NA61/SHINE Hadron Production Measurements for Neutrino Oscillation Analyses

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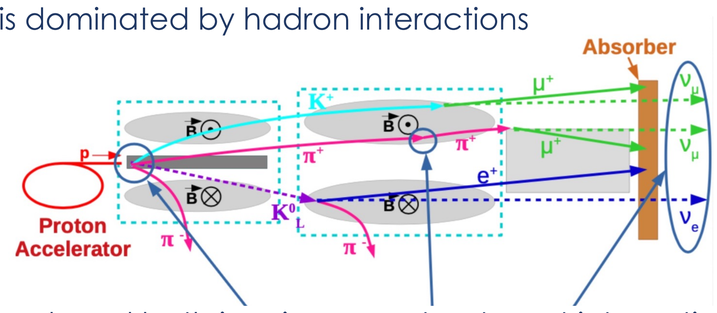
Neutrino Flux Uncertainty

Long-baseline neutrino experiments aim to measure neutrino oscillation parameters: T2K, NOvA, Hyper-K & DUNE in the future.

Large uncertainties in predicted neutrino beam properties limit the precision of neutrino oscillation measurements.

- Neutrino oscillation experiments require precise prediction of neutrino flux at the near detector
- Uncertainty is dominated by hadron interactions



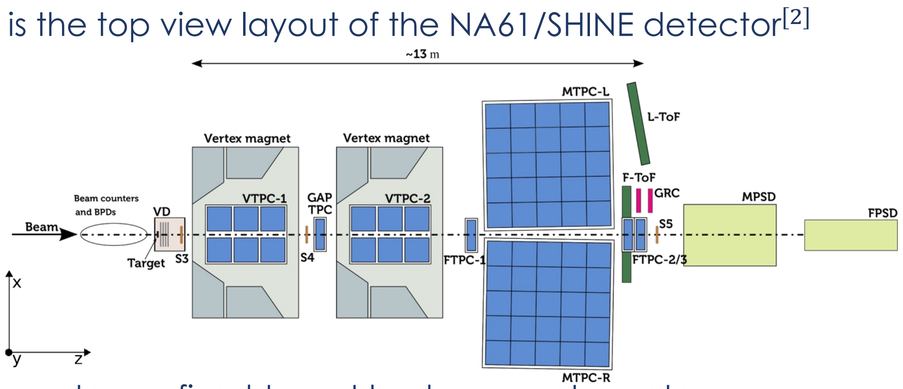
Neutrinos are produced both in primary proton-target interactions and subsequent reinteractions with beamline components [1].

NA61/SHINE Experiment

NA61: North **A**rea **61**

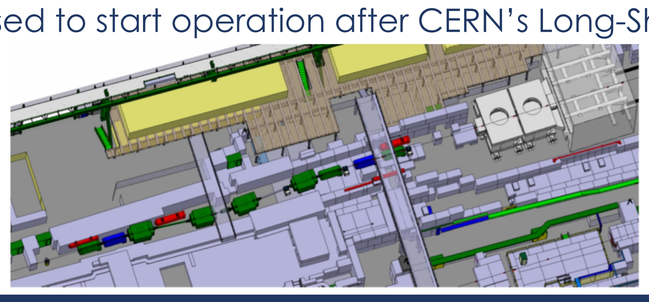
SHINE: (**S**uper-Proton-Synchrotron) **S**PS **H**eavy **I**on and **N**eutrino **E**xperiment

- Heavy ion/strong interaction, cosmic-ray production, and **neutrino** physics programs
- Records reactions of 13 to 350 GeV/c protons, charged pions, charged kaons, and heavy ions on various target materials
- Below is the top view layout of the NA61/SHINE detector[2]



Large-acceptance fixed-target hadron spectrometer:

- Eight Time Projection Chambers (TPCs) provide 3-D tracking and particle identification via specific ionization energy loss (dE/dx)
- Two superconducting bending magnets (Vertex I and II) deflect particles for momentum measurements
- Three Time-of-Flight (ToF) walls allow 2-D separation of particle species by measuring m^2 for additional particle information
- Technical feasibility and beamline design study are complete for a low-energy branch of CERN's SPS H2 beamline that will deliver low-energy (2 to 30 GeV/c) hadron beams to NA61/SHINE[3]. Proposed to start operation after CERN's Long-Shutdown 3

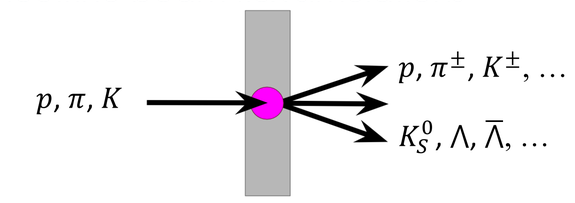


Hadron Production Measurements

Neutrino program focuses on hadron production measurements relevant to neutrino beam creation for long-baseline neutrino experiments **(See Y. Nagai's Monday talk)**.

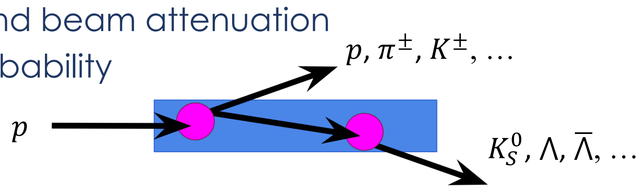
Measurements of Thin-target (Aluminum, carbon, titanium, …):

- Inelastic, production, and total cross sections
- Differential charged and neutral hadron yields from proton-nucleus interactions that can be applied to any experiment
- Input to reweight neutrino beam flux simulations



Measurements of Replica-target (used in T2K, NuMI, DUNE, …) :

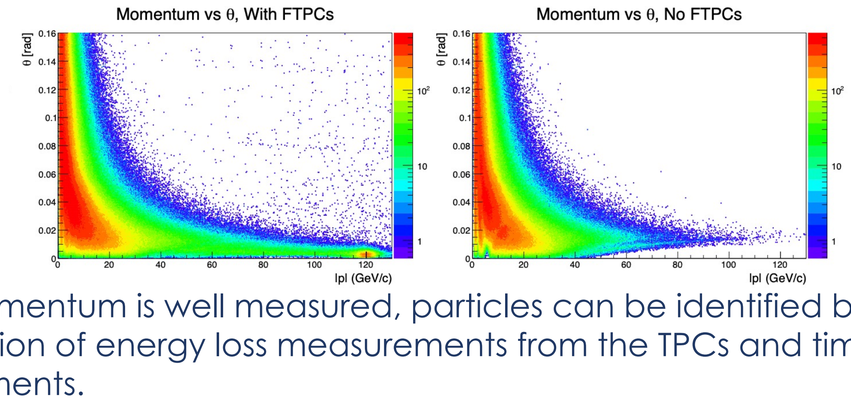
- Input to constrain neutrino beam flux by including particle reinteractions
- Differential production yield measurements from the surface of the target which are only useful for specific experiments
- Input to understand beam attenuation
- Beam survival probability



NA61/SHINE Measurements

The addition of Forward TPCs in 2017 increased the forward coverage of NA61/SHINE, now extending up to the beam momentum. In analysis, the number of produced particles in momentum bins and bins of production angle with respect to the beamline is measured.

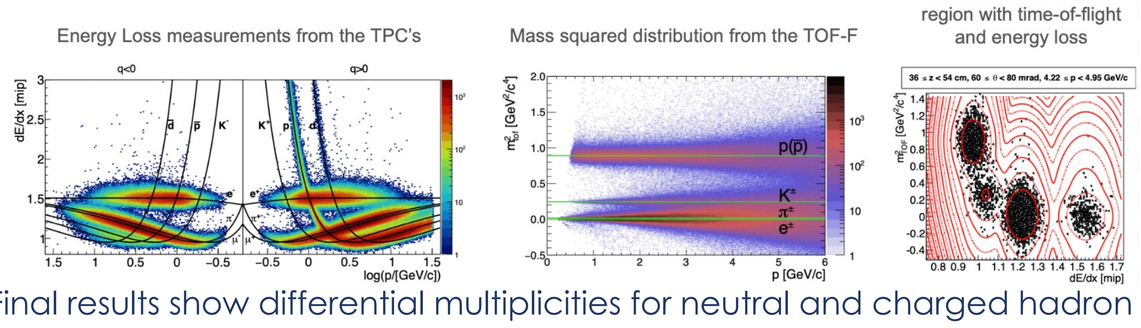
- Plots below show the reconstructed phase space coverage of tracks in recorded interactions of a proton beam of 120 GeV/c on a thin carbon target with and without the inclusion of Forward TPC tracks [6]



Once momentum is well measured, particles can be identified by a combination of energy loss measurements from the TPCs and time-of-flight measurements.

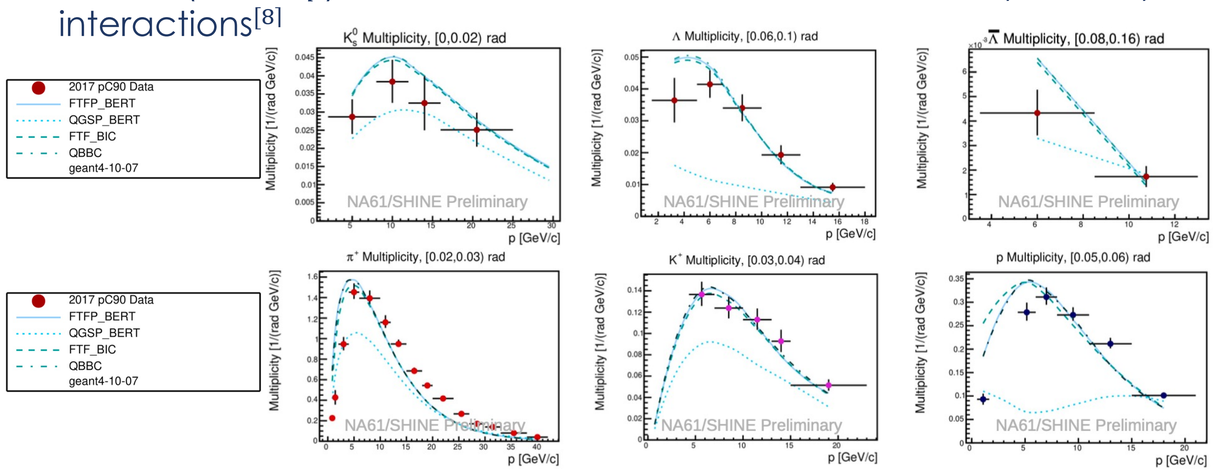
- Time-of-flight is used to fill in the Bethe-Bloch crossover regions by mass determination
- Below are T2K replica target results from the analysis using a 31 GeV/c proton beam[7]

Mass determination in Bethe-Bloch crossover region with time-of-flight and energy loss



Final results show differential multiplicities for neutral and charged hadron production and inelastic cross sections.

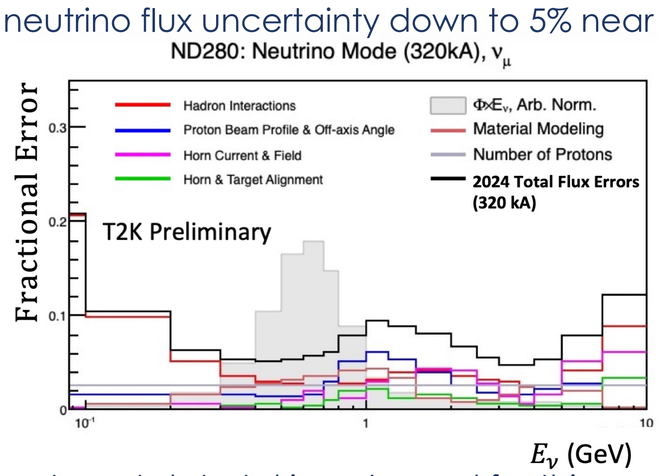
- The differential multiplicity is the average number of particles produced per production event for each species as a function of total momentum and polar angle
- Below are recent thin target results from the analysis of 90 GeV/c proton-carbon interactions which will help accurately model neutrino flux for long-baseline neutrino oscillation experiments
- Top plots show neutral hadrons (K_S^0, Λ, $\overline{\Lambda}$), bottom plots show charged hadrons (π^+, K^-, p). These measurements will constrain secondary + tertiary interactions[8]



Summary

NA61/SHINE provides many hadronic production measurements to support long-baseline neutrino experiments.

- Recent results will benefit neutrino oscillation programs at Fermilab
- Reduced T2K neutrino flux uncertainty down to 5% near the flux peak [9]



- DUNE prototype target data taking planned for this year

References & Acknowledgments

[1] B. Rumberger. Diss. University of Colorado Boulder, (2021).
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[4] Y. Nagai *et al.* [NA61/SHINE], *Additional Information concerning the Low energy Beam project* (SPSC-M-793), CERN (2022).
[5] Y. Nagai *et al.* [NA61/SHINE], *Addendum to the NA61/SHINE Proposal: A Low-Energy Beamline at the SPS H2* (SPSC-P-330-ADD-12), CERN (2021).
[6] B. Rumberger, *et al. JINST* **15**, no.07, P07013 (2020).
[7] N. Abgrall *et al.* [NA61/SHINE], *Eur. Phys. J. C* 79, no.02, 100 (2019).
[8] K. Allison. Diss. University of Colorado Boulder, (2024).
[9] Lucas N Machados, NuInt 2024.

This work was supported by DOE award DE-SC0007914.