Pion-argon and proton-argon inclusive cross-section measurement using ProtoDUNE-SP 1 GeV beam data

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

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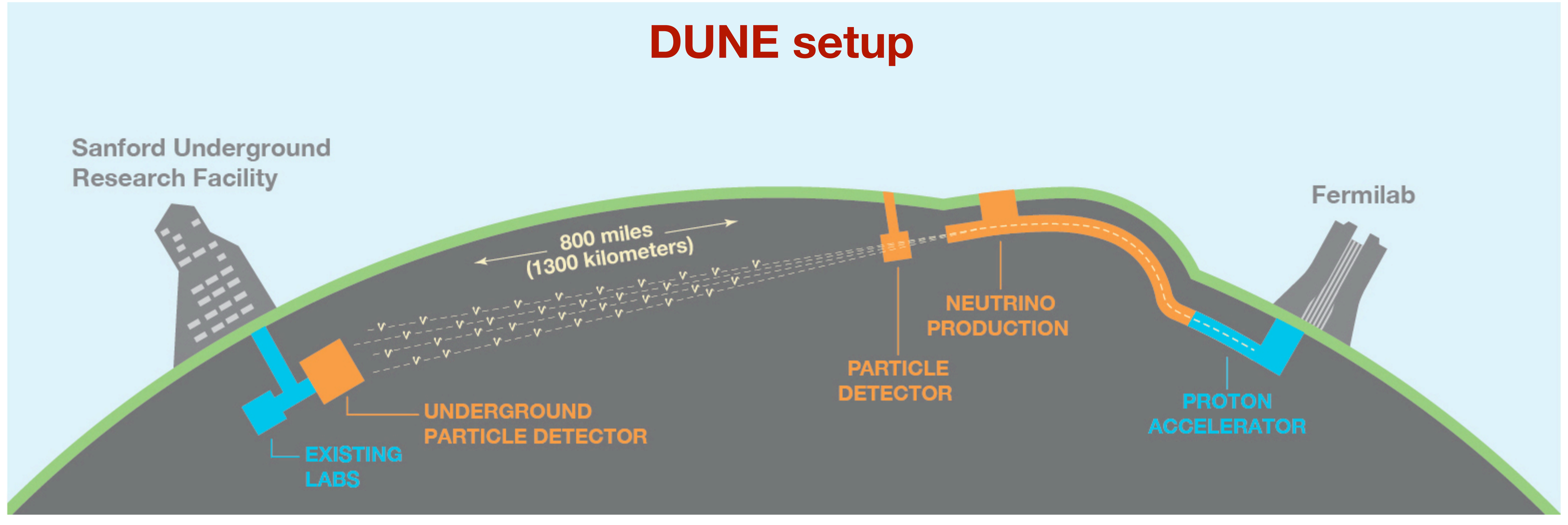
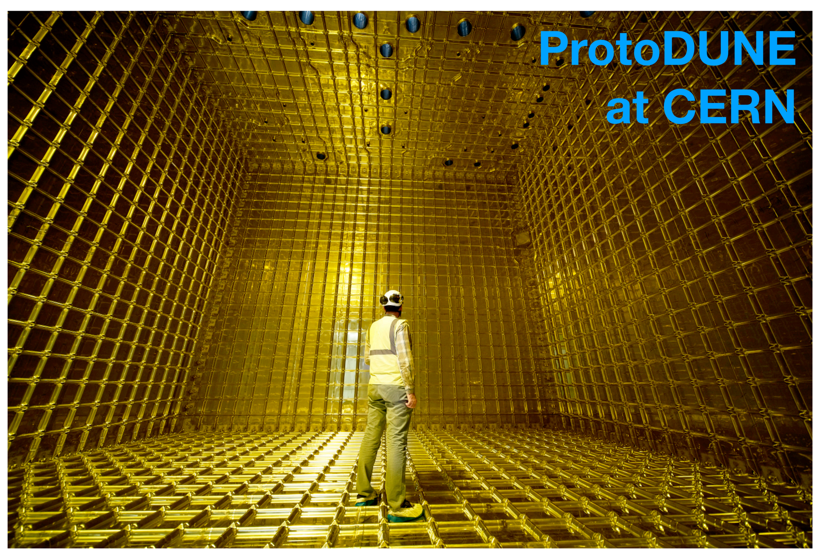
Introduction

DUNE setup

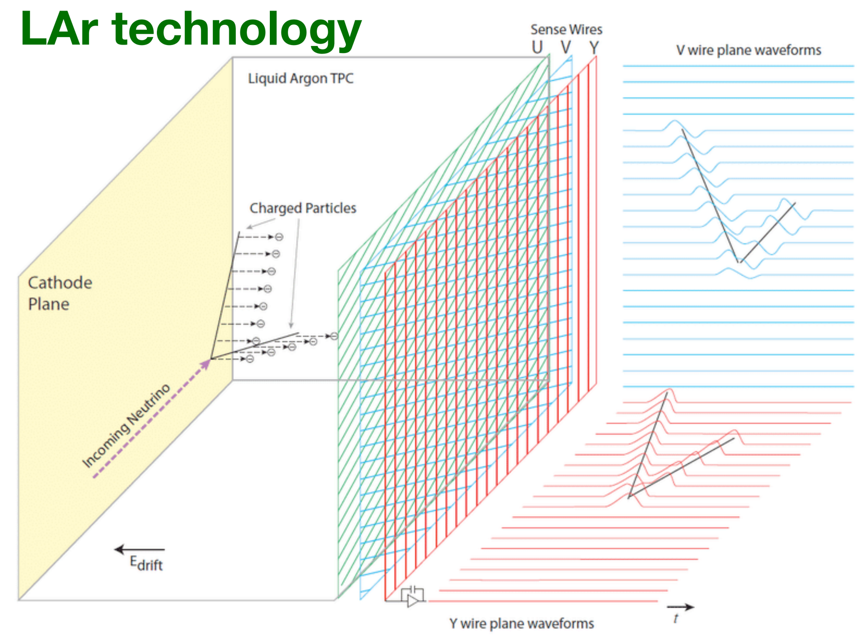


DUNE is a next-generation neutrino oscillation experiment hosted by Fermilab. It employs **liquid argon (LAr)** to detect neutrinos, with a scale of tens of kilotons.

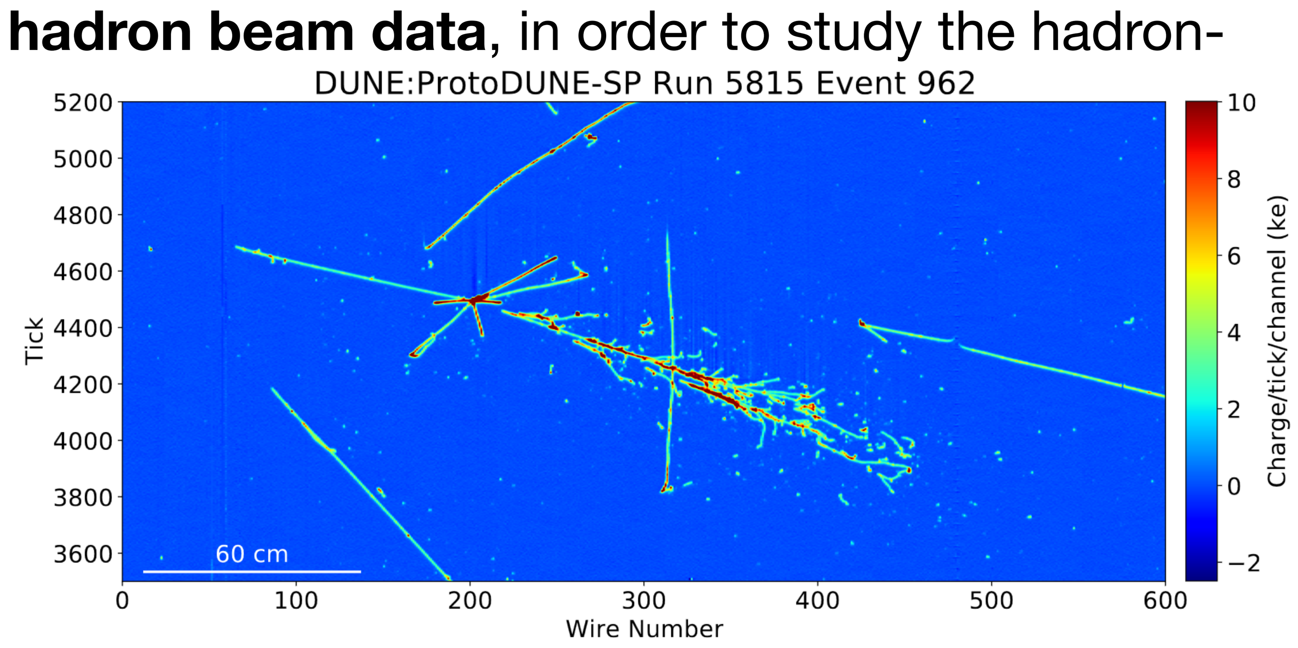
To prove the feasibility at this unprecedentedly large scale, prototype detectors called **ProtoDUNE**s were built at CERN. ProtoDUNE-SP (single-phase) is one of them.



LAr technology



In addition to its R&D purposes, ProtoDUNE-SP also took **hadron beam data**, in order to study the hadron-argon interactions. This is important because when a neutrino interacts with an argon nucleus, many hadrons (such as pions, neutrons and protons) can be produced. These particles are crucial for reconstructing the neutrino energy and identifying the type of interaction. A lack of knowledge on **hadron-argon cross sections** is currently a major source of systematic uncertainties for neutrino oscillation analyses.



Slicing method

The LArIAT collaboration proposes the **thin-slice method** (PRD 106 052009), which divides the detector into several thin slices, hypothetically treating each slice as an individual thin target. Building on this concept, we have developed the **energy-slicing method**, which slices the beam track directly by energy without the need for rebinning. This approach enables the multi-dimensional unfolding described later.

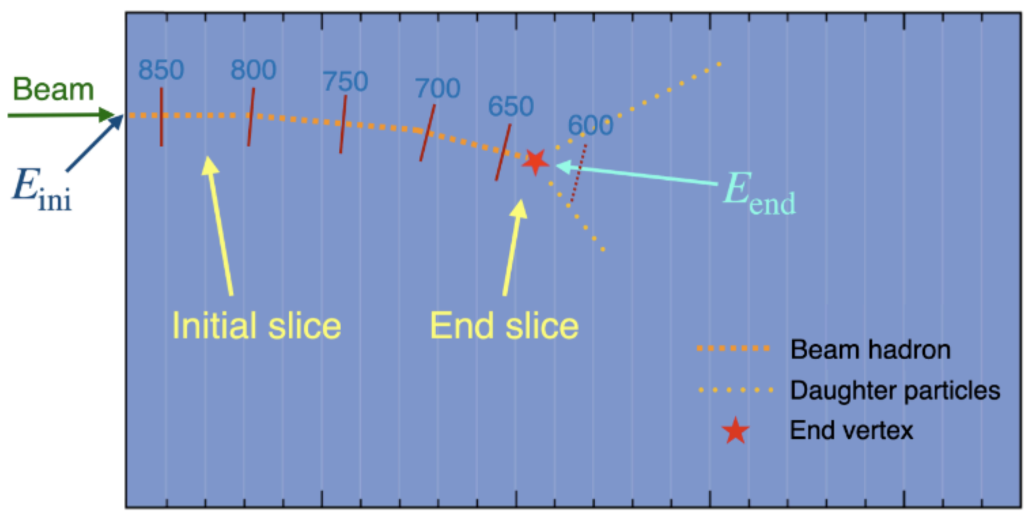
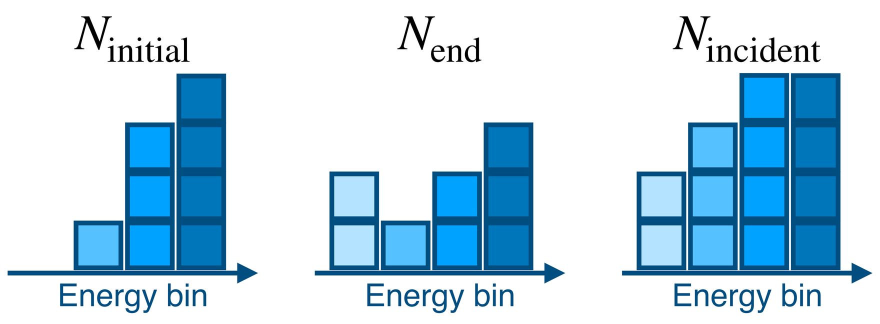


Illustration of the energy-slicing method



Given the definition of cross section

$$N_{interaction} = N_{incident}(1 - e^{-n\sigma(E)\delta x}),$$

the cross section is calculated by

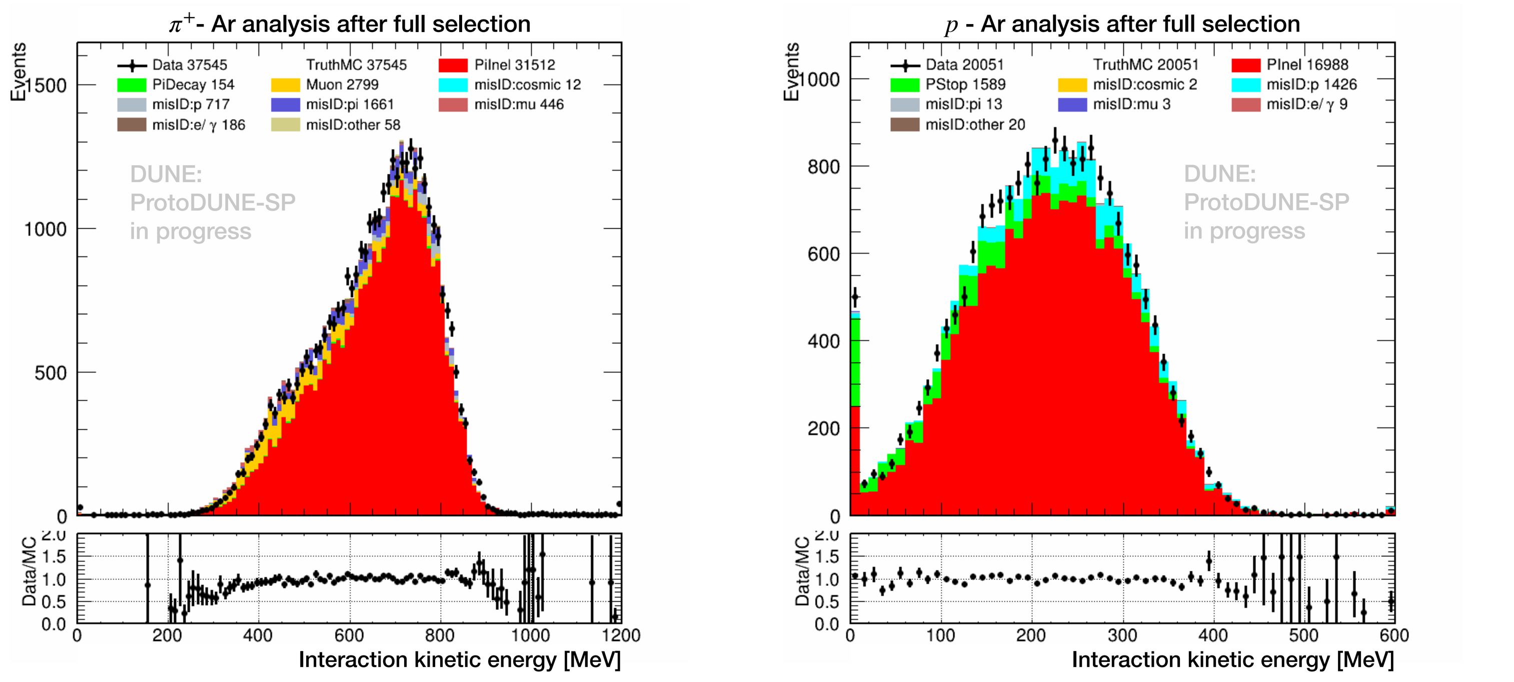
$$\sigma(E) = \frac{N_{interaction}(E)}{nN_{end}(E)\delta E}\frac{dE}{dx}(E)\ln\left(\frac{N_{incident}(E)}{N_{incident}(E) - N_{end}(E)}\right)$$

Simulation sample

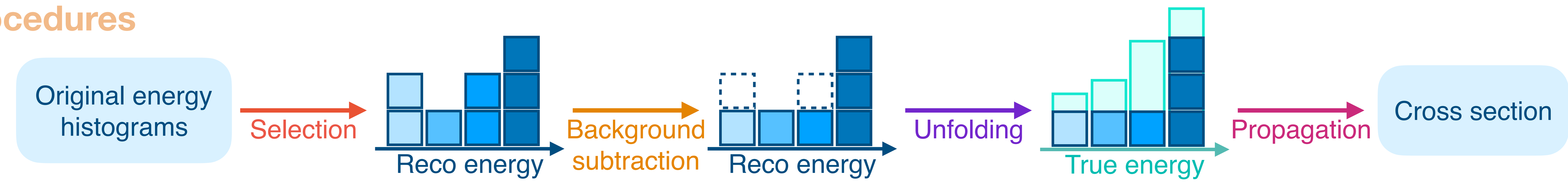
Monte Carlo (MC) samples are generated, which are used to evaluate the selection efficiency, model the background histograms, and model the response matrix in unfolding.

MC reweighting is performed for better agreement between data and MC on variables independent of cross-section measurement.

Comparison between data and MC



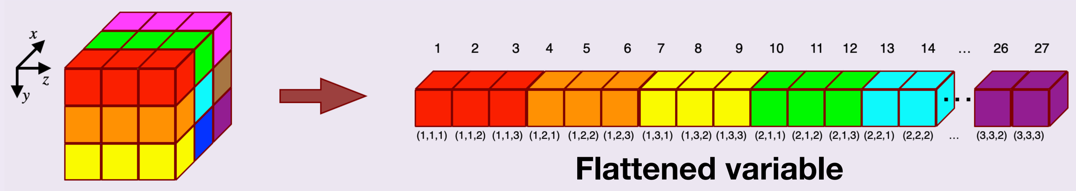
Analysis procedures



In order to **select pion/proton beam events**, full selection includes Beamline PID, some technical cuts, constraints on beam quality, and some background-specific cuts. The **purity** is about 85%, and the **efficiency** is about 50%.

The remaining backgrounds are subtracted by histograms modeled by MC. A **data-driven scale factor** for each background component is included to account for the differences between data and MC.

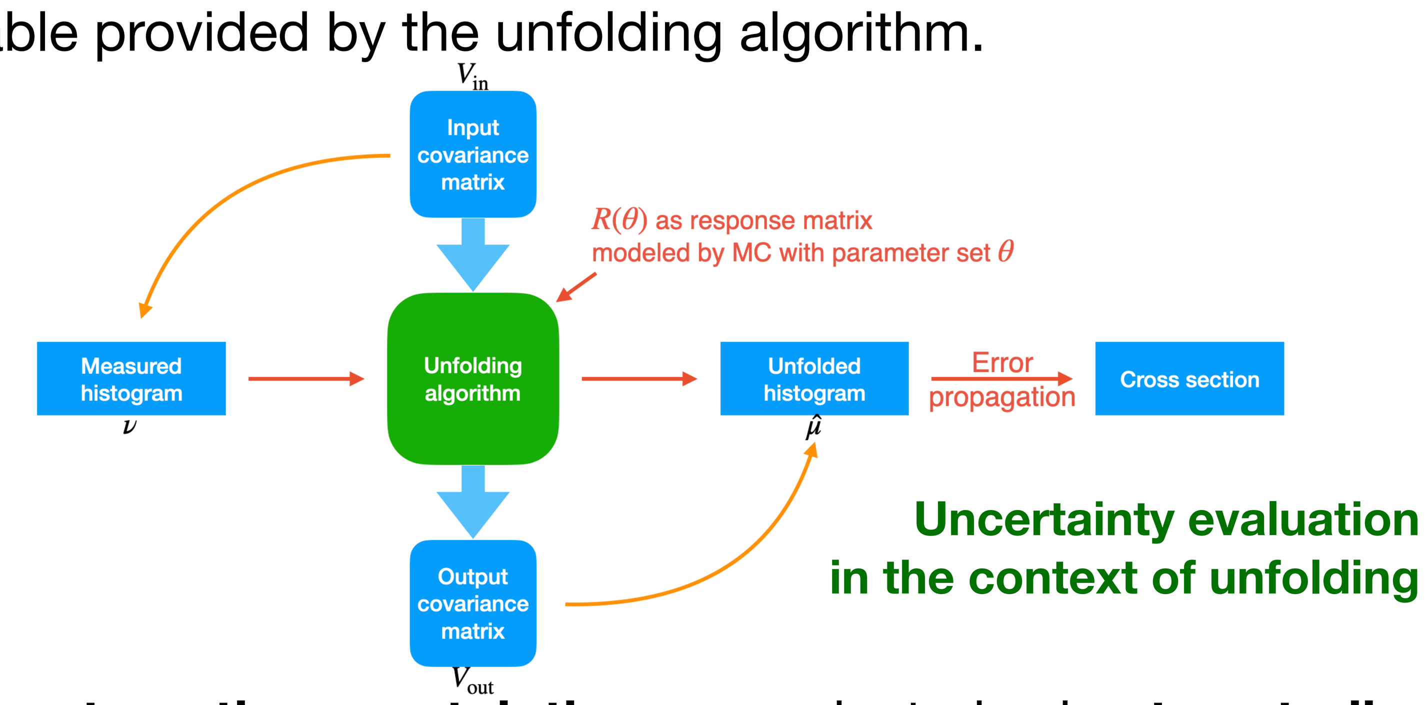
To account for correlations among different energy histograms, we employ **multi-dimensional unfolding**, where we combine the three directly measured variables into a single **flattened variable**, which is used for unfolding.



After unfolding, we convert the flattened variable back to energy histograms. The data cross sections are derived by the **formula** in the slicing method. Standard **error propagation** is also employed.

Evaluation of uncertainties

The **statistical uncertainty** is derived from analytical **error propagation**, starting from the covariance matrix of the flattened variable provided by the unfolding algorithm.



Uncertainty evaluation in the context of unfolding

The **systematic uncertainties** are evaluated using **toy studies**. By changing parameters used in the simulation, the analysis is repeated, and the fluctuation in the final results is the estimated uncertainty.

Work-in-progress results