NA61/SHINE NuMI Target Analysis

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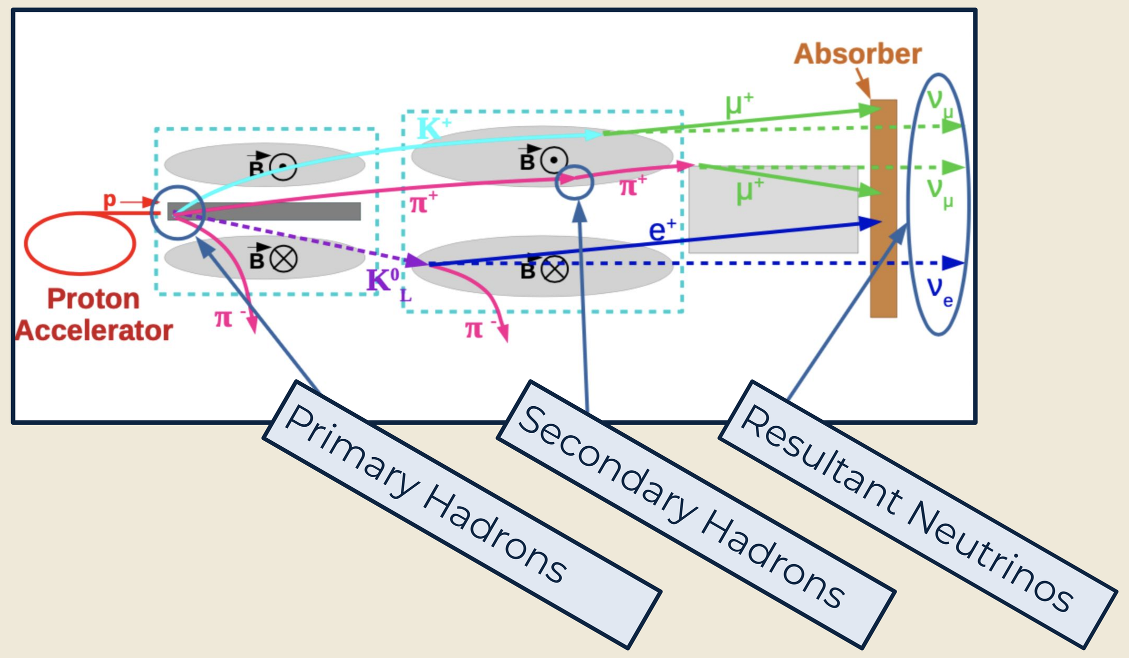
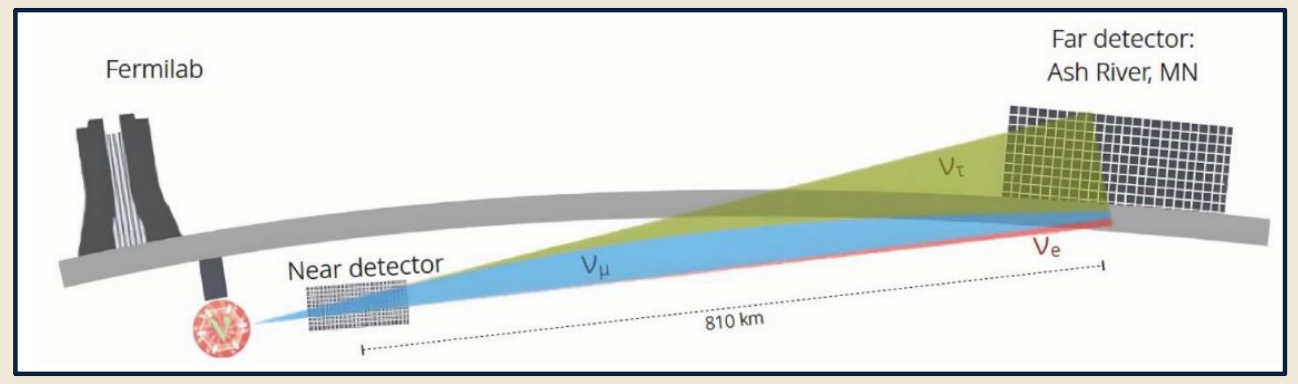
Neutrino Flux

- The number of neutrinos passing through a given area in a given time.
- Flux uncertainty is a direct contributor to oscillation uncertainties in long-baseline neutrino experiments.
  - Experiments like DUNE, T2K, NOvA are vital for the future of the field!
- Neutrino beams are produced by decaying beams of hadrons.
- Hadron production uncertainty is **the largest** single source of uncertainty in neutrino flux.

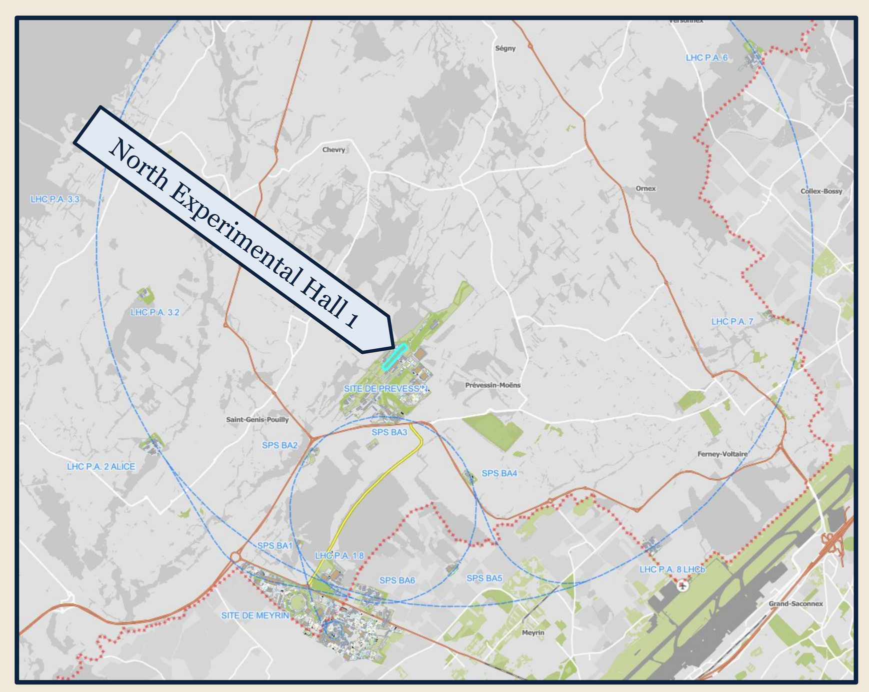




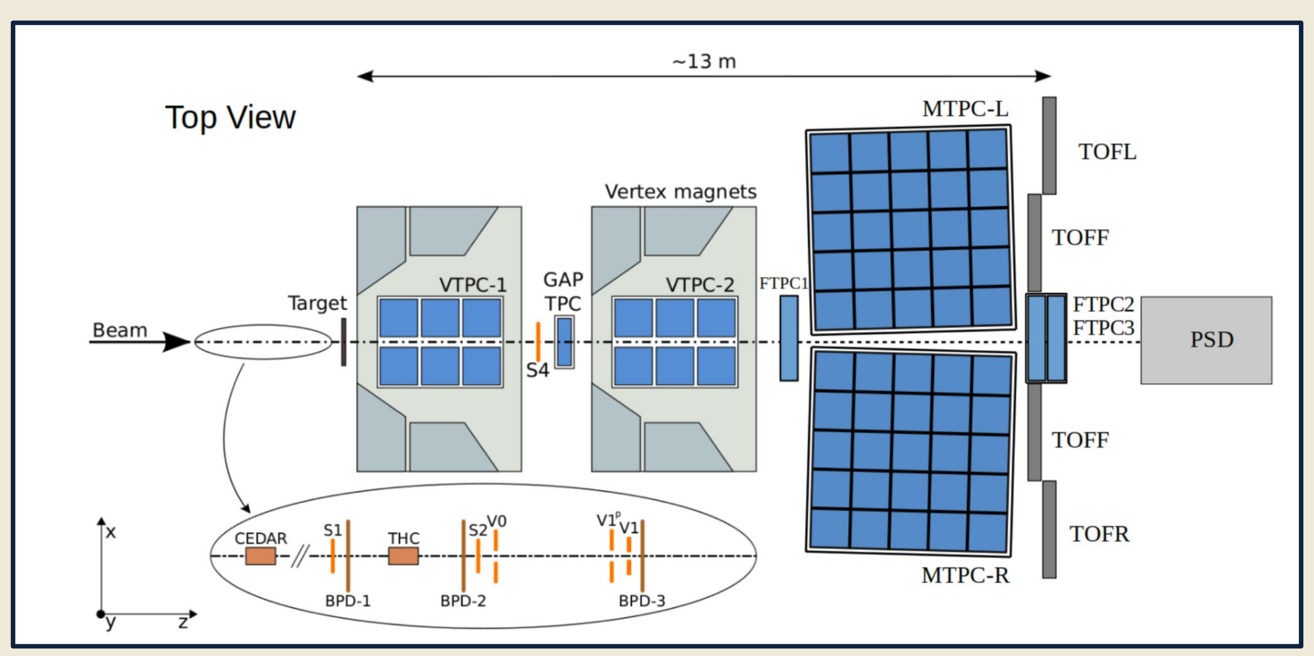
Above: Long-baseline experiments such as NOvA require precise estimations of neutrino flux [1].

The NA61/SHINE Experiment

- NA61/SHINE is the 61st experiment in CERN's North Area [3].
- The experiment receives beams from the Super Proton Synchrotron (SPS) [3].
- SHINE stands for SPS Heavy Ion and Neutrino Experiment [1].
- NA61/SHINE has a very broad physics program.
- The experiment's neutrino program studies hadron production relevant for neutrino beam production [1].
- The goal of this study: **Reduce hadron production uncertainties.**



Above: North Experimental Hall 1 receives beams from the Super Proton Synchrotron.



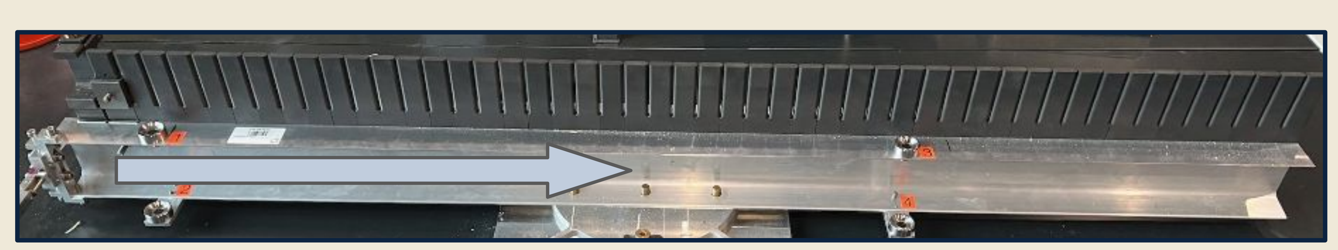
Left: The NA61/SHINE experimental setup as it was during 2018 NuMI data taking.

$$\frac{d^2 n_i}{dp\,d\theta} = \frac{c_i^{\text{total}}}{\Delta p\,\Delta\theta}\frac{y_i}{N_{\text{POT}}}$$

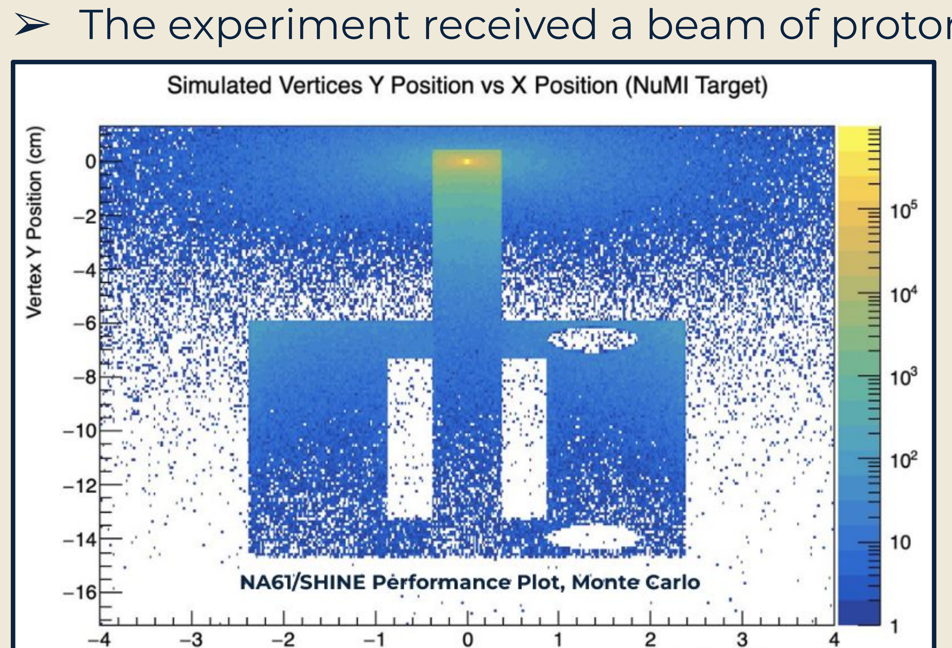
Above: Double-differential multiplicity. c_i^{total} is the product of correction factors, y_i is the yield of a particle species in bin i, N_{POT} is the number of protons on target. Δp and $\Delta\theta$ are the sizes of the p and θ bins [1].

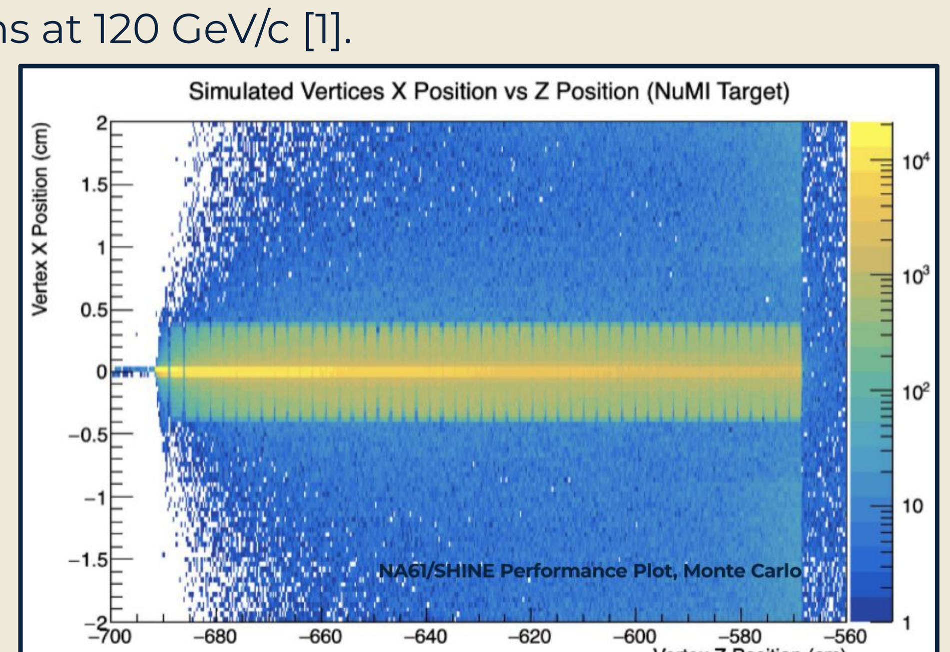
NuMI Replica Target Data Taking

- Data was taken on a NuMI replica target during the summer and fall of 2018 [1].
  - NuMI: Neutrinos at the Main Injector; a neutrino beamline at Fermilab.
- This target is a 123 cm graphite rectangle, with fins cut out along its length [1].
- The experiment received a beam of protons at 120 GeV/c [1].



Above: The NuMI Replica Target on a table. Arrow added to show beam direction.



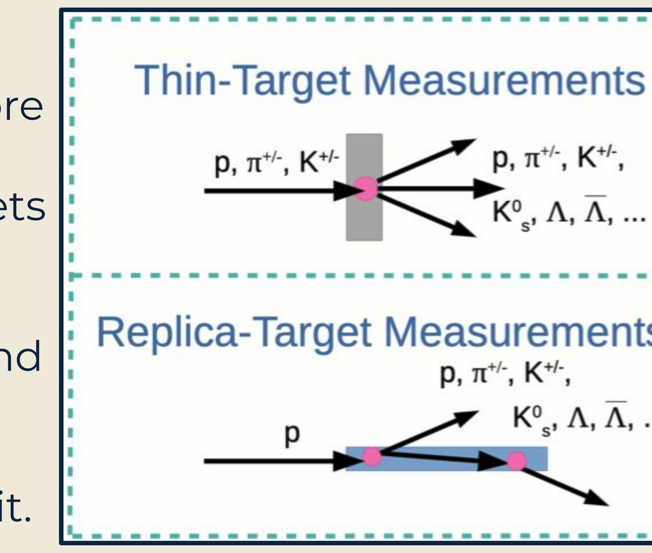


Left: Simulated exit positions of tracks, ZX plane. The graphite fins of the target are visible, viewed from above. NA61/SHINE Performance.

Leftmost: Simulated exit positions of tracks, XY plane. The target profile is visible, including various supporting structures. NA61/SHINE Performance.

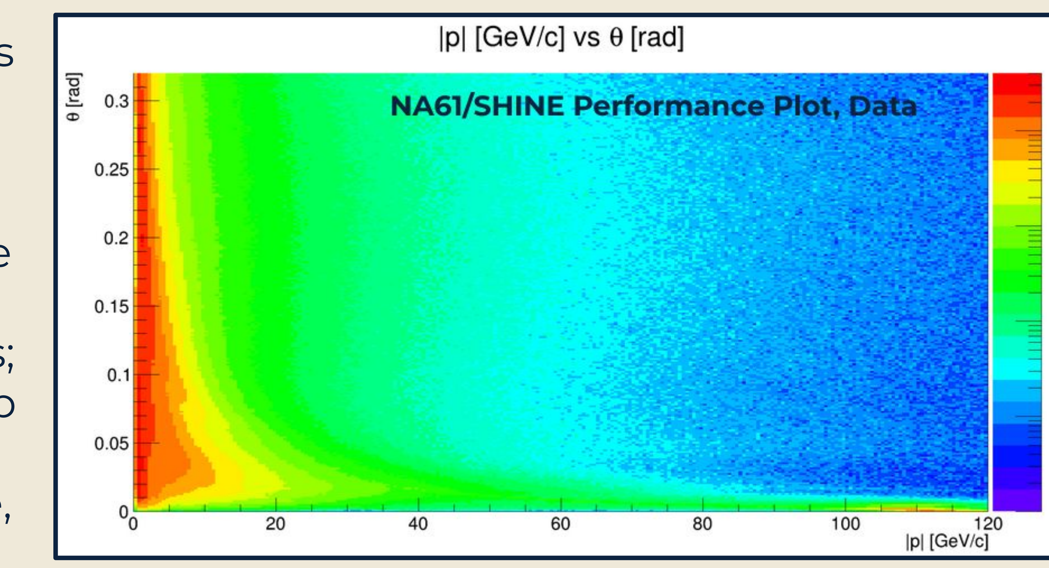
Why Use a Long Target?

- A thin target is useful for constraining individual types of interaction.
- Long targets, or replica targets, allow a wider ensemble of interactions.
  - Hadrons produced in the target often interact in the target material before exiting.
- They also allow normalization directly to protons on target, whereas thin targets necessitate the study of production cross section in addition to particle yields.
- Other neutrino experiments send us replicas of their targets to study.
  - Data has been taken with replica/prototype targets for T2K, NuMI, and LBNF/DUNE [1].
- These other experiments can use our data to reduce their flux uncertainties!
  - Experiments such as NOvA, MicroBooNE, ICARUS, and MINERvA stand to benefit.
- This methodology has been proven with a T2K replica target [2].



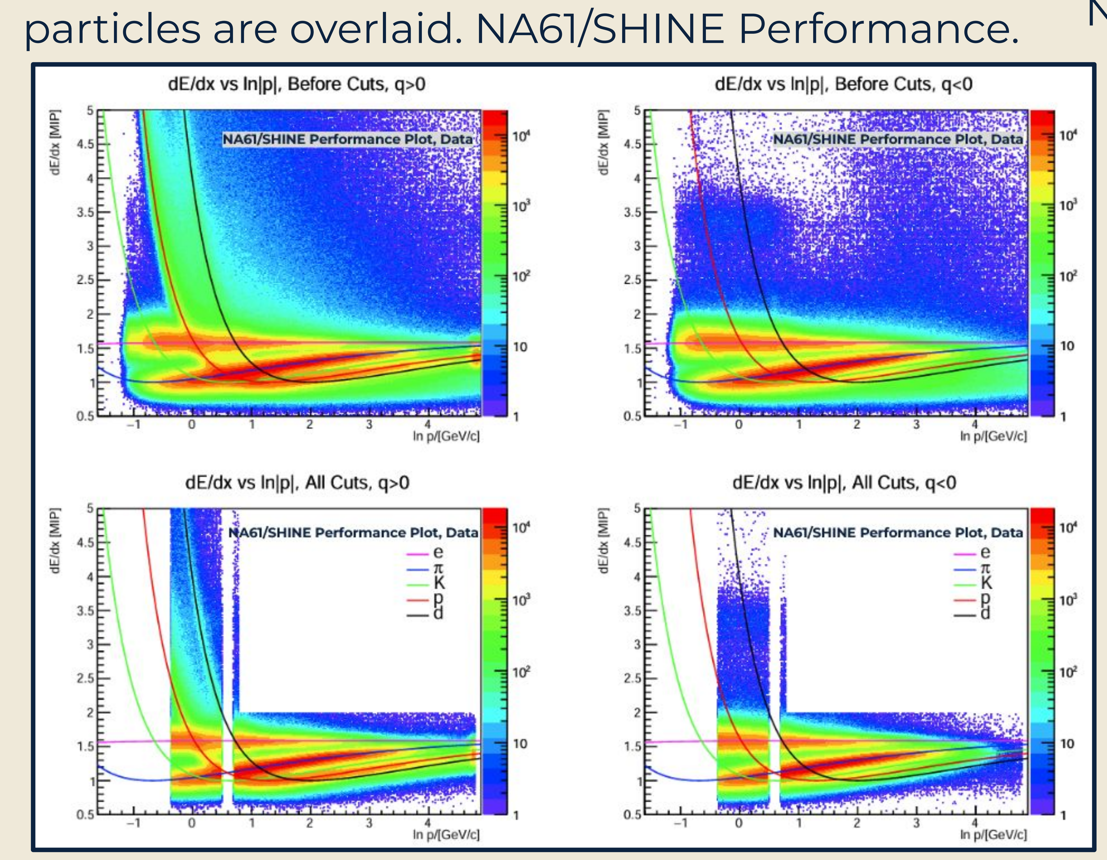
NuMI Replica Target Data Analysis

- Before the data itself can be properly examined, various calibrations are performed [1].
- The analysis then begins with raw yields, seen at right.
- To select high-quality events, selection cuts are applied.
- Energy loss (dE/dx) fitting is performed to separate particle species within each p-θ bin.
  - θ is the angle between the particle track and the beam axis; p is the total momentum. Both are measured in the lab frame.
- Various corrections are applied to account for acceptance, selection and reconstruction efficiencies, and other factors.
- A wide range of systematic uncertainties are calculated.
- The final result, multiplicity, is defined as the average number of particles (of a given species) in a given bin per proton on target.

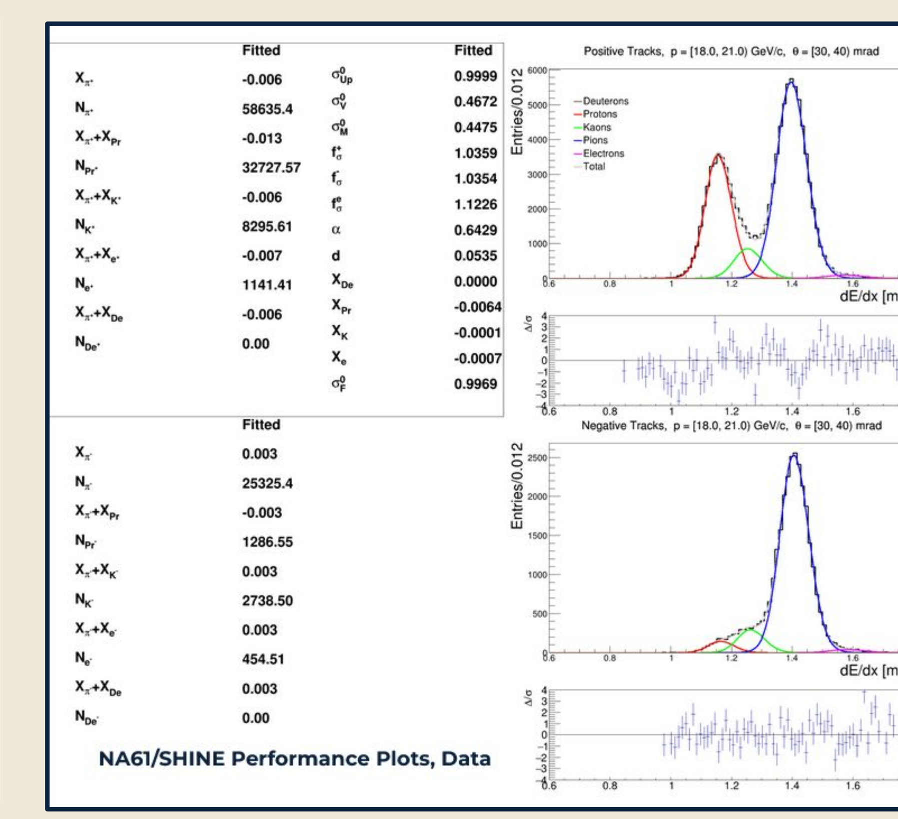


Above: Raw yields, prior to any corrections or cuts. Momentum (|p|) vs θ. Beam spot is visible at high p and low θ. NA61/SHINE Performance.

Below: Plots of energy loss (dE/dx) vs mometum (ln|p|) for positive and negative charge, before and after all cuts. Bethe-Block lines for common particles are overlaid. NA61/SHINE Performance.

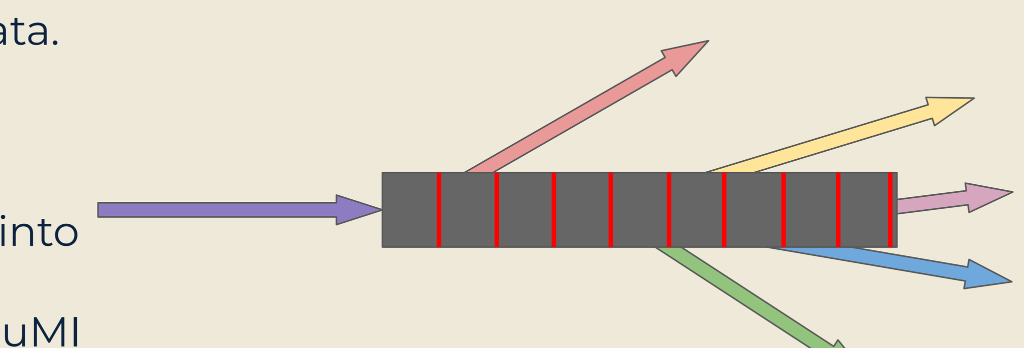


Below: Example dE/dx fits for one bin of data, positively- and negatively-charged tracks. Fit parameters, fit peaks, and ratio plots are shown. NA61/SHINE Performance.



Next Steps

- The analysis software was built to handle thin-target data.
- Thin targets can be modeled as a plane.
- For replica targets, the geometry becomes relevant.
- Adaptation of the code is required to account for this.
- Current work focuses on dividing the target into longitudinal "z-bins" along the beam axis.
- Once this adaptation has been completed for the NuMI replica target, it can be applied for a future analysis with a DUNE prototype target (data taken in 2024/2025).



Above: Cartoon illustration of z-bin divisions.

[1] D. Battaglia, Constraining Hadron Production Uncertainty with NA61 Proton-NuMI Replica Target Data, Ph.D. thesis, University of Notre Dame (2026). Forthcoming.

[2] N. Abgrall *et al.* Measurements of π±, K± and proton double differential yields from the surface of the T2K replica target for incoming 31 GeV/c protons with the NA61/SHINE spectrometer at the CERN SPS, *Eur. Phys. J. C* **79**, 100 (2019), doi:10.1140/epjc/s10052-019-6583-0.

[3] N. Abgrall *et al.* NA61/SHINE facility at the CERN SPS: beams and detector system, *JINST* **9**, P06005 (2014), doi:10.1088/1748-0221/9/06/P06005.