Experiments needs from theory: *neutrino-nucleus cross sections*

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Support from:
U.S. Department of Energy award
DE-SC0015903

Office of Science
U.S. Department of Energy

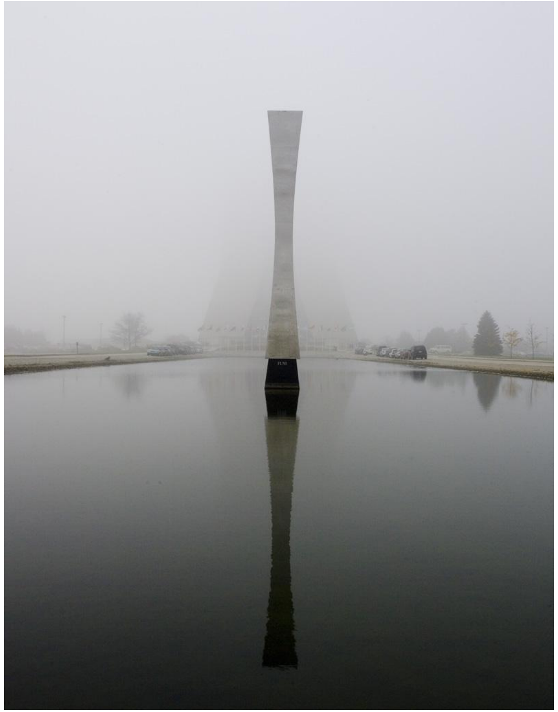
Thank you for a lovely workshop! and for support to attend

Pandemic challenge: difficulty seeing the landscape for what it is.

It has been great to be here **with** people

What follows is my view + informal polling of workshop participants. Themes:

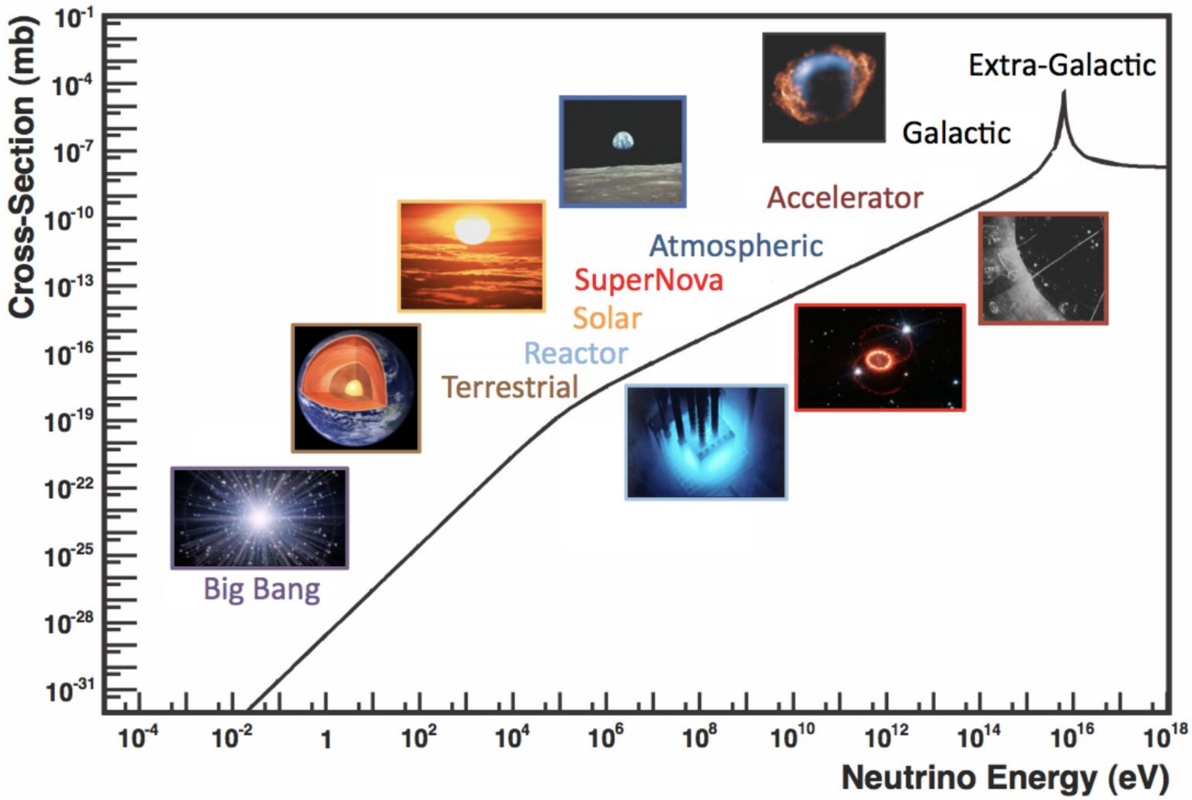
1. Neutrino-nucleus cross sections needs are complex and varied
2. Solutions require sustained support of, and communication, collaboration between, experimenters and theorists



Credit: Valerie Higgins, Twitter - https://twitter.com/ValerieH137/status/1453408717156884486

The scale of neutrino interactions

[Rev. Mod. Phys. 84, 1307 (2012)]



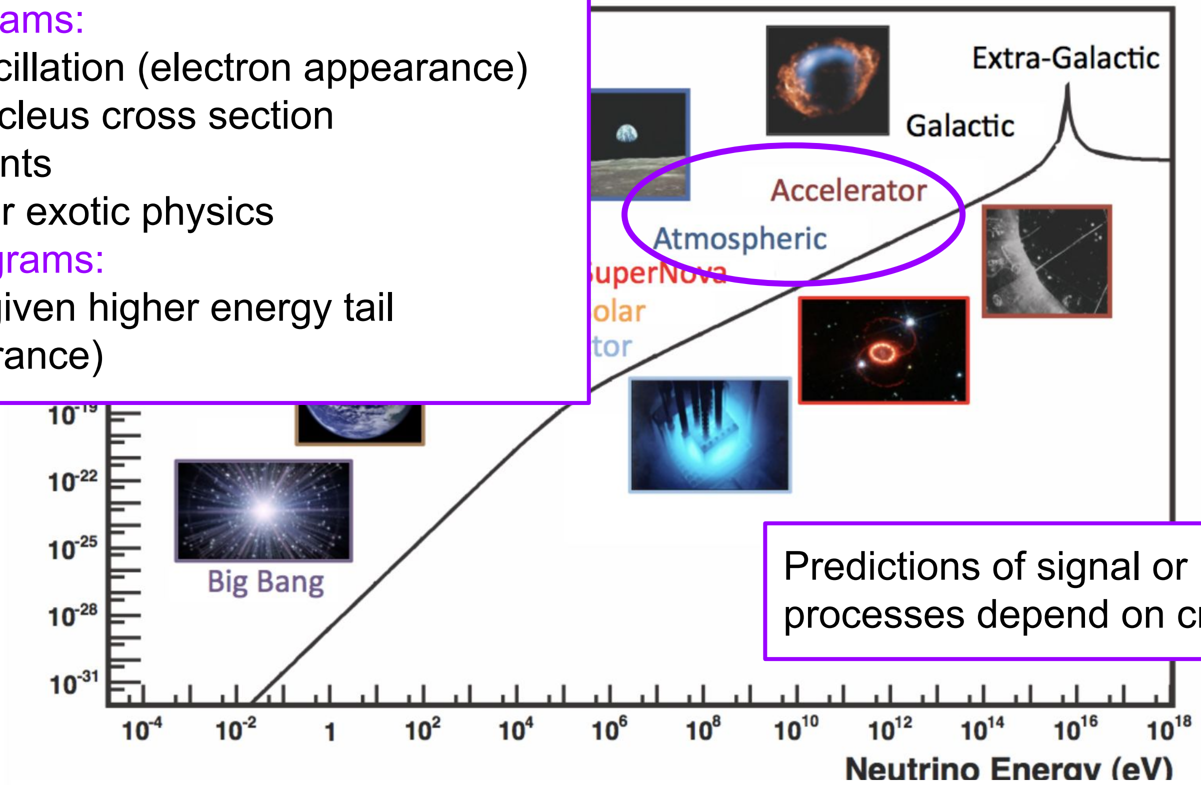
The scale of neutrino interactions: intermediate, ~0.1-20 GeV

Accelerator programs:

- Neutrino oscillation (electron appearance)
- Neutrino-nucleus cross section measurements
- Searches for exotic physics

Atmospheric programs:

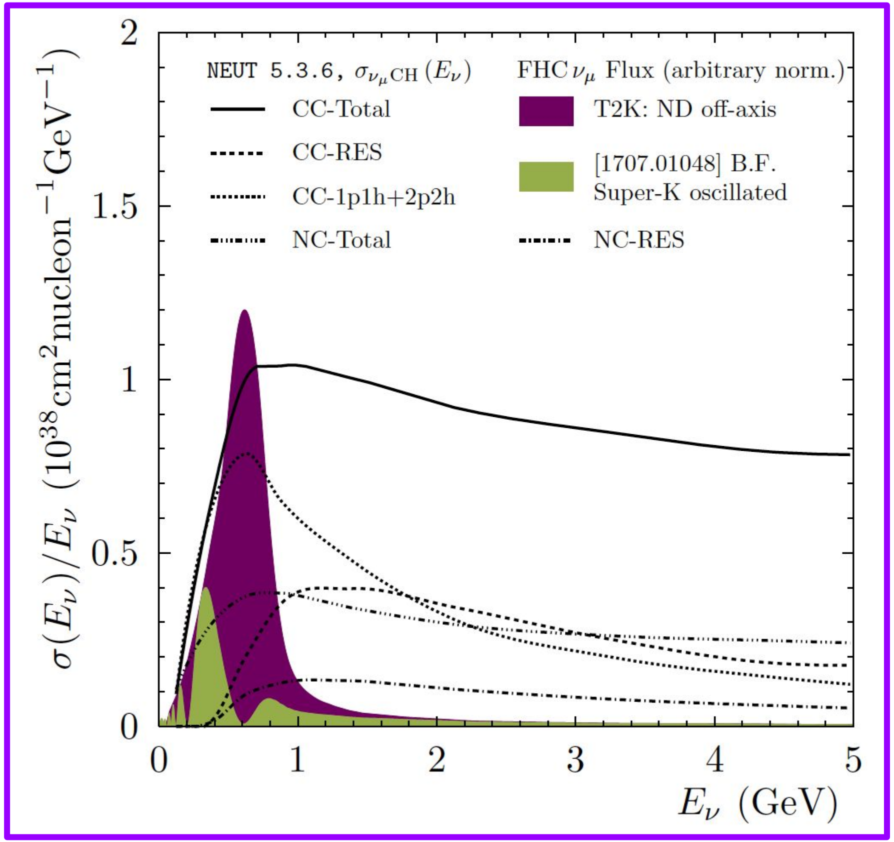
- Same, but given higher energy tail (tau appearance)



Predictions of signal or background processes depend on cross section

$$N_{FD} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{FD}P(\nu_\mu \rightarrow \nu_e)$$

Why do interactions matter to experiments?



Example: Tokai-to-Kamioka (T2K) experiment

Basic challenges:

- Need prediction across energy

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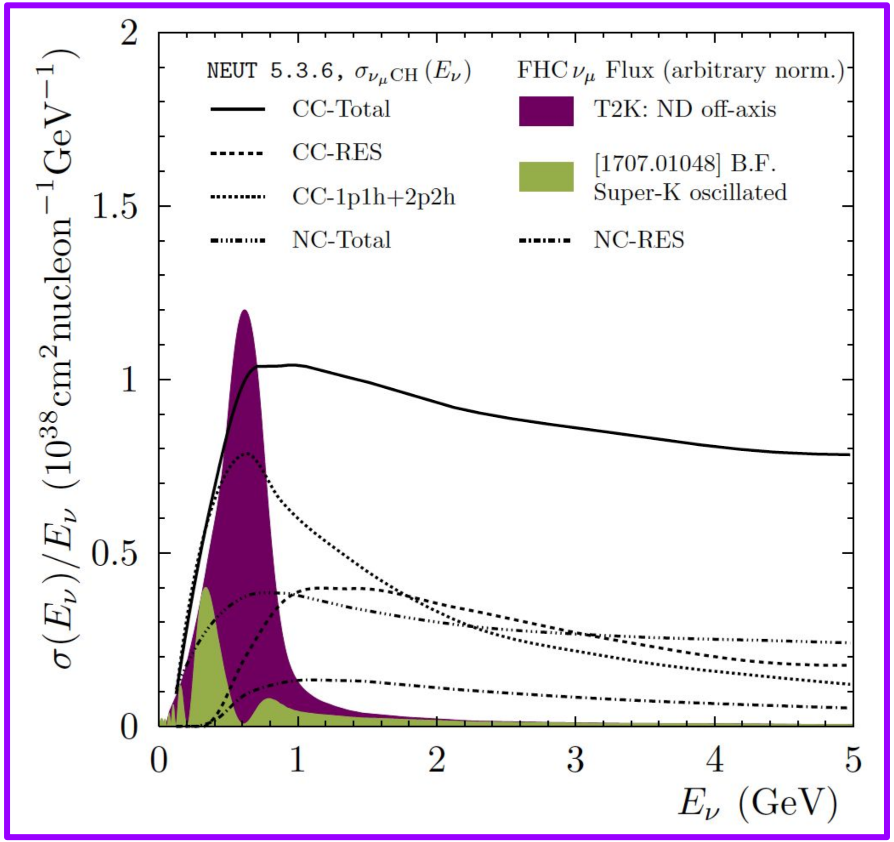

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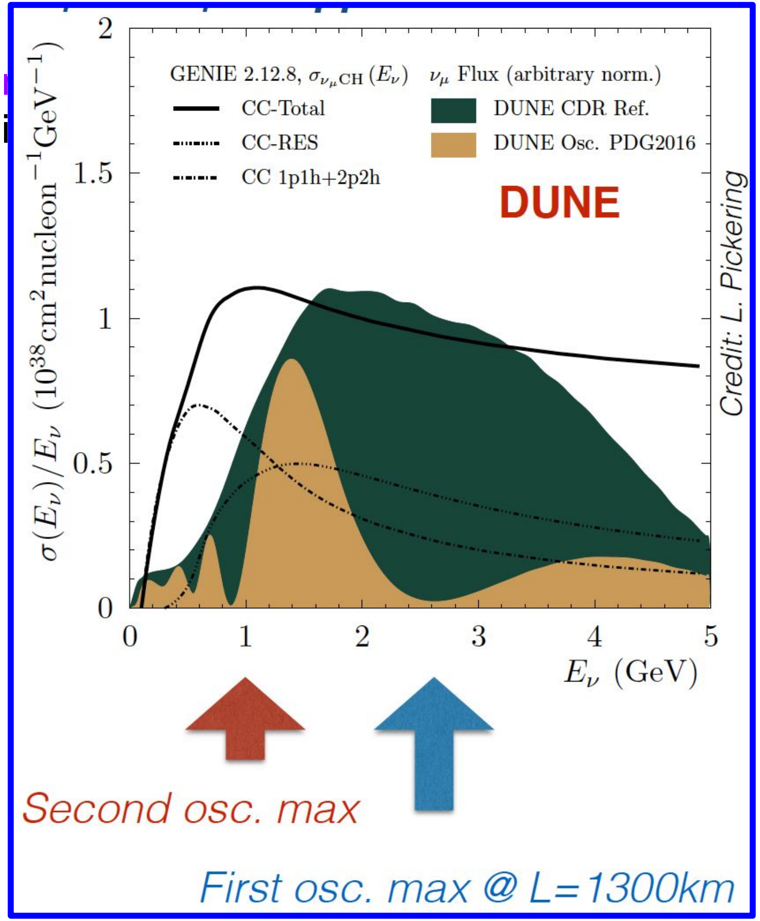

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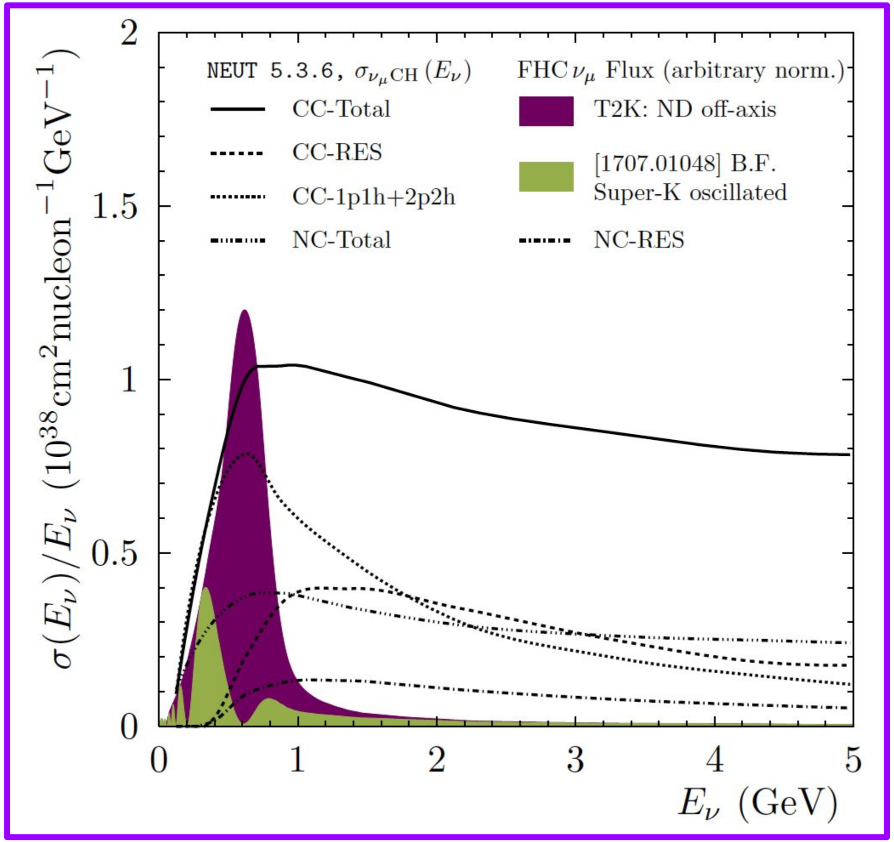

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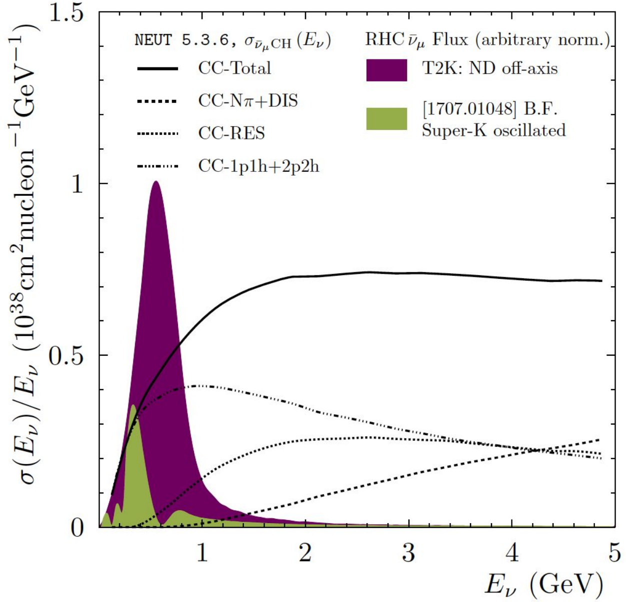

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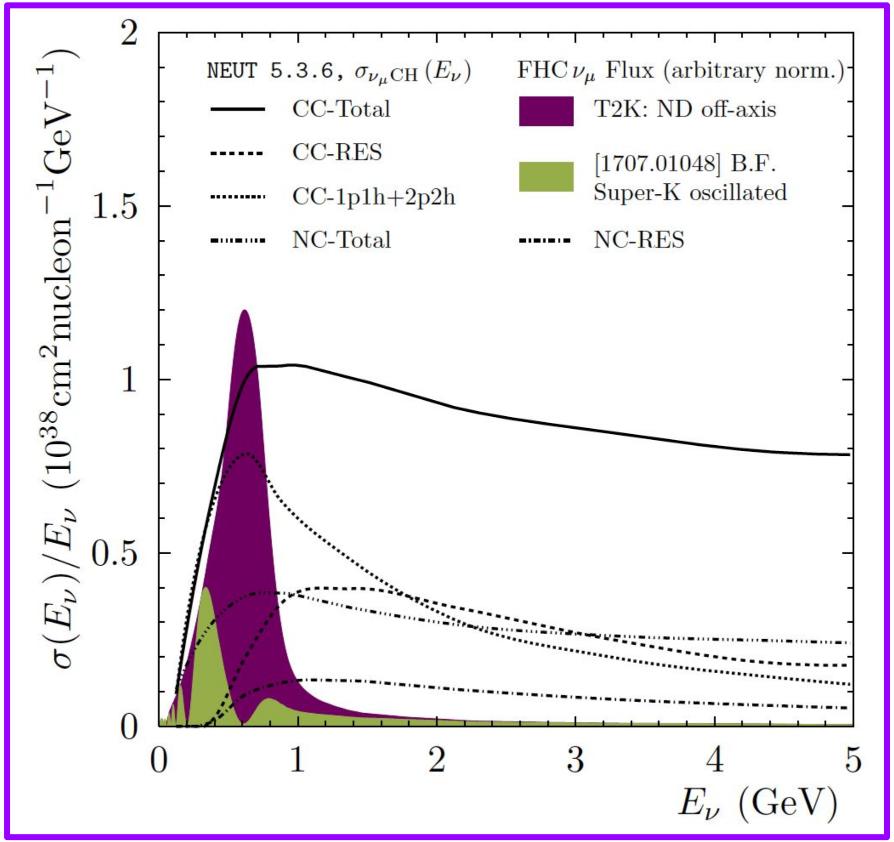

Example: Tokai-to-Kamioka (T2K) experiment

Basic challenges:

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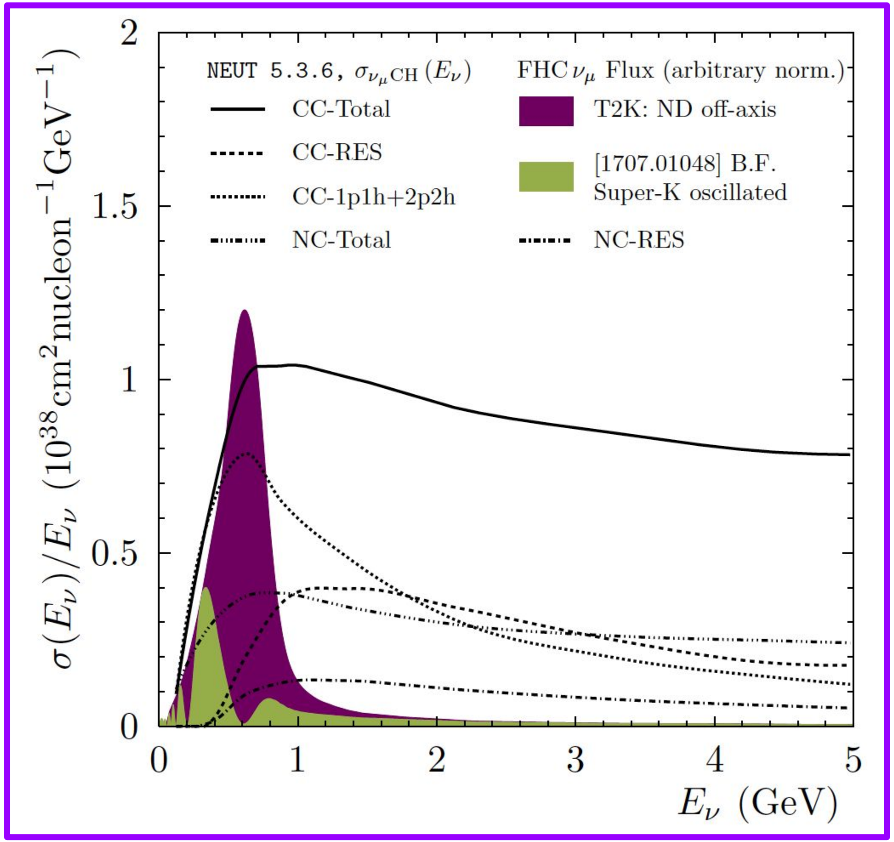
- Event rates are a mix of processes
  - Need CC/NC

Why do interactions matter to experiments?

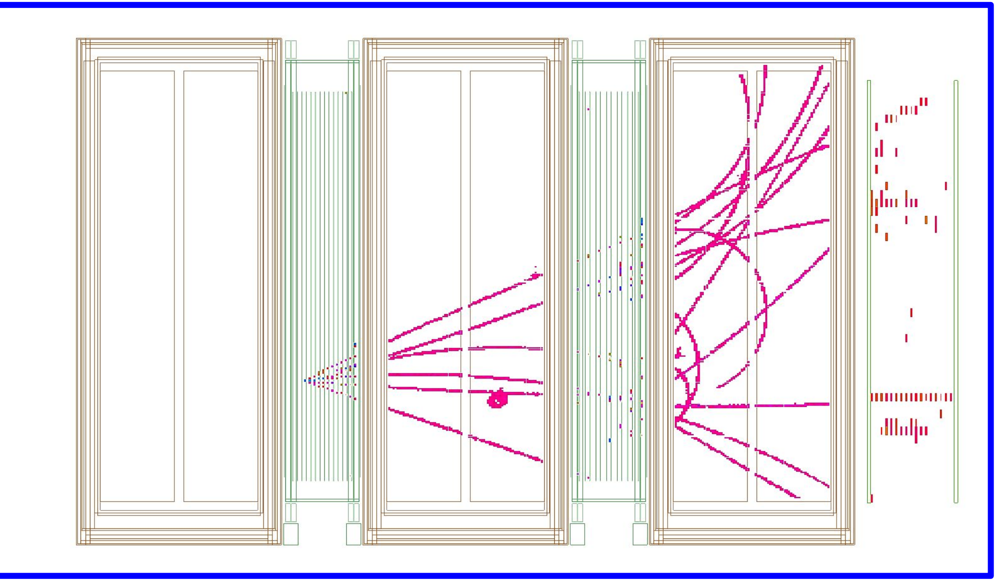


Example: Tokai-to-Kamioka (T2K) experiment

Basic challenges:

- Need prediction across energy
- Need all flavors (neutrino, antineutrino, electron, muon, tau)
- Event rates are a mix of processes
  - Need CC/NC
- **Need exclusive measurements**

Why exclusive?



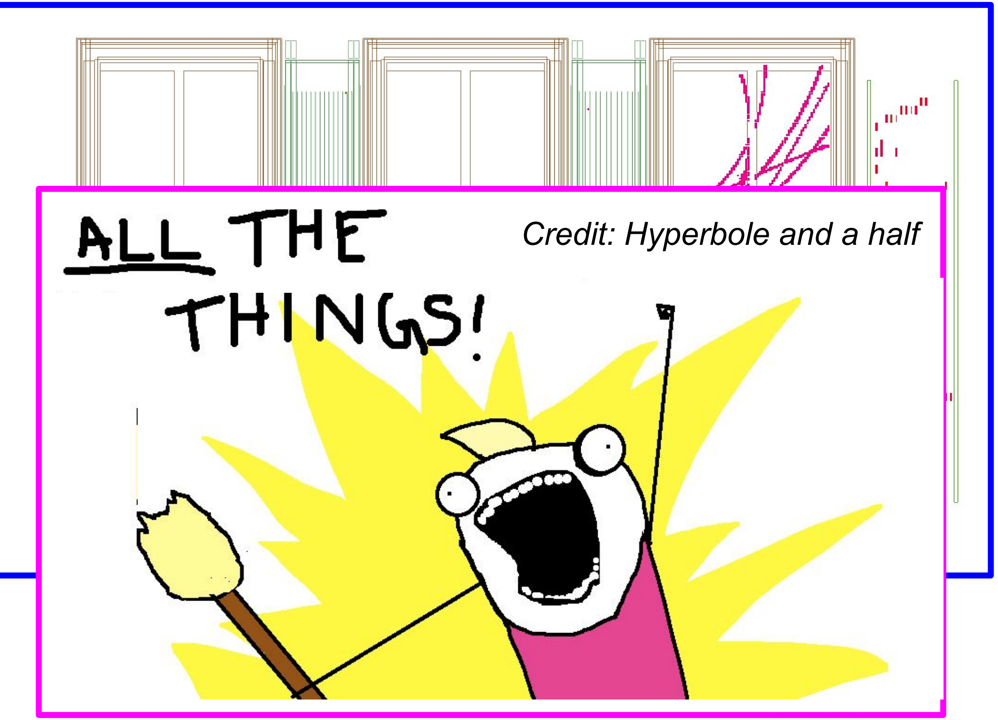
Example of a multiparticle shower,
T2K ND280 detector

Models predict final state particles, and associate those to the correct final state

The cross section model is important for **efficiency** and for the **true-reco relationship** (R) and energy estimators

$$N_{FD}^{\alpha\to\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

Why exclusive?



Example of a multiparticle shower, T2K ND280 detector

Models predict final state particles, and associate those to the correct final state

The cross section model is important for **efficiency** and for the **true-reco relationship** (R) and energy estimators

… oh and I also want multiple target materials (H, C, O, Ar…)

$$N_{FD}^{\alpha\rightarrow\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

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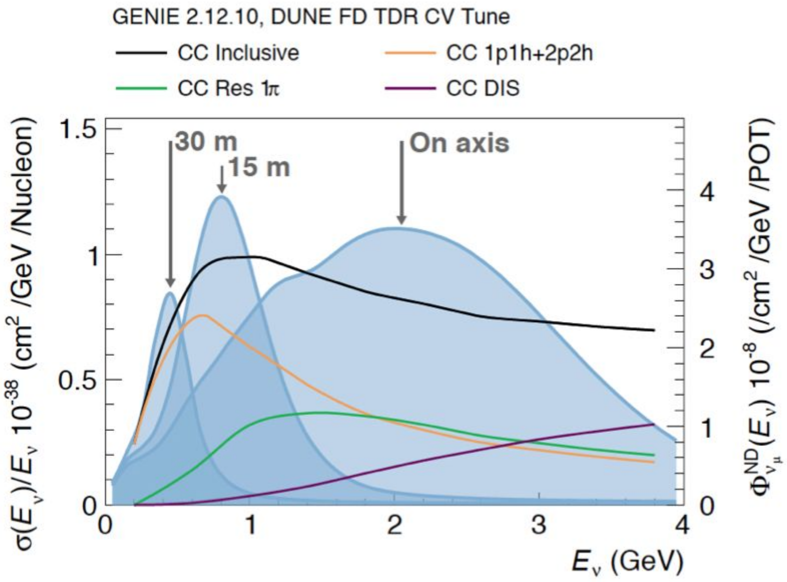
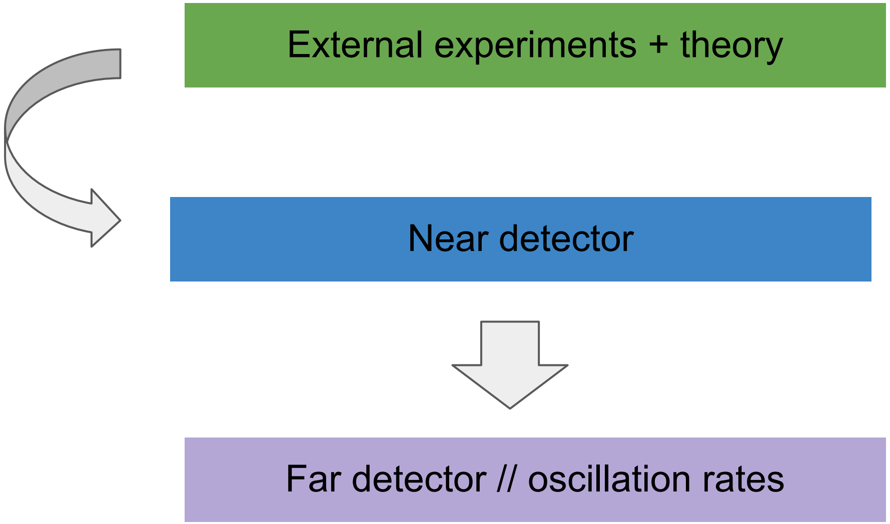
$$N_{ND}^{\alpha} E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\alpha^i(E_{true}) \times \epsilon_\alpha(E_{true}) \times R_i(E_{true}; E_{reco})$$

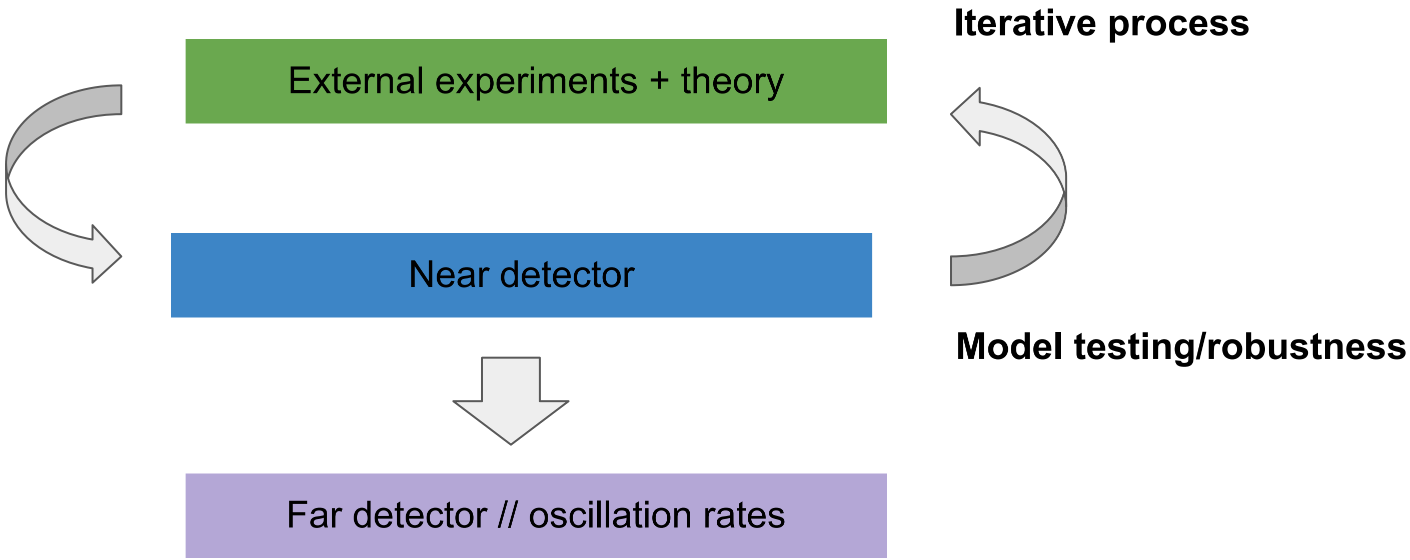
- Near detector information provide stability monitoring, improved event rate prediction and reduces shared systematic uncertainty from flux, interaction model
- Example ND sample: nu-e scattering (low rate, but well known cross section, direct constraint of flux)
- Example: PRISM, ND rates will be sampled at a range of energies





“Inputs” are important - they determine parameterization, uncertainties

- External experiments: electron scattering, pion scattering, neutrino H/D, nucleus scattering
- **Theory**



“Inputs” are important - they determine parameterization, uncertainties

The process is iterative and takes time

- Did this work? Let’s try it in an ND fit (1x / year)
- The needs of the experiment evolve with time

Broadly speaking, what do experiments need?

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Specifically speaking, what does T2K need?

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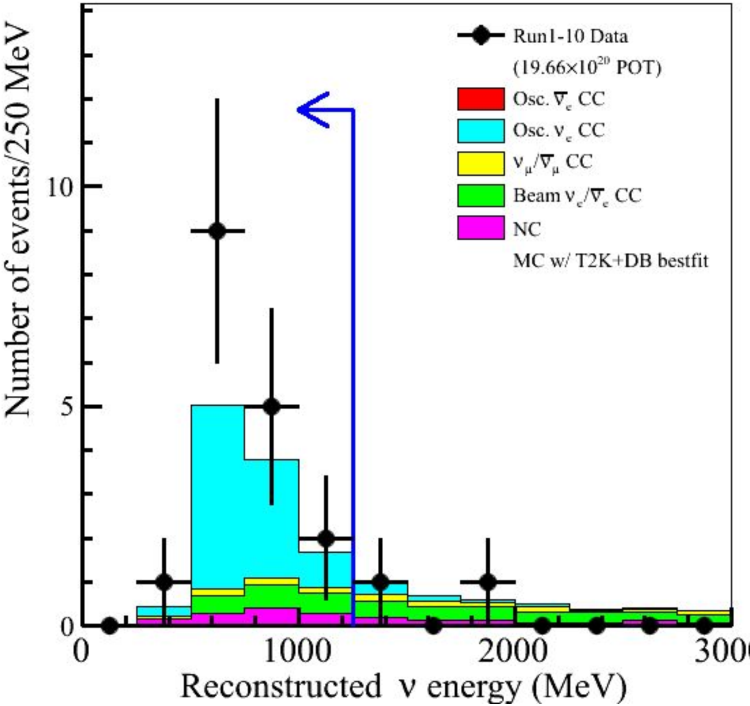
~~Specifically speaking, what does T2K need?~~

… how do I know what matters?

T2K Preliminary

First attempt: Look at event rates

- Discrepancies with prediction (e.g. CC1π+ with low momentum pion sample has a excess)
- Personal fears: NC1γ and NC1π+ difficult to validate experimentally *theoretical checks welcome*



What matters: event rates

2020 era T2K

Error source (units: %)	$1R\mu$ FHC	$1R\mu$ RHC	$1Re$ FHC	$1Re$ RHC	$1Re$ FHC $CC1\pi^+$	$1Re$ FHC/RHC
Flux	2.9	2.8	2.8	2.9	2.8	1.4
Xsec (ND constr)	3.1	3.0	3.2	3.1	4.2	1.5
Flux+Xsec (ND constr)	2.1	2.3	2.0	2.3	4.1	1.7
Xsec (ND unconstrained)	0.6	2.5	3.0	3.6	2.8	3.8
SK+SI+PN	2.1	1.9	3.1	3.9	13.4	1.2
Total	3.0	4.0	4.7	5.9	14.3	4.3

Differences in the nue/numu cross section are 2-3%
- Difficult to constrain at ND
- validation with future ICARUS x NuMI and DUNE ND data
- *Needs theory*

What matters: event rates

2020 era T2K

Error source (units: %)	$1R\mu$ FHC	$1R\mu$ RHC	$1Re$ FHC	$1Re$ RHC	$1Re$ FHC CC$1\pi^+$	$1Re$ FHC/RHC
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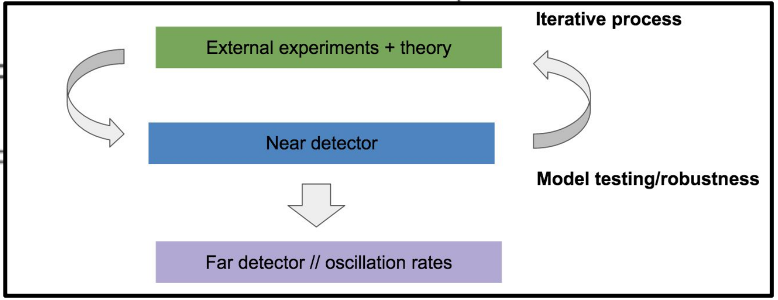


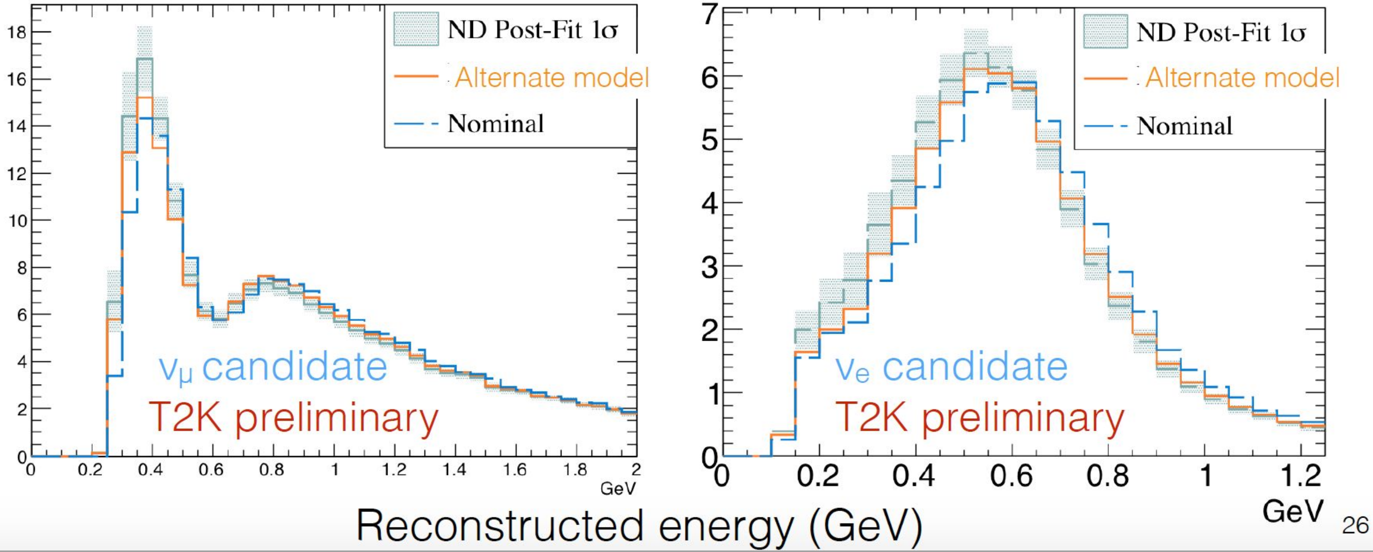
ND constrained uncertainties

- Processes not in isolation, convolved with ND flux - *come back to this*

We can tune it, but we are uneasy - *keep iterating*

What matters: robustness tests

- Create a “data” set corresponding to an alternate QE model
- Run entire T2K oscillation analysis chain (fit near detector with nominal cross section uncertainties and propagate) to evaluate effect on oscillation parameters

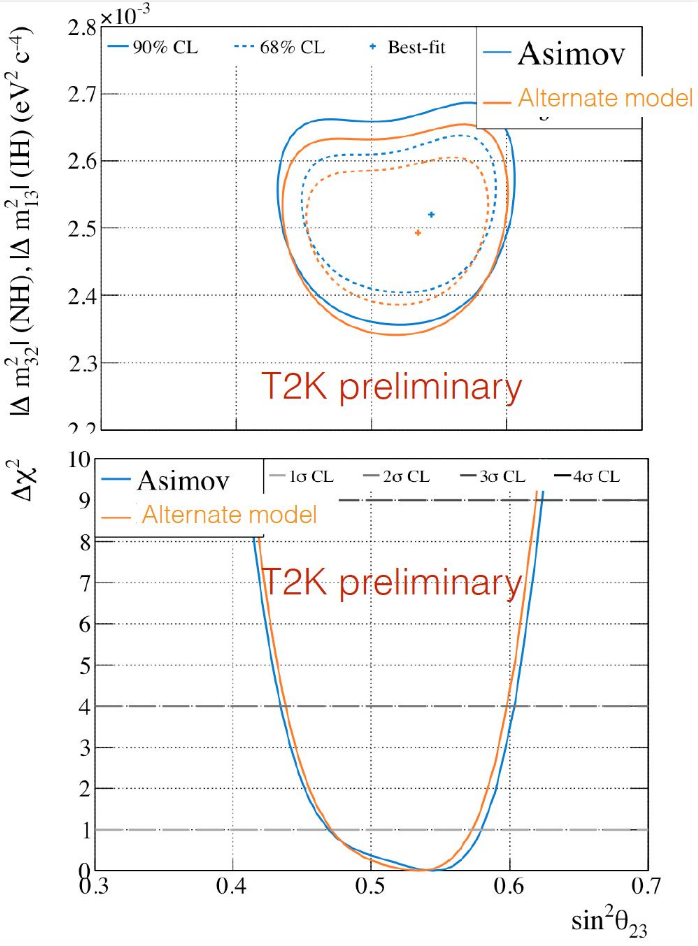


2019 era analysis as an example, not the latest T2K analysis!

What matters: robustness tests

- Alternate models may create biases for current analysis; T2K adds additional uncertainty

- We mustn't run away!



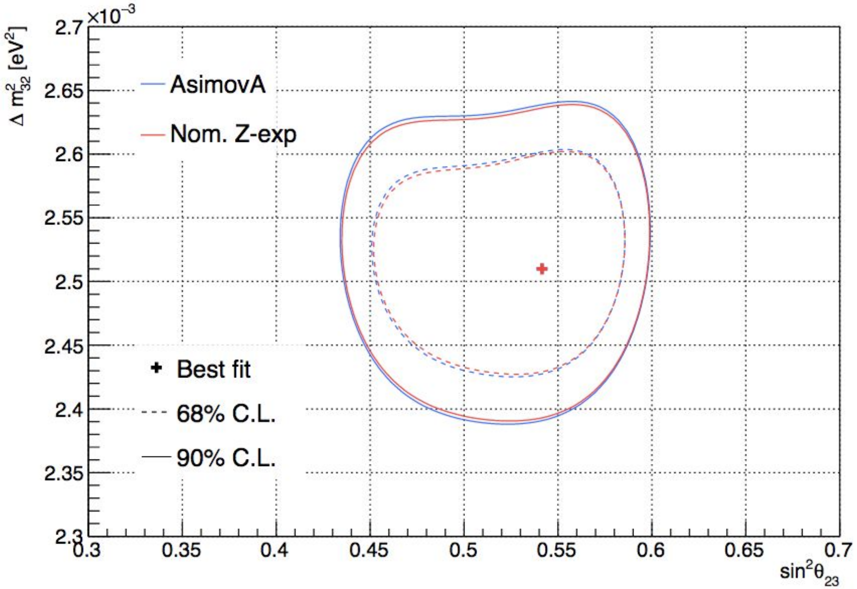
2019 era analysis as an example, not the latest T2K analysis!

Complexities:

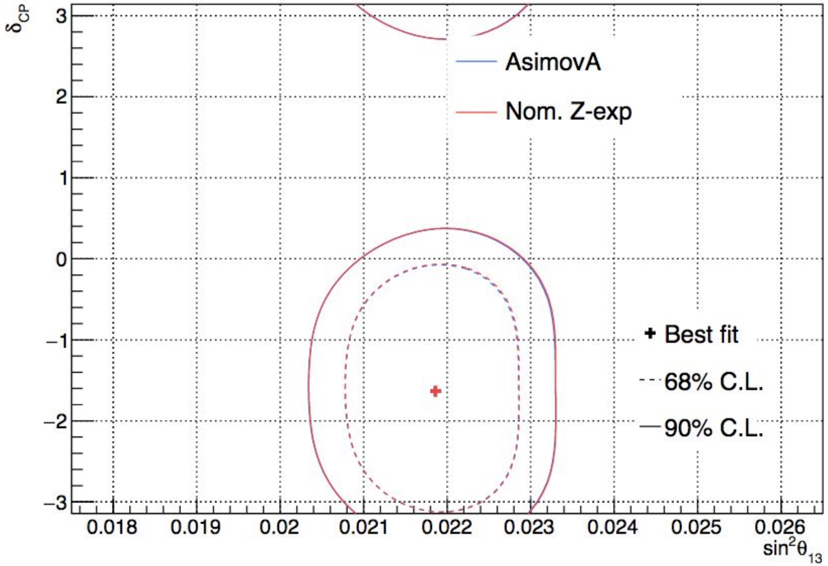
- Event rates don't always indicate if we will see bias.
- Depends on statistical exposure for when effects matter

What matters: robustness tests

T2K 2020 analysis vintage



(a) $\sin^2\theta_{23}$–Δm^2_{23}



(b) $\sin^2\theta_{13}$–δ_{CP}

Successful ingredients for theory-experimental collaboration

<u>Accessible, general tests with event rates/cross section</u>

- Experiment provides flux, data release
- Comparison of new model to our notional model
- Benchmarking against ND data and/or tune
- Used to inform uncertainties, develop new models to experiment

<u>Robustness tests</u>

- Needs experimental chain (ND fit)
- Need suitable interface to experiment - *not always through generator, but it sure helps*

<u>Iterative</u>

- Direct, extended communication is what has worked - *theorists within T2K attend meetings, guest speakers.*

What does T2K need?

State of experiment

- New ND (upgrade) coming online - increased acceptance
- Outstanding puzzles in data
  - Difficulty to reconcile low and high pion momenta samples
  - High angle differences in oxygen enhanced sample vs. carbon
- New FD has new neutron tagging capabilities (SK-Gd)
- Still. Stats. Limited.

Please, help us!

- Exclusive predictions provided in a generator-implementable way (QE, RES, 2p2h)
- Further assessment of how cascade/generator FSI compares to microscopic distorted wave function FSI - *a good start:* *https://arxiv.org/abs/2202.01689*
- Assessment of the impact of nuclear effects in RES interactions, detailed input on nucleon-level effects that can impact hadron kinematics
- More guidance on how we can safely extrapolate constraints on carbon to oxygen
  - Related: T2K/DUNE; ANNIE/SBN comparisons of O/Ar
- Low energy neutron multiplicity predictions (for SK-Gd)

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- Further as... storted wave func...
- Assessme... on nucleon-le...
- More guid... en
  - Relat...
- Low energy neutron multiplicity predictions (for SK-Gd)

Very exciting work at this meeting

Radiative corrections (nue/numu) - *R. Hill, R. Plestid talks*
ACHILLES! - *J. Issacson talk*
Consideration of how to communicate via tuning meaningfully - *S. Li talk*
Benchmarking and uncertainty quantification! - *A. Lovato talk*

Reach of ND upgrade - *example comparators?*

Let's work together to define useful model effort and comparisons

- Is parameterization sufficient?
- Can be connected to osc OR comparable sensitivity of ND

Phys.Rev.D 105 (2022) 3, 032010

TABLE II. A list of fit parameters, their prior constraints and notes regarding their application. While not a fit parameter, the bin-to-bin uncorrelated uncertainty is also listed.

Parameter	Prior Constraint	Notes
p-shell normalization	30%	
s-shell normalization	30%	
SRC strength	30%	
total QE normalization	10%	
Removal energy shift	Unconstrained	
2p2h, low	Unconstrained	$<$ 600 MeV
2p2h, high	Unconstrained	$>$ 600 MeV
Undetected pions	Unconstrained	
Pion FSI contribution	Unconstrained	
Nucleon FSI strength	30%	
Flux (binned E_{vis})	T2K covariance	
Hydrogen normalization	5%	$\bar{\nu}$ only
Uncorrelated Uncertainty	11.6% (at 6×10^{21} POT)	No parameter fit, POT dependence

parametrized as a function of the fit variables and implemented as nuisances with priors included mostly as Gaussian penalty terms in the likelihood. The prior uncertainties and fit variables are those discussed in Sec. II B 2. One exception to the treatment of the prior uncertainties is an *ad-hoc* bin-to-bin uncorrelated uncertainty (as also detailed in Sec. II B 2) which is added directly to the

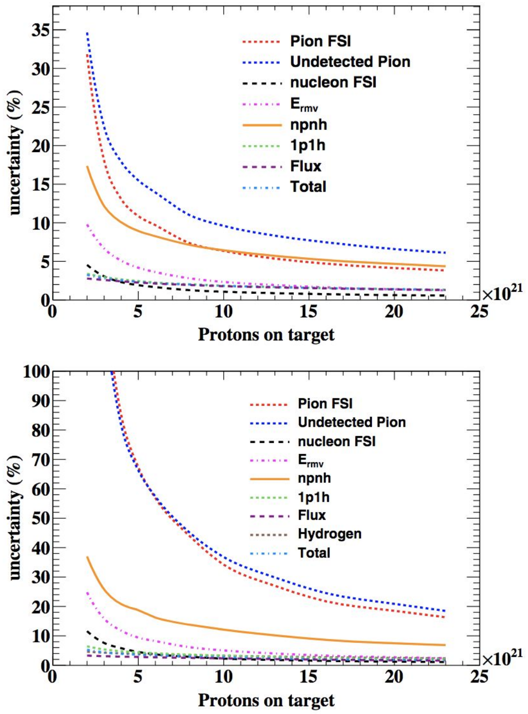


FIG. 7. The 1σ sensitivity to systematic parameters as function of POT in neutrino case (top) and antineutrino case (bottom) when fitting the reconstructed CC0π data binned in δp_T and E_{vis}. The values in the plot are the ratio of the parameter uncertainty to the parameter nominal value expressed as a percentage.

What does DUNE need?

State of experiment

- Still learning about ultimate reach of experiment
    - New capabilities outside current program (e.g. PRISM, ND-Gar, nu-e scattering) will be crucial, but are being assessed
- First pass of uncertainties in TDR (next page)

Start with? infrastructure building and lines of communication

- Expect that many of the previous problems will be faced by DUNE in some capacity, especially resonance production

What we learn at the ND: parameter constraints

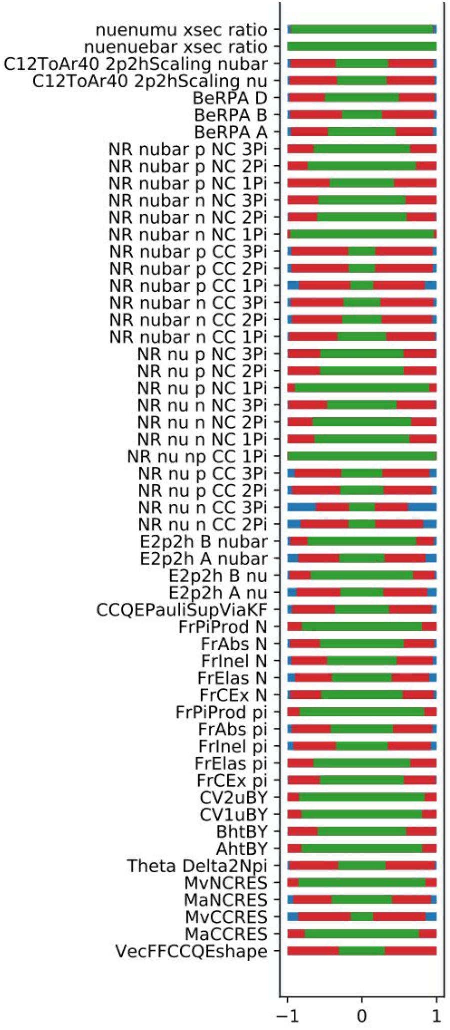
From: DUNE Physics TDR, Fig 5.34

https://arxiv.org/pdf/2002.03005.pdf

Gives sense of what the ND is not able to reduce

But, does not quantify:

- What input is needed from theory, and at what level
    - for external measurements (electron scattering)
- How the model development needs go with time (iterative process takes time, this is at the end)
-



What do we need as a community to move forward?

Establish lines of communication, scope of roles. What is needed from each group with their unique expertise?

- What material can only experimentalists provide and is more needed? (event rates, tunes) - *let's request*
- For sustained collaboration, funding support may be needed for theorists - *lots of really good work here!*

Strengthen ability to pass work across; lower barriers to entry

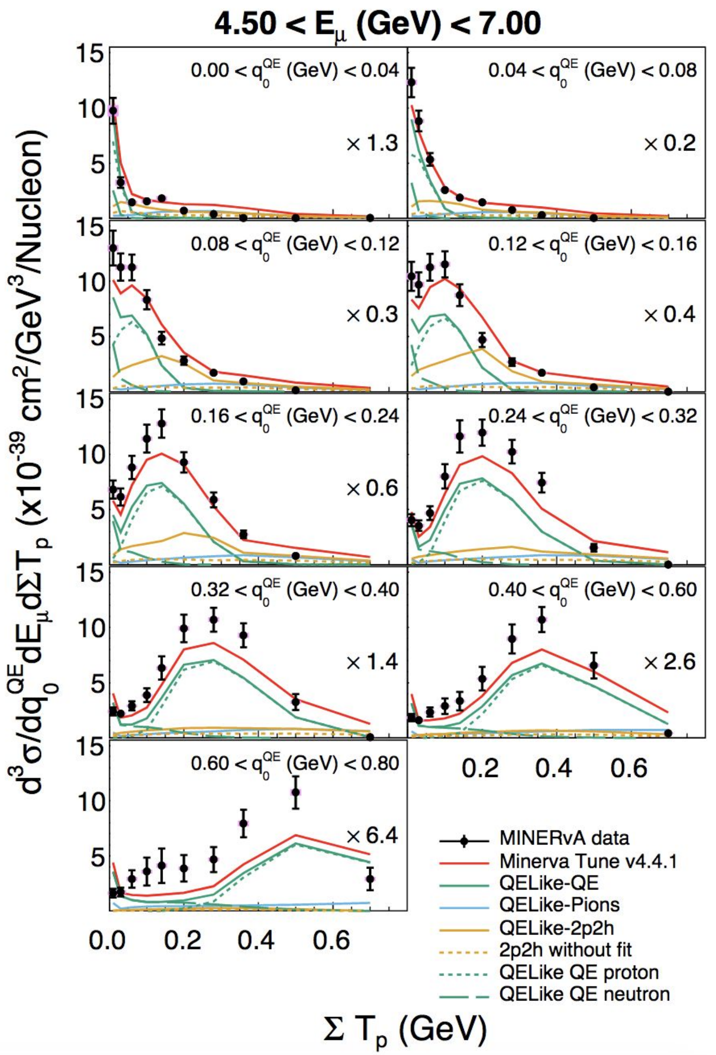
- Generator interface improvements; standard outputs
- Theory driven generator efforts
- Work together on infrastructure (e.g. interface, speed of calculations)

Benchmarking is key, use above tools with initial set of problems

- What do we all agree on (parameterization choice, open problems)
- Comparisons to ND data. What are the current disagreements and possible origins?
- (same as above-- does this process happen together?)

Then, we iterate

What do we need as a community to move forward?



Benchmarking is key.

- Compare model + uncertainties
  - both theory and experiment
- Example: MINERvA
  https://arxiv.org/pdf/2203.08022.pdf

Summary

A robust understanding of neutrino interactions is important to answer many of the open questions we face today:

BSM: sterile neutrinos, light dark matter, NSI, precision tests of SM

Three flavor oscillation: θ_{23} octant, mass hierarchy, CP violation.
Tests of neutrino mixing model

More BSM: proton decay

Near detectors are important to provide data on neutrino-nucleus interactions, but recall… they are also where we search for BSM signal

We need theory!

Summary

Including theory and developing a robust model takes time and sustained contact

- In my view, the pandemic has really impeded progress

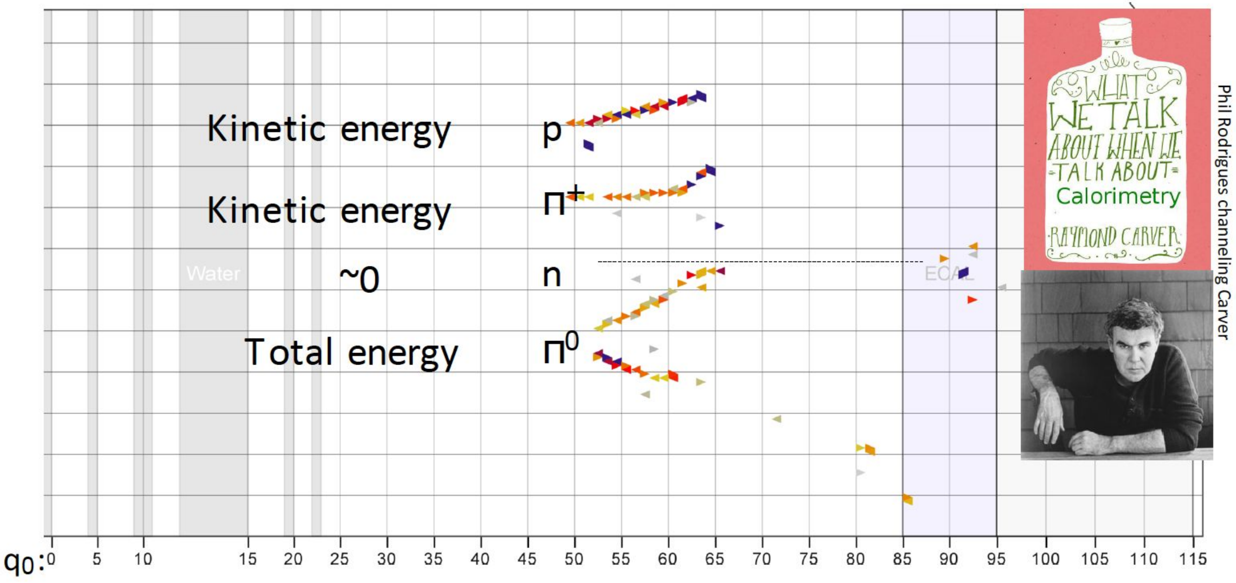
There are important efforts in theory which are beneficial to future experiments

- We may not yet have clear “I need X to Y precision” targets, but we do have good general sense of what is needed + specific actions underway
    - Lower barriers to entry, new generator/interface efforts
    - Confirm where we are: benchmarking, what can we agree on?
- Will be an iterative process - *worth considering how we want to iterate for maximal benefit*

backup

What we mean when we say "visible energy"

Courtesy: Kevin McFarland, Phil Rodrigues



$E_{avail} \equiv$ (Proton and $\pi^{\pm}$ KE) + (Total E of other particles except neutrons)

April 2016 K. McFarland, Identifying Nuclear Effects @ MINERvA

Calorimetric detectors energy estimation depends on particle type -> exclusive

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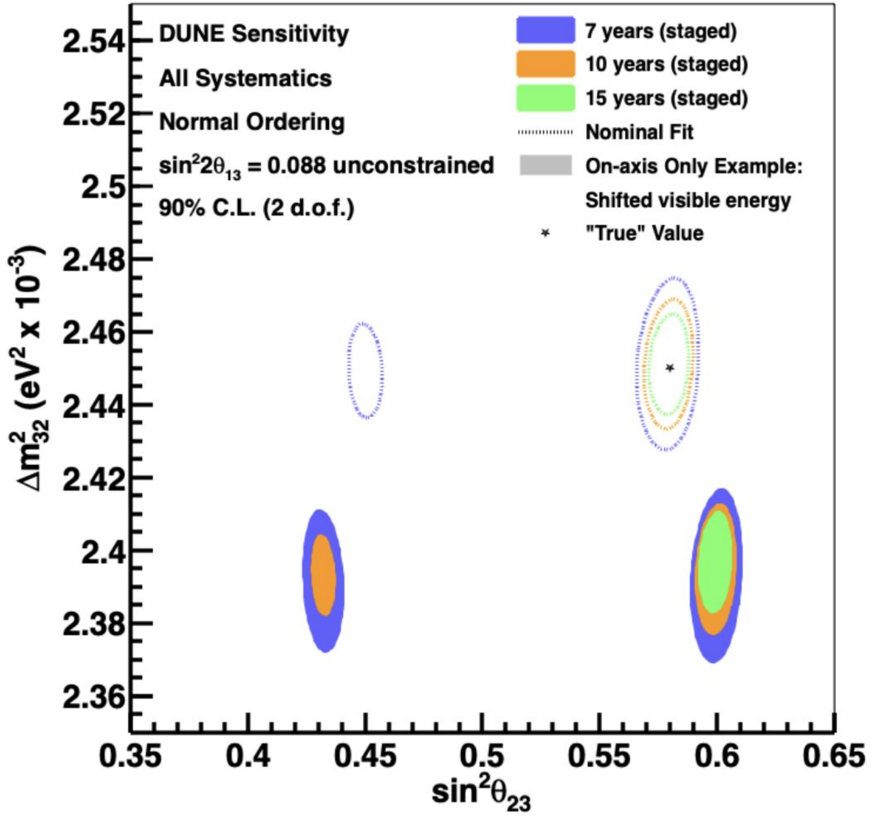
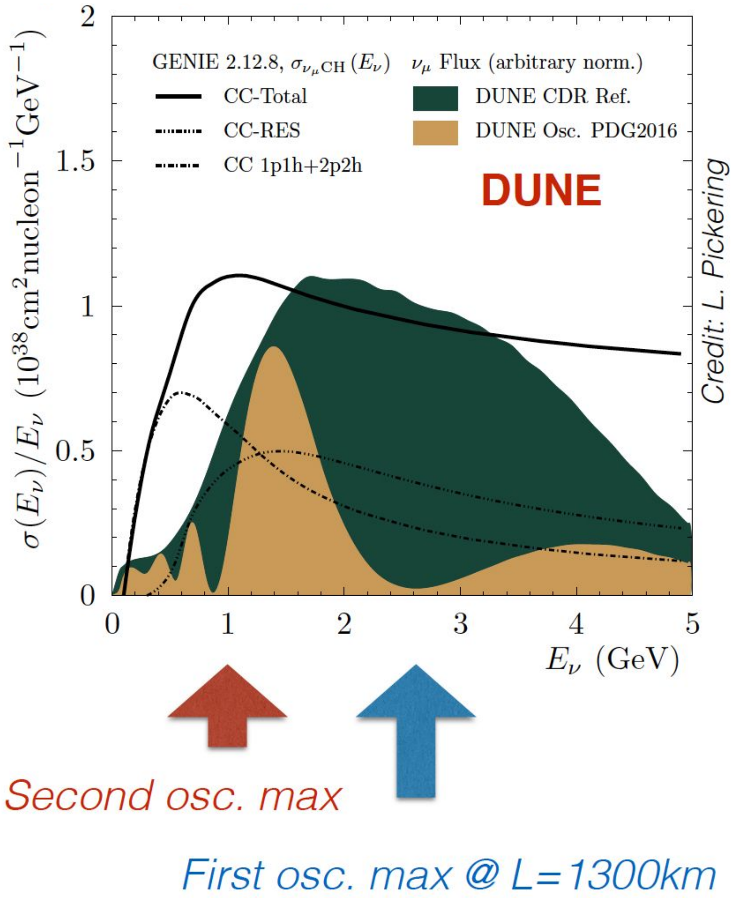
Why neutrino interactions matter - DUNE example

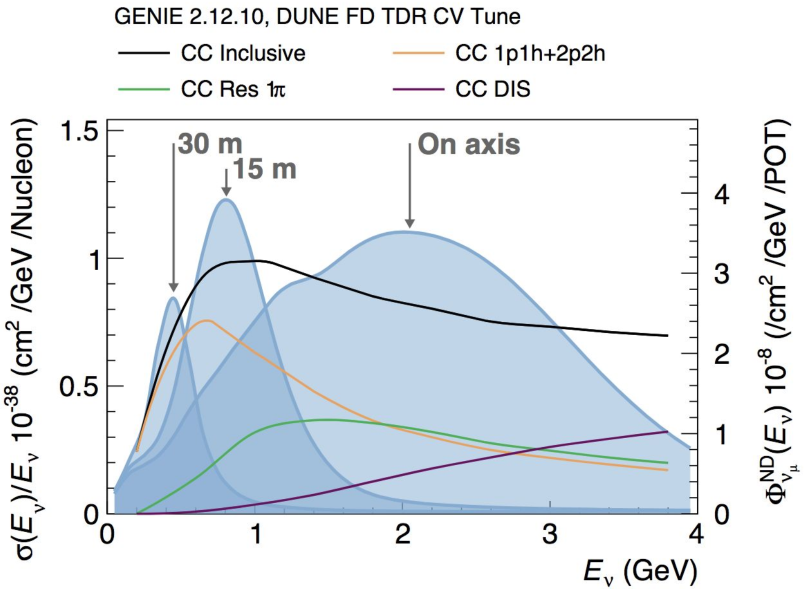
DUNE Physics TDR arxiv. 2002.03005



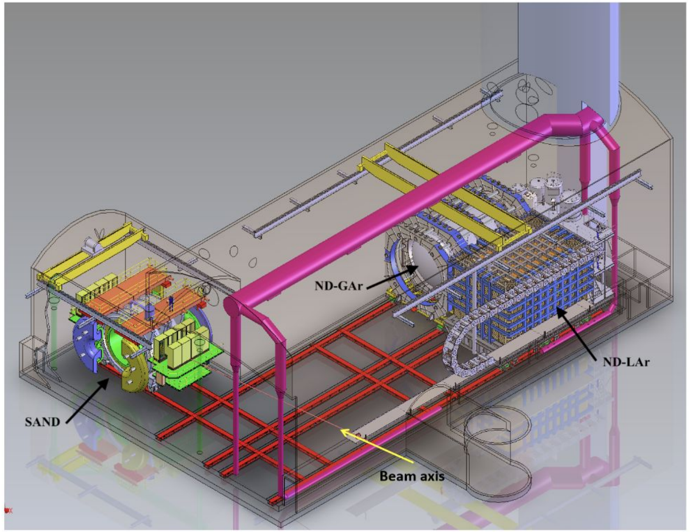
Possibility of bias in key oscillation parameters

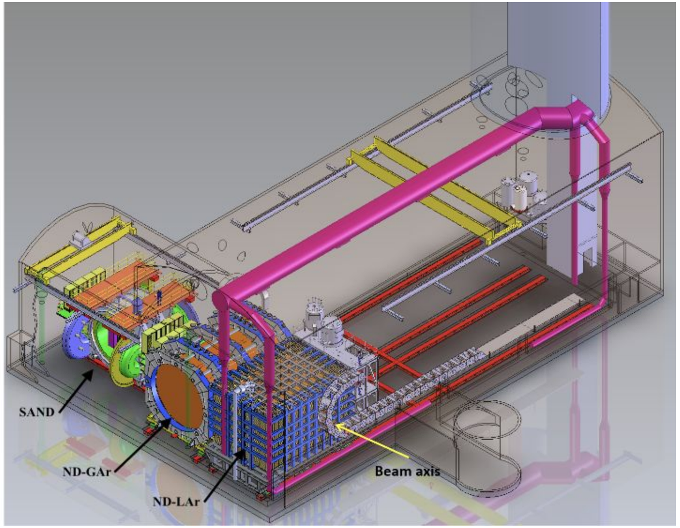


New approach: PRISM



Place detectors at different positions relative to beam to measure different energy spectra [arxiv 2103.13910](https://arxiv.org/abs/2103.13910)





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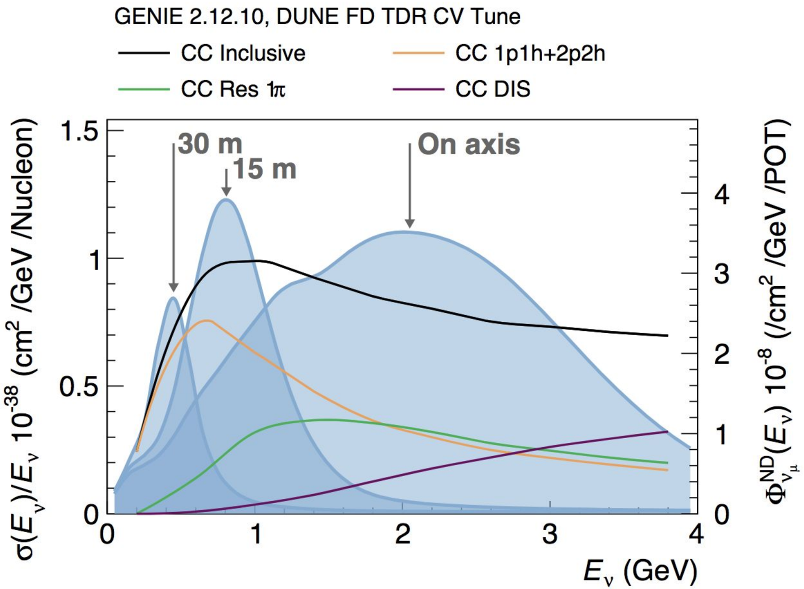
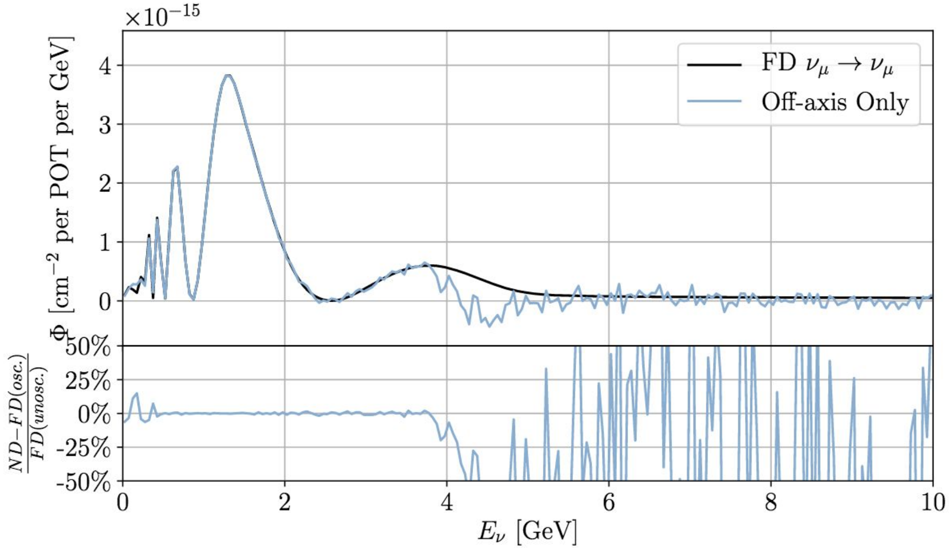
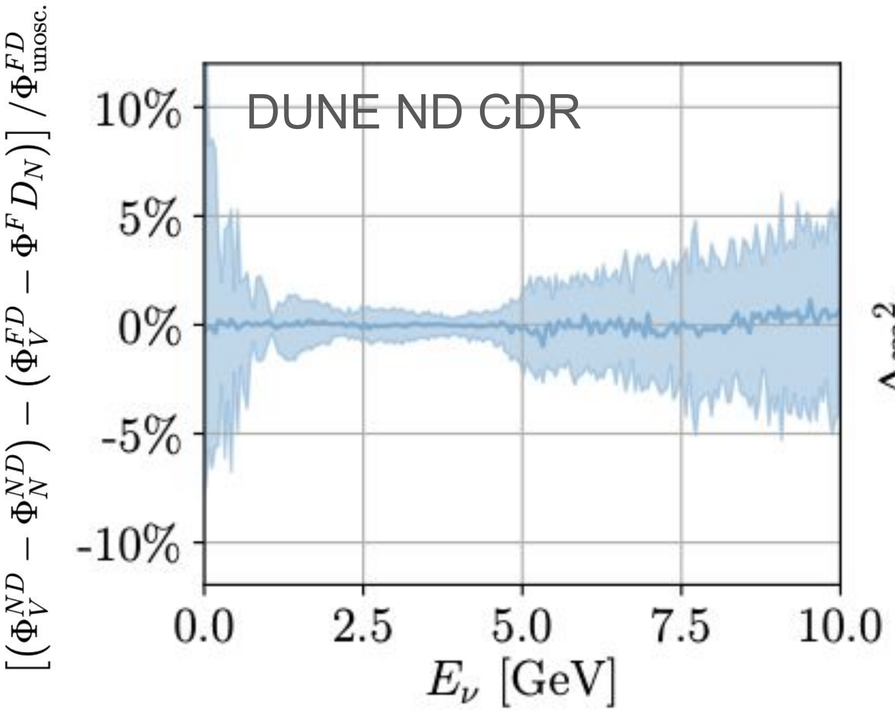
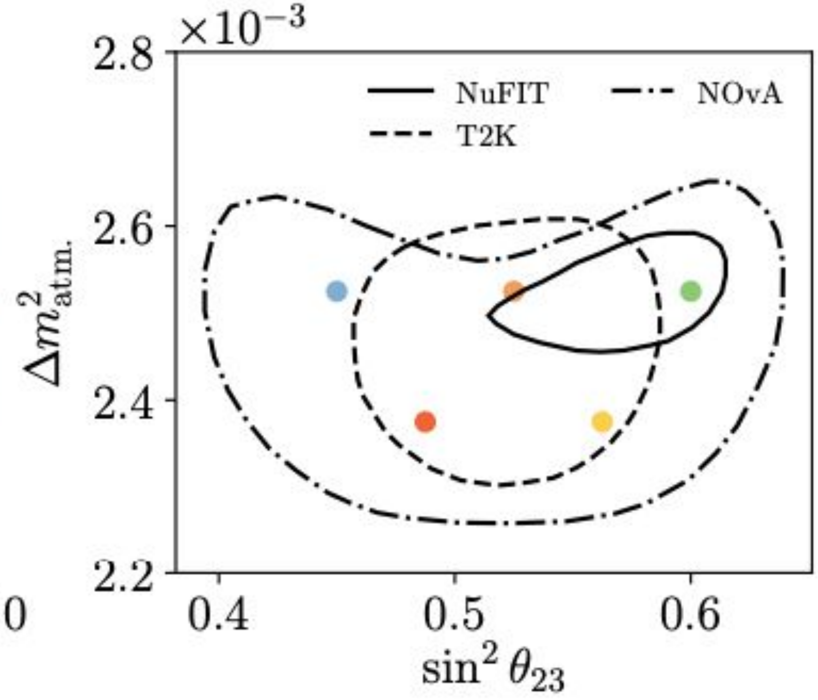




Combine spectra for an oscillation-matched flux

PRISM provides robustness against mismodelling





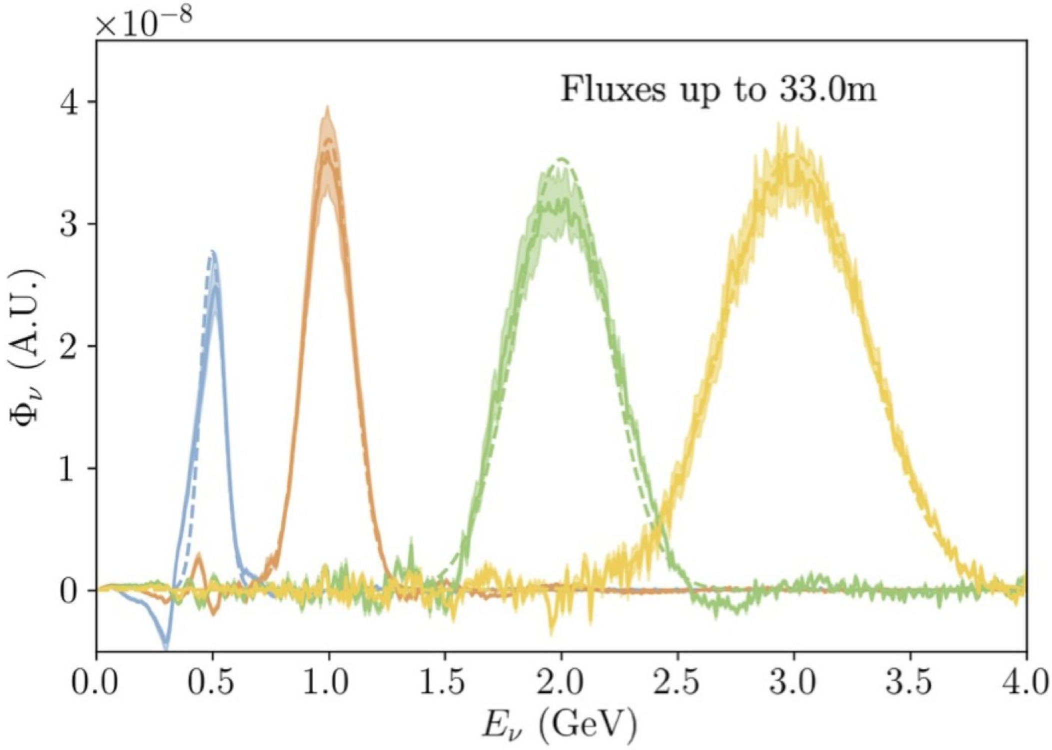
Allows for novel nuclear physics studies

Other DUNE detectors (ND-GAr, SAND) also have unique measurement opportunities

Another view of the necessity of precision modelling

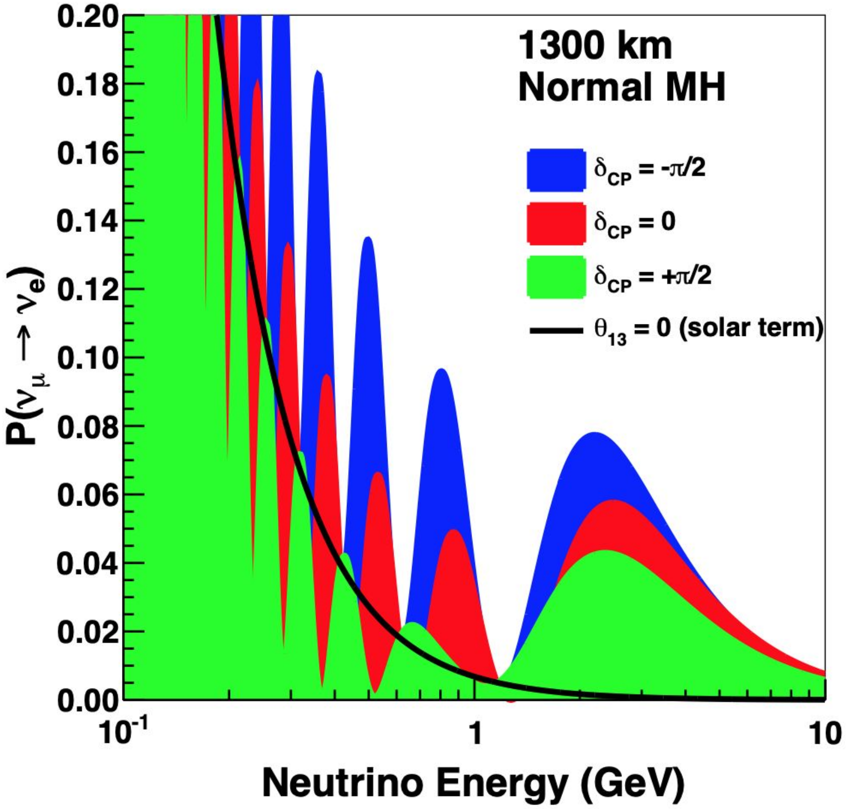
From: DUNE ND CDR:

https://arxiv.org/pdf/2103.13910.pdf



What is the amount of tolerable uncertainty on dCP? *Hot take*

- Event rates tell you about dCP.
    - Current experiments and future may be dominated by FD or ND detector response
- However, we need a robust model
    - Note the interesting behavior of how dCP changes the location of 2nd osc max
    - Dm2 also modifies this feature
    - Dm2 can be sensitive to the incorrect model
    - **It's important to measure all parameters! Correctly**
- We need to assess role of residual systematics AND robustness
    - What physics is not currently captured sufficiently well?
    - Don't forget atm nu or NC measurements for completeness of 3 flavor model



DUNE Physics TDR