\(\pi^+\)-Ar inclusive cross-section measurement on ProtoDUNE-SP

*Unblind data & preliminary systematics studies*

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Energy-slicing method

Each selected beam track has an initial slice and an end slice.

\[ N_{\text{initial}} \quad \text{and} \quad N_{\text{end}} \]

Energy bin

The incident histogram is calculated by \( N_{\text{initial}} \) and \( N_{\text{end}} \)

\[ N_{\text{inc}}(i) = \sum_{j=i}^{N} N_{\text{end}}(j) - \sum_{j=i+1}^{N} N_{\text{int}}(j) \]

Energy bin

If there is pion inelastic scattering (signal) at the interaction vertex, then the end slice is also an interaction slice.

\[ E_{\text{ff}} \]

Pre-defined energy bins/slices

\[ E_{\text{int}} \]

Initial slice

End slice

The cross-section is calculated by incident histogram and interaction histogram

\[
\sigma(E) = \frac{M_{\text{Ar}}}{\rho N_{A}} \frac{dE}{dx} (E) \ln \left( \frac{N_{\text{inc}}(E)}{N_{\text{inc}}(E) - N_{\text{int}}(E)} \right)
\]
For inclusive cross-section measurement, we need to select *pion beam events* (regardless of what daughter particles are).

- Pandora identification
- Precuts
- Beam quality cut
- Proton cut
- Michel score cut
- Track length cut

After full selections, we have about **80%** pion inelastic events (signals)

New cuts

- **Beam scraper cut**

  ![CaloSize, Data](image)

  **Selection:** $\sqrt{\Delta x_{\text{inst}}^2 + \Delta y_{\text{inst}}^2} < 4.5$

  - $\Delta x_{\text{inst}}$ is $(x_{\text{inst}} - \mu_{x_{\text{inst}}})/\sigma_{x_{\text{inst}}}$
  - $\mu_{x_{\text{inst}}}$ and $\sigma_{x_{\text{inst}}}$ are derived before beam quality cut

- **Short track cut**

  ![Data sel.](image)
Muon bkg reweight

- We found there are more long tracks (length > 150 cm) in data than MC.

- This could be improved if we scale up the muon beam fraction in MC.

Fit result:
Weight = 1.71 ± 0.03
FOM = 3.03/8 = 0.38
Beam momentum reweight

- We select stopping muon sample to fit between data and MC
- The fit parameters are $\mu$ and $\sigma$ for the MC true momentum
Extra shifting/smearing

- After the momentum reweighting, we assume data and MC have consistent true momentum distributions. The remaining difference is accounted for by momentum/energy measuring effects.

- We add an extra random Gaus(-7.26, 22.31) MeV to each MC event.

\[
\text{Difference in upstream momentum loss. } \mu_{\text{data}} - \mu_{\text{MC}}
\]

\[
\text{Difference in momentum resolution. Extra smearing: } \sqrt{\sigma_{\text{data}}^2 - \sigma_{\text{MC}}^2}
\]
After reweighting and extra shifting/smearing

After full selections; secondary proton and pion bkg scaling included
Analysis flow

Original sample

\[ N_{\text{reco}} \ (N_{\text{initial}}, N_{\text{end}} \text{ or } N_{\text{interaction}}) \]

Selections

Background constraints

\[ N_{\text{reco}}^{\text{sig}} = N_{\text{reco}} \cdot \left( 1 - f_{\text{bkg}} \right) \]

Unfolding

\[ N_{\text{true}}^{\text{sig}} = M_{\text{unfolding}} \cdot N_{\text{reco}}^{\text{sig}} \]

Muon scaling factor: 0.97 ± 0.12
Proton scaling factor: 1.67 ± 0.14
Pion scaling factor: 1.24 ± 0.12

3D unfolding of \((N_{\text{ini}}, N_{\text{end}}, N_{\text{int}})\)
Data results

- After bkg subtraction

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Initial histogram

End histogram

Interaction histogram

Data+MC statistical errors only
Data results

Data+MC statistical errors only

- After unfolding (4 iterations)
Data results

\[ N_{\text{initial}} = \sum_{j=i}^{N} N_{\text{end}}(j) - \sum_{j=i+1}^{N} N_{\text{ini}}(j) \]

- True MC
- Measured data
Data results

Data+MC statistical errors only

Data XS

Correlation matrix of XS in energy bins

PRELIMINARY
Uncertainties

- Data statistics
- MC statistics
- Bkg estimations / scale factors
- Reweight factors
- Energy reconstruction
- MC cross-section
- Elastics cross-section
- Detector effects: dE/dx calibration, recombination; SCE map
- Other factors result in difference in data/MC efficiency
Uncertainties - bkg + MC statistics

\[ \chi^2 = (x_{\text{data sig}}^{\text{reco}} - x_{\text{MC sig}}^{\text{reco}}) \cdot C^{-1} \cdot (x_{\text{data sig}}^{\text{reco}} - x_{\text{MC sig}}^{\text{reco}})^T \]

- MC statistics
- Data statistics
- Bkg estimations / scale factors \( \alpha \)
- The uncertainties of \( (x_{\text{data sig}}^{\text{reco}} - x_{\text{MC sig}}^{\text{reco}}) \) are included in the covariance matrix \( C \), which will be input to unfolding.

Reference Section VI. A  
Uncertainties - bkg + MC statistics
Uncertainties — reweight factors

- Muon bkg reweight and beam momentum reweight

- Treatment:
  - Muon bkg reweight can be included in the muon scale factor $\alpha$.
  - Reweight factor $1.71 \pm 0.03$
  - For momentum reweight, float the fit parameters $(\mu, \sigma)$
    - $r = \text{RandGaus}(0, 1)$; $\phi = \text{RandUni}(0, 2\pi)$
    - $\mu = c_{\mu} + r \cdot (a \cos \theta \cos \phi - b \sin \theta \sin \phi)$
    - $\sigma = c_{\sigma} + r \cdot (a \sin \theta \cos \phi + b \cos \theta \sin \phi)$
Uncertainties — reweight factors

- Covariance matrices (130 toys)
Uncertainties — reweight factors
Uncertainties — energy reconstruction

- We currently have an extra shifting/smearing Gaus(-7.26, 22.31) MeV to account for data/MC difference in energy reconstruction.

- Treatment:
  - Add an overall shift $\delta E_{\text{ini}} = \text{Gaus}(0, 20)$ MeV and smearing $\delta E_{\text{dep}} = \text{Gaus}(0, 10)$ MeV to all events, so the new extra shifting/smearing is Gaus(-7.26+$\delta E_{\text{ini}}$, 22.31+$\delta E_{\text{dep}}$) MeV
Uncertainties — energy reconstruction

- Covariance matrices (125 toys)
Uncertainties — energy reconstruction
Uncertainties — MC cross-section

- MC signal events are used to construct the response matrix for unfolding.
- The difference of data/MC XS can cause bias in modeling the response matrix.
- Treatment:
  - Using Geant4reweight, scale the MC cross-section by Gaus(1, 0.2).
Uncertainties — MC cross-section

- Covariance matrices (142 toys)
Uncertainties — MC cross-section

PRELIMINARY

Pion Inelastic Cross Section

σ_{inelastic} (mb)

Pion Kinetic Energy (MeV)

Data + MC stat
Data sys: MCXS
MC truth
Geant4 input
Uncertainties — elastic cross-section

- We fully rely on MC to subtract elastic scattering events.
- Treatment:
  - Scale the MC elastic events by $\text{Gaus}(1, 0.2)$. 

Uncertainties — elastic cross-section
Further discussion on systematics

- Data statistics
- MC statistics
- Bkg estimations / scale factors
- Reweight factors
- Energy reconstruction
- MC cross-section
- Elastics cross-section
- Detector effects: dE/dx calibration, recombination; SCE map
- Other factors result in difference in data/MC efficiency