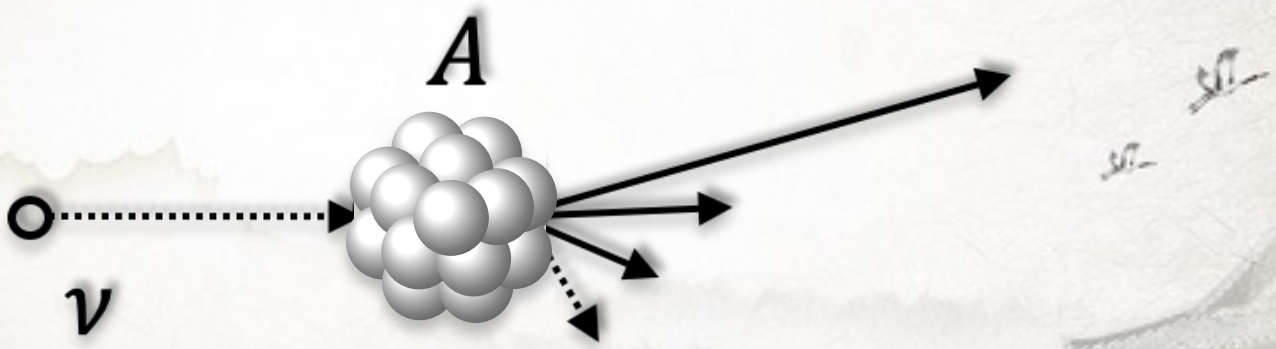
The impact of cross sections on physics searches

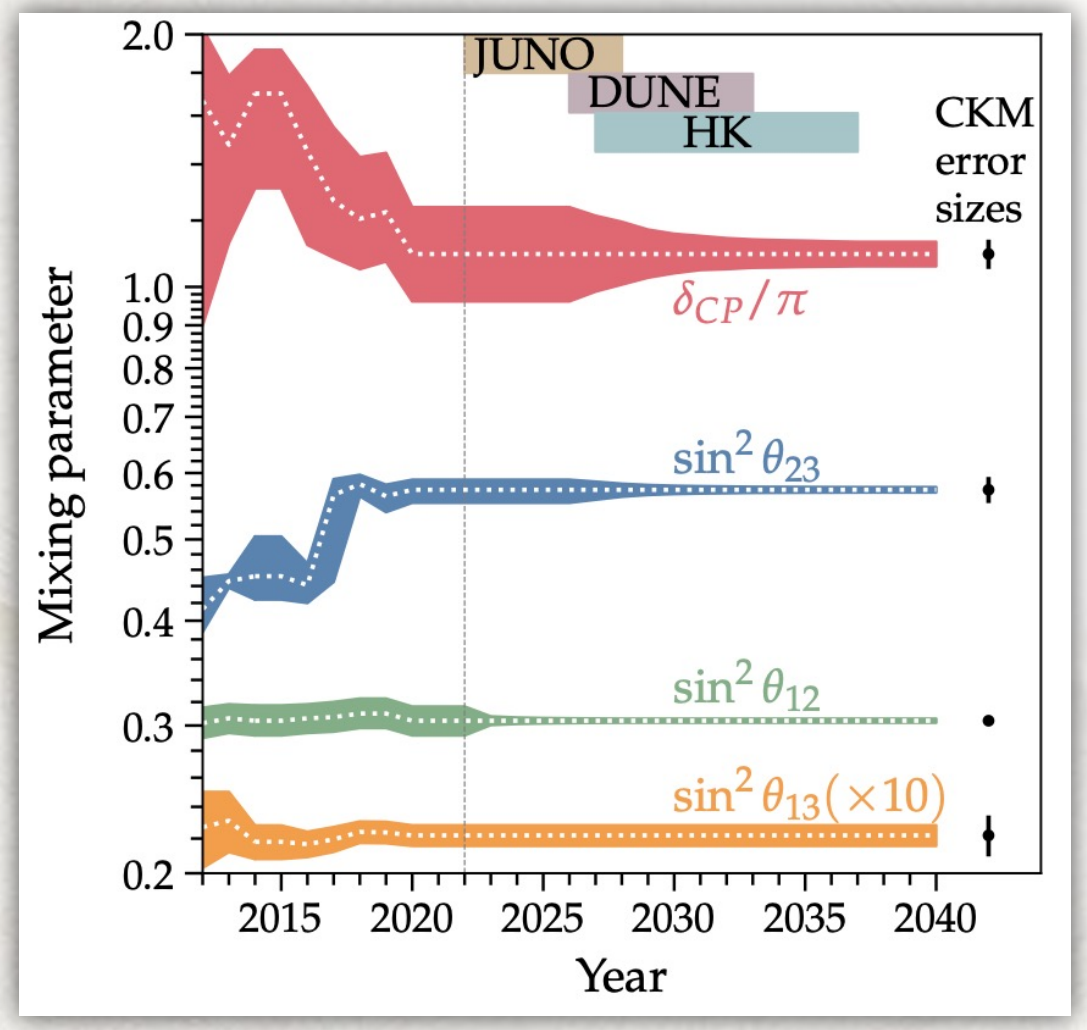


Shirley Li (UC Irvine)

What is the problem?

Accelerator-Based Long-Baseline Experiments

Precision measurements of the neutrino sector



T2K / Hyper-K (~ 0.6 GeV)

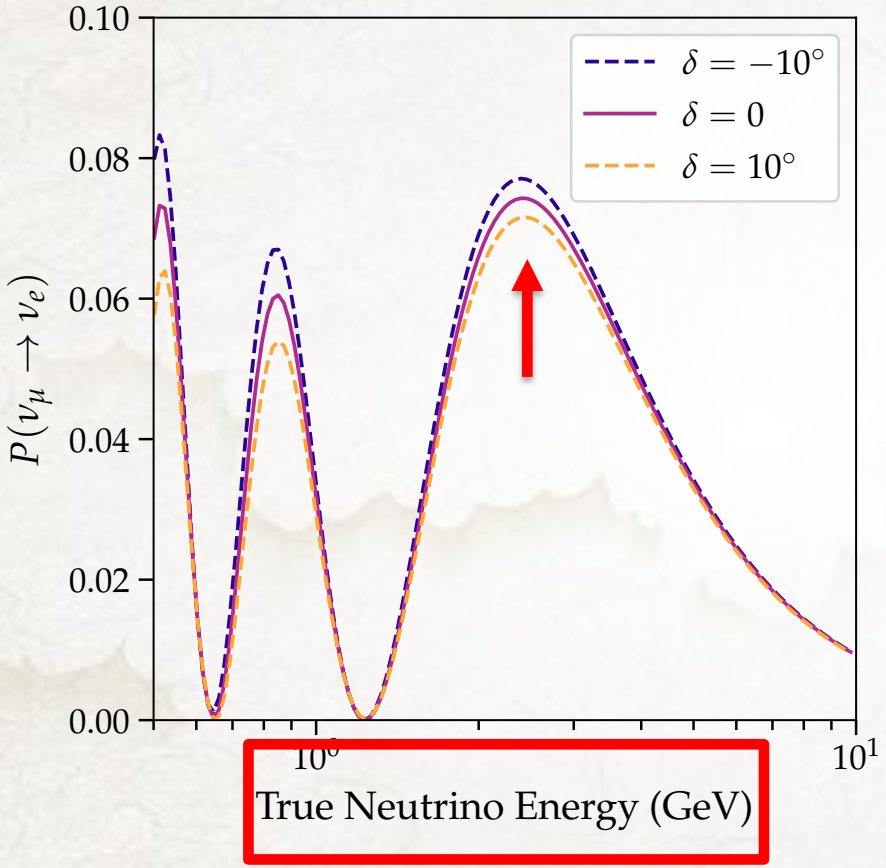
NOvA / DUNE (2—3 GeV)

Detection via ν-A interaction

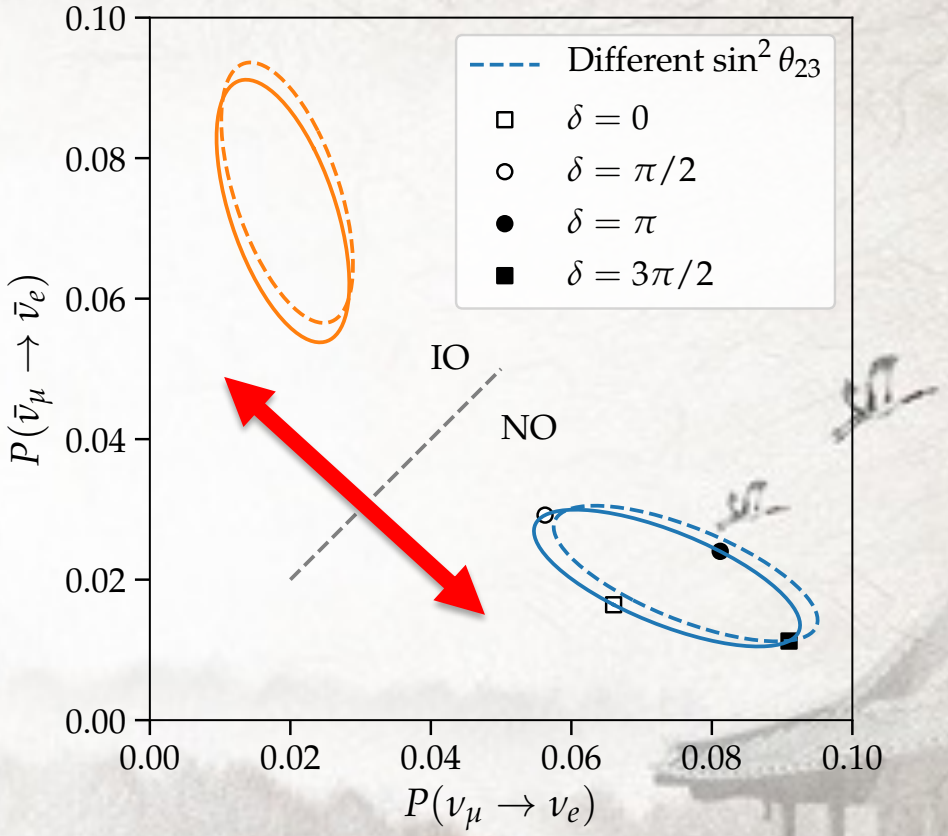
Figure modified from Song *et al.*, 2020

Measuring δ_{CP}

Neutrino Mode



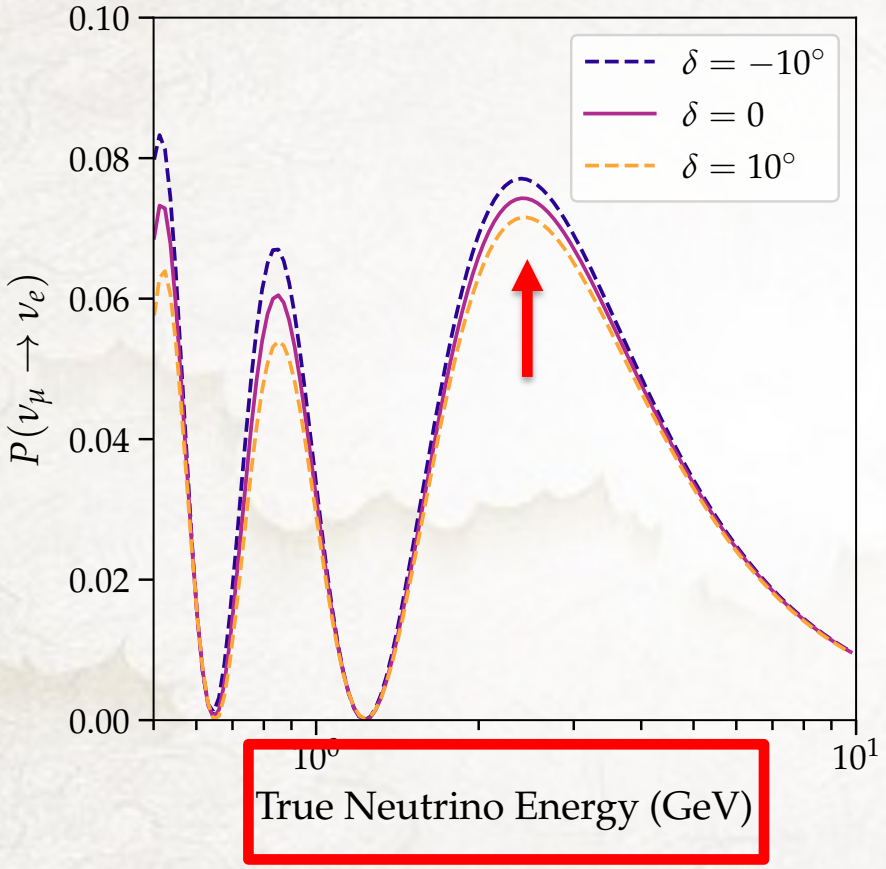
Bi-Probability



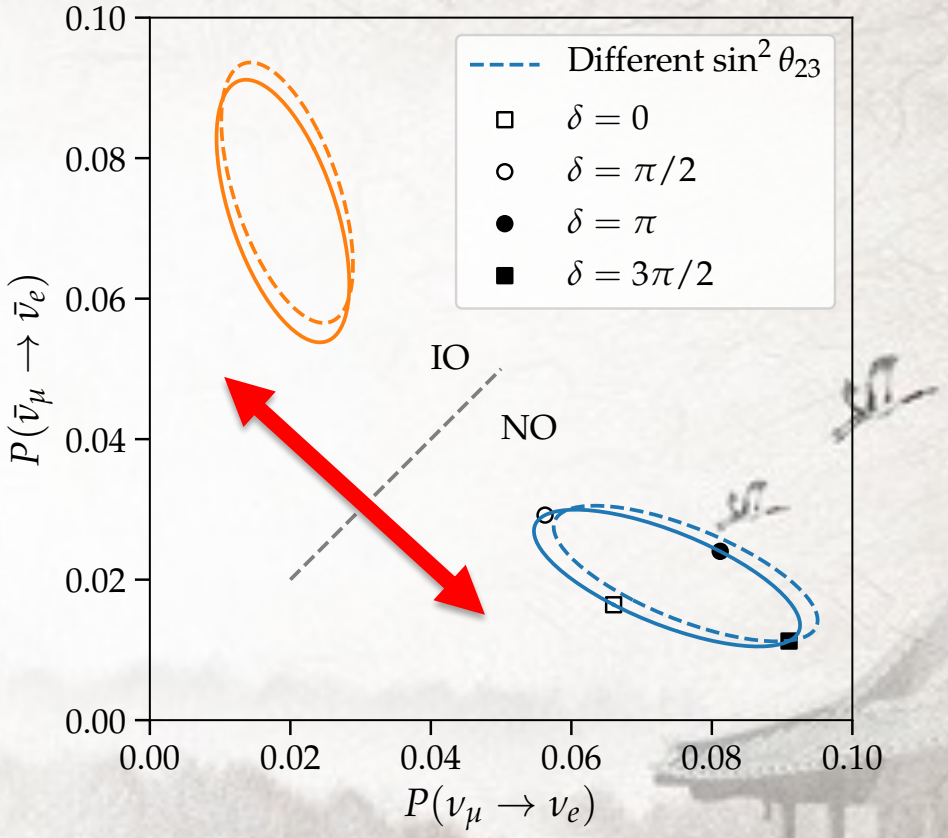
1. Differences Between ν-A and $\bar{\nu}$-A Are Important
2. Neutrino Energy Reconstruction Is Important
3. Level of Accuracy: $\simeq$5%

Measuring δ_{CP}

Neutrino Mode



Bi-Probability

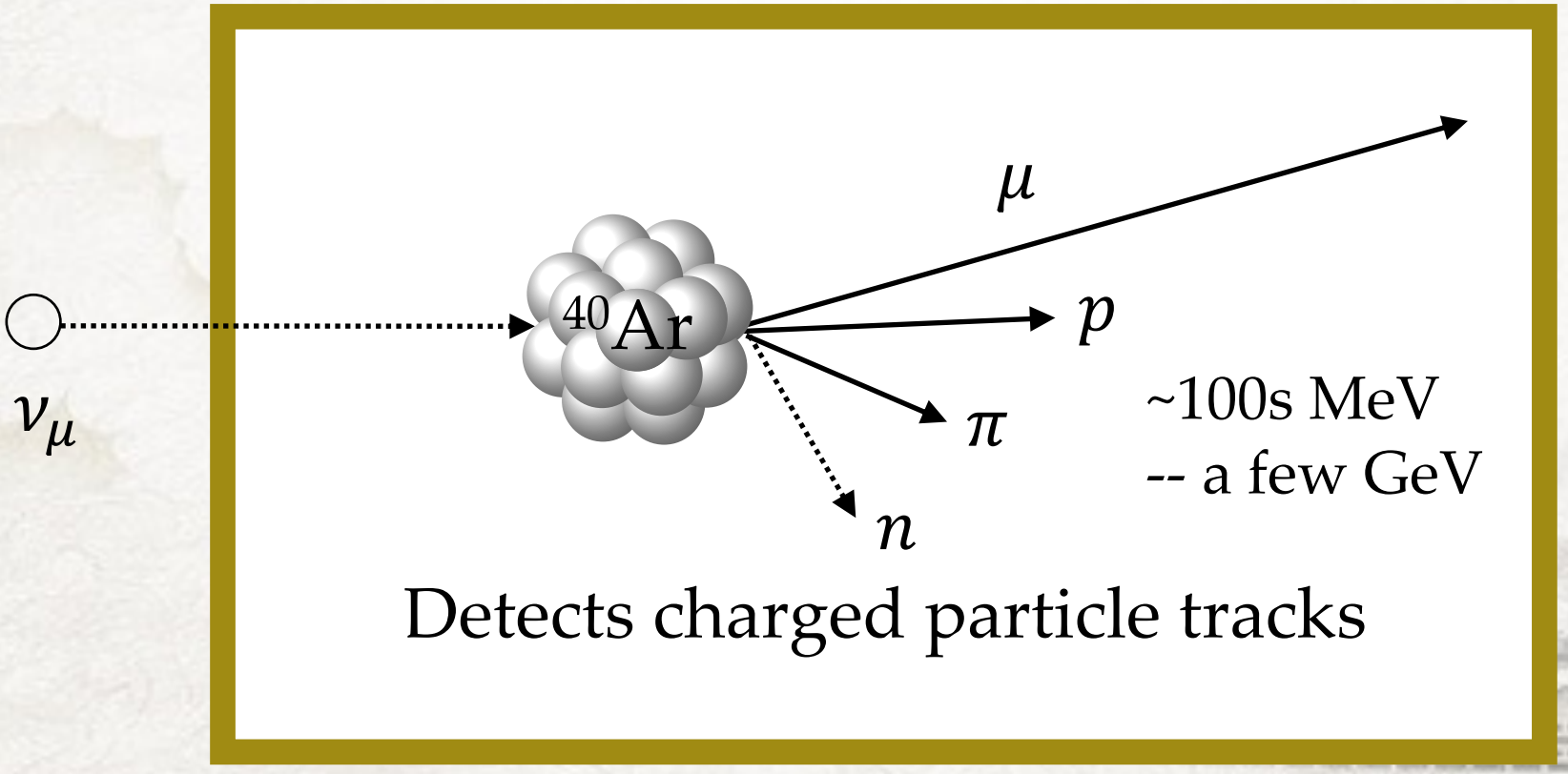


1. Differences Between ν-A and $\bar{\nu}$-A Are Important
2. Neutrino Energy Reconstruction Is Important
3. Level of Accuracy: $\simeq$5%

How Are Neutrinos Detected

Use DUNE as an example

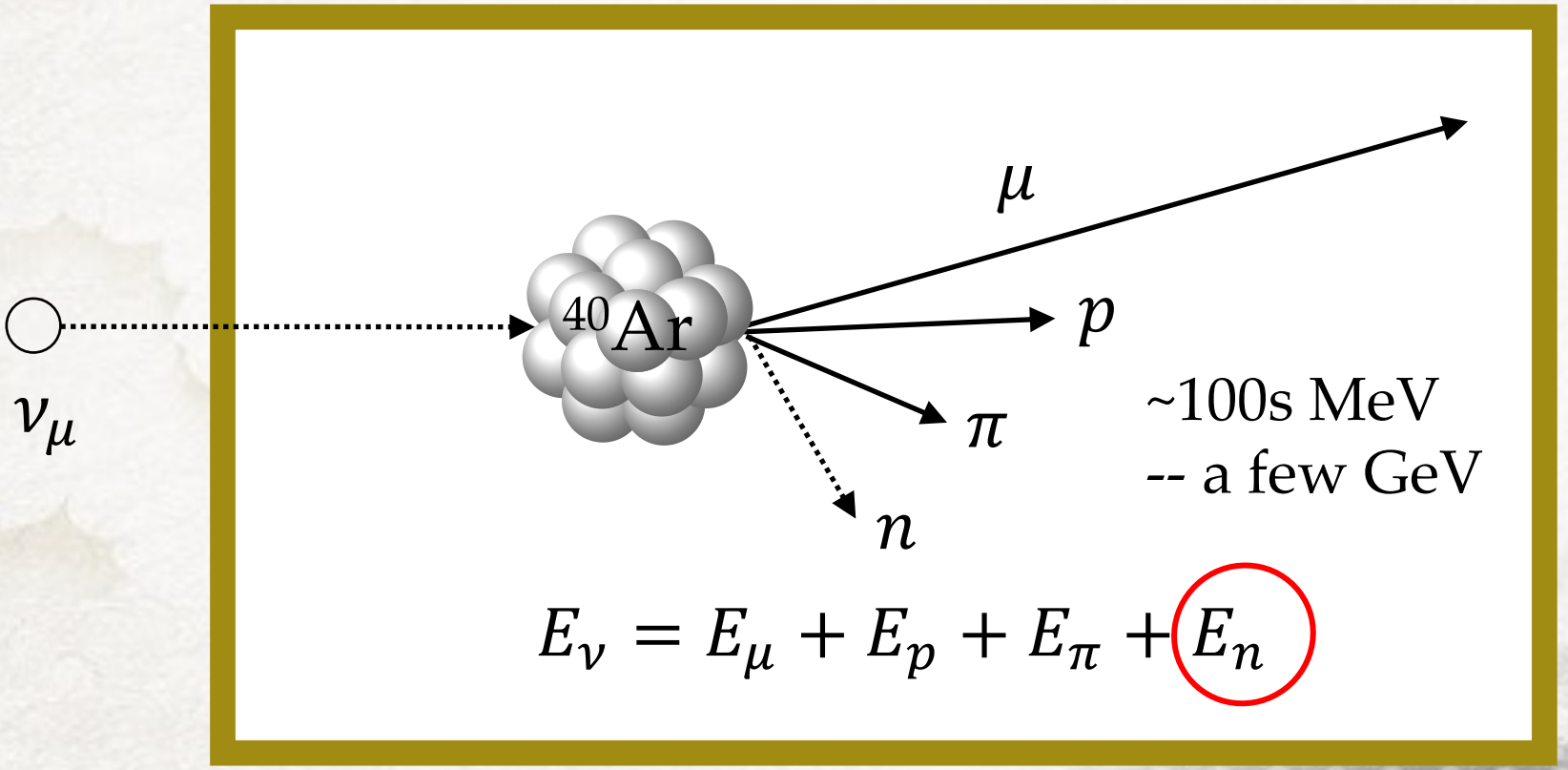
liquid argon time-projection chamber



Energy Reconstruction to a Theorist

Use DUNE as an example

liquid argon time-projection chamber

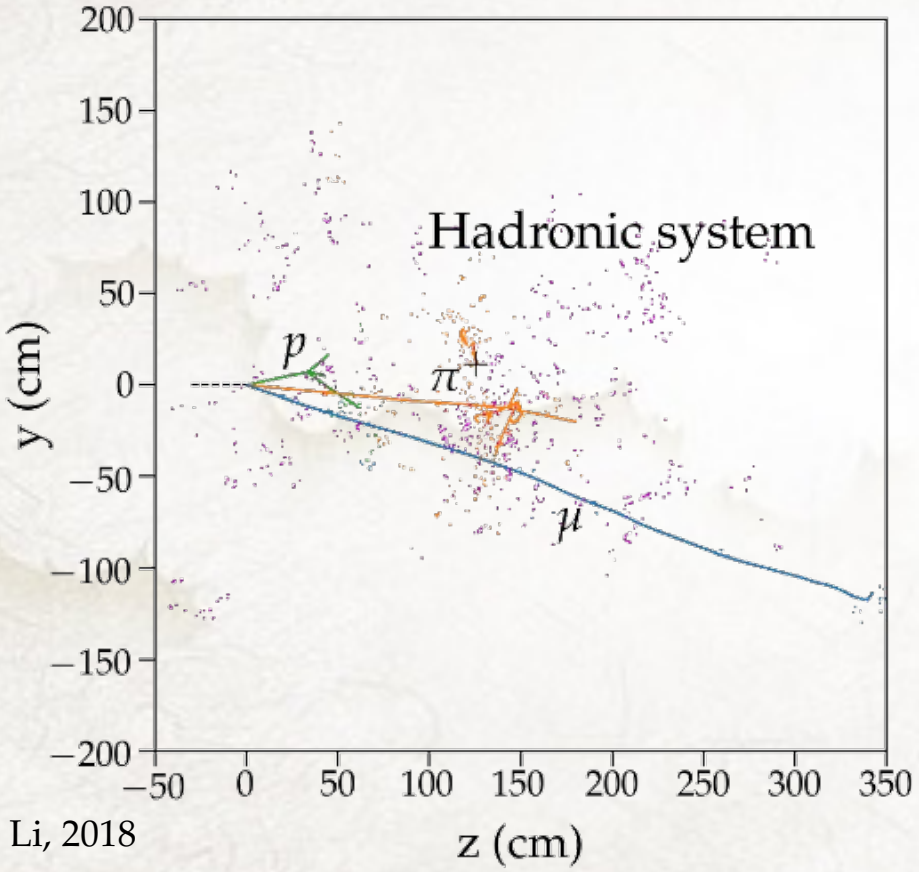


Theoretical prediction: missing energy

Only predictions of neutron fraction are important

More Realistic Energy Reconstruction

A simulated ν event in LAr



Friedland & Li, 2018
1811.06159

- Final-State Composition:
  Proton vs. Pion: Quenching
- Spectrum:
  Particle Below Thresholds
- Number of Final-State Particles:
  Nuclear Breakup Energy
- Containment

All Exclusive Final States Play A Role

The Cross Section Predictions That We Need:

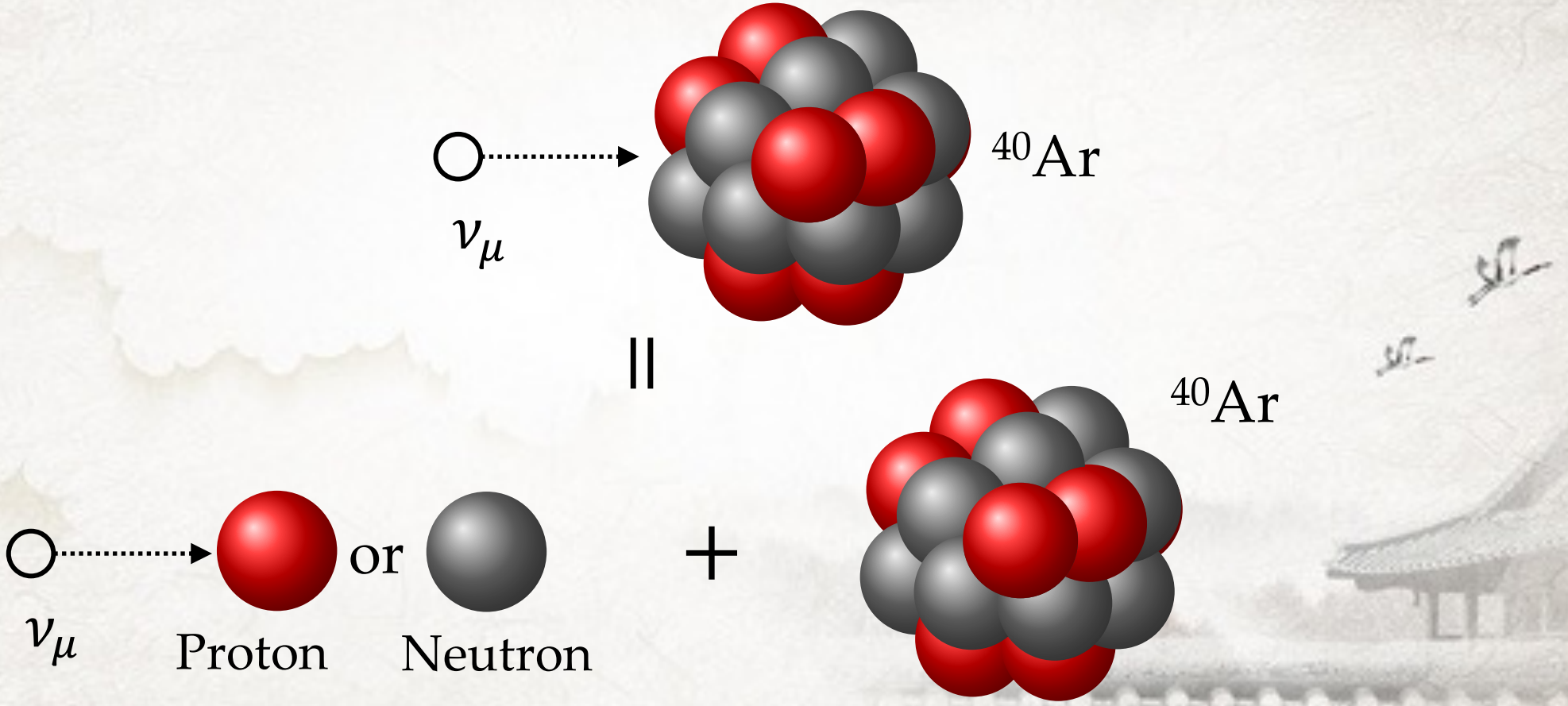
$$\frac{\mathrm{d}^n \sigma}{\mathrm{d}E_1 \mathrm{d}E_2 \ldots \mathrm{d}E_n}$$

Not Only:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_\mu}$$

Computing ν-Nucleus Cross Sections Is Hard

ν beam energy: 0.5 GeV – 5 GeV

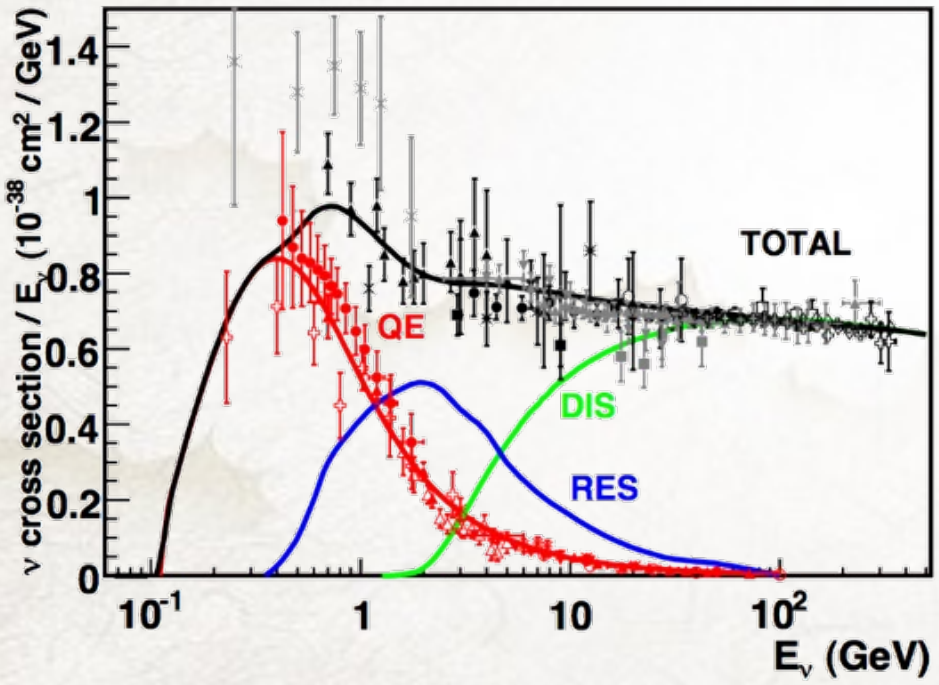


^{12}C, ^{16}O for other experiments

Even ν-Nucleon Cross Sections Are Hard

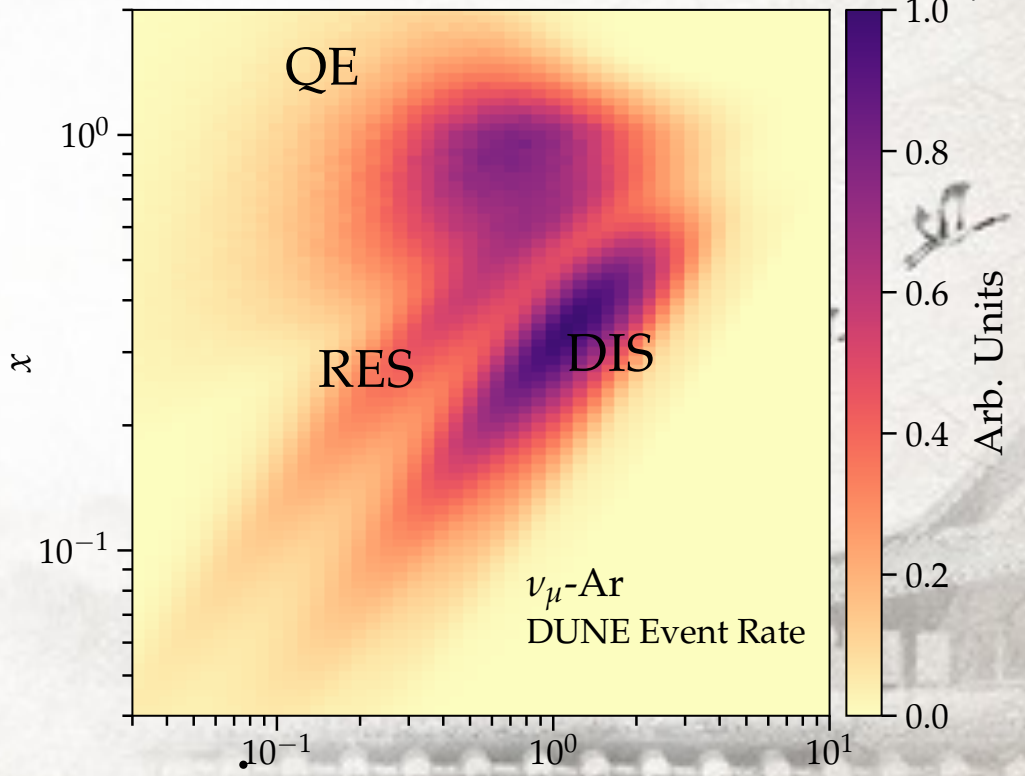
Beam energy: 0.5 GeV – 5 GeV

QE: $\nu_\mu + n \to \mu + p$; RES: $\nu_\mu + n \to \mu + \Delta$; DIS: $\nu_\mu + d \to \mu + u$;



Formaggio & Zeller, 2013
Figure from 1205.2671

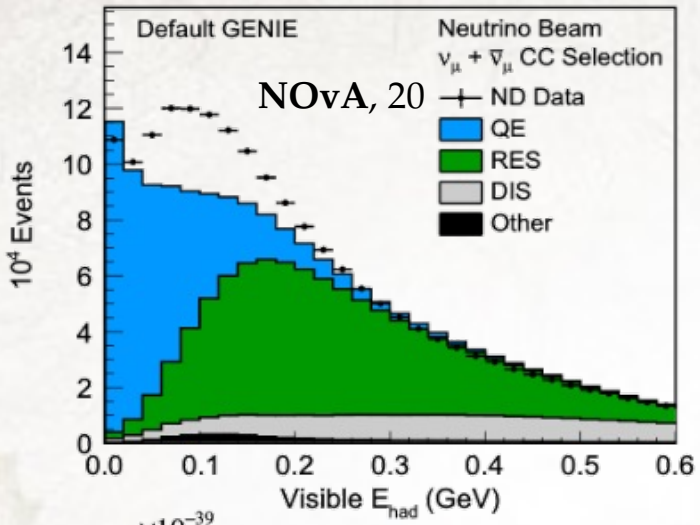
Simulated w/ GiBUU



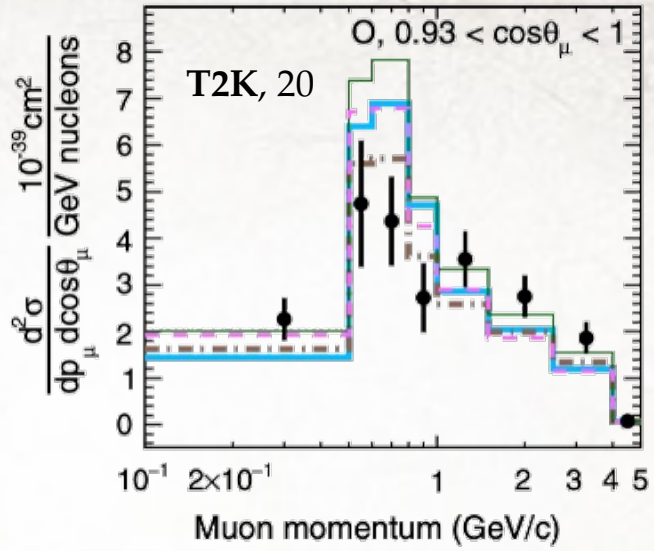
No controlled expansion

$Q^2 \cong 1\ \text{GeV}^2$

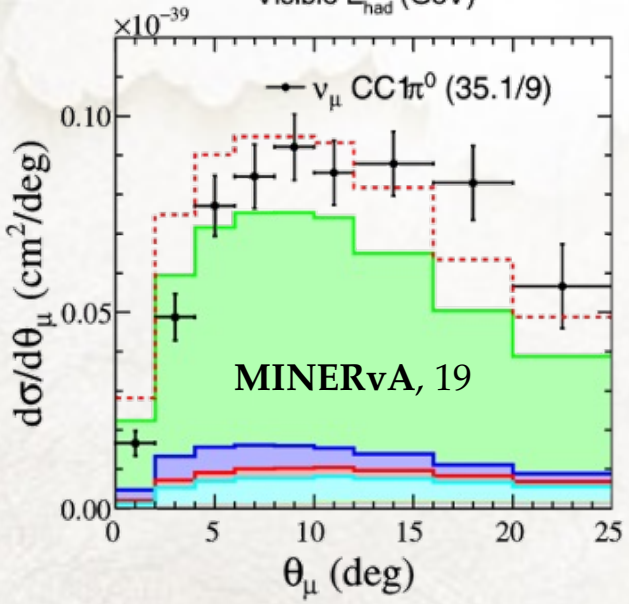
Current Calculations Show Large Discrepancies



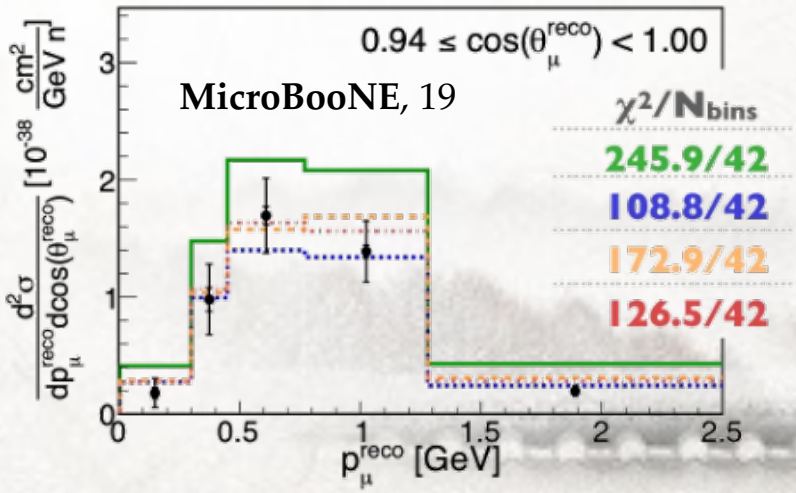
NOvA, 20



T2K, 20



MINERvA, 19



MicroBooNE, 19

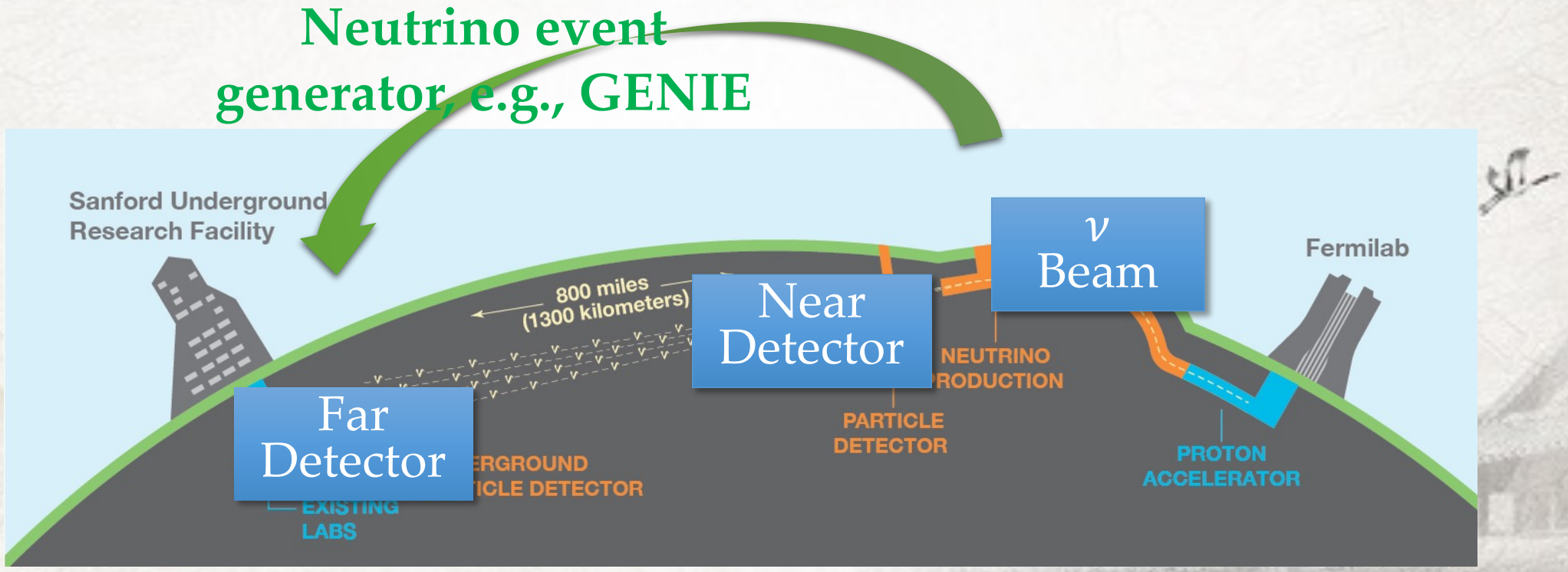
No models / tunes can reproduce all data sets

How do cross section predictions impact physics searches?

The current experimental strategy

How Are Cross Section Uncertainties Dealt with?

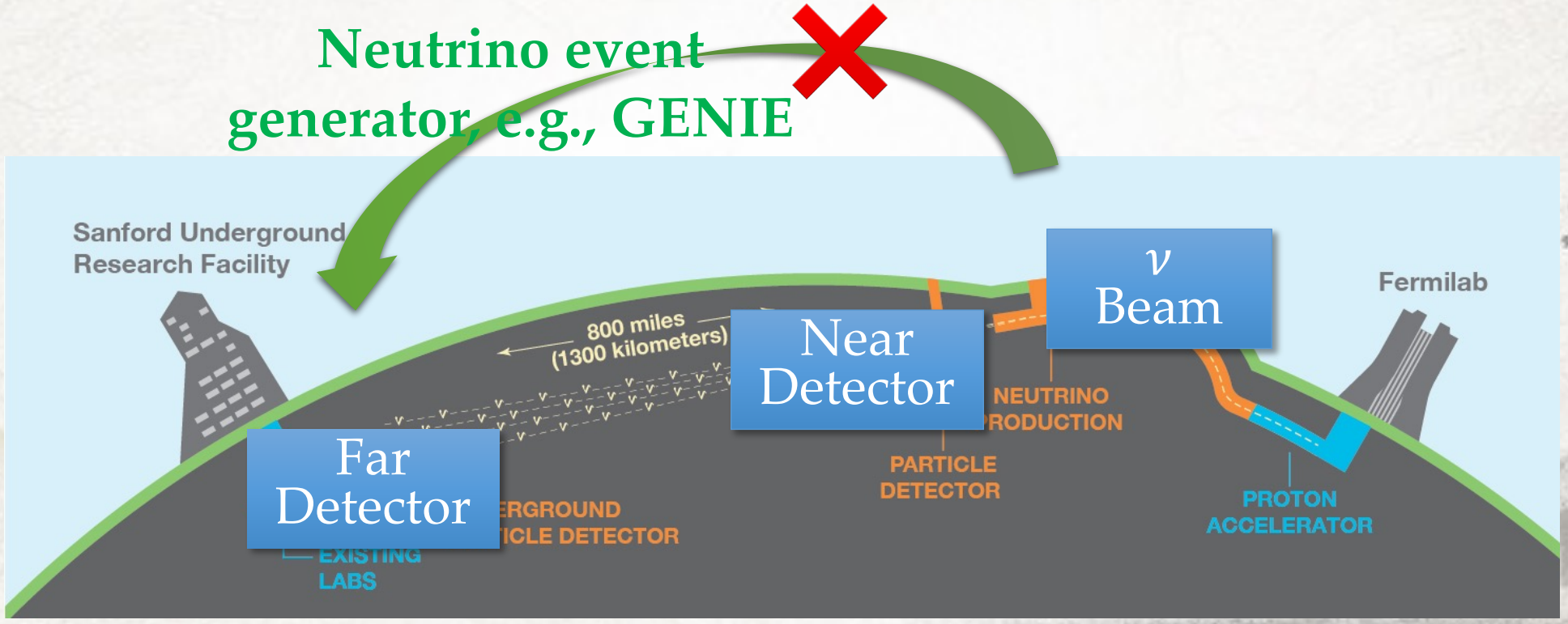
Near detector tuning



DUNE, 15

How Are Cross Section Uncertainties Dealt with?

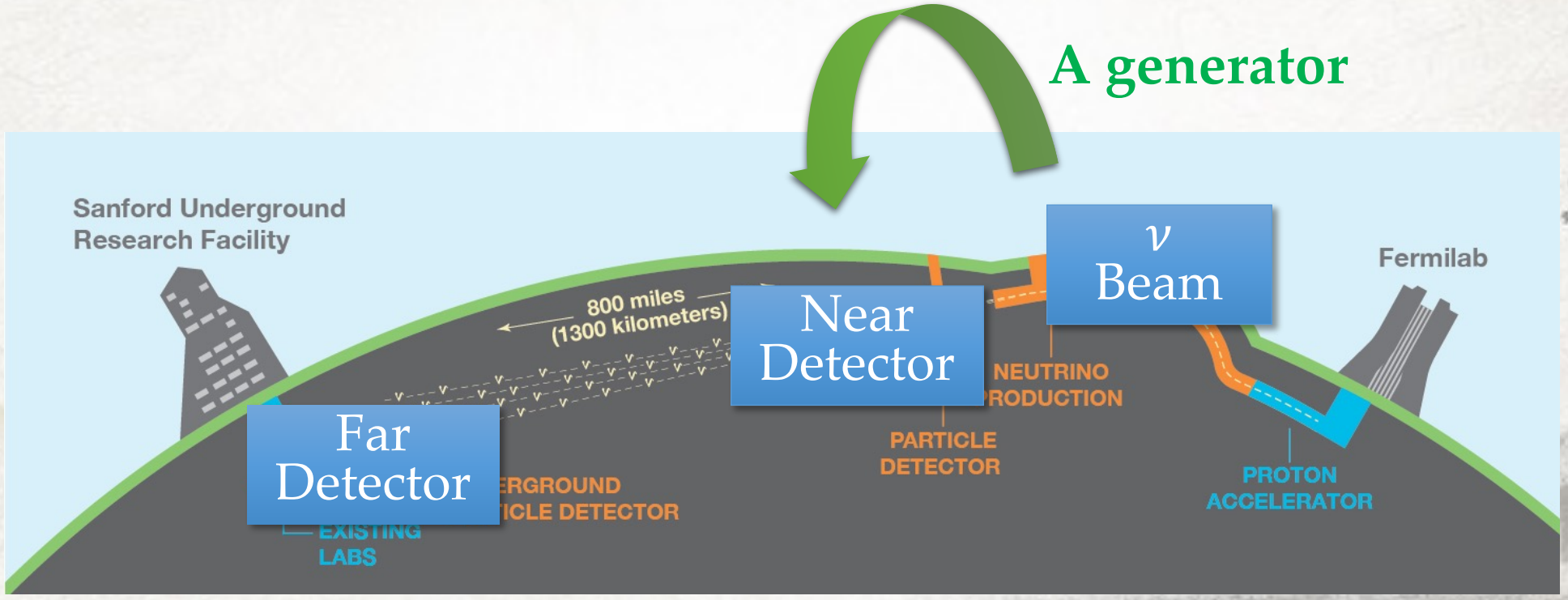
Near detector tuning



DUNE, 15

How Are Cross Section Uncertainties Dealt with?

Near detector tuning



DUNE, 15

How Are Cross Section Uncertainties Dealt with?

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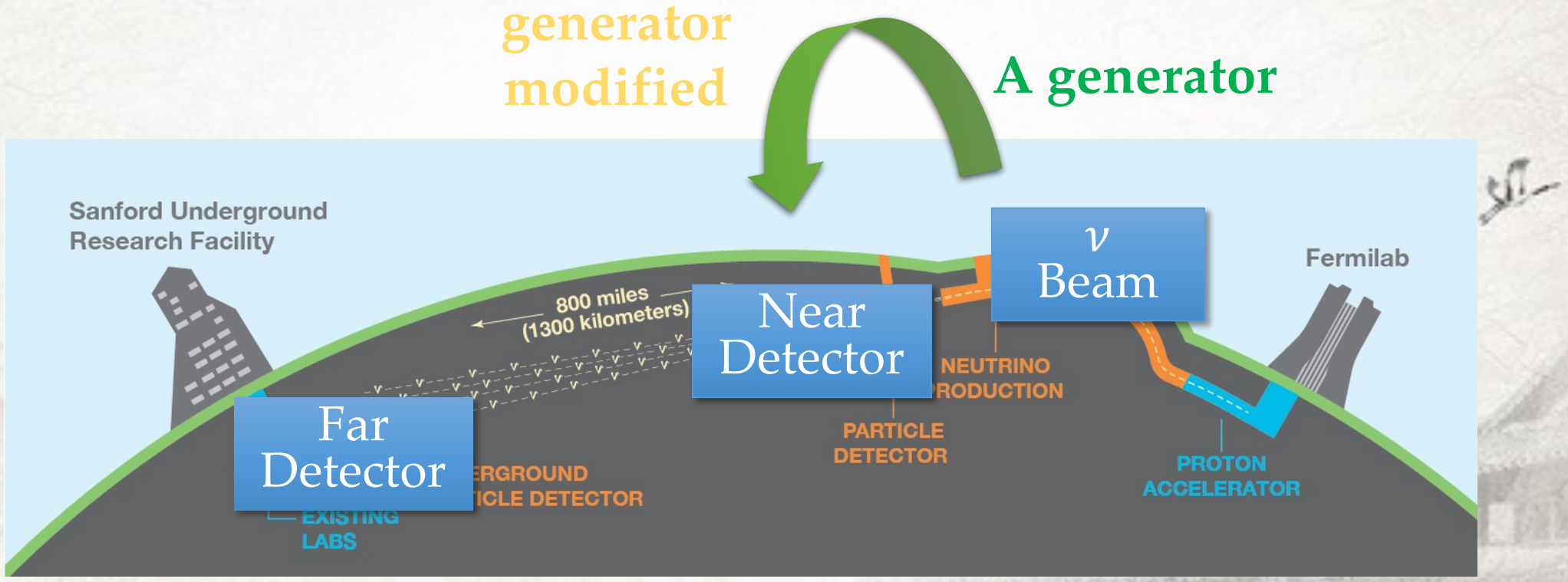
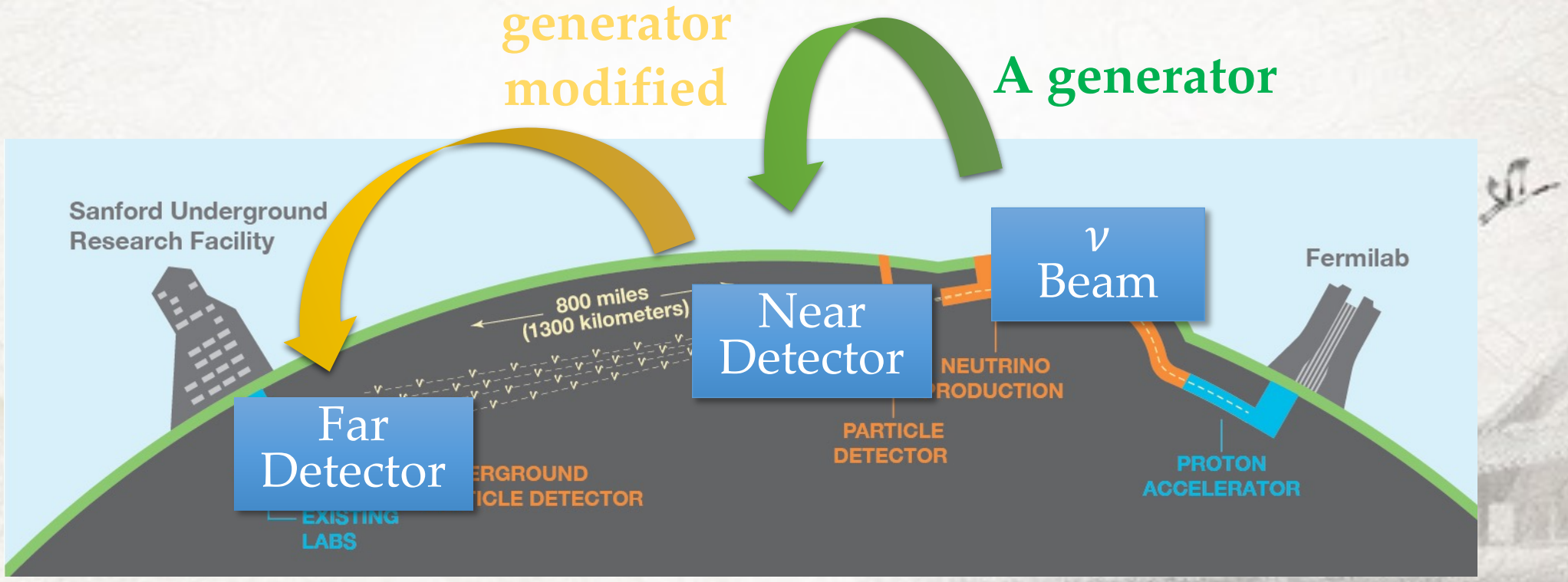


DUNE, 15

How Are Cross Section Uncertainties Dealt with?

Near detector tuning



DUNE, 15

Tuning significantly impacts how cross section predictions' role in experimental searches

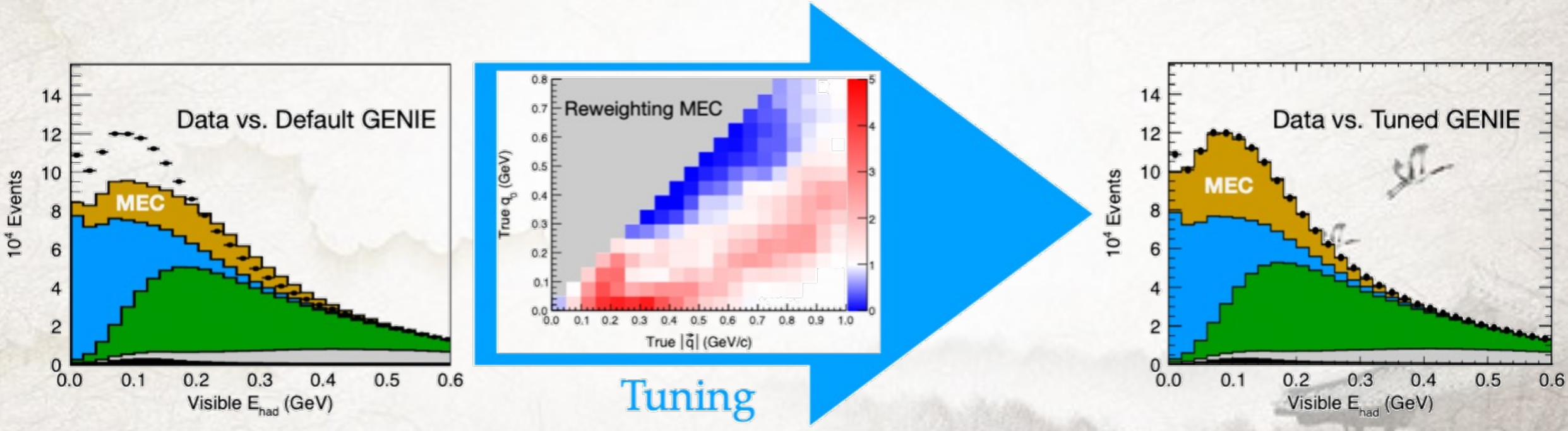
Each experiment has their own tune

Most experimental tunes are not public

The Example We Follow: NOvA Tuning Procedure

NOvA 2020
2006.08727

The main step: MEC tune



Large changes to MEC cross sections

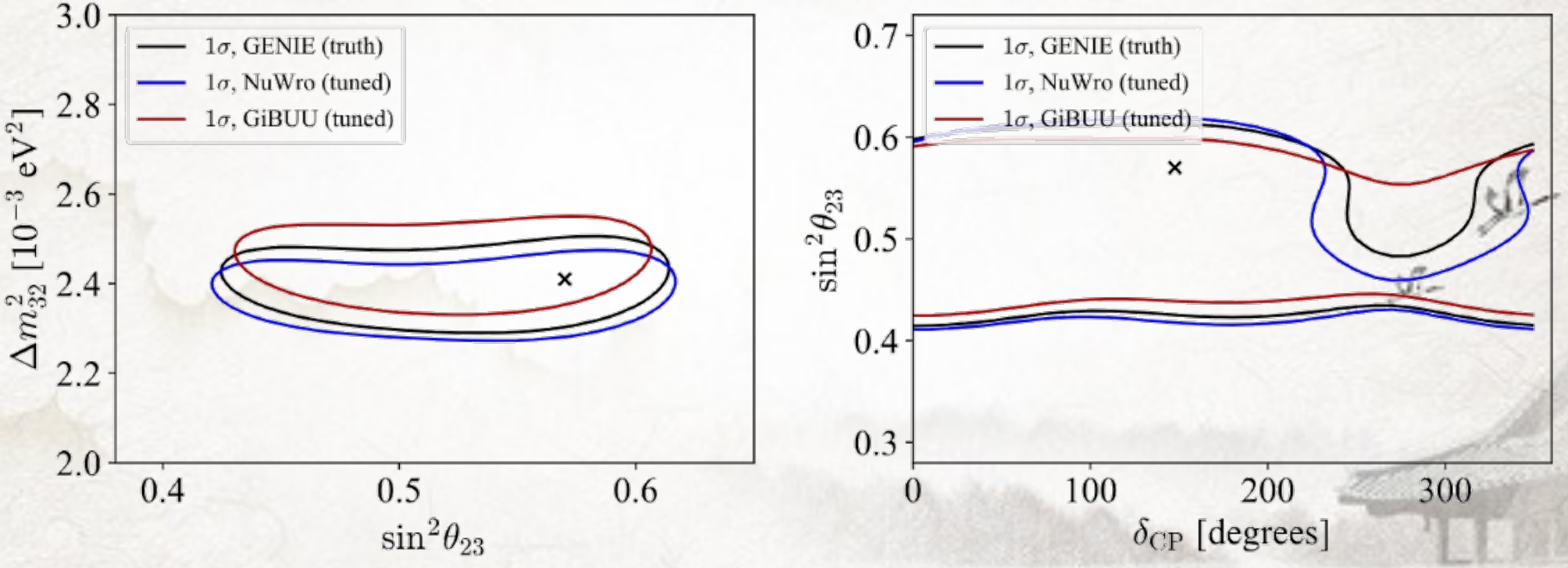
Added many unphysical degrees of freedom

Impact of cross section mis-modeling on physics searches

Standard Oscillation Analysis, Mock NOvA

Coyle, SL, Machado, 2025
2502.19467

Assuming cross section mismodeling is the differences between event generators

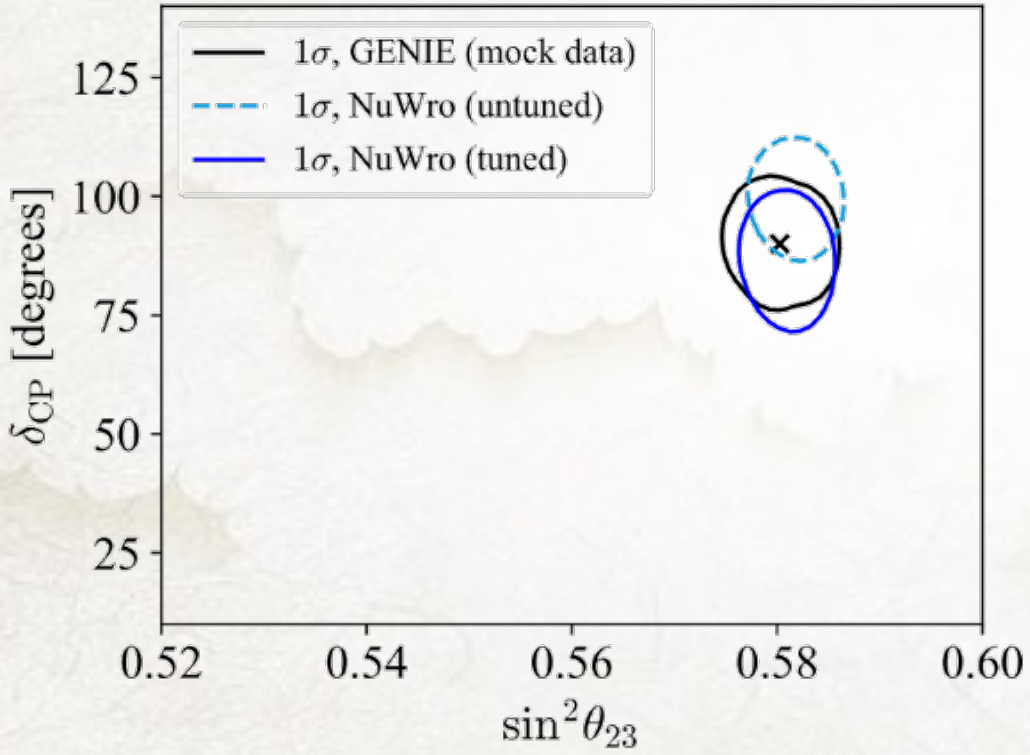


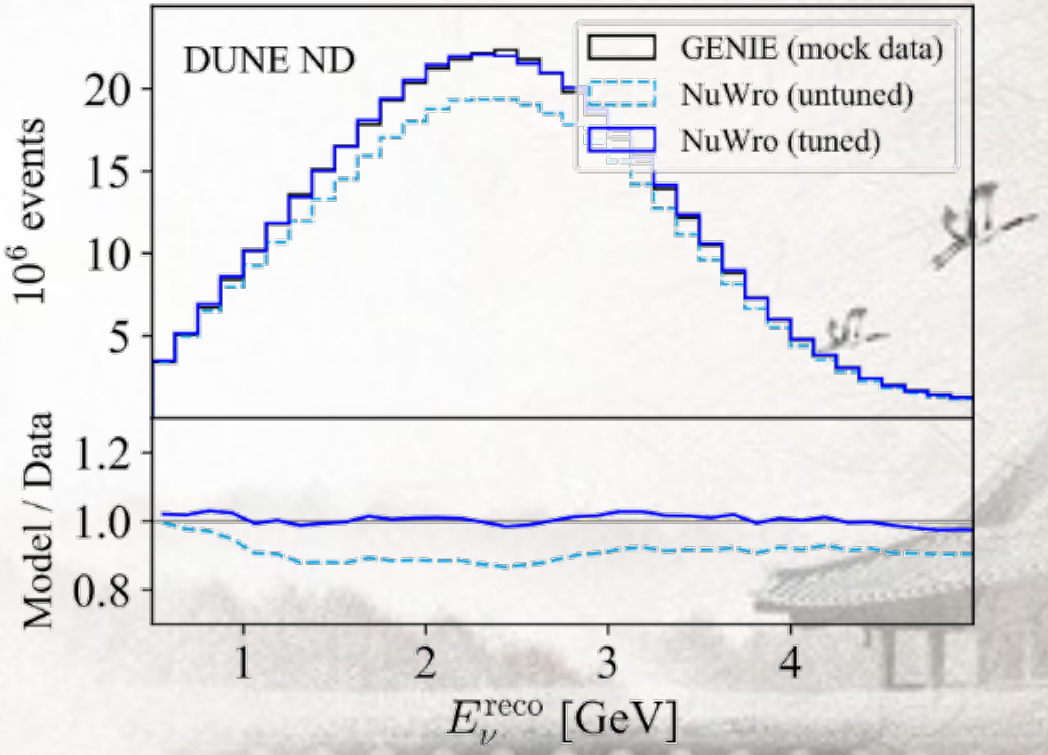
As expected: current experiments are statistically dominated. Cross section-related systematics are not crucial, with and without tuning

Standard Oscillation Analysis, Mock DUNE

Coyle, SL, Machado, 2025
2502.19467

Generate data using GENIE, analysis with NuWro



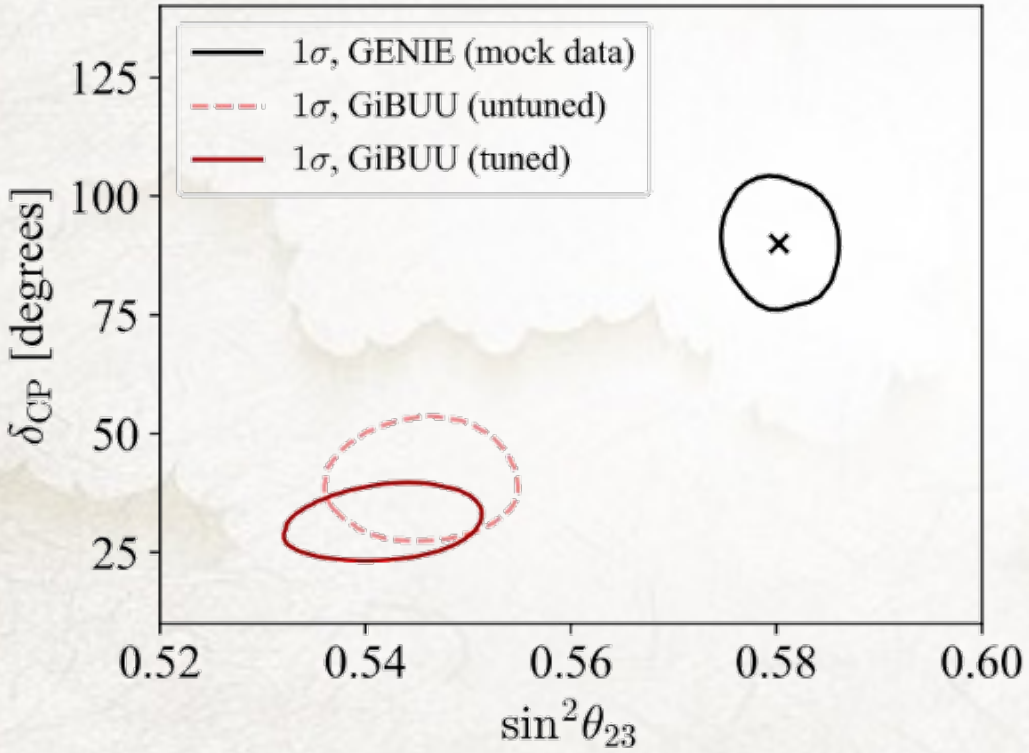


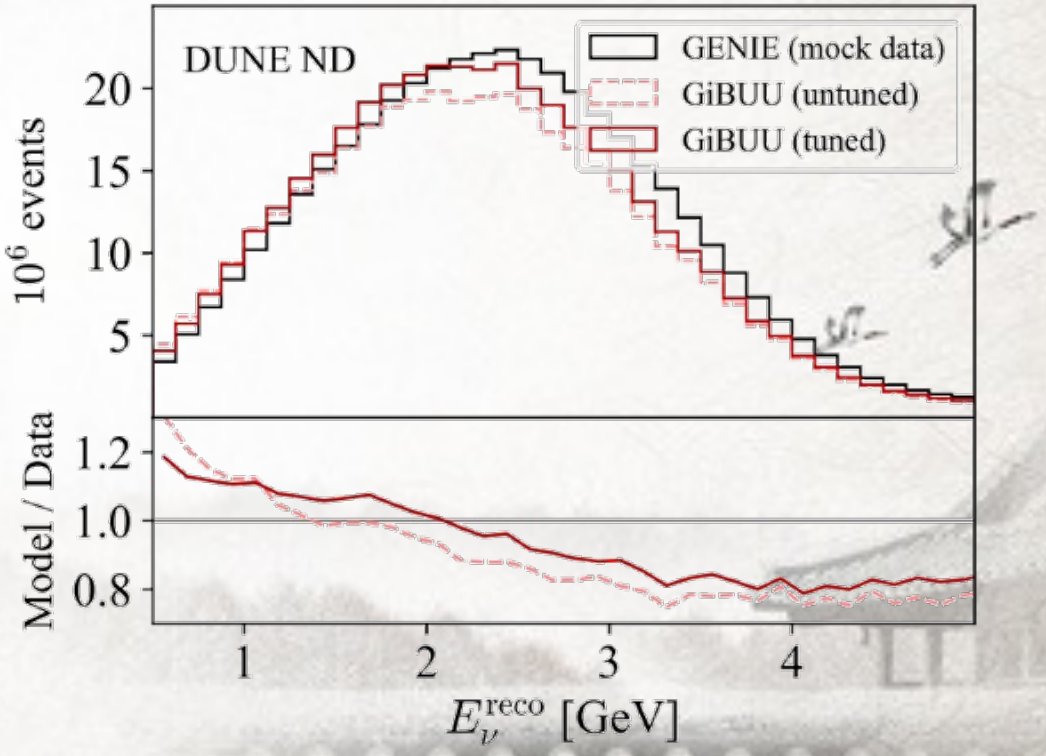
NuWro and GENIE differences are "small" for this analysis; tuning improves the result slightly

Standard Oscillation Analysis, Mock DUNE

Coyle, SL, Machado, 2025
2502.19467

Generate data using GENIE, analysis with GiBUU



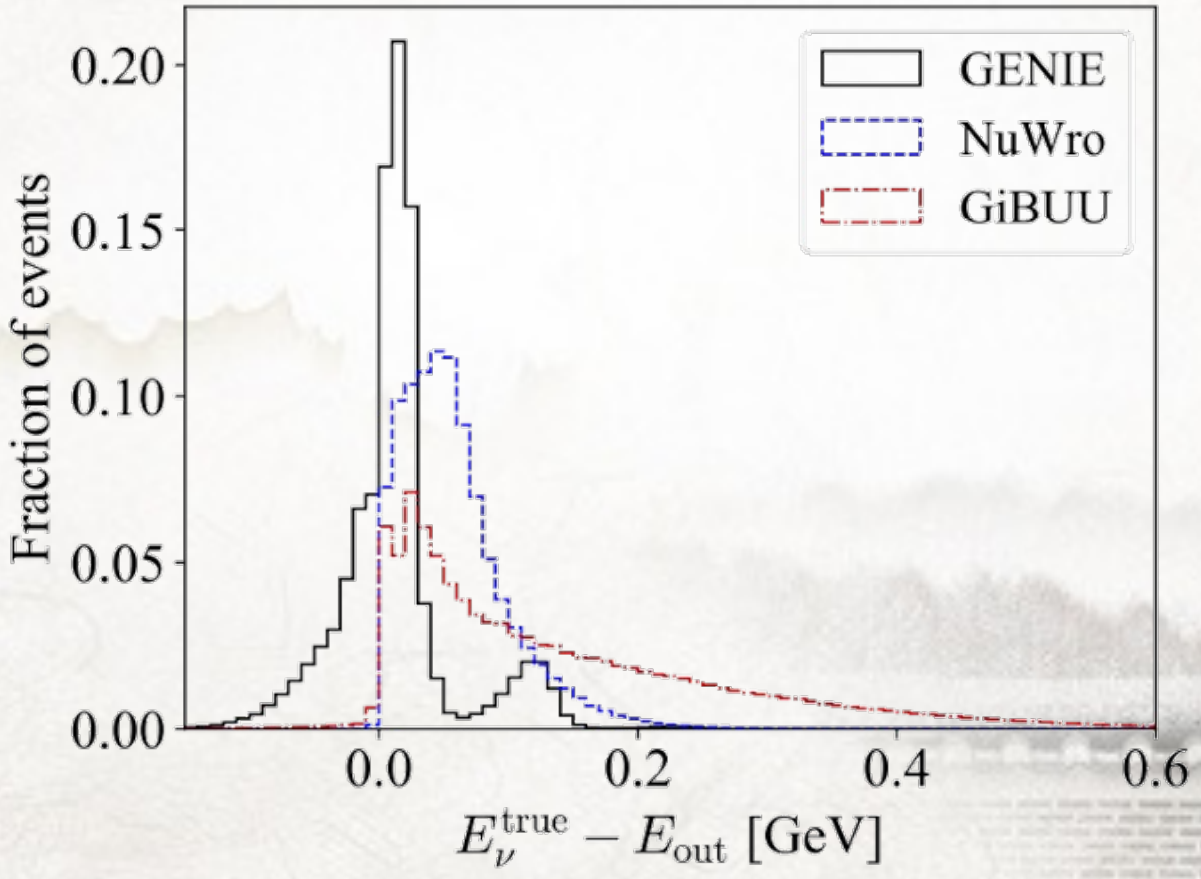


GiBUU and GENIE differences are "huge" for this analysis; tuning does NOT improve the result

Why so different?

Coyle, SL, Machado, 2025
2502.19467

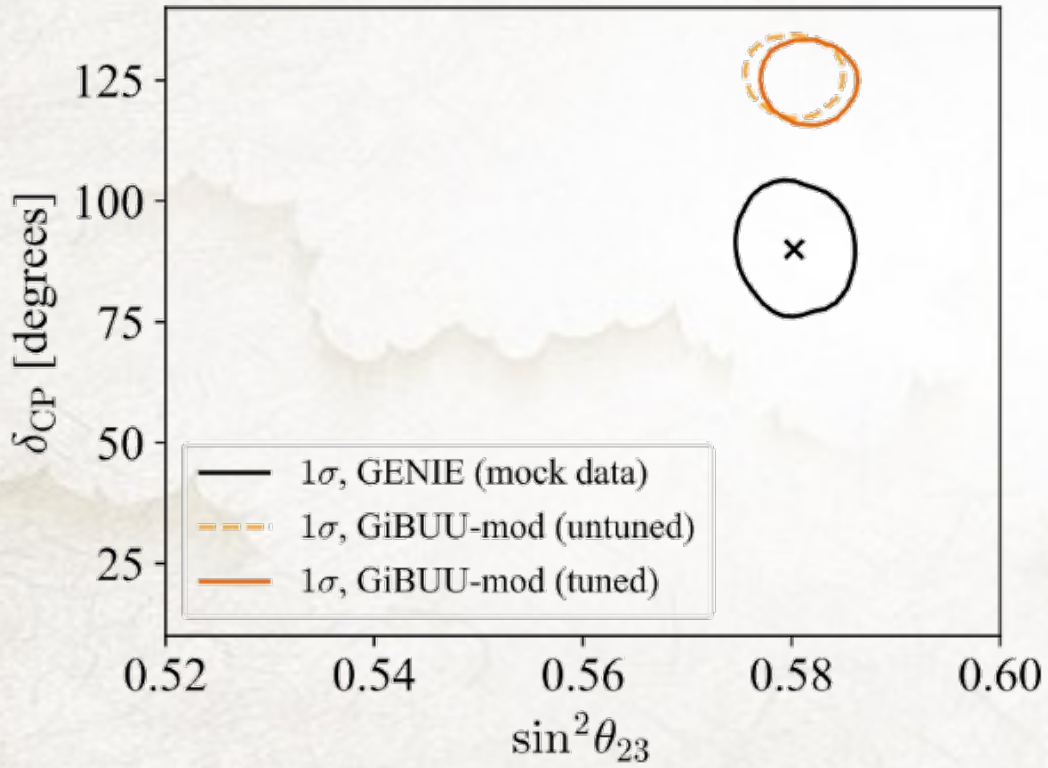
The biggest impact seems to be from apparent energy balance

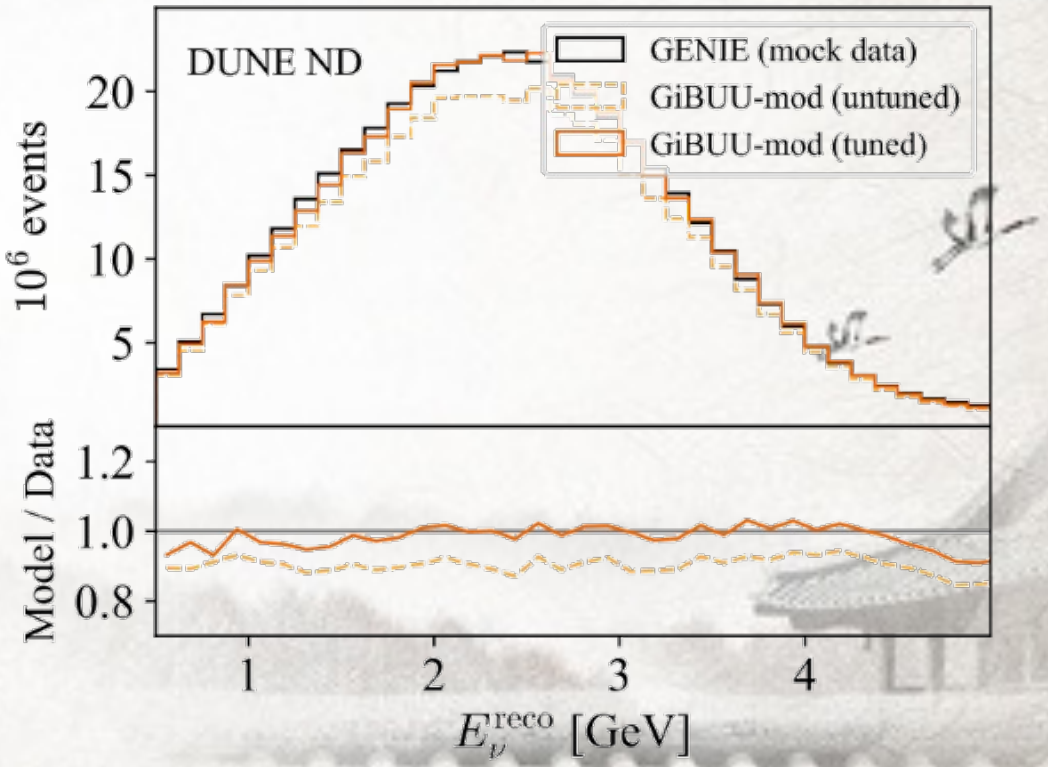


What If We Modify GiBUU A Little?

Coyle, SL, Machado, 2025
2502.19467

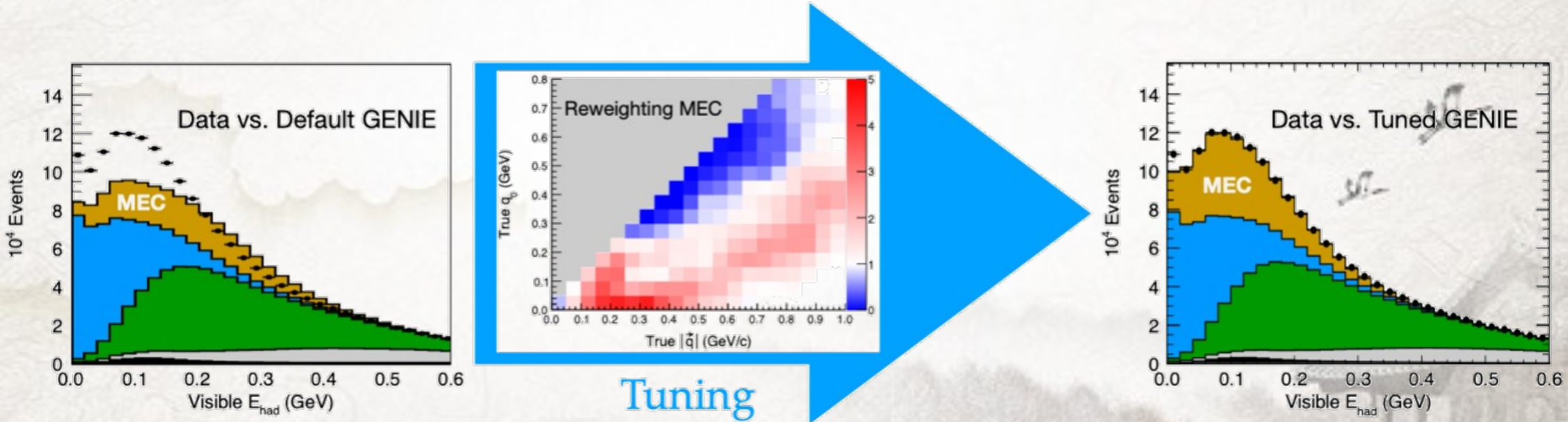
Generate data using GENIE, analysis with GiBUU-mod





It is possible to have an apparent good ND tuning but bad oscillation result; PRISM may break the degeneracy

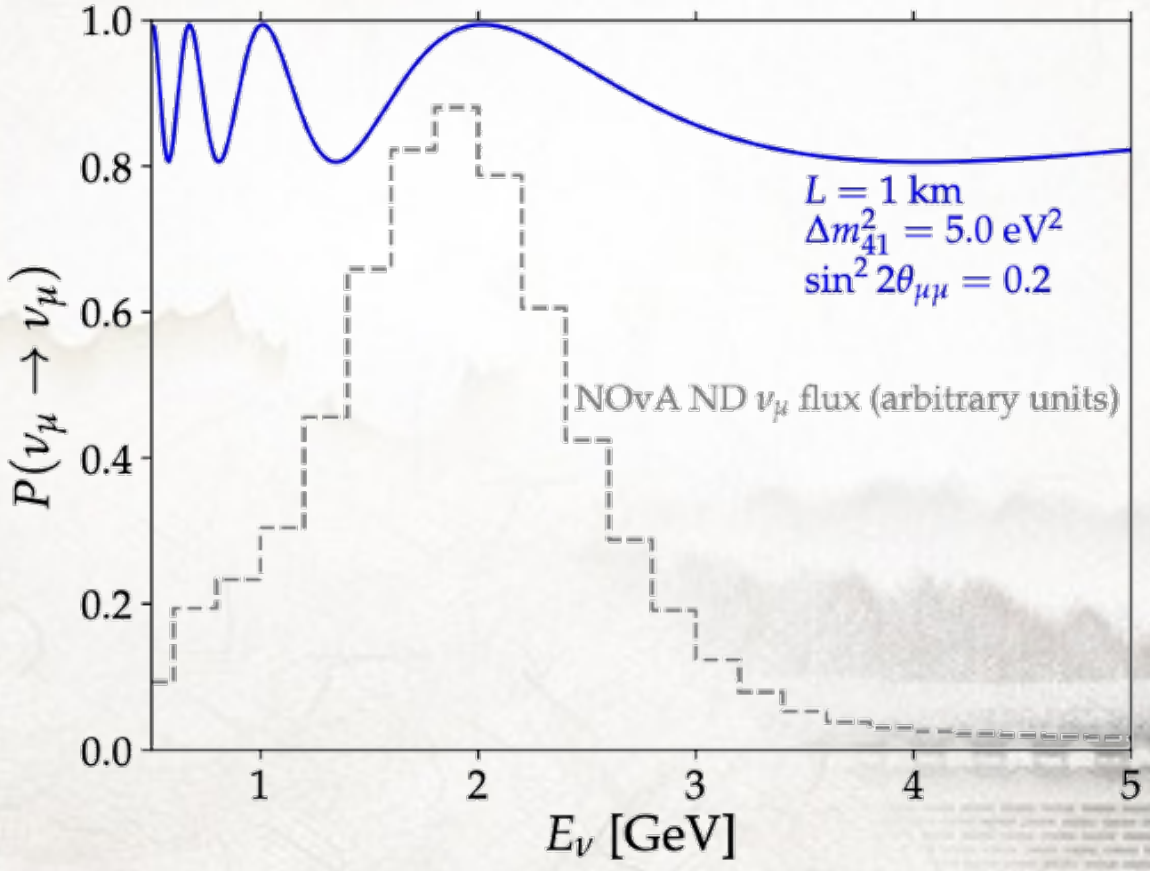
What if there is BSM signal in near detectors?



Case Study 1: Looking for Sterile Neutrinos

Coyle, SL, Machado, 2022
2210.03753

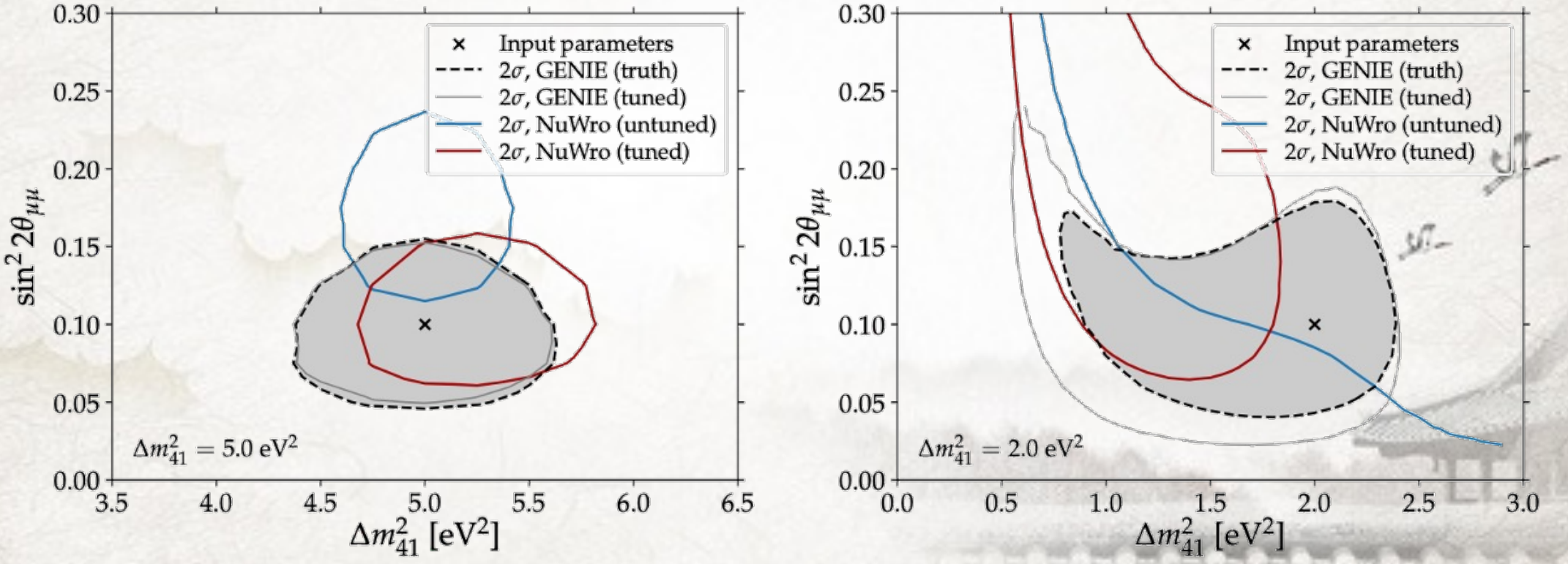
Experimental signature



Sterile Neutrino Results

Coyle, SL, Machado, 2022
2210.03753

Sensitivity regions



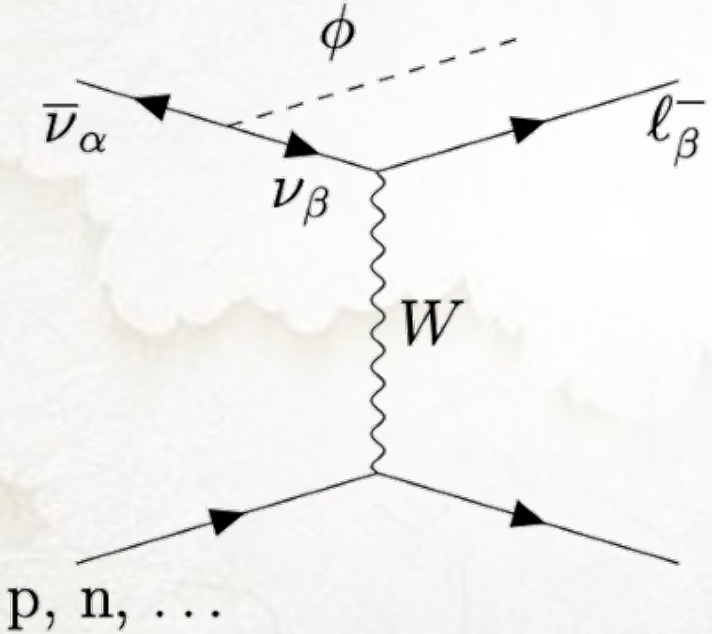
Cross section mis-modeling bias results

Tuning does not entirely fix the issue

Case Study 2: Looking for Neutrinophilic Scalar

Coyle, SL, Machado, 2022
2210.03753

The model

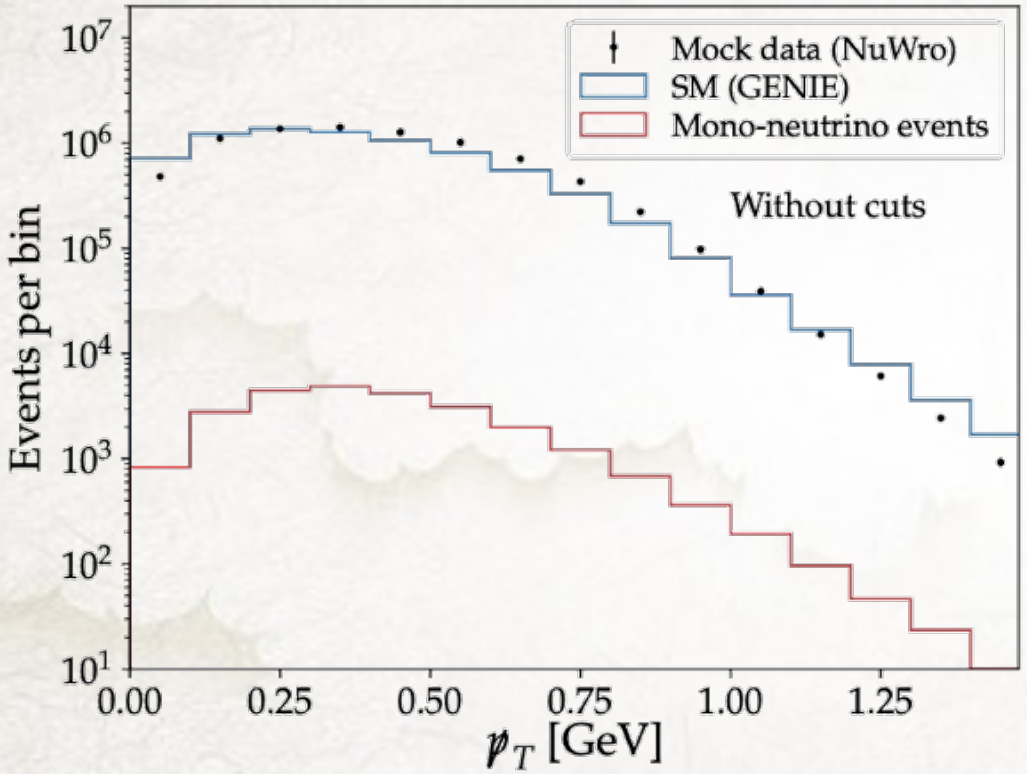


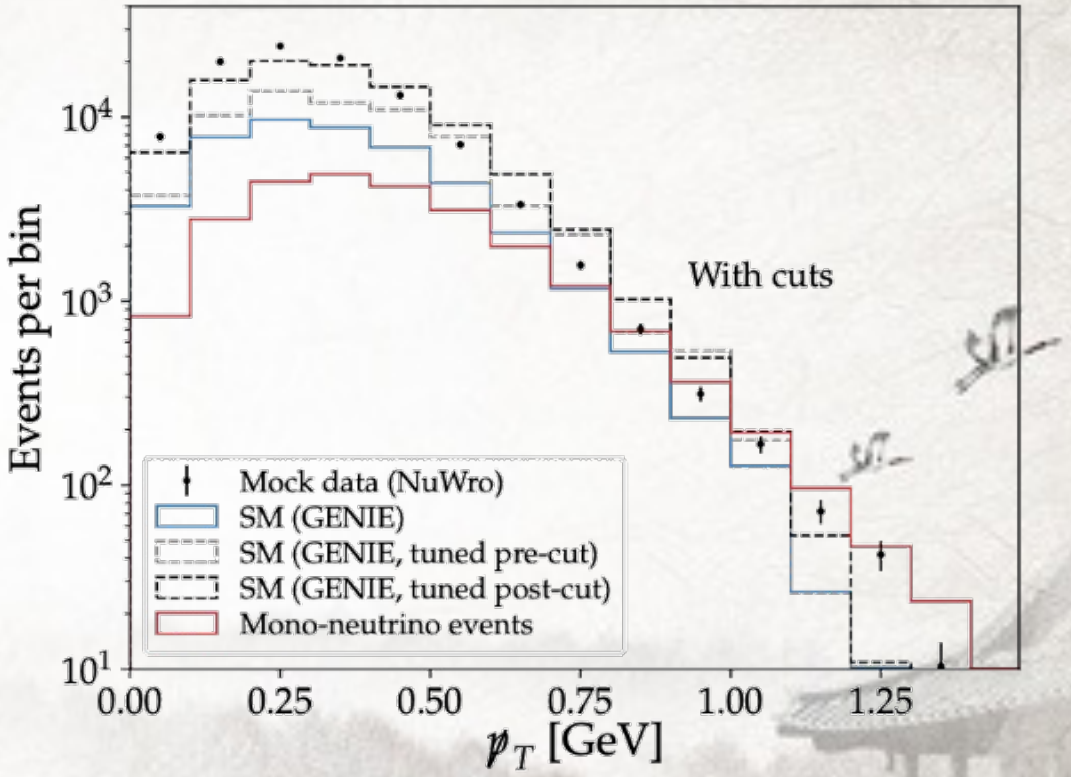
$$\mathcal{O} = \frac{(L_\alpha H)(L_\beta H)}{\Lambda_{\alpha\beta}^2}\phi \to \frac{1}{2}\lambda_{\alpha\beta}\nu_\alpha\nu_\beta\phi$$

Signature: missing p_T

To Cut Or Not To Cut

Coyle, SL, Machado, 2022
2210.03753





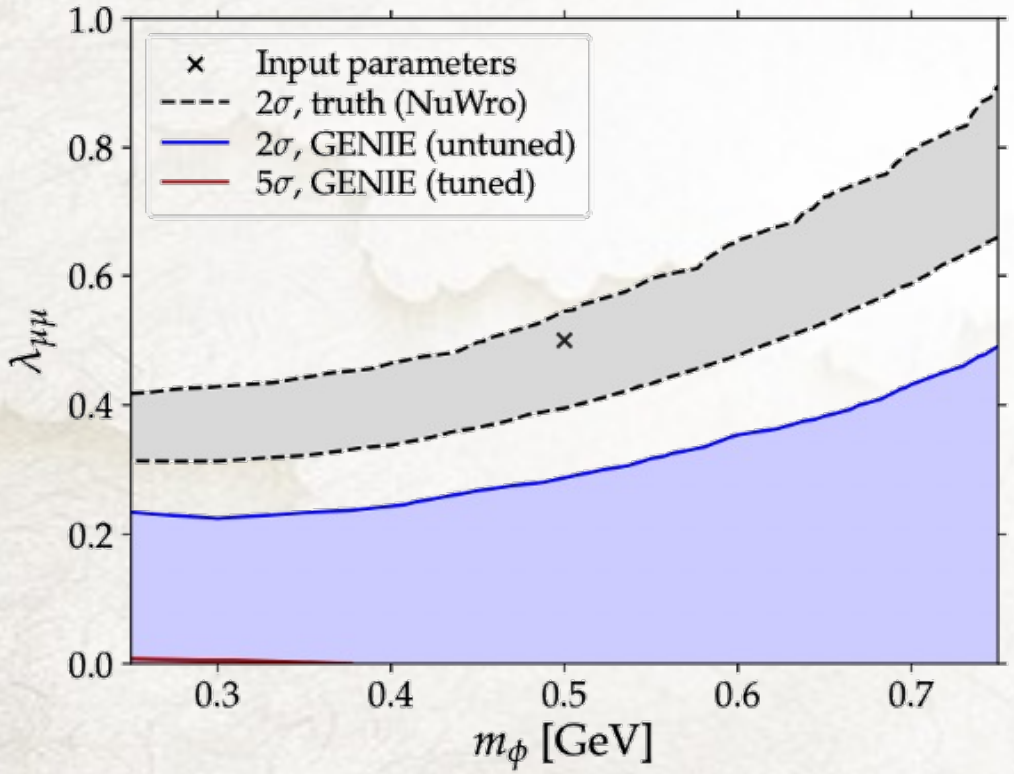
Not cut: background >> signal

Cut: background mis-modeling >> signal

Neutrinophilic Scalar Results

Coyle, SL, Machado, 2022
2210.03753

Sensitivity regions



General lessons

New physics likely lives in a corner of phase space

Even worse cross section uncertainties than integrated over entire phase space

Conclusions

1. GeV neutrino-nucleus scattering is crucial to the success of long-baseline neutrino experiments

2. Experiments tune cross section models to ND data

3. Experimental tunes are not sufficient. We need robust theoretical predictions of the exclusive cross sections AND uncertainties