Neutrino-Nucleus interaction cross section analysis with DUNE-PRISM

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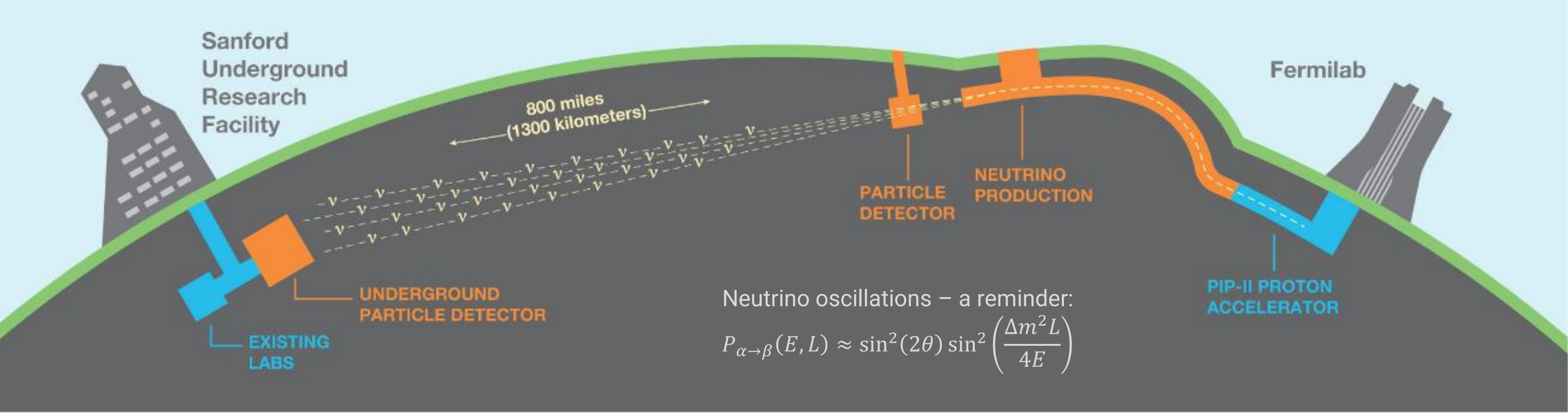
DUNE – Deep Underground Neutrino Experiment

- 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

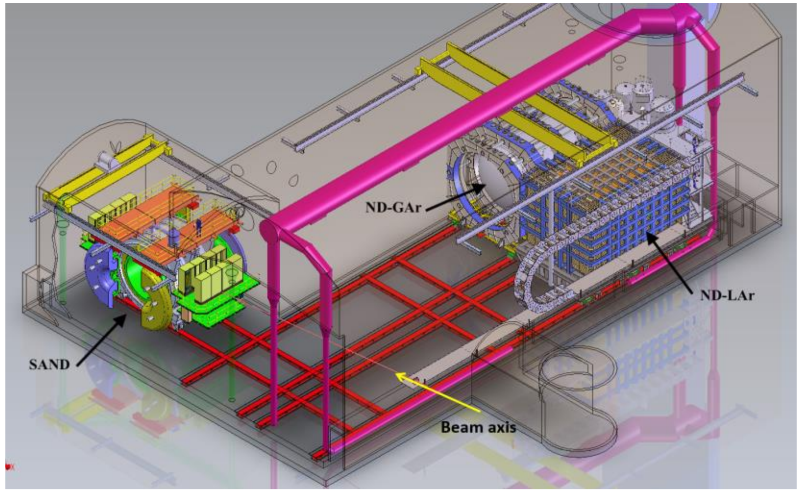


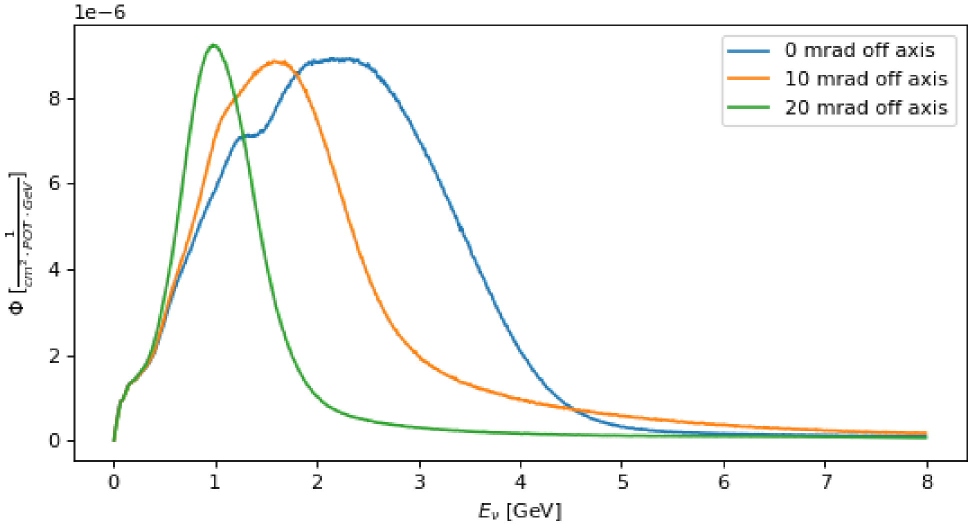
Neutrino oscillations – a reminder:

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

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

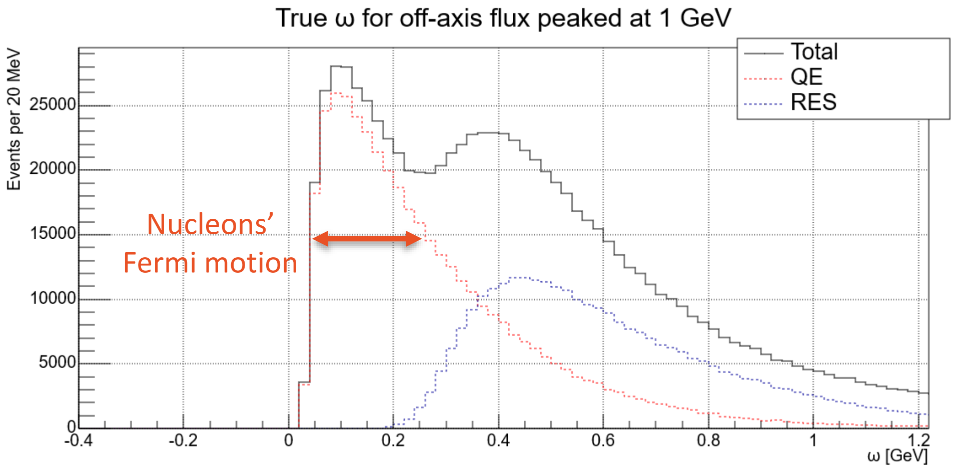
Neutrino physics

- In oscillation analyses,

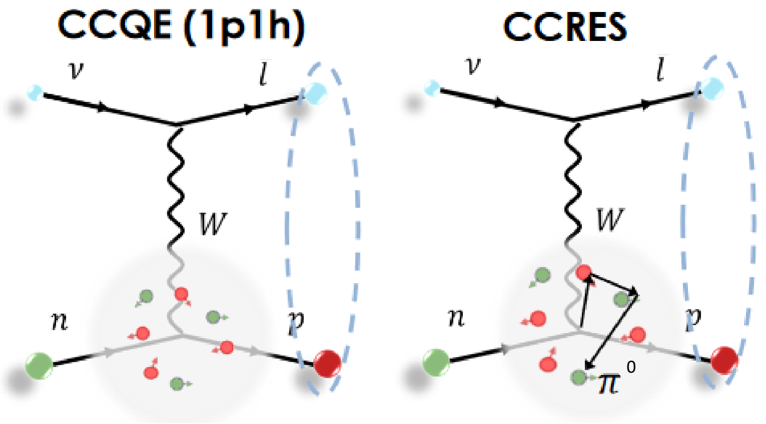
$$N_{pred}(E_\nu^{true}) \propto \boldsymbol{\sigma(E_\nu^{true})}\Phi(E_\nu^{true})P(\alpha \rightarrow \beta, E_\nu^{true})$$

Nuclear physics

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



Nucleons' Fermi motion



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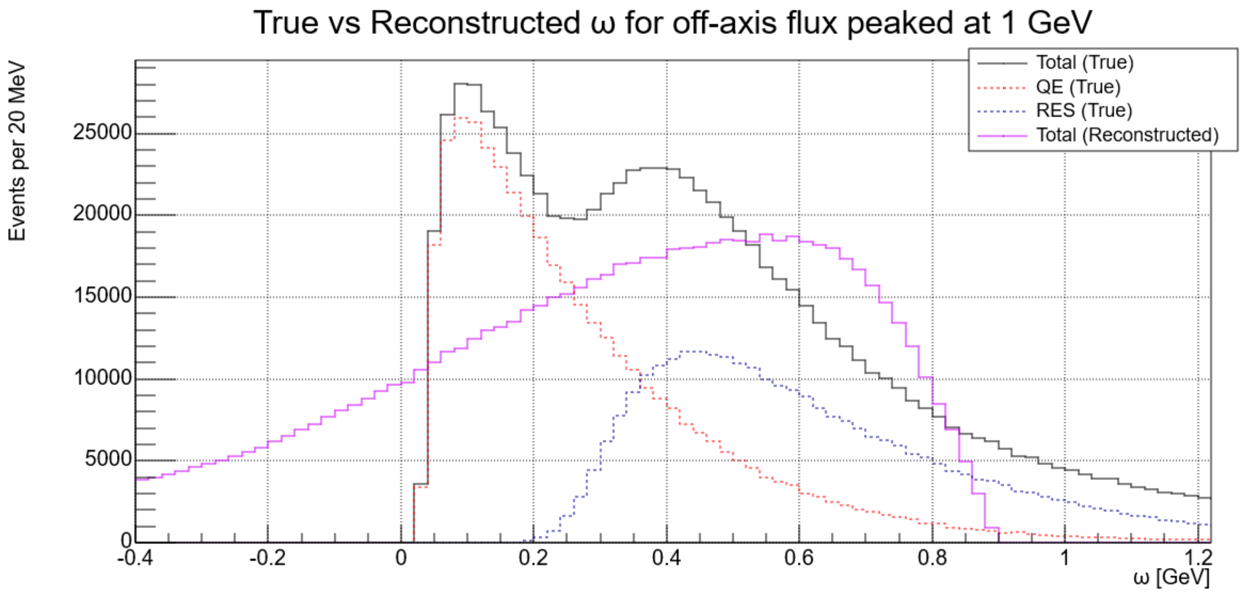
- Similar final states make different nuclear processes hard to separate from one another

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

Cross section measurements for DUNE

- Naïve approach for reconstructing ω – using a single off-axis flux assuming:
  - $\Phi(E_\nu) \to \delta(E_\nu - E)$



⟹ Incoming flux very (very!) different from monochromatic

- No simple way to measure ω with a wide-band beam (such as DUNE’s)

Result: Impossible to resolve different interaction features

Virtual flux recipe

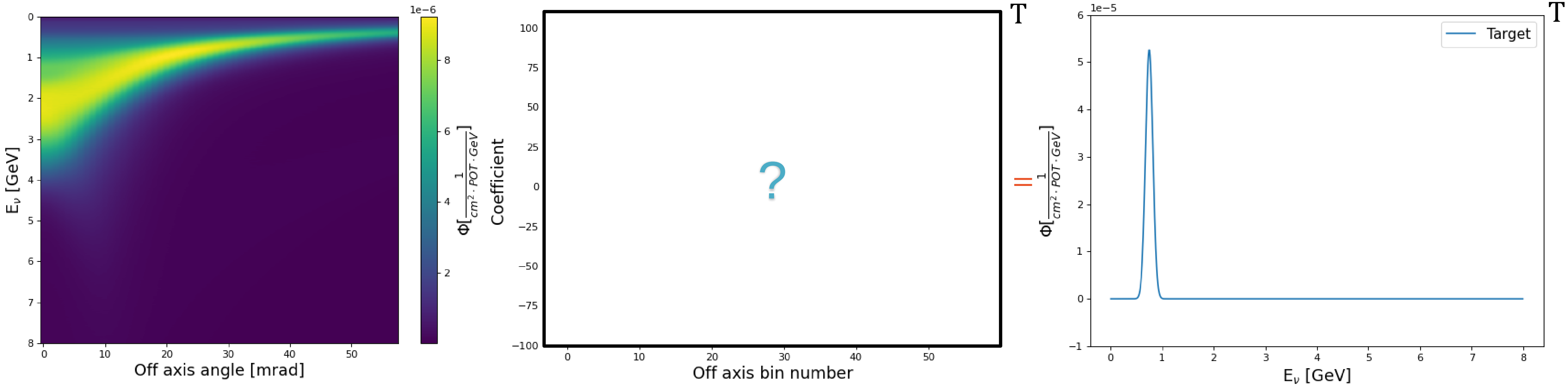
Ingredients:

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 $\boldsymbol{F\vec{c}} = \boldsymbol{\vec{T}}$ - find a solution that will give an approximation of our target as a linear combination of fluxes



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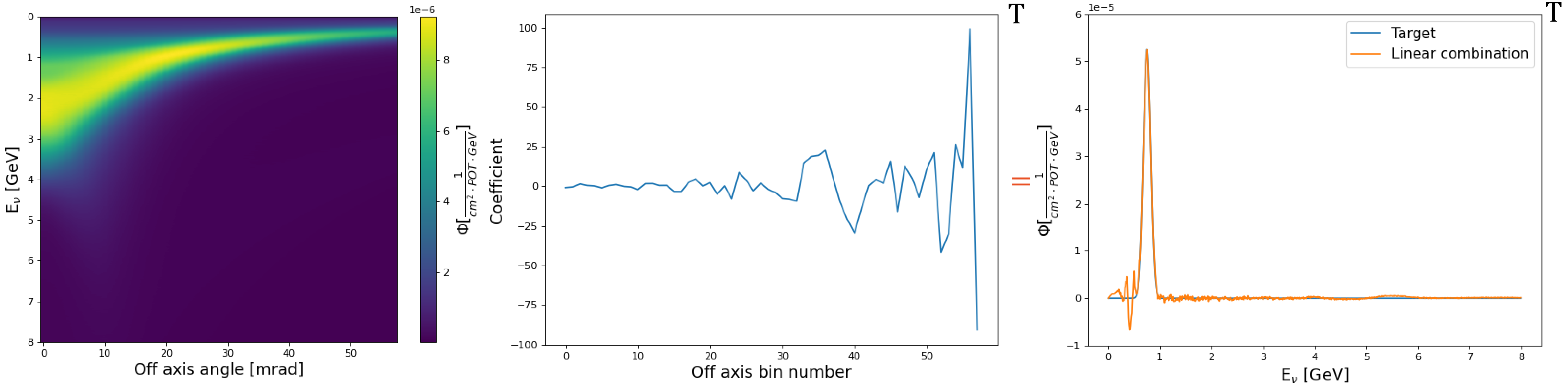
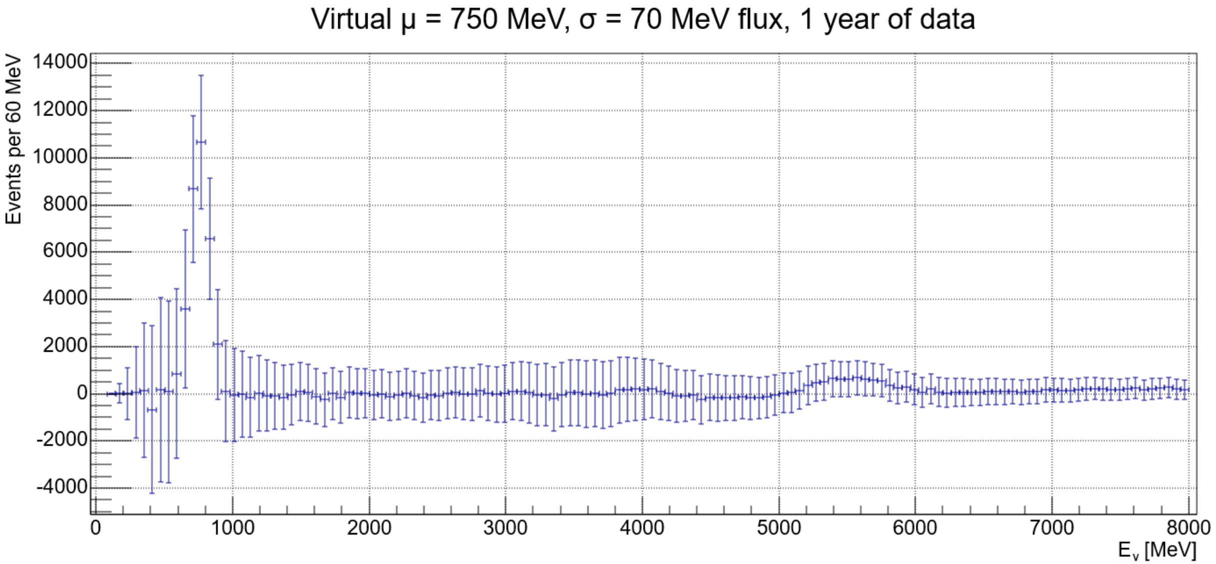


Virtual flux → Virtual event rate

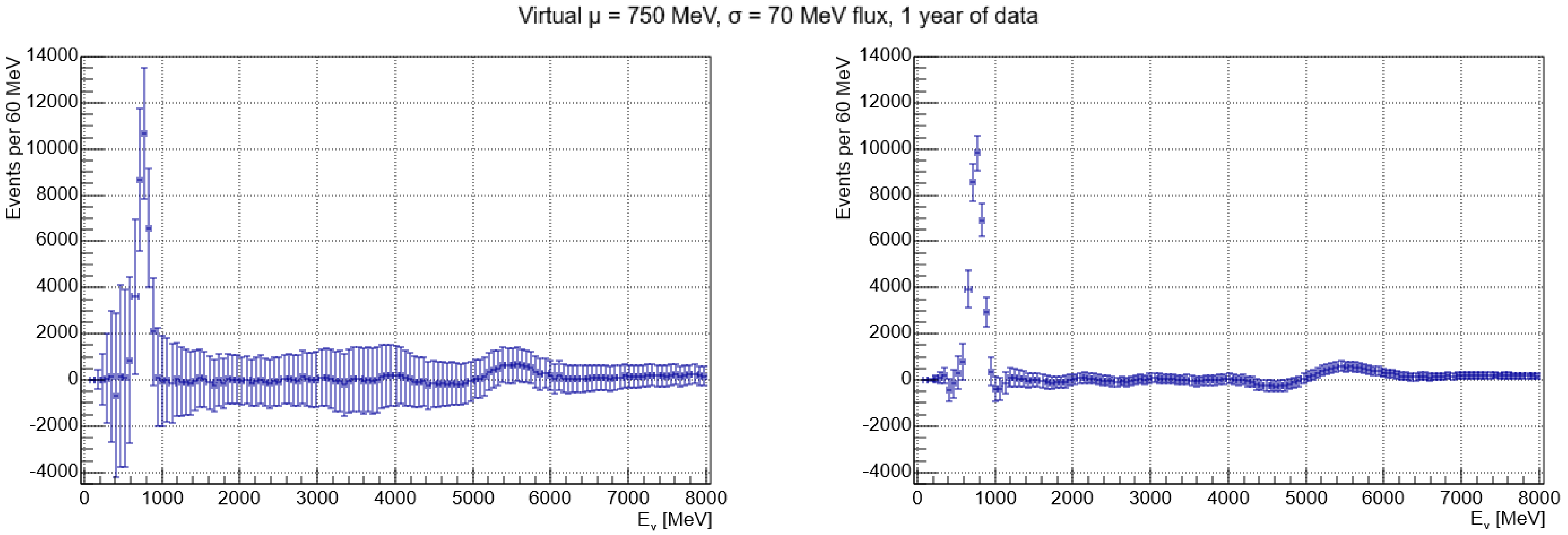


- Relative statistical uncertainty in each virtual flux bin depends on event statistics and the chosen coefficients:

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

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

Applying regularization methods



Ordinary least squares

$\mu = \mathbf{750\ MeV}$

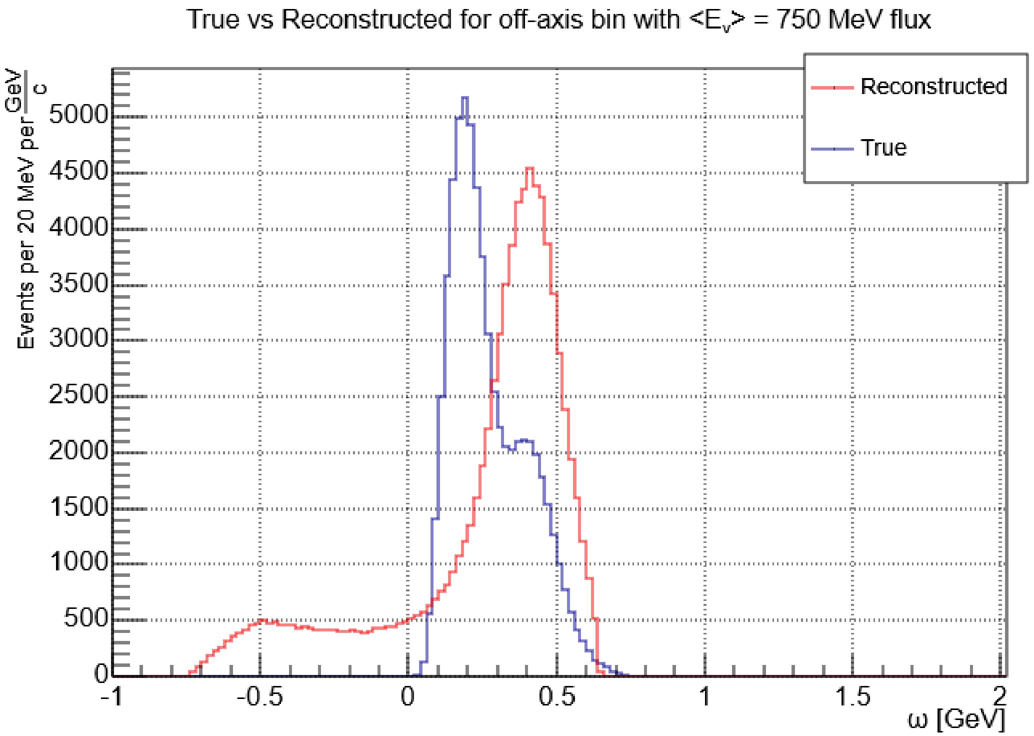
$\sigma = \mathbf{71\ MeV}$ ⟷

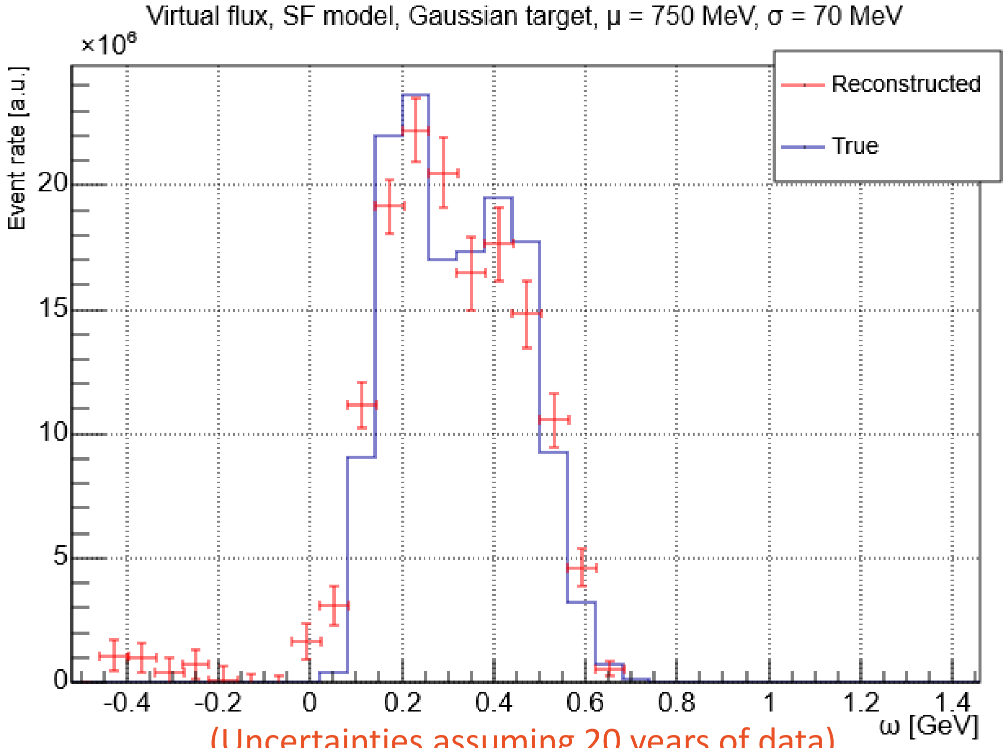
Tikhonov regularization (Ridge regression) with $\alpha = 10^{-12}$

$\mu = \mathbf{750\ MeV}$

$\sigma = \mathbf{78\ MeV}$

Preliminary cross section analysis


True vs Reconstructed for off-axis bin with <E$_\nu$> = 750 MeV flux


Virtual flux, SF model, Gaussian target, μ = 750 MeV, σ = 70 MeV

(Uncertainties assuming 20 years of data)

- 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 – could be $O(10)$ 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
- **Multiple fluxes at different energies**

Thank you!