Neutrino-Nucleus interaction cross section analysis with DUNE-PRISM

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CERN Summer Student Programme 2022 - Student Sessions
05.08.2022
DUNE – Deep Underground Neutrino Experiment

• Designed to measure neutrino oscillation – the probability to measure each neutrino flavor varies when a neutrino propagates through space

• Comprised of LArTPC detectors, capable of measuring charged particle kinematics to high precision

Neutrino oscillations – a reminder:

\[ P_{\alpha \rightarrow \beta} (E, L) \approx \sin^2 (2\theta) \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) \]
DUNE-PRISM: a detector on tracks

- Part of the DUNE near detector
- Movable detector that will collect measurements at different positions with respect to the DUNE neutrino beam (LBNF)
- Different detector positions → Different flux distributions $\Phi_i(E_\nu)$

- Virtual fluxes can be produced by adding fluxes - $\Phi_{\text{virtual}} = \sum_i c_i \Phi_i$
Motivation for cross section measurements for DUNE

• In oscillation analyses,
  \[ N_{pred}(E_{\nu}^{true}) \propto \sigma(E_{\nu}^{true}) \Phi(E_{\nu}^{true}) P(\alpha \to \beta, E_{\nu}^{true}) \]

• \( \frac{d\sigma}{d\omega} (\omega) \) (*) can tell us a lot about nuclear properties and structure:

\[ \omega = E_{\nu} - E_{\text{lepton}} \] - Transfer energy of the interaction

• Similar Final states make different nuclear processes hard to separate from one another

(*) \( \omega = E_{\nu} - E_{\text{lepton}} \) - Transfer energy of the interaction
Cross section measurements for DUNE

- Naïve approach for reconstructing $\omega$ – using a single off-axis flux assuming:
  - $\Phi(E_\nu) \to \delta(E_\nu - E) \Rightarrow$ Incoming flux very (very!) different from monochromatic
  - $\sigma(E_\nu) \approx$ constant $\Rightarrow \sigma(E_\nu) \neq$ constant over smeared distributions, no simple way to $\Phi \to N$

  ![True vs Reconstructed $\omega$ for off-axis flux peaked at 1 GeV](image)

- No simple way to compare simulation to data (without $\sigma$, which we're trying to measure!)

  **Result:** Impossible to resolve different interaction features
Virtual flux recipe

- **Ingredients:**
  - **Flux matrix** $F$ - an estimation of what flux distribution we will get for each off-axis angle
  - **Target flux** $\overrightarrow{T}$ – a flux distribution we would like to approximate

- **Directions:**
  - **Solve** $F\overrightarrow{c} = \overrightarrow{T}$ - find a solution such that will give an approximation of our target as a linear combination of fluxes
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Virtual flux → Virtual event rate

- Relative statistical uncertainty in each virtual flux bin depends on event statistics and the chosen coefficients:

$$\sigma_{stat,j} = \sqrt{\sum_i c_i^2 N_{ij}} / \sum_i c_i N_{ij}$$

- Example - Large negative coefficients have a strong impact on $\sigma_{stat}$
- Idea – penalize solutions with large coefficients
Applying regularization methods

Ordinary least squares
\[ \mu = 750 \text{ MeV} \]
\[ \sigma = 71 \text{ MeV} \]

Tikhonov regularization (Ridge regression) with \( \alpha = 10^{-12} \)
\[ \mu = 750 \text{ MeV} \]
\[ \sigma = 78 \text{ MeV} \]
Preliminary cross section analysis

- Visible improvement over measurement with single flux
- Main features reconstructed – separated QE and RES peaks
- Caveat - many years of data needed; could be further optimized

![Graphs showing true vs reconstructed cross sections and virtual flux distributions with 20 years of data uncertainty]
Conclusions

• Main features of different Neutrino-nucleus processes as a function of $\omega$ could be reconstructed with DUNE-PRISM

• High statistics are needed – at least 10 years of DUNE-PRISM data

What’s Next?

• Model testing – checking if we can resolve changes in features between models

• Unfolding/Deconvolution – Going from $\omega_{\text{reco}}$ to $\omega_{\text{true}}$ using the known smearing function

• Nuclear spectral function analysis – using outgoing nucleon kinematics

• Independent fluxes - producing multiple independent flux production to minimize correlations (using regularizations that minimize the number of non-zero coefficients)
Thank you!
Backup