Decoding Neutrino Interactions:
A Model-Independent Approach with DUNE-PRISM

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The DUNE-PRISM Detector

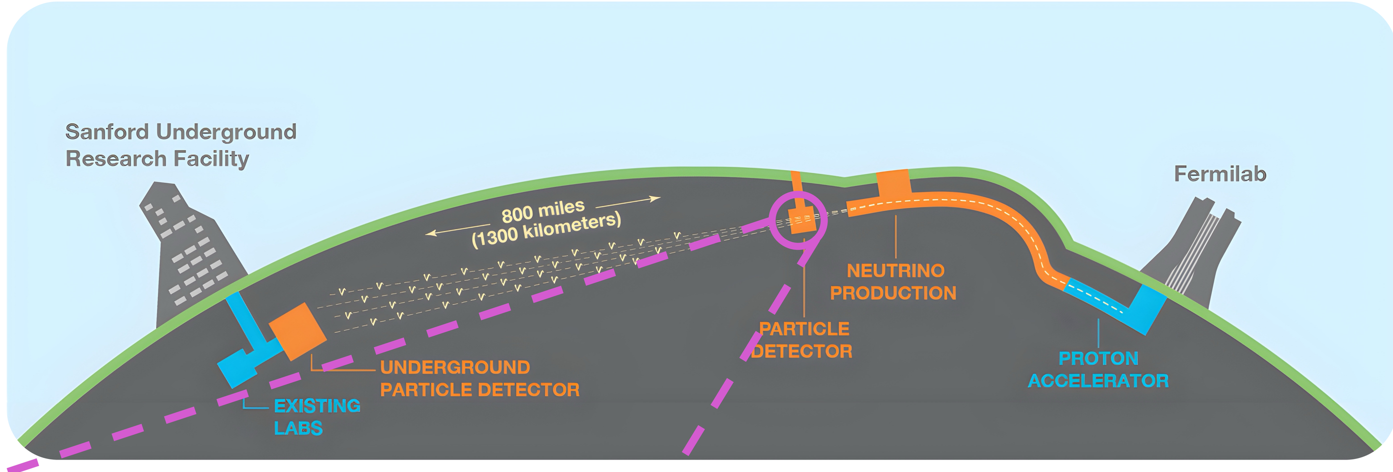
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

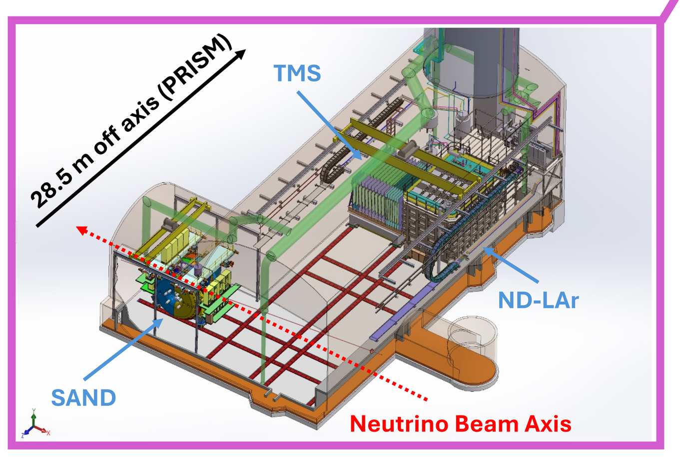
Next-generation oscillation experiment, measuring:

$P(\nu_\mu \to \nu_\mu)$

$P(\nu_\mu \to \nu_e)$

δ_{CP} U_{PMNS}





Movable Near Detector
- Shifts **off-axis** to scan multiple fluxes

↑ **robust** oscillation results

↑ **control on systematics**

Motivation

Neutrino oscillation needs σ(E)

$$N(E_\nu) = P(\nu_\alpha \to \nu_\beta) \cdot \sigma(E_\nu) \cdot \Phi(E_\nu) \cdot \epsilon(E_\nu)$$

Why Now?

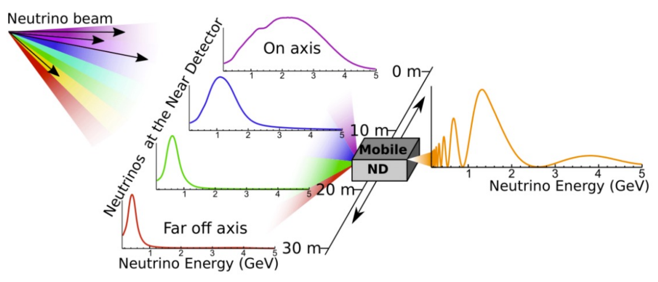
Statistical error is shrinking — model systematics will dominate without σ(E) control.

What DUNE-PRISM Solves:

- Enables **data-driven** constraints on σ(E)
- Helps separate flux and cross-section effects

From Off-Axis Flux to σ(E)

Step 1: Input Flux



$\Phi_{\nu_\mu,j}(E_i) \dashrightarrow M_{ij}$

$\Phi_{\nu_e,j}(E_i)$

MC

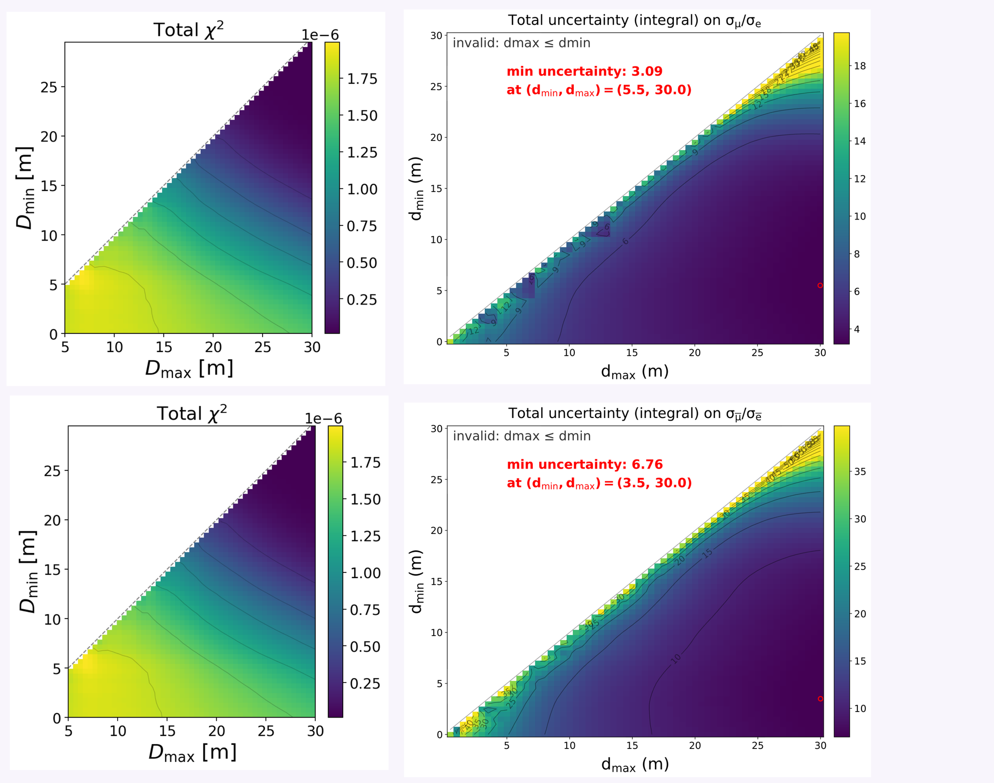
Step 2: Target Definition

$$\Phi_{\nu_e,j}(E_i) \to F_i$$

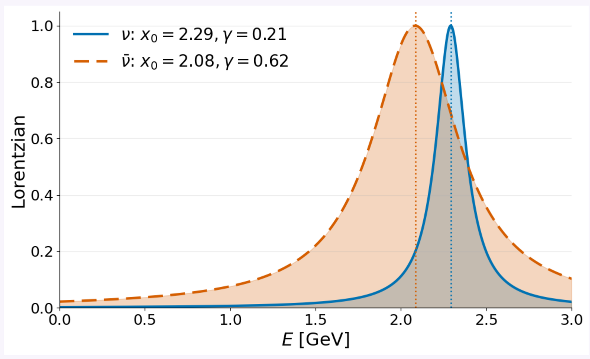
Method 1:
Off-axis position range

$$F_i = \sum_{j=j(d_{\min})}^{j=j(d_{\max})} \Phi_{\nu_e,j}(E_i)$$

Best choice?



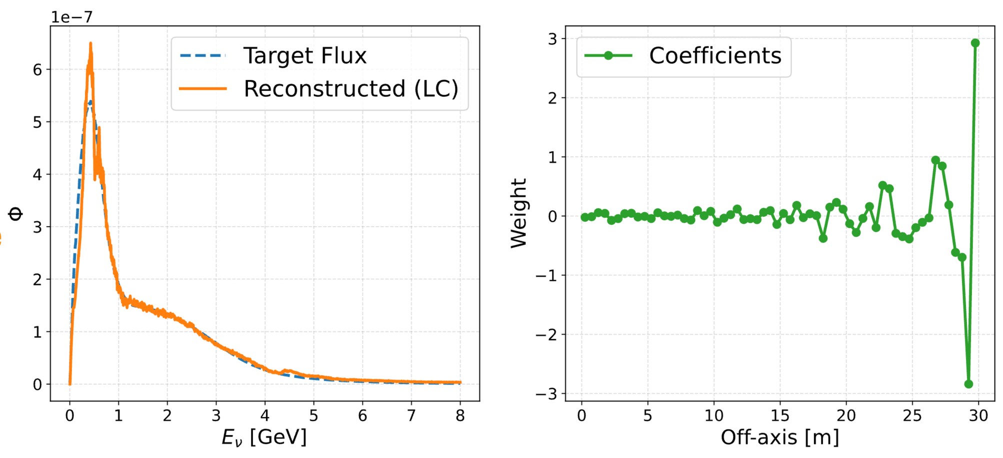
Method 2:
Linear combine to fit a function



Step 3: Flux Matching

$$\Phi_{\nu_e}(E_i) = \sum_j c_j \Phi_{\nu_\mu,j}(E_i)$$

Best fit possible

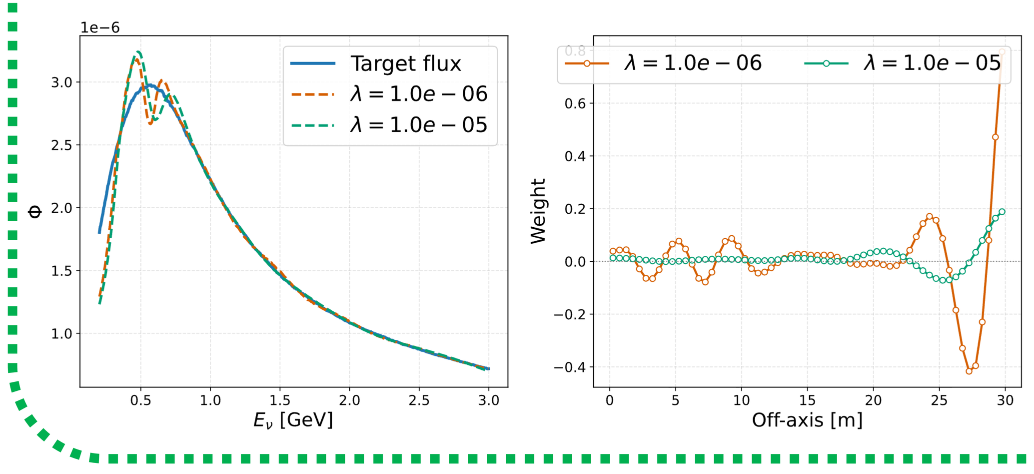


Large weights Erratic behaviour

Solution: $\min_{\vec{c}} \left\| \vec{F} - W M \vec{c} \right\|^2 + \lambda \|\vec{c}\|^2$

Focus on lower energies

Fixing the chaos: regularization



Smaller weights Smooth behaviour

Step 4: Event Rate

$$R_{\nu_e} \quad R_{\nu_\mu}$$

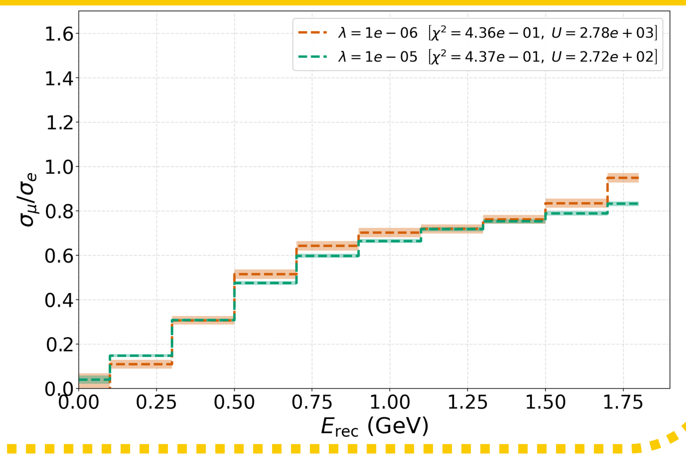
$$R(E) \approx \Phi(E)\sigma(E)$$

$$R^{LC}_{\nu_\mu} = \sum_j c_j R_{\nu_\mu,j}$$

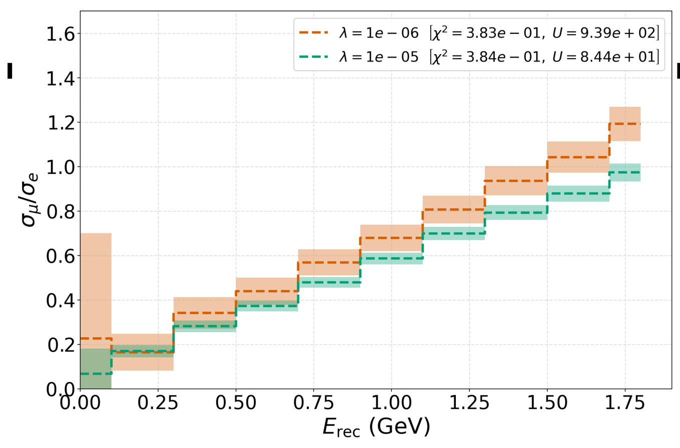
Coefficients from flux matching

Step 5: Cross section ratio

$$\frac{R^{LC}_{\nu_\mu}(E)}{R_{\nu_e}(E)} = \frac{\sigma_\mu(E)}{\sigma_e(E)}$$

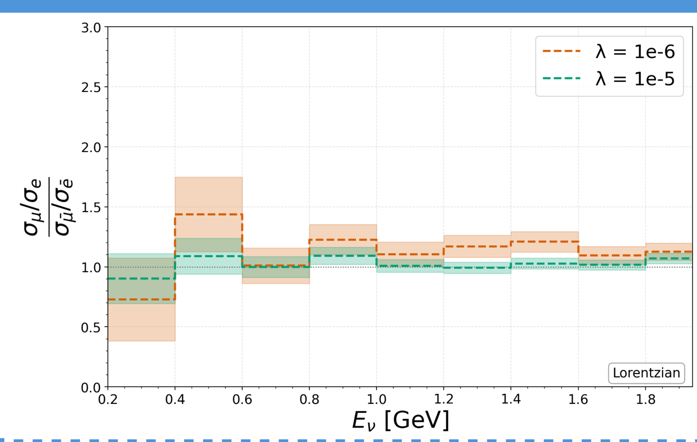


Step 6: Repeat for antineutrinos



Step 7: Double Cross section ratio

$$\frac{\sigma_{\nu_\mu}/\sigma_{\nu_e}}{\sigma_{\bar{\nu}_\mu}/\sigma_{\bar{\nu}_e}}$$



Forward folding: $E_{\text{true}} \to E_{\text{rec}}$

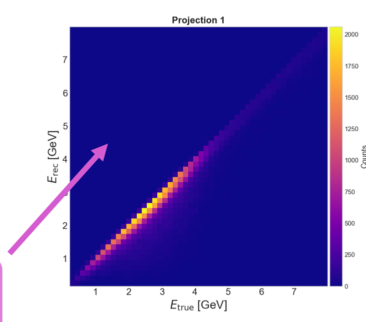
MC events $R_{\nu_\alpha}(E^{(j)}_{\text{true}})$

×

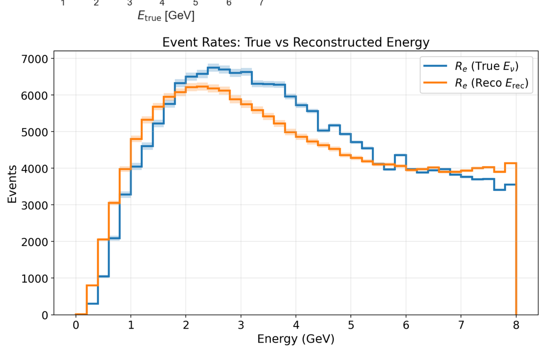
Response matrix $\mathbf{R}(E^{(i)}_{\text{reco}}, E^{(j)}_{\text{true}})$

↓

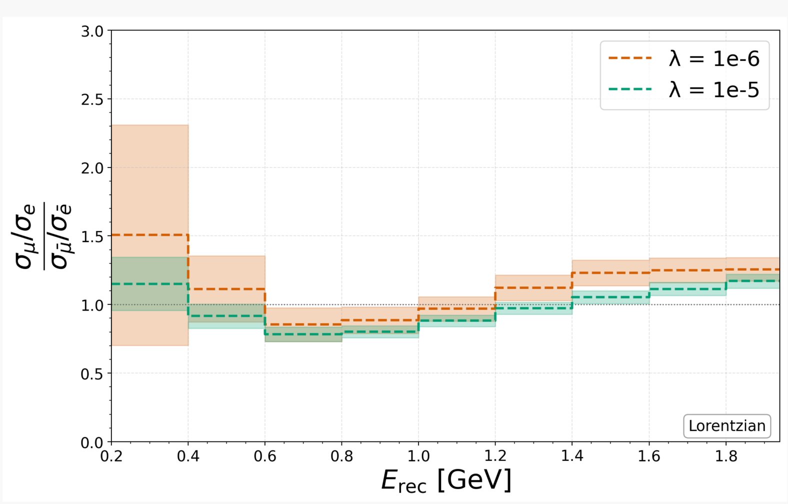
Measured events $R_{\nu_\alpha}(E^{(i)}_{\text{reco}})$



Off-diagonal → smearing



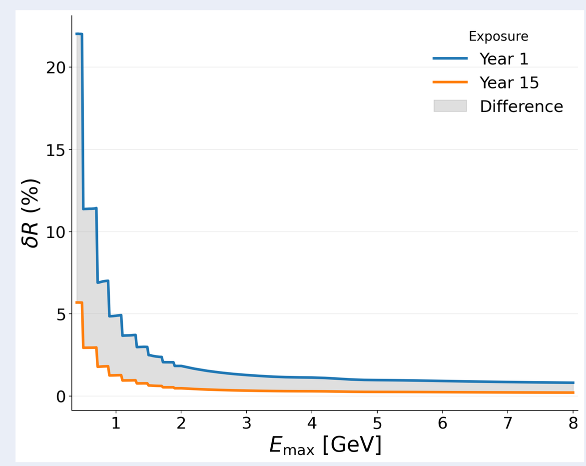
Double cross section ratio



Conclusions

Target optimization reduces uncertainties: Choosing parameters via χ^2 and total uncertainty scans ensures stable flux definitions.

Linear combination fitting is the best strategy: Produces smoother weights and lower errors than window methods.



Uncertainty shrinks with exposure: From ~20% at 1 year to **below 5% after 15 years.**

References:

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C. Hasnip, *DUNE-PRISM: Reducing neutrino interaction model dependence with a movable neutrino detector*, CERN, presented at NuFact2023, 25th Int. Workshop on Neutrinos from Accelerators, 2023.

S. Dolan, *Uncertainties in modelling neutrino interactions*, NOW 2022, Italy, Sept. 2022; and *Neutrino Interactions: The Nucleus Strikes Back*, Neutrino Summer School, CERN, Aug. 2021.

Full Report