The Theoretical Cross Section Needs of Future Long Baseline Experiments

Kendall Mahn, Michigan State University

INT workshop
“Theoretical physics uncertainties to empower neutrino experiments”
Oct 30th, 2023

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Michigan State University Founded 1855

Office of Science
U.S. Department of Energy

Thank you to the organizers for this invitation!
Thank you to the INT for the support to be here.

Disclaimer: I get excited, and I talk too fast. My intent is for a dialogue-- *interruptions are OK! Let's clarify*

I will also want to follow up with others not present for the workshop -

- *I may not be aware of the latest progress, and welcome correction*
- *I want to share my ideas for the future and hear yours*

What I want: *dream big, make specific plans*

Big dream: a baseline model with theory motivated degrees of freedom and with genuine exclusive predictive power I can use on T2K and DUNE

Outline for my talk:

- What I want this for - *oscillation, exotic physics results*
- Why are theoretical uncertainties important - *fast overview*
- Which uncertainties are important - *T2K current status, specific problems which need theoretical insight or development*
- Planning how we can work effectively - *formats, interfaces, ways to collaborate*
- Conclusion: Wishlist! - *and let's talk!*

Current:

Atmospheric: Super-Kamiokande, IceCube

Accelerator: T2K, NOvA, Short-Baseline Neutrino Program (SBN)

Future:

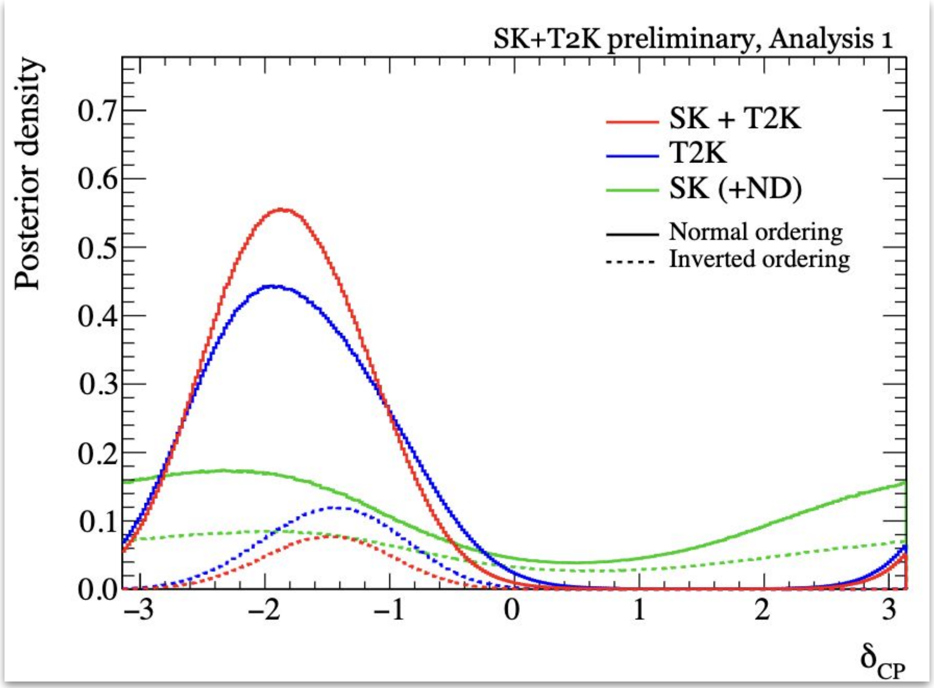
Accelerator/Atmospheric: Hyper-Kamiokande, Deep Underground Neutrino Experiment

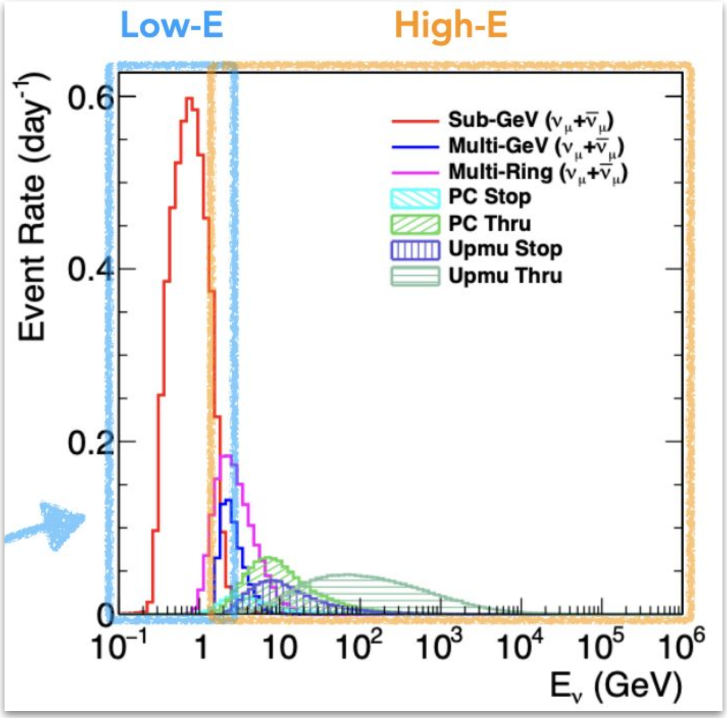
Current program is broad.

Neutrino oscillation, exotica (e.g. sterile neutrino, dark matter searches), proton decay

Signal (or background) processes are 0.1-20 GeV charged current (CC) or neutral current (NC) neutrino or antineutrino interactions for **atmospheric and accelerator based programs**

Shameless example: new SK+T2K joint analysis





Current and future experiments need to have models and uncertainties across energy ranges - *here, 0.2 - 100 GeV*

- More details: A. Eguchi @ NNN2023

Neutrino oscillation fast primer

Oscillation depends on:

- Amplitude determined by mixing angles: θ_{12}, θ_{23}, θ_{13}

  Is $\sin^2(\theta_{23})=0.5$? (maximal mixing?)

- Frequency determined by mass splittings: $|\Delta m^2_{32/31}|$, Δm^2_{21}

  What is the ordering of the masses ($\Delta m^2_{32/31} > 0$?)

- CP violating phase (CPV)

  Is there CPV in neutrinos?

Neutrino oscillation fast primer

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- Frequency determined by mass splittings: $|\Delta m^2_{32/31}|$, Δm^2_{21}
- CP violating phase (CPV)

_ν_e and $\bar{\nu}_e$ appearance channel_

SAMPLE	PREDICTED			
	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$
ν_e appearance	73.8	61.6	50.0	62.2
$\bar{\nu}_e$ appearance	11.8	13.4	14.9	13.2

Changing δ_{CP} increases ν_e and decreases anti-ν_e appearance rates

Neutrino oscillation fast primer

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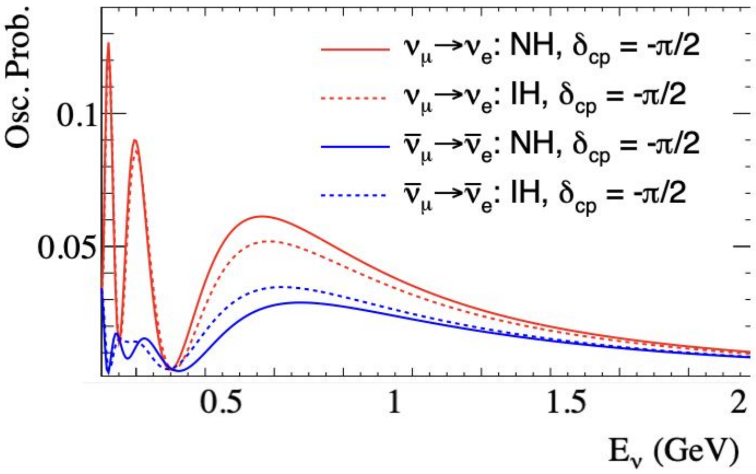

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Normal to inverted hierarchy suppresses ν_e appearance, enhances $\bar{\nu}_e$ appearance

Neutrino oscillation fast primer

Oscillation depends on:

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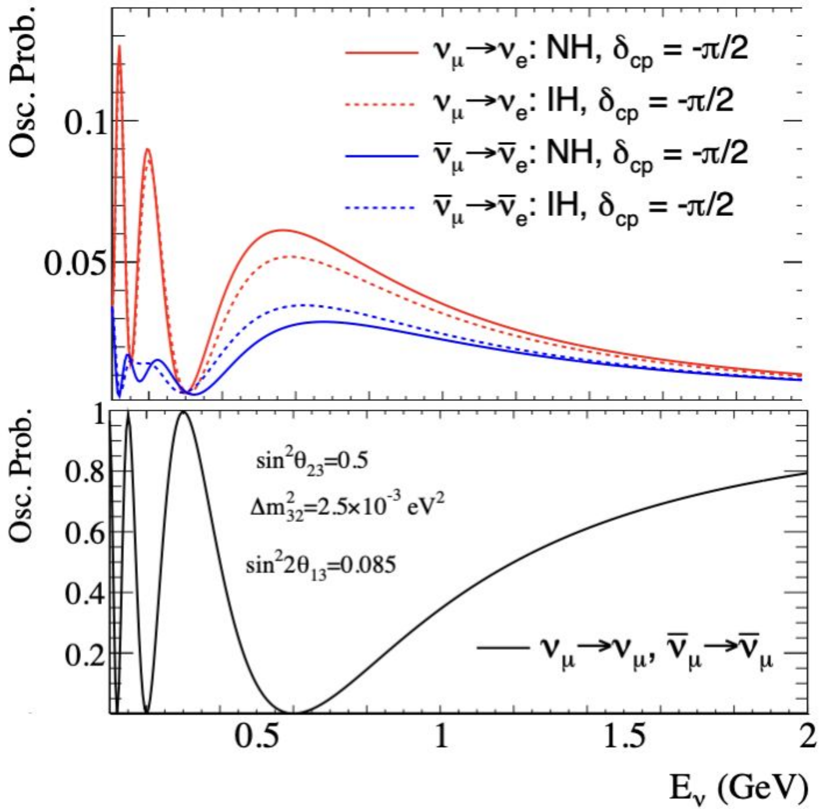
- Frequency determined by mass splittings: $|\Delta m^2_{32/31}|$ Δm^2_{21}
- CP violating phase (CPV)

Largely independent of δ_{CP} effects

ν_μ and $\bar{\nu}_\mu$ disappearance channel



Neutrino oscillation fast primer

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- Frequency determined by mass splittings: $|\Delta m^2_{32/31}|$, Δm^2_{21}
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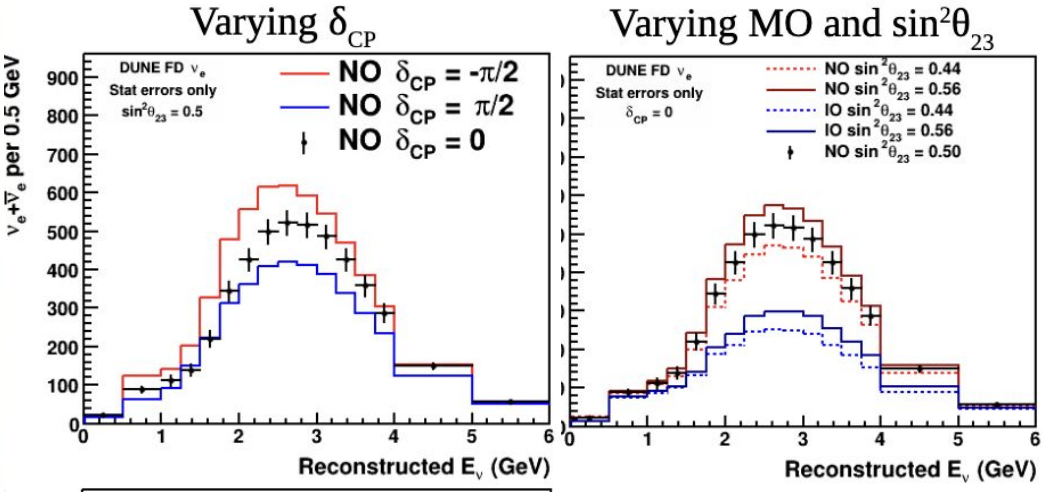


C. Marshall, P5 town hall@FNAL

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

Event rate used to infer oscillation physics

Oscillation analysis depends on interaction model

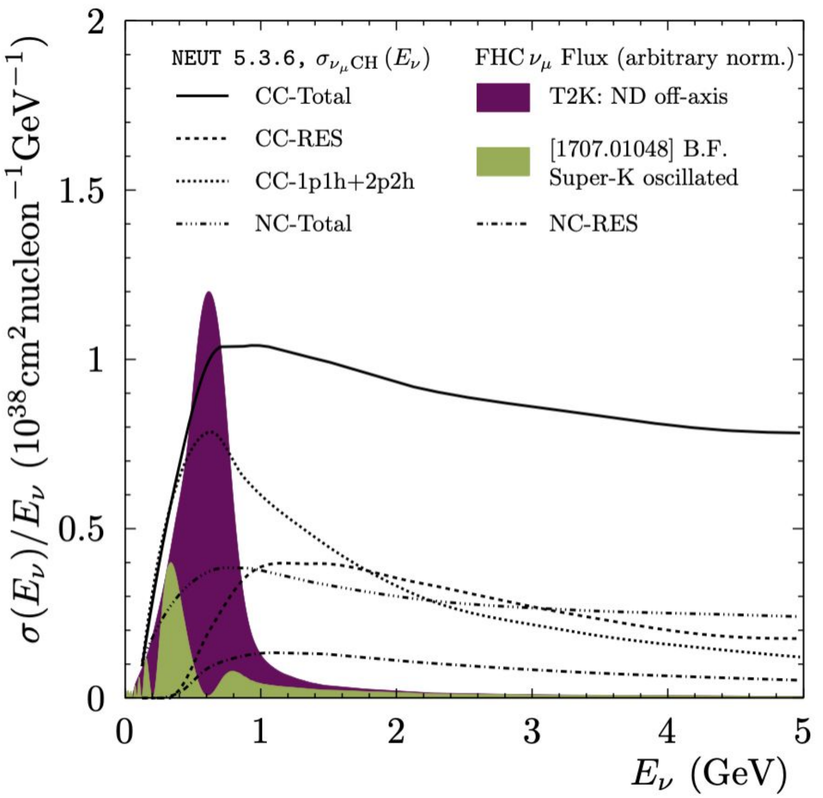
Cross section (true kinematics)

Efficiency (true kinematics)

Relationship between true and reconstructed kinematics)

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

Oscillation analysis depends on interaction model



All plots this pretty are from L. Pickering

Incident energy is not known. Spread of beam is larger than nuclear effects.

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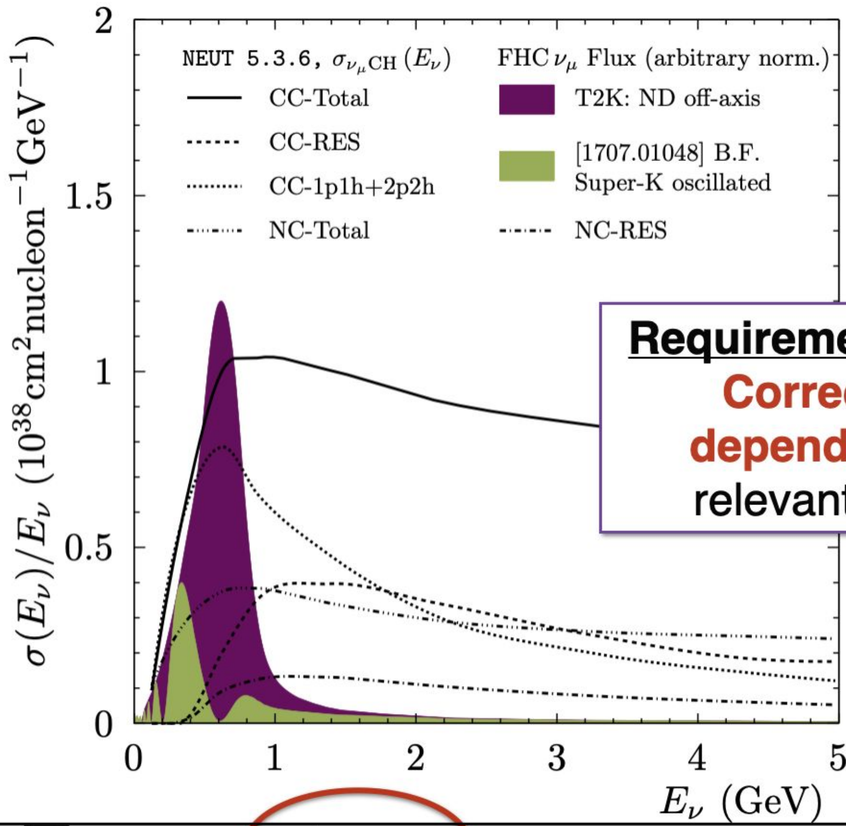
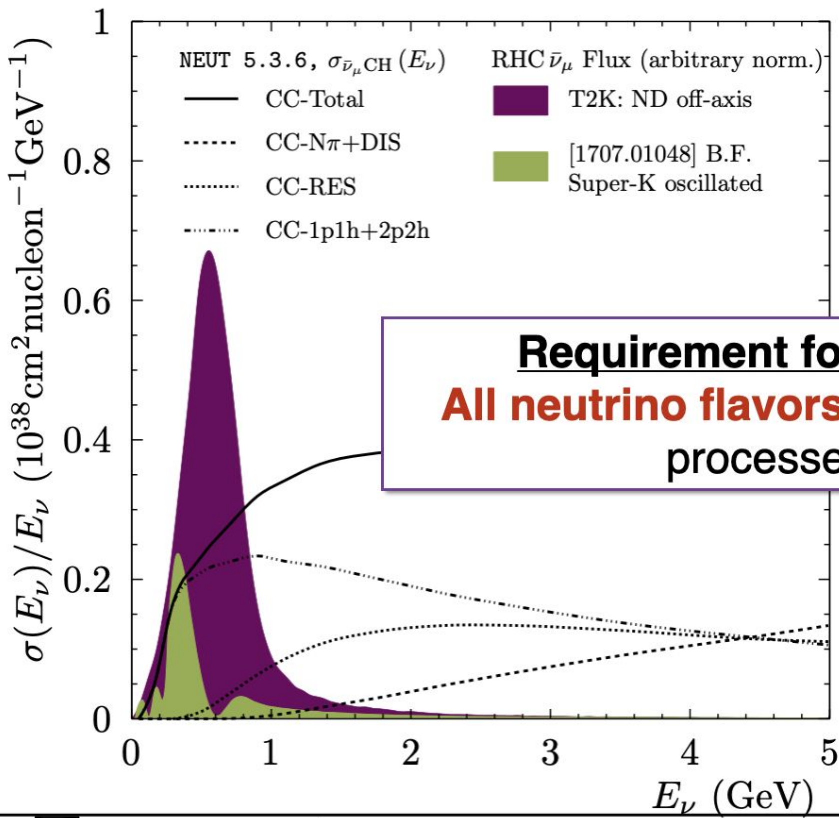
Oscillation analysis depends on interaction model



Requirement for model:
Correct energy dependance for all relevant processes

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

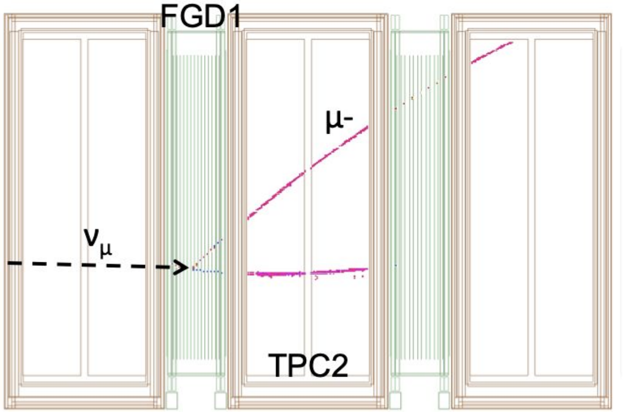
Oscillation analysis depends on interaction model



Requirement for model:
All neutrino flavors! for relevant processes

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

Need: hadronic state description



- T2K event display
- CC0π "topology": 1 muon, no pion
- Includes CCQE, 2p2h, CC1π (pion absorbed in nucleus)

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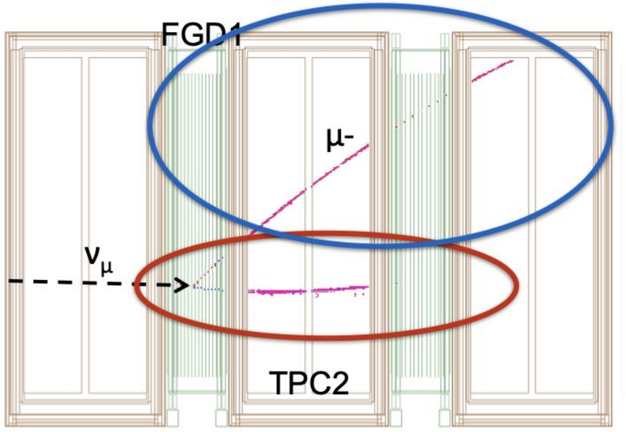

- T2K event display
- CC0π “topology”: 1 muon, no pion
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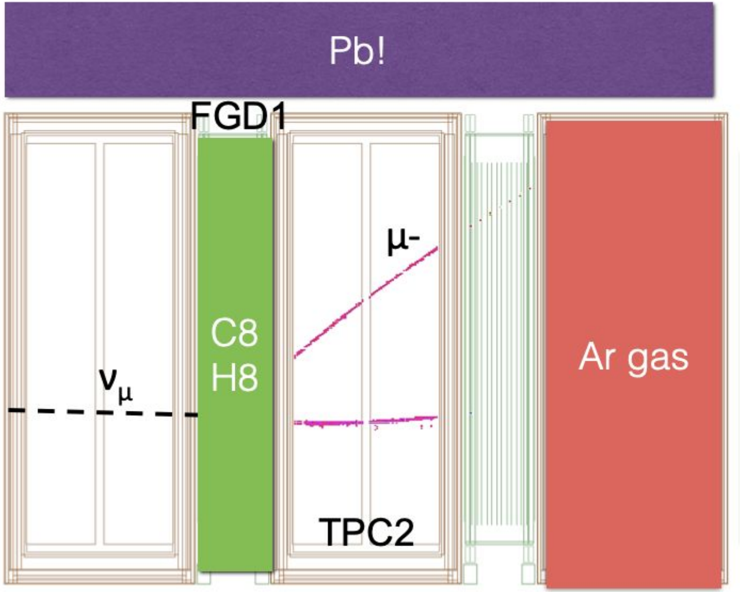
Requirement for model:

- All visible particles for efficiency (background) and energy estimates

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

Needs: target material



Target materials:

- T2K: H2O
- NOvA: CH+Cl
- SBN, DUNE: Ar

Requirement for model:

- Most nuclear targets, esp C, O, Ar

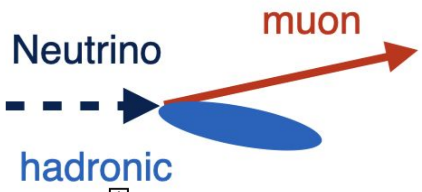
Also: Uncertainties and correlations between nuclear targets

Needs: energy estimation

- Oscillation depends on energy
    - Estimate from hadronic and/or leptonic information

$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos\theta_\mu)}$$

$$E_\nu = E_\mu + \sum E_{hadronic}$$



T2K
Super-Kamiokande

SBN
DUNE

NOvA

Needs: energy estimation

- Nuclear effects bias true and estimated neutrino energy

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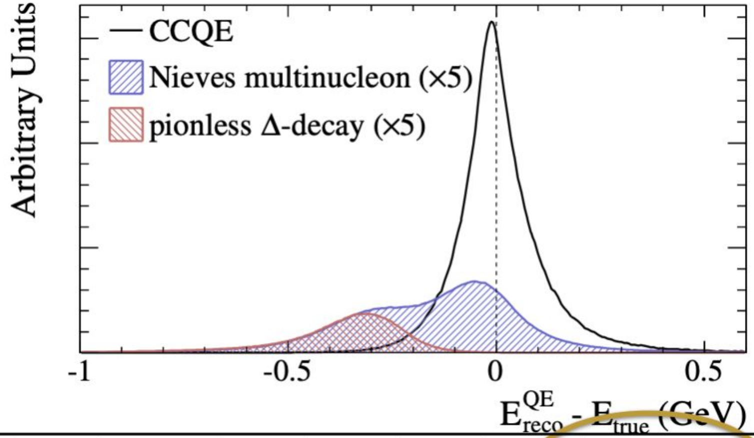
T2K, PRL 112, 181801 (2014)

Requirement for model:
- Correct mix of processes per topology
- true - reconstructed kinematic relationship



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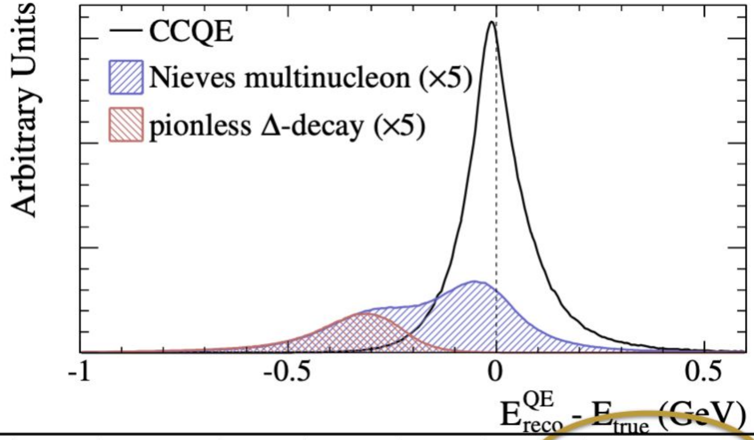

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Also: models which can work simultaneously in both estimators

Recent MINERvA paper: PRL 129 (2022) 2, 021803

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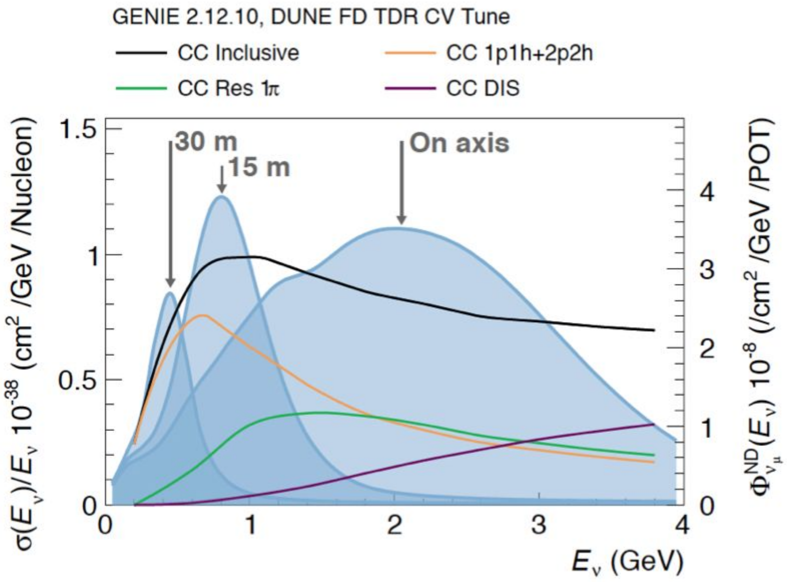
- Near detector information provide stability monitoring, improved event rate prediction and reduces shared systematic uncertainty from flux, interaction model
- Example ND sample: nu-e scattering (low rate, but well known cross section, direct constraint of flux)
- Example: PRISM, ND rates will be sampled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



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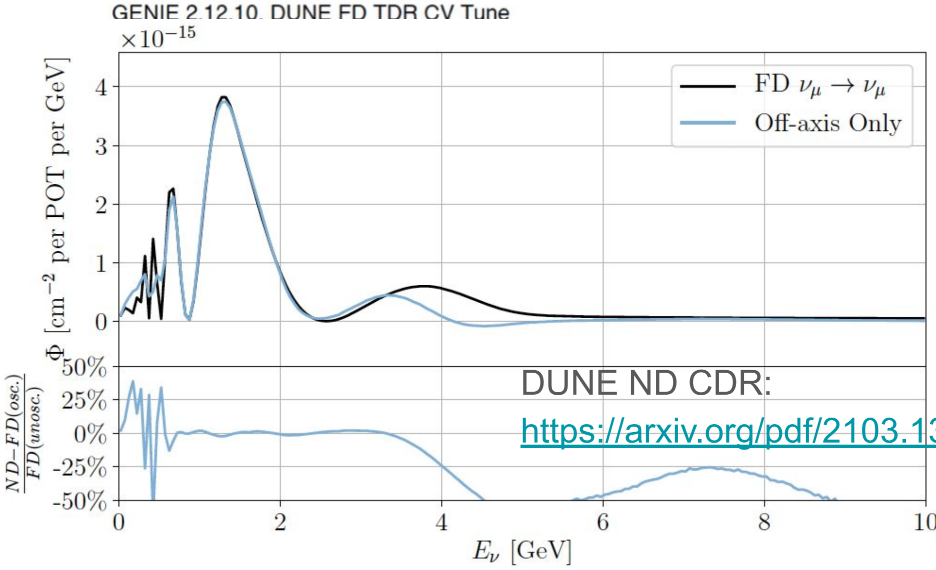
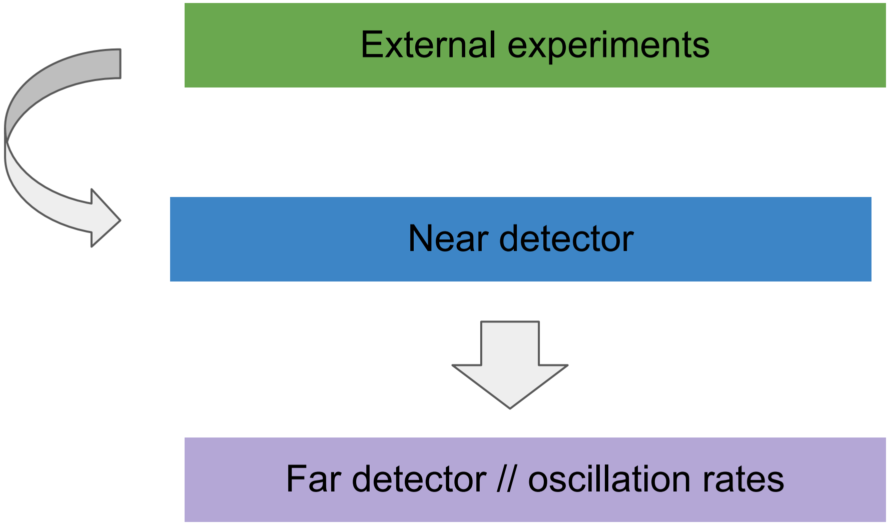


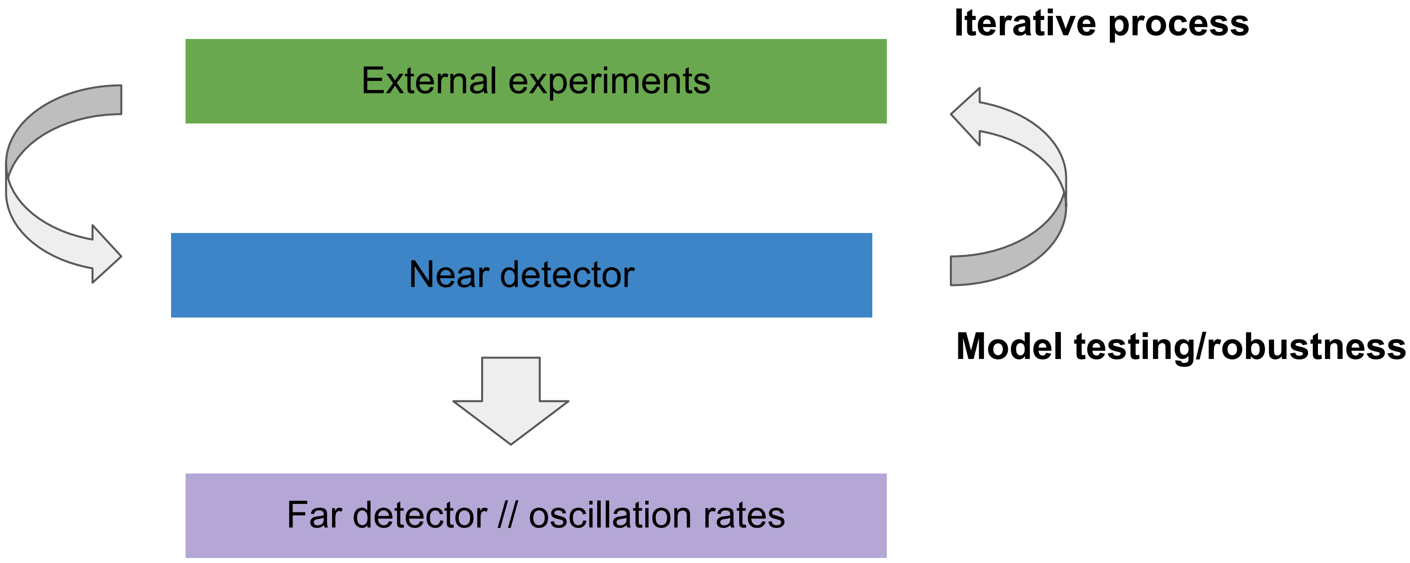
DUNE ND CDR:
https://arxiv.org/pdf/2103.13910.pdf



External experiments and theory are very important; determine parameterization, uncertainties

- Electron, pion scattering
- Neutrino H/D data
- Neutrino nucleus scattering

Snowmass Neutrino Cross Section Topical Group report: https://arxiv.org/abs/2209.06872



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Iteration is necessary, and takes time

Persistent challenges: addiction to ad hoc

Simulations are using inclusive calculations (quasielastic plus 2p2h plus pion production) with a fragmentation model, plus an FSI cascade or transport.

- “Franken-model”
- “Paper over problems”

We have been building ourselves a layer cake with shaky foundation

- Difficult to attribute correctly which layer is crumbling under pressure

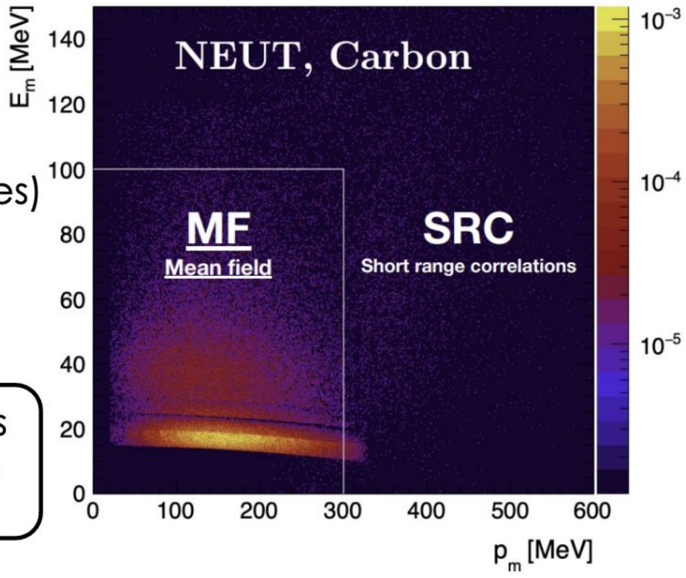
We’re trying to break this habit, by moving toward theoretically motivated degrees of freedom

https://www.madnessandmethod.com/

Recent work to theoretically motivated uncertainties

- **Fermi motion and removal energy** in the mean field region:
  - Change **relative occupancy** of the shells (2 shells for C, 3 for O)
  - Change **shape of the momentum distribution** of each shell
  - Shift the **whole removal energy distribution**
  - Plausible alterations derived from $(e \rightarrow e', p)$ data

- **Short range correlations**:
  - **Normalisation of the SRC contribution** (high nucleon momentum tail, 2 nucleon final states)
  - NEUT predicts 5%, other models predict closer to 20%

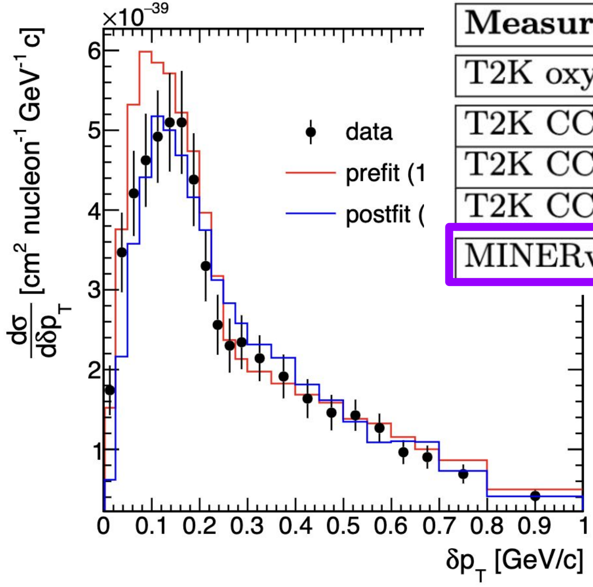


Crucial check: the parameter constraints from T2K's near detector are reasonable given electron scattering data

Based on Benhar SF model

More details: S. Dolan, NuInt2022

Persistent challenges: disagreement with experimental data



Measurement	Prefit χ^2	Postfit χ^2	Number of bins
T2K oxygen + carbon (Sec. IV B 1)	98.79	30.30	58
T2K CC0πNp δp_T only (Sec. IV B 2)	15.72	8.48	8
T2K CC0π0p ($p_\mu, \cos\theta_\mu$) only (Sec. IV B 2)	107.57	62.55	50
T2K CC0π0p + CC0πNp (Sec. IV B 2)	107.57 + 16.76	64.19 + 11.83	50 + 8
MINERvA δp_T (Sec. IV B 3)	114.32	76.14	24

Disagreements in semi-inclusive data seen for some time (e.g. MINERvA, PRL 121, 022504 (2018))
MINERvA data compared to newer T2K model: https://arxiv.org/pdf/2308.01838.pdf

We need semi-inclusive theory for the hadronic state (NOvA, SBN DUNE… and T2K's neutron tagging…)

We must continue to interrogate simplifications/approximations/extrapolations

Planning how to work together - *lowering barriers*

“Implementation of some of the exclusive models that are available in such a way that we can easily access the parameters that plausibly alter model predictions.” - *how do we make this simple and easy for all of us?*

- Generator format standardization - NEW: https://arxiv.org/pdf/2310.13211.pdf
- Data comparisons (format again)
- Shared tools, defined interfaces

Planning how to work together - *collaboration mechanisms*

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On T2K, we regularly have guest members join our interaction development meetings, and we also do smaller author papers ('opt in'). We also try to cite theoretical effort within our oscillation papers.

Let us know how we can support 'external' effort. Where are there barriers to progress we can work on together or simplify workflow?

Model development and uncertainties wishlist

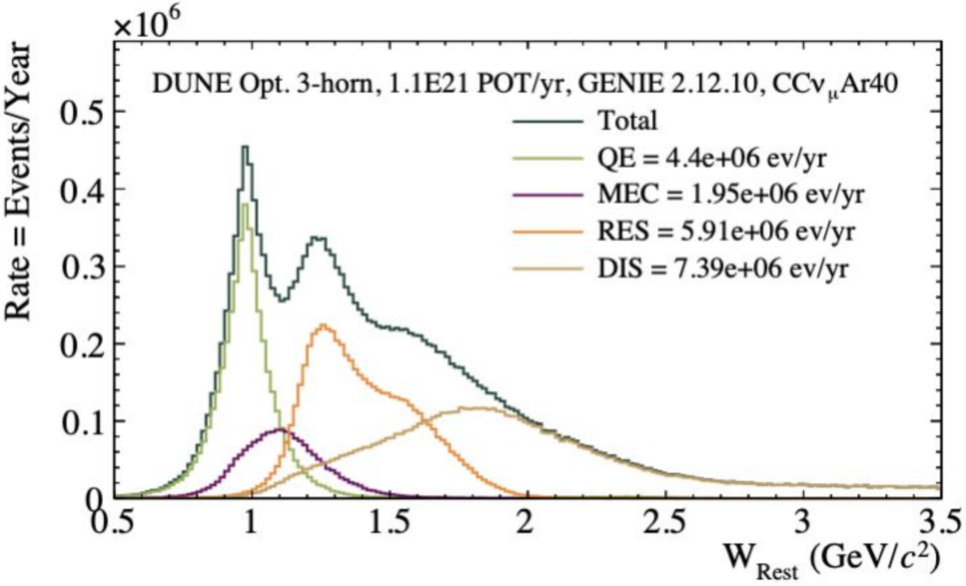
- Resonance model development
  - Fudge is here! This is a major process for DUNE
  - CC (osc signal) and NC (exotic physics, background)
  - Description of pion, proton kinematics; FSI beyond cascades)
  - Leverage electron scattering data here?

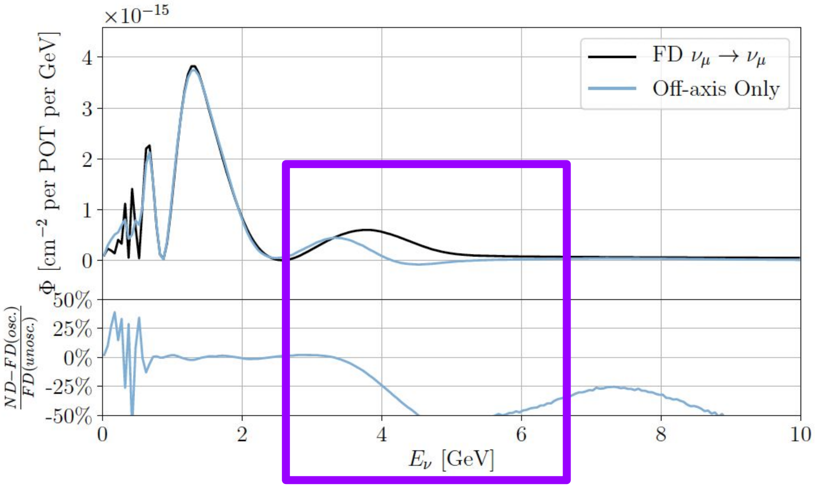
Obscure reference to Jujutsu Kaisen, “resonance” ability, though, I do often daydream of smashing my laptop

https://static.wikia.nocookie.net/jujutsu-kaisen/

Model development and uncertainties wishlist

- Resonance model development
- Transition region - *Incomplete expermental and theoretical footing*
  - *Little to no single nucleon data*
  - *How do we handle double counting? Extrapolations/approximations?*





Model development and uncertainties wishlist

- Resonance model development
- Transition region
- Continued work on QE/multinucleon processes
  - Heavier targets (Ar) and uncertainties which relate C,O to Ar

Model development and uncertainties wishlist

- Resonance model development
- Transition region
- Continued work on QE/multinucleon processes
- nue/numu uncertainties - *important for all apperance measurements*

Error source	FHC1Re	RHC1Re
Flux	2.90%	3.09%
Cross-section	4.31%	4.20%
2p2h Edep	0.20%	0.18%
IsoBkg Low-p_π	0.05%	1.76%
$\sigma(\nu_e)$, $\sigma(\bar{\nu}_e)$	2.40%	1.40%
NC γ	1.28%	2.22%
NC Other SK	0.20%	0.40%
Flux x cross-section	3.16%	3.70%
SK det	3.06%	3.92%
Total Syst.	4.57%	5.65%

Uncertainties are from: second class currents, radiative corrections, and (soon) collective nuclear effects which lead to differences in electron-muon and neutrino-antineutrino cross section

2020 T2K analysis, *Eur. Phys. J. C 83, 782 (2023)*

Summary

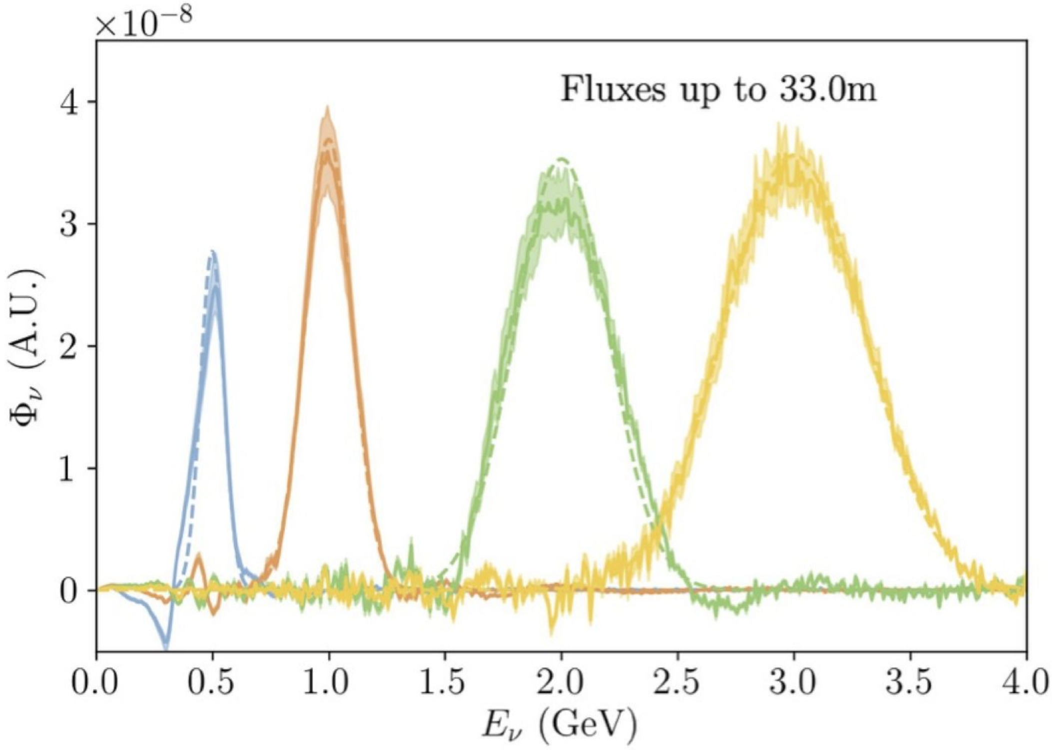
- We continue to need theory for robust interpretation of oscillation, cross section and exotic physics
    - “*We know that all our models are strongly rejected by global cross section measurements (even when we fit the uncertainties within them) and that we know from T2K that the scope for bias from mismodelling is close to 100% of our existing systematic uncertainty budget on Delta m^2.*”
- Dream big: *“Implementation of exclusive models that are available in such a way that we can easily access the parameters that plausibly alter model predictions.”*
    - On T2K, we are trying to move toward a baseline model with theory motivated degrees of freedom and with genuine exclusive predictive power
- Plan specific: We have a wishlist of work we would benefit from theoretical help
    - Let’s discuss: What specific topics are of interest to the folks here?
    - Let’s discuss: How we can work together effectively

Backup

Another view of the necessity of precision modelling

From: DUNE ND CDR:

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



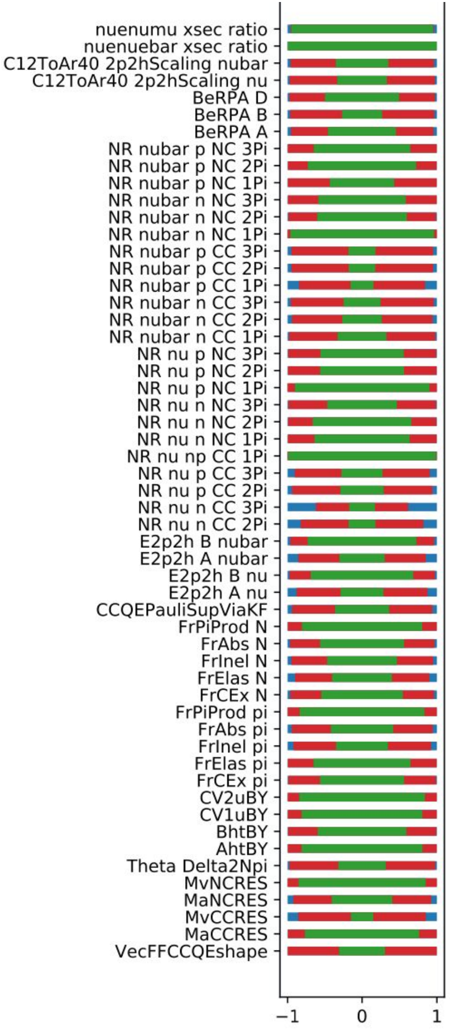
What we learn at the ND: parameter constraints

From: DUNE Physics TDR, Fig 5.34

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

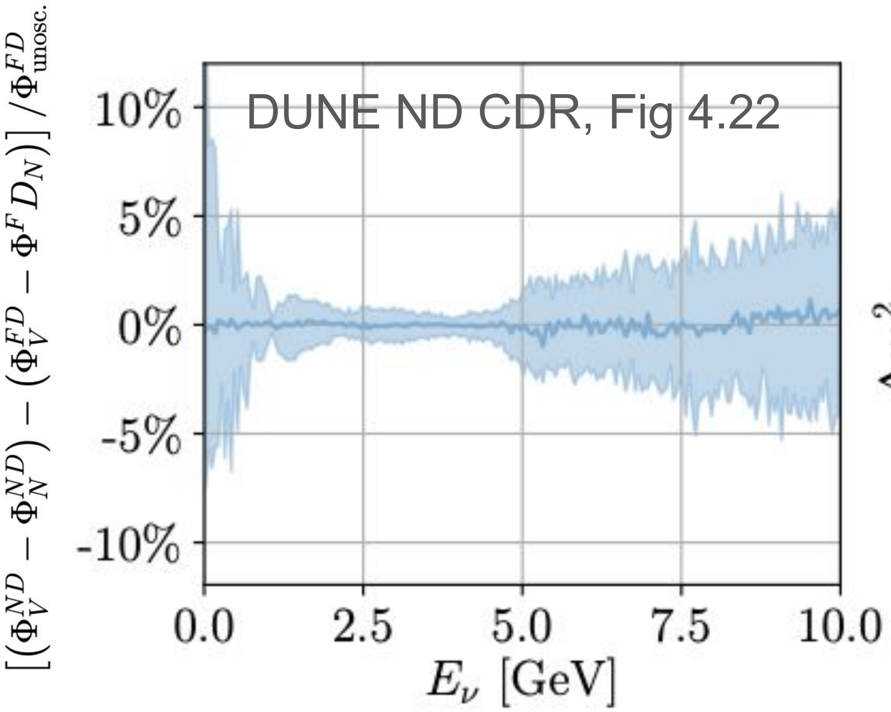
What's not obvious here:

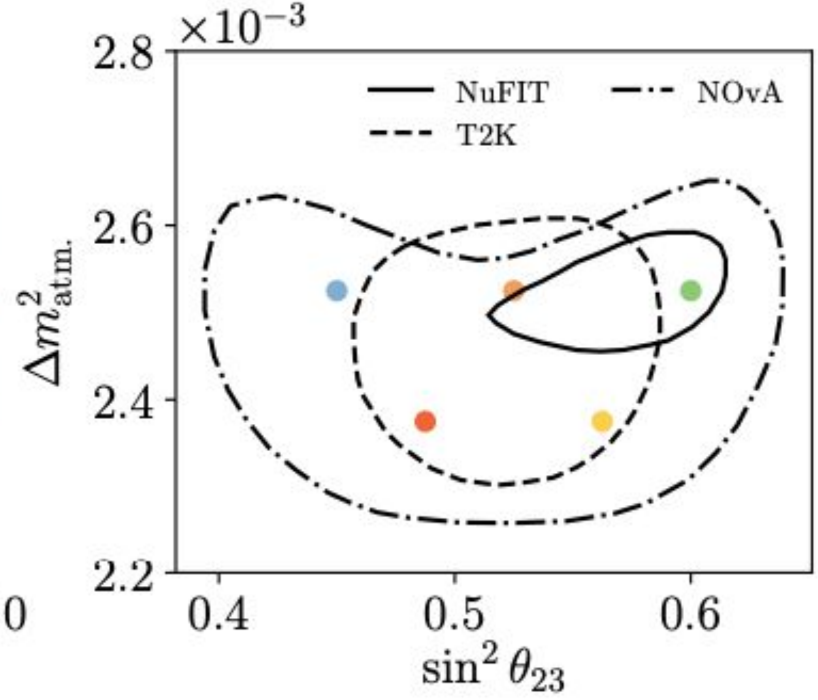
- Important measurements needed by THEORY from electron scattering
- How the model development needs go with time (iterative process takes time, this is at the end)
- What if the model is wrong? (PRISM, electron scattering)



Prior FD-only ND+FD

What we learn at the ND: robustness tests w/ PRISM

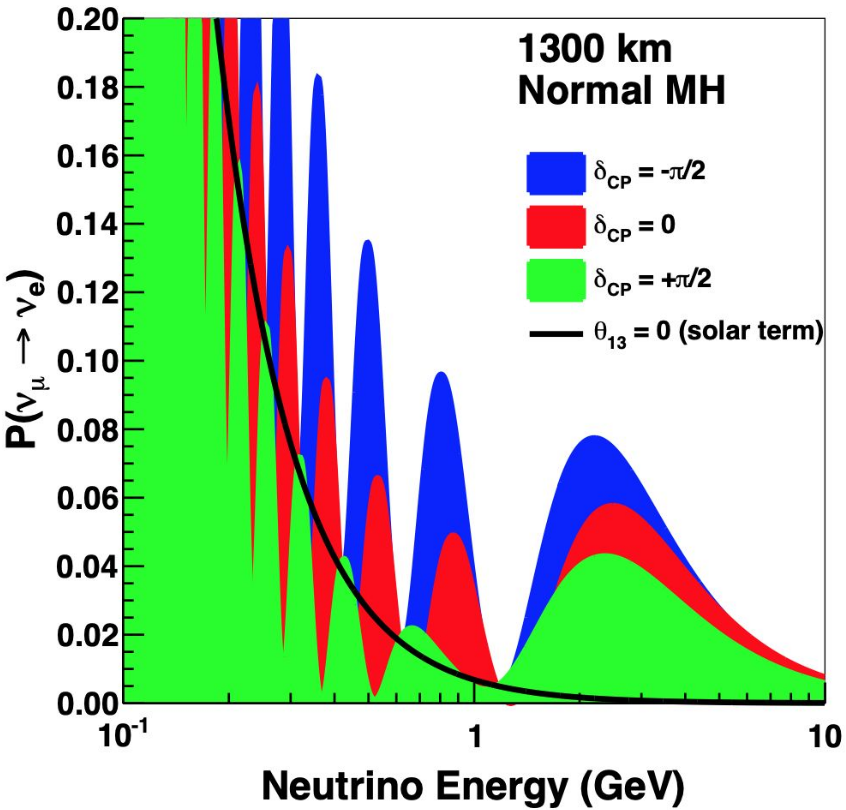




PRISM needs a reasonable initial model with correct parameterization -
electron scattering is very useful to accomplish that goal

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

Why is electron scattering a key component of the current and future program?

From: Electron scattering white paper https://arxiv.org/abs/2203.06853 - *credit of many here!*

To have a robust model requires multiple tests of the model

- *Elec scattering is highly complementary to the ND program, and enhances ND physics reach in a novel way;*
- *Resonance region expected to be very important - major discrepancies and need for electron measurements for theory*

We know next to nothing in transition region, which is also where the power of PRISM decreases

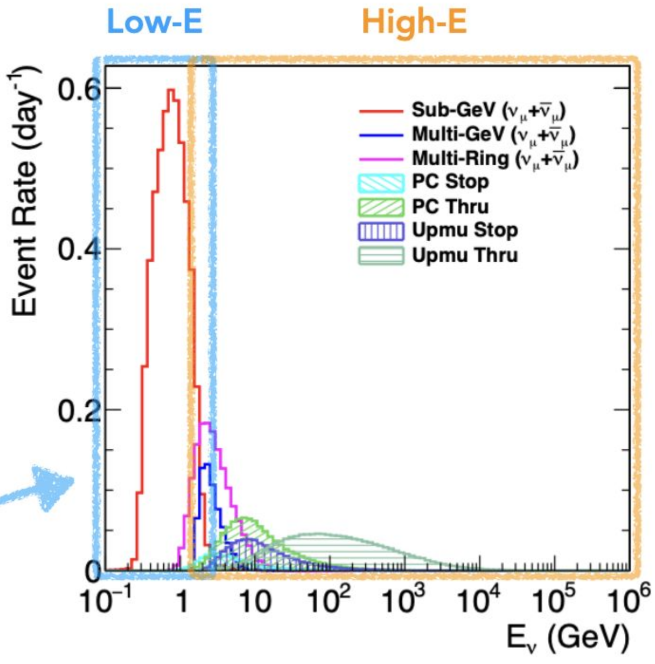
- *need H/D measurements and need to build a basic and complete model of multiplicity and final state composition; atm nu physics may also really need this region*

Both of these problems need TIME and DATA to confront

- *mature state of T2K/NOvA combined with electron scattering program is exciting*

A. Eguchi, NNN2023, SK+T2K combined analysis

- SK atmospheric covers a wider range of energies than T2K.
  - Use different models for low-energy and high-energy samples.



Use a common cross-section model with T2K

	Low-energy sub-GeV atm + beam	High-energy multi-GeV atm
CCQE	T2K model with ND280 constraint, correlated in low-E/highE (except for high-Q^2)	
	high-Q^2 params w/ND280	high-Q^2 params w/o ND
	add ν_e/ν_μ ratio unc. (CRPA)	
2p2h	T2K model w/ND280	SK model (100% error) + T2K-style shape
Resonant	T2K model w/ND280 + new pion momentum dial + NC1π0 uncertainties	SK model for 3 dials common with T2K, use more recent larger T2K priors
DIS	T2K model w/ND280	SK model
ν_τ	SK model (25% norm on top of other syst) for other systematics checked that we have no numerically unstable values	
FSI	T2K model w/ND280	T2K model w/o ND280 should be mostly same as SK model
SI	T2K model, correlated in low-E/high-E only applied to FC and PC for atm, PN not applied to atm	

- SK atmospheric covers a wider range of energies than T2K.
  - Use different models for low-energy and high-energy samples.

- **Low energy** (beam and atmospheric Sub-GeV samples)
  - Use the T2K model [ref] as the base which is **constrained by the T2K near detector**.
  - Some extra parameters are added to cover important uncertainties for the atmospheric analysis.

- **High energy** (rest of atmospheric samples)
  - Use a modified SK model [ref] including additional systematics uncertainties.

	Low-energy sub-GeV atm + beam	**High-energy** multi-GeV atm
CCQE	T2K model with ND280 constraint, correlated in low-E/highE (except for high-Q^2)	
	high-Q^2 params w/ND280	high-Q^2 params w/o ND
	add ν_e/ν_μ ratio unc. (CRPA)	
2p2h	T2K model w/ND280	SK model (100% error) + T2K-style shape
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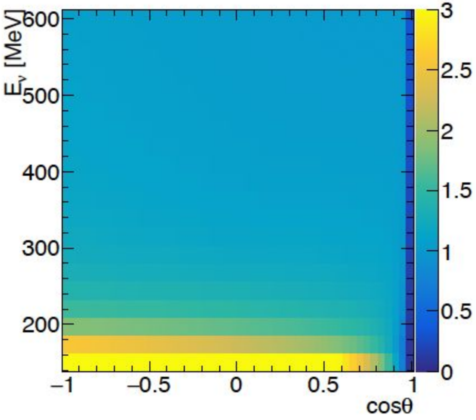
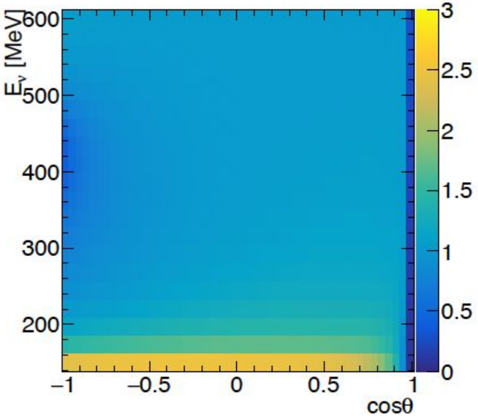
Model development and uncertainties wishlist

- Resonance model development
- Transition region
- Continued work on QE/multinucleon processes
- nue/numu uncertainties - *important for all apperance measurements*



(c) Ratio of $d\sigma_{\nu_e}/d\sigma_{\nu_\mu}$ for CRPA model.



(d) Ratio of $d\sigma_{\bar{\nu}_e}/d\sigma_{\bar{\nu}_\mu}$ for CRPA model.

Uncertainties are from: second class currents, radiative corrections, and collective nuclear effects which lead to differences in electron-muon and neutrino-antineutrino cross section