Neutrino-Nucleus interaction cross section analysis with DUNE-PRISM

Amir Gruber, Tel Aviv University (amirgruber@gmail.com)

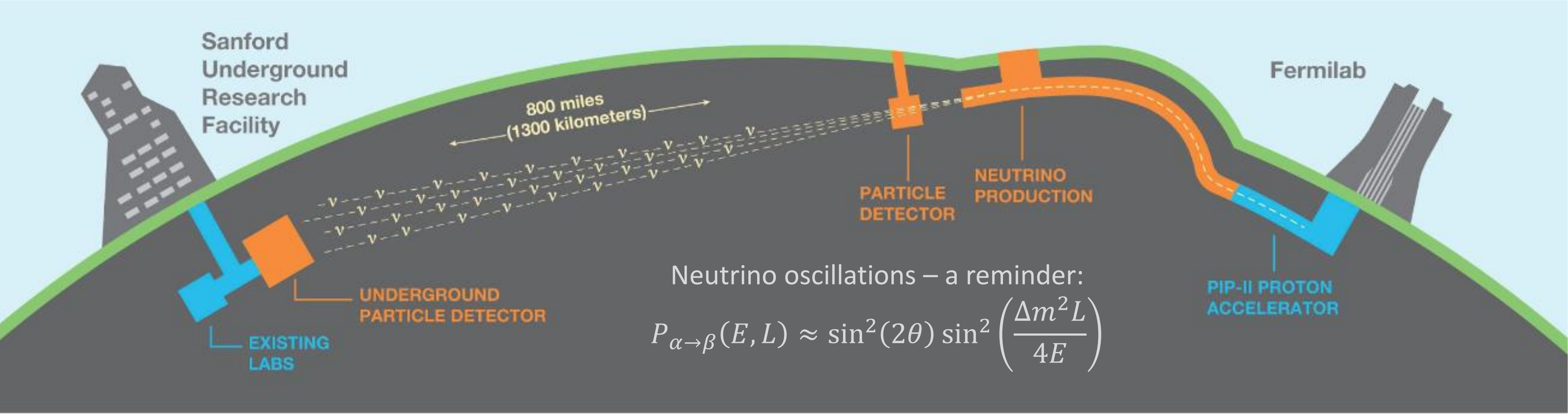
Supervisors: Dr Stephen Dolan and Dr Cristóvão Vilela

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

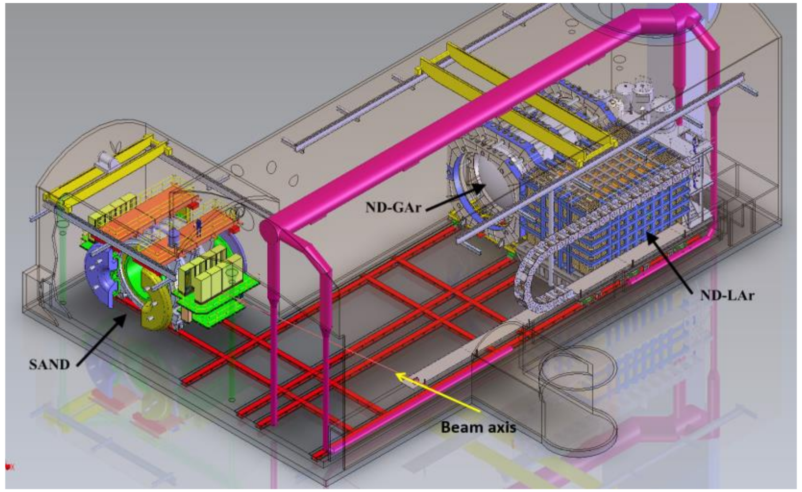


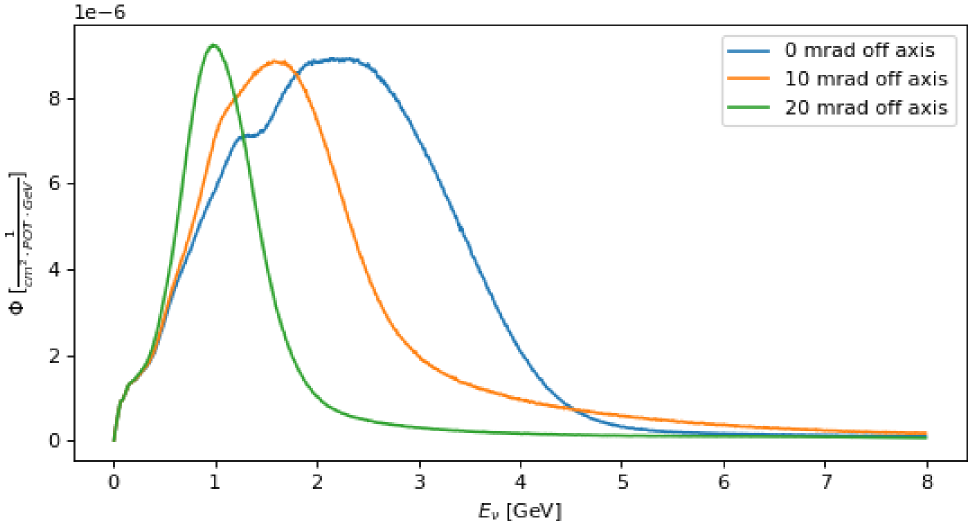
Neutrino oscillations – a reminder:

$$P_{\alpha\rightarrow\beta}(E,L) \approx \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

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 $\Phi_i(E_\nu)$





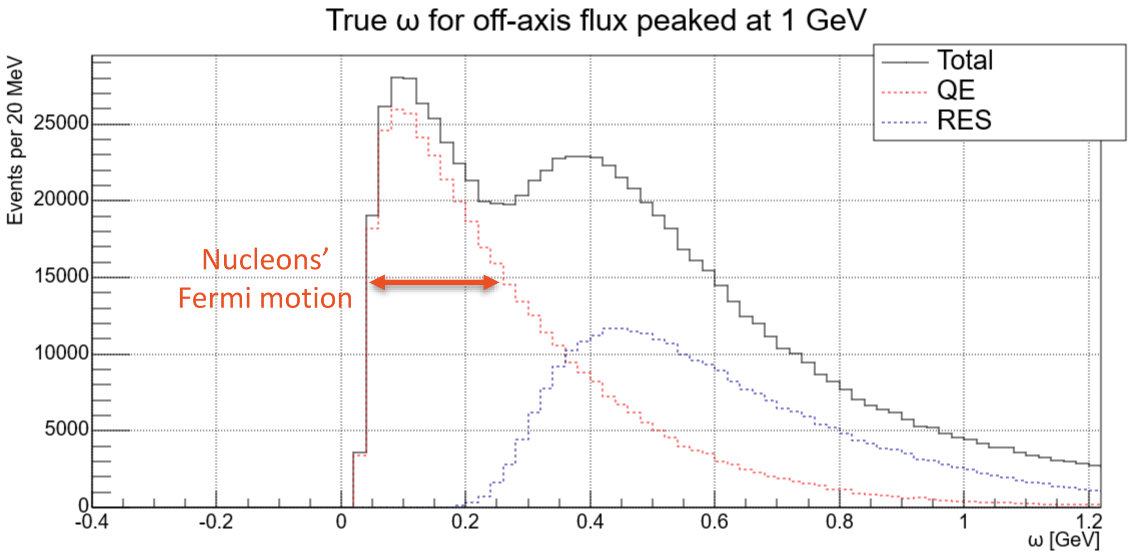
- Virtual fluxes can be produced by adding fluxes - $\Phi_{virtual} = \sum_i c_i \Phi_i$

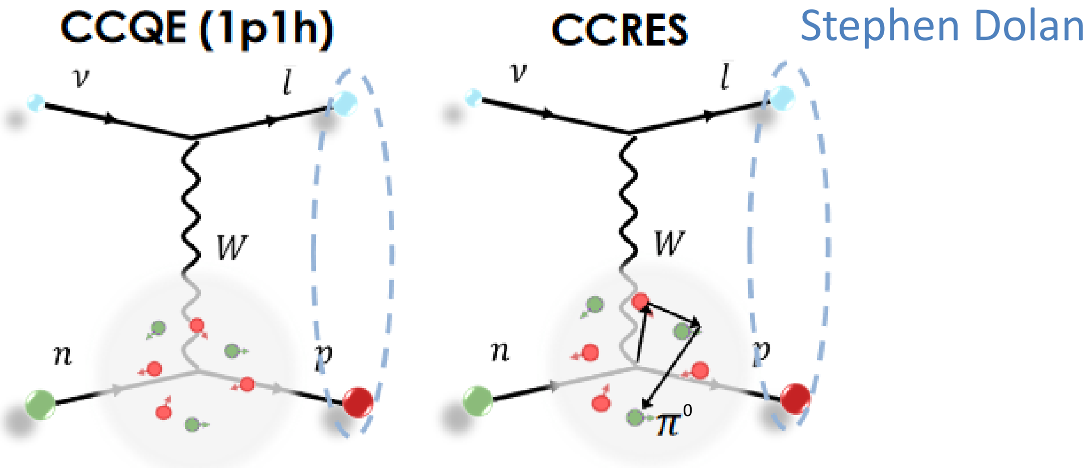
Motivation for cross section measurements for DUNE

- In oscillation analyses,

$$N_{pred}(E_\nu^{true}) \propto \boldsymbol{\sigma(E_\nu^{true})}\Phi(E_\nu^{true})P(\alpha \to \beta, E_\nu^{true})$$

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



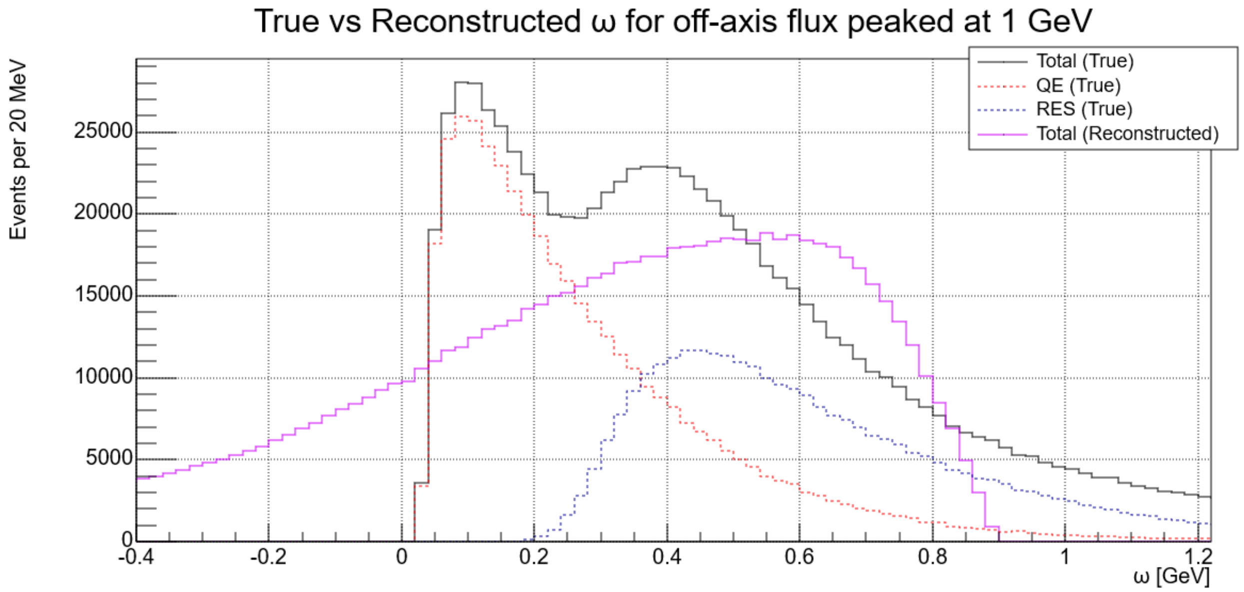


- Similar Final states make different nuclear processes hard to separate from one another

$(*)\ \omega = E_\nu - E_{lepton}$ - Transfer energy of the interaction

Cross section measurements for DUNE

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

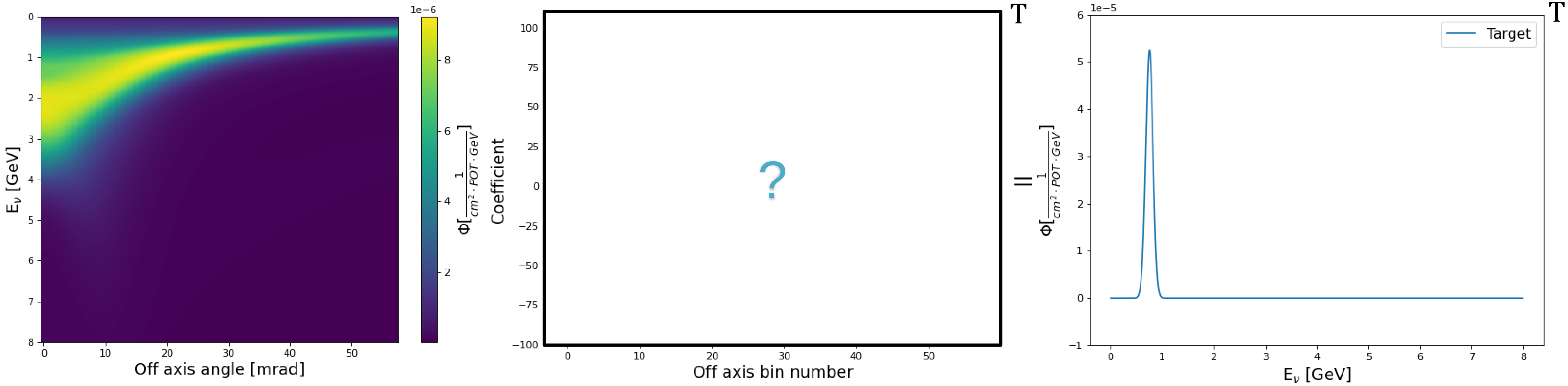


- No simple way to compare simulation to data (without σ, which we're trying to measure!)

  Result: Impossible to resolve different interaction features

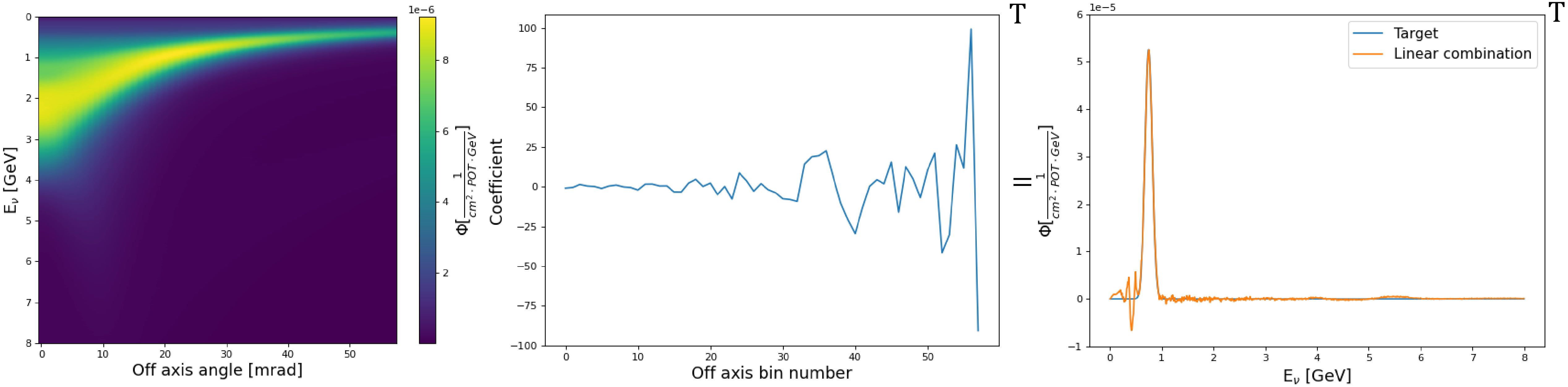
Virtual flux recipe

- **Ingredients:**
  - Flux matrix F - an estimation of what flux distribution we will get for each off-axis angle
  - Target flux $\vec{T}$ – a flux distribution we would like to approximate
- **Directions:**
  - **Solve $F\vec{c} = \vec{T}$** - find a solution such that will give an approximation of our target as a linear combination of fluxes

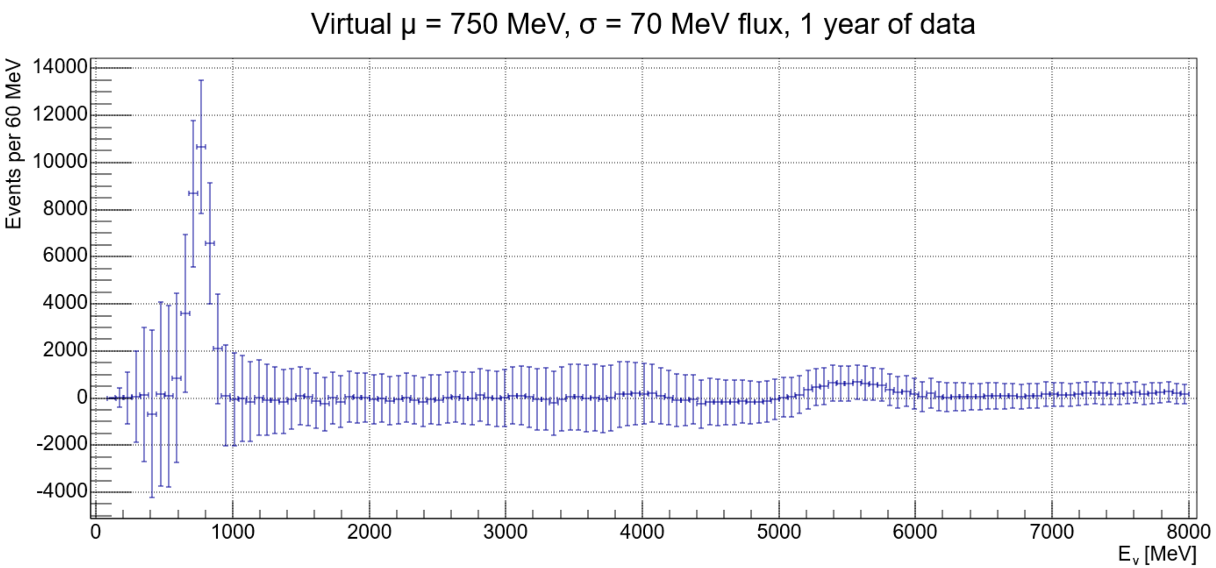


Virtual flux recipe

- **Ingredients:**
  - Flux matrix F - an estimation of what flux distribution we will get for each off-axis angle
  - Target flux $\vec{T}$ – a flux distribution we would like to approximate
- **Directions:**
  - **Solve $F\vec{c} = \vec{T}$** - find a solution such that will give an approximation of our target as a linear combination of fluxes



Virtual flux → Virtual event rate



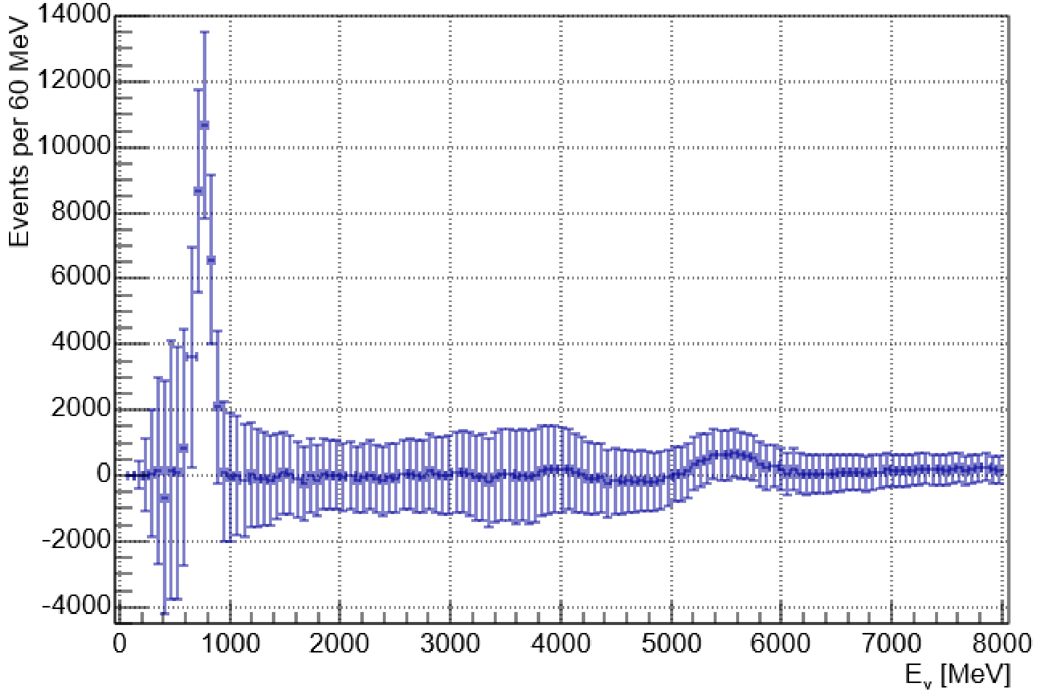
- Relative statistical uncertainty in each virtual flux bin depends on event statistics and the chosen coefficients:

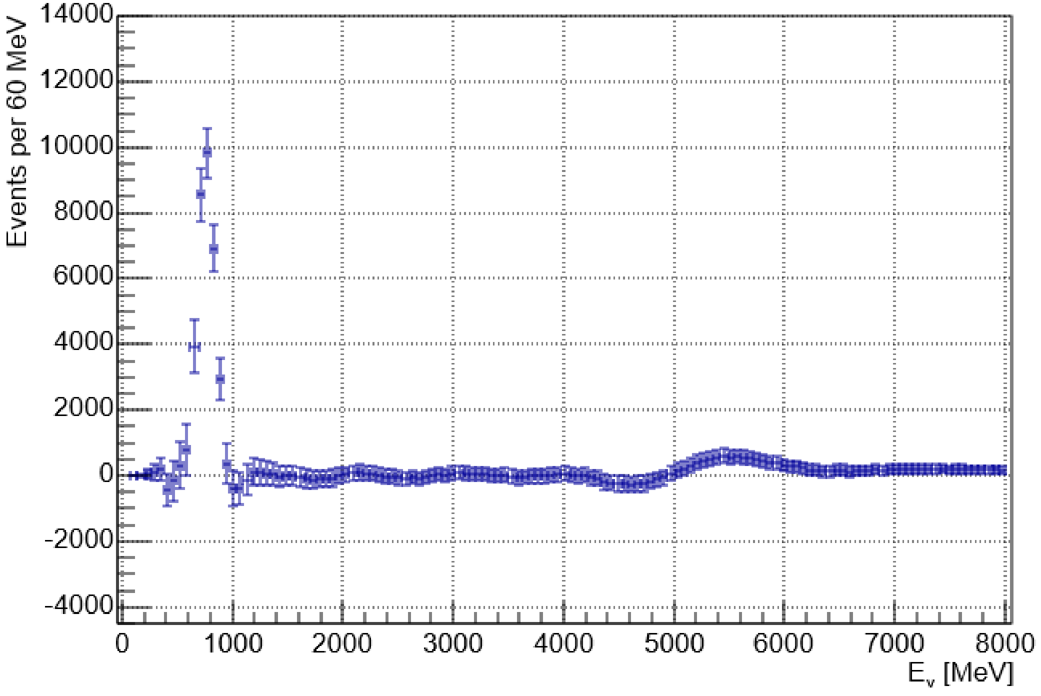
$$\sigma_{stat_j} = \frac{\sqrt{\sum_i c_i^2 N_{ij}}}{\sum_i c_i N_{ij}}$$

- Example - Large negative coefficients have a strong impact on σ_{stat}
- Idea – penalize solutions with large coefficients

Applying regularization methods

Virtual μ = 750 MeV, σ = 70 MeV flux, 1 year of data

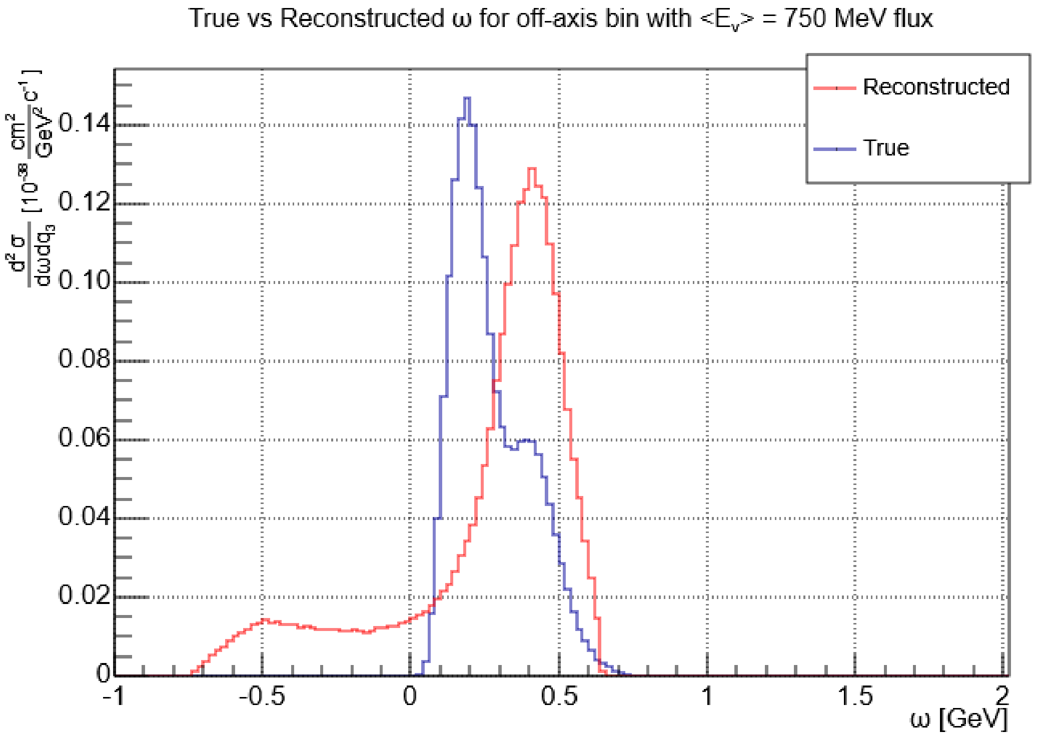


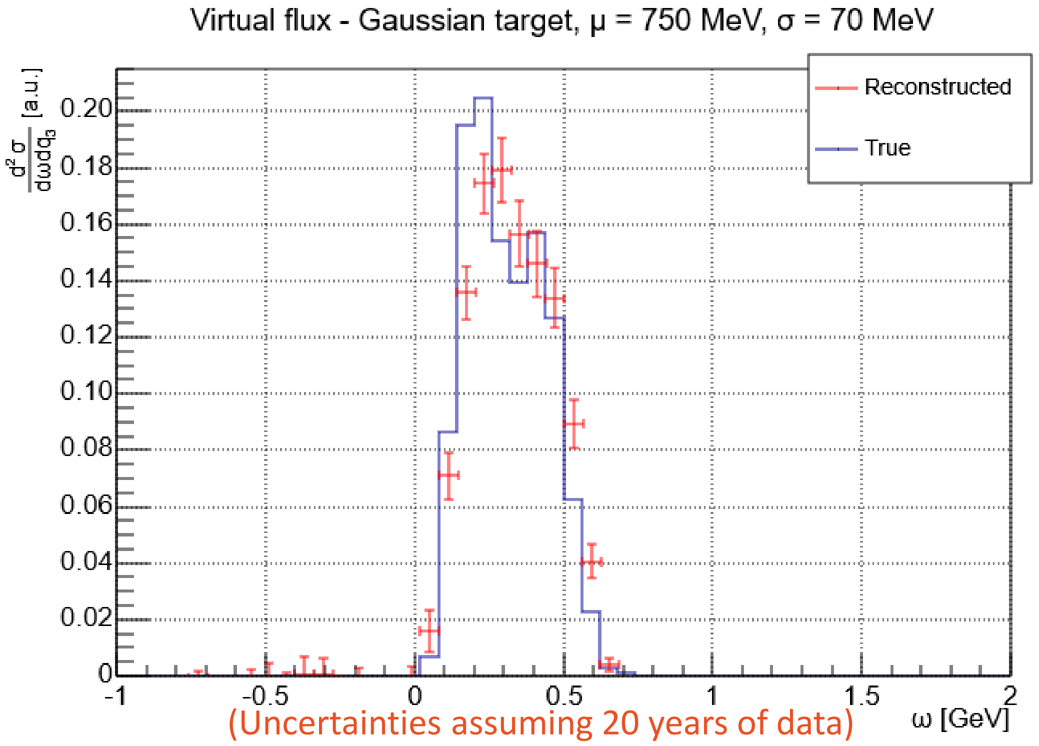


Ordinary least squares
$\mu = 750\ MeV$
$\sigma = 71\ MeV$

Tikhonov regularization (Ridge regression) with $\alpha = 10^{-12}$
$\mu = 750\ MeV$
$\sigma = 78\ MeV$

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

Conclusions

- Main features of different Neutrino-nucleus processes as a function of ω 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 ω_{reco} to ω_{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