# The status of constraining Fermilab long-baseline neutrino fluxes

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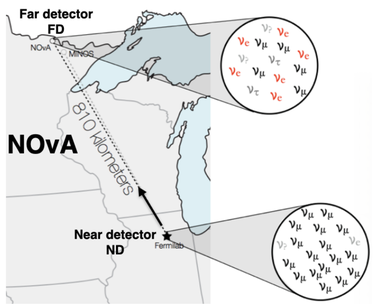
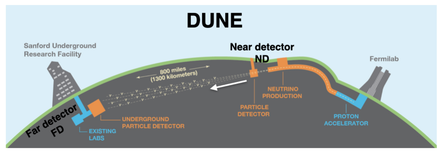
## Introduction

Current and upcoming experiments, such as NOvA and DUNE, are actively working on making precise modeling of the neutrino flux from NuMI and LBNF beamlines, respectively.

- Accurate modeling of neutrino beam fluxes is needed to construct baseline prediction in neutrino oscillation experiments.
- Accurate modeling is also needed to fix the normalization of neutrino-nucleus cross-section measurements.



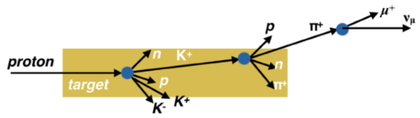

The largest uncertainty on the neutrino flux comes from the hadronic interaction model used in the baseline simulation. External data such as NA49 (CERN) is used to constrain $pC$ interactions, and its impact is a reduced uncertainty.

Primary proton coming from accelerators interacts with a thick target (Carbon) at large energies (120 GeV). It generates a hadronic cascade creating other nucleons and short-lived particles, such as pions and kaons that will decay to the neutrino.

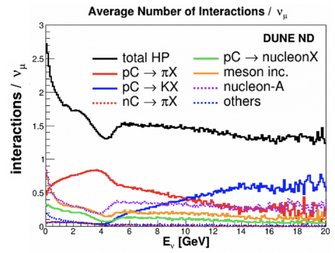
**⋆ This poster is about the current efforts to implement the recent NA61/SHINE (CERN) incident pion data at 60 GeV/c [1] into the neutrino beam flux simulation.**

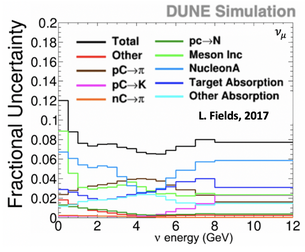
## Interactions and uncertainties

The procedure that we will follow is to constrain each simulated interaction in the beamline that produces neutrino.

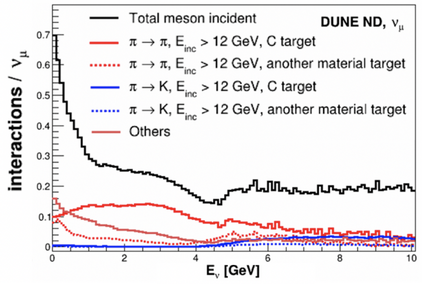



- Most of the interactions come from $pC \rightarrow \pi$ interactions. We constrain them using NA49 data, and then it makes final neutrino uncertainty small.
- Other interactions, such as pion interactions are not constrained by data, and we assume $40\%$ uncertainty for these interactions for NuMI and LBNF.



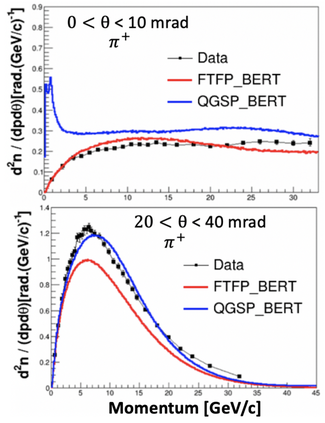

Splitting meson interactions, $\pi \rightarrow \pi$ component with energies $> 12$ GeV is dominant.




## NA61/SHINE data

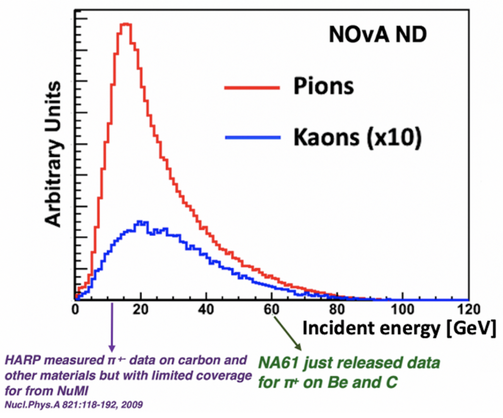
- NA61/SHINE experiment releases particle multiplicities ($\pi^+, \pi^-, K^+, K^-$ and $p$) at 60 GeV/c using $\pi^+$ projectiles on C and Be targets.

Some examples comparing NA61 data with FTFP_BERT and QGSP_BERT models (currently used in LBNF beam simulation) are shown below.

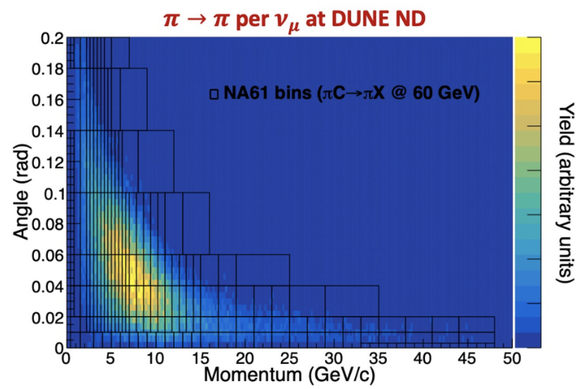



## Pion kinematics at DUNE and NOvA

Incident pions at LBNF and NuMI peaked at $\sim 20$ GeV with a wider spectrum in 10-40 GeV. NA61 data is at 60 GeV. Our current efforts include a scaling the data to lower energies.




However, NA61 provides good data coverage for $\pi \rightarrow \pi$ for LBNF and NuMI, and with a small uncertainties (typically statistical $\sim 2\%$ and systematics $\sim 5\%$).




## Summary & Current efforts

**→ Interacting pions are not currently constrained by data at LBNF and NuMI.**

**→ Our current effort is to use the recent NA61 data at 60 GeV to constrain those interactions.**

**→ One of the challenges we have is to a scale it to lower energies (10-40 GeV).**

**→ Applying this data will reduce the current systematic uncertainties coming from hadron interactions mismodeling.**

**→ Experiments like NA61 and EMPHATIC (Fermilab) are working to make new hadron production measurements at different energies with different targets and particle projectiles.**

## REFERENCES

[1] Measurements of hadron production in $\pi^+$ + C and $\pi^+$ + Be interactions at 60 GeV/$c$, Phys. Rev. D 100, 112004, 2019.