Measurement of pion cross-section in ProtoDUNE SP detector at CERN

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NuFact2021
Outline

- Deep Underground Neutrino Experiment (DUNE)
- ProtoDUNE
- ProtoDUNE cross section measurements:
  - Motivations & Strategies
  - Particle Identification
  - Slicing method for cross section measurement
  - Analysis status and future
- Summary
Deep Underground Neutrino Experiment - DUNE

- DUNE is a future long-baseline **neutrino oscillation** experiment
- 1300 km baseline, new broadband (0.5-7 GeV) megawatt scale beam $\nu_\mu$/anti-$\nu_\mu$ from Fermilab to SURF
  - High power proton beam: 1.2 MW (2026) up to 2.4 MW (2032)
  - Deep underground (4850 m.w.e) far detector modules
- Large international collaboration: 1100+ physicists, 178+ institutions, 32+ countries
DUNE Goals - Flagship of Neutrino Physics in the US

- Precise oscillation parameters measurement
- Non-standard ν interactions
- Probing the 3-neutrino paradigm
- Mass hierarchy (matter effects)
- δ_{CP} ≠ 0?
- θ_{23} octant
- Supernova ν detection
DUNE - Far Detector

- Deep Underground - 1.5 km
  - Excavation started in 2017
  - Progressing well
- 4 x 17 kton modules
  - Horizontal and vertical drift
  - LArTPC
DUNE is a challenge

- Working in a cryogenic environment is not trivial! When things cool down, they shrink......
  - Must carefully design every element to avoid stress/breaking components
  - Must carefully select materials, similar shrinking rates if possible
- Liquid argon must be as pure as possible
  - Need a good cryogenic system with recirculation and filters
  - Need to prevent adding contaminants to the LAr
- DUNE is a large underground detector
  - Traditional dewars/cryostats cannot be scaled up
  - How to build such a detector with limited space and access?
- Need to have a good understanding of detector response and calibration

Need R&D and prototypes !!!
protoDUNE - Single Phase

- **Prototype of DUNE far detector**
- Membrane cryostat + cryogenic system
- The TPC component are 1:1 scale with respect to DUNE’s Single Phase Far Detector
  - 2 drift volumes divided by cathode (made of 3 CPAs)
  - Wire planes divided into 2x3 APAs
  - Integrated FE cold-electronics
  - Photon detectors for triggering and calorimetry
- **60 photon detector modules**
  - 10 per APA
protoDUNE Scientific Goals

● Prototype the production and installation procedures for DUNE’s SP far detector
● Validate the design in terms of basic detector performance
● Accumulate test-beam data to understand calibration of the detector response
  ○ Improve LArTPC reconstruction -> optimize particle identification, in particular e/γ separation
● Demonstrate the long-term operational stability
● **Physics : Hadron - Argon Scattering**
  ○ Study the behavior of different hadrons in LArTPC
  ○ Final state interaction in neutrino nucleus scattering
Hadronic Scattering - Pion Nucleus Interaction

- **Total** - calculated from attenuation of initial beam
- **Elastic Scattering**
  - Nucleus stays intact
- **Inelastic Scattering**
  - Nucleus in excited state /broken
  - Charge Exchange
    - Single Charge Exchange ($\pi^+ \rightarrow \pi^0$)
    - Double Charge Exchange ($\pi^+ \rightarrow \pi^-$) - Need to distinguish $\pi^+$ and $\pi^-$ - difficult for LArTPC
  - Absorption
    - No pions in the final state - need to distinguish pions from nucleons
    - Subtraction of other processes

*Dominant pion-nucleus interactions in sub-GeV region (Ref: arxiv 1611.05612)*
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Charge Exchange (CX)

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**Absorption (ABS)**

$\pi^+$

A

N

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Previous Experimental Results

- Charge Exchange and Absorption process cross sections shown on the left with statistical and systematic error bars
- DUET vs previous experimental result
  - 265 MeV pi+ on oxygen Asheryat.al
- NEUT v5.3.5 cascade model
- GEANT4 v9.04.04: Bertini cascade model
- FLUKA: cascade model
- No more pion absorption experimental data above 400 MeV
  - *ProtoDUNE can do it !!!*

Ref: arXiv: 1611.05612
Particle Identification

- $dE/dx$ is predicted by Bethe-Bloch formula
- Residual Range: distance from a reconstructed deposit (hit) to the stop point of a reconstructed track
- Particle identification is based on energy deposition per unit of length ($dE/dx$)
Event Display in LArTPC

Monte Carlo LArTPC Event Display

- Tracks: Proton, muon, pion and so on
- Showers: EM activities including electron, photon and photon from $\pi^0$
Shower Identification

- A cut value = 0.4 is performed in order to identify EM activities - showers
Particle Identification

- Combination of Truncated Mean dE/dx and $\chi^2$/ndof is used for particle (proton identification)
  - Truncated Mean dE/dx was divided into 3 regions
    - I and III transition region, II: Pion region(0.6, 2.6); IV: Proton region(>3.4)
  - $\chi^2$/ndof is only required for the transition region (>70 for proton)
The Slicing Method

- First TPC was divided into thin slices (each slice width = 10cm)
- Slice ID is defined based on endz position (truth or reco after SCE correction)
  - Each event has a reco slice ID and true slice ID
- Slice ID = -1 is kept in calculation due to the upstream event
The Slicing Method

\[ \sigma = \frac{M_{Ar}}{\rho t N_A} \log \left( \frac{N_{inc}}{N_{inc} - N_{int}} \right) \]

- \( M_{Ar} \) -- Mass of Ar
- \( t \) -- Thickness of slice
- \( \rho \) -- Density of Ar

- \( M_{Ar} \), \( N_A \) are constants

- **Thickness**: 10/0.95983081[cm]. Angle correction.

- **Number of interactions**
  - Pion Absorption in each slice

- **Number of Incidents** (pions)
  - Calculated from the number of all the pion interactions in each slice
  - Convert Pion interactions to incidents

Credit: Jake Calcutt
**Pre-selection: Beam Quality**

- Delta X/Y/Z measure the distance of the reconstructed beam track start from the true track/measured by beam instruments, and the cosine measures the angle between the two.

- Distributions are shifted to 0 and normalized by the RMS.

- Cuts are +/- $3\sigma$ for the X/Y/Z and cos > 0.95.
Migration Matrix

- Selected mostly pion inelastic interactions with a small fraction of muon events
- For both muon and pion beam track reconstruction is pretty good
Cross Sections

Pion Inelastic

Pion Absorptions

Beam Kinetic Energy [MeV]

σ (mb)

G4 Prediction
Measured (MC)
Absorption/Inelastic

- Same strategy of pion absorption selection performed to protoDUNE data and MC
- Compared to protoDUNE data, pion absorptions are slightly overestimated
Summary

- A large amount of Hadron-Argon scattering data from protoDUNE has been collected and ready for analysis.
- A sophisticated algorithm for particle identification and event selection for pion absorption has been developed and validated.
- Slicing method and RooUnfold were first used for the cross section measurement of pion absorption; validated with MC sample.
- Next
  - Add systematics uncertainties
  - Move to real data to further test the method
Pre-selections

- Pass Pandora Slice Cut
  - Track-like beam particle

- Pass **Beam Quality Cut (Owen)**
  - Remove on-beam (misidentified) background

- Pass APA3 Cut
  - reco_beam_calo_endZ < 226
  - remove muons

- Pass **Calo Size Cut**
  - Require vector size of calorimetric information on collection plane greater than 0

- Pass **Truncated Mean dEdx Cut**
  - Remove background from mis-identified events
RooUnfold Method

RooUnfold: a framework for testing and using different binned unfolding methods:

- Resource: [https://gitlab.cern.ch/RooUnfold/RooUnfold](https://gitlab.cern.ch/RooUnfold/RooUnfold)
- Iterative Bayes method was implemented for RooUnfold
  - Based on D'Agostini (1995), with corrected error calculation
  - This method seems to be used by the majority of RooUnfold users
- Other Methods: Dynamically Stabilized (IDS) unfolding, Singular Value Decomposition (SVD) method
- Techniques: Matrix inversion, iteration, in-by-bin correction factors, with no inter-bin migration
Cross Section of Pion Absorptions