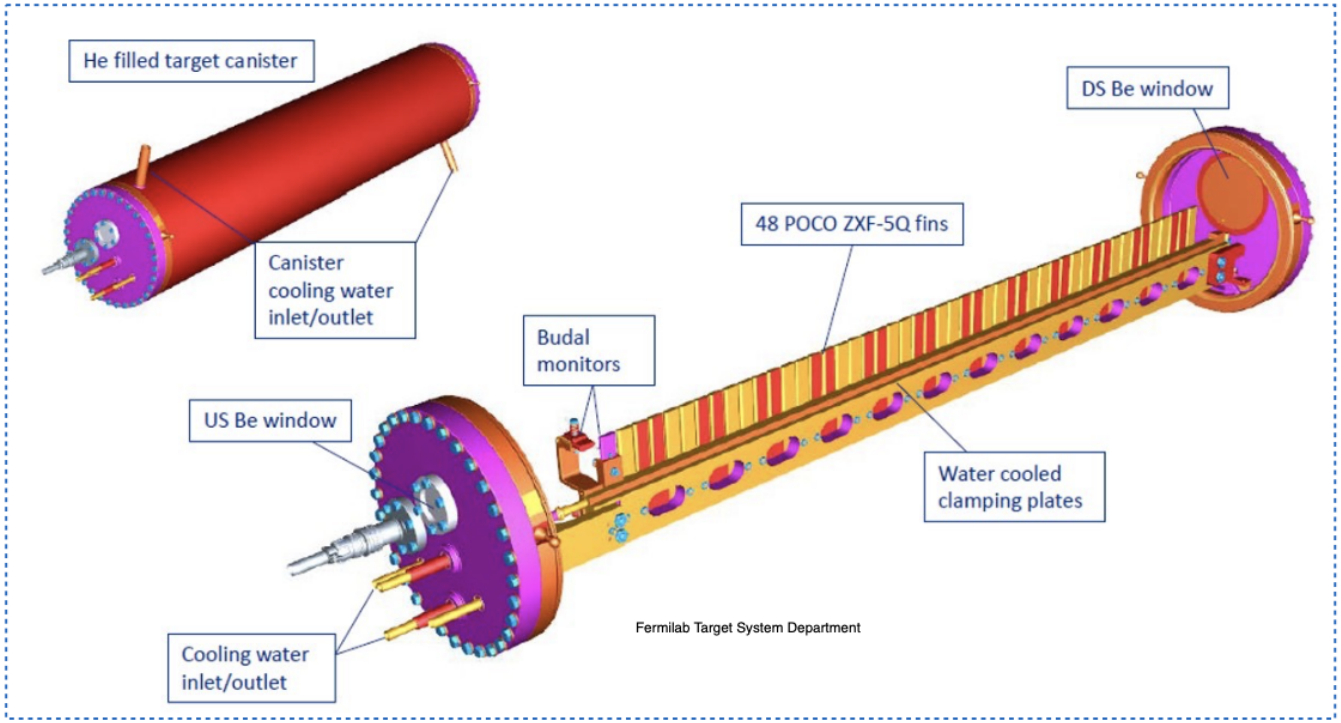
Main contribution from $\pi \to \pi$ in the whole neutrino energy spectrum.

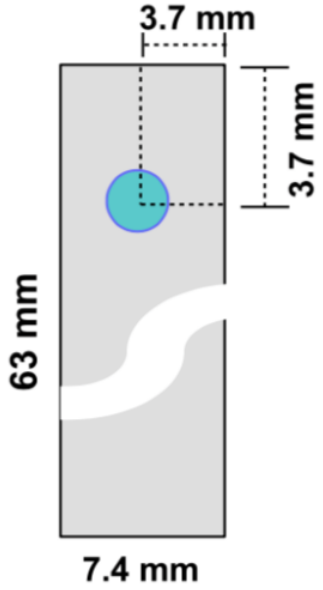
Currently, we are working to include the NA61 incident pion on Be and C (Phys. Rev. D 100, 112004 (2019))

NuMI target

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

50 fins in total: 1.2 m (~2.5 λ).





Particle absorption

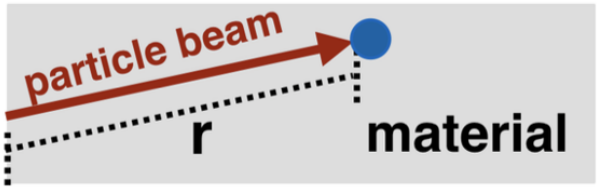
L. Aliaga, NA61/SHINE at Low Energy Workshop , 2020

Particle absorption:

Interacting

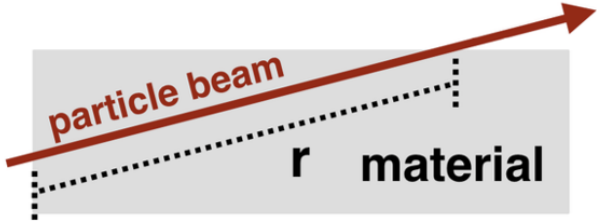
$$correction(r) = \frac{\sigma_{Data}}{\sigma_{MC}} e^{-r\frac{N_A \rho(\sigma_{Data}-\sigma_{MC})}{A}}$$

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:

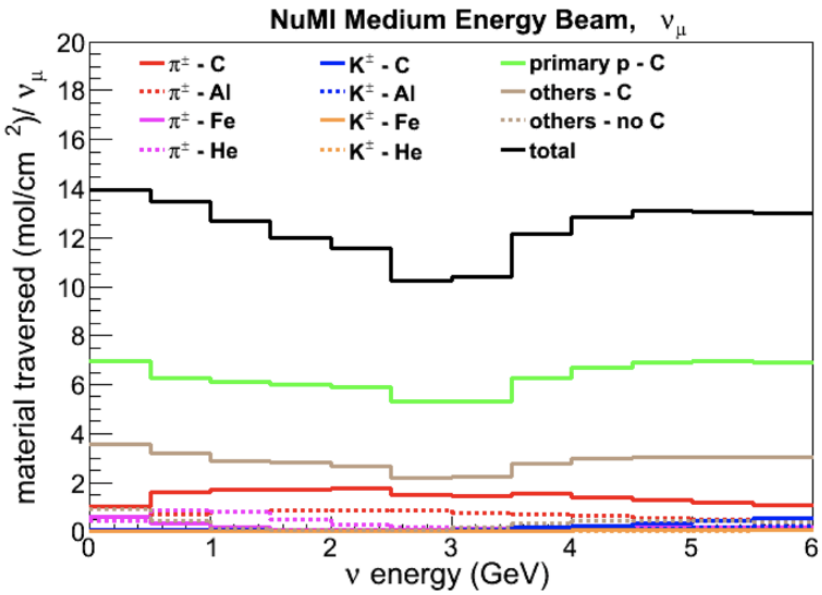
- The amount of material: $\mathbf{rN_A\rho/A}$.
- The $\boldsymbol{\sigma_{Data}}$ and $\boldsymbol{\sigma_{MC}}$ disagreement .

Absorption correction

L. Aliaga, NA61/SHINE at Low Energy Workshop , 2020

Absorption correction

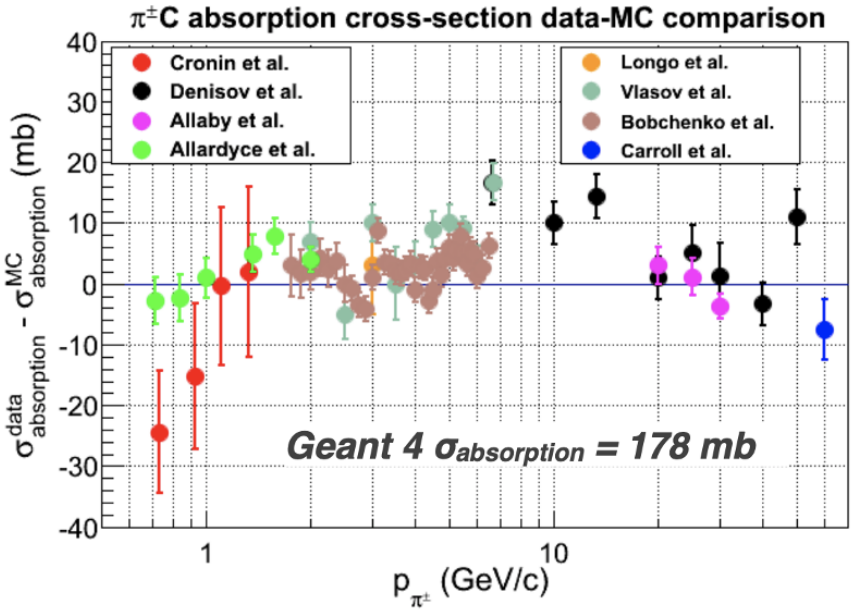
<rNAρ/A>



» C: 6 mol/cm² ≈ 40 cm

» Al: 1 mol/cm² ≈ 10 cm

» He: 1 mol/cm² ≈ 500 m

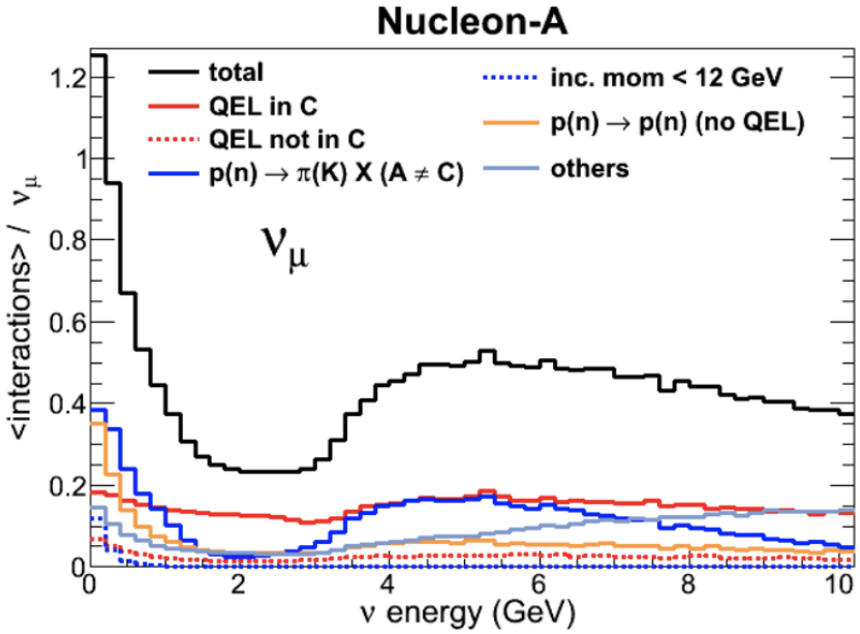


» We apply 10 mb uncertainty (~5%)

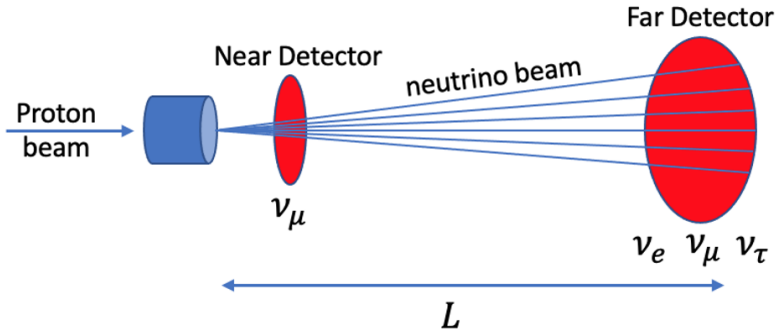
Nucleon-A

- **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.

L. Aliaga, NA61/SHINE at Low Energy Workshop , 2020



Accelerator-based neutrino experiments



- Accelerator-based neutrino experiments allow to explore the region of the $\Delta m^2 \geq 2 \times 10^{-3}$eV^2 with $E \sim 1$ GeV and long distance L.

$$\frac{L}{E} \lesssim 10^3 \text{ km/GeV} \qquad \Longrightarrow \qquad \Delta m^2 \gtrsim 10^{-3}\text{eV}^2. \tag{1}$$

- The probability of a two-neutrino oscillation case, in SI, for $p \sim E$

$$P_{\nu_\alpha \to \nu_\beta} = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right), \qquad \alpha \neq \beta, \tag{2}$$

$\rightarrow$ '1.27' assumes that L is in km, E in GeV and Δm^2 in eV^2/c^4 units.

Correcting Neutrino Flux Simulations

- To correct the flux predictions, we have to use the external data.
- Currently, it is done with a reweighting.
- Complete information for the hadronic cascades leading to a neutrino is recorded for each POT and stored in the flux tuples.
- For NuMI and DUNE, neutrino events are weighted using:

$$w_{HP} = \frac{f_{Data}(x_F, p_T, E)}{f_{MC}(x_F, p_T, E)}, \; f = E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3}. \tag{3}$$

- Events weight with multiple interactions in the ancestor chain are the the weights for each interaction.
- We also apply to account for exponential decay of beam, ρ, nuclei volume density, L is traversing a distance of particle:

$$w_{att} = \exp\{-L\rho(\sigma_{Data} - \sigma_{MC})\}. \tag{4}$$