Panel discussion:
What do we need measured?
How well do we need to measure it?
Tuning vs. precision modelling

Kendall Mahn (MSU)

Thank you for the opportunity to comment and thank you for a lovely workshop!

What follows is my personal view. Let’s keep talking! And I welcome corrections

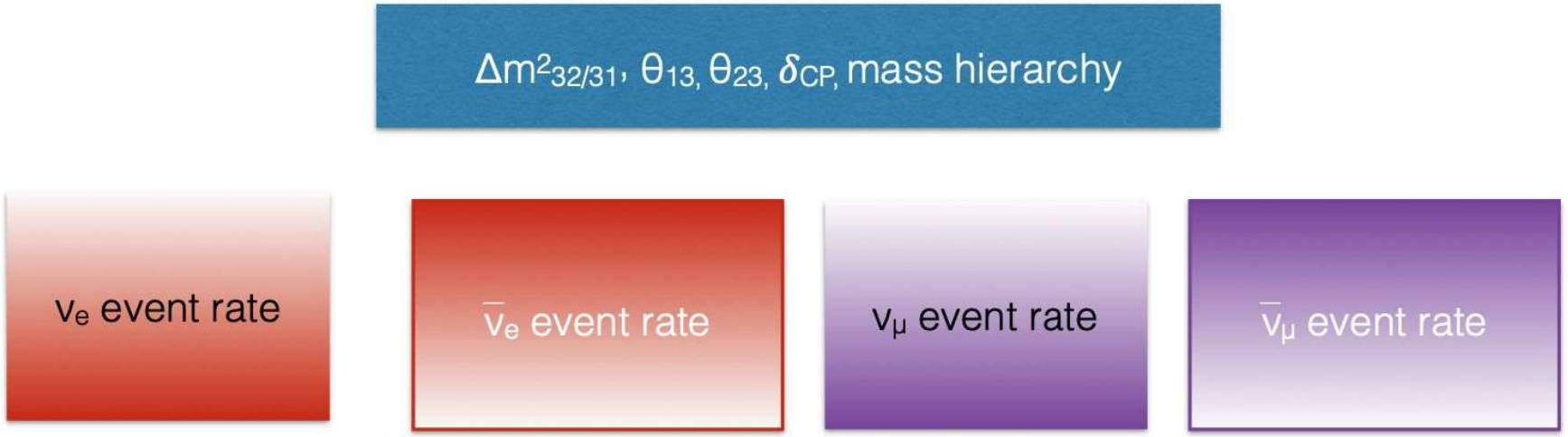
What do we want to measure?

Signal (or background) processes are 0.1-20 GeV charged current (CC) or neutral current (NC) neutrino or antineutrino interactions are used for…

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

Will give examples for accelerator based programs, also applicable to atmospheric neutrino sources

Oscillation measurements depend on event rates



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

- Fit **event rate** to determine oscillation parameters for muon, electron neutrino and antineutrino subsamples

And the event rates depend on the cross section/interaction model

Cross section (true kinematics)

Efficiency (true kinematics)

Relationship between true and reconstructed kinematics)

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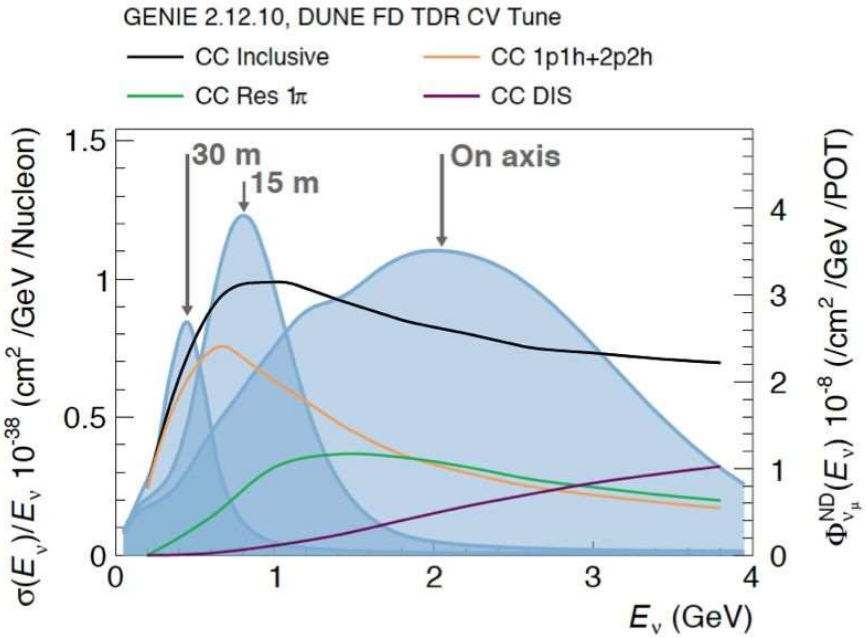
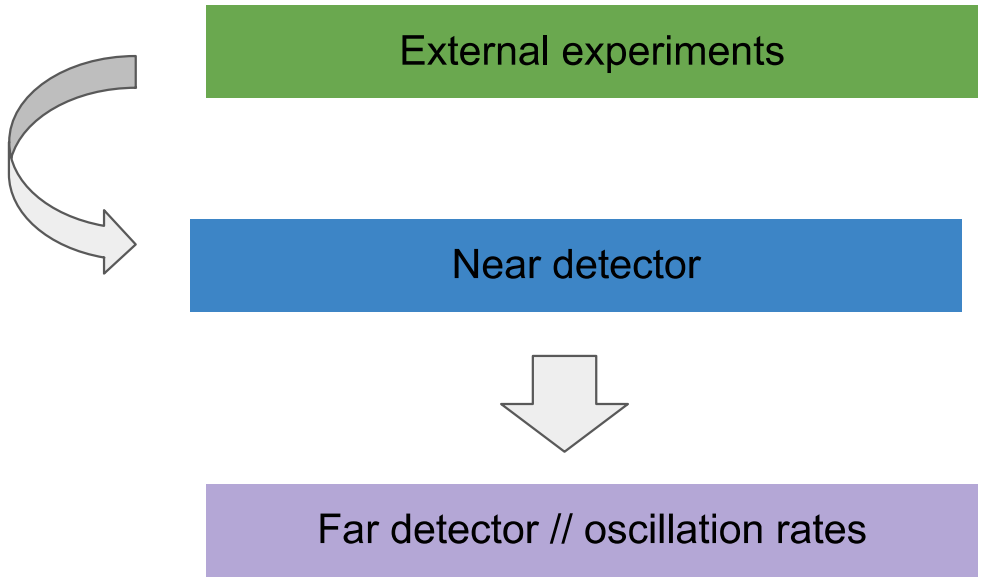
$$N_{ND}^{\alpha} E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\alpha^i(E_{true}) \times \epsilon_\alpha(E_{true}) \times R_i(E_{true}; E_{reco})$$

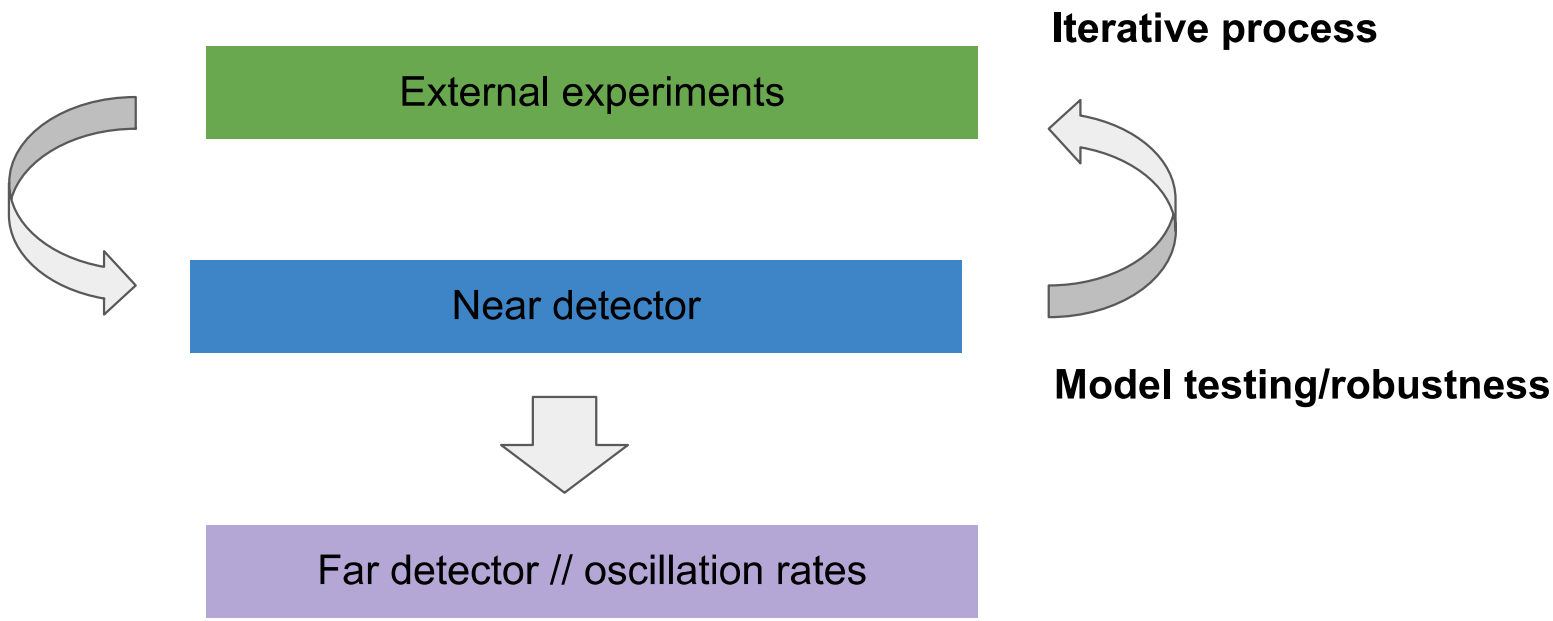
- Near detector information provide stability monitoring, improved event rate prediction and reduces shared systematic uncertainty from flux, interaction model
- Example ND sample: nu-e scattering (low rate, but well known cross section, direct constraint of flux)
- Example: PRISM, ND rates will be sampled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





External experiments are important; determine parameterization, uncertainties

- Electron scattering
- Pion scattering
- Neutrino H/D data
- Neutrino nucleus scattering



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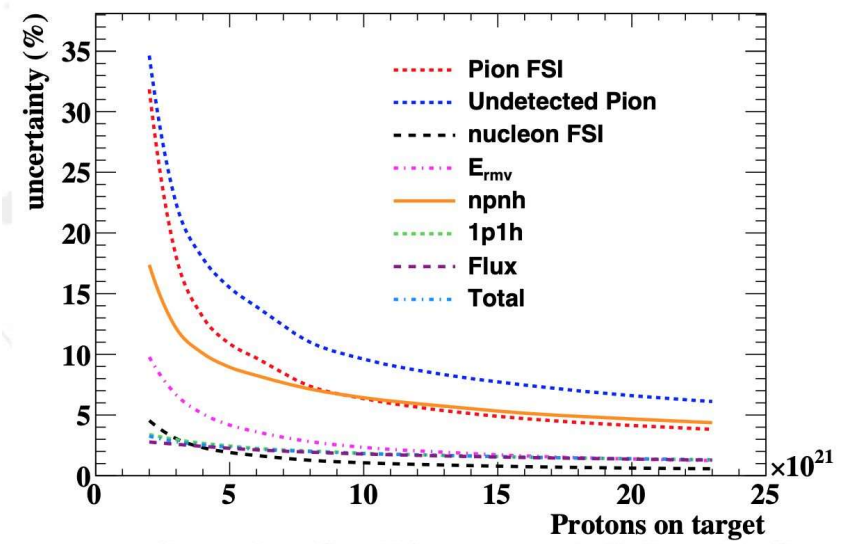
Tuning vs. precision modelling:

Do you care? YES, enormously, that we move toward precision modelling

What we make isn't perfect, it's to parameterize our ignorance, and to be open to, test explicitly any new physics. I would not say the output of the T2K ND fit is a meaningful physics tune (convolved with our flux), however, what matters in the oscillation analysis is the right overall rate prediction

A key and good outcome of this workshop:
Let's work together to define useful general categories of what's important to model

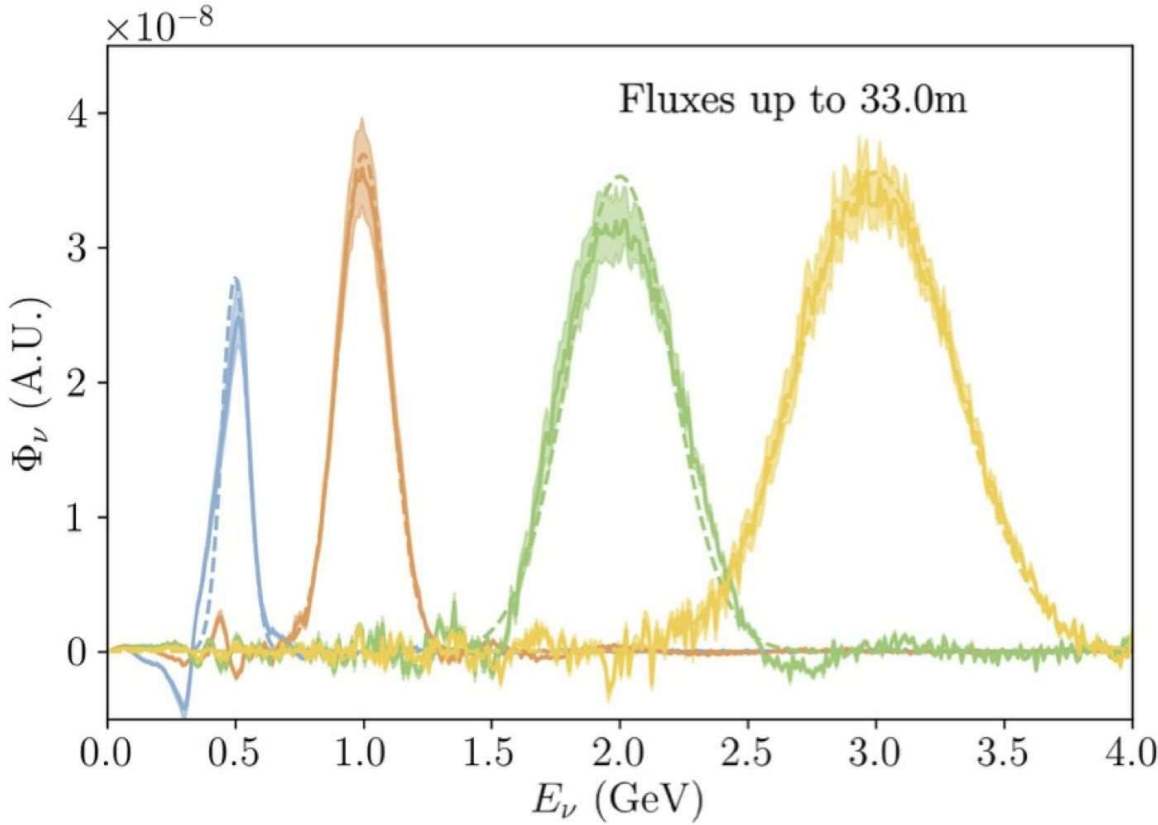
- Example: Phys.Rev.D 105 (2022) 3, 032010
- Can be connected to osc OR comparable sensitivity of ND



Another view of the necessity of precision modelling

From: DUNE ND CDR:

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



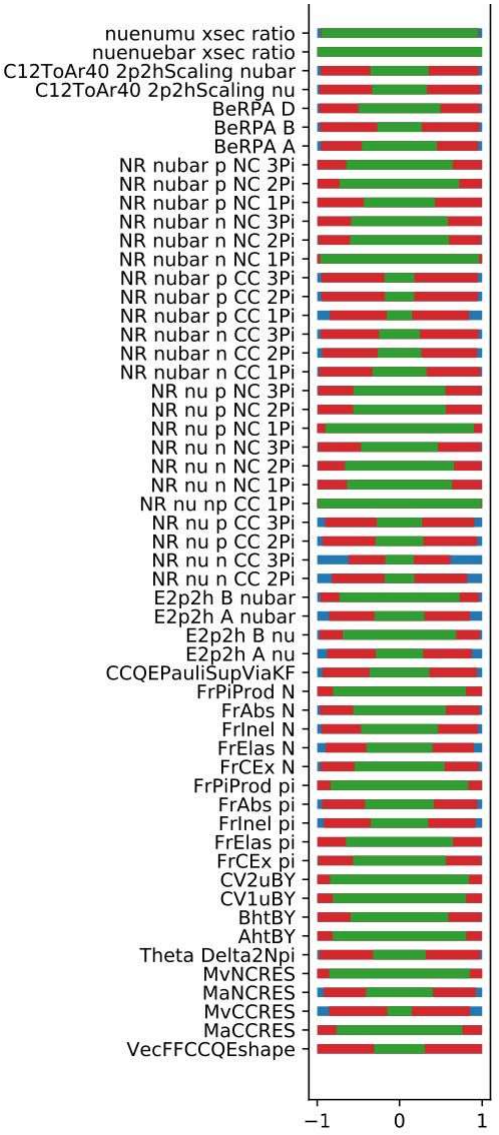
What we learn at the ND: parameter constraints

From: DUNE Physics TDR, Fig 5.34

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

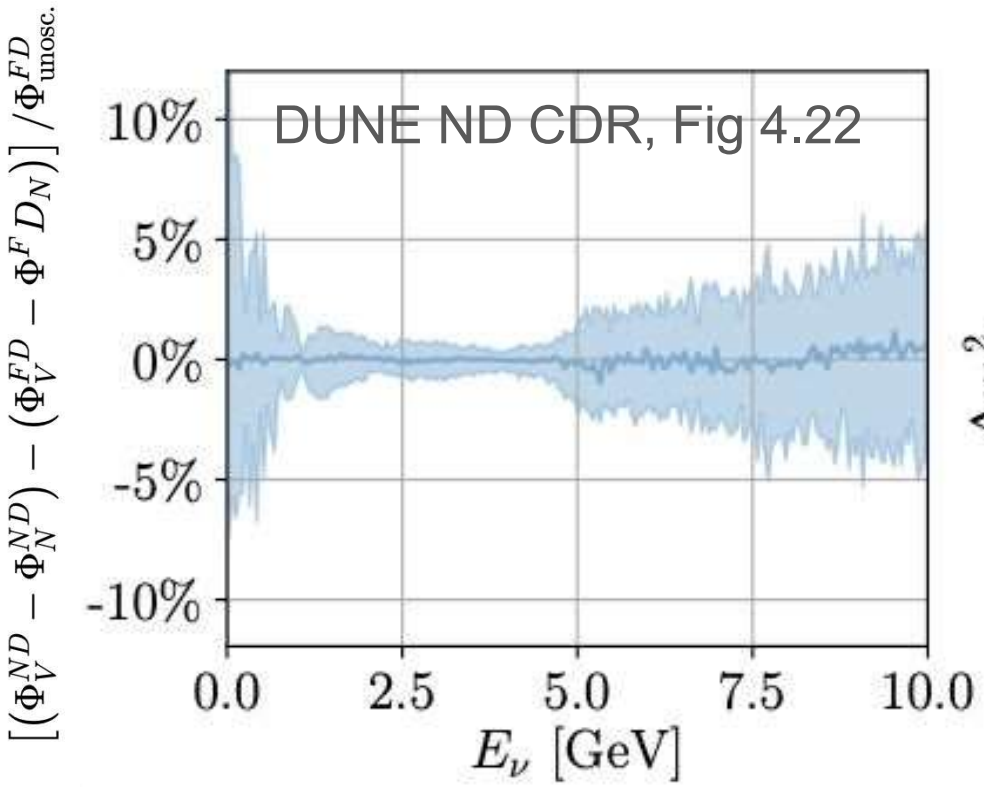
What's not obvious here:

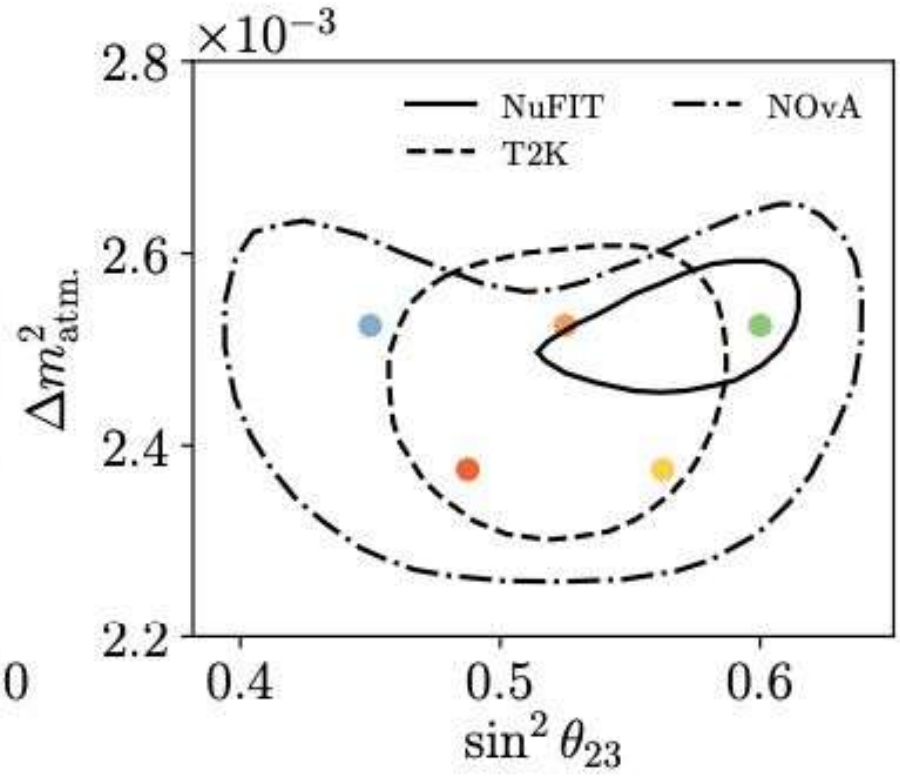
- Important measurements needed by THEORY from electron scattering
- How the model development needs go with time (iterative process takes time, this is at the end)
- What if the model is wrong? (PRISM, electron scattering)



Prior FD-only ND+FD

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

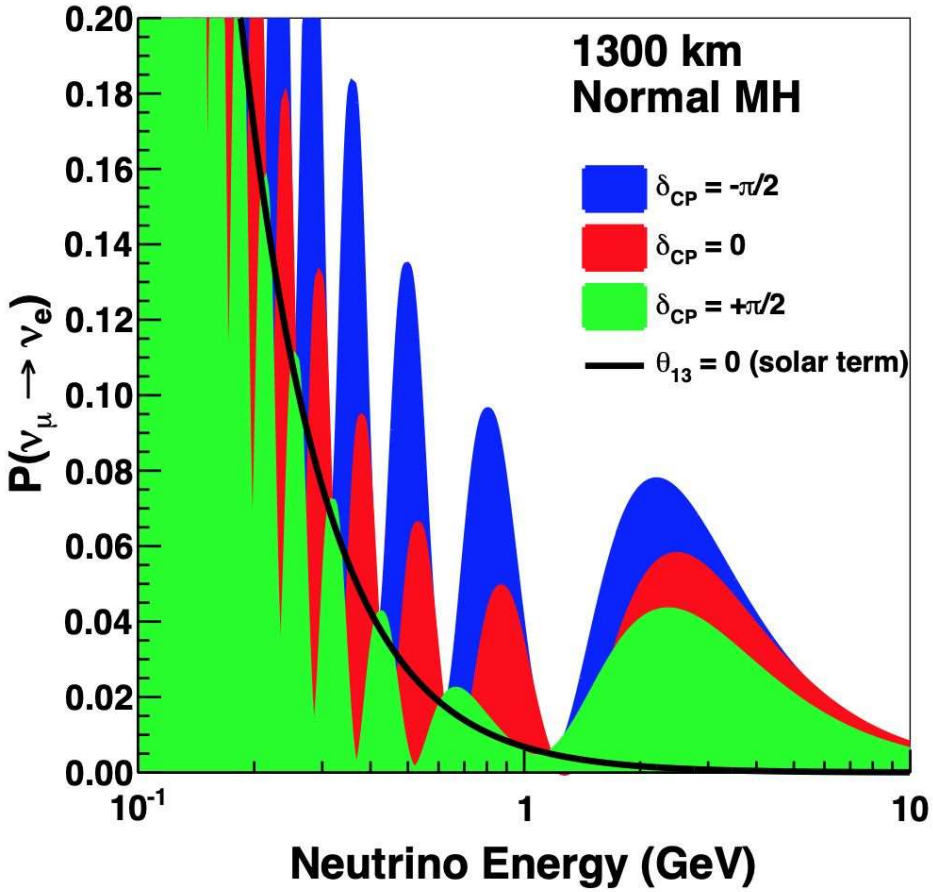




PRISM needs a reasonable initial model with correct parameterization -
electron scattering is very useful to accomplish that goal

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 do I think electron scattering is 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*